Cold antihydrogen

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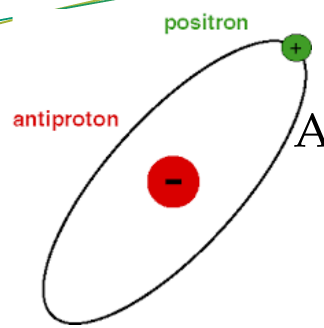
- Anti-atoms and antihydrogen
- Why cold antihydrogen
- Methods and results
- Perspectives (see also next talk, F. Sorrentino and L. Venturelli)

Anti-atoms



$\bar{p}\, e^{+}$

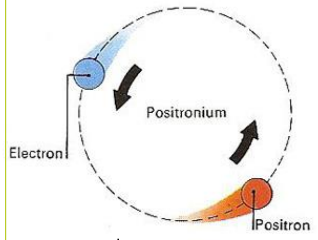
Antiproton- positron   Anti-Hydrogen

CERN: 5 International collaborations@CERN
about 100 Institutes

- ALPHA
- ATRAP
- ASACUSA
- AEgIS
- GBAR (from the year 2017-2018)
- BASE (no antiH)

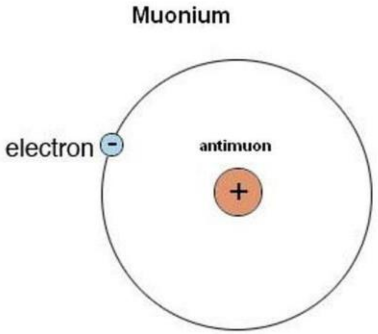
INFN (comm3) now   - AEgIS
- ASACUSA
(1998-2007   -ATHENA)

Positronium



$e^{+}e^{-}$

a) A. Mills (Univ. California Riverside)
b) S. Hogan &S. Cassidy   UCL London
c) P. Crivelli et al, (ETH- Zurigo)
d) Tokyo University
e) ….
f) AEgIS : AntiH made through charge exchange with pbar Rydberg Positronium

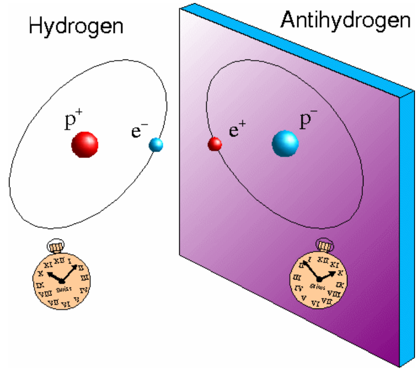


$\mu^{+}e^{-}$

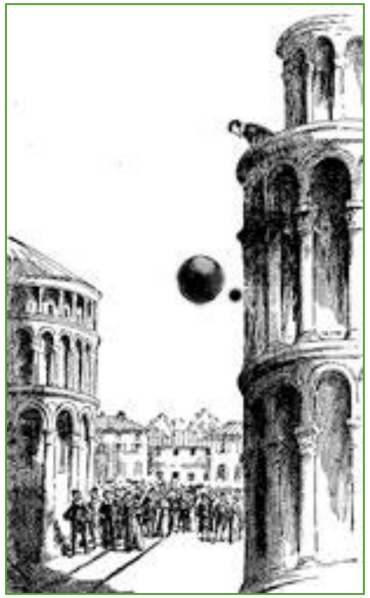
Muonium   a) K. Kirch (ETH- PSI)

Physics Motivations (antihydrogen)

1) Spectroscopy and high accuracy CPT verification
   1S-2S line
   GSHFS Ground Stare HyperFine Structure: (see L. Venturelli)



1) Direct measurement of the validity of WEP for antimatter:
   measure the Earth gravitational acceleration g on antiH



The experimental requirements are very similar

CPT

- Quantum field theory with local interactions and Lorentz invariance: must respect CPT

(Charge Parity and Time Reversal)

Test of foundation of Quantum Field Theory

- Mass
- magnetic moment
- lifetime
- transition frequency in bound systems

Must be equal for matter and antimatter systems of each type

A.D. Dolgov, Ya.B. Zeldovich, Rev. Mod. Phys. 53, 1 (1981)
O. Bertolami et al., Phys. Lett. B 395, 178 (1997

Cosmology:

CPT violation + non conservation of barion number → matter-antimatter asymmetry in thermal equilibrium

- Large interest in Lorentz violation: it may happen in theory beyond the Standard Model
- Standard-Model extension (SME): low energy framework to describe effects of a theory at Planck scale

Effective theory which contains:

- General Relativity (GR)
- Standard Model (SM)
- Arbitrary coordinate independent CPT & Lorentz violating terms (LV)
- parametrized with coefficients particle dependent $L_{SME} = L_{GR} + L_{SM} + L_{LV}$

Reverse CPT theorem:
CPT violation→Lorentz invariance violation
PRL 89 231602 (2002)

Search for CPT violation is a search for a signal of a theory beyond the Standard Model

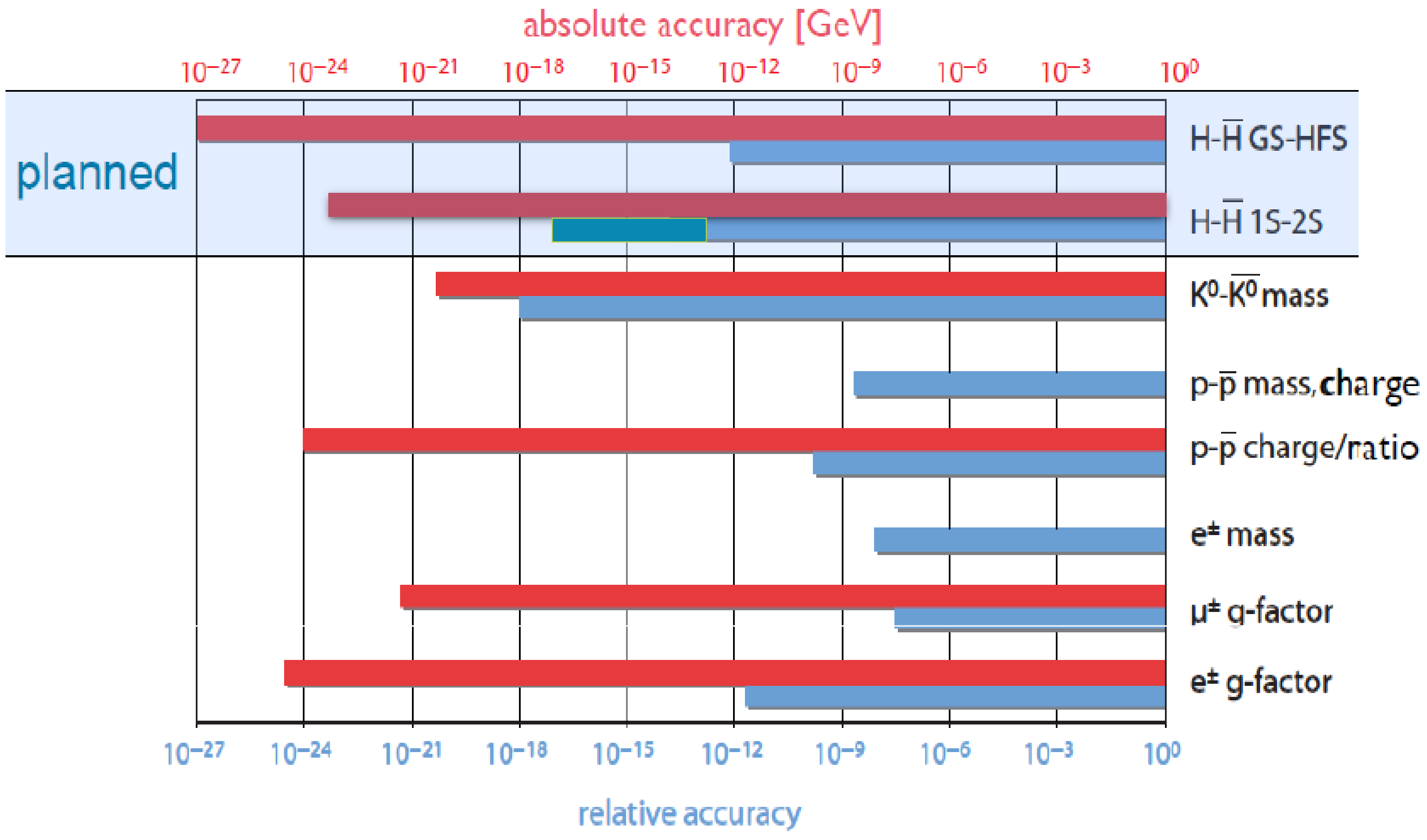
A. Kostelecky	http://www.physics.indiana.edu/~kostelec/

http://physics2.nmu.edu/~nrussell/

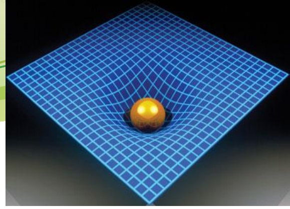
J. Tasson http://www.stolaf.edu/people/tasson1/
http://people.carleton.edu/~jtasson

Accuracy of the CPT tests

SME coeff. have dimension of energy



Many… many…. many… tests of the Equivalence Principle…..



WEP & UFF (Universality Freel Fall)

$$\eta = \frac{\Delta a}{a} = \frac{a_1 - a_2}{(a_1 + a_2)/2} = (0.3 \pm 1.8)10^{-13}$$

Eot-Wash PRL 2008

Be-Ti Bulk matter

$$\frac{\Delta g}{g} \approx 10^{-10}$$

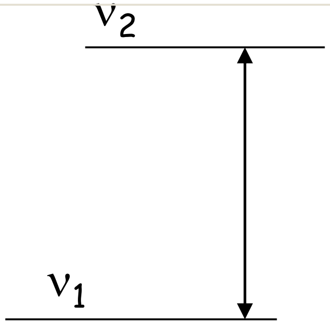
A. Peters et al, Nature 400 (1999) 849

Cold atoms

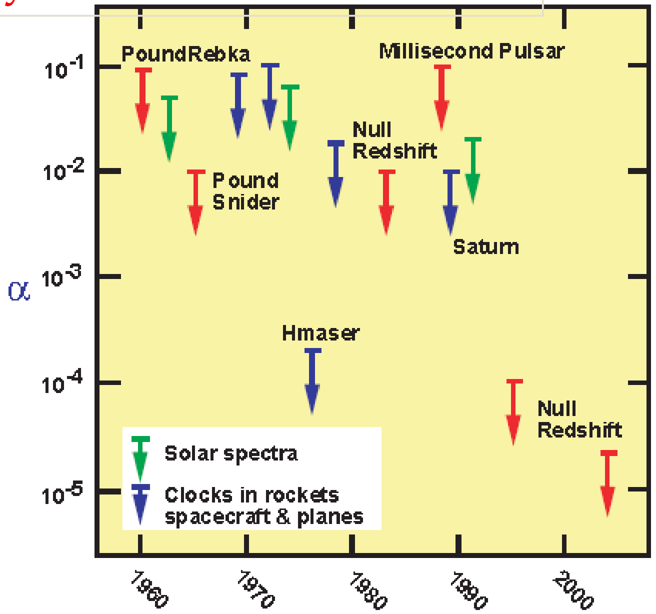
Bulk matter in space (STEP): expected

6 order of magnitude better

UGR Universality Gravitational Redshift



$$\frac{\Delta \upsilon}{\upsilon} = \left((1+\alpha) \frac{\Delta U}{c^2} \right)$$



C.M. Will Living Rev. Rel. 9(2006) 3

S. G. Turishev Phys.Usp. 52 (2009) 1-27

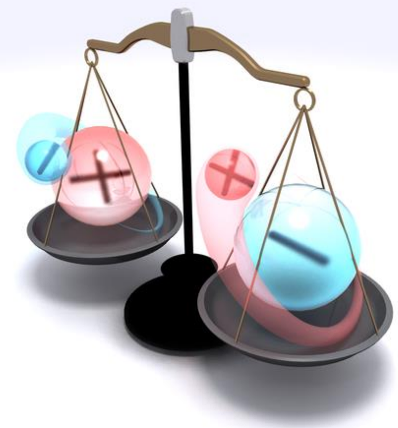
+ search for time variation of fundamental constants

+ isotropy of light propagation

+ …………………

Only for matter

WEP and Antimatter



- No direct measurements:
- e+ e- (Witteborn and Fairbank Phys. Rev. Lett., 19, 1049, 1967) dominated by sistematic effects
  (proposal for repeating it in space.. General relativity and Gravitation Vol. 36 N. 3 March 2004
- PS200 p and pbar (CERN) : g never measured, base of present day exp on antiH
- ALPHA g on antiH $m_g/m_i > 110$ and $m_g/m_i < -65$ excluded at 95% CL ALPHA Coll.,Nat. Comm 4 1785 (2013).

- If we assume GR we expect no difference
- Quantum gravity theories may (I'm not saying must) allow for differences
- Example SME: WEP violation results from Lorentz and CPT violation
  in a formally corrected model

J. Tasson Hyperfine Interactions (2012) 213:137-146

a subset of the SME lagrangian with gravity[1]

$$L_{\text{fermion}} = \tfrac{1}{2} i e^{\mu}{}_{a}\, \overline{\psi}(\gamma^a - c_{\nu\lambda} e^{\nu a} e^{\lambda}{}_{b} \gamma^b - e_{\nu} e^{\nu a}) \overleftrightarrow{D}_{\mu} \psi$$
$$- \overline{\psi}(m + a_{\mu} e^{\mu}{}_{a} \gamma^a)\psi + \ldots$$

coefficients for Lorentz violation
- particle-species dependent

- vierbein – gravitational effects

Adapted from J. Tasson WAG 2013

$$L = \underbrace{\tfrac{1}{2}(m + \tfrac{5}{3} N^w m^w \overline{c}^w_{TT})}_{m_{\text{i,eff}}} v^2 - \underbrace{gz(m + N^w m^w \overline{c}^w_{TT} + 2\alpha N^w (\overline{a}_{\text{eff}})^w_T)}_{m_{\text{g,eff}}}$$

matter $m_{\text{i,eff}} = m_{\text{g,eff}}$, $\text{a} = g$

$m_{\text{i,eff}} \neq m_{\text{g,eff}}$, $\bar{\text{a}} = g(1 - \frac{4 m^w N^w}{3m} \overline{c}^w_{TT})$ **antimatter**

J. Tasson PRD 2011

WEP – antimatter: another way → scalar and vector fields

Quantum scalar and vector fields are allowed in some models (Kaluza Klein) in addition to the tensor gravitational field

These fields may mediate interactions violatine the equivalence principle

Under very general assumptions: Phys. Rev. D 33 (2475) (1986)

Scalar always attractive

Vector repulsion between like particles, attractive between particle with opposite *charge*

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

Assuming that the non standard interaction is coupled to standard quantum number then a,b,r,v, are strongly constrained by the UFF experiments and $\frac{g_H - g_{\overline{H}}}{g_H}$ should be very small

But the conclusion is model dependent

M. Nieto and T. Goldman, Phys. Rep. 205, 5 221-281,(1992)
Bellucci & Faraoni, Phys. Lett. B 377 (1996) 55
J. Scherk, Phys. Lett. B 88 (1979) 265.

M. Nieto et al Phys. Rep. 205 (5) 221 (1991)
T. Goldmann et al, PRL 67,8 (1048) 1991
M. Charlton et al Phys. Rep 241 65 (1994)
R. Hughes Hyp. Int.76 3 (1996)

M. Fischler et al.,arXiv:0808.3929 [hep-th] (2008)
D. S. Alves et al., 0907.4110v1 [hep-ph] (2009)

Indirect limits on validity of the Equivalence Principle for antimatter systems

"Red shift type" argument — R. J. Hughes et al., PRL 66,7 (1991)

Cyclotron frequency of p and pbar in the same magnetic field

$$\left|\frac{\omega_c - \overline{\omega}_c}{\omega_c}\right| < 9\cdot 10^{-11}$$

G. Gabrielse et al PRL 82 (3198) (1999)

If matter and antimatter are coupled to the same tensor field $\alpha_{p\bar{p}} < 3\cdot 10^{-6}$

For anomalous interaction coupling to antimatter with R_{Earth} < range < Distance Earth-Sun $\alpha_{p\bar{p}} < 10^{-1}$

- The limit is model dependent
- Exact CPT is assumed

SN1987A

$\alpha_{\nu\bar{\nu}} < 10^{-5} - 10^{-6}$

Neutrino-antineutrino arrival time difference

S. Pakvasa et al., Phys. Rev. D 39 (1989) 176
G.T. Gillies Class. Quantum Grav. **29** (2012) 232001

- unclear how many neutrino and anti-neutrino
- No sensitivity due to relativistic effects

The "Schiff argument" — S.I. Schiff PRL 1 254 (1958)

Virtual e+ e- pairs in the atoms

WEP violation for e+ → m_I-m_G should depend on Z

$\alpha_{e+e-} < 10^{-6}$

- Several criticisms
- Uncorrected remormalization procedure…

M. Nieto et al Phys. Rep. 205 (5) 221 (1991)
M. Charlton et al Phys. Rep 241 65 (1994)
R. Hughes Hyp. Int.76 3 (1996)

K_0 $\overline{K}_0$

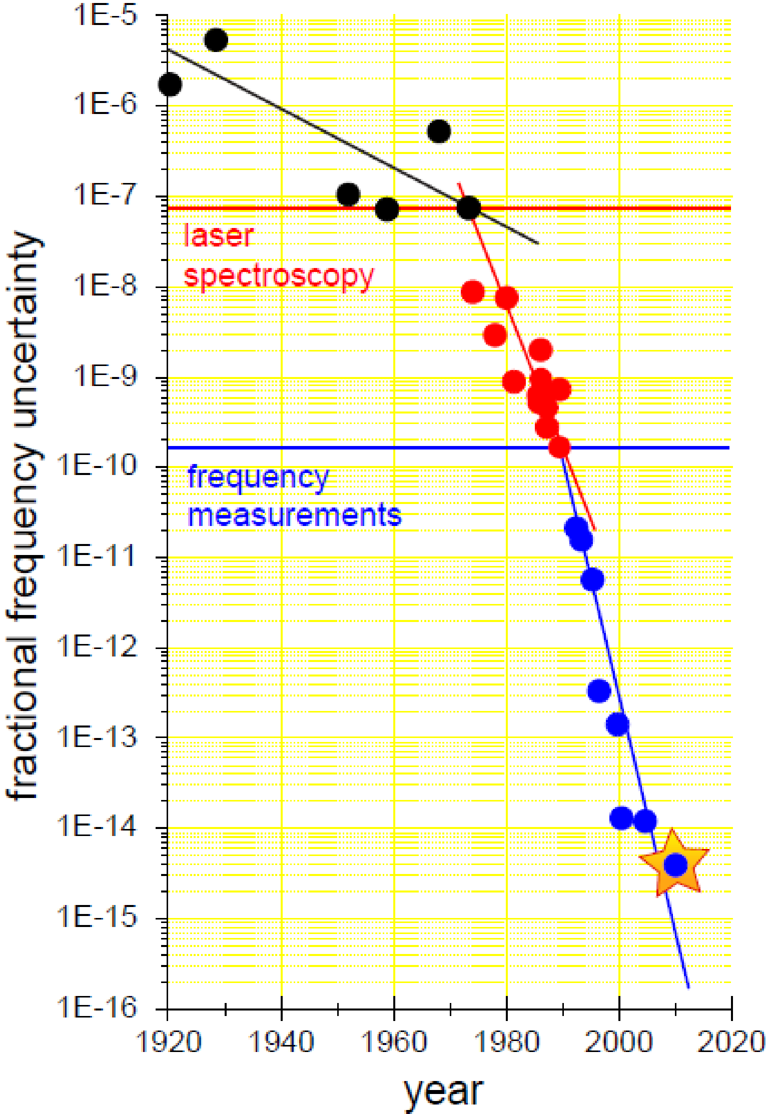
CPLEAR coll. Phys. Lett. B 452 (1999) 425

Very stringent limits for the K0 system

$\alpha_{K_0\overline{K}_0} < 10^{-9} - 10^{-14}$

Depending on the range of the anomalous interaction

Learning from matter experiments: 1S-2S transition in Hydrogen



1S-2S Doppler free two photons spectroscopy 243 nm

Natural width 1.3 Hz

- Beam of hydrogen (Haensch group)

  PRL 107 (203001) 2011 C.G.Parthey et al.

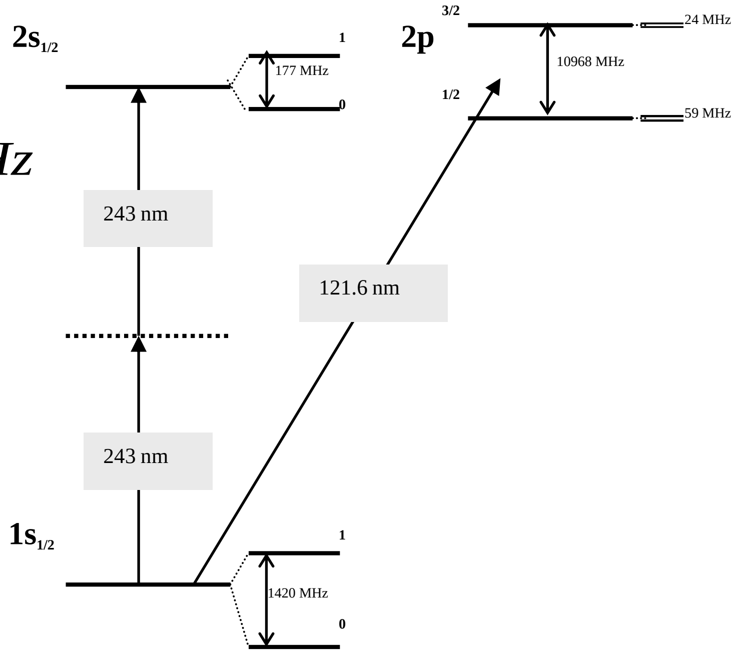
$$f_{1S-2S} = 2\,466\,061\,413\,187\,035\,(10)\ Hz$$

$$\frac{\delta f}{f} = 4.2\,10^{-15} \qquad E \approx 100 \quad mK$$

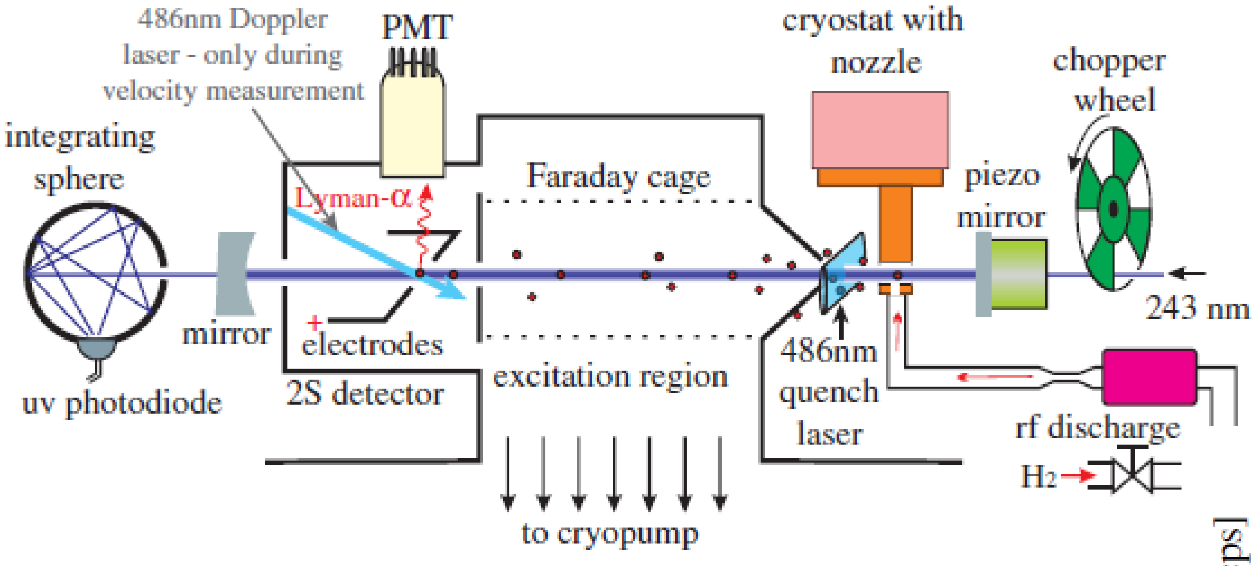
- Trapped hydrogen (Kleppner group)

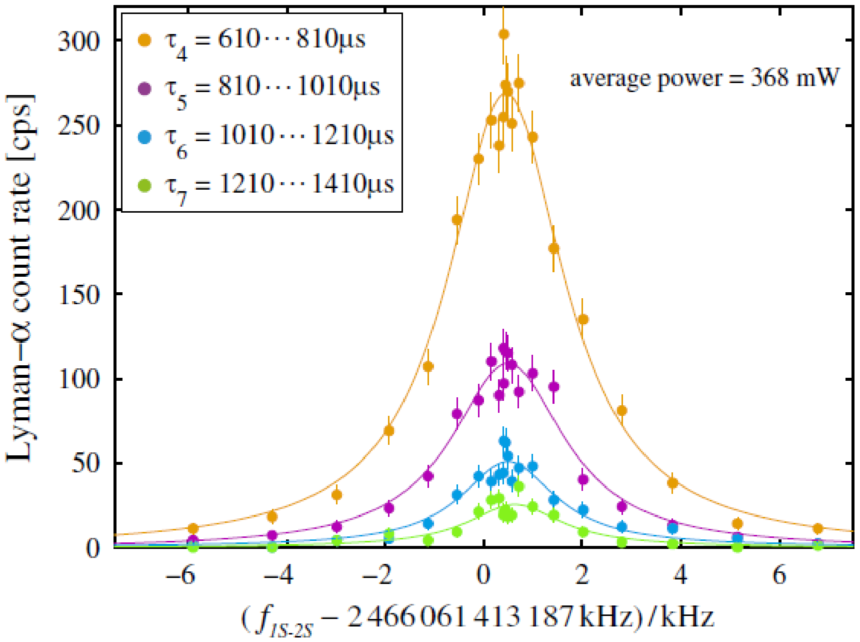
  PRL 77 255 (1996) C. Cesar et al

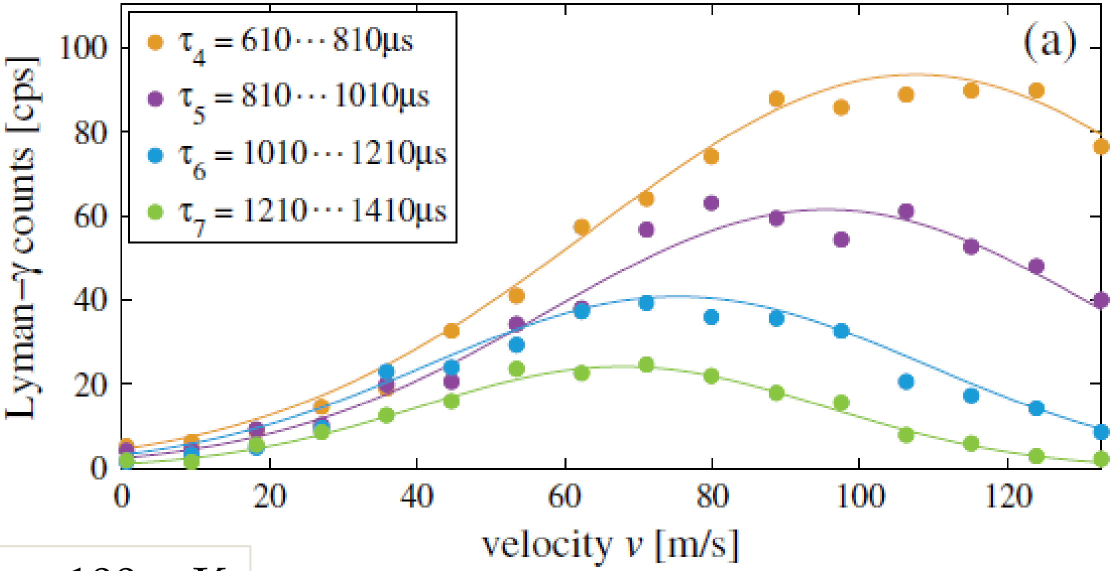
$$\frac{\delta f}{f} = 10^{-12} \qquad E \approx 100\,\mu K$$



We need Cold antiH: 1S-2S with a beam







- Beam of H
- 243 standing wave
- 1S-2S plus mixing in electric field
- 2P-1S Lya photons
- Velocity resolved spectroscopy
- Useful atoms: around 100 m/s

PRL 107 (203001) 2011 C.G.Parthey et al.

50 m/s @ 100 mK

We need cold antiH if we want to trap it

$$U = -\vec{\mu} \cdot \vec{B} = \pm \mu B$$

$$F = \vec{\nabla}(\vec{\mu} \cdot \vec{B}) = \mp \mu \vec{\nabla} B$$

$$\omega << \mu \frac{B}{\hbar} \quad \Rightarrow B_{\min} \neq 0$$

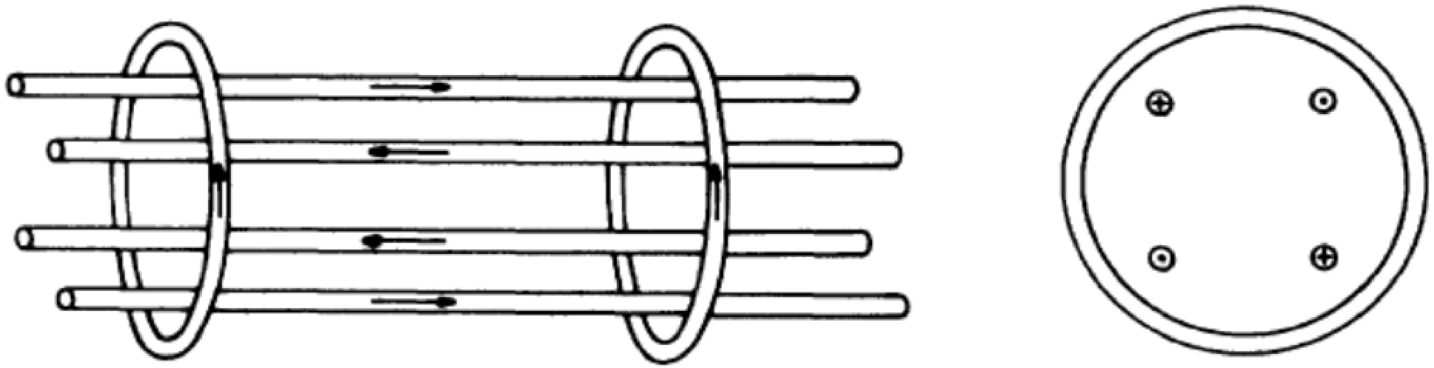
$$\mu = 670 \ \ mK / T$$

$$\Delta B \approx T \qquad \Delta r \approx cm$$

Not uniform magnetic field with a minimum B_{min}

Adiabatic condition: frequency of the motion << Larmor frequency (spin flip)

The orientation of the spin is maintened



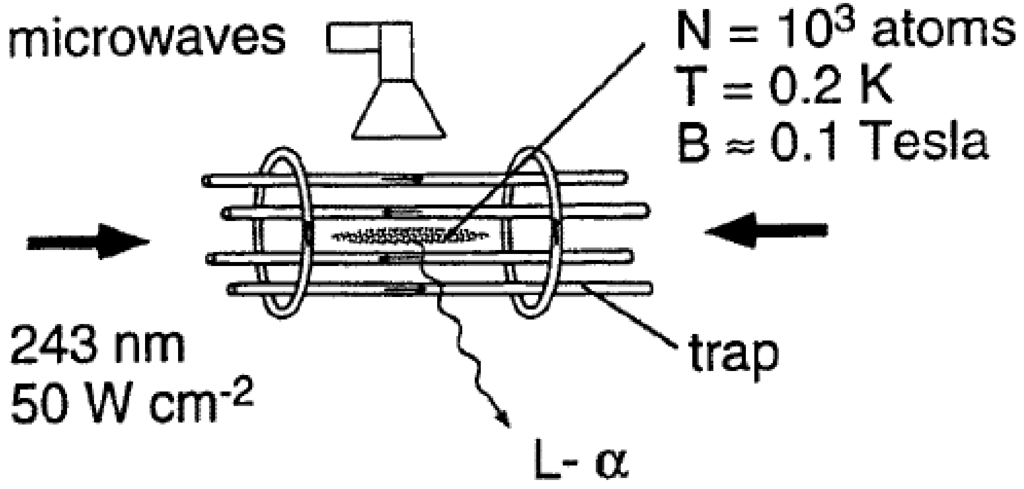
Quadrupolo Joffe Pritchard

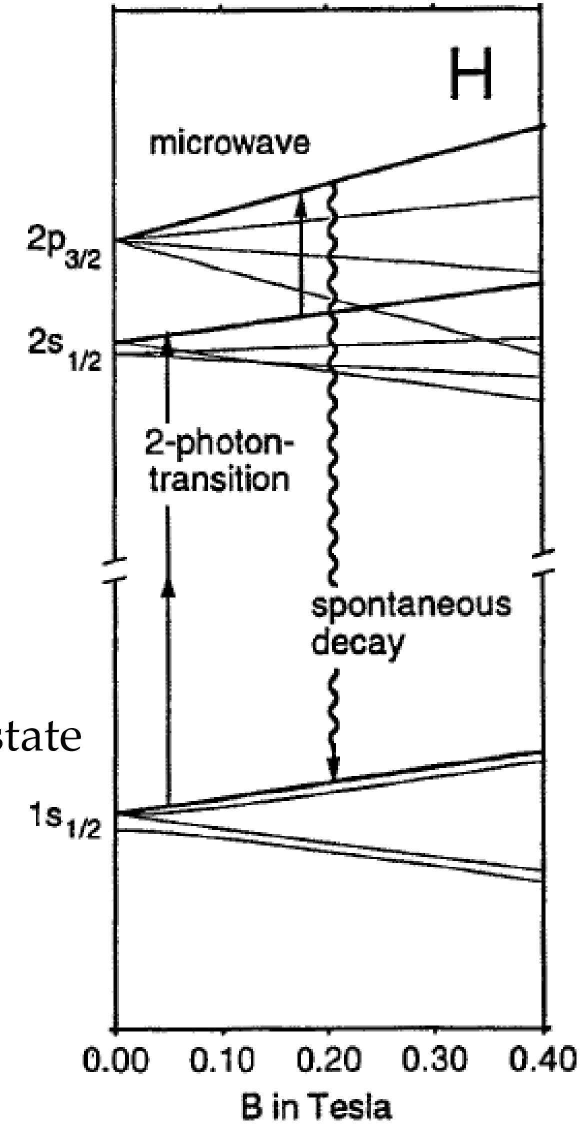
- Trap depth: few hundreds mK

$$U = \mu \ \Delta B$$

- Need subKelvin antiH for trapping it

1S-2S in a magnetic trap





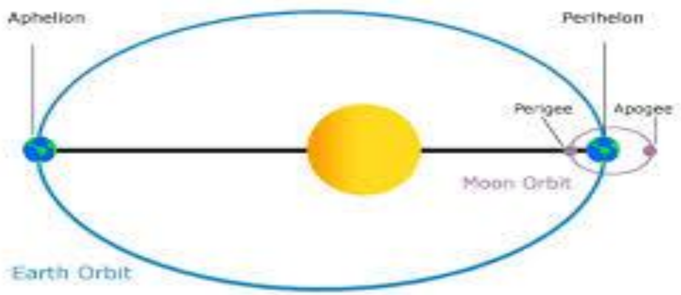
- 1S-2S
- excite with microwaves to $^2P_{3/2}$
- It decays toward the original trapped state
- Detect Lyalpha photons
- Atoms recycled

- 1000 atoms $\Delta v/v = 10^{-12}$
- 1% det eff Ly alpha
- recycle atoms 60 times

T.W.Haensch Hyp. Int. 76 (1993) 47

Annual variation of the 1S-2S transition frequency and equivalence principle

Equivalence Principe $\longrightarrow$ $\frac{\Delta f}{f} = \frac{\Delta U}{c^2}$



$$\frac{\Delta U}{c^2} \approx 3.2 \quad 10^{-10}$$

U changes because the Earth to Sun distance changes during the year

$$\frac{f_{1S-2S}^{\overline{H}} - f_{1S-2S}^{\overline{H}}}{f_{1S-2S}^{\overline{H}}} \approx 10^{-15} \Rightarrow (\alpha_{\overline{H}} - 1) \approx 3\,10^{-6}$$

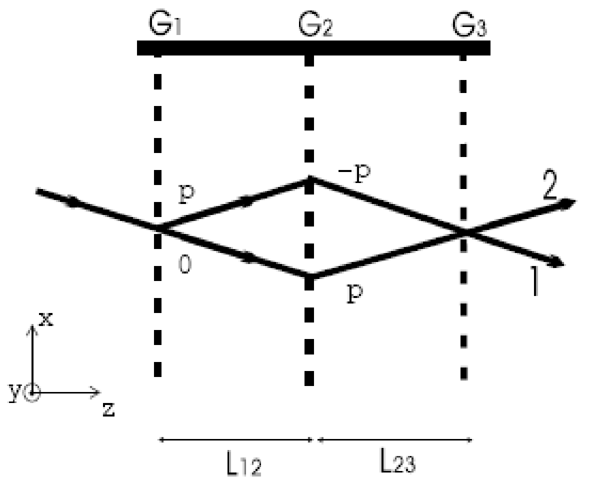
$$\frac{\Delta f}{f} = (1+\alpha_{\overline{H}})\frac{\Delta U}{c^2}$$

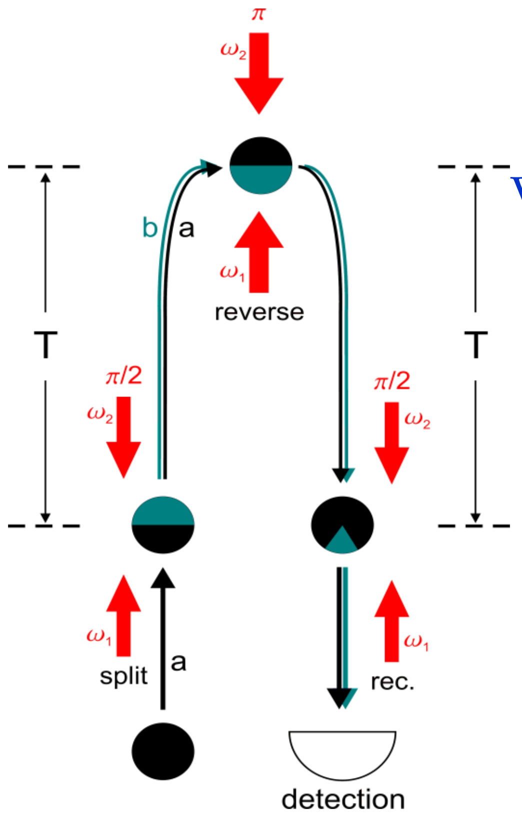
We need cold antiH : g measurement using Atom Interferometry

Matter wave interference:

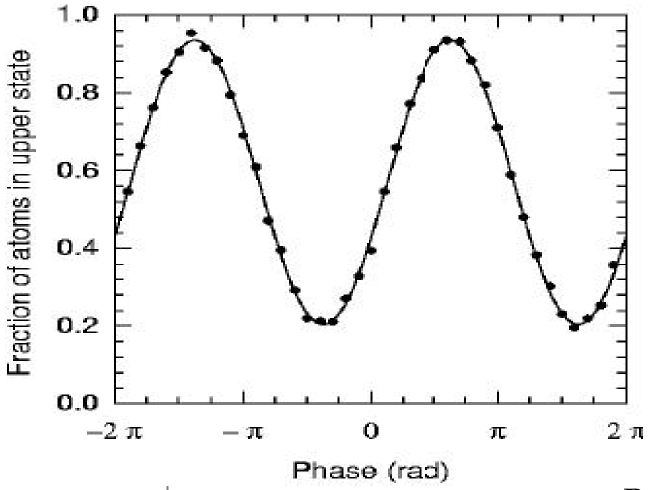
- Material grating
- Light
- Light and change of internal state population

-Split and recombination of cold atomic beams
-Interference pattern -
Phase shift due to gravity





Very cold Cs atoms: μK ..nK



$$\Delta\Phi_g = k_{eff}\, g\, T^2$$

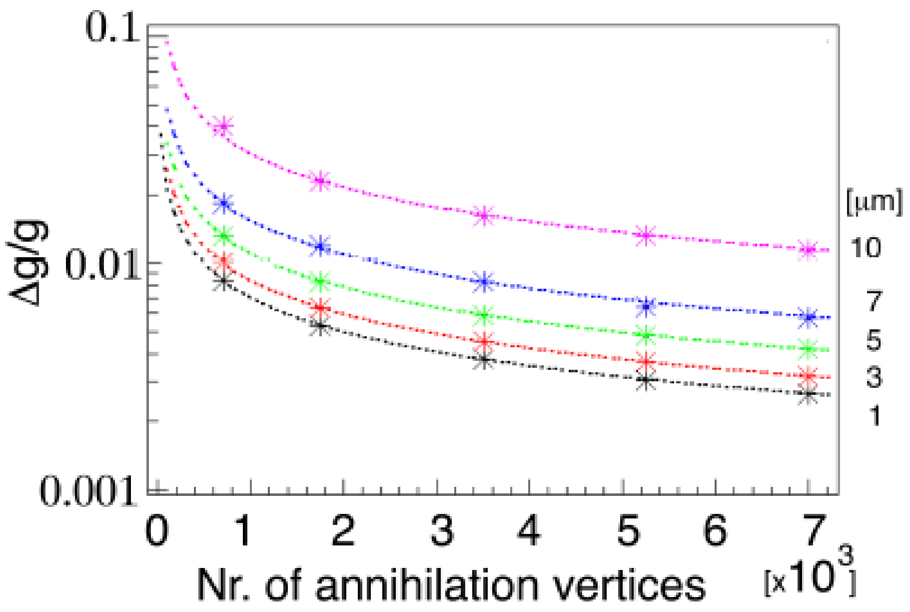
$$\frac{\Delta g}{g} \propto 10^{-10} \propto T^2$$

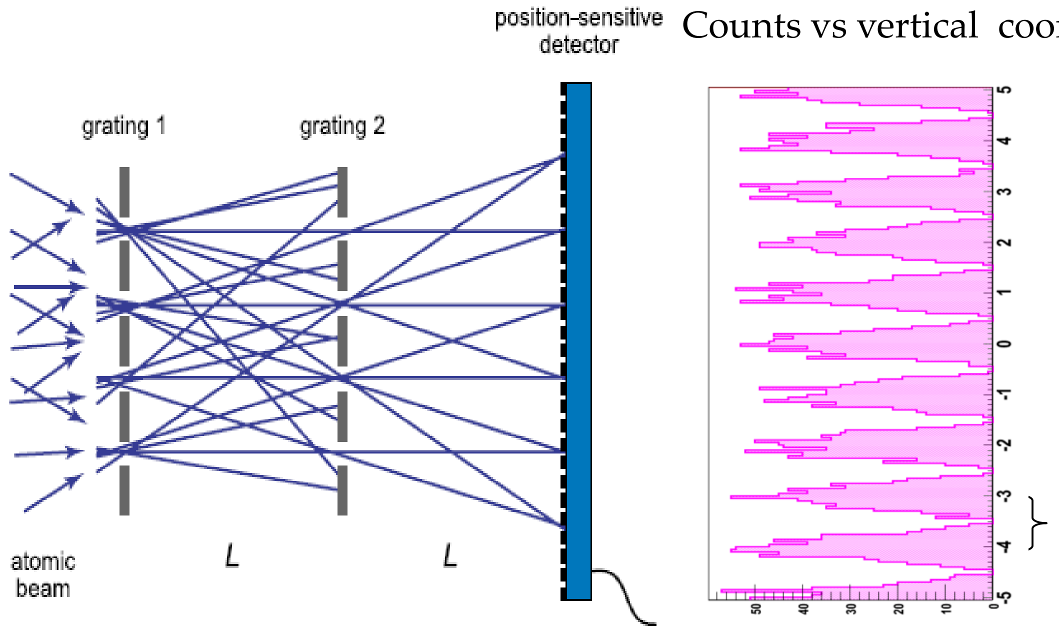
A. Peters et al, Nature 400 (1999) 849

Classical moire deflectometer: AEgIS

- Hbar beam (few 100 m/s; 100 mk transverse energy)
- moiré deflectometer

Grating period a : few tens μm
High resolution position detector : few μm (silicon + emulsion)
Shift of the periodic pattern due to vertical forces (gravity)





L=few tens cm

Phase shift

$$\Phi(T^2) - \Phi_0 = \frac{2\pi}{d} g T^2 = k g T^2$$

AEgIS Coll. Nature Comm 5 (2014) 4538
AEgIS Coll 29 (18) 184009 (2012)

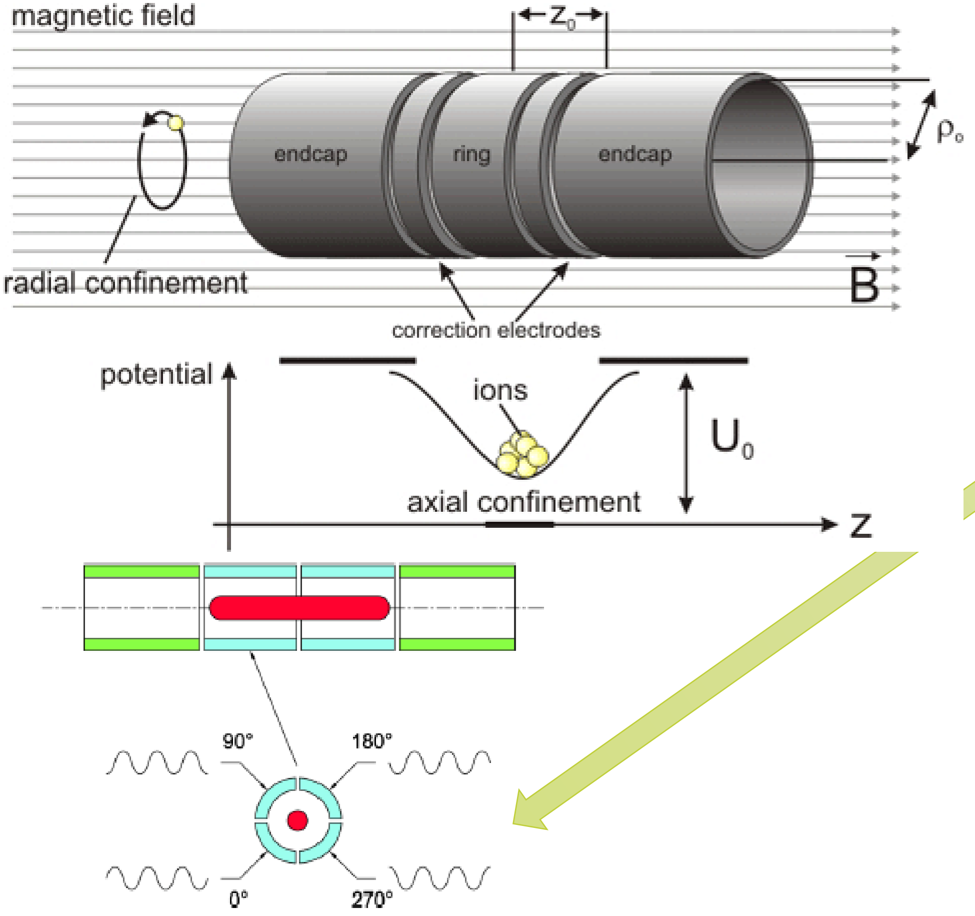
Forming cold anti-Hydrogen

- Make antihydrogen from cold antiprotons and positrons:
  cooling (ultracooling) of charged particles

- Cool antihydrogen once is formed (laser cooling, Stark manipulation…)

Charged particles are manipulated using traps

Antiprotons, positrons confined, accumulated, manipulated and cooled in electromagnetic traps



Radial compression of the Trapped plasma with RF field: Rotating Wall

- radius: 0.5-2 cm
- lenght: about 2 m in AEgIS
- B   5 T, 1T   0.1 T in the e+ accumulation region
- Volts or tens of KV, static or pulsed
- RF signals for manipulation
- Cryogenic (4 K-10 K) environment
- AEgIS will go to 100 mK
- Pressure P<<$10^{-13,15}$…(no gauges!!)

3 regimes

1) Single particles
2) Many particles: plasma like a gas $\Gamma << 1$
3) Many particles, very cold Coulomb crystal $\Gamma >> 1$

$$E_C = \frac{1}{4\pi\varepsilon_0 \langle r \rangle}$$

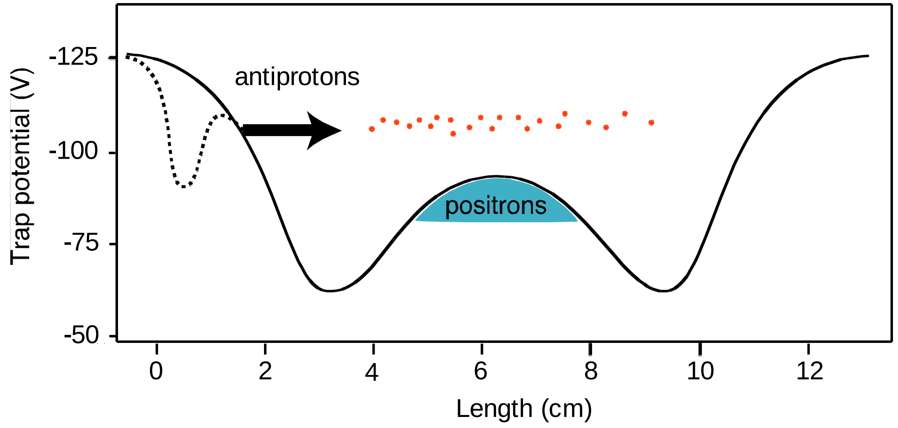
$$\langle r \rangle = \frac{1}{\sqrt[3]{n_e}}$$

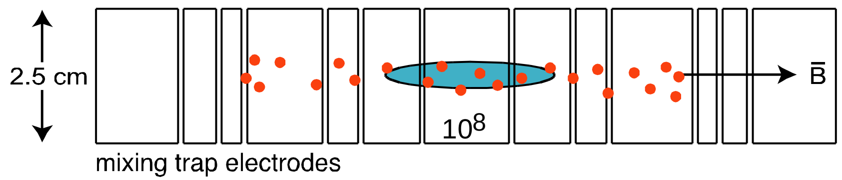
$$\Gamma = \frac{E_C}{K_B T}$$

AntiH formation

First results in
M. Amoretti et al. (ATHENA Collaboration)
NATURE 419 (2002) 456

1) Recombination of e+ pbar in cold trapped and merged plasmas (ATHENA; ALPHA; ATRAP; ASACUSA)





- 10^4-10^5 antiprotons
- 10^7-10^8 e+
- 10 - 4 K
- 15% of the pbar recombines
- Initial peak and then recomb. for tens of sec
- Continuos production

a) Radiative recombination $\bar{p} + e^+ \rightarrow \bar{H} + h\nu$

Populate low n (n<10)

$$R \propto n_{e^+} T_{eff}^{-1}$$

b) 3 body recombination $\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$

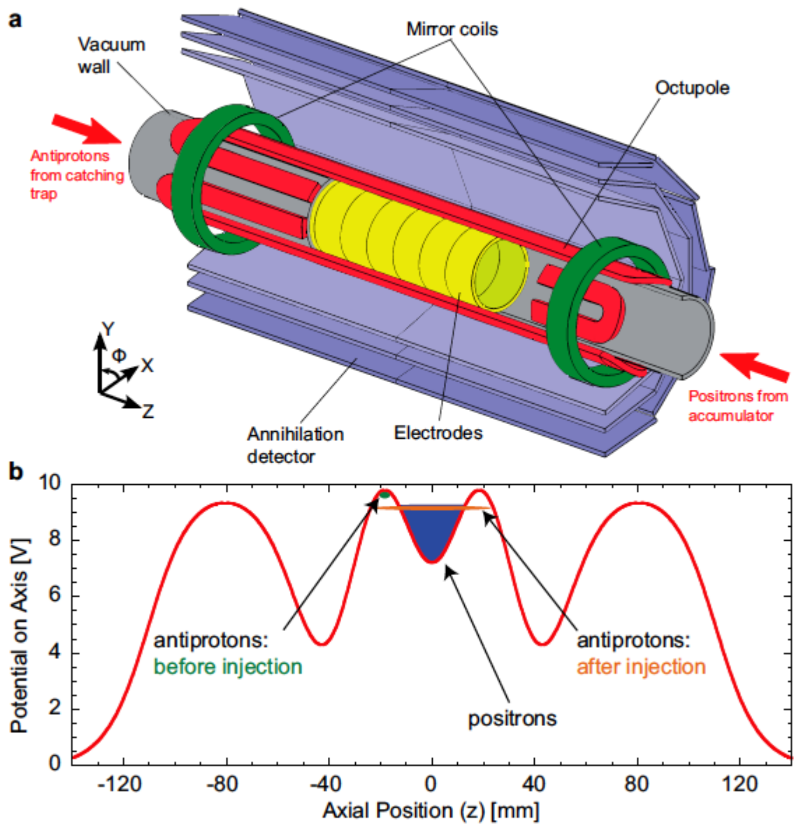
Populate high n, ionization by collisions and field ionization)

$$R \propto n_{e^+}^2 T_{eff}^{-9/2}$$

1) 3 body dominates
2) Pbar energy higher thant e+ energy
3) Cooling, recombination before thermalization
2) Antih energy= Pbar energy at recombination
3) antiH temperature: tens –hundreds Kelvin
3) Big efforts in reducing the injection energy (ALPHA)

AntiH Trapping (ALPHA and ATRAP)

G. Gabrielse et al., (ATRAP Coll) PRL 108 113002 (2012)
G.B.Andersen et al., (ALPHA Coll) Nature Phys. 7 558 (2011)



Example: the ALPHA setup

- Surround the nested trap with a trap for neutral
- Not uniform magnetic field makes the charged plasma unstable
- May prevent getting very cold plasma

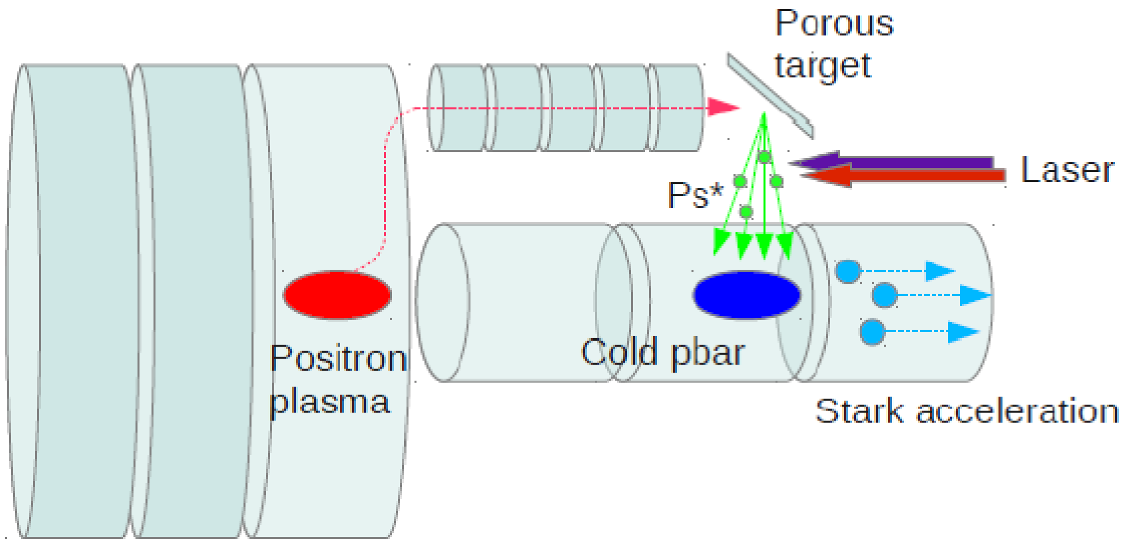
M. Amoretti et al, Phys,. Lett. A (2006) 360 (1) 141

- Use high order multipole field to mitigate the effect
- Trap depth for neutral: few hundreds mK
- Mix antiprotons and positrons
- Trap the coldest Hbar : **4 trapped anti-atoms/hour ALPHA**
- **5+- 1 trapped antiH/ 2 hour ATRAP**

Storage time very long : up to 1000 sec

AntiH formation: charge exchange between Rydberg positronium and antiprotons (AEgIS)

- Pionereed by ATRAP
- It is the key method for AEgIS



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

- Cool antiprotons in a trap
- **Do not move them during the Hbar formation**
- Form Rydberg positronium n=18-20…

- Temperature of Hbar: temperature of pbar
  2 mK due to kinematics

High cross section for low velocity Ps*
(need Ps* with about 10^4 m/s)

$$\approx 10^{-9}\, cm^2 \;@\; n_{Ps} = 18 \quad v = 10^4 \quad m/s$$

$$\approx 8\, 10^{-9}\, cm^2 \;@\; n_{Ps} = 18 \quad v = 3\, 10^3 \quad m/s$$

G. Testera et al., to be published

- Predictable n state distribution
- Ps shot is pulsed (few tens ns)
- AntiH formation is pulsed

Make a beam using Stark forces on Rydberg (anti)atoms : AEgIS

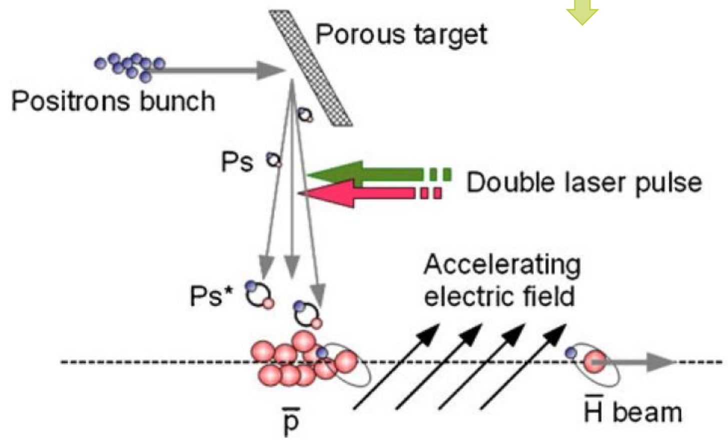
Stark Forces on Rydberg atoms:

T. Breeden, J. Metcalf PRL 47 (1726) 1981

- ➢Acceleration,
- ➢Deceleration,
- ➢Trapping

Demonstrated with Hydrogen (ETH, F. Merkt group)

PRA 76 (2007) 023405



Energy levels of Hydrogen in electric field F (AU)

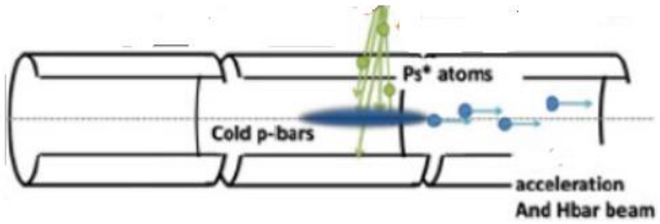
$$E = -\frac{1}{2n^2} + \frac{3}{2} nkF$$

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

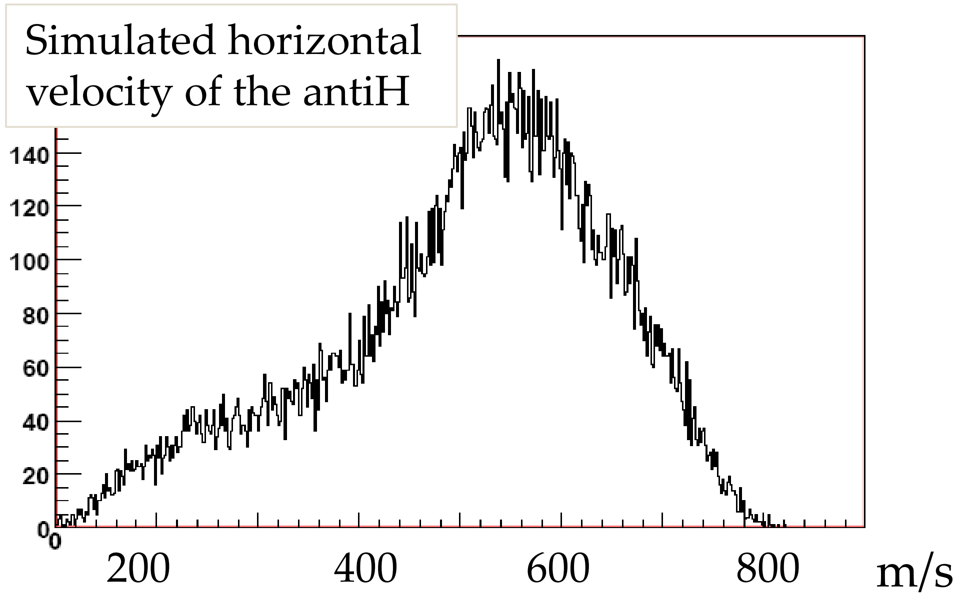
(n,l,m) n, n_1, n_2, m $k = n_1 - n_1$

- Δv of several 100 m/s within about 1 cm (n=20-30)
- Electric fields: few 100 V/cm
- limited by field ionization: crossing of the Stark states traversed diabatically
- Some complication due to magnetic field

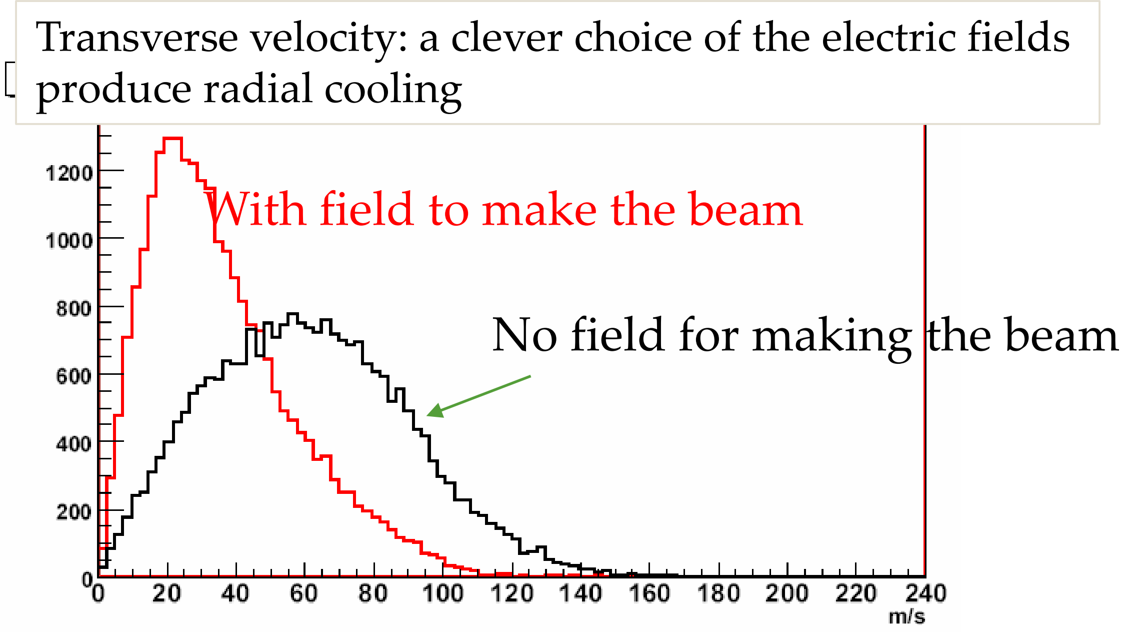
A pulsed antiH beam in AEgIS



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



- Simulation with 100 mk antiprotons
- Apply proper voltages to sectors of the trap electrodes after Hbar formation



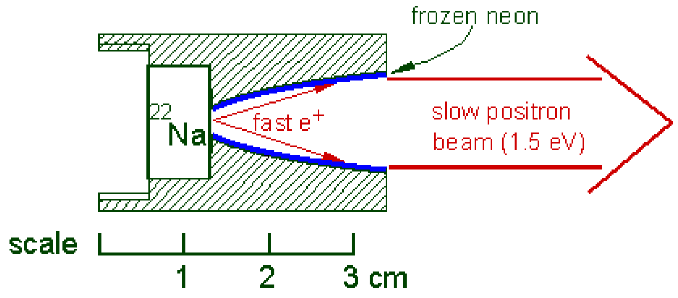
- g measurement: primary goal

- Transport Hbar and trap in a region separate from the production region (under study)

G. Testera et al(AEgIS Coll) AIP Conf Proc. 1037 (5) (2008)

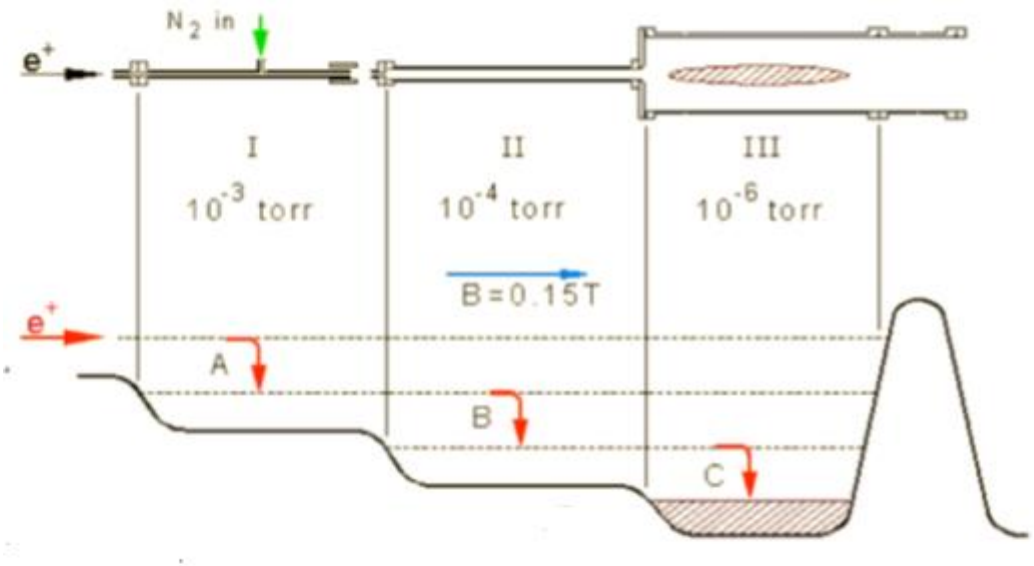
Preparing the Hbar ingredients: positrons

^{22}Na source
Continuous emission of e+ with high energy
Moderation through solid neon



Eff 0.7%
Spectrum FWHM=0.58 eV

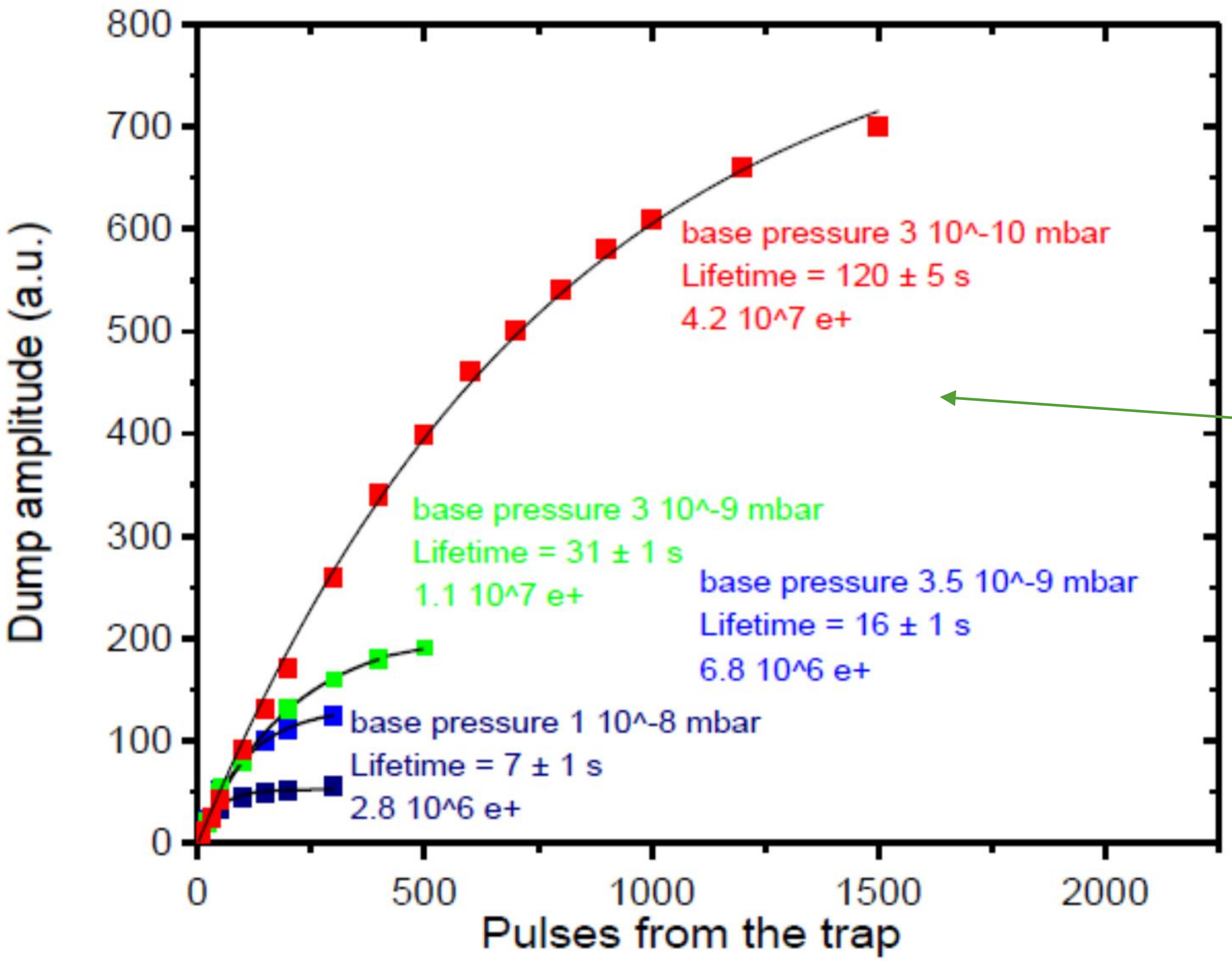
The basic idea



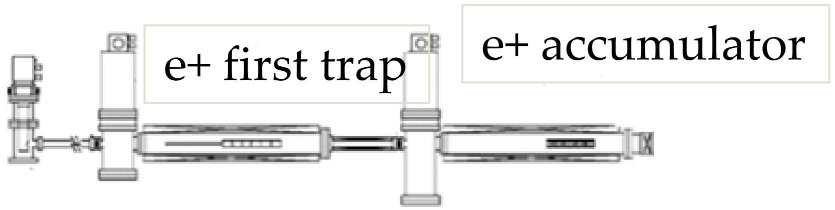
- Buffer gas cooling plus transfer in UHV trap
- Accumulation in a trap in UHV with B=0.1-0.15 T
- Radial compression of the cloud (RW)
- 1-1.2 10^8 positrons in few minutes

It is used by all the present AD experiments
GBAR (next years): install a LINAC source + trap for accumulation
expected 3 10^{10} e+ in trap every 110 sec

Example: Positrons data in AEgIS



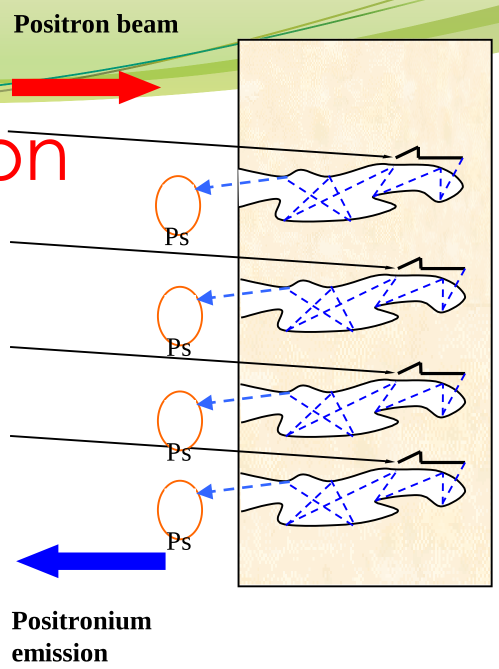
- Source activity (now)= 14 mCi
- we expect 1.2 10^8 e+ with 50 mCi source

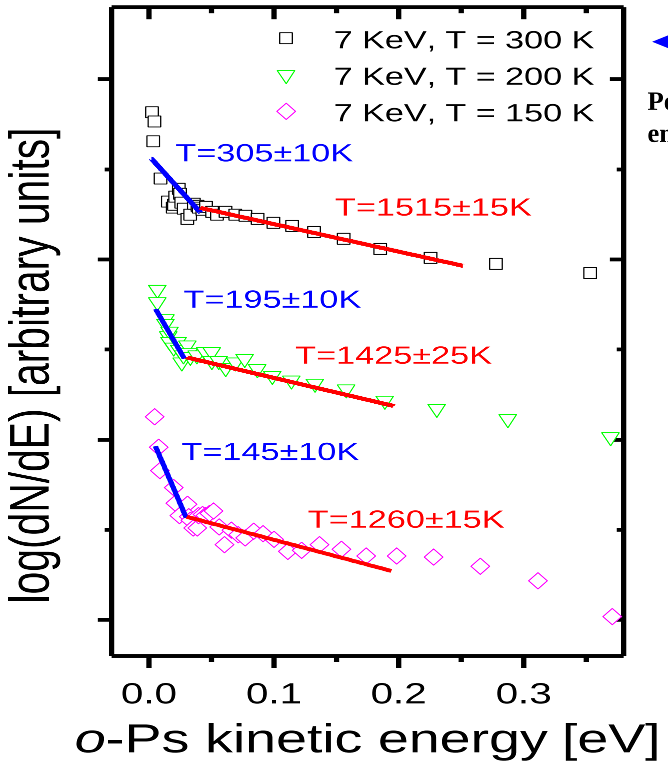


Preparing the Hbar ingredients: Positronium formation

- Implantation of e+ in a nanoporous material (converter) SiO_2 on Si substrate
- Tunable nanochannel size: few nm to few tens ns
- Formation of Ps (eV energy)
- Cooling inside the pore and the channels
- at 7 keV 27 % of implanted positrons escape into the vacuum as *o*-Ps
- Ordered and disordered channels studied in AEgIS

Laser excitation of Ps to Rydberg states outside the converter



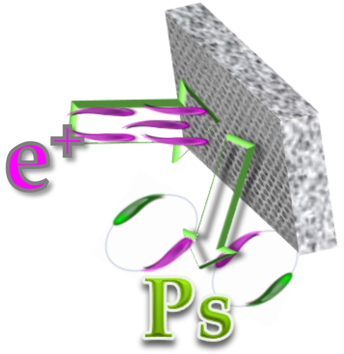


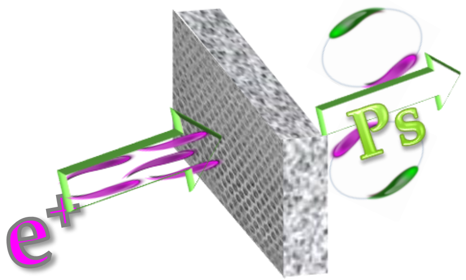
Observed cooling by collisions with pore walls
5-8 nm channels
2-3% Ps thermalized with the target

Mariazzi S. et al., *PRL 104 (2010) 243401*
G. Consolati et al., Chemical Society Reviews, **43** (2013) 3821

What next about positron and positronium

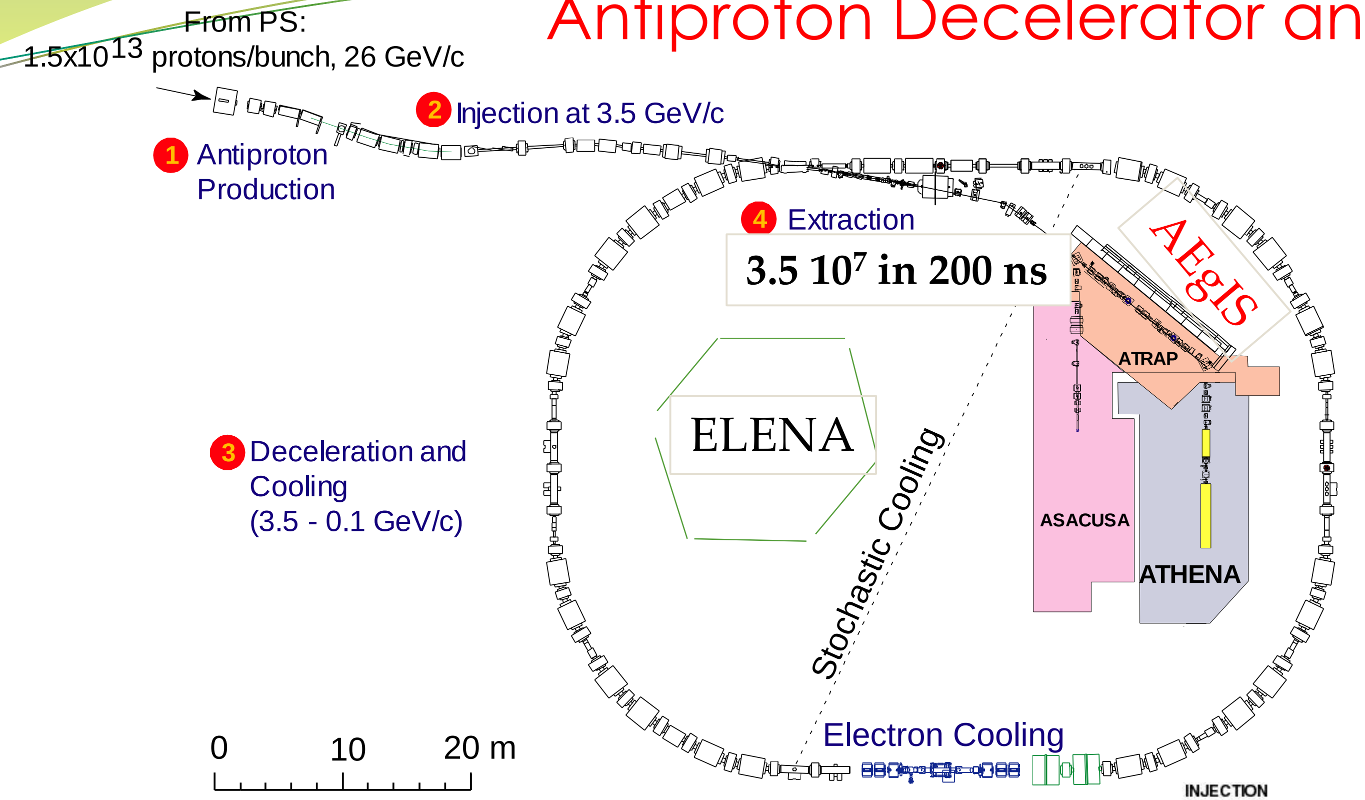
- Increase the number **of cold** positronium: optimization of the targets
- Use trasmission target
- Direction of the emission from the target
- More intense sources : LINAC?





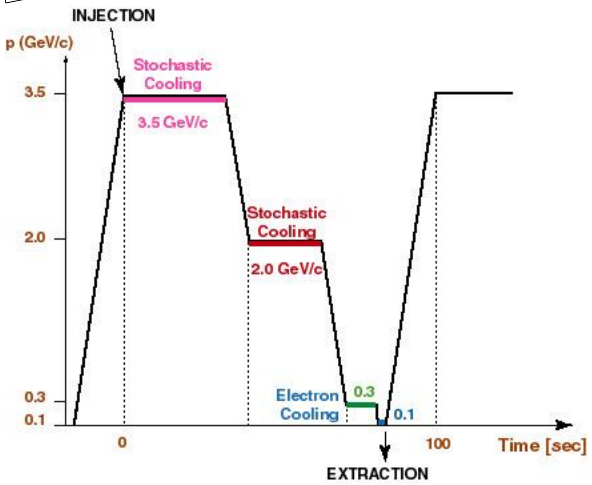
- Laser cooling of Ps: compression and deceleration before the interaction with pbar
  laser cooling of Ps in fundamental state
- Use Ps reflection
- Use electric field to compress Rydberg Ps

Antiproton Decelerator and ELENA at CERN

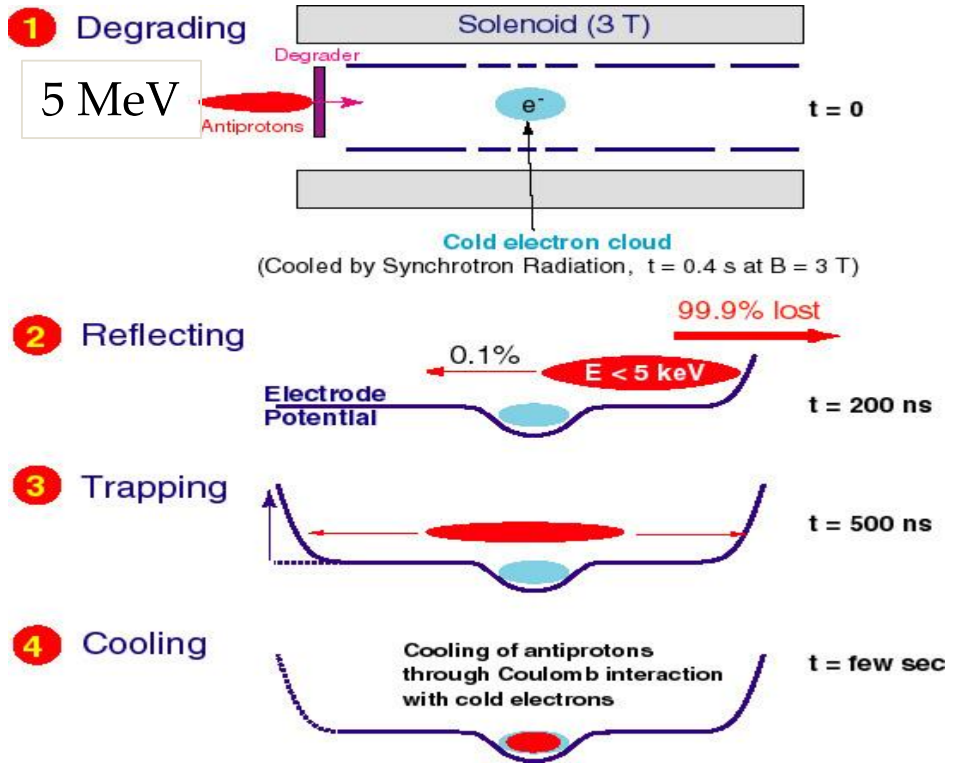


- From 2017-2018: ELENA:
- New ring inside AD
- Antiprotons @100 keV
- 4 bunches
- More than a factor 100 increase of the
- usable antiprotons

Decleration+ phase space compression
3.5 10^7 in 200 ns antiprotons
100 sec rep. Rate
5 MeV kinetic energy

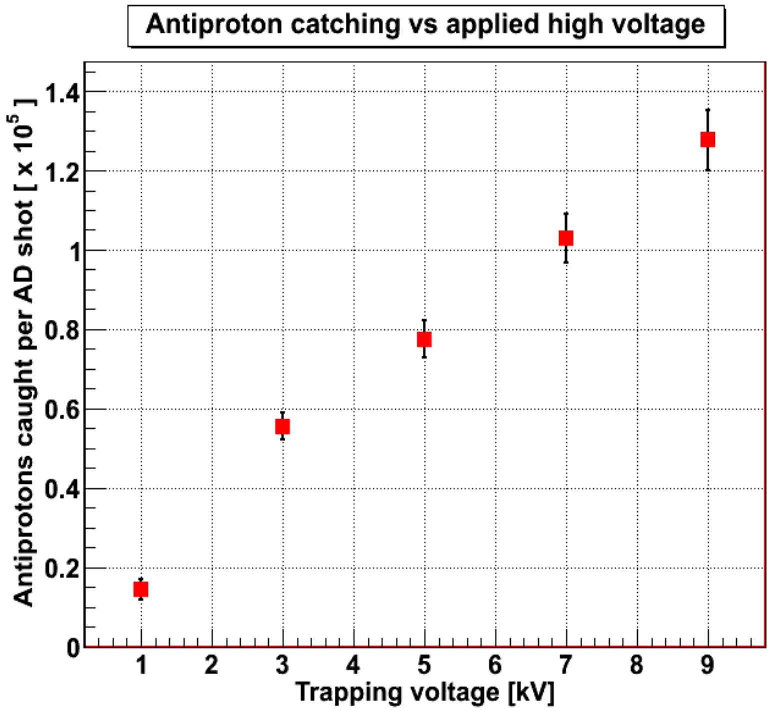


Preparing the antiH ingredients: trapping antiprotons



Trap in flight after traversing a degrader
Pulsed electrodes (several KV) in few tens ns
Used by all the experiments but ASACUSA

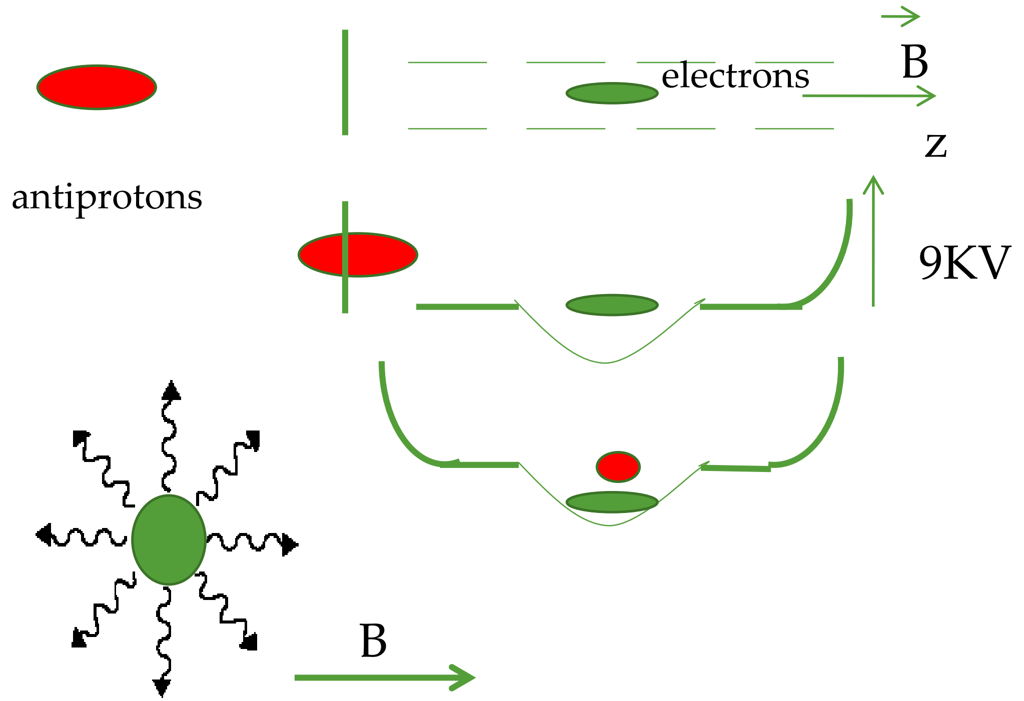
Example of trapped antiprotons in AEGIS



$1.3\ 10^5$ /shot

WHAT next: increase the number of trapped antiprotons
by a factor 100
with ELENA

Antiproton cooling : electron cooling

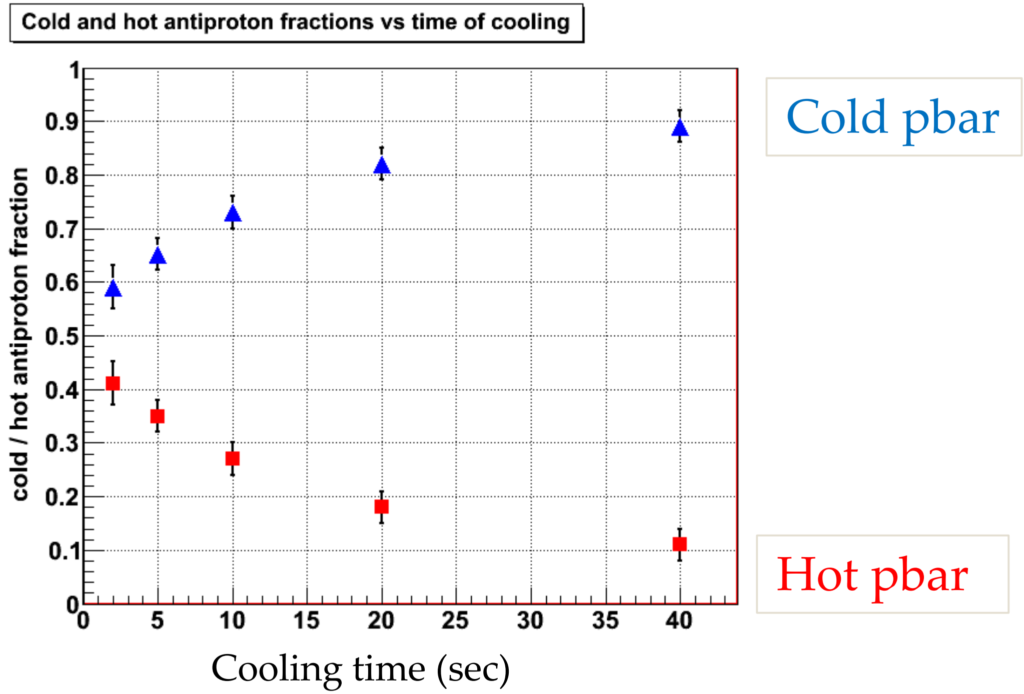


e- (and also positrons)
radiation in high magnetic field (cyclotron cooling)

$$T = T_{iniz} e^{-t/\tau_{rad}} + T_{trap}$$

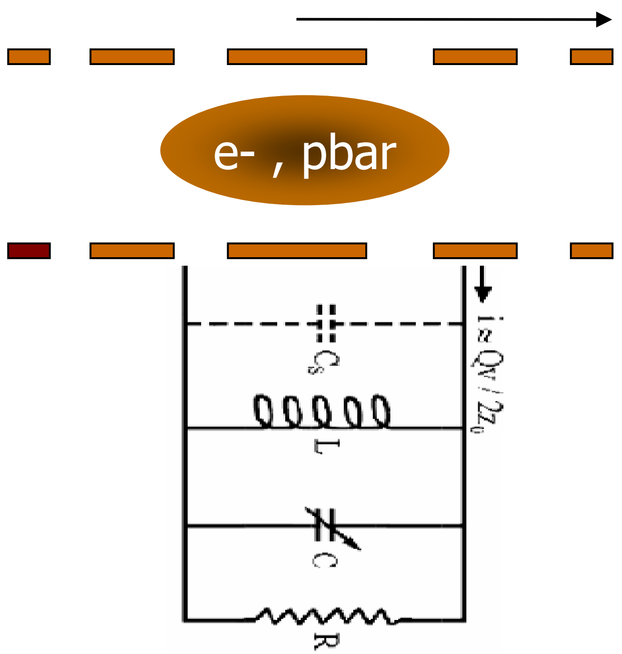
$$\tau_{rad} \propto \frac{m^3}{B^2}$$

e^-, e^+	$\tau_{rad} \cong 0.1 \sec @ 5T$
$\bar{p}$	$\tau_{rad} \cong 10^9 \sec @ 5T$



Cyclotron radiation + Coulomb collisions
= thermal equilibrium for e- and pbar

Antiproton ultra-cooling in AEgIS: toward subK antiprotons (100 mK..)



$$T = T_{iniz} e^{-t/\tau_{rad}} + T_{trap}$$

Make the trap colder and colder

Traps in 100 mK region (dilution refrigerator)

e- radial energy: quantum limit 800 mK@ 1 T
400 mK@ 0.5 T

$$n_c + \frac{1}{2}\hbar\omega_c$$

Add an additional cooling mechanism:

- Resonant circuit removing energy form the axial electron motion of the electrons
- The axial temperature of the electron reach 100 mK
- Antiprotons cooled by Coulomb collision
- Tech development: high noise and low power cryo-amplifier
- Plasma physics: energy exchange at low energy in magnetic field

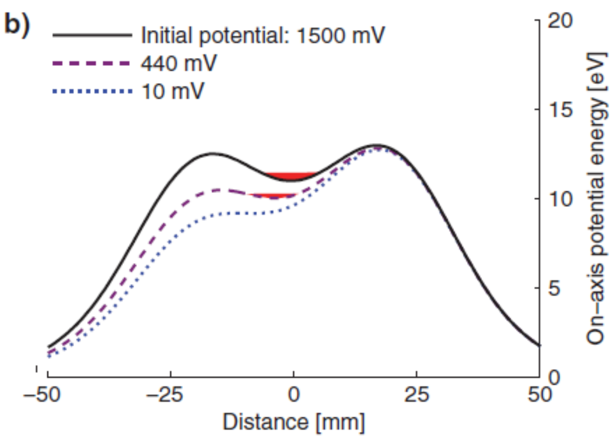
Toward sub-Kelvin resistive cooling and non destructive detection of trapped non-neutral electron plasma
S. Di Domizio, D. Krasnický, V. Lagomarsino, G. Testera, R. Vaccarone and S. Zavatarelli
JINST 2015 *JINST* **10** P01009

Antiproton ultracooling

1) Evaporative cooling of antiprotons: 9 K

2) Adiabatic cooling (no losses) 3.5 K

ATRAP Coll., PRL 106, 073002 2011)



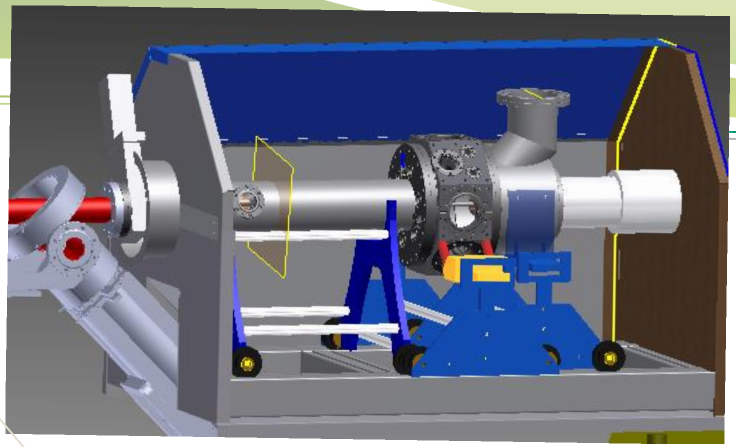
ALPHA Coll.(PRL 105,013003 2010)

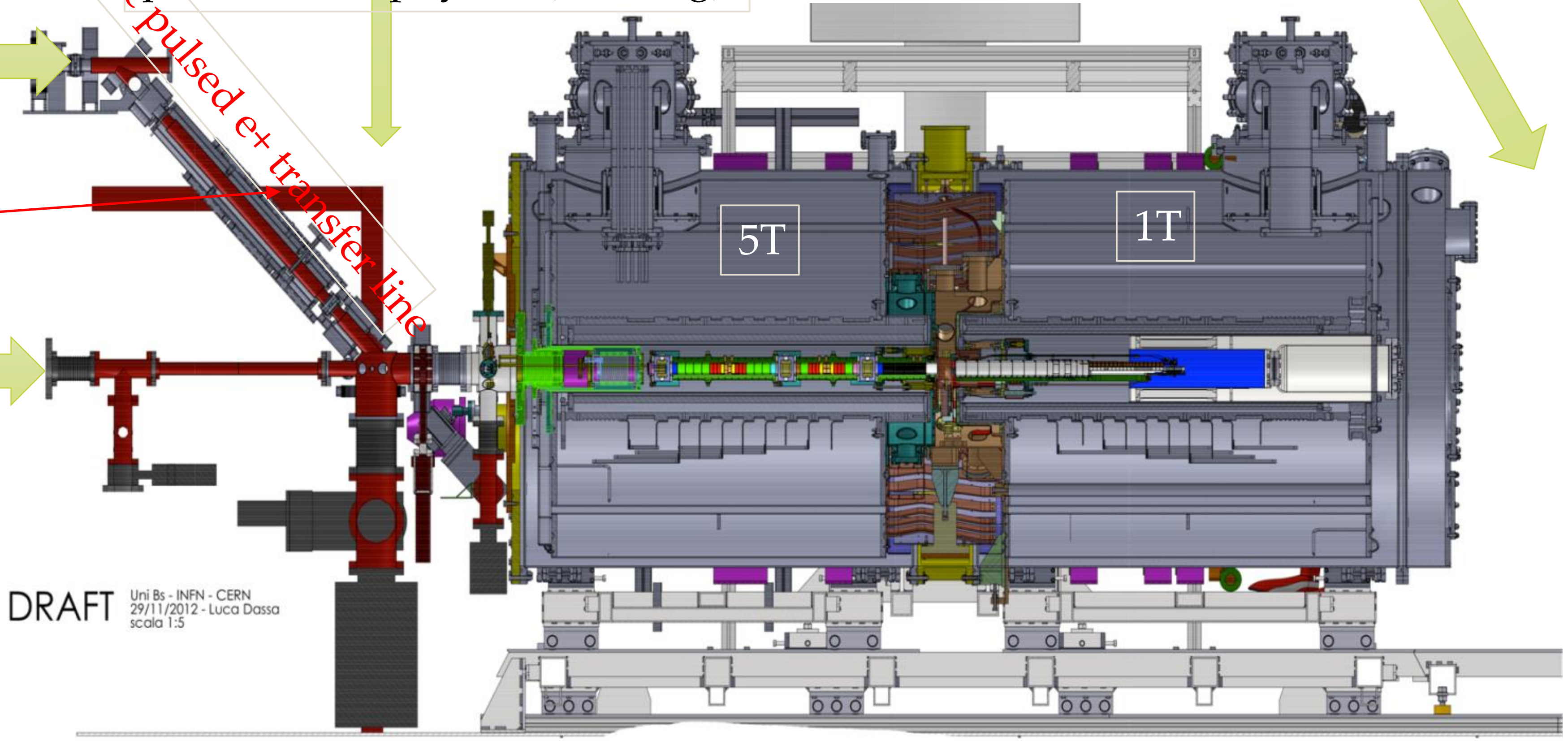
3) Trap antiprotons and negative ions together
Evaporative cooling of negative ions by photodetachment
Sympatetic cooling of antiprotons

K. Blaum et al, WAG 2013

4) Go to sub-mK antiprotons:
Trap antiprotons and negative ions or negative molecules
LASER cooling of negative ions or molecules
Sympathetic cooling of antiprotons
(see next talk)

The AEgIS setup installed at CERN





Conclusions

- Physics goal is clear: high precision CPT and WEP tests
- We need cold antiH: mK range or colder (μK)
- Production by charge exchange seems to be the best way
- Pulsed production, formation of a beam (not monochromatic): measure velocity by TOF
- Key points: ultracooling of antiprotons
  Optimisation of positronium formation and manipulation
- Transport antiH by Stark forces and trap it in a magnetic trap (not discussed here)

CERN is improoving the pbar source, 5 int. Collaborations, high competition