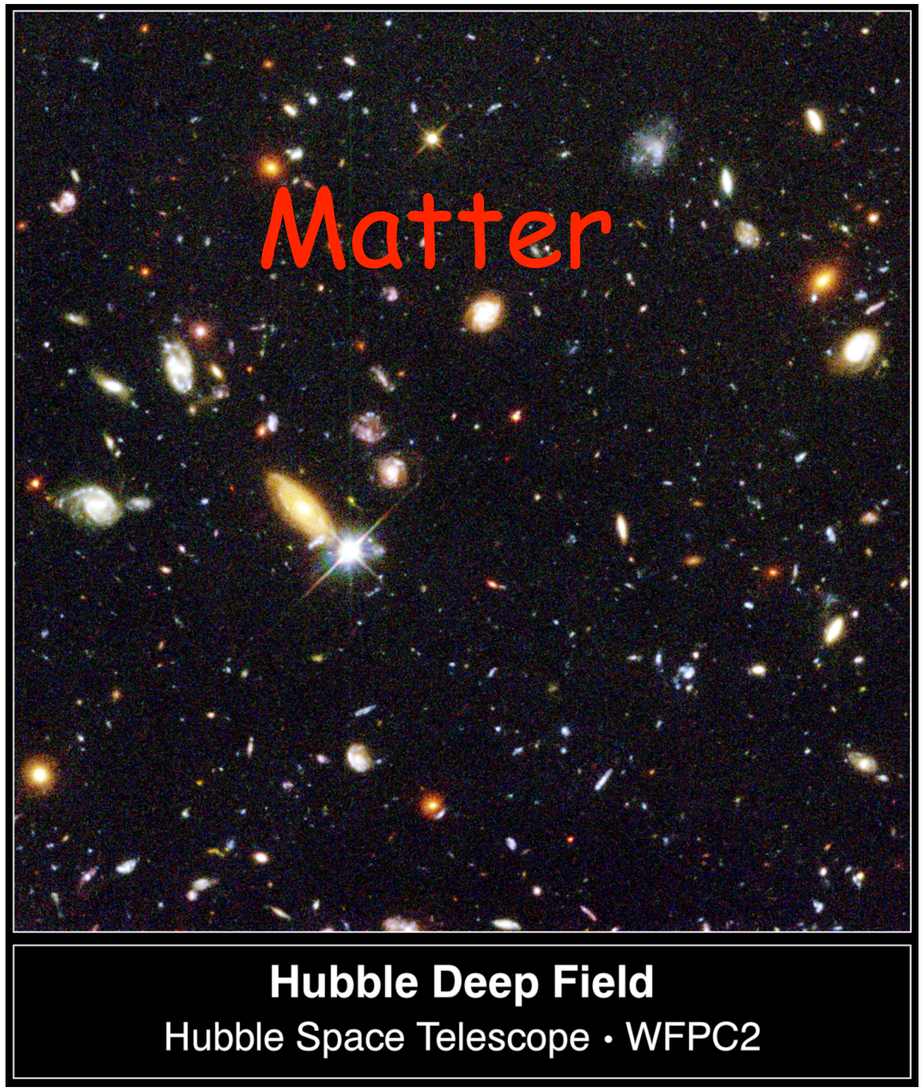
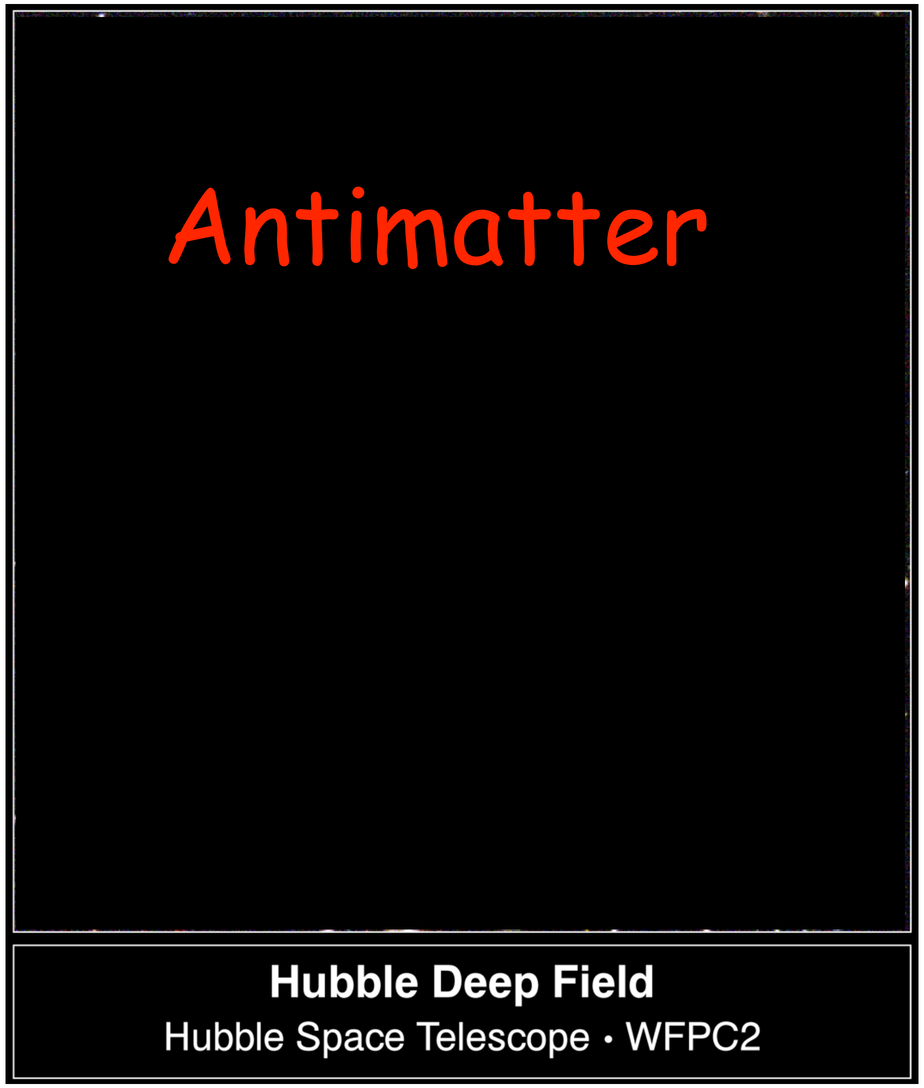
Roads into the Anti-world

Michael Doser
CERN

Observational fact: the Universe is unexpectedly *not* symmetric





Why is the Universe lopsided?

How can the absence of antimatter be explained?

Baryon asymmetry

Search for antimatter

Antiprotons, positrons in cosmic rays;
Positron-electron annihilation in space

Study antimatter

Investigate symmetries and
try to find an asymmetry

use (accelerator, detector) technologies to:

produce and trap stable (anti)particles,
[combine them to form (anti)atoms]
carry out precision measurements of their properties

↓

Search for some form of asymmetry between matter and antimatter : ~~CP~~ and ~~CPT~~

↓

do particles (atoms) have the same properties as antiparticles (antiatoms) ?

Precision measurements with Antimatter:

1) Precise comparison between matter and antimatter

test of fundamental symmetry (CPT - Charge, Parity, Time)

comparing antiprotons with protons, electrons with positrons, and hydrogen with antihydrogen

2) Measurement of the gravitational behavior of antimatter

test of the Weak Equivalence Principle

impossible to work with charged (anti) particles;
only neutral systems (atoms) are sensitive enough

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

CPT & Lorentz violation

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu$$
$$- \tfrac{1}{2} H^e_{\mu\nu} \sigma^{\mu\nu} + i c^e_{\mu\nu} \gamma^\mu D^\nu + i d^e_{\mu\nu} \gamma_5 \gamma^\mu D^\nu) \psi = 0 \, .$$

Lorentz violation

- 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

Weak equivalence principle

- 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

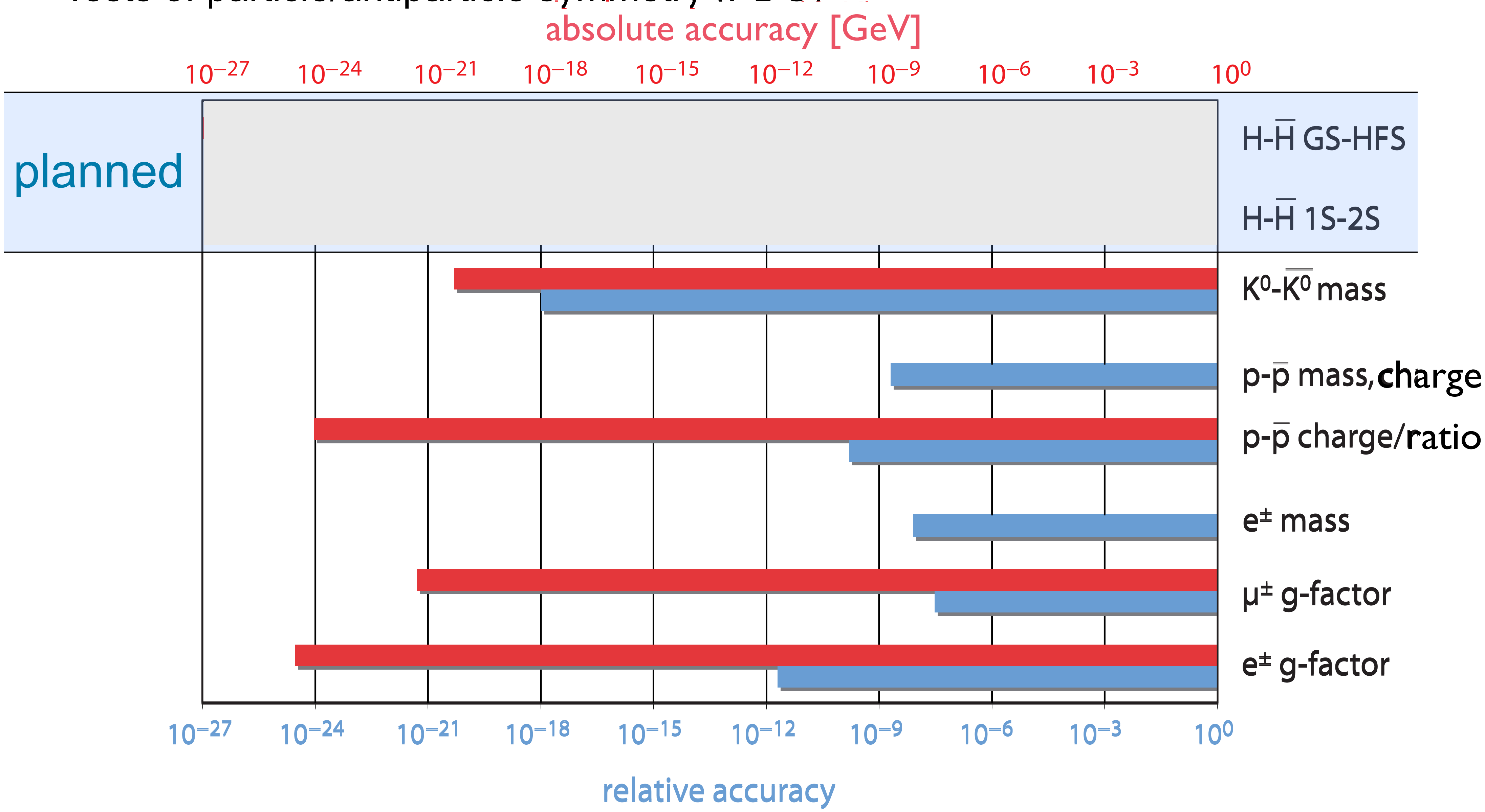
$$V = -\frac{G_\infty}{r} m_1 m_2 \left(1 \mp a\, e^{-r/v} + b\, e^{-r/s} \right)$$

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

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

Verifications of CPT symmetry

Tests of particle/antiparticle symmetry (PDG)

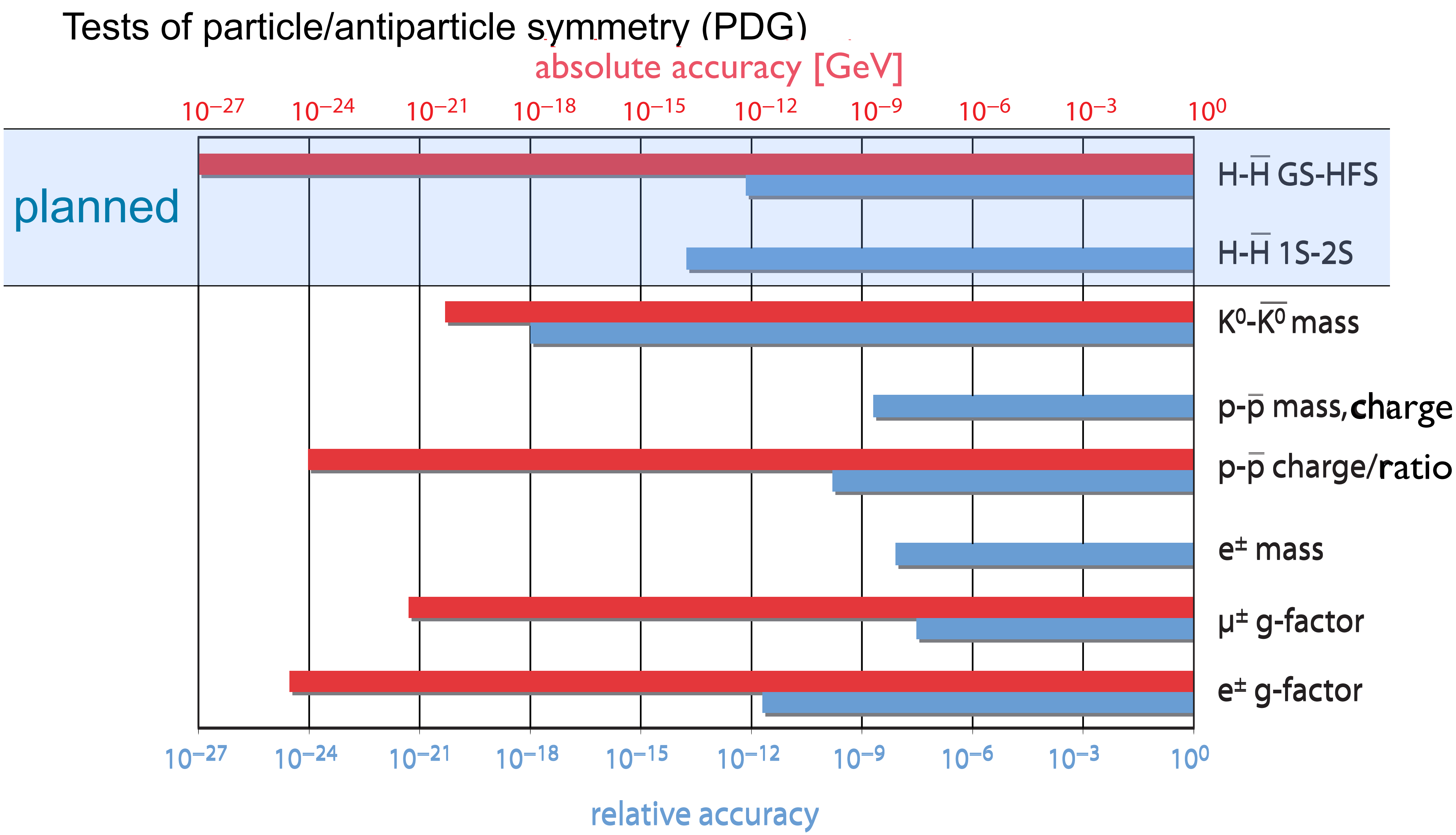


Inconsistent definition of figure of merit: comparison difficult

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

Absolute energy scale: standard model extension (Kostelecky PRL 82, 2254 (1999))

Verifications of CPT symmetry



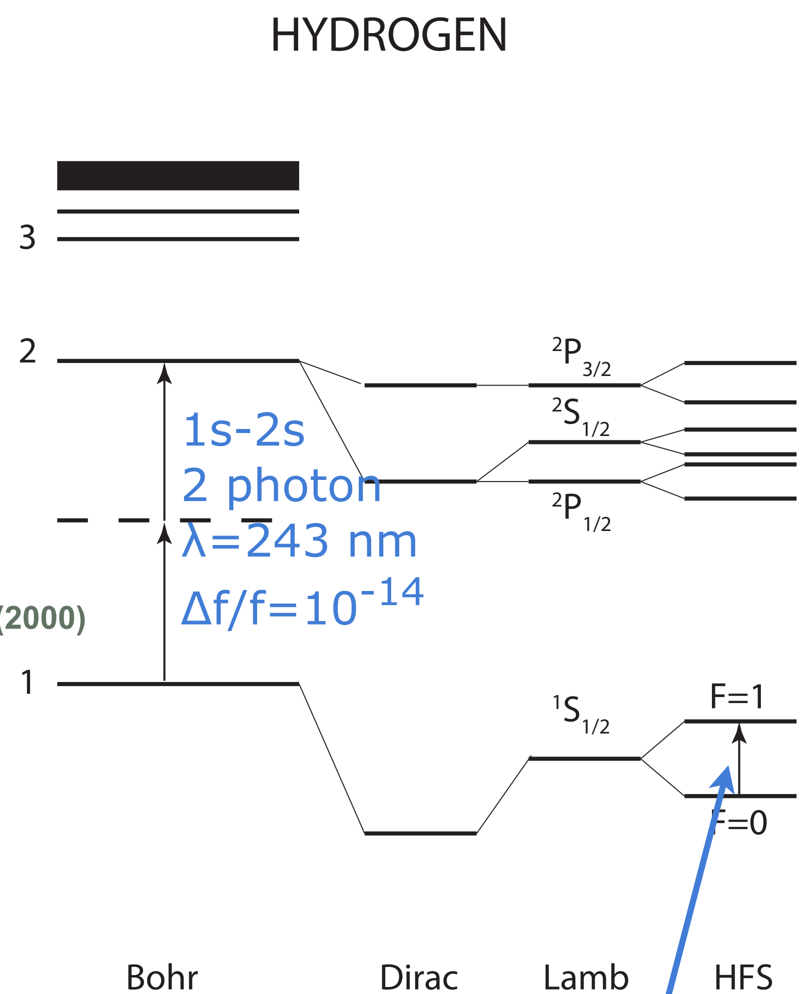
Inconsistent definition of figure of merit: comparison difficult

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

Absolute energy scale: standard model extension (Kostelecky PRL 82, 2254 (1999))

Goal of comparative spectroscopy: test CPT symmetry

Hydrogen and Antihydrogen

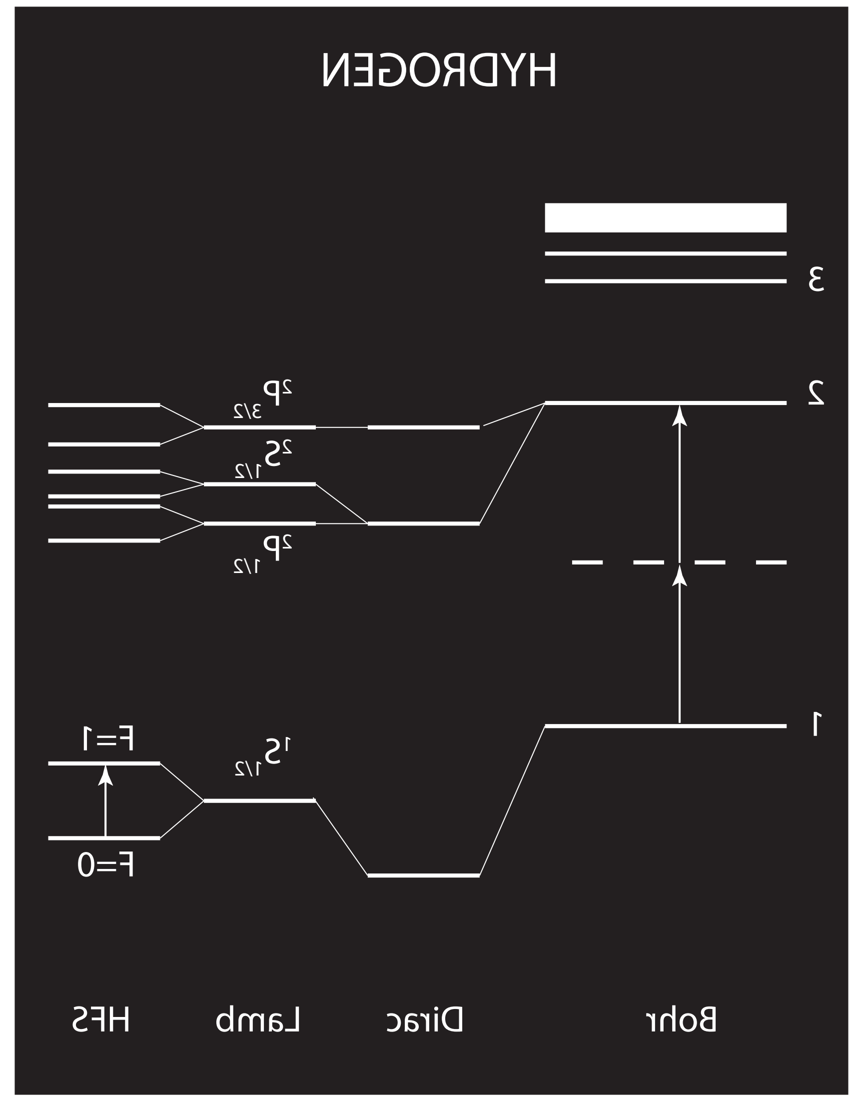


1s-2s
2 photon
λ=243 nm
$\Delta f/f = 10^{-14}$

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)



Summary of results of precision tests with Antihydrogen:

Summary of results of precision tests with Antihydrogen:

This page left intentionally blank

The challenge:

Making Antihydrogen

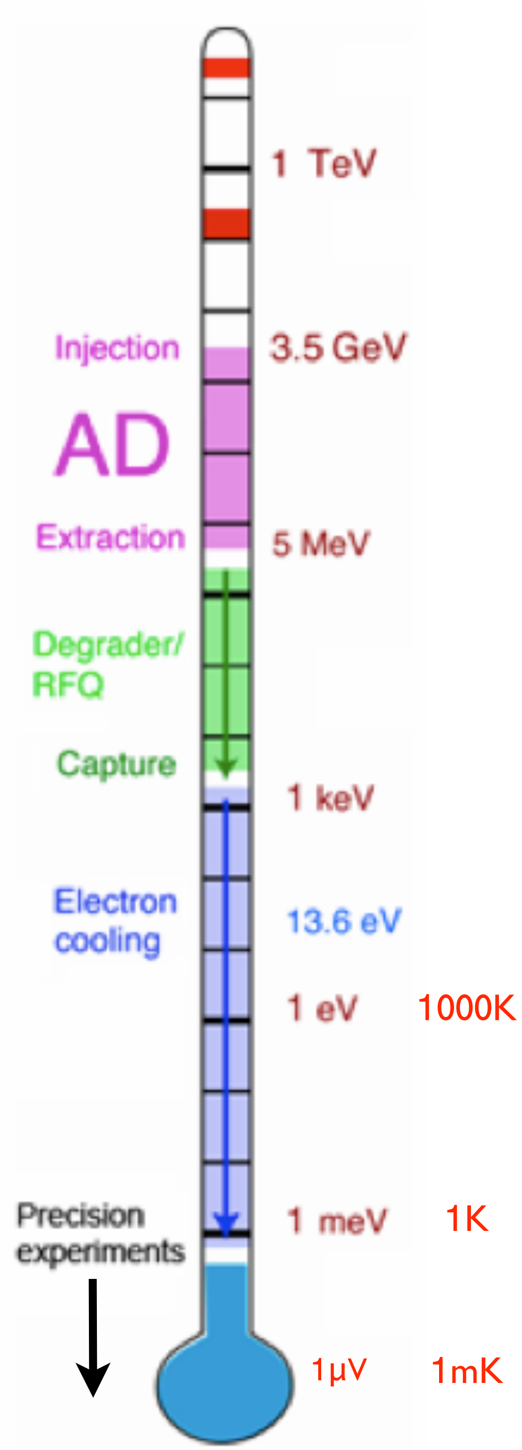
Route A:

Trapping Antihydrogen

Cooling Antihydrogen

Studying Antihydrogen

ALPHA
ATRAP



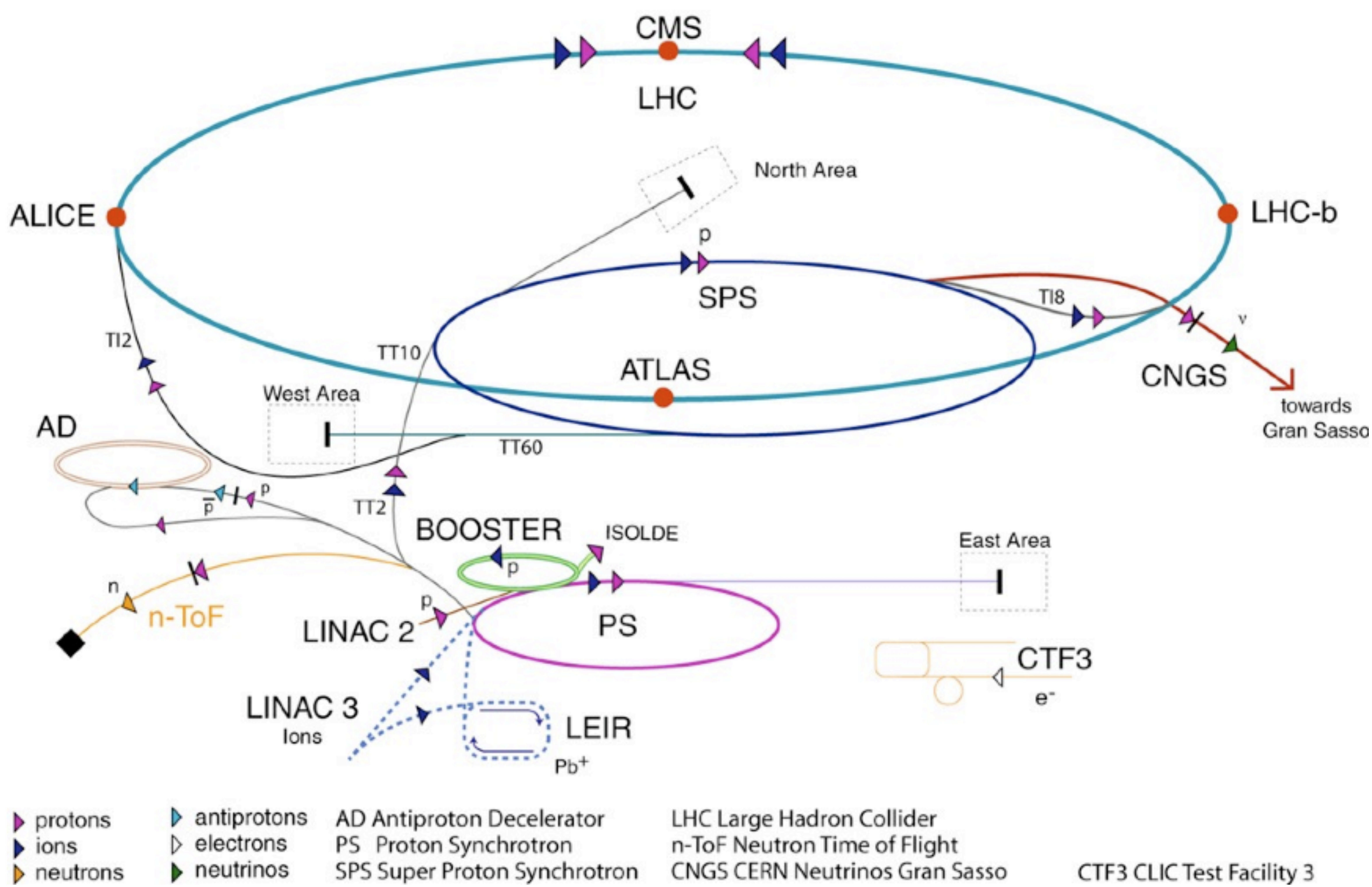
Route B:

Forming a beam
of Antihydrogen

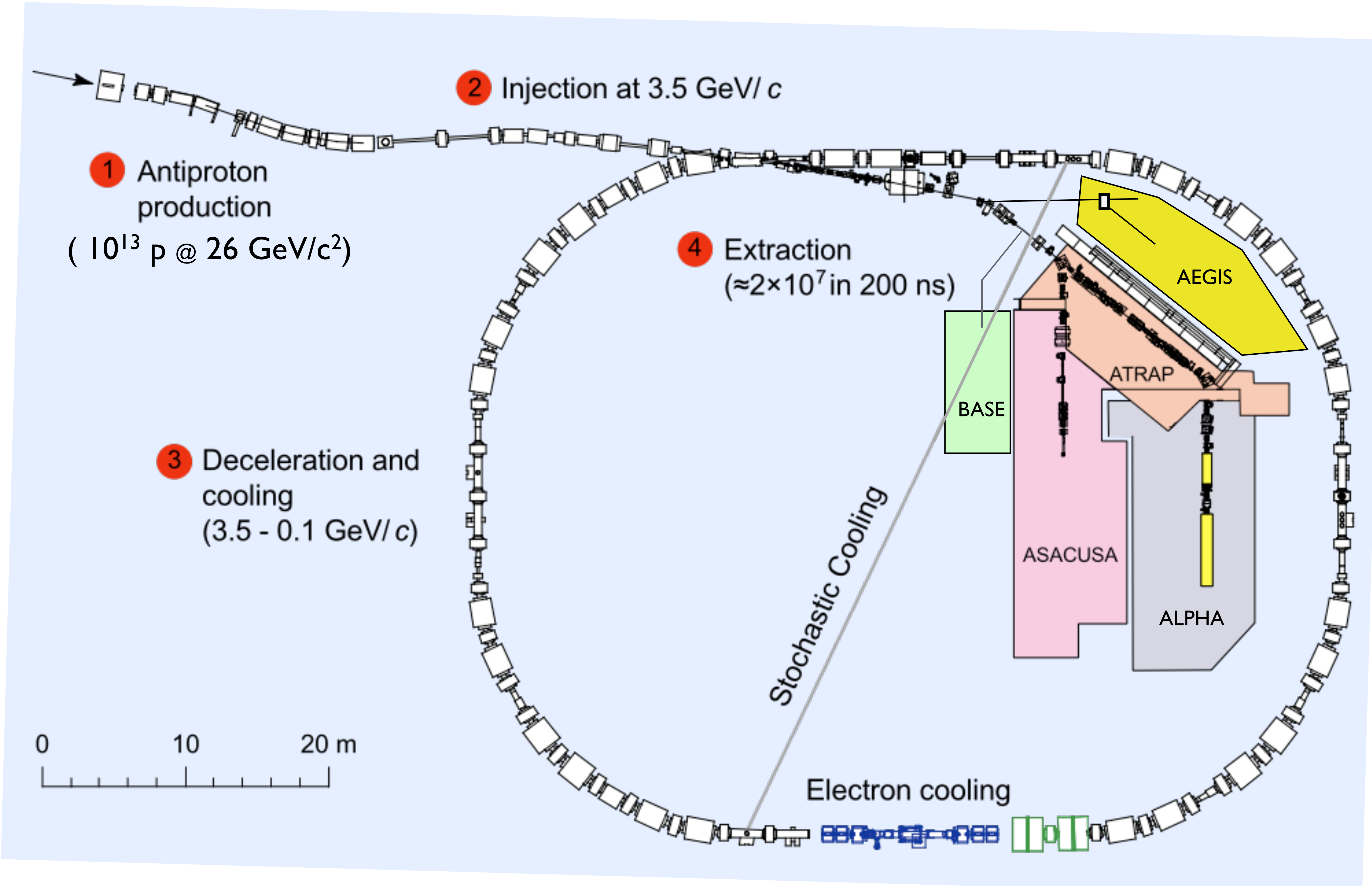
Studying Antihydrogen

ASACUSA
AEḡIS

CERN Accelerator Complex



Antiproton decelerator



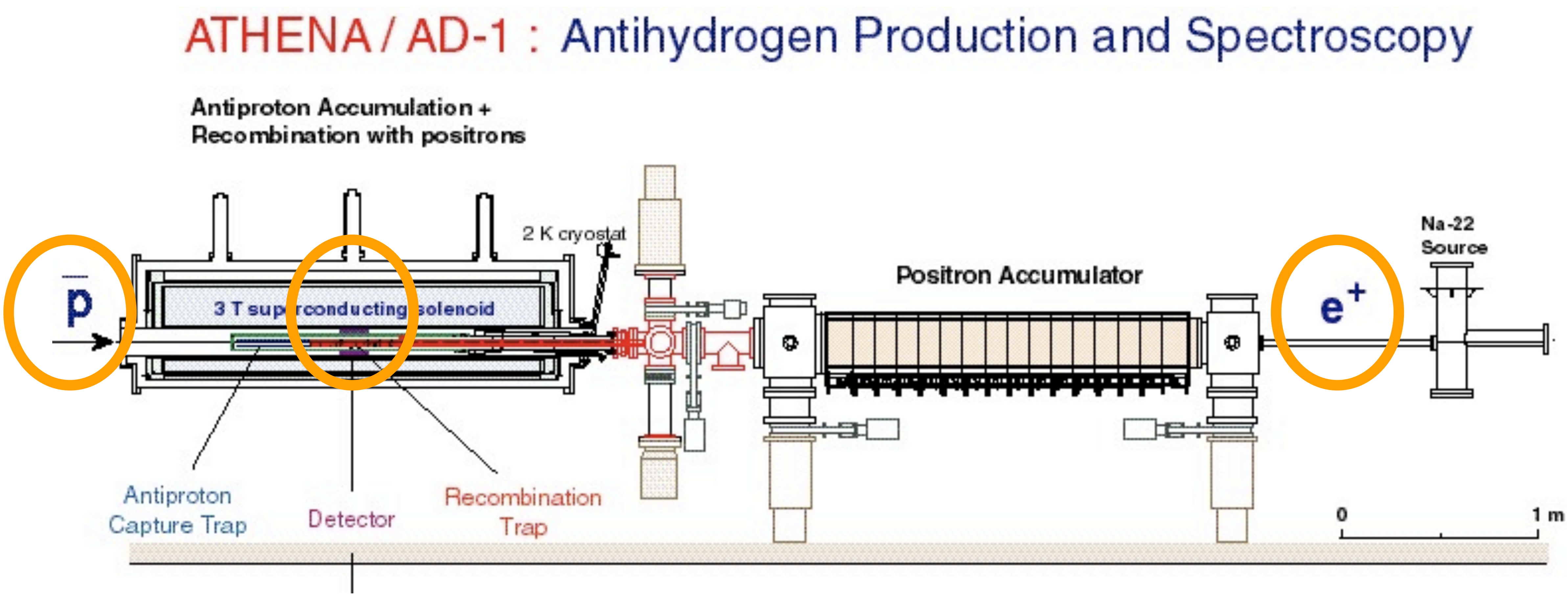
Typical Antihydrogen Experiment

- Capture, trap, cool antiprotons
- Capture, trap, cool positrons
- Merge and recombine
  to form antihydrogen atoms

10^7 (AD) ➟ 10^5 (trapped)

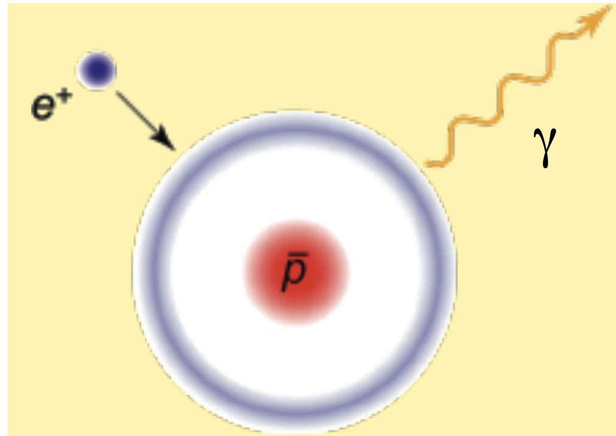
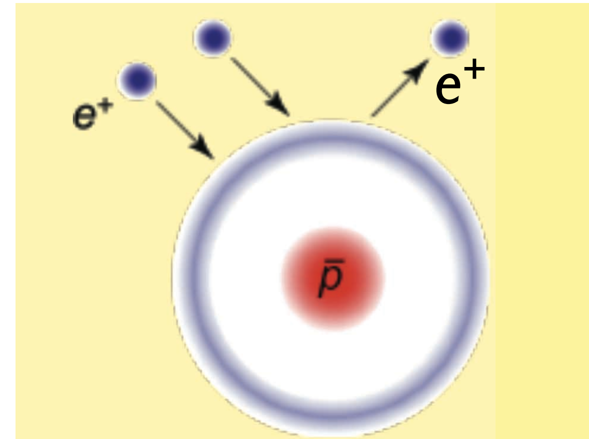
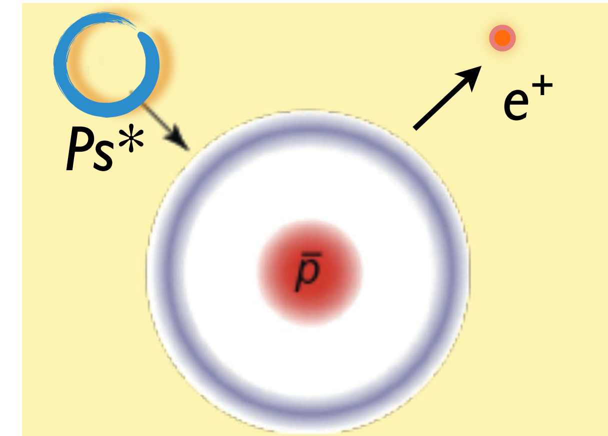
1.5 GBq ^{22}Na ➟ 10^8 (trapped)

1-10^3 Hz



Boundary conditions: UHV: 10^{-15} mbar; cryogenic: T~ 1K; B~1-5T

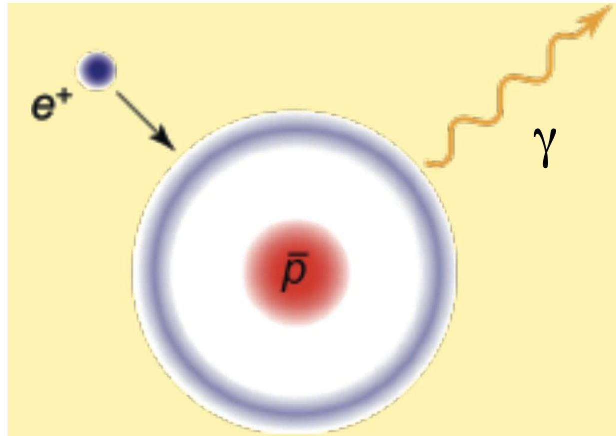
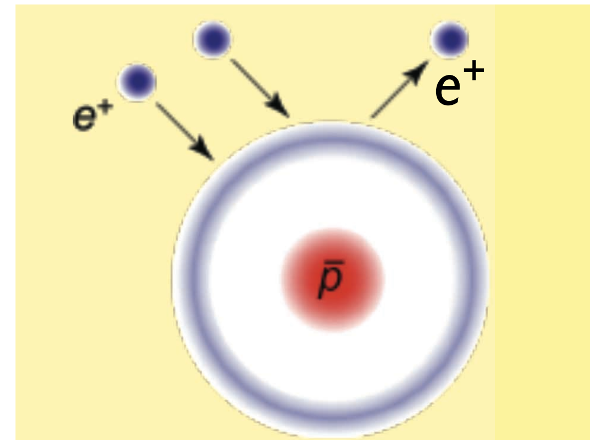
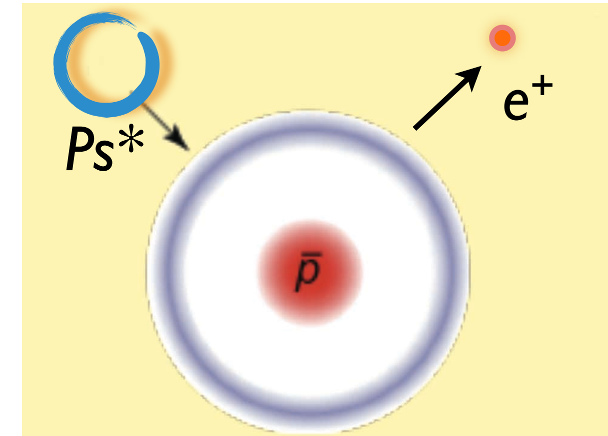
Recombination processes

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!

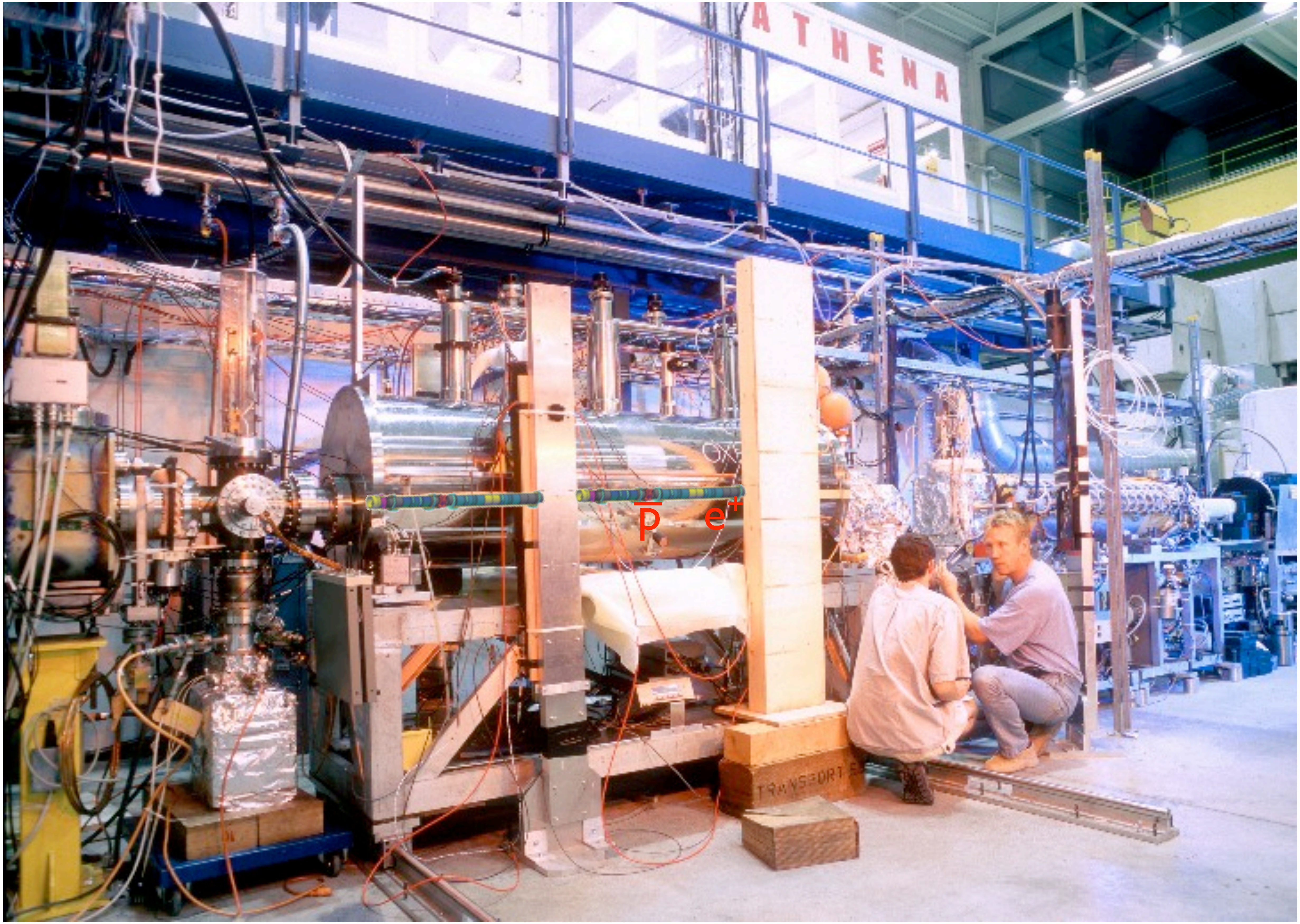
J. Stevefelt et al., PRA 12 (1975) 1246
Robicheaux F 2004 Phys. Rev. A 70 022510
M. E. Glinsky et al., Phys. Fluids B 3 (1991) 1279
Robicheaux, J. Phys. B: At. Mol. Opt. Phys. 41 (2008) 192001

Recombination processes

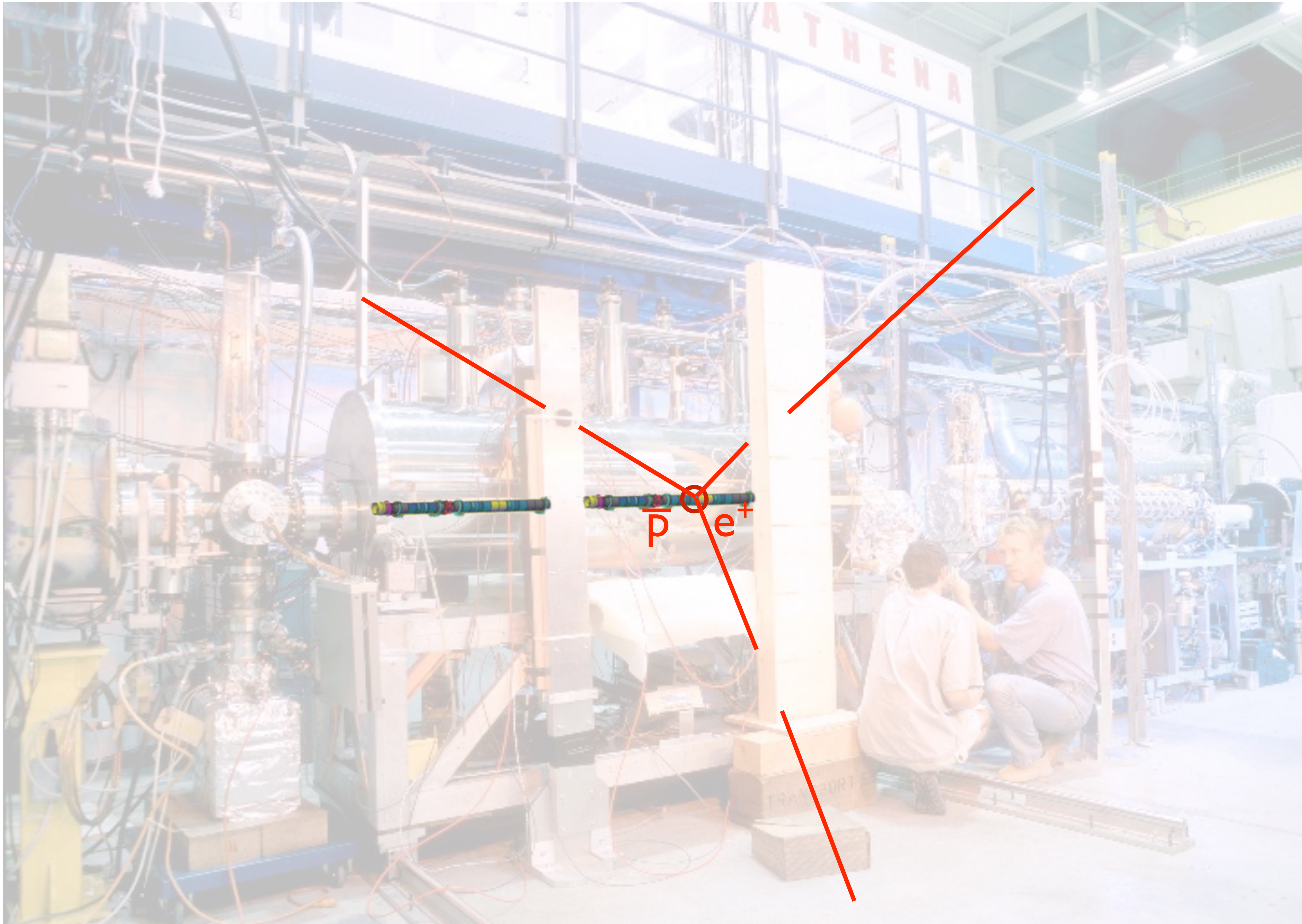
Principle			
Temperature dependence	$\propto T^{-2/3}$	$\propto T^{-2/3}$	$\propto T^{-x}$
e+ density dependence	$\propto n_e$	$\propto n_e^2$	
Cross section at 1K	10^{-16} cm^2	10^{-7} cm^2	10^{-9} cm^2
Final internal states	n<10	n>>10	$f(n_{Ps})$
Expected rates	few Hz	high	1Hz (?)

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

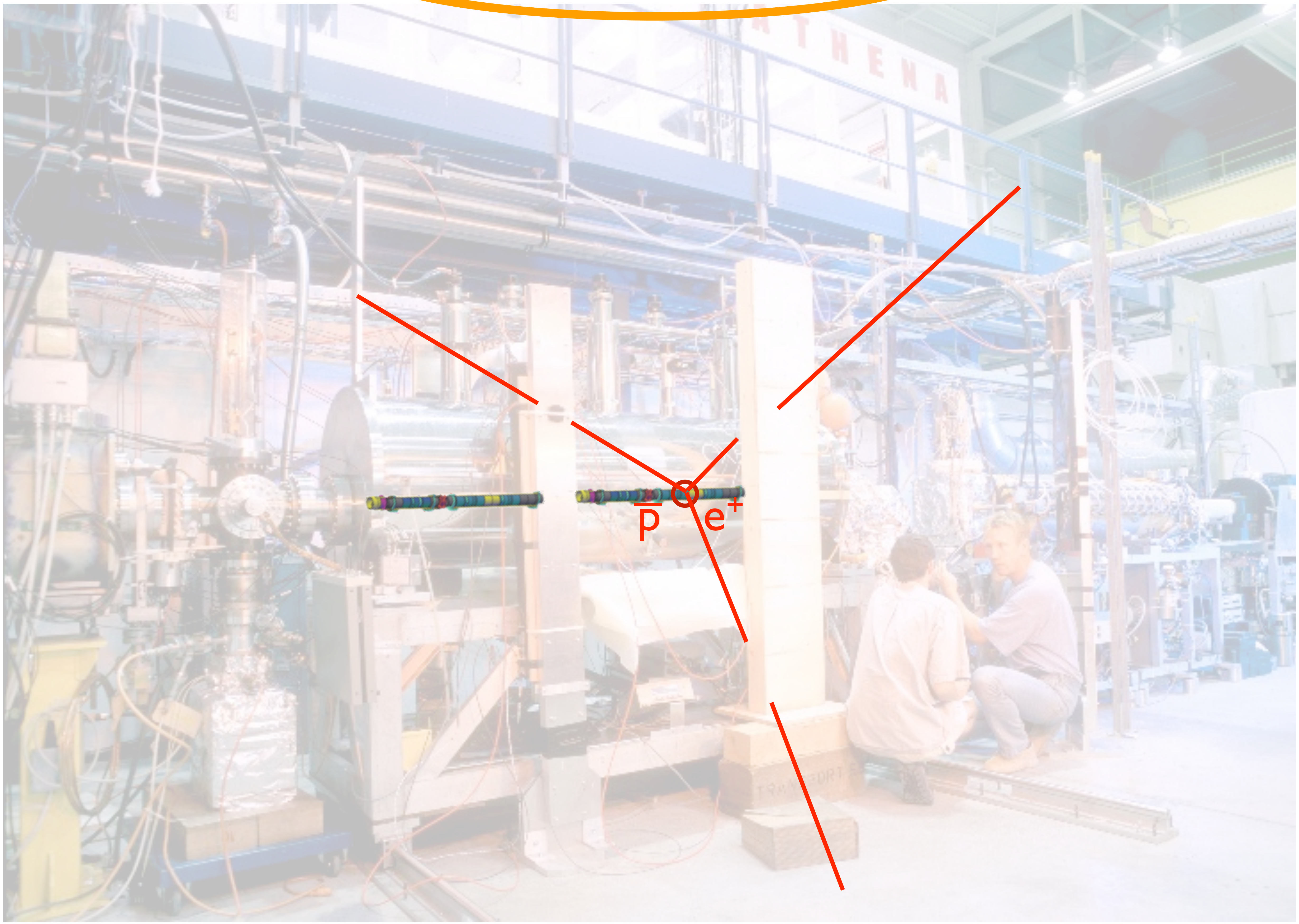
J. Stevefelt et al., PRA 12 (1975) 1246
Robicheaux F 2004 Phys. Rev. A 70 022510
M. E. Glinsky et al., Phys. Fluids B 3 (1991) 1279
Robicheaux, J. Phys. B: At. Mol. Opt. Phys. 41 (2008) 192001


ATHENA
$\bar{p}$
e^+
TRANSPORT


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


ATHENA
$\bar{p}$
e^+

2002: first production of $\overline{H}$



First Cold Antihydrogen 2002 @ AD

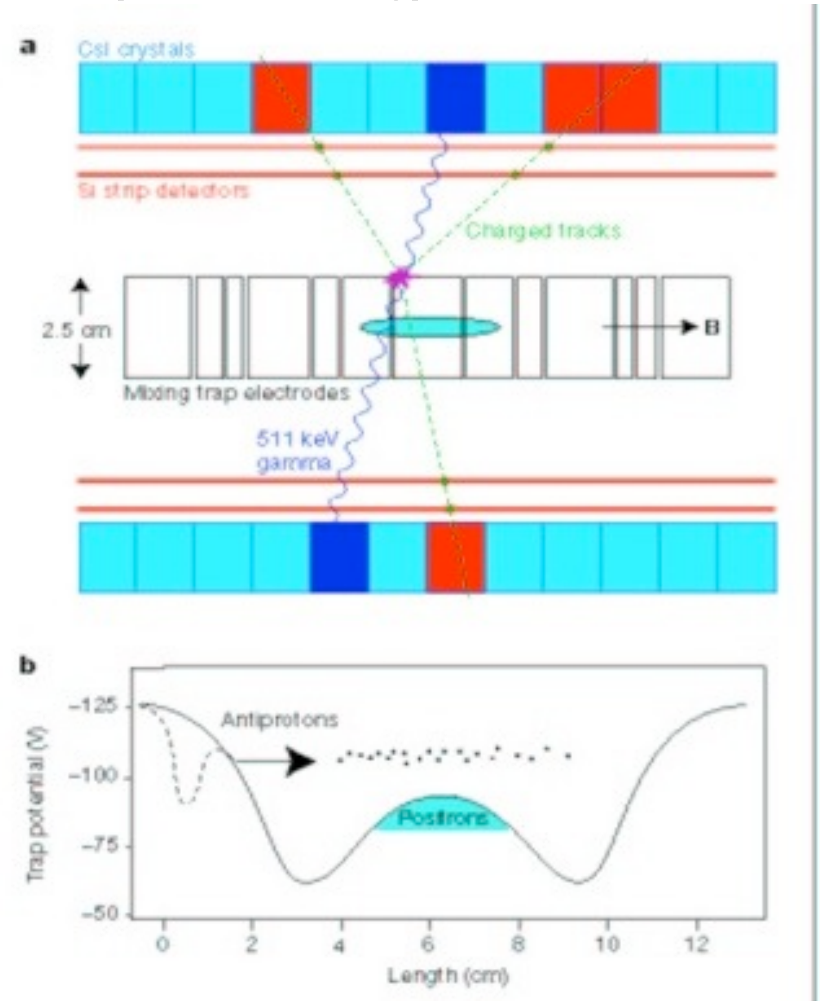
advance online publication

Production and detection of cold antihydrogen atoms

M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe‖, C. Carraro*, C. L. Cesar¶‖, M. Charlton#, M. J. T. Collier#, M. Doser‡, V. Filippini☆, K. S. Fine‡, A. Fontana☆**, M. C. Fujiwara††, R. Funakoshi††, P. Genova☆**, J. S. Hangst‖, R. S. Hayano††, M. H. Holzscheiter‡, L. V. Jorgensen#, V. Lagomarsino*‡‡, R. Landua‡, D. Lindelöf†, E. Lodi Rizzini§☆, M. Macri*, N. Madsen†, G. Manuzio*‡‡, M. Marchesotti☆, P. Montagna☆**, H. Pruys†, C. Regenfus†, P. Riedler‡, J. Rochet†#, A. Rotondi☆**, G. Rouleau‡#, G. Testera*, A. Variola*, T. L. Watson# & D. P. van der Werf#

ATHENA
Nature 419
(2002) 456

Nested Penning traps
Capture energy: few keV



VOLUME 89, NUMBER 21 PHYSICAL REVIEW LETTERS 18 NOVEMBER 2002

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]

(ATRAP Collaboration)

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138*
[2]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[3]*CERN, 1211 Geneva 23, Switzerland*
[4]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany*
[5]*Ludwig-Maximilians-Universität München, Schellingstrasse 4/III, 80799 München, Germany*
[6]*York University, Department of Physics and Astronomy, Toronto, Ontario, Canada M3J 1P3*
(Received 11 October 2002; published 31 October 2002)

ATRAP PRL 89 (2002) 213401

First "Cold" Antihydrogen 2002 @ AD

advance online publication

Production and detection of cold antihydrogen atoms

M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe‖, C. Carraro*, C. L. Cesar¶, M. Charlton#, M. J. T. Collier#, M. Doser‡, V. Filippini☆, K. S. Fine‡, A. Fontana☆**, M. C. Fujiwara††, R. Funakoshi††, P. Genova☆**, J. S. Hangst‖, R. S. Hayano††, M. H. Holzscheiter‡, L. V. Jørgensen#, V. Lagomarsino*‡‡, R. Landua‡, D. Lindelöf†, E. Lodi Rizzini§☆, M. Macri*, N. Madsen†, G. Manuzio*‡‡, M. Marchesotti☆, P. Montagna☆**, H. Pruys†, C. Regenfus†, P. Riedler‡, J. Rochet†#, A. Rotondi☆**, G. Rouleau‡#, G. Testera*, A. Variola*, T. L. Watson# & D. P. van der Werf#

ATHENA
Nature 419
(2002) 456

VOLUME 89, NUMBER 21 PHYSICAL REVIEW LETTERS 18 NOVEMBER 2002

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

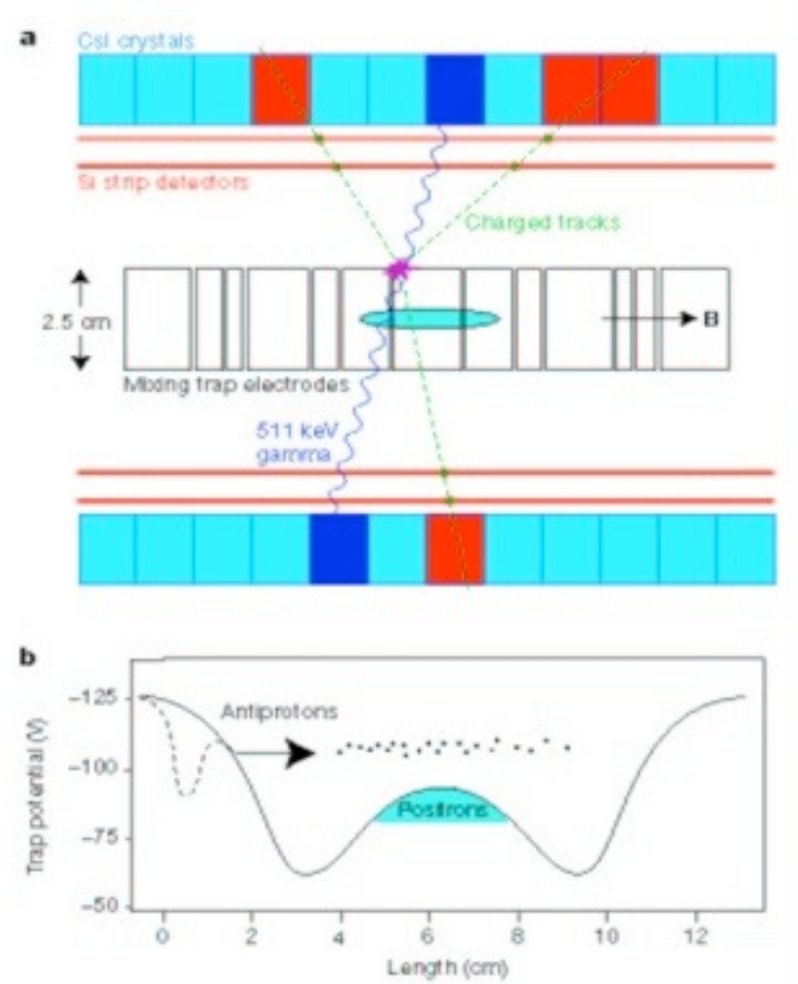
G. Gabrielse,[1,*] N. S. Bowden,[1] P. Oxley,[1] A. Speck,[1] C. H. Storry,[1] J. N. Tan,[1] M. Wessels,[1] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2] T. Sefzick,[2] J. Walz,[3] H. Pittner,[4] T. W. Hänsch,[4,5] and E. A. Hessels[6]

(ATRAP Collaboration)

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138*
[2]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[3]*CERN, 1211 Geneva 23, Switzerland*
[4]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany*
[5]*Ludwig-Maximilians-Universität München, Schellingstrasse 4/III, 80799 München, Germany*
[6]*York University, Department of Physics and Astronomy, Toronto, Ontario, Canada M3J 1P3*
(Received 11 October 2002; published 31 October 2002)

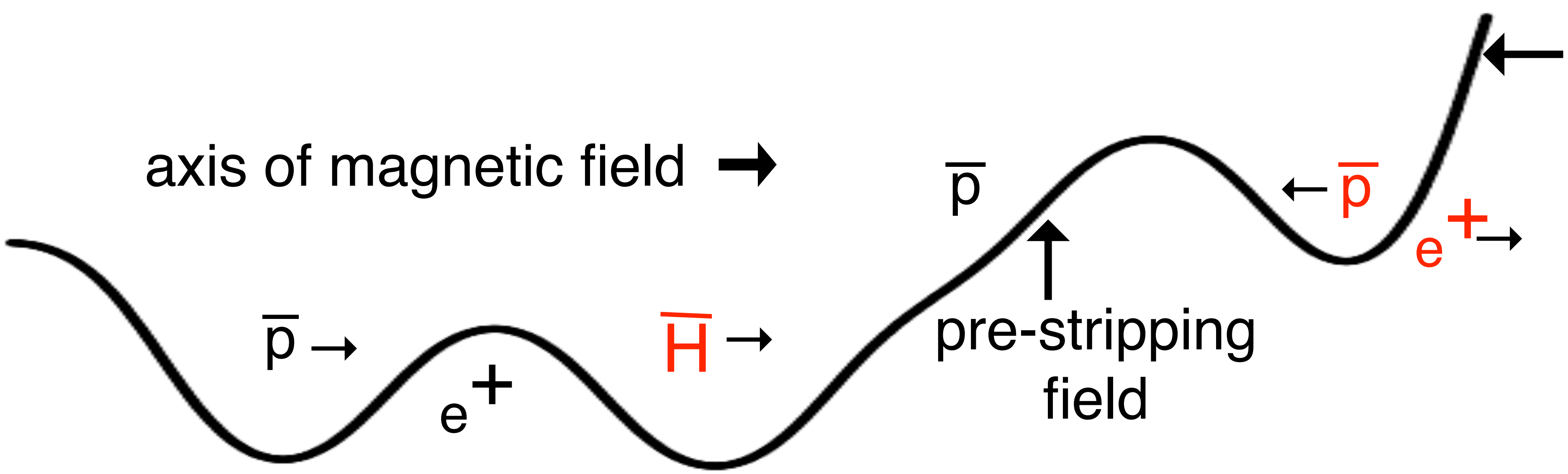
ATRAP PRL 89 (2002) 213401

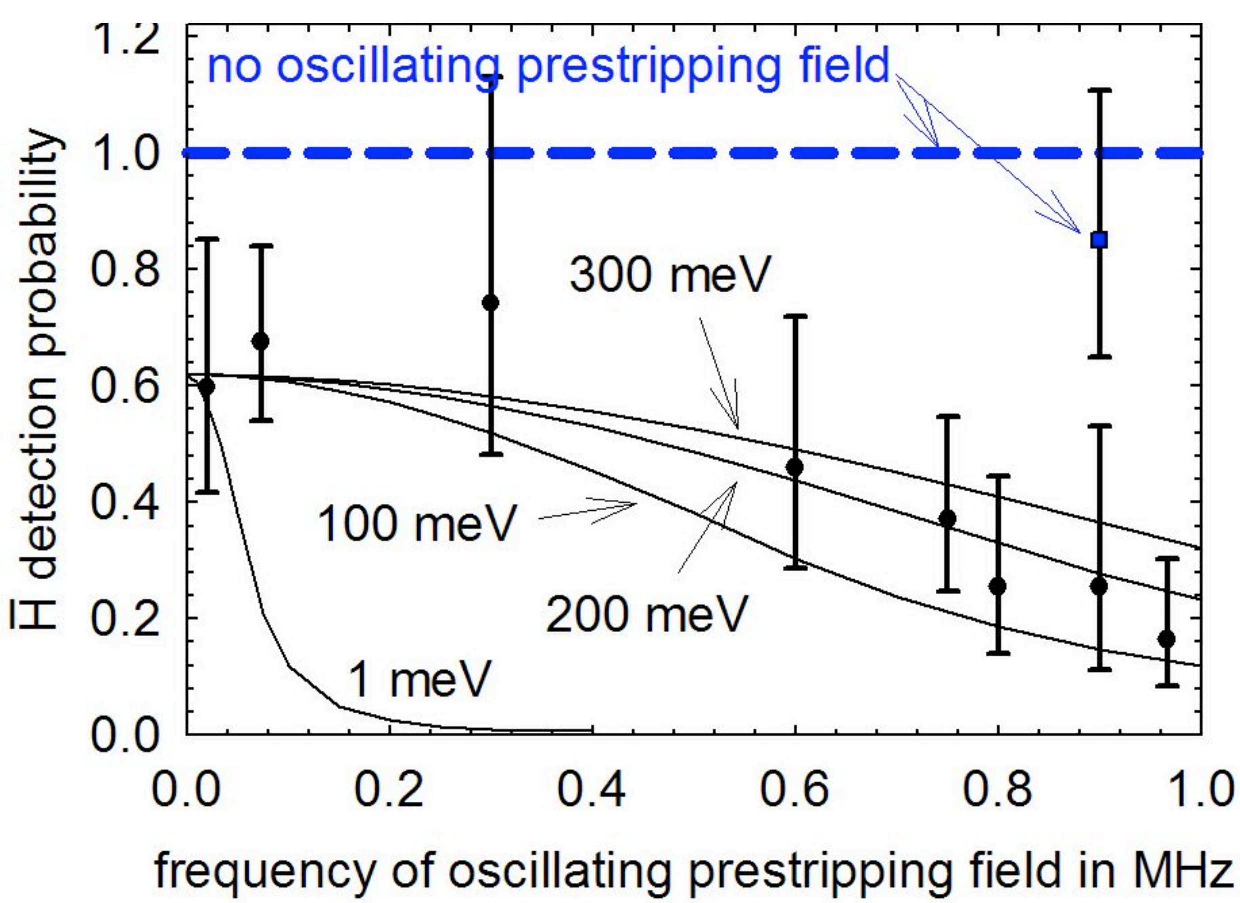
Nested Penning traps
Capture energy: few keV



Temperature of produced $\bar{H}$

measurement through field-ionization of the excited atoms





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

BUT

4.2 K $\bar{H}$ ~ 0.3 meV

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

Trapping of $\overline{H}$?

Challenges to trapping of produced $\bar{H}$

temperature considerations:

- $\bar{p}$ cooling: typically cooled via electrons, but electrons can ionize produced $\bar{H}$; 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 $\bar{H}$: depends on formation mechanism

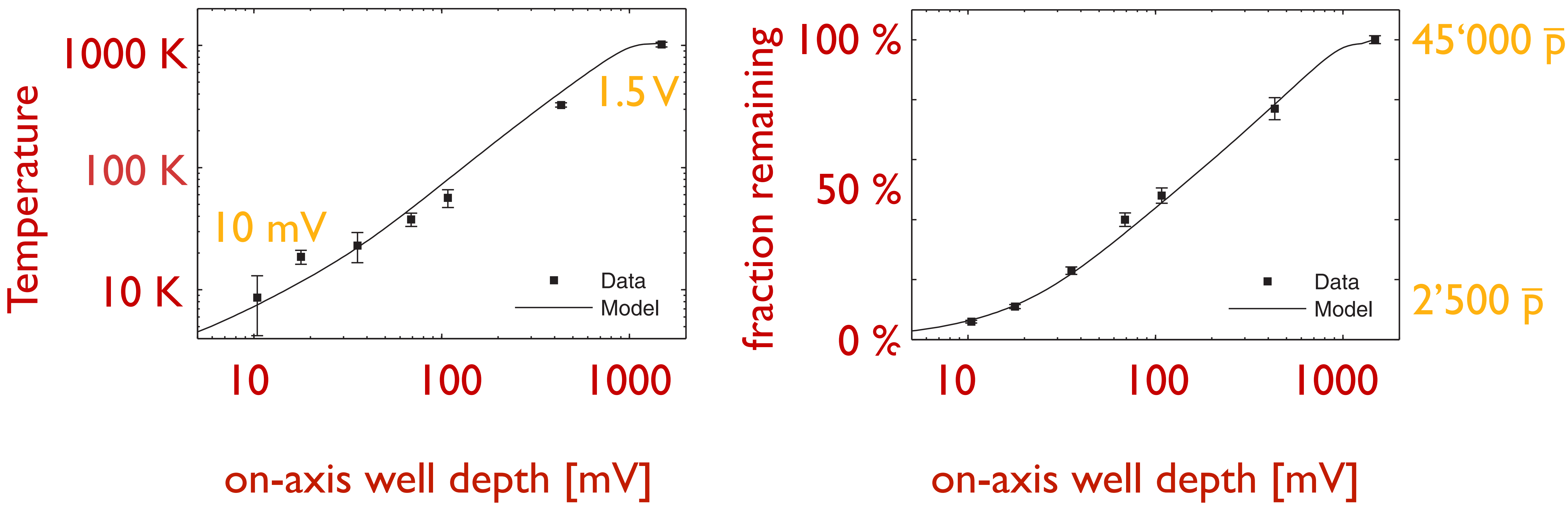
magnetic field considerations

- 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)

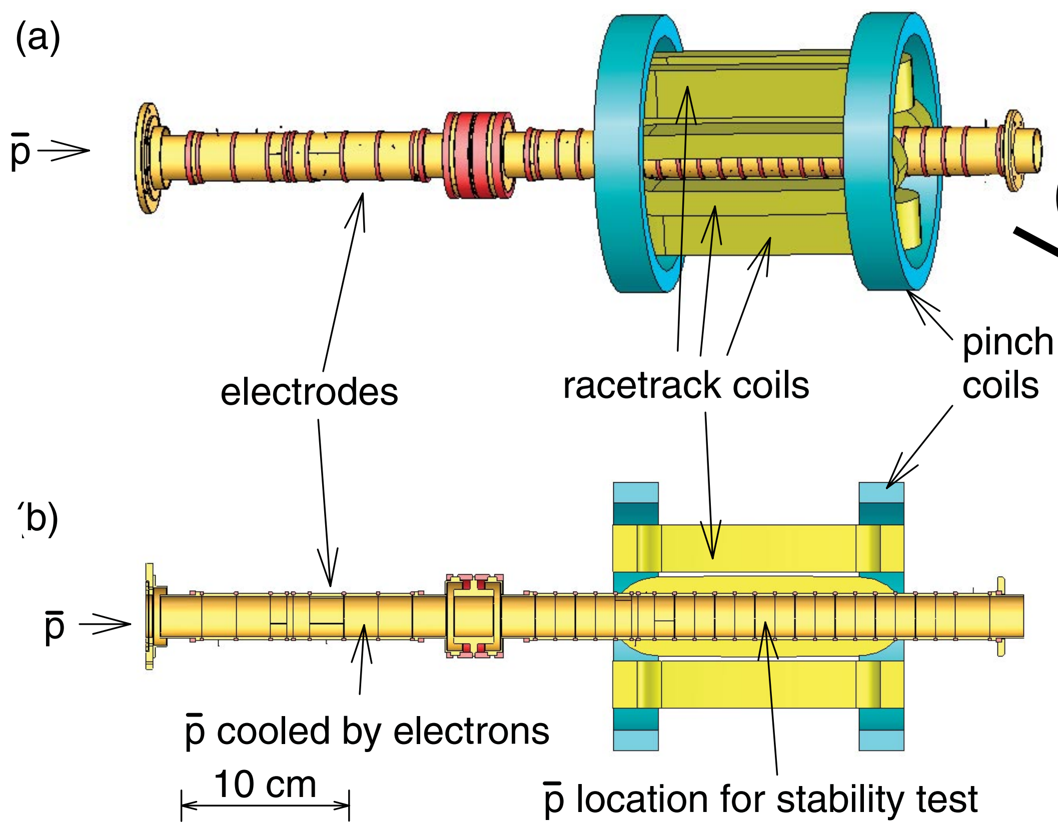


essential to avoid reheating:

- great care needed on noise reduction;
- can not use electron cooling to pre-cool
- bring e^+ to cold $\bar{p}$, not vice-versa, or use autoresonant excitation of $\bar{p}$

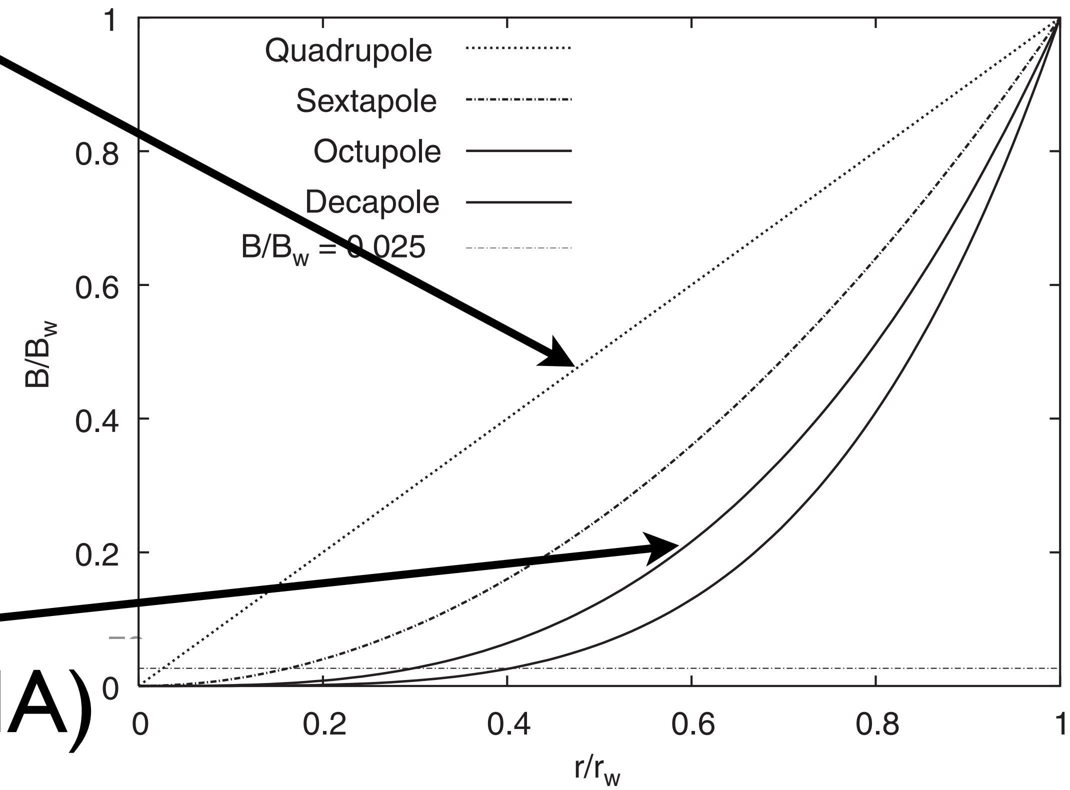
Antihydrogen Production within a Penning-Ioffe Trap

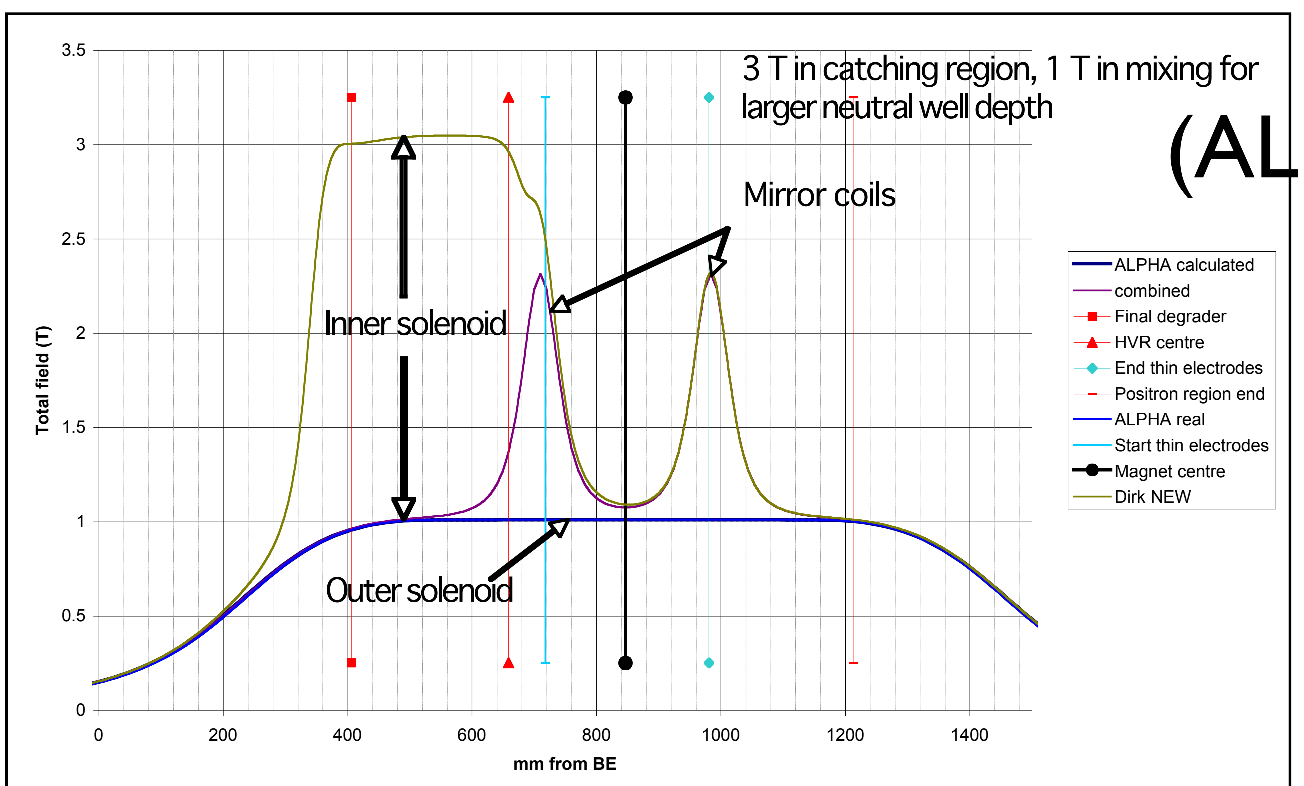
G.Gabrielse et al., Phys. Rev. Lett. 100, 113001 (2008)



(ATRAP)

trap depth ~500 mK





(ALPHA)

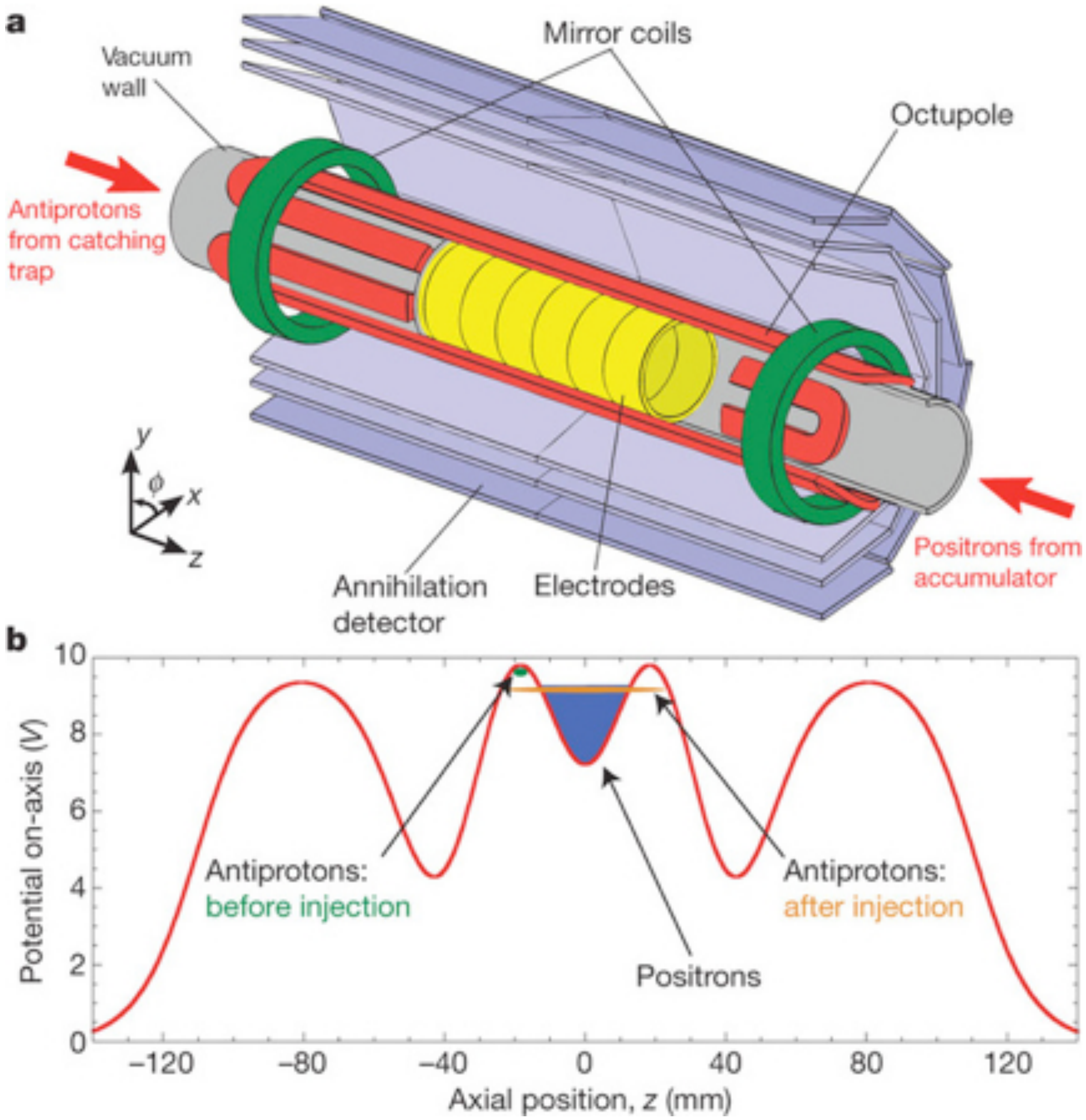
plasma stability/temperature

n >> 1

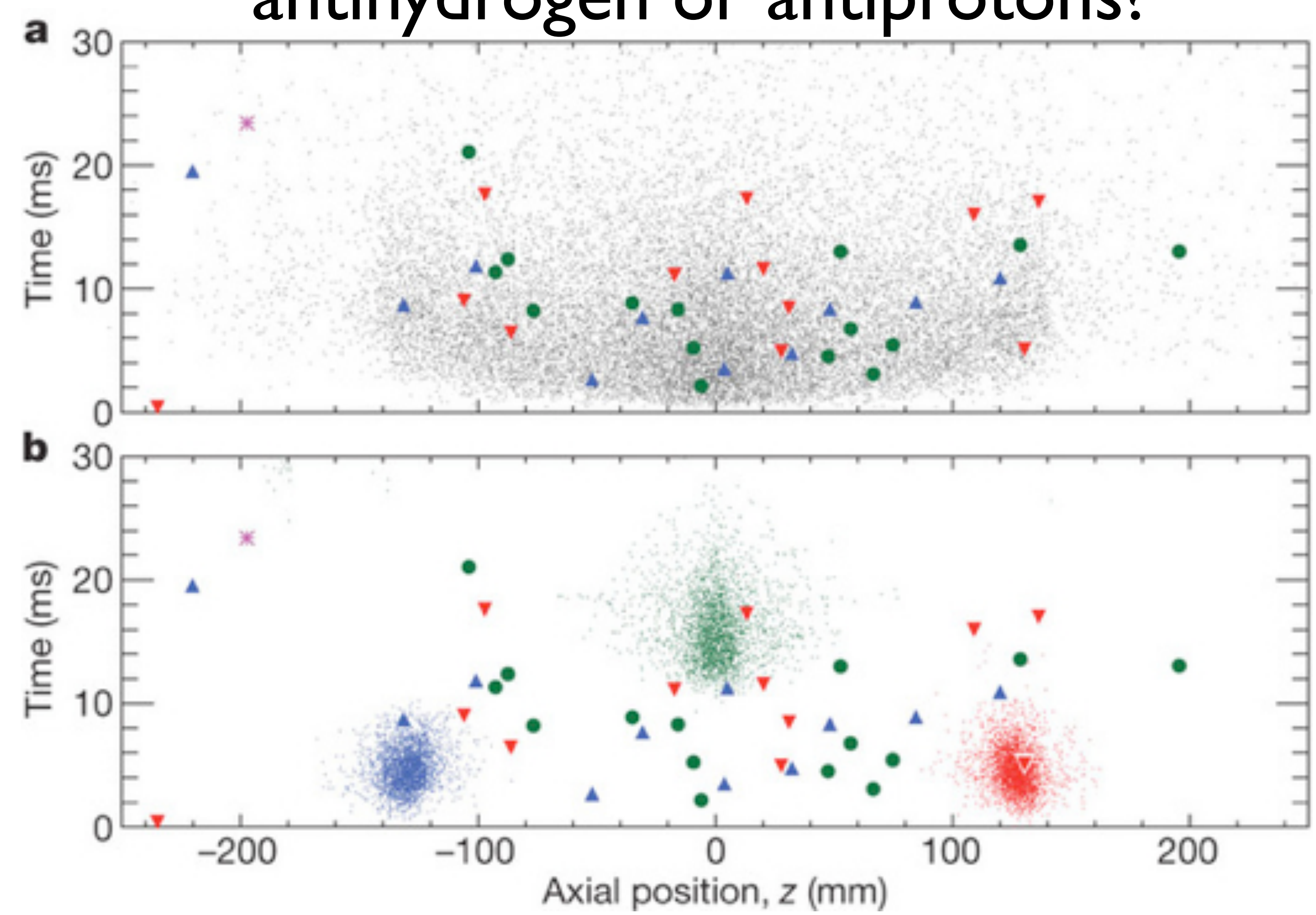
spin flips during de-excitation

2010: Successful trapping! (of single atoms!)

(ALPHA) GB Andresen et al., Nature 468, 673 (2010)



antihydrogen or antiprotons?

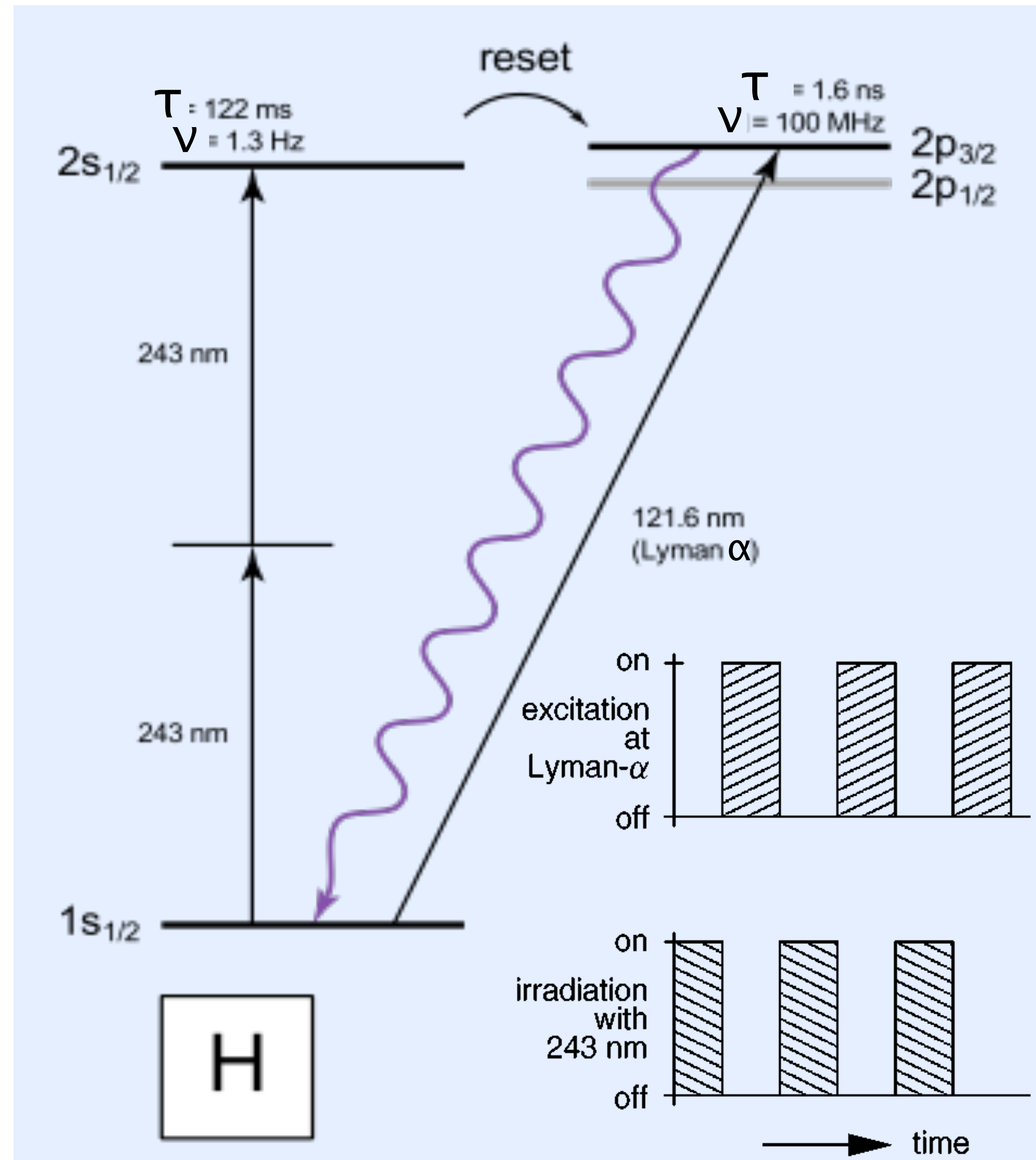


quick opening of magnetic trap (20 ms)
+ sensitive detector for antihydrogen

ATRAP has managed to trap several atoms at once

Spectroscopy in traps

- 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]

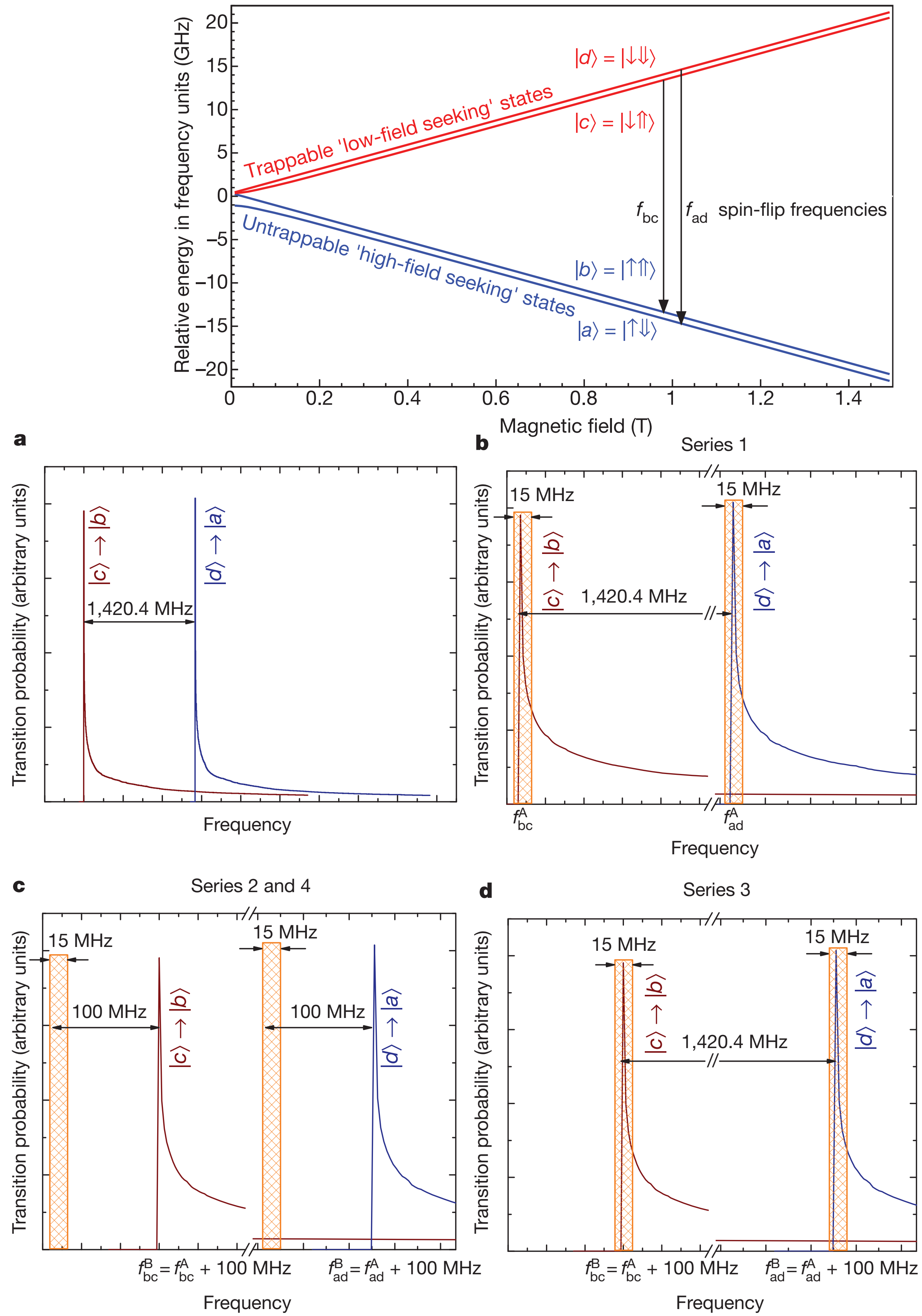


1 nW CW can cool 1K $\bar{H}$ in about 10s

but... more power required for this scheme

Spectroscopy with trapped antihydrogen?

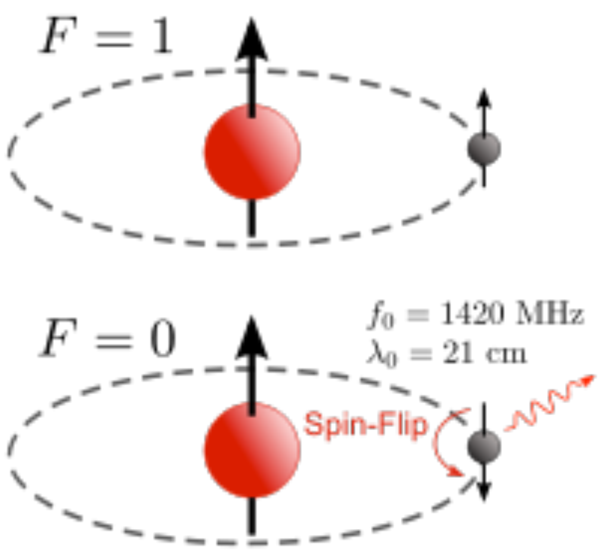
C Amole et al., Nature 483, 439 (2012)

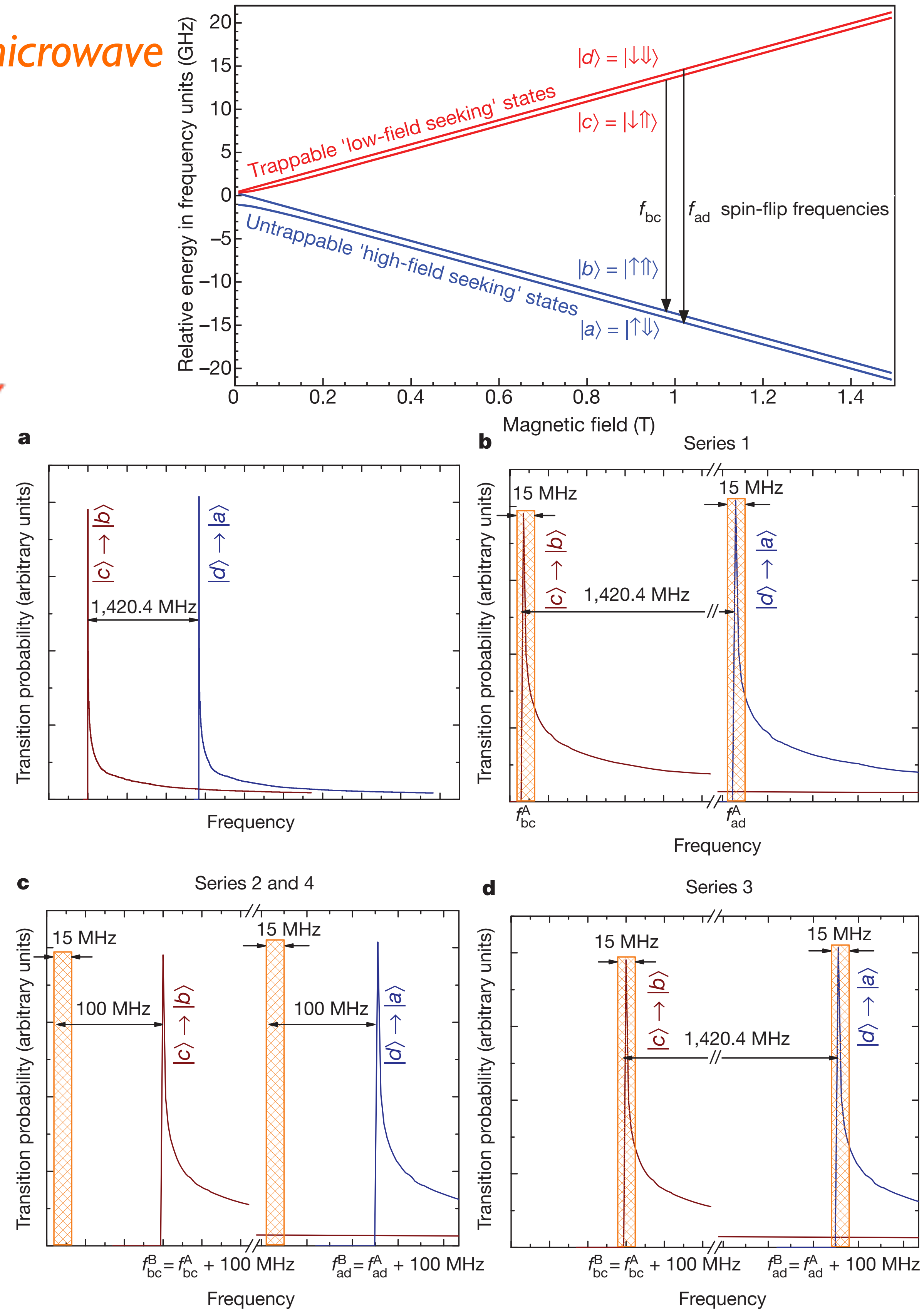


Spectroscopy with trapped antihydrogen?

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

Spectroscopy: HFS via microwave

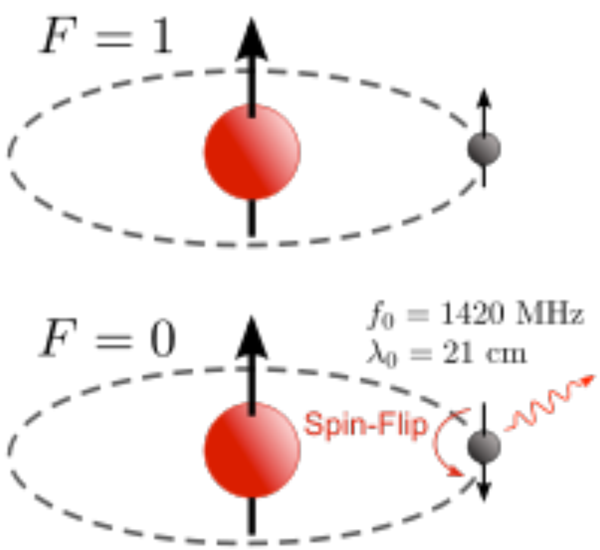


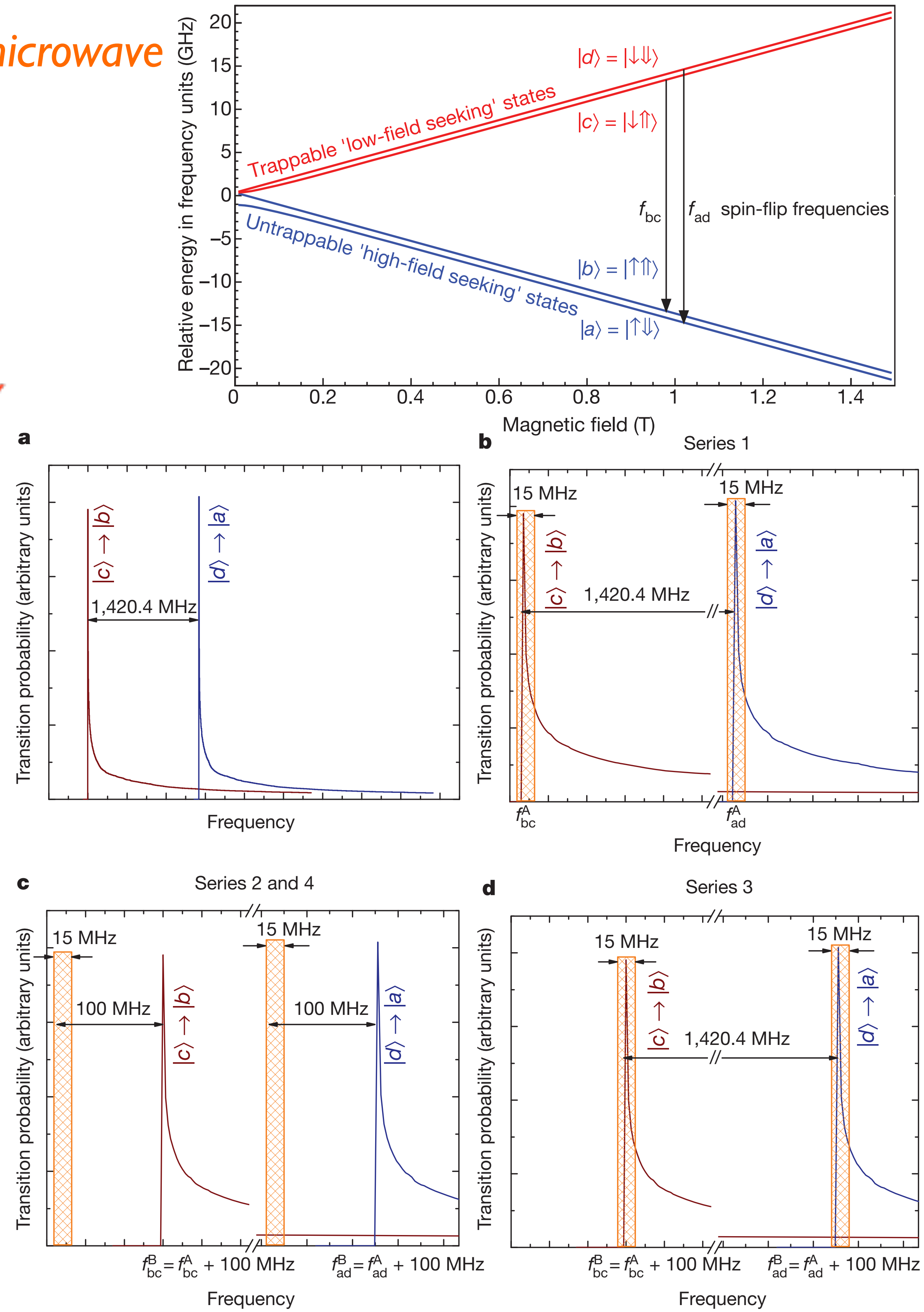


Spectroscopy with trapped antihydrogen!

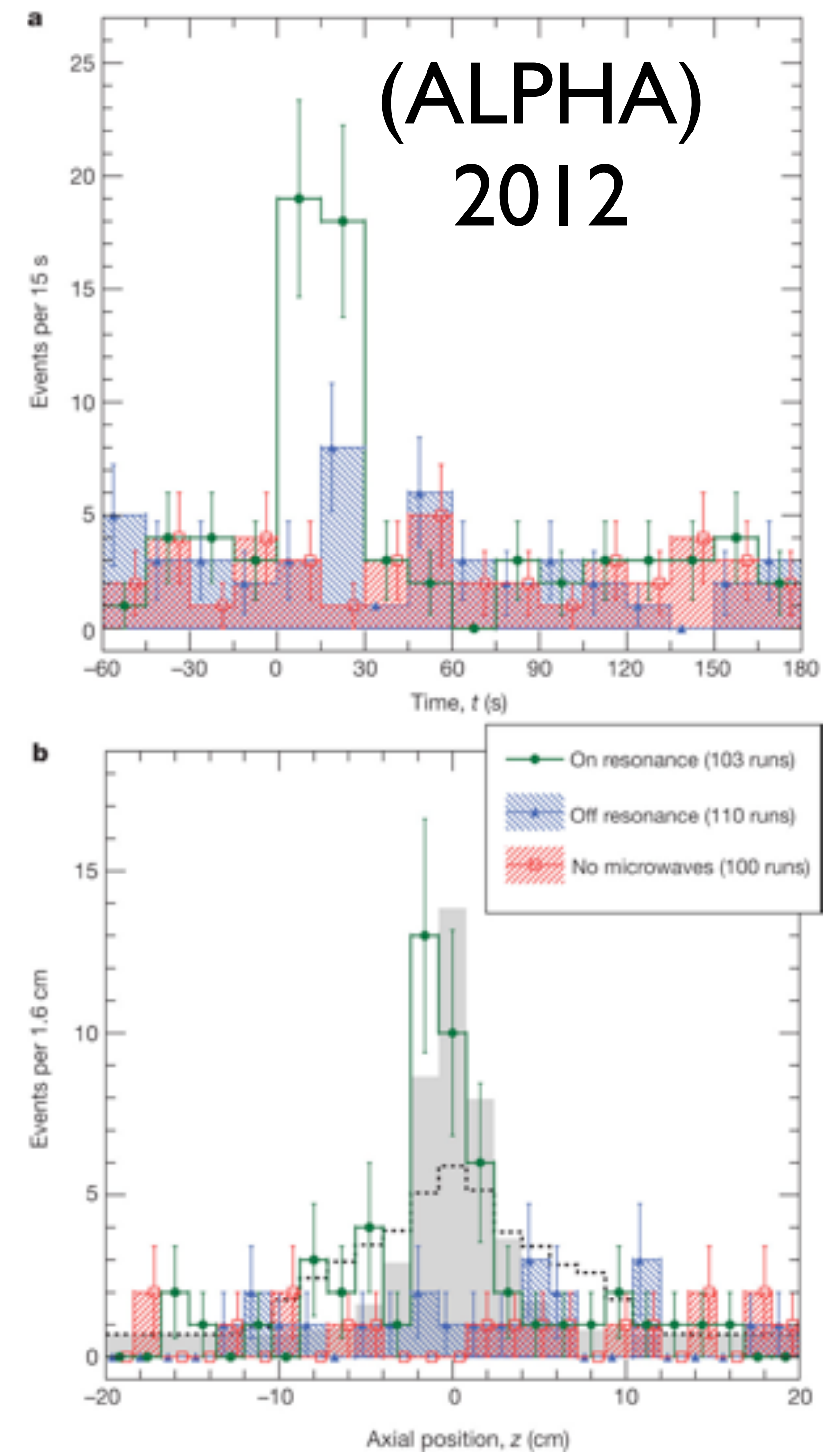
C Amole et al., Nature 483, 439 (2012)

Spectroscopy: HFS via microwave





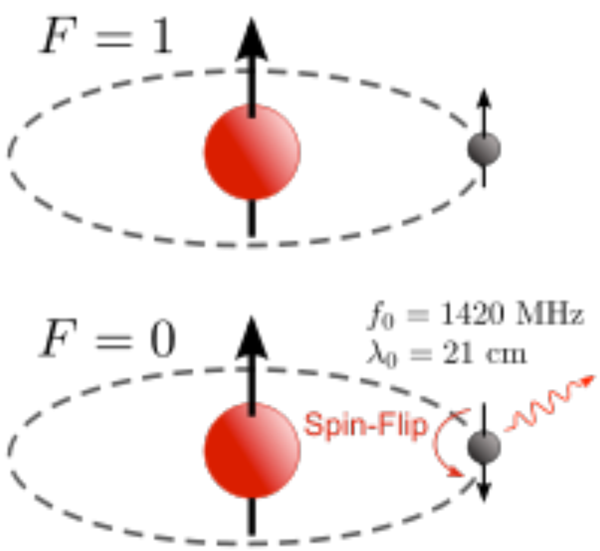
but: B-field varies strongly over trap

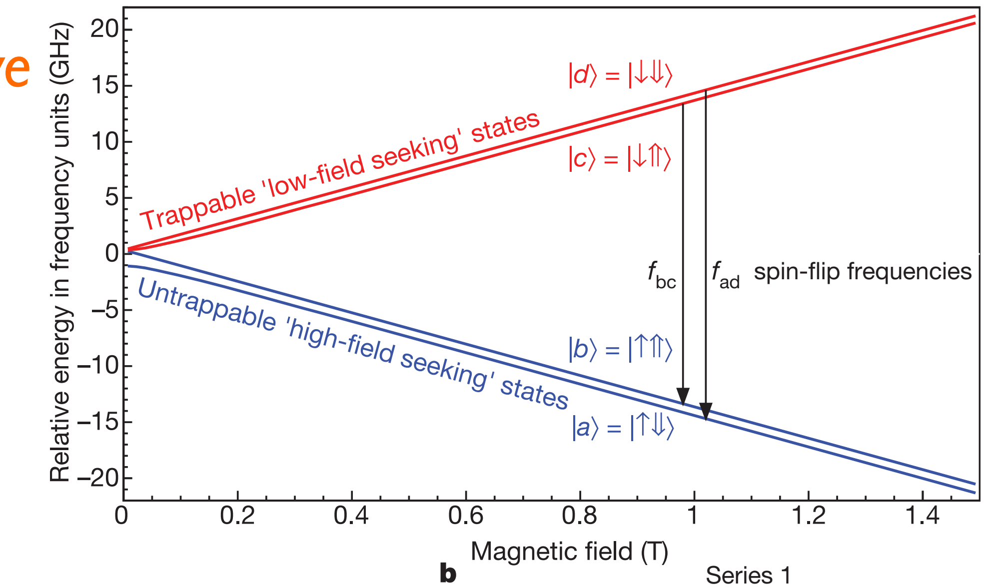


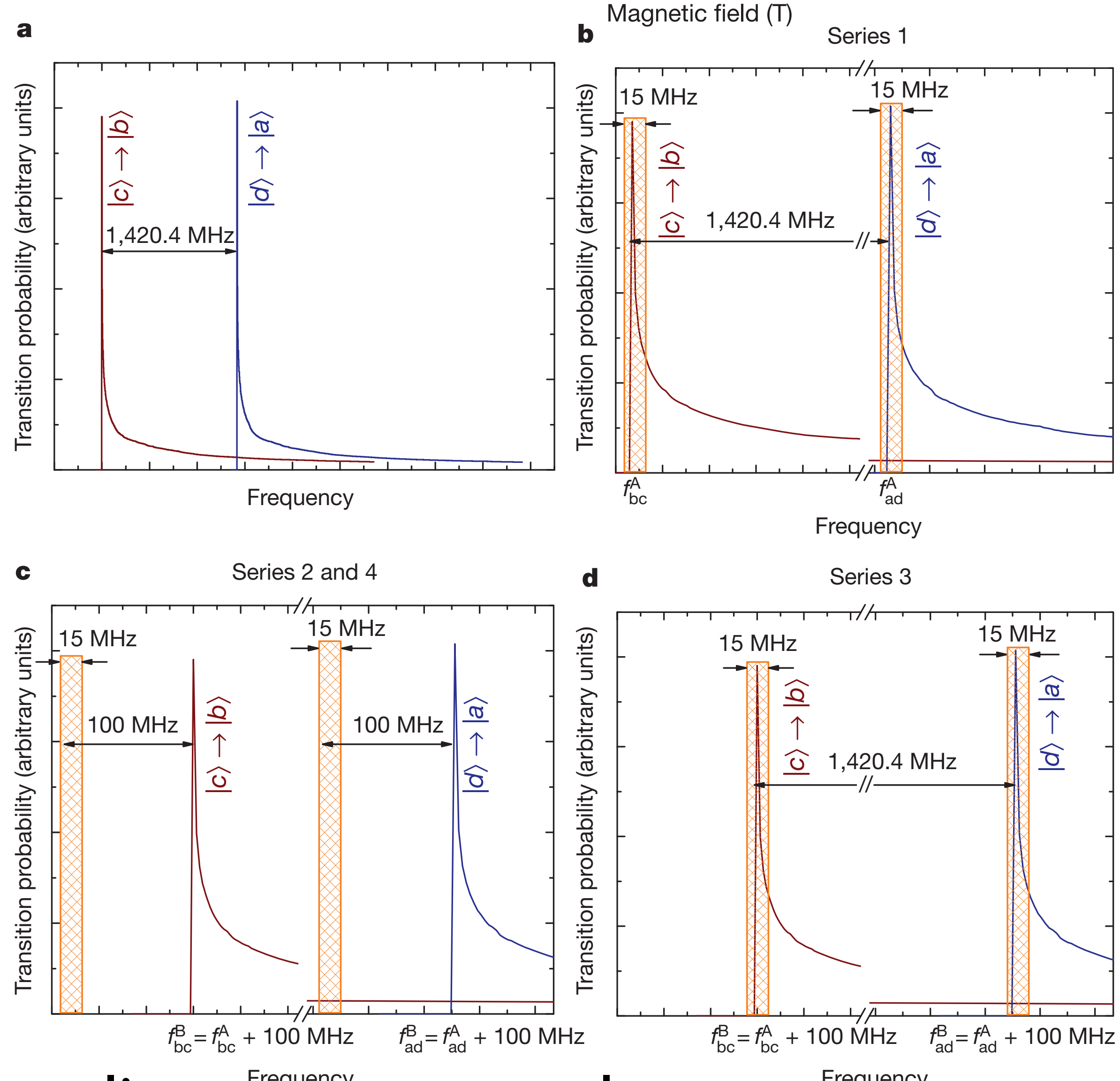
Spectroscopy with trapped antihydrogen!

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

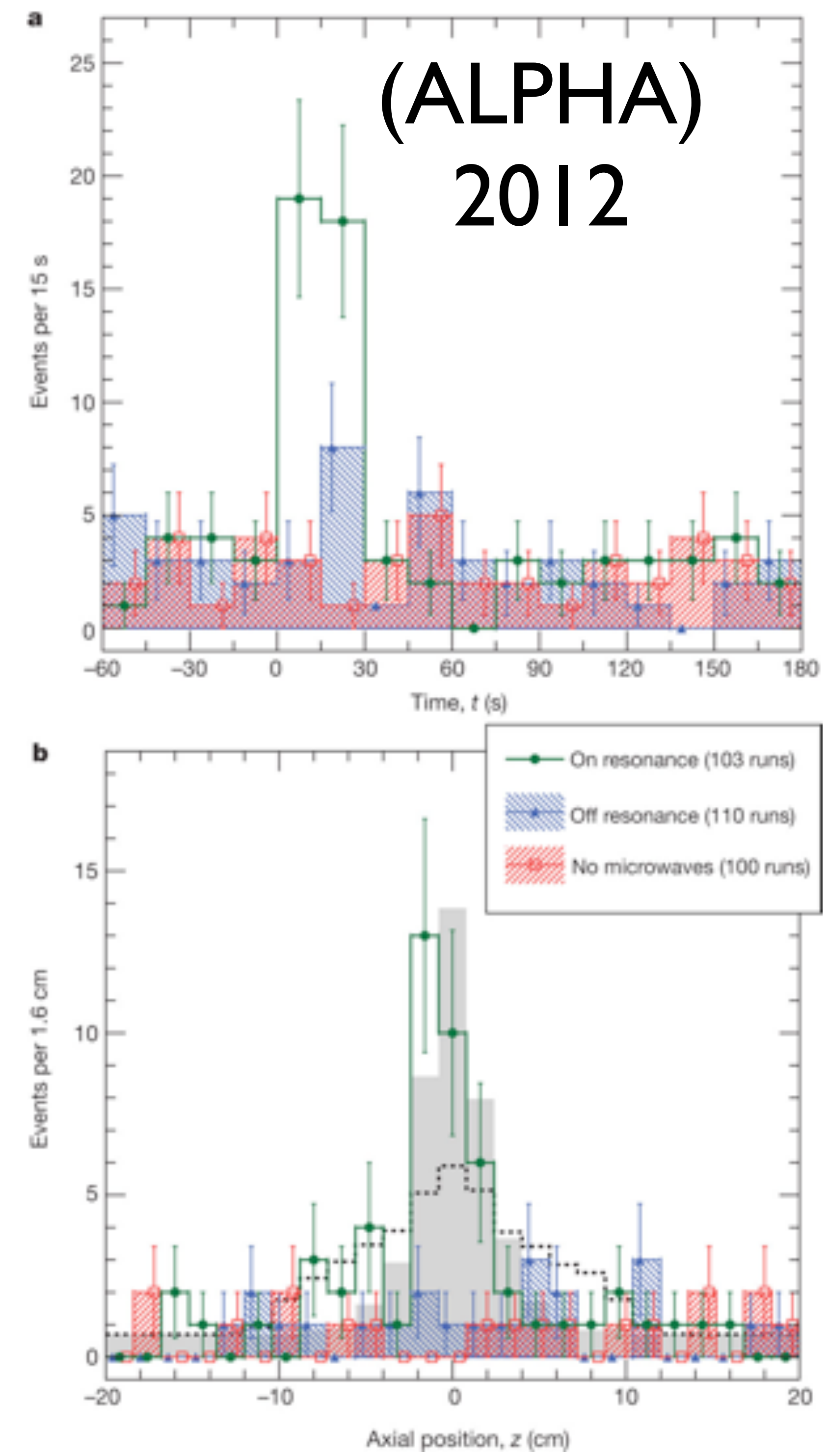
Spectroscopy: HFS via microwave







but: B-field varies strongly over trap



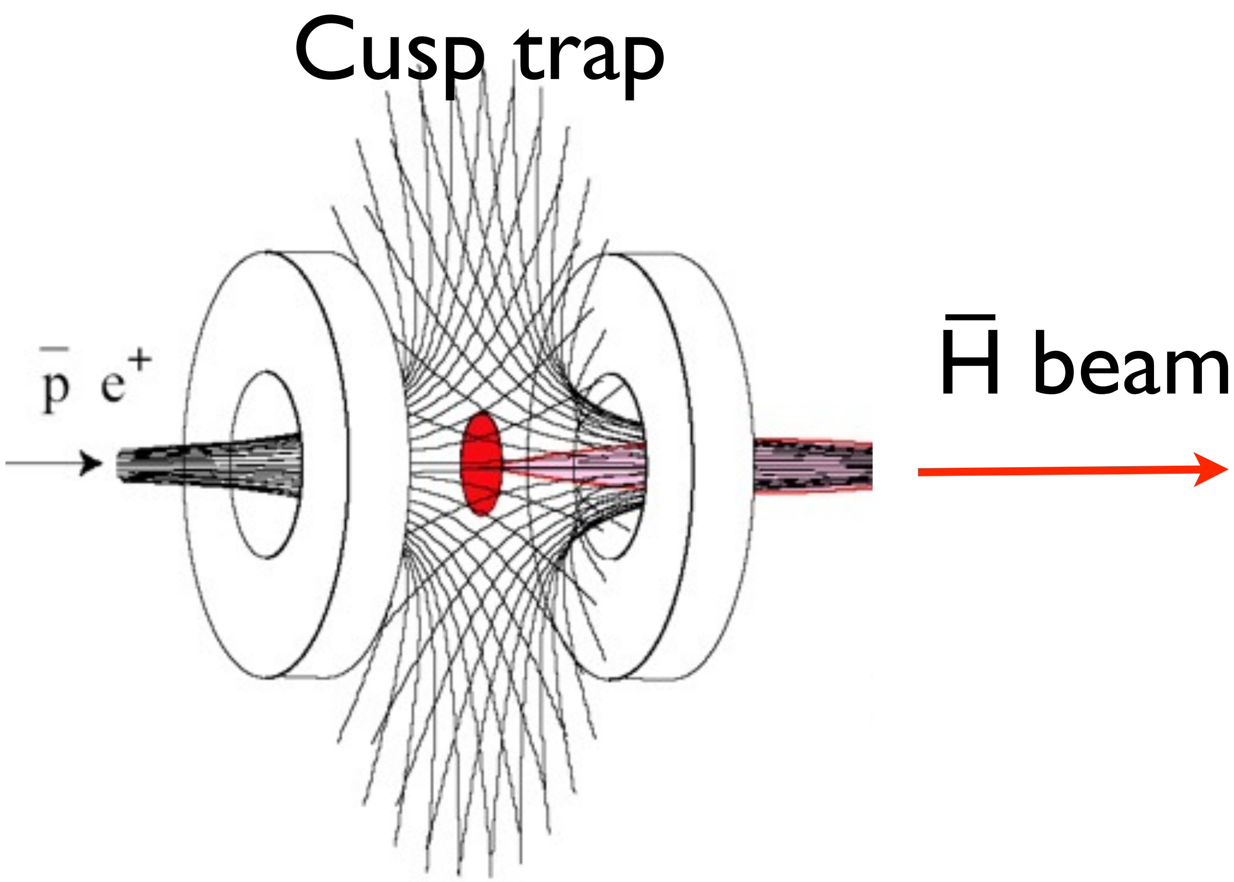
Next steps: better cooling, more atoms, laser spectroscopy: *much tinkering will be needed*

Alternatives to traping?

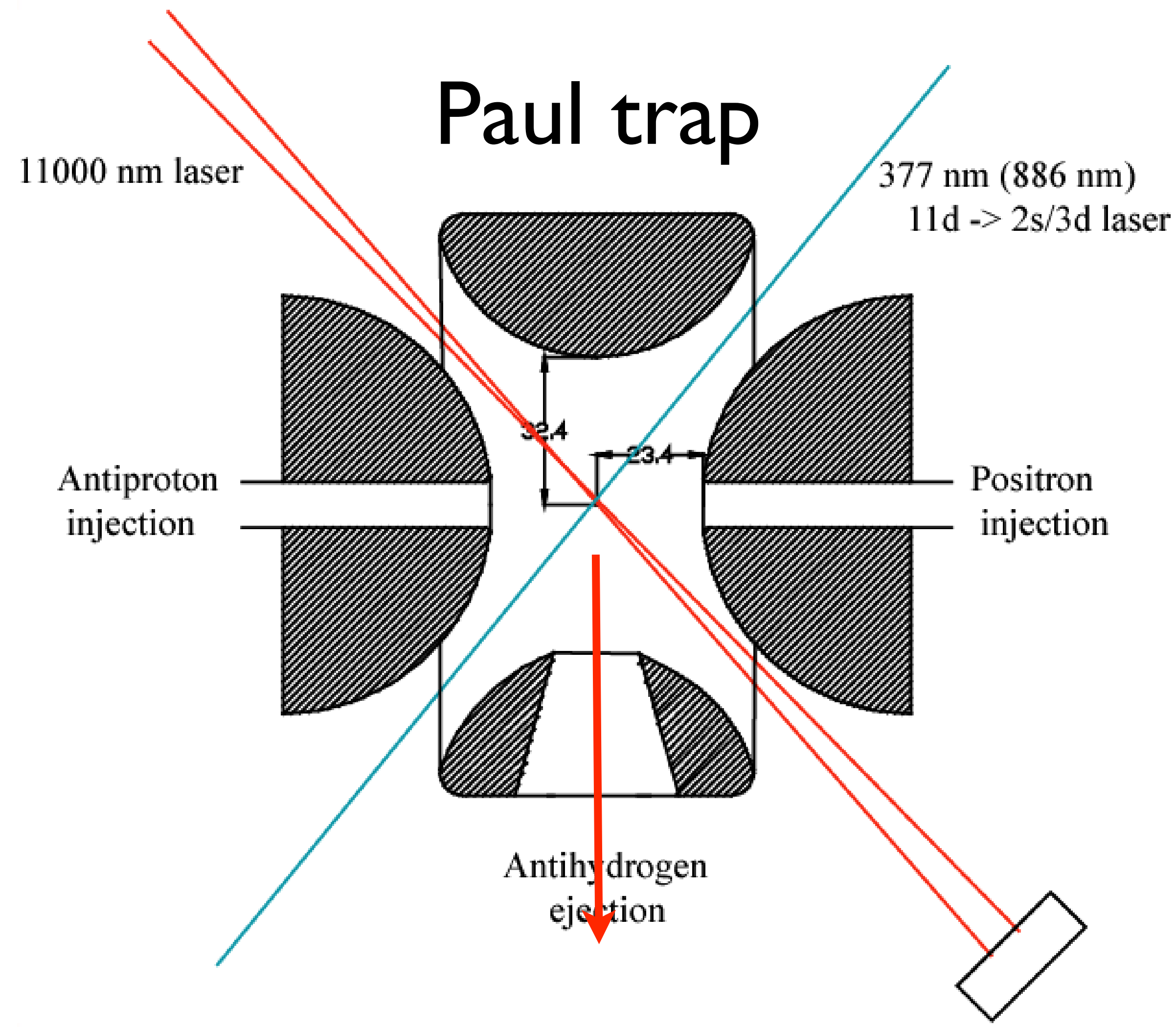
Alternatives to Penning-Ioffe traps?

- 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?



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



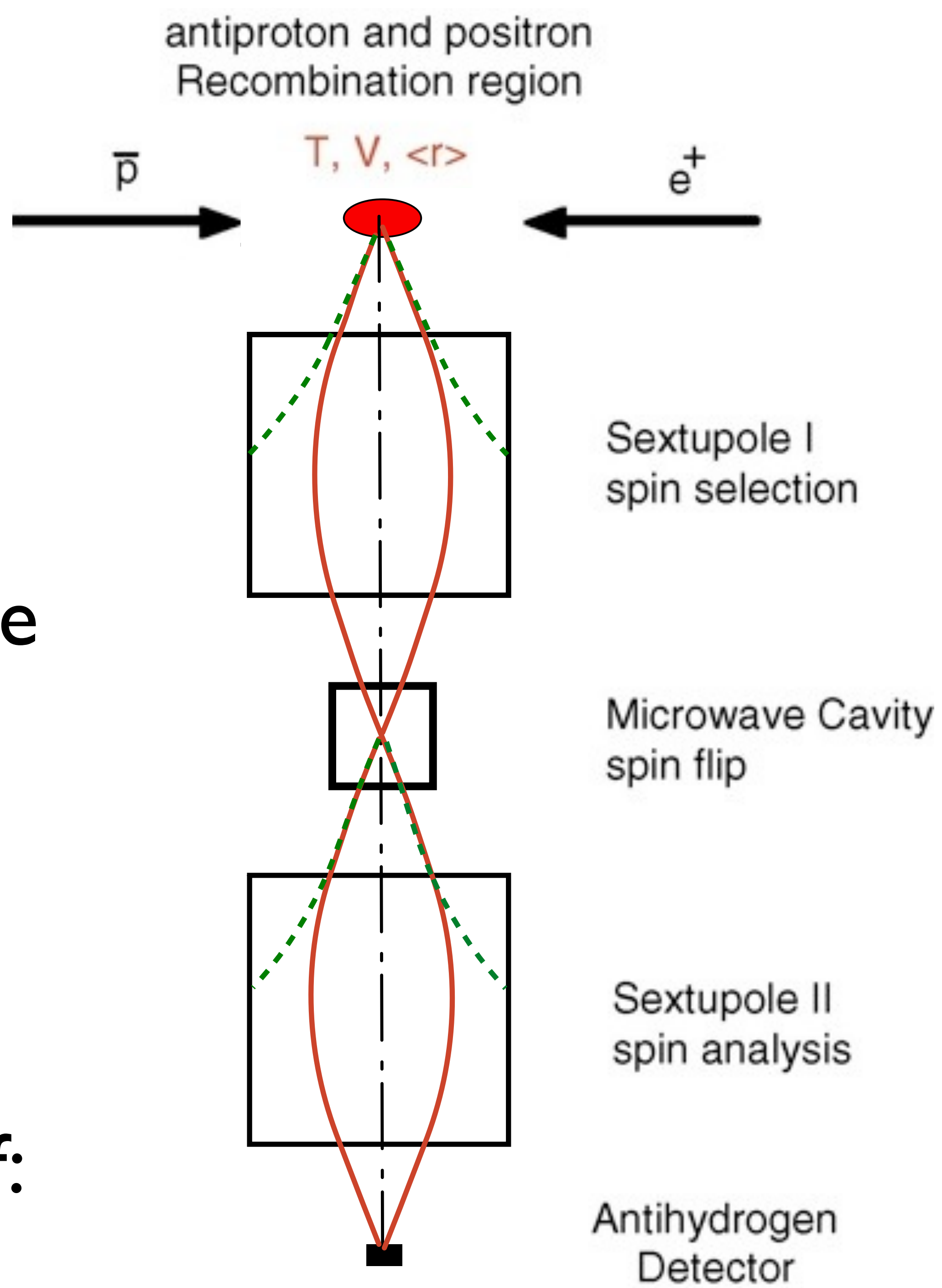
Experiment with $\bar{H}$ beam: ground state HFS

ASACUSA

- much higher precision on HFS: 10^{-6}
- but: formation of beam is not simple

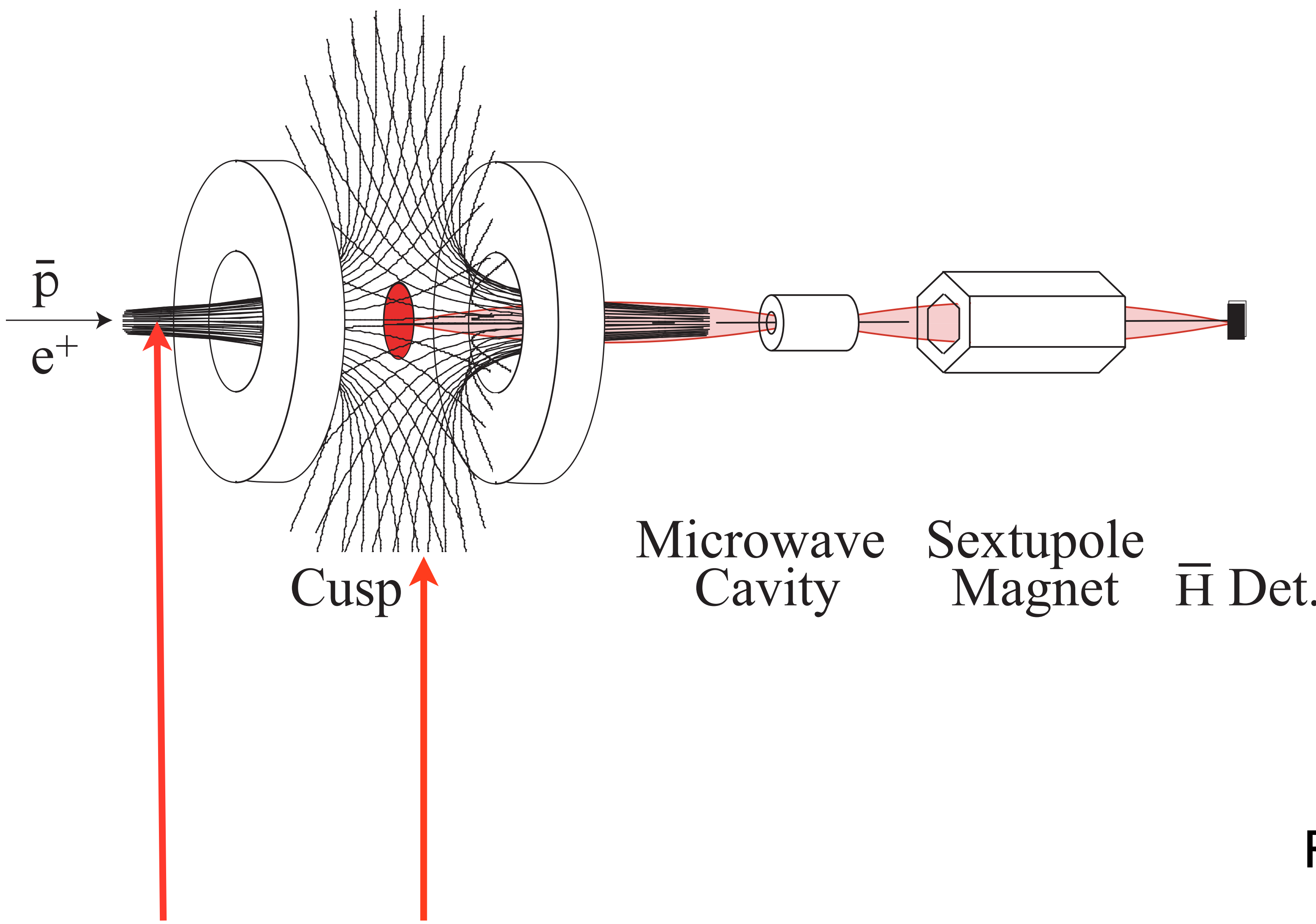
much tinkering will be needed

(in parallel, many successful studies of:
exotic atom $\bar{p}$He
interactions between $\bar{p}$ and nuclei)



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

ASACUSA “beam” (2014)



Formation

Focusing of low-field seekers

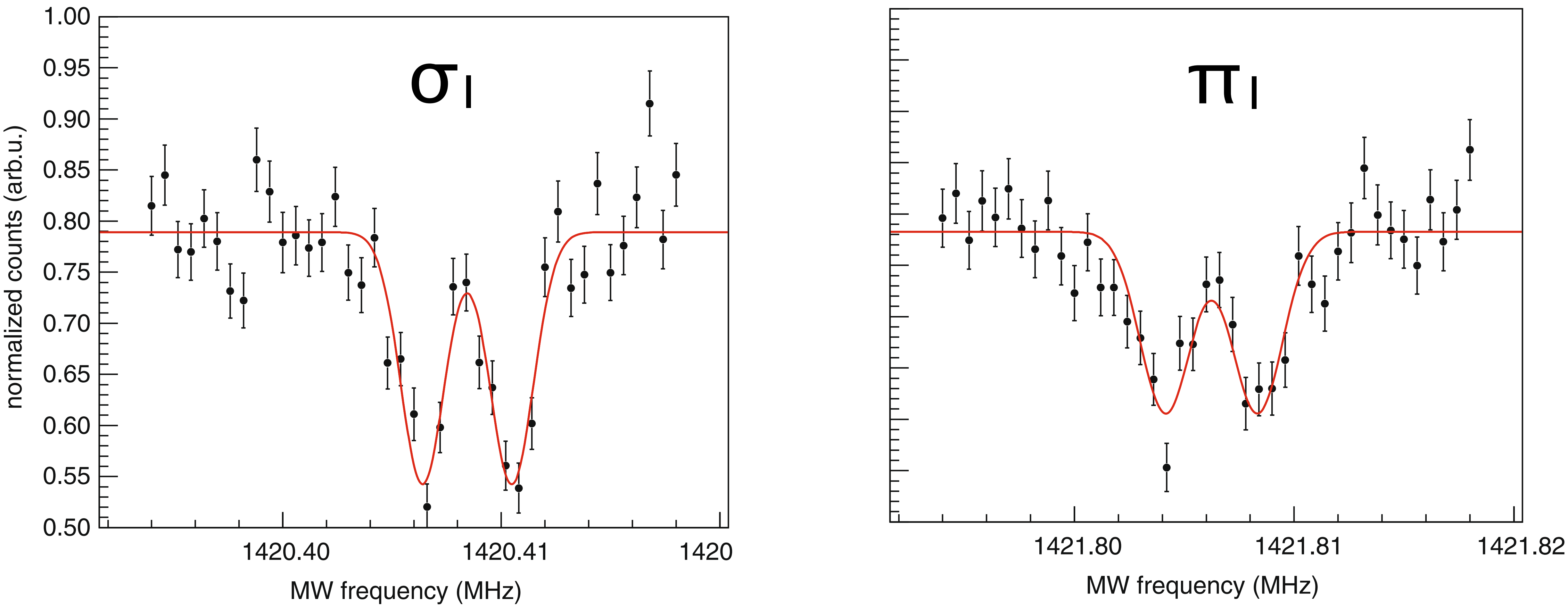
Rate: few atoms/hour

Rydberg states ? Many still in n>29

Velocity? T~ 100K-1000K?

Simulation of expected signal

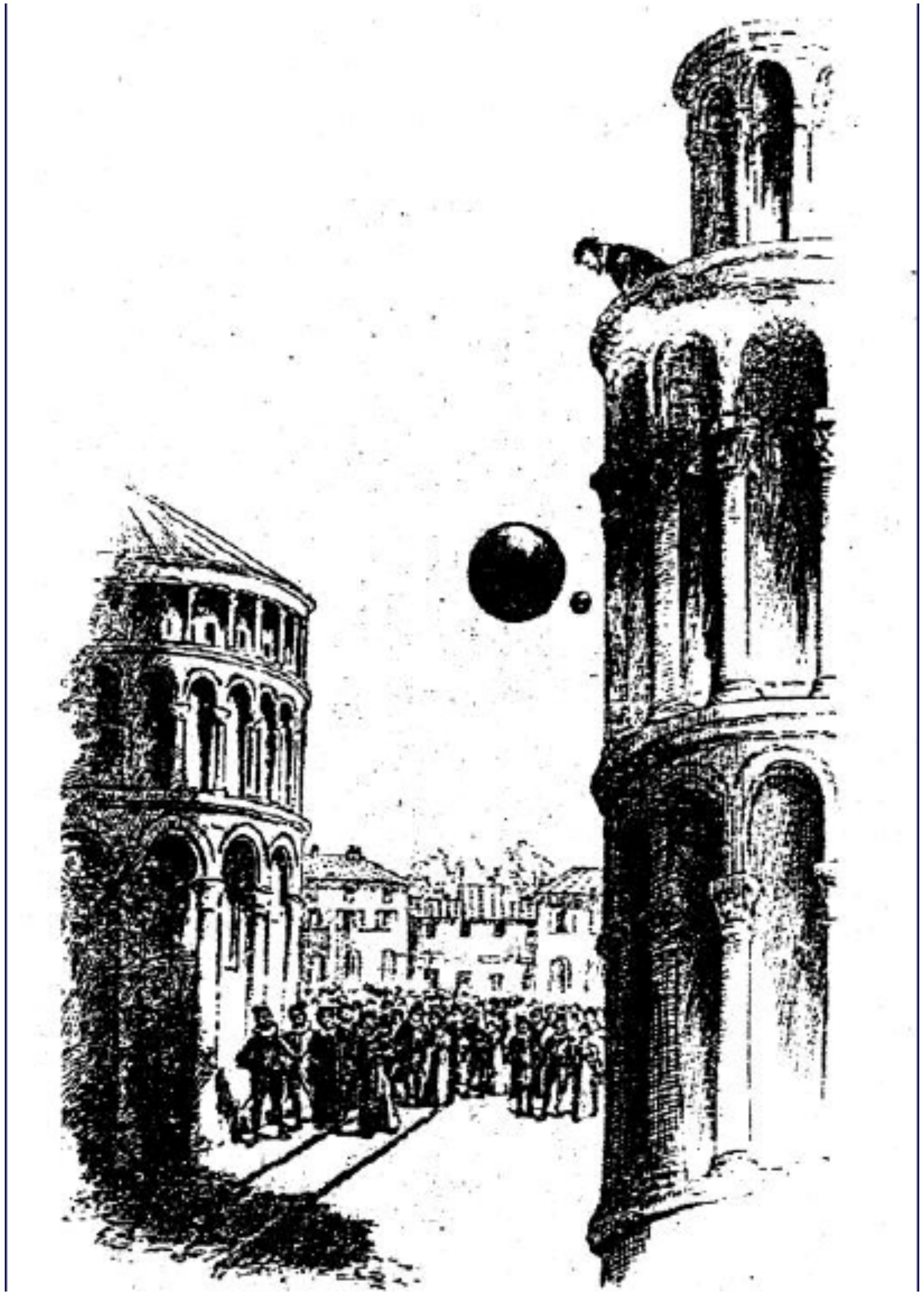
B.Juhasz, E. Widmann, Hyperfine Interact (2009) 193:305



(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 1×10^{-7} appears possible (with a rate of ~ 1HZ of ground-state atoms)

AEḡIS experiment: 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 ~ 100nV/m on $\bar{p}$

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

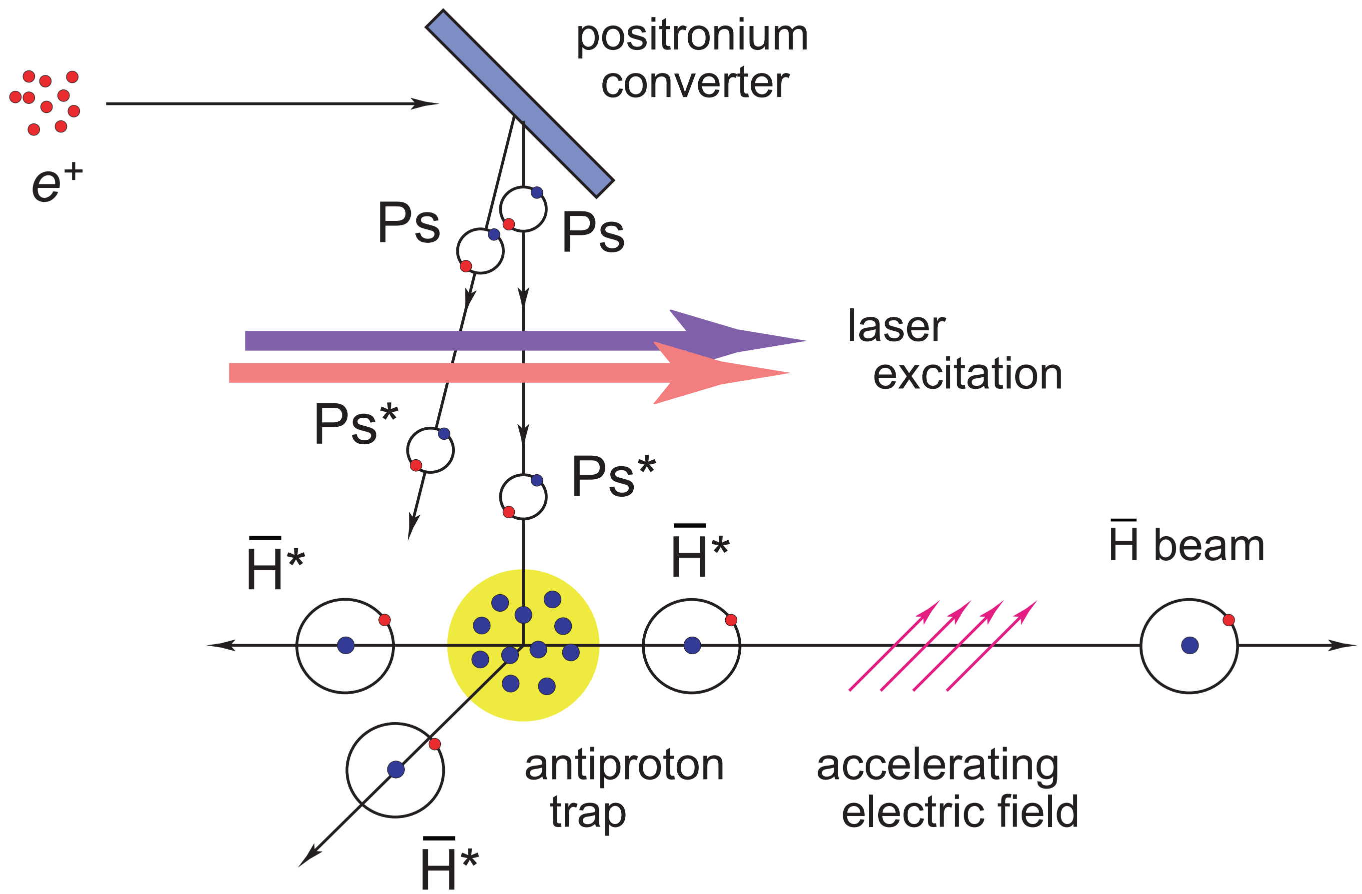
(first direct measurement on antimatter)

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

b) measurement of the beam deflection with a Moiré deflectometer

Schematic overview: pulsed horizontal beam of $\bar{\mathrm{H}}$

production: charge exchange



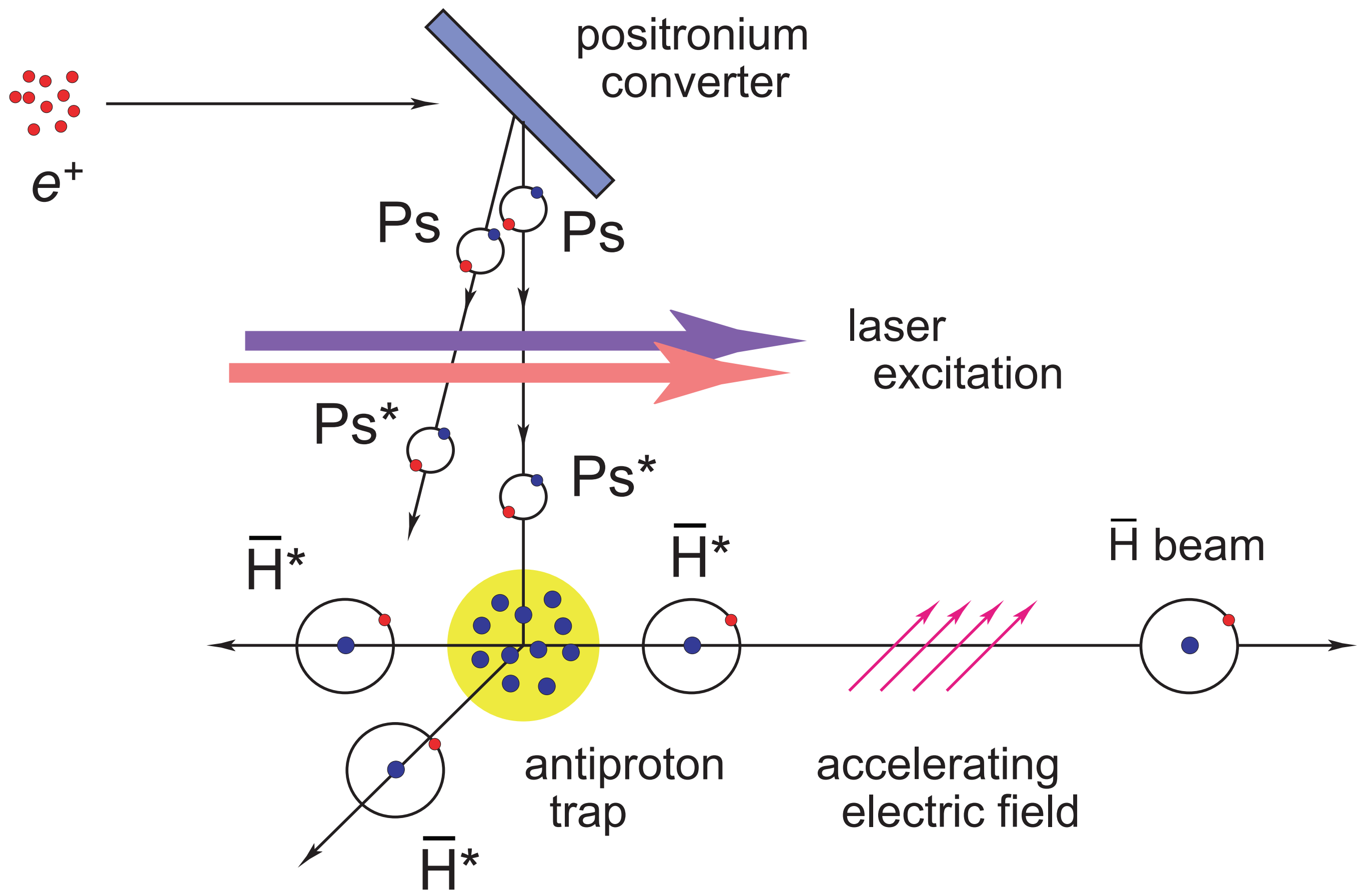
$\sigma \approx a_0 n^4$

time-of-flight: pulsed production

beam divergence: ultra-cold $\bar{p}$

Schematic overview: pulsed horizontal beam of $\bar{H}$

beam formation: Stark acceleration



$\sigma \approx a_0 n^4$

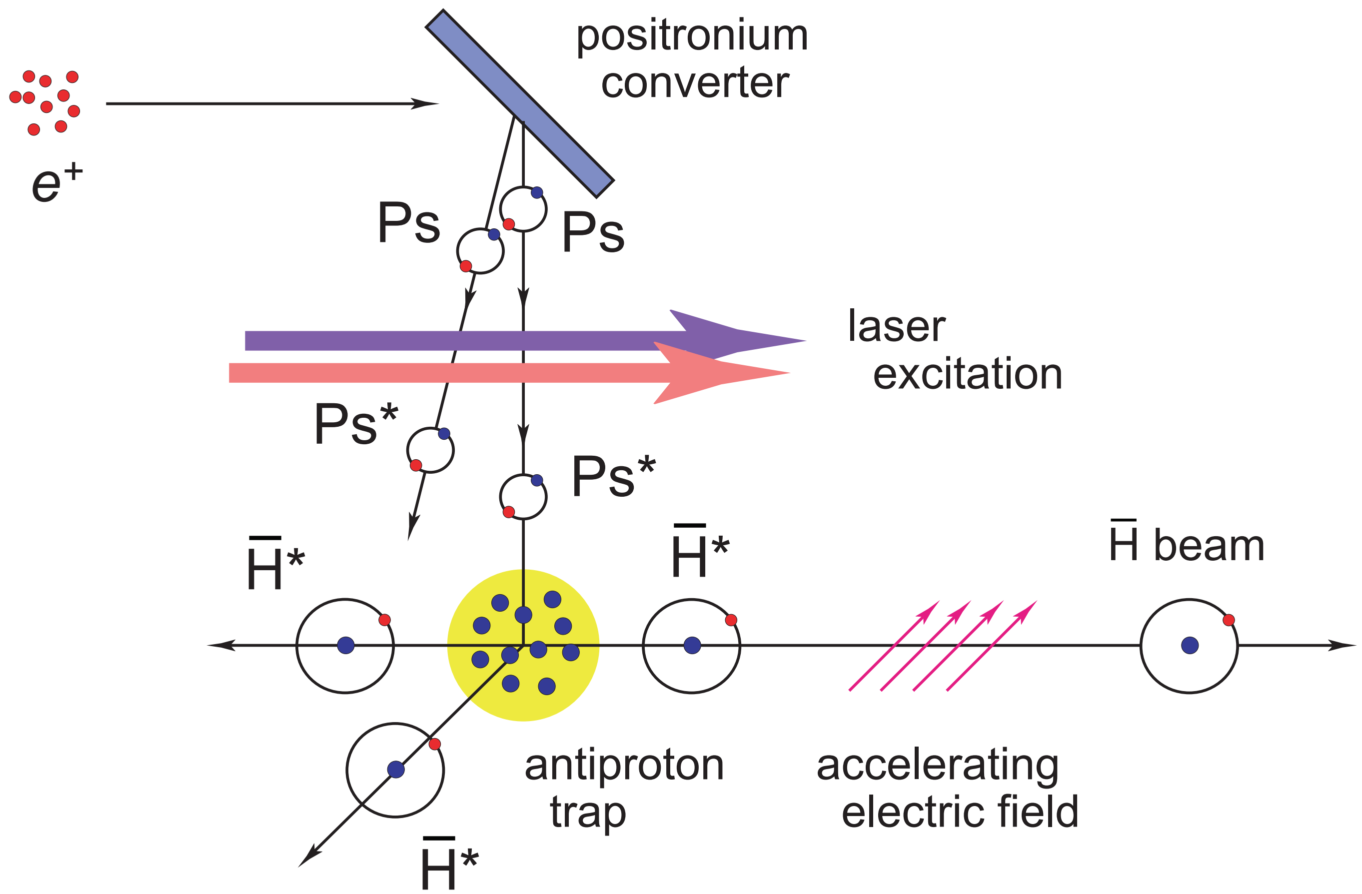
$F = -\frac{3}{2} n k \vec{\nabla} E$

time-of-flight: pulsed production

beam divergence: ultra-cold $\bar{p}$

Schematic overview: pulsed horizontal beam of $\bar{\mathrm{H}}$

beam formation: Stark acceleration



$\sigma \approx a_0 n^4$

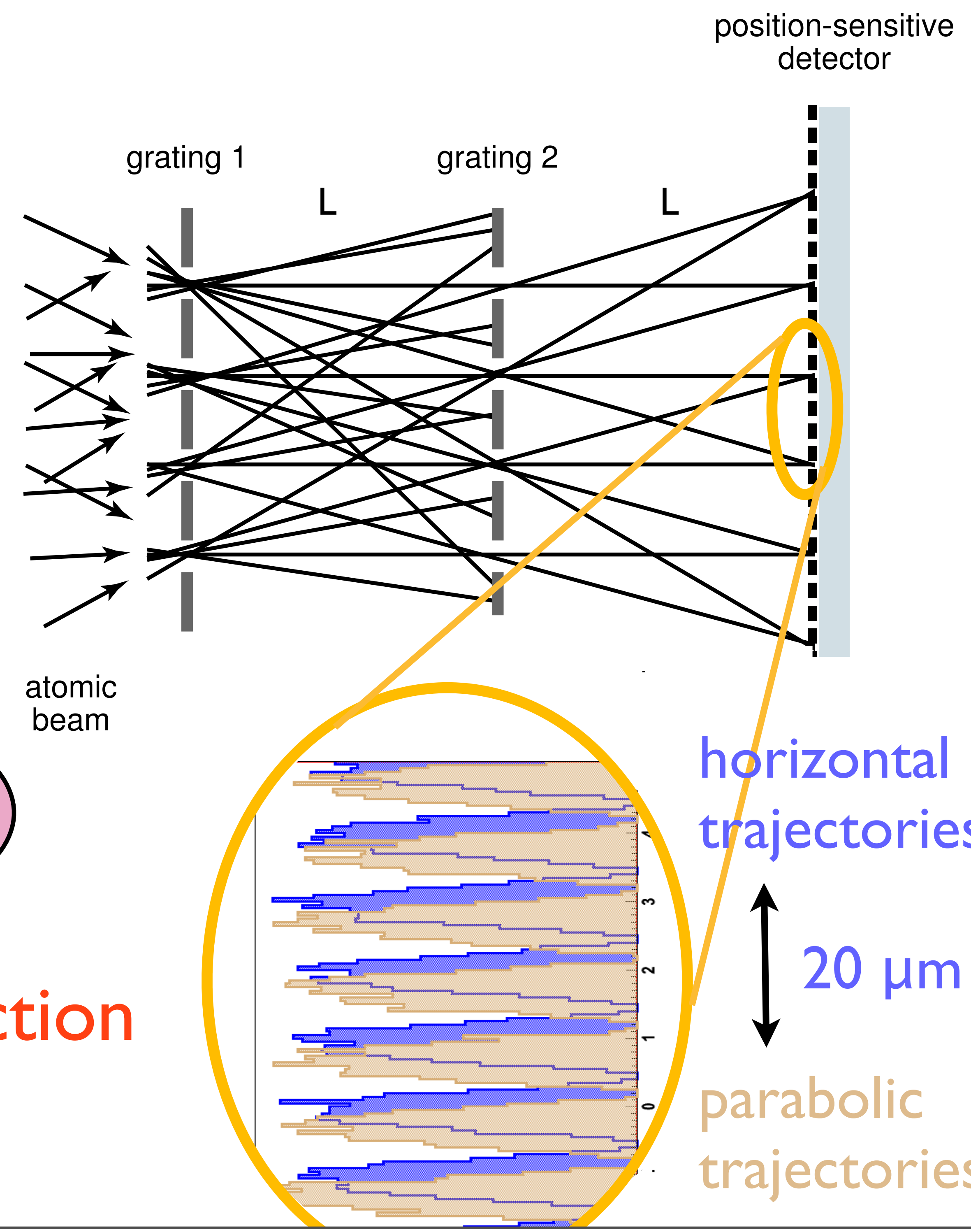
$F = -\frac{3}{2} n k \vec{\nabla} E$

time-of-flight:
beam divergence:

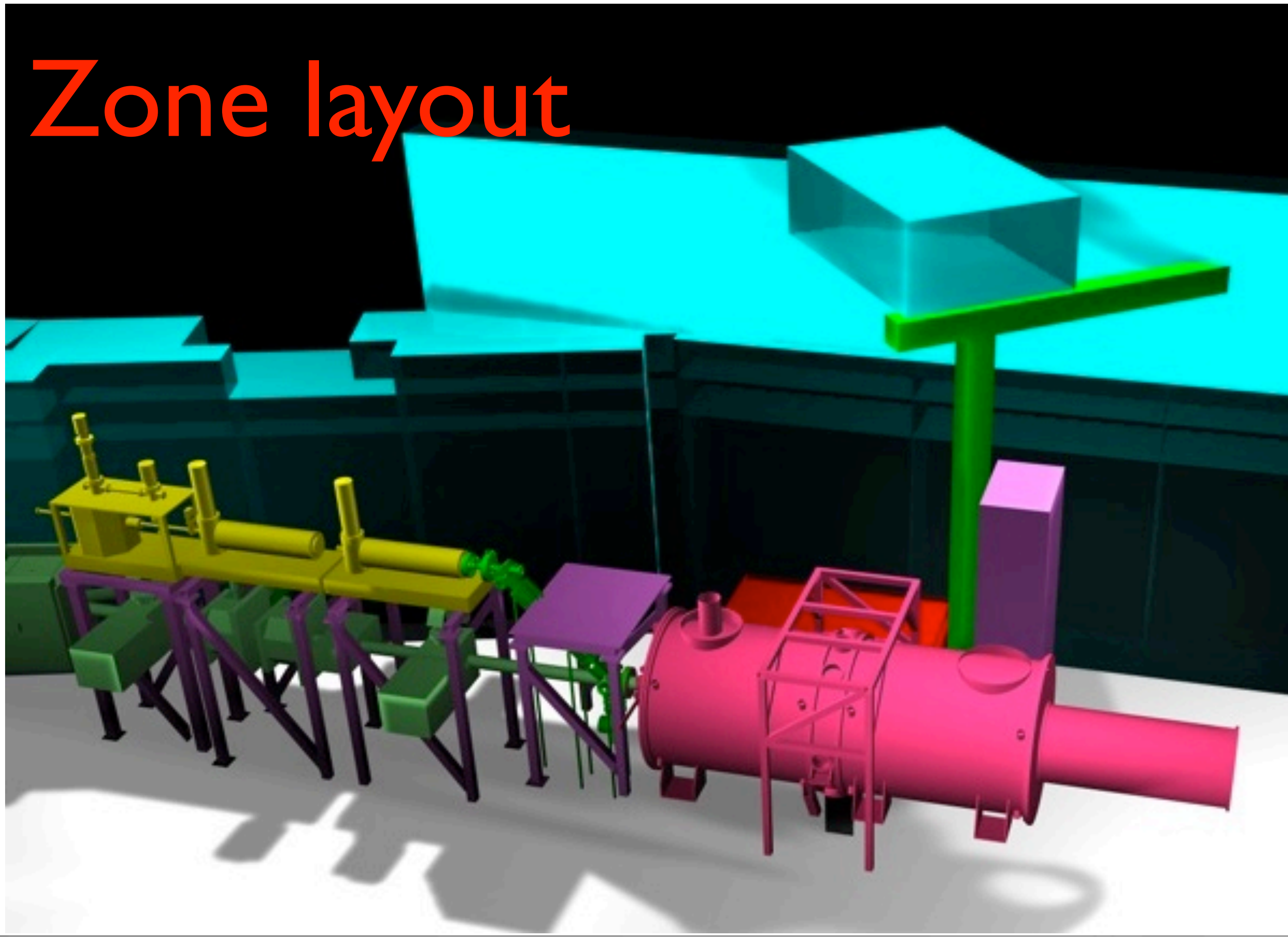
pulsed production
ultra-cold $\bar{\mathrm{p}}$

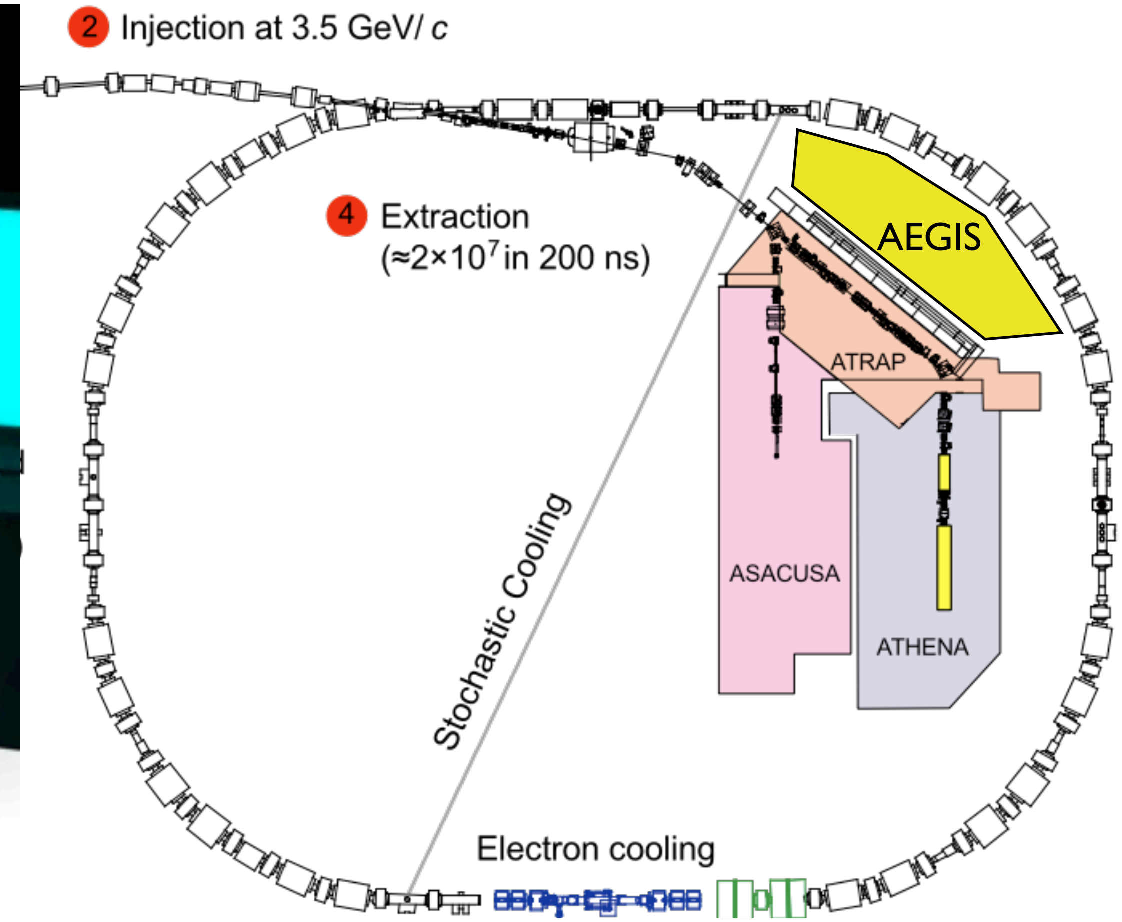
measurement: deflectometer

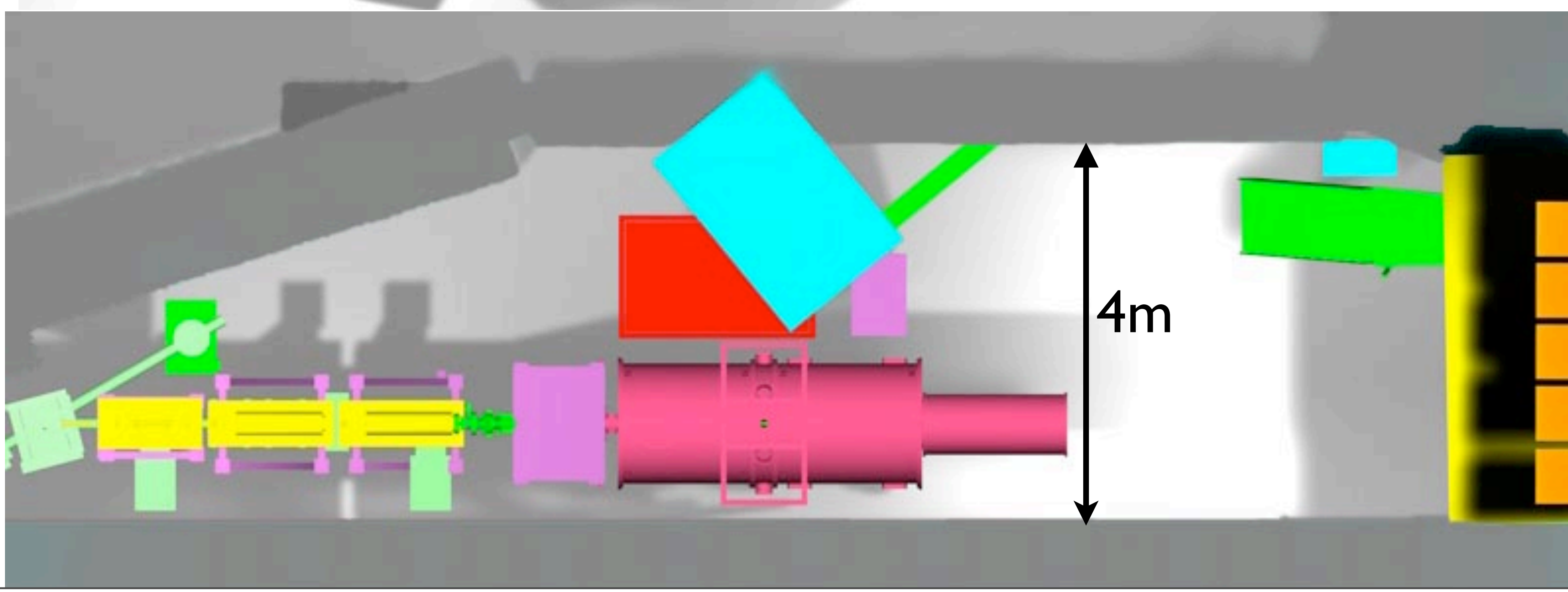
[M. K. Oberthaler *et al.*, Phys. Rev. A **54** (1996) 3165]
[A. Kellerbauer *et al.*, Phys. Rev. A **54** (1996) 3165]



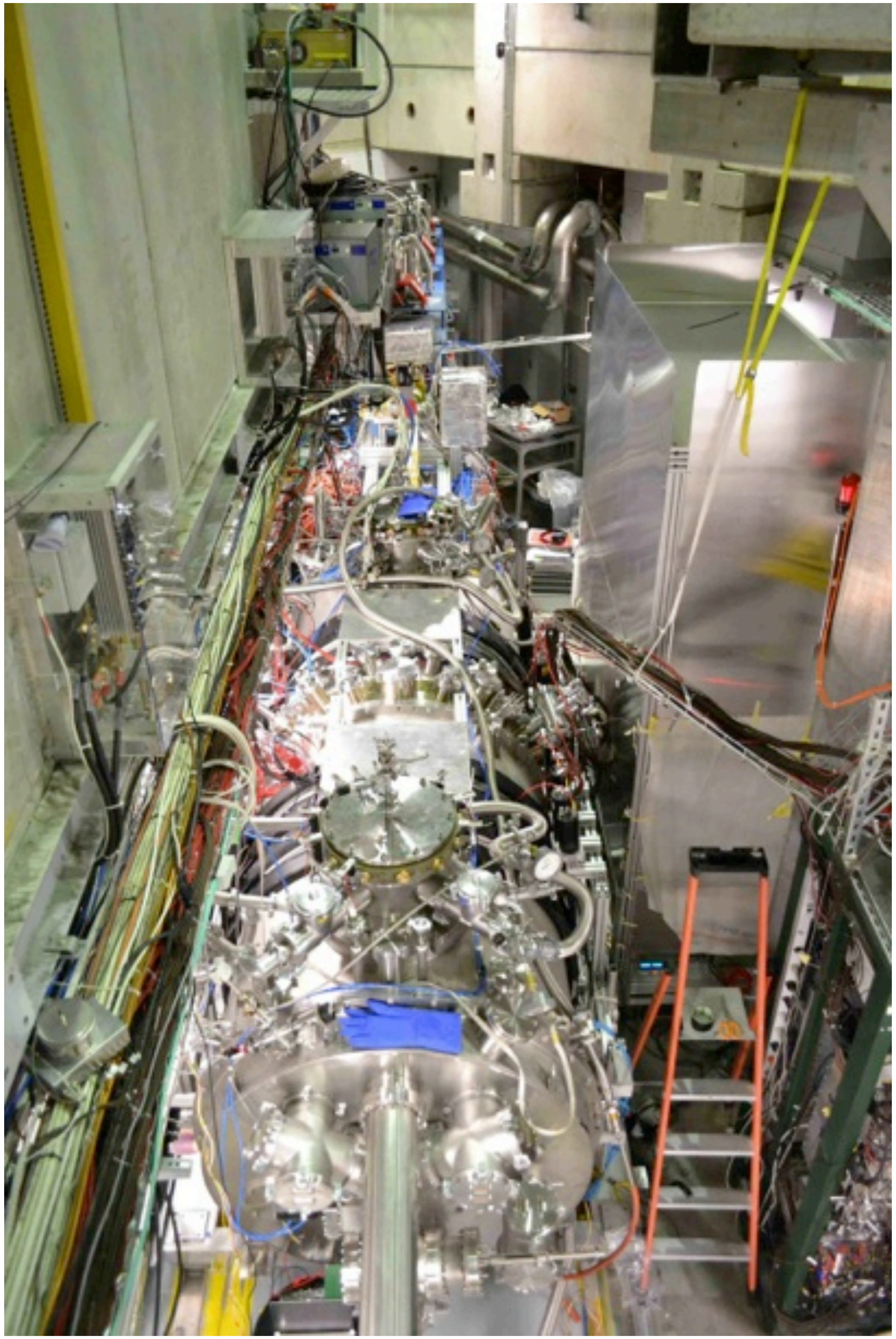
AEḡIS experiment

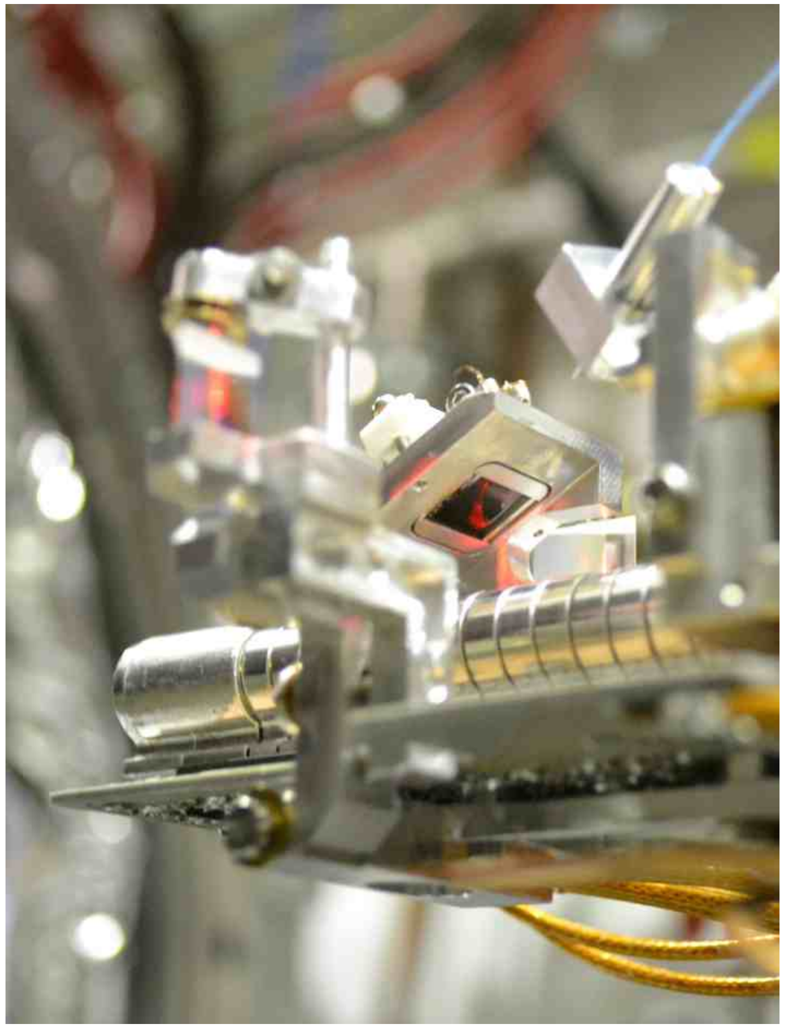




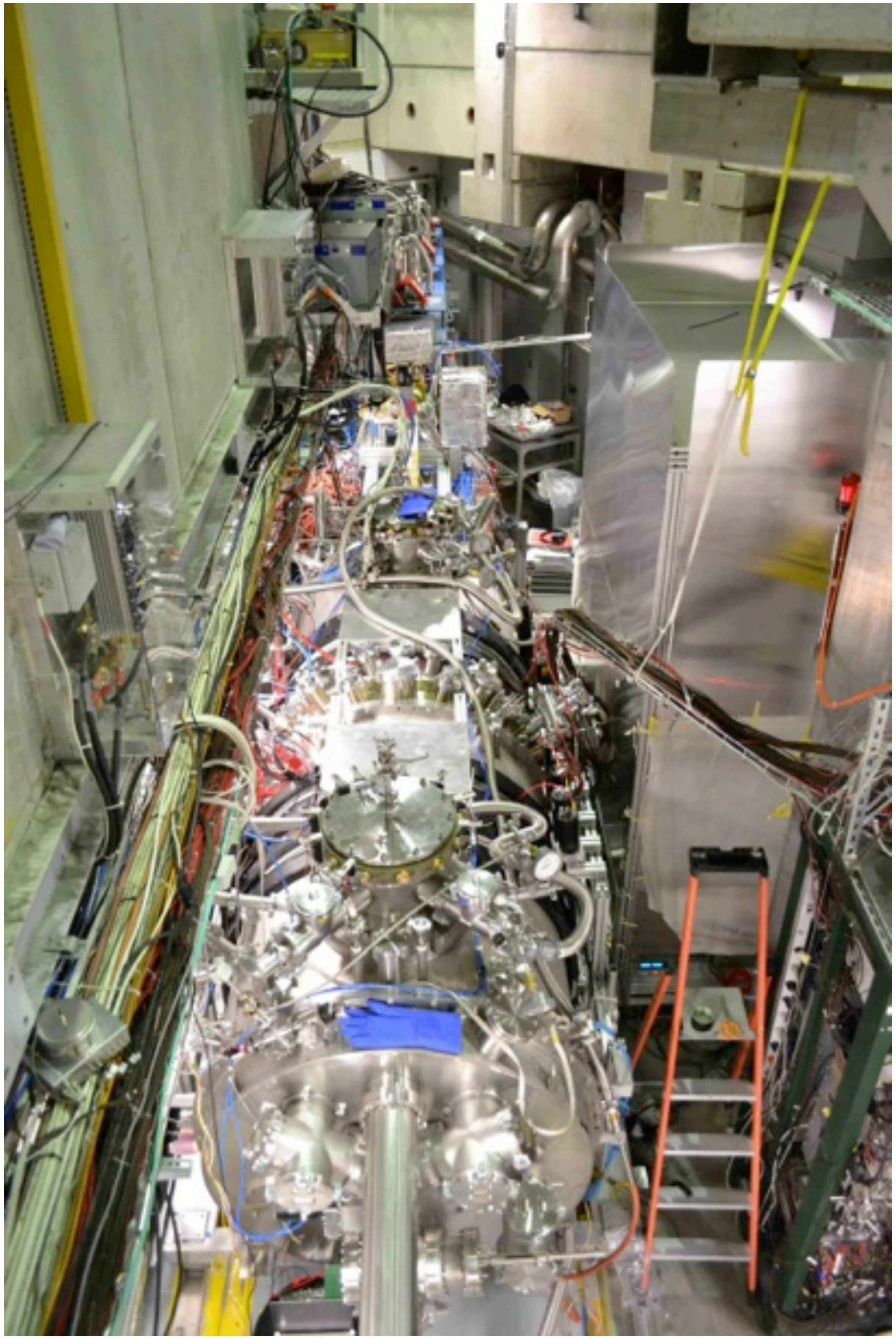


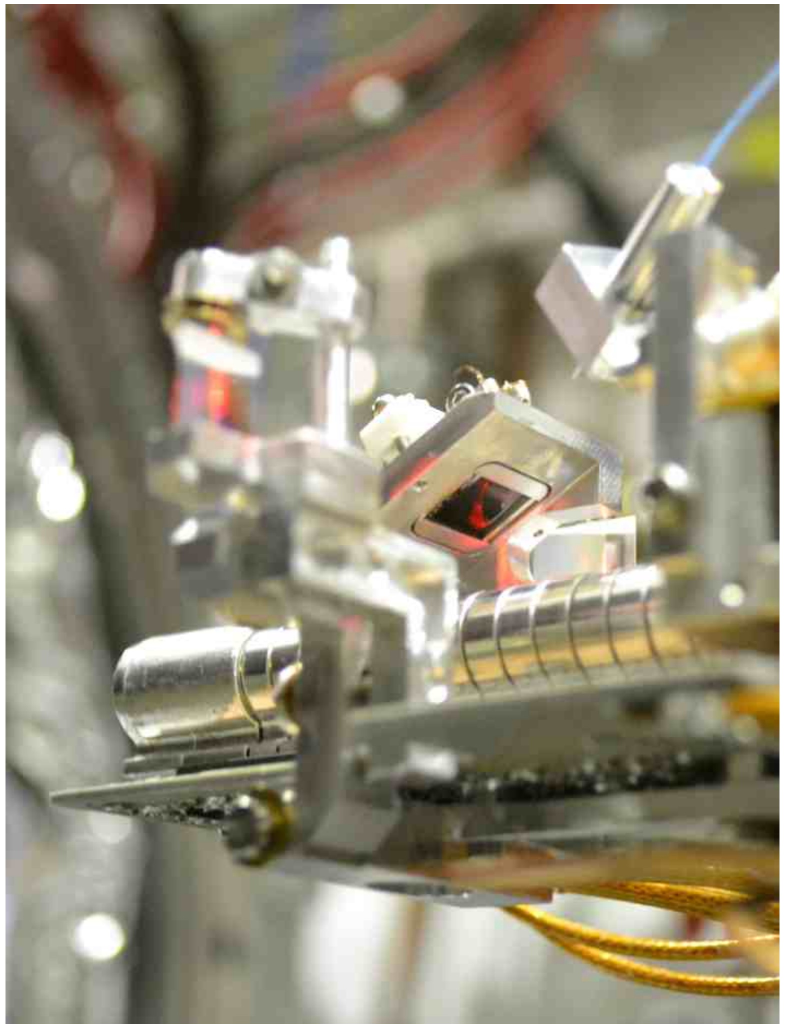
AEḡIS experiment

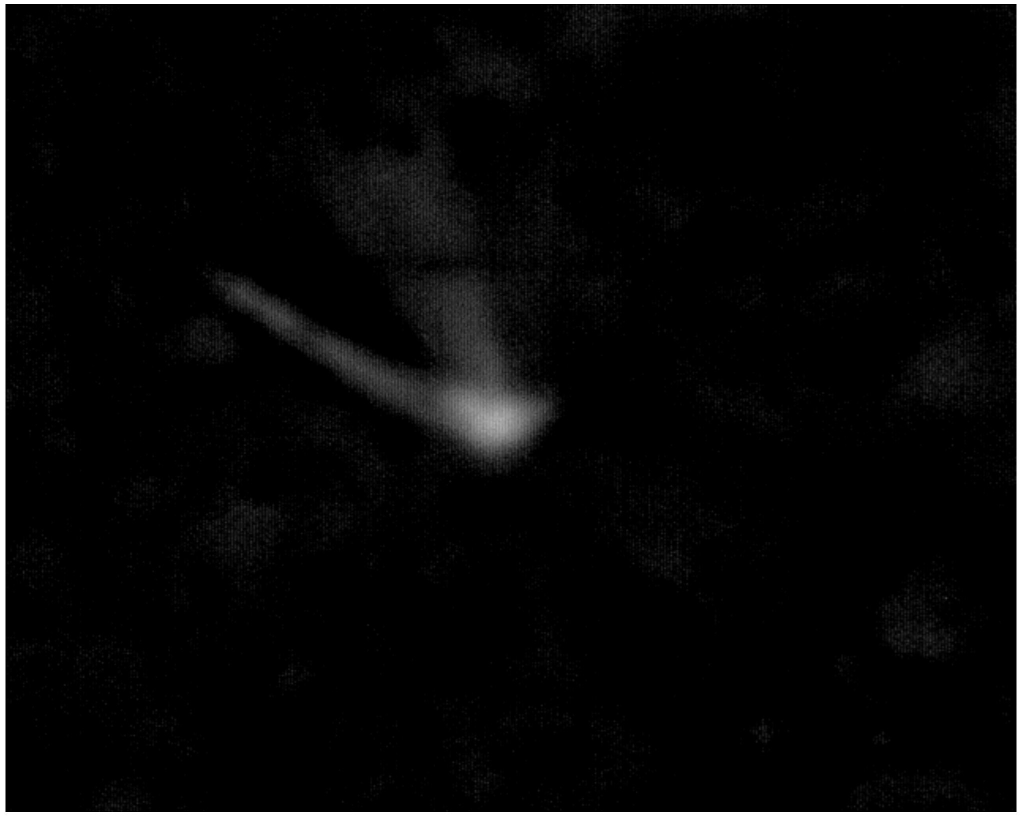




AE$\bar{g}$IS experiment

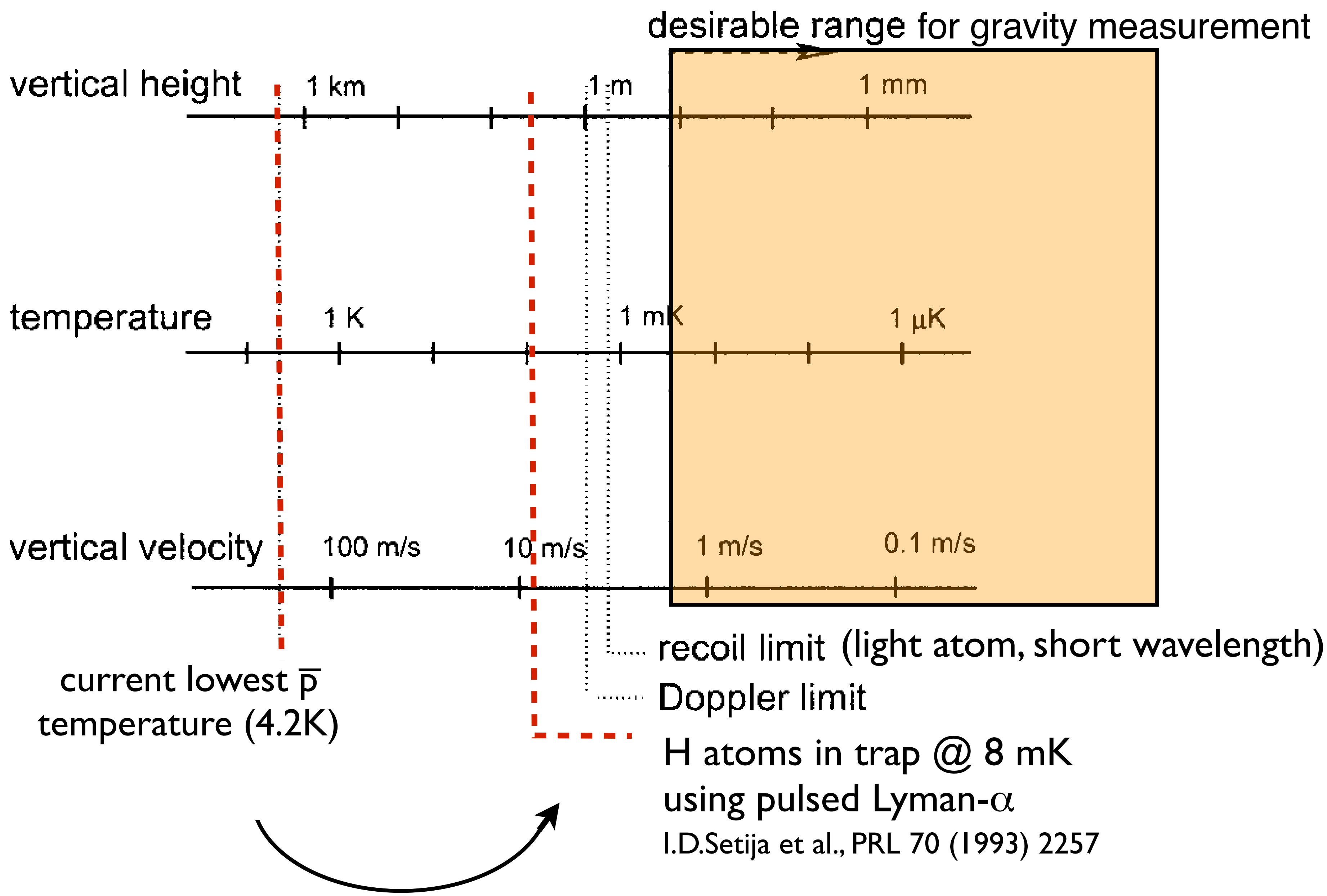






"Ultra-cold" (~1 μK) Antihydrogen

“Ultra-cold” (~1 μK) Antihydrogen



1S→2P laser cooling: cw Lyman-α source

Eikema, Walz, Hänsch, PRL 86 (2001) 5679

sympathetic cooling to the rescue

GBAR experiment at AD

cooling of $\overline{H}^+$

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

Anion cooling for AEgIS

sympathetic cooling to the rescue

GBAR experiment at AD

cooling of $\overline{H}^+$

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

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

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

Roy & Sinha, EPJD 47 (2008) 327

Anion cooling for AEgIS

sympathetic cooling to the rescue

GBAR experiment at AD

cooling of $\overline{H}^+$

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

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

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

Roy & Sinha, EPJD 47 (2008) 327

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

e.g. $In^+ \rightarrow 20\ \mu K$

Anion cooling for AEgIS

sympathetic cooling to the rescue

GBAR experiment at AD

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. $In^+ \rightarrow 20\ \mu K$

photodetachment at ~6083 cm^{-1}

Anion cooling for AEgIS

sympathetic cooling to the rescue

GBAR experiment at AD

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. $In^+ \rightarrow 20\ \mu K$

photodetachment at ~6083 cm^{-1}

gravity measurement via "TOD"

Anion cooling for AEgIS

sympathetic cooling to the rescue

GBAR experiment at AD

cooling of $\overline{H}^+$

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

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

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

Roy & Sinha, EPJD 47 (2008) 327

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

e.g. $In^+ \rightarrow 20\ \mu K$

photodetachment at ~6083 cm^{-1}

gravity measurement via "TOD"

Anion cooling for AEgIS

cooling of $\overline{p}$

Warring et al, PRL 102 (2009) 043001

Fischer et al, PRL 104 (2010) 073004

sympathetic cooling to the rescue

GBAR experiment at AD

cooling of $\overline{H}^+$

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

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

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

Roy & Sinha, EPJD 47 (2008) 327

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

e.g. In^+ → 20 μK

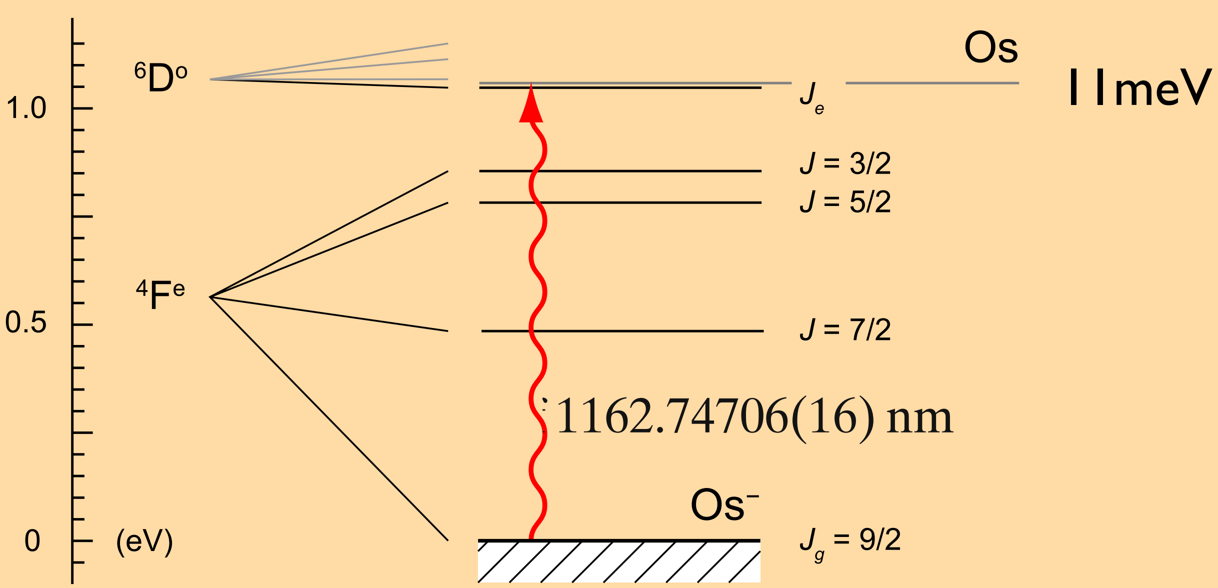
photodetachment at ~6083 cm^{-1}

gravity measurement via "TOD"

Anion cooling for AEgIS

cooling of $\overline{p}$

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



sympathetic cooling to the rescue

GBAR experiment at AD

cooling of $\overline{H}^+$

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

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

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

Roy & Sinha, EPJD 47 (2008) 327

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

e.g. In^+ → 20 μK

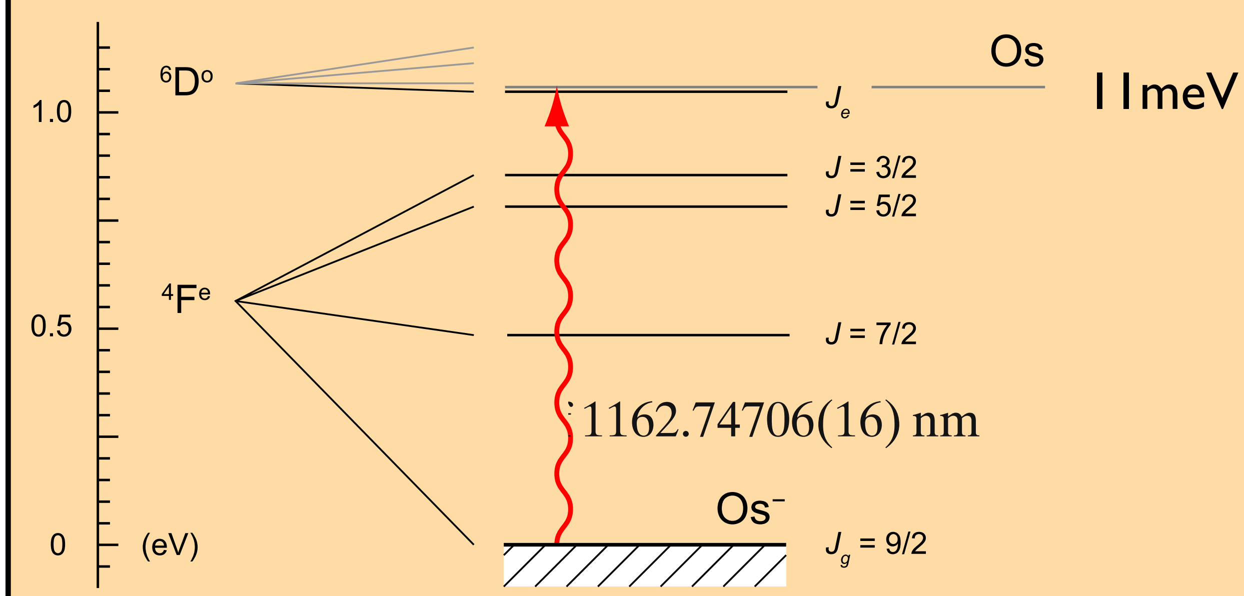
photodetachment at ~6083 cm^{-1}

gravity measurement via "TOD"

Anion cooling for AEgIS

cooling of $\overline{p}$

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 ($T_D \approx 0.24\ \mu K$)

sympathetic cooling to the rescue

GBAR experiment at AD

cooling of $\overline{H}^+$

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

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

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

Roy & Sinha, EPJD 47 (2008) 327

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

e.g. $In^+ \rightarrow 20\ \mu K$

photodetachment at ~6083 cm^{-1}

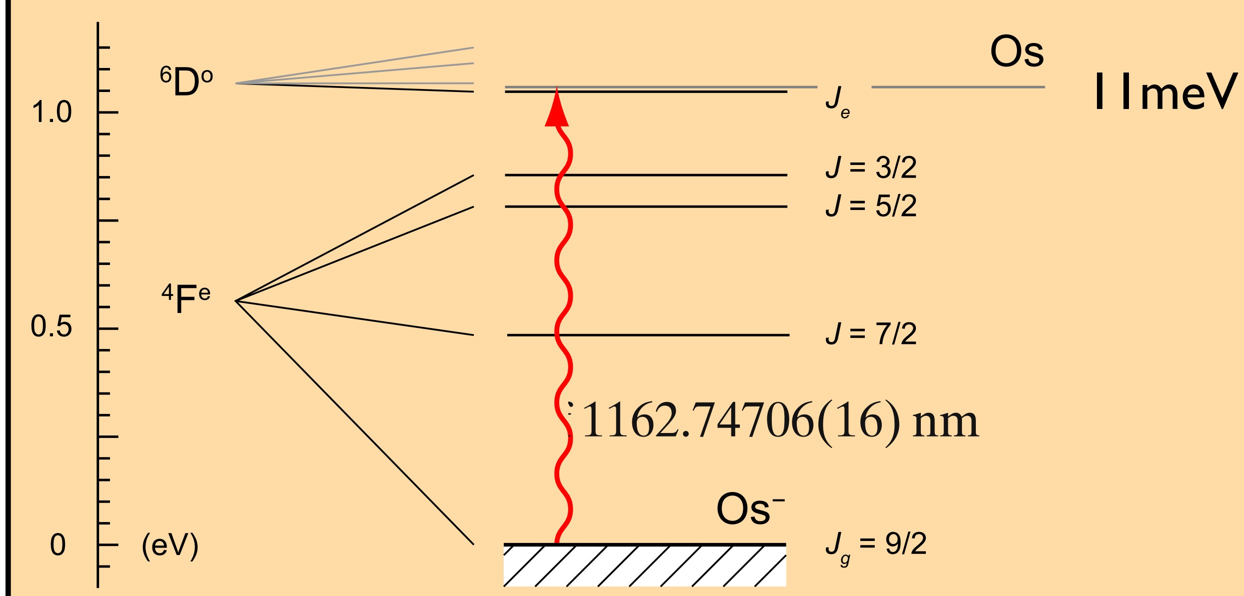
gravity measurement via "TOD"

Anion cooling for AEgIS

cooling of $\overline{p}$

Warring et al, PRL 102 (2009) 043001

Fischer et al, PRL 104 (2010) 073004



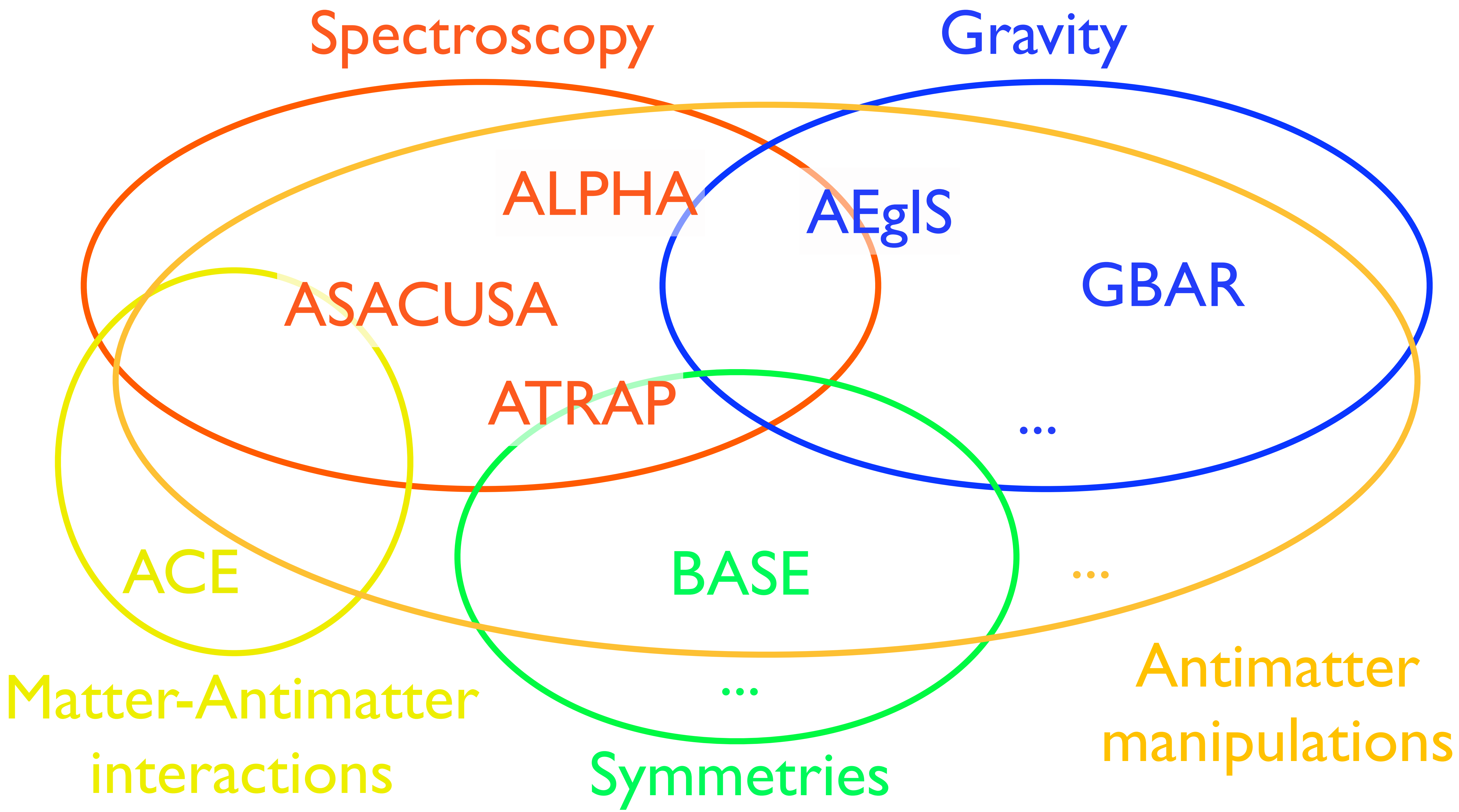
very weak cooling

→ 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)

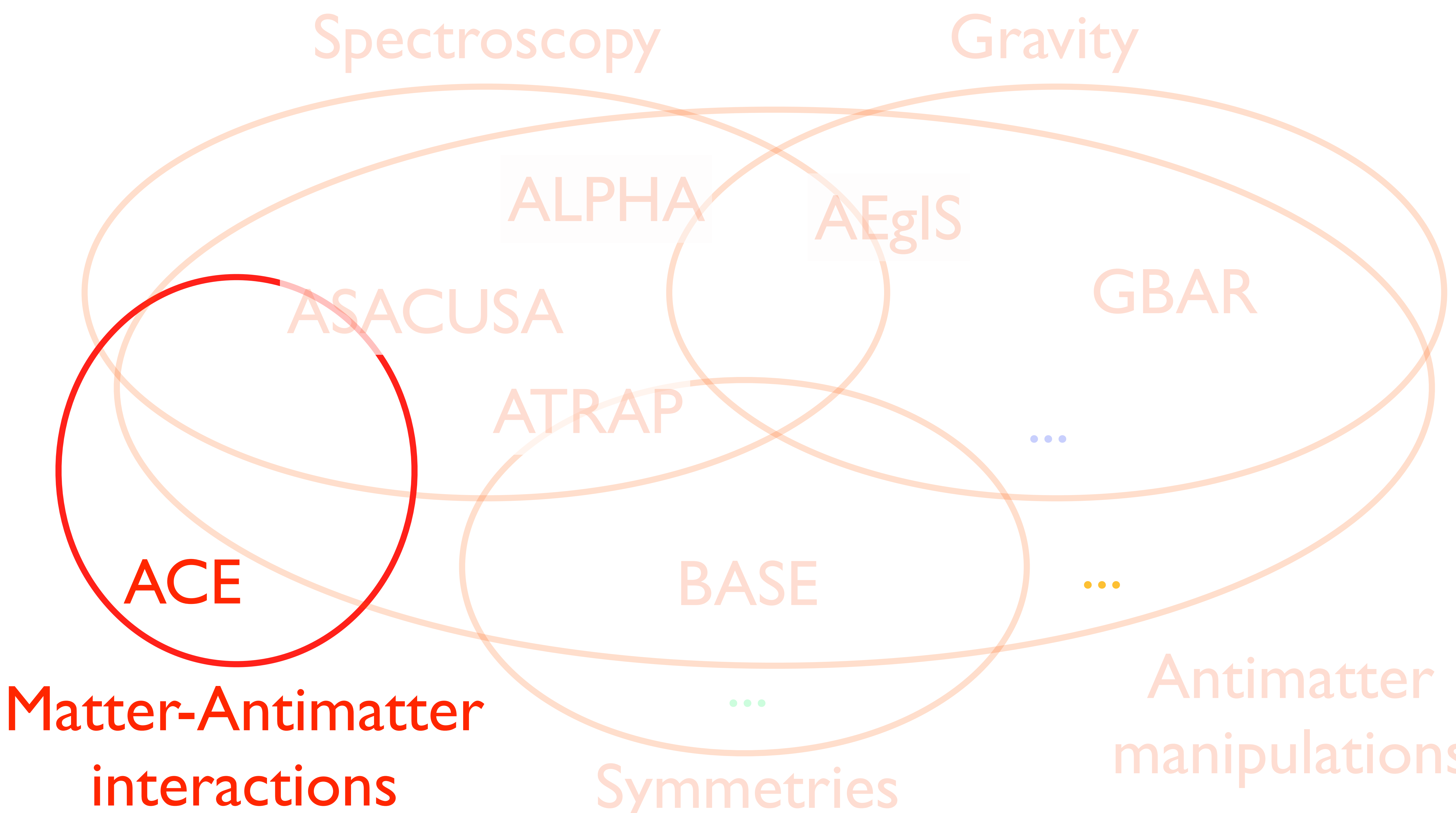
to summarize the situation...

Antiproton and antihydrogen experiments at the AD:



to summarize the situation...

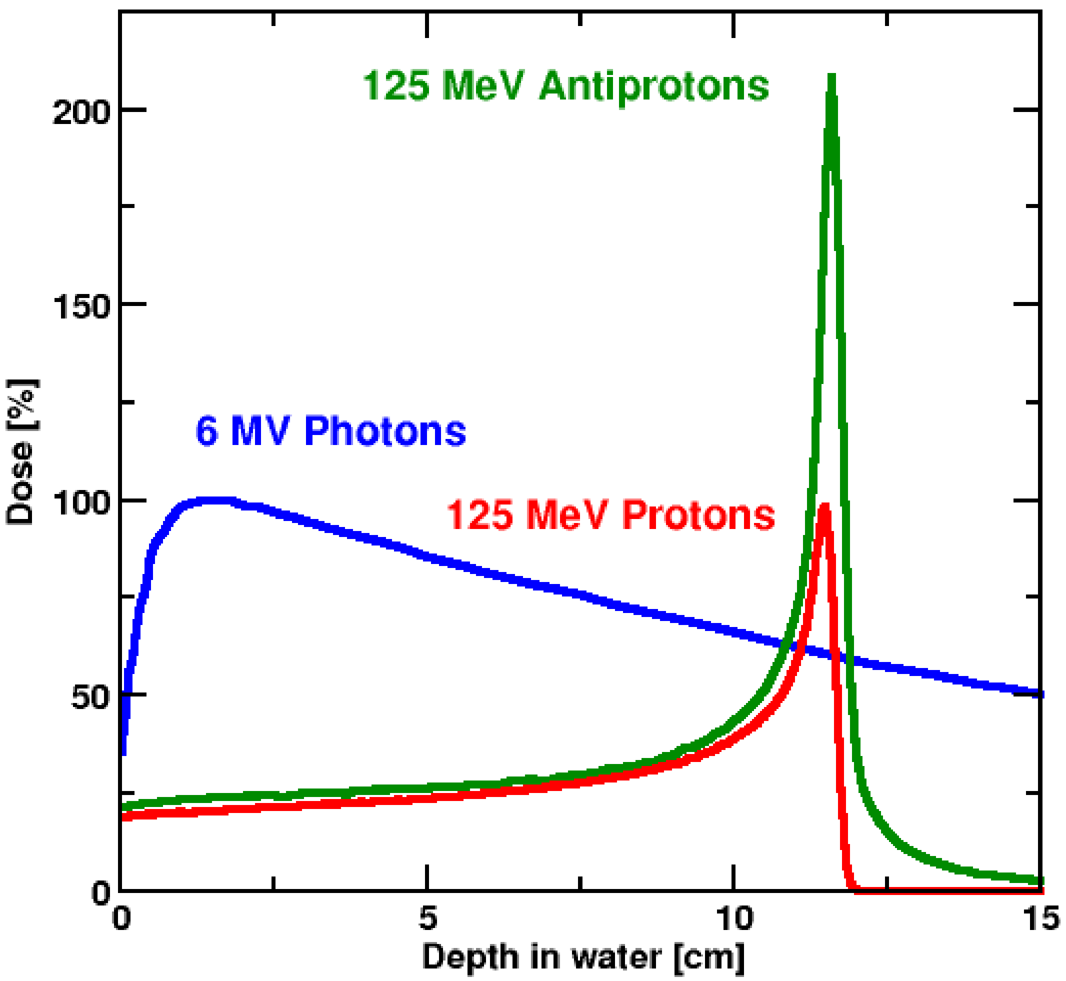
Antiproton and antihydrogen experiments at the AD:

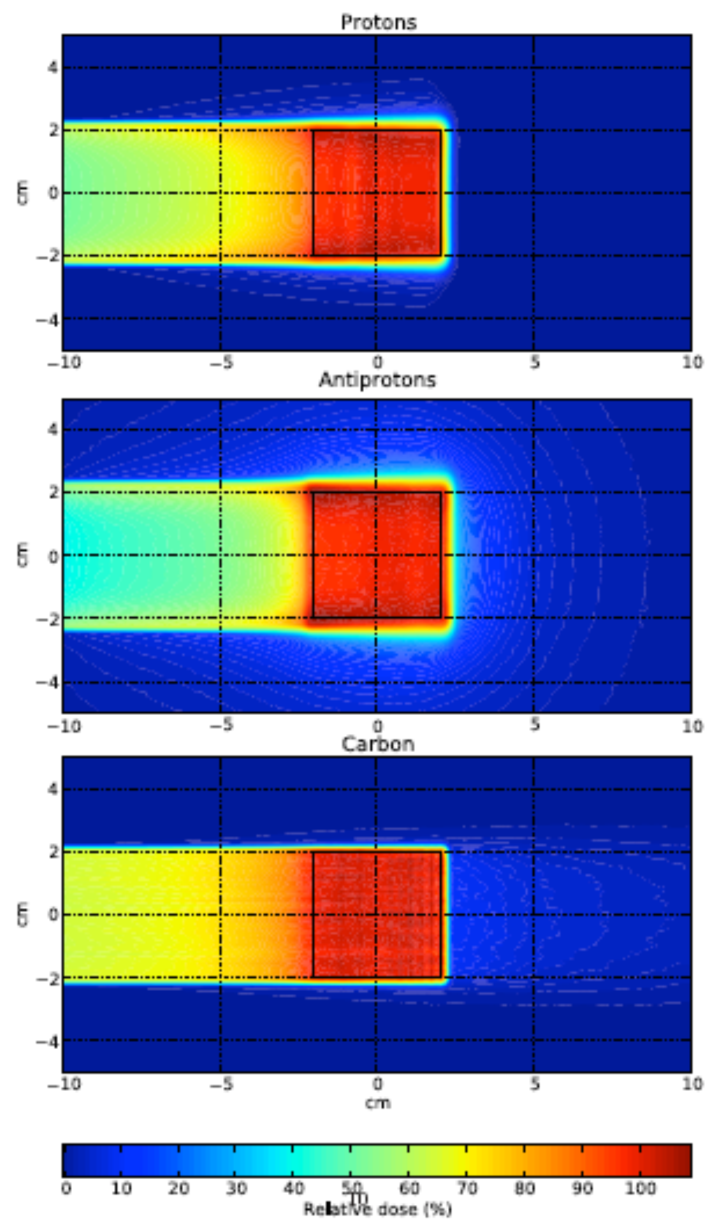


AD-4/ACE

Biological Effects of Antiprotons

Are Antiprotons a Candidate for Cancer Therapy?

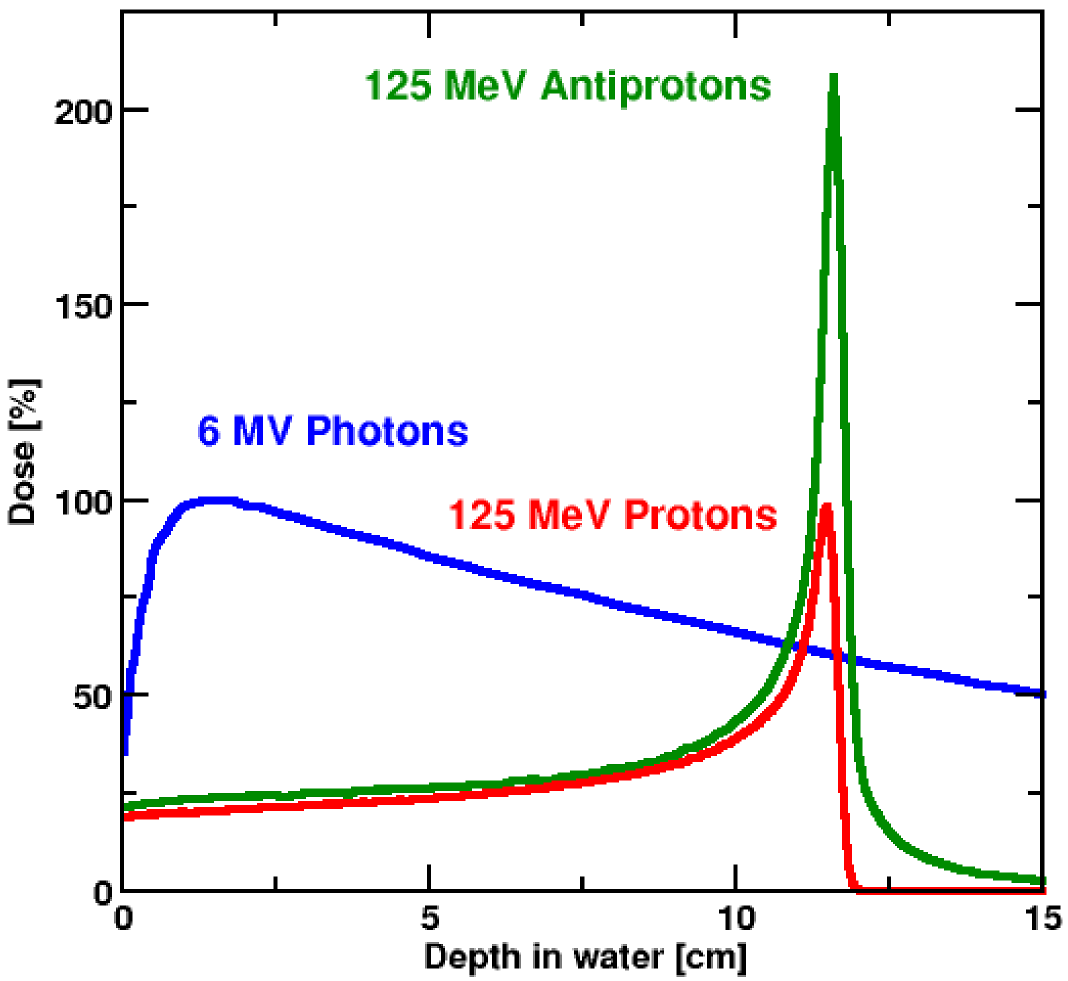


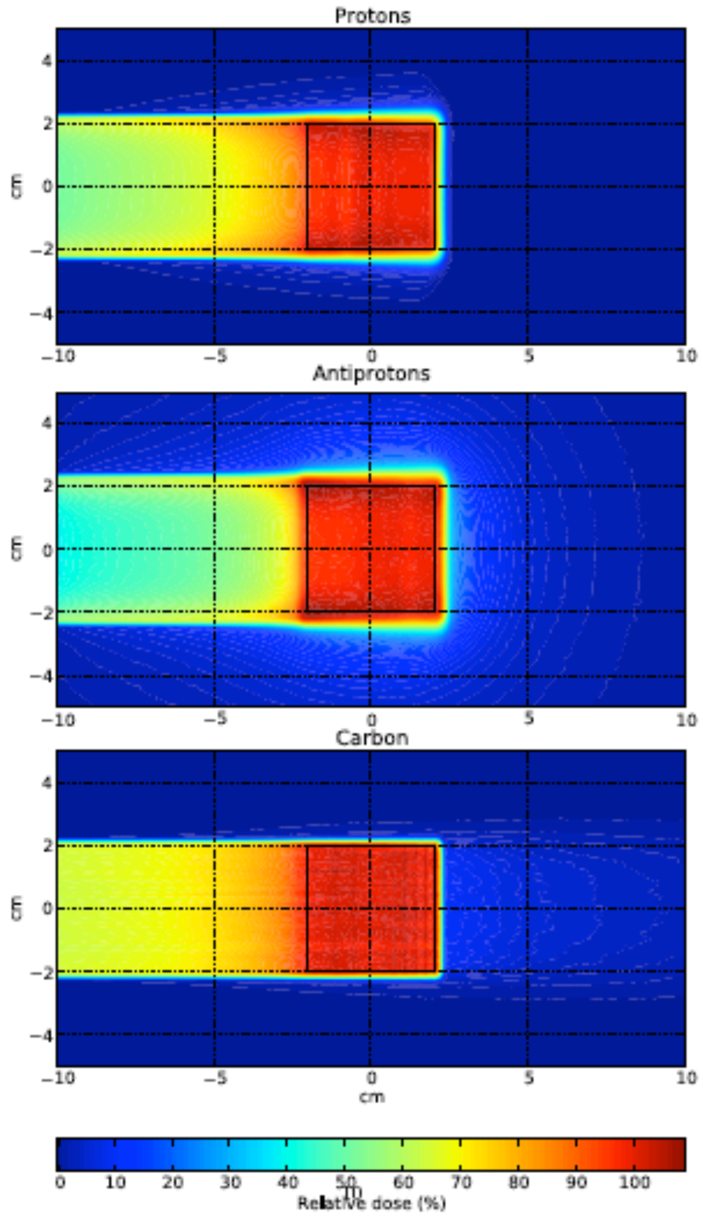


AD-4/ACE

Biological Effects of Antiprotons

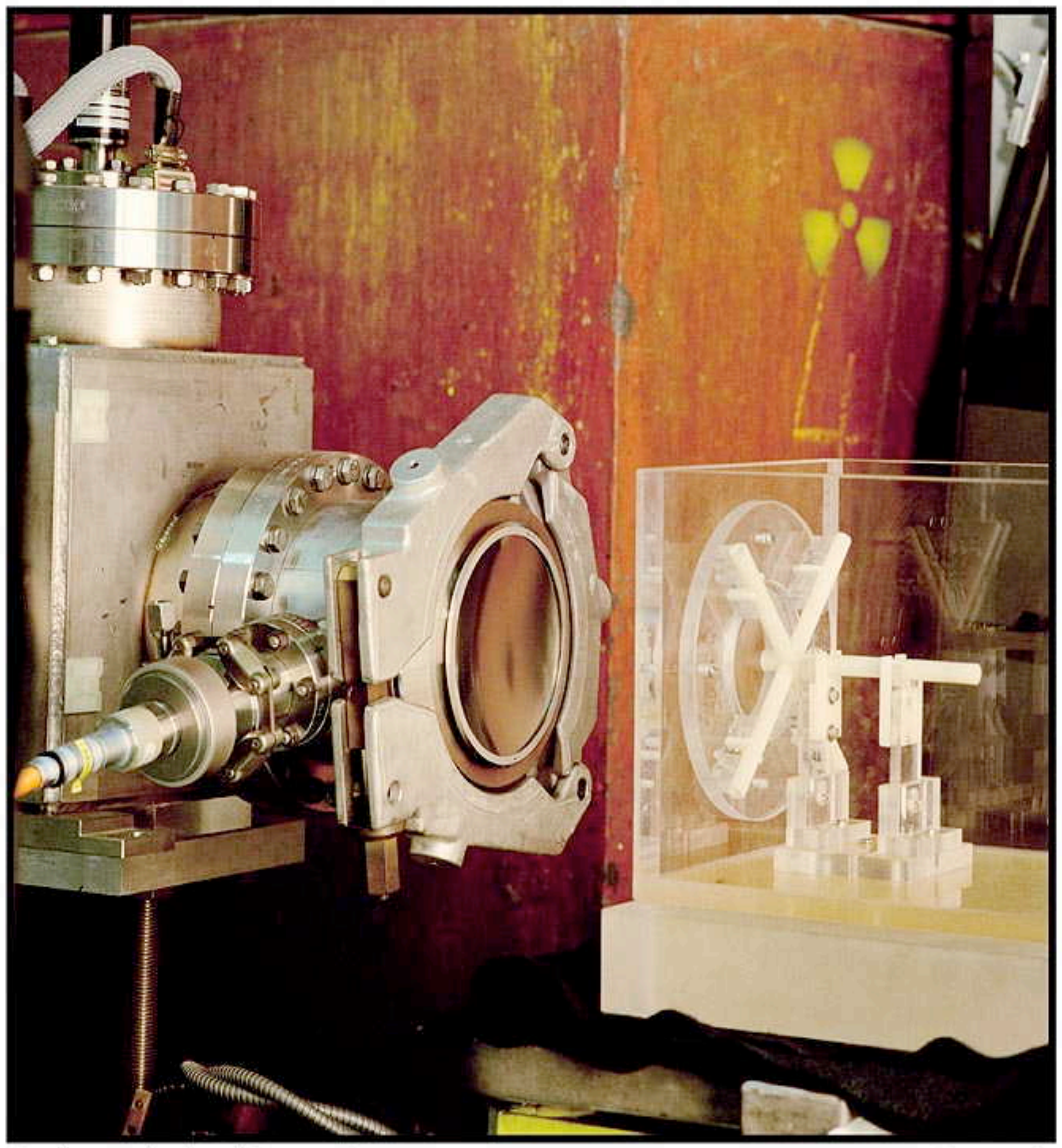
Are Antiprotons a Candidate for Cancer Therapy?





Detailed dose plans (<u>including RBE</u>) will need to be developed to assess applicability of particle types for different tumor types and locations!

The AD-4 Experiment at CERN



© Alban Kakulya / STRATES
CERN, Genève, Suisse, le 6 août 2003

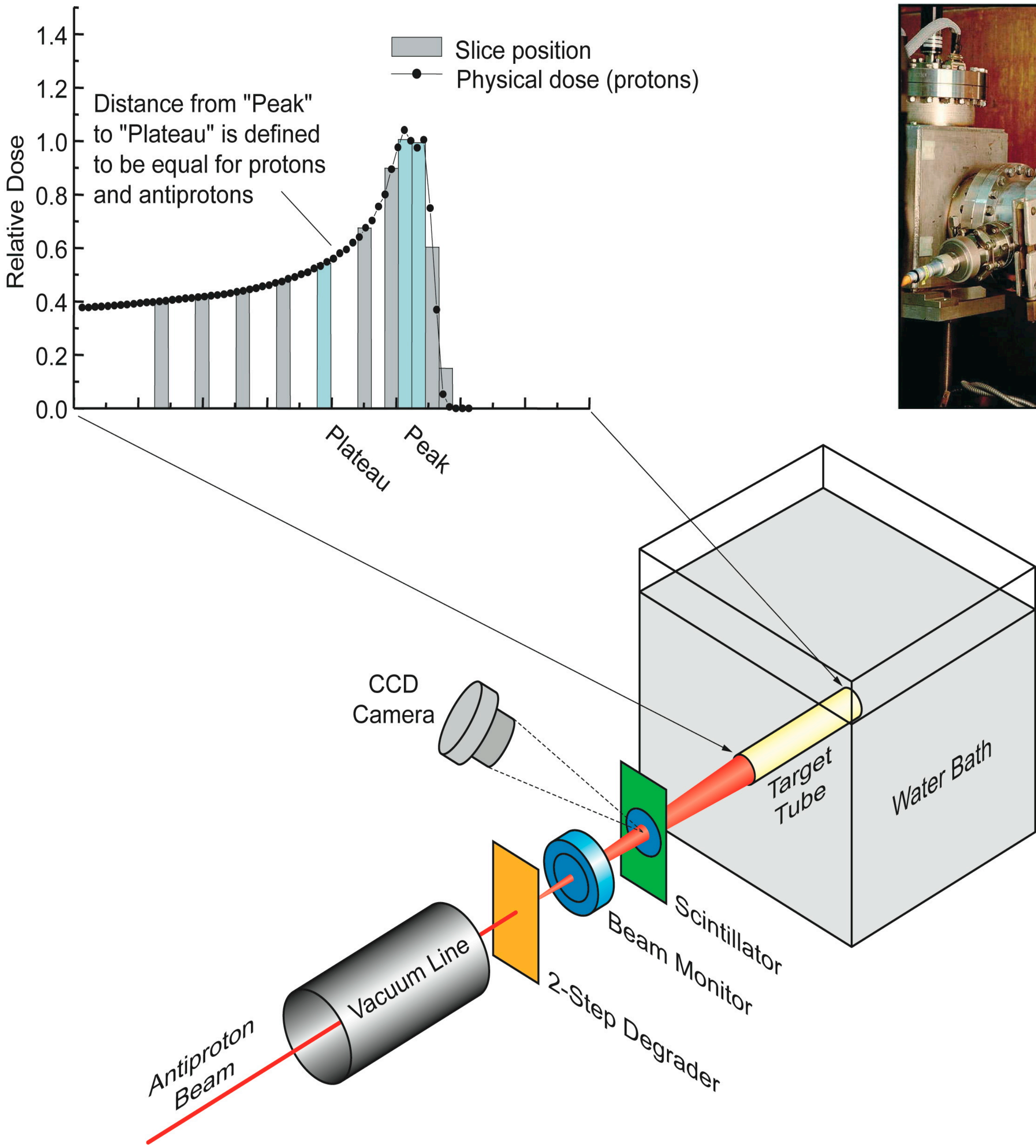
OA 414/1

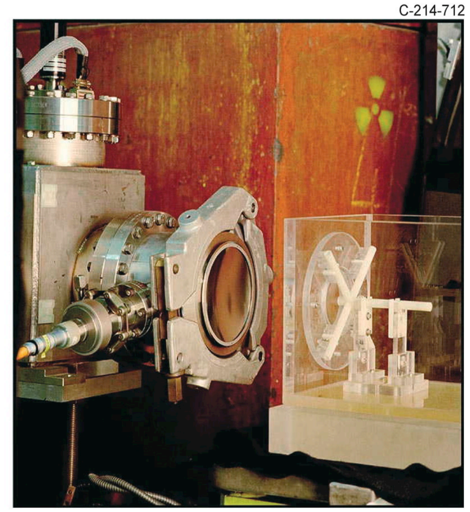
Number of Surviving cells

INGREDIENTS:

- **V-79 Chinese Hamster cells embedded in gelatin**
- **Antiproton beam from AD (126 MeV)**

The AD-4 Experiment at CERN





INGREDIENTS:

- V-79 Chinese Hamster cells embedded in gelatin
- Antiproton beam from AD (126 MeV)

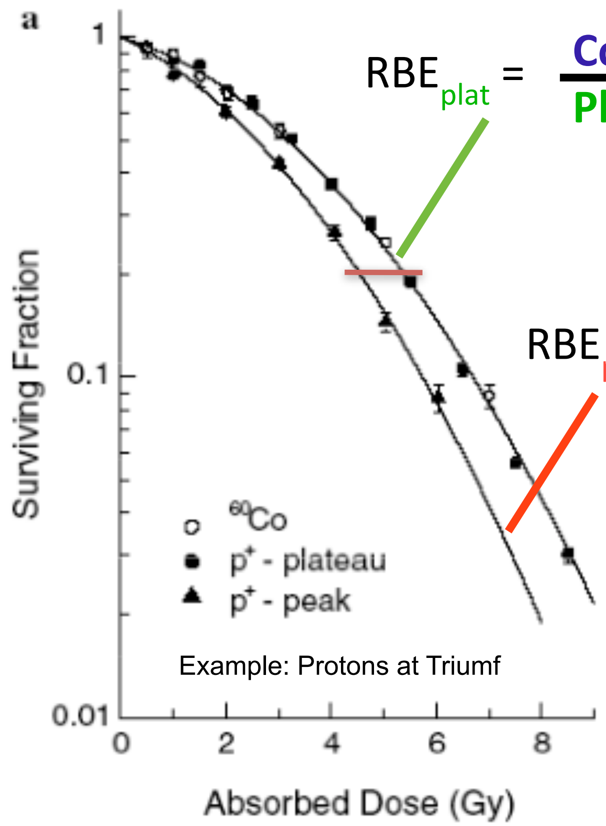
METHOD:

- Irradiate cells with dose levels to give survival in the peak is between 0 and 90 %
- Slice samples, dissolve gel, incubate cells, and look for number of colonies

ANALYSIS:

- Study cell survival in peak (tumor) and plateau (skin) and compare the results to protons (and carbon ions)

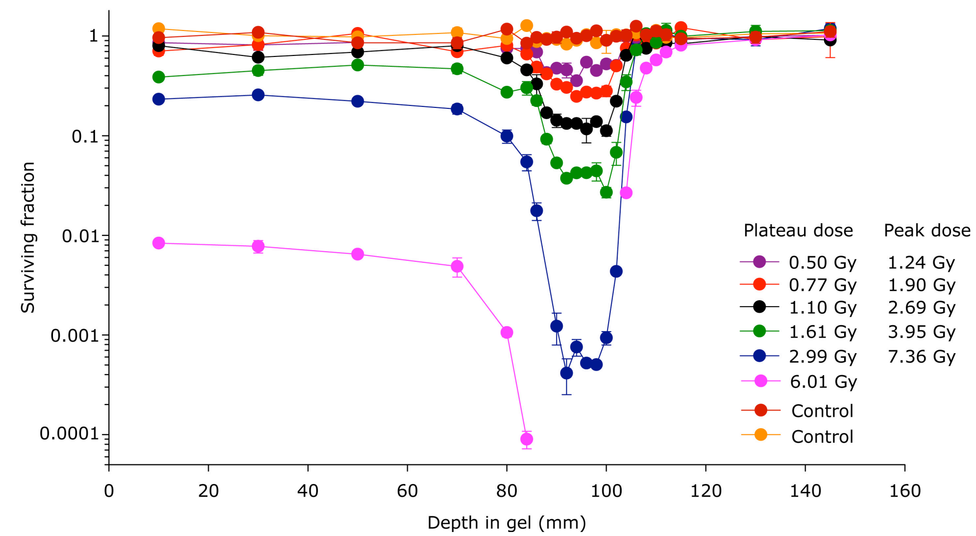
Plot “peak” or “plateau” survival vs. absolute dose and compare to ^{60}Co irradiation
comparing dose values needed for **Iso-Effect**
for peak, plateau, and ^{60}Co irradiation: **Relative Biological effectiveness RBE**



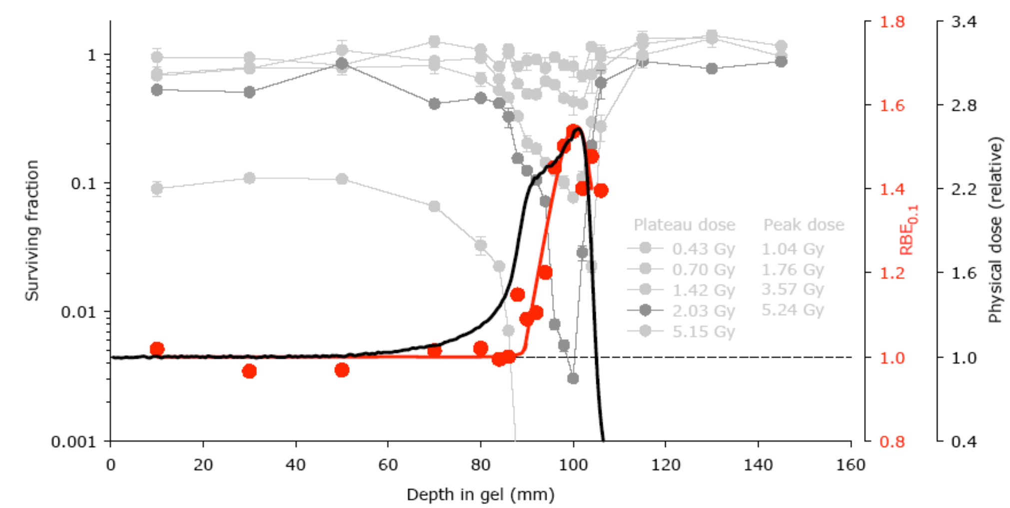
$$RBE_{plat} = \frac{\text{Co-60 Dose}}{\text{Plateau Dose}} = 1.0$$

$$RBE_{peak} = \frac{\text{Co-60 Dose}}{\text{Peak Dose}} = 1.15$$

Antiprotons 2008



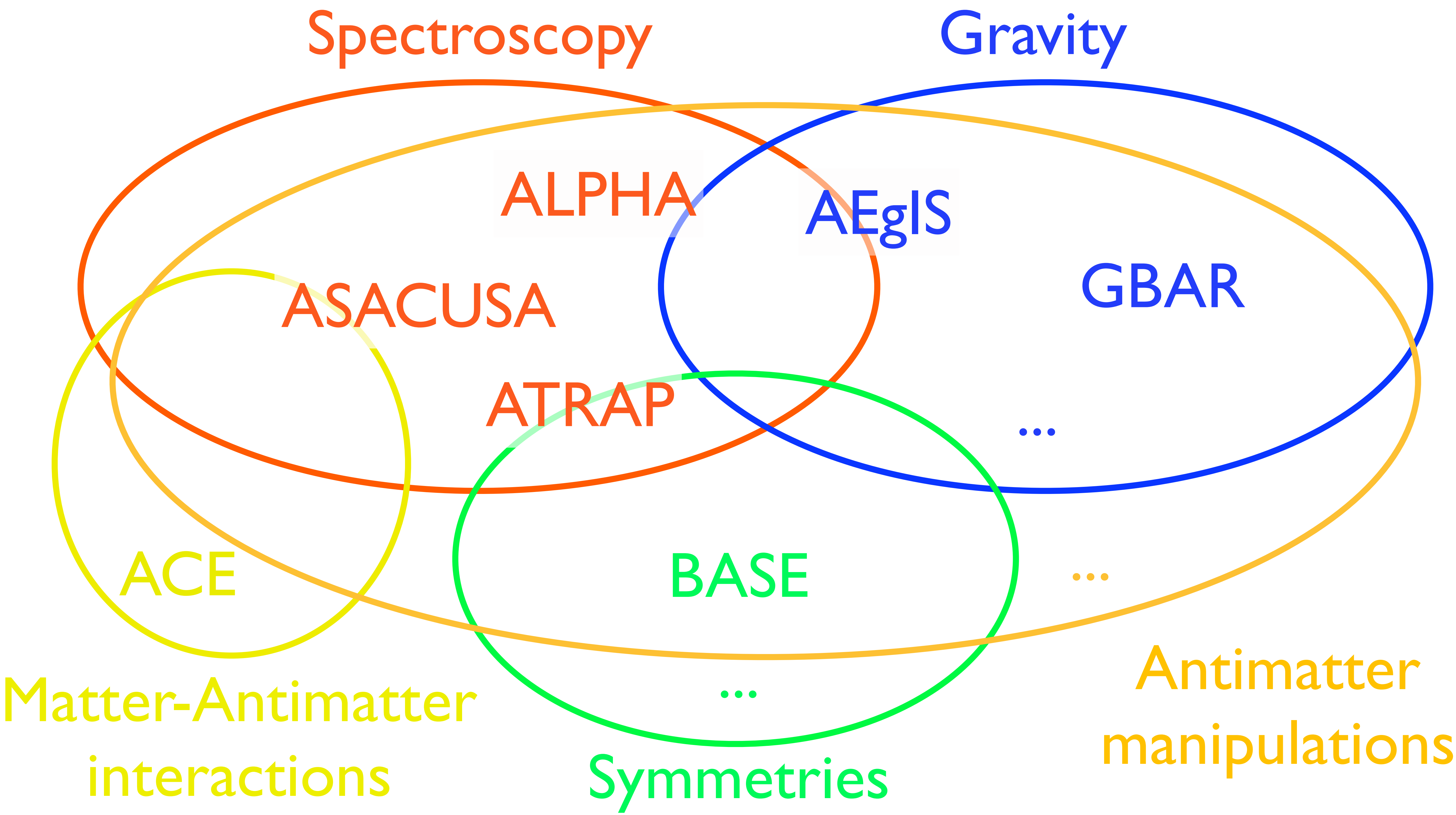
Antiprotons 2007



- **Confinement of RBE Enhancement to Bragg peak has been confirmed**
- **DNA damage assays for studies of late effects achieved higher resolution**
- **dosimetry, biology now mostly understood; further data needed?**

to summarize the situation...

Antiproton and antihydrogen experiments at the AD:



to summarize the situation...

Trapping of antihydrogen:

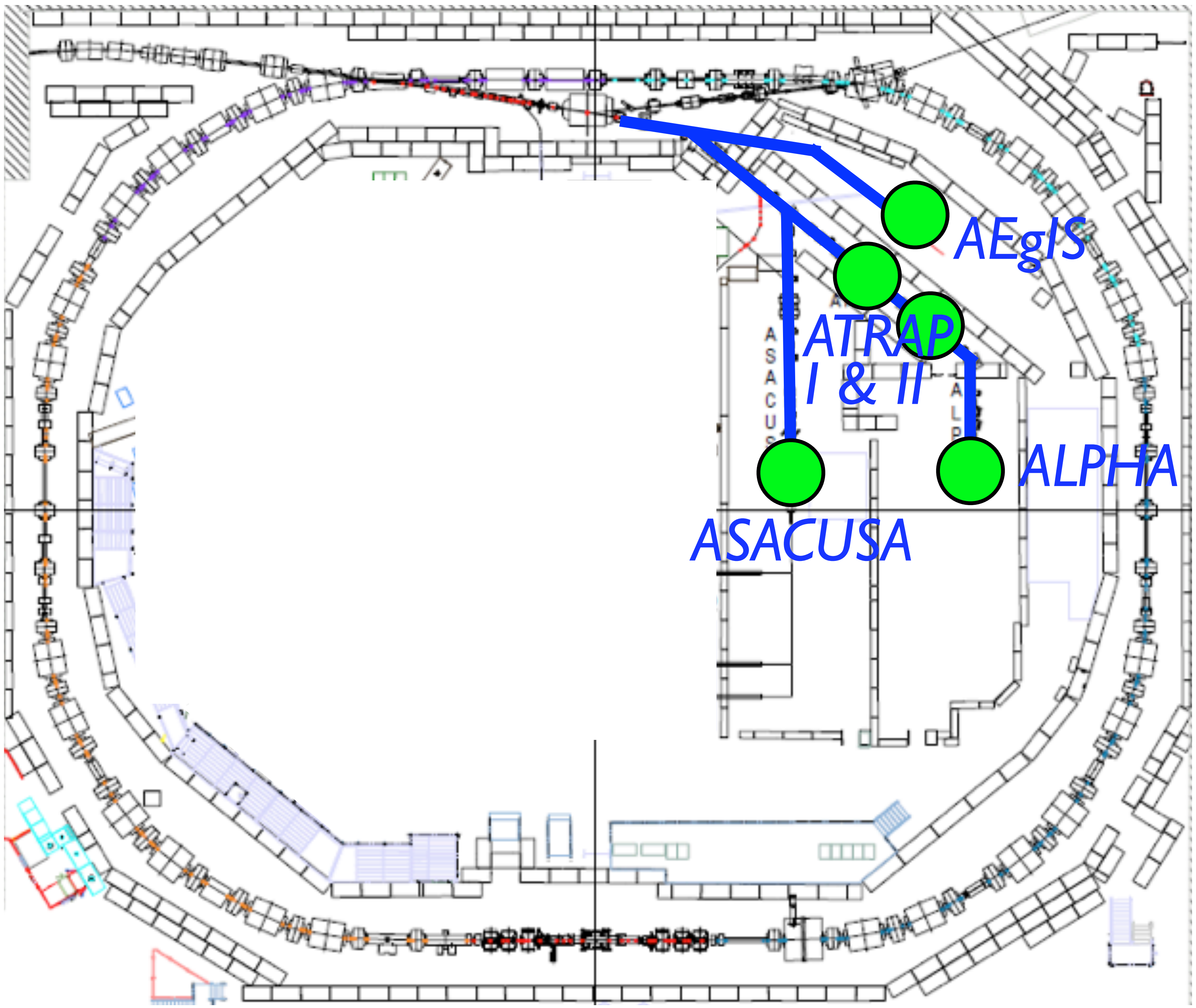
ATRAP and ALPHA: progress in making colder ingredients
main challenge now: enough cold enough constituents
small numbers of antihydrogen atoms in the ground state trapped (2010)
assuming 1 mK: 1s-2s spectroscopy to ~ 10^{-12} (perhaps in a "few" years)

Beam of antihydrogen:

ASACUSA: continuous beam (ground state atoms!) (2014?)
AEGIS: pulsed sub-K beam (2014/2015?) @ 1Hz
main challenge now: formation mechanisms and rates, cold enough $\bar{p}$
low precision gravity measurement and in-flight spectroscopy of
HFS to 200 Hz (10^{-6})
1s-2s spectroscopy to ???? (will depend on temperature of $\bar{H}$)

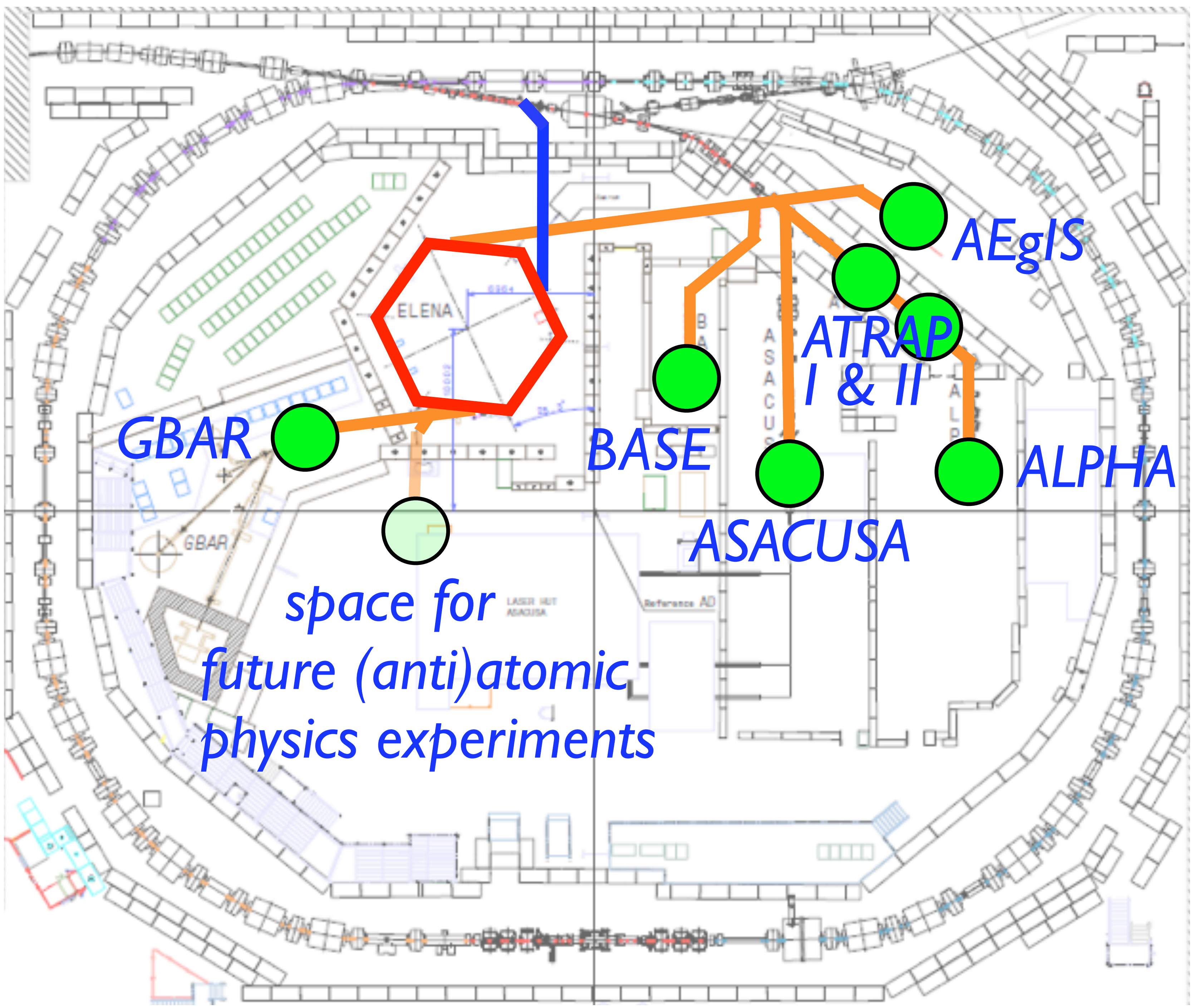
From 2017, new low energy $\bar{p}$ accelerator ELENA: new experiments, new experimental opportunities increasing & continuous demand for antiprotons, current methods for trapping them are very inefficient

current situation



increasing & continuous demand for antiprotons, current methods for trapping them are very inefficient

ELENA to the rescue



Outlook

Antiproton and antihydrogen research *covers a wide range*

- atomic physics
- gravity
- nuclear physics
- plasma physics
- cosmology
- material science

requires modest resources but much patience & time

relies on many technologies from many fields of science

is very educational and of great interest to the media

requires breakthroughs in cooling, manipulations, ...

Outlook

Antiproton and antihydrogen research *covers a wide range*

- atomic physics
- gravity
- nuclear physics
- plasma physics
- cosmology
- material science

requires modest resources but much patience & time

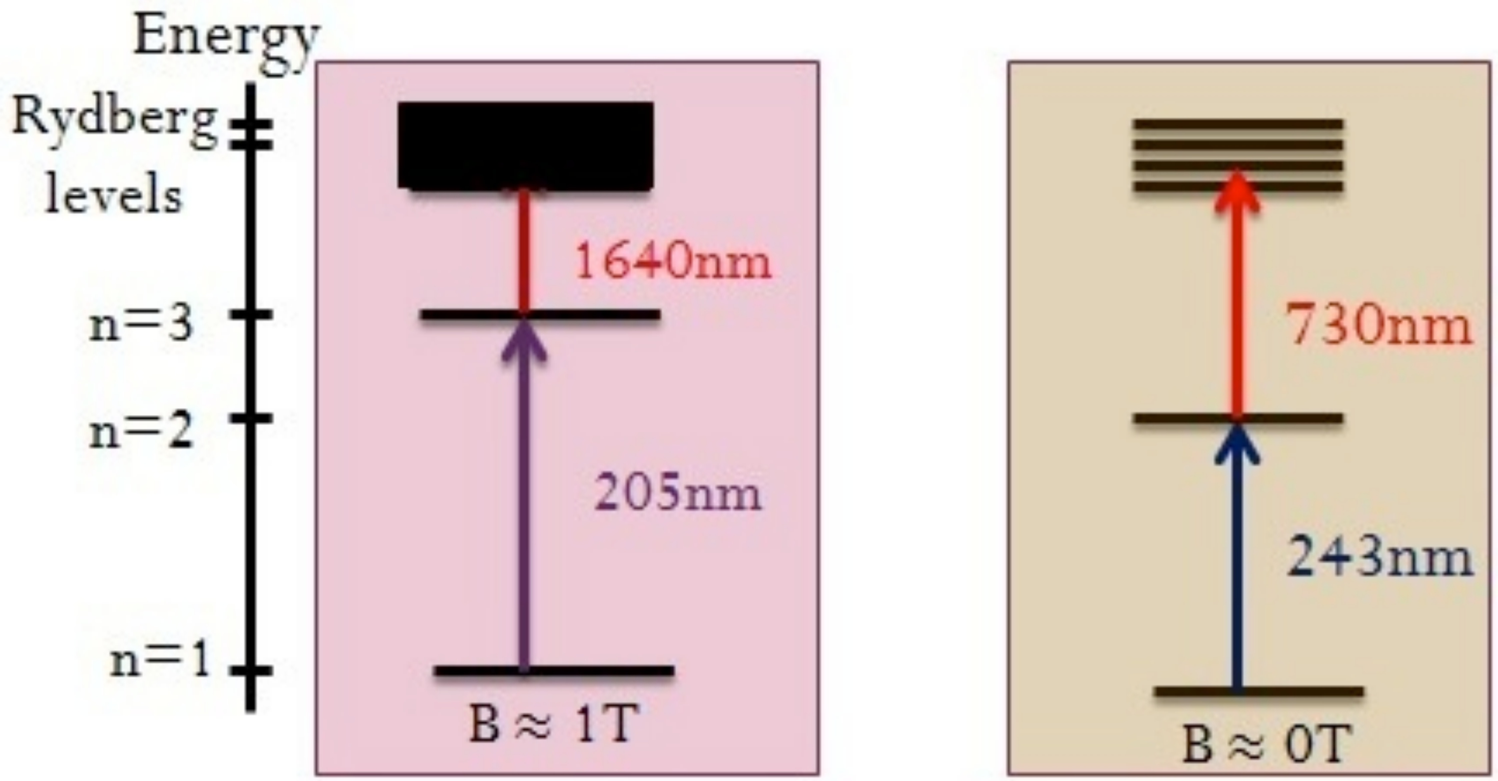
relies on many technologies from many fields of science

is very educational and of great interest to the media

requires breakthroughs in cooling, manipulations, ...

... and has a lively and long future !

Ps excitation laser system(s)



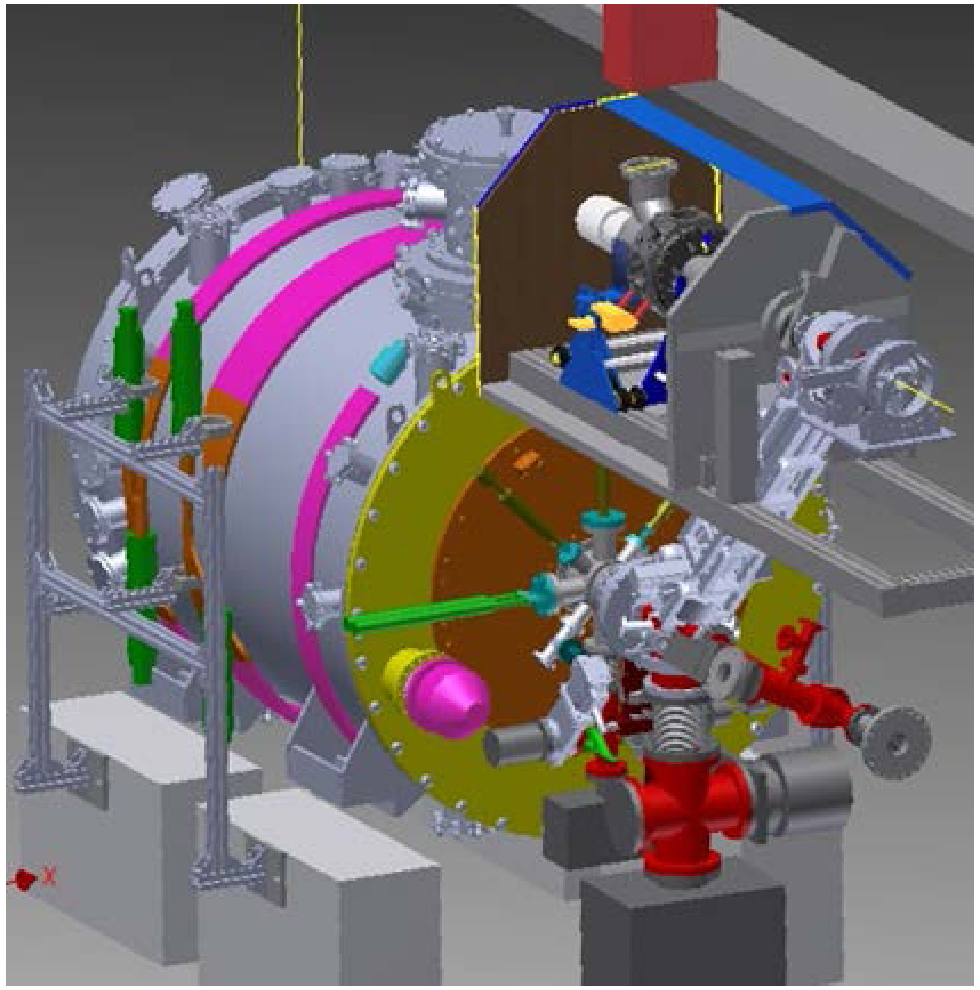
Broad-band laser installation completed and commissioned in 2013:

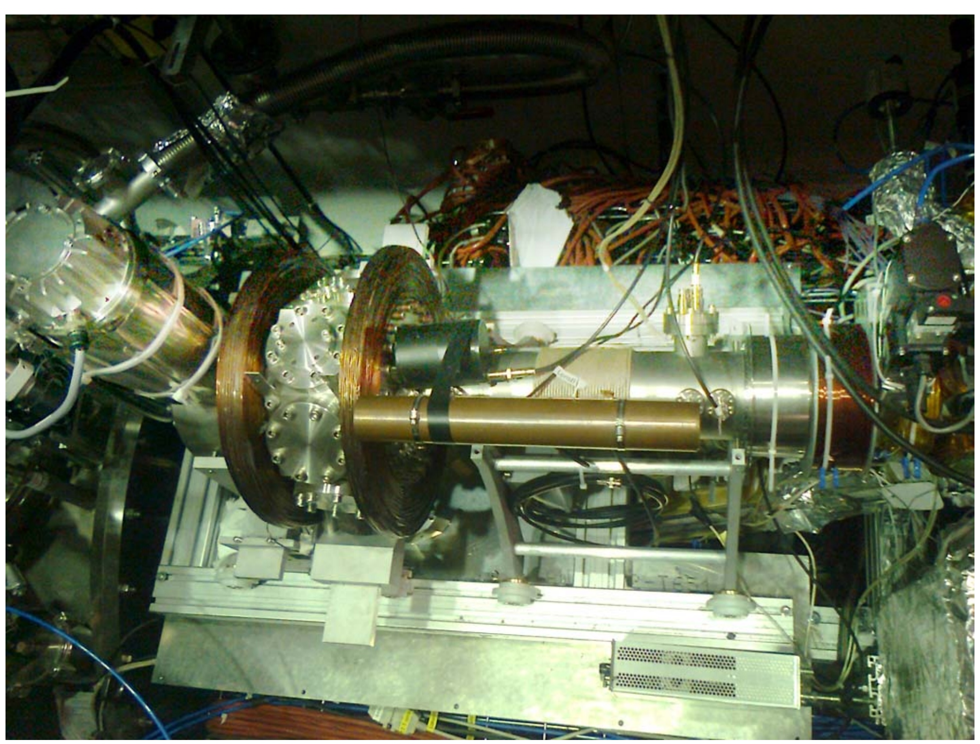
- alignment and tuning:

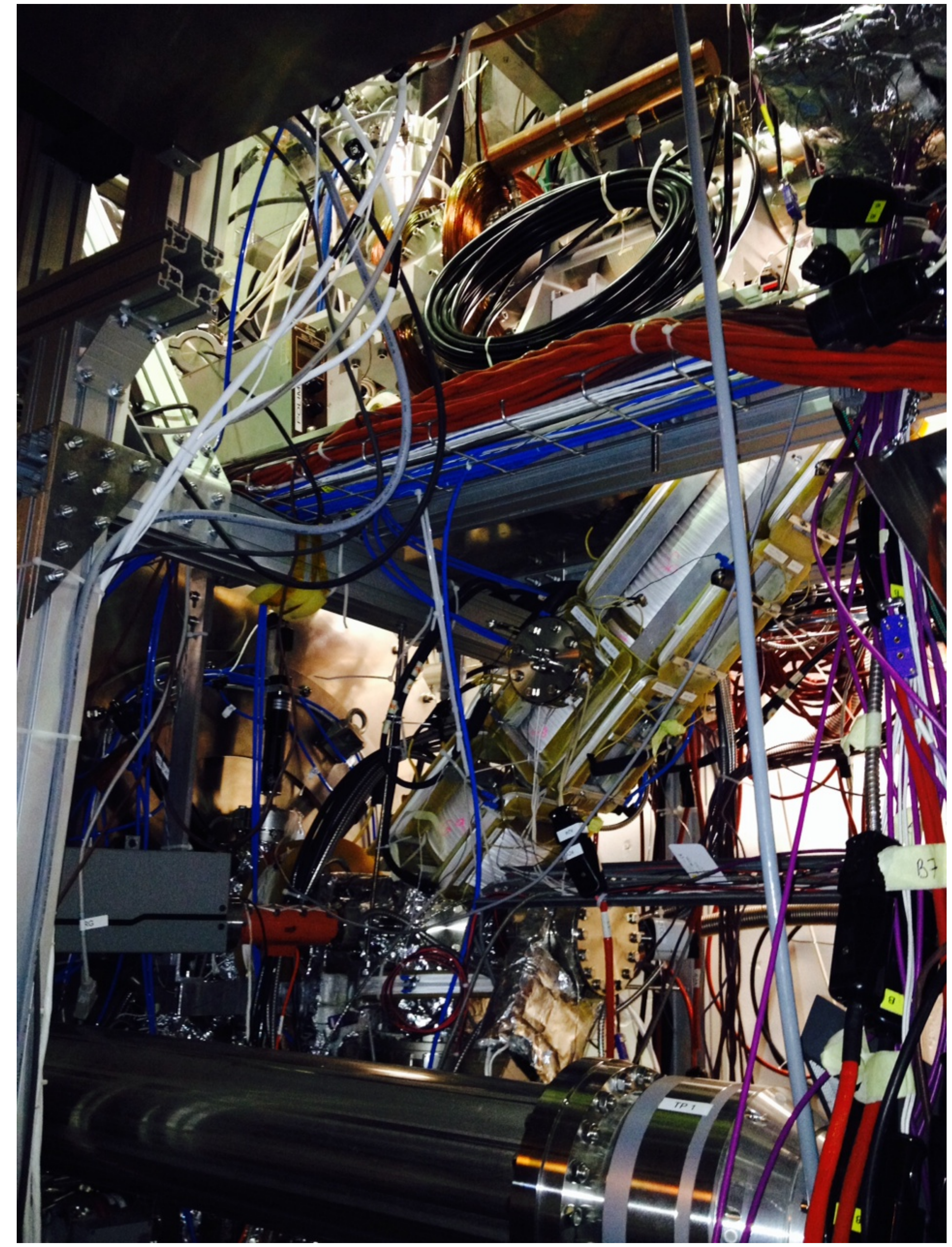
Transition	Wavelength	Est. saturation energy	Max. produced energy
1 → 3	205 nm	32 μJ	106 μJ
3 → 26	1664 nm	350 μJ	4000 μJ

- measurements of monochromaticity
- measurements of intensity profile

Positronium test station: installation and commissioning







magnetic shielding will be installed in June for simultaneous operation with 5T magnet

Motivation

EEP (Einstein Equivalence Principle) $\Leftrightarrow$ General relativity

WEP "if an uncharged test body is placed at an initial event in spacetime and given an initial velocity there, then its subsequent trajectory will be independent of its internal structure and composition" (Weak Equivalence Principle)

LLI The outcome of any local non-gravitational experiment is independent of the velocity of the freely falling apparatus (Local Lorentz Invariance)

LPI The outcome of any local non-gravitational experiment is independent of where and when in the Universe it is performed (Local Position Invariance)

} EEP

C.Will "Theory and experiment in gravitational physics" (Cambridge Univ. Press)

Indirect limits on EEP validity 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

- Only one ■$_e$ detected, several caveats
- Model dependent

S. Pakvasa et al., Phys. Rev. D 39 (1989) 176

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 renormalization 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

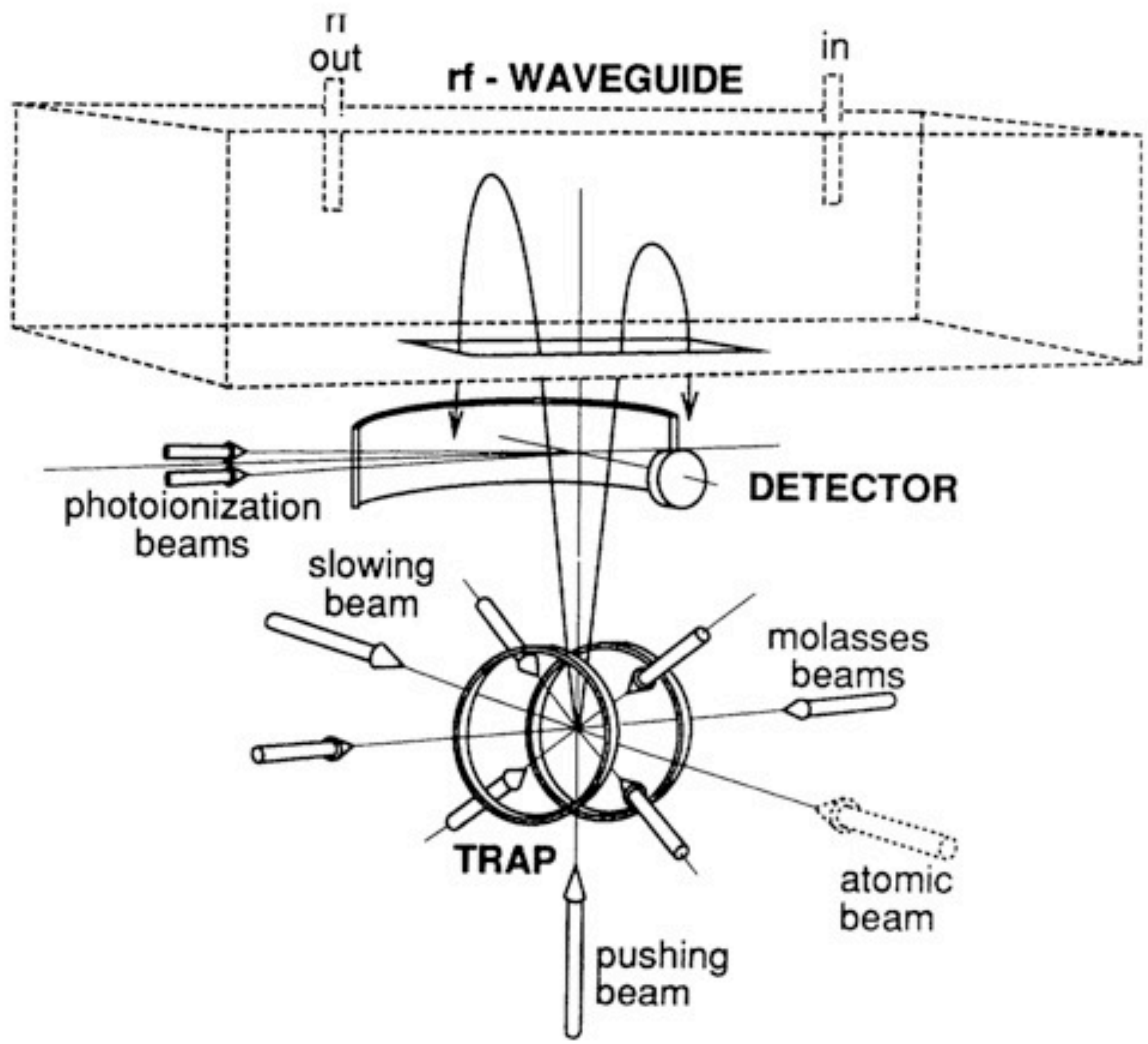
Very stringent limits

$\alpha_{K_0\bar{K}_0} < 10^{-9} - 10^{-14}$ Depending on the range of the anomalous interaction

..but of course, also spectroscopy (very long-term)

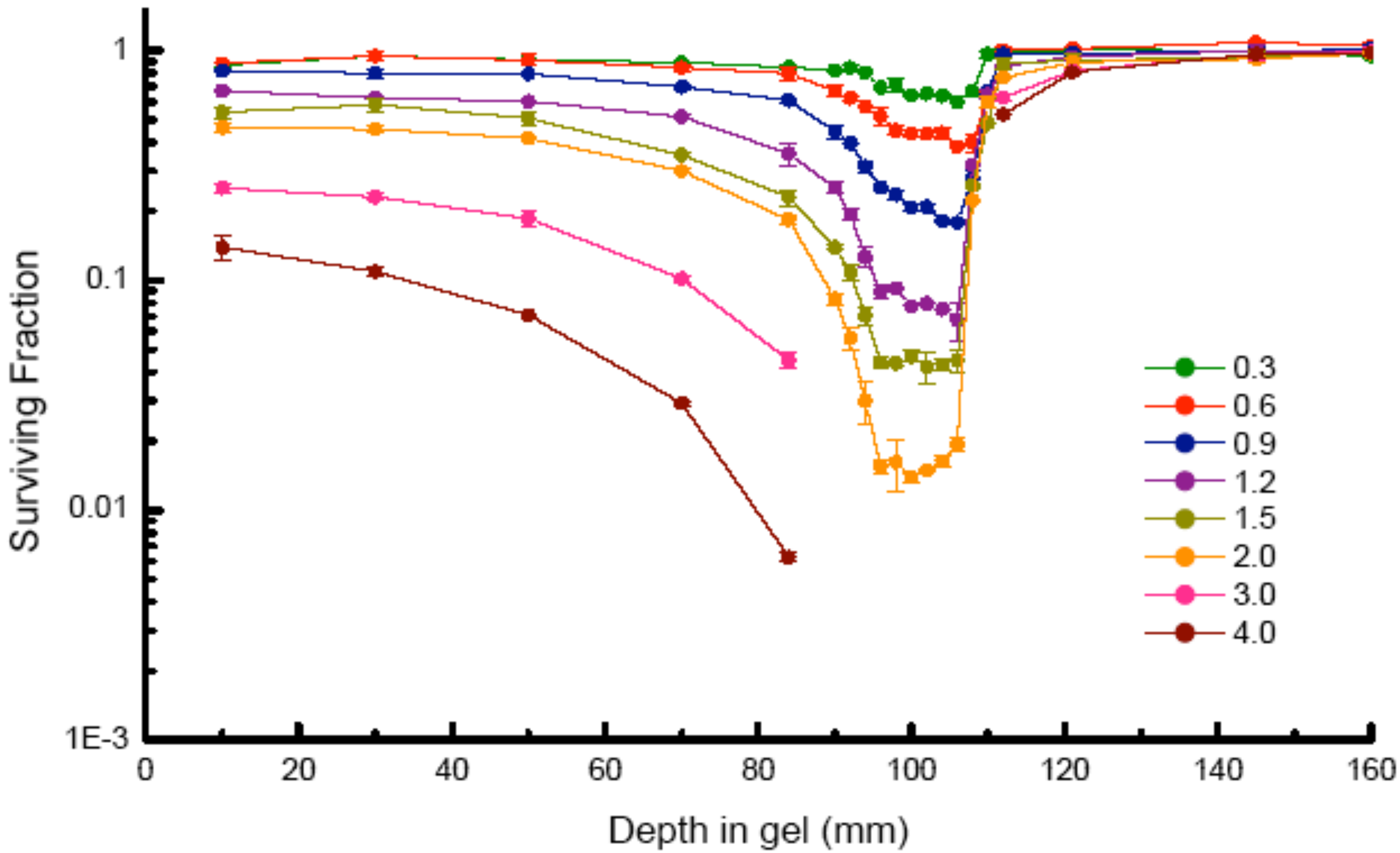
- 1s-2s spectroscopy of trapped Antihydrogen: 10^{-12}
  (very few atoms, B-field)

- Hyperfine structure of antihydrogen
  - Microwave resonance of ultra-cold antihydrogen in field-free region
  - Atomic fountain



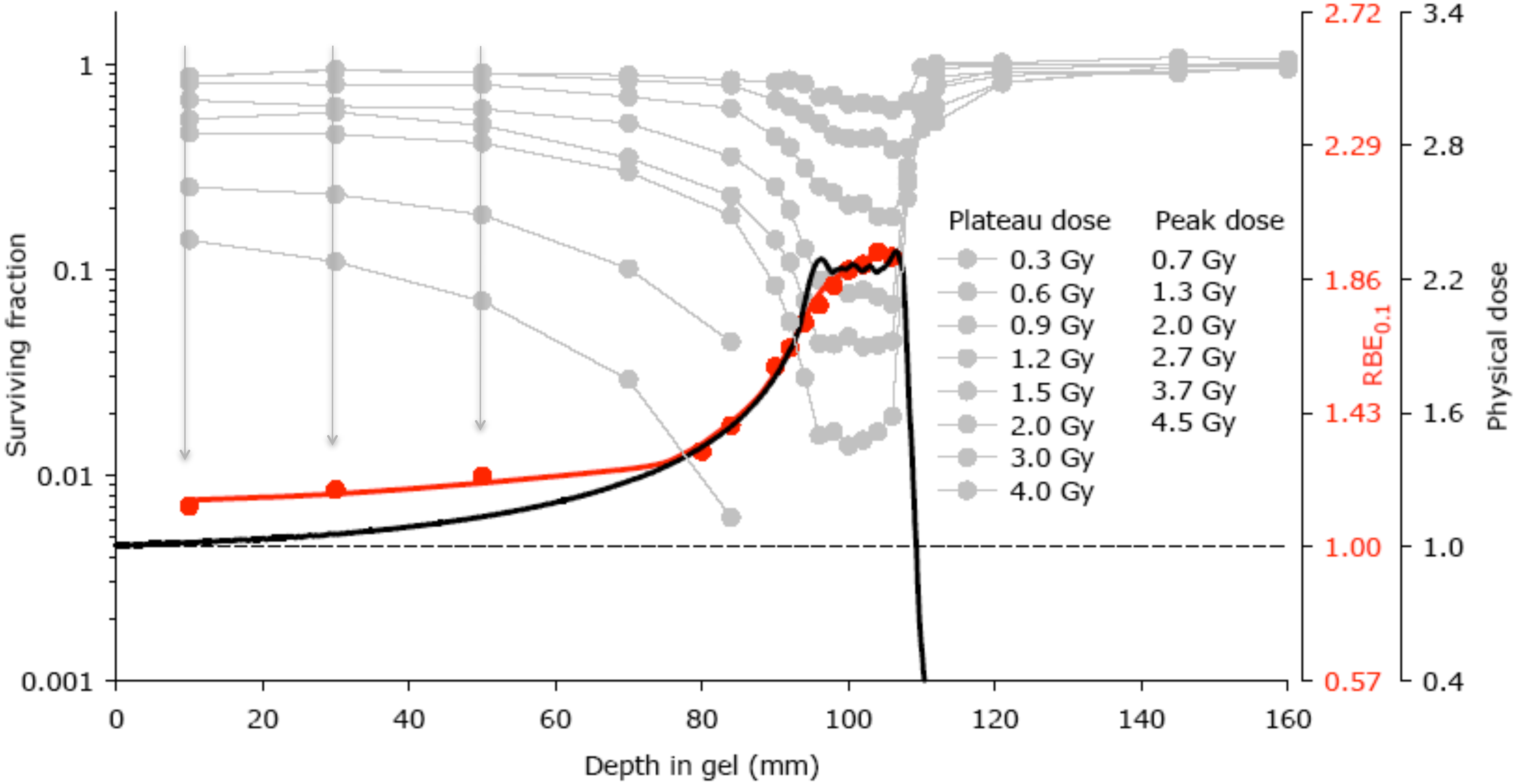
Far in the future!

Carbon Ions – SOBP at GSI



note: clinical beams with precise dosimetry and fast dose delivery ....
Energy to achieve same clinical relevant depth and form SOBP as at CERN....

RBE for Carbon Ions



Extract survival vs. dose plot for each depth slice and calculate $RBE_{SF=10\%}$

$RBE_{plateau}$ = 1.2 RBE_{peak} = 2.0 RBE_{distal} = 1.5