KVI

New Opportunities in the Physics Landscape at CERN

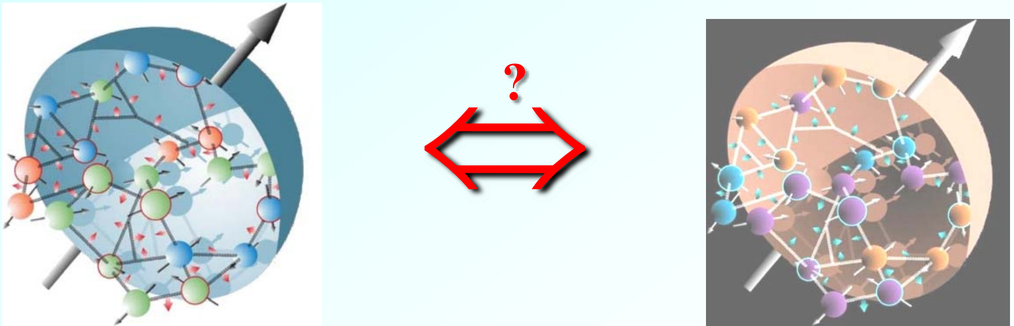
Antiproton Decelerator (AD)

Summary and Prospects

Klaus Jungmann, KVI, University of Groningen, NL

- **Physics Motivation**
- **Unique Possibilities**
- **Tests of Fundamental Theories**
- **Precision Measurements**
- **Novel Techniques and Instrumentation**
- **Applications**
- **High Visibility**

$\overline{P}$



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Physics Motivation

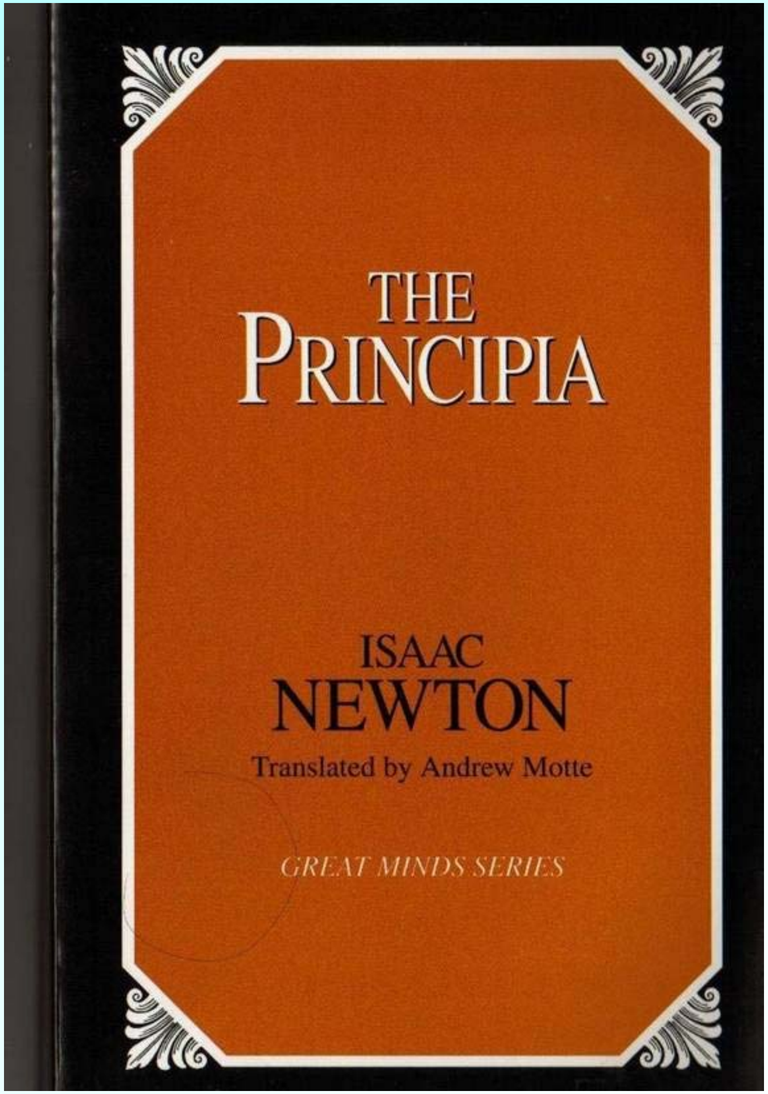
How do we work in Physics ?

Sir Isaac Newton

(1642 - 1727)

⇓

Basic Principles on which Scientists work in Physics



First Theory on Gravity

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RULES OF REASONING IN PHILOSOPHY.

RULE I.

We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.

To this purpose the philosophers say that Nature does nothing in vain, and more is in vain when less will serve; for Nature is pleased with simplicity, and affects not the pomp of superfluous causes.

RULE II.

Therefore to the same natural effects we must, as far as possible, assign the same causes.

As to respiration in a man and in a beast; the descent of stones in *Europe* and in *America*; the light of our culinary fire and of the sun; the reflection of light in the earth, and in the planets.

RULE III.

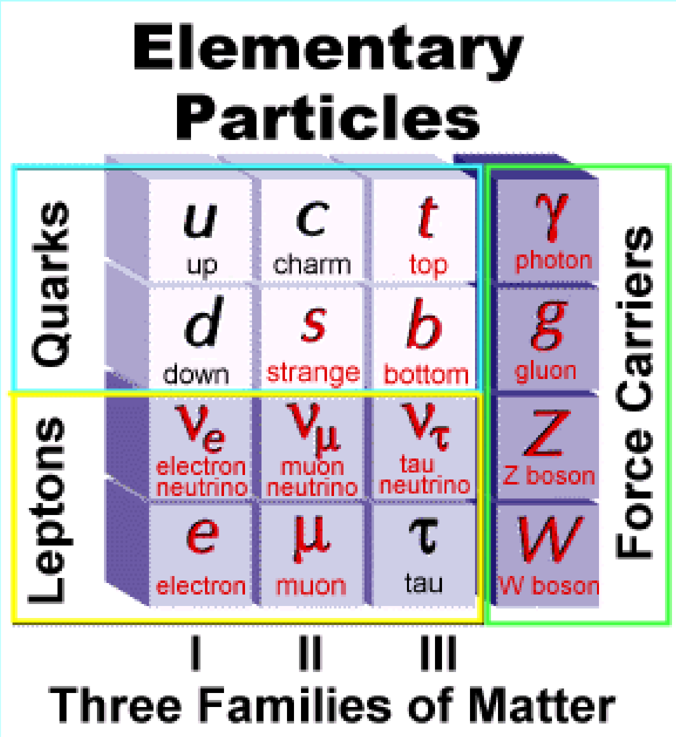
bodies which we have seen. The extension, hardness, impenetrability, mobility, and *vis inertiæ* of the whole, result from the extension, hardness, impenetrability, mobility, and *vires inertiæ* of the parts; and thence we conclude the least particles of all bodies to be also all extended, and hard and impenetrable, and moveable, and endowed with their proper *vires inertiæ*. And this is the foundation of all philosophy. Moreover, that the divided but contiguous particles of bodies may be separated from one another, is matter of observation; and, in the particles that remain undivided, our minds are able to distinguish yet lesser parts, as is mathematically demonstrated. But whether the parts so distinguished, and not yet divided, may, by the powers of Nature, be actually divided and separated from one another, we cannot certainly determine. Yet, had we the proof of but one experiment that any undivided particle, in breaking a hard and solid body, suffered a division, we might by virtue of this rule conclude that the undivided as well as the divided particles may be divided and actually separated to infinity.

Lastly, if it universally appears, by experiments and astronomical observations, that all bodies about the earth gravitate towards the earth, and that in proportion to the quantity of matter which they severally contain; that the moon likewise, according to the quantity of its matter, gravitates towards the earth; that, on the other hand, our sea gravitates towards the moon; and all the planets mutually one towards another; and the comets

- A Theory is only as good as it is experimentally verified.
- A Theory without experimental verification has no standing.

notwithstanding any contrary hypotheses that may be imagined, till such time as other phænomena occur, by which they may either be made more accurate, or liable to exceptions.

The Standard Model(s)



- Excellent Description of ALL Observations

- However, many Open Questions

  Why 3 generations ?
  Why some 30 parameters?
  Why one electric charge ?
  What about CP violation ?
  Why matter-antimatter asymmetry?
  …..

- Gravity not included

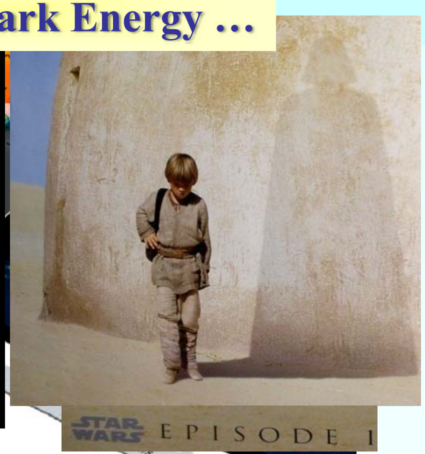
  No Combind Theory of Gravity and Quantum Mechanics.

- Contents of the Cosmos

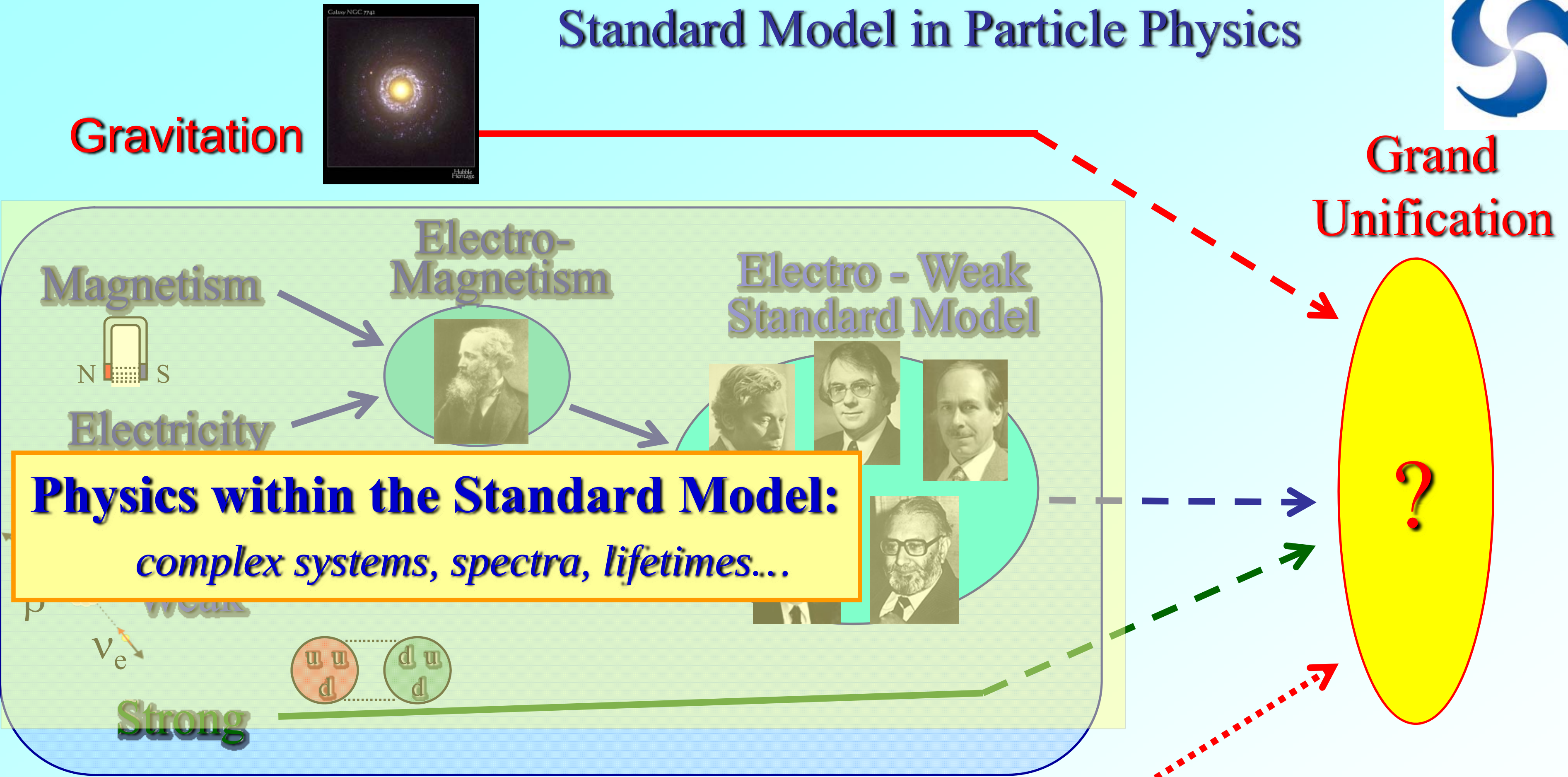
  What's the other 96% beyond matter ?

Dark Matter – Dark Energy …

© Hu & White Scientific American 2004



Standard Model in Particle Physics



Speculative Models:

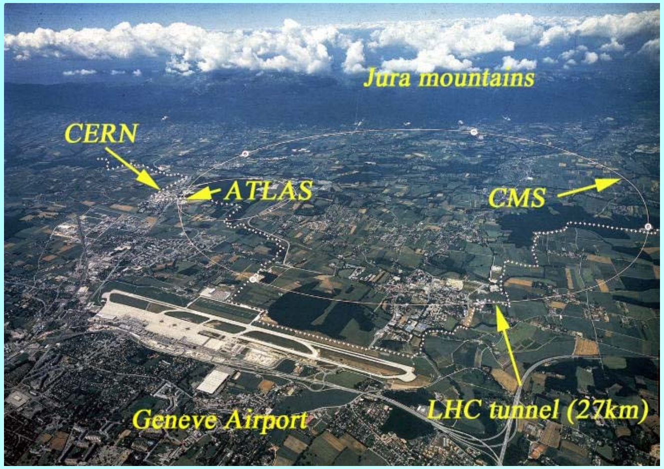
Supersymmetry, Cold dark matter, Tachyons, Radiative muon generation, Technicolor, Leptoquarks, Extra gauge bosons, Extra dimensions, LeftRight Symmetry, Compositeness, Lepton flavour violation, ….

⇒ No Status in Physics , yet: "Not Even Wrong"

Experiments at the Frontiers of Standard Theory

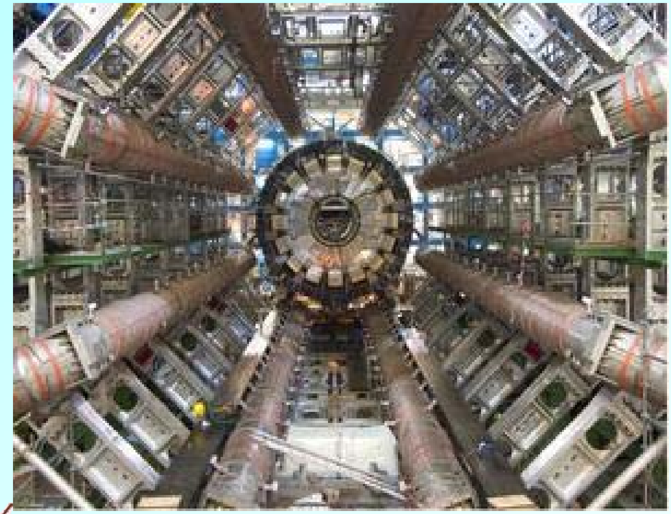
Direct Search Frontier

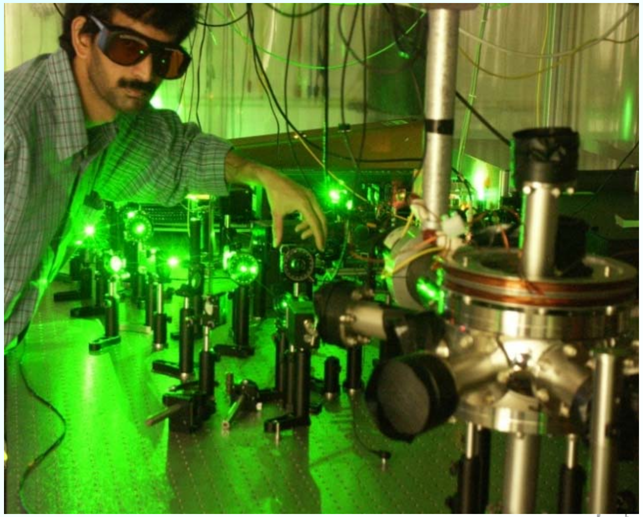
Precision Frontier



⇔

complementary
approaches





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Test of Fundamental Symmetries
Precison Measurements

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PHYSICAL REVIEW LETTERS 17 NOVEMBER 1986

First Capture of Antiprotons in a Penning Trap: A Kiloelectronvolt Source

G. Gabrielse, X. Fei, K. Helmerson, S. L. Rolston, R. Tjoelker, and T. A. Trainor
Department of Physics, University of Washington, Seattle, Washington 98195

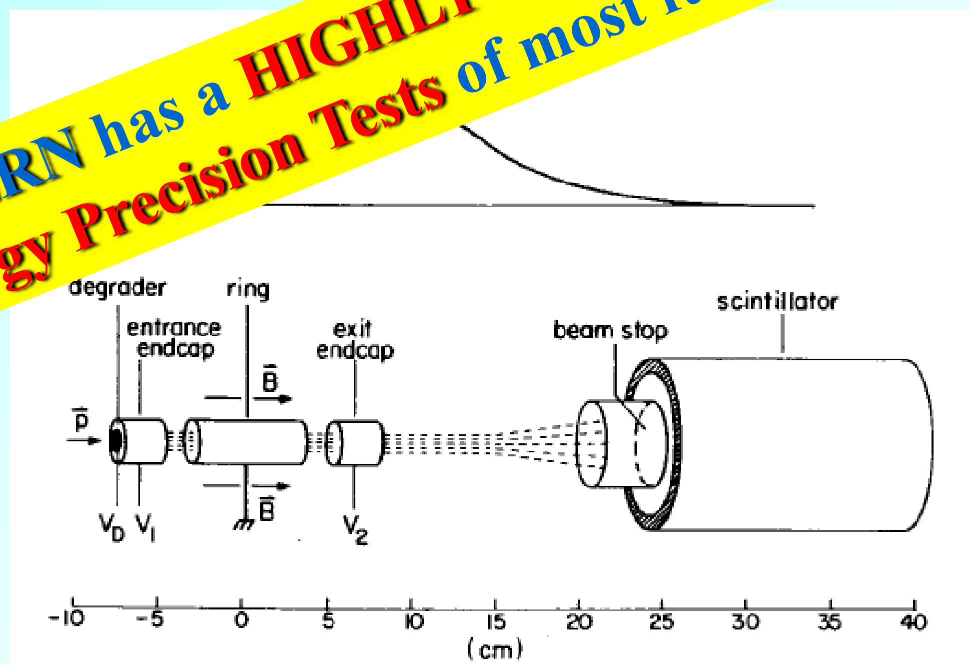
H. Kalinowsky and J. Haas
Institute für Physik, University of Mainz, West Germany

and

W. Kells
Fermi National Accelerator Laborator

(Received 8 Se

Since then CERN has a HIGHLY PUBLICLY VISIBLE program on Low Energy Precision Tests of most fundamental theories



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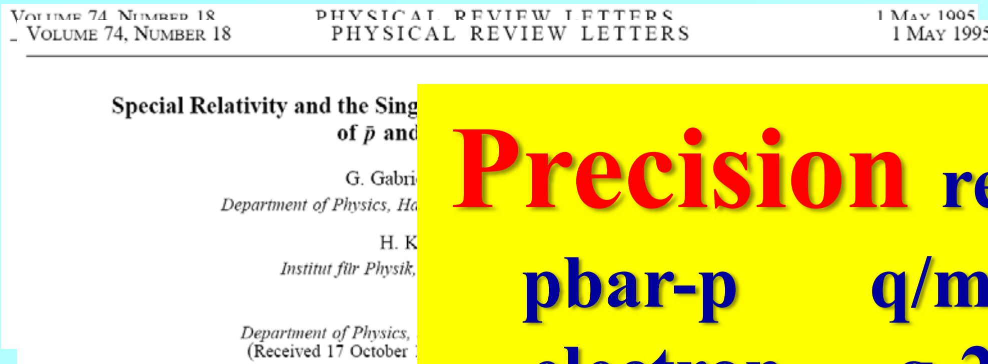


VOLUME 74, NUMBER 18 PHYSICAL REVIEW LETTERS 1 MAY 1995

Special Relativity and the Sing…
of $\bar{p}$ and…

G. Gabri…
Department of Physics, Ha…

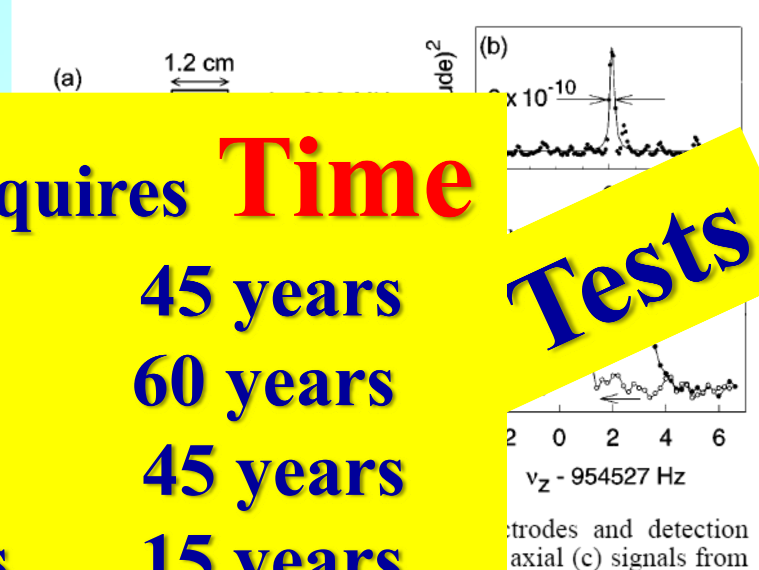
H. K…
Institut für Physik,…

Department of Physics,…
(Received 17 October 1…

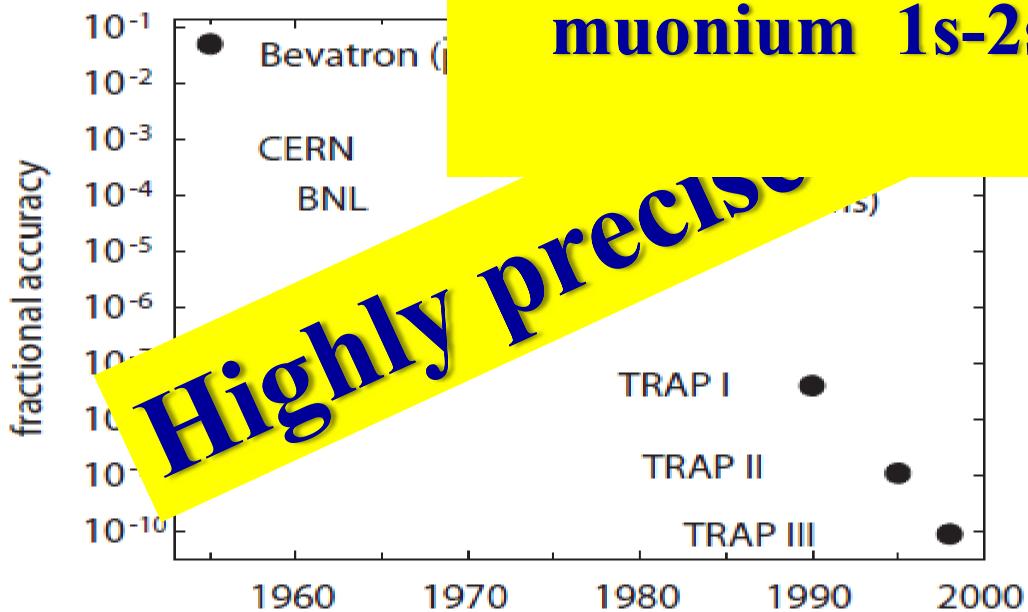
Precision requires Time

pbar-p	q/m	45 years
electron	g-2	60 years
muon	g-2	45 years
muonium	1s-2s	15 years

Tests



Highly precise…



p and pbar charge to mass ratio (circles)

p and pbar inertial mass ratio (squares)

⇒

Proton and Antiproton q/m compare to 0.1 ppb

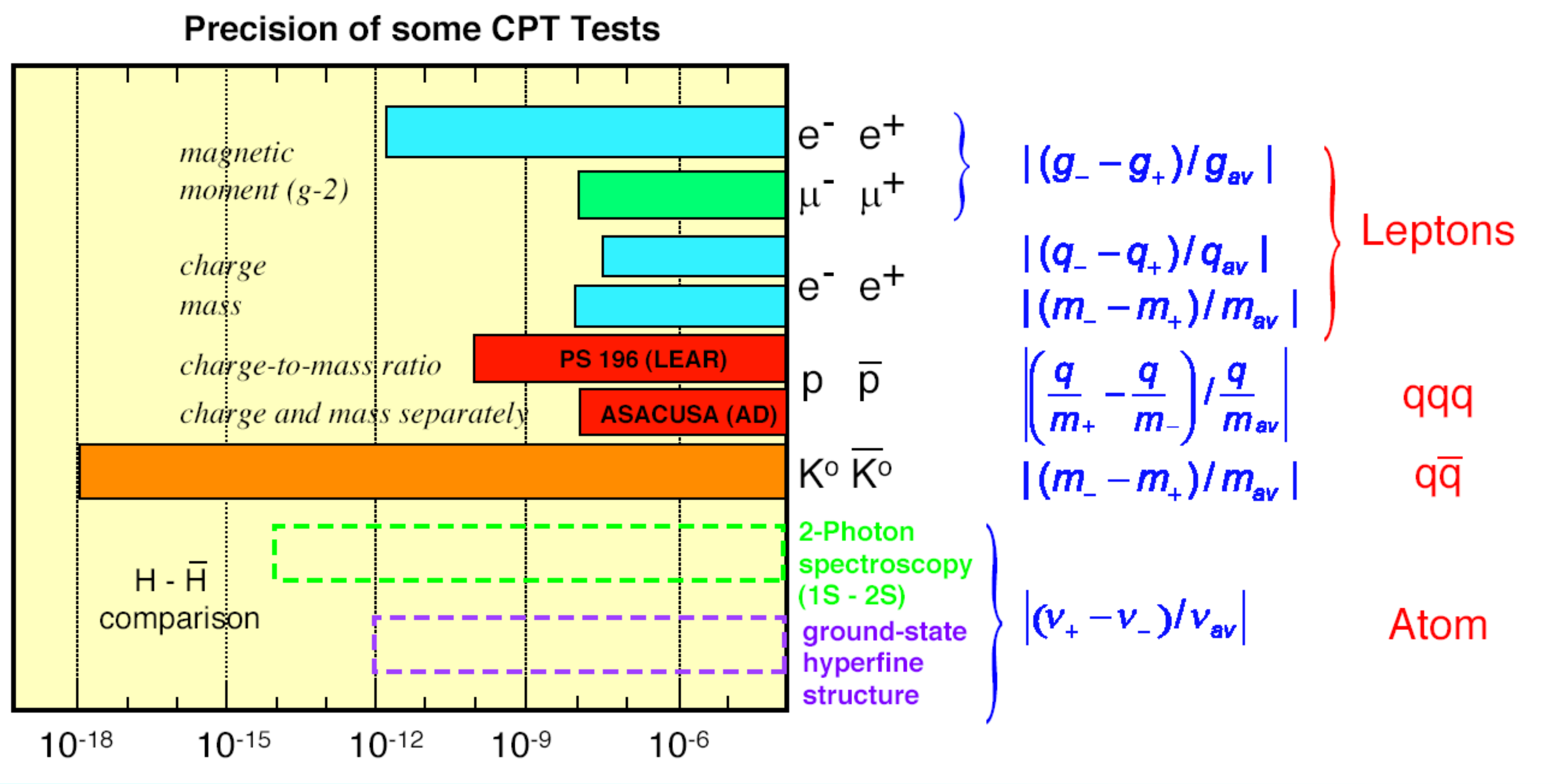
Clock Comparisons

⇒

Proton and Antiproton gravitational accceleration equal to 1 ppm

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)

→ **Arbitrary number joggling to get "accuracy" better than experiments !!!**

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CPT – Violation & Lorentz Invariance Violation

generic CPT and Lorentz violating DIRAC equation

$$(i\gamma^{\mu}D_{\mu} - m - a_{\mu}\gamma^{\mu} - b_{\mu}\gamma_5\gamma^{\mu} - \frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^{\mu}D^{\nu} + id_{\mu\nu}\gamma_5\gamma^{\mu}D^{\nu})\psi = 0$$

$$iD_{\mu} \equiv i\partial_{\mu} - qA_{\mu}$$

a_{μ}, b_{μ} break CPT

$a_{\mu}, b_{\mu}, c_{\mu\nu}, d_{\mu\nu}, H_{\mu\nu}$ break Lorentz Invariance

Kostelecky *et al.*:

- **Interaction with a finite strength**
- **Figure of merit energy based**

→ Completely different systems appear much more interesting !

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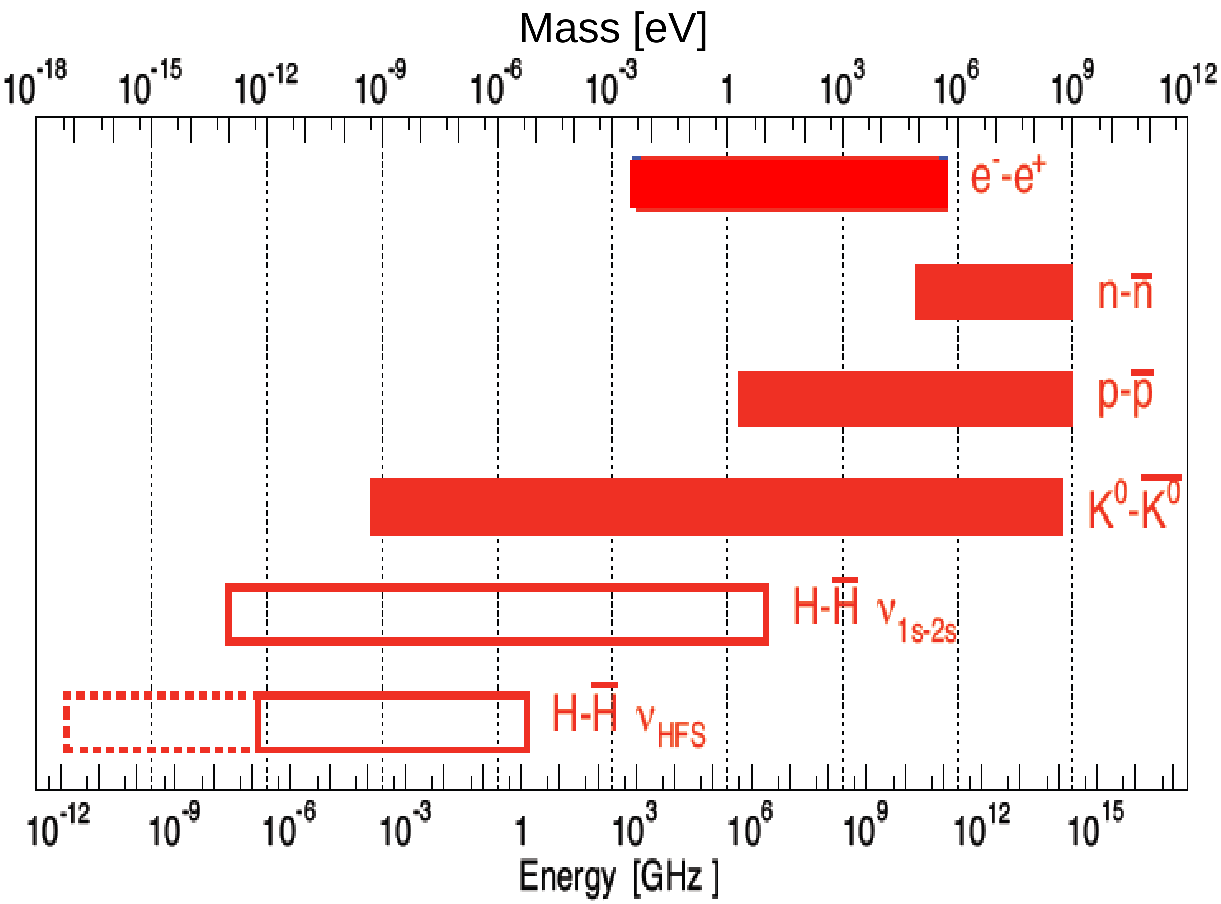
Verifications of CPT symmetry

Using the Kostelecky *et al.* Standard Model Extension scheme



$|(g_- - g_+)/g_{av}|$

$|(q_- - q_+)/q_{av}|$

$|(m_- - m_+)/m_{av}|$

$\left|\left(\frac{q}{m_+} - \frac{q}{m_-}\right)/\frac{q}{m_{av}}\right|$

$|(m_- - m_+)/m_{av}|$

$|(\nu_+ - \nu_-)/\nu_{av}|$

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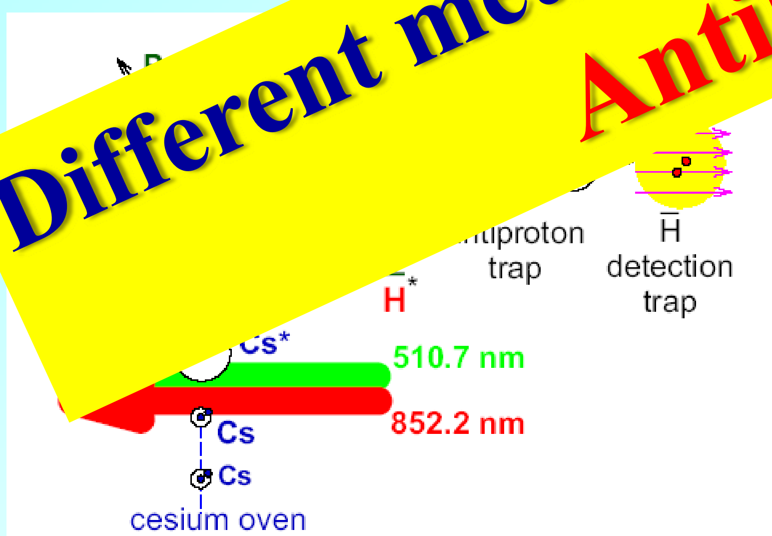
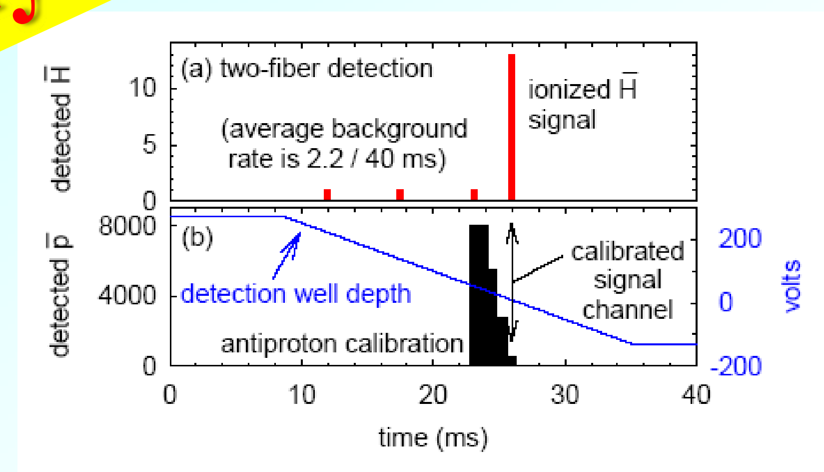
First Laser-Controlled Antihydrogen Production

C.H. Storry,[1] A. Speck,[1] D. Le Sage,[1] N. Guise,[1] G. Gabrielse*,[1] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2] T. Sefzick,[2] H. Pittner,[3] M. Herrmann,[3] J. Walz,[3] T.W. Hänsch,[3,4] D. Comeau,[5] and E.A. Hessels[5]
(ATRAP Collaboration)
[1]*Department of Physics, Harvard University, Cambridge, MA 02138*
[2]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, German*
[3]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 857*
[4]*Ludwig-Maximilians-Universität München, Schellingstrasse 4/III, 8*
[5]*York University, Department of Physics and Astronomy, Tor*
(Dated: Submitted to PRL: 17 A

Lasers are used for the first time to control th
resonant charge exchange collisions are invol
other method used so far – producing
Penning trap. Two attractive feat
and that the production of
needed for confinement

Different methods available to produce Antihydrogen





ATHENA

ATRAP

advance online publication
letters to nature

Production and detection of cold antihydrogen atoms

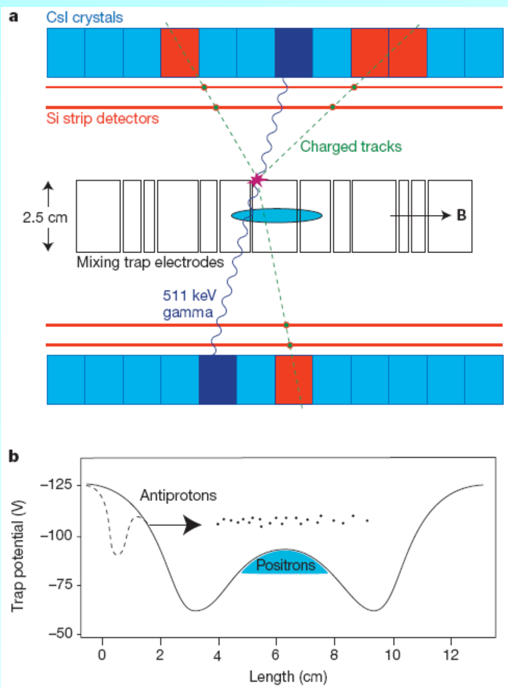
M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe||,
C. Carraro*, C. L. Cesar¶, M. Charlton#, M. J. T. Collier#, M. Doser‡,
V. Filippini☆, K. S. Fine‡, A. Fontana☆**, M. C. Fujiwara††,
R. Funakoshi††, P. Genova☆**, J. S. Hangst||, R. S. Hayano††,
M. H. Holzscheiter‡, L. V. Jørgensen#, V. Lagomarsino*‡‡, 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#

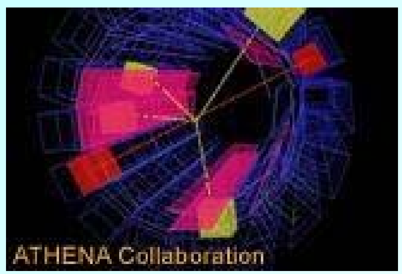
PHYSICAL REVIEW LETTERS

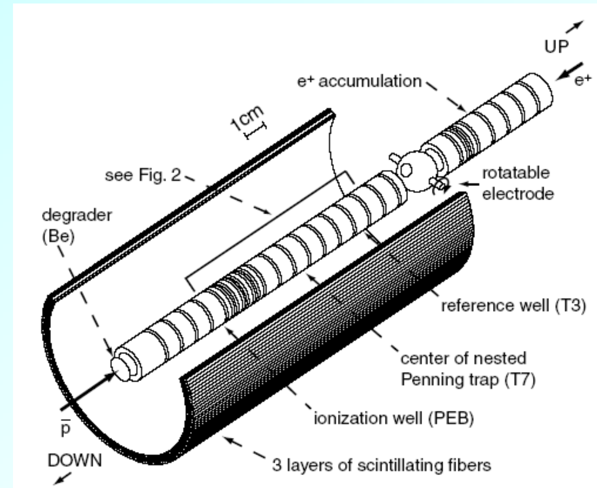
Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States

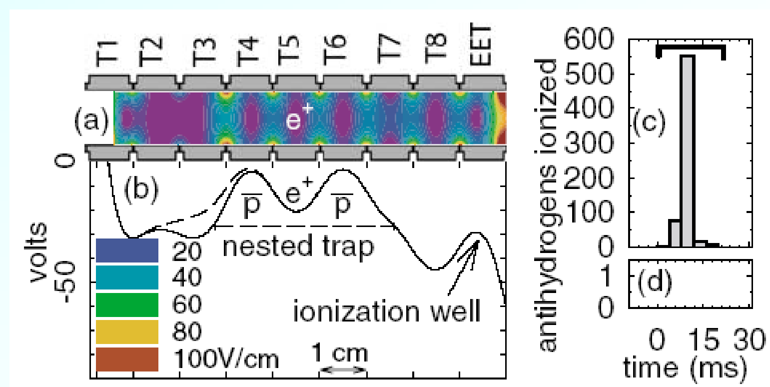
G. Gabrielse,[1,*] N. S. Bowden,[1] P. Oxley,[1] A. Speck,[1] C. H. Storry,[1] J. N. Tan,[1] M. Wessels,[1] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2] T. Sefzick,[2] J. Walz,[3] H. Pittner,[4] T. W. Hänsch,[4,5] and E. A. Hessels[6]

(ATRAP Collaboration)





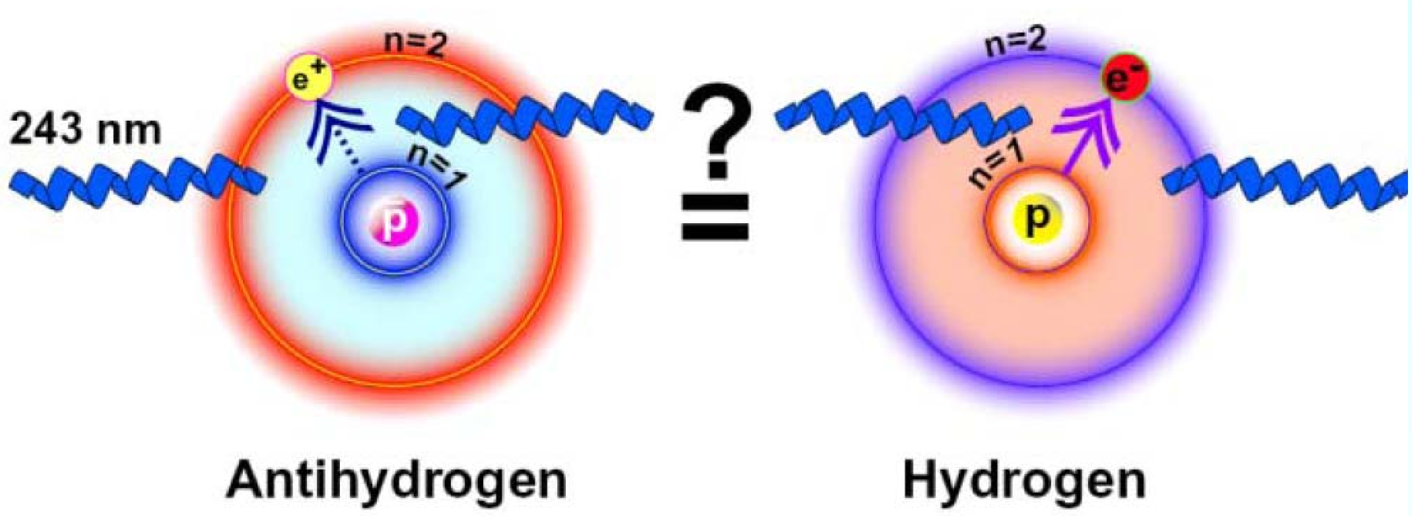




Scientists Create 'Star Trek' Antihydrogen in Quantity

By Alex Dominguez
Associated Press
posted: 02:59 pm ET
18 September 2002

(Anti-)Hydrogen CPT Tests



Laser spectroscopy 1s-2s -------- **Microwave spectroscopy**
1s Hyperfine Structure

$\Delta\nu_{1s2s} = \frac{3}{4} * R_\infty + \varepsilon_{QED} + \varepsilon_{nucl} + \varepsilon_{weak} + \varepsilon_{CPT}$ $\Delta\nu_{HFS} = \text{cons.} * \alpha^2 R_\infty + \varepsilon'_{QED} + \varepsilon'_{nucl} + \varepsilon'_{weak} + \varepsilon'_{CPT}$

"Long distance" Interaction

"Contact" interaction

$R_\infty = m_e c^2 * \alpha^2 / 2h$

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(Anti-)Hydrogen Spectroscopy*

Hydrogen 1s-2s Saturation Intensity I_s = 0.9 W/cm2
Excitation Rate R_e = 4π*84*(I/W/s* … Δν/Hz
Photo Ionization Rate R_p = 9*I/W/s …
Zeeman shift $\delta\nu_Z$ = 9.2 …
ac Stark shift $\delta\nu_{ac}$ …

Velocity at 1mK
Time-of-flight broadening … (1 mK, 600 μm beam diam.)

Lyman a detect… = Ω * eff_{MCP} (= 10^{-4} * 10^{-2})

10^{11} H …) $\delta\nu/\nu_{1s2s}$ = 10^{-13} *(1s integration time)*

Just one H … detection via field quenching => atoms can be used once only
(all 1s, m_F states get equally populated)

Antihydrogen experiments benefit from more particles

Line center accuracy in absence of systematic errors:

$$\delta\nu = \Delta\nu_{exp.} / (\mathrm{Sign./Noise}) \approx \Delta\nu_{exp.} / \sqrt{N_{particles}}$$

* numbers verified with L. Willmann

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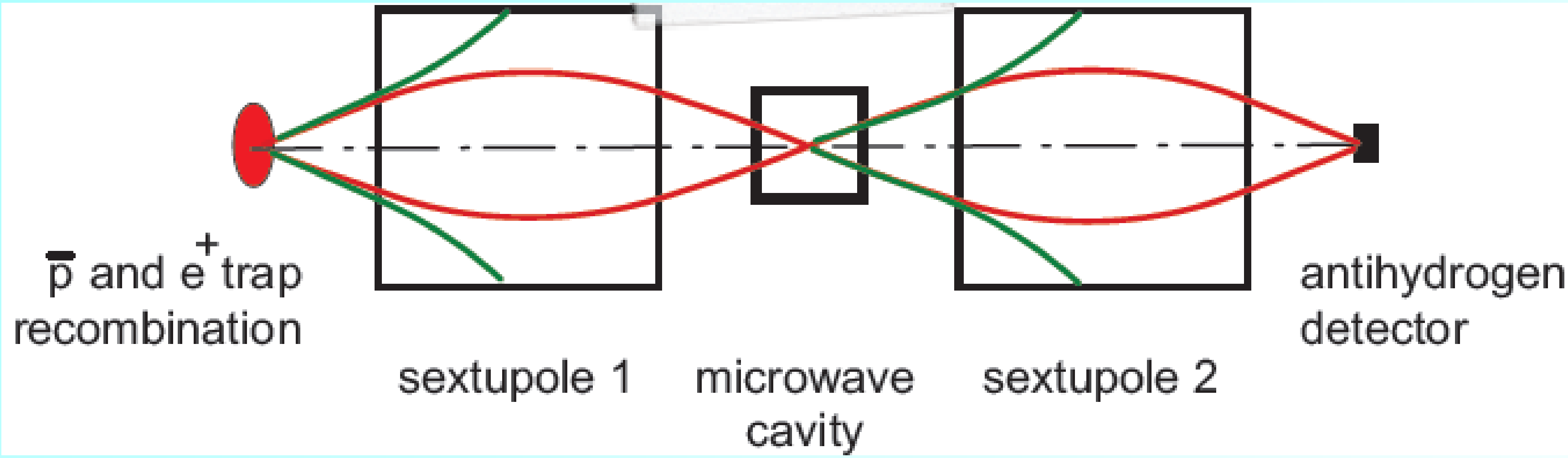
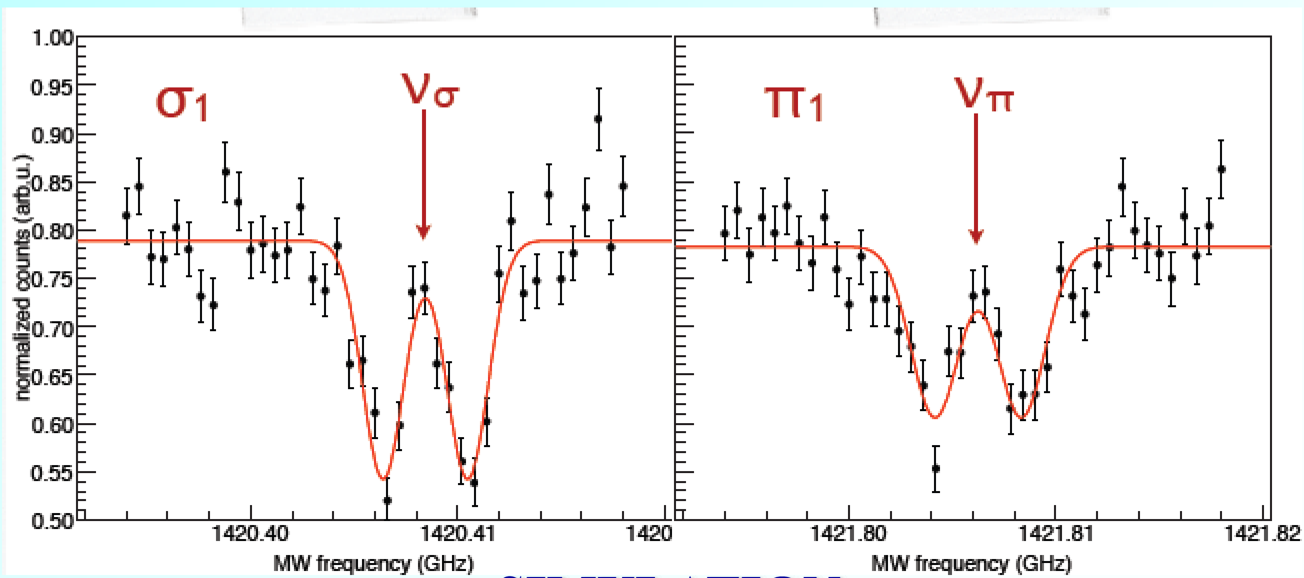
$\bar{p}$H Ground-state Hyperfine Structure



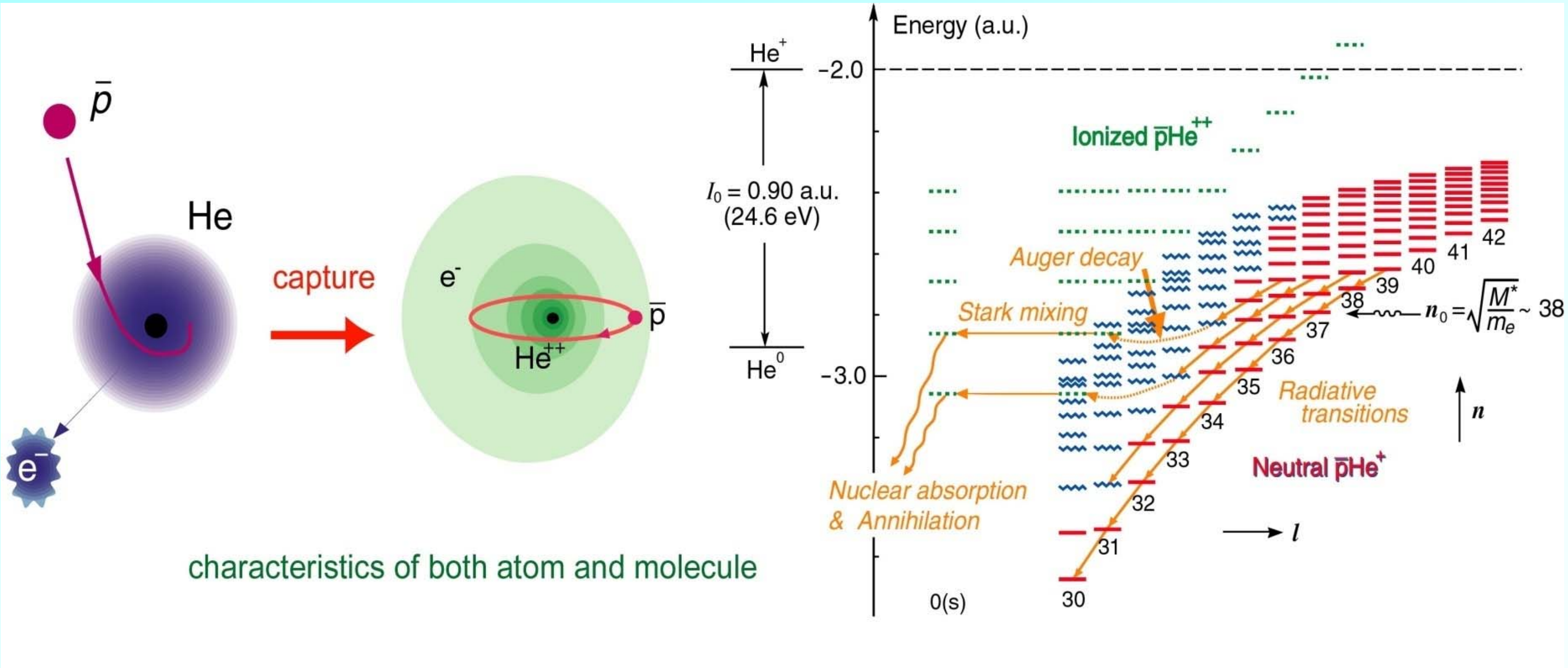


SIMULATION

Need less particles (2 $\bar{p}$H / s) because of narrow natural linewidth

from B. Juhasz

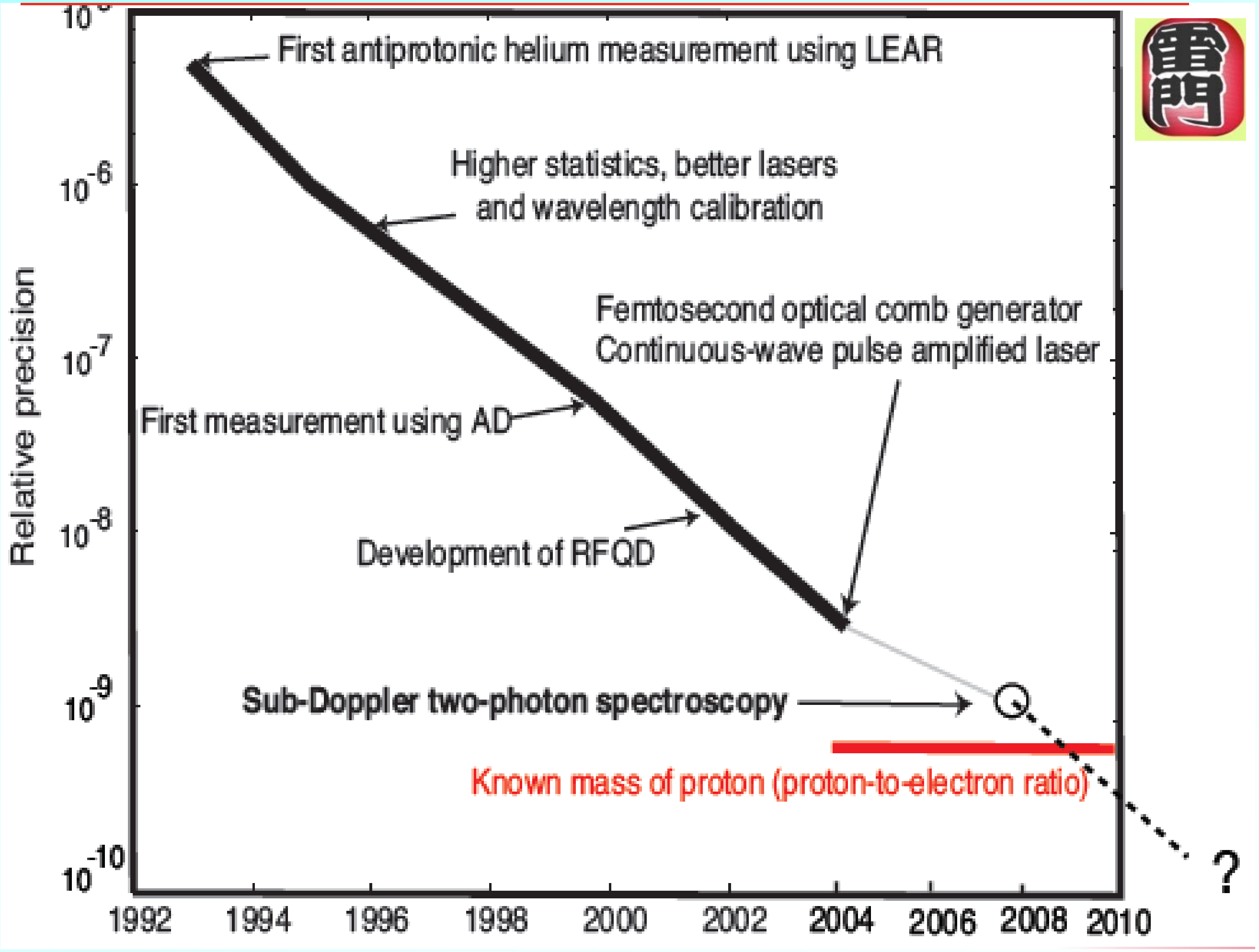
$\bar{p}He^+$ Atom – a naturally occurring trap for antiprotons



- Serendipitously discovered by Tokyo group at KEK
- 3-body system, Metastable
- ~ 3% of stopped antiprotons survive with average lifetime of ~ 3 μs
- Precision laser spectroscopy by ASACUSA:
  - best test of 3-body QED theories
  - proton-antiproton mass & charge comparison (PDG)
- Enters CODATA constant adjustment significantly

Hayano, Yamazaki et al.

Progress in atomcule spectroscopy



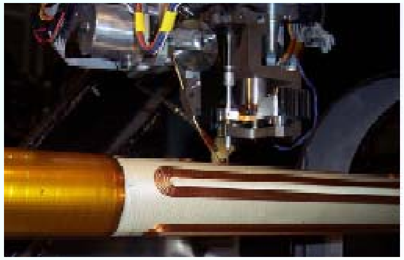
year

CPT Tests @ CERN AD

At the CERN AD a number of unique, important CPT tests were already conducted and improved ones are on their way :

- **ASACUSA** $\bar{p}$He , $\bar{p}He^{+}$, $\bar{p}$H , $\bar{p}$

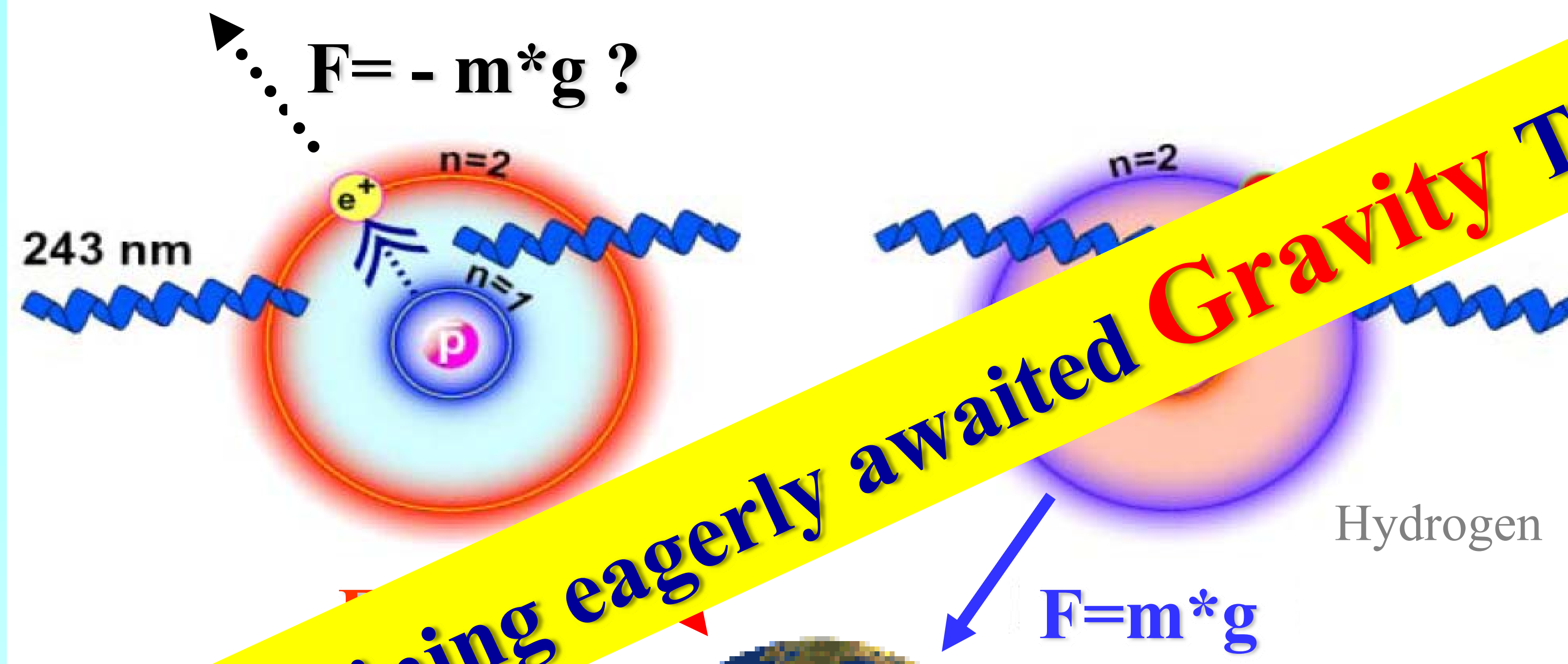
- **ATRAP** $\bar{p}$, $\bar{p}$H



- **ALPHA** $\bar{p}$H

One can expect significant steering of Model Building and High Visibility next to a robust discovery potential.

(Anti-)Hydrogen Gravity Tests



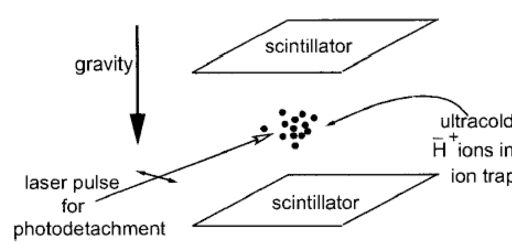
The Remaining eagerly awaited Gravity Test

General Relativity and G… …04)

A Propos… …ravity Using
Ultra…

Jochen Wa… …eodor W. Hänsch[1,2]

Received September 19, 2003

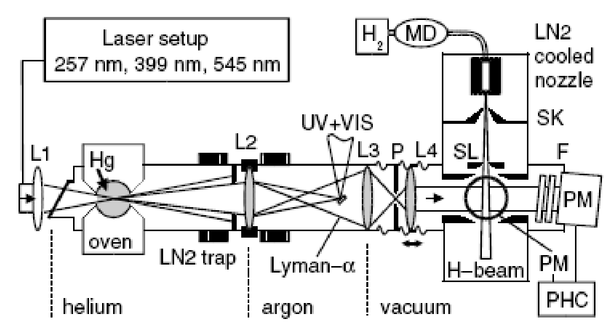


- Lyman –α laser required
- Lyman –α laser developed

VOLUME 86, NUMBER 25 PHYSICAL REVIEW LETTERS

Continuous Coherent Lyman-α Excitation of Atomic Hydrogen

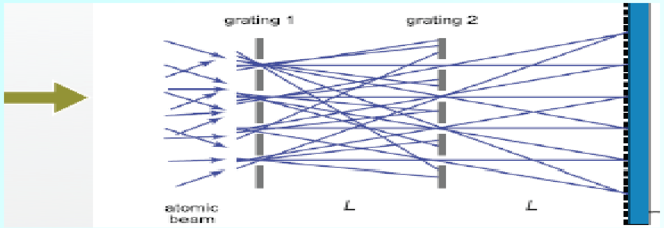
K. S. E. Eikema,* J. Walz,† and T. W. Hänsch

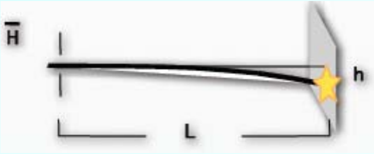


Gravity Tests @ CERN AD

At the CERN AD is the place to answer the most urgent question on antimatter gravity :

- **AEGIS** $\bar{p}H$
- **ATRAP** $\bar{p}H$
- **Free Fall** $\bar{p}H$





$$h = \frac{1}{2} g T^2 = \frac{g}{2}\left(\frac{L}{v_z}\right)^2$$

One can expect an answer to a most fundamental question to question, which only can be answered by experiment! High Visibility next to a robust discovery potential.

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Standard Model Physics Applications

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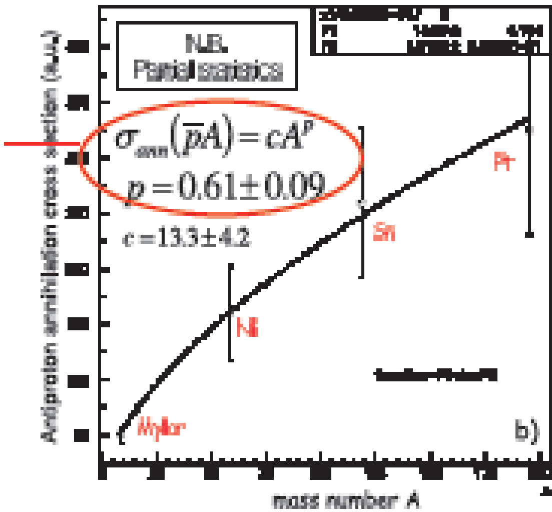
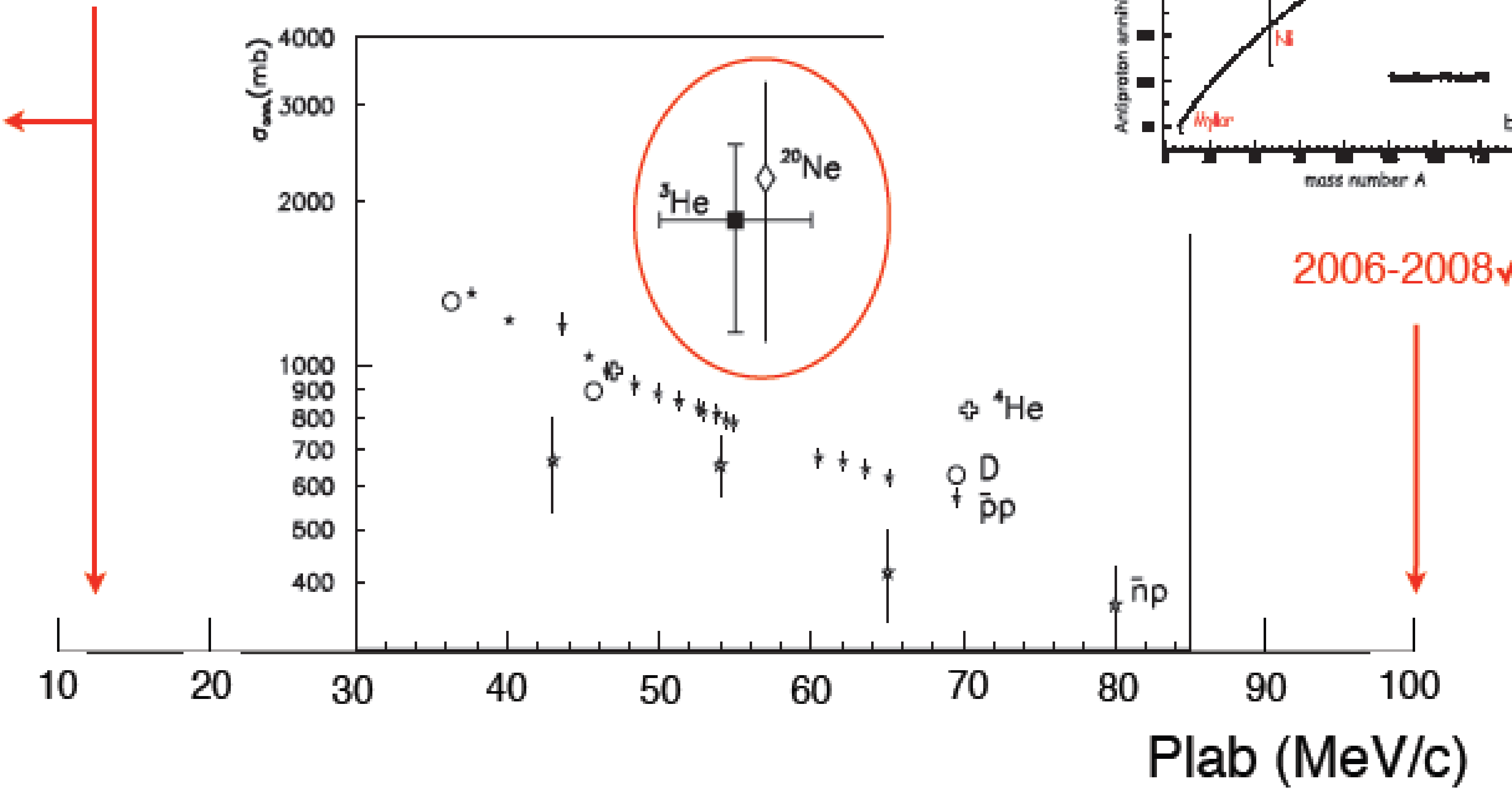
Antiprotonic Radioactive Atoms

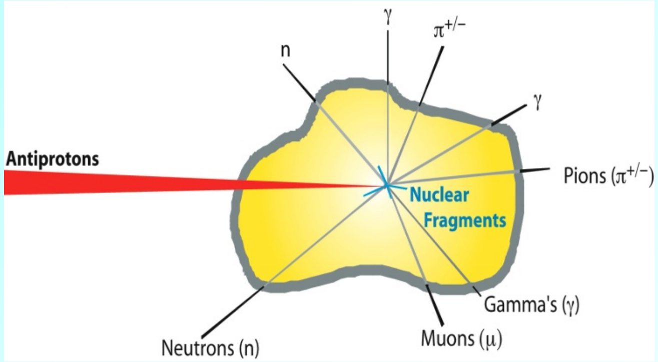
ASACUSA
using RFQD &MUSAHI

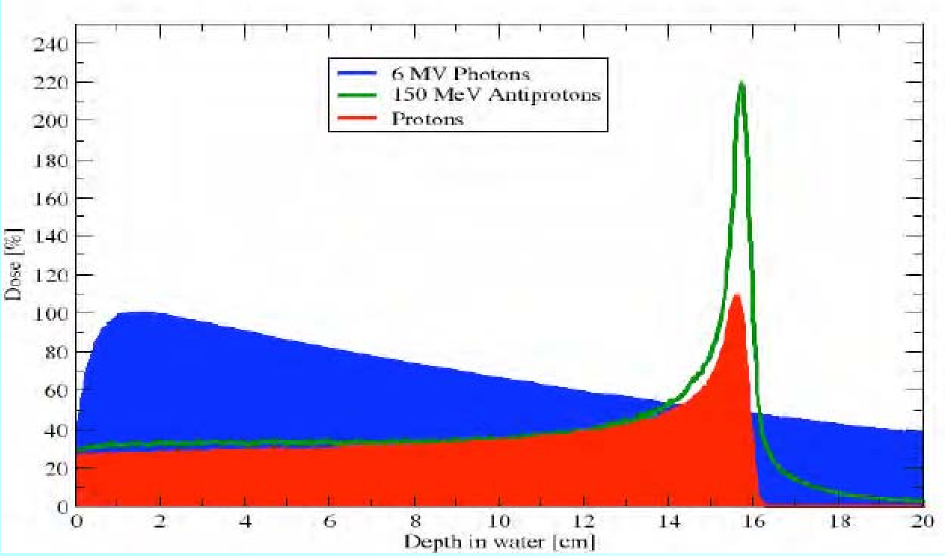
Consistent with $A^{2/3}$
No surprise yet at 5 MeV

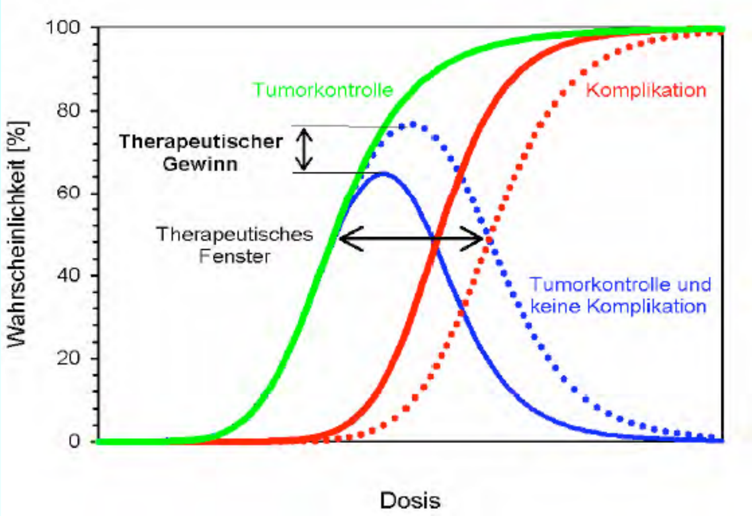


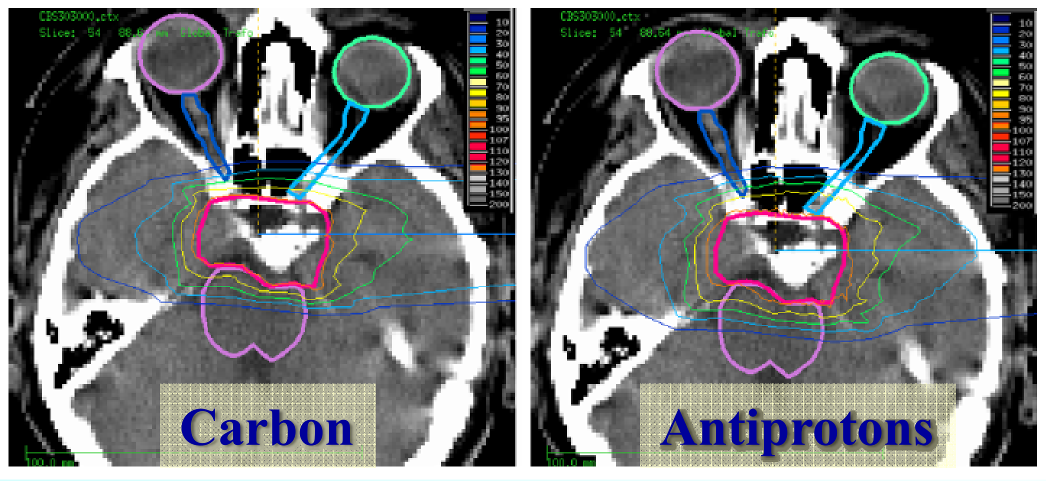


Antiproton Radio-Therapy









A significant win (factor ~4) in a sensitive window for tumor treatment and healthy tissue sparing

Physics within Standard Model and Applied Research @ CERN AD

At the CERN AD also SM physics and Applied Research is conducted:

- **ASACUSA** — $\bar{p}$-nucleus annihilation, atomic collisions
- **Double-Strangeness Production** — $\bar{p}$-nucleus dedicated experiment
- **PAX** — $\bar{p}$ polarization, $\bar{p}^{\uparrow}$– p interactions
- **ACE** — $\bar{p}$ radiation-therapy
- **…** — …

One can expect deeper insights and the development of novel techniques to the benefit of physics and society.

Antiproton Sources

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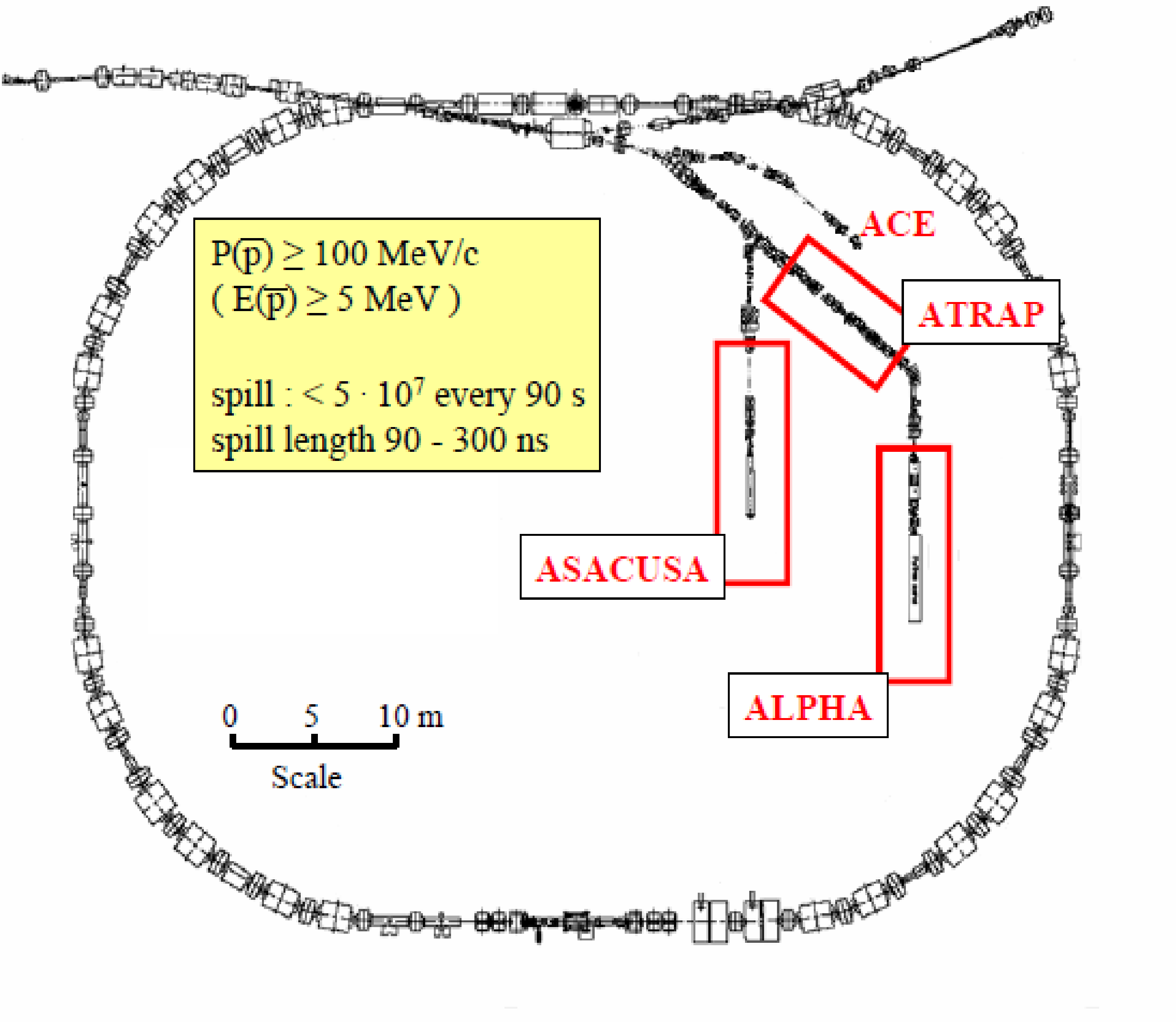
Antiproton Decelerator (AD) @ CERN



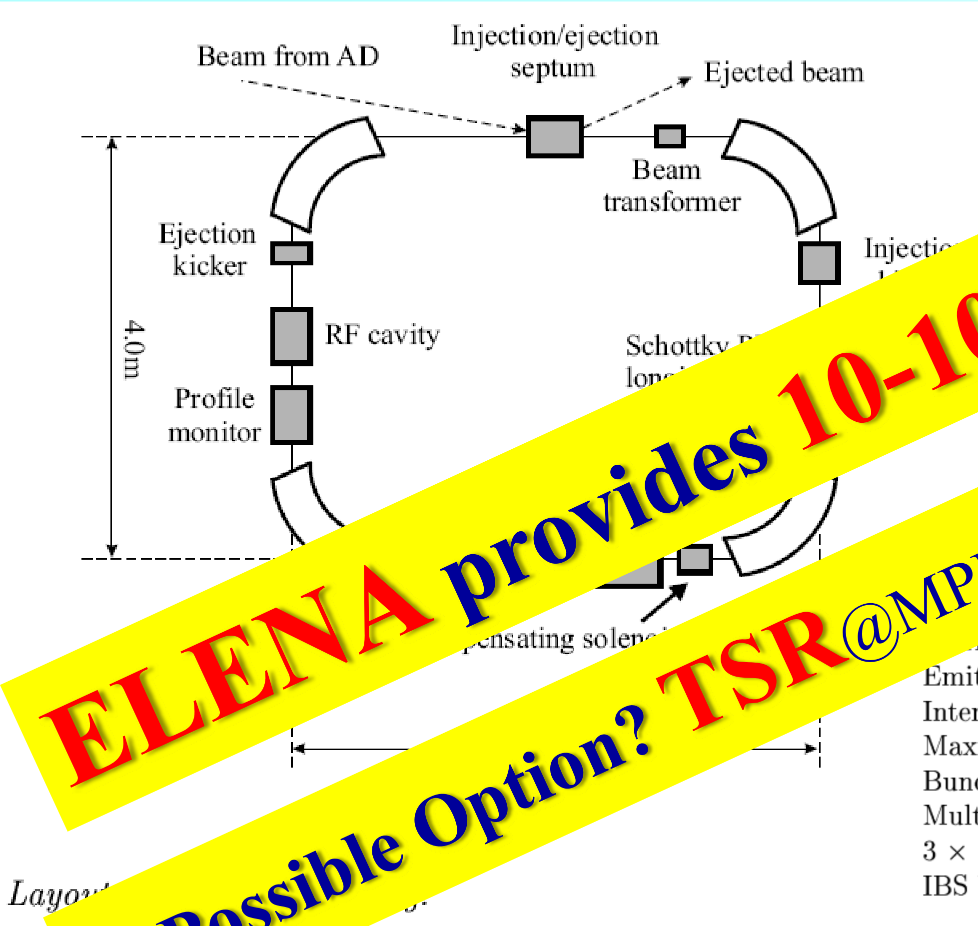
- **Started operation** July 6, **2000**

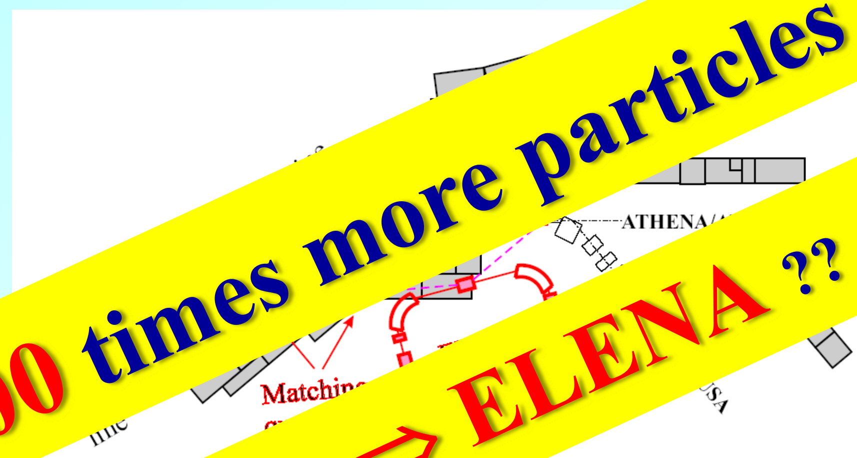
  Antiproton capture, deceleration, cooling
- **Pulsed extraction**
- **Many Experiments**
  - ASACUSA
  - ATRAP
  - ALPHA
  - AEGIS
  - Free Fall
  - PAX
  - ACE
  - .....
- **Request for more and better antiproton beams**
  - To speed up progress
  - To boost accuracy

$\Rightarrow$ **ELENA**

Consequent Future Development

ELENA@CERN



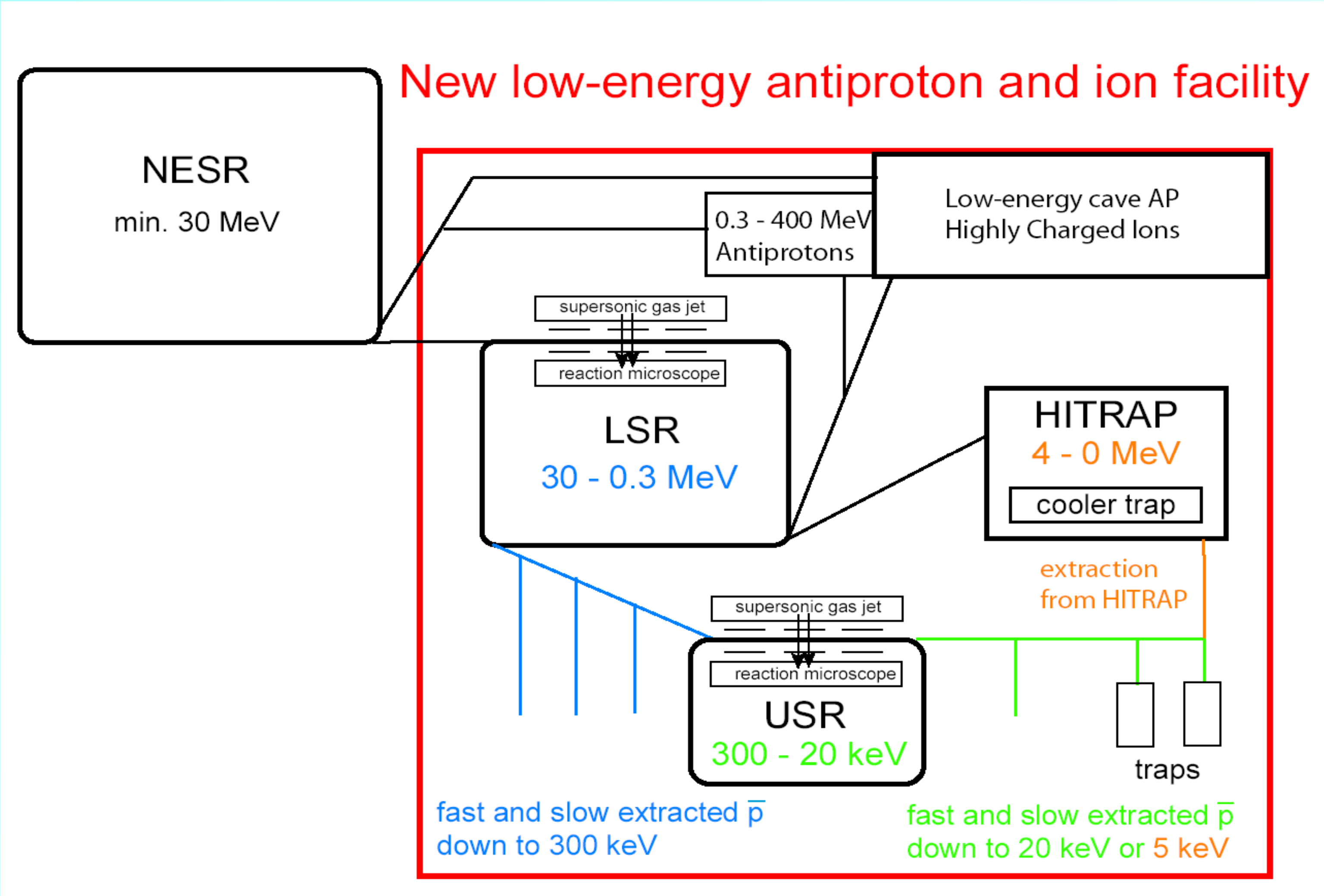


...eV	5.3 - 0.1
...ence, m	16.7
...ing point	1.64 / 1.62
Emittances at 100 keV, π mm mrad	5 / 5
Intensity limitations due to space charge	1.7×10^{7}
Maximal incoherent tune shift	0.10
Bunch length at 100 keV, m / ns	1.3 / 300
Multiple scattering blow up rate for 3×10^{-12} Torr (N_2 equiv.), $\pi mm\ mrad/s$	0.5
IBS blow up times, s ($\Delta p/p = 2\ 10^{-3}$)	3.2 /-30.6 / 3.9

ELENA provides 10-100 times more particles

?Possible Option? TSR@MPIK(Heidelberg) ⇒ ELENA ??

FLAIR @ GSI /FAIR



Factor 100 more pbar trapped or stopped in gas targets than now

New Facilities @ CERN AD or GSI/FAIR

New Facilities can provide up to 100 times more particles:

- **MUSASHI** ASACUSA 's device to recycle $\bar{p}$'s
- **ELENA** Generic low cost CERN solution, Start possible now
- **FLAIR** GSI/FAIR solution not before 2015

One can expect faster progress and better results from more $\bar{p}$'s

→ CERN and GSI should synchronize

university of groningen

Summary and Conclusions

- **Highly Motivated Urgent Antiproton Experim**
  with robust Discovery Potential and Hi
  - CPT, Gravity, Determination of Fundamental
  - SM Physics, Applications (Therapy)
- **Unique Facility world**
- **Creative and** **g Community**
  - Young
  - echnology
- **good on Time Path**
- **Program needs more particles**
  → **ELENA** well motivated
- **Productive and Prosperous Future Ahead**

Low Energy Antiproton contributions to Physics just started

Precision takes Time Care and Particles


ASACUSA
HARVARD
ATRAP
ATHENA

Thank YOU !