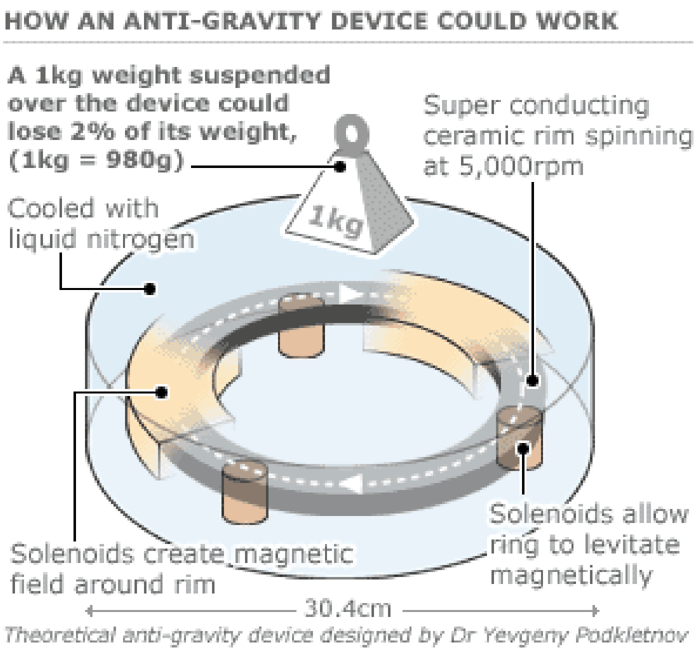
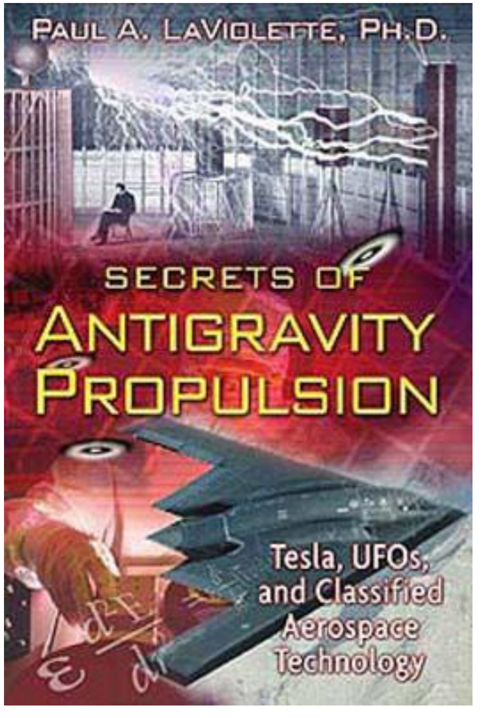
# *Rydberg positronium for a free-fall matter-antimatter gravity measurement*

*David B. Cassidy*

*Department of Physics and Astronomy,*
*University College London, UK*




d.cassidy@ucl.ac.uk

The gravity shield is “real”!

J. Phys. D: Appl. Phys. 29 (1996) 1–6. Printed in the UK

# Gravitational shielding properties of composite bulk $YBa_2Cu_3O_{7-x}$ superconductor below 70 K under an electromagnetic field

E E Podkletnov and P T Vuorinen

Tampere University of Technology, Institute of Materials Science, P O Box 589, SF-33101 Tampere, Finland

Received 5 December 1995, in final form 13 May 1996

**Abstract.** A high-temperature $YBa_2Cu_3O_{7-x}$ ceramic superconductor sample with composite structure has revealed shielding properties against gravitational force in the state of levitation at temperatures below 70 K. A bulk ceramic superconductor sample with the shape of a toroidal disc was prepared using conventional ceramic technology in combination with melt-texture growth. Two solenoids were placed around the disc in order to initiate the current inside it and also to provide the rotation around its central axis. Samples placed over the rotating disc demonstrated a weight loss of 0.3–0.5%. When the rotation speed was slowly reduced by the electromagnetic field in the solenoids, the shielding effect became considerably higher and reached 1.9–2.1% at maximum.

# What is meant by “antigravity”?

1. **antimatter-antimatter repulsion**
   not too likely given what we know about matter

2. **matter-antimatter repulsion**
   probably the most interesting possibility

3. **matter-antimatter/antimatter-antimatter attraction**
   Consistent with general relativity, (and what most people expect)

A mutual gravitational repulsion between matter and antimatter could (possibly) help to explain some of the mysteries of science, such as CP violation, Dark Matter and the lack of observed antimatter in the universe. *But should we expect such a thing to occur?*

# One simple example: photons in a gravitational field

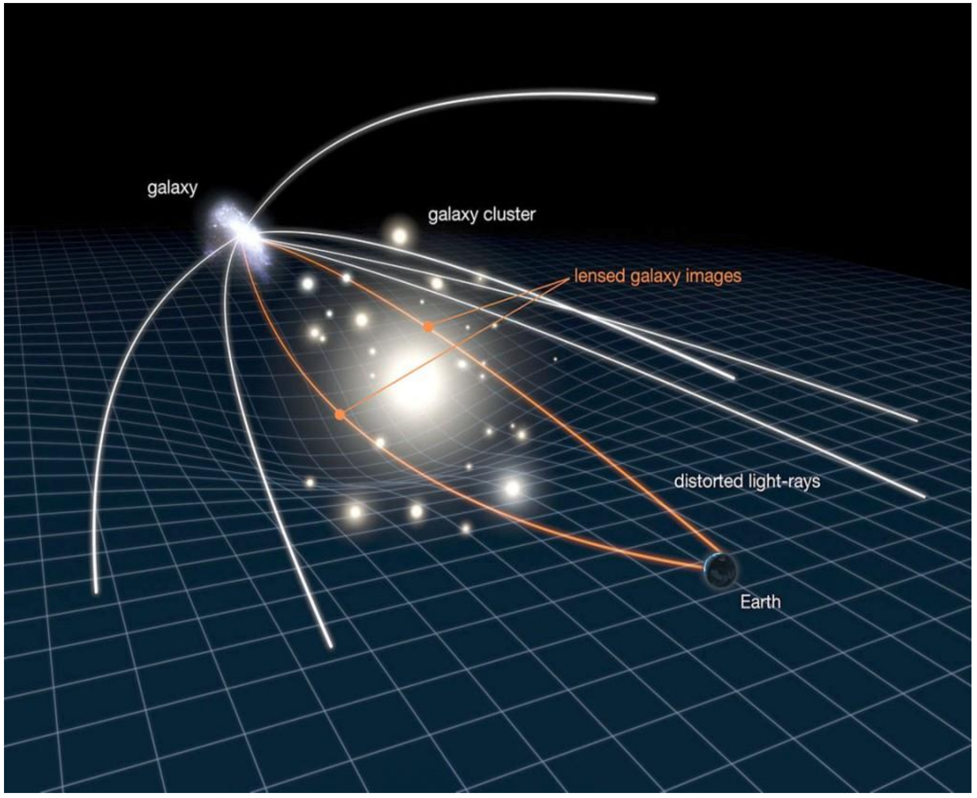



Image: NASA/ESA

**Gravitational lensing** is well known and is used all the time in astronomy. It proves that photons are deflected by gravitational fields just as predicted by Einstein.

But they are their own antiparticles, so why should we expect other antiparticles be different?

This argument also implies that (under certain conditions) one could make a perpetual motion machine [Morrison] since a matter-antimatter pair could be transported in a gravitational field with no change in potential energy, but a photon produced by annihilating the pair *would* gain energy in moving to a higher potential

# Why look for a possible antigravity effect? And How?

- Possible answers to questions about Dark matter/Energy or even quantum gravity
- Matter-antimatter asymmetry in the universe
- There has never been a DIRECT MEASUREMENT
- No matter what theorists say, only DATA can tell us what is going on (everything else is speculation)
- The experiment couldn't be more simple: just drop some neutral antimatter and see what it does……….
- Only reasonable choices are Ps, Hbar or muonium. They all have some difficulties. (availability)
- Ps only lives for 100 ns (bit tricky to observe 0.05 pm free fall). Therefore we need RYDBERG STATES.

# Measuring Rydberg Ps free-fall: numerous experimental problems must be overcome:

- Production of a point source positron(ium) pulse
- Efficient creation of Ps in a cryogenic environment
- Excitation of Ps to long-lived states
- Control/manipulation of Ps beam
- Detection of small beam deflections

# What might a Ps Rydberg gravity experiment look like?*

Zero or low B field

need a point $e^+$ source

What n states will be optimal?

How does this mirror/lens work?

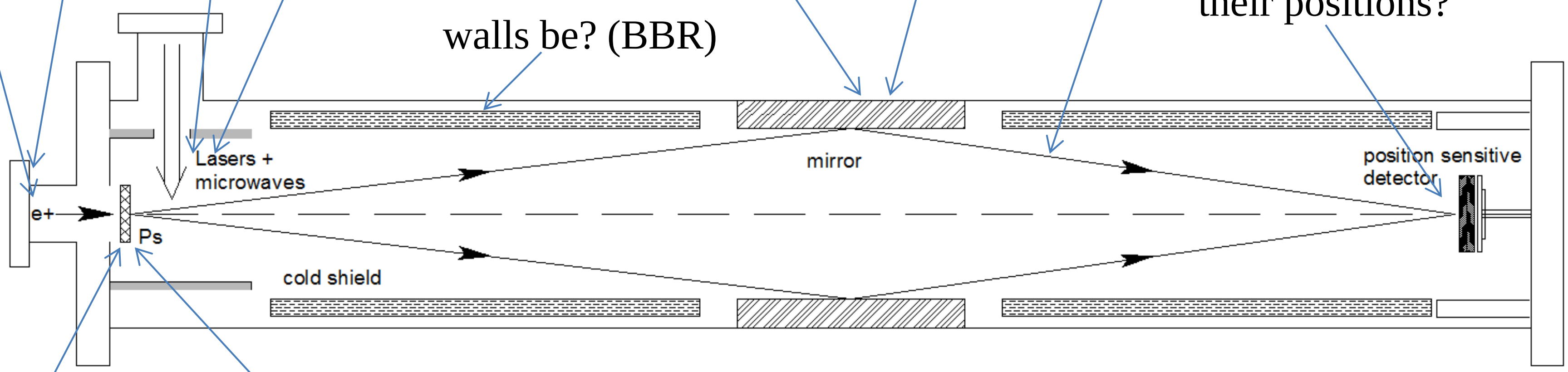
Will patch fields deflect the beam?

How will the circular states be produced?

Will the "atom-optics" work on circular states?

Can very slow atoms be detected without perturbing their positions?

How cold must the walls be? (BBR)




How long does the flight tube have to be?

Ps has to be very cold

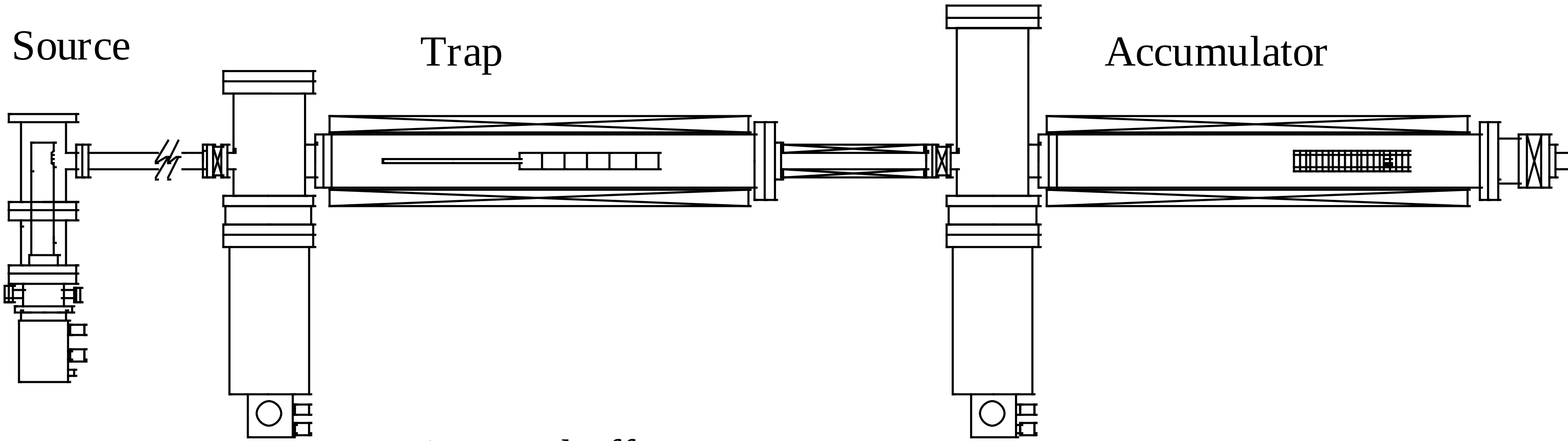
what Ps converter will work at low temp?

**Can we really do this?**
**Where are we now?**

*Any similarity between the diagram shown here and a real experiment is purely coincidental

# Experimental methods: positron plasma production

## 2-stage Surko trap + accumulator




$^{22}$Na source

Neon moderator

Efficiency ~ 1%

> $10^6$ $e^+$/sec

Nitrogen buffer gas

$e^+$ lifetime ~ 2 seconds

Single particle RW compression

efficiency ~ 10%,

2 Hz rep rate

> 150,000 $e^+$/pulse

$SF_6$ cooling gas (~ 1 x $10^{-7}$ Torr)

$e^+$ lifetime > 500 seconds

efficiency ~ 80%

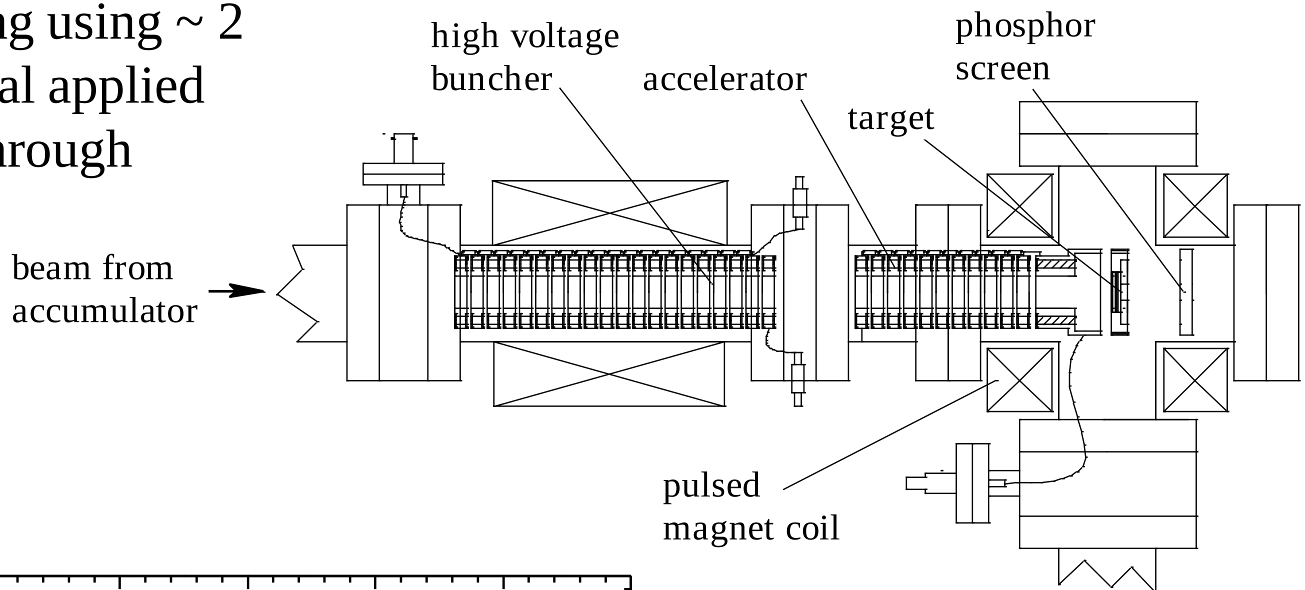
Maximum $10^8$ $e^+$

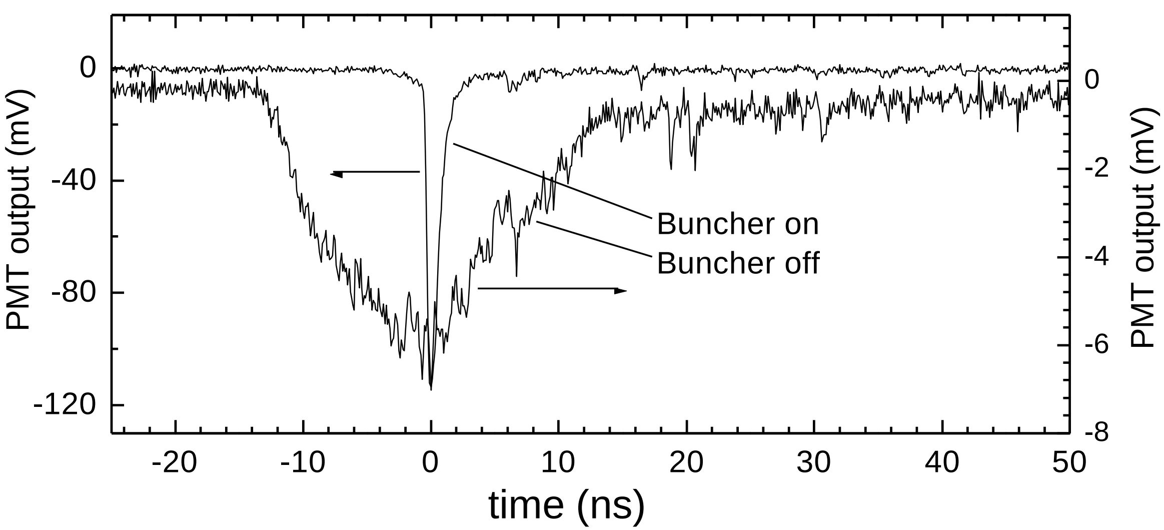
Typical 2 x $10^7$ $e^+$

Pulse out ~ 10-50 ns FWHM

RSI **77**, 073106 (2006)

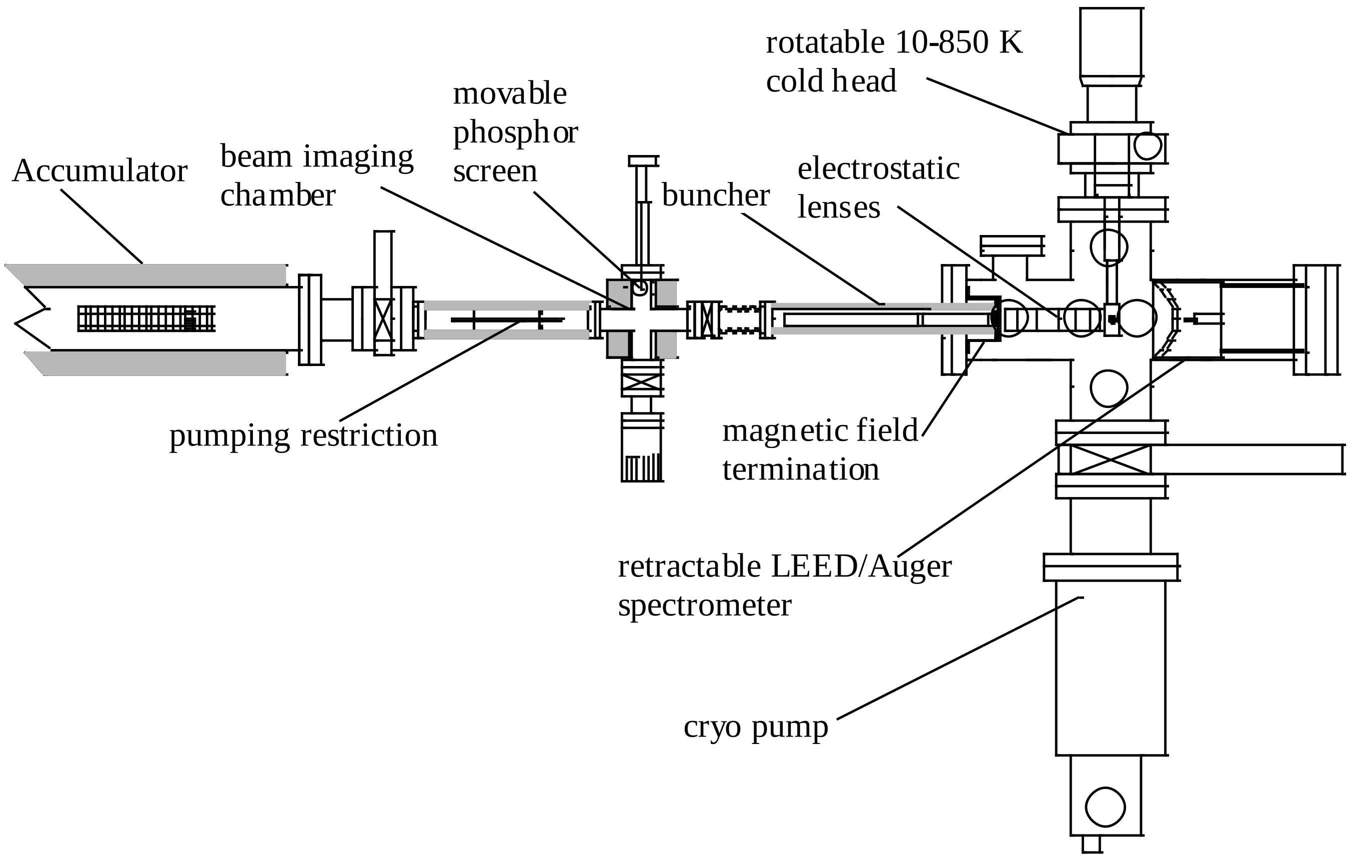
**Time compression**: Important to sync Ps with pulsed lasers: Electrostatic bunching using ~ 2 kV harmonic potential applied while beam passes through



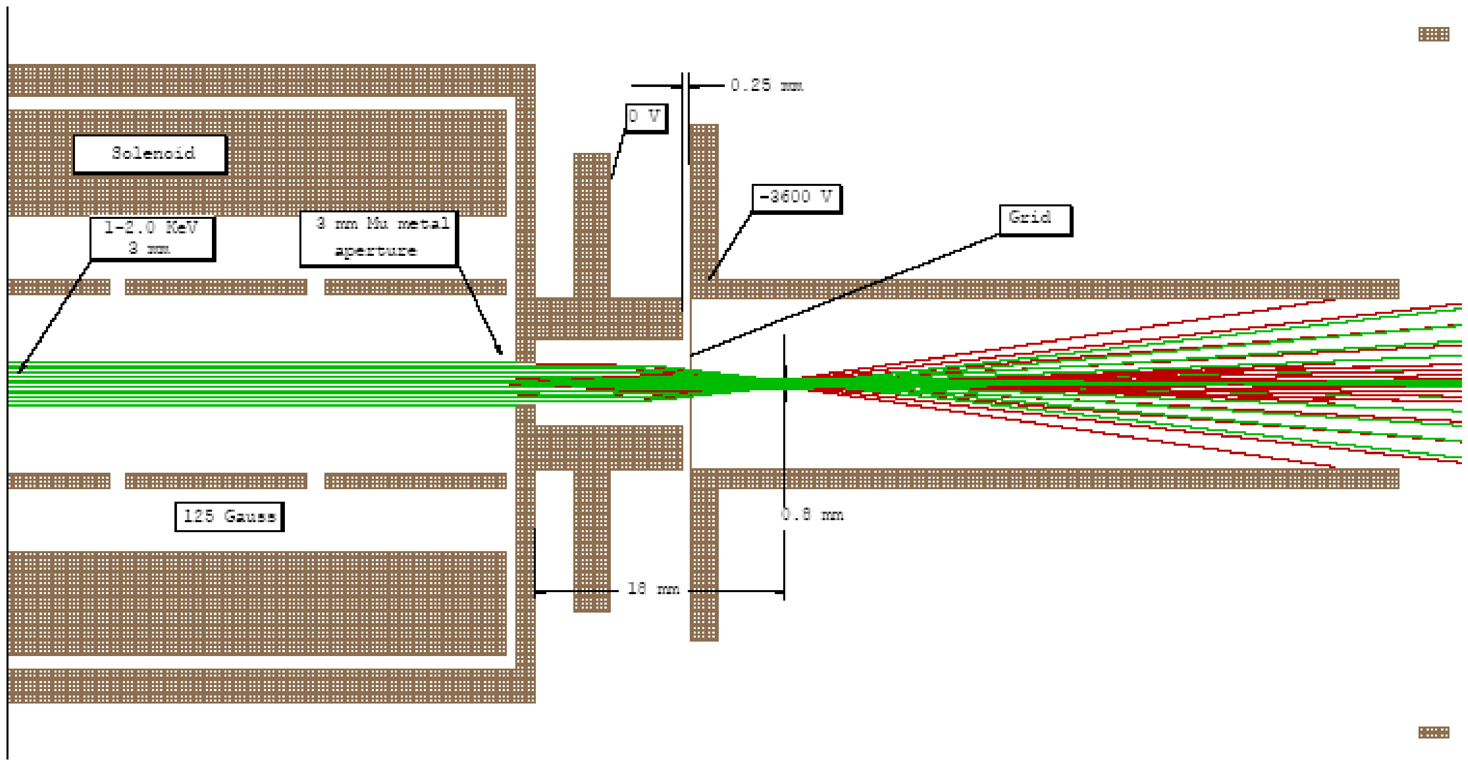




Creation of ~ 1 ns FWHM pulses routine. No dependence on number of positrons apart from requirement of beam to fit in buncher

**Remoderation** of positron bunch: beam has to be bunched in time, extracted from the trap magnetic field and focused into a thin (~ 100 nm) Ni foil. Thereafter beam transport is purely electrostatic

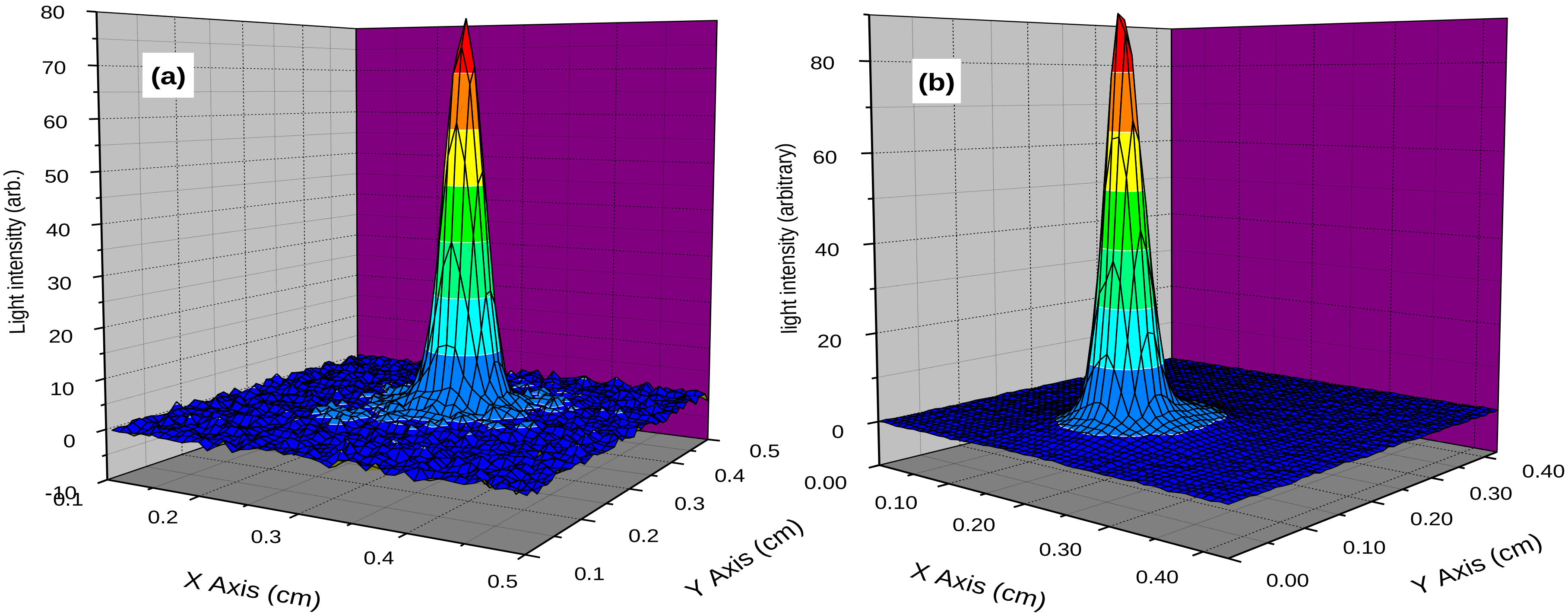


# Extraction of beam from magnetic field and remoderation:




Final spot size on *target* ~ 10-50 microns (depends on energy spread from bunching)

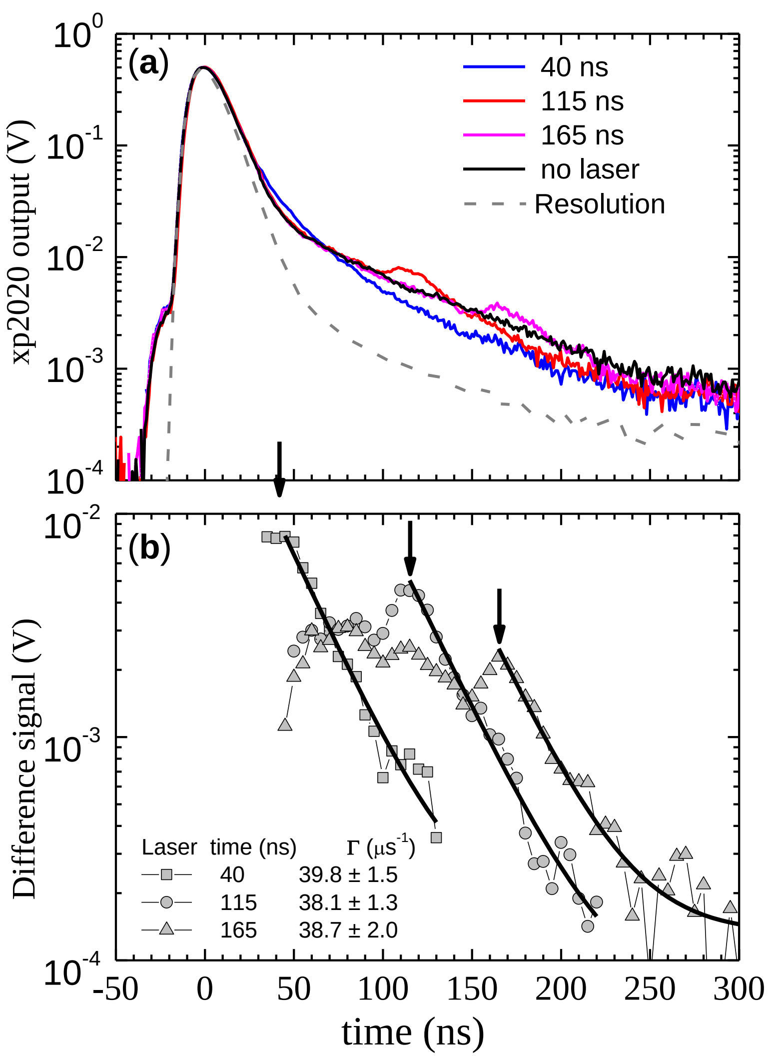
Remoderator efficiency ~ 10%.




Positron beam profiles measured in the imaging chamber (a) just after the accumulator (in an axial magnetic field of ~ 700 Gauss) and on a phosphor screen placed in the position of the remoderator foil (b) where the magnetic field is essentially zero.

Remoderation of our trap beam has not yet been demonstrated

Silica films are often used as positronium converters, but laser (or positron) irradiation can create paramagnetic centers in these targets that increase the Ps annihilation rate.




Phys Rev B **75** 085415 (2007)

These centers can be stable (long-lived) at low temperatures: silica films or similar converters may not survive for very long

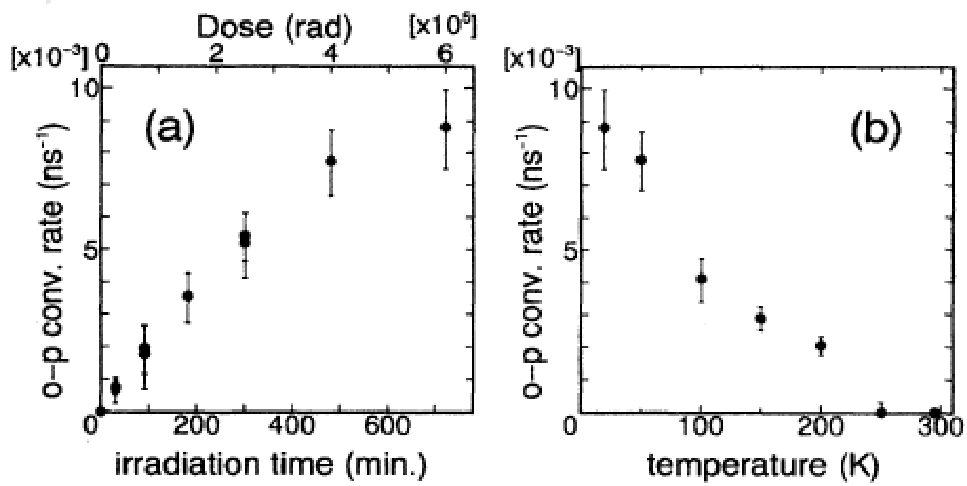
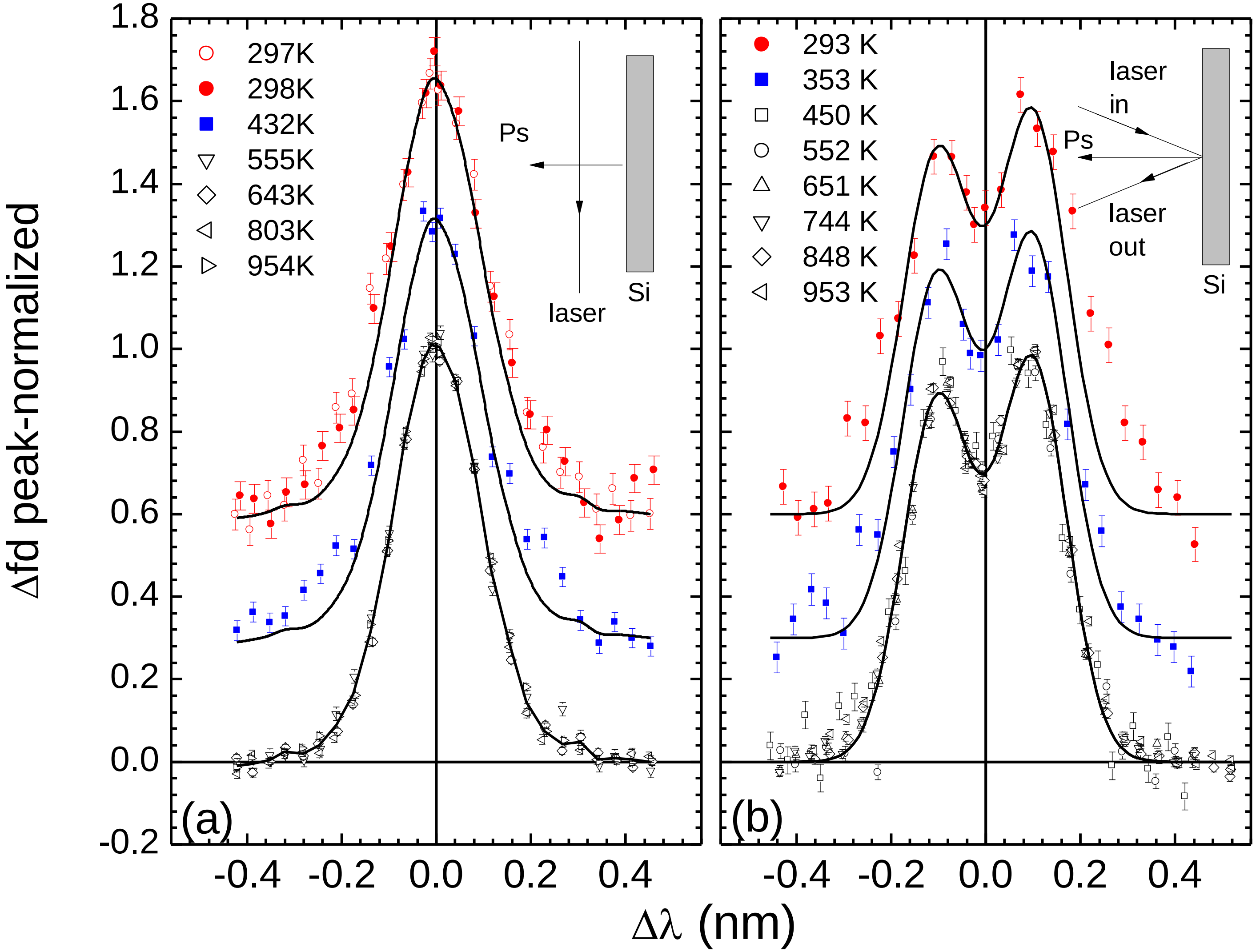



FIG. 4. (a) Ortho-para conversion rate vs irradiation time (dose) in silica aerogel at 14 K. (b) Ortho-para conversion rate vs temperature in silica aerogel during heating up after irradiation. The measurement at each temperature took 4 h.

H. Saito, Y. Nagashima, T. Hyodo & T. Chang, Phys Rev B **52** R689 (1995)

Ps created from an **exciton-like** surface state is only indirectly affected by the sample temperature.

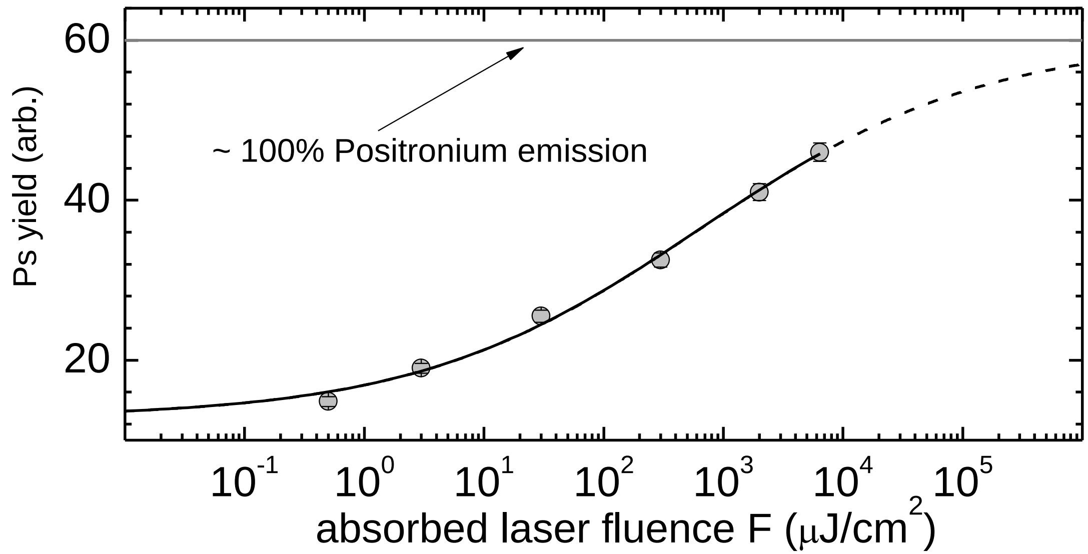


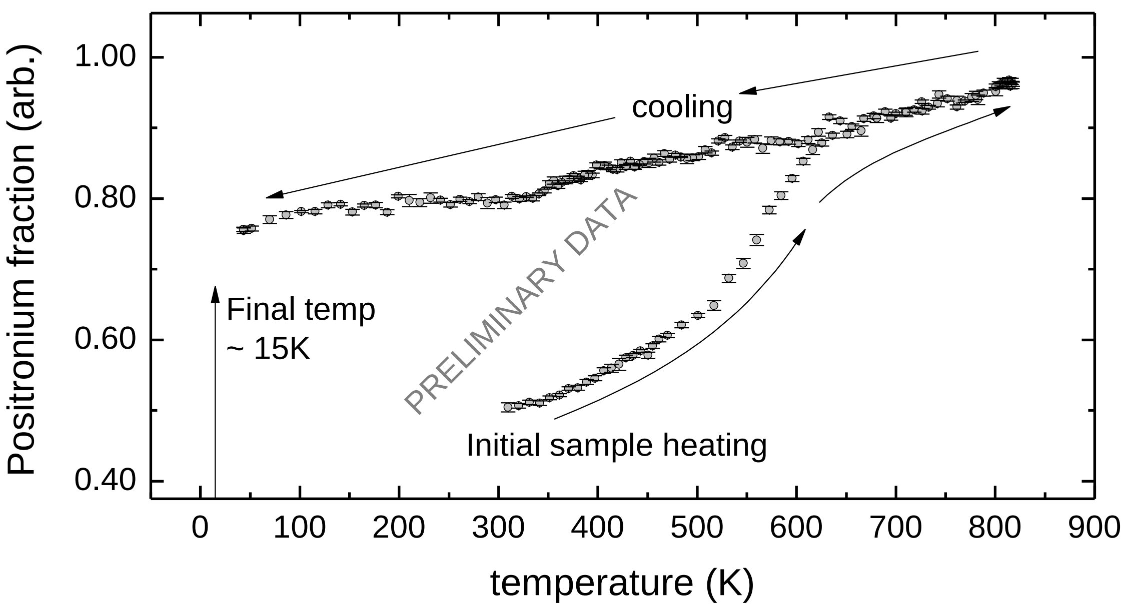

PRL **106** 173401 (2011)

Phys. Rev. B **84** 195312 (2011).

For this type of target laser irradiation actually produces *more* Ps so the target will survive *and* stay clean and produce Ps at any sample temperature

It is possible that this Ps formation mechanism can be used to produce mono-energetic and/or cold Ps if the surfaces are prepared in the right way



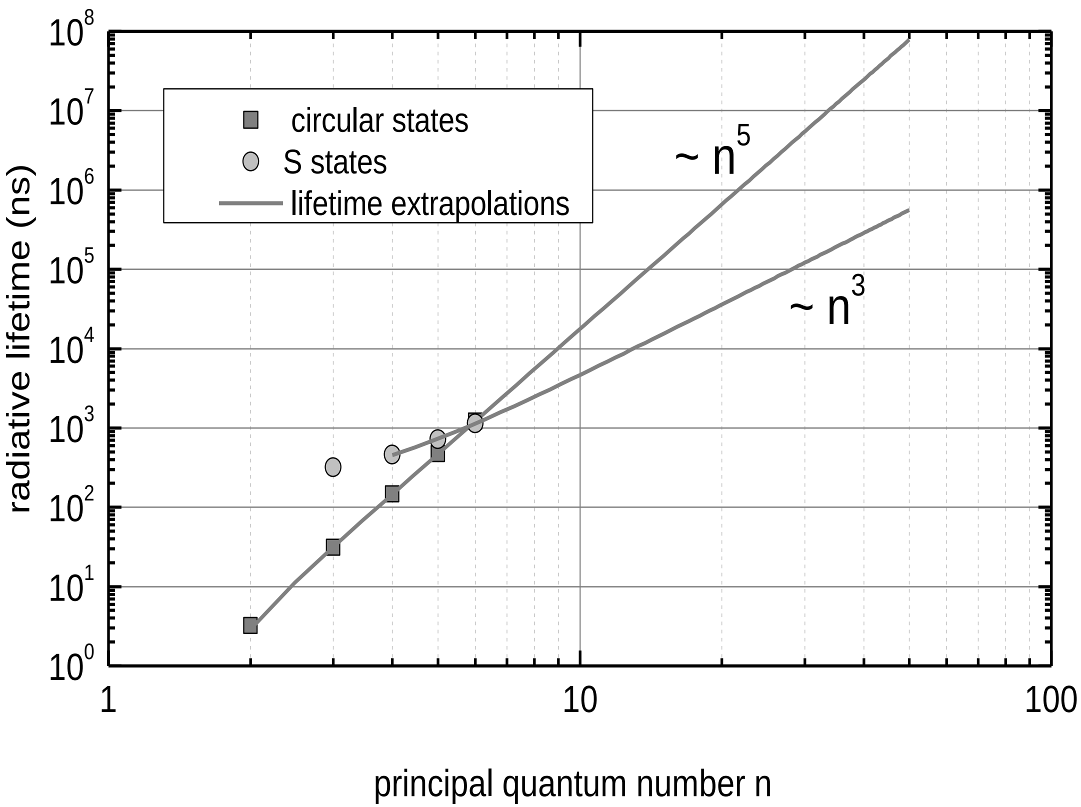

Initial work suggests that Photoemission of Ps is just as efficient at low temperatures, and it should be possible to produce the required Ps *at any sample temperature*

PRL **107** 033401 (2011)

# Long lifetimes needed for gravity deflection experiment:

**How long does it have to be?**

Suppose a 20μm spot, we might need 20μm displacement so $S = 1/2gt^2$ (assuming normal gravity….) gives 2 ms.




Must also remember that

1) High n states easily ionised by black body radiation (BBR)
2) Circular states are hard to make unless starting from a pure Rydberg level
3) Even BBR induced transitions between n, (n-1) or (n+1) may deflect the beam too much

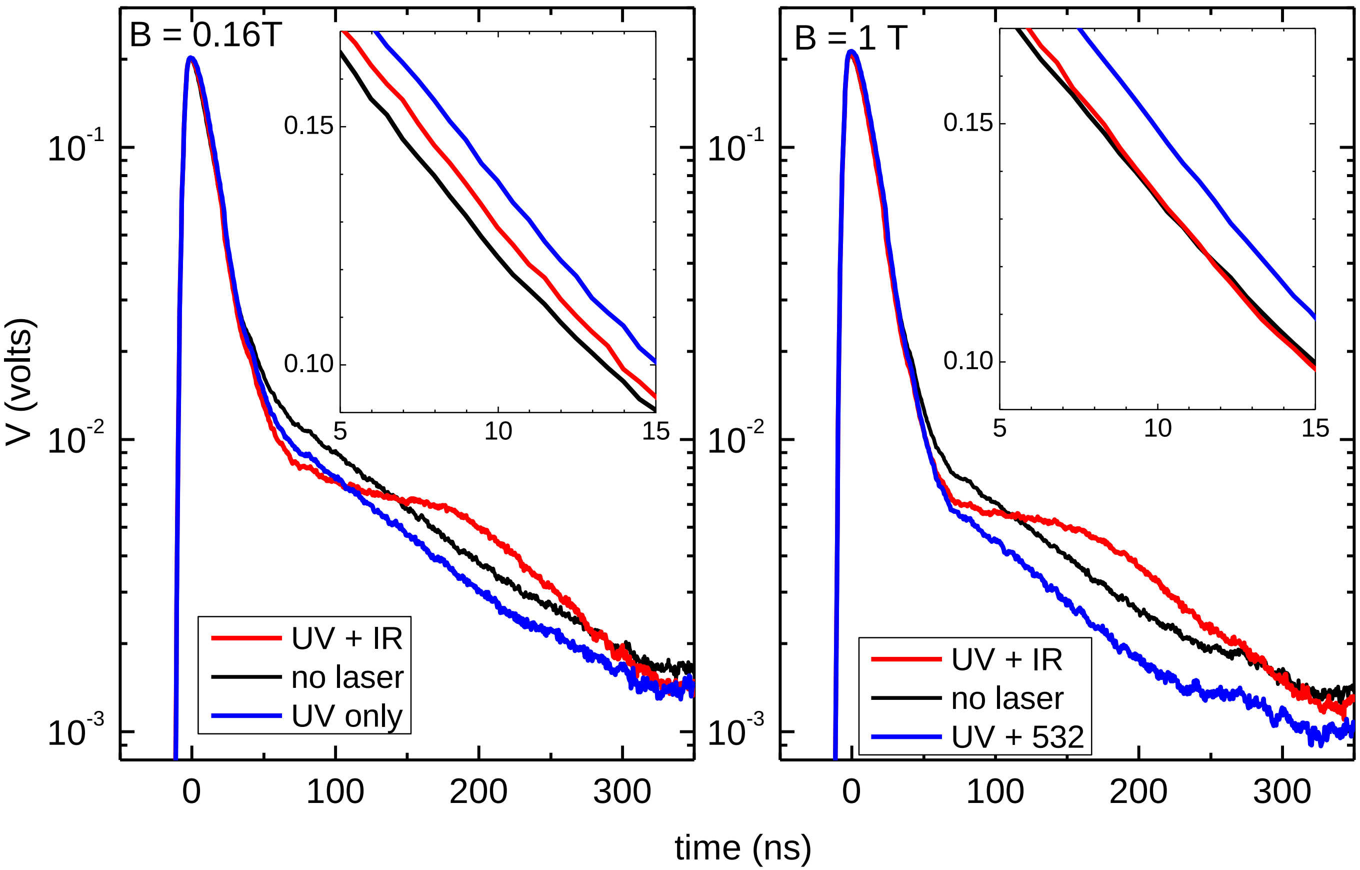
The final state we choose will be a compromise between mitigating BBR effects, optimizing the Ps beam focusing and obtaining the longest lifetime consistent with the flight length/Ps energy

# We can produce Rydberg Ps fairly easily using a two-step excitation scheme:

$$1^3S_1 + h\nu(243nm) \rightarrow 2P$$

$$2P + h\nu(\sim 750nm) \rightarrow nS/nD$$

Overall efficiency is determined mostly by the spectral coverage of the primary excitation laser (1S-2P)



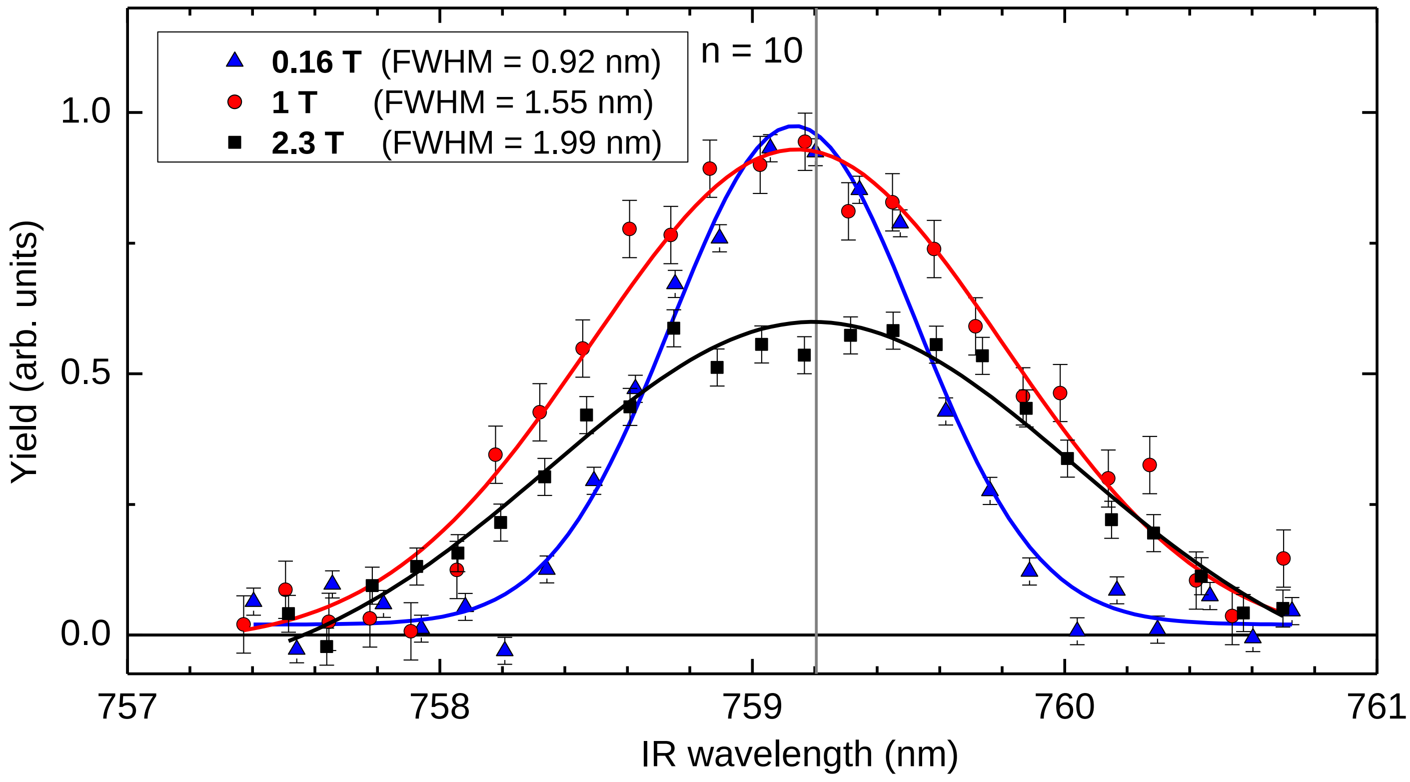

In this expt Ps annihilates when it hits the chamber walls

749.6 nm (n = 12)

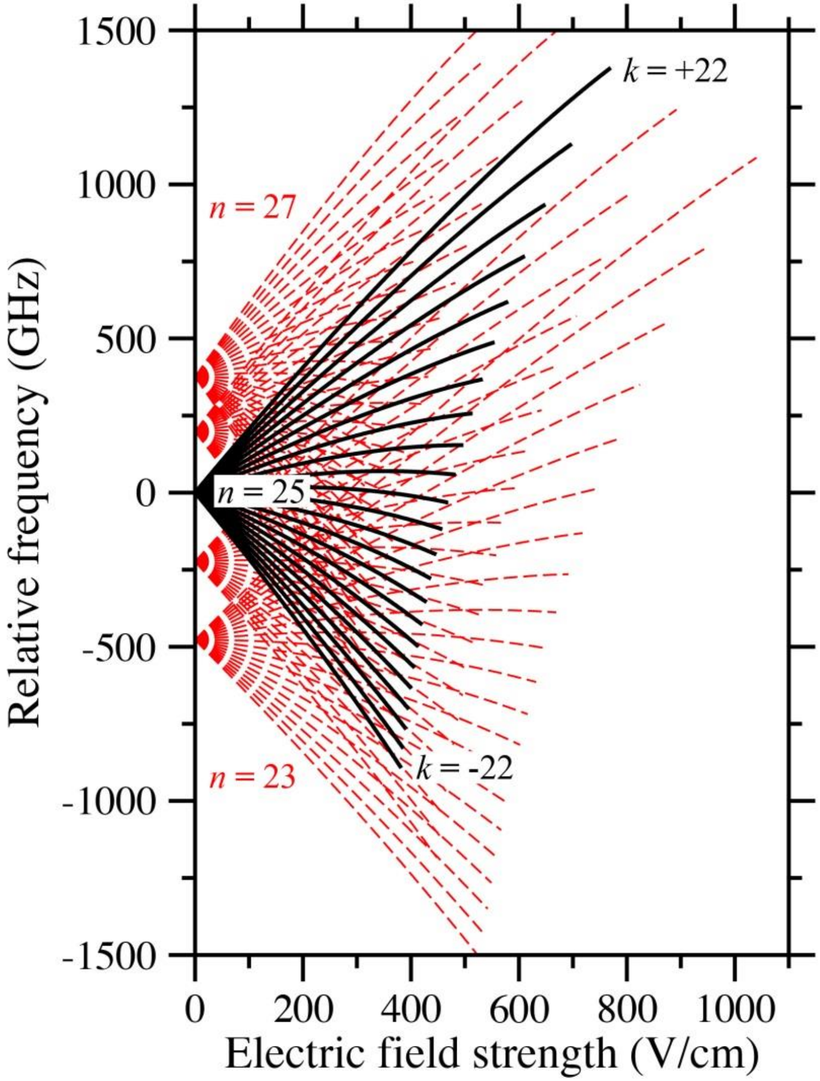
*NB: For high field there is no magnetic quenching of 2P Ps before the IR laser can excites it to a Rydberg state*

PRL **108** 043401 (2012)

We start with all three triplet ground states (|m=1|, m = 0) and use broad band linearly polarised light. As a result we populate all of the Stark sub-levels




The increased width of the lineshape measured at different magnetic fields demonstrates that the we are almost certainly populating the entire Stark manifold (motional Stark effect). This makes the line very wide, even more so than the (not inconsiderable) Doppler broadening.



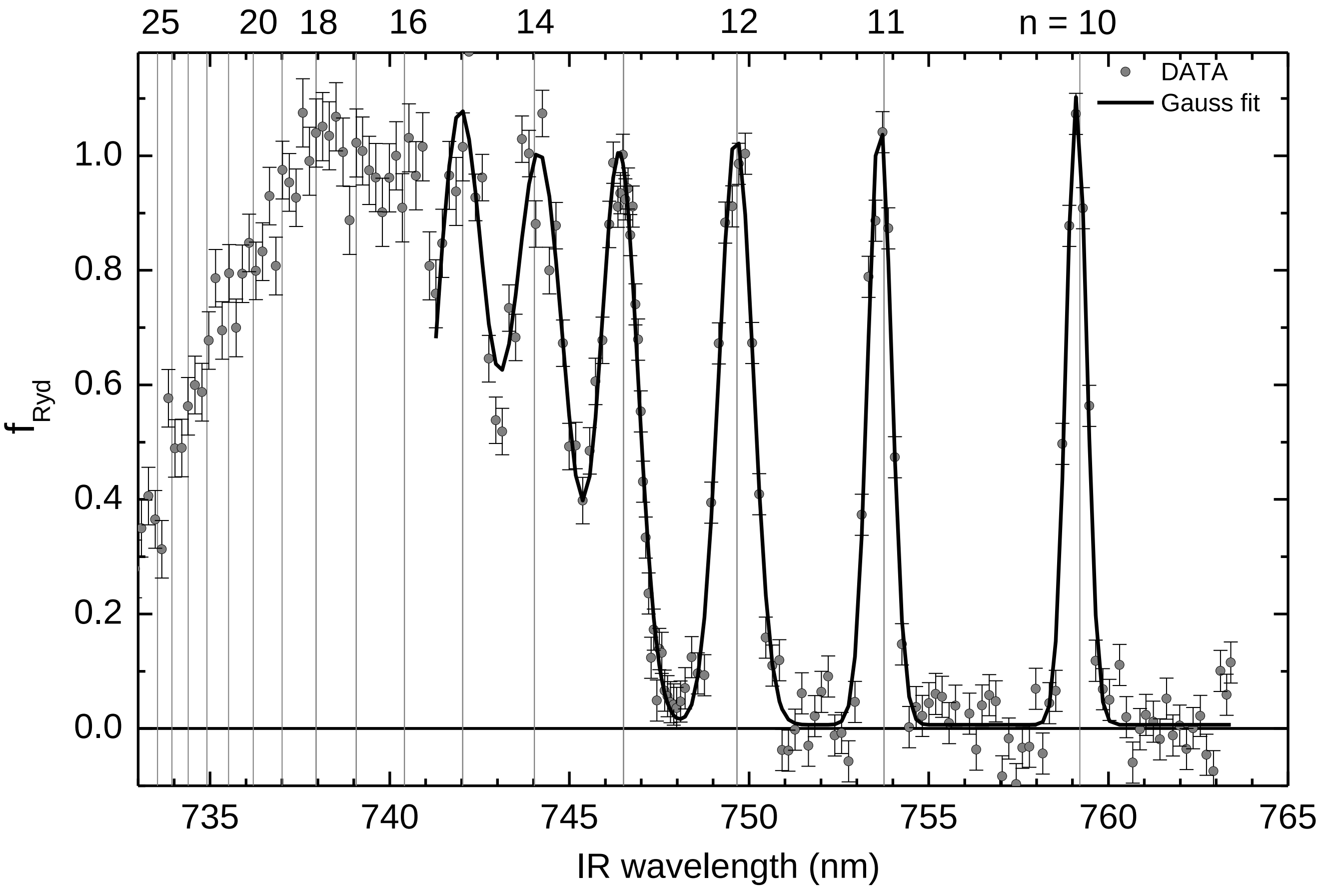

Stark map showing the electric field strengths for, which |m| = 2 Ps sub level ionization rates exceed $10^8$ $s^{-1}$ (i.e., likely to occur in a typical experiment)

Rydberg states are quite loosely bound and can be field ionized for relatively modest electric fields which can be a problem in an experiment

Because of the way the different Stark sublevels respond to electric fields they will ionize for different field strengths: in principle one can use this to preferentially select certain states (albeit in a sacrificial way)

S. D. Hogan, *Calculated photoelectron spectra of positronium Rydberg states* Phys Rev A **87** 063423 (2013)

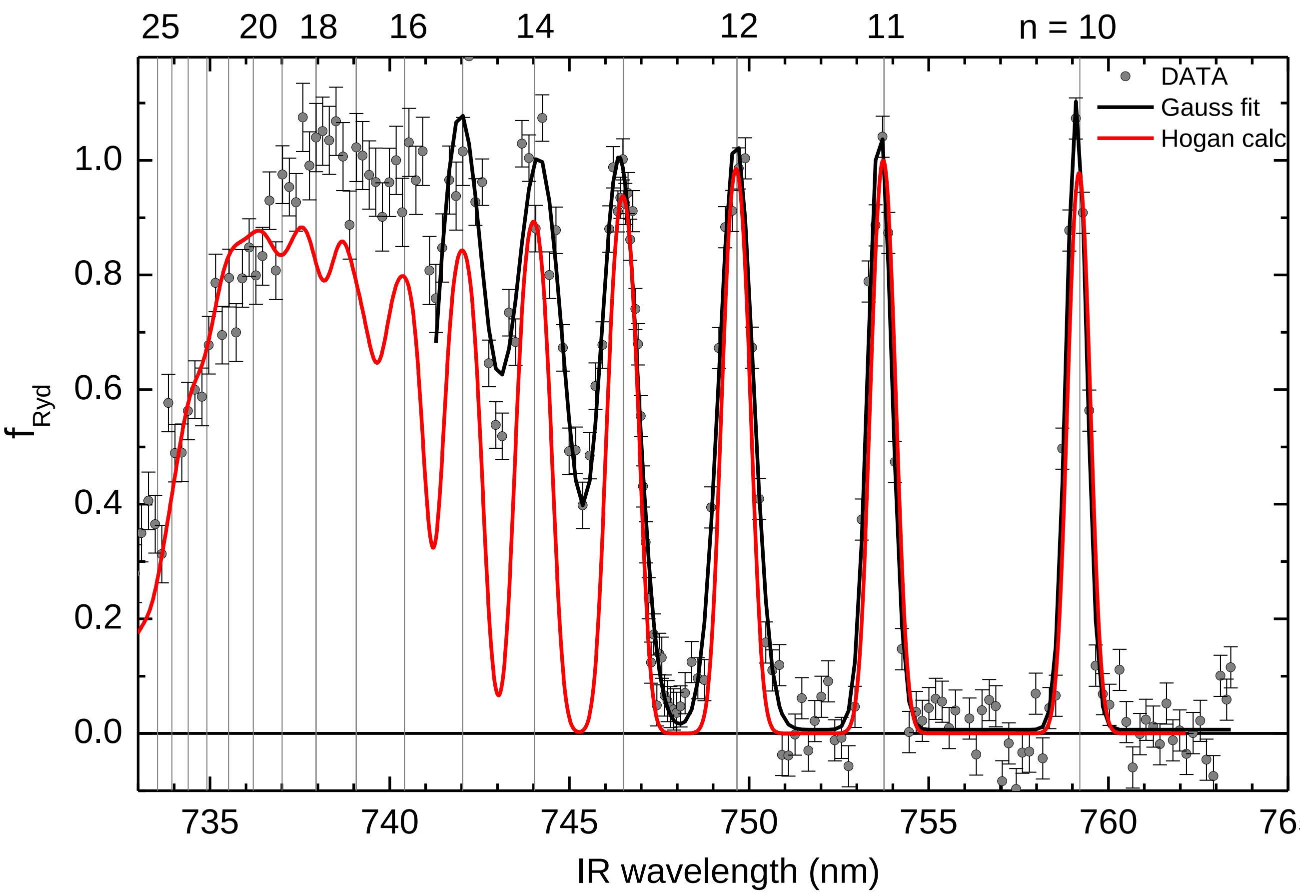
Population of Rydberg Ps states in 0.16 T magnetic field with an electric field present




PRL **108** 043401 (2012)

Population of Rydberg Ps states in 0.16 T magnetic field with an electric field present

Including field ionisation, saturation and Doppler broadening can describe the observed data fairly well

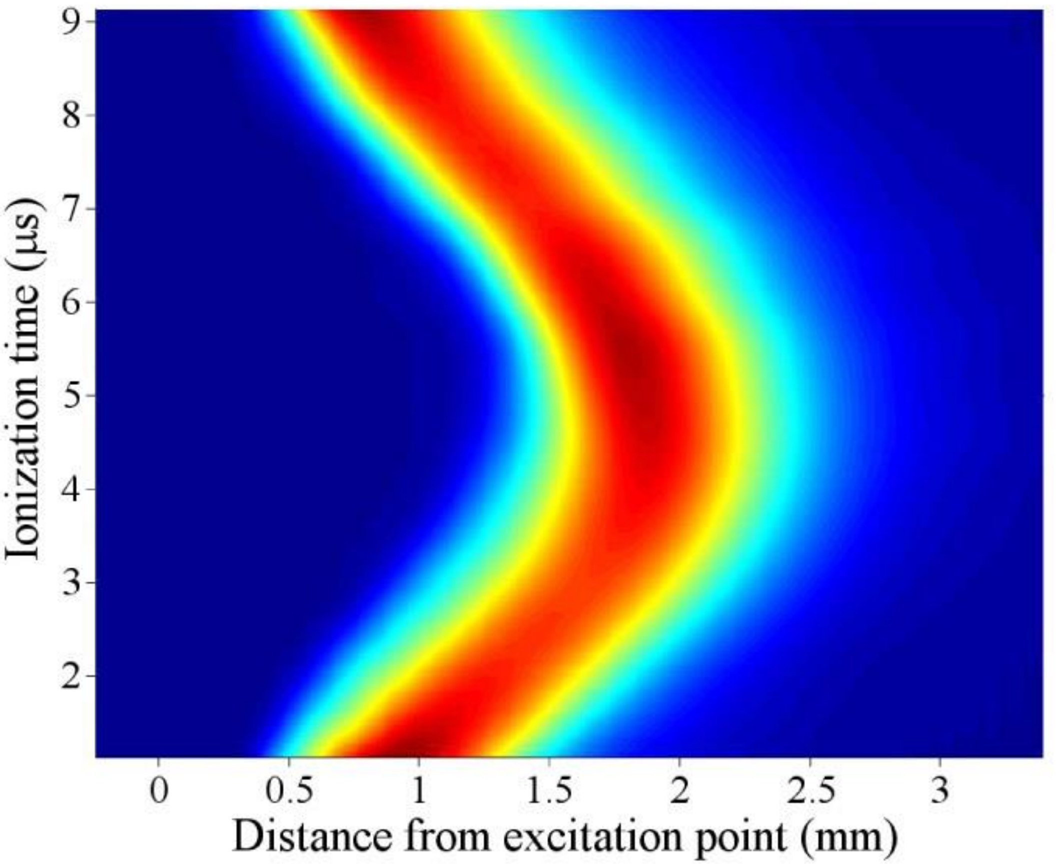



A 2-photon 1S-nD transition might make it possible to populate selected Rydberg Stark states, as is likely to be required for efficient population of the longer-lived high angular momentum states.

PRL **108** 043401 (2012)

S. D. Hogan, Phys Rev A **87** 063423 (2013)

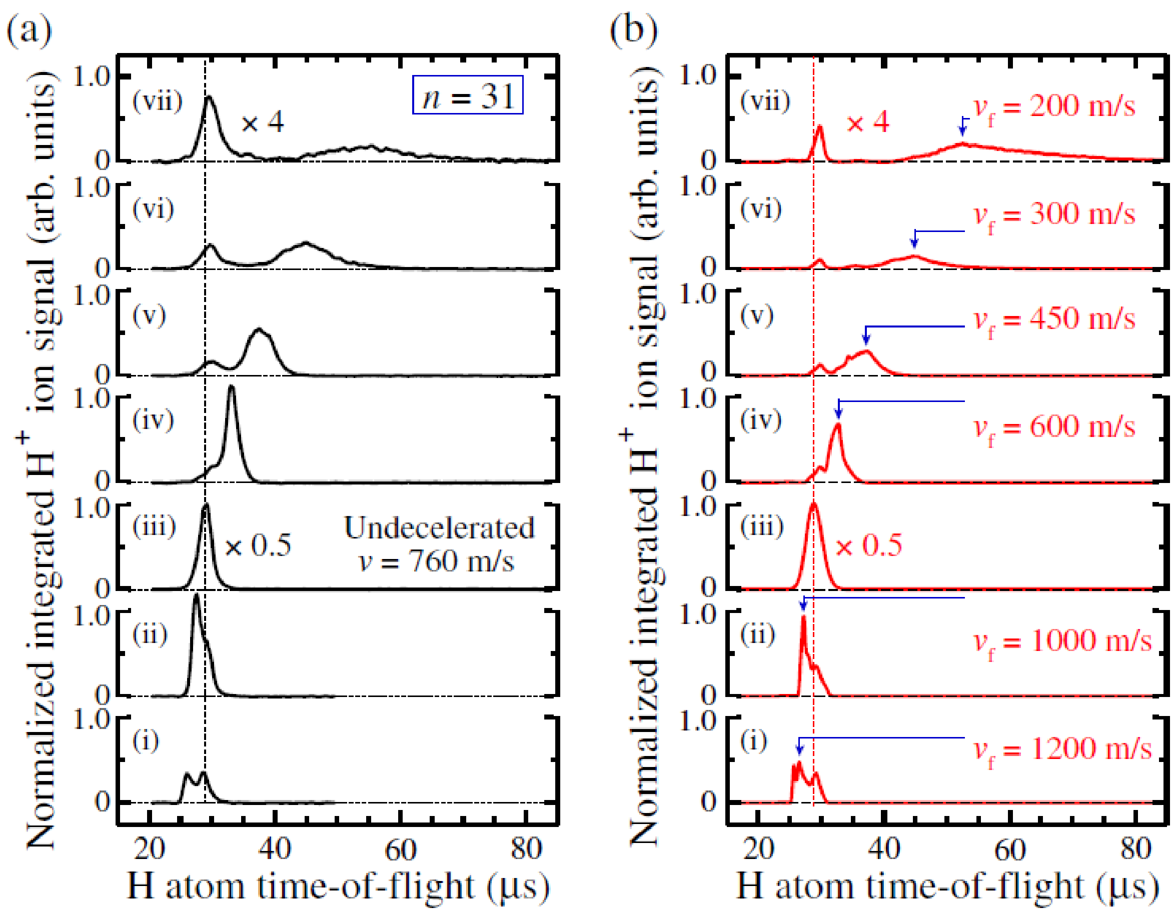
# Rydberg atoms have large electric dipole moments and so can be manipulated by field gradients: For example, **Electrostatic Rydberg Mirror**




The maximum induced electric dipole moment in Ps is
$\mu \sim 3n^2 e a_B$
(it is different for different sub states) so can get quite large for Rydberg atoms. The Stark energy shifts mean that field gradients can exert a force on such atoms, making it possible to manipulate them. Also, Ps is light and highly polarizable which suggests that this might be a very efficient way to control Ps atoms, even in the ground states (with a strong laser field)

E. Vliegen and F. Merkt "*Normal-Incidence Electrostatic Rydberg Atom Mirror*" Phys. Rev. Lett. **97**, 033002 (2006)

# Fast (Rydberg) Ps atoms can be slowed down using Stark deceleration:




Experiment (a) and simulation (b) of Stark acceleration and deceleration of n = 31 Hydrogen atoms

If it can be implemented with reasonable efficiency this technique could also be very useful for many different experiments using Ps, such as scattering or precision spectroscopy

S. D. Hogan, *et al.*, *Surface-Electrode Rydberg-Stark Decelerator,* Phys. Rev. Lett. **108**, 063008 (2012)

# Concluding remarks:

- Ps gravity experiments are not going to be easy, the main problems being related to the production of sufficiently cold Ps and appropriate Rydberg Ps states as well as the implementation of Ps "atom optics"
- The first stages of the experiment are now beginning at UCL, including remoderation of the pulsed beam, production of cold Ps, and evaluation of Doppler free two-photon transitions and BBR effects on Rydberg states.  Once these are understood it will be easier to plan for focusing and circular state production
- There are a lot of interesting stand alone experiments to be done as part of the larger project that can be useful for other work (spectroscopy, atom trapping and deceleration, scattering etc)
- As we have essentially no data, any measurement resulting from this experiment will be of great importance *no matter what the outcome* (same for hbar)

# Collaborators

Allen P. Mills, UCR

Adric Jones, Vincent Meligne, Tomu Hisakado, Harry Tom, *UCR*
Rod Greaves, *First Point Scientific Inc*.
Laszlo Liszkay, Patrice Perez, *CEA*, *Saclay*
Stephen Hogan, Peter Barker *UCL*

*Funding from US Air Force & NSF,*
*EPSRC*, *Leverhulme Trust*, *UK*

Thank you for your attention