NOVA UNIVERSIDADE NOVA DE LISBOA

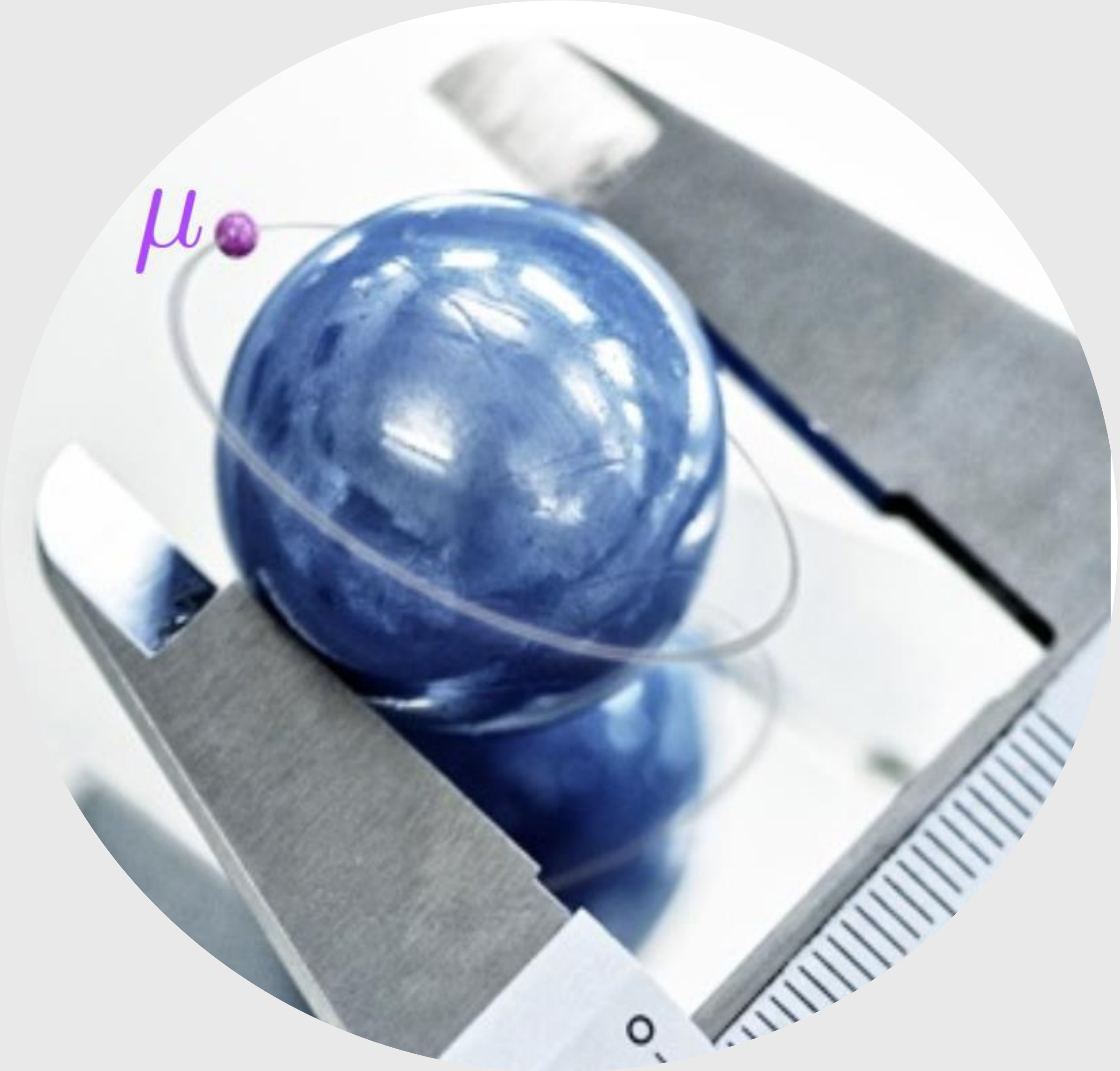
NOVA SCHOOL OF SCIENCE & TECHNOLOGY

LIBPhys-UNL

Laser excitation of the ground-hyperfine transition in muonic hydrogen

Outline

CREMA	Charge Radius Experiments with Muonic Atoms
Past	μH Lamb shift
Present	μHe Lamb shift
Future	μH hyperfine structure



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CREMA COLLABORATION

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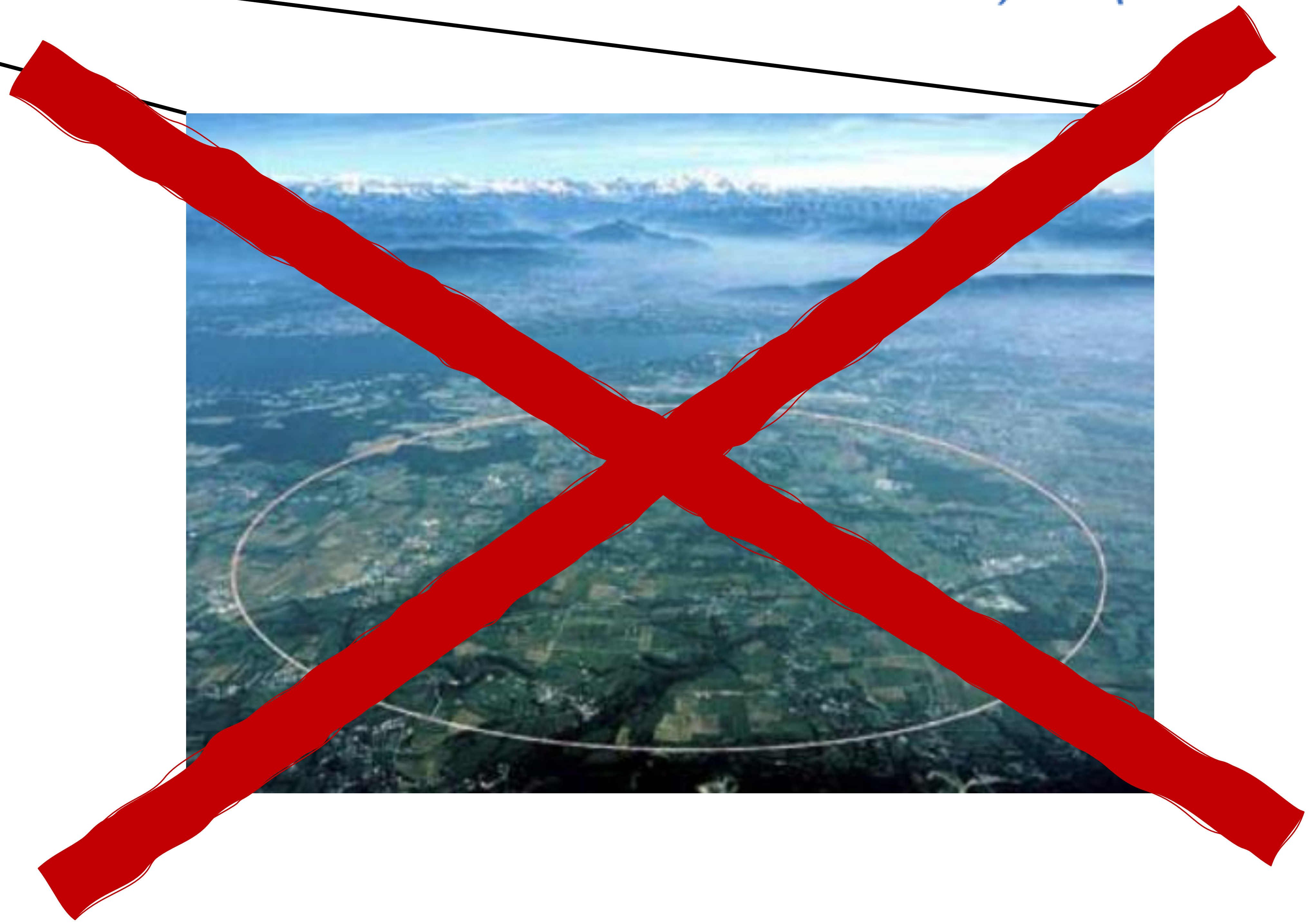

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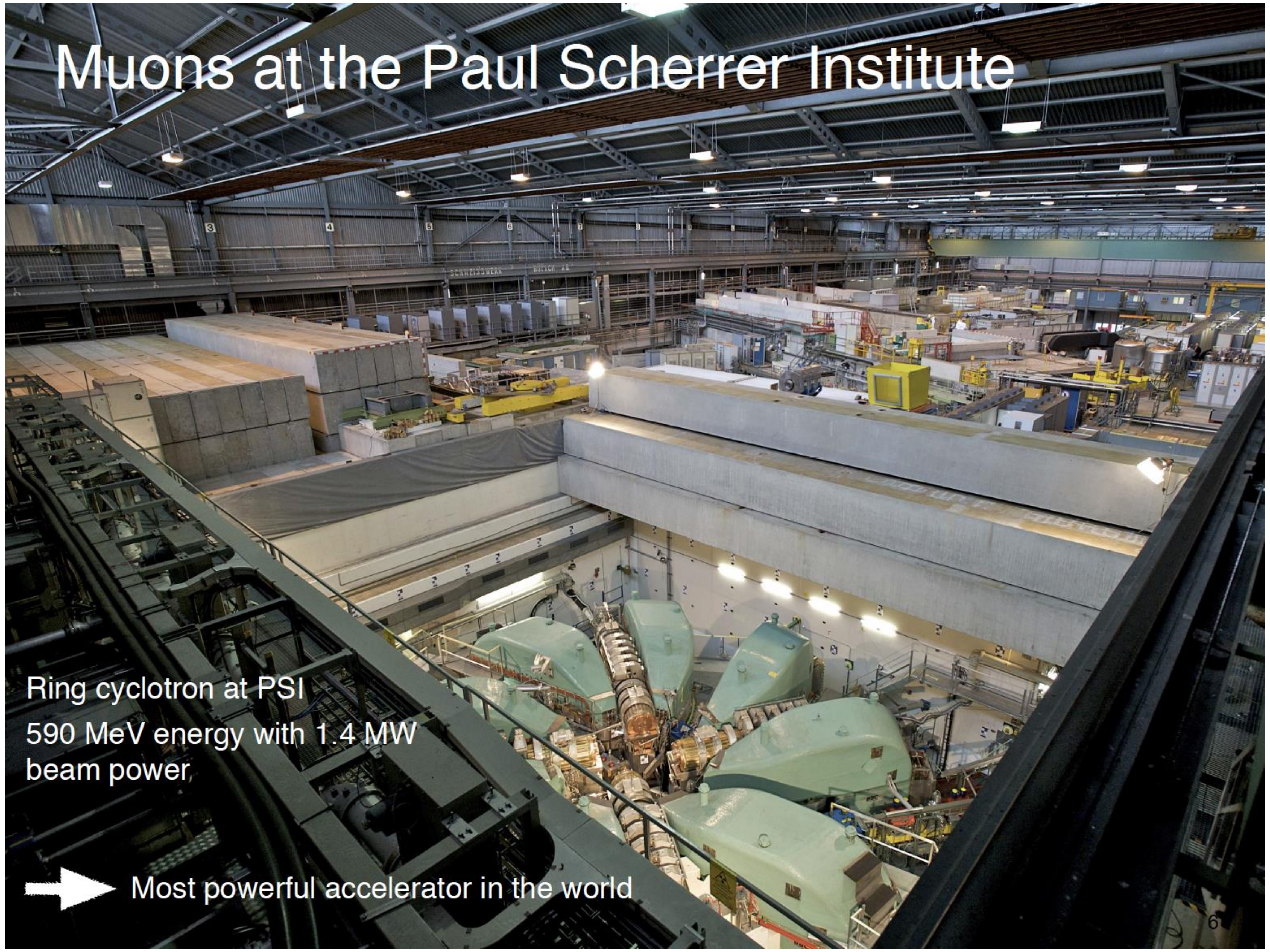
World's highest intensities of:

Mesons: π^+, π^-, π^0

Leptons: μ^+, μ^-



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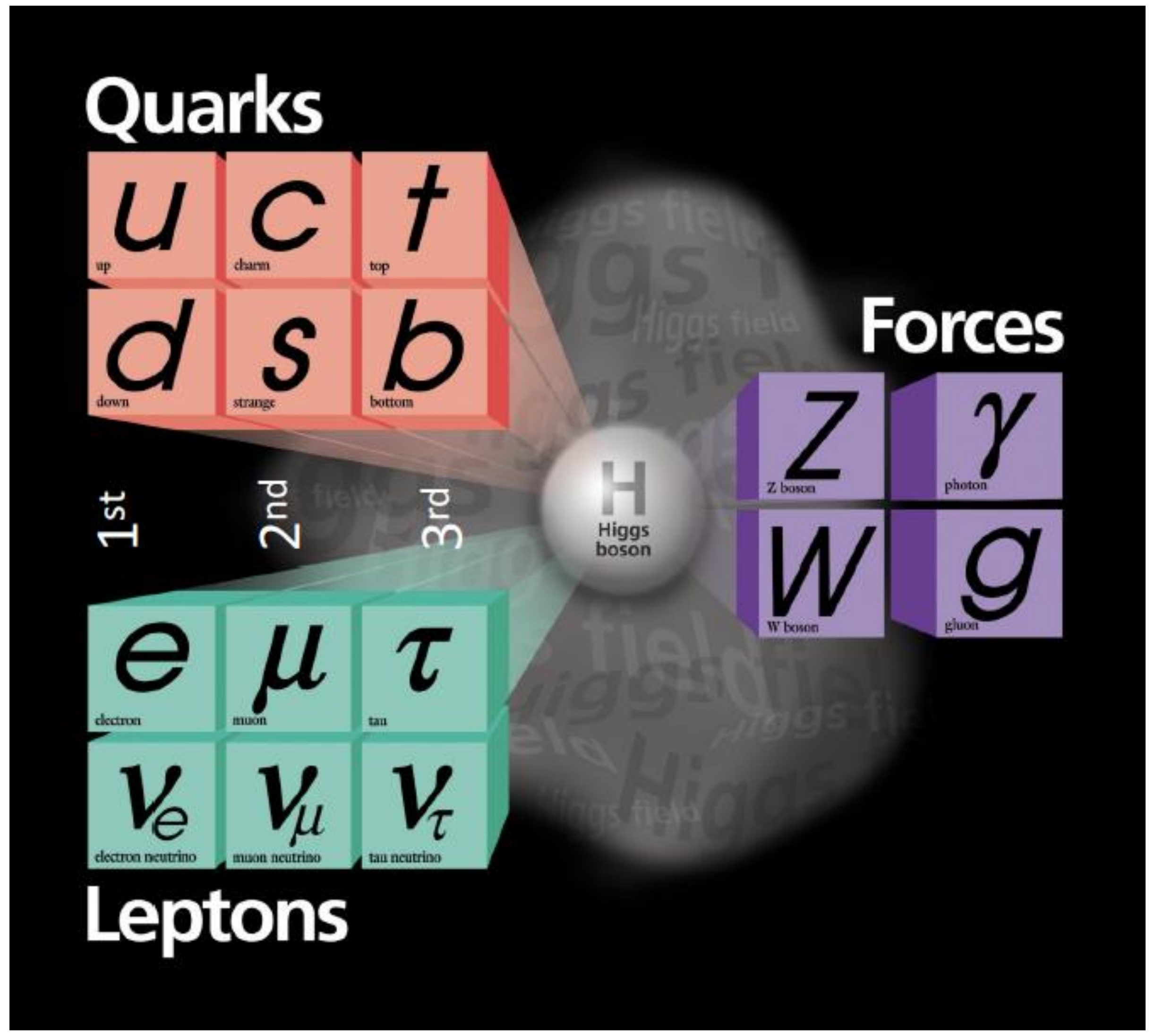
MUONIC ATOMS



- **Muon**
  - heavy "cousin" of the electron:

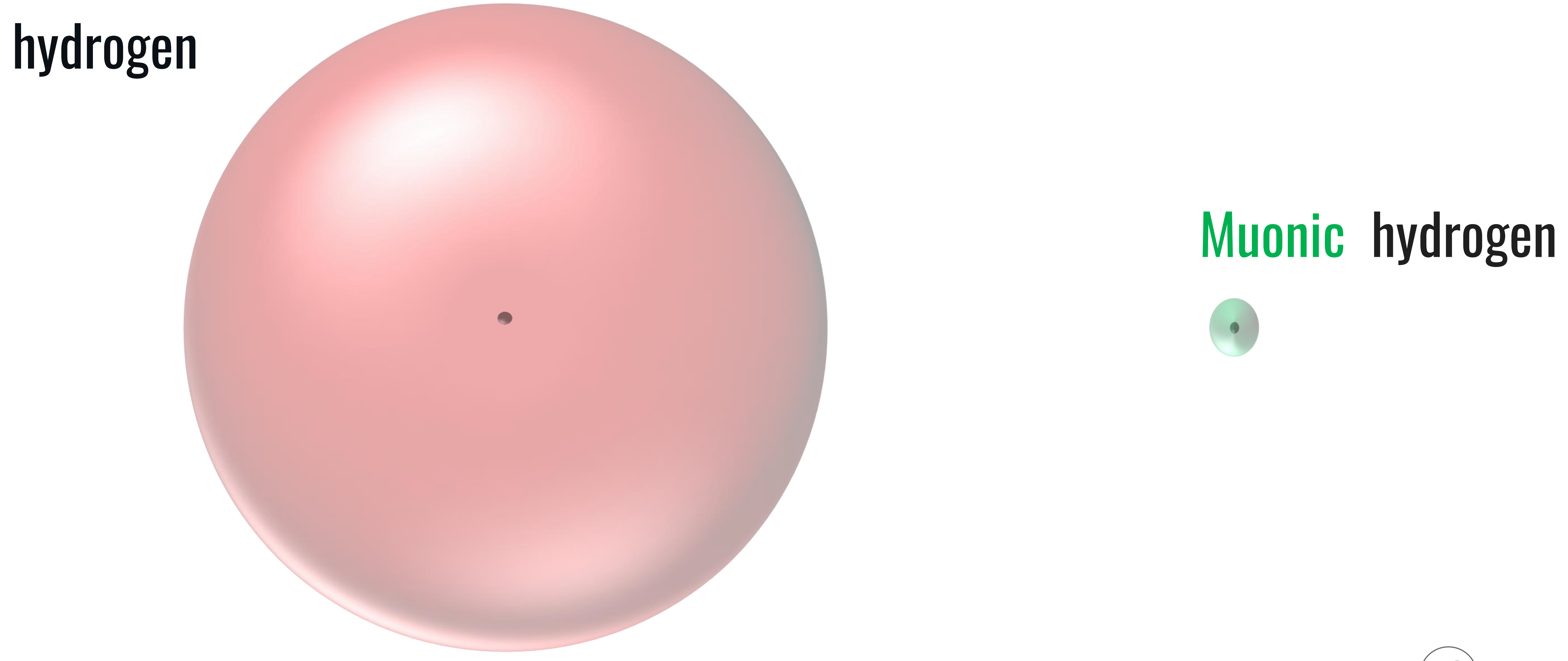
$$m_\mu \approx 200 m_e$$

  - short lifetime

$$\tau_\mu = 2.2\ \mu s$$

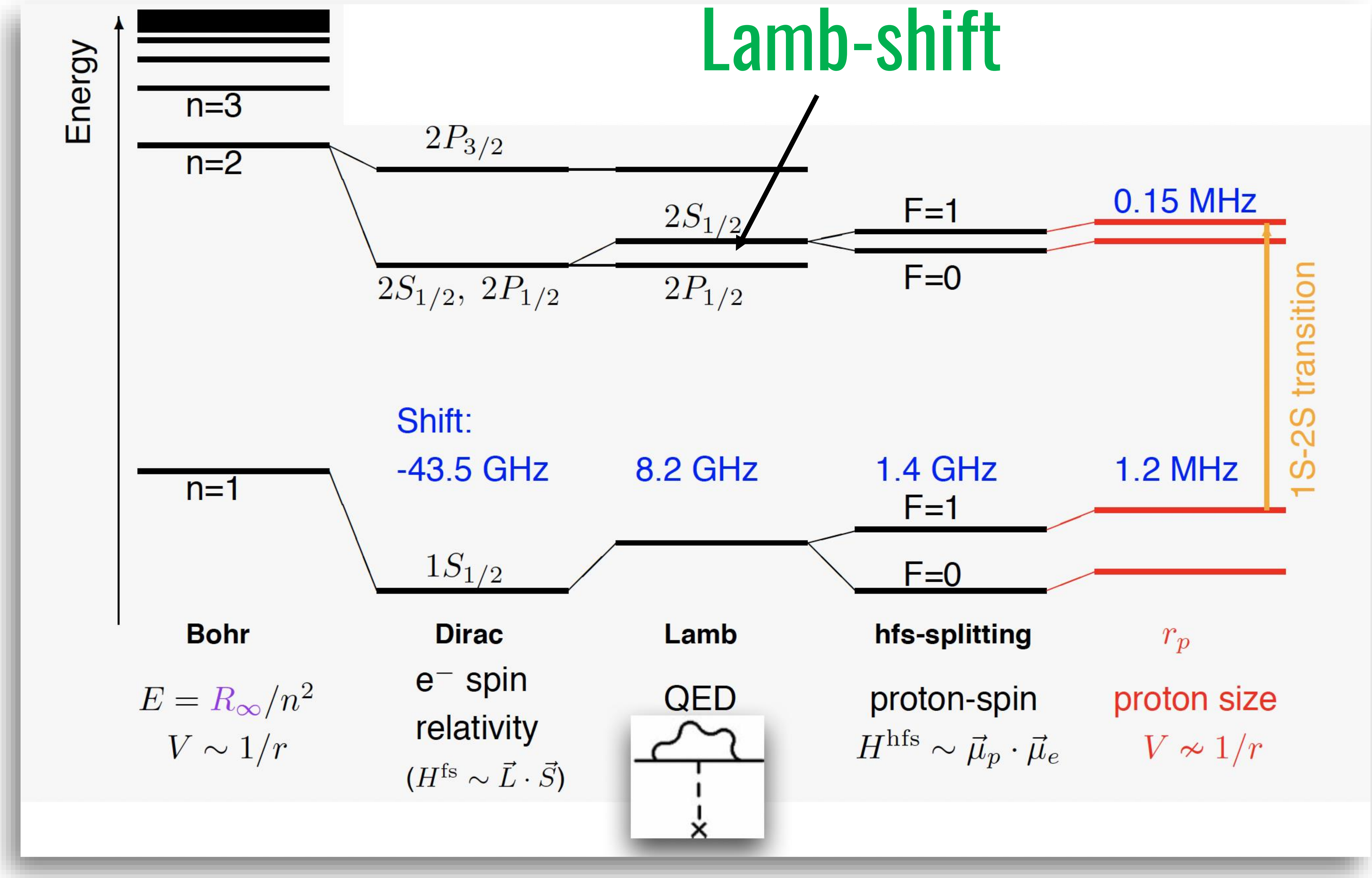
$$r_\mu \approx \frac{r_e}{200}$$

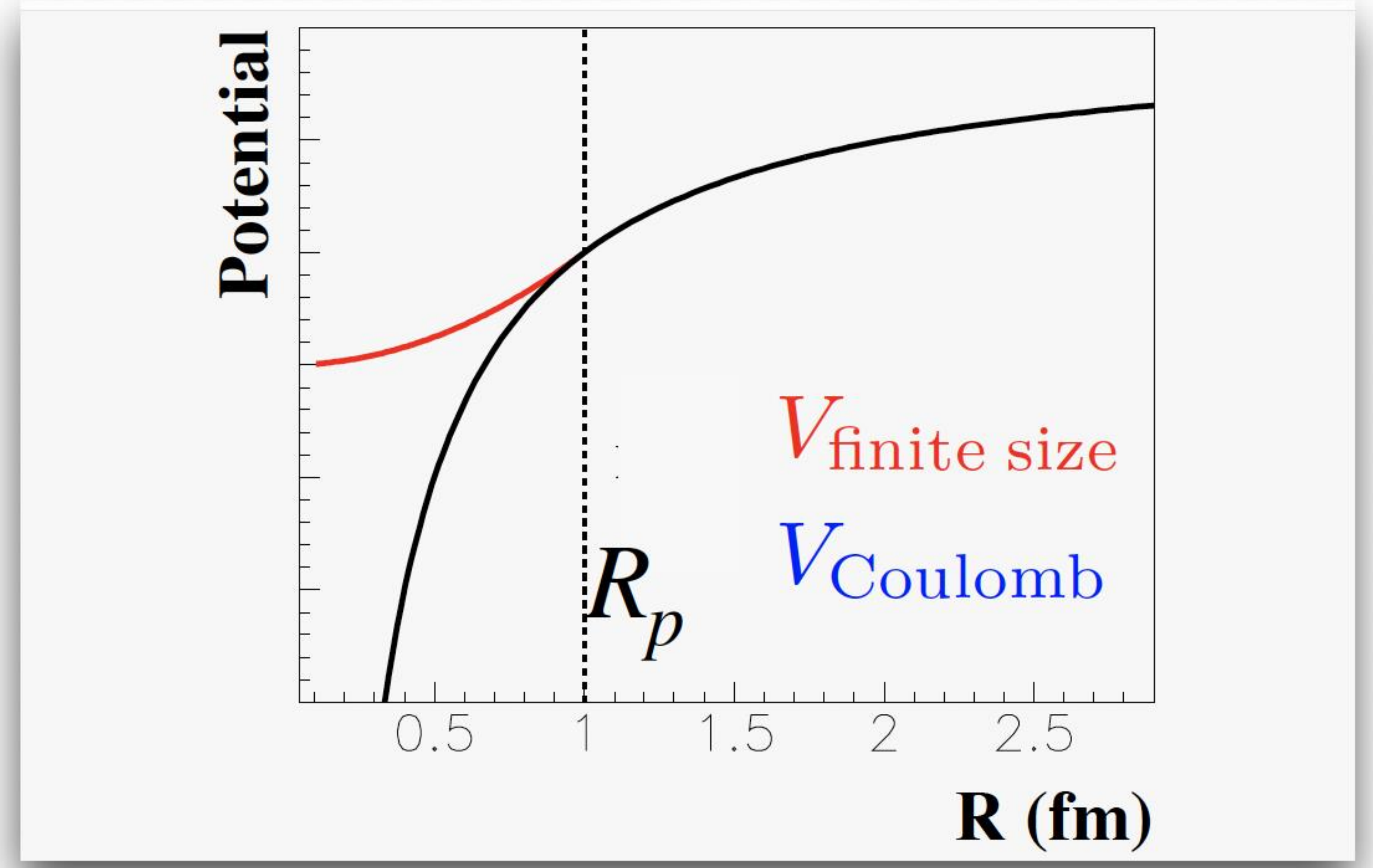
$$V_\mu(inside\ the\ proton) \approx 200^3 V_e$$



MUONIC ATOMS

Hydrogen energy levels

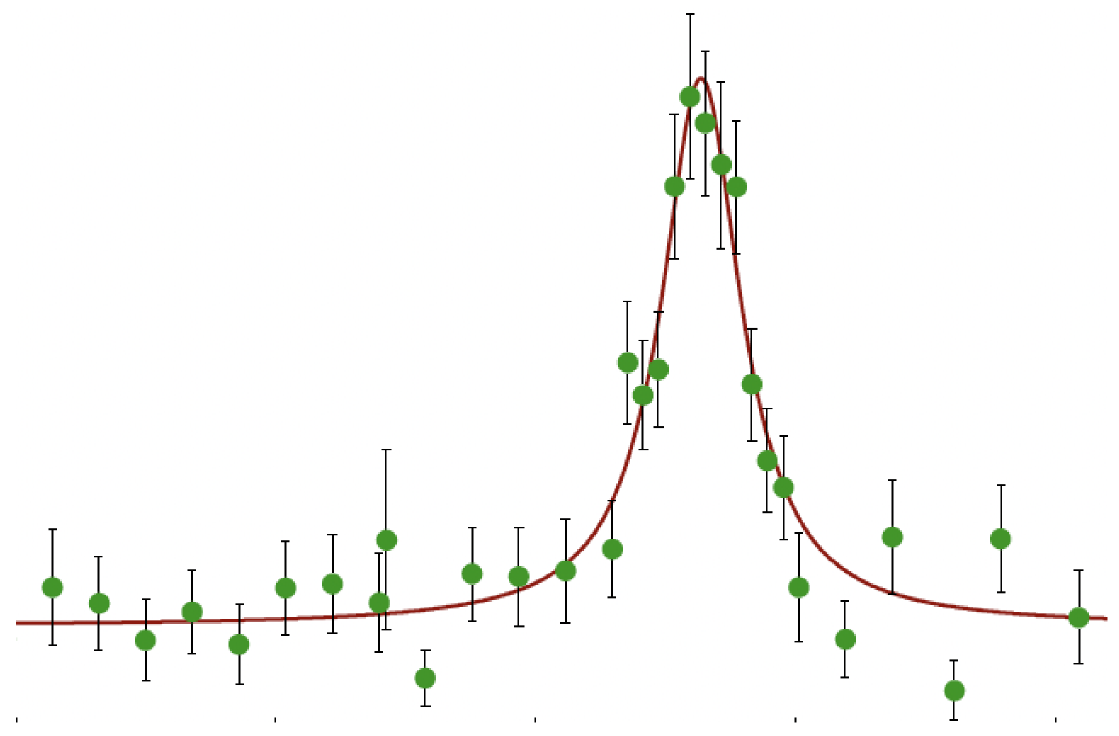




$$\Delta E_{\text{size}} = \langle \bar{\Psi} | V_{\text{Coulomb}} - V_{\text{finite size}} | \Psi \rangle$$

$$\Delta E_{\text{size}} = \langle \bar{\Psi}(r) | \Delta V(r) | \Psi(r) \rangle$$

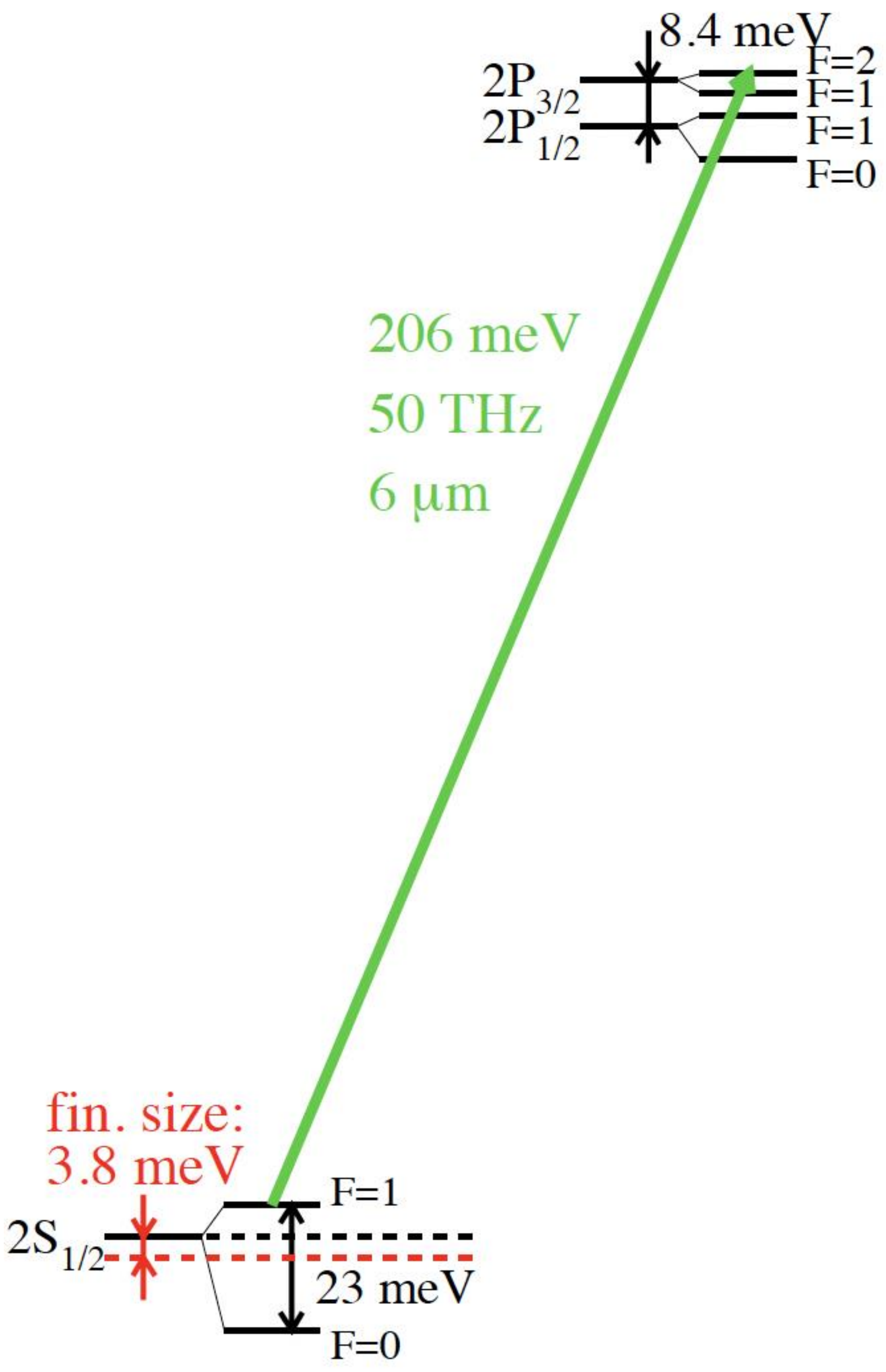
$$\Delta E_{\text{size}} = \frac{2\pi(Z\alpha)}{3} R_p^2 \, |\Psi_{nl}(0)|^2 = \frac{2(Z\alpha)^4}{3n^3} m_r^3 \, R_p^2 \, \delta_{l0}$$



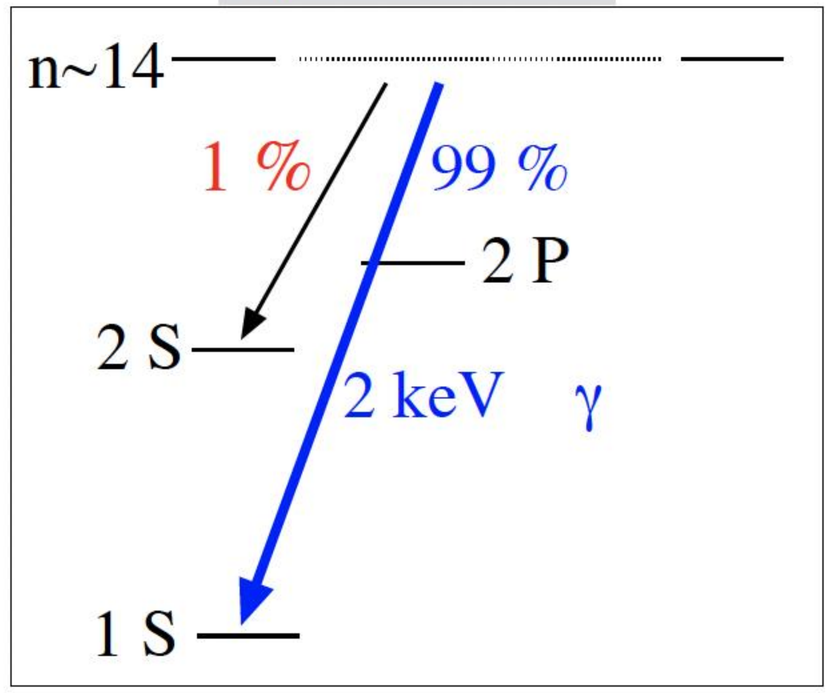
μH Lamb shift

Extracting the proton radius

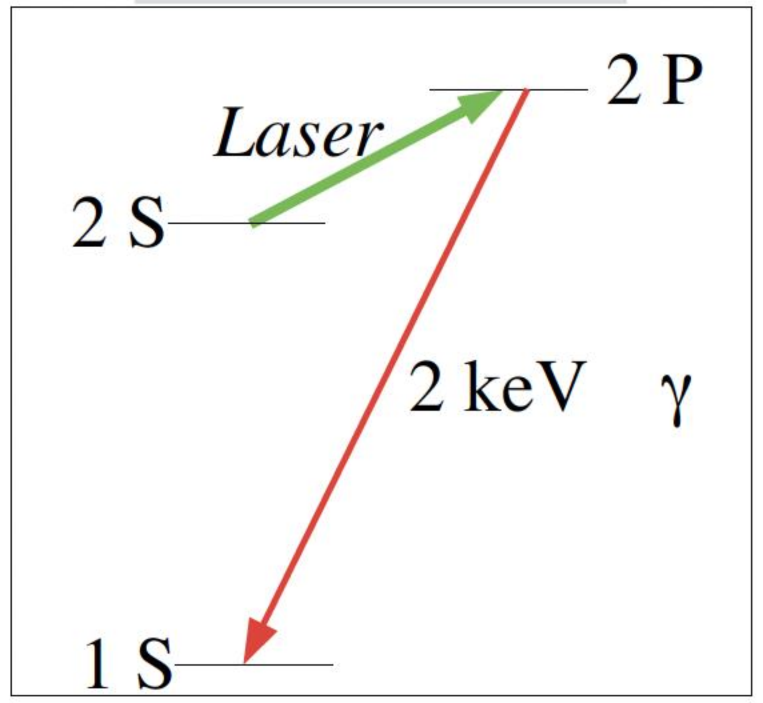
Lamb-shift (2s-2p)



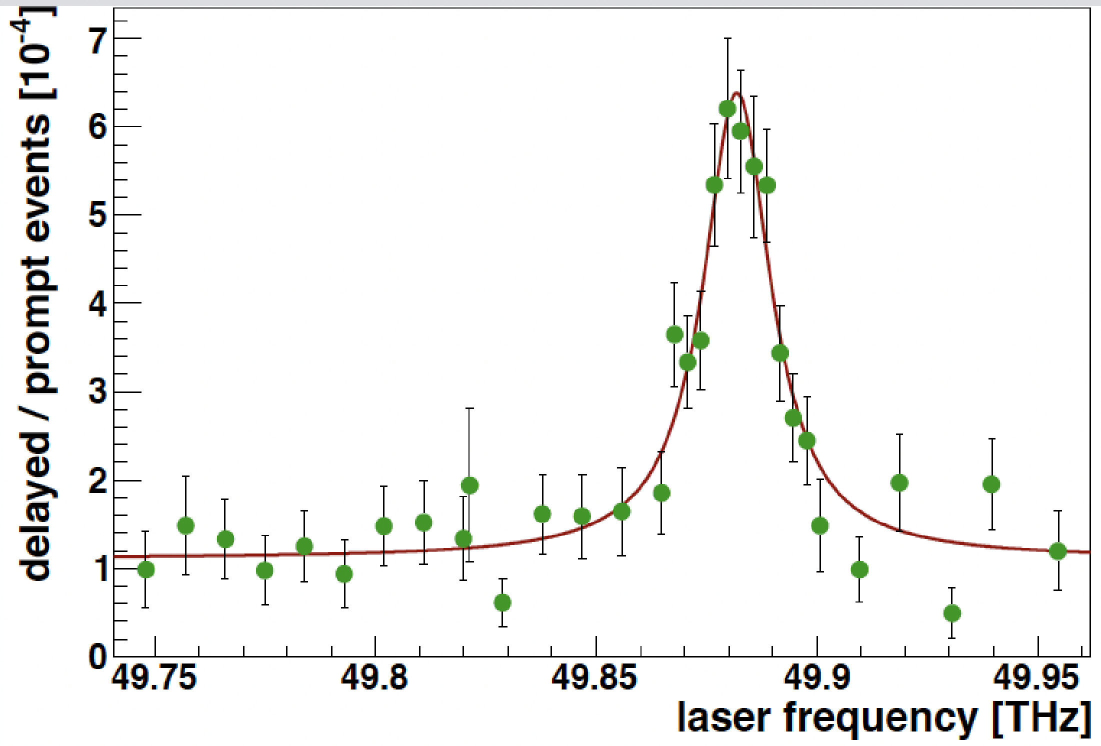
µp formation



Laser excitation



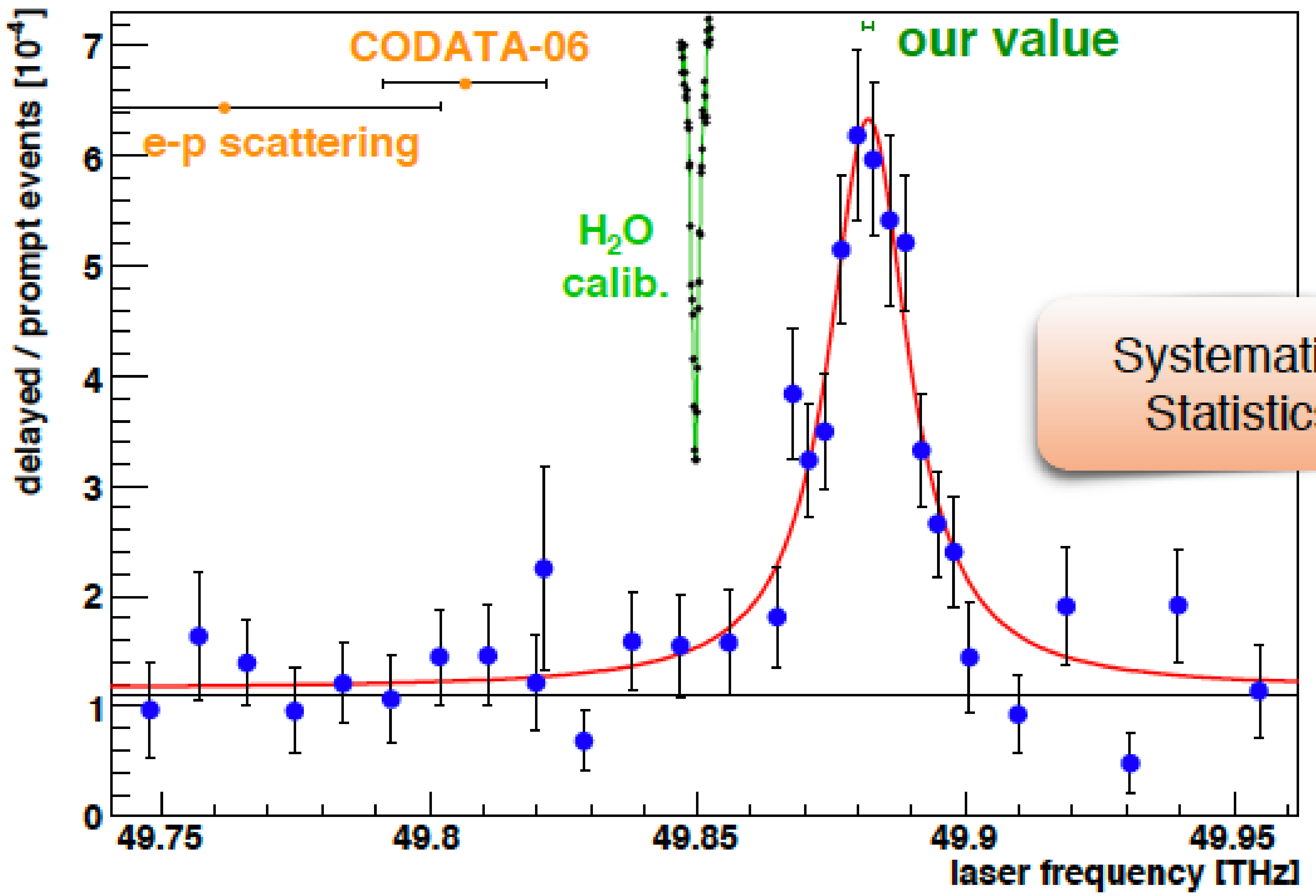
Plot number of X-rays vs laser frequency



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

Proton radius extracted

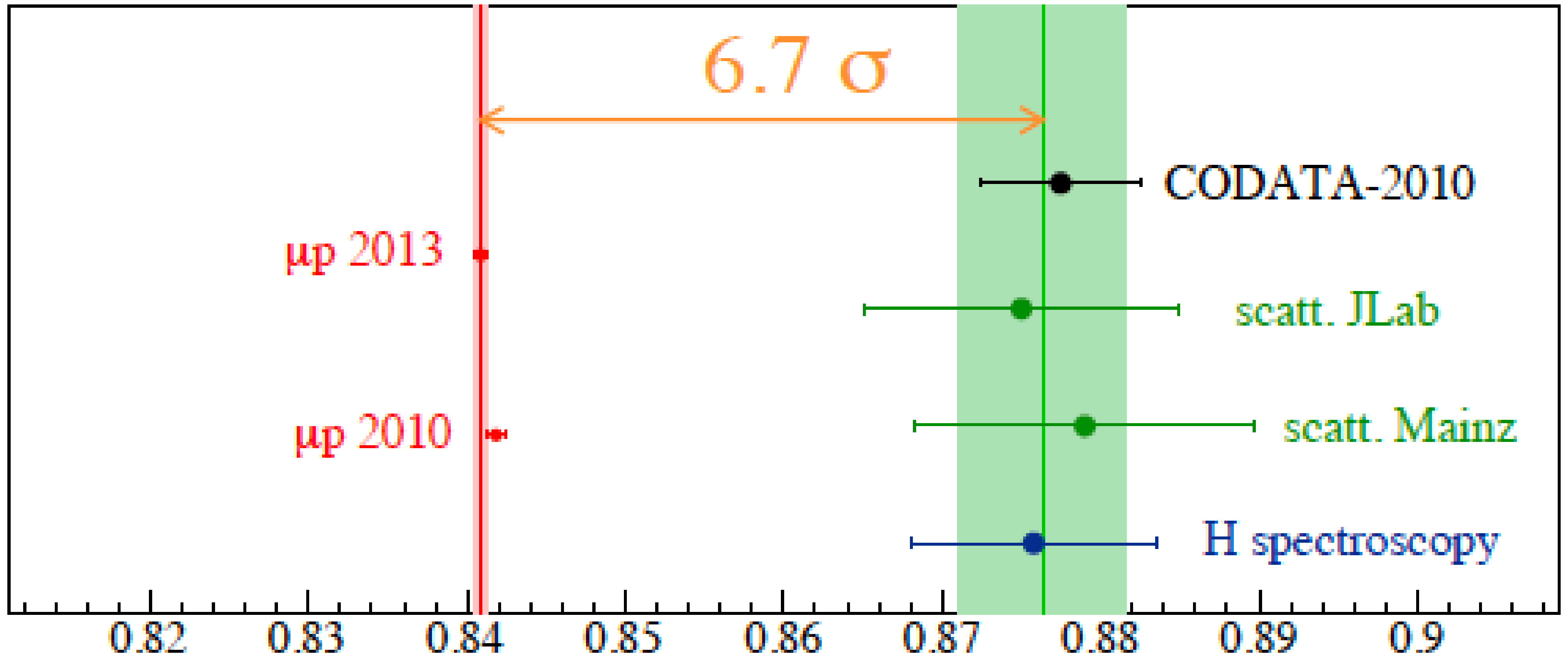
Discrepancy:
$5.0\sigma \leftrightarrow 75\text{ GHz} \leftrightarrow \delta\nu/\nu = 1.5 \times 10^{-3}$



Systematics: 300 MHz
Statistics: 700 MHz

Pohl et al., Nature 466, 213 2010

- **Charge radius with 0.1% uncertainty**
- **10x more accurate than the average of all combined measurements**
- **Yet was 6.7σ smaller than recommended value**



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

Proton radius puzzle

$$E^{\mathrm{exp}}_{2\mathrm{P}-2\mathrm{S}} = E^{\mathrm{th}}_{2\mathrm{P}-2\mathrm{S}}$$

$$E^{\mathrm{exp}}_{2\mathrm{P}-2\mathrm{S}} = \mathrm{QED} + \mathrm{TPE} + kR_p^2$$

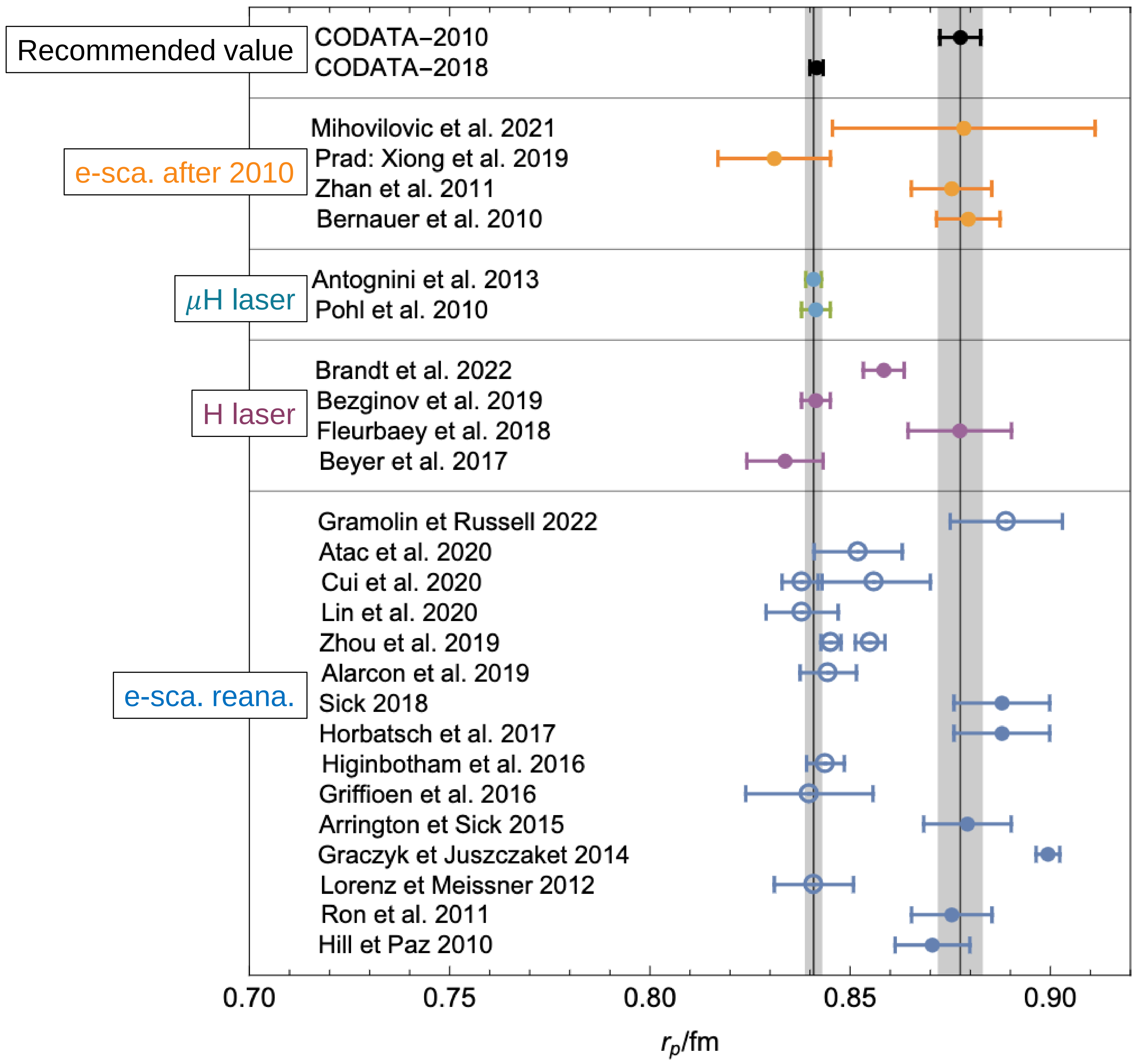
measure

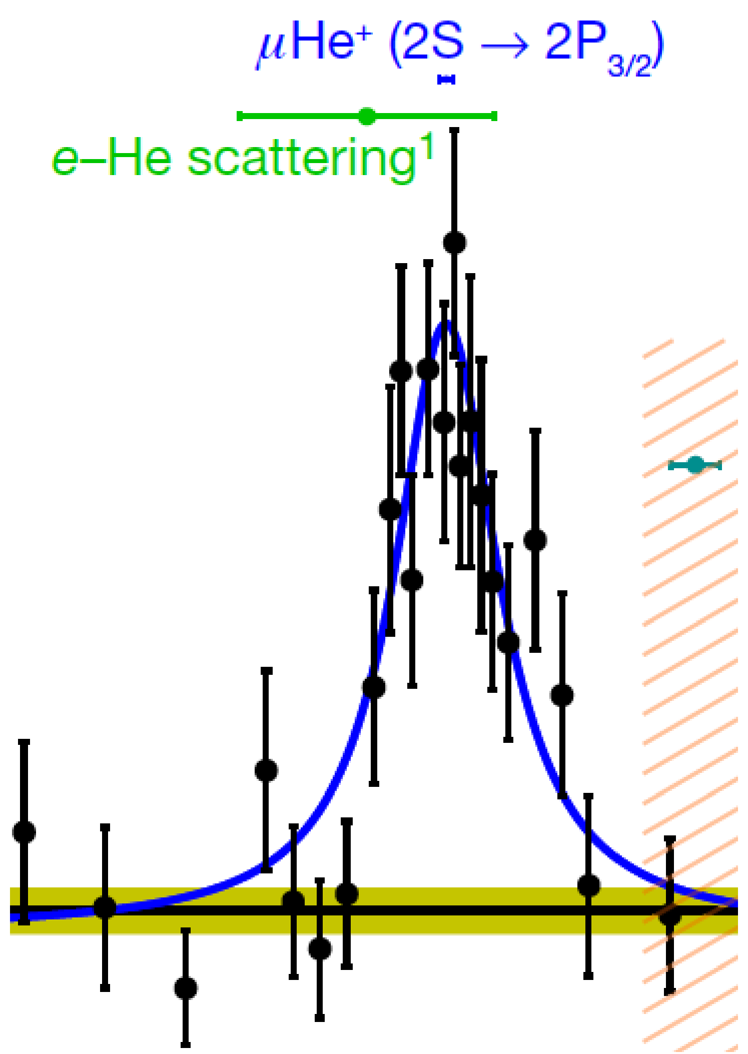
know (calculated)

extract

- Experiment is wrong?
- QED prediction is wrong?
- Proton structure not well understood?
- The radii as determined from other experiments are wrong?
- other?

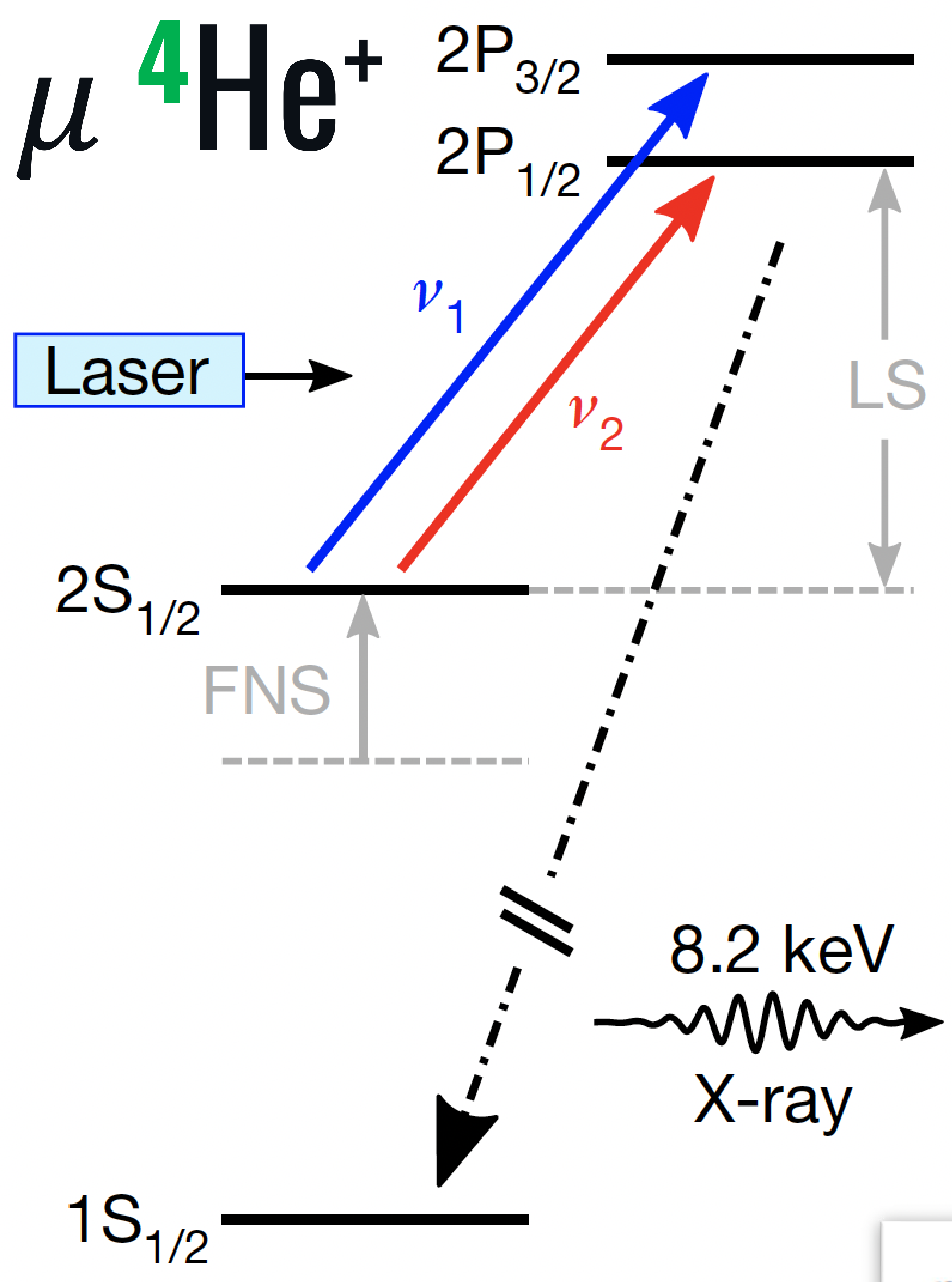
Antognini, Annual Reviews, 2022
Walcher, ArXiv 2304.07035, 2023



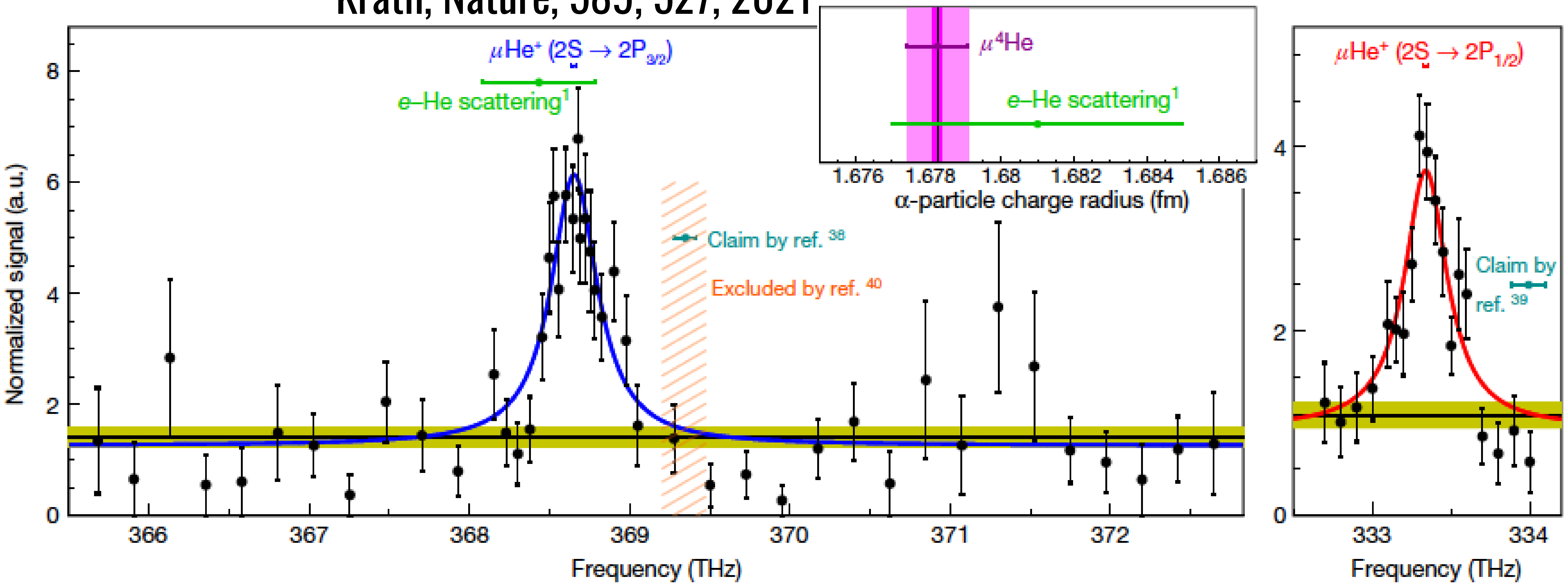


μ He Lamb shift

Alpha radius extracted



Krath, Nature, 589, 527, 2021



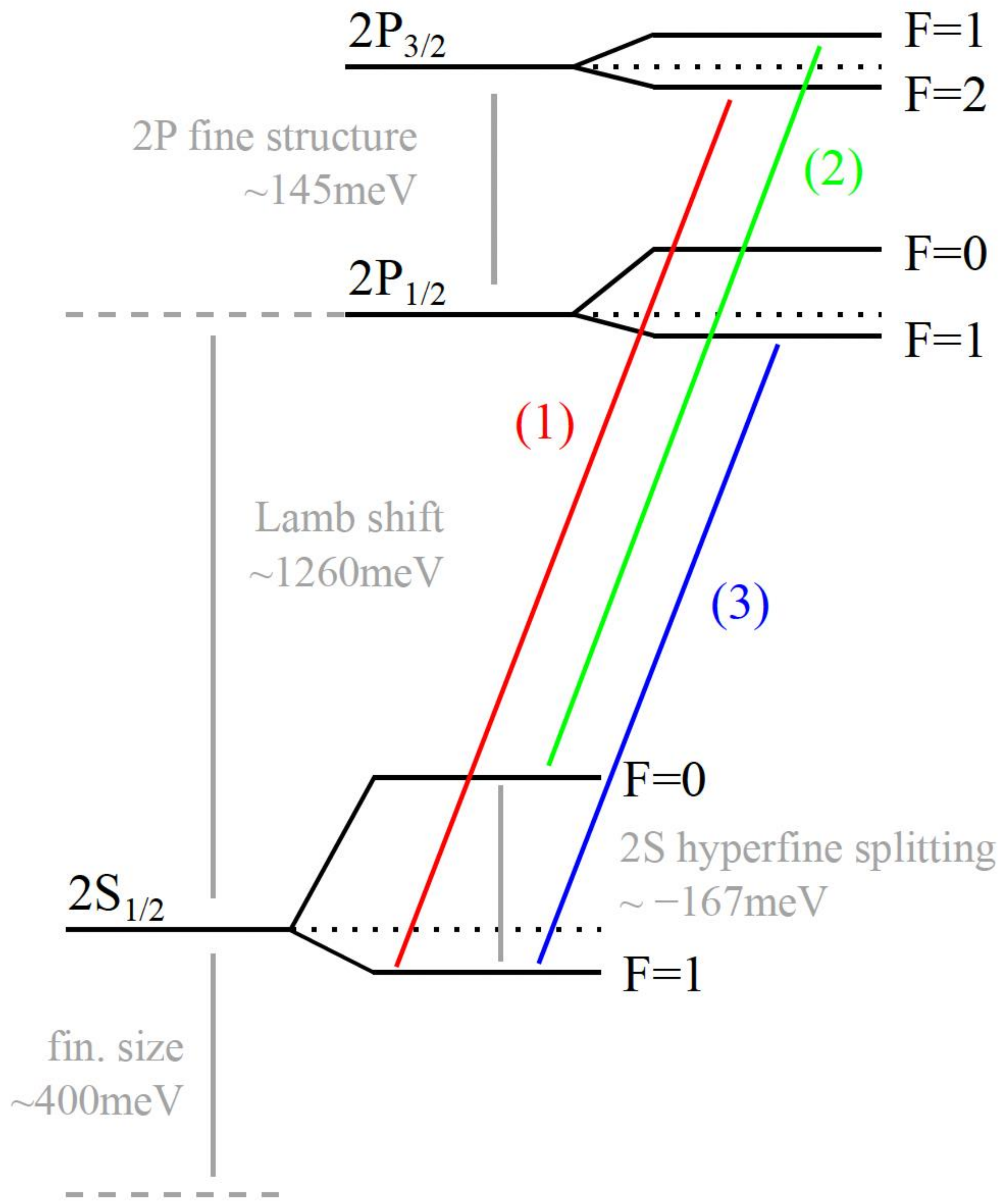
alpha particle radius

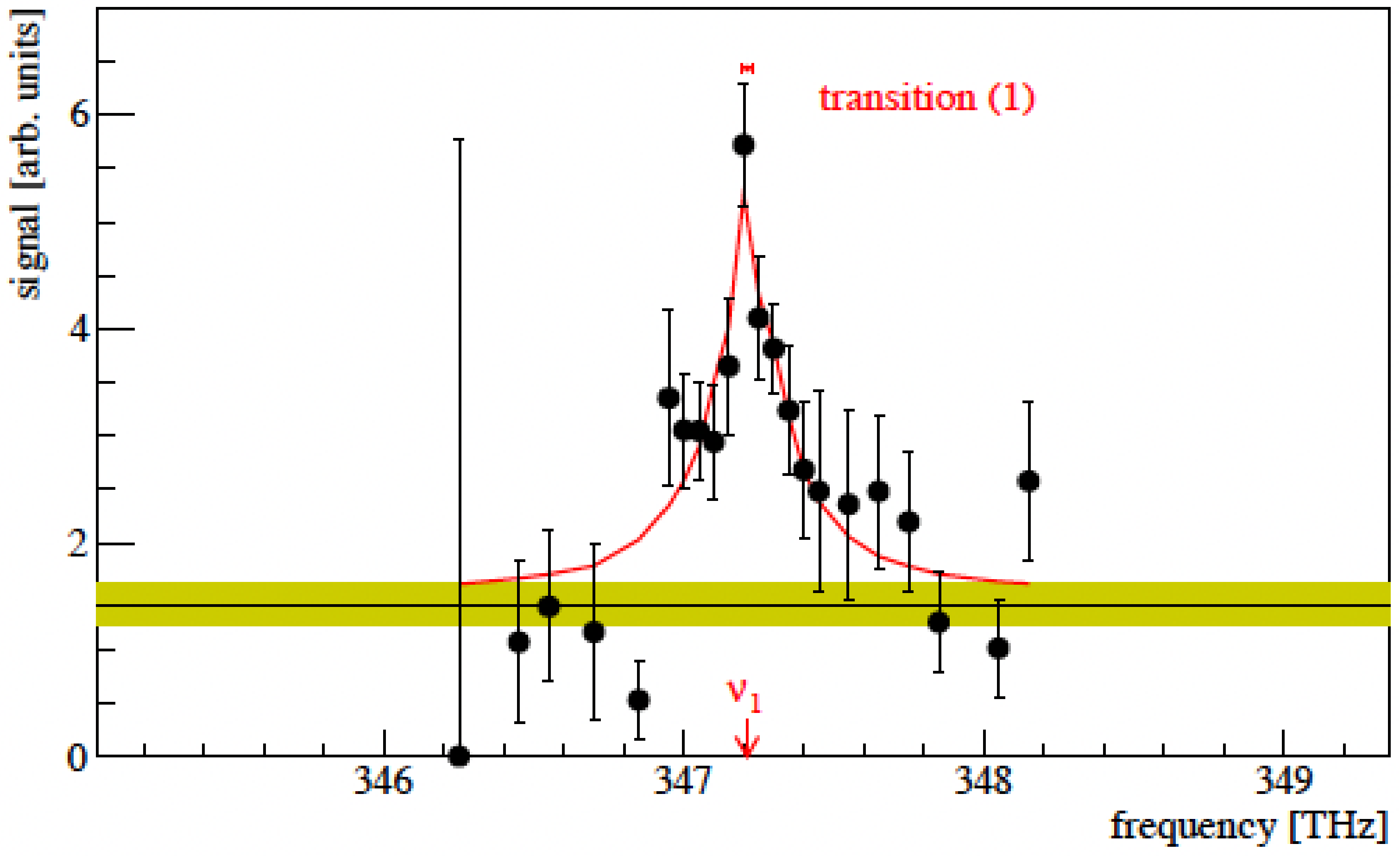
$$r_\alpha = 1.67824(13)_{\text{exp}}\ (82)_{\text{theo}}\ \text{fm}$$

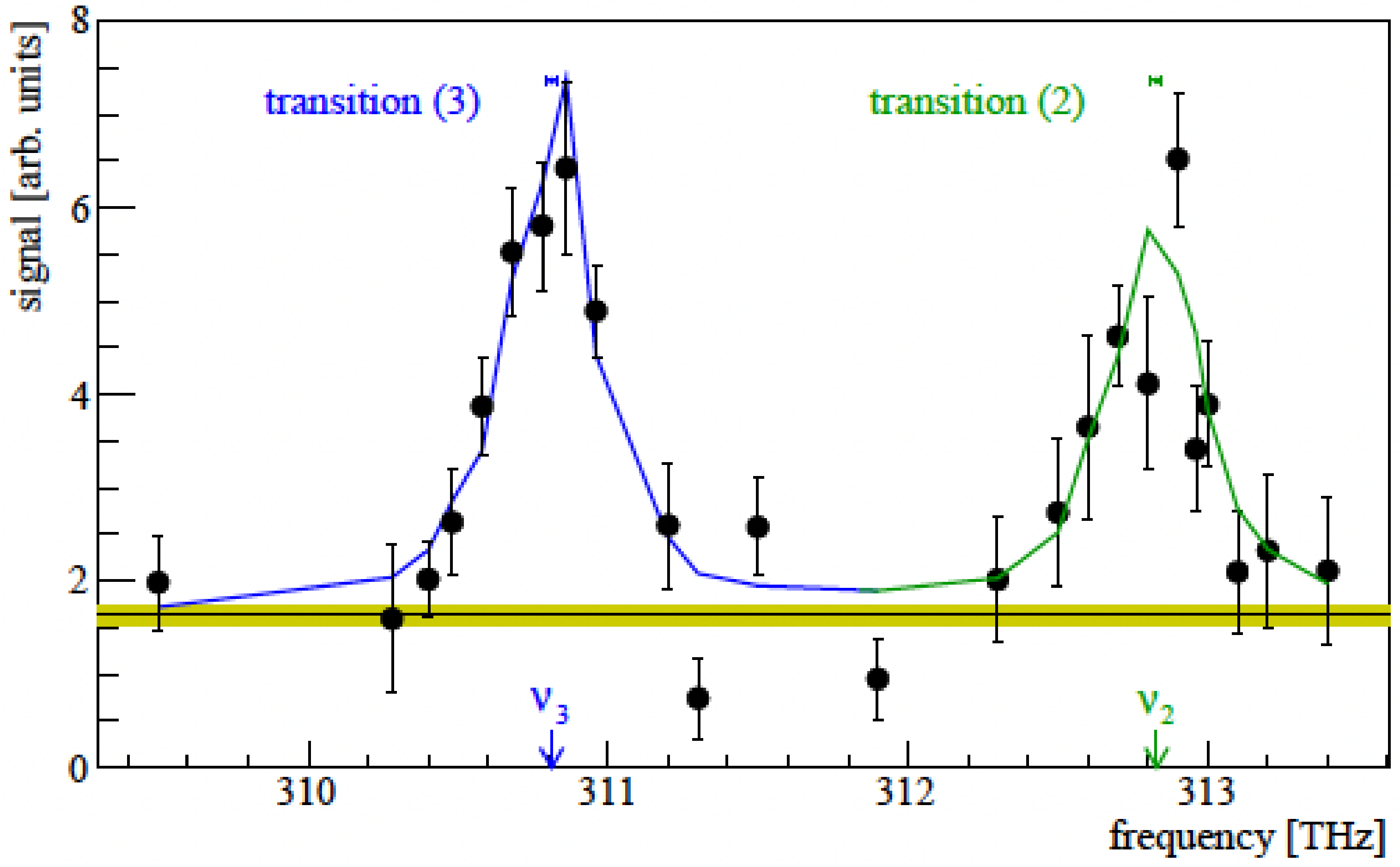
- Most precise measurement of the alpha particle radius
- 0.05% uncertainty
- Agreement with e-He scattering but 4.8x more accurate
- Benchmark few-nucleon theories
- Bounds nuclear flavour-violating interactions

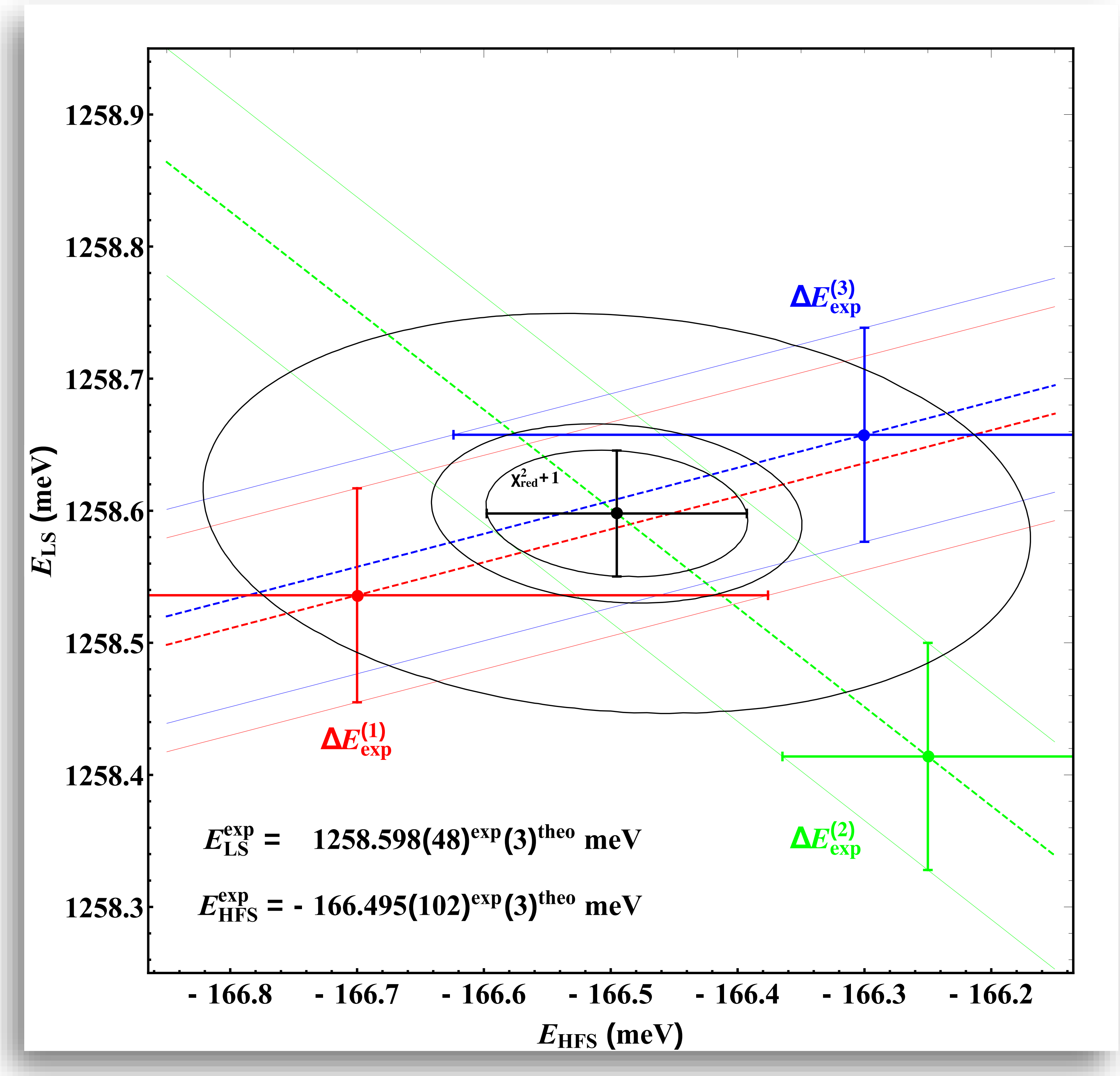
Helion radius extracted

$\mu\ {}^{3}He^{+}$









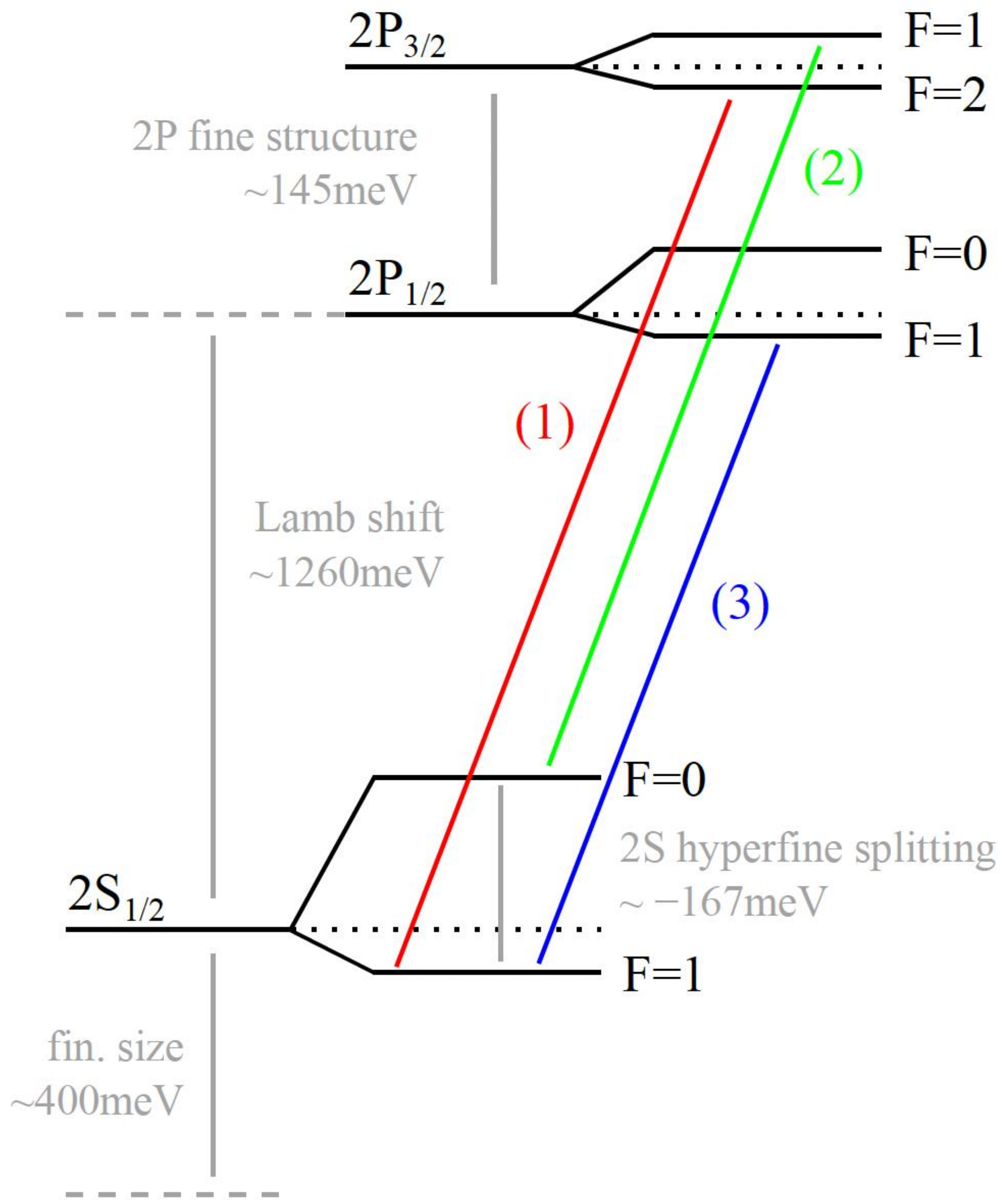
$$\nu_1 = \Delta E_{LS}^{KP} + \frac{1}{4}\beta_0 + \Delta E_{FS}^{K} - \frac{3}{8}HFS_{\{3/2\}}^{K} - \frac{3}{4}\Delta$$

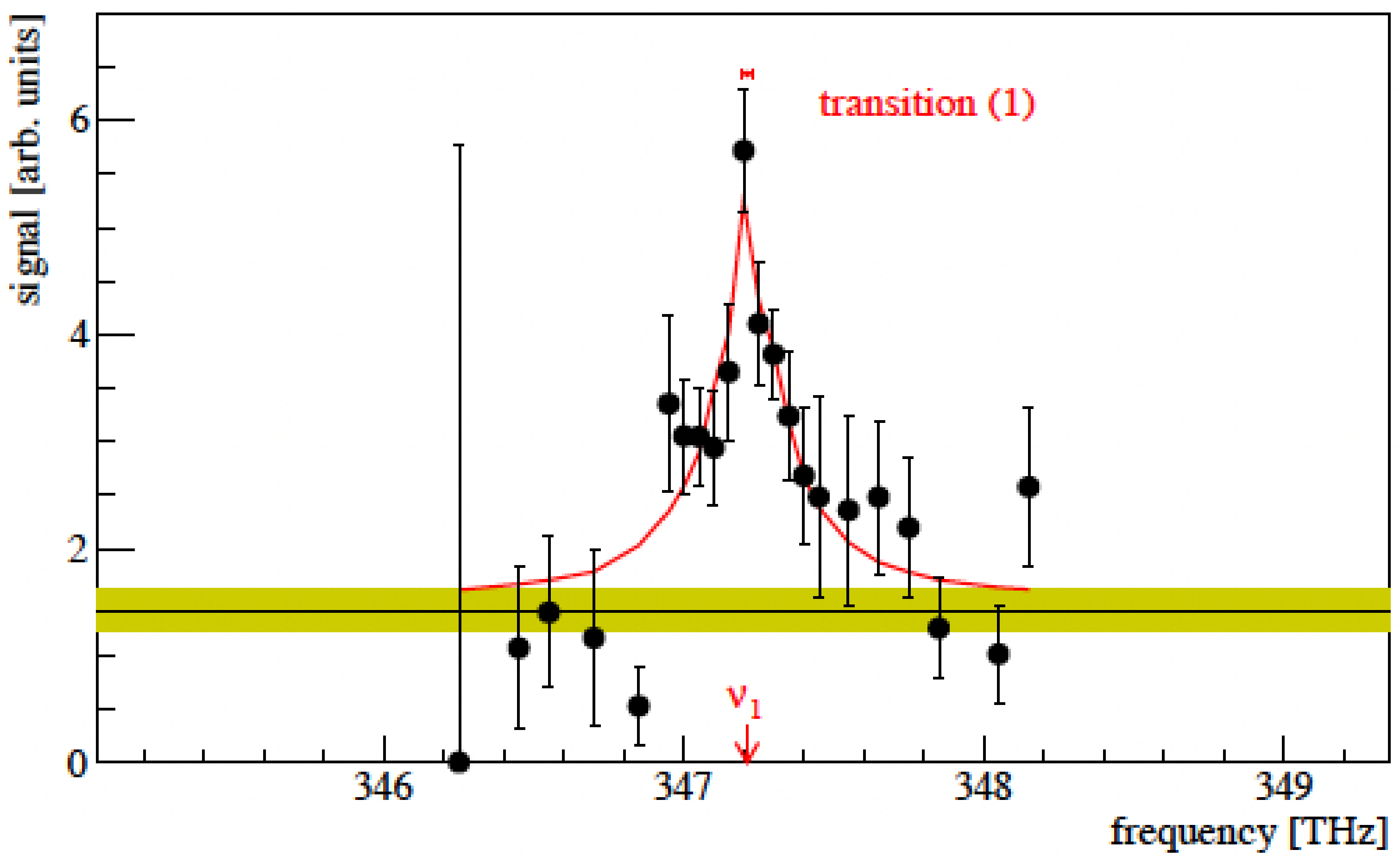
$$\nu_2 = \Delta E_{LS}^{KP} - \frac{3}{4}\beta_0 + \Delta E_{FS}^{K} + \frac{5}{8}HFS_{\{3/2\}}^{K} - \frac{3}{4}\Delta$$

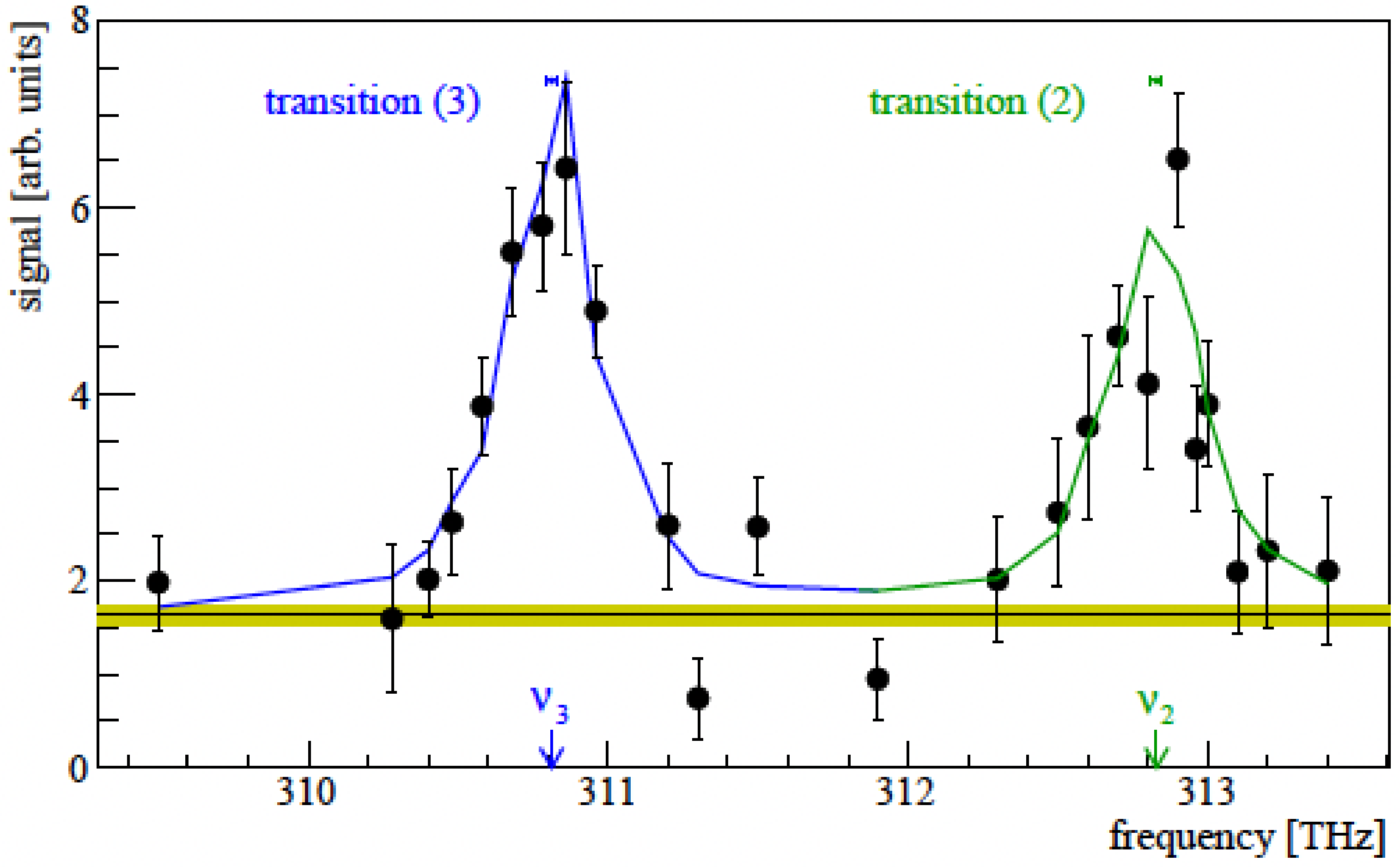
$$\nu_3 = \Delta E_{LS}^{KP} + \frac{1}{4}\beta_0 - \frac{1}{4}HFS_{\{1/2\}}^{K} - \frac{3}{4}\Delta$$

Helion radius extracted

$\mu\ {}^3He^+$



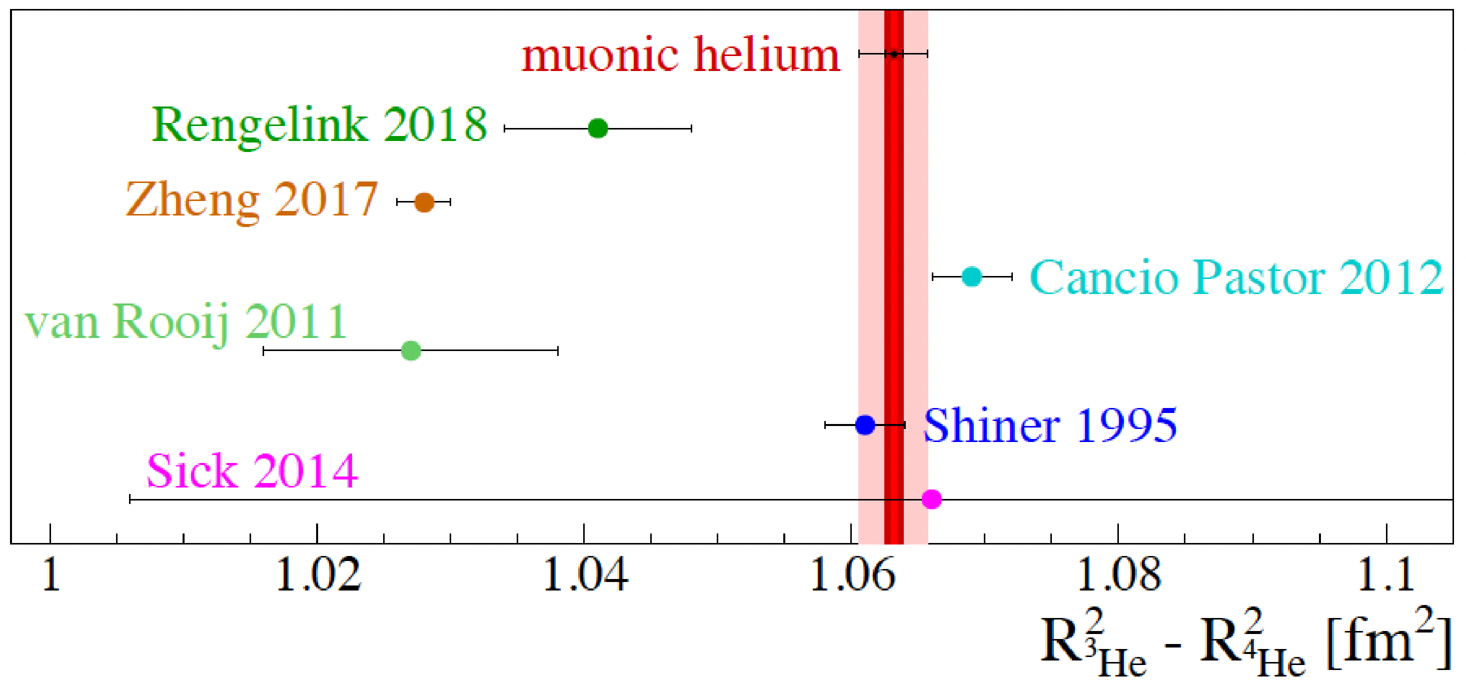




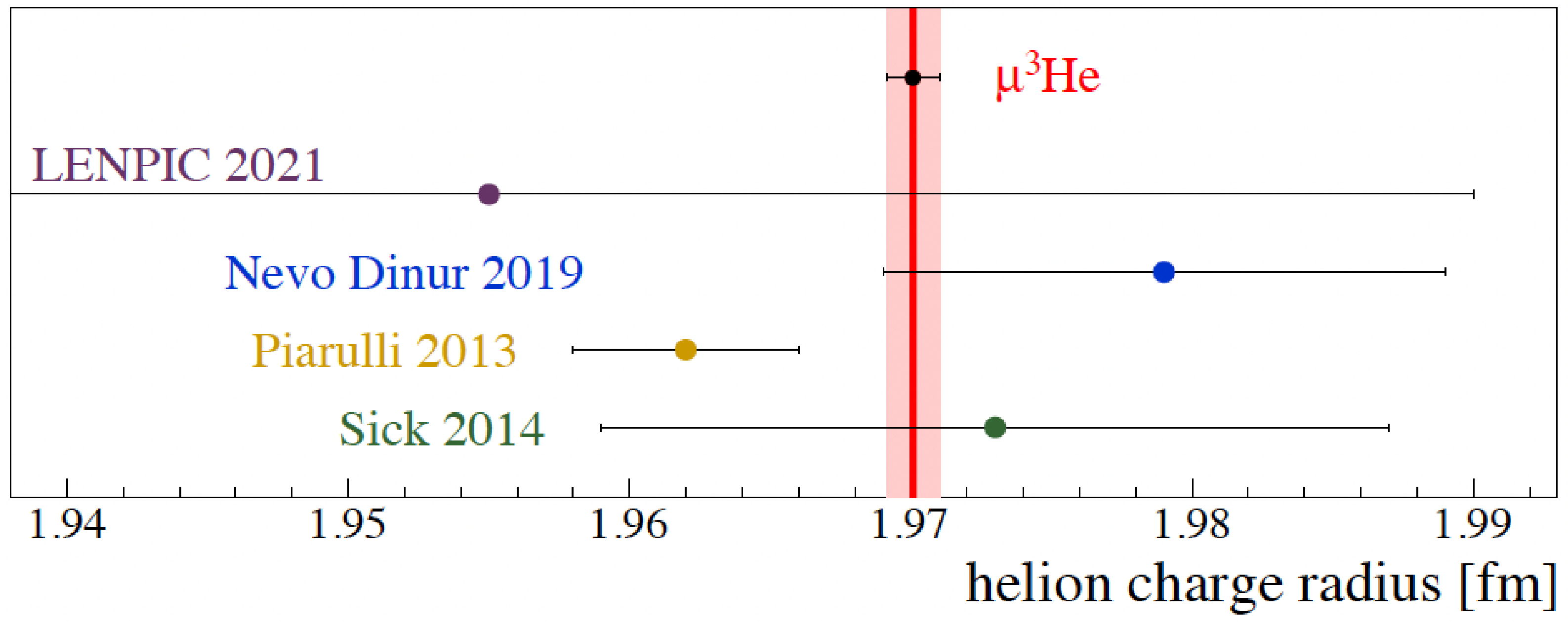
2s hyperfine

Isotopic shift

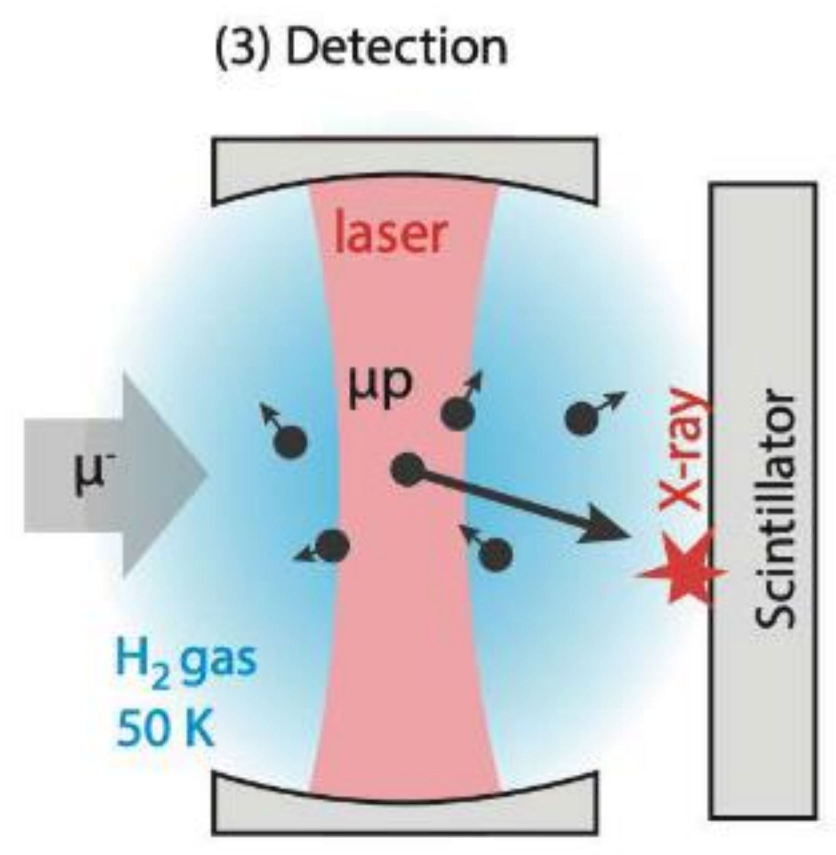
$$E_{\mathrm{HFS}}^{\mathrm{exp}} = -166.496(104)^{\mathrm{exp}}(3)^{\mathrm{theo}}\ \mathrm{meV}$$



helion radius



Schuhmann, Science, under review

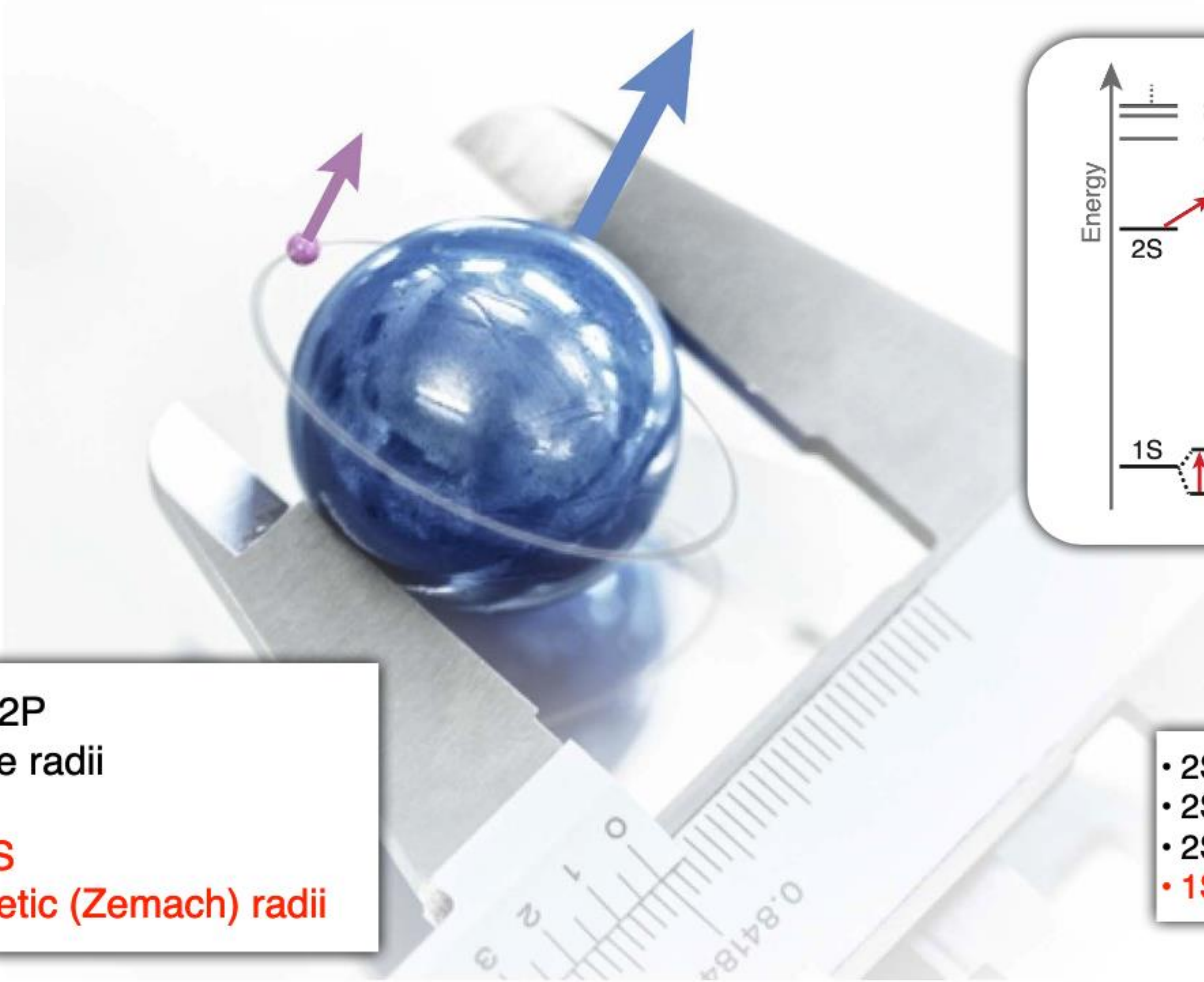


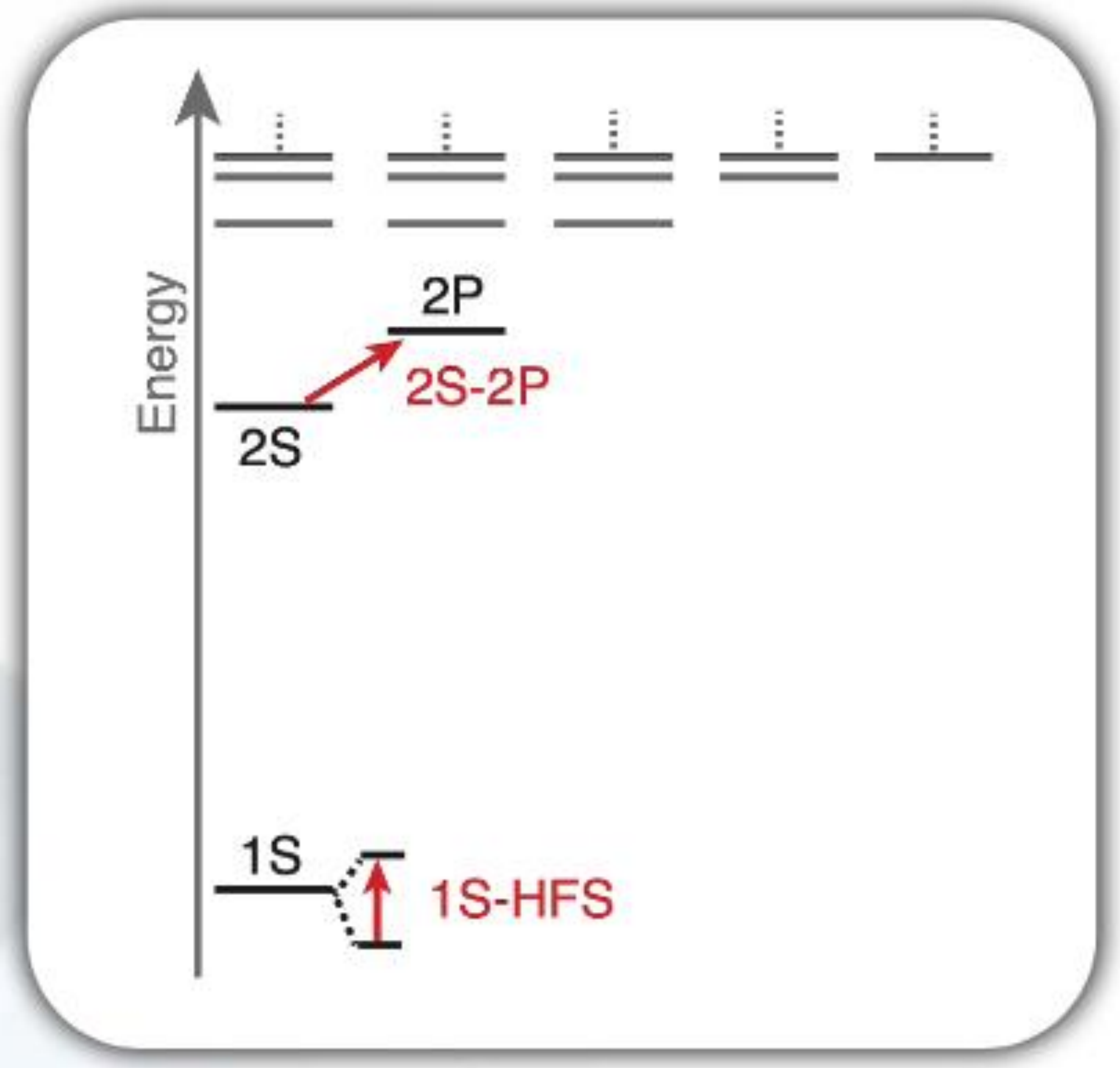
μp hyperfine structure

Hyperfine splitting of muonic hydrogen - HyperMu

HyperMu

Switzerland (PSI, ETHZ), France, Germany, Portugal, Taiwan, Poland





- From 2S-2P
  → charge radii
- From HFS
  → magnetic (Zemach) radii

- 2S-2P μp
- 2S-2P μd
- 2S-2P μ³He, μ⁴He
- 1S-HFS μp

Hyperfine splitting of muonic hydrogen

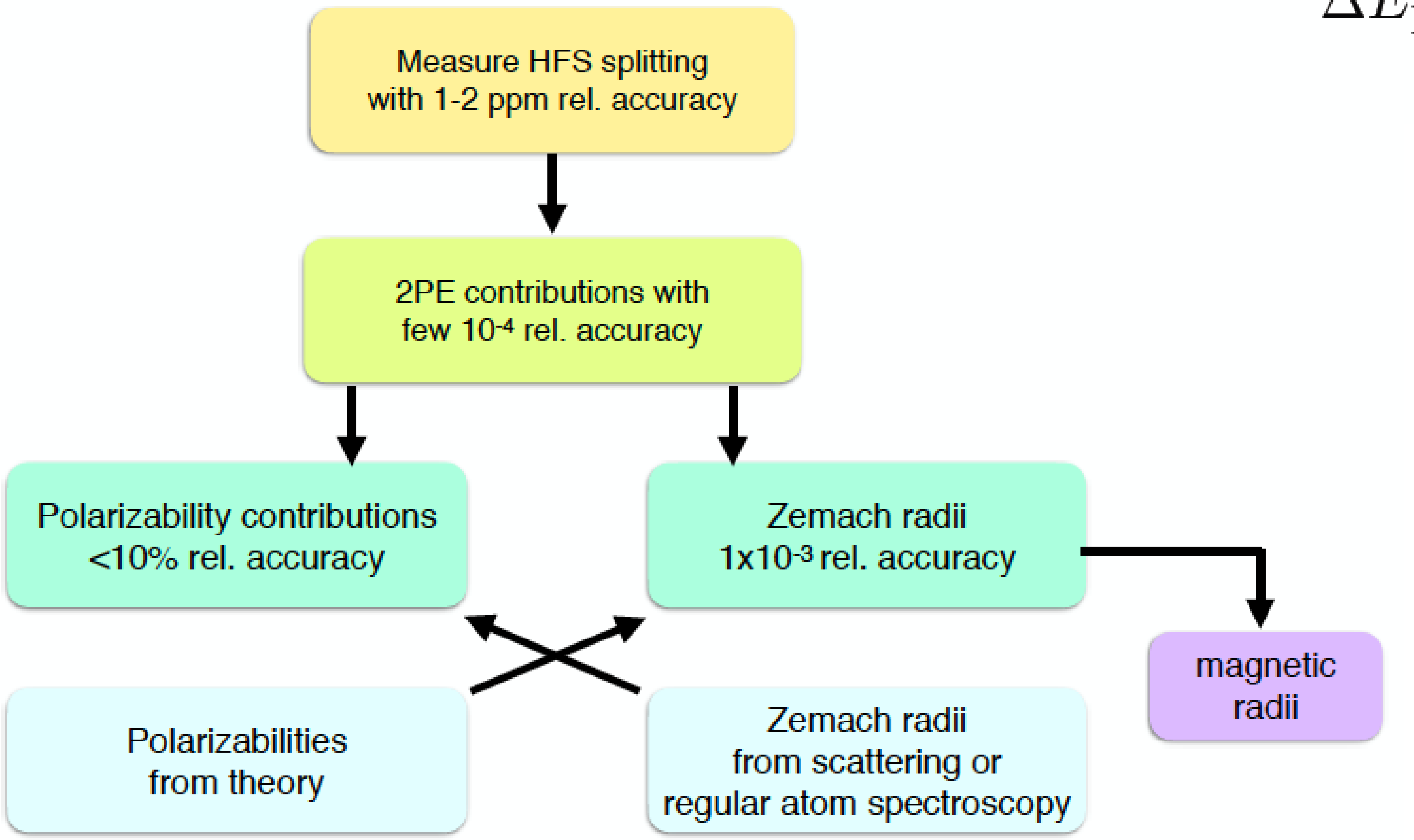
Goal

Measure the 1S-HFS in μp with 1-2 ppm accuracy

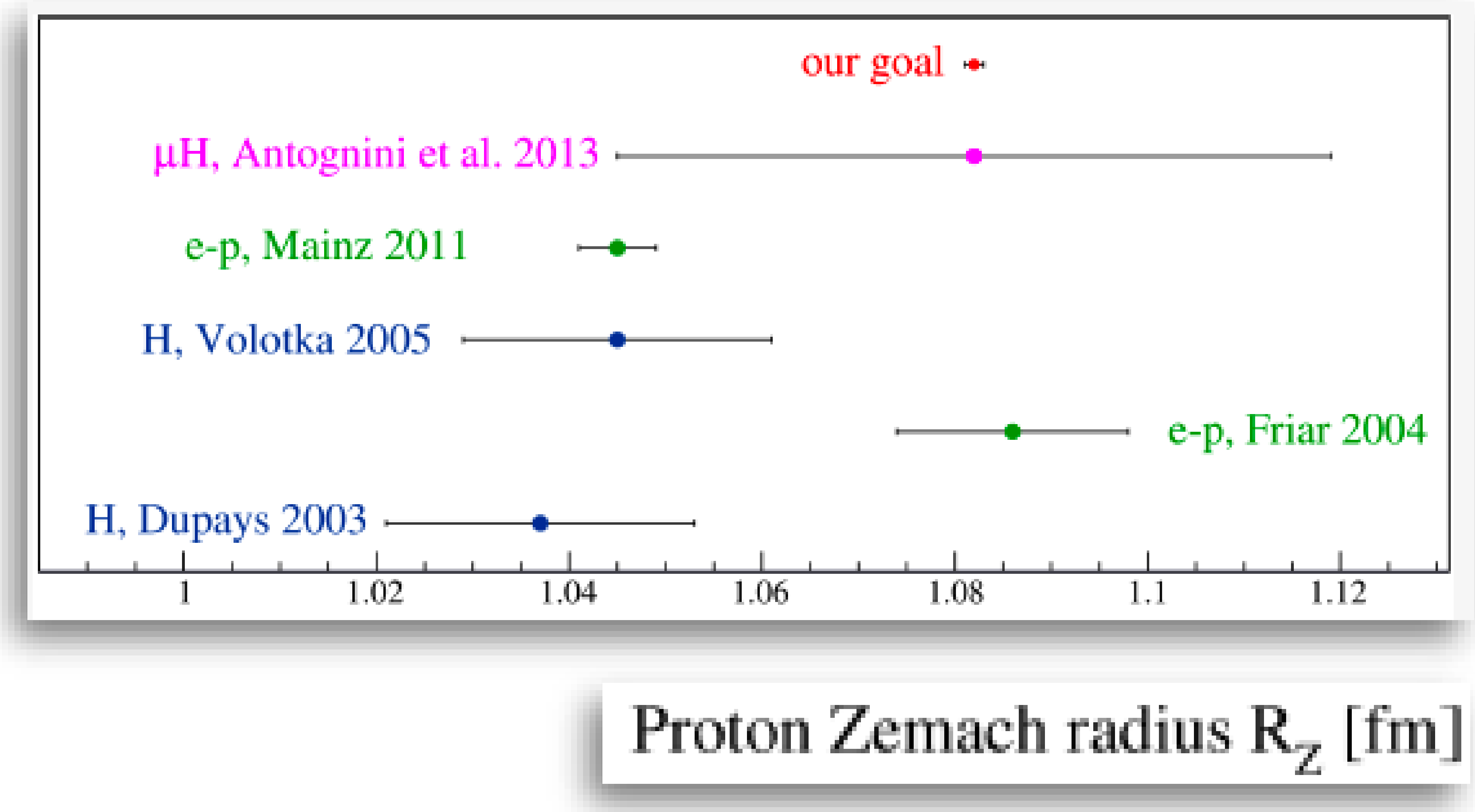
Impact

- TPE contribution with 3×10^{-4} rel. accuracy
- Zemach radius and polarisability contributions

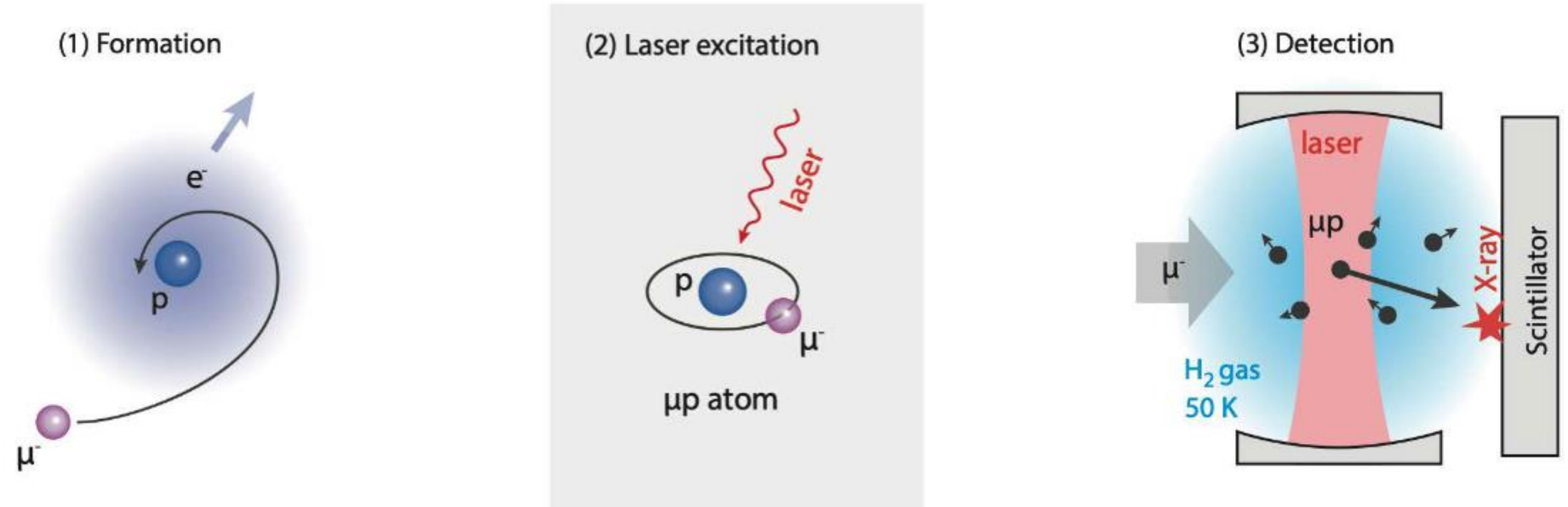
$$\Delta E^{\mathrm{th}}_{\mathrm{HFS}} = 182.819(10) - \underbrace{1.301 R_Z + 0.064(21)}_{\mathrm{TPE}} + \cdots \quad \mathrm{meV}$$



Test of fundamental nuclear theories:
Quiral PT, dispersion theories, QCD, etc



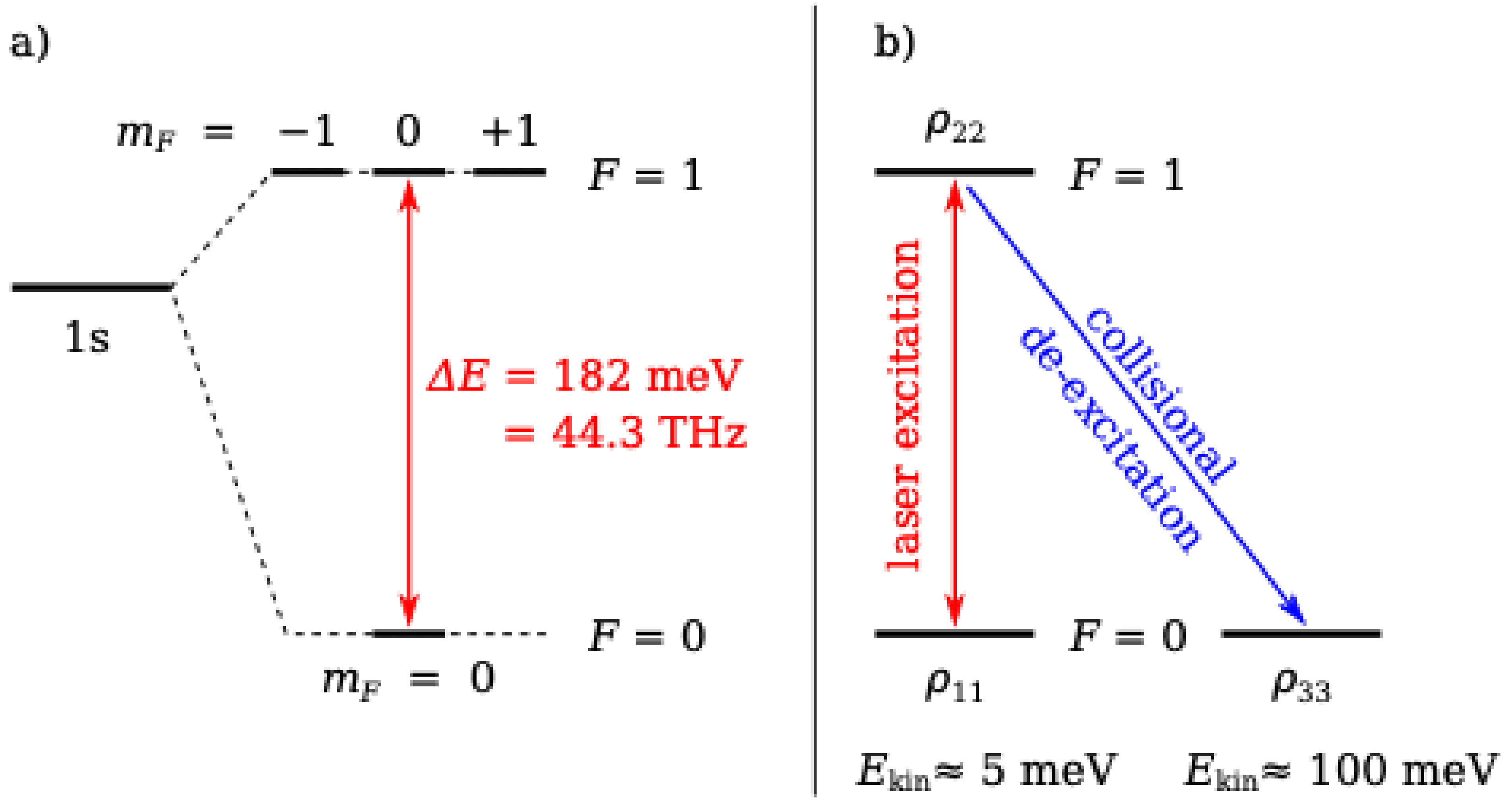
Experiment HyperMu

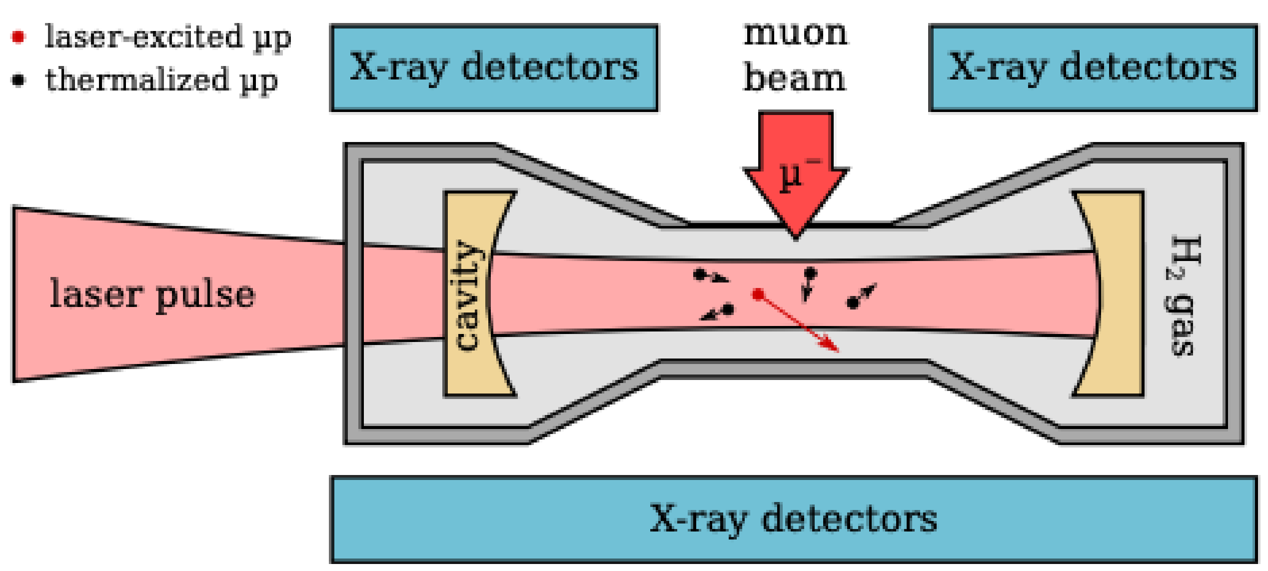


Challenges to overcome

Signal detection

Laser wavelength with power





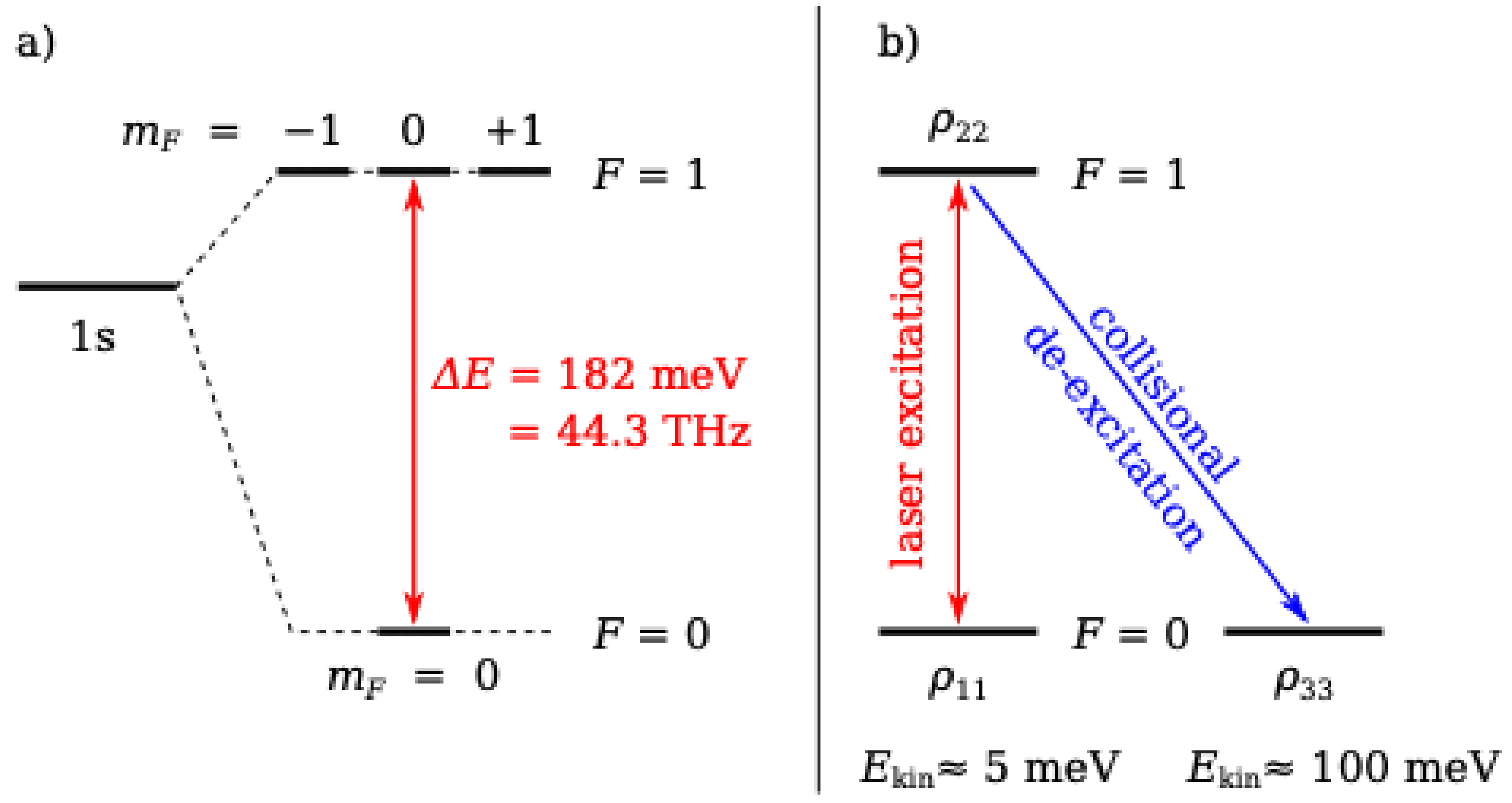
- Laser pulse: $\mu p(F{=}0) + \gamma \rightarrow \mu p(F{=}1)$
- De-excitation: $\mu p(F{=}1) + H_2 \rightarrow \mu p(F{=}0) + H_2 + E_{kin}$
- Diffusion: X-rays produce at target walls
- Resonance: Number of X-ray vs laser freq.

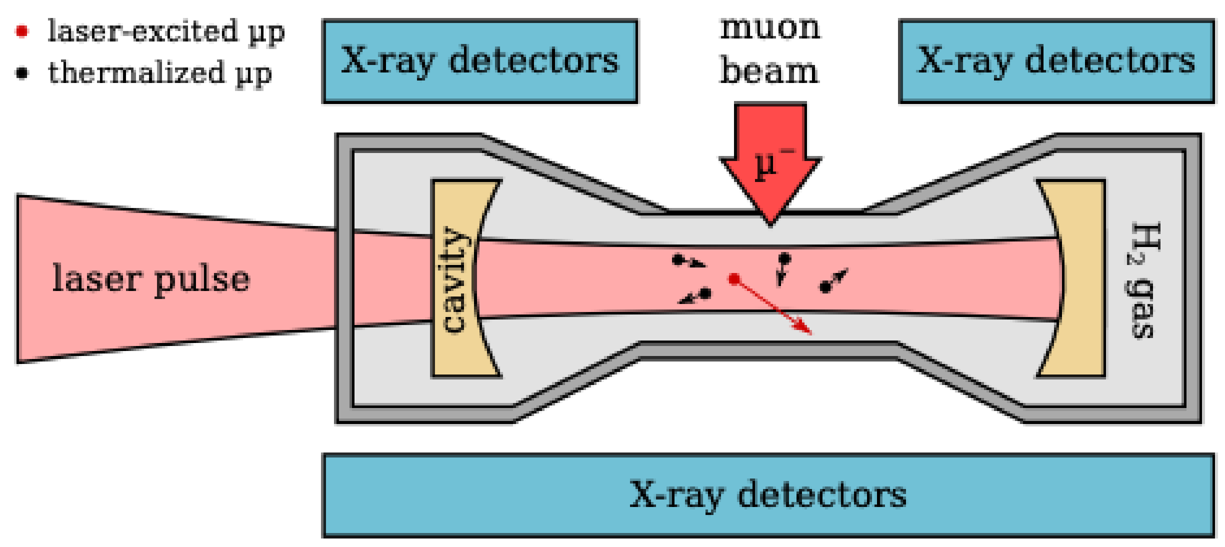
Model of the experiment HyperMu

- laser requirements?
- gas conditions ?
- target geometry ?
- are correlated ?

Monte-Carlo simulation checklist

- Capture probability
- Differential collision rate/thermalization
- Laser excitation/collisional de-excitation
- Transfer random walk





Laser excitation/deexcitation with Bloch equations

$$\begin{aligned}
\frac{d\rho_{11}}{dt}(t) &= -\mathrm{Im}\left(\Omega\rho_{12}e^{i\Delta t}\right)+\Gamma_{sp}\rho_{22}\,,\\
\frac{d\rho_{22}}{dt}(t) &= \mathrm{Im}\left(\Omega\rho_{12}e^{i\Delta t}\right)-(\Gamma_i+\Gamma_{sp})\rho_{22}\,,\\
\frac{d\rho_{12}}{dt}(t) &= \frac{i\Omega^*}{2}(\rho_{11}-\rho_{22})e^{-i\Delta t}-\frac{\Gamma_c}{2}\rho_{12}\,,\\
\frac{d\rho_{33}}{dt}(t) &= \Gamma_i\rho_{22}\,,
\end{aligned}$$

P. Amaro *et al*, SciPost Phys. 13, 020 (2022)

Laser excitation/collisional de-excitation

$$
\begin{aligned}
\frac{d\rho_{11}}{dt}(t) &= -\mathrm{Im}\left(\Omega\rho_{12}e^{i\Delta t}\right) + \Gamma_{\mathrm{sp}}\rho_{22}\,,\\
\frac{d\rho_{22}}{dt}(t) &= \mathrm{Im}\left(\Omega\rho_{12}e^{i\Delta t}\right) - (\Gamma_i + \Gamma_{\mathrm{sp}})\rho_{22}\,,\\
\frac{d\rho_{12}}{dt}(t) &= \frac{i\Omega^*}{2}(\rho_{11} - \rho_{22})e^{-i\Delta t} - \frac{\Gamma_c}{2}\rho_{12}\,,\\
\frac{d\rho_{33}}{dt}(t) &= \Gamma_i\rho_{22}\,,
\end{aligned}
$$

- Laser-atom strength
- molecular collisions
- Laser bandwidth
- Doppler broadening

Laser excitation/collisional de-excitation

$$
\begin{aligned}
\frac{d\rho_{11}}{dt}(t) &= -\mathrm{Im}\left(\Omega\rho_{12}e^{i\Delta t}\right) + \Gamma_{sp}\rho_{22}\,, \\
\frac{d\rho_{22}}{dt}(t) &= \mathrm{Im}\left(\Omega\rho_{12}e^{i\Delta t}\right) - (\Gamma_i + \Gamma_{sp})\rho_{22}\,, \\
\frac{d\rho_{12}}{dt}(t) &= \frac{i\Omega^*}{2}(\rho_{11}-\rho_{22})e^{-i\Delta t} - \frac{\Gamma_c}{2}\rho_{12}\,, \\
\frac{d\rho_{33}}{dt}(t) &= \Gamma_i\rho_{22}\,,
\end{aligned}
$$

Laser-atom strength

$$\Omega = \sqrt{\frac{8\pi\alpha\mathcal{I}}{\hbar}}\mathcal{M}$$

Atom	Transition	$\mathcal{M}$ [m]	$\frac{\Omega}{\sqrt{\mathcal{I}}}$ [m/$\sqrt{\text{Js}}$]
μp	$2s^{F=1} \to 2p^{F=2}_{3/2}$	$\sqrt{5}a_\mu = 6.367 \times 10^{-13}$	2.65×10^4
μ^3He$^+$	$2s^{F=1} \to 2p^{F=2}_{3/2}$	$\frac{\sqrt{5}}{2}a_\mu = 2.969 \times 10^{-13}$	1.24×10^4
μp	$1s^{F=0} \to 1s^{F=1}$	$\frac{\hbar}{4m_\mu c}\left(g_\mu + \frac{m_\mu}{m_p}g_p\right) = 1.228 \times 10^{-15}$	5.12×10^1 [a]
μ^3He$^+$	$1s^{F=1} \to 1s^{F=0}$	$\frac{\hbar}{4\sqrt{3}m_\mu c}\left(g_\mu + \frac{m_\mu}{m_{He}}g_{He}\right) = 4.965 \times 10^{-16}$	2.07×10^1

[a] 1.77×10^1 m/$\sqrt{\text{Js}}$ according to Ref. [37]

- Laser-atom strength
- molecular collisions
- Laser bandwidth
- Doppler broadening

Molecular collisions and laser bandwidth

$$\frac{d\rho_{11}}{dt}(t) = -\mathrm{Im}\left(\Omega\rho_{12}e^{i\Delta t}\right) + \Gamma_{sp}\rho_{22}\,,$$
$$\frac{d\rho_{22}}{dt}(t) = \mathrm{Im}\left(\Omega\rho_{12}e^{i\Delta t}\right) - (\Gamma_i + \Gamma_{sp})\rho_{22}\,,$$
$$\frac{d\rho_{12}}{dt}(t) = \frac{i\Omega^*}{2}(\rho_{11}-\rho_{22})e^{-i\Delta t} - \frac{\Gamma_c}{2}\rho_{12}\,,$$
$$\frac{d\rho_{33}}{dt}(t) = \Gamma_i\rho_{22}\,,$$

$$\Gamma_c = 2\pi\Delta_l + \Gamma_e^{F=0} + \Gamma_e^{F=1} + \Gamma_i + \Gamma_{sp}$$

$$\Gamma = \overline{v_r\sigma(v_r)}\rho_{H_2}$$

	$T = 22$ K		$T = 30$ K		$T = 50$ K	
$p = 0.5$ bar	Stat.	Boltz.	Stat.	Boltz.	Stat.	Boltz.
$\Gamma_e^{F=0}$	20	20	15	15	9	9
$\Gamma_e^{F=1}$	52	29	41	24	28	18
Γ_i	82	93	59	66	34	37
$p = 1$ bar						
$\Gamma_e^{F=0}$	40	39	30	30	19	19
$\Gamma_e^{F=1}$	104	59	83	47	55	37
Γ_i	164	187	118	133	68	74
$p = 2$ bar						
$\Gamma_e^{F=0}$	79	79	61	61	38	37
$\Gamma_e^{F=1}$	208	118	165	94	110	74
Γ_i	328	374	235	265	137	148

- Laser-atom strength
- Molecular collisions
- Laser bandwidth
- Doppler broadening

Doppler broadening

$$\gamma_D = \omega_r\sqrt{\frac{kT}{(m_\mu + m_p)c^2}} \simeq 7.98\times 10^7\sqrt{T}\ [\mathrm{rad/s}]$$

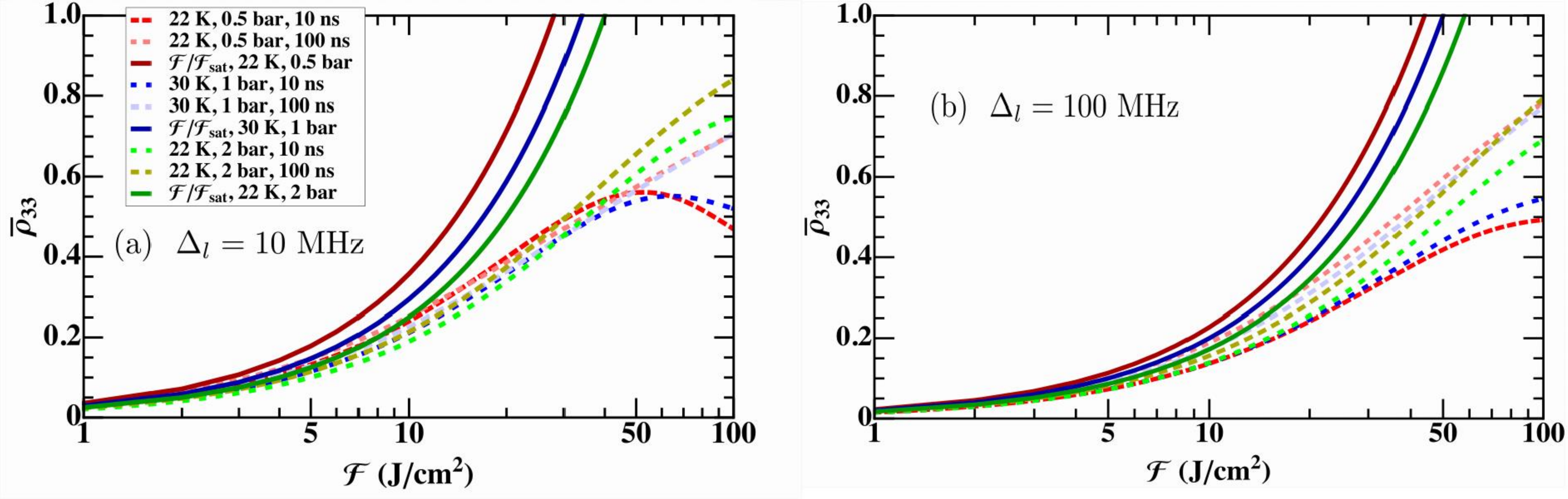
Laser excitation and shape depend on gas temperature and pressure via collisional and Doppler

Laser excitation/collisional de-excitation

Saturation fluences

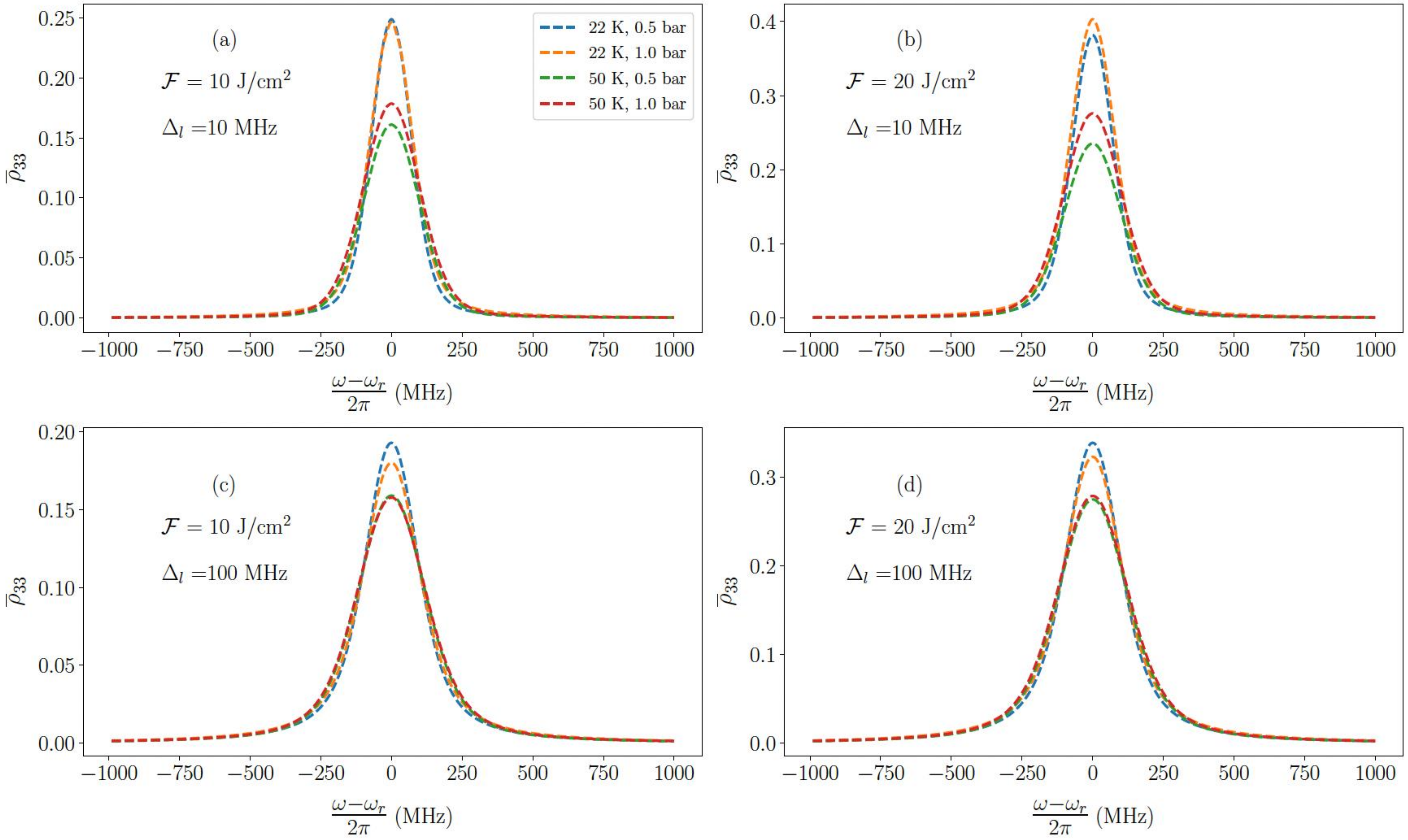
Atom	Transition	T [K]	p [bar]	ν_r [THz]	Γ_{sp} [MHz]	$\Gamma_c^{\Delta_l \to 10}$ [MHz]	$\Gamma_c^{\Delta_l \to 100}$ [MHz]	σ_D [MHz]	$\mathcal{F}_{sat}^{\Gamma_c \to 0}$ [J/cm^2]	$\mathcal{F}_{sat}^{\Delta_l \to 10}$ [J/cm^2]	$\mathcal{F}_{sat}^{\Delta_l \to 100}$ [J/cm^2]
μp	$2s^{F=1} \to 2p_{3/2}^{F=2}$	300	0.001	49.9	1.16×10^5		1.16×10^5	2.48×10^2			0.0165
μ^3He$^+$	$2s^{F=1} \to 2p_{3/2}^{F=2}$	300	0.004	379	2.00×10^6		2.00×10^6	1.13×10^3			1.304
μp	$1s^{F=0} \to 1s^{F=1}$			44.2	1.23×10^{-11}						
		22	0.5			205	770	60	23	28	44
		22	1			348	913	60	23	32	49
		22	2			633	1198	60	23	40	58
		30	0.5			168	733	70	27	31	47
		30	1			273	838	70	27	34	50
		50	0.5			128	693	90	35	37	53
		50	1			192	757	90	35	39	55

Laser excitation/collisional de-excitation

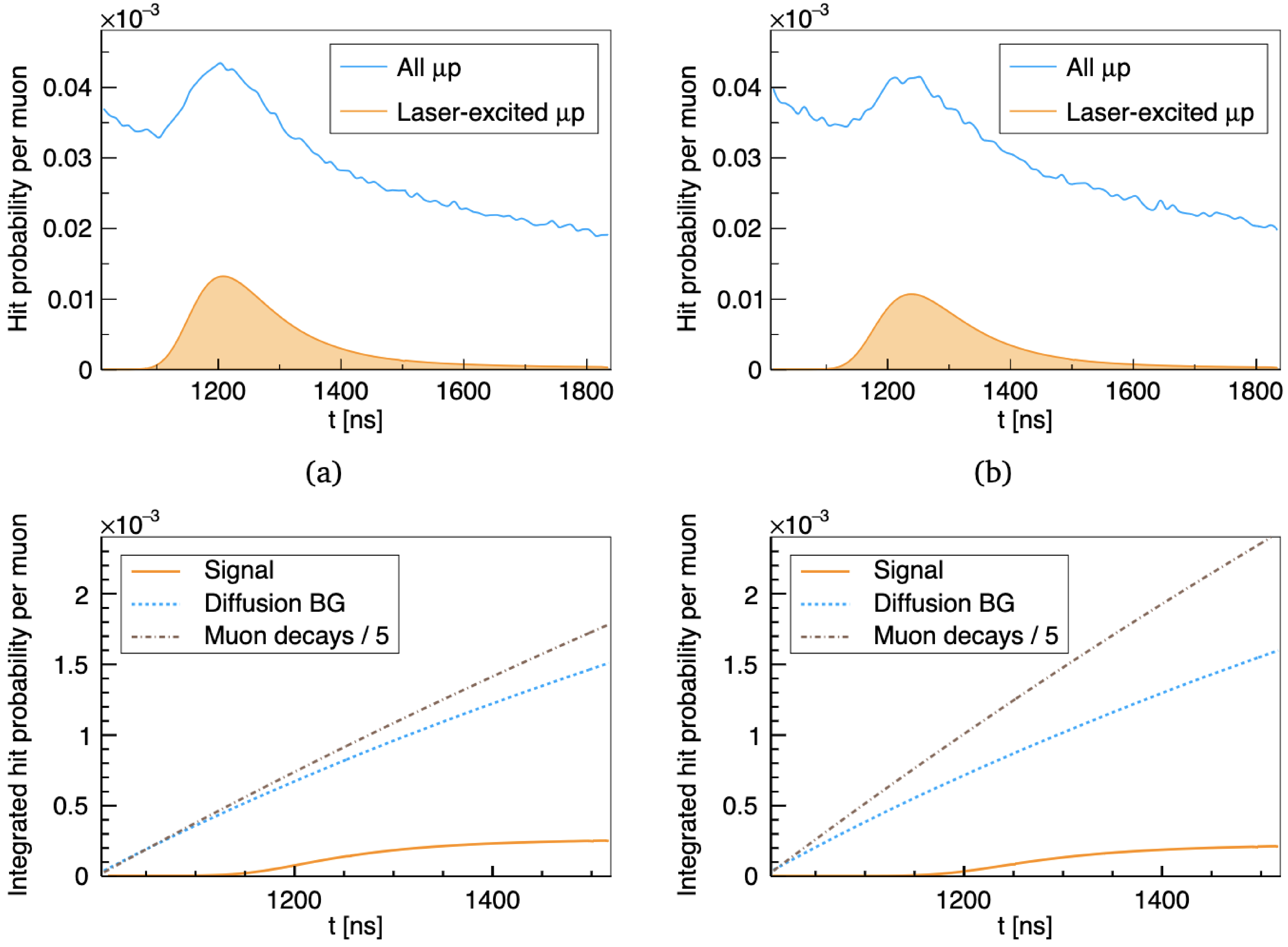


Signal shape

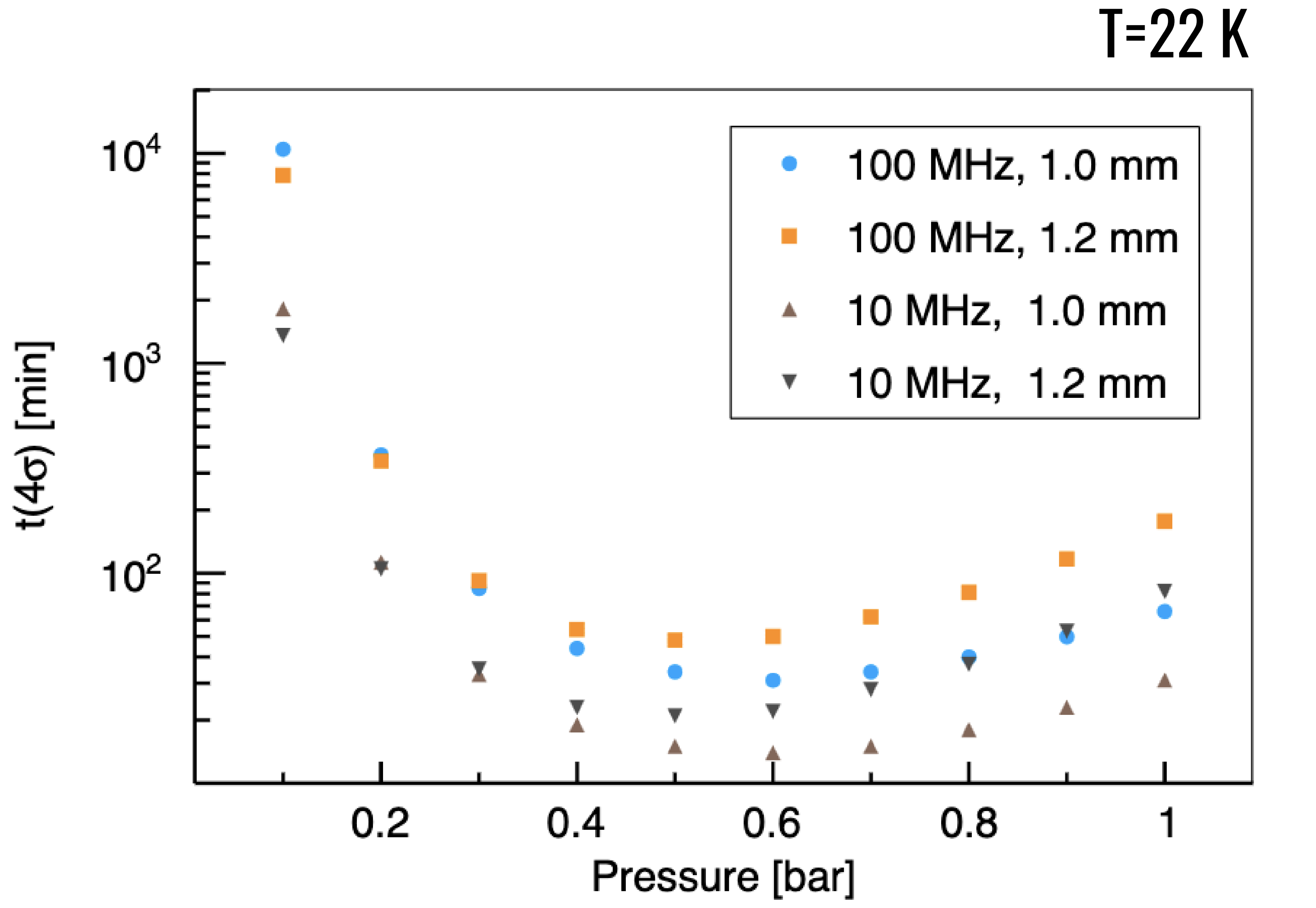
Laser excitation/collisional de-excitation



Monte-Carlo results HyperMu



J. Nuber *et al*, SciPost Phys. Core 6 57 2023



Concluding remarks

Past μH Lamb shift

Accurate radius extraction

Proton radius puzzle is **still not** solved

Present μHe Lamb shift

Latest alpha and helion radius measurements

Agreement with most of previous exps.

Future μH hyperfine structure

Introduction and challenges

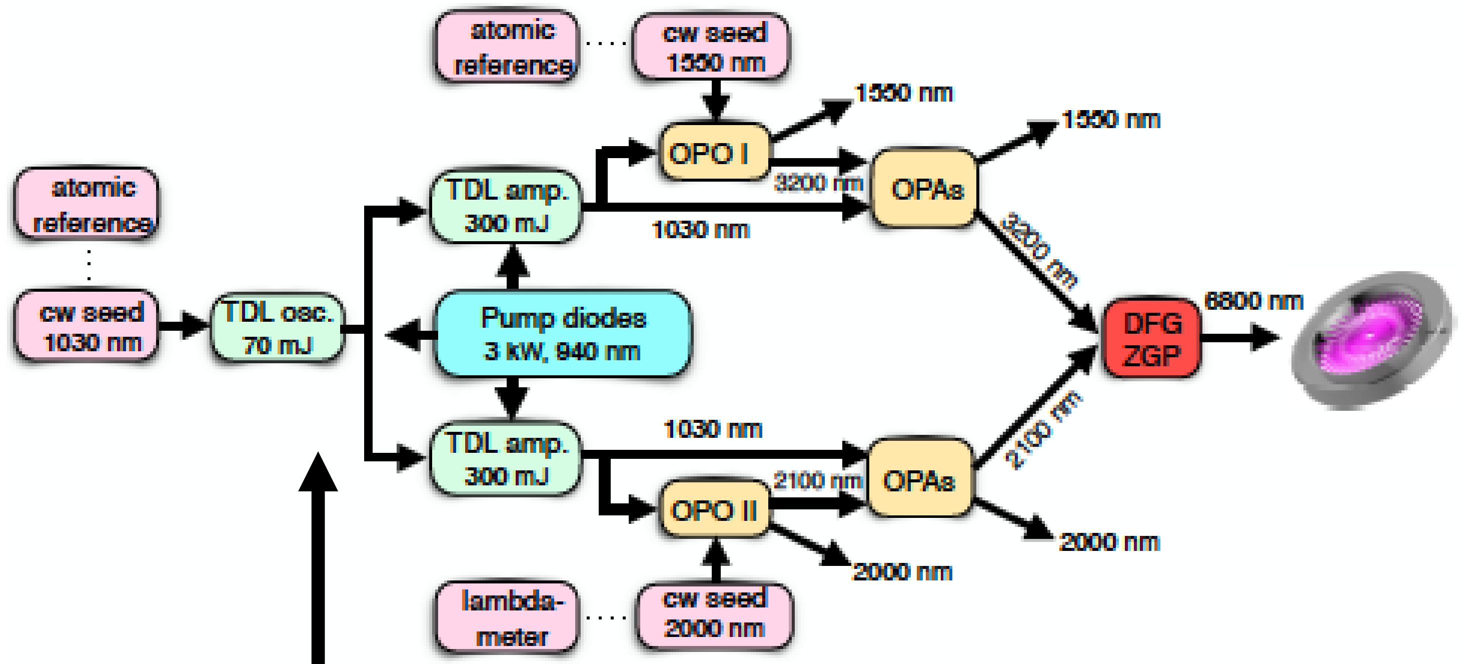
Exp model gives 10-60 min for 4σ detection

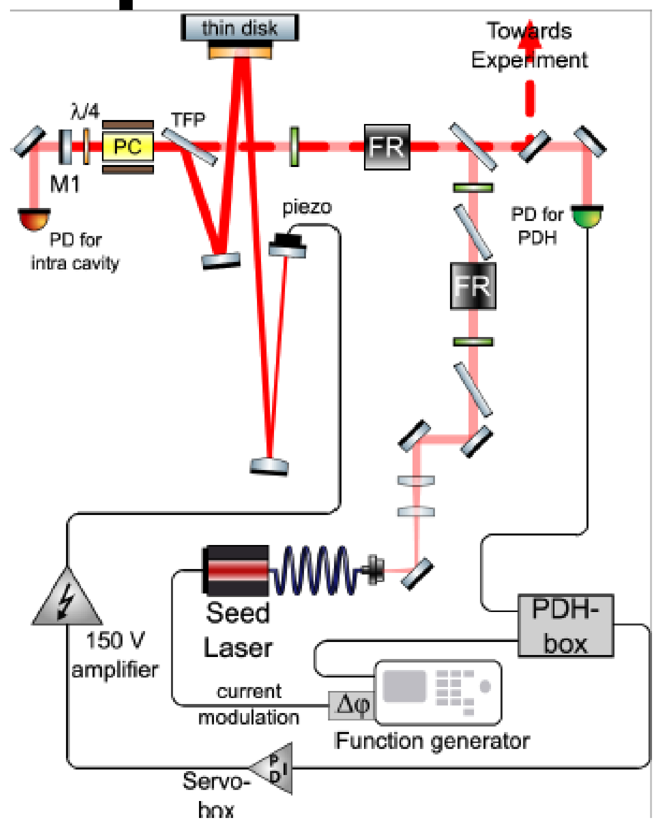
Hyperfine splitting of muonic hydrogen

- Preparations and prospects for the measurement

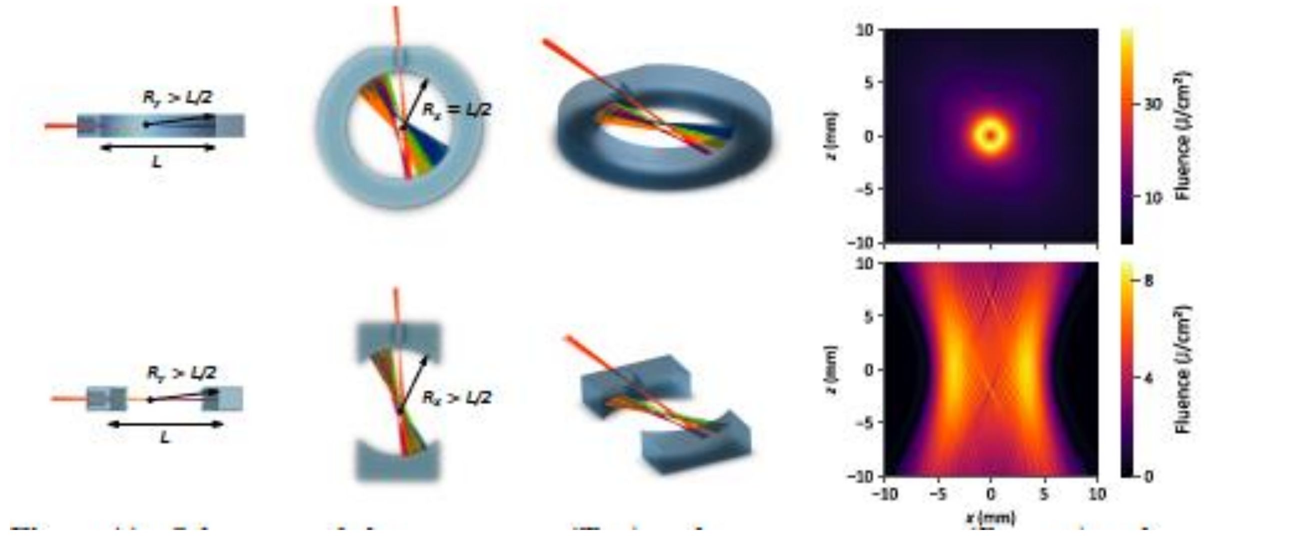
Laser system development

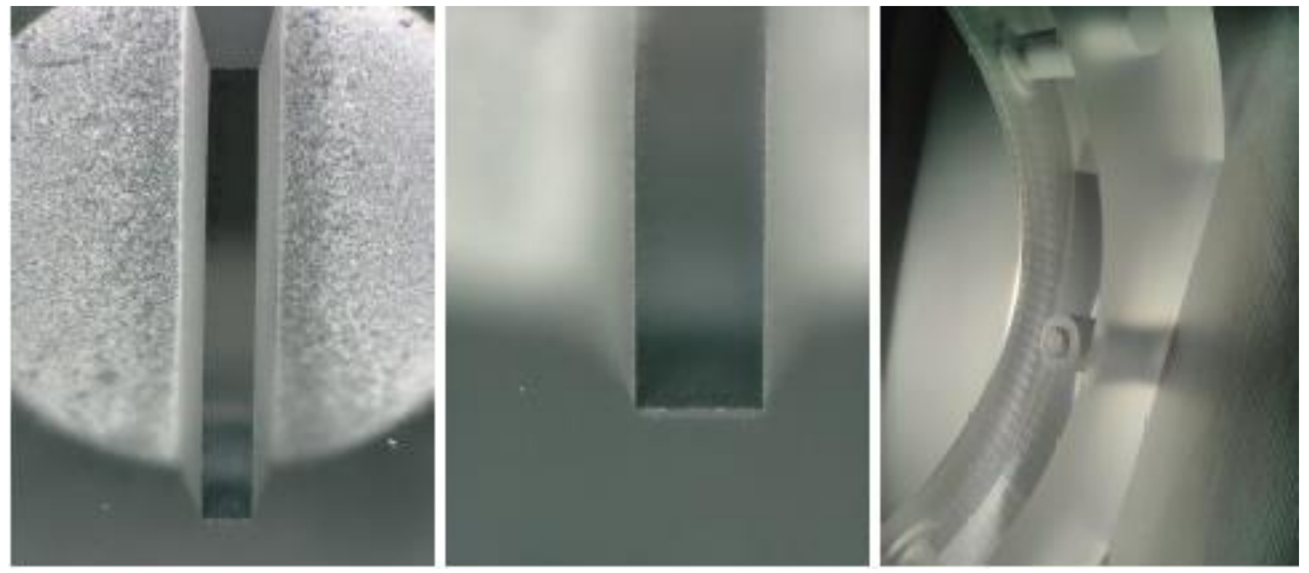
Patent: European Patent Office entitled *Powers scalable optical system for nonlinear frequency conversion*

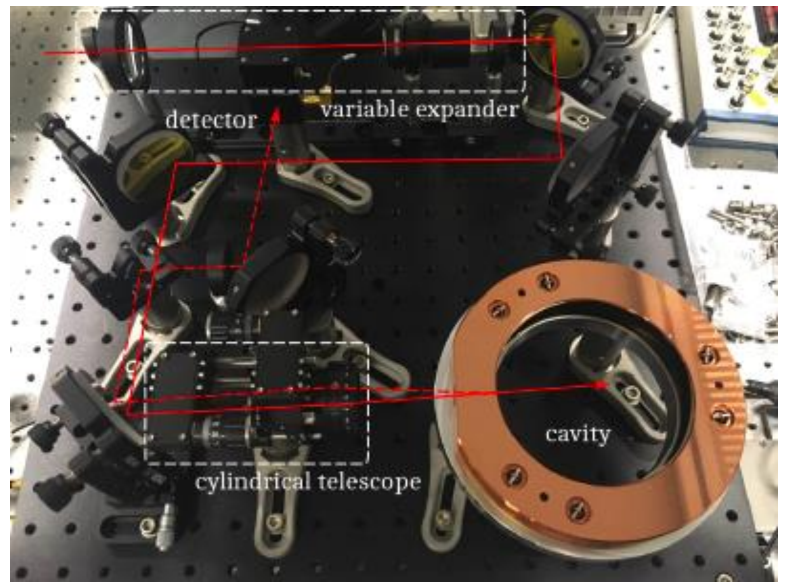




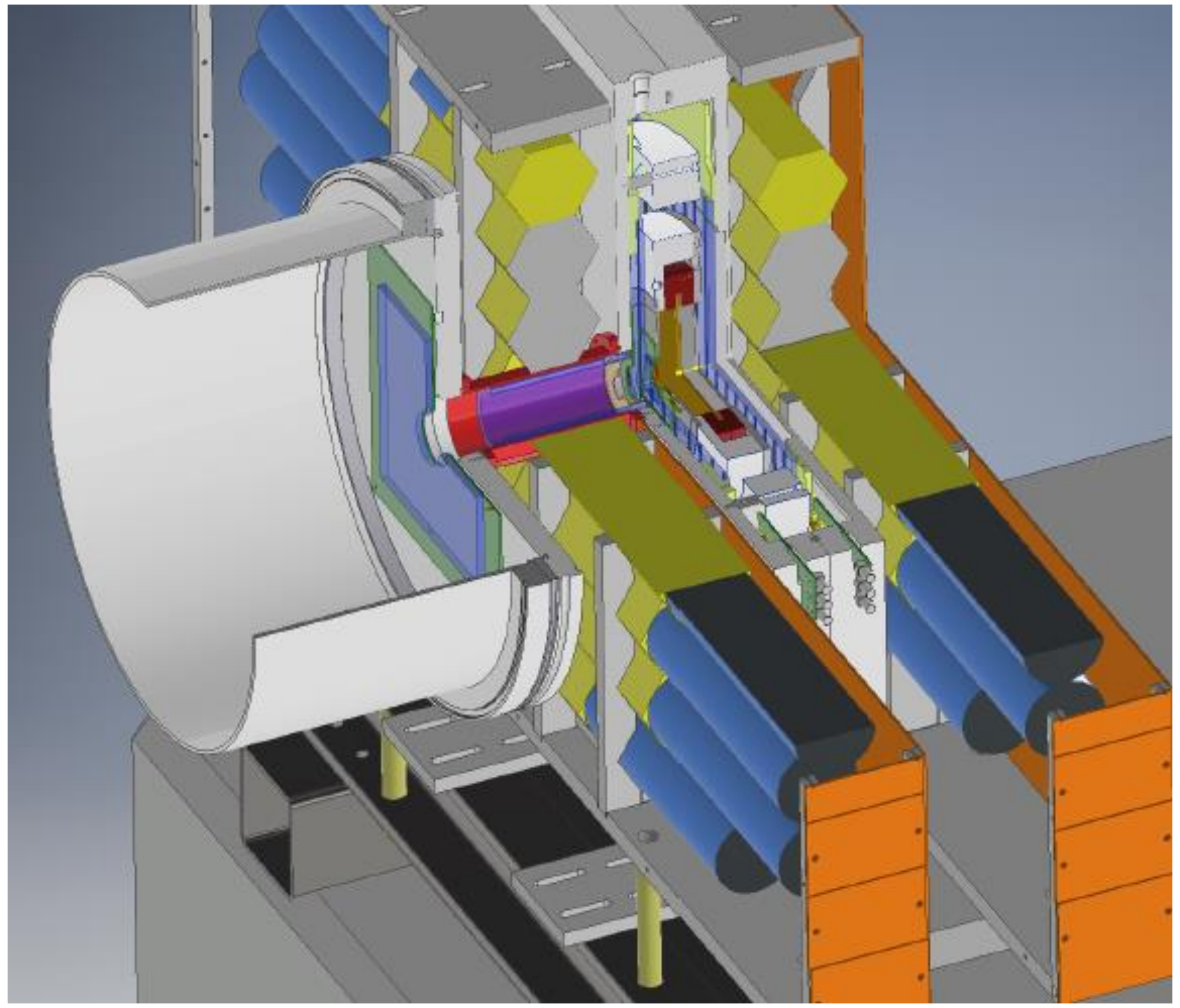
Target cavity







Detector system




Thank you!