Measuring the Free Fall of Antihydrogen

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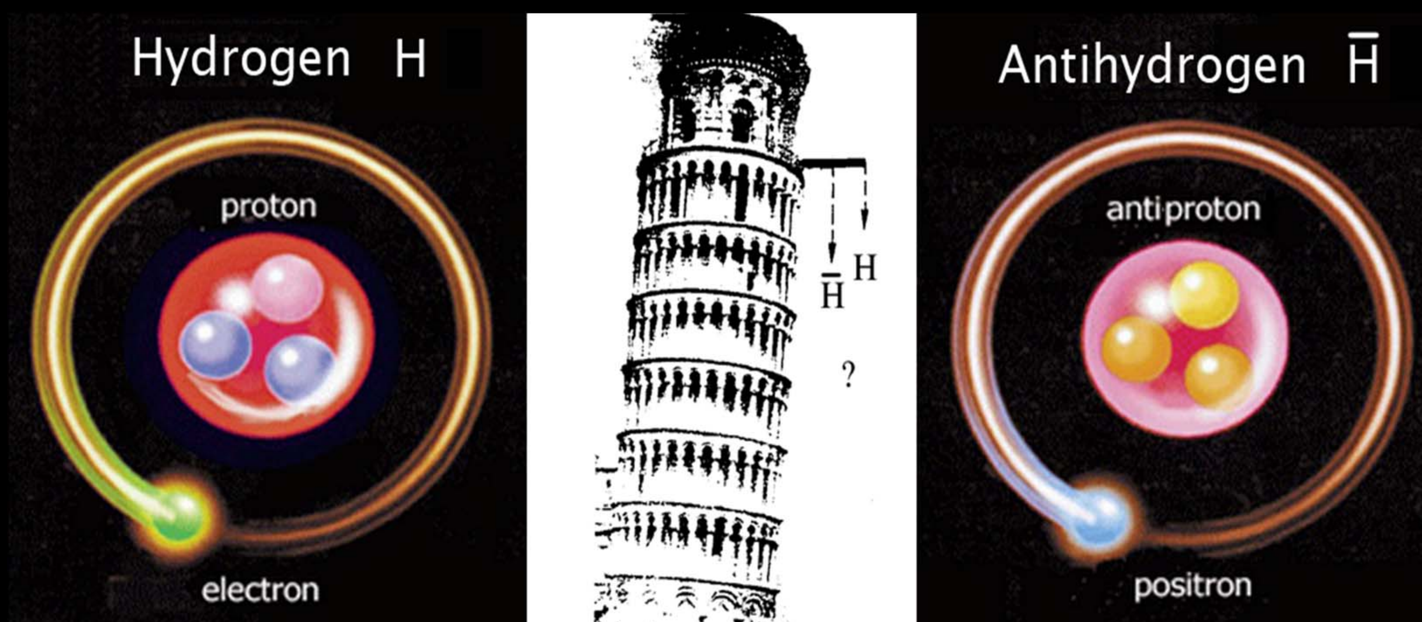
on behalf of the AEgIS Collaboration



AEḡIS: **Antimatter Experiment: Gravity, Interferometry, Spectroscopy**

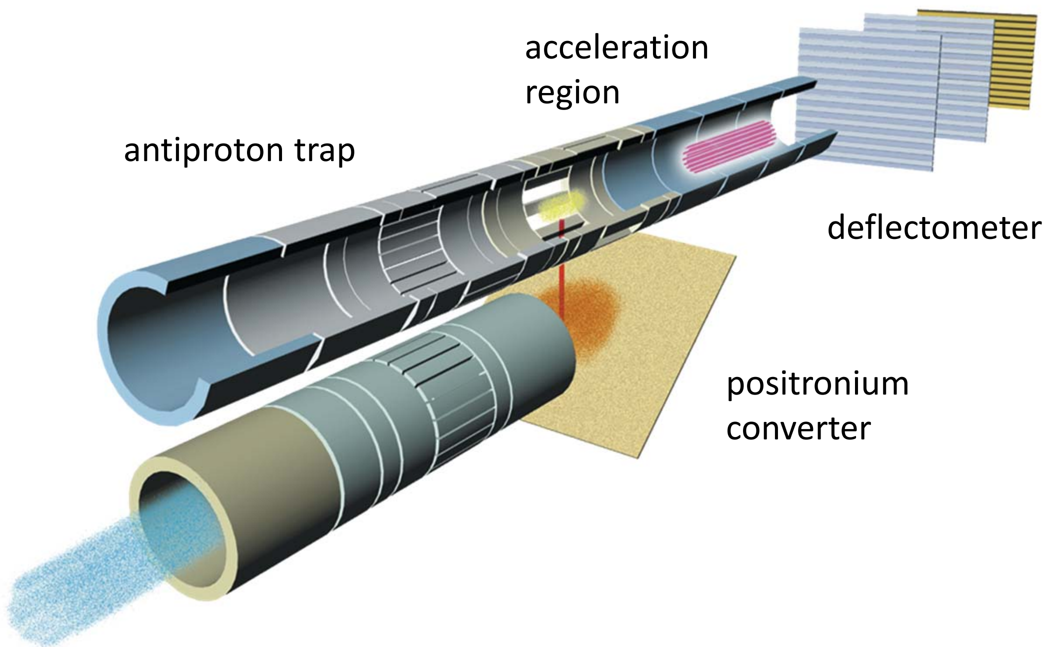
- Main goal: Measurement of g with 1% precision* on antihydrogen

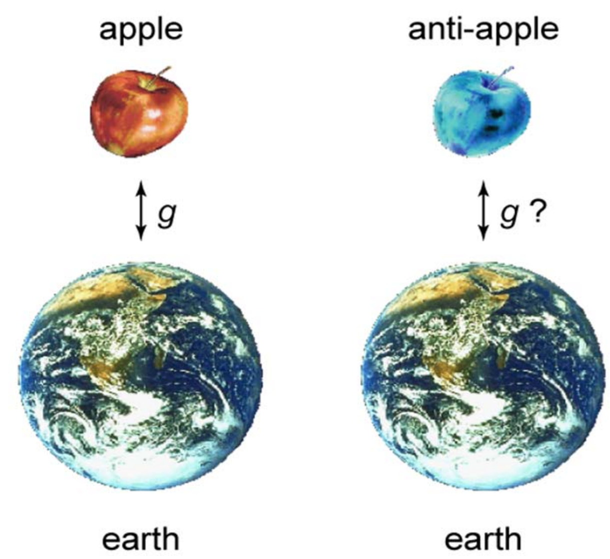
  * (initially)

- Proposed in 1997 by Tom Phillips (Duke U)

  [T. J. Phillips, Hyp. Int. **109** (1997) 357]

- Requirements / challenges:
  - Production of a **bunched cold beam of antihydrogen** (100 mK)
  - Measurement of vertical beam deflection (10 µm drop over 1 m)





Outline

- Motivation / Prospects for anti-gravity
- AEGIS principle and setup
- Current status
- Conclusions and outlook

Motivation

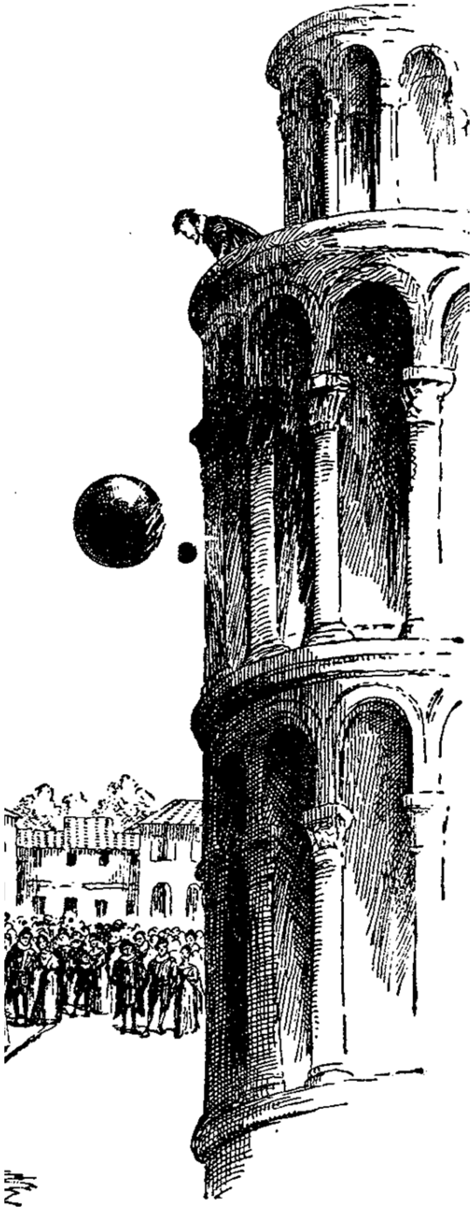
- **Weak equivalence principle (WEP):**

  In a uniform gravitational field all objects fall with the same acceleration, regardless of their composition.

- WEP extremely well tested with matter, but never with antimatter

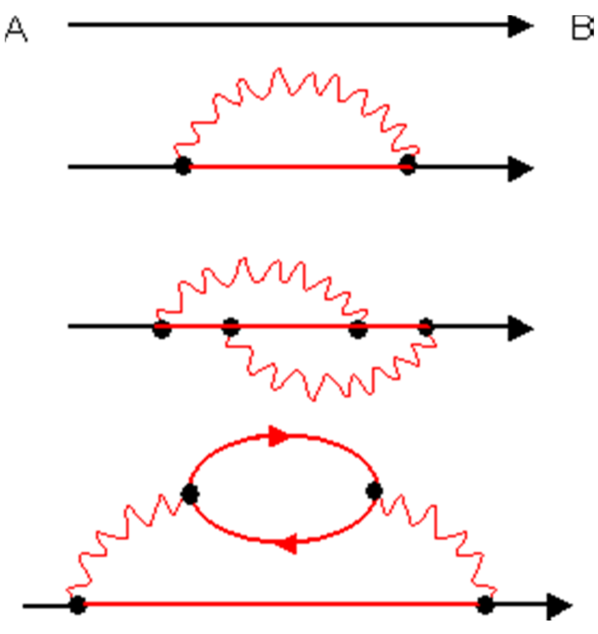
- electric charge of subatomic particles

$$\overline{m}_g \stackrel{?}{=} \overline{m}_i$$



Motivation

- Gravity is the only force **not** described by a quantum field theory



- QFT formulations of gravity open the way for
  - Non-Newtonian gravity
  - WEP violation
  - Fifth forces etc.

- Since 2002 copious amount of neutral antiatoms have become available

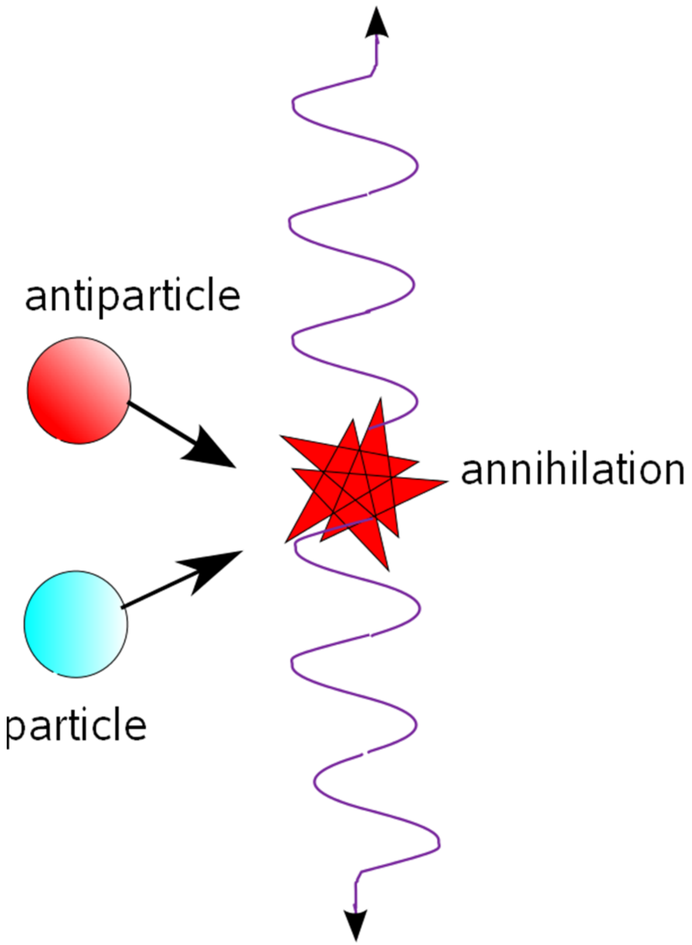
[M. Amoretti *et al.*, Nature **419** (2002) 456;
G. Gabrielse *et al.*, Phys. Rev. Lett. **89** (2002) 213401]

Antimatter

- Antimatter perfect mirror image of matter
- When matter and antimatter collide particles anihilate
- CPT conjugate

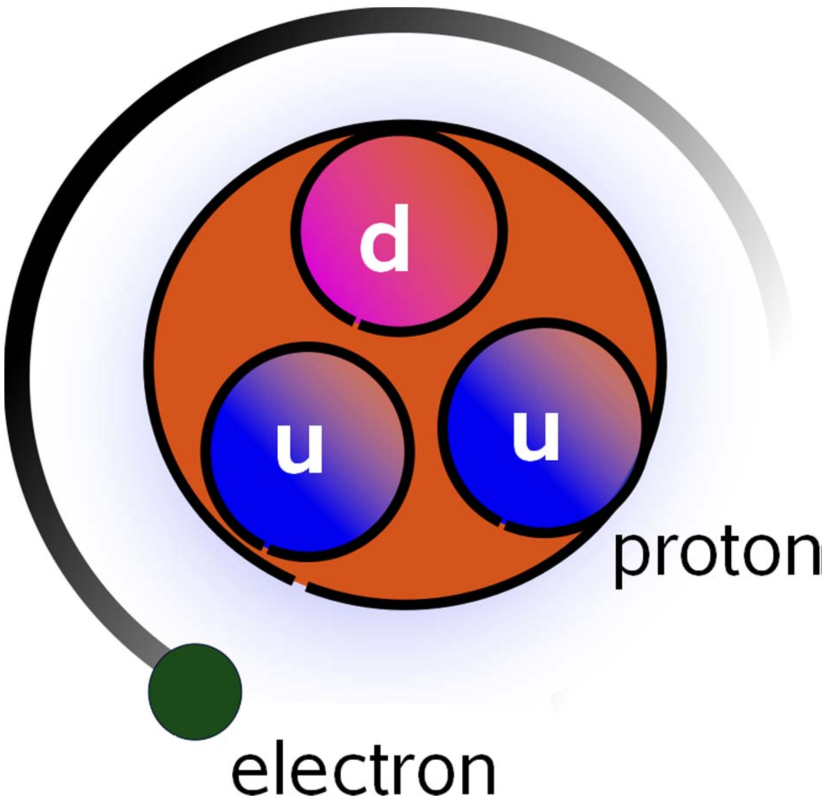
CPT theorem by W. Pauli:

Every canonical quantum field theory is invariant under simultaneous inversion of charge, parity, and time.

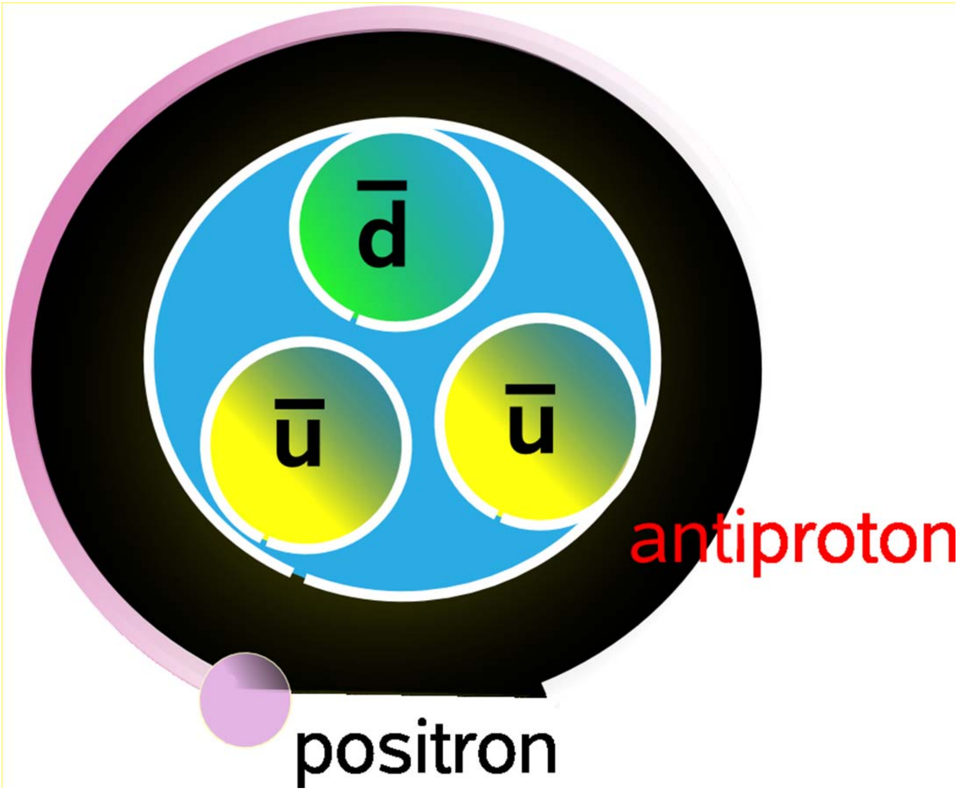


Antihydrogen

hydrogen

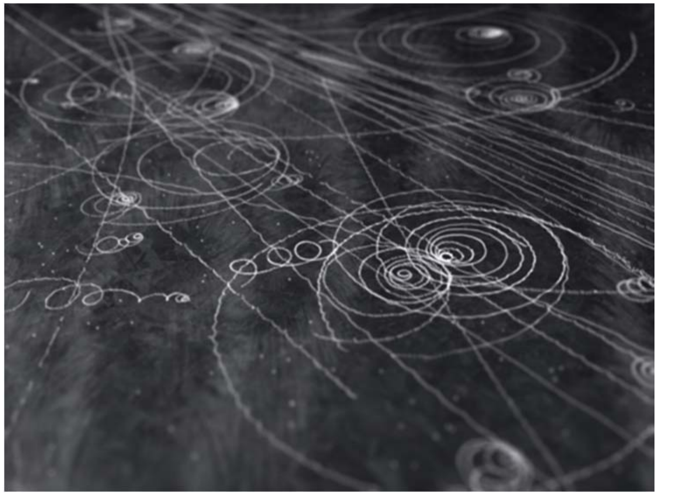


antihydrogen

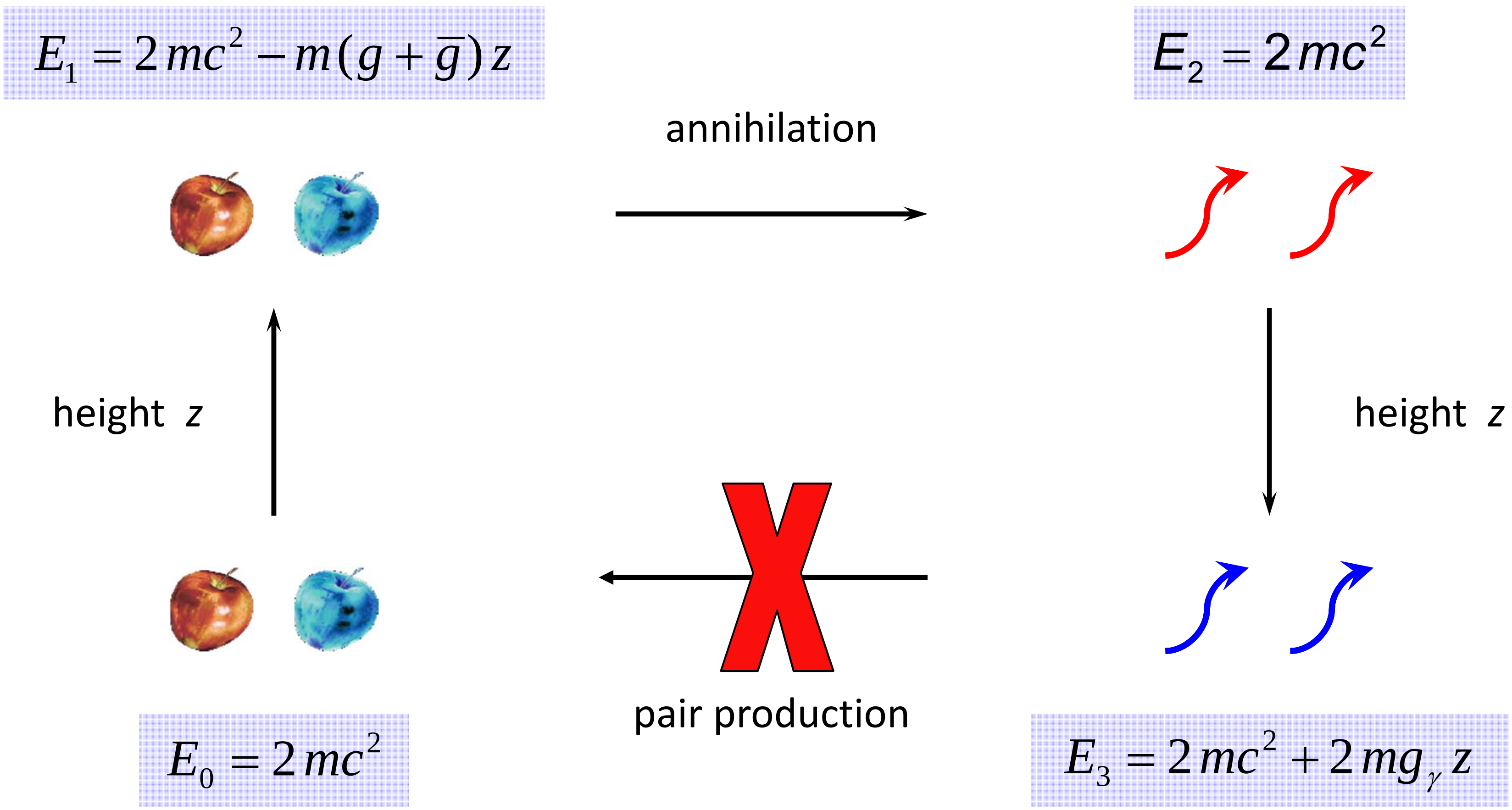


Antimatter

- 1928 Paul Dirac predictes antimatter
- 1932 Carl Anderson discovers
  the positron in cosmic rays
- 1955 Owen Chamberlain et al. publish
  "Observation of antiprotons "
- 1956 discovery of antineutrons
- 2002 first production of cold antihydrogen atoms
- 2011 first storage of antiatoms for 1000 s



The Morrison argument



- Energy conservation violated if $\bar{g} = -g$
- Valid argument against anti-*tensor* gravity
- Irrelevant for other scenarios (scalar/vector, other couplings)

[P. Morrison, Am. J. Phys. **26** (1958) 358;
M. M. Nieto & T. Goldman, Phys. Rep. **205** (1991) 221]

Quantum gravity

- Quantum gravity could accommodate non-Newtonian components (scalar, vector), coupling to various charges…
- Hypothetical exchange particles:

• Tensor graviton	(Spin 2, "Newtonian")	always attractive
• Vector graviton	(Spin 1)	repulsive between like charges
• Scalar graviton	(Spin 0)	always attractive

- Quantum gravity potential (static limit):

$$V = -\frac{Gm_1m_2}{r}\left(1 \pm \alpha_v e^{r/\lambda_v} + \alpha_s e^{r/\lambda_s}\right)$$

where α_v, λ_v – vector c.c./range
α_s, λ_s – scalar c.c./range

- Non-Newtonian terms could (almost) cancel out if $\alpha_v \approx \alpha_s$ and $\lambda_v \approx \lambda_s$, but produce a striking effect on antimatter

Indirect experimental limits on antigravity

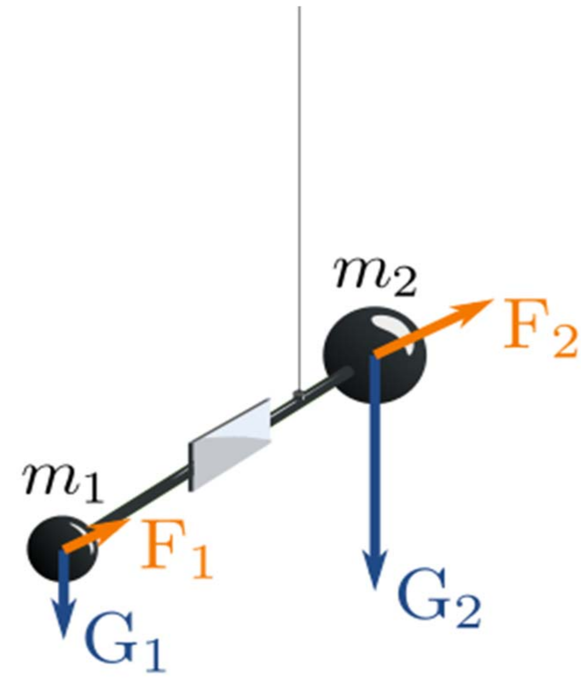
A.) “Newtonian experiments”

(force / acceleration / deflection)

$$F = m \cdot a$$

– Eötvös-type experiments, “Fifth force” searches
– Fraction of nuclear mass due to virtual antiquarks

→ coupling of gravity to virtual particles not understood;

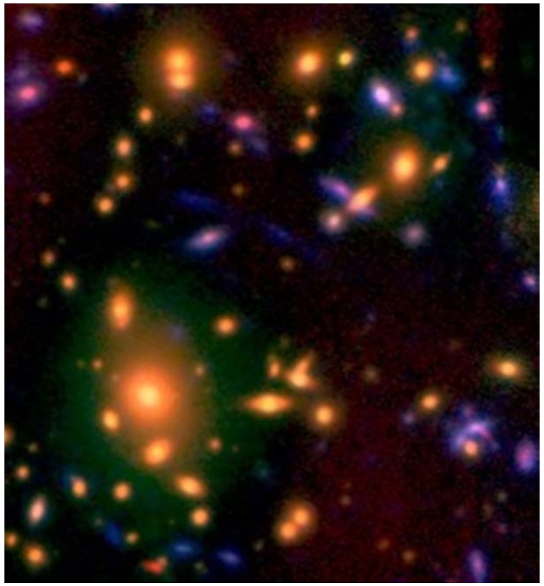


[T. Ericson & A. Richter, Europhys. Lett. **11** (1990) 295; E. Adelberger *et al.*, Phys. Rev. Lett. **66** (1990) 850;
M. M. Nieto & T. Goldman, Phys. Rep. **205** (1991) 221; S. Bellucci & V. Faraoni, Phys. Rev. D **49** (1994) 2992;]

Indirect experimental limits on antigravity

B.) "Einsteinian experiments"

(red shift / rescaling of observed time)



- $p/\bar{p}$ cyclotron frequency, K^0–$\bar{K}^0$ non-regeneration (beyond CP violation)
- Despite CPT invariance, observed frequencies influenced by spacetime metric: $\alpha_g < 5\times10^{-4}$
- K^0–$\bar{K}^0$ oscillation rate dependent on gravitational potential:

$$\alpha_g < 2\times10^{-9}$$

→Depends on CPT invariance, absolute gravitational potential, choice of potential

[G. Gabrielse et al., Phys. Rev. Lett. 82 (1999)3198]
[M. Fischler *et al.*, Fermilab report FN-0822-CD-T (2008)]

Indirect experimental limits on antigravity

C. Astronomical (anti-)neutrino observations

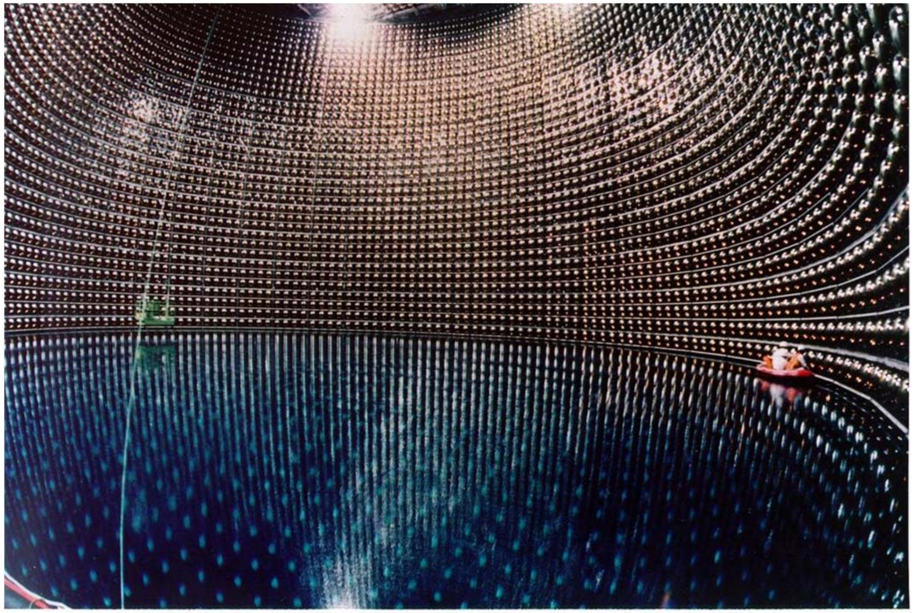
- Contribution to flavor oscillations due to gravitational potential

  Solar neutrinos: $\alpha_g < 0.2$ or 2×10^{-4}, depending on potential (Earth, galactic supercluster)

- Supernova SN1987A $\overline{\nu}/\nu$ arrival time: $\alpha_g < 0.5\%$ (galactic supercluster)

Restricted to neutrino sector;

depends on absolute gravitational potential



[M. Fischler *et al.*, Fermilab report FN-0822-CD-T (2008)]

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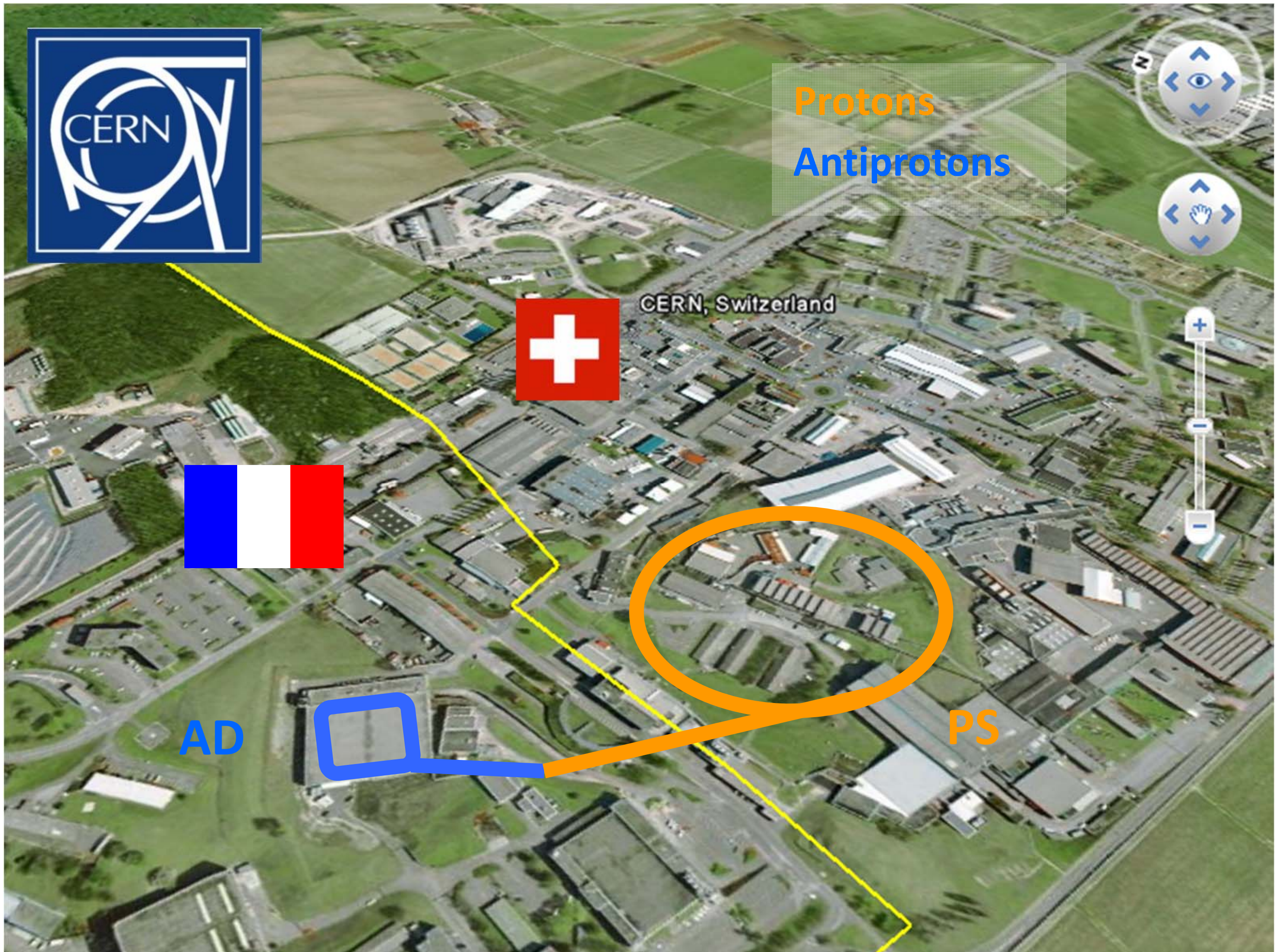
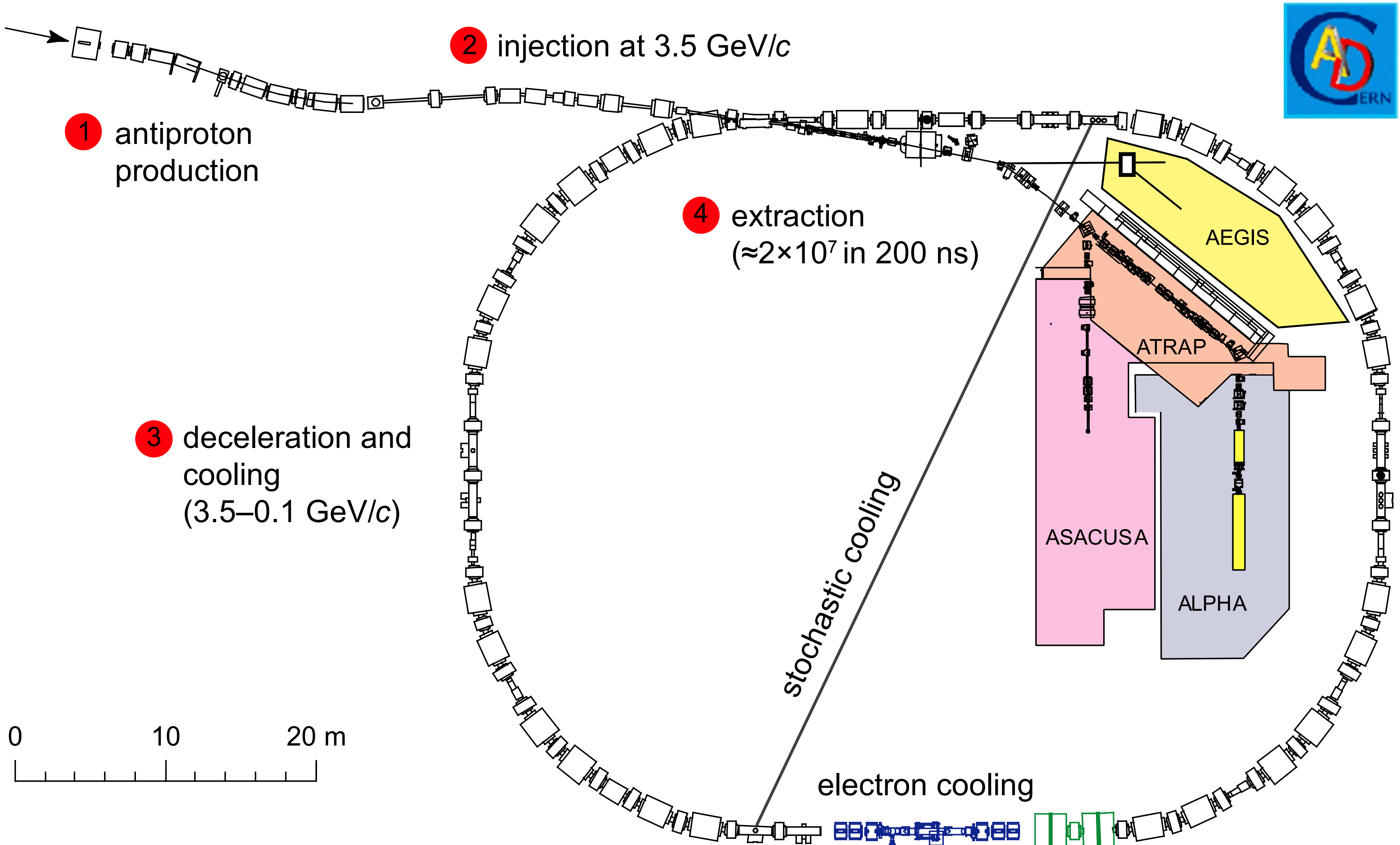
Antiproton Decelerator at CERN



- $10^7\,\overline{p}$ produced every ≈ 90 s
- Deceleration p = 3.5 GeV/c → 100 MeV/c
- Fast extraction (200-ns bunches)

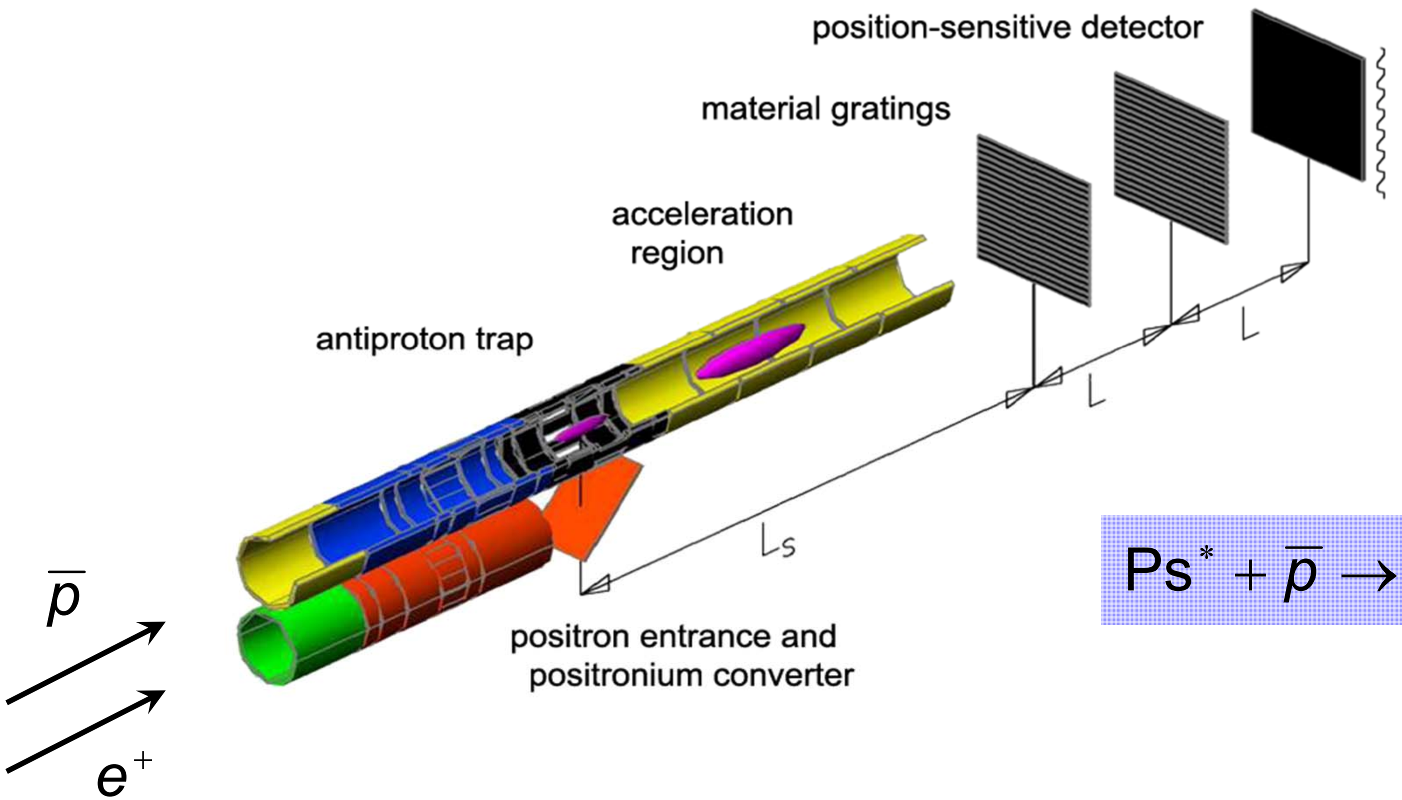
AD experiments



[J. Y. Hémery & S. Maury, Nucl. Phys. A **655** (1999) 345c]

Experimental sequence

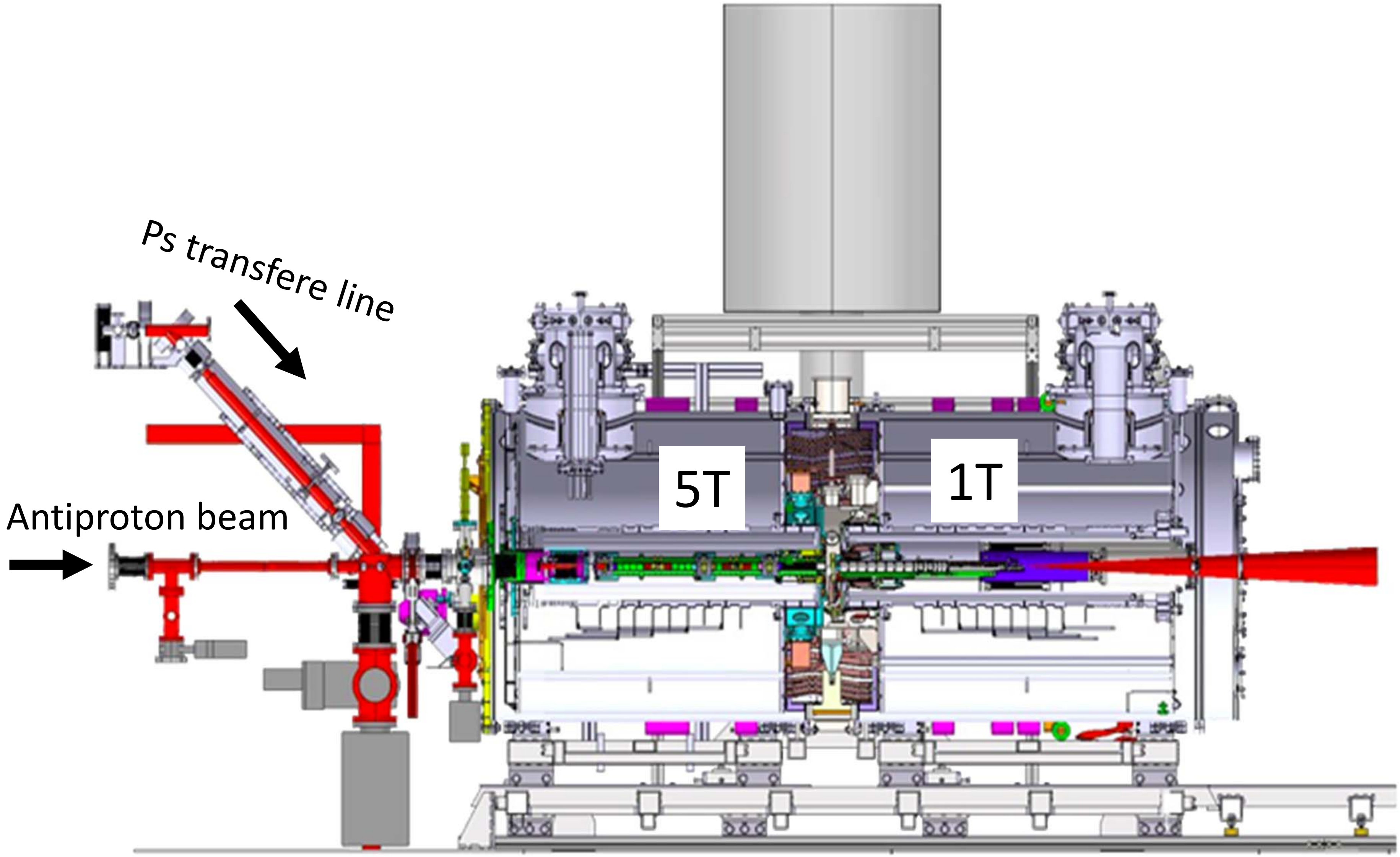
- Principle sketch (not to scale):



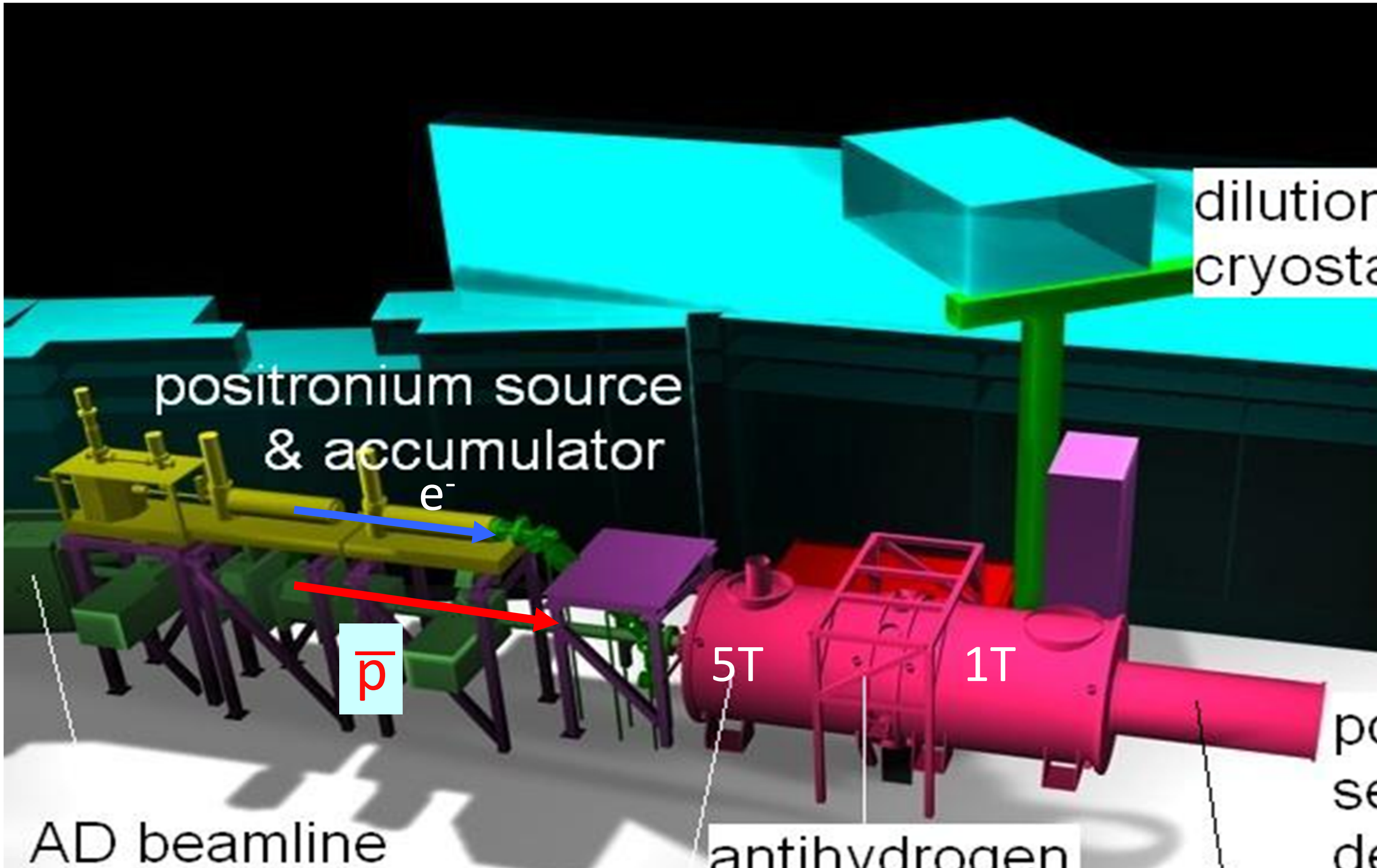
$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$

1) Antiproton capture & cooling
2) Positron production
3) Positronium conversion
4) Positronium excitation
5) Antihydrogen recombination
6) Antihydrogen beam formation
7) Gravity measurement
8) Data analysis

Scematic overview of the apparatus

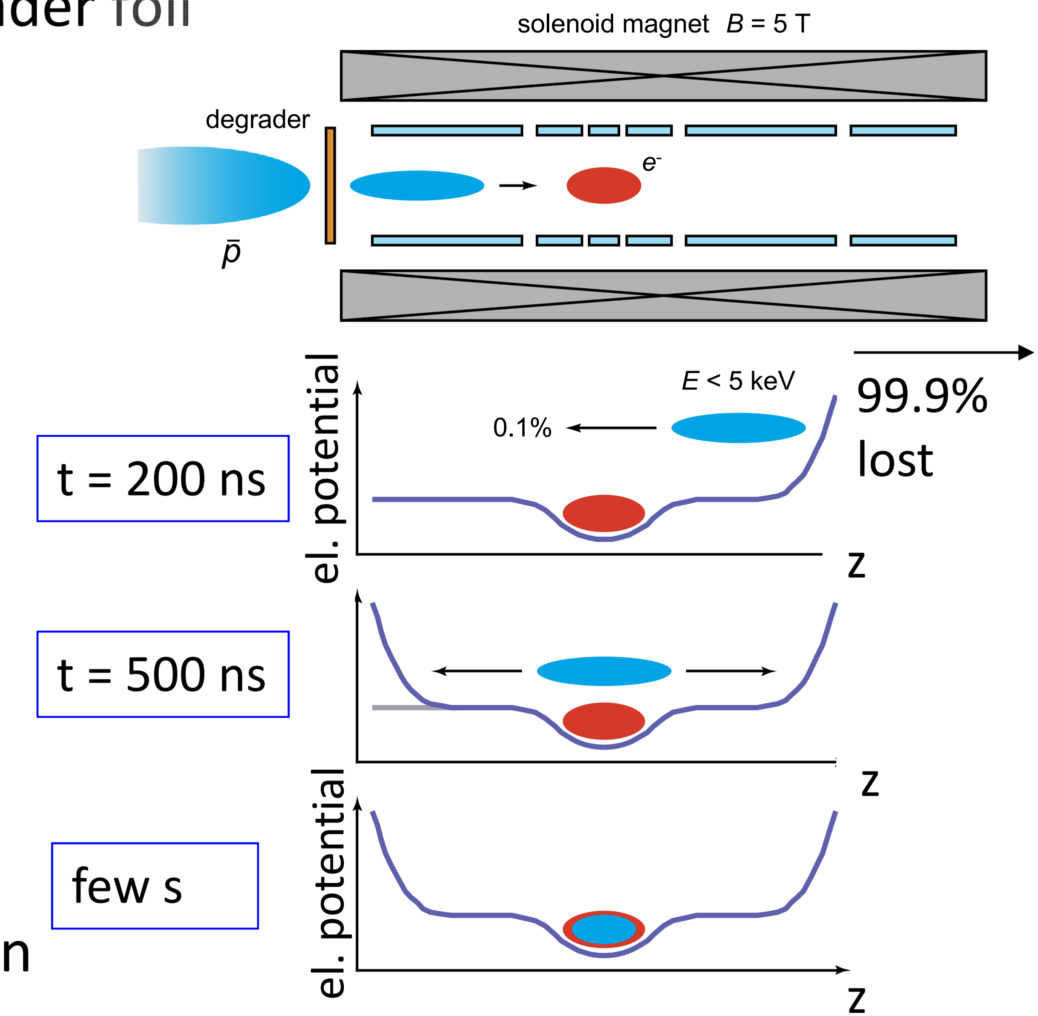


AEGIS overview sketch



Antiproton capture and cooling

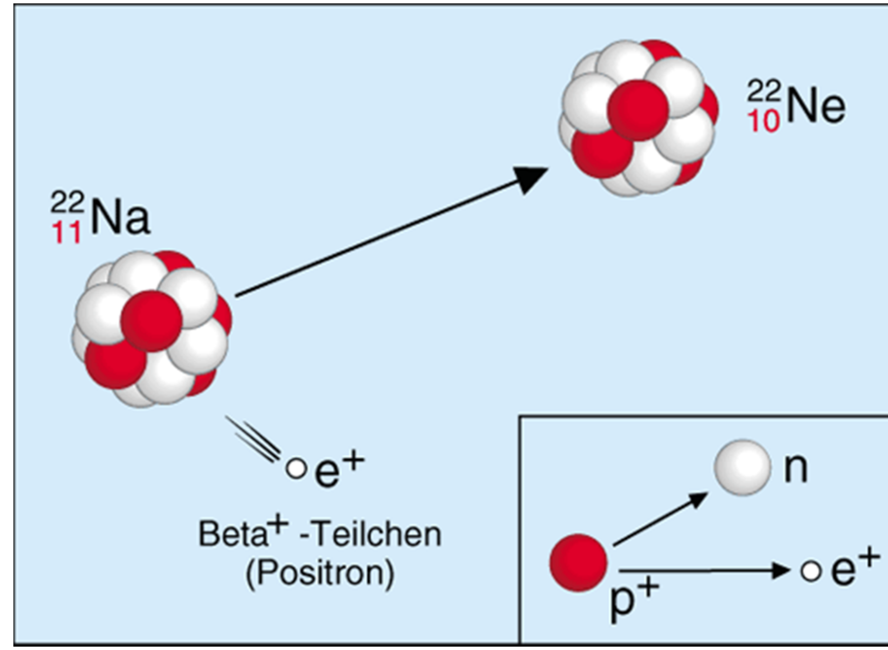
- Energy reduced by 50-µm Al degrader foil
- Trapping sequence:
  1. Trap is prepared with plasma of 10^8 cold electrons
  2. Small fraction of antiprotons with $E < 5$ keV is reflected
  3. Axial potential on entrance side is raised to trap $\bar{p}$
  4. Antiprotons are sympathetically cooled by electrons
- Trap cooled to 100 mK by a dilution refrigerator



> 10^4 antiprotons @ 100 mK

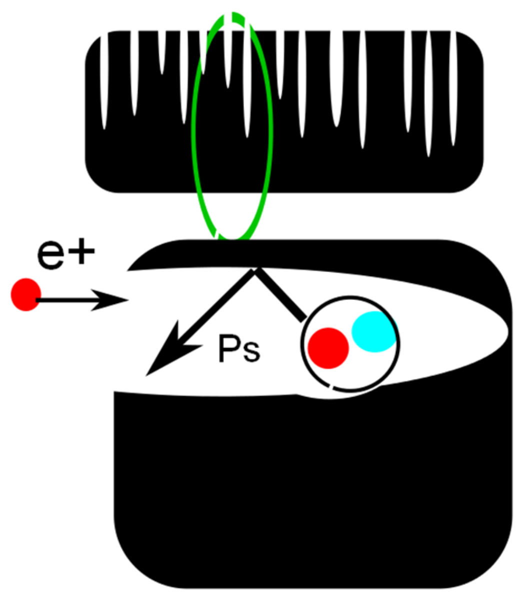
Positronium production

- Positrons from a ^{22}Na source
- Formation of positronium in nano-porous silica based materials



Ortho Ps
τ = 140 ns

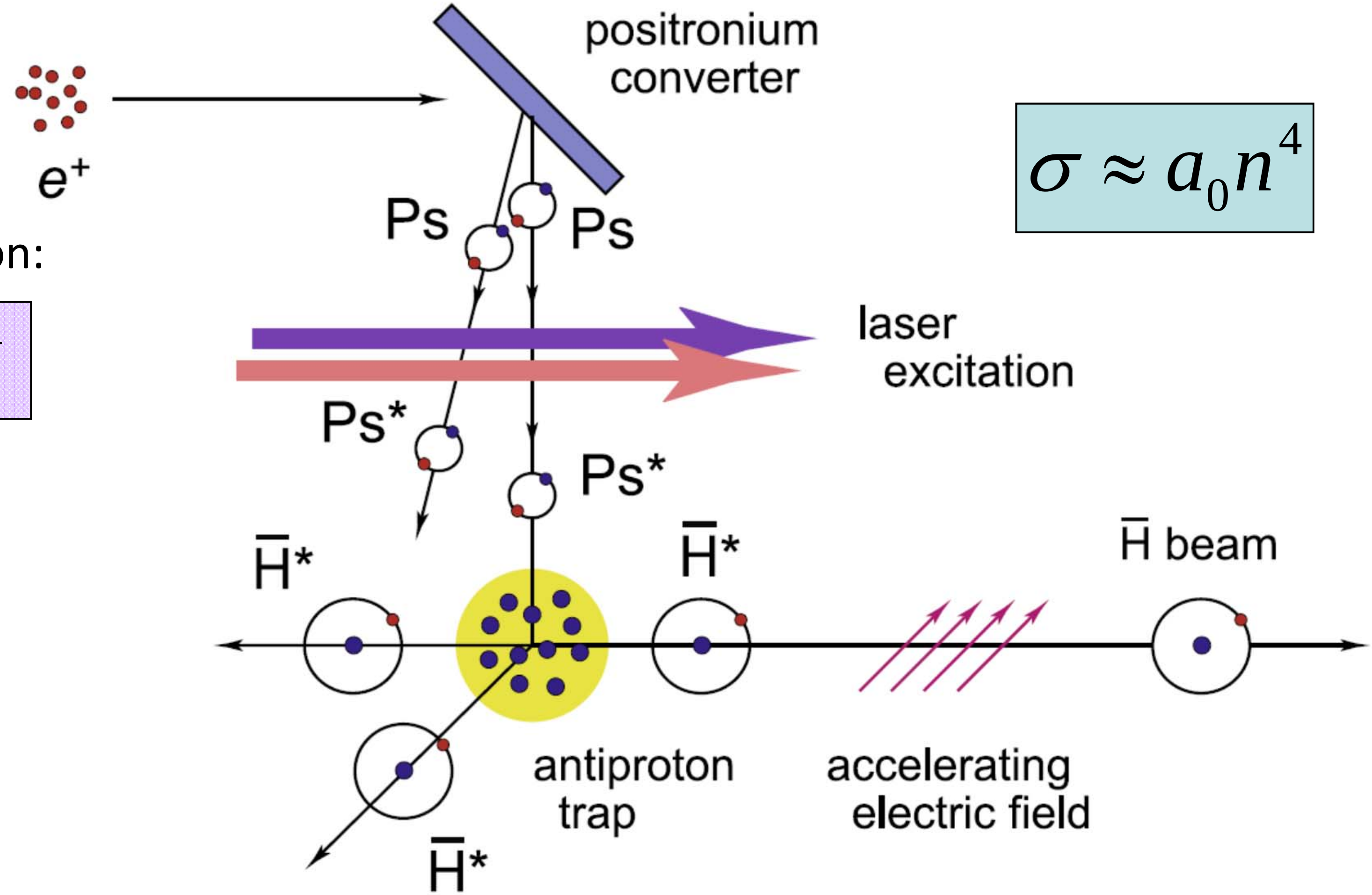
Para PS
τ = 125 ps



- Measurements ongoing at Trento and Munich (NEPOMUC) to optimize Ps conversion targets
  - at 50 K, 9% of positrons converted to Ps
  32% of Ps with velocities $v < 5 \times 10^{-4} \frac{m}{s}$

[S. Mariazzi, P. Bettotti, et al. Phys. Rev. B 81, 235418 (2010)]

Antihydrogen recombination



- Charge exchange reaction:

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

- Principle demonstrated

  by ATRAP

  Cs* $\rightarrow$ Ps* $\rightarrow$ $\bar{\mathrm{H}}$*

- Advantages:
  - Large cross-section:

$$\sigma \approx a_0 n^4$$

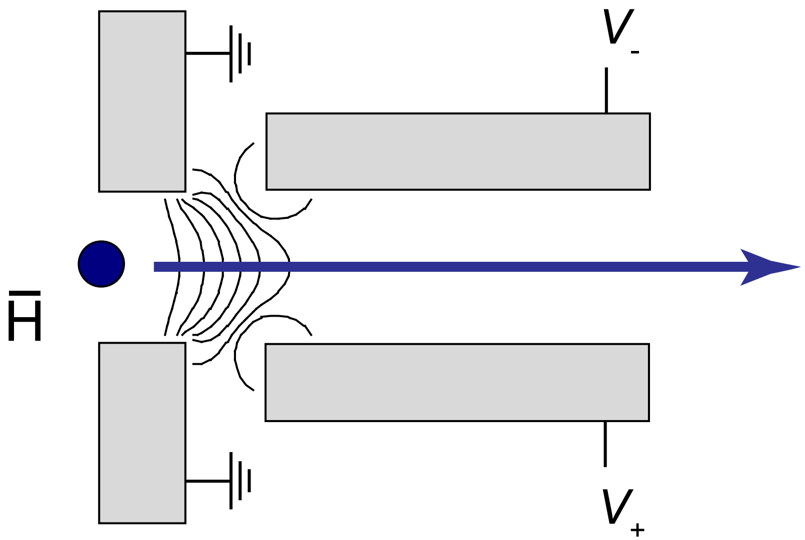
  - Narrow and well-defined *n*-state distribution
  - Antiproton temperature determines antihydrogen temperature

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

Antihydrogen acceleration

- Rydberg antihydrogen accelerated into a beam by inhomogeneous electric field

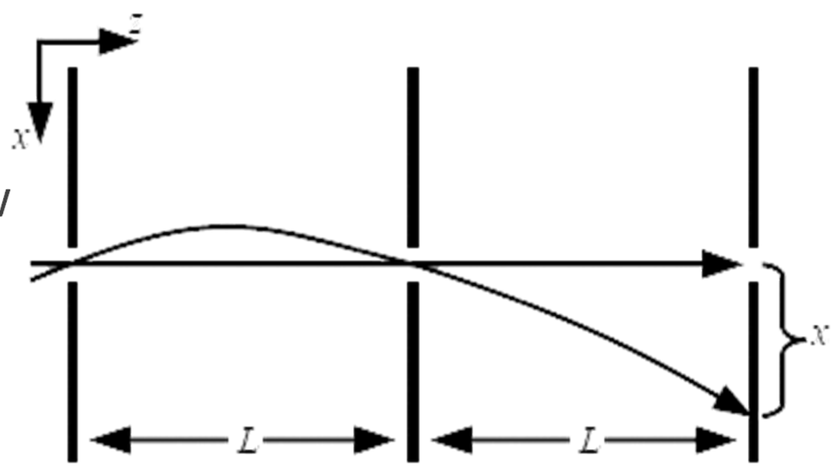
$$F = -\frac{2}{3} e a_0 n(n-1) \nabla E$$



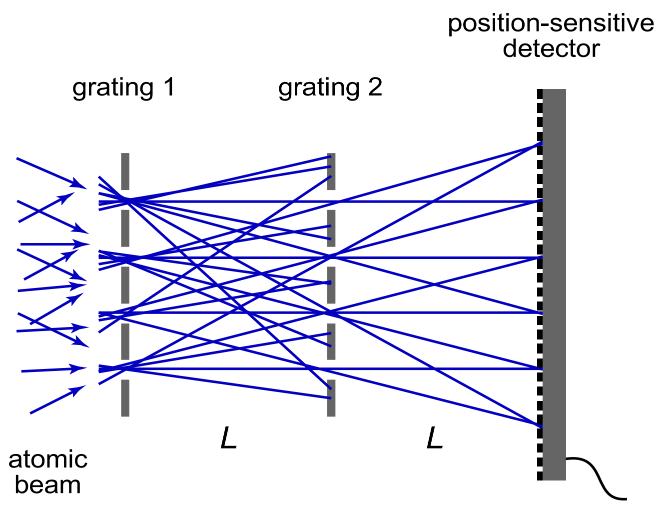
[E. Vliegen & F. Merkt, J. Phys. B **39** (2006) L241]

Gravity measurement

- Forces can be measured with a series of slits
  - Formation of an interference or shadow pattern with two slits
  - Measurement of the vertical deflection δx with a third (analysis) slit



- Many slits: interferometer/deflectometer



- Vertical deflection due to gravity:

  $\delta x \approx -10\ \mu m$

- Vertical beam extent:

  $\Delta x \approx 5.8\ cm$

(antihydrogen beam at 100 mK, accelerated to 500 m s^{-1}, $L \approx 0.5$ m)

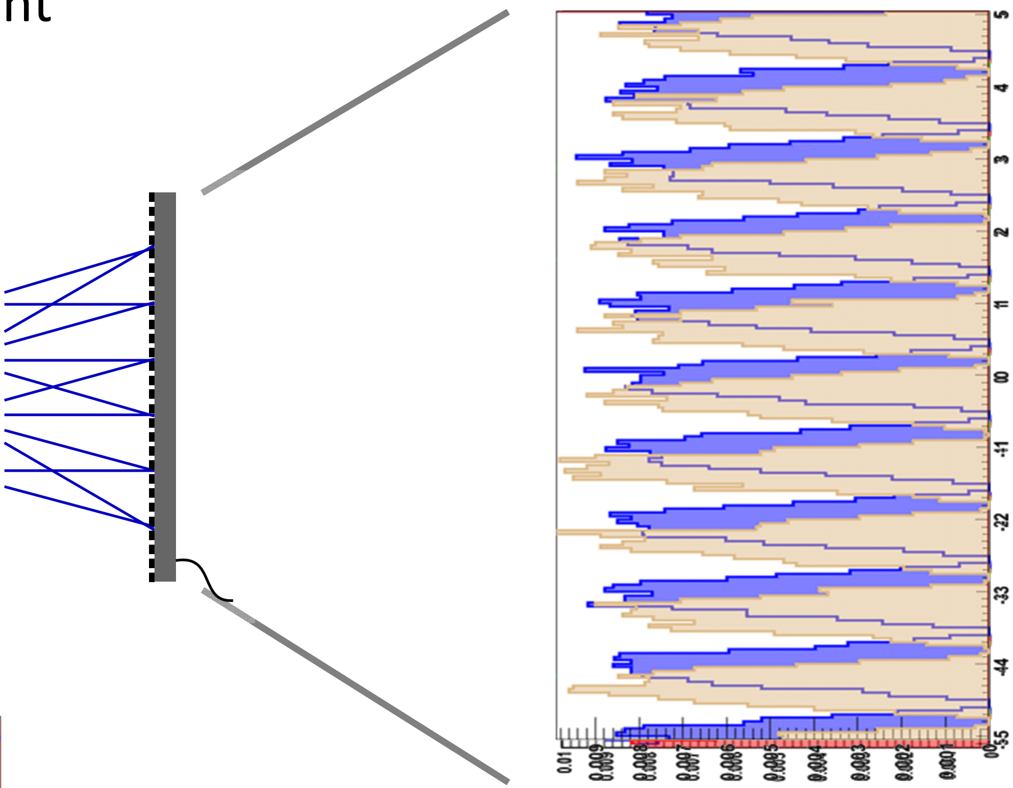
Data analysis

- Record vertical position for each event as a function of TOF/velocity:

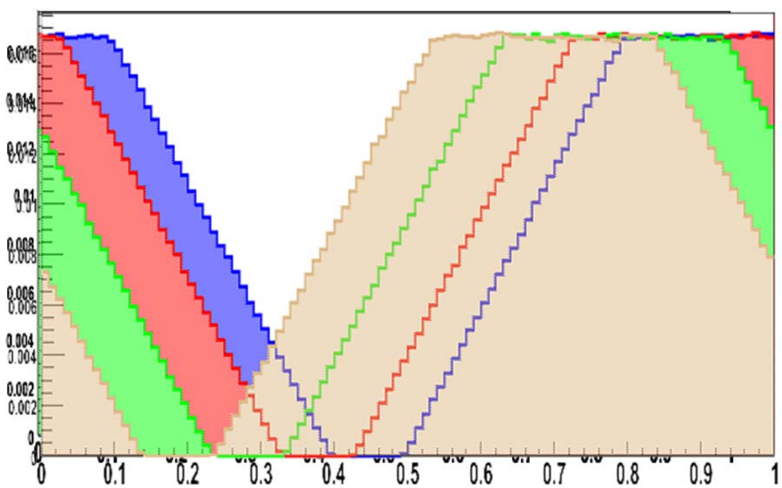
v_{beam} = 600, 400, 300, 250 m s^{-1}

$$\delta x = -gT^2 = -g(L/v)^2$$

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



- Summing up the peaks:



Measurement of g to 1%:

- ≈ 10^5 atoms at 100 mK
- 2 weeks of beam time

Outline

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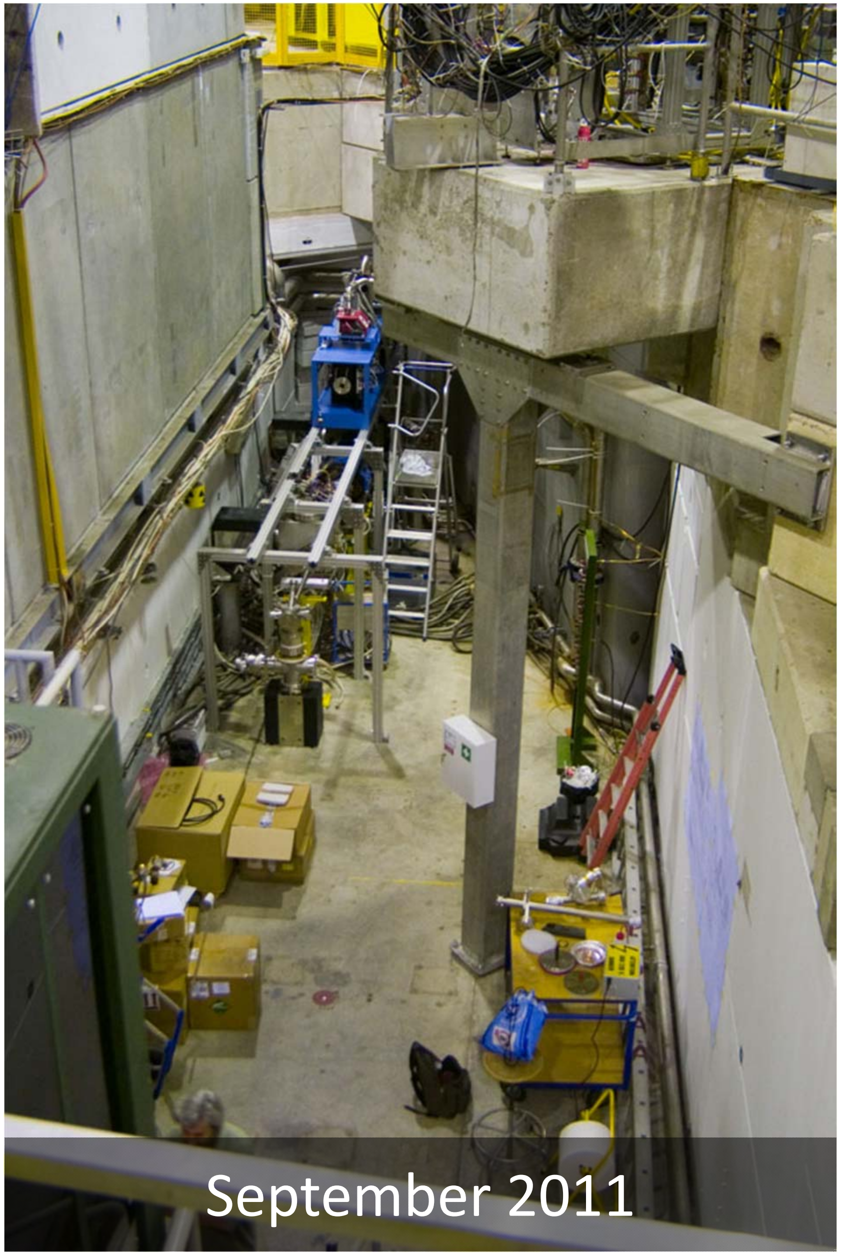
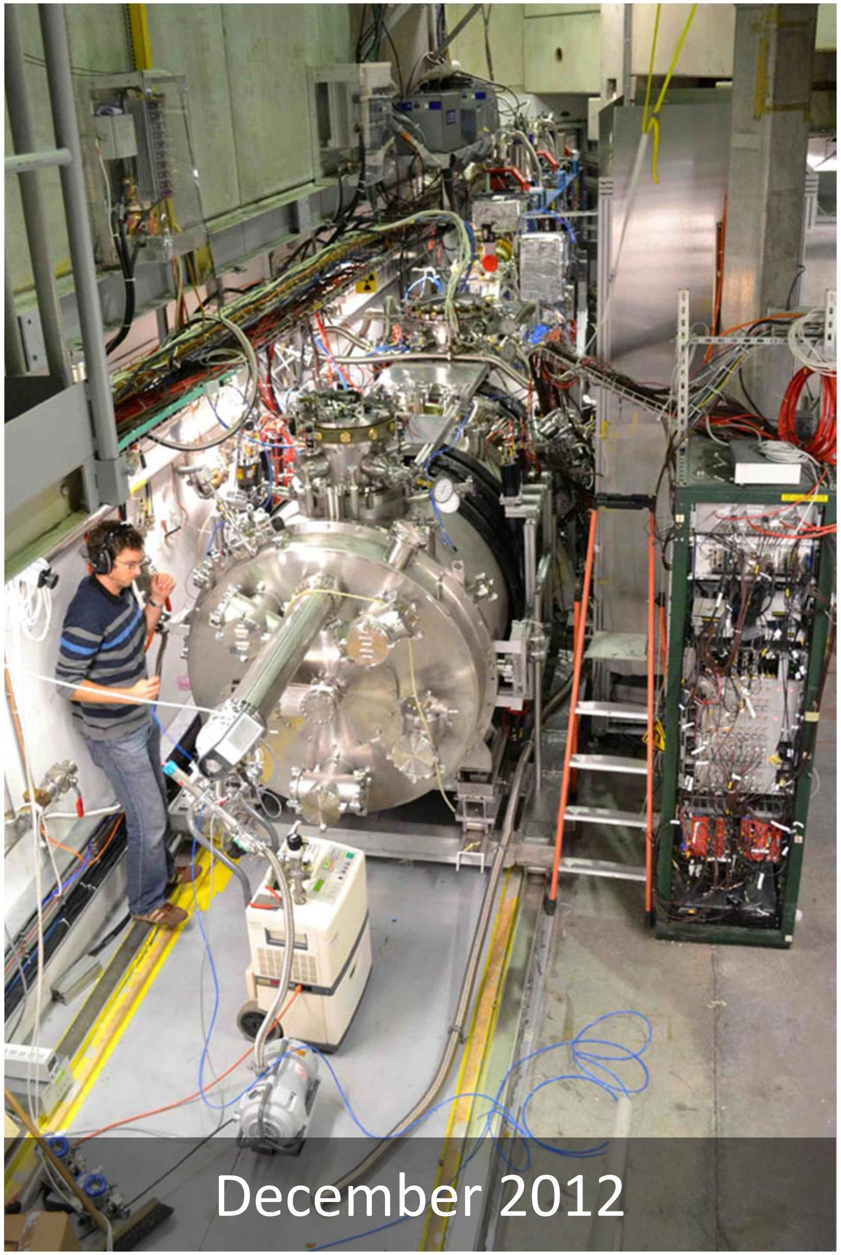
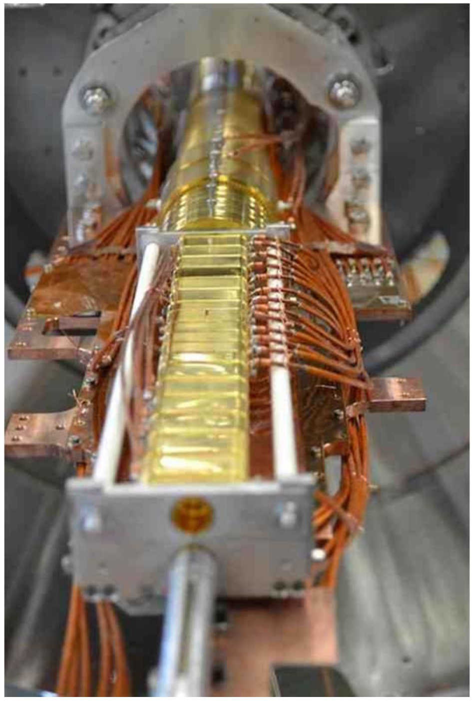
AEGIS construction 2010–2012


September 2011

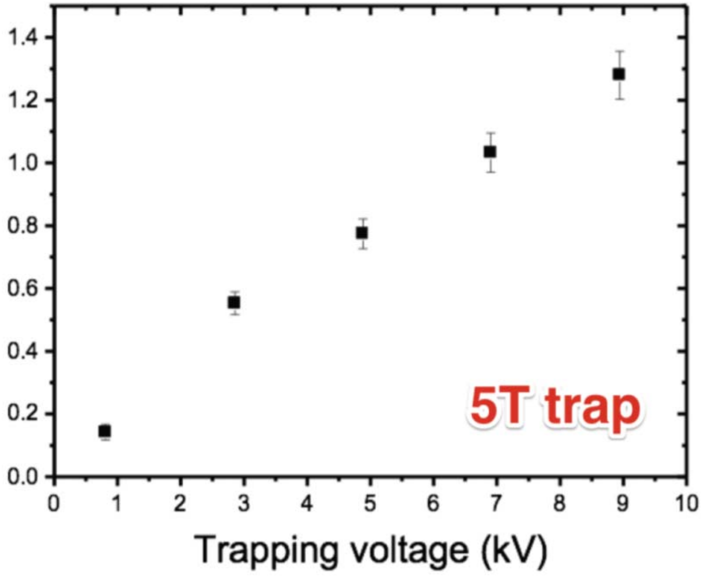

December 2012

Magnets and traps

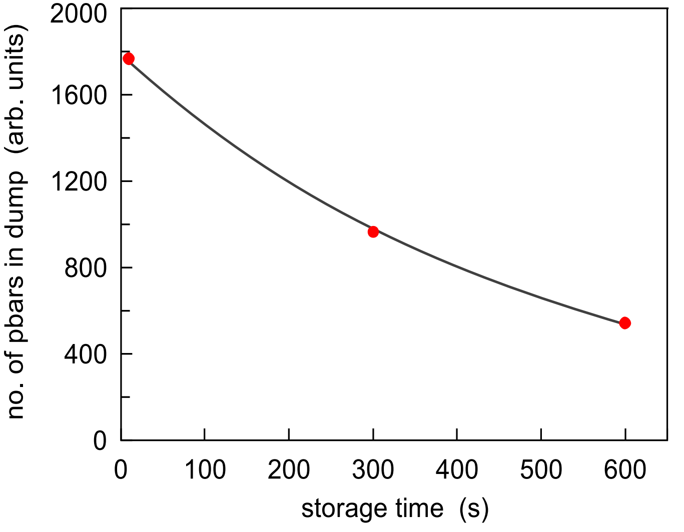
- 5 T magnet (capture) and 1 T magnet (reco) installed and commissioned
- All traps completed & commissioned



- Beam times May & Dec. 2012:
  - Successful $\bar{p}$ stacking (4 shots, 4×10^5 $\bar{p}$)
  - Storage of cooled $\bar{p}$ (τ = 570 s)

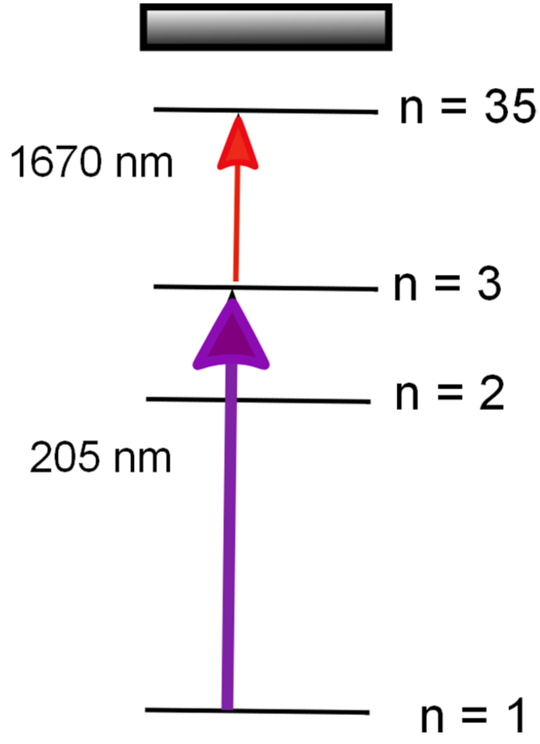


About 13 10^4 p caught at 9kV per AD bunch ~3 10^7



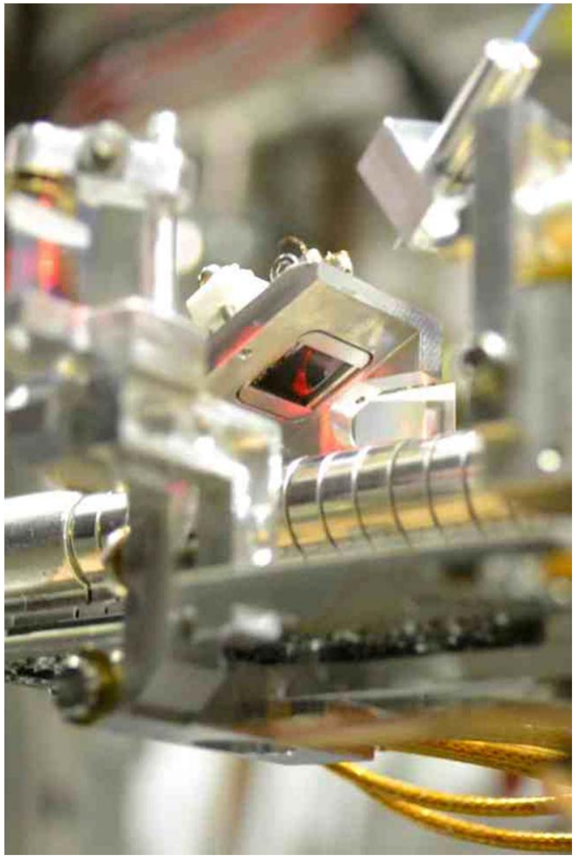
Ps target and lasers

- Laser system for two-step excitation of Ps completed



200 μJ at 1670 nm

2 μJ at 205 nm



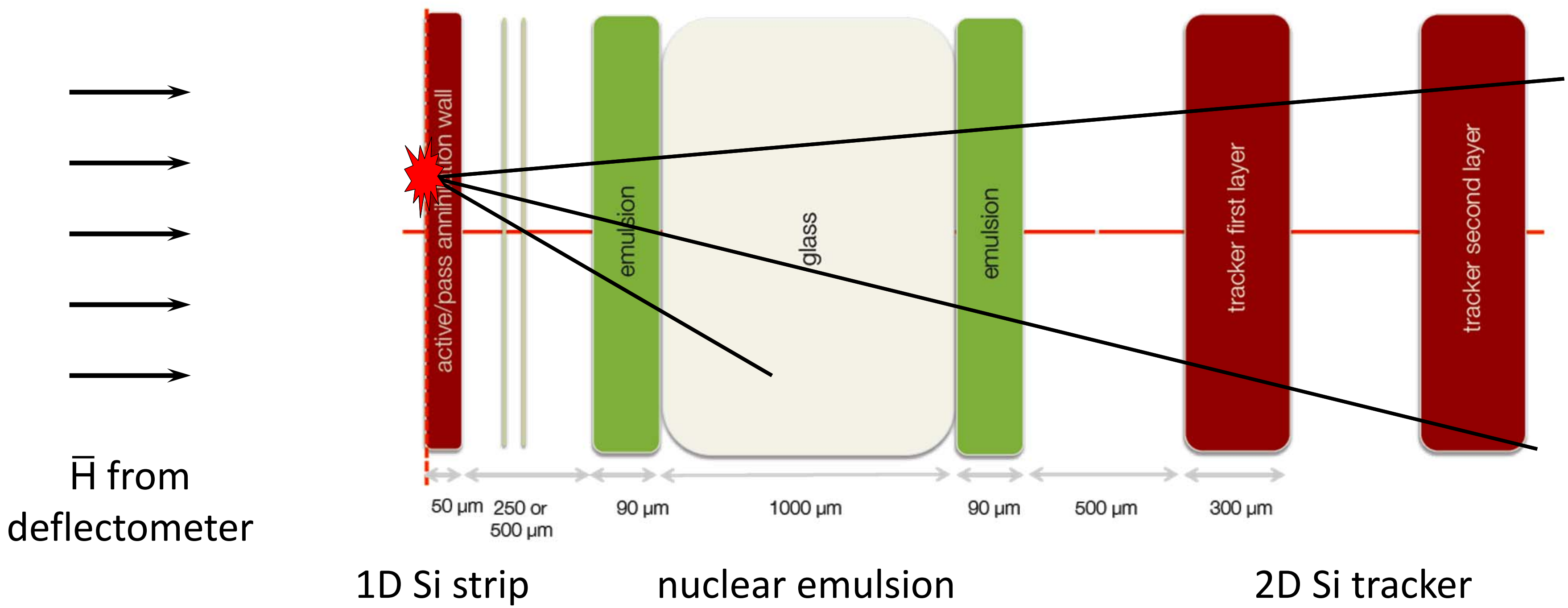
- Transfer lines to recombination region completed:
  - UV 205 nm, 2 μJ: fused-silica prisms
  - IR 1670 nm, 200 μJ: optical fibers

> 65% transfer efficiency

Moiré $\bar{H}$ detector

- Requirement: Detect $\bar{H}$ annihilations with resolution $\Delta t \approx 1$ µs, $\Delta x \approx 10$ µm
- Currently favored design:

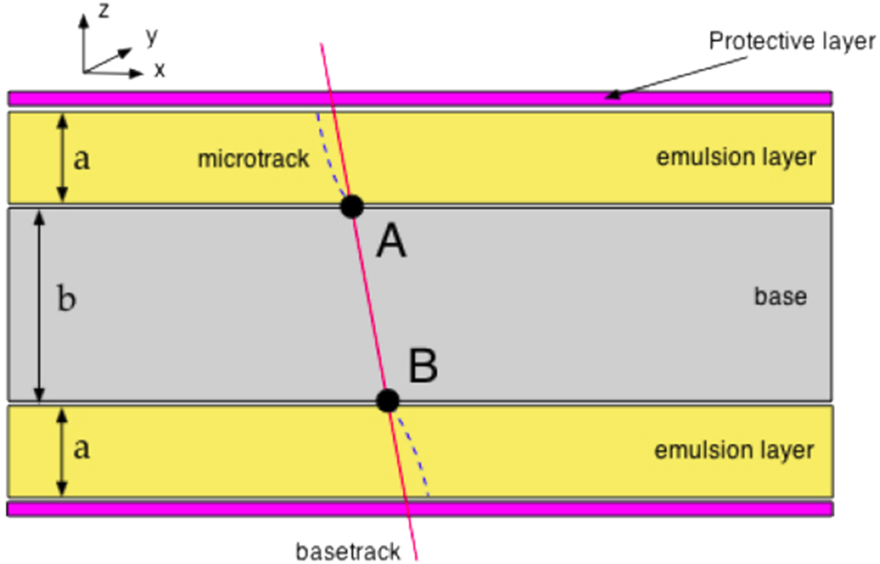
(distances and thicknesses not to scale)

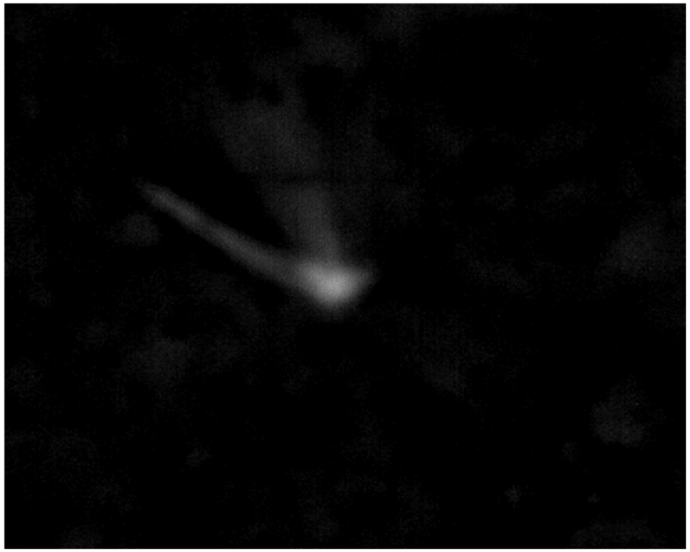


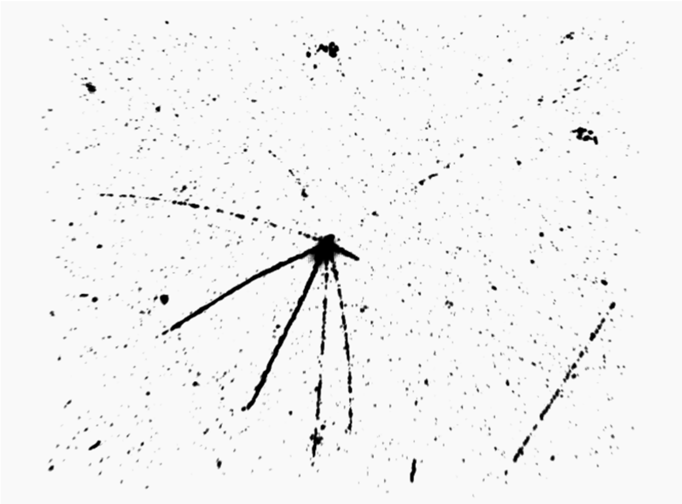
  - Time of flight from 1D Si strip
  - High spatial resolution provided by emulsion
  - 2D Si tracker correlates emulsion tracks with timed events

Moiré $\bar{H}$ detector

- Nuclear emulsions:
  - 90 µm thick gels on glass substrate (0.5…1 mm thick)





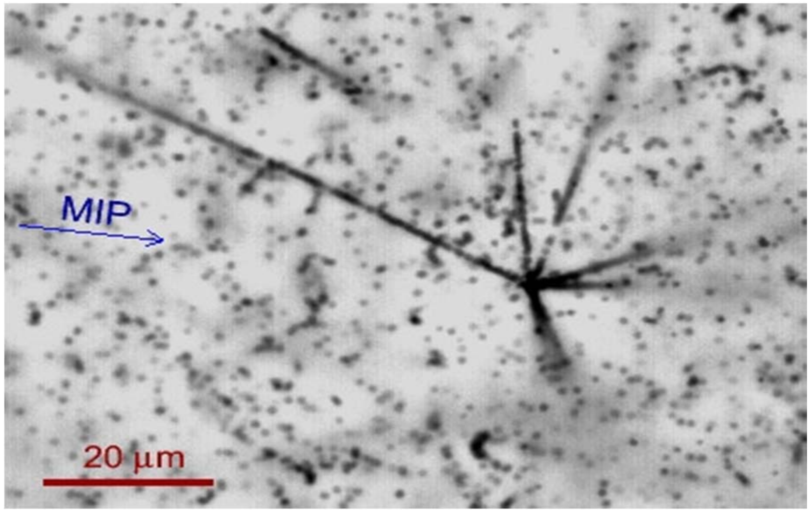


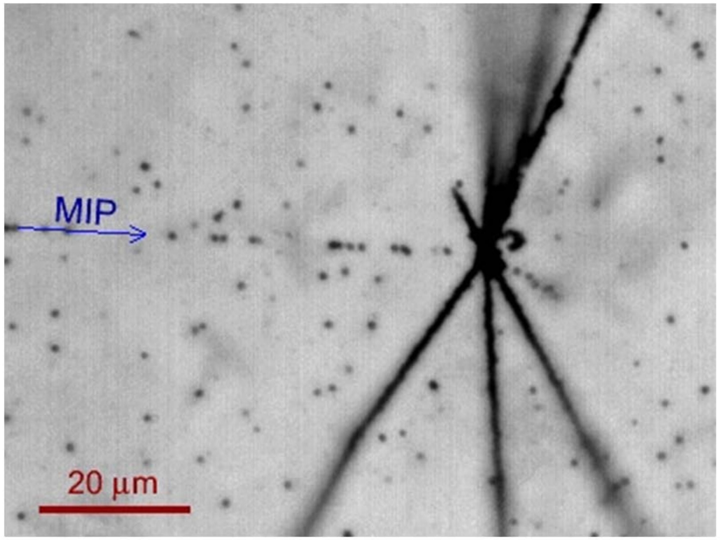
  - Based on technology developed for OPERA, modified for vacuum operation and tested at low temp
  - Off-line analysis by automatic 3D scanning microscope (3 days for 20x20 cm emulsion)
    $\Rightarrow$ tomographic image

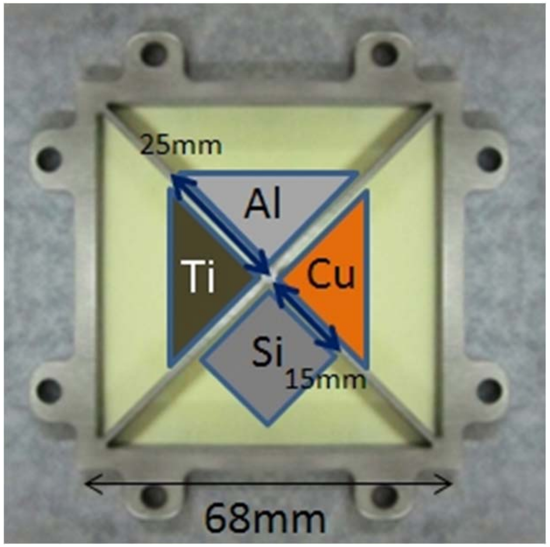
Intrinsic resolution 58 nm

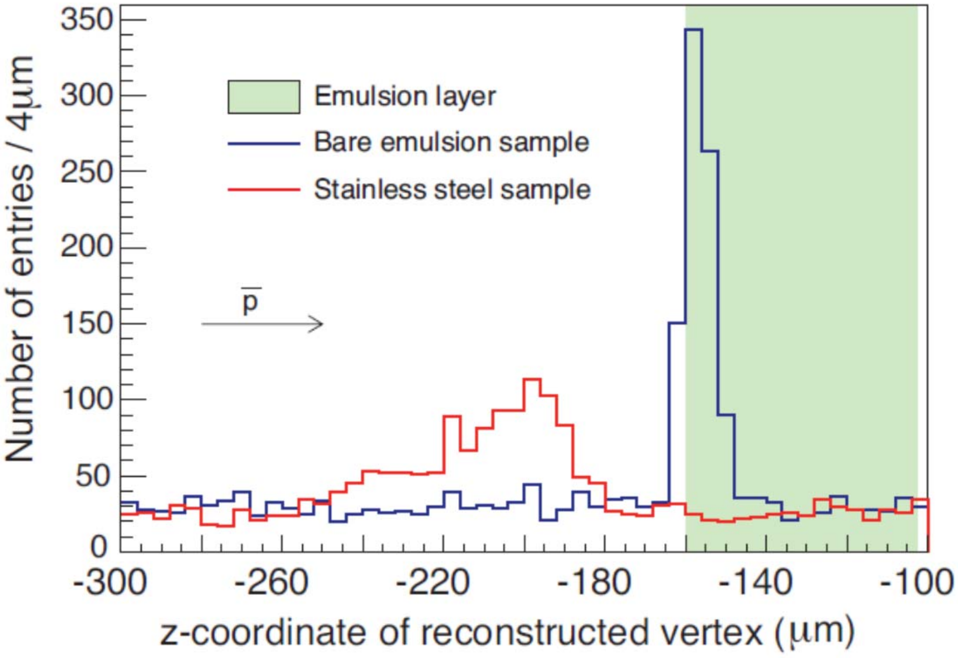
Vertex resolution ≈ 1.4…2.3 µm

Emulsion detector





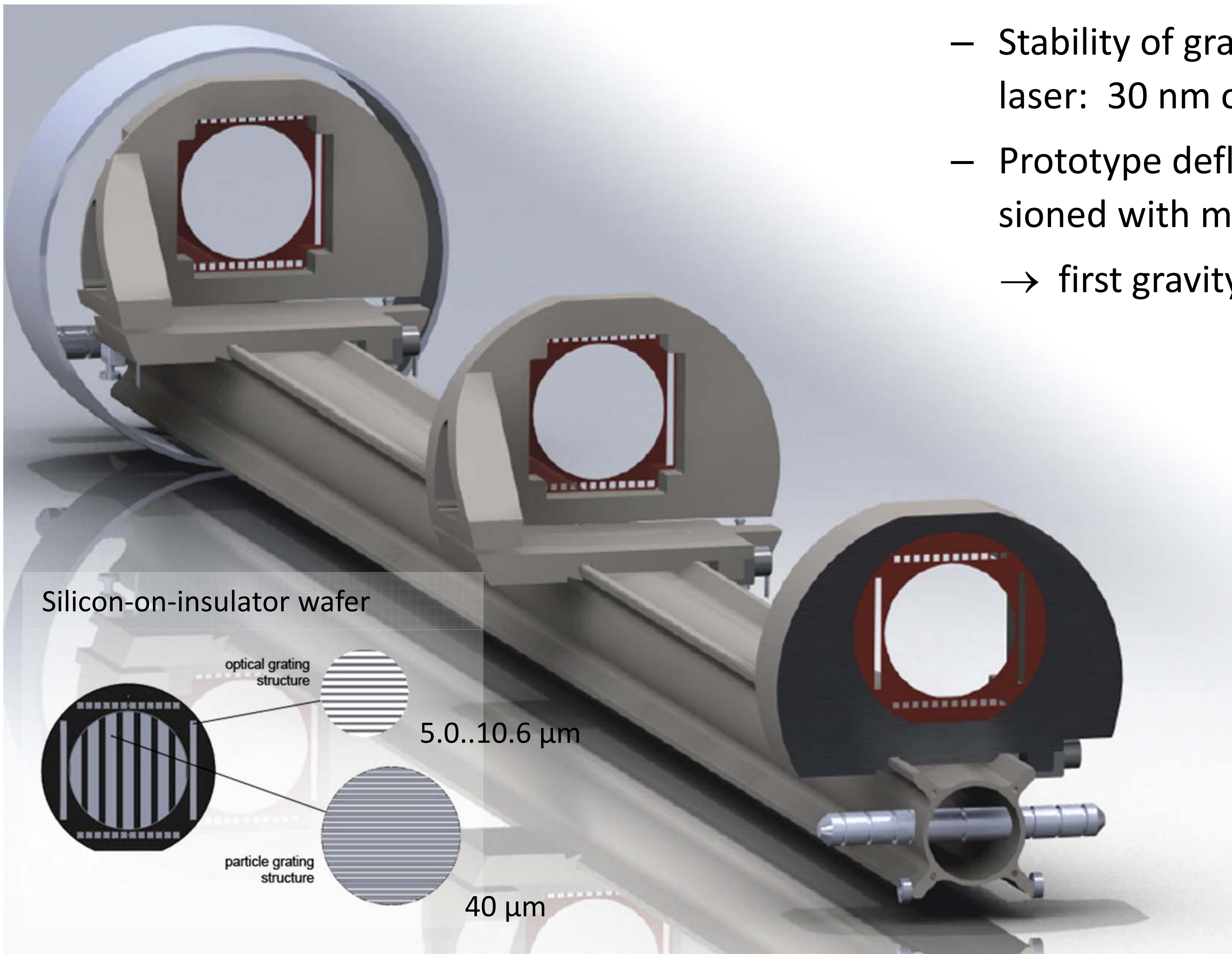




[arXiv:1306.5602v1 [physics.ins-det] 24 Jun 2013]

Moiré deflectometer

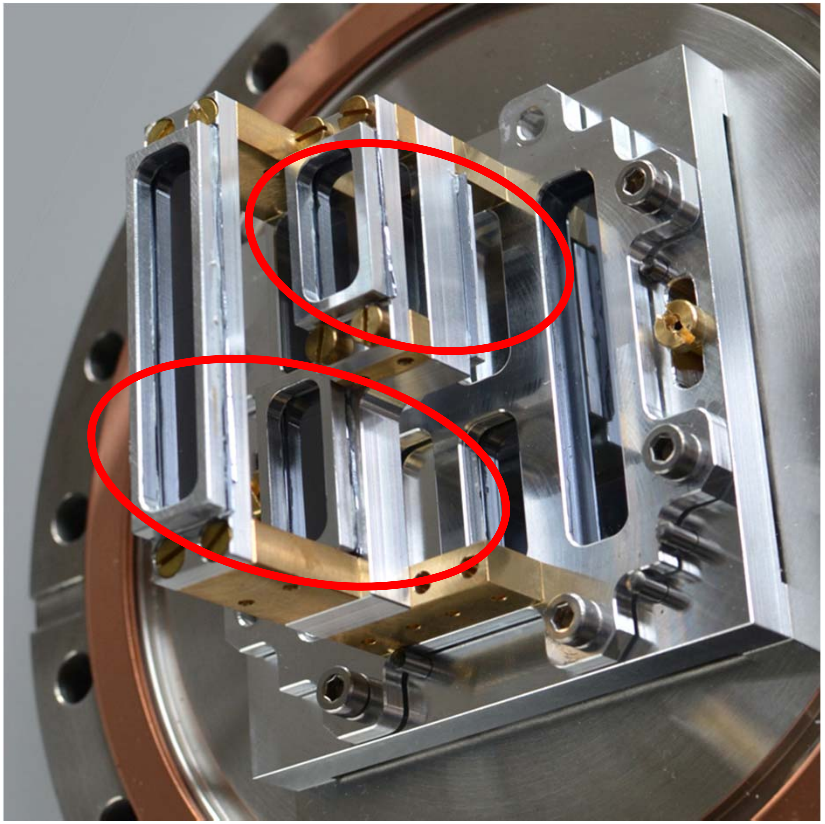
- Deflectometer test setup (U Heidelberg group):

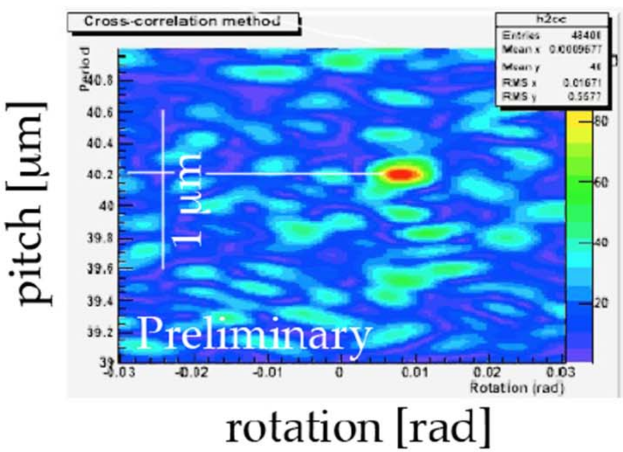


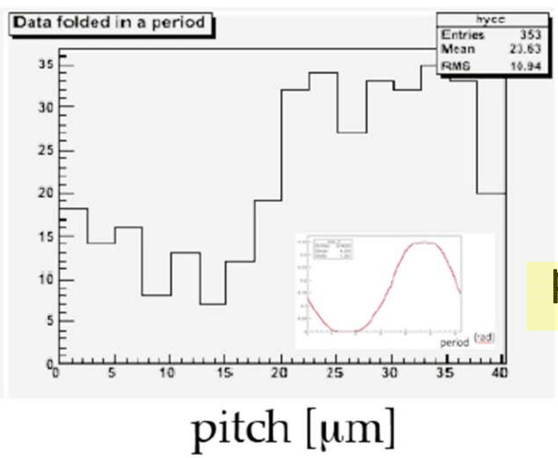
  - Stability of gratings measured with laser: 30 nm over 1 h
  - Prototype deflectometer comis-sioned with metastable Ar atoms
    → first gravity measurement

Moiré deflectometer

- December 2012:
  Deflectometry measurement with $\bar{p}$ in "mini moiré" setup
  - d = 40 µm, L = 16.7 mm, 25 mm
  - 100 keV $\bar{p}$, 7 h exposure
  - Reference measurement with laser light in Talbot-Laue regime







preliminary

[P. Brauning , et. al. (2013) in preparation]

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Conclusions & outlook

- The effect of gravity on antimatter has never been measured
- Depending on the chosen model, effect could be nil or dramatic
- The AEGIS experiment intends to measure *g* of antihydrogen to (initially) 1% precision
- Construction and commissioning of AEGIS apparatus largely completed
- Next milestones:
  - 2013 / first half 2014: Commissioning of all remaining components; Installation of proton source, test of charge-conjugate H formation process
  - from second half 2014: First antimatter gravity experiment

AEGIS Collaboration

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