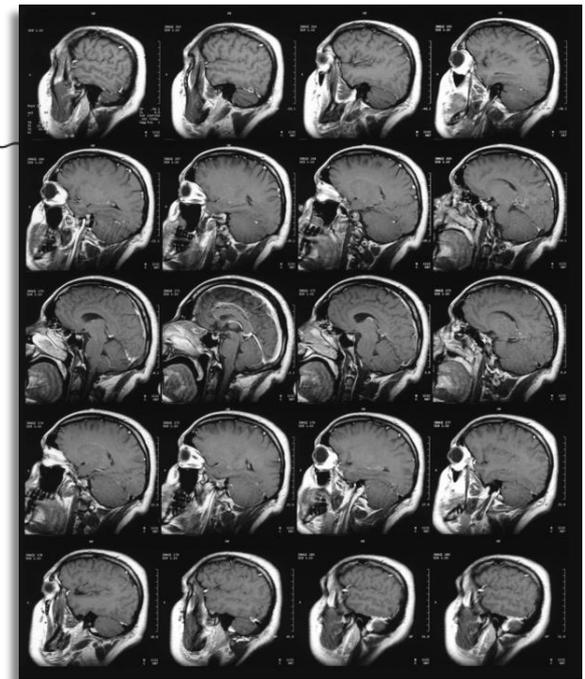
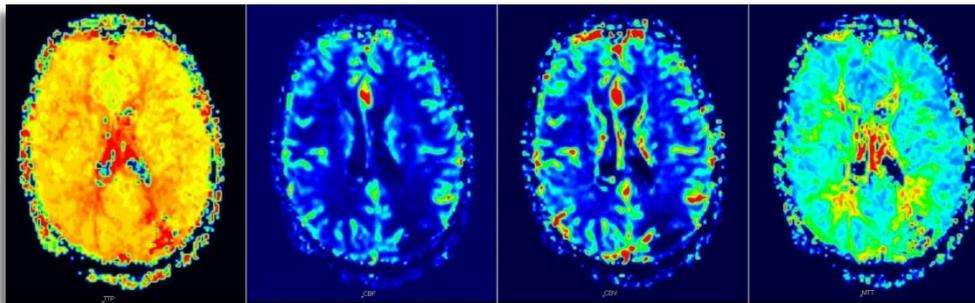
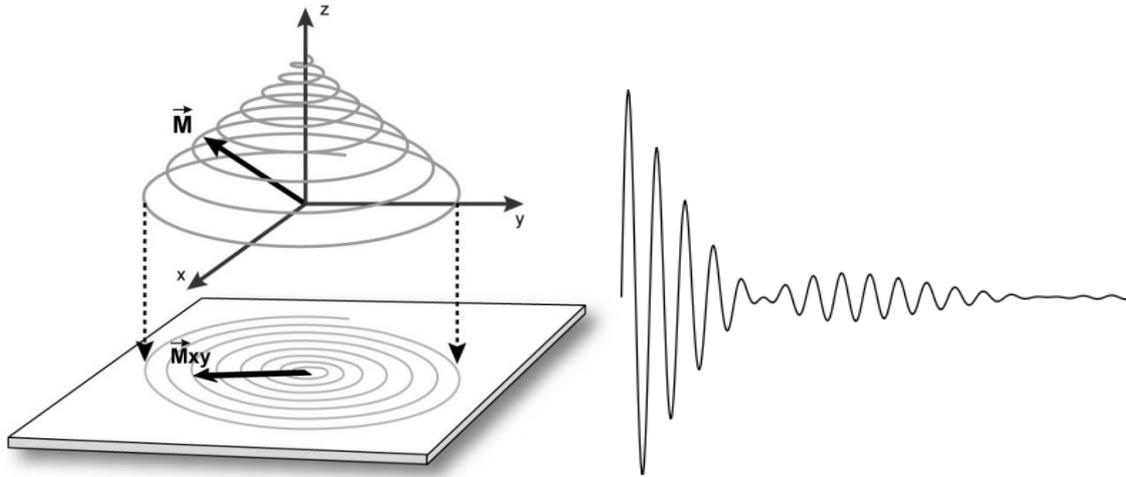


# MAGNETISME & RMN

UE3 – Organisation des Appareils et des Systèmes  
Bases physiques des méthodes d'exploration



# MAGNETISME & RMN

## Plan du cours

### Contexte

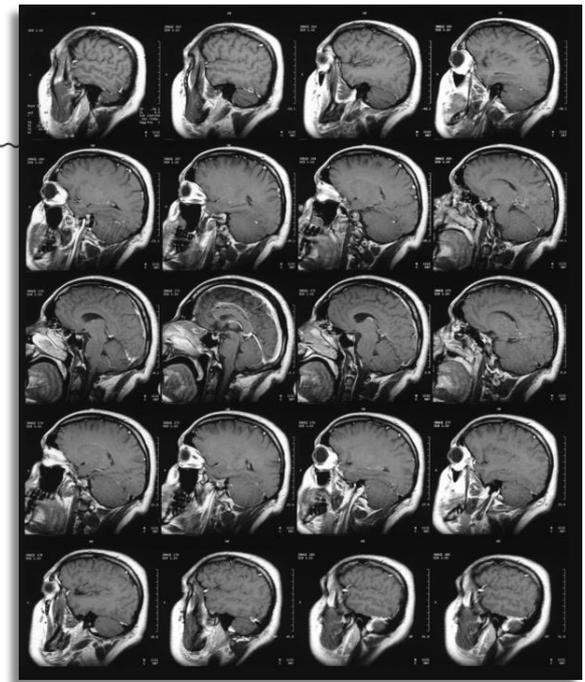
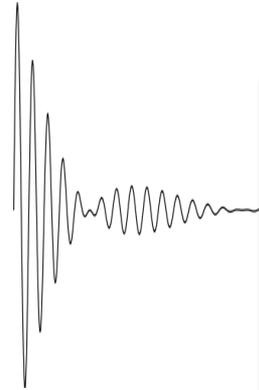
Champ et interaction électrique  
Champ et interaction magnétique

Electron atomique  
Mécanique quantique

Magnétisme dans la matière  
Magnétisme nucléaire

RMN – principe  
RMN – séquence  
RMN – contraste

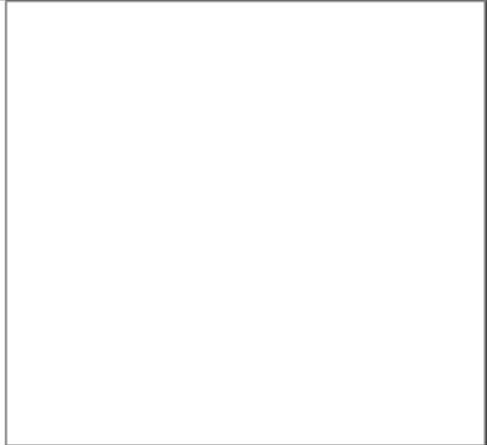
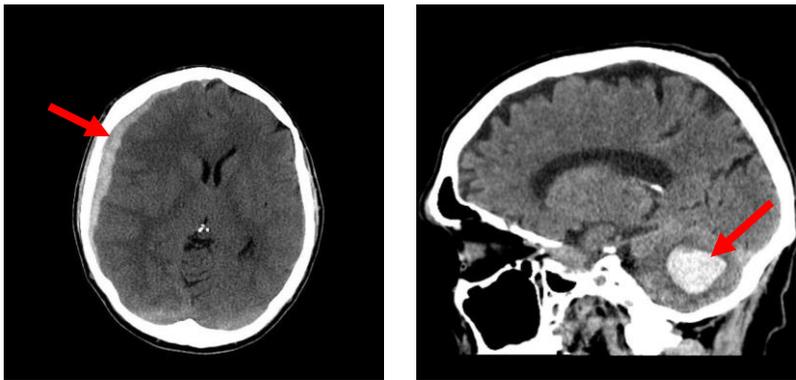
Applications : IRM & SRM  
Illustrations



# Contexte

## Explorations morphologiques en coupe

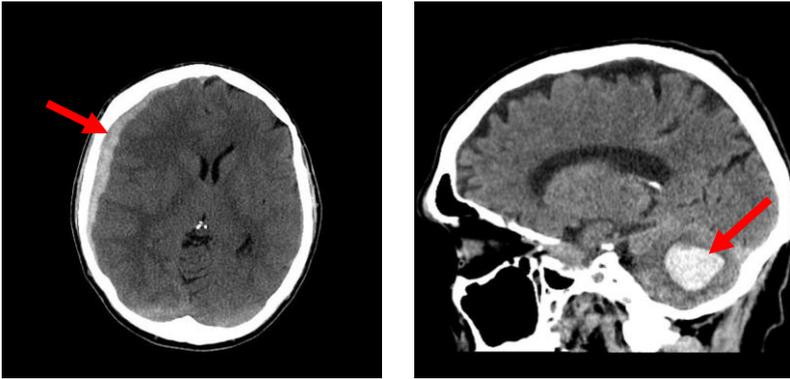
Scanner (TDM, tomodensitométrie)



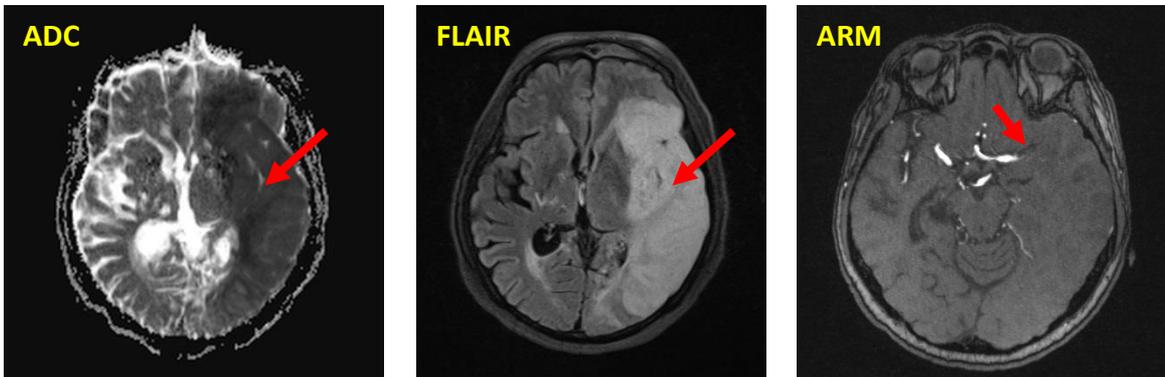
# Contexte

## Explorations morphologiques en coupe

Scanner (TDM, tomodensitométrie)



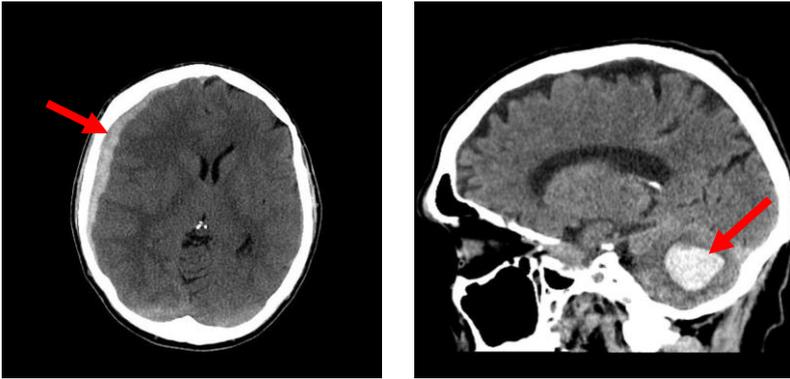
Résonance magnétique (IRM)



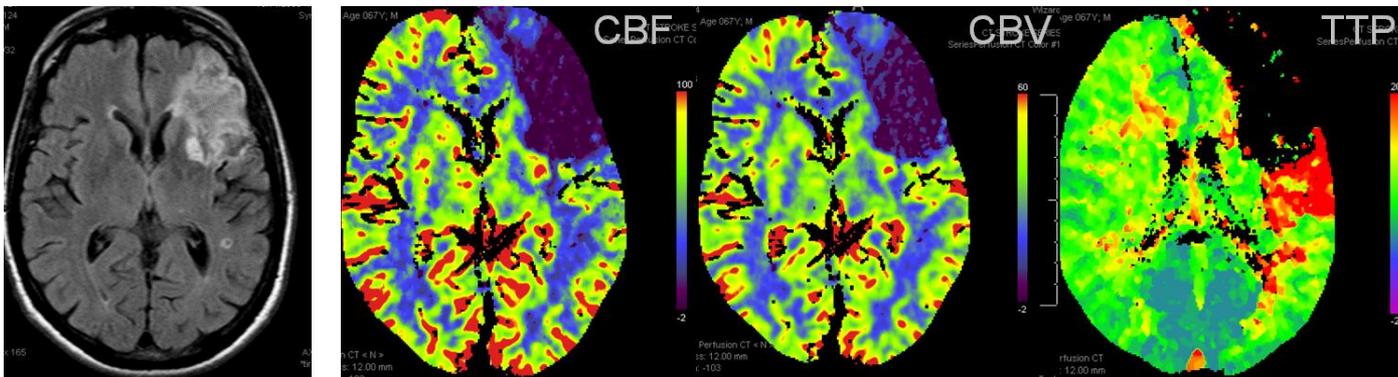
# Contexte

## Explorations morphologiques en coupe

Scanner (TDM, tomodensitométrie)



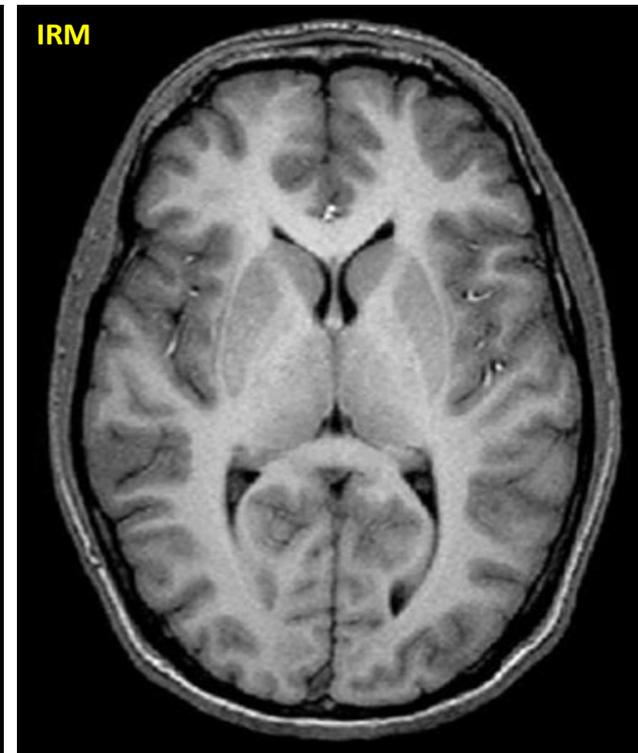
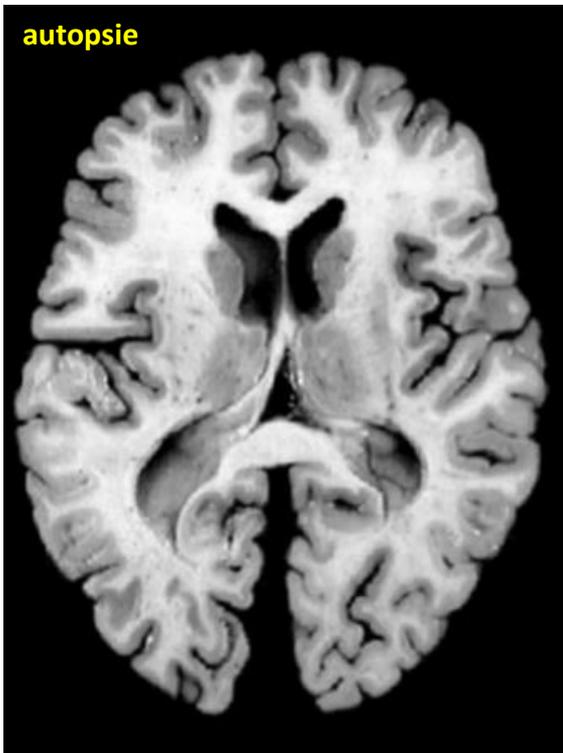
Résonance magnétique (IRM)



# Contexte

## Explorations morphologiques en coupe

IRM : excellent contraste des tissus mous

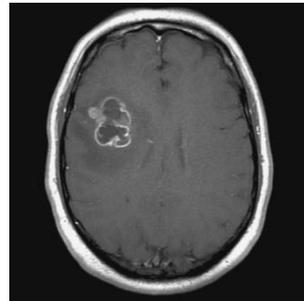


# Contexte

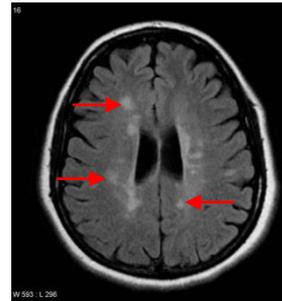
## Explorations morphologiques en coupe

IRM = examen de référence

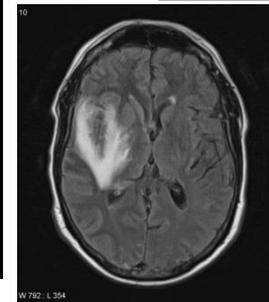
- Neurologie : neuro-vasculaire  
tumeurs  
pathologies SB  
infections  
MAV



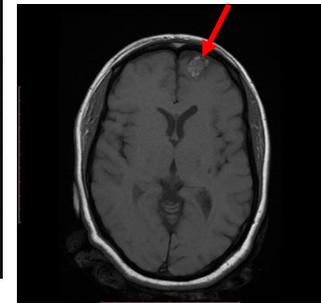
glioblastome



SEP



Encéphalite HSV



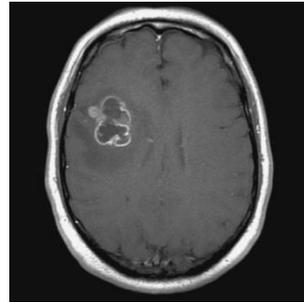
cavernome

# Contexte

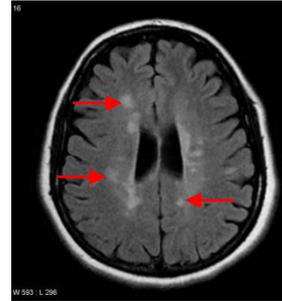
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IRM = examen de référence

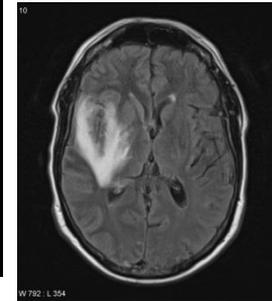
- Neurologie : neuro-vasculaire  
tumeurs  
pathologies SB  
infections  
MAV
- Cardiologie : fonction VG/VD  
cardiopathies...



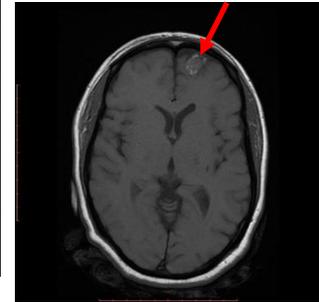
glioblastome



SEP



Encéphalite HSV



cavernome

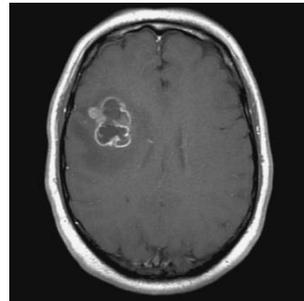


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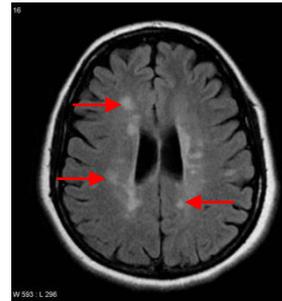
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IRM = examen de référence

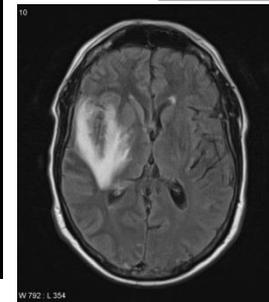
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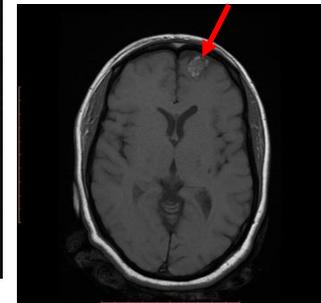
glioblastome



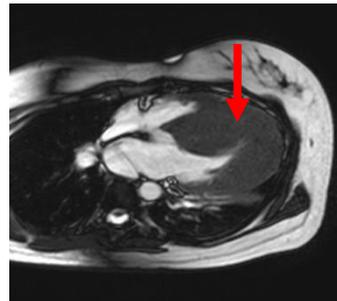
SEP



Encéphalite HSV



cavernome



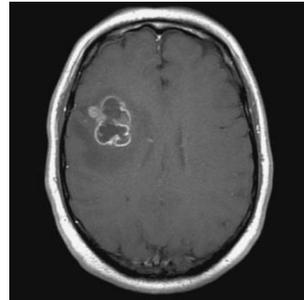
CMH

# Contexte

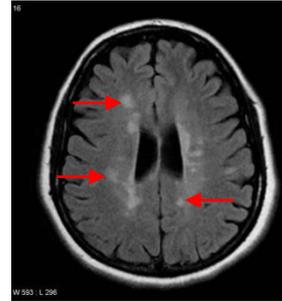
## Explorations morphologiques en coupe

IRM = examen de référence

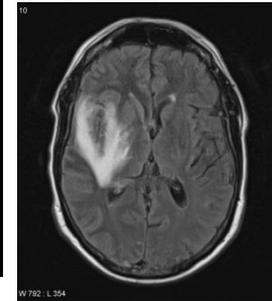
- Neurologie : neuro-vasculaire  
tumeurs  
pathologies SB  
infections  
MAV
- Cardiologie : fonction VG/VD  
cardiopathies...
- Ostéo-articulaire
- Rachis



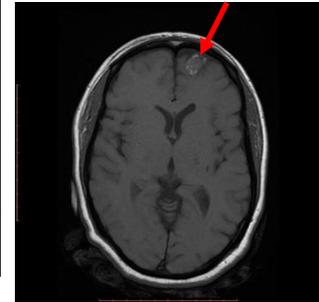
glioblastome



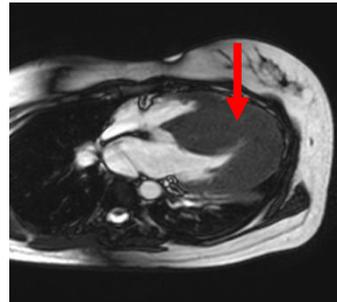
SEP



Encéphalite HSV



cavernome



CMH



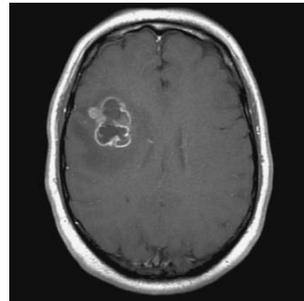
Compression médullaire

# Contexte

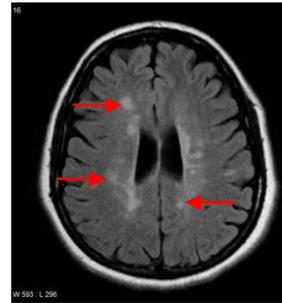
## Explorations morphologiques en coupe

IRM = examen de référence

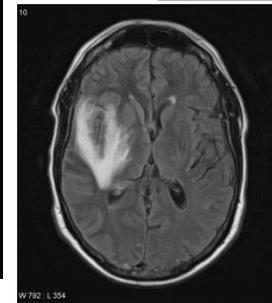
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tumeurs  
pathologies SB  
infections  
MAV
- Cardiologie : fonction VG/VD  
cardiopathies...
- Ostéo-articulaire  
- Rachis
- Abdomen : foie, pancréas
- Pelvis : rectum, prostate



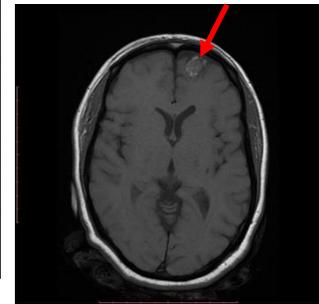
glioblastome



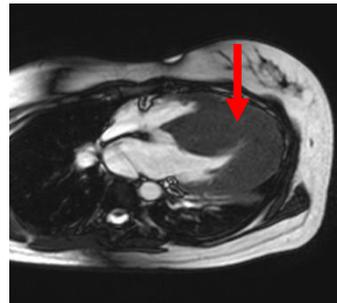
SEP



Encéphalite HSV



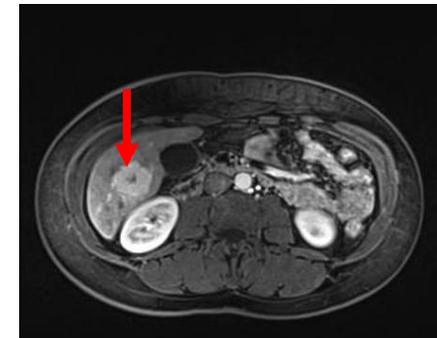
cavernome



CMH



Compression médullaire



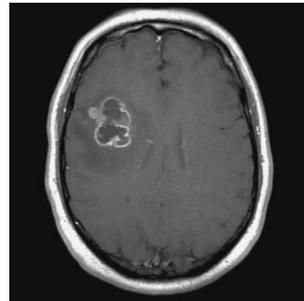
HNF

# Contexte

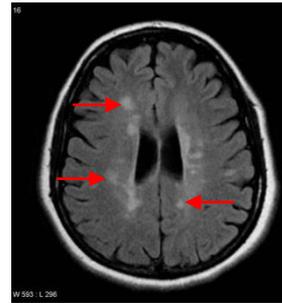
## Explorations morphologiques en coupe

IRM = examen de référence

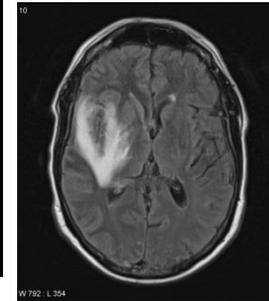
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infections  
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- Cardiologie : fonction VG/VD  
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- Ostéo-articulaire
- Rachis
- Abdomen : foie, pancréas
- Pelvis : rectum, prostate
- Sein



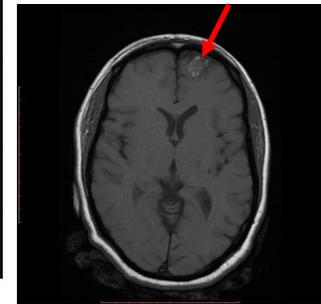
glioblastome



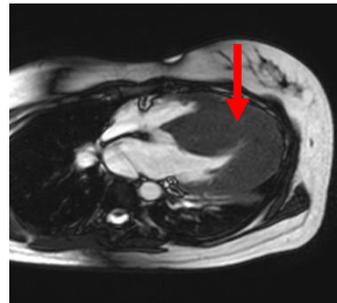
SEP



Encéphalite HSV



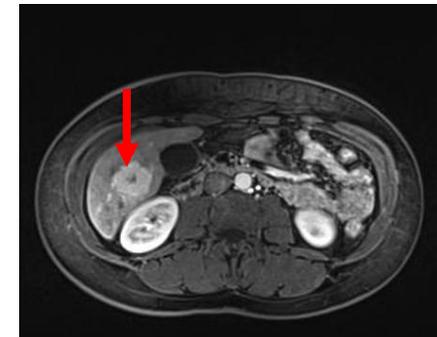
cavernome



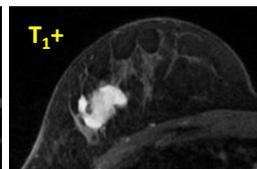
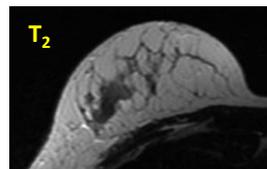
CMH



Compression médullaire



HNF



CLI sein droit



# Objectifs

---

- **Expliciter les propriétés magnétiques de l'électron / du proton : spin, moment magnétique, énergie magnétique.**
- **Décrire le comportement d'un dipôle magnétique dans un champ magnétique externe : précession, fréquence de Larmor, alignement.**
- **Exposer le principe d'une expérience de RMN : préparation (aimantation), perturbation (résonance), recueil du signal.**
- **Détailler les étapes d'une séquence d'acquisition RMN ainsi que les différents paramètres ajustables (temps de répétition, temps d'écho, angle de bascule).**
- **Décrire les bases physiques des phénomènes de relaxation ( $T_1$  et  $T_2$ ).**
- **Analyser la manière dont le choix des paramètres ajustables influe sur le contraste dans l'image IRM.**

# Rappels & conventions

---

Grandeurs scalaires :

$$x, y, z, t$$

$$m, q, e$$

$$V(x, y, z)$$

$$\hbar = h/2\pi$$



# Rappels & conventions

---

**Grandeurs scalaires :**

$$x, y, z, t$$

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$$V(x, y, z)$$

$$\hbar = h/2\pi$$

**Grandeurs vectorielles :**

$$\mathbf{x} = (x, y, z)$$

$$\mathbf{F}, \mathbf{\Gamma}$$

$$\mathbf{B}(\mathbf{x})$$

$$\mathbf{L} = (L_x, L_y, L_z)$$

$$\omega = |\boldsymbol{\omega}|$$

$$\nabla f = \left( \frac{\partial f}{\partial x} ; \frac{\partial f}{\partial y} ; \frac{\partial f}{\partial z} \right)$$



# Rappels & conventions

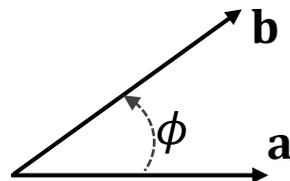
**Grandeurs scalaires :**  $x, y, z, t$   
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$$\nabla f = \left( \frac{\partial f}{\partial x} ; \frac{\partial f}{\partial y} ; \frac{\partial f}{\partial z} \right)$$

**Produit scalaire :**

$$\mathbf{a} \cdot \mathbf{b} = a_x b_x + a_y b_y + a_z b_z$$
$$= a b \cos(\phi)$$



# Rappels & conventions

Grandeurs scalaires :

$$x, y, z, t$$

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$$V(x, y, z)$$

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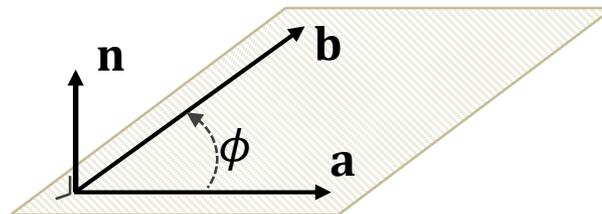
$$\omega = |\boldsymbol{\omega}|$$

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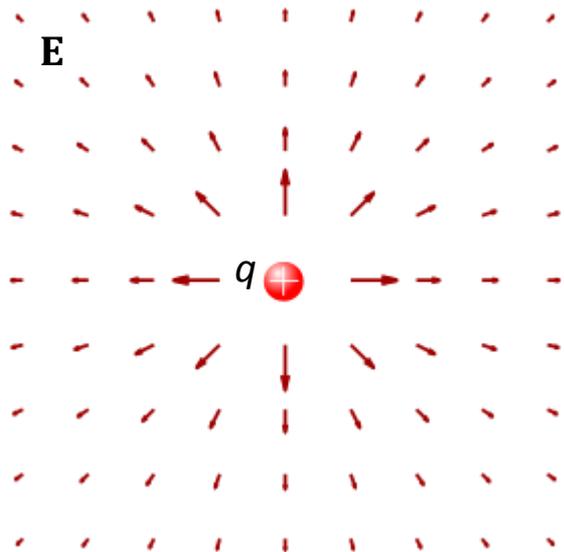
Produit vectoriel :

$$\mathbf{a} \wedge \mathbf{b} = (a_y b_z - a_z b_y, a_z b_x - a_x b_z, a_x b_y - a_y b_x)$$

$$= a b \sin(\phi) \mathbf{n}$$

# Champ & interaction électrique

Source = charge  $q$  (monopôle électrique)

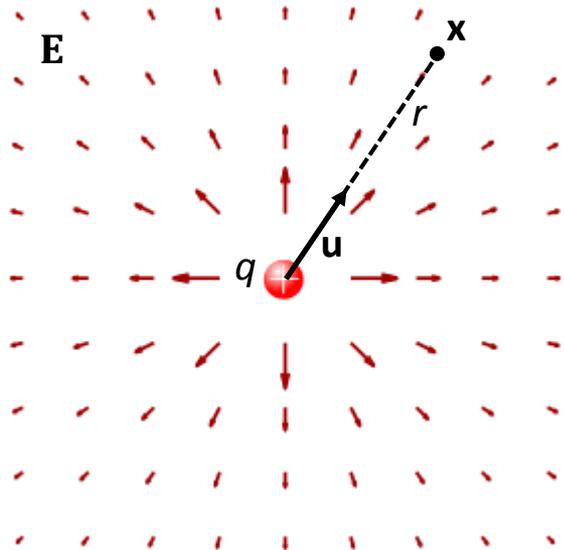


# Champ & interaction électrique

Source = charge  $q$  (monopôle électrique)

Champ : 
$$\mathbf{E}(\mathbf{x}) = \frac{q}{4\pi\epsilon_0 r^2} \mathbf{u} \quad [\text{Vm}^{-1}]$$

$\epsilon_0$  = permittivité diélectrique du vide

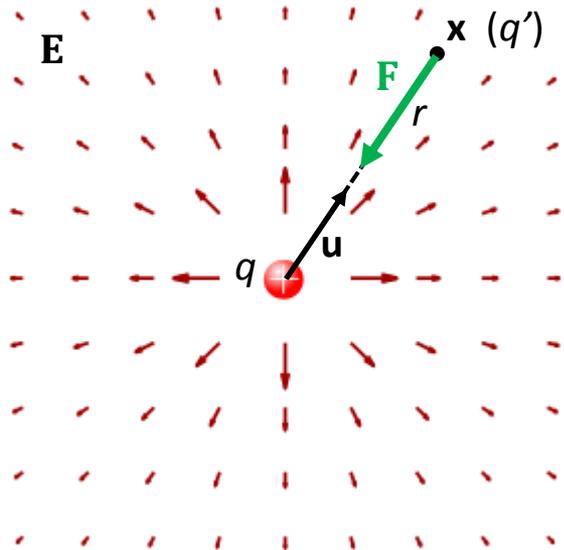


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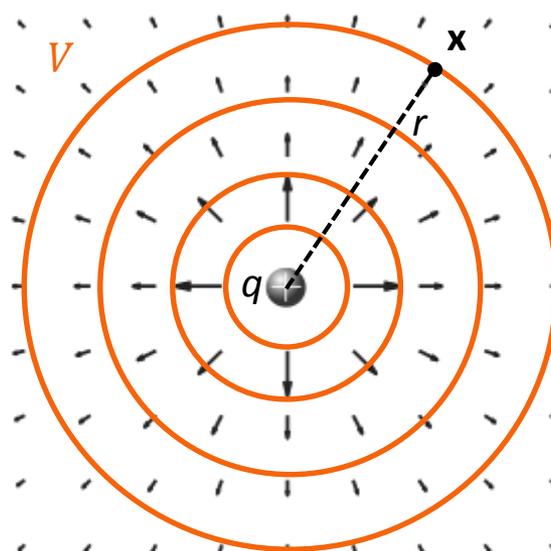
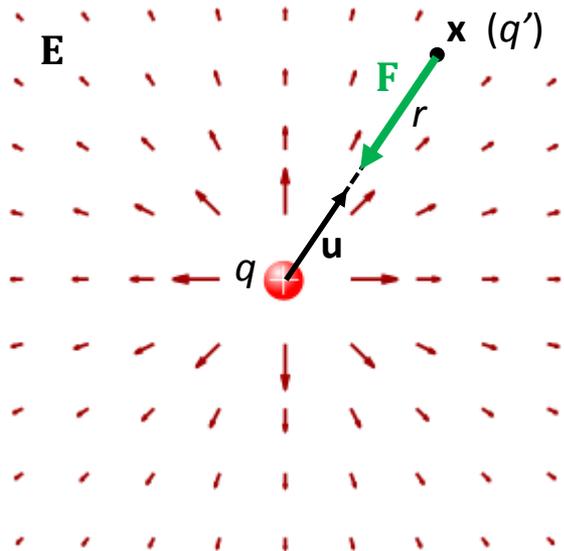


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Potentiel :  $V(\mathbf{x}) = \frac{q}{4\pi\epsilon_0 r}$  [V]     $\mathbf{E} = -\nabla V$

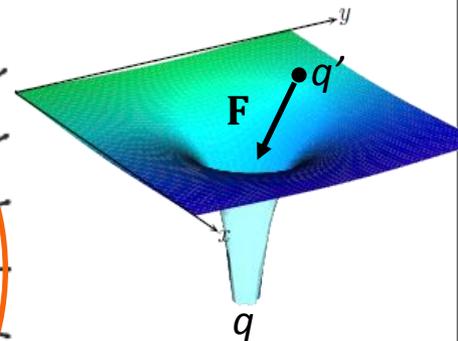
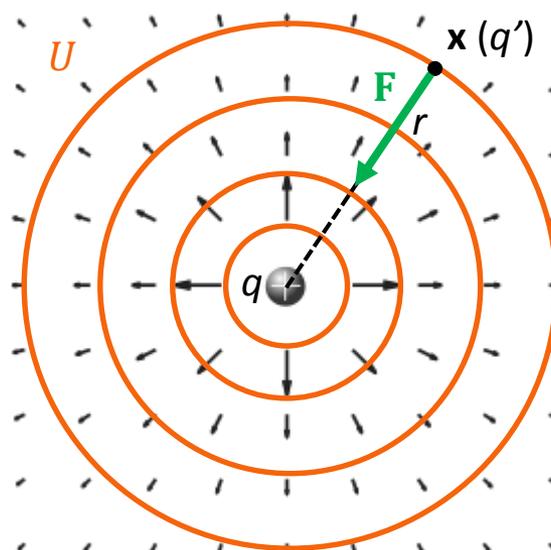
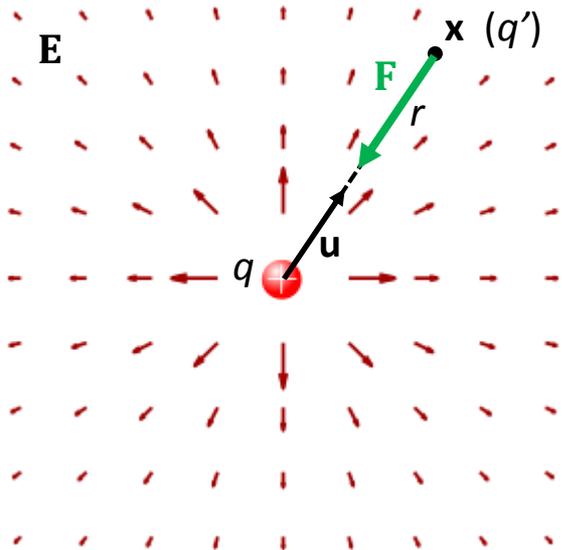


# Champ & interaction électrique

Source = charge  $q$  (monopôle électrique)

Champ :  $\mathbf{E}(\mathbf{x}) = \frac{q}{4\pi\epsilon_0 r^2} \mathbf{u}$  [Vm<sup>-1</sup>]      Force :  $\mathbf{F}(\mathbf{x}) = q'\mathbf{E}(\mathbf{x}) = \frac{q q'}{4\pi\epsilon_0 r^2} \mathbf{u}$  [N]

Potentiel :  $V(\mathbf{x}) = \frac{q}{4\pi\epsilon_0 r}$  [V]      Energie :  $U(\mathbf{x}) = q'V(\mathbf{x}) = \frac{q q'}{4\pi\epsilon_0 r}$  [J]

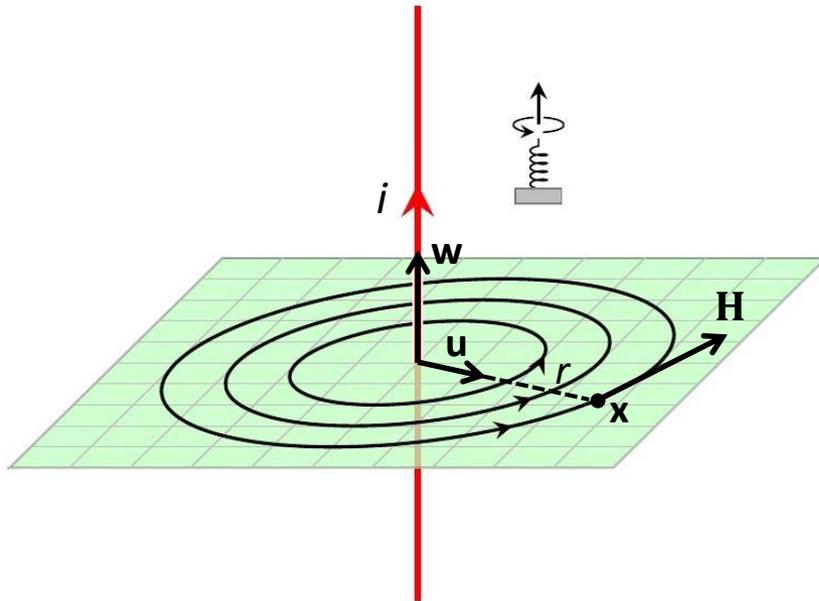


$$\mathbf{F} = -\nabla U$$

# Champ & interaction magnétique

Source = courant  $i = dq/dt$

Champ : 
$$\mathbf{H}(\mathbf{x}) = \frac{i}{4\pi r^2} \mathbf{w} \wedge \mathbf{u} \quad [\text{Am}^{-1}]$$

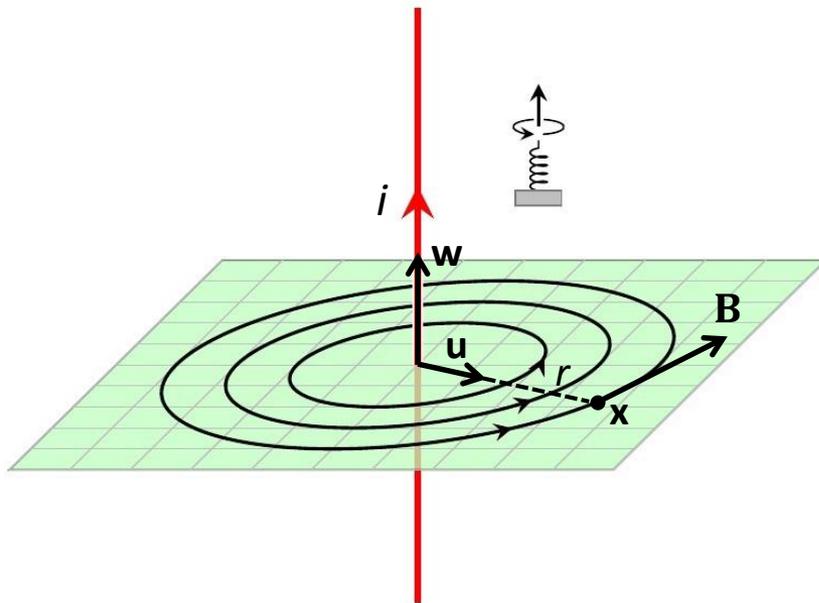


# Champ & interaction magnétique

Source = courant  $i = dq/dt$

Champ :  $\mathbf{H}(\mathbf{x}) = \frac{i}{4\pi r^2} \mathbf{w} \wedge \mathbf{u}$  [ $\text{Am}^{-1}$ ]

Champ (d'induction) :  $\mathbf{B}(\mathbf{x}) = \mu \mathbf{H}(\mathbf{x}) = \frac{\mu i}{4\pi r^2} \mathbf{w} \wedge \mathbf{u}$  [T Tesla]



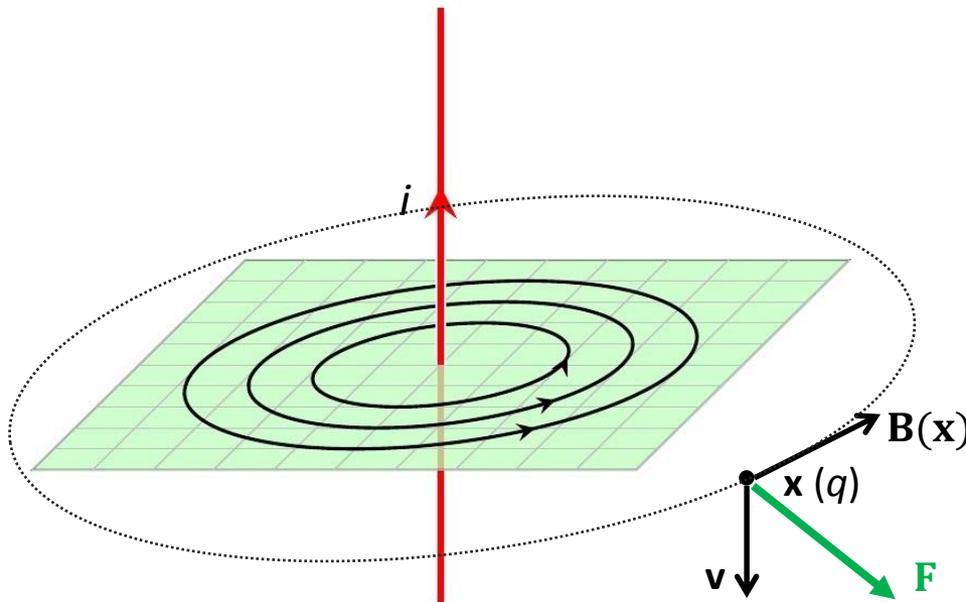
$\mu$  = perméabilité magnétique  
Dans l'air :  $\mu = \mu_0$

# Champ & interaction magnétique

Source = courant  $i = dq/dt$

Champ :  $\mathbf{H}(\mathbf{x}) = \frac{i}{4\pi r^2} \mathbf{w} \wedge \mathbf{u} \quad [\text{Am}^{-1}]$

Champ (d'induction) :  $\mathbf{B}(\mathbf{x}) = \mu \mathbf{H}(\mathbf{x}) = \frac{\mu i}{4\pi r^2} \mathbf{w} \wedge \mathbf{u} \quad [\text{T Tesla}]$



$\mu$  = perméabilité magnétique  
Dans l'air :  $\mu = \mu_0$

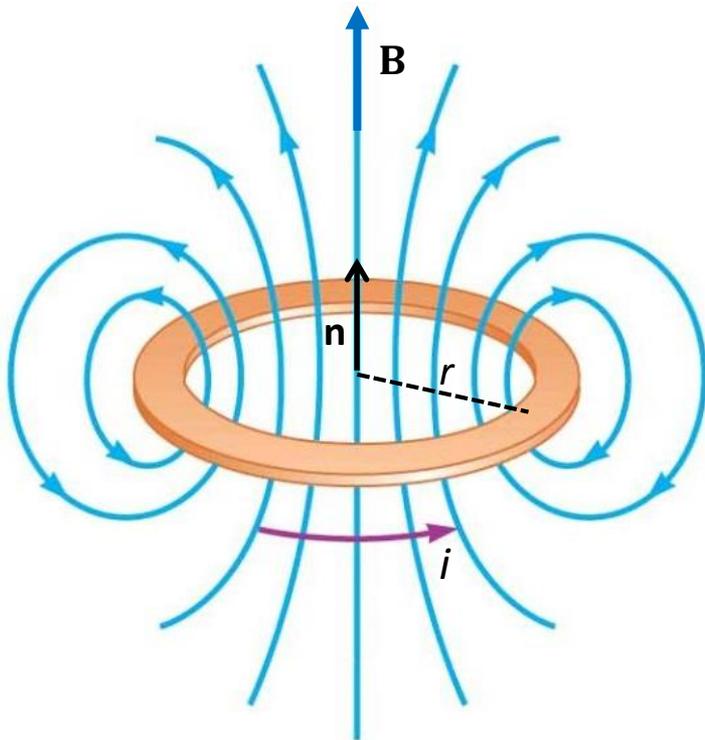
Force (Lorentz) :

$$\mathbf{F}(\mathbf{x}) = q \mathbf{v} \wedge \mathbf{B}(\mathbf{x}) \quad [\text{N}]$$

# Champ & interaction magnétique

Source = boucle de courant  $i$  = dipôle magnétique

Champ : 
$$\mathbf{B} = \frac{\mu i}{2r} \mathbf{n}$$



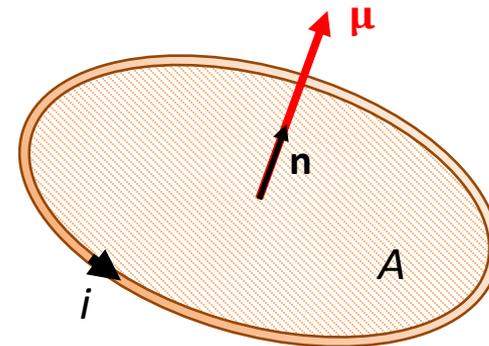
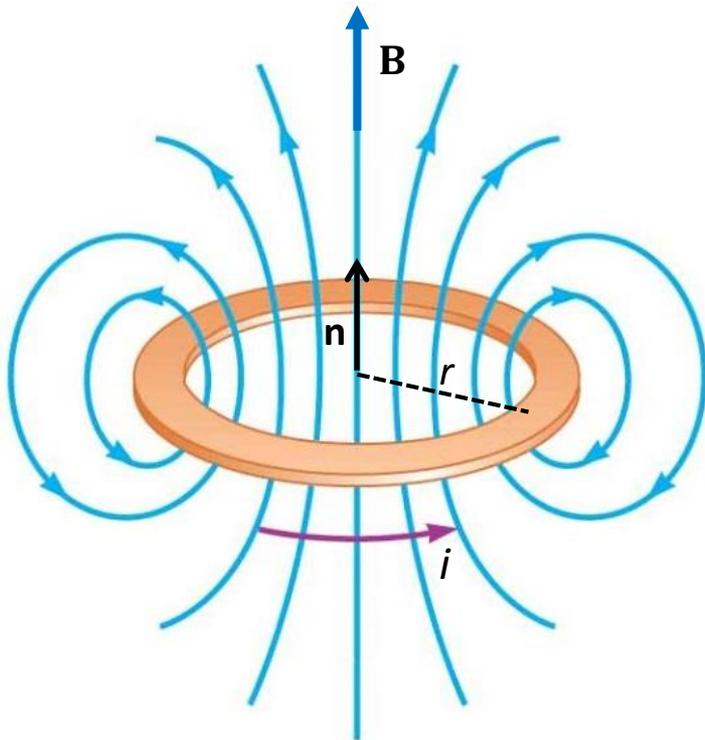
# Champ & interaction magnétique

Source = boucle de courant  $i$  = dipôle magnétique

Champ : 
$$\mathbf{B} = \frac{\mu i}{2r} \mathbf{n}$$

Cible = dipôle magnétique

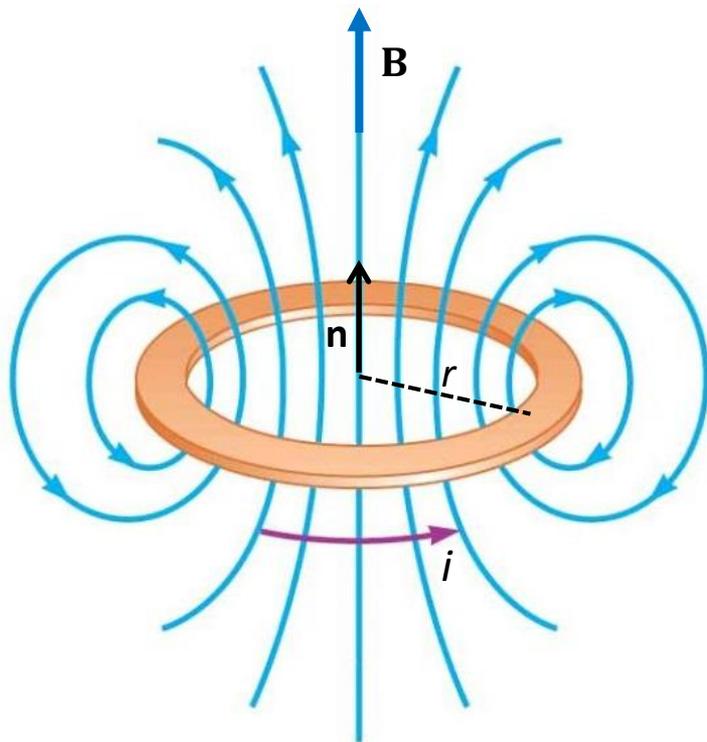
Moment magnétique : 
$$\boldsymbol{\mu} = A i \mathbf{n} \quad [\text{Am}^2]$$



# Champ & interaction magnétique

Source = boucle de courant  $i$  = dipôle magnétique

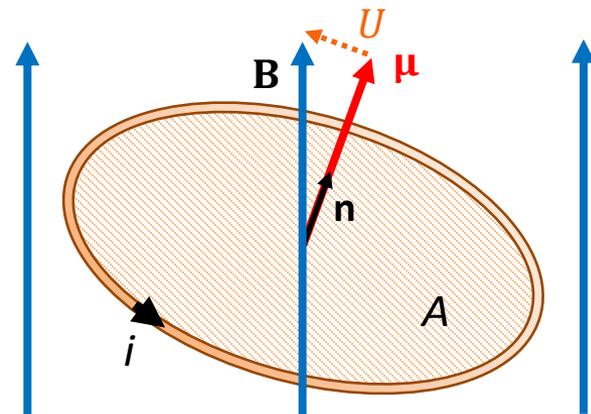
Champ :  $\mathbf{B} = \frac{\mu i}{2r} \mathbf{n}$



Cible = dipôle magnétique

Moment magnétique :  $\boldsymbol{\mu} = A i \mathbf{n}$  [ $\text{Am}^2$ ]

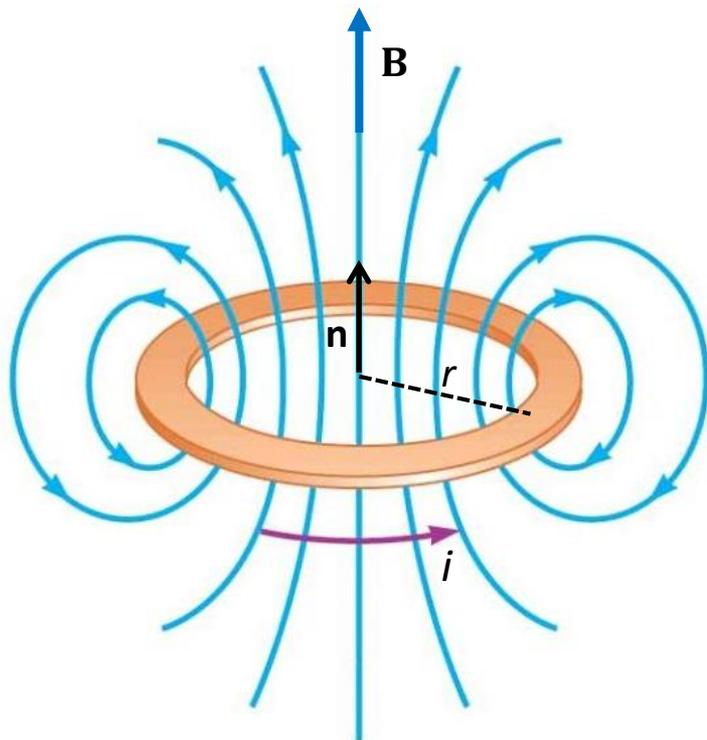
Energie :  $U = -\boldsymbol{\mu} \cdot \mathbf{B}$  [J]



# Champ & interaction magnétique

Source = boucle de courant  $i$  = dipôle magnétique

Champ :  $\mathbf{B} = \frac{\mu i}{2r} \mathbf{n}$

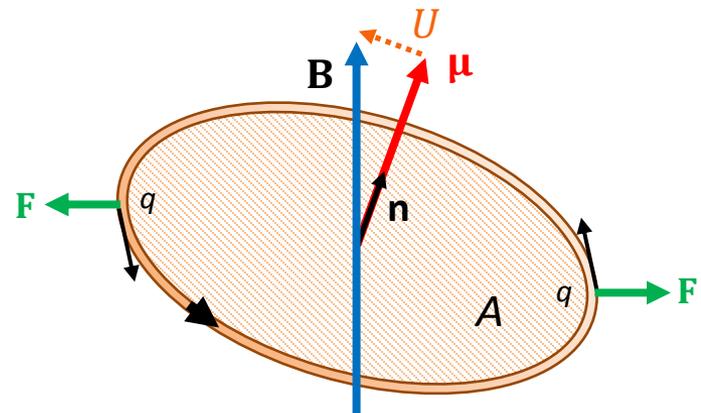


Cible = dipôle magnétique

Moment magnétique :  $\boldsymbol{\mu} = A i \mathbf{n}$  [ $\text{Am}^2$ ]

Energie :  $U = -\boldsymbol{\mu} \cdot \mathbf{B}$  [J]

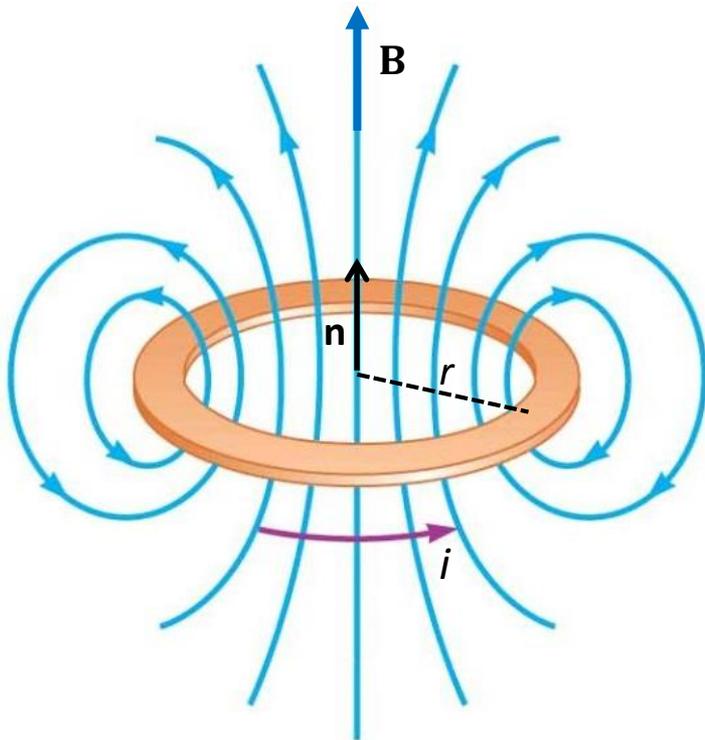
Forces de Lorentz



# Champ & interaction magnétique

Source = boucle de courant  $i$  = dipôle magnétique

Champ :  $\mathbf{B} = \frac{\mu i}{2r} \mathbf{n}$

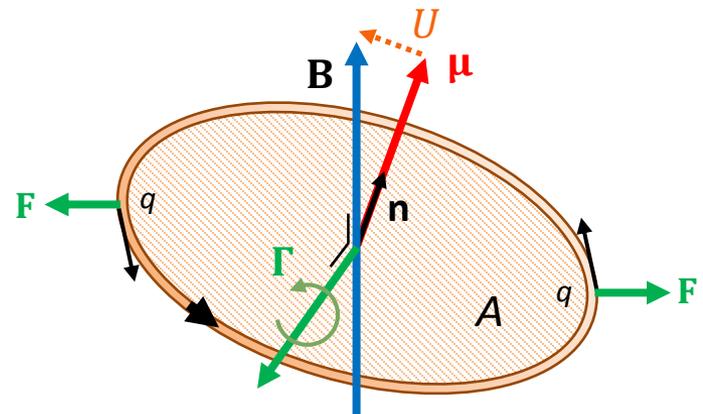


Cible = dipôle magnétique

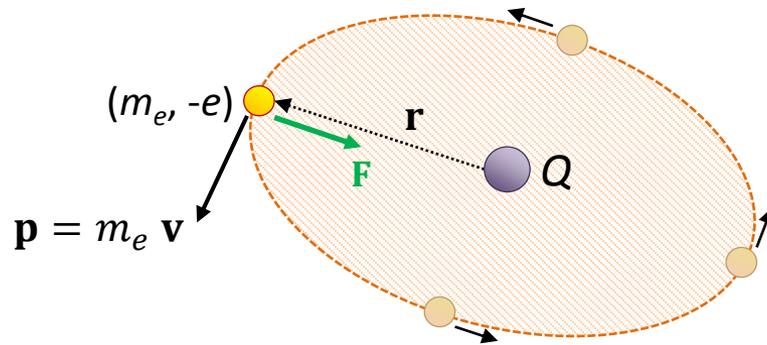
Moment magnétique :  $\boldsymbol{\mu} = A i \mathbf{n}$  [ $\text{Am}^2$ ]

Energie :  $U = -\boldsymbol{\mu} \cdot \mathbf{B}$  [J]

Couple :  $\boldsymbol{\Gamma} = \boldsymbol{\mu} \wedge \mathbf{B}$  [Nm]



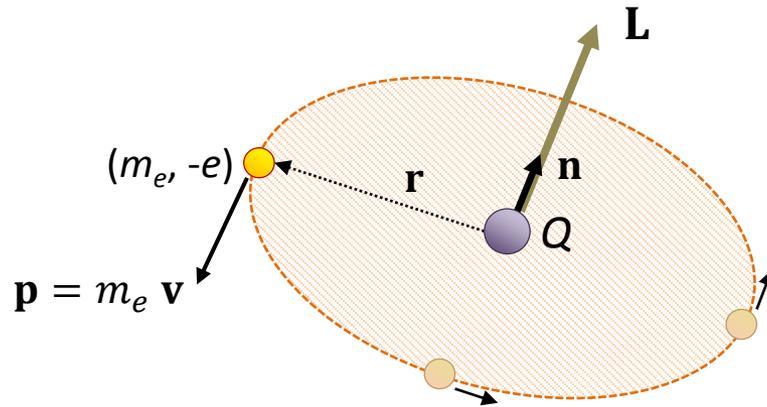
# Cas de l'électron atomique



$$\frac{d\mathbf{p}}{dt} = \mathbf{F} \Rightarrow \text{mouvement circulaire uniforme}$$

$$i = \frac{dq}{dt} = \frac{-e}{T} = \frac{-e}{2\pi r/v} = \frac{-e v}{2\pi r}$$

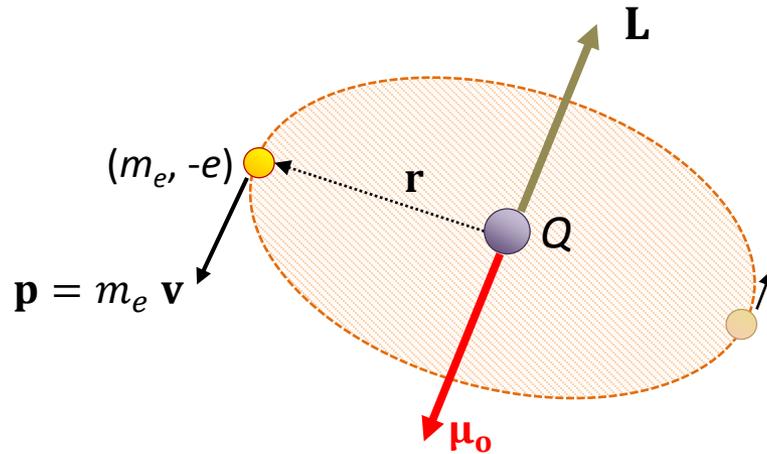
# Cas de l'électron atomique



$$i = \frac{dq}{dt} = \frac{-e}{T} = \frac{-e}{2\pi r/v} = \frac{-e v}{2\pi r}$$

**Moment cinétique :**  $\mathbf{L} = \mathbf{r} \wedge \mathbf{p} = r m_e v \mathbf{n}$

# Cas de l'électron atomique

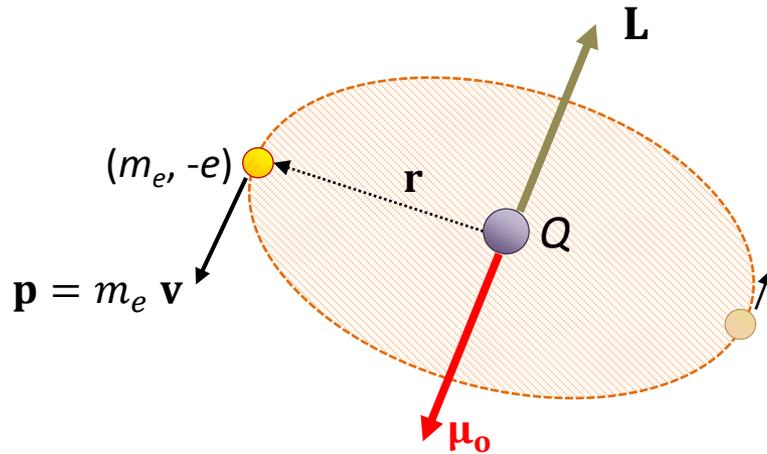


$$i = \frac{dq}{dt} = \frac{-e}{T} = \frac{-e}{2\pi r/v} = \frac{-e v}{2\pi r}$$

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**Moment magnétique :**  $\boldsymbol{\mu}_o = A i \mathbf{n} = -\pi r^2 \frac{e v}{2\pi r} \mathbf{n} = -\frac{r e v}{2} \mathbf{n}$

# Cas de l'électron atomique



$$i = \frac{dq}{dt} = \frac{-e}{T} = \frac{-e}{2\pi r/v} = \frac{-e v}{2\pi r}$$

**Moment cinétique :**  $\mathbf{L} = \mathbf{r} \wedge \mathbf{p} = r m_e v \mathbf{n}$

**Moment magnétique :**  $\boldsymbol{\mu}_0 = A i \mathbf{n} = -\pi r^2 \frac{e v}{2\pi r} \mathbf{n} = -\frac{r e v}{2} \mathbf{n}$

$$\boldsymbol{\mu}_0 = -\frac{e}{2 m_e} \mathbf{L} = \gamma_0 \mathbf{L}$$

$$\gamma_0 = -\frac{e}{2 m_e}$$

**Rapport gyromagnétique**

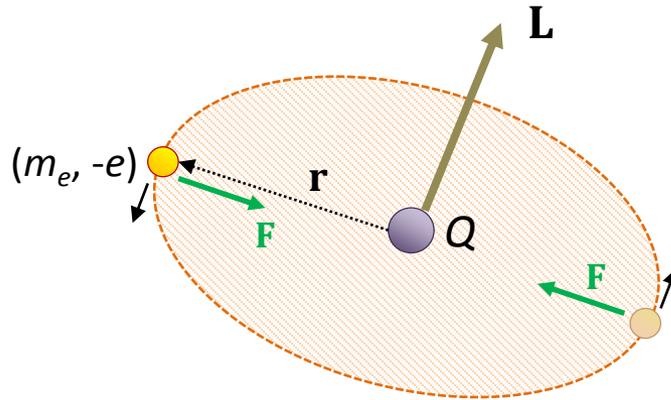
[C Kg<sup>-1</sup>] ou [rad s<sup>-1</sup> T<sup>-1</sup>]

$$\bar{\gamma}_0 \simeq 14 \text{ GHz T}^{-1}$$

$$\bar{\gamma} = \frac{\gamma}{2\pi} [\text{Hz T}^{-1}]$$



# Cas de l'électron atomique



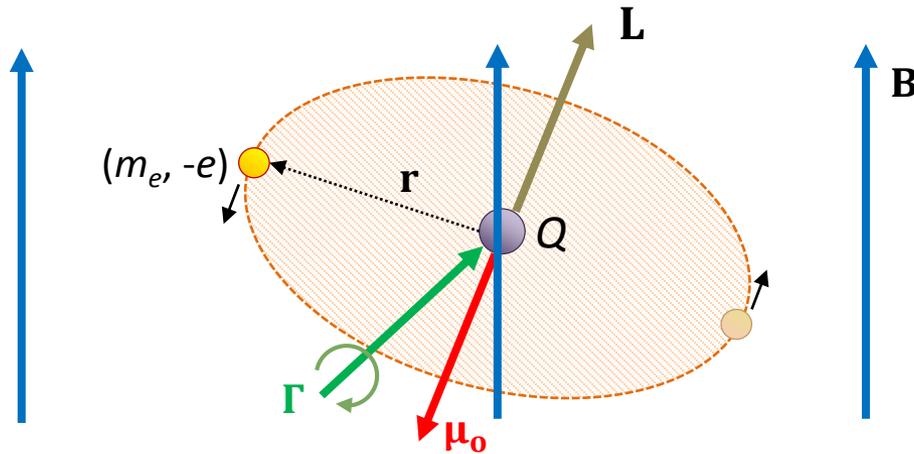
Dans le champ électrostatique du noyau

Energie : 
$$U = \frac{-Q e}{4\pi\epsilon_0 r}$$

Couple : 
$$\Gamma = \mathbf{r} \wedge \mathbf{F} = \mathbf{0} \quad (\text{Force centrale } \mathbf{F})$$

Evolution : 
$$\frac{d\mathbf{L}}{dt} = \Gamma \Rightarrow \mathbf{L} = \text{cste}$$

# Cas de l'électron atomique



Dans le champ électrostatique du noyau + champ magnétique externe

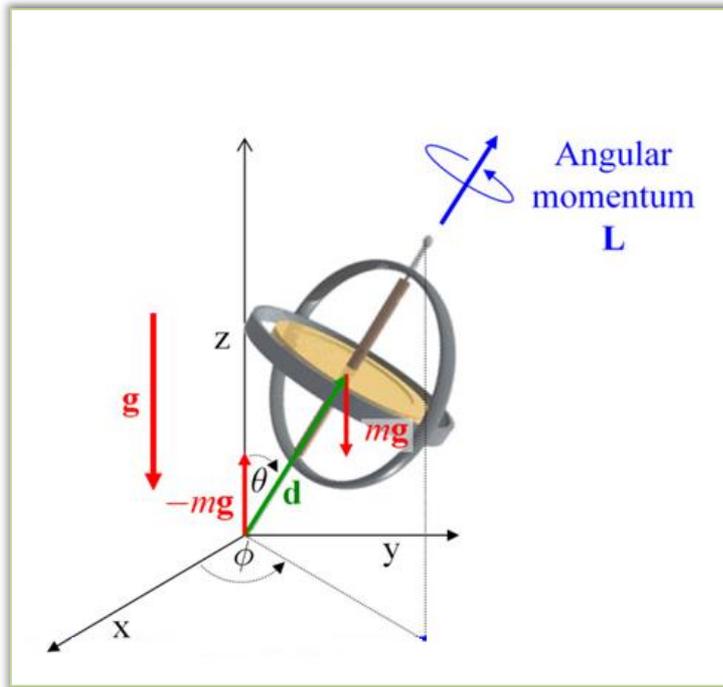
Energie : 
$$U = \frac{-Q e}{4\pi\epsilon_0 r} - \boldsymbol{\mu}_0 \cdot \mathbf{B}$$

Couple : 
$$\boldsymbol{\Gamma} = \boldsymbol{\mu}_0 \wedge \mathbf{B}$$

Evolution : 
$$\frac{d\mathbf{L}}{dt} = \boldsymbol{\Gamma} \Rightarrow \frac{d\mathbf{L}}{dt} = \boldsymbol{\mu}_0 \wedge \mathbf{B}$$

# Cas de l'électron atomique

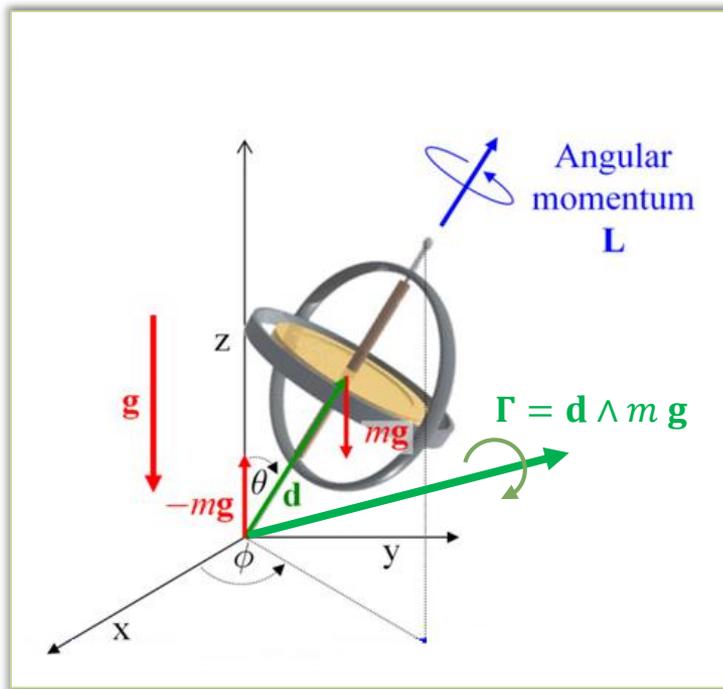
## Analogie de la toupie



Evolution : 
$$\frac{d\mathbf{L}}{dt} = \boldsymbol{\Gamma}$$

# Cas de l'électron atomique

## Analogie de la toupie



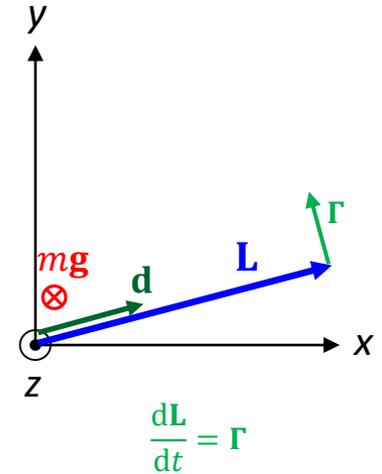
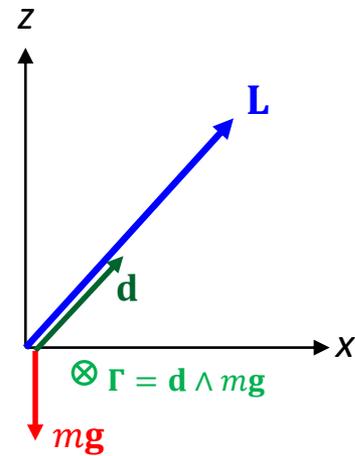
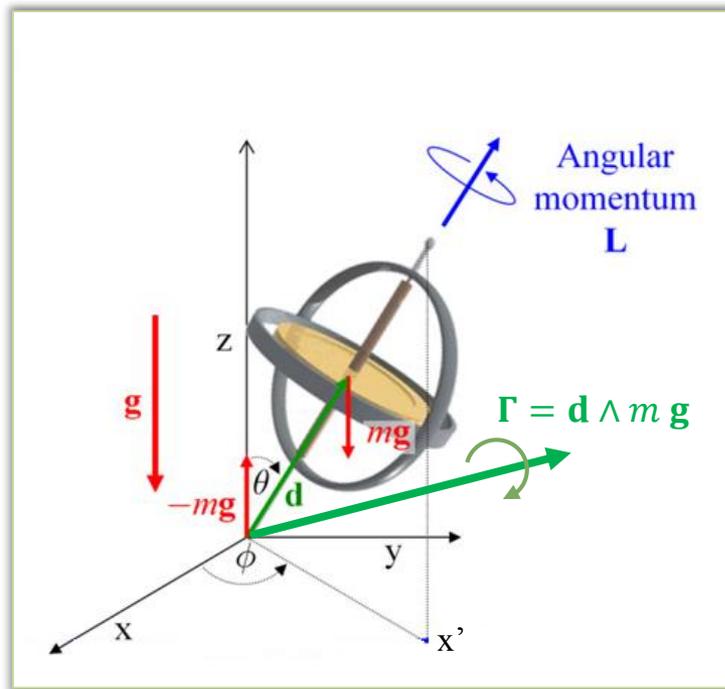
Evolution :

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# Cas de l'électron atomique

## Analogie de la toupie

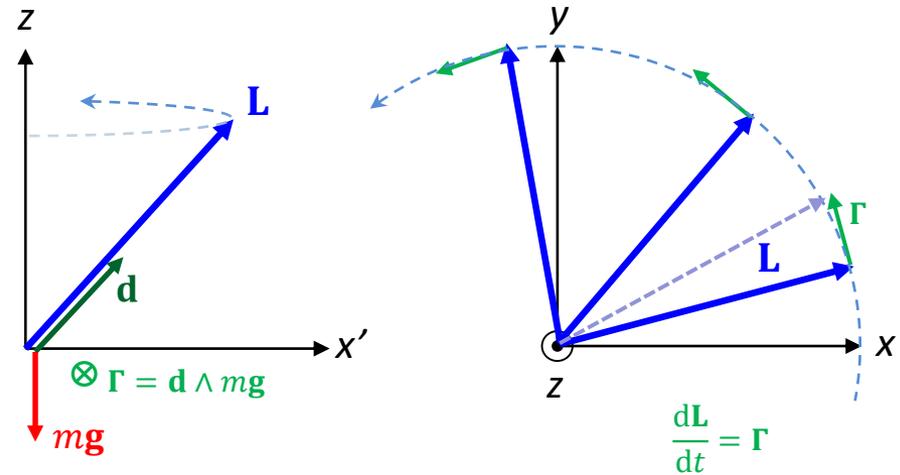
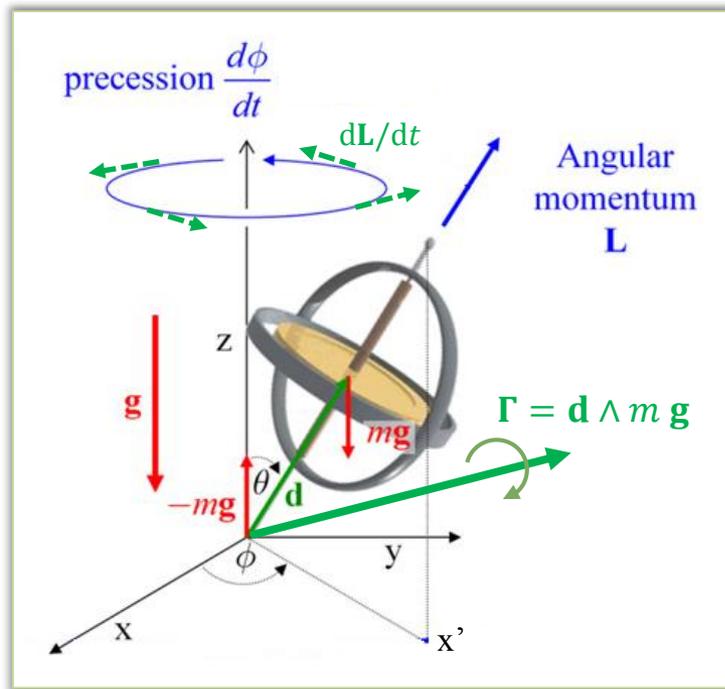


Evolution :  $\frac{d\mathbf{L}}{dt} = \boldsymbol{\Gamma}$



# Cas de l'électron atomique

## Analogie de la toupie

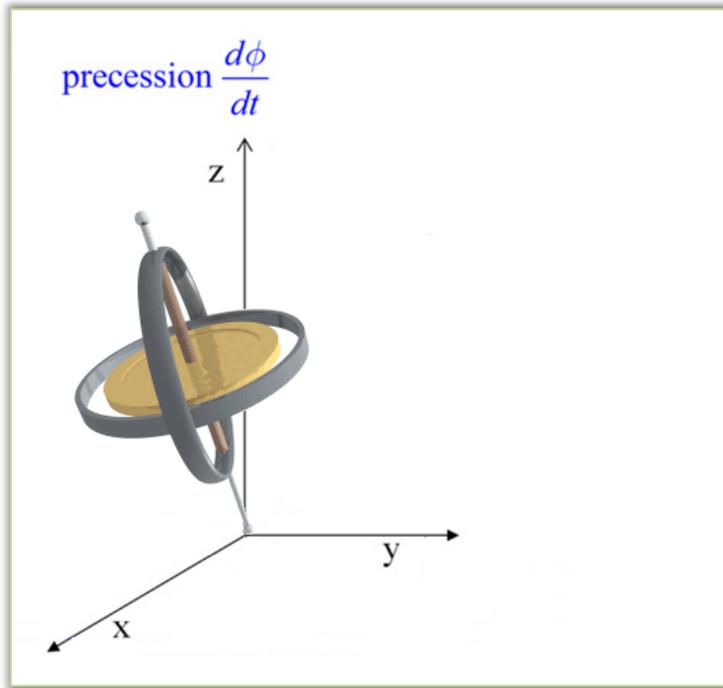


Evolution : 
$$\frac{d\mathbf{L}}{dt} = \boldsymbol{\Gamma}$$



# Cas de l'électron atomique

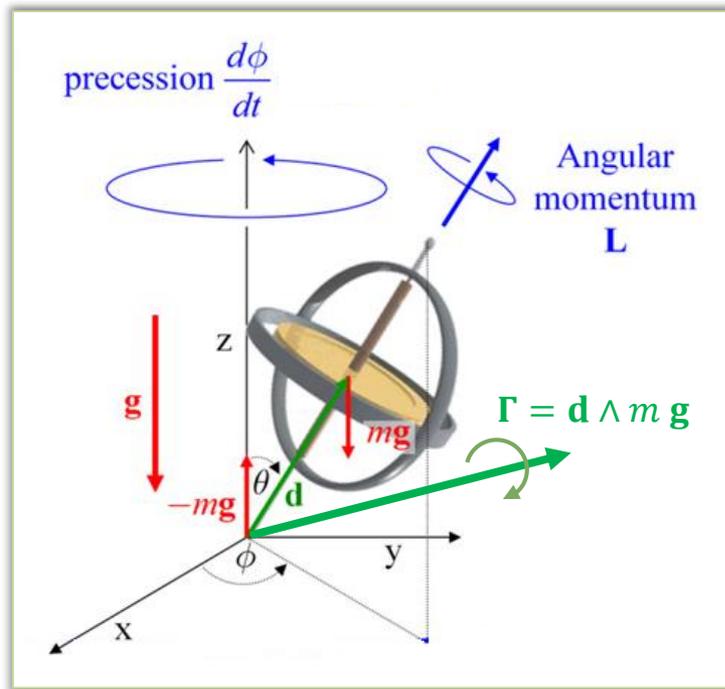
## Analogie de la toupie



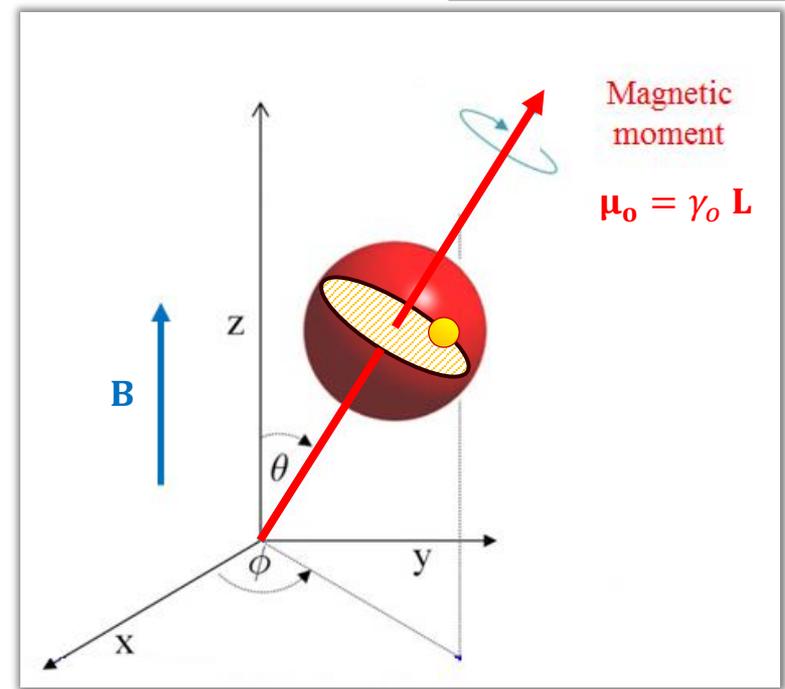
Evolution : 
$$\frac{d\mathbf{L}}{dt} = \boldsymbol{\Gamma}$$

# Cas de l'électron atomique

## Analogie de la toupie

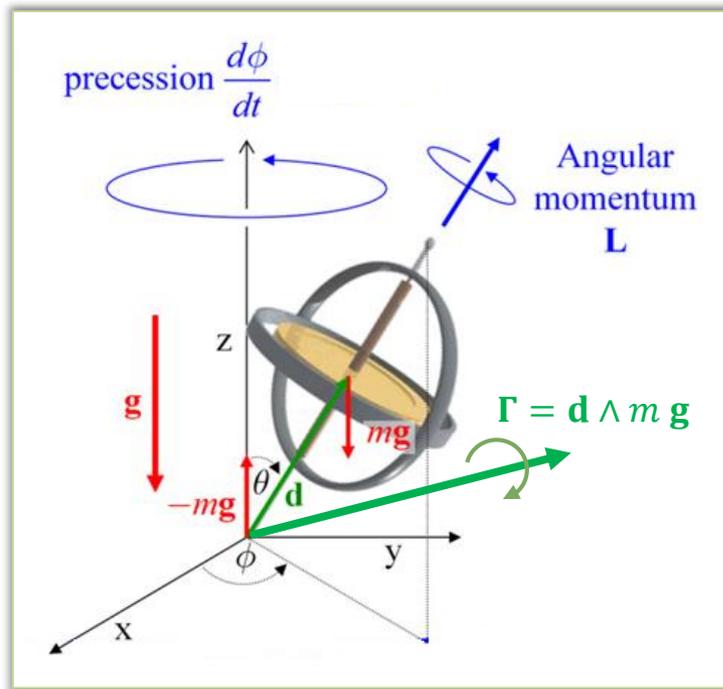


Evolution : 
$$\frac{d\mathbf{L}}{dt} = \boldsymbol{\Gamma}$$

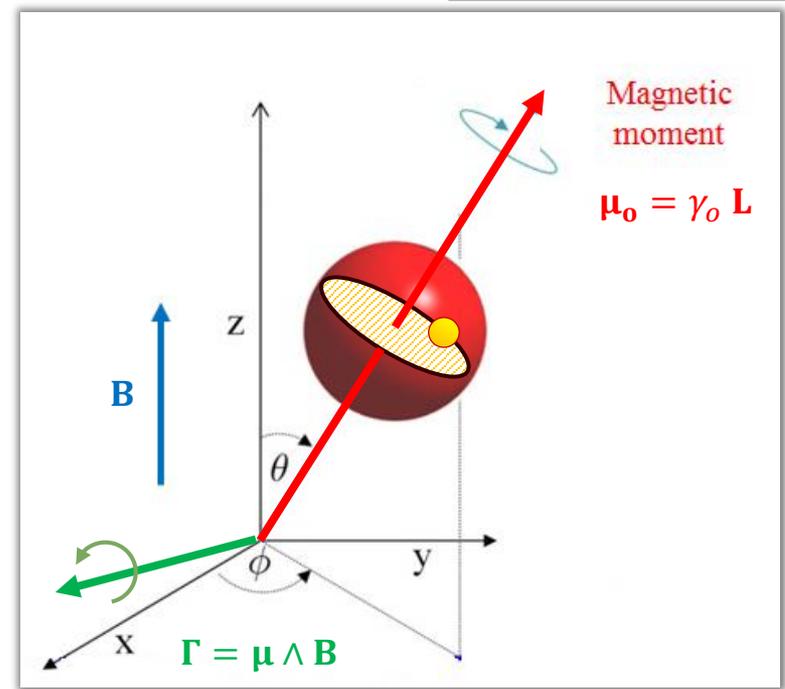


# Cas de l'électron atomique

## Analogie de la toupie



Evolution : 
$$\frac{d\mathbf{L}}{dt} = \boldsymbol{\Gamma}$$

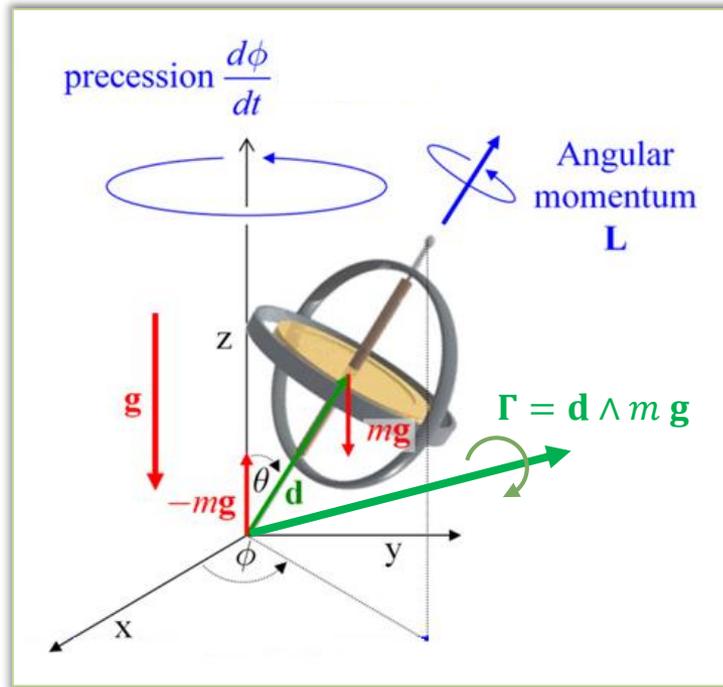


$$\frac{d\mathbf{L}}{dt} = \boldsymbol{\mu}_o \wedge \mathbf{B}$$

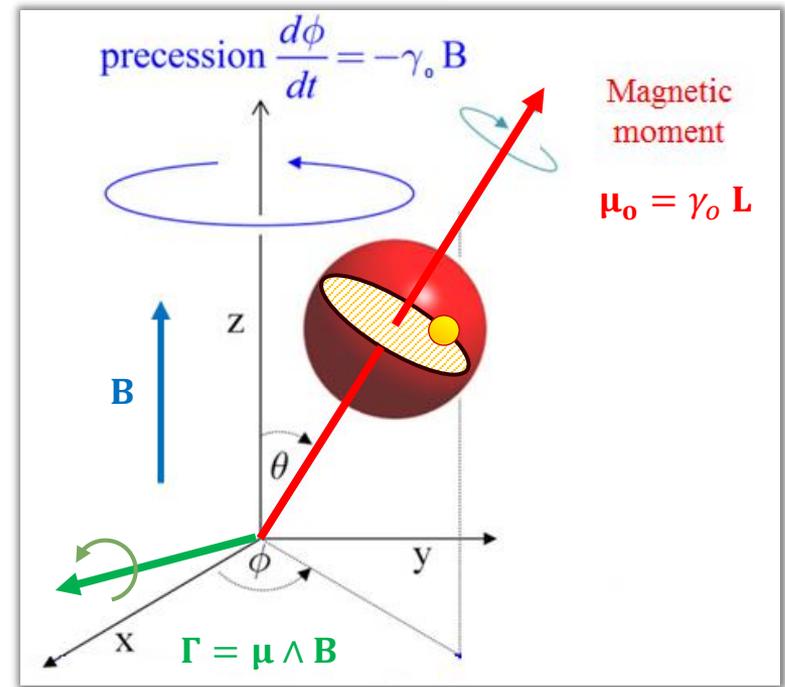
Magnetic moment  
$$\boldsymbol{\mu}_o = \gamma_o \mathbf{L}$$

# Cas de l'électron atomique

## Analogie de la toupie



Evolution :  $\frac{d\mathbf{L}}{dt} = \mathbf{\Gamma}$

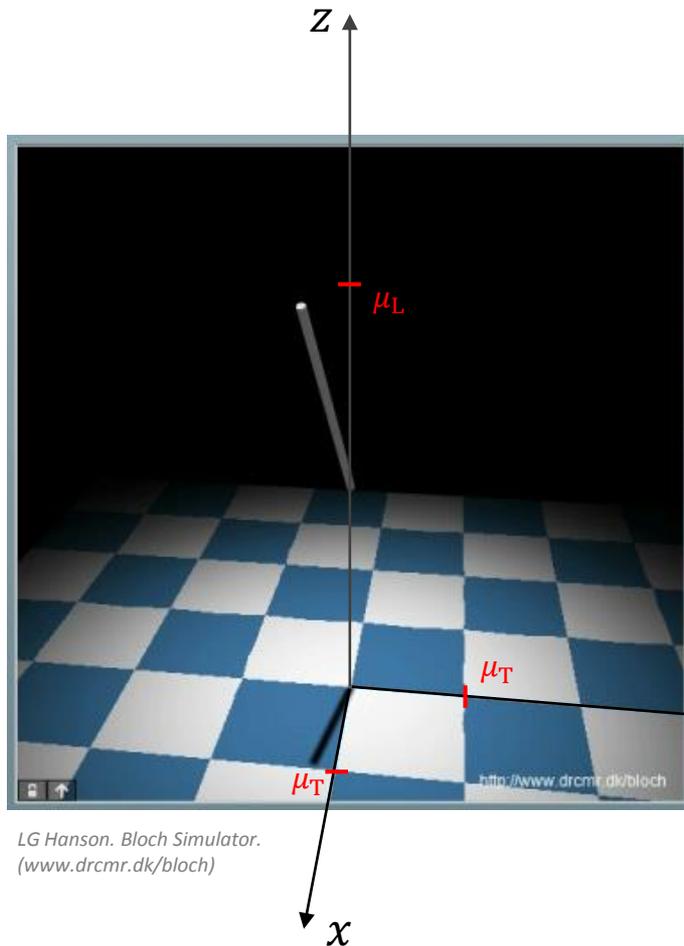


$\frac{d\mathbf{L}}{dt} = \mu_0 \wedge \mathbf{B}$        $\frac{d\mu_0}{dt} = \gamma_0 \mu_0 \wedge \mathbf{B}$

Précession de Larmor



# Cas de l'électron atomique



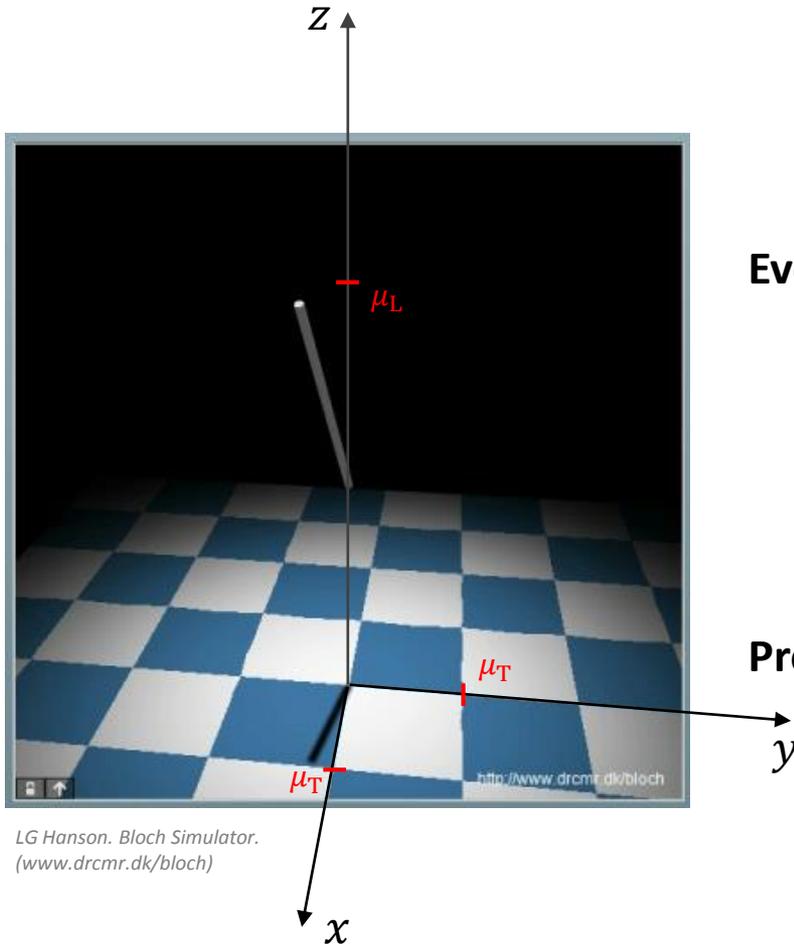
Evolution :  $\frac{d\boldsymbol{\mu}_0}{dt} = \gamma_0 \boldsymbol{\mu}_0 \wedge \mathbf{B}$

$$\begin{cases} \mu_{0x} = \mu_T \cos(\omega t) \\ \mu_{0y} = \mu_T \sin(\omega t) \\ \mu_{0z} = \mu_L \end{cases}$$

Précession de Larmor :  $\omega = -\gamma_0 \mathbf{B}$      $\mathbf{v} = -\bar{\gamma}_0 \mathbf{B}$

Dans un champ de  $1 \text{ T}$  :  $\nu = 14 \text{ GHz}$  (micro-onde)

# Cas de l'électron atomique



LG Hanson. Bloch Simulator.  
([www.drcmr.dk/bloch](http://www.drcmr.dk/bloch))

Evolution :  $\frac{d\boldsymbol{\mu}_0}{dt} = \gamma_0 \boldsymbol{\mu}_0 \wedge \mathbf{B}$

$$\begin{cases} \mu_{0x} = \mu_T \cos(\omega t) \\ \mu_{0y} = \mu_T \sin(\omega t) \\ \mu_{0z} = \mu_L \end{cases}$$

Précession de Larmor :  $\omega = -\gamma_0 B$        $\mathbf{v} = -\bar{\gamma}_0 \mathbf{B}$

$$\boldsymbol{\mu}_0 = \begin{pmatrix} \mu_T \cos(\omega t) \\ \mu_T \sin(\omega t) \\ \mu_L \end{pmatrix} \quad \frac{d\boldsymbol{\mu}_0}{dt} = \omega \begin{pmatrix} -\mu_T \sin(\omega t) \\ \mu_T \cos(\omega t) \\ 0 \end{pmatrix}$$

$$\gamma_0 \boldsymbol{\mu}_0 \wedge \mathbf{B} = \gamma_0 \begin{pmatrix} \mu_T \cos(\omega t) \\ \mu_T \sin(\omega t) \\ \mu_L \end{pmatrix} \wedge \begin{pmatrix} 0 \\ 0 \\ B \end{pmatrix} = \gamma_0 B \begin{pmatrix} \mu_T \sin(\omega t) \\ -\mu_T \cos(\omega t) \\ 0 \end{pmatrix}$$



# Ce que dit la mécanique quantique

$$i\hbar \frac{\partial \Psi}{\partial t} = \left[ -\frac{\hbar^2}{2m_e} \Delta_R + V(R) - \left( \frac{q_e}{2m_e} \vec{B} \cdot \vec{L}_R + \vec{\Omega} \cdot \vec{L}_R \right) - q_e \vec{R} \cdot \vec{E} \right] \Psi$$

$$\langle \psi(t) | \chi(t) \rangle = \int (\psi_+^*(\mathbf{r}, t) \chi_+(\mathbf{r}, t) + \psi_-^*(\mathbf{r}, t) \chi_-(\mathbf{r}, t)) d^3r$$

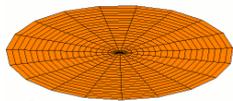
$$[L_x, L_y] = i\hbar \epsilon_{xyz} L_z$$

**Cadre conceptuel adéquat  
Mais formalisme complexe**

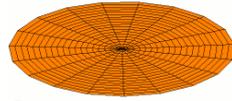


# Ce que dit la mécanique quantique

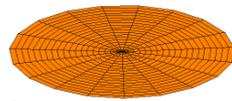
L'électron est décrit par une onde :  $\Psi(\mathbf{x}, t) : \mathbb{R}^3 \times \mathbb{R}^+ \rightarrow \mathbb{C}$



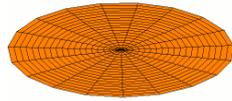
1s



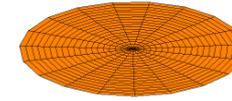
2s



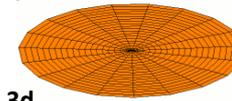
3s



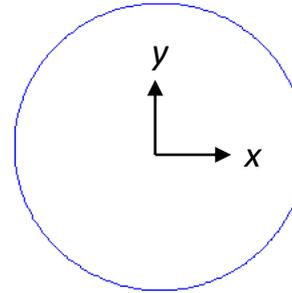
2p



3p



3d

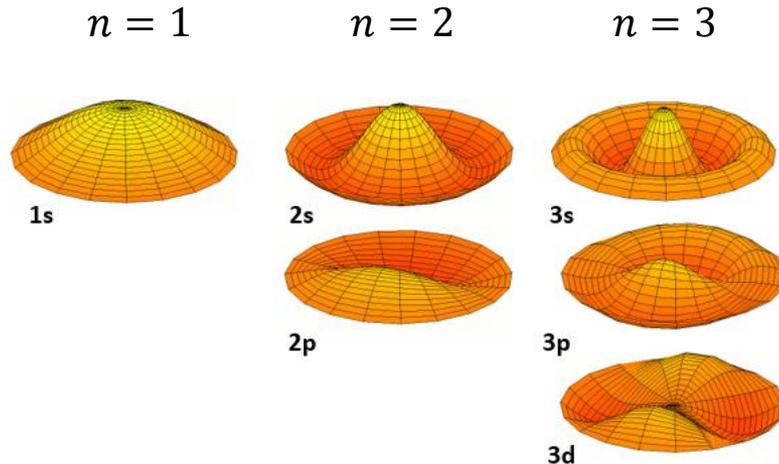


# Ce que dit la mécanique quantique

L'électron est décrit par une onde :  $\Psi(\mathbf{x}, t) : \mathbb{R}^3 \times \mathbb{R}^+ \rightarrow \mathbb{C}$

La description complète fait apparaître 3 nombres quantiques

$n$  : quantification de l'énergie  $E$



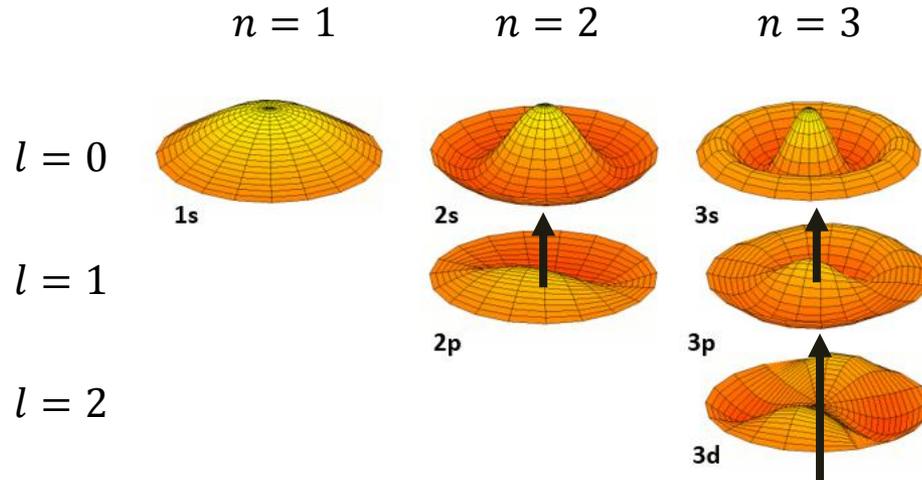
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L'électron est décrit par une onde :  $\Psi(\mathbf{x}, t) : \mathbb{R}^3 \times \mathbb{R}^+ \rightarrow \mathbb{C}$

La description complète fait apparaître 3 nombres quantiques

$n$  : quantification de l'énergie  $E$

$l$  : quantification du moment cinétique  $|\mathbf{L}| = \hbar \sqrt{l(l+1)}$  ( $l$  entier)



# Ce que dit la mécanique quantique

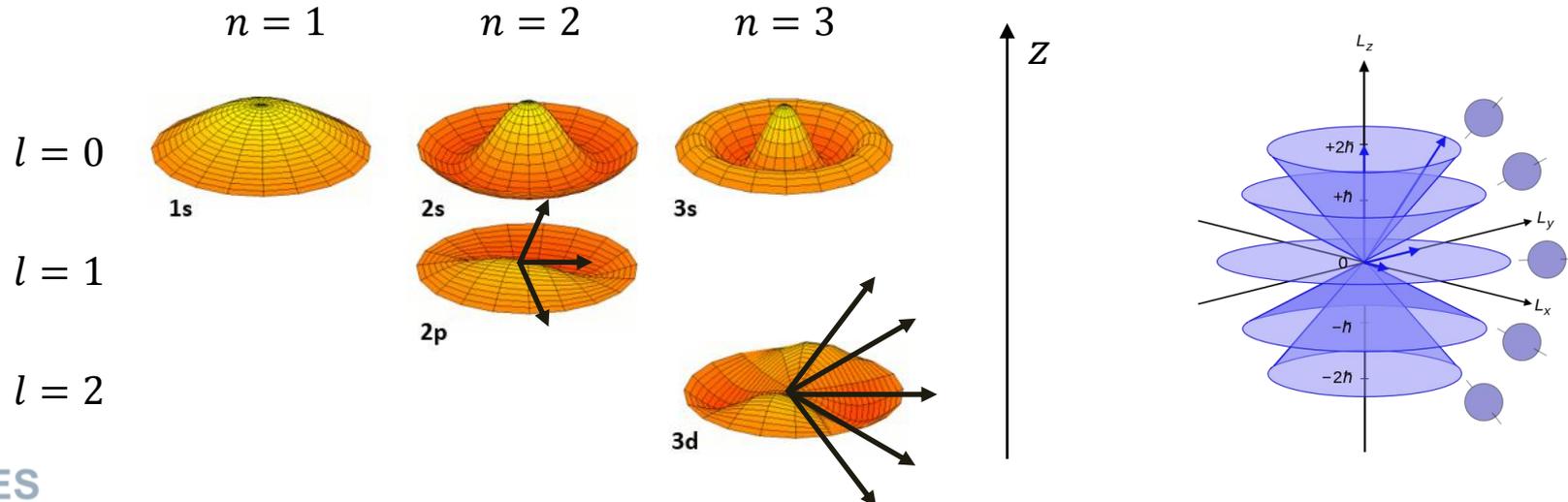
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$m$  : quantification de  $L_z = m\hbar = -l\hbar \dots 0 \dots l\hbar$



# Ce que dit la mécanique quantique

L'électron est décrit par une onde :  $\Psi(\mathbf{x}, t) : \mathbb{R}^3 \times \mathbb{R}^+ \rightarrow \mathbb{C}$

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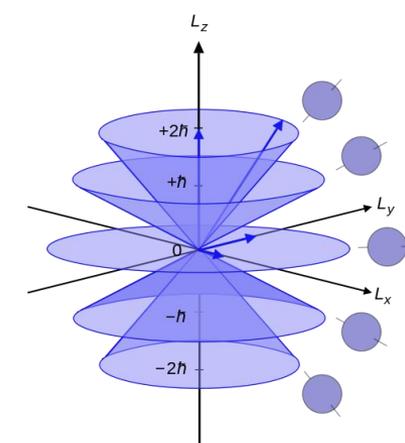
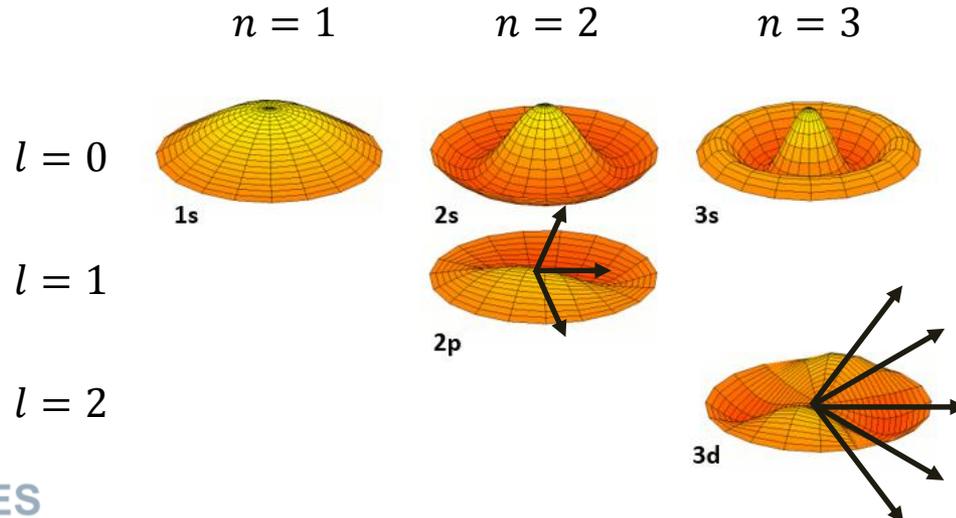
$m$  : quantification de  $L_z = m\hbar = -l\hbar \dots 0 \dots l\hbar$

Indétermination de  $L_x$  et  $L_y$  : quelle est la longitude du pôle nord ?

$$\boldsymbol{\mu}_o = \gamma_o \mathbf{L}$$

$$|\boldsymbol{\mu}_o| = \gamma_o \hbar \sqrt{l(l+1)}$$

$$\mu_{oz} = \gamma_o m \hbar$$



# Ce que dit la mécanique quantique

---

L'électron est décrit par une onde :  $\Psi(\mathbf{x}, t) : \mathbb{R}^3 \times \mathbb{R}^+ \rightarrow \mathbb{C}$

La description complète fait apparaître 3 nombres quantiques

$(n, l, m)$

... MAIS

$L_z = m\hbar = -l\hbar \dots 0 \dots l\hbar$  2l + 1 valeurs

Particules dans  $\partial B / \partial z$   
déviées en fonction de  $L_z$

# Ce que dit la mécanique quantique

L'électron est décrit par une onde :  $\Psi(\mathbf{x}, t) : \mathbb{R}^3 \times \mathbb{R}^+ \rightarrow \mathbb{C}$

La description complète fait apparaître 3 nombres quantiques

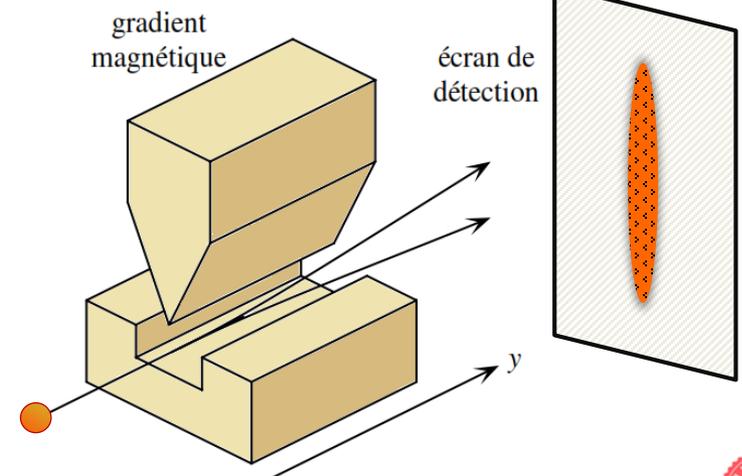
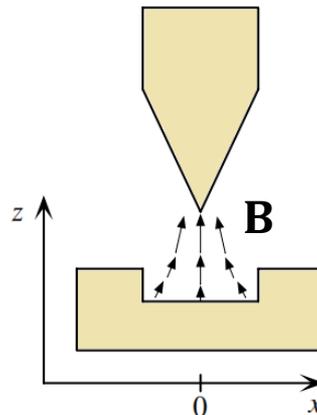
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$2l + 1$  valeurs

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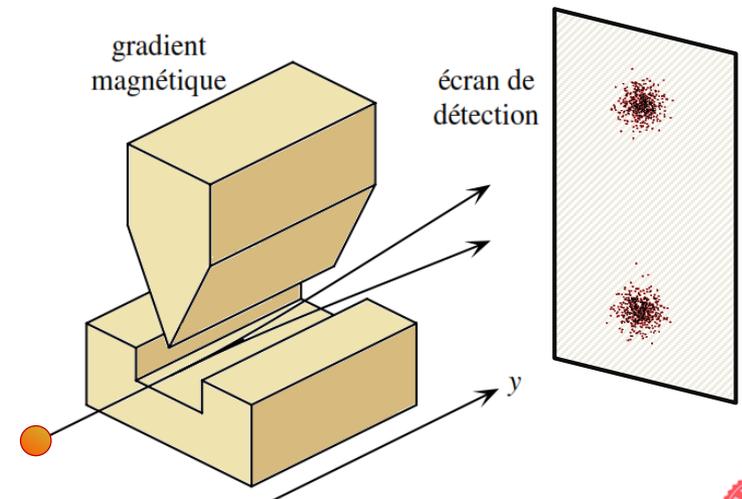
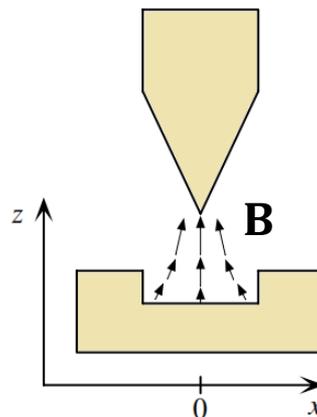
$2l + 1$  valeurs

Particules dans  $\partial B / \partial z$   
déviées en fonction de  $L_z$

Nombre pair de taches

Il existe un moment  
cinétique demi-entier  
intrinsèque

**SPIN**



# Ce que dit la mécanique quantique

L'électron est décrit par une onde :  $\Psi(\mathbf{x}, t, \sigma) : \mathbb{R}^3 \times \mathbb{R}^+ \times \begin{pmatrix} + \\ - \end{pmatrix} \rightarrow \mathbb{C}$

La description complète fait apparaître **4** nombres quantiques

$(n, l, m, \sigma)$



W. Pauli

**SPIN S**

tel que :  $|\mathbf{S}| = \hbar \sqrt{s(s+1)}$  ( $s$  entier **OU** demi-entier)

$$S_z = \sigma \hbar = -s\hbar \dots s\hbar$$

# Ce que dit la mécanique quantique

L'électron est décrit par une onde :  $\Psi(\mathbf{x}, t, \sigma) : \mathbb{R}^3 \times \mathbb{R}^+ \times \left(\begin{smallmatrix} + \\ - \end{smallmatrix}\right) \rightarrow \mathbb{C}$

La description complète fait apparaître **4** nombres quantiques

$(n, l, m, \sigma)$



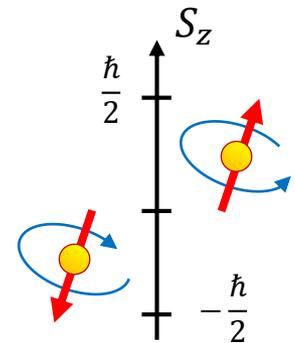
W. Pauli

## SPIN $S$

tel que :  $|\mathbf{S}| = \hbar \sqrt{s(s+1)}$  ( $s$  entier **OU** demi-entier)

$$S_z = \sigma \hbar = -s\hbar \dots s\hbar$$

pour l'électron :  $s = \frac{1}{2}$     $\sigma = \pm \frac{1}{2}$



# Ce que dit la mécanique quantique

L'électron est décrit par une onde :  $\Psi(\mathbf{x}, t, \sigma) : \mathbb{R}^3 \times \mathbb{R}^+ \times \left(\begin{smallmatrix} + \\ - \end{smallmatrix}\right) \rightarrow \mathbb{C}$

La description complète fait apparaître **4** nombres quantiques  
( $n, l, m, \sigma$ )



W. Pauli

## SPIN S

tel que :  $|\mathbf{S}| = \hbar \sqrt{s(s+1)}$  ( $s$  entier **OU** demi-entier)

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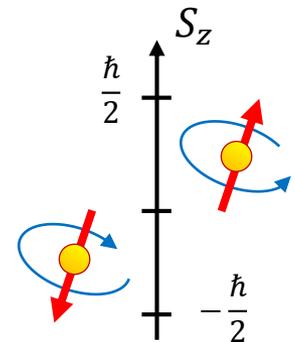
il s'y associe un moment magnétique :

$$\boldsymbol{\mu}_s = \gamma_s \mathbf{S} = g \gamma_0 \mathbf{S}$$

$$\bar{\gamma}_s \approx 28 \text{ GHz T}^{-1}$$

$$g \approx 2$$

facteur de Landé de spin



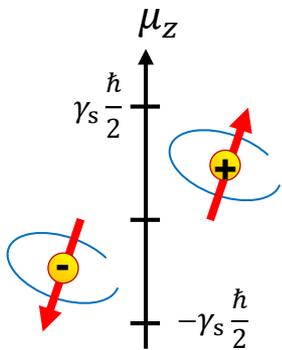
# Ce que dit la mécanique quantique

## Considérations énergétiques

$$\mathbf{B} = 0$$

$$U = \frac{-Q e}{4\pi\epsilon_0 r}$$

**B**



$$E_+ = E_- = \hat{E}$$

**E**

# Ce que dit la mécanique quantique

## Considérations énergétiques

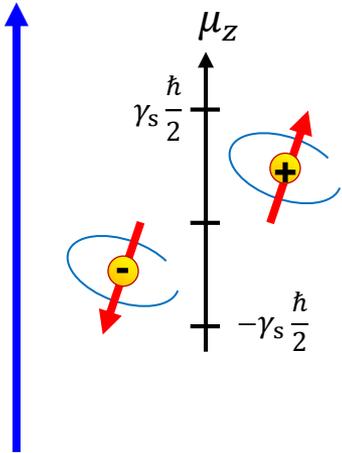
$$\mathbf{B} = 0$$

$$U = \frac{-Q e}{4\pi\epsilon_0 r}$$

$$\mathbf{B} > 0$$

$$U = \frac{-Q e}{4\pi\epsilon_0 r} - \boldsymbol{\mu}_s \cdot \mathbf{B} = \frac{-Q e}{4\pi\epsilon_0 r} - \gamma_s S_z B$$

$\mathbf{B}$



$$E_+ = E_- = \hat{E}$$

$E$

# Ce que dit la mécanique quantique

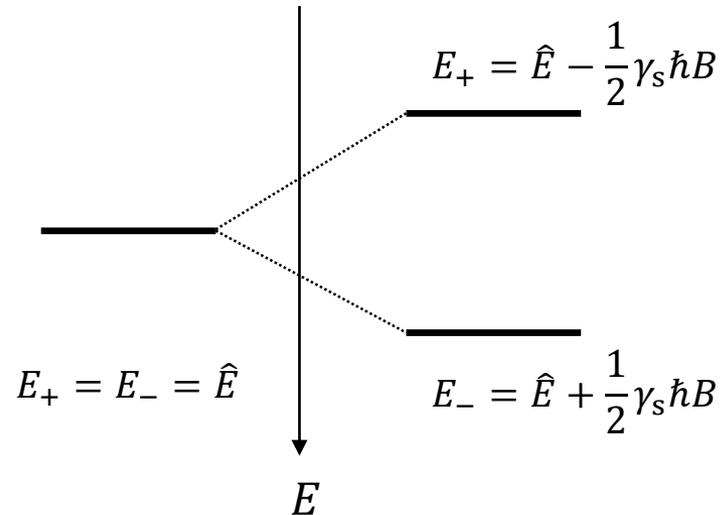
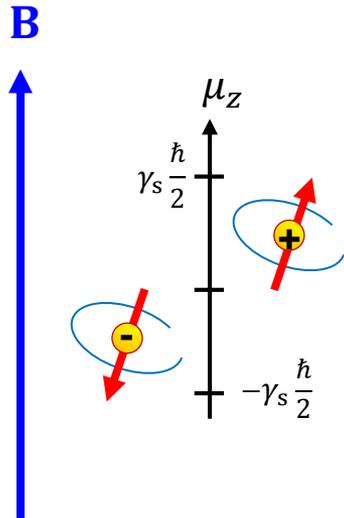
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# Ce que dit la mécanique quantique

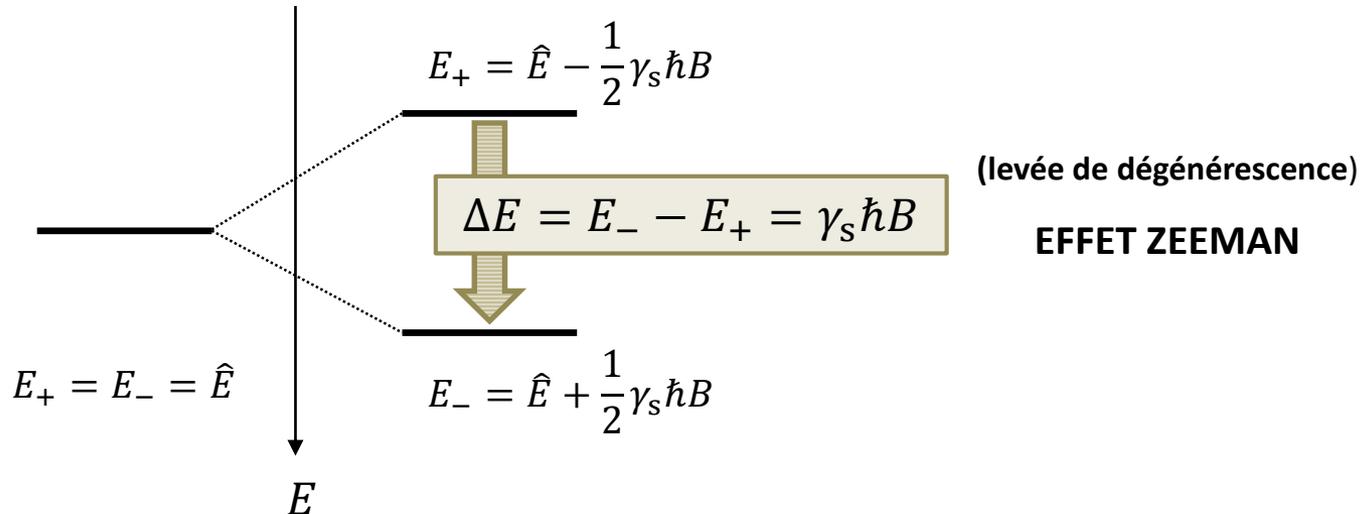
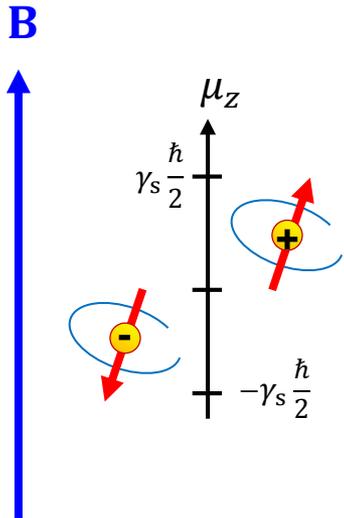
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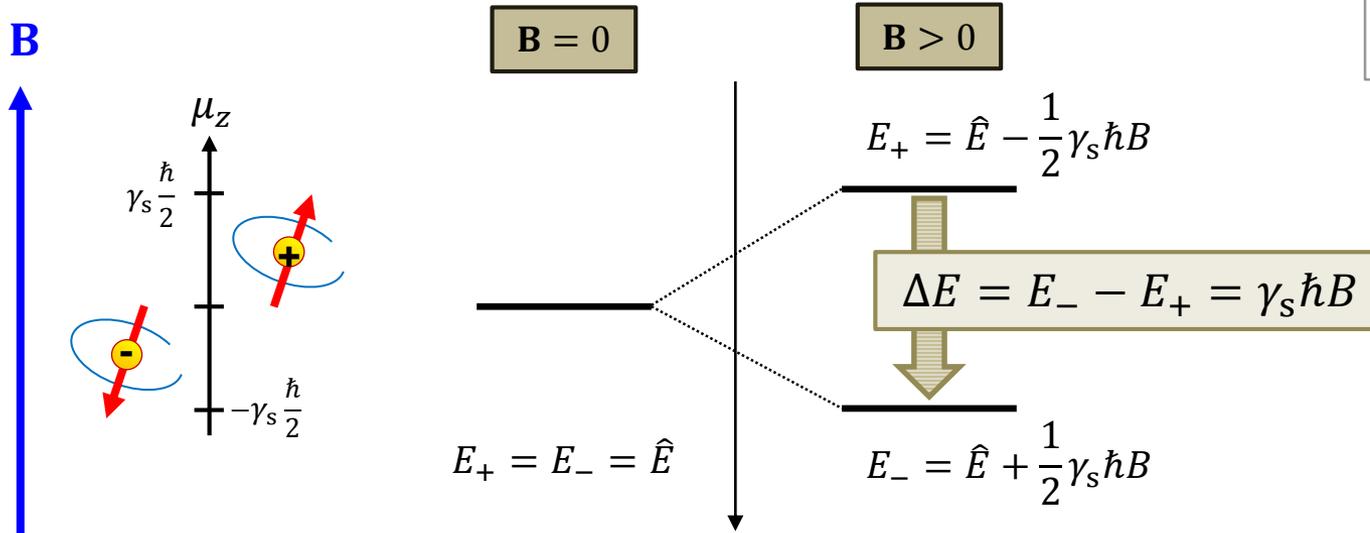


(levée de dégénérescence)

**EFFET ZEEMAN**

# Ce que dit la mécanique quantique

## Considérations énergétiques



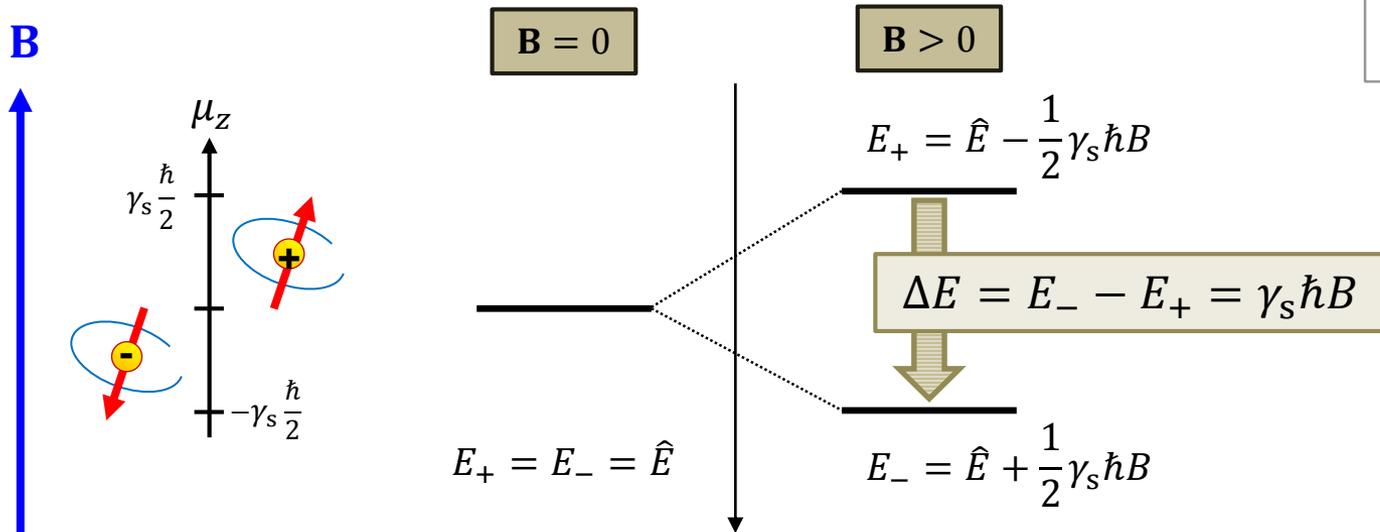
## Principe de superposition

$$|\psi_s\rangle = \alpha|\oplus\rangle + \beta|\ominus\rangle$$

$$\wp(\oplus) = \alpha^2 \quad \wp(\ominus) = \beta^2$$

# Ce que dit la mécanique quantique

## Considérations énergétiques



## Principe de superposition

$$|\psi_s\rangle = \alpha|\oplus\rangle + \beta|\ominus\rangle$$

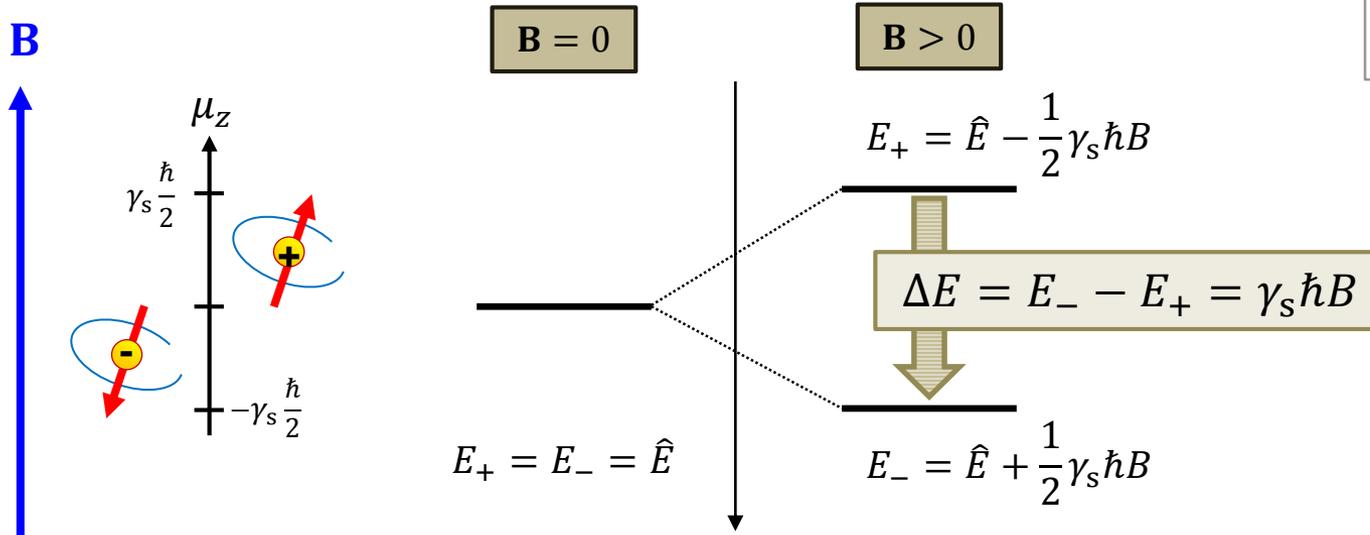
$$\wp(\oplus) = \alpha^2 \quad \wp(\ominus) = \beta^2$$

$$B = 0 \left\{ \begin{array}{l} |\psi_s\rangle = \frac{1}{\sqrt{2}}|\oplus\rangle + \frac{1}{\sqrt{2}}|\ominus\rangle \\ \wp(\oplus) = \wp(\ominus) = 50\% \end{array} \right.$$



# Ce que dit la mécanique quantique

## Considérations énergétiques



## Principe de superposition

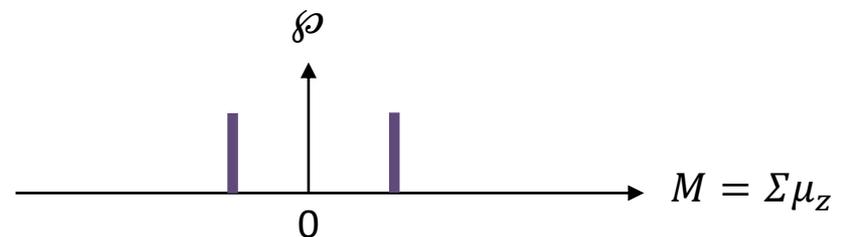
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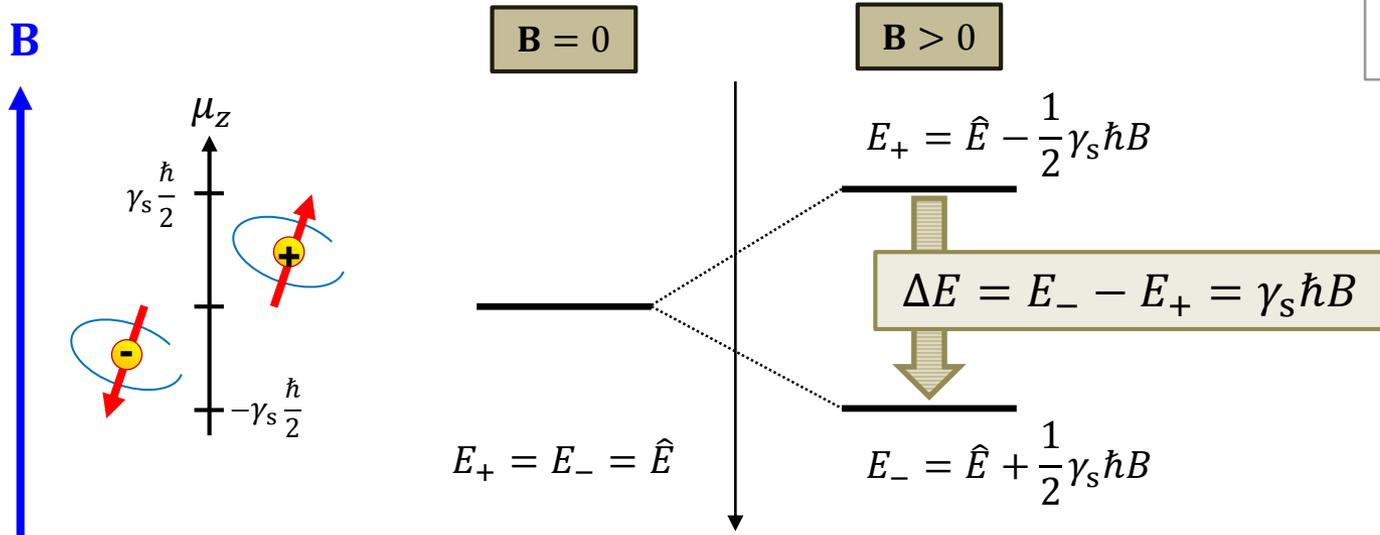
Un dipôle  $|\oplus\rangle$  : 50%

$|\ominus\rangle$  : 50%



# Ce que dit la mécanique quantique

## Considérations énergétiques



## Principe de superposition

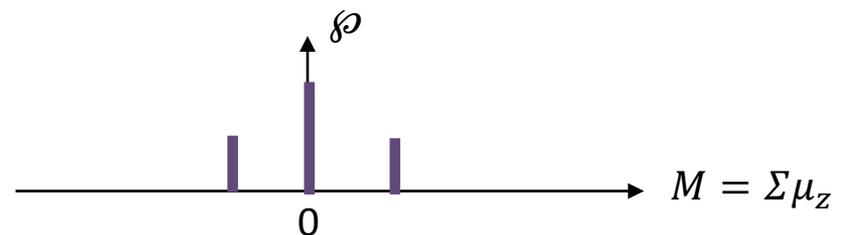
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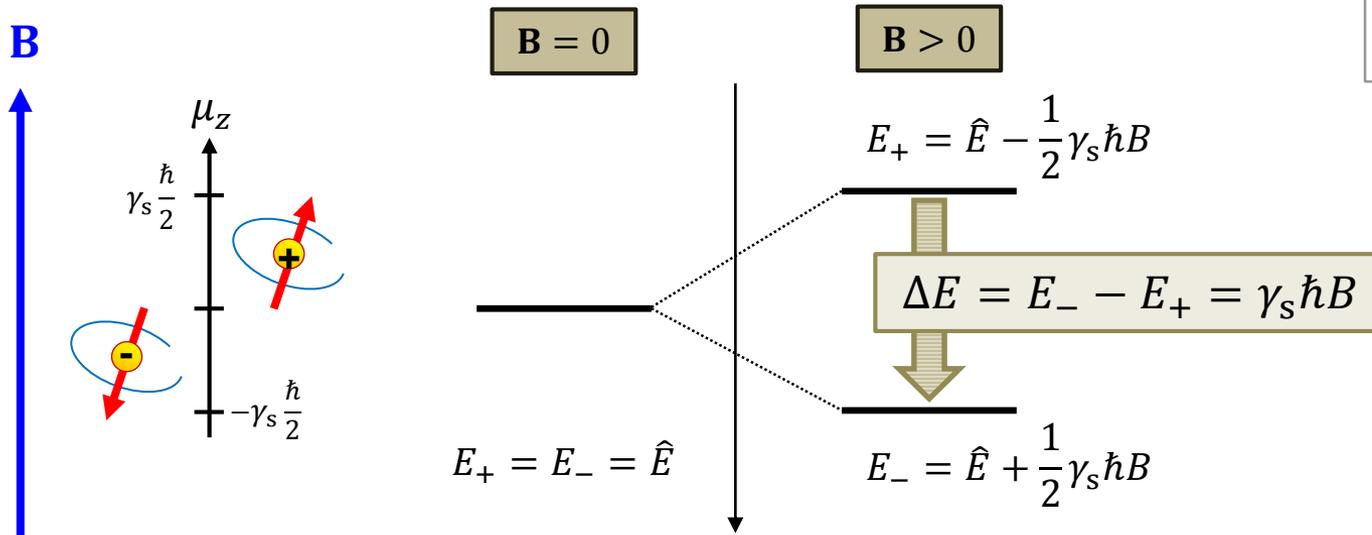
2 dipôles

$ \oplus\rangle  \oplus\rangle$ : 25%	
$ \ominus\rangle  \oplus\rangle$ : 25%	$ \oplus\rangle  \ominus\rangle$ : 25%
50%	
$ \ominus\rangle  \ominus\rangle$ : 25%	



# Ce que dit la mécanique quantique

## Considérations énergétiques



## Principe de superposition

$$|\psi_s\rangle = \alpha|\oplus\rangle + \beta|\ominus\rangle$$

$$\wp(\oplus) = \alpha^2 \quad \wp(\ominus) = \beta^2$$

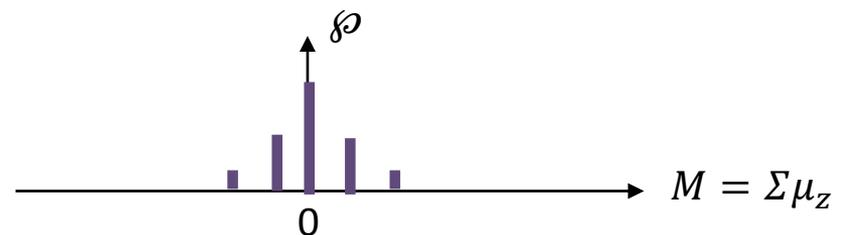
$B = 0$

{

$$|\psi_s\rangle = \frac{1}{\sqrt{2}}|\oplus\rangle + \frac{1}{\sqrt{2}}|\ominus\rangle$$

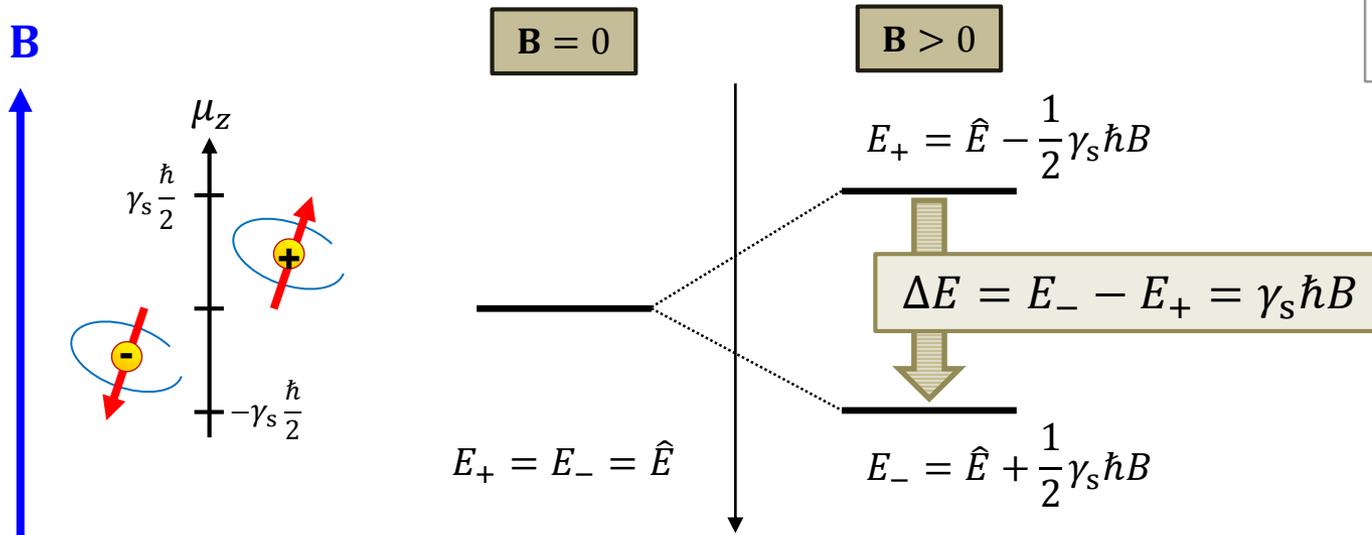
$$\wp(\oplus) = \wp(\ominus) = 50\%$$

## 4 dipôles



# Ce que dit la mécanique quantique

## Considérations énergétiques



## Principe de superposition

$$|\psi_s\rangle = \alpha|\oplus\rangle + \beta|\ominus\rangle$$

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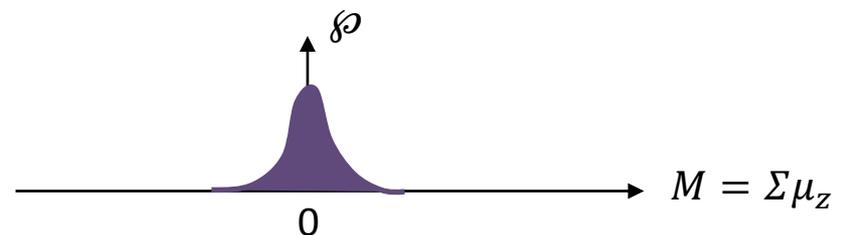
$B = 0$

{

$$|\psi_s\rangle = \frac{1}{\sqrt{2}}|\oplus\rangle + \frac{1}{\sqrt{2}}|\ominus\rangle$$

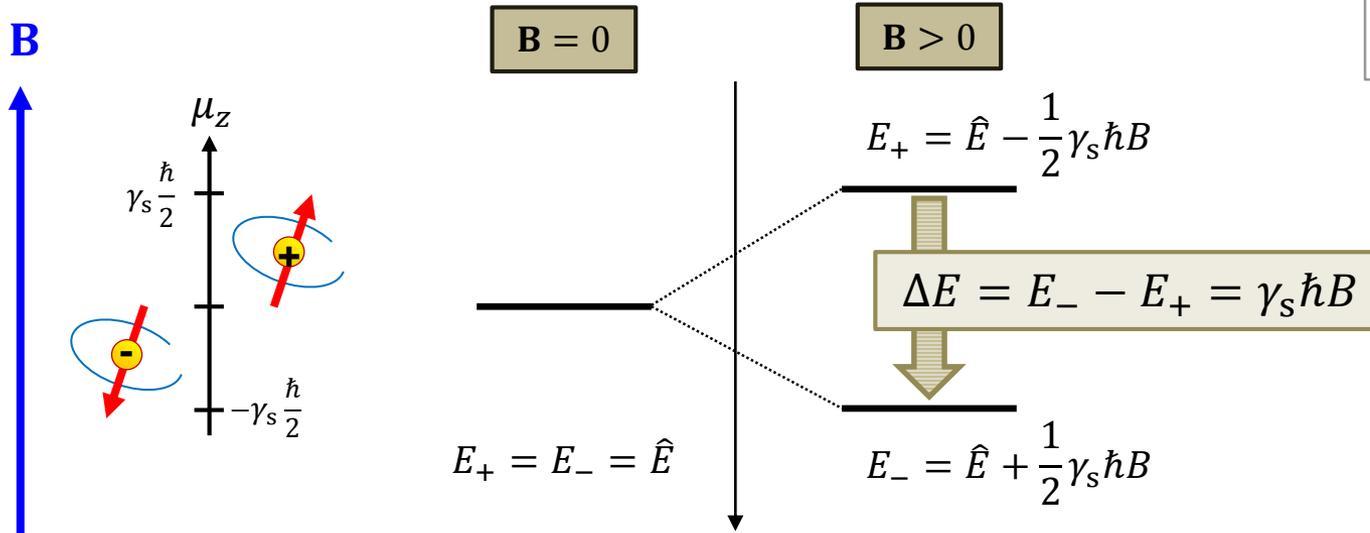
$$\wp(\oplus) = \wp(\ominus) = 50\%$$

1000 dipôles



# Ce que dit la mécanique quantique

## Considérations énergétiques



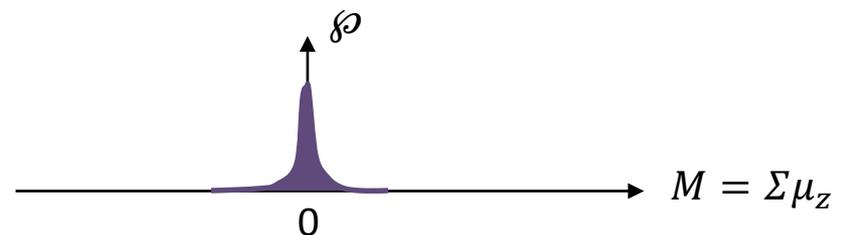
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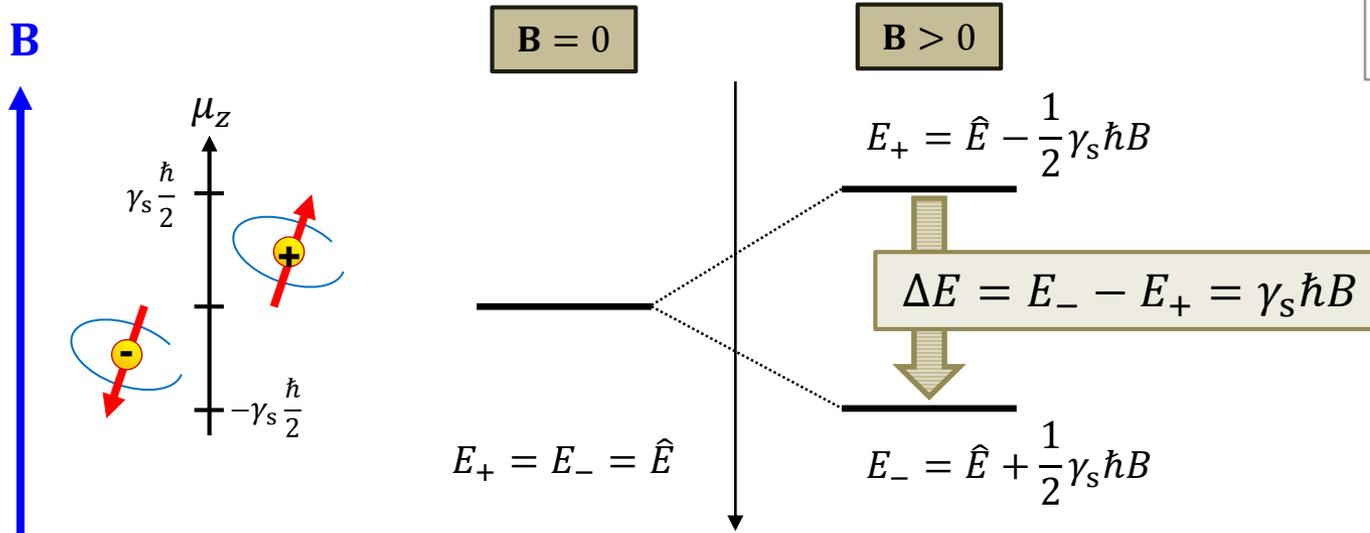
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$10^6$  dipôles



# Ce que dit la mécanique quantique

## Considérations énergétiques



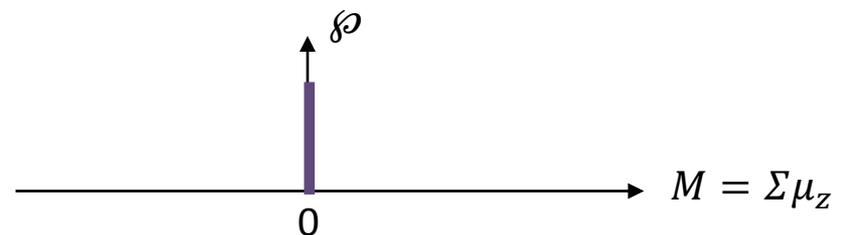
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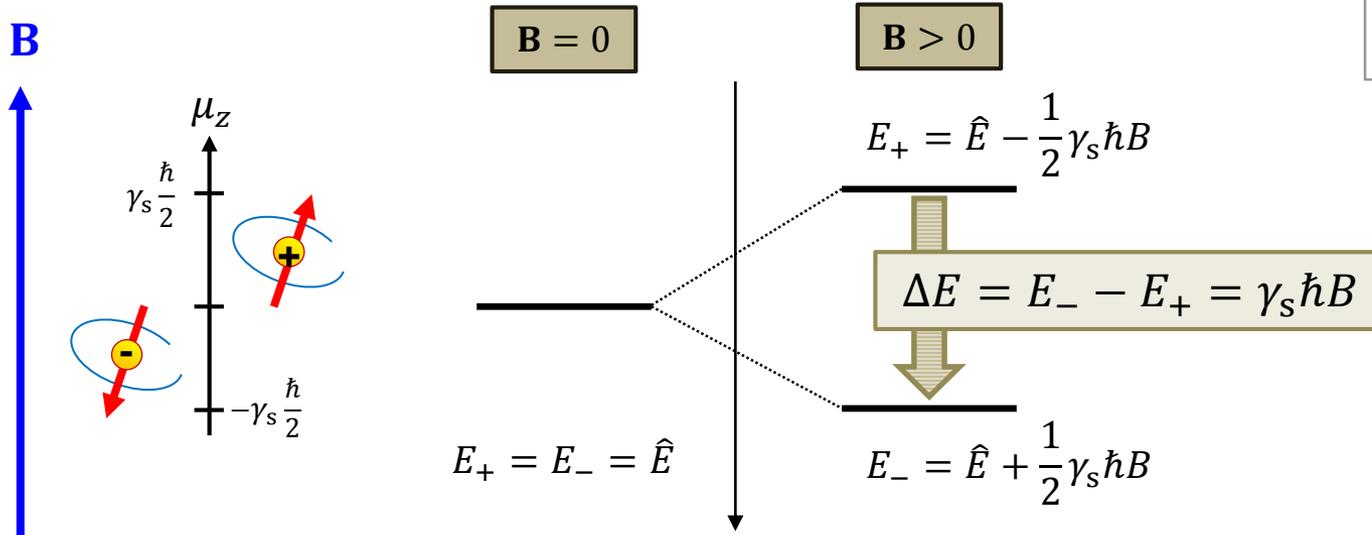
$$B = 0 \left\{ \begin{array}{l} |\psi_s\rangle = \frac{1}{\sqrt{2}}|\oplus\rangle + \frac{1}{\sqrt{2}}|\ominus\rangle \\ \wp(\oplus) = \wp(\ominus) = 50\% \end{array} \right.$$

$10^{20}$  dipôles



# Ce que dit la mécanique quantique

## Considérations énergétiques



### Principe de superposition

$$|\psi_s\rangle = \alpha|\oplus\rangle + \beta|\ominus\rangle$$

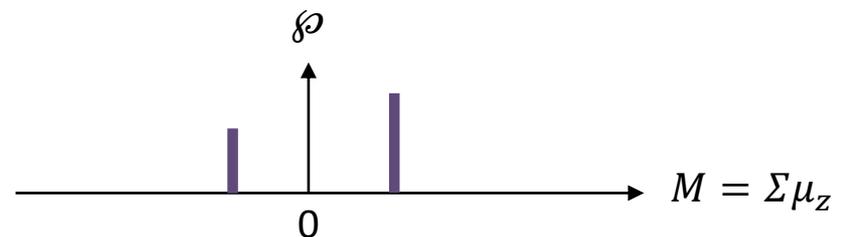
$$\wp(\oplus) = \alpha^2 \quad \wp(\ominus) = \beta^2$$

$$B > 0$$

$$\wp(\oplus) > \wp(\ominus)$$

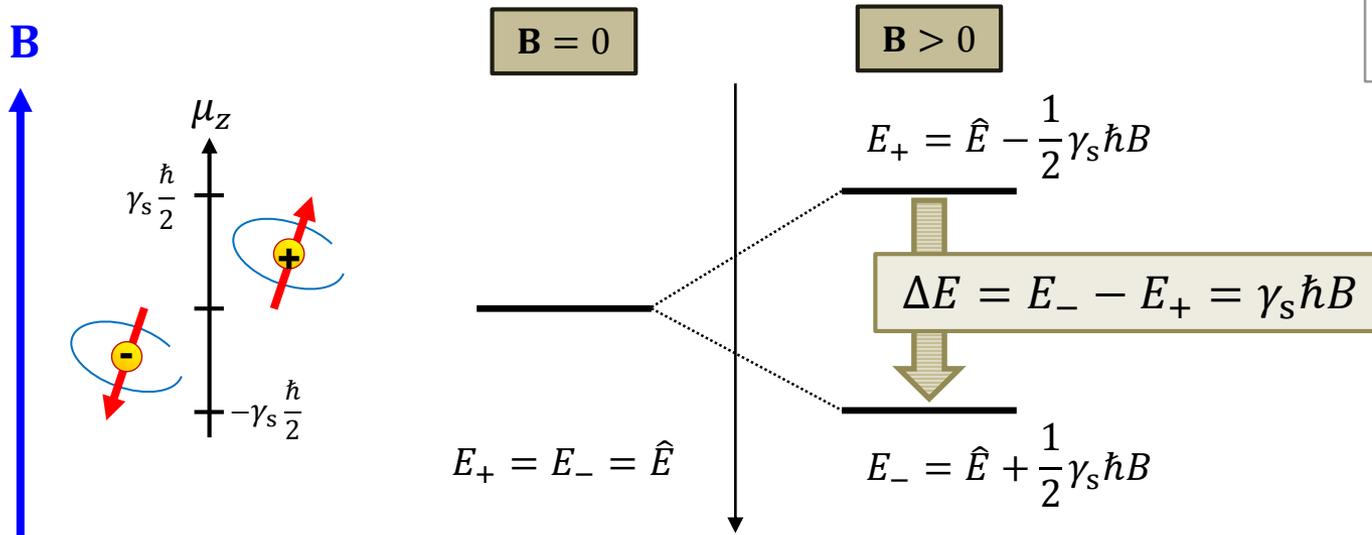
Un dipôle  $|\oplus\rangle > 50\%$

$|\ominus\rangle < 50\%$



# Ce que dit la mécanique quantique

## Considérations énergétiques



### Principe de superposition

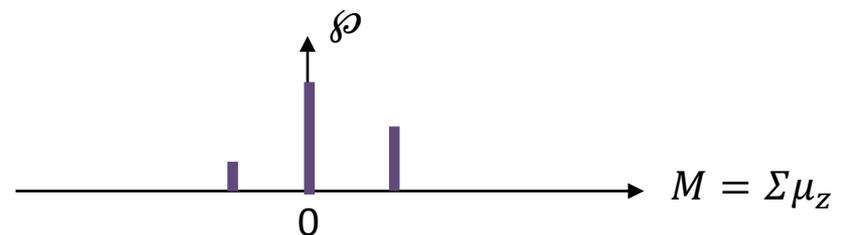
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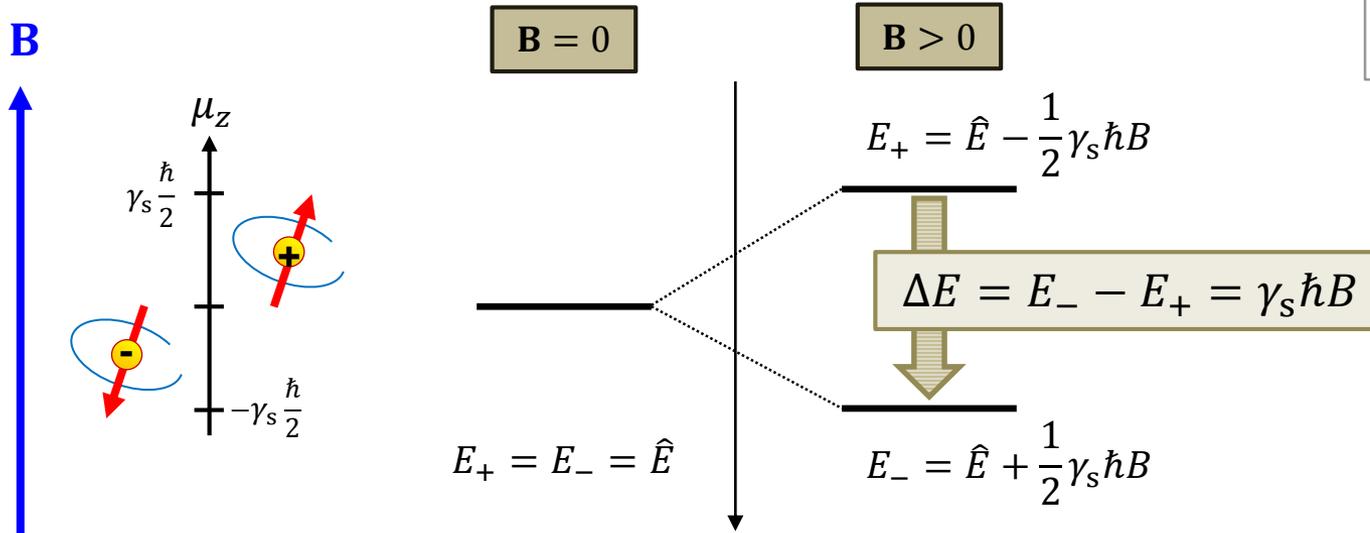
2 dipôles

$ \oplus\rangle  \oplus\rangle$	$> 25\%$
$ \ominus\rangle  \oplus\rangle$	$\sim 25\%$
$ \oplus\rangle  \ominus\rangle$	$\sim 25\%$
$ \ominus\rangle  \ominus\rangle$	$< 25\%$



# Ce que dit la mécanique quantique

## Considérations énergétiques



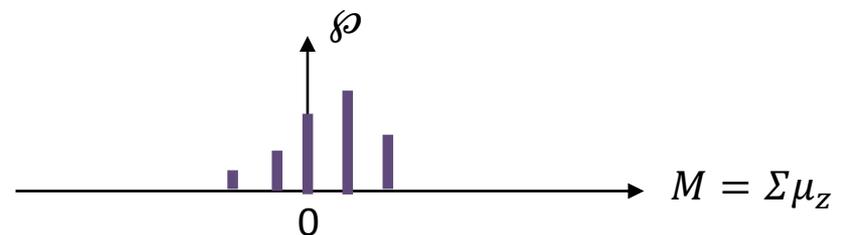
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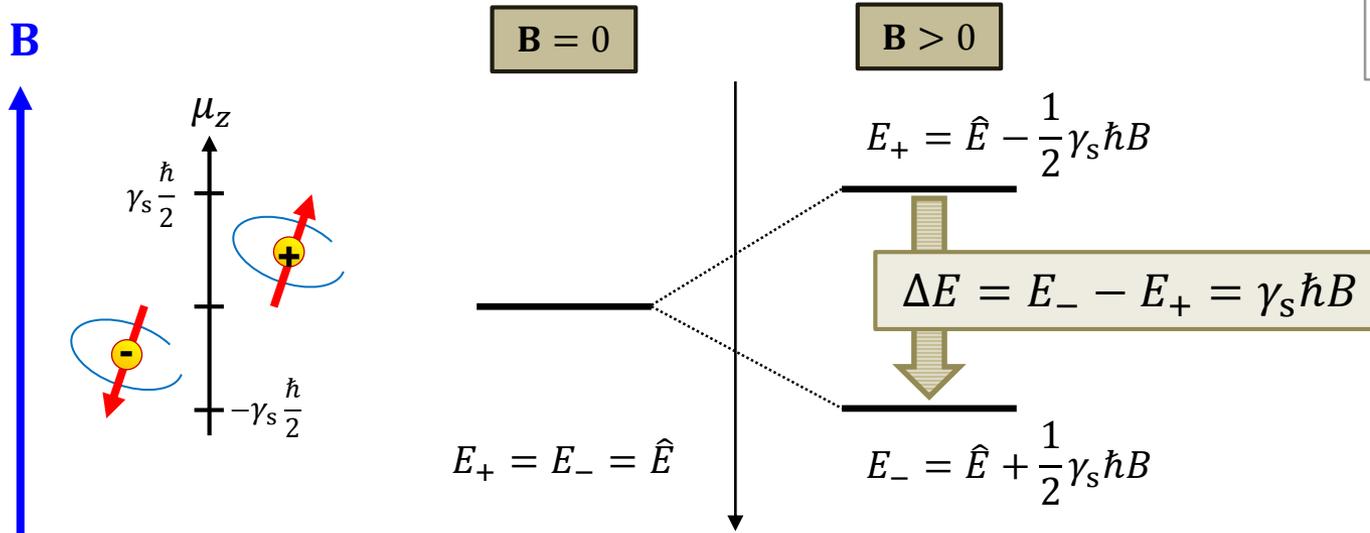
$B > 0$      $\wp(\oplus) > \wp(\ominus)$

## 4 dipôles



# Ce que dit la mécanique quantique

## Considérations énergétiques



## Principe de superposition

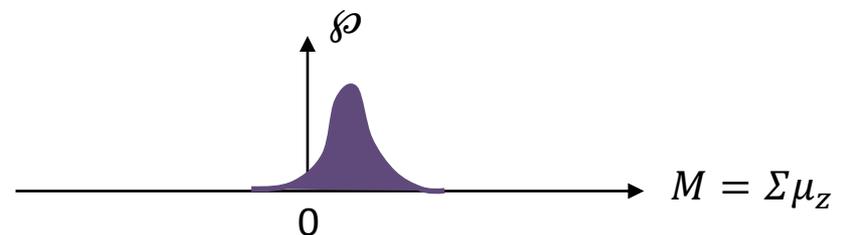
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$$B > 0$$

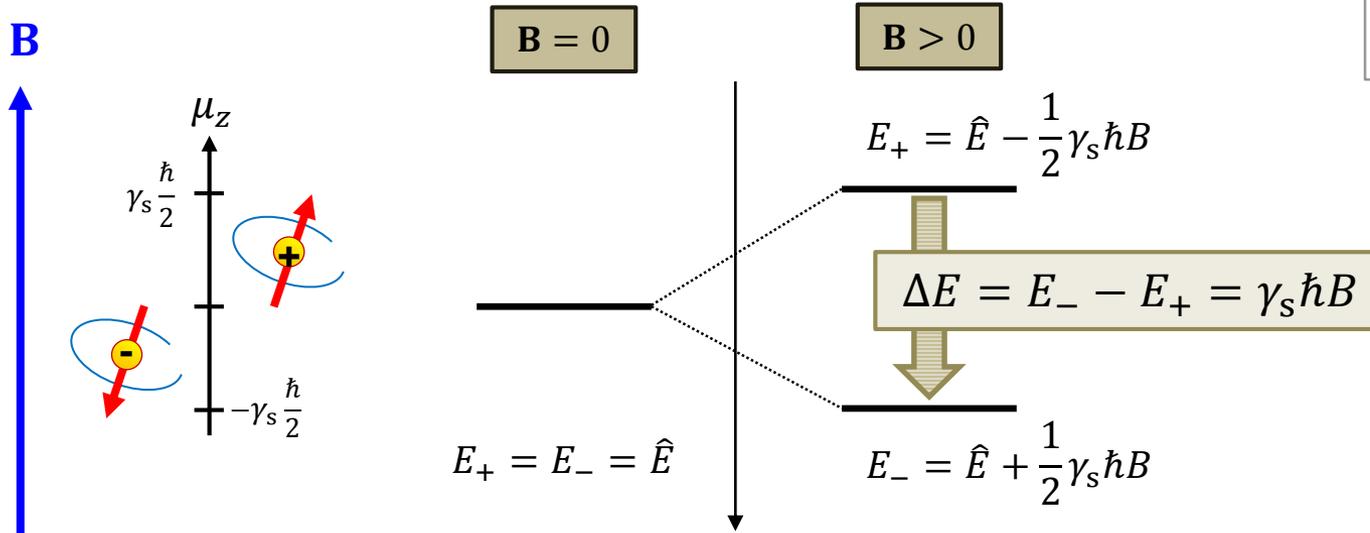
$$\wp(\oplus) > \wp(\ominus)$$

1000 dipôles



# Ce que dit la mécanique quantique

## Considérations énergétiques



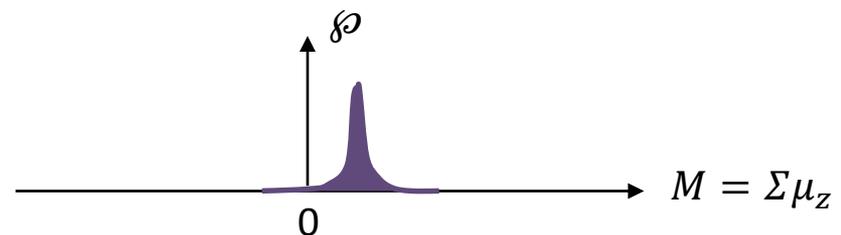
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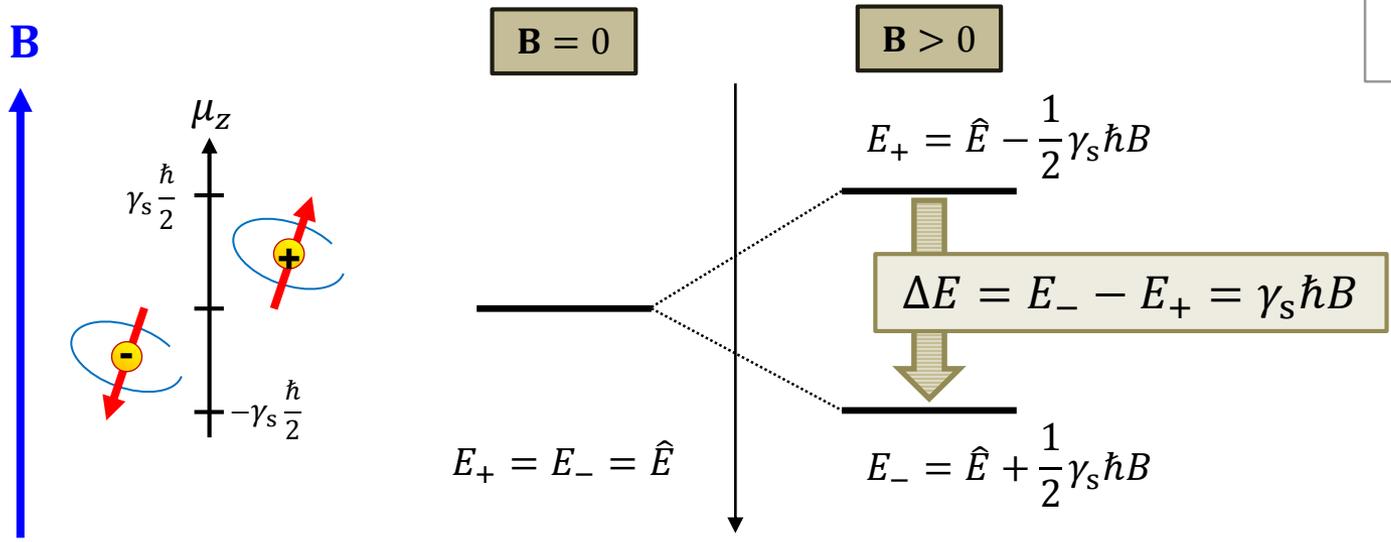
$B > 0$      $\wp(\oplus) > \wp(\ominus)$

$10^6$  dipôles



# Ce que dit la mécanique quantique

## Considérations énergétiques



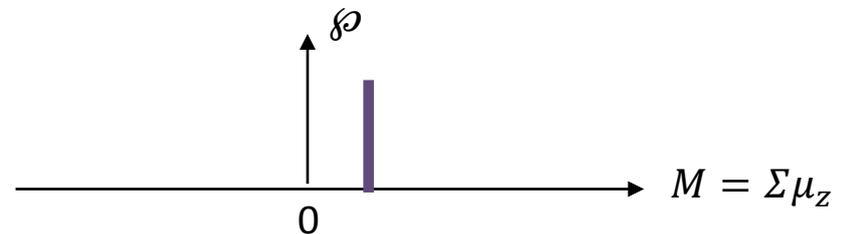
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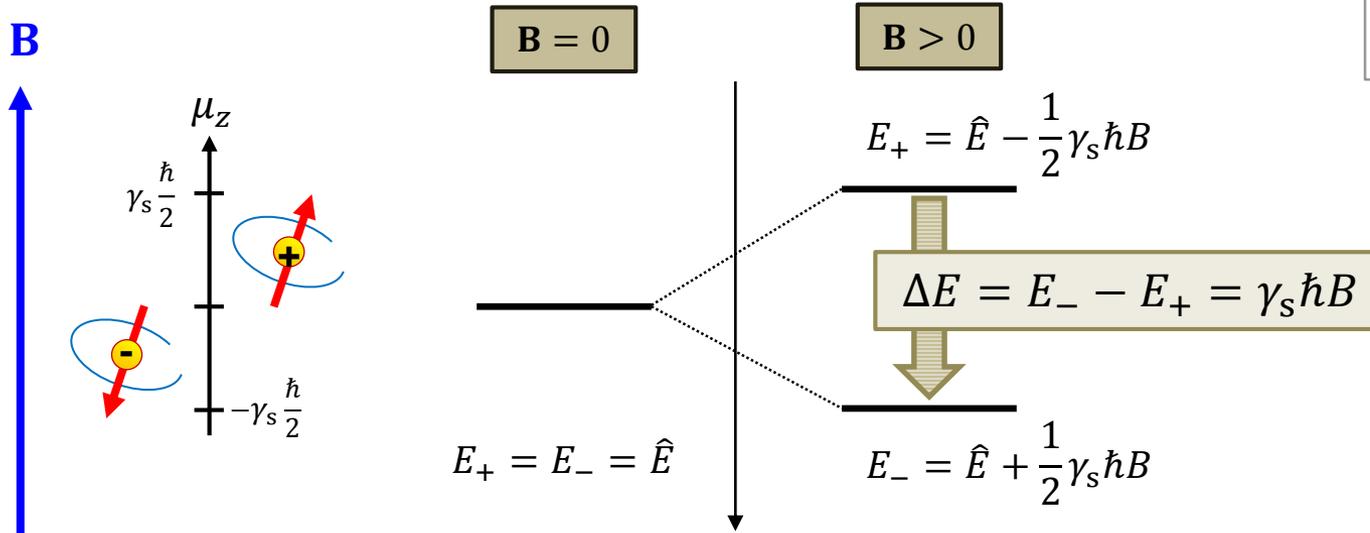
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$10^{20}$  dipôles



# Ce que dit la mécanique quantique

## Considérations énergétiques



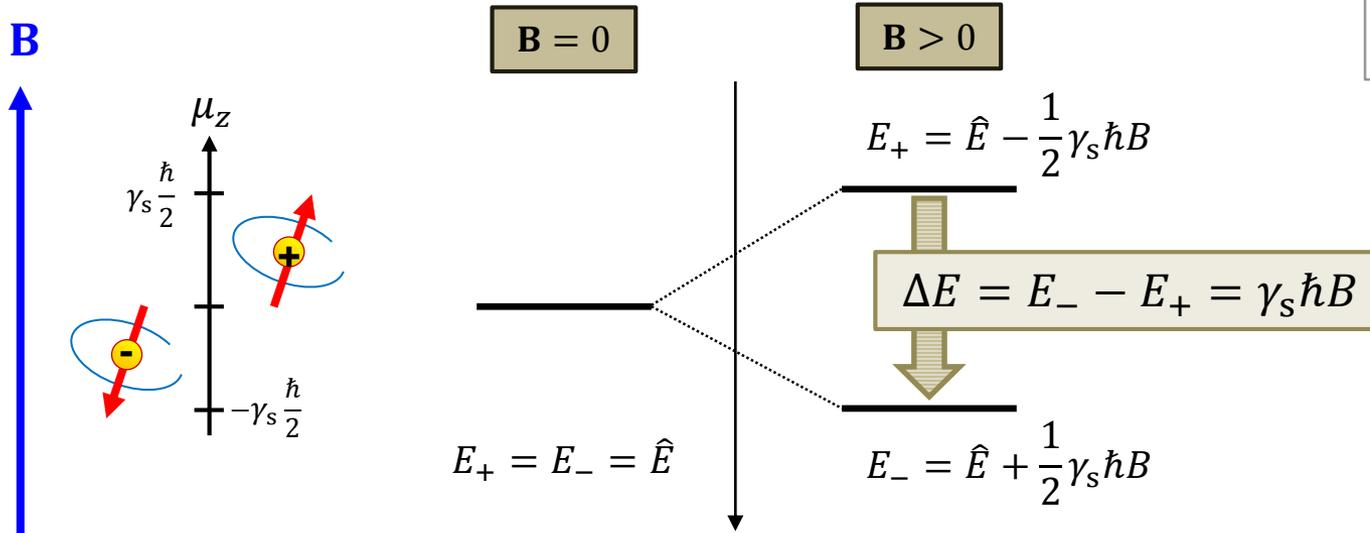
## Ce que dit la physique statistique :

Particule indépendantes  
Etats  $i$  d'énergie  $E_i$   
Température suffisante  
Equilibre thermique

$$\wp_i \propto e^{-\frac{E_i}{kT}}$$
$$N_i = N \wp_i$$

# Ce que dit la mécanique quantique

## Considérations énergétiques



## Ce que dit la physique statistique :

*Particule indépendantes  
Etats  $i$  d'énergie  $E_i$   
Température suffisante  
Equilibre thermique*

$$\wp_i \propto e^{-\frac{E_i}{kT}}$$

$$N_i = N \wp_i$$

$$\frac{\Delta N}{N} = \frac{N_+ - N_-}{N_+ + N_-} = \frac{\frac{N_+ - 1}{N_-} - 1}{\frac{N_+ - 1}{N_-} + 1}$$

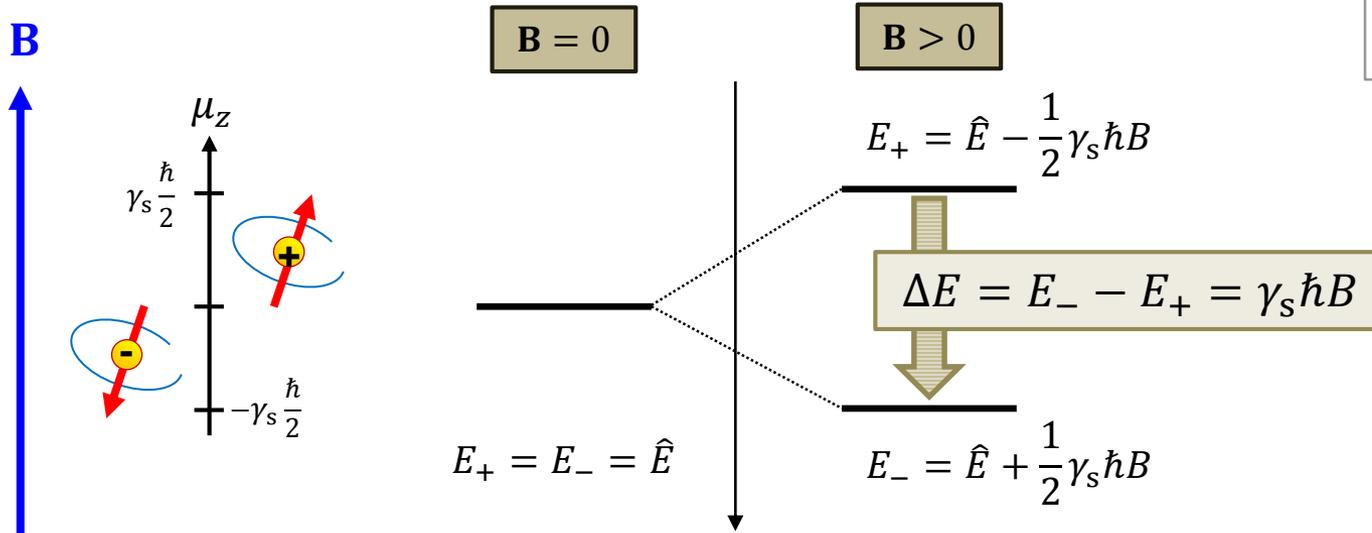
$$= \frac{\frac{\Delta E}{e^{kT}} - 1}{\frac{\Delta E}{e^{kT}} + 1} \approx \frac{\frac{\Delta E}{kT}}{\frac{\Delta E}{kT} + 2}$$

$$\sim \frac{\Delta E}{2kT} \sim \frac{1}{1000}$$



# Ce que dit la mécanique quantique

## Considérations énergétiques



## Ce que dit la physique statistique :

*Particules indépendantes  
Etats  $i$  d'énergie  $E_i$   
Température suffisante  
Equilibre thermique*

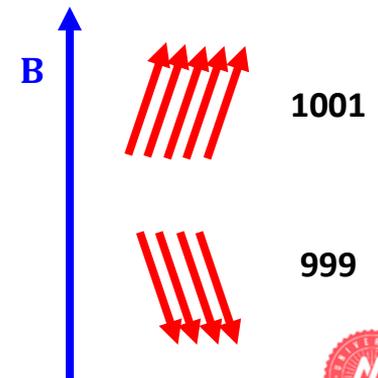
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$$\sim \frac{\Delta E}{2kT} \sim \frac{1}{1000}$$



# Ce que dit la mécanique quantique

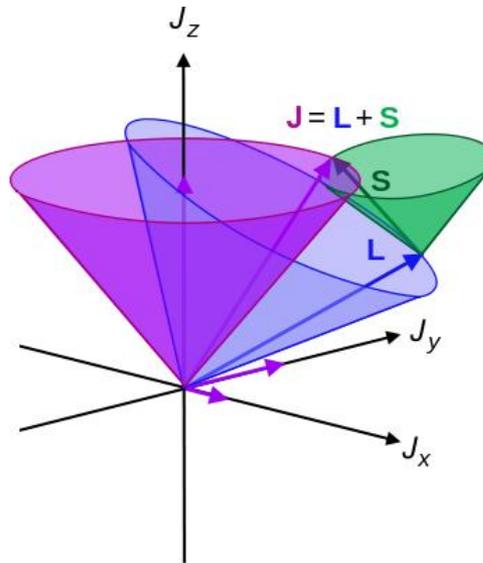
## Composition des moments cinétiques

Moment cinétique total  $\mathbf{J}$

$$\mathbf{J} = \mathbf{L} + \mathbf{S}$$

$$|\mathbf{J}| = \hbar \sqrt{j(j+1)}$$

$$j = |l - s|, \dots, l + s$$



# Ce que dit la mécanique quantique

## Composition des moments cinétiques

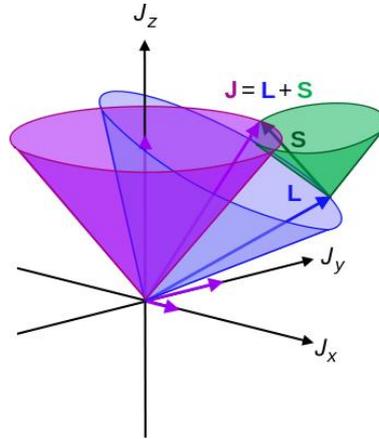
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$$\mathbf{J} = \mathbf{L} + \mathbf{S}$$

$$|\mathbf{J}| = \hbar \sqrt{j(j+1)}$$

$$j = |l - s|, \dots, l + s$$

$$\text{Electron : } j = l - \frac{1}{2}, l + \frac{1}{2}$$



$l$	
2	<u>d</u>
1	<u>p</u>
0	<u>s</u>

# Ce que dit la mécanique quantique

## Composition des moments cinétiques

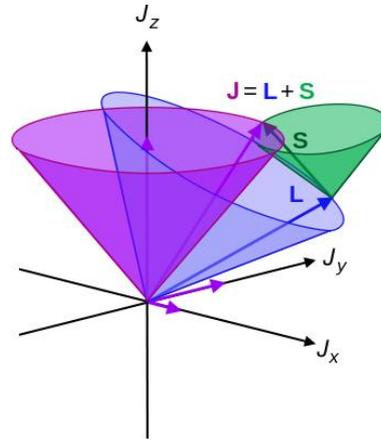
Moment cinétique total  $\mathbf{J}$

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$$j = |l - s|, \dots, l + s$$

$$\text{Electron : } j = l - \frac{1}{2}, l + \frac{1}{2}$$



$l$		$j$
2	d	$d_{5/2}$ 5/2
		$d_{3/2}$ 3/2
1	p	$p_{3/2}$
		$p_{1/2}$ 1/2
0	s	$s_{1/2}$

# Ce que dit la mécanique quantique

## Composition des moments cinétiques

Moment cinétique total  $\mathbf{J}$

$$\mathbf{J} = \mathbf{L} + \mathbf{S}$$

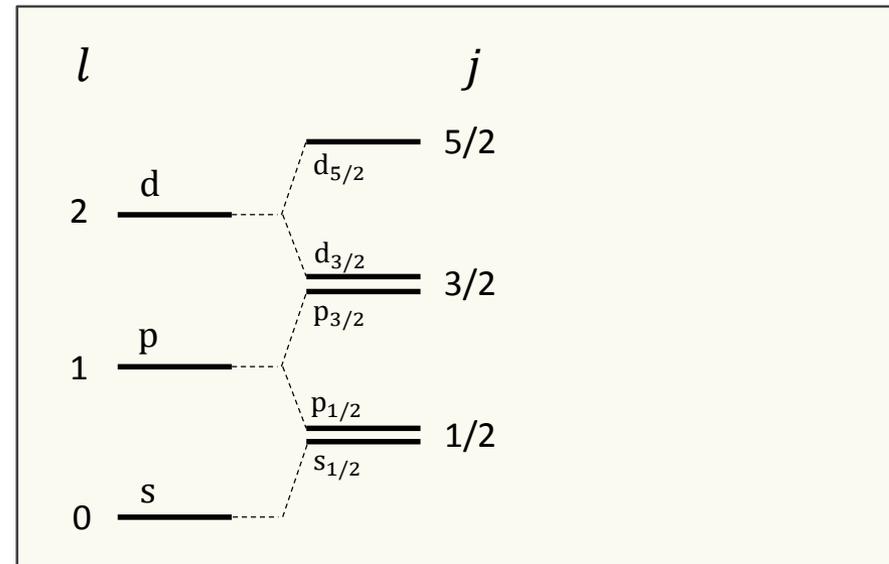
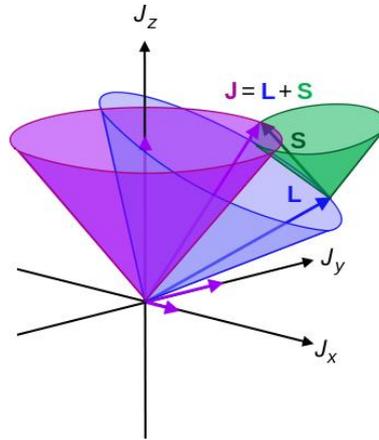
$$|\mathbf{J}| = \hbar \sqrt{j(j+1)}$$

$$j = |l - s|, \dots, l + s$$

$$\text{Electron : } j = l - \frac{1}{2}, l + \frac{1}{2}$$

$$J_z = m_j \hbar = -j\hbar \dots j\hbar$$

Etat  $(n, l, j, m_j)$



# Ce que dit la mécanique quantique

## Composition des moments cinétiques

Moment cinétique total  $\mathbf{J}$

$$\mathbf{J} = \mathbf{L} + \mathbf{S}$$

$$|\mathbf{J}| = \hbar \sqrt{j(j+1)}$$

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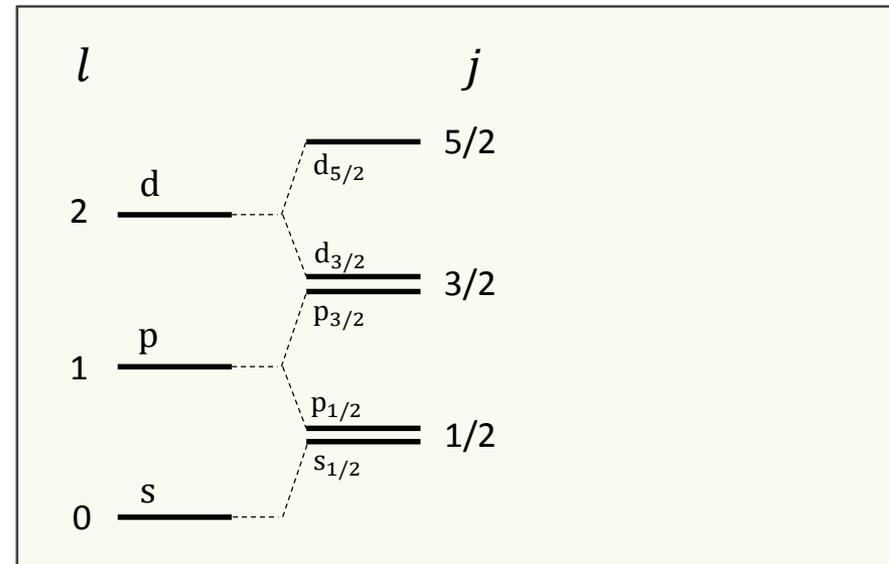
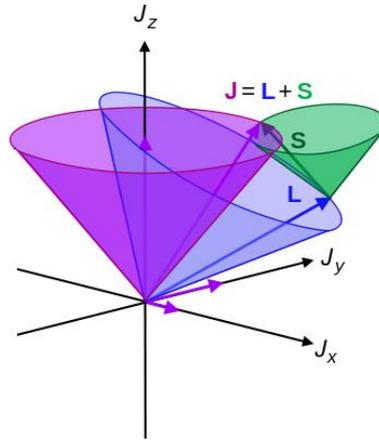
$$J_z = m_j \hbar = -j \hbar \dots j \hbar$$

Etat  $(n, l, j, m_j)$

Il s'y associe un moment magnétique :

$$\boldsymbol{\mu} = \gamma \mathbf{J} = g \gamma_0 \mathbf{J}$$

$\gamma$  rapport gyromagnétique  
 $g$  facteur de Landé



# Ce que dit la mécanique quantique

## Composition des moments cinétiques

Moment cinétique total  $\mathbf{J}$

$$\mathbf{J} = \mathbf{L} + \mathbf{S}$$

$$|\mathbf{J}| = \hbar \sqrt{j(j+1)}$$

$$j = |l - s|, \dots, l + s$$

$$\text{Electron : } j = l - \frac{1}{2}, l + \frac{1}{2}$$

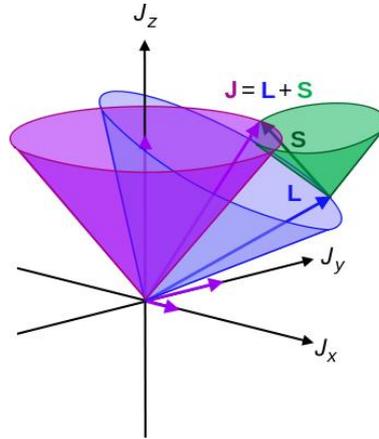
$$J_z = m_j \hbar = -j\hbar \dots j\hbar$$

Etat  $(n, l, j, m_j)$

Il s'y associe un moment magnétique :

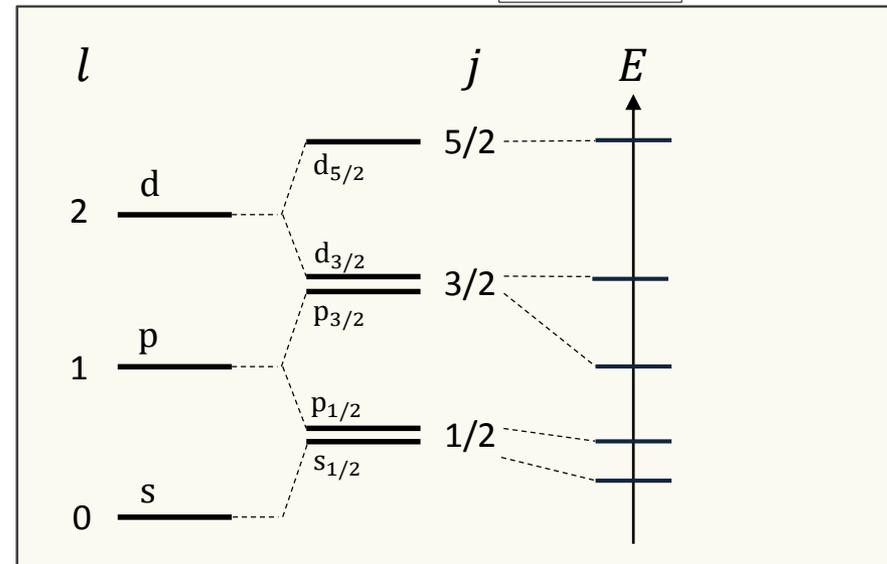
$$\boldsymbol{\mu} = \gamma \mathbf{J} = g \gamma_0 \mathbf{J}$$

$\gamma$  rapport gyromagnétique  
 $g$  facteur de Landé



$$\mathbf{B} = 0$$

$$E \sim (n, l, j)$$



# Ce que dit la mécanique quantique

## Composition des moments cinétiques

Moment cinétique total  $\mathbf{J}$

$$\mathbf{J} = \mathbf{L} + \mathbf{S}$$

$$|\mathbf{J}| = \hbar \sqrt{j(j+1)}$$

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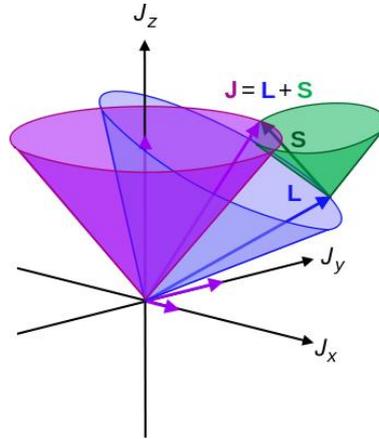
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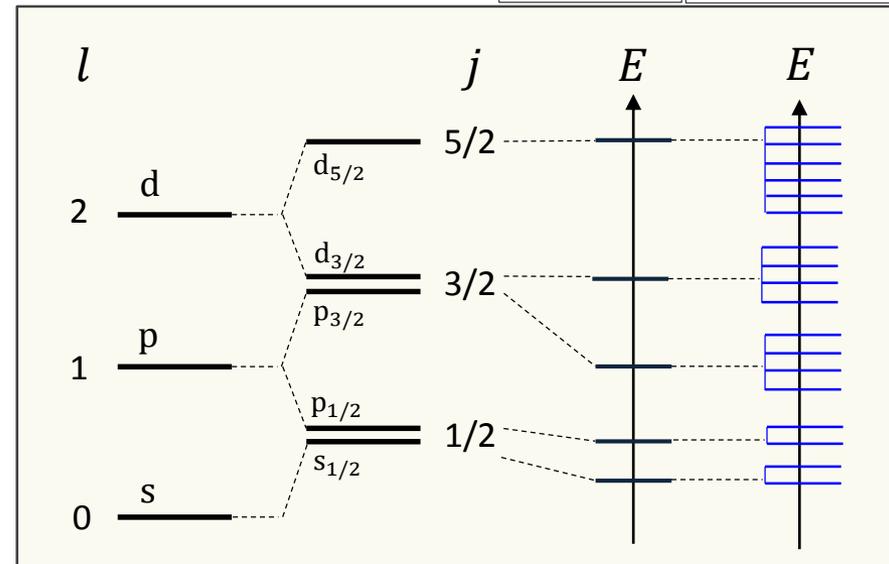
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$\gamma$  rapport gyromagnétique  
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$\mathbf{B} = 0$	$\mathbf{B} > 0$
$E \sim (n, l, j)$	$E \sim (n, l, j, m_j)$



# Ce que dit la mécanique quantique

## Composition des moments cinétiques

Moment cinétique total  $\mathbf{J}$

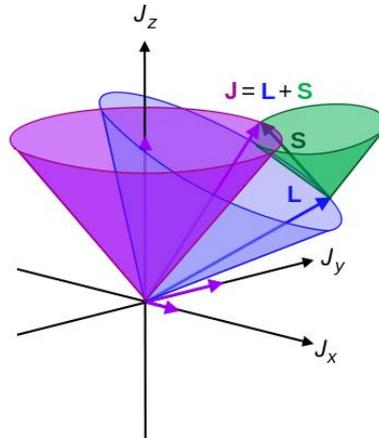
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$$j = |l - s|, \dots, l + s$$

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Etat  $(n, l, j, m_j)$

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$$\Delta E = \Delta \mu_z B$$

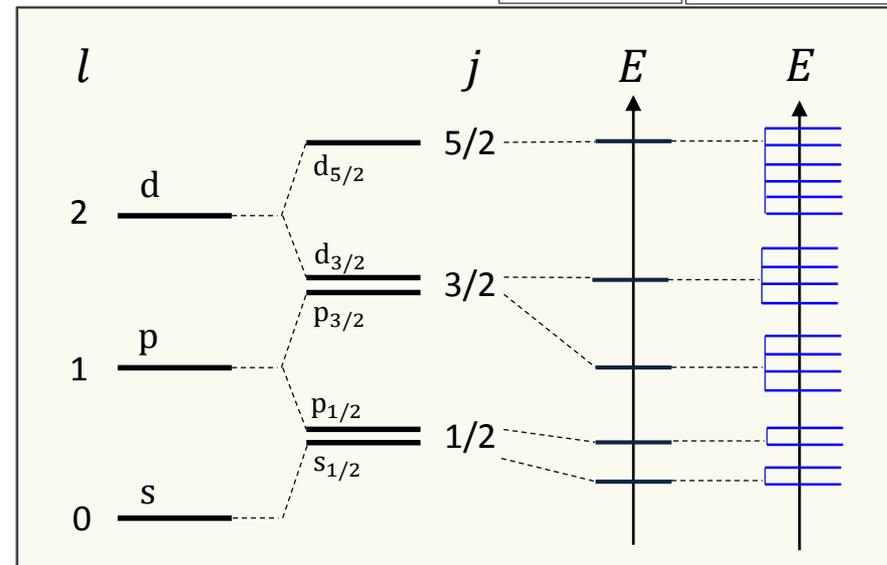
$$= \gamma \Delta J_z B = \gamma \hbar B$$

$$= g \gamma_0 \hbar B = g B \mu_B$$

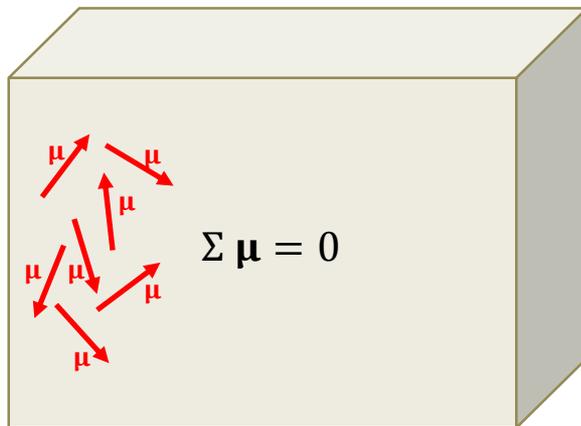
$$\text{magnéton de Bohr } \mu_B = \frac{e \hbar}{2 m_e}$$

$$\mu_z = g m_j \mu_B$$

$\mathbf{B} = 0$	$\mathbf{B} > 0$
$E \sim (n, l, j)$	$E \sim (n, l, j, m_j)$

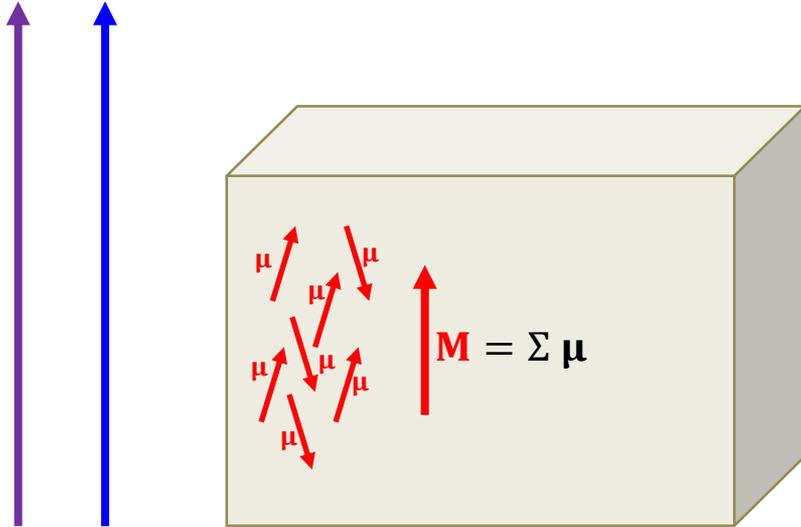


# Magnétisme dans la matière



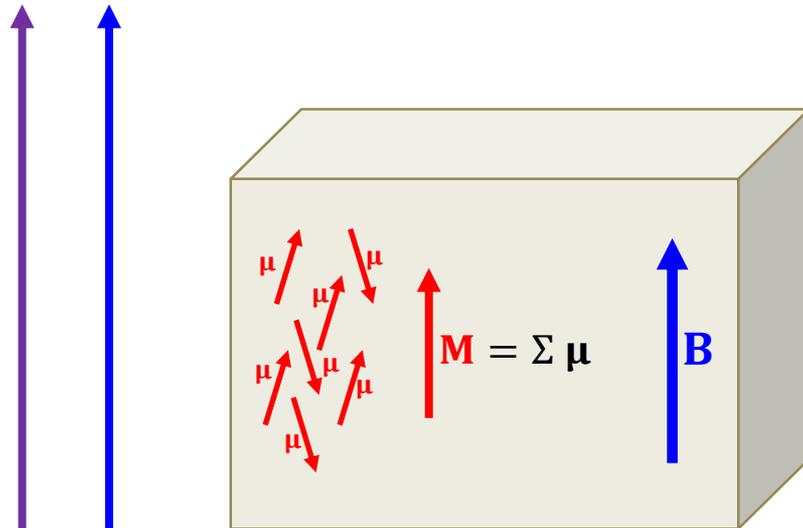
# Magnétisme dans la matière

$\mathbf{H}$     $\mathbf{B}_0 = \mu_0 \mathbf{H}$     $\mu_0$  : perméabilité magnétique du vide



# Magnétisme dans la matière

$\mathbf{H}$   $\mathbf{B}_0 = \mu_0 \mathbf{H}$   $\mu_0$  : perméabilité magnétique du vide



$$\mathbf{B} = \mu \mathbf{H}$$

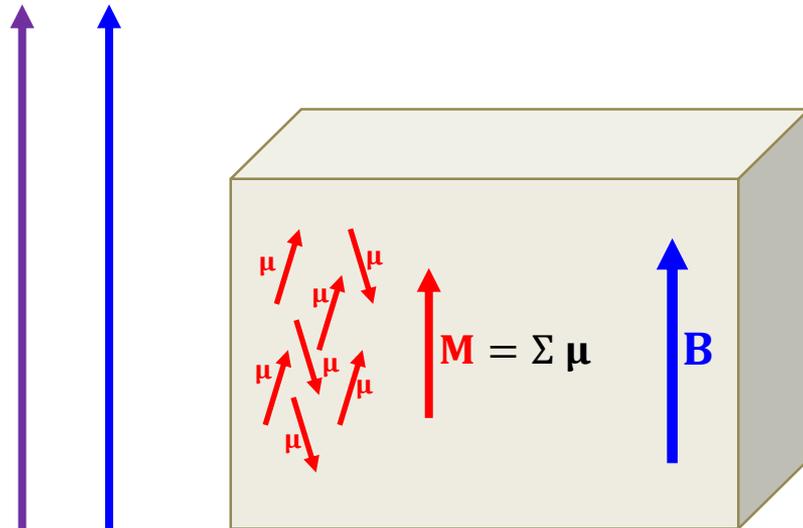
$$= \mu_0 (1 + \chi) \mathbf{H}$$

$\mu$  : perméabilité magnétique du matériau

$\chi$  : susceptibilité magnétique

# Magnétisme dans la matière

$\mathbf{H}$   $\mathbf{B}_0 = \mu_0 \mathbf{H}$   $\mu_0$  : perméabilité magnétique du vide



$$\mathbf{B} = \mu \mathbf{H}$$

$$= \mu_0 (1 + \chi) \mathbf{H}$$

$$= \mu_0 (\mathbf{H} + \mathbf{H}')$$

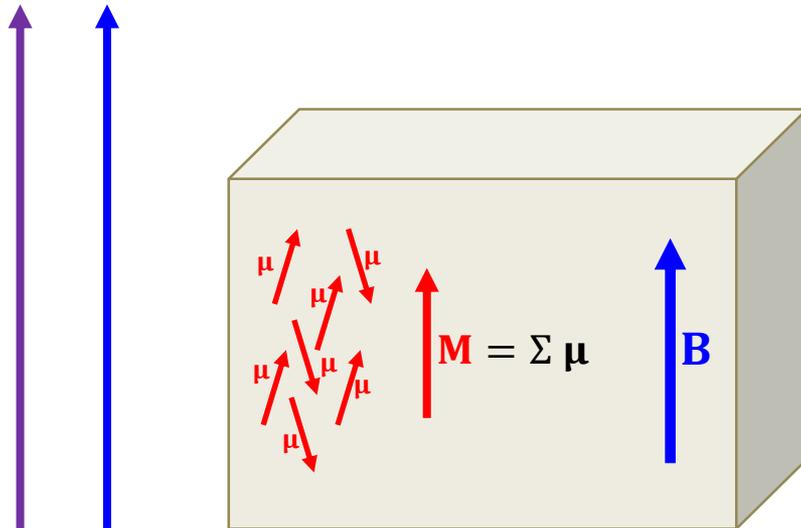
$\mu$  : perméabilité magnétique  
du matériau

$\chi$  : susceptibilité magnétique

$\mathbf{H}' = \frac{d\mathbf{M}}{dV}$  : aimantation volumique

# Magnétisme dans la matière

$\mathbf{H}$   $\mathbf{B}_0 = \mu_0 \mathbf{H}$   $\mu_0$  : perméabilité magnétique du vide



$$\mathbf{B} = \mu \mathbf{H}$$

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$\mu$  : perméabilité magnétique du matériau

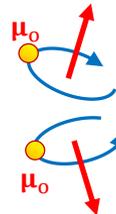
$\chi$  : susceptibilité magnétique

$\mathbf{H}' = \frac{d\mathbf{M}}{dV}$  : aimantation volumique

## Diamagnétisme

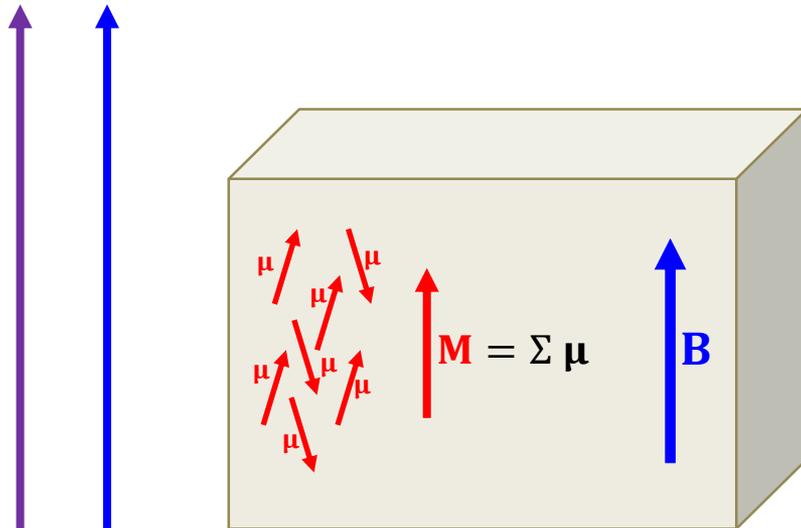
*Doublets d'électrons*

*Absence de moment permanent  $\mathbf{J} = 0$*



# Magnétisme dans la matière

$\mathbf{H}$   $\mathbf{B}_0 = \mu_0 \mathbf{H}$   $\mu_0$  : perméabilité magnétique du vide



$$\mathbf{B} = \mu \mathbf{H}$$

$$= \mu_0 (1 + \chi) \mathbf{H}$$

$$= \mu_0 (\mathbf{H} + \mathbf{H}')$$

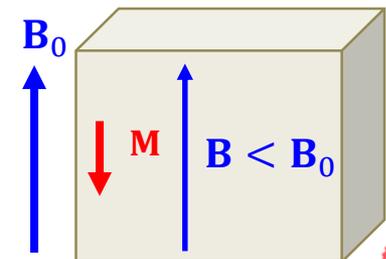
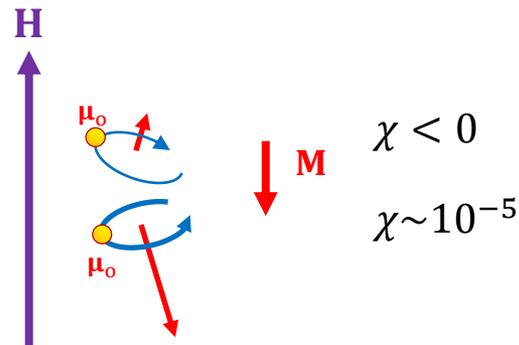
$\mu$  : perméabilité magnétique du matériau

$\chi$  : susceptibilité magnétique

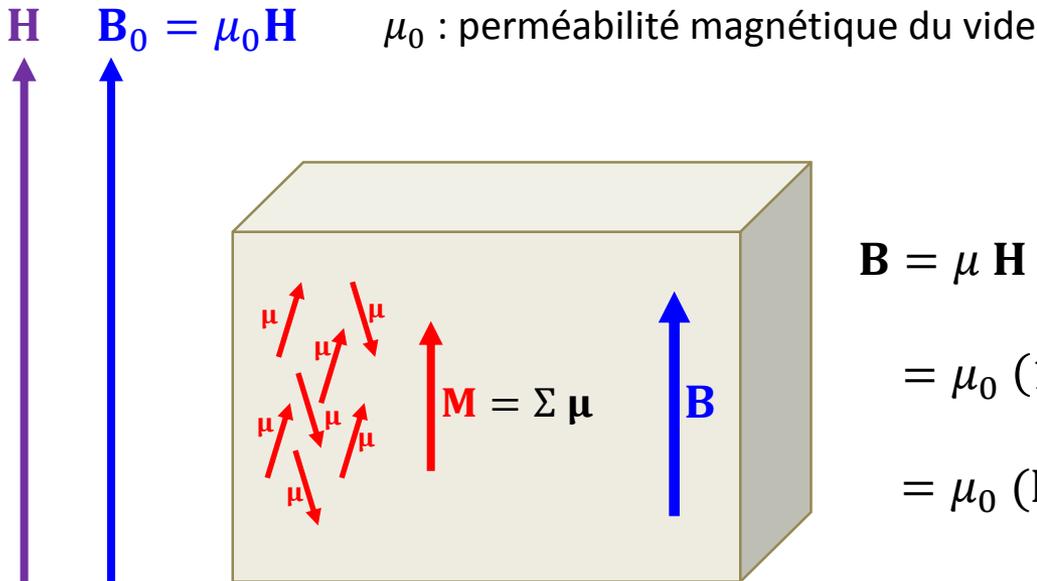
$\mathbf{H}' = \frac{d\mathbf{M}}{dV}$  : aimantation volumique

## Diamagnétisme

*Doublets d'électrons*  
*Absence de moment permanent  $\mathbf{J} = 0$*   
*Modification du mouvement orbital*



# Magnétisme dans la matière



$$\mathbf{B} = \mu \mathbf{H}$$

$$= \mu_0 (1 + \chi) \mathbf{H}$$

$$= \mu_0 (\mathbf{H} + \mathbf{H}')$$

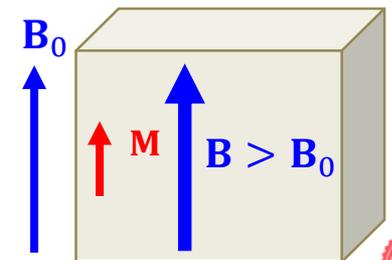
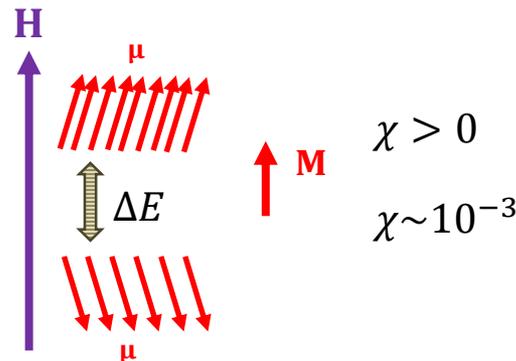
$\mu$  : perméabilité magnétique du matériau

$\chi$  : susceptibilité magnétique

$\mathbf{H}' = \frac{d\mathbf{M}}{dV}$  : aimantation volumique

## Paramagnétisme

*Electrons de valence non appariés*  
*Moment permanent  $\mathbf{J}$*   
*Alignement sur  $\mathbf{B}_0$*   
*Température dépendant*

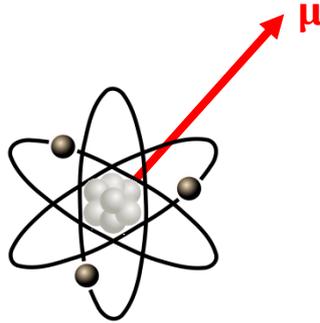


# Magnétisme nucléaire

## Magnétisme atomique essentiellement électronique

- Moment cinétique total  $\mathbf{J}$
- Moment magnétique permanent  $\boldsymbol{\mu}$

$$\boldsymbol{\mu} = \gamma_e \mathbf{J} \quad \bar{\gamma}_e \sim \text{GHz T}^{-1}$$



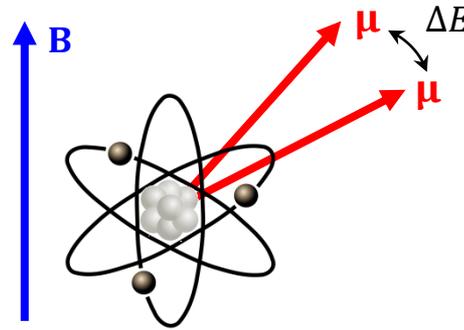
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$$\Delta E = \Delta \mu_z B = g B \mu_B$$



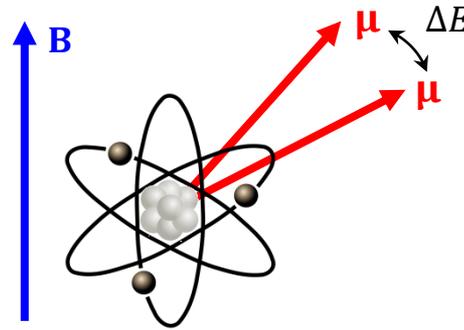
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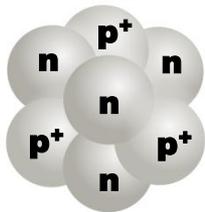
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## Noyau = protons + neutrons



- Moment cinétique total  $\mathbf{J}$  : « SPIN »
- Moment magnétique permanent  $\boldsymbol{\mu}$  : « SPIN »

$$\boldsymbol{\mu} = \gamma_N \mathbf{J} \quad \bar{\gamma}_N \sim \text{MHz T}^{-1}$$

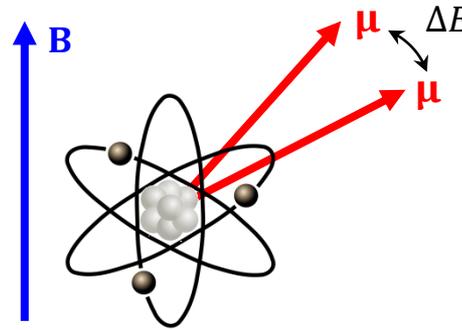
# Magnétisme nucléaire

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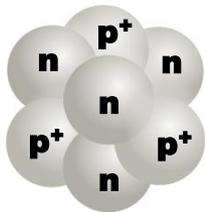
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$$\boldsymbol{\mu} = \gamma_N \mathbf{J} \quad \bar{\gamma}_N \sim \text{MHz T}^{-1}$$

$$\Delta E = \Delta \mu_z B = g B \mu_N$$

$$\text{magnéton nucléaire} \quad \mu_N = \frac{e \hbar}{2 m_p} \ll \mu_B$$

$$\gamma_N = g \frac{e}{2 m_p}$$

**Proton** :  $g = 5,6$       **Neutron** :  $g = -3,8$



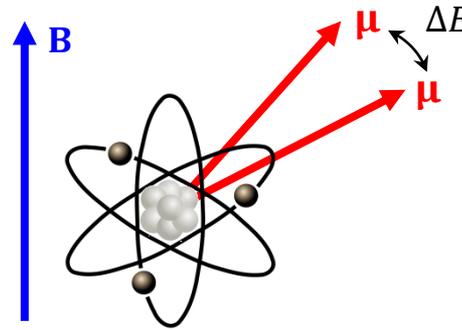
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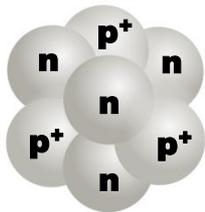
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## Noyau = protons + neutrons



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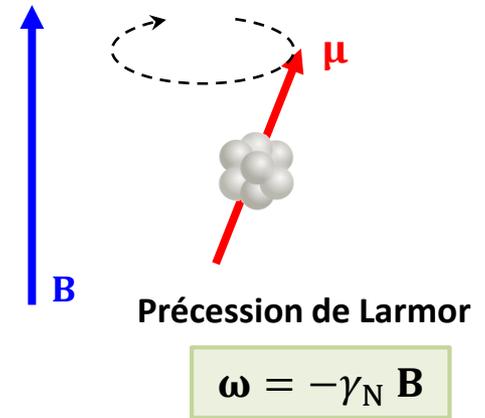
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magnéton nucléaire  $\mu_N = \frac{e \hbar}{2 m_p} \ll \mu_B$

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Précession de Larmor

$$\boldsymbol{\omega} = -\gamma_N \mathbf{B}$$

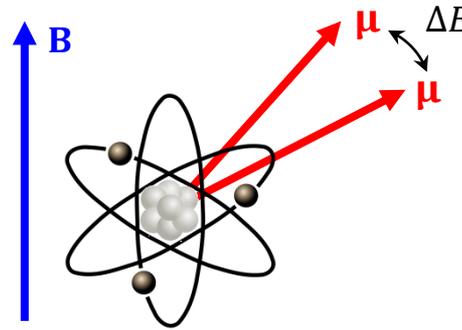
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## Noyau $^1\text{H} = 1$ proton

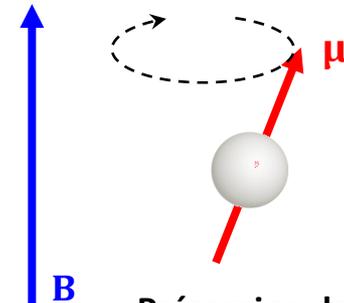


- Moment cinétique total  $\mathbf{J}$  : « SPIN »
- Moment magnétique permanent  $\boldsymbol{\mu}$  : « SPIN »

$$\boldsymbol{\mu} = \gamma_p \mathbf{J}$$

$$\Delta E = \Delta \mu_z B = g B \mu_N$$

$$\bar{\gamma}_p = 42,6 \text{ MHz T}^{-1}$$



### Précession de Larmor

$$B = 1,5 \text{ T} : \nu = 64 \text{ MHz}$$

$$B = 3 \text{ T} : \nu = 128 \text{ MHz}$$

ondes radio

# Magnétisme nucléaire

<i>Nucleus</i>	<i>Spin</i>	<i>Landé factor</i>
proton p	1/2	5.5883
neutron n	1/2	-3.8263
deuteron ${}^2_1\text{D}$	1	0.85742
${}^3_2\text{He}$	1/2	-4.255
${}^4_2\text{He}$	0	—
${}^{12}_6\text{C}$	0	—
${}^{16}_8\text{O}$	0	—
${}^{39}_{19}\text{K}$	3/2	0.2609
${}^{67}_{30}\text{Zn}$	5/2	0.35028
${}^{85}_{37}\text{Rb}$	5/2	0.54108
${}^{129}_{54}\text{Xe}$	1/2	-1.5536
${}^{133}_{55}\text{Cs}$	7/2	0.7369
${}^{199}_{80}\text{Hg}$	1/2	1.0054
${}^{201}_{80}\text{Hg}$	3/2	-0.37113

➤ Spin dépend de la composition du noyau



# Magnétisme nucléaire

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➤ Spin dépend de la composition du noyau

➤ Pas de spin  $\Leftrightarrow$  Pas de magnétisme



# Magnétisme nucléaire

<i>Nucleus</i>	<i>Spin</i>	<i>Landé factor</i>
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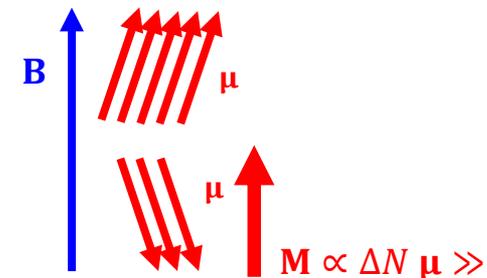
- Spin dépend de la composition du noyau
- Pas de spin  $\Leftrightarrow$  Pas de magnétisme
- ${}^1\text{H} = \text{p}^+$  : magnétisme maximal

# Magnétisme nucléaire

<i>Nucleus</i>	<i>Spin</i>	<i>Landé factor</i>
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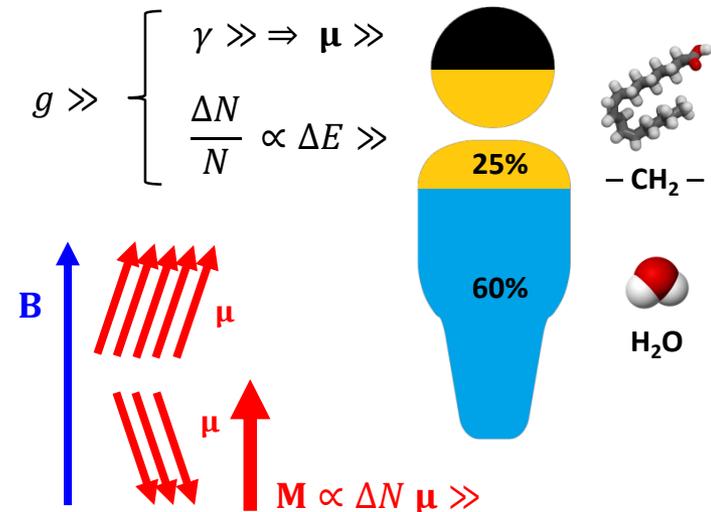
$$g \gg \begin{cases} \gamma \gg \Rightarrow \mu \gg \\ \frac{\Delta N}{N} \propto \Delta E \gg \end{cases}$$



# Magnétisme nucléaire

<i>Nucleus</i>	<i>Spin</i>	<i>Landé factor</i>
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# RMN – principe

## Prix Nobel

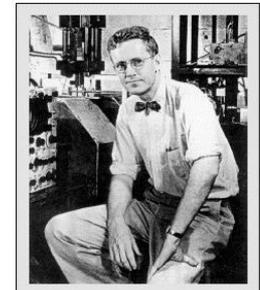
<i>Lauréats</i>	<i>Année</i>	<i>Discipline</i>	<i>Travaux</i>
O. Stern	1943	Physique	Moment magnétique du proton (1933)
I. Rabi	1944	Physique	RMN
F. Bloch & E. Purcell	1952	Physique	RMN
R. Ernst	1991	Chimie	Spectroscopie RMN haute résolution
P. Lauterbur & P. Mansfield	2003	Médecine	IRM



I. Rabi



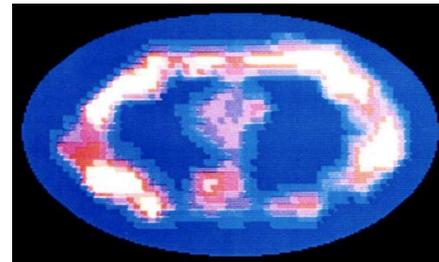
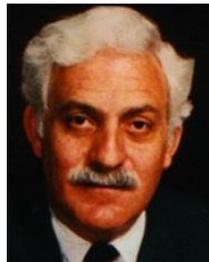
F. Bloch (Stanford)



E. Purcell (Harvard)

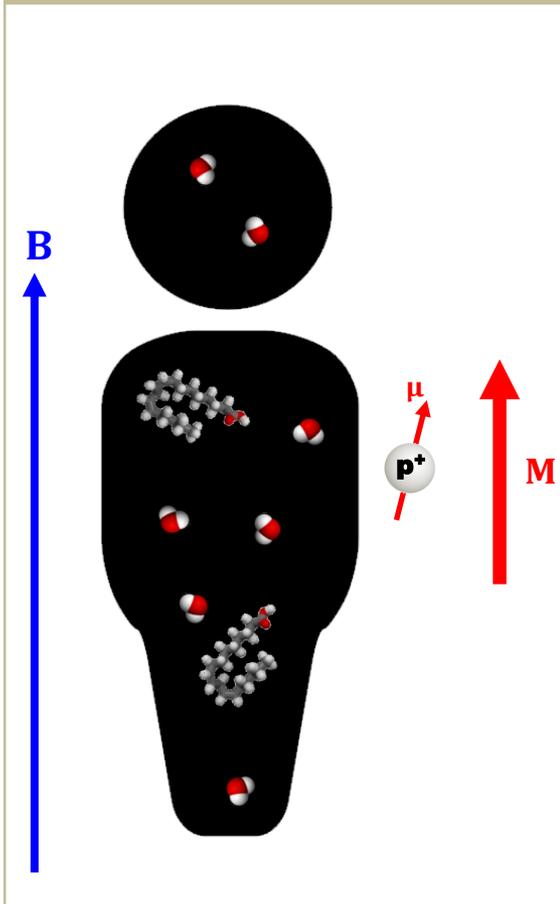
*et bien d'autres...*

**R. DAMADIAN**



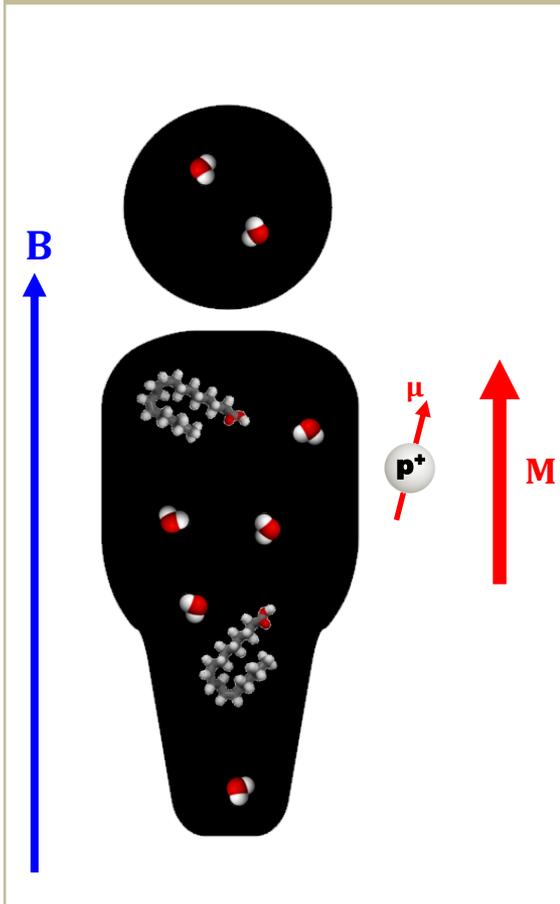
# RMN – principe

## 1. Préparation (aimantation)

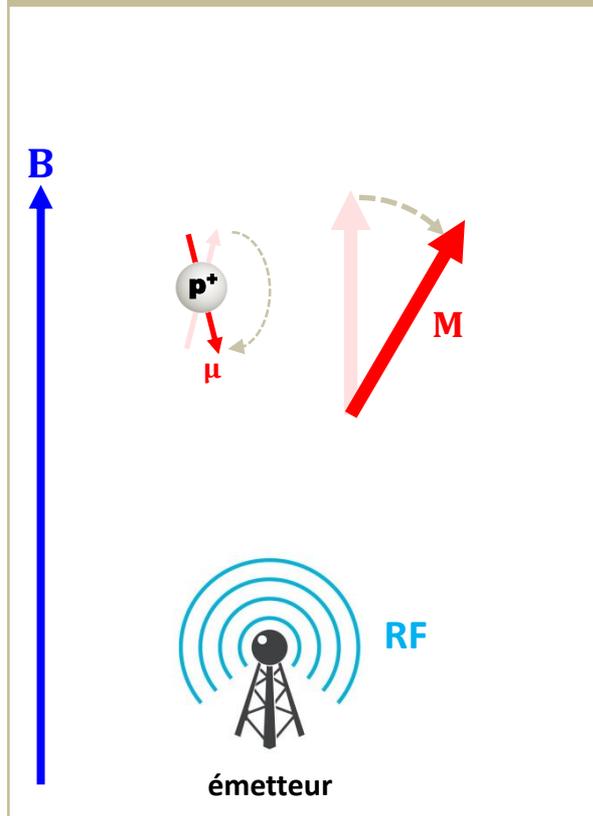


# RMN – principe

## 1. Préparation (aimantation)

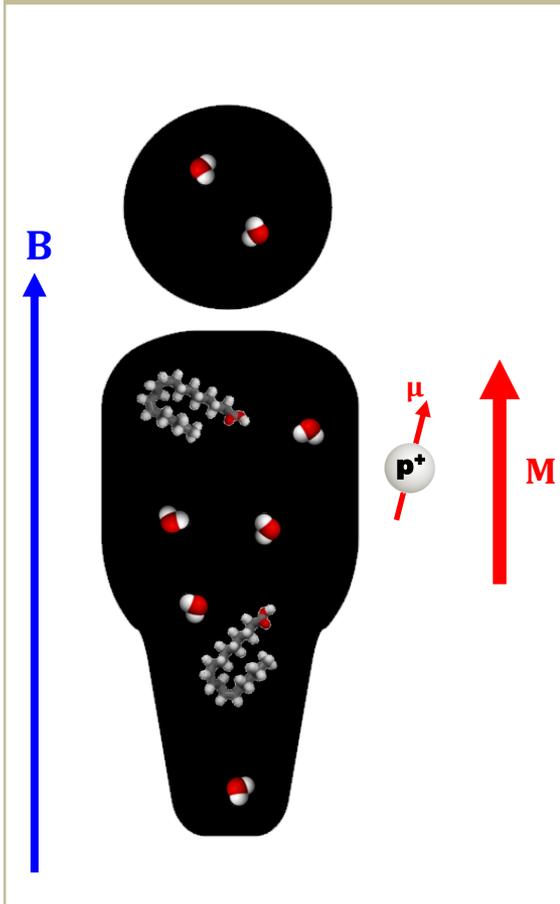


## 2. Perturbation (résonance)

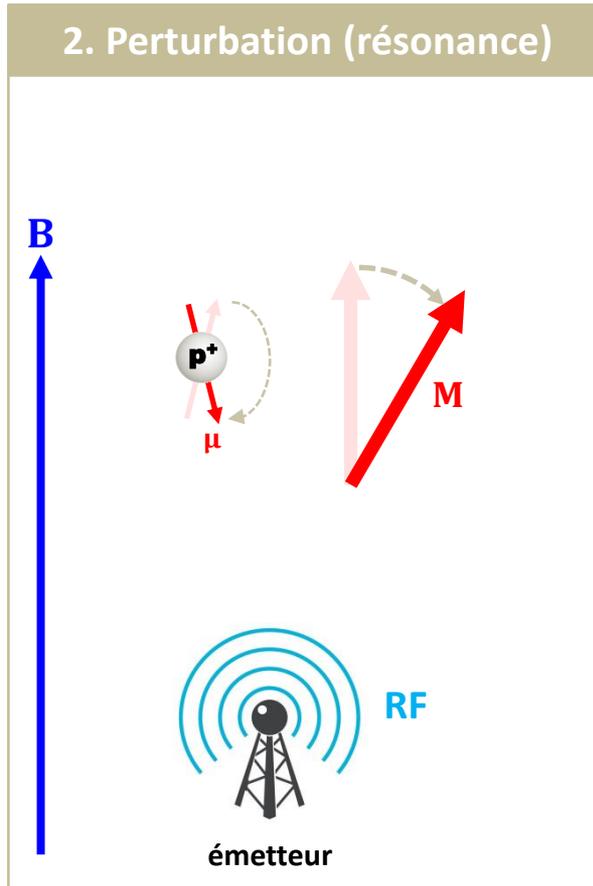


# RMN – principe

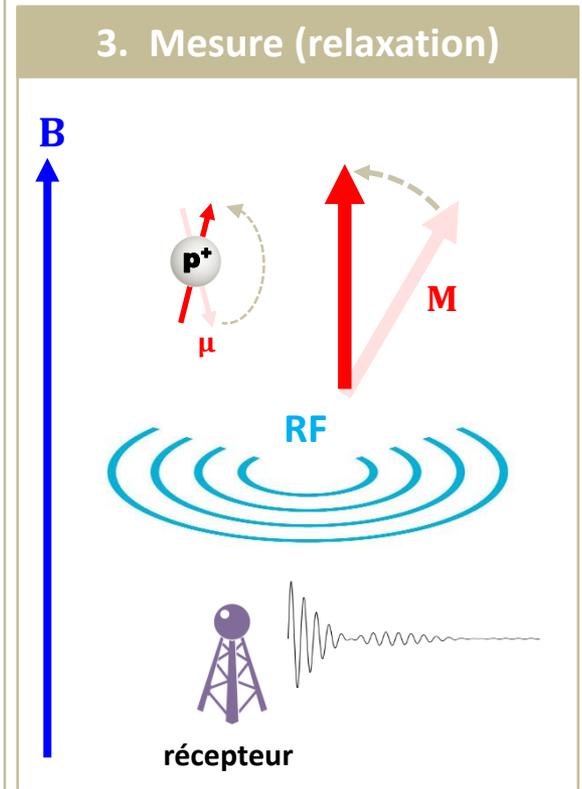
## 1. Préparation (aimantation)



## 2. Perturbation (résonance)

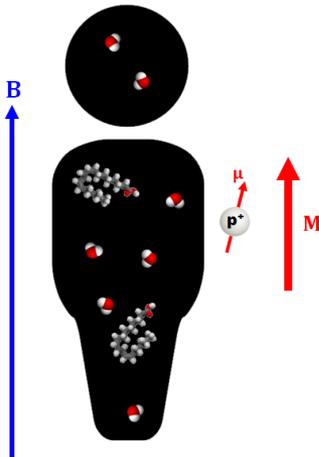


## 3. Mesure (relaxation)

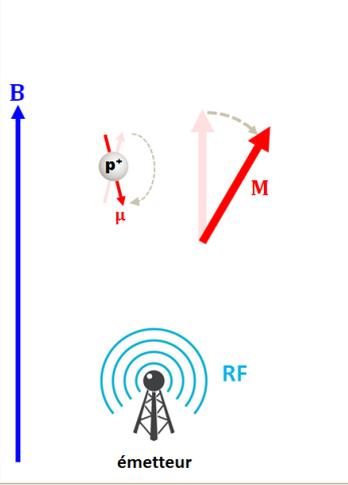


# RMN – principe

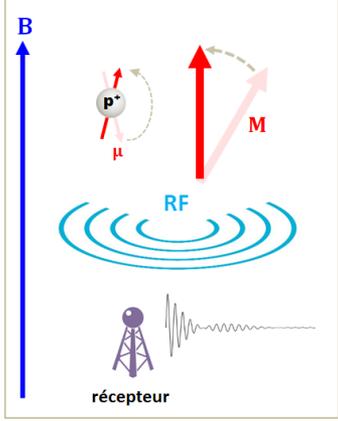
## 1. Préparation (aimantation)



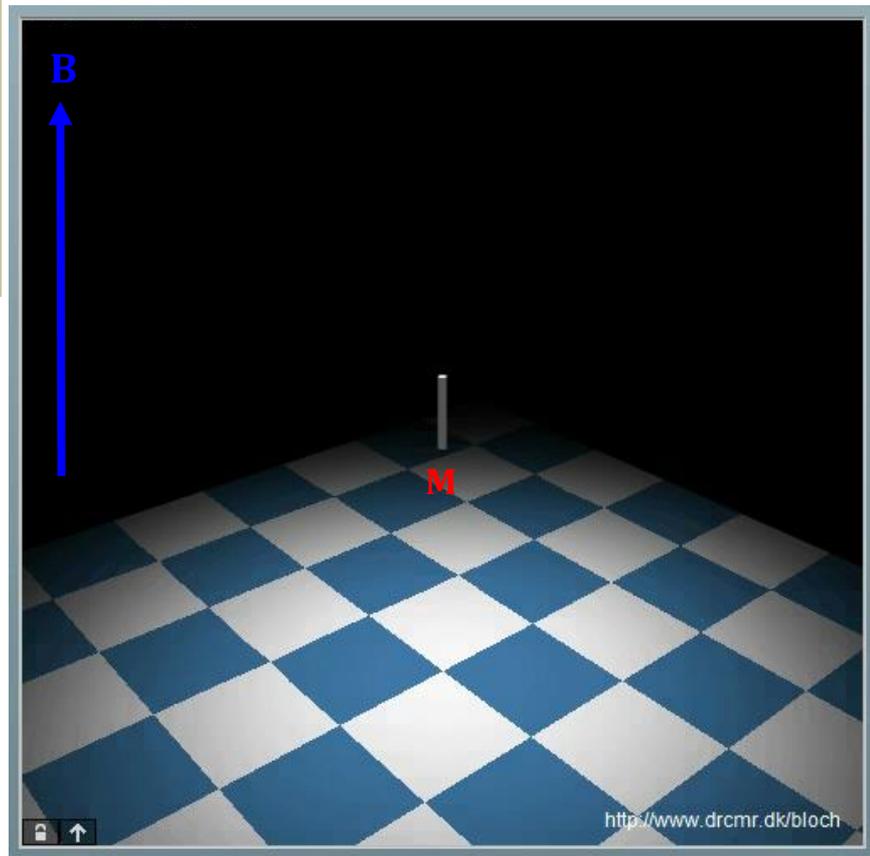
## 2. Perturbation (résonance)



## 3. Mesure (relaxation)



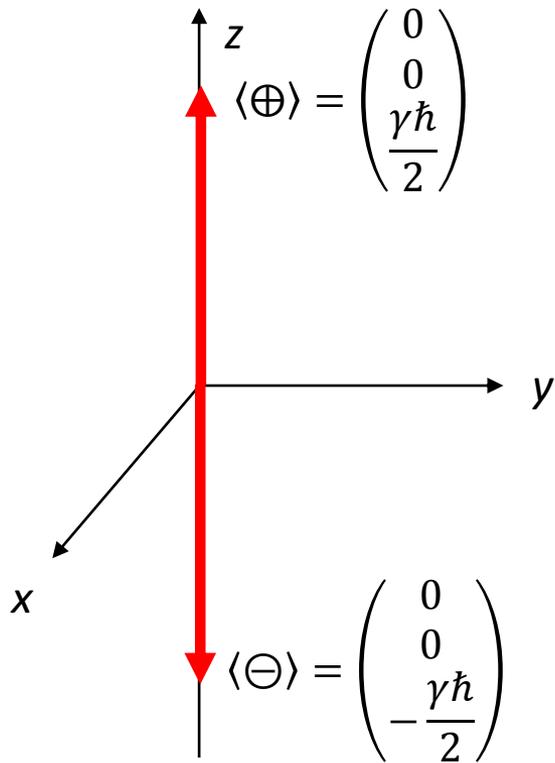
LG Hanson. Bloch Simulator.  
([www.drcmr.dk/bloch](http://www.drcmr.dk/bloch))



<http://www.drcmr.dk/bloch>

# RMN – principe

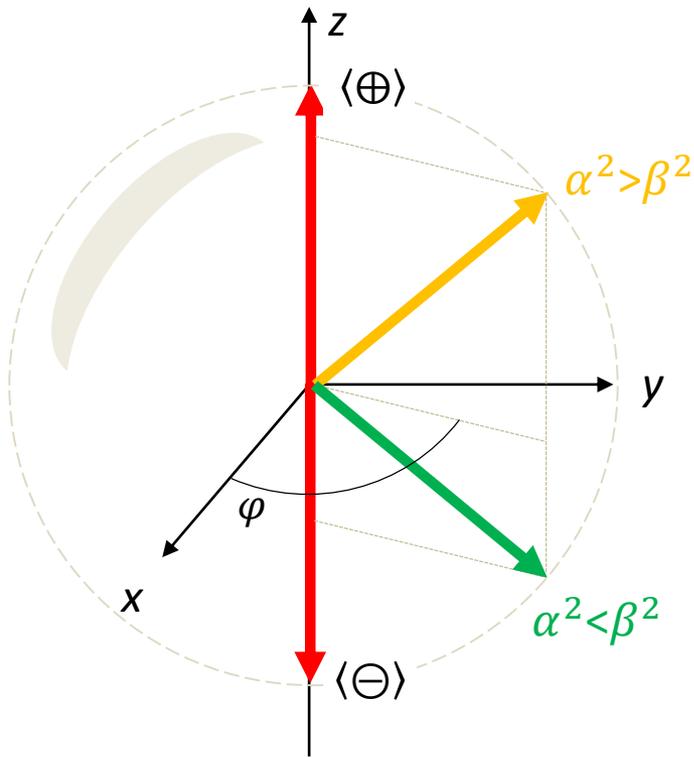
Représentation des spins  $\mu$  via  $\langle \mu \rangle$



$$\langle \mu \rangle = \begin{pmatrix} \langle \mu_x \rangle \\ \langle \mu_y \rangle \\ \langle \mu_z \rangle \end{pmatrix}$$

# RMN – principe

Représentation des spins  $\mu$  via  $\langle \mu \rangle$



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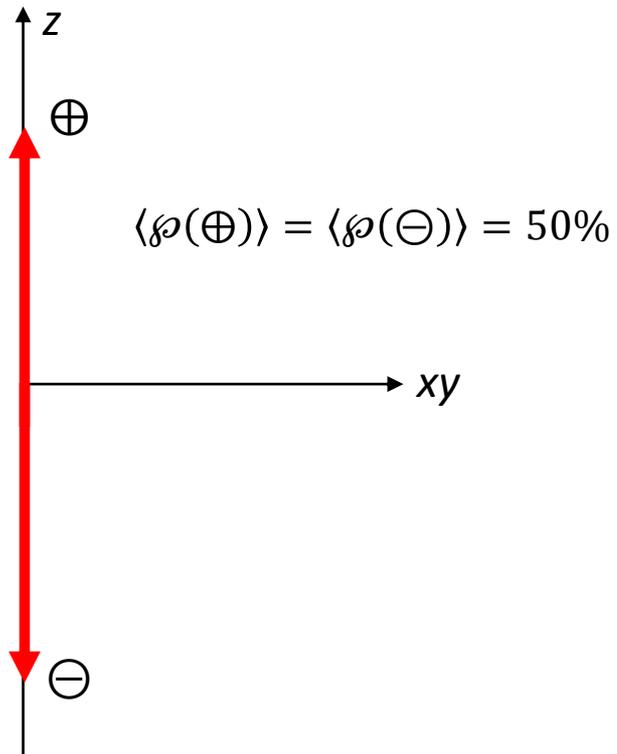
$$|\mu\rangle = \alpha|\oplus\rangle + \beta|\ominus\rangle$$

# RMN – principe

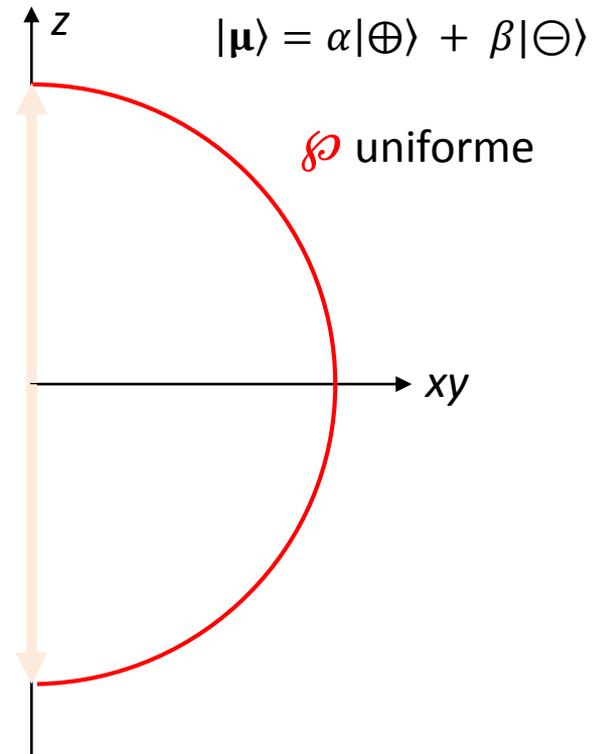
## Représentation statistique (fréquentiste) des spins

$$B_0 = 0$$

### Mesures individuelles accessibles



### Etats superposés

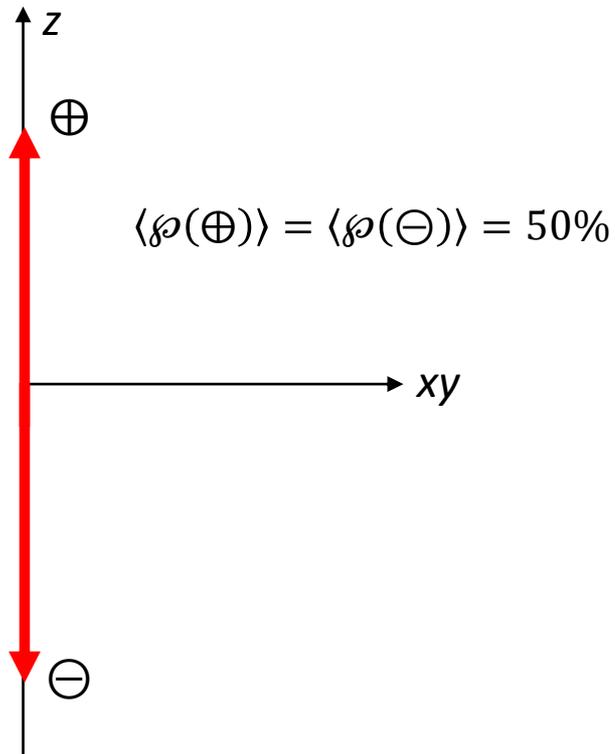


# RMN – principe

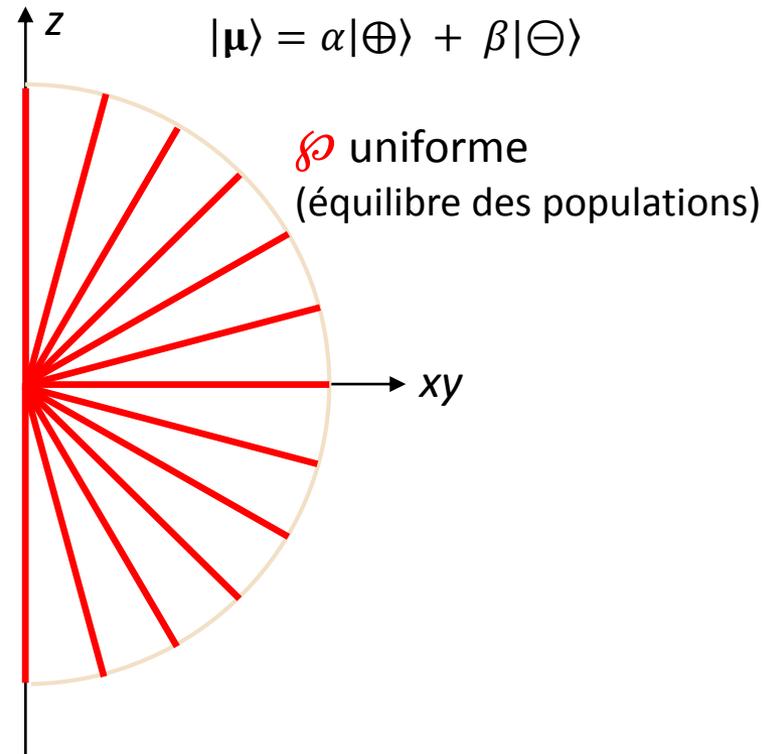
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### Etats superposés

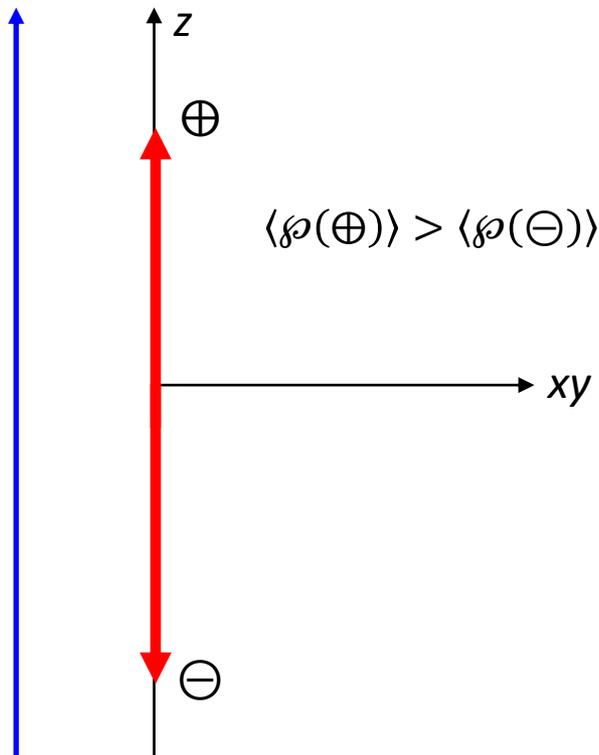


# RMN – principe

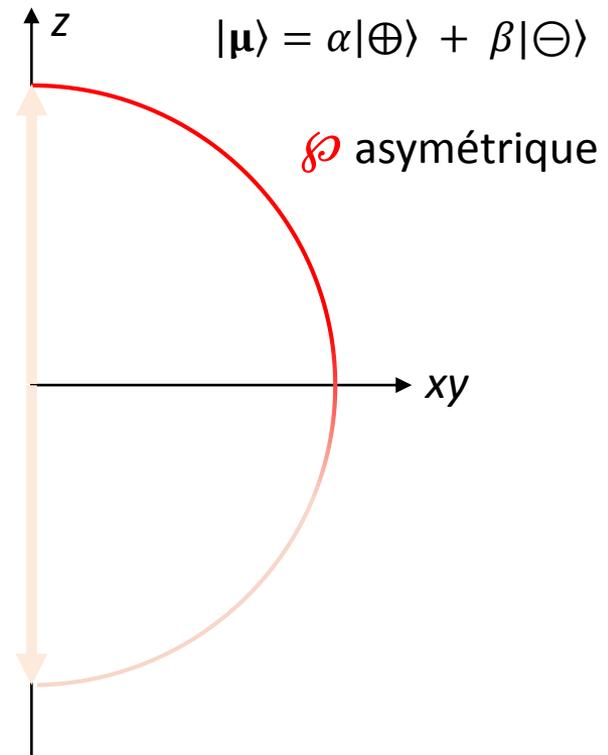
## Représentation statistique (fréquentiste) des spins

$$B_0 > 0$$

### Mesures individuelles accessibles



### Etats superposés

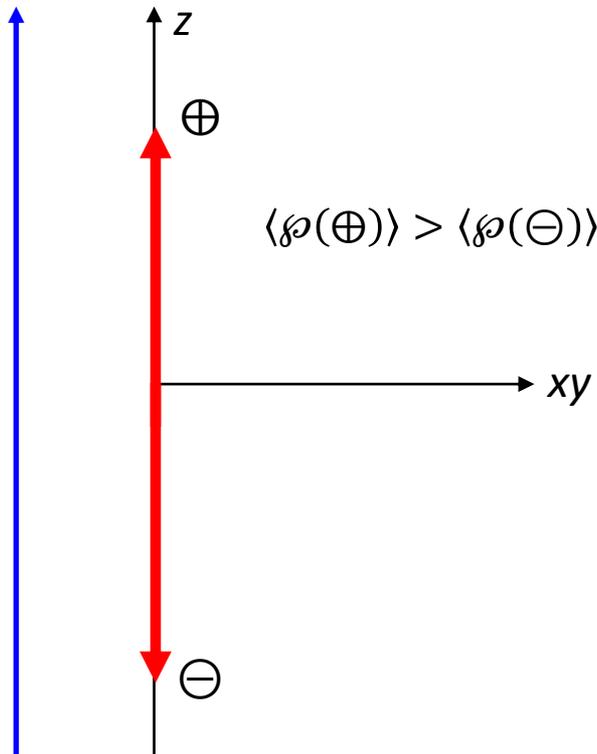


# RMN – principe

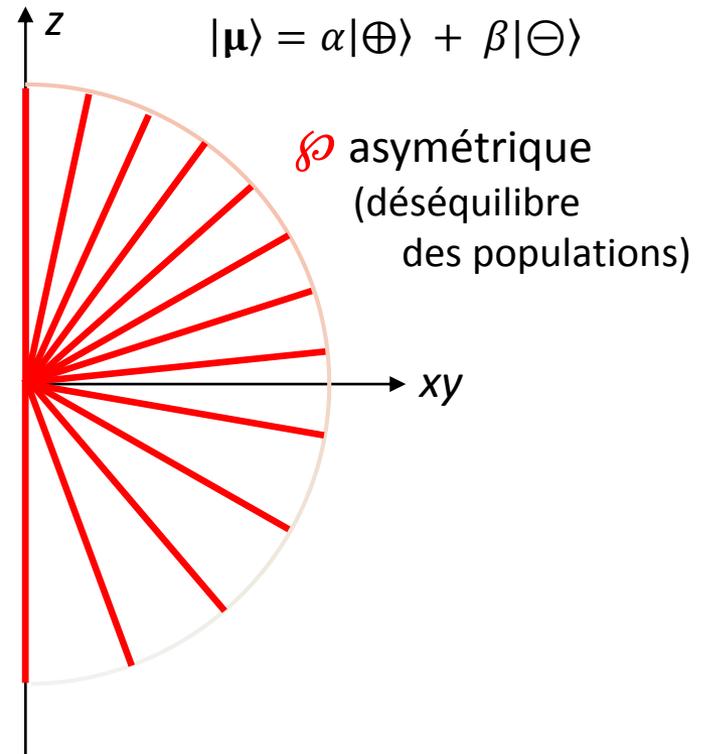
## Représentation statistique (fréquentiste) des spins

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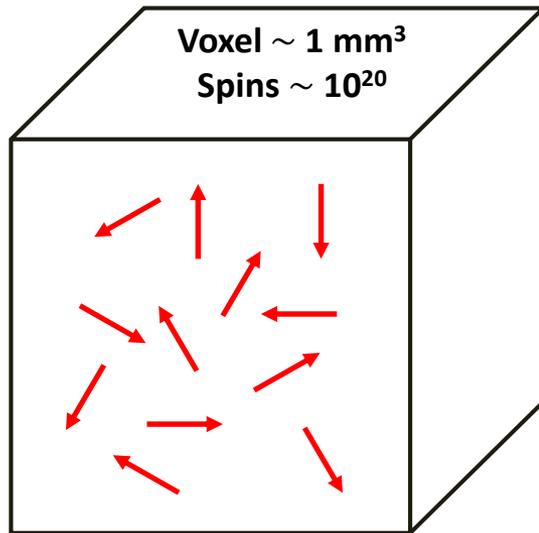
### Mesures individuelles accessibles



### Etats superposés

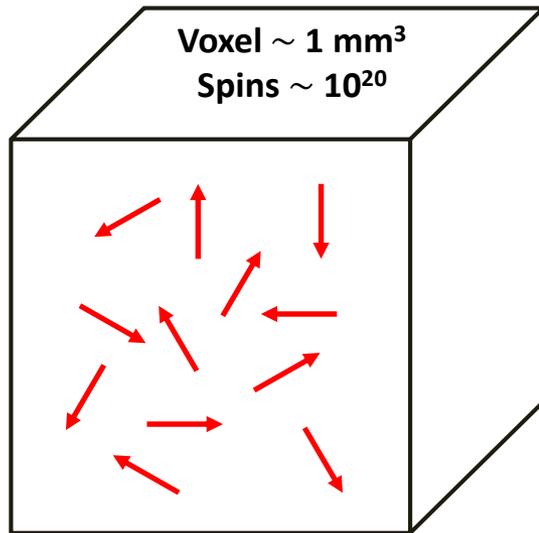


# RMN – principe



$B \sim 0$  (champ magnétique terrestre =  $47 \mu\text{T}$ )

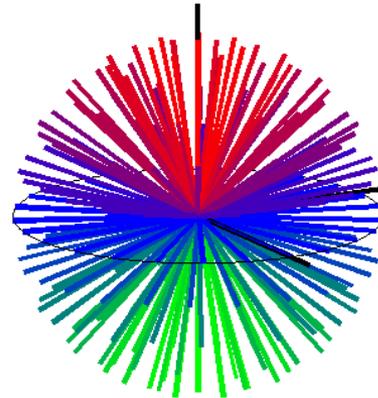
# RMN – principe



$B \sim 0$  (champ magnétique terrestre =  $47 \mu\text{T}$ )

Agitation thermique  $\gg$  effets magnétiques

$M = 0$

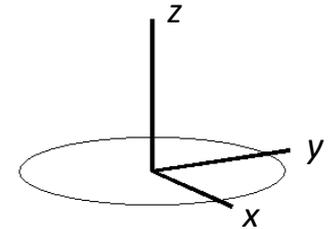
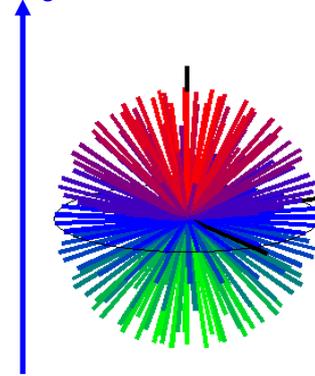


# RMN – principe

## 1. Préparation (aimantation)

Précession de Larmor :  $\omega_0 = \gamma B_0$

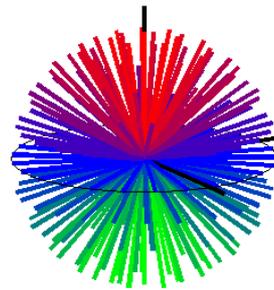
$B_0 \sim 1 - 3 \text{ T}$



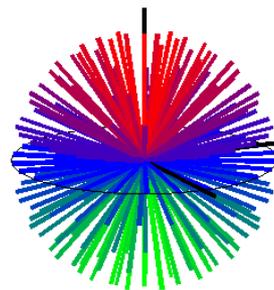
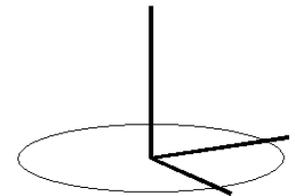
# RMN – principe

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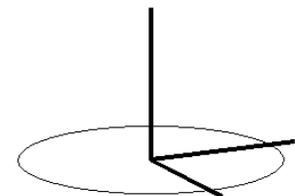
Précession de Larmor :  $\omega_0 = \gamma B_0$



*référentiel fixe*



*référentiel tournant*  
"  $B_0 = 0$  "



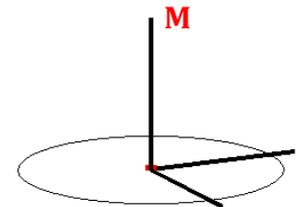
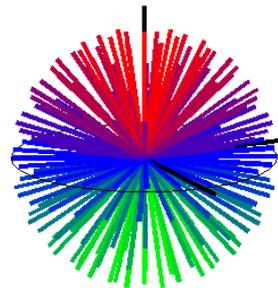
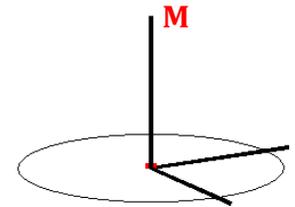
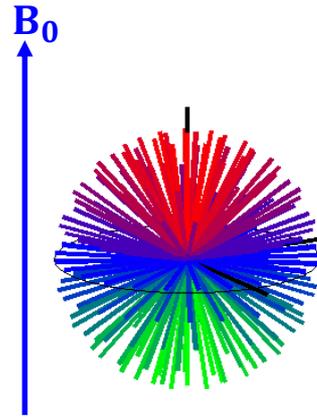
# RMN – principe

## 1. Préparation (aimantation)

Précession de Larmor :  $\omega_0 = \gamma B_0$

Alignement sur le champ

- Aimantation longitudinale  $M_z$



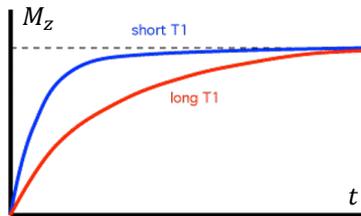
# RMN – principe

## 1. Préparation (aimantation)

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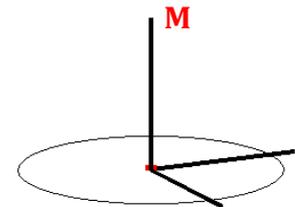
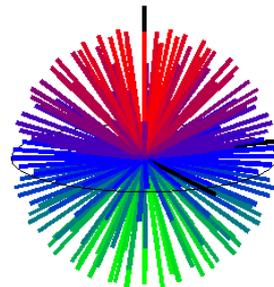
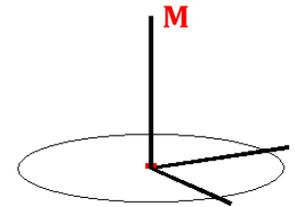
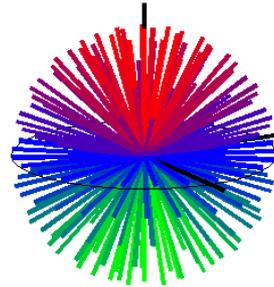
Alignement sur le champ

- Aimantation longitudinale  $M_z$
- Cinétique exponentielle  $T_1$



$$M_z(t) = M_L(1 - e^{-t/T_1})$$

$B_0$



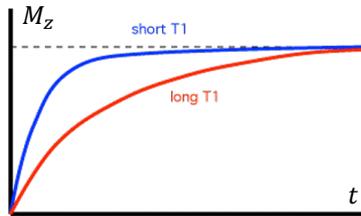
# RMN – principe

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Précession de Larmor :  $\omega_0 = \gamma B_0$

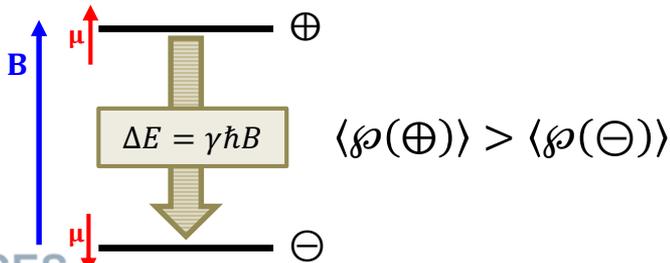
Alignement sur le champ

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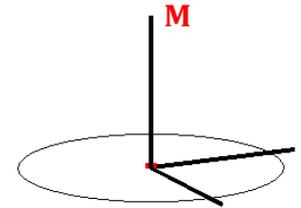
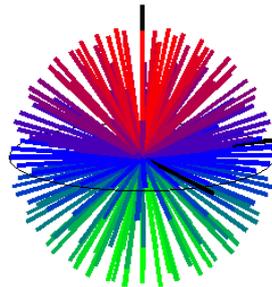
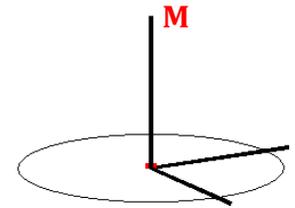
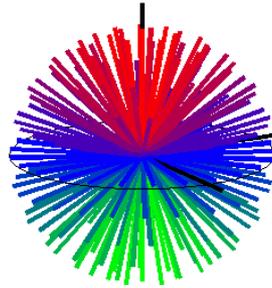


$$M_z(t) = M_L(1 - e^{-t/T_1})$$

- Echanges énergétiques :  $E = -\mu \cdot B$



$B_0$

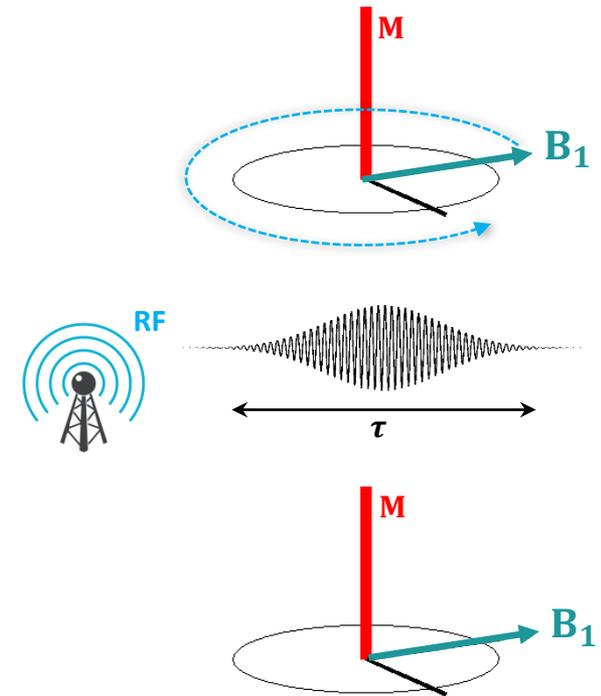
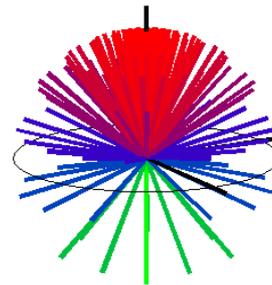
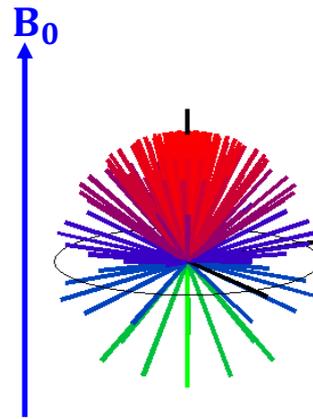


# RMN – principe

## 2. Perturbation (résonance)

Application d'un champ tournant  $B_1$

- de fréquence  $\omega_0/2\pi$
- pendant une durée  $\tau$  (~ms)



# RMN – principe

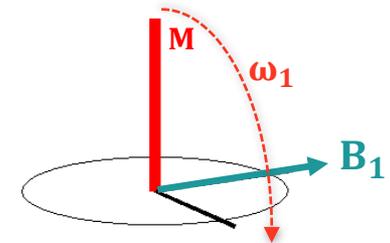
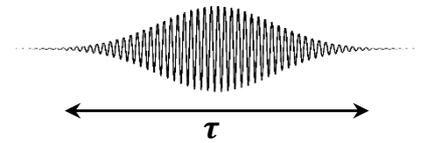
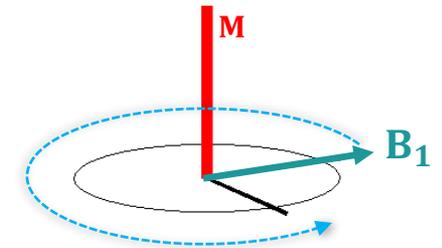
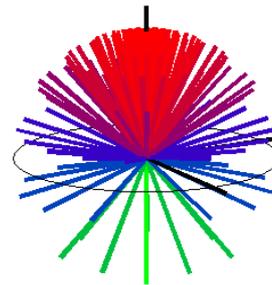
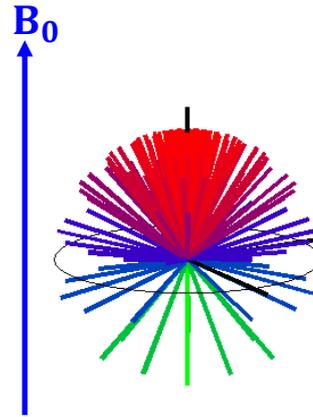
## 2. Perturbation (résonance)

Application d'un champ tournant  $B_1$

- de **fréquence**  $\omega_0/2\pi$
- pendant une durée  $\tau$  (~ms)

Précession de  $M$  autour de  $B_1$

- $\omega_1 = \gamma B_1$
- **Bascule** (nutation) d'un angle  $\eta = \tau \omega_1$



# RMN – principe

## 2. Perturbation (résonance)

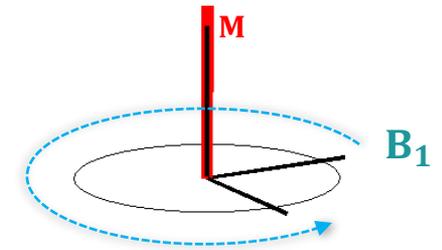
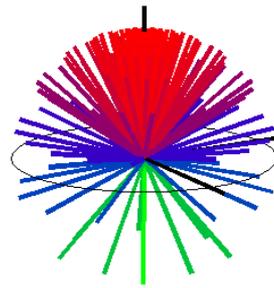
Application d'un champ tournant  $B_1$

- de **fréquence**  $\omega_0/2\pi$
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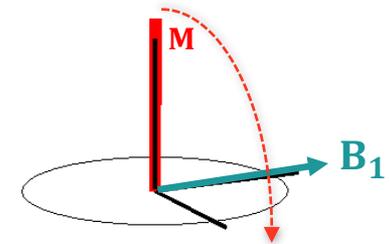
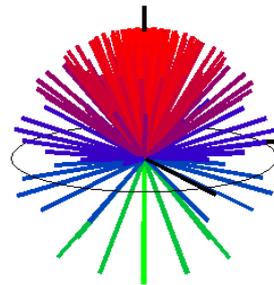
Précession de  $M$  autour de  $B_1$

- $\omega_1 = \gamma B_1$
- **Bascule** (nutation) d'un angle  $\eta = \tau \omega_1$

$B_0$



$$\eta = \frac{\pi}{2}$$



# RMN – principe

## 2. Perturbation (résonance)

Application d'un champ tournant  $B_1$

- de **fréquence**  $\omega_0/2\pi$
- pendant une durée  $\tau$  (~ms)

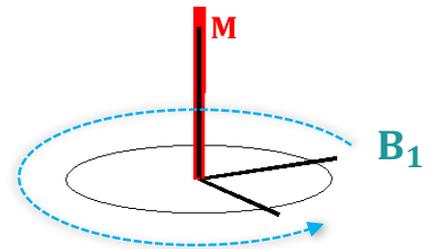
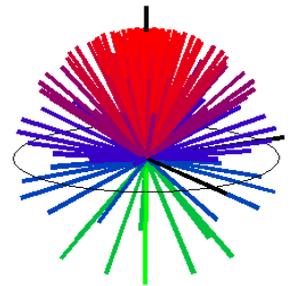
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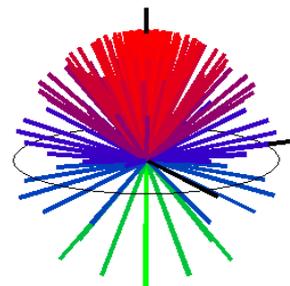
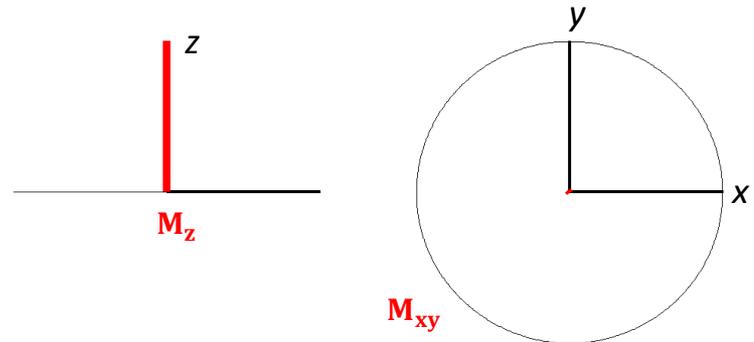
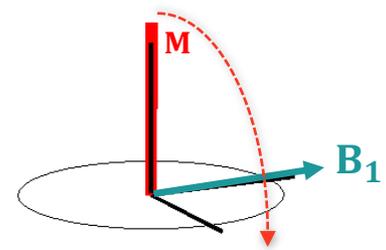
Disparition de  $M_z$

Apparition de  $M_{xy}$  (aimantation transverse)

$B_0$



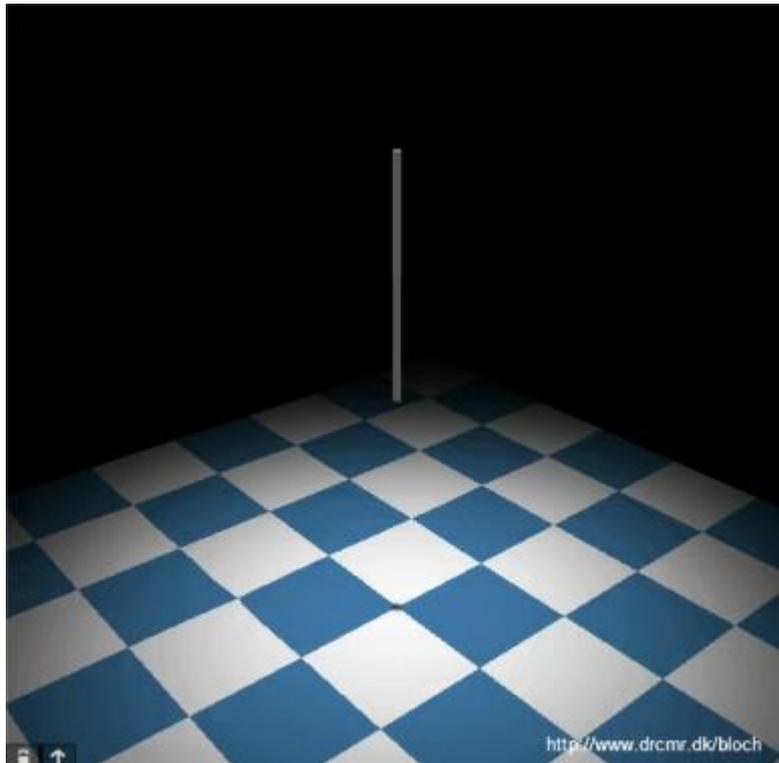
$$\eta = \frac{\pi}{2}$$



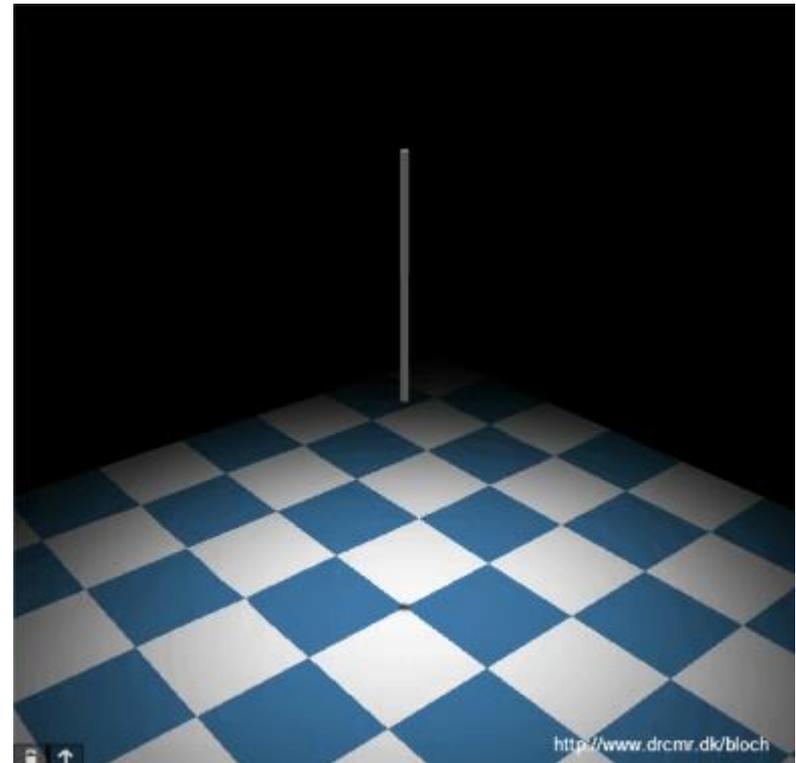
# RMN – principe

## 2. Perturbation (résonance)

Résonance



Hors résonance



# RMN – principe

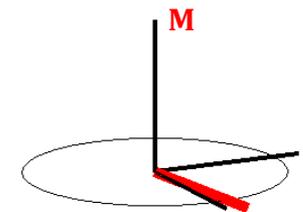
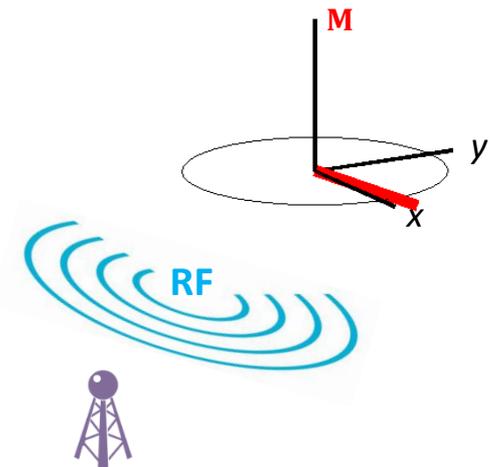
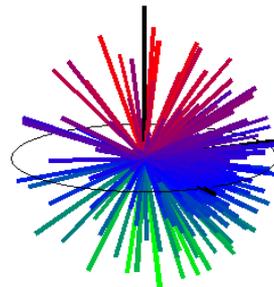
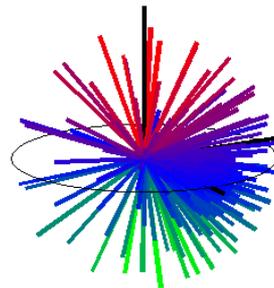
## 3. Mesure (relaxation)

Arrêt de la stimulation RF  $B_1$

Signal =  $M_{xy}$



$B_0$



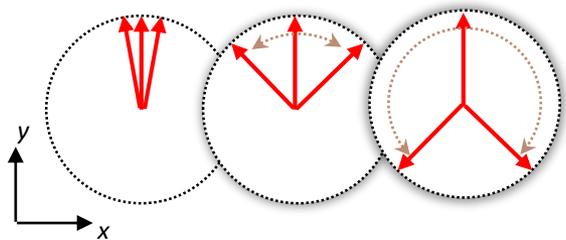
# RMN – principe

## 3. Mesure (relaxation)

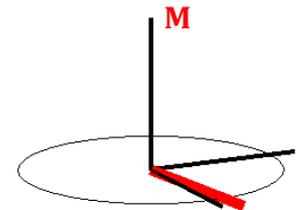
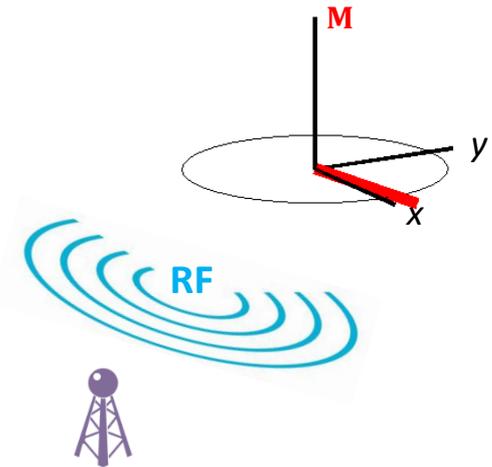
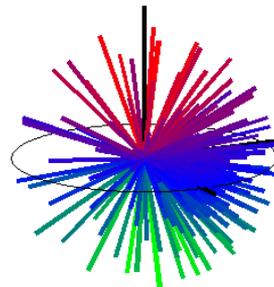
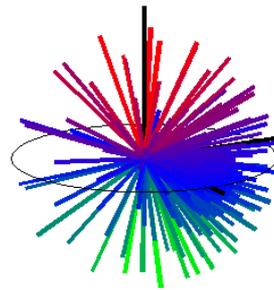
Arrêt de la stimulation RF  $B_1$

Signal =  $M_{xy}$

- Déphasage progressif
- Inhomogénéités de champ
- Phénomène entropique



$B_0$

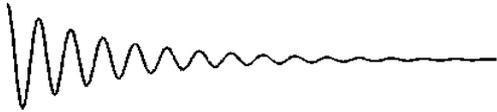


# RMN – principe

## 3. Mesure (relaxation)

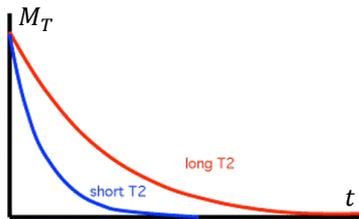
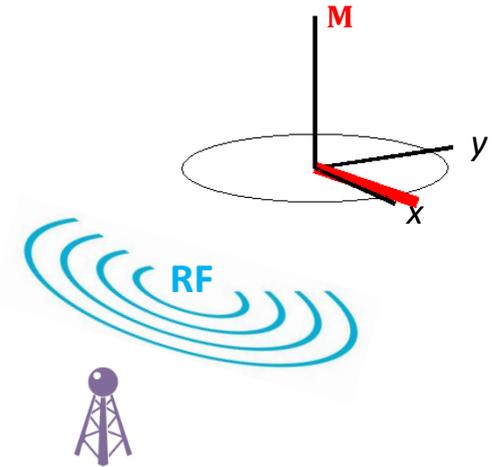
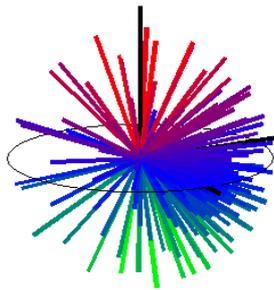
Arrêt de la stimulation RF  $B_1$

Signal =  $M_{xy}$

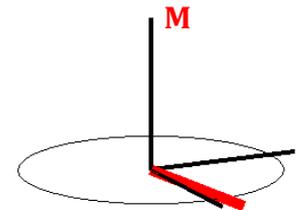
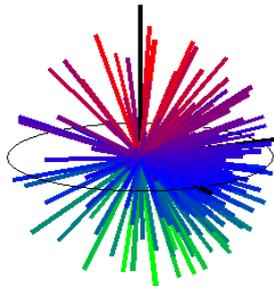


- Déphasage progressif
- Inhomogénéités de champ
- Phénomène entropique
- Cinétique  $T_2$

$B_0$



$$M_{xy}(t) = M_T e^{-t/T_2}$$

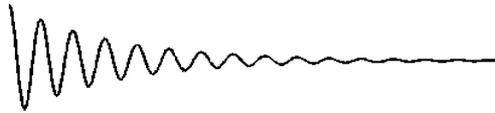


# RMN – principe

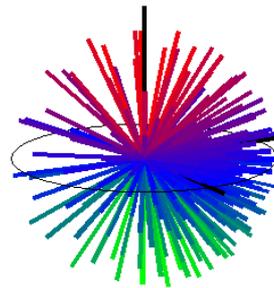
## 3. Mesure (relaxation)

Arrêt de la stimulation RF  $B_1$

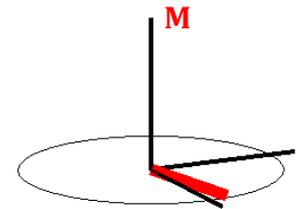
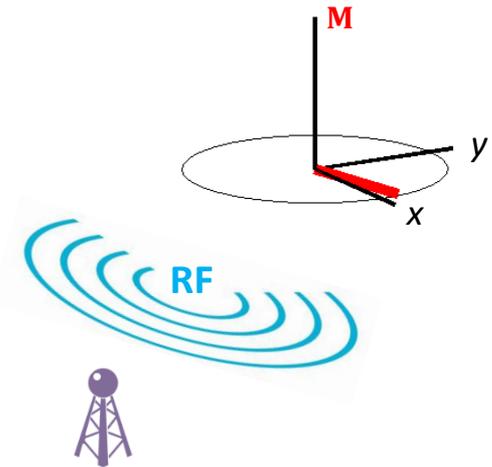
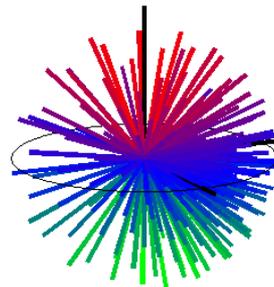
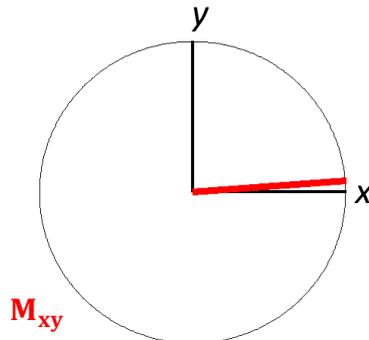
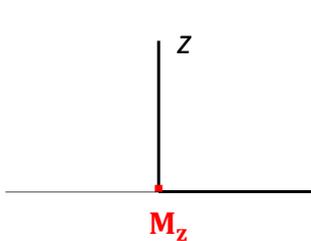
Signal =  $M_{xy}$



$B_0$



Disparition de  $M_{xy}$   
Repousse de  $M_z$

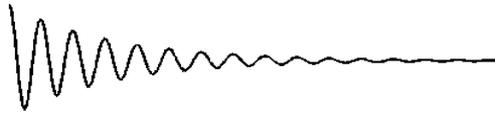


# RMN – principe

## 3. Mesure (relaxation)

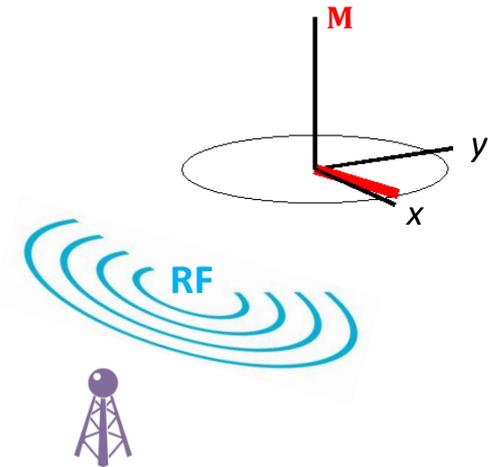
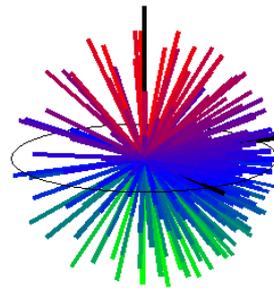
Arrêt de la stimulation RF  $B_1$

Signal =  $M_{xy}$

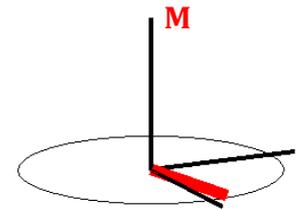
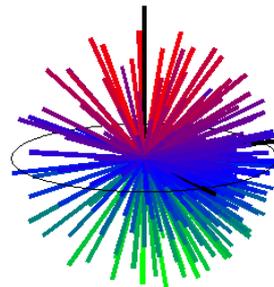
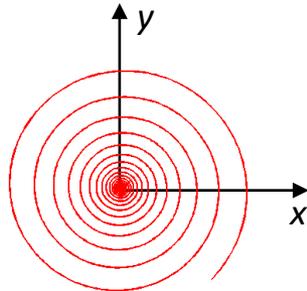
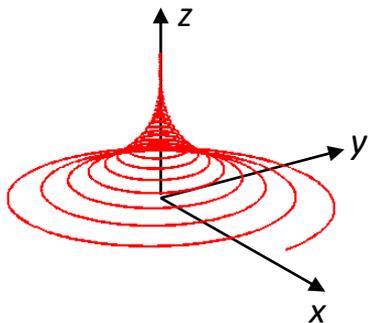


Disparition de  $M_{xy}$   
Repousse de  $M_z$

$B_0$



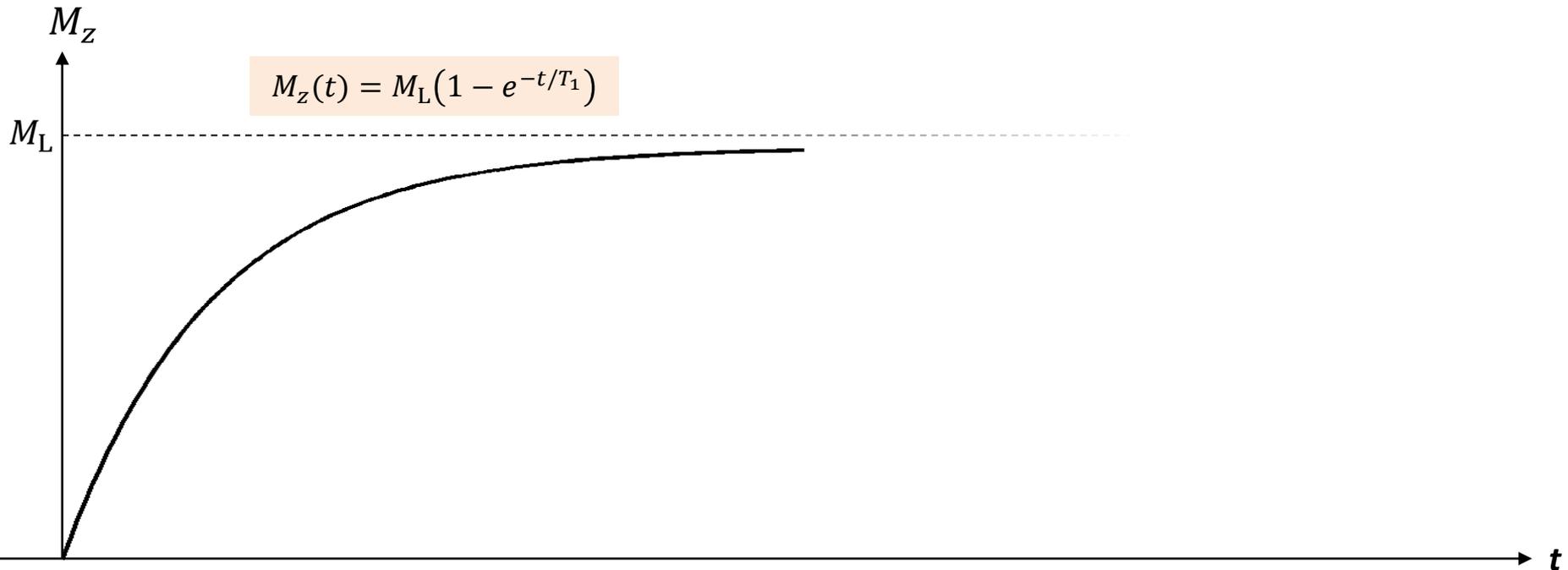
Dans les tissus biologiques :  $T_1 \sim 10 T_2$



# RMN – séquence

## Préparation

Aimantation longitudinale dans  $B_0$   
Relaxation  $T_1$



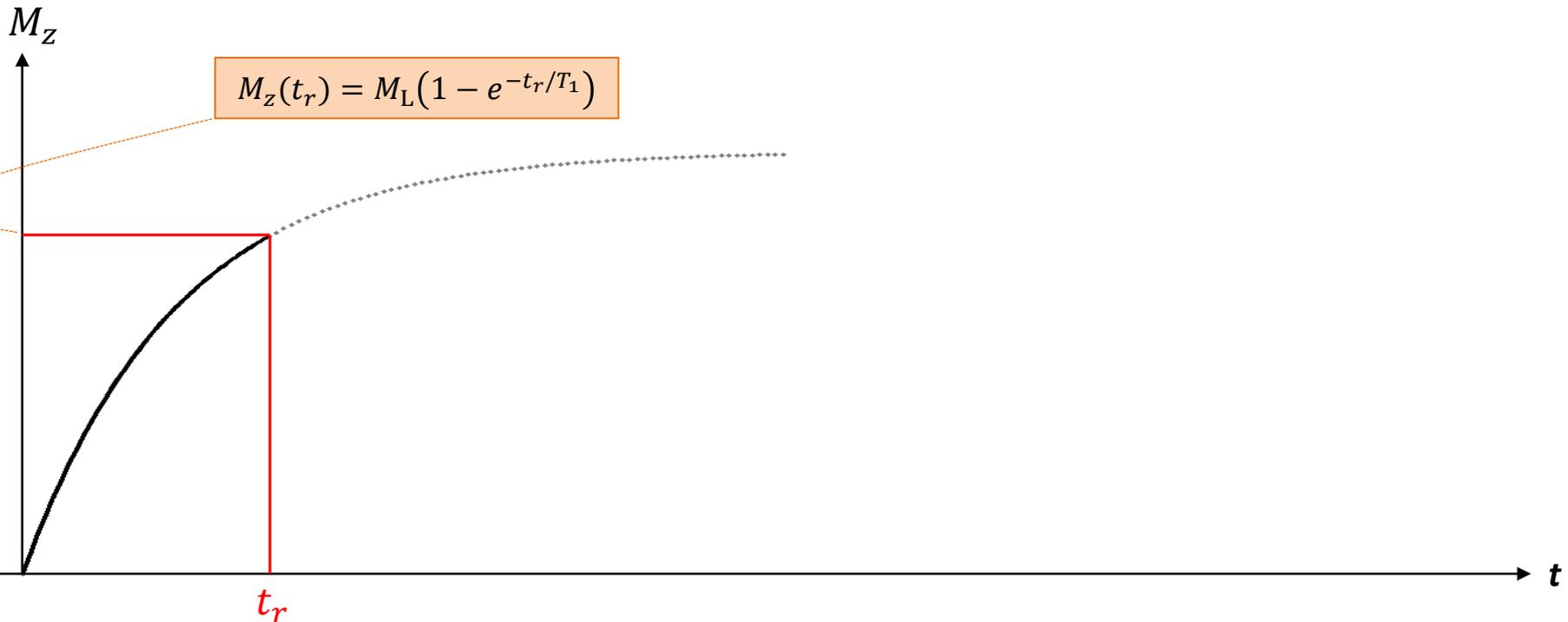
# RMN – séquence

## Préparation

Aimantation longitudinale dans  $B_0$

Relaxation  $T_1$

Durant un temps  $t_r$  (temps de répétition)

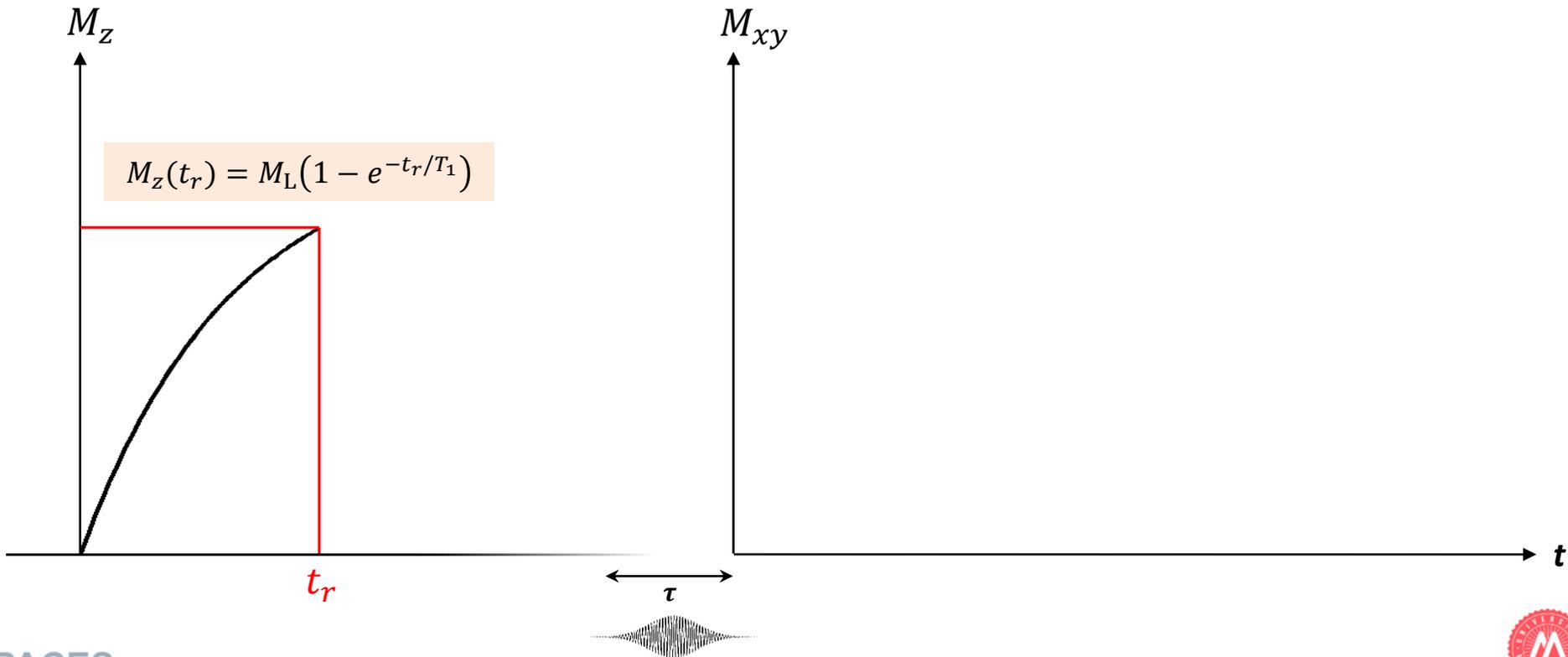


# RMN – séquence

Préparation

RF

Stimulation RF durant un temps  $\tau$   
Bascule de l'aimantation d'un angle  $\eta$   
Apparition d'une aimantation transverse

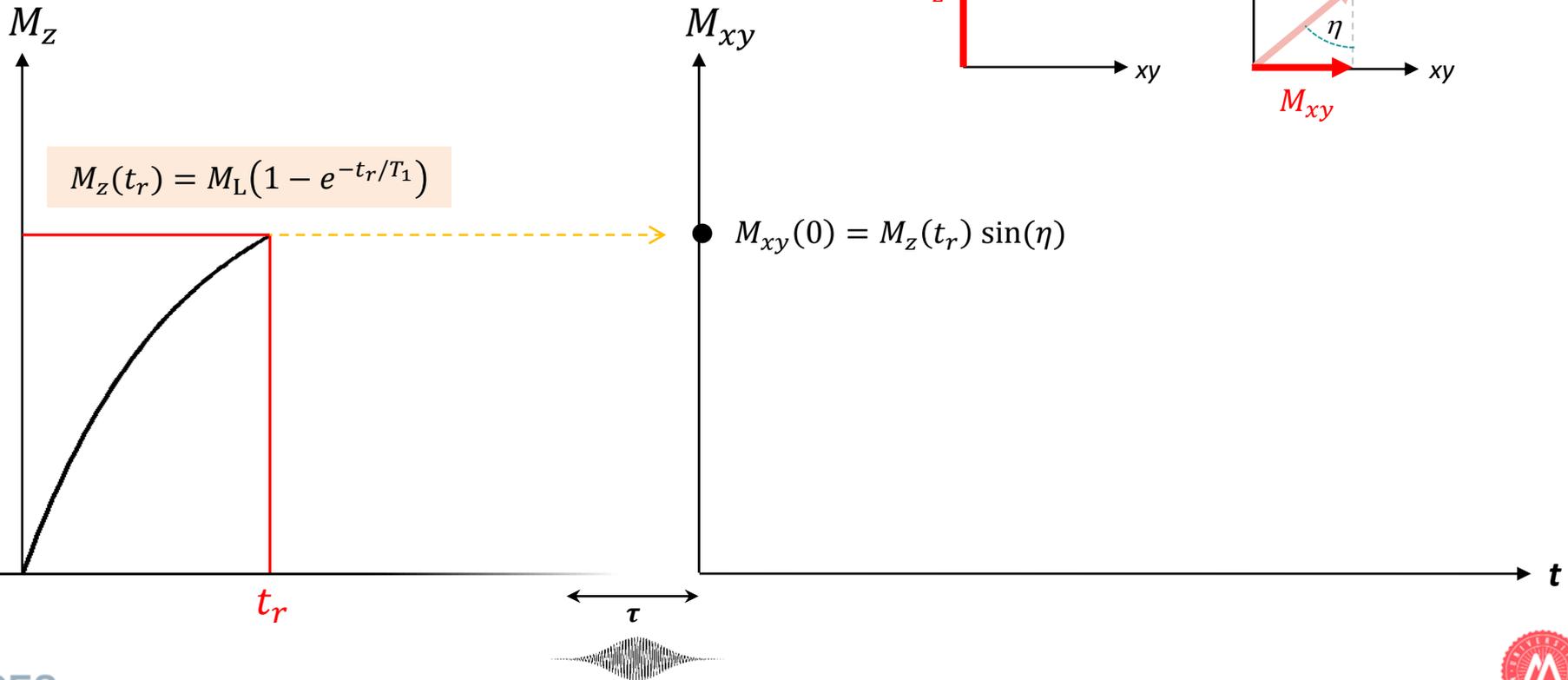


# RMN – séquence

Préparation

RF

Stimulation RF durant un temps  $\tau$   
Bascule de l'aimantation d'un angle  $\eta$   
Apparition d'une aimantation transverse



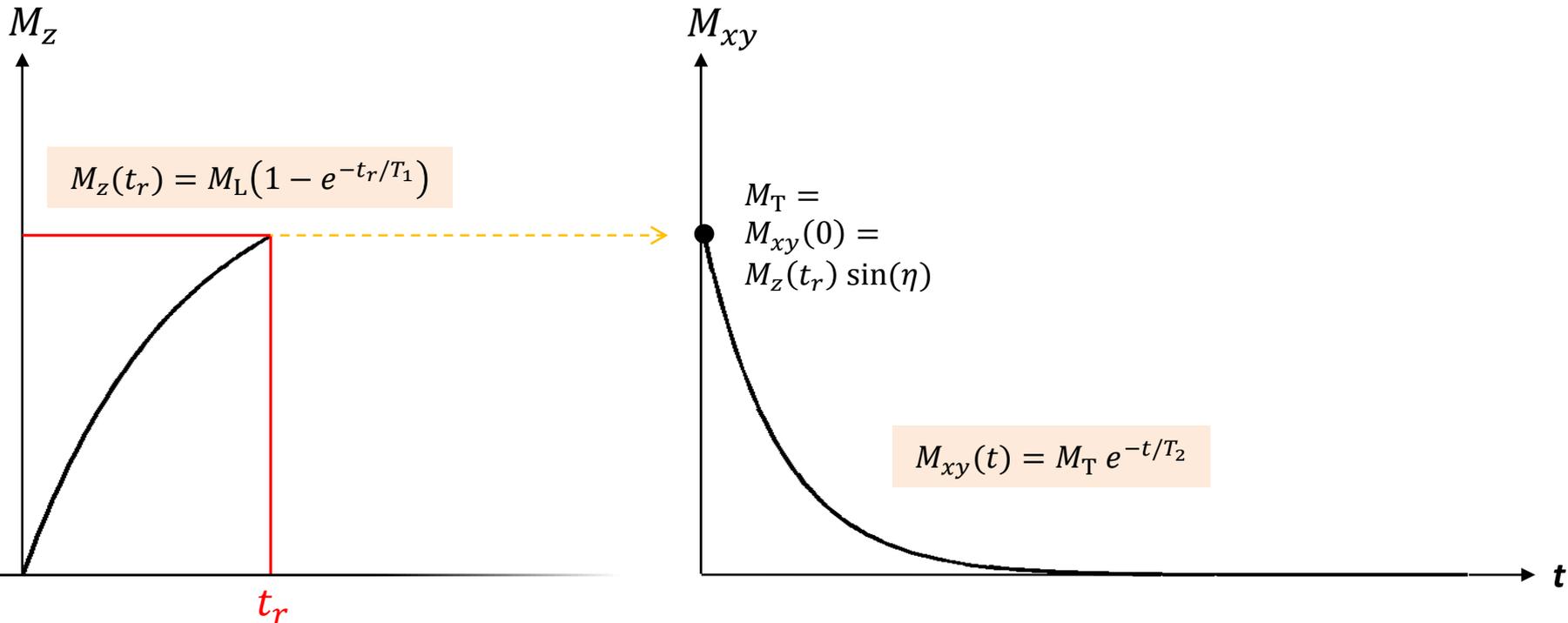
# RMN – séquence

Préparation

RF

Mesure

Retour à l'équilibre  
Relaxation  $T_2$



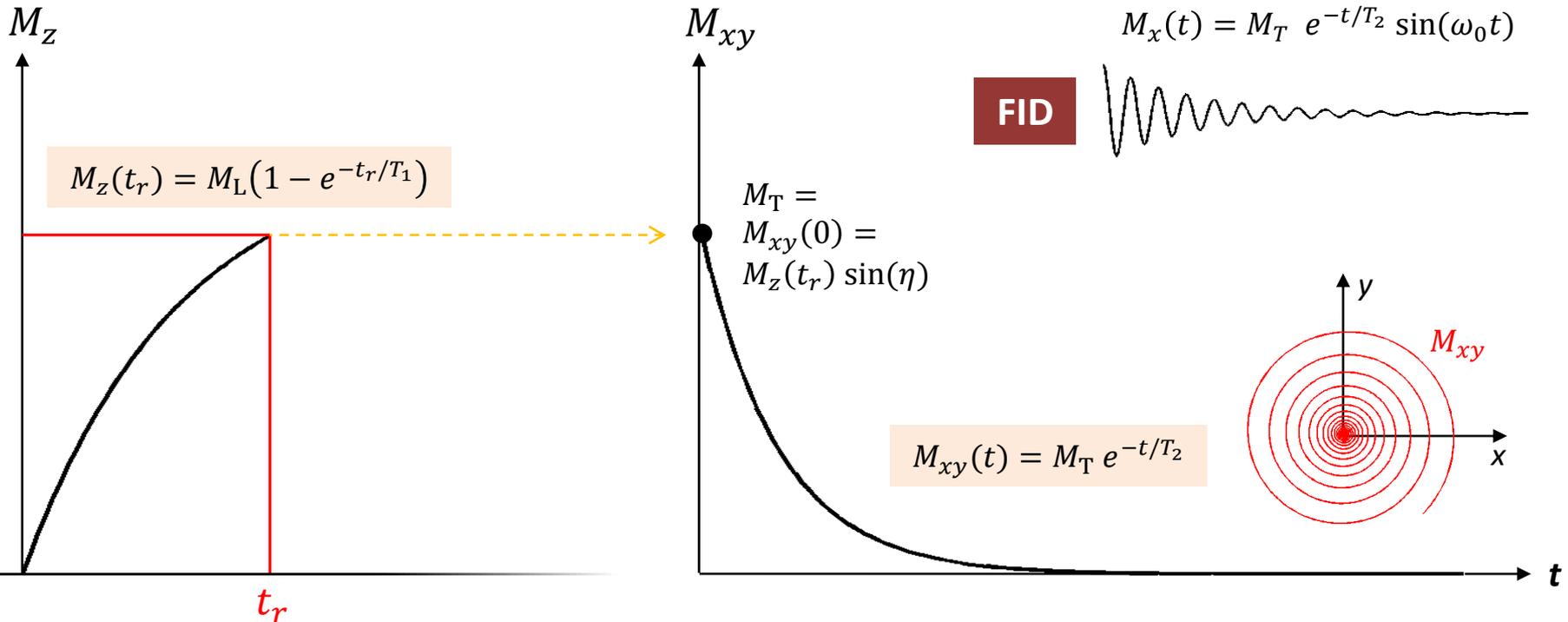
# RMN – séquence

Préparation

RF

Mesure

Retour à l'équilibre  
Relaxation  $T_2$



# RMN – séquence

Préparation

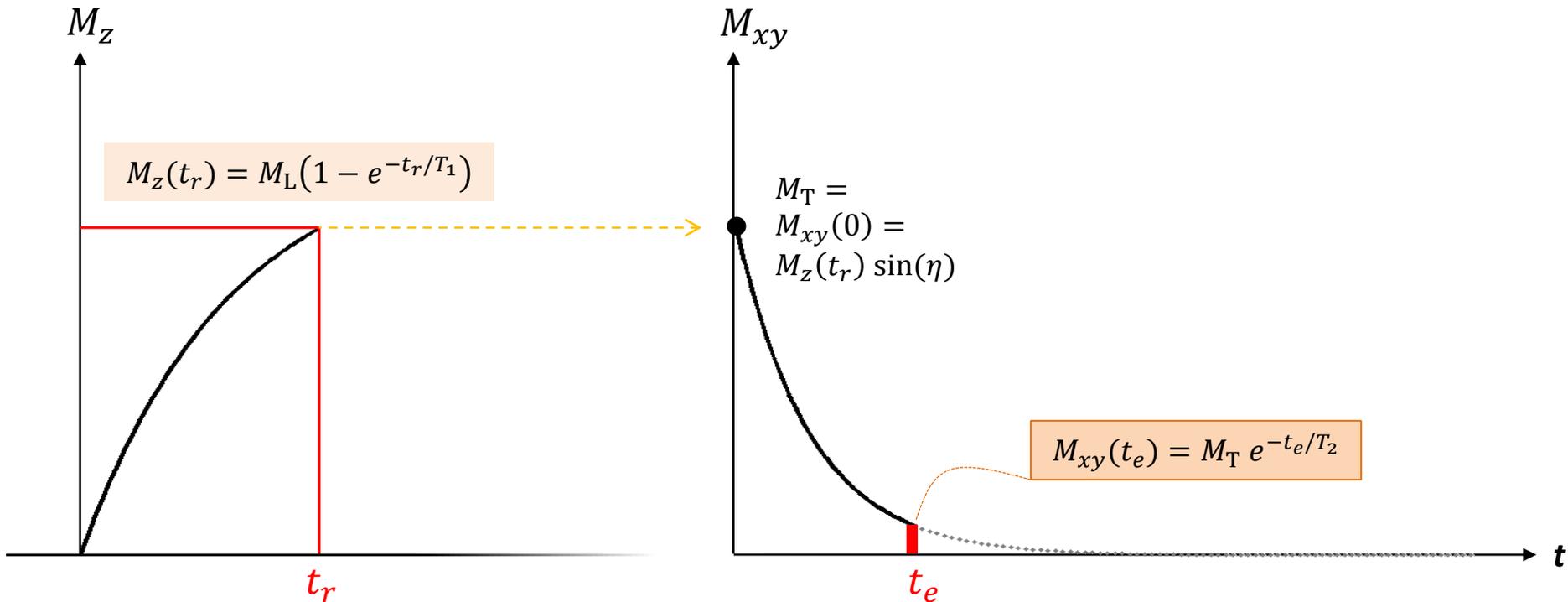
RF

Mesure

Retour à l'équilibre

Relaxation  $T_2$

Recueil du signal (**FID**) au temps  $t_e$  (temps d'écho)



# RMN – séquence

Préparation

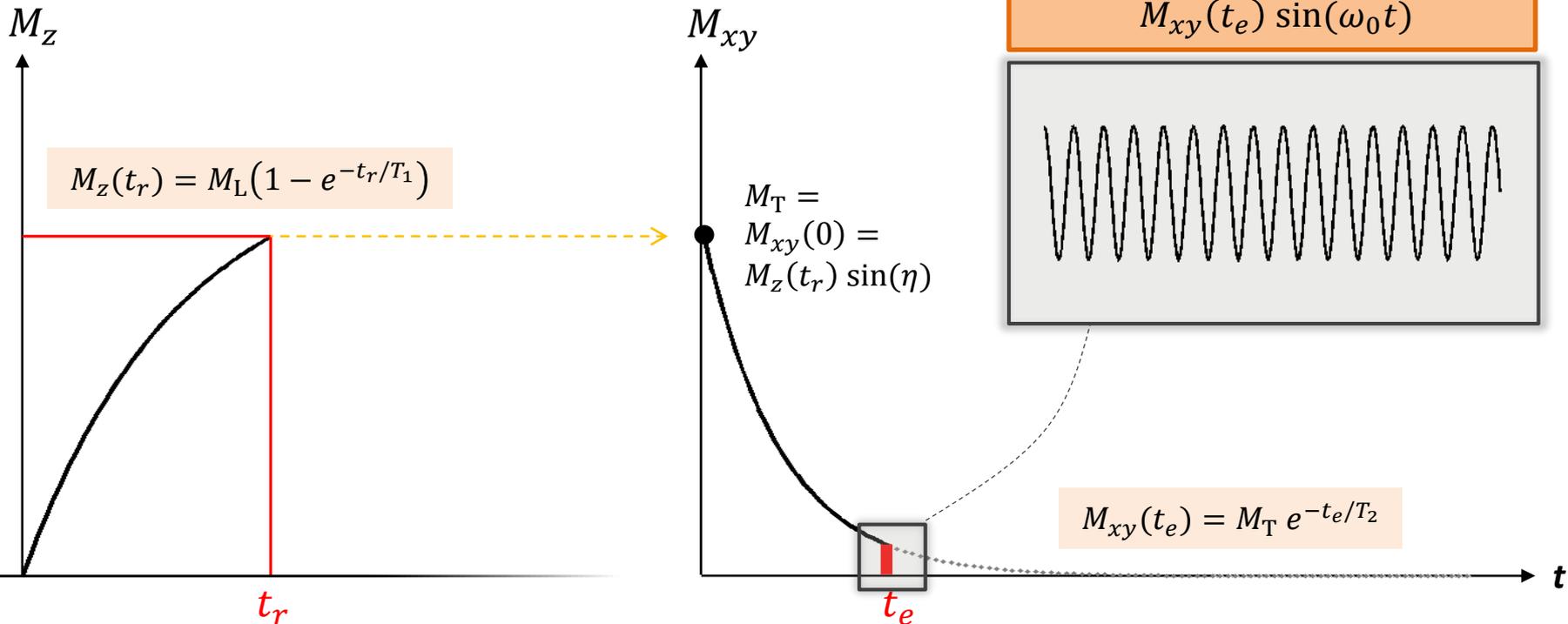
RF

Mesure

Retour à l'équilibre

Relaxation  $T_2$

Recueil du signal (**FID**) au temps  $t_e$  (temps d'écho)



# RMN – séquence

Préparation

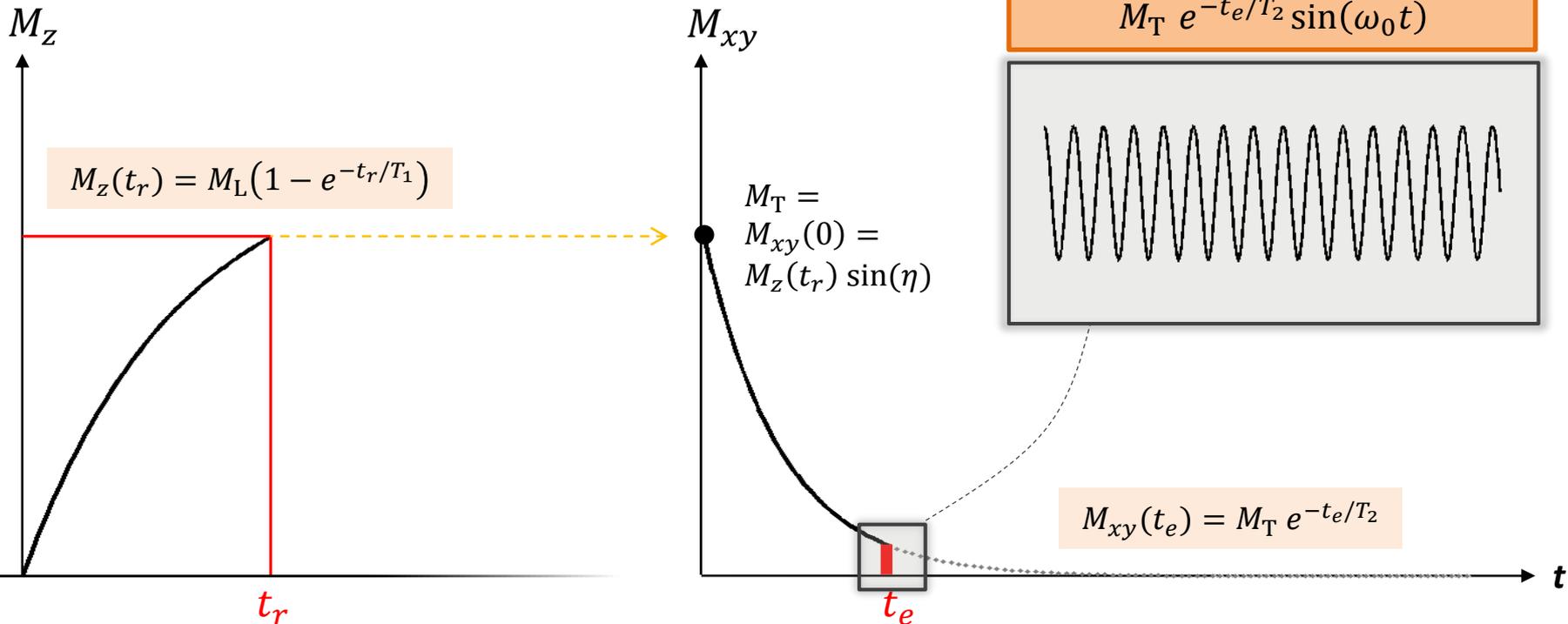
RF

Mesure

Retour à l'équilibre

Relaxation  $T_2$

Recueil du signal (**FID**) au temps  $t_e$  (temps d'écho)



# RMN – séquence

Préparation

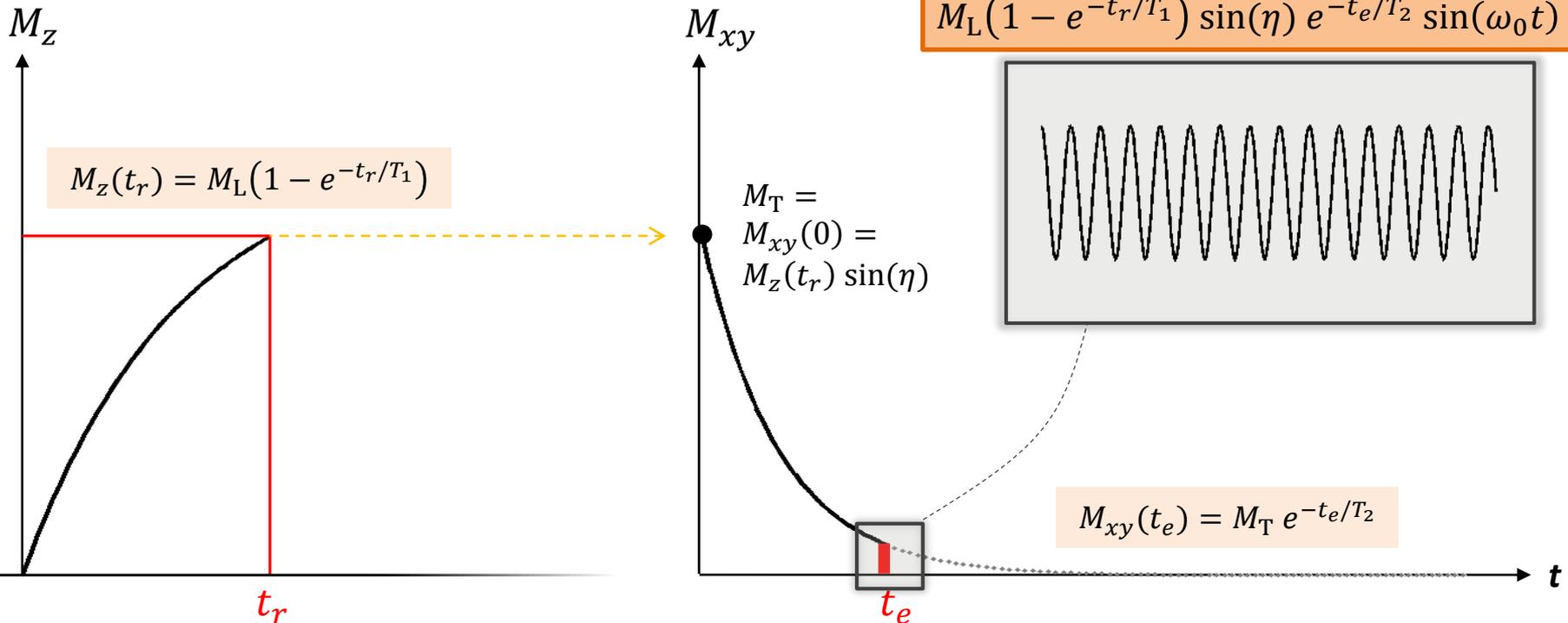
RF

Mesure

Retour à l'équilibre

Relaxation  $T_2$

Recueil du signal (**FID**) au temps  $t_e$  (temps d'écho)



# RMN – contraste

$$FID(t) = M_L(1 - e^{-t_r/T_1}) \sin(\eta) e^{-t_e/T_2} \sin(\omega_0 t)$$

Déterminants du signal :

$$M_L = \sum \mu_z \left\{ \begin{array}{l} \propto \mu \propto \gamma \quad \textit{intrinsèque} \\ \propto \rho(^1\text{H}) \quad \textit{intrinsèque} \\ \propto \frac{\Delta N}{N} \propto \frac{B_0}{T} \quad \textit{extrinsèque} \end{array} \right.$$

$$T_1, T_2 \quad \textit{intrinsèque}$$

$$t_r, t_e, \eta \quad \textit{extrinsèque}$$

# RMN – contraste

$$FID(t) = M_L(1 - e^{-t_r/T_1}) \sin(\eta) e^{-t_e/T_2} \sin(\omega_0 t)$$

Déterminants du signal :

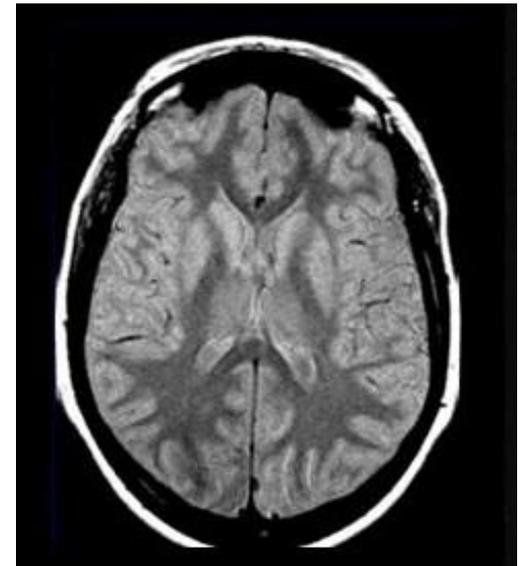
$$M_L = \sum \mu_z \left\{ \begin{array}{l} \propto \mu \propto \gamma \quad \textit{intrinsèque} \\ \propto \rho(^1\text{H}) \quad \textit{intrinsèque} \\ \propto \frac{\Delta N}{N} \propto \frac{B_0}{T} \quad \textit{extrinsèque} \end{array} \right.$$

$$T_1, T_2 \quad \textit{intrinsèque}$$

$$t_r, t_e, \eta \quad \textit{extrinsèque}$$

Densité de protons  $\rho$  :

Degré d'hydratation / lipidation



# RMN – contraste

$$FID(t) = M_L(1 - e^{-t_r/T_1}) \sin(\eta) e^{-t_e/T_2} \sin(\omega_0 t)$$

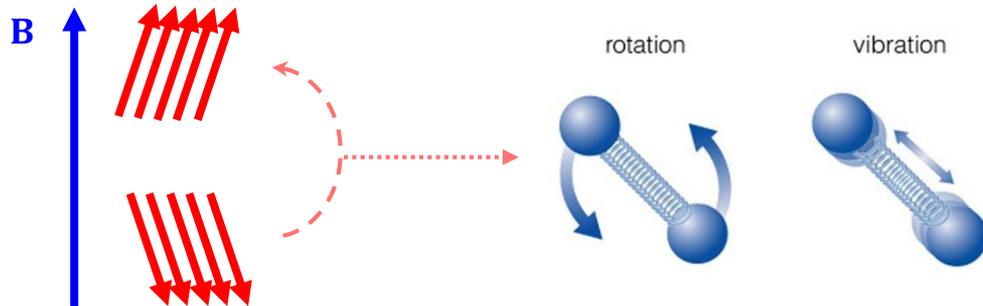
Déterminants du signal :

$$M_L = \sum \mu_z \begin{cases} \propto \mu \propto \gamma & \textit{intrinsèque} \\ \propto \rho(^1\text{H}) & \textit{intrinsèque} \\ \propto \frac{\Delta N}{N} \propto \frac{B_0}{T} & \textit{extrinsèque} \end{cases}$$

$T_1, T_2$  *intrinsèque*

Relaxation  $T_1$  : échanges énergétiques avec le réseau

$t_r, t_e, \eta$  *extrinsèque*

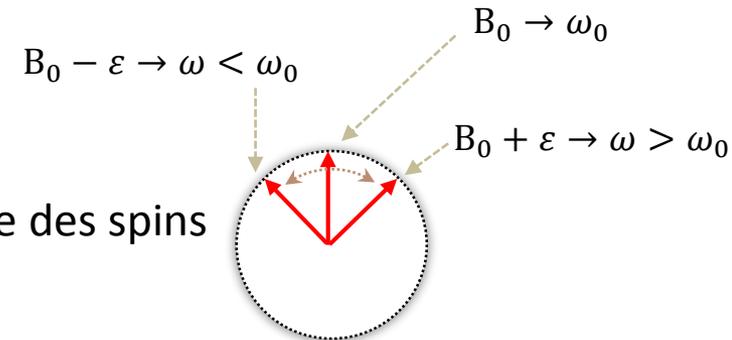


# RMN – contraste

$$FID(t) = M_L(1 - e^{-t_r/T_1}) \sin(\eta) e^{-t_e/T_2} \sin(\omega_0 t)$$

Déterminants du signal :

$$M_L = \sum \mu_z \begin{cases} \propto \mu \propto \gamma & \textit{intrinsèque} \\ \propto \rho(^1\text{H}) & \textit{intrinsèque} \\ \propto \frac{\Delta N}{N} \propto \frac{B_0}{T} & \textit{extrinsèque} \end{cases}$$



$T_1, T_2$  *intrinsèque*

Relaxation  $T_2$  : déphasage des spins

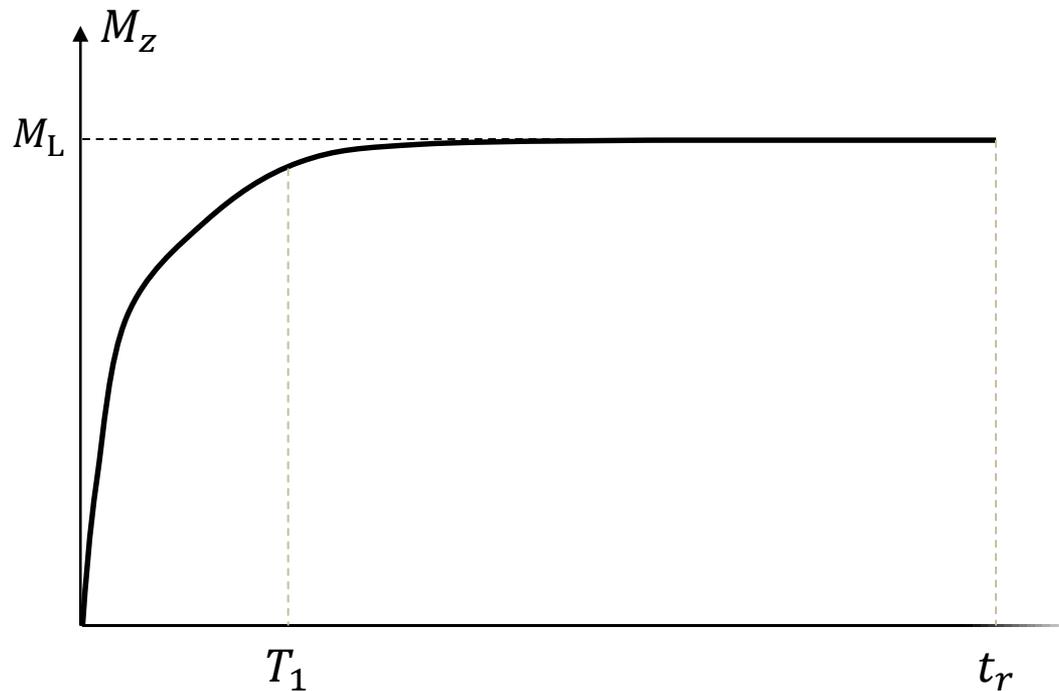
$t_r, t_e, \eta$  *extrinsèque*

- Inhomogénéités technologiques de champ  $B_0$  ( $T_2^*$ )
- Fluctuations locales dues à l'environnement chimique ( $T_2$ )

# RMN – contraste

Pondération  $\rho$  (densité de protons)

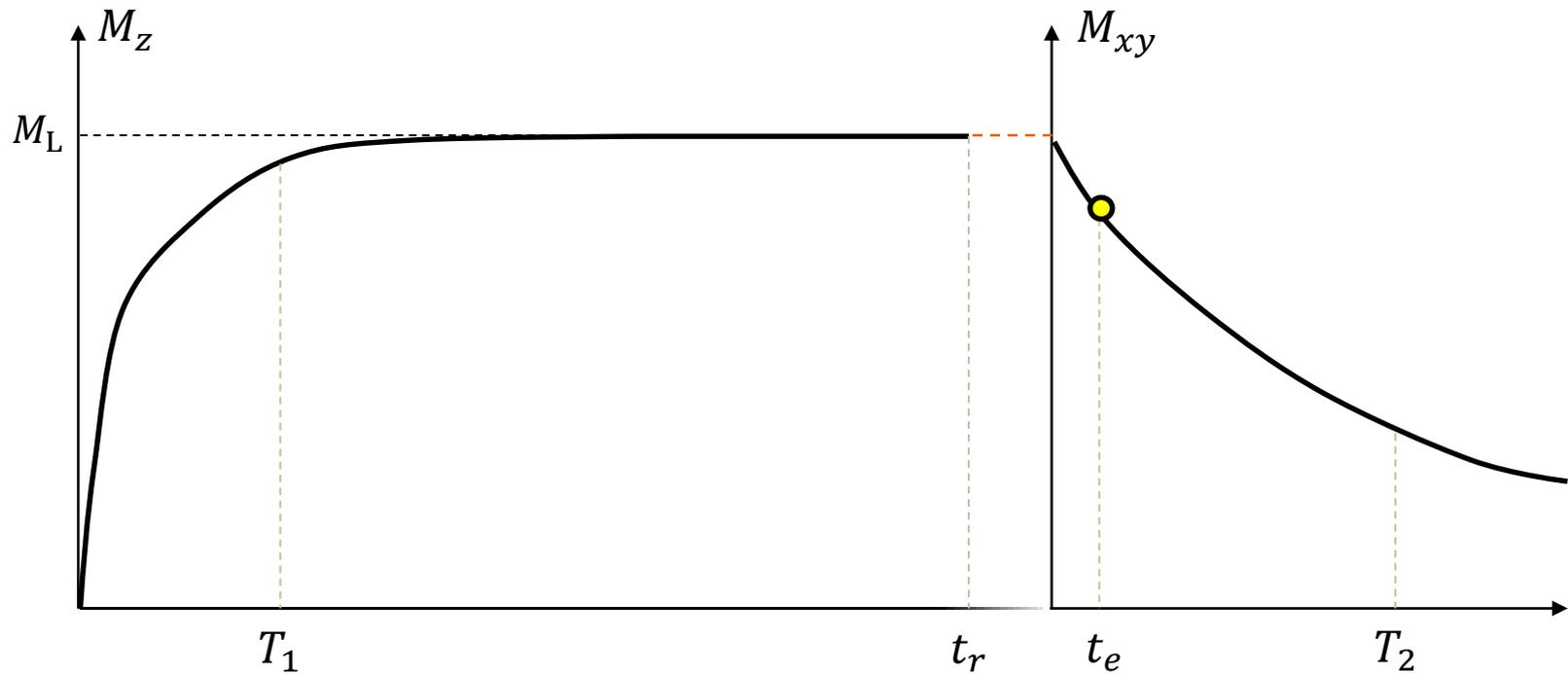
$$t_r \gg T_1$$
$$t_e \ll T_2$$



# RMN – contraste

Pondération  $\rho$  (densité de protons)

$$t_r \gg T_1$$
$$t_e \ll T_2$$



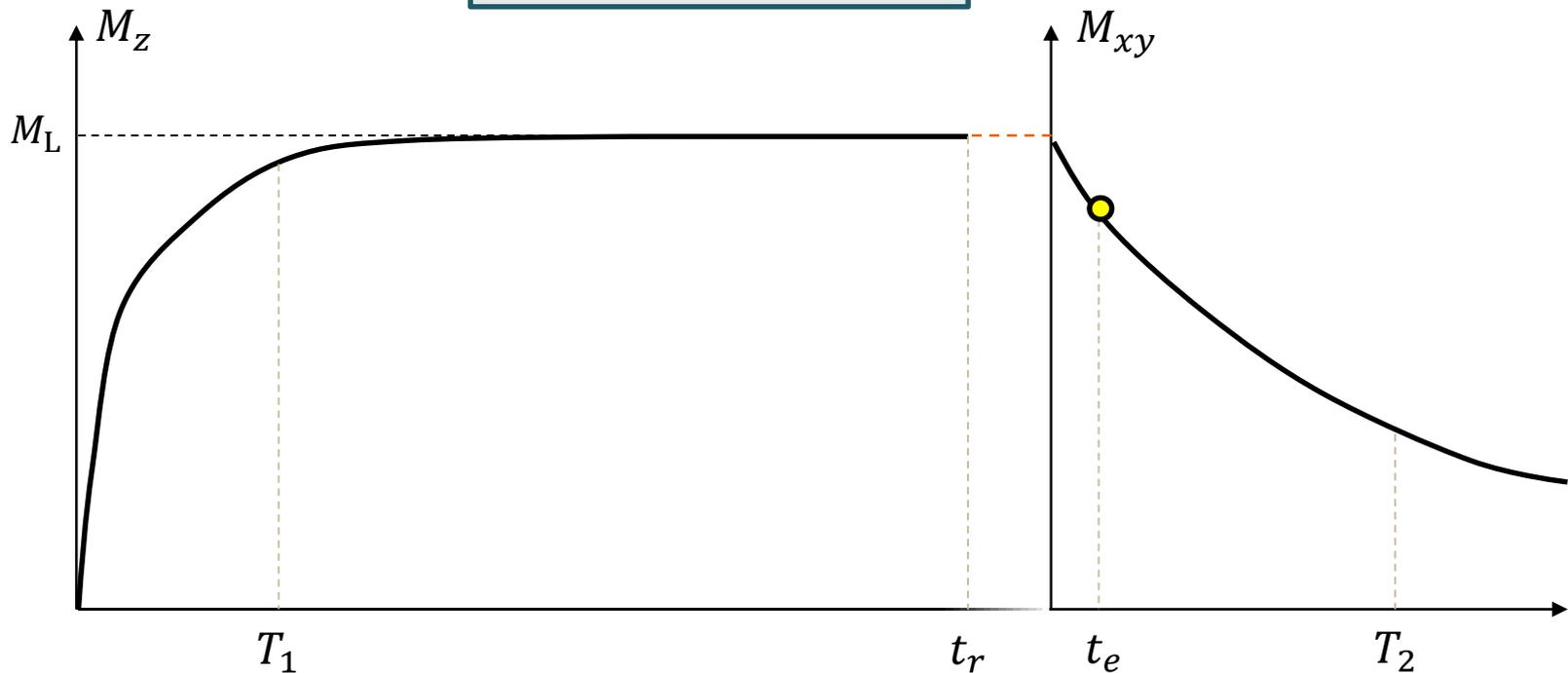
# RMN – contraste

Pondération  $\rho$  (densité de protons)

$$\begin{matrix} t_r \gg T_1 \\ t_e \ll T_2 \end{matrix}$$

$$FID(t) = M_L(1 - e^{-t_r/T_1}) \sin(\eta) e^{-t_e/T_2} \sin(\omega_0 t)$$

Signal  $\propto M_L \propto \rho(^1\text{H})$



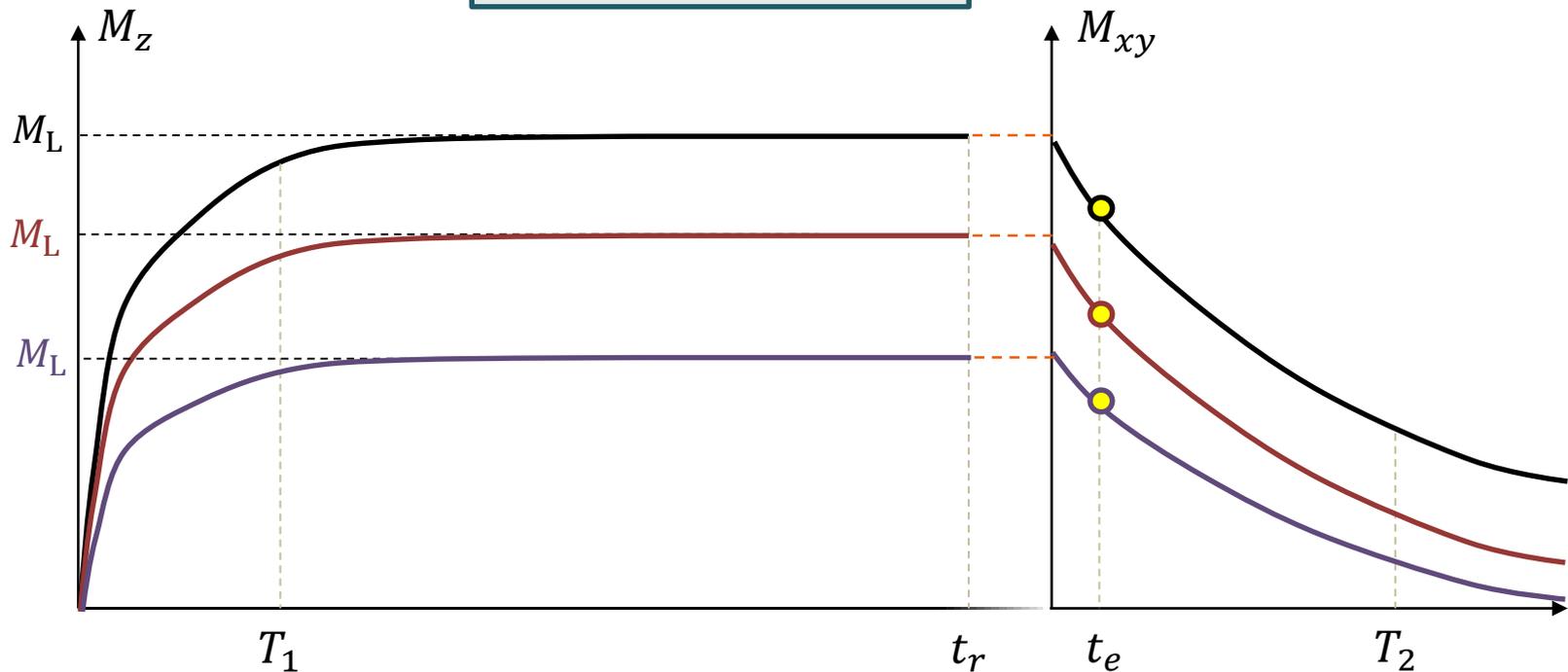
# RMN – contraste

Pondération  $\rho$  (densité de protons)

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$$FID(t) = M_L(1 - e^{-t_r/T_1}) \sin(\eta) e^{-t_e/T_2} \sin(\omega_0 t)$$

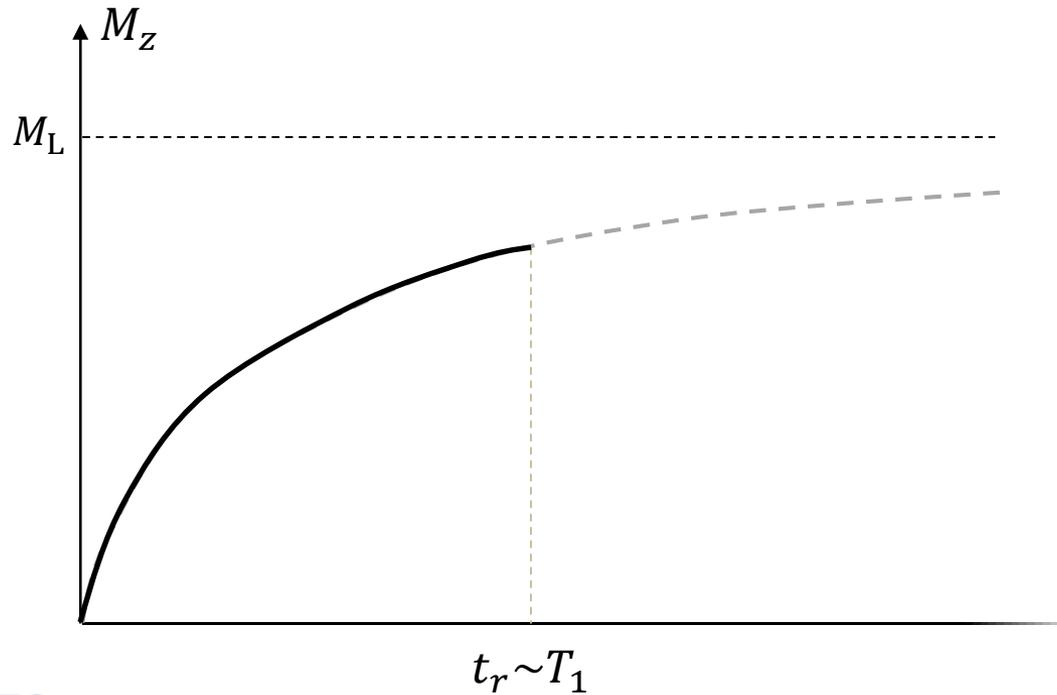
Signal  $\propto M_L \propto \rho(^1\text{H})$



# RMN – contraste

Pondération  $T_1$

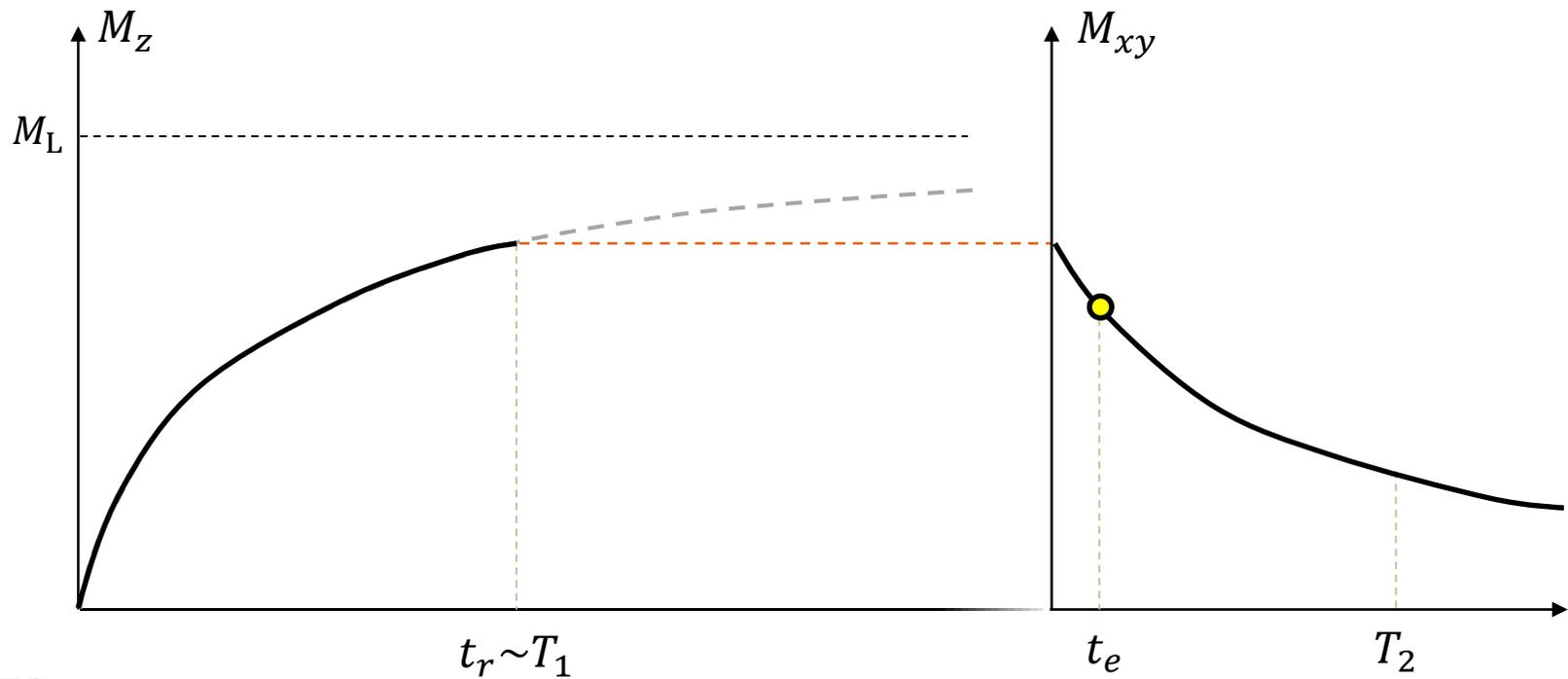
$$\begin{aligned} t_r &\sim T_1 \\ t_e &\ll T_2 \end{aligned}$$



# RMN – contraste

Pondération  $T_1$

$$t_r \sim T_1$$
$$t_e \ll T_2$$



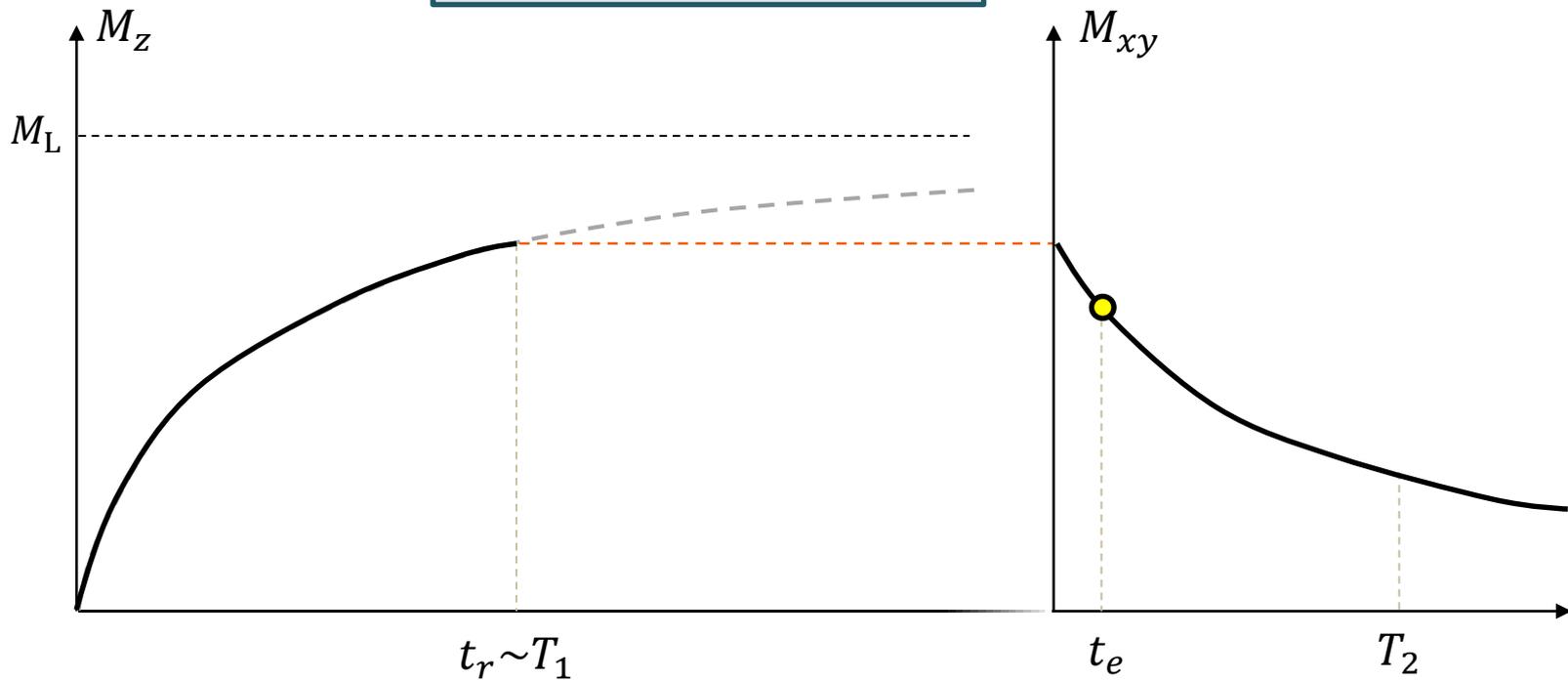
# RMN – contraste

Pondération  $T_1$

$$\begin{matrix} t_r \sim T_1 \\ t_e \ll T_2 \end{matrix}$$

$$FID(t) = M_L(1 - e^{-t_r/T_1}) \sin(\eta) e^{-t_e/T_2} \sin(\omega_0 t)$$

$$\text{Signal} \propto M_L(1 - e^{-t_r/T_1})$$



# RMN – contraste

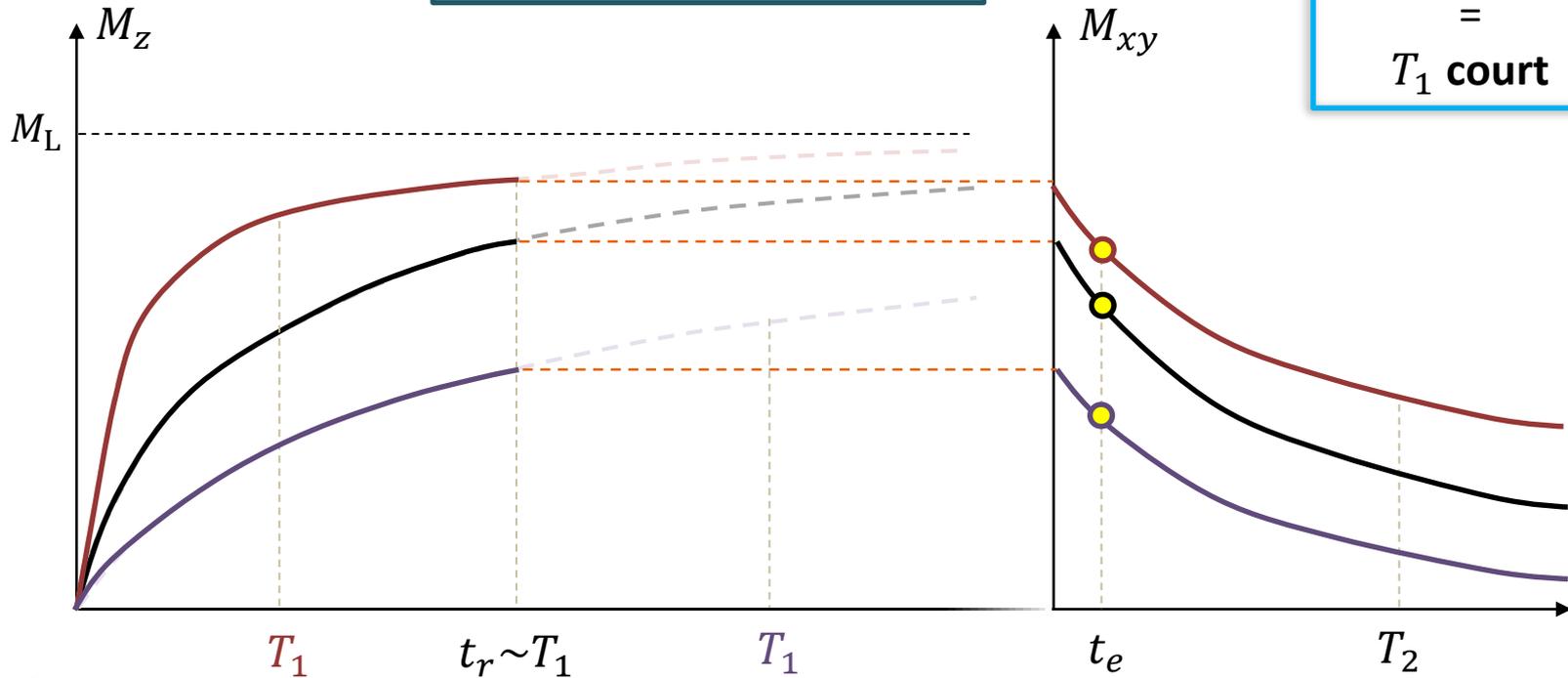
Pondération  $T_1$

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$$\text{Signal} \propto M_L(1 - e^{-t_r/T_1})$$

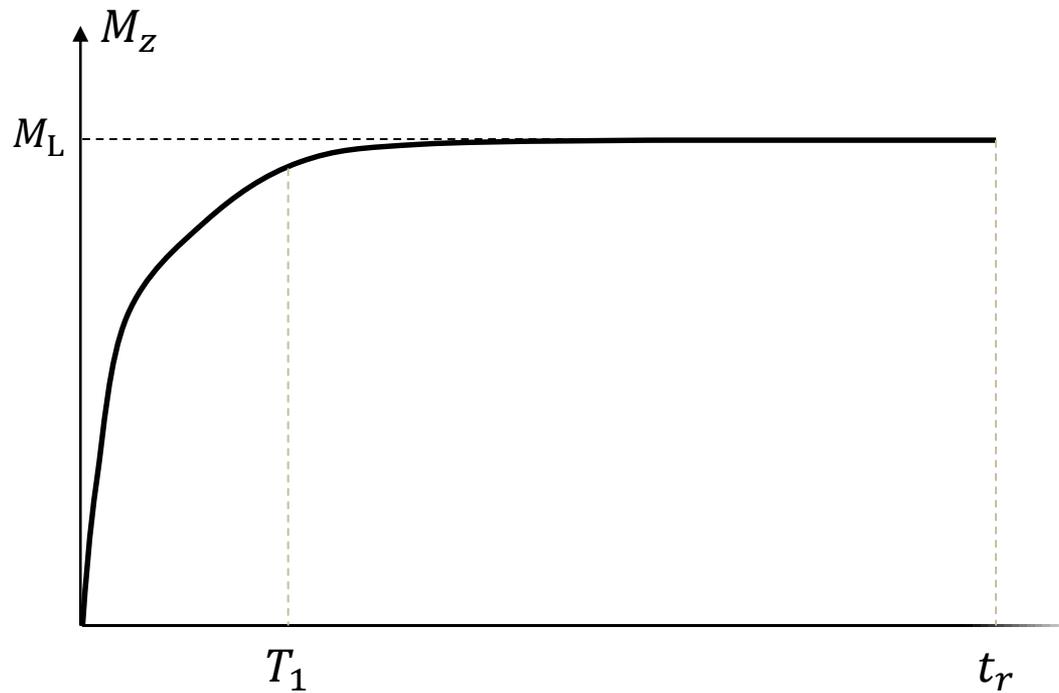
Hyper- $T_1$   
=  $T_1$  court



# RMN – contraste

Pondération  $T_2$

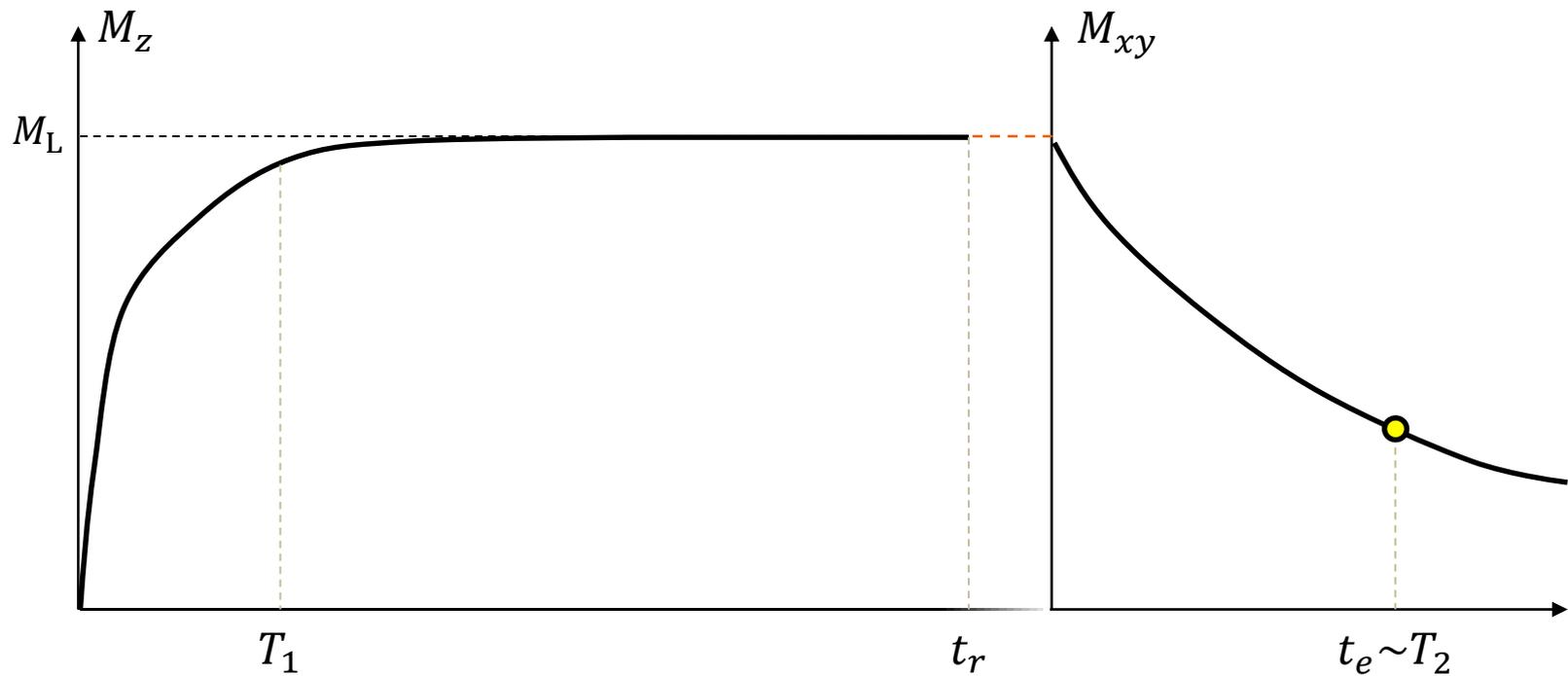
$$t_r \gg T_1$$
$$t_e \sim T_2$$



# RMN – contraste

Pondération  $T_2$

$$t_r \gg T_1$$
$$t_e \sim T_2$$



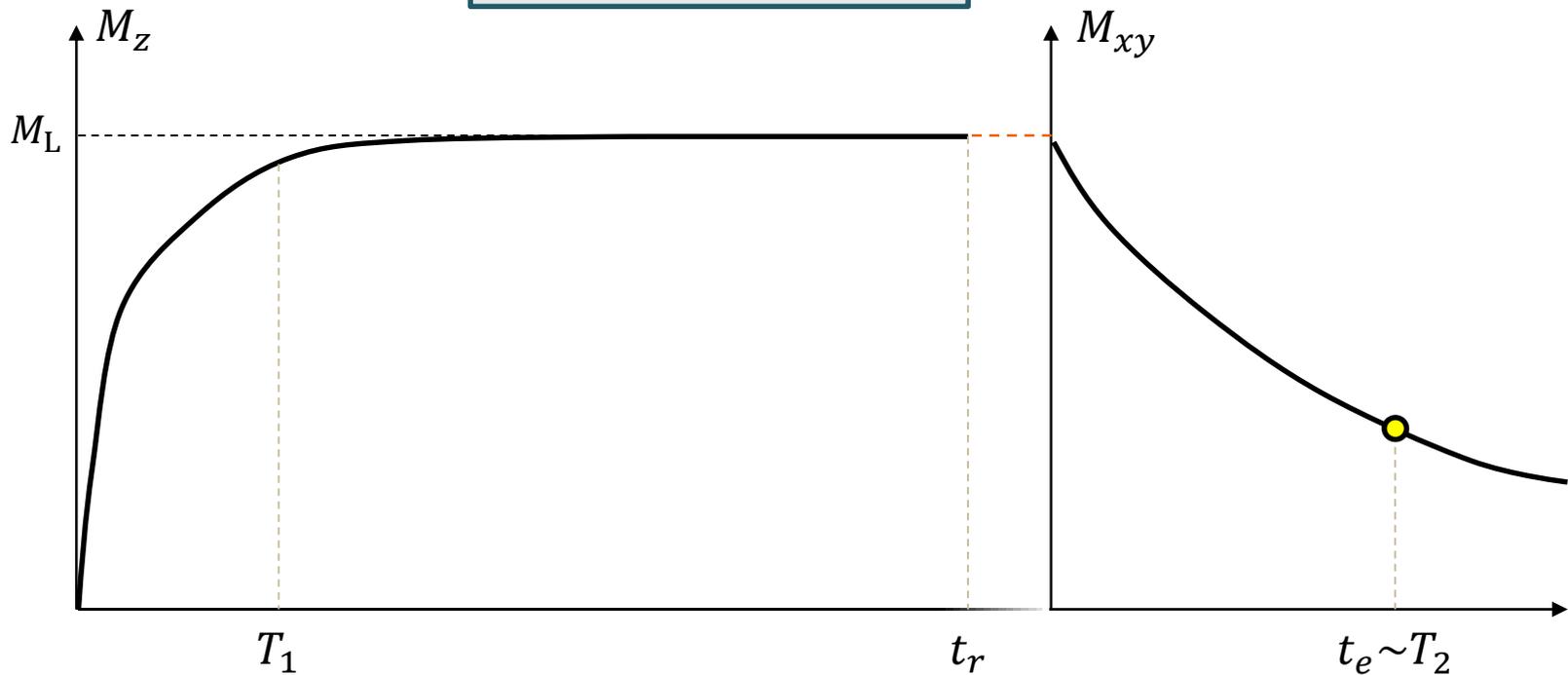
# RMN – contraste

Pondération  $T_2$

$$\begin{aligned} t_r &\gg T_1 \\ t_e &\sim T_2 \end{aligned}$$

$$FID(t) = M_L(1 - e^{-t_r/T_1}) \sin(\eta) e^{-t_e/T_2} \sin(\omega_0 t)$$

$$\text{Signal} \propto M_L(e^{-t_e/T_2})$$



# RMN – contraste

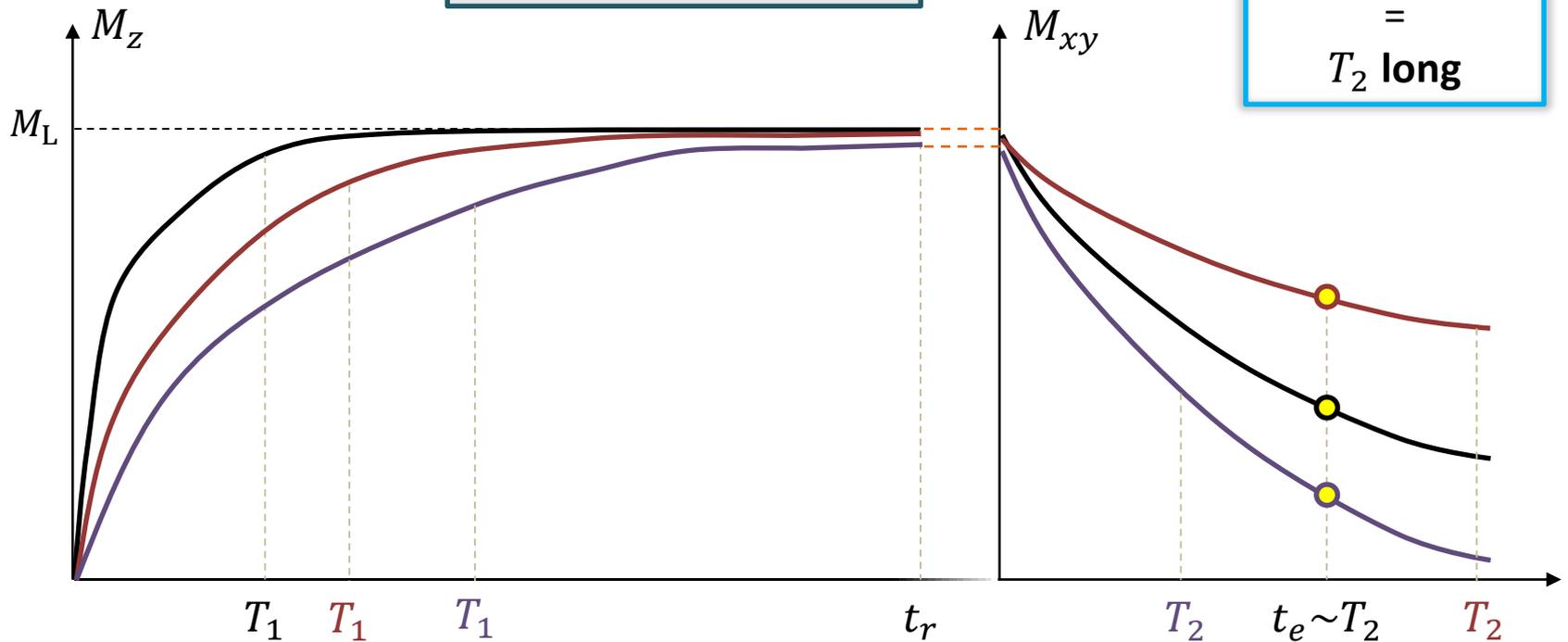
Pondération  $T_2$

$$\begin{aligned} t_r &\gg T_1 \\ t_e &\sim T_2 \end{aligned}$$

$$FID(t) = M_L(1 - e^{-t_r/T_1}) \sin(\eta) e^{-t_e/T_2} \sin(\omega_0 t)$$

$$\text{Signal} \propto M_L(e^{-t_e/T_2})$$

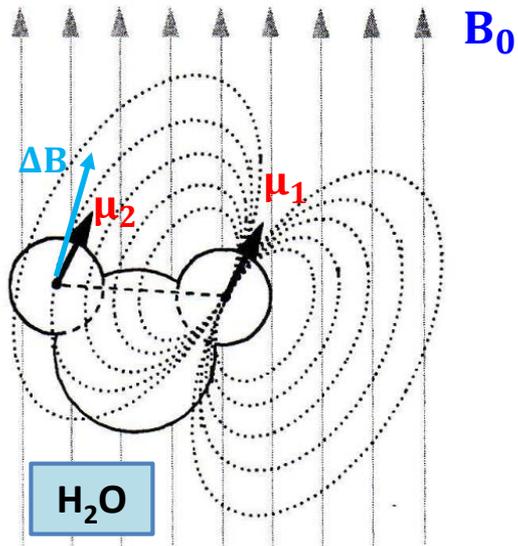
Hyper- $T_2$   
=  
 $T_2$  long



# RMN – contraste

## Relaxation :

- Couplage dipolaire
- Mouvements moléculaires

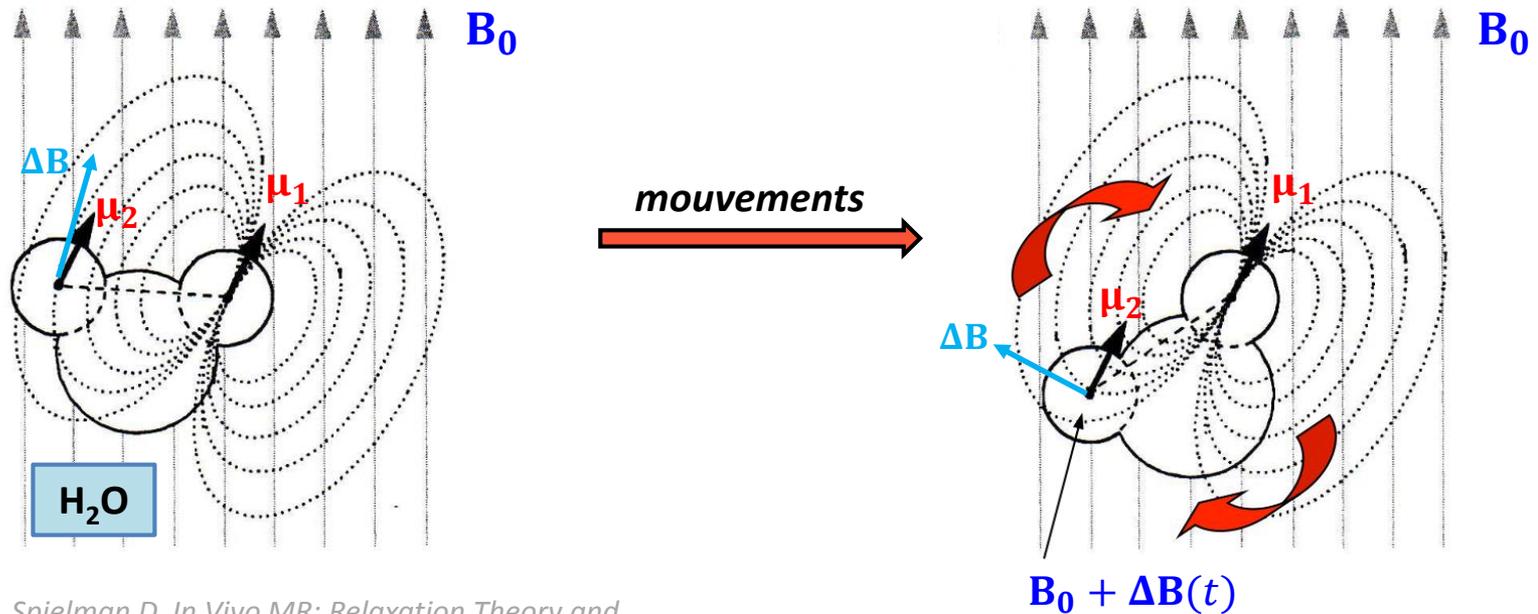


*Spielman D, In Vivo MR: Relaxation Theory and Contrast Mechanisms (<https://www.stanford.edu>)*

# RMN – contraste

## Relaxation :

- Couplage dipolaire
- Mouvements moléculaires

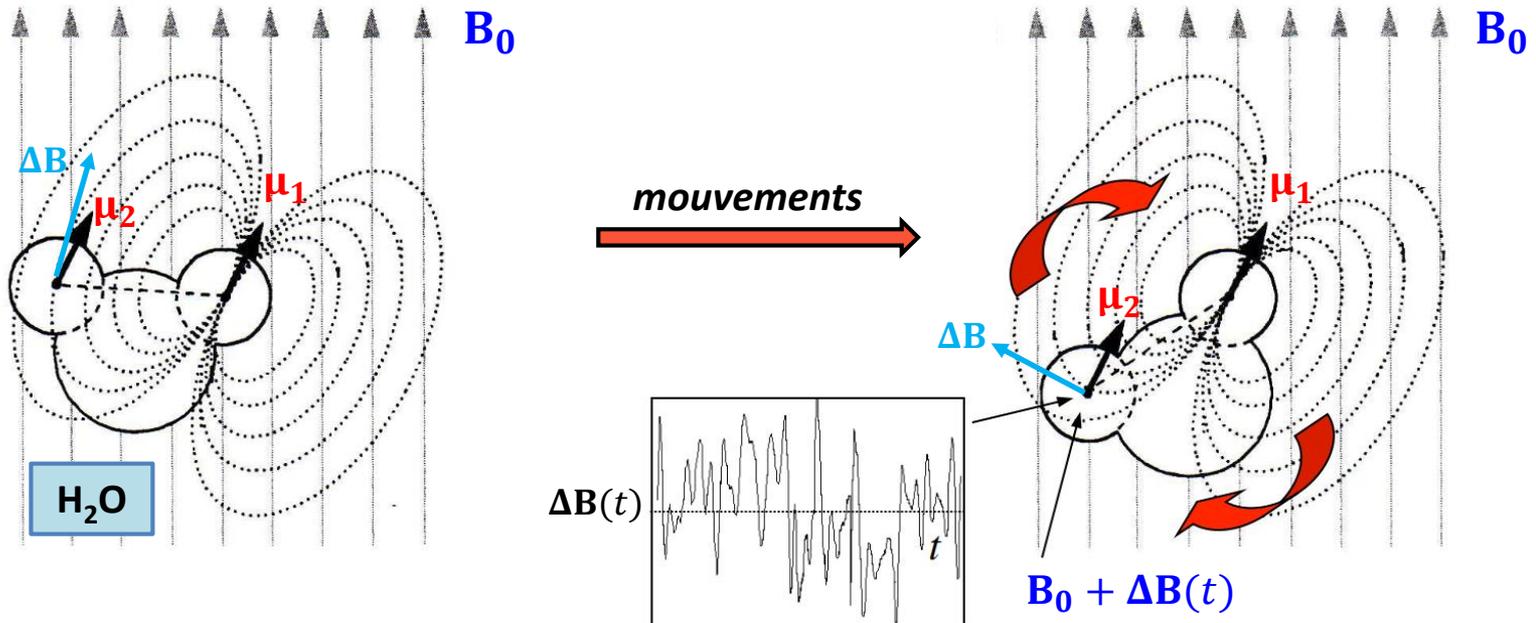


Spielman D, *In Vivo MR: Relaxation Theory and Contrast Mechanisms* (<https://www.stanford.edu>)

# RMN – contraste

## Relaxation :

- Couplage dipolaire
- Mouvements moléculaires



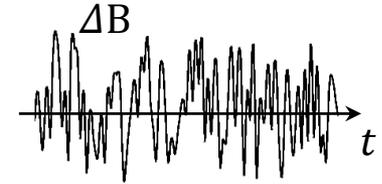
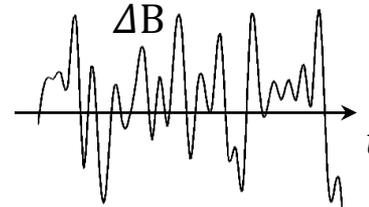
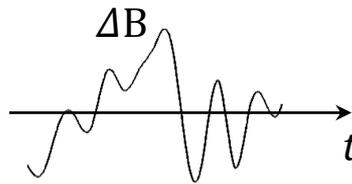
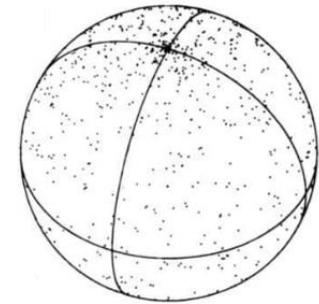
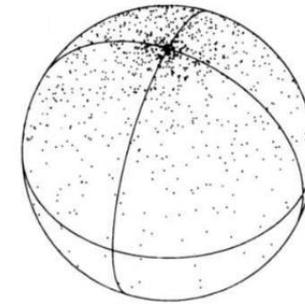
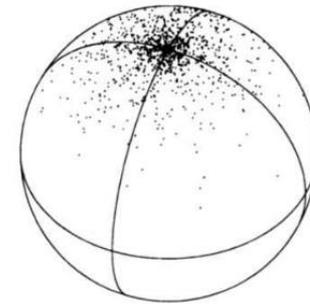
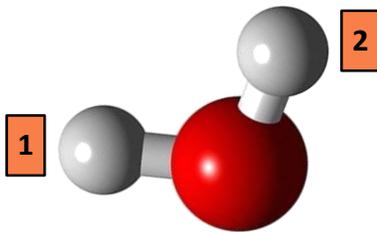
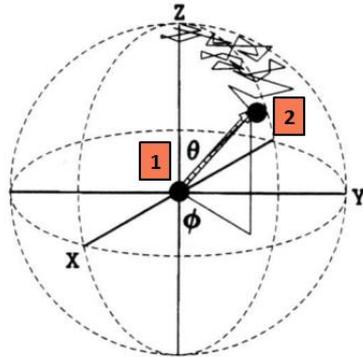
$$\langle \Delta B \rangle = 0$$

$$\langle \Delta B_x^2 \rangle = \langle \Delta B_y^2 \rangle = \langle \Delta B_z^2 \rangle = \langle \Delta B^2 \rangle$$

# RMN – contraste

Relaxation :

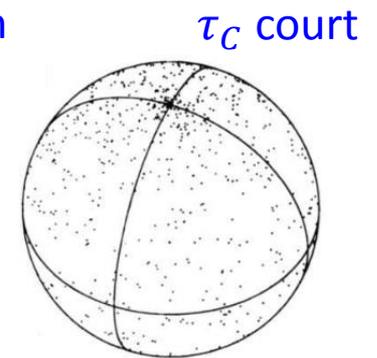
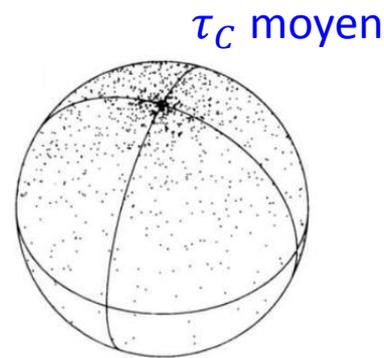
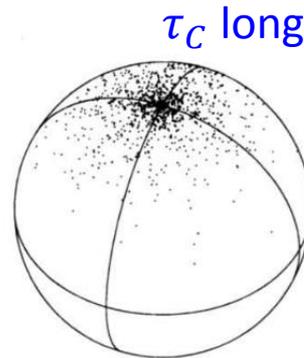
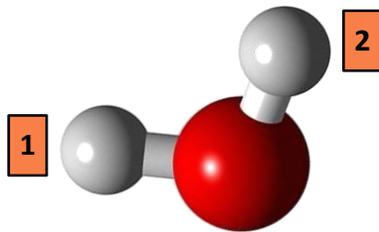
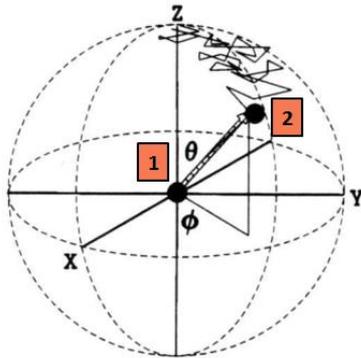
- Couplage dipolaire
- Mouvements moléculaires



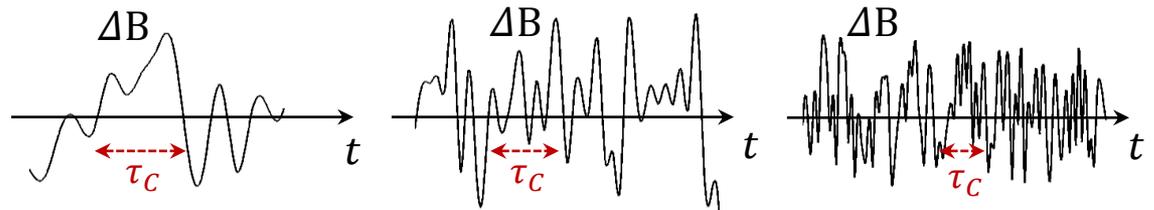
# RMN – contraste

## Relaxation :

- Couplage dipolaire
- Mouvements moléculaires



Mouvements aléatoires. Autocorrélation :  $G(\tau) \propto e^{-\tau/\tau_c}$



$$\tau_c \propto \frac{V \eta}{kT}$$

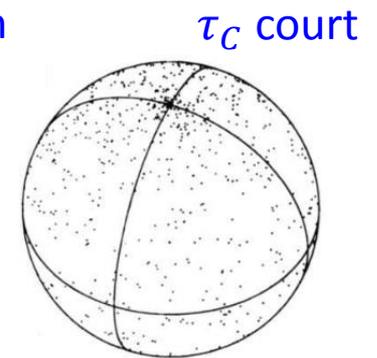
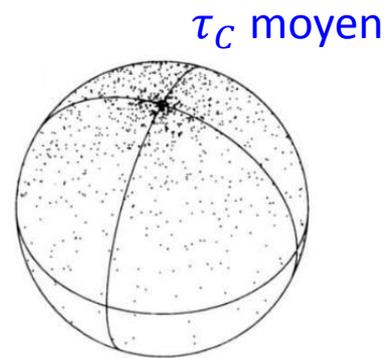
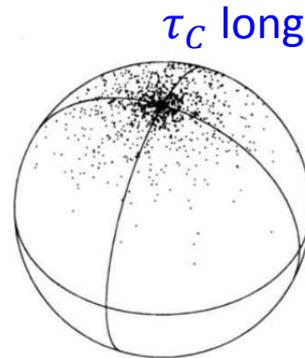
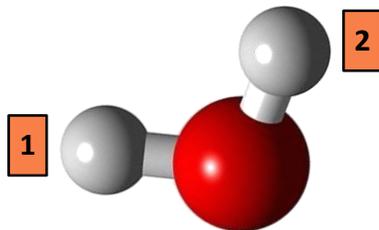
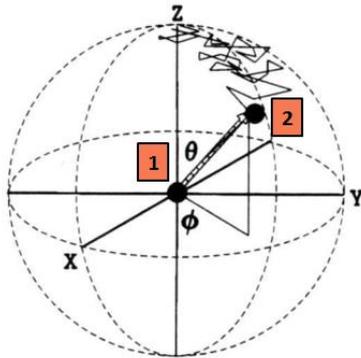
$V$  volume moléculaire  
 $\eta$  viscosité



# RMN – contraste

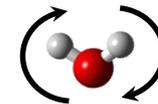
## Relaxation :

- Couplage dipolaire
- Mouvements moléculaires

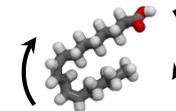


Mouvements aléatoires. Autocorrélation :  $G(\tau) \propto e^{-\tau/\tau_C}$

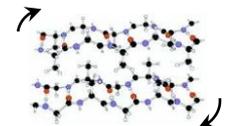
Eau libre : mouvement rapide :  $\tau_C$  court



Eau liée / lipides :  $\tau_C$  moyen



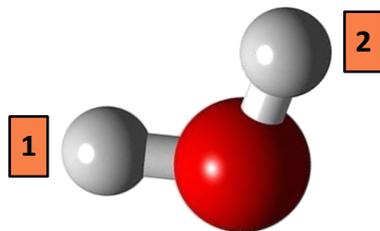
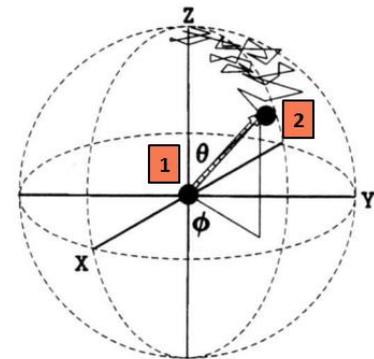
Macromolécules : mouvement lent :  $\tau_C$  long



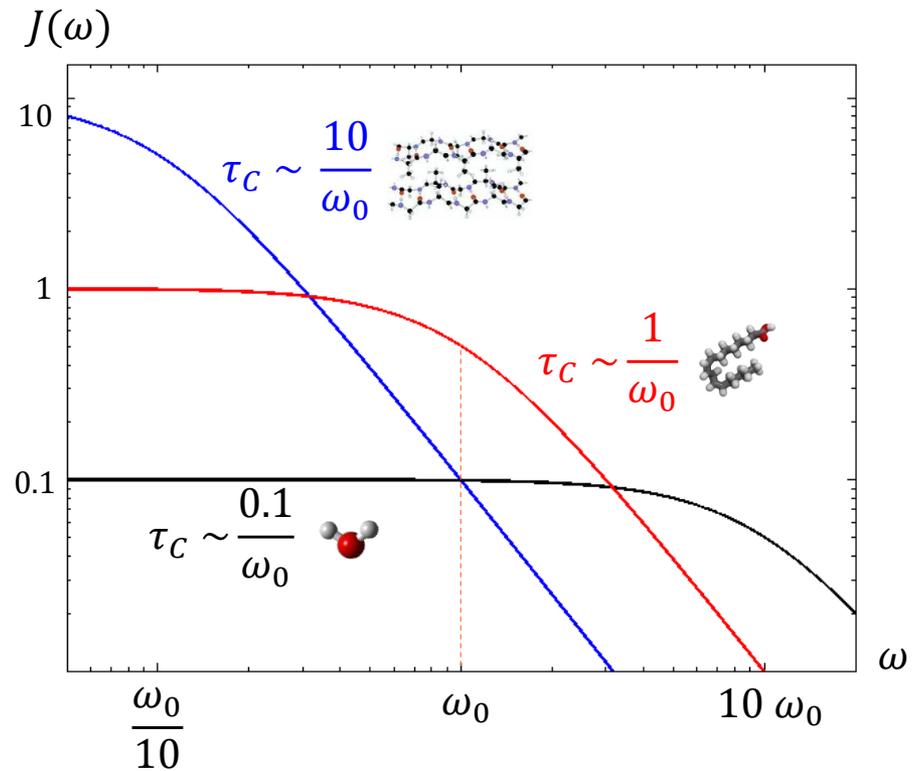
# RMN – contraste

## Relaxation :

- Couplage dipolaire
- Mouvements moléculaires



$J(\omega)$  : spectre de  $G(\tau)$



# RMN – contraste

## Relaxation :

$T_1$

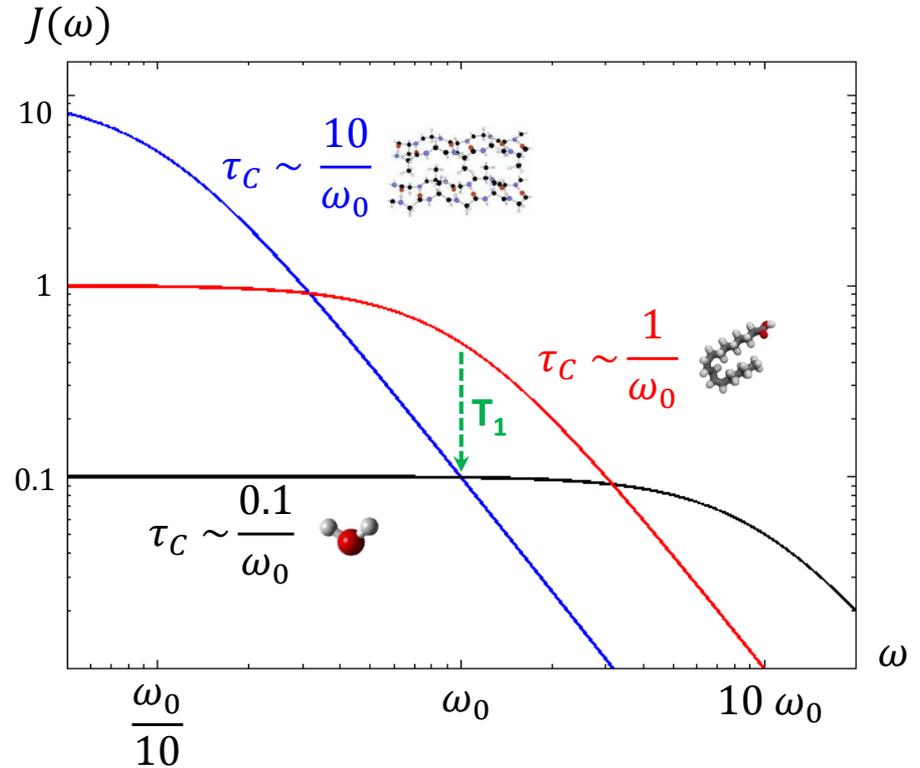
Fluctuations transverses  
→ Échanges d'énergie

$$\frac{1}{T_1} = \gamma^2 (\langle \Delta B_x^2 \rangle + \langle \Delta B_y^2 \rangle) J(\omega_0)$$

$$= 2\gamma^2 \langle \Delta B^2 \rangle J(\omega_0)$$

Intensité du  
champ fluctuant

Proportion de fluctuation  
à la fréquence de Larmor



# RMN – contraste

## Relaxation :

**T<sub>1</sub>**

Fluctuations transverses  
→ Échanges d'énergie

$$\frac{1}{T_1} = \gamma^2 (\langle \Delta B_x^2 \rangle + \langle \Delta B_y^2 \rangle) J(\omega_0)$$

$$= 2\gamma^2 \langle \Delta B^2 \rangle J(\omega_0)$$

Intensité du  
champ fluctuant

Proportion de fluctuation  
à la fréquence de Larmor

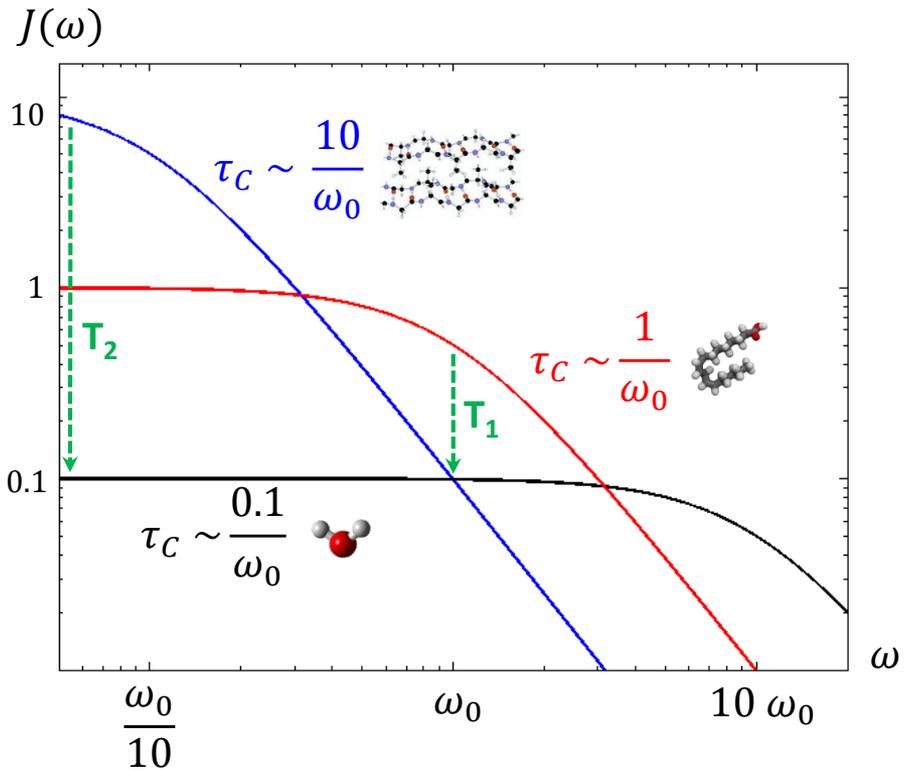
**T<sub>2</sub>**

Fluctuations longitudinales  
→ Déphasage des spins

$$\frac{1}{T_2} = \frac{1}{2T_1} + \gamma^2 \langle \Delta B_z^2 \rangle J(0)$$

$$= \gamma^2 \langle \Delta B^2 \rangle (J(0) + J(\omega_0))$$

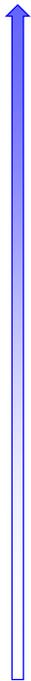
Proportion de  
champ statique



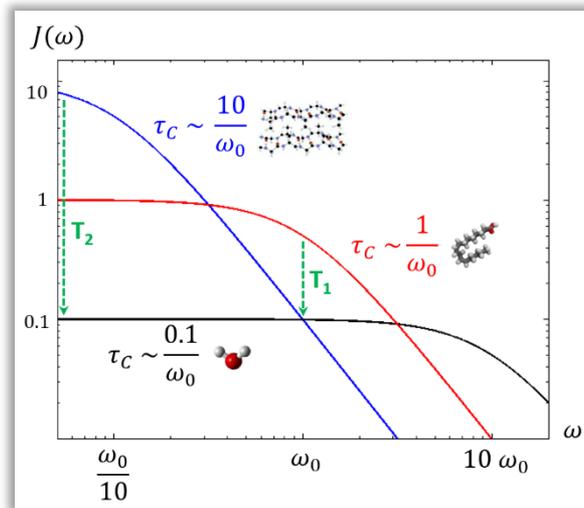
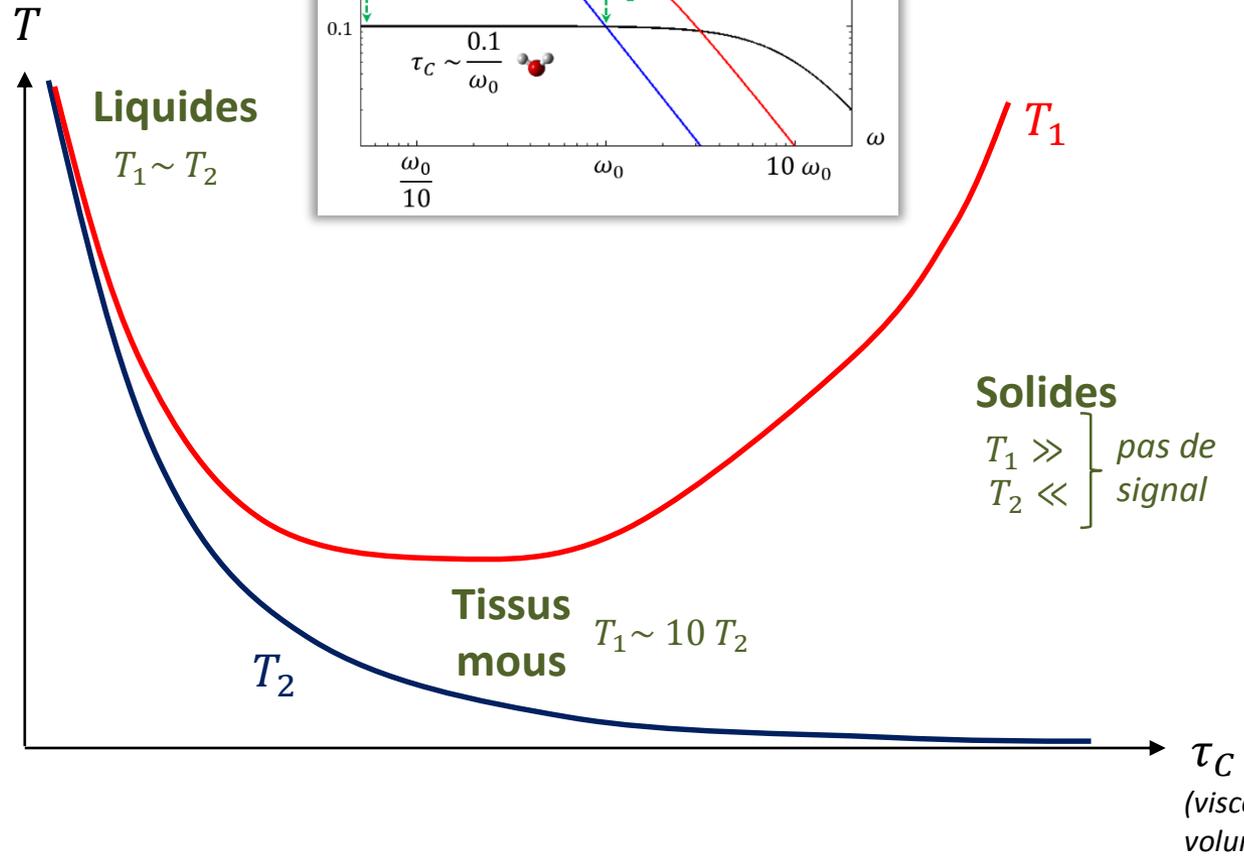
# RMN – contraste

Relaxation :

hyper  $T_2$

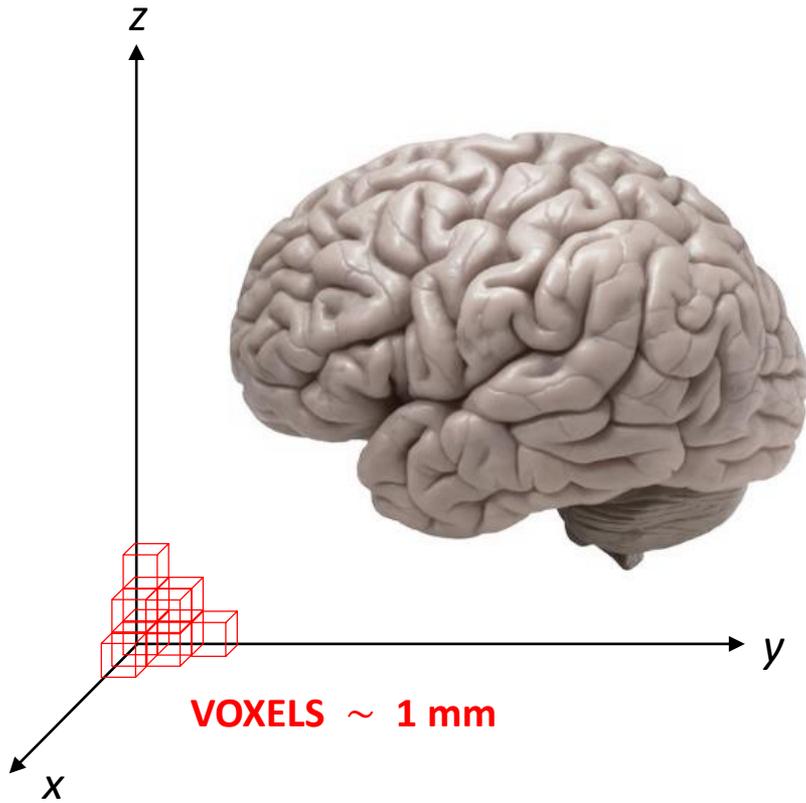


hyper  $T_1$



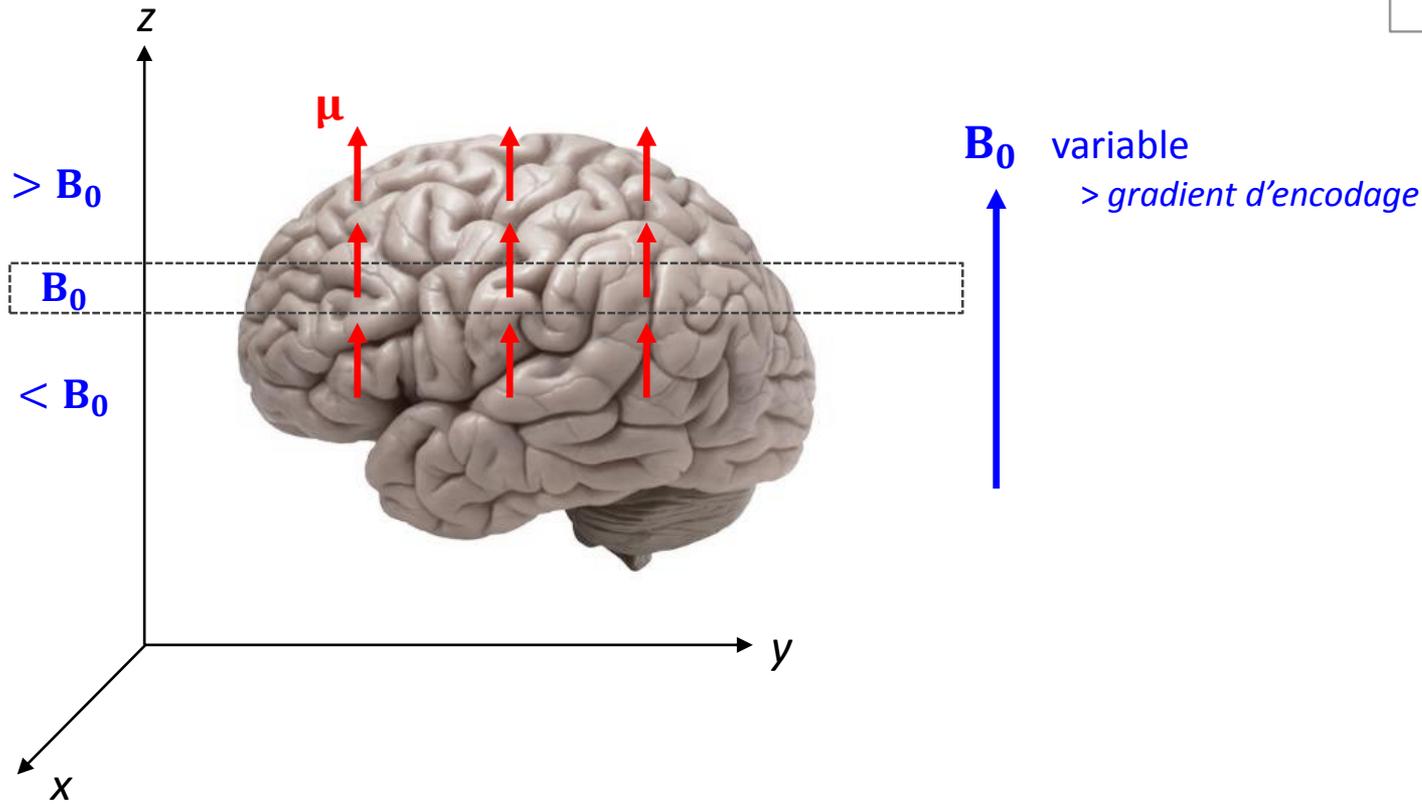
# Applications : IRM / SRM

Imagerie : IRM



# Applications : IRM / SRM

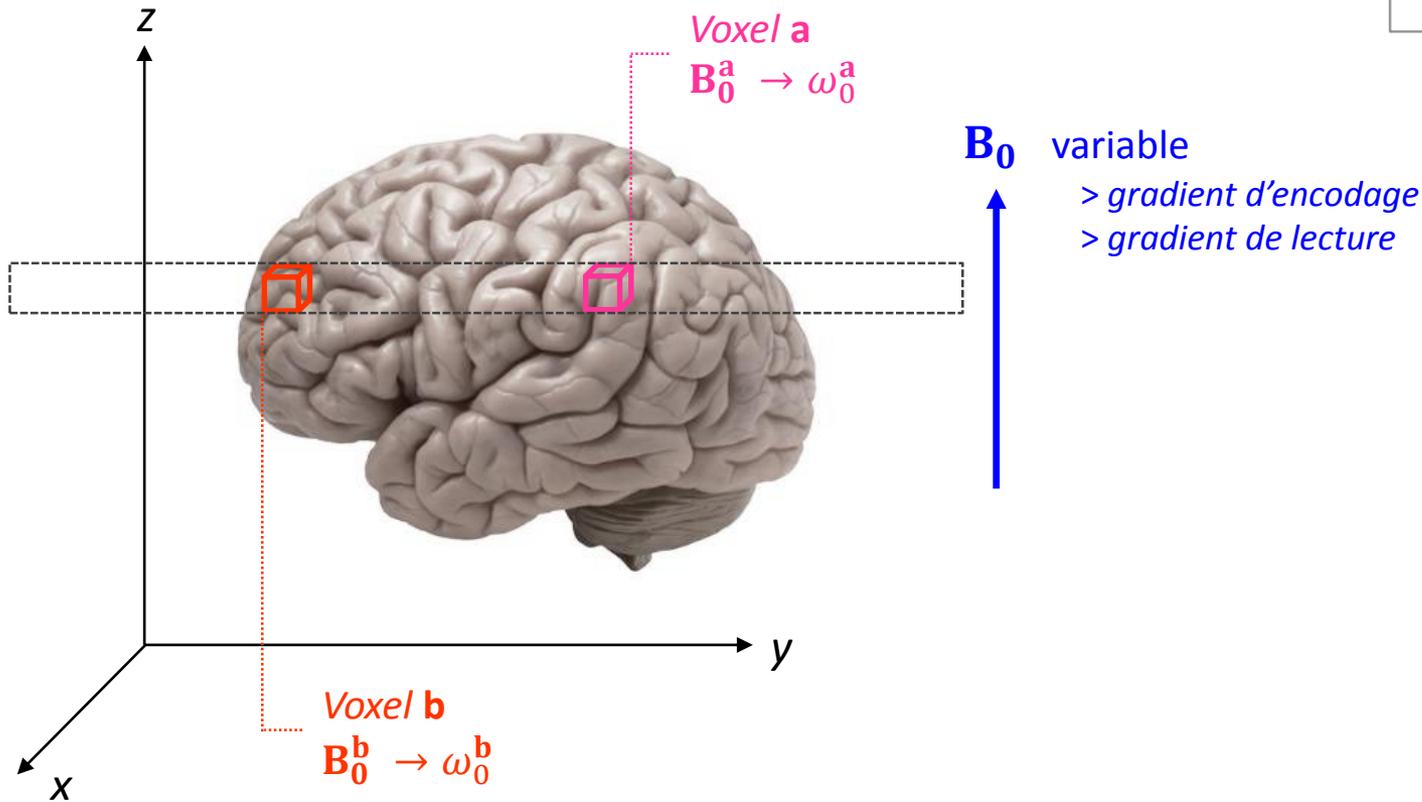
## Imagerie : IRM





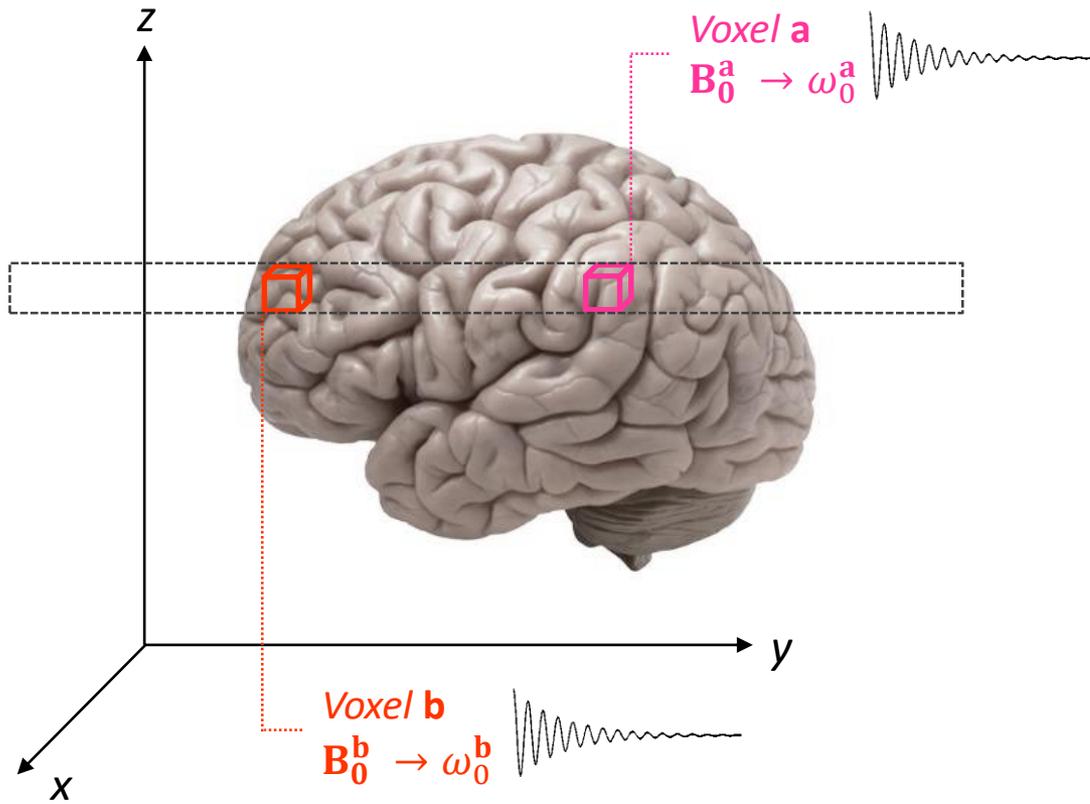
# Applications : IRM / SRM

## Imagerie : IRM

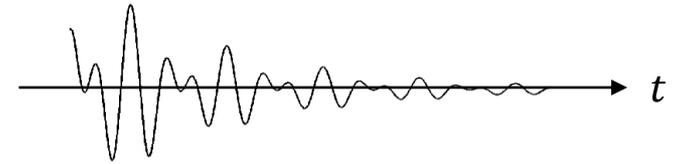


# Applications : IRM / SRM

## Imagerie : IRM

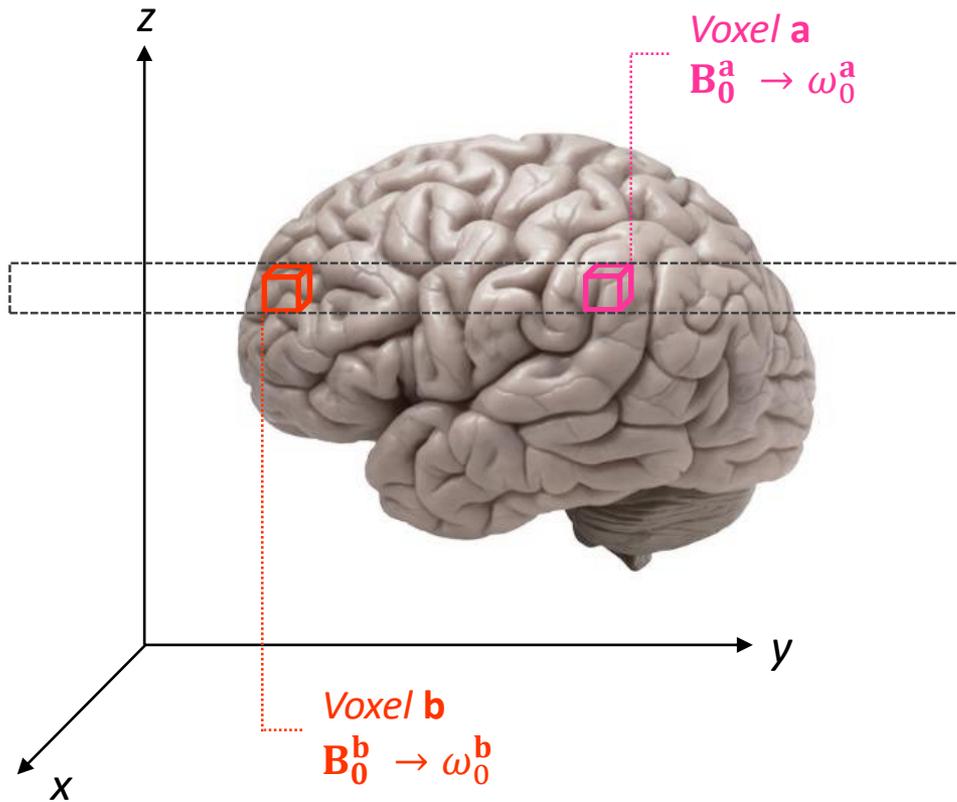


**FID = signal (a) + signal(b)**



# Applications : IRM / SRM

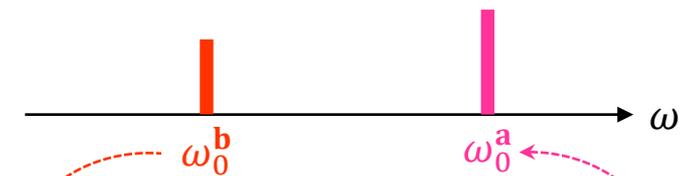
## Imagerie : IRM



**FID = signal (a) + signal(b)**



**Spectre (FID)**

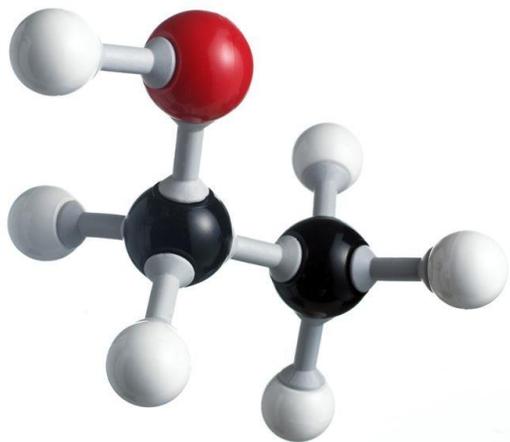


# Applications : IRM / SRM

## Spectroscopie : SRM

Ethanol  $\text{CH}_3\text{-CH}_2\text{-OH}$

$B_0$

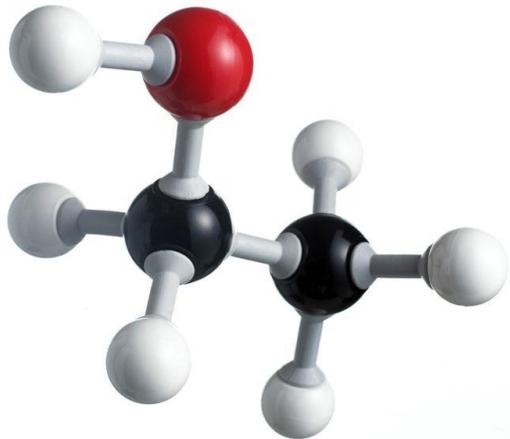


# Applications : IRM / SRM

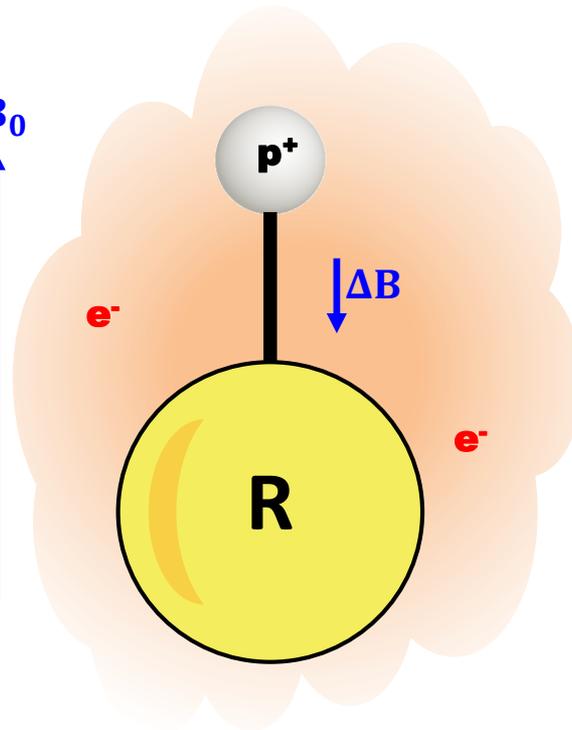
## Spectroscopie : SRM

Ethanol  $\text{CH}_3\text{-CH}_2\text{-OH}$

$B_0$



$B_0$



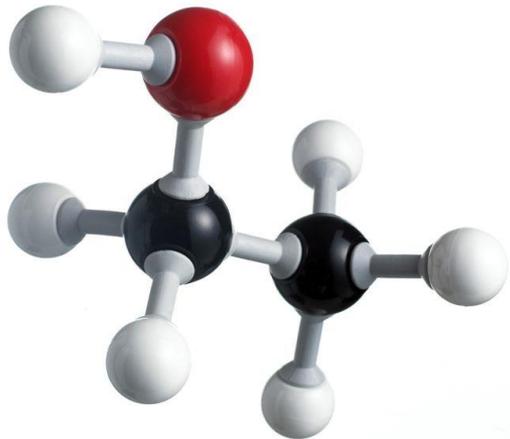
$$B_0^{eff} = B_0 + \Delta B$$

# Applications : IRM / SRM

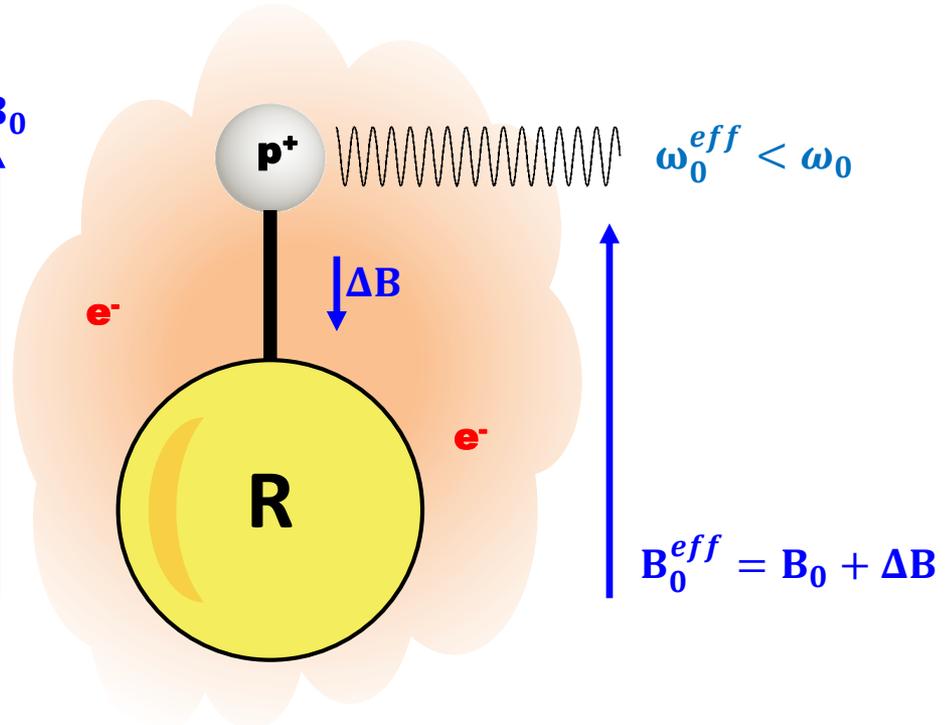
## Spectroscopie : SRM

Ethanol  $\text{CH}_3\text{-CH}_2\text{-OH}$

$B_0$



$B_0$



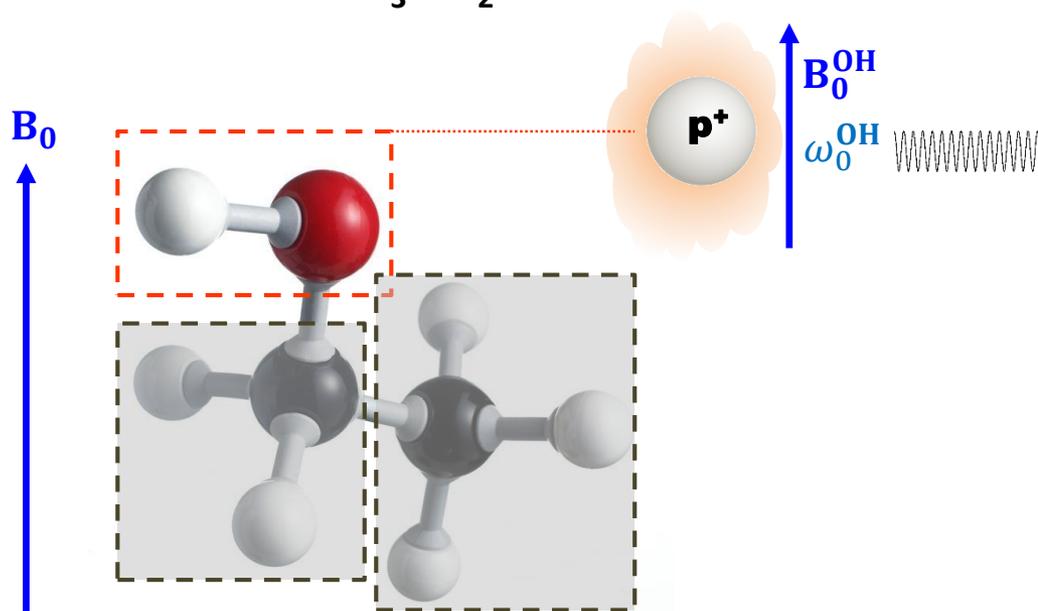
Déplacement chimique :  $\delta = 10^6 \frac{\omega_0^{eff} - \omega_0^{ref}}{\omega_0^{ref}}$  [ppm]



# Applications : IRM / SRM

## Spectroscopie : SRM

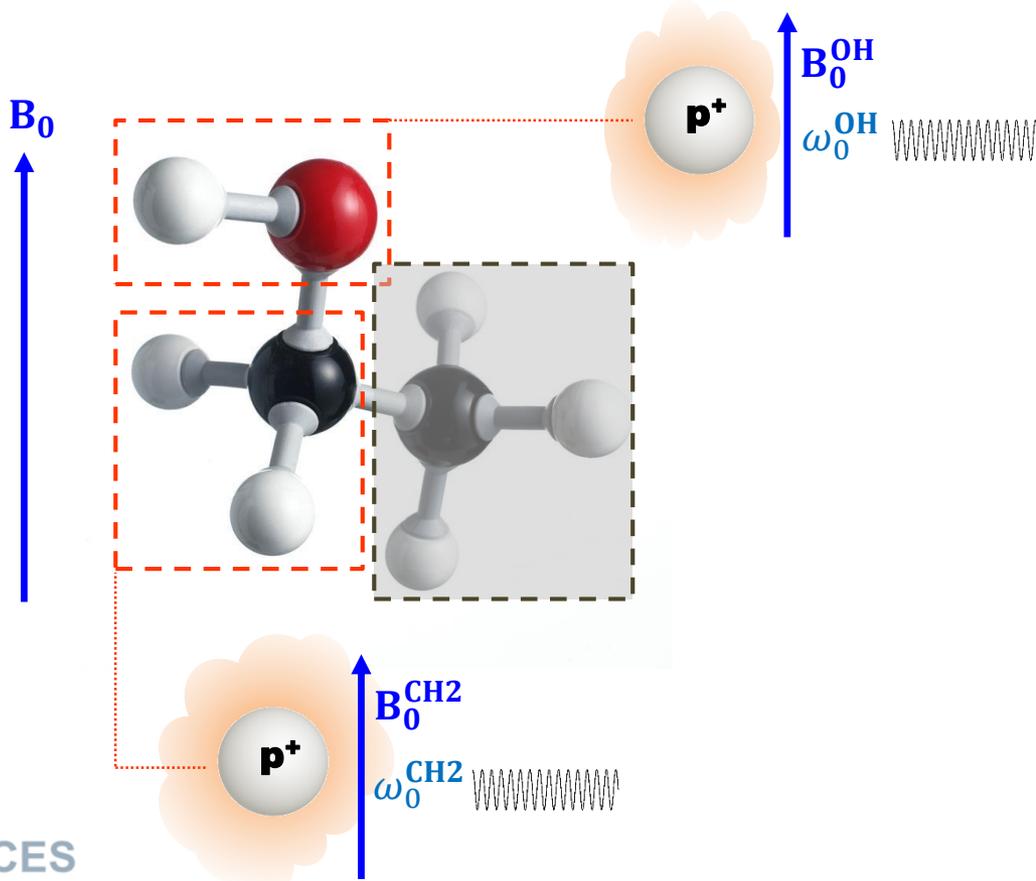
Ethanol  $\text{CH}_3\text{-CH}_2\text{-OH}$



# Applications : IRM / SRM

## Spectroscopie : SRM

Ethanol  $\text{CH}_3\text{-CH}_2\text{-OH}$

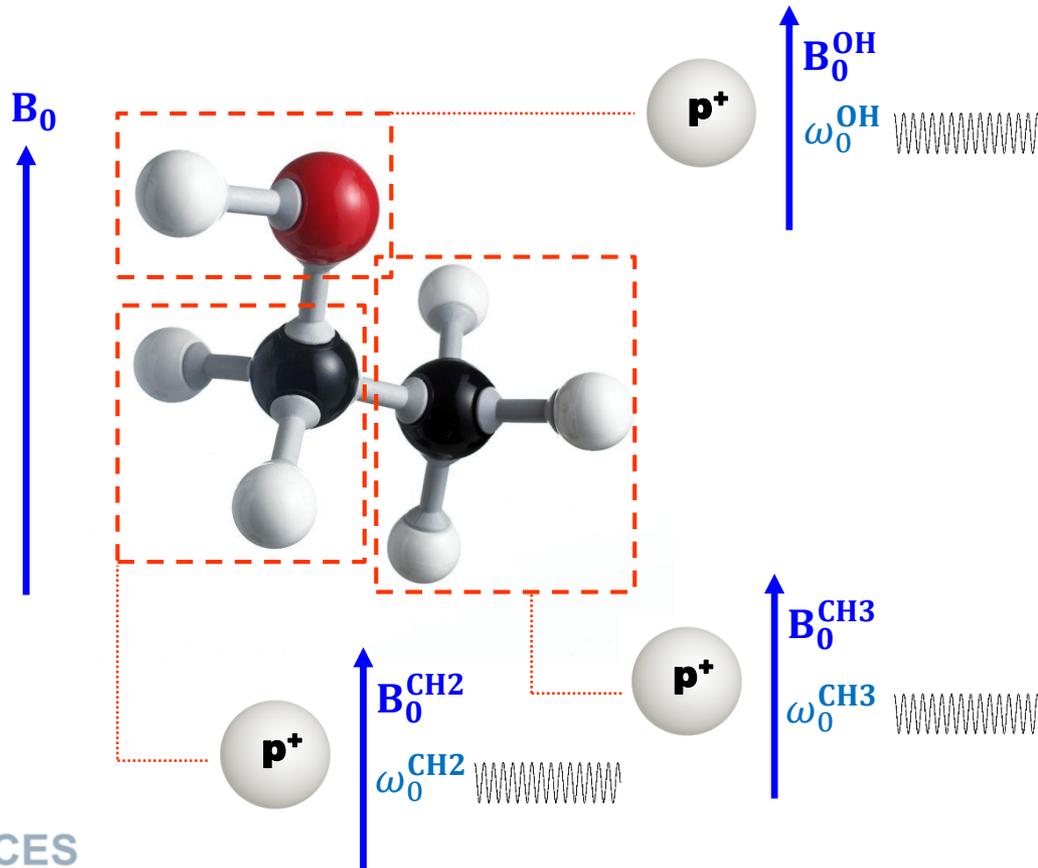




# Applications : IRM / SRM

## Spectroscopie : SRM

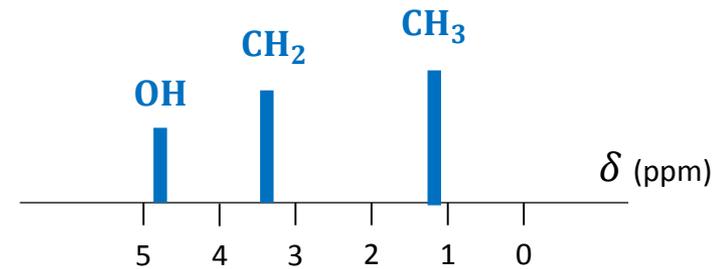
Ethanol  $\text{CH}_3\text{-CH}_2\text{-OH}$



FID = signal (OH) + signal(CH<sub>2</sub>) + signal(CH<sub>3</sub>)

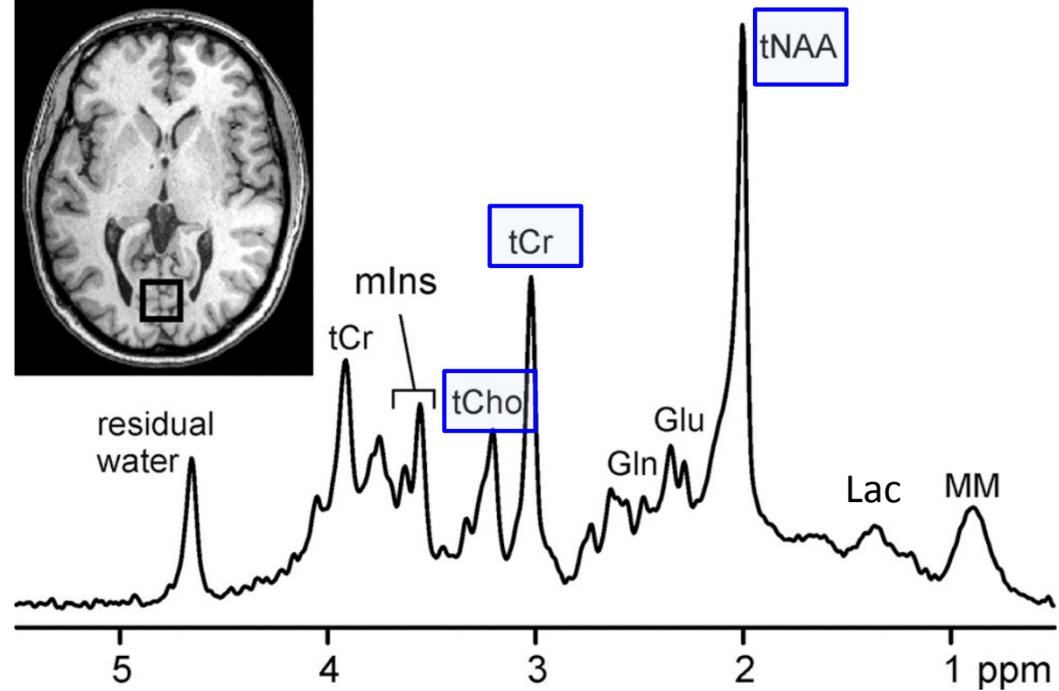
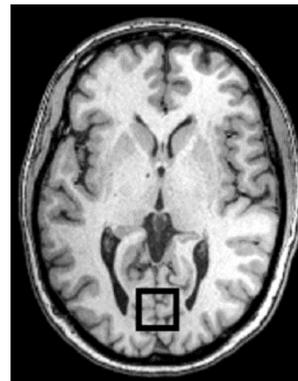
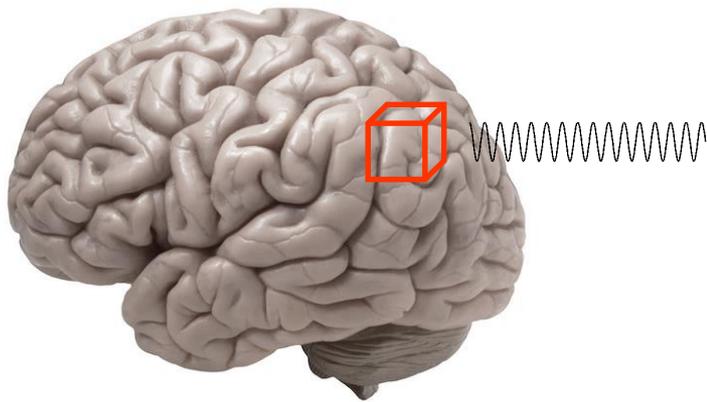


Spectre (FID)



# Applications : IRM / SRM

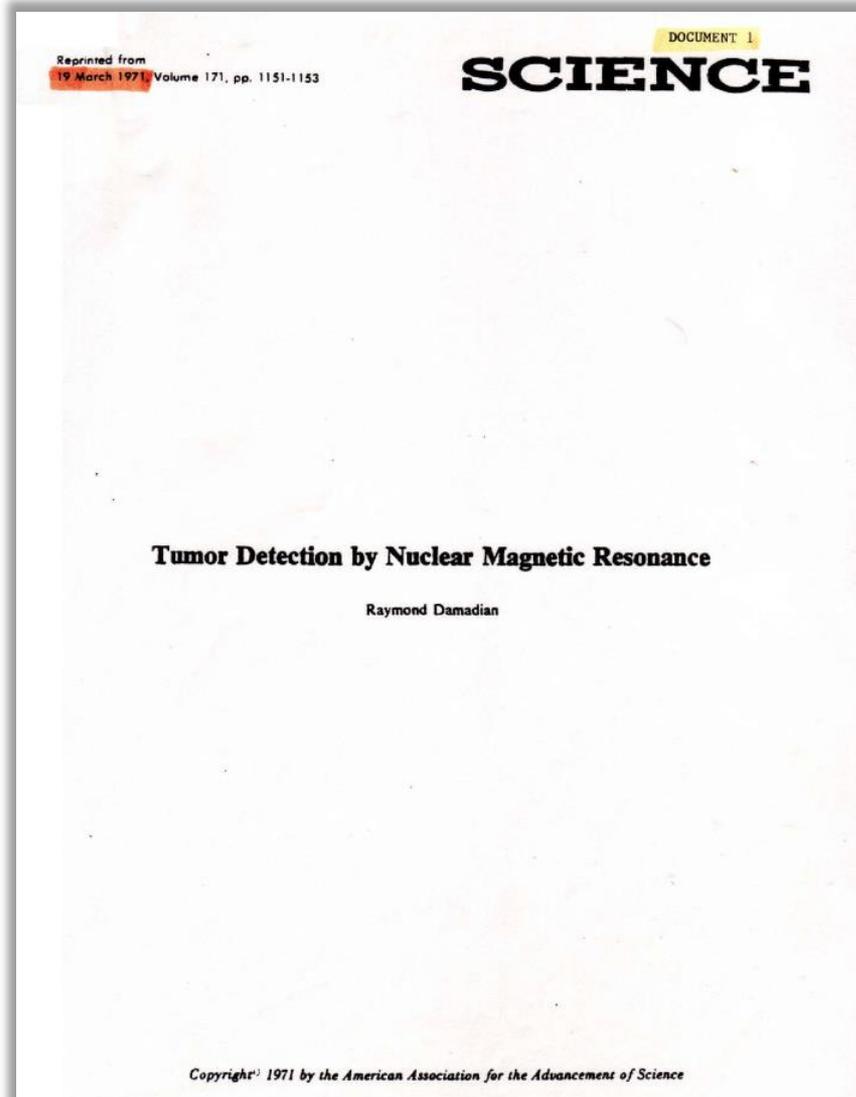
## Spectroscopie : SRM



- Cho** : choline - catabolisme membranaire
- Cr** : créatine - métabolisme aérobie
- NAA** : N-acétylaspartate - viabilité cellulaire
- Lac** : lactates - métabolisme anaérobie
- MM** : macro-molécules

Gülin et al. Radiology 2014.

# IRM – exemples



# IRM – exemples

Table 1. Spin-lattice ( $T_1$ ) and spin-spin ( $T_2$ ) relaxation times (in seconds) of normal tissues.

Tissue							
Rectus muscle		Liver		Stomach	Small intestine	Kidney	Braun
$T_1$	$T_2$	$T_1$	$T_2$	$T_1$	$T_1$	$T_1$	$T_1$
0.493	0.050	0.286	0.050	0.272	0.280	0.444	0.573
548	350	322	060	214	225	503	573
541	350	241	050	260	316	423	596
576 (0.600)*	070	306 (0.287)*	048	247 (0.159)*	316 (0.280)*	541 (0.530)*	620 (0.614)
531		300		360	150	489	612
<i>Mean and standard error</i>							
0.538 ± 0.015	0.055 ± 0.005	0.293 ± 0.010	0.052 ± 0.003	0.270 ± 0.016	0.257 ± 0.030	0.480 ± 0.026	0.595 ± 0.007

relaxation time after the specimen stood overnight at room temperature.



# IRM – exemples

Table 1. Spin-lattice ( $T_1$ ) and spin-spin ( $T_2$ )

Rectus muscle		Liver	
$T_1$	$T_2$	$T_1$	$T_2$
0.493	0.050	0.286	0.050
.548	.050	.322	.060
.541	.050	.241	.050
.576 (0.600)*	.070	.306 (0.287)*	.048
.531		.300	
Mean and S.E.			
0.538 ± 0.015	0.055 ± 0.005	0.293 ± 0.010	0.052 ± 0.002

relaxation time after the specimen stood overnight at room

Table 2. Spin-lattice ( $T_1$ ) and spin-spin ( $T_2$ ) relaxation times (in seconds) in tumors.

Rat No.	Weight (g)	$T_1$	$T_2$
<i>Walker sarcoma</i>			
6	156	0.700	0.100
7	150	.750	.100
8	495	.794 (0.794)*	.100
9	233	.688	
10	255	.750	
Mean and S.E.		0.736 ± 0.022	.100
P		< .01†	
<i>Novikoff hepatoma</i>			
11	155	0.798	0.120
12	160	.852	.120
13	231	.827	.115
Mean and S.E.		0.826 ± 0.013	0.118 ± 0.002
P		< .01†	
<i>Fibroadenoma (benign)</i>			
14		0.448	
15		.537	
Mean		.492	
<i>Distilled water</i>			
		2.691	
		2.690	
		2.640	
Mean and S.E.		2.677 ± 0.021	

\* Spin-lattice relaxation time after the specimen stood overnight at room temperature. † The P values are the probability estimates of the significance of the difference in the means of  $T_1$  for the malignant tumor and for brain.

ues.

Kidney $T_1$	Brain $T_1$
	0.573
	.573
	.596
41 (0.530)*	520 (0.614)
89	512
480 ± 0.026	0.595 ± 0.007

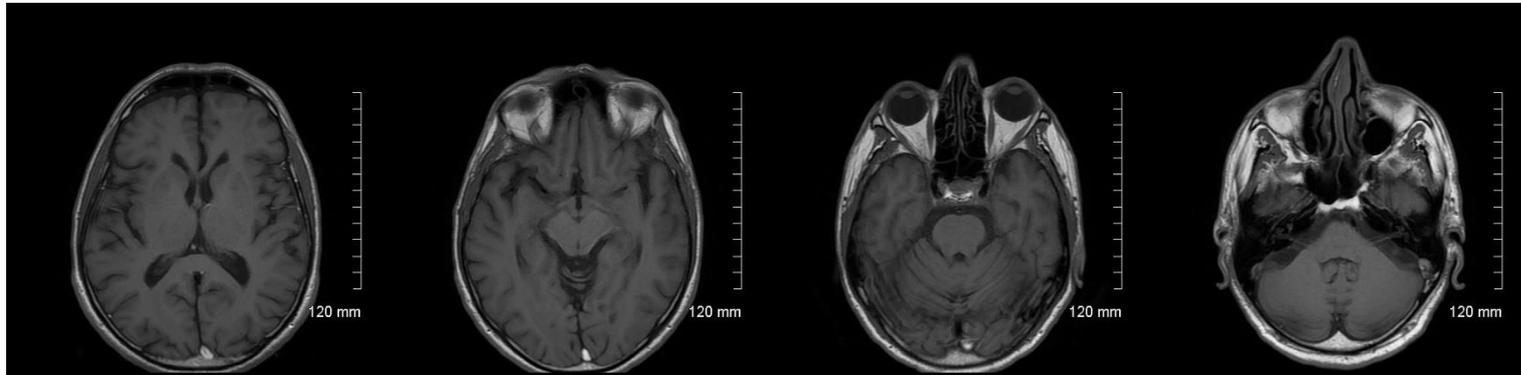


# IRM – exemples

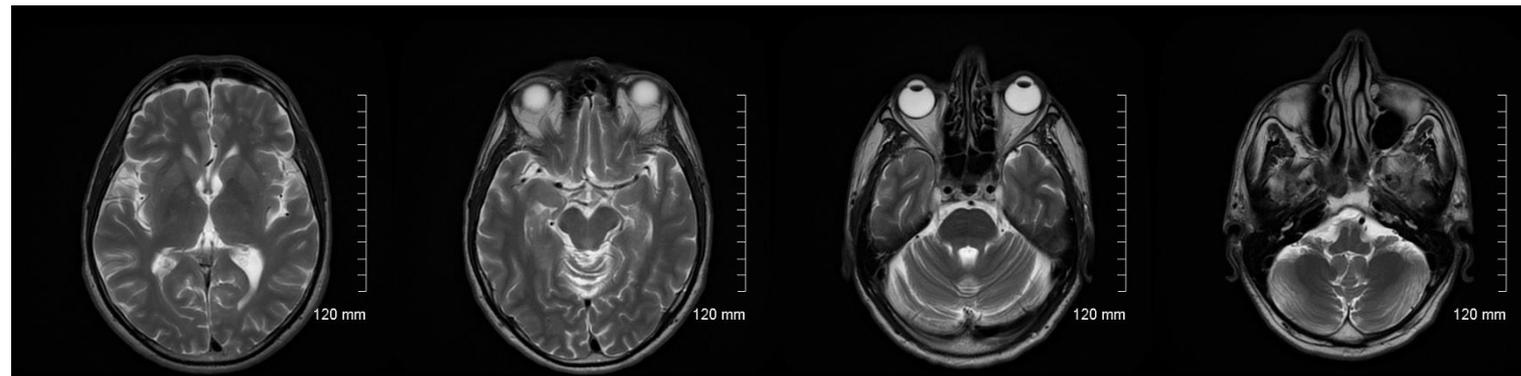
$T_1$  : contraste anatomique

$T_2$  : contraste « inversé »

$T_1$



$T_2$

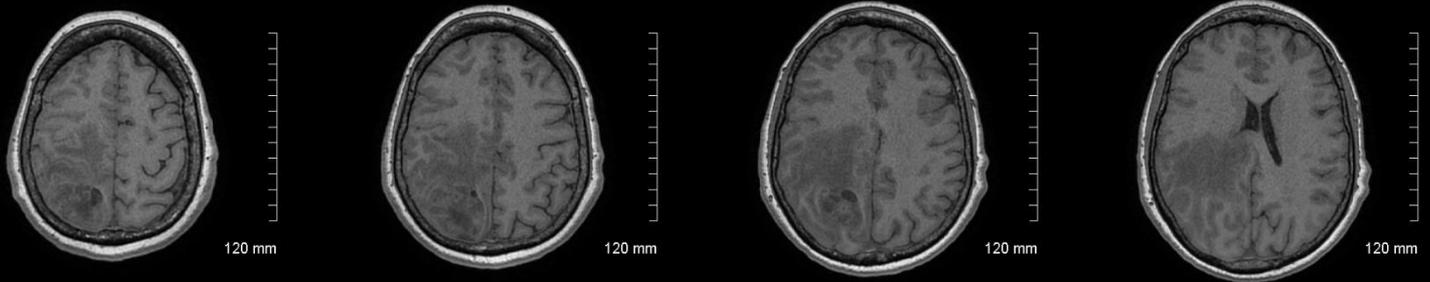


# IRM – exemples

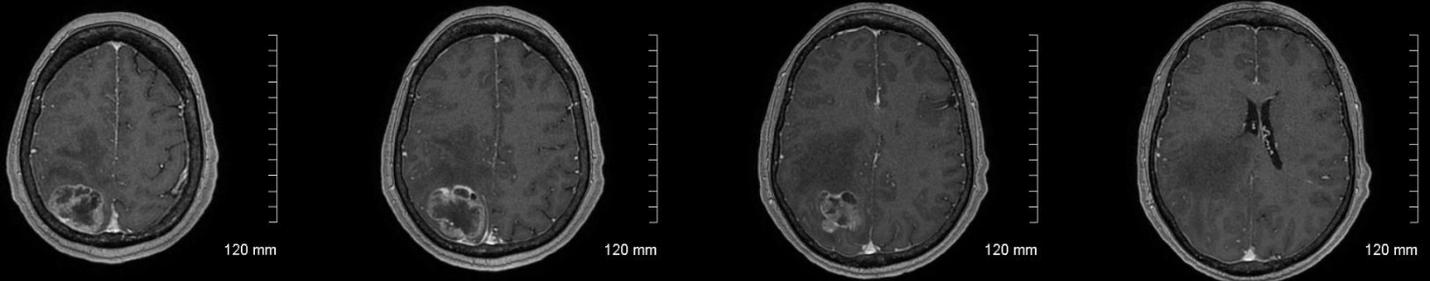
## Métastase cérébrale

- Rupture BHE
- Effet de masse
- Oedème

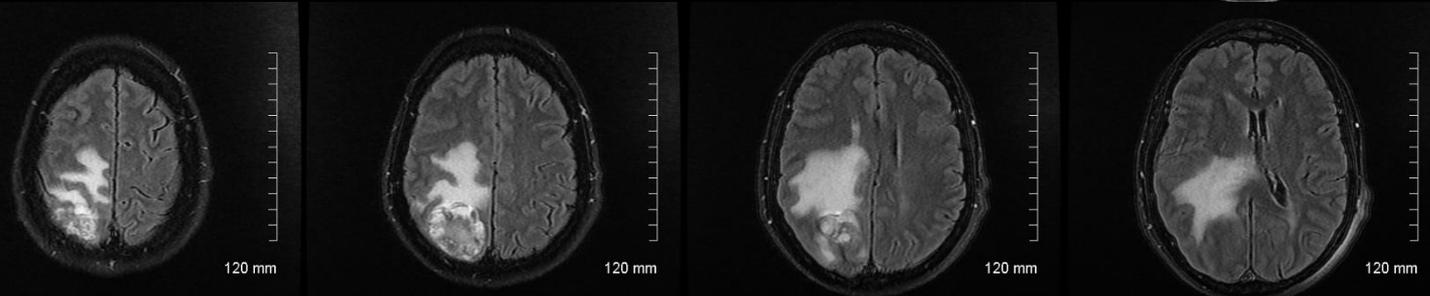
T<sub>1</sub>



T<sub>1</sub> gado.



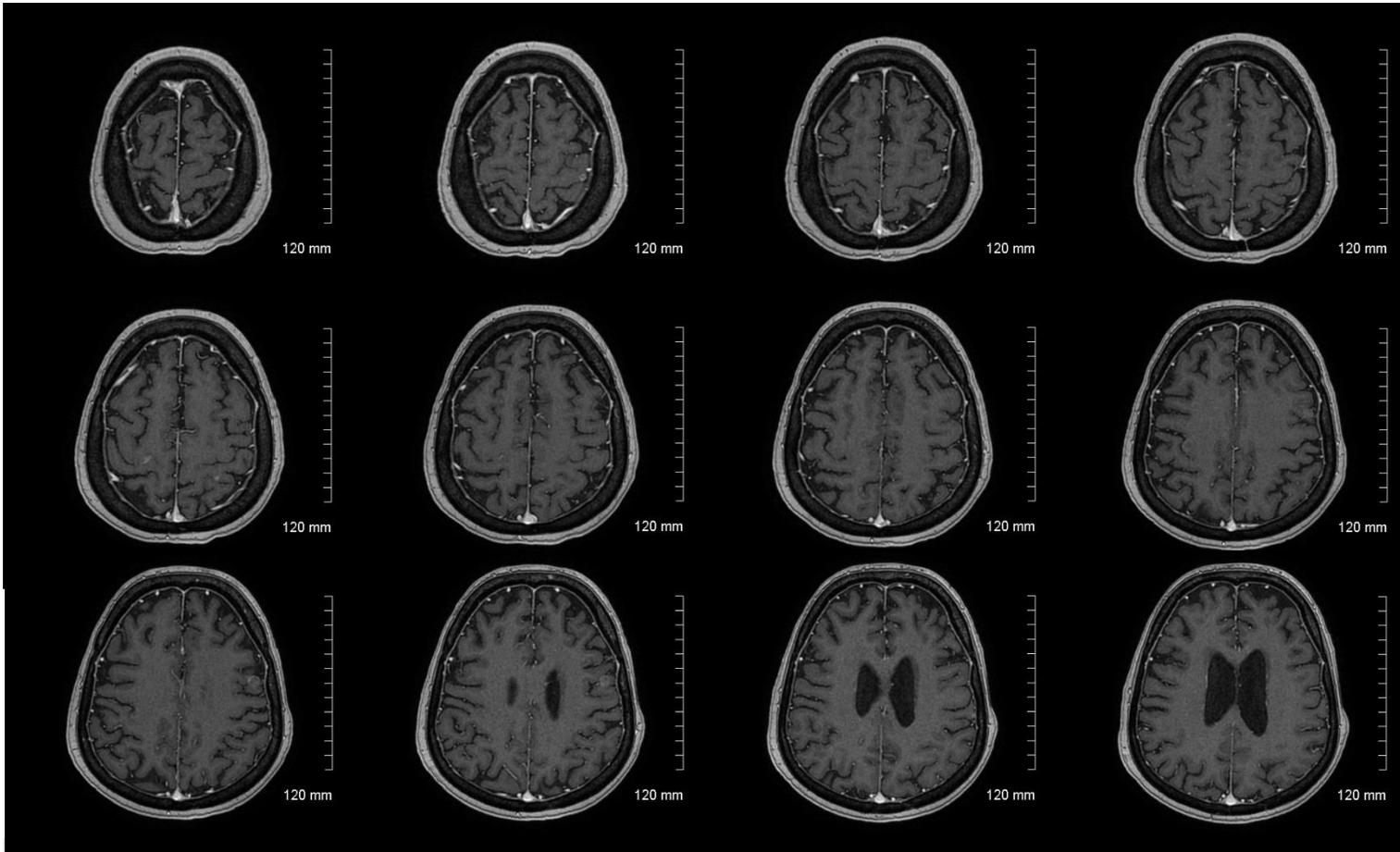
T<sub>2</sub> FLAIR



# IRM – exemples

Bilan initial ADK pulmonaire

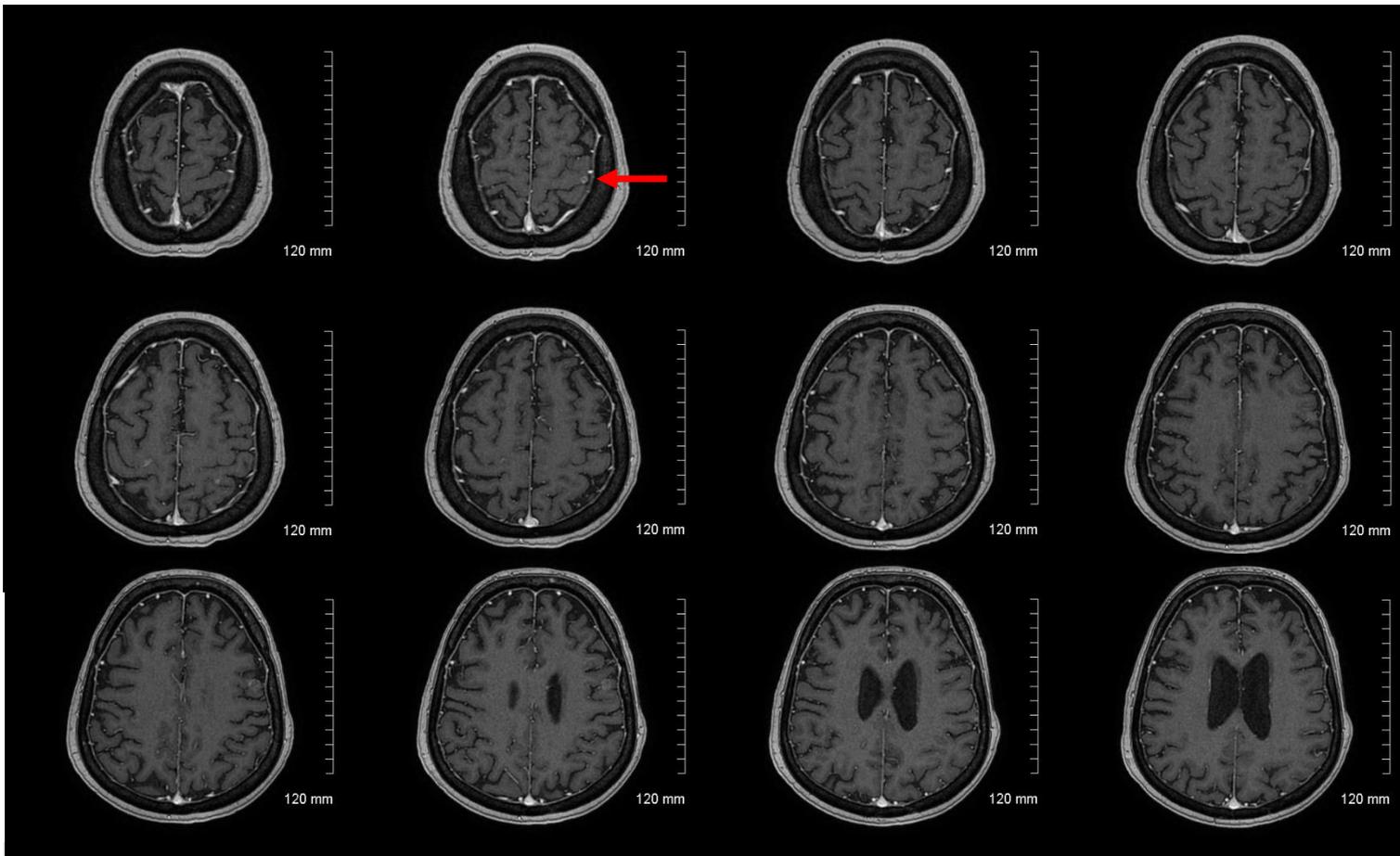
T<sub>1</sub> gado.



# IRM – exemples

Bilan initial ADK pulmonaire

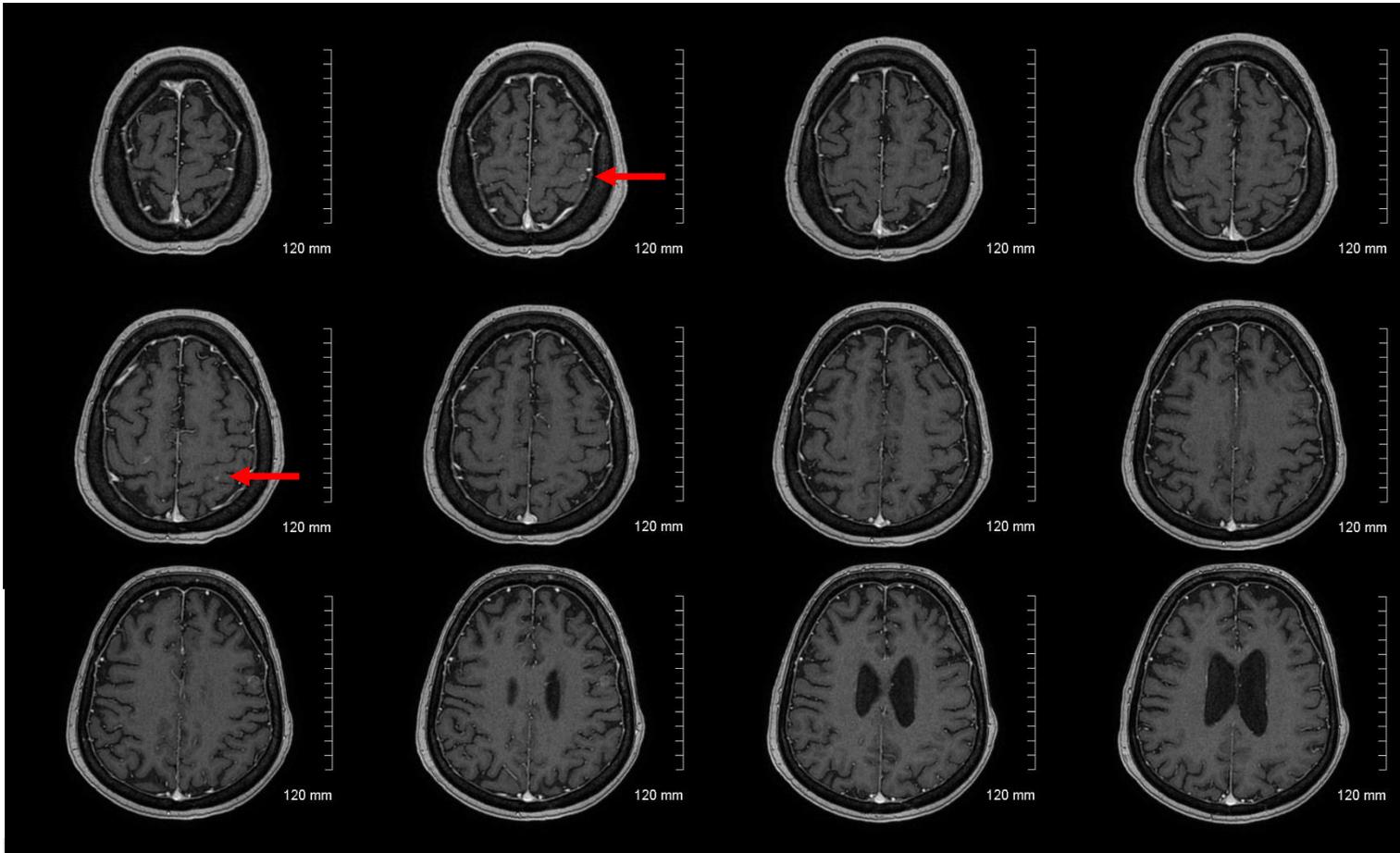
T<sub>1</sub> gado.



# IRM – exemples

Bilan initial ADK pulmonaire

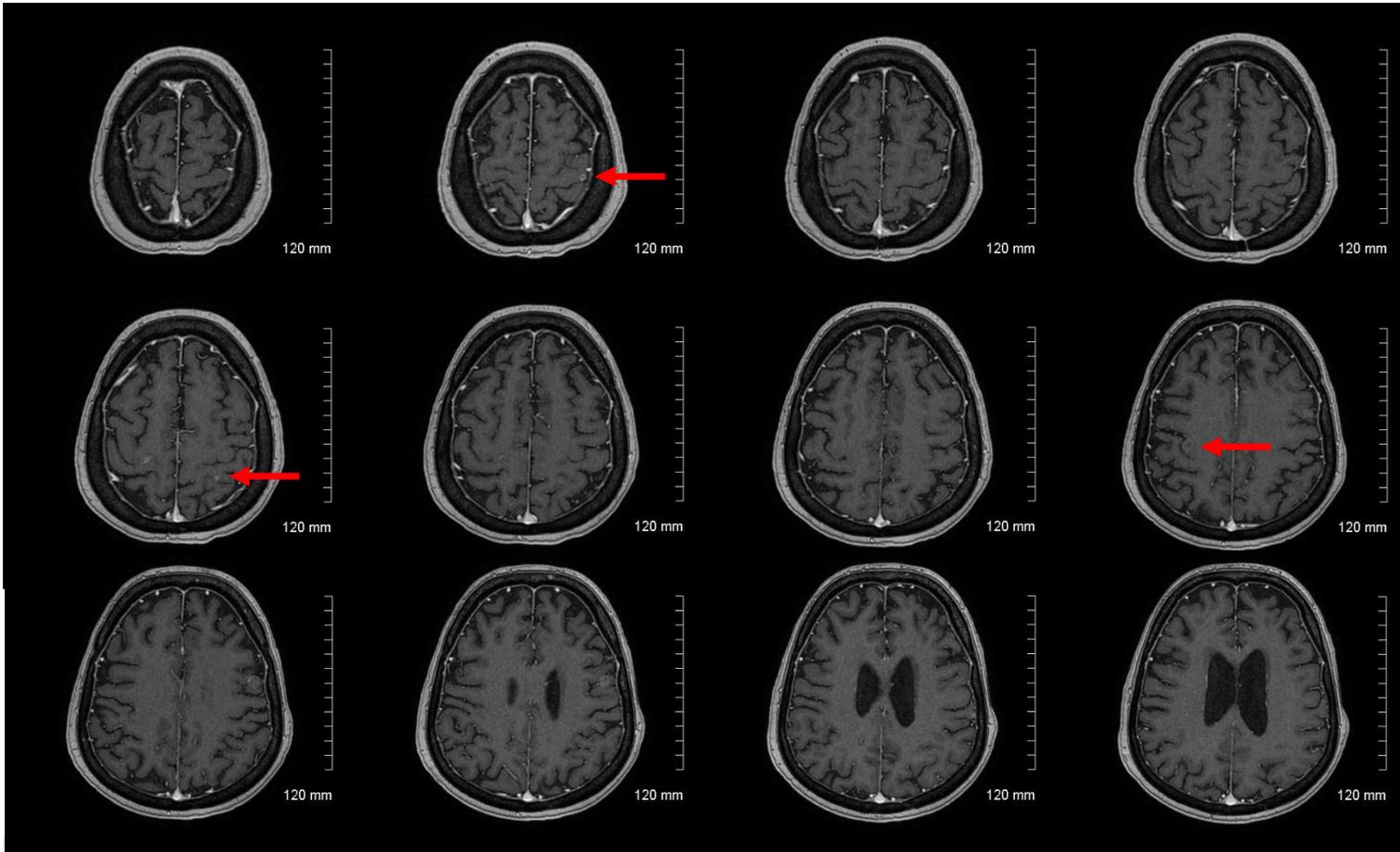
T<sub>1</sub> gado.



# IRM – exemples

Bilan initial ADK pulmonaire

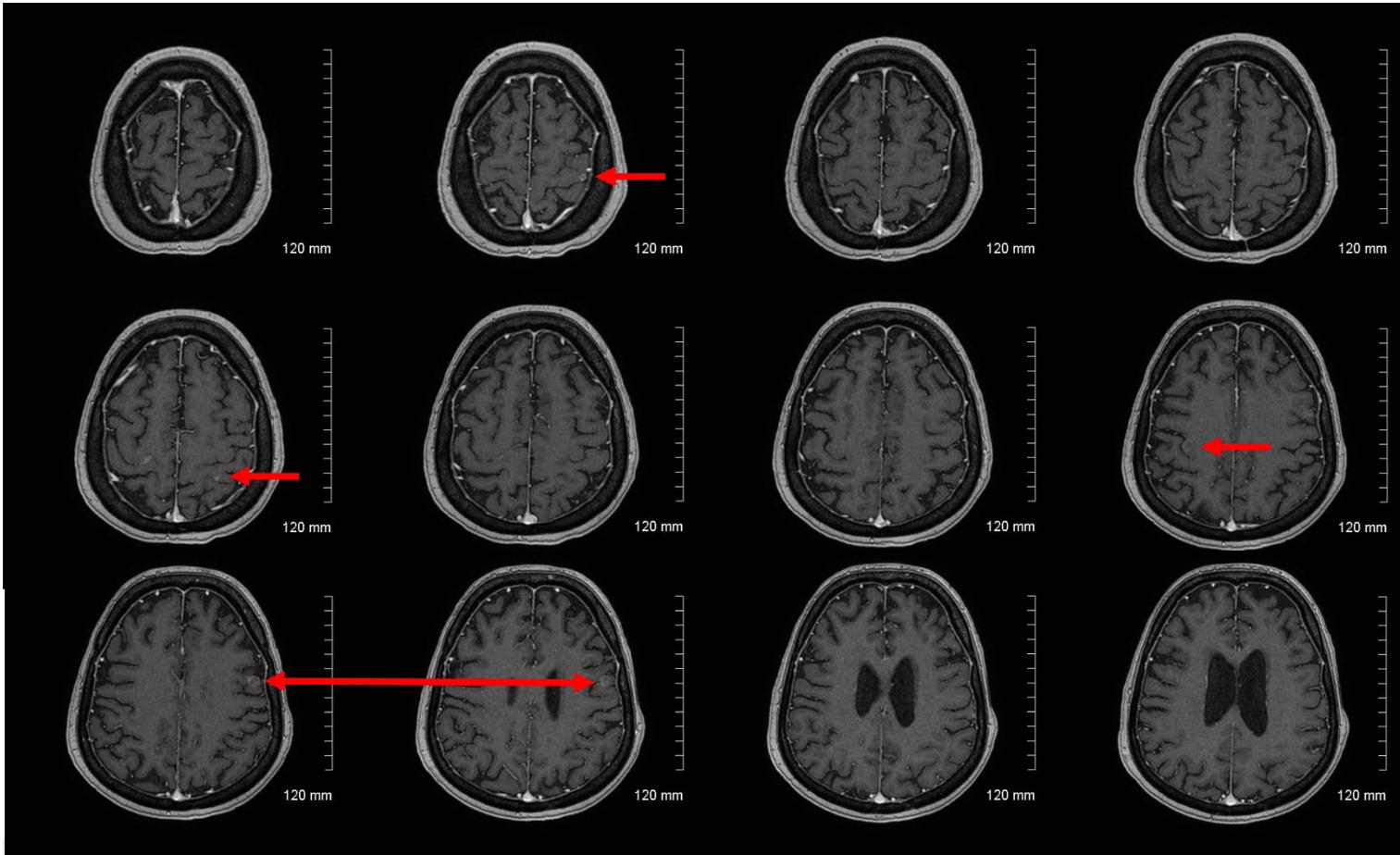
T<sub>1</sub> gado.



# IRM – exemples

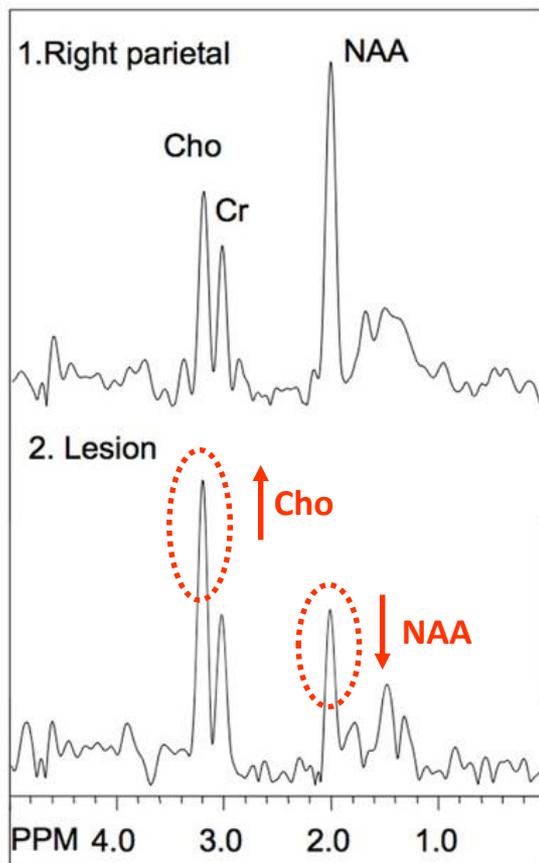
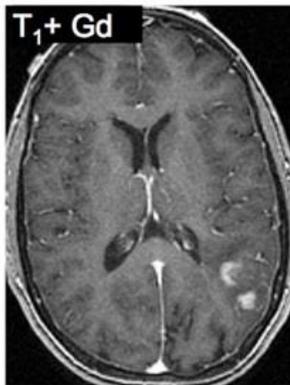
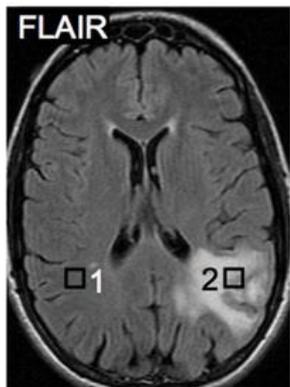
Bilan initial ADK pulmonaire

T<sub>1</sub> gado.



# IRM – exemples

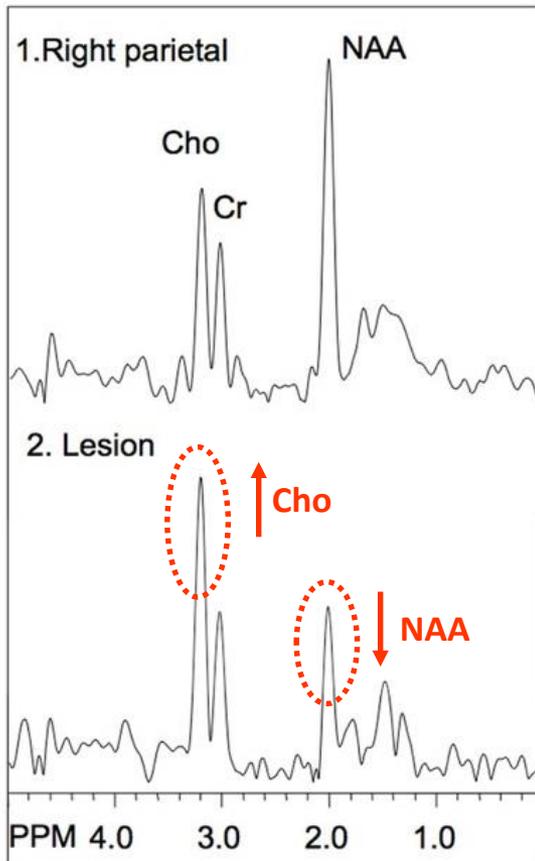
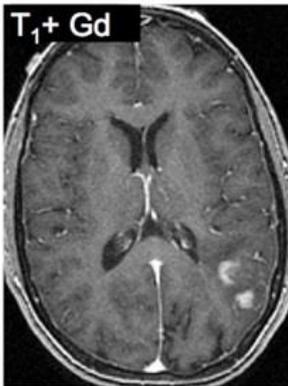
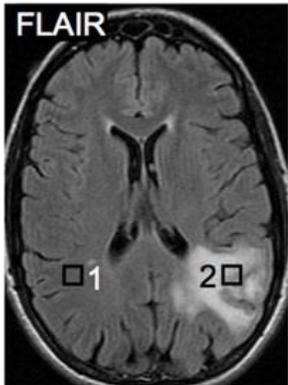
## Lymphome cérébral



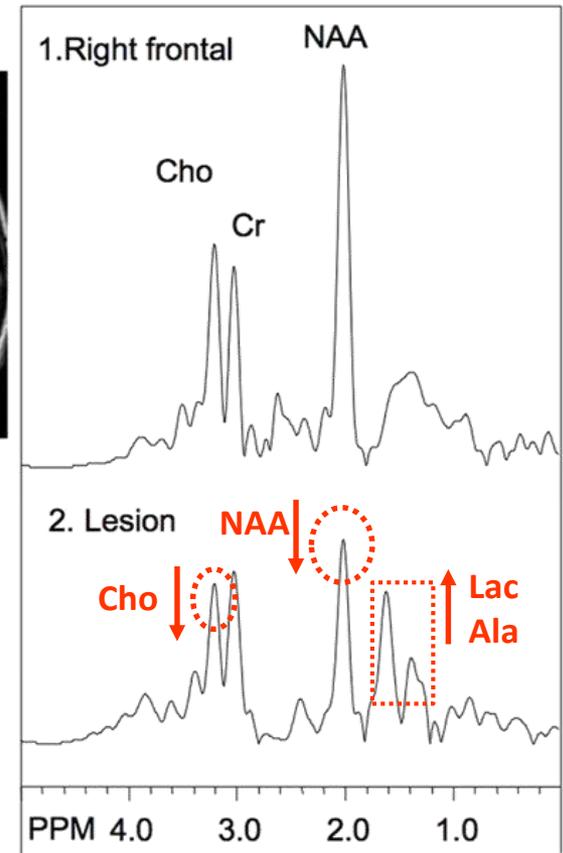
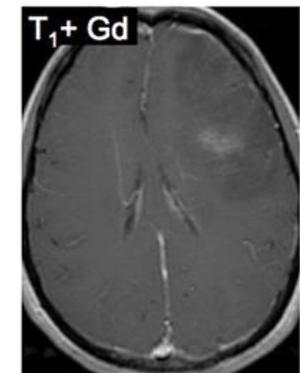
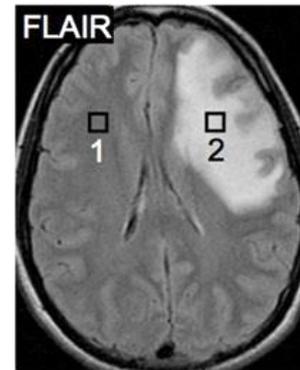
Horská et al. Neuroimaging Clin N Am 2010.

# IRM – exemples

## Lymphome cérébral

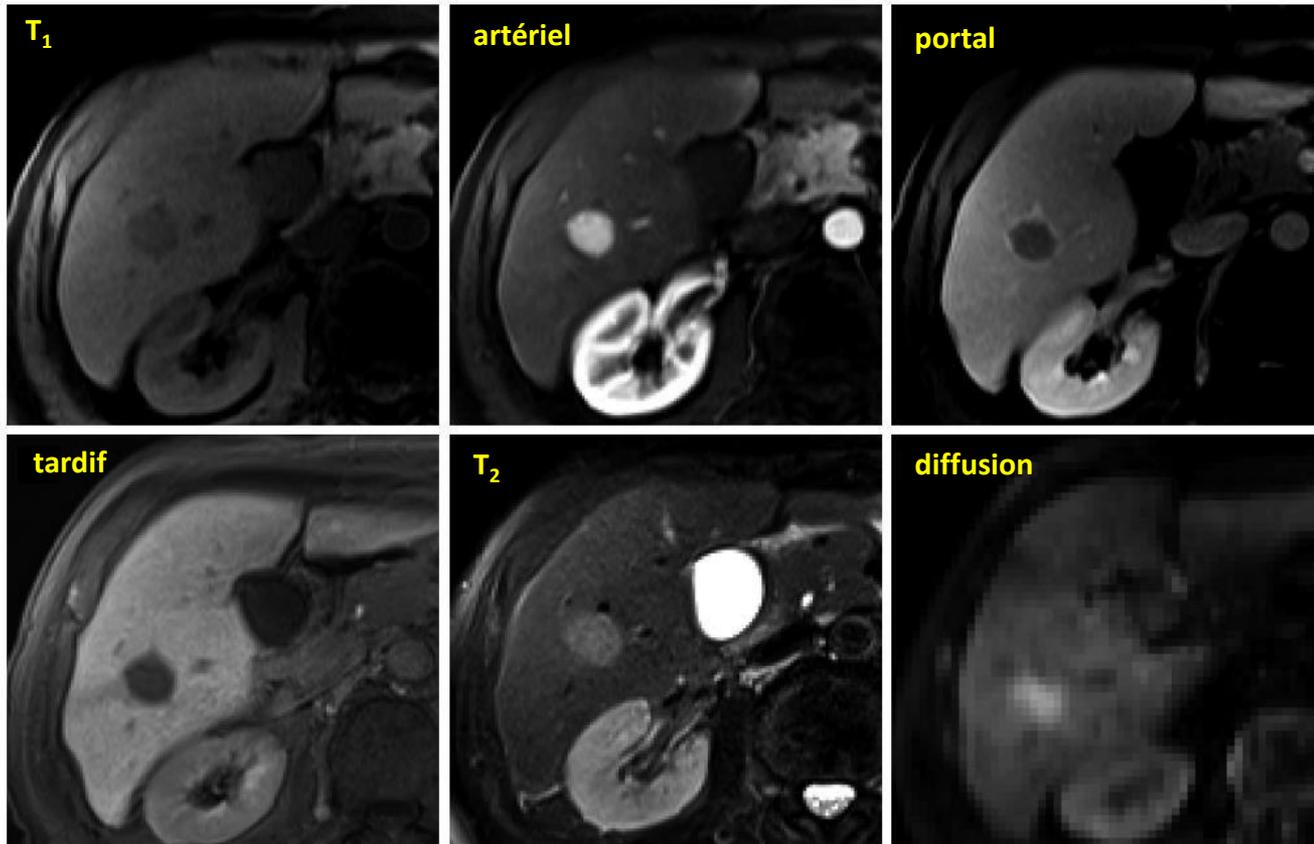


## Méningoencéphalite



# IRM – exemples

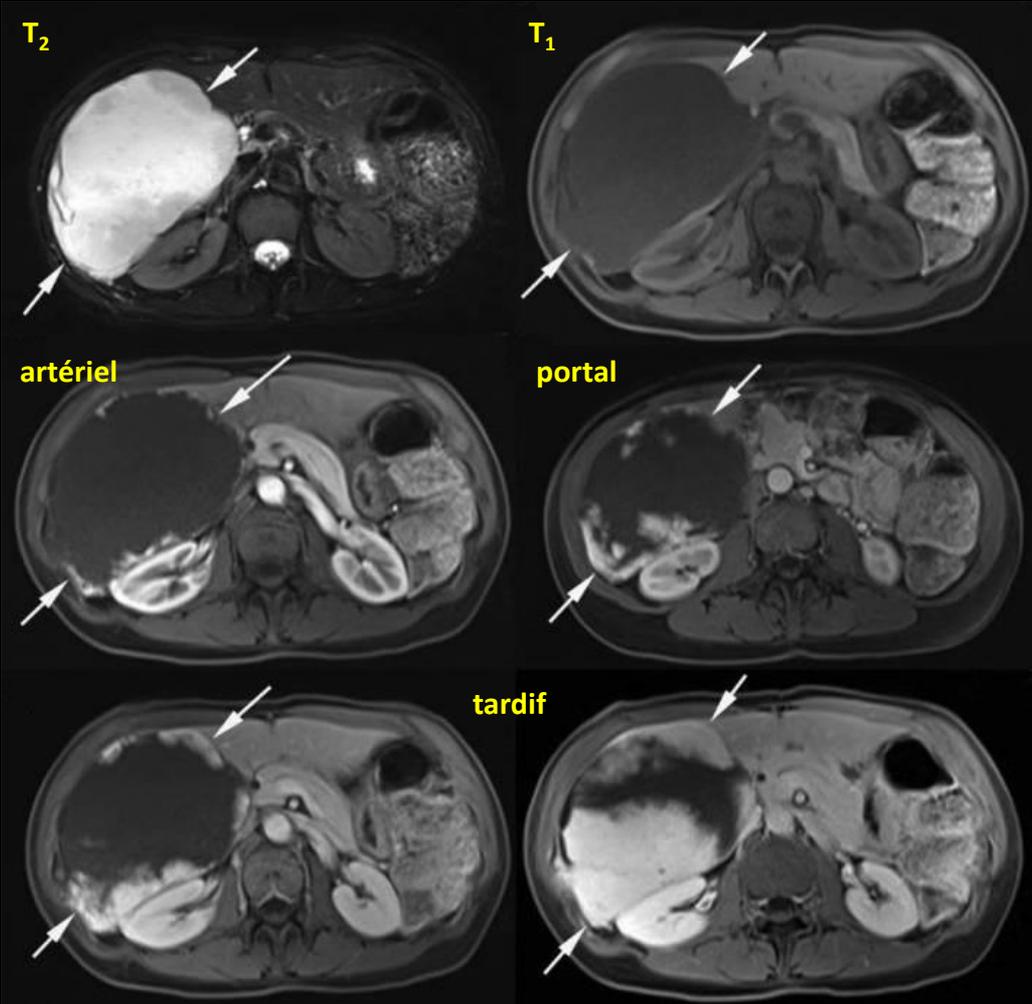
## Carcinome hépatocellulaire



*Park et al. World J Gastroenterol 2016.*

# IRM – exemples

## Angiome hépatique



**Merci de votre attention**

