Charged Particles for Antihydrogen

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Physics with Trapped Charged Particles
Ecole de Physique des Houches, January 20, 2015

Brief History of Antihydrogen

1996: CERN: First Antihydrogen (beam)

2002: ATHENA: Firs

2010: A

2011: A

2012: A

2013: ALPH

measureme

2014: ALPH

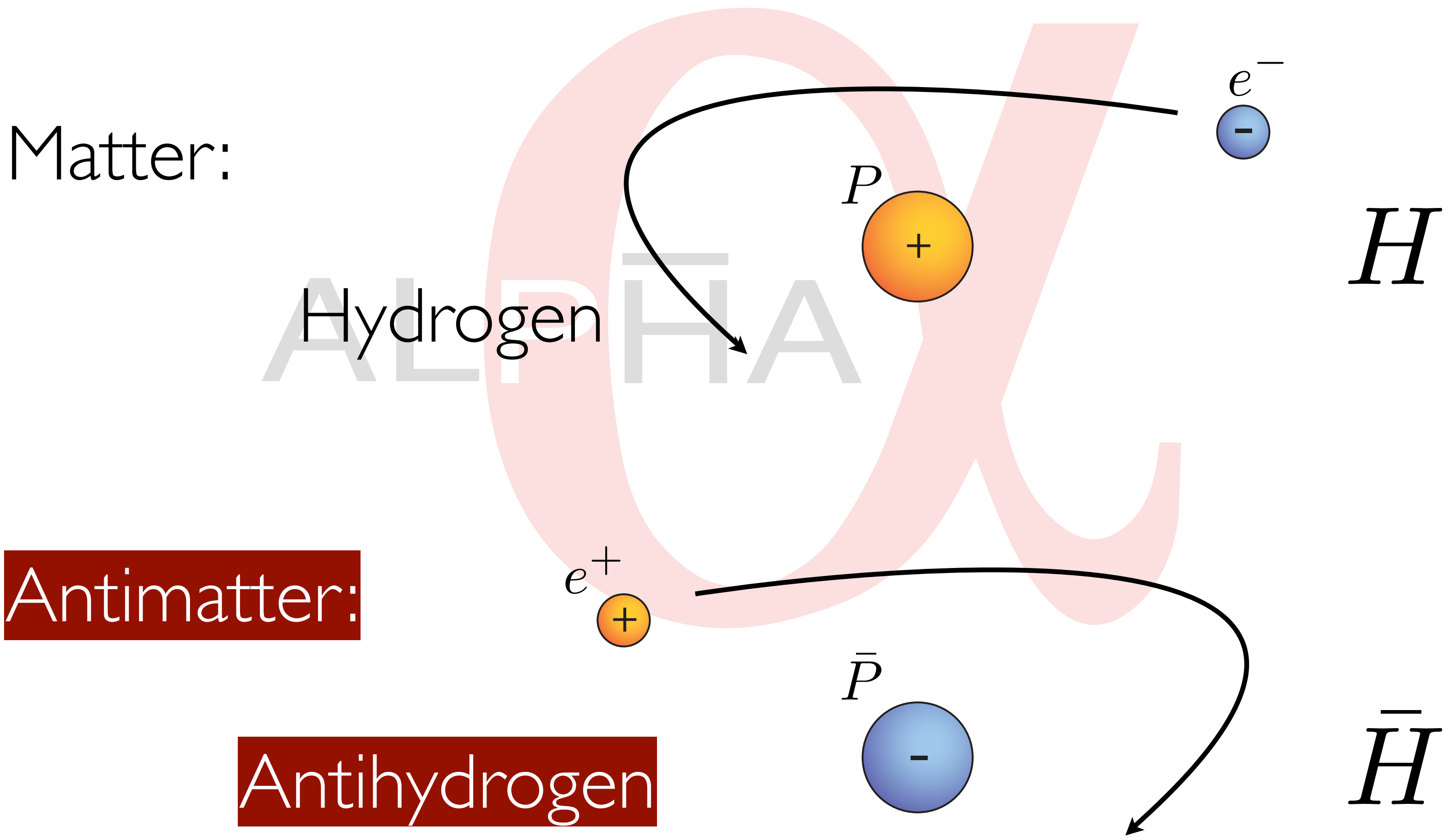
What is antimatter?

- Particles have “twins” same mass, opposite charge

	Electron	Proton
Matter:	- e^-	+ P
Antimatter:	**Positron** + e^+	**Antiproton** - $\bar{P}$

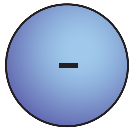
What is antimatter?

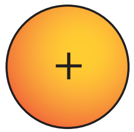
- Neutral antimatter atoms



What is Antimatter?

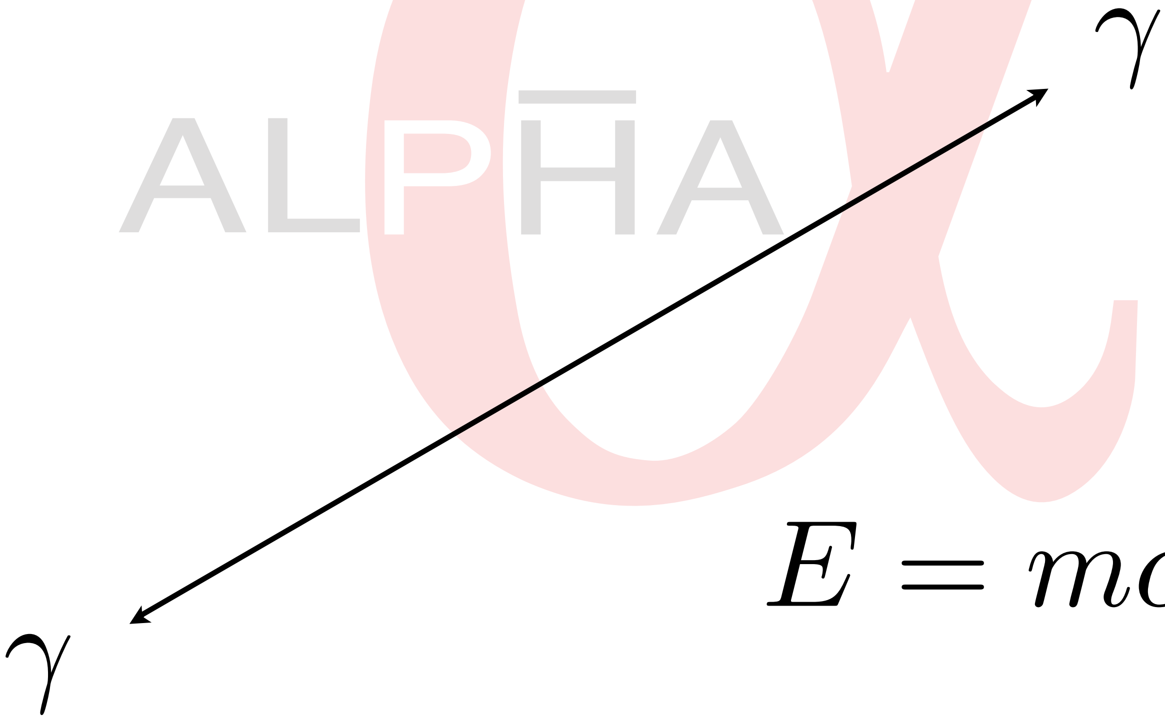
- Watch out when they meet their twin!





What is Antimatter?

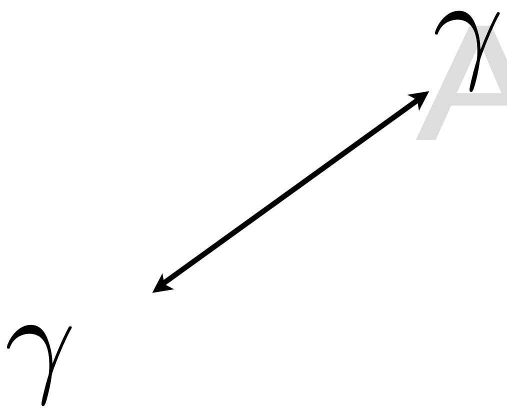
- Annihilation!



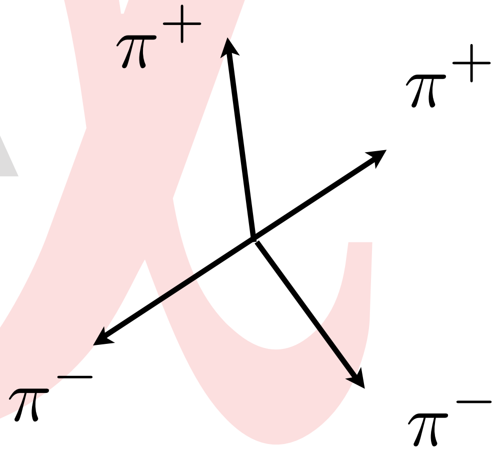
$$E = mc^2$$

Annihilations

- Positron / Electron: photons (511 keV)
- Antiproton / Proton: Many possibilities - Pions, etc.



positron / electron
Annihilation

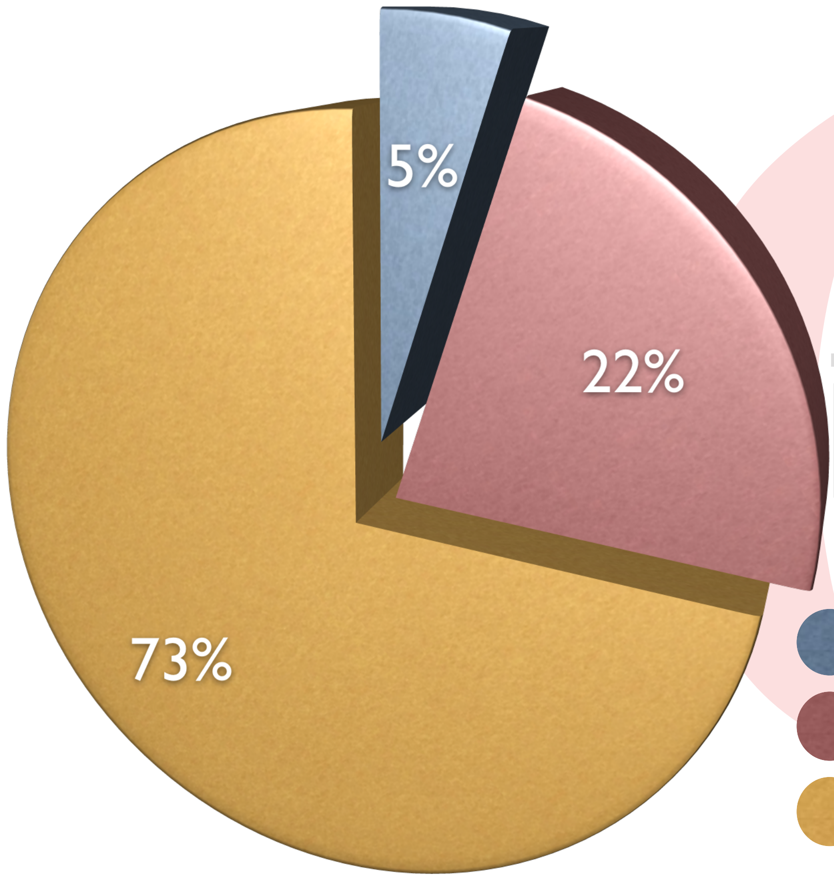


proton / antiproton
Annihilation

Why make Antihydrogen

- Physical laws identical under CPT transformation: Antihydrogen must be identical to Hydrogen!
- Baryon Asymmetry: The universe seems made almost entirely of matter! Really? Why?
- Gravity: How does antimatter respond to gravity? Weak equivalence principle! Insights for quantum gravity? Dark Energy ?
- Note: ANY difference between $\bar{H}$ and H will imply new physics!

Energi Budget of the Universe



Known [normal matter]

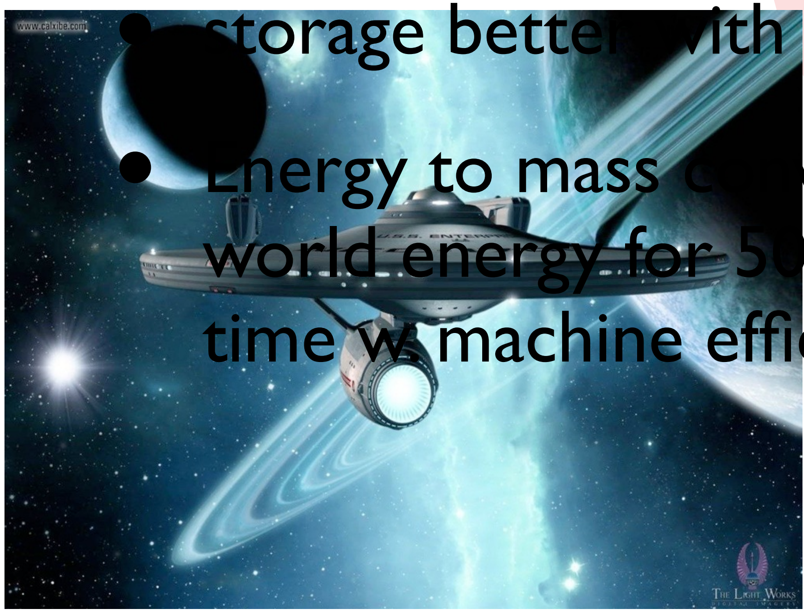
Known unknowns [dark matter]

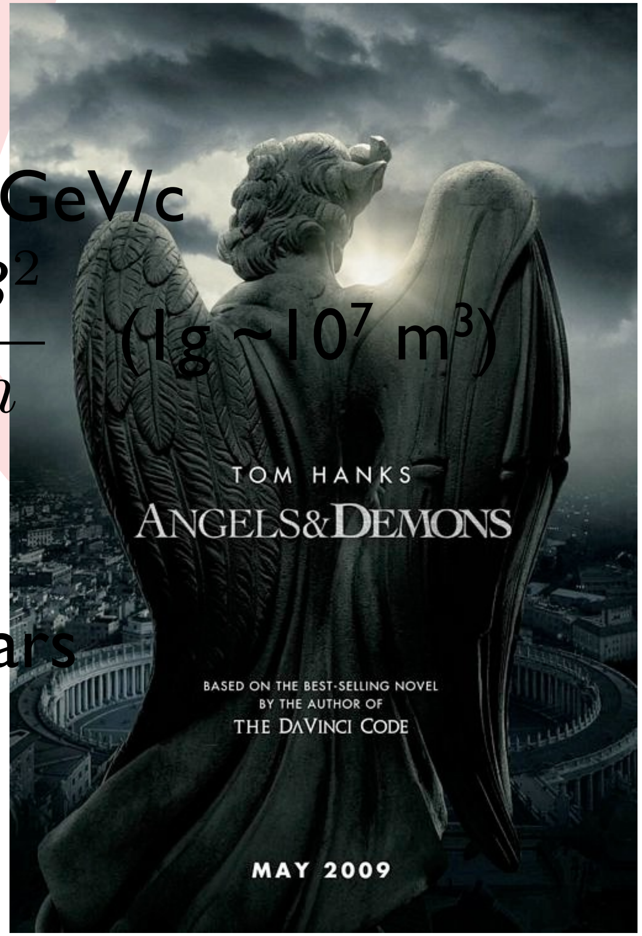
Unknown unknowns [dark energy]

Antimatter ? : 0%

Forgot one purpose?

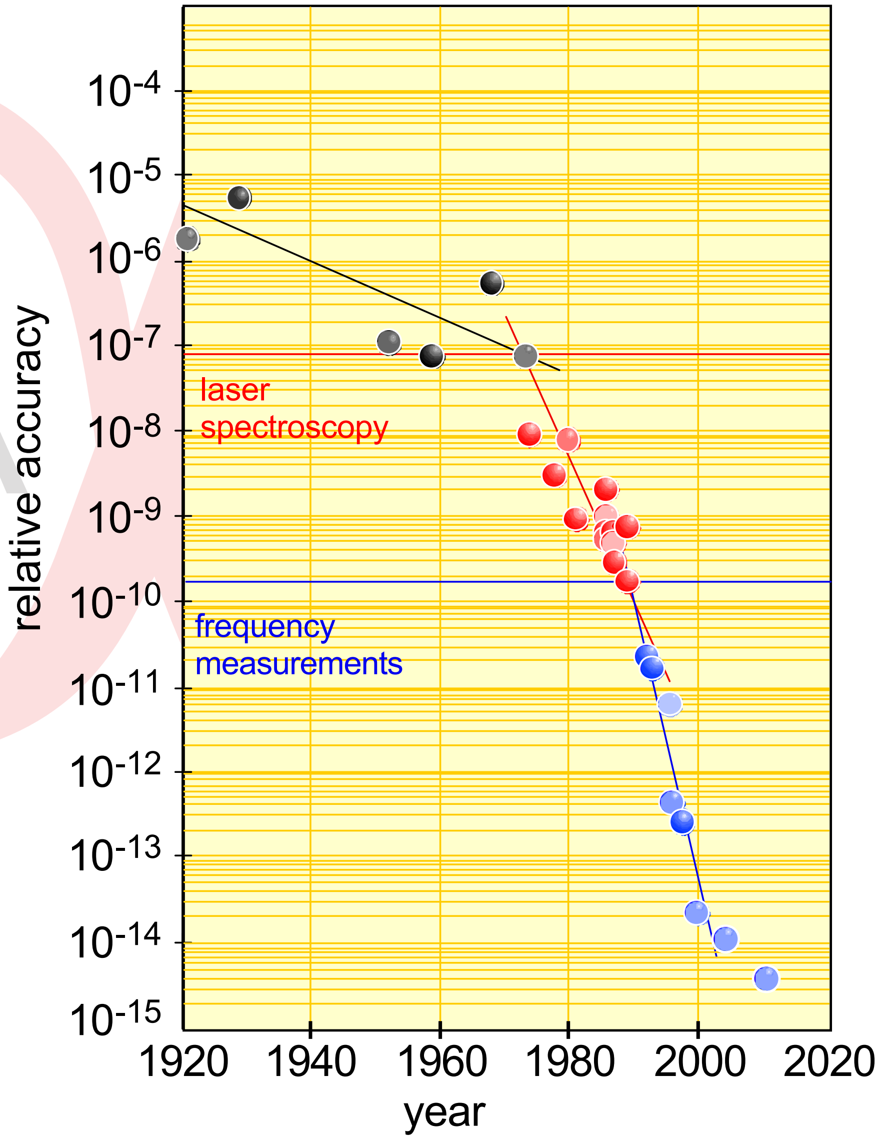
- Starships!? - “only” 1 ton to go to alpha centauri!
- Bombs!? - “only” 1/4g to blow up the vatican!
- FORGET IT :
- $\bar{p}$ fundamental limit : $p \rightarrow 10^{-6}\,\bar{p}$ @ 20 GeV/c
- storage better with neutrals : $n < \dfrac{\epsilon_0 B^2}{2m}$ (1g ~10^7 m^3)
- Energy to mass conversion (1g):
  world energy for 50M years
  time w. machine efficiency : 50000G years





Why/how does $\bar{H}$ help?

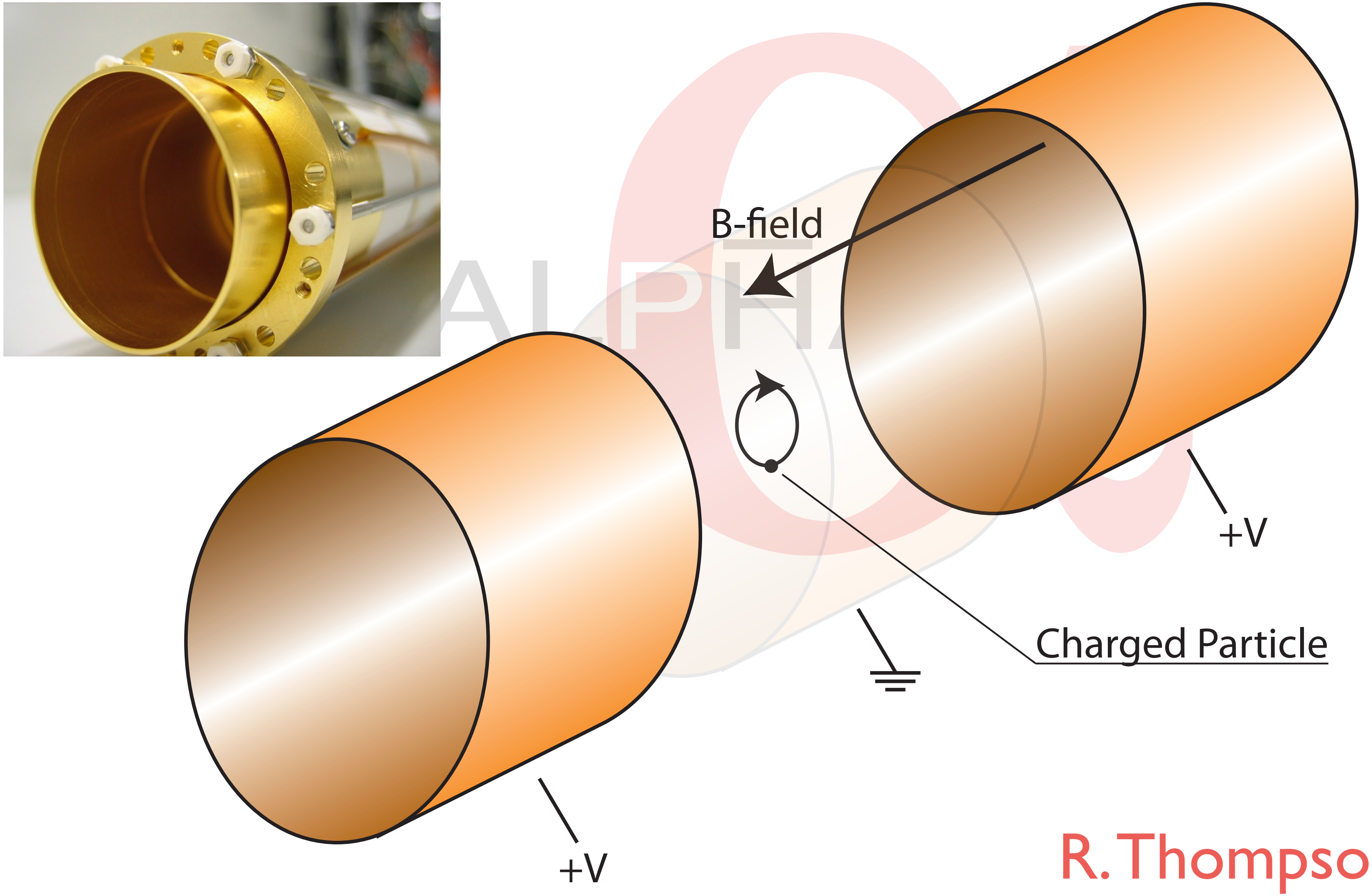
- Only pure antimatter system so far!
- Antihydrogen is neutral!
- Spectroscopic techniques can be brought to bear.
- Ex: H-$\bar{H}$ comparison by 1s-2s two photon spectroscopy.



ALPHA

Charged Particle Traps

- All our traps are Penning-Malmberg traps

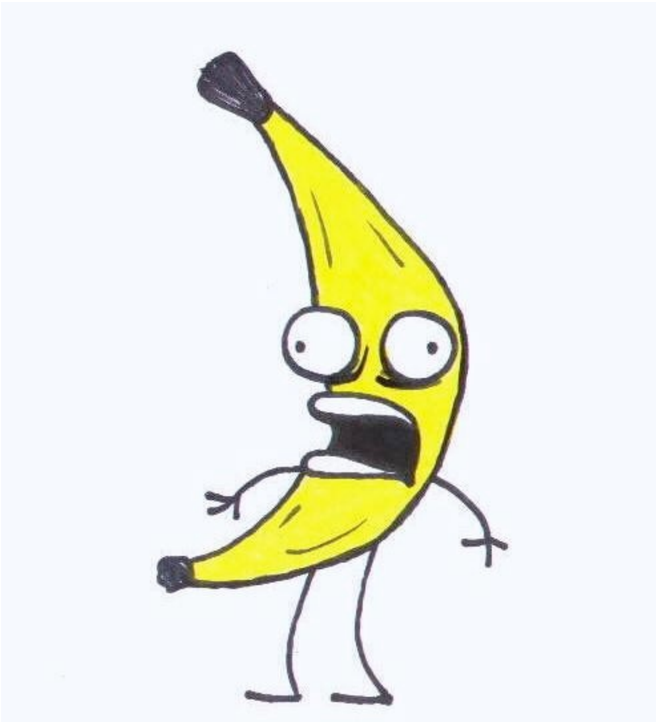


R. Thompsons talks!

Where do Positrons come from?

- Fairly Easy: Positive β^+ decay in radioactive isotopes
  - Potassium-40 in Bananas: ~ 15 Positrons / sec
  - We use Sodium-22 source: ~ 10 M / sec

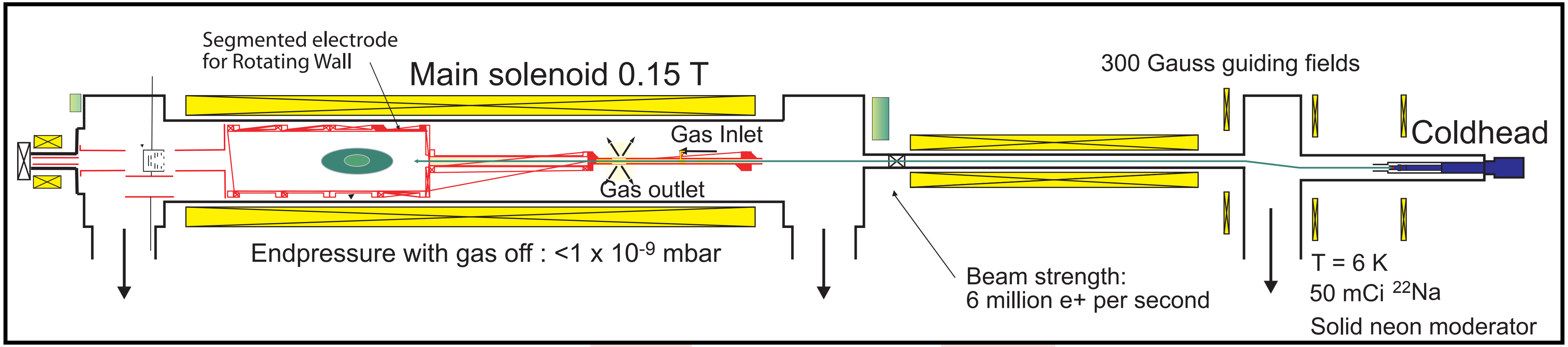
$$^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne} + e^+ + \nu_e + \gamma$$

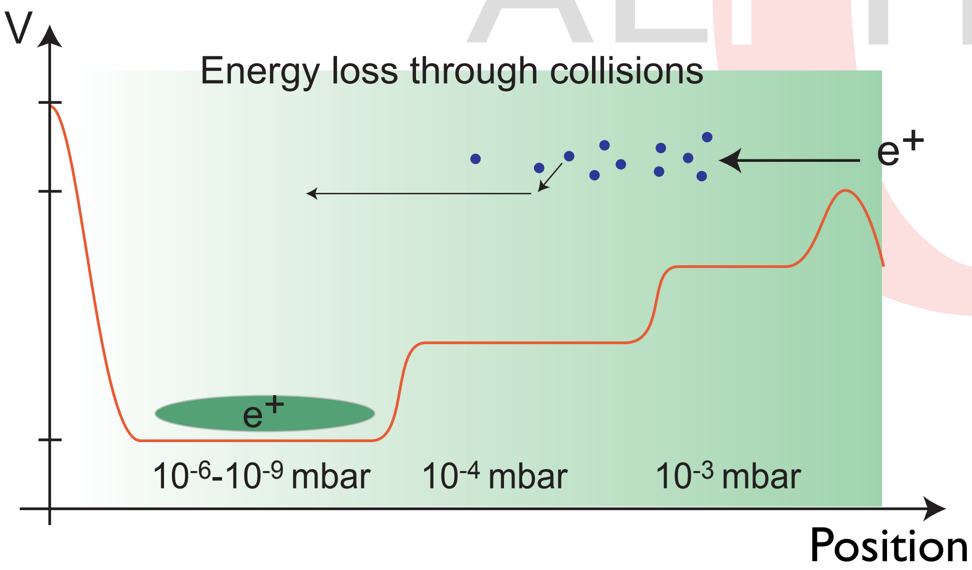


"I am a banana!" Don Hertzfeld

T.J. Murphy, C.M. Surko, Phys. Rev. A 46 (1992) 5696.

Positron Accumulation



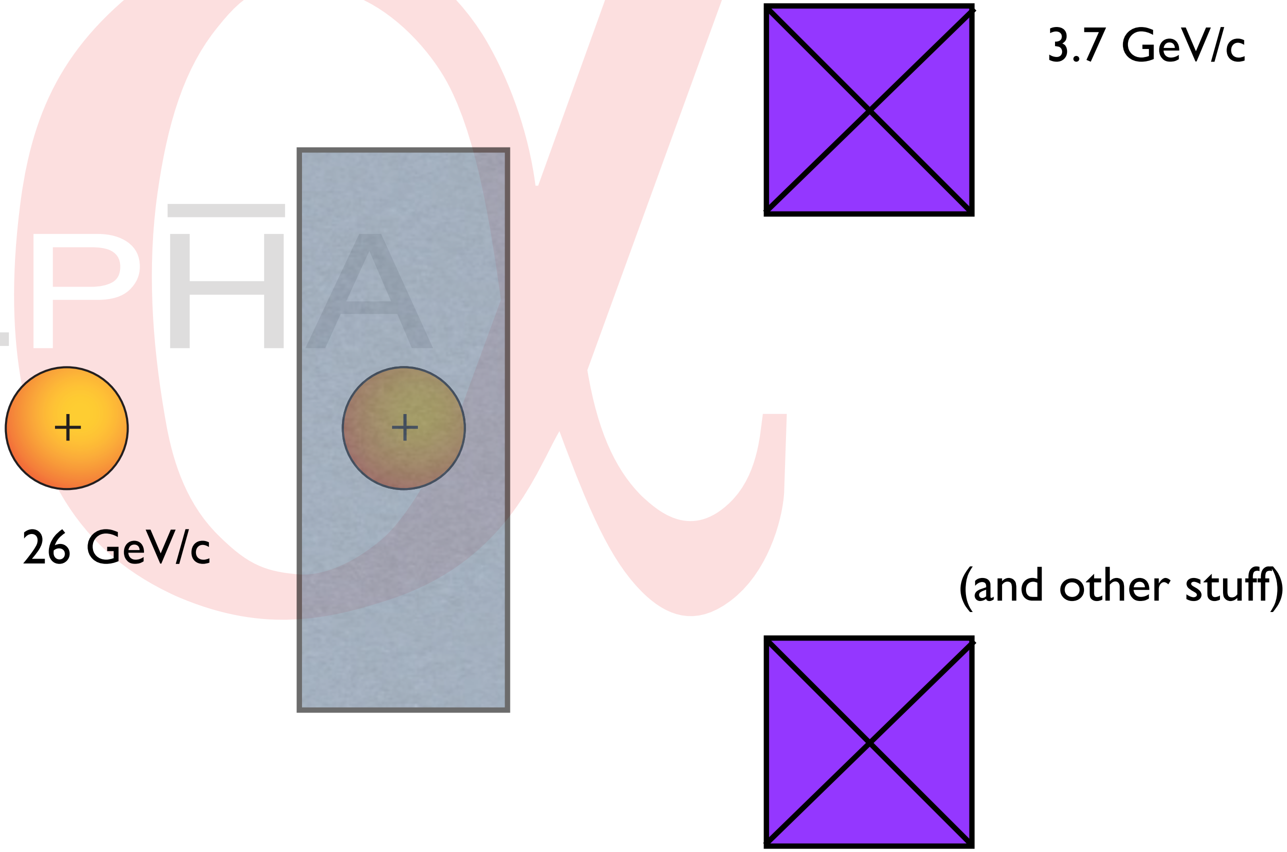


- Accumulation rate : ~ 10^6 e^+/sec
- Transferred (sans gas!) and cooled : ~ 150 x 10^6 e^+ / 5 min.
- In practice we use 2-5 x 10^6 e^+ in each experiment.

Where do Antiprotons come from?

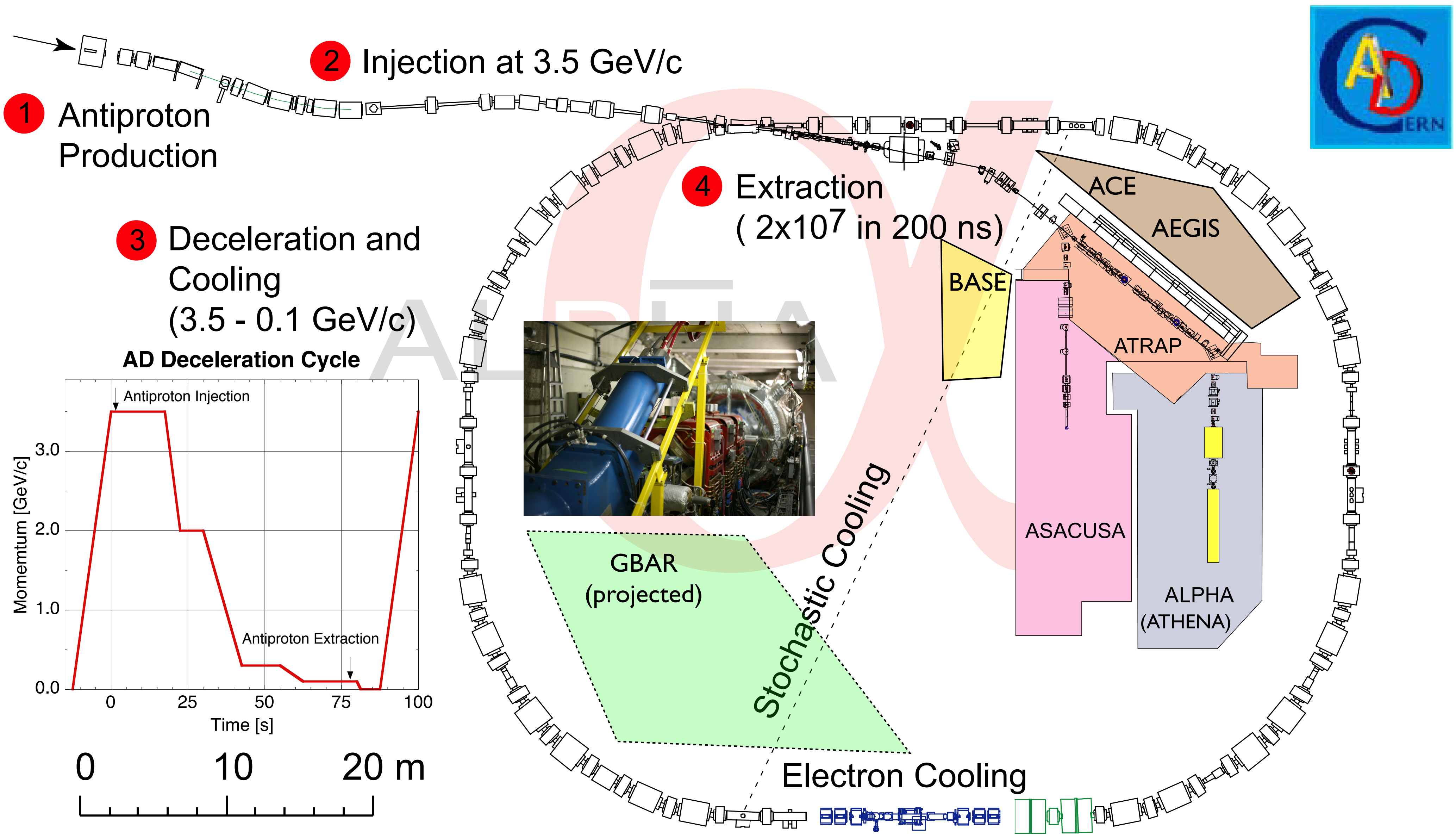
- Energetic proton creates Proton/Antiproton pair
- Charge/Mass selected

Cern Proton Synchrotron



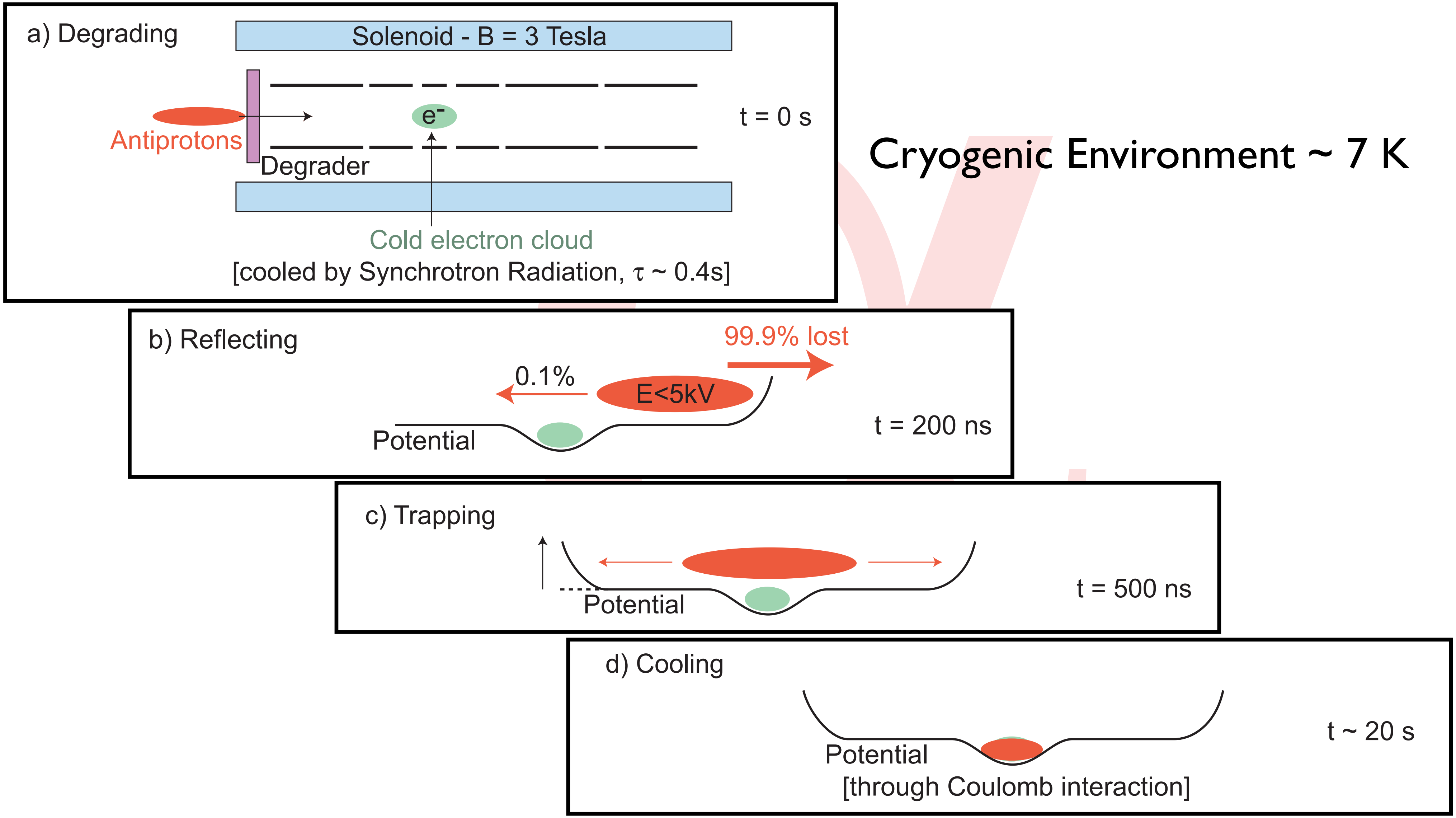
Maury. S.

Antiproton Decelerator



Gabrielse, G. et al. Phys. Rev. Lett.

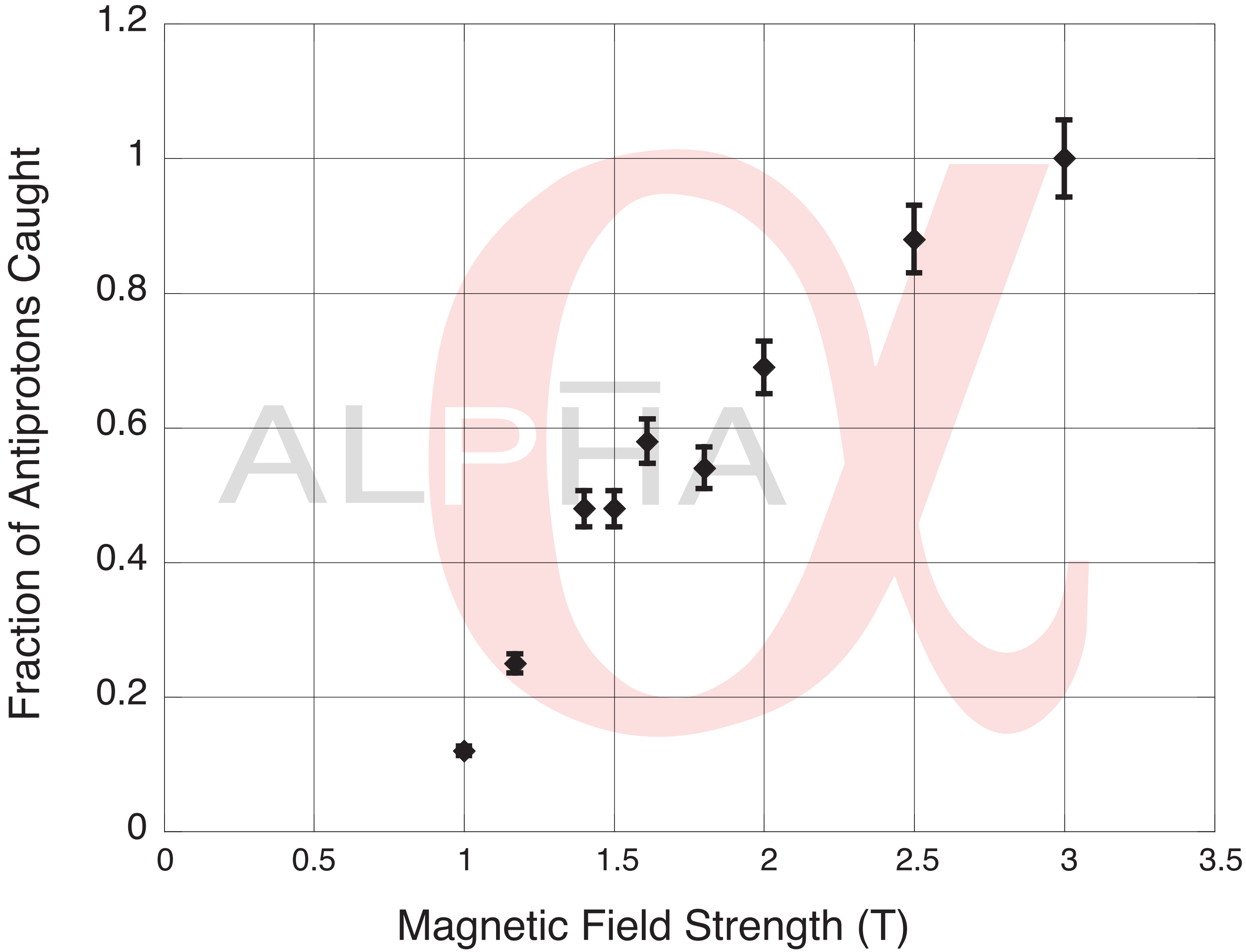
Antiproton Catching



Cryogenic Environment ~ 7 K

Result : ~ 60000 cooled $\bar{p}$ / AD shot (every ~100s)

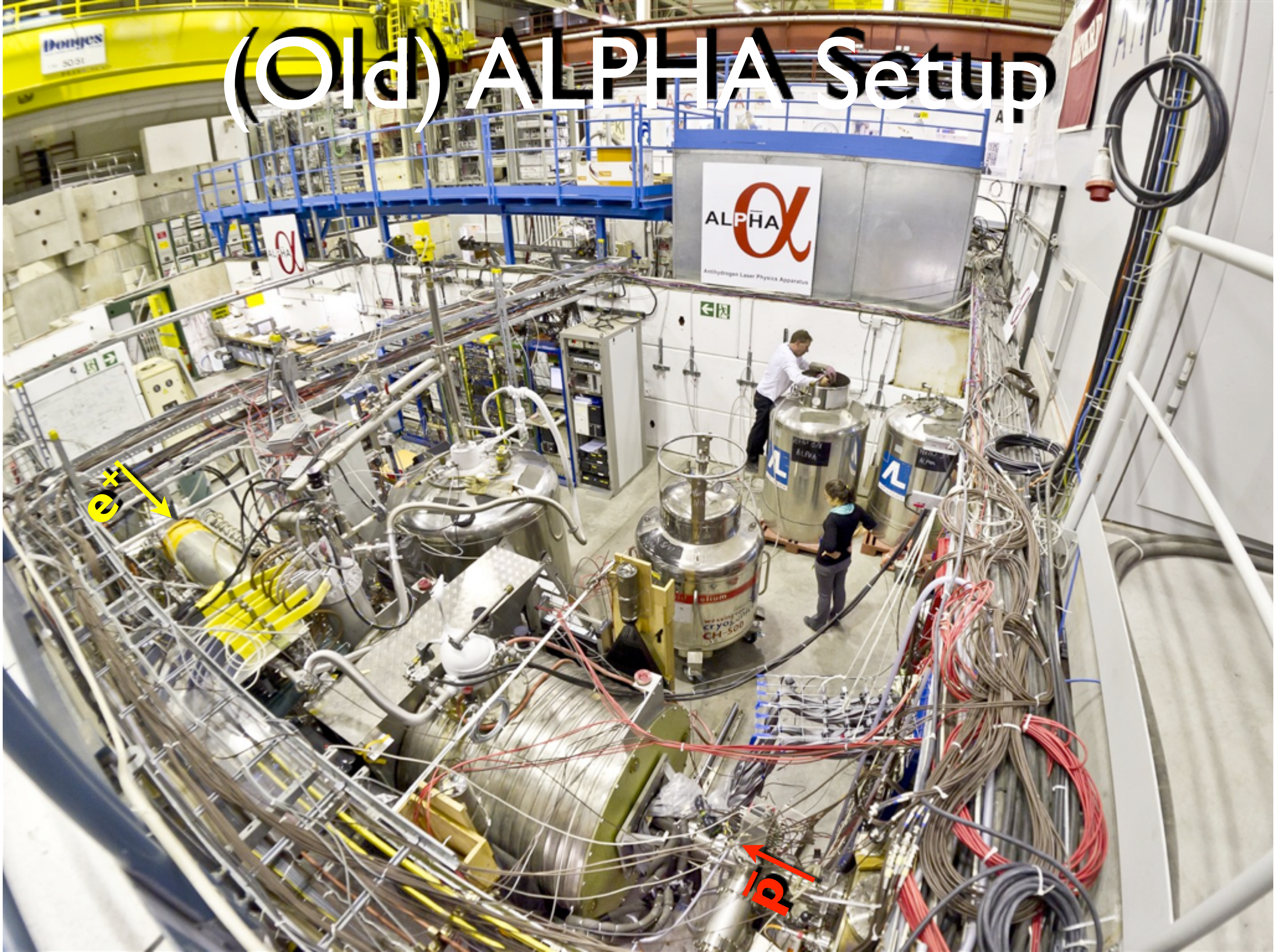
Antiproton Capture



- Why ? : Cyclotron radius….

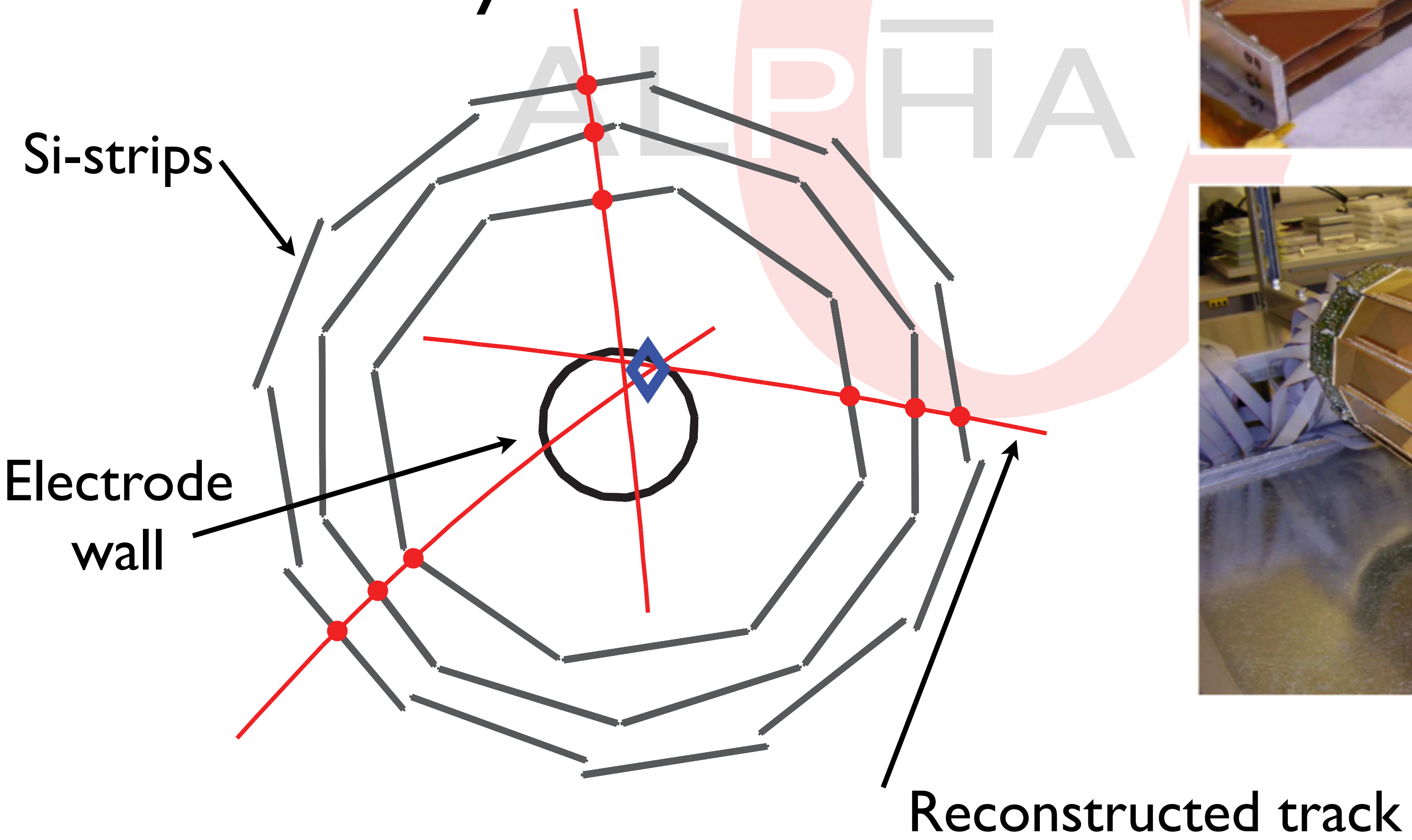
AD Experimental Area

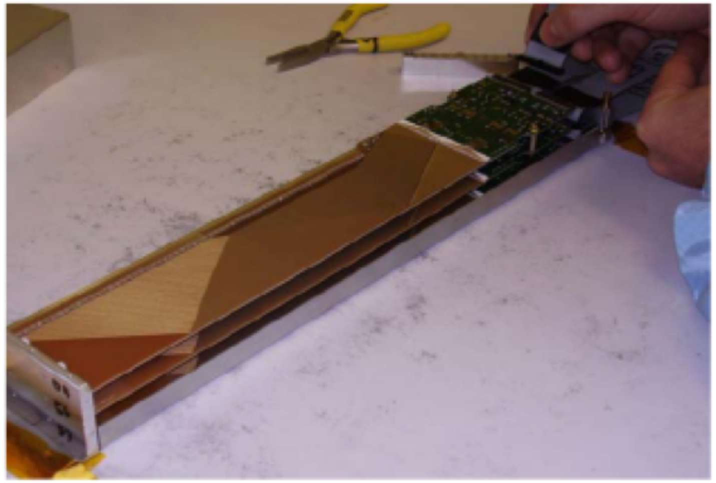
(Old) ALPHA Setup

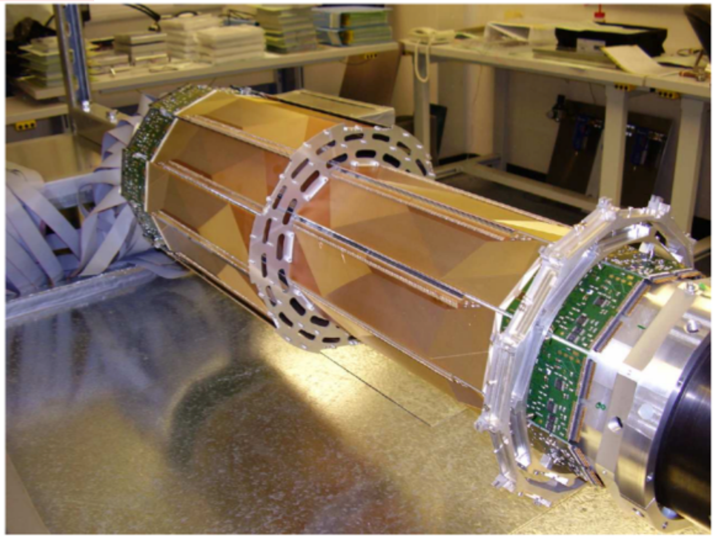


Annihilation Detection

- Si-strip detection
- Vertex resolution ~ 1mm
- Efficiency ~ 50%

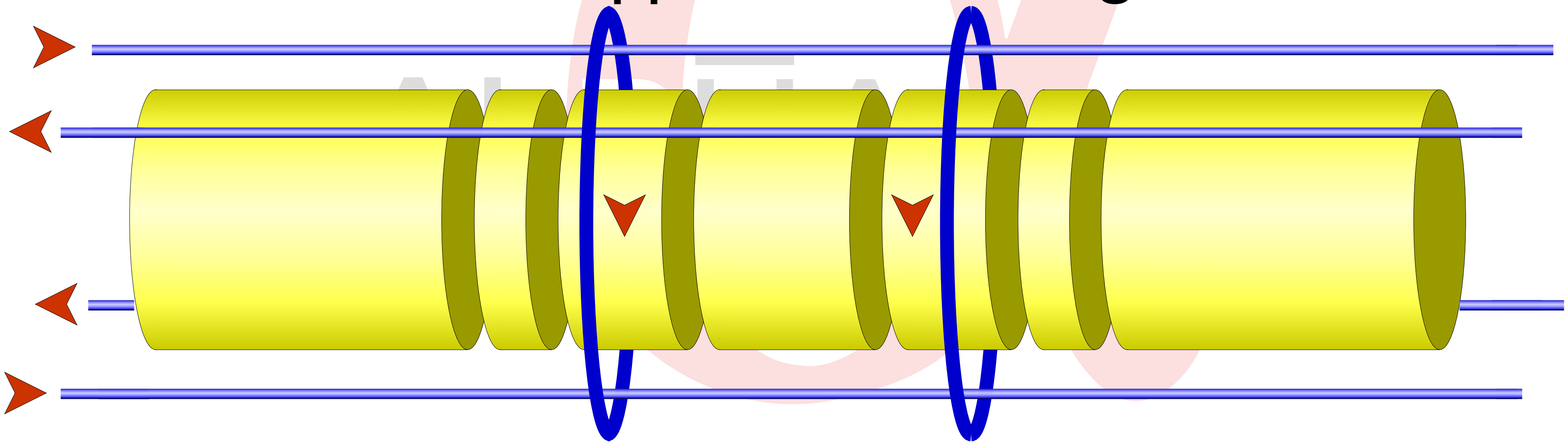






(Anti)Atom Trap

- Atoms can be trapped on their magnetic dipole-moment. $U = -\bar{\mu} \cdot \bar{B}$
- Atoms can be trapped in a 3D magnetic minimum.



Ioffe-Pritchard Geometry

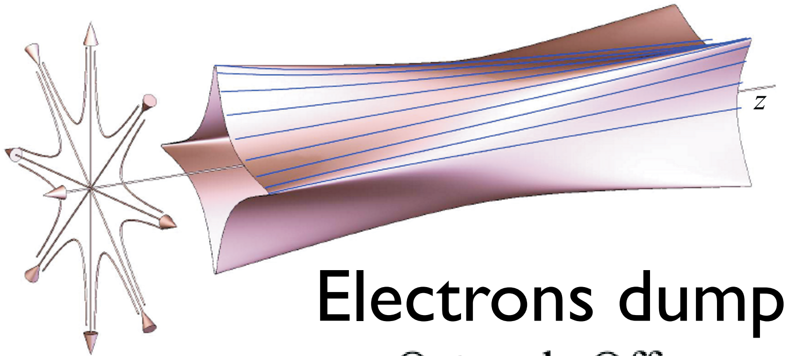
$$\Delta B = \sqrt{B_{sol}^2 + B_{wall}^2} - B_{sol}$$

Shallow : ~ 0.7 K/T for H ground state

ALPHA, Phys. Plas.

Plasma in Multipole I

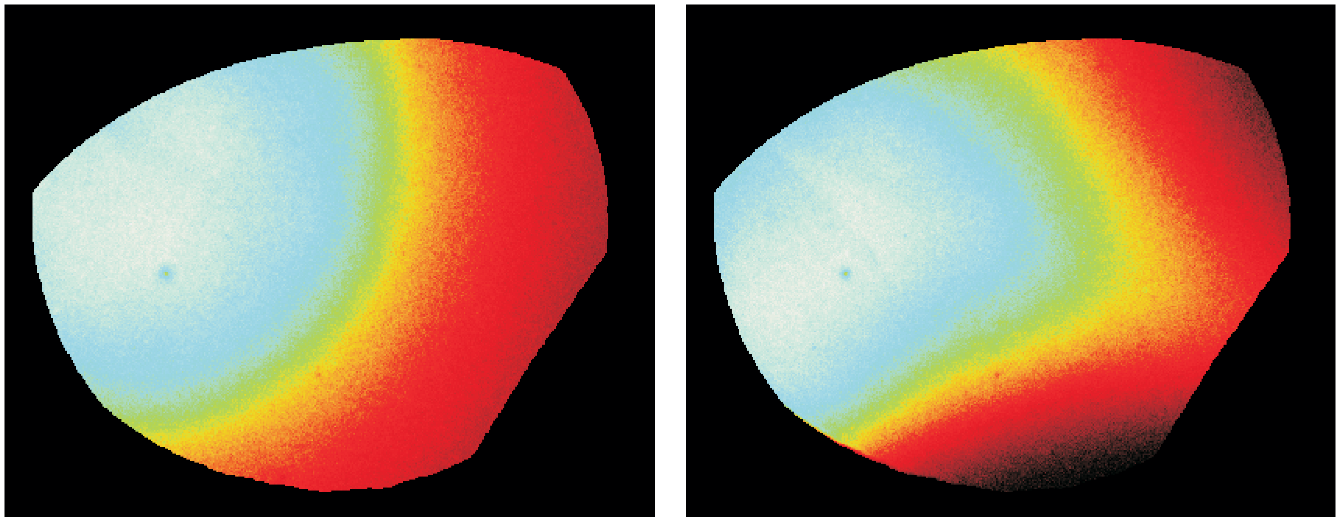
- The azimuthal symmetry of the Penning-Malmberg trap is broken by the neutral trap multipole.



$$r_c = \frac{R_W}{\sqrt{1 + \frac{B_W}{B_S}\frac{L}{R_W}}}$$

Electrons dumped through octupole:

Octupole Off — Octupole On

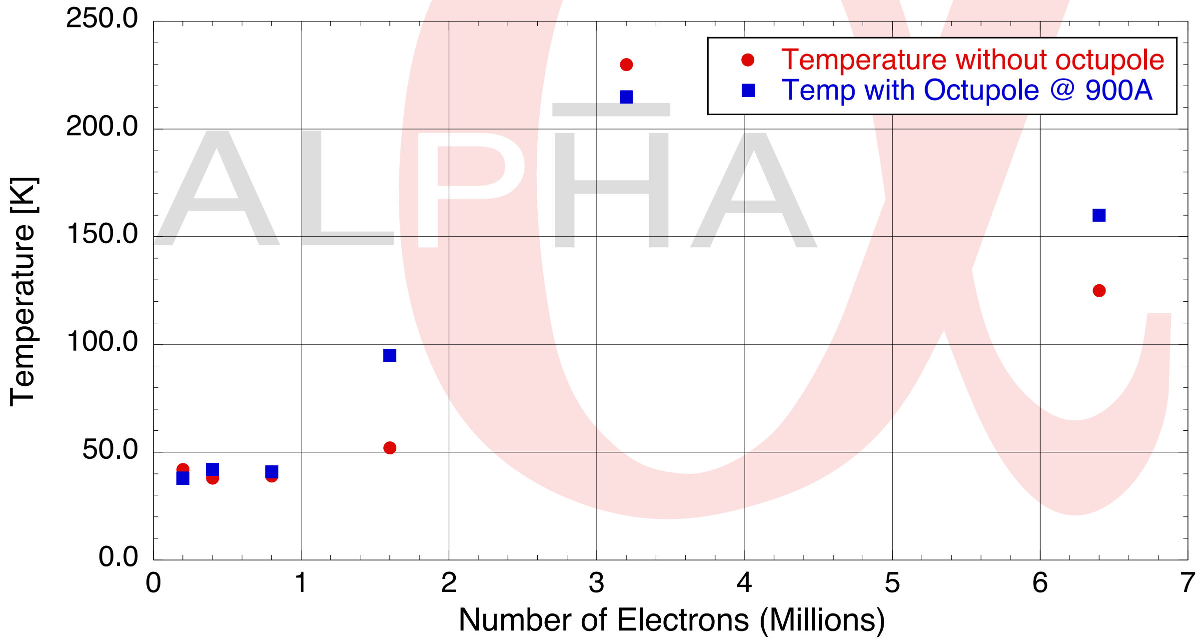


- There is a critical radius beyond which particles will hit the wall which depending on octupole strength and particle (antiproton) orbit length.

Plasma in Multipole II

- Even well below the critical radius we see heating effects!

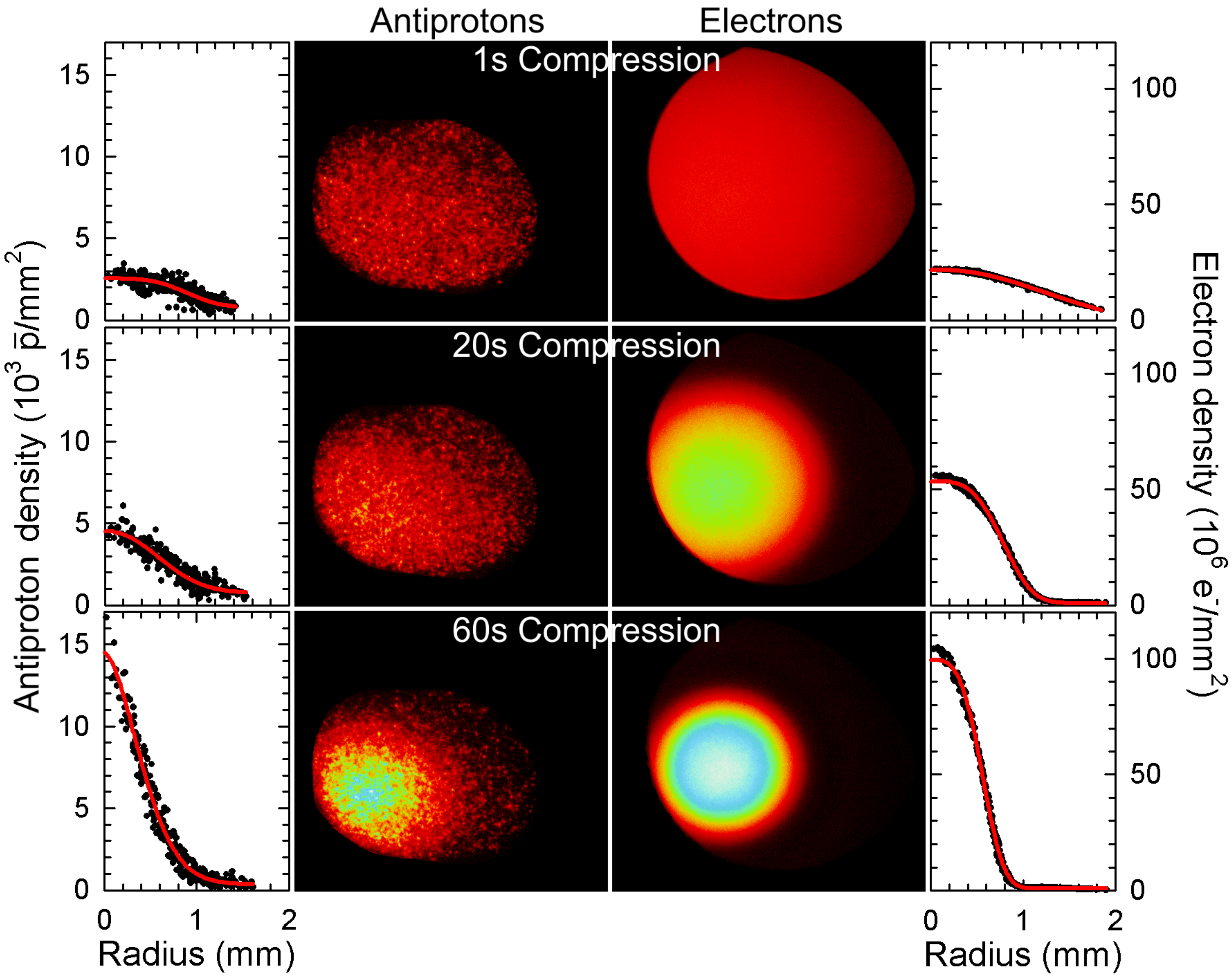
  0.7mm radius e^- plasma in short well, r_{crit} > 12 mm



- We need small antiproton and positron plasmas.

  [Note: Also the equilibrium-rotation means small is good]

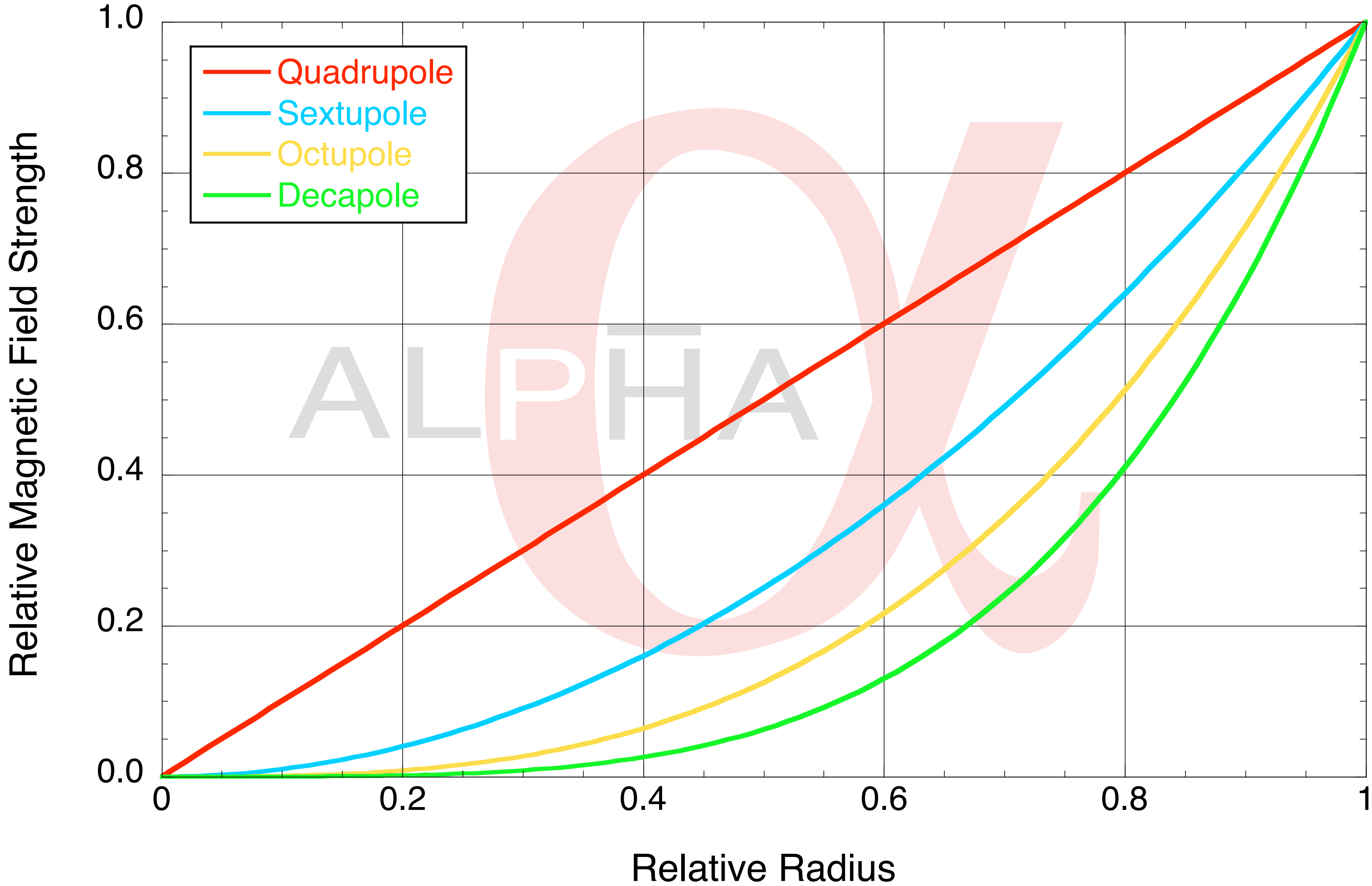
'Sympathetic' compression



Typical results : ~ 0.25mm p̄ plasma

F. Anderegg Talks!

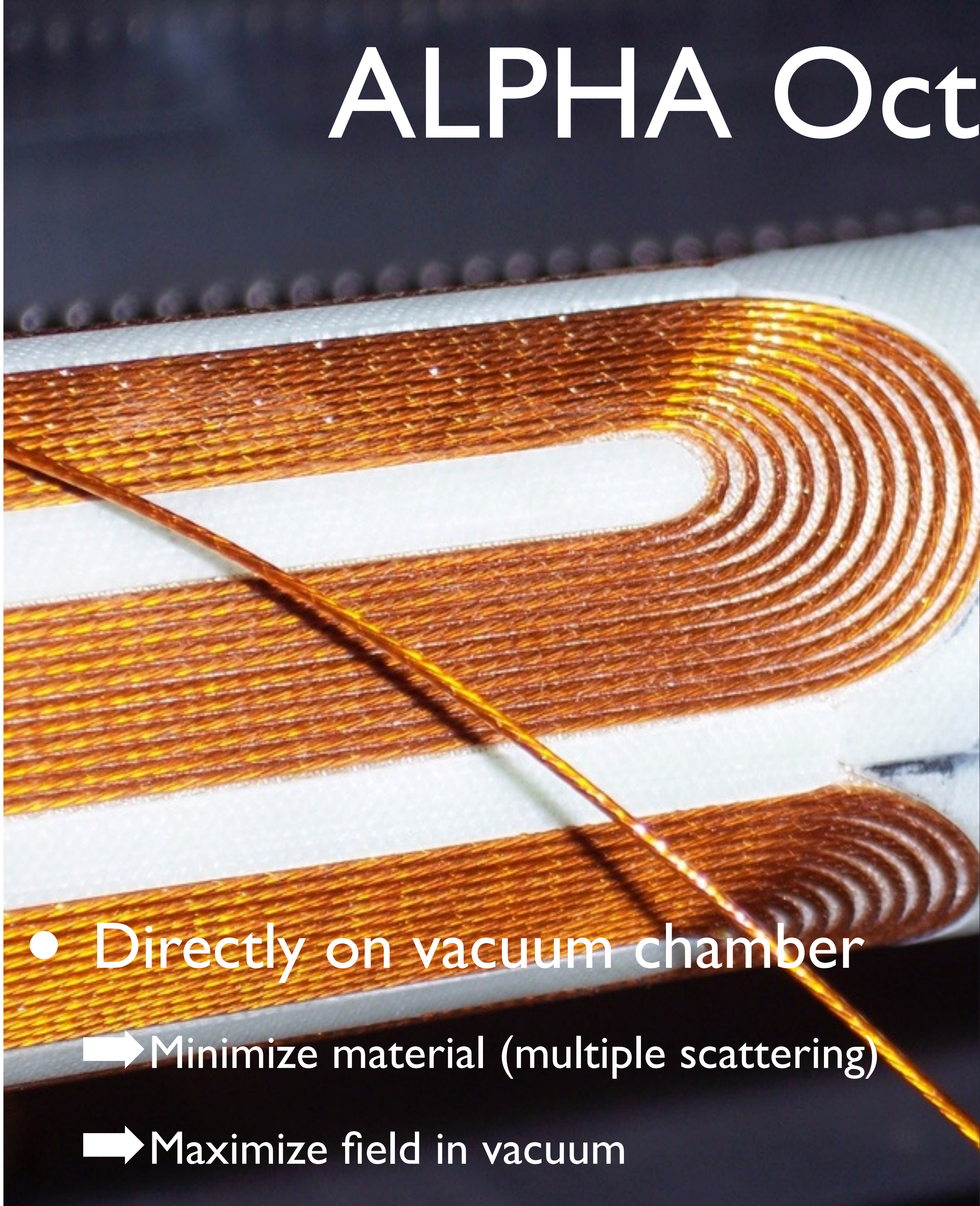
Multipole Choice



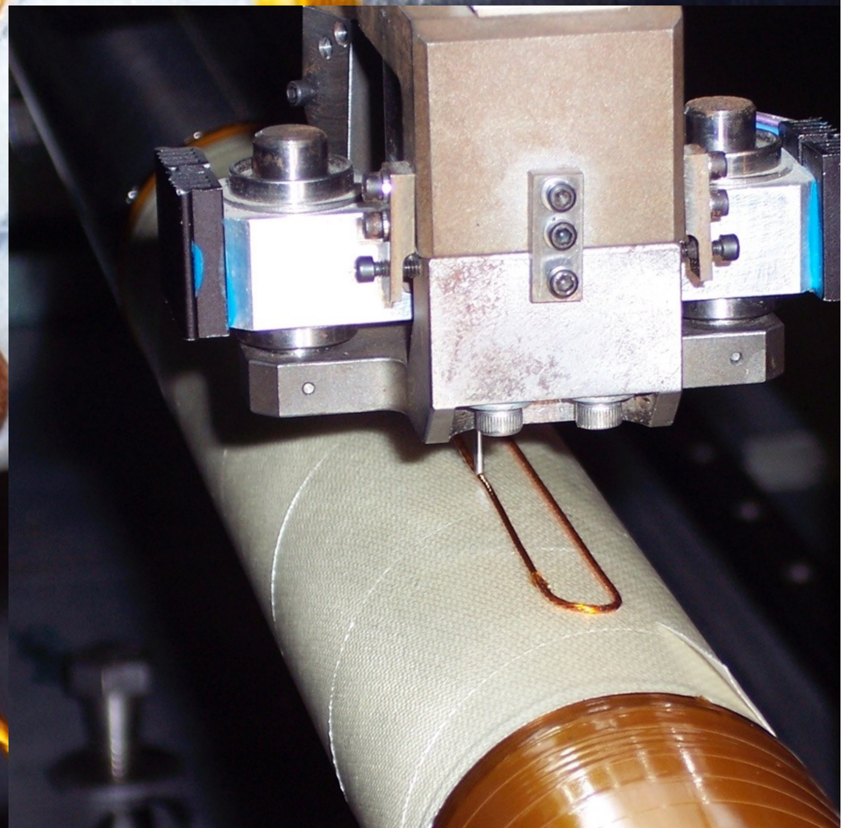
➡ ALPHA chose an octupole.

ALPHA, Nucl. Inst. & Meth. A

ALPHA Octupole



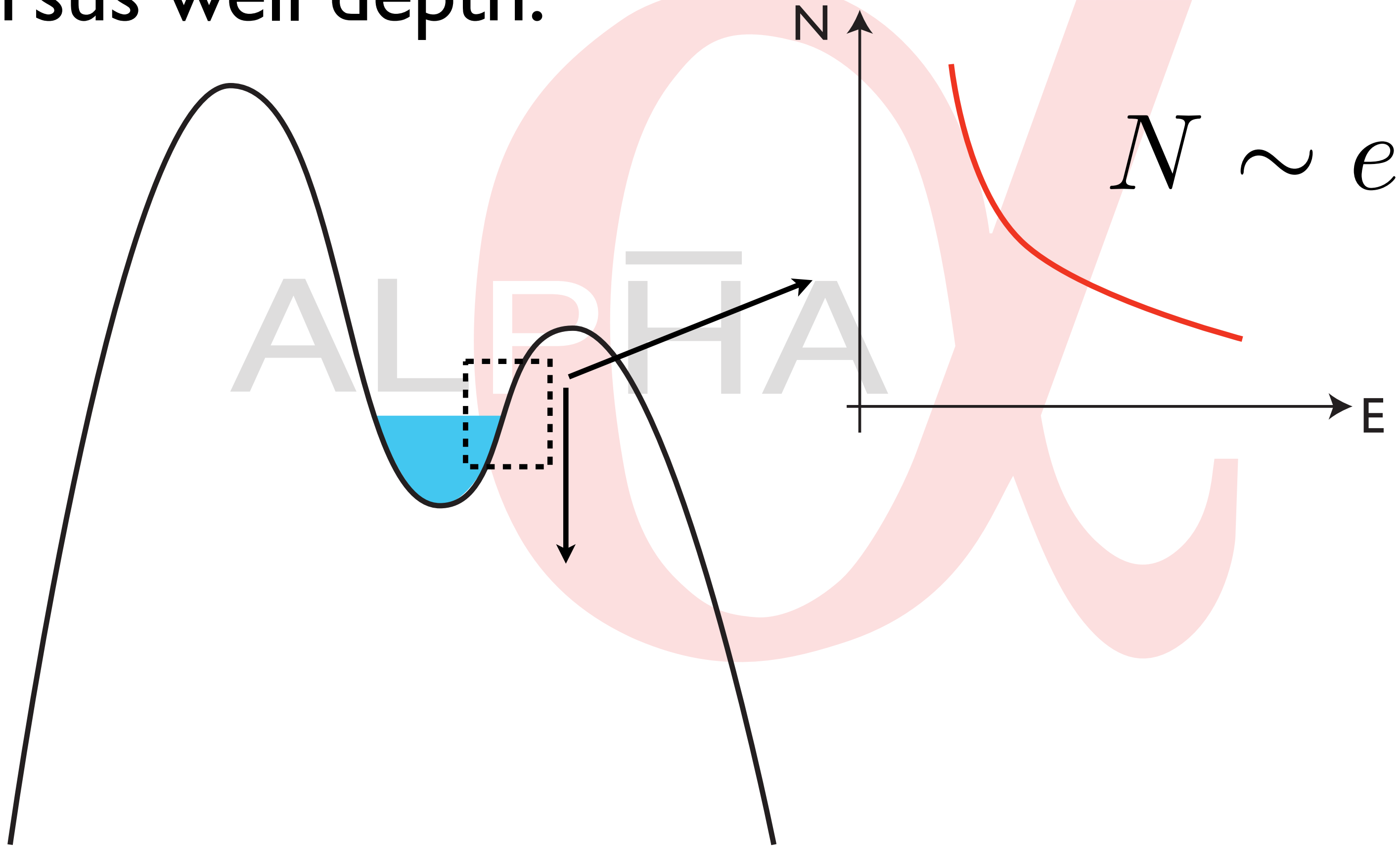
- Directly on vacuum chamber
  - ➡ Minimize material (multiple scattering)
  - ➡ Maximize field in vacuum



Eggleston, D. L.,

Measuring Temperatures

- Dump particles to a detector and record number versus well depth.

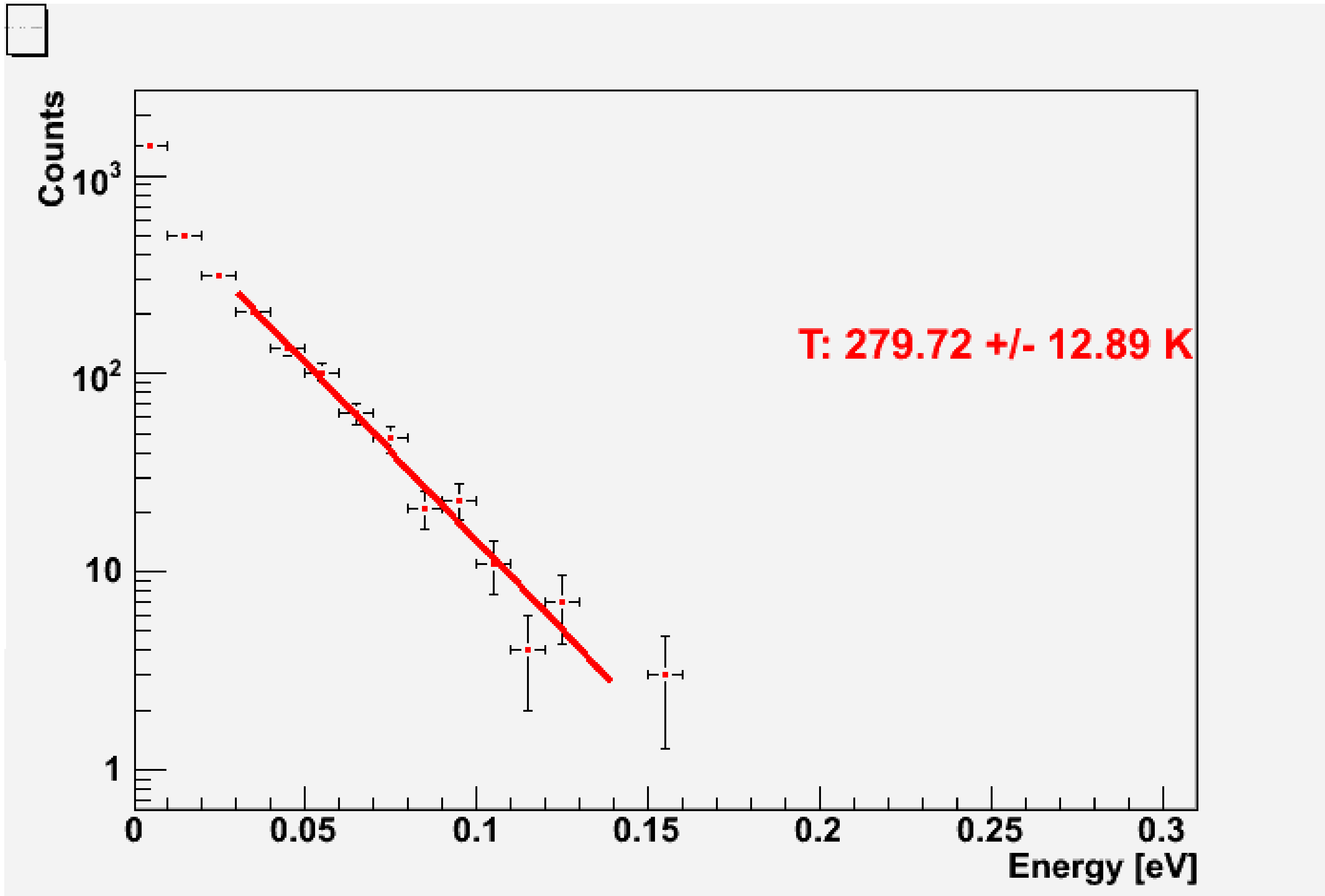


$$N \sim e^{-\frac{E}{k_B T}}$$

- Use scintillator/PMT for $\bar{p}$ and MCP for e^+/e^-.

Temperature Measurement

- For about 40000 antiprotons.



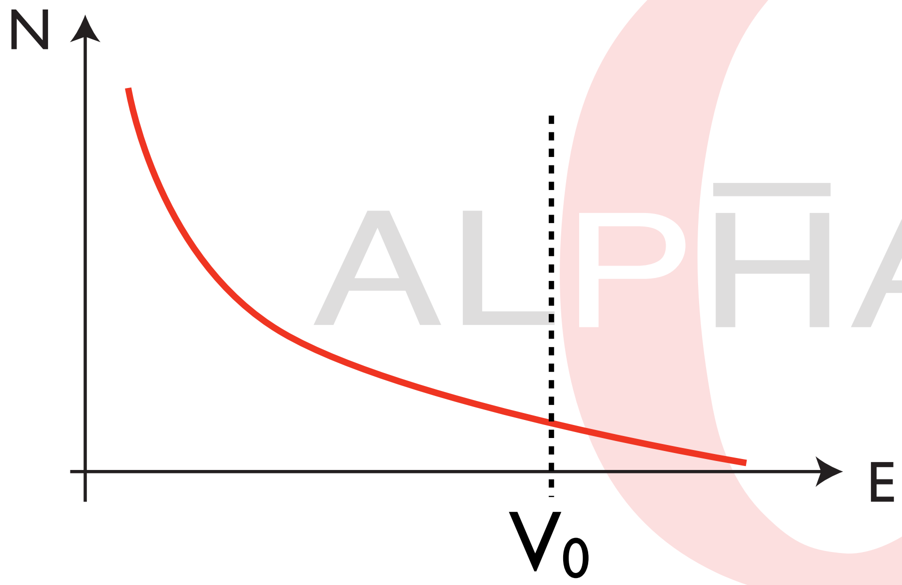
Recall: Electrodes @ 7.5K

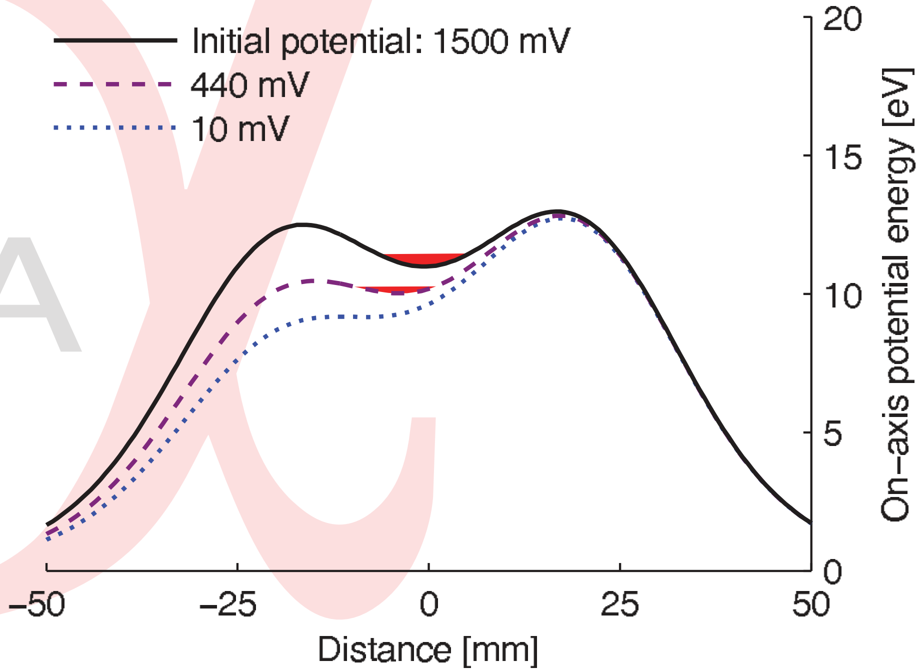
- But, 300K !?, is it good enough ?

J. Fajans Talks

Evaporative Cooling

- Let the hot particles, with more than the average energy, evaporate and the remaining will be colder

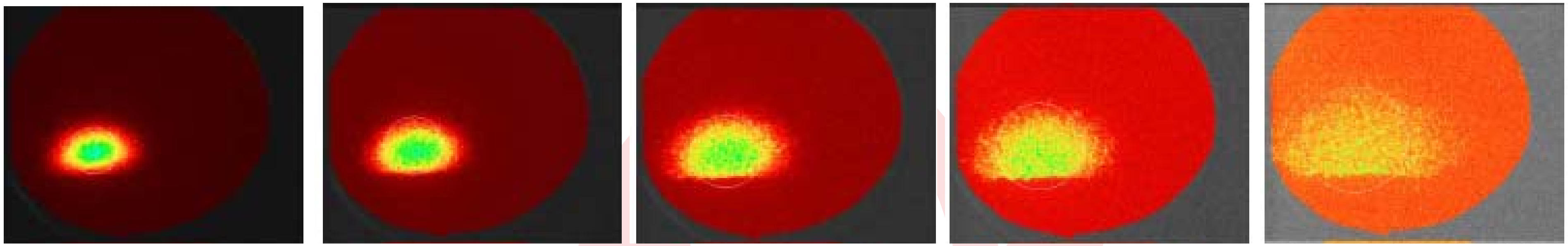


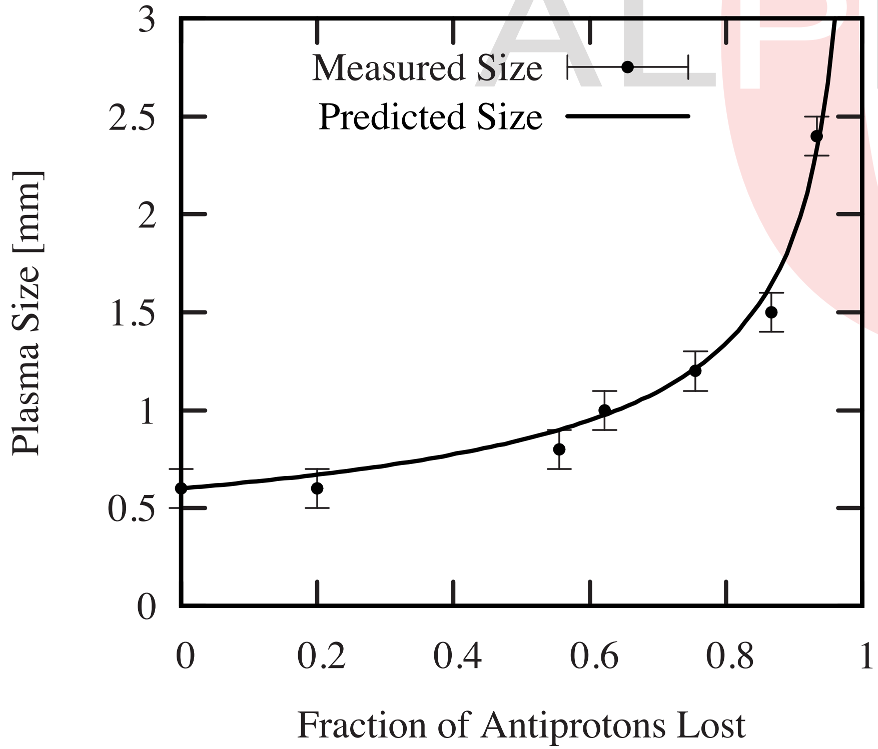


- In a Penning trap particles escape only along the axis and essentially on the axis as the potential is the most shallow there. => 9 ± 4 K antiprotons!

Radial expansion with EVC

Shallower Wells ⟶

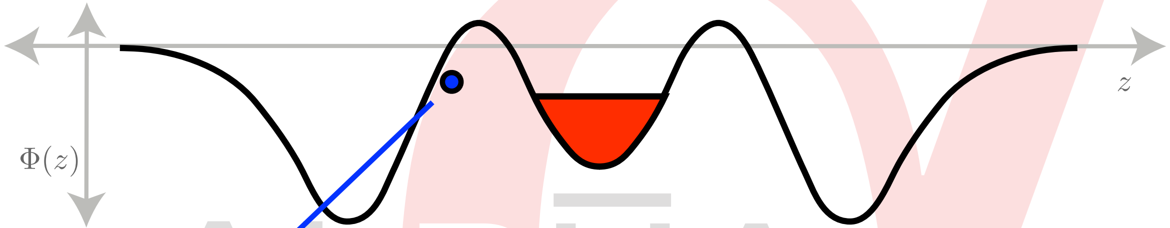




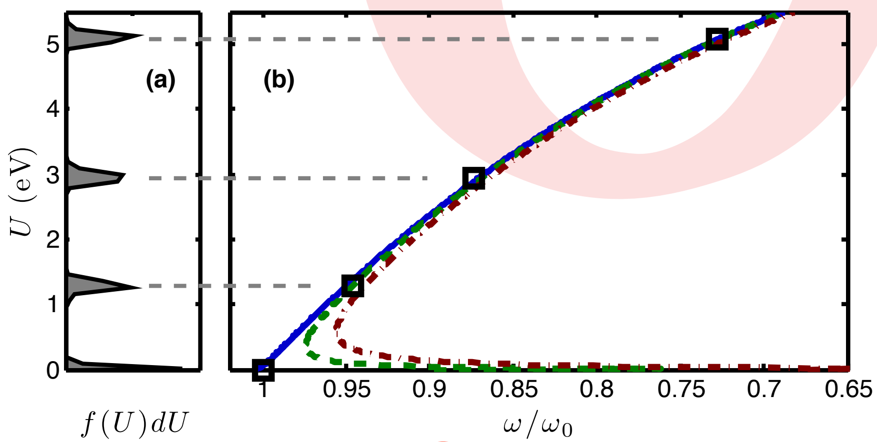
Note: We're losing a lot of $\bar{p}$, but the number below 1K is in fact increasing.

Drive on cloud of antiprotons?

- Counterintuitively, when plasma is cold and dense: Behaves as a single particle to drive

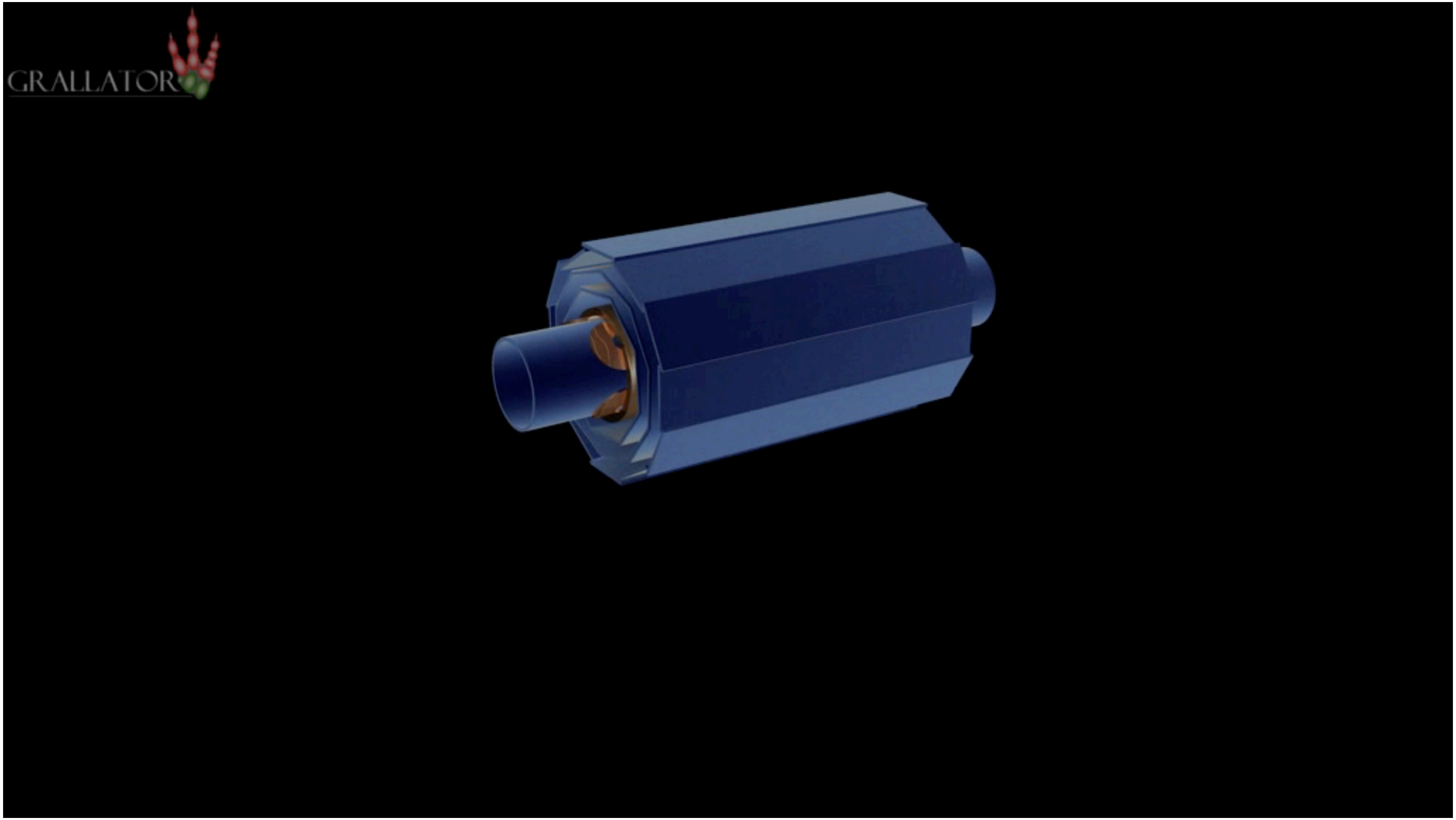


$$\ddot{\theta} + \omega_0^2 \sin\theta = \bar{\epsilon}\cos(\omega t)$$



Autoresonance: One key step to trapping!

Antihydrogen trapping



Mirror Trapping

- But $\bar{p}$ are not (necessarily) $\bar{H}$!
- $\bar{p}$ can be trapped by magnetic fields as their motional magnetic moment is an adiabatic invariant! $U = -\bar{\mu} \cdot \bar{B}$
- Their trapping depends on their energy

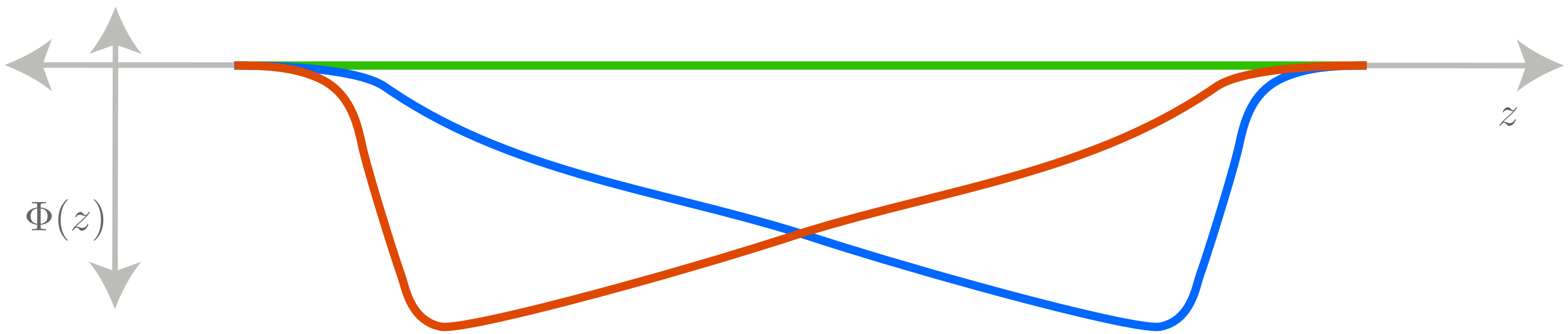
$$\alpha = \left(\frac{v_{||}}{v_{\perp}}\right) = \sqrt{\frac{B_{max}}{B_{min}} - 1}$$

- To avoid these we apply clearing fields before the trap is turned off.

New J. Phys.

Procedure to check $\bar{p}$ is $\bar{H}$

- Clean-out not guaranteed (>20eV)
- Heat the positrons and turn of antihydrogen production.
- We distinguished charged particles from neutral using a bias-field (during quench) which does not influence the neutrals!



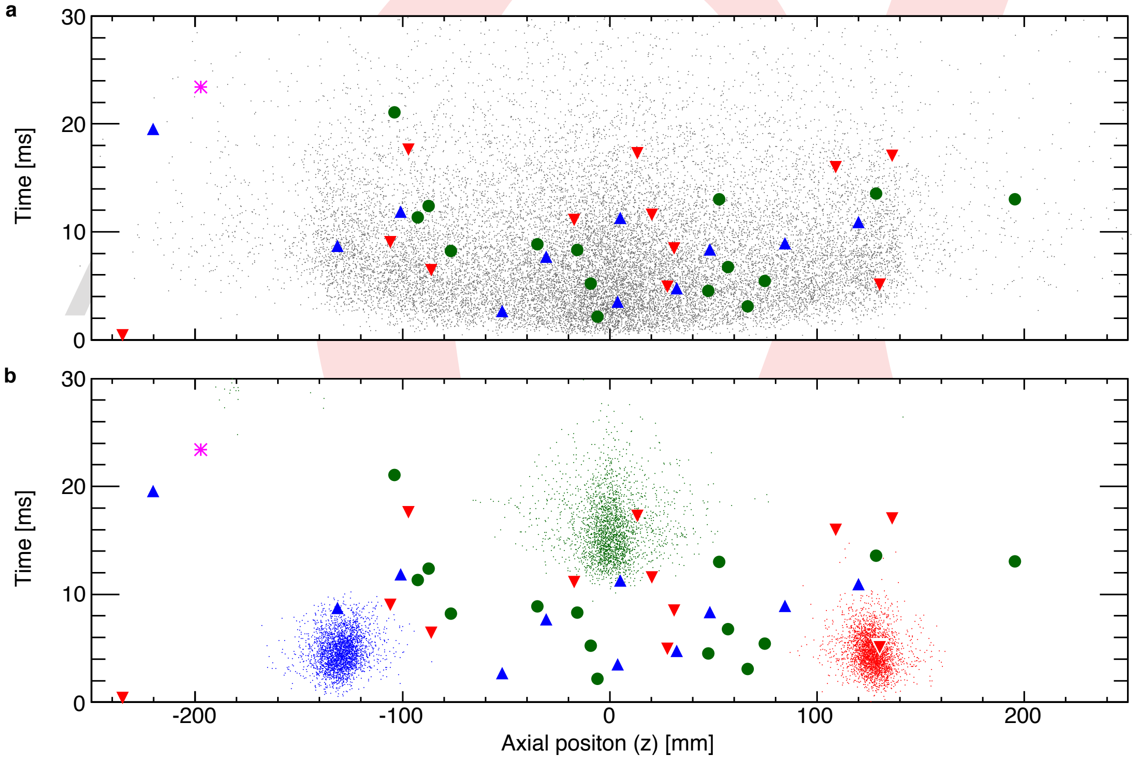
Trapping Results

- No spatial bias in signal; Heating ‘turns off’ signal

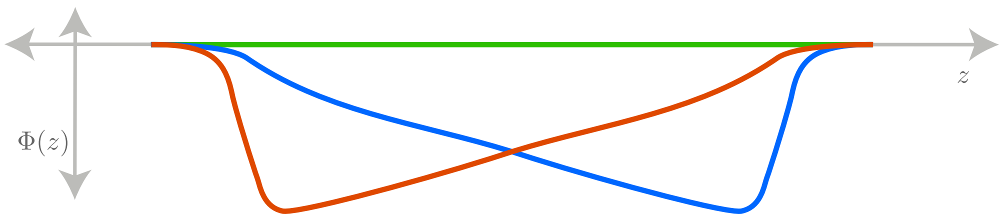
38 Antihydrogen atoms trapped! Background 1.4±1.4

Simulation: Antihydrogen

Simulation: Antiprotons

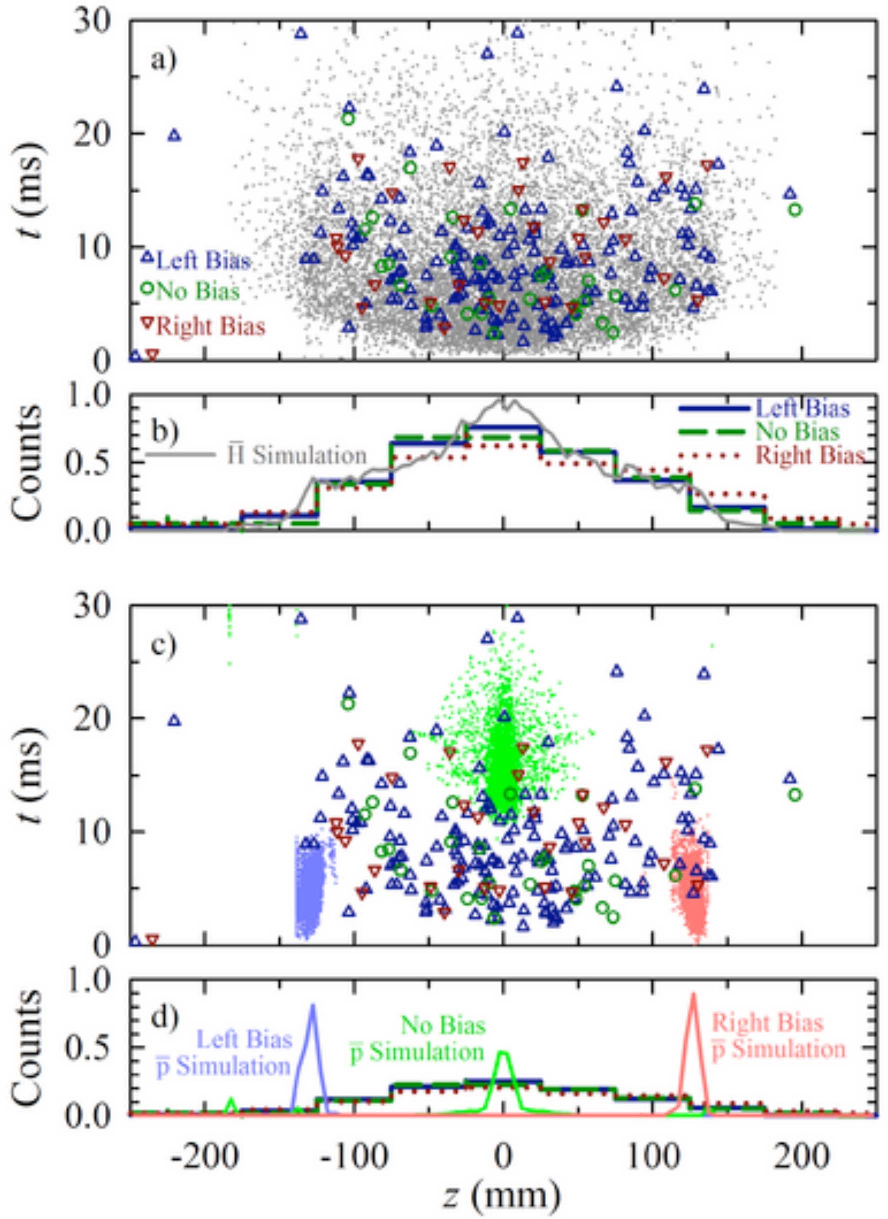


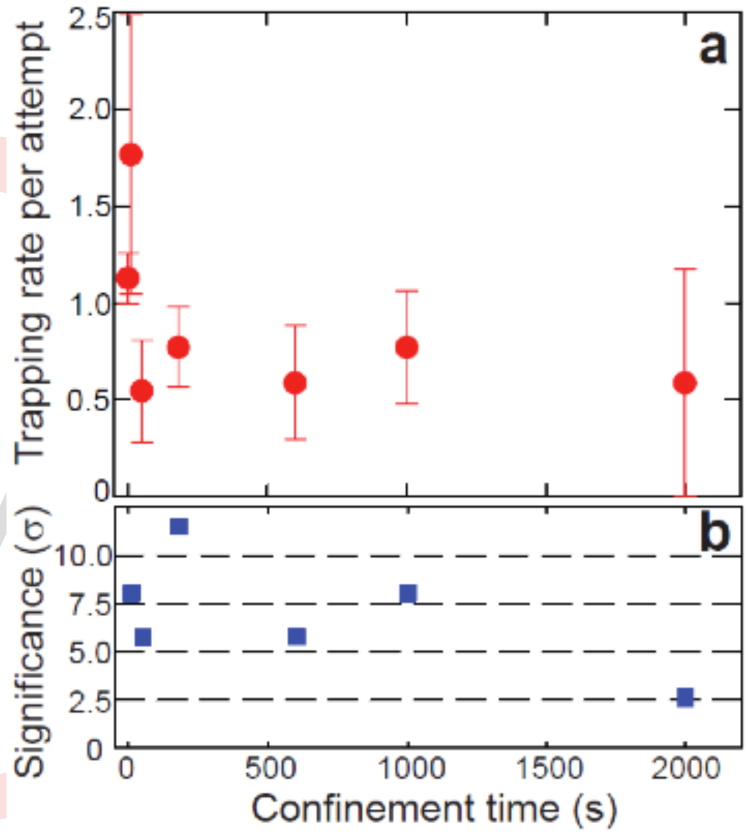
No Bias
Left Bias
Right Bias
(* Heating)



Nature

Long time confinement





>300 events!
stored for a 1000s!
1 trapped/experiment!

Nature Physics

Why “only” ~1 per exp. ?

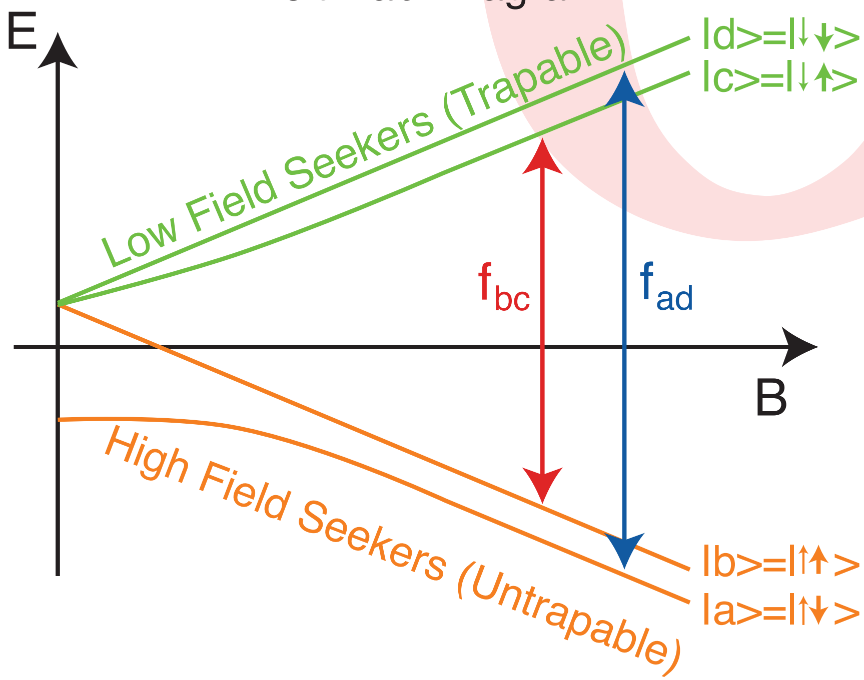
- Antiprotons from AD decelerated to 5.3 MeV
- Trap potentials < 1keV
- Plasma potentials 30mV ($\bar{p}$) 10V (e^+)
- Neutral trap depth 50 μV (0.6 K)

- $\bar{H}$ must be cold to be trapped!
- Many techniques developed to reduce energy.
- BUT : Even 1 atom can be interrogated!

Quantum Transitions

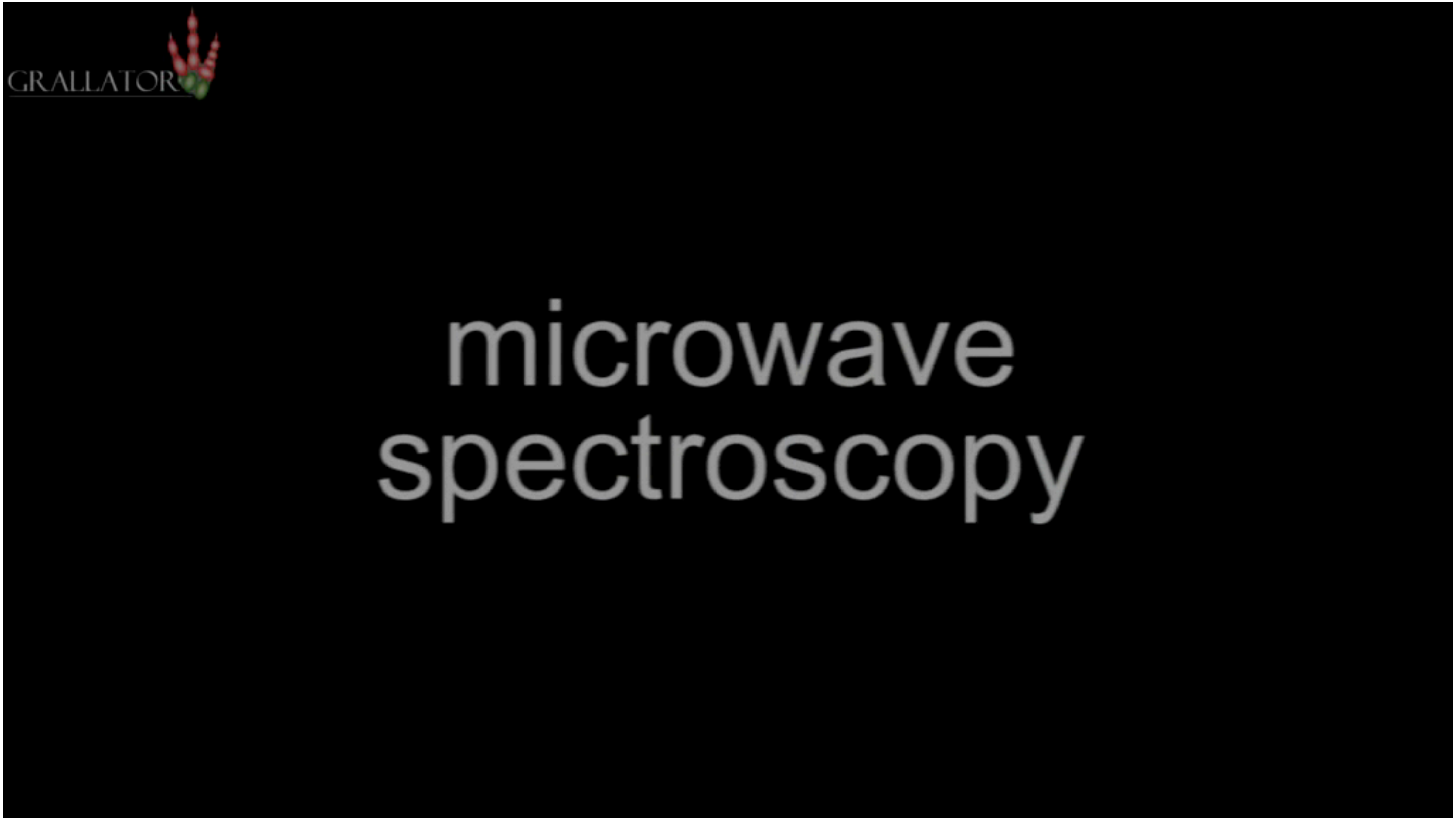
- Trapped atom(s) in the ground state - even if there's only one it is a platform for starting to compare antihydrogen and hydrogen.
- Diagnostic of one $\bar{H}$: Annihilation detection
- Method : Lose $\bar{H}$ resonantly from trap - spin flip.

Breit Rabi Diagram

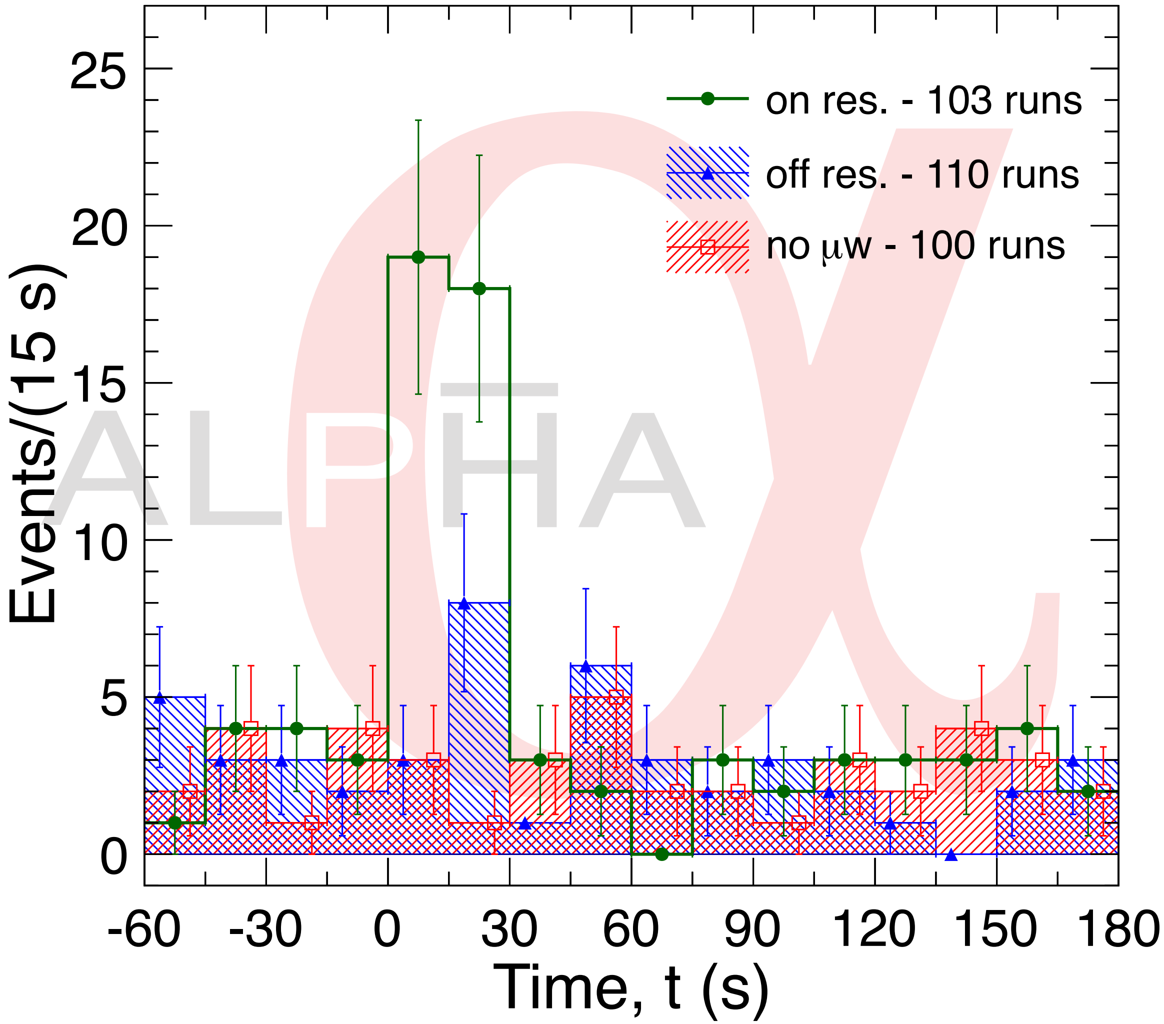


Nature, March 7th (2012)

Microwave Spectroscopy



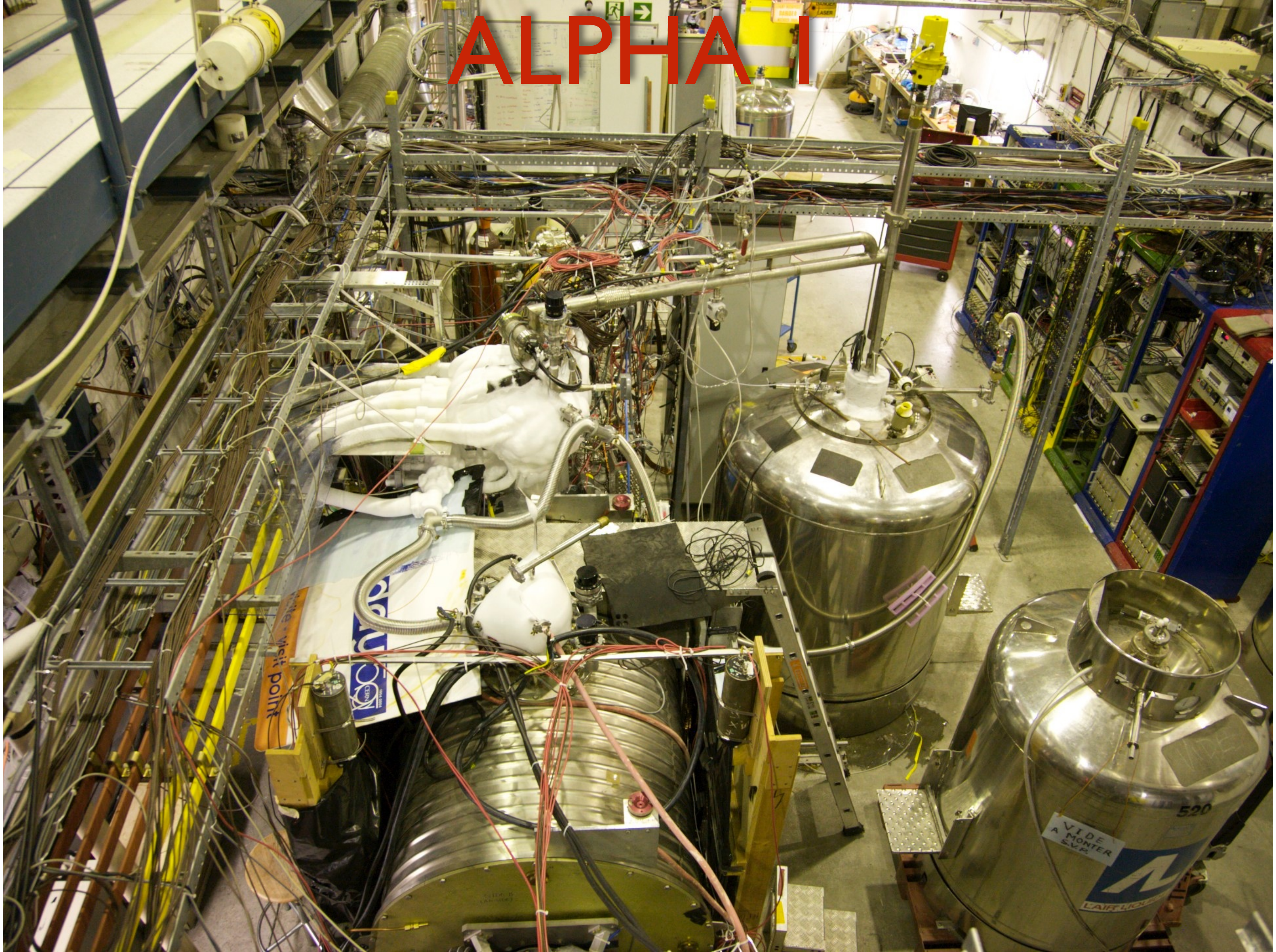
Appearance Measurement



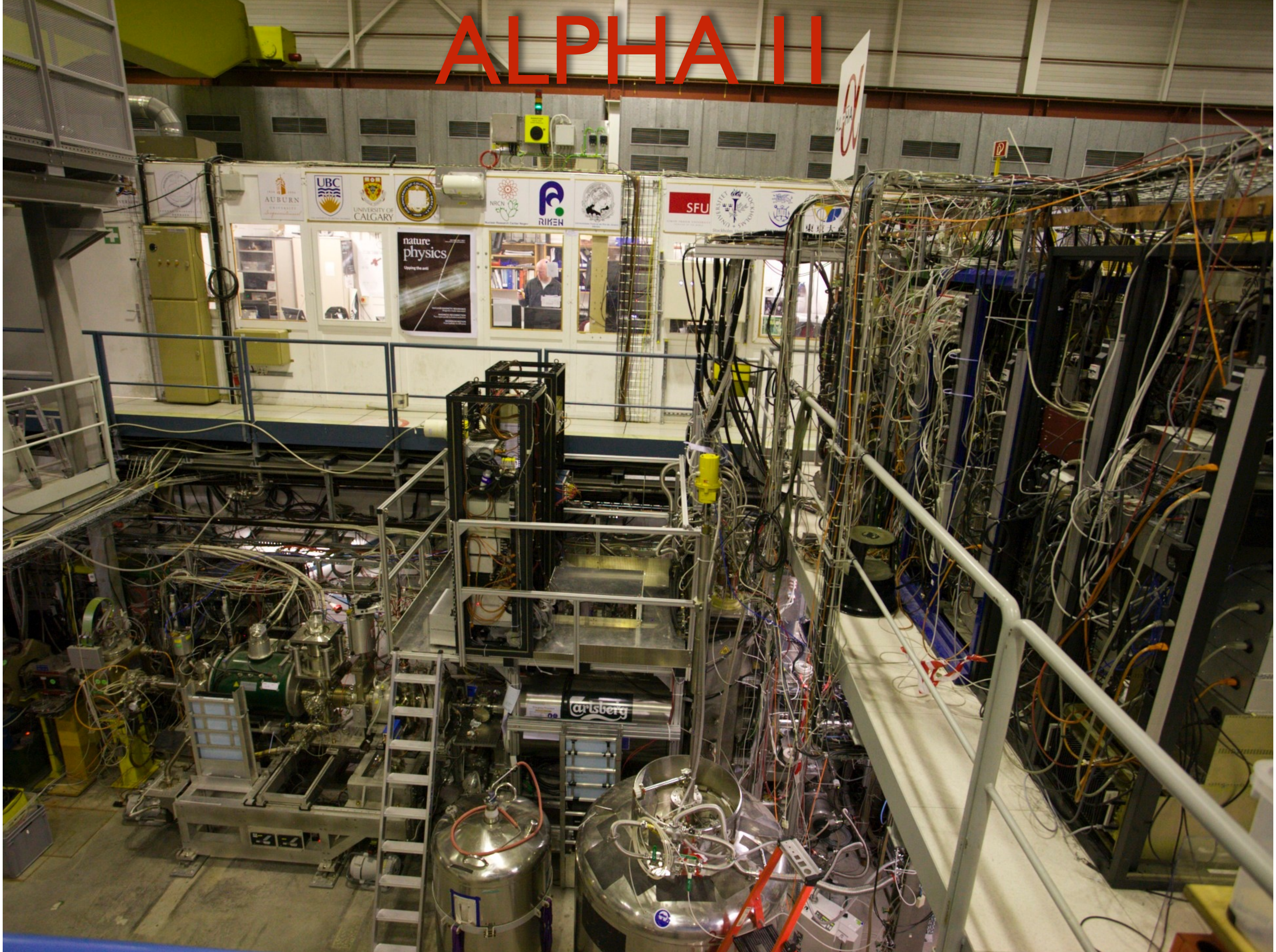
NB: 313 attempts 20min each - 104h - 2w (no hickups)

Nature, March 7th (2012)

ALPHA I



ALPHA II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nature physics
Carlsberg


Thank you for listening