Experiments on antimatter gravity

- Motivations
- State of the art
- Experiments with antihydrogen
- Experiments with leptons

Motivations

It has never been measured!

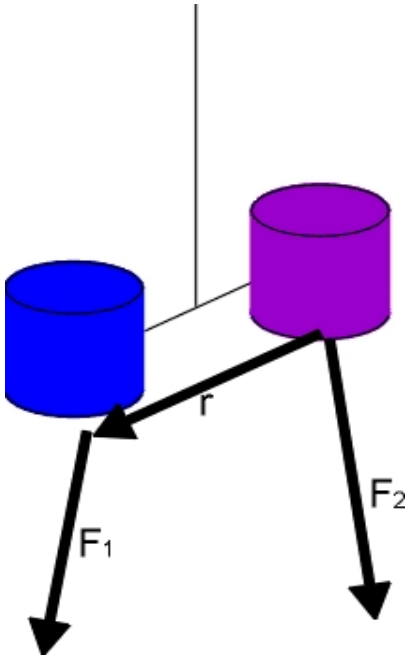
- Cosmological mysteries:
  - Big Bang model → same quantity of matter and antimatter, but Antimatter not seen!
  - energy content: matter (4%), dark matter(22%), dark energy (74%) of **unknown nature**

  →modified gravity? Or even antigravity?

- Attempts to construct cosmology with matter-antimatter symmetry + mechanism to keep them apart:
  - negative gravitational masses *(Chardin)*
  - gravitational dipoles *(Blanchet, Hajdukovic)*

- **Quantum** theories (superstrings, SUSY, …) contain tensor + scalar and vector
  → components of repulsive gravity *(Scherk)*
- SM Extension *(Kostelecky & Tasson)* → gravity may depend on flavour content
- *Note:* $\Gamma(K^0 \to \pi^+\pi^-) \neq \Gamma(\bar{K}^0 \to \pi^+\pi^-)$
- *small matter/antimatter differences exist in the Standard Model*

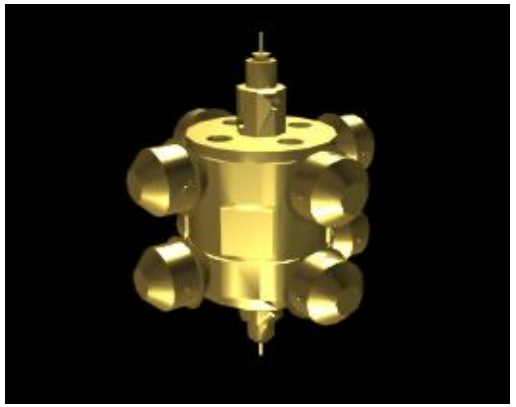
Matter Experiments: best constraint



Weak Equivalence Principle (Torsion pendulum – Eötwash)

$$(\Delta a / a)_{Be/Ti} = (0.3 \pm 1.8) \times 10^{-13}$$

T.A. Wagner et al., Class. Quantum Grav. 29, 184002 (2012)

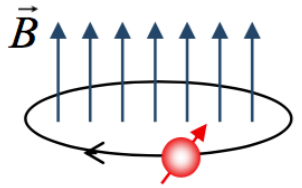


Strong Equivalence Principle (Lunar Laser Ranging)

$$(\Delta a / a)_{Earth/Moon} = (-1.0 \pm 1.4) \times 10^{-13}$$

J.G. Williams et al., Phys. Rev. Lett. 93 (2004) 261101

AntiMatter Experiments: example constraint



- ***Cyclotron frequency of p & $\bar{p}$ in same B field***

$$\omega = qB/2\pi m + \alpha U/c^2 \qquad \left|\omega - \bar{\omega}\right| / \omega = \left(9 \pm 9\right) x10^{-11}$$

$$\rightarrow \left|g - \bar{g}\right| / g \leq 510^{-6}$$

G. Gabrielse et al. Phys Rev Lett 82 (1999) 3198

now superseded by BASE → 8.7 10 $^{-7}$

S. Ulmer, et al., Nature 524, 196 (2015)

- ***Arrival time of 1 (? : 90 % CL) neutrino and 18 antineutrinos from SN1987a***

$$\left|\gamma(\upsilon_e) - \gamma(\bar{\upsilon}_e)\right| / \gamma(\bar{\upsilon}_e) < 10^{-6}$$

S. Paksava et al. Phys Rev D 39 (1989) 1761

AntiMatter Experiments: prospects

- Positrons (e^+) or Antiprotons ($\bar{p}$)

  $$\frac{m_e g}{e} = 5.6\ 10^{-11}\ V\ /\ m$$

  gravity force on $e^\pm$ ~ force from 1 elementary electric charge at 5 m

- Antineutrons

  difficult to slow down and keep enough

- AntiNeutrinos

  wait for next supernova ?

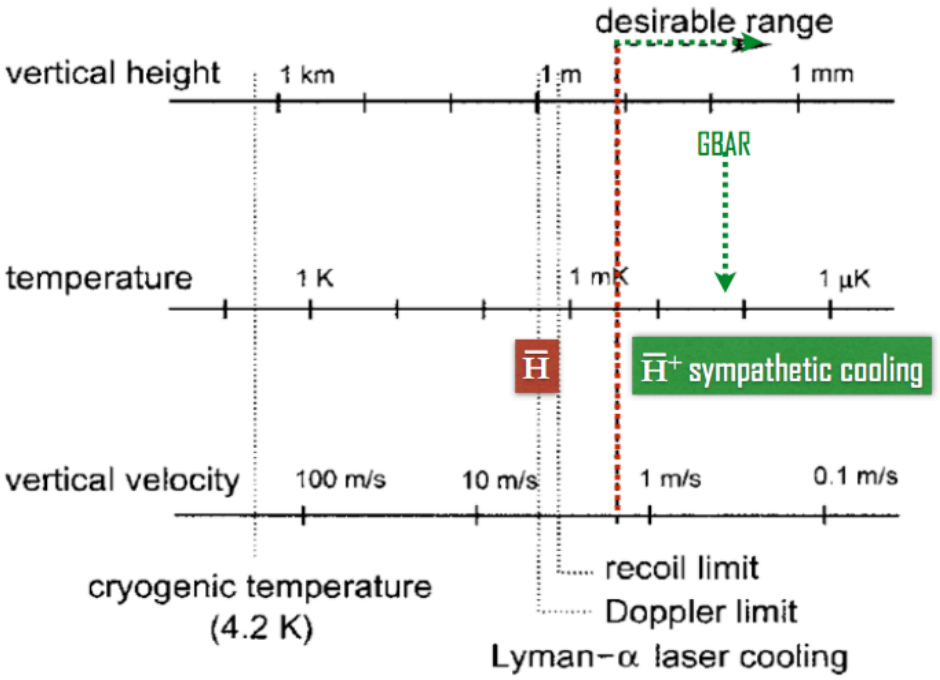
- Positronium (e^+e^-) or Muonium (μ^+e^-)

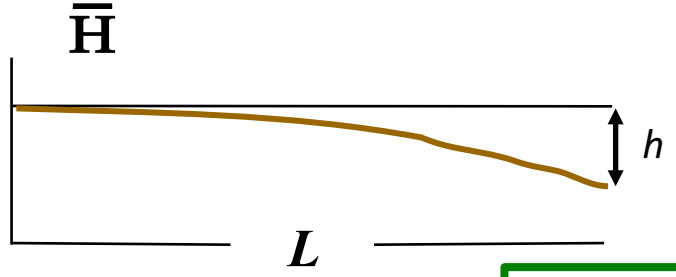
  Ps lifetime 142 ns, cooling, ionisation by black body radiation

  projects by D. Cassidy at UCL & P. Crivelli at ETHZ, or D. Kaplan at PSI

- Antihydrogen

Antihydrogen free fall





$$m_i \vec{a} = m_g \vec{g}$$

$$h = v_z^0 t + \frac{1}{2}\frac{m_g}{m_i} g t^2 = v_z^0 \left(\frac{L}{v_h}\right) + \frac{1}{2}\frac{m_g}{m_i} g \left(\frac{L}{v_h}\right)^2$$

	AEGIS : $\bar{H}$ beam	GBAR : cooled $\bar{H}^+$ → slow $\bar{H}$
L	1 m	0.1 m
h	20 μm	20 cm
v_h	500 m/s	0.5 m/s
T_H	100 mK	10 μK

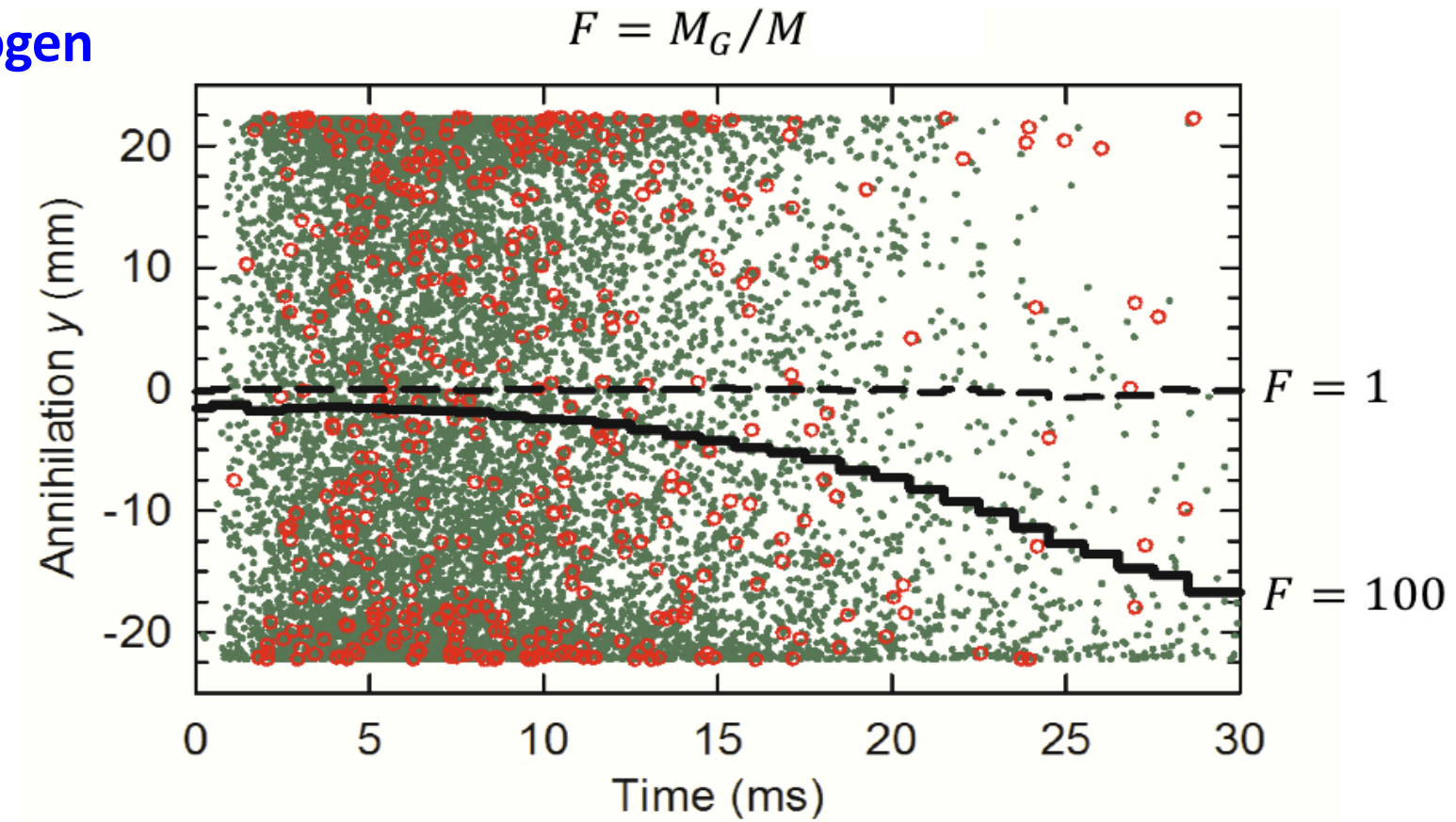
Goal

$$\frac{\Delta g}{g} \leq 1\%$$

ALPHA-g
10 % in 2018 ?

AntiMatter Experiments: one result

Antihydrogen



Vertical position of annihilation vertex during release of trapping field

Antihydrogen Experiments: 3 projects

- **AEgIS**

  produce $\overline{\mathrm{H}}$ horizontal beam and observe vertical deflection due to gravity

- **ALPHA-g**

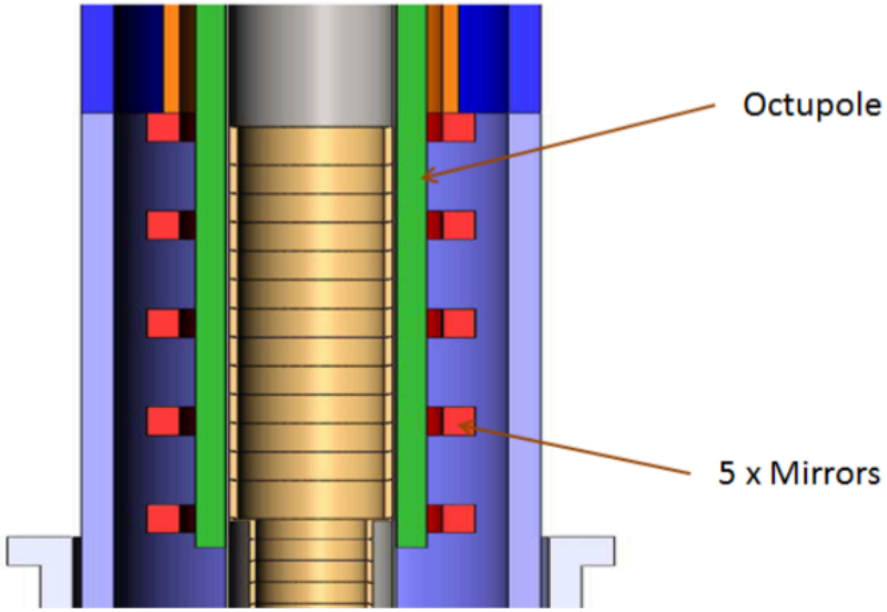
  trap $\overline{\mathrm{H}}$ and observe annihilation point after release of trapping forces

- **GBAR**

  obtain $\overline{\mathrm{H}}$ at rest and observe free fall

ALPHA-g

CERN-SPSC-2016-031 / SPSC-P-325-ADD-1



principle → up/down in 2018

- $\overline{\mathrm{H}}$ in vertical trap
- apply B field gradient to counteract gravity
- top and bottom mirror coils repel low field seeking states
- atoms bounce every 5 ms between top and bottom mirrors
- release force by slowly turning off mirror coils (10 s)
- measure fractions upward/downward (71% downward for normal gravity)

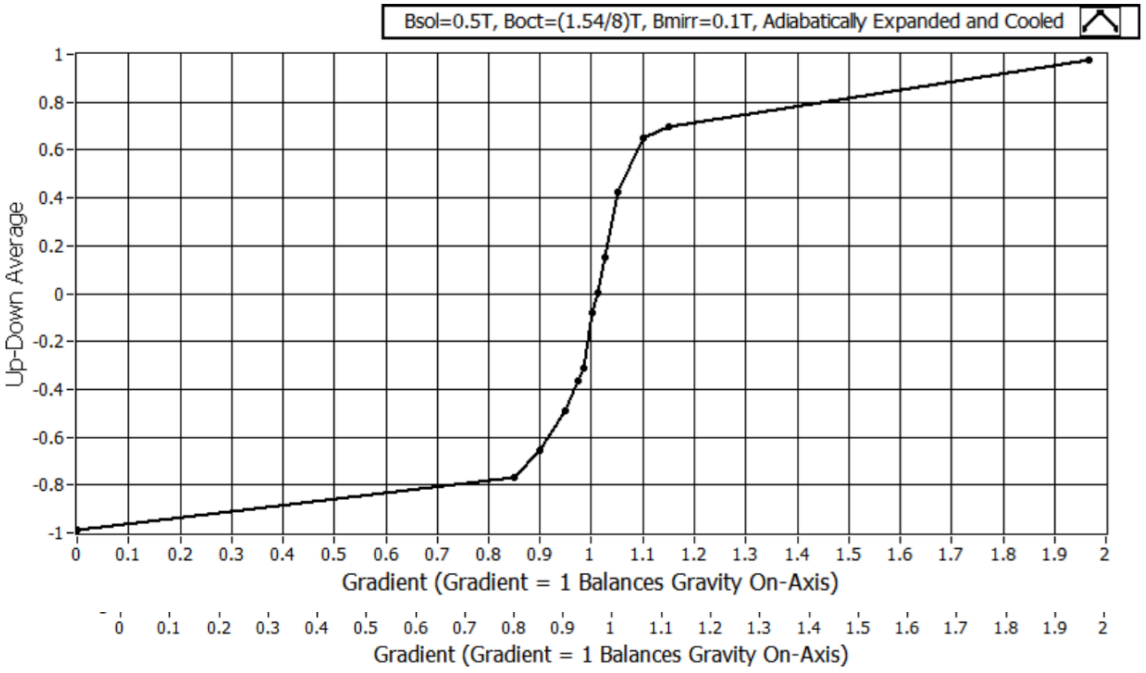
ALPHA-g

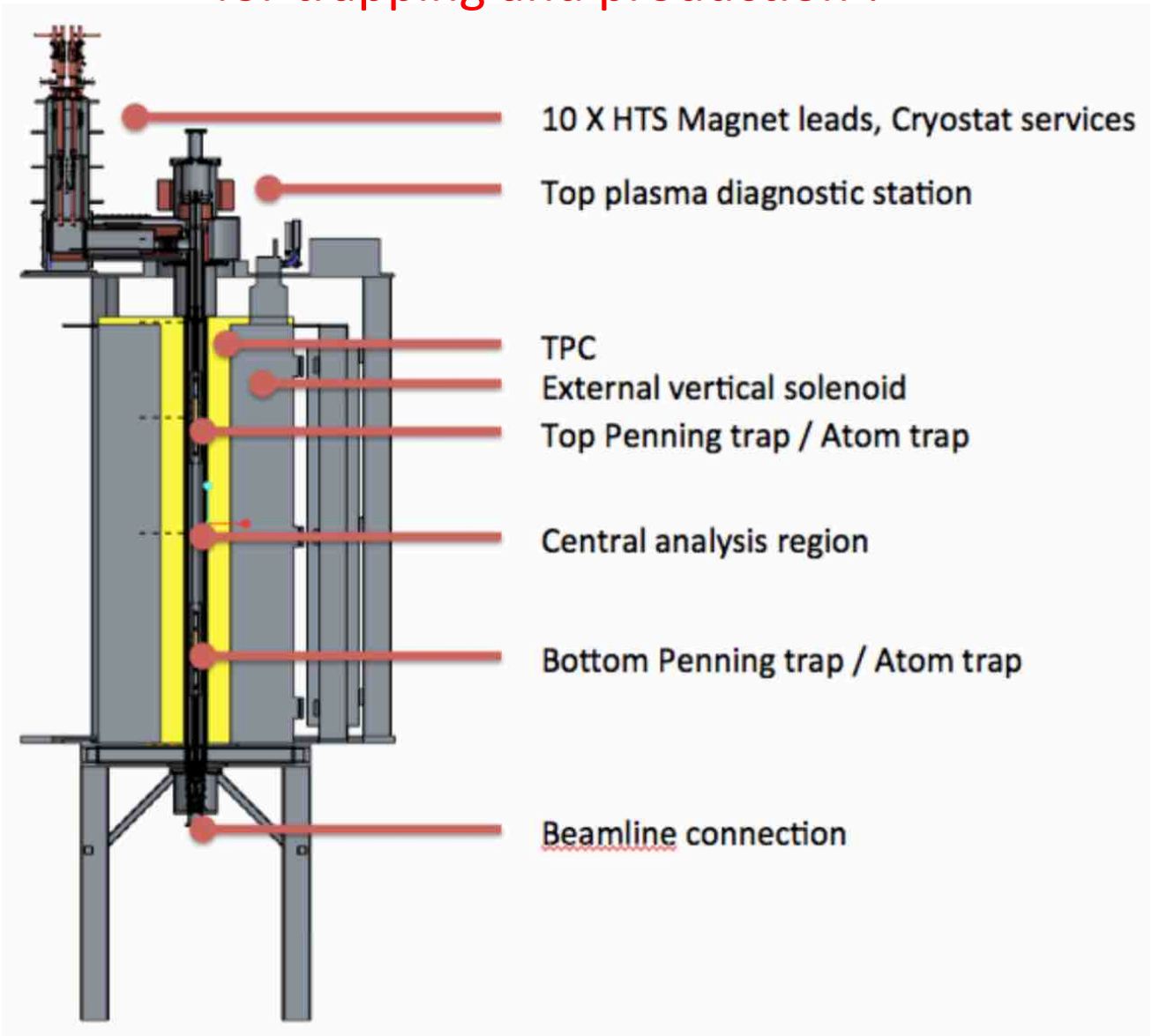
well proven and reproducible methods for trapping and production !

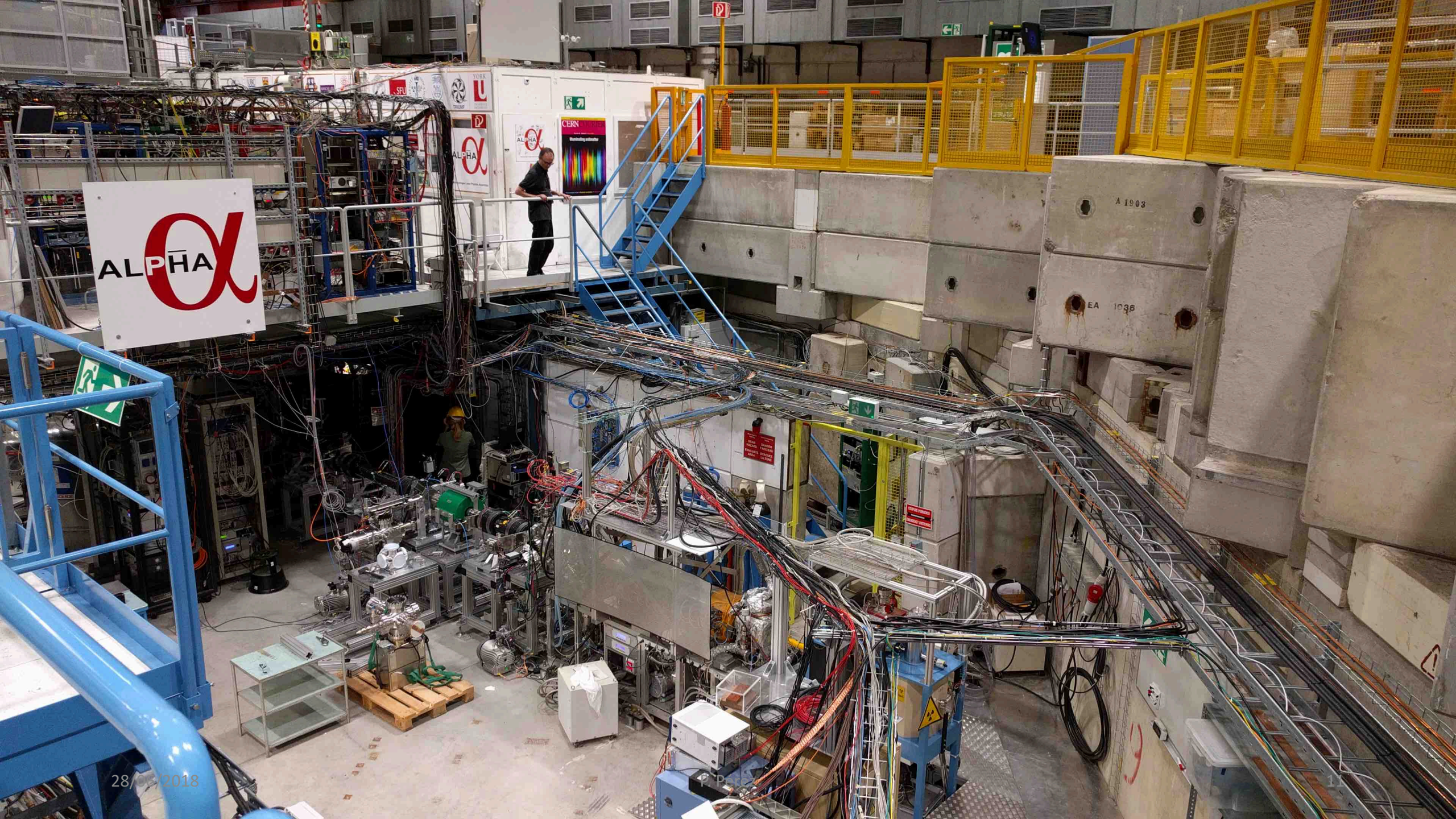
precision 1%

field gradient 0.018 T/m

control errors on B at 10^{-5} T

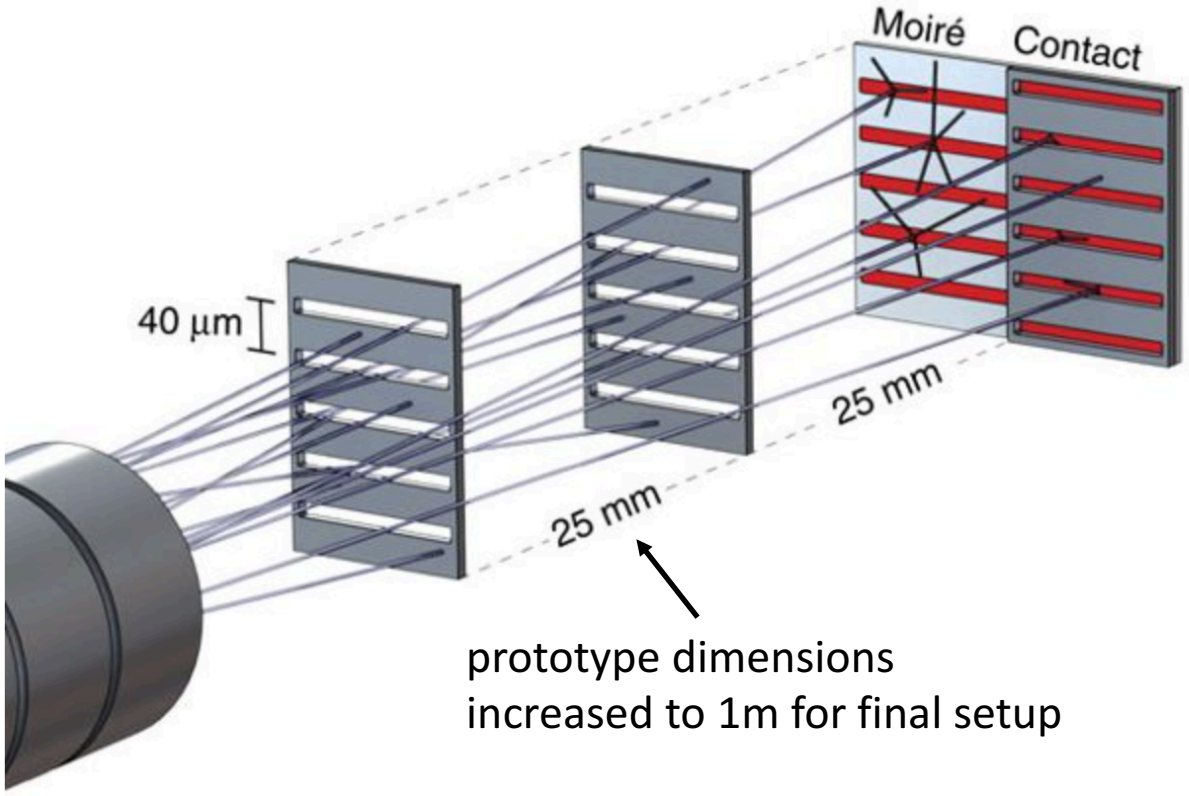


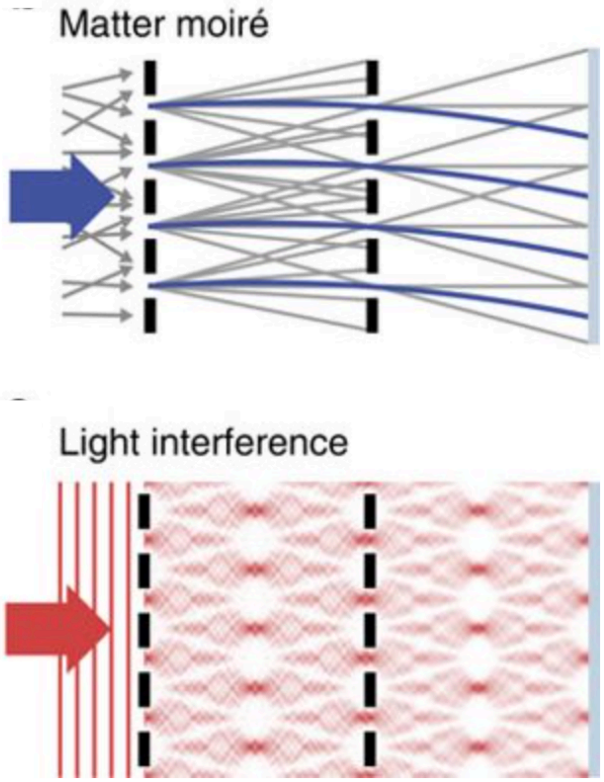



ALPHA
CERN

AEgIS

precision 1%





v ~ 500 m/s

1 m path → 20 μm

Moiré pitch 40 μm

resolution 1 μm

emulsion detector

<u>requires:</u>

$T_{\bar{p}}$ = 100 mK

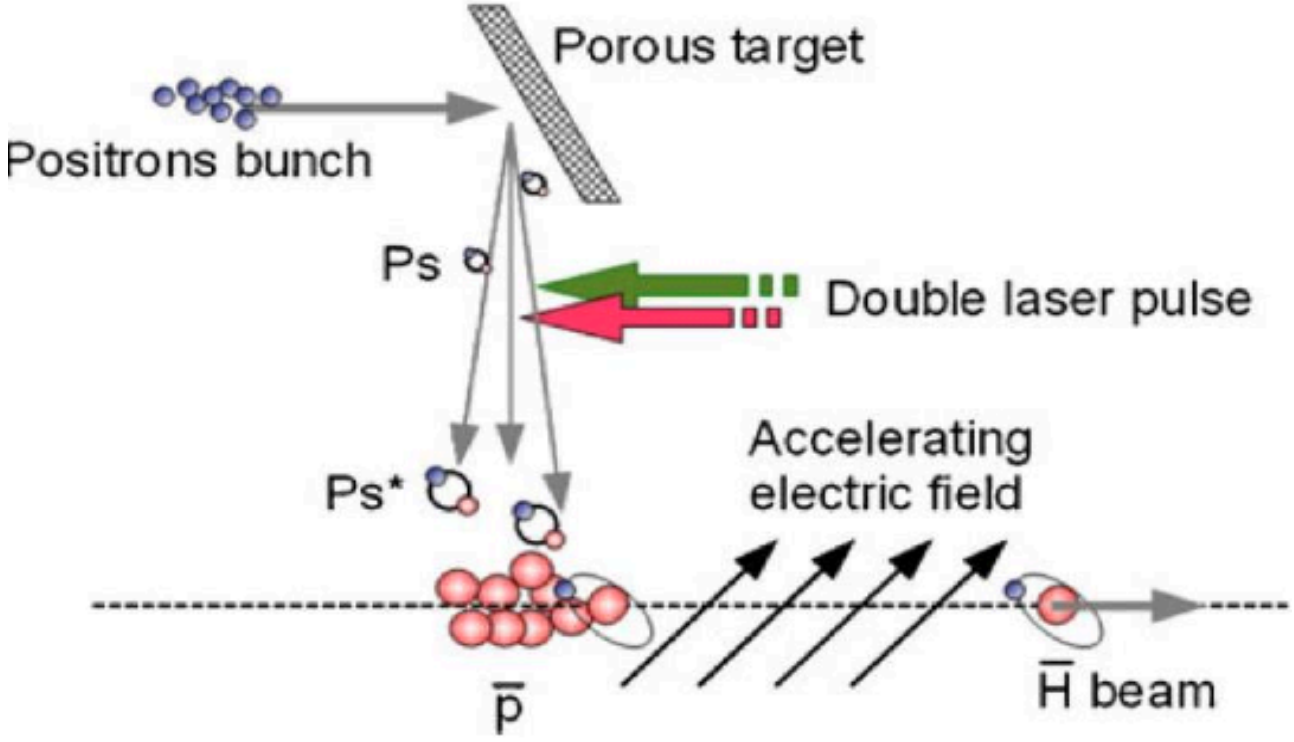
beam ⌀ 10 cm

AEgIS

beam production

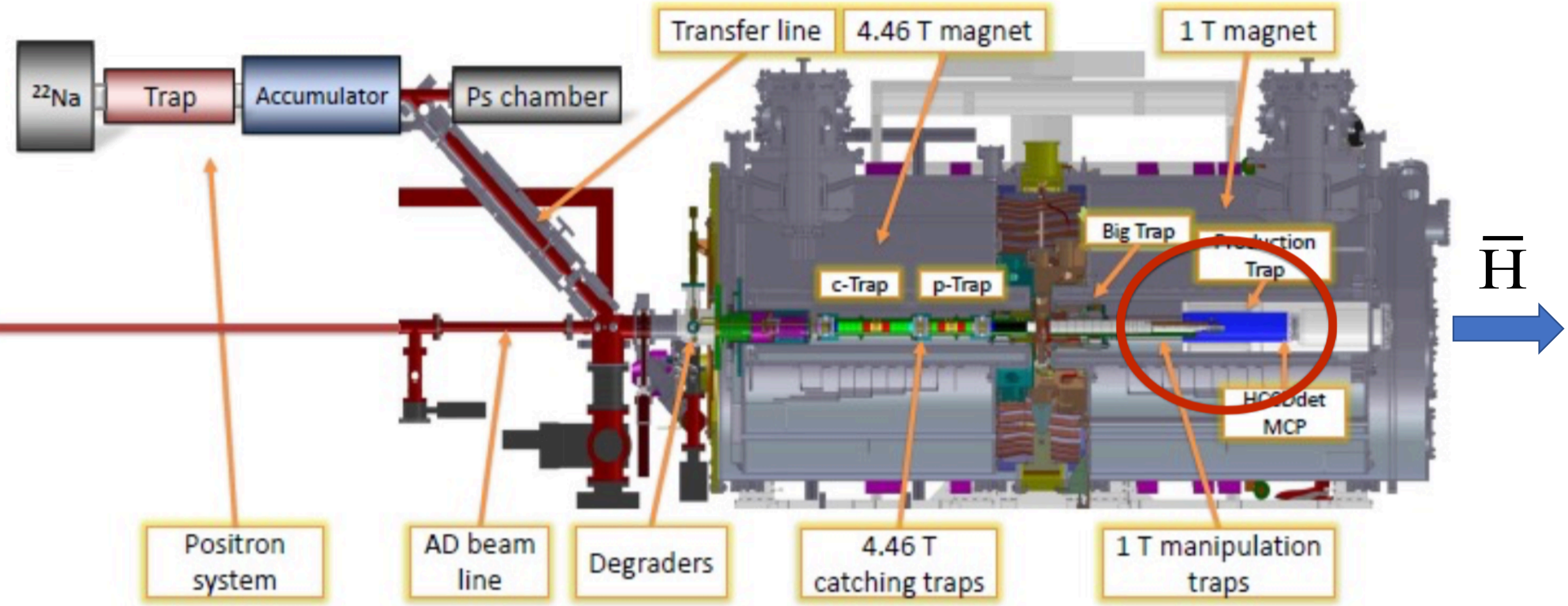
- trap and cool $\bar{p}$ to 100 mK
- sympathetic cooling with La^- or C_2^-
- convert e^+ to Ps in porous SiO_2
- excite Ps to increase lifetime

  and $\bar{H}$ production
- accelerate $\bar{H}$ and let decay to n=1



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

AEgIS

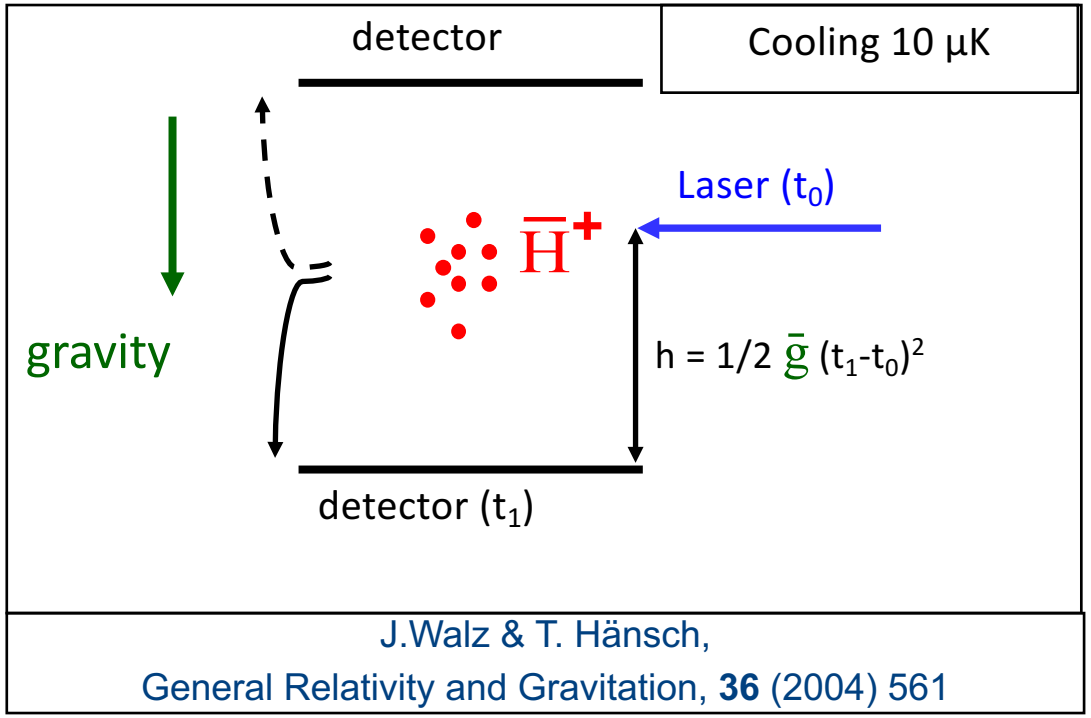

^{22}Na
Trap
Accumulator
Ps chamber
Transfer line
4.46 T magnet
1 T magnet
Big Trap
Production Trap
c-Trap
p-Trap
MCP
$\bar{H}$
Positron system
AD beam line
Degraders
4.46 T catching traps
1 T manipulation traps

AEgIS

GBAR

principle

- $\bar{H}^+ = \bar{p}\, e^+ e^+$
- Sympathetic cooling with Be^+ → 10 µK
- Photodetachment of e^+
- Time of flight (h = 10 cm → Δt = 0.14 s)



J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561

beam production

- instead of 3-body process with 2 e^+
- use Ps = e^+e^- (~ AEgIS), twice
- excite Ps (n=3)

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

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

P.Pérez & A. Rosowsky, NIM **A 532** (2004) 523

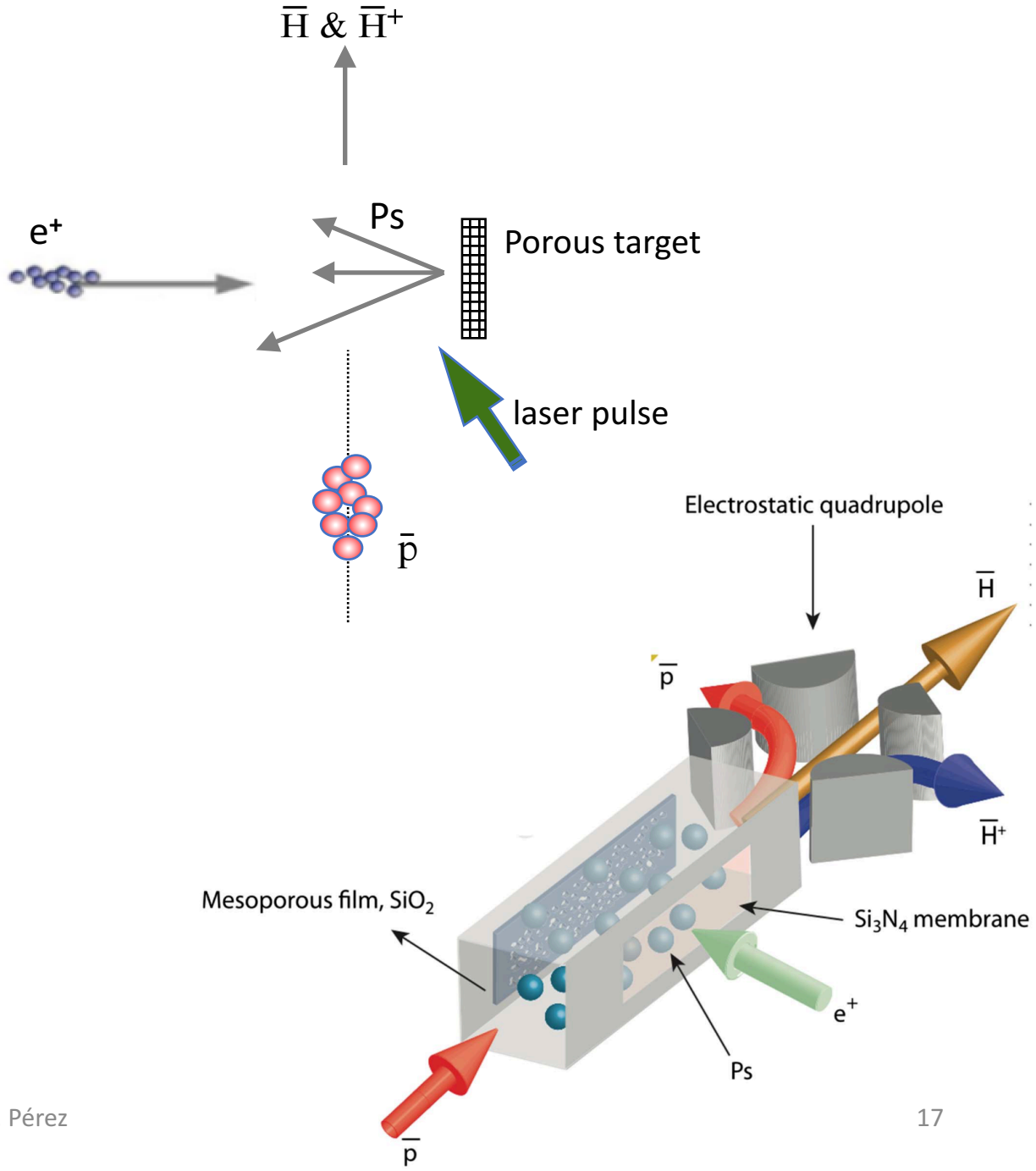
GBAR

beam production

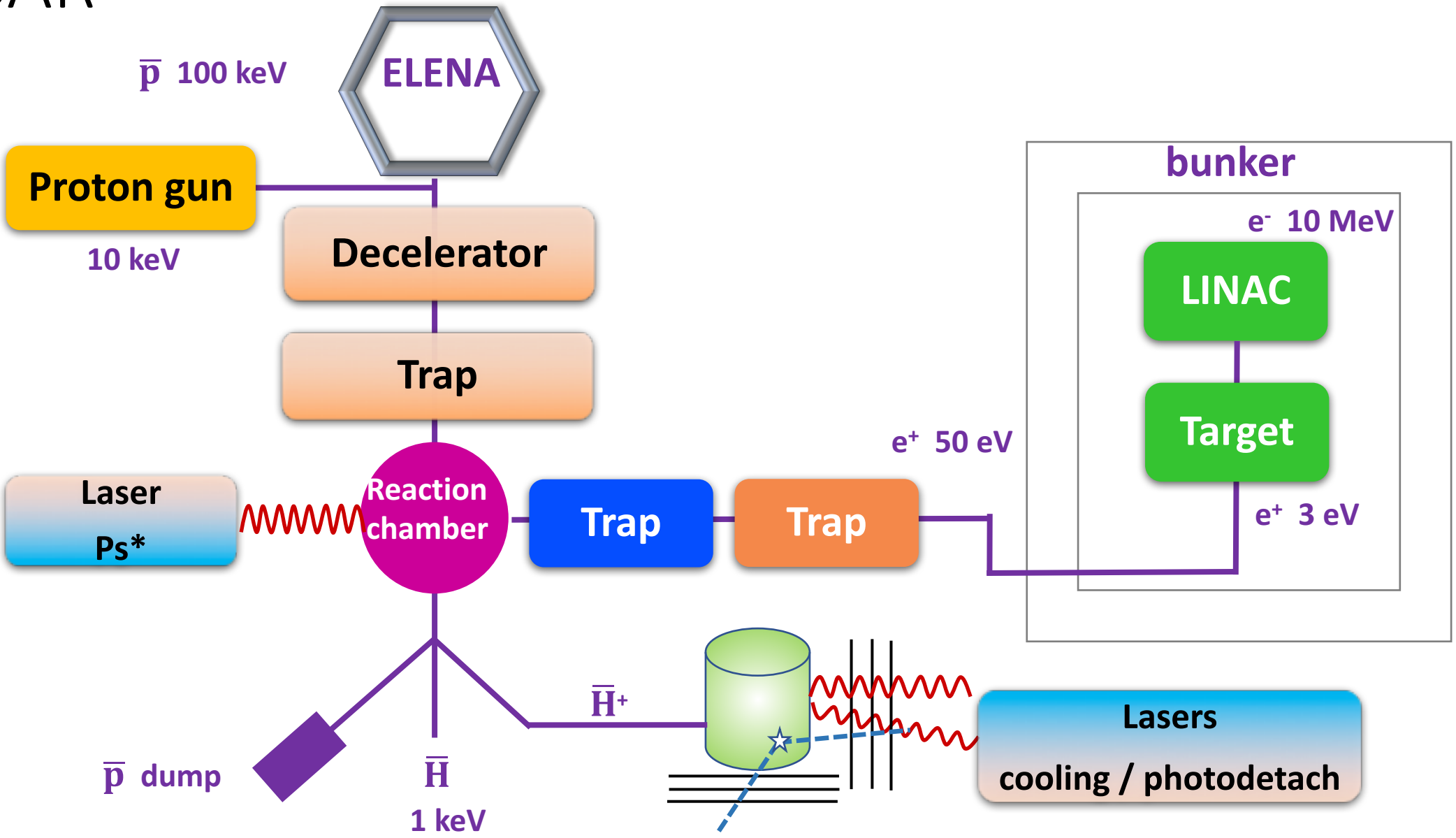
- ELENA will provide 1 bunch / 110 s

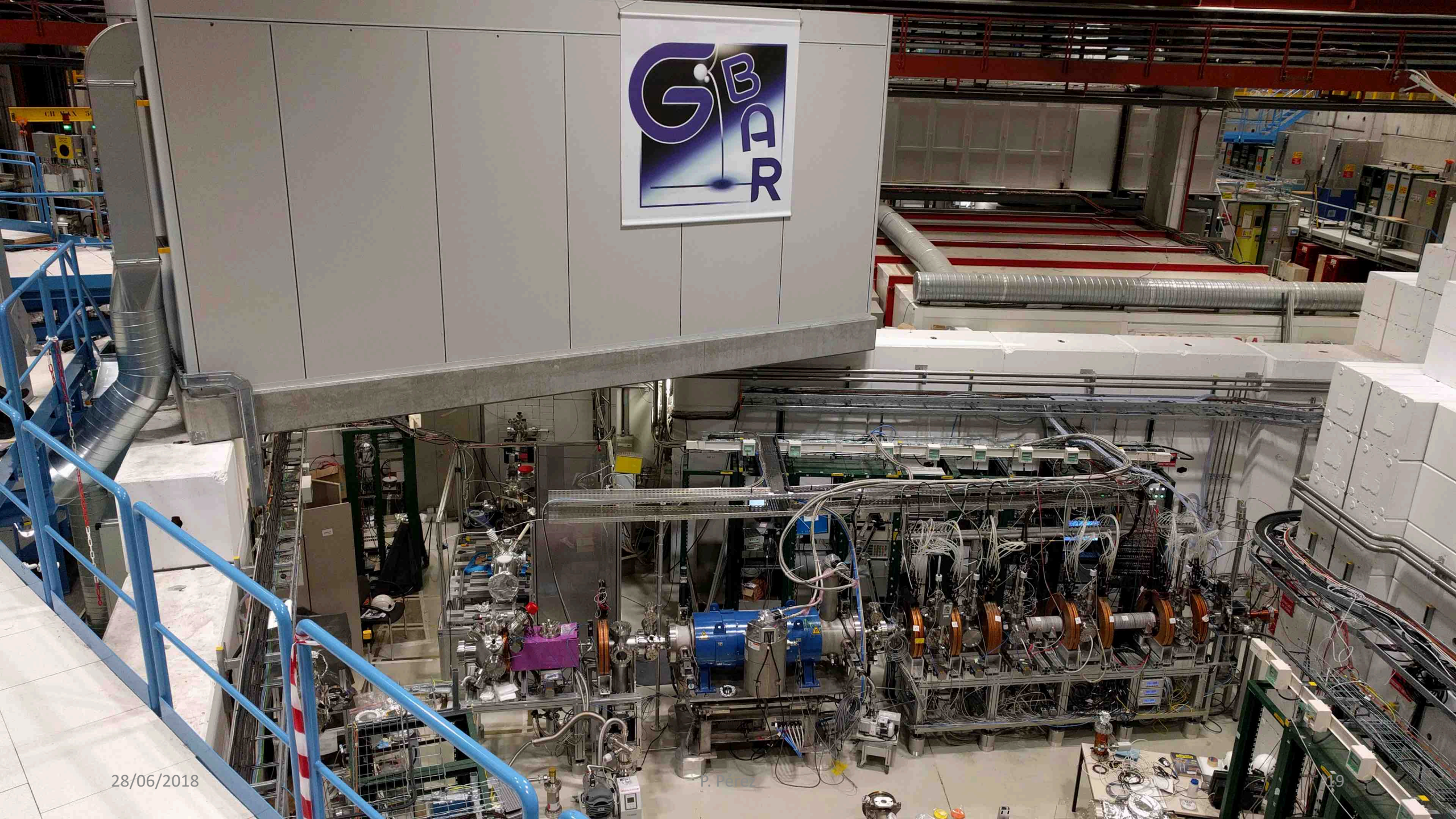
$\sim 0.5\ 10^7\ \bar{p}$
$10^{12}\ P_S\ /cm^2$
} → $10^4\ \bar{H}$
$1\ \bar{H}^+$

- use e^- linac → high intensity e^+

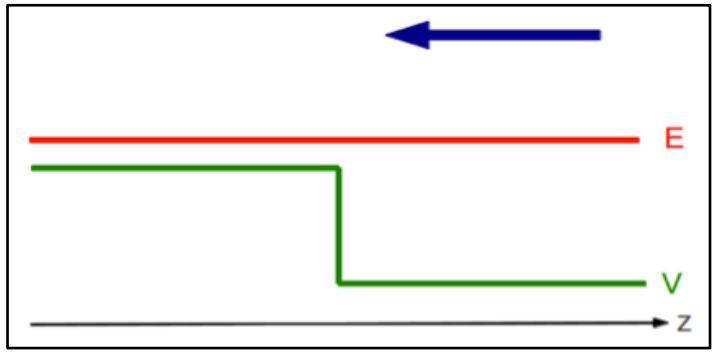


GBAR


$\bar{p}$ 100 keV
ELENA
Proton gun
10 keV
Decelerator
Trap
Laser
Ps*
Reaction chamber
Trap
Trap
e⁺ 50 eV
bunker
e⁻ 10 MeV
LINAC
Target
e⁺ 3 eV
$\bar{H}^+$
$\bar{p}$ dump
$\bar{H}$
1 keV
Lasers
cooling / photodetach

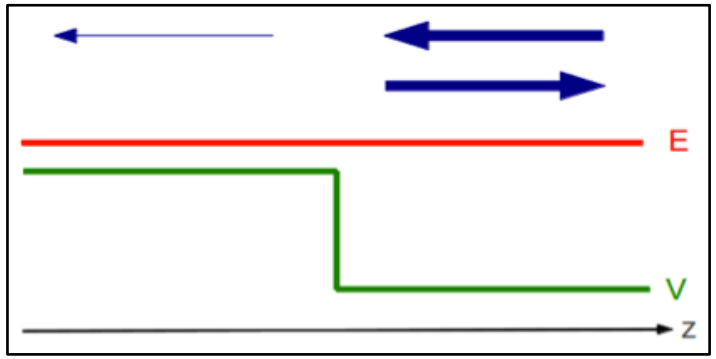

GBAR

Quantum reflection on a step



plane wave incident on a potential step:

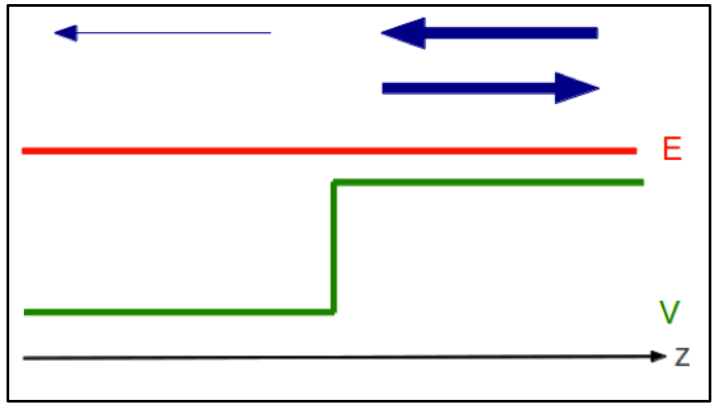
$$\Psi_{\text{in}}(z) \propto \exp(-ikz) \text{ with } k = \sqrt{2m(E-V)}\ /\ \hbar$$



wave function partly transmitted, partly reflected

$$\text{reflection:} \quad r_{12} = \frac{k_2 - k_1}{k_1 + k_2}$$

$$\text{transmission:} \quad t_{12} = \frac{2\sqrt{k_1 k_2}}{k_1 + k_2}$$



reflection from attractive potential

Reflection probability unchanged when $1 \leftrightarrow 2$

$$|r_{12}|^2 = |r_{21}|^2$$

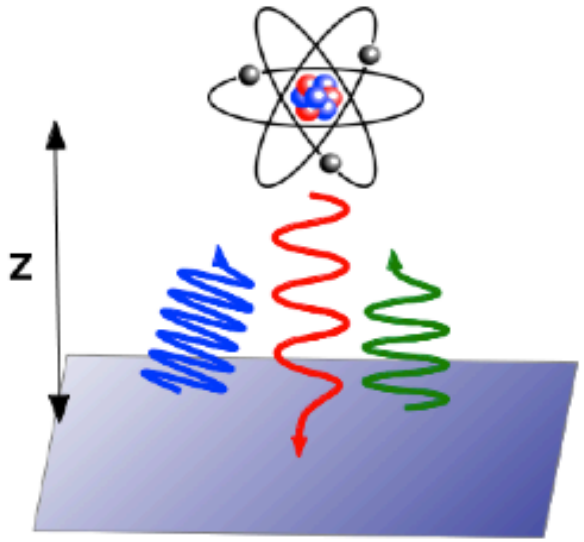
The Casimir - Polder force

G. Dufour et al., Int. Journal Mod. Phys: Conf. Series, 30 (2014) 1460265.

Electromagnetic (EM) modes are modified when the atom comes close to the detector:

$\Rightarrow$ the EM ground state (vacuum) energy changes

$\Rightarrow$ attractive Casimir-Polder force between atom and detector



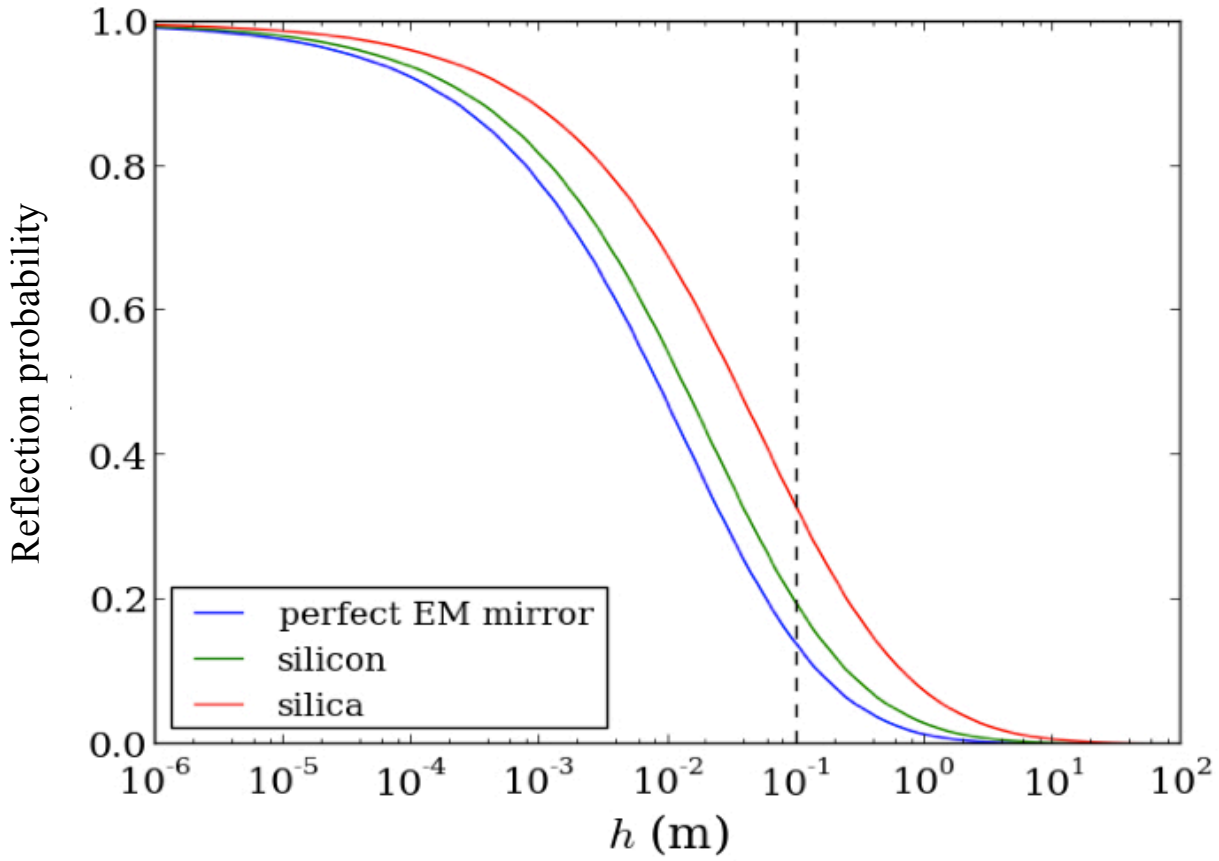
Casimir 1948 : long-range interaction energy between an atom and a perfectly conducting mirror:

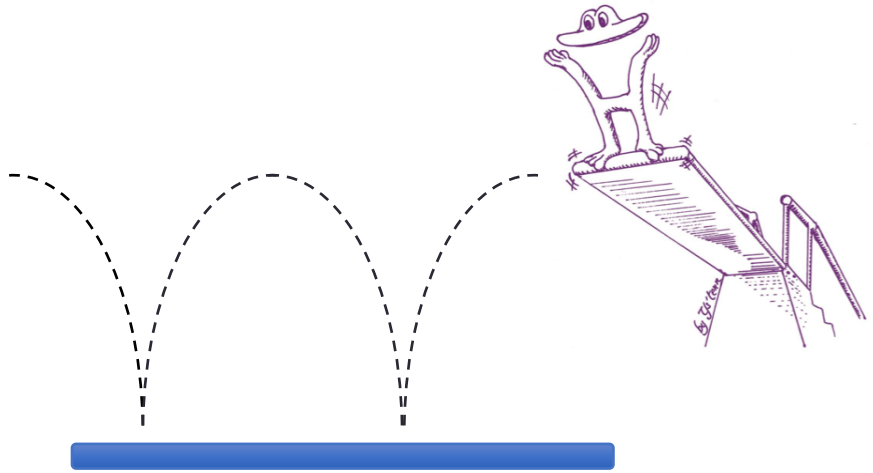
$$V^*(z) = -\frac{3\hbar c}{8\pi z^4}\frac{\alpha(0)}{4\pi\epsilon_0} = -\frac{C_4^{perfect}}{z^4}$$

For H and $\overline{\mathrm{H}}$, $C_4^{perfect} \approx 73.6\ E_h a_0^4$

$V(35\ \mathrm{nm}) \approx -\ mg \times 10\ \mathrm{cm}$

Spectroscopy of gravitational states





altitudes are quantized
→ spectroscopy
i.e. improved precision

already demonstrated with ultra cold neutrons
at ILL (*V. Nesvizhevsky*)

Experiments with leptons

- 1S-2S spectroscopy of Ps at 0.1 ppb as a function of position wrt Sun

P. Crivelli et al. , ETH Zürich

D. A. Cooke PC et al. , J. Phys. B: At. Mol. Opt. Phys. 49 014001 (2016) and LEAP 2018

- Ps free-fall

D. Cassidy et al. , UC London

R. Alonso talk at LEAP 2018

- Muonium (μ^+e^-) free fall

D. Kaplan et al. , PSI

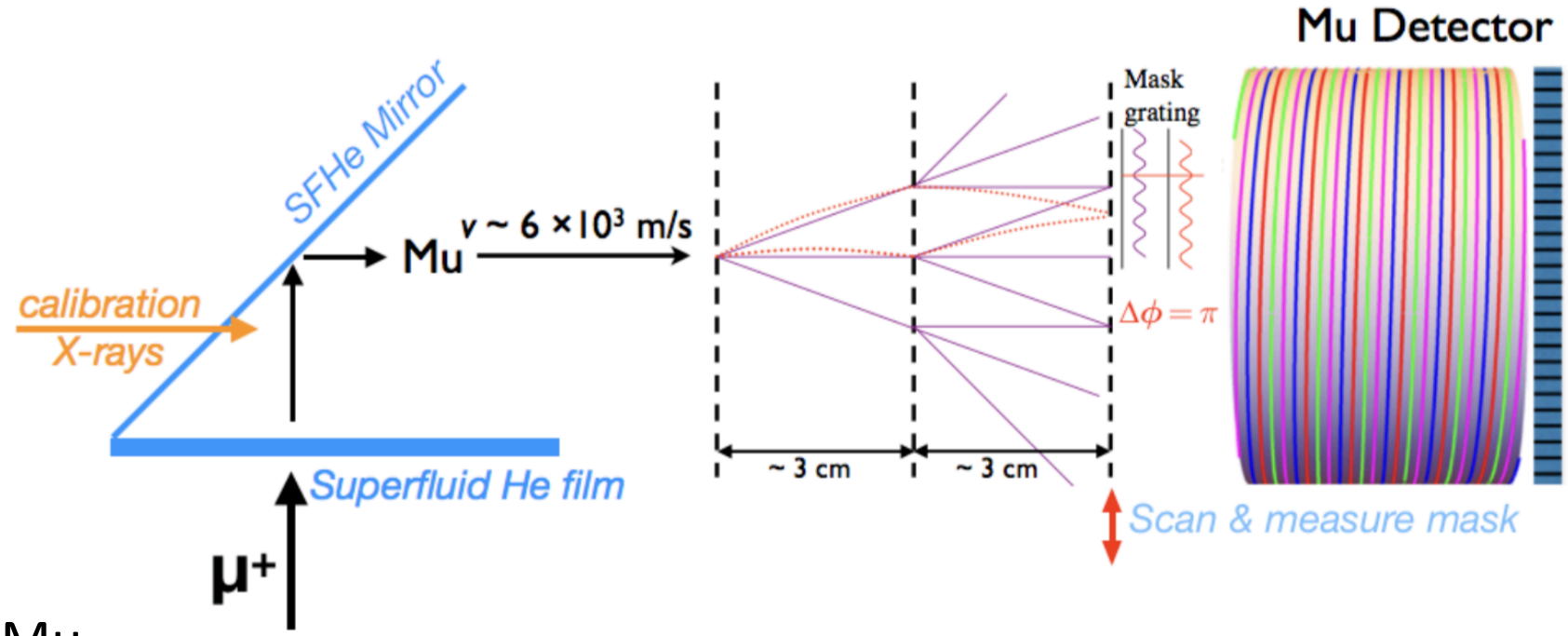
MAGE Collaboration Mu (μ^+e^-) free fall

arXiv:1802.01438

deflection 0.2- 0.5 nm in 2 x 2.2 μs

$$Goal$$
$$\frac{\Delta g}{g} \leq 1\%$$

in 100 days



μ^+ beam interacts with Superfluid He to produce Mu