Probing Antimatter Gravity

Progress report for the AEGIS antimatter gravity experiment

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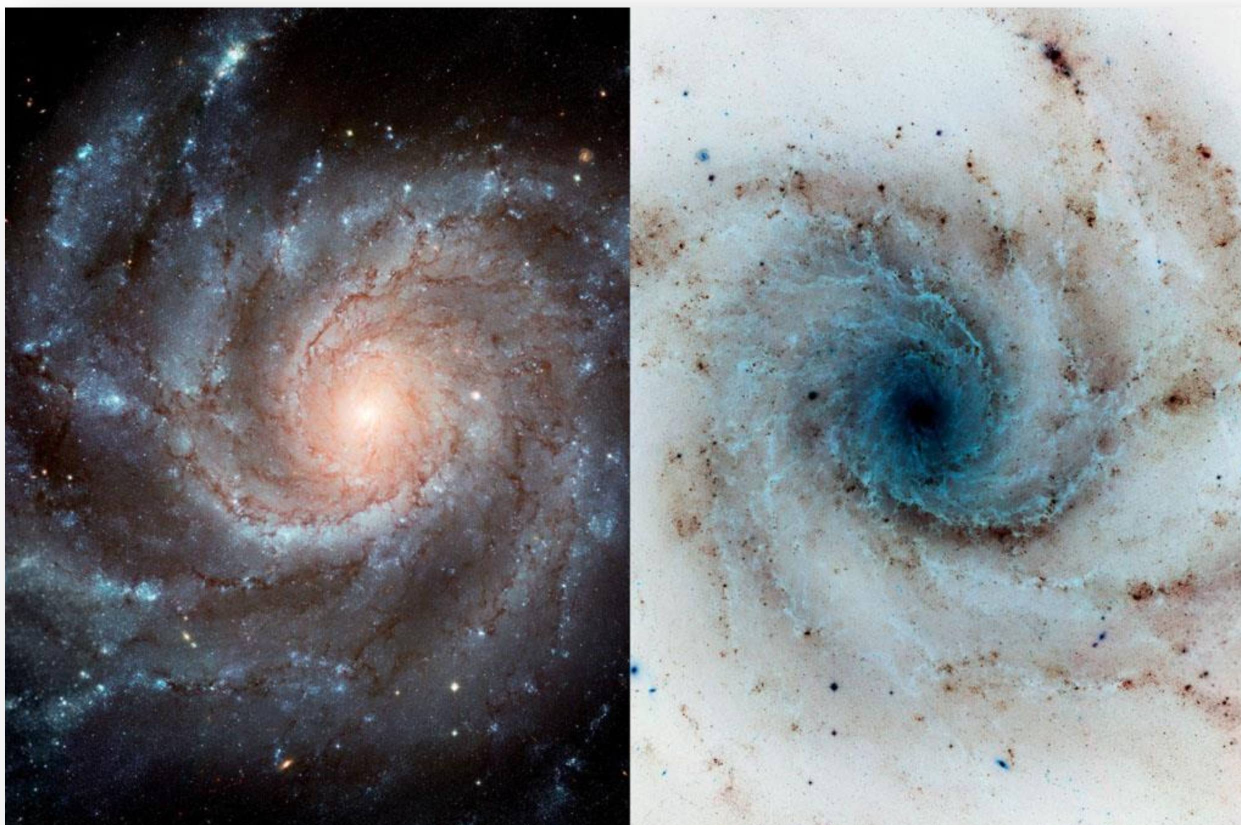
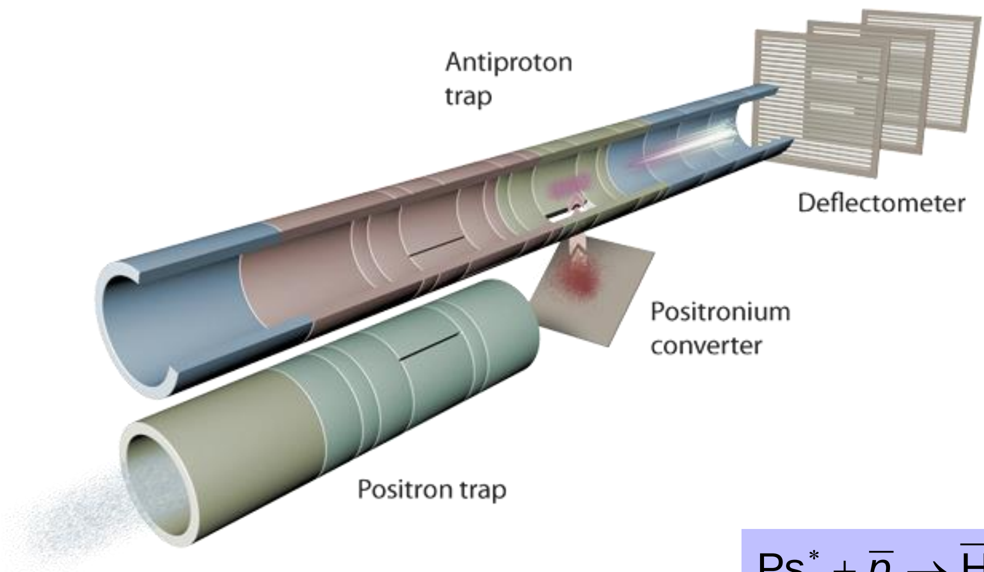
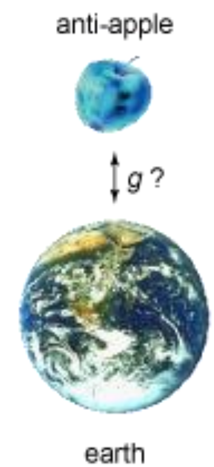


AEGIS experiment

- AEGIS: Antimatter Experiment: Gravity, Interferometry, Spectroscopy
- Main goal: Measurement of *g* with 1% precision on antihydrogen
- Requirements / challenges:
  - Production of a **bunched cold beam of antihydrogen** (100 mK)
  - Measurement of vertical beam deflection (10 µm drop over 1 m)





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

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Outline

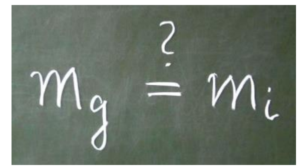
- Antimatter gravity
- How to measure gravity?
- Status and recent results
- Conclusions and outlook

Antimatter gravity

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

- Weak equivalence principle (WEP):

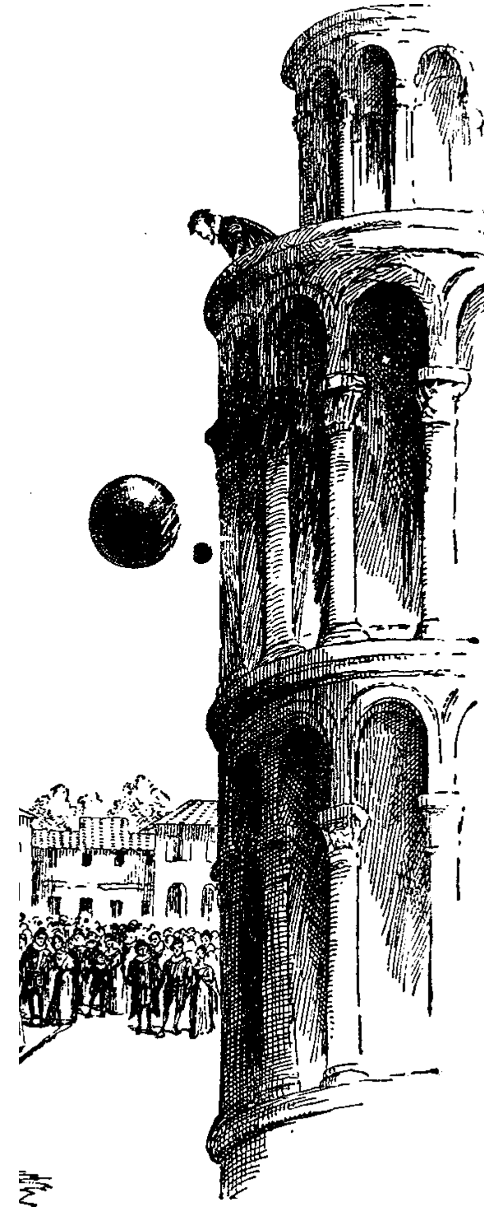
  "The trajectory of a falling test particle is independent of its composition."



- WEP extremely well tested with matter, but never with <u>antimatter</u> (electric charge of subatomic particles)

- Indirect limits on *g* for antimatter can be derived under certain assumptions

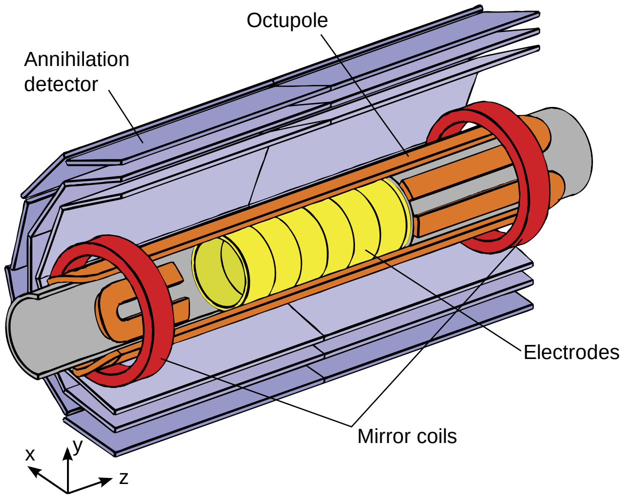
- Antimatter gravity test requires <u>neutral</u> particles (such as antihydrogen)

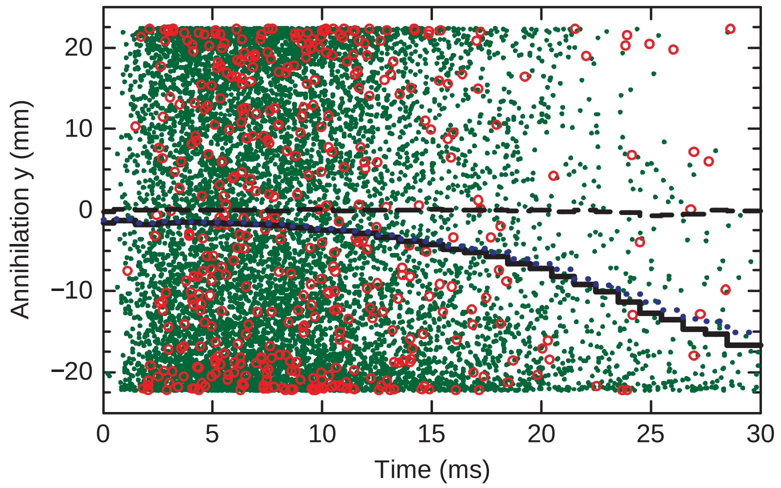


ALPHA gravity measurement attempt

(2013 reanalysis of 2010/2011 data)

- Release of $\overline{\mathrm{H}}$ from magnetic trap at 0.5 K (trap shutoff time constant $\tau \approx 9.5$ ms)
- 434 annihilation events observed
- Vertical position of annihilations:





– red circles: data

– green dots: simulation for $\bar{g}/g = 100$

[C. Amole *et al.*, Nature Comm. **4** (2013) 1785]

- Result:

$$\bar{g} = (-65 \ldots +110)\, g$$

(95% confidence level)

- Compare with "worst case" expectation:

$$\bar{g} = (-1 \ldots +2)\, g$$

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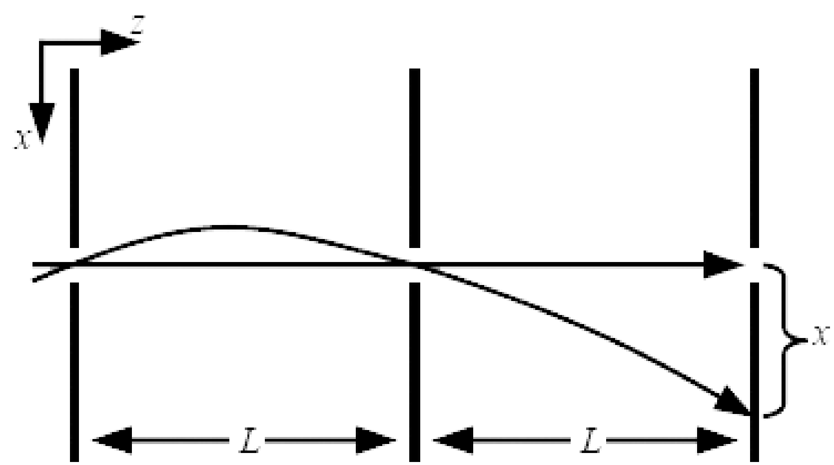
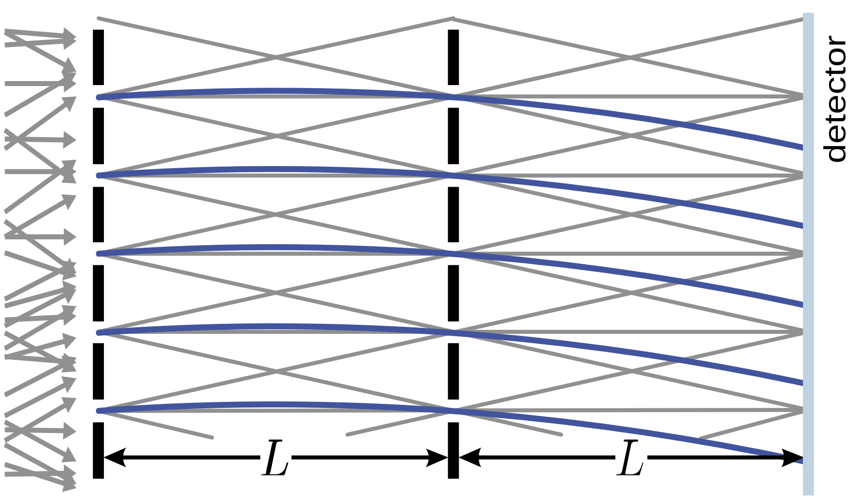
Gravity measurement

- 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:

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

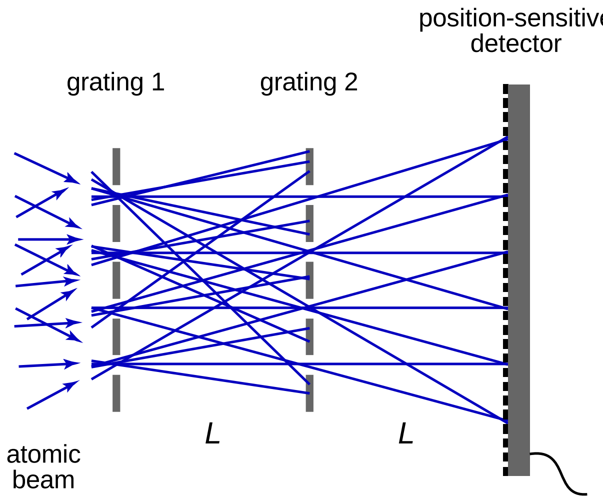
- Vertical beam extent:

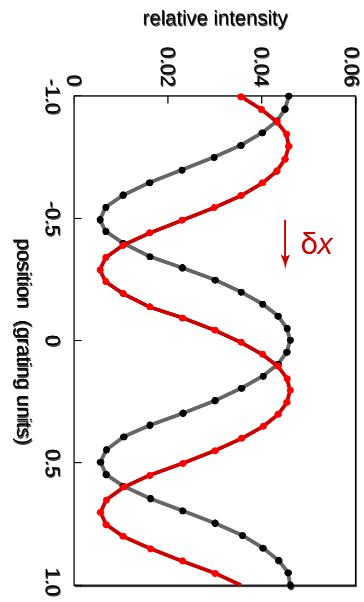
  $\Delta x \approx 5.8$ cm

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

Gravity measurement

- Interferometer/deflectometer:





Fringe pattern "falls" by

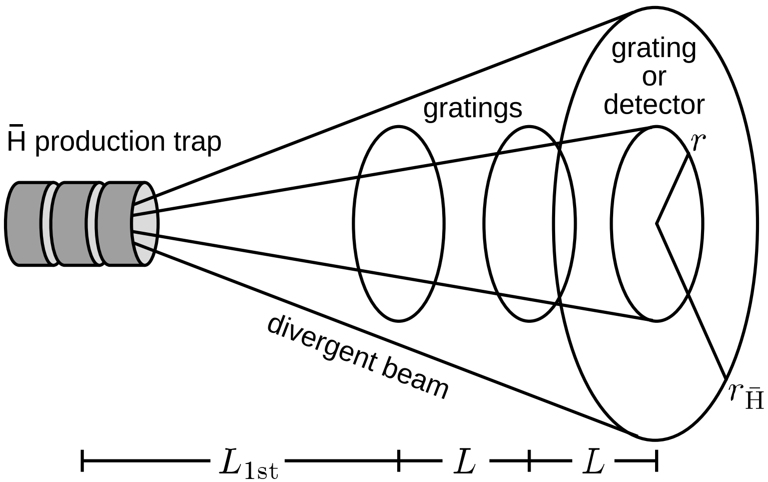
$$\delta x = -g\left(\frac{L}{v}\right)^2$$

- Two gratings create shadow pattern on third grating
- "Self-focusing" effect (works with uncollimated beam)
- Deflectometer used for gravity measurement on Ar atoms, $\sigma(g)/g = 2\times10^{-4}$

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

Measurement precision

- Shot noise limit:



d	–	grating period
η	–	grating open fraction
V	–	visibility
τ	–	time of flight
r	–	radius
L_{1st}	–	distance to first grating
L	–	distance between gratings
N_{det}	–	no. of detected atoms
N_{prod}	–	no. of produced atoms

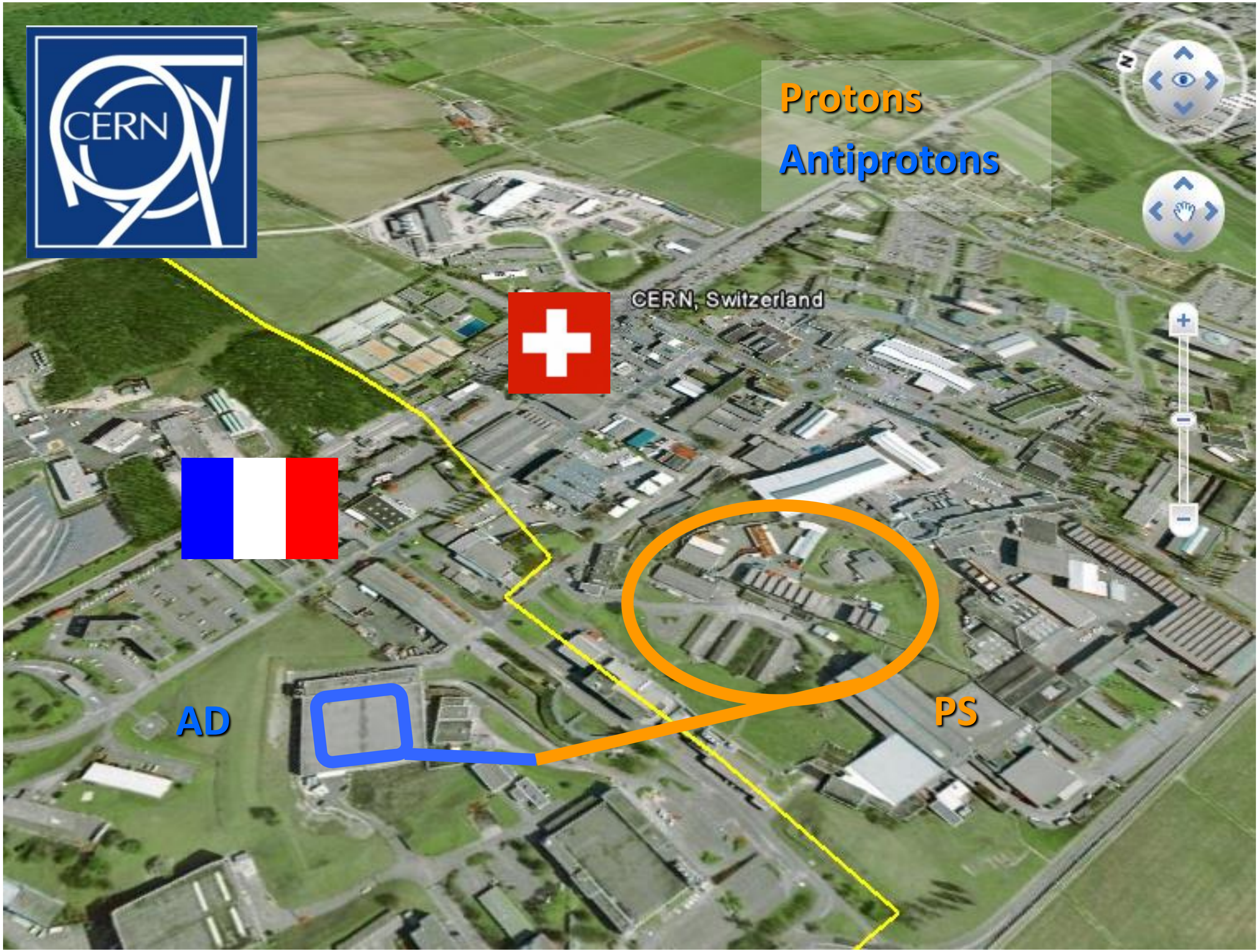
$$a_{min} = \frac{d}{2\pi V \tau^2 \sqrt{N_{det}}}$$

$$= \frac{d}{2\pi V \eta r} \times \frac{2(L_{1st} + 2L)}{L^2} \times \frac{2kT}{m} \frac{1}{\sqrt{N_{prod}}}$$

gratings — geometry — $\bar{H}$ source

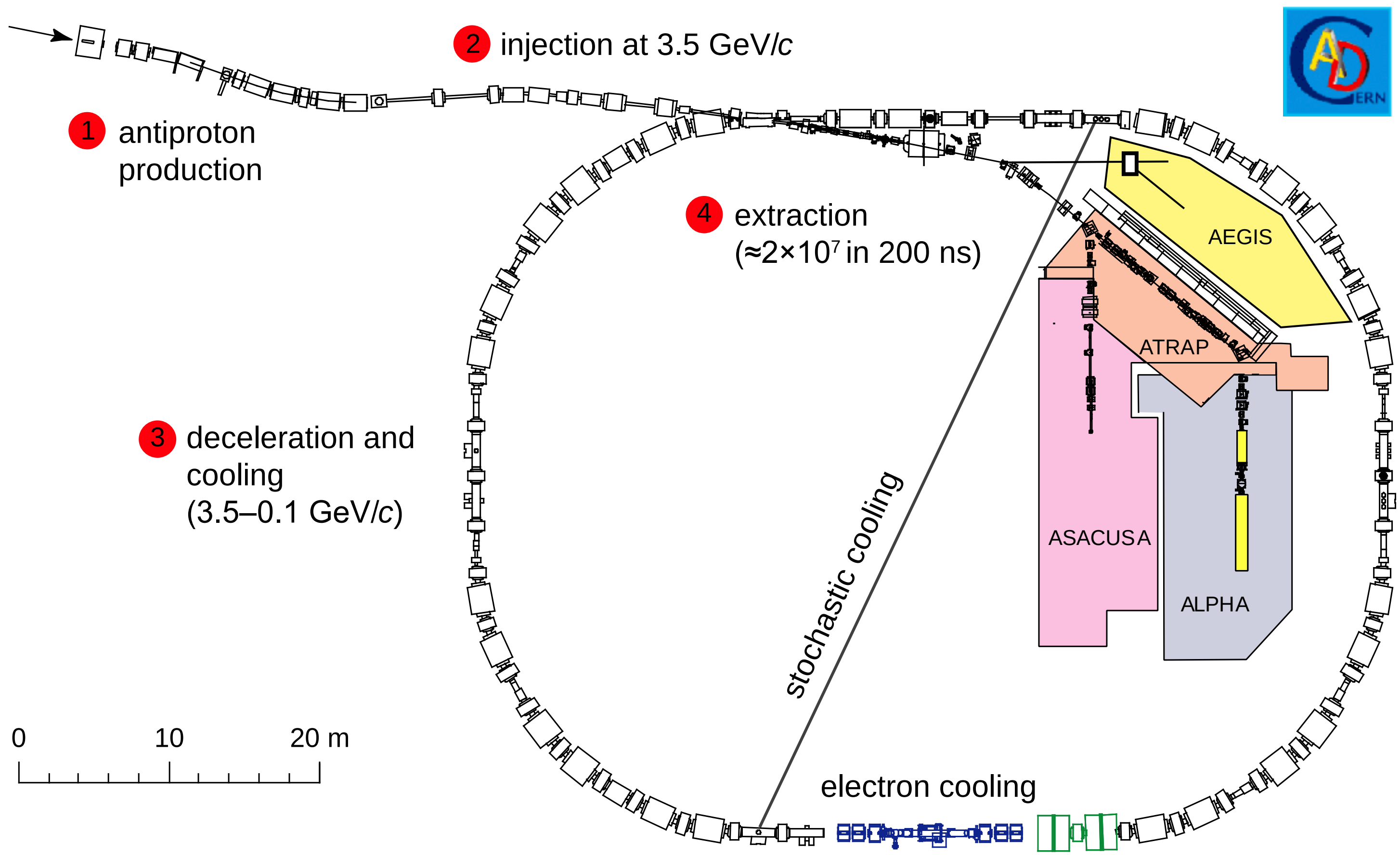
$\Rightarrow$ small grating period
large distance
low temperature

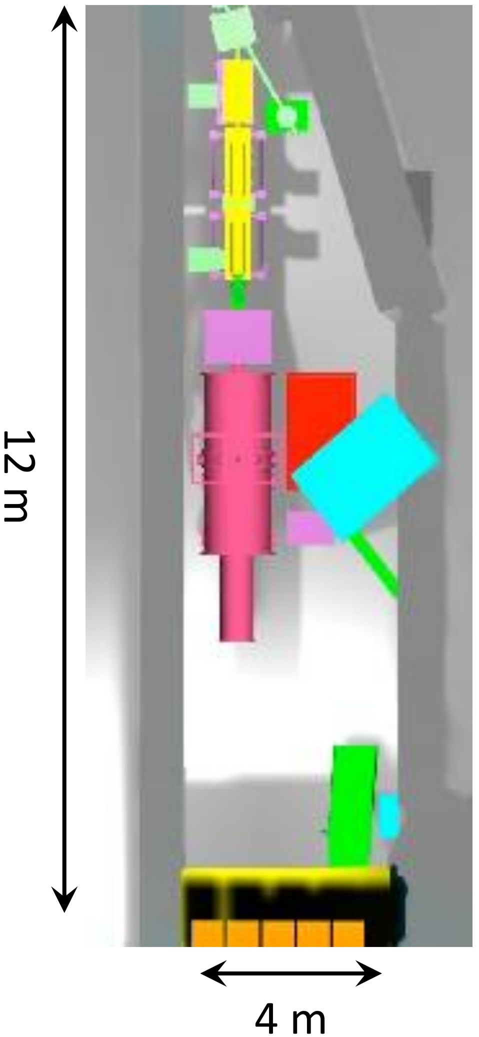
“Antimatter Factory” at CERN



Antiproton Decelerator

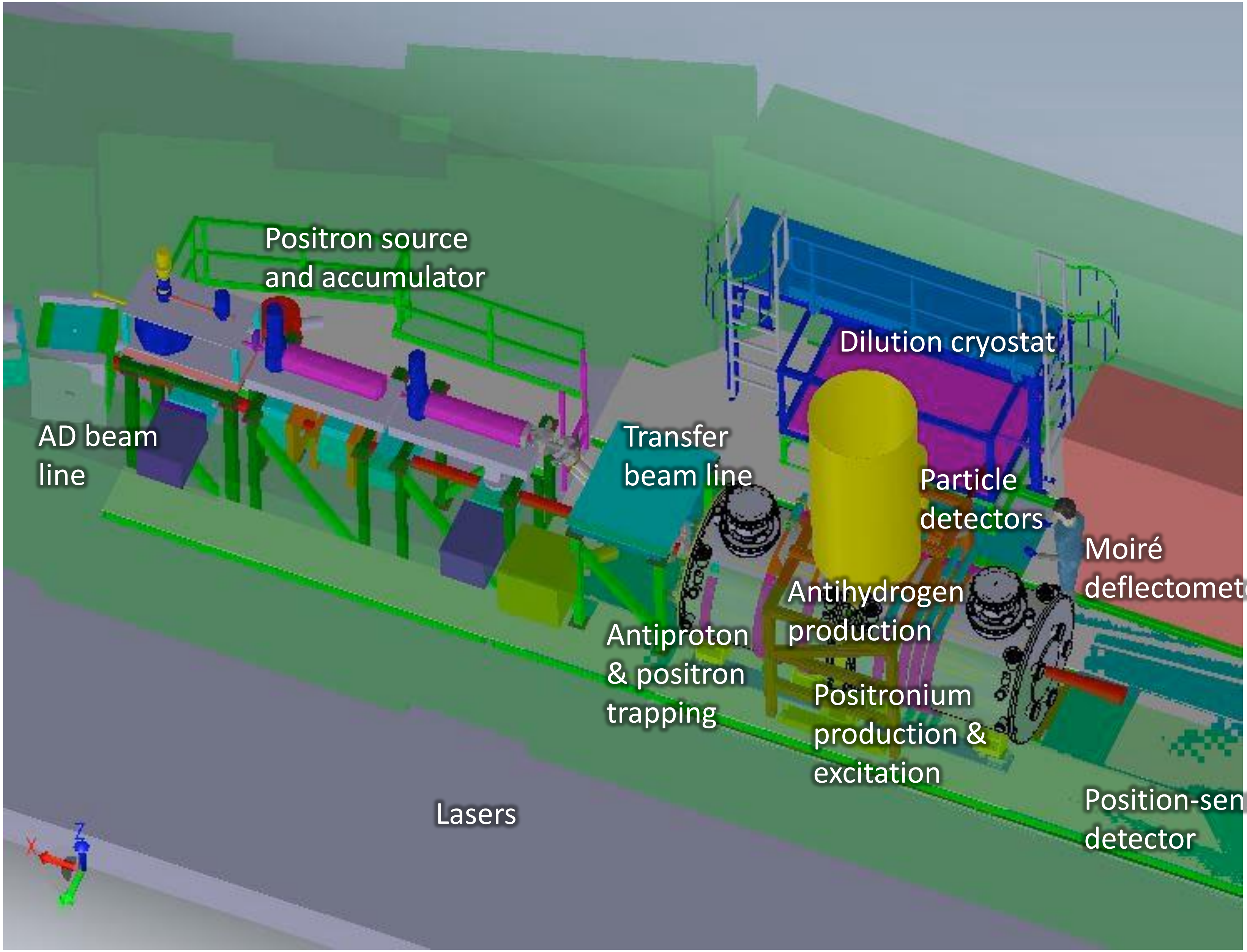
AEGIS at the Antiproton Decelerator





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

AEGIS overview sketch

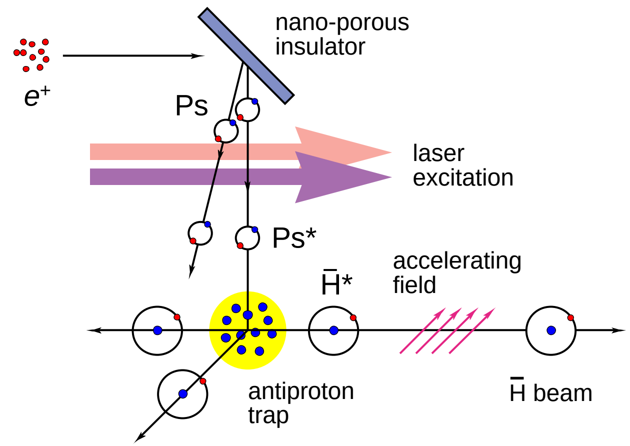


Antihydrogen recombination

- Charge exchange reaction:

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

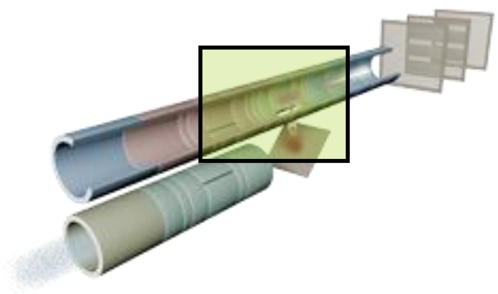
- Principle demonstrated by ATRAP
  Cs* → Ps* → $\bar{\mathrm{H}}$*
  [C. H. Storry *et al.*, Phys. Rev. Lett. **93** (2004) 263401]



- Advantages:
  - Large cross-section:

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

  - Narrow and well-defined $\bar{\mathrm{H}}$ *n*-state distribution



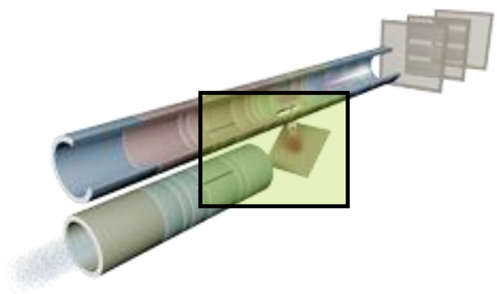
  - Antiproton temperature essentially determines antihydrogen temperature:

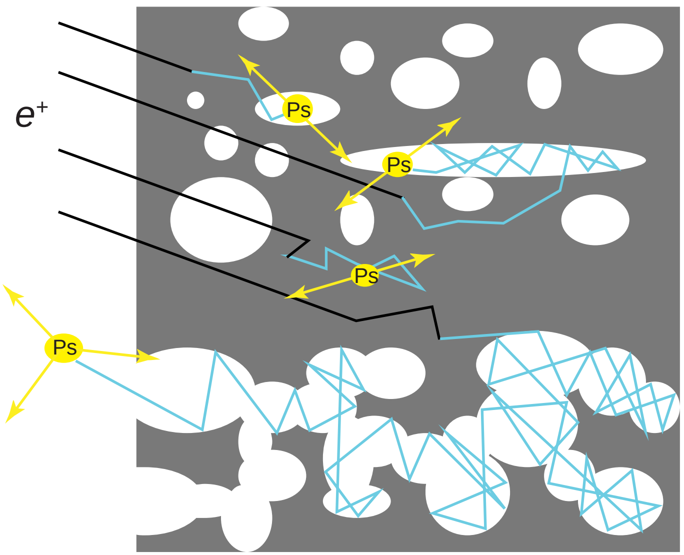
at $T(\bar{p}) = 100$ mK, $n_{\mathrm{Ps}} = 35$
$\Rightarrow$ $v(\bar{\mathrm{H}}) \approx 45$ m/s
$T(\bar{\mathrm{H}}) \approx 120$ mK

$\Rightarrow$ cold / ultracold $\bar{\mathrm{H}}$

Positronium conversion

- Ps formation in nanoporous insulators:
  - Implanted positrons scatter and slow to eV in few ns
  - Positronium forms by capture of electrons
  - Reduced dielectric strength in defects $\Rightarrow$ accumulation of positronium in voids
  - If pores are fully interconnected, ortho-Ps diffuses out of the film
- ortho-Ps yield and velocity distribution depend on
  - Converter material
  - Implantation depth (energy)
  - Target temperature
  - $\rightarrow$ up to 30% at 50 K





[D. W. Gidley *et al.*, Annu. Rev. Mater. Res. **36** (2006) 49]

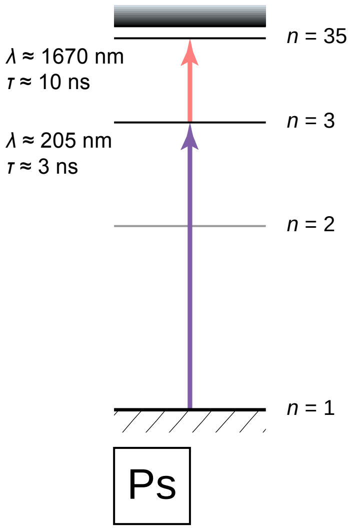
High-efficiency positronium converter

Positronium excitation

- Cross-section of Ps charge exchange reaction enhanced for large *n*: $\sigma \approx a_0 n^4$

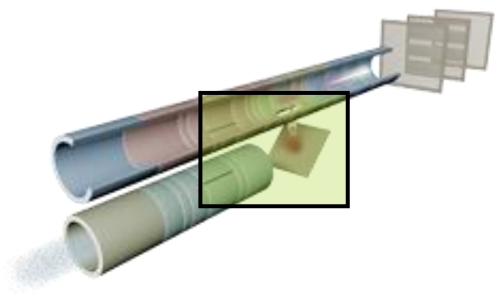
- Two-step excitation:
  UV $n = 1 \rightarrow 3$
  IR $n = 3 \rightarrow$ Rydberg

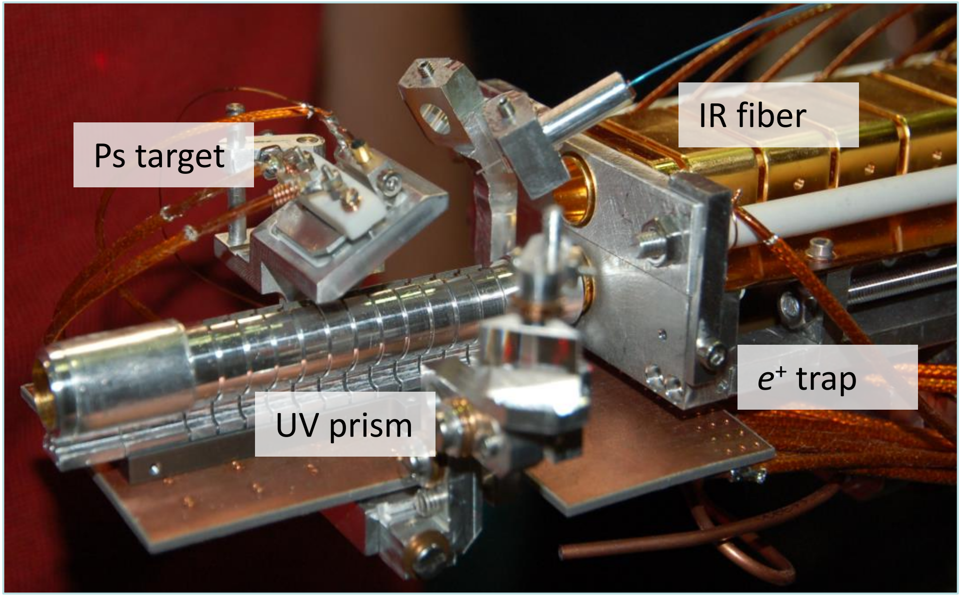
  Excitation efficiency ≈ 30%



- Laser bandwidth must be matched to (broadened) levels

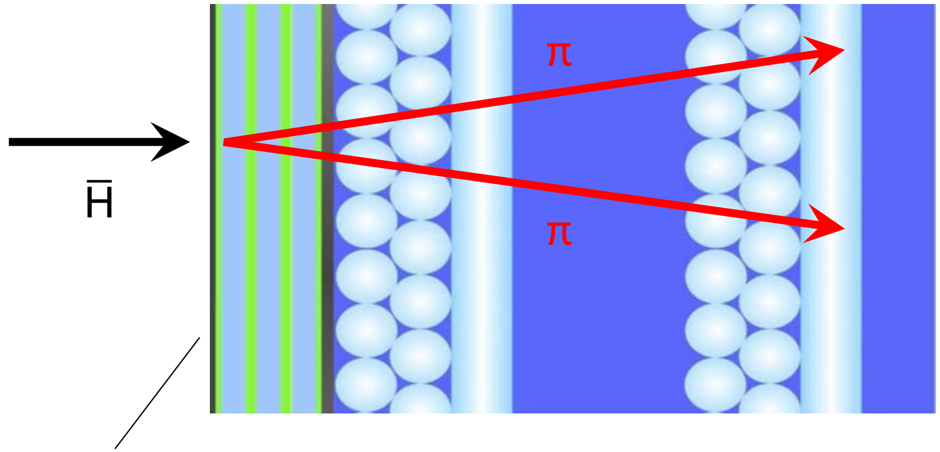
[F. Castelli *et al.*, Phys. Rev. A **78** (2008) 052512]

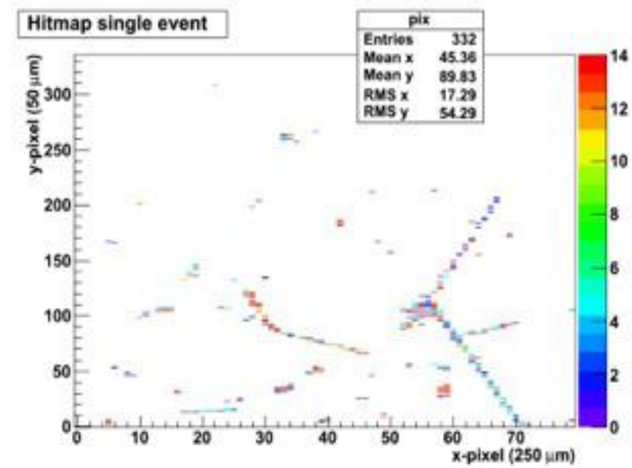




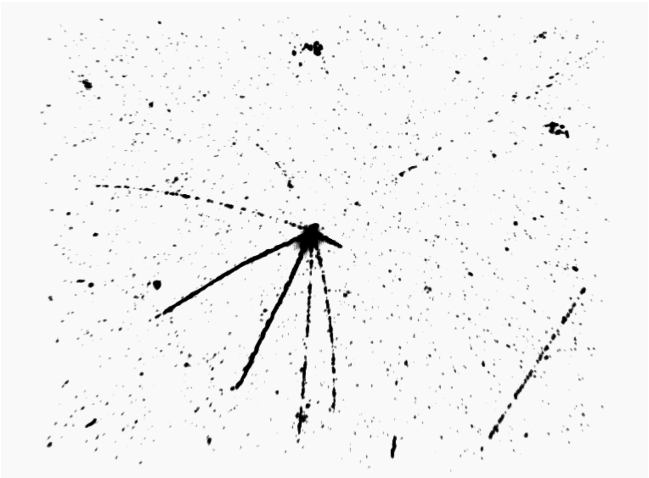
$\bar{H}$ detection

- Hybrid detector:



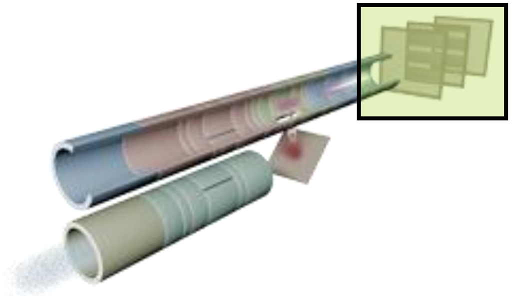


Si strip detector



nuclear emulsion

  - TOF; position resolution ≈ 10 µm

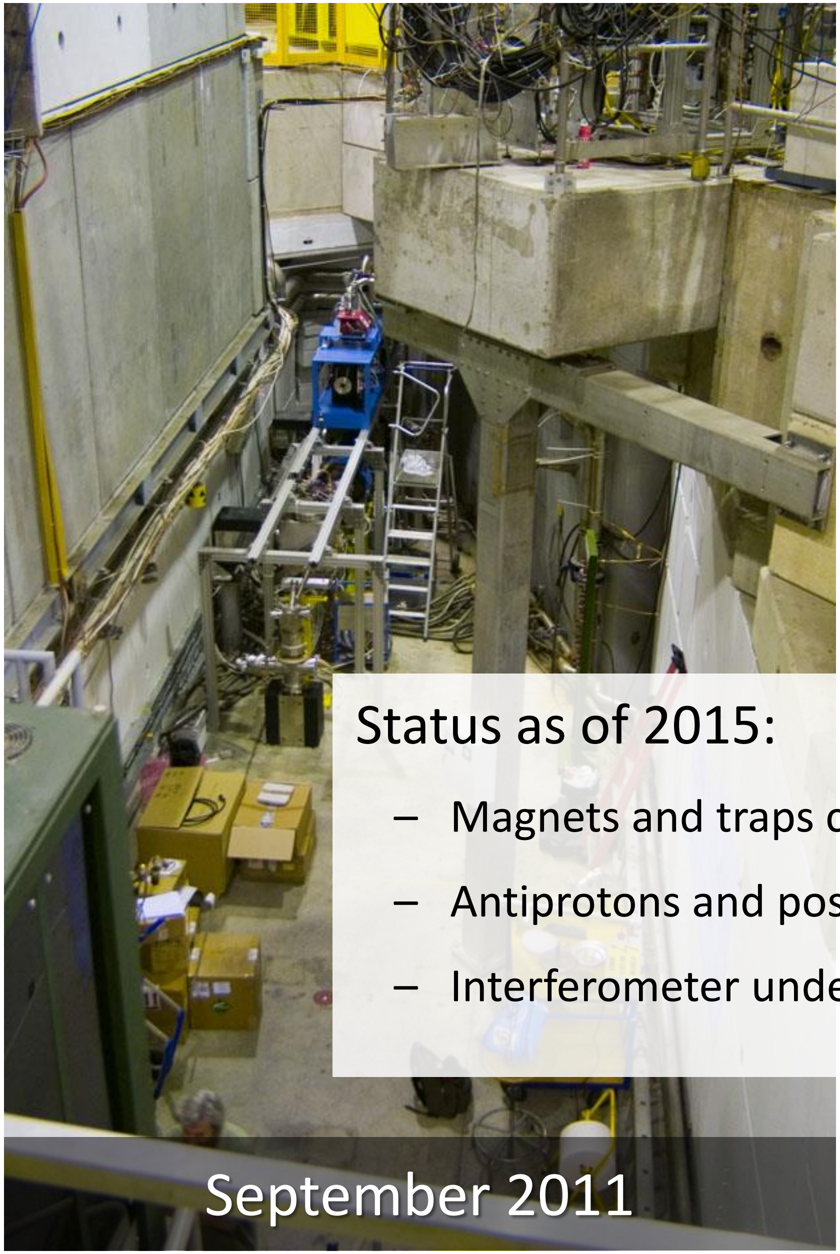


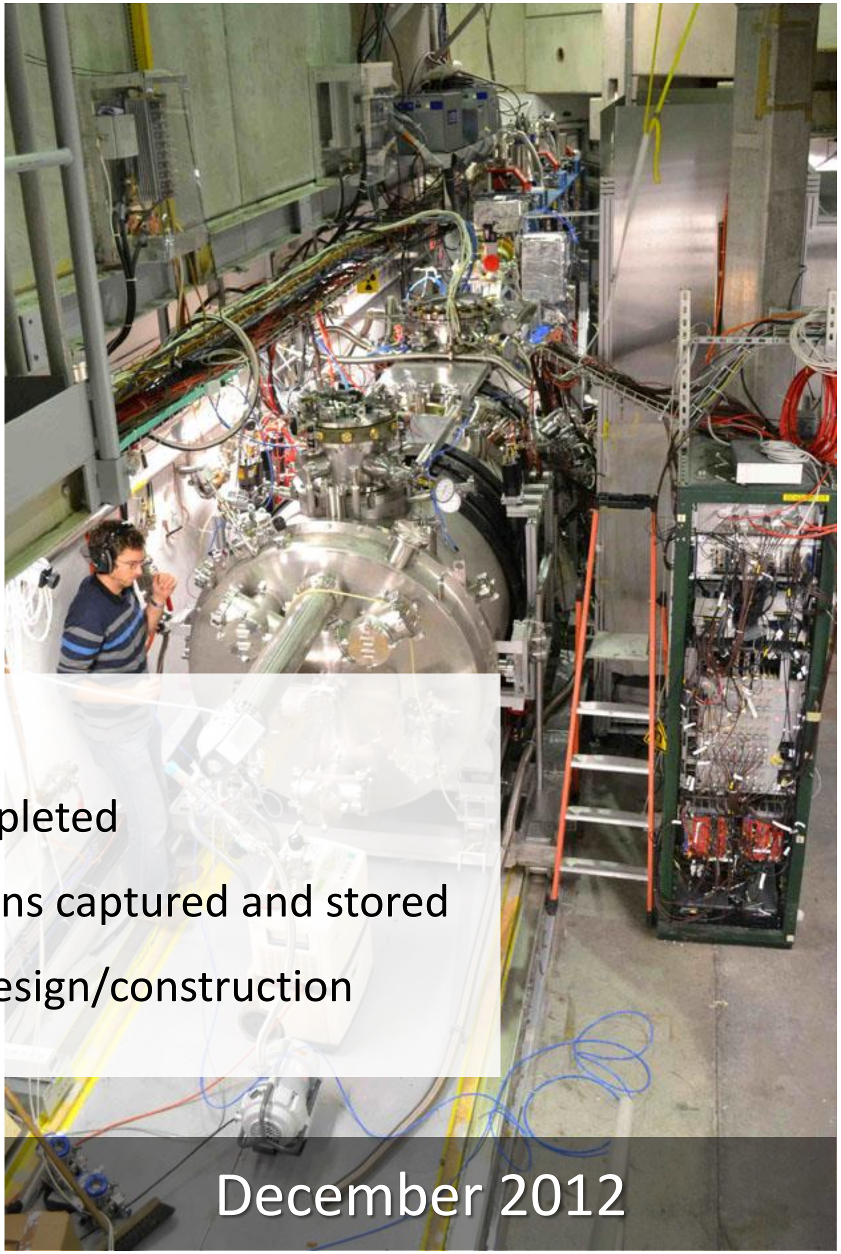
[J. Storey *et al.*, Hyp. Int. **228** (2014) 151]

Outline

- Antimatter gravity
- How to measure gravity?
- Status and recent results
- Conclusions and outlook

AEGIS status


September 2011

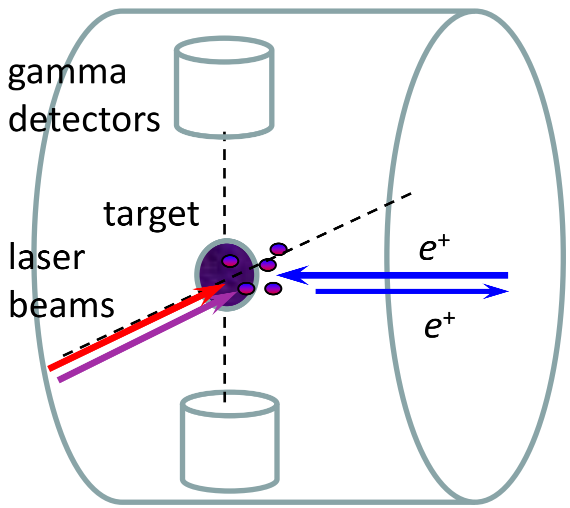

December 2012

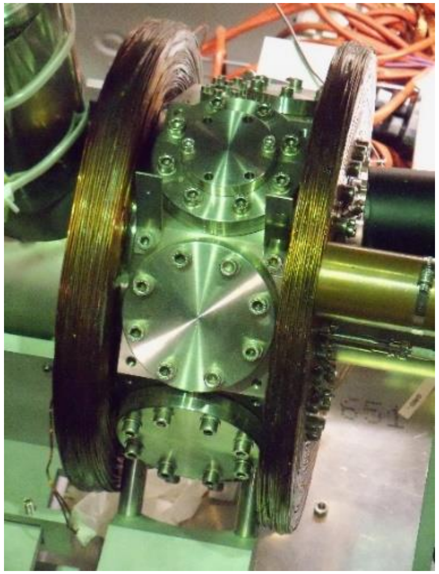
Status as of 2015:

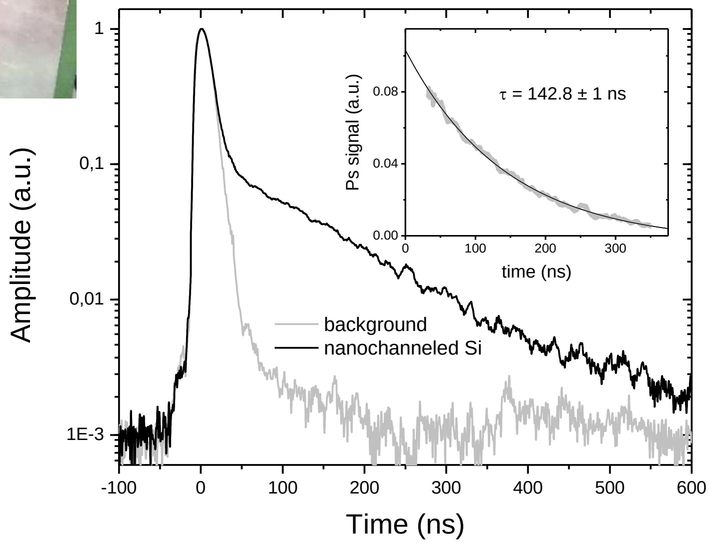
- Magnets and traps completed
- Antiprotons and positrons captured and stored
- Interferometer under design/construction

Positronium excitation & spectroscopy

- Detection of e^+ annihilations by **SSPALS** (single-shot positron annihilation lifetime spectroscopy)







  - Tail in annihilation signal due to delayed Ps decay
  - Time constant 142.8 ns (= o-Ps lifetime)

[S. Aghion *et al.*, submitted to NIM A]

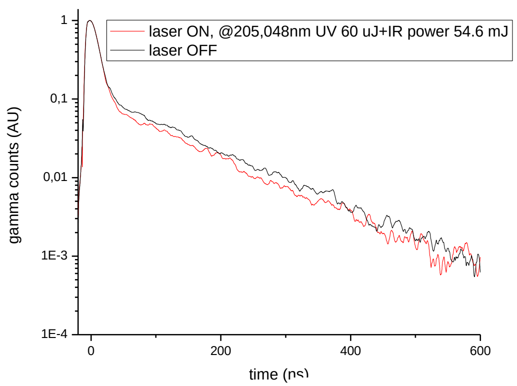
Positronium excitation & spectroscopy

1. Photoionization

$n = 1 \rightarrow 3 \rightarrow$ continuum

Reduction of annihilations in 50…250 ns

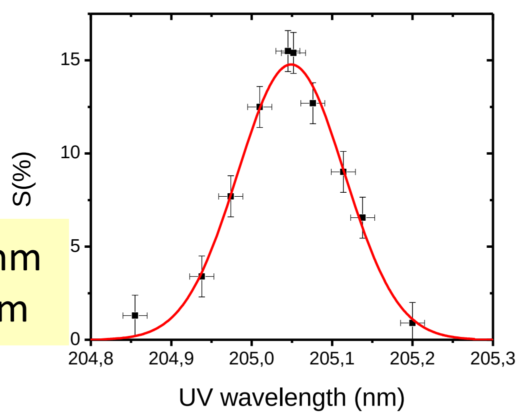
preliminary



Resonance of UV laser:

λ_{exp} = 205.049(5) nm
λ_{theo} = 205.0474 nm

preliminary

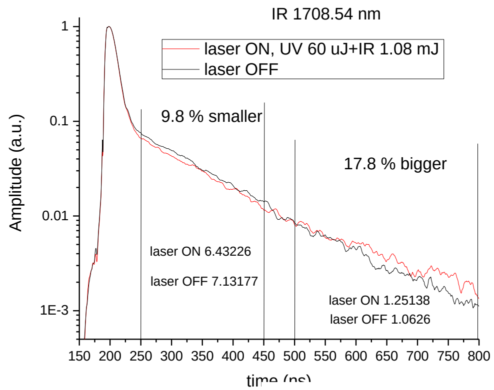


2. Rydberg excitation

$n = 1 \rightarrow 3 \rightarrow$ Rydberg

Delay of annihilations to > 600 ns

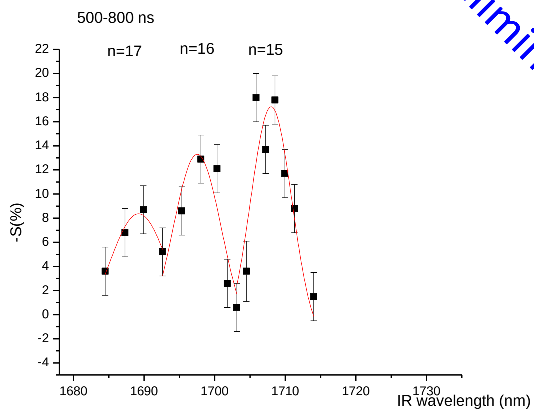
preliminary



Resonance of IR laser:

n = 15, 16, 17 peaks

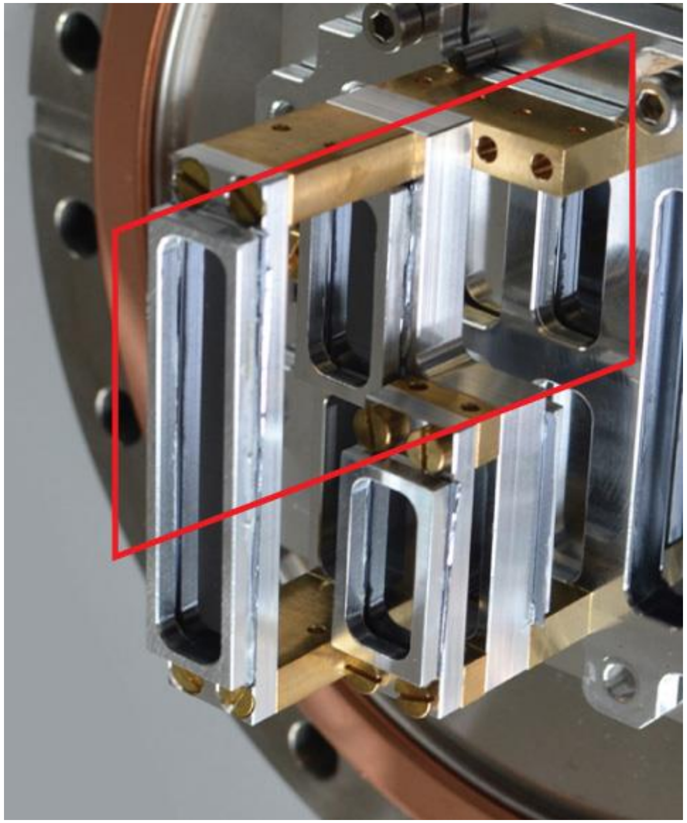
preliminary

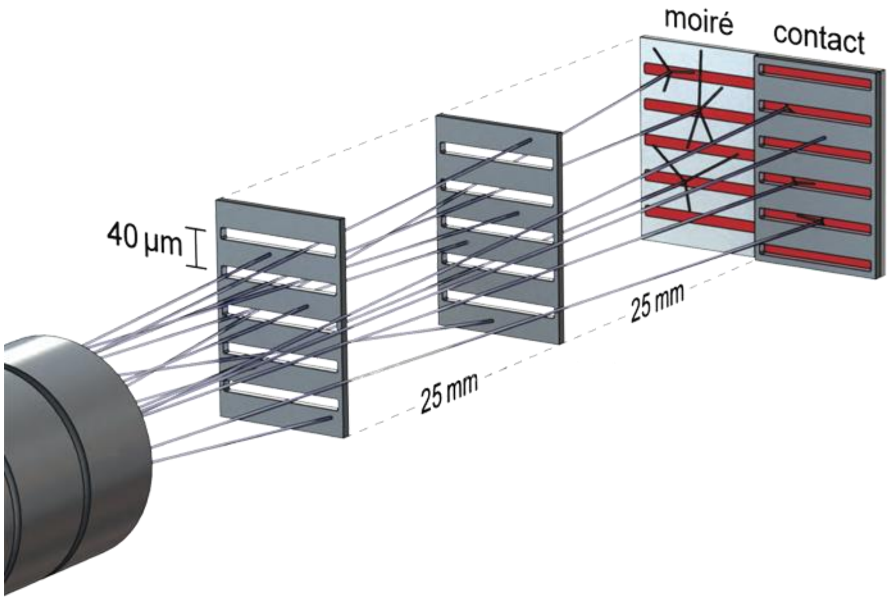


[S. Aghion *et al.*, submitted to Phys. Rev. Lett.]

Moiré deflectometer test with $\bar{p}$

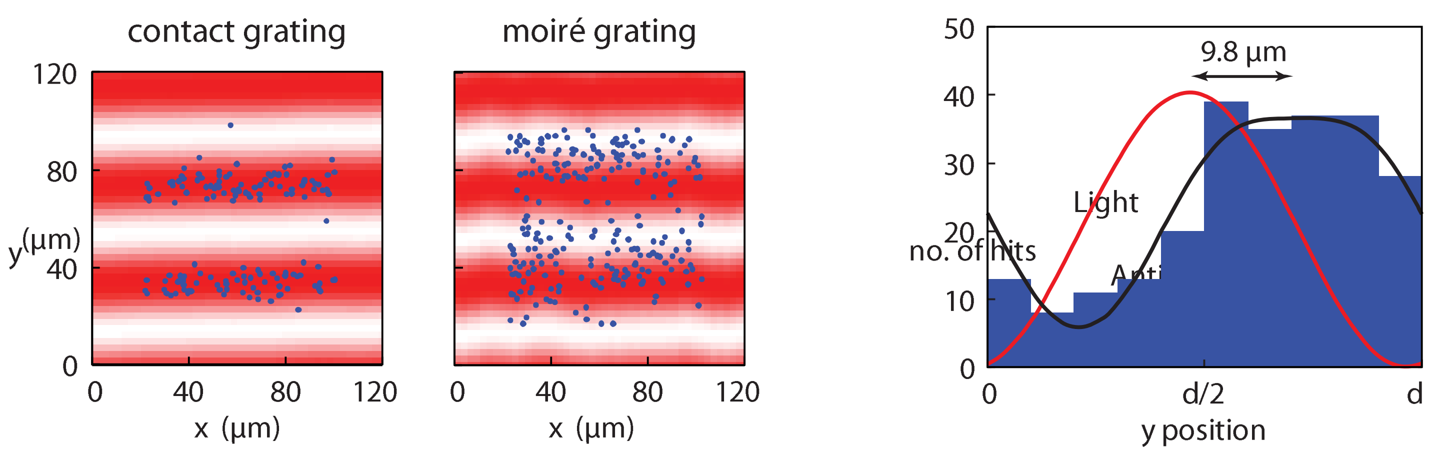
- Deflectometry measurement with $\bar{p}$ in "mini moiré" setup
  - d = 40 µm, L = 25 mm
  - 110 keV $\bar{p}$, 6.5 h emulsion exposure
  - Reference measurement with diode light in Talbot-Lau regime





Moiré deflectometer test with $\bar{p}$

- Light and antiprotons detected on emulsion



[S. Aghion *et al.*, Nature Comm. **5** (2014) 4538]

- Result:
  - Force on $\bar{p}$ (upward): 530 ± 50 (stat) ± 350 (syst) aN
  - Corresponds to magnetic field $|B| \approx 8$ G or electric field $F \approx 34$ V/m
- Absolute shift comparable to that expected for $\bar{\mathrm{H}}$ measurement
- Force 10 orders of magnitude smaller, but sensitivity 11 orders of magnitude larger (8 for lower *v*, 3 for longer *L*)

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Conclusions & outlook

- AEGIS is gearing up to perform a gravity measurement with neutral antihydrogen $\Rightarrow$ First WEP test with antimatter

- Experimental setup almost complete

- Recent results:
  - Spectroscopy of the $n = 1 \rightarrow 3$ transition in positronium
  - Proof-of-principle deflectometry measurement with $\bar{p}$ beam

- First gravity measurement expected within few years