Possibilities for a Bose-Einstein Condensed Positronium Annihilation Gamma Ray Laser

Allen Mills, Jr.,

University of California Riverside

in collaboration with

David Cassidy and Harry Tom (UCR)

Rod Greaves - *First Point Scientific*

Work supported in part by the National Science Foundation PHY-0140382, DMR-0216927, PHY-0537431 and PHY-0555701

What does it take to deter a 1 km diameter asteroid?

- Gravitational binding energy

$\mathrm{m} = 10^{12}\,\mathrm{kg};\ \mathrm{v}_{esc} \approx 5\,\mathrm{cm/s}$

$$\frac{m^2 G}{r} = 150\,\mathrm{GJ} = 30\ \mathrm{Tons\ of\ TNT}$$

- Deflection by

$\Delta\mathrm{m} = 0.01\mathrm{m};\ \mathrm{v}_{esc} \approx 3\,\mathrm{km/s}$

$$\theta = \frac{\Delta p}{p} = 10^{-3}$$

$\approx 10\ \mathrm{MTons\ TNT}$

- Solar energy in 1 year

10 MTons TNT

- Impact energy

$$\tfrac{1}{2} m v_{orbit}^2 = 100\ \mathrm{GTons\ TNT} = 1\ \mathrm{Tambora}$$

- Annihilation gamma ray laser (10^{19} e^{+})

$1\,\mathrm{MJ} \approx 0.001\,\mathrm{Ton\ TNT}$

(Extrapolated by 10 orders of magnitude)

You can't hit a 1 km diameter asteroid from earth

•Angular size of target

$$\frac{1\text{km}}{1\text{au}} = 6\times10^{-12}\,\text{radians}$$

•Angular resolution of laser

$$\frac{\lambda_C}{1\mu\text{m}} = 2\times10^{-6}\,\text{radians}$$

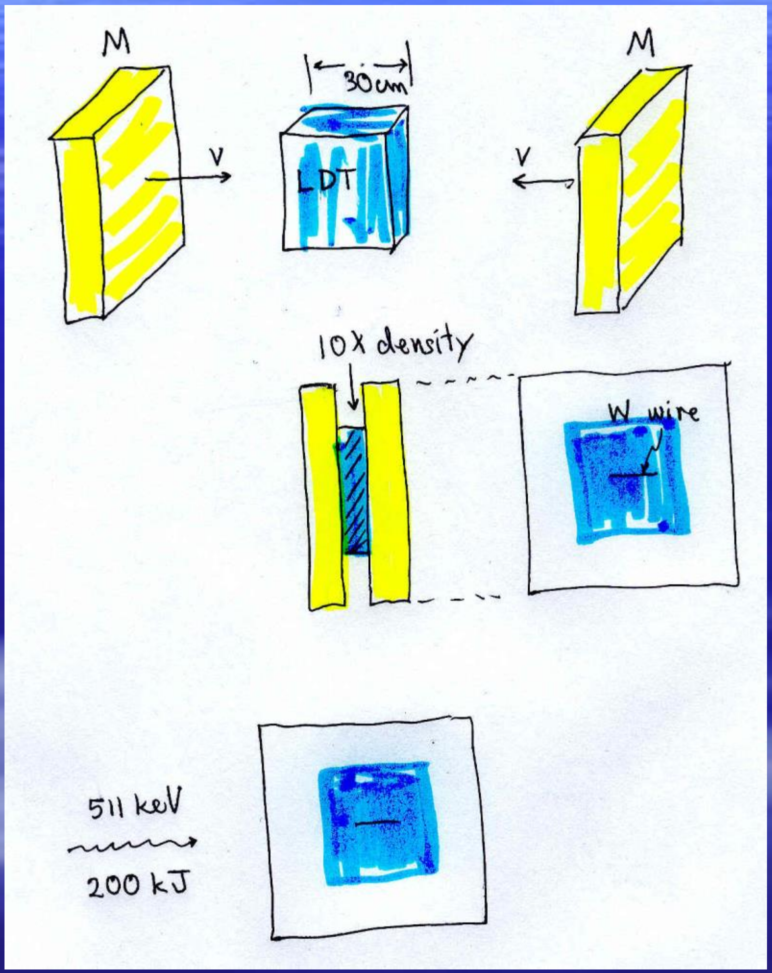
So what is a little gamma ray laser good for?

Fusion ignition without actinides for

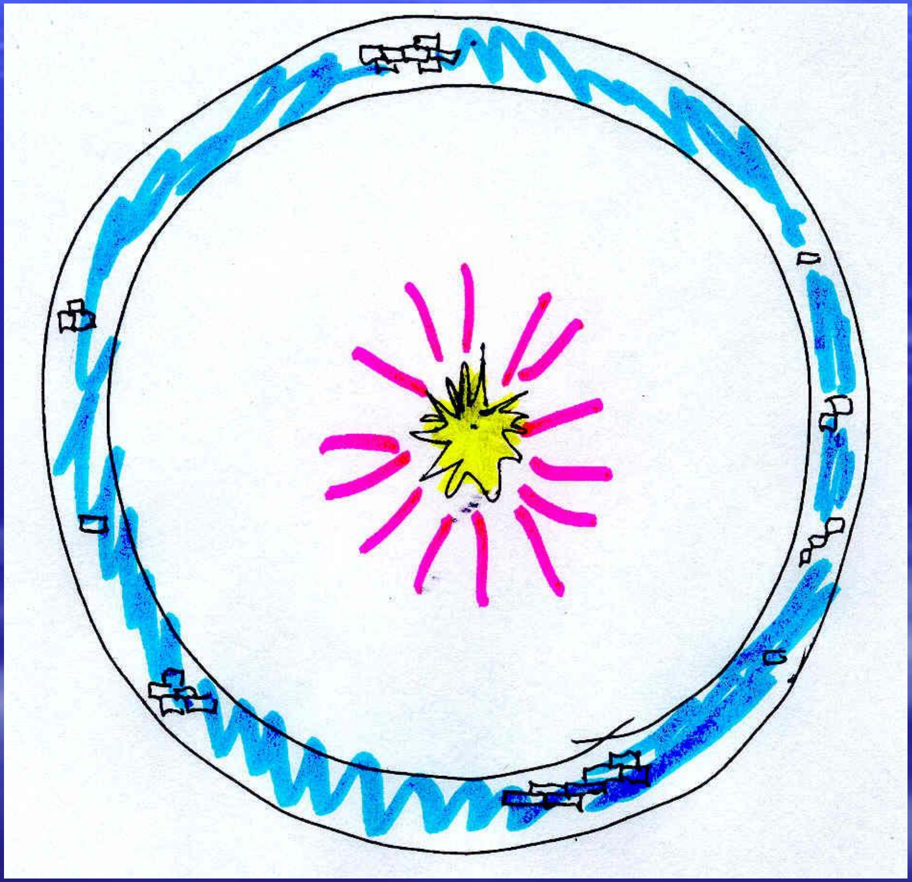
- Providing clean impulses for deflection
- Fusion power plants back home

Some of the Components

Inertial Compression



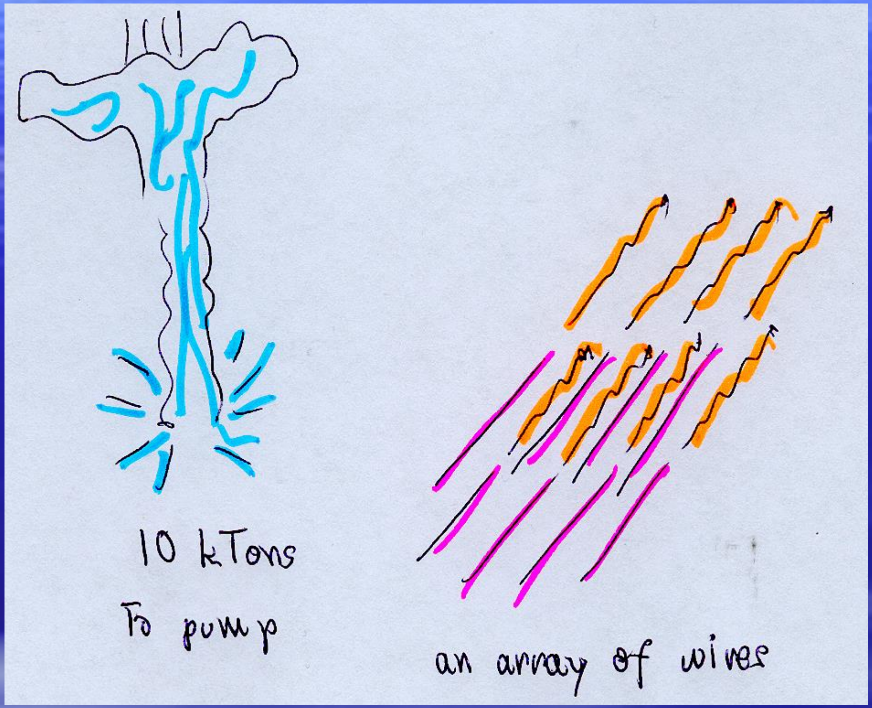
Gamma ray laser ignition



Containment and heat extraction

Ordinary X-Ray laser

Energy storage lifetime is pico seconds



Laser output is at most 1 keV per atom = 1 GJ/kg

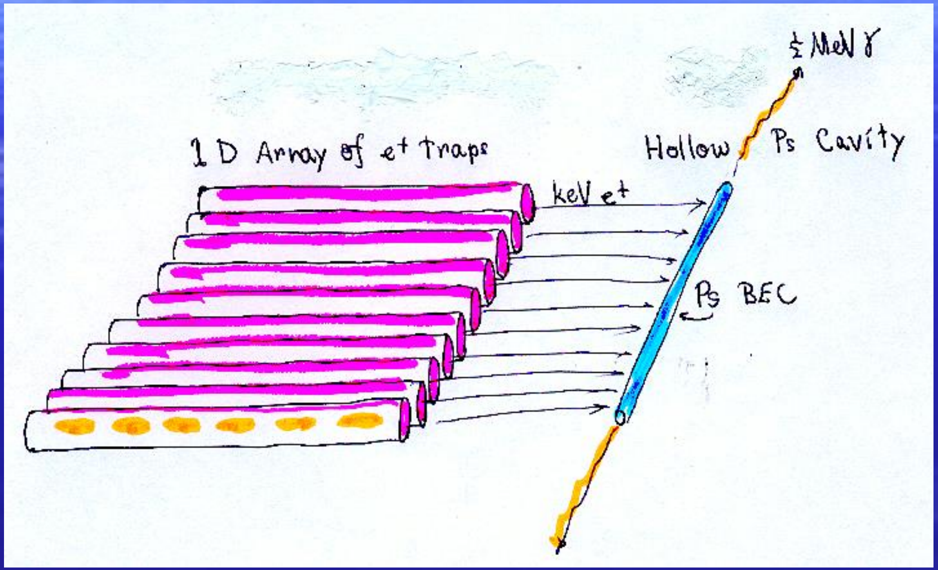
5 kg or wires →1 Ton TNT

Great efficiency (10^{-4})

But you can only fire it once because there is no energy storage.

Annihilation γ-Ray laser

Energy storage lifetime is days



Laser output could be 1 MJ for 10^{19} Ps atoms

OK wall plug efficiency (10^{-5})

You might fire it repeatedly because the positrons are stored at eV's and assembled slowly (in 100 ns).

1 m^2 1D array 300×300 1 mm^3 traps = 10^{16} e^+ = 1kJ (in a 5 T field)

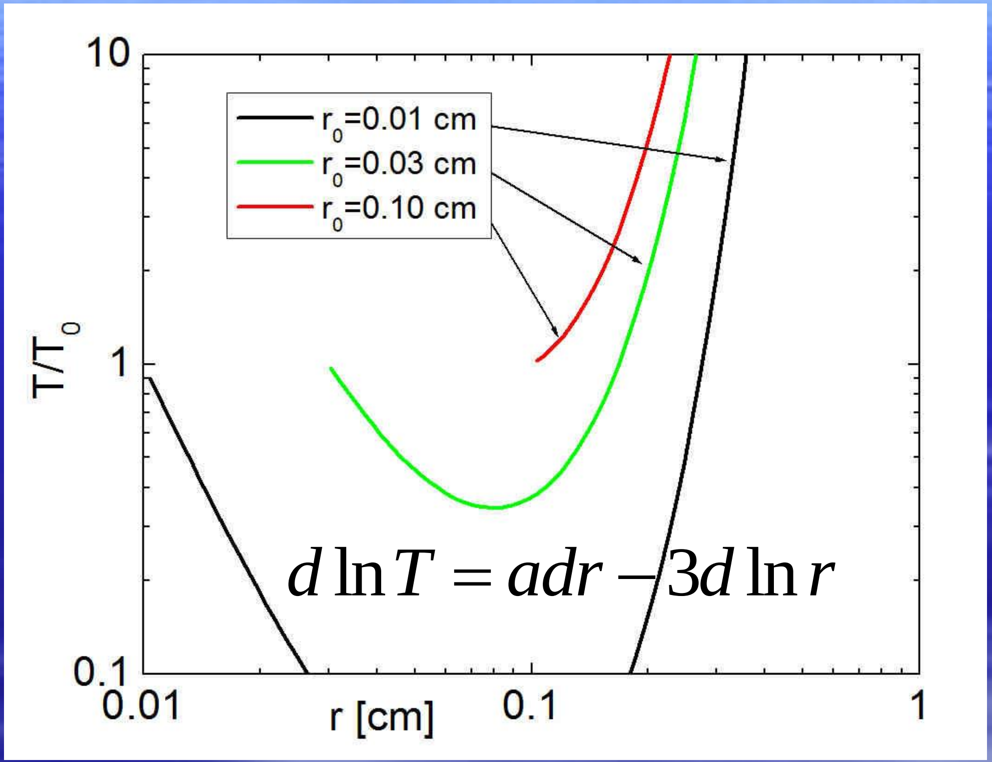
1 m^3 array = 1 MJ

Preliminary estimate of ignition of a DT reaction using a 0.5 MJ annihilation gamma ray laser pulse.

Model: Spherical plasma

Differential equation for change dT due to locally deposited energy dE is due to one 3.5 MeV alpha particle per DT reaction as burn radius increases dr: $d\ln T = adr - 3d\ln r$.

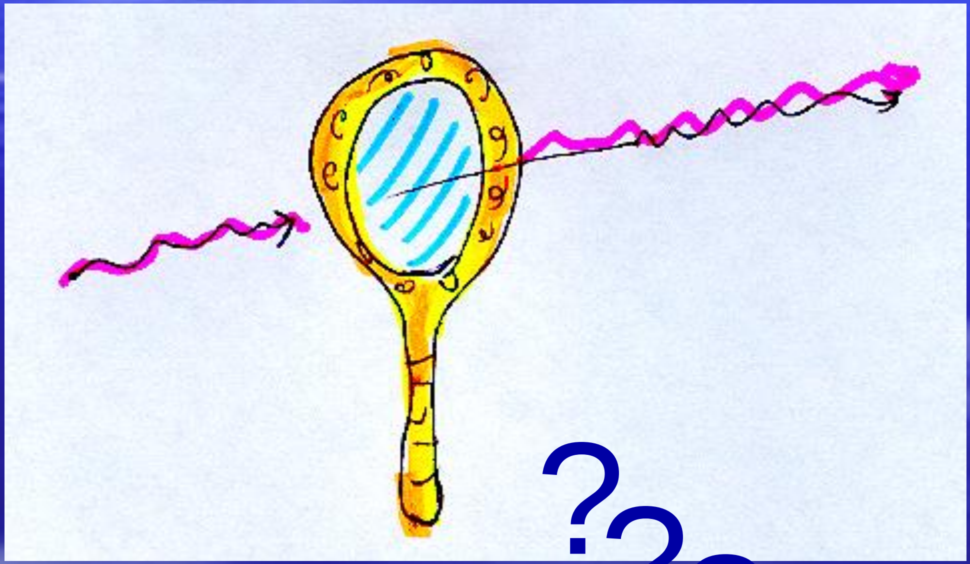
Solution is $T/T_0 = (r_0/r^3)\exp\{a(r-r_0)\}$



The deposited energy required for ignition at T_0= 20 keV is about 0.5 MJ for an initial plasma radius of 300 μm. By the time the burn has expanded to 3 mm radius, the energy yield will be 5 GJ or 1 ton of TNT

Hey, wait a minute!

How can you make a laser with no mirrors?



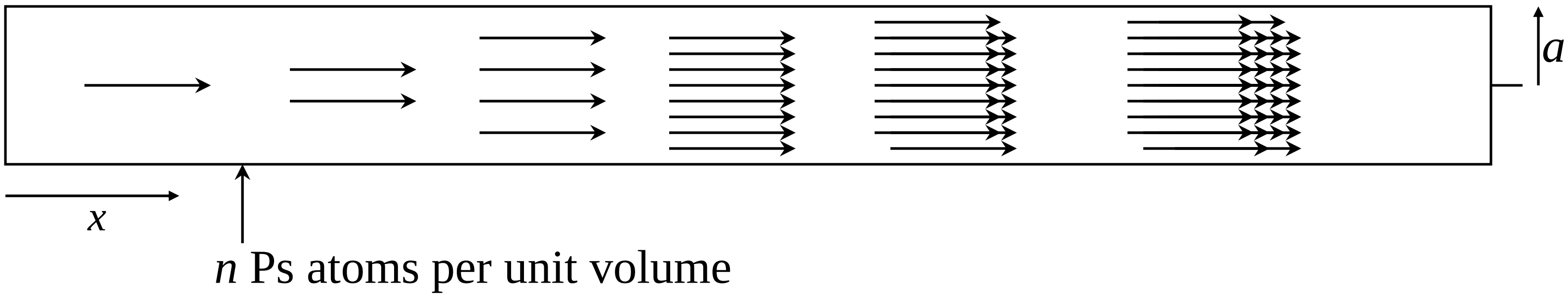
???

Mirrors are only to make an effectively long gain medium.

A long soda straw filled with excited atoms makes a Dicke super-radiant laser without mirrors.

Stimulated emission

P.A.M. Dirac (1930)



•*For Ps at rest and photons exactly on resonance*:

$$\sigma_s = \lambda^2/2\pi = 0.937\times 10^{-20}\text{cm}^2.$$

This cross section is at the unitarity limit, i.e. σ_s is as big as it can possibly be!

•The Ps has to have very slow velocities so that the Doppler shift of the annihilation photons is less than the line width $v/c < \Delta E/E = \pi\alpha^5 = 6 \times 10^{-11}$.

•The **only possibility** is for the Ps to be in the ground state of its container, i.e. in the **Bose-Einstein condensed state**, as pointed out by Liang and Dermer.

•Need about 10^{13} Ps to see stimulated emission.

Can we get there?

We are about to make the first Ps BEC.

We have to extrapolate by ~6 orders of magnitude to make the first 1 J laser.

So far everything we know has been discovered by single investigators.

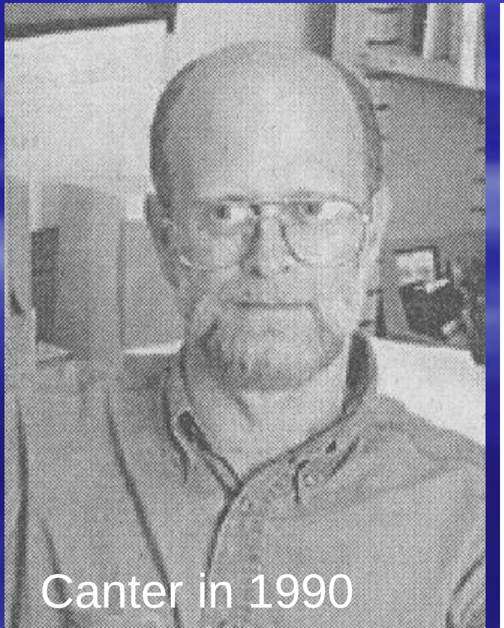
This could be a sufficient knowledge base to allow one to move more rapidly.

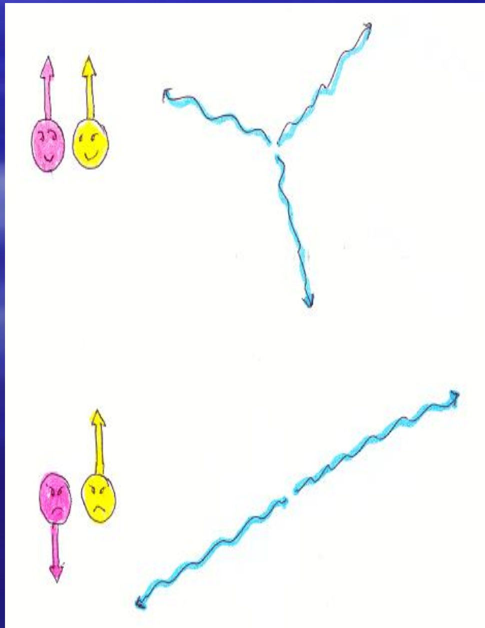
Positronium History

- 1946 J. A. Wheeler – Polyelectron series, e+, Ps, Ps^-, Ps_2, Ps_4, ...
- 1951 M. Deutsch – Ps discovered
- 1972 K. F. Canter – Practical slow positron moderator
- 1981 APM – Negative ion Ps^- formed
- 1985 C. M. Surko – Positron trapping and storage
- 2007 D. B. Cassidy & APM – Ps_2 produced

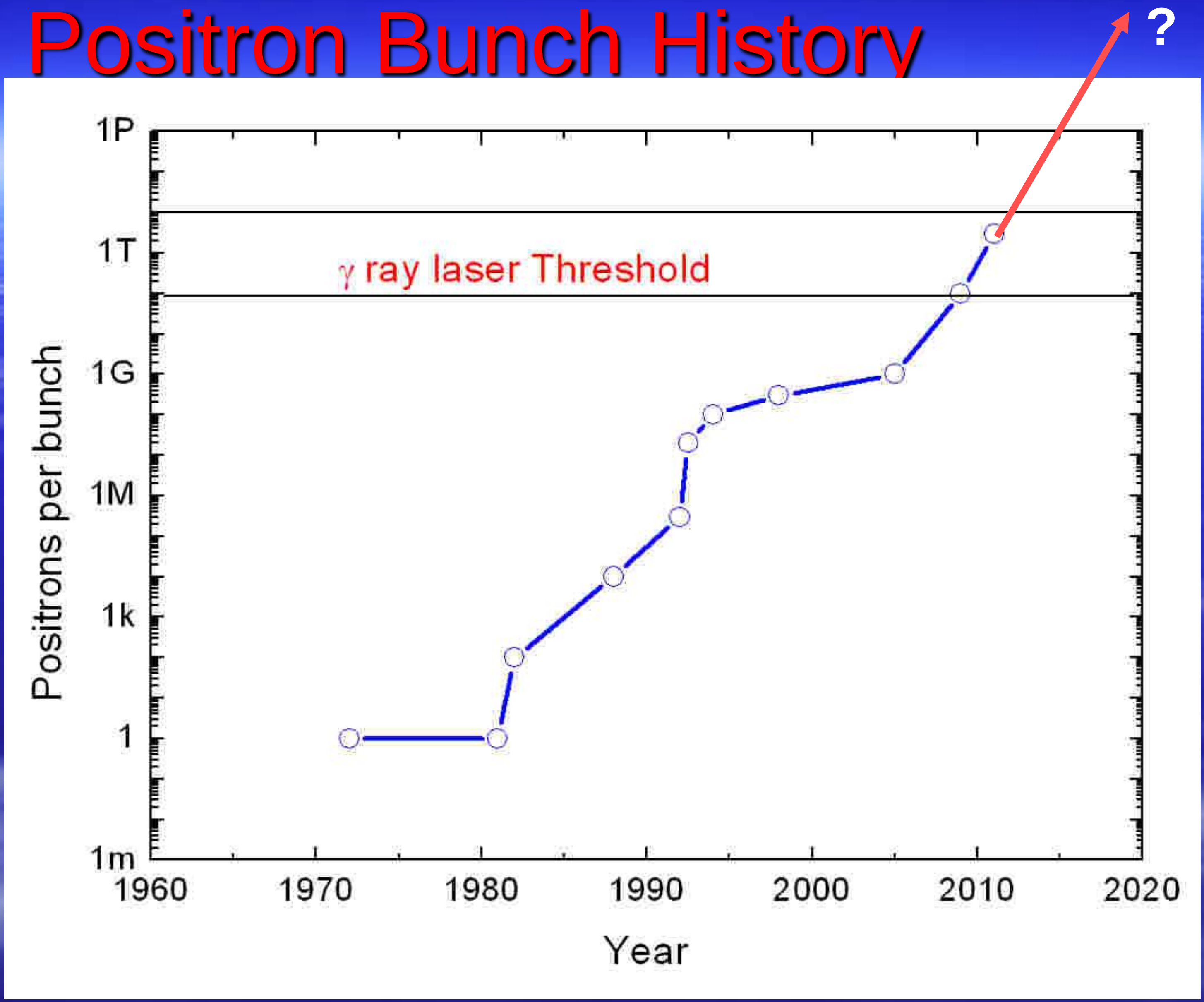

Wheeler in 1938


Deutsch in 1954


Canter in 1990



Positron Bunch History



In a 5 years we could have a 1J γ laser & 1 MJ by ~2020.

We are working on making more e+ to fill the traps

Scalable N-13 and Kr-79 positron sources

Recently we made Ps_2 – so what?

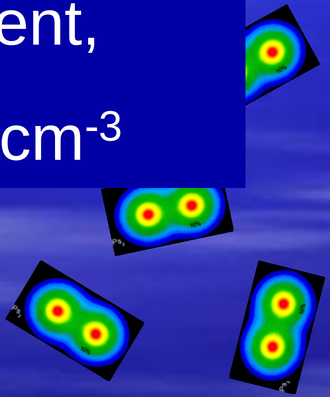
This represents a high density milestone at which

Ps atoms were made to interact with each other for the first time.

Dense Positronium

Making Ps_2 marks a new era in Ps physics

- Ps densities > 10^{15} cm^{-3} [20 mtorr], an increase in density by 10^{11} since the 1992 1S-2S experiment,
- A stepping stone to the BEC threshold 10^{18} cm^{-3}



Current NSF supported program at UCR is working toward:

- Spectroscopy of Ps_2
- Laser cooling of Ps as a prelude to BEC and 1S-2S

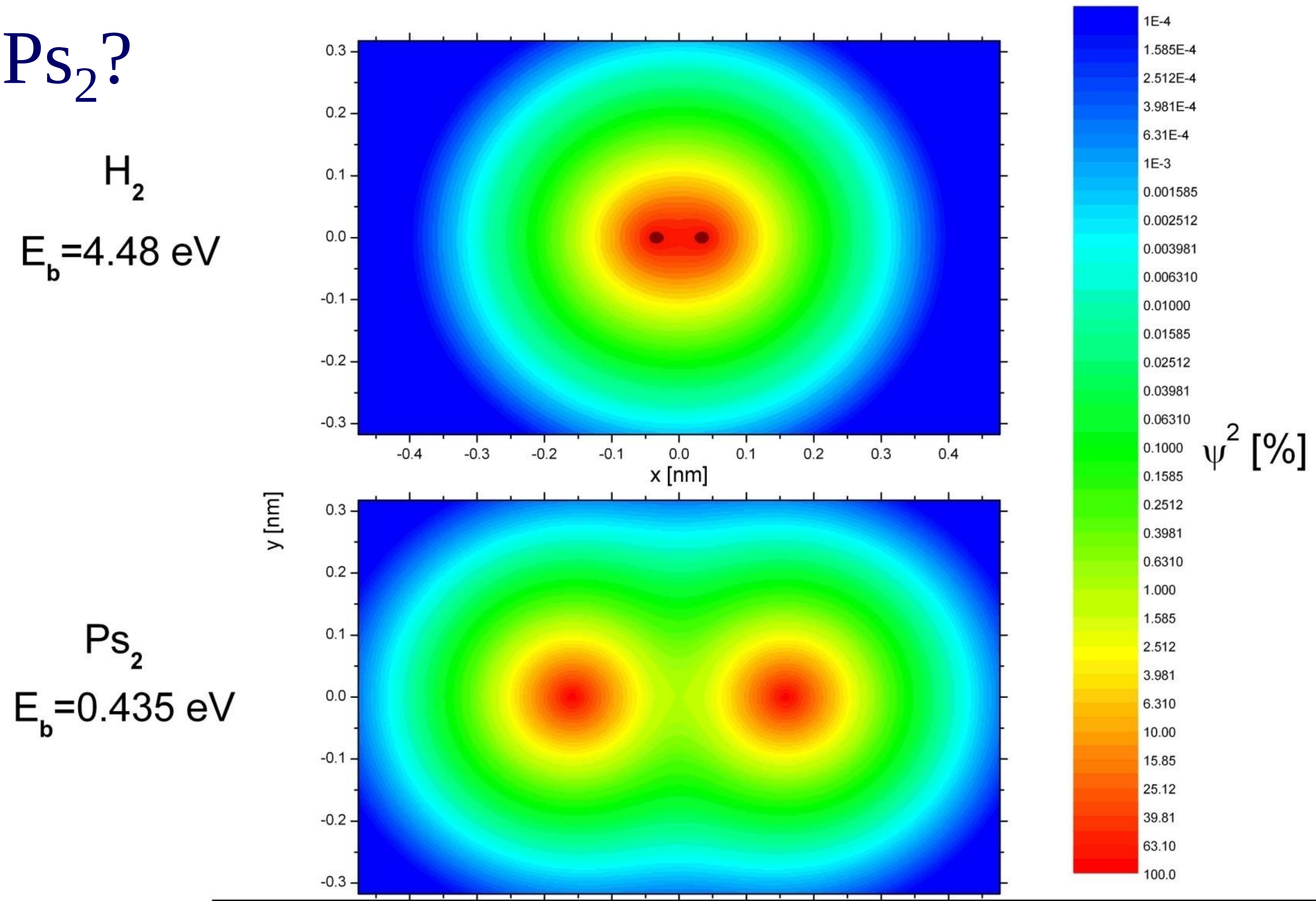
Significance

For many years people have discussed the annihilation gamma ray laser.

Now maybe we have the technology to actually make one.

Wheeler's quadrielectron $e^+e^-e^+e^-$ (1946)

What is Ps_2?



Upper frame: Approximate snapshot of a central slice of the square of the sum of the electron wavefunctions of H_2 when the two protons happen to be at their equilibrium separation and on the horizontal axis.
The dark red spots indicate the locations of the two protons.
Lower frame: Same, but for Ps_2 at an instant when the centers of mass of the two positronium atoms happen to be at roughly their mean separation and on the horizontal axis.

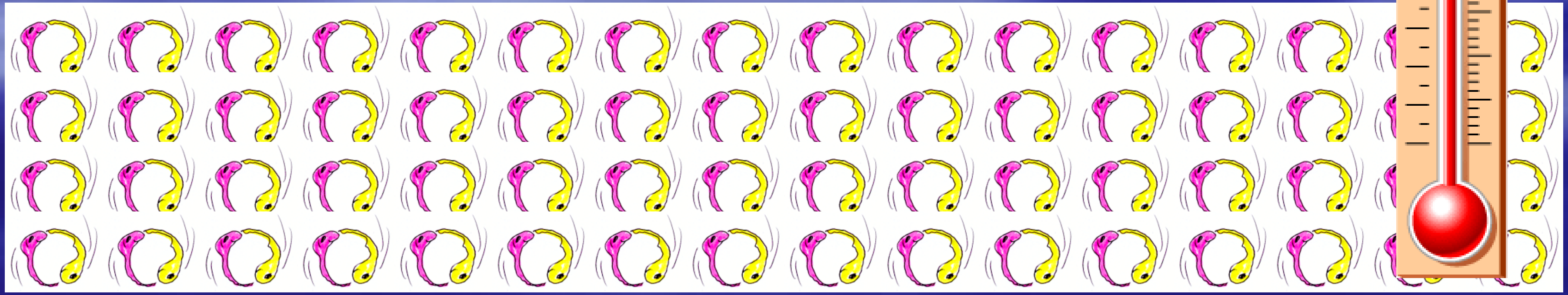
What is a Bose Einstein Condensate?

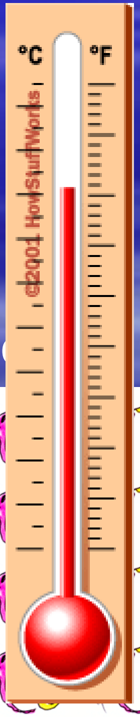
When a good fraction of all the particles are in the unique ground state of their container.

Ps BEC 10^6 laser-cooled Ps atoms in 1 μm^3,

T_c = 15K

Many positronium atoms can form a BEC at relatively high temperatur

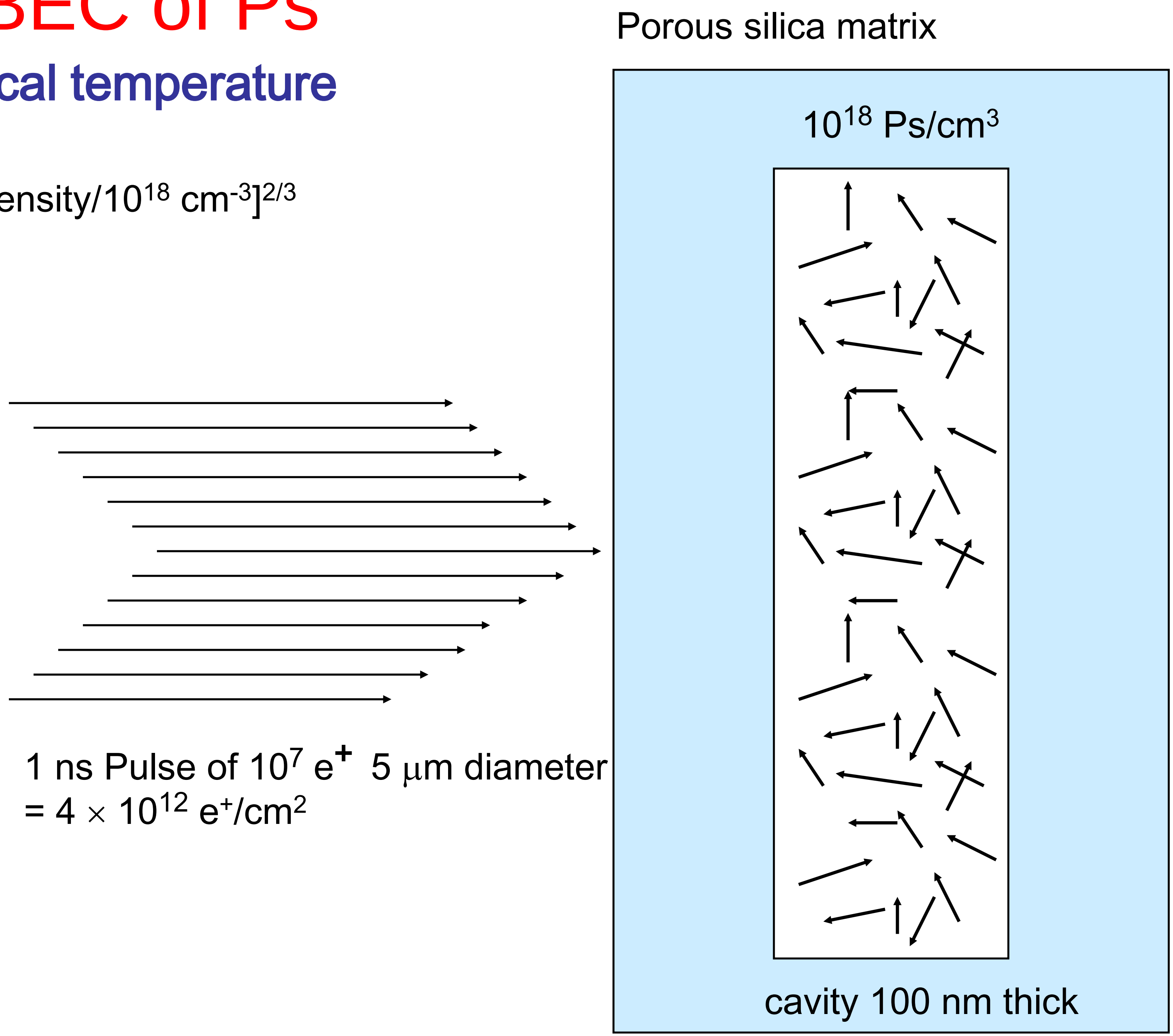




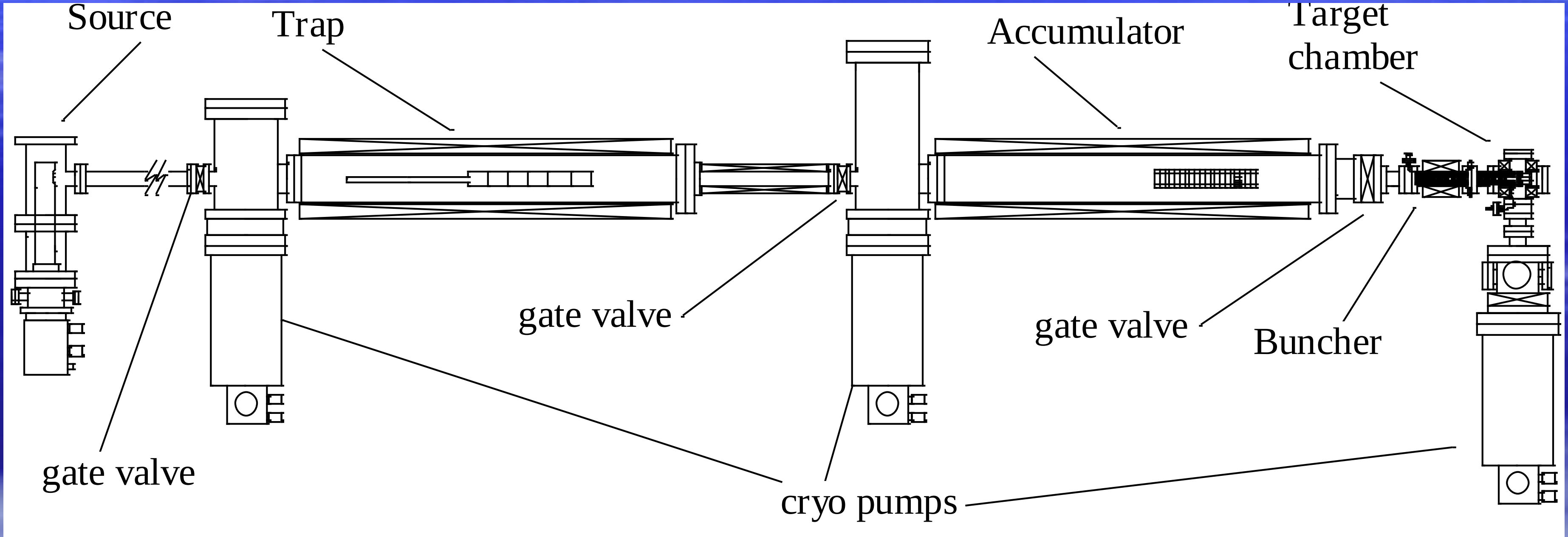
BEC of Ps

BEC critical temperature

$T_C = 15\ \mathrm{K} \times [\mathrm{density}/10^{18}\ \mathrm{cm}^{-3}]^{2/3}$



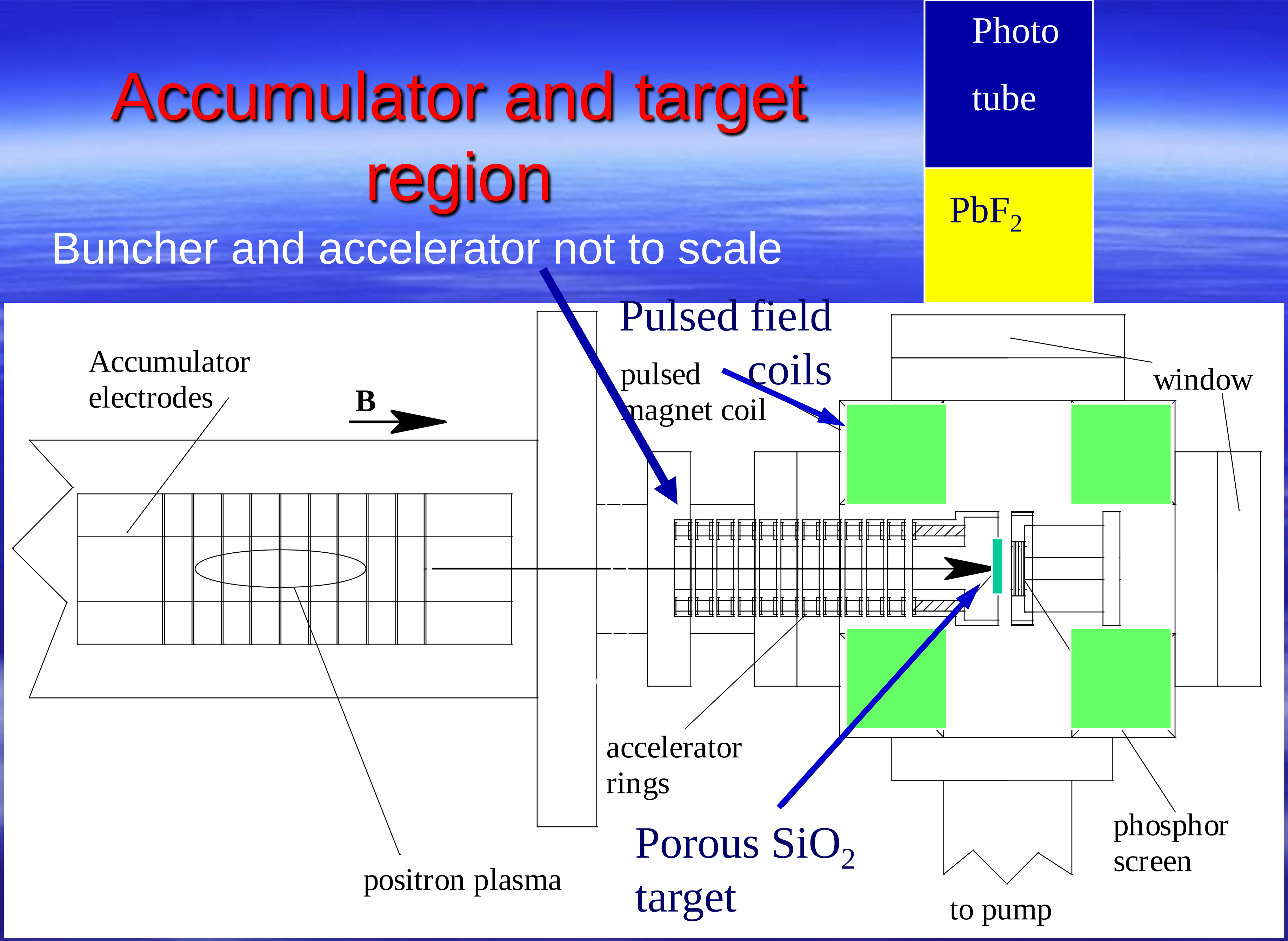
Apparatus

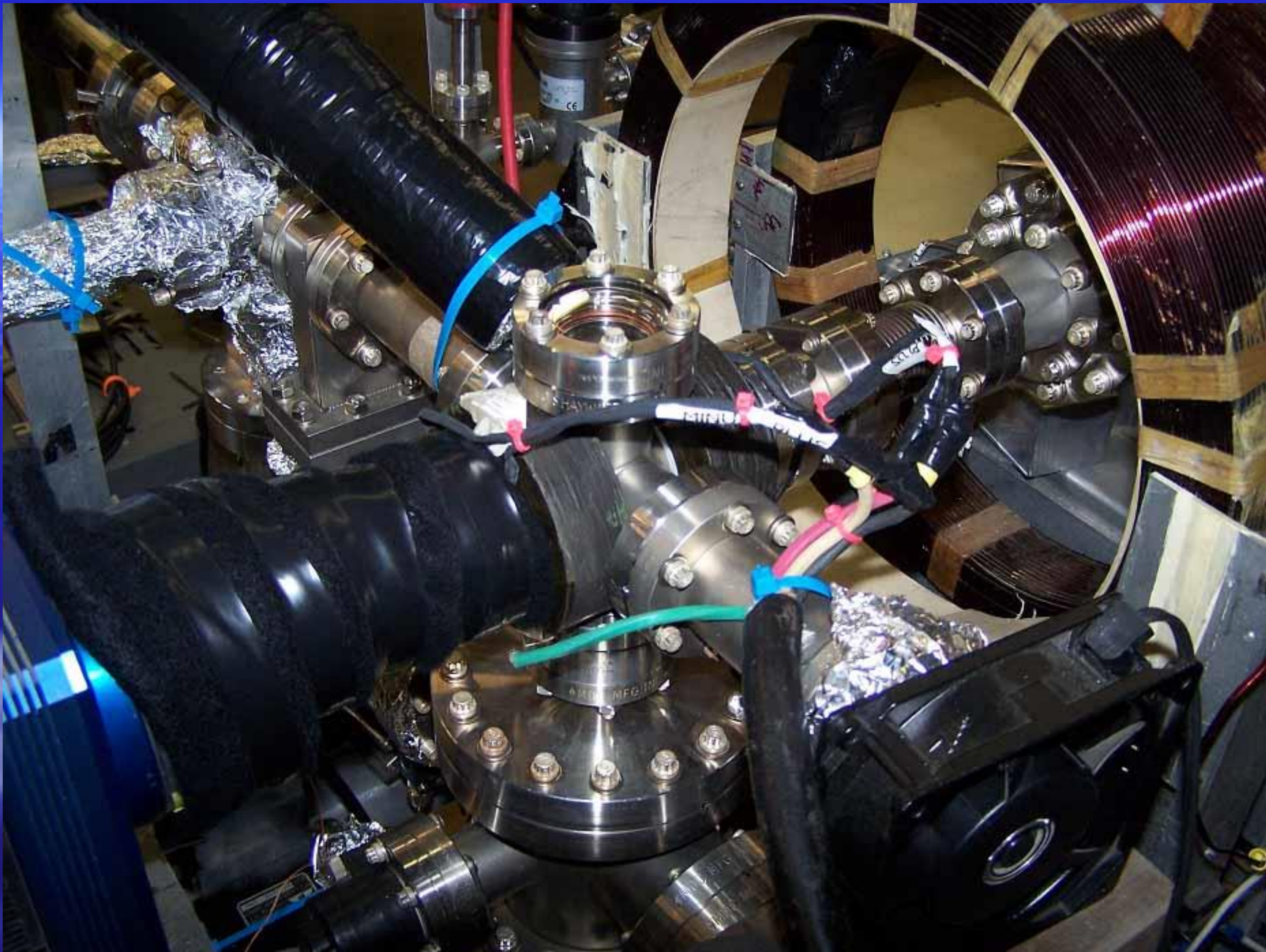


Source
Trap
Accumulator
Target
chamber
gate valve
gate valve
Buncher
gate valve
cryo pumps

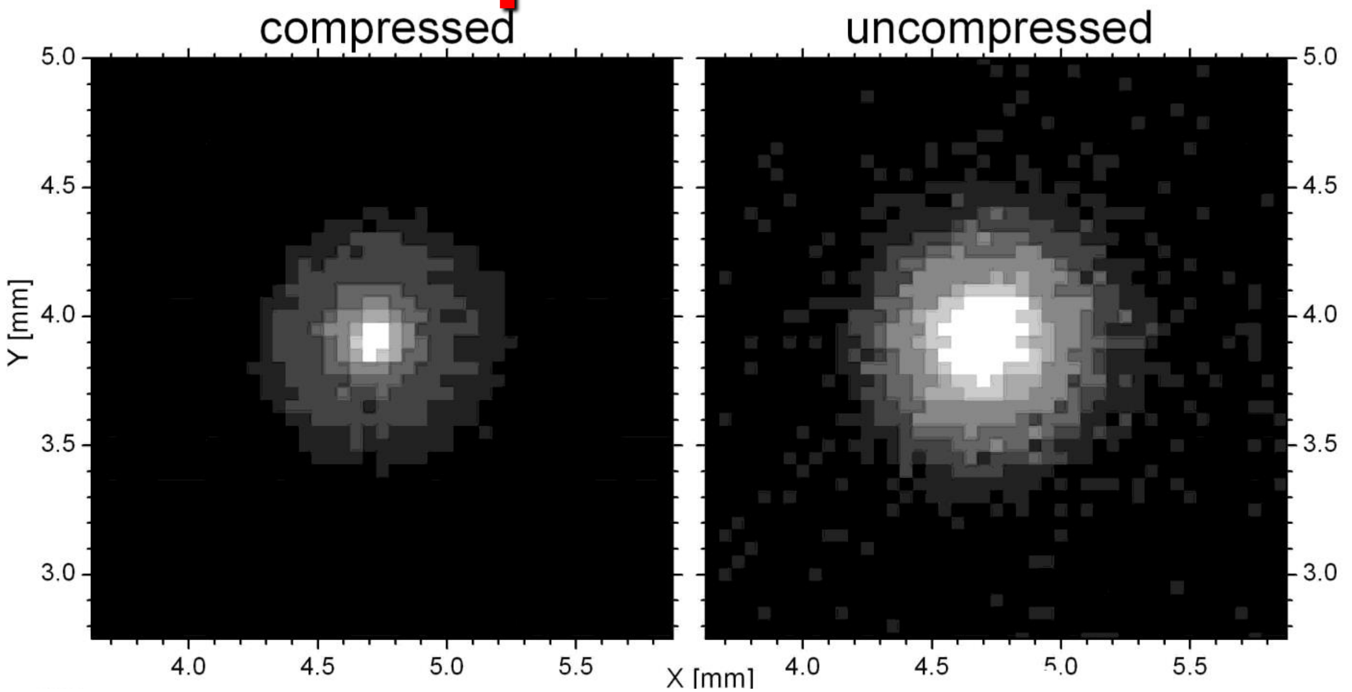
Accumulator and target region

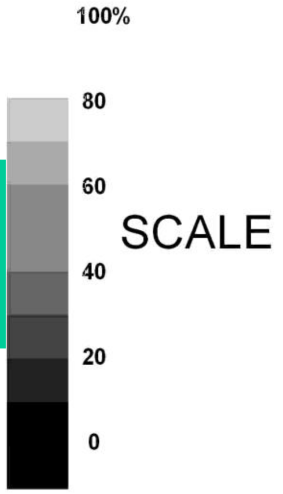
Buncher and accelerator not to scale





Beam profiles at 1 T

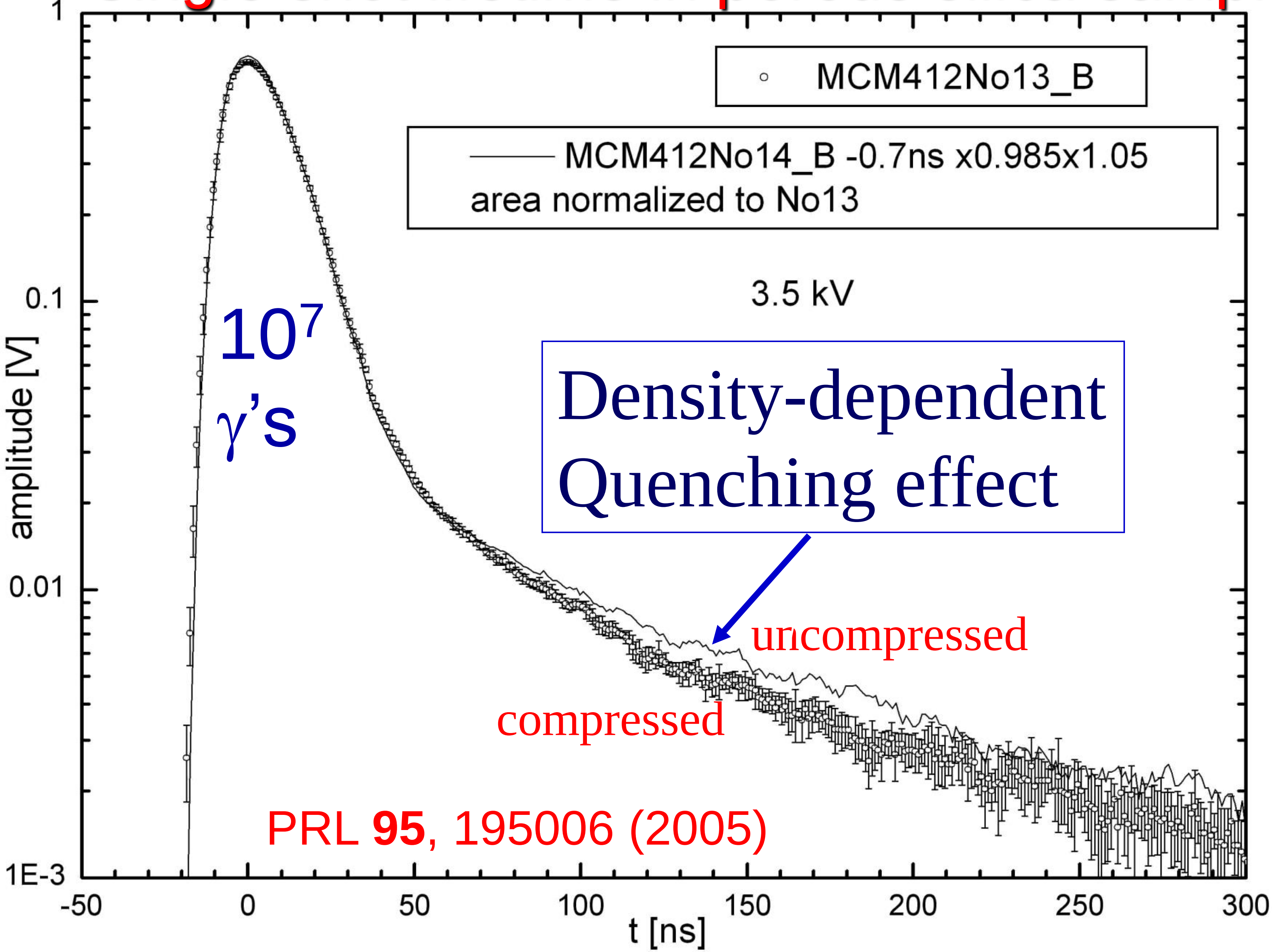




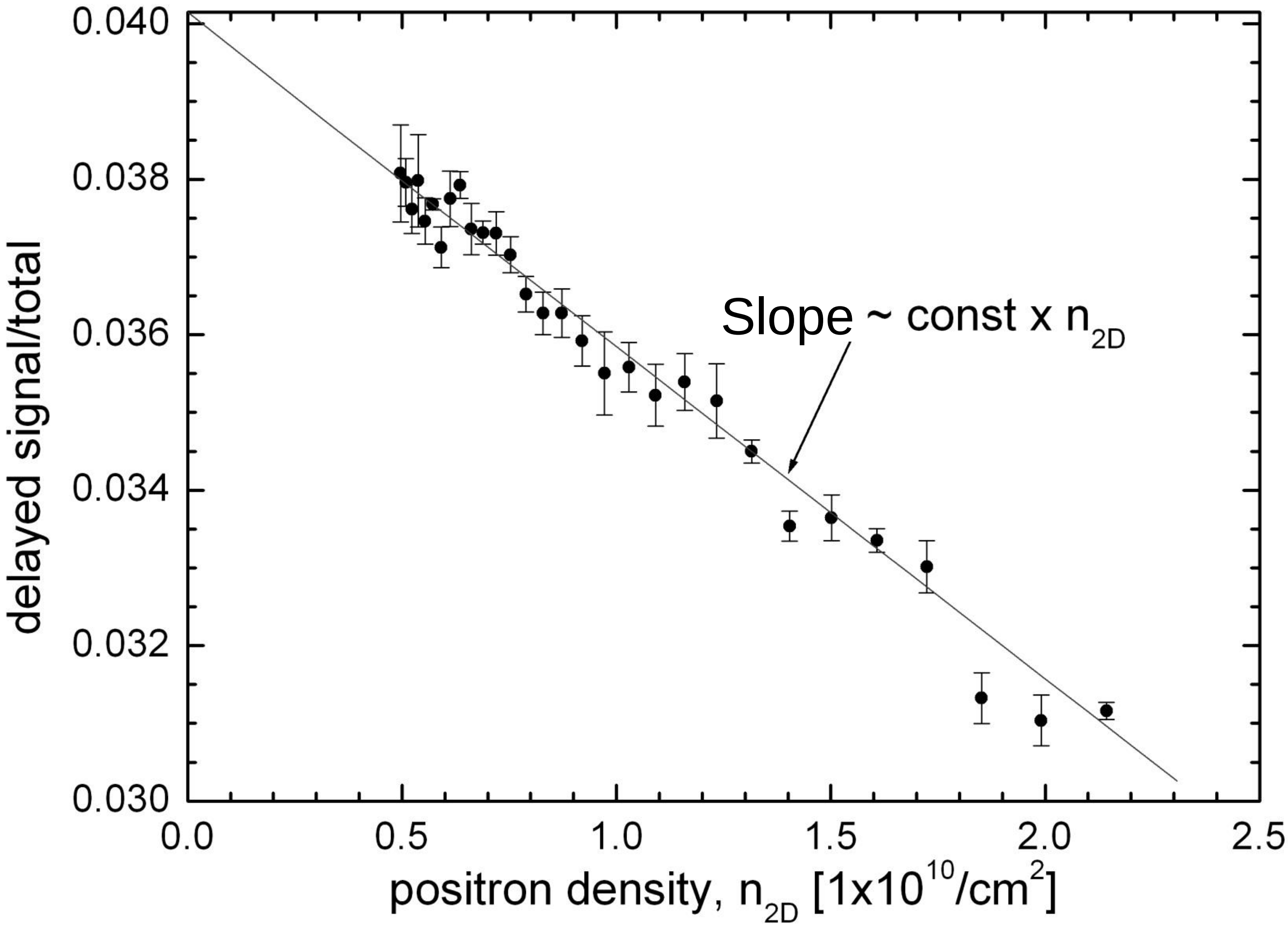
Beam is compressed using the “rotating wall effect”.

PRODUCTION OF HIGH DENSITY Ps

Single shot lifetime in porous silica sample



Linear quenching effect vs density



Is Quenching due to

spin exchange

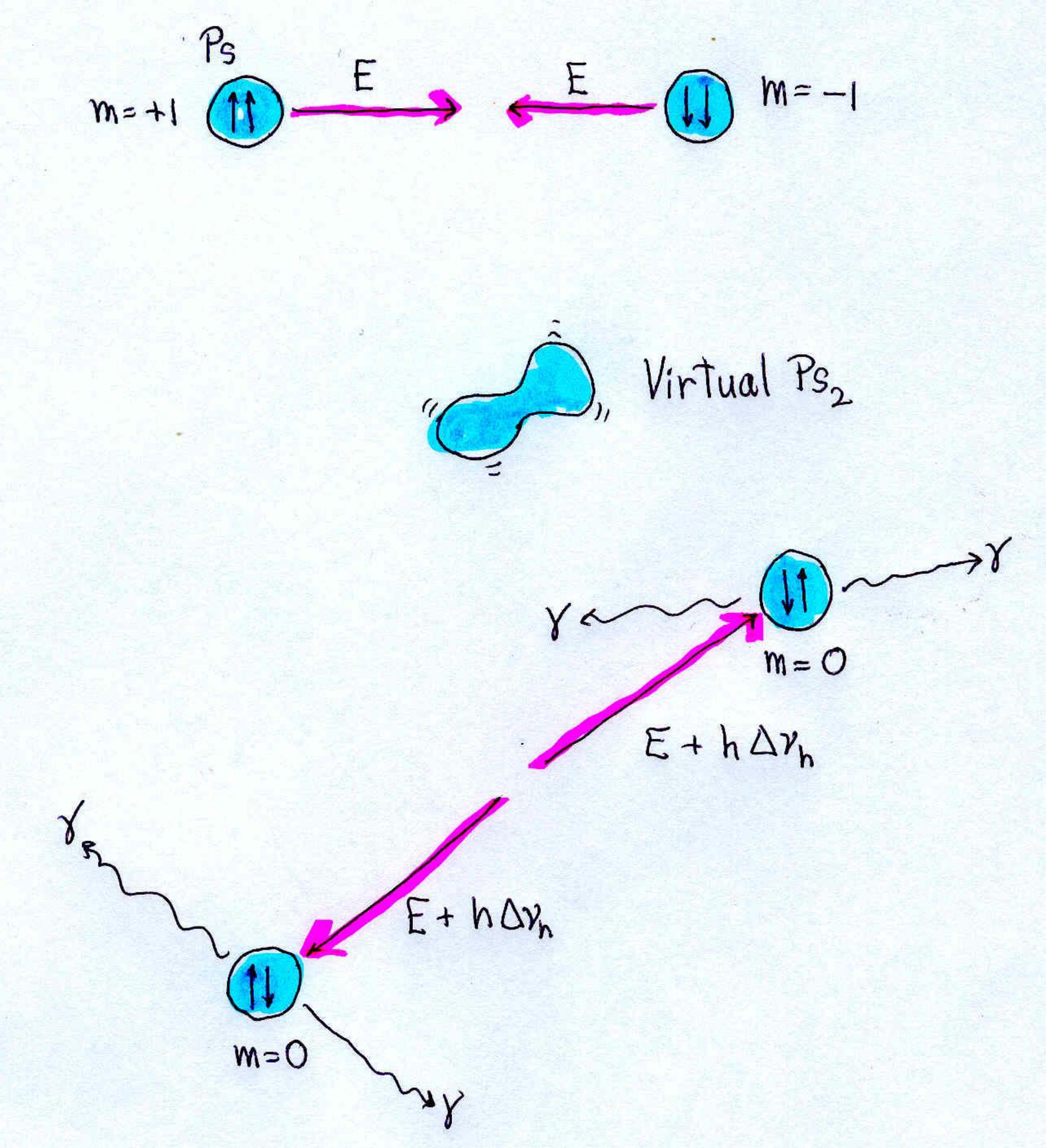
or

Ps_2 formation

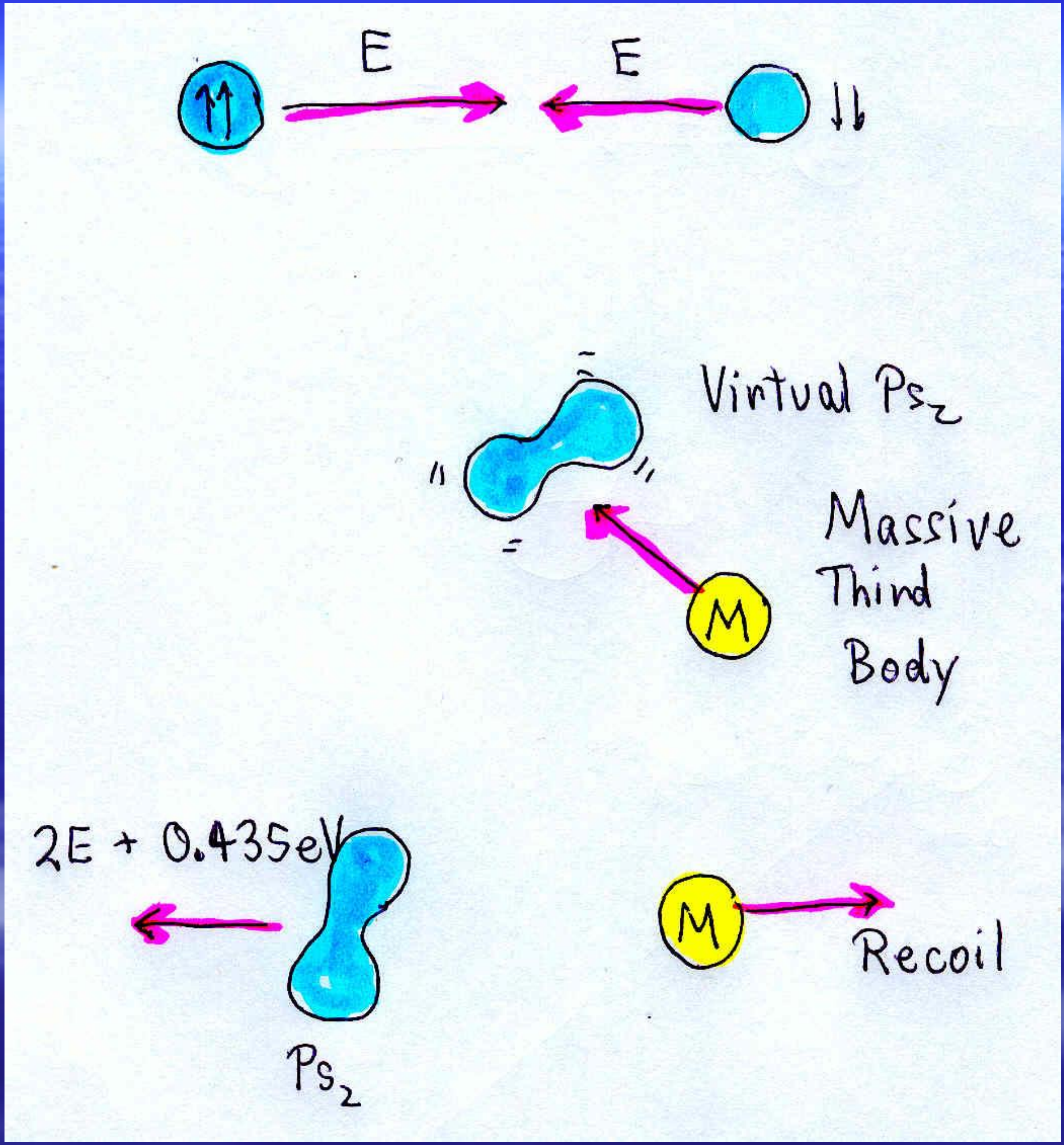
or

both?

Ps-Ps spin exchange



Ps_2 formation



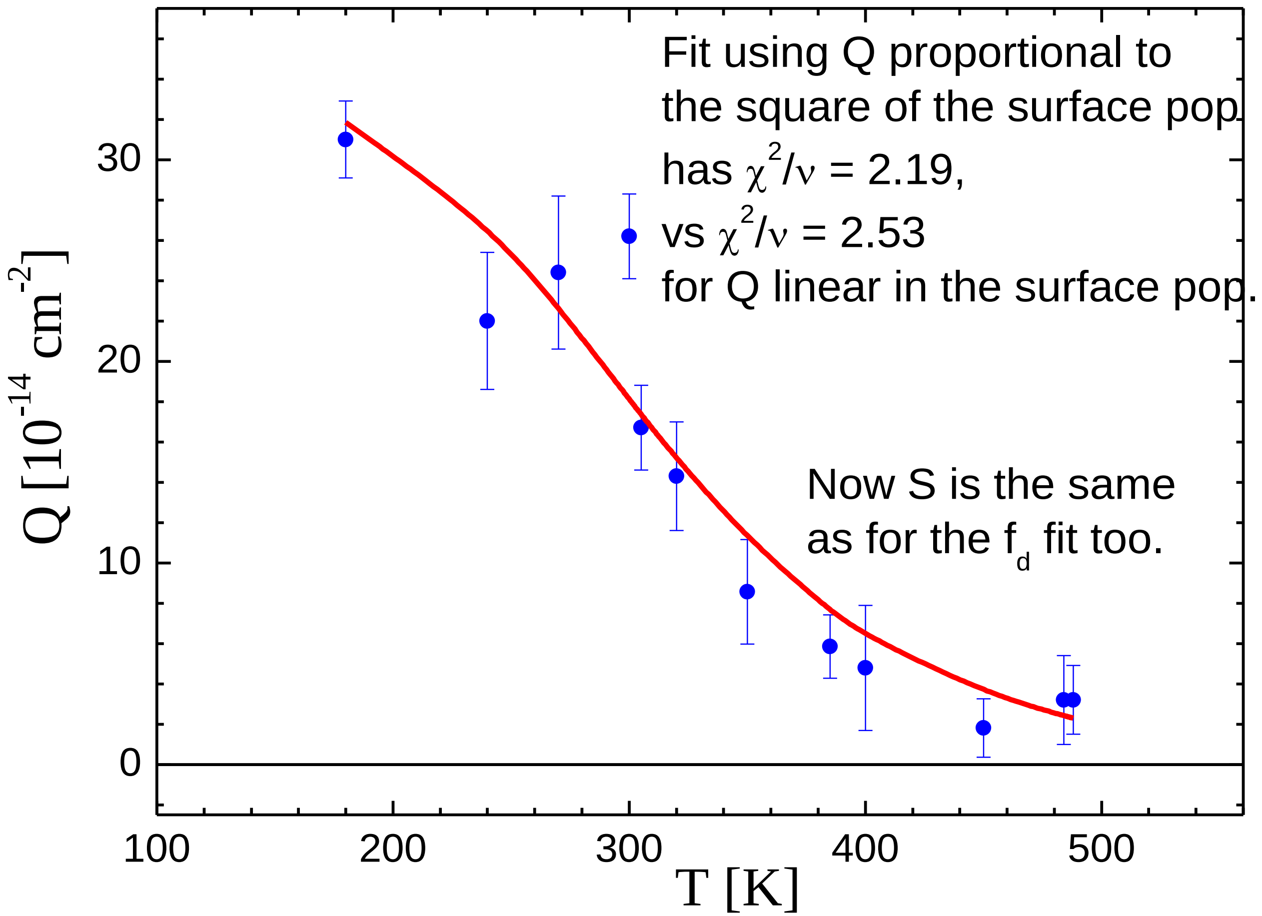
Third body can be a molecule or a wall.

Conclusion

Data is consistent with Q being associated with two surface Ps atoms.

We conclude that the density-dependent quenching effect in the random porous silica sample is mostly due to Ps_2 formation

(since Q drops by an order of magnitude at high temperature when the surface state is depopulated).



What is next?

- We can measure the predicted 250.9 nm 1S1S-1S2P (L=0 to L=1) energy interval in Ps_2.
- 1000x more density needed to make a Ps BEC.
- Ps atom laser and precision measurements.
- Stimulated annihilation.
- Gamma ray laser?
- ….

The End