Precision nucleon and nuclear structure from muonic atoms

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Universität Mainz

for the
CREMA, muX,
ReferenceRadii and
QUARTET Collab.
at PSI

Bormio, 26.1.24

ToDo for today

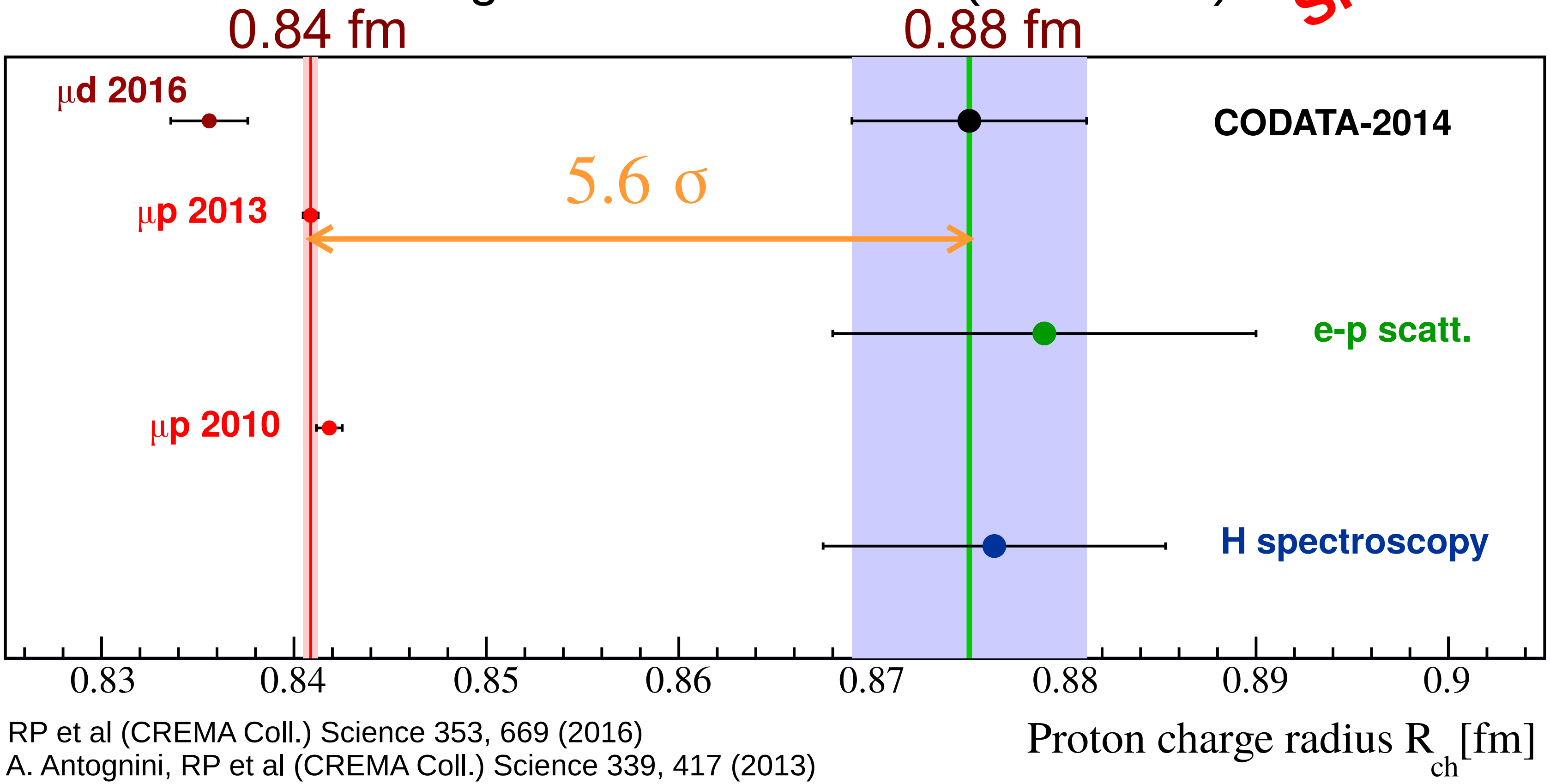
- Proton radius
- CREMA: **Laser spectroscopy** of μD, μ^3He^+, μ^4He^+
- muX: X-ray spectroscopy with **few μg target** material
- ReferenceRadii: radii for **King plots, V_{ud}**
- QUARTET: 10x better radii for Z=3...10 with **MMCs**
- HyperMu: The **proton's magnetic** properties
- T-Rex @ Mainz: the **triton radius**

The “Proton Radius Puzzle”

Measuring R_p using electrons: 0.88 fm (+- 0.7%)

using muons: 0.84 fm (+- 0.05%)

Situation 2016



μd 2016: RP et al (CREMA Coll.) Science 353, 669 (2016)
μp 2013: A. Antognini, RP et al (CREMA Coll.) Science 339, 417 (2013)

The “Proton Radius Puzzle”

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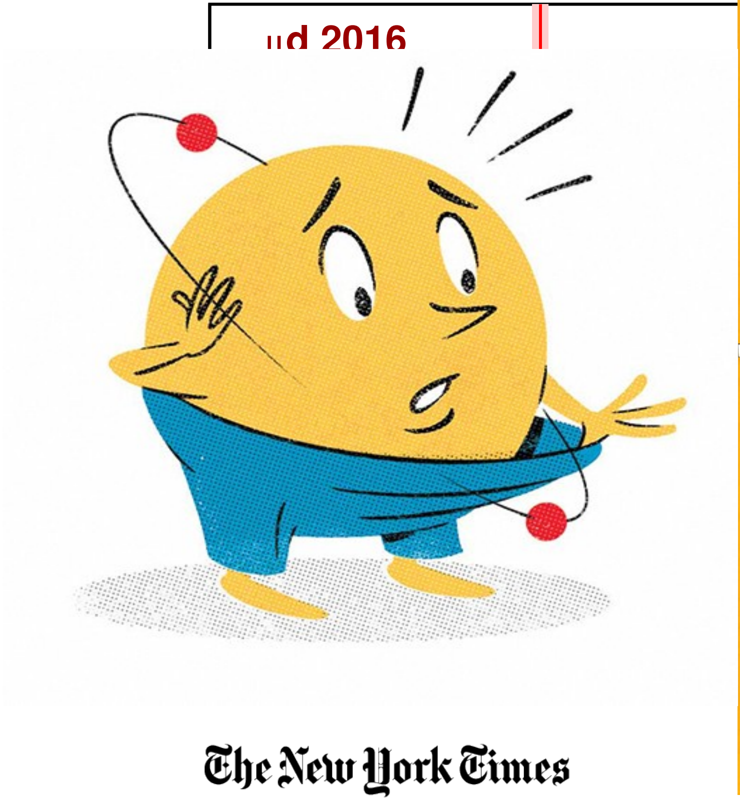
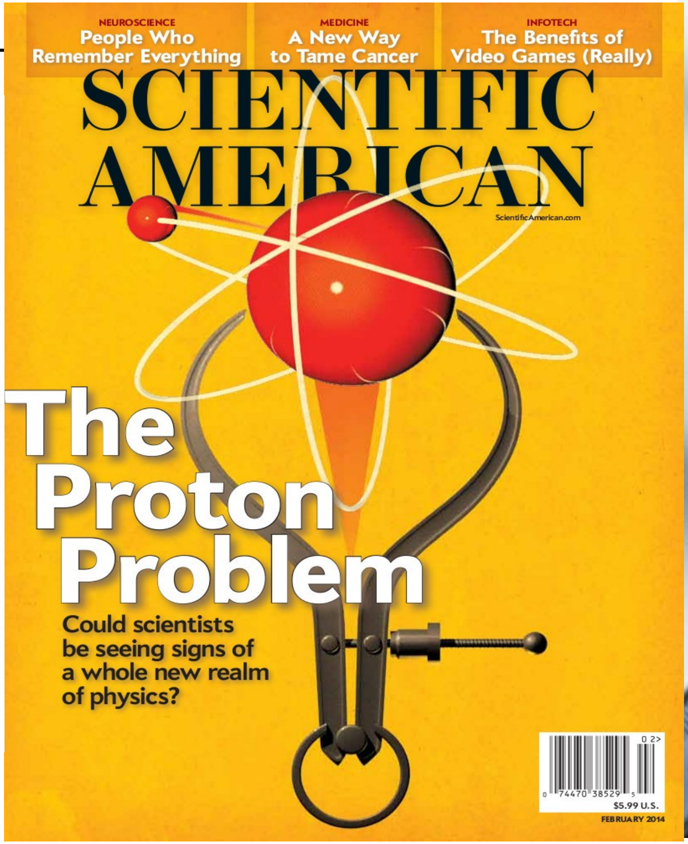
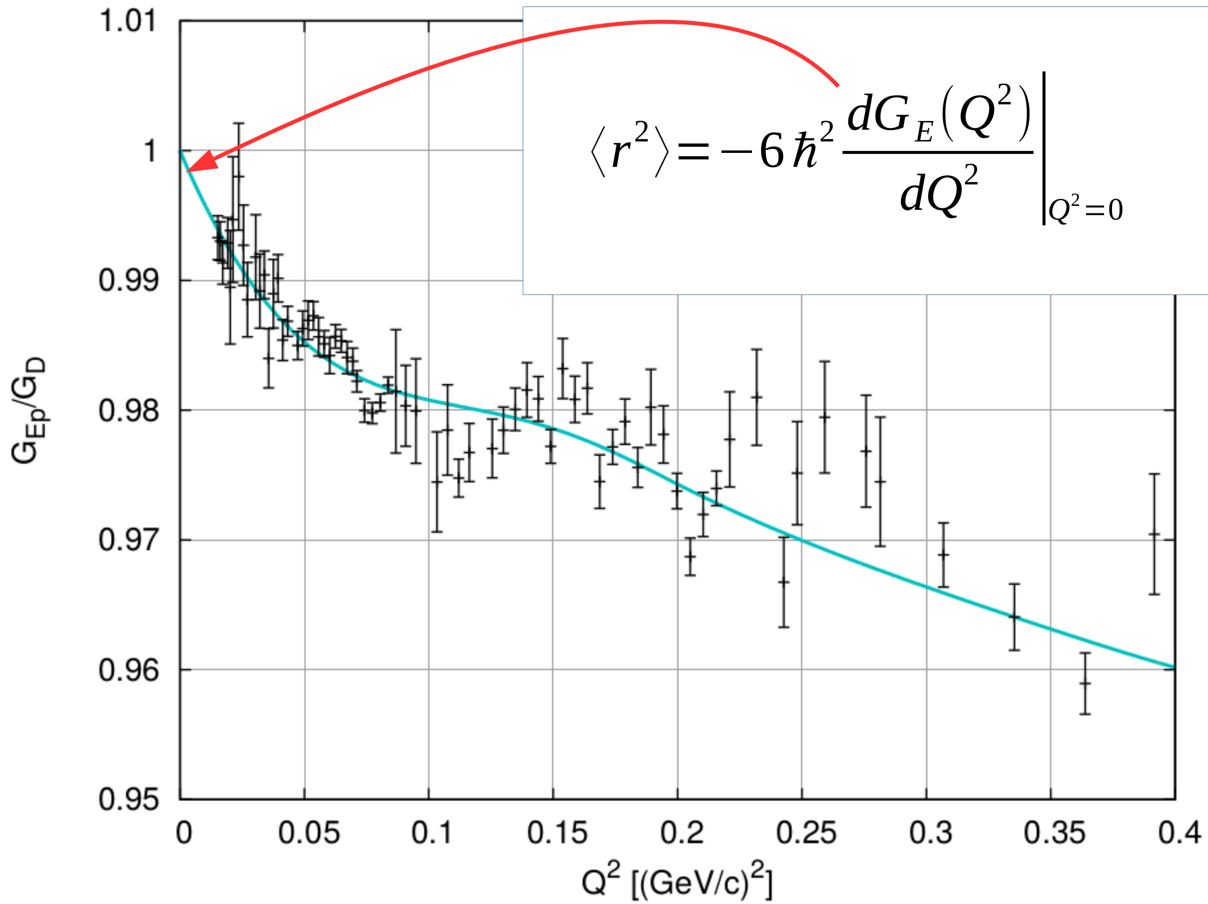




Electron scattering



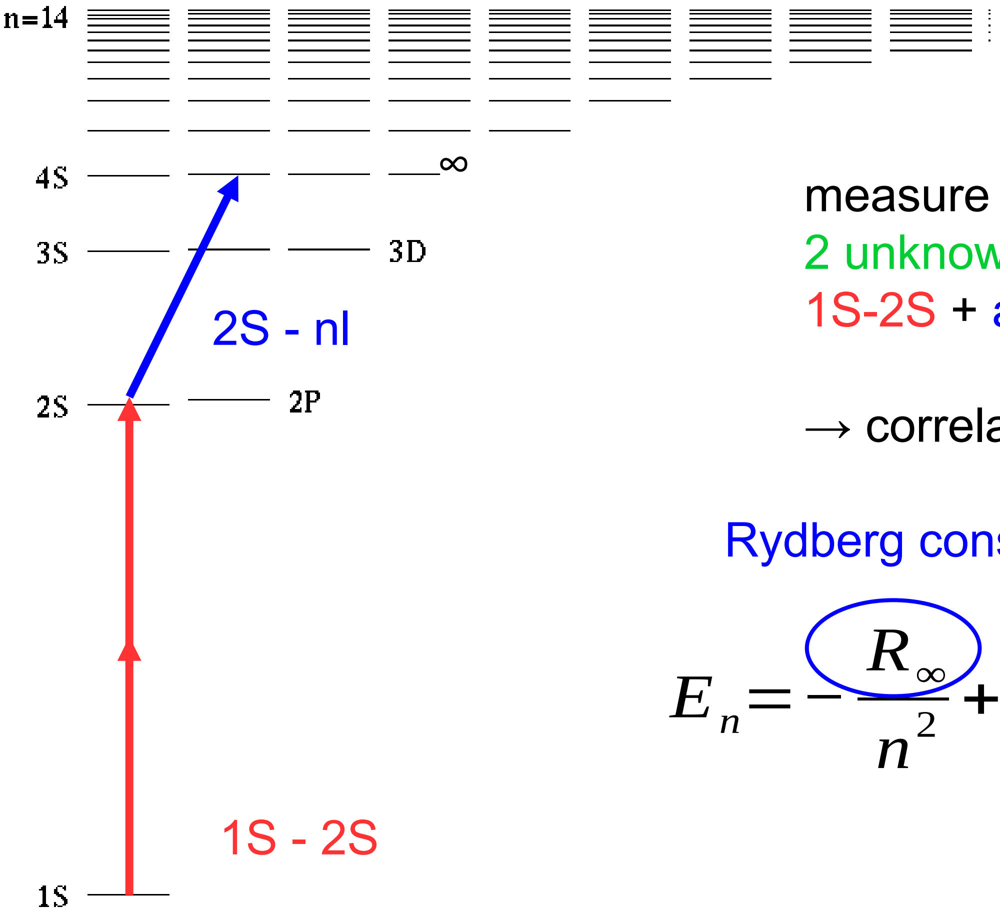
$$\langle r^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

extrapolation to $Q^2 = 0$ required

Vanderhaeghen, Walcher: 1008.4225

Mainz MAMI data 2010

Energy levels of hydrogen



measure between different **n**

2 unknowns → measure 2 transitions:

1S-2S + any other

→ correlated Rydberg/radius pairs

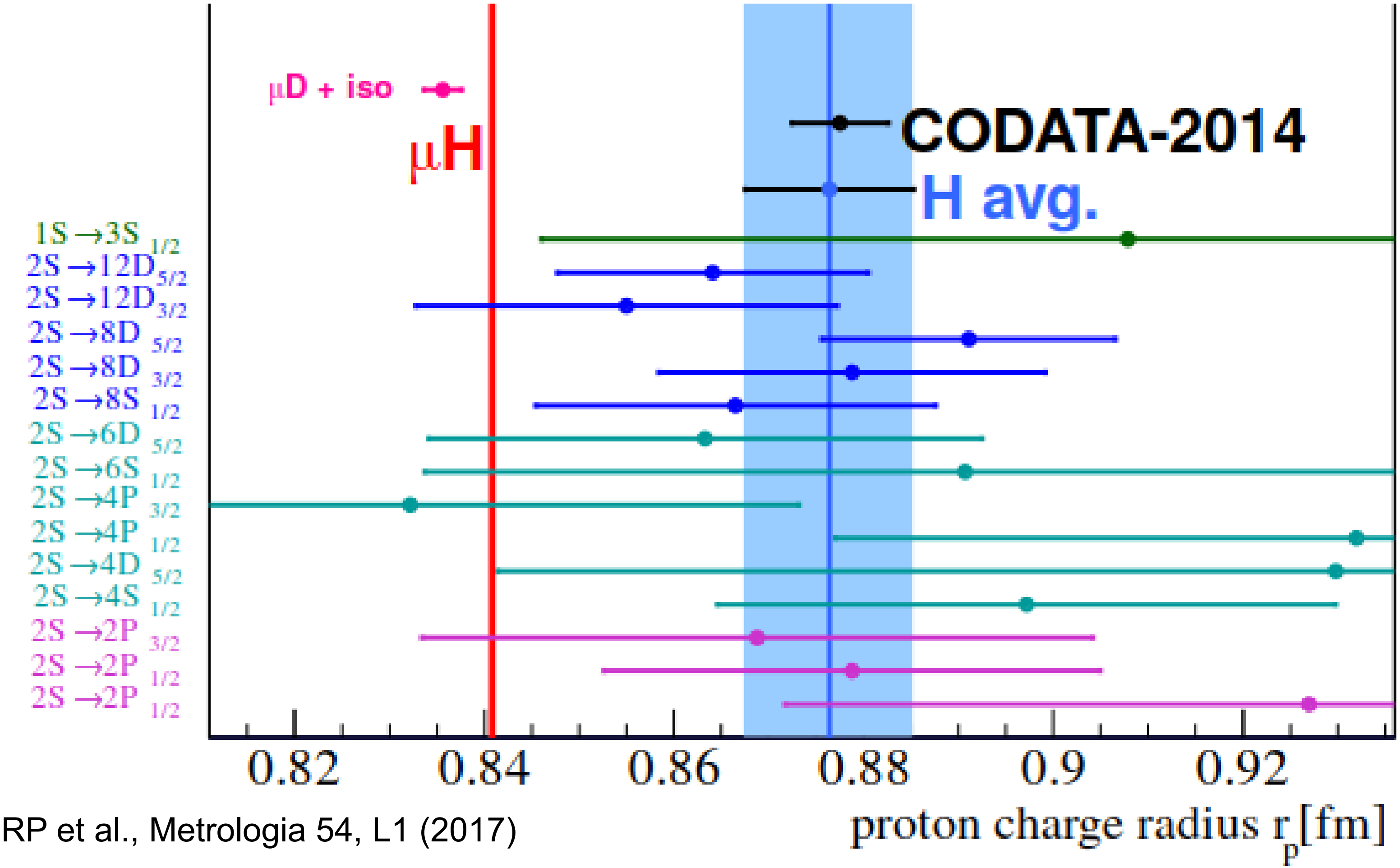
Rydberg constant

QED etc.

$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2\rangle \delta_{l0} + \Delta(n,l,j)$$

proton radius

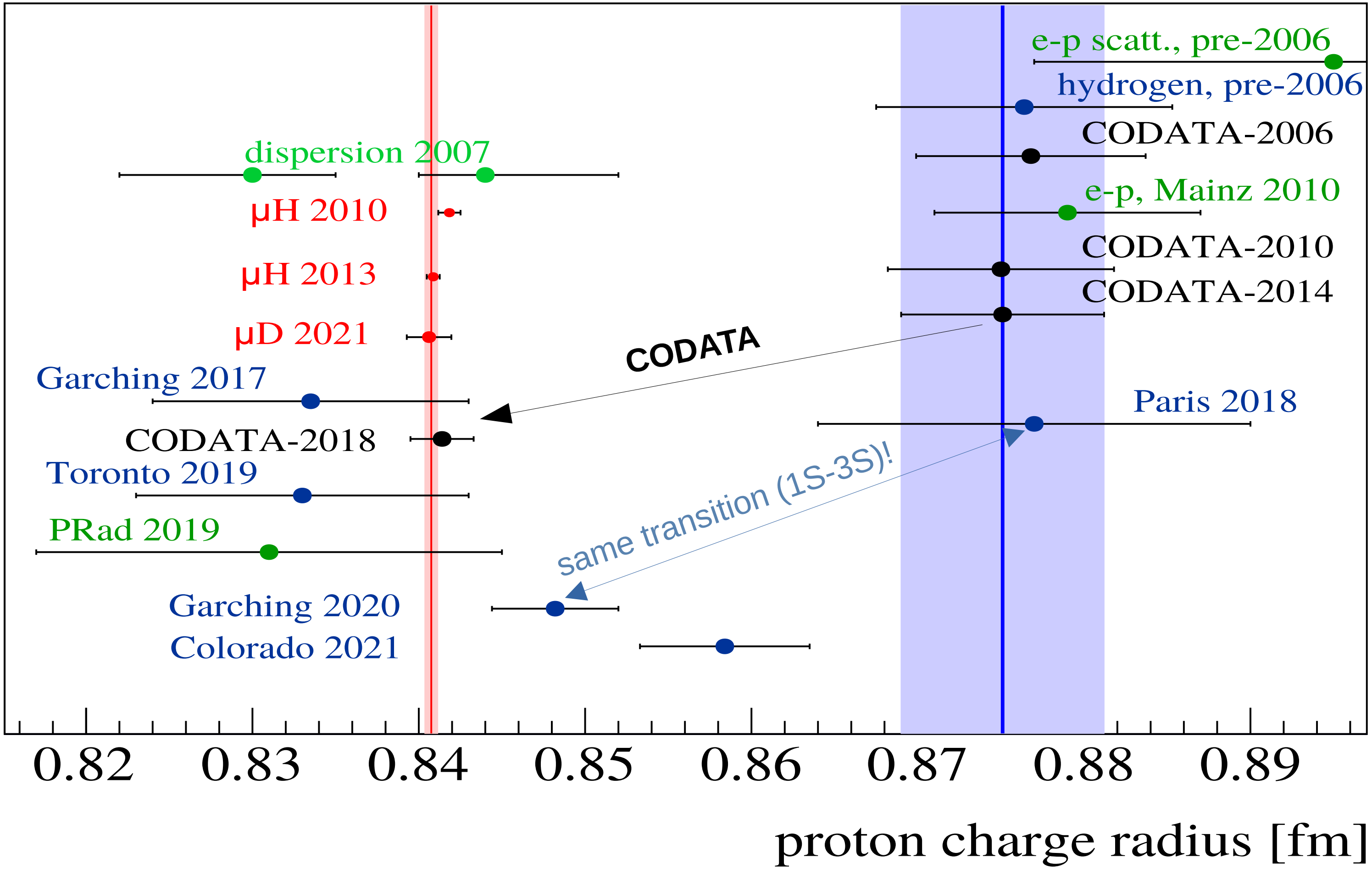
Rp from H spectroscopy



Situation 2016

RP et al., Metrologia 54, L1 (2017)

The situation today

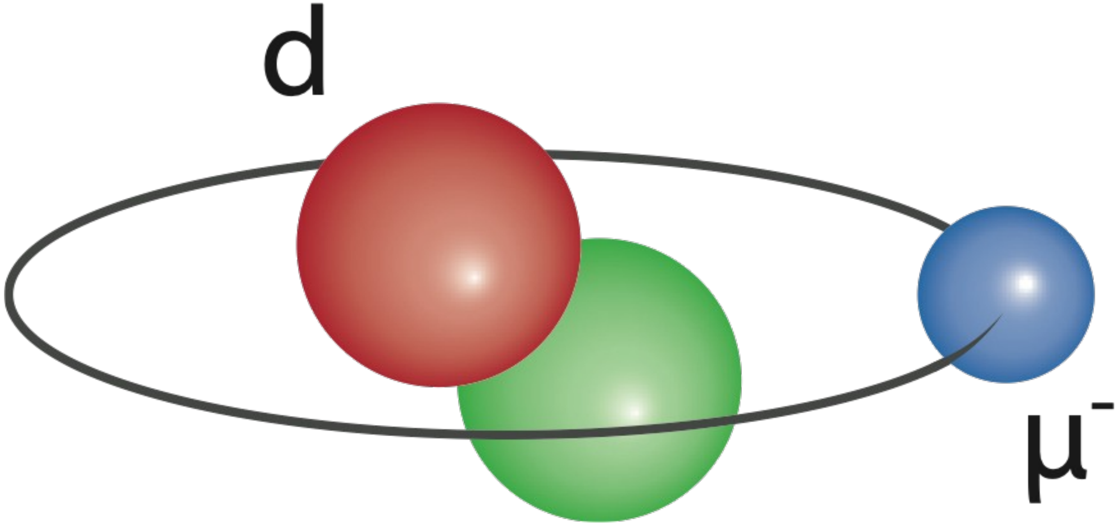


Not really “solved”

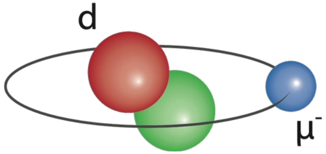
CREMA:
Laser spectroscopy of light muonic atoms

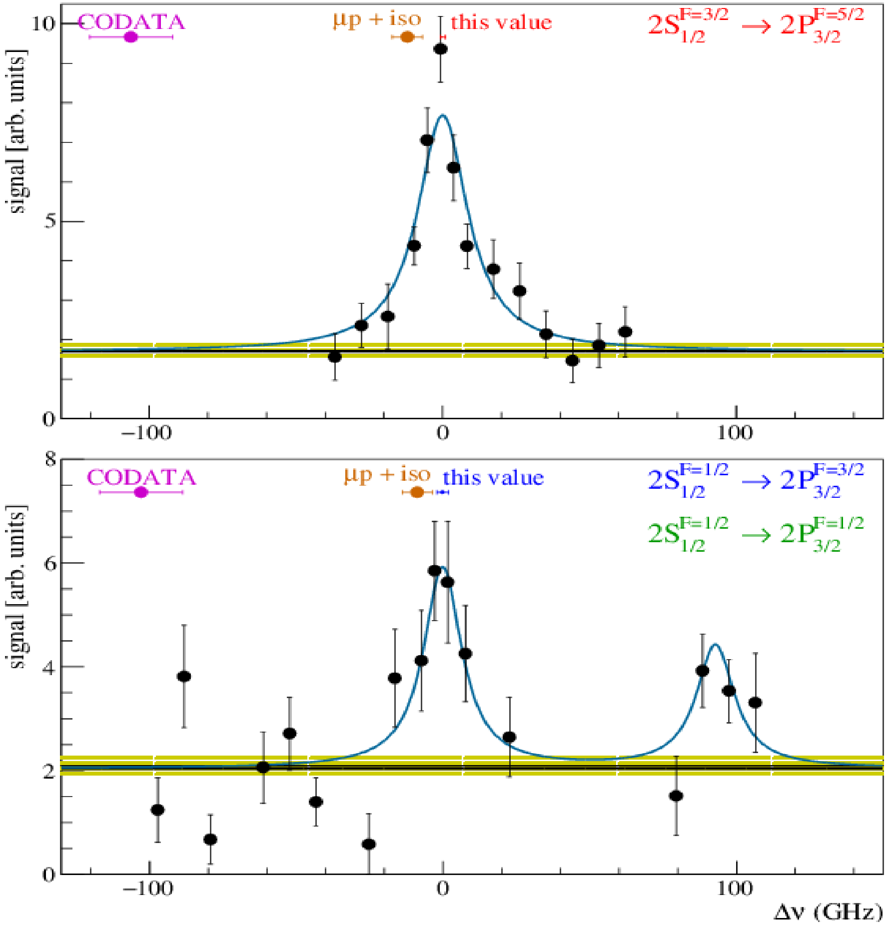
Randolf Pohl, JGU Mainz

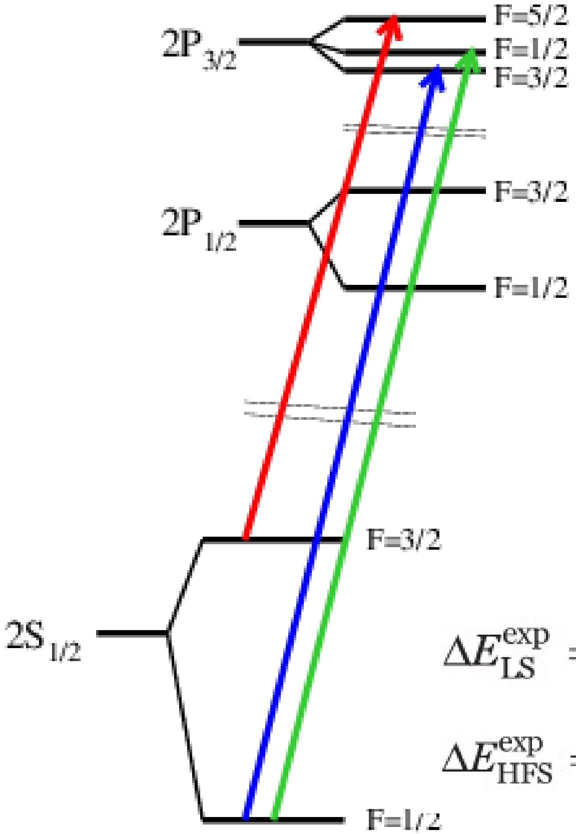
Muonic Deuterium



2.5 transitions in muonic D







$$\Delta E_{\mathrm{LS}}^{\mathrm{exp}} = 202.8785(31)_{\mathrm{stat}}(14)_{\mathrm{syst}}\ \mathrm{meV}$$

$$\Delta E_{\mathrm{HFS}}^{\mathrm{exp}} = 6.2747(70)_{\mathrm{stat}}(20)_{\mathrm{syst}}\ \mathrm{meV}$$

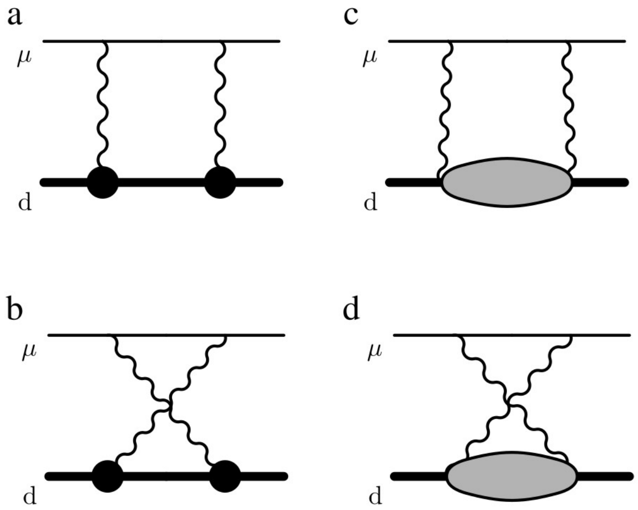
Pohl et al. (CREMA Coll.), Science 353, 669 (2016)

Theory: Lamb shift in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7740\,(3)\ \mathrm{meV}_{QED} + 1.7503\,(\mathbf{200})\ \mathrm{meV}_{TPE} - 6.1074\ \ \mathrm{meV/fm}^2 * \mathbf{R_d}^2$$

$$\Delta E^{\mathrm{exp}}_{\mathrm{LS}} = 202.8785(31)_{\mathrm{stat}}(14)_{\mathrm{syst}}\ \mathrm{meV}$$

Nuclear structure two (and three!)-photon contributions to the Lamb shift in muonic deuterium.



Pachucki, RP et al, arXiv 2212.13782

see also Krauth, RP et al. (2016) using calculations from
Pachucki (2011), Friar (2013), Carlson, Gorchtein, Vanderhaeghen (2014), Hernandez et al. (2014), Pachucki + Wienczek (2015)

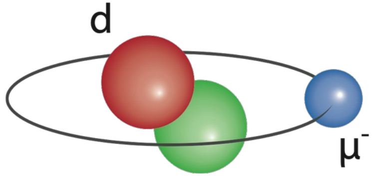
+ Pachucki et al., PRA 97, 062511 (2018): Sizeable three-photon !!

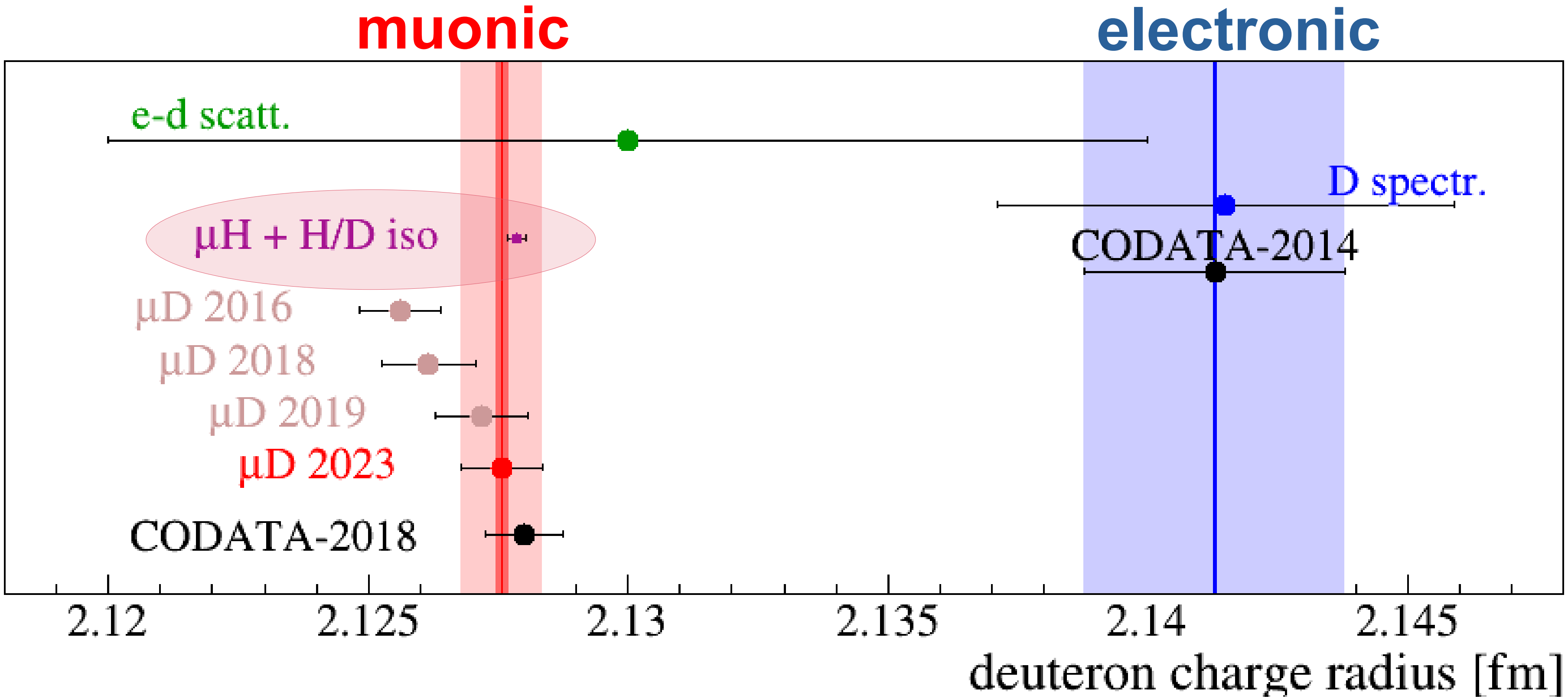
+ Hernandez et al., PLB 778, 377 (2018): χEFT

+ Kalinowski (2019): eVP to nucl. struct.

+ Acharya et al., PRC 103, 024001 (2021)
χEFT + Disperson relations

Muonic Deuterium





μD: 2.12758 $(13)_{exp}$ $(78)_{theo}$ fm

μH + H/D(1S-2S): 2.12785 (17) fm

Theory in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7740\,(3)\ \text{meV}_{QED} + 1.7503\,(\mathbf{200})\ \text{meV}_{TPE} - 6.1074\ \text{meV/fm}^2 * \mathbf{R_d}^{2}$$

ΔE_{TPE} (theo) = 1.7503 +- 0.0200 meV **Bacca group**

vs. +- 0.0034 meV experimental uncertainty

(1) **charge radius**, using **calculated TPE**

r_d (μD) = 2.12758 $(13)_{exp}$ $(78)_{theo}$ fm

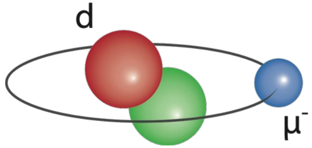
(2) **polarizability**, using **charge radius from isotope shift**

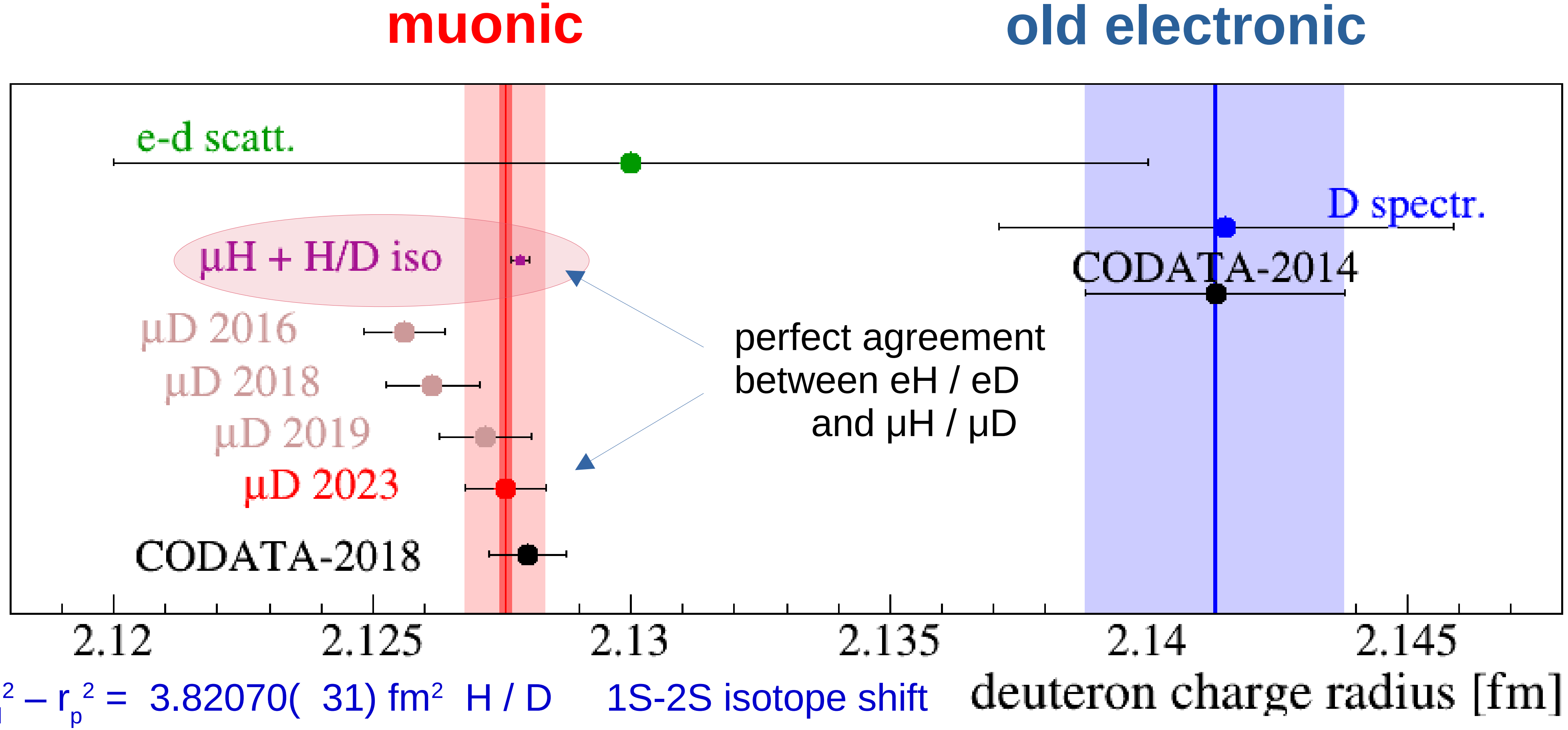
ΔE_{TPE} (theo) = 1.7503 (200) meV vs.

ΔE_{TPE} (exp) = 1.7591 (59) meV 3x more accurate

Pachucki, Lensky, Hagelstein, LiMuli, Bacca, Pohl, RMP (2024)

Muonic Deuterium

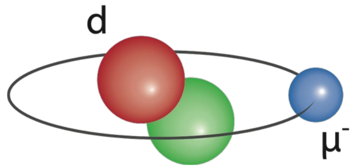




$r_d^2 - r_p^2 =$ 3.82070(31) fm² H / D 1S-2S isotope shift

3.82028(232) fm² μH / μD 2S-2P isotope shift (0.18 σ)

H/D isotope shift

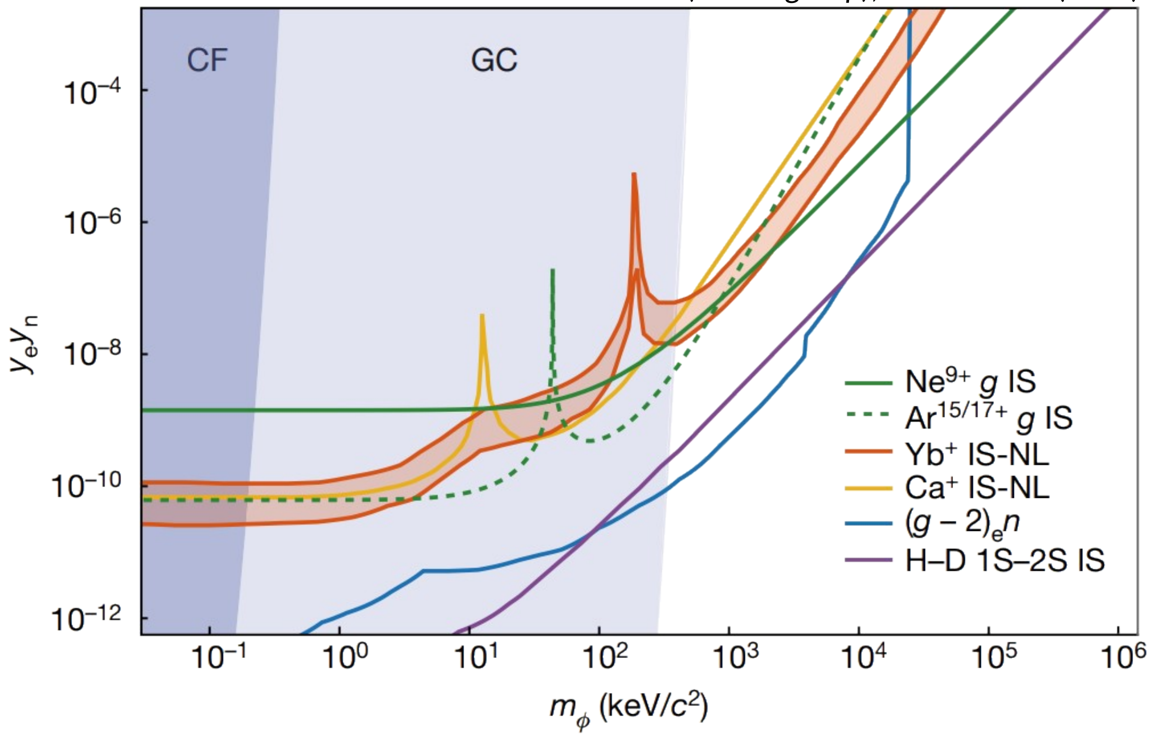


electronic H/D (1S-2S): $r_d^2 - r_p^2 = 3.8207(3)_{theo}\ \mathrm{fm}^2$

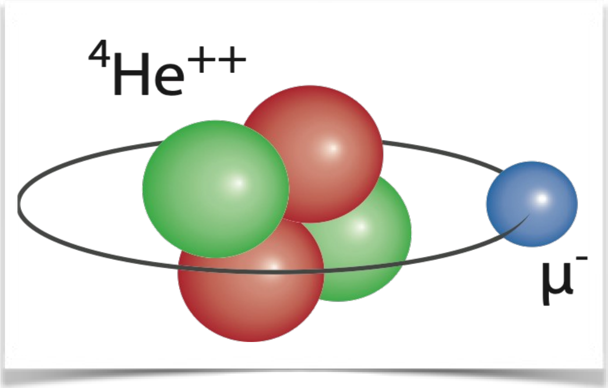
muonic H/D (2S-2P): $r_d^2 - r_p^2 = 3.8200(7)_{exp}(30)_{theo}\ \mathrm{fm}^2$

→ Best bound on 5th force

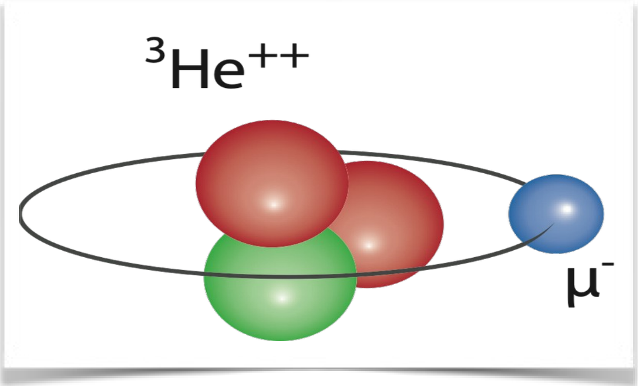
T. Sailer *et. al.* (*Blaum group*), Nature 606 (2022)



Muonic Helium

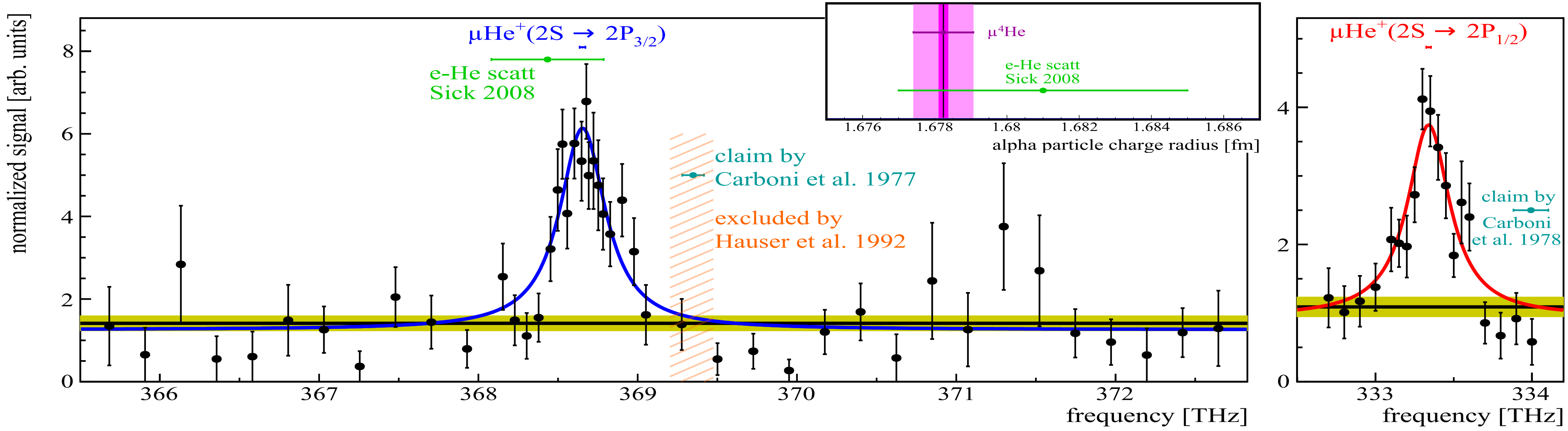


Krauth et al. (CREMA), Nature (2021)



arXiv 2305.11679

muonic ^{4}He ions



$2P_{3/2}$: ±17 GHz **$2P_{1/2}$: ±15 GHz**

$R(^4He) = 1.67854\ (13)_{exp}\ (120)_{theo}$ fm

$(120)_{theo} = (112)_{2PE}\ \ (46)_{3PE}$

2-photon exchange: Bacca group

3-photon exchange: our educated guess based on Pachucki et al.

Exp: Krauth, RP et al. (CREMA Coll.) Nature 589, 527 (2021) Theory updated in Pachucki, RP et al., arXiv 2212.13782

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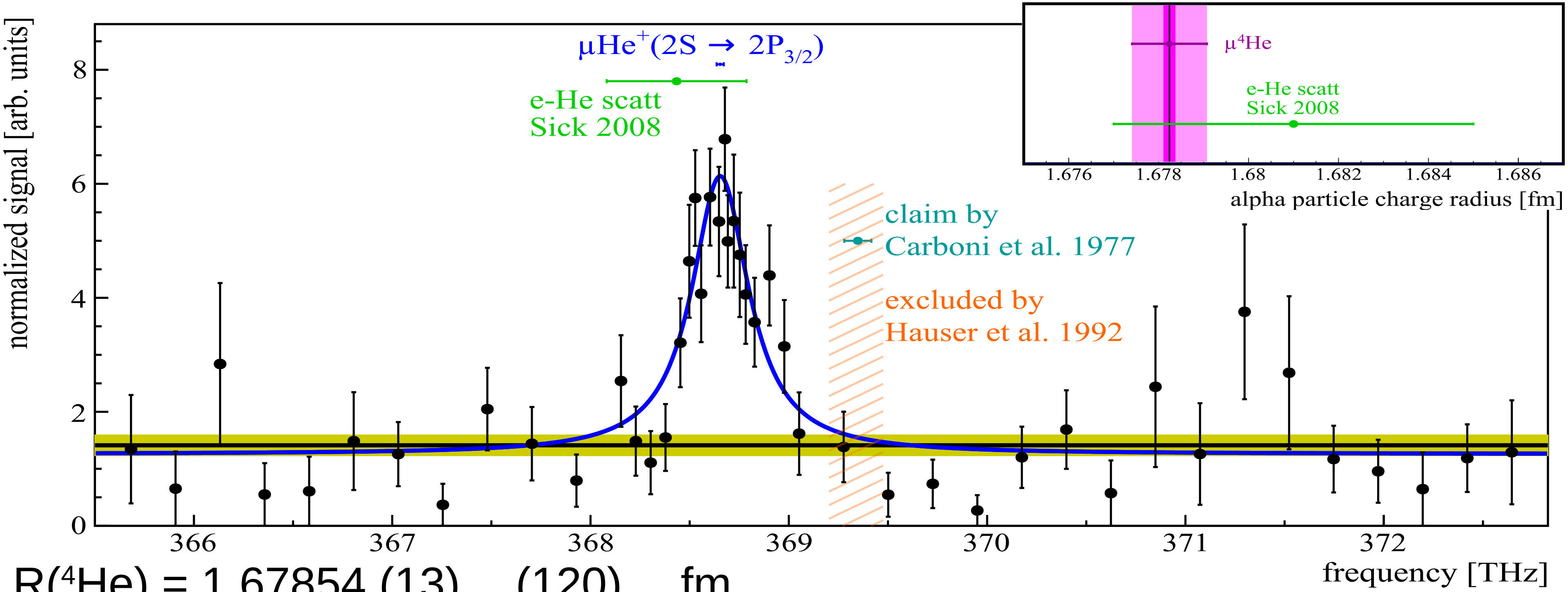

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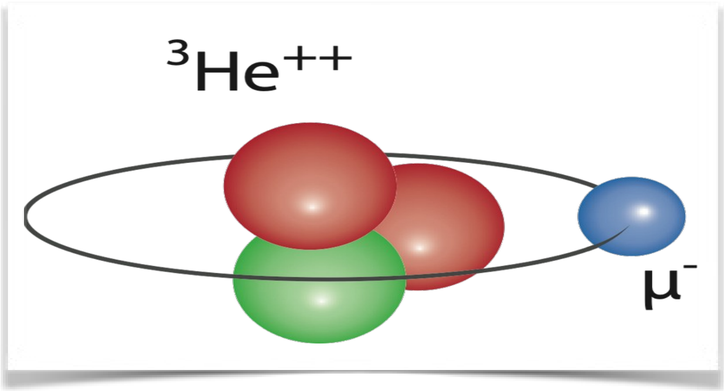
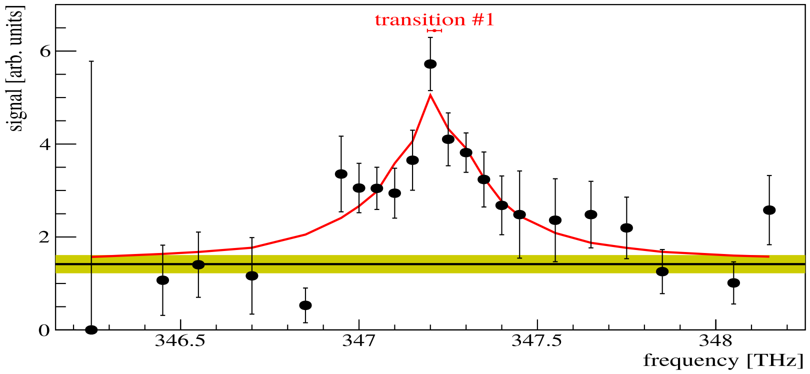
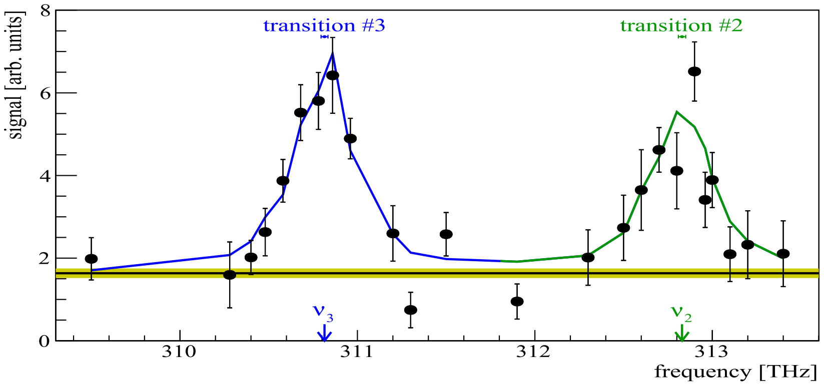
Muonic Helium-3

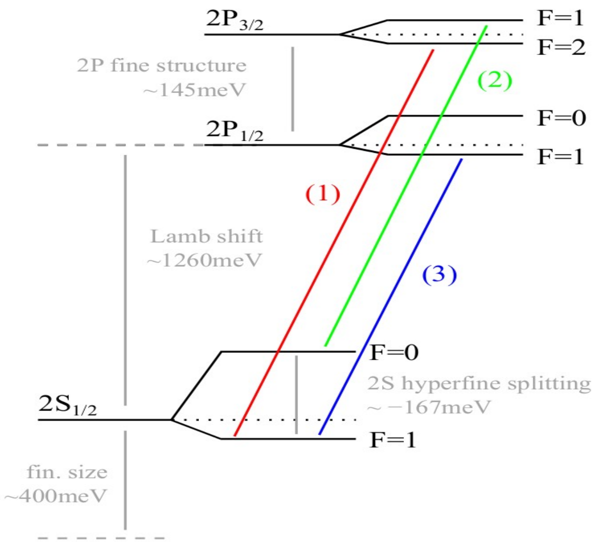


arXiv 2305.11679

muonic ^{3}He ions







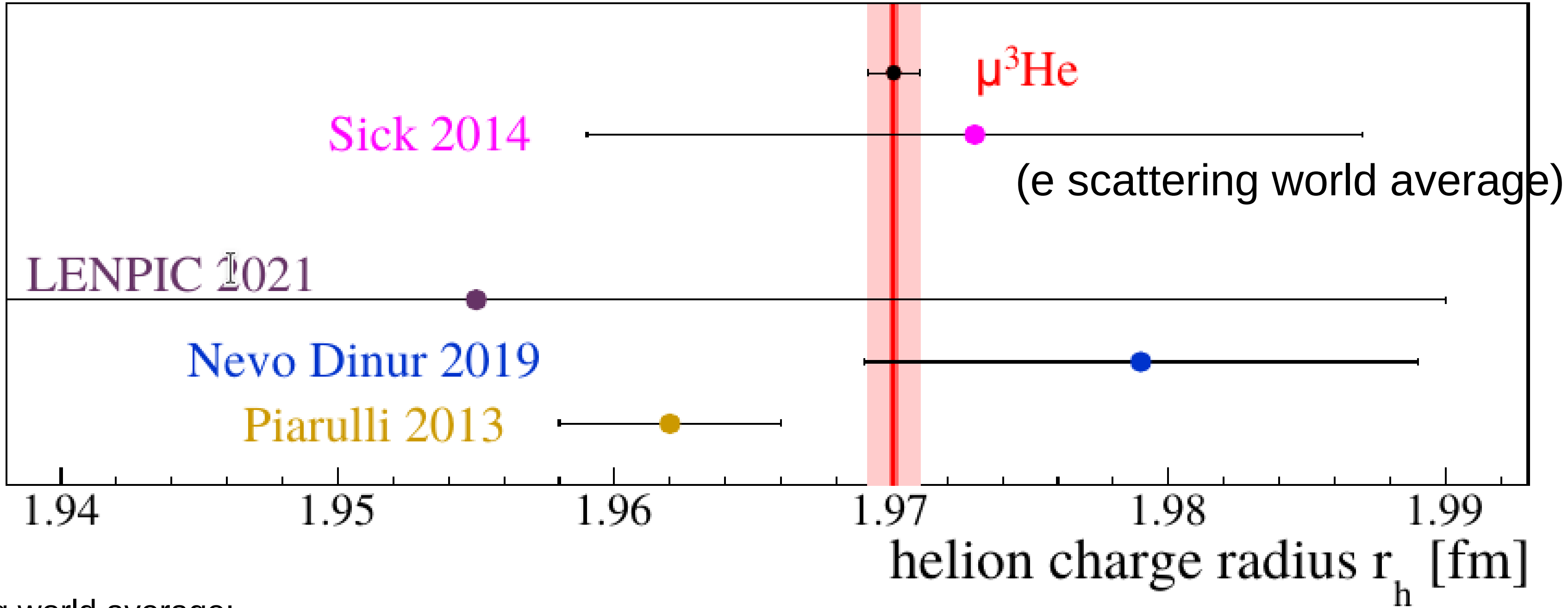
CREMA Coll., arXiv 2305.11679

exp: each line has +-20 GHz(stat) +- 1 GHz (syst)

R(^{3}He) = 1.97007 $(12)_{exp}$ $(93)_{theo}$ fm preliminary!

theo = +- 0.00076 fm 2PE
+- 0.00052 fm 3PE
+- 0.00001 fm R^2 coeff.
+- 0.00002 fm QED

Muonic Helium-3



e-scattering world average:

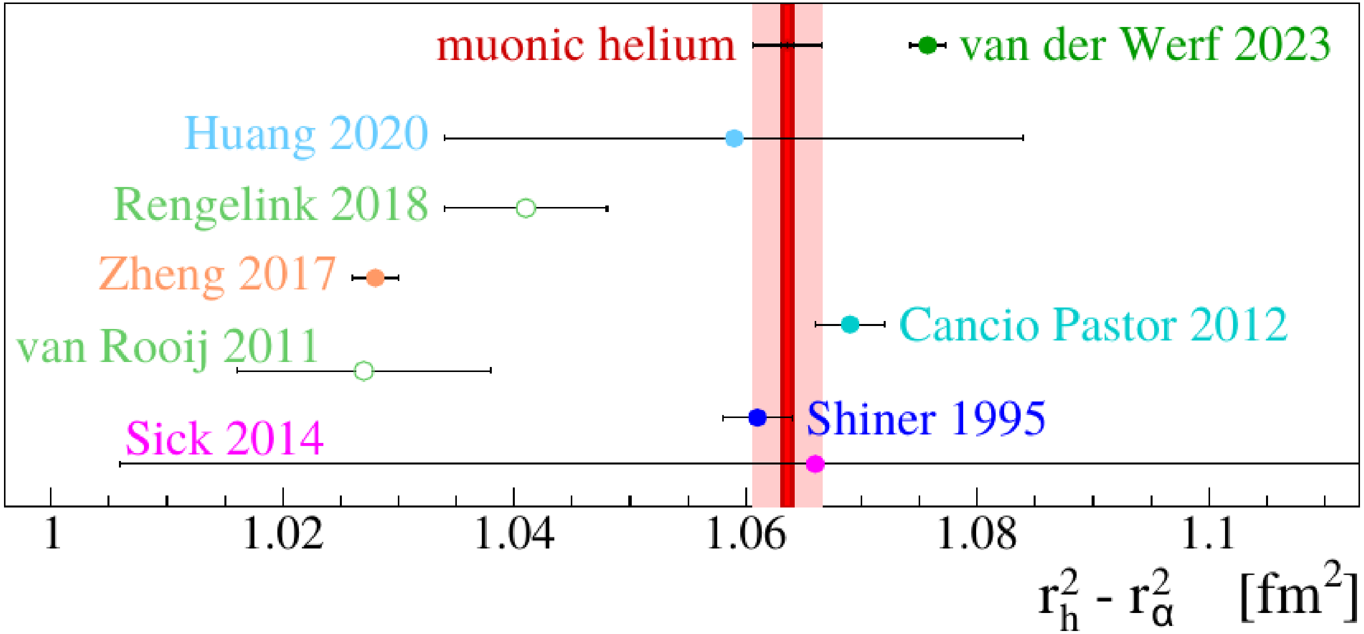
Sick 2014: PRC 90, 064002 (2014)

nuclear theory:

LENPIC: Maris et al., PRC 106, 064002 (2022)
Nevo Dinur et al., PRC 99, 034004 (2019)
Piarulli et al., PRC 87, 014006 (2013)

CREMA Coll., arXiv 2305.11679

Helium-3 – Helium-4 Isotope Shift



Huang: PRA 101, 062507 (2020)
Rengelink: Nature Physics 14, 1132 (2018)
Zheng: PRL 119, 263002 (2017)
van Rooij: Science 333, 196 (2011)
Cancio Pastor: PRL 108, 143001 (2012)
Shiner: PRL 74, 3553 (1995)

CREMA Coll., arXiv 2305.11679

LiMuli, Bacca et al:
4σ discrepancy!!

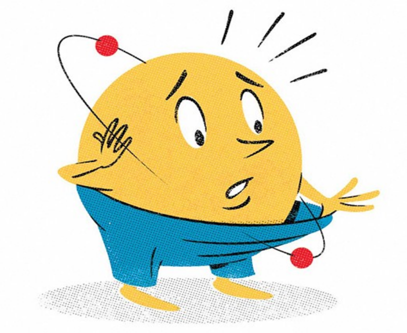
Intermediate conclusions

Muonic atoms / ions provide:

- **~10x more accurate charge radii**, when combined with

calculated polarizability

	^{3}He 1.9701* (10) ~~1.9730 (160)~~	^{4}He 1.6786 (12) ~~1.6810 (40)~~
^{1}H 0.8406 (4) ~~0.8751 (61)~~	^{2}D 2.1279 (2) ~~2.1413 (25)~~	^{3}T 1.7550 (860)



The New York Times

Intermediate conclusions

Muonic atoms / ions provide:

- **~10x more accurate charge radii**, when combined with **calculated polarizability**

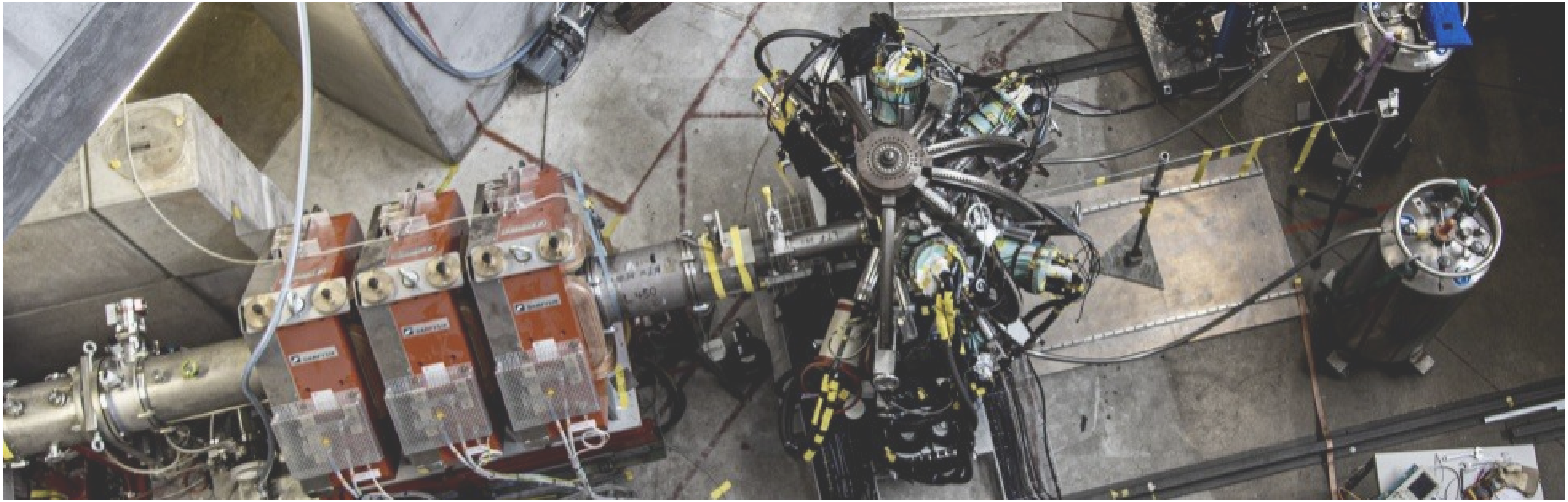
- few times more accurate **nuclear polarizability**, when combined with **charge radius from regular atoms**

Muonic atoms are a cool tool for proton and new-nucleon properties!

muX

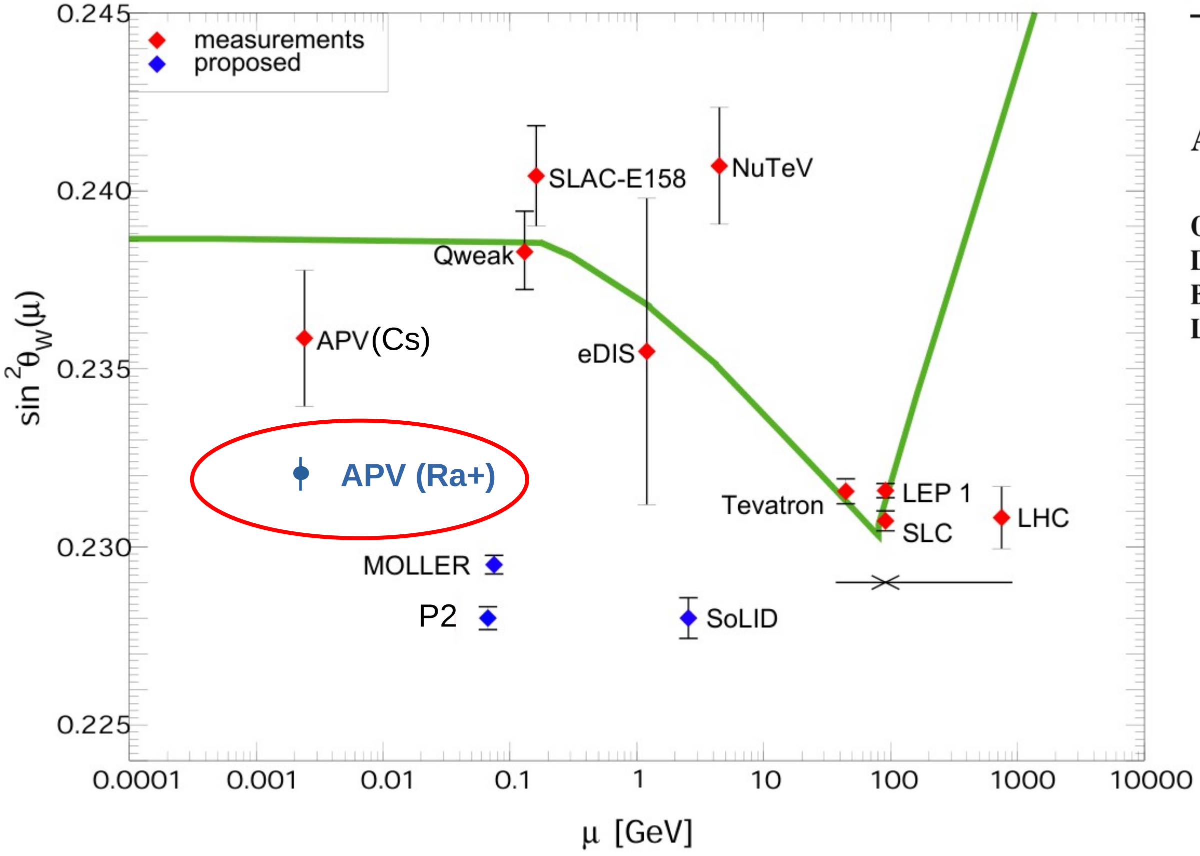
X-rays from **O(10s of µg) target material** using Ge detectors (Miniball)

→ rare, or radioactive



muX: Radii of O(10μg) material

rare stuff, or **radioactive** isotopes



Hyperfine Interact (2011) 199:9–19
DOI 10.1007/s10751-011-0296-6

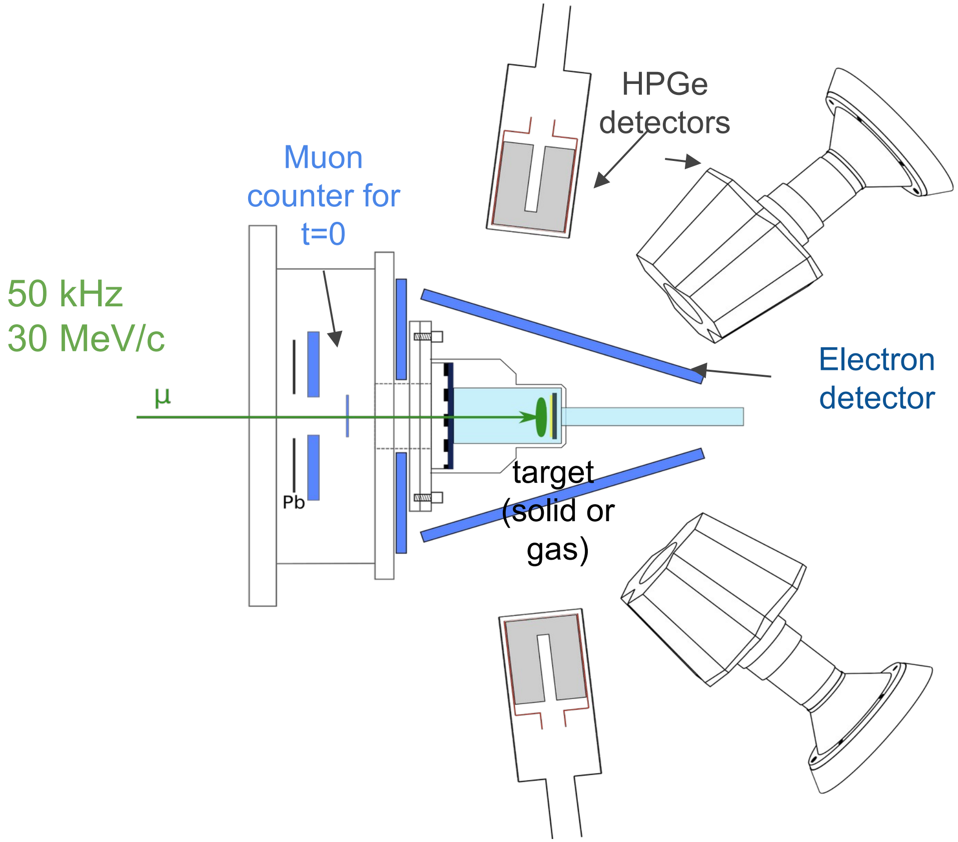
Atomic parity violation in a single trapped radium ion

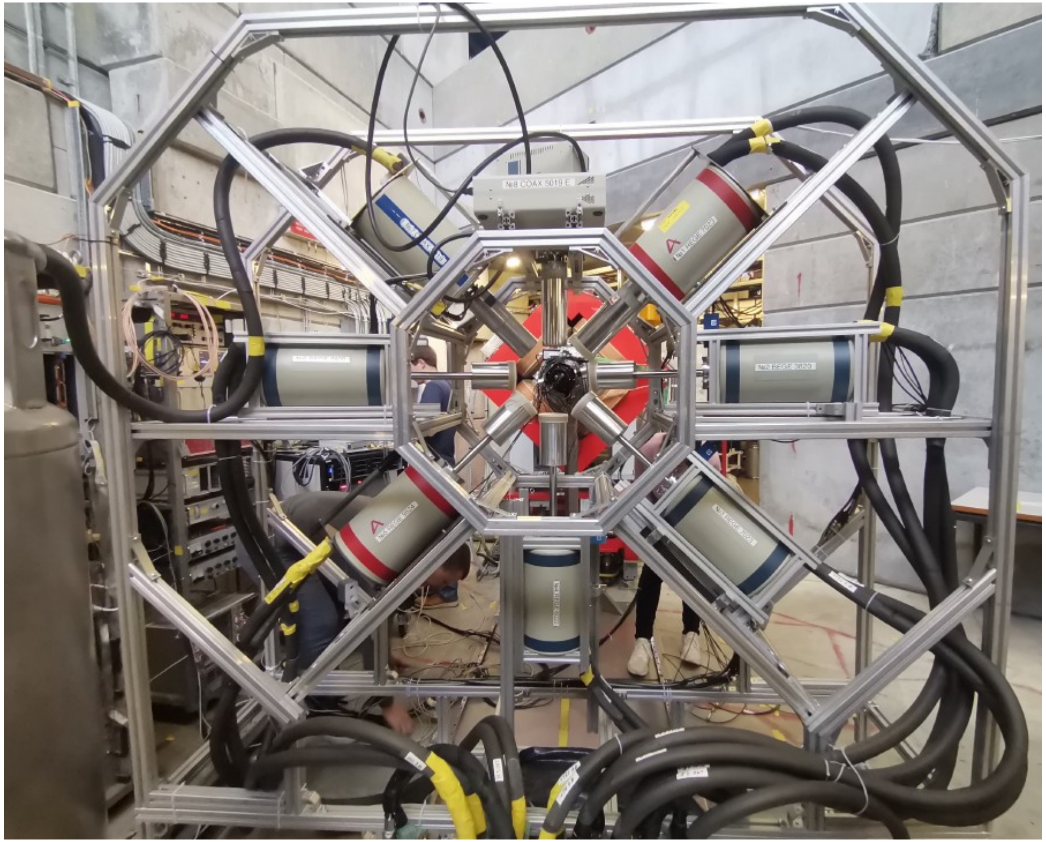
O. O. Versolato · L. W. Wansbeek · G. S. Giri · J. E. van den Berg · D. J. van der Hoek · K. Jungmann · W. L. Kruithof · C. J. G. Onderwater · B. K. Sahoo · B. Santra · P. D. Shidling · R. G. E. Timmermans · L. Willmann · H. W. Wilschut

INPUT: need δR to 0.2%

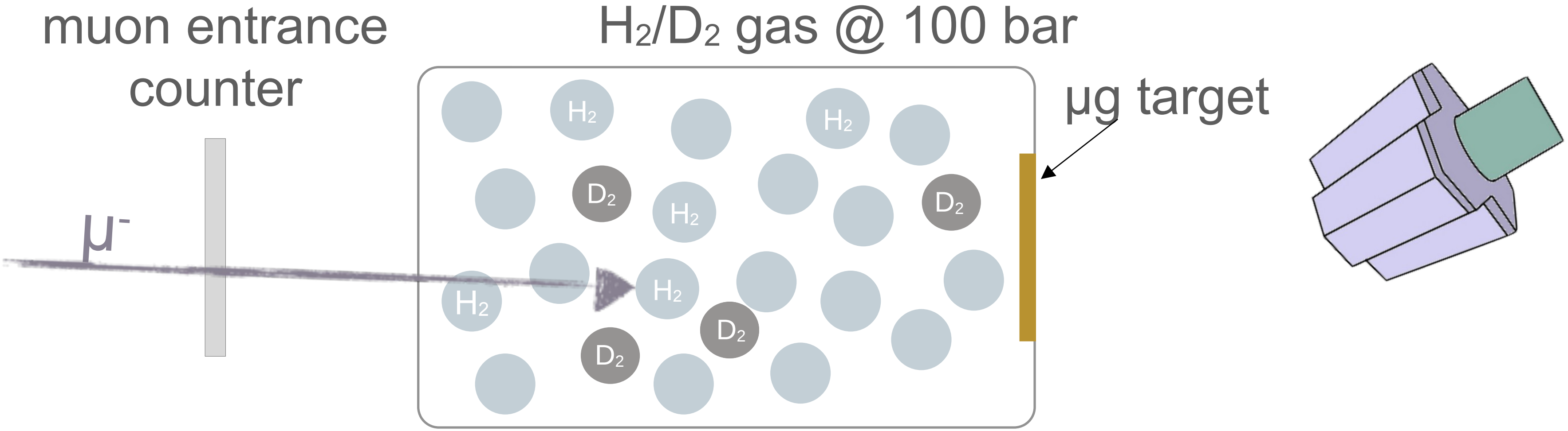
$$E1_{PNC} = K_r \, Z^3 \, Q_W$$

muX Setup


HPGe
detectors
Muon
counter for
t=0
50 kHz
30 MeV/c
μ
Electron
detector
Pb
target
(solid or
gas)

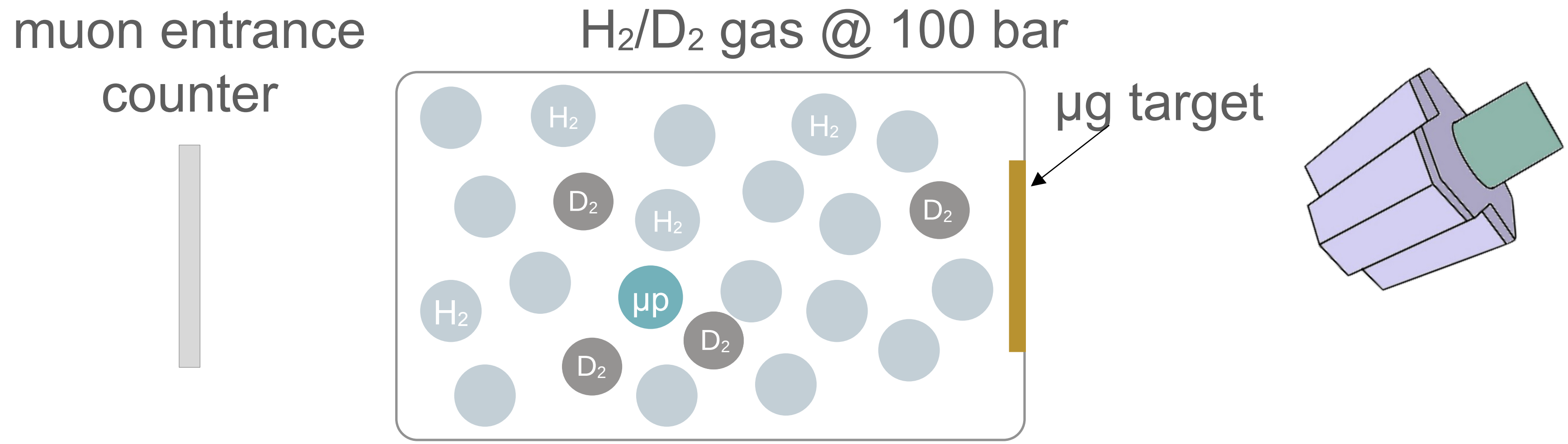


Muon transfer to microgram targets



1. μ^- stops in 100 bar of H_2 + 0.25% D_2 & forms muonic hydrogen μp
2. transfer to deuterium μp → μd
3. μd moves almost freely in the H_2 gas
4. transfer to high-Z element μd μZ when hitting target & emission of x rays during the atomic cascade

Muon transfer to microgram targets



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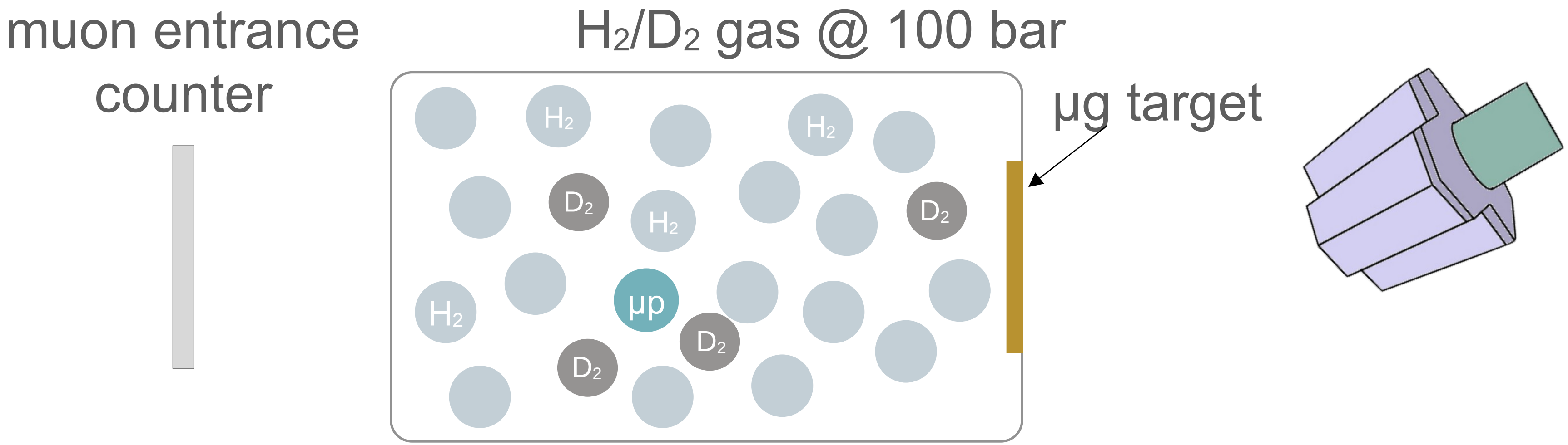

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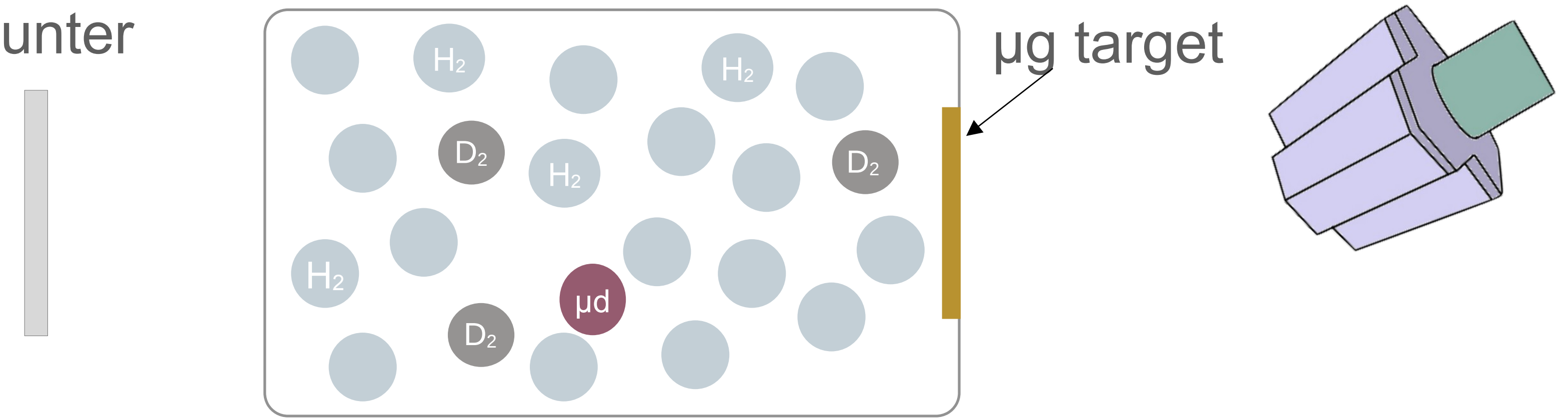

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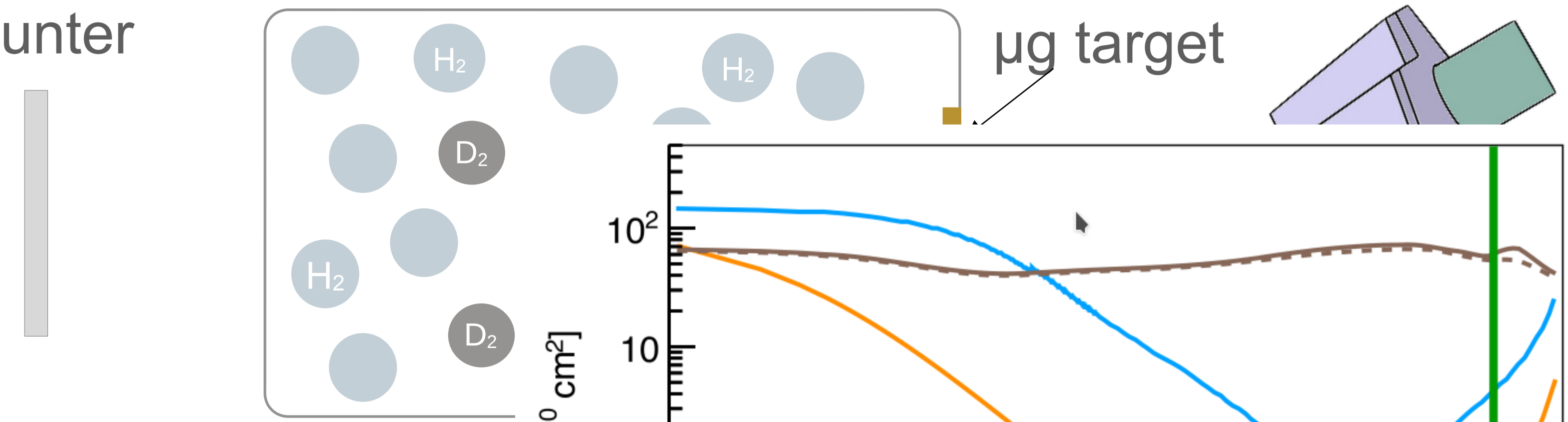

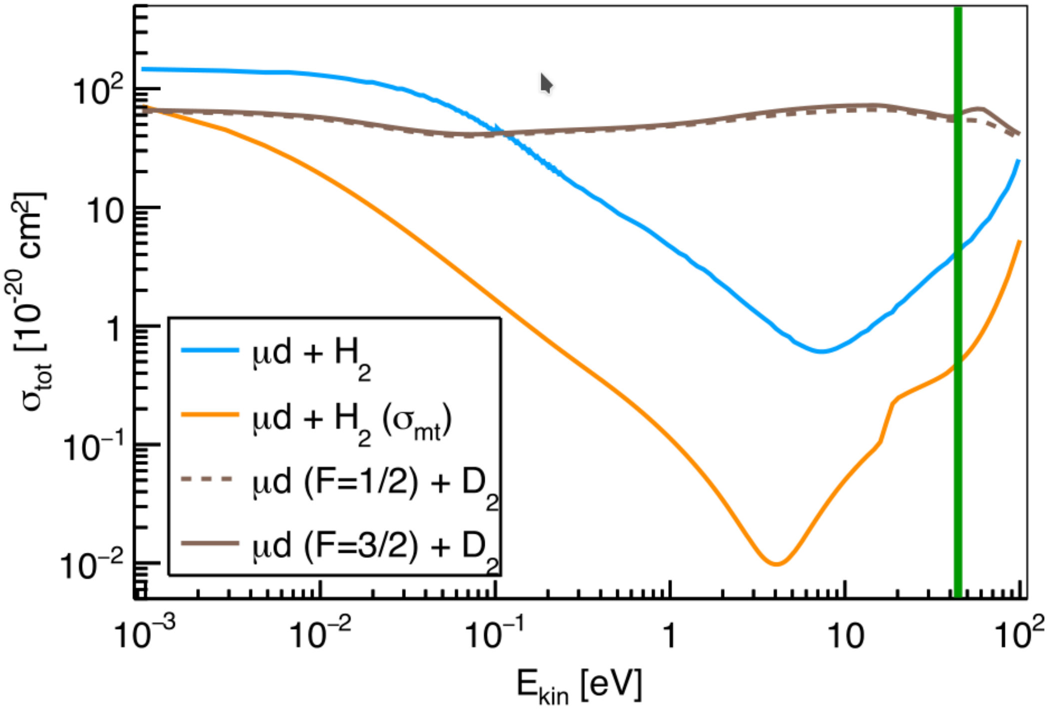

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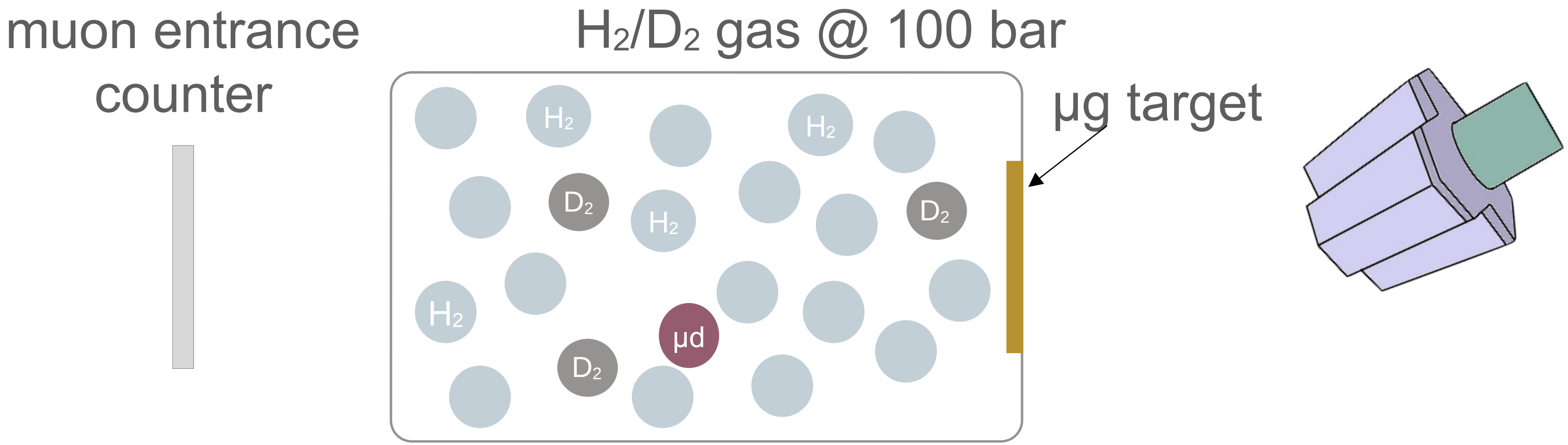
4. transfer to high-Z element μd emission of x rays during the atoı

Muon transfer to microgram targets



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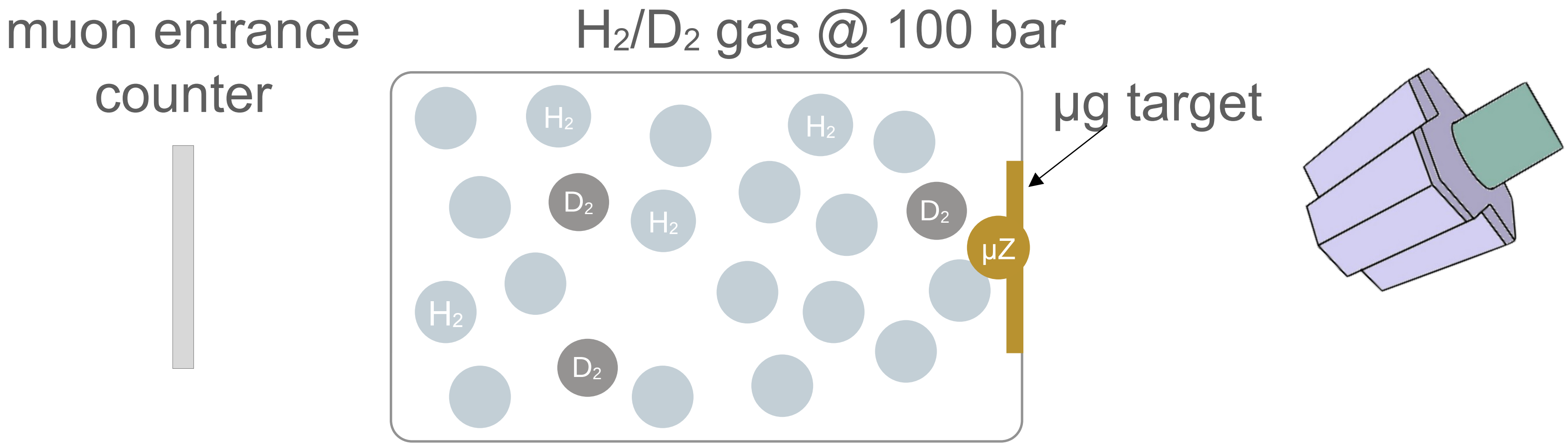

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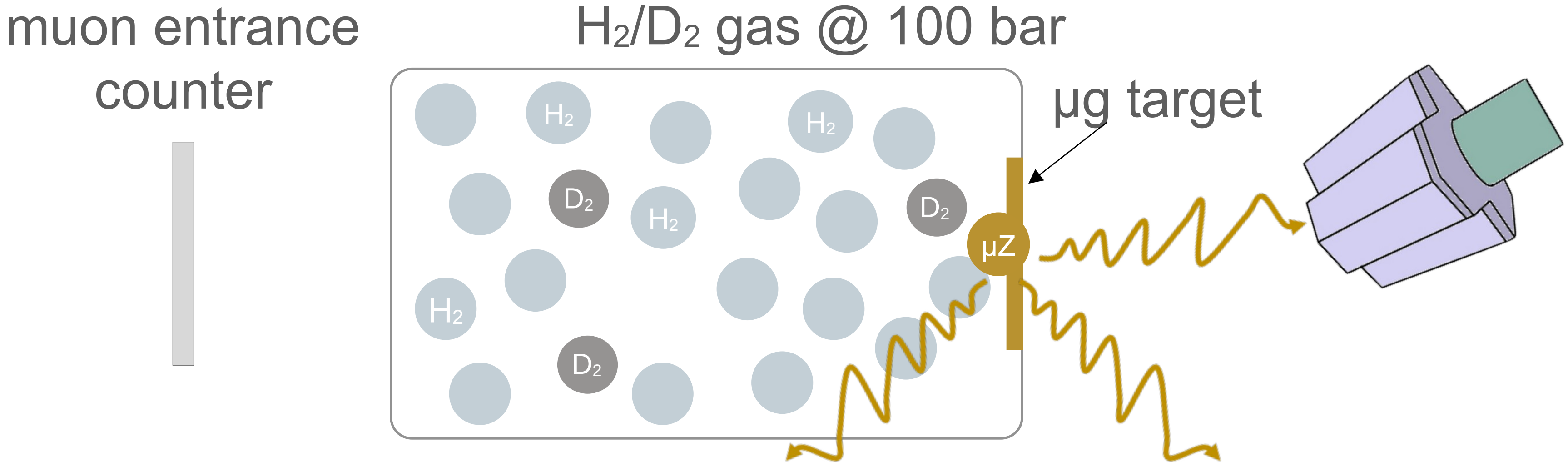
Muon transfer to microgram targets



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4. transfer to high-Z element µd $\rightarrow$ µZ when hitting target & emission of x rays during the atomic cascade

Proof-of-principle

So far problems with the uniformity of Ra target.

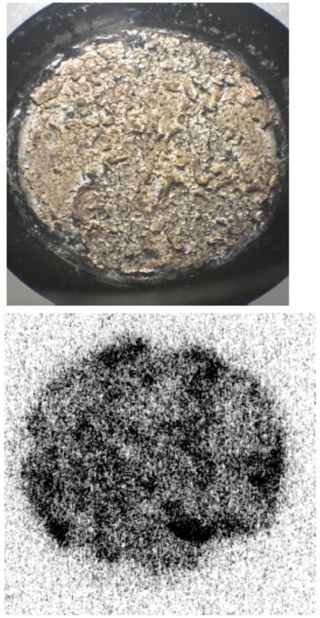
Measured Re and Cm

First physics result:

$Q(^{185}Re) = 2.07(5)$ b
$Q(^{187}Re) = 1.94(5)$ b

PRC 101, 054313 (2020)

15 µg of ^{248}Cm

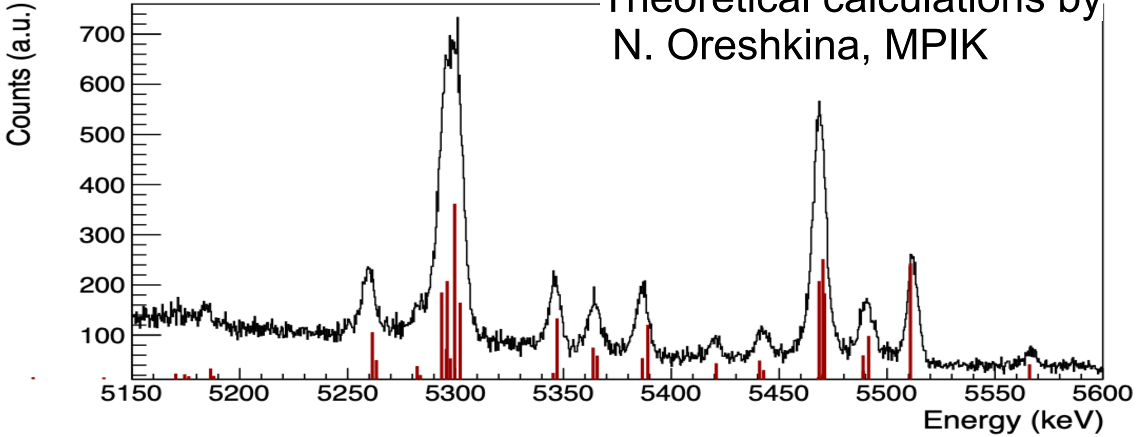


4 µg of ^{226}Ra

Nuclear charge radius in ^{185,187}Re

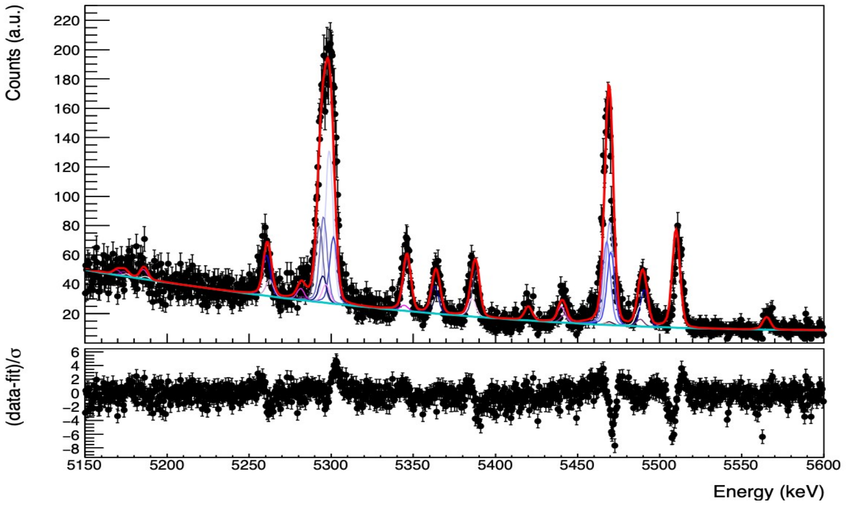
The extraction of the nuclear charge radius from the analysis of the 2p1s hyperfine transitions

Theoretical calculations by N. Oreshkina, MPIK



Preliminary results:

$R(^{185}Re) = 5.297(2)_{stat}(6)_{sys}$ fm
$R(^{187}Re) = 5.288(2)_{stat}(4)_{sys}$ fm

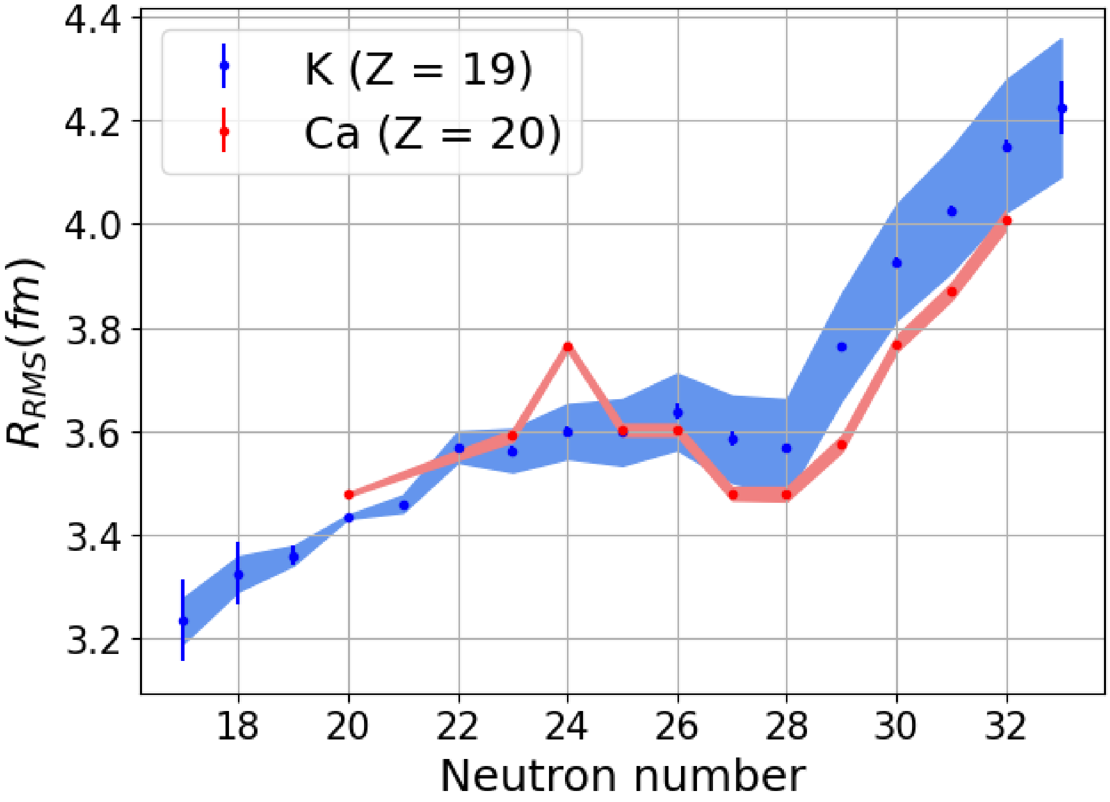


Not all the systematics are taken into account.

ReferenceRadii

muX with lighter nuclei

absolute radii and King plots



ReferenceRadii

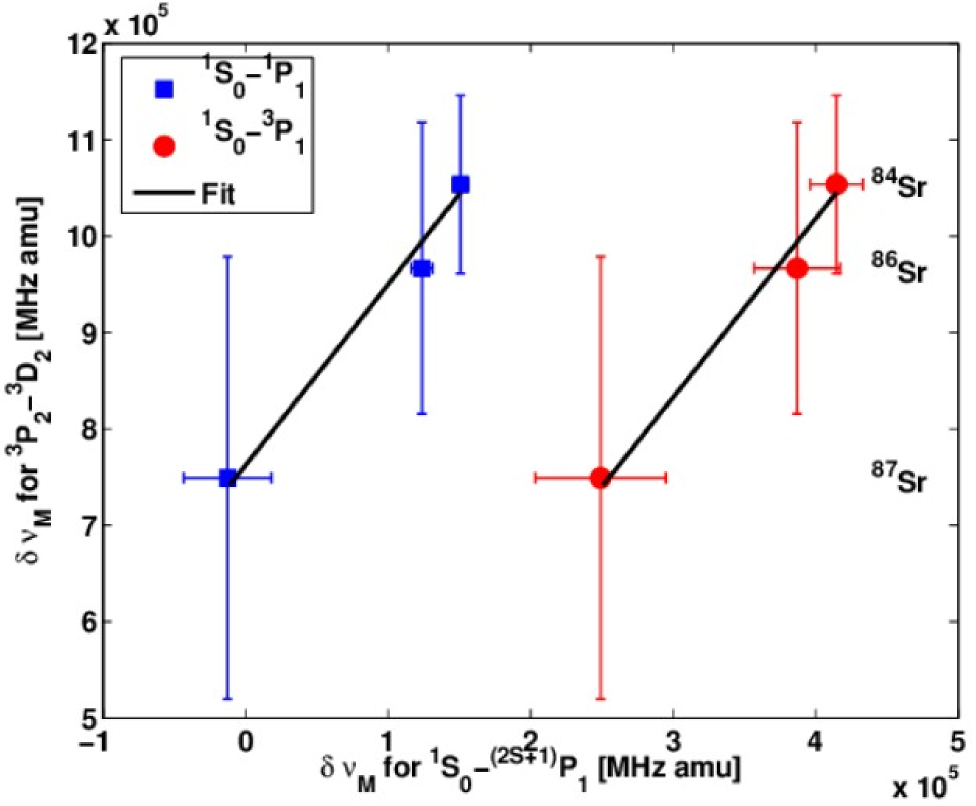
muX with lighter nuclei

absolute radii and King plots

$$\delta < r^2 >^{A,A'} = \frac{1}{F_i}\left(\delta \nu^{A,A'} - \frac{A - A'}{A\,A'} M_i\right)$$

M_i Mass shift
F_i Field shift

different for each element and transition



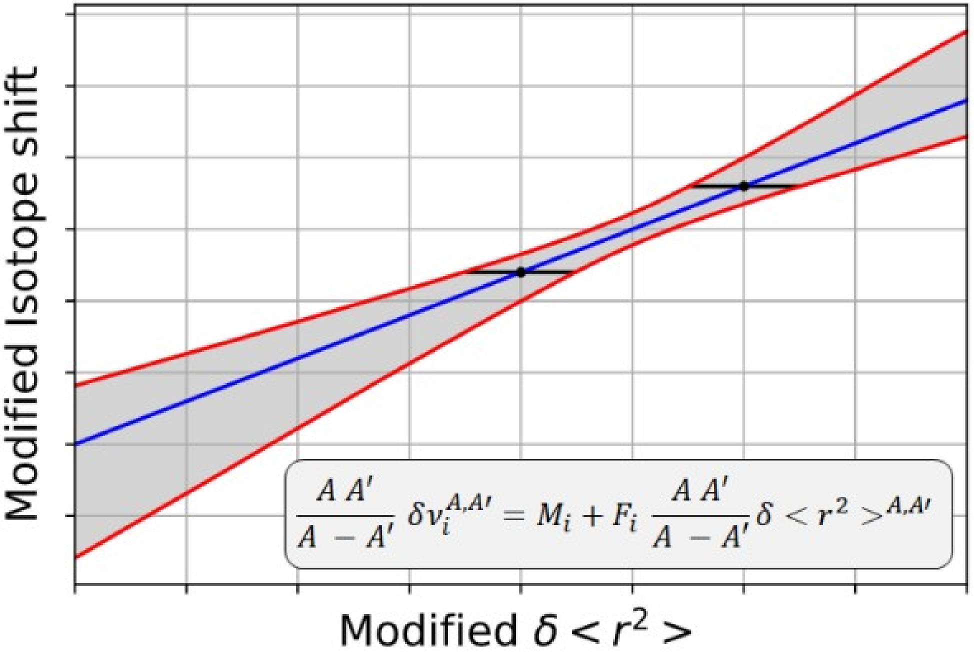
ReferenceRadii

Modified King plot

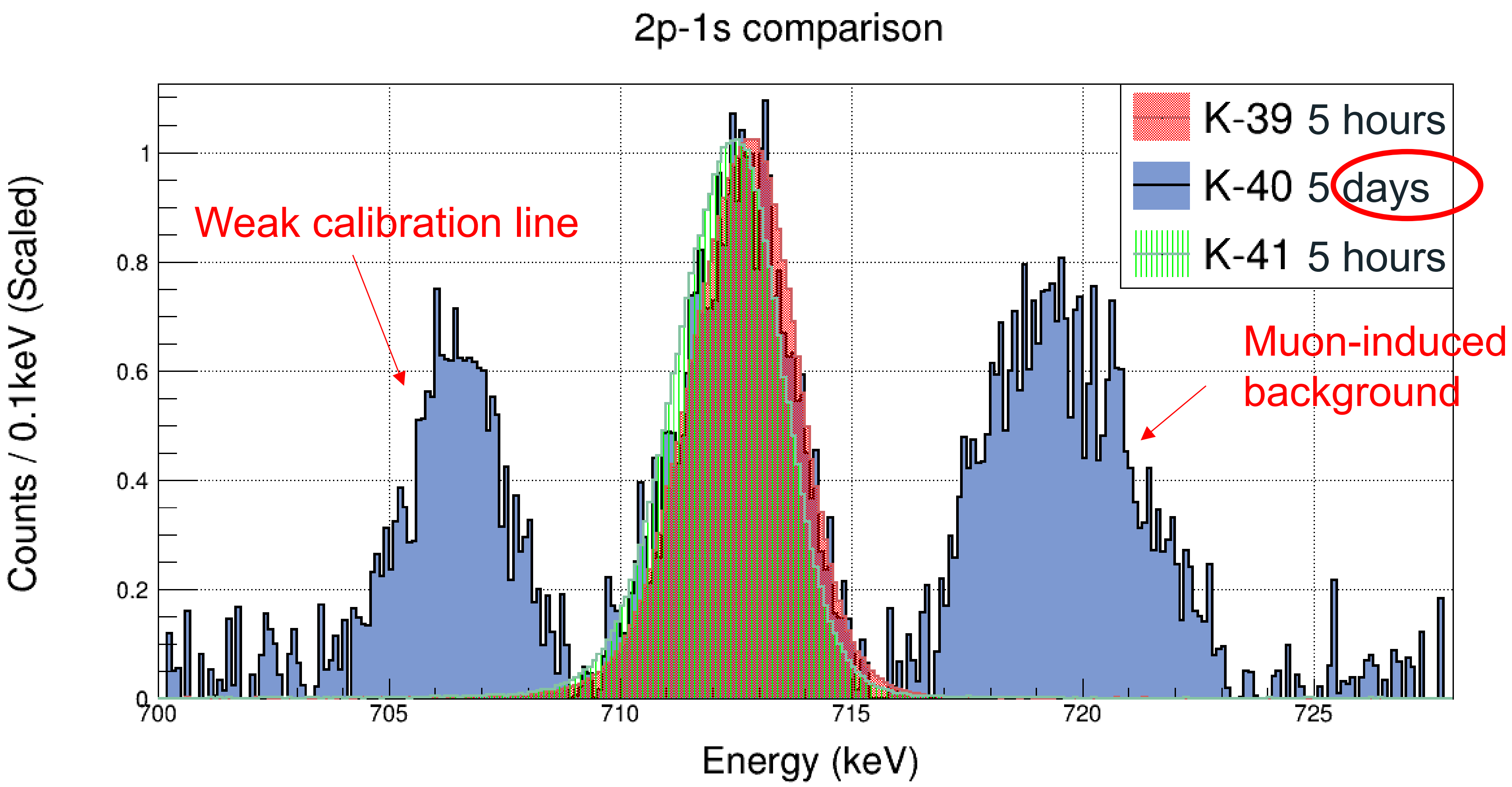
$$\frac{A-A'}{A\,A'}\delta\nu_i^{A,A'} = M_i + F_i\frac{A-A'}{A\,A'}\delta<r^2>^{A,A'}$$

- Mass shift: intercept
- Field shift: slope

- Absolute charge radii
  - One → Absolute values
  - Two → $\frac{M_i}{F_i}$
  - Three → M_i and F_i

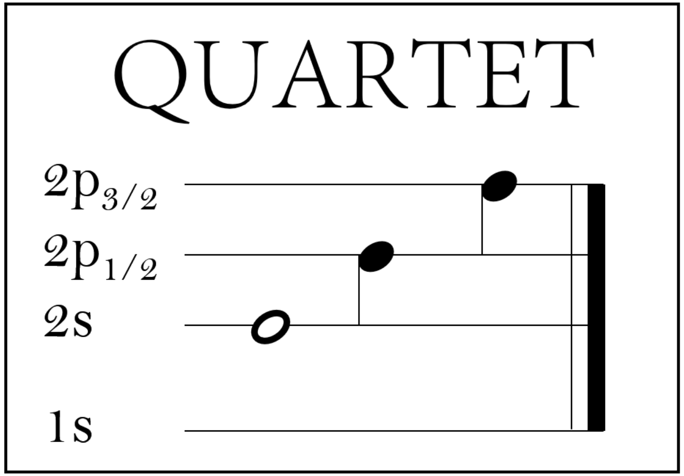


Potassium muonic isotope shift

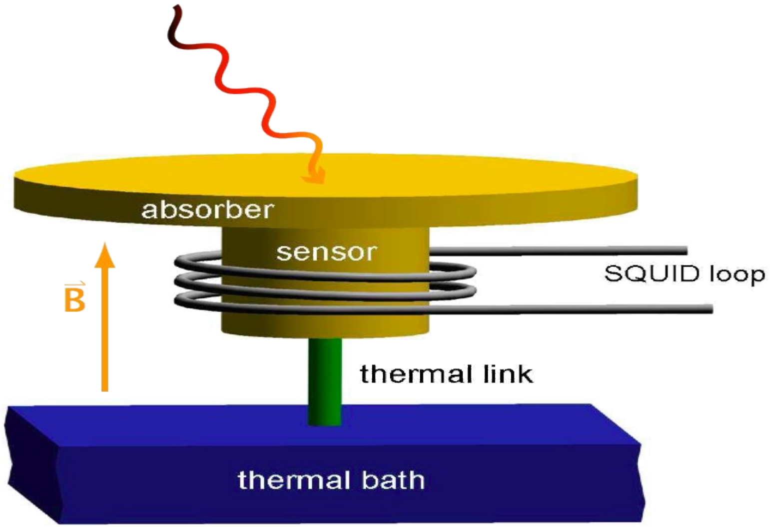


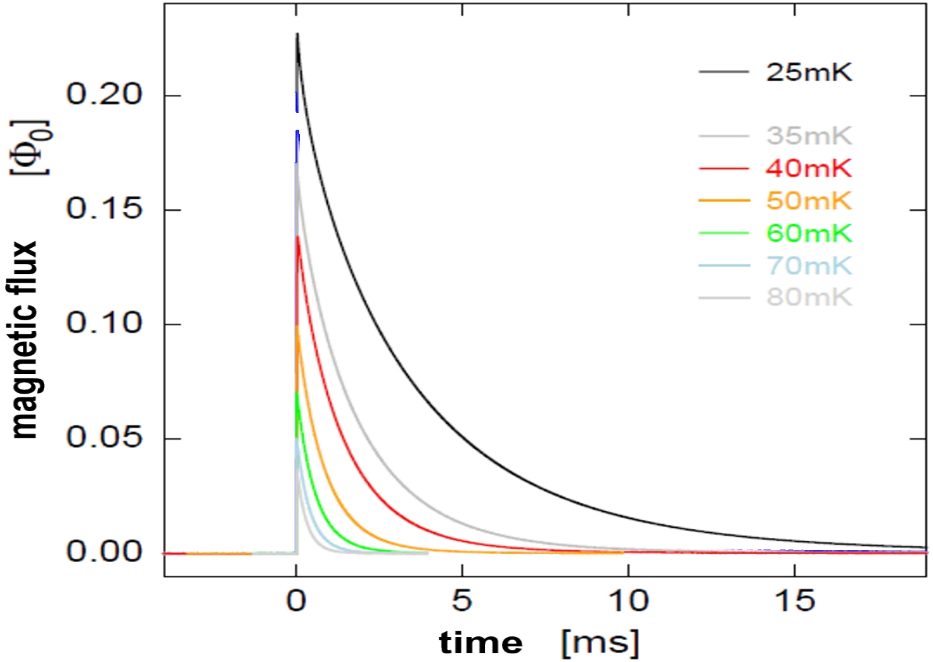
QUARTET: Radii of Z=3 10

“muX with MMCs”

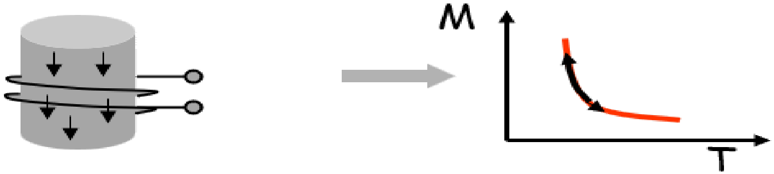


Metallic Magnetic Calorimeters (MMCs) from KIP (Heidelberg)





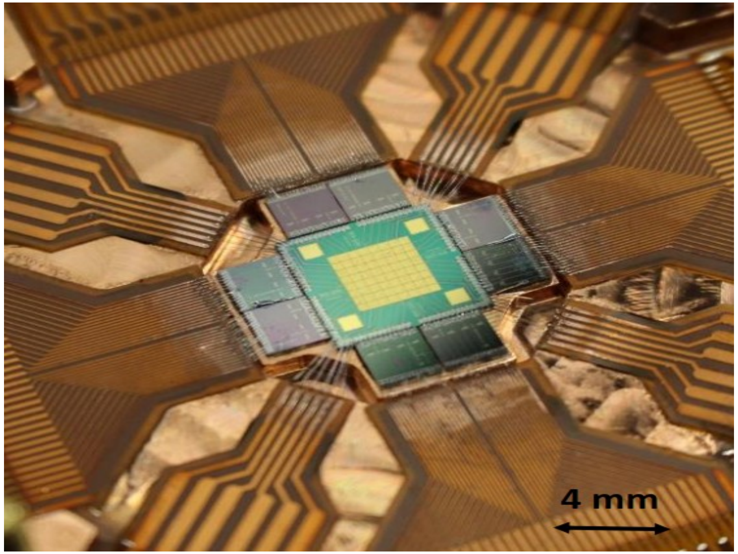
Magnetization of paramagnetic material:



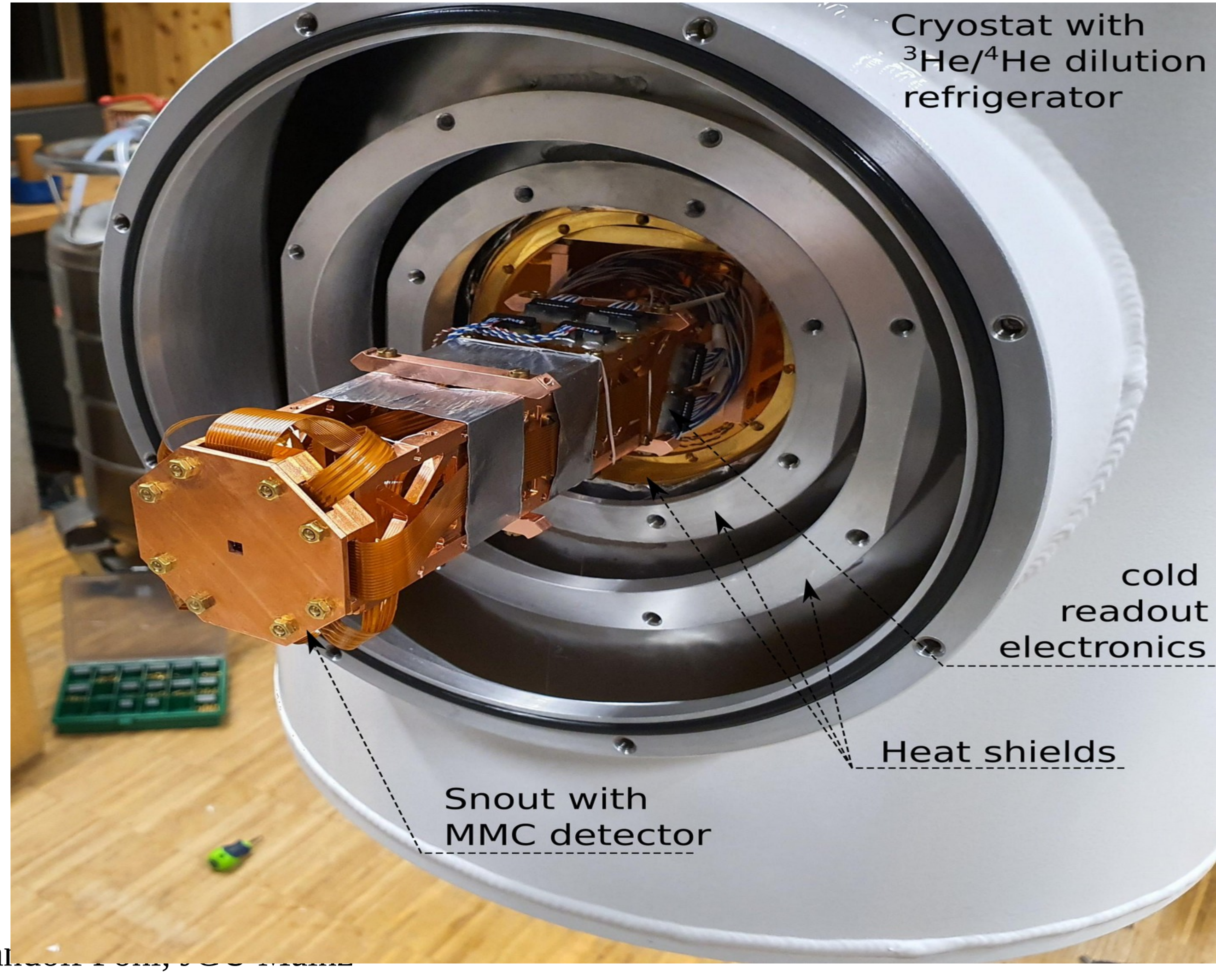
Decay time 3ms@30mK
Keep rates < 10 Hz
per pixel to avoid pileup

Metallic Magnetic Calorimeters (MMCs)

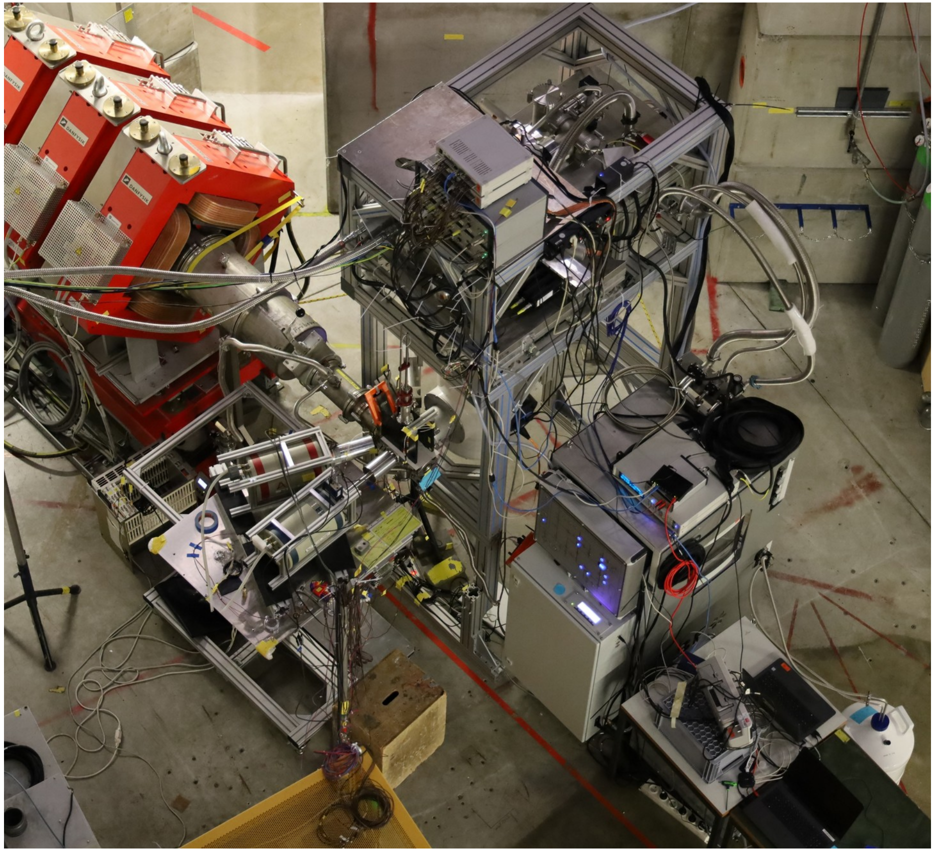
pixel array, area 16mm^2

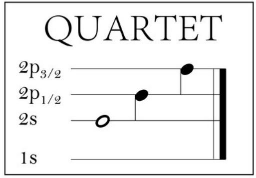


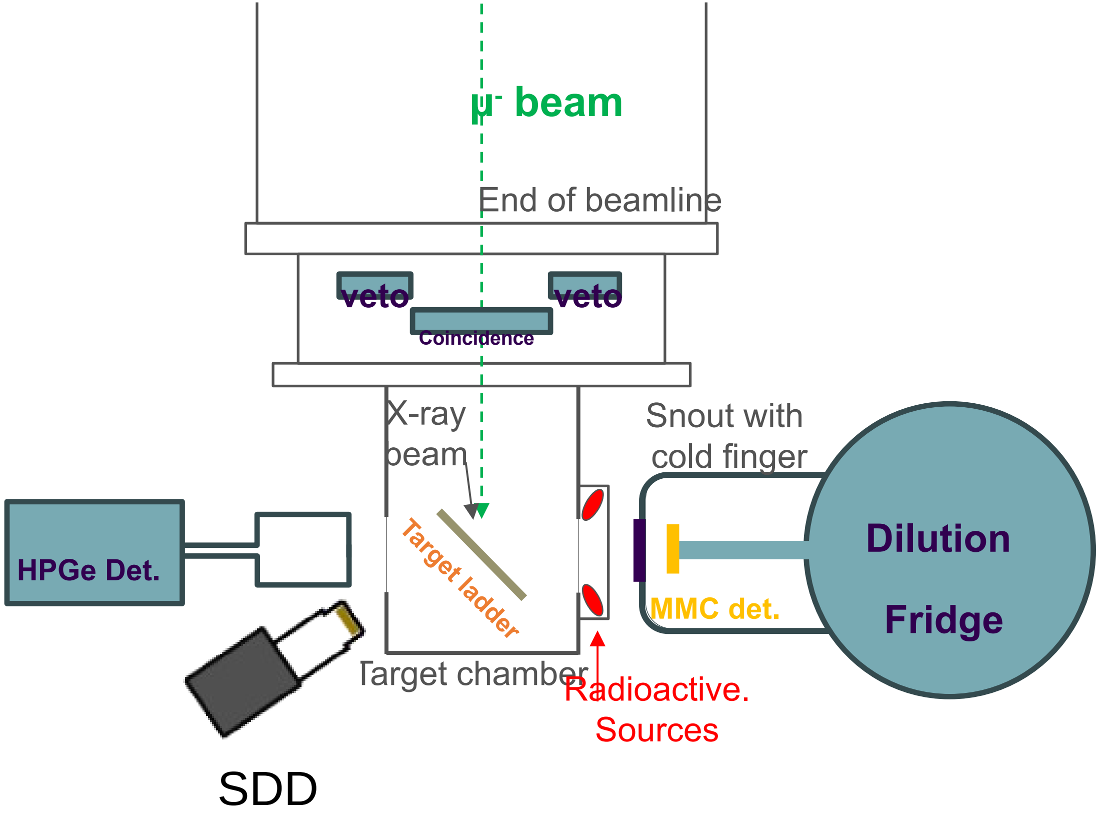
High efficiency (>90%) for photons 10-60 keV



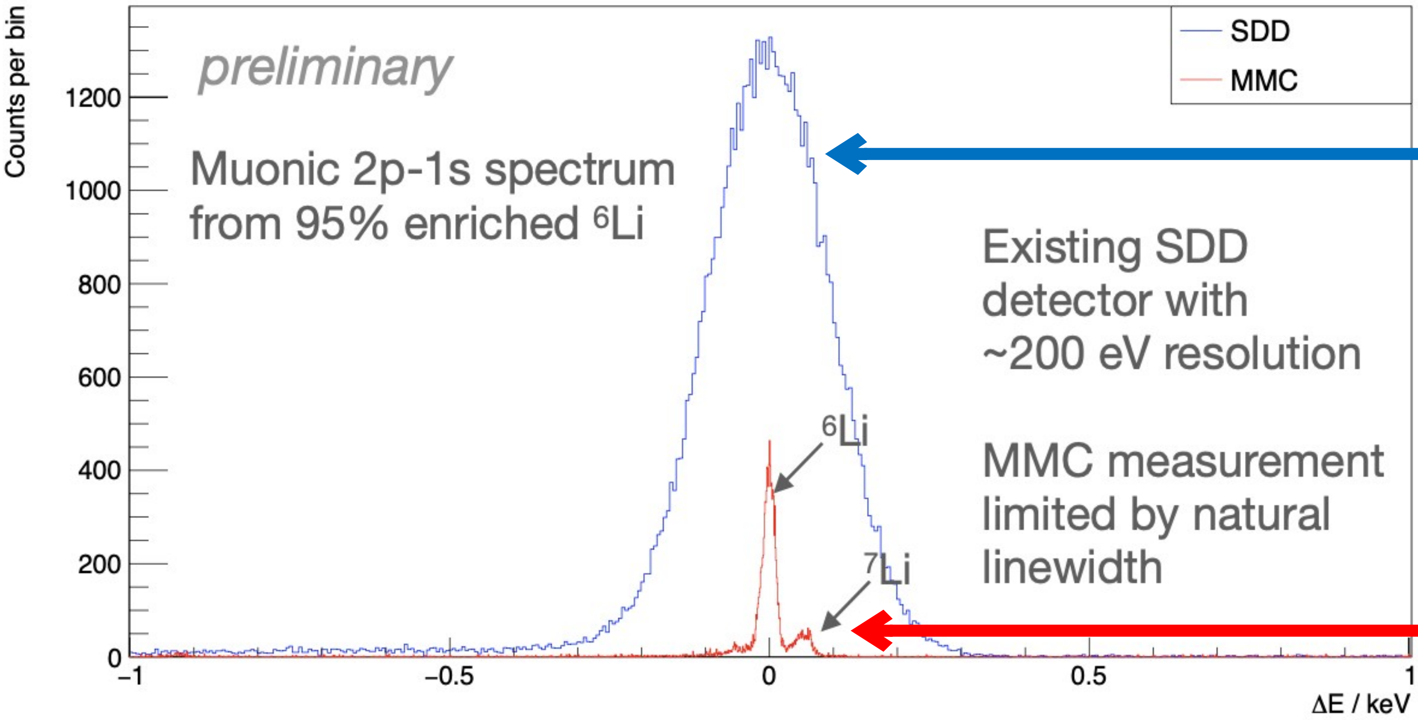
QUARTET: 1st test beam in 2023

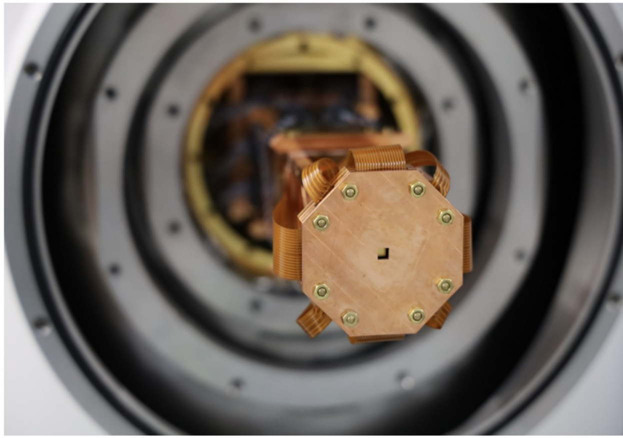






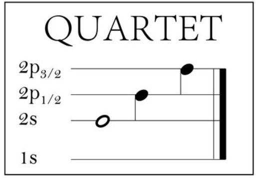
QUARTET: 1st test beam in 2023

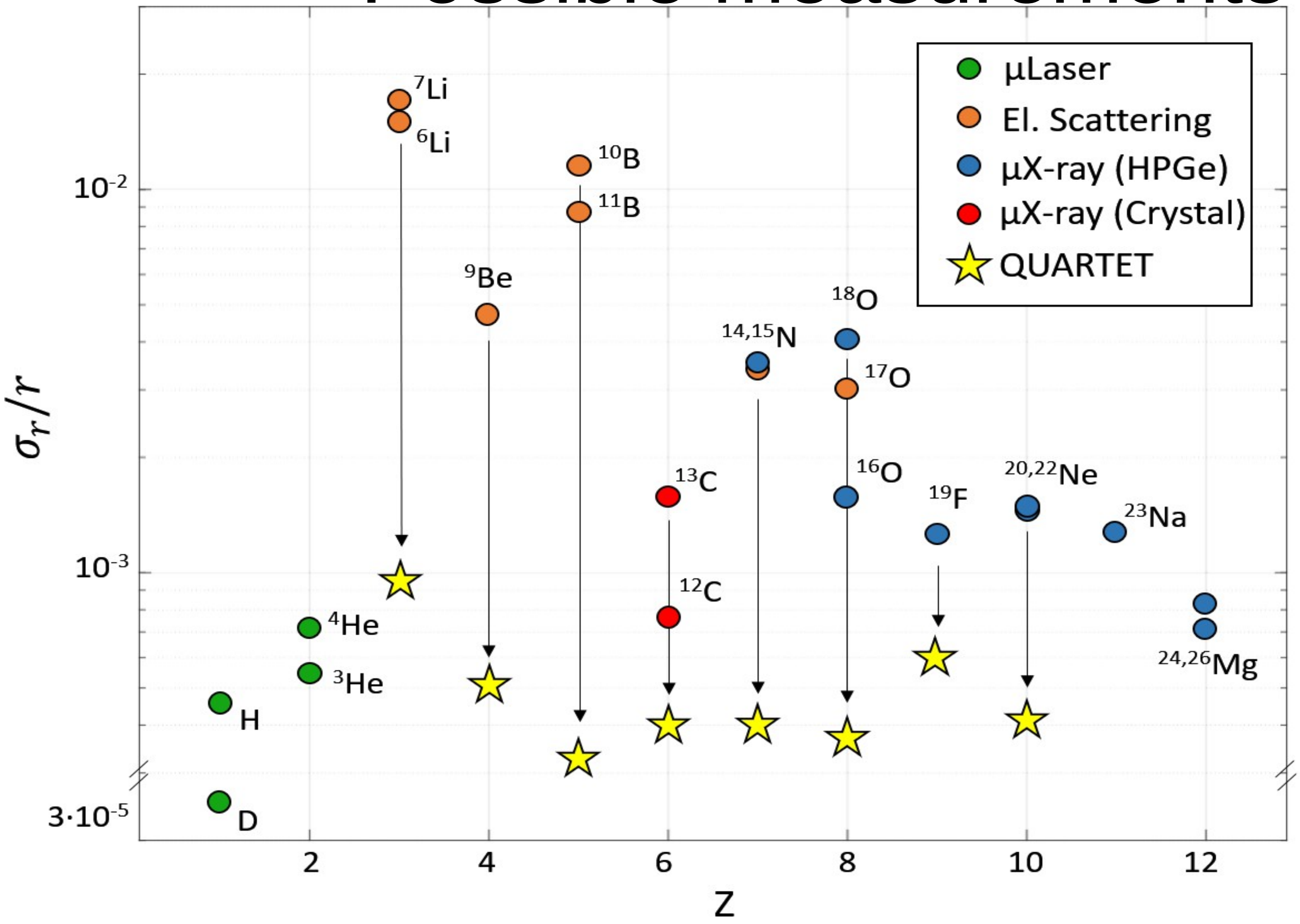




Randolf Pohl, JGU Mainz

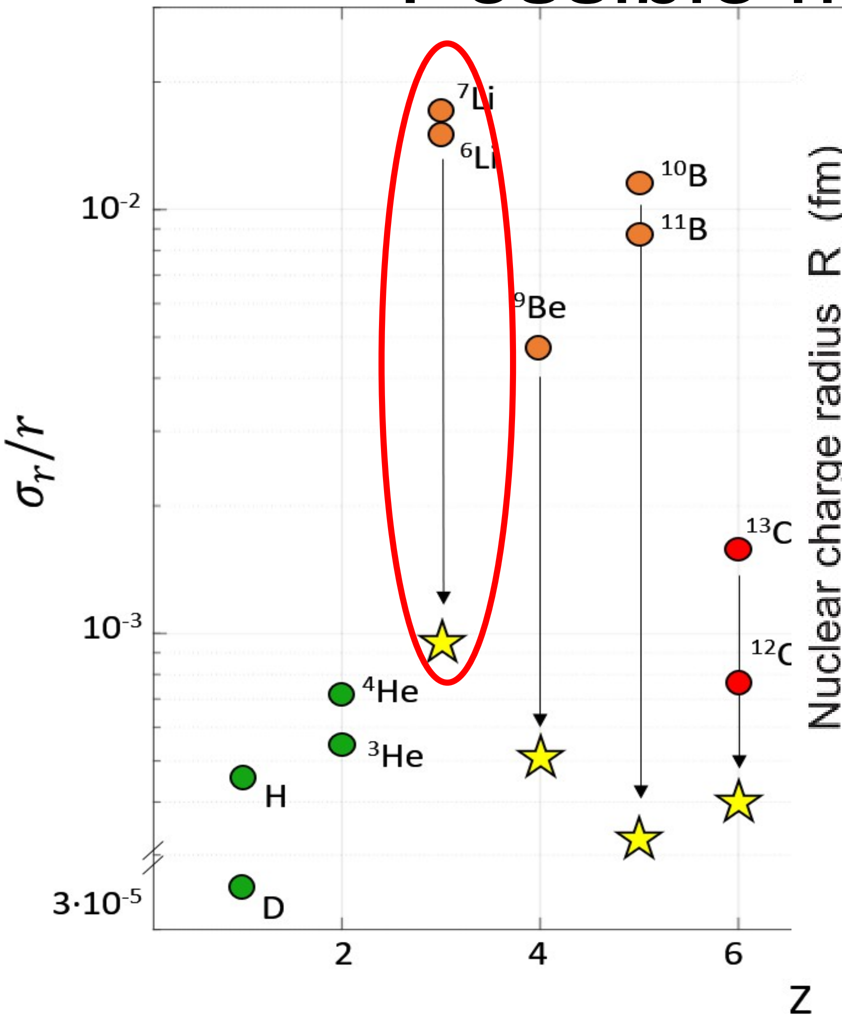
Possible measurements

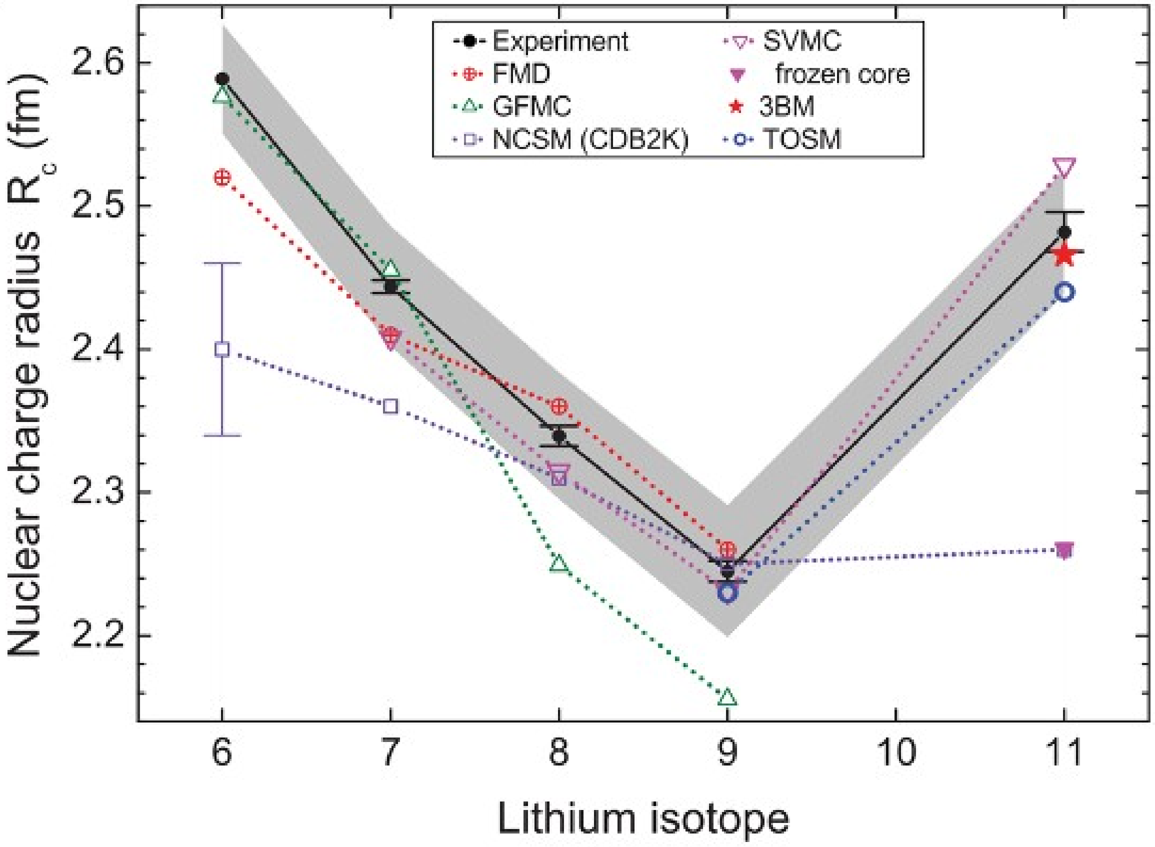




Possible measurements

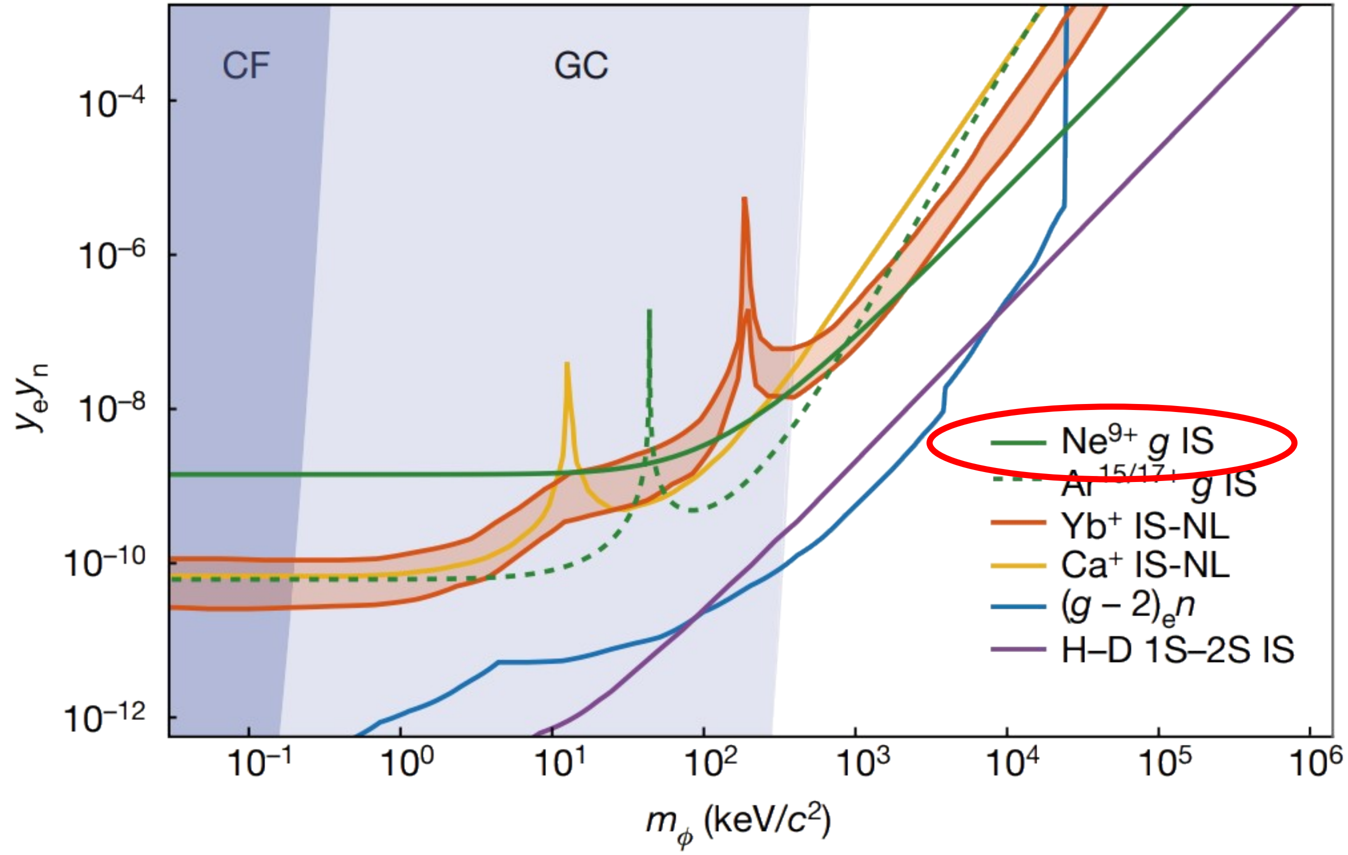
QUARTET



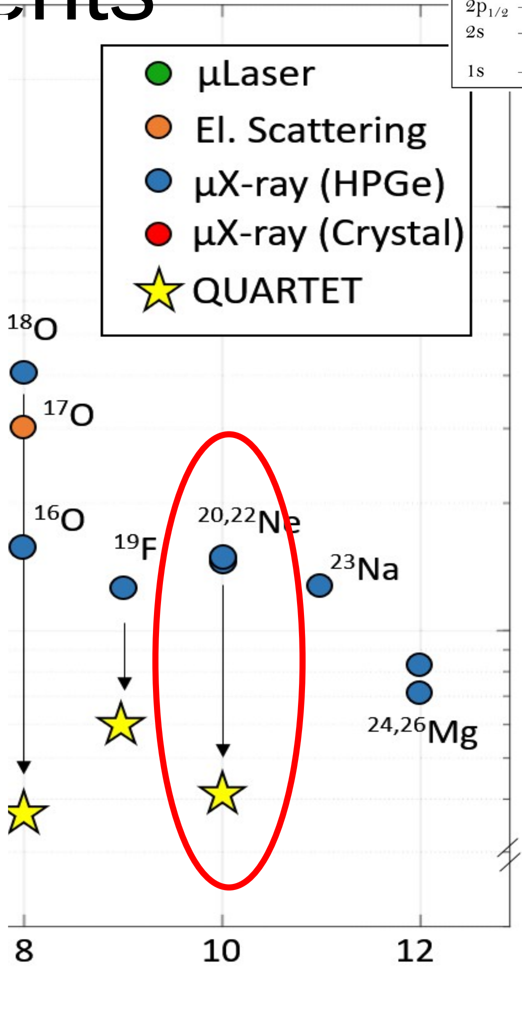


PRC 84, 024307 (2011)

Possible measurements

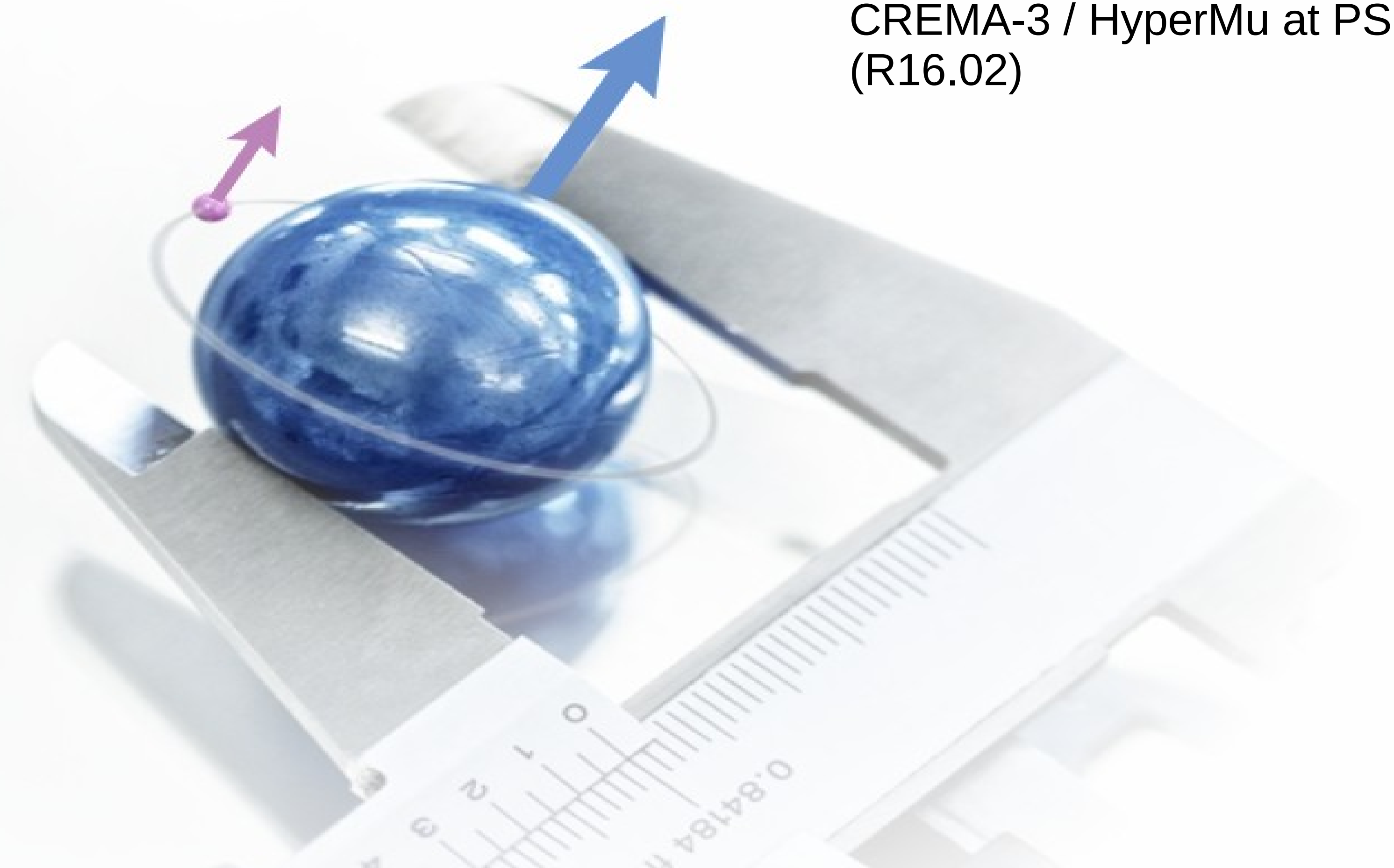


T. Sailer *et. al.*, Nature 606 (2022)

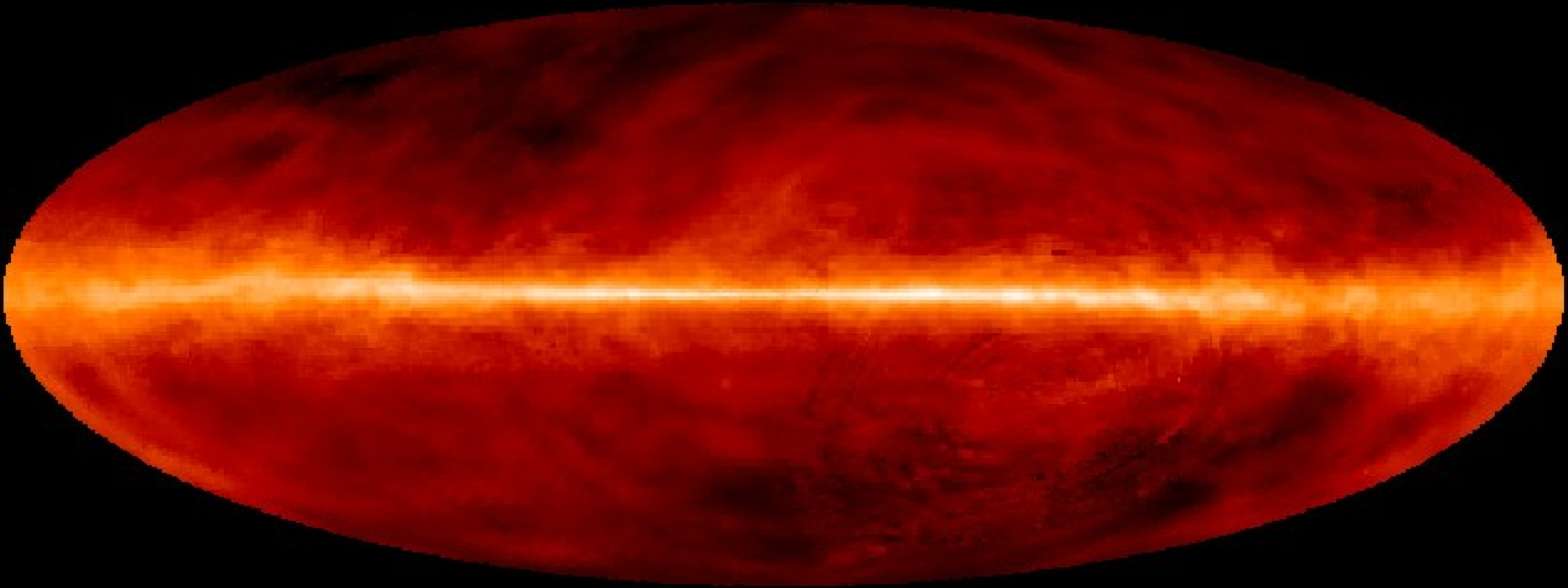


Hyperfine structure in muonic H

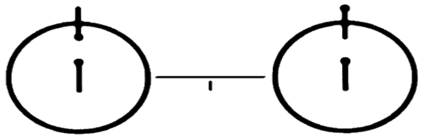
CREMA-3 / HyperMu at PSI
(R16.02)



The sky in hydrogen



Hyperfine structure in H / μp



The 21 cm line in hydrogen (1S hyperfine splitting) has been **measured** to 12 digits (0.001 Hz) in 1971:

$$\nu_{exp} = 1\,420\,405.\,751\,766\,7 \pm 0.000\,001 \text{ kHz}$$

Essen et al., Nature 229, 110 (1971)

QED test is limited to 6 digits (800 Hz) because of proton structure effects:

$$\nu_{theo} = 1\,420\,403.\,1 \pm 0.6_{\text{proton size}} \pm 0.4_{\text{polarizability}} \text{ kHz}$$

Eides et al., Springer Tracts 222, 217 (2007)

Proton Zemach radius

HFS depends on “Zemach” radius:

$$\Delta E = -2(Z\alpha) m \langle r \rangle_{(2)} E_F$$

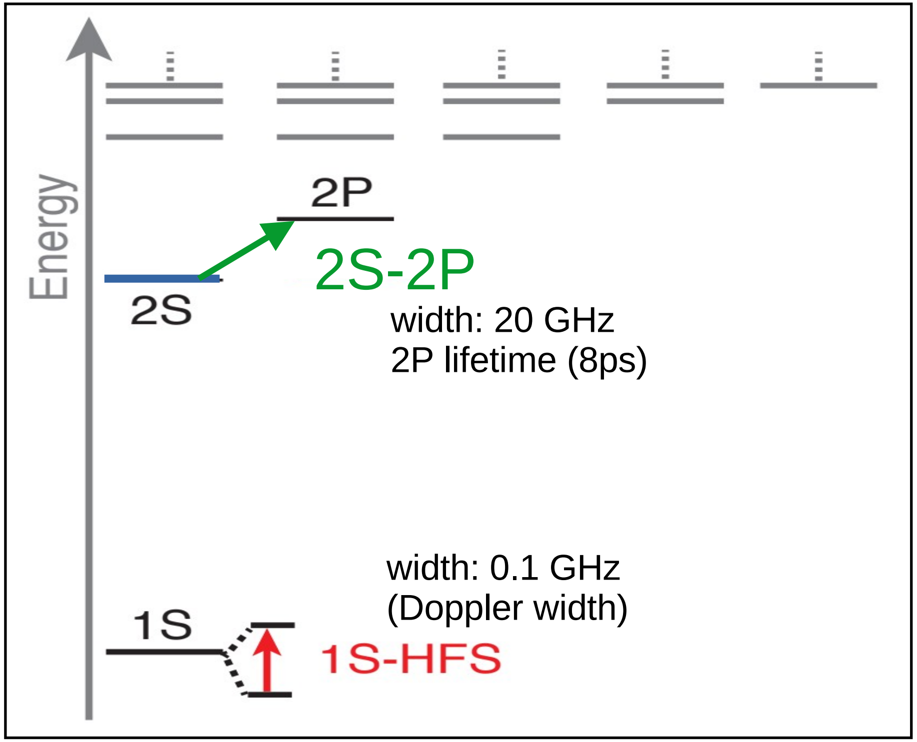
$$\langle r \rangle_{(2)} = \int d^3r\, d^3r'\, \rho_E(r)\, \rho_M(r')\, |r - r'|$$

Zemach, Phys. Rev. 104, 1771 (1956)

$$\Delta E = \frac{8(Z\alpha)m}{\pi n^3} E_F \int_0^\infty \frac{dk}{k^2} \left[\frac{G_E(-k^2)\, G_M(-k^2)}{1+\kappa} \right]$$

Form factors and momentum space

From charge to magnetic properties



2S-2P = Lamb shift

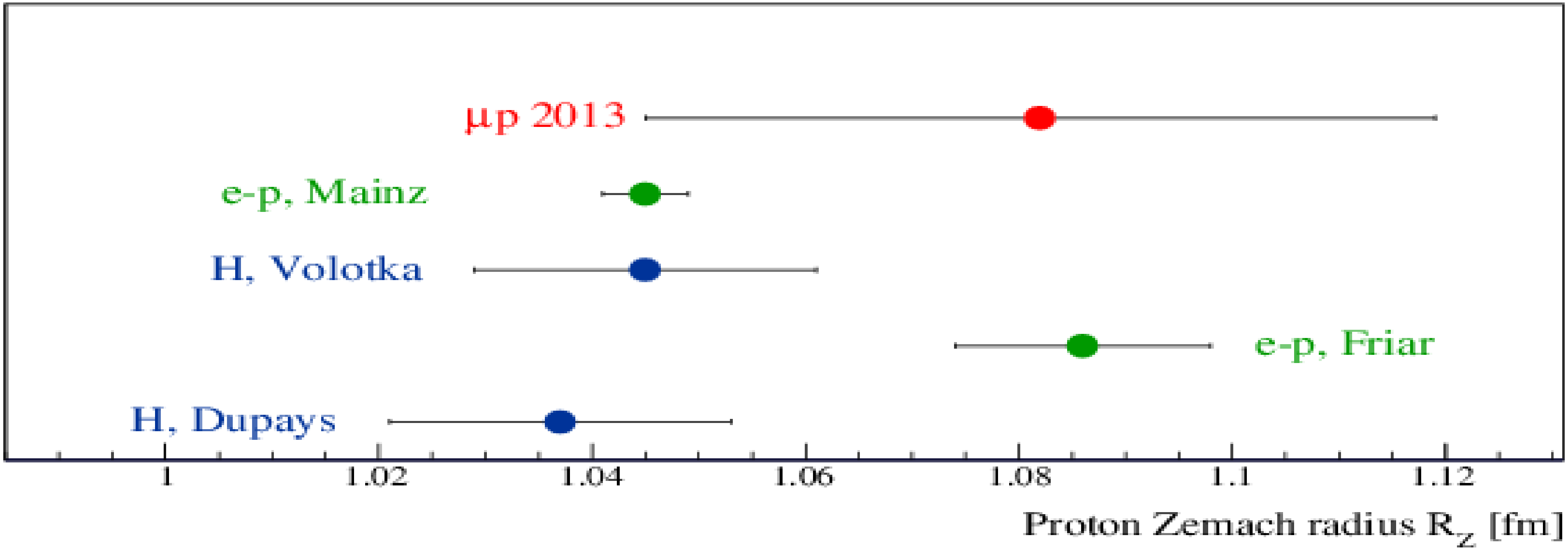
is sensitive to CHARGE radius

1S-HFS = Hyperfine splitting

is sensitive to ZEMACH radius

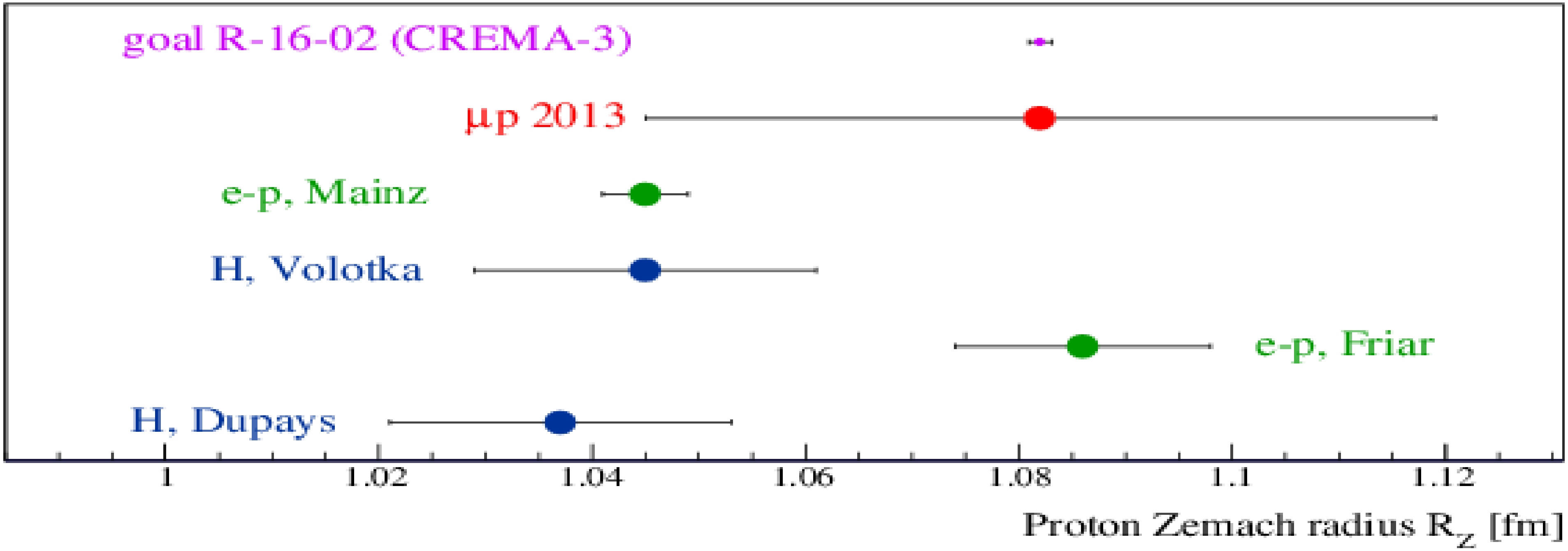
Amaro et al [CREMA], 2112.00138

Proton Zemach radius from μp



μp 2013: Antognini et al. (CREMA Coll.), Science 339, 417 (2013)

Proton Zemach radius from μp



PSI Exp. R-16-02: Antognini, RP et al. (CREMA-3 / HyperMu)
see e.g. Schmidt, RP et al., J. Phys. Conf. Ser 1138, 012010 (2018); arXiv 1808.07240

also: FAMU @ RIKEN/RAL, and a Collaboration at J-PARC

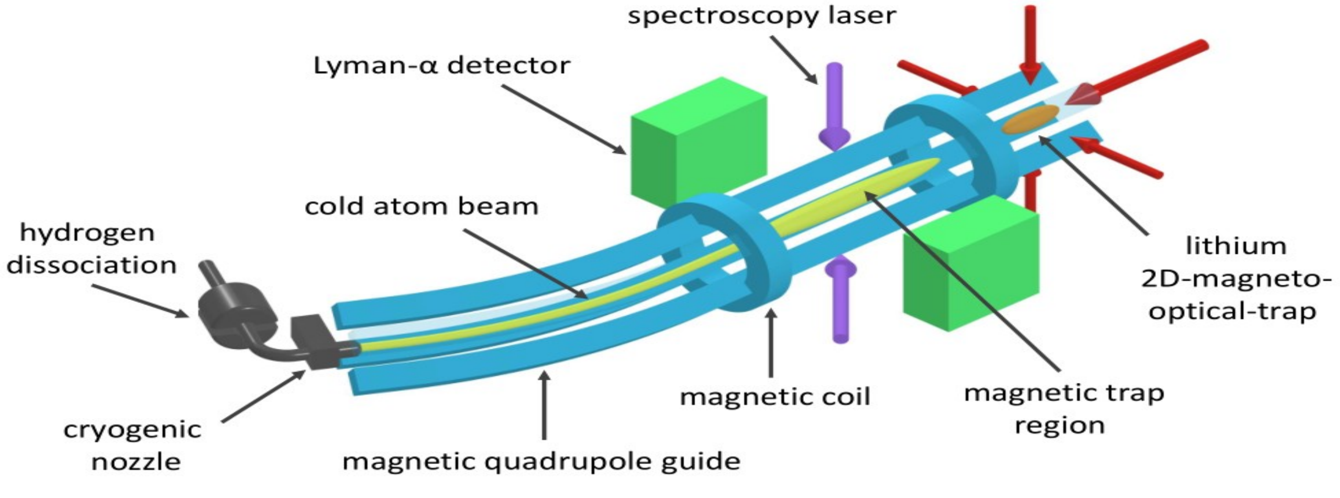
Triton charge radius from Tritium 1S-2S

	^{3}He 1.9701*(10) ~~1.9730 (160)~~	^{4}He 1.6786 (12) ~~1.6810 (40)~~
^{1}H 0.8406 (4) ~~0.8751 (61)~~	^{2}D 2.1279 (2) ~~2.1413 (25)~~	^{3}T **1.7xxx (2)** 1.7550 (860)

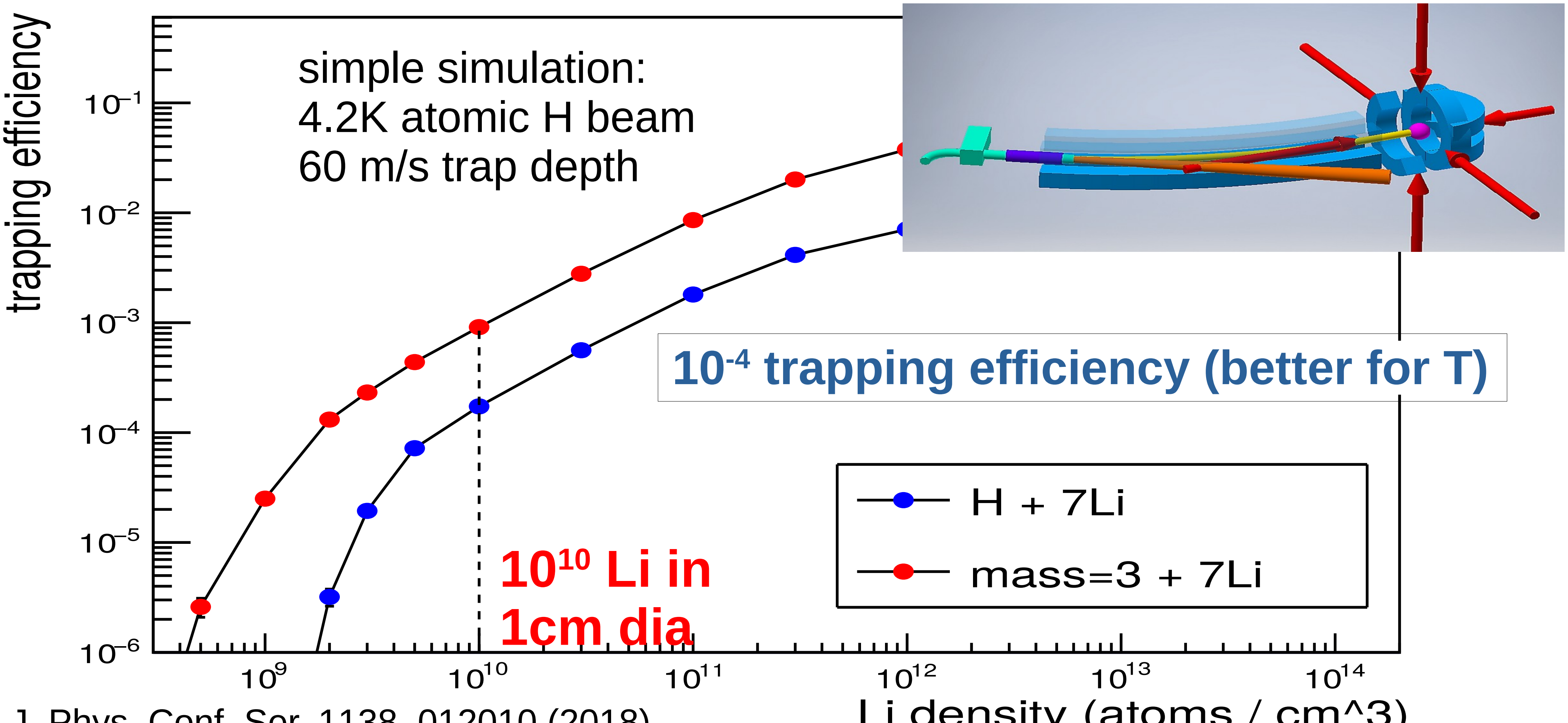
Triton-Radius EXperiment
Mainz

400x better radius
with 1 kHz measurement
(vs. 0.01 kHz for H, D)

- cryogenic H nozzle (4.2K)
- magnetic quadrupole guide
- Li MOT -> cold buffer gas
- magnetic trapping of H/D/T



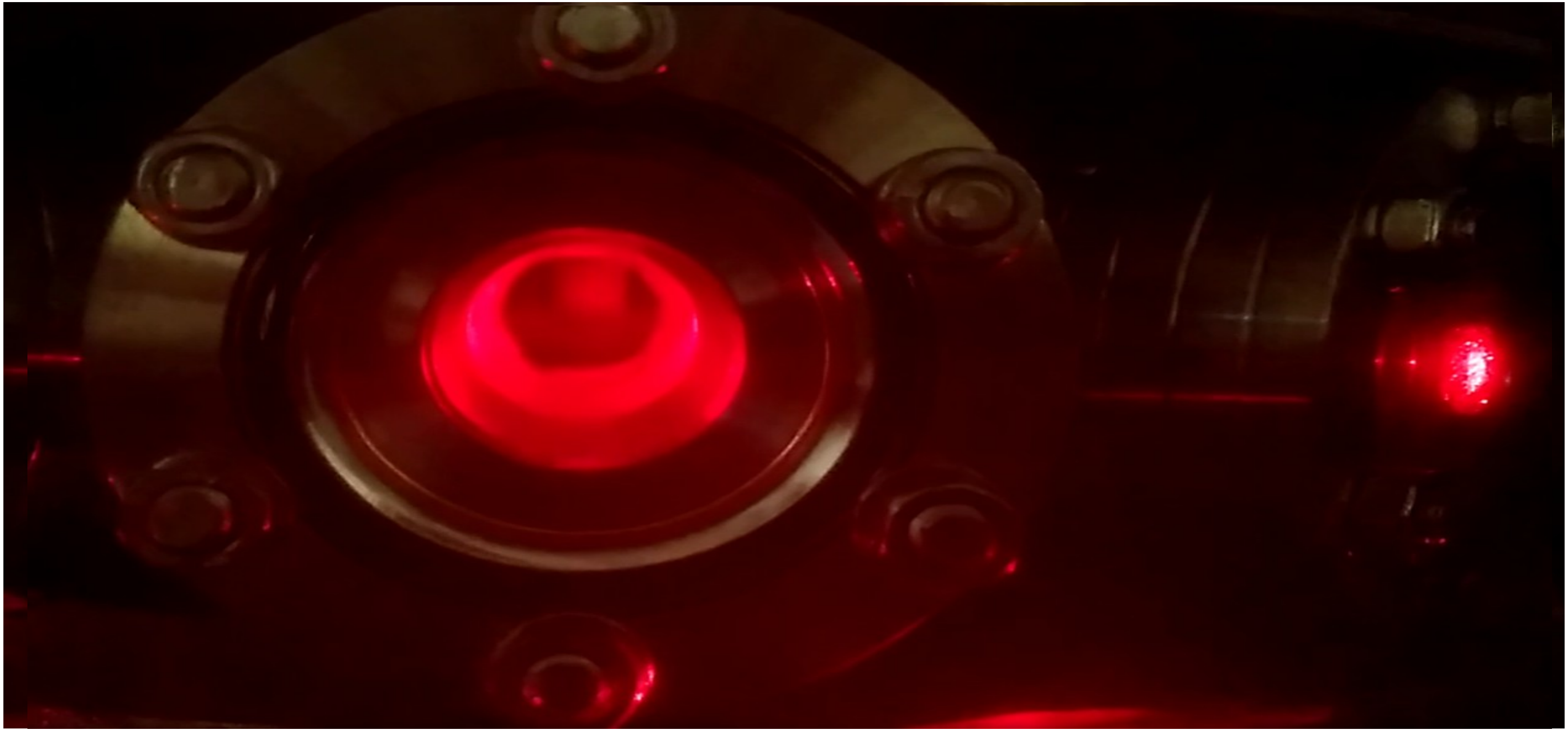
Simulated trapping efficiency



J. Phys. Conf. Ser. 1138, 012010 (2018)

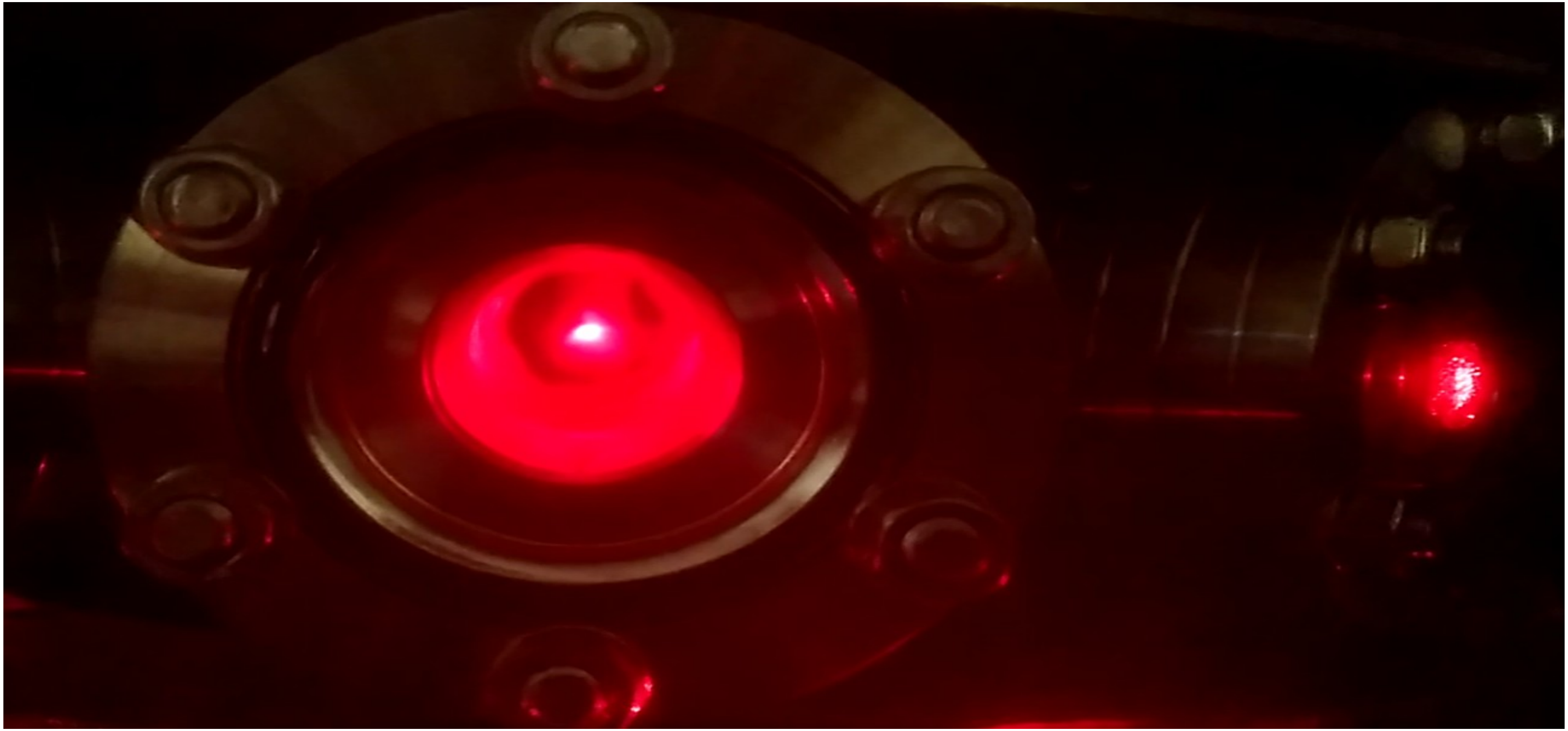
Li MOT

magneto-optical trap



Li MOT

magneto-optical trap



Triton charge radius from Tritium 1S-2S

	^{3}He	^{4}He
	1.9679*(14)	1.6782 (8)
	~~1.9730 (160)~~	~~1.6810 (40)~~

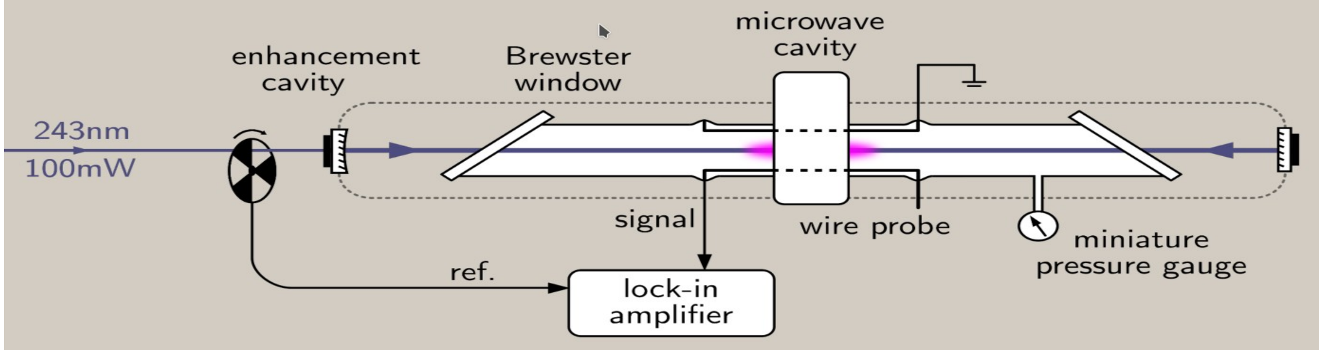
^{1}H	^{2}D	^{3}T
0.8409 (4)	2.1279 (2)	**1.7xxx (200)**
~~0.8751 (61)~~	~~2.1413 (25)~~	1.7550 (860)

Triton-Radius EXperiment Mainz

4x better radius with 100 kHz measurement

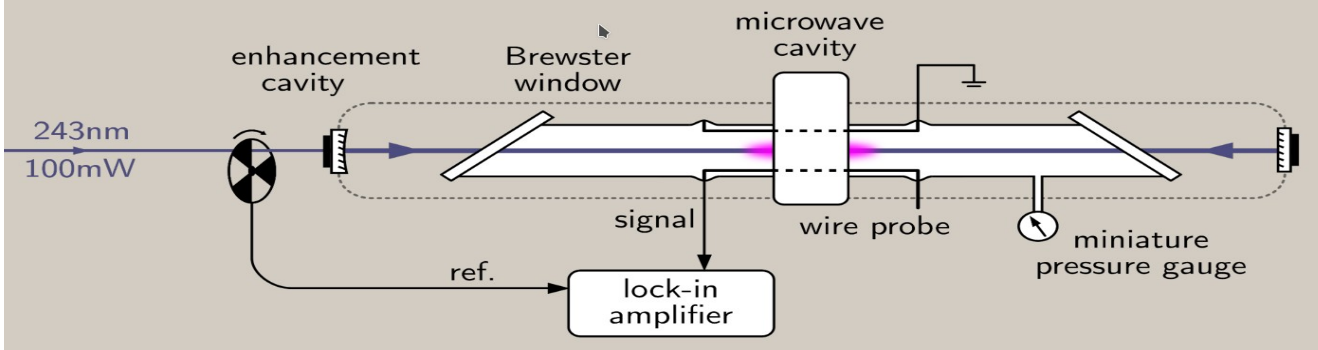
(vs. 0.01 kHz for H, D)

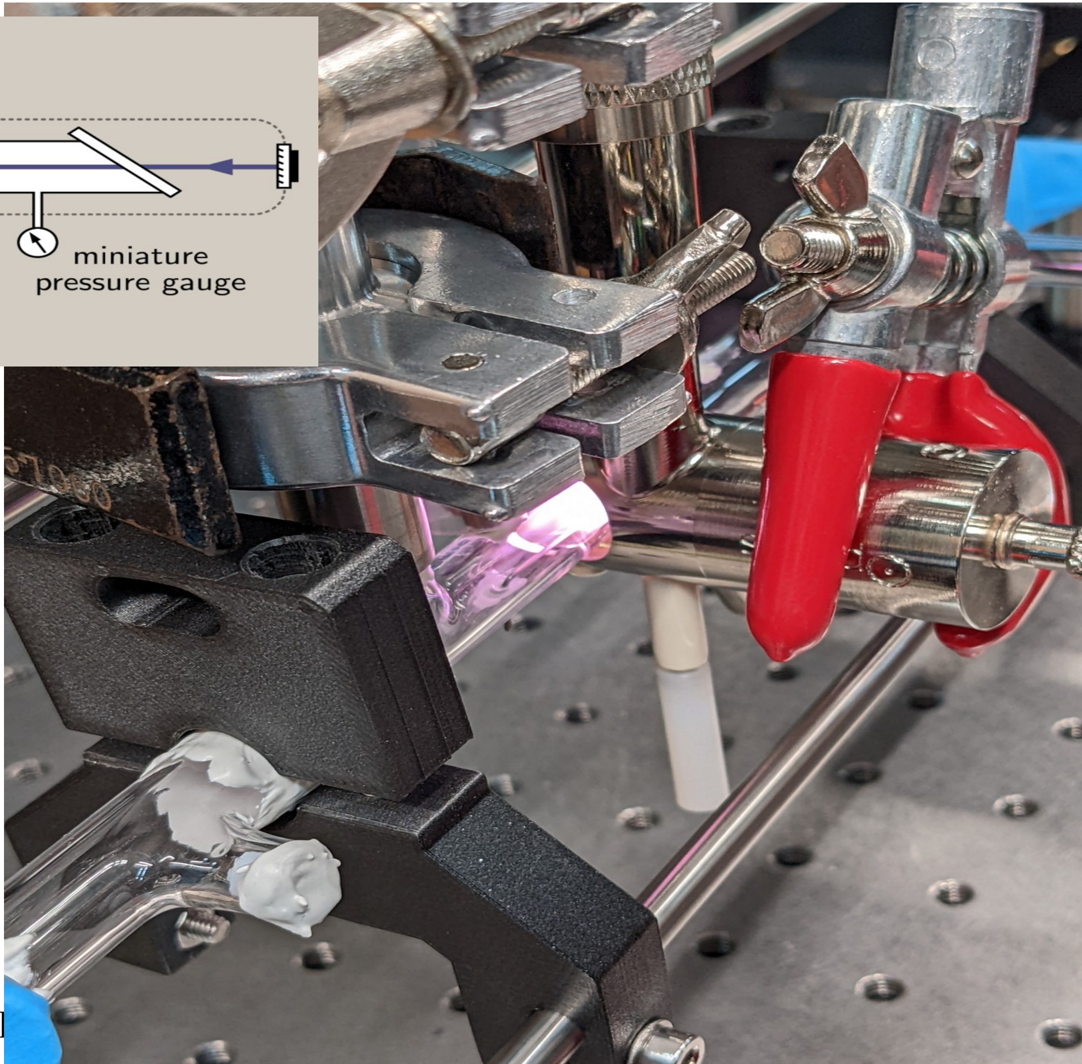
- Optogalvanic spectroscopy in a cell
- Syst. extrapolation w/ H,D
- Tritium confined.



staged approach

Triton charge radius from Tritium 1S-2S



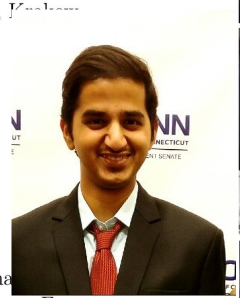


Status:
Hunting for the signal in H

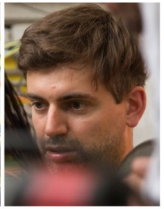
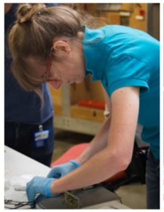
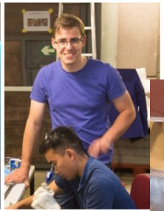
Thanks a lot!

A. Adamczak[1], A. Antognini[2,3], N. Berger[4], T. Cocolios[5], R. Dressler[2],
C. Düllmann[4], R. Eichler[2], P. Indelicato[6], K. Jungmann[7], K. Kirch[2,3],
A. Knecht[2], J. Krauth[4], J. Nuber[2], A. Papa[2], R. Pohl[4], M. Pospelov[8,9],
E. Rapisarda[2], D. Renisch[4], P. Reiter[10], N. Ritjoho[2,3], S. Roccia[11],
N. Severijns[5], A. Skawran[2,3], S. Vogiatzi[2], F. Wauters[4], and
L. Willmann[7]

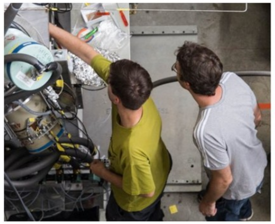




[11]CSNSM, Université Paris Sud, CNRS/IN2P3, Orsay Campus, France

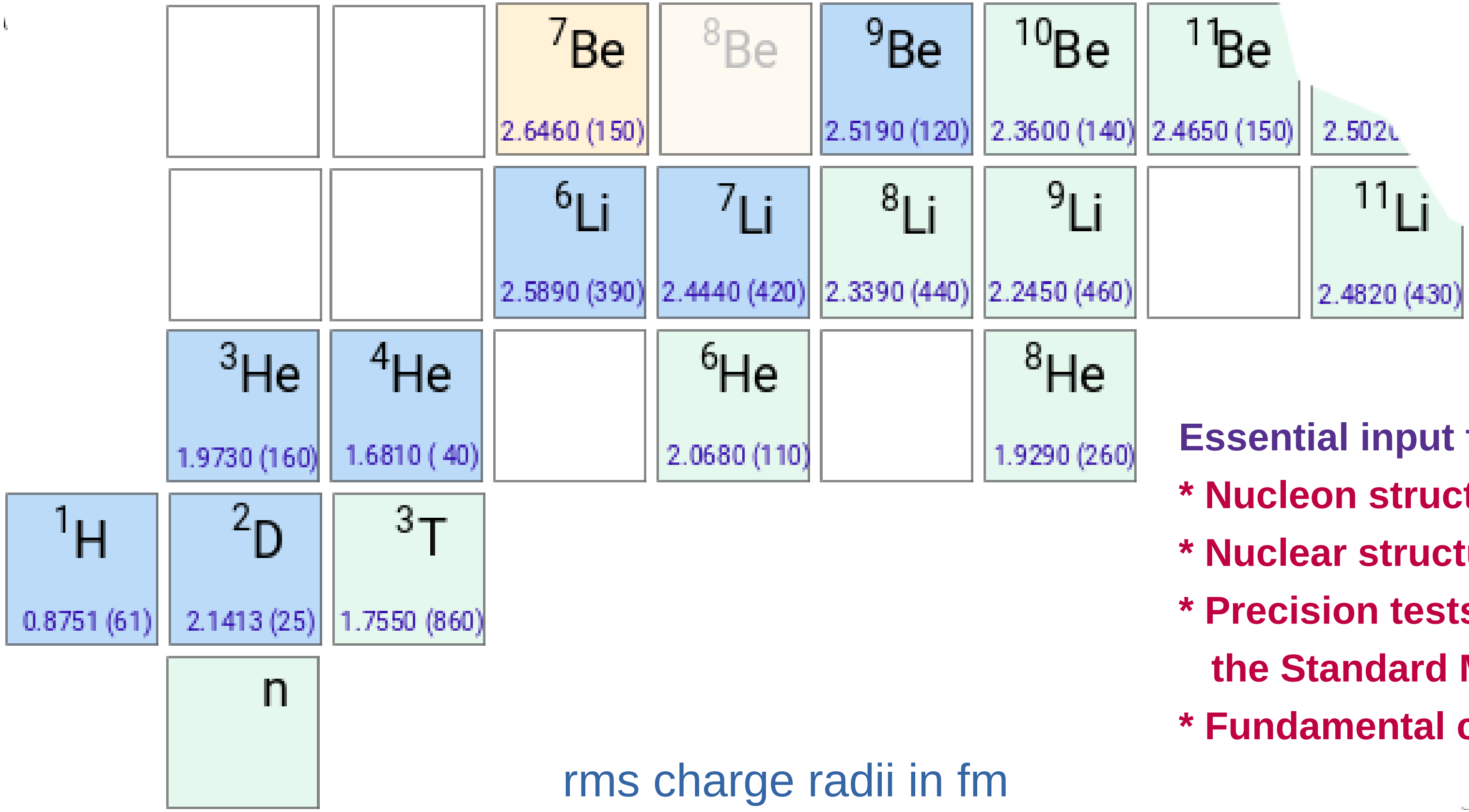






Slides from:
- Stella Vogiatzi
- Michael Heines
- Frederik Wauters
- Nancy Paul

Thanks a lot
for your attention

Nuclear radii

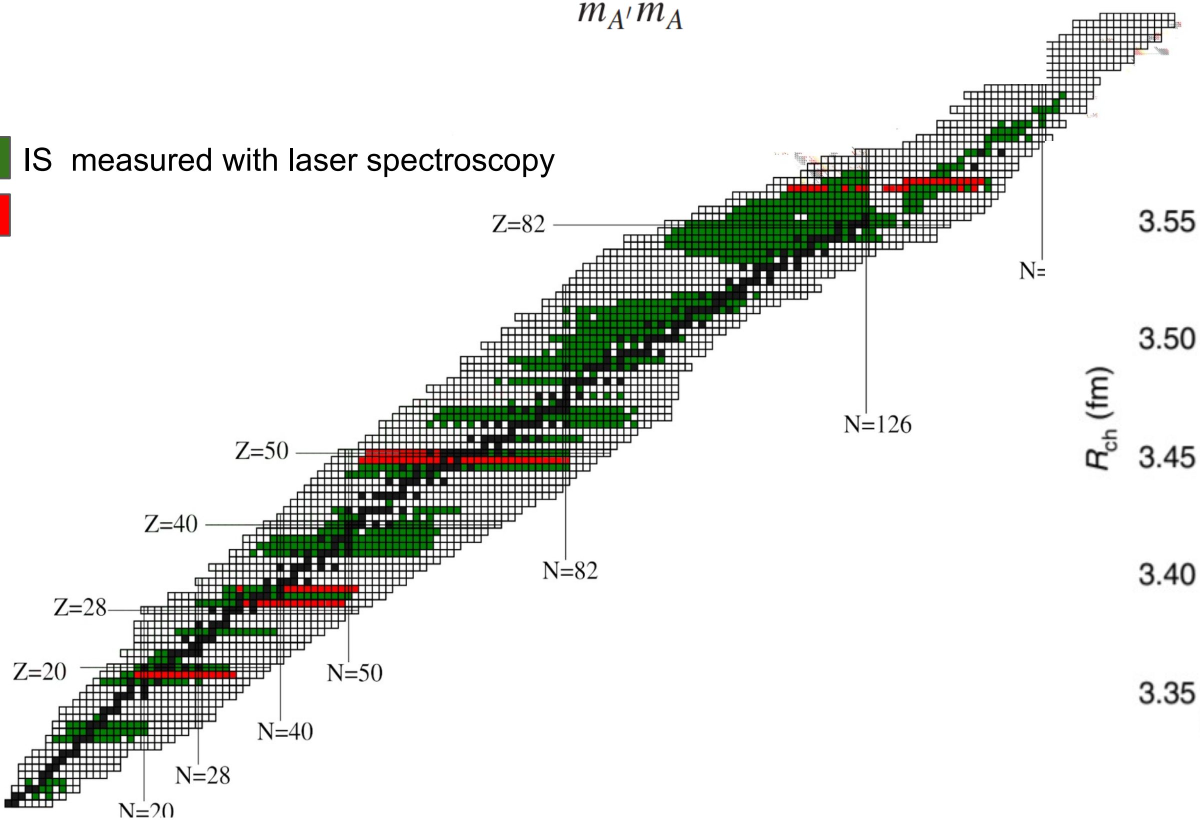


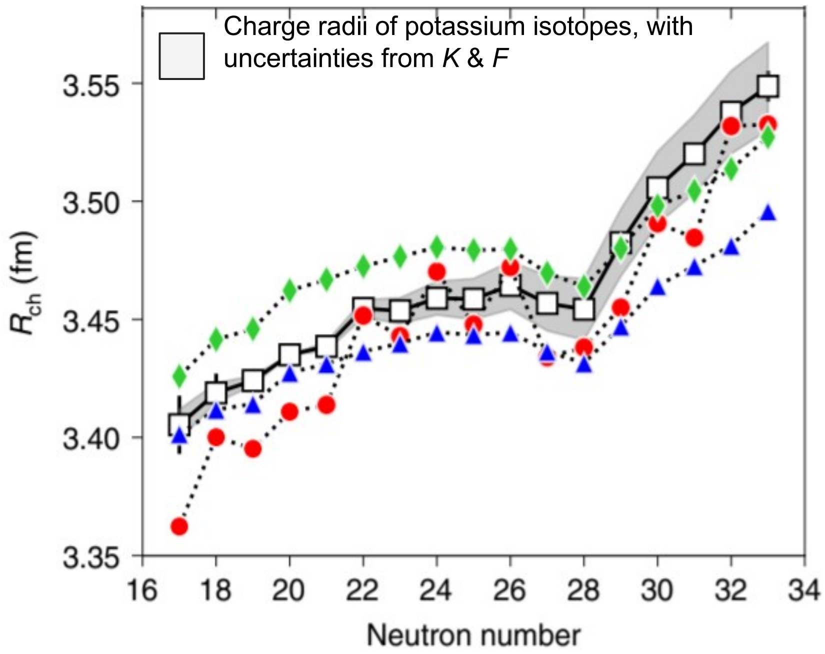
Essential input for:

- **Nucleon structure (proton)**
- **Nuclear structure and models**
- **Precision tests of QED and the Standard Model**
- **Fundamental constants (CODATA)**

$$\delta\nu^{AA'} = \nu^{A'} - \nu^{A} = K\frac{m_{A'} - m_A}{m_{A'}m_A} + F\delta\langle r^2\rangle^{AA'},$$

IS measured with laser spectroscopy





Proton Zemach radius from μp HFS