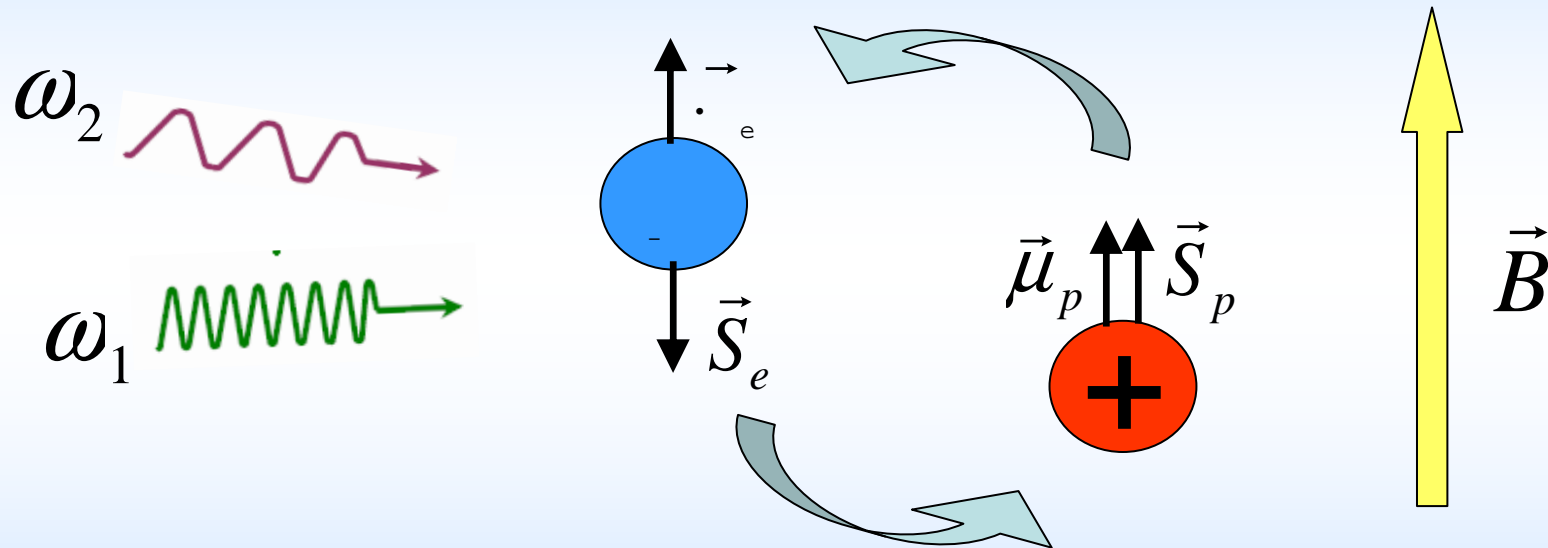


# Positronium Excitation and Spectroscopy



Positronium (Ps): a pure leptonic atom!  
QED at work!



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# Outline

- ♪ **The structure of Positronium (Ps) energy levels**
- ♪ **Positronium spectroscopy: past experiments**
  - ♪  **$n = 2$  – QED corrections**
  - ♪ **Rydberg**
- ♪ **Ps spectroscopy in AEGIS?**
- ♪ **Possible experiments (with or without magnetic field)**
  - ♪  **$n = 3$**
  - ♪ **Rydberg and  $n, l$  mixing**

# field free Ps energy levels

$$E_{n,l,j,s} = -\frac{1}{2n^2} \mu c^2 \alpha^2 + \Delta E_{n,l,j,s}$$

$$+ O(\alpha^n \cdot \ln \alpha)$$

other QED terms,  
Lamb shift,  
(perturbative series)

Coulombic interaction  
with reduced mass  $\mu = \frac{1}{2} m_e$ ,  
energy levels =  $\frac{1}{2}$  of H,  
first orbit radius  $a_{Ps} = 2a_0$  (Bohr)

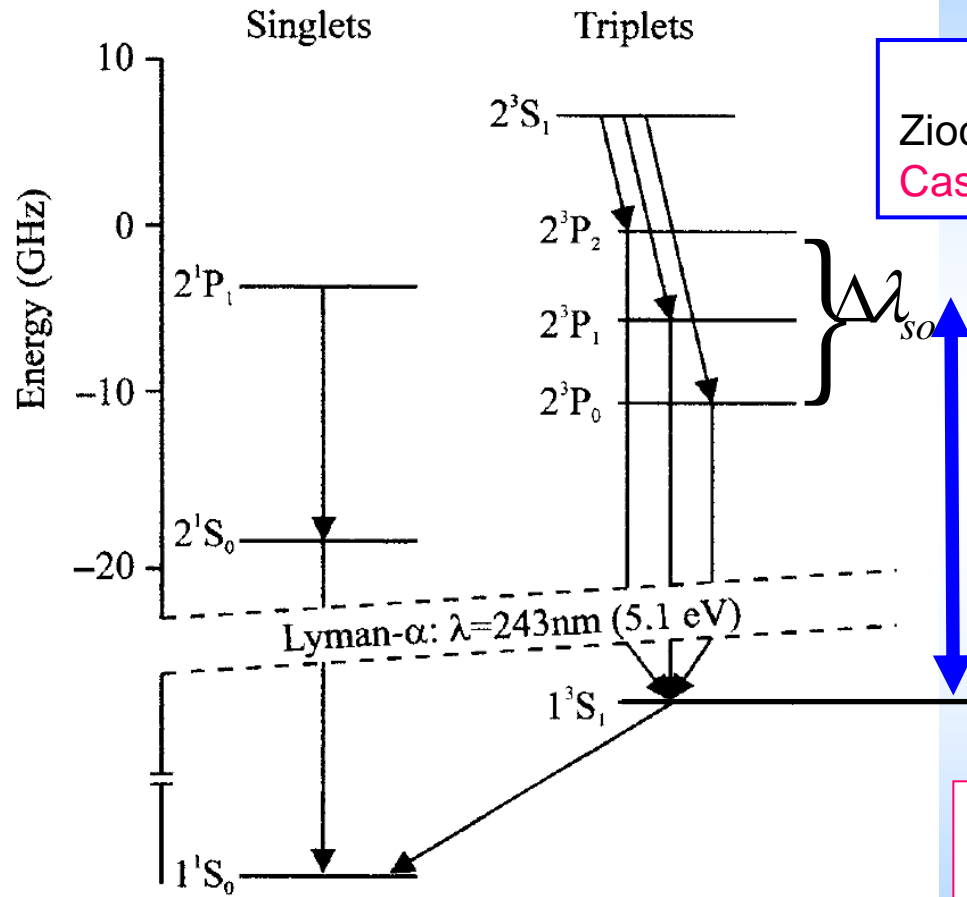
Spin-orbit  
hyperfine  
relativistic inter.

$$\frac{\Delta E}{E} \propto \frac{\alpha^2}{n}$$

$$\Delta E = \frac{\mu c^2 \alpha^4}{4n^2} \left[ -\frac{4}{n(2l+1)} + \frac{11}{8n^2} + \delta_{s,1} \cdot \left( \delta_{l,0} \frac{14}{3n} + \frac{2(1-\delta_{l,0})}{l(2l+1)(l+1)n} \cdot \left\{ \begin{array}{ll} -(3l-1) \frac{l+1}{2l-1} & \text{if } j=l-1 \\ -1 & \text{if } j=l \\ (3l+4) \frac{l}{2l+3} & \text{if } j=l+1 \end{array} \right\} \right) \right]$$

No degeneration on  $l$   
(at variance with H)

# Ps spectroscopy experiments with lasers (I): 1S ↔ 2P excitation – Lyman α



para-Ps ( $S=0$ )  
0.125 ns lifetime

ortho-Ps ( $S=1$ )  
142 ns lifetime

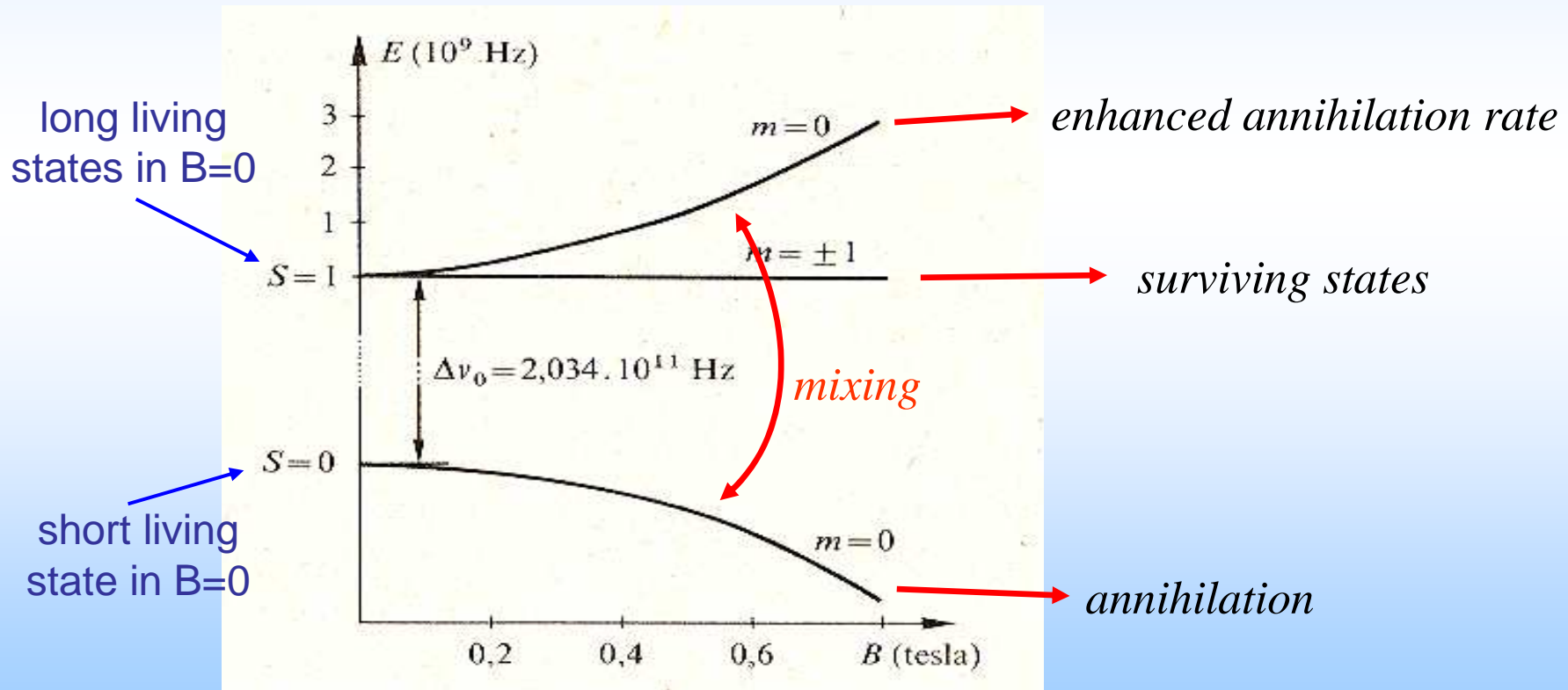
$1^3S \leftrightarrow 2^3P$     243 nm  
Ziock et al, J.Phys.B 23, 329 (1990)  
Cassidy et al, PRA 81, 012715 (2010)

study of Ps cooling  
in silica via Doppler  
spectroscopy

No resolution of fine  
structure ↔ Doppler effect  
 $\Delta\lambda_D \gg \Delta\lambda_{so}$

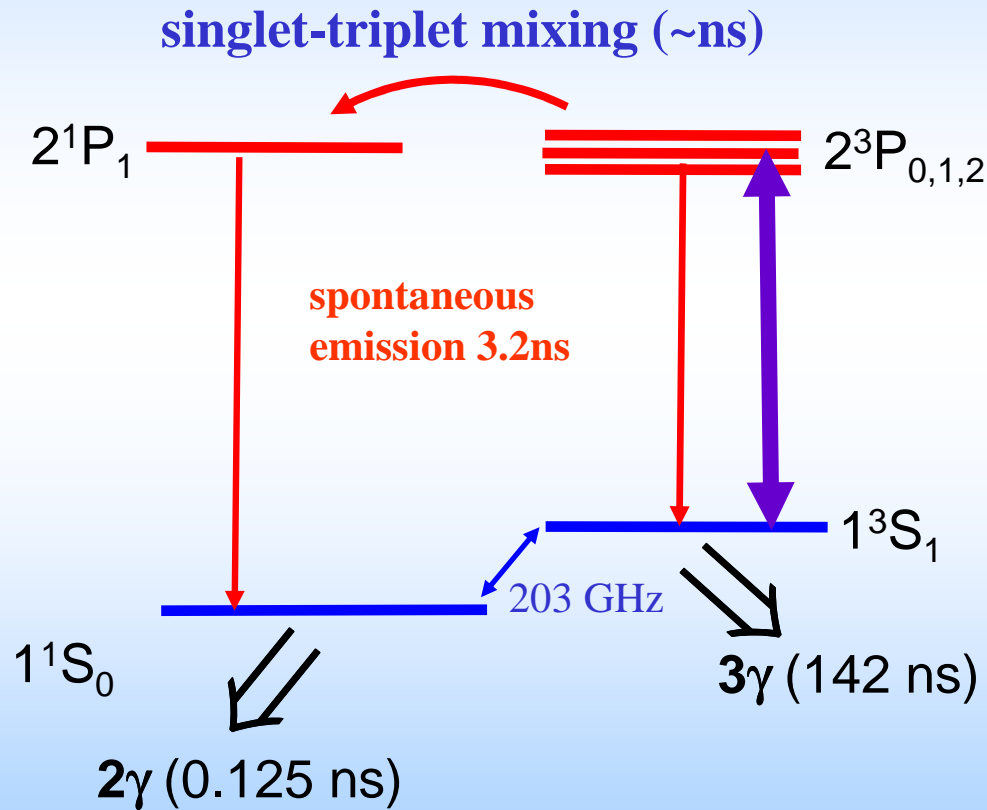
# Diagnostics of optical saturation of $1^3S \leftrightarrow 2^3P$ (I)

by singlet-triplet mixing in weak  $B$  field ( $\ll 0.1T$ )  
 $\Rightarrow$  magnetic quenching with  $\Delta m=0$

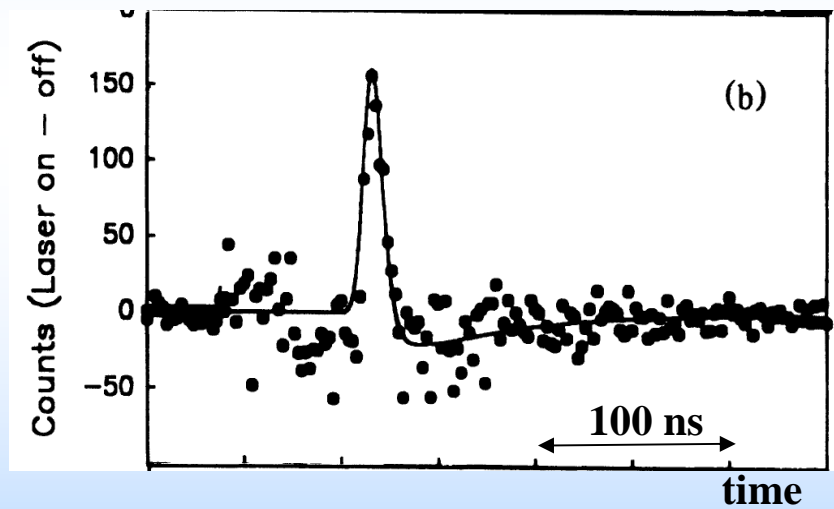


Example:  $n=1$  energy levels

# Diagnostics of optical saturation of $1^3S \leftrightarrow 2^3P$ (II)



Observation of enhanced  $2\gamma$  annihilation rate at the time of laser on



optical pulse 10ns,  $B=0.02T$   
0.07 nm Doppler band

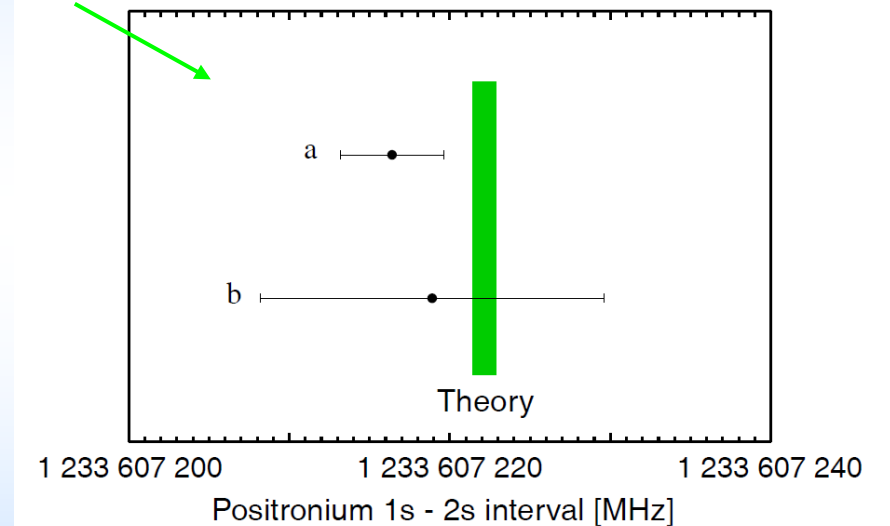
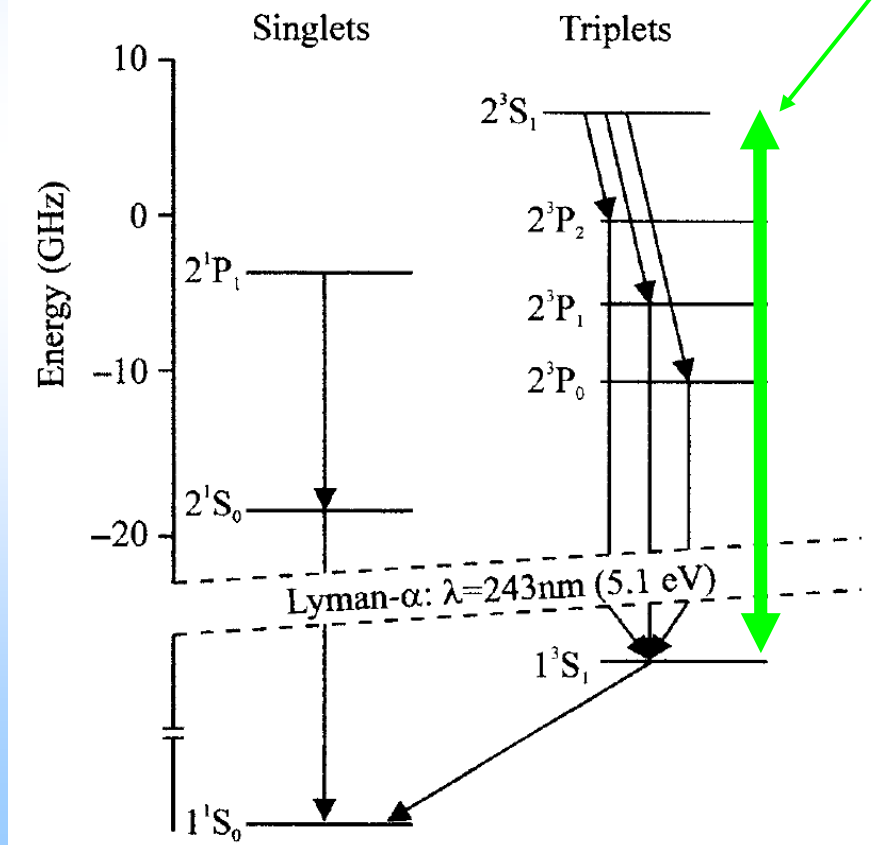
# Ps spectroscopy experiments with lasers (II): QED corrections to fine structure $n = 1, 2$ up to $\alpha^7 \ln \alpha$

$1^3S_1 \leftrightarrow 2^3S_1$  486 nm two photon trans. (Doppler free)

- S.Chu, A.P.Mills, PRL 48, 1333 (1982);

(b) S.Chu, A.P.Mills, J.L.Hall, PRL 52, 1689 (1984);

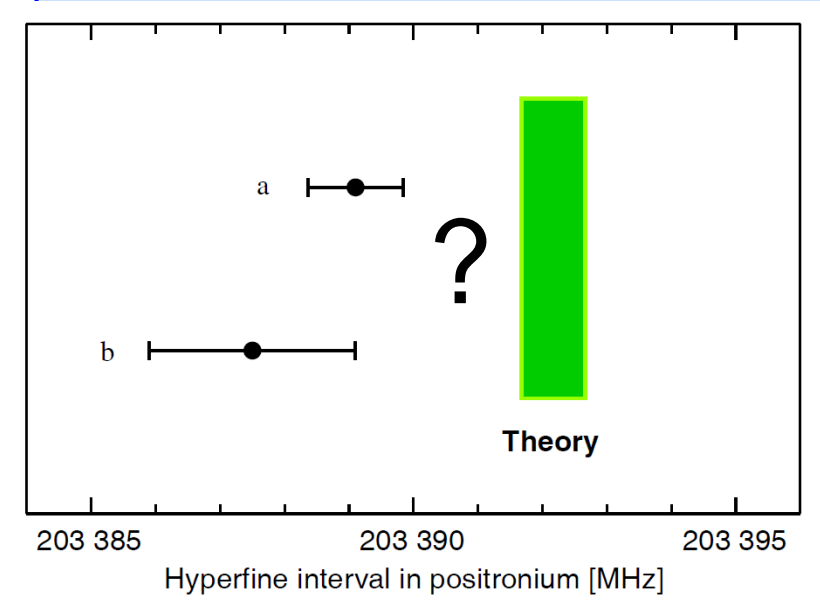
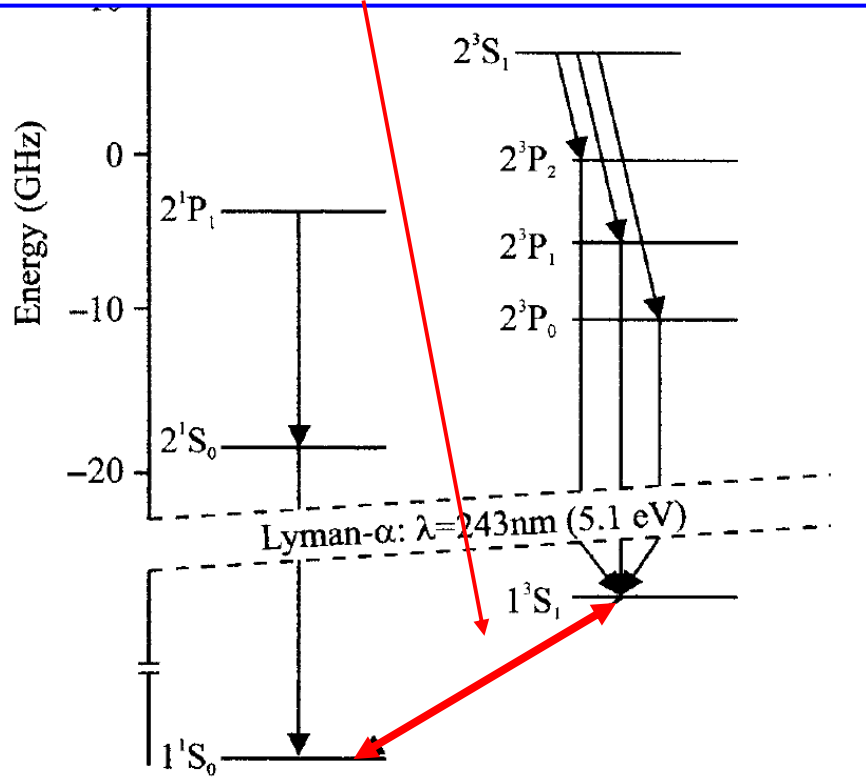
(a) M.S.Fee et al, PRL 70, 1397 (1993);



***Diagnostics:***  
 $2^3S$  ionization with a 532 nm laser pulse, acceleration of  $e^+$  and detection with channeltron

other Ps spectroscopy experiments: **with microwaves (I)**  
 QED corrections to 1S hyperfine structure up to  $\alpha^7 \ln \alpha$

$1^1S_0 \leftrightarrow 1^3S_1$  203.4 GHz  
 (with microwaves in magnetic field (NMR))  
 - M.Deutsch, S.C.Brown, Phys.Rev. 85, 1047 (1952)  
 .....  
 (b) A.P.Mills , PRA 27, 262 (1983)  
 (a) M.W.Ritter et al, PRA 30, 1331, (1984)



**Diagnostics:**  
 observation of enhanced  
 $2\gamma$  annihilation rate

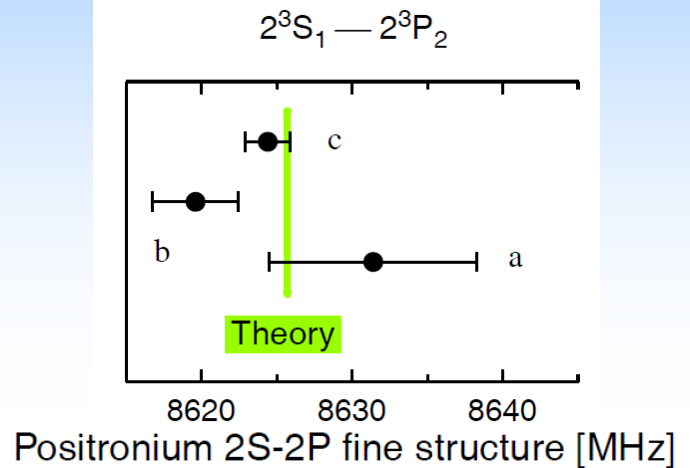
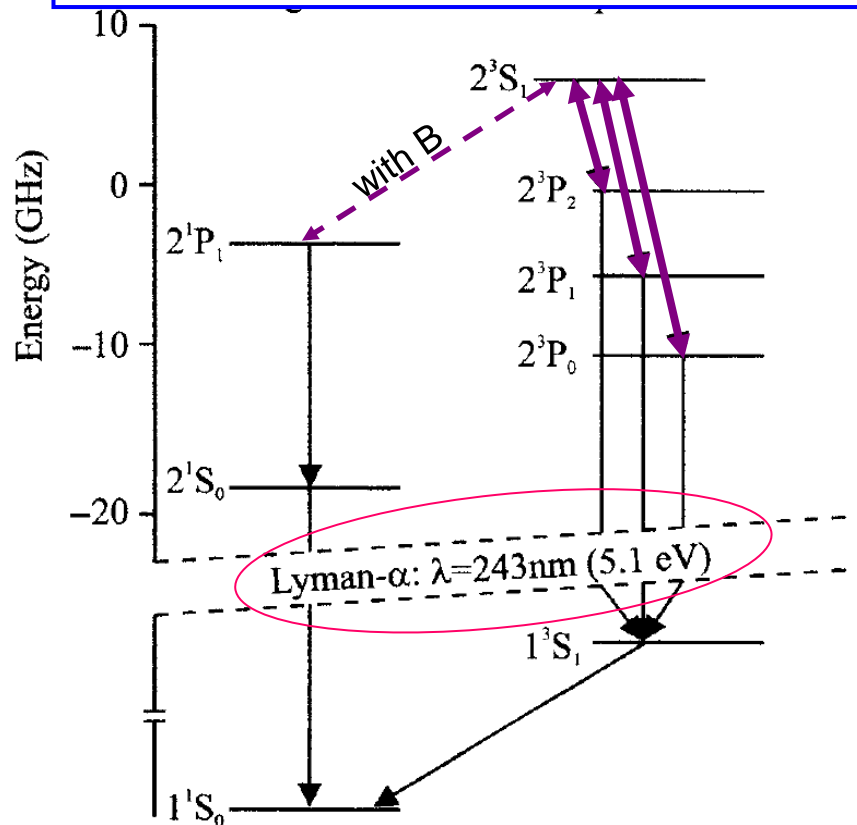
other Ps spectroscopy experiments: **with microwaves (II)**  
 QED corrections to 1S hyperfine structure up to  $\alpha^6 \ln \alpha$

$2^3S_1 \leftrightarrow 2^3P_{0,1,2}$  microwave trans. (~Doppler free)

(a) A.P.Mills et al, PRL 34, 1541 (1975)

(b) S.Hatamian et al, PRL 58, 1833 (1987)

(c) R.Ley et al, Hyperf.Interact. 89, 327 (1994)



⇒ using the small fraction of n=2 Ps exiting from target

⇒ microwave power ~ 10 mW to 1 W

**Diagnostics:**  
 observation of enhanced  
 Lyman- $\alpha$  emission

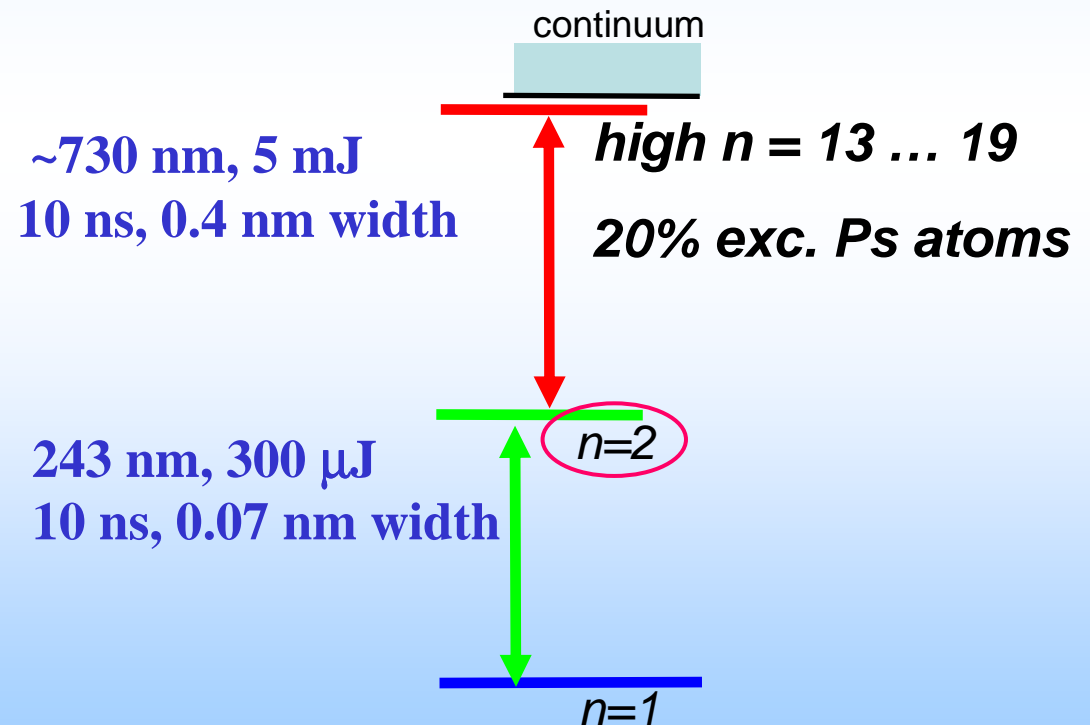
# Rydberg Ps spectroscopy:

study of basic electrodynamic interactions on long living Ps?

only one experiment: Ziock et al, Phys. Rev. Lett. 64, 2366 (1990)

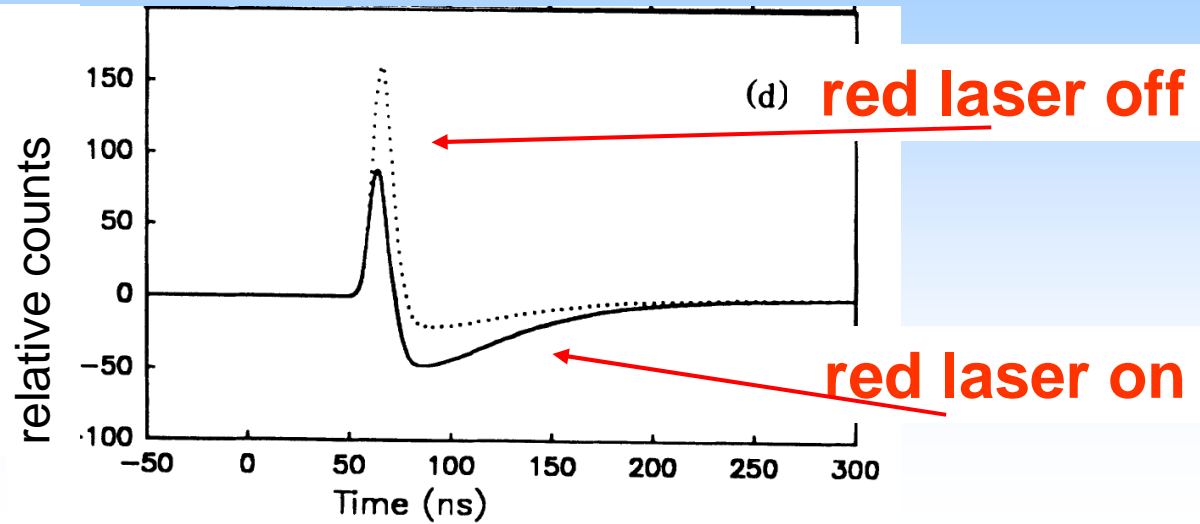
Two step pulsed excitation  
(ultraviolet + red lasers)  
in a magnetic field 0.02 T

strong Doppler effect (1000 K)  
 $\Delta\lambda_D \sim 0.15$  and  $0.5$  nm  
moderate motional Stark effect

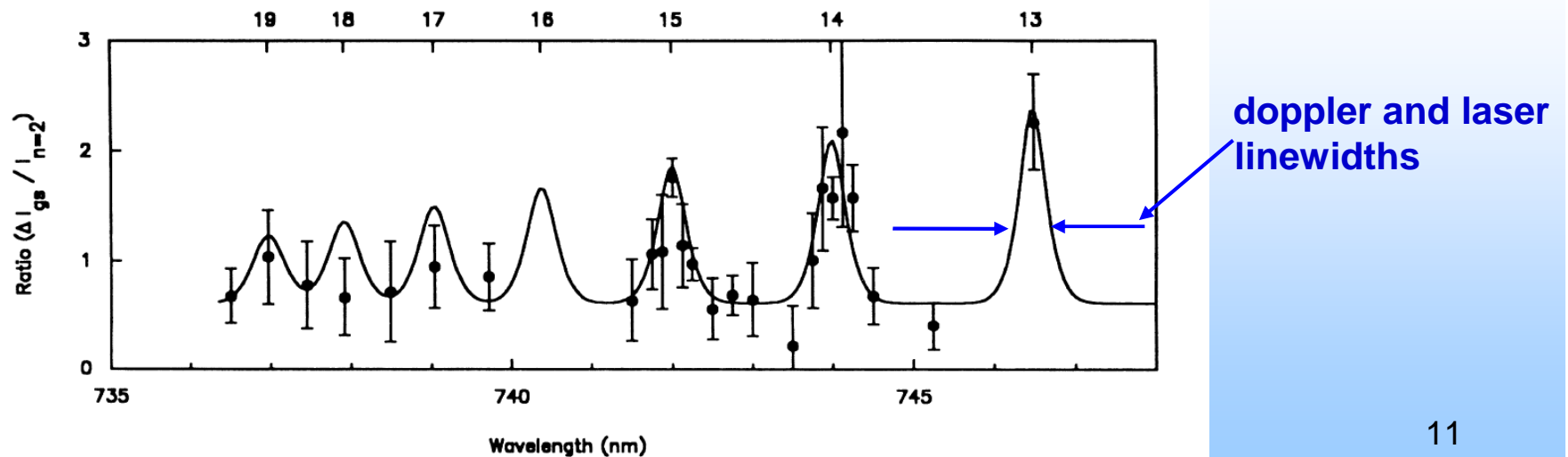


## Diagnostics:

**$2\gamma$  annihilation rate variation  
(singlet-triplet mixing in B field)**



Decrease in ground state population with red laser on  $\rightarrow$  Rydberg excitation



# Ps spectroscopy: proposals in AEGIS

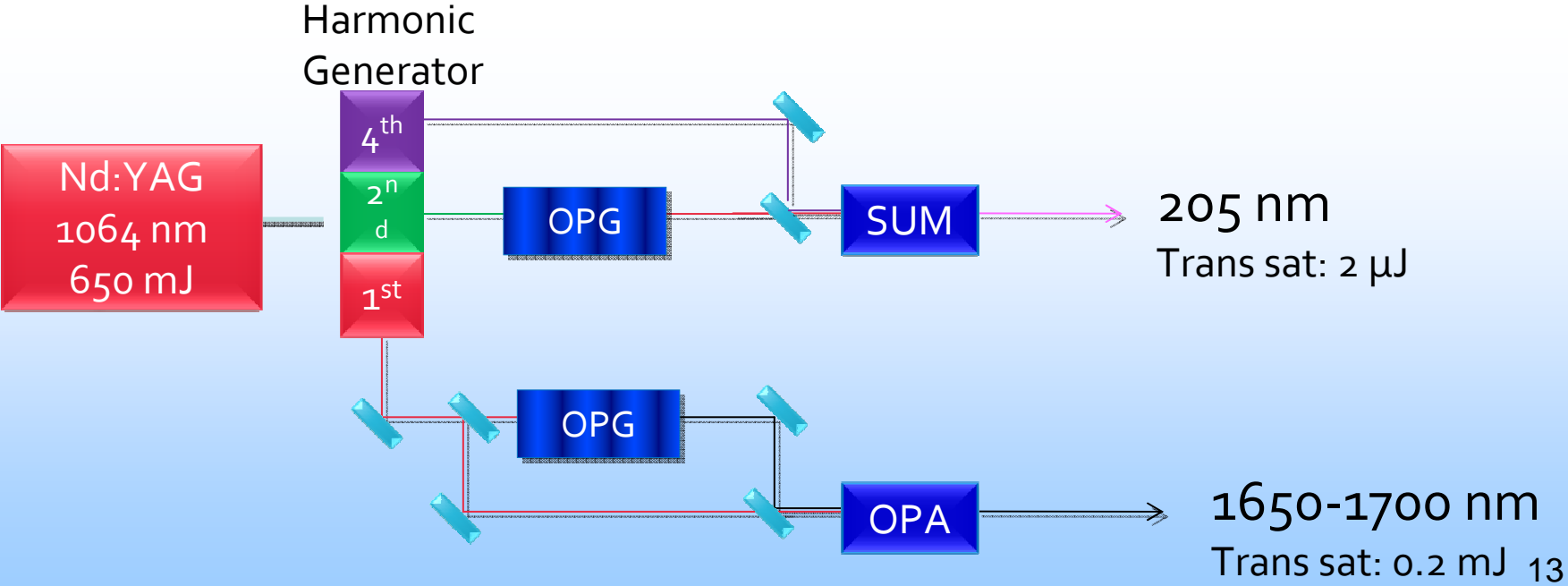
General idea:

- ♪ Produce a positron bunch as foreseen for antihydrogen production
- ♪ Send the bunch to the dedicated Ps-table
- ♪ Use same converters as for antihydrogen
- ♪ Excite with the same laser system as for antihydrogen production
- ♪ Set suitable diagnostic methods
- ♪ Study the effect of magnetic and electric fields (useful for antihydrogen!)

**Guideline: use as much as possible the equipment foreseen for antihydrogen!**

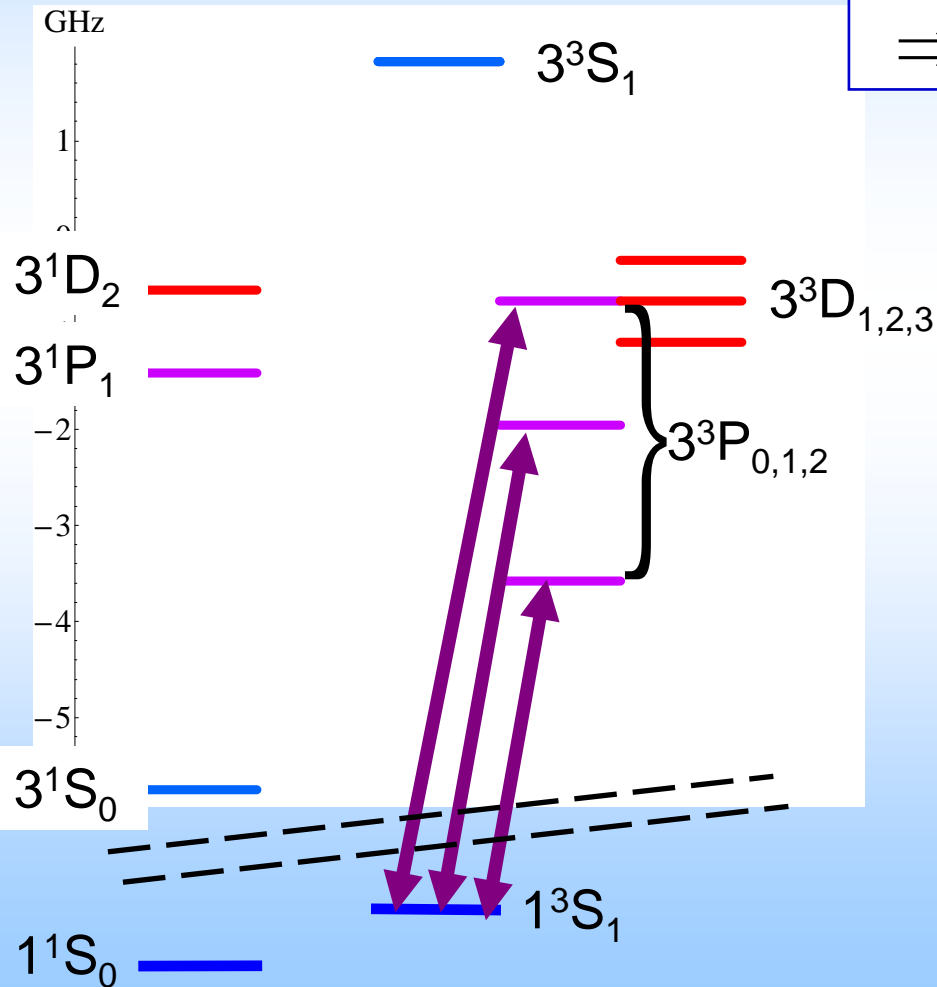
# Aegis laser system

	wavelength	pulse length	laser bandwidth	Energy
ultraviolet radiation	205 nm	2~4 ns	0.015 nm	100 $\mu$ J ?
infrared radiation	1650 ~ 1720 nm	4 ns	2 nm	2 mJ



# Ps spectroscopy: proposals in AEGIS (1)

With the 205 nm pulse,  
⇒ excitation of  $n = 3$  ( ${}^3P$  states)



Timing:  
pulse length 2 ns  
decay time 10 ns

No resolution of fine structure  
↔ Doppler effect ( $\sim 100K$ )  
 $\Delta\lambda_D \approx 0.04 \text{ nm} \gg \Delta\lambda_{s0} \approx 0.0004 \text{ nm}$

## Demonstration of $n = 3$ excitation: diagnostics

### Without magnetic field:

- a) delayed (10.5 ns) spontaneous emission at 205 nm photomultiplier orthogonal to the laser flux (eventually with annihilation coincidence)
- b) photoionization with a delayed  $\lambda < 1600$  nm pulse (second laser system with new crystals)

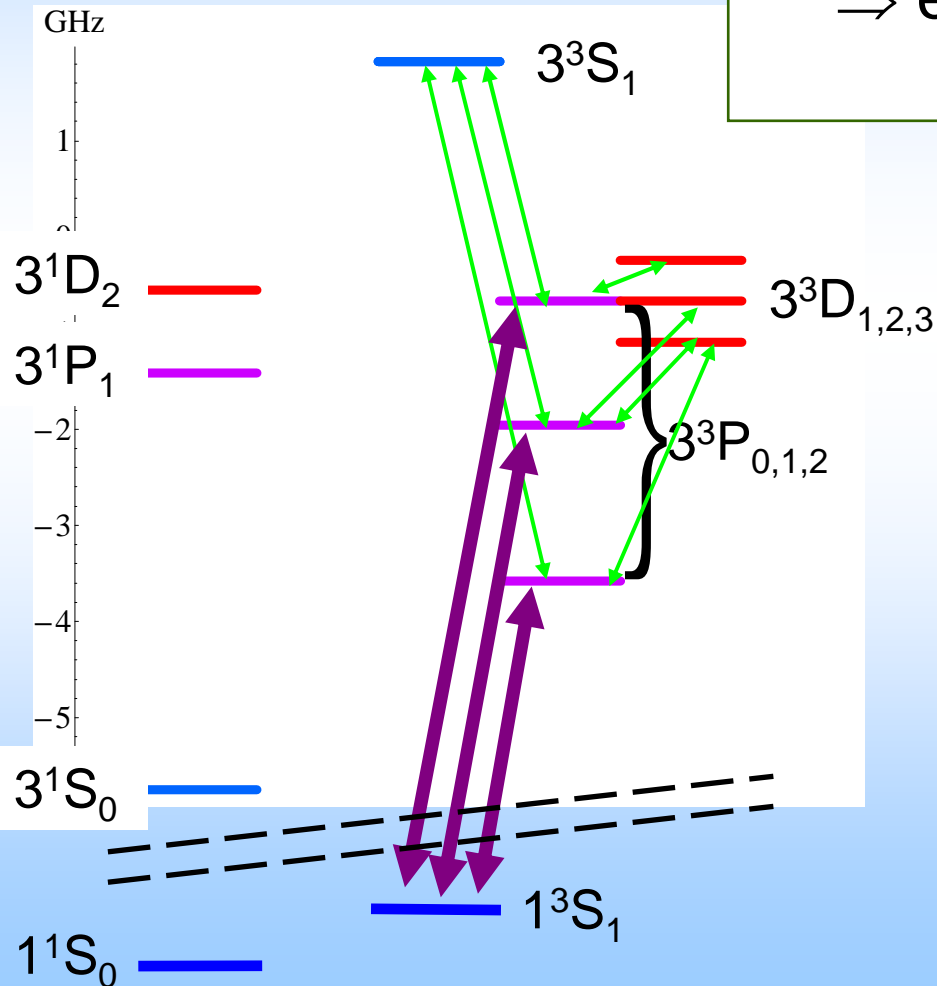
### With a weak magnetic field ( $< 0.01 T$ ):

enhanced  $2\gamma$  annihilation rate due to triplet-singlet mixing  
*(the same technique for  $n = 2$ )*

**Note: in strong magnetic field ( $\sim 1 T$ )  
no fine structure, no mixing  
 $\leftrightarrow$  only the Doppler line**

# Ps spectroscopy: proposals in AEGIS (2)

With the 205 nm pulse and microwaves  
⇒ excitation of  $n = 3$  fine structure  
⇒ **QED corrections**



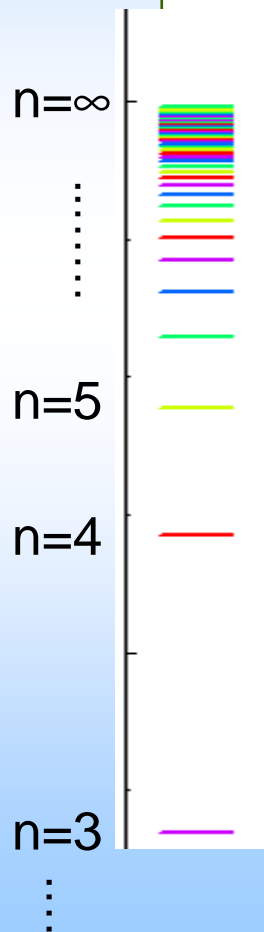
**Resolution of fine structure  
with resonant microwaves**  
400 to 5400 MHz (up to 2 W?)  
max Doppler  $\Delta\nu_D \approx 1.2 \text{ MHz} \ll \Delta\nu_{so}$

## *Diagnostics*

by reduced delayed spontaneous  
emission at 205 nm at 10 ns  
(very long decay of 3S and 3D states!)

# Ps spectroscopy: proposals in AEGIS (3)

With the 1650 ~ 1720 nm pulse  
⇒ excitation of Rydberg states starting from  $n = 3$   
(*Hic sunt leones.....new physics?*)



states from  $n = 14$  to  $n = 36$  excitable

**weak (or zero) e.m. fields ( $B < 0.02T$ )**

Resolution on quantum number  $n$ :

- 1) Doppler effect  $\Delta\lambda_D \approx 0.36 \text{ nm} < \Delta\lambda_{36-35} \approx 0.62 \text{ nm} \Rightarrow \text{OK}$
- 2) Laser bandwidth  $\Rightarrow$  up to  $n = 24$  OK  
necessary bandwidth reduction for  $n > 24$

Note: for radiative Rydberg Ps in B field, no singlet-triplet mixing!

## Demonstration of Rydberg Ps excitation: diagnostics

- ✓ Direct (1) : ionization of Rydberg Ps with pulsed electric potential ( $10^2 \leftrightarrow 10^3$  V), charge collection and final annihilation  $2\gamma$   
 $\Rightarrow$  **energy selective** (*most used method*)
- ✓ Direct (2) : photoionization of Rydberg Ps with microwaves, same detection as above
- ✓ Indirect (1): reduced  $2\gamma$  annihilation rate in weak magnetic field ( $\sim 0.01$ T)  
(*the same technique as in Ziock, probably less sensitive here, for timing and efficiency reasons*)

## Rydberg Ps in AEGIS:

Magnetic interactions in strong B field (1 Tesla)  
( *Hic sunt leones.....new physics!* )

$$E_{n,\dots} = -\frac{13.6 \text{ eV}}{2n^2} + \Delta E_Z + \Delta E_{dia} + \Delta E_{MS}$$

*principal term*  
*4n<sup>2</sup> degenerate*  
*(for l,m,s,m<sub>s</sub>*  
*quantum numbers)*

*(linear) Zeeman*

*diamagnetic*  
*(or quadratic*  
*Zeeman)*

*motional Stark*

$$\vec{E}_{\perp} = \vec{v}_{Ps} \times \vec{B} \quad \text{induced electric field acting on moving Ps}$$

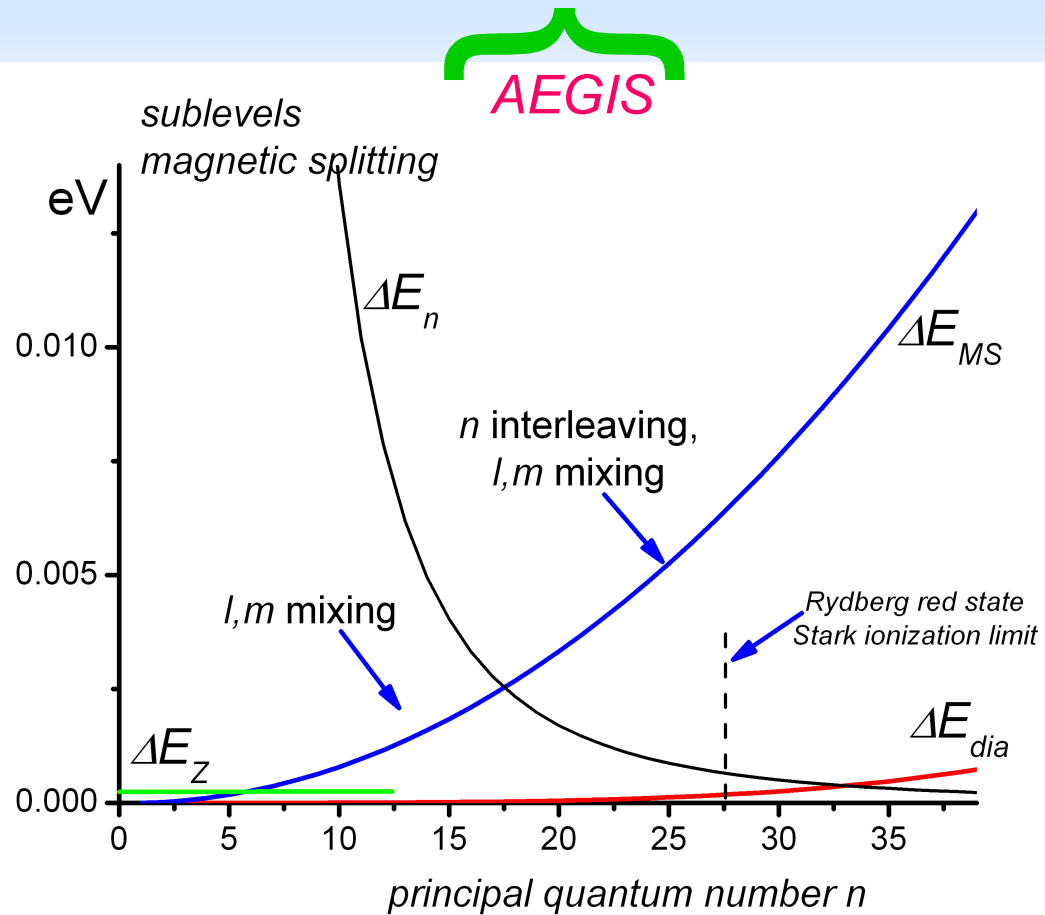
moving Rydberg Ps in magnetic field:  
max. energy splitting contributes and sublevel structure

$\Delta E_n$  energy difference between adjacent  $n$

$\Delta E_Z$  Zeeman energy, only for spins

$\Delta E_{dia}$  diamagnetic energy, axial symmetry

$\Delta E_{MS}$  motional Stark energy, no symmetry

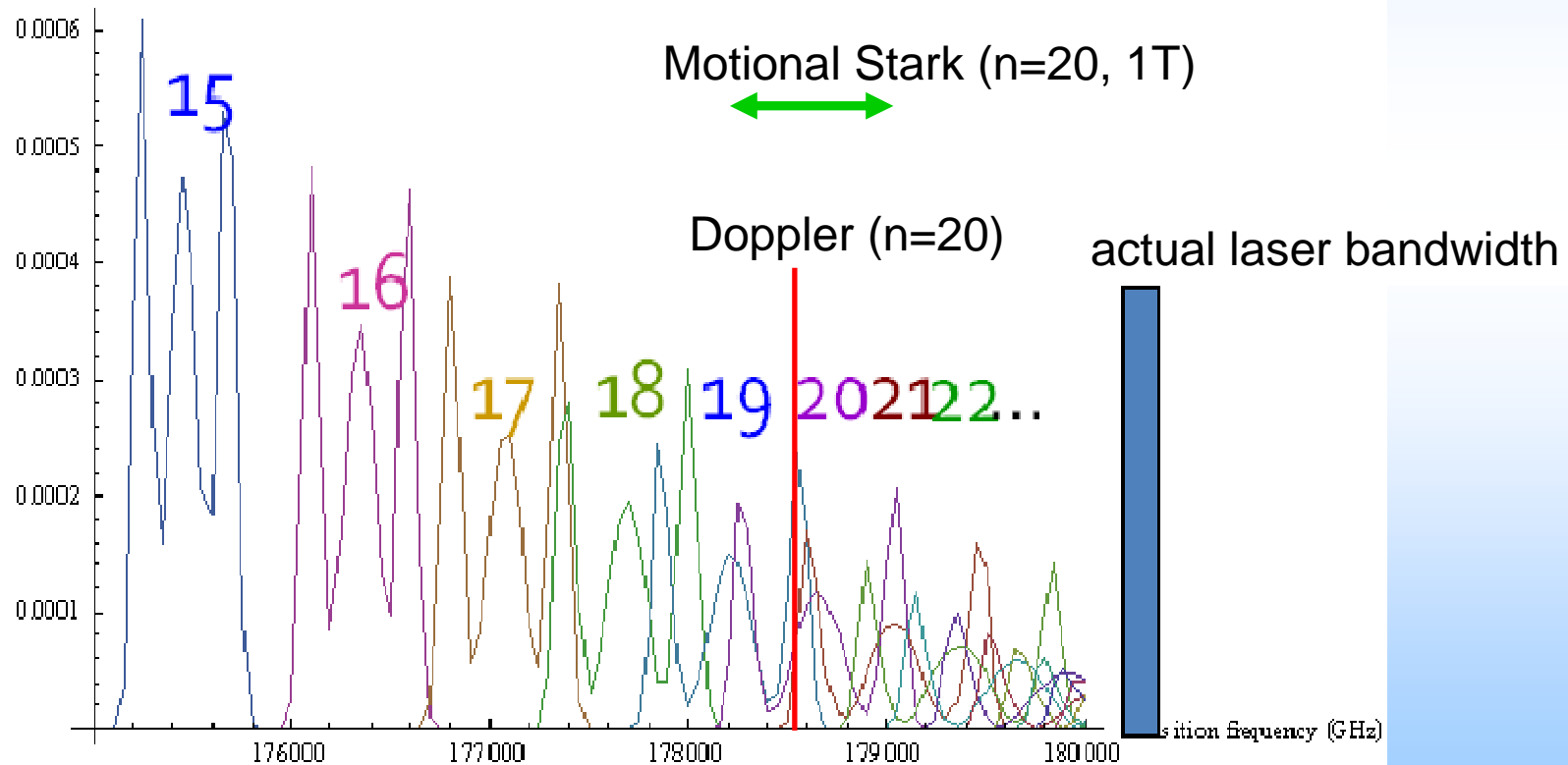


## strong e.m. fields ( $B > 0.2\text{T}$ )

- ⇒ mixing of  $l, m$  sublevels (for low  $n$ )
- ⇒ superposition of neighboring  $n$  sublevel structures!

Transition probability

$\{(3,1,0) \rightarrow (n,2,0)\}$



credits: Fabio Villa

## Ps spectroscopy: proposals in AEGIS (4)

Simulation of motional Stark effect (in zero or weak B)  
on Ps Rydberg states

with a transverse electric field ( $10^2 \leftrightarrow 10^3$  V)!

using the same apparatus as in excitation diagnostics

**Diagnostics** : ionization of Rydberg Ps with pulsed electric potential  
( $10^2 \leftrightarrow 10^3$  V), charge collection and final annihilation  $2\gamma$   
 $\Rightarrow$  **energy selective** (*most used method*)

**excitation  $\leftrightarrow$  Rydberg level band**

**study of interacting sublevels band density**

- $\Rightarrow$  by varying static electric field**
- $\Rightarrow$  by varying weak magnetic field**
- $\Rightarrow$  by reducing laser bandwidth**
  - $\Rightarrow$  by scanning laser central frequency**

**Probably no question about strongly uniform B field ?  
or Ps thermalization ?**

**Necessity of a dedicated Ps interaction chamber**

# Conclusions

- ♪ **Some proposals for Ps spectroscopy experiments with actual equipment**
- ♪ **with zero or weak magnetic field**
  - ♪  **$n = 3$**
  - ♪ **Rydberg and  $n, l$  mixing (by adding ionization apparatus)**
- ♪ **with microwaves ????**
  - ♪  **$n = 3$  fine structure**

**Trento and Milano are applying for a funding request at Italian University Ministry**

(but very low probability .....)