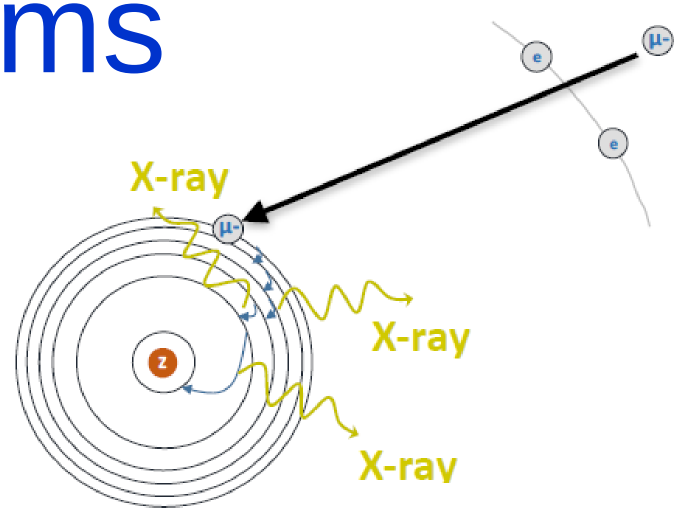
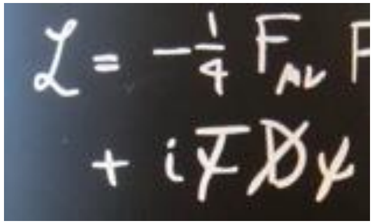
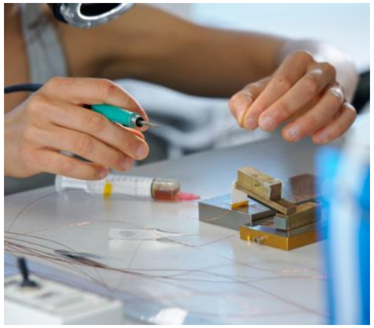
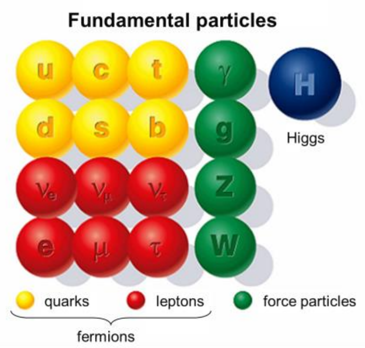
# Physics with exotic atoms

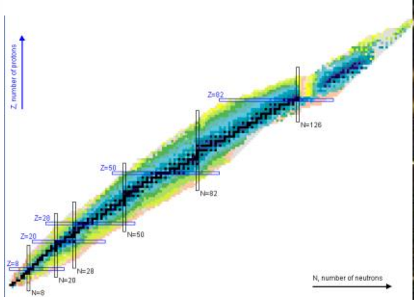


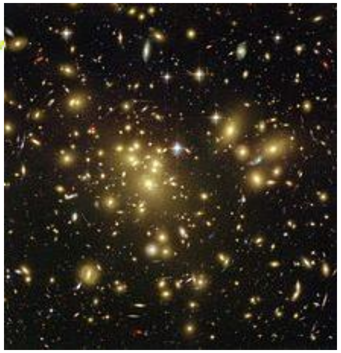



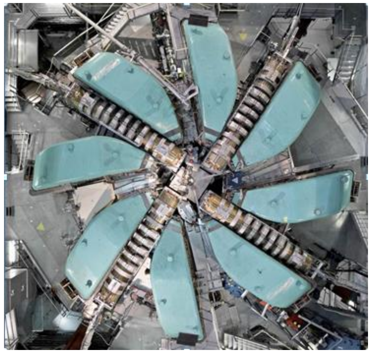


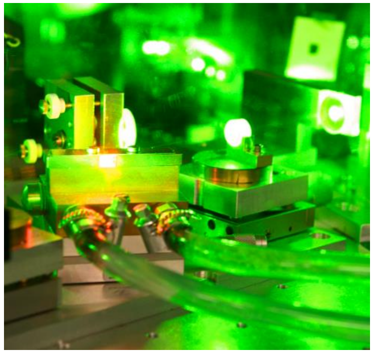
Klaus Kirch, ETH Zürich – PSI Villigen, Switzerland



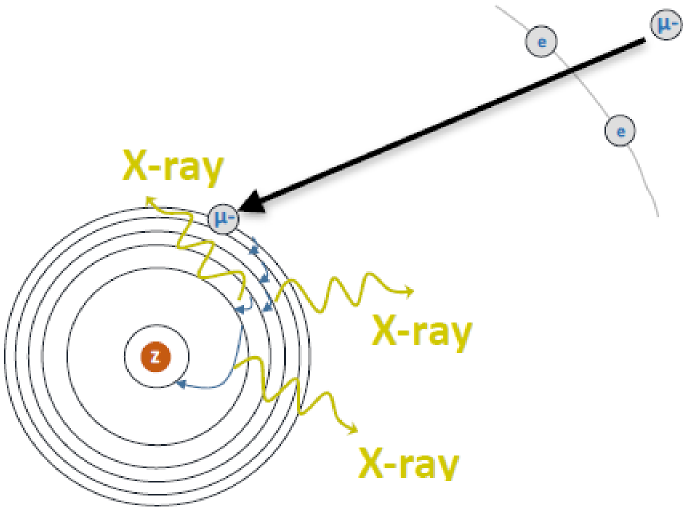









# Exotic Atoms




- Atoms in which an electron is replaced by an exotic negatively charged particle ($\mu$, $\pi$, K, pbar) orbiting an ordinary nucleus (p, …, $^{248}$Cm)
- Atoms with an exotic positive particle ($e^+$, $\mu^+$) and an electron (Ps, M)
- Atoms made from two oppositely charged exotic particles (Hbar=$e^+$pbar, $\pi^+\pi^-$, $K^+\pi^-$, …)

# Exotic Atoms

- Systems bound by electromagnetic interaction
- Partially influenced by strong and weak interaction between the bound particles
- If cold enough, measurably affected by Earth's gravity

Allow:

- Tests of bound state QED
- Determination of fundamental constants and particle masses
- Extraction of nuclear properties, in particular charge radii
- Determination of nucleon form factors (el-m and weak)
- Determination of hadronic scattering lengths at low $Q^2$
- Precision tests of fundamental symmetries, P, CPT
- Test of the equivalence principle with antimatter

# Technical challenges

- Produce exotic particles
- Generate beams of sufficient quality
- Produce exotic atoms at low energies
  - low mass materials, small stop distributions
  - in vacuum, small spatial extension
- Observe and manipulate the exotic atoms

# Facilities in Europe and Worldwide with exotic atoms research

- Pions, Muons: PSI, J-PARC, RIKEN-RAL
- Kaons: DAΦNE, J-PARC
- Antiprotons: CERN (&HE pions, kaons)
- Positrons: several laboratories

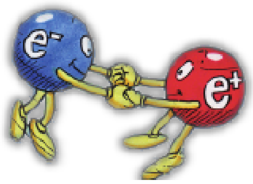
# Selected examples

- Positronium
- Antihydrogen
- Antiprotonic helium
- Muonic atoms
- Muonium

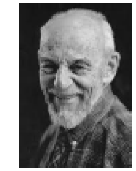
Gratefully acknowledge input from:

- A. Antognini
- P. Crivelli
- C. Curceanu
- M. Doser
- D. Gotta
- M. Hori
- P. Kammel
- A. Knecht
- A. Soter
- A. Vacchi
- E. Widmann

- &many slides in the backup material

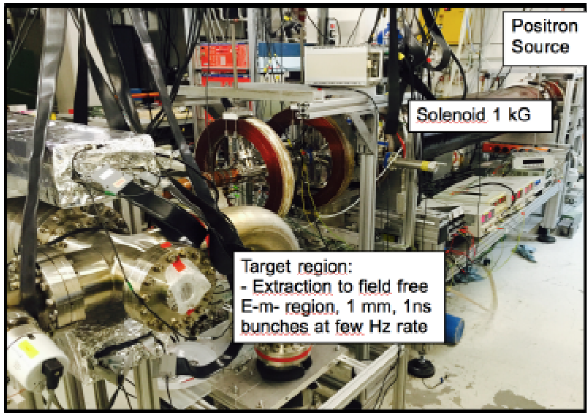


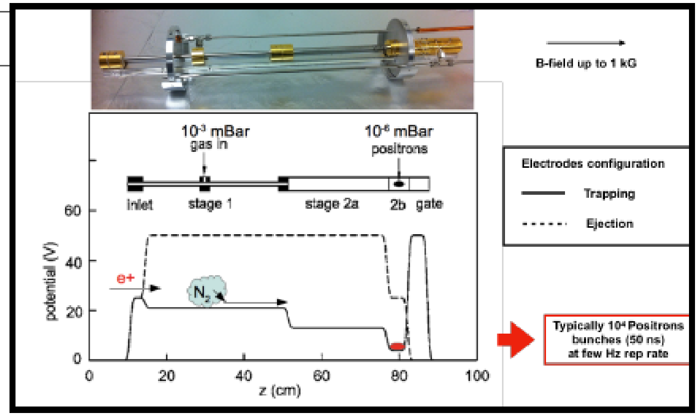

**POSITRONIUM:** 1st predicted exotic atom (1934), discovered in 1951 by Martin Deutsch.



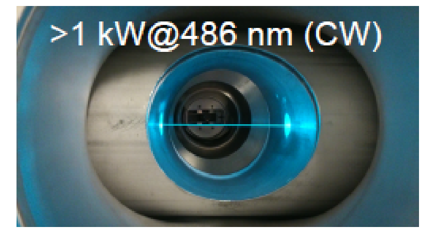
**Workhorse for development of bound state QED for many years.**

Still very active field of research! Advances in positron manipulation (buffer gas traps, laser technology and detectors) great boost to the field!



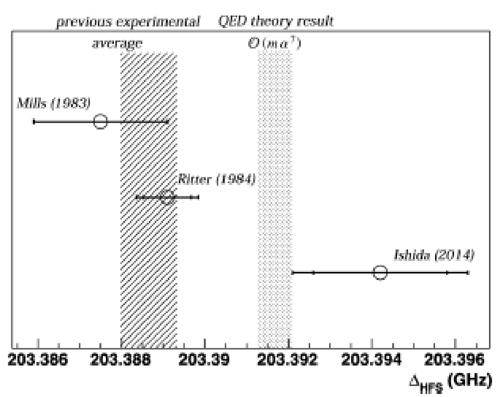




RECENT REVIEWS
J. R. Danielson et al. Rev. Mod. Phys. 87, 247 (2015)
D. B. Cassidy Eur. Phys. J. D (2018) 72: 53




**ACCURATE TEST OF BOUND STATE QED:** 1S-2S transition (ETHZ), Hyperfine splitting (Tokyo U.), fine structure (UCL),

**GOAL:** catch up with theory $\mathcal{O}(m\alpha^7)$. As a byproduct test CPT/Lorentz invariance (SME).




SOME RECENT REFERENCES

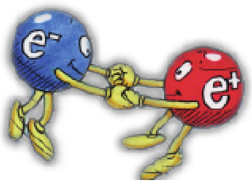
EXP:

Ishida et al., Phys. Lett. B 734, 338 (2014).
M. Heiss et al., J. Phys.: Conf. Ser. 1138, 012007 (2018).
A. M. Alonso et al., Phys. Rev. A,95, (2017), 033408

TH QED:

M. I. Eides and V. A. Shelyuto, Phys. Rev. D 92, 013010 (2015)
G. S. Adkins et al. Phys. Rev. Lett. 115, 233401 (2015)
TH SME: Kostelecky and Vargas, Phys. Rev. D 92, 056002 (2015)

Courtesy: P. Crivelli



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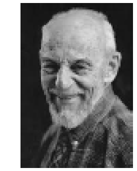


**Workhorse for development of bound state QED for many years.**

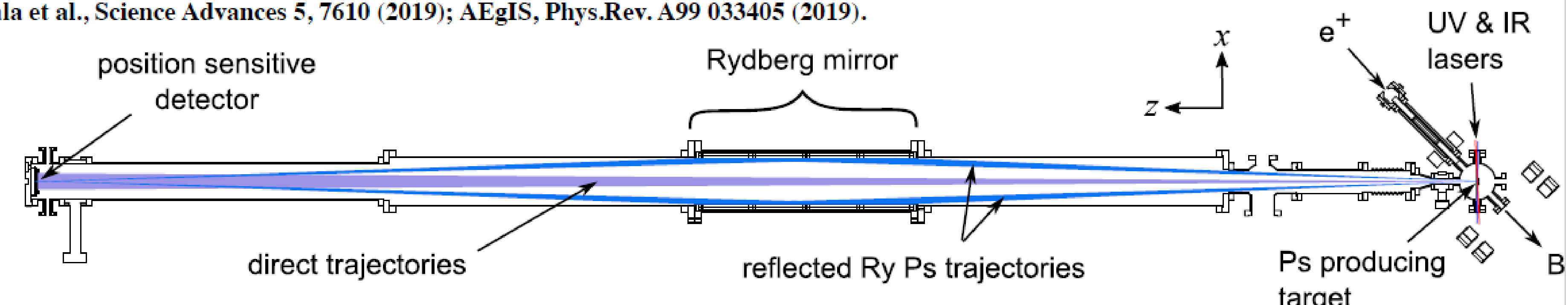
Still very active field of research! Advances in positron manipulation (buffer gas traps, laser technology and detectors) great boost to the field!

**SEARCHES FOF NEW PHYSICS AND TEST OF FUNDAMENTAL SYMMETRIES:** searching for massless Dark photons (ETHZ), searches for CP and CPT violation on leptonic sector (Tokyo U., Jagiellonian U.)

T. Yamazaki, et al. Phys. Rev. Lett. 120, 239902 (2018)
D. Kaminska et al. Eur Phys J C Part Fields. 2016; 76(8): 445.

**EFFECT OF GRAVITY ON POSITRONIUM:** test of the equivalence principle for antimatter (UCL, U. Riverside California, AEgIS, QUPLUS)

D. Cassidy and S. Hogan, Int. J. Mod. Phys.: Conf. Ser. 30, 1460259 (2014);A. Jones et al. Phys. Rev. Lett. 119, 053201 (2017)
S. Sala et al., Science Advances 5, 7610 (2019); AEgIS, Phys.Rev. A99 033405 (2019).




**POSITRONIUM for production of anti hydrogen and antihydrogen ions**

G. Testera et al. (AEgIS Collaboration), Hyperfine Interact. 233, 13 (2015).
P. Perez et al. (GBAR Collaboration), Hyperfine Interact. 233, 21 (2015).

Courtesy: P. Crivelli

# Antihydrogen

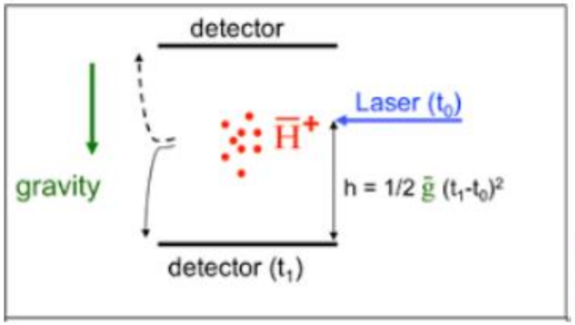
**GBAR:** Measure gravitational accelaration of anti-hydrogen

**GOAL:** - step 1 accuracy of 1% CERN-SPSC-2011-029

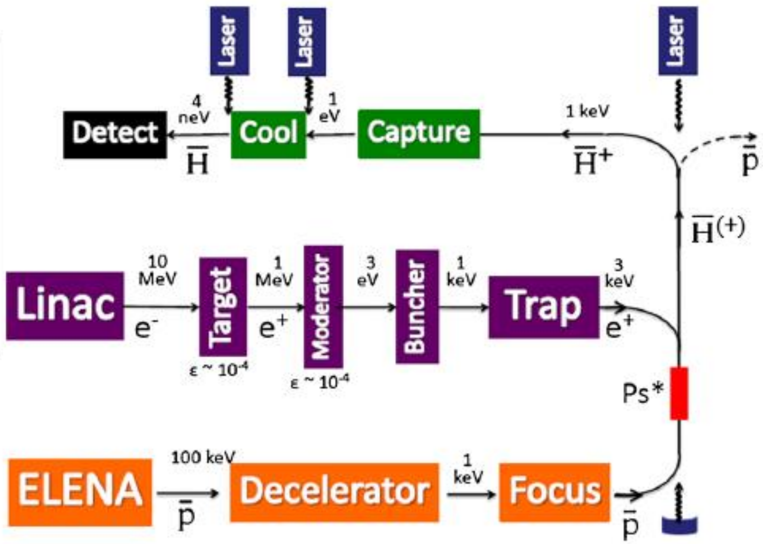
- step 2: accuracy $10^{-6}$ using quantum gravitational states

P.-P. Crépin et al., Phys. Rev. A 99, 042119 (2019)

- determination of Lamb shift at 100 ppm P. Crivelli et al., Phys. Rev. D 94, 052008(2016)




**Free fall measurement**




**Anti-ions production**

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

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

**STATUS AND PLANS:**

- installation at CERN started 2017
- LINAC operational (half of nominal intensity achieved)
- under commissioning with protons during LS2
- Start data taking after LS2

Irfu, Laboratoire Kastler Brossel, ILL Neutrons for Science, ETH Zürich, Swansea University Prifysgol Abertawe, Johannes Gutenberg Universität Mainz, Stockholm University, RIKEN, CSNSM, Narodowe Centrum Badań Jądrowych, 서울대학교 Seoul National University, 東京大学 The University of Tokyo, IPCMS, ibs Institute for Basic Science, UNIST Ulsan National Institute of Science and Technology, Korea University

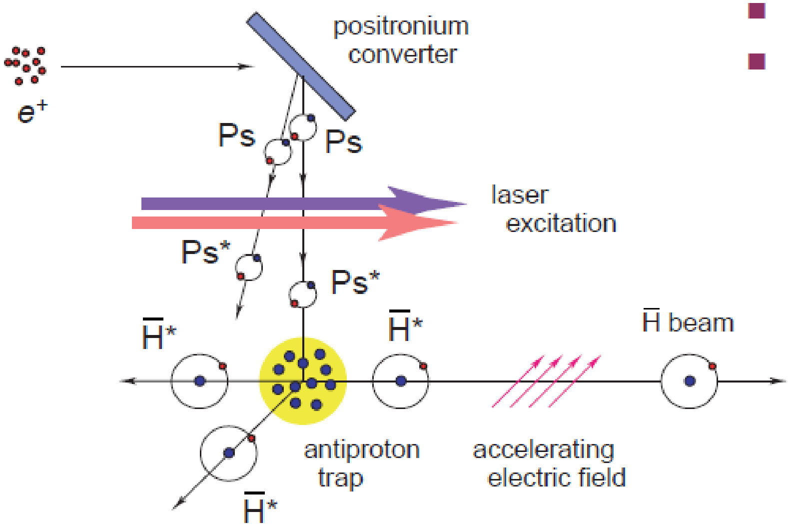
**Courtesy: P. Crivelli**

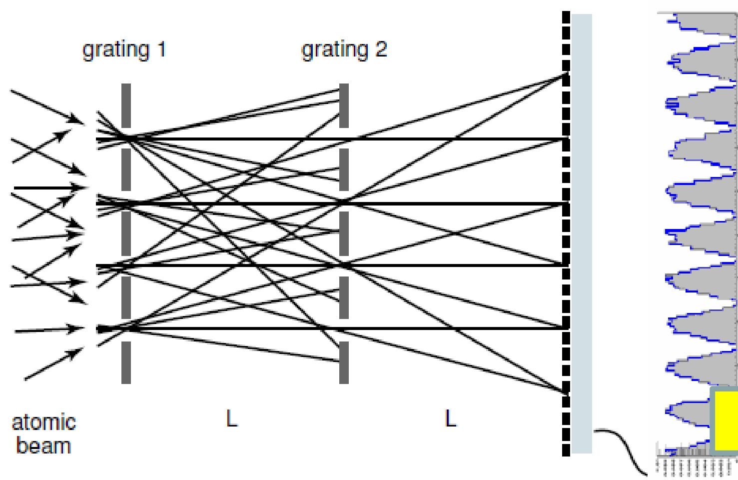
# Schematic overview: AEgIS (Antimatter Experiment: gravity, Interferometry, Spectroscopy)

Physics goals: measurement of the gravitational interaction between matter and antimatter, $\overline{\mathrm{H}}$ spectroscopy, antiprotonic atoms ($p\bar{p}$, $\bar{p}$Cs), ...

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

- Anti-hydrogen formation via Charge exchange process with Ps*
  - o-Ps produced in $SiO_2$ target close to $\bar{p}$; laser-excited to Ps*
  - $\overline{\mathrm{H}}$ temperature defined by $\bar{p}$ temperature
- Advantages:
  - Pulsed $\overline{\mathrm{H}}$ production (time of flight – Stark acceleration)
  - Narrow and well-defined $\overline{\mathrm{H}}$ *n*-state distribution
  - Colder production than via standard process possible
  - Rydberg Ps & $\sigma \approx a_0 n^4$ → $\overline{\mathrm{H}}$ formation enhanced



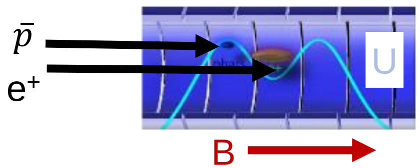



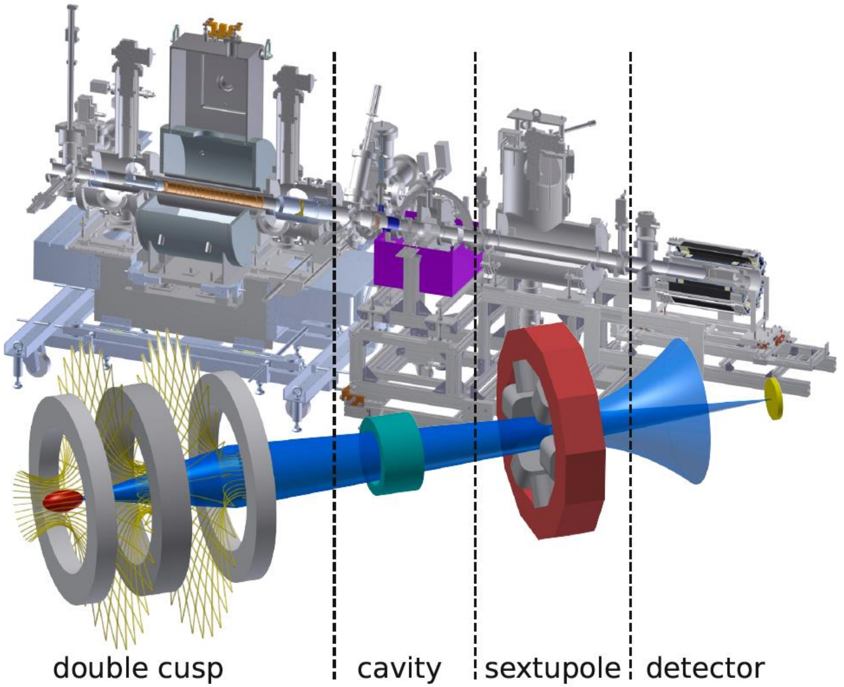

Courtesy: M. Doser

pulsed production of $\overline{\mathrm{H}}$* | beam formation | gratings produce periodic pattern on detector; measure gravity-induced vertical shift of fringes

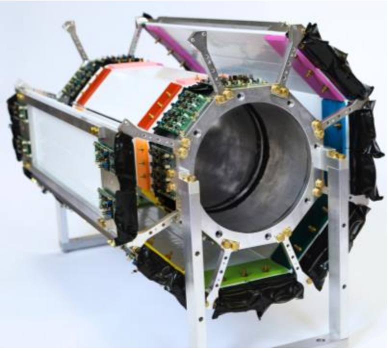
# ASACUSA Antihydrogen beam for HFS

- $\overline{\text{H}}$ production 1st time in 2010 in nested Penning trap
- Three body recombination expected to produce Rydberg states
- Measured parameters
  - n<14: 0.395(96)/cycle
  - Needed: few 1000 $\overline{\text{H}}$(1S) for 1 ppm

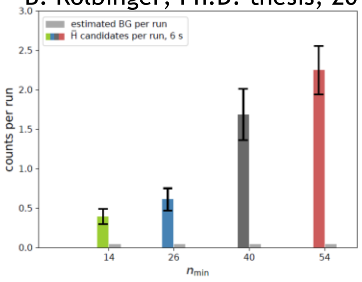



Antihydrogen detector



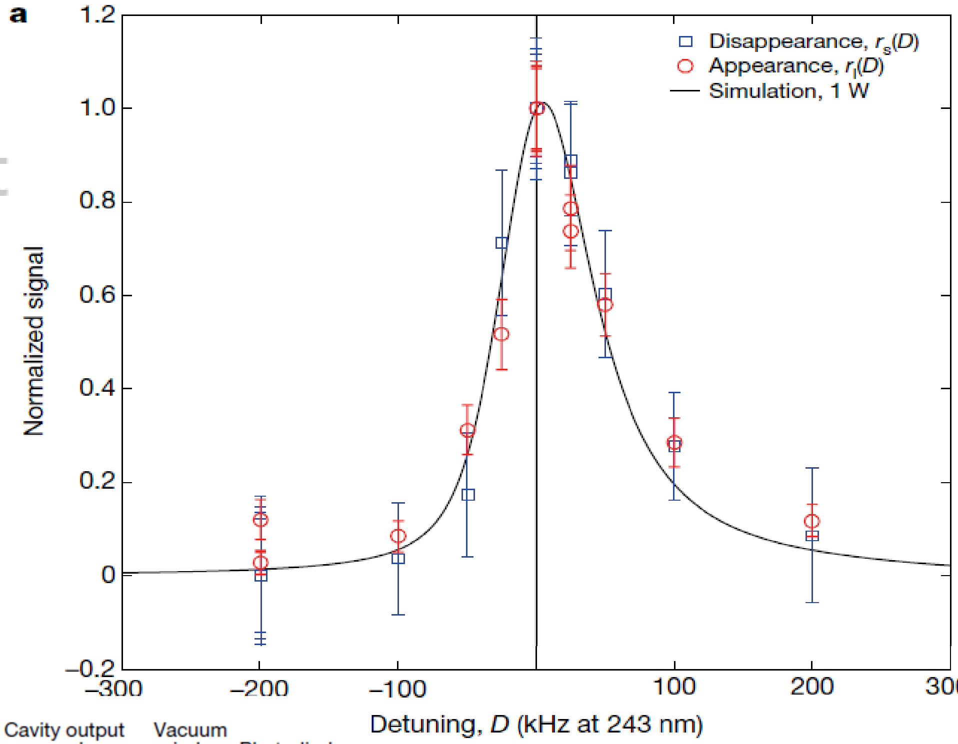
*n* distribution by machine learning
B. Kolbinger, Ph.D. thesis, 2019

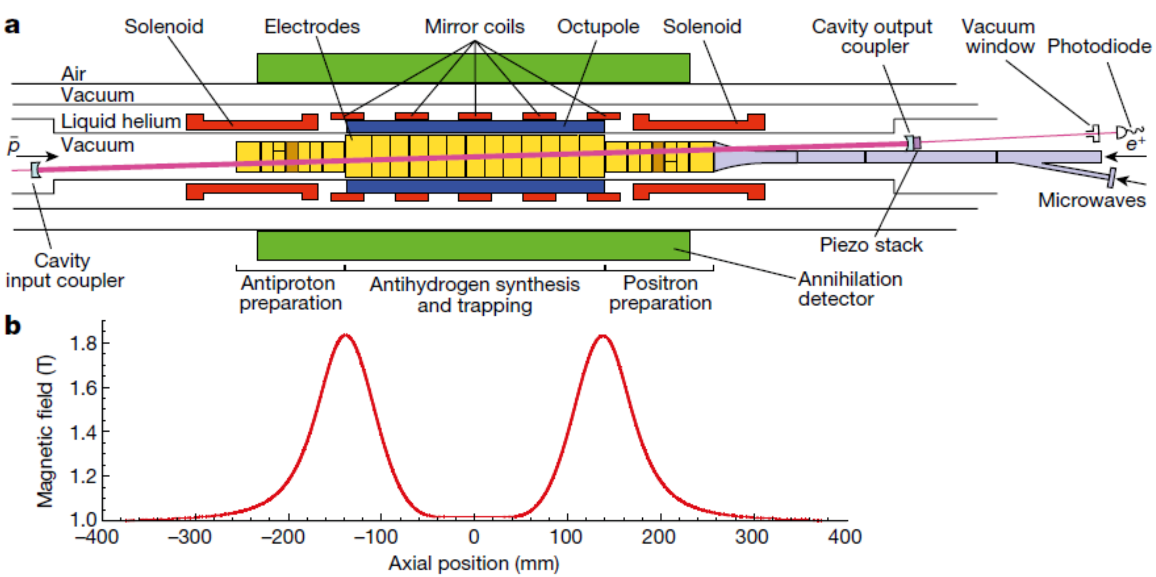



Courtesy: E. Widmann

alphaexperiment

# Hbar(1S-2S)



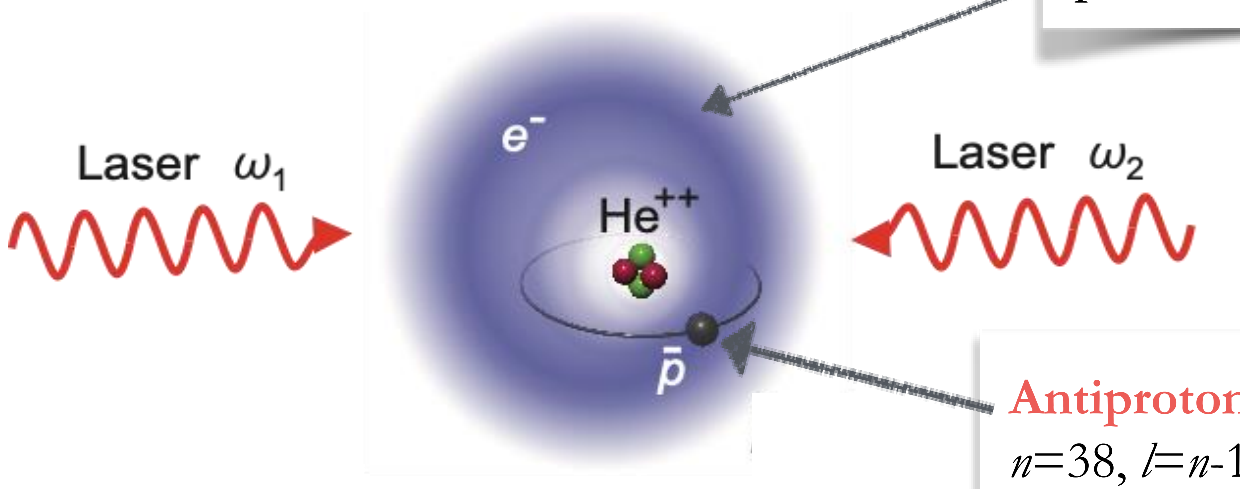




## Compared to H(1S-2S) testing CPT at 2 x $10^{-12}$

Nature 557(2018)71

# Antiprotonic and pionic helium

# Antiprotonic helium atom studied by ASACUSA




**Electron** in 1s orbital protects antiproton.

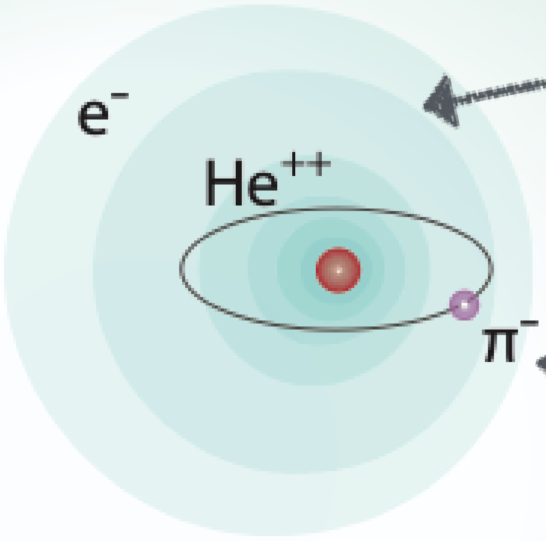
**Antiproton** in a 'circular' Rydberg orbital $n$=38, $l$=$n$-1 with diameter of 100 pm.

- Localized away from the nucleus.
- Average lifetime of 3 microseconds

Longest-lived hadron-antihadron system which is experimentally known. UV transition energies measured to $10^{-9}$ precision by sub-Doppler two photon laser spectroscopy and compared with QED calculations. Potential to reach $10^{-11}$ in future experiments at ELENA.

Courtesy: M. Hori

# Metastable pionic helium ($\pi He^+$) atom




**Electron** in 1s orbital protects pion.

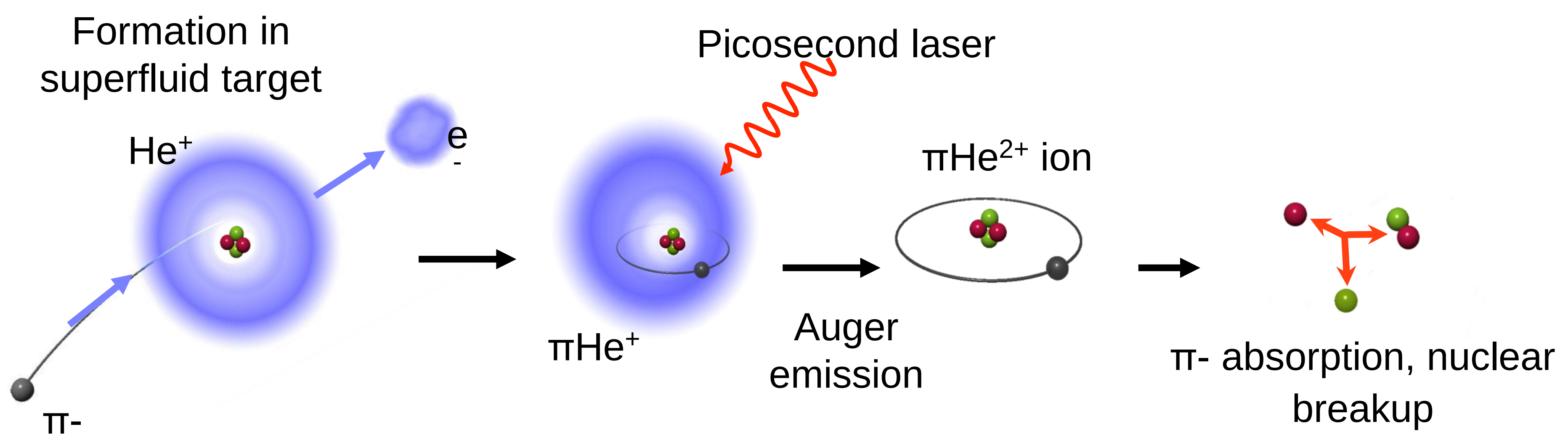
**Negatively-charged pion** in a 'circular' Rydberg orbital $n$=16, $l$=$n$-1

- **7 ns lifetime** even in liquid helium targets, >1000 times longer than other mesonic atoms.

- First laser excitation and spectroscopy of an atom containing a meson.
- Would show that this long-lived exotic object actually **exists**.
- Possibility to determine **pion mass** with $<10^{-8}$ scale precision.
- Constrain **exotic forces** involving pions, as in the antiproton case.

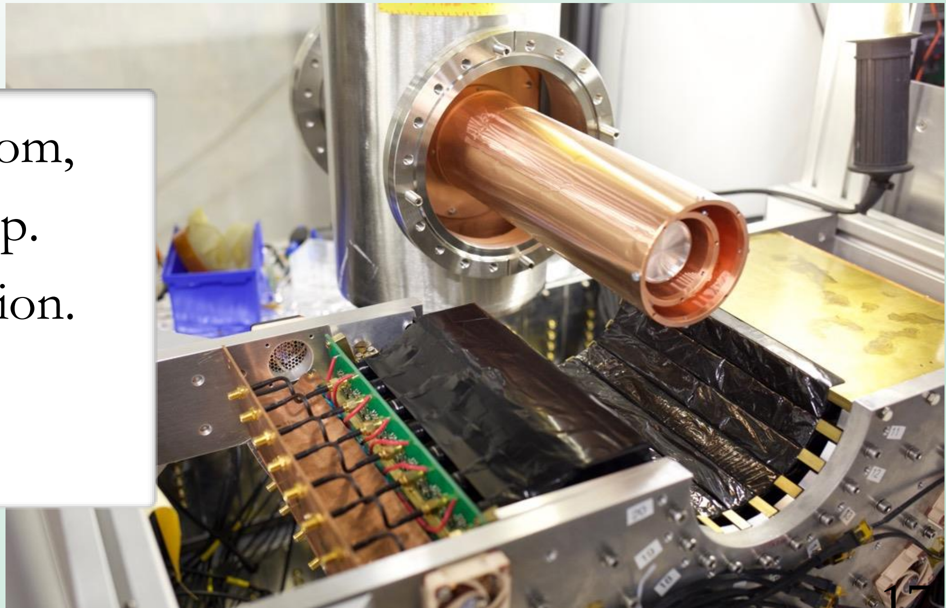
Courtesy: M. Hori

# Principle of laser spectroscopy @ PSI




- When the laser is in resonance with the atom, the nucleus absorbs the pion and breaks up.
- Attempted by MPI-PSI-CERN collaboration.

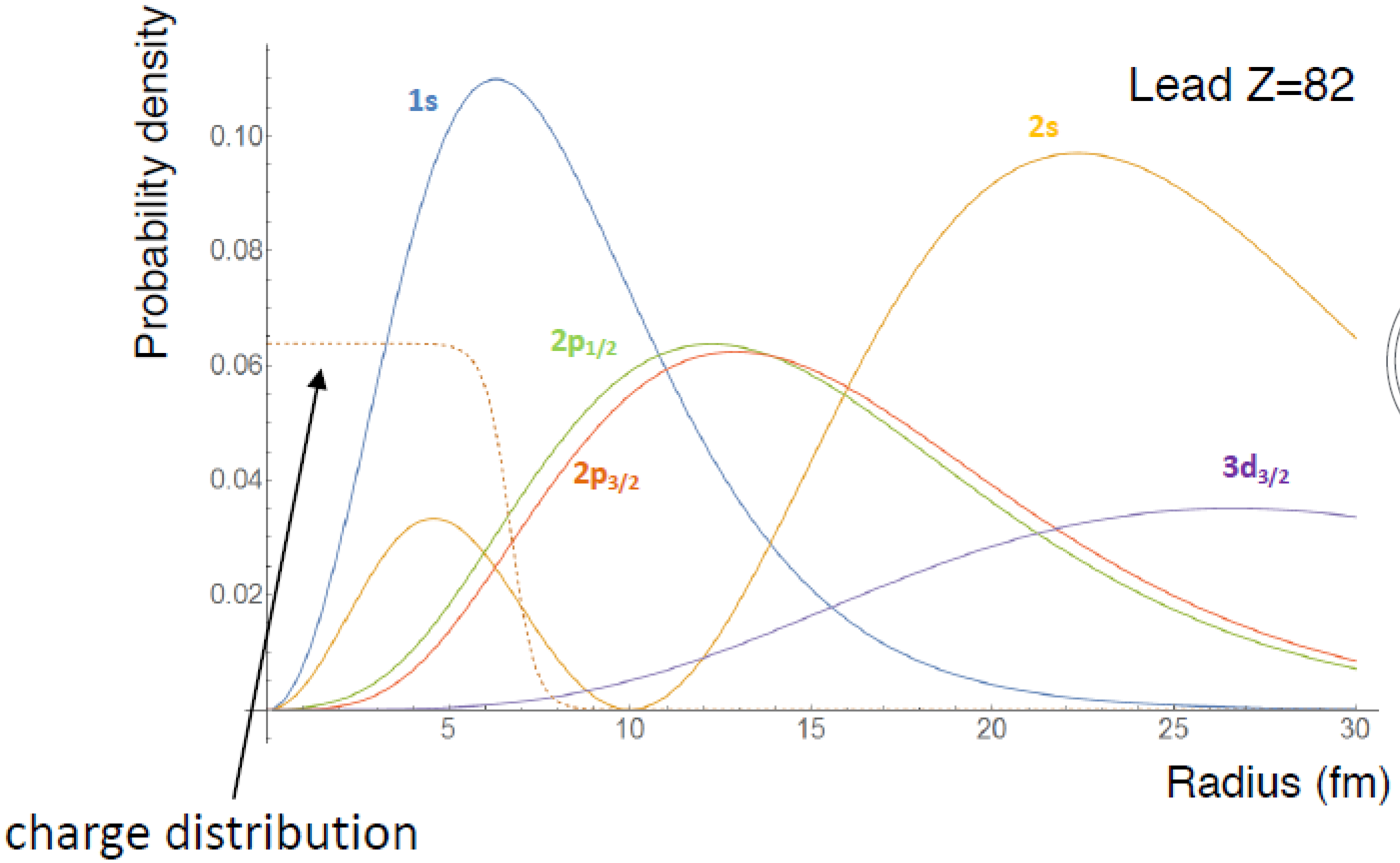
- First results submitted to a journal.

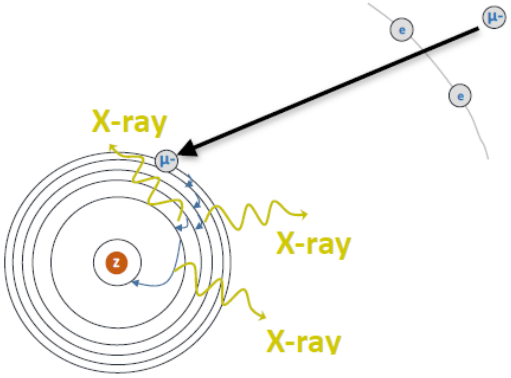


**Courtesy: M. Hori**

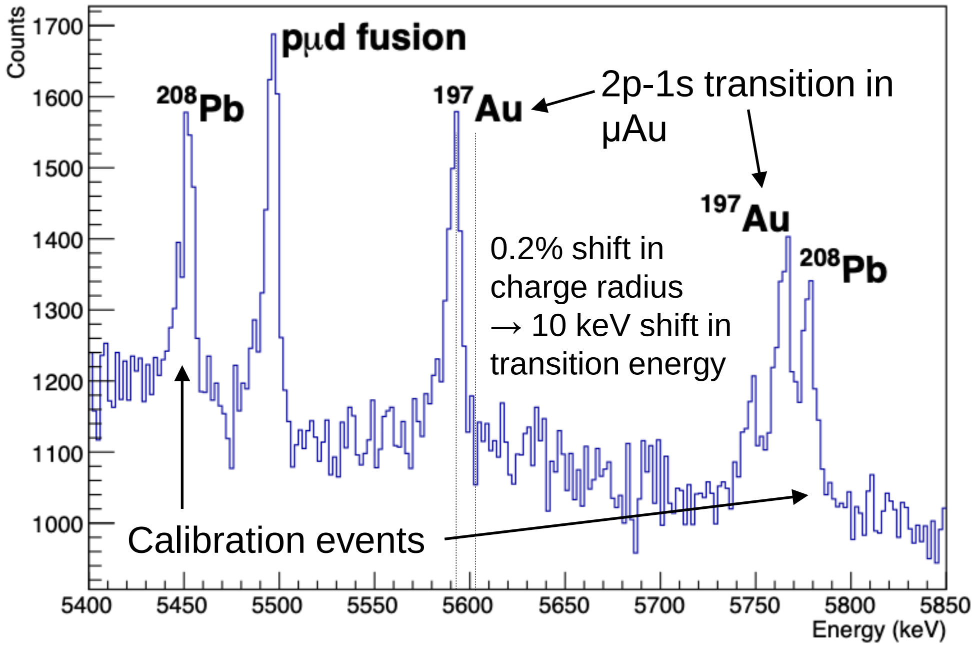
# Muonic atoms

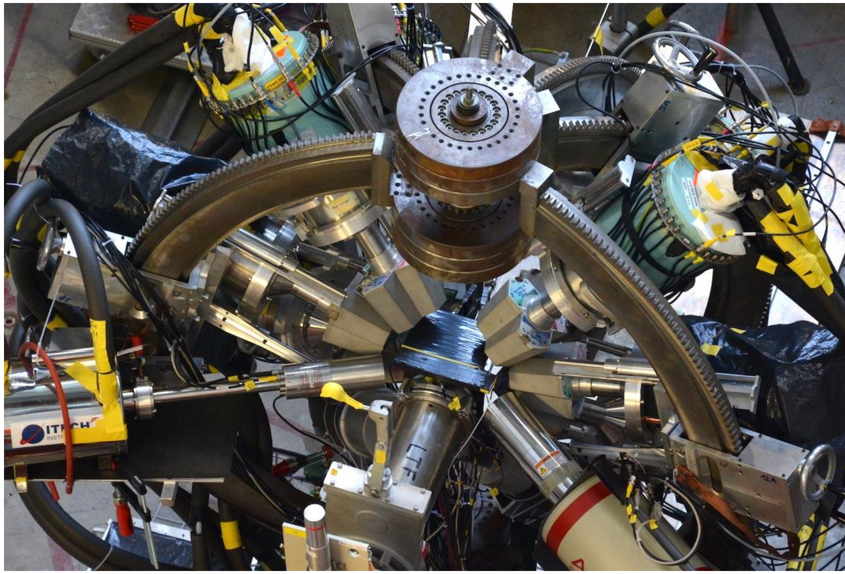
# Muonic Pb-208



# muX Experiment

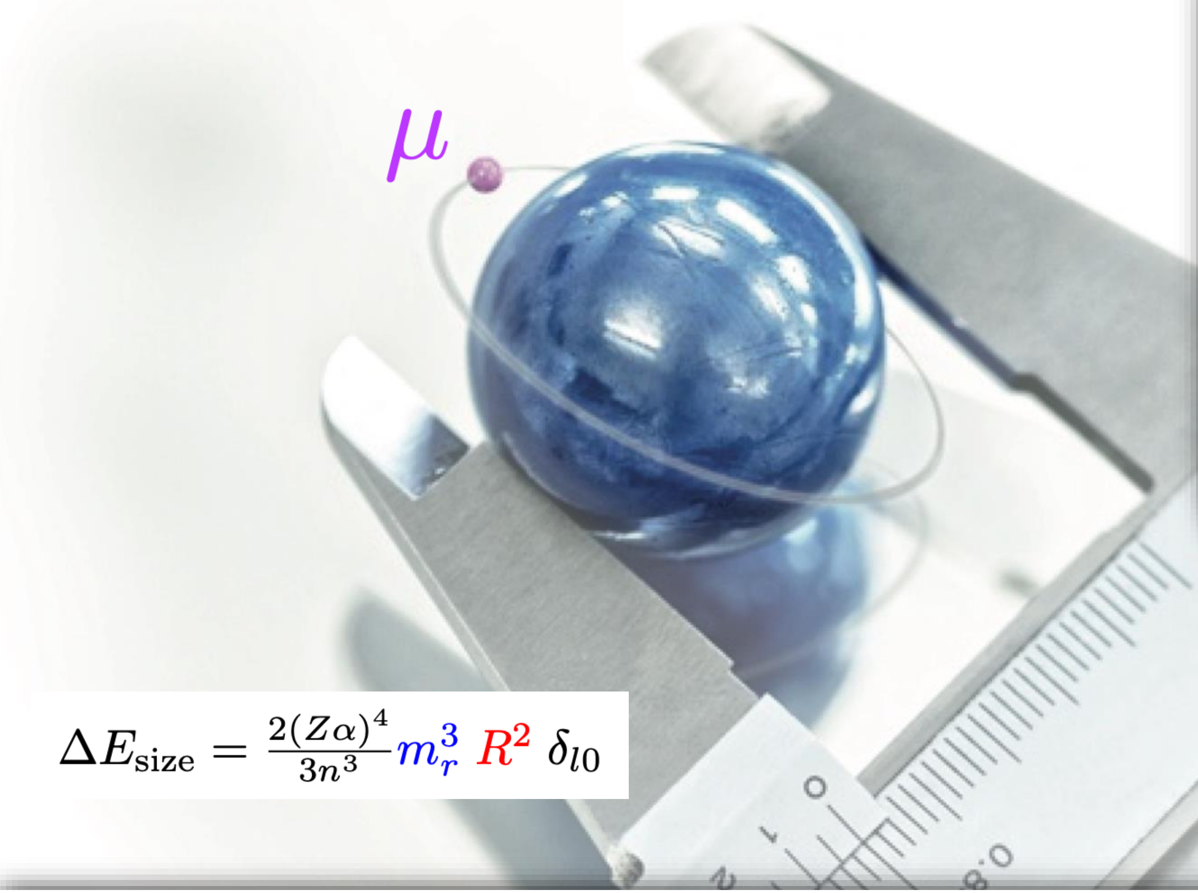


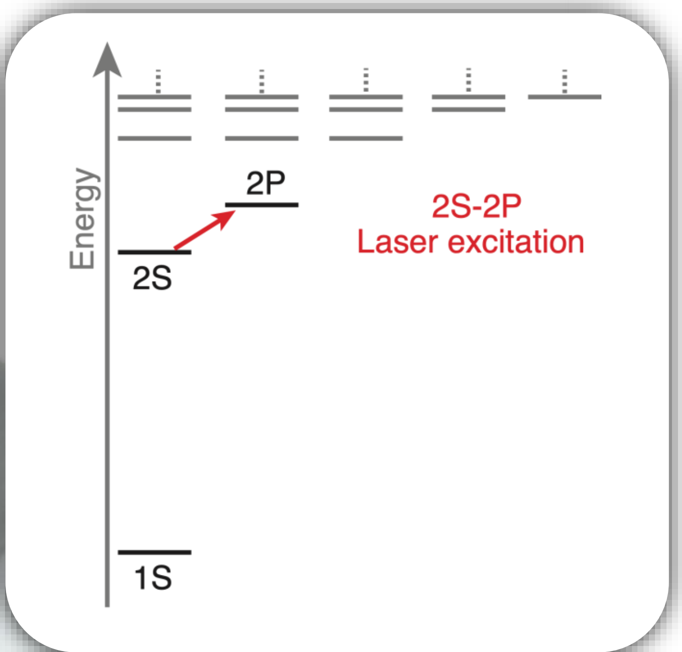



- Method developed using French/UK loan pool germanium detectors
- Proof-of-principle measurement with **5 μg** gold target
- Currently Miniball detector array at PSI:
  - Measurements of charge radii of $^{248}Cm$ and $^{226}Ra$ (relevant for atomic parity violation (APV))
  - Muon capture rate measurements relevant for neutrinoless double beta decay
  - Test of muonic APV measurement by detecting 2s-1s transition
  - Exploring elemental analysis using muons

**Courtesy: A. Knecht**

# Laser spectroscopy of light muonic atoms




$$\Delta E_{\text{size}} = \frac{2(Z\alpha)^4}{3n^3} m_r^3 \, R^2 \, \delta_{l0}$$

Measured:
ten 2S-2P transitions in
μp, μd, $\mu^3He^+$, $\mu^4He^+$
with 10 ppm accuracy

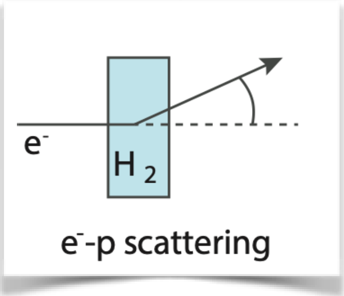
\+

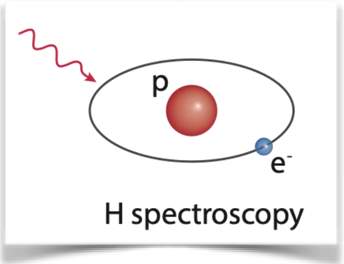
Theoretical predictions:
QED + Nuclear structure

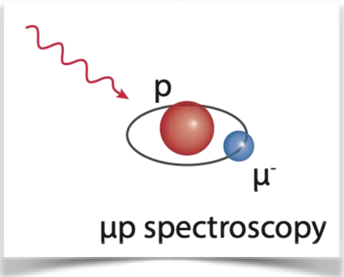
⇨

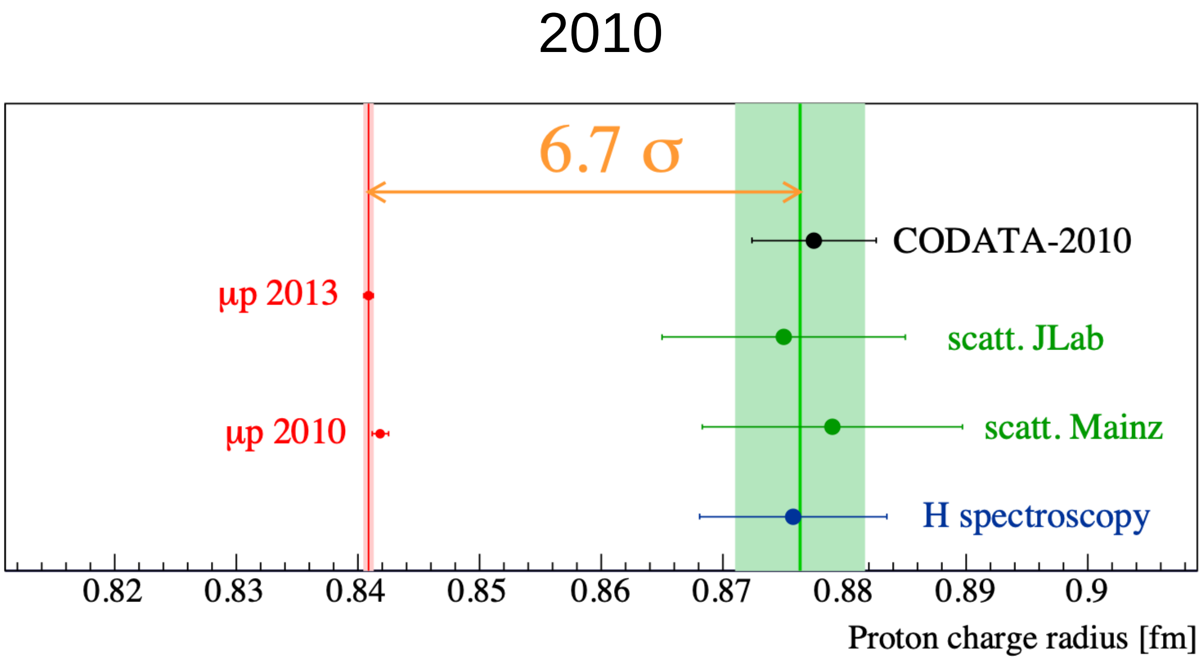
p, d, $^3He$, $^4He$
charge radii
with $10^{-3}$ red. acc.

# The proton radius puzzle



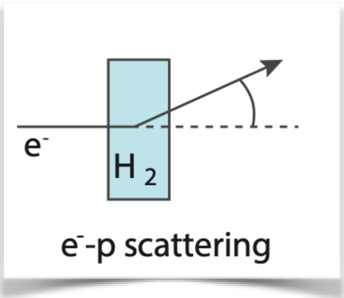



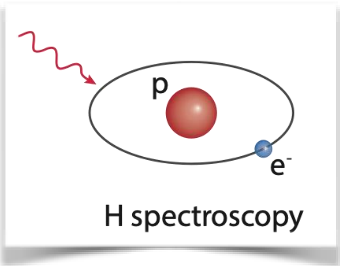



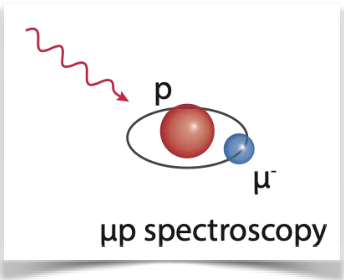

Pohl et al., Nature 466, 213 (2010)
Antognini et al., Science 339, 417 (2013)
Pohl et al., Science 353, 669 (2016)

**Courtesy: A. Antognini**

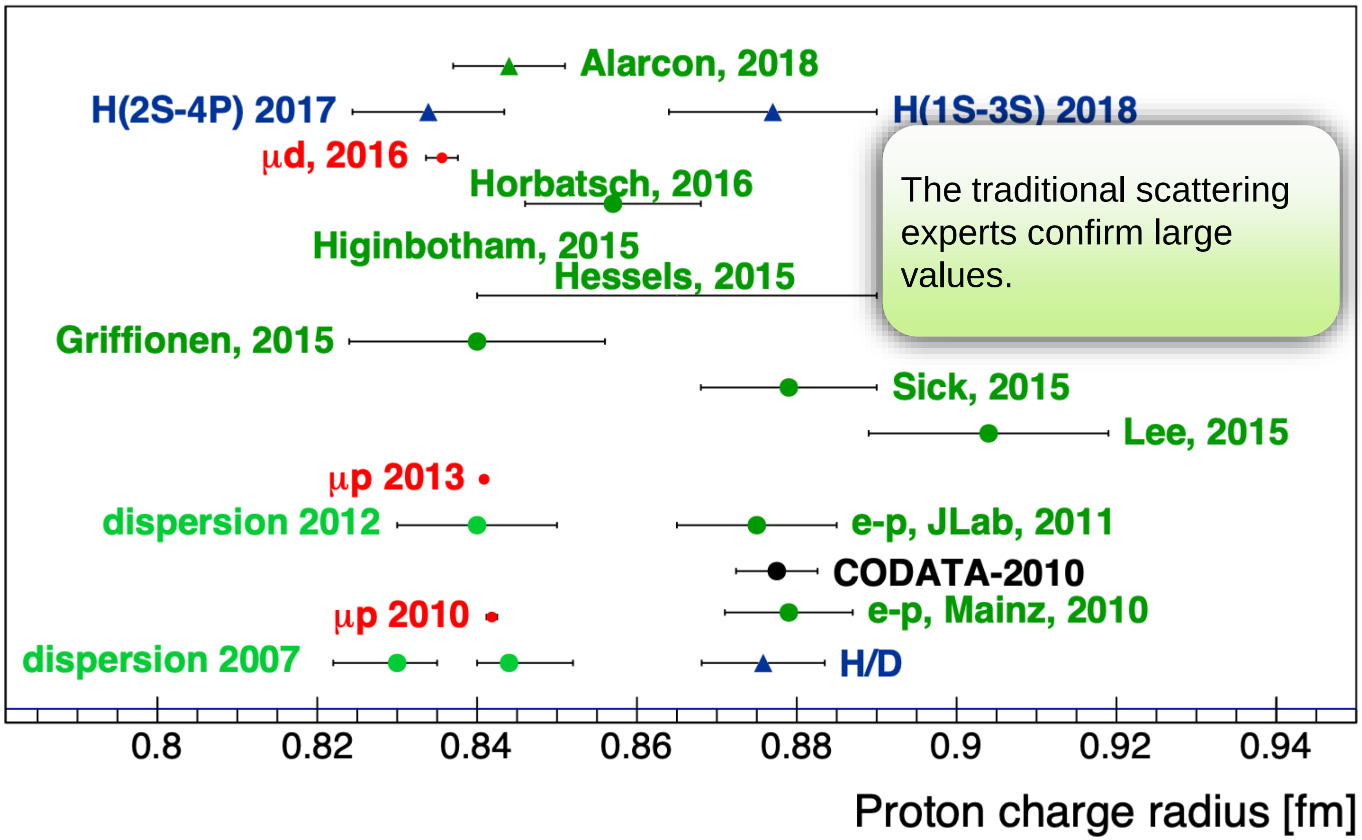
# The proton radius puzzle




2010 -2018




Courtesy: A. Antognini

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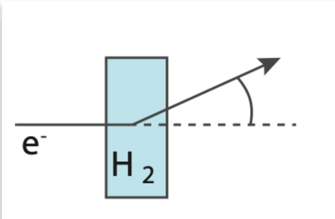
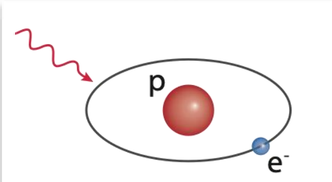
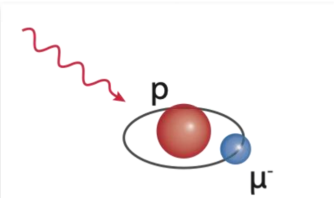


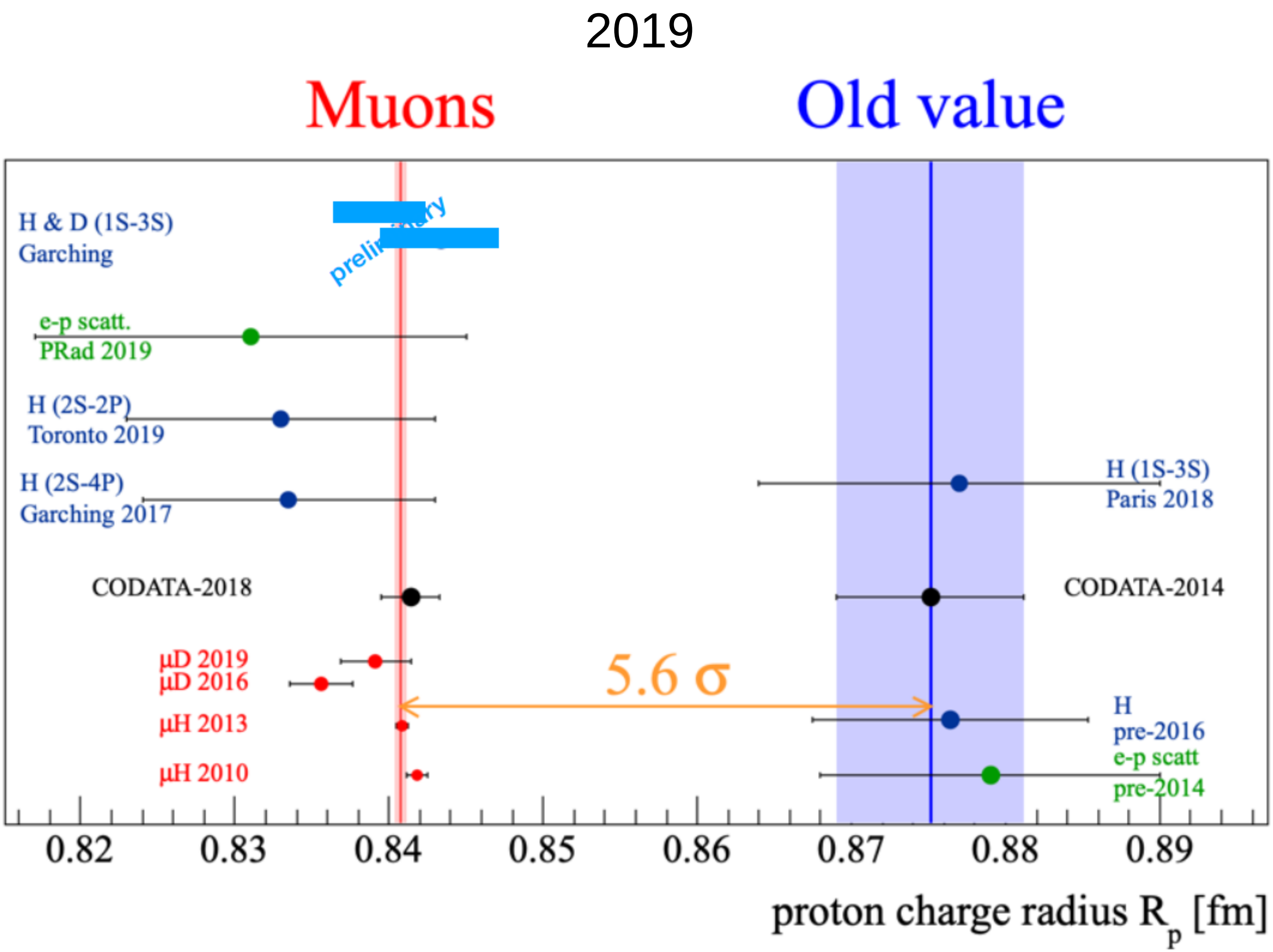
e⁻-p scattering



H spectroscopy

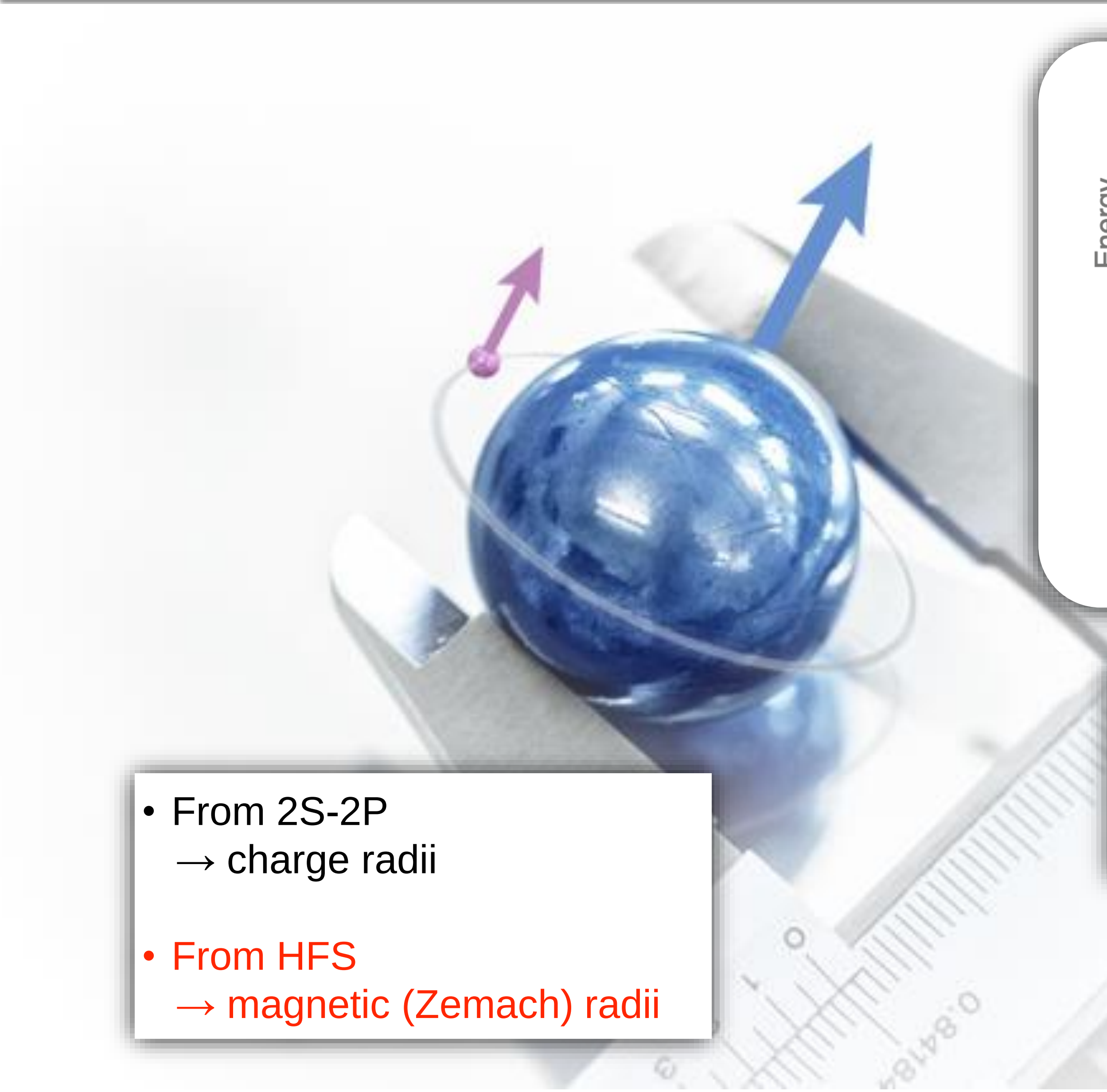


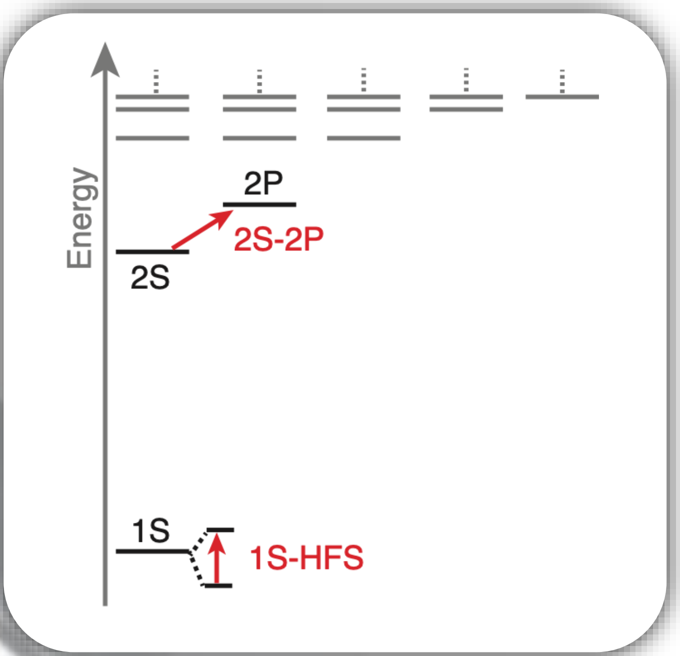
μp spectroscopy




**Courtesy: A. Antognini**

# The hyperfine splitting in μp






- 2S-2P μp
- 2S-2P μd
- 2S-2P $\mu^3He$, $\mu^4He$
- 1S-HFS μp

- From 2S-2P
  → charge radii

- From HFS
  → magnetic (Zemach) radii

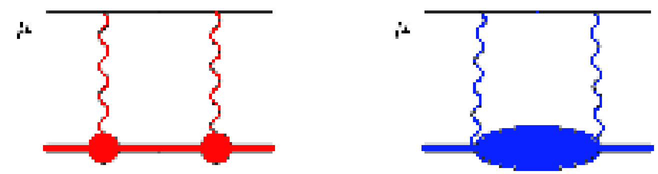
Courtesy: A. Antognini

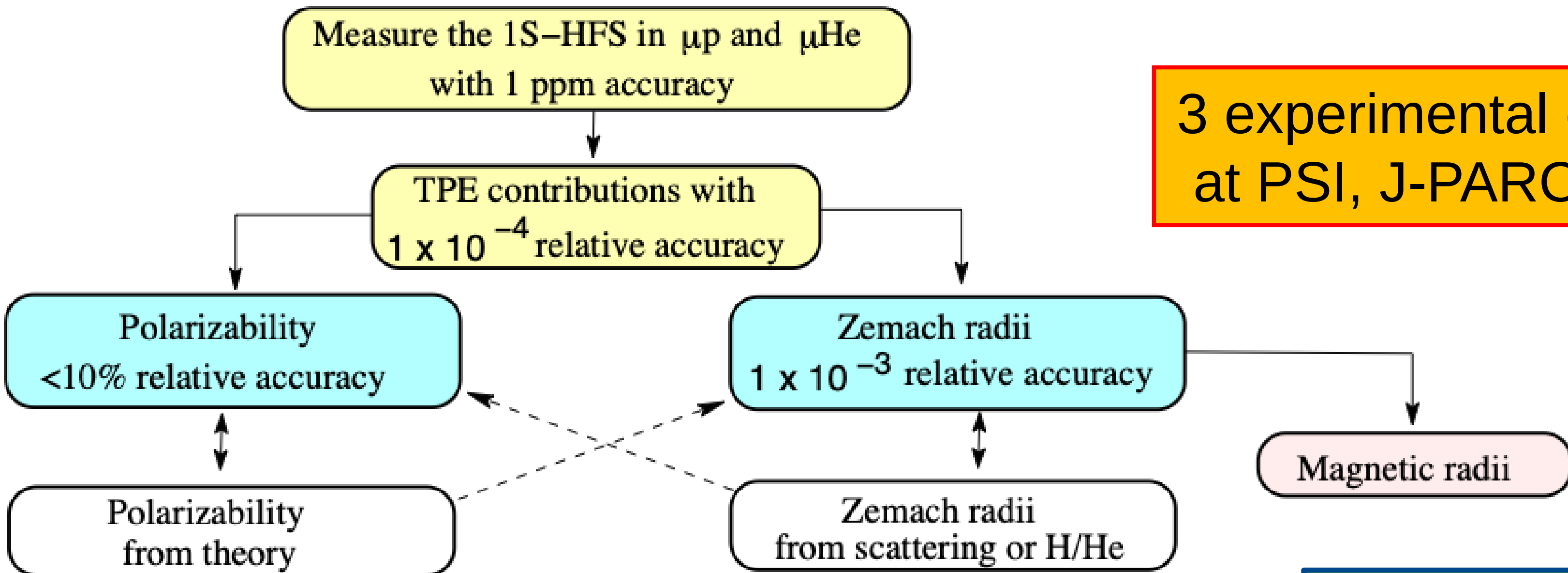
# Hyperfine splitting theory and goals

Measure for the first time the 1S-HFS in μp and μHe+ and compare them with the theoretical predictions

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

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

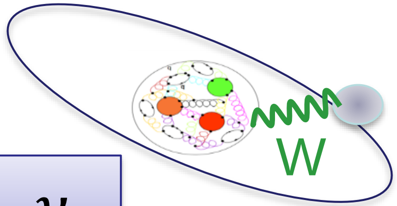





3 experimental efforts: at PSI, J-PARC, RAL

**Courtesy: A. Antognini**

# Muon capture on protons

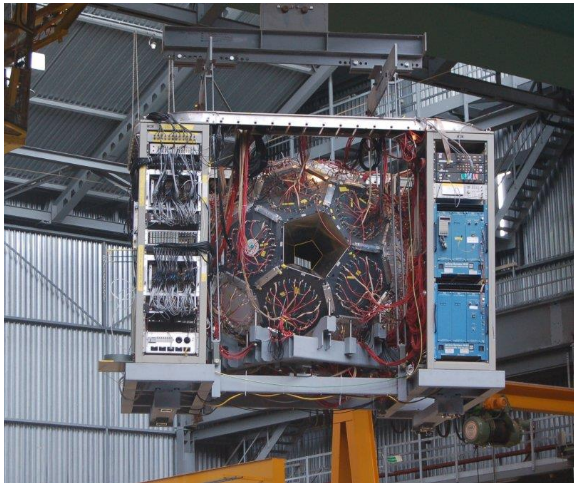



$$\mu + p \rightarrow n + \nu$$

## Positive muon lifetime: MuLan

The most precise measurement of any lifetime: **MuLan**´s $\mu^+$ and a 0.6 ppm determination of the **Fermi coupling constant**

**$\tau$ = 2 196 980.3 ± 2.2 ps (1.0 ppm)**



www.npl.washington.edu/muon/

**D.M. Webber et al., PRL 106(2011)041803**

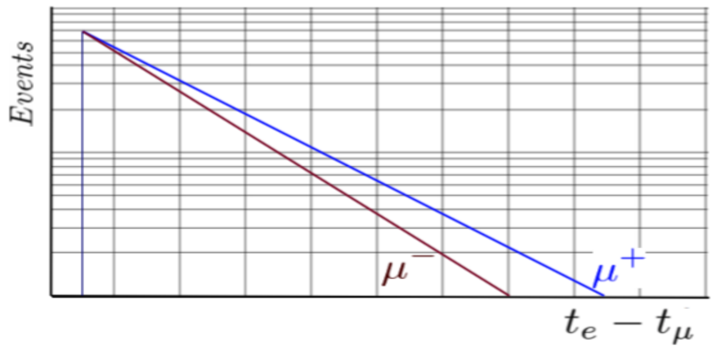
**V.A.Andreev et al., PRL 110(2013)012504**

## Negative muon lifetime: MuCAP

The most precise measurement (10ppm) of the $\mu^-$ lifetime in pure hydrogen yields **MuCap**´s 1% determination of the $\mu^-$p capture rate resolving the longstanding issue with the **Pseudoscalar coupling $g_p$**

capture rare, only 0.16% of $\mu \rightarrow e\nu\nu$

Lifetime method




$\Lambda_S = 1/\tau_{\mu-} - 1/\tau_{\mu+}$

measure lifetime to 10ppm !!

# New perspective on nucleon axial form factor

Nucleon axial radius and muonic hydrogen - a new analysis and review
R J Hill , P Kammel, W J Marciano and A Sirlin
Rep. Prog. Phys. **81** (2018) 096301

$$g_A(q^2) = g_A(0)(1 + \frac{1}{6} r_A^2 q^2 + \ldots)$$

*2% for MuCap*

- Nucleon axial radius $r_A$ has surprisingly large uncertainty

$$r_A^2(z \text{ exp.}) = 0.46 \pm 0.22 \text{ fm}^2 \qquad \nu_\mu d \to \mu^- pp$$

Phys.Rev. D93 113015, (2016)

  - basic nucleon property
  - doubles uncertainty in CCQE $\nu n \to p\mu$ cross section prediction (important for DUNE, T2HK)

- Problem and opportunity for muon capture
  - Can $g_P$ still be reliably extracted from MuCap?
  - Can one use MuCap to extract the axial radius?

Courtesy: P. Kammel

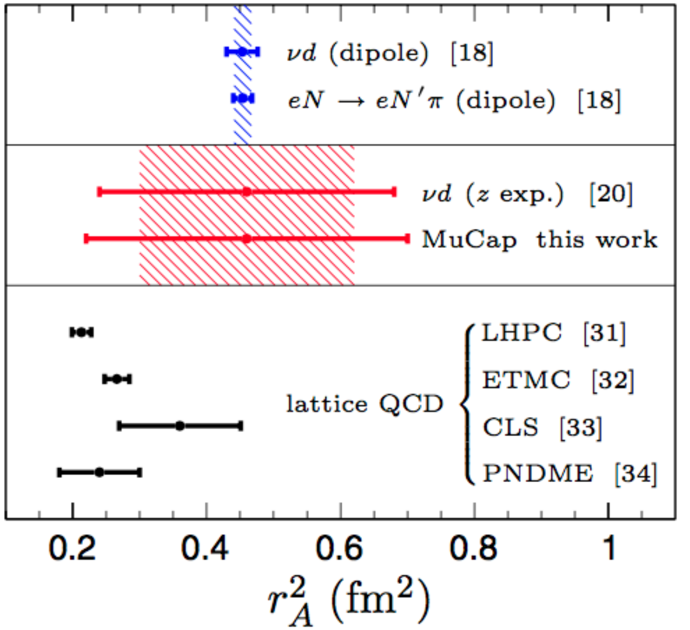
# Axial Radius from MuCap

Use

- $g_A(q^2, r_A^2)$
- $g_P(q^2, r_A^2)$ from EFT

(with $g_{\pi NN}$= 13.12(10))

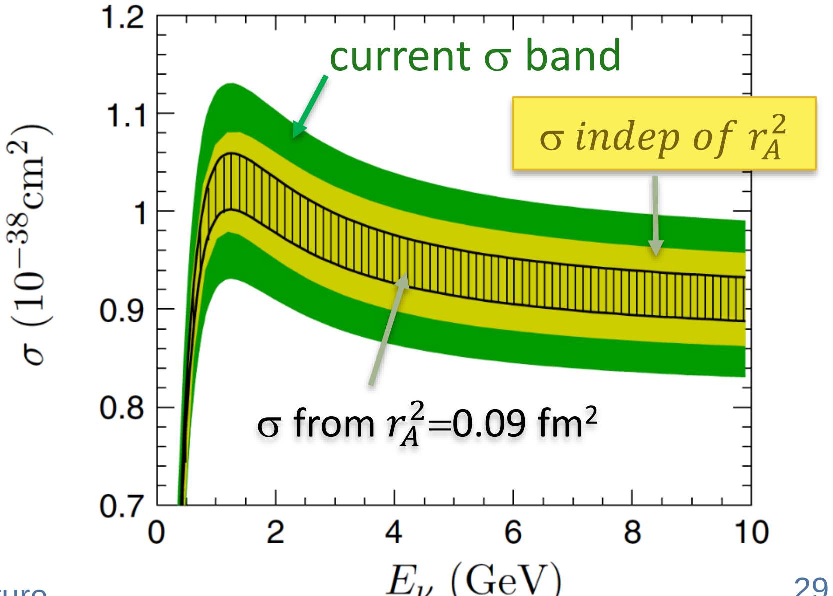
$$r_A^2(\text{ave.}) = 0.46(16)\ \text{fm}^2$$




Future **3x** improved precision MuCap experiment could reduce

- $\Delta r_A^2$ from 0.22 to **0.09** fm$^2$
- uncertainty in CCQE σ(νn) by nearly **2**

surprising leverage to GeV scale




**Courtesy: P. Kammel**

# Satellite to PSI2019 www.psi.ch/psi2019

## NuMu2019 Workshop @PSI

25-26 October 2019
PSI
Europe/Zurich timezone

- Overview
- Scope of the NuMu workshop
- Call for Abstracts
- Timetable
- Registration
- Participant List
- Homepage PSI2019

**Contact**

psi2019@psi.ch

Exploring synergies between Muon Capture and Neutrino Scattering: prospects for a next generation muon capture experiment with ultimate precision and its impact on neutrino oscillation physics.

WebEx link (video conferencing): https://psi-ch.webex.com/psi-ch/j.php?MTID=m231630f0578582ee1cd2523ce9b93975

**Starts** 25 Oct 2019, 14:00
**Ends** 26 Oct 2019, 16:00
Europe/Zurich

PSI
WHGA/001

Auditorium - Paul Scherrer Institut
Forschungsstrasse 111
5232 Viligen PSI

Peter Kammel
Federico Sanchez Nieto
Klaus Stefan Kirch
Bernhard Lauss
Stefan Ritt
Adrian Signer

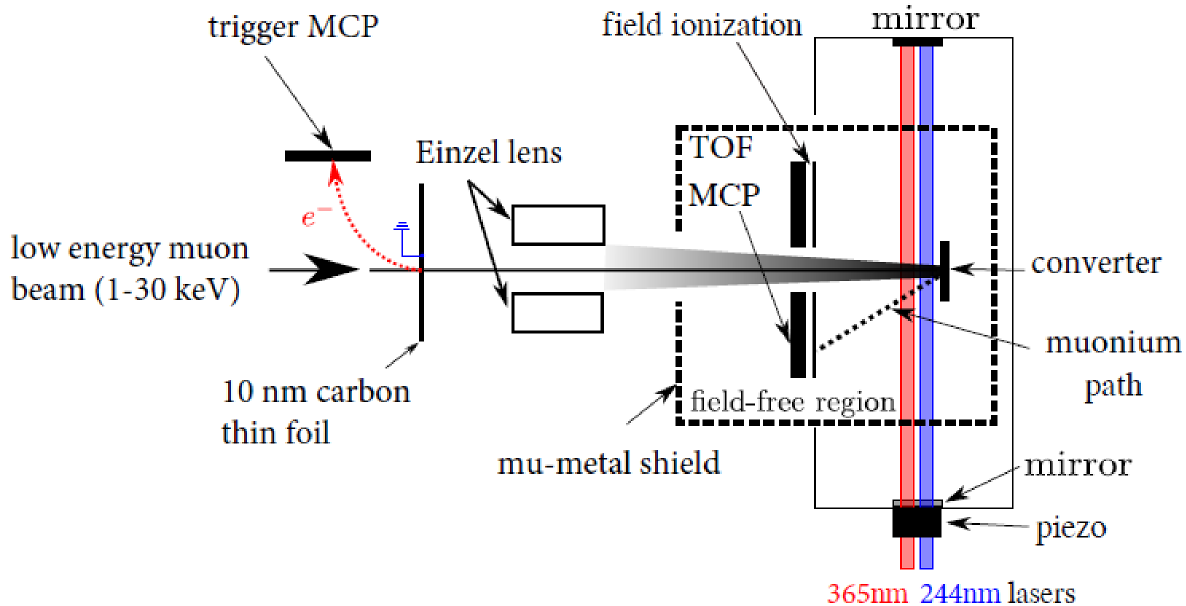
# Muonium

**Mu-MASS:** Measure **1S-2S transition** with Doppler free laser spectroscopy

**GOAL:** improve by 3 orders of magnitude (10 kHz, 4 ppt)

Crivelli, P. Hyperfine Interact (2018) 239: 49

- Low energy $\mu^+$ beam
- ↓ Muonium production
- ↓ Muonium 2S excitation
- ↓ Muonium 20P excitation
- ↓ Muonium field ionisation $\mu^+$ detection




**OUTPUT**

→ **Muon mass @ 1 ppb**

→ Ratio of $q_e/q_\mu$ @ 1 ppt

→ Test of Standard Model Extension

→ **Rydberg constant @ ppt level**

→ **Test of bound state QED ($1\text{x}10^{-9}$)**

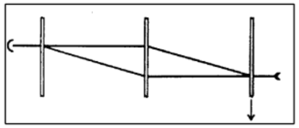
→ New determination of $\alpha$ @ 1 ppb

**STATUS AND PLANS:**

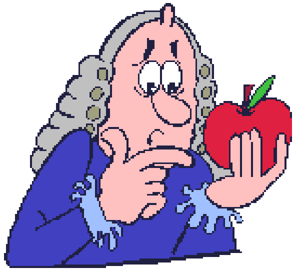
- laser system and detectors being prepared
- test at the PSI low energy muon beam line, Dec19
- Data taking starting end of 2020

PAUL SCHERRER INSTITUT PSI — Colorado State — IPA — ETH zürich — erc

**Courtesy: P. Crivelli**



# Testing Gravity with Muonium:



**The mass of M ($\mu^+e^-$) is to 99.5% given by an antimatter lepton of the 2nd generation.**

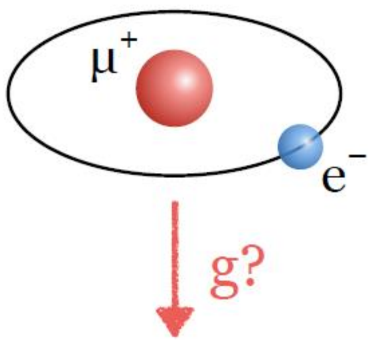
**Will it fall just as ordinary matter does?**

**„It would be the first test of gravity, i.e. general relativity, in the realm of antimatter (*and of the the 2nd generation*).
Even if the experiment finds exactly what one expects,
it would be a classic, one for the text books …
Of course, if a new effect were found,
then there would be no telling
what exciting physics could follow."**

(freely quoted from Nieto&Goldman [1991] wrt antiprotons)

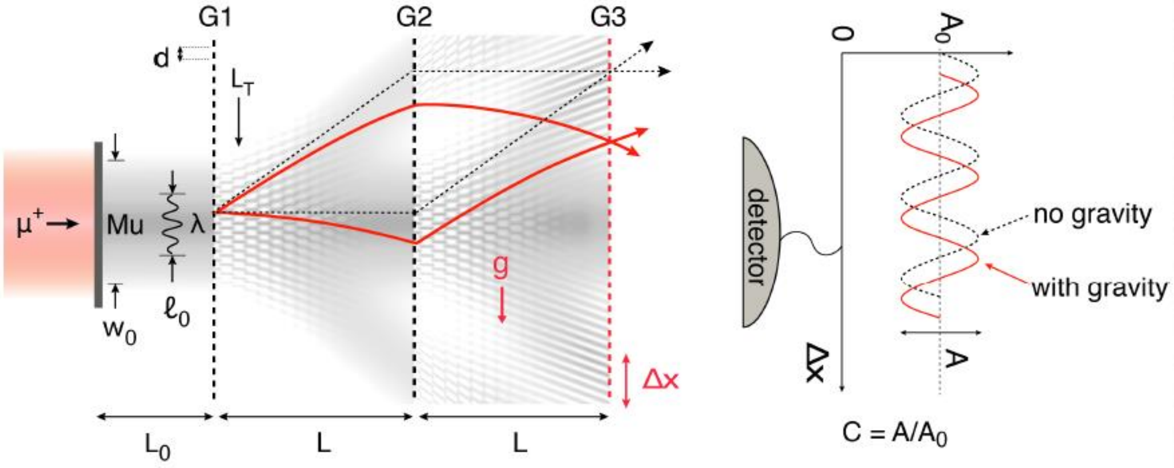
# Exotic gravity experiment using muonium

**Muonium: exotic atom with elementary antimatter**




Test of the weak equivalence principle using second generation leptonic antimatter

**Method: atomic interferometer**




Sensitivity: $$\Delta g \approx \frac{1}{2\pi T^2}\frac{d}{C\sqrt{N}}$$

Small grating period ($d$~100 nm) to measure sub-nm shifts

Interaction time with gravity~ few μs !

Large contrast ($C$~0.3)
Many atoms ($N_0$~$10^4$/s)

**Courtesy: A. Soter**

# Exotic Atoms

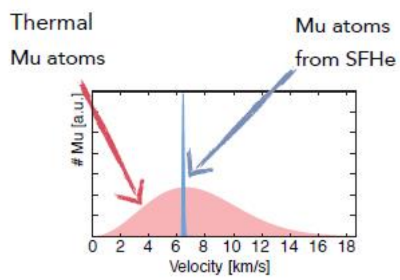
- Broad spectrum in fundamental physics between atomic, nuclear and particle physics
- Major progress from novel exotic particle sources, laser spectroscopy, traps and modern detection technology
- Many exciting and challenging projects ahead
- Often PhD students and young postdocs can make a difference

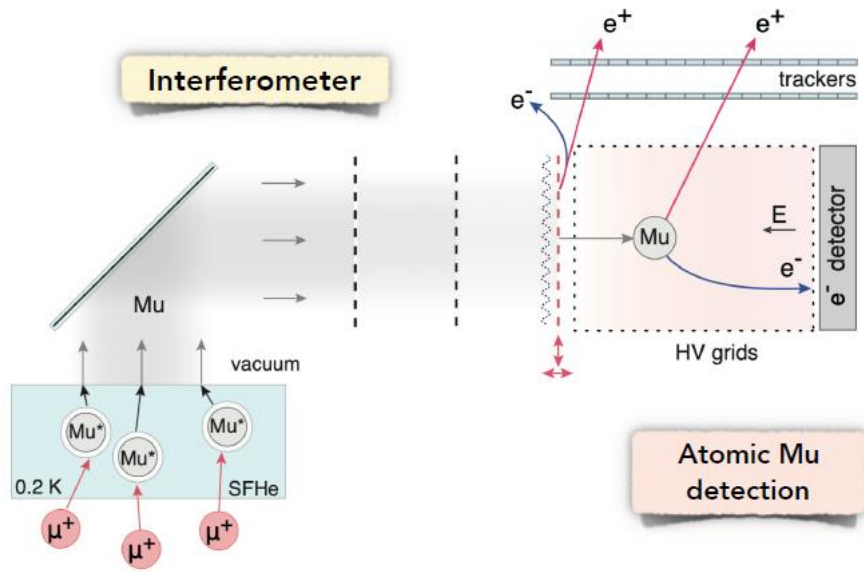

Thank you!

# Backup

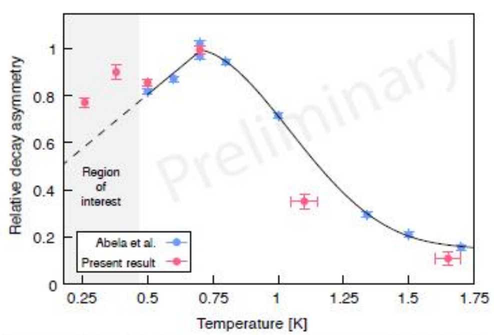
# Cold Mu from superfluid He: developments at PSI and ETHZ

**$\mu^+ \rightarrow$ vacuum Mu conversion in superfluid helium (SFHe)**

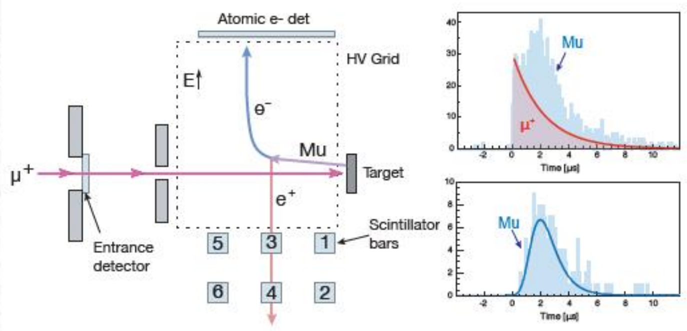



## Efficient (>70%) Mu production @ 0.25 K

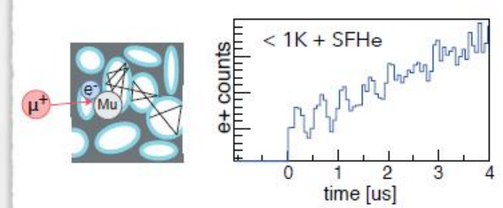



## Background-free detection of vacuum Mu



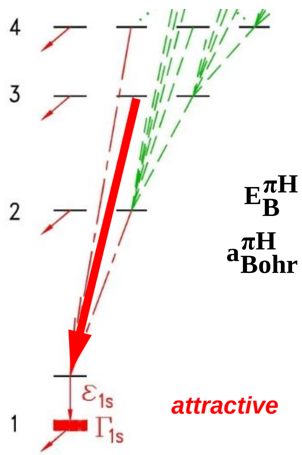

## Mu in SFHe-coated nanopores

- Hints of free Mu precessing in aerogel nanopores coated with superfluid He



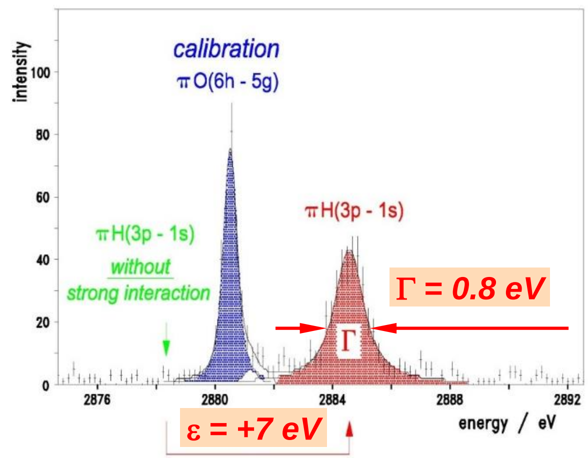

**Courtesy: A. Soter**

# PIONIC HYDROGEN LEVEL SHIFT $\varepsilon_{1S}$ and BROADENING $\Gamma_{1S}$




$E_B^{\pi H} = -3238$ eV

$a_{Bohr}^{\pi H} = 140$ fm




*measured X-ray lines*

πH(2p-1s)

πH(3p-1s)

πH(4p-1s)

$H_2$ density 0.5% - 100% $LH_2$

| | *only 2 independent scattering lengths* $a^+$ *and* $a^-$ | | | $\Delta$ *experiment* | *Trueman correction* | $\chi PT$ * |
|---|---|---|---|---|---|---|
| πH | *elastic scattering* $\pi^- p \to \pi^- p$ | $\varepsilon_{1s} \propto a^+ + a^-$ | + … | ± 0.2% | … ≈ 1% | + (–9.0 ± 3.5)% |
| | *charge exchange* $\pi^- p \to \pi^0 n$ | $\Gamma_{1s} \propto (a^-)^2$ | + … | ± 2.6% | … ≈ 1% | + (+0.5 ± 1.0)% |
| πD | *coherent sum* $\pi^- p \to \pi^- p + \pi^- n$ | $\varepsilon_{1s} \propto 2 \cdot a^+$ | + … | ± 1.3% | … ≈ 1% | + ± 4% |

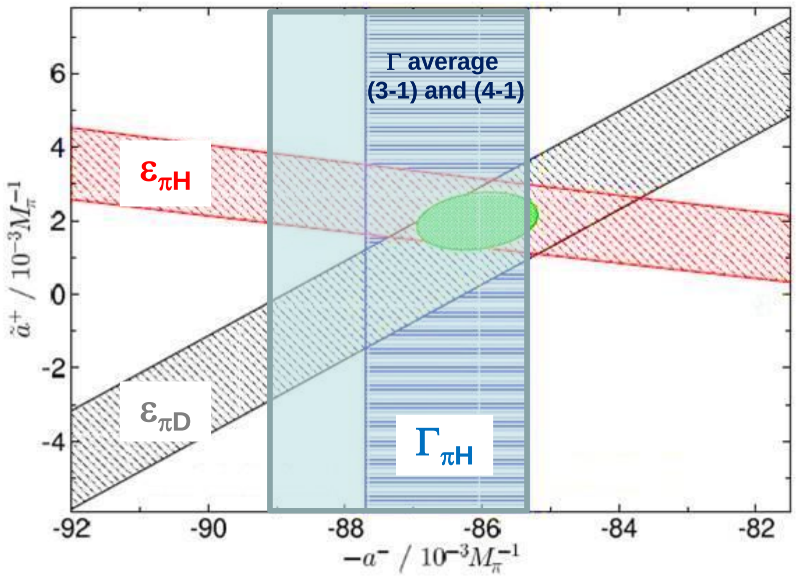

* J. Gasser et al., Phys. Rep. 456 (2008) 167
M. Hoferichter et al., Phys. Lett. B 678 (2009) 65
V. Baru et al., Phys. Lett. B 694 (2011) 473


Courtesy: D. Gotta

# $\pi N$ *ISOSPIN SCATTERING LENGTHS* $a^+$ *and* $a^-$

Δ exp (*Coulomb de-excitation*) ≈ 3 × Δ theory

Δ exp << Δ theory




Δ exp << Δ theory

FIG. 2: Combined constraints in the $\tilde{a}^+$–$a^-$ plane from data on the width and energy shift of $\pi H$, as well as the $\pi D$ energy shift.

*χPT: J. Gasser et al., Phys. Rep. 456 (2008) 167*
*M. Hoferichter et al., Phys. Lett. B 678 (2009) 65*
*V. Baru et al., Phys. Lett. B 694 (2011) 473*
*data: πH - R-98.01 : D. Gotta et al., Lect. Notes Phys. 745 (2008) 165*
*M. Hennebach et al., Eur. Phys. J. A 50 (2014) 190*
*πD - R-06.03 : Th. Strauch et al., Eur. Phys. J. A 47 (2011) 88*

- consistency ✓
- $\varepsilon_{\pi D}$ decisive constraint
- $a^+ > 0$ **!**

***large discrepancy*** ***between pionic-atoms analysis and***
$a^+ = -15 \cdot 10^{-3} M_\pi^{-1}$ ***from lattice*** $\sigma$ ***– term***

*Hoferichter et al. , arXiv: 1602.07688v2*
*Crivellin et al., Phys. Rev. D 89, 054021 (2014)*
*Ellis et al., Phys. Rev D,065026 (2008)*
*…*

***Outlook***

- high statistics experiment of $\pi$H(4-1) and $\pi$H(5-1) lines:
*less Coulomb de-excitation*

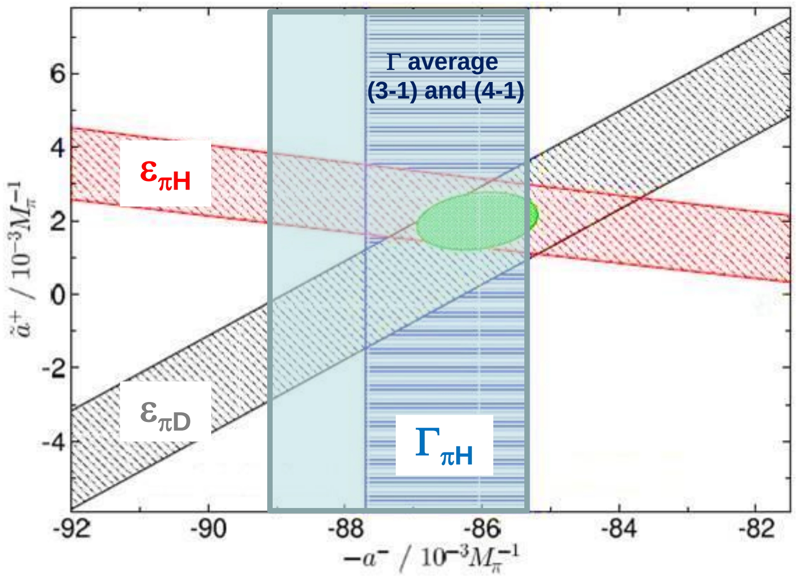
$\Delta\Gamma/\Gamma$ 3% → 1%

**Courtesy: D. Gotta**

# πN ISOSPIN SCATTERING LENGTHS $a^+$ and $a^-$

Δ exp (*Coulomb de-excitation*) ≈ 3 × Δ theory

Δ exp << Δ theory

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*V. Baru et al., Phys. Lett. B 694 (2011) 473*
*data:* *πH - R-98.01 : D. Gotta et al., Lect. Notes Phys. 745 (2008) 165*
*M. Hennebach et al., Eur. Phys. J. A 50 (2014) 190*
*πD - R-06.03 : Th. Strauch et al., Eur. Phys. J. A 47 (2011) 88*

**Courtesy: D. Gotta**

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- $\varepsilon_{\pi D}$ decisive constraint
- $a^+ > 0$ **!**

***large discrepancy* between pionic-atoms analysis *and***
***$a^+ = -15 \cdot 10^{-3} M_\pi^{-1}$ from lattice σ* term***

*Hoferichter et al. , arXiv: 1602.07688v2*
*Crivellin et al., Phys. Rev. D 89, 054021 (2014)*
*Ellis et al., Phys. Rev D,065026 (2008)*
*…*

***Outlook***

- high statistics experiment of πH(4-1) and πH(5-1) lines:
*less Coulomb de-excitation*

*ΔΓ/Γ 3% → 1%*

*precise knowledge of the πN σ-term is important for many experiments from DM direct detection to μ→e conversion

# *MASS of the CHARGED PION*

***simultanuous measurement with curved crystal spectrometer***

***$N_2$ /$O_2$ mixture (10% / 90%) @ 1.4 bar***

***history***

***with exotic atoms***

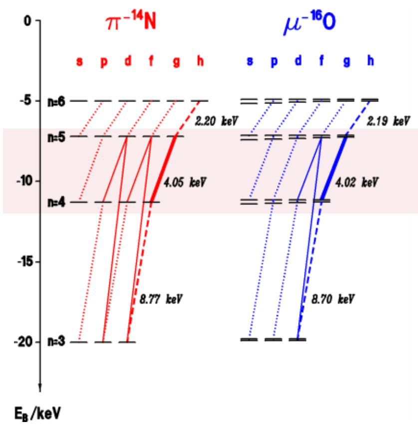
***measurement*** ***calibration***

- **point like Coulomb potential**
- **no electron screening**
- $E_{\mu O(5g-4f)} / E_{\pi N(5g-4f)} = m_\mu / m_\pi + \ldots$

$m_\pi = 139.57077 \pm 0.0018$ ***eV***

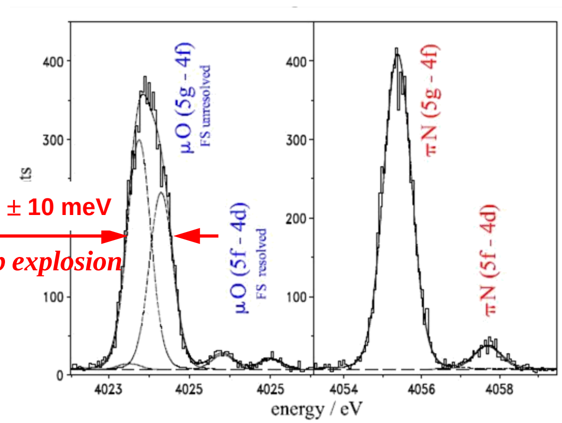
***( ± 1.3ppm)***

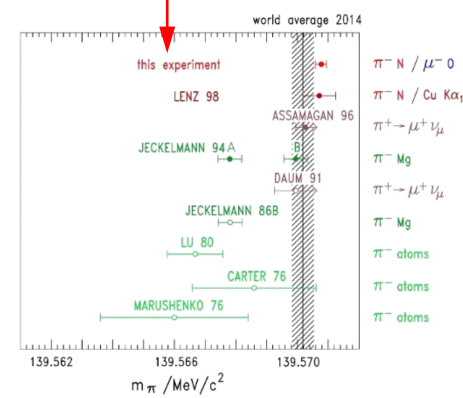
***M. Trassinelli et al., Phys. Lett. B 759 (2016) 583***




**ΔE = 750 ± 10 meV**

***Coulomb explosion***

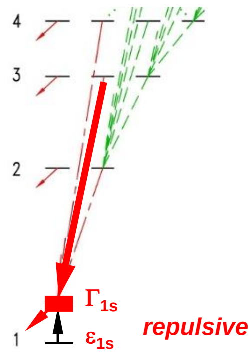


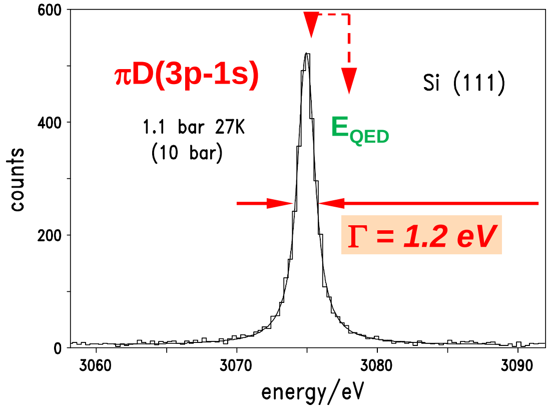




| | | |
|---|---|---|
| ***Outlook*** | ***- $\pi^-$Ne (no Coulomb explosion) and double flat crystal spectrometer*** | ***Δm/m → 0.5ppm*** |
| | ***- Laser-induced excitation of metastable $\pi^-He^+$ states*** | ***Δm/m → 0.1ppm*** |

**Courtesy: D. Gotta**

# $NN \Leftrightarrow \pi NN$ threshold parameter $\alpha$



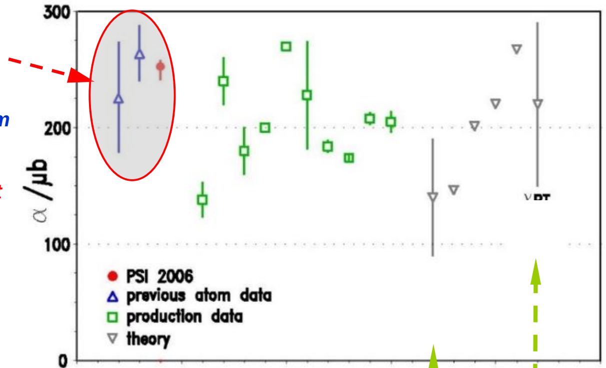




*Th. Strauch et al., Phys.Rev.Lett.104 (2010)142503; Eur.J.Phys.47 (2011)88*

*exotic-atom results*

*earlier πD-atom results*

*new PSI result*




*charge symmety* *detailed balance (T invariance)*

$\sigma_{\pi^- d \to nn} \leftrightarrow \sigma_{\pi^+ d \to pp} \leftrightarrow \sigma_{pp \to \pi^+ d}$

*only 1 parameter α*

πD *„true“ absorption* $\pi^- d \to nn$ $\Gamma_{1s} \propto \alpha + \ldots$

*Δ experiment*

$+2\%$
$-4\%$

χPT

*at present*

$\Delta\alpha/\alpha \approx 30\%$

→ few % !?

χPT NLO

χPT LO

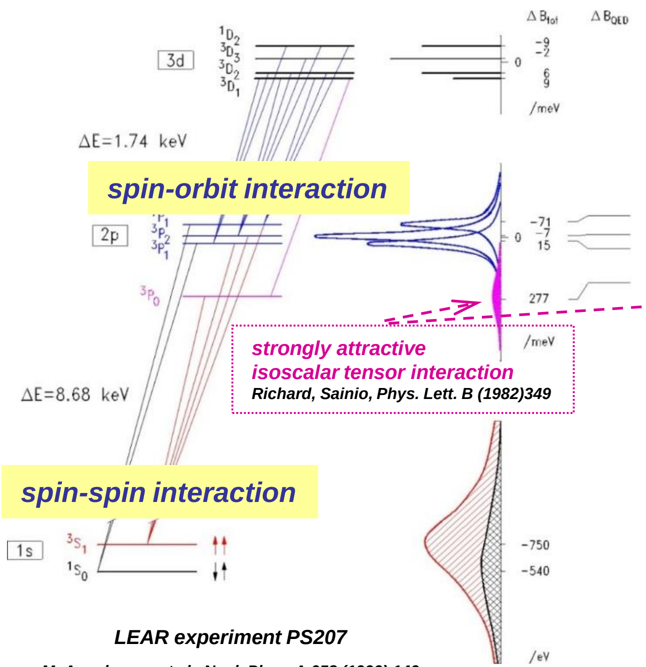
*V. Lensky et al., Eur. Phys. J. A 27 (2006) 37*

*Outlook* — *high statistics experiment* $\Delta\Gamma/\Gamma \to 1\%$

— *theoretical progress needed*

**Courtesy: D. Gotta**

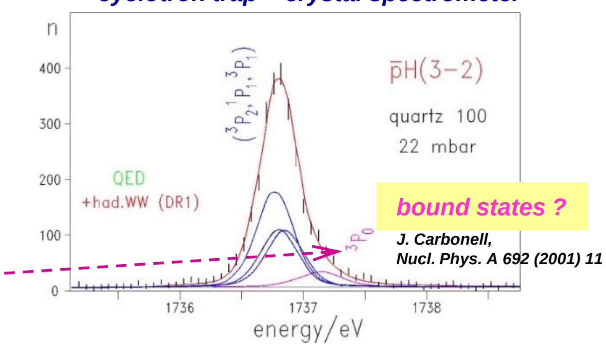
# PROTONIUM - SEARCH for HFS



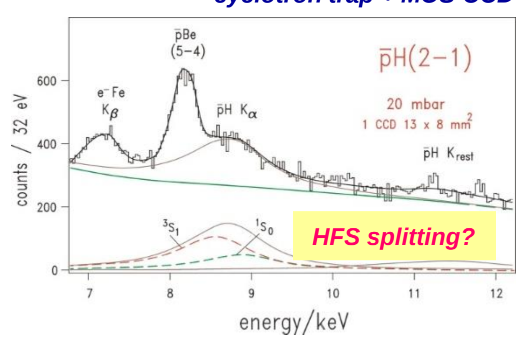

**LEAR experiment PS207**

*M. Augsburger et al., Nucl. Phys. A 658 (1999) 149*
*D. Gotta et al., Nucl. Phys. A 660 (1999) 283*

*cyclotron trap + crystal spectrometer*




*cyclotron trap + MOS CCD*




## *Outlook*

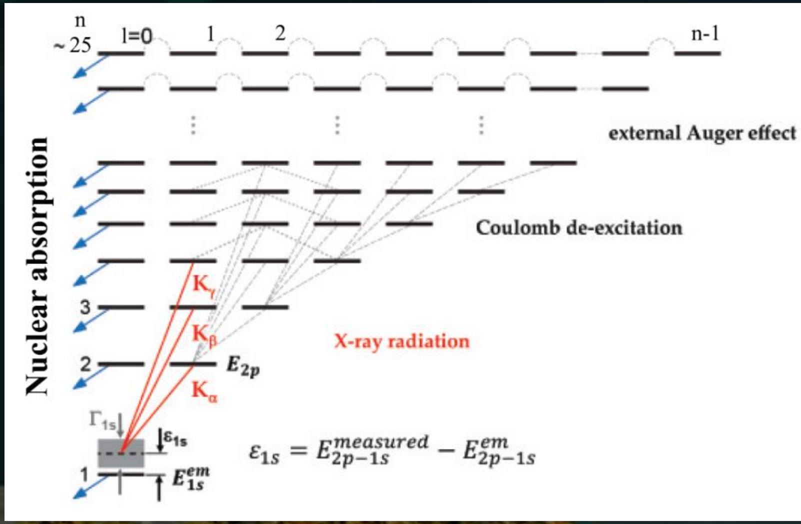
- **2p state:**
  **better resolution**
  ***factor of 2 possible***
- **1s state:**
  **much higher statisctics**
  **lower background**
  ***fast read-out CCDs***
- ***mandatory:***
  ***≥ LEAR-type beams***

**Courtesy: D. Gotta**

# Kaonic atoms spectroscopy: overview and perspectives

**Kaonic atoms are fundamental tools for studying the QCD with strangeness in non-perturbative regime, to investigate:**

- **Explicit and spontaneous chiral symmetry breaking**
- **Role of strangeness in Neutron Stars (EOS)**




***Kaonic atom cascade to the fundamental level where the strong interaction shifts and broadens the level -> measured by X ray spectroscopy***

**Kaonic atoms research is being performed at:**

- **DAΦNE collider at LNF-INFN (Italy): SIDDHARTA, SIDDHARTA-2 experiments**
- **J-PARC in Japan: E57 and E62 experiments**

**SIDDHARTA performed the most precise measurement of kaonic hydrogen: Phys. Lett. B704 (2011), 113; of kaonic helium-3 and -4, Phys. Lett. B 681 (2009), 310, Phys. Lett. B 697(2011) 19, Eur.Phys.J. A50 (2014) 91**

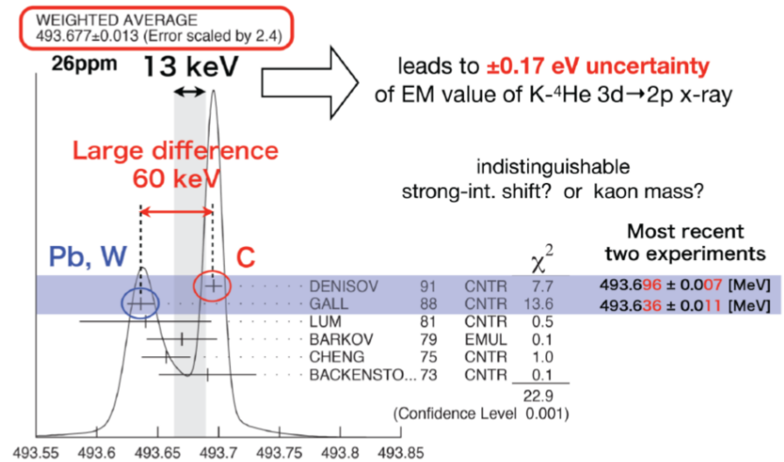
**Courtesy: C. Curceanu**

# *Future programme and perspectives*
# at DAΦNE and J-PARC

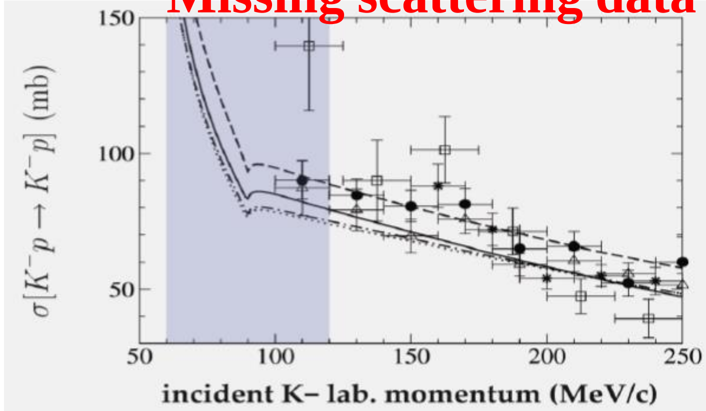
Courtesy: C. Curceanu

- Kaon mass - precision measurement at a level < 3-5 keV by low-Z kaonic atoms
- Kaonic helium transitions to the 1s level
- Other light kaonic atoms ($K^-O$, $K^-C$,…)
- Heavier kaonic atoms ($K^-Si$, $K^-Pb$…)
- Radiative kaon capture – Λ(1405) study
- Investigate the possibility of the measurement of other types of hadronic exotic atoms (sigmonic hydrogen ?)
- Studies of kaon-nuclei interactions at low-energies (E15 at J-PARC and AMADEUS at DAFNE)

**Kaon mass problem**




**Missing scattering data**



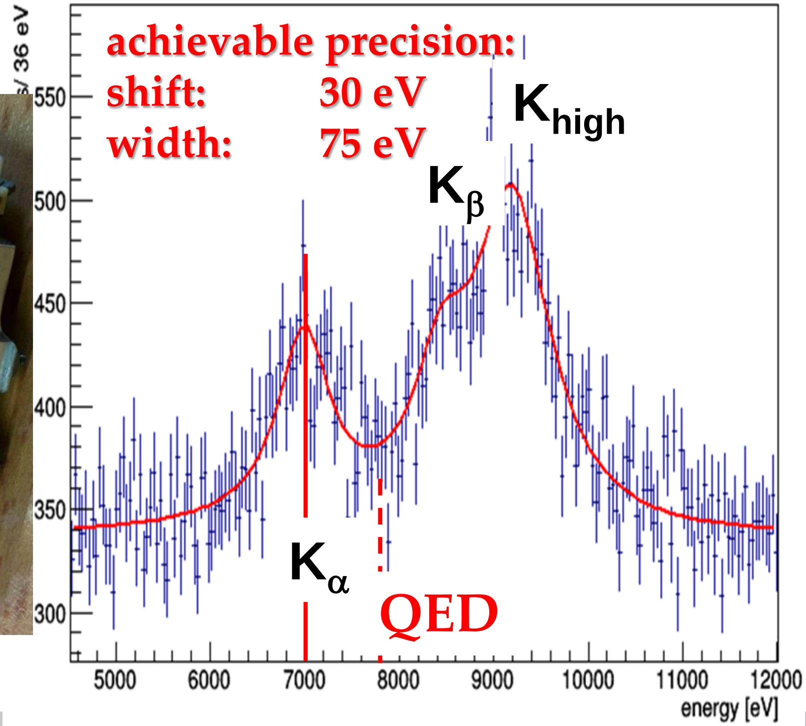

*More infos: "The modern era of light kaonic atom experiments"*
*Rev. Mod. Phys 91(2019)025006*

# Exotic atoms at DAΦNE

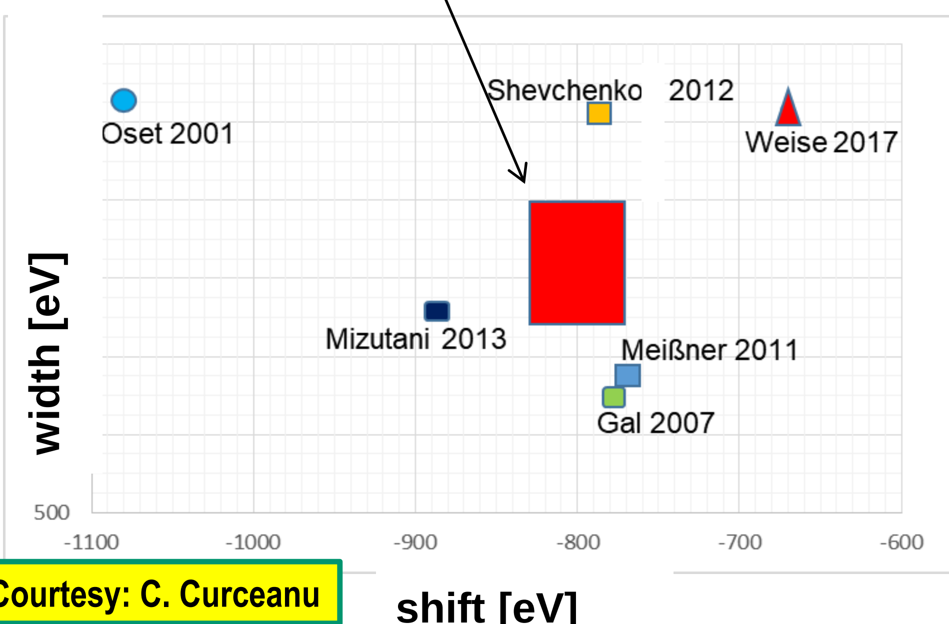
## *SIDDHARTA-2 experiment:*

***Kaonic deuterium in 2019-2020:***

***800 pb$^{-1}$*** **to perform the first measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state (similar precision as $K^-p$) with new <u>SDD detectors</u>**




**Theories and SIDDHARTA-2 precision**



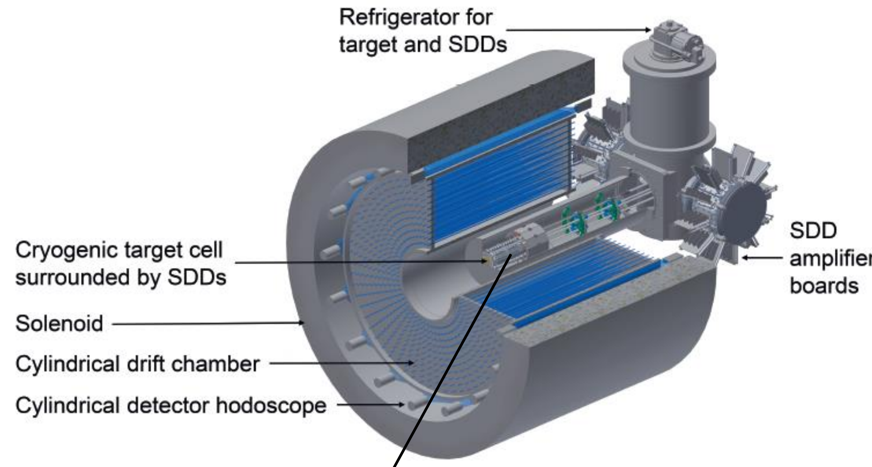

**Courtesy: C. Curceanu**

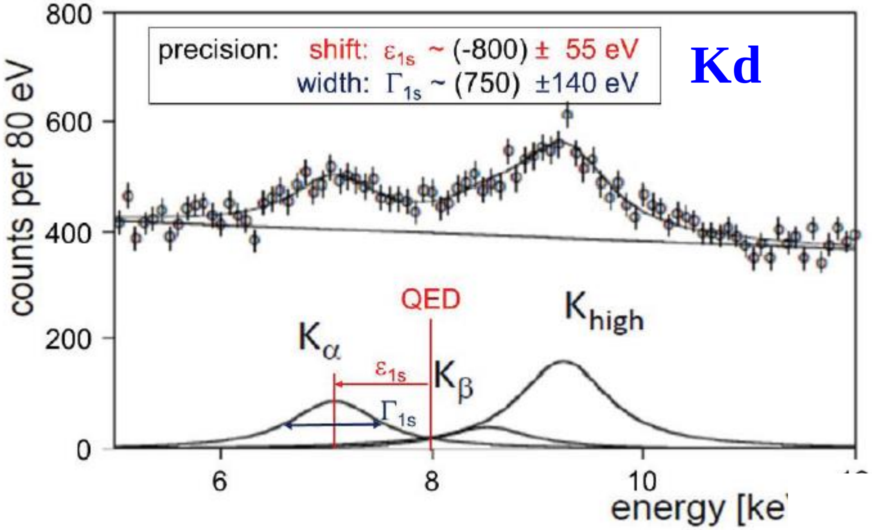
# Exotic atoms at J-PARC

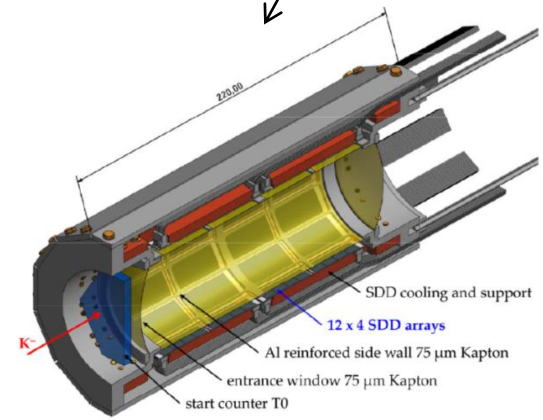
## *E57 experiment:*

***Kaonic deuterium in 2020:***

**to perform the measurement of the strong interaction induced energy shift and width of the kaonic deuterium ground state with new SDD detectors and different background sources than SIDDHARTA-2**



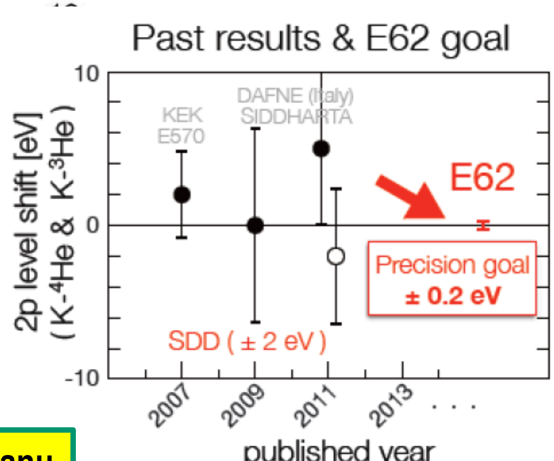



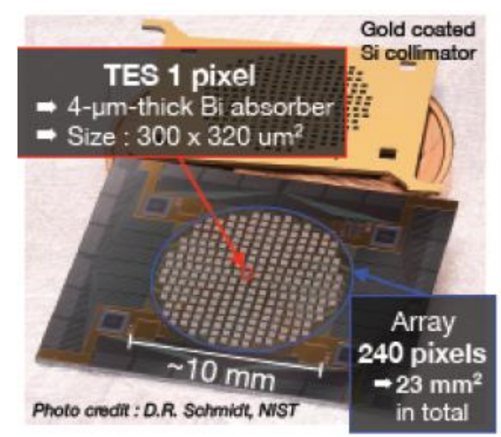




## *E62 experiment:*

***Kaonic helium3 and 4 in 2018:***

**the ultra-high precision measurement of the strong interaction induced energy shift and width of the kaonic helium3 and 4 2p –level with novel TES detectors (PTEP 2016, 091D01)**

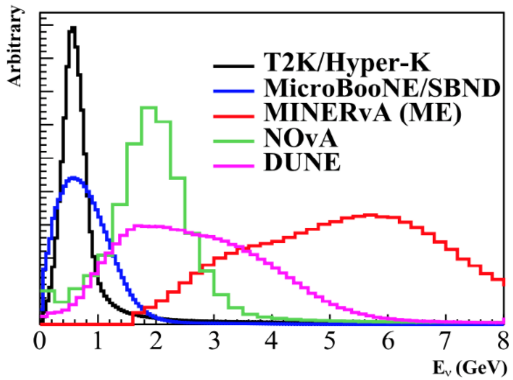


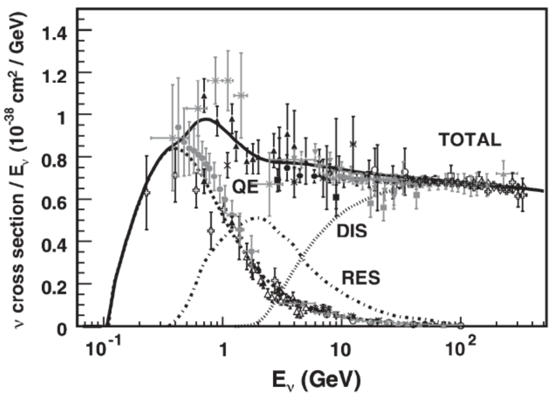

**Courtesy: C. Curceanu**

# Elementary targets for LBL experiments

- DUNE/T2HK




Katori and Martini, J. Phys. G: Nucl. Part. Phys. 45 (2018) 013001




Formaggio and Zeller, Rev.Mod.Phys. 84 (2012) 1307-1341

- Neutrino Scattering Theory Experiment Collaboration
  - http://nustec.fnal.gov

Review

NuSTEC[1] White Paper: Status and challenges of neutrino–nucleus scattering

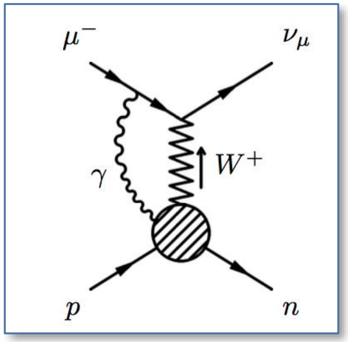
- INT Workshop INT-18-2a

  *From nucleons to nuclei: enabling discovery for neutrinos, dark matter*
  - Elementary neutrino-nucleon amplitudes
    - Study $H_2/D_2$ target option recommended by DUNE board

**Courtesy: P. Kammel**

# Axial Radius and Muon Capture Review

- Theory improvements
  - Theory uncertainties in $\Lambda_S$ reduced to 0.2% level. (ignoring $r_A^2$ input uncertainty)

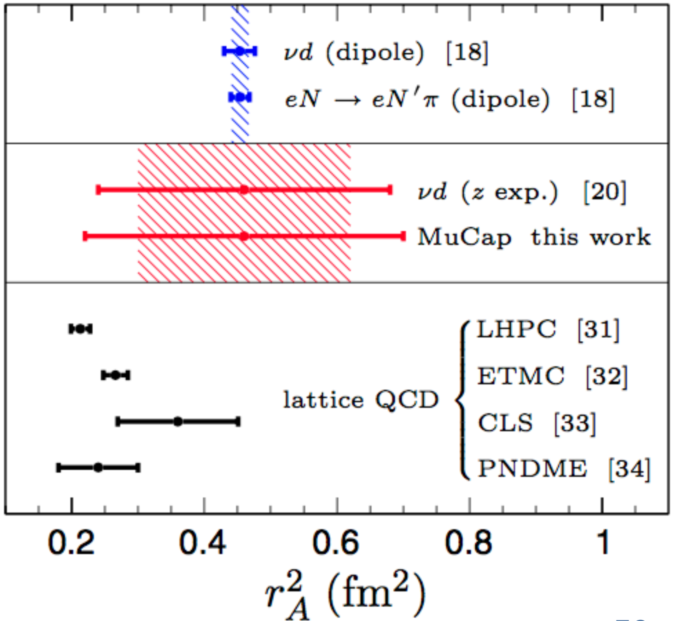



- $g_P$ determination from muon capture
  - $\Delta r_A^2$ dominates uncertainty in $g_A$ and $g_P$ from theory.
  - MuCap still provides QCD test at 8% level: $g_P^{\text{theory}}/g_P^{\text{MuCap}} = 1.00(8)$

- $r_A^2$ determination from muon capture
  - Use EFT expression and $g_{\pi NN}$

$$g_p(q^2) = \frac{2m_\mu g_{\pi NN}(q^2)F_\pi}{m_\pi^2 - q^2} - \frac{1}{3} g_a(0) m_\mu m_N r_A^2$$

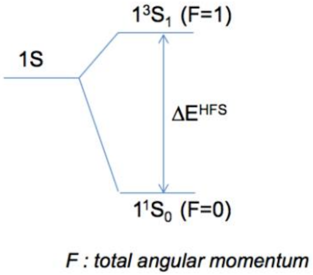
  - 0.3% future precision measurement of $\Lambda_S$ would reduce
    - $\Delta r_A^2$ from 0.22 to 0.09 fm$^2$.
    - uncertainty in QE $\sigma(\nu d)$ by factor ~2.

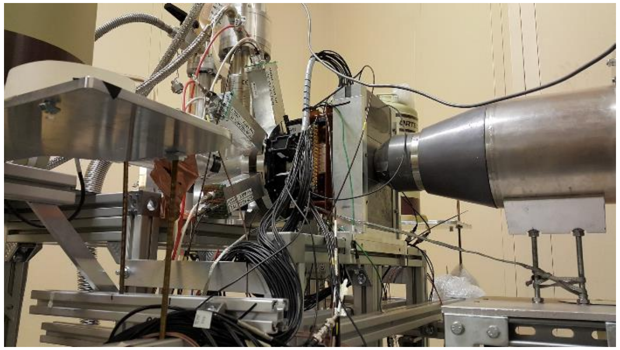



Courtesy: P. Kammel

# The FAMU experiment for the measurement of muonic hydrogen HFS

## measuring the Zemach radius of the proton from laser spectroscopy of the 1S hyperfine splitting



A. Vacchi for the FAMU collaboration

https://web.infn.it/FAMU/


Courtesy: A. Vacchi

# the FAMU Collaboration

*INFN Trieste*: A. Vacchi (also *Università di Udine*), V. Bonvicini, H. Cabrera, E. Furlanetto, E. Mocchiutti, C. Pizzolotto, A. Rachevsky, L. Stoychev,, E. Vallazza, G. Zampa, ***Elettra-Sincrotrone***: M. Danailov, A. Demidovich, *ICTP*: J. Niemela, K.S. Gadedjisso-Tossou, José J. Suárez-Vargas,

***INFN Bologna***: L. Andreani, G. Baldazzi, G. Campana, I. D'Antone, M. Furini, F. Fuschino, A. Gabrielli, C. Labanti, A. Margotti, M. Marisaldi, S. Meneghini, G. Morgante, L. P. Rignanese, P. L. Rossi, M. Zuffa, ***INAF-IASF Bologna***: V. Fioretti,

***INFN Milano Bicocca***: A. Baccolo, R. Benocci, R. Bertoni, M. Bonesini, T. Cervi, F. Chignoli, M. Clemenza, A. Curioni, V. Maggi, R. Mazza, M. Moretti, R. Ramponi *(also Politecnico Milano CNR)*

*INFN Pavia*: A. De Bari, C. De Vecchi, A. Menegolli, M. Rossella, R. Nardò, A. Tomaselli

*INFN Roma3*: L. Colace, M. De Vincenzi, A. Iaciofano, L. Tortora, F. Somma

*INFN Seconda Università di Napoli*: E. Fasci, L. Gianfrani, L. Moretti

CNR-INO: B. Patrizi, A. Piori, G. Toci, M. Vannini

***RIKEN-RAL***: K. Ishida

***INP, Polish Academy of Sciences***: A. Adamczak

***INRNE, Bulgarian Academy of Sciences***: D. Bakalov, M. Stoilov, P. Danev

**ISIS Neutron and Muon Source STFC Rutherford Appleton Laboratory** P. King ,A. Hiller

**Dalian Institute of Chemical Physics , Chinese Academy of Sciences (DICP-CAS)** Chunlei Xiao

**Courtesy: A. Vacchi**

# A 25 YEARS OLD IDEA AND ITS EVOLUTION

Physics Letters A 172 (1993) 277–280
North-Holland

PHYSICS LETTERS A

## Experimental method to measure the hyperfine splitting of muonic hydrogen $(\mu^-p)_{1S}$

D. Bakalov [1], E. Milotti, C. Rizzo, A. Vacchi and E. Zavattini
*Dipartimento di Fisica dell'Università di Trieste, via Valerio 2, Trieste 34017, Italy and Sezione INFN di Trieste, Area di Ricerca, Padriciano 99, Trieste 34012, Italy*

Received 31 July 1992; revised manuscript received 17 October 1992; accepted for publication 8 November 1992
Communicated by B. Fricke

We propose an experimental method to measure the hyperfine splitting of the energy level of the muonic hydrogen ground state $(\mu^-p)_{1S}$ by inducing a laser-stimulated para-to-ortho transition. The method requires an intense low energy pulsed $\mu^-$ beam and a high power tunable pulsed laser.

**1. Introduction**

The theoretical expression for the hyperfine splitting



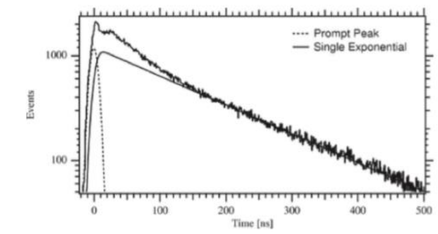



Figure 2. Background subtracted time distribution of muonic oxygen $\mu O(2–1)$ X-rays measured in a gaseous mixture of $H_2 + 0.4\% O_2$ at 15 bar and room temperature. The prompt peak corresponds essentially to muons directly captured in oxygen whereas the delayed part is due to muon transfer from the ground state of the $(\mu p)_{1s}$ atom. The solid line represents a pure exponential function to stress the additional structure.

F. Mulhauser, H. Schneuwly, Hyperfine Interact. 82 (1993).
A. Werthmüller, et al., Hyperfine Interact. 116 (1998).

For few gases the muon-transfer rate $\lambda_{pZ}$ is energy dependent

***Oxygen exhibits a peak in the muon transfer rate $\lambda_{pZ}^{epith}$ at epithermal energy.***

start with H and O gas mixture (around 1% O) at 80K

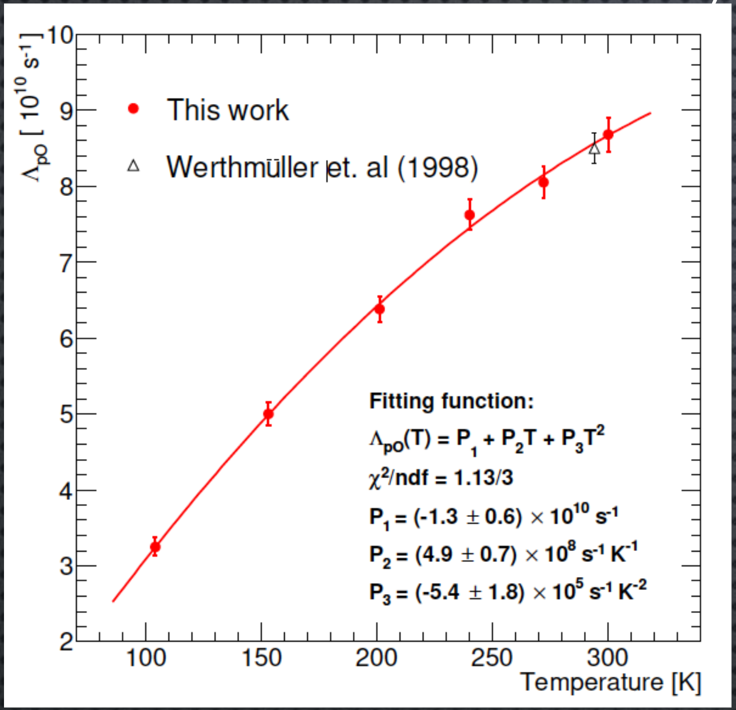
I. • $\mu$H in F=0, $\mu^-p(\uparrow\downarrow)$
II. • laser photons, at the correct frequency, $\mu^-p(\uparrow\downarrow) \rightarrow \mu^-p(\uparrow\uparrow)$
III. • F=1 revert to F=0 by collisional deexcitation, but get kick
IV. • moving $\mu$H have different capture rate on O, see more X-rays
V. • measure the time distribution of O characteristic X-rays.

$$\mu p + Z \Rightarrow \mu Z^* + p$$

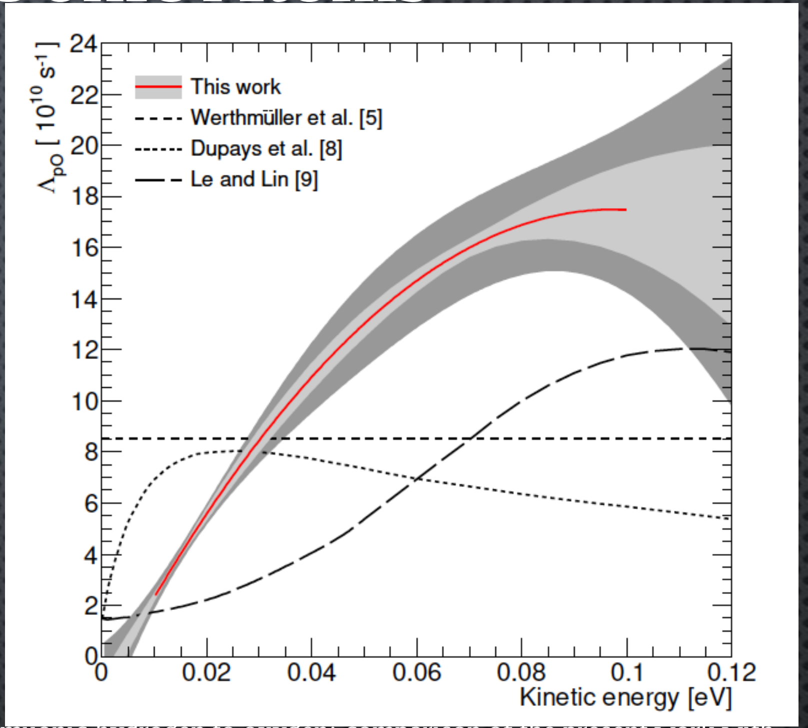
D. Bakalov, A. Adamczak et al., Phys. Lett. A379 (2014).
A. Adamczak et al. Hyperfine Interactions 136: 1–7, 2001.

**Courtesy: A. Vacchi**

# FAMU – Physics of MUonic Atoms




Fit to the FAMU data (circles) using a parabolic dependence of the muon transfer rate on temperature T (solid line). PSI measurement is also shown (triangle).




Transfer rate from muonic hydrogen to oxygen: comparison of the present work with the experimental and the theoretical results. Shaded region represents the propagation of experimental uncertainties on the fit. The solid line represents our best fit within its range of validity. The shaded region represent the main uncertainties: propagation of experimental uncertainties on the fit (light gray) and fitting-model-related uncertainties (dark gray).

The first measurement of the temperature dependence of muon transfer rate from μp atoms to oxygen between 100 and 300K. Data were obtained from the X-ray spectra of delayed events in gaseous target H2/O2 exposed to a muon beam at RAL. Based on the data, we determined the muon transfer energy dependence up to 0.1~eV, showing an 8-fold increase in contrast with the predictions of constant rate in the low energy limit. This result set constraints on theoretical models of muon transfer, and is of fundamental importance for the measurement of the hyperfine splitting of μp by the FAMU collaboration.



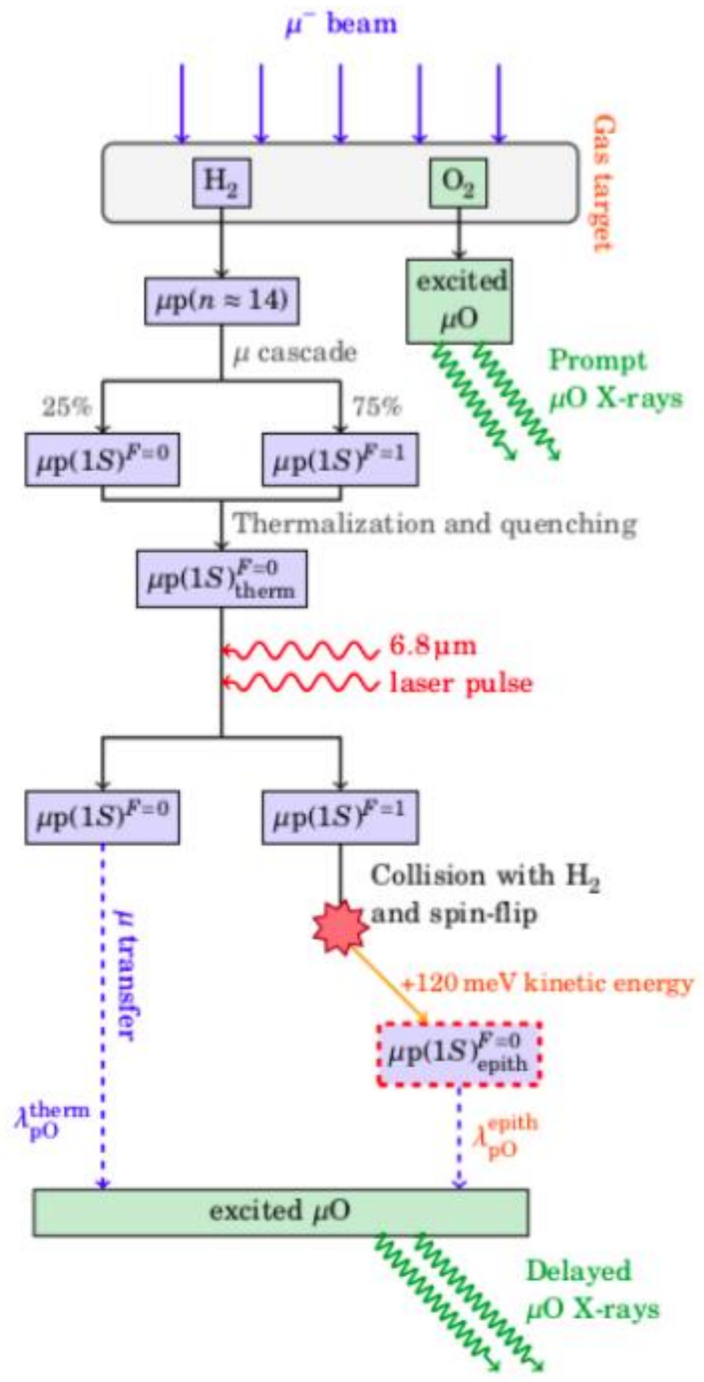
http://arxiv.org/abs/1905.02049

Courtesy: A. Vacchi

# FAMU Principle of operation

μp formation =>>

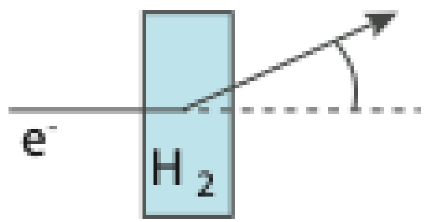
μp termalization =>>




Courtesy: A. Vacchi

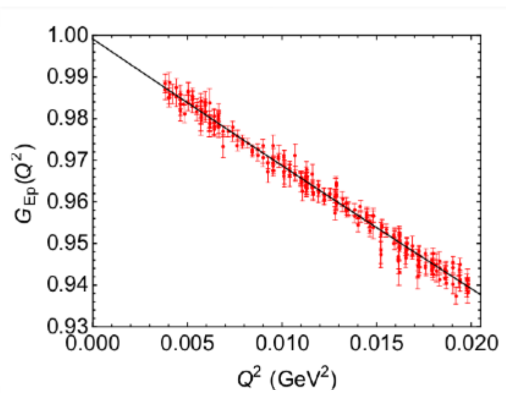
# The proton radius puzzle

## e-p scattering at low Q2

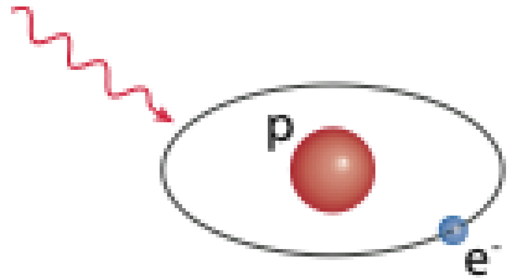



- measure elastic $\sigma$ with 1% acc.
- Statistics: ok
- Challenge: small sensitivity
- Challenge: extrapolation to Q2=0

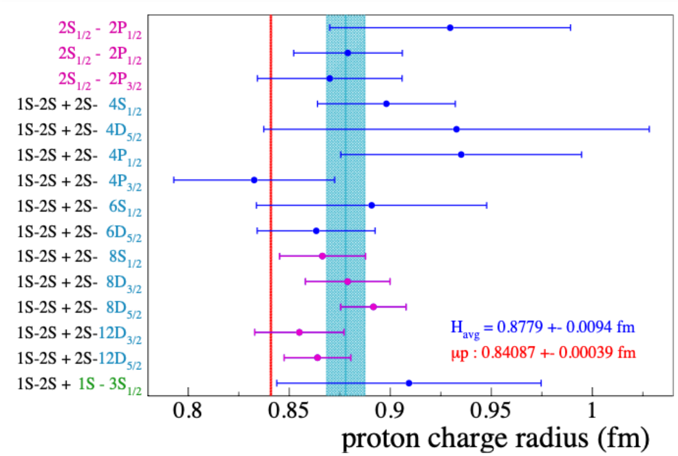
$$r_{\mathrm{p}}^2 = -6\frac{dG_E(Q^2)}{dQ^2}\Big|_{Q^2=0}$$



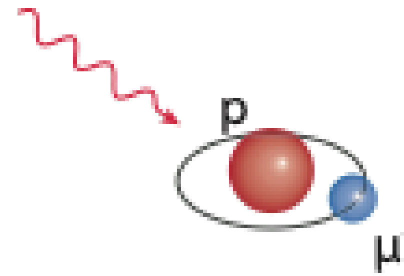

## Laser spectroscopy in H




- 4$\sigma$ discrepancy only with least square adjustment
- High-precision laser spectroscopy
- Challenge: systematic effects for large n-states




## Laser spectroscopy in μp



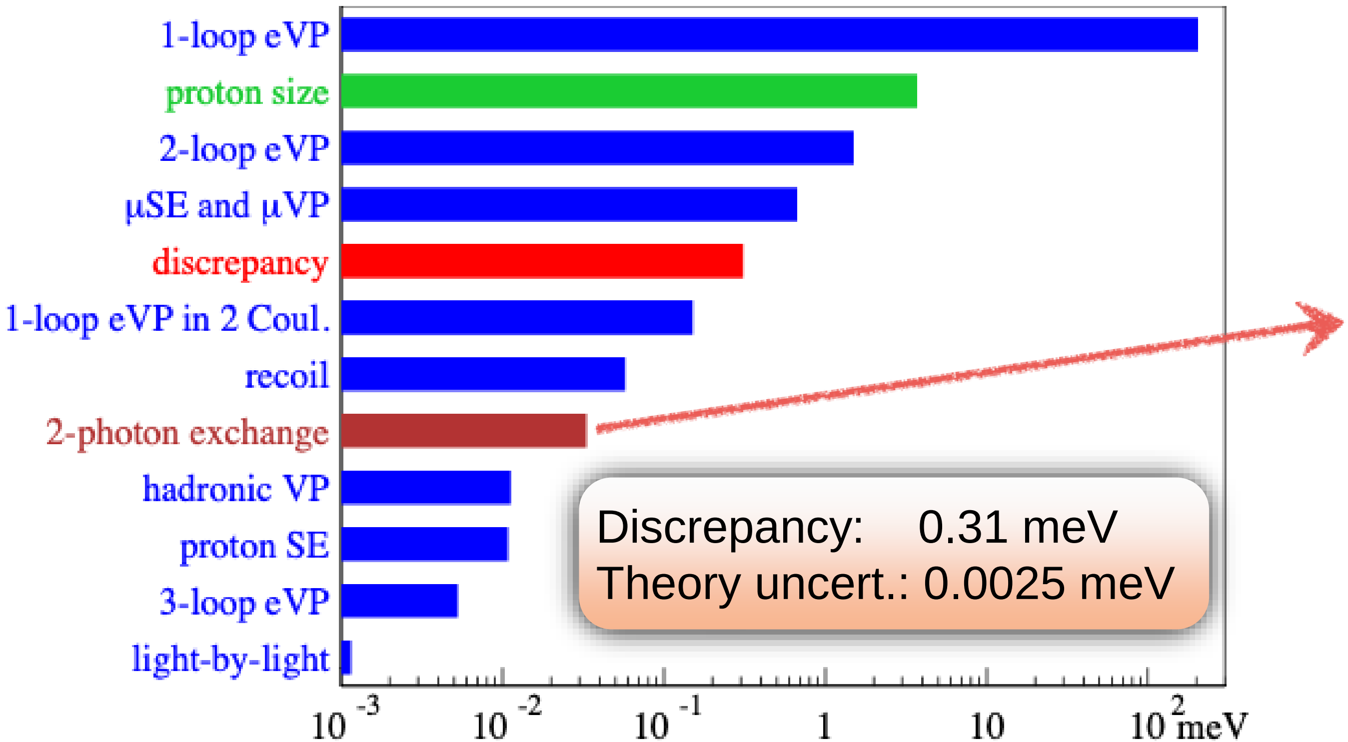

$$\Delta E_{\mathrm{size}} = \frac{2\pi(Z\alpha)}{3}\, r_{\mathrm{p}}^2\, |\Psi_{nl}(0)|^2 = \frac{2(Z\alpha)^4}{3n^3} m_r^3\, r_{\mathrm{p}}^2\, \delta_{l0}$$

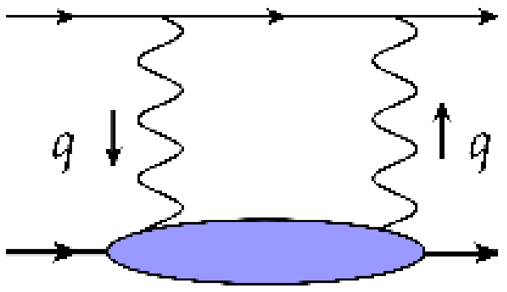
- High sensitivity to proton radius
- Challenge: statistics (laser power, muon rates)

**Courtesy: A. Antognini**

# Why is the μp theory reliable?

$$\Delta E^{\mathrm{th}}_{2P-2S} = 206.0336(15) - 5.2275(10)\, r_p^2 + 0.0332(20) \quad [\mathrm{meV}]$$



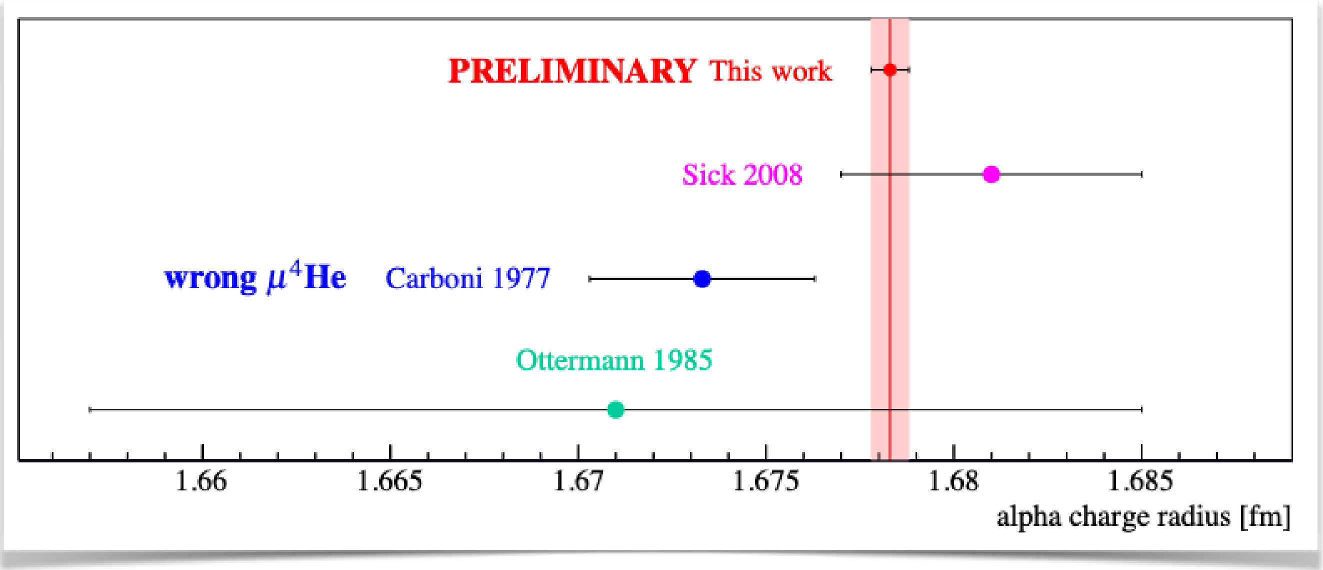

Pachucki, Carlson, Birse, McGovern, Pineda, Gorchtein, Pascalutsa, Vanderhaeghen, Alarcon, Miller, Paz, Hill…

Pachucki, Borie, Eides, Karschenboim, Jentschura, Martynenko, Indelicato Pineda, Miller, Karrol…

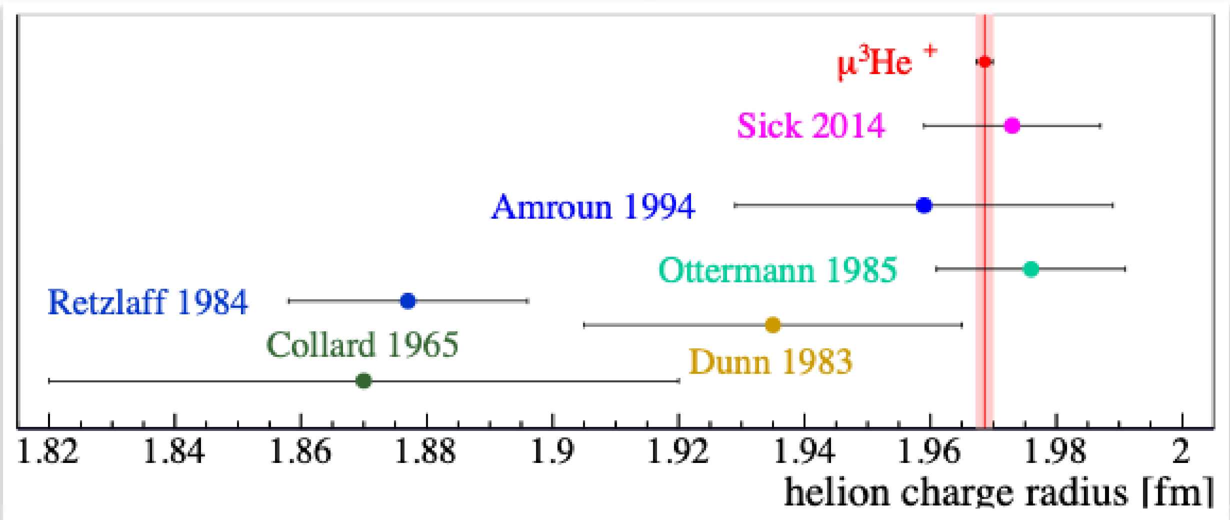
Hill, Paz, arXiv:1611.09917
Birse, McGovern, arXiv1206.3030
Hagelstein et al., arXiv:1512.03765
Peset and Pineda, arXiv:1406.4524

**Courtesy: A. Antognini**

# Alpha-particle and helion radii from μHe+ spectroscopy




Extraction of these charge radii from muonic helium is limited by the polarisability contributions.

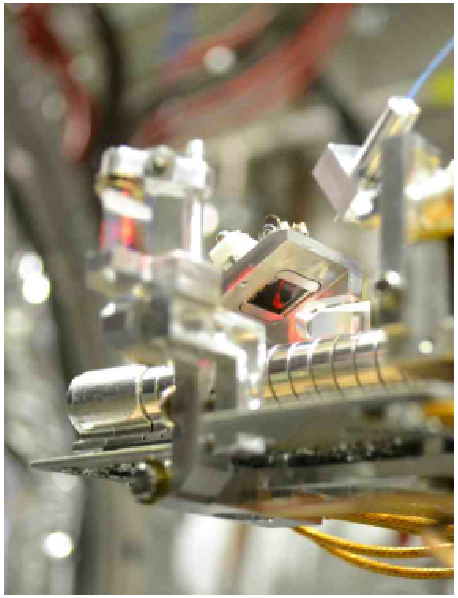


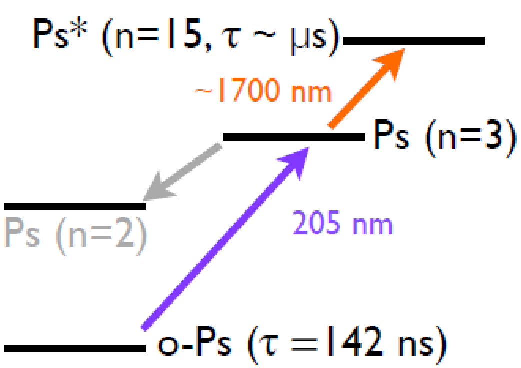

Courtesy: A. Antognini

# Challenges:

## Pulsed formation:

$\bar{H}$ formation region: $\bar{p}$ Penning traps, Ps production target






pulsed formation of $\bar{H}$ @ end 2018

Ps(2s) beam formation under way

S. Aghion et al., Phys. Rev. A 98, 013402 (2018)

## Temperature:

**cooling of $\bar{p}$**

sympathetic cooling of $\bar{p}$ to ~ mK through anions

A. Kellerbauer & J. Walz, New J. Phys. 8 (2006) 45

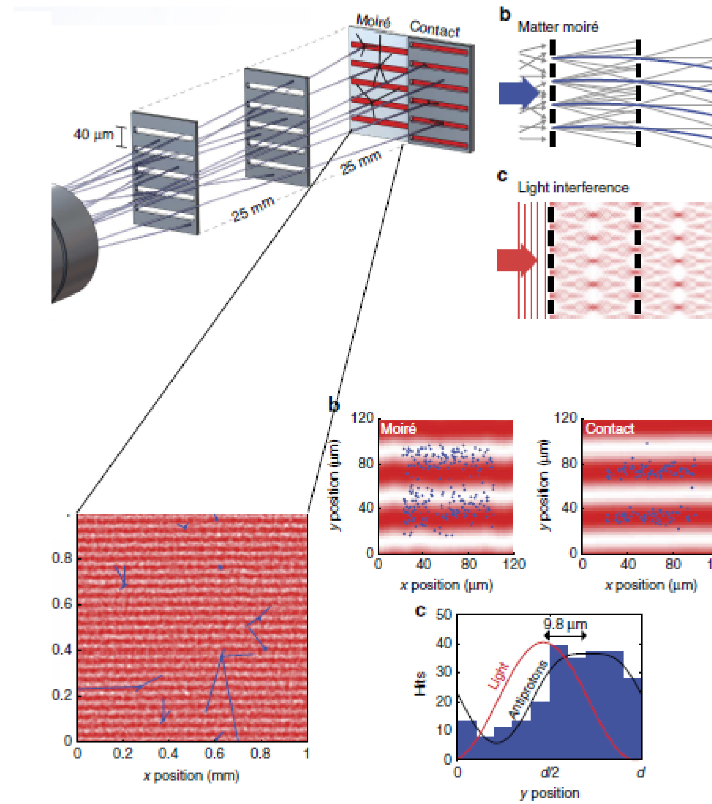
$La^-$ Warring et al, PRL 102 (2009) 043001
E. Jordan et al., PRL 115 (2015) 113001

$C_2^-$ P. Yzombard et al., PRL 114, 213001

*<u>Note: beam experiments have a weak</u>* dependence of gravity measurement on (transverse) temperature (→ figure of merit is the flux into gravity-sensitive detector) as long as flight times are ~ ms or longer

dedicated experiments to establish laser-cooling of anionic systems under way

## Measurement:



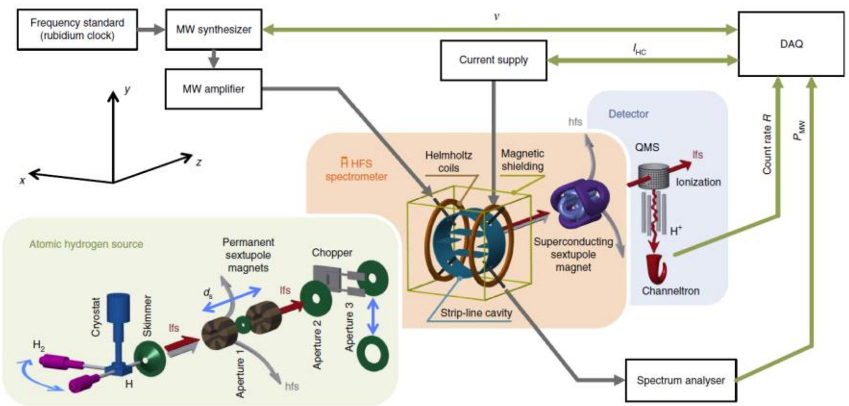

principle established with $\bar{p}$; displacement of $\bar{p}$ annihilation vertices (blue dots) measured relative to light (red)

S. Aghion et al.,"A moiré deflectometer for antimatter", Nature Communications 5 (2014) 4538

and many more...

Courtesy: M. Doser

# σ-transition in H using $\bar{\mathrm{H}}$ setup



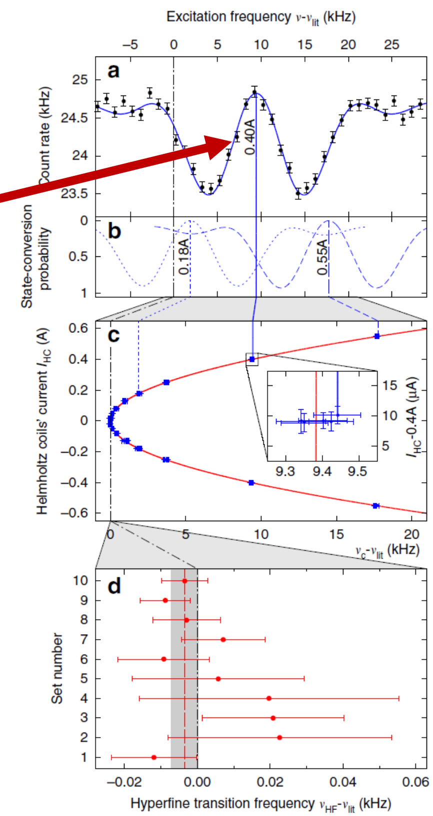

$$\nu_{\mathrm{HF}} = 1\ 420\ 405\ 748.4(3.4)(1.6)\ \mathrm{Hz}$$

Received 4 Oct 2016 | Accepted 24 Apr 2017 | Published 12 Jun 2017 DOI: 10.1038/ncomms15749 OPEN

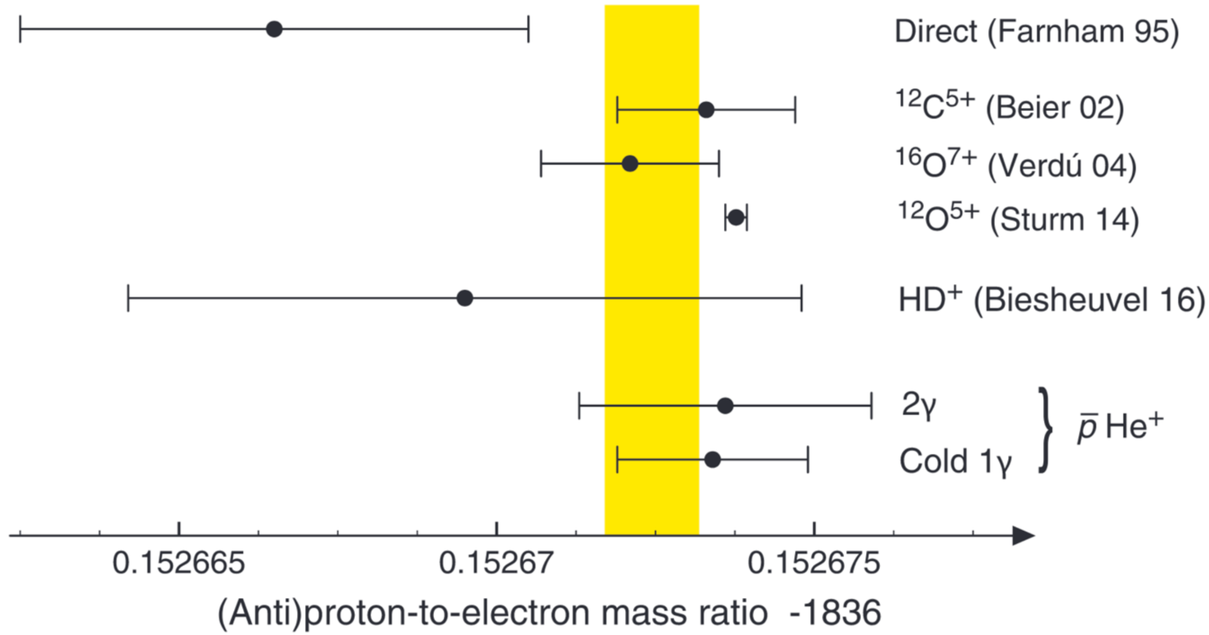
In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy

M. Diermaier[1], C.B. Jepsen[2,†], B. Kolbinger[1], C. Malbrunot[1,2], O. Massiczek[1], C. Sauerzopf[1], M.C. Simon[1], J. Zmeskal[1] & E. Widmann[1]

Line width ~ 6 kHz:
4 ppm
(v~900 m/s)




Error **2.7 ppb**: 18x improvement over *Kush, Phys. Rev. 100, 1188 (1955)*
Deviation from maser ($\Delta f/f \sim 10^{-12}$) :
**3.4 Hz** < 1σ error
Extrapolation to $\bar{\mathrm{H}}$: **8000** atoms needed to achieve **1 ppm**




Antiproton-to-electron mass ratio determined from antiprotonic helium compared with proton-to-electron values.

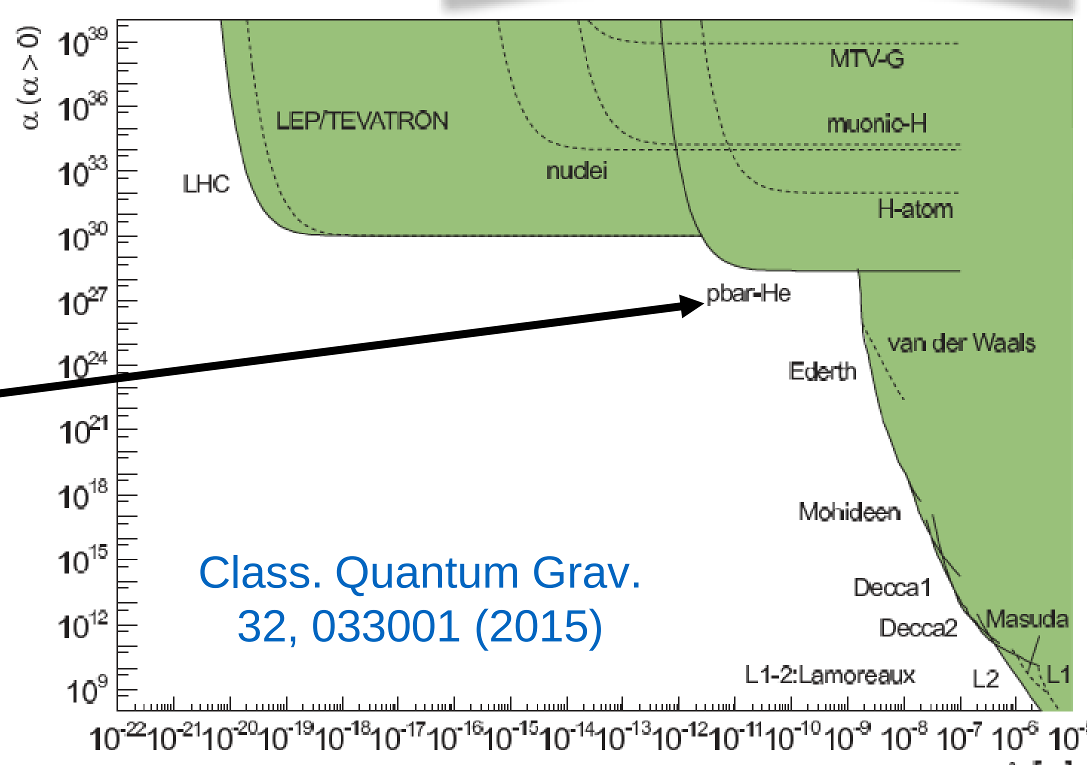
Factor >100 improvement may be possible with ELENA facility.

Science 354, 610 (2016)

Constrains exotic spin-dependent forces mediated by axions etc.
PRL 120, 183002 (2018)

Sets bounds on **fifth force** at Angstrom length scales

$$V(r) = -G_\infty \frac{Mm}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

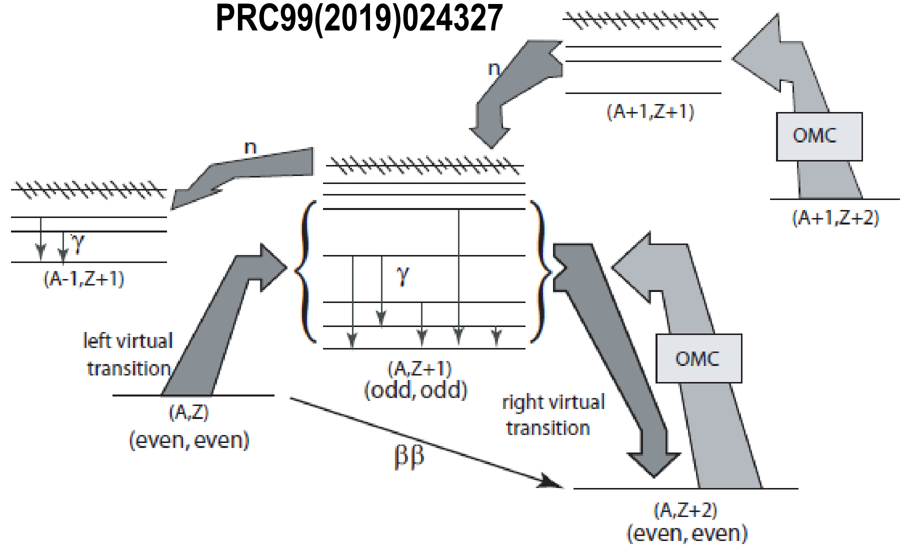



Courtesy: M. Hori

# muX measurements relevant to neutrino-less double beta decay

Zinatulina et al., arXiv:1803.10960 (2018)

**PRC99(2019)024327**




- Muon capture measurement on nuclei relevant for double beta decay ($^{82}$Kr, $^{130}$Xe)
- Compare measurements to nuclear shell model predictions for $^{24}$Mg as a benchmark for NSM to calculate higher mass nuclei
- Measure muon capture rates and branches to the different daughter isotopes

| target | enr-ment | composition | element mass | thickness mg/cm$^2$ |
|---|---|---|---|---|
| $^{82}$Kr | 99.9% | Kr gas | 1.0 l (1 atm.) | 37.3 |
| $^{nat}$Kr | – | Kr gas | 1.0 l (1 atm.) | 37.3 |
| $^{130}$Xe | 99.9% | Xe gas | 1.0 l (1 atm.) | 58.1 |
| $^{nat}$Xe | – | Xe gas | 1.0 l (1 atm.) | 58.1 |
| $^{24}$Mg | 99.89% | MgO powder | 1.0 g | 250 |