

11 juillet 2007

**Effets cohérents et résonants  
dans un cristal dopé aux ions erbium :  
oscillations cohérentes de population  
et transparence induite électromagnétiquement**

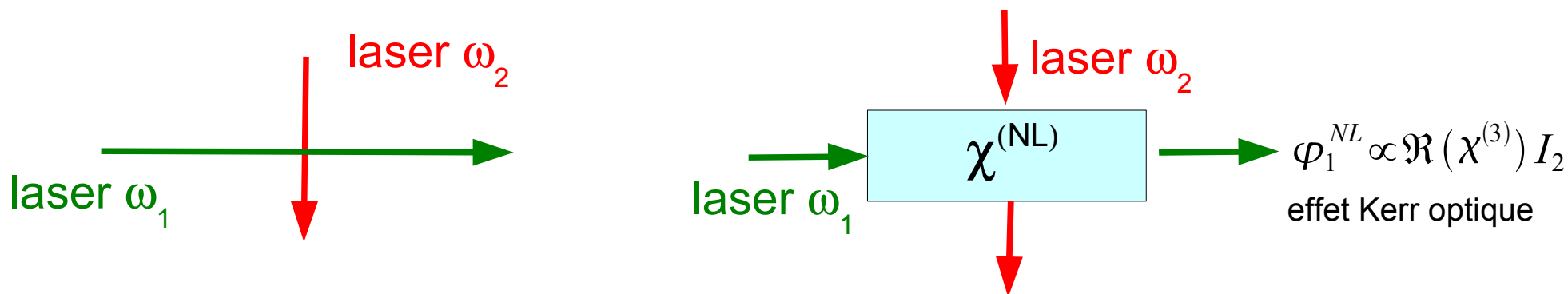
Elisa Baldit,

directeurs de thèse : Ariel Levenson, Kamel Bencheikh

Laboratoire de Photonique et de Nanostructures, Marcoussis  
groupe PHOTONIQ

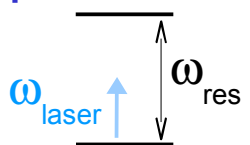
# Effets cohérents et résonants....

manipuler la lumière avec la lumière ... besoin de la matière

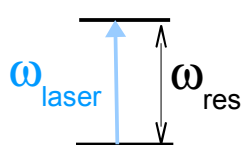


$\omega_{\text{laser}} / \omega_{\text{res}}$

**Non résonant / Transparent**  
silice  $\chi^{(3)} = 10^{-22}(\text{m/V})^2$



**Résonant / Absorbant**  
résonance atomique  
 $\chi^{(3)} = 10^{-7}(\text{m/V})^2$



relation de phase

**Incohérent**

**Cohérent**

- optique
- atomique

milieu

**Dilués**  
vapeurs,  
atomes froids

**Solides**  
cristaux,  
puits boîtes  
quantiques...

# Effets cohérents et résonants ....

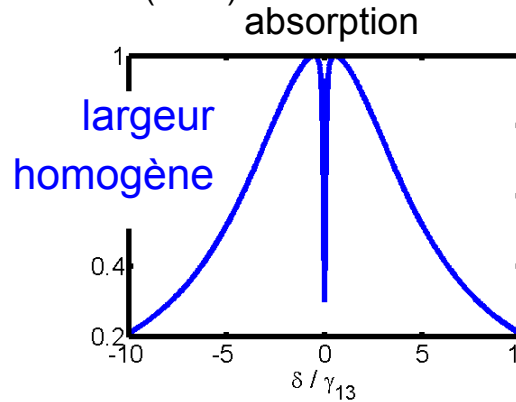
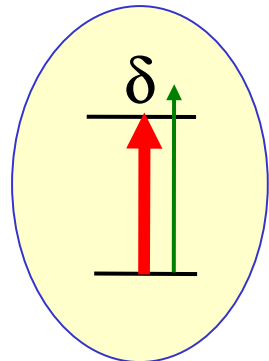
- contrôle de l'absorption et de la dispersion
- réponse exacerbée

...pour faire

- Ralentissement de la lumière
- Mémoires optiques / quantiques
- Effets non linéaires "géants"

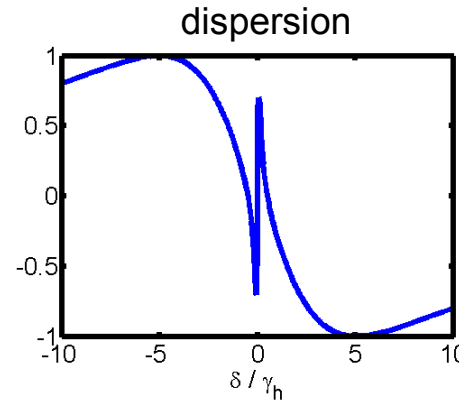
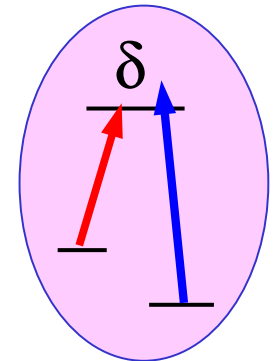
## oscillations cohérentes de population

Sargent PR43 (1978)



## transparence induite électromagnétiquement

Harris PT50 (1997)



Largeurs homogène naturelle ↔ temps de vie cohérence population

sout  $\Delta\nu \sim 1/T$  2007



# ...dans un cristal dopé aux ions erbium

Résonant  
Cohérent  
Matière condensée

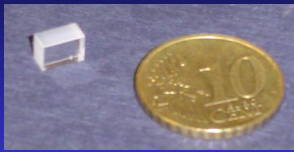
Cristaux dopés aux ions Terre Rare  
faible interaction avec la matrice cristalline  
propriétés proches des milieux dilués  
> largeurs naturelle & homogène fines  
> résonances : structure hyperfine

|        |            |         |            |          |          |            |         |            |         |        |         |           |          |    |       |    |       |    |       |    |       |    |       |    |       |    |       |
|--------|------------|---------|------------|----------|----------|------------|---------|------------|---------|--------|---------|-----------|----------|----|-------|----|-------|----|-------|----|-------|----|-------|----|-------|----|-------|
| 58     | 140,1      | 59      | 140,9      | 60       | 144,2    | 61         | (145)   | 62         | 150,4   | 63     | 152,0   | 64        | 157,4    | 65 | 158,9 | 66 | 162,5 | 67 | 164,9 | 68 | 167,3 | 69 | 168,9 | 70 | 173,0 | 71 | 175,0 |
| Ce     | Pr         | Nd      | Pm         | Sm       | Eu       | Gd         | Tb      | Dy         | Ho      | Er     | Tm      | Yb        | Lu       |    |       |    |       |    |       |    |       |    |       |    |       |    |       |
| Cérium | Praséodyme | Néodyme | Prométhium | Samarium | Eurélium | Gadolinium | Terbium | Dysprosium | Holmium | Erbium | Thulium | Ytterbium | Lutétium |    |       |    |       |    |       |    |       |    |       |    |       |    |       |

EIT Ham et al. OL 1995

$^{167}\text{Er}^{3+}$  résonance à 1.5  $\mu\text{m}$   
structure hyperfine

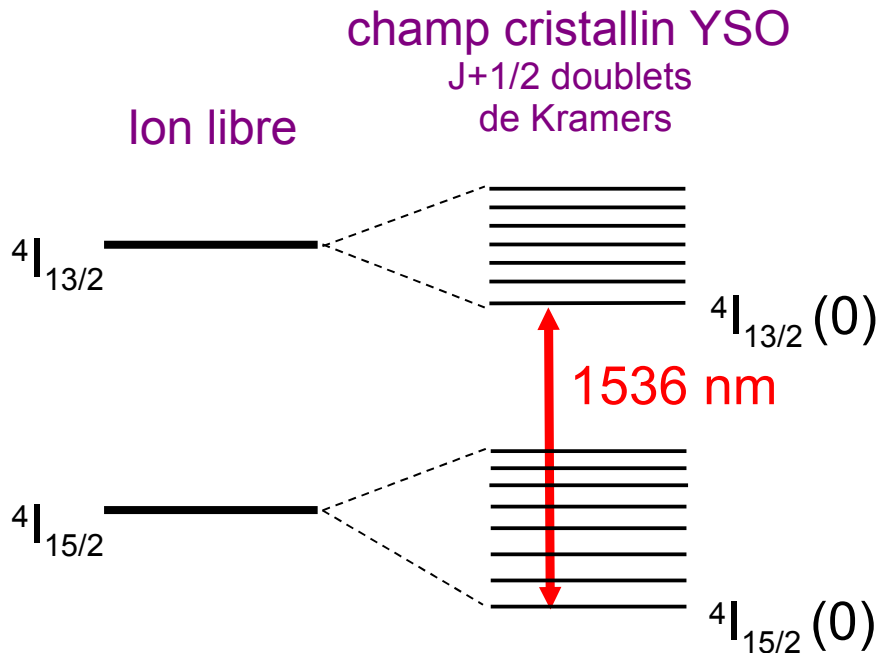
- Er:YSO
- Ralentissement de la lumière
  - Définition
  - Oscillations cohérentes de population
  - Résultats
- Transparence induite électromagnétiquement
  - Définition
  - Identification de systèmes en  $\Lambda$
  - Premiers résultats
- Conclusions et perspectives



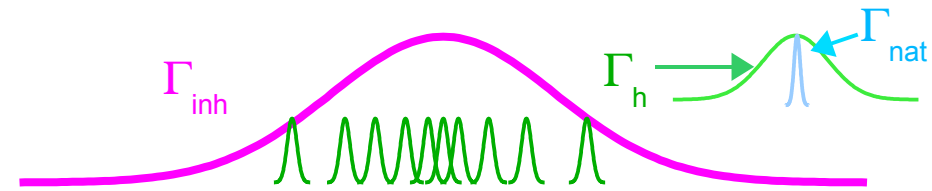
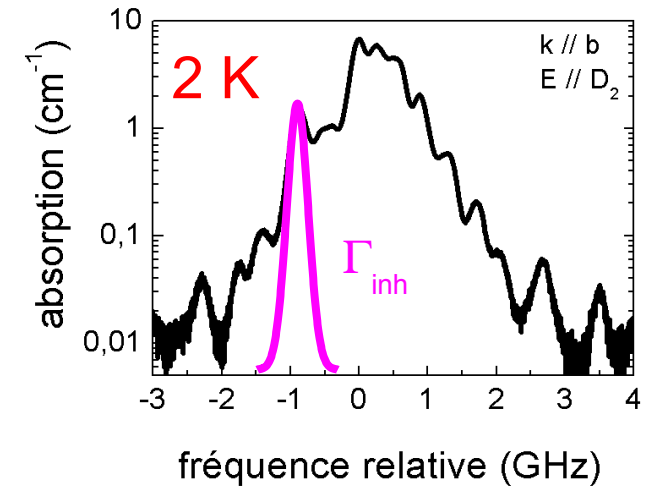
- Préservation des cohérences atomiques

matrice  $\text{Y}_2\text{SiO}_5$   
 faible dopage 0.005%  $\sim 10^{16}\text{at/cm}^3$   
 basse température 2K

- Diagramme d'énergie  $^{167}\text{Er}^{3+}$



- Absorption à 1536 nm



Largeurs

naturelle  $\Gamma_{nat} = 16 \text{ Hz}$

homogène  $\Gamma_h = 90 \text{ kHz}$

inhomogène  $\Gamma_{inh} \sim 250 \text{ MHz}$

Temps carac.

$T_1 = 10 \text{ ms}$

$T_2 = 3 \mu\text{s}$

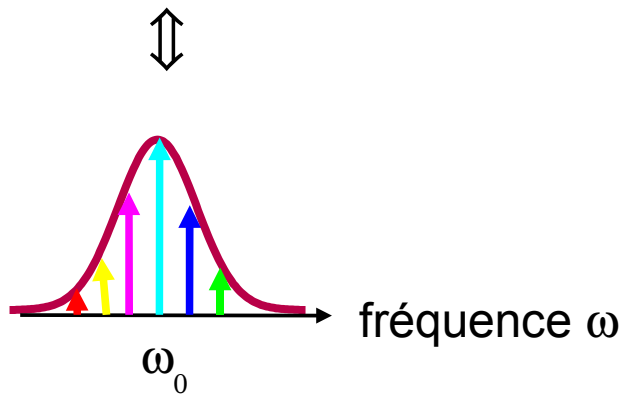
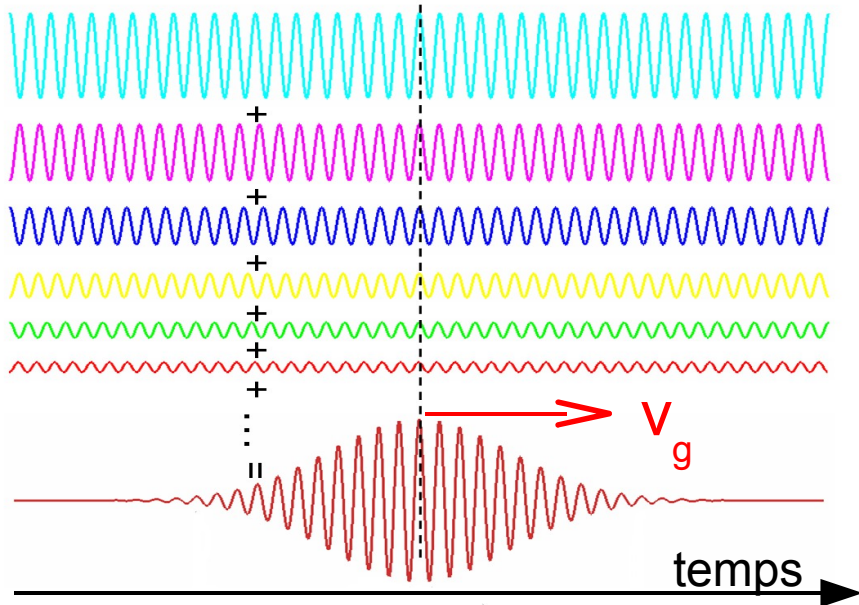
# ralentissement de la lumière

définition

oscillations cohérentes de population

dispositif et résultats expérimentaux

- Onde monochromatique et paquet d'onde



Vitesse de phase  $v_\varphi = \omega/k = c/n$

Vitesse de groupe  $v_g = \partial\omega/\partial k]_{\omega_0}$

$$v_g = \frac{c}{n_0 + \omega_0 \left( \frac{\partial n}{\partial \omega} \right)_{\omega_0}} = \frac{c}{n_g}$$

$$\frac{\partial n}{\partial \omega} \gg 1$$

$$v_g \ll c$$

dispersion

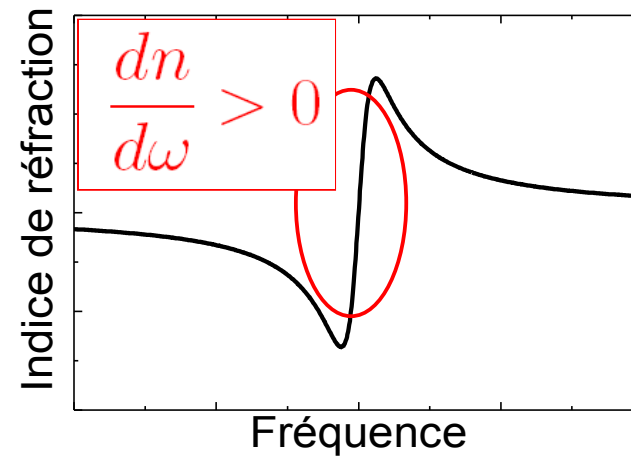
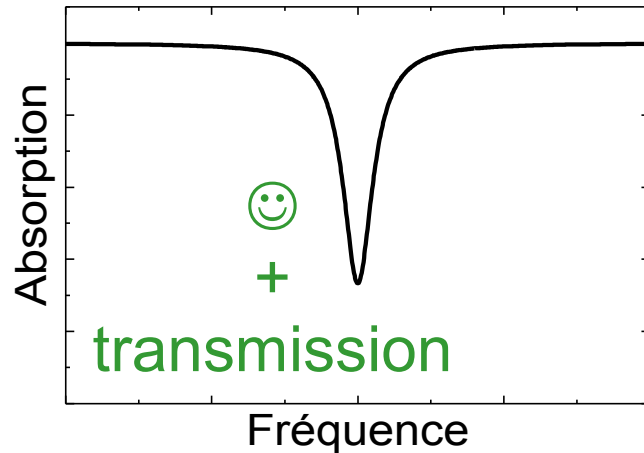
ralentissement



- Relations de Kramers Krönig

$$\alpha(\omega) = -\frac{4\omega^2}{\pi c} \mathcal{P} \int_0^\infty \frac{n(s) - 1}{s^2 - \omega^2} ds$$

$$n(\omega) = 1 + \frac{c}{\pi} \mathcal{P} \int_0^\infty \frac{\alpha(s)}{s^2 - \omega^2} ds$$



fenêtre de transparence  $\Leftrightarrow$  forte dispersion  
 $\Leftrightarrow$  fort ralentissement

# Différentes méthodes de ralentissement

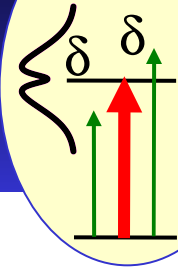
- Effets non résonants  
cristaux photoniques,  
cavités couplées  
automodulation de phase..
- Effets non cohérents  
Raman  
creusement spectral...
- Effets résonants et cohérents

## Transparence induite électromagnétiquement

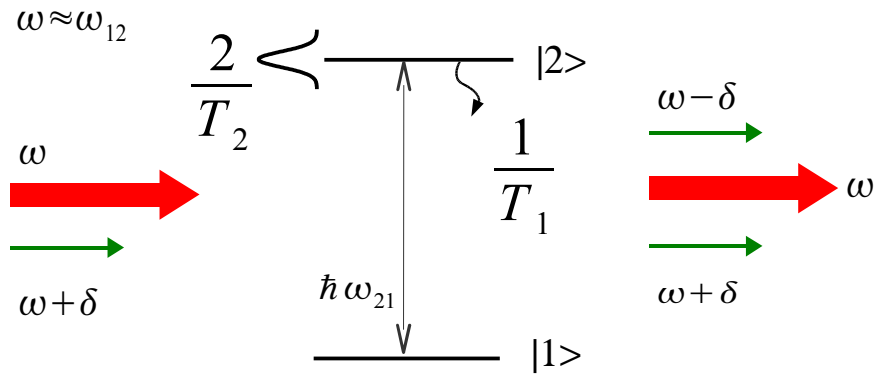
|            |                     | milieu | vg    |
|------------|---------------------|--------|-------|
| Hau et al. | <i>Nature(1999)</i> | Na BEC | 17m/s |

## Oscillations Cohérentes de Population

|                   |                    | milieu | vg     |
|-------------------|--------------------|--------|--------|
| Bigelow et al.    | <i>PRL90(2003)</i> | Ruby   | 57m/s  |
| Baldit et al.     | <i>PRL95(2005)</i> | Er:YSO | 3m/s   |
| Palinginis et al. | <i>OE13(2005)</i>  | GaAsQW | 550m/s |

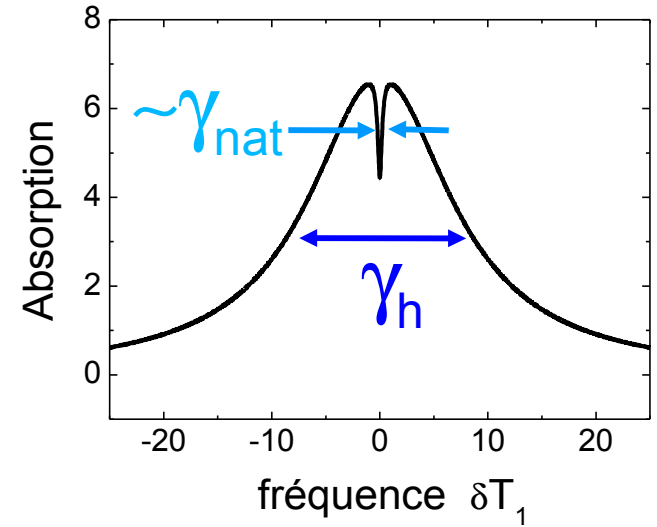


$$T_1 \gg T_2 \quad \gamma_{\text{nat}} \ll \gamma_h$$

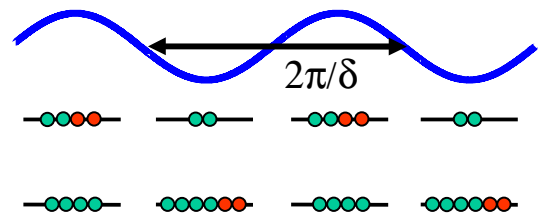


Absorption à  $\omega_p + \delta$

$$\alpha = \alpha_{\text{inc}} - \alpha_{\text{coh}}$$



Interférences temporelles pompe sonde



Oscillation de la population

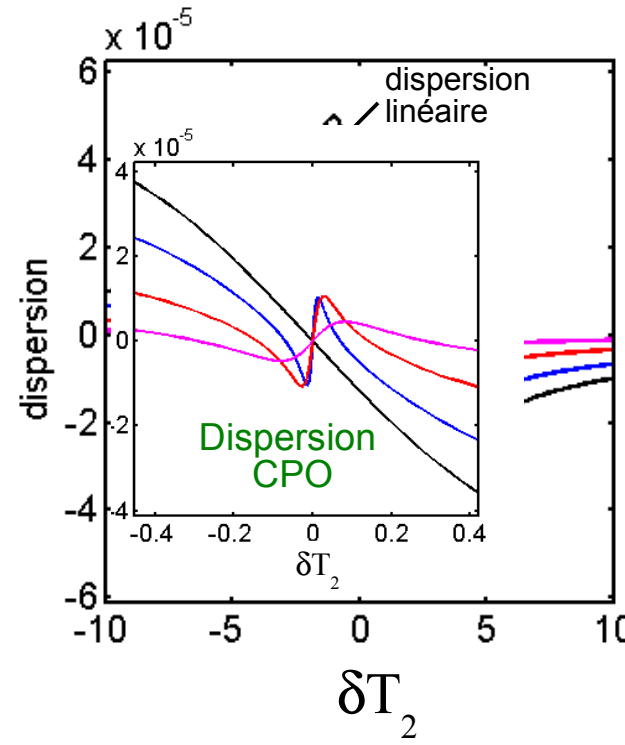
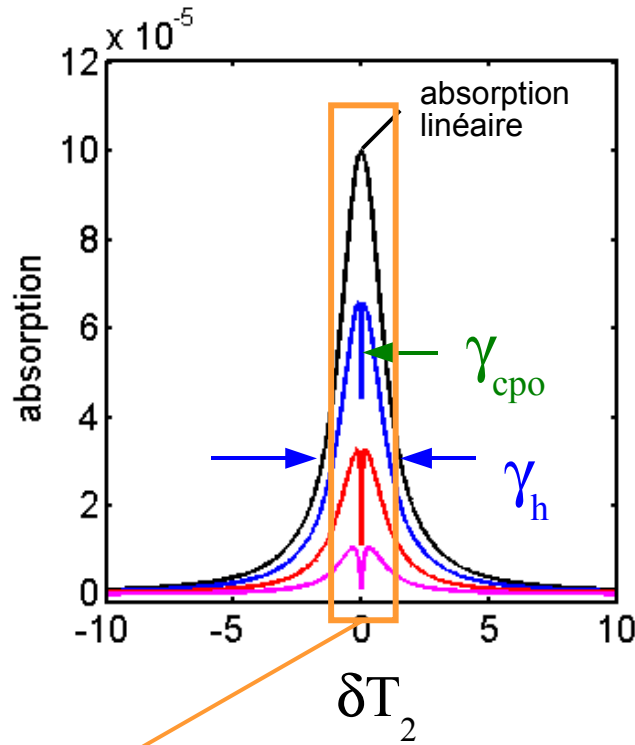
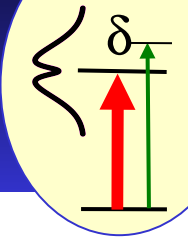
$$\Delta n = \Delta n_0 + \Delta n_{-1} e^{i\delta t} + \Delta n_1 e^{-i\delta t}$$

important si  $\delta < \gamma_{\text{nat}} = 1/T_1$

M. Sargent, Phys. Reports **43** 223 (1978)  
R. Boyd et al., PRA **24**, 411 (1981)

Besoin : résonance

# Oscillations cohérentes de population



$$S = I_{\text{pump}} / I_{\text{sat}}$$

$$S = \Omega_p^2 T_1 T_2$$

— 0  
 — 1/2  
 — 2  
 — 8

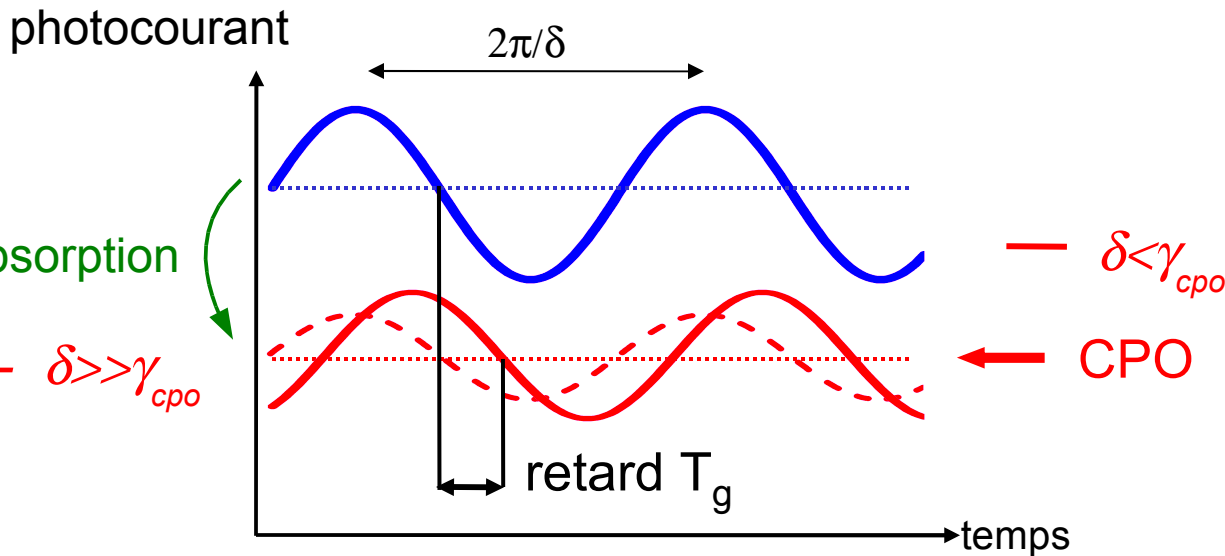
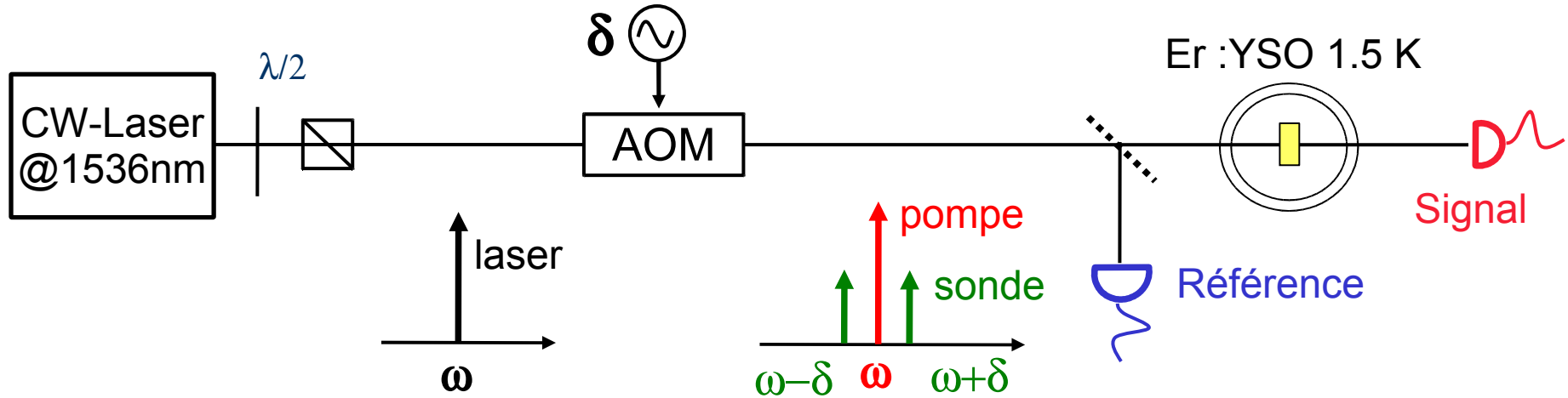
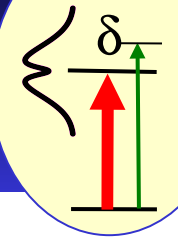
largeur fenêtre cpo

$$\gamma_{CPO} = \frac{S+1}{T_1} = \gamma_{nat} (S+1)$$

⇒ temps de propagation

$$T_g = \alpha_0 T_1 L \cdot \frac{S}{1+S} \cdot \frac{1}{(\delta T_1)^2 + (1+S)^2}$$

- { Paramètres de l'excitation :  $I_{\text{pompe}}, \delta$
- { Paramètres du milieu :  $\alpha_0, T_1, I_{\text{sat}}(T_2), L$



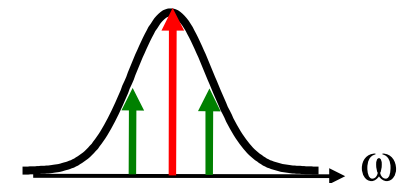
## Mesures?

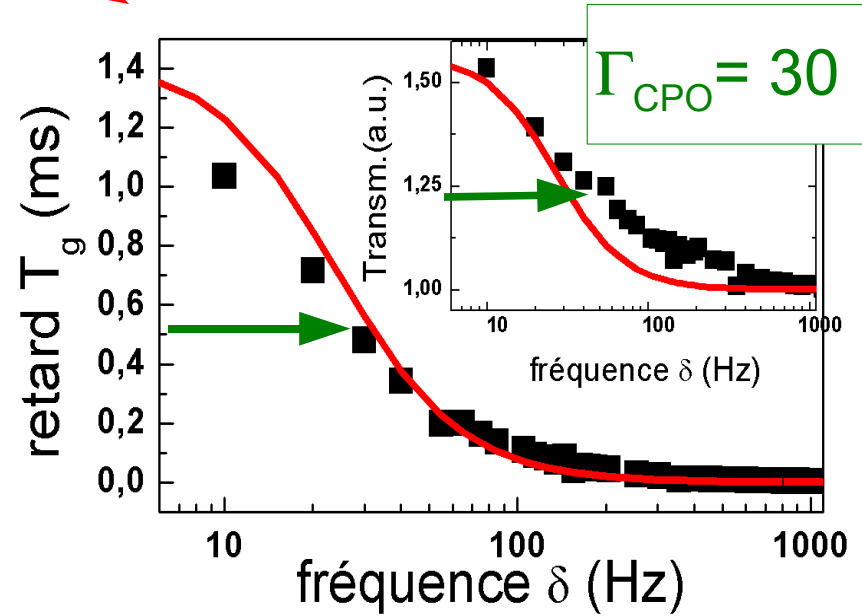
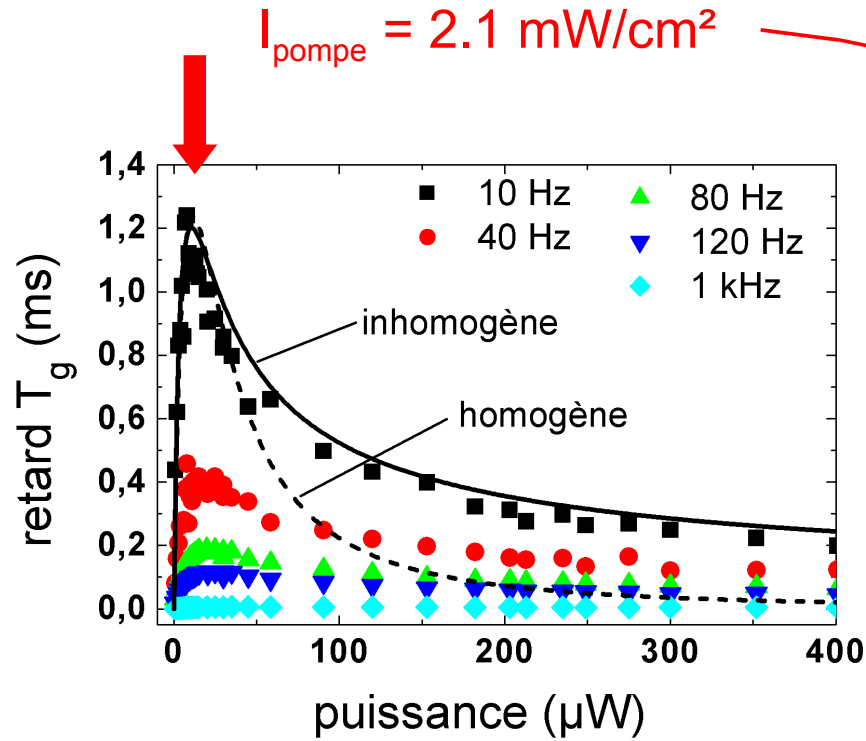
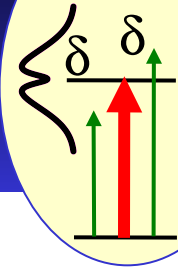
- 1- transmission
- 2- retard temporel

$$T_g = (\varphi_{\text{ref}} - \varphi_{\text{sig}}) / 2\pi\delta$$

⇒ vitesse de groupe

$$v_g \sim L / T_g$$

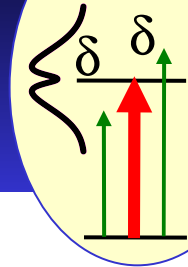




- à 10 Hz
- $I_{\text{pompe}} = 2.1 \text{ mW/cm}^2$
  - 55% ↗ transmission :  $T_{\text{sonde}} \sim 40\%$
  - $T_g = 1.1 \text{ ms} \Rightarrow v_g = (2.7 \pm 0.2) \text{ m/s}$

bande passante

$$\Gamma_{\text{CPO}} \propto \frac{1}{T_1}$$



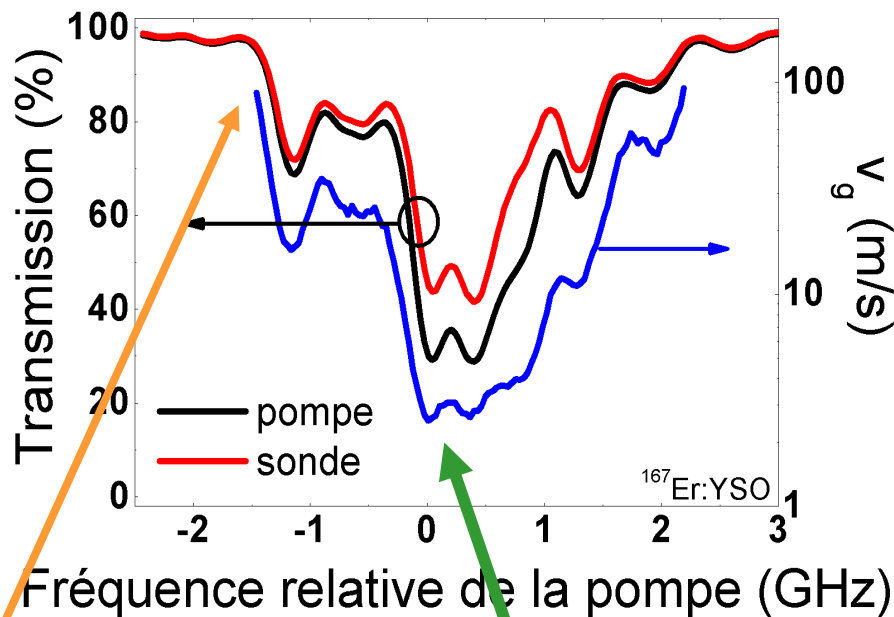
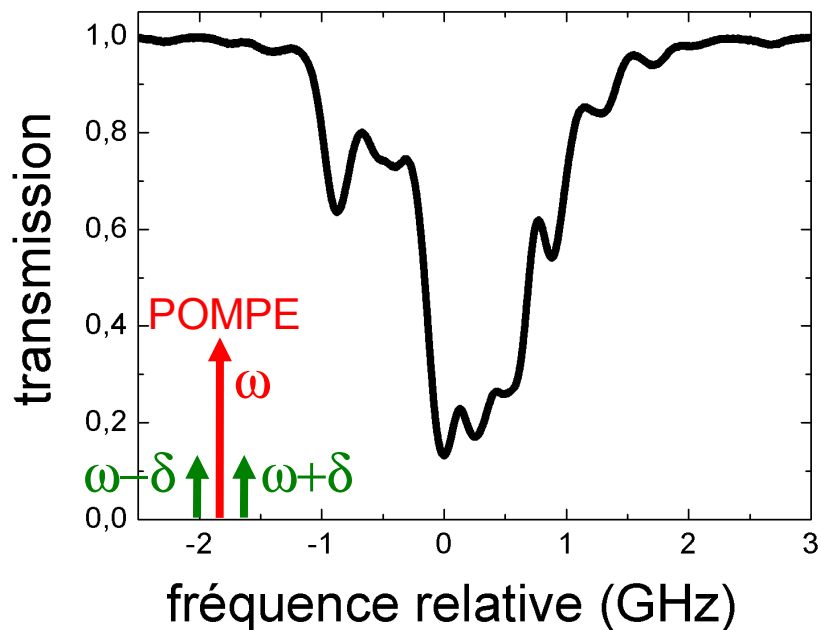
$$T_g = \alpha_0 T_1 L \cdot \frac{S}{1+S} \cdot \frac{1}{(\delta T_1)^2 + (1+S)^2}$$

Elargissement inhomogène  
 $\Rightarrow$  distribution  $\alpha_0$



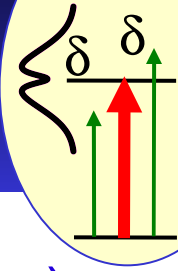
accordabilité

$\delta = 10$  Hz



$v_g = 100$  m/s  
 $T = 90$  %

$v_g = 3$  m/s  
 $T = 40$  %



- Ralentissement mesure directe (propagation d'impulsions ms) et indirecte

$$v_g = 2.7 \text{ m/s @ } 2.1 \text{ mW/cm}^2$$

Transmission : 40 %

- Inversion de population  $v_g = -20 \text{ m/s}$   
gain + ingénierie du temps d'arrivée de l'impulsion
- Utilisation originale de l'élargissement inhomogène  
⇒ accordabilité ( $v_g$ , Transmission)

$$v_g = 100 \text{ m/s}$$

$$T = 90 \%$$

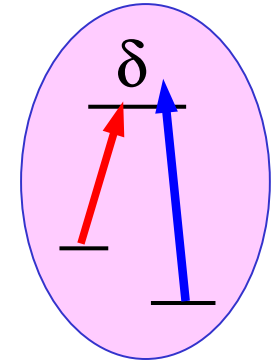
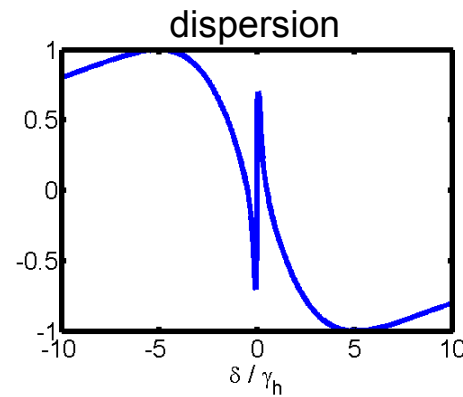
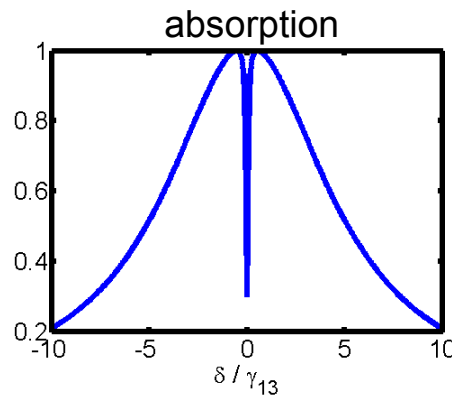
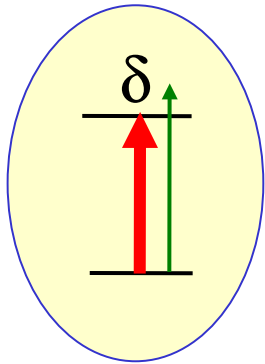


$$v_g = 3 \text{ m/s}$$

$$T = 40 \%$$



## oscillations cohérentes de population



- Pas de transparence totale en théorie
- Importance de  $T_1 / \gamma_{\text{nat}}$
- Expériences à  $T_{\text{ambiante}}$
- Perspectives : semi conducteurs

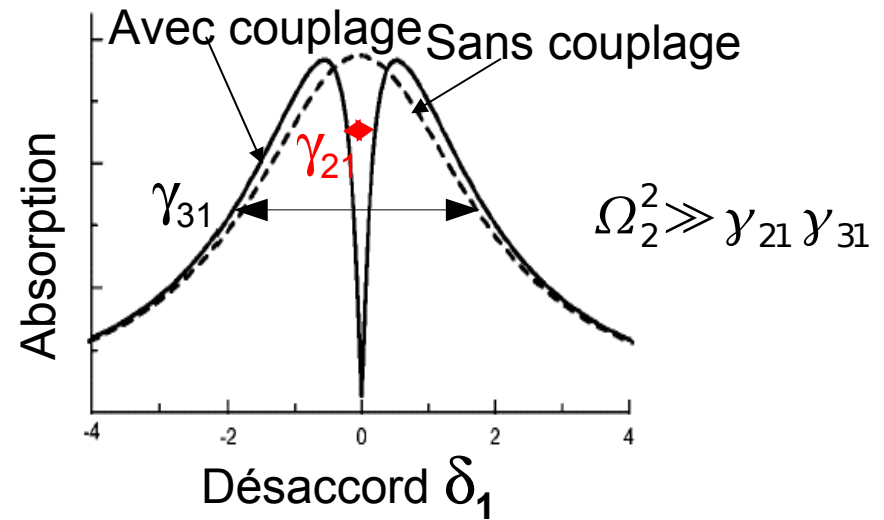
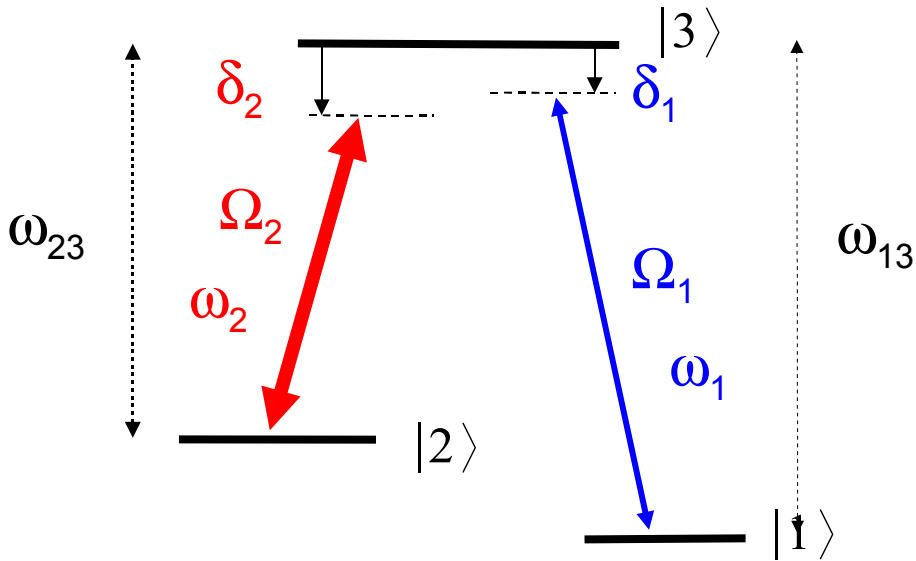
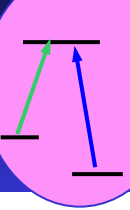
- Transparence totale
- Importance de  $T_2$   
 $\gamma_h$  optique/hyperfin
- Ralentissement => mémoire

# Transparence induite électromagnétiquement

Définition

Identification de systèmes en  $\Lambda$  dans  $^{167}\text{Er}^{3+}:\text{YSO}$

Dispositif et premiers résultats expérimentaux



- Interférences quantiques des probabilités

$$1 \rightarrow 3$$

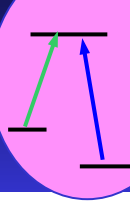
$$1 \rightarrow 3 \rightarrow 2 \rightarrow 3$$

- état noir

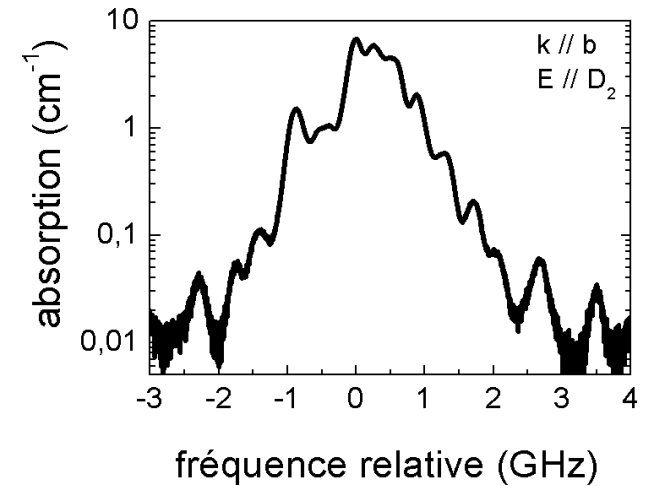
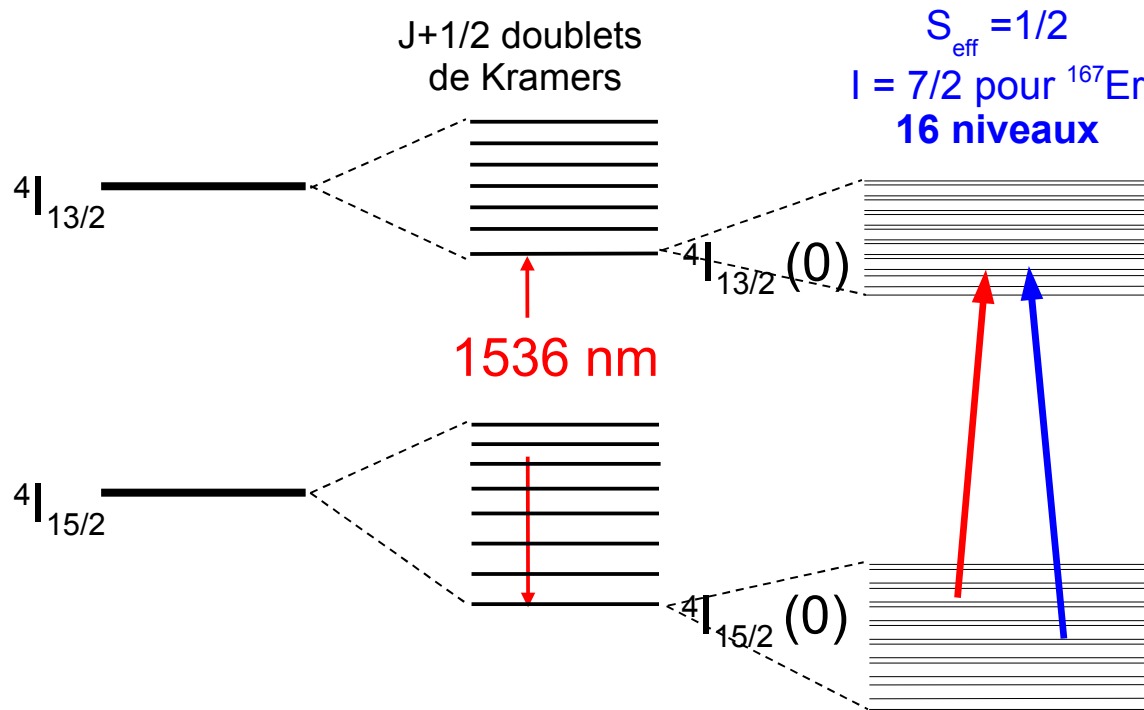
$$|atome\rangle = \alpha|1\rangle + \beta|2\rangle$$

- Possibilités :
- Ralentissement
  - Arrêt de la lumière

- Besoins :
- Résonances
  - Cohérence



champ cristallin YSO interaction hyperfine

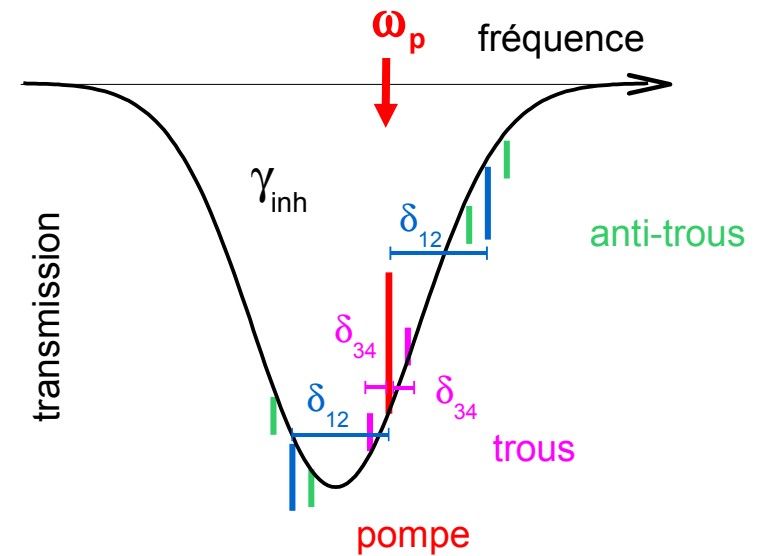
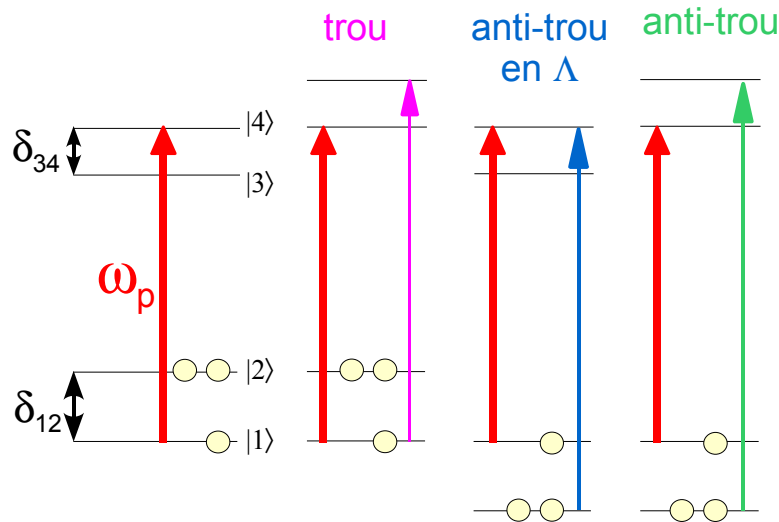
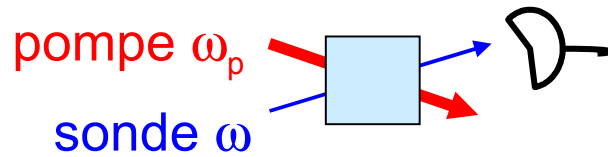
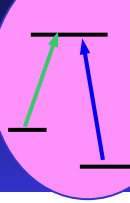


éclatement hyperfin MHz-GHz

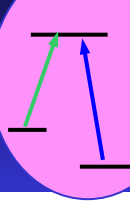
inconnu

Trouver les niveaux et les temps caractéristiques

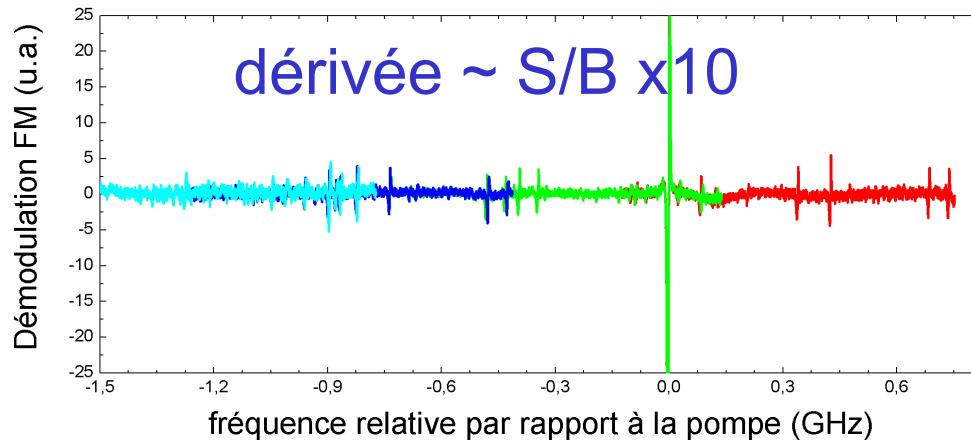
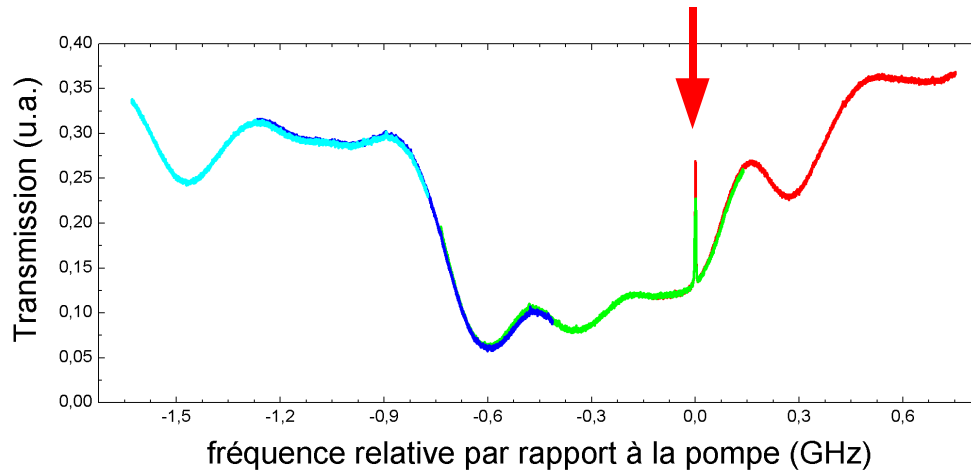
- Creusement spectral  
 coll. LAC V. Crozatier, I. Lorgeré, F. Bretenaker, JL Legouët
- Résonance paramagnétique électronique  
 coll. LCAES O. Guillot-Noël P. Goldner



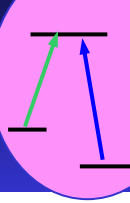
- Possibilité de retrouver la structure hyperfine
- Repérer les anti-trous en  $\Lambda$  tels que  $\omega = \omega_p \pm \delta_{12}$



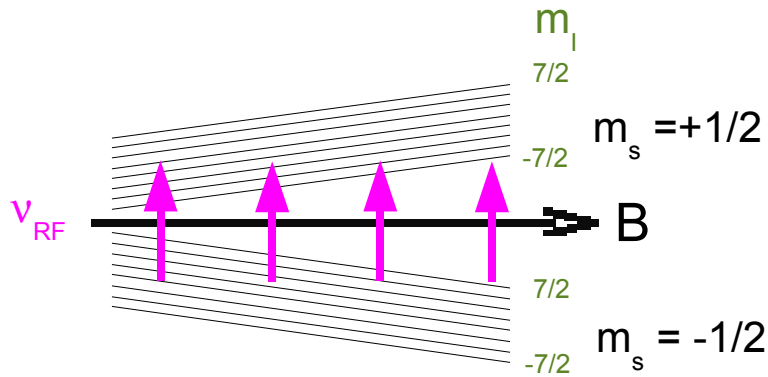
## Exemple de Spectre



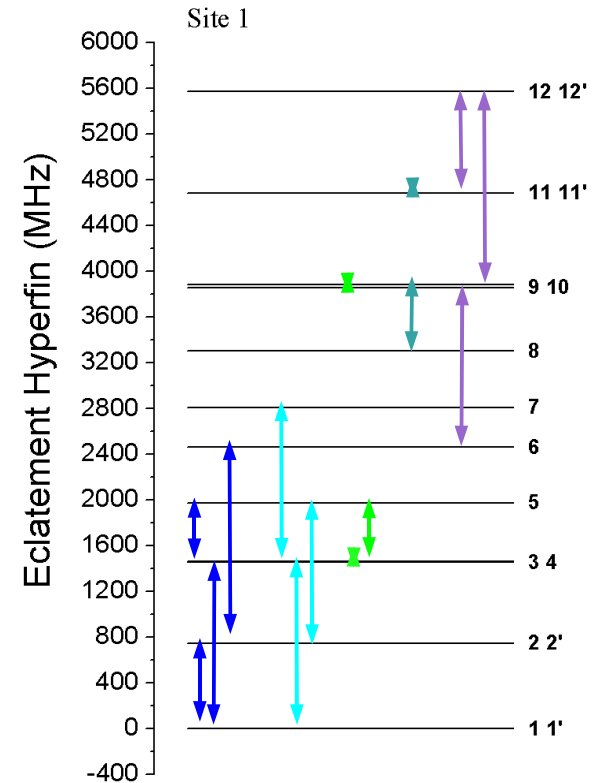
- difficultés d'interprétation
  - nombre de niveaux
  - probabilité de transition
  - $\delta_{hf} < \Gamma_{inh} < \delta_{hf}$
  
- difficile de retrouver les systèmes en  $\Lambda$



<sup>nat</sup>Er:YSO ~6 K → éclatement hyperfin du fondamental

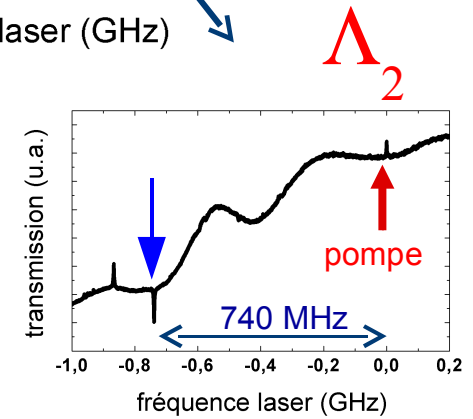
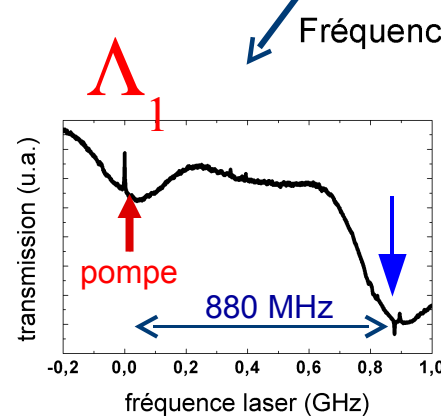
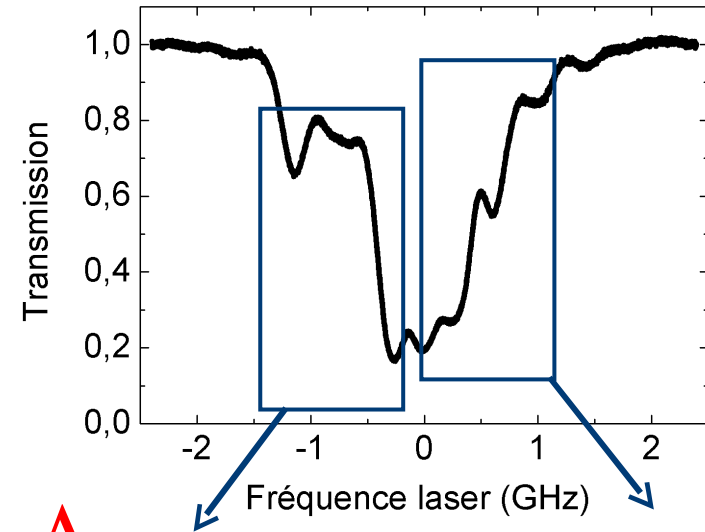
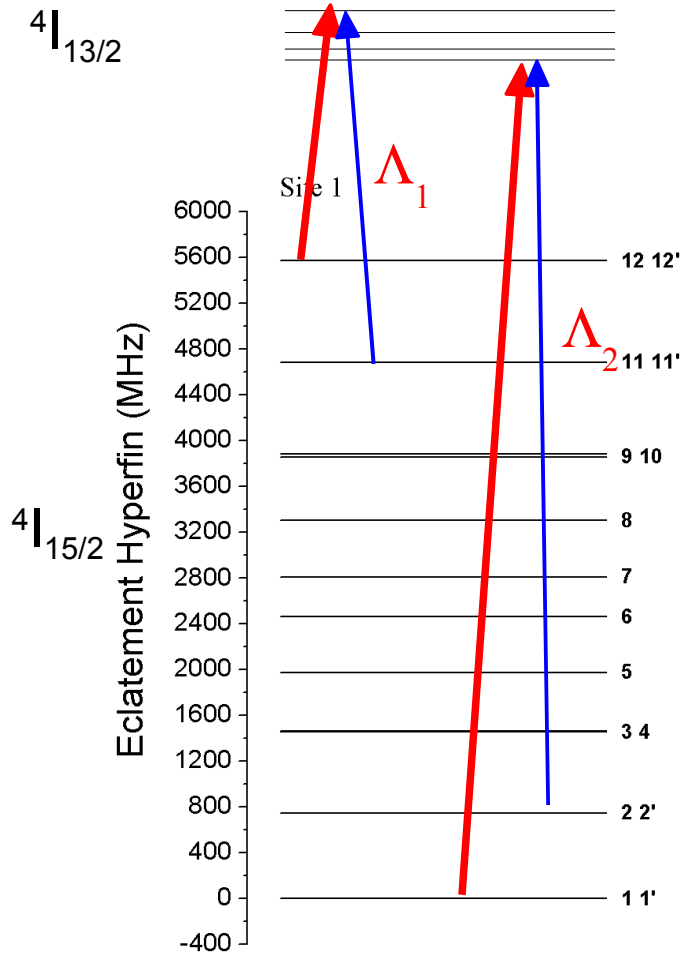
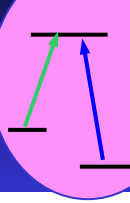


$$\begin{aligned}
 H_{ef} = & \beta_e \vec{S}_{ef} \tilde{g} \vec{B} \\
 & + \vec{I} \tilde{A} \vec{S}_{ef} \\
 & + \vec{I} \tilde{P} \vec{I} \\
 & + \beta_N g_N \vec{I} \vec{B}
 \end{aligned}$$

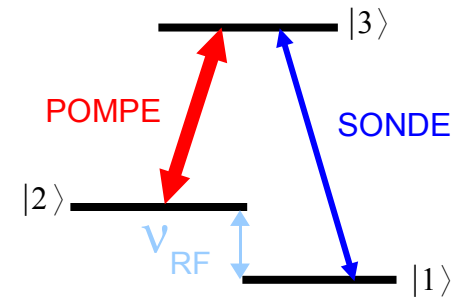
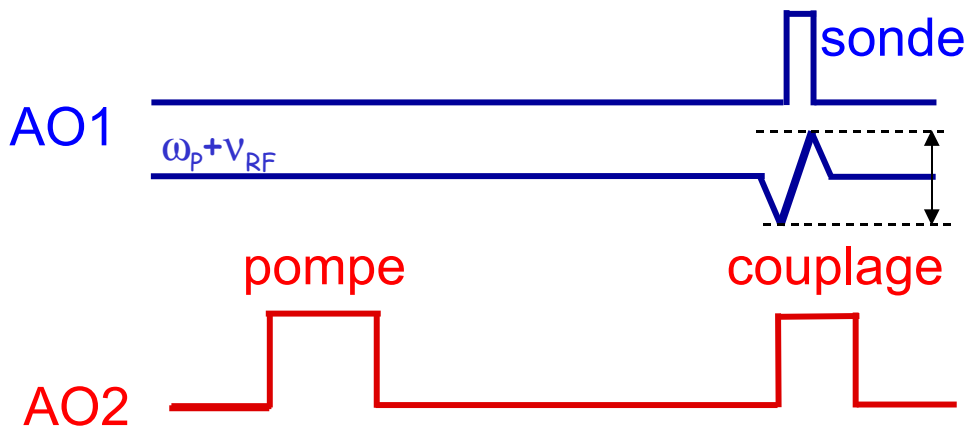
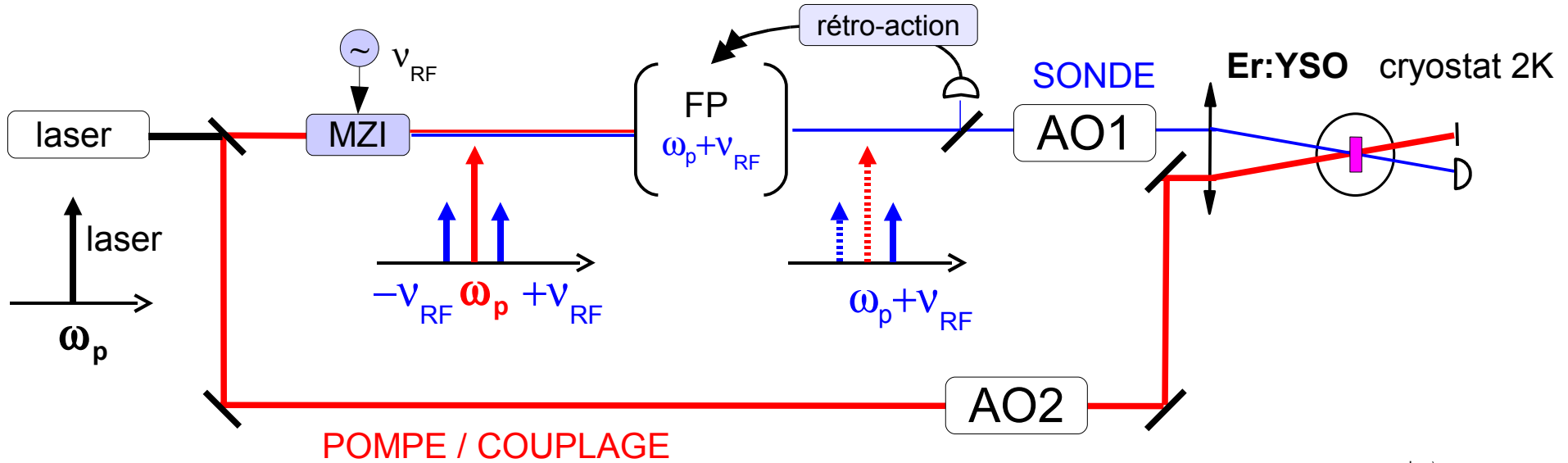
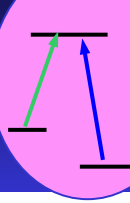


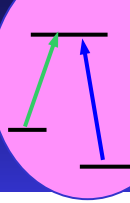
14 niveaux hyperfins au lieu de 16

13 anti-trous en  $\Lambda$  repérés optiquement

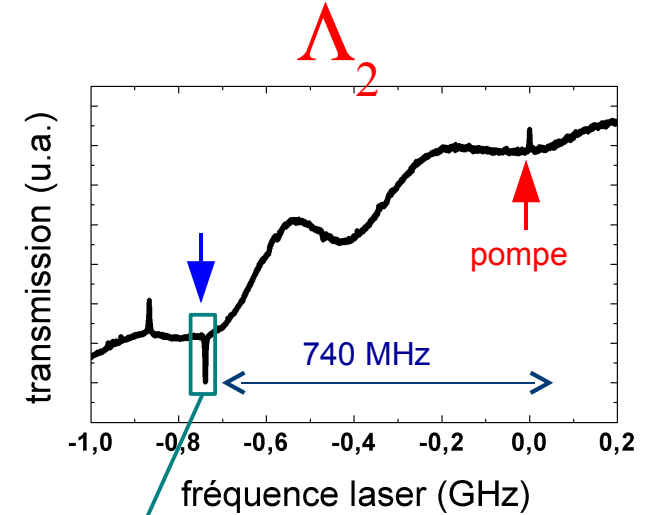
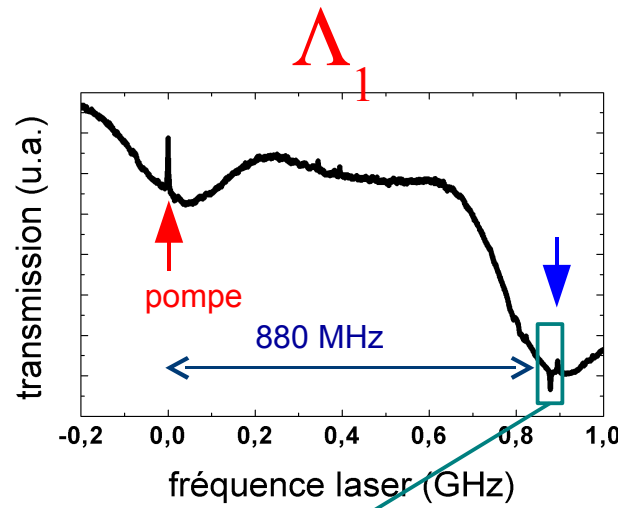
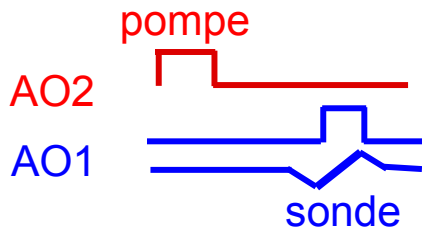




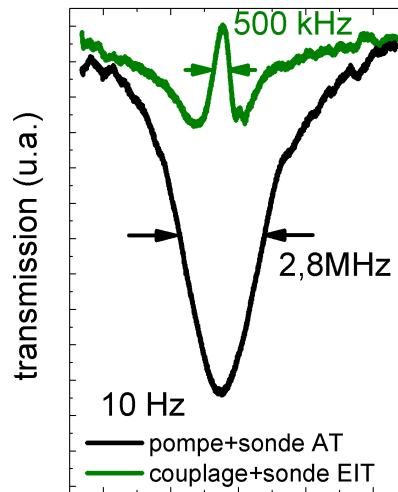
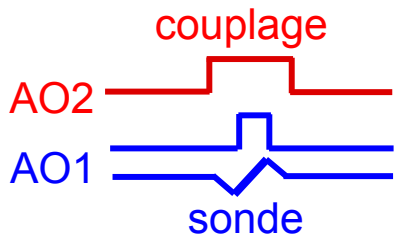




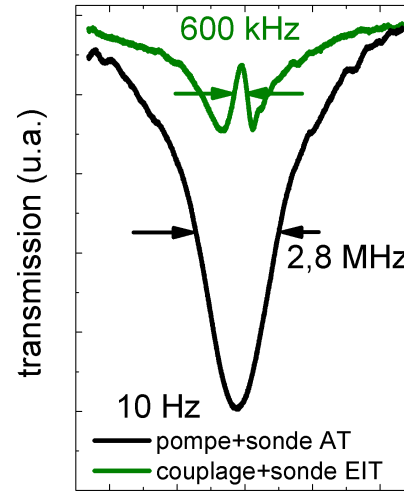
## 1. Anti-trou incohérent



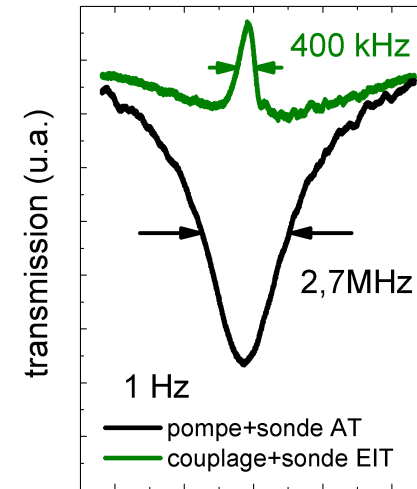
## 2. EIT cohérent



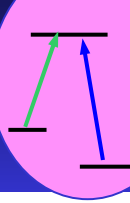
fréquence sonde  
autour de 880 MHz



fréquence sonde  
autour de 740 MHz



fréquence sonde  
autour de 740 MHz

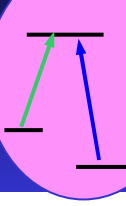


## Premières caractérisations spectroscopiques de $^{167}\text{Er}^{3+} : \text{Y}_2\text{SiO}_5$

- Identification de 13 **systèmes en  $\Lambda$** 
  - Creusement spectral LAC
  - + Résonance paramagnétique LCAES
- Temps de vie des populations
  - $T_1$  optique = 10 ms
  - **$T_1$  hyperfin ~190 ms**

## Premiers résultats de Transparence Induite

- Dispositif expérimental accordable adapté à  $^{167}\text{Er}^{3+} : \text{Y}_2\text{SiO}_5$ 
  - Modulation AM+ filtrage FP
- Spectres montrant une **transparence** sur 2 systèmes en  $\Lambda$ 
  - ~ 400 kHz

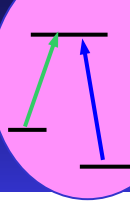


## Court terme

- Optimisation configuration expérimentale (puissances, recouvrement)
- Exploration des 11 autres systèmes (rapports de branchement)
- Préparation des systèmes en  $\Lambda$  (population,  $B$ ,  $T_2$ )

## Long terme

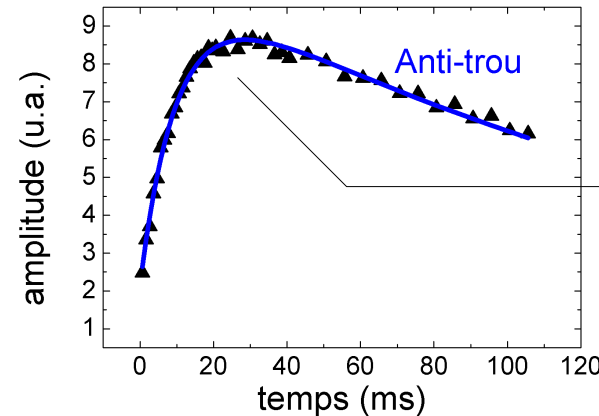
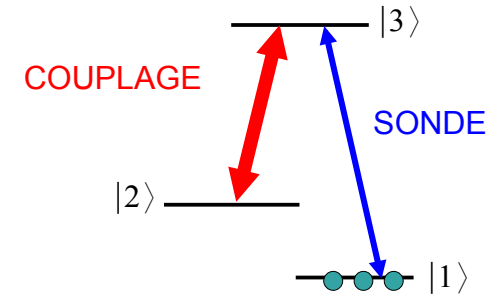
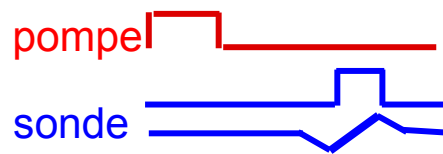
- Application de l'EIT mémoire et effets non linéaires géants



- Idée : préparer dans l'état noir

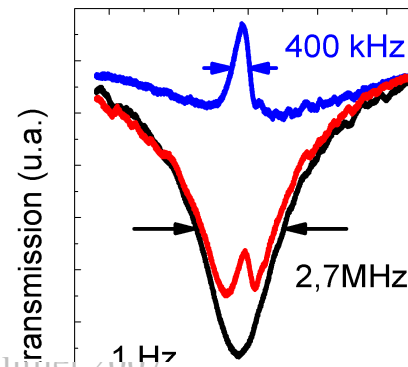
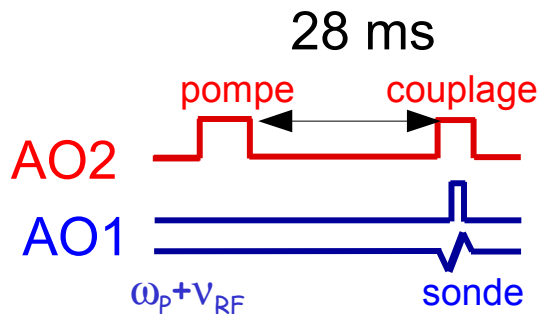
$\text{Pr}^{3+}:\text{YSO}$  Turukhin *et al.* PRL88 (2002).

- Préparation incohérente



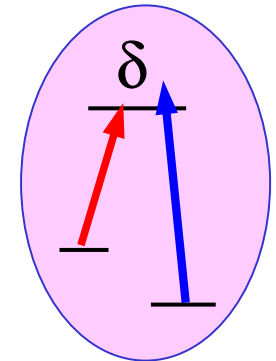
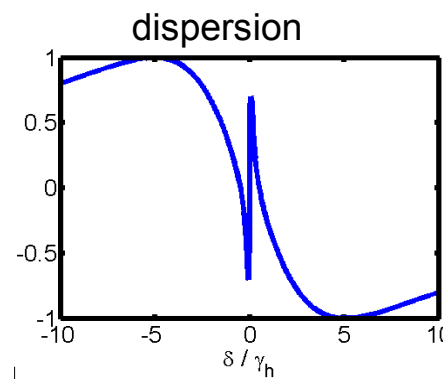
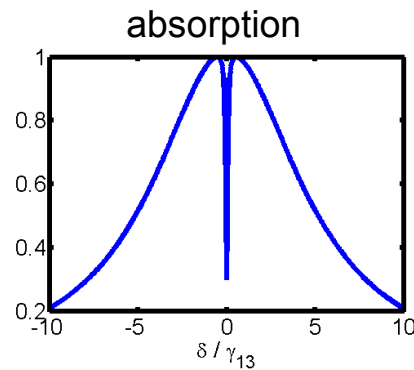
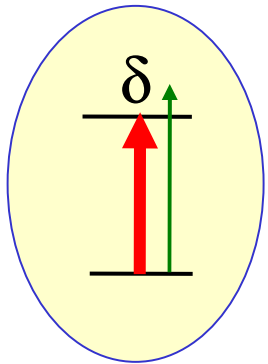
28 ms : population  $|1\rangle$  maximale

- 1<sup>er</sup> résultat



oscillations cohérentes  
de population

transparence induite  
électromagnétiquement



$V_g = 3\text{m/s}$   
accordabilité  $\Gamma_{inh}$

Systèmes en  $\Lambda$   
Transparence Induite

$^{167}\text{Er}^{3+} : \text{Y}_2\text{SiO}_5$   
système riche et complexe  
début de l'étude



*Merci*

