Plasmas and Trap-Based Beams as Drivers for New Science with Antimatter

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* Supported by the U. S. NSF, DoE and the UCSD Foundation

GEC October 9, 2020

Well, a better title for this audience is:

Gaseous Electronics with Antimatter

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The Mirror World of Antimatter

positron ↔ electron

antiproton ↔ proton

New Particles:

Positron

$e^- + e^+ \Rightarrow$ gamma rays

$2\gamma^*$ $(S = 0)$ or 3γ $(S = 1)$

(2γ decay: $\varepsilon_\gamma = m_e c^2 = 511$ keV)

Antiproton

$p + \bar{p} \Rightarrow$ shower of pions (e.g., π^+, π^-)

New Atoms:

Antihydrogen ($\bar{p}e^+$) : $E_B = 13.6$ eV (stable)

Positronium atom (e^+e^-): $E_B = 6.8$ eV

$\tau_{s=0} = 0.12$ ns; $\tau_{s=1} = 140$ ns

Tailoring and Delivery of Trapped Antimatter

Antiparticles are scarce in our world of matter

Confine antiparticles as a **single-component plasma**
in an electromagnetic trap

Accumulate, tailor the plasma, then tailor
the delivery for specific applications

Outline

Tools for antimatter studies

- Trapped antimatter
  - Efficient trapping
  - Cooling
  - Radial compression (for density control)
- Beams and delivery
  - Narrow energy spreads
  - Time bunching
  - Merging plasmas
  - High quality Ps beams

New science

- Positron binding to matter
- Precision measurements on Ps and $\bar{H}$
- Ps BEC and e^+- e^- ("pair") plasma

Sources of e^+ and $\bar{p}$

Positrons (energies ~ keV - MeV)

Radioisotopes (^{18}F, ^{58}Co, ^{22}Na)

(portable, or reactor-based)

Electron accelerators (e.g., LINACs)

($\varepsilon \geq 2m_e c^2 = 1$ MeV)

Antiprotons (energies ~ GeV)

Particle accelerators (CERN, Fermilab)

(fast protons: $\varepsilon_p \geq 6\ m_p c^2 \sim 5.6$ GeV)

Use materials (degraders or moderators) to slow antiparticles to eV energies

History of Trapped Antimatter – the March Goes On

Antiprotons, Penning trap, Gabrielse, 1986

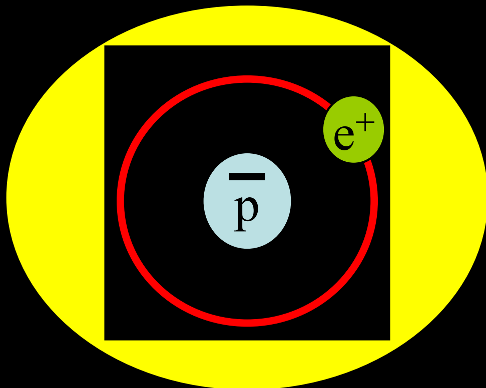
Positron plasma, Penning-Malmberg trap, 1989

Merge antiprotons & positrons for antihydrogen
ATHENA, ATRAP, 2002

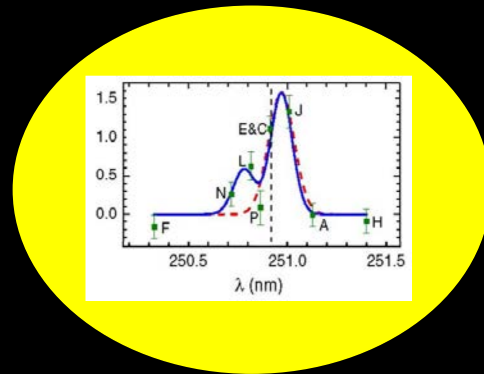
Trap antihydrogen, ALPHA, 2010

High-quality positronium atom beams
Riverside, London, and Tokyo (~2018 - 2020)

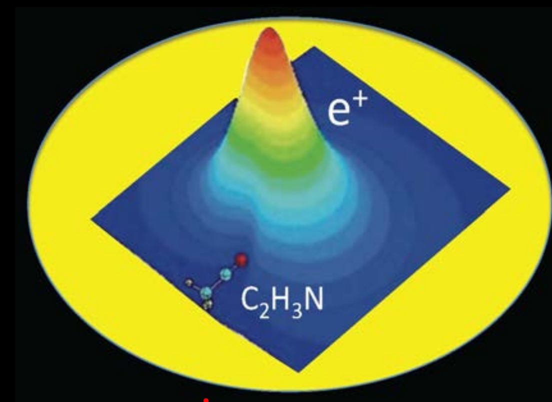
Antimatter
Exploiting the Plasma Connection



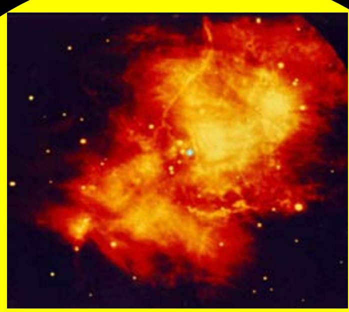
antihydrogen



Positronium physics
Ps_2, Ps beams

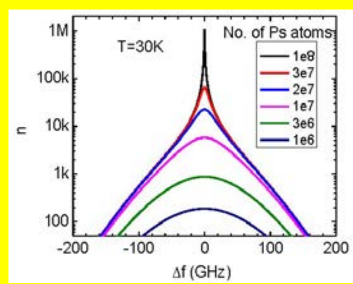


positron-matter binding



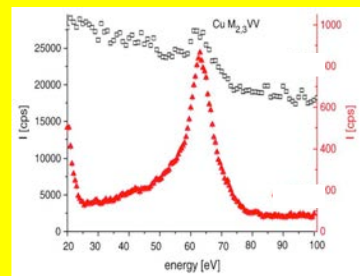
Pulsar crab nebula

e^+- e^- (pair) plasmas



γ-ray line

Ps-atom BEC



positron-Auger

trap-based beam
Munich high-flux positron source

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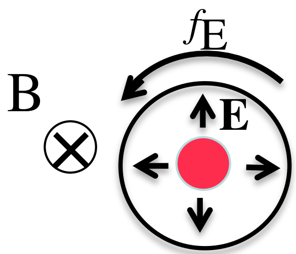
Trapping antiparticles

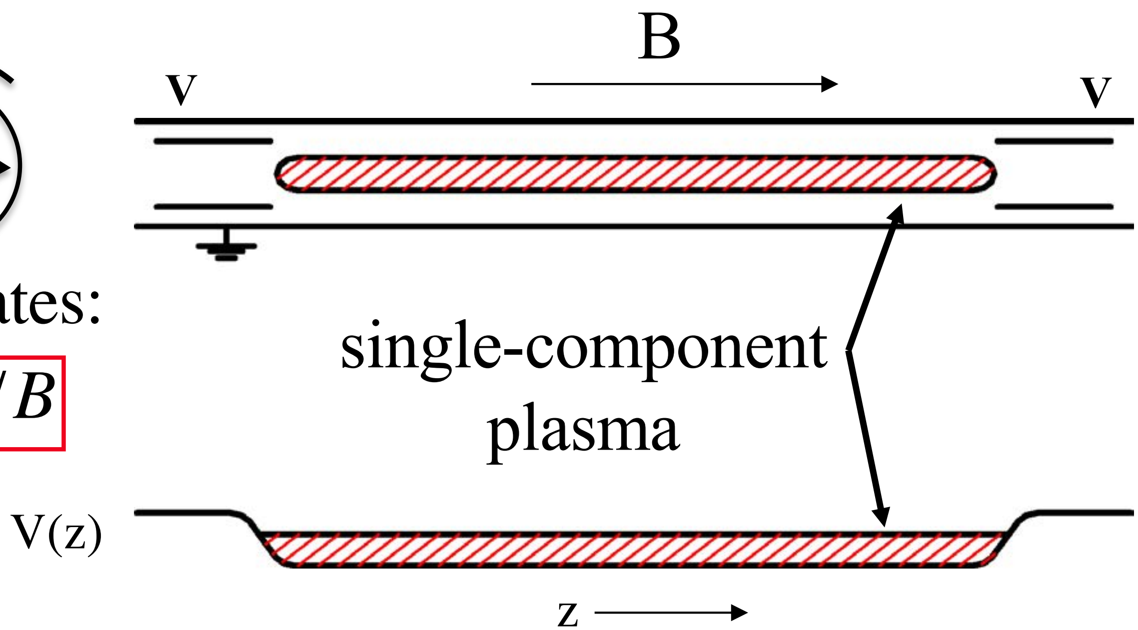
A Near-Perfect "Antimatter Bottle"

the Penning-Malmberg Trap



plasma rotates:

$$f_E = cne/B$$



John Malmberg
(1927 – 1992)

Canonical angular momentum $L_z \approx -\frac{m\omega_c}{2}\sum_j r_j^2$

No torques $\Rightarrow$ $\sum_j r_j^2$ constant. No expansion!

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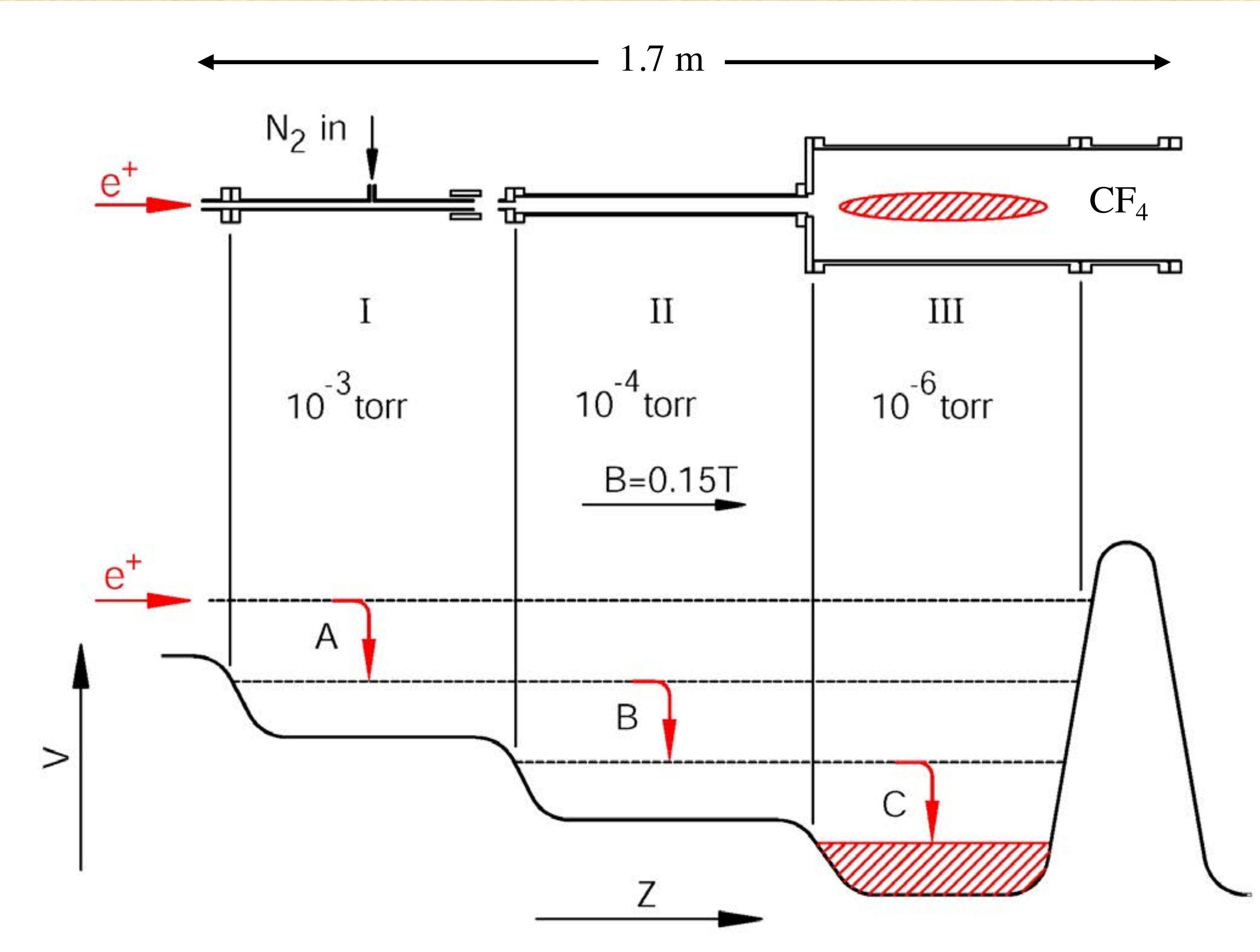
(Malmberg & deGrassie '75; O'Neil '80)

Buffer-Gas Positron Trap
(*down-home gaseous positronics!*)

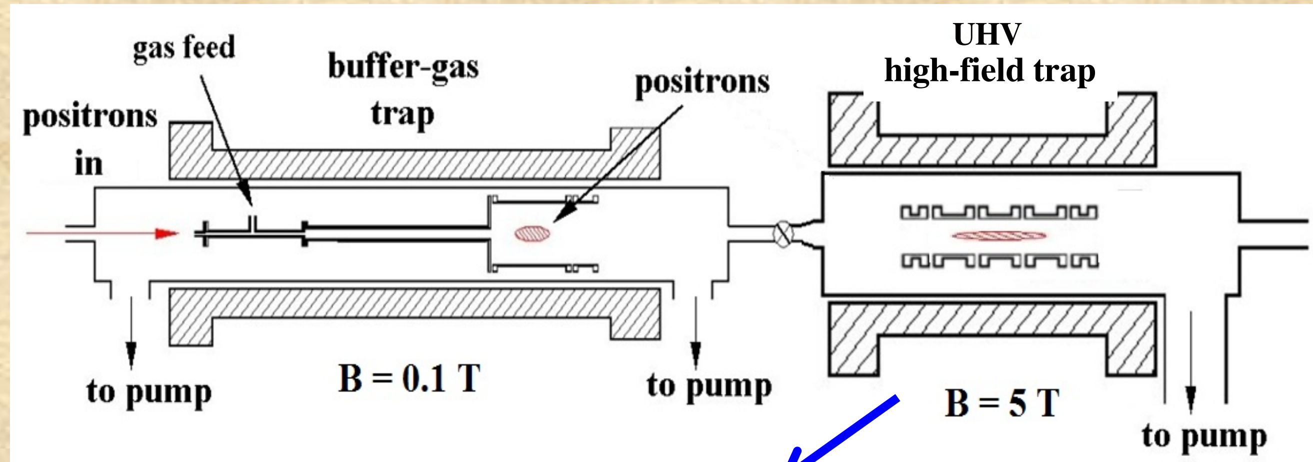


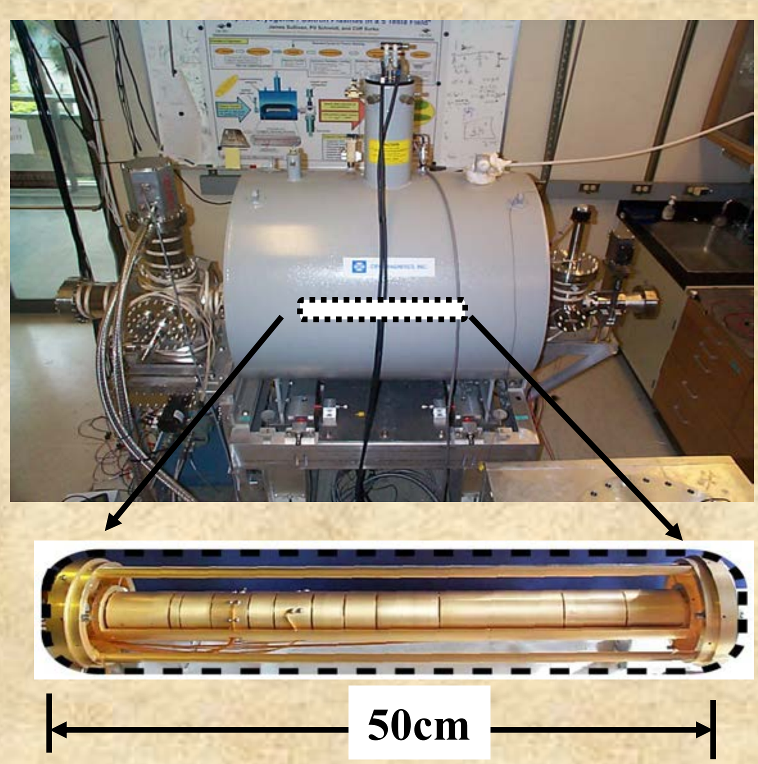
- Trap using electronic excitation of N_2
- Positrons cool to 300K on CF_4 in ~ 0.1s

30% trapping efficiency
using Ne moderator

Surko PRL '88; Murphy, PR '92

Shuttle to UHV for Long Term Storage





annihilation negligible

Plasma cools by cyclotron radiation

$\Gamma = 0.26\ \mathrm{B}^2(T)\ s^{-1}$

$\tau_c \approx 0.2\ s$

Confinement times of days possible

Surko, Greaves, Charlton
Hyperfine Int. 1997

Antiparticle Cooling

Critical for Most Applications

Collisional cooling on molecules 50 K

Cyclotron radiation for positrons and electrons 10 K

Laser cooling (sympathetic on Be^{+}, for positrons) 5 K

Evaporation (positrons or antiprotons) 10 K

Latest result:

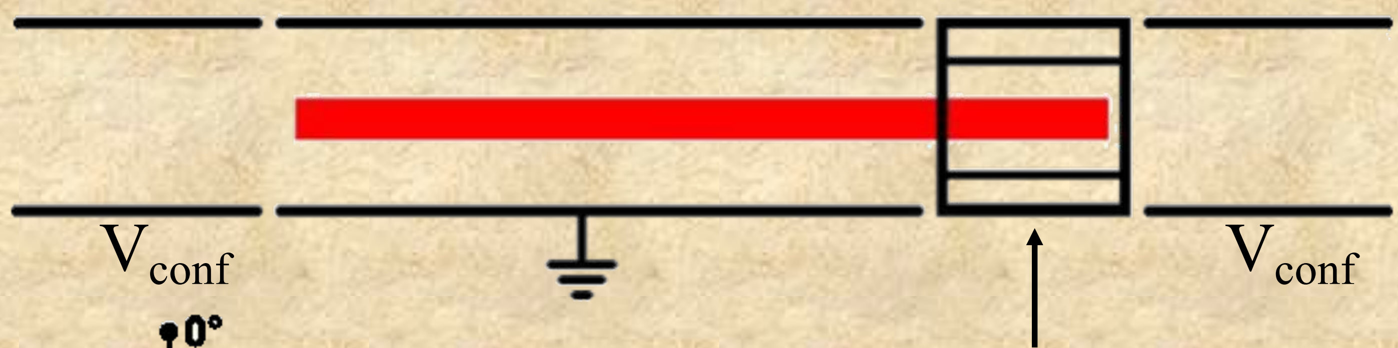
Cyclotron cooling in a resonant cavity increases cooling rate by x 100!* **T = 10 K** (B = 0.15 tesla)

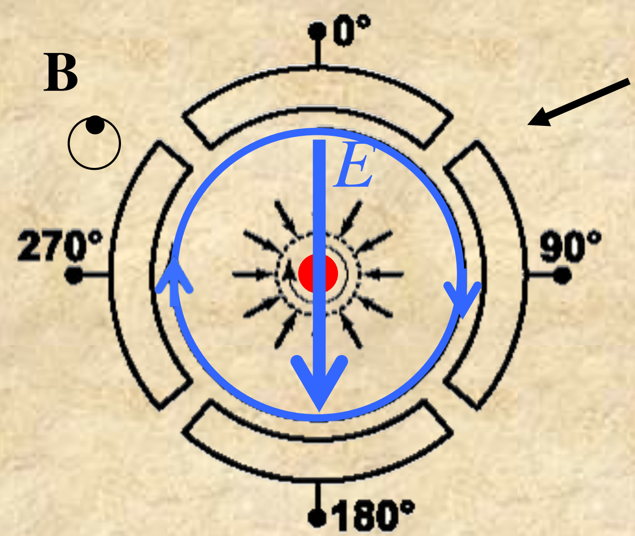
estimates of temperatures achieved to date

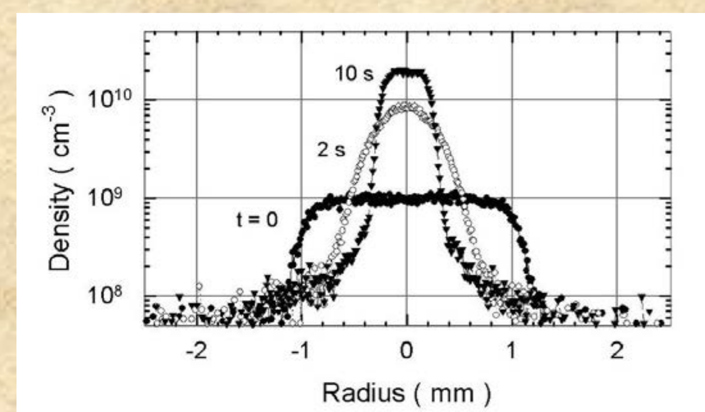
*Hunter & Fajans Phys. Pl. (2018)

Increase Density by Radial Compression with Rotating Electric Fields

"The Rotating Wall Technique"







$V = \mathbf{V_{RW}} \cos[(2\pi \boldsymbol{f}_{\mathbf{RW}})\, t + \phi]$

(Huang, Anderegg, Hollmann, Greaves, Danielson, 1997 - 2007)

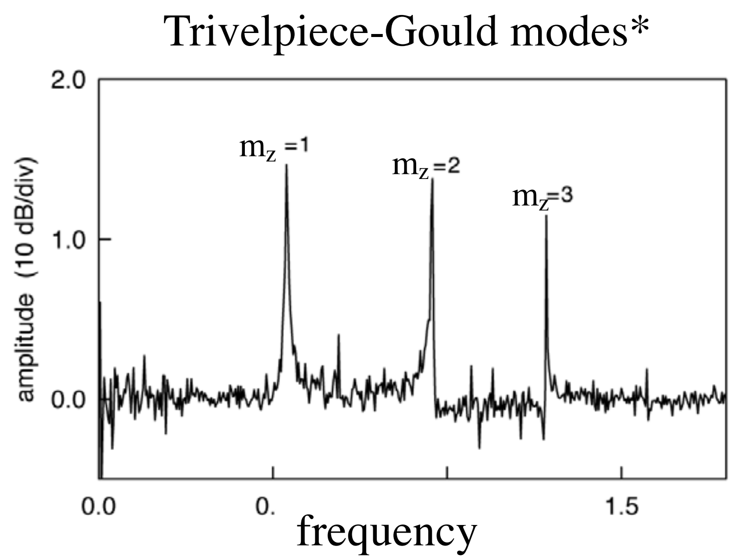
Apply a torque using a rotating electric field =>
radial compression for $f_{RW} > f_E$

Positron Plasma Parameters

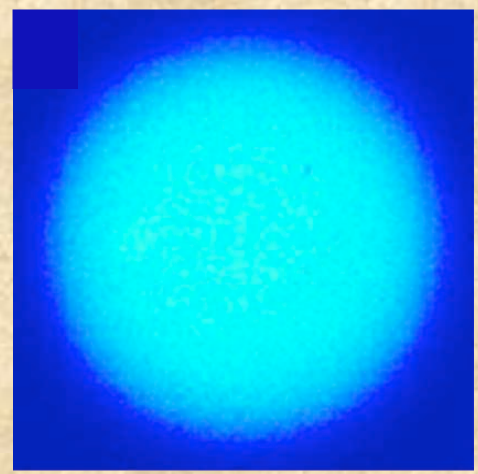
Magnetic field	10^{-2} – 5 tesla
Number	10^{4} - 10^{9}
Density	10^{5} - 10^{10} cm^{-3}
Space charge	10^{-3} – 10^{3} eV
Temperature	10^{-3} – 1 eV
Plasma length	1 – 30 cm
Plasma radius	0.5 – 10 mm
Debye length	10^{-2} – 1 cm
Confinement time	10^{2} – 10^{6} s

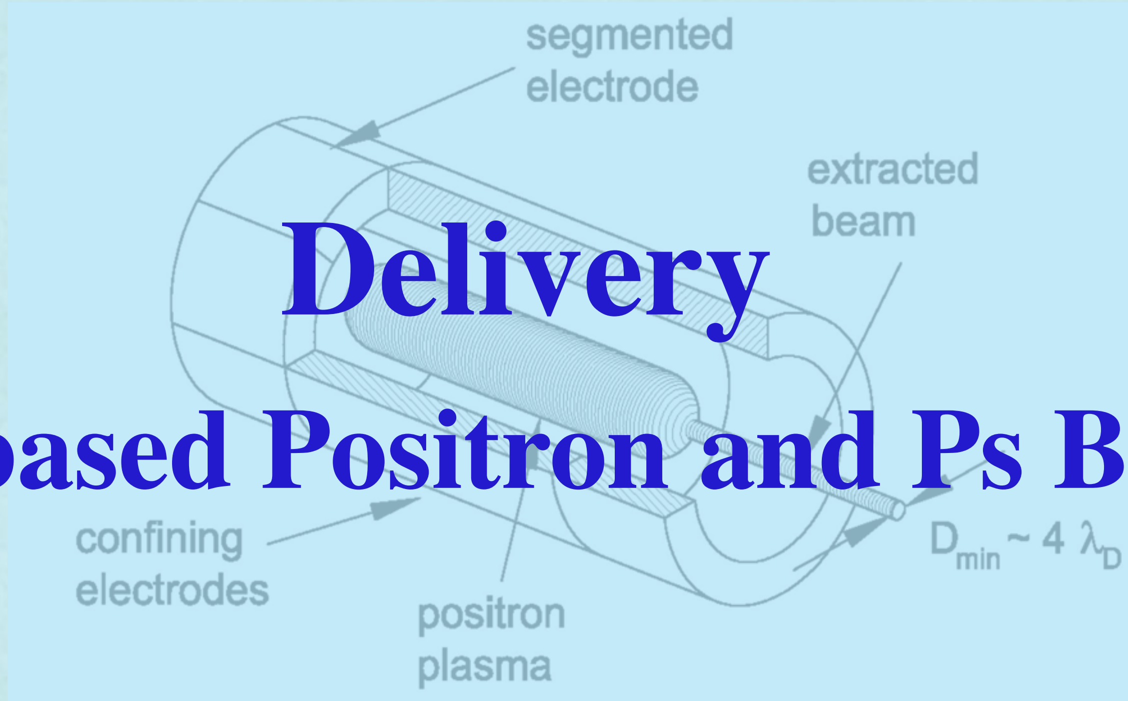
Diagnostics:

- modes to measure N, n, T, & aspect ratio
- evaporate to measure temperature
- 2D CCD images



Dubin PF '93, Tinkle PP '94


Surko AIP '99, Weber PP '08



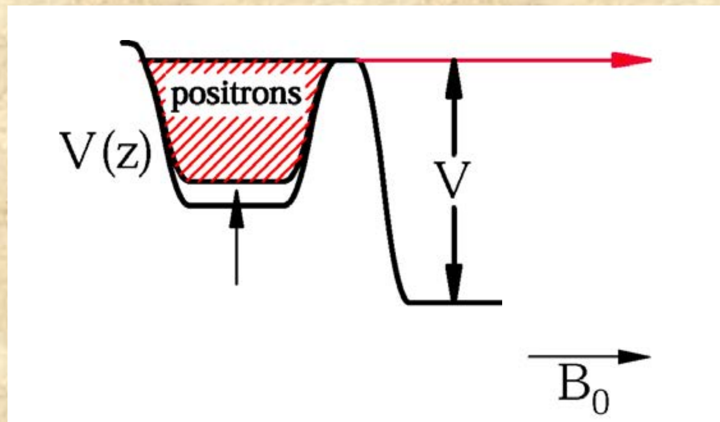
Delivery

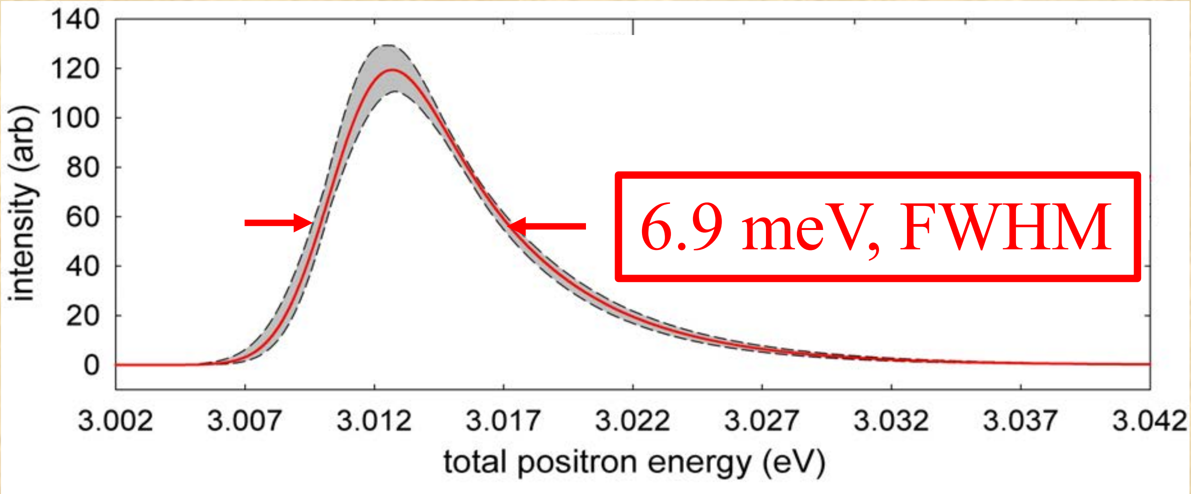
Trap-based Positron and Ps Beams

Cold Positron Beam

Cryogenic Buffer-Gas Trap at 50 K

Trap, cool and release:





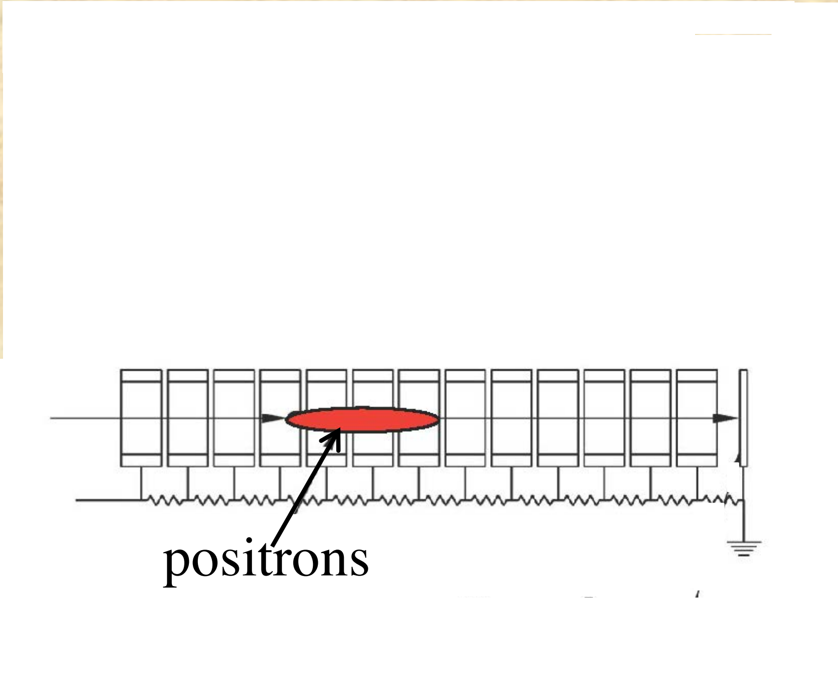
CO cooling gas

Tunable from ~ 20 meV to tens of volts

Natisin, et al., APL (2016)

Trap-based Beams – **Bunch in Time**

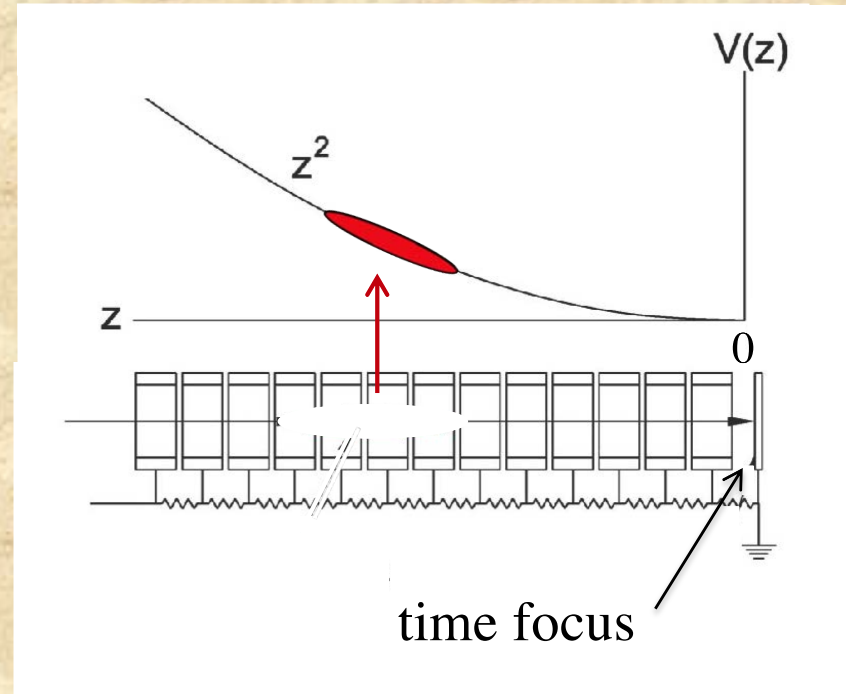
"harmonic bunching" using a parabolic potential



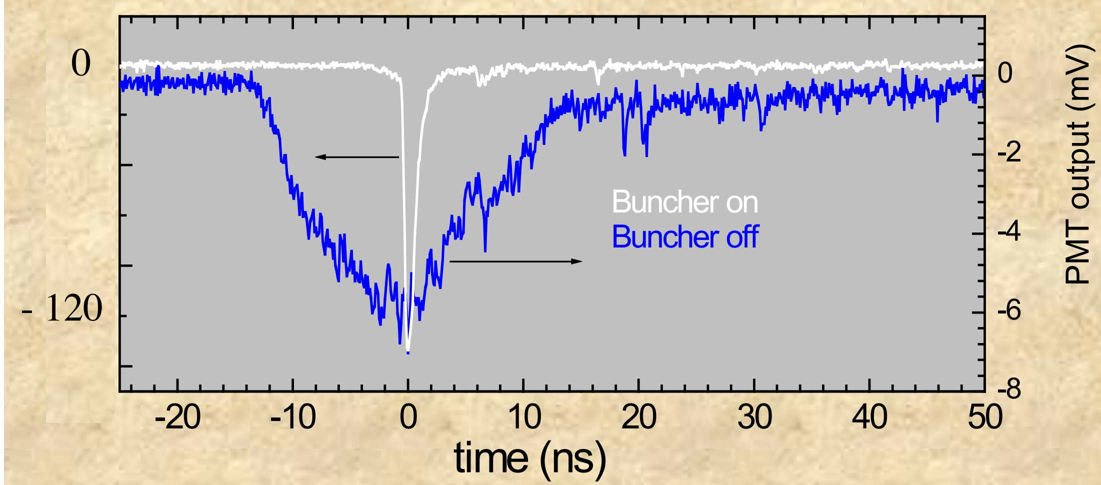
Cassidy, RSI 2006

Trap-based Beams – **Bunch in Time**

"harmonic bunching" using a parabolic potential



positrons



15 ns pulse -> 1 ns pulse

Cassidy, RSI 2006

Manipulating Ps Atoms and Novel Ps Beams

exploiting pulsed lasers

Trap efficiently

Cool

Compress radially

Bunch in time

=> then laser excitation

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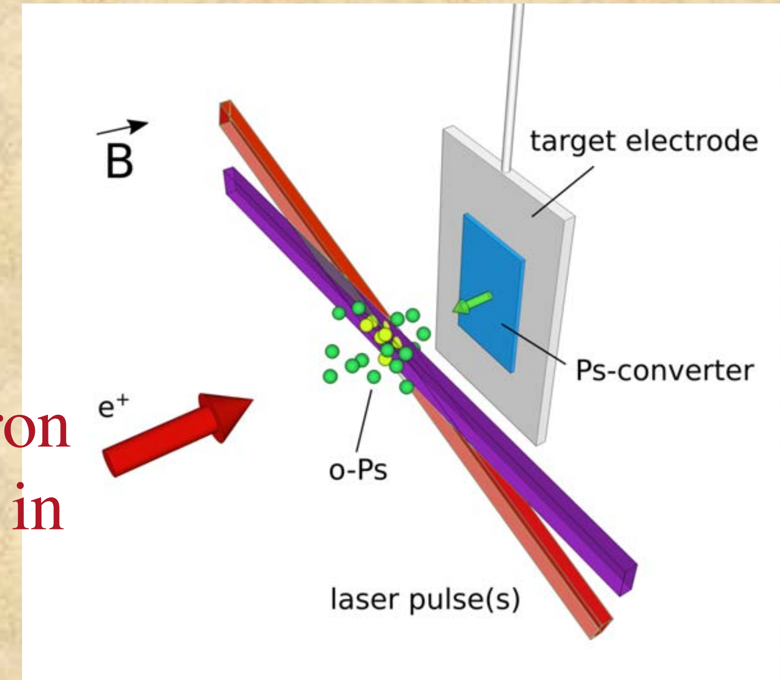
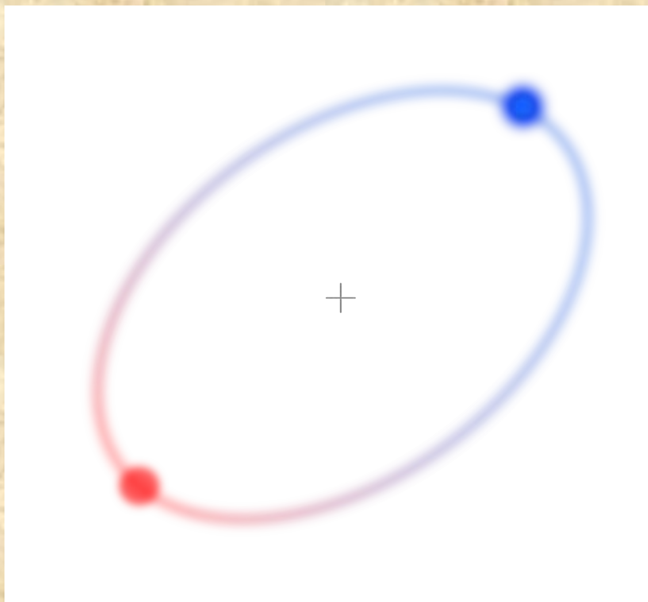
High-Rydberg-state Positronium

Tailored positron pulses, cooled, compressed in space and time

Positron pulse in





S = 1 positronium atoms

Large principle quantum number n
=> weak positron-electron overlap, so long lifetime

Short e+ Pulses Enable Laser Manipulation

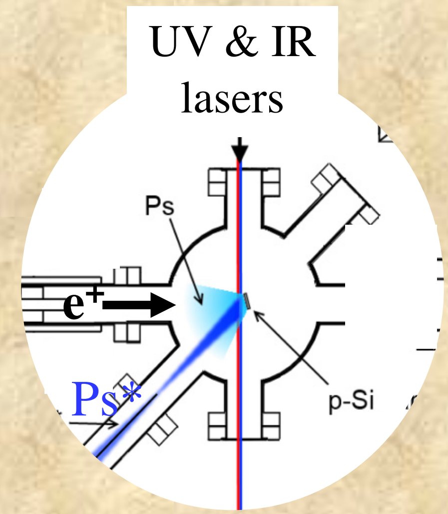
High-Rydberg Ps Beams

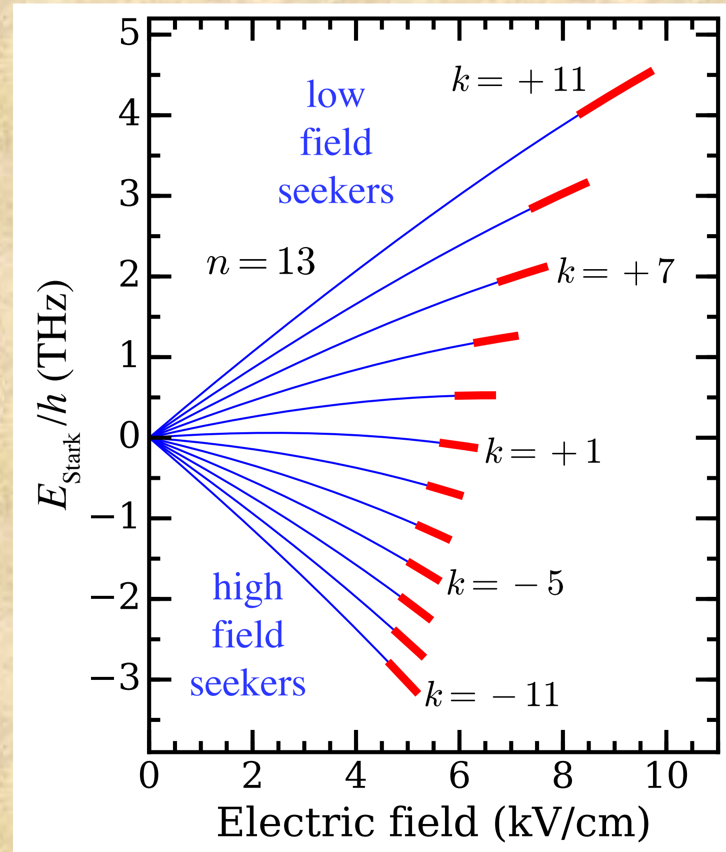
Positron pulses, cooled, compressed in space and time. Match to lasers

Stark states

Create Ps in an electric field => E-field manipulation

Positrons in



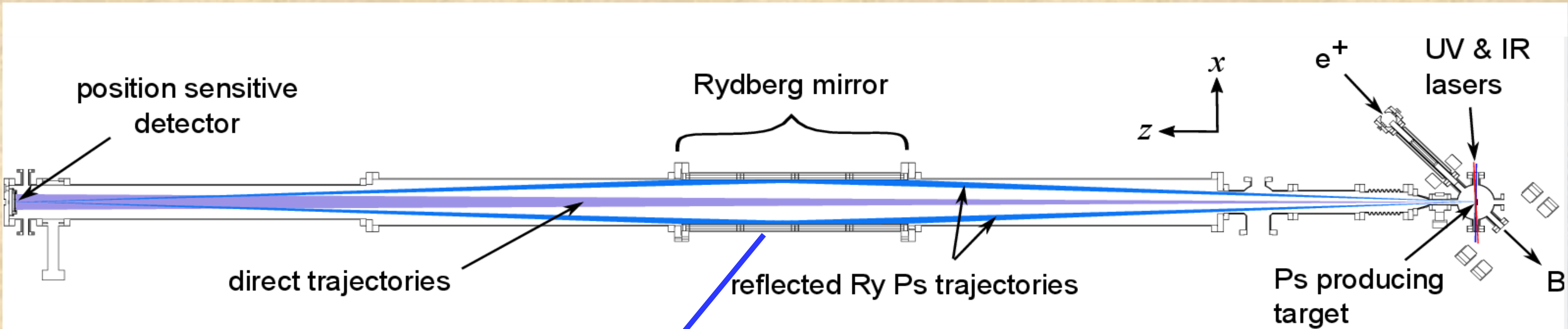


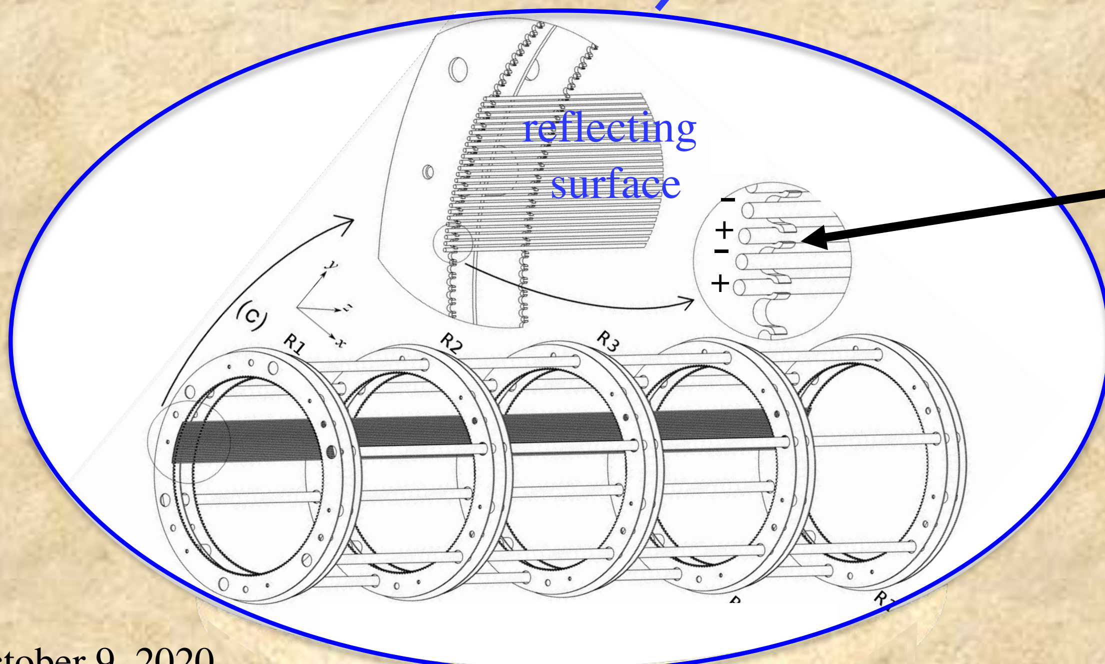
giant dipole moments

Rydberg Ps Atom Stark Focusing Mirror

Focus low-field seekers

L ~ 6.0 m





ε_{Ps} ~ 0.25 eV

High electric field repels the low-field seekers

Jones, PRL (2017)

Higher-energy Ps Beams

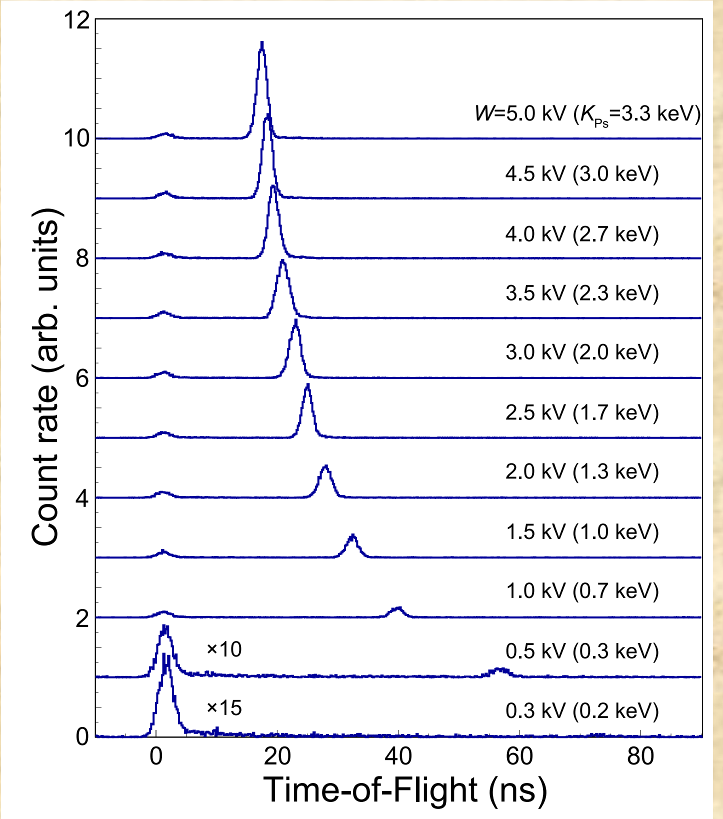
Positron pulses, cooled, compressed in space and time - <u>match to laser</u>

Accelerate and laser-strip Ps^-

Na-coated W film

$$e^+ \rightarrow Ps^-$$
$$Ps^- + h\nu \rightarrow \mathrm{Ps}$$

beam energy	0.3 – 3 keV
divergence	0.3°



One goal: Ps diffraction from material surfaces

Michishio, Nakagima, et al., RSI (2019)

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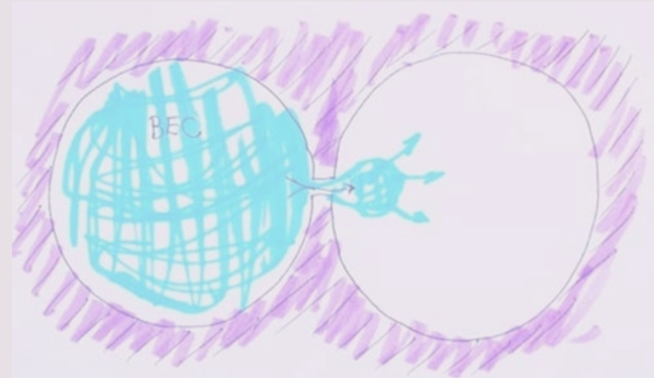
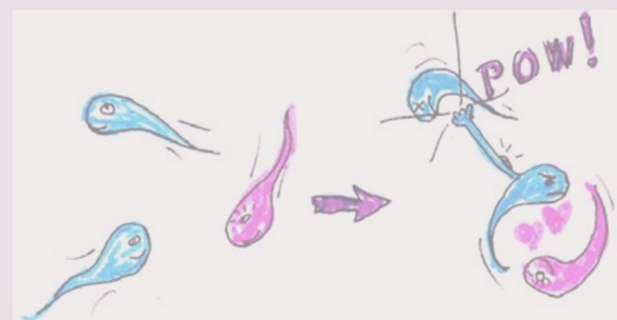


New Science with Antimatter

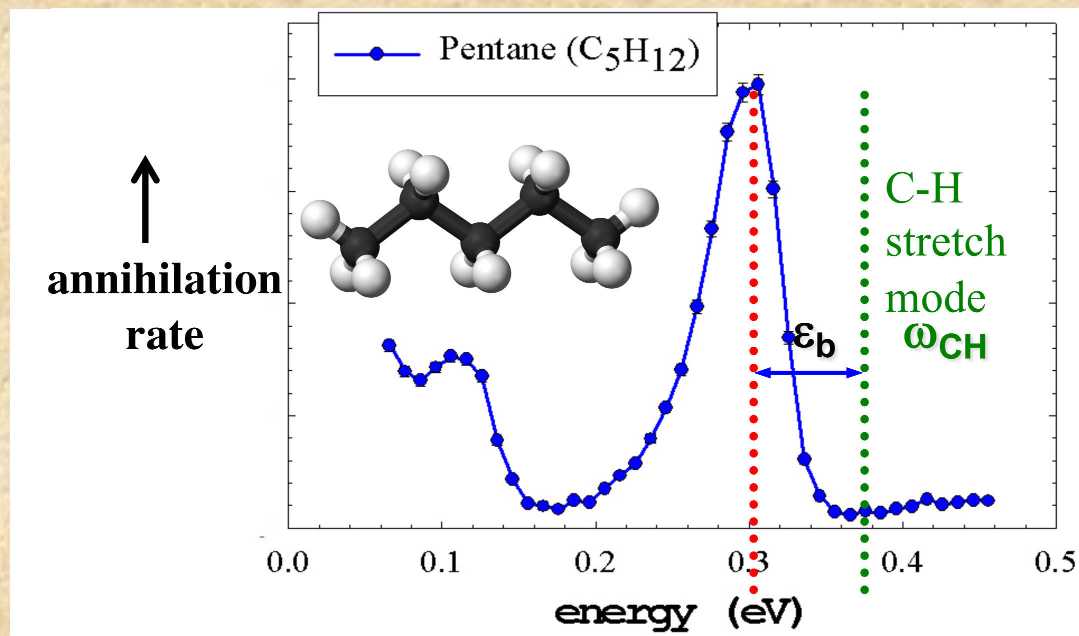


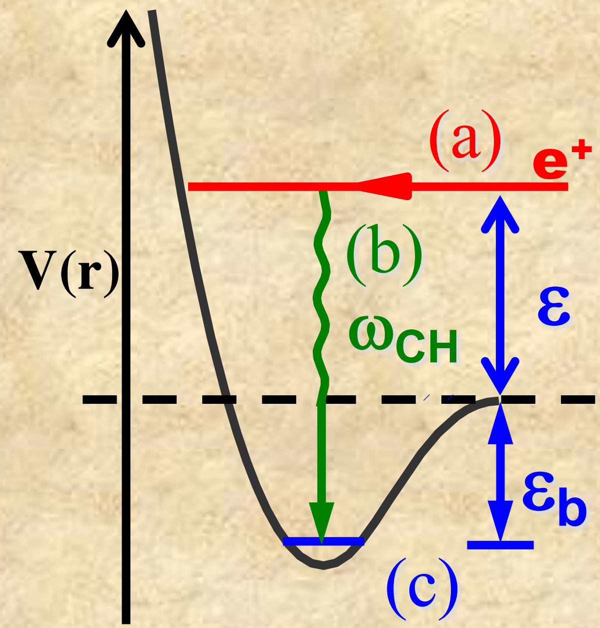
Sketches by
A. P. Mills, Jr.

Atomic Physics

Positrons Bind to Atoms and Molecules

vibrational
Feshbach resonances





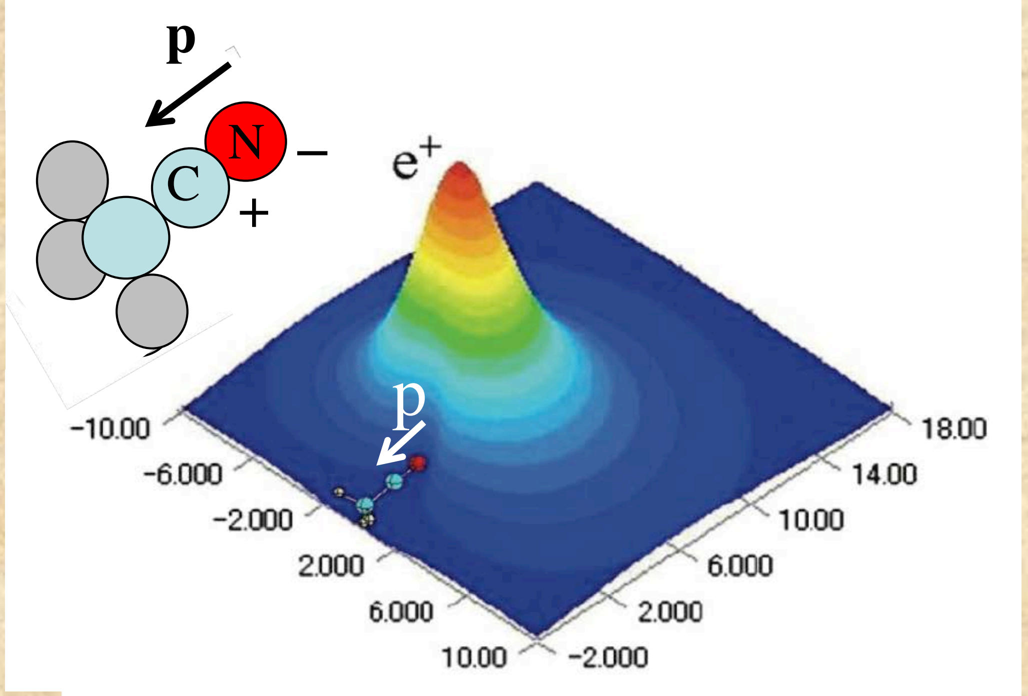
$$\varepsilon = \omega_{CH} - \varepsilon_b$$

Using cold positron beam, measured binding energies for > 85 molecules

Gilbert PRL, 2002; Gribakin RMP, 2010

Positron Binding to Molecules

Acetonitrile (C_2H_3N)



predicted: $\varepsilon_b = 135$ meV
measured: $\varepsilon_b = 180$ meV

Tachikawa, PCCP 2011

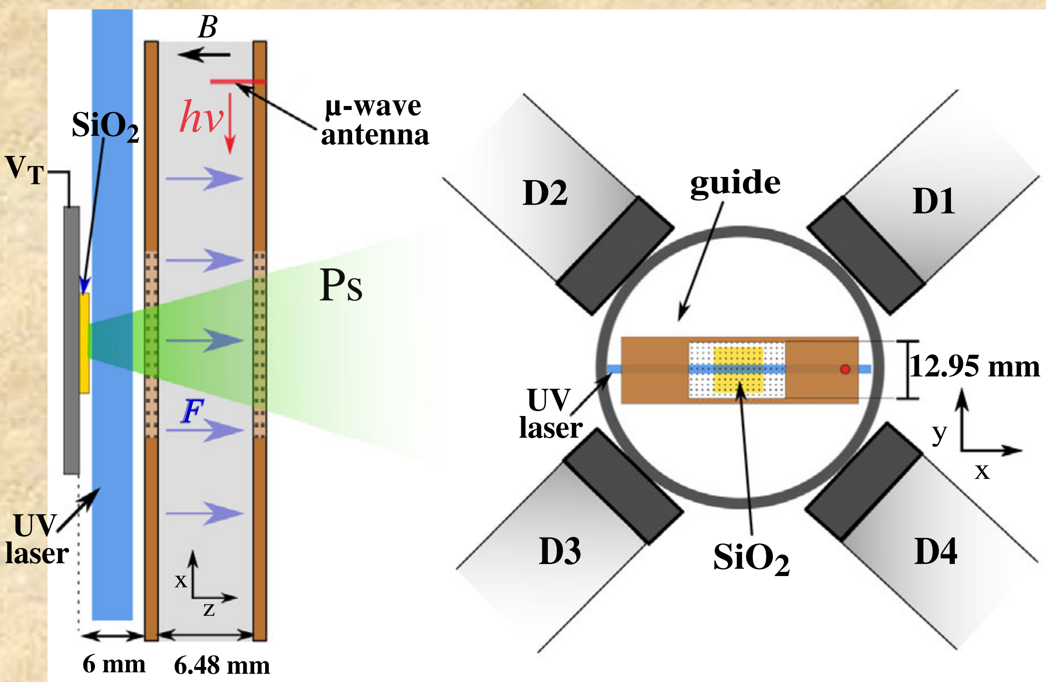
Complementary theory by
Swann, Gribakin
Dermot Green
(Belfast)

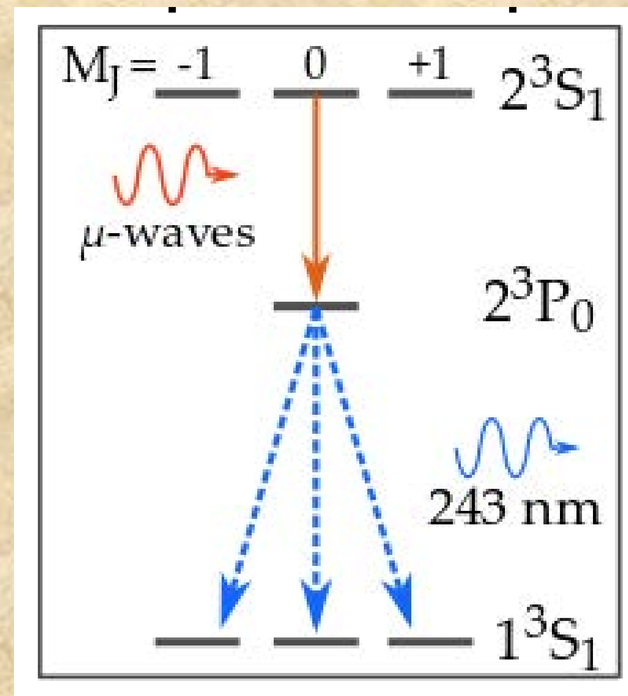
Want to understand $e^+ - e^-$ correlation & virtual positronium effects

Atomic Physics

Precision Measurement of the Fine Structure Positronium 2^3S_1 -> 2^3P_0 Transition

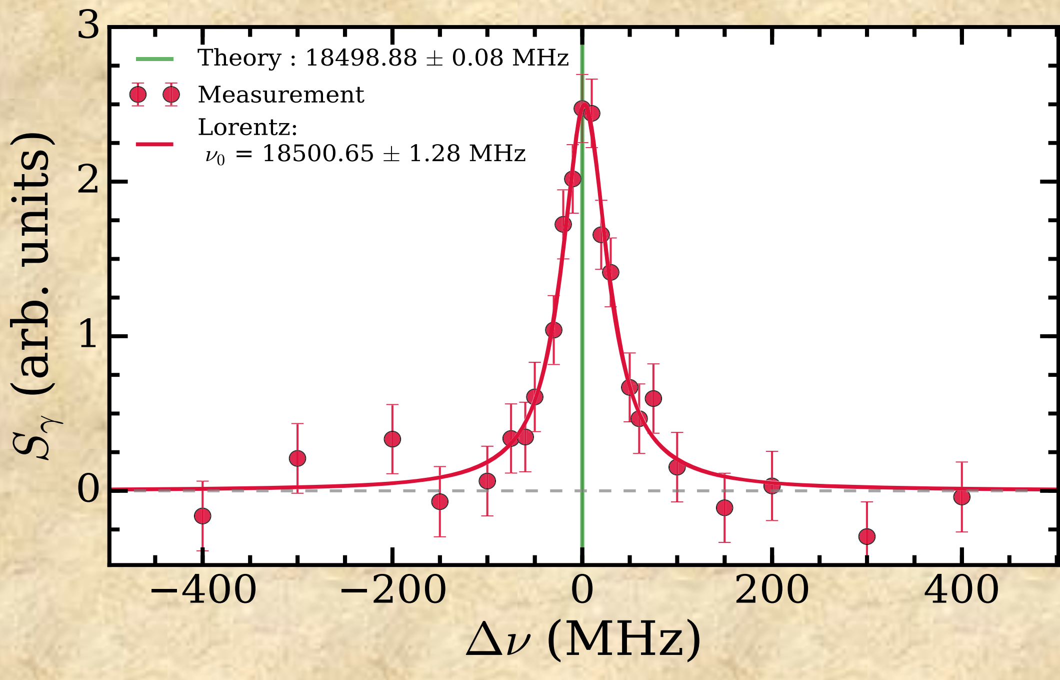
Positron pulses, cooled, compressed in space and time





Gurung, PRL (2020)

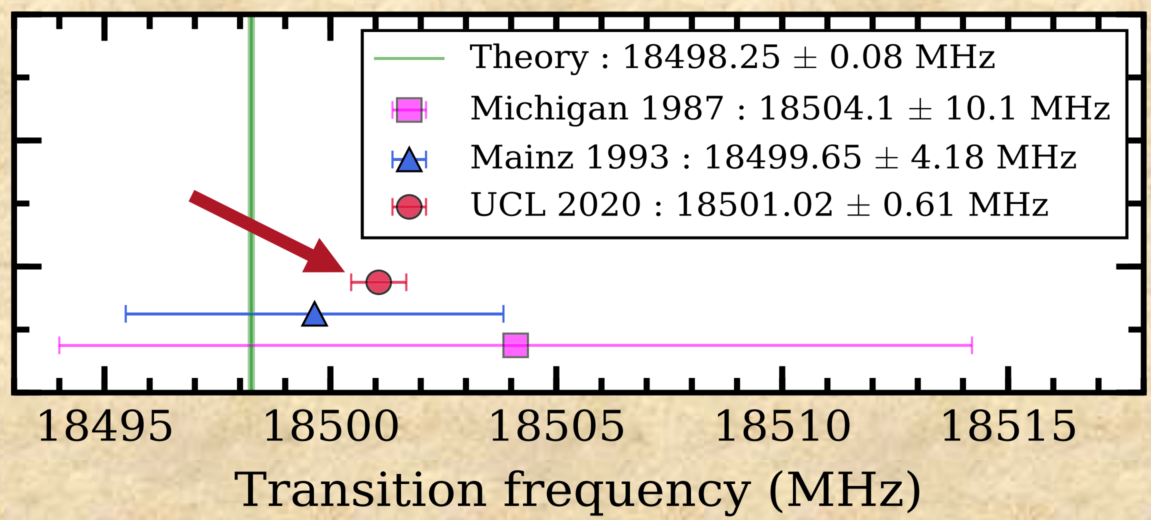
Positronium 2^3S_1 -> 2^3P_0 Transition



4.5 σ disagreement with theory at the mα^6 level.

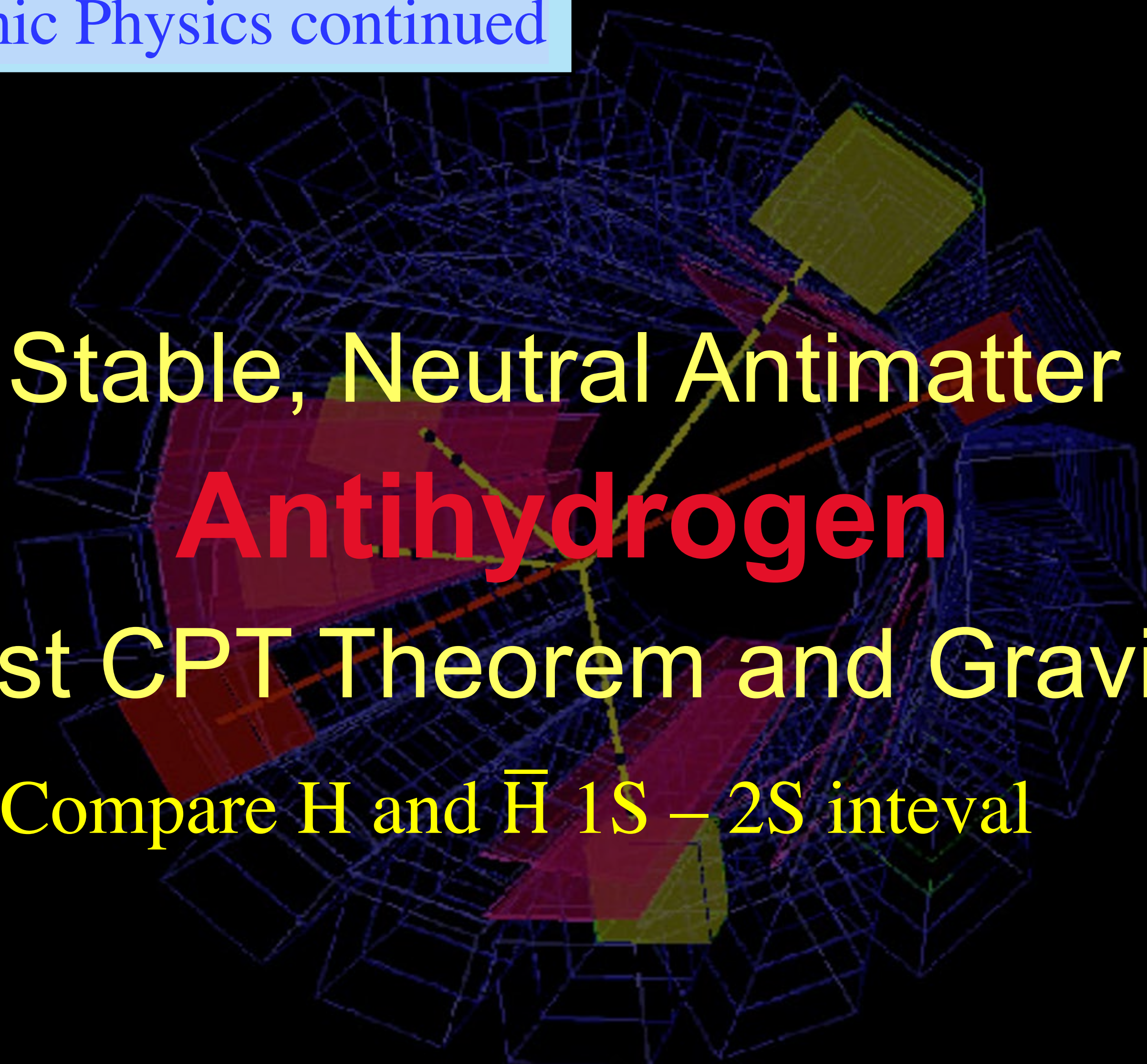
mα^7 in progress

A discrepancy!
theory?
experiment?
new physics?



Gurung, PRL (2020)

Atomic Physics continued



Stable, Neutral Antimatter

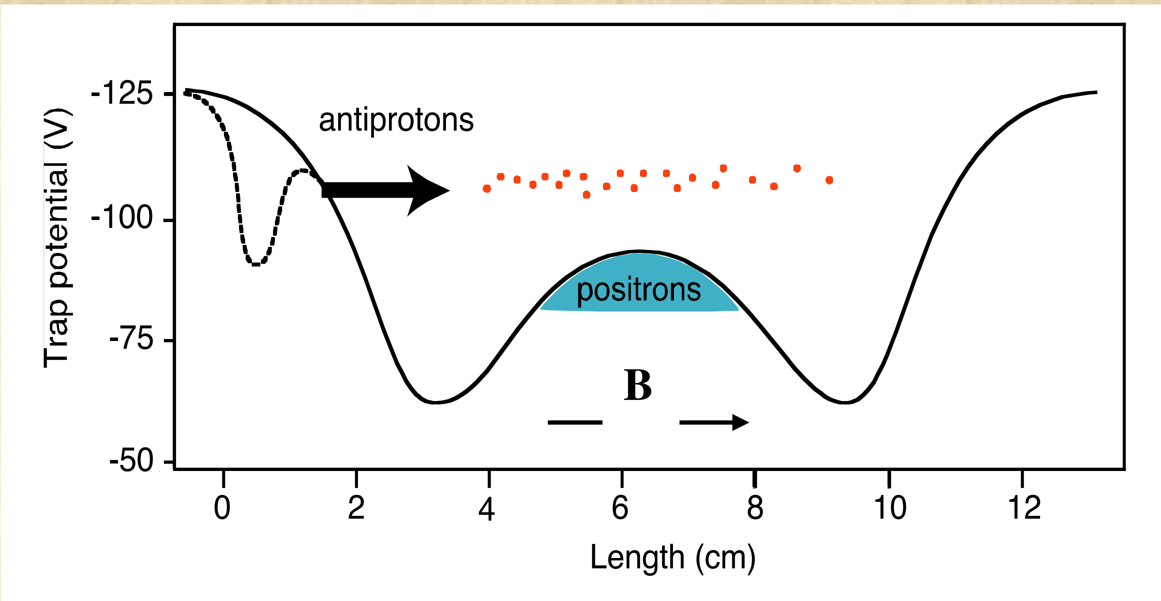
Antihydrogen

Test CPT Theorem and Gravity

Compare H and $\overline{\mathrm{H}}$ 1S – 2S inteval

Antihydrogen Production

Nested Penning traps



$\bar{p}$, e$^+$ plasmas trapped, cooled, RW-compressed

Trap positrons

Launch antiprotons into mixing region

Mix – make lots of antihydrogen!

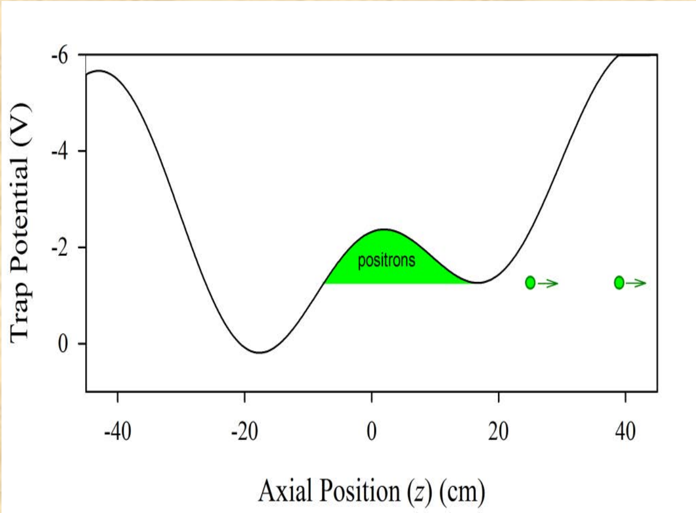
Formed by three-body collisions: $\overline{p} + e^+ + e^+ = \overline{H} + e^+$

ATHENA/ALPHA (2002-2007)

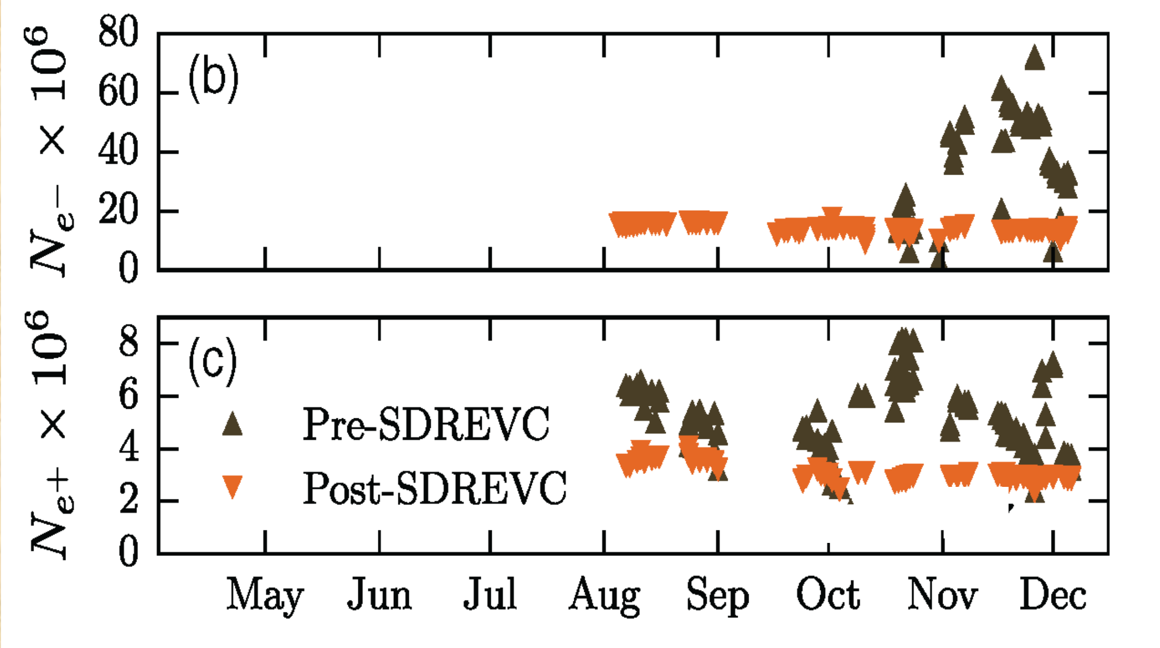
ATRAP similar

New Protocol for $\bar{H}$ Production (*gaseous leptonics*)

- Use Rotating Wall
  to set n
- Use evaporative cooling to
  set the plasma potential
- -> sets N, n and r_p



Use for
e^- **and** e^+ plasma
reproducibility

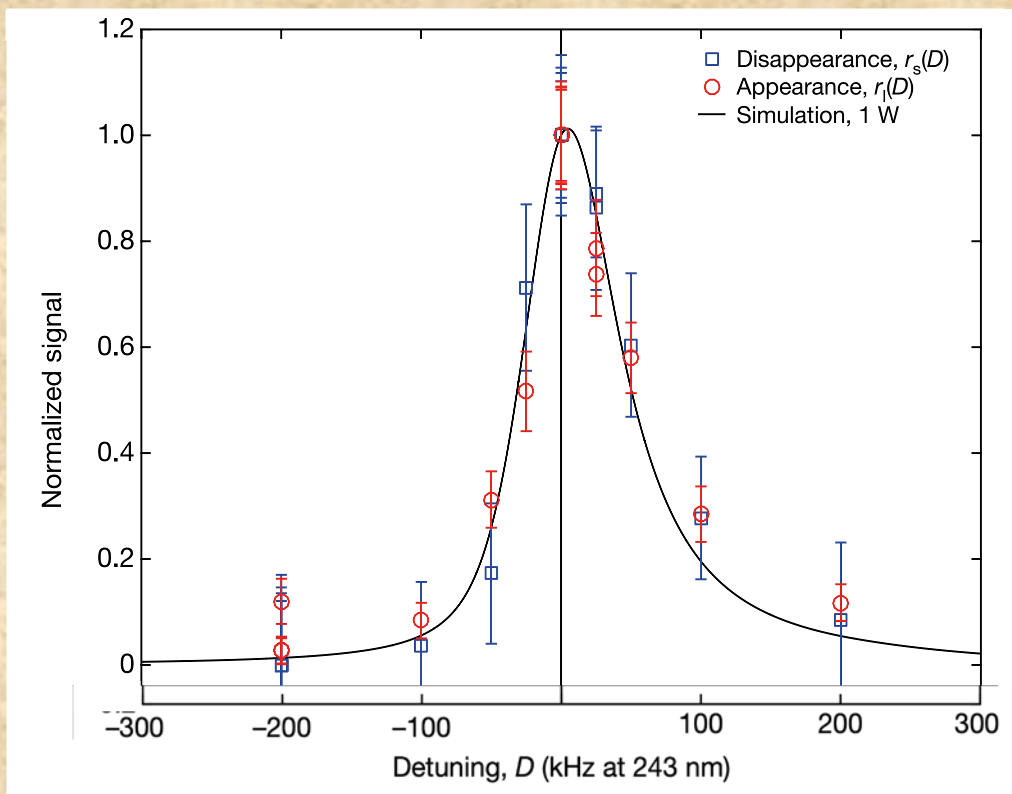


Number of trappable $\bar{H}$ increased tenfold!

Ahmadi, PRL (2018)

2-Photon Spectroscopy 1S – 2S Transition in $\bar{H}$ measured using SDREVC

Relative precision 2×10^{-12}!



Refined spectroscopy, & gravity tests in progress by several groups

Near term goal ~ 3×10^{-15}

Ahmadi, Nature (2018)

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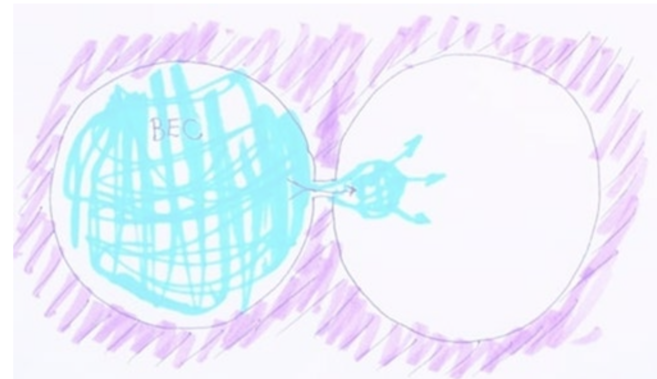
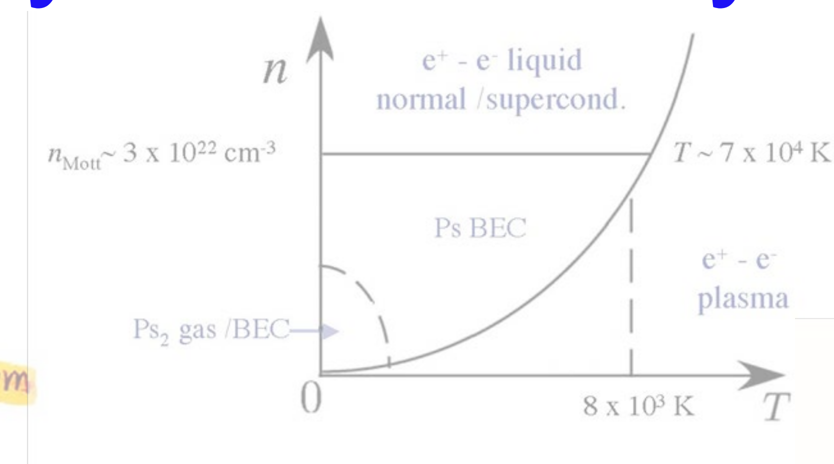


Many-Electron
Many-Positron System



Sketches by
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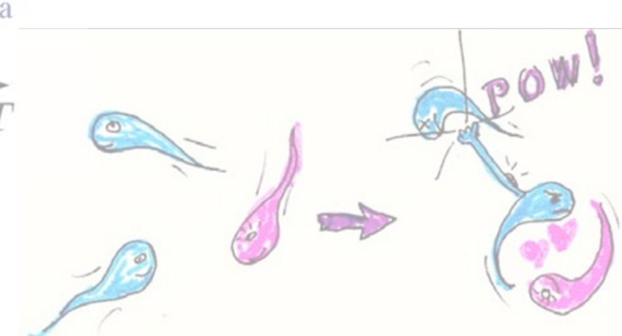
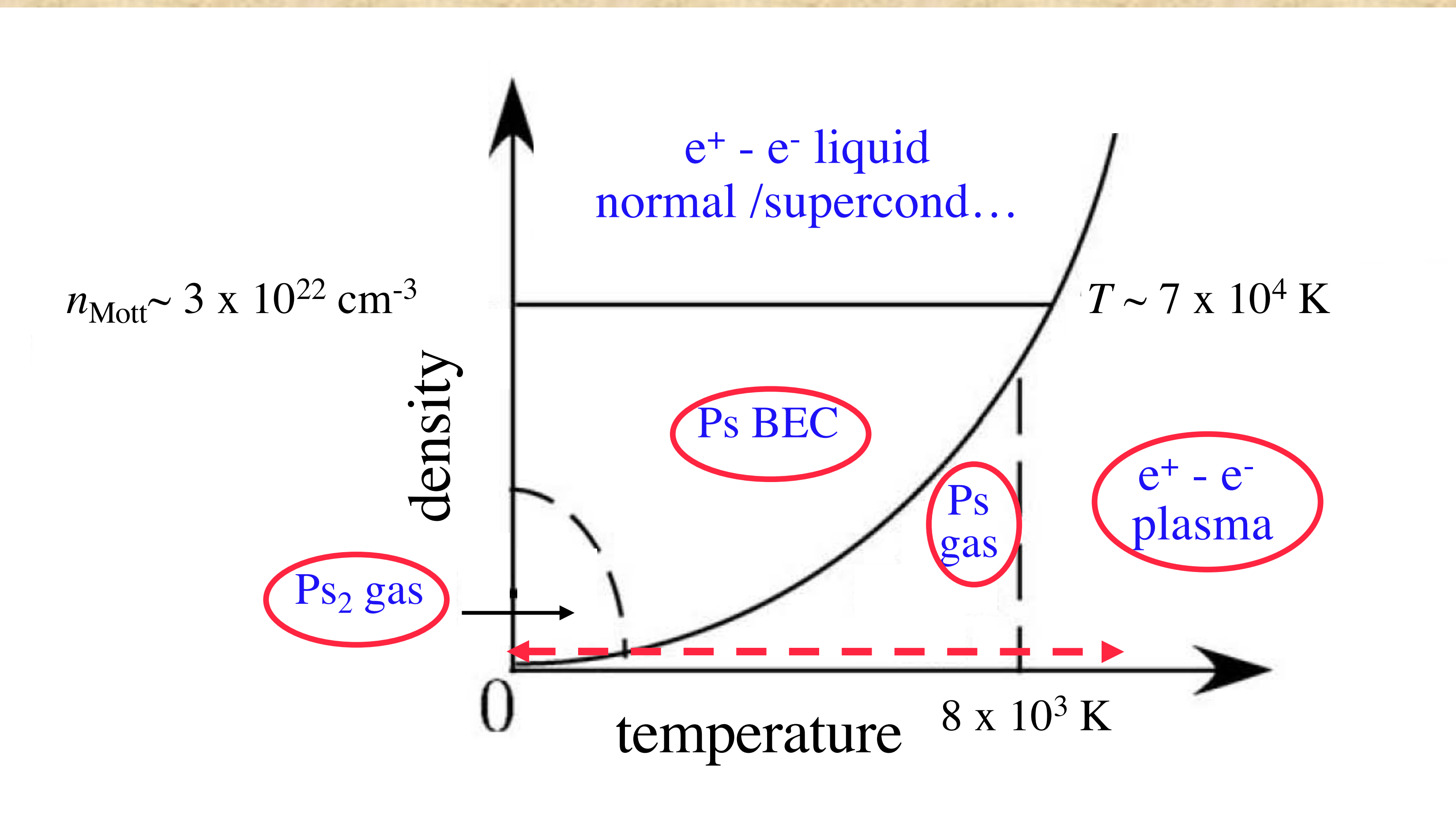


Many Body Physics with Antimatter

electron-positron phase diagram



(BEC ≡ Bose-Einstein condensate)

Yabu, NIMB '04

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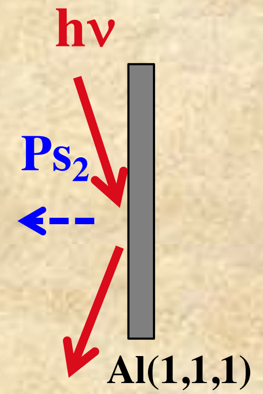
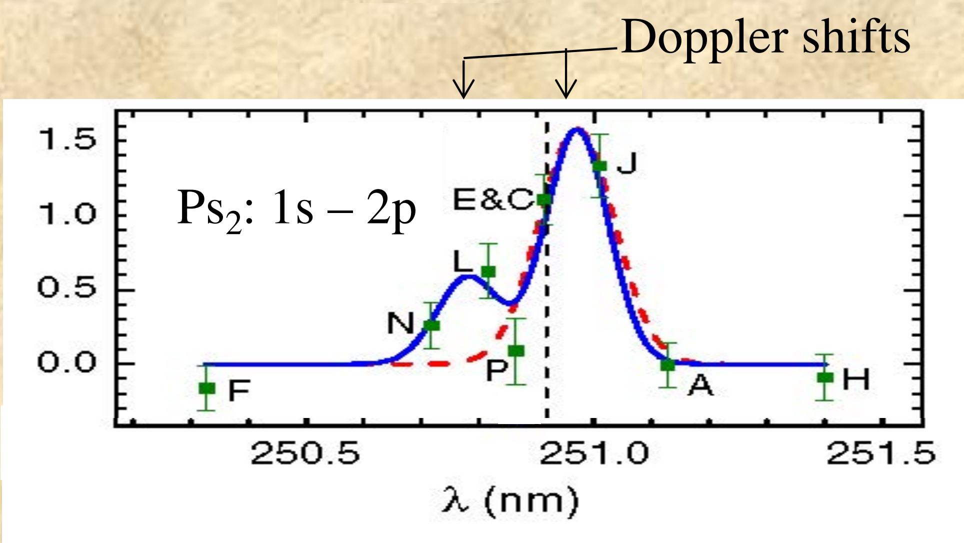
Spectroscopy of Ps_2



Optical spectrum of the **Ps_2 molecule** ($e^+e^-e^+e^-$)

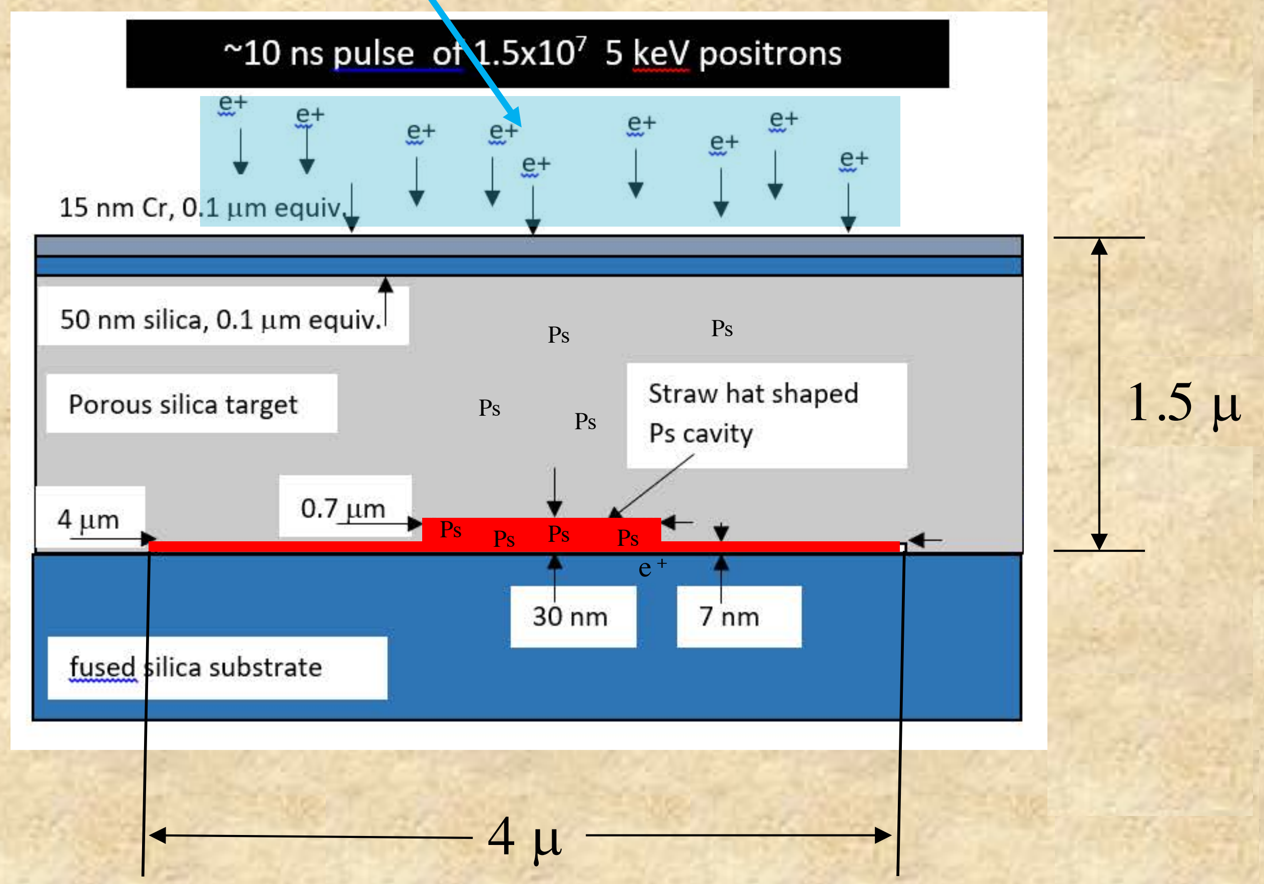
First many-electron many-positron state



Cassidy, PRL 2012

Route to a Ps BEC

remoderated beam



10^8 e^+ from accumulator
5 keV -> Ni remoderator
5 keV -> porous silica

5 x 10^5 hat brim
1 x 10^5 top of the hat

goal
$n \sim 10^{19}$ cm^{-3}
$T_c = 70$ K

many challenges
e.g., sample heating

Mills, Proc. ICPA (AIP 2019)

Classical Electron-Positron ("Pair") Plasmas

Novel nonlinear phenomena for $T_+ = T_-$ and $n_+ = n_-$

- Remarkably good confinement
- Heavily damped acoustic mode
- Faraday rotation absent
- Very strong nonlinear growth and damping processes*

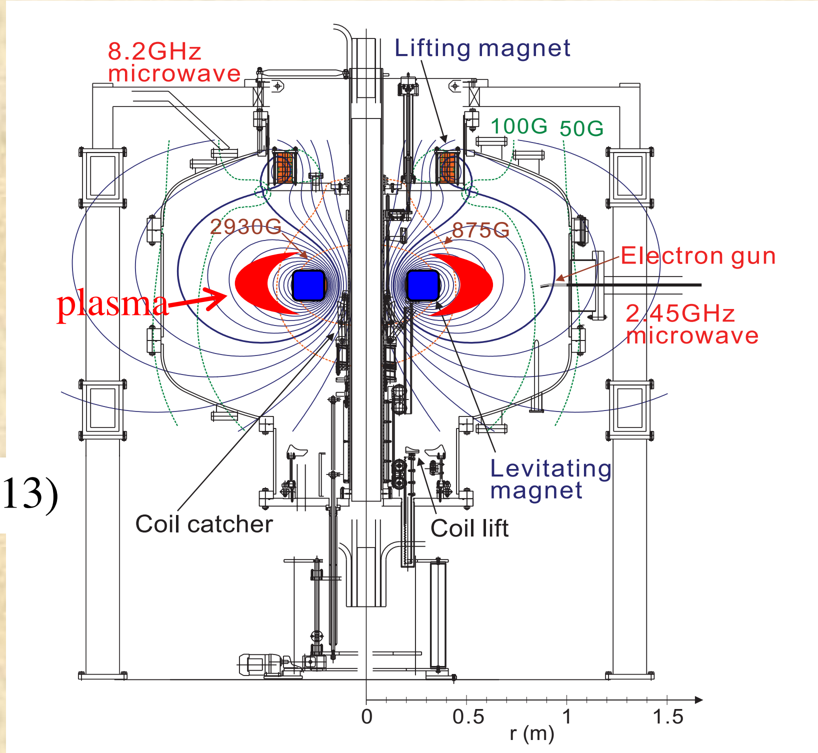
* Tsytovich & Wharton, Comm. on Pl. Phys. (1978)

Relativistic e^- - e^+ plasmas

- Astrophysical relevance

Electron beam – positron plasma experiment
Greaves, PRL (1995); Gilbert, PP (2001)

e^- - e^+ ("Pair") Plasma– the APEX Collaboration
Levitated Superconducting Magnetic Dipole



Yoshida, PP (2013)

Positron test experiments with permanent magnet

Stenson, PRL 2018

Horn-Stanja, PRL 2018

Advantages

300 s confinement

Can confine e^+ & e^-

Reviews:

Stoneking, JPP (in press)

Pedersen, NJP (2012)

A Positron Trap on the NEPOMUC Beam in Munich

(~ 5 x 10^8 e^+/s)

Immediate goal: giant pulses for e^+ - e^- plasmas
(the APEX collaboration)

Will need a "multicell trap" for large N*

Goals for other NEPOMUC experiments:

Positron-Auger spectroscopy using bunched e^+

Single-shot PALS (buncher for ≤ 300 ps timing)

RW and centerline-extraction for positron microscope

* Hurst, Phys. Plasmas (2019)

Antimatter in the Laboratory
Gaseous Positronics is the Driver

Much Progress and Many Opportunities

- Materials and atomic physics
- Tests of fundamental physics
- Antimatter plasmas & BEC Ps

Future of Antimatter Plasma Technology

Tools
- Improved plasma compression
- Colder antimatter plasmas

Antihydrogen
- Improved $\bar{p}$ -positron mixing
- **Antihydrogen beams**

Positron and Ps Physics
- Larger numbers of positrons
- **Higher quality Ps beams**
- ***Portable antimatter traps***

Thanks to many for material and advice:

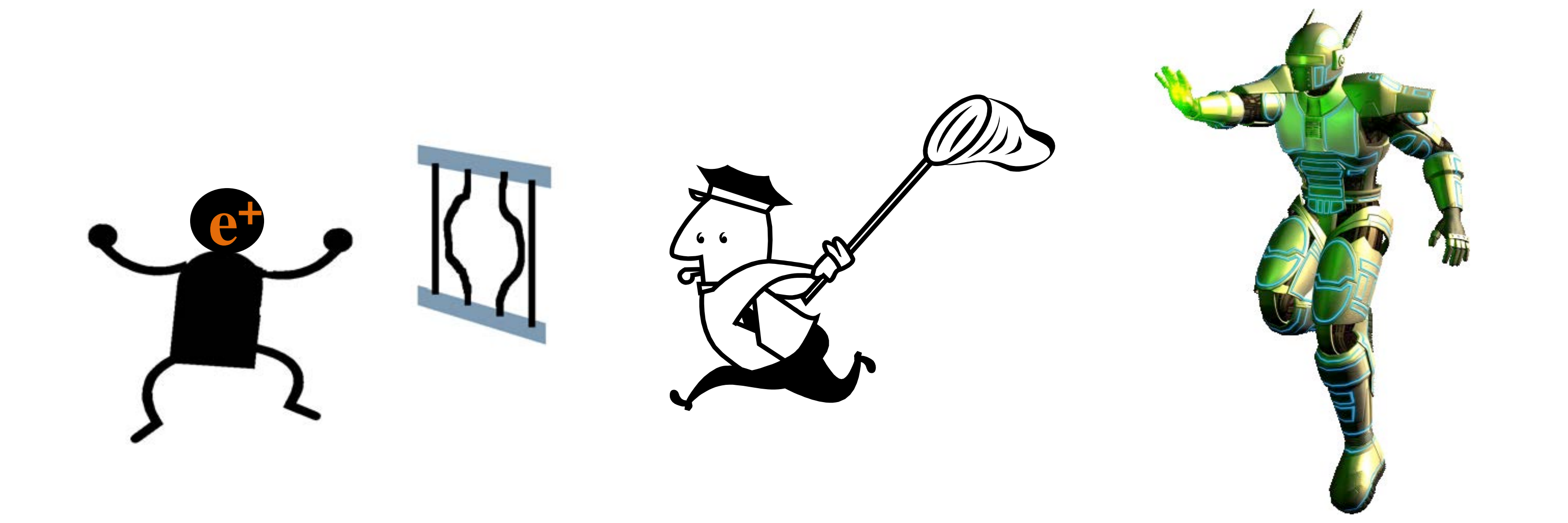
David Cassidy, Mike Charlton, Joel Fajans, Gleb Gribakin, Christoph Hugenschmidt, Adric Jones, Allen Mills, Yasayuki Nagashima, Andrew Swann.

and present and former collaborators:

L Barnes, S. Buckman, J. Danielson, A. Deller, D. Dubin, S. Gilbert, S. Ghosh, R. Greaves, G. Gribakin, C. Hugenschmidt, N. Hurst, E. Jerzewski, M. Leventhal, J. Marler, T. Murphy, M. Natisin, T. O'Neil, A. Passner, T. Pedersen, E. Stenson, M. Stoneking, J. Sullivan, M. Tinkle, T. Weber, J. Young, the APEX Collaboration.

Thanks too for support from AT&T Bell Labs, ONR, NSF, DOE, DTRA, and the UCSD Foundation.

GEC October 9, 2020



Review Articles:

Plasma and Trap-Based Techniques for Science with Positrons

J. R. Danielson, et al., *Rev. Mod. Phys.* **87**, 247 (2015).

Experimental Progress in Positronium Laser Physics

D. B. Cassidy, *Euro. Phys. J. D.* **72**, 53 (2018)

Plasma and Trap-Based Techniques for Science with Antimatter

J. Fajans and C. M. Surko, Phys. Plasmas 27, 030601 (2020)

positrons.ucsd.edu