Perspectives for precision tests with antihydrogen

Michael Doser
CERN

Summary of results of precision tests with Antihydrogen:

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1) Motivation for precision studies of antihydrogen

2) Status of formation of antihydrogen

3) Attempts at trapping antihydrogen

4) Attempts at forming a beam of Antihydrogen

5) Related atomic physics topics

6) Outlook

Why do precision measurements with Antihydrogen?

1) Precise comparison between matter and antimatter

test of fundamental symmetry (CPT)

2) Measurement of the gravitational behavior of antimatter

test of the Weak Equivalence Principle

The ultimate fundamental symmetry: CPT

- C - charge conjugation particle ⇔ antiparticle
- P - parity (space inversion)
- T - time reversal
- Consequences : particles/antiparticles have
  - same masses, lifetimes, g-factors, |charge|, etc.
- CPT invariance is a mathematical theorem:
  - consequence of Lorentz-invariance
  - local interactions
  - unitarity
    - point-like particles
      - Lüders, Pauli, Bell and Jost, 1955
- QED, standard model quantum field theories are all CPT invariant
  - Assumptions are invalid in string theory, quantum gravity

although CPT is part of the “standard model”, the SM can be extended to allow CPT violation

CPT violation and the standard model

Don Colladay and V. Alan Kostelecký
Department of Physics, Indiana University, Bloomington, Indiana 47405

(Received 22 January 1997)

Phys. Rev. D 55, 6760–6774 (1997)

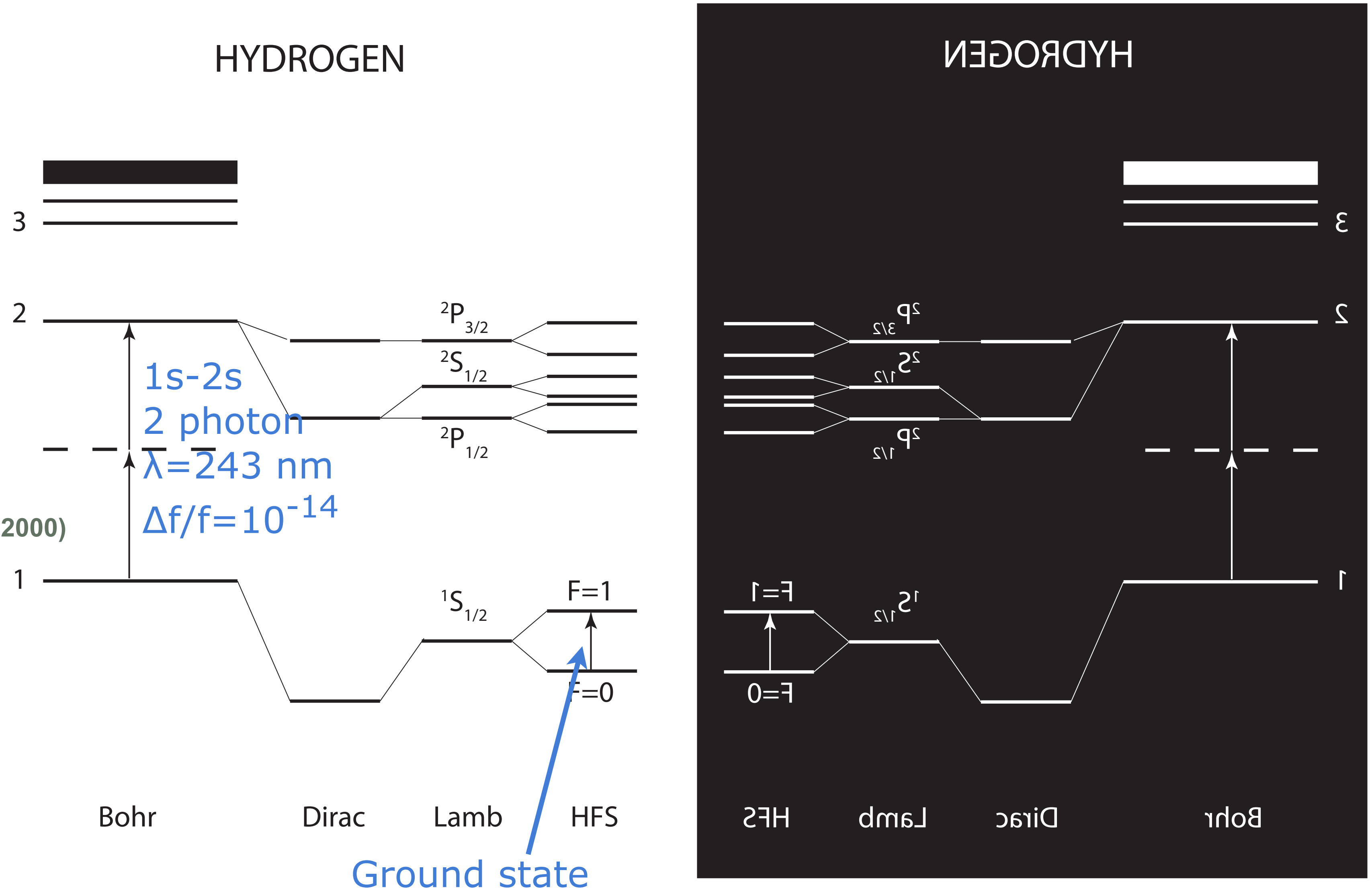
Modified Dirac eq. in SME

$$\begin{aligned}
&\Big(i\gamma^\mu D_\mu - m_e - \overbrace{\boxed{a^e_\mu\gamma^\mu - b^e_\mu\gamma_5\gamma^\mu}}^{\text{CPT \& Lorentz violation}} \\
&- \underbrace{\boxed{\tfrac{1}{2}H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^\mu D^\nu + id^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu}}_{\text{Lorentz violation}}\Big)\psi = 0\,.
\end{aligned}$$

- Spontaneous Lorentz symmetry breaking by (exotic) string vacua
- Note: if there is a preferred frame, sidereal variation due to Earth’s rotation might be detectable

Goal of comparative spectroscopy: test CPT symmetry

Hydrogen and Antihydrogen



1s-2s
2 photon
λ=243 nm
$\Delta f/f=10^{-14}$

T. Hänsch et al.,
Phys. Rev. Lett. 84, 5496–5499 (2000)

Ground state
hyperfine splitting
f = 1.4 GHz
$\Delta f/f=10^{-12}$

N. F. Ramsey,
Physica Scripta T59, 323 (1995)

HFS, CPT and SME

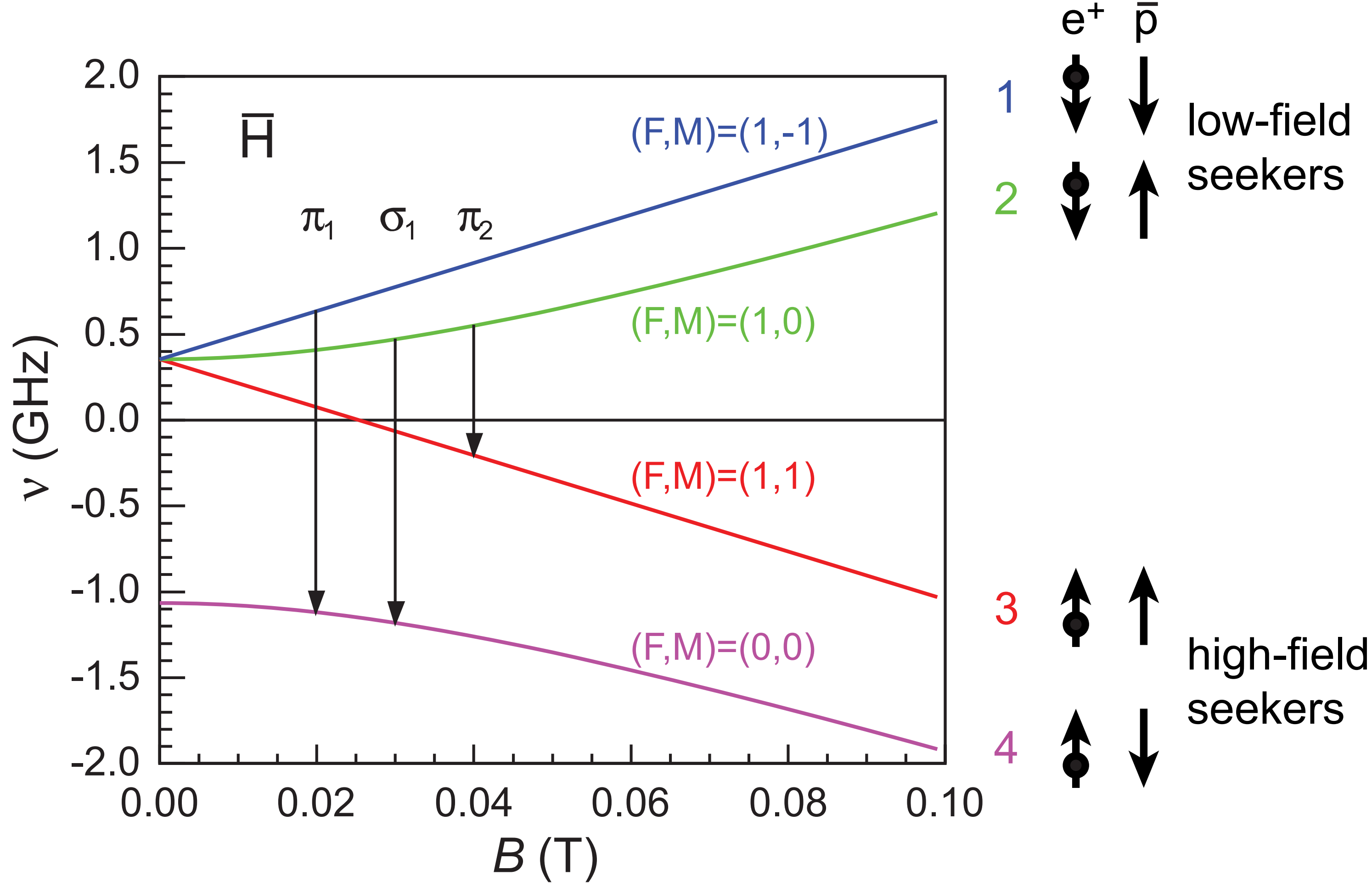
$$\nu_{\mathrm{HFS}} = \frac{16}{3}\left(\frac{m_p}{m_p+m_e}\right)^3 \frac{m_e}{m_p}\frac{\boxed{\mu_p}}{\mu_N}\alpha^2 c\, R_\infty (1+\Delta)$$

$\mu_{\overline{\mathrm{p}}}$ only known to 0.3%

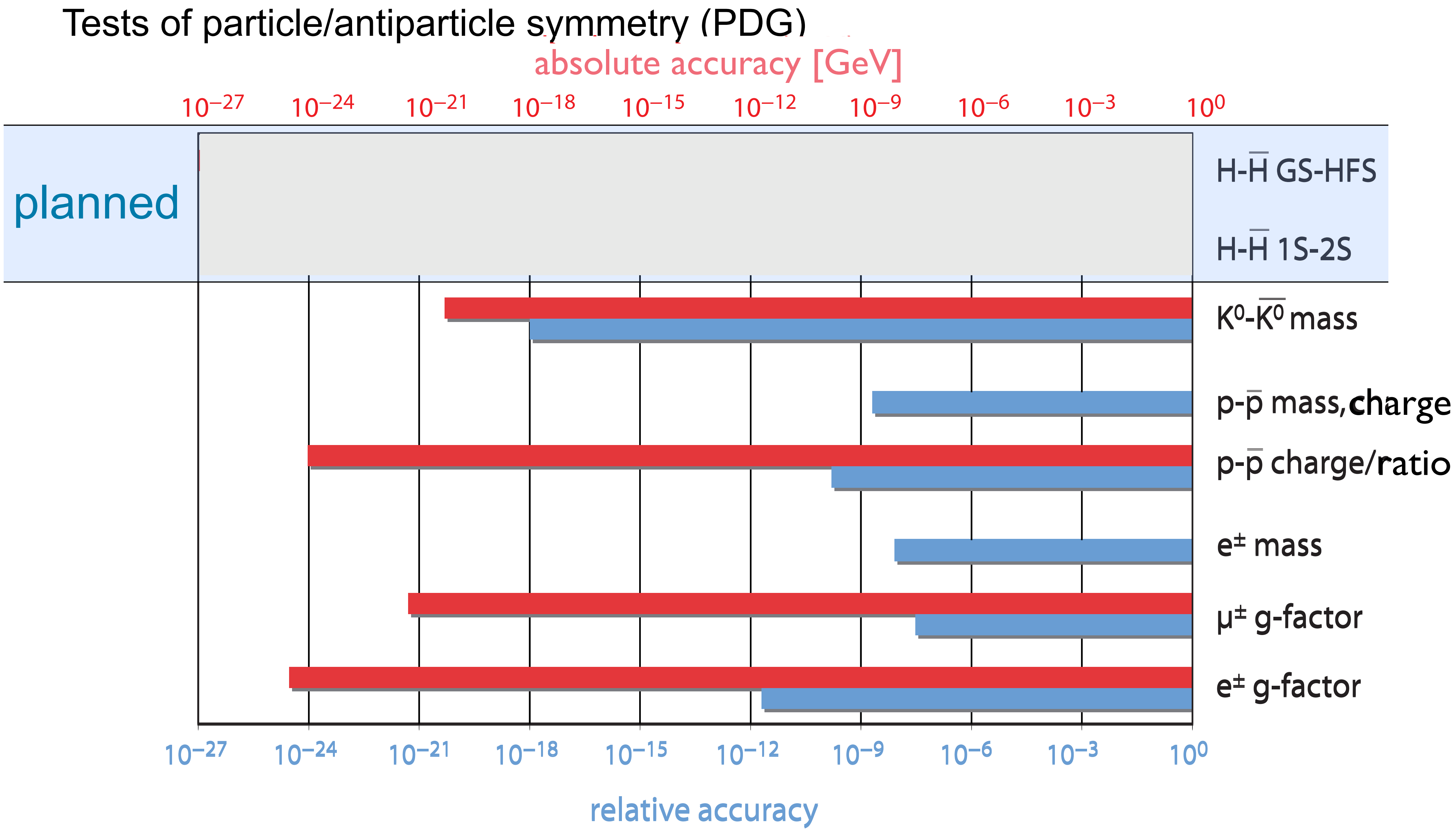
$$\begin{aligned}\Delta E^{\mathrm{H}}(m_J, m_I) = {} & \boxed{a_0^e} + \boxed{a_0^p} - c_{00}^e m_e - c_{00}^p m_p \\ & + \left(-b_3^e + \boxed{d_{30}^e} m_e + \boxed{H_{12}^e}\right) m_J/|m_J| \\ & + \left(-b_3^p + \boxed{d_{30}^p} m_p + \boxed{H_{12}^p}\right) m_I/|m_I|,\end{aligned}$$

Bluhm, R., Kostelecký, V.A., Russell, N.: Phys. Rev. Lett. **82**, 2254 (1999)

Transitions between HF levels are sensitive to CPTV, but not 1s → 2s



Verifications of CPT symmetry



Inconsistent definition of figure of merit: comparison difficult

Pattern of CPT violation unknown (P: weak interaction; CP: mesons)

Absolute energy scale: standard model extension (Kostelecky)

Motivation

- General relativity is a classical (non quantum) theory;
- EEP violations may appear in some quantum theory
- New quantum scalar and vector fields are allowed in some models (Kaluza Klein ….)

Einstein field: tensor graviton (Spin 2, "Newtonian")

+ Gravi-vector (spin 1)

+ Gravi-scalar (spin 0)

- These fields may mediate interactions violating the equivalence principle

M. Nieto and T. Goldman, Phys. Rep. 205, 5 221-281,(1992)

Scalar: "charge" of particle equal to "charge of antiparticle" : attractive force
Vector: "charge" of particle opposite to "charge of antiparticle": repulsive/attractive force

$$V = -\frac{G_\infty}{r} m_1 m_2 \left(1 \mp a\, e^{-r/v} + b\, e^{-r/s} \right)$$

Phys. Rev. D 33 (2475) (1986)

Cancellation effects in matter experiment if a ≈ b and v ≈ s

The reality

Making Antihydrogen

Plan A:
Trapping Antihydrogen
Cooling Antihydrogen
Boundary conditions (magnetic field, limited solid angle, *low* numbers of particles)

Plan B:
Atomic beam

Principle of antihydrogen production

Antiprotons

Production GeV

Deceleration MeV

Trapping keV

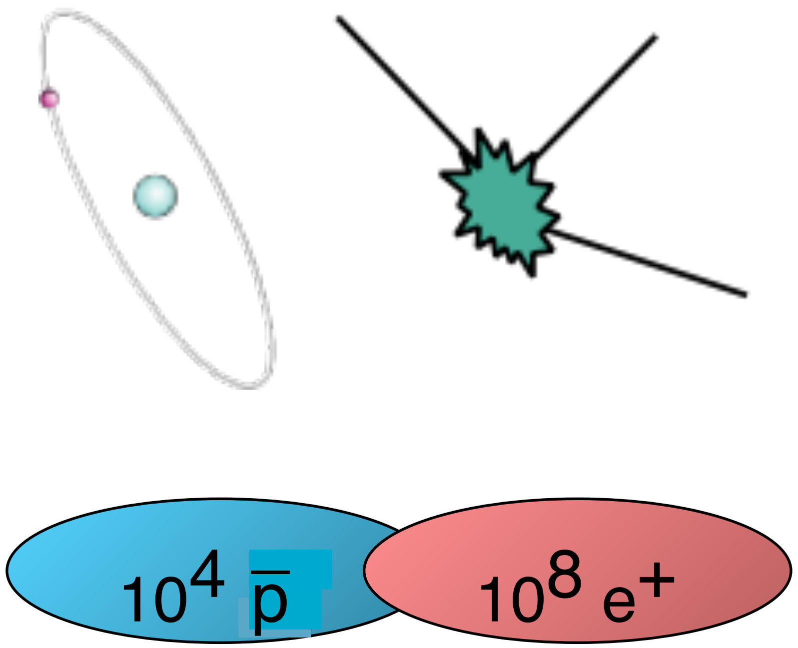
Cooling meV

Positrons

Production MeV

Moderation

Accumulation eV



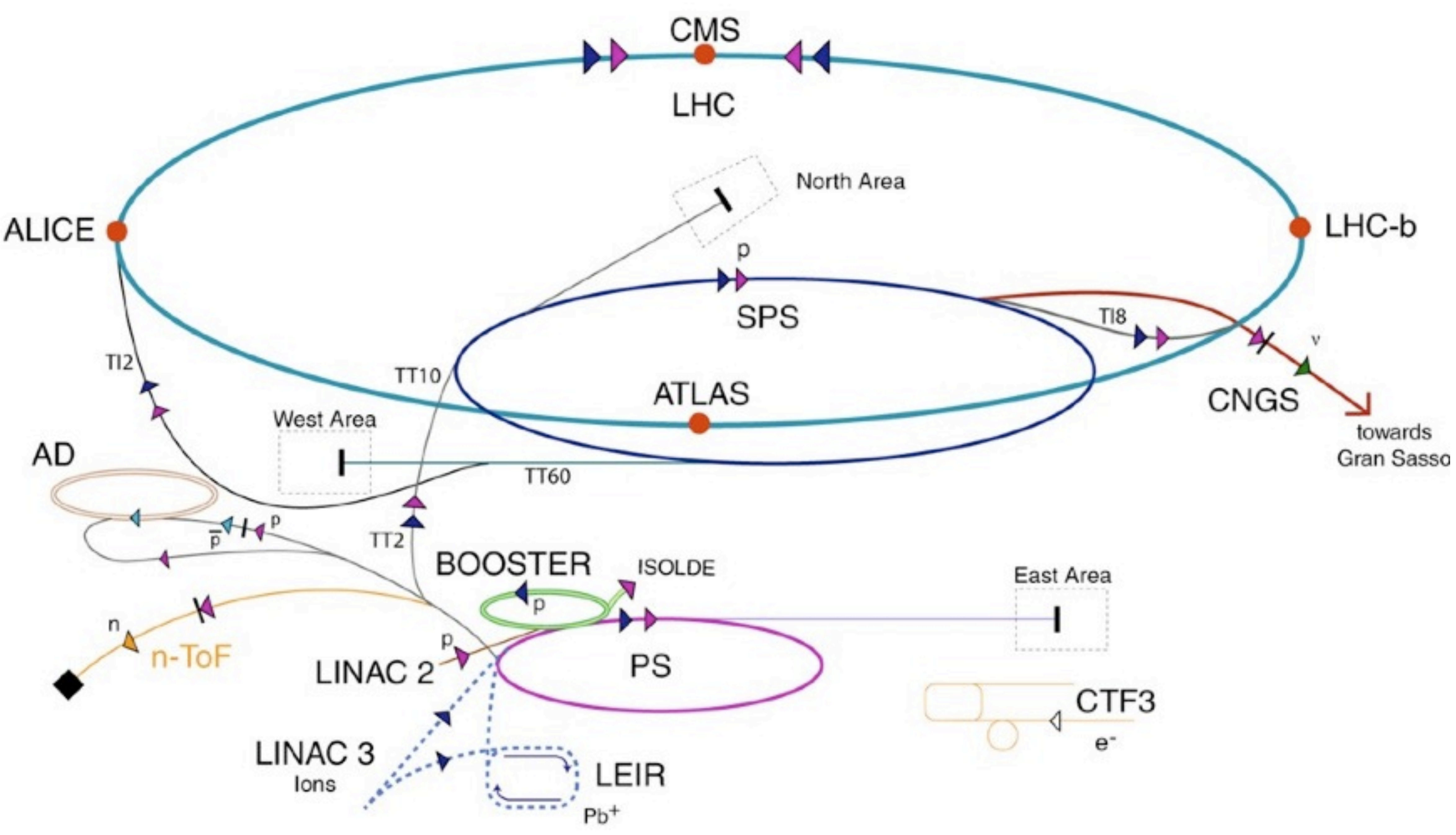
Mixing trap:

mixing and manipulation

Antihydrogen formation

Detection of annihilation

CERN Accelerator Complex



▶ protons
▶ ions
▶ neutrons

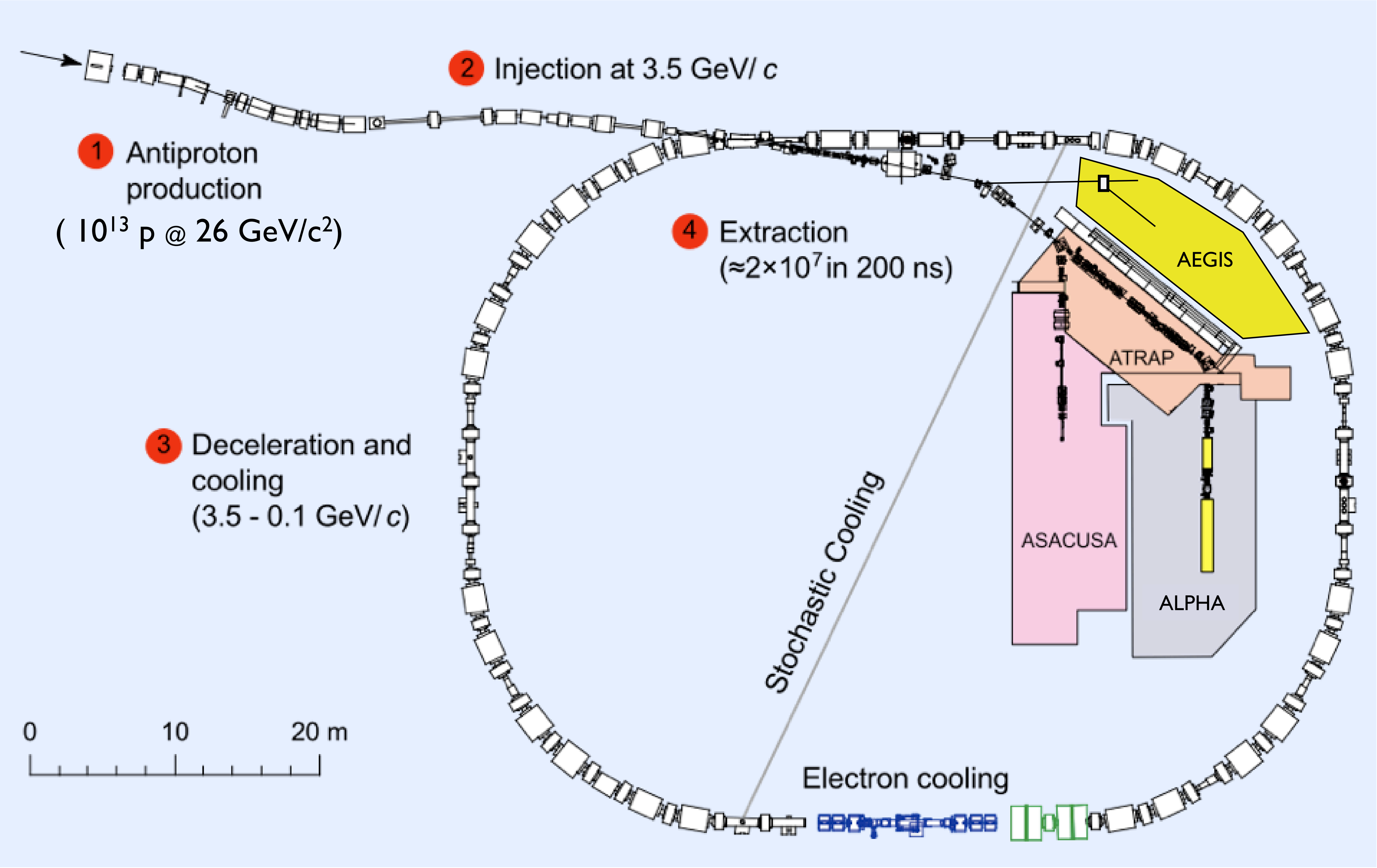
▶ antiprotons
▷ electrons
▶ neutrinos

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS CERN Neutrinos Gran Sasso

CTF3 CLIC Test Facility 3

Antiproton decelerator



① Antiproton production
(10^{13} p @ 26 GeV/c^2)

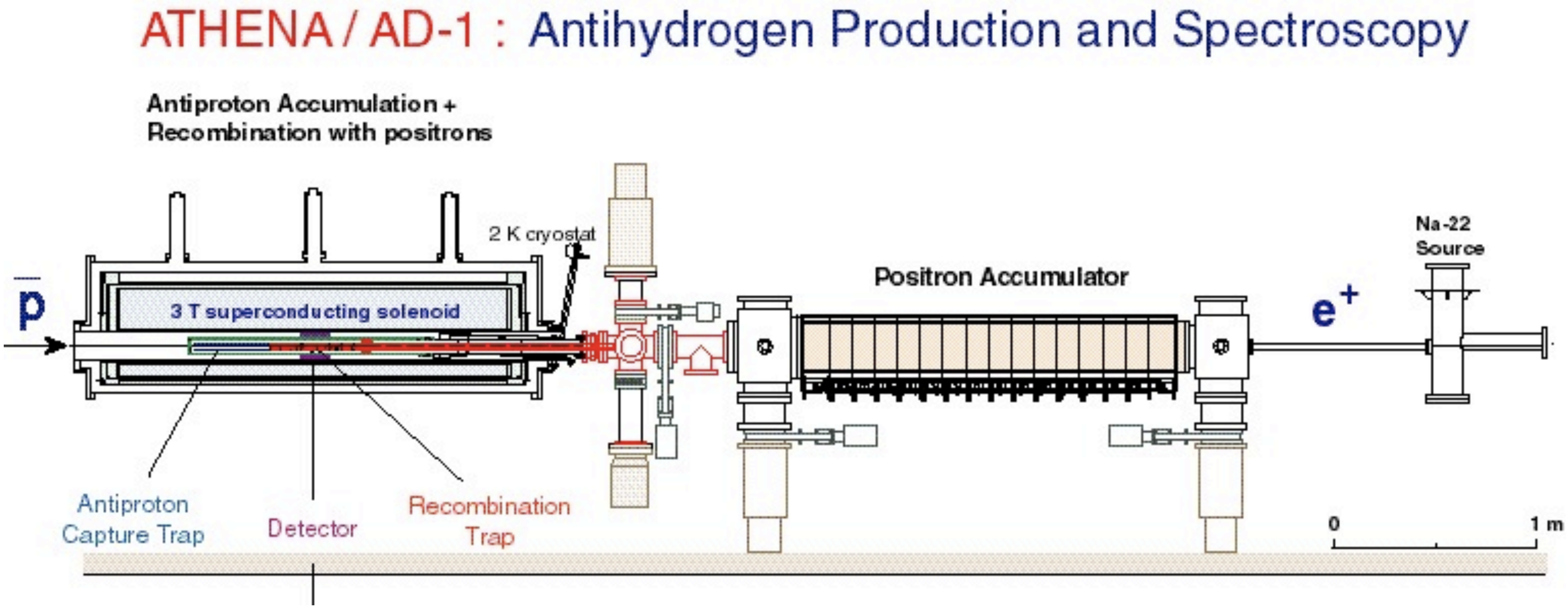
② Injection at 3.5 GeV/ *c*

③ Deceleration and cooling
(3.5 - 0.1 GeV/ *c*)

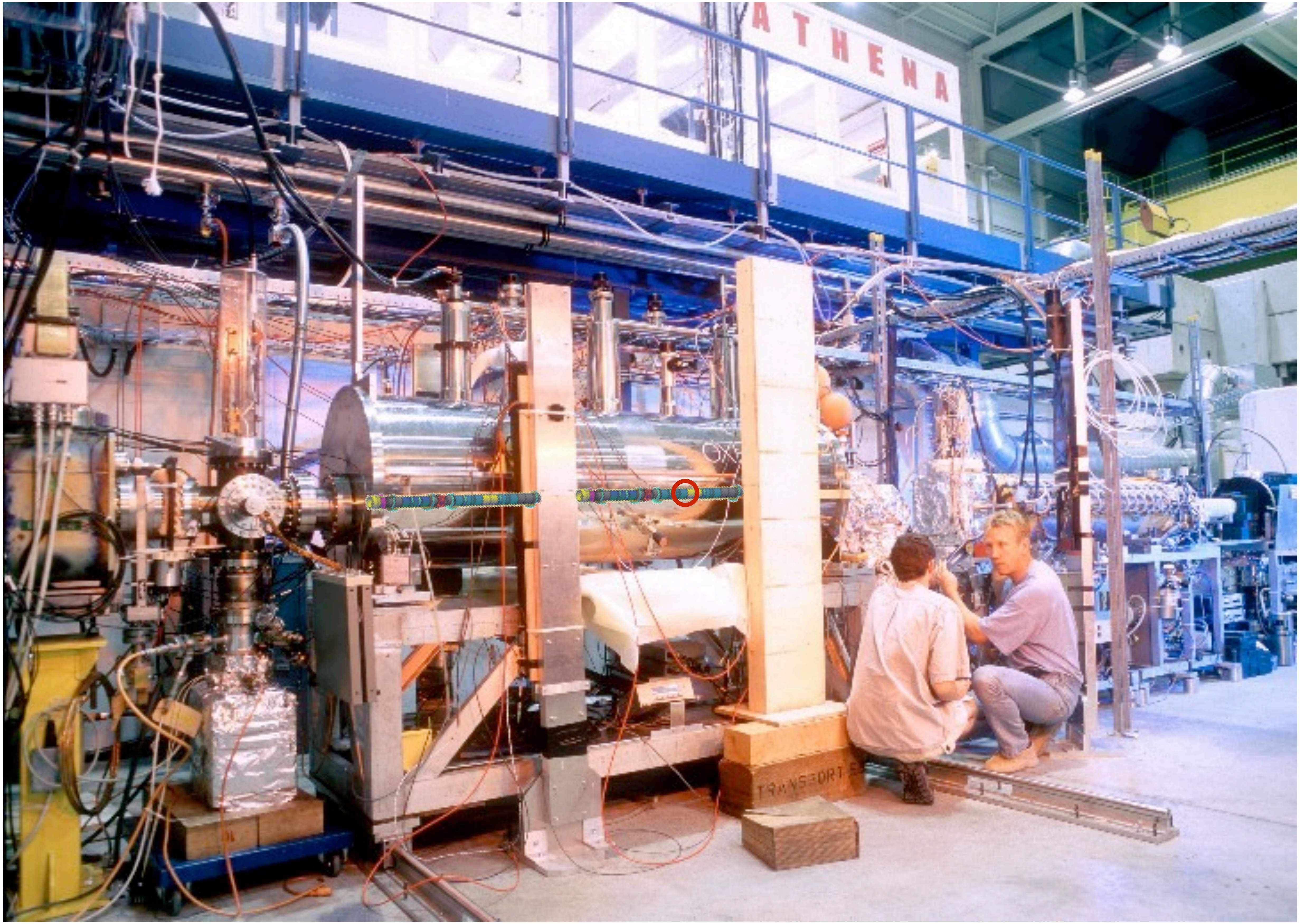
④ Extraction
(≈2×10^7 in 200 ns)

Typical Antihydrogen Experiment

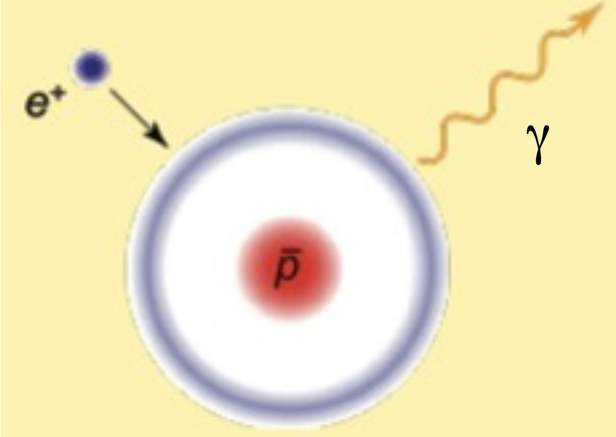
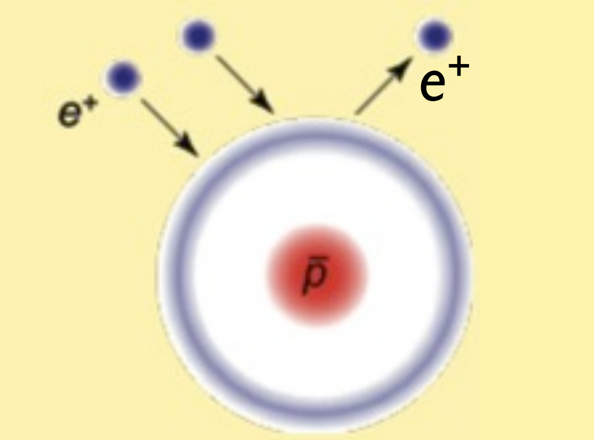
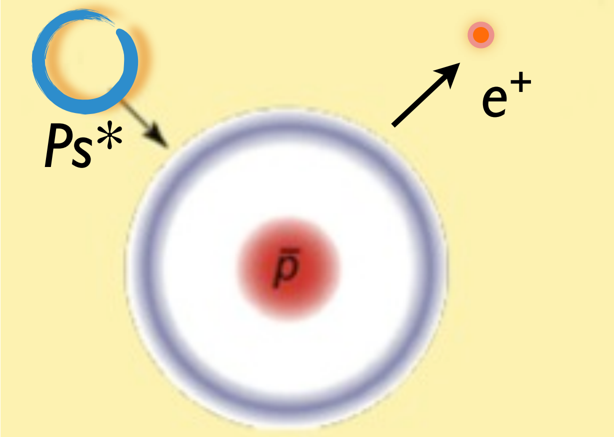
• Capture, trap, cool antiprotons	10^7 (AD) ➡ 10^5 (trapped)
• Capture, trap, cool positrons	1.5 GBq ^{22}Na ➡ 10^8 (trapped)
• Merge and recombine	1-10^3 Hz



Formation



Recombination processes

Principle			
Temperature dependence	$\propto T^{-2/3}$	$\propto T^{-2/3}$	$\propto T^{-x}$
e+ density dependence	$\propto n_e$	$\propto n_e^2$	
Cross section at 1K	10^{-16} cm^2	10^{-7} cm^2	10^{-9} cm^2
Final internal states	$n<10$	$n>>10$	$f(n_{Ps})$
Expected rates	few Hz	high	1Hz (?)

but: B, interactions in e$^+$ plasma can't be neglected!

J. Stevefelt et al., PRA 12 (1975) 1246

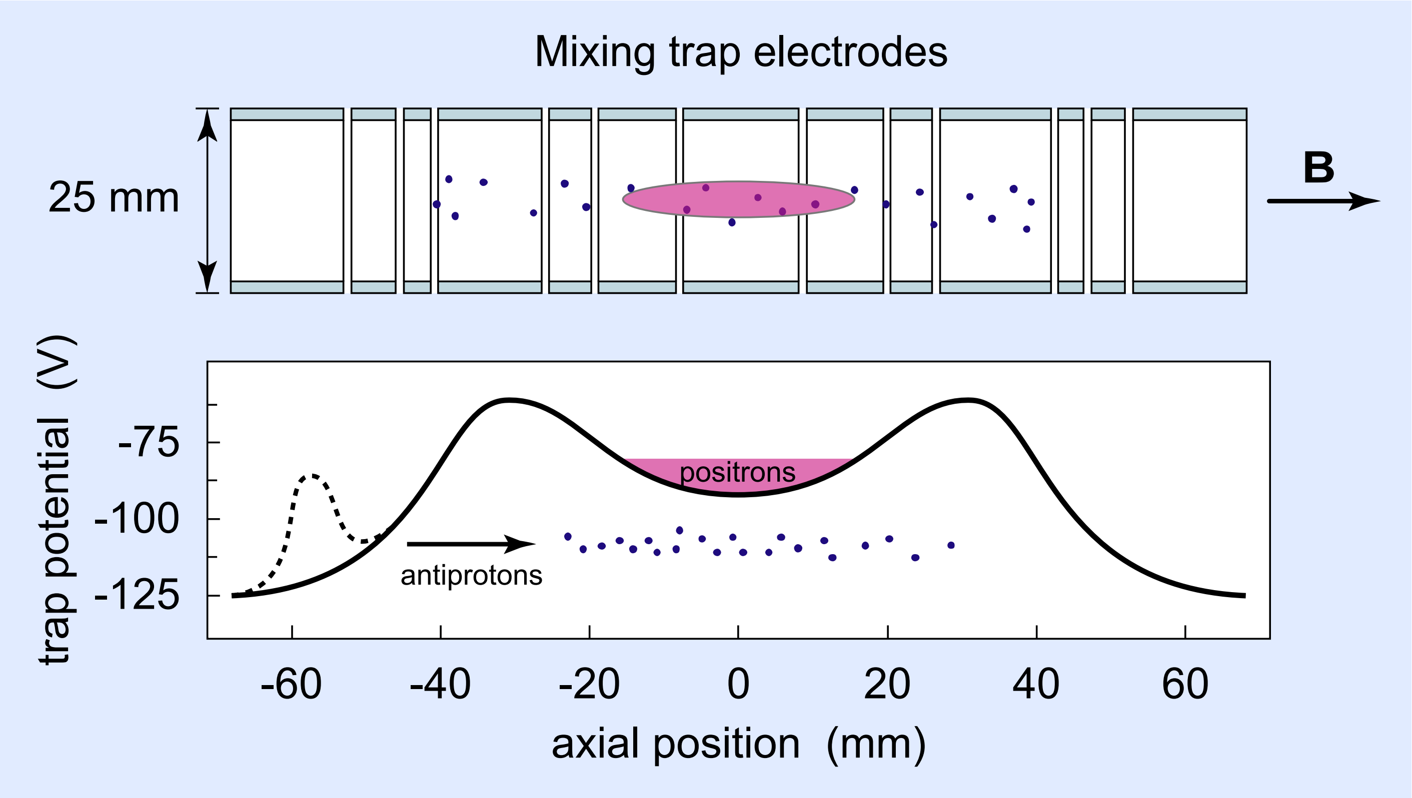
Robicheaux F 2004 Phys. Rev. A 70 022510

M. E. Glinsky et al., Phys. Fluids B 3 (1991) 1279

Robicheaux, J. Phys. B: At. Mol. Opt. Phys. 41 (2008) 192001

Antihydrogen production (I)

Nested-well technique: Penning trap for $\bar{p}$, e^+ : B=1T (plasma stability)



ATHENA

e^+ $N \approx 5\times10^7$ $n \approx 2\times10^8$ cm^{-3}

$\bar{p}$ $N \approx 10^4$

ATRAP

e^+ $N \approx 2\times10^6$

$\bar{p}$ $N \approx 10^5$

[G. Gabrielse *et al.*, Phys. Lett. A **129** (1988) 38]

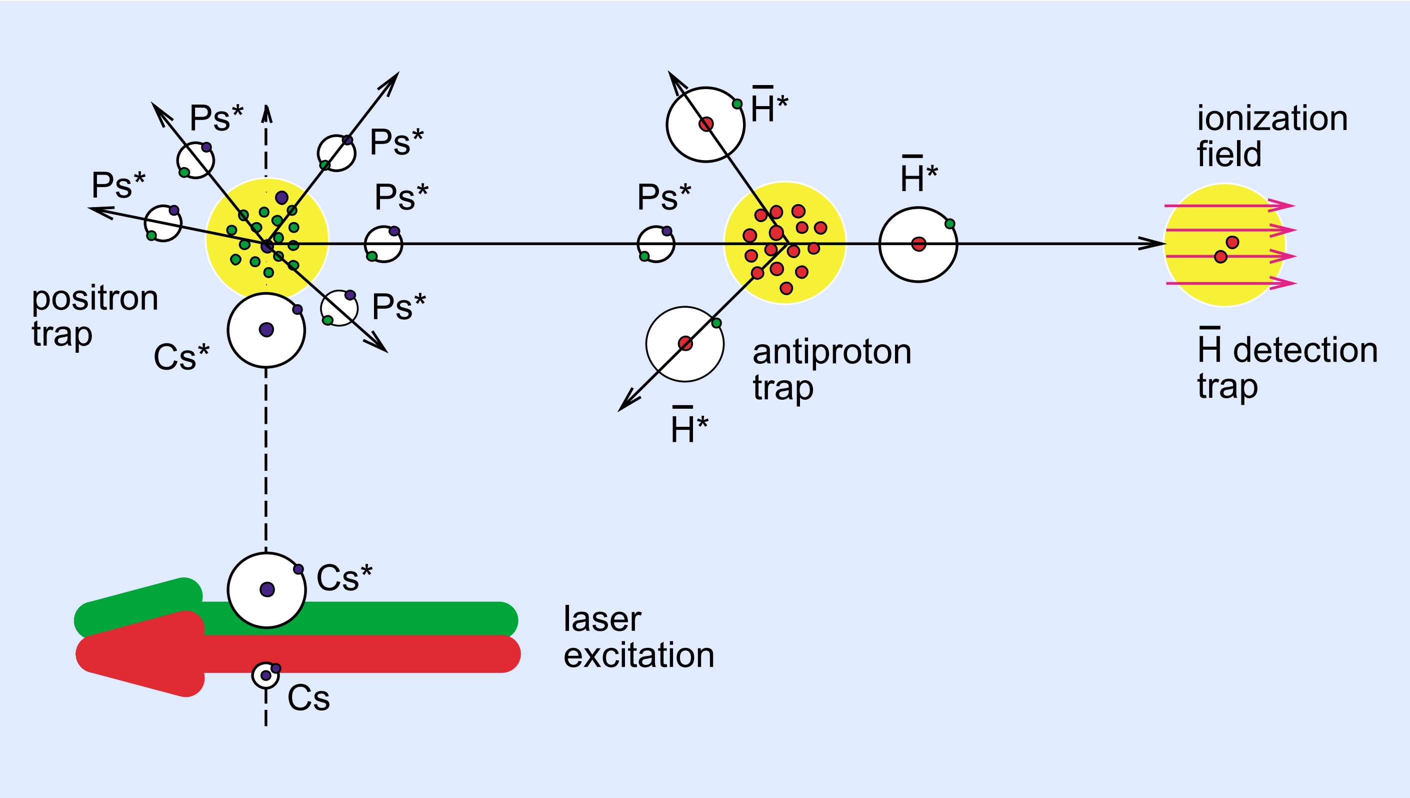
- Positrons cool by emission of synchrotron radiation
- Antiprotons launched into pre-cooled positrons
- $\overline{\text{H}}$ production sets in spontaneously at high rates
- Disadvantage:

plasma temperature, re-ionization, high-n states

[G. Gabrielse *et al.*, Phys. Rev. Lett. **93** (2004) 073401;
N. Madsen *et al.* (ATHENA), Phys. Rev. Lett. **94** (2005) 033403]

Antihydrogen production (II)

Cesium charge exchange technique:



$$\mathrm{Cs}^* + e^+ \rightarrow \mathrm{Cs}^+ + \mathrm{Ps}^*$$

$$\mathrm{Ps}^* + \overline{p} \rightarrow \overline{\mathrm{H}}^* + e^-$$

ATRAP

e^+ $N \approx 1.4\times10^6$

$\bar{p}$ $N \approx 2.4\times10^5$

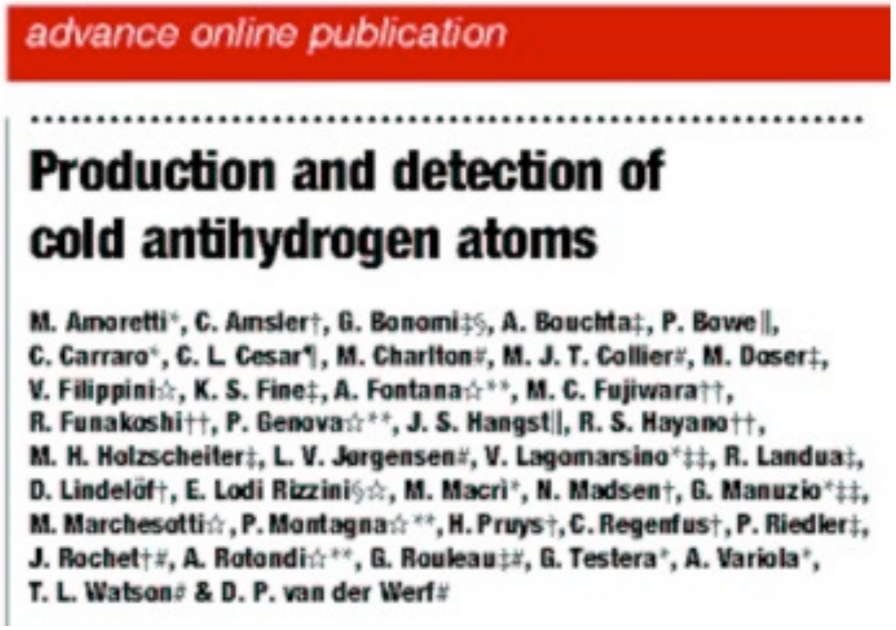
densities not given

[C. Storry *et al.* (ATRAP),
Phys. Rev. Lett. **93** (2004) 263401]

- Two-stage resonant charge exchange
- $\overline{\mathrm{H}}$ produced at well-defined quantum state and (presumably) at the temperature of $\bar{p}$ prior to recombination
- Disadvantage:

Small solid angle $\Rightarrow$ low rates

First "Cold" Antihydrogen 2002 @ AD



advance online publication

Production and detection of cold antihydrogen atoms

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ATHENA
Nature 419
(2002) 456

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Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States

G. Gabrielse,[1,*] N. S. Bowden,[1] P. Oxley,[1] A. Speck,[1] C. H. Storry,[1] J. N. Tan,[1] M. Wessels,[1] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2] T. Sefzick,[2] J. Walz,[3] H. Pittner,[4] T. W. Hänsch,[4,5] and E. A. Hessels[6]

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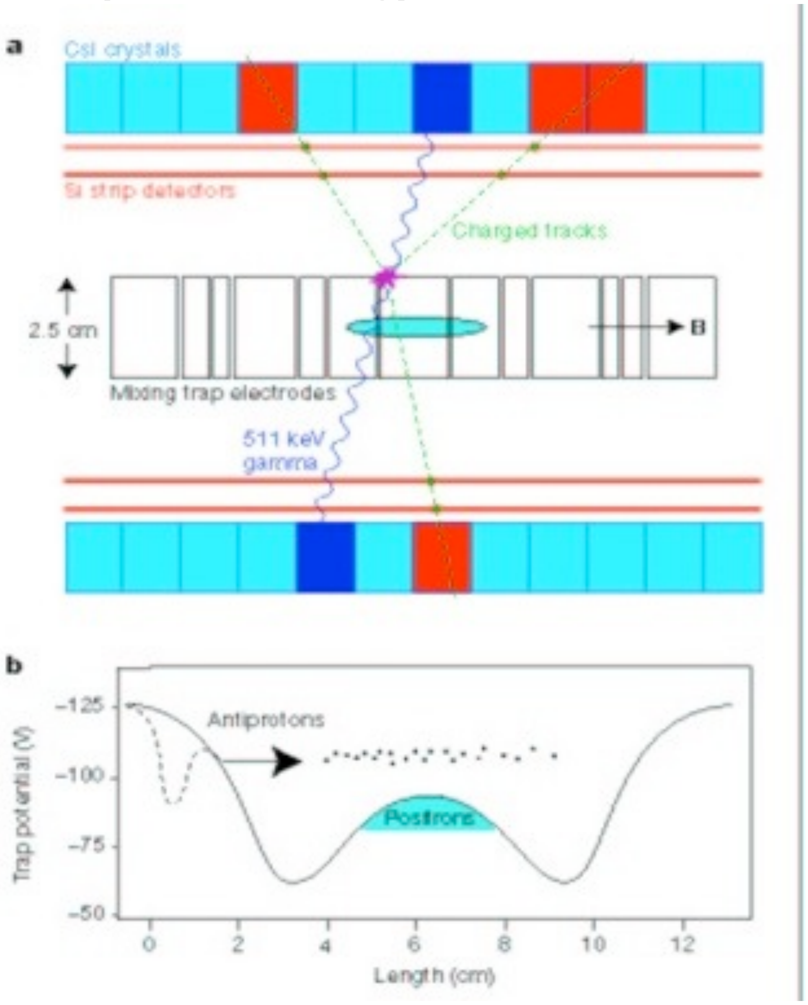
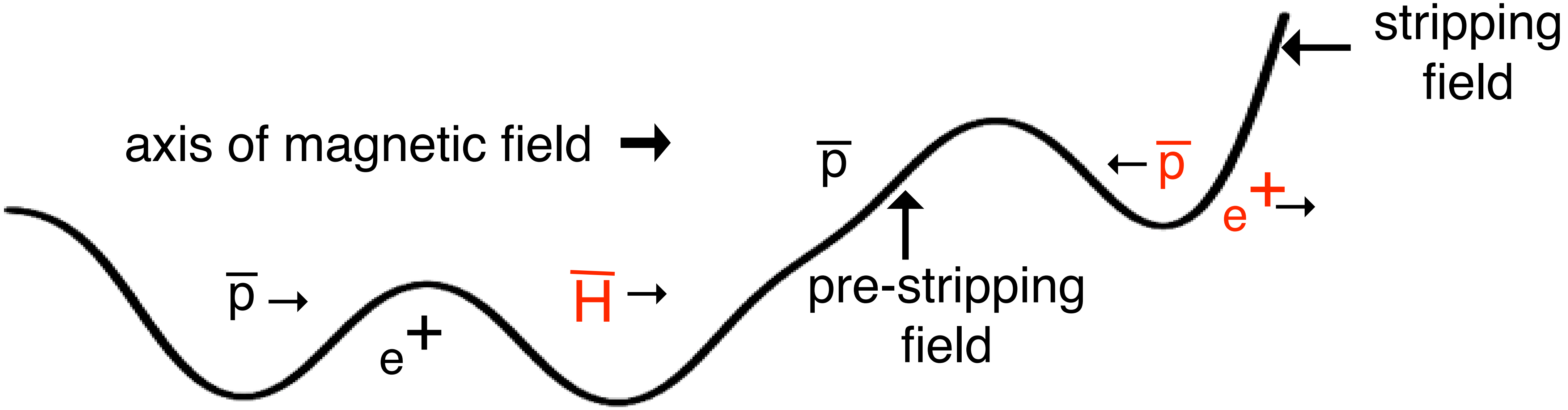
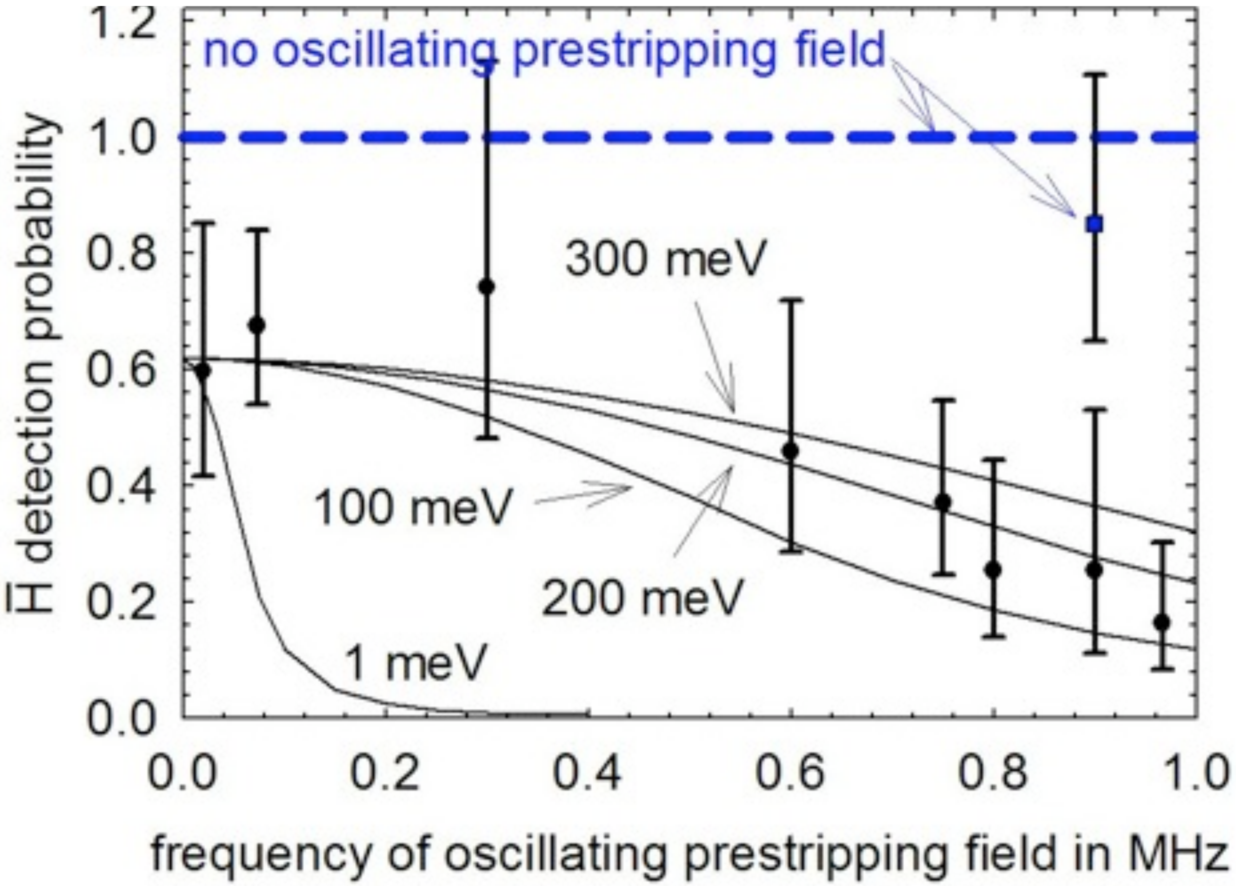
ATRAP PRL 89 (2002) 213401

Nested Penning traps
Capture energy: few keV



Temperature of produced $\bar{H}$





Fraught with uncertainty: collisions, plasma temperature, selectivity to lightly bound states, lack of control on initial conditions...

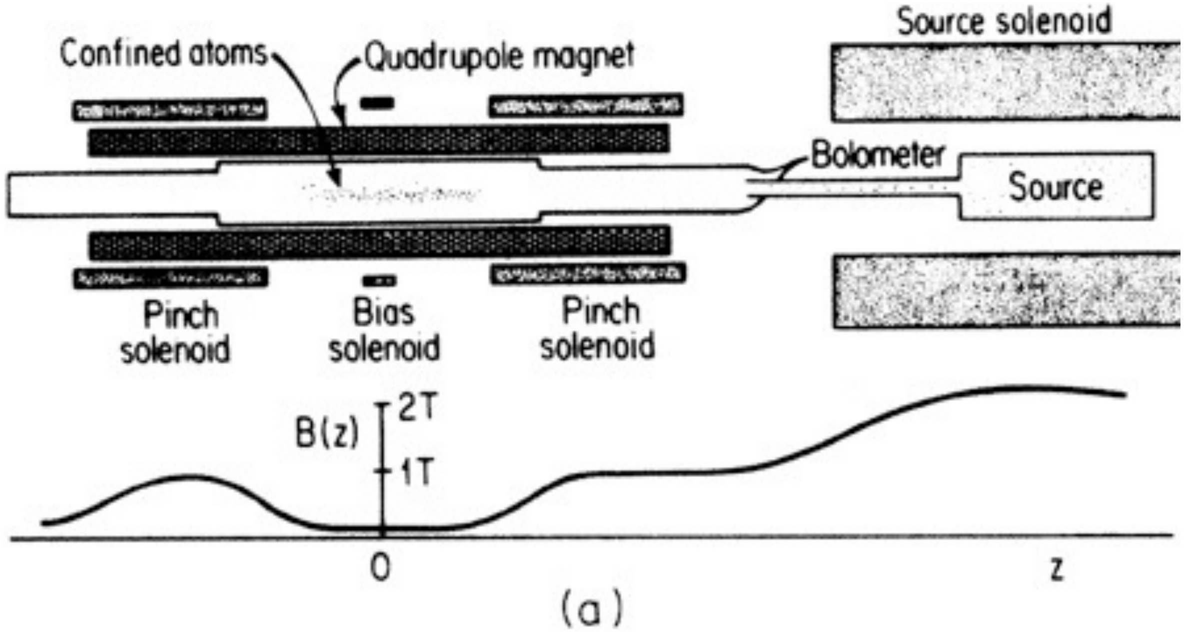
BUT

4.2 K H ~ 0.3 meV

[G.Gabrielse et al., Phys. Rev. Lett. 93, 073401 (2004)]

Trapping of $\bar{\mathrm{H}}$?

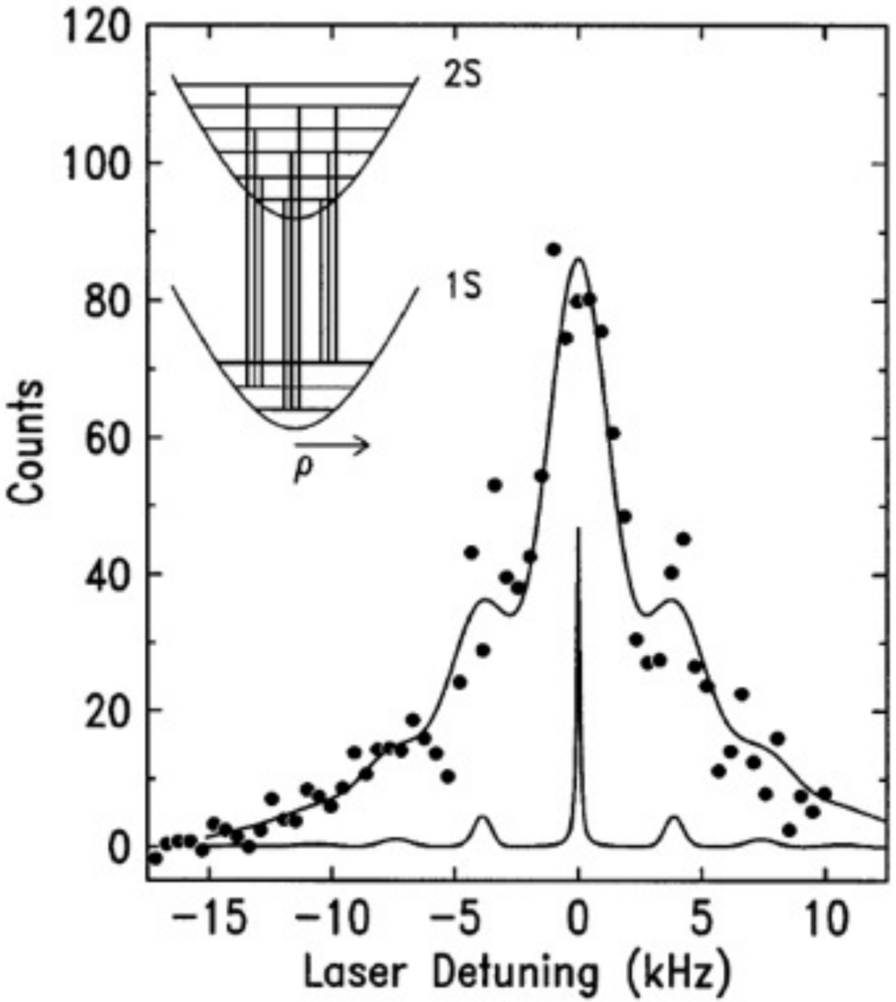
- Force of magnetic field gradient on magnetic moment of atom
- “depth” typically < 1 K (50 μeV)
- Constant holding-field $B_{z,0}$ to avoid spin flips
- Typical configuration:



- Trapped hydrogen C. Cesar et al., Phys. Rev. Lett. 77, 255 (1996)

10^{13} - 10^{10} atoms at 25 mK to 100 μK

$B_{z,0} = 2 \times 10^{-4}$ T



$\bar{\mathrm{H}}$: Confine both *charged* plasmas and *neutral* atoms *without heating* them

-Preserve cylindrical symmetry (plasma confinement)

-Magnetic field minimal in center (atom confinement)

-Antihydrogen must be formed inside its trap

Challenges to trapping of produced $\overline{\mathrm{H}}$

temperature considerations:

- $\bar{p}$ cooling: typically cooled via electrons, but electrons can ionize produced $\overline{\mathrm{H}}$; however, e^- kick-out heats antiprotons

  ➟ cooling of $\bar{p}$?

- e^+ cooling: high density ➟ plasma regime ➟ high angular momentum ➟ strong radial compression needed!

- temperature of $\overline{\mathrm{H}}$: depends on formation mechanism

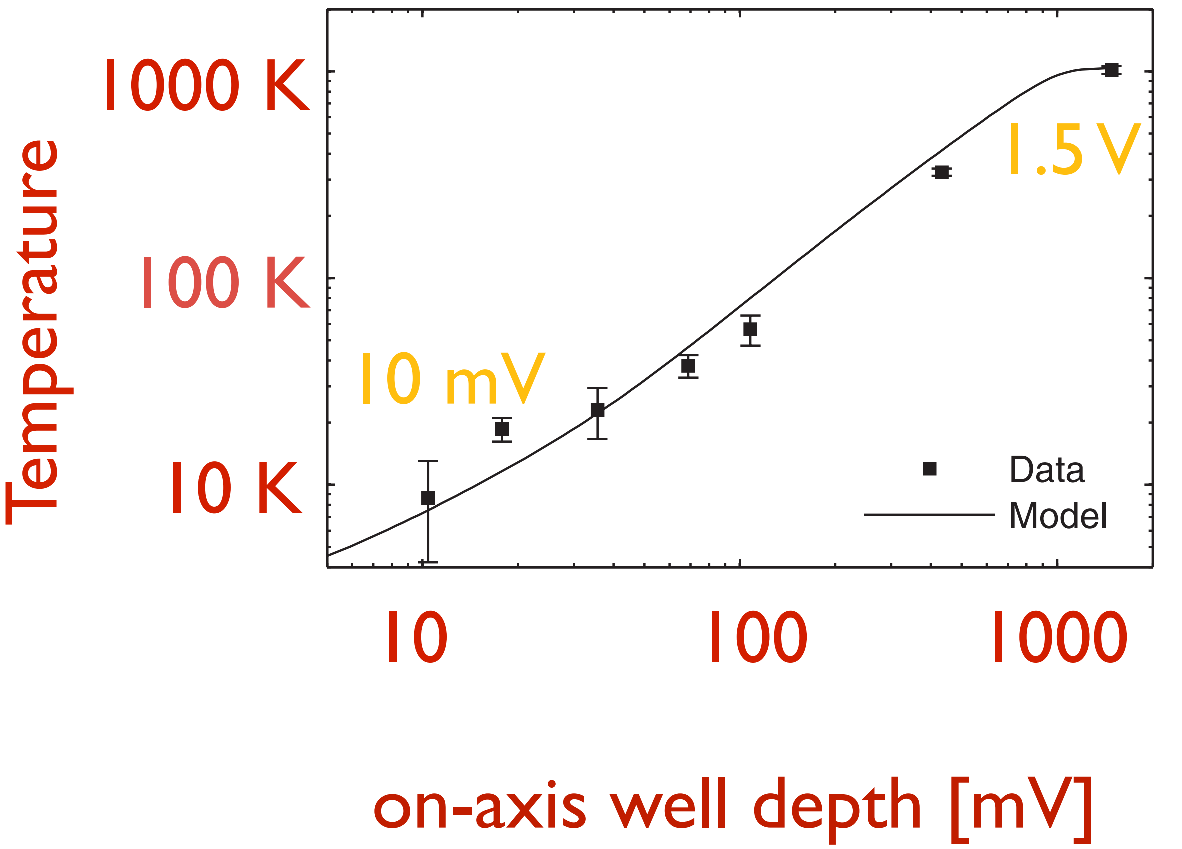
magnetic field considerations

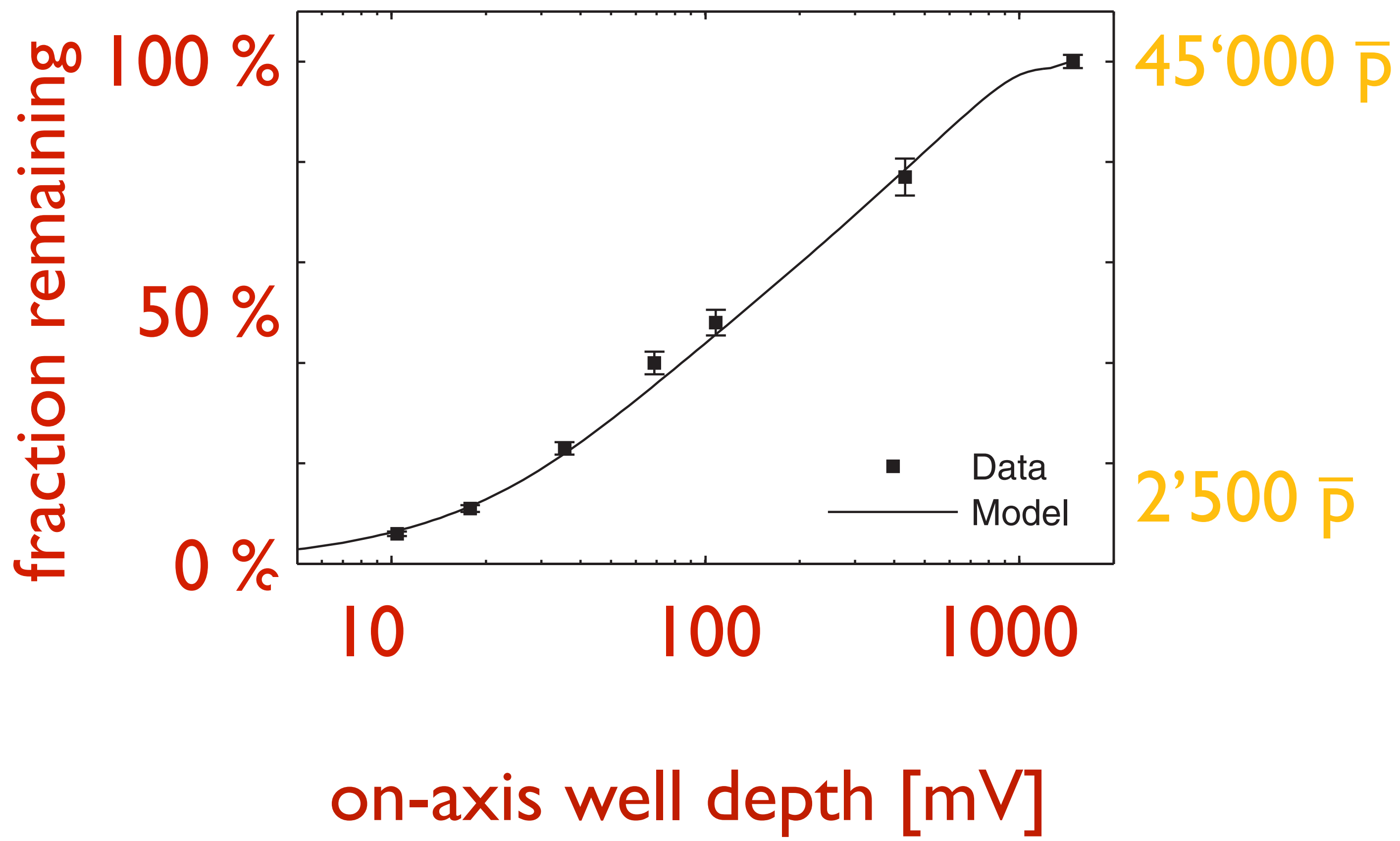
- e^+ plasma stability in magnetic multipole traps: expansion due to anisotropies ➟ possibly higher effective temperature

Reaching the few K regime

evaporative cooling of antiprotons (ALPHA)

PRL **105,** 013003 (2010)



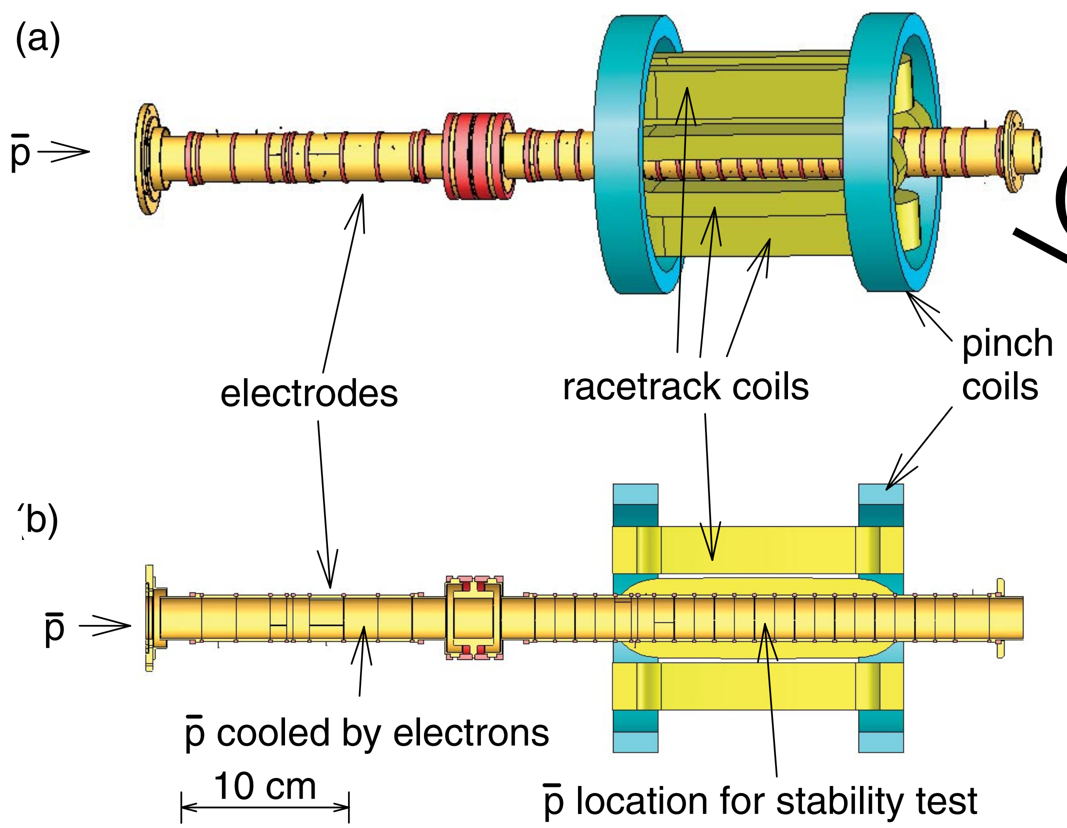


essential to avoid reheating:

- great care needed on noise reduction;
- can not use electron cooling to pre-cool
- bring e^+ to cold $\bar{p}$, not vice-versa (?)
- (alternatively, coherently excite cold $\bar{p}$ and interact with cold e^+)

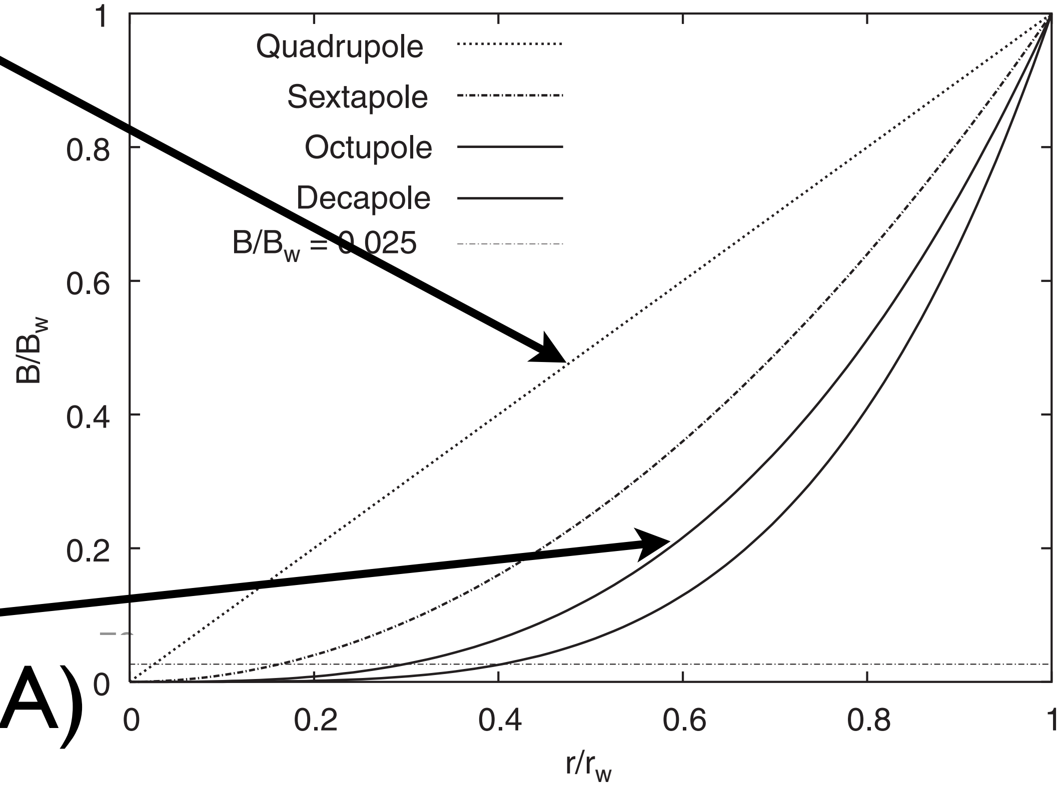
Antihydrogen Production within a Penning-Ioffe Trap

G.Gabrielse et al., Phys. Rev. Lett. 100, 113001 (2008)

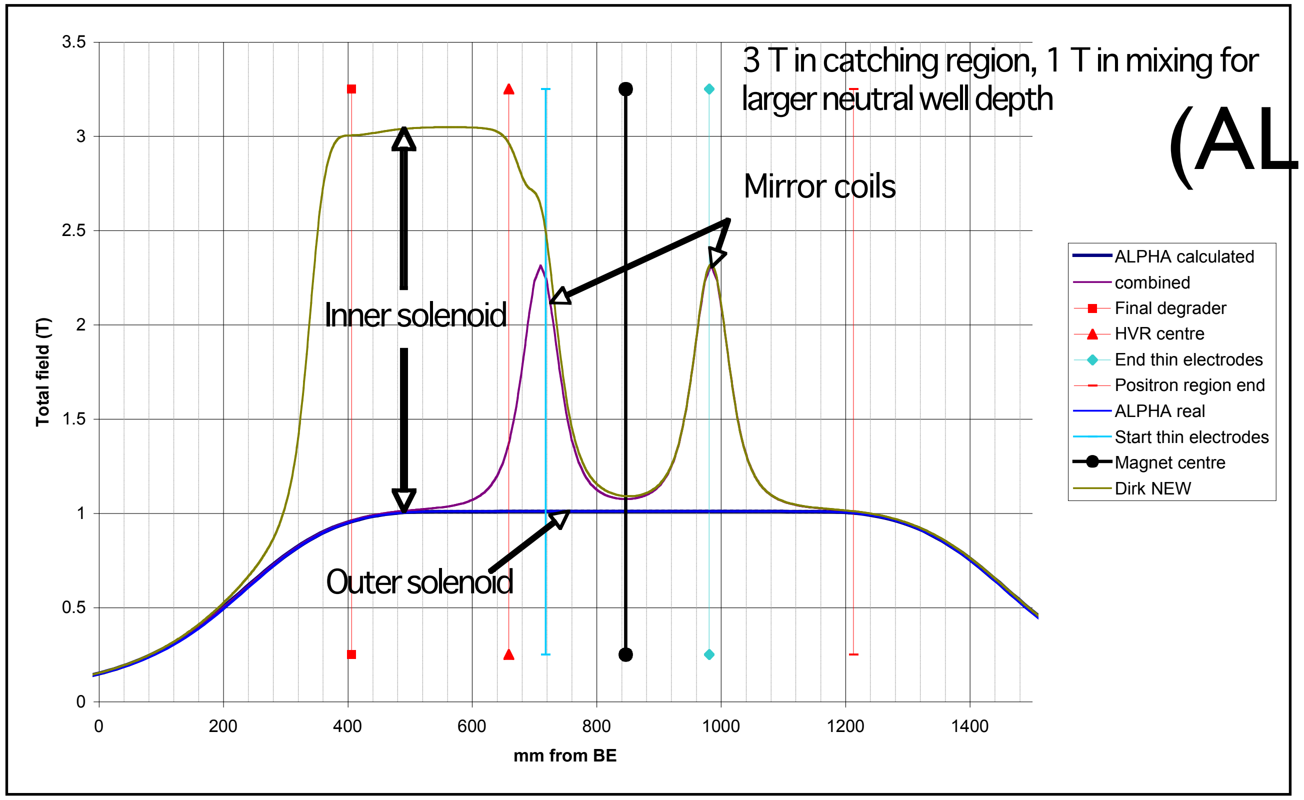


(ATRAP)

trap depth ~500 mK



(ALPHA)



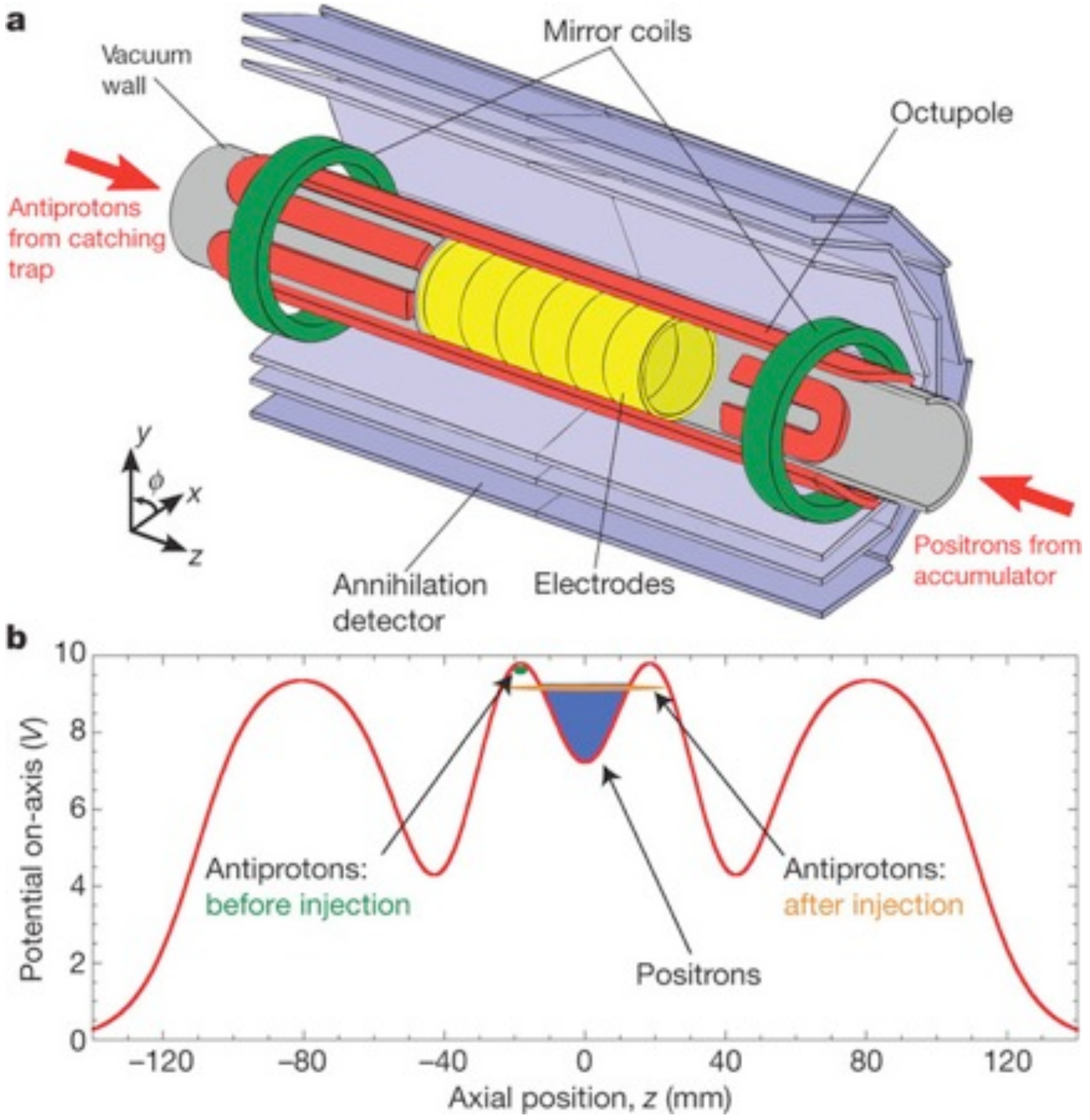
plasma stability/temperature

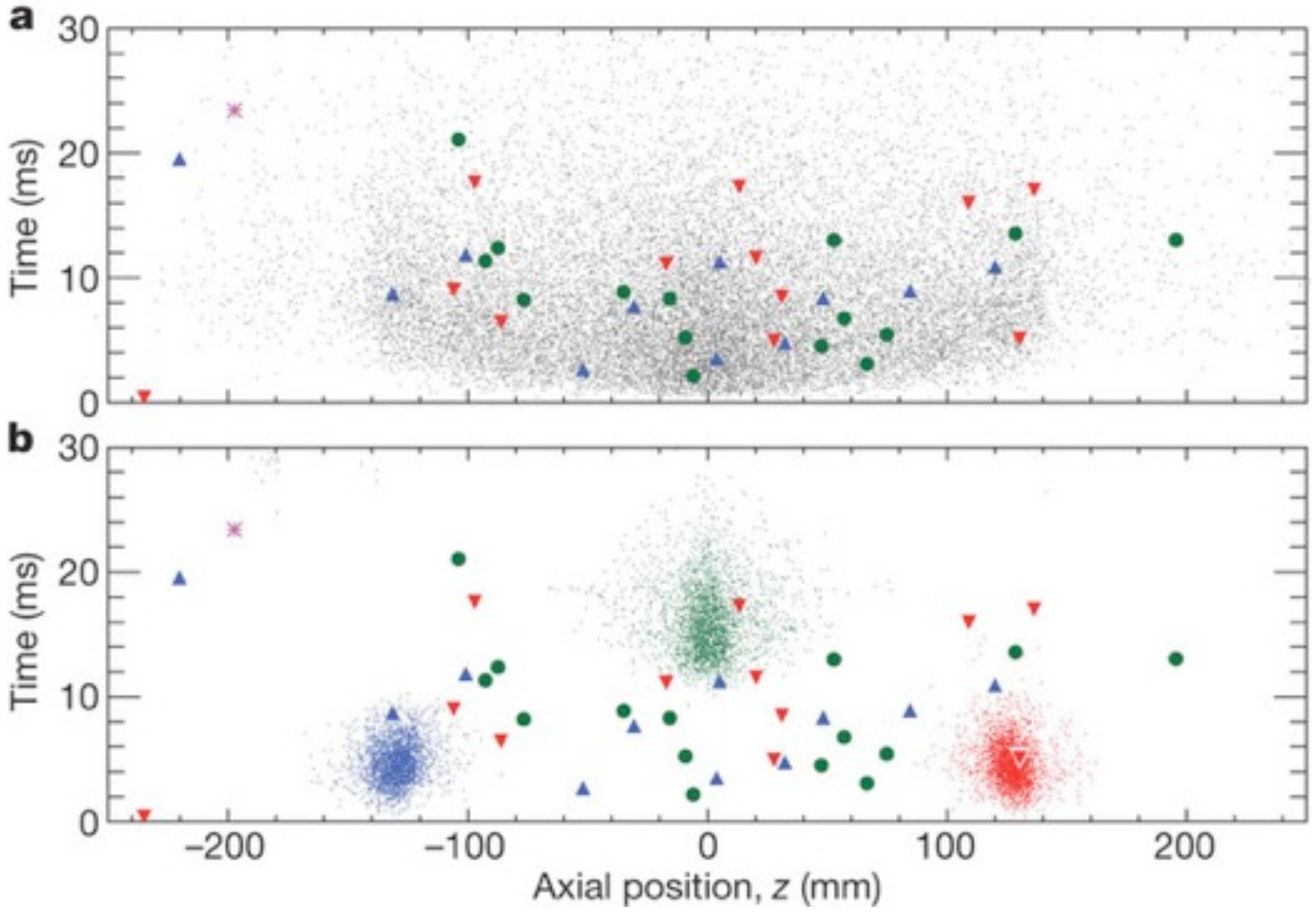
n >> 1

spin flips during de-excitation

Successful trapping!

(ALPHA)

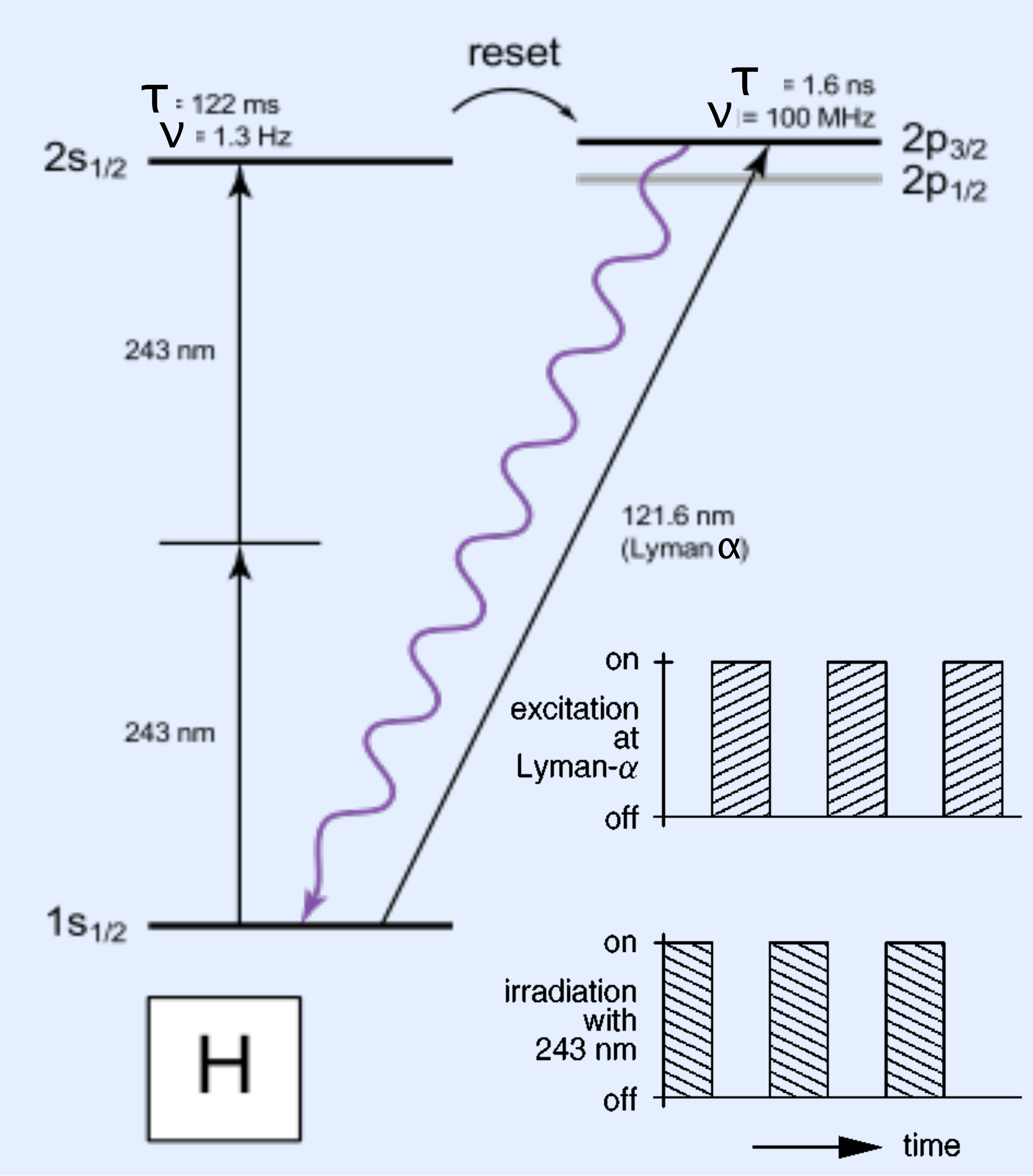




quick opening of magnetic trap (20 ms)
+ sensitive detector for antihydrogen

Spectroscopy with trapped antihydrogen?

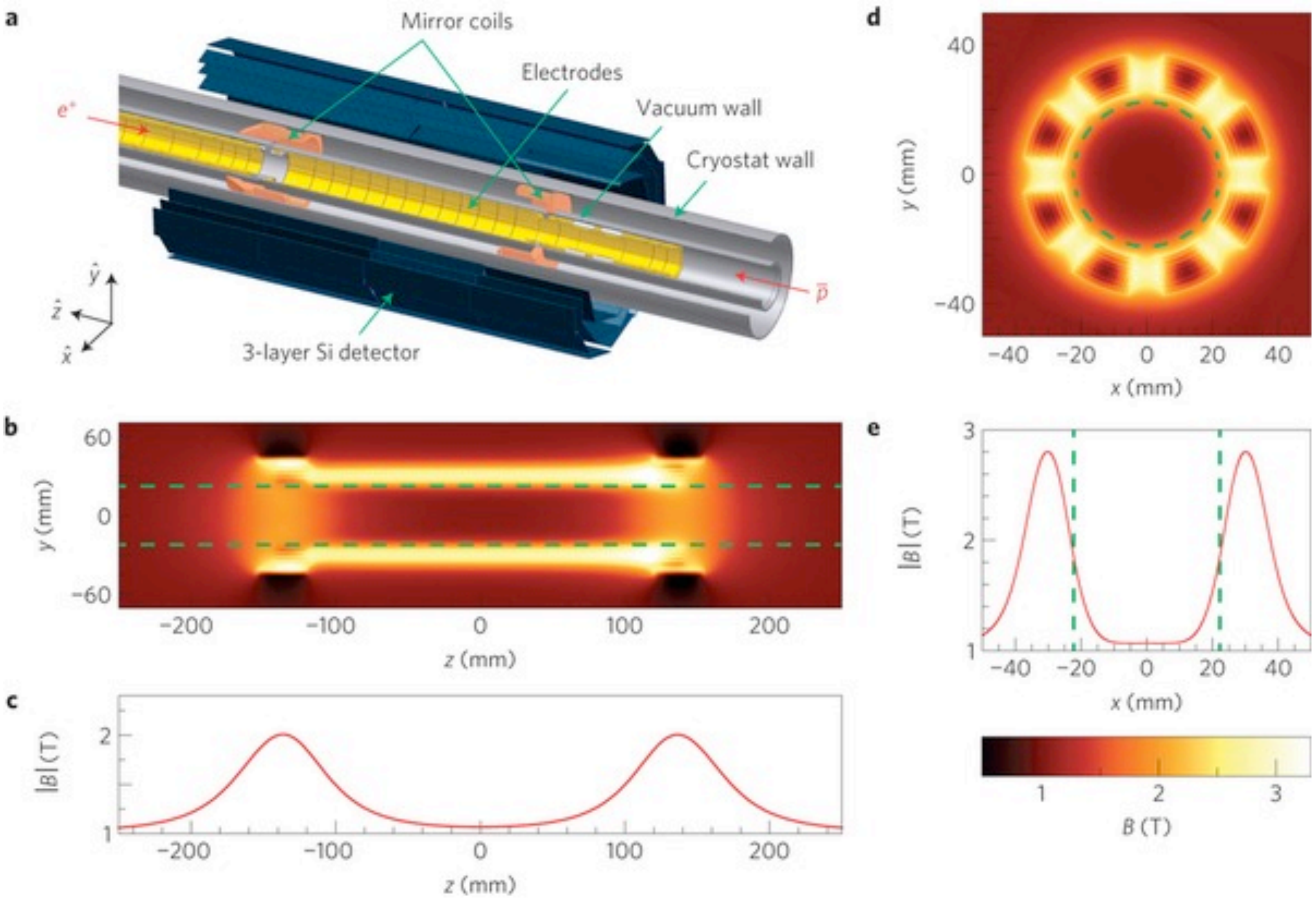
- Detection?
- Present schemes for H spectroscopy require large numbers of atoms: 10^{10}–10^{13} (trap), 10^{15}–10^{17} (beam)
- Only 10^3–10^5 $\bar{H}$ atoms available
- "Shelving" scheme:
  - Strong Lyman-α transition is excited and fluoresces
  - Metastable 2s state is populated by Doppler-free 2-photon excitation
  - "Shelving" suppresses fluorescence
  - 2s state is "reset" with microwave field
  - Resolution (nat. linewidth): 4×10^{-16}
  - [J. Walz et al., Hyp. Int. 127 (2000) 167]

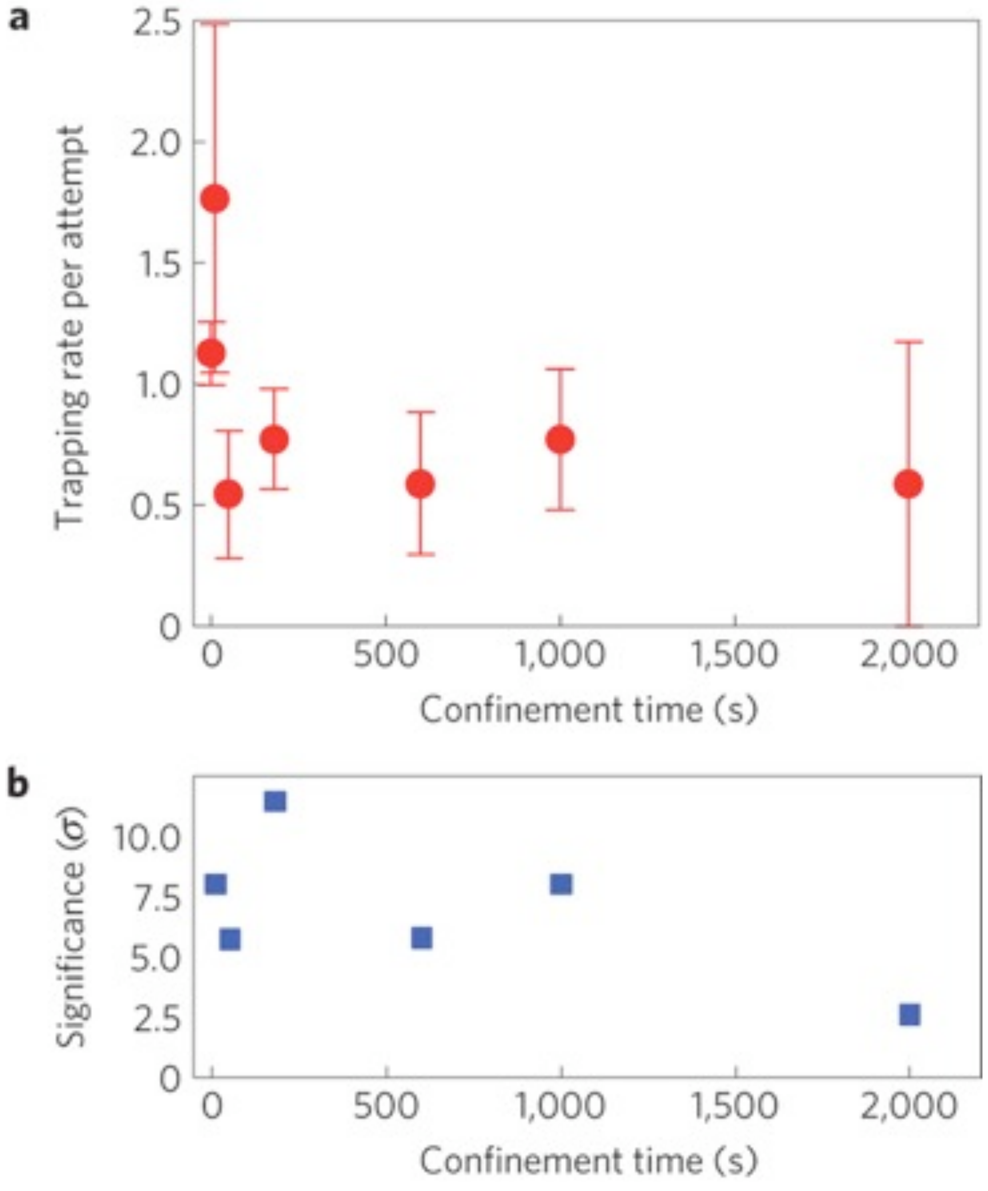


1 nW CW can cool 1K $\bar{H}$ in about 10s

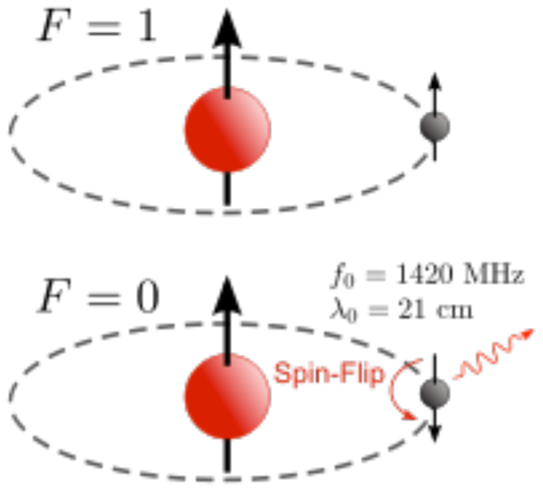
but... more power required for this scheme

Spectroscopy with trapped antihydrogen?





Spectroscopy: plan B
HFS via microwave



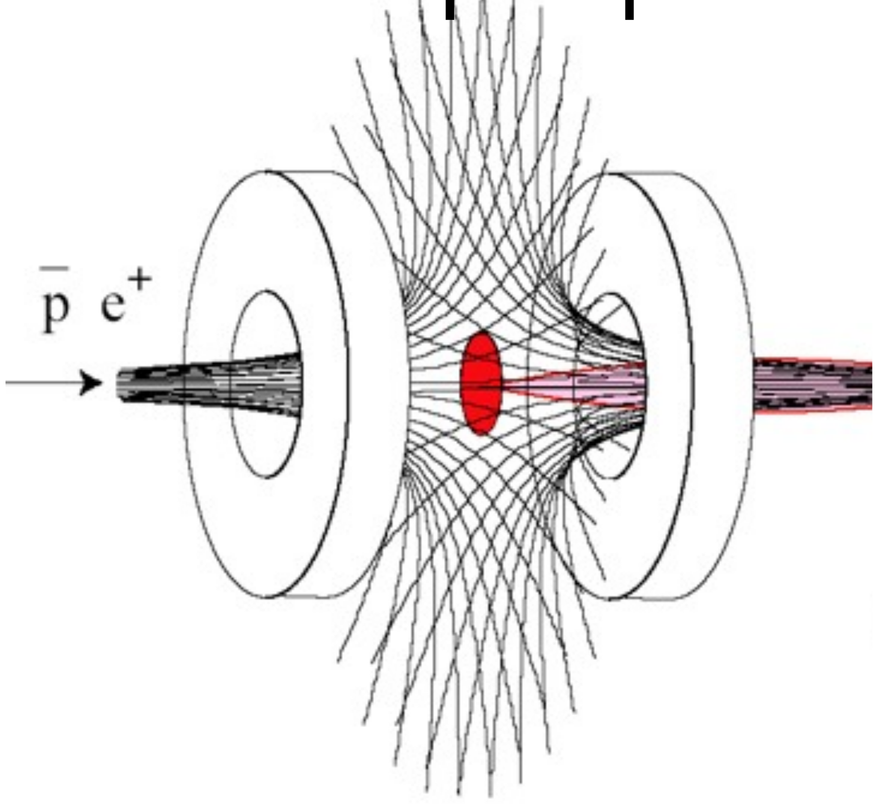
but: B-field at position of antihydrogen poorly defined (1T<B<2T)

Alternatives to Penning-Ioffe traps?

- Magnetic bottle
- e^- trapping achieved
- Neutral atoms were also trapped!

Formation by 3-body recombination
Formed Hbar spin-selected
Polarized beam?
Cold atoms could be trapped?

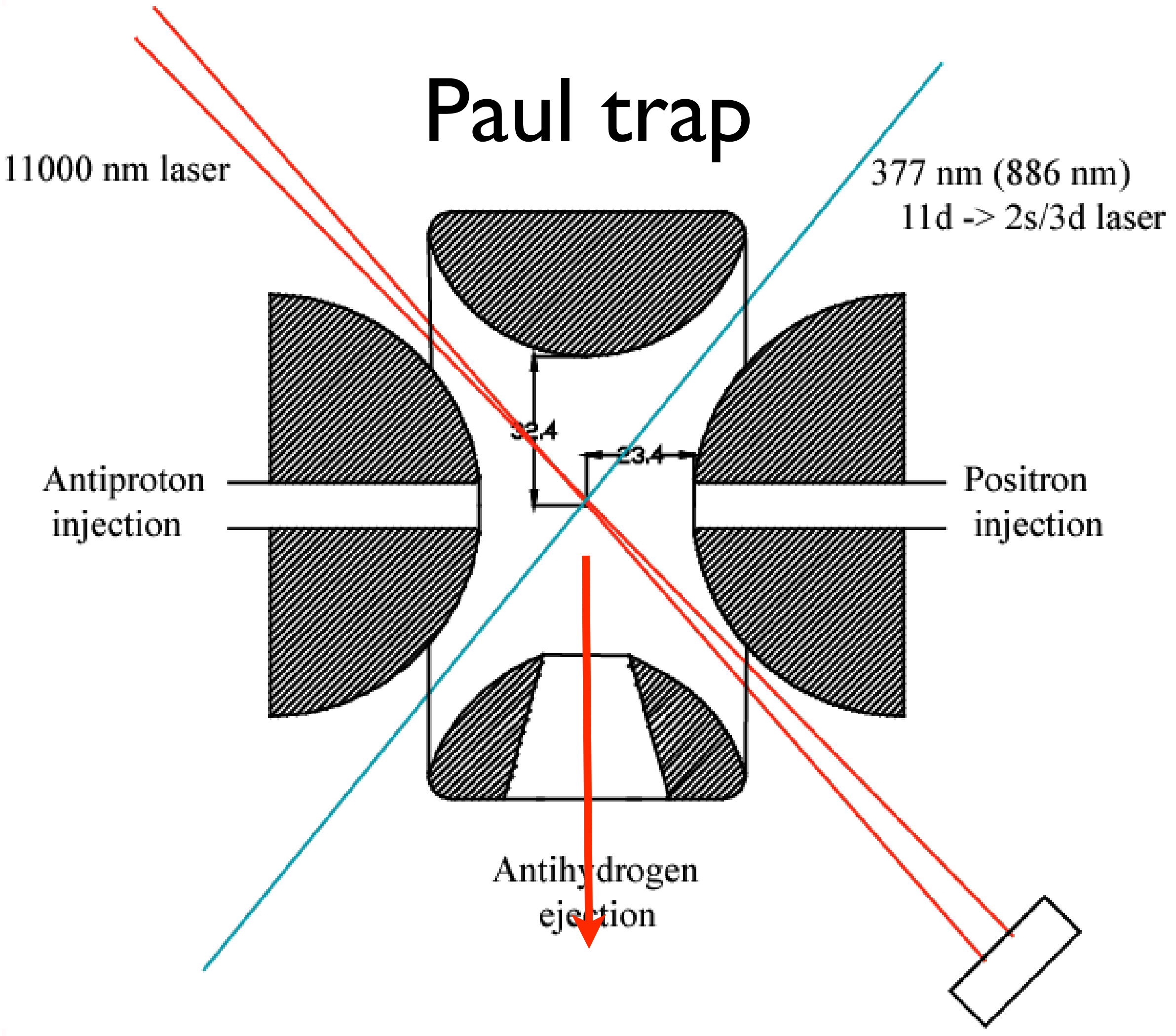
Cusp trap



$\bar{H}$ beam

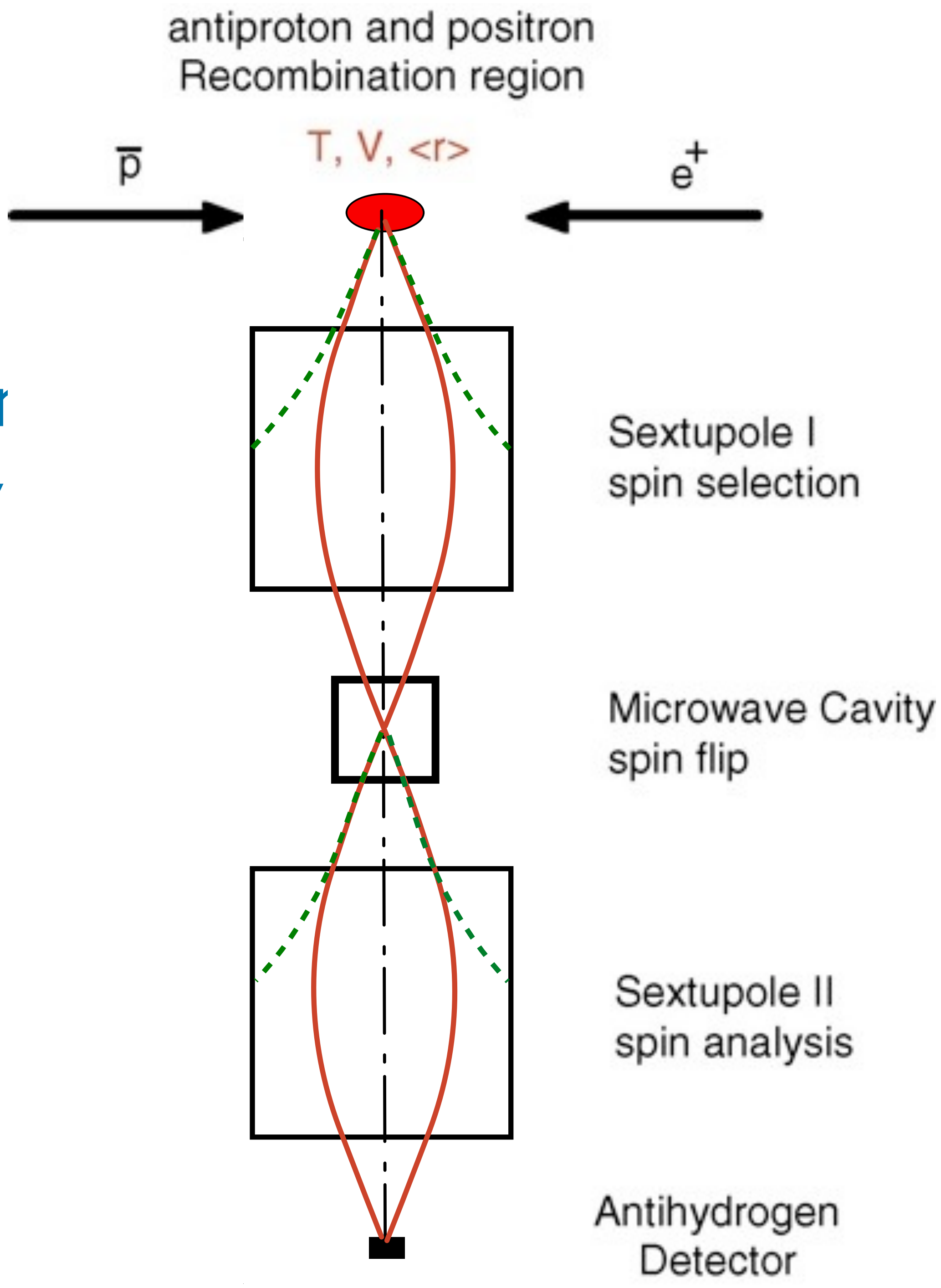
Mohri A and Yamazaki Y 2003 Europhys. Lett. 63 207

Paul trap



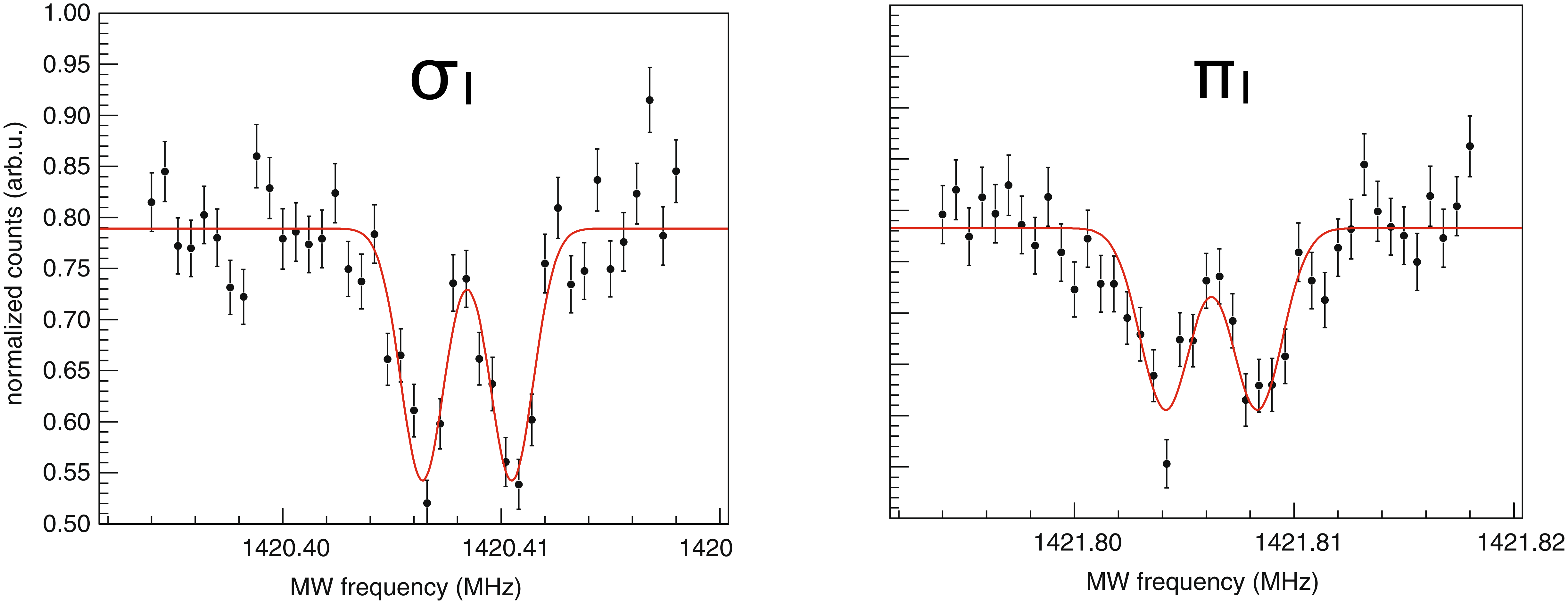
Experiment with $\bar{H}$ beam: ground state HFS

- atoms “evaporate”
  - No trapping needed !!
- atomic beam for focussing and
- spin-flip by microwave radiatio
- low-background high-efficiency through annihilation
- achievable resolution
  - better than 10^{-6} for T<100K
  - 100 $\bar{H}$/s in 1S state needed
- ultimate precision:
  - atomic fountain
- higher temperature is OK



B.Juhasz, E. Widmann, Hyperfine Interact (2009) 193:305

Simulation of expected signal

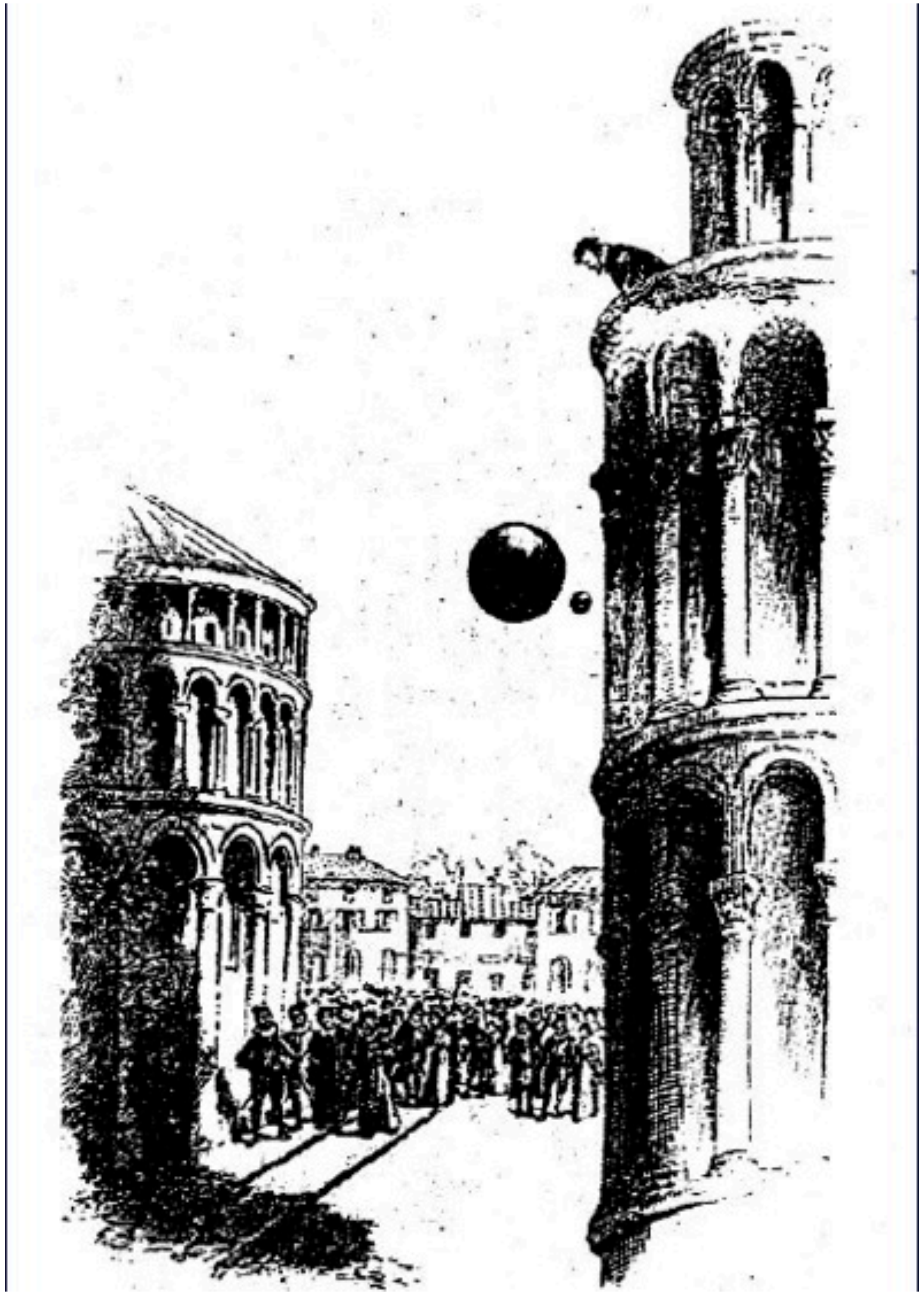


B.Juhasz, E. Widmann, Hyperfine Interact (2009) 193:305

(double dip due to structure - and thus modes - of the microwave cavity between the sextupoles)

Under reasonable assumptions & measuring both resonances to extrapolate to zero field ➠ measurement to 1x10^{-7} appears possible

One step further: a beam of $\bar{H}$ to test gravity



Tests of gravity require very cold trapped $\bar{H}$ or a pulsed cold beam of $\bar{H}$

$G \sim 100 nV/m$ on $\bar{p}$

Experimental goal: g measurement with 1% accuracy* on antihydrogen

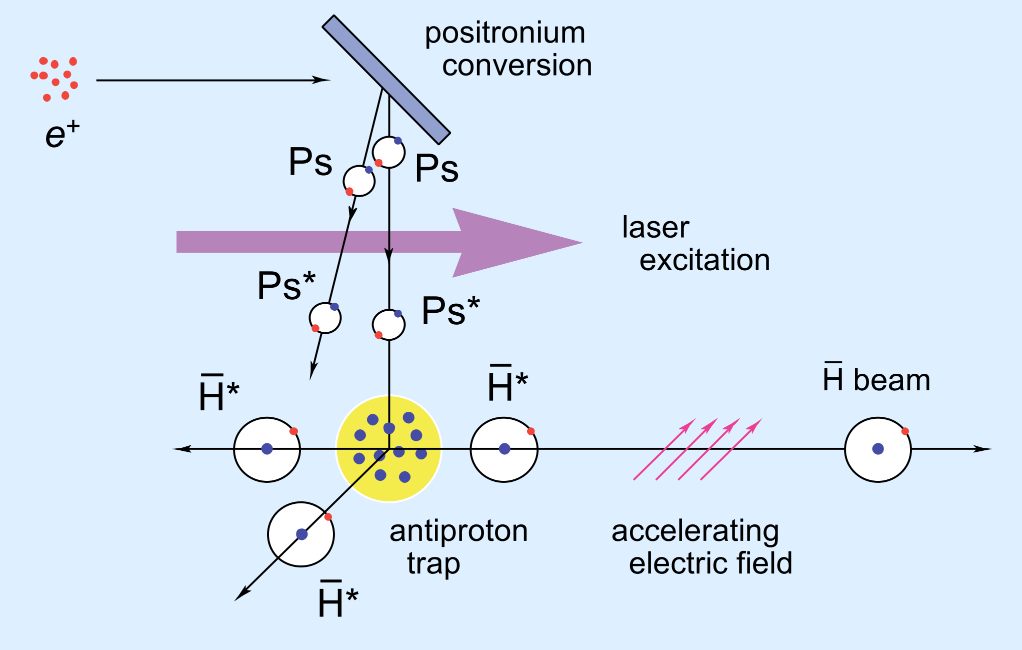
(first direct measurement on antimatter)

a) production of a pulsed cold beam of antihydrogen (T~0.1K)

b) measurement of the beam deflection with a Moiré deflectometer

Step i) antihydrogen formation

- Charge exchange reaction:



$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$

- cold antiprotons (T~0.1K)
- production of Rydberg positronium
- production of antihydrogen atoms

- Principle demonstrated by ATRAP (Cs* → Ps* → $\bar{H}$*)
  [C. H. Storry *et al.*, Phys. Rev. Lett. **93** (2004) 263401]

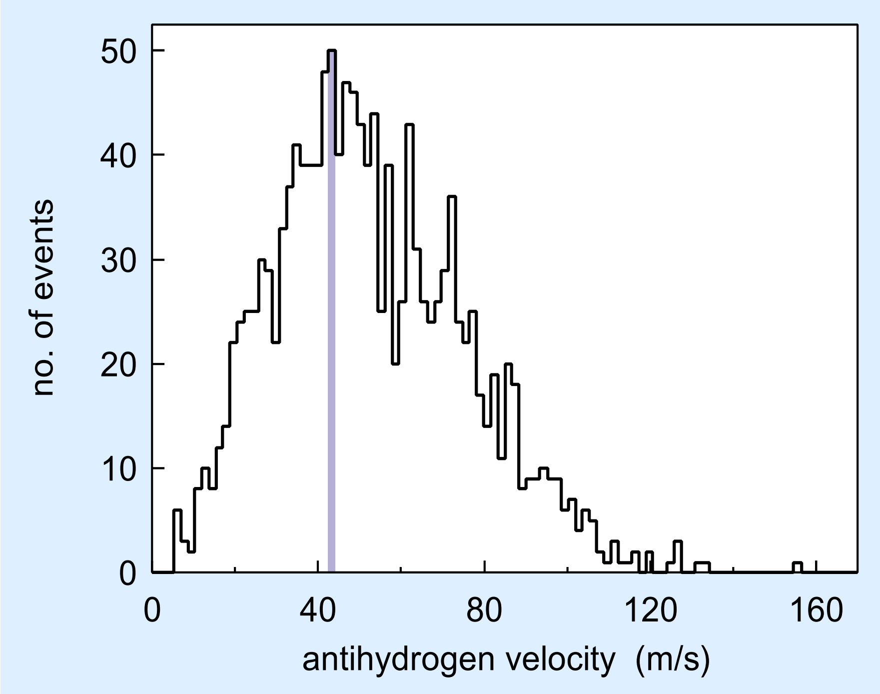
- Advantages:

– Large cross-section: $\sigma \approx a_0 n^4$

– Narrow and well-defined $\bar{H}$ *n*-state distribution

– $\bar{H}$ production from $\bar{p}$ at rest → ultracold $\bar{H}$

- pulsed production of $\bar{H}$



At T(p) = 100mK,
n(Ps) = 35
⇒ v(H) ≈ 45 m/s
T(H) ≈ 120mK

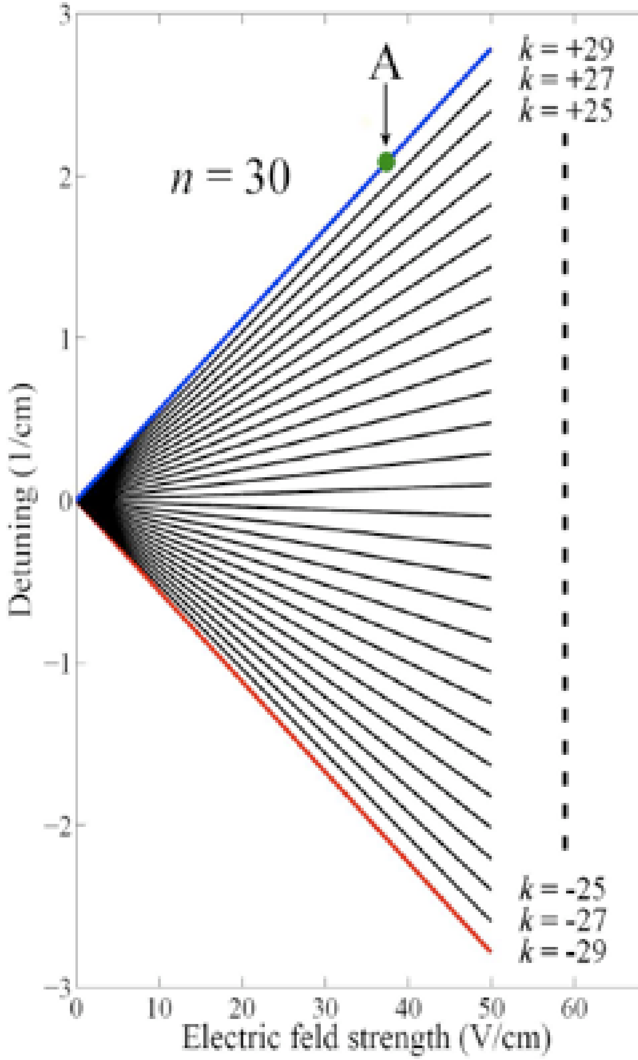
Step ii) beam formation

- Neutral atoms are not sensitive to static electric and magnetic fields
- Electric field gradients exert force on electric dipoles:

$$E = -\frac{1}{2n^2} + \frac{3}{2}nkF$$

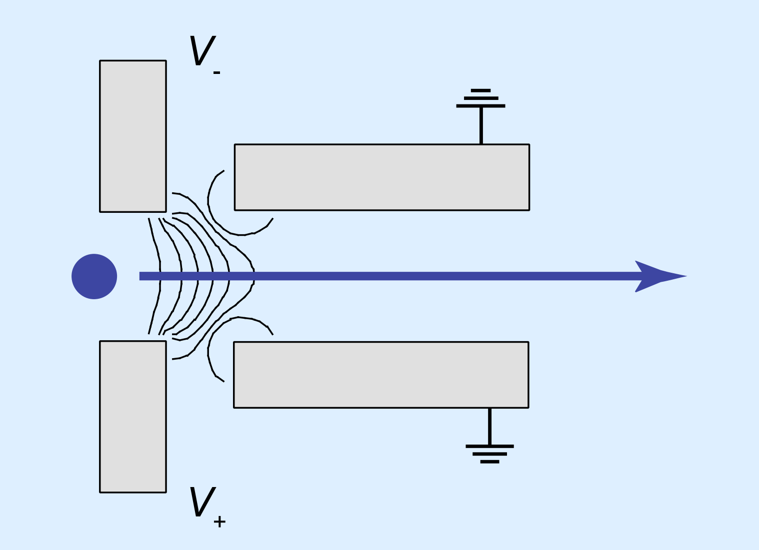
$$Force = -\frac{3}{2}nk\vec{\nabla}F$$

⇒ Rydberg atoms are very sensitive to inhomogeneous electric fields



- Stark deceleration of hydrogen demonstrated

[E. Vliegen & F. Merkt, J. Phys. B **39** (2006) L241 - ETH Physical Chemistry]

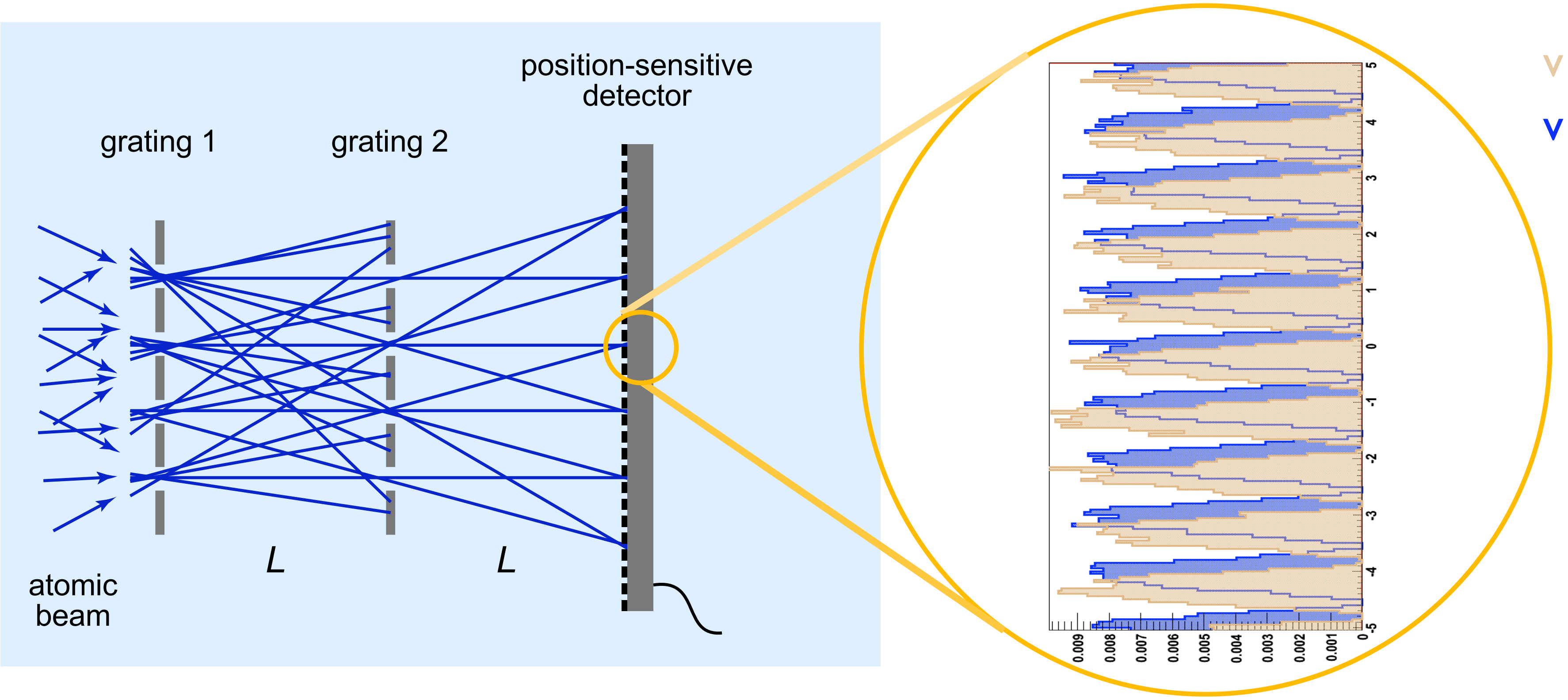


- n = 22,23,24
- Accelerations of up to 2×10^8 m/s² achieved
- Hydrogen beam at 700 m/s can be stopped in 5 µs over only 1.8 mm
- ongoing work on Zeeman deceleration, Stark deceleration and trapping of H

Step iii) trajectory measurement

- Classical counterpart of the Mach-Zehnder interferometer
  - Decoherence effects reduced
  - "Self-focusing" effect – beam collimation uncritical

Fringe phase <u>and</u> phase shift identical to Mach-Zehnder interferometer!



$$\delta = \frac{gt^2}{a}$$

- Replace the third grating and detector by position-sensitive detector

  ⇒ Transmission increases by ~ factor 3

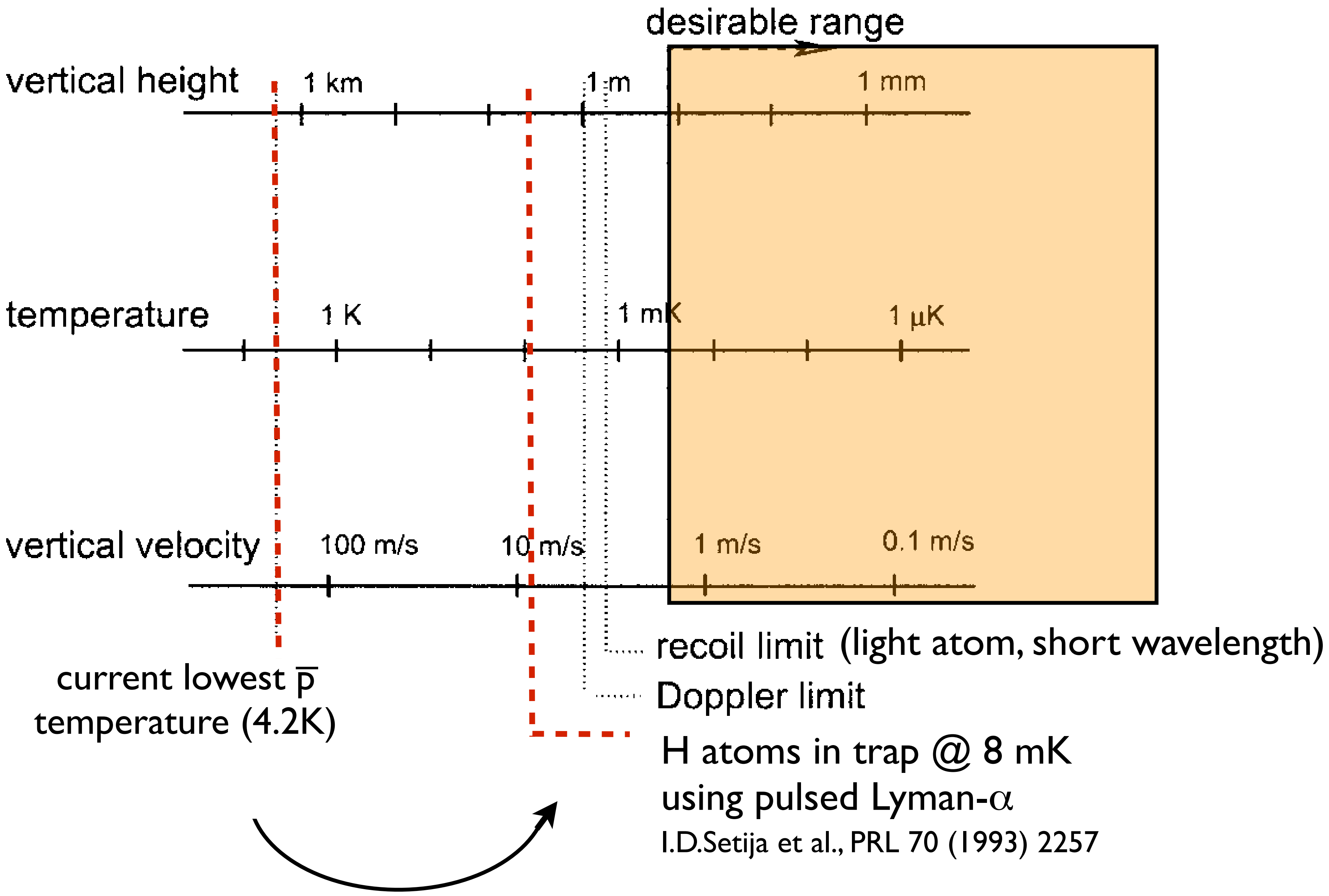
- Has been successfully used for a gravity measurement with ordinary matter, $\sigma(g)/g = 2\times10^{-4}$

[M. K. Oberthaler *et al.*, Phys. Rev. A **54** (1996) 3165]

- with 10^5 $\overline{\mathrm{H}}$ at 100mK, $\sigma(g)/g = 1\%$ (expected)

[A. Kellerbauer *et al.*, Phys. Rev. A **54** (1996) 3165]

"Ultra-cold" (~1 μK) Antihydrogen



current lowest $\bar{p}$ temperature (4.2K)

recoil limit (light atom, short wavelength)

Doppler limit

H atoms in trap @ 8 mK
using pulsed Lyman-α
I.D.Setija et al., PRL 70 (1993) 2257

1S→2P laser cooling: cw Lyman-α source
Eikema, Walz, Hänsch, PRL 86 (2001) 5679

sympathetic cooling to the rescue

cooling of $\bar{H}^+$

J.Walz and T. Hänsch, Gen. Rel. and Grav. 36 (2004) 561

formation of $\bar{H}^+$ (binding energy = 0.754 eV)

how? perhaps through $Ps(2p)+\bar{H}(1s) \rightarrow \bar{H}^+ + e^-$

Roy & Sinha, EPJD 47 (2008) 327

sympathetic cooling of $\bar{H}^+$

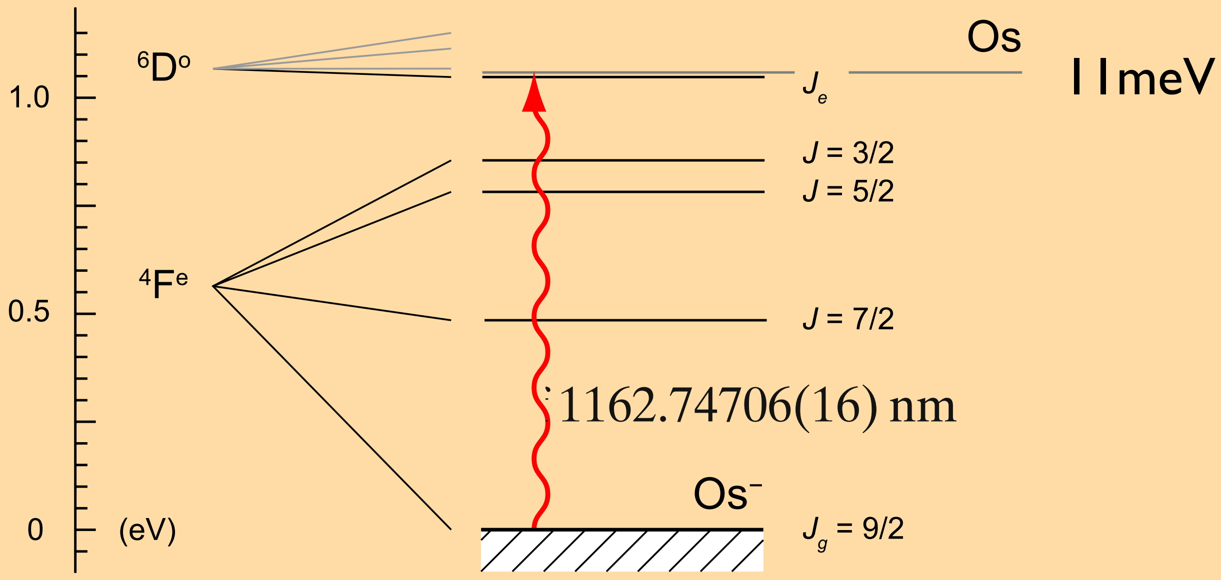
e.g. In^+ → 20 μK

photodetachment at ~6083 cm^{-1}

gravity measurement via TOF

cooling of $\bar{p}$

Warring et al, PRL 102 (2009) 043001
Fischer et al, PRL 104 (2010) 073004



very weak cooling
→ best to start at ~ 4K and cool to Doppler limit ($T_D \approx 0.24\ \mu K$)

should allow reaching same precision on **g** as with atoms (10^{-6} or better)

the other bottleneck: $\bar{p}$'s

The Antiproton decelerator produces 10^7 $\bar{p}$/cycle (100s)

Trapping efficiency ~ 0.1% = 10^7 $\bar{p}$/cycle (100s)

Build new deceleration stage 100 MeV/c ➠ 100 keV/c

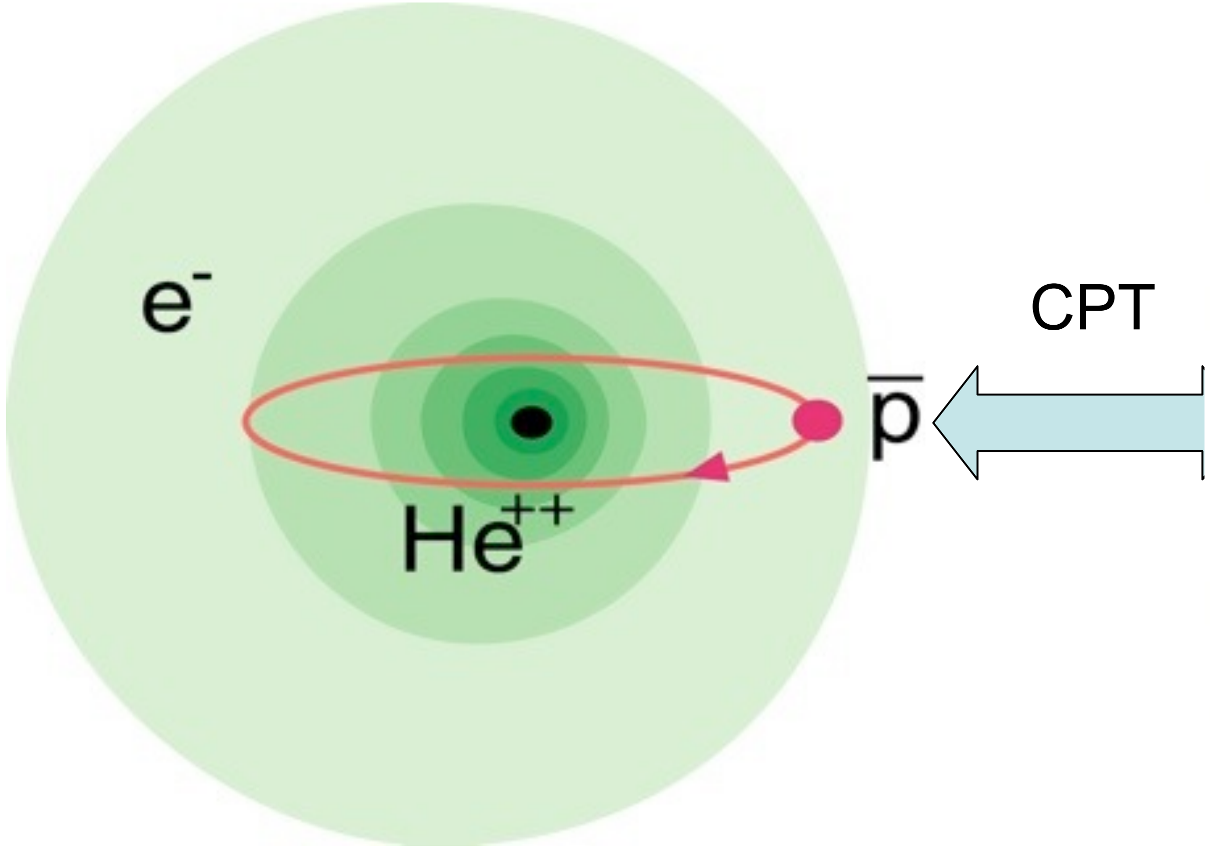
Trapping efficiency ~ O(100 %)

ELENA = Extra Low ENergy Antiproton ring

A final detour: other antimatter spectroscopy
Antiprotonic helium and CPT

ASACUSA

- Three-body system $He^{++}e^{-}\,\bar{p}$
  - $\bar{p}$ in highly excited, near circular states (n,l) ~ (38,37)
- Easy (automatic) formation
- Comparison to 3-body QED calculations that use proton mass



$$E_{nr} = \left\langle -\frac{1}{2m_{13}}\nabla^2_{\mathbf{r}_1} - \frac{1}{2m_{23}}\nabla^2_{\mathbf{r}_2} - \frac{1}{m_3}\nabla_{\mathbf{r}_1}\nabla_{\mathbf{r}_2} + \frac{Z_1Z_3}{r_1} + \frac{Z_2Z_3}{r_2} + \frac{Z_1Z_2}{r_{12}} \right\rangle.$$

$$E_{rc} = \alpha^2 \left\langle -\frac{\nabla_i^4}{8m_e^3} + \frac{1}{8m_e^2}\left[Z_{\mathrm{He}}4\pi\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}4\pi\delta(\mathbf{r}_{\bar{p}})\right] \right\rangle.$$

$$E_{rc-qed} = \alpha^2 \left\langle \frac{2a_e}{8m_e^2}\left[Z_{\mathrm{He}}4\pi\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}4\pi\delta(\mathbf{r}_{\bar{p}})\right] \right\rangle.$$

$$E_{se} = \alpha^3 \left\langle \frac{4Z_i}{3}\delta(\mathbf{r}_i)\left\{\left[\ln\frac{1}{\alpha^2} - \ln\frac{k_0(n)}{\mathrm{Ry}} + \frac{5}{6} - \frac{3}{8}\right] + (Z_i\alpha)3\pi\left(\frac{139}{128} - \frac{1}{2}\ln 2\right) - \frac{3}{4}(Z_i\alpha)^2\ln^2\frac{1}{(Z_i\alpha)^2}\right\}\right\rangle.$$

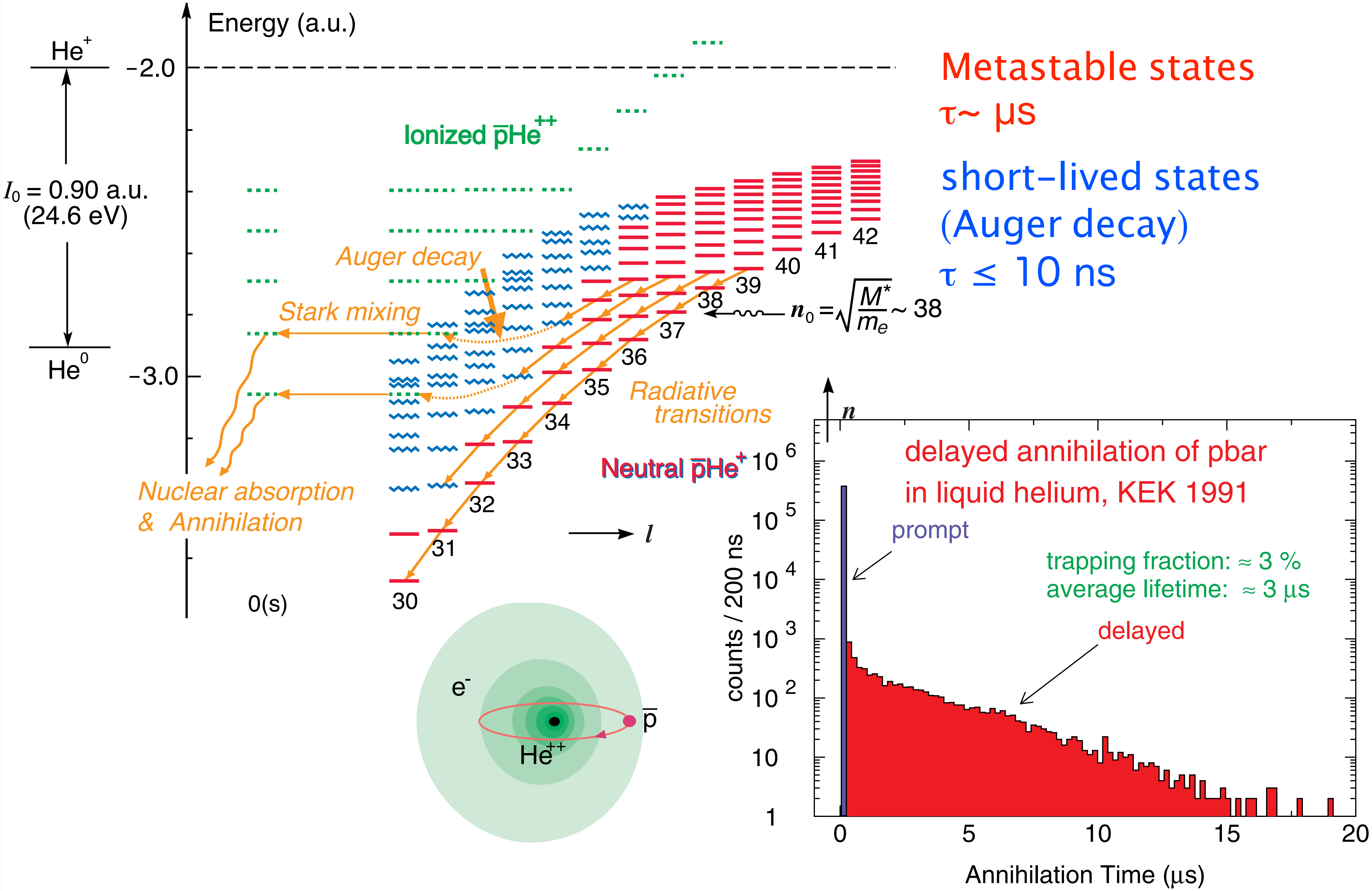
$$E_{vp} = \alpha^3 \left\langle \frac{4Z_i}{3}\left[-\frac{1}{5} + (Z_i\alpha)\pi\frac{5}{64}\right] \right\rangle.$$

$$E_{RMC} = -\alpha^2 \left\langle \frac{\nabla^4_{\mathrm{He}}}{8m^3_{\mathrm{He}}} + \frac{\nabla^4_{\bar{p}}}{8m^3_{\bar{p}}} \right\rangle.$$

$$E_{ret} = \alpha^2 \sum_{i>j} \frac{Z_iZ_j}{2m_im_j} \left\langle \frac{\nabla_i\nabla_j}{r_{ij}} + \frac{\mathbf{r}_{ij}(\mathbf{r}_{ij}\nabla_i)\nabla_j}{r^3_{ij}} \right\rangle.$$

$$E_{two-loop} = \alpha^4 \left\langle \frac{Z_i}{\pi}\left[-\frac{6131}{1296} - \frac{49\pi^2}{108} + 2\pi^2\ln 2 - 3\zeta(3)\right]\delta(\mathbf{r}_i) \right\rangle$$

Antiprotonic helium (“atomcules”)



Metastable states

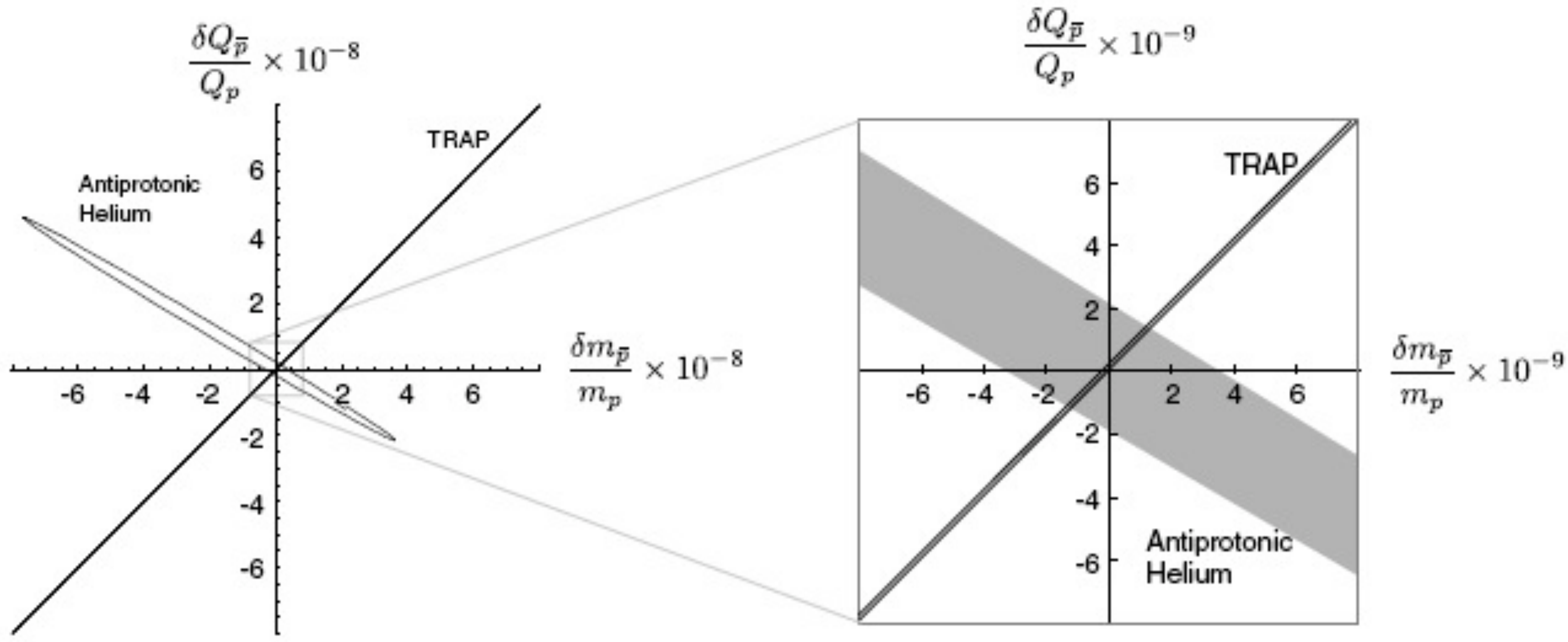
τ~ µs

short-lived states

(Auger decay)

τ ≤ 10 ns

$\bar{p}$/p charge and mass: $\bar{p}$He + TRAP



- Q/M of proton/antiproton

$$\frac{|Q/M(\bar{p}) - Q/M(p)|}{\text{average}} < 9 \times 10^{-11}$$

- Gabrielse et al
  Phys. Rev. Lett. 82 (1999) 3198

$$\left|\frac{M_{\bar{p}} - M_p}{M_p}\right| \approx \left|\frac{Q_{\bar{p}} - Q_p}{Q_p}\right| < \begin{cases} 6 \times 10^{-8} & (2000) \\ 1 \times 10^{-8} & (2003) \end{cases}$$

3×10^{-9} (2006)

RS Hayano, M Hori, D Horvath and E Widmann Rep. Prog. Phys. 70 (2007) 1995-2065

Summary:

Trapping of antihydrogen:

ATRAP and ALPHA: progress in making colder ingredients
main challenge now: enough cold enough constituents
individual antihydrogen atoms trapped in the ground state (2010)
assuming 1 mK: 1s-2s spectroscopy to ~ 10^{-12} (perhaps in a few years)
first (rough) HFS measurements perhaps in 2011 or 2012

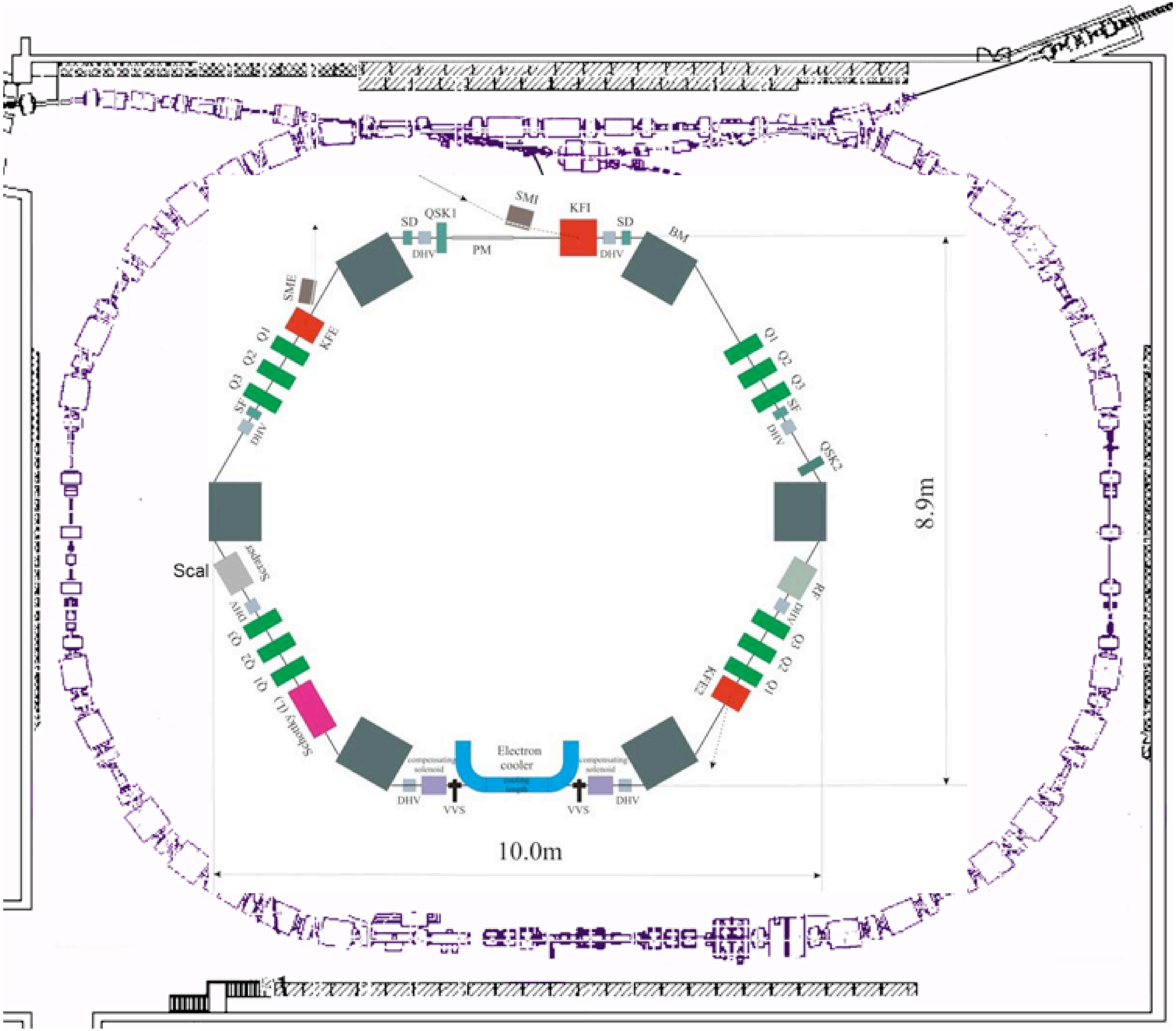
Beam of antihydrogen:

ASACUSA: continuous beam (2011?)
AEGIS: pulsed sub-K beam (2012/2013) @ 1Hz
main challenge now: formation mechanisms and rates

these may allow in-flight spectroscopy of
HFS to 200 Hz (10^{-6})
1s-2s spectroscopy to ???? (will depend on temperature of $\bar{H}$)
and may also lead to an alternative $\bar{H}$ trapping scheme

Soon: New infrastructure (ELENA) and experiments

Outlook


SMI
KFI
SD
QSK1
DHV
PM
SD
DHV
BM
SME
KFE
Q1
Q2
Q3
SF
DHV
Q1
Q2
Q3
SF
DHV
QSK2
8.9m
Scal
Scraper
DHV
Q3
Q2
Q1
Schottky (L)
RF
DHV
Q3
Q2
Q1
KFE2
Electron
cooler
compensating solenoid
compensating solenoid
DHV
VVS
VVS
DHV
10.0m

Outlook