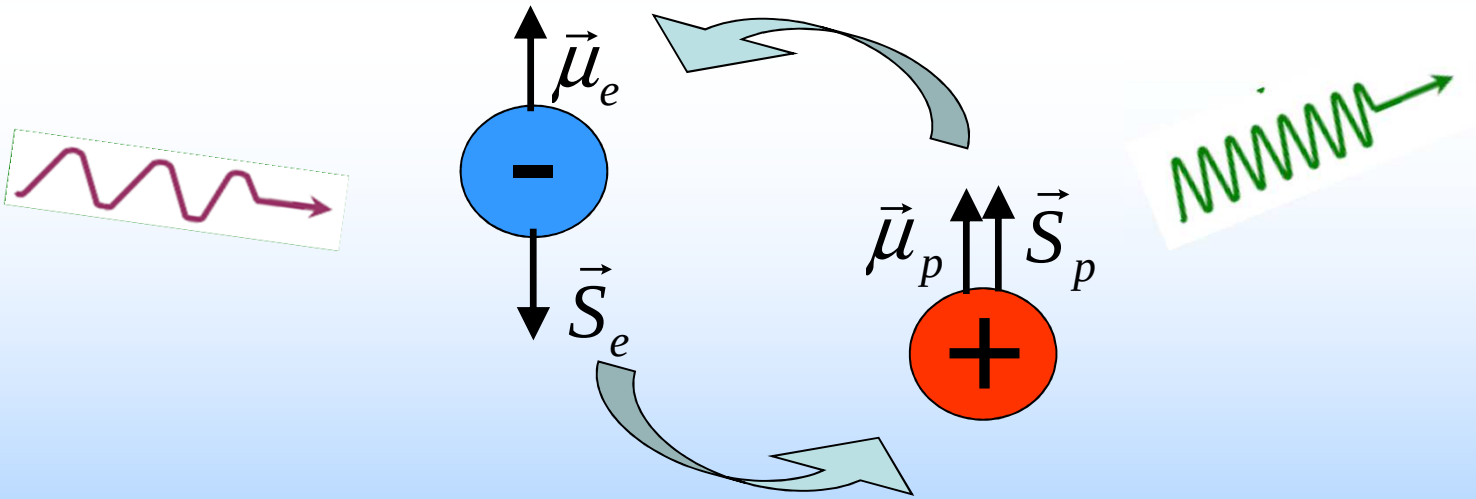
Positronium and Fundamental Physics

What Next ?

What Next Florence 2015



F. Castelli,

INFN and Dept. of Physics, University of Milan

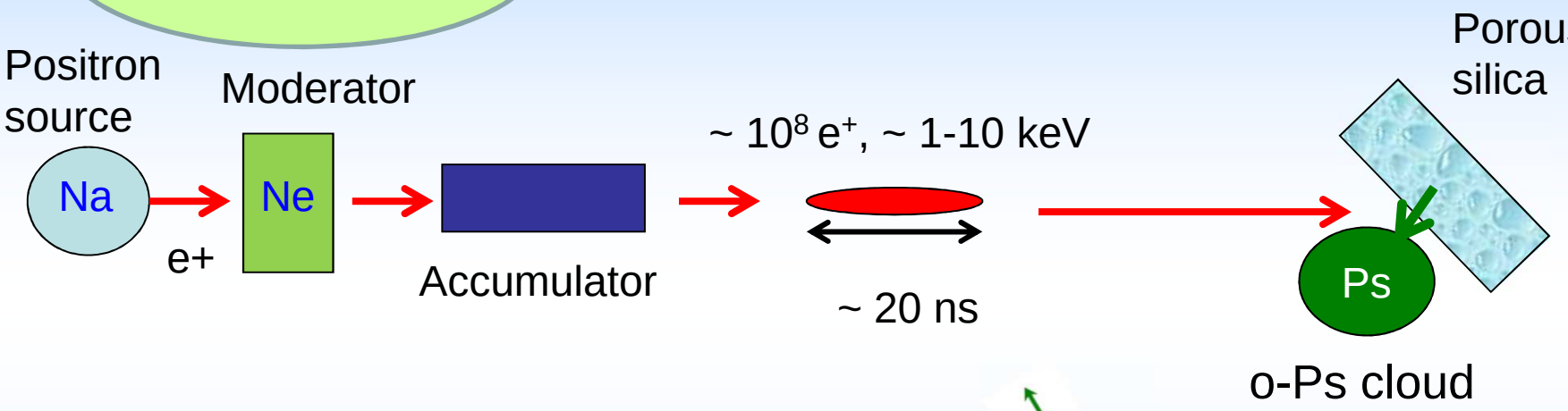
Outline: physics with positronium (Ps)

- **Quantum Electrodynamics with Ps**
- **Atomic Physics with Ps**
- **Quantum Interferometry with Ps**
- **Laser Cooling of Ps**
- **Bose Einstein Condensation with Ps**
- **Gravitational studies with Ps**
- **Quantum entangled states from Ps**

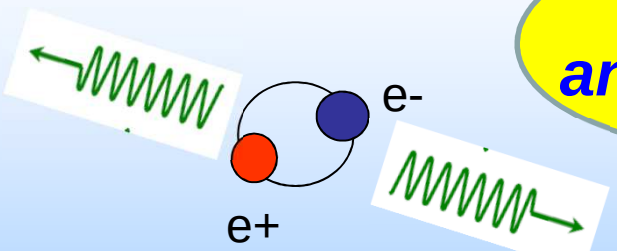
JUST TO START...

Positronium (Ps): e^+ e^- bound state

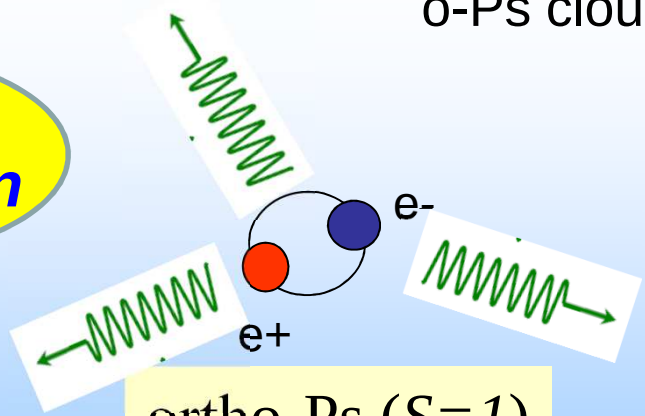
A typical Ps production method



γ ray annihilation



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



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

Quantum Electrodynamics with Ps

Positronium (Ps):
a pure leptonic atom
(no hadronic interactions)

Ps energy levels

$$E_{n,l,j,s} = -\frac{1}{2\,n^2}\,\mu\,c^2\,\alpha^2 + \Delta E_{n,l,j,s}(\propto \alpha^4) + O(\alpha^n)$$

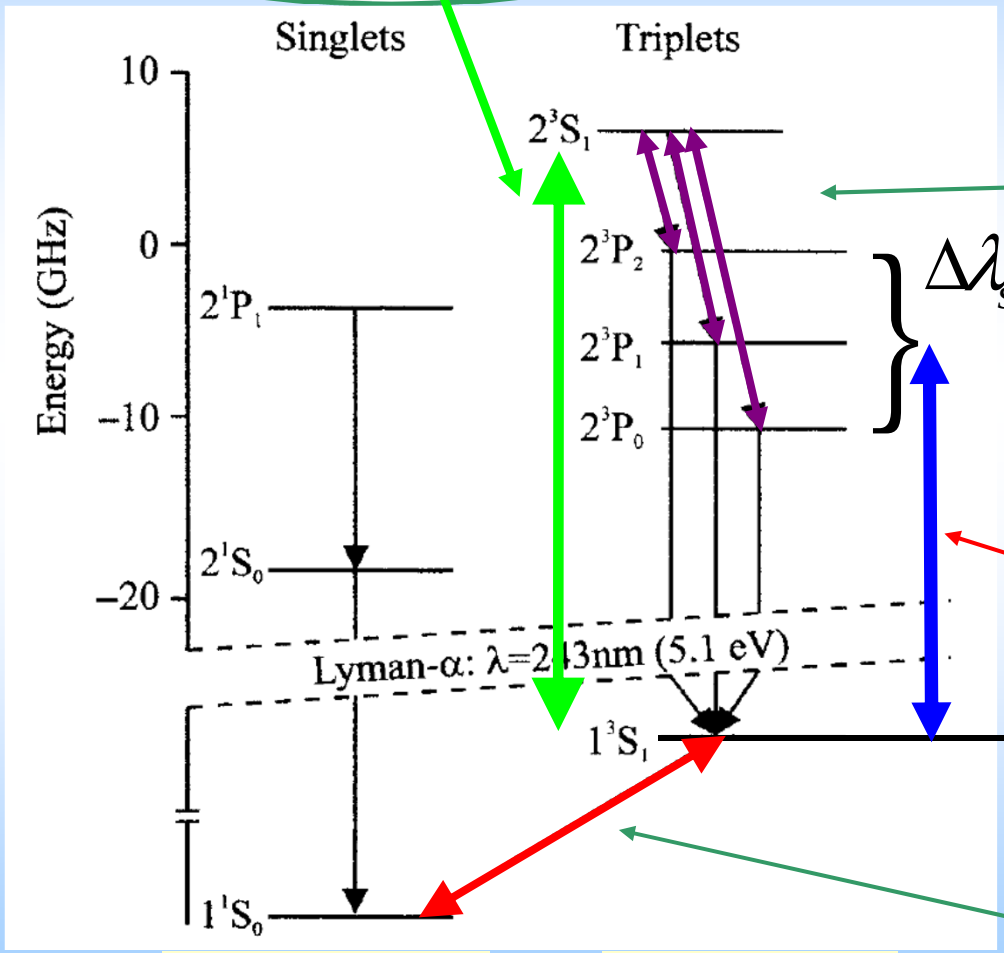
Coulombic interaction with reduced mass $\mu = \frac{1}{2}\, m_e$, energy levels = ½ of H, first orbit radius $a_{Ps} = 2a_0$ (Bohr)

Spin-orbit hyperfine relativistic inter.

other QED terms, Lamb shift, (perturbative series)

State of the art: Ps spectroscopy exp. with lasers and microwaves:
n=1 ⇔ n=2 excitation

two photon trans. (Doppler free)
QED corrections up to α^6 (~10^{-9})



microwaves 8 ÷ 20 GHz
QED corrections to fine structure up to α^6 (~ 10^{-5})

fundamental 1S ⇔ 2P transition
243 nm

microwaves 203.4 GHz, in magnetic field
QED corrections to 1S hyperfine structure up to α^7 (~ 10^{-6})

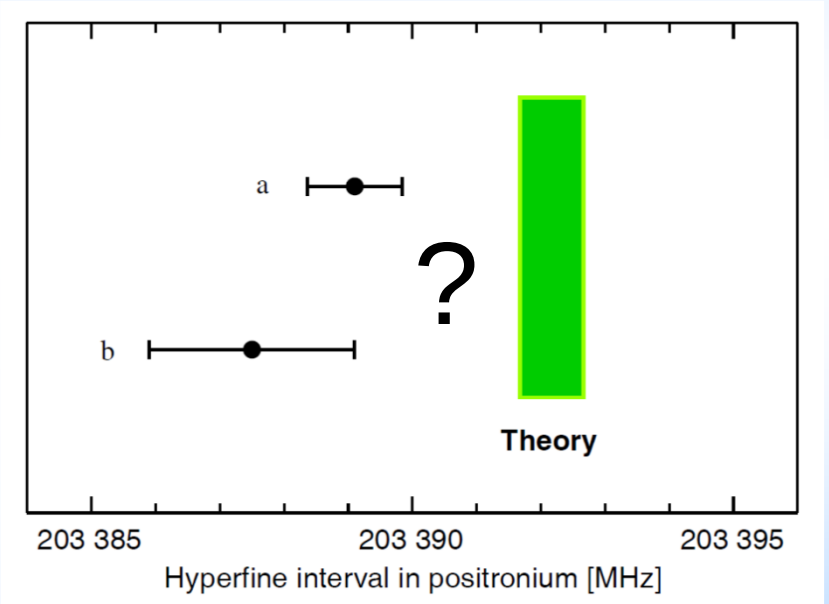
para-Ps (*S=0*)
0.125 ns lifetime

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

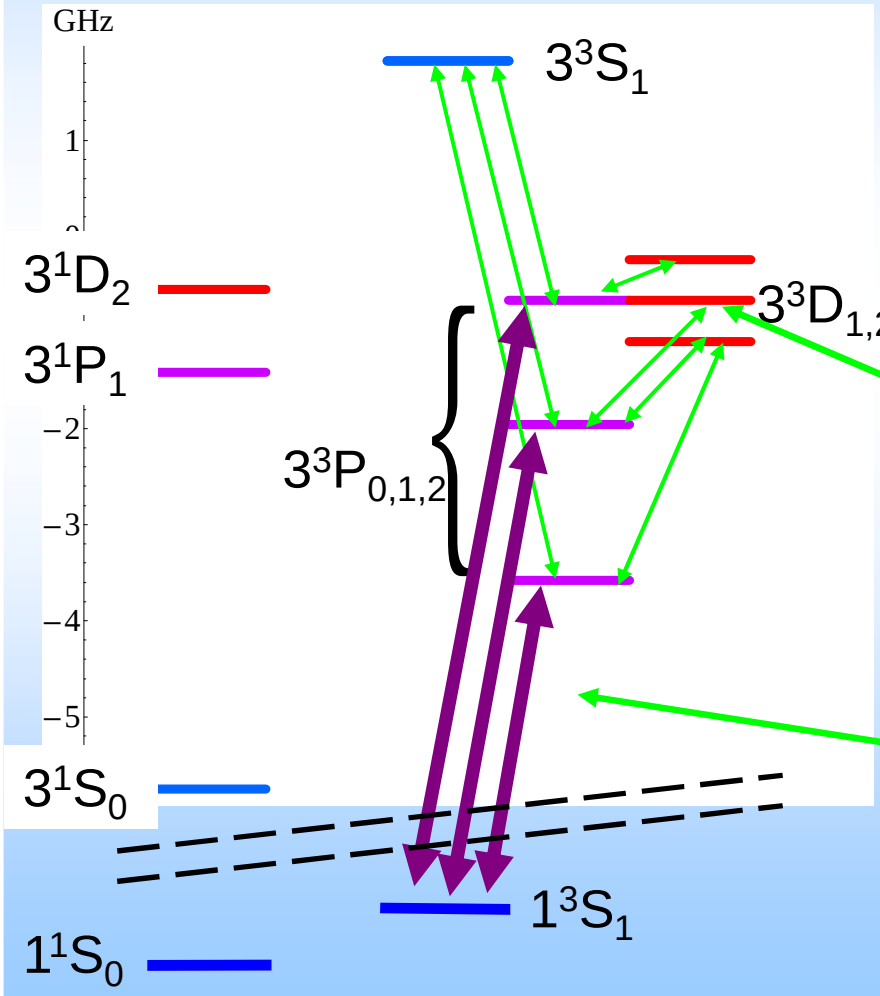
Open problems ?

Ps spectroscopy experiments: QED corrections to 1S hyperfine structure up to $\alpha^7 mc^2$ (1 MHz)

$1^1S_0 \leftrightarrow 1^3S_1$ 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)



Possible other exp for QED corrections: Ps spectroscopy at n=3



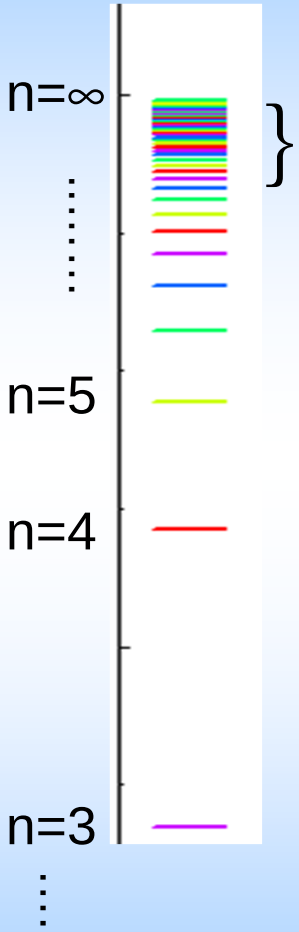
Resolution of fine structure with resonant microwaves
400 to 5400 MHz
max Doppler $\Delta\nu_D \approx 1.2$ MHz << $\Delta\nu_{so}$

of special interest: up to α^4
$E(^3P_2) = E(^3D_2)$

205 nm laser pulse
$1 \Rightarrow 3$

Atomic Physics with Ps

Ps excitation to Rydberg levels (12 < n < 35)



- **Enhanced lifetime:**
  ⇒ from 142 ns (annihilation o-Ps)
  to 10 μs ÷ 1 ms (radiative decay)

- **High sensitivity to magnetic and electric fields**
  (Stark acceleration - manipulation of Ps beams)

- **Strongly evidence of motional Stark effect**
  ⇒ special feature of Ps atoms
  (Ps is the lightest atom!)

Rydberg Ps - magnetic interactions

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

principal term $4n^2$ ~degenerate (for l,m,s,m_s quantum numbers)

(linear) Zeeman

diamagnetic (or quadratic Zeeman)

motional Stark

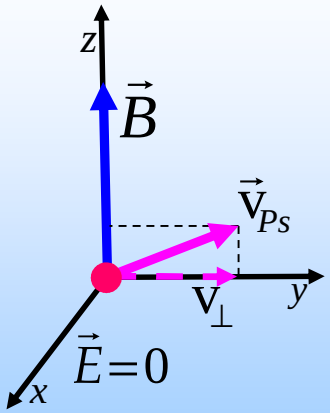
$$\vec{E}_\perp = \vec{v}_{Ps} \times \vec{B}$$

induced electric field acting on moving Ps

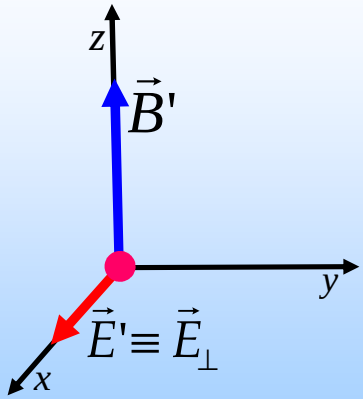
thermal Ps velocity:

$$v_{Ps} = \sqrt{k_B T / m_{Ps}} > 10^5\ \text{m/s}$$

laboratory frame



Ps rest frame

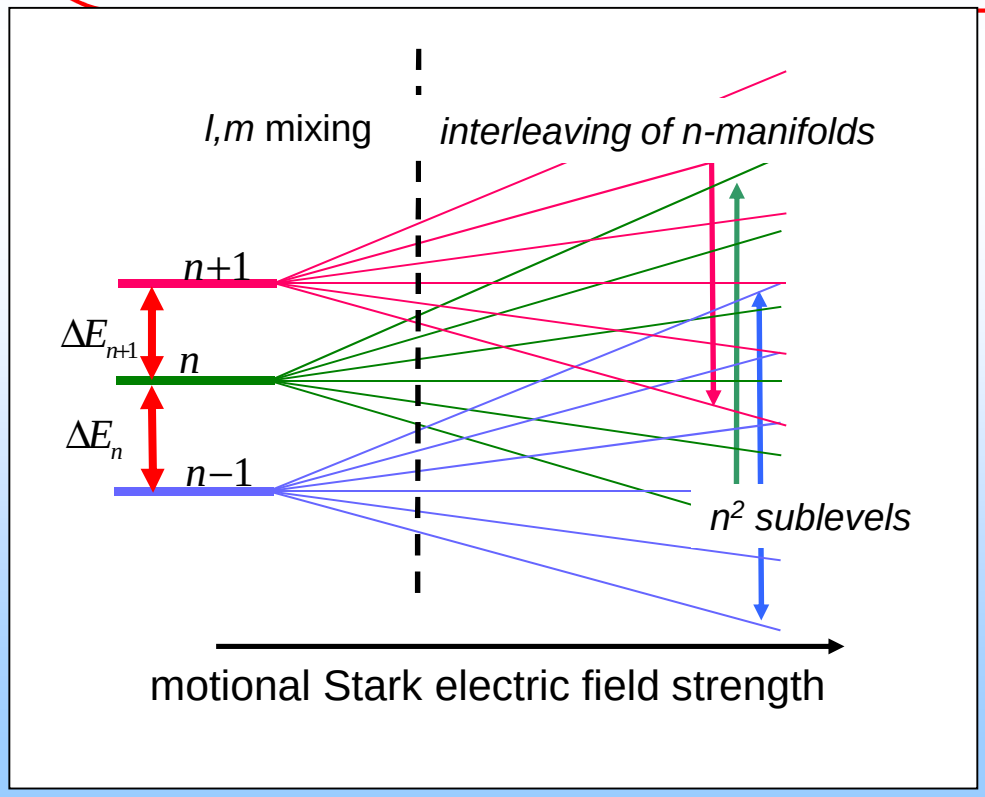


breaking of the axial symmetry around the *B* axis!

complete mixing of *l* , *m* substates of a *n* manifold ⟷ **l , m are no longer good quantum numbers**

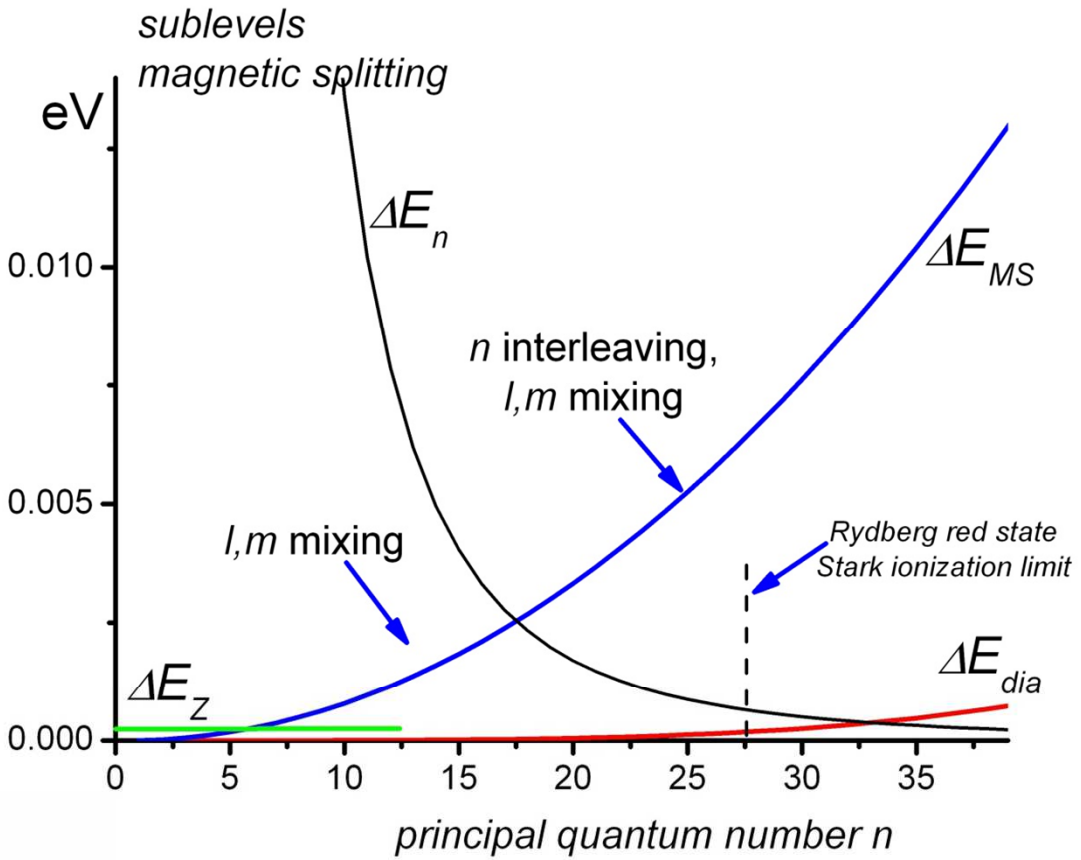
No known proper quantum numbers for this problem!

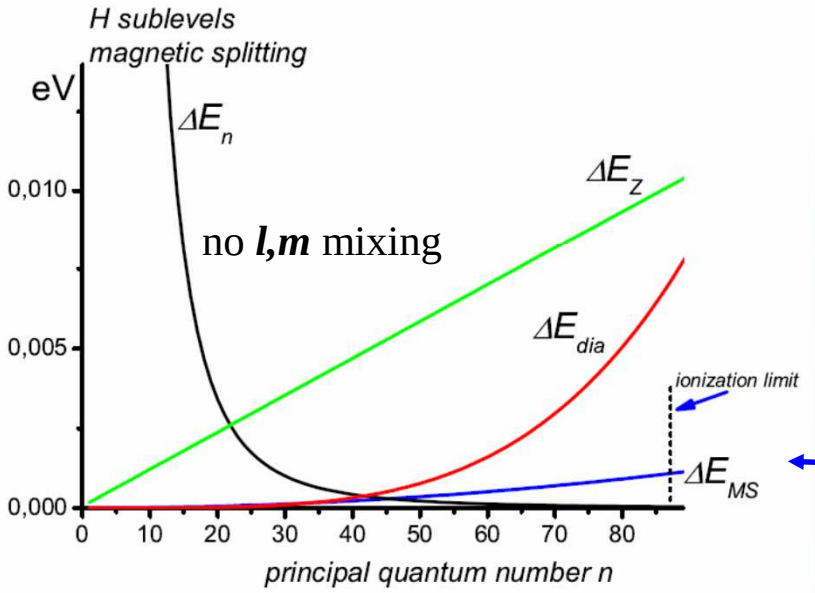
no electric dipole selection rules for interaction with e.m. radiation



More:
interleaving of different *n*-sublevel manifolds!

motional Stark effect is largerly the dominant contribution to sublevel splitting energy for Rydberg Ps

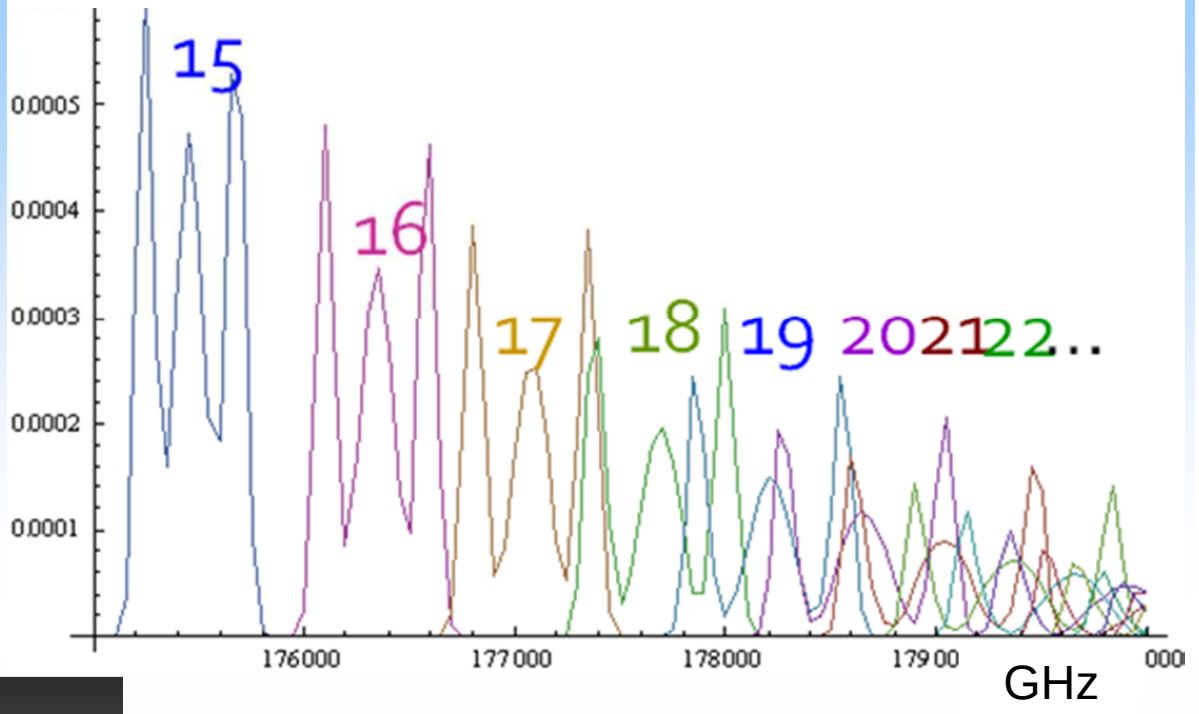




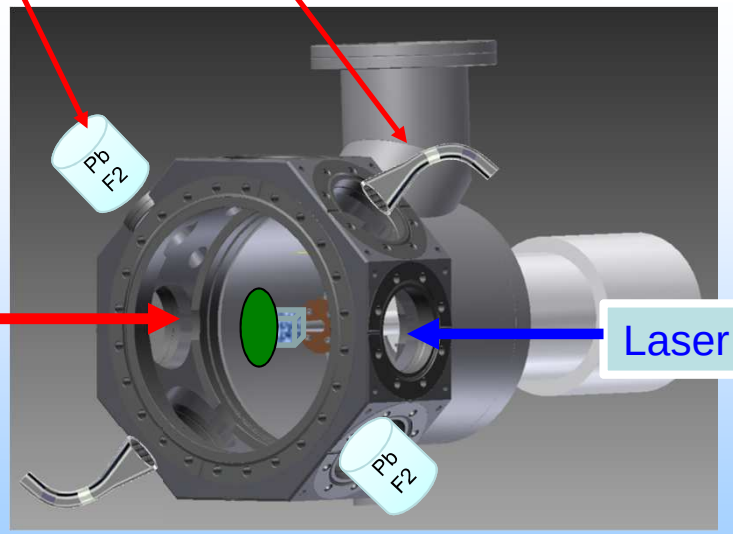
comparison with a H atom

a very complex structure (two laser pulses excitation, 1 → 2,3 → n)

Transitions prob. from (3,1,0) to (n,?,?) in B=0.1T

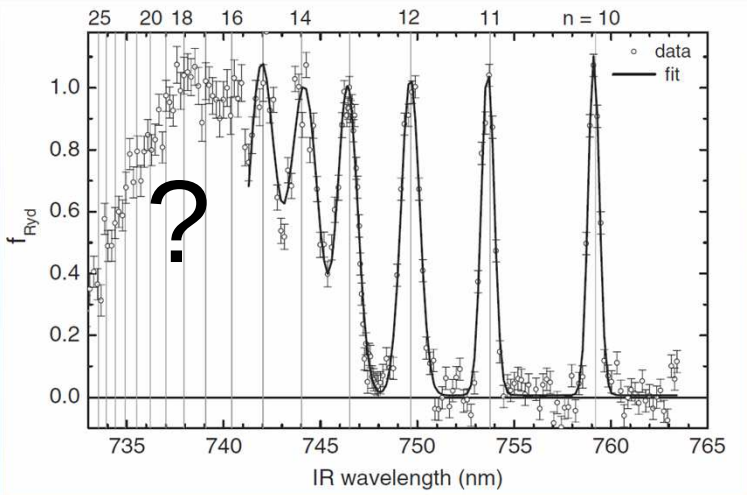


Annihilation and charge particles detectors



e+

Laser pulses

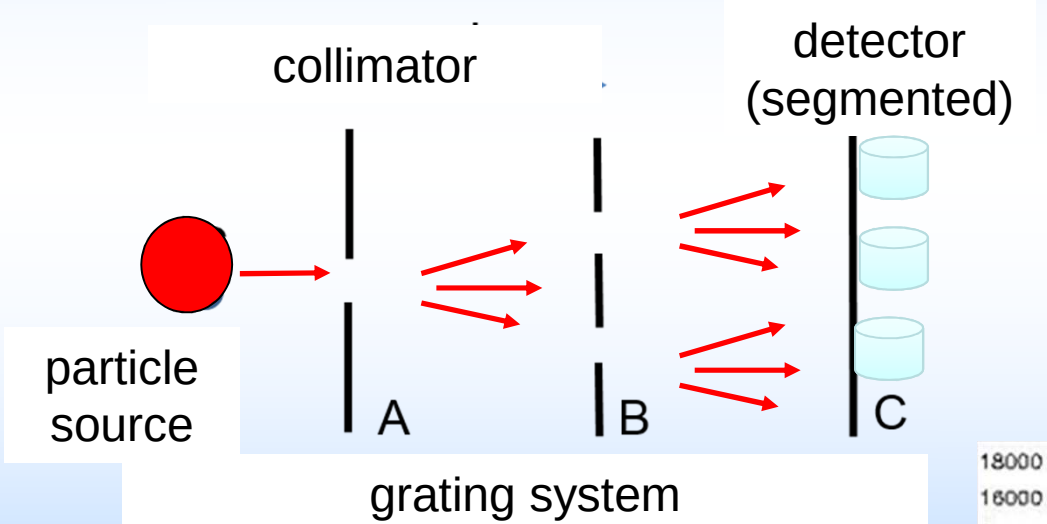


Exp. Results from Cassidy et al, PRL108, 043401 (2012)

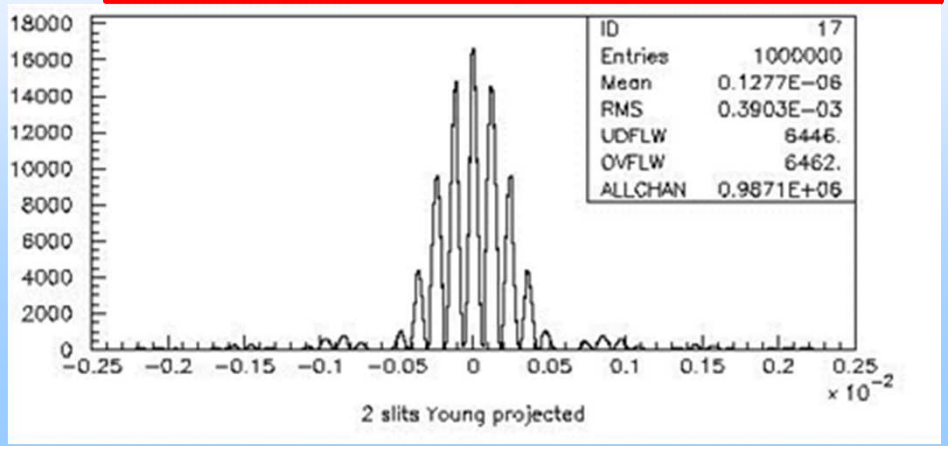
Quantum Interferometry with Ps

Antimatter quantum waves?
CPT symmetry ⇒ yes!

schematic of an interference experiment



Proposed Fraunhofer (far field) scheme with positrons:
continuous source ~ 10 KeV,
λ_{dB} ~ 0.01 nm,
slits ~ some micron,
length ~ meters
fringes ~ micron



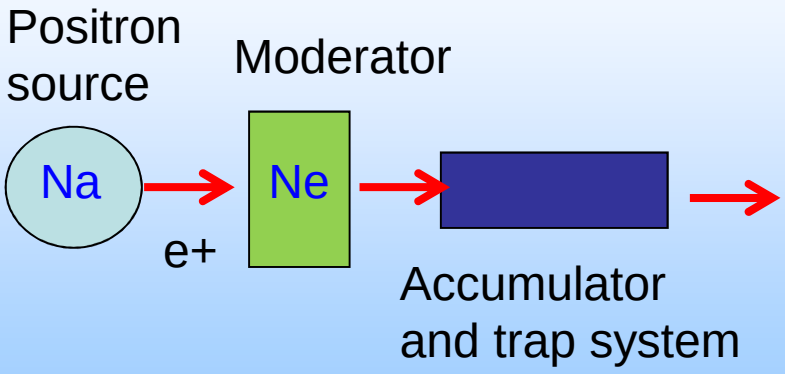
Problems: well collimated beam, stray fields (also Earth magnetic field), interaction slit - e+ , very low rate …

With Ps atoms ?
(a symmetric matter – antimatter system)

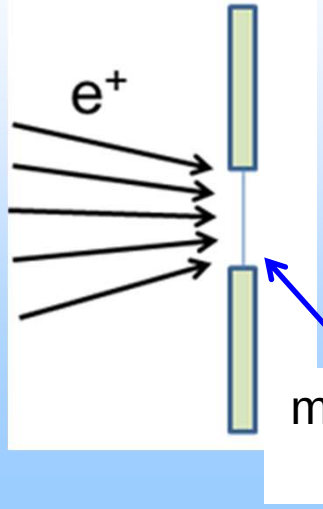
Problems: neutrality (no guiding), coherence of the Ps beam, o-Ps 142 ns living (free path ~ a few cm), detection (not ionizing particle)

Very challenging experiment!

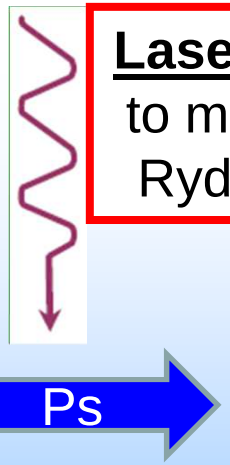
Bunched mode



Ps production in transmission configuration

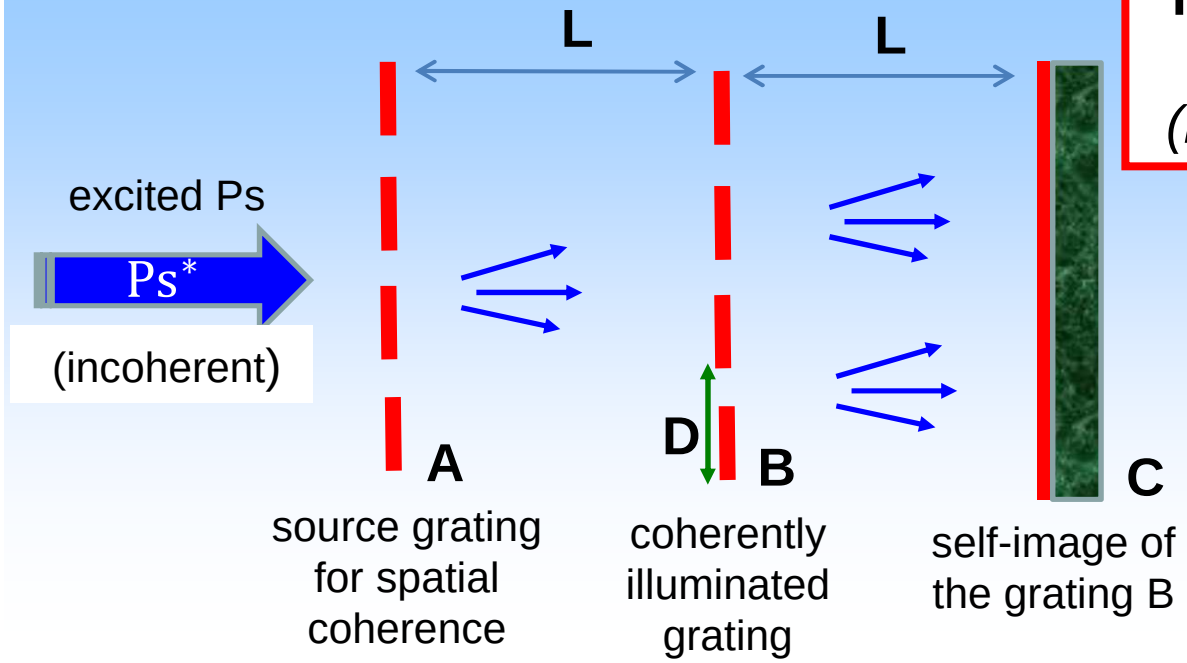


Laser excitation to metastable or Rydberg states



not collimated Ps bunch

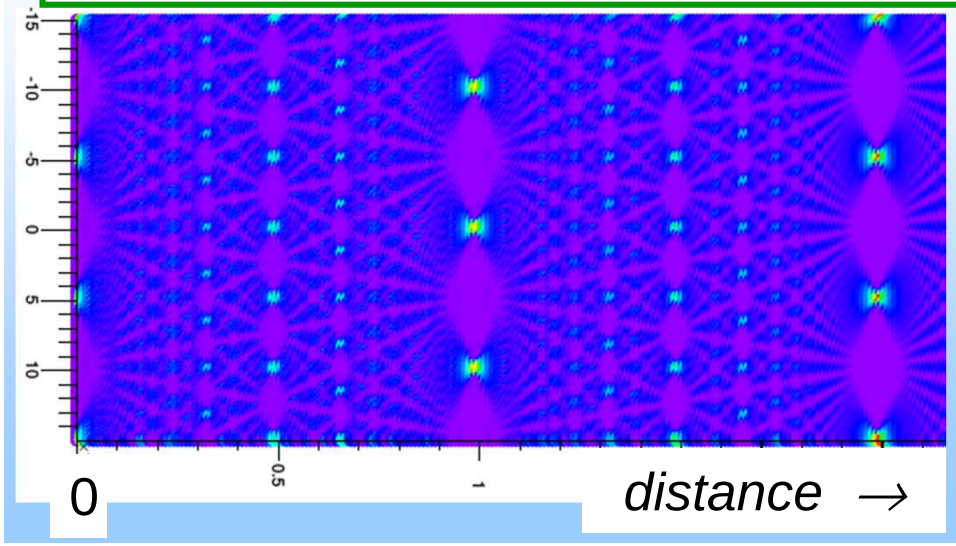
The core of the experiment:
Talbot-Lau configuration
(near field – Fresnel scheme)



$$L = D^2/\lambda$$

Talbot length: condition for high contrasted fringes on C

Talbot carpet: pattern of self-images

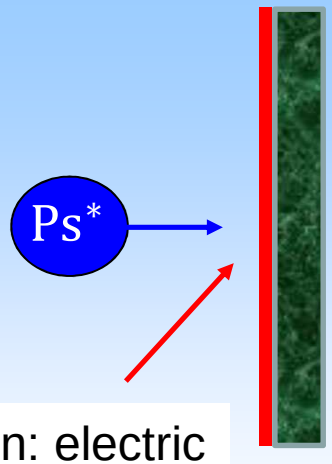


For Ps:
v ~ 10^5 m/s
λ_{dB} ~ 3.6 nm,
L (Talbot length) ~ 1 cm
grating period ~ 6 μm,

S.Sala, F.Castelli, M.Giammarchi, S.Siccardi and S.Olivares, submitted to J. Atom. Phys. B

Detection system:

emulsions sensible to charged particles → Ps* must be ionized



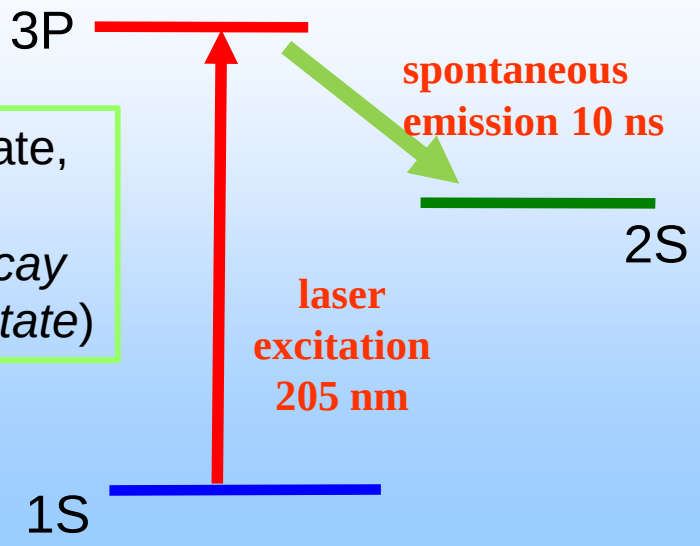
Ionization: electric field or laser ?

emulsion

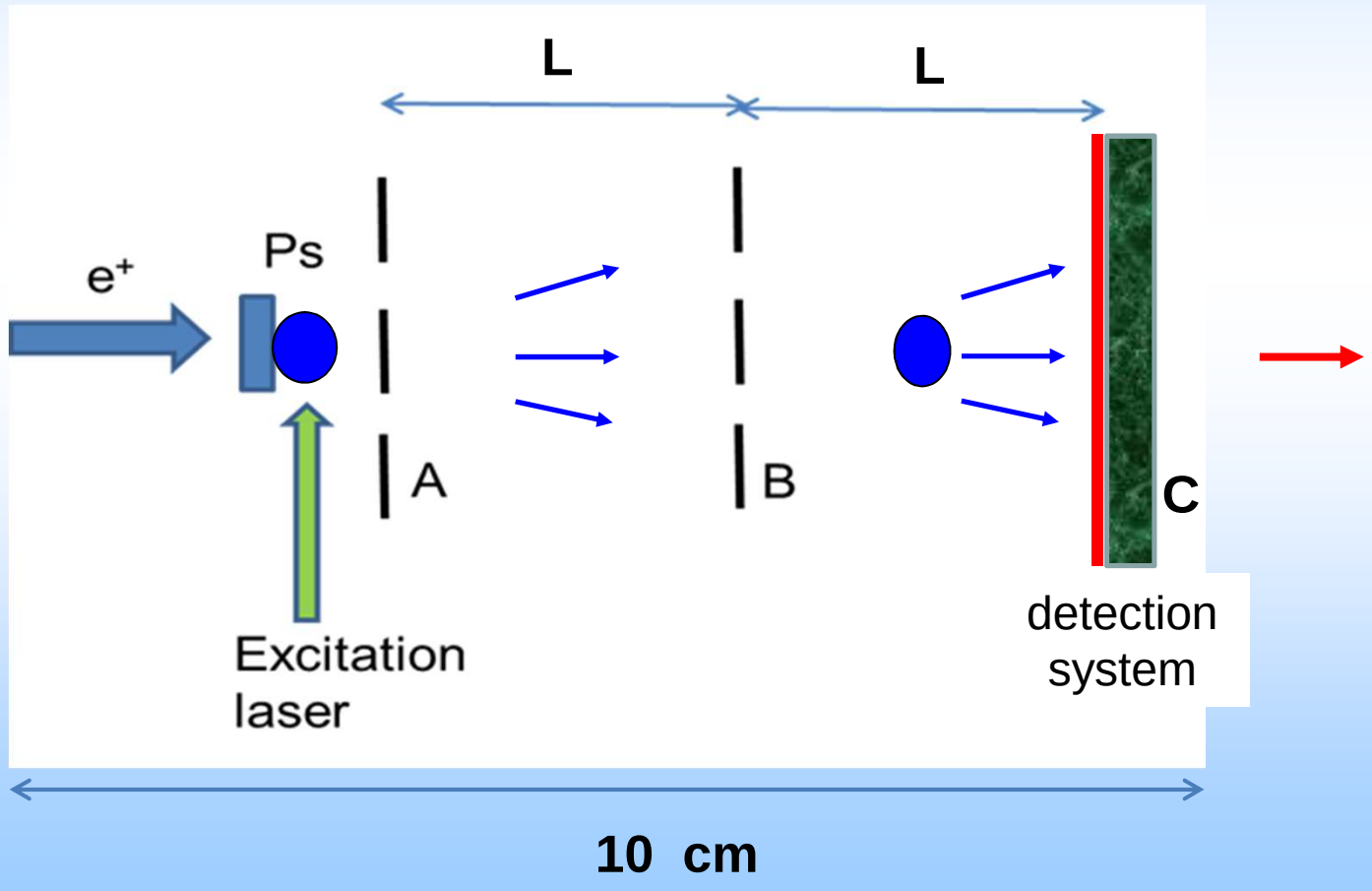
Working Ps states

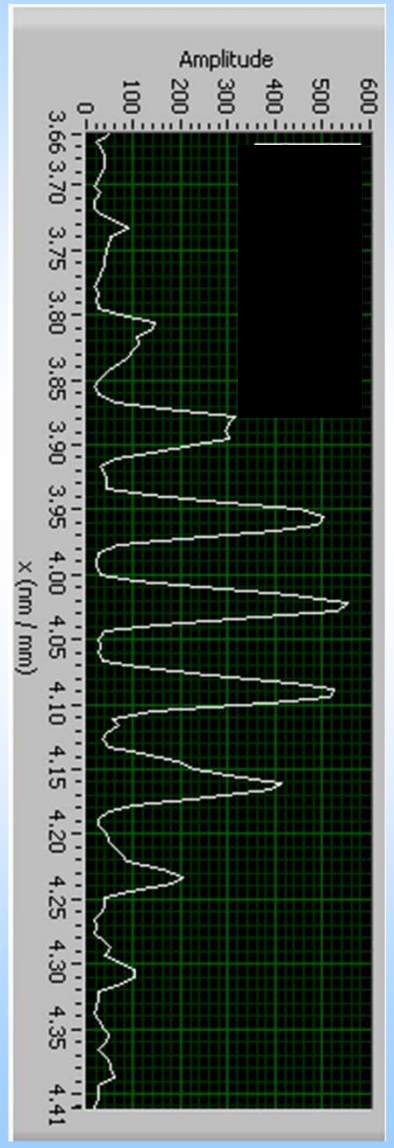
Rydberg, μs to ms lifetime
but : possible interaction with material gratings, measure of atomic dimensions?

Metastable 2S state, lifetime 1.5 μs (*spontaneous decay from n=3 excited state*)

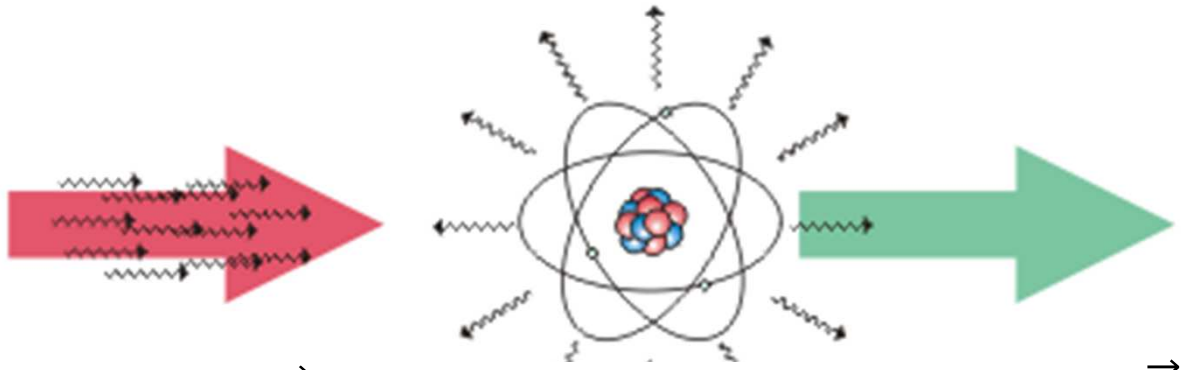


Possible final scheme for Ps atom interferometry





Laser Cooling of Ps



$\Delta\vec{p} = \hbar\,\vec{k}$

Incident photons absorbed: momentum transfer = $\hbar$k

$\Delta\vec{p} = 0$

Spontaneous emission: total momentum transfer = 0

$\Delta\vec{p}_{net} = \hbar\vec{k}$

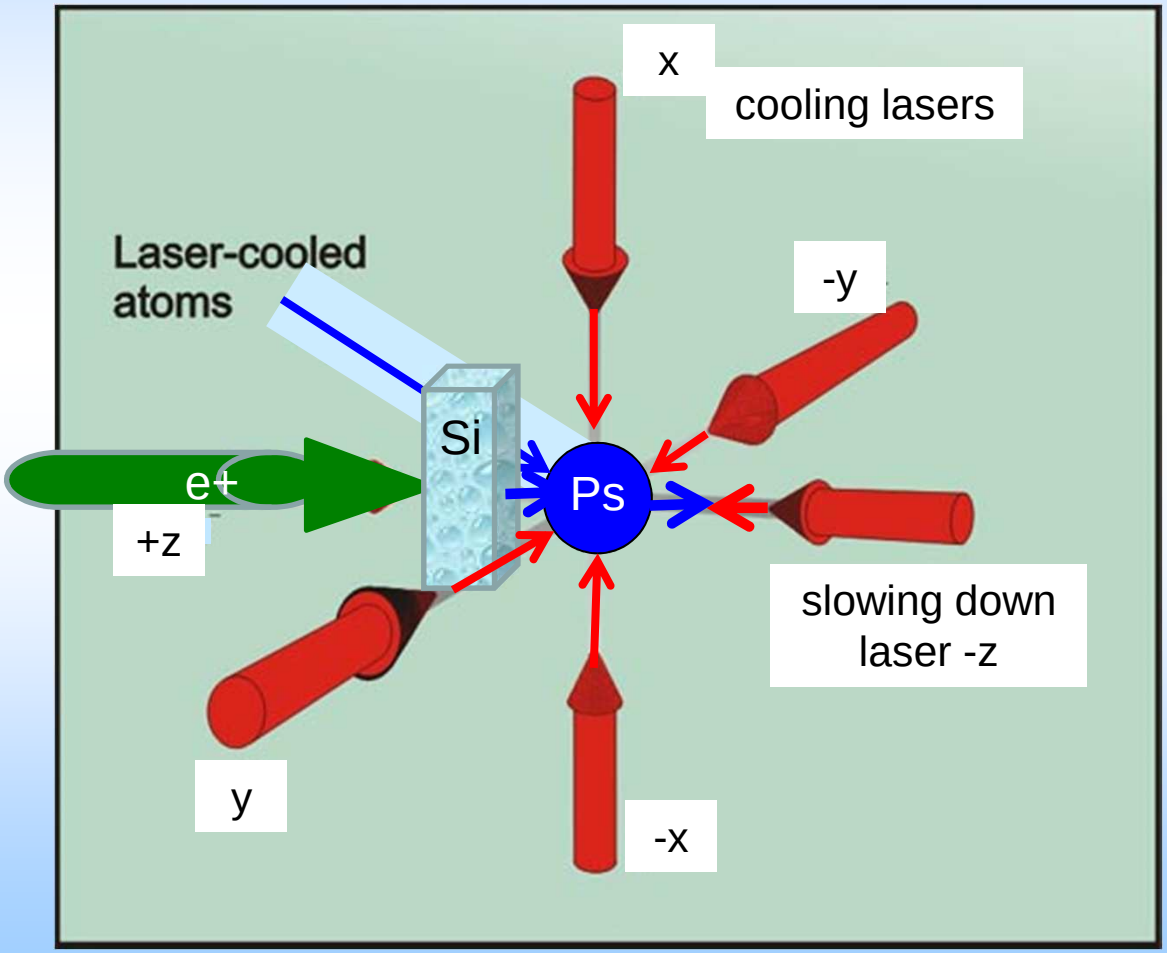
Net momentum transfer to atom in direction of laser

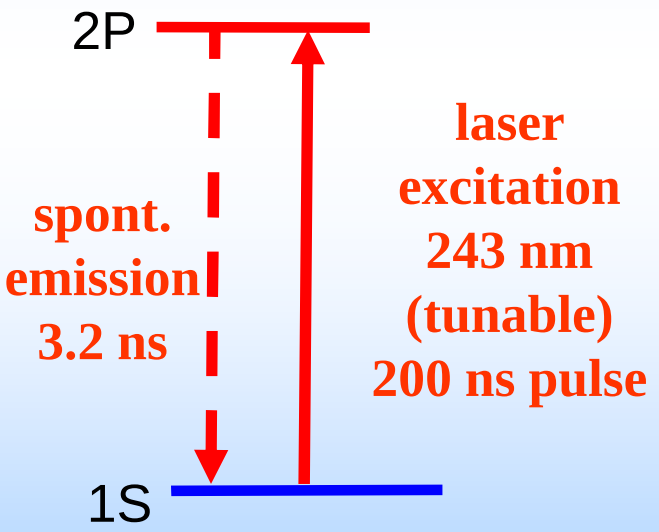
velocity reduction and
Temperature lowering
Ps recoil limit: 0.1 K

- ✓ Reduction of Doppler effect
- ✓ High sensitivity spectroscopy
- ✓ High density cloud of cold Ps
- ✓ Bose Einstein Condensation
- ✓ Gamma-ray laser
- ✓ Gravity studies

A proposed scheme for Ps laser cooling

Time for cooling limited by o-Ps decay time:
32 cycles of absorb./emiss.
6.4 ns length
T final ~ 0.1 K



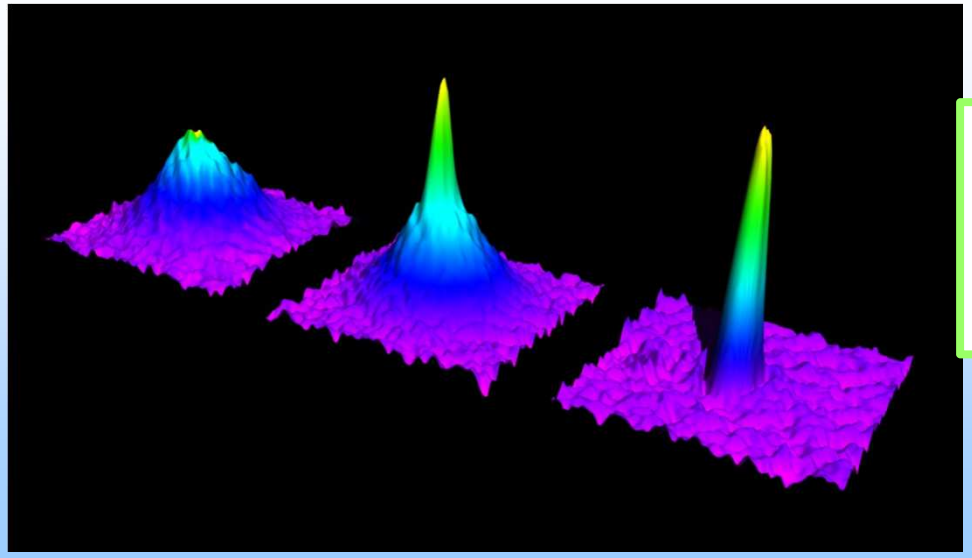


T.Hirose et al, J. Phys. Soc. Japan, 70 3255 (2001)

Bose Einstein Condensation with Ps

Ps atoms:
weakly interacting bosons
with very low mass

BEC at (relatively) high temperature
(>> alkali atoms)
with N/V ~ $10^{16}\ cm^{-3} \Rightarrow T_C \sim 1\ K$



Example of cooling and condensation in momentum space (from exp. with alkali atoms)

A.P.Mills, D.B.Cassidy and R.G.Greaves,
Mat. Sci. Forum 445, 424 (2004)

511 KeV γ - ray lasing

condensed p-Ps (singlet state)

0.125 ns

Collective annihilation decay

exp. gain

Self-amplifying spontaneous emission

long-living condensed o-Ps (triplet state, spin polarized) at 10 K

0.2 THz pulse

10 μm

Cigar shaped o-Ps condensate

1.5 cm

N γ ~ 10^7

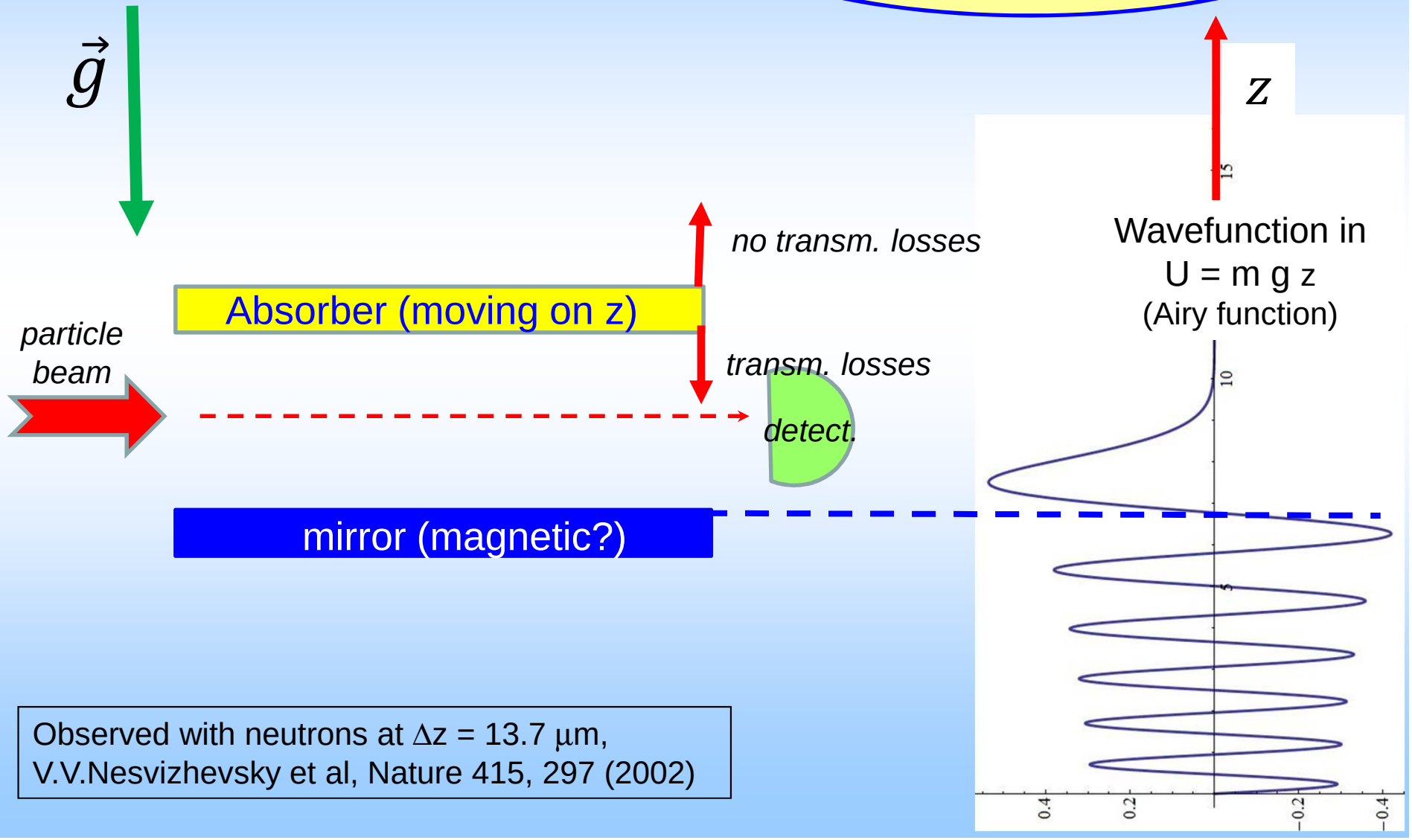
N γ ~ 10^7

$N/V \sim 10^{20}\ cm^{-3}$; $T_C \sim 100\ K$

H.K.Avetissian et al, Phys. Rev. Lett. 113, 023904 (2014)

Gravitational studies with Ps (I)

Observation of quantum gravitational states

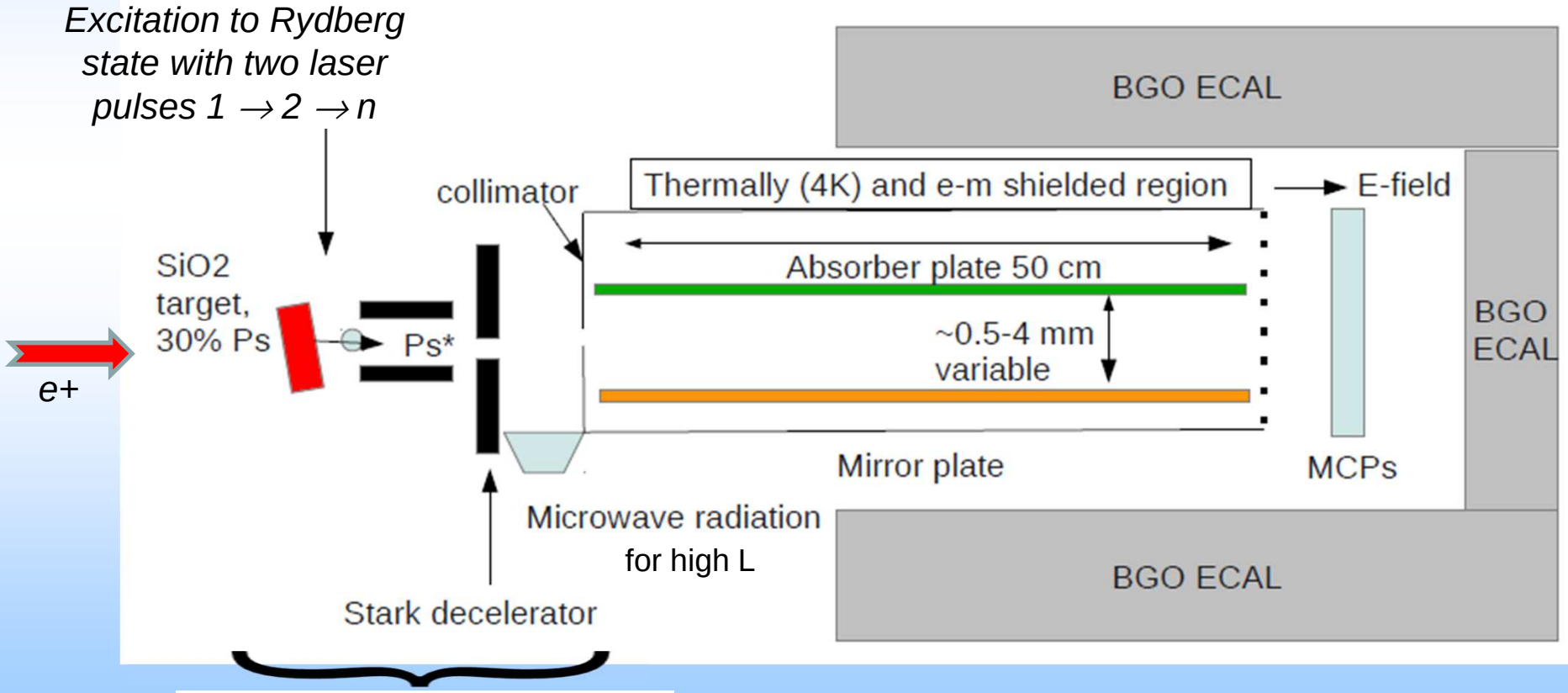


Observed with neutrons at Δz = 13.7 μm,
V.V.Nesvizhevsky et al, Nature 415, 297 (2002)

A proposed scheme for observation of Ps gravitational states

for Ps: Δz = 1.3 mm,
energy level = 0.13 peV
$\rightarrow$ observation time (from uncertatinty) ~ 4.5 ms >> lifetime

it is necessary to use Rydberg states with high angular momentum!



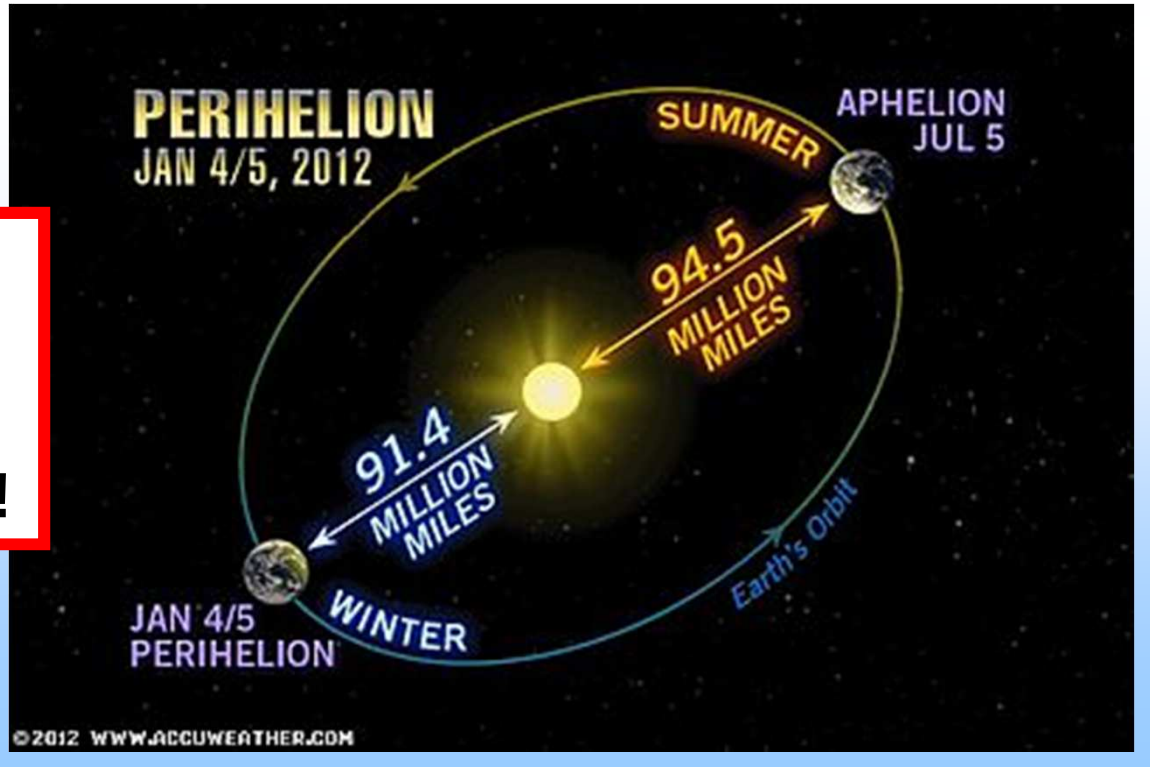
P.Crivelli, V.V.Nesvizhevsky, A.Yu.Voronin, from ArXiv

Gravitational studies with Ps (II)

Ps: a symmetric matter-antimatter system
CPT and WEP?

Observation of annual variation of 1S – 2S transition

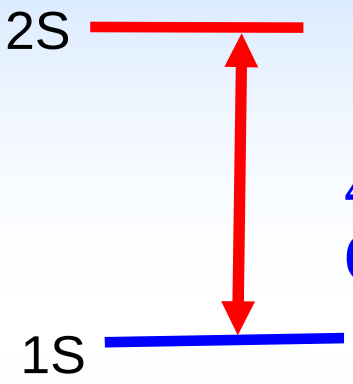
gravitational red shift from potential variation on > 3 MKm



expected relative shift of the line:
with WEP $3.2 \cdot 10^{-10}$
with antigravity *no shift* !

A proposal: comparison with 1S - 2S in H line
(two photon 243 nm, known accuracy ~ 10^{-14},
contributes from proton dimension, hypherfine shift etc.)

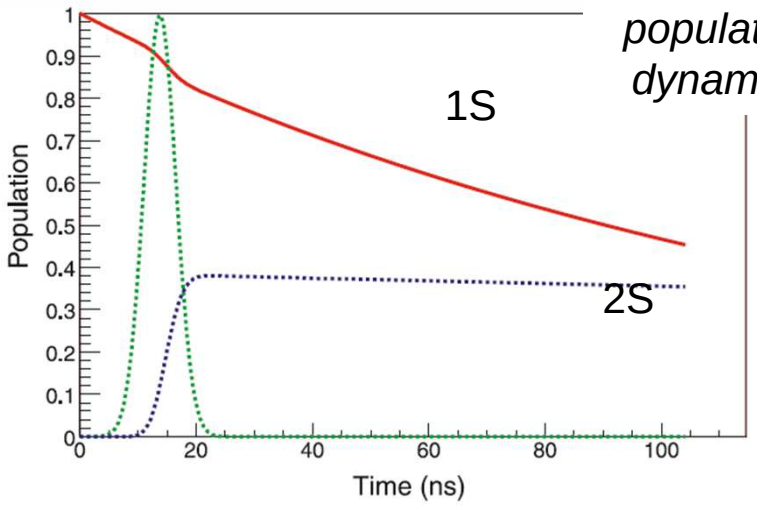
Ps: leptonic atom, only QED



Doppler free Two photon transition
486 nm pulse, 300 mW
(frequency doubling of 972 diode laser)

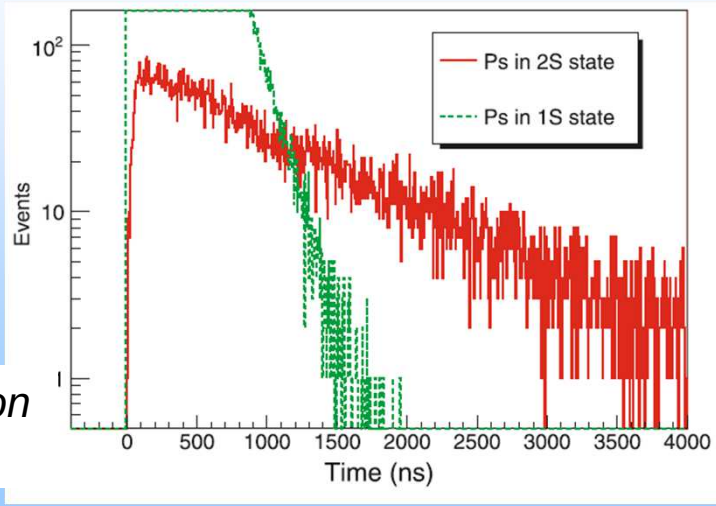
known accuracy ~ $2.6 \cdot 10^{-9}$
(to the α^6level)

desired accuracy ~ 10^{-10}
(to the α^7level)



population dynamics

P.Crivelli, G.L.Cesar, U.Gendotti,
Can. J. Phys. 89, 29 (2011)

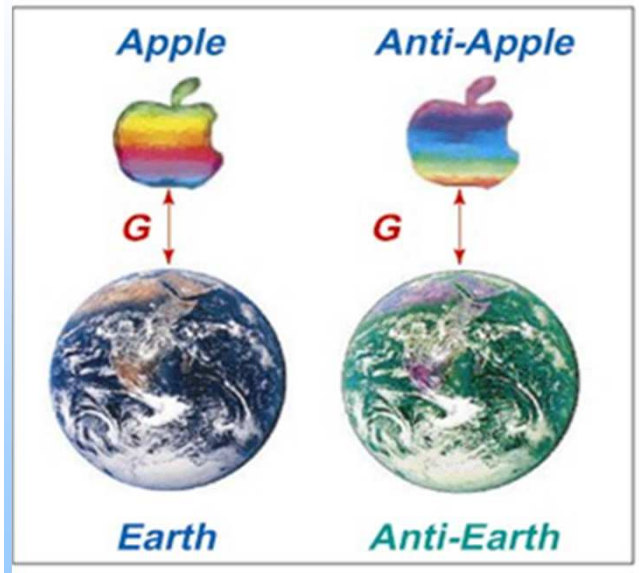


annihilation rates

Gravitational studies with Ps (III)

Ps: a symmetric matter-antimatter system
CPT and WEP?

Observation of Ps free fall in earth gravitational field



slow beam of Ps atoms
~ 100 m/s horizontal speed

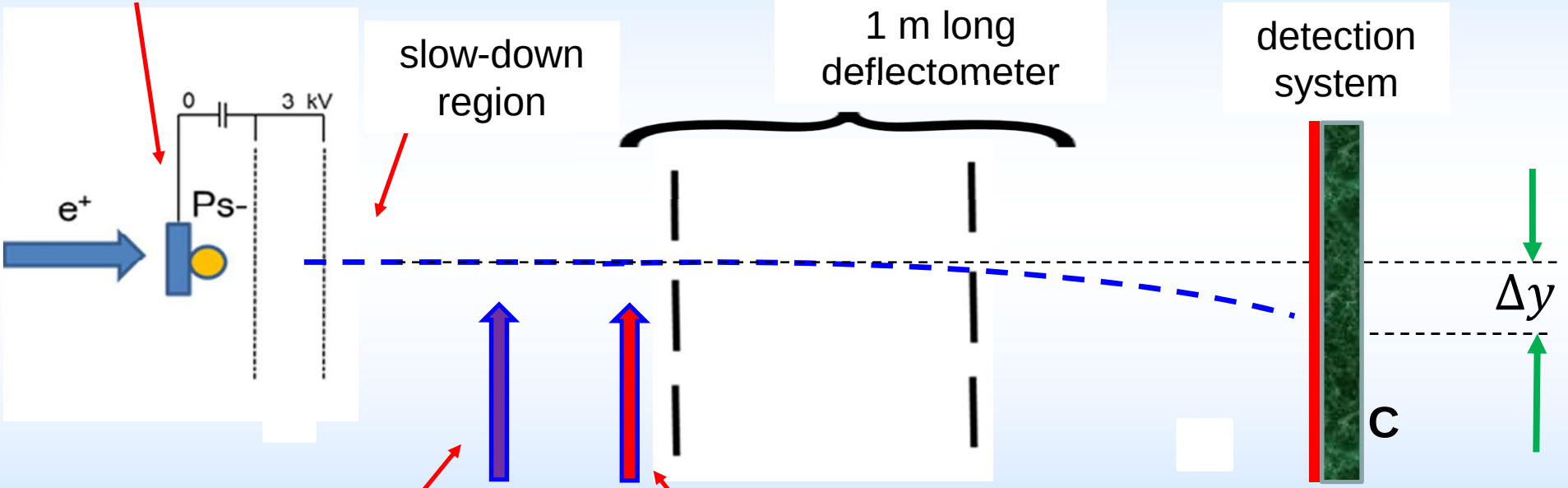
Rydberg states to increase lifetime

a set of gratings (moiré deflectometer) to measure vertical fall ~ 100 μm

Creation of a slow Ps beam ~ 100 m/s: starting from Ps negative ion!

$\Delta y \sim 450$?m

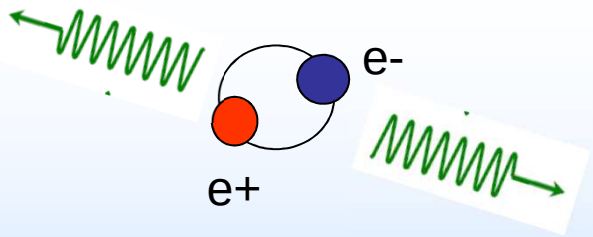
Formation of Ps^- (negative ion) from silica Cs coated



Quantum entangled states from Ps

QM violates Bell'inequalities (based on local realism)

some violation of Bell's – experimental demonstrated in double atomic decay

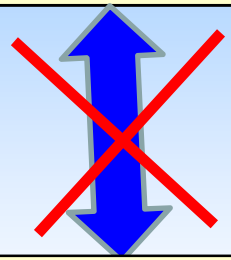


decay of p-Ps:
source of two entangled space-separated particles
(proposed in 1969)

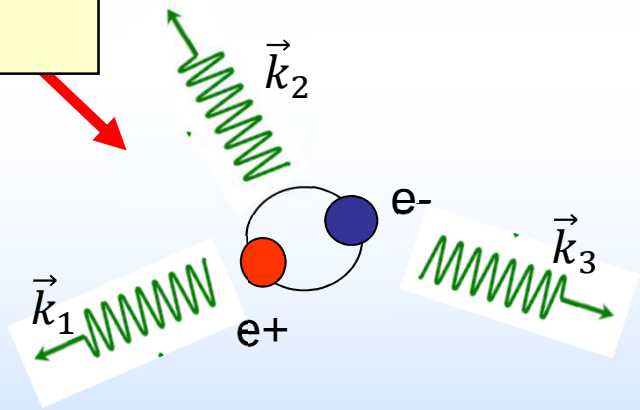
$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|+\,+\rangle - \ |-\,-\rangle)$$

maximal violation of Bell's !

quantum correlations (EPR correlations) on spatially separated systems



local realism



decay of o-Ps:
source of three entangled space-separated particles
(proposed in 2001, ~ GHZ state)

$$|\Psi\rangle(\vec{k}_1, \vec{k}_2, \vec{k}_3) = \ \ldots.$$

Final considerations

- **Positronium is an useful tool for studying fundamental physics topics**
- **a variety of experiments has been proposed**
- **and only in a very few case performed** 

What Next ? - Florence 2015