11th Japan-US Seminar on Quantum Electronics and Laser Spectros
April 08-12, 2013,

Toward Precision Measurements of Antihydrogen Atoms and Antiprotons for the CPT symmetry Test

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Cusp trap collaborators

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Motivation

☆Tests of CPT (Charge conjugation, Parity, Time reversal) symmetry employing high precision spectroscopy of atomic physics techniques

P, CP, T violations already known!

Matter dominance in the universe!

(CPV + baryon# non cons.+ non-thermal eq.)

☆Gravitational interaction between matter – antimatter

antihydrogen-earth

CPT symmetry

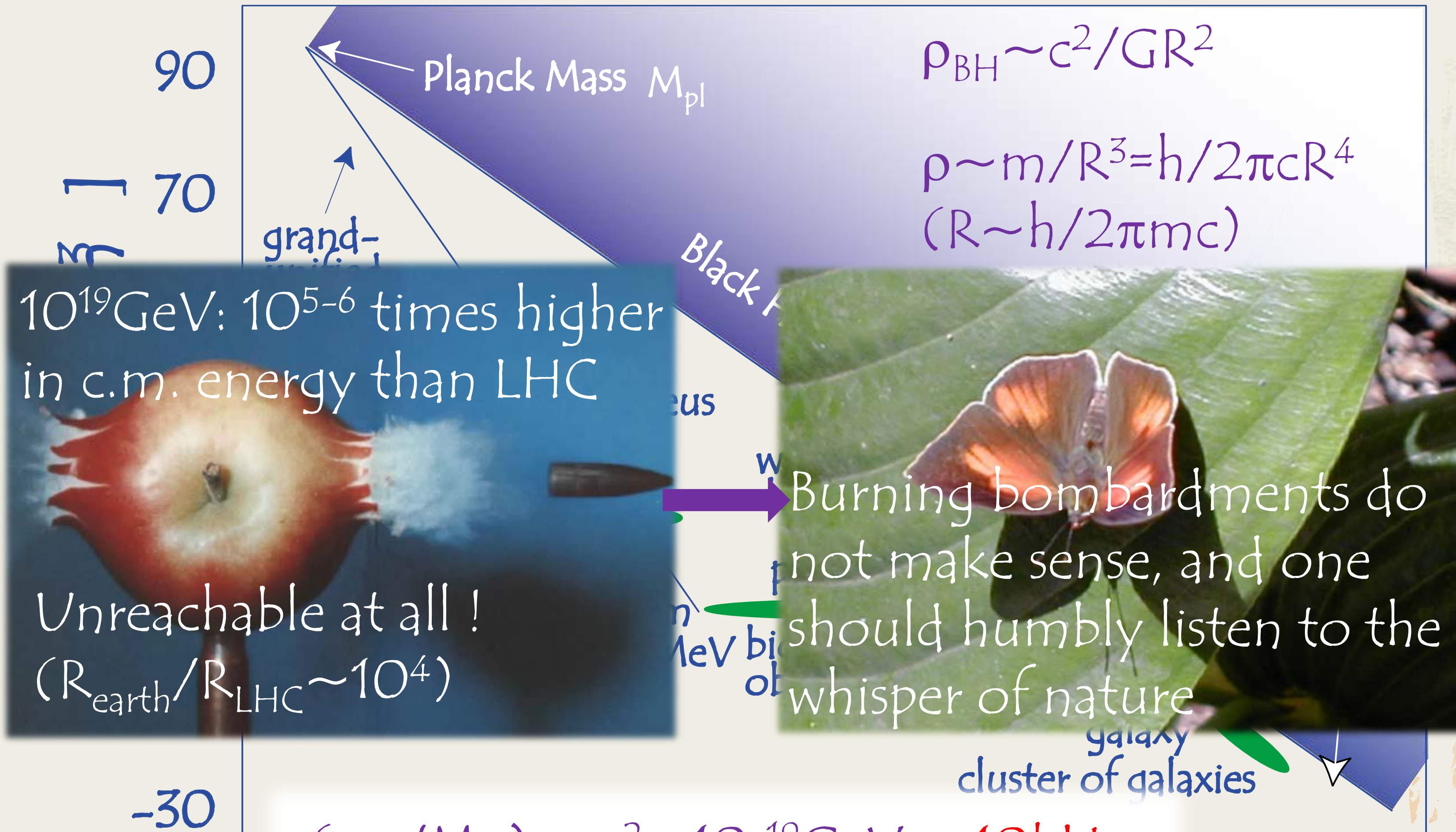
CPT symmetry is guaranteed by local quantum field theories constructed on a flat space-time fulfilling Lorentz invariance and unitarity

CPT theorem concludes: m, |q|, |μ|, total lifetime are exactly the same

→

What happens then if the space-time is curved by the gravitational interaction, and/or, if non-local interactions present (no quantum theories with gravity till now though.....)?

CPT symmetry



$\rho_{BH} \sim c^2/GR^2$

$\rho \sim m/R^3 = h/2\pi c R^4$

$(R \sim h/2\pi mc)$

10^{19}GeV: $10^{5\text{-}6}$ times higher in c.m. energy than LHC

Unreachable at all !

$(R_{earth}/R_{LHC} \sim 10^4)$

Burning bombardments do not make sense, and one should humbly listen to the whisper of nature

$(m_p/M_{pl})m_p c^2 \sim 10^{-19}$GeV ~10kHz

池内了　観測的宇宙論

CPT symmetry

Consideration of CPTV sensitive quantities by artificially adding CPT violating interactions (Standard Model Extension: Kostelecky et al.)

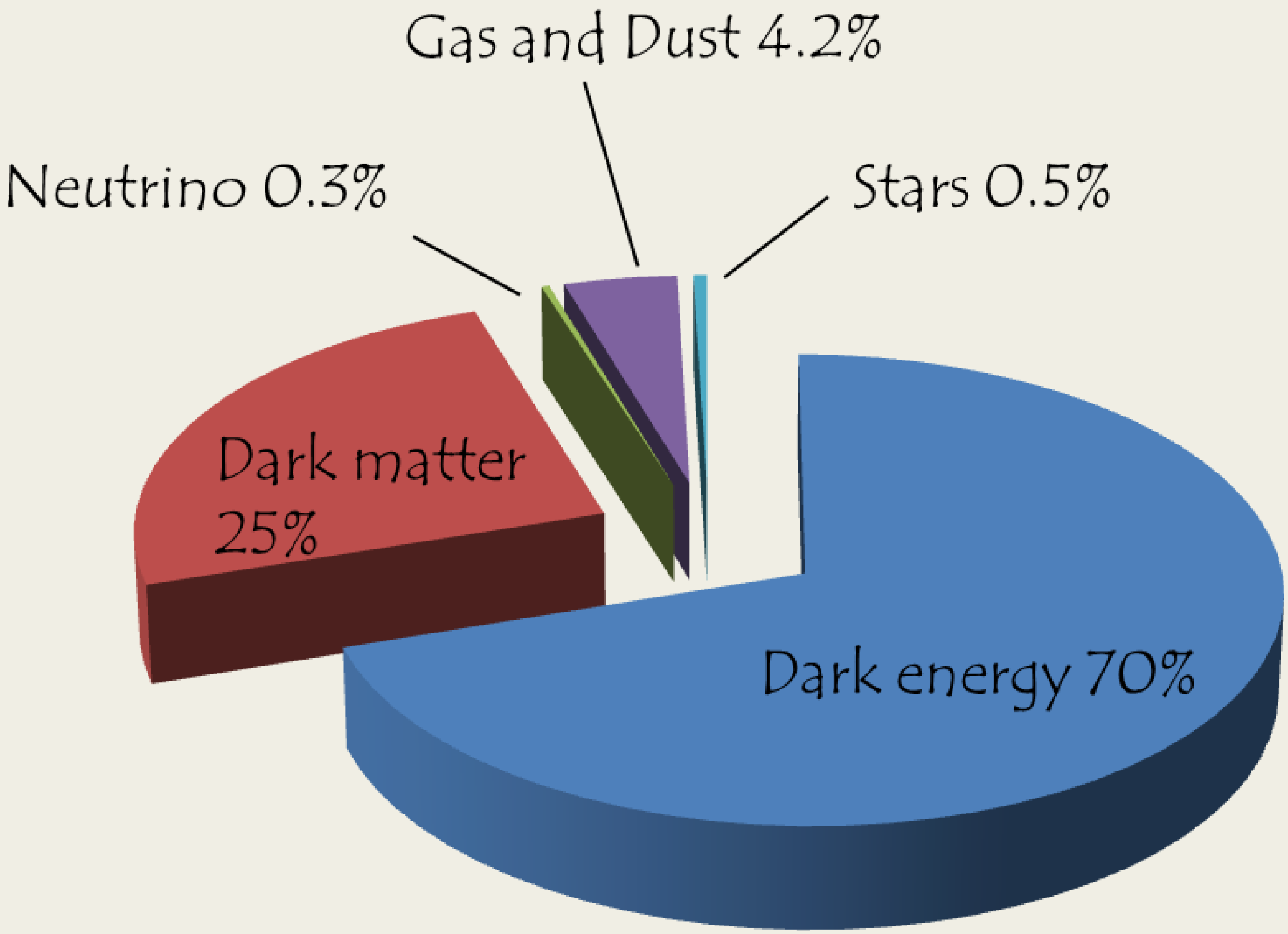
$$\left(i\gamma^{\mu}D_{\mu} - m - a_{\mu}\gamma^{\mu} - b_{\mu}\gamma_{5}\gamma^{\mu} - \frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^{\mu}D^{\nu} + id_{\mu\nu}\gamma_{5}\gamma^{\mu}D^{\nu}\right)\psi = 0$$

where $iD_{\mu} = i\partial_{\mu} - qA_{\mu}$ and $\hbar = c = 1$

→ Hyperfine transitions have the 1st order sensitivity to the above CPT violating terms but not for 1S-2S transition. Comparison in the absolute energy scale is important (LIV…)

R. Bluhm et al., PRL82(1999)2254

CPT symmetry



Our imagination is limited in 5% of the total energy of the universe.... ← a frog in a well

CPT symmetry

What is known regarding K^0 & $\mathbf{K}^0$:

$|m(K^0)-m(\mathbf{K}^0)|/m(K) < 6 \times 10^{-19}$

Or $|m(K^0)-m(\mathbf{K}^0)| < 4 \times 10^{-19}$ GeV
(cf. gravitational deformation)

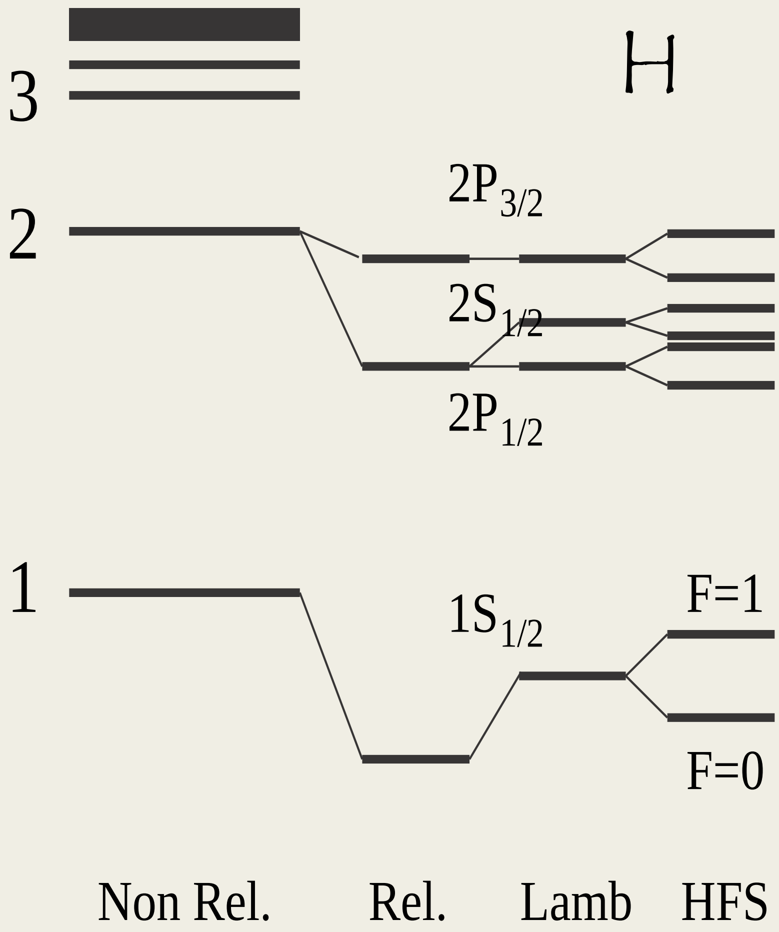
Cf. $\mathrm{Im}(m_{12}) \sim 1.1 \times 10^{-17}$ GeV
→Still several % of CP violation*

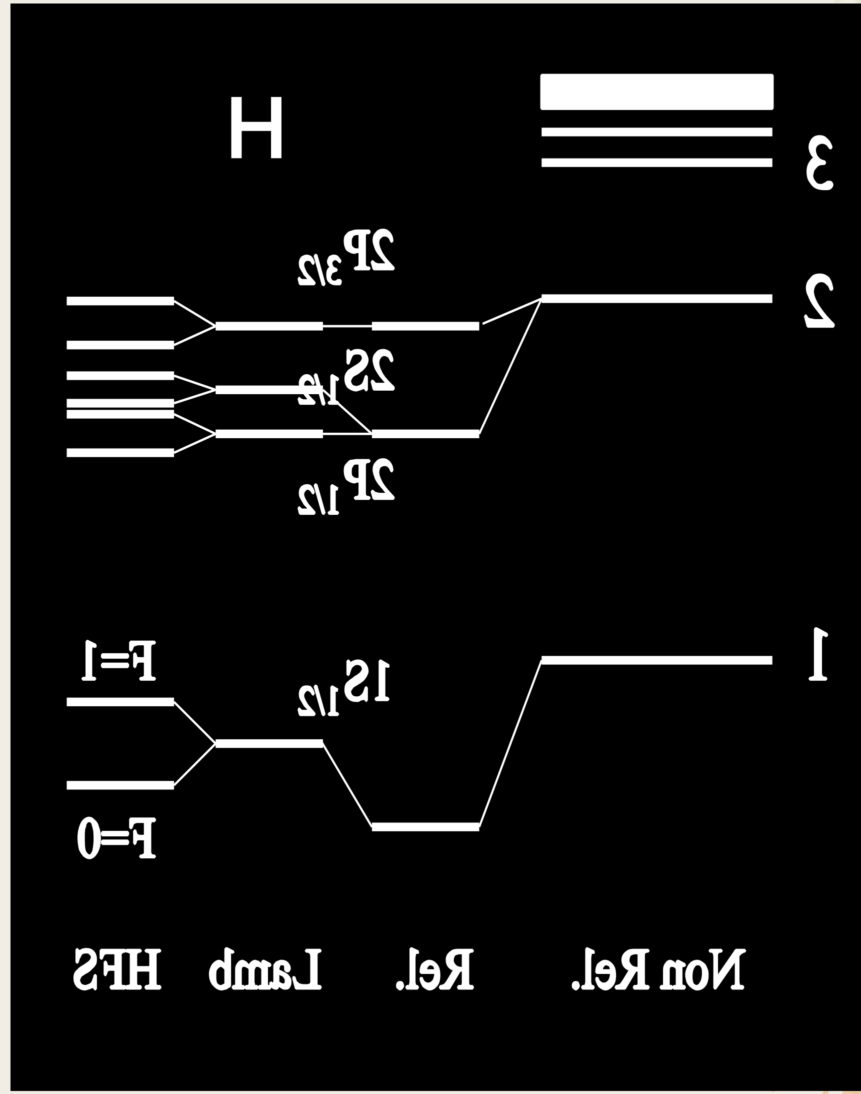
*M. Kobayashi and A.I. Sanda, PRL 69 (1992) 3139

Why antihydrogen?

- The simplest antimatter
- Hydrogen, the opposite number of antihydrogen, has been studied with extremely high precision, an excellent reference
- Important quantities to be compared
  - HF and 1S-2S transitions of **H** and H

Why antihydrogen?





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- Important quantities to be compared

  HF and 1S-2S transitions of **H** and H

  Mass, magnetic moment between **p** and p

  (Gravity between antimatter (**H**) and matter (the earth))

- And anyway, exotic!

Why antihydrogen?

	$\lvert m_m - m_a \rvert / m$	$\lvert q_m + q_a \rvert / \lvert q \rvert$	$\lvert g_m - g_a \rvert / \lvert g \rvert$
e^- vs e^+	$<8\times10^{-9}$	$<4\times10^{-8}$	$(-0.5\pm2.1)\times10^{-12}$
p vs **p**	$<7\times10^{-10}$	$<7\times10^{-10}$	Till this year → $< 5\times10^{-3}$

Spectroscopy of hydrogen atom

g_p=5.585694713(46)

	experiments (Hz)	$\Delta\nu_{exp}/\nu$	$\lvert \nu_{th} - \nu_{exp} \rvert / \nu$
ν_{1S-2S}	2,466,061,413,187,035 (10)*	4.2×10^{-15}*	1×10^{-11}
ν_{HF}	1,420,405,751.7667 (9)	6.3×10^{-13}	$(3.5\pm0.9)\times10^{-6}$

*C.G.Parthey et al., PRL107(2011)203001

Why antihydrogen?

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10days ago! →

Spectroscopy of hydrogen atom

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Red letter: theoretical limit for H

○ : achievable precision

Unknown physics if at all should be seen below this theoretical limit, i.e., should at least be 10^4 Hz or better, which is again 10^{-19}GeV

J. DiSciacca et al., PRL110(2013)130801, *C.G.Parthey et al., PRL107(2011)203001

Why antihydrogen?

$$\nu_{1S-2S} = \frac{3}{4}\frac{1}{2}\left(\frac{1}{1+\frac{m_e}{m_p}}\right)\frac{m_e(\alpha c)^2}{h} \qquad \alpha = \frac{q_e q_p}{4\pi\varepsilon_0 \hbar c}$$

$$\nu_{1HF} = \frac{8}{3}\left(\frac{1}{1+\frac{m_e}{m_p}}\right)^3 \frac{m_e}{m_p}\frac{\mu_e}{\mu_B}\frac{\mu_p}{\mu_N}\frac{m_e\alpha^2(\alpha c)^2}{h}$$

	1,418.83 MHz
g_e=2.002	1,420.24 MHz
QED, Zemach	1,420,401 (1)
experiment	1,420,405,751.7667 (9)

→ ν_{HF} is the right quantity to measure!

→ $\Delta\nu_{HF}$~3.5ppm

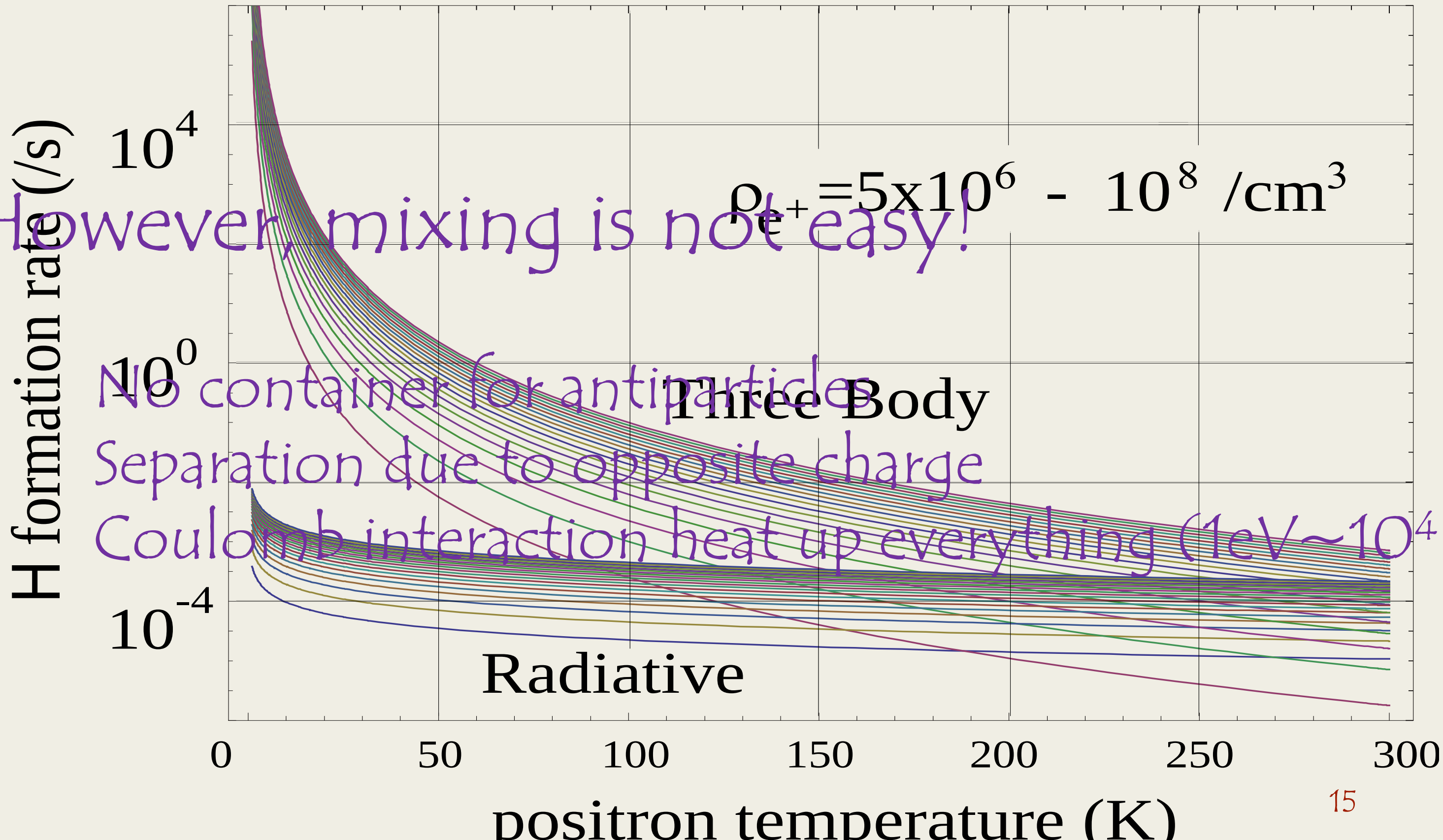
H Synthesis and manipulation

(1) p + e^+ → H + hν $\Gamma = 3 \cdot 10^{-11} (4.2/T)^{1/2} \rho_e \rho_p\ s^{-1}$

(2) p + e^+ + e^+ → H + e^+ $\Gamma = 6 \cdot 10^{-13} (4.2/T)^{9/2} \rho_e^2 \rho_p\ s^{-1}$

(3) p + (e^+e^-) → H + e^-

(4) (e^-,p) + e^+



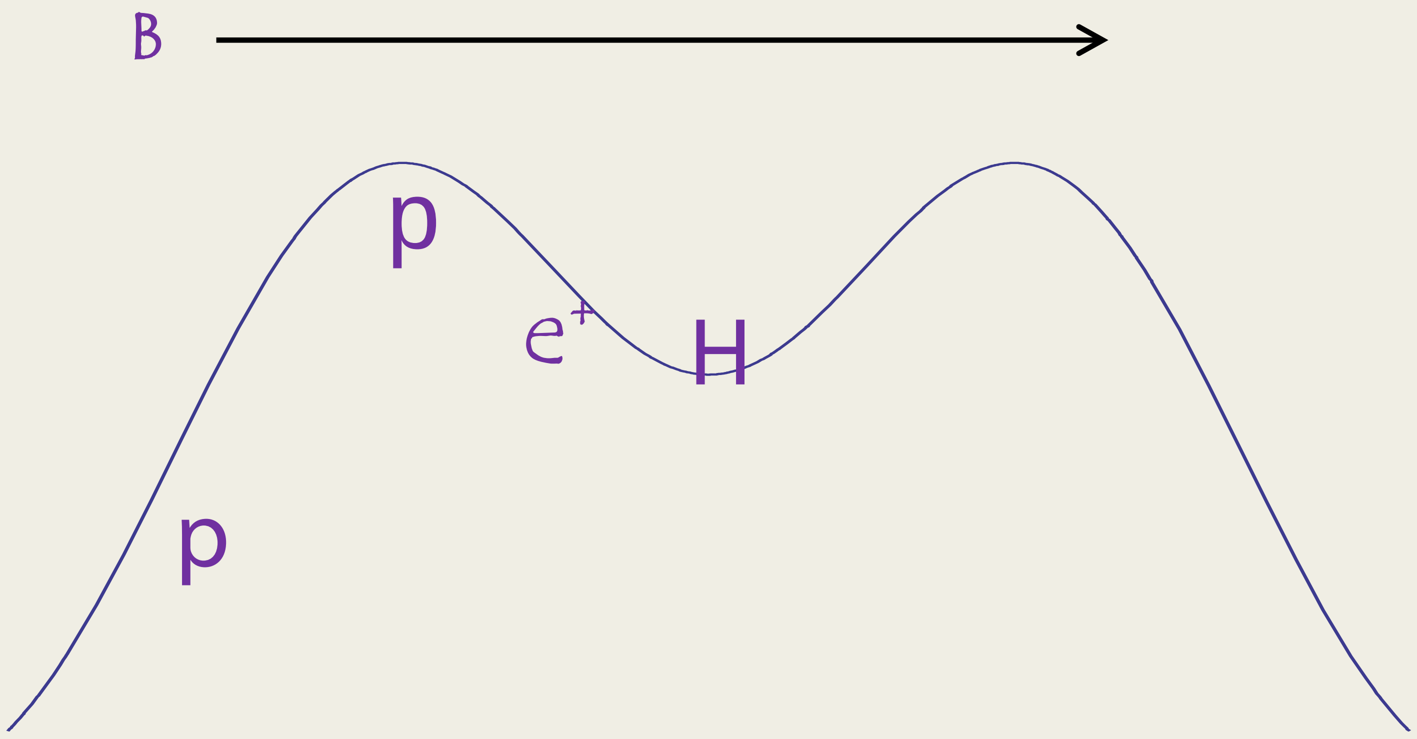
However, mixing is not easy!

No container for antiparticles

Separation due to opposite charge

Coulomb interaction heat up everything (1eV~10^4 K)

H Synthesis and manipulation



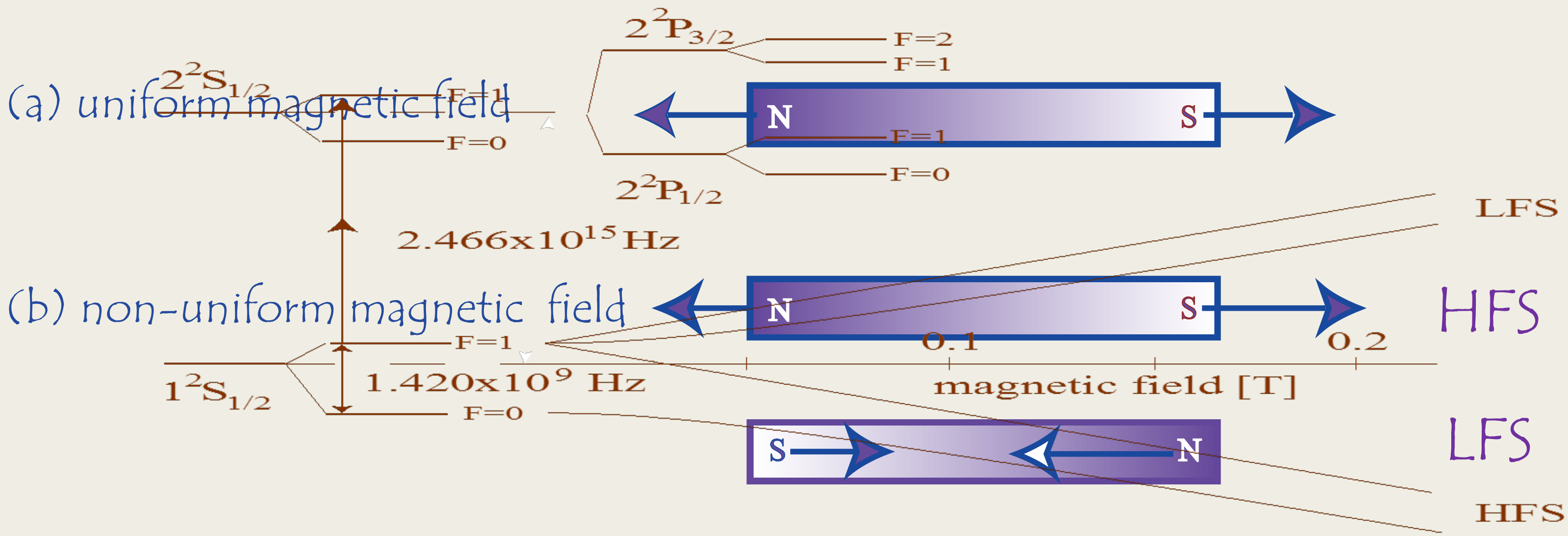
ATHENA Nature 419(2002)456

ATRAP Phys.Rev,Lett89(2002)213401

H Synthesis and manipulation

H is neutral, and not manipulatable with electric fields.

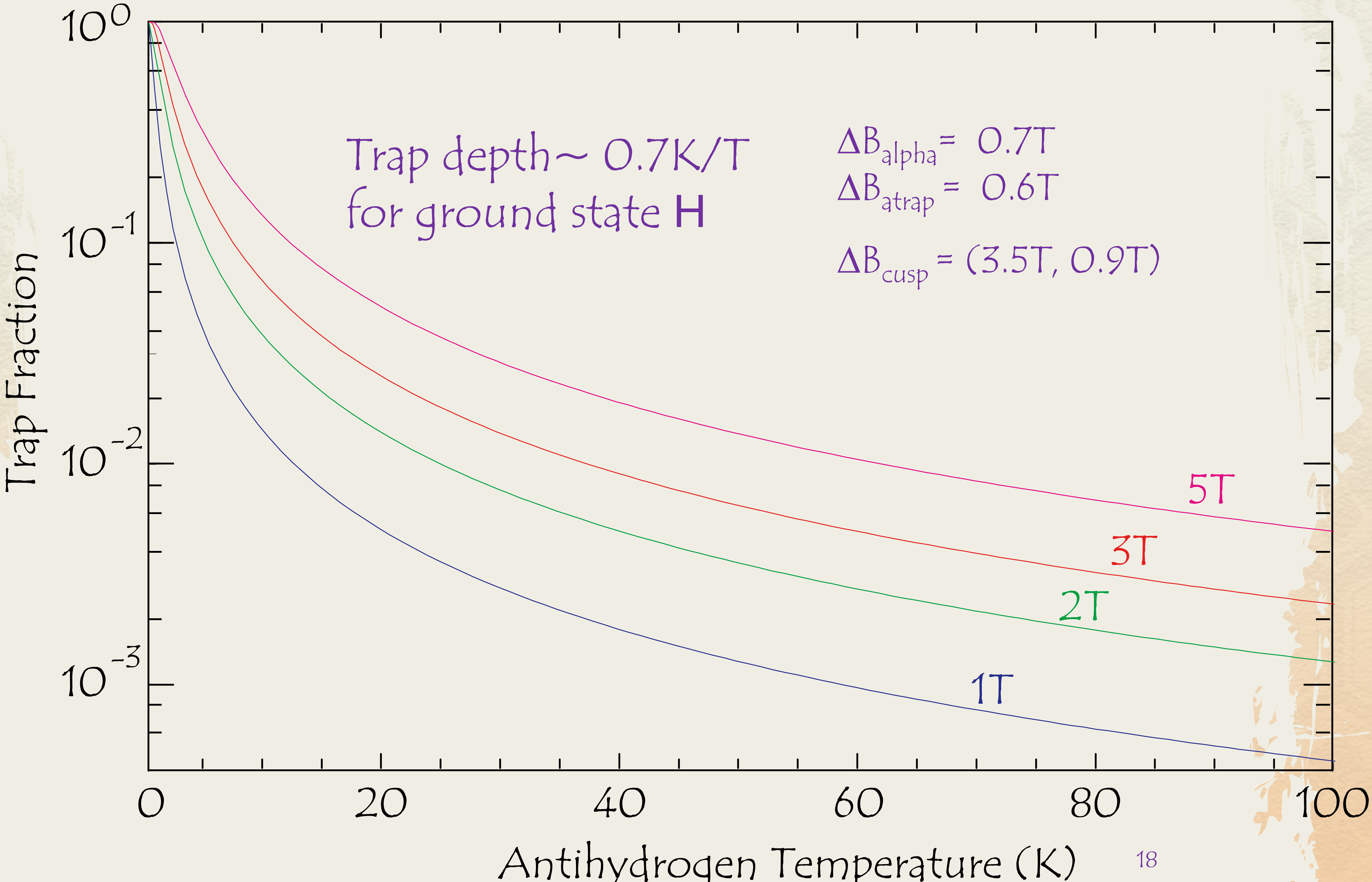
On the other hand, **H** is a small magnet, which can be manipulated by magnetic fields



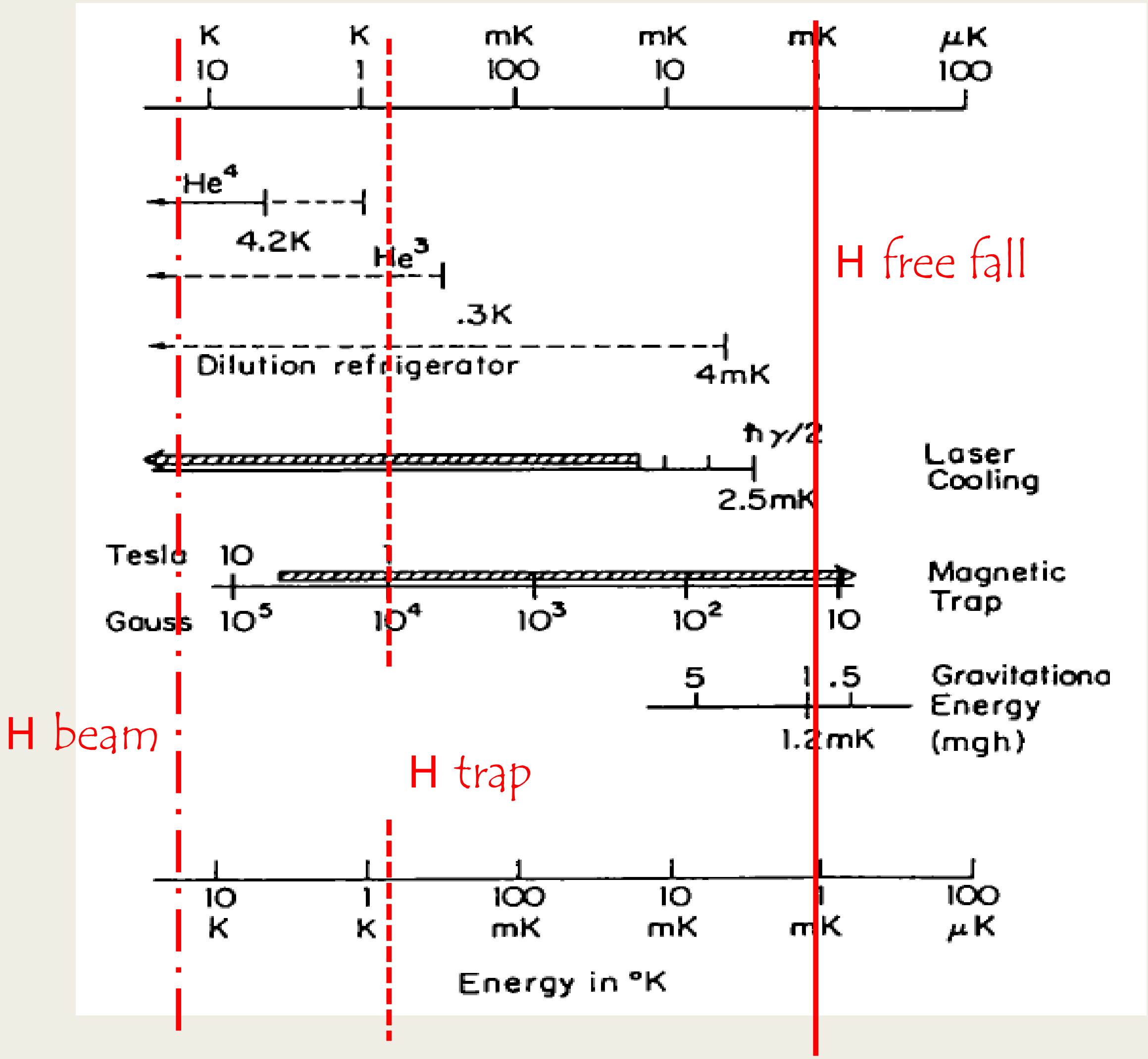
LFS: Low field seeking states   HFS: High field seeking states

→ Magnetic field gradient can control **H**, and minimum B field configuration can trap **H** in LFS states

H Synthesis and manipulation



Expected temperature of H

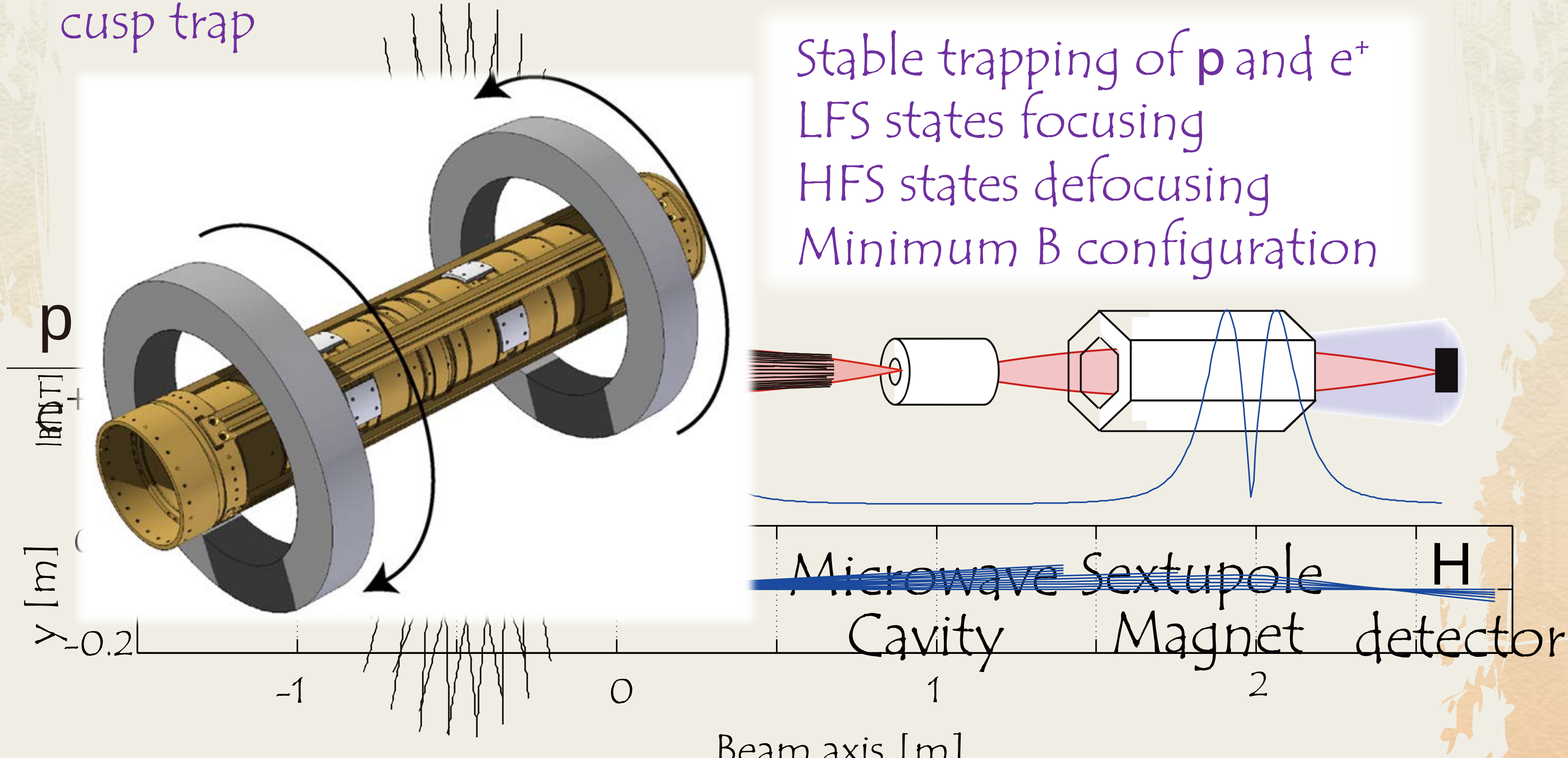


~0.7K/T

H Synthesis and manipulation: CUSP

Hyperfine Transition microwave spectroscopy →
H extraction in a field-free region →
cusp trap

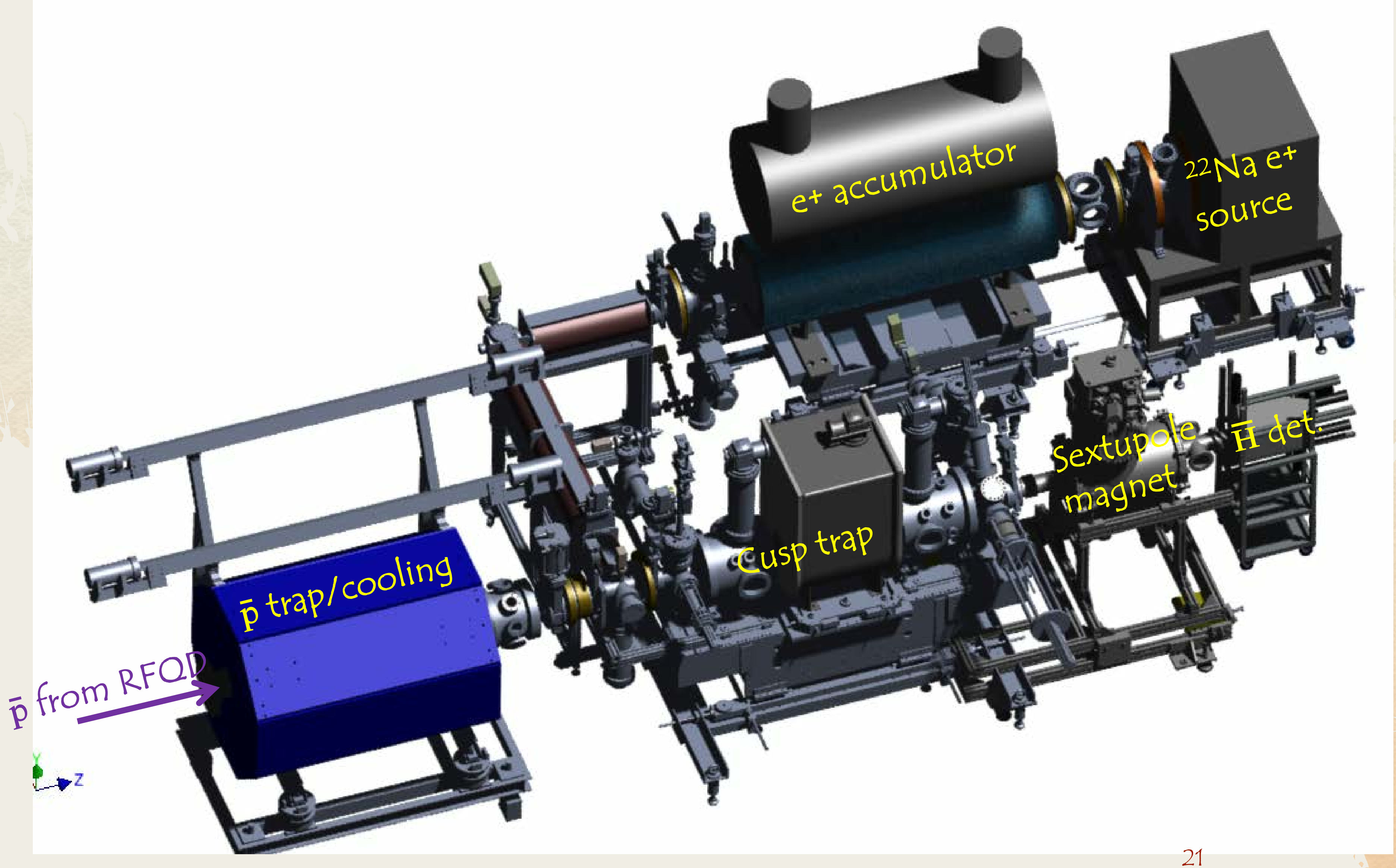
Stable trapping of **p** and e^{+}
LFS states focusing
HFS states defocusing
Minimum B configuration



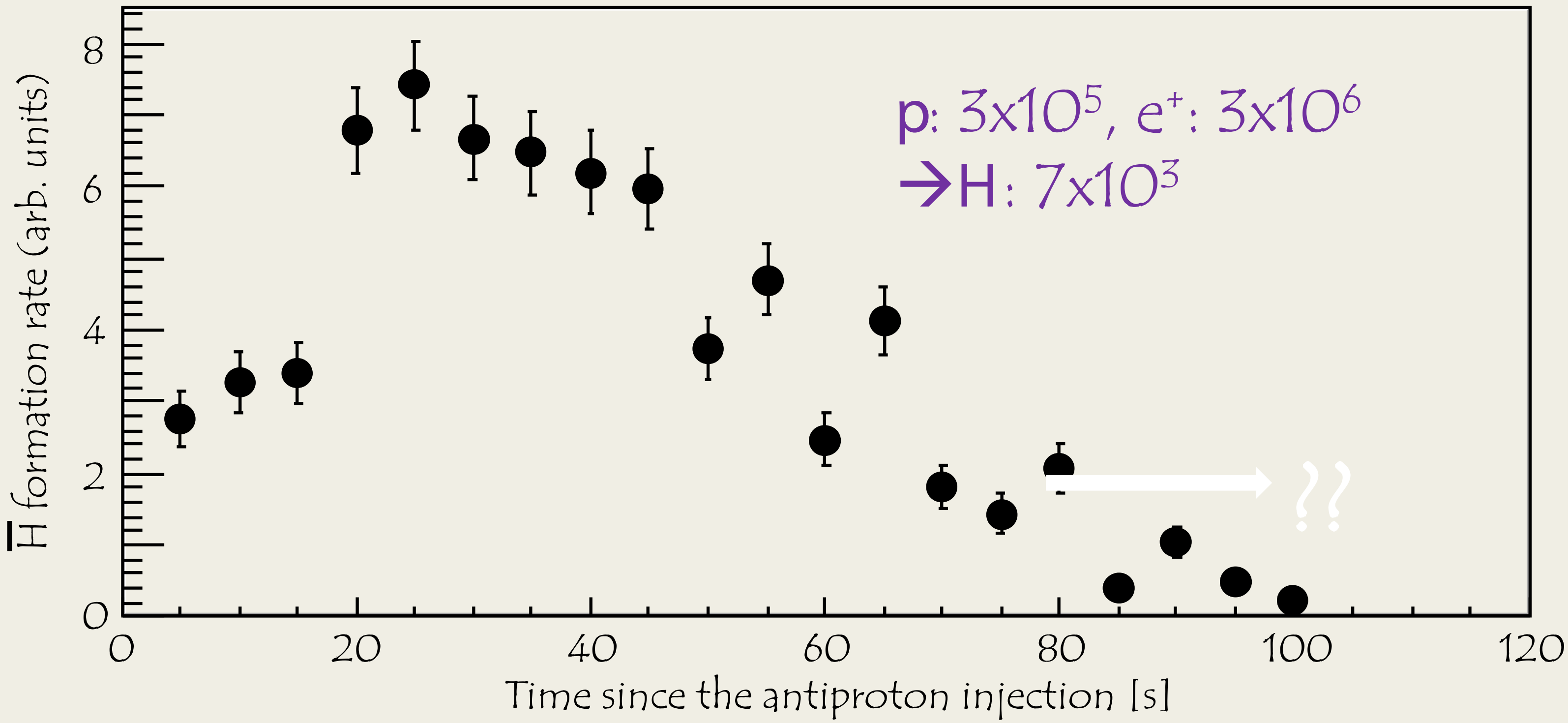
CUSP trap

A kind of Molecular beam methods

H Synthesis and manipulation: CUSP



H Synthesis and manipulation: CUSP

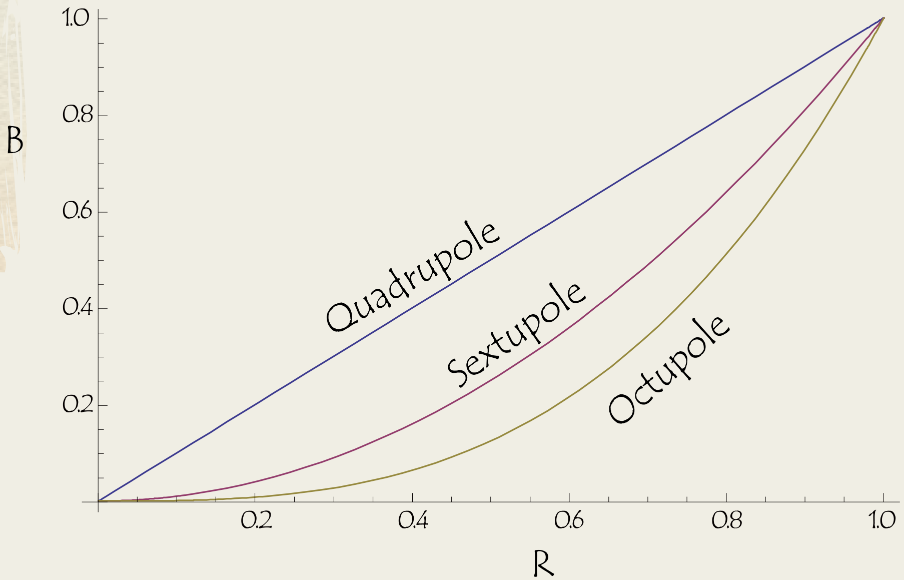


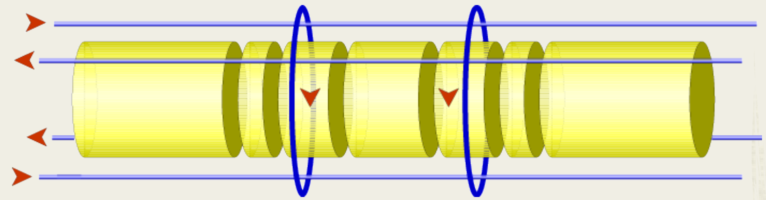
Successful synthesis of H in the cusp trap (2010)
→ Extraction of antihydrogen downstream of the cusp trap
→ Toward MW spectroscopy

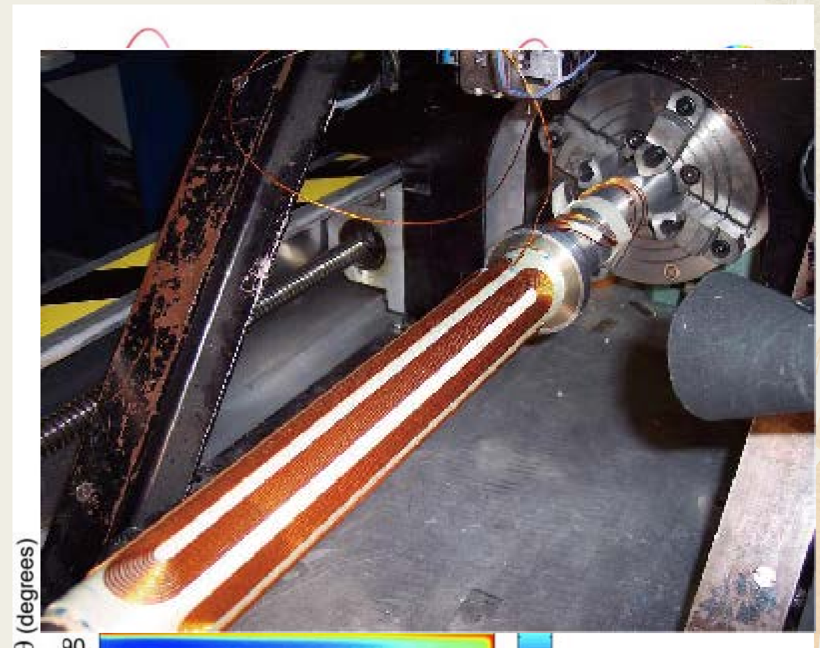
Enomoto et al., Phys. Rev. Lett. 105 (2010) 243401

Magnetic bottle scheme: ALPHA

1S-2S laser spectroscopy → long time **H** trapping → magnetic bottle (minimum B configuration)



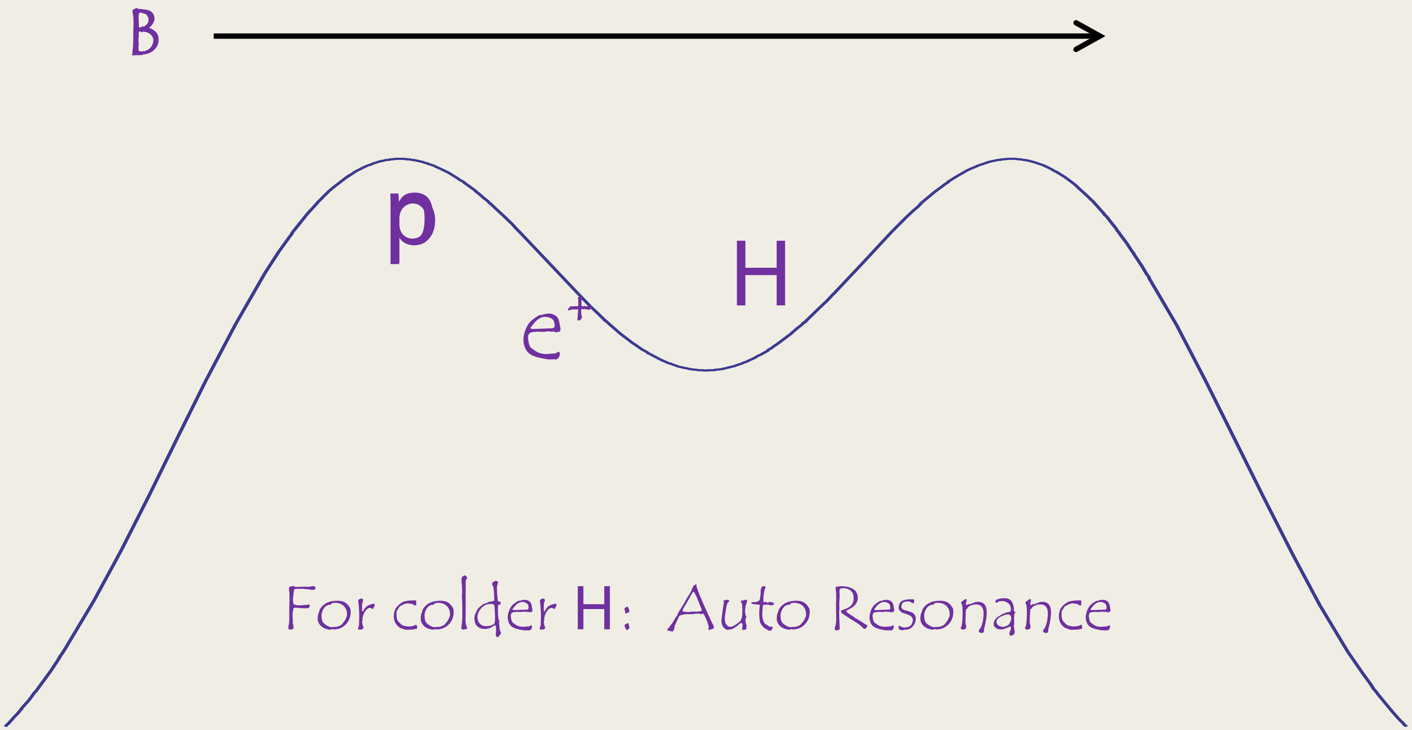




ALPHA: Octupole coil

→ Charged particles unstable
→ higher multipole for uniform field near the axis

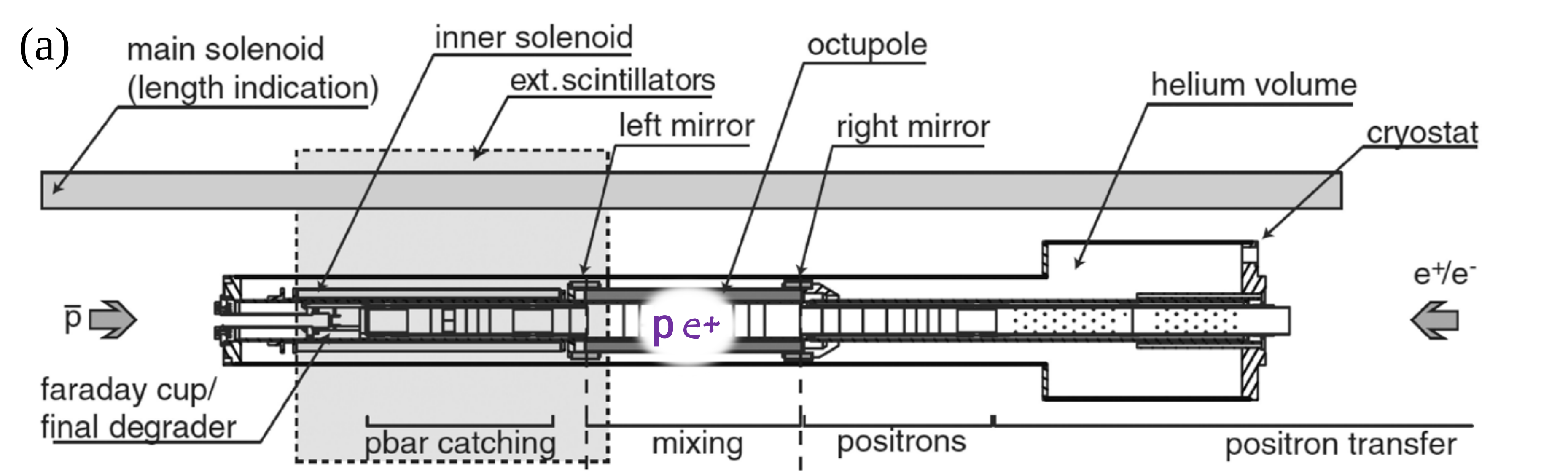
$\bar{H}$ synthesis



ν depends on amplitude → amplitude control by external RF

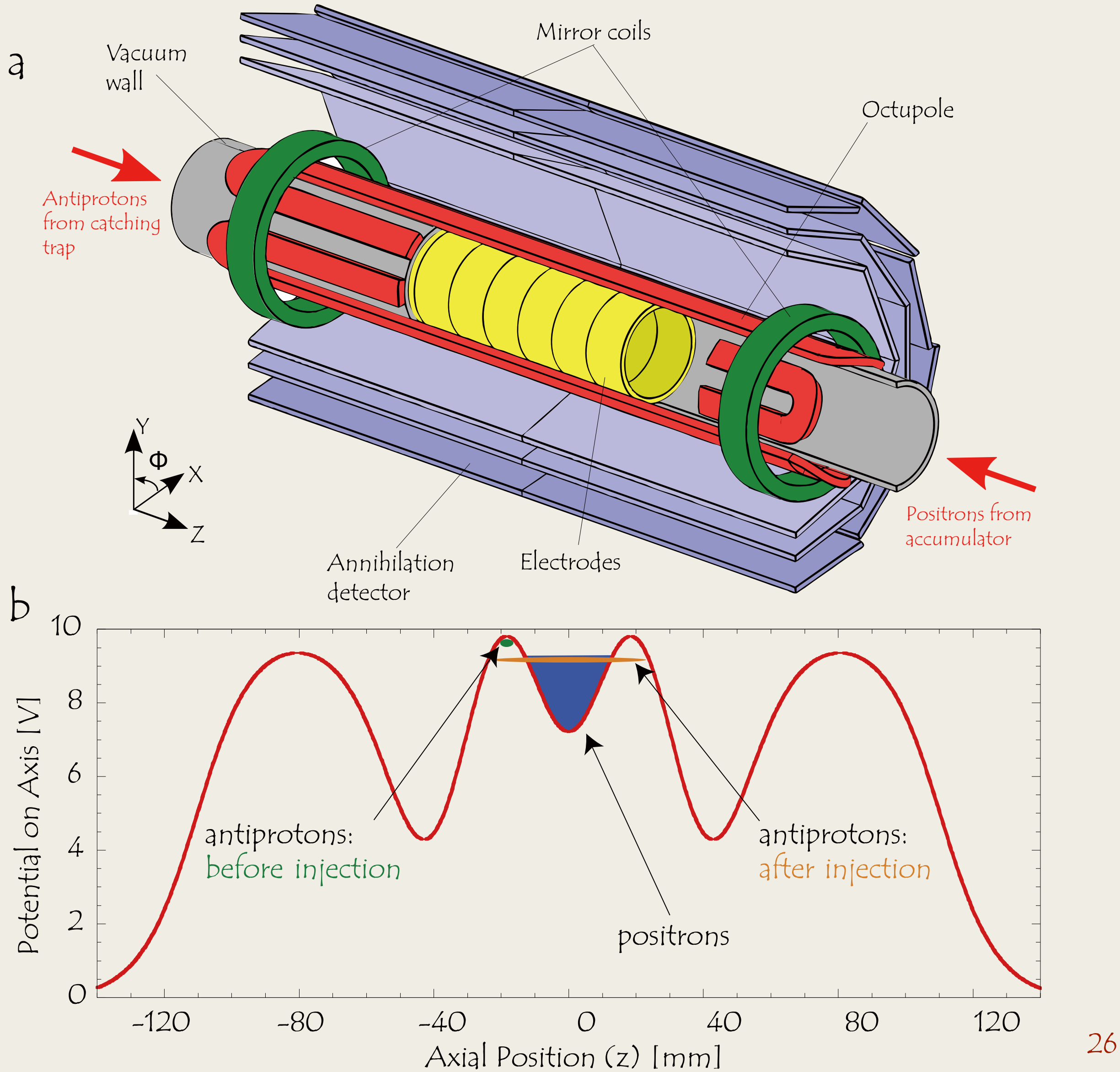
ALPHA, Andressen et al., PRL106(2011)025002

H Synthesis and manipulation: ALPHA

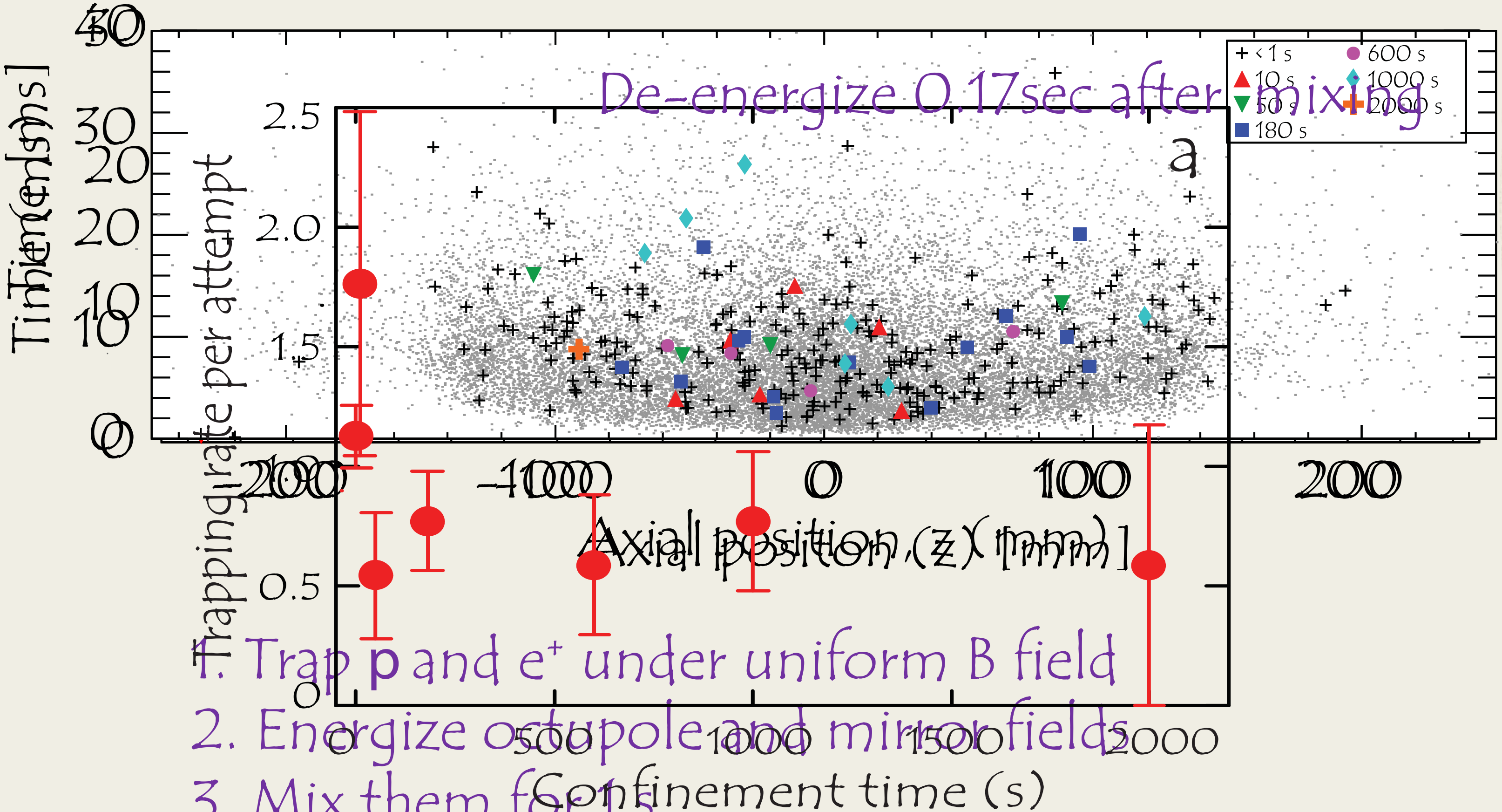


1. Trap **p** and e^+ under uniform B field
2. Energize magnetic bottle
   (octupole and mirror fields)
3. Mix them for 1 s
4. Remove all **p** and e^+
5. de-energize the magnetic bottle
(octupole and mirror coils)

Magnetic bottle scheme: ALPHA



H Synthesis and manipulation: ALPHA



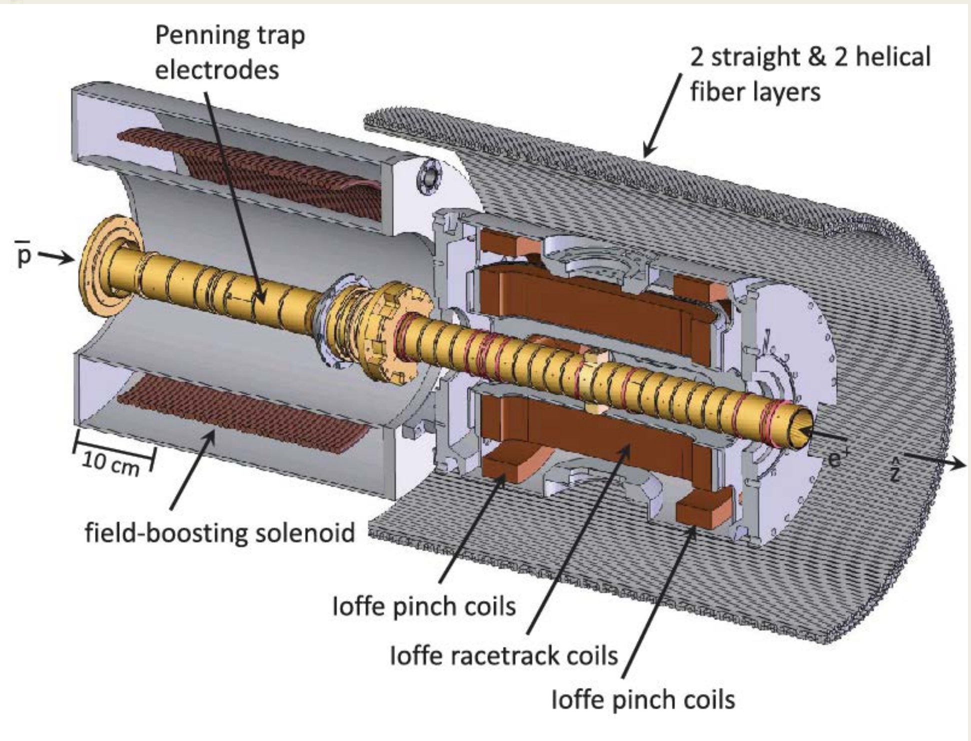
De-energize 0.17sec after mixing

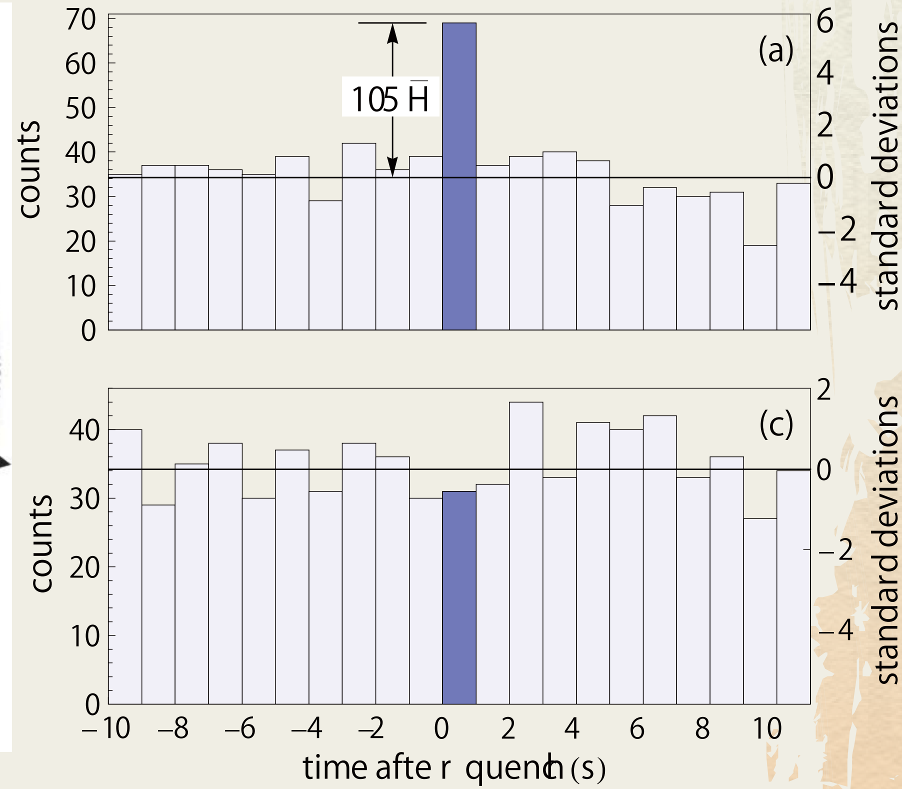
1. Trap p and e^+ under uniform B field
2. Energize octupole and mirror fields
3. Mix them for 1 s
4. Remove all p and e^+
5. de-energize the magnetic bottle (octupole and mirror coils)

~200 H trapped as long as 2000s!

Andresen et al., Nature 468 (2010) 673, and Fujiwara et al, Nature Phys. 7(2011)558.

Magnetic bottle scheme: ATRAP



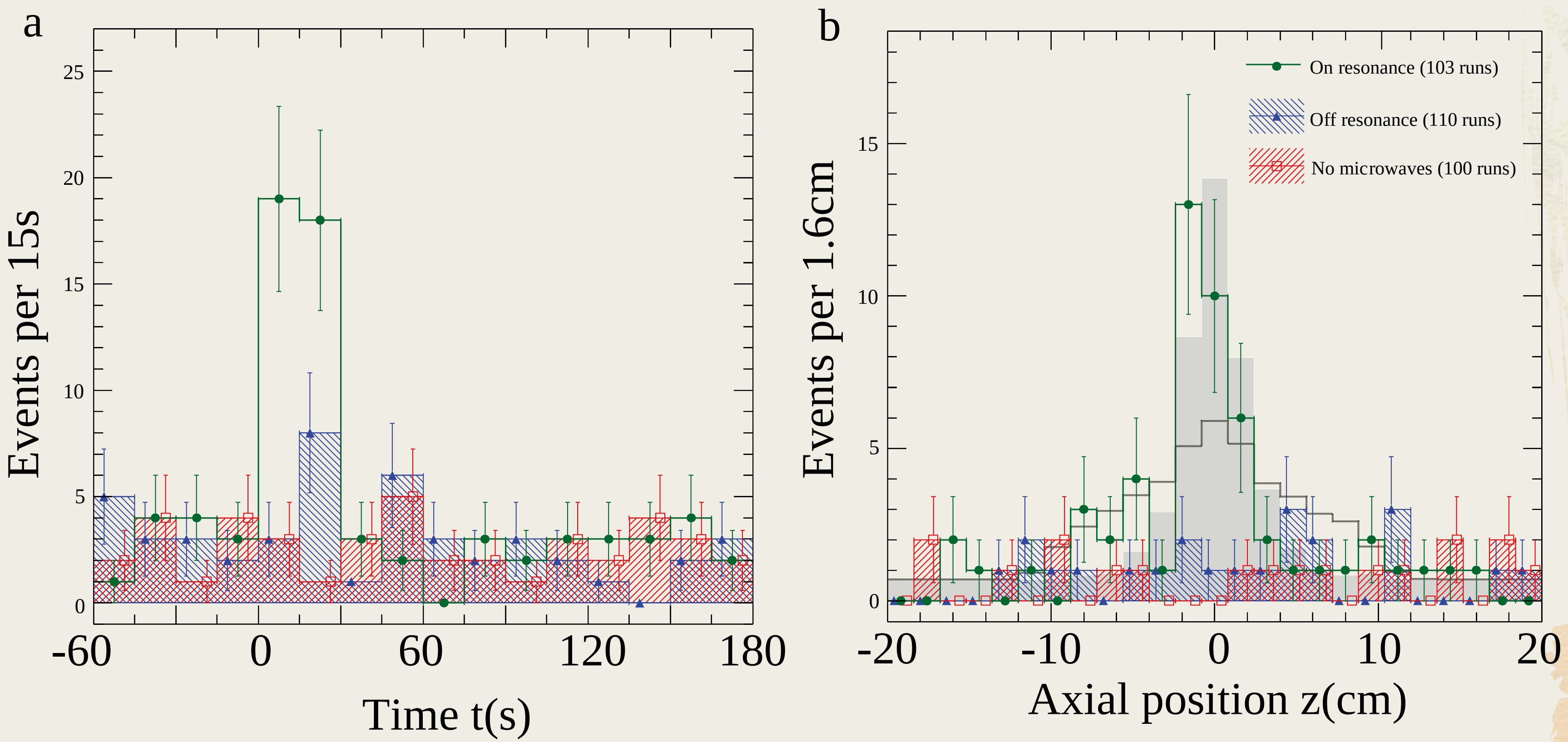


$\bar{p}$:10^6, e^+:$3x10^7$ ~5$\bar{H}$/mixture

G.Gabrielse et al., PRL108_113002(12)

Magnetic bottle scheme: ALPHA

Hyperfine transition in strong inhomogeneous magnetic field



→ Precision criteria fulfilled?

→ Laser spectroscopy in a future?

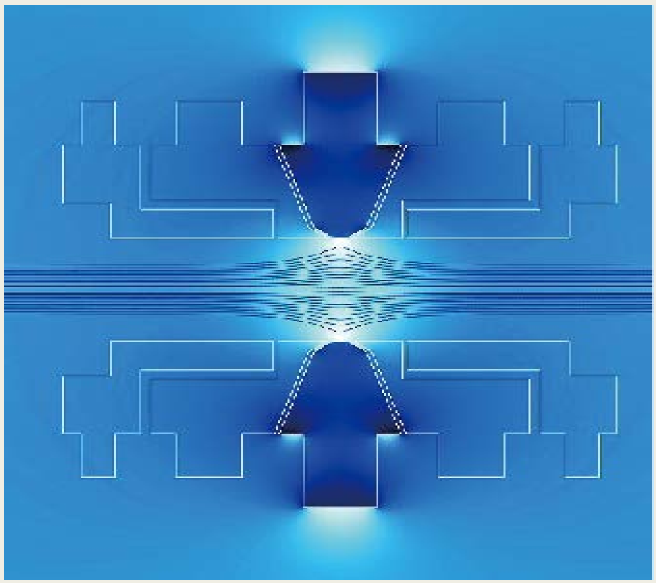
p:2×10^4, e^+:2×10^6

~1Htrapped/mixture

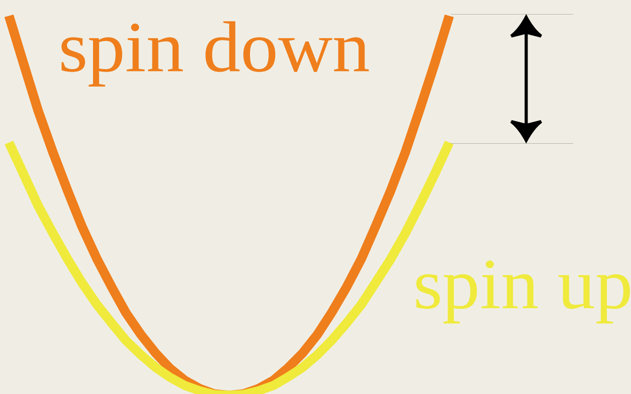
(~6×10^3H formed)

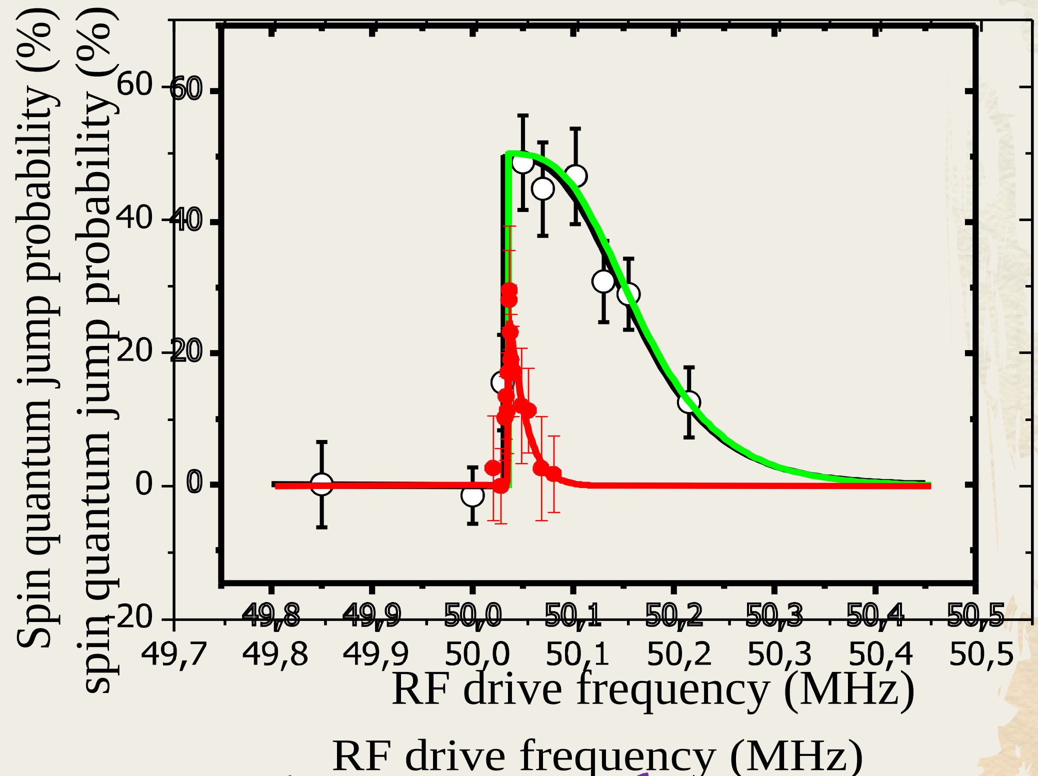
C.Amole et al., Nature 483(2012)439

Spinflip of p/**p**: Complementary exp.



Δε=0.8neV





2011 (S. Ulmer): p spinflip, 10^{-5}

2012 (C C Rodegheri): p spinflip, 10^{-6}

2012(J. DiSciacca): p spinflip, 10^{-6}

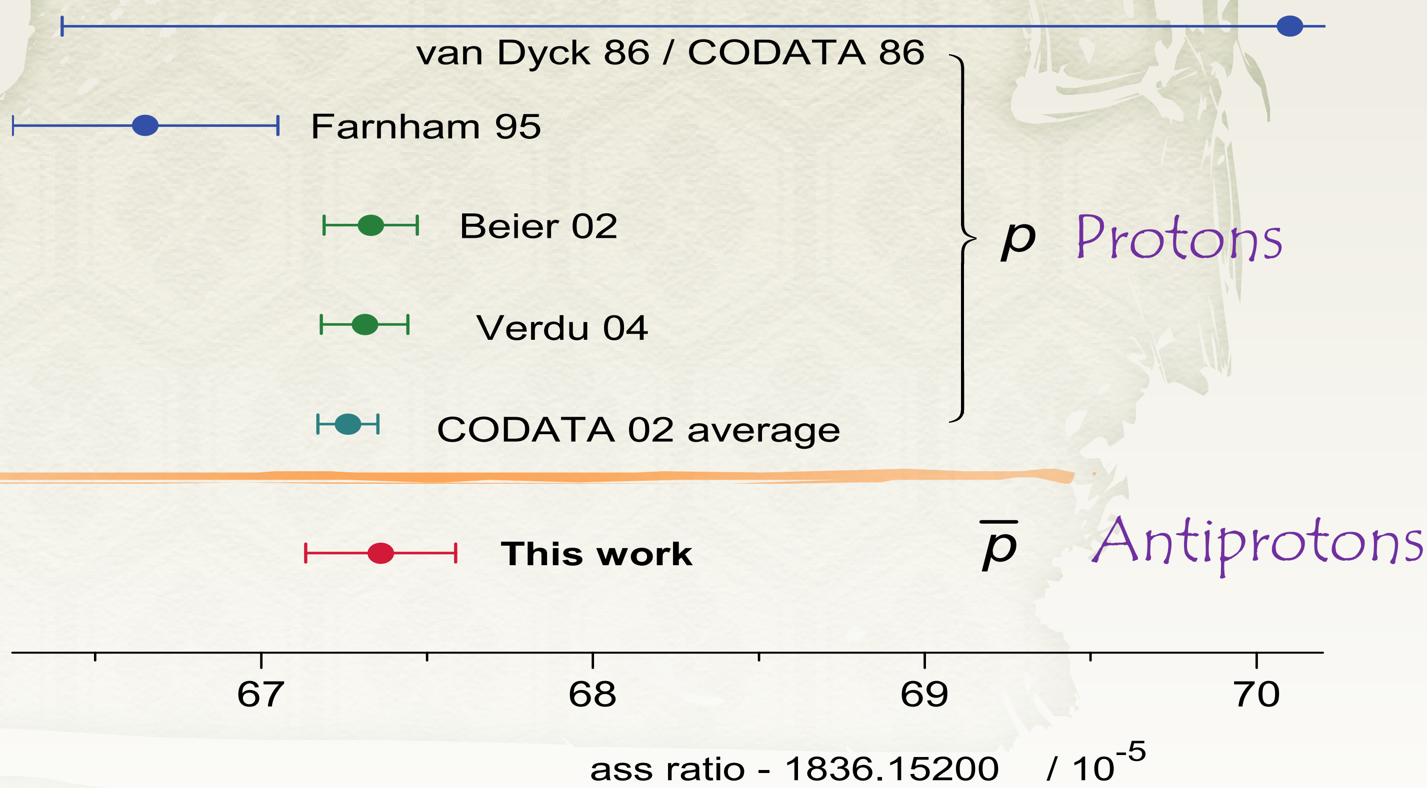
2013 (J. DiSciacca): **p** spinflip, 10^{-6}

Complementary to **H** HF

S. Ulmer et al., PRL106(2011)253001

pHe^+ (e^-pHe^{++})laser spectroscopy:

Antiproton-to-electron mass ratio measurements: 1836.1526736(23)



p mass will soon be known with better precision than the mass of p, the most abundant matter in our universe!

(note that this is a CPT confirming experiment)

(Hori et al., Nature 475, 484 (2011))

Summary and outlook

Antihydrogen: successful manipulation, now at the entrance of the physics research, i.e., CPT symmetry test starts now via

ground-state hyperfine transitions: ASACUSA
1S-2S transition: ALPHA, ATRAP

p spinflip in a penning trap: BASE, ATRAP
pHe: ASACUSA
antimatter-matter gravity: AEgIS, Gbar

ELENA provides 10-100 times more ps hopefully from 2017

$p\mu^{+}$ vs $p\mu^{-}$: more sensitive to CPTV than H vs H?

d (p + p → d + π^{+}: uud + uud → uududd + ud)

Antihydrogen research

Chinese red

Thank you very much for your attention!

We are looking for active and motivated young people who want to join our **H** activities at ASACUSA-MUSASHI (working place: Geneve)!

A robber family who steals precious Chinese red from King's grave digging a long tunnel for many generations

Now we are at the entrance of the real antihydrogen research!