Precision measurements with ultracold neutrons, muons, positrons, and antiprotons

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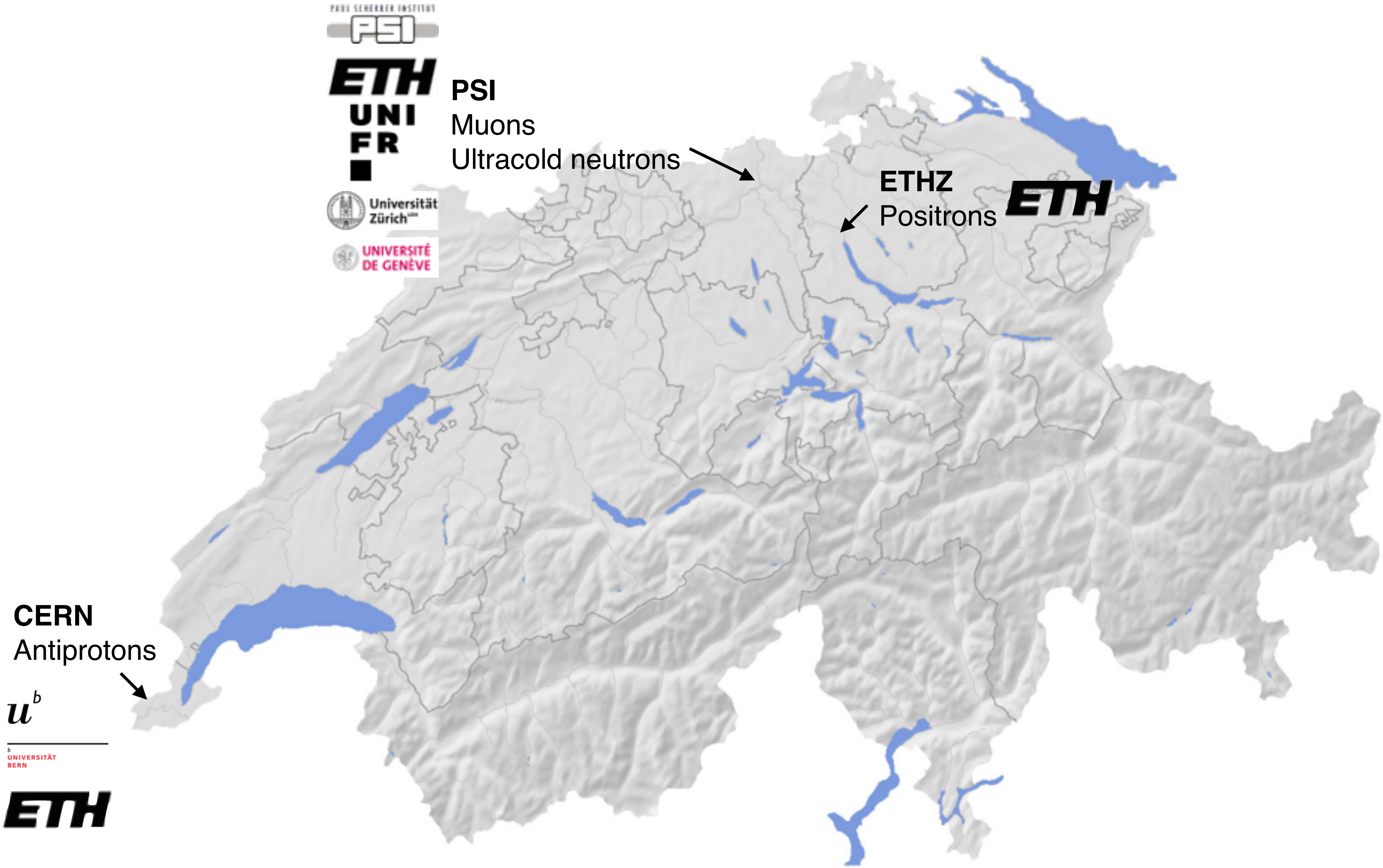
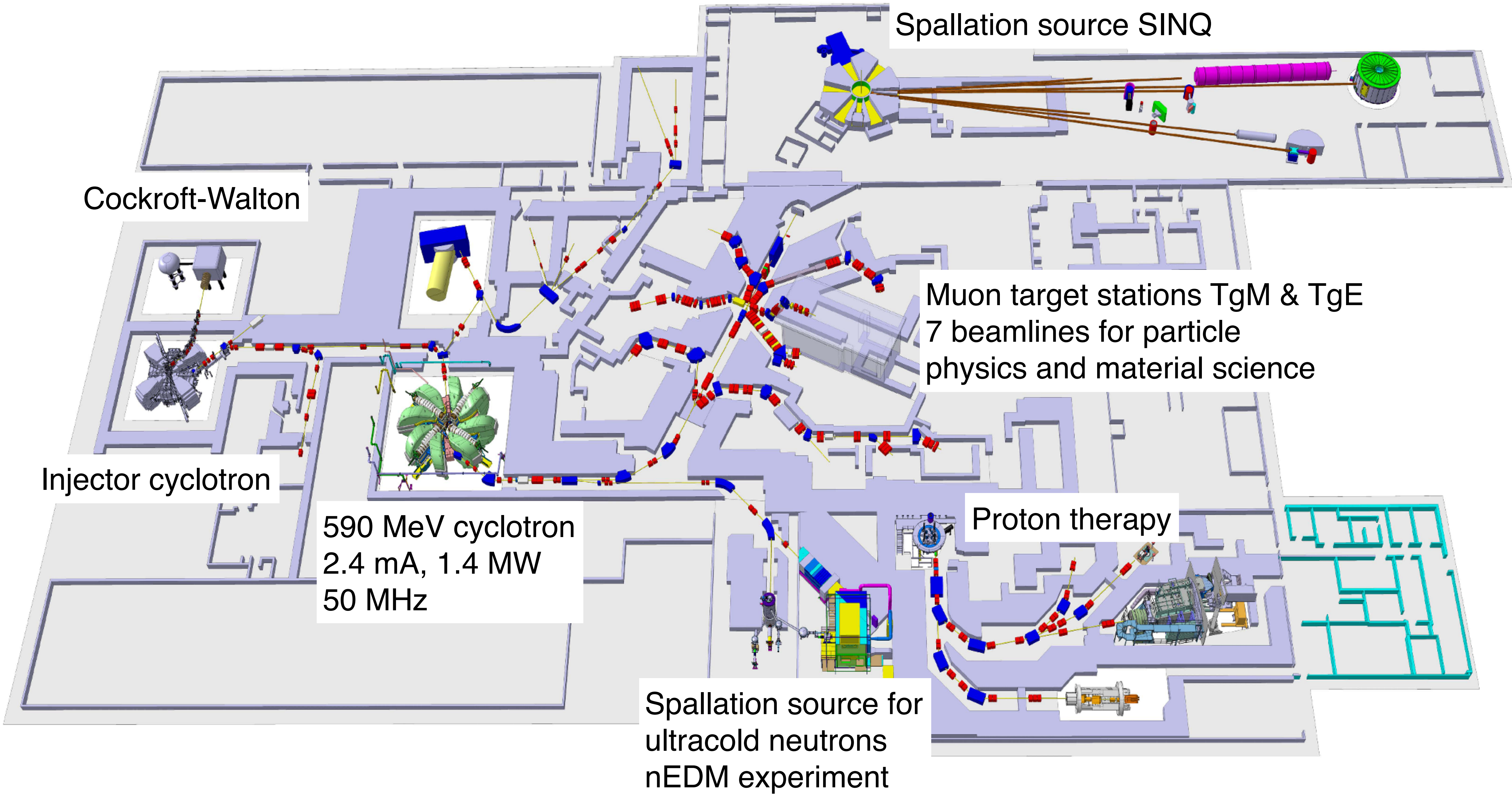
Overview

- Particles & Facilities
- Muon beam developments
- Muonic Atoms
- Antimatter gravity
- Positronium
- Ultracold neutrons

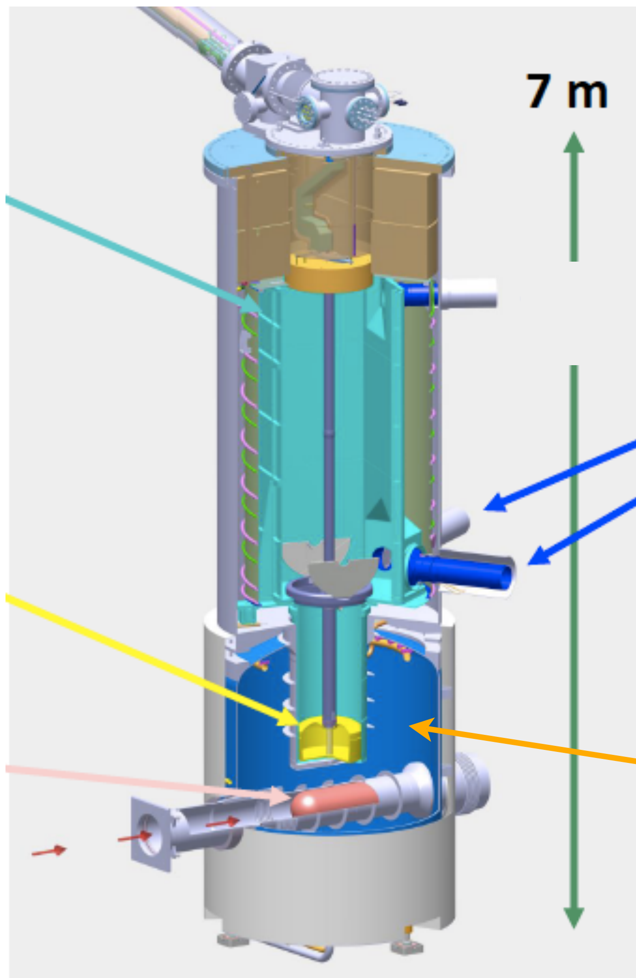
Particles & Facilities



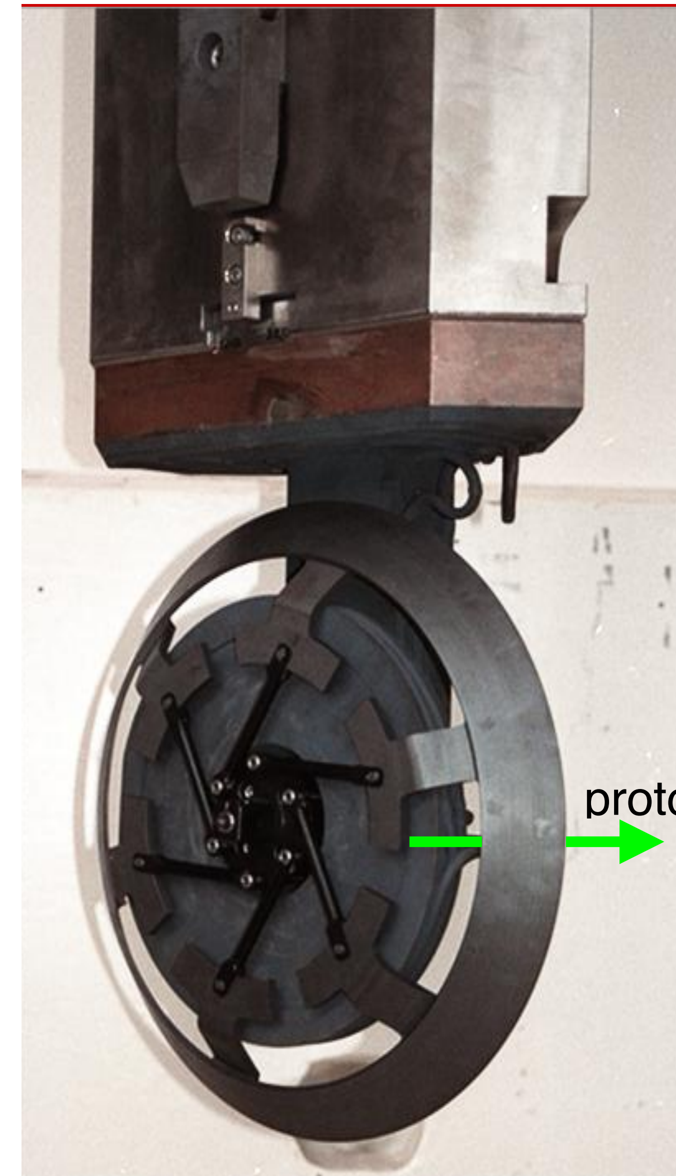
PSI Proton Accelerator HIPA



PSI UCN & Muon Production



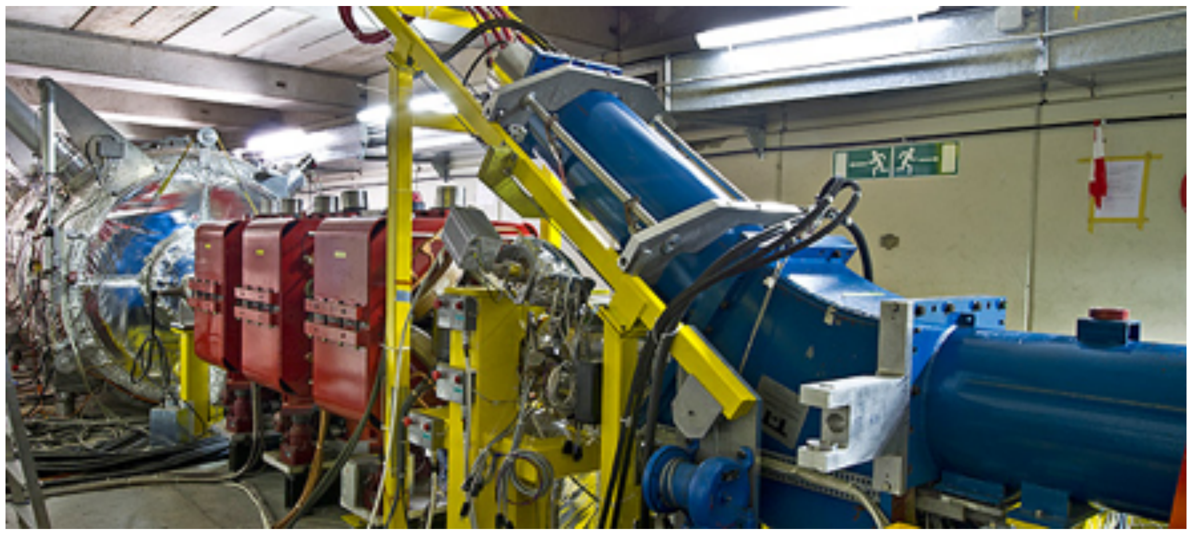
UCN spallation source

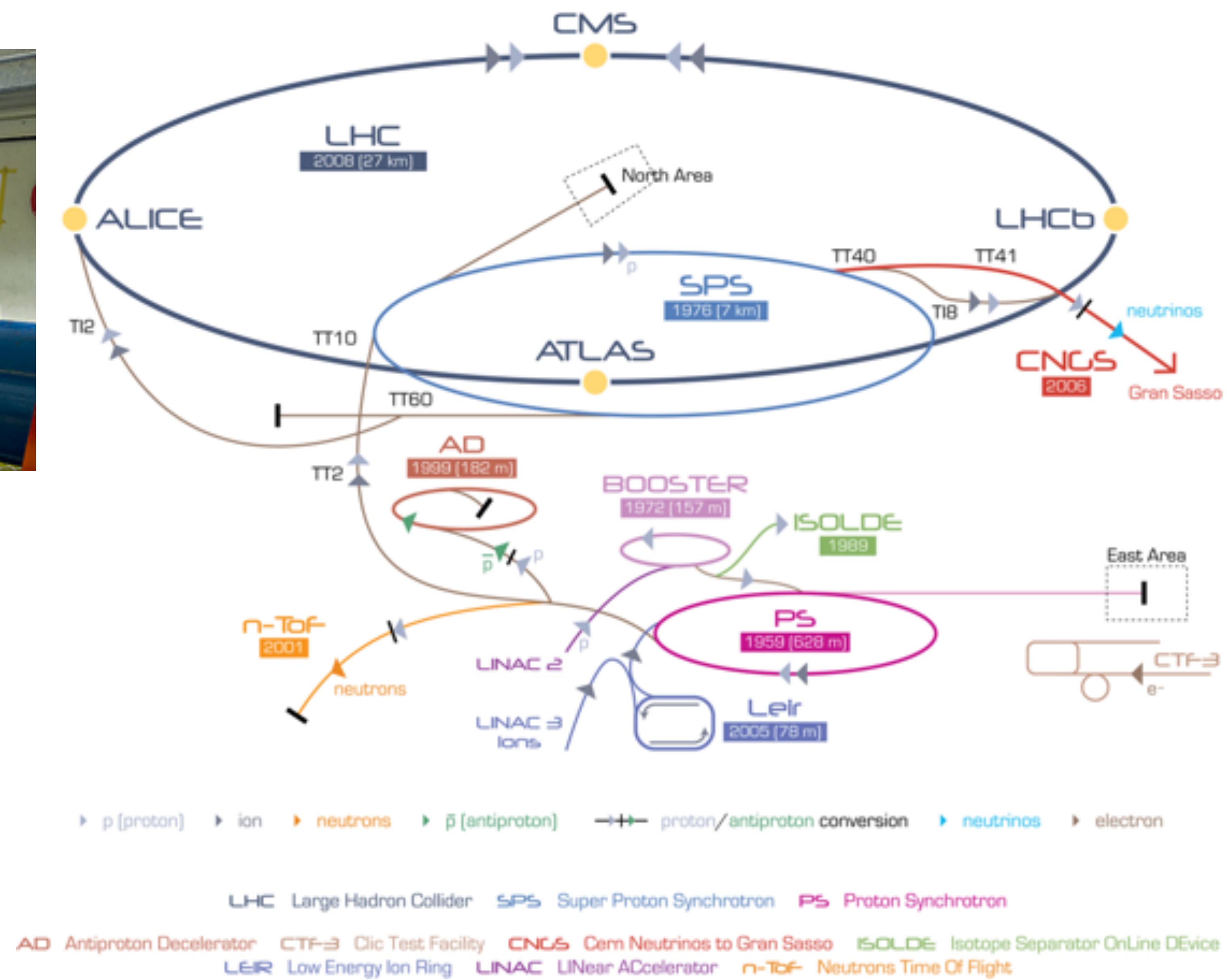


Rotating muon production target

- Strongest UCN & muon sources world-wide!

CERN Antiproton Decelerator

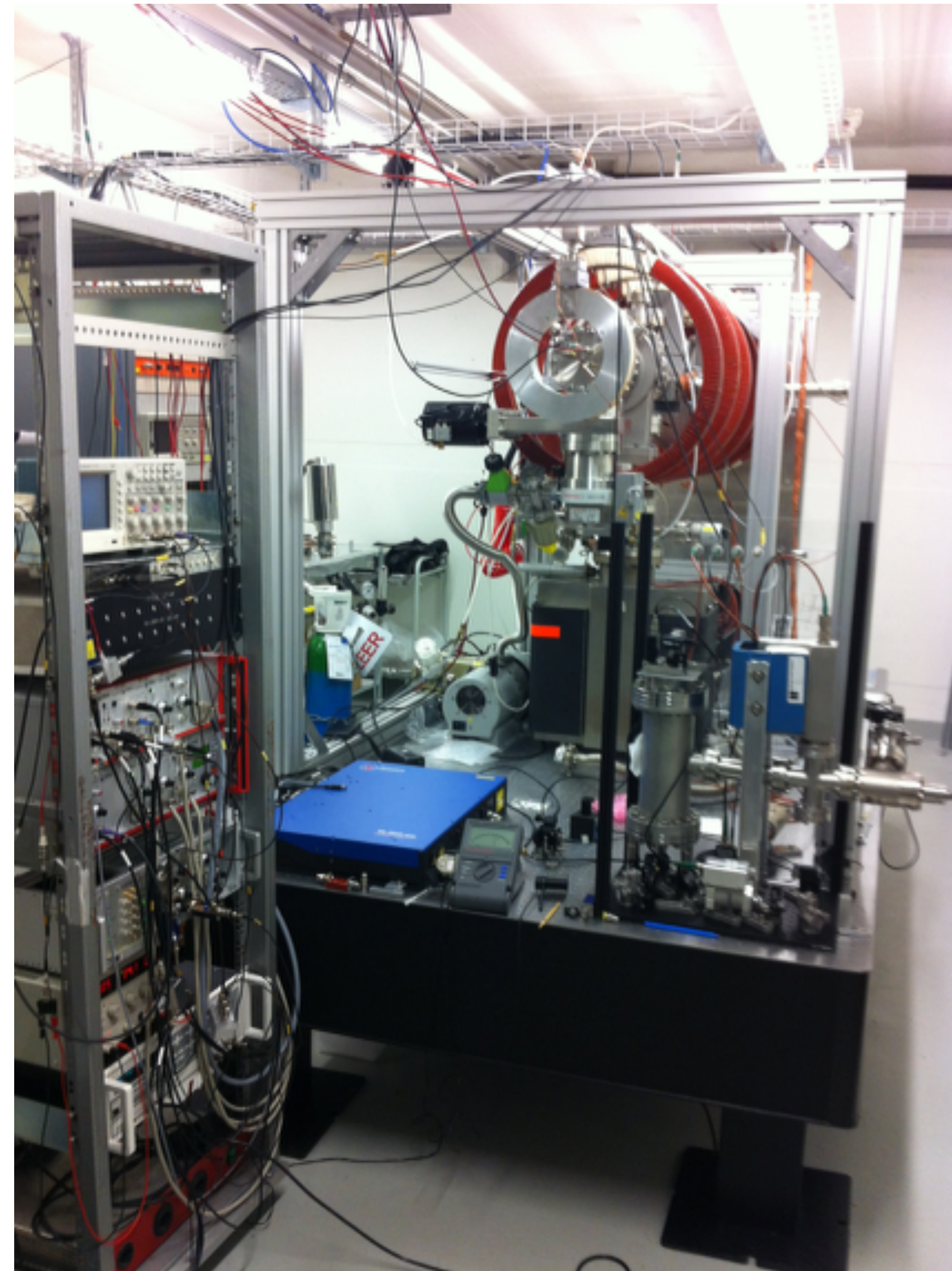




- Only place world-wide for low-energy antiprotons suitable for precision experiments
- From 2017: AD + ELENA → decelerate antiprotons from 5.3 MeV to 100 keV

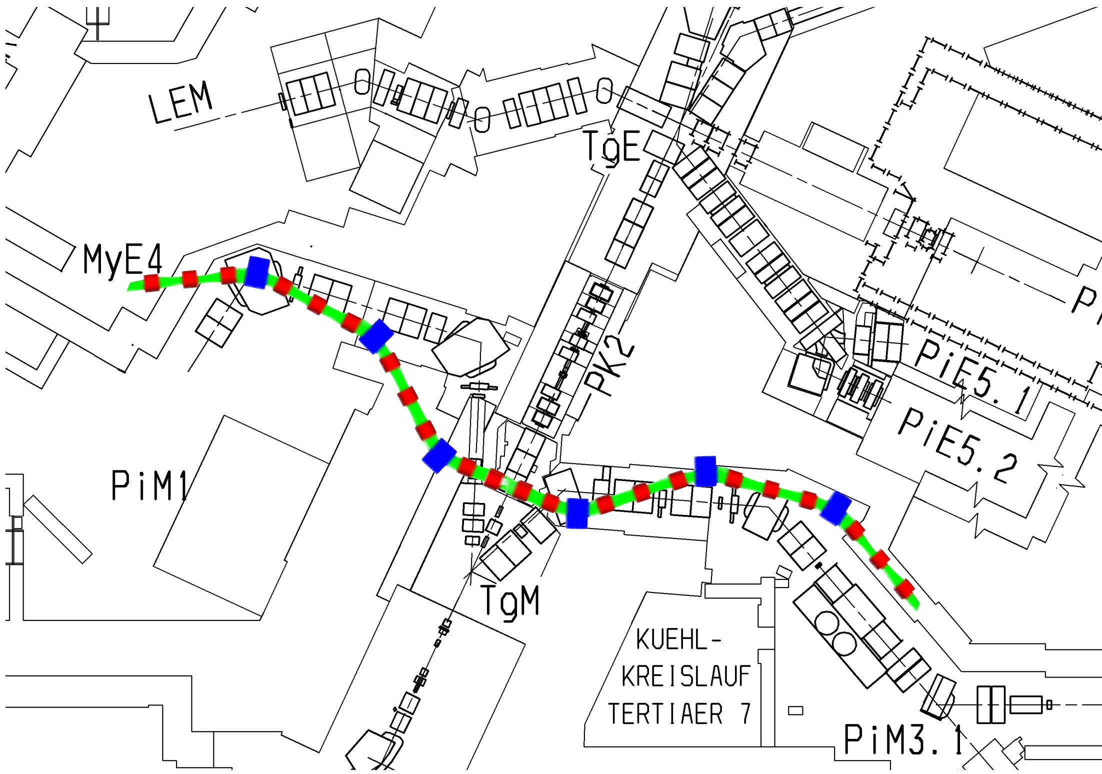
ETHZ Positrons

- Two 10 mCu ^{22}Na sources
- Positrons cooled and captured
- Continuous and pulsed beam
- Two positron beams for experiments



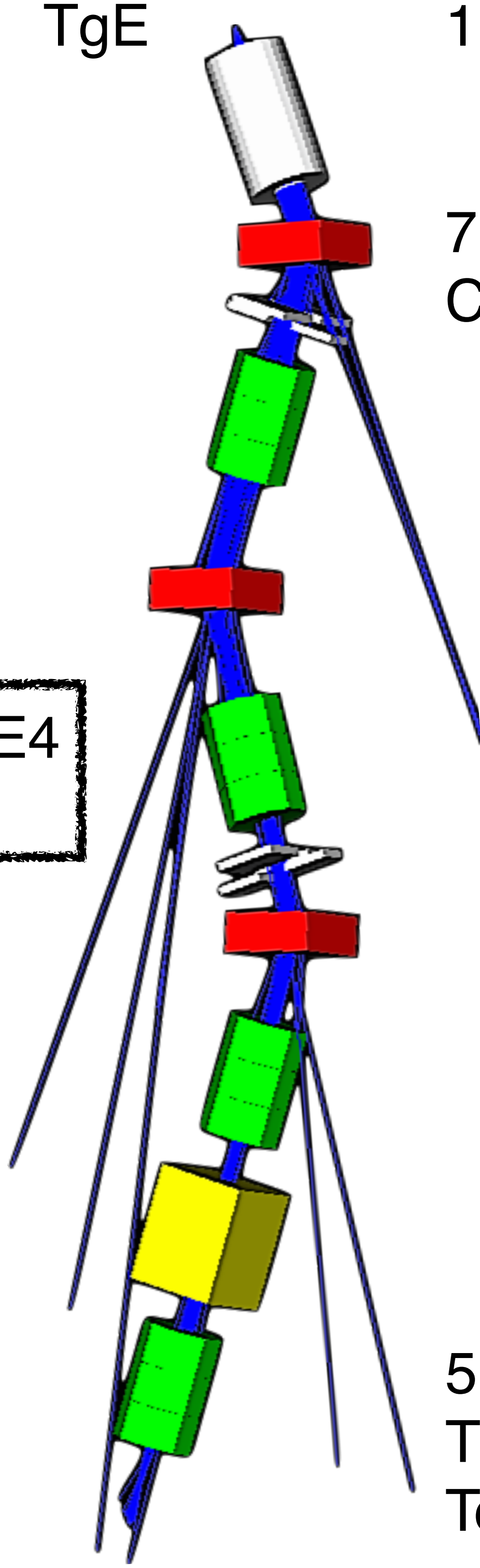
HiMB Project

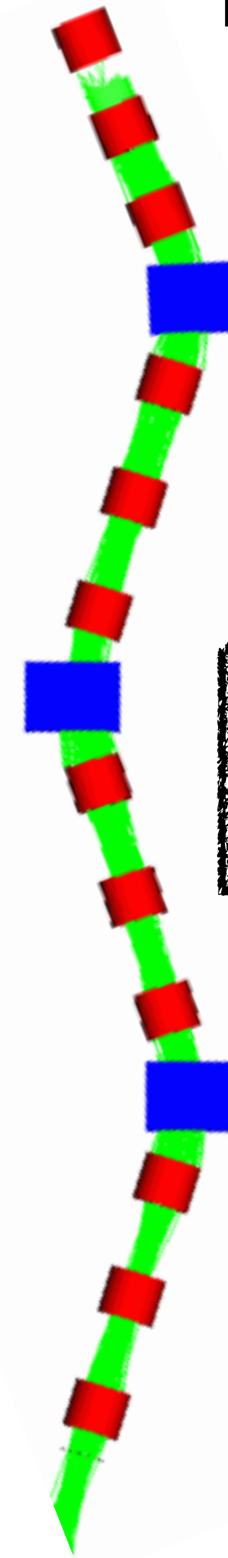
- Development of high-intensity beam by modification of existing target (TgM) and beam lines → goal of 10^{10} surface-μ^+/s
- New Target M Station (TgM*) with 20 mm thick graphite slab at 5°
- Split capture solenoid channel close to target
  - One side: particle physics (high-intensity)
  - Other side: materials science (high-intensity, high-polarization)



- Normal conducting solenoids
  - Front-end: radiation hard
  - Copy of existing µE4 solenoids
- First (simple) beam optics shows that $O(10^{10})$ μ^+/s can be transported (so far: µE4: 5×10^8 μ^+/s, πE5: 1×10^8 μ^+/s)

HiMB Beam Line





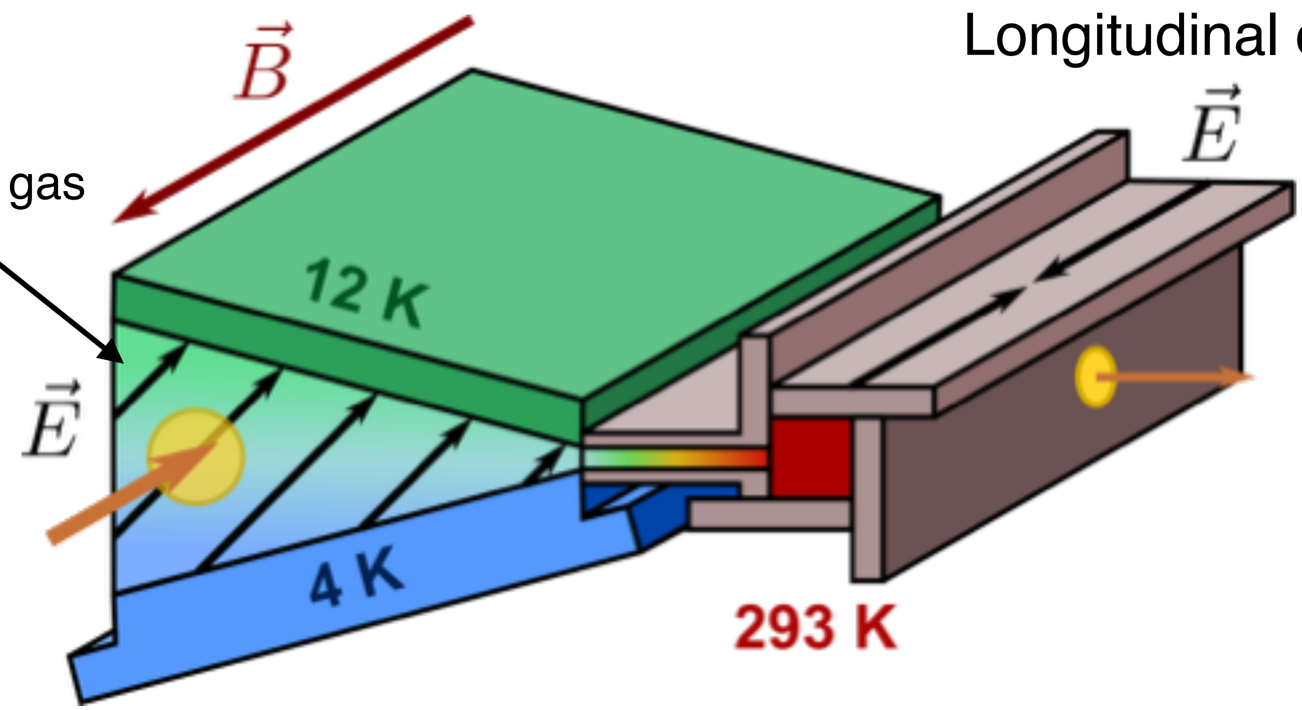
TgE		TgM*
1.2×10^{11} μ+/s	Source	1.3×10^{11} μ+/s
7.2×10^{9} μ+/s C ~ 6%	Capture	3.4×10^{10} μ+/s C ~ 26%
5×10^{8} μ+/s T ~ 7% Total ~ 0.4%	Transmission	1.3×10^{10} μ+/s T ~ 40% Total ~ 10%

Existing μE4 beam line

Proposed solenoid beam line

⇨ Gain due to high capture and transmission efficiency

muCool Project



Secondary μ⁺ beam
D ≈ 10 mm
E ≈ 4 MeV
continuous
polarized

Tertiary μ⁺ beam
D < 1 mm
E < 1 eV
pulsed, tagged
polarized

- Development of high-brightness ultralow-energy beam by stopping and compression of surface muon beam
- Reduction of phase space by factor 10^{10}

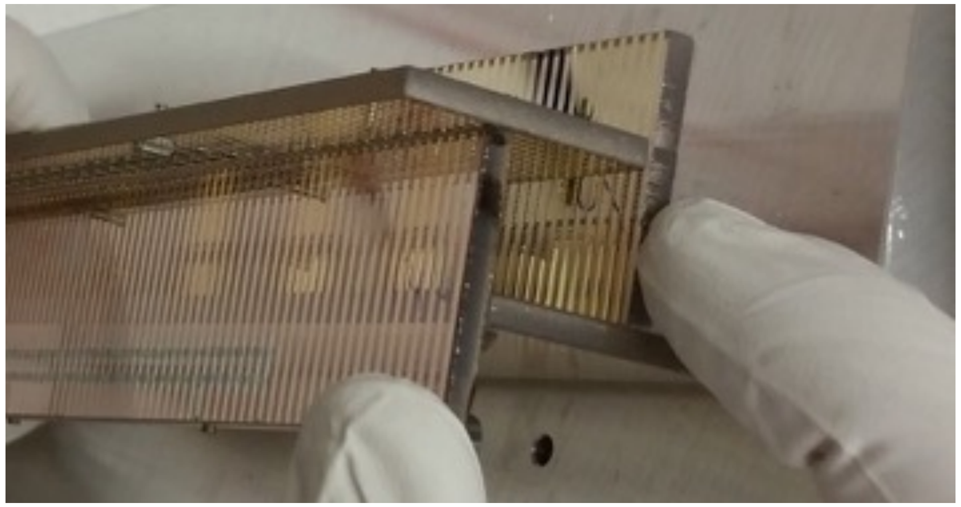
Muon swarm compression inside a helium gas target employing position-dependent muon drift velocity followed by extraction into vacuum.

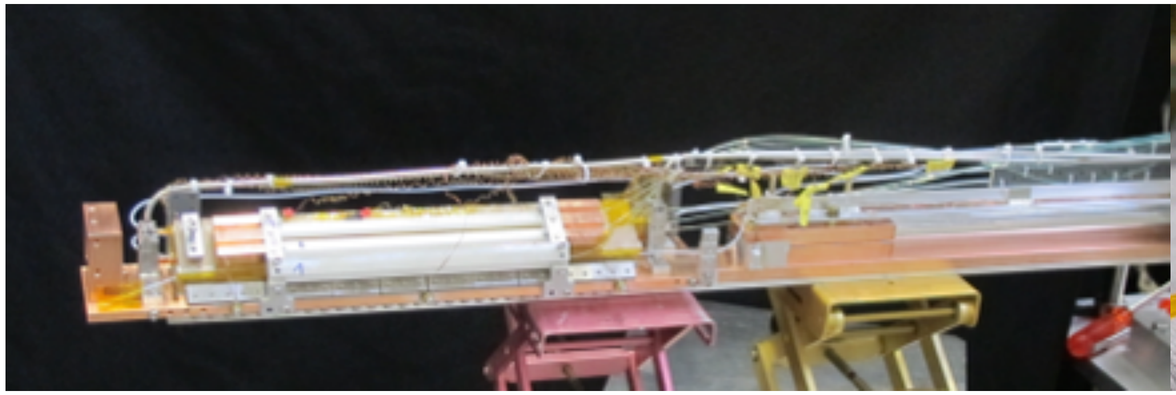
$$\vec{v}_D = \frac{\mu E}{1+\omega^2\tau^2}\left[\hat{E} + \omega\tau\hat{E}\times\hat{B} + \omega^2\tau^2(\hat{E}\cdot\hat{B})\hat{B}\right]$$

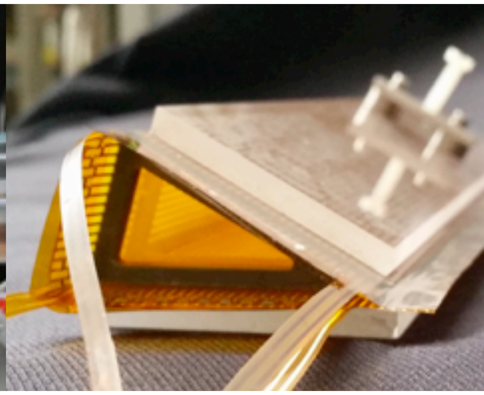
$\mu = e\tau/m$: mobility
$\tau = \tau(p,T)$: time between collisions
$\omega = eB/m$: cyclotron frequency

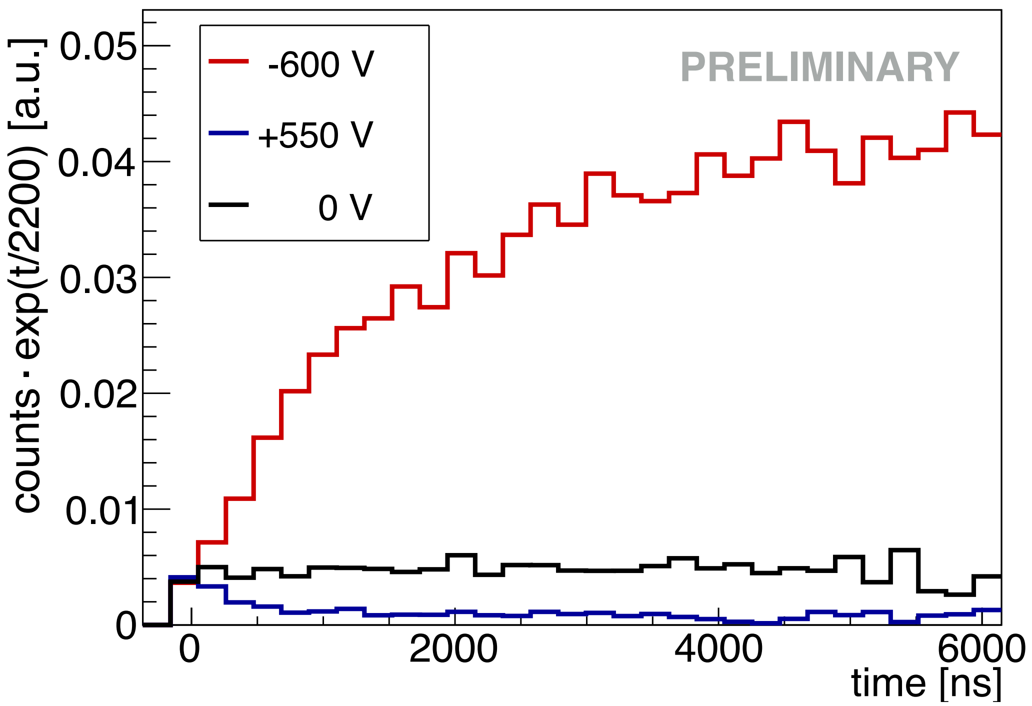
D. Taqqu, Phys. Rev. Lett. **97**, 194801 (2006)

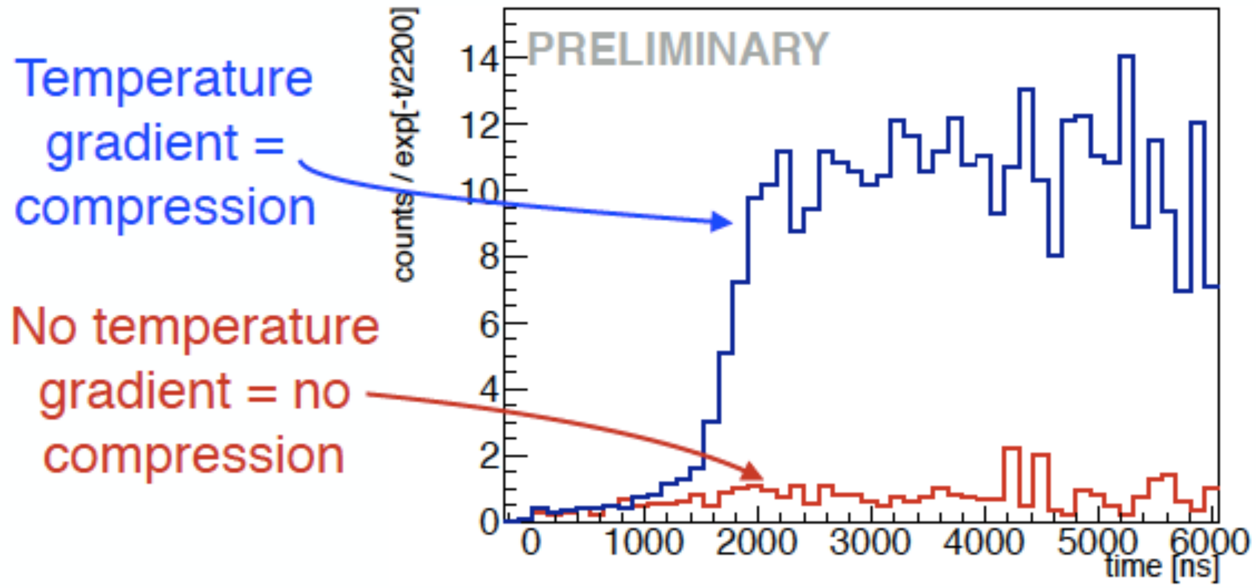
muCool Results











- Longitudinal compression demonstrated experimentally
- Transverse compression demonstrated experimentally
- Next steps: Combined transverse/ longitudinal compression, extraction into vacuum

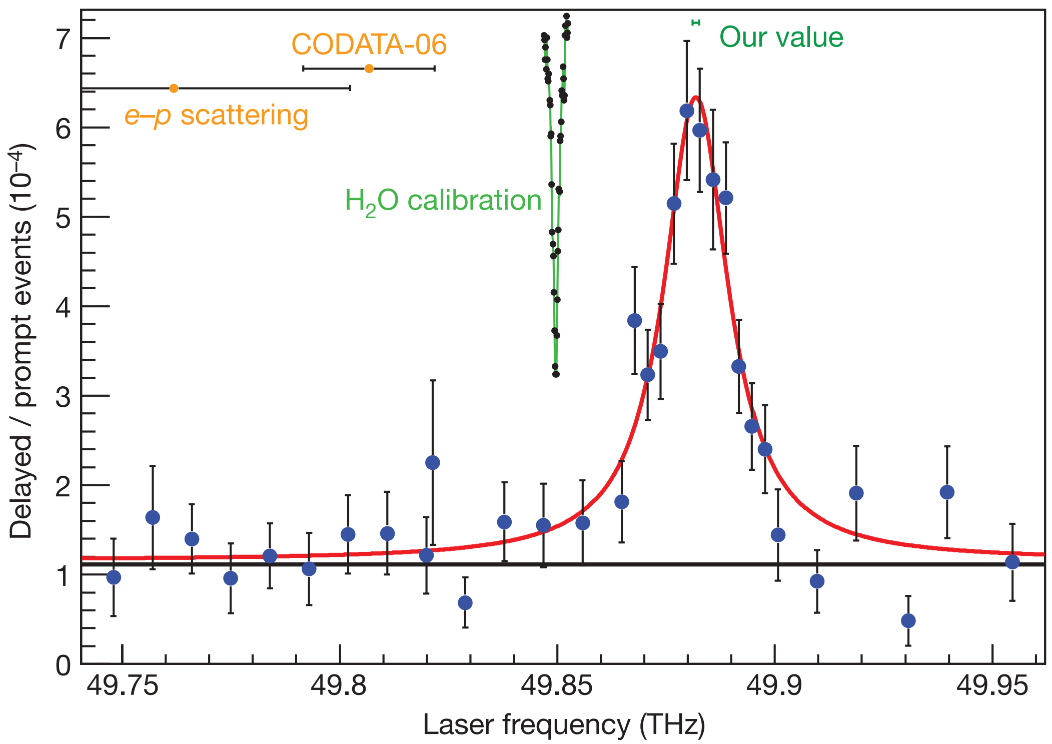
Bao et al., Phys. Rev. Lett. **112**, 224801 (2014)

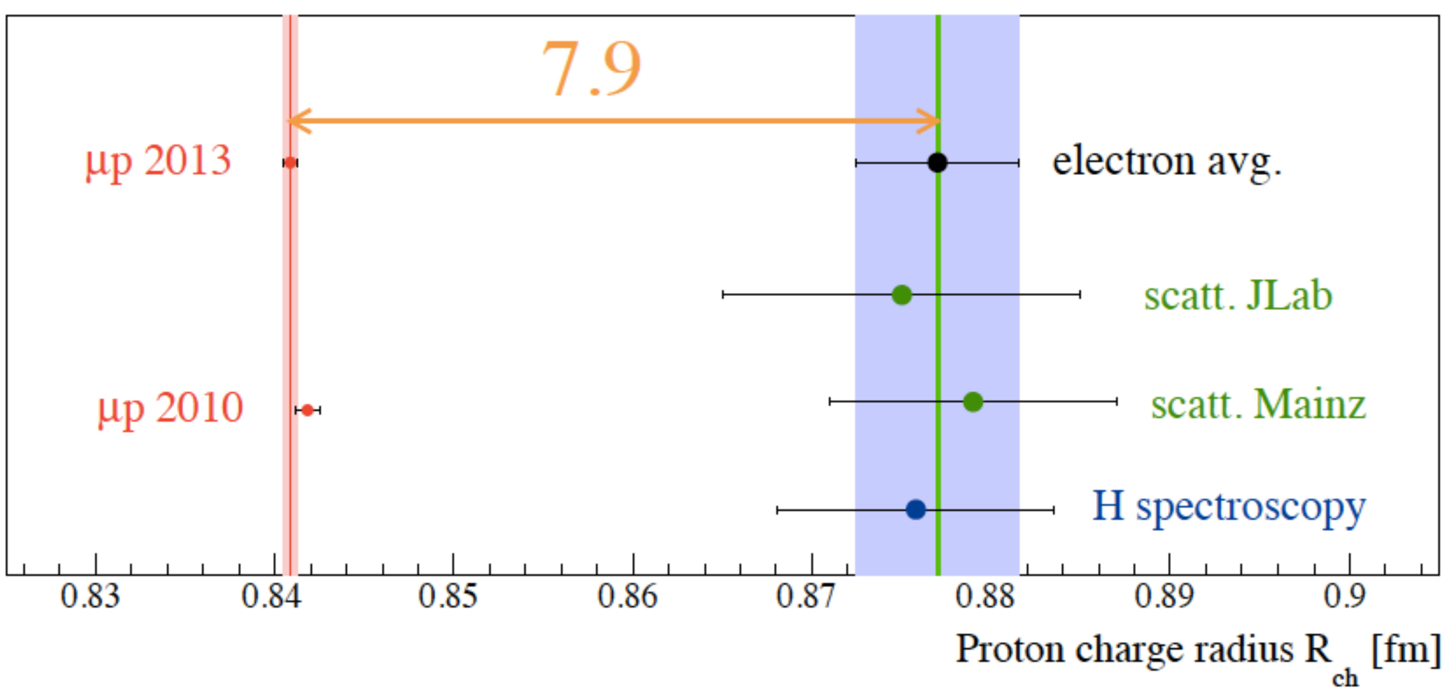
muCool Beam Applications

- Experiments needing a high-brightness muon beam:
  - Production of high-brightness muonium beam
    - Measurement of gravitational interaction of muonium
    - Measurement of 1*s* - 2*s* energy interval in muonium
  - Muon g-2, muon EDM
  - Surface material science (µSR technique)

Spectroscopy of Muonic Atoms

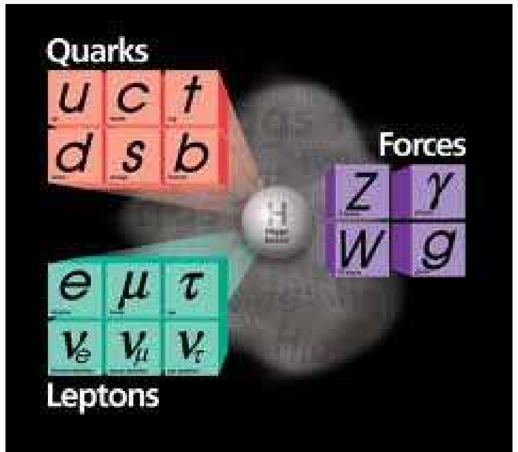
- Atomic physics techniques for particle/nuclear physics questions
- Measurement of proton radius using muonic hydrogen. Strong enhancement w.r.t. ordinary hydrogen: $(m_\mu/m_e)^3$
- Proton radius very discrepant from measurements with electrons!





Pohl et al., Nature **466**, 213 (2010)
Antognini et al., Science **339**, 417 (2013)

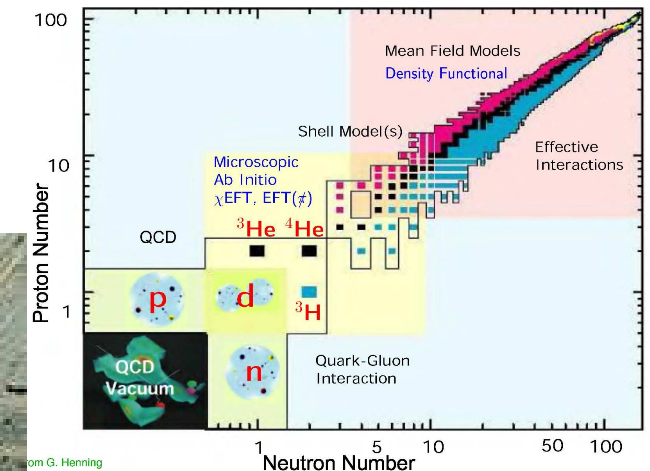
Landscape of Muonic Atoms



Test of H energy levels
Bound-state QED

Mu= $\mu^+ e^-$

Ps= $e^+ e^-$



New physics?

Scattering

$e + p \rightarrow e + p$

$e + d \rightarrow e + d$

$\mu + p \rightarrow \mu + p$

$\gamma + p \rightarrow \gamma + p$

...

r_p, r_d, r_{He}

EFT, χpt, lattice

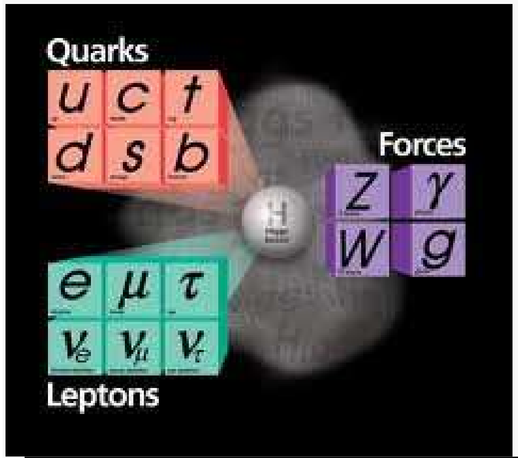
few-nucleon th.

H, He spectroscopy

μp, μd, $\mu\,\mathrm{He}^+$ (2S-2P)

Fundamental constants

Landscape of Muonic Atoms



Test of H energy levels
Bound-state QED

Mu= μ^+e^-
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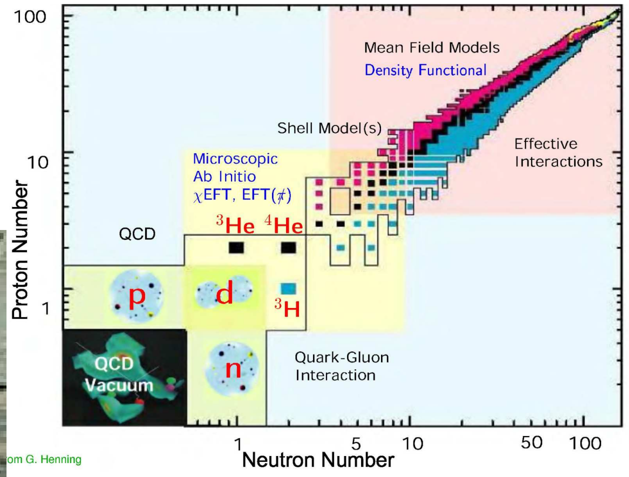


New physics?
Parity violation?

r_p, r_d, r_{He}
EFT, χpt, lattice
few-nucleon th.

high-Z radii
quadrupole mom.
mean-field nucl. th.

magnetic radii

Scattering
$e + p \to e + p$
$e + d \to e + d$
$\mu + p \to \mu + p$
$\gamma + p \to \gamma + p$
$e + Z \to e + Z$
...

H, He spectroscopy

μp, μd, $\mu\,\mathrm{He}^+$ (2S-2P)
high-Z muonic atoms (radioactive)
HFS in μp and $\mu\,\mathrm{He}^+$

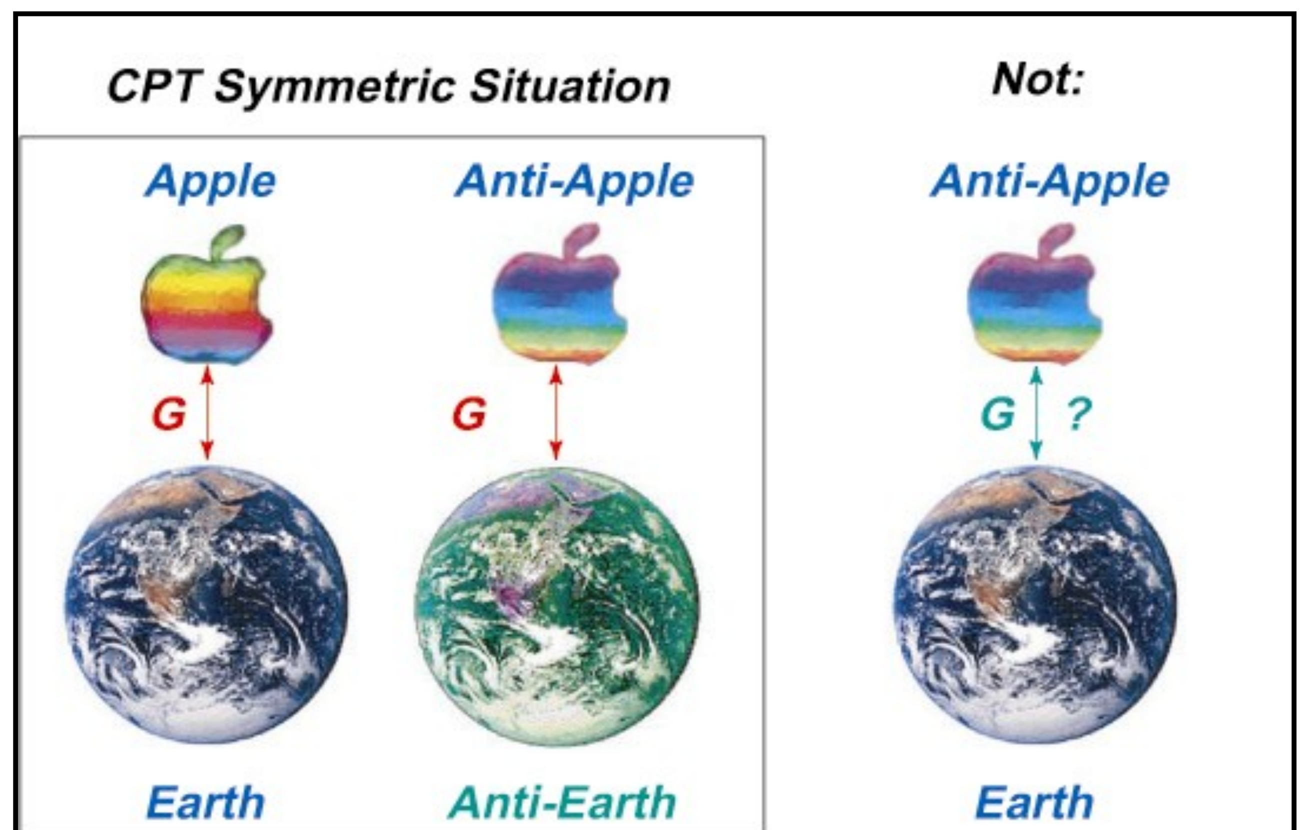
Fundamental constants

Antimatter Gravity

- Test of the Weak Equivalence Principle involving antimatter
- Direct tests so far only for matter systems (apart from one antihydrogen result: $-65\,g < \bar{g} < 110\,g$)
- Validity for antimatter inferred from heavily debated indirect arguments

- Candidates for measurements:
  - Antihydrogen (AEgIS, GBAR)
  - Positronium (spectroscopy, interferometry)
  - Muonium (spectroscopy, interferometry)

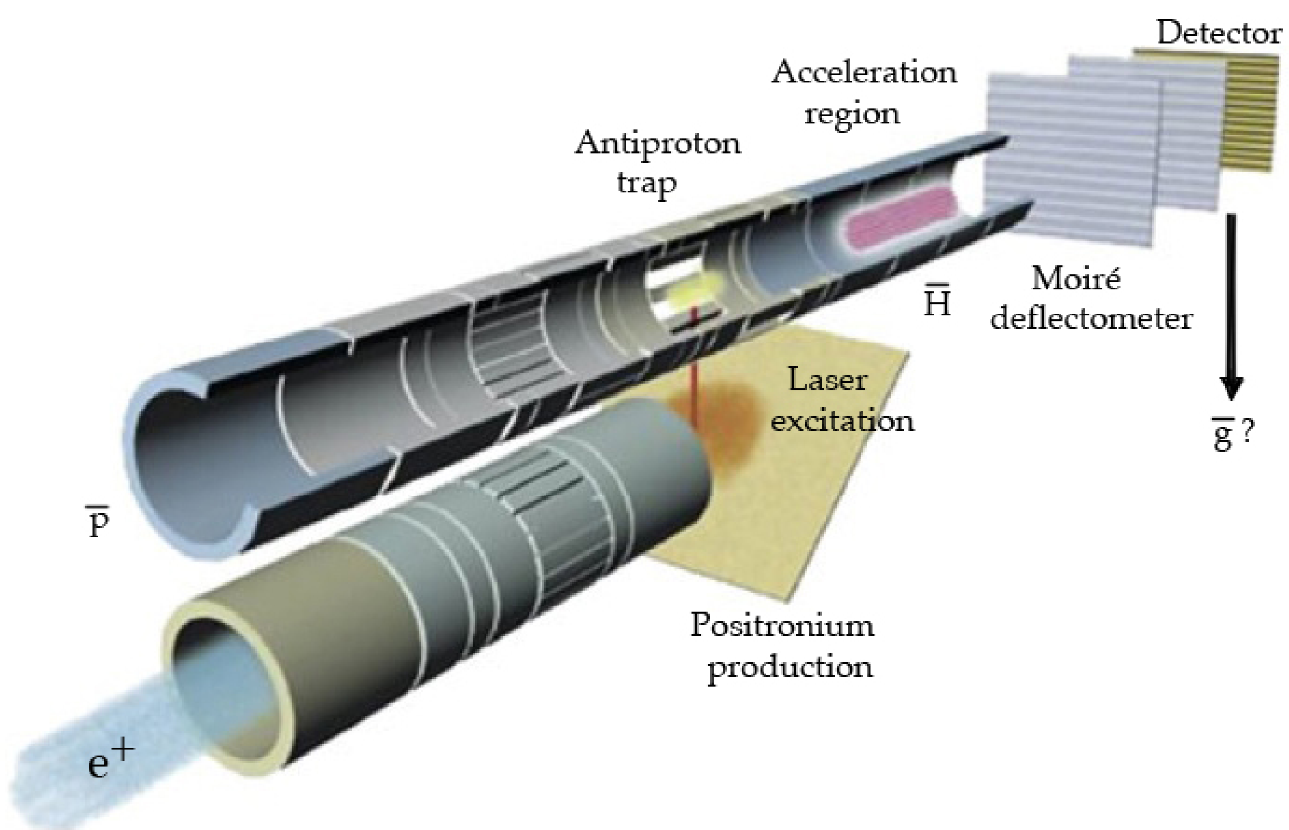
- Potential synergies between different groups?

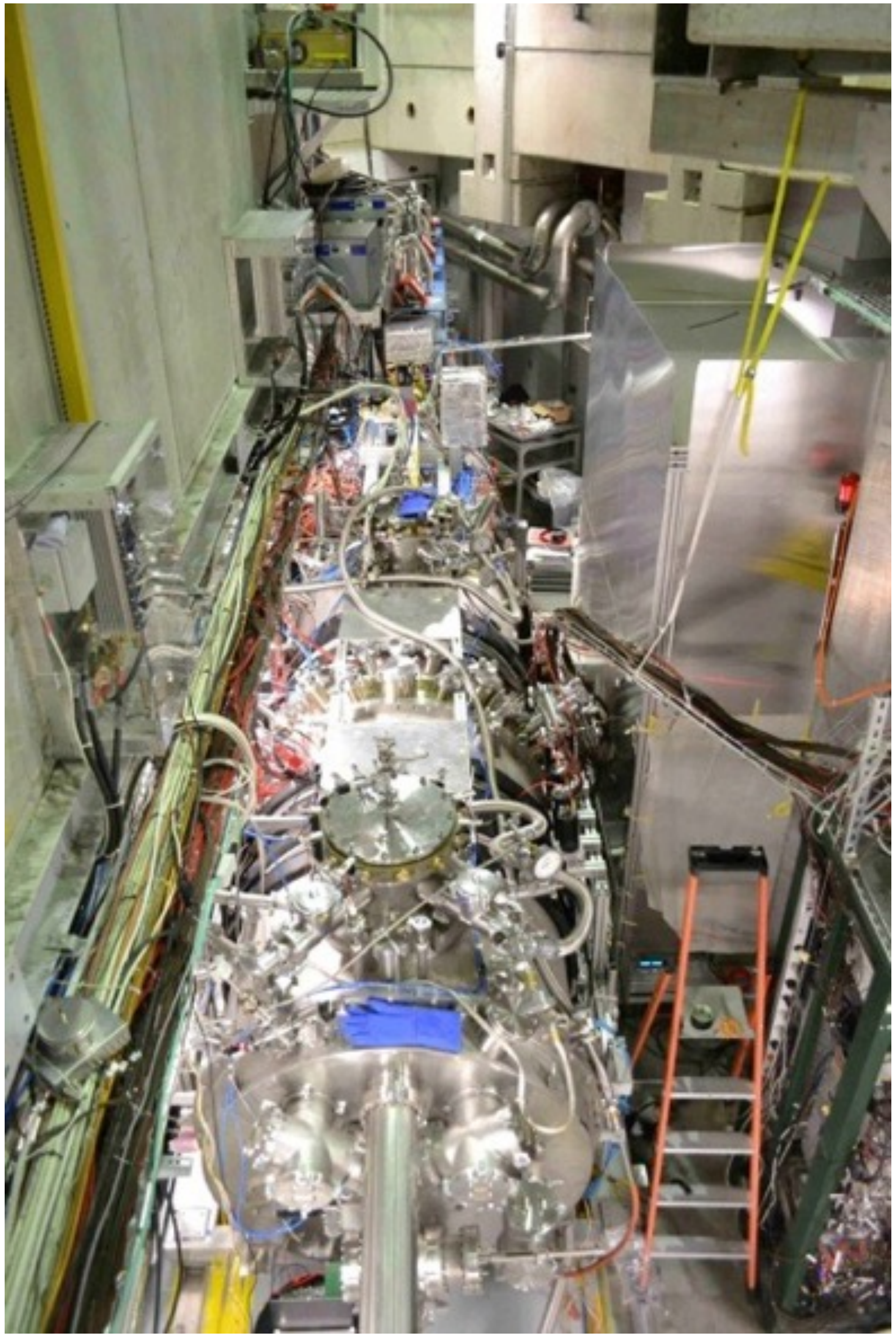


Nieto and Goldman, Phys. Rep. **205**, 221 (1991)
Amole et al., Nat. Comm. **4,** 1785 (2013)

AEgIS Experiment at CERN

- Measurement of gravitational acceleration $\bar{g}$ for antihydrogen with 1% accuracy
- Test of weak equivalence principle (WEP) for antimatter
- First direct measurement of $\bar{g}$





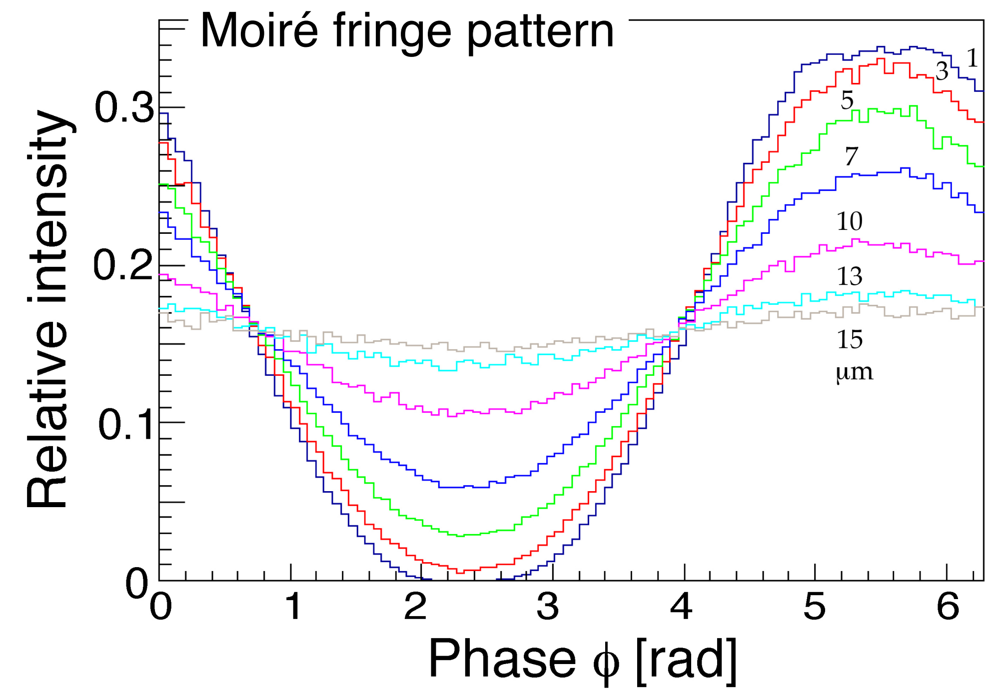
Aghion et al., NIM B **362**, 86 (2015)
Testera et al., Hyp. Int. **233**, 13 (2015)
Pistillo et al., Hyp. Int. **233**, 29 (2015)

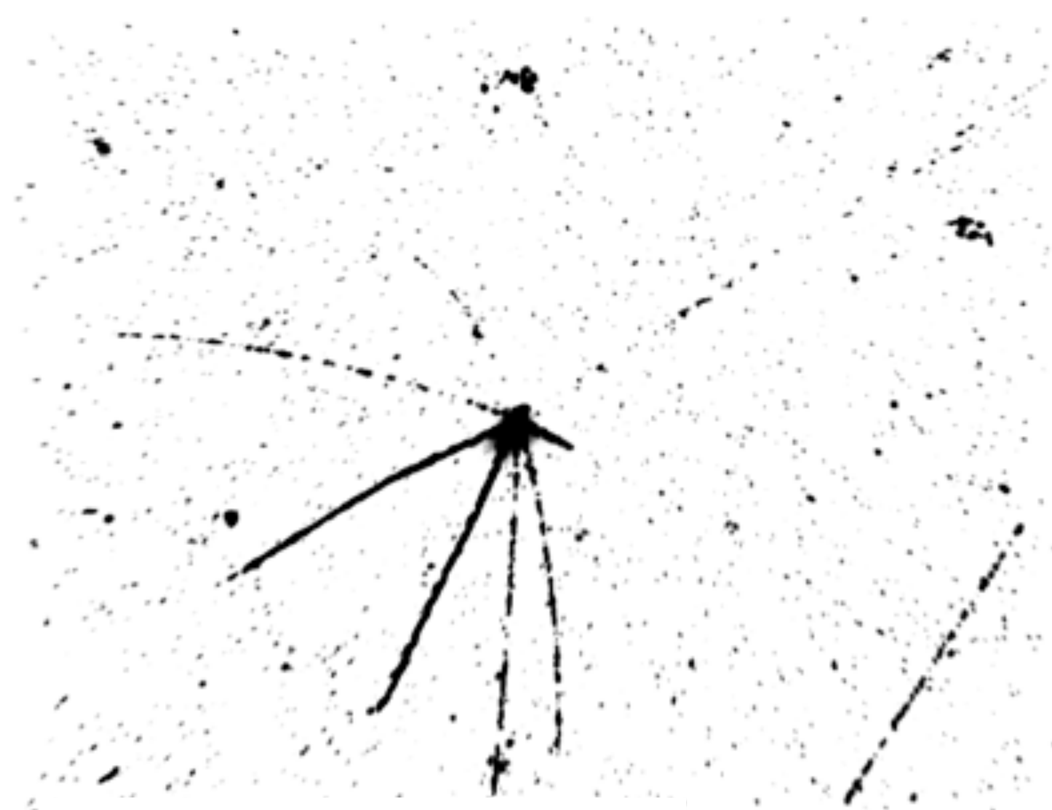
Moiré Deflectometer

- The two gratings of deflectometer generate fringe pattern

- Less detected antihydrogen atoms needed if vertices detected with micrometer resolution
→ emulsion detectors

- Bern responsible for the emulsion detector of the deflectometer





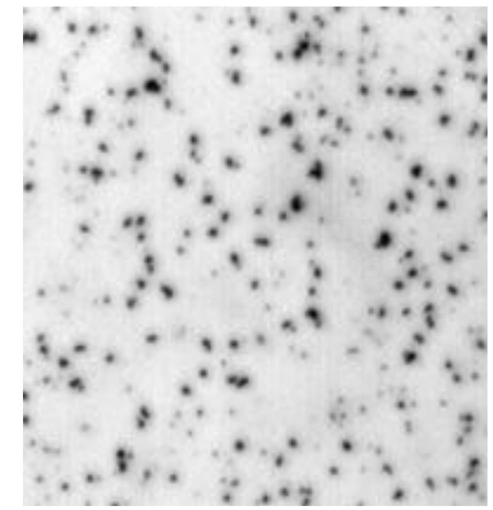
Antiproton annihilation vertex

Aghion et al., JINST **8**, P08013 (2013)
Aghion et al., Nature Comm. **5**, 4538 (2014)

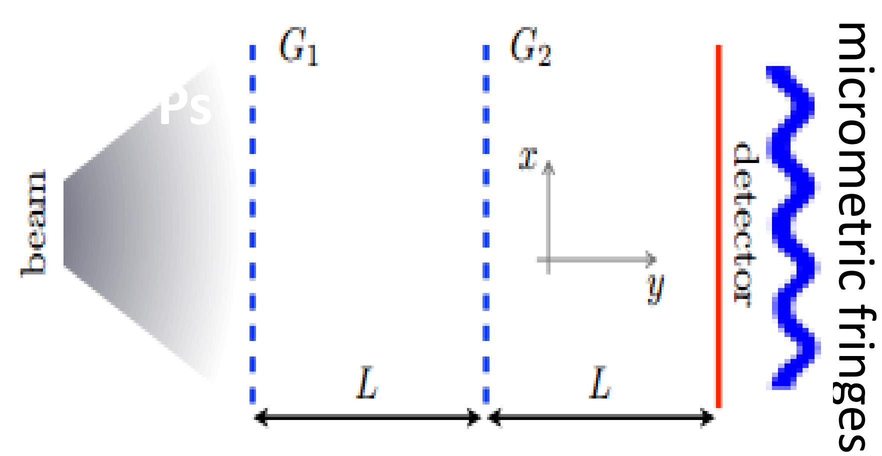
QUPLAS project

- Interferometry of positrons and positronium using emulsion detectors
- First interferometry with antimatter
- Interferometer under construction
- First results summer 2016

15 keV positron detected on 50x50 μm² emulsion

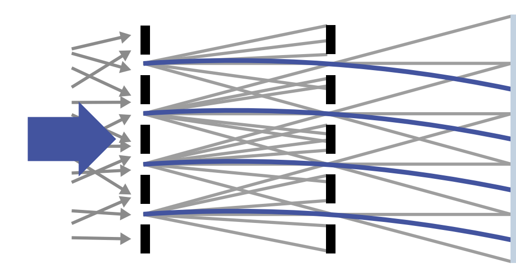


Talbot-Lau interferometer

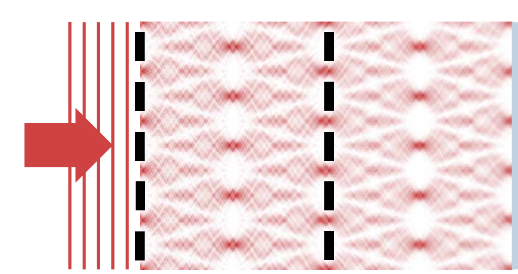


T = 10 keV, L = 33 cm
→ 2 μm fringes

Deflectometer



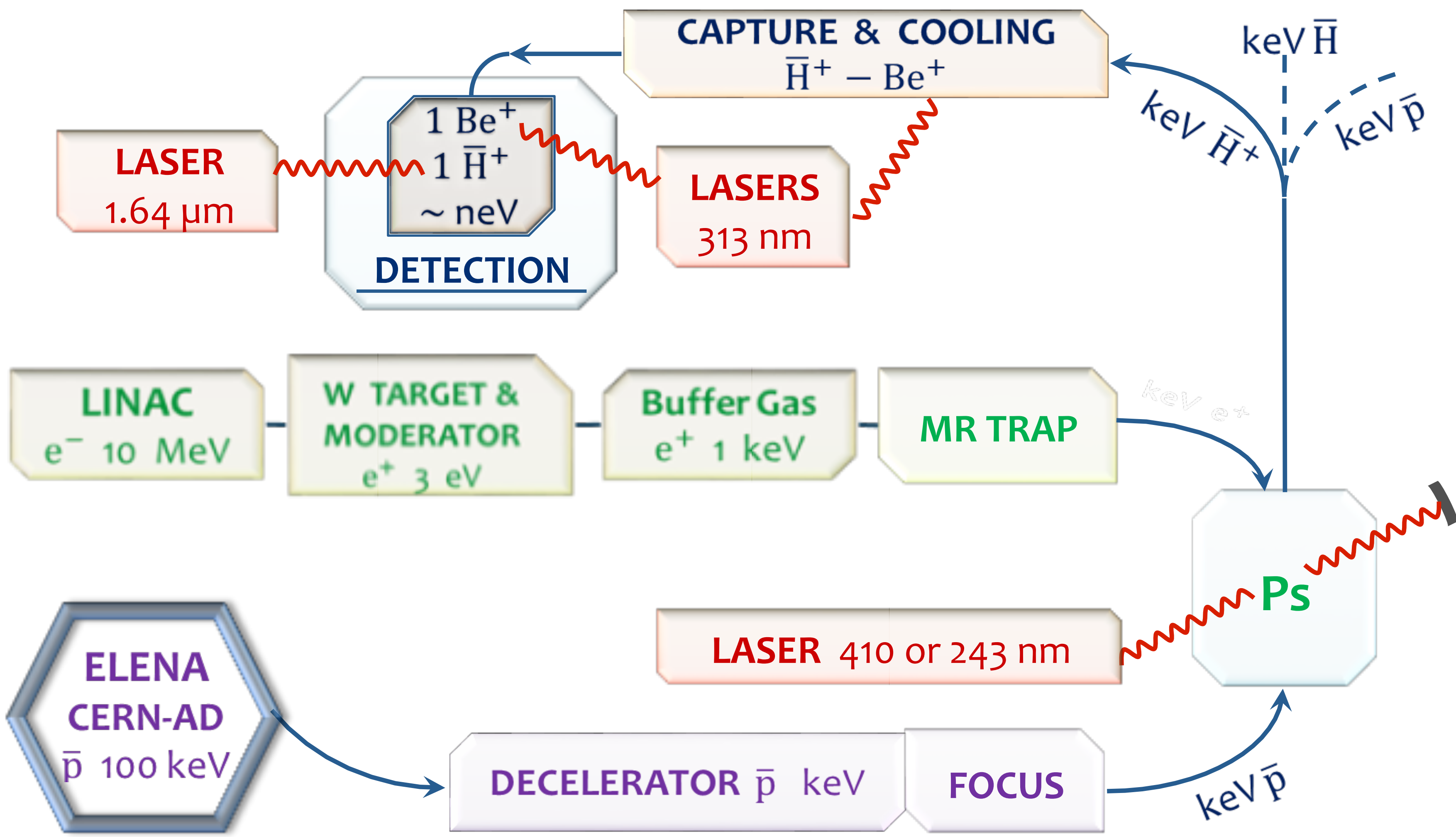
Interferometer



Sala et al., J. Phys. B **48**, 195002 (2015)
Aghion et al., Nature Comm. **5**, 4538 (2014)

GBAR Experiment at CERN

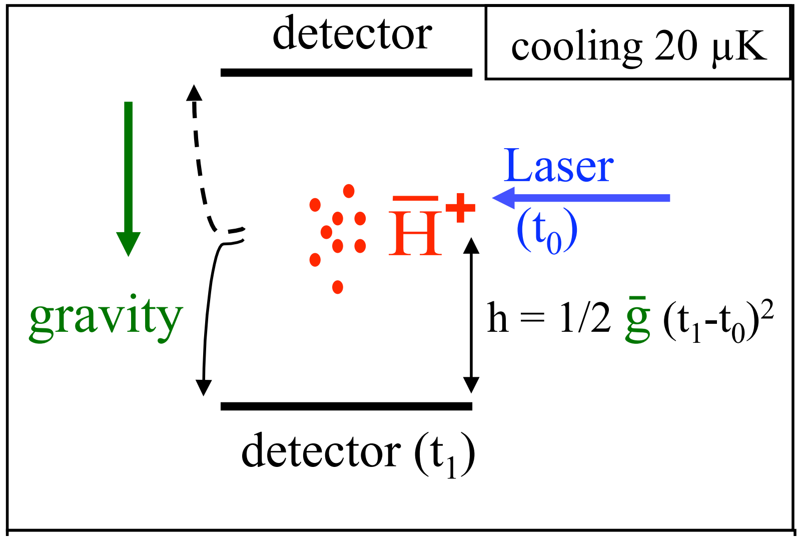
- Measurement of gravitational acceleration $\bar{g}$ for antihydrogen with 1% accuracy
- First antiprotons from ELENA in summer 2017



Perez et al., Hyp. Int. **233**, 21 (2015)
gbar.web.cern.ch

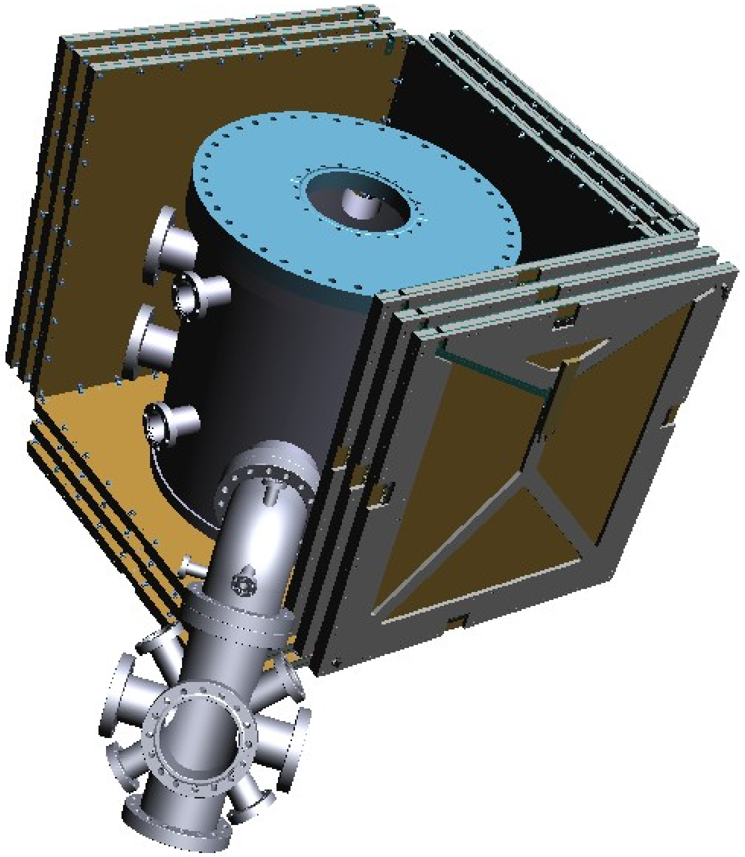
Free-Fall Detector

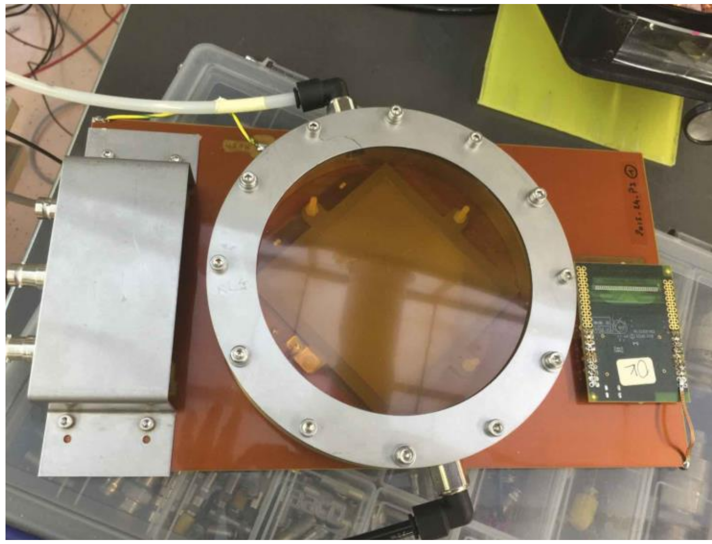
Walz and Hänsch, General Rel. and Grav. **36**, 561 (2004)



- Measure time-of-flight after photo-detachment of positron
- ETHZ involved in construction of micromegas detector ($\sigma_t < 150$ µs, $\sigma_x < 1$ mm)

Free-fall chamber

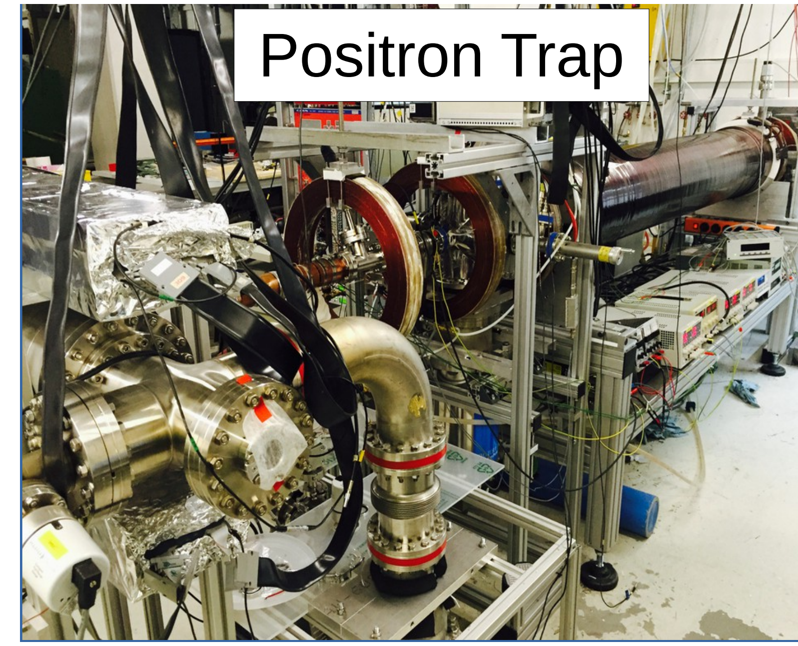


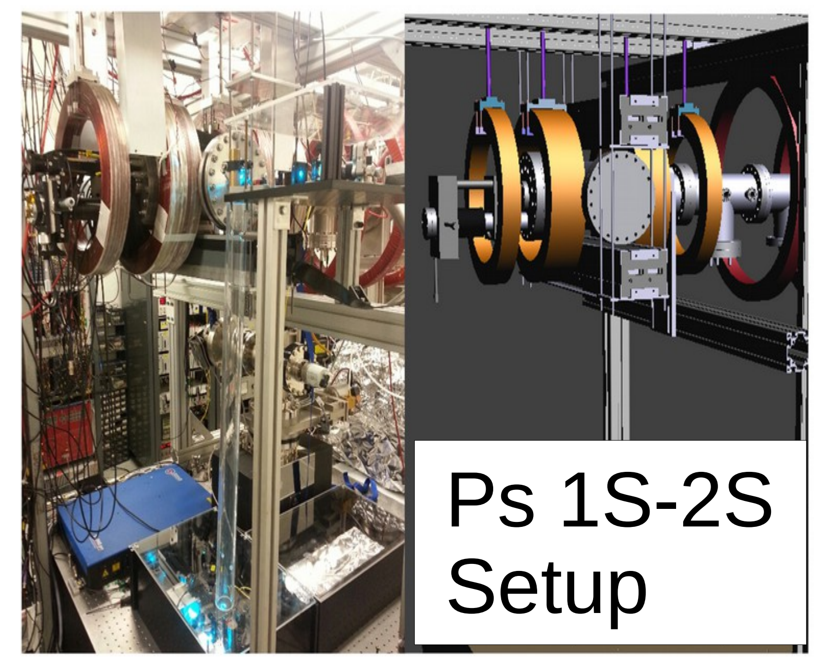


Micromegas prototype
~120 µm resolution measured

Positronium at ETHZ

- Measurement of 1*s*-2*s* energy interval
  - Bound-state QED test at ppb level (no finite-size, no nuclear effects)
  - Gravitational interaction of Ps
- Measurement of 2s HFS in positronium
- Deceleration of Rydberg positronium
- Measurement of quantum gravitational states (in analogy to neutrons)
- Material science with Ps (determination of porosity)

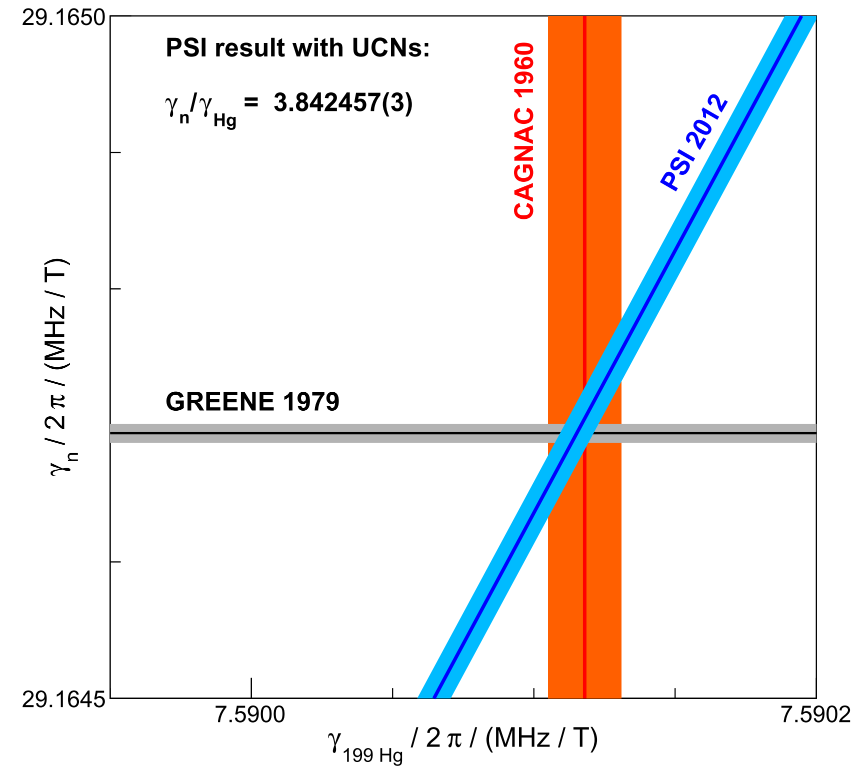




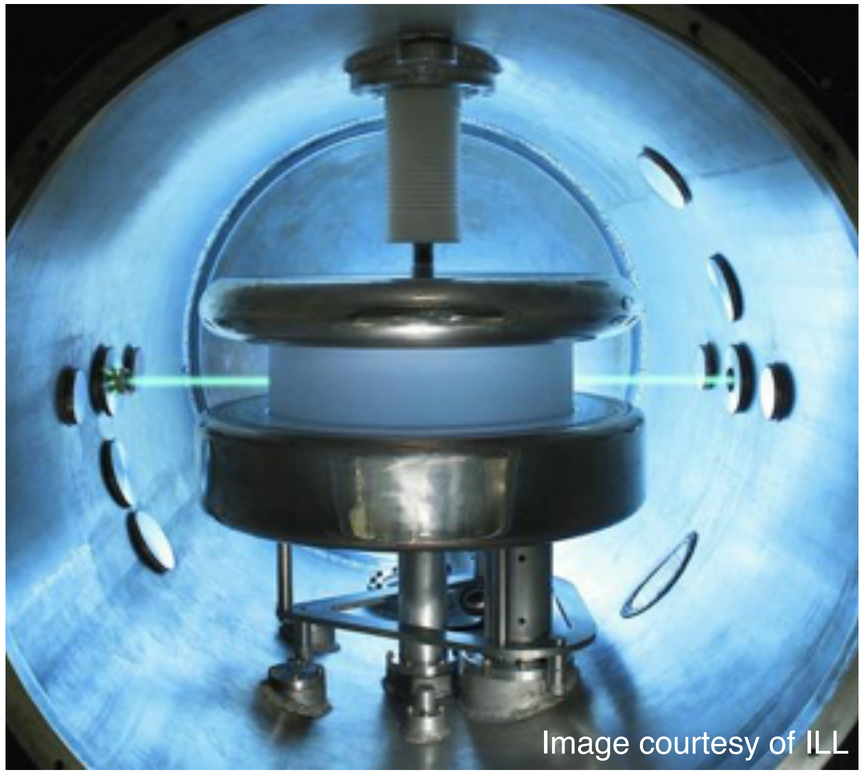
Cooke et al., Hyp. Int. **223**, 67 (2015)
Crivelli et al., Adv. High Energy Phys **2015**, 173572 (2015)
Crivelli et al., Int. J. Mod. Phys. Conf. Ser. **30**, 1460257 (2014)
Milina et al., Nature Comm. 4922 (2014)
Nesvizhevsky et al., Nature **415**, 297 (2002)

UCN at PSI: Magnetic Moments

- Alternative measurements with nEDM apparatus
- Precision measurement of ratio of neutron to ^{199}Hg magnetic moment
- Performance test of nEDM apparatus
- Control of systematic effects relevant to nEDM analysis



$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lightshift}} \right)$$



Afach et al., Phys. Lett. B **739**, 128 (2014)

UCN at PSI: Spin-Dependent Forces

- Polarized UCN ideal tool to search for new spin-dependent forces mediated by axion-like particles (ALPS)
- Interaction between UCN and nucleons of electrode
- Interaction leads to pseudo-magnetic field and thus change in precession frequency

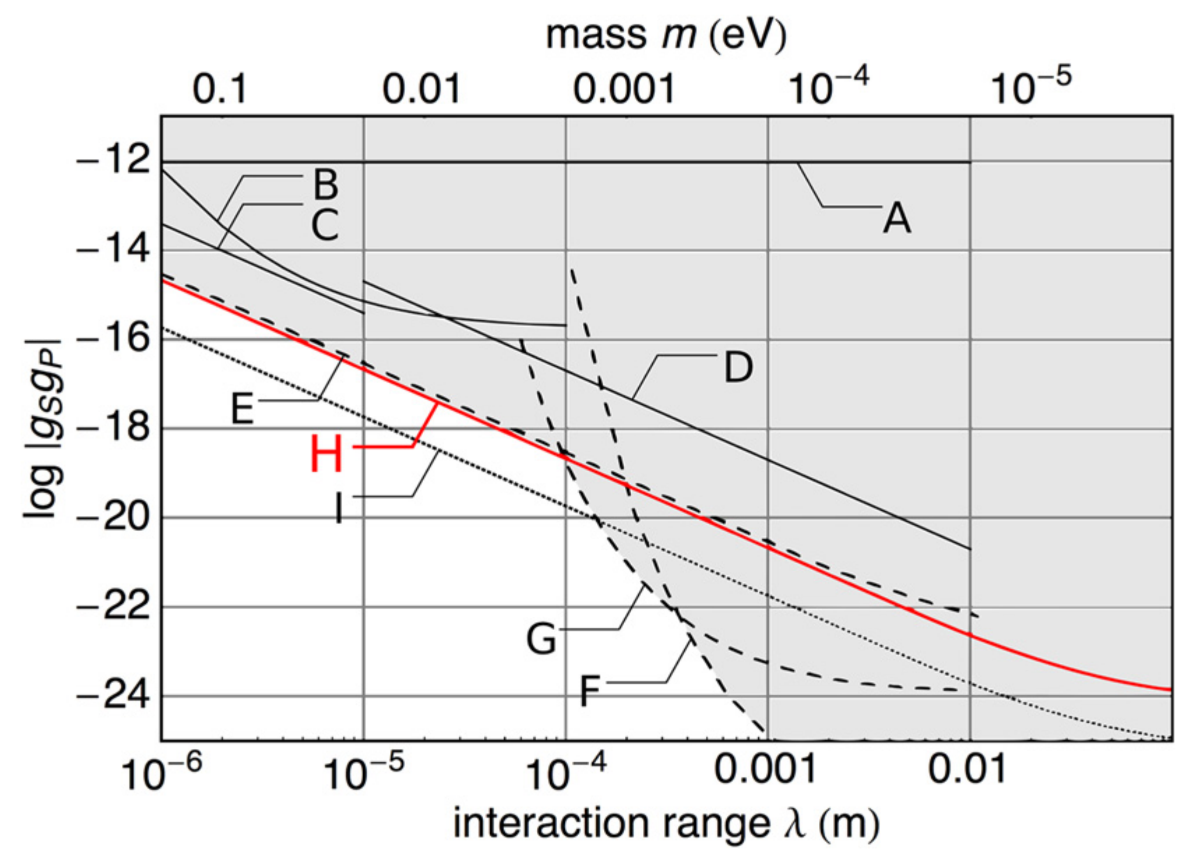
$$V(\vec{r}) = g_s g_p \frac{(\hbar c)^2}{8\pi m c^2} (\vec{\sigma} \cdot \hat{\vec{r}}) \left(\frac{1}{r\lambda} + \frac{1}{r^2} \right) e^{\frac{-r}{\lambda}}$$

Afach et al., Phys. Lett. B **745**, 58 (2015)

MACROSCOPIC FORCES

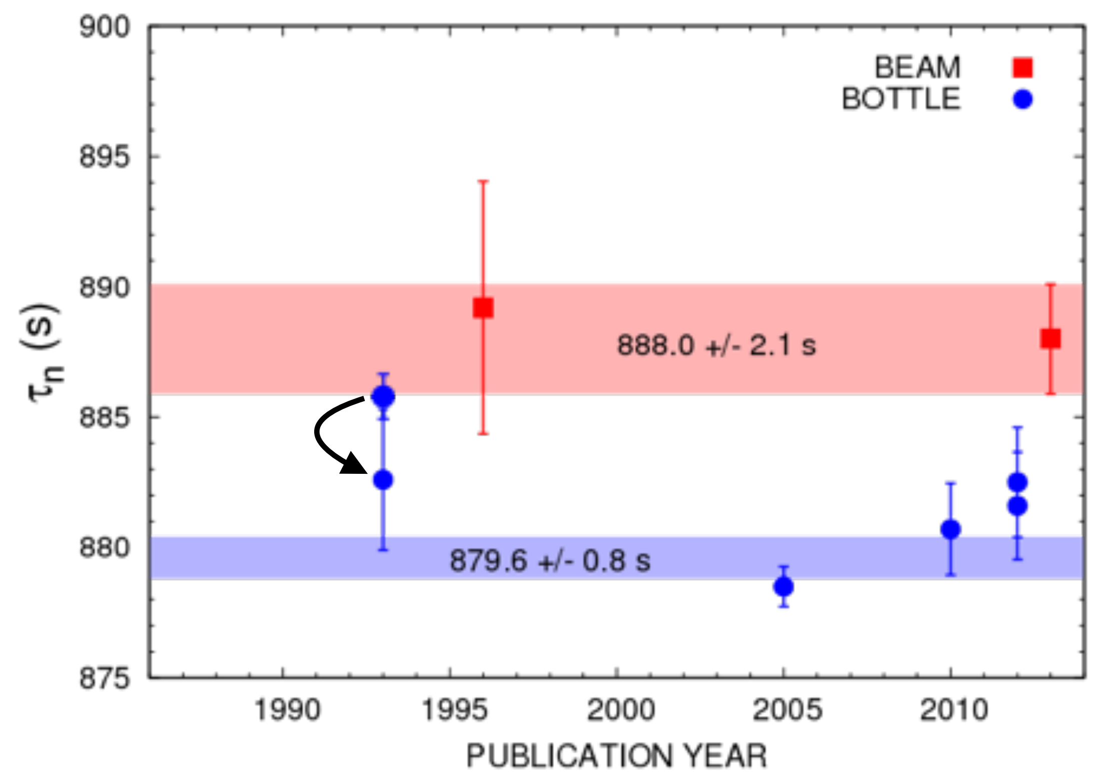
Very light, weakly coupled bosons are occasionally suggested in the literature, for example, axions,[1] familons,[2] majorons,[3] arions,[4] and spin-1 antigravitons.[5] Such particles must couple very weakly to ordinary matter to have eluded detection thus far. A boson with small enough mass (say, 10^{-5} eV) would have a macroscopic Compton wavelength (say, 2 cm) and would mediate a force on laboratory scales. Even if very weakly coupled at the single-particle level, a macroscopic body with 10^{23} constituents could produce a measurable, coherent light-boson field.

Moody and Wilczek, PRD **30**, 130 (1984)



UCN at PSI: Neutron Lifetime

- Recent major discrepancy in neutron lifetime measurements resolved
- Currently tension between measurements of neutron lifetime through storage and in-beam methods
- World-leading UCN source at PSI ideal place for updated measurement
- Experimental approach currently under investigation



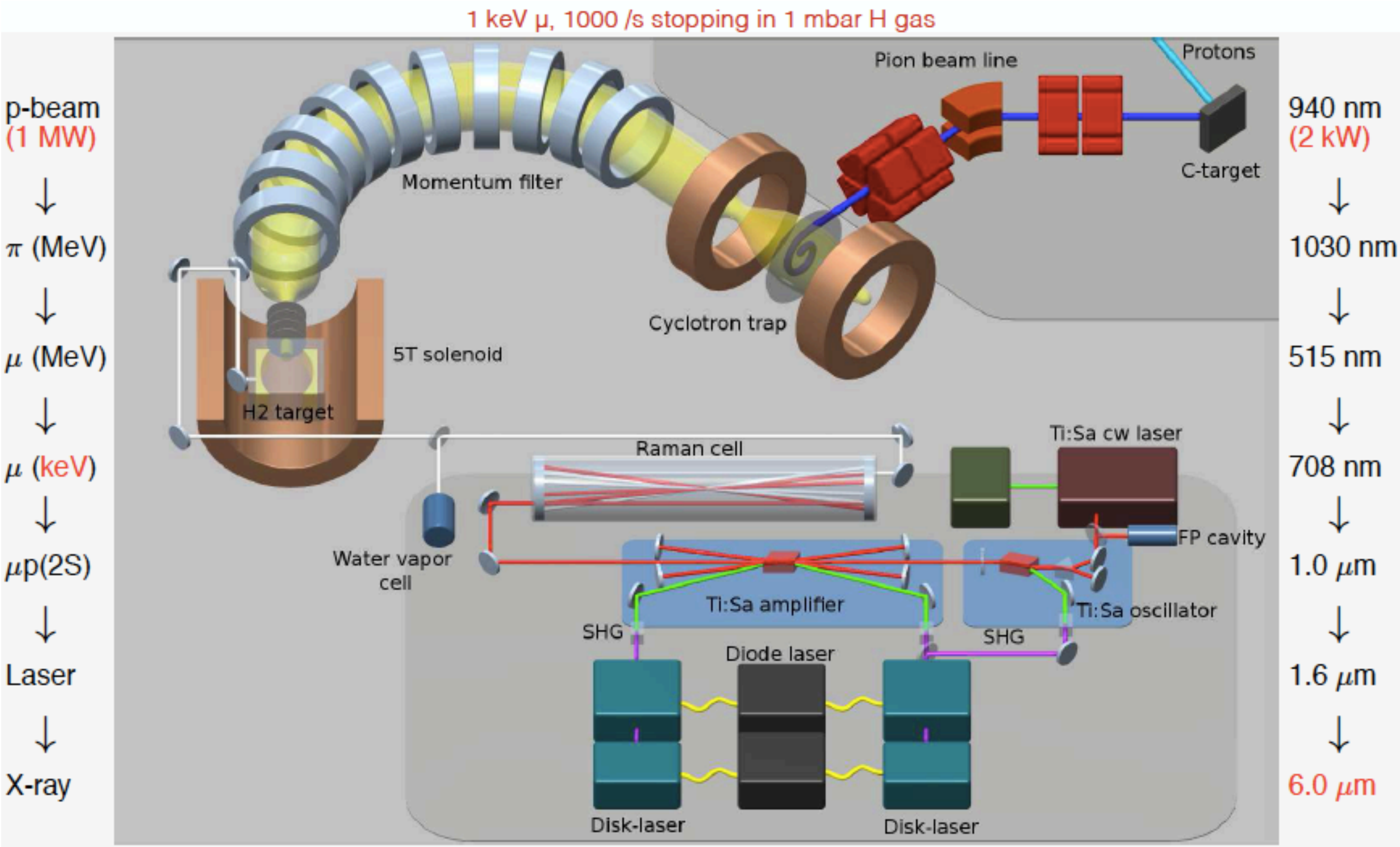
Yue et al., Phys. Rev. Lett. **111**, 222501 (2013)
Serebrov et al., Phys. Lett. B **605**, 72 (2005)
Arzumanov et al., Phys. Lett. B **483**, 15 (2000)
Arzumanov et al., JETPL **95**, 224 (2012)

Conclusions

- Privileged location with so many different probes available within small country
- Rich physics at low-energy with experiments searching for new effects in various directions

Backup

Proton Radius Experimental Setup

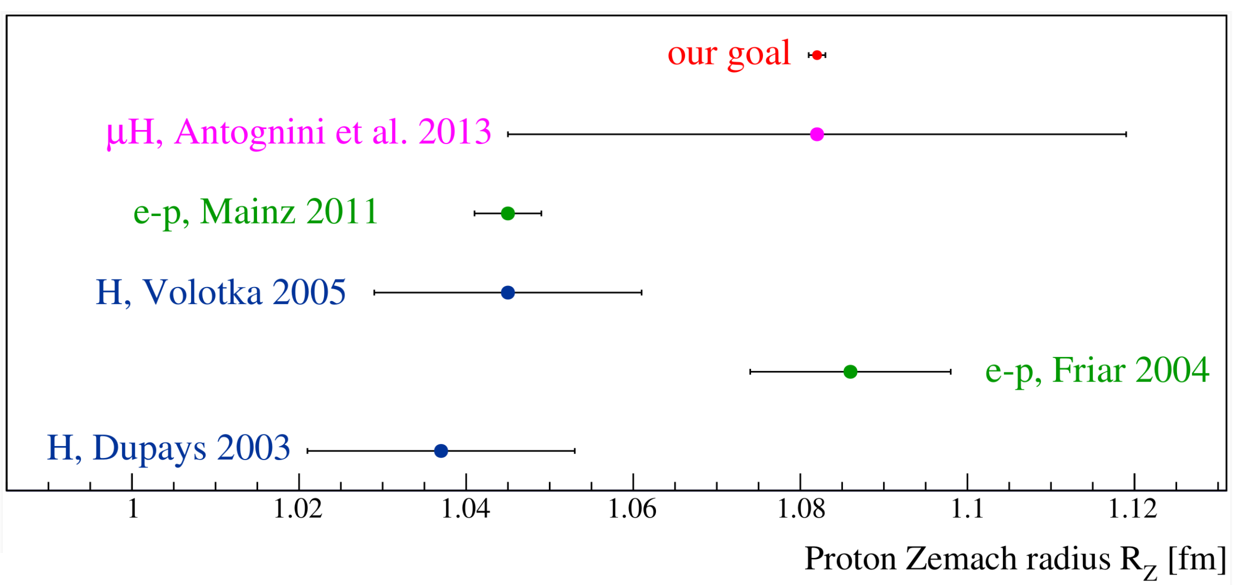


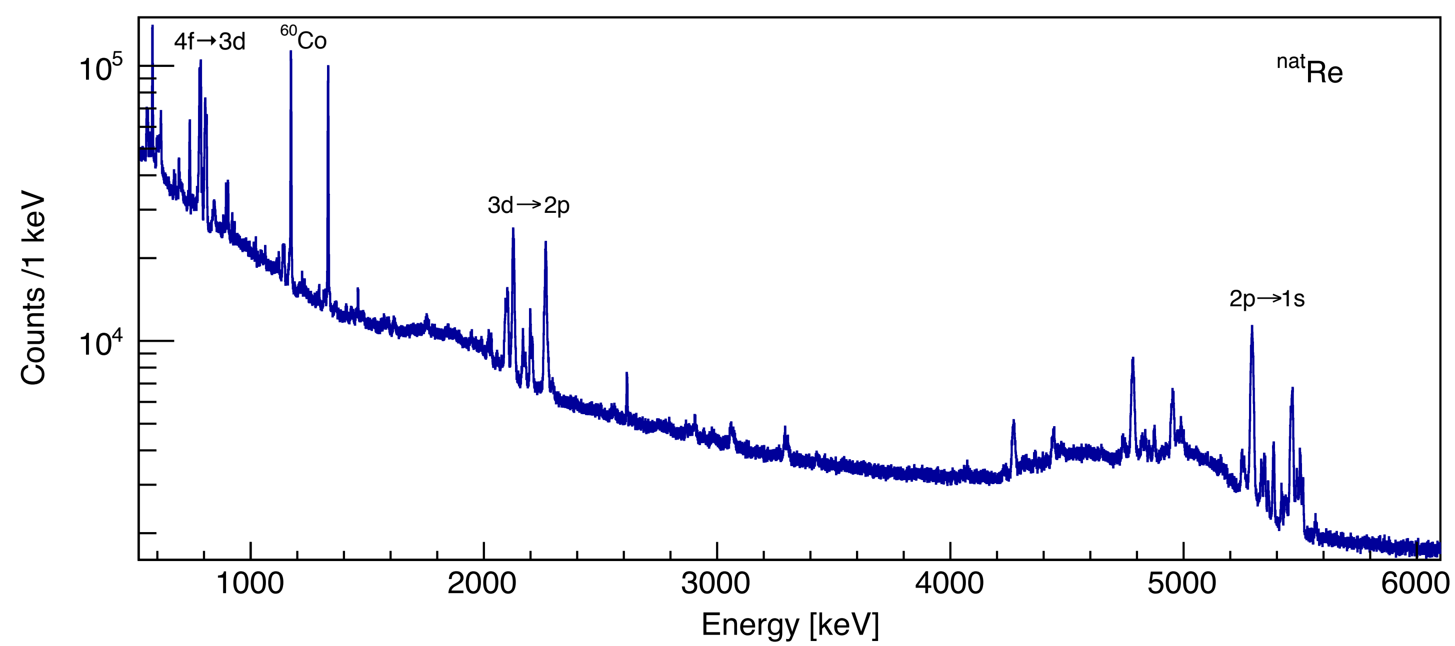
- Low energy muons, laser system, hydrogen target & X-ray detectors

New Measurements with Muonic Atoms

- Ground-state HFS in μH & μ³He
- Laser spectroscopy experiment
- Access to two-photon-exchange contributions, magnetic structure and polarizability

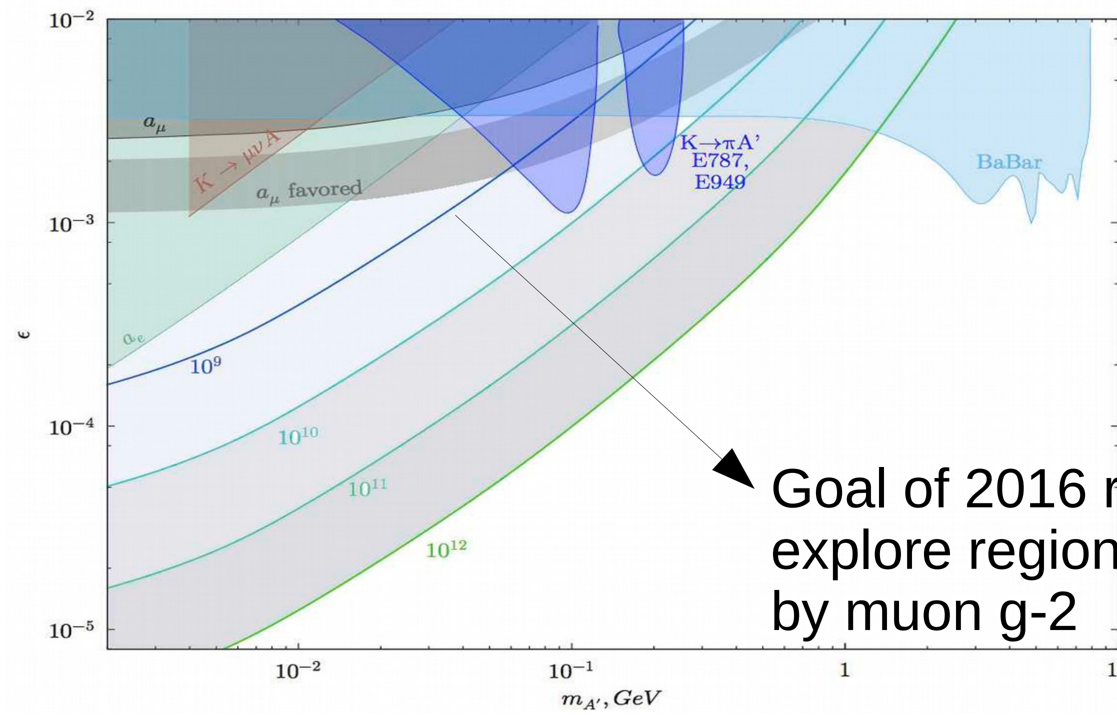
- Charge radii of high-Z, radioactive atoms
- Gamma spectroscopy using HPGe detectors
- Charge radius of radium needed for measurement of atomic parity violation





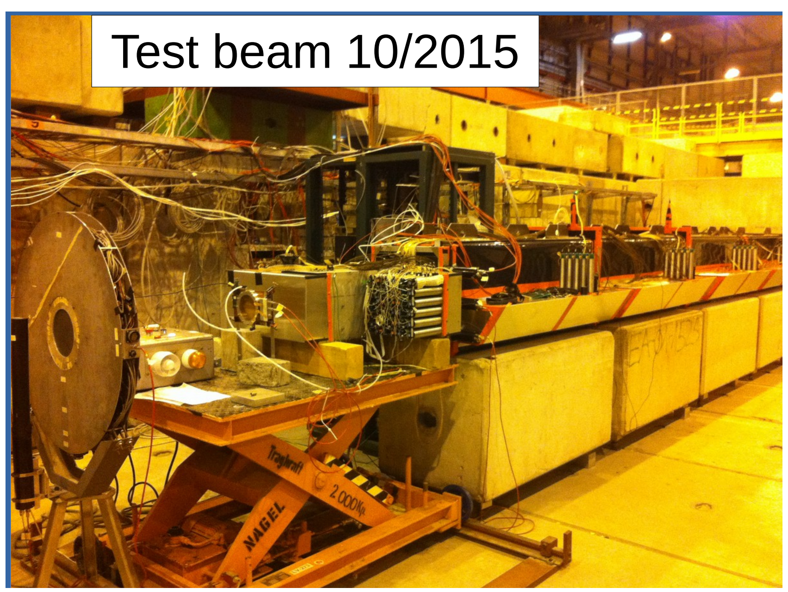
NA64 at CERN SPS

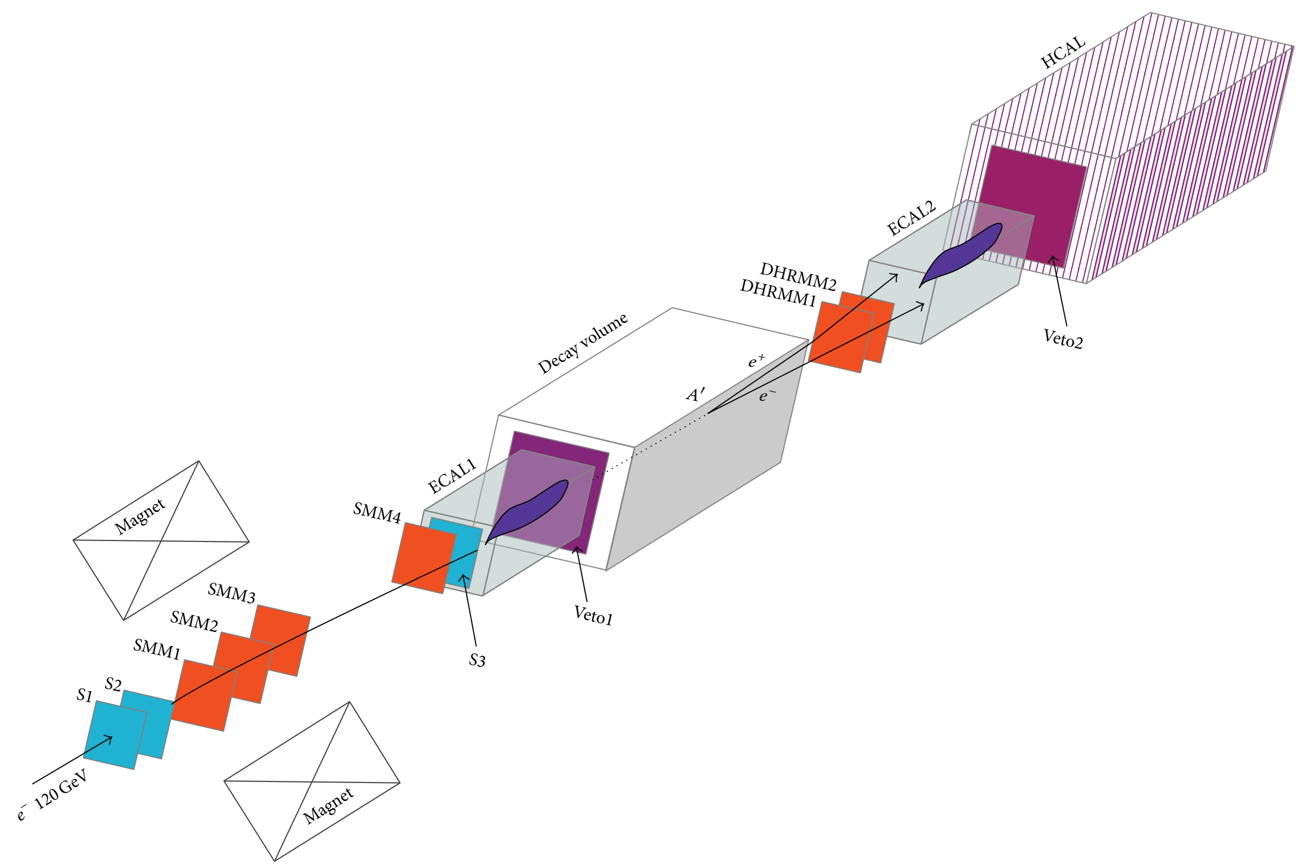
- Search for dark sectors in missing energy or “light shining through the wall”
- Sensitive to light dark bosons (Z’), dark photons (A’) or invisible decays of mesons



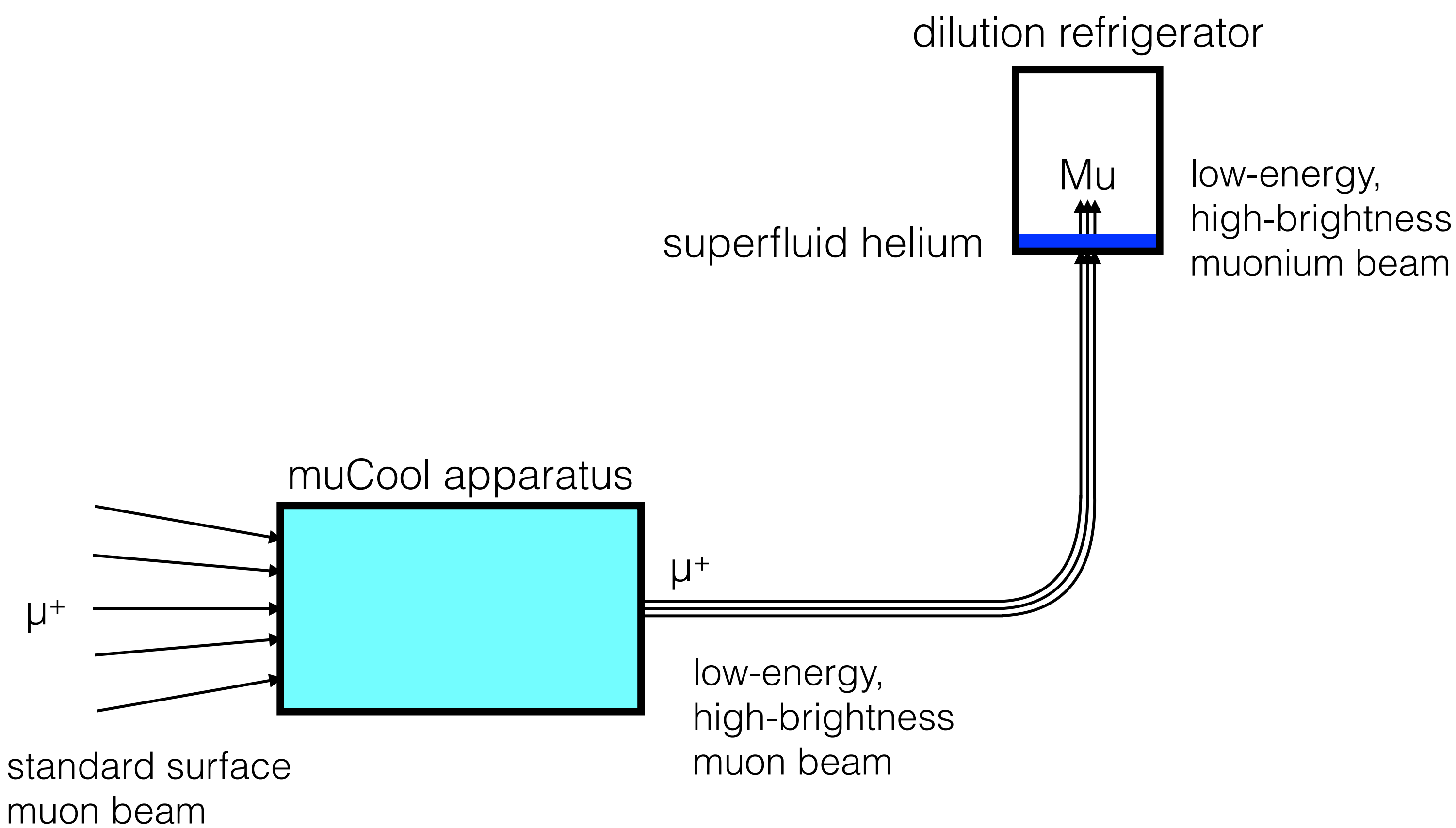
Goal of 2016 run, explore region favored by muon g-2

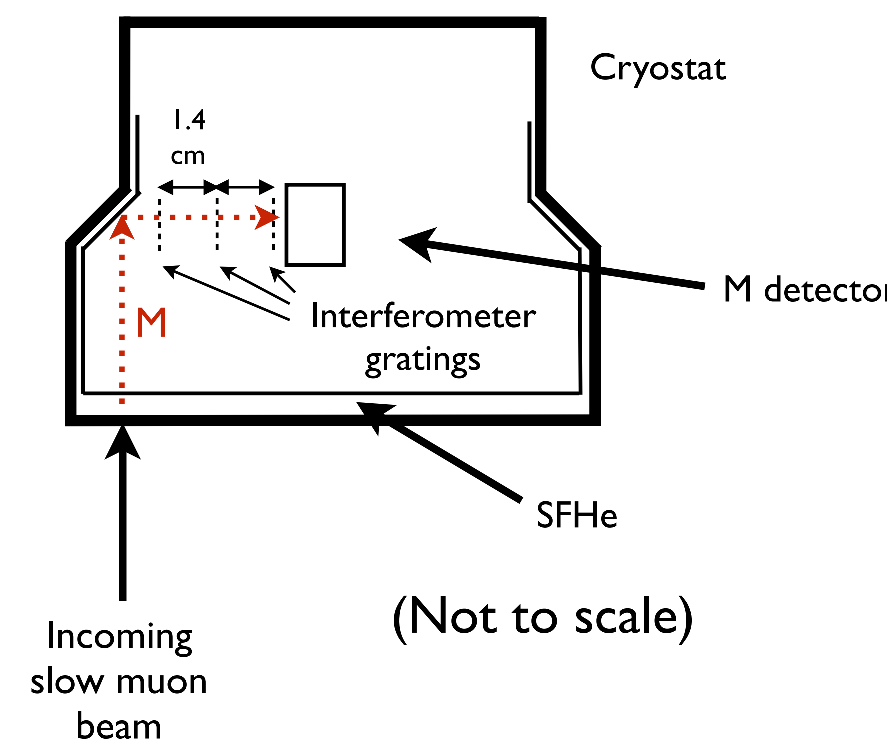
- ETHZ responsible of synchrotron radiation tagging and micromegas tracker



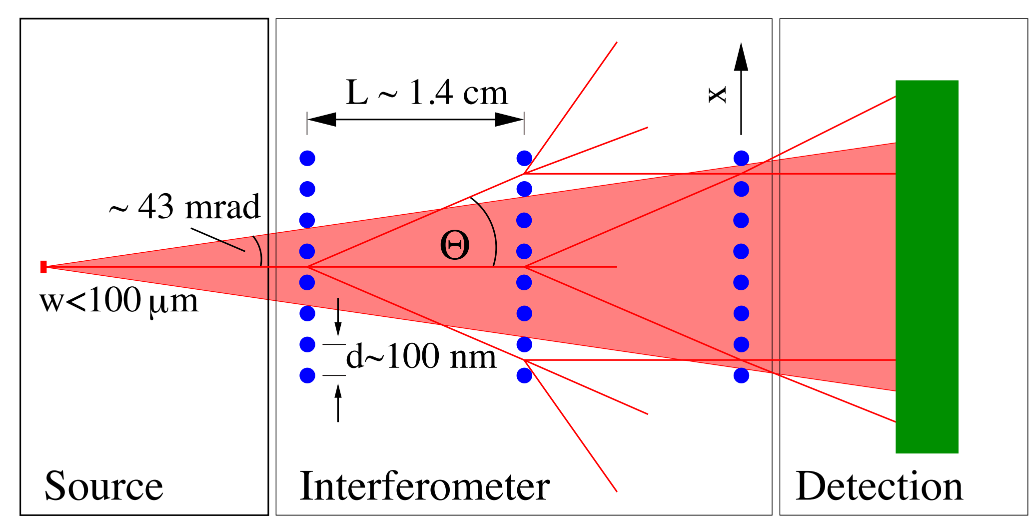


Muonium Production & Gravity





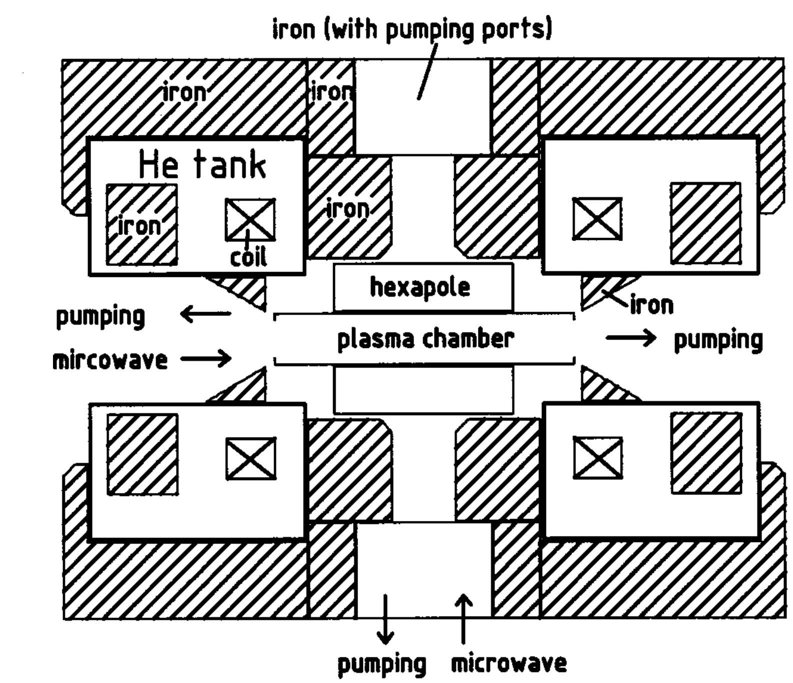
- Production of muonium beam in superfluid helium film
- Deflection measurement of horizontal muonium beam with three gratings



Neutron Lifetime

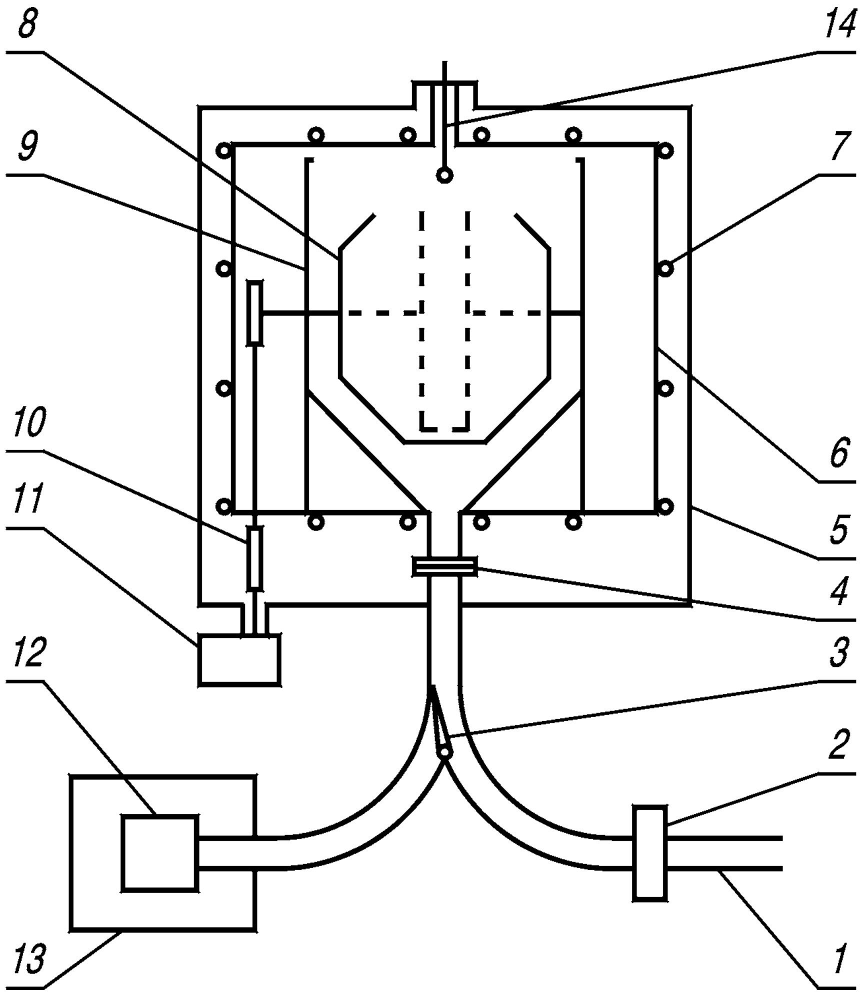
- Currently investigating whether cyclotron trap with an internal multipole magnet can be used as a magnetic storage bottle for UCN
- Internal UCN and UCN decay detectors for the measurement of the lifetime

Cyclotron trap with internal hexapole magnet as UCN storage trap (previously used as ECR ion source)

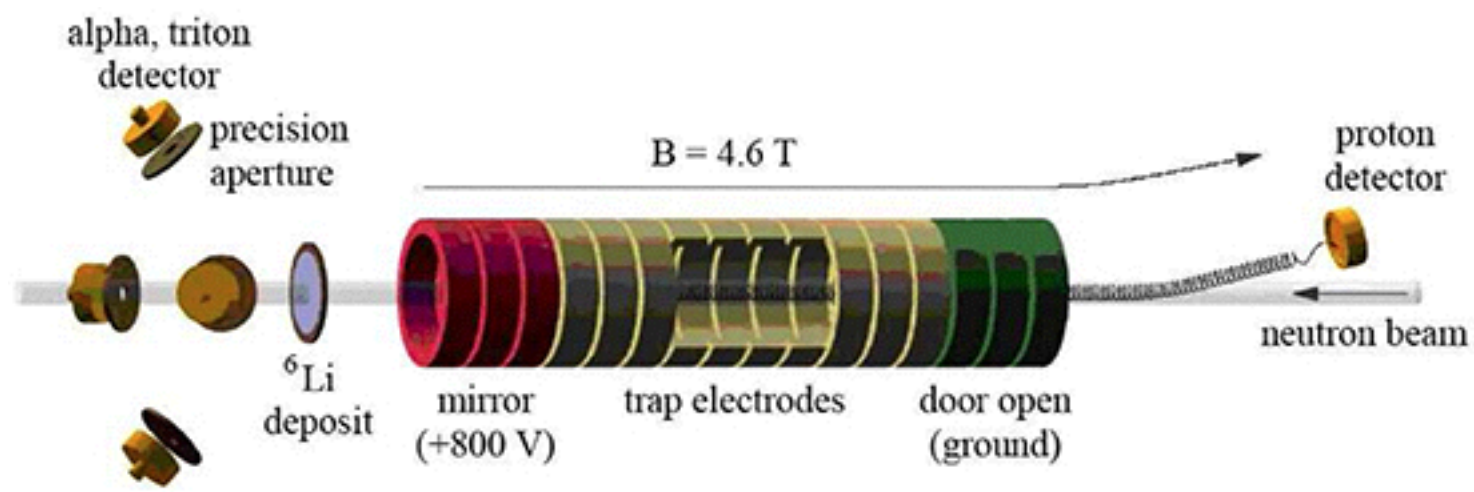


Biri et al., Rev. Sci. Inst. **71**, 1116 (2000)

Neutron Lifetime



Gravitrap neutron storage apparatus

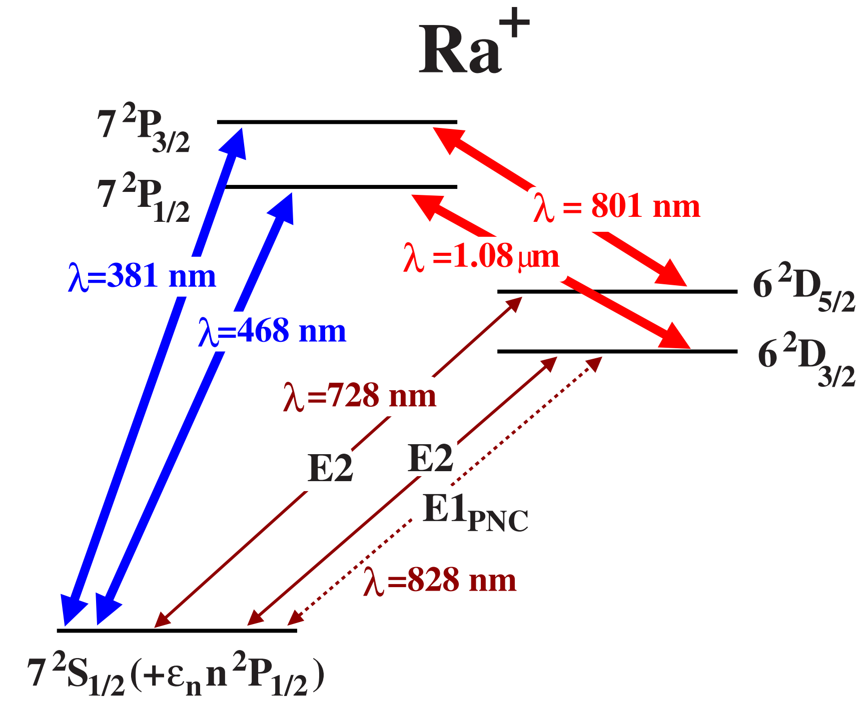


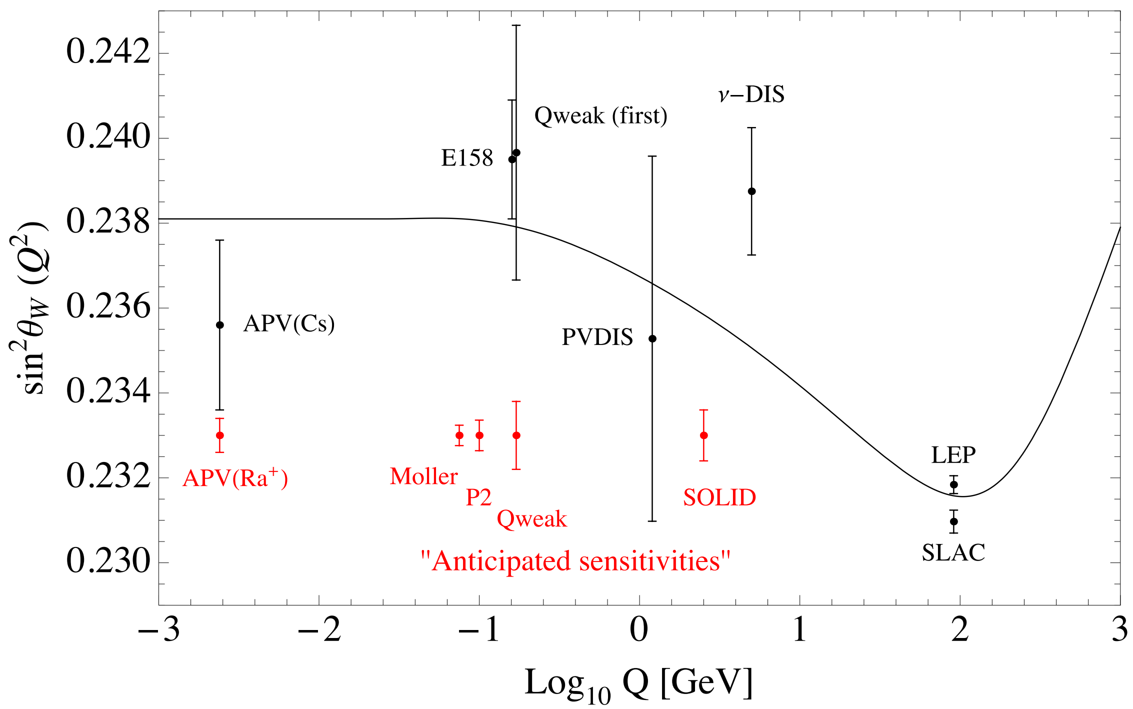
NIST neutron decay experiment

Yue et al., Phys. Rev. Lett. **111**, 222501 (2013)
Serebrov et al., Phys. Lett. B **605**, 72 (2005)

Atomic Parity Violation in Radium

- Electron-quark neutral weak interaction mixes states of opposite parity
- Measure $E1_{PNC}$ admixture in E2 transition and extract weak charge using precision atomic calculations
- Needs knowledge of the radium charge radius with 0.2% accuracy
- Potential of improving Cs result by factor 5





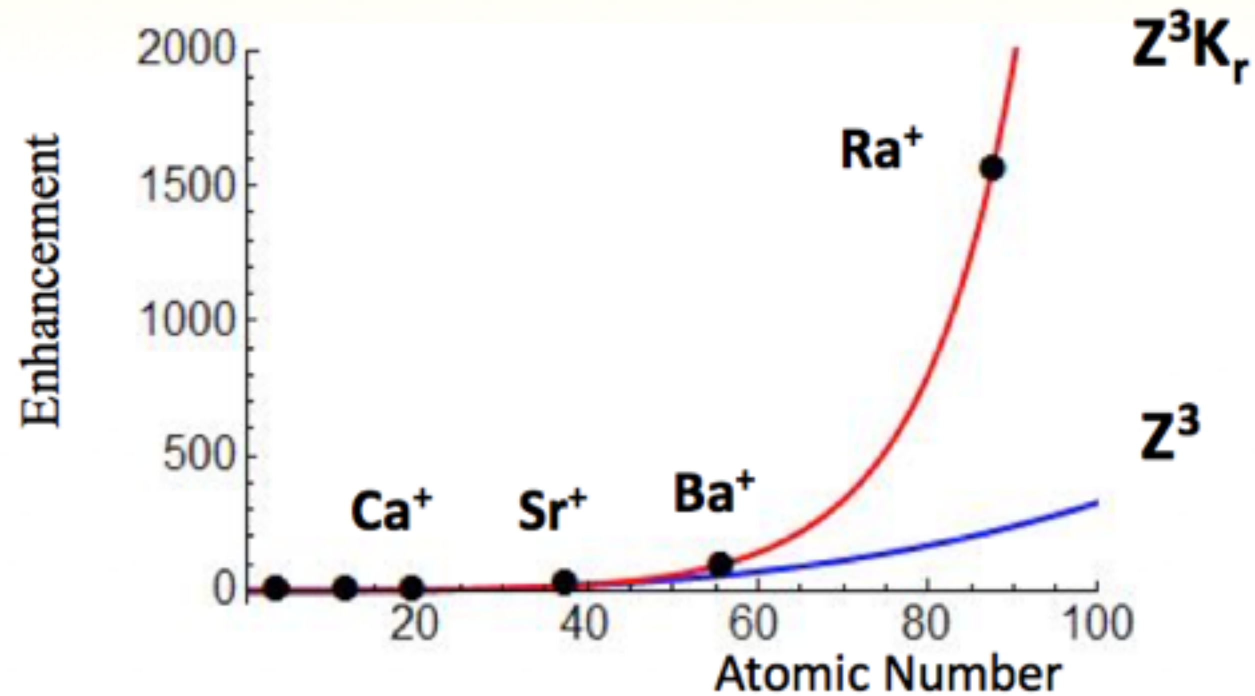
Wansbeek et al., PRA **78**, 050501 (2008)
Wood et al., Science **275**, 1759 (1997)
Lee, arXiv:1511.03783 (2015)

Atomic Parity Violation

Scaling of the APV

increase faster than Z^3 (Bouchiat & Bouchiat, 1974)

$\langle nS_{1/2} | H_W | nP_{1/2} \rangle \propto K_r Z^3$ K_r relativistic enhancement factor



Ra⁺ effects larger by:

20 (Ba⁺)

50 (Cs)

L.W. Wansbeek *et al.*, Phys. Rev. A **78**, 050501 (2008)

→ 5-fold improvement over Cs feasible in 1day

Relativistic coupled-cluster (CC) calculation of $E1_{APV}$ in Ra⁺

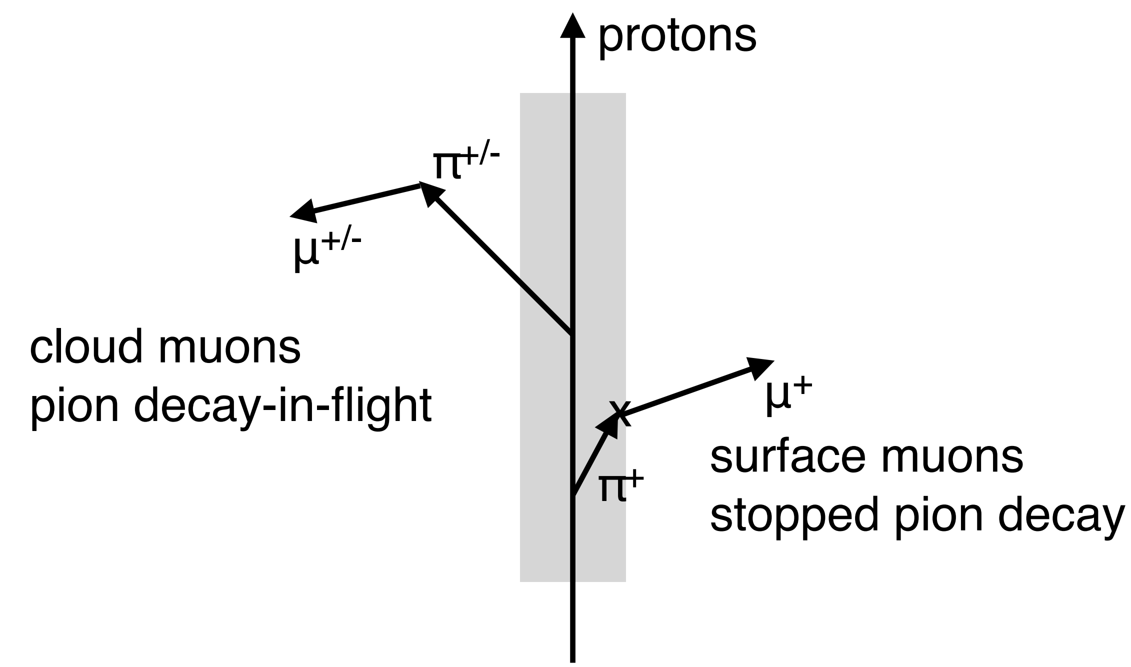
$$\mathbf{E1_{APV} = 46.4(1.4) \cdot 10^{-11}\, iea_0 (-Q_w/N)} \quad \textbf{(3\% accuracy)}$$

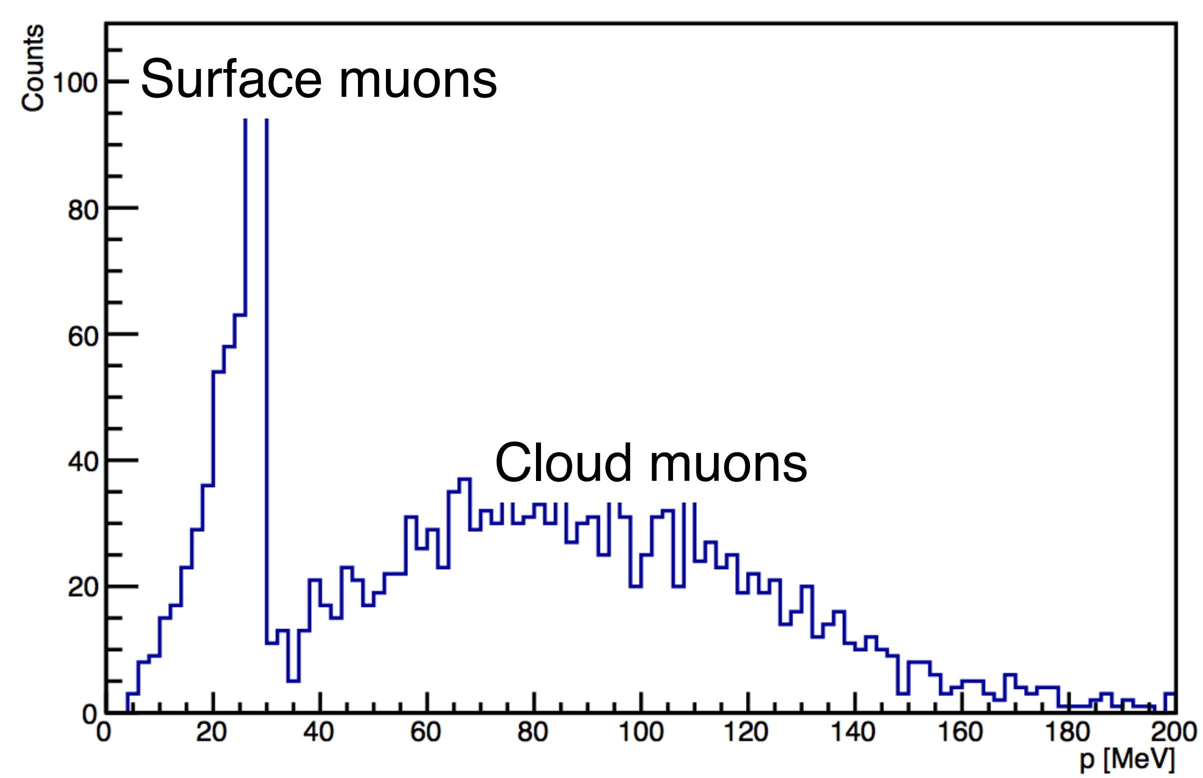
Other results:

$45.9 \cdot 10^{-11}\, iea_0 (-Q_w/N)$ (R. Pal *et al.*, Phys. Rev. A **79**, 062505 (2009), Dzuba *et al.*, Phys Rev. A **63**, 062101 (2001).)

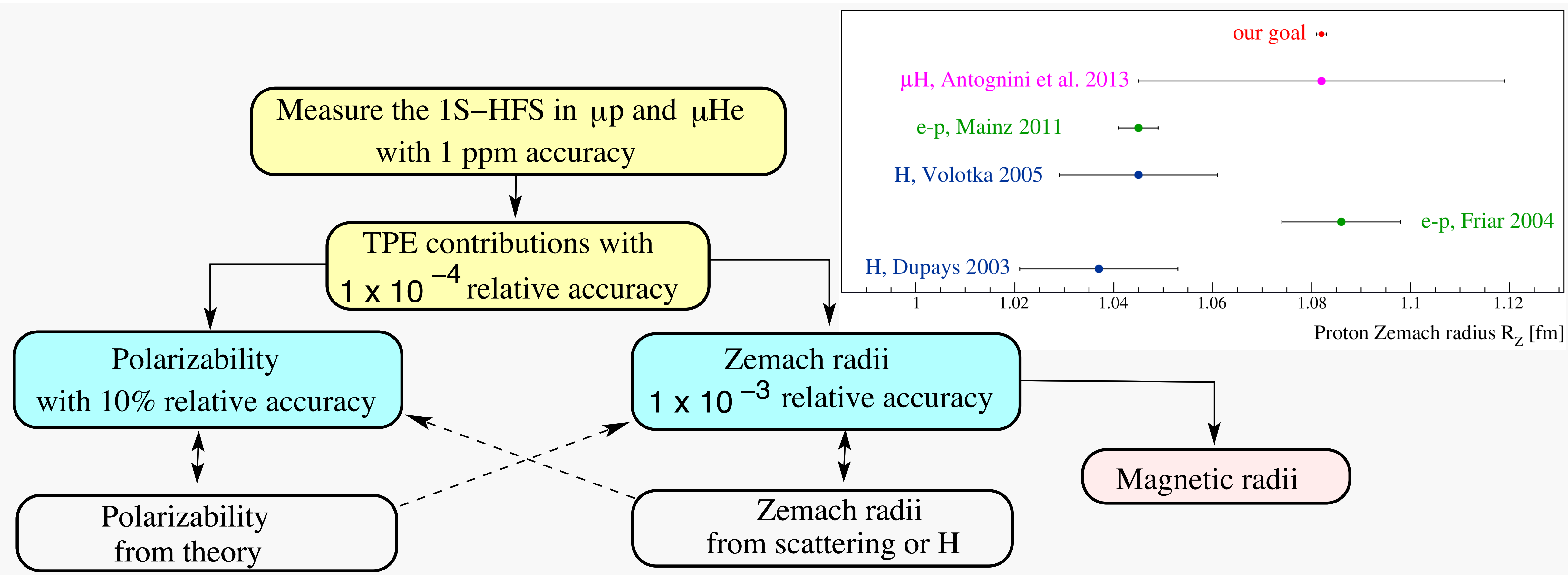
Surface muons

- Low-energy muon beam lines typically tuned to surface-μ^+ at ~ 28 MeV/c
- Contribution from cloud muons at similar momentum about 100x smaller
- Negative muons only available as cloud muons
- Time structure of cyclotron smeared out by pion lifetime → DC muon beams





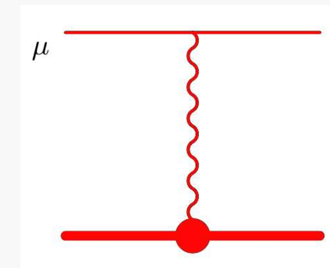
Muonic $H_2/^3He$ HFS



- Precision experiment:	→	hold the potential for surprises
- Radii:	→	benchmarks for lattice QCD and few-nucleon th.
	→	compare with scattering and H/He spectroscopy
	→	solve discrepancy between proton R_M
- Polarizabilizty contributions	→	compare to ChPT, dispersion+data, few-nucleon th.
- TPE contributions	→	compare to dispersion+data, few-nucleon th.

Muonic H/^{3}He HFS

- The 2S-2P energy splitting (Lamb shift)

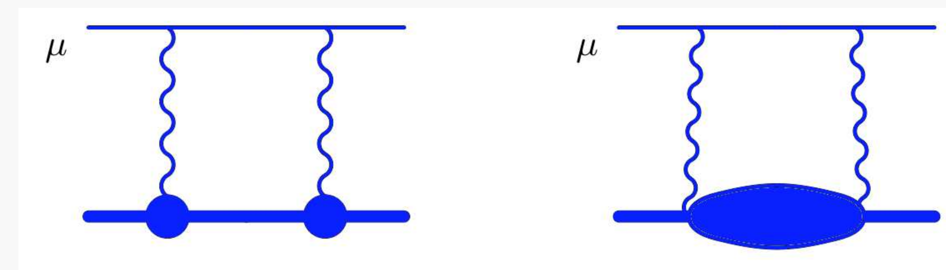


$$E_L^{th} = 206.0336(15) - 5.2275(10) R_E^2 + 0.0332(20) \text{ meV}$$

$$\Delta E_{\text{finite size}} = \frac{2\pi Z\alpha}{3} |\phi(0)|^2 R_E^2$$

$$R_E = -\frac{6}{G_E(0)} \frac{dG_E}{dQ^2}\Big|_{Q^2=0}$$

$$R_E^2 \approx \int d\vec{r}\, \rho_E(\vec{r}) r^2$$



TPE: Two photon exchange

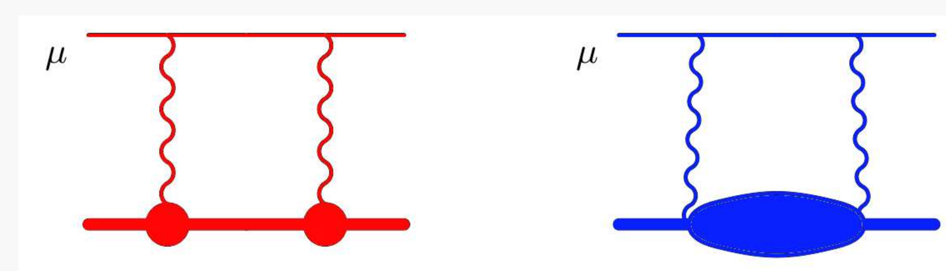
- The hyperfine splitting $\Delta E^0_{\text{HFS}} \sim (Z\alpha)\langle\vec{\mu}_\mu \cdot \vec{\mu}_N\rangle |\phi(0)|^2$

$$\Delta E^{th}_{\text{HFS}} = 182.819(1) - 1.301 R_Z + 0.064(21) \text{ meV}$$

$$\Delta E_{\text{finite size}} = -2(Z\alpha) m_r \Delta E^0_{\text{HFS}} R_Z$$

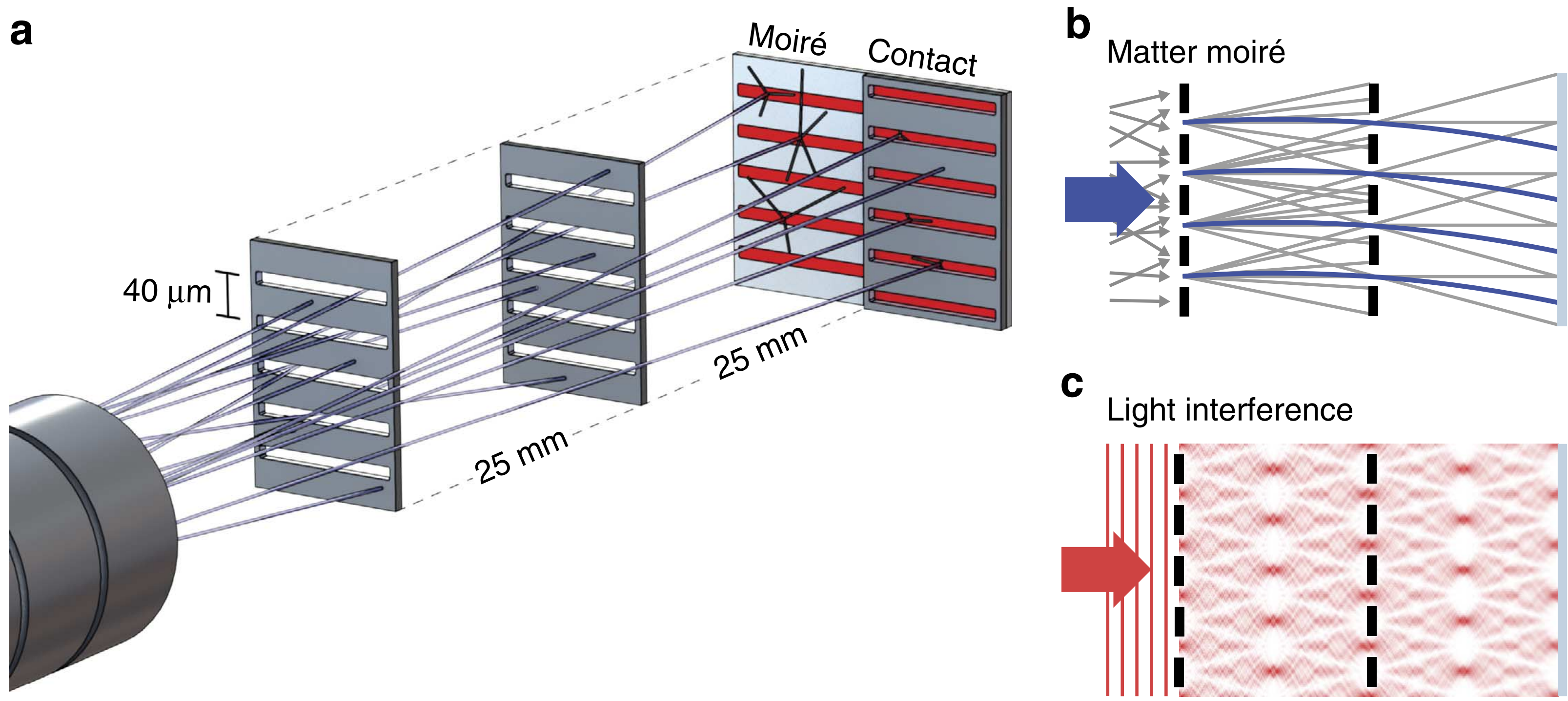
$$R_Z = -\frac{4}{\pi} \int_0^\infty \frac{dQ}{Q^2} \left(G_E(Q^2) \frac{G_M(Q^2)}{1+\kappa_p} - 1 \right)$$

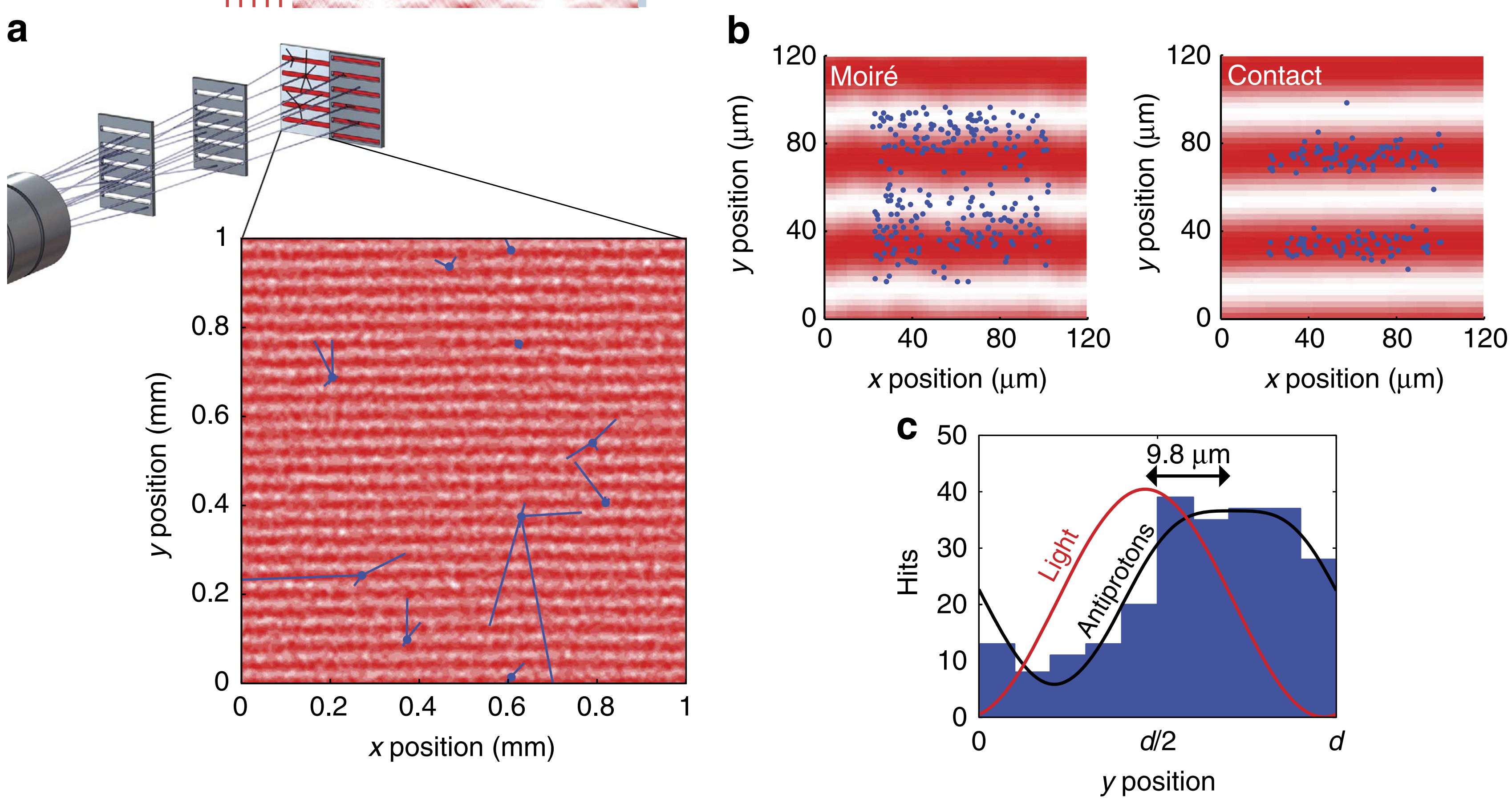
$$R_Z = \int d^3\vec{r}\, |\vec{r}| \int d^3\vec{r'} \rho_E(\vec{r} - \vec{r'}) \rho_M(\vec{r'})$$



TPE: Two-photon-Exchange

Test of Moiré Deflectometer





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