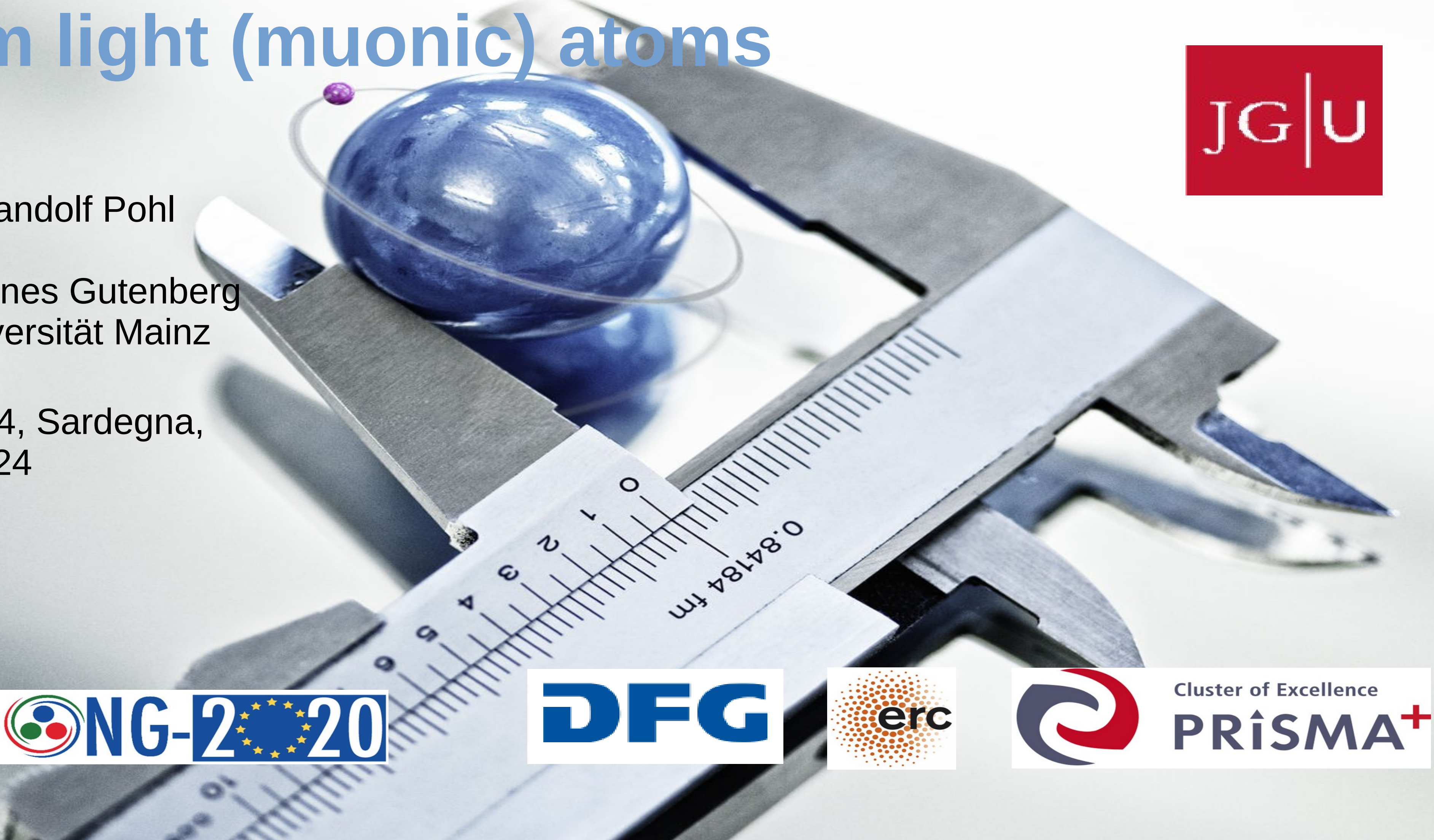
Precision nucleon and nuclear structure from light (muonic) atoms



Randolf Pohl

Johannes Gutenberg
Universität Mainz

EPIC24, Sardegna,
24.09.24

JG|U
STRONG-2020
DFG
erc
Cluster of Excellence PRISMA+

Hydrogen-like atoms

“There's a reason physicists are so successful with what they do,
and that is they study the hydrogen atom and the helium ion
and then they stop.”

- Richard Feynman

ToDo for today

- Proton radius
- CREMA: **Laser spectroscopy** of μD, μ^3He^+, μ^4He^+
- muonic atoms:

  muX: X-ray spectroscopy with **few μg target** material

  QUARTET: 10x better radii for Z=3...10 with **MMCs**

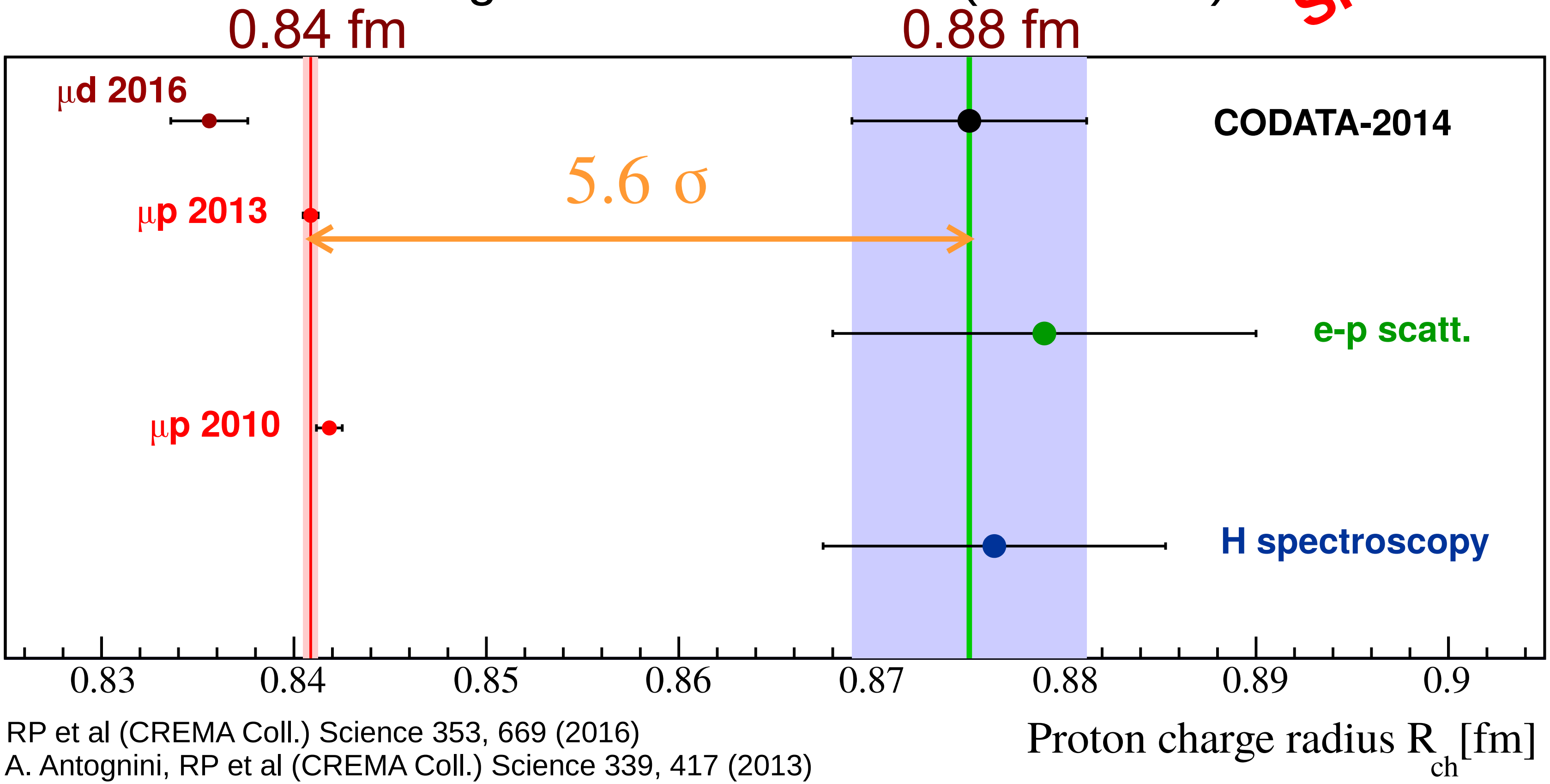
  → **See talk by F. Wauters tomorrow**
- T-Rex @ Mainz: the **triton radius**
- **Li** isotope shift
- HyperMu: The **proton's magnetic** properties

The “Proton Radius Puzzle”

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

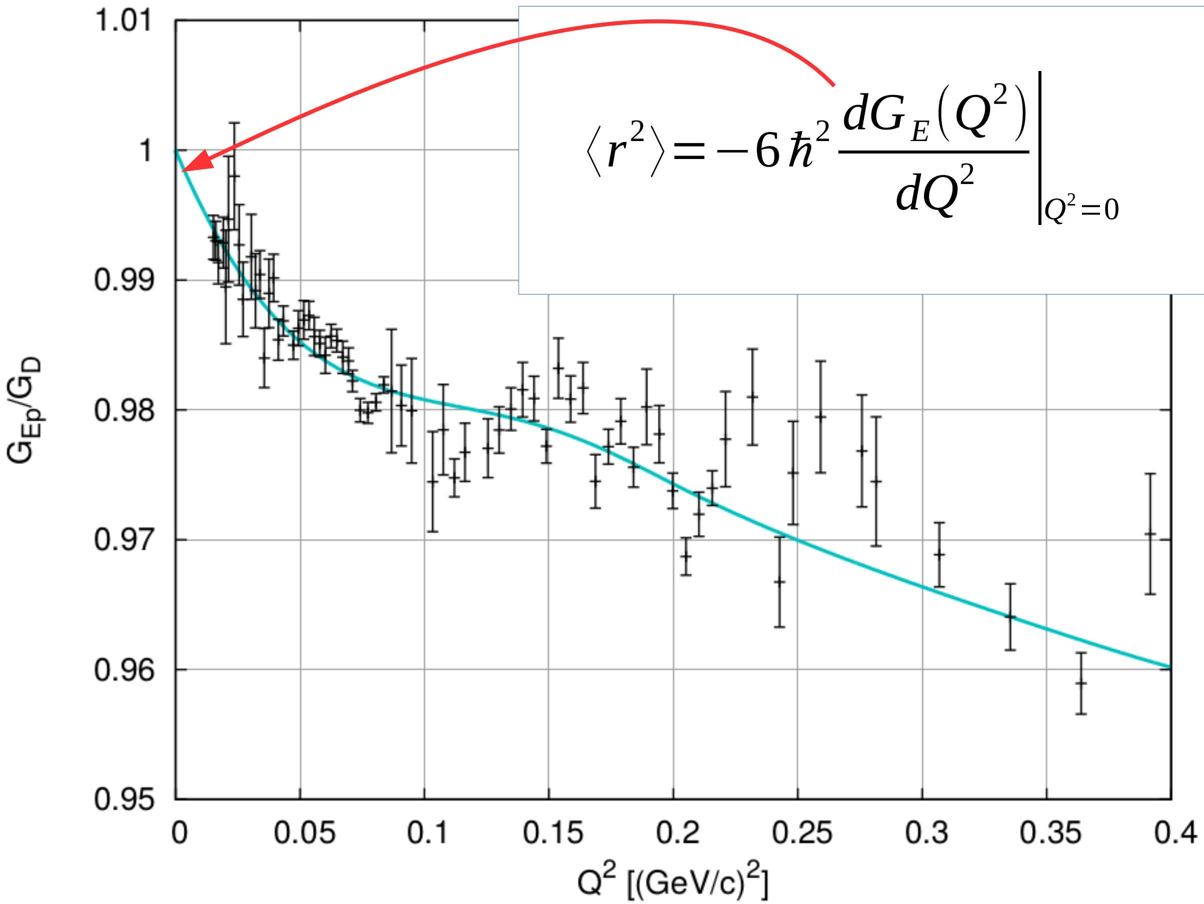
using muons: 0.84 fm (+- 0.05%)

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)

Electron scattering



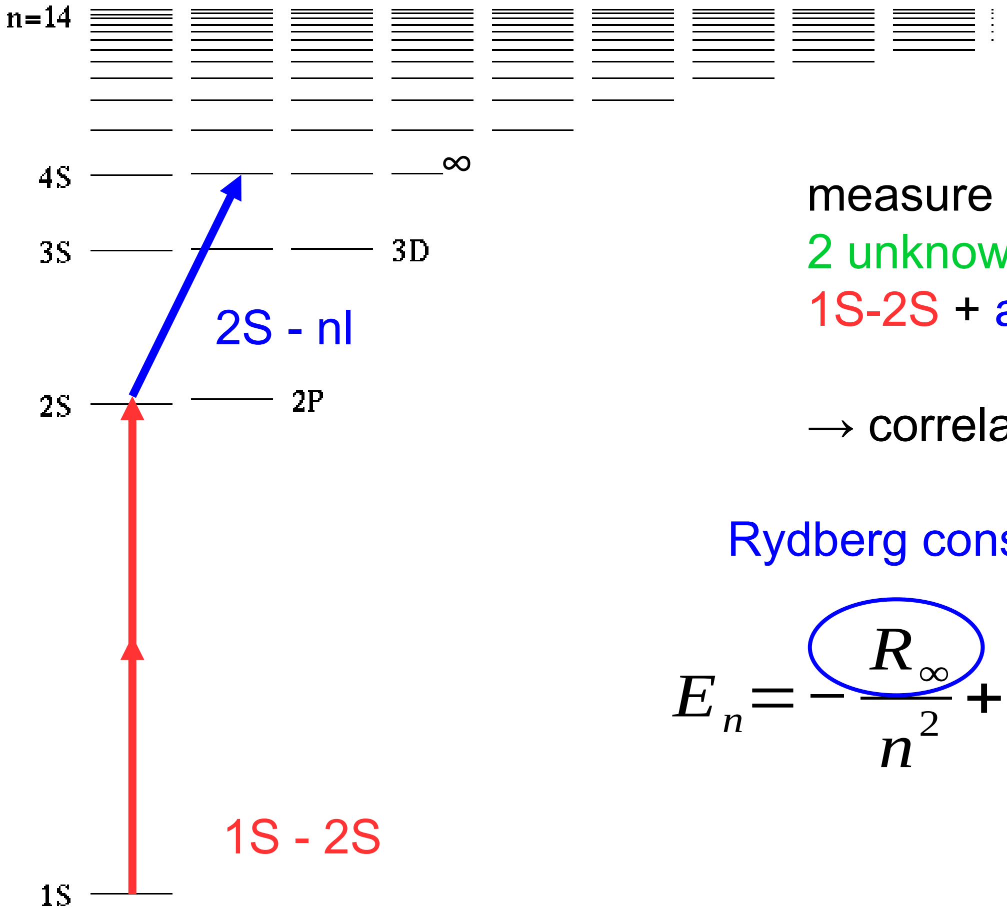
$$\langle r^2\rangle = -6\,\hbar^2 \left.\frac{dG_E(Q^2)}{dQ^2}\right|_{Q^2=0}$$

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

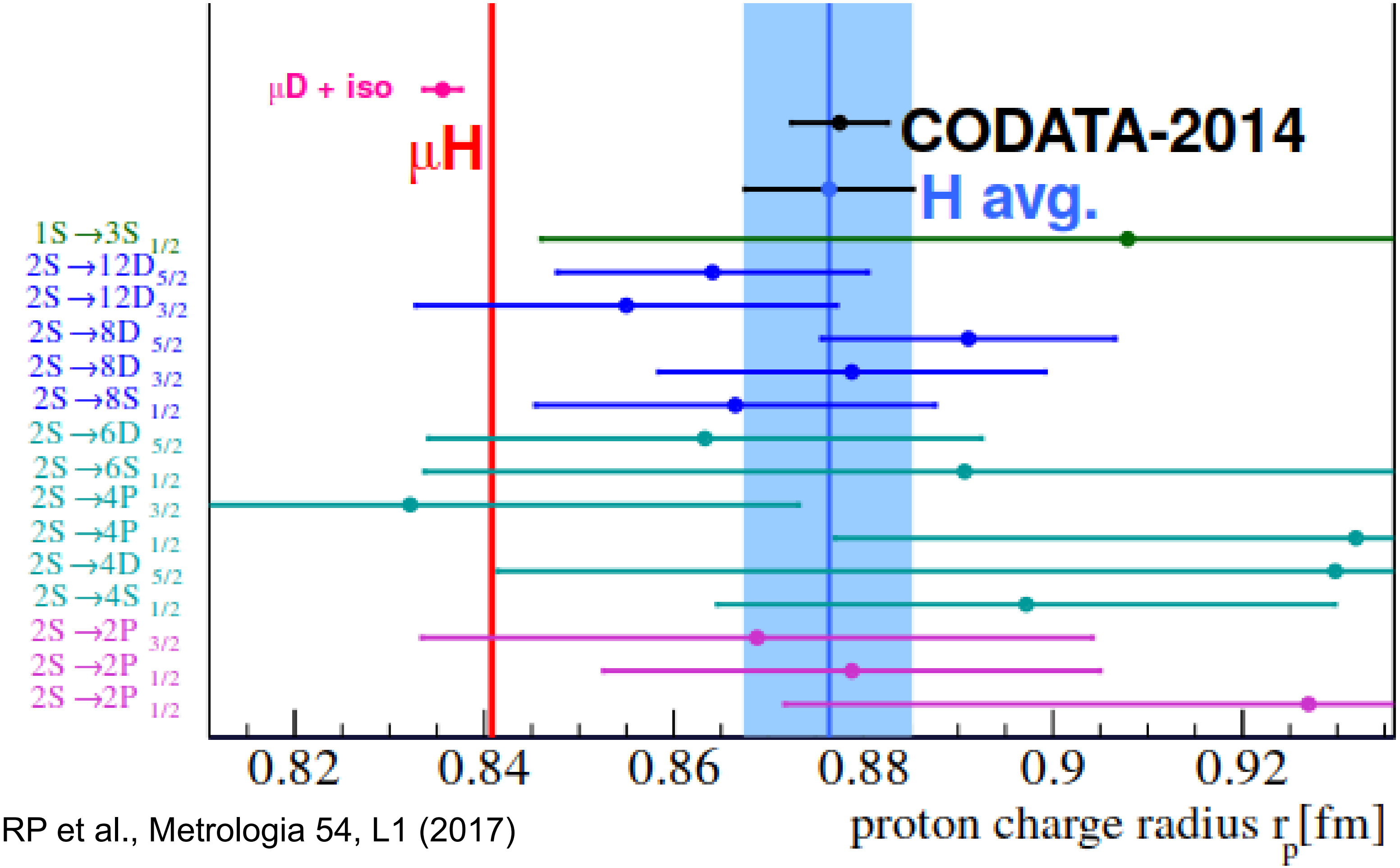
Rydberg constant

QED etc.

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

proton radius

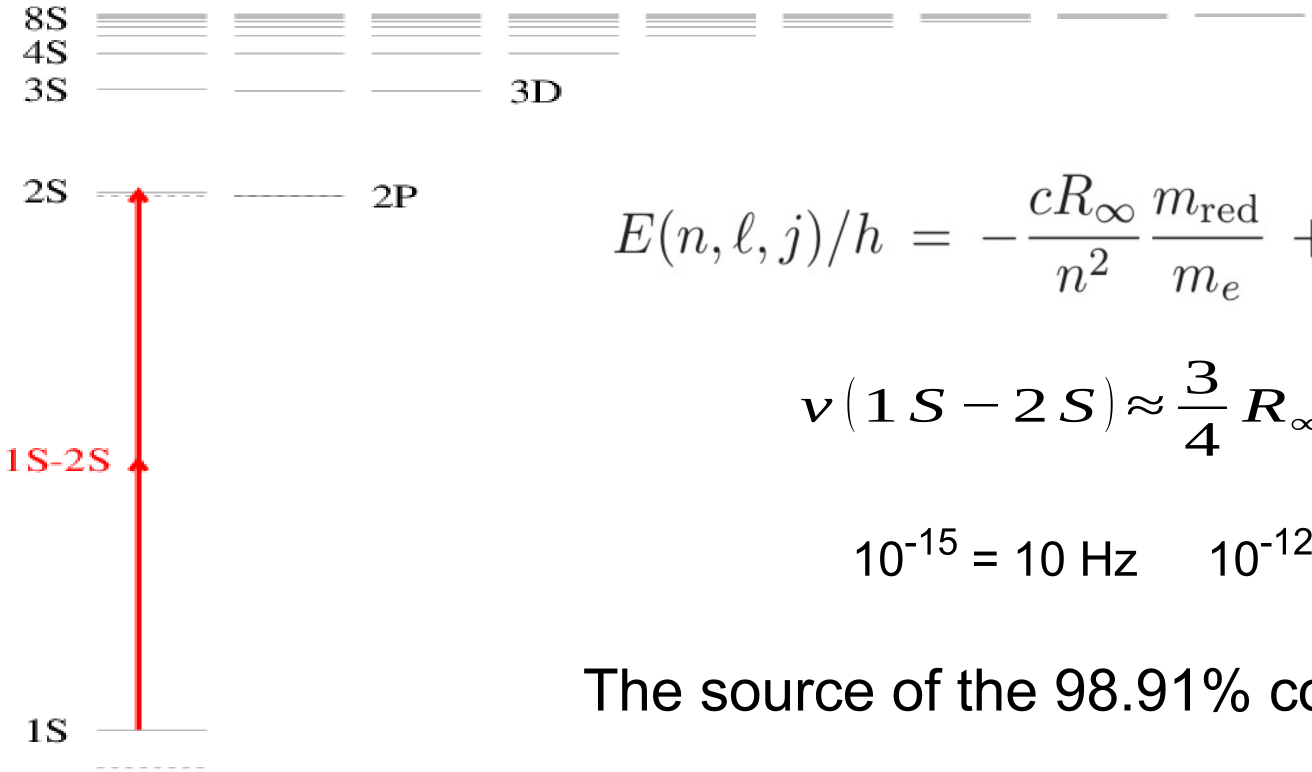
Rp from H spectroscopy



Situation 2016

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

Correlation between R_∞ and R_p / R_d



$$E(n,\ell,j)/h = -\frac{cR_\infty}{n^2}\frac{m_\text{red}}{m_e} + \frac{E_{NS}}{n^3}\delta_{\ell 0} + \Delta(n,\ell,j). \quad (7)$$

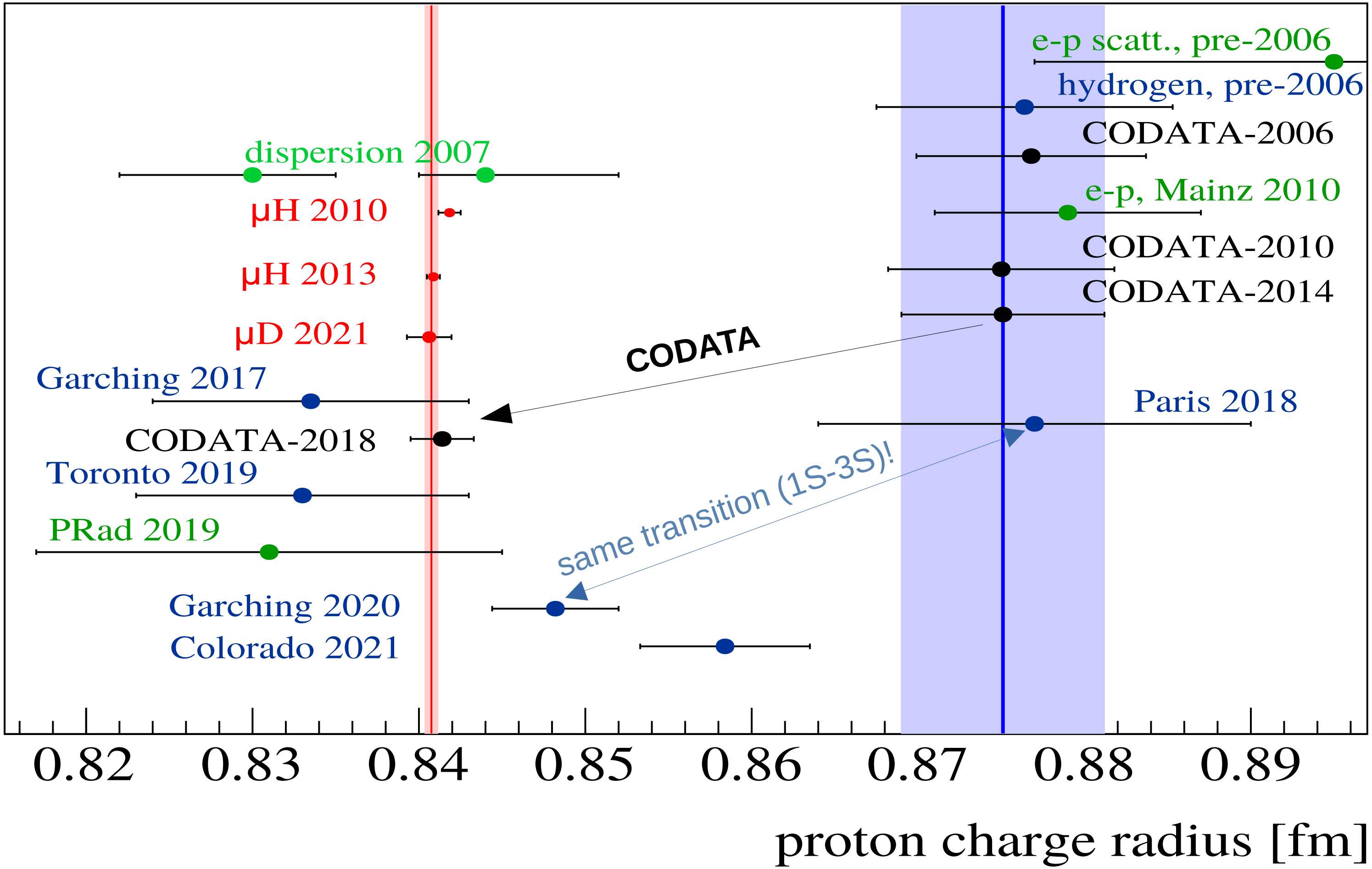
$$\nu(1S-2S) \approx \frac{3}{4}R_\infty - \frac{7}{8}E_{NS}$$

10^{-15} = 10 Hz 10^{-12} = 20 kHz

The source of the 98.91% correlation of R_∞ and R_p

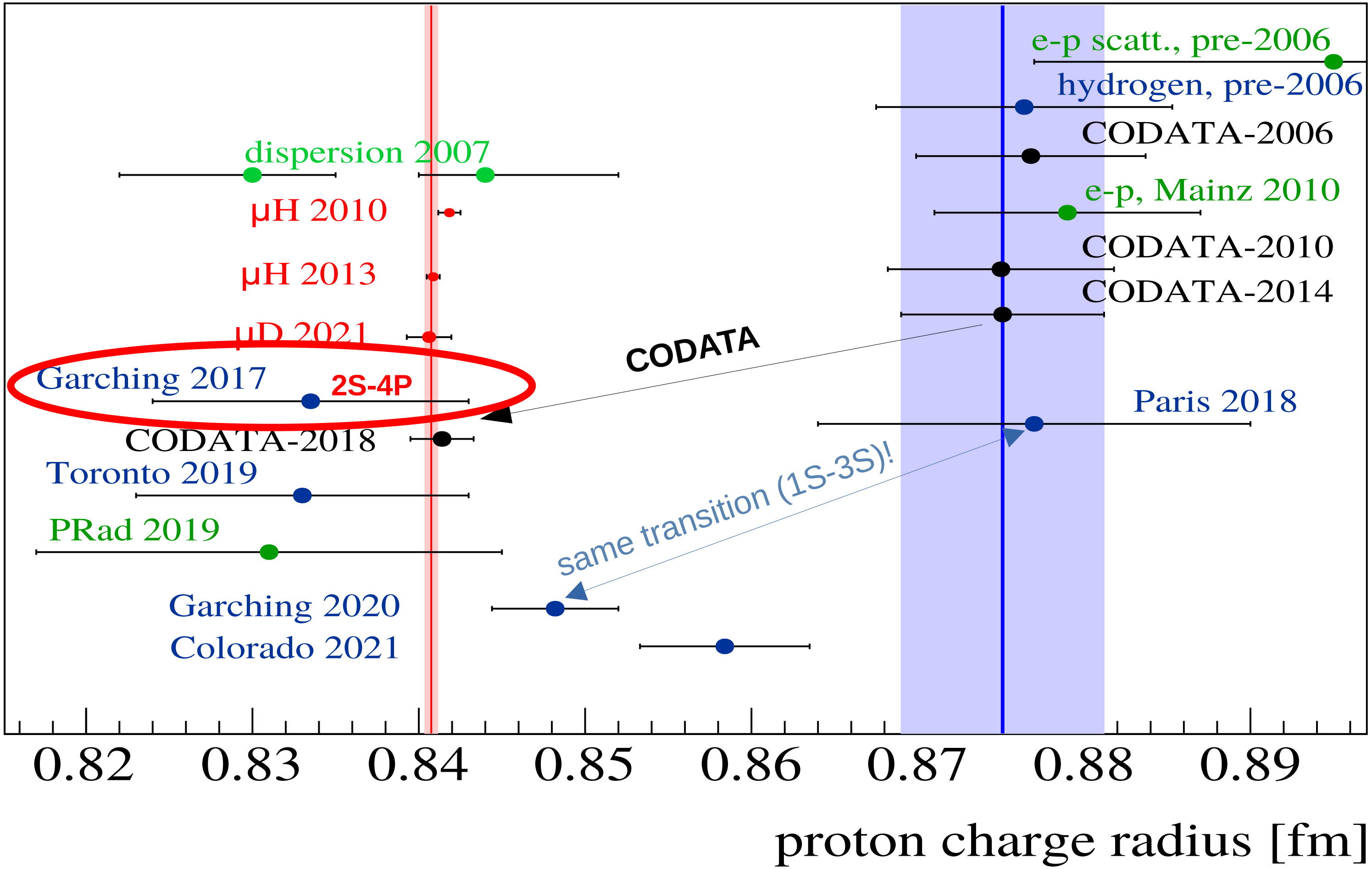
[Pohl et al., Metrologia 54, L1 (2017)]

The situation until recently



Not really “solved”

The situation until recently



Not really “solved”

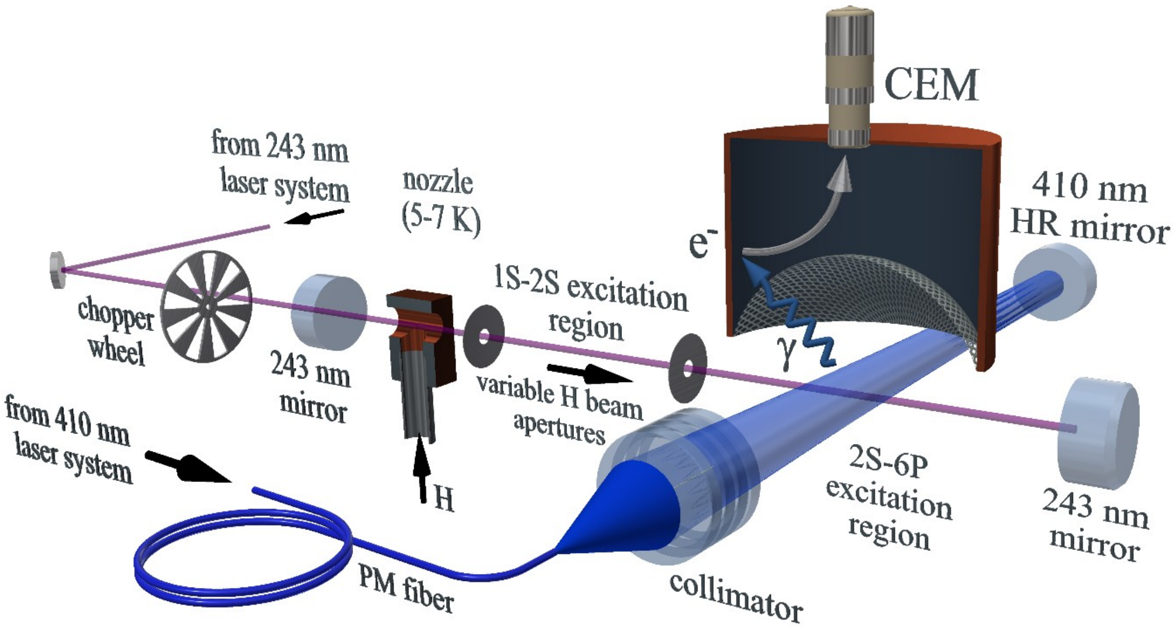
H (2S-6P)

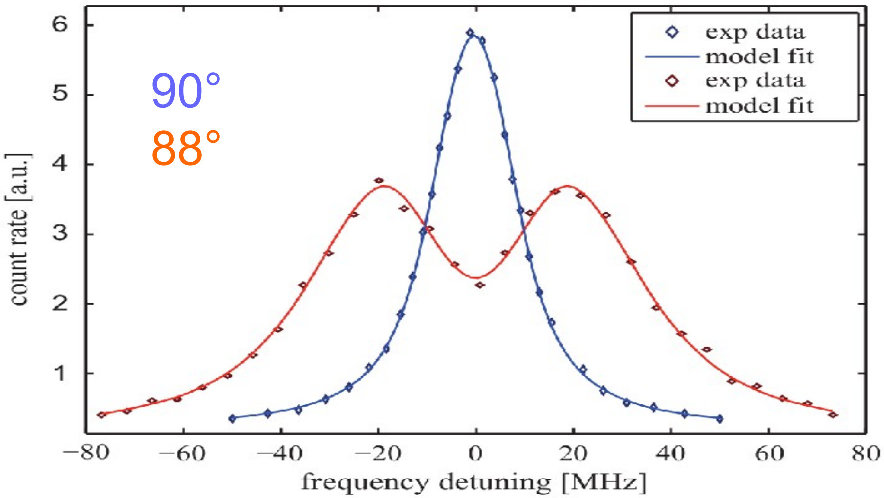
V. Wirthl, L. Maisenbacher

Th. Udem, RP, T.W. Hänsch

(MPQ Garching)

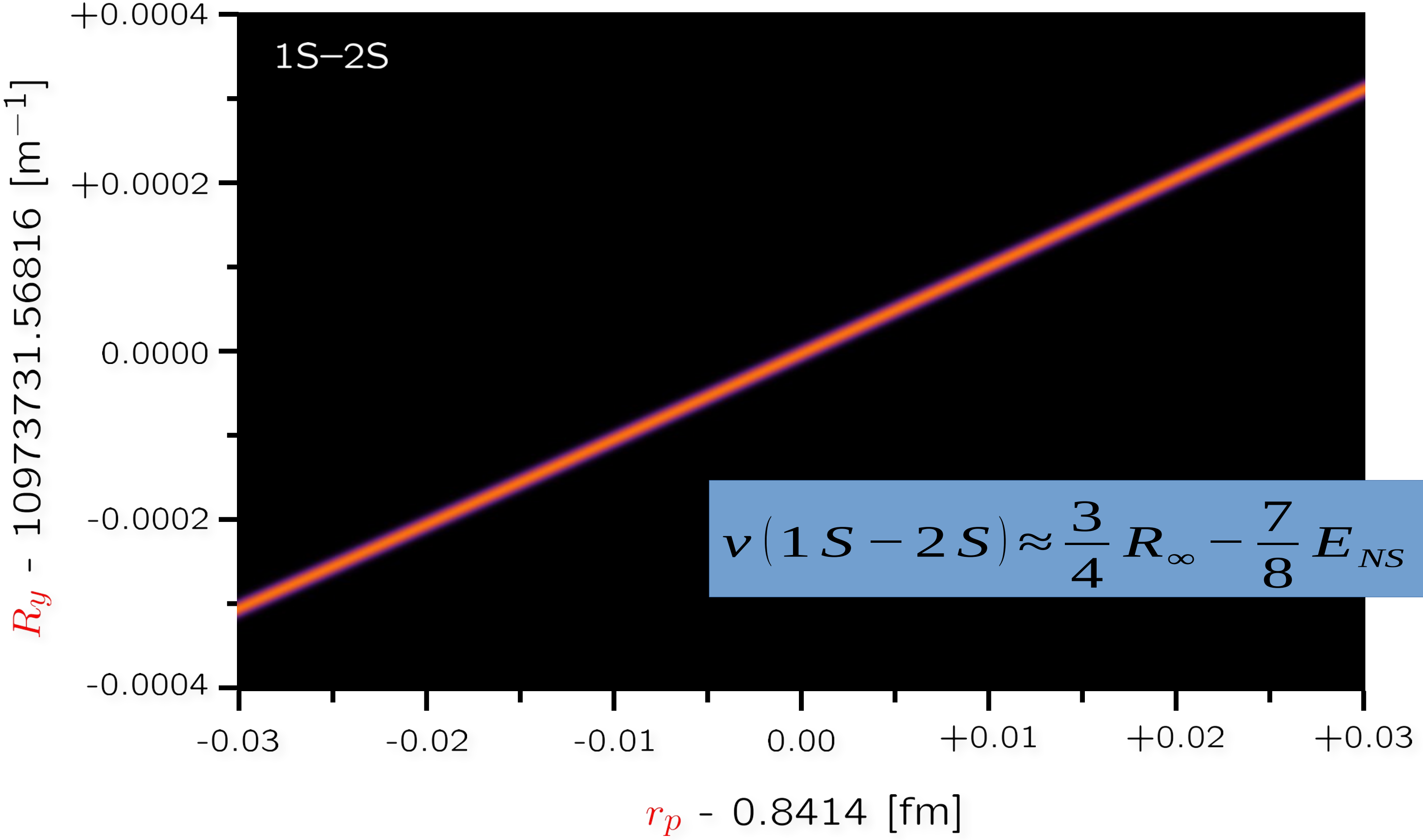
Garching H(2S-6P)




1st order Doppler cancellation

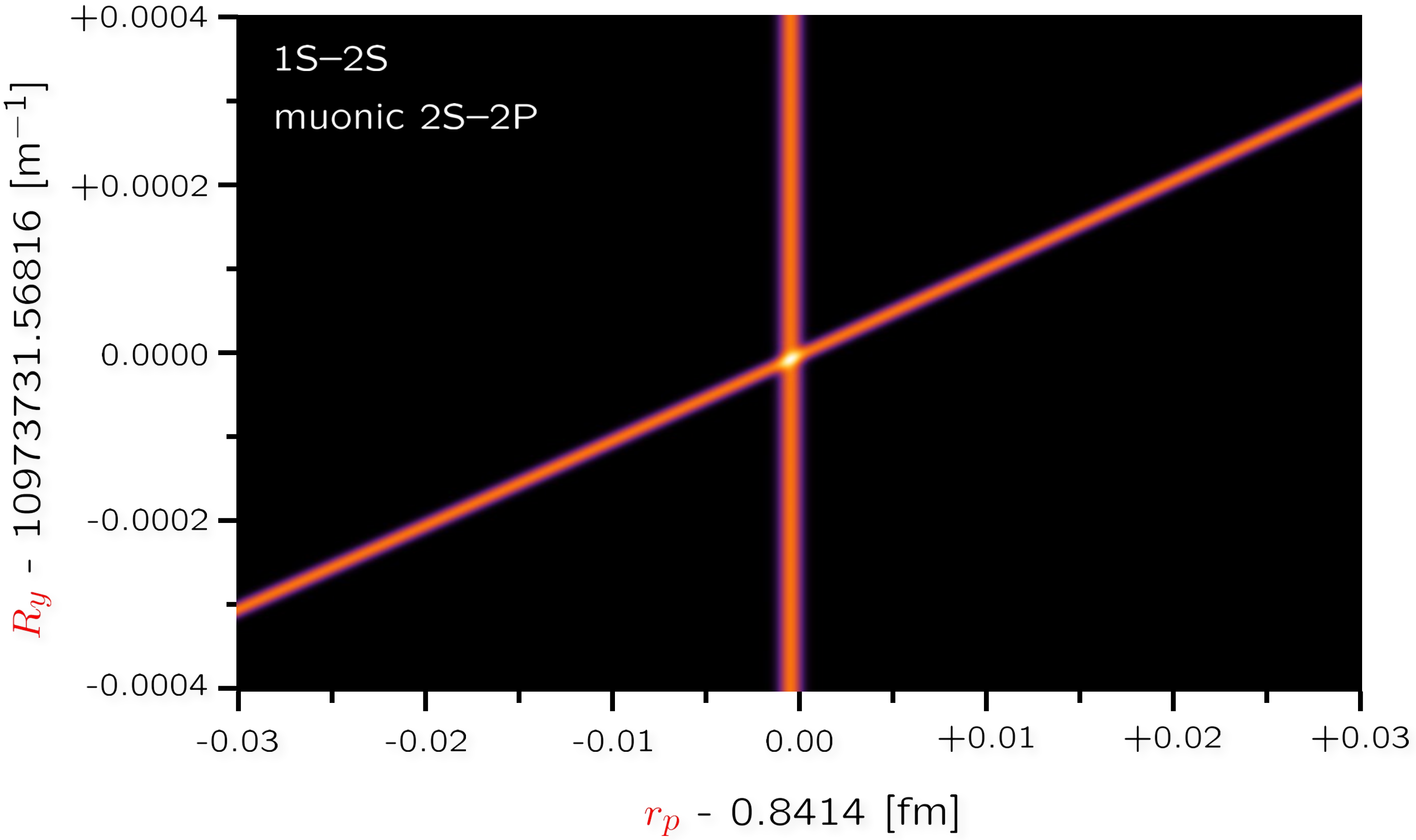
- cryogenic H beam (6 K)
- optical 1S-2S excitation (2S, F=0)
- 2S-6P transition is 1-photon: retroreflector
- split line to 10^{-4} !

Hydrogen 2S-6P measurement result

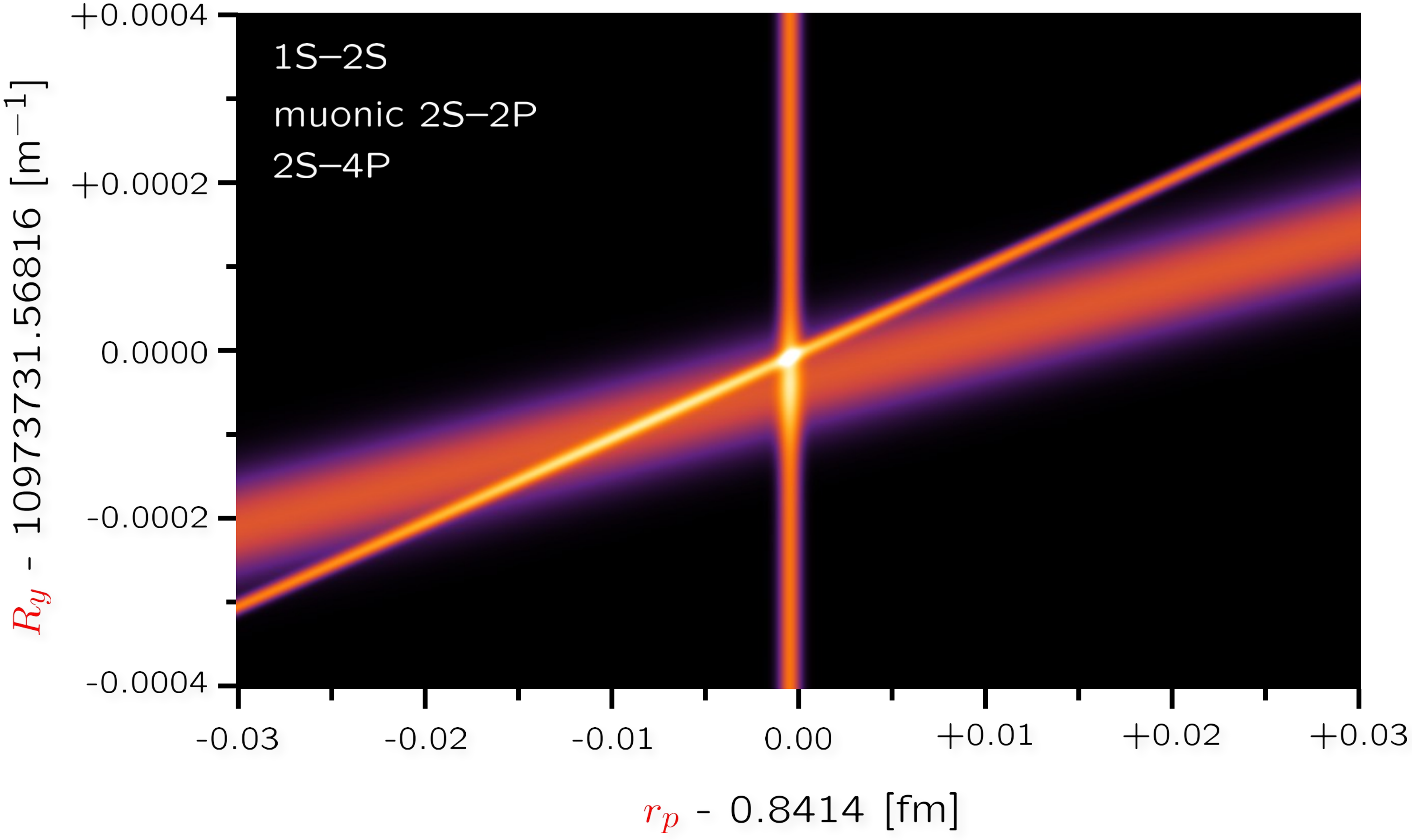


$$\nu\left(1S-2S\right)\approx\frac{3}{4}R_{\infty}-\frac{7}{8}E_{NS}$$

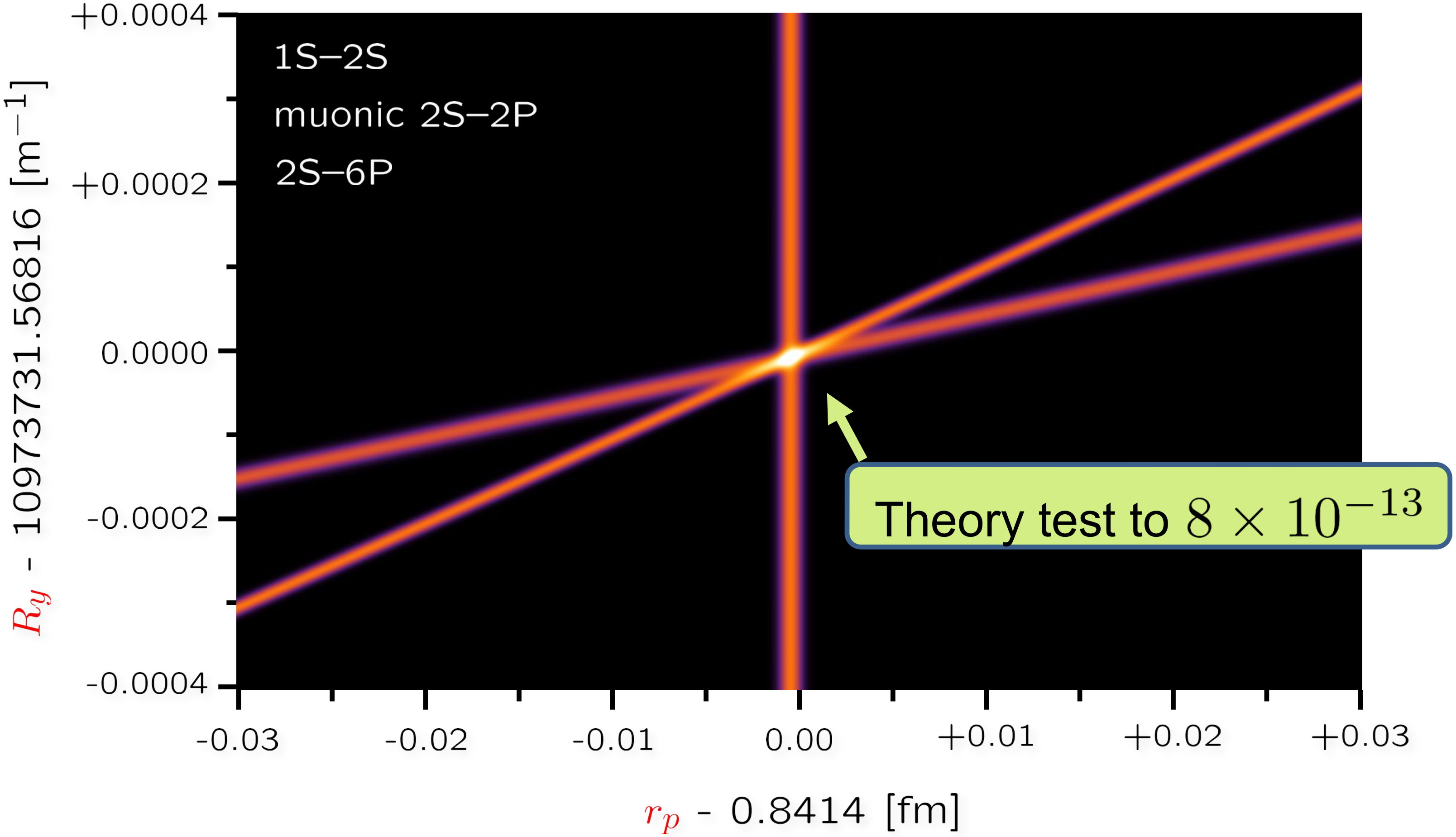
Hydrogen 2S-6P measurement result



Hydrogen 2S-6P measurement result

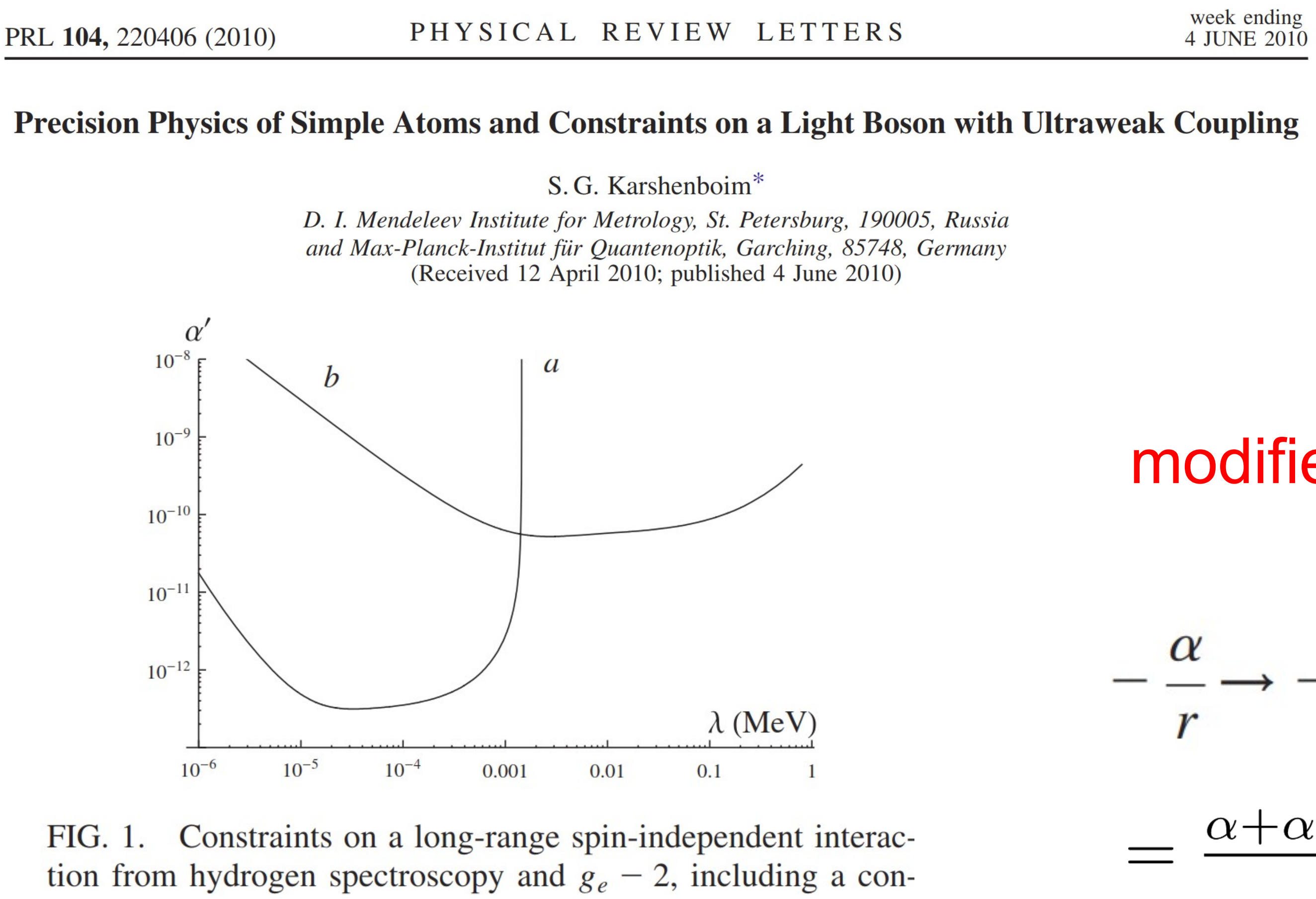


Hydrogen 2S-6P measurement result



Theory test to 8×10^{-13}

‚New Physics constraints



PRL **104,** 220406 (2010) PHYSICAL REVIEW LETTERS week ending 4 JUNE 2010

Precision Physics of Simple Atoms and Constraints on a Light Boson with Ultraweak Coupling

S. G. Karshenboim*

D. I. Mendeleev Institute for Metrology, St. Petersburg, 190005, Russia
and Max-Planck-Institut für Quantenoptik, Garching, 85748, Germany
(Received 12 April 2010; published 4 June 2010)

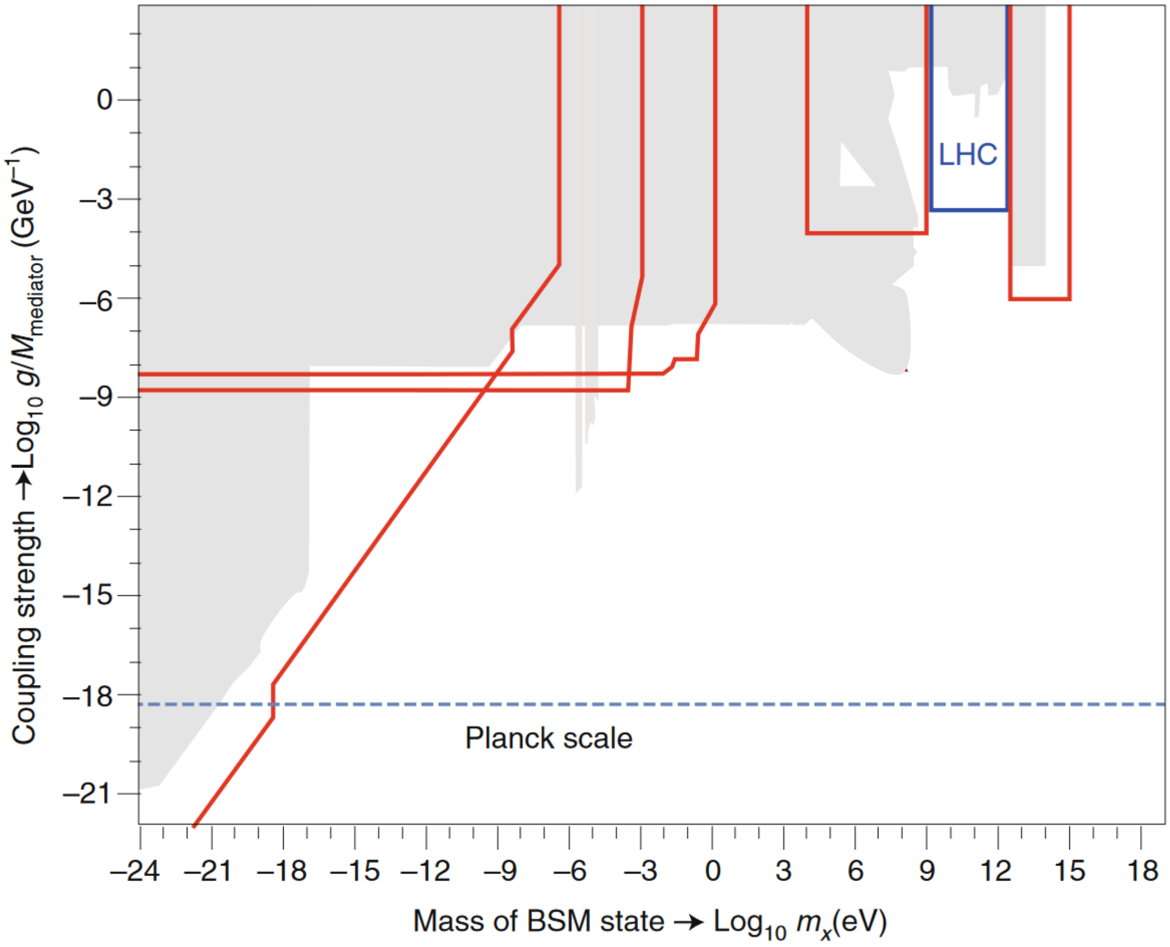
FIG. 1. Constraints on a long-range spin-independent interaction from hydrogen spectroscopy and $g_e - 2$, including a con-

modified Coulomb potential:

$$-\frac{\alpha}{r} \longrightarrow -\frac{\alpha_{\text{eff}}(r)}{r}$$

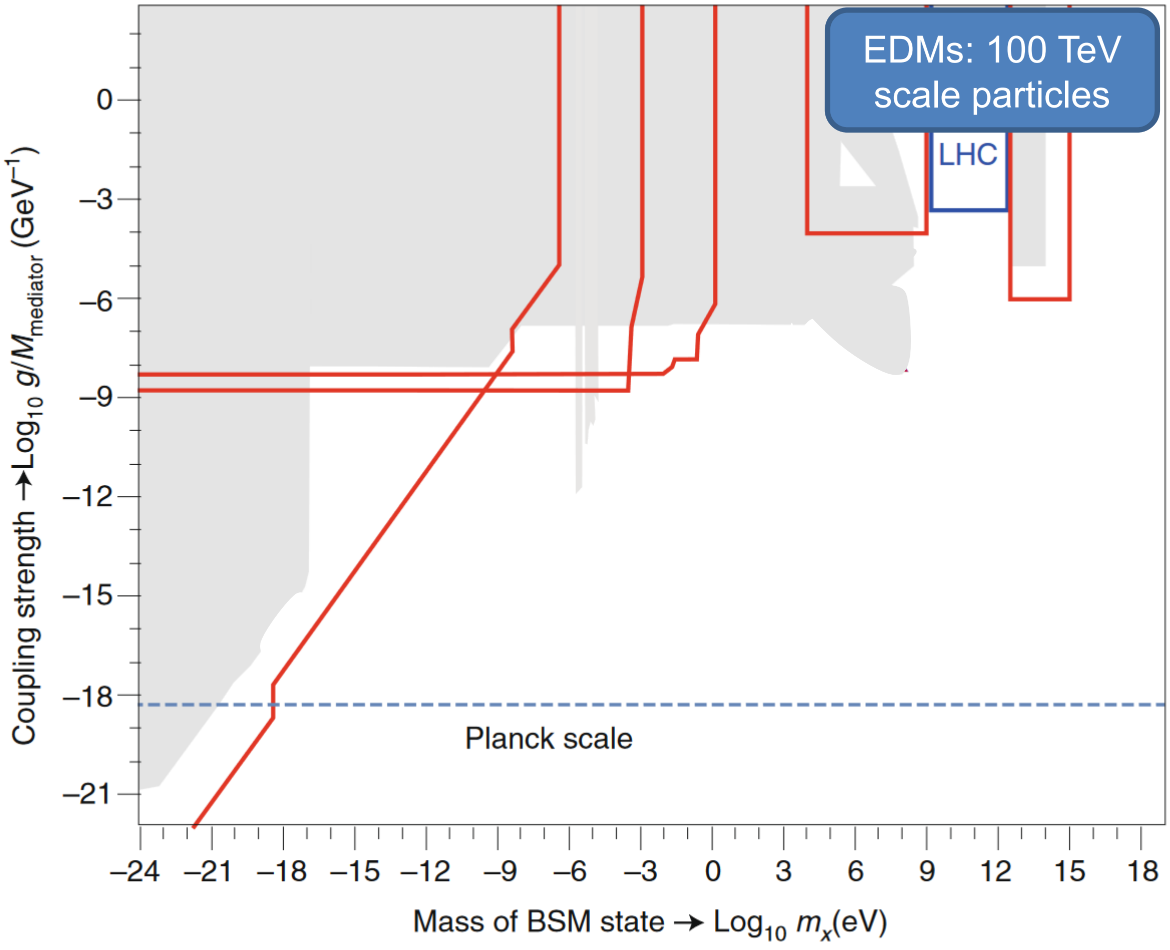
$$= \frac{\alpha+\alpha' \exp(-m_X r)}{r}$$

New Physics constraints



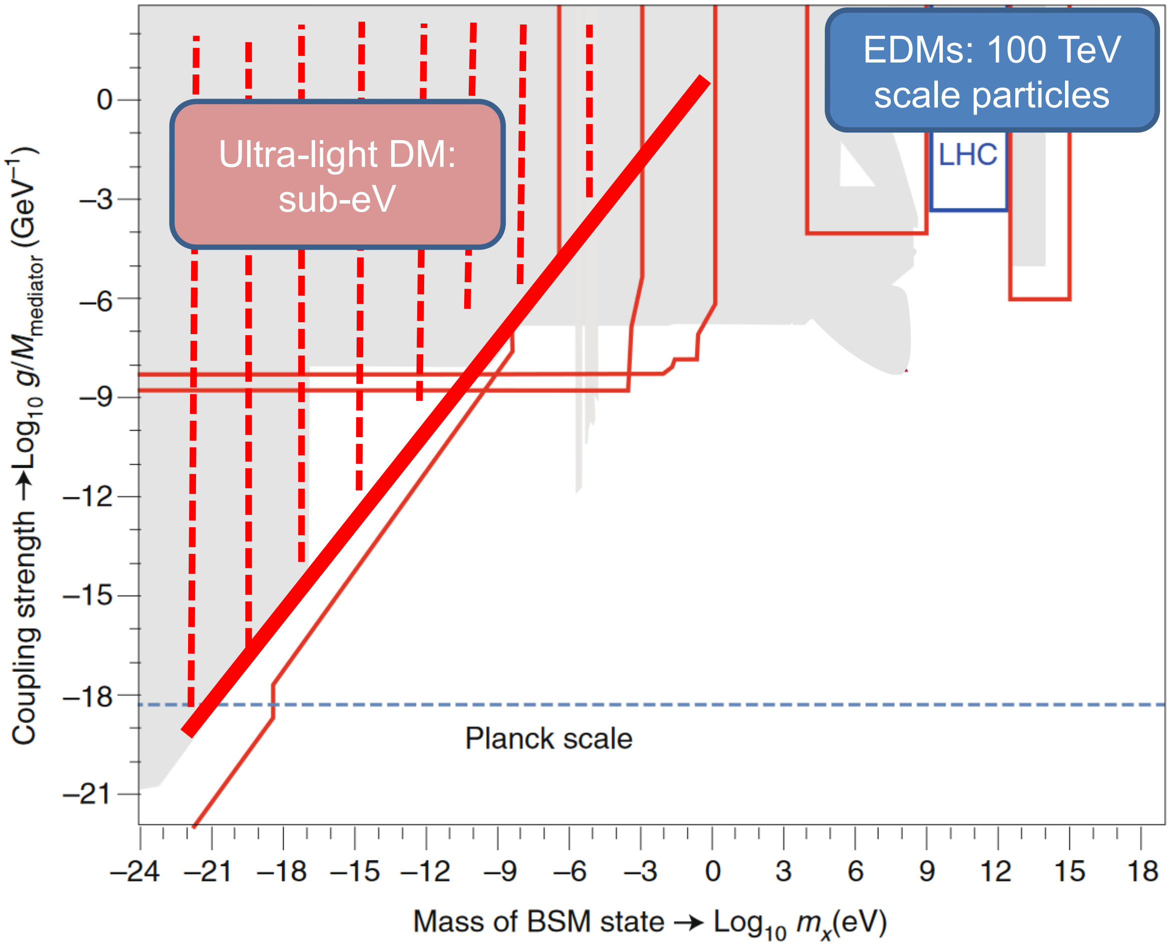
modified from J. Jaeckel et al., Nat. Phys. 16, 393-401 (2020)

New Physics constraints



modified from J. Jaeckel et al., Nat. Phys. 16, 393-401 (2020)

New Physics constraints



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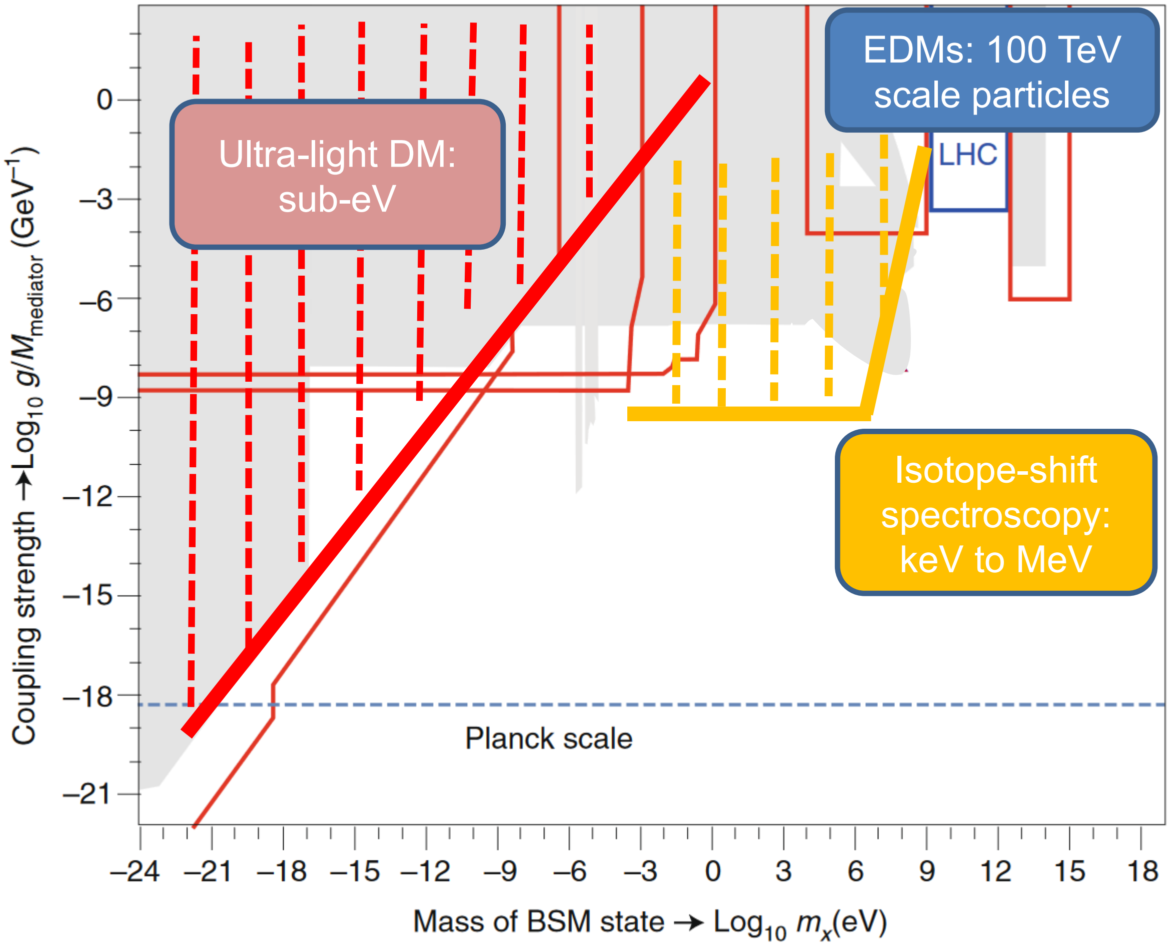
New Physics constraints



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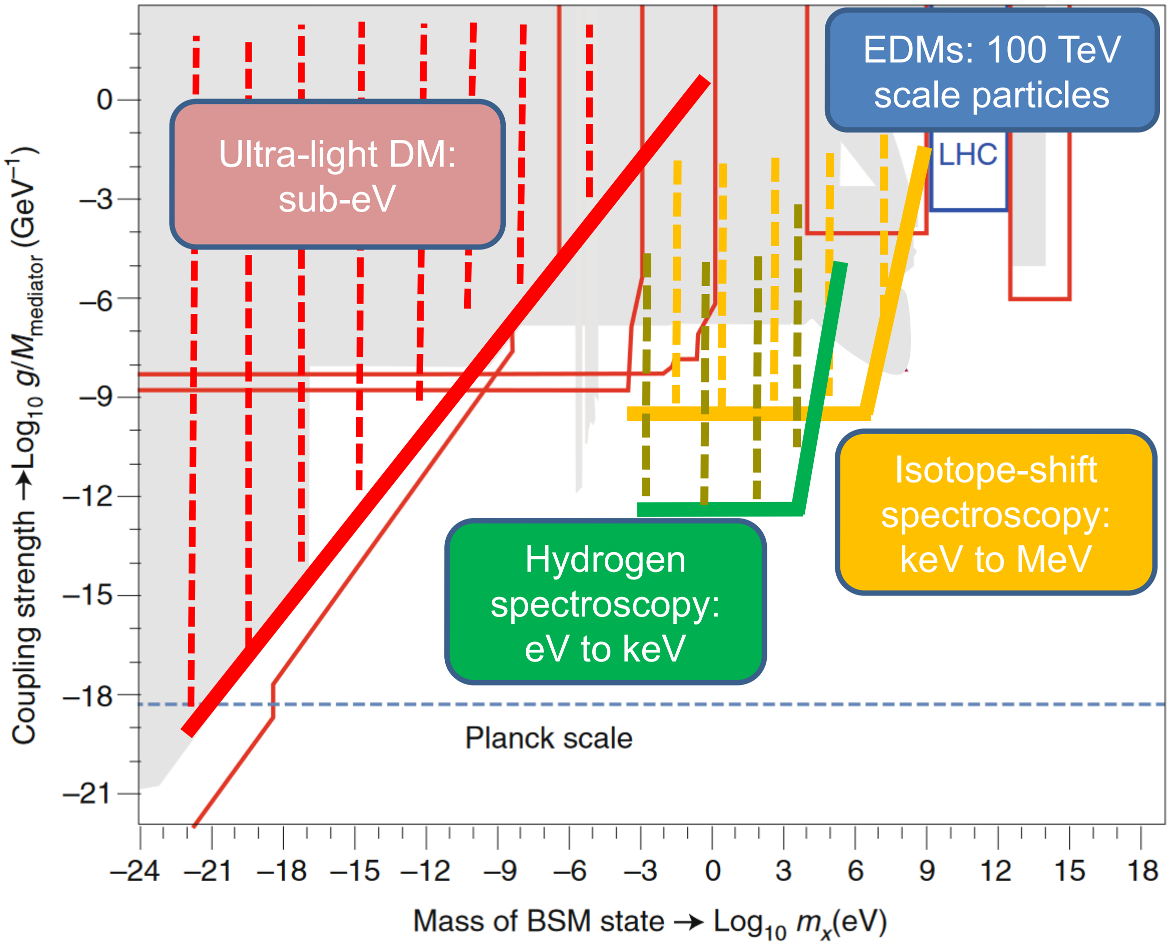


Ultra-light DM: sub-eV

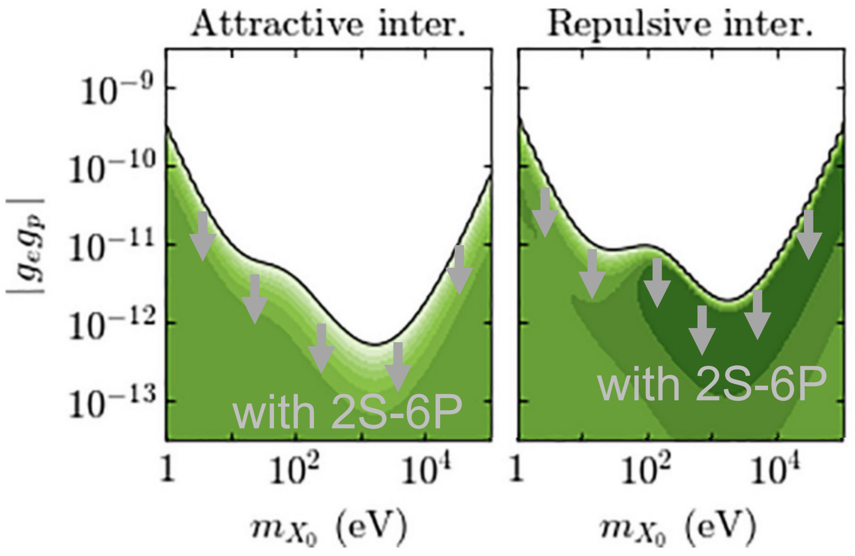
EDMs: 100 TeV scale particles

Hydrogen spectroscopy: eV to keV

Isotope-shift spectroscopy: keV to MeV

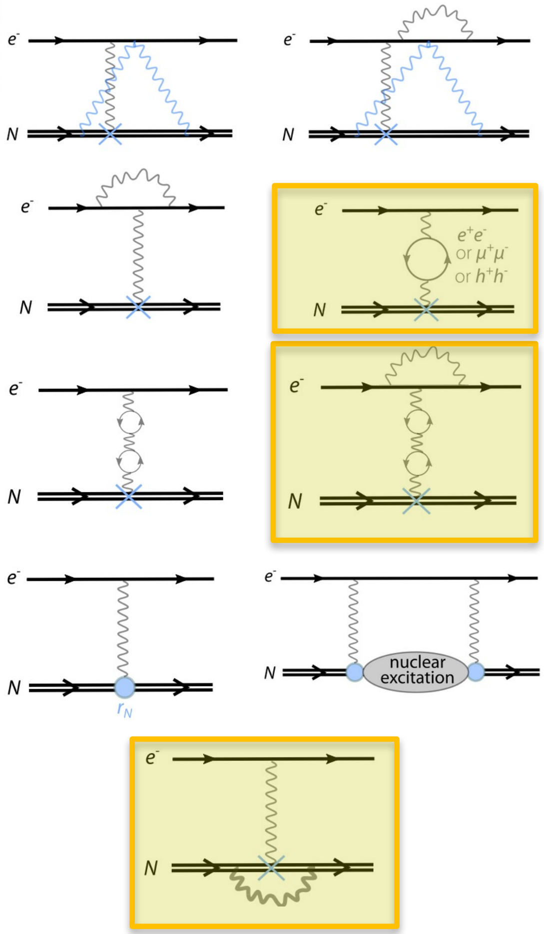
modified from J. Jaeckel et al., Nat. Phys. 16, 393-401 (2020)

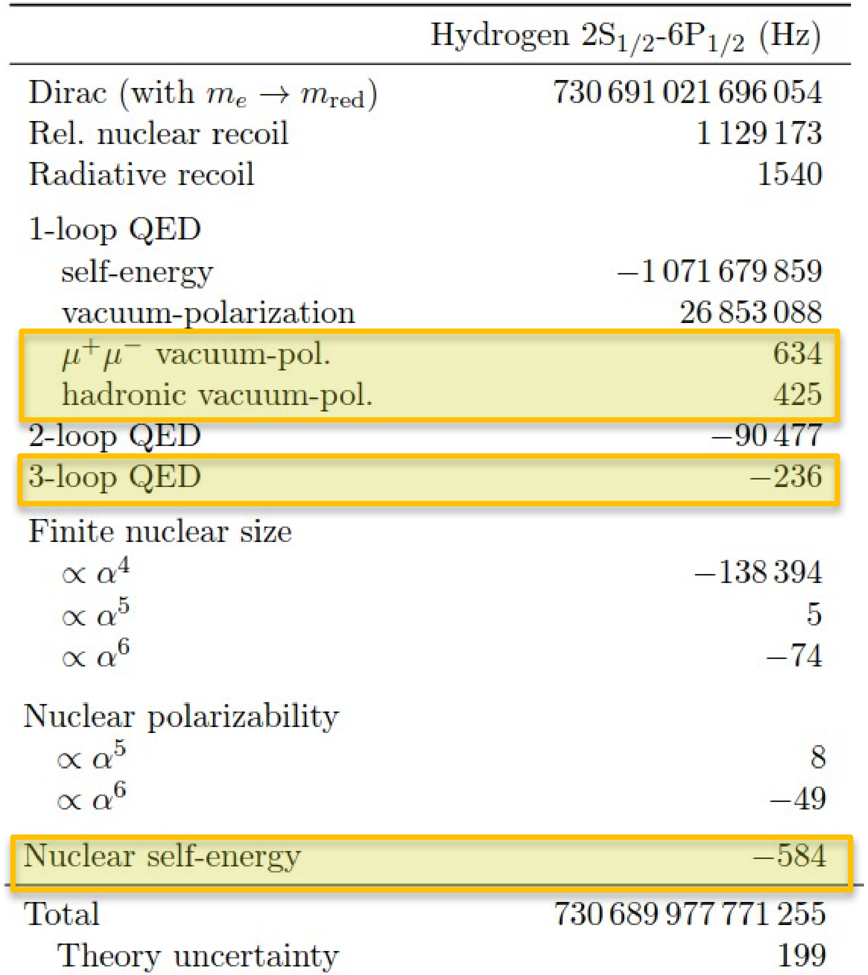
Hydrogen spectroscopy probes new bosons with masses in the **eV to keV range,** our 2S-6P result pushes bounds to relative **couplings down to 10^{-12} to 10^{-13}**



modified from R. M. Potvliege et al., PRA 108 052825 (20

Hydrogen 2S-6P: which contributions are being tested





	Hydrogen $2S_{1/2}$-$6P_{1/2}$ (Hz)
Dirac (with $m_e \to m_{\mathrm{red}}$)	730 691 021 696 054
Rel. nuclear recoil	1 129 173
Radiative recoil	1540
1-loop QED	
self-energy	−1 071 679 859
vacuum-polarization	26 853 088
$\mu^+\mu^-$ vacuum-pol.	634
hadronic vacuum-pol.	425
2-loop QED	−90 477
3-loop QED	−236
Finite nuclear size	
$\propto \alpha^4$	−138 394
$\propto \alpha^5$	5
$\propto \alpha^6$	−74
Nuclear polarizability	
$\propto \alpha^5$	8
$\propto \alpha^6$	−49
Nuclear self-energy	−584
Total	730 689 977 771 255
Theory uncertainty	199

Our 2S-6P meas. uncert.:

490 Hz

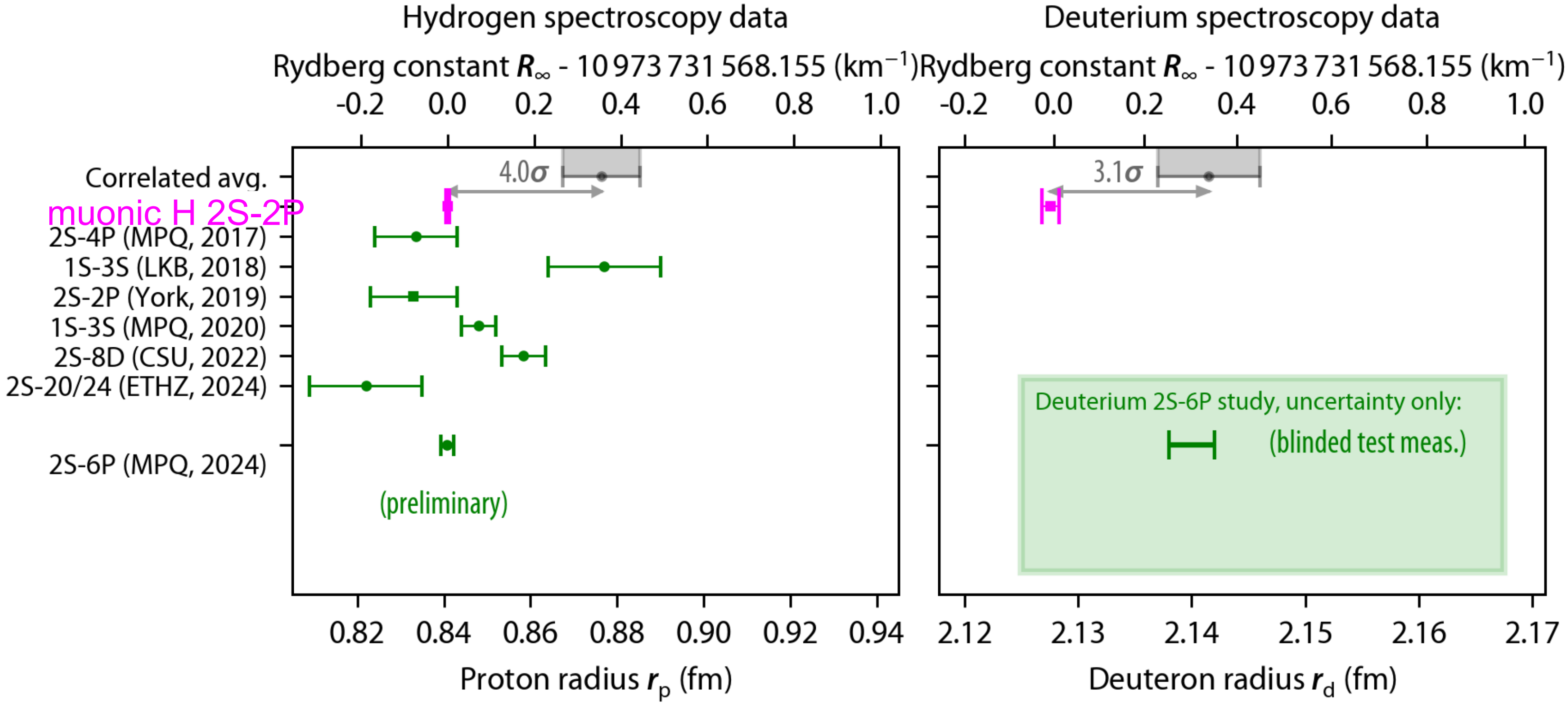
Start seeing muons and hadrons in vacuum

Start seeing 3-loop bound-state vacuum effects

Start seeing Nuclear self-energy

Preliminary deuterium 2S-6P test measurement

Preliminary blinded deuterium 2S-6P test measurement
cam

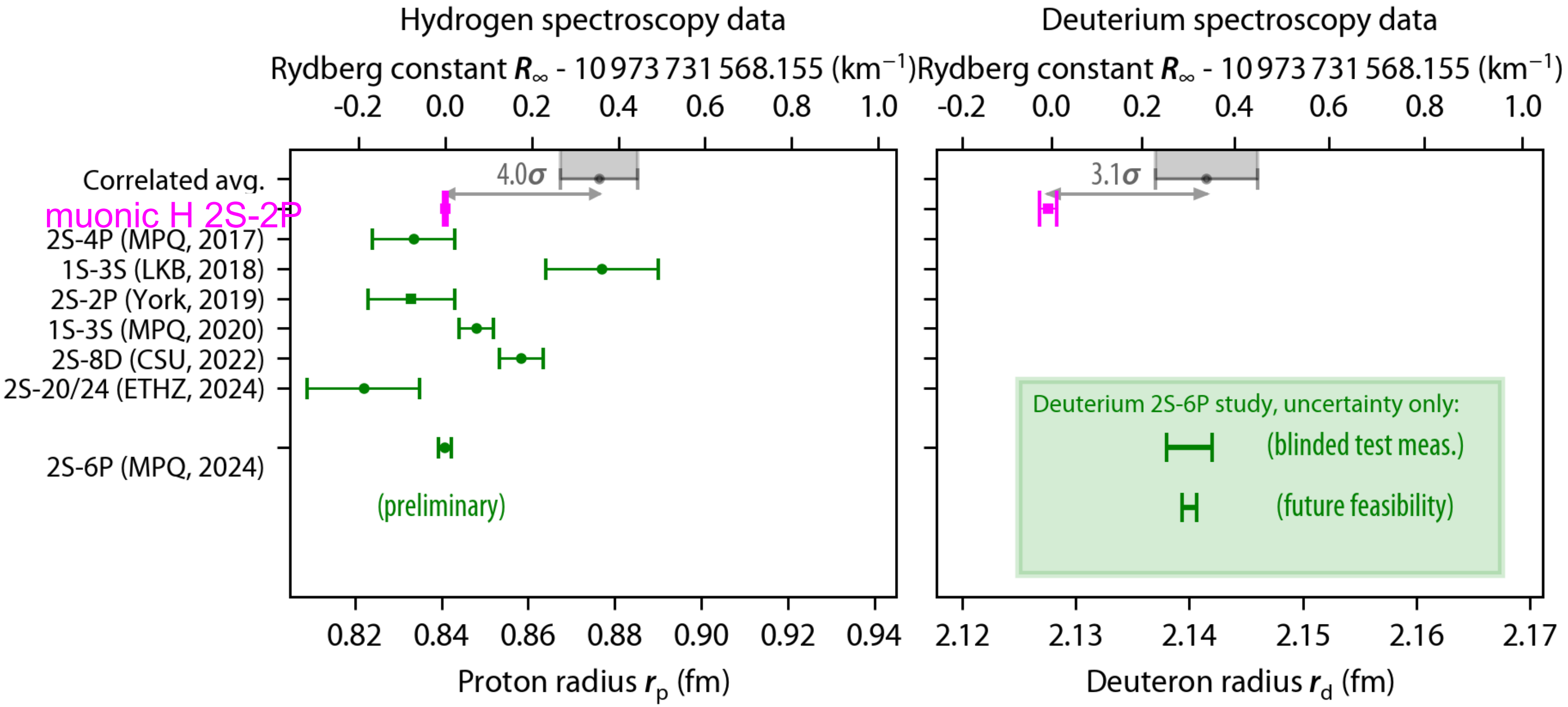


Deuterium 2S-6P measurement campaign currently in preparation
➔ feasible with a similar precision as in hydrogen

Preliminary deuterium 2S-6P test measurement

Preliminary blinded deuterium 2S-6P test measurement

cam



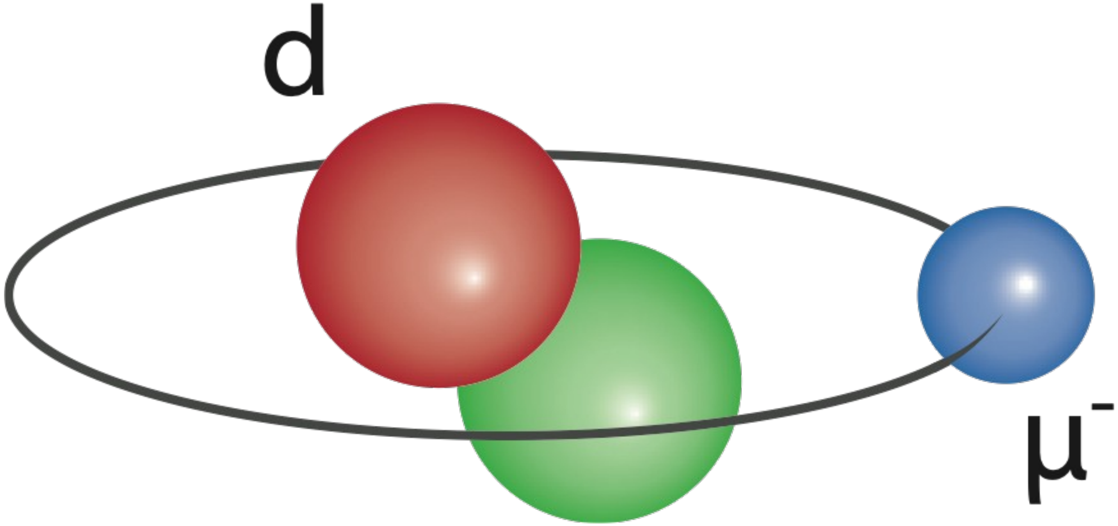
Deuterium 2S-6P measurement campaign currently in preparation
➔ feasible with a similar precision as in hydrogen

CREMA:
Laser spectroscopy of light muonic atoms

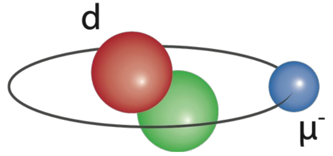
EPIC’24, 24.9.2024

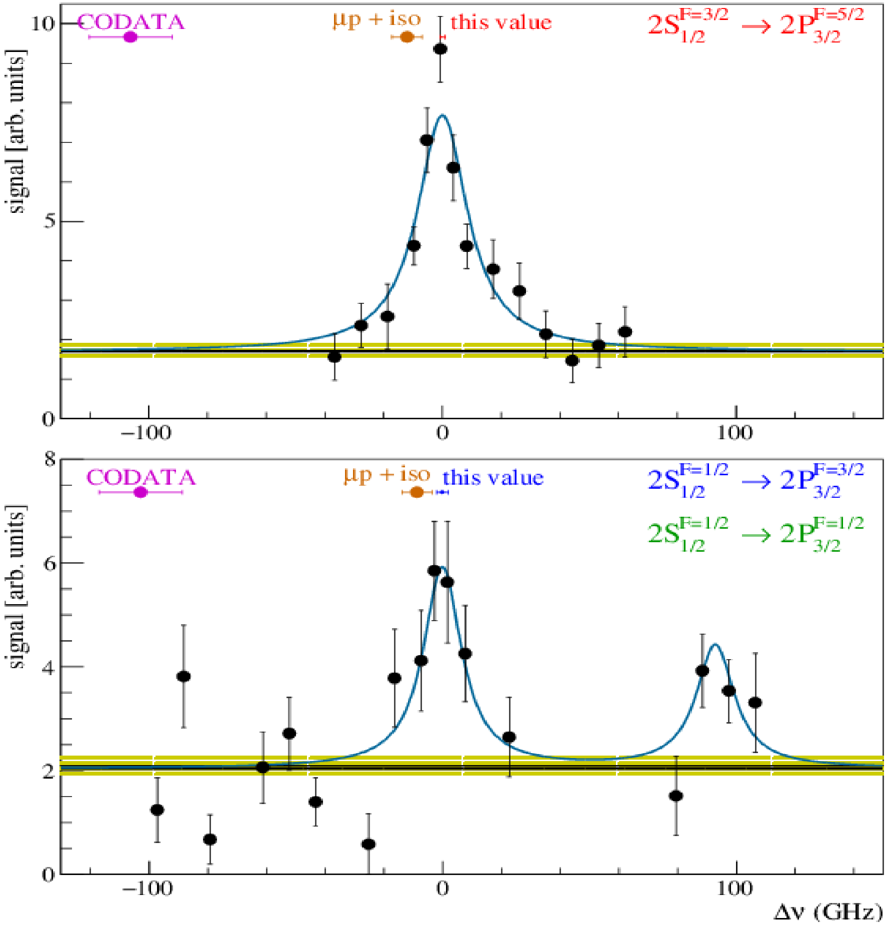
Randolf Pohl, JGU Mainz

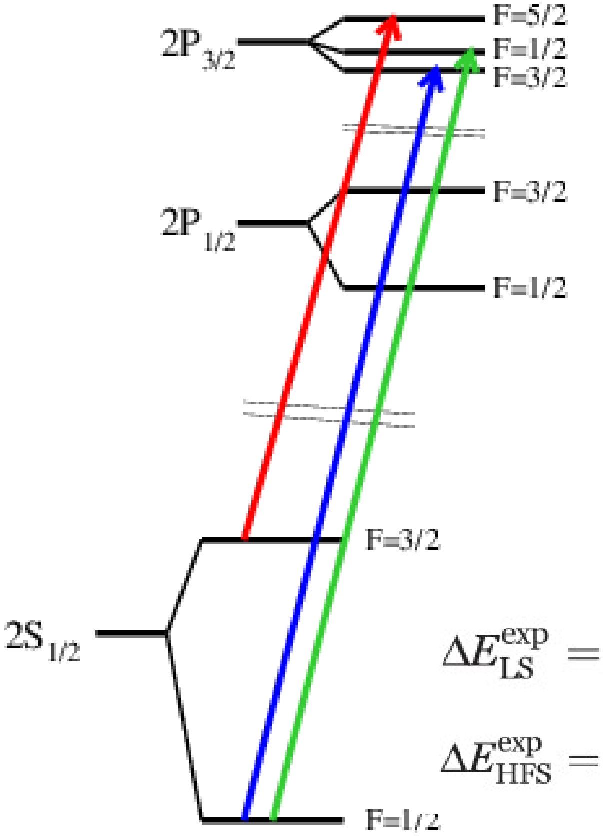
Muonic Deuterium



2.5 transitions in muonic D







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

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

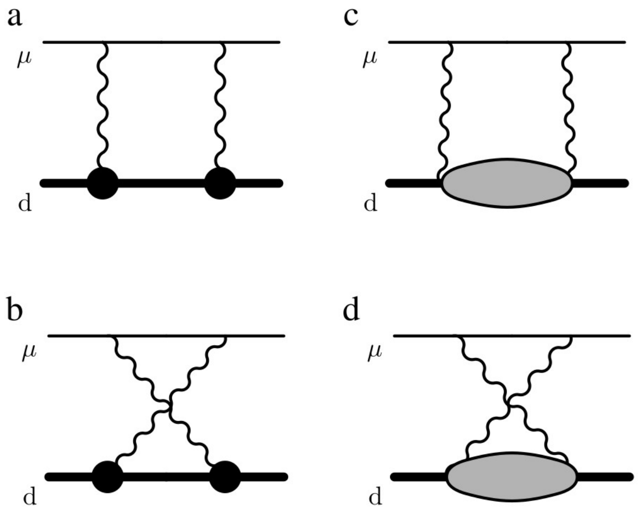
Pohl et al. (CREMA Coll.), Science 353, 669 (2016)

Theory: Lamb shift in muonic D

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

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

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

Theory: Lamb shift in muonic D

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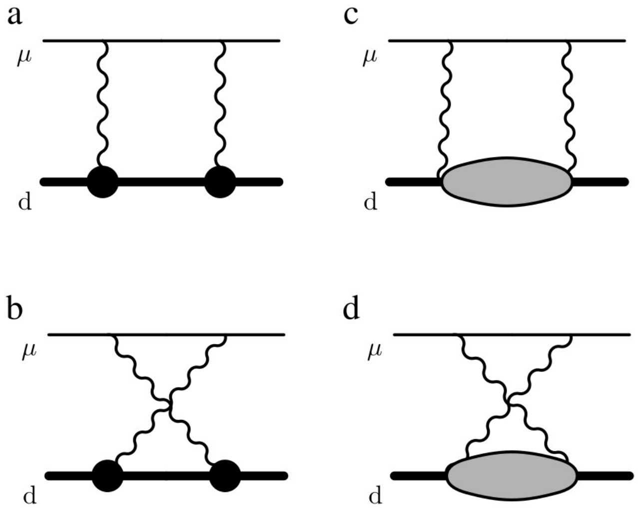
Nuclear structure two (and three!)-photon contributions to the Lamb shift in muonic deuterium.



Pachucki, RP et al, arXiv 2212.13782

Theory in light muonic atoms:

see next Talk by Vadim Lensky

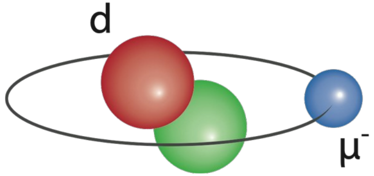
en

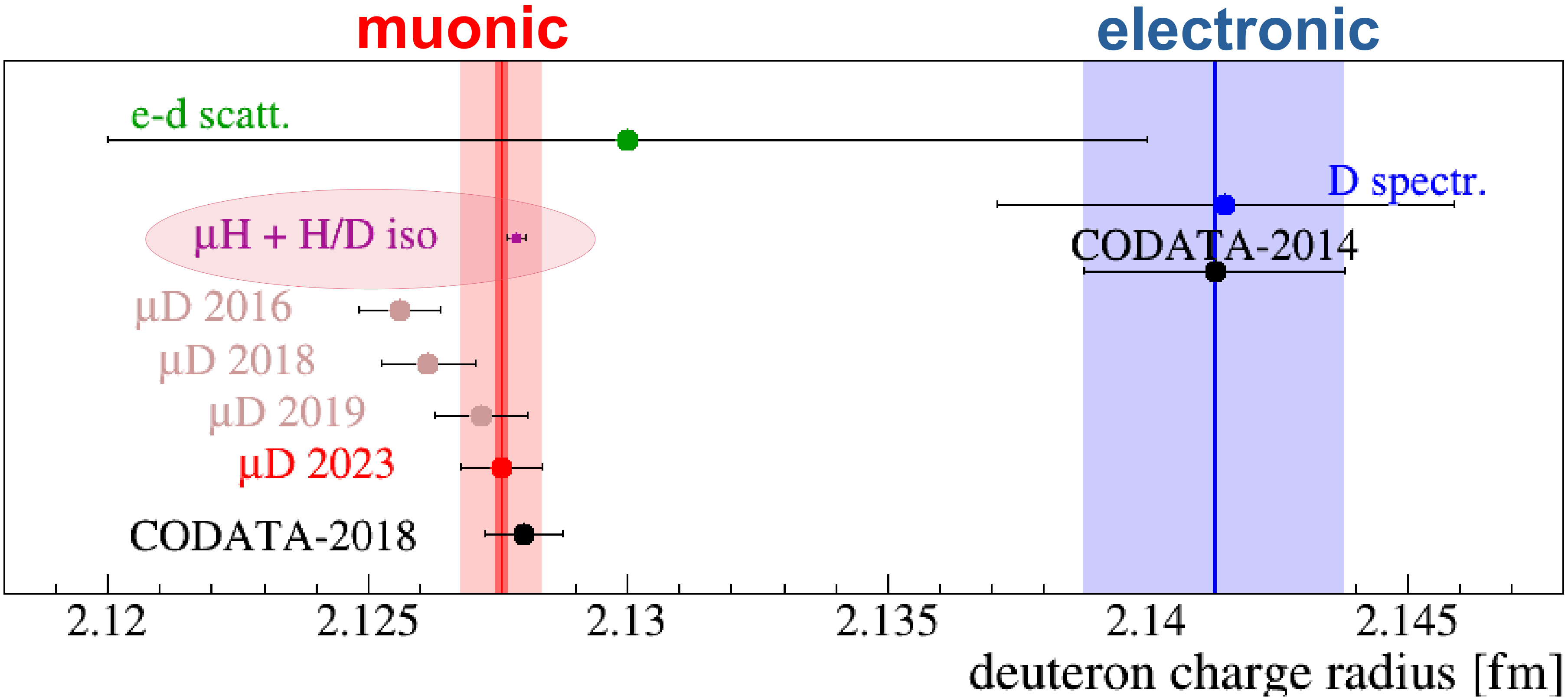
!!

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

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

Muonic Deuterium





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

μH + H/D(1S-2S): 2.12785 (17) fm

Theory in muonic D

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

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 $(13)_{\mathrm{exp}}$ $(78)_{\mathrm{theo}}$ fm

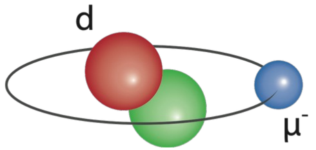
(2) **polarizability**, using **charge radius from isotope shift**

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

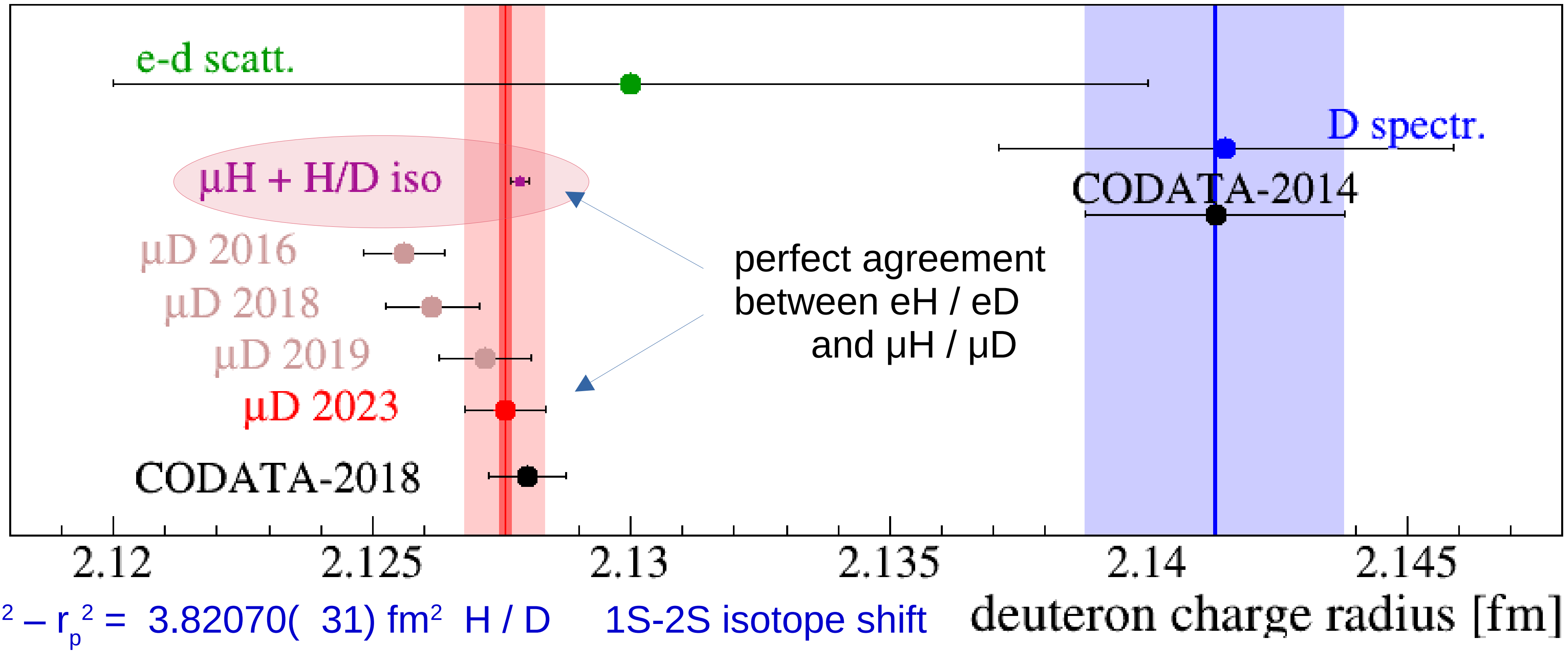
ΔE_{TPE} (exp) = 1.7591 (59) meV 3x more accurate

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

Muonic Deuterium



muonic **old electronic**

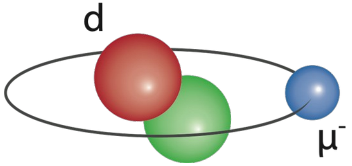


perfect agreement between eH / eD and μH / μD

$r_d^2 - r_p^2 =$ 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

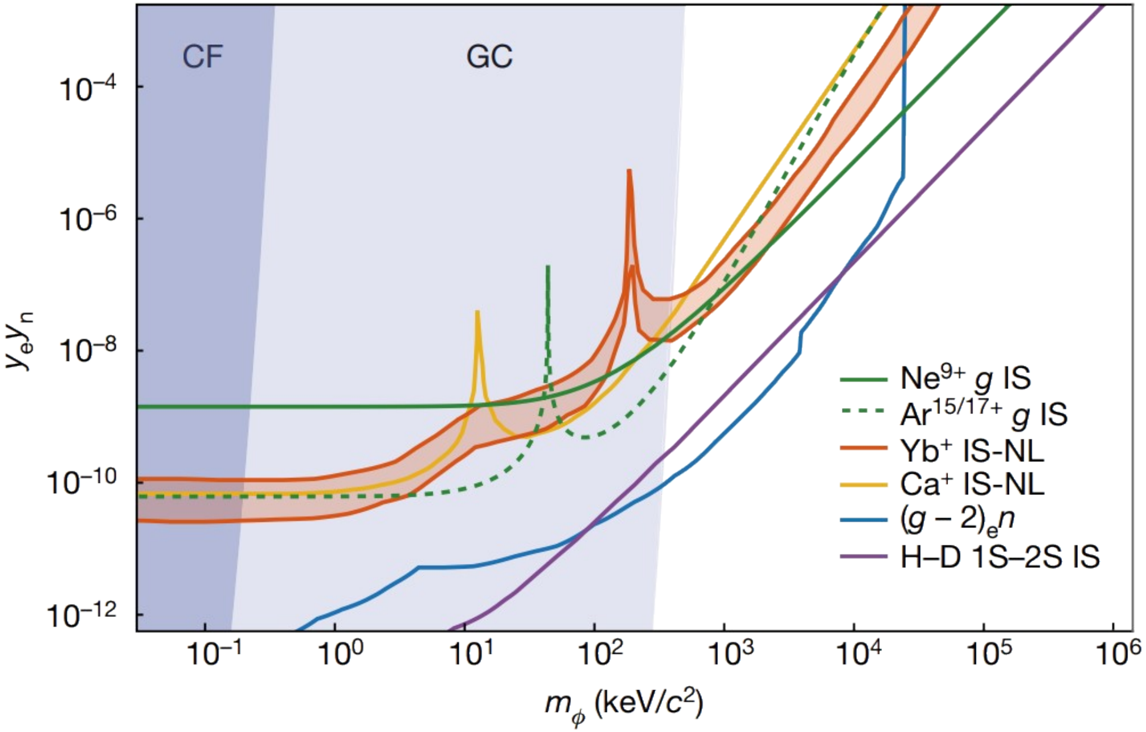


electronic H/D (1S-2S): $r_d^2 - r_p^2 = 3.8207(3)_{theo}\ \mathrm{fm}^2$

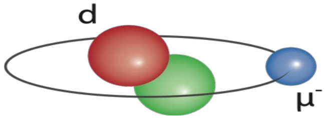
muonic H/D (2S-2P): $r_d^2 - r_p^2 = 3.8200(7)_{exp}(30)_{theo}\ \mathrm{fm}^2$

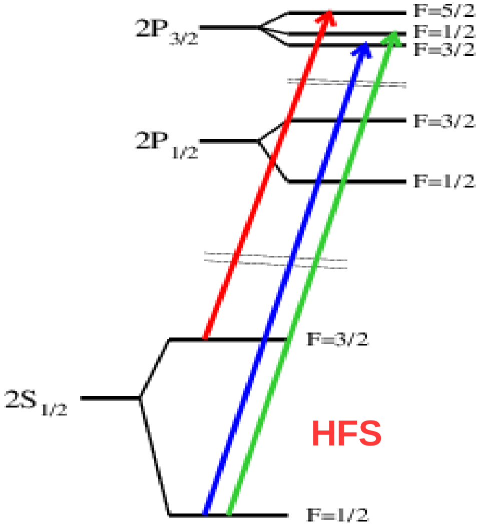
→ Best bound on 5th force

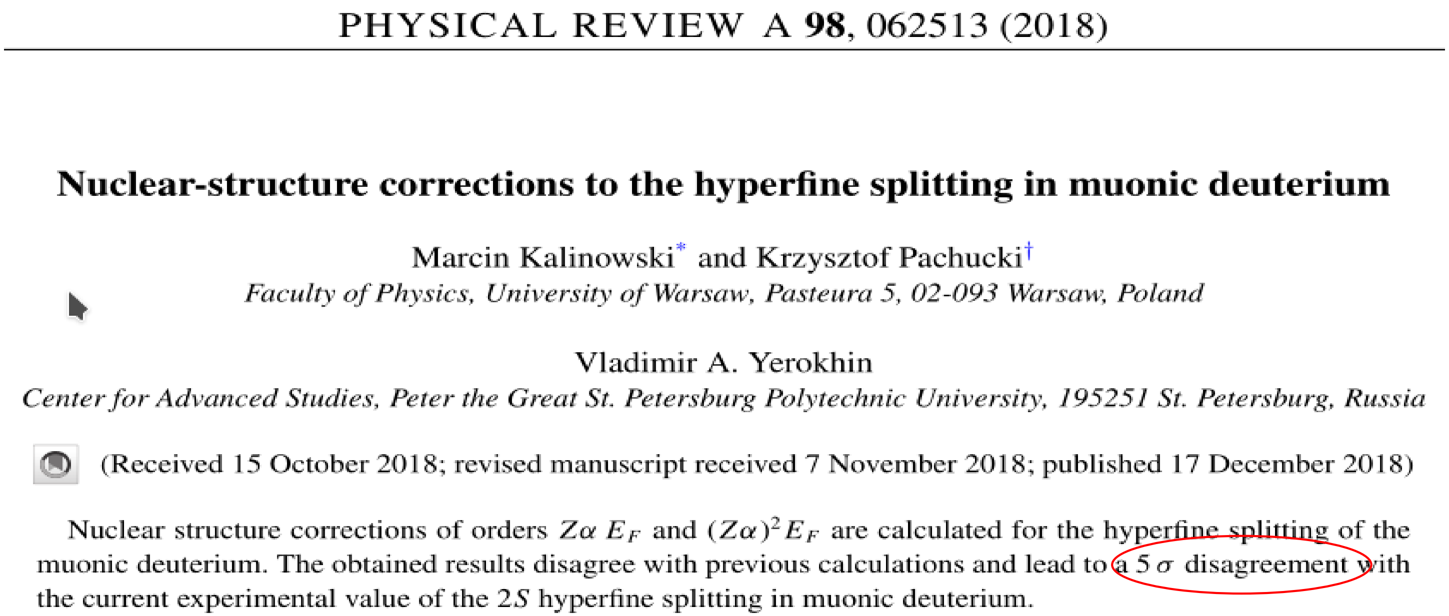
T. Sailer *et. al.* (*Blaum group*), Nature 606 (2022)



HFS in muonic D







PHYSICAL REVIEW A **98**, 062513 (2018)

Nuclear-structure corrections to the hyperfine splitting in muonic deuterium

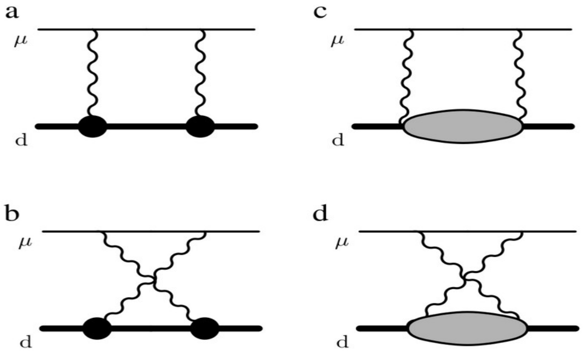
Marcin Kalinowski[*] and Krzysztof Pachucki[†]
Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland

Vladimir A. Yerokhin
Center for Advanced Studies, Peter the Great St. Petersburg Polytechnic University, 195251 St. Petersburg, Russia

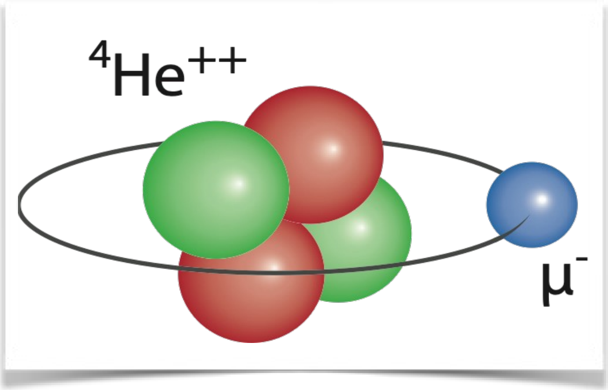
(Received 15 October 2018; revised manuscript received 7 November 2018; published 17 December 2018)

Nuclear structure corrections of orders $Z\alpha\, E_F$ and $(Z\alpha)^2 E_F$ are calculated for the hyperfine splitting of the muonic deuterium. The obtained results disagree with previous calculations and lead to a 5 σ disagreement with the current experimental value of the 2S hyperfine splitting in muonic deuterium.

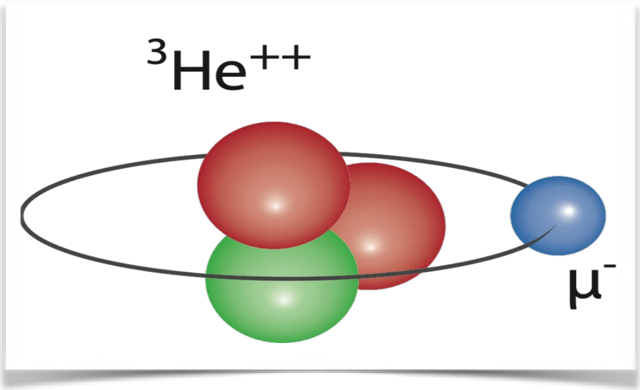
5σ disagreement between theory and experiment !!!



Muonic Helium

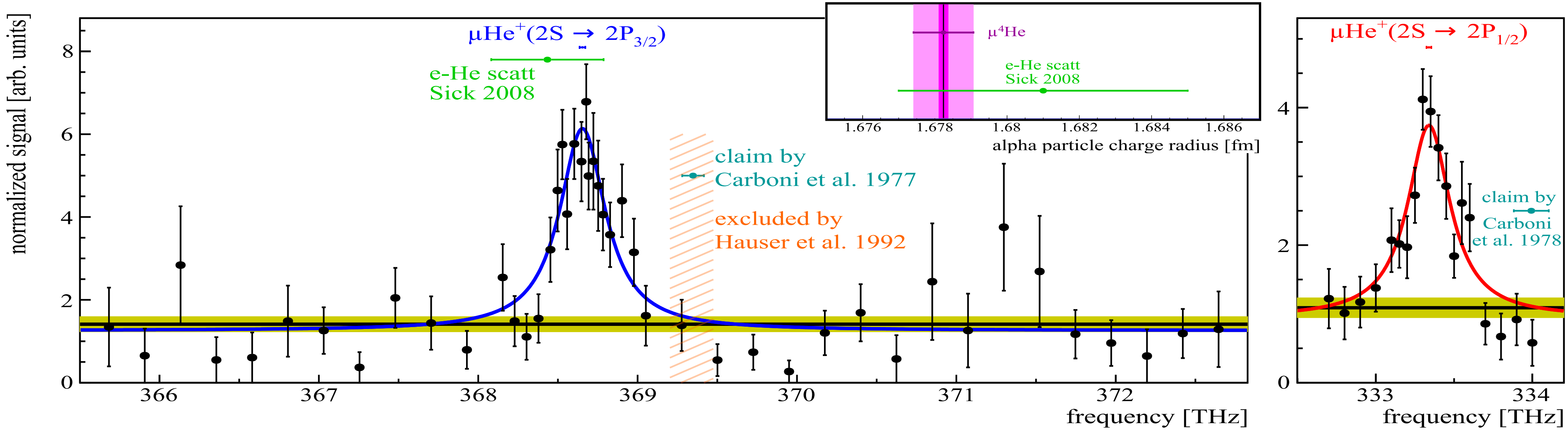


Krauth et al. (CREMA), Nature (2021)



arXiv 2305.11679

muonic ^{4}He ions



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

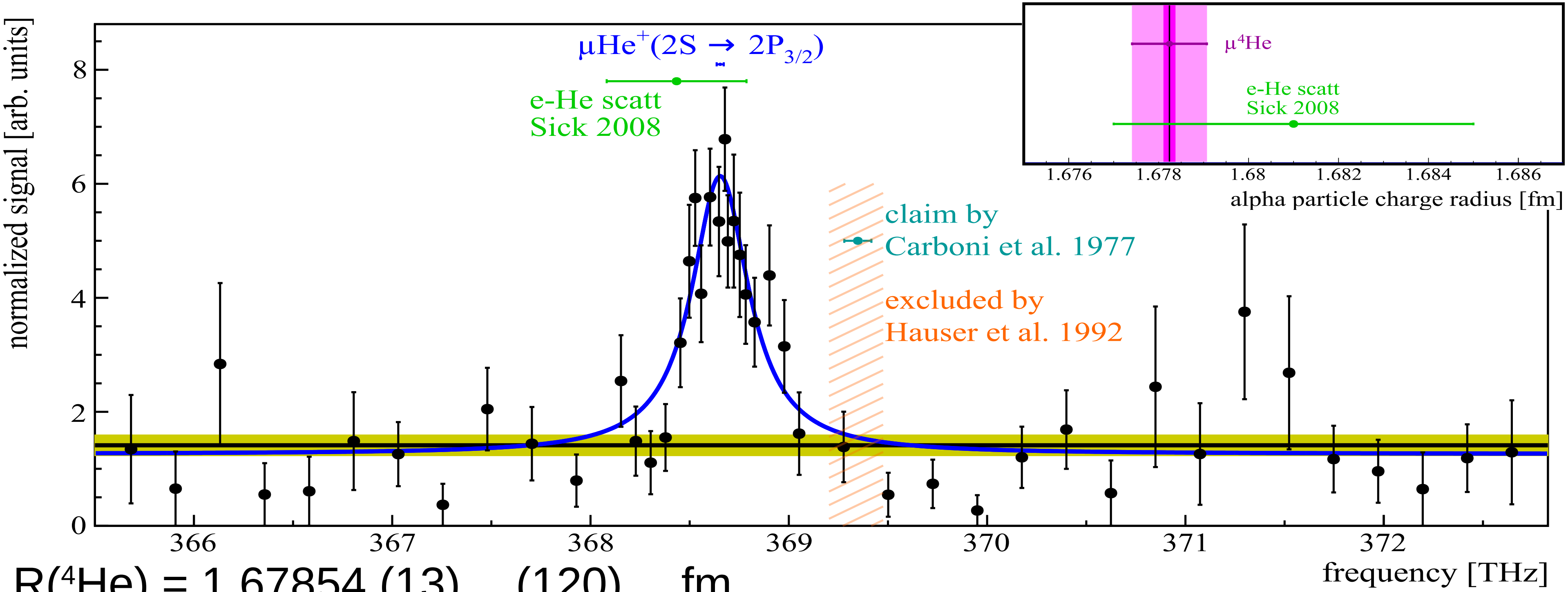
$$R(^4He) = 1.67854\ (13)_{exp}\ (120)_{theo}\ \text{fm}$$

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

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

muonic ^{4}He ions



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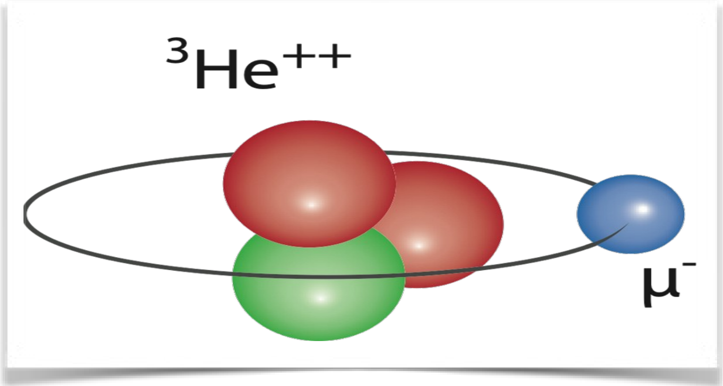
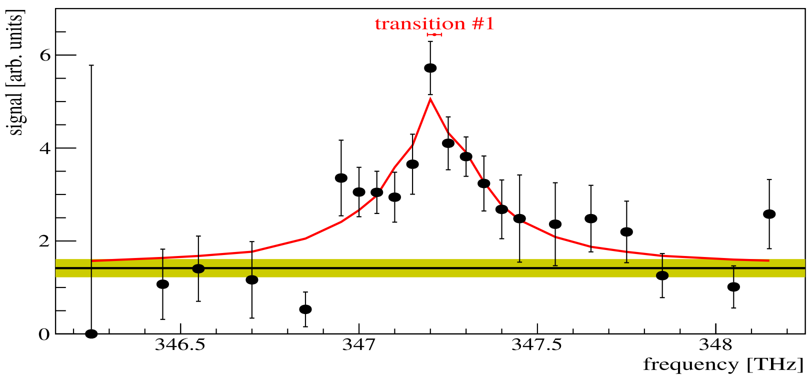
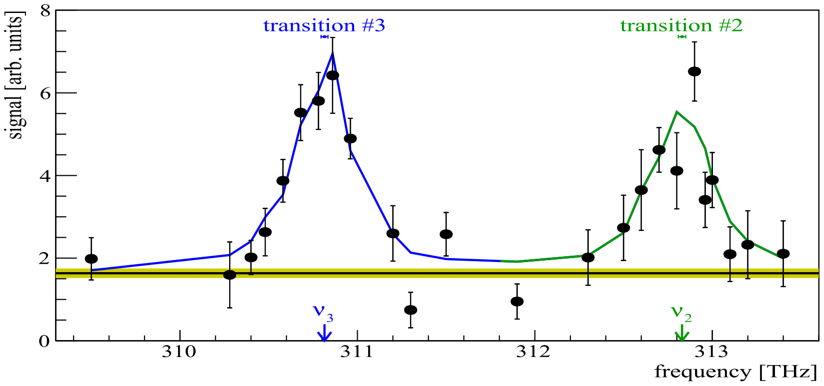
Muonic Helium-3

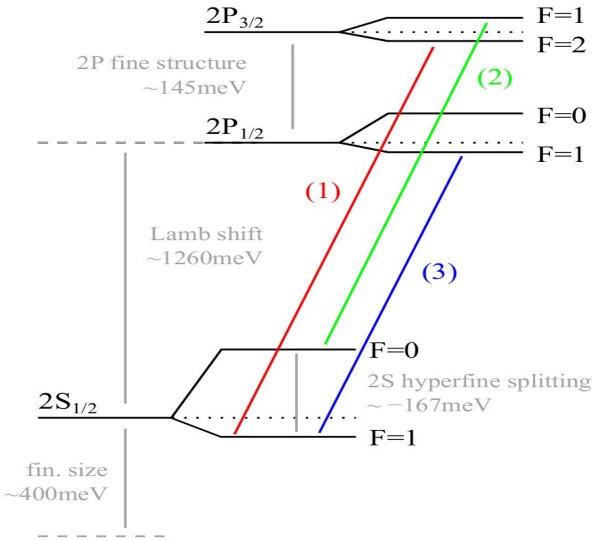


arXiv 2305.11679

muonic ^{3}He ions







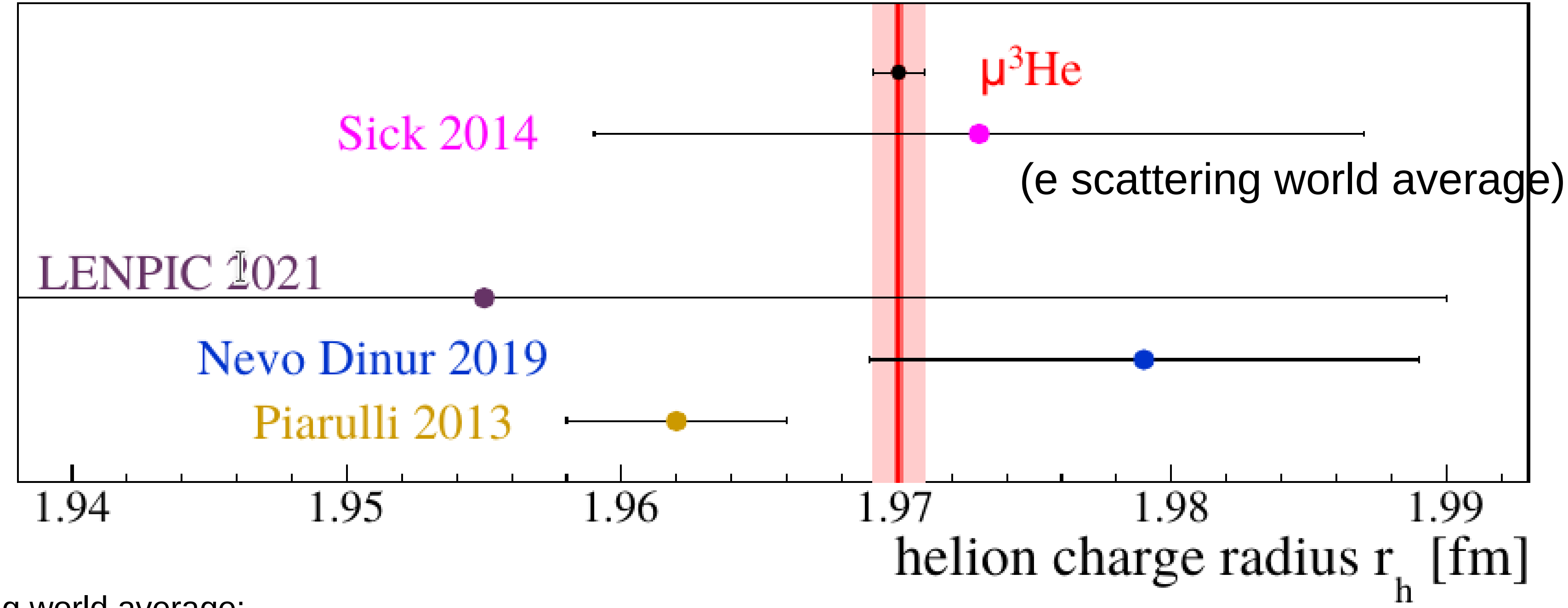
CREMA Coll., arXiv 2305.11679

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

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

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

Muonic Helium-3

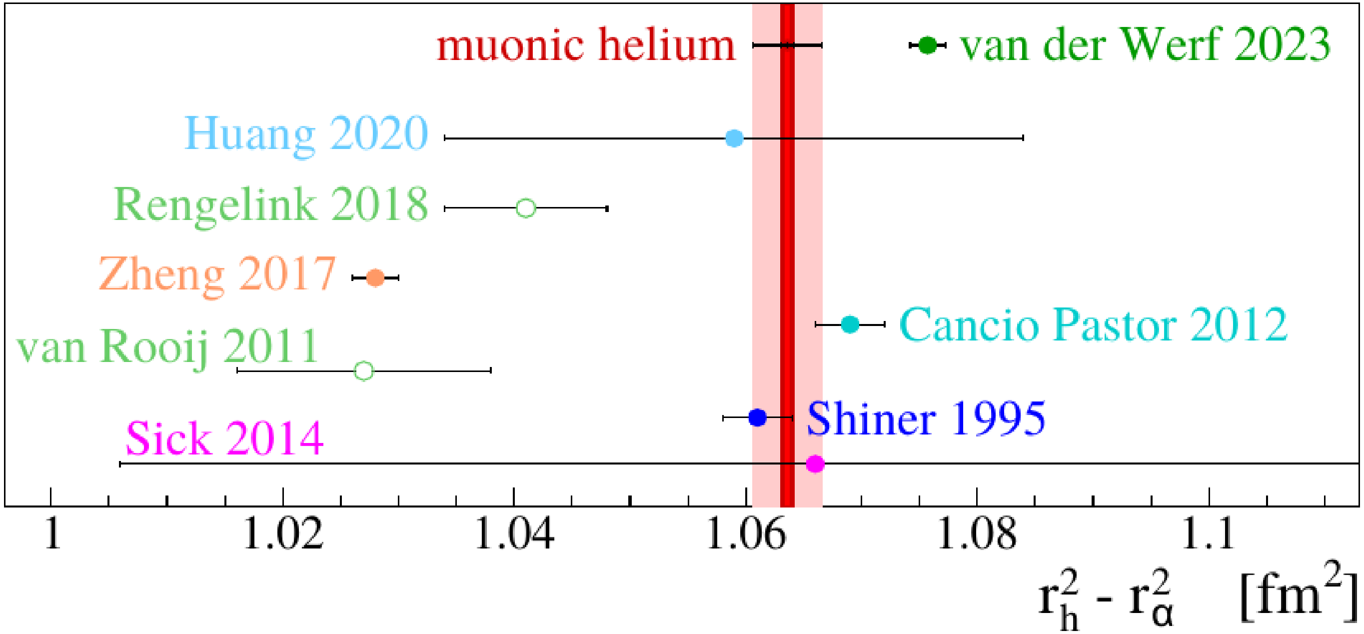


e-scattering world average:
Sick 2014: PRC 90, 064002 (2014)

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



3.6σ !

CREMA Coll., arXiv 2305.11679

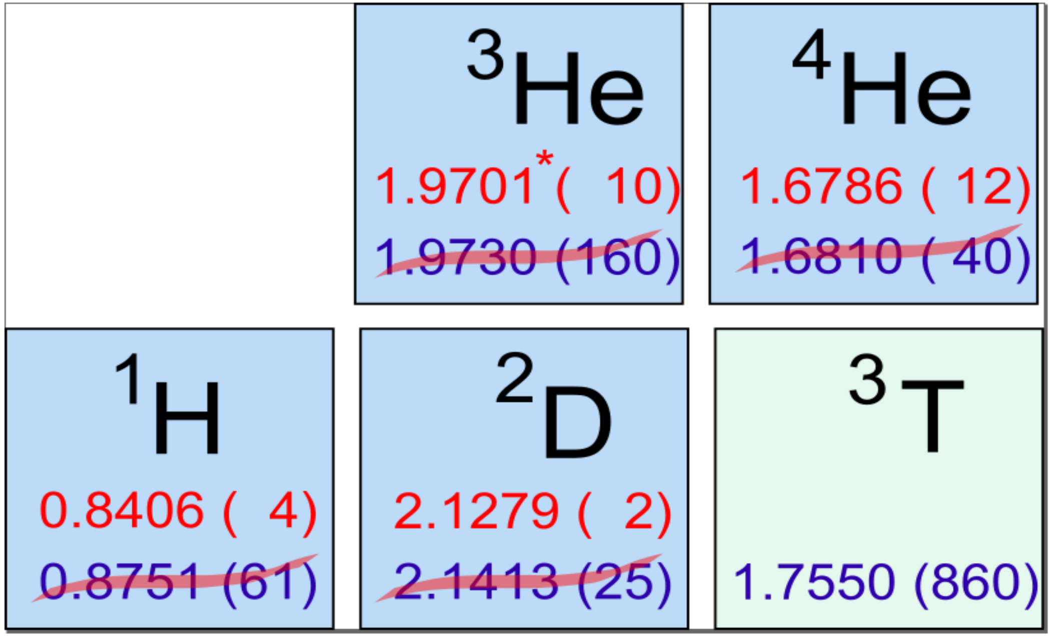
Huang: PRA 101, 062507 (2020)
Rengelink: Nature Physics 14, 1132 (2018)
Zheng: PRL 119, 263002 (2017)
van Rooij: Science 333, 196 (2011)
Cancio Pastor: PRL 108, 143001 (2012)
Shiner: PRL 74, 3553 (1995)

Intermediate conclusions

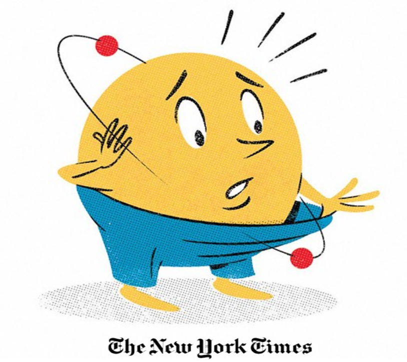
Muonic atoms / ions provide:

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

calculated polarizability



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



Intermediate conclusions

Muonic atoms / ions provide:

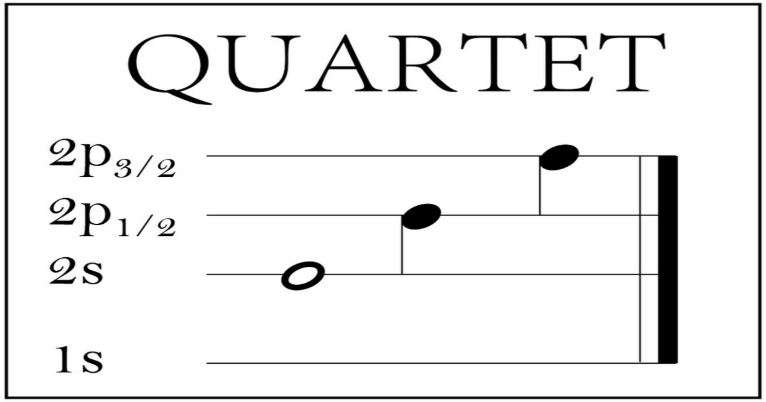
- **~10x more accurate charge radii**, when combined with **calculated polarizability**
- few times more accurate **nuclear polarizability**, when combined with **charge radius from regular atoms**

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

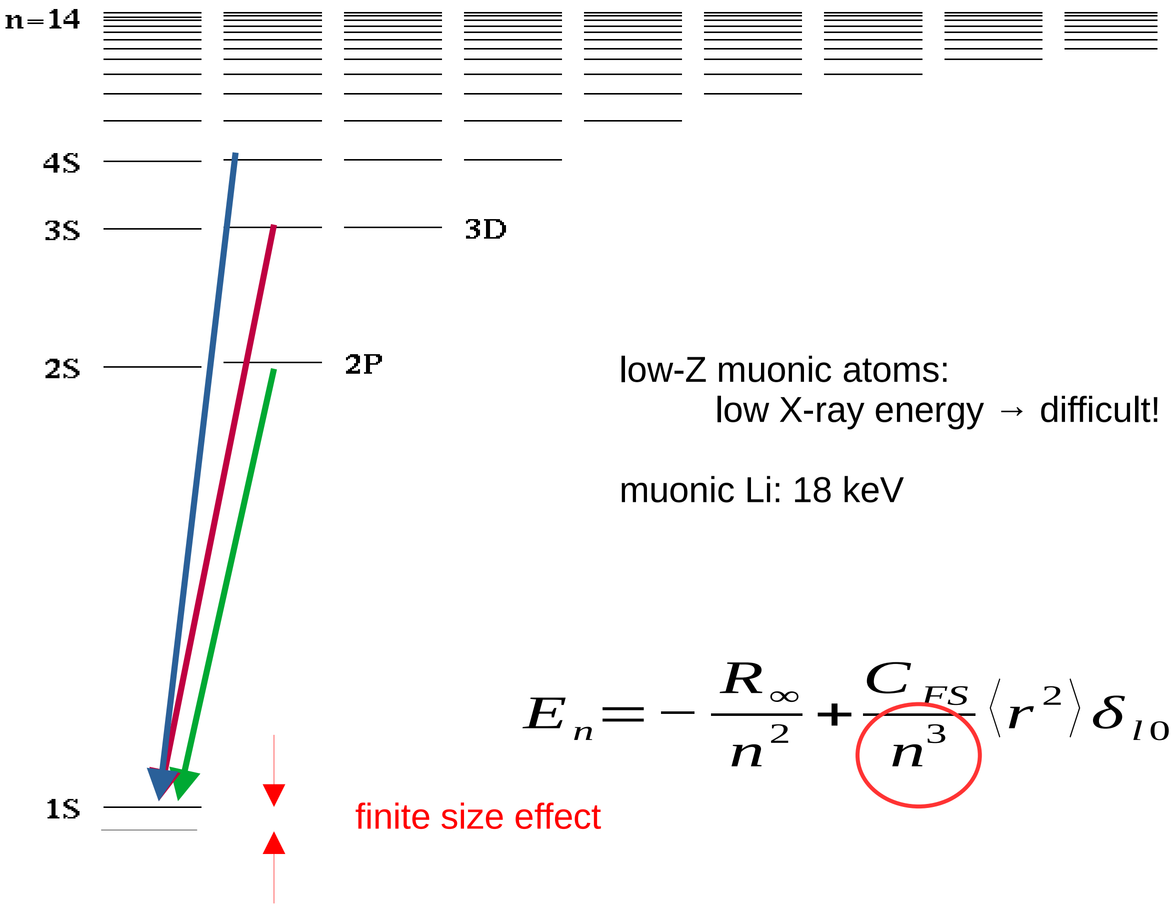
Radii of Z=3 …. 10

Xray spectroscopy

of muonic atoms



X-ray spectroscopy

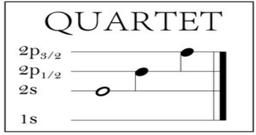


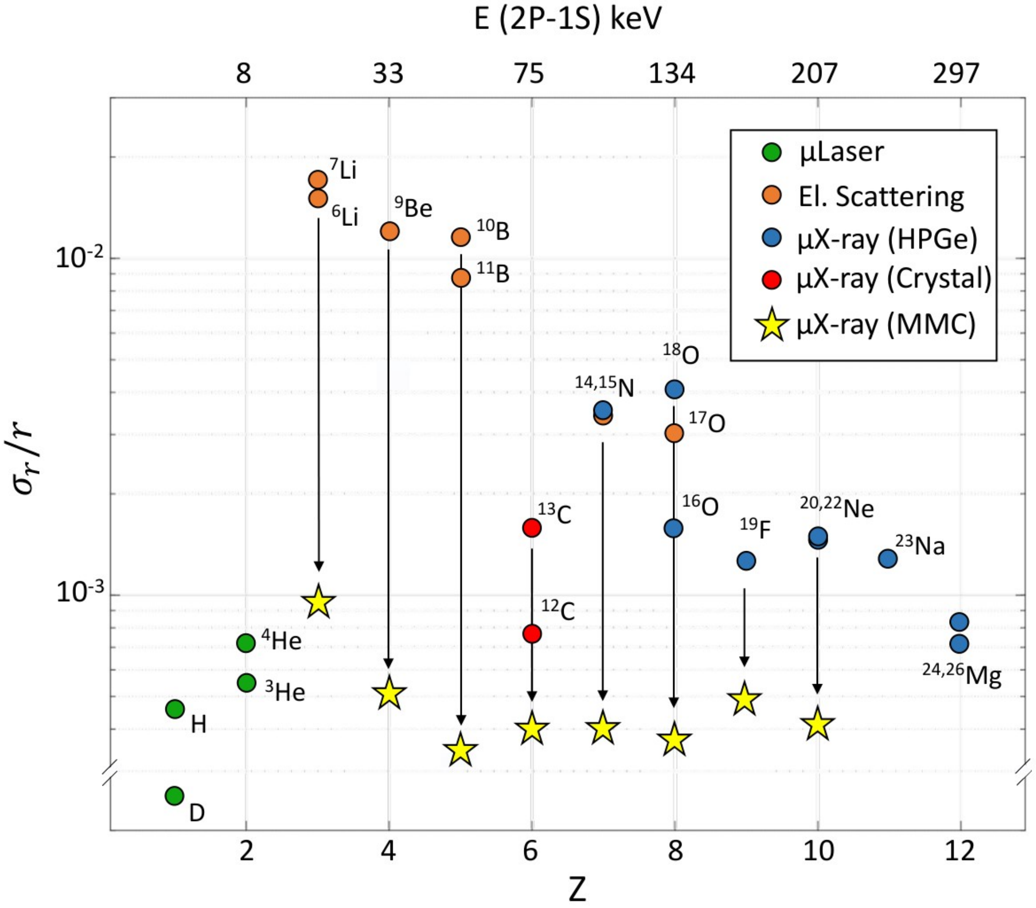
low-Z muonic atoms:
low X-ray energy → difficult!

muonic Li: 18 keV

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

QUARTET Goals





10x improved nuclear charge radii → challenging nuclear few-body calculations

Current knowledge on radii of the lightest nuclei:

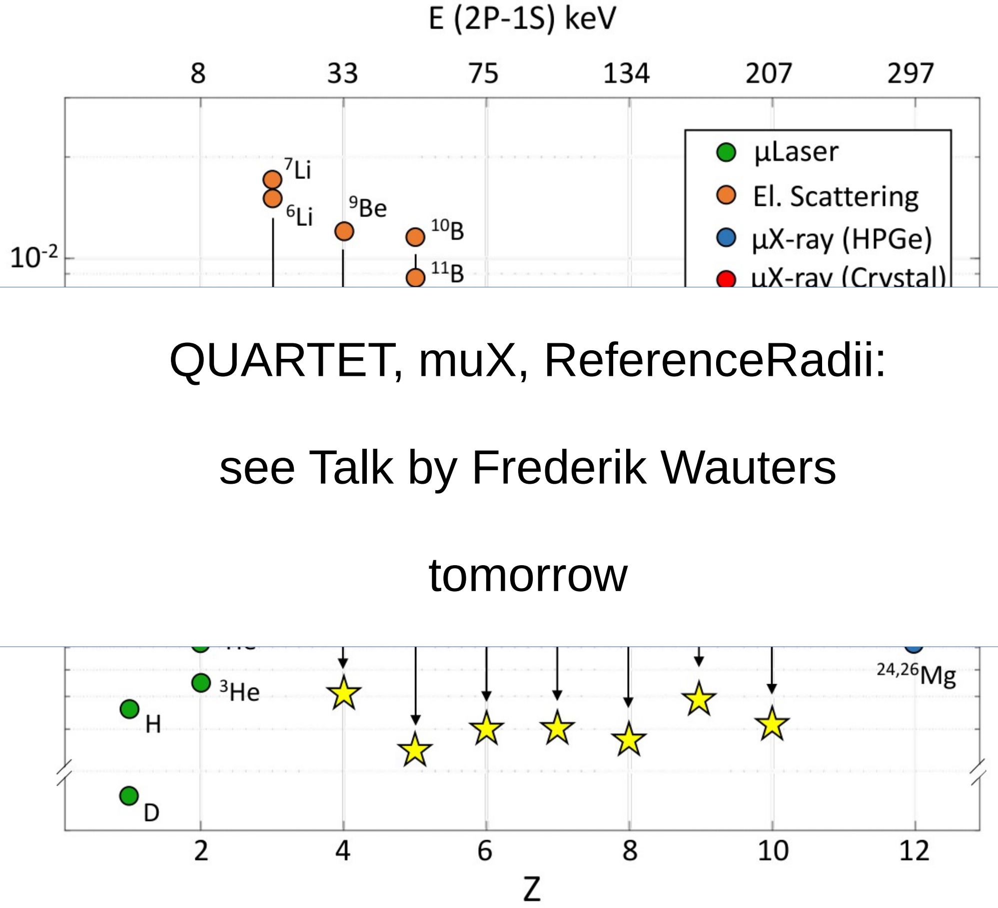
Z=1,2: muonic atom
laser spectroscopy

Z>3: mostly e-scattering

Z=6: some muonic X-rays
(crystal spectrometer)

Z>8: muonic X-rays
(Ge detectors)

QUARTET Goals



QUARTET, muX, ReferenceRadii:

see Talk by Frederik Wauters

tomorrow

Current knowledge on radii of the lightest nuclei:

Z=1,2: muonic atom laser spectroscopy

Z>3: mostly e-scattering

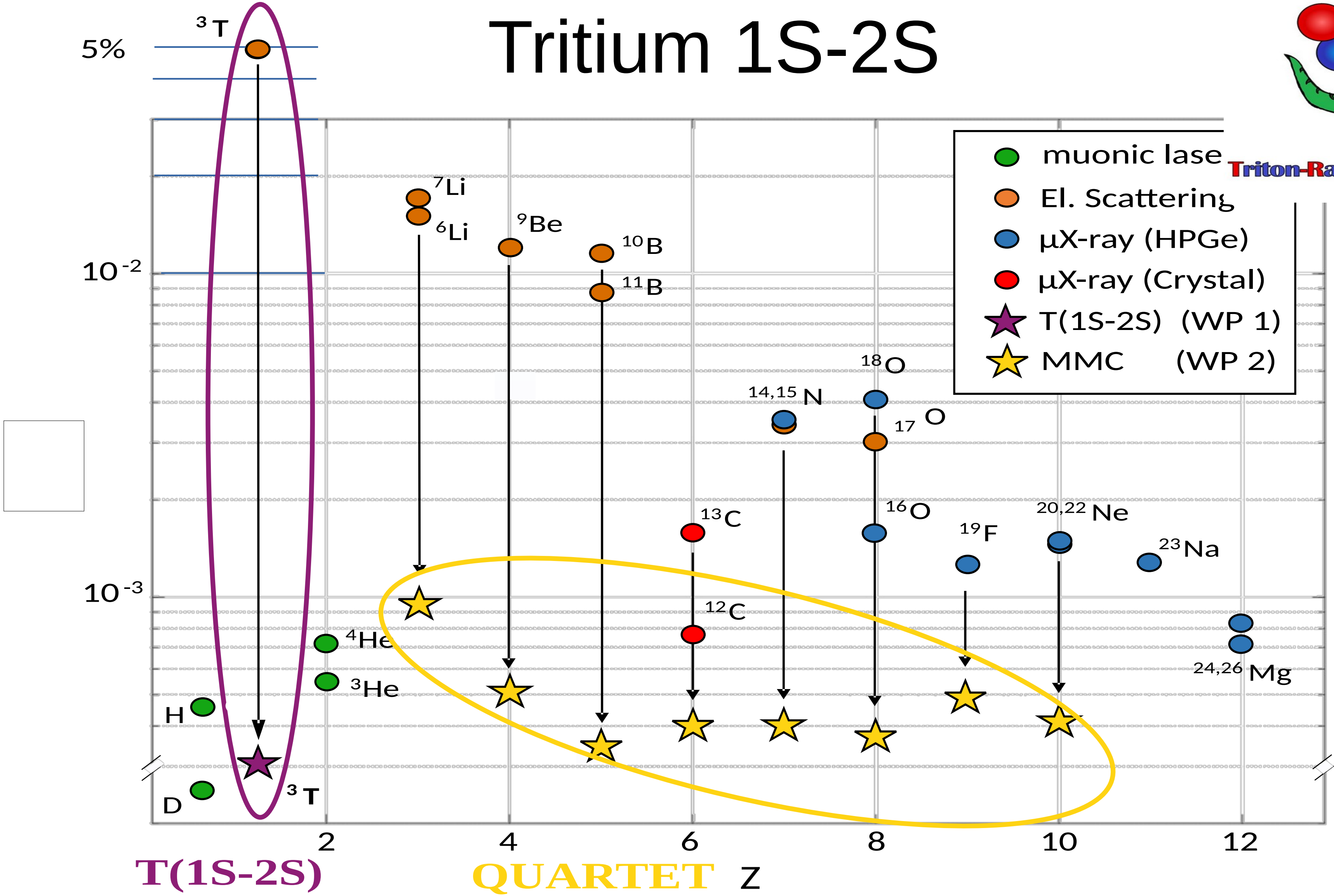
Z=6: some muonic X-rays (crystal spectrometer)

Z>8: muonic X-rays (Ge detectors)

10x improved nuclear charge radii → challenging nuclear few-body calculations

1S – 2S in (ordinary) atomic tritium

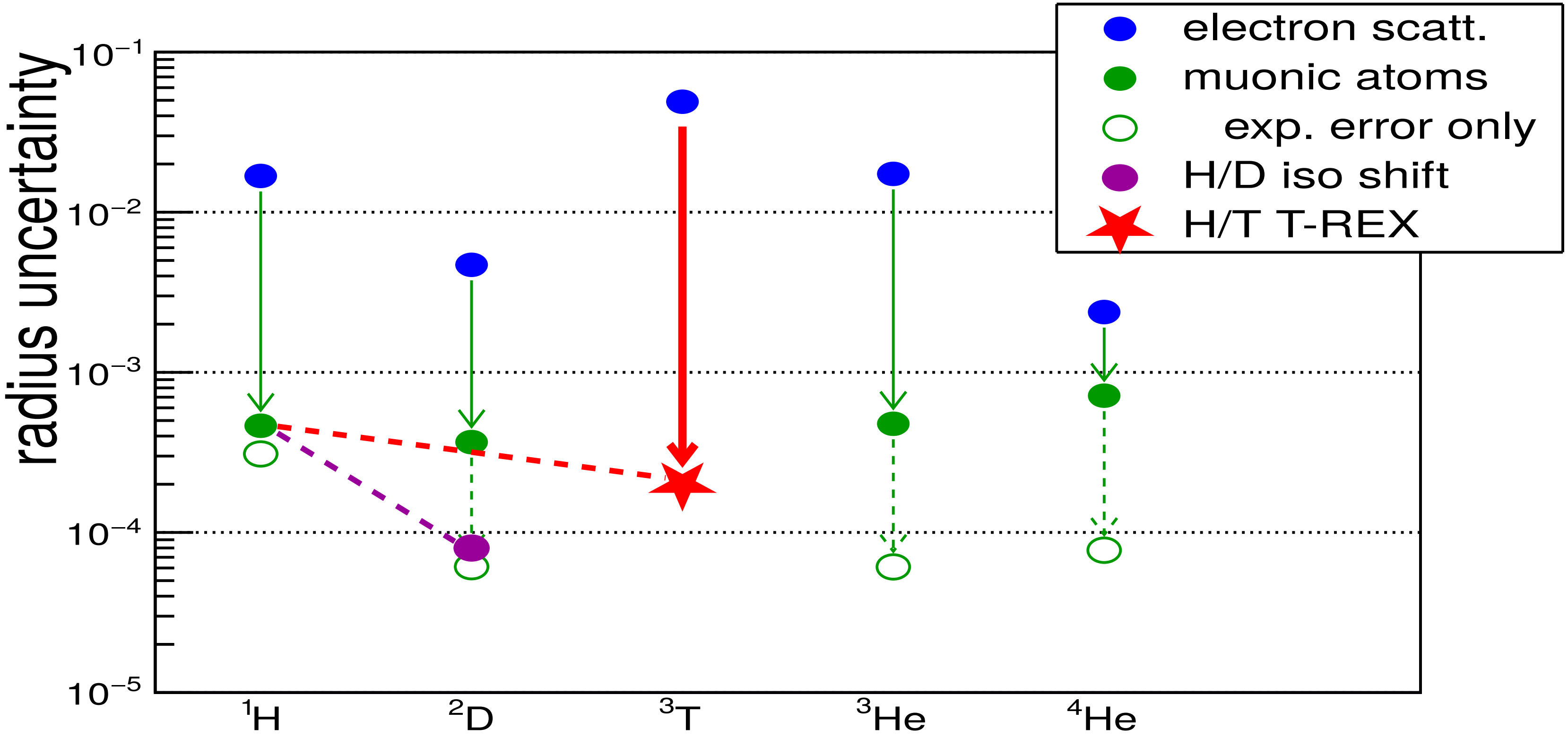
Tritium 1S-2S



Triton-Radius EXperiment
Mainz

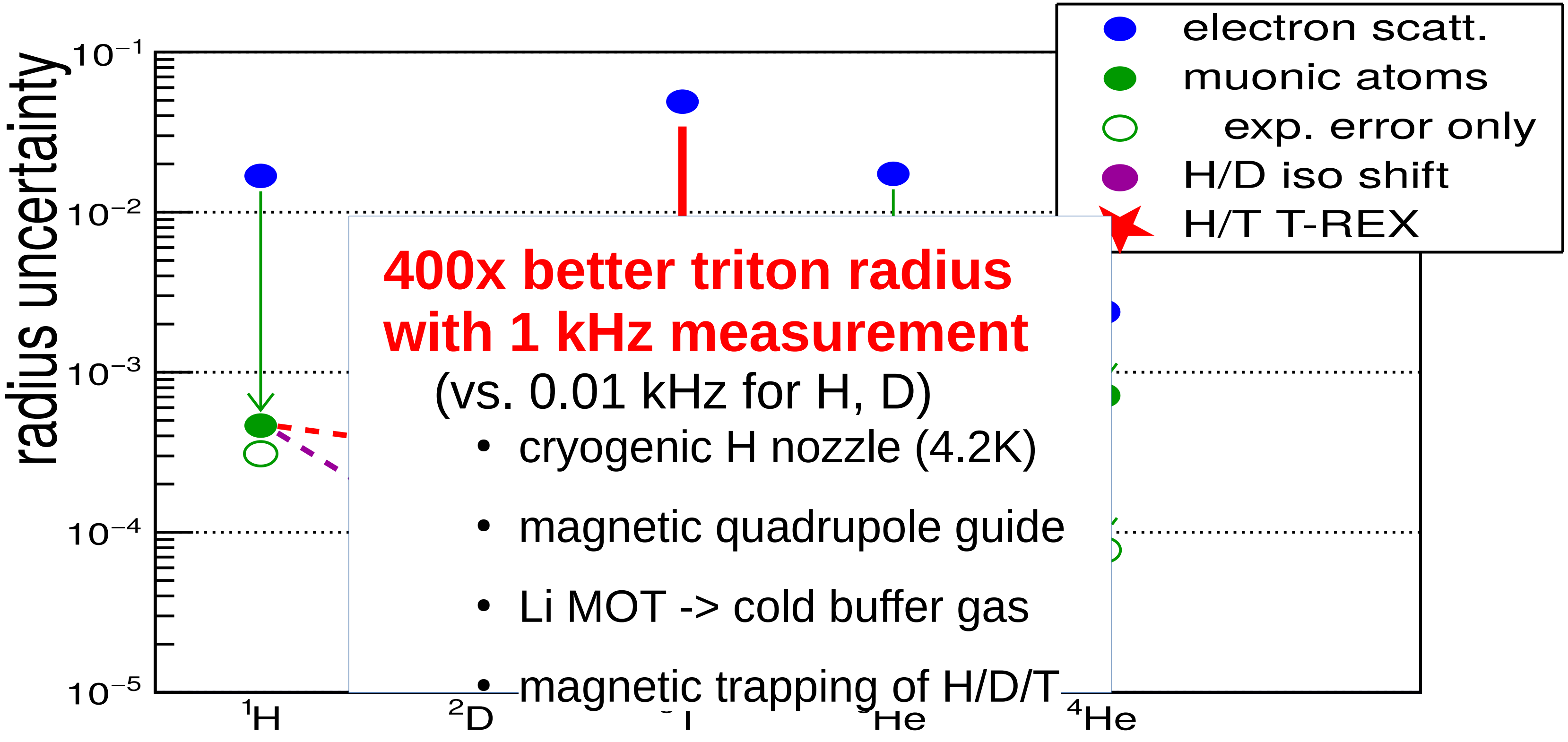
Tritium 1S-2S

Triton-Radius EXperiment



Tritium 1S-2S

Triton-Radius EXperiment
inz



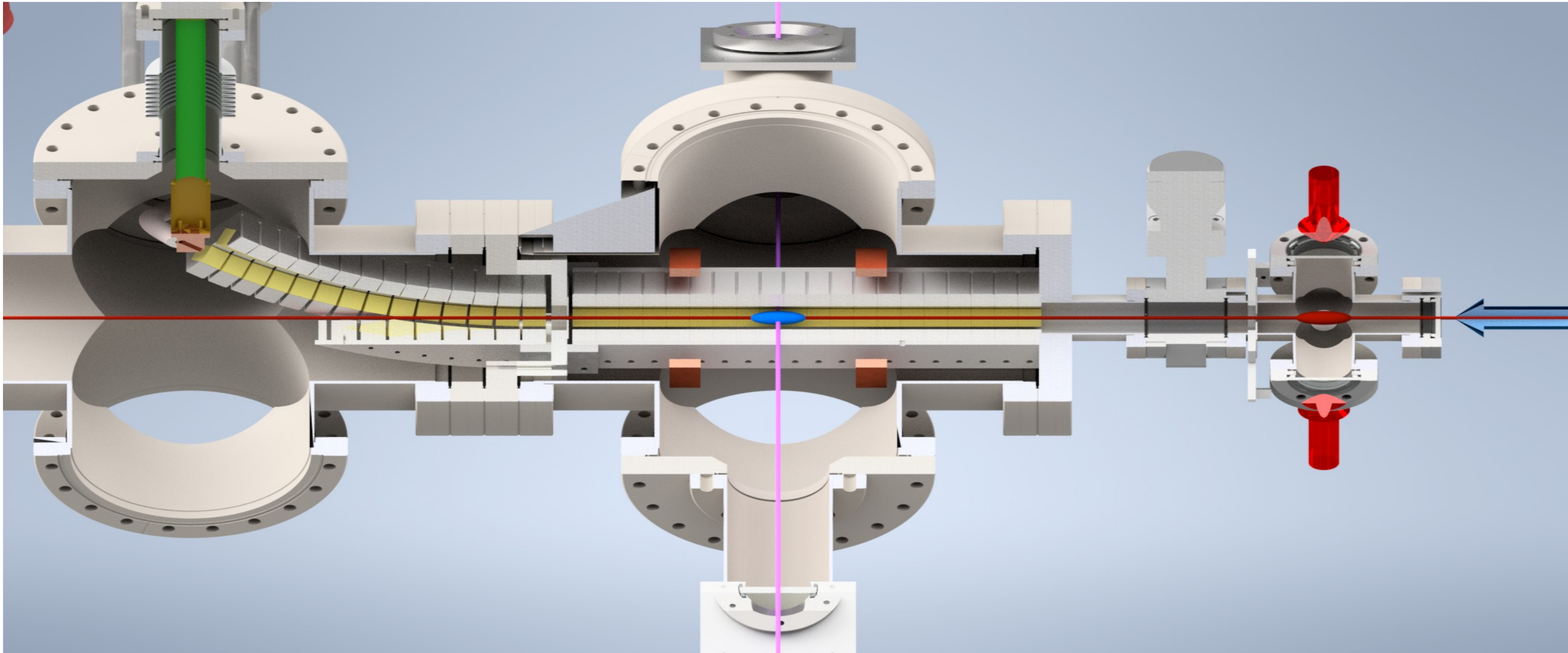
400x better triton radius with 1 kHz measurement

(vs. 0.01 kHz for H, D)

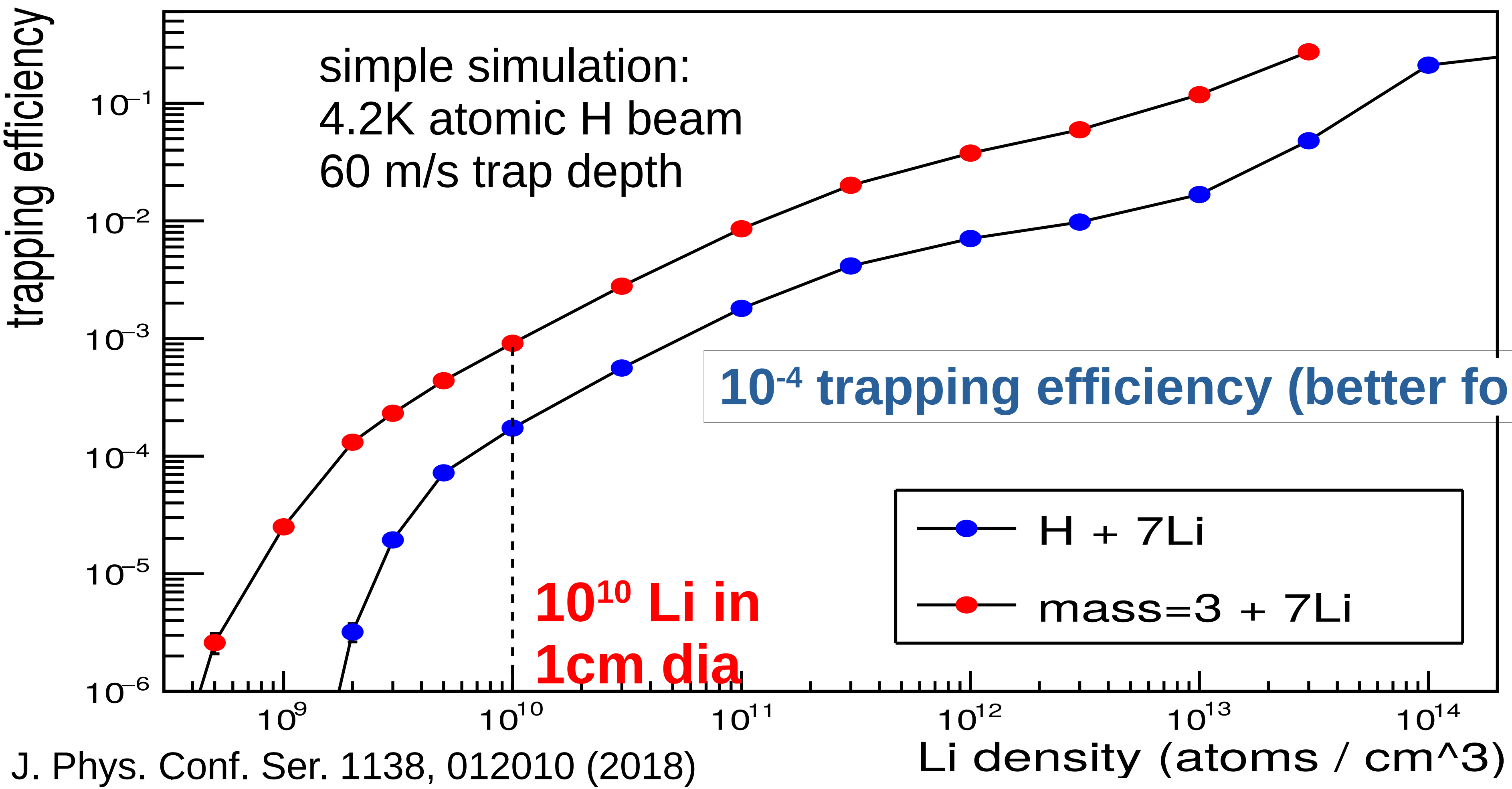
- cryogenic H nozzle (4.2K)
- magnetic quadrupole guide
- Li MOT -> cold buffer gas
- magnetic trapping of H/D/T

Trapping and spectroscopy

Triton-Radius EXperiment
Mainz



Simulated trapping efficiency



simple simulation:
4.2K atomic H beam
60 m/s trap depth

10^{-4} trapping efficiency (better for T)

**10^{10} Li in
1cm dia**

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

Triton charge radius from Tritium 1S-2S

^{3}He
1.9679*(14)
~~1.9730 (160)~~

^{4}He
1.6782 (8)
~~1.6810 (40)~~

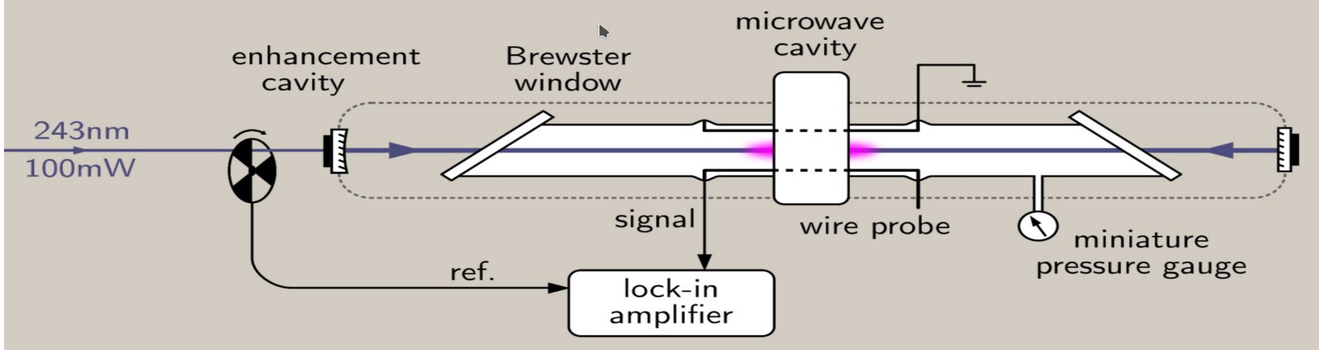
^{1}H
0.8409 (4)
~~0.8751 (61)~~

^{2}D
2.1279 (2)
~~2.1413 (25)~~

^{3}T
1.7xxx (200)
1.7550 (860)

Triton-Radius EXperiment
Mainz

4x better radius
with 100 kHz measurement
(vs. 0.01 kHz for H, D)

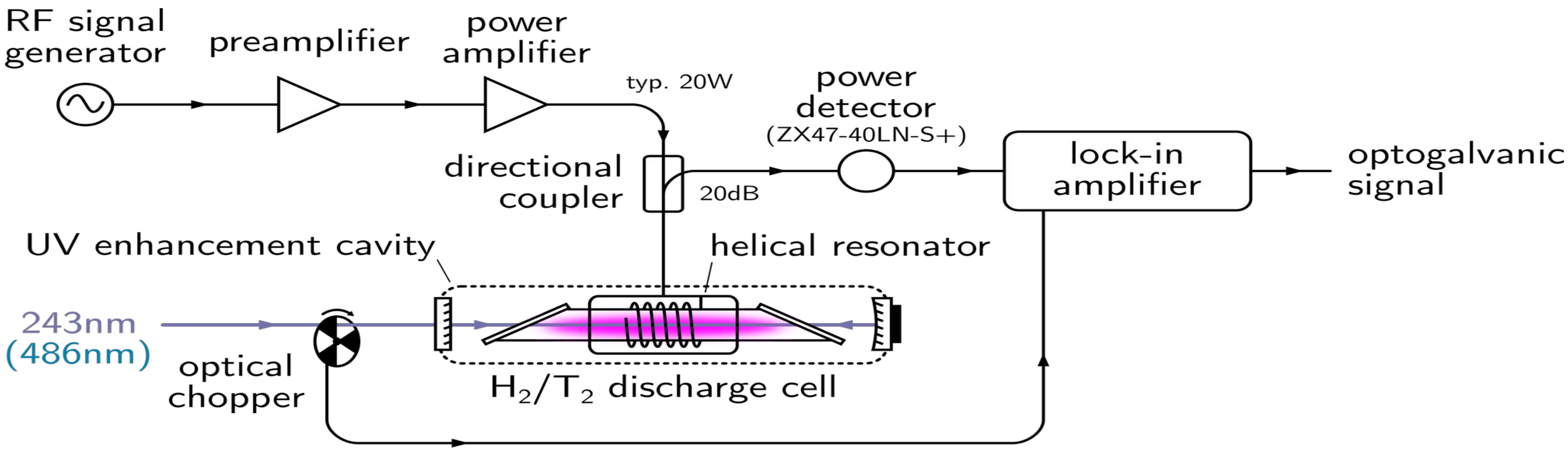


- Optogalvanic spectroscopy in a cell
- Syst. extrapolation w/ H,D
- Tritium confined.

staged approach

Hydrogen/Tritium Laser Spectroscopy in RF Discharge Cell

Spectroscopy Setup



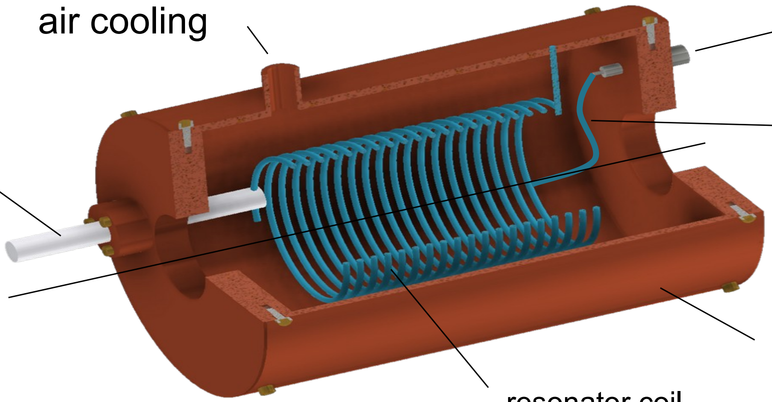
optogalvanic detection → laser-induced impedance change of the plasma

- monitoring reflected (or forward) RF power via directional coupler (shown above)
- pickup-coil around plasma tube

+ avoid optical detection within the fluorescence background of the discharge glow
+ containment of radioactive tritium samples in a compact sealed glass cell
− large systematic effects expected due to electric fields and collision processes

Hydrogen/Tritium Laser Spectroscopy in RF Discharge Cell

Spectroscopy Setup



air cooling

tuning rod (PTFE)
→ tune resonance freq.
(very coarsely ± 1 MHz)

discharge tube axis

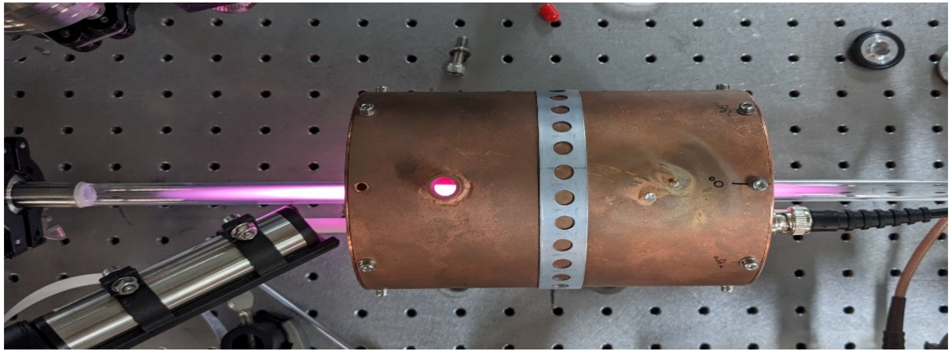
coaxial input connector

tap wire coupling
→ impedance matching

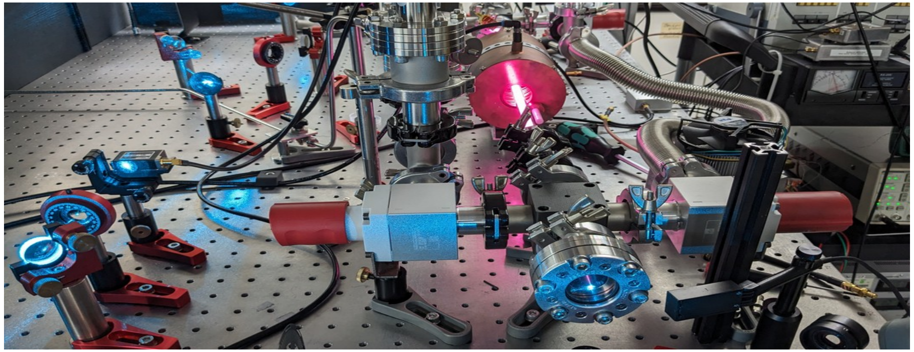
copper shielding

resonator coil

Resonator design inspired by [Tate, *Investigations of simple atomic systems by laser spectroscopy*, Phd thesis, Oxford (1987)]



▲ discharge tube (reduced power)



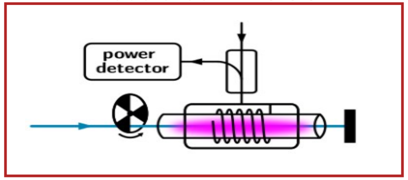
overview▲

Hydrogen/Tritium Laser Spectroscopy in RF Discharge Cell

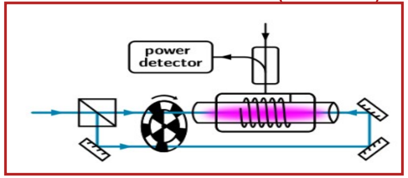
Balmer-β Transition / Overview

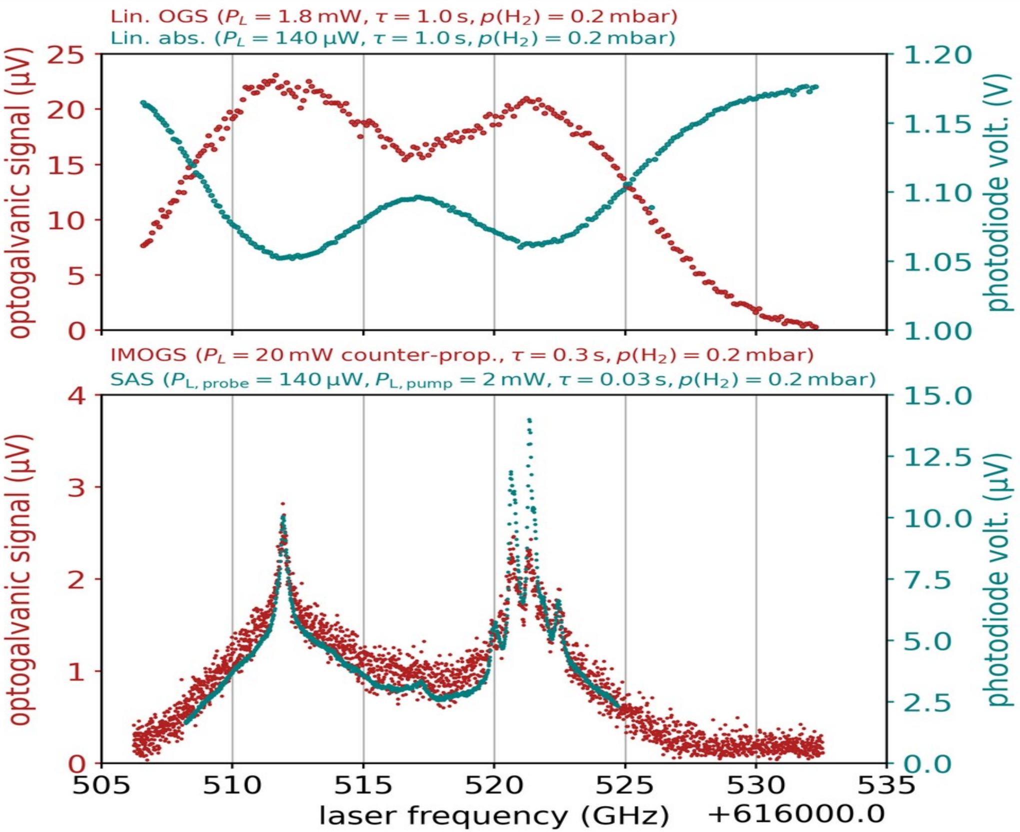
optogalvanic spectroscopy (OGS)

modulated lin. OGS



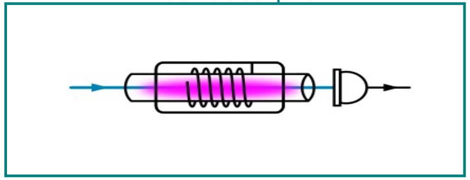
intermodulated OGS (IMOGS)



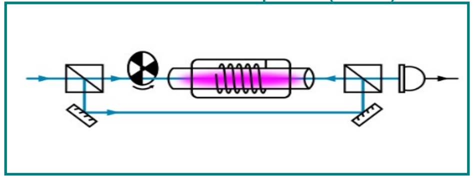


absorption spectroscopy

linear absorption

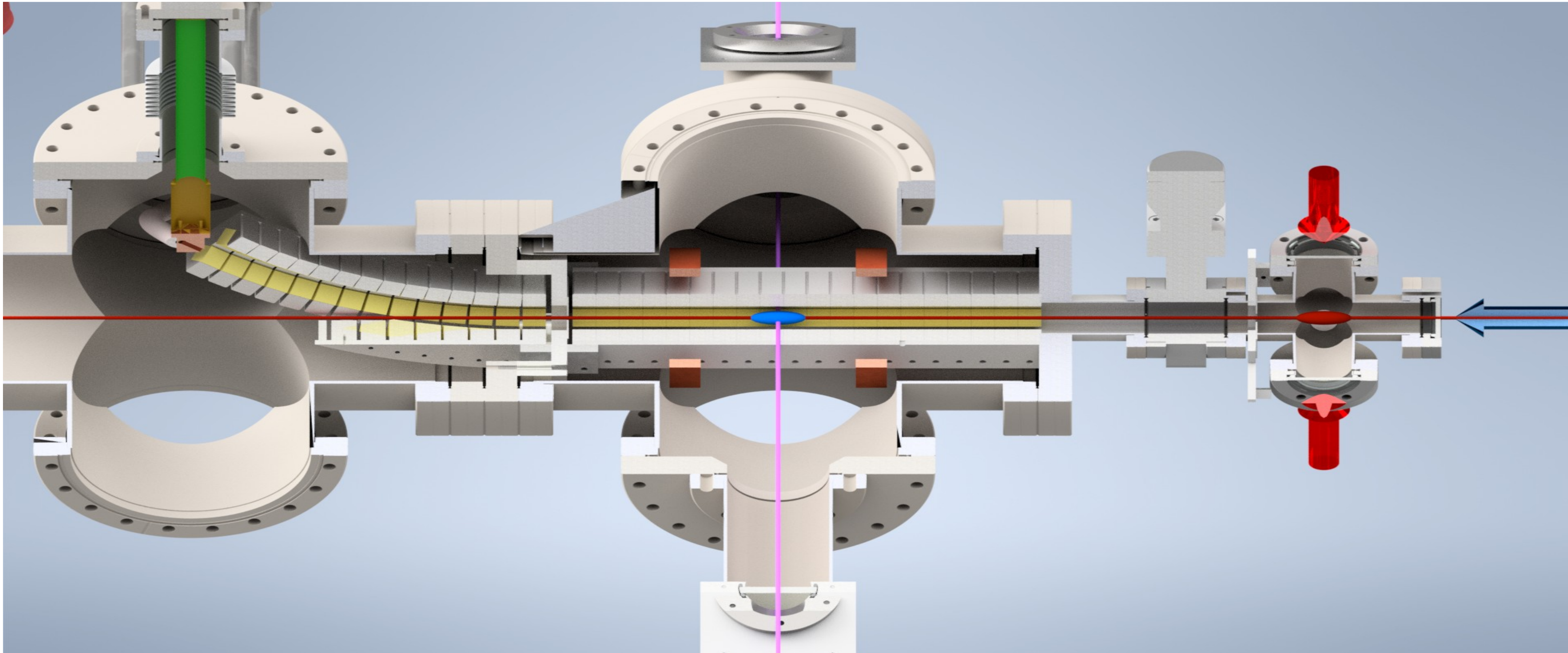


saturated absorption (SAS)



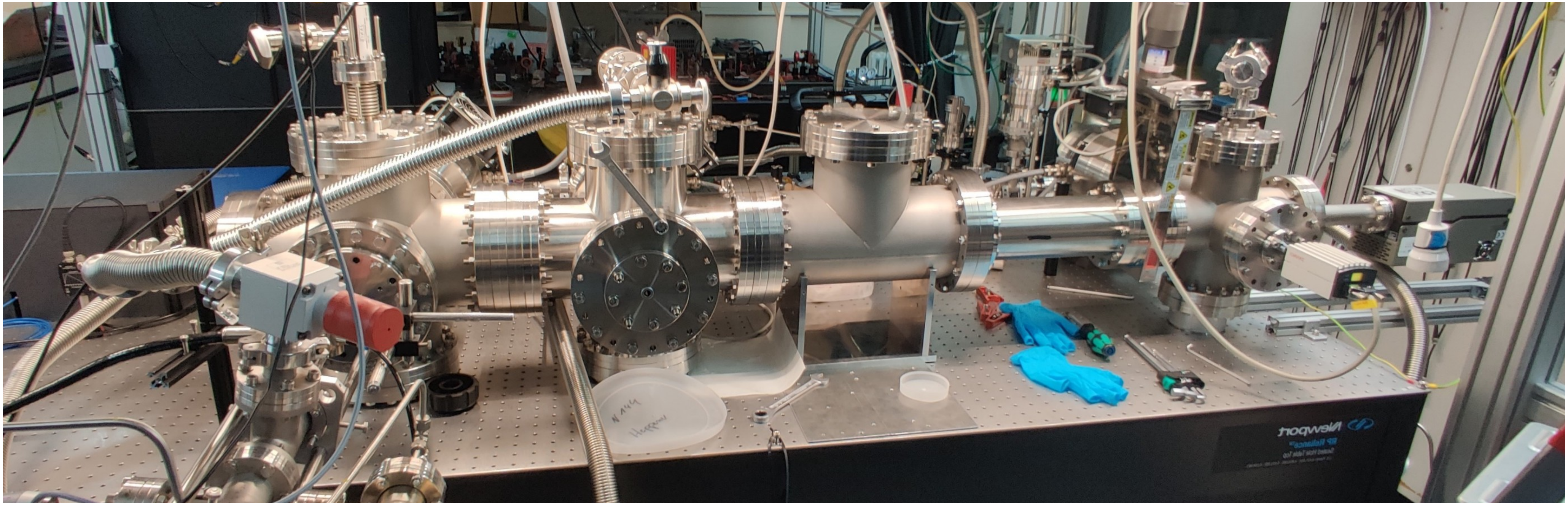
Towards trapping and spectroscopy

Triton-Radius EXperiment
Mainz

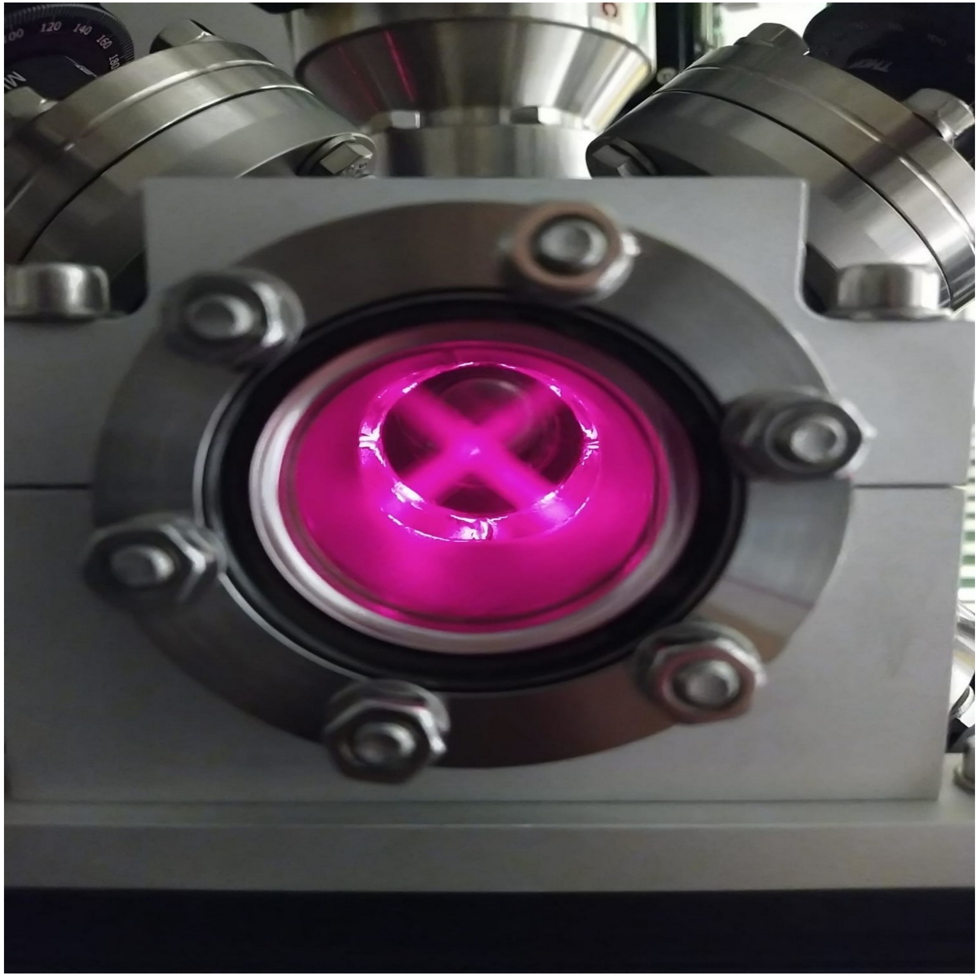


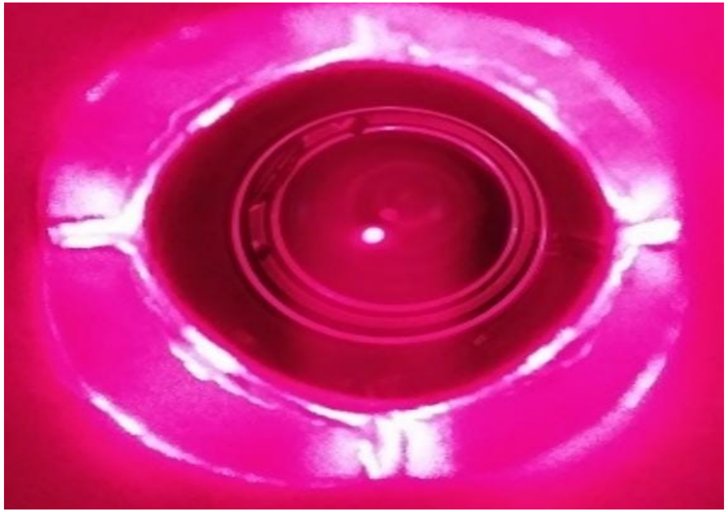
H Trap Setup: Beam Characterization

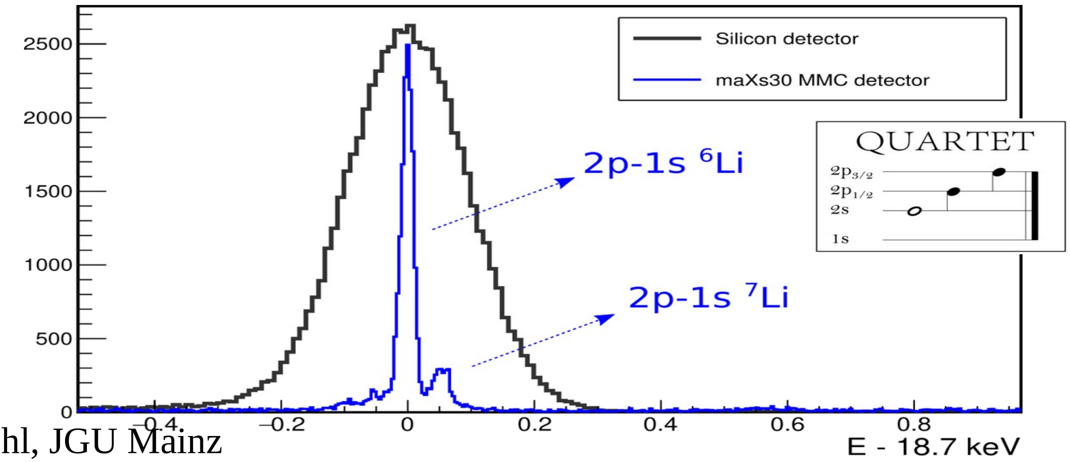
- Hydrogen beam dissociation
- Cryogenic nozzle design and atom beam shape
- Quadrupole cut-off velocity



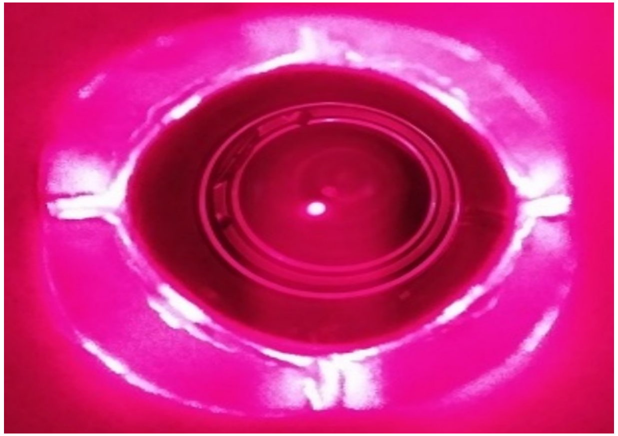
Atomic Lithium

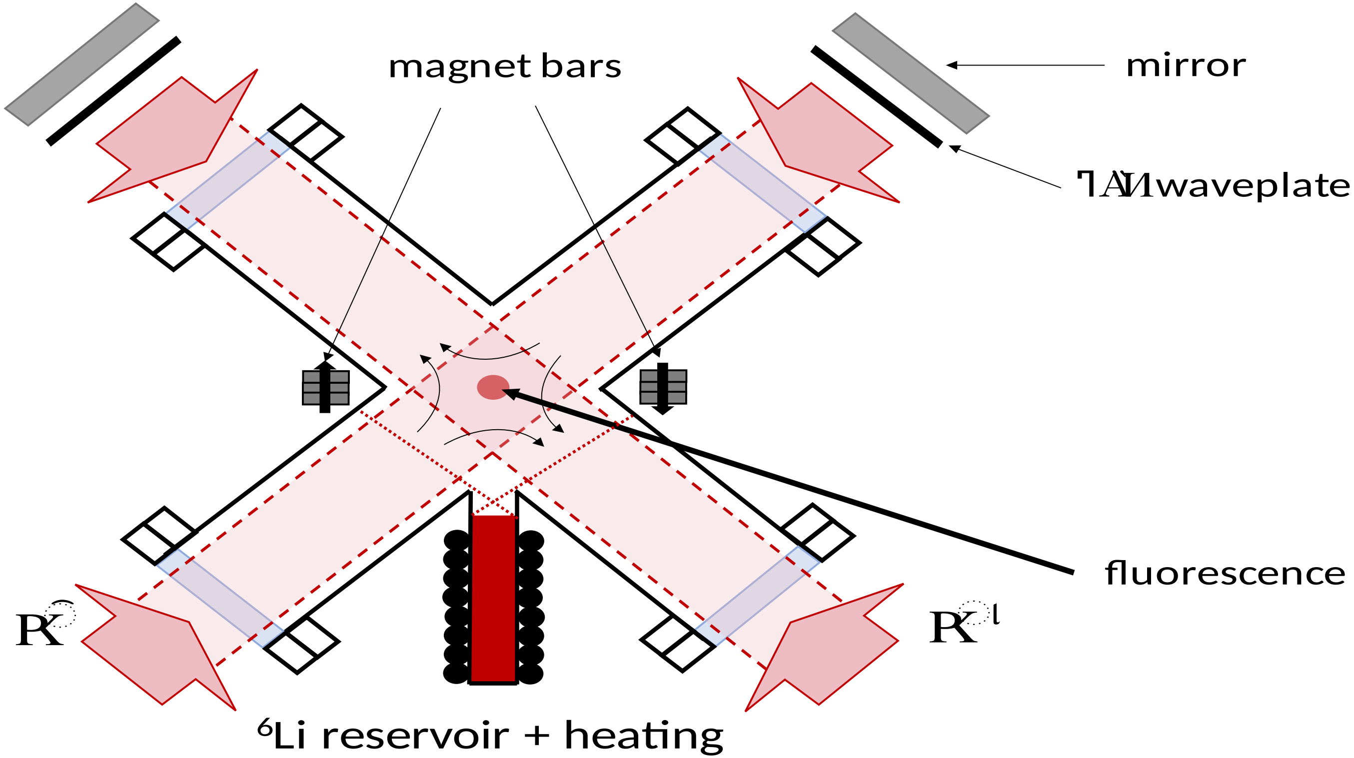






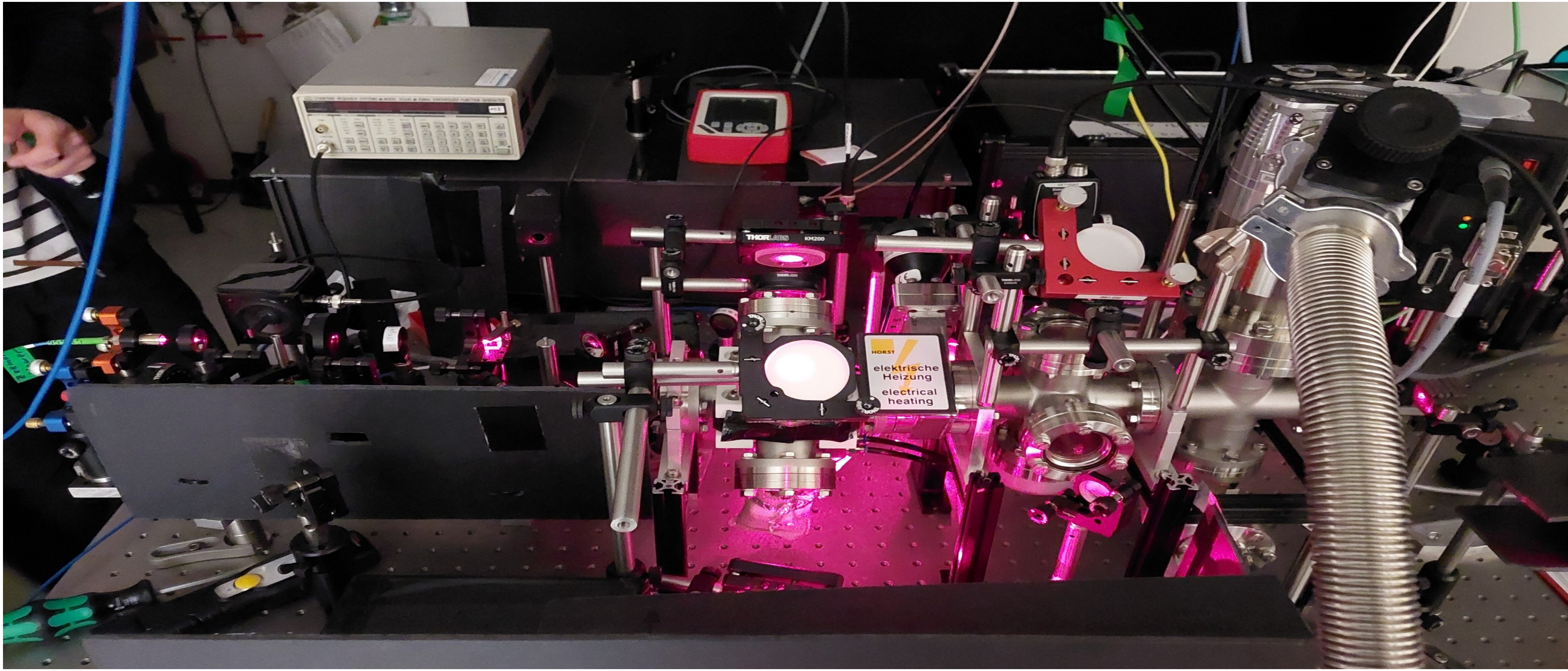
2D MOT as cold Li beam source





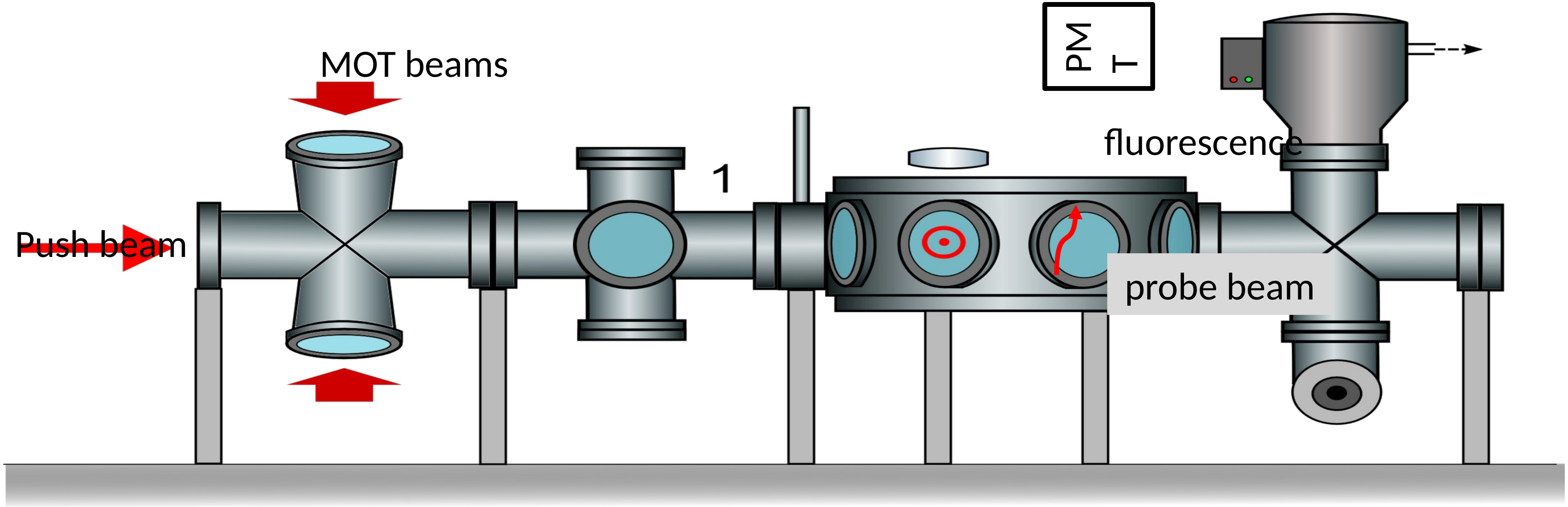
2D-MOT design: Tiecke, Walraven et al, PRA 80, 013409 (2009)

2D MOT for cold Li (old)



2D-MOT design: Tiecke, Walraven et al, PRA 80, 013409 (2009)

Vacuum Setup / Beamline



Our 1st spectroscopy on cold Li

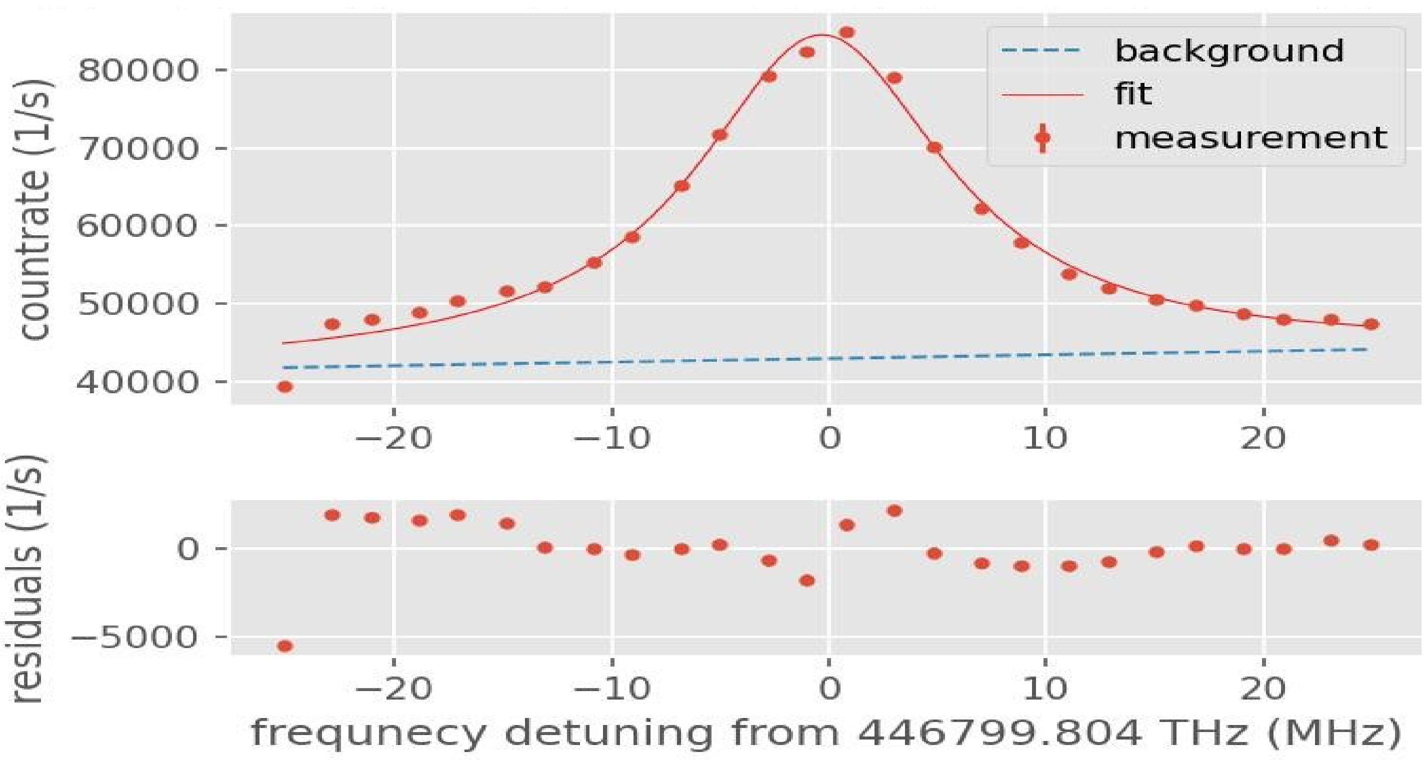
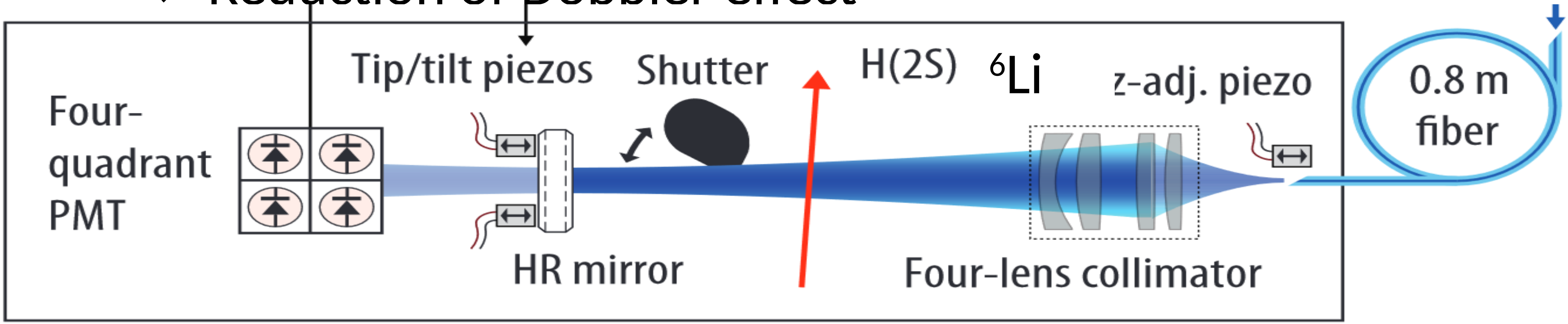


Fig.1: Fluorescence spectrum with a probe beam power μW measured over 1 s.

Next up: AFR

- Use of Active fiber-based Retroreflector:

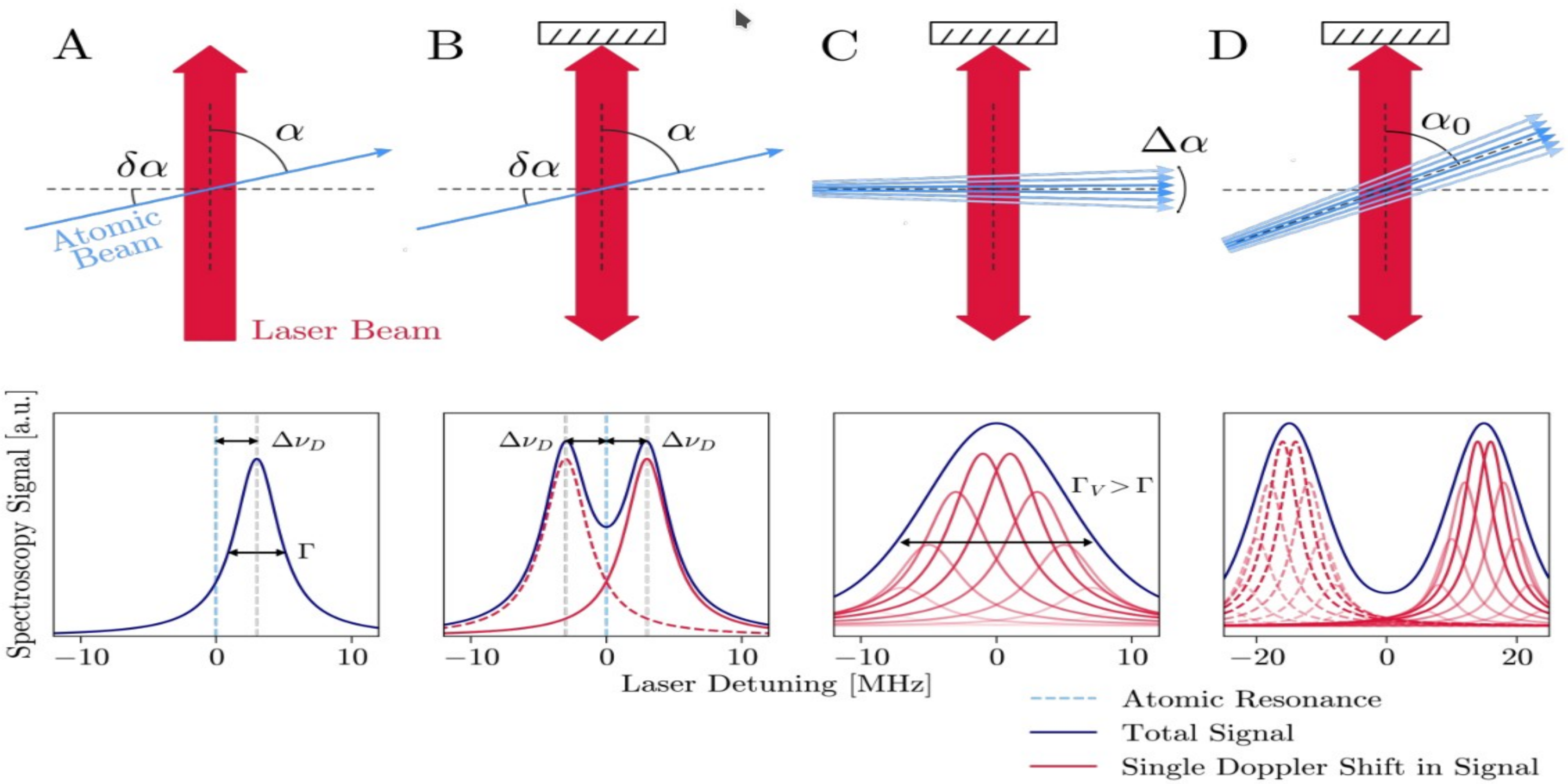
→ Reduction of Doppler effect



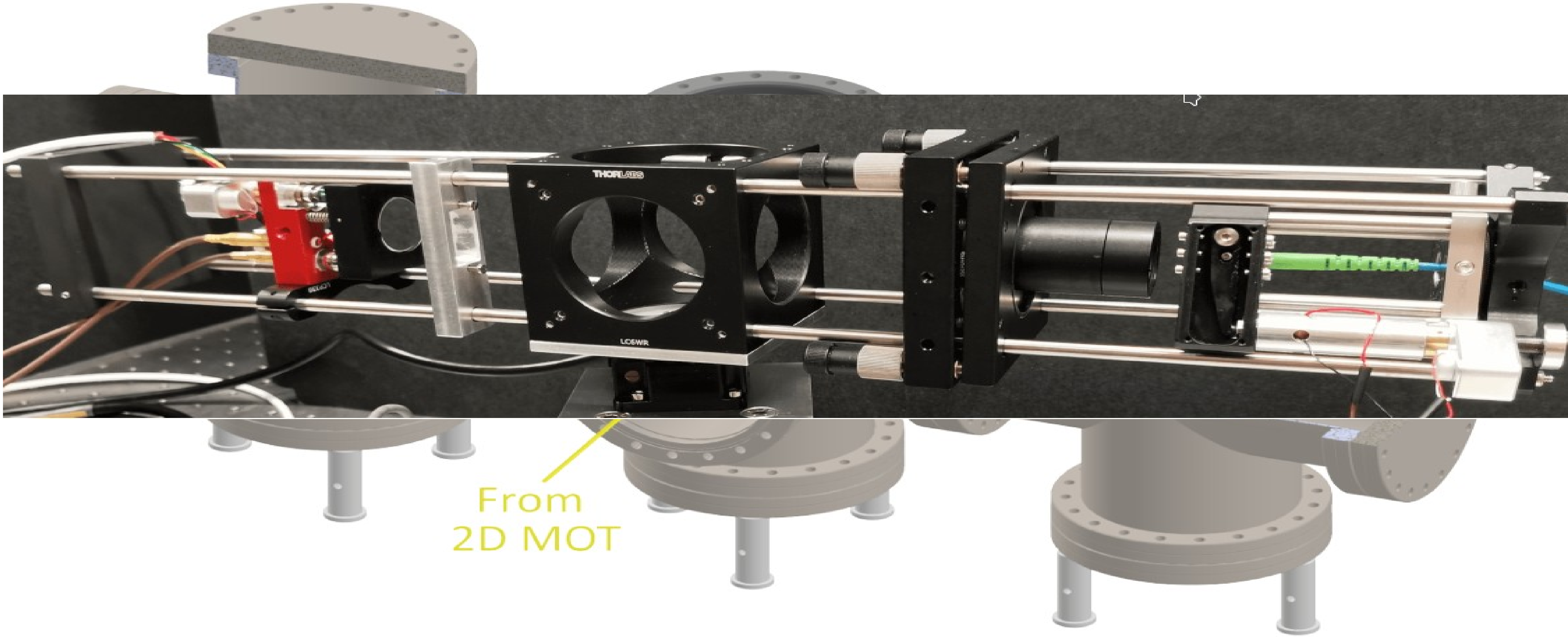
[A. Beyer, “Active fiber-based retroreflector providing phase-retracing anti-parallel laser beams for precision spectroscopy”, 2016]

[V. Wirthl, “Improved active fiber-based retroreflector with intensity stabilization and a polarization monitor for the near UV”, 2022]

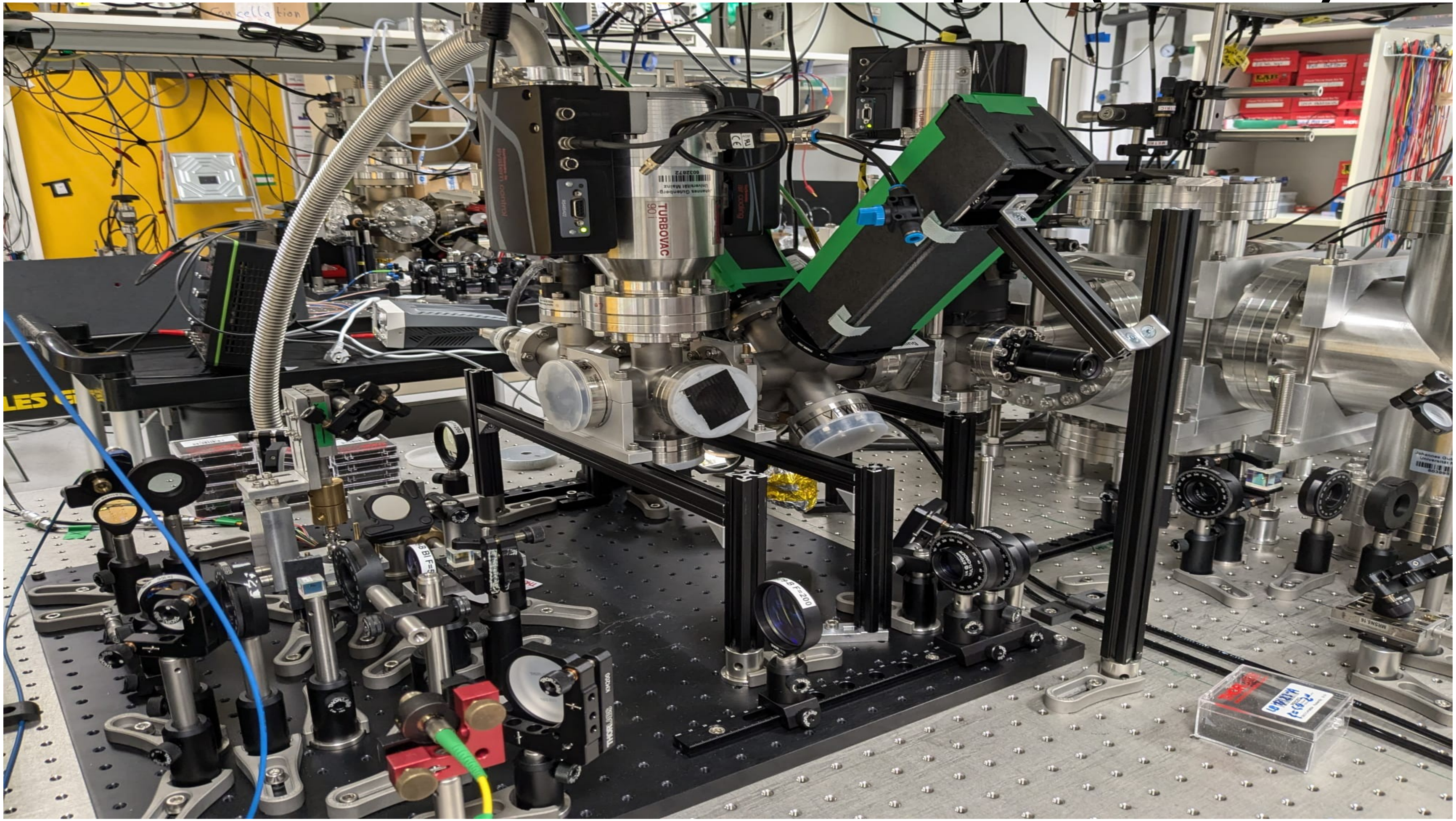
AFR: Actively stabilized Fiber-based Retro-Reflector



AFR: Actively stabilized Fiber-based Retro-Reflector

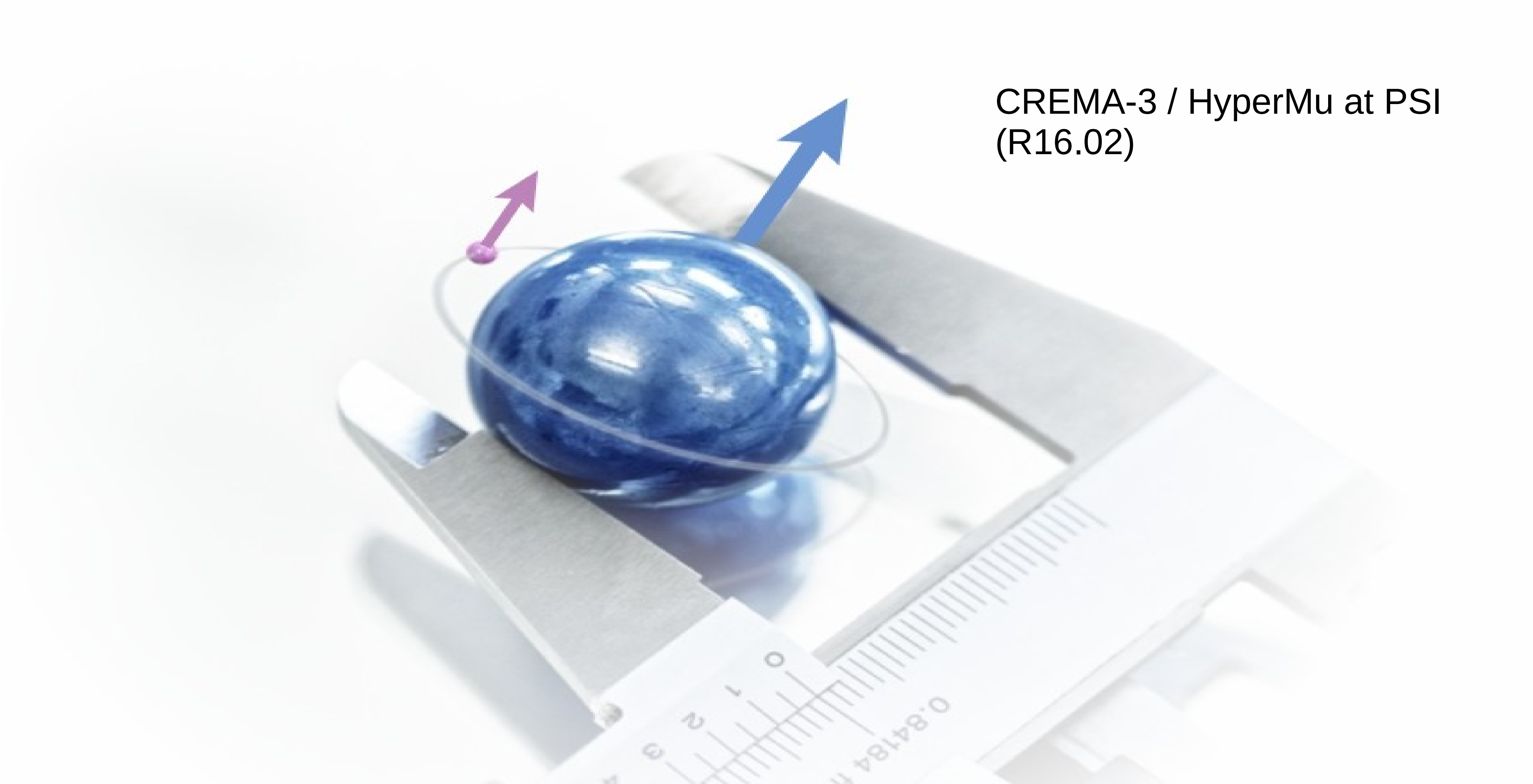


2D MOT + spectroscopy (AFR)



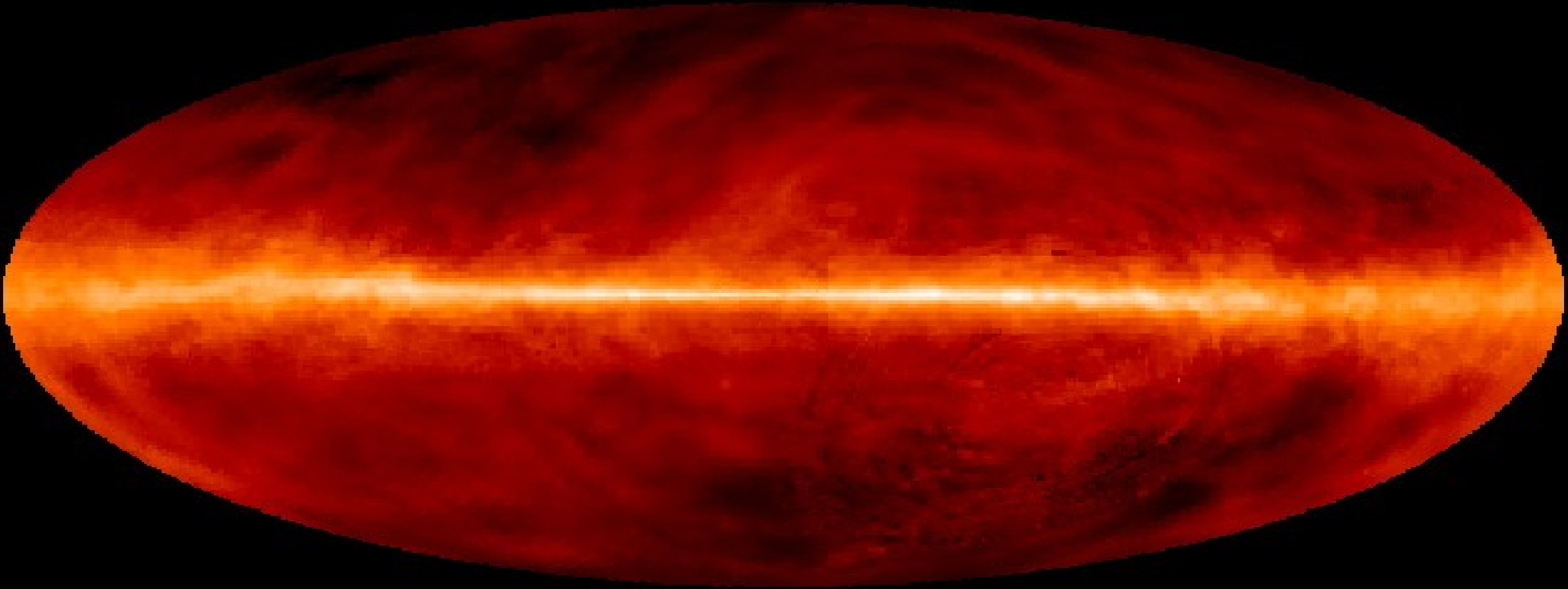
2D-MOT design: Tiecke, Walraven et al, PRA 80, 013409 (2009)

Hyperfine structure in muonic H

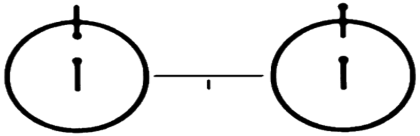


CREMA-3 / HyperMu at PSI
(R16.02)

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:

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

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

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

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

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

Proton Zemach radius

HFS depends on “Zemach” radius:

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

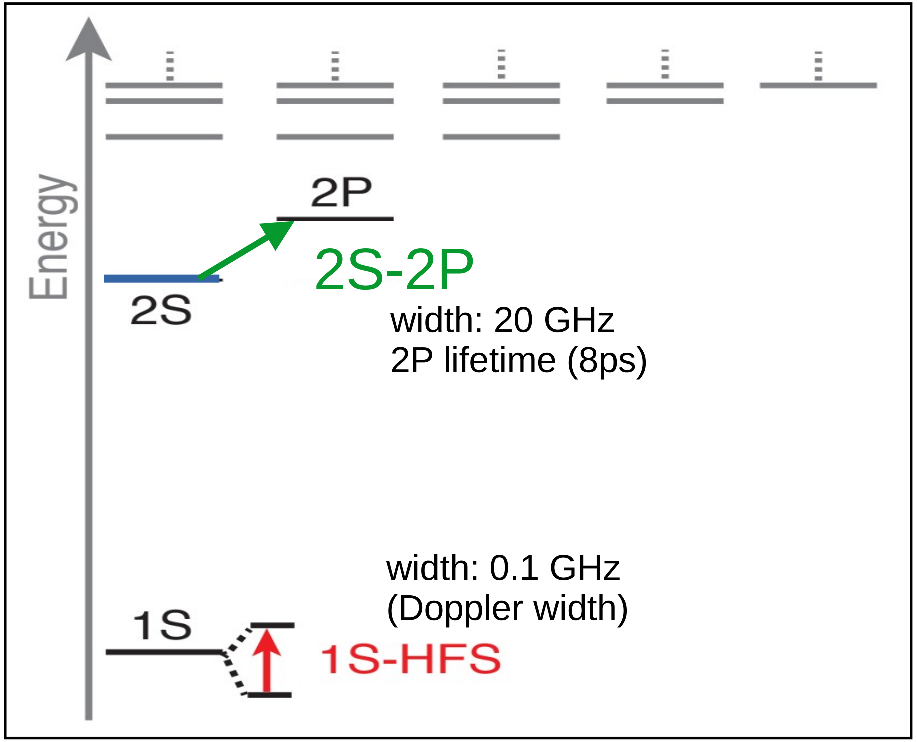
$$\langle r \rangle_{(2)} = \int d^3r\, d^3r'\, \rho_E(r)\, \rho_M(r')\, |r - r'|$$

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

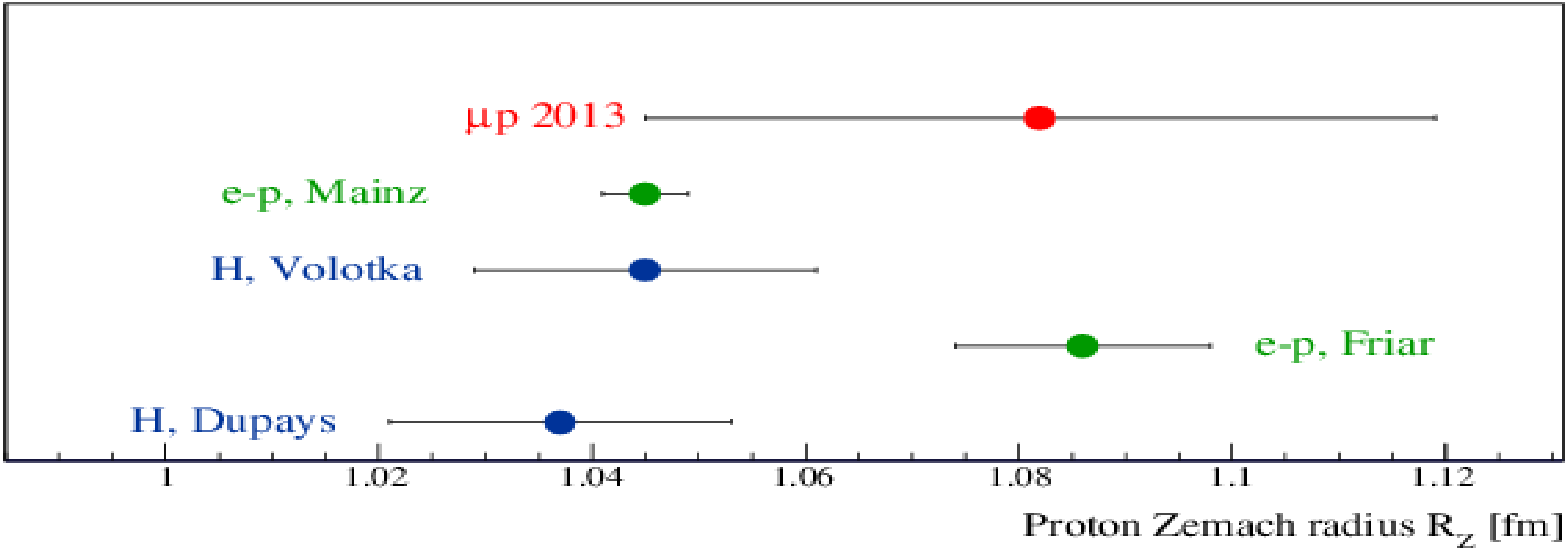
is sensitive to CHARGE radius

1S-HFS = Hyperfine splitting

is sensitive to ZEMACH radius

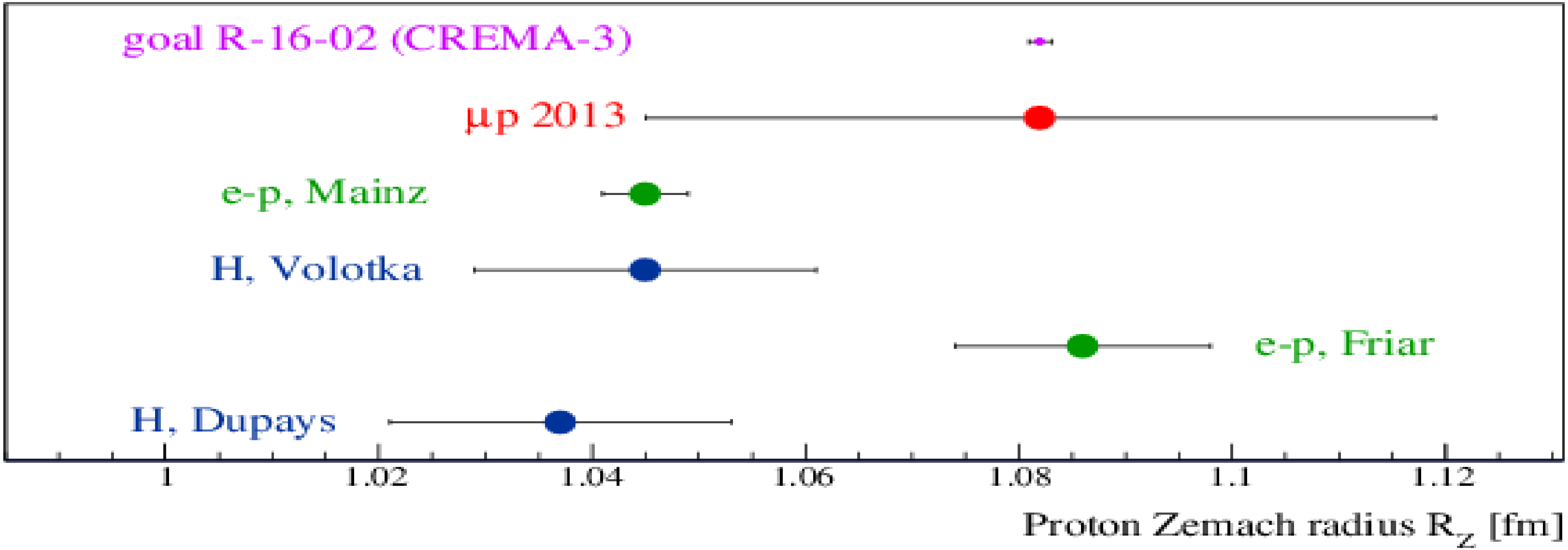
Amaro et al [CREMA], 2112.00138

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

Summary

* Proton Radius Puzzle “solved” (but not understood)

* Muonic helium isotope shift has a new problem

* Hyperfine structure has a problem

* New experiments for charge radii of Z=3….10

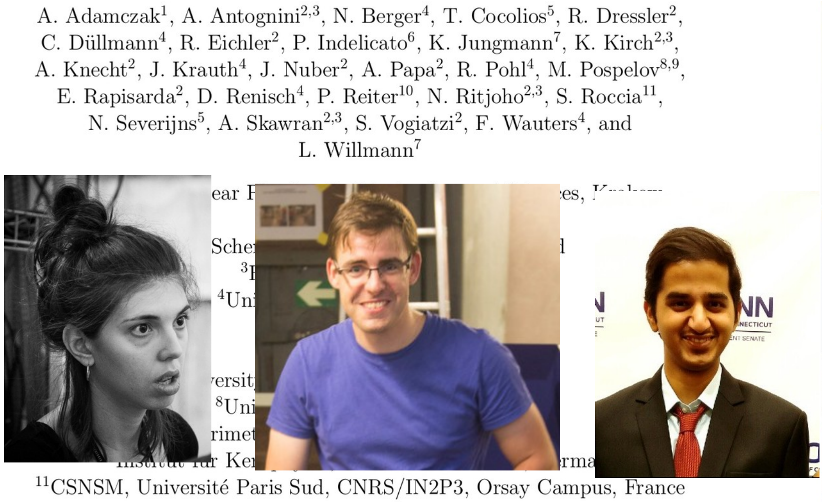
* Triton charge radius

* Li-6 / Li-7 isotope shift revisited

* Zemach (magnetic) radius of the proton from muonic hydrogen HFS

Thanks a lot!

Slides from:
Stella Vogiatzi
Michael Heines
Frederik Wauters
Nancy Paul



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]

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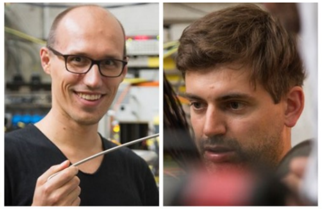

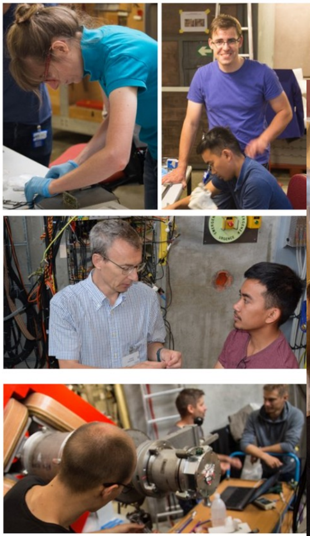

Thanks a lot
for your attention