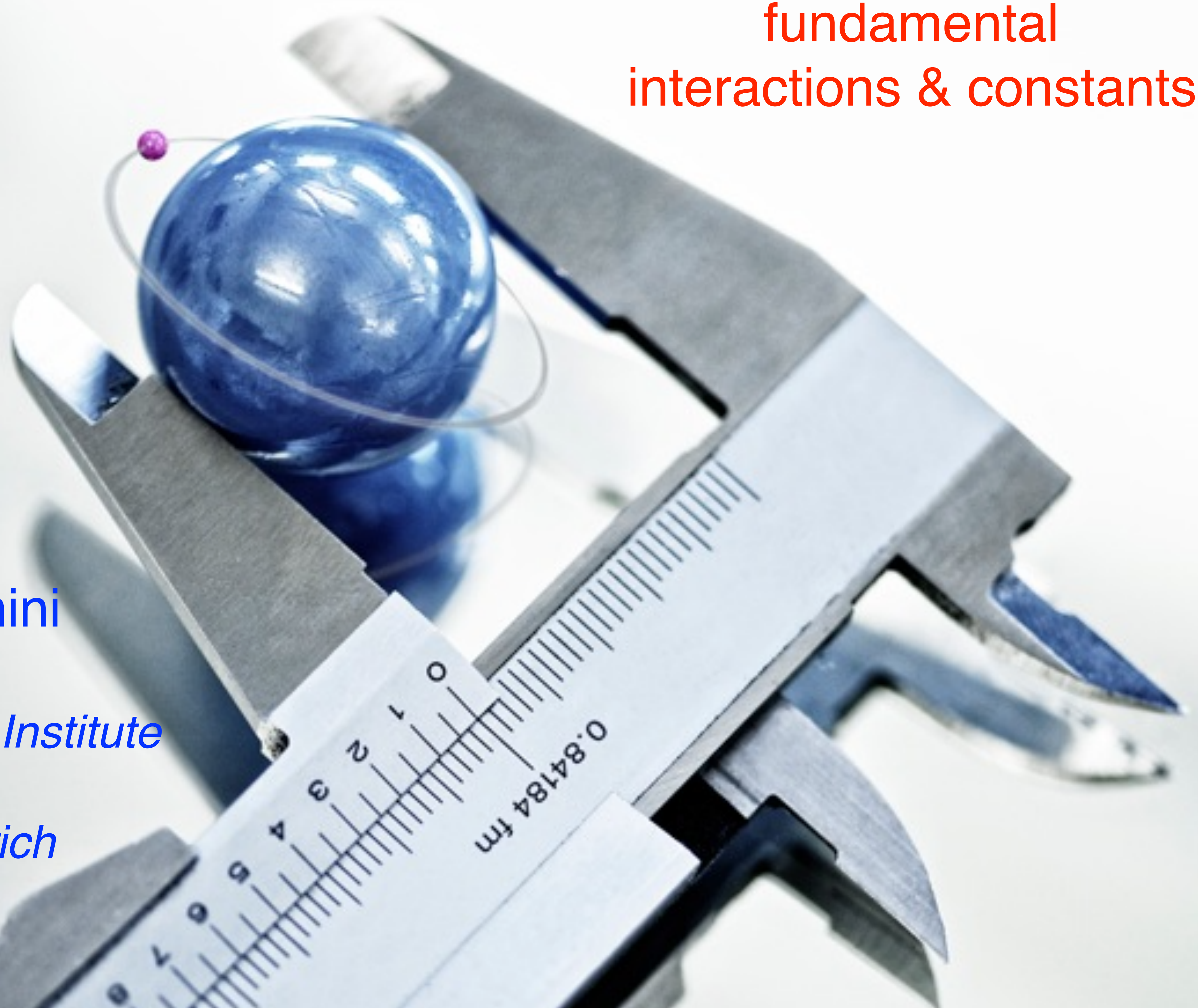
Exotic atoms

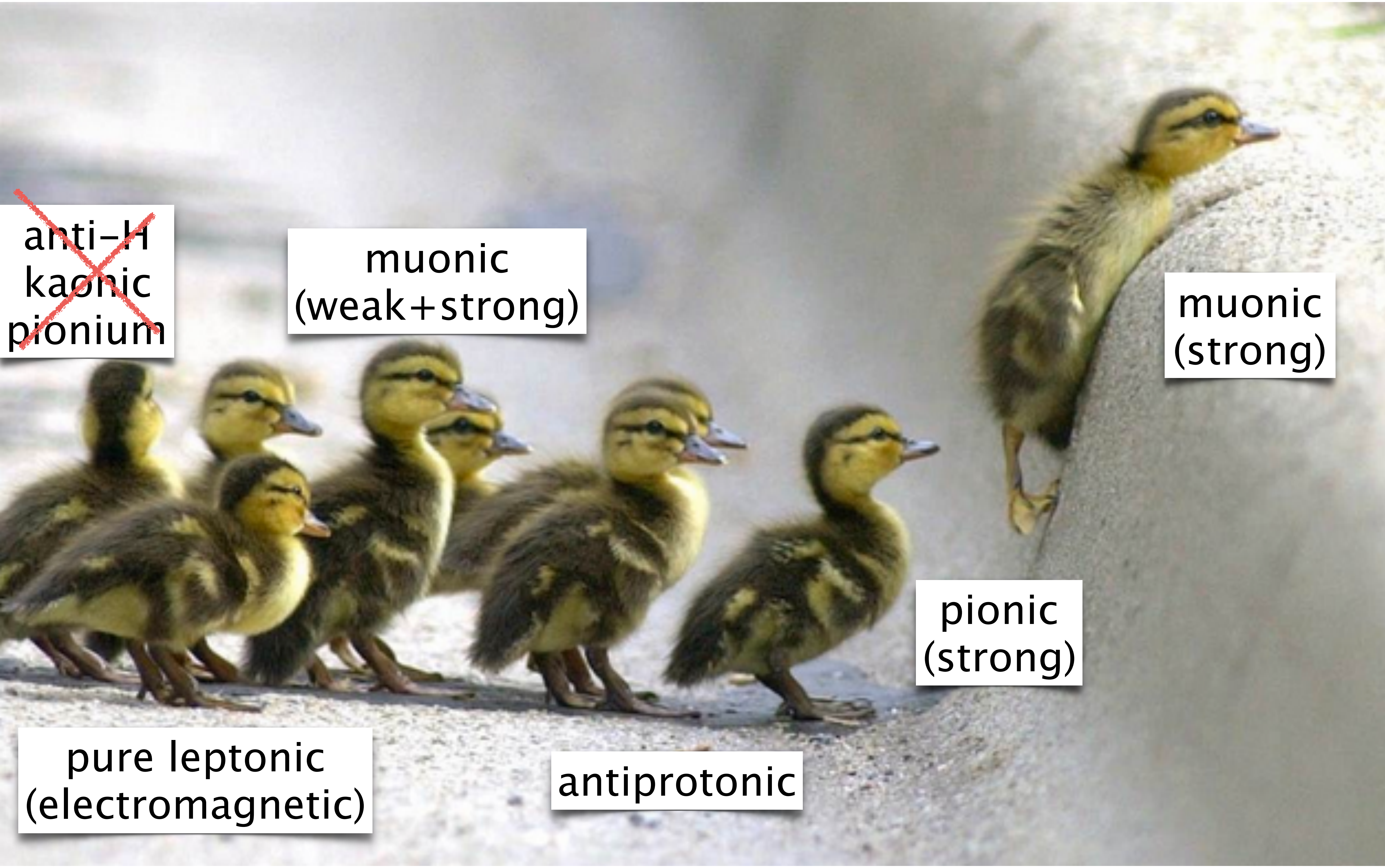
fundamental interactions & constants



A. Antognini

Paul Scherrer Institute
&
ETH, Zurich

A walk through exotic atoms by examples

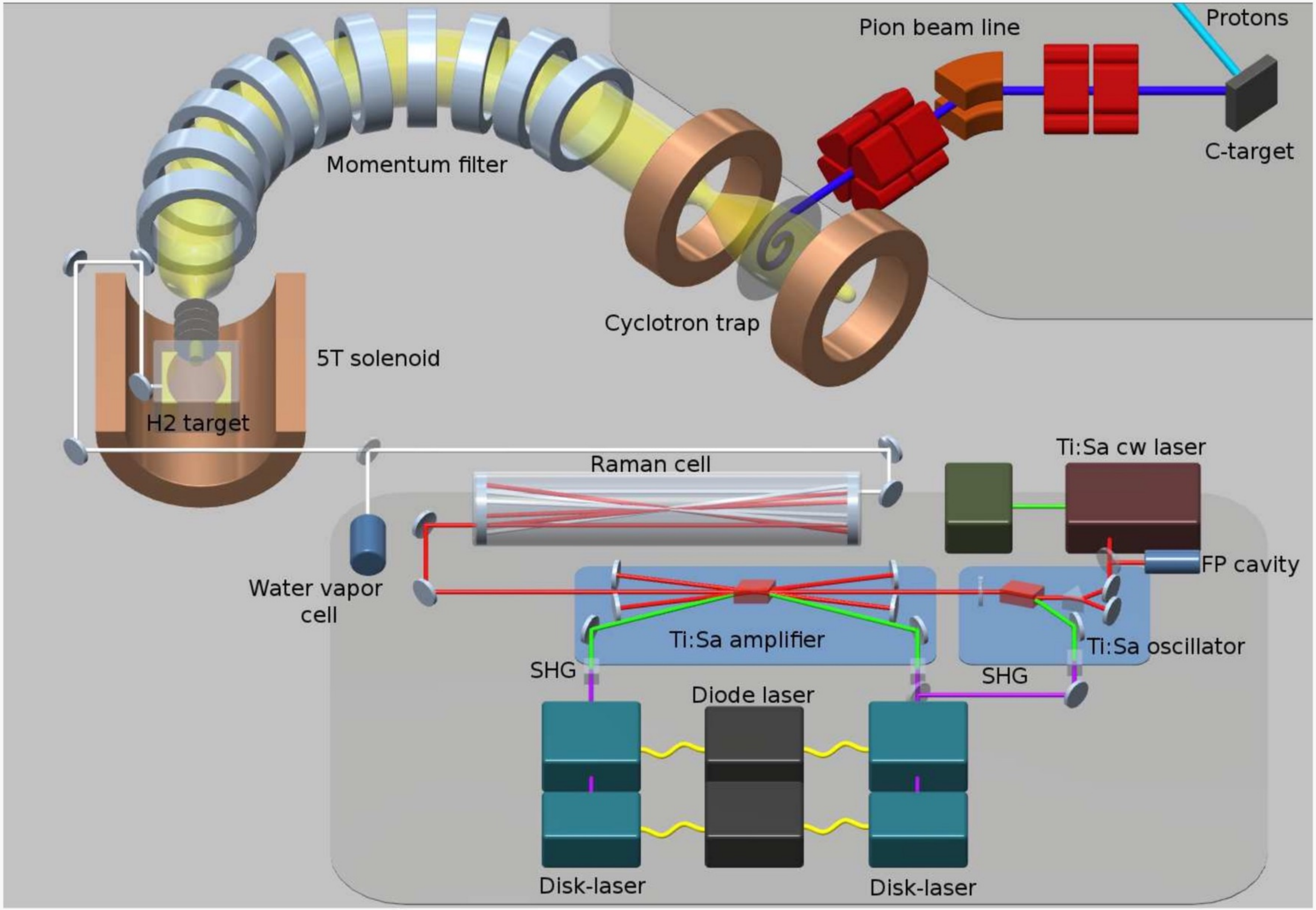


Laser spectroscopy of μp, μd, μ^3He and μ^4He

The CREMA collaboration has measured ten 2S-2P transitions in μp, μd, μ^3He and μ^4He
→ nuclear charge radii

The setup

p-beam (1 MW)
↓
π (MeV)
↓
μ (MeV)
↓
μ (keV)
↓
μp(2S)
↓
Laser
↓
X-ray



940 nm (2 kW)
↓
1030 nm
↓
515 nm
↓
708 nm
↓
1.0 μm
↓
1.6 μm
↓
6.0 μm

Extracting the proton radius from µp

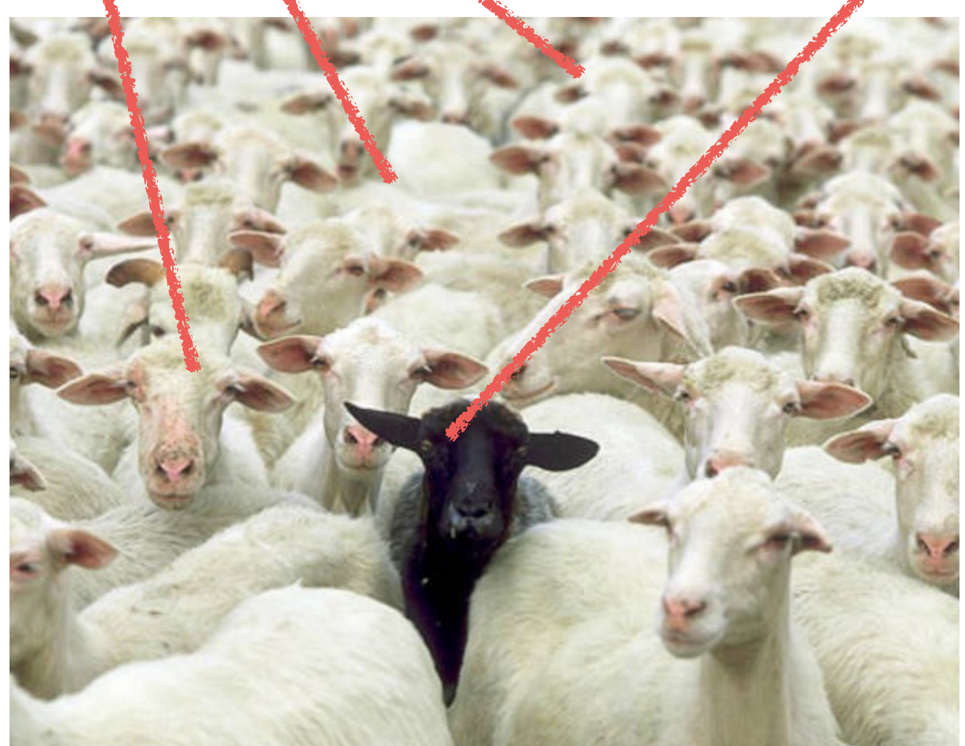
Measure 2S-2P splitting and compare with theory → proton radius

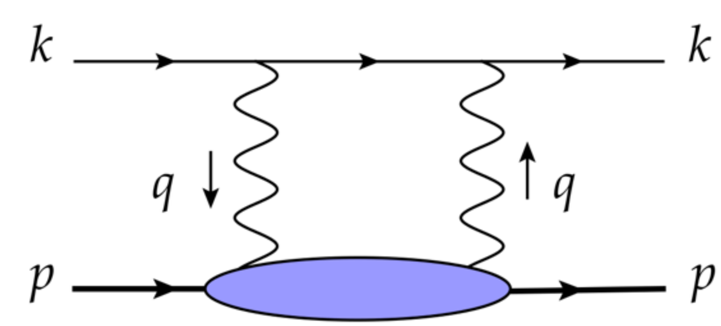
$$\Delta E_{\text{size}} = \frac{2\pi(Z\alpha)}{3} r_{\text{p}}^2 \, |\Psi_{nl}(0)|^2 = \frac{2(Z\alpha)^4}{3n^3} m_r^3 \, r_{\text{p}}^2 \, \delta_{l0}$$

$m_\mu \approx 200 m_e$

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

talk: Pachucki

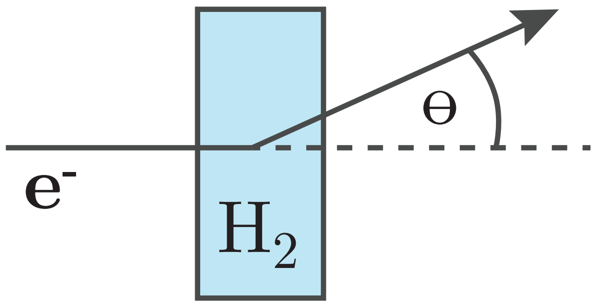




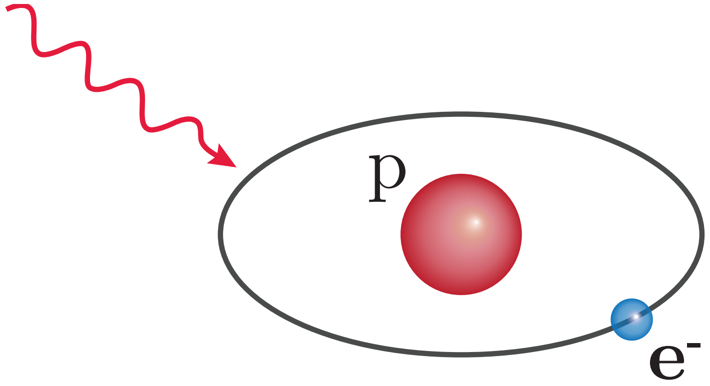
Pachucki, Borie, Eides, Karschenboim, Jentschura, Martynenko, Indelicato Pineda…

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

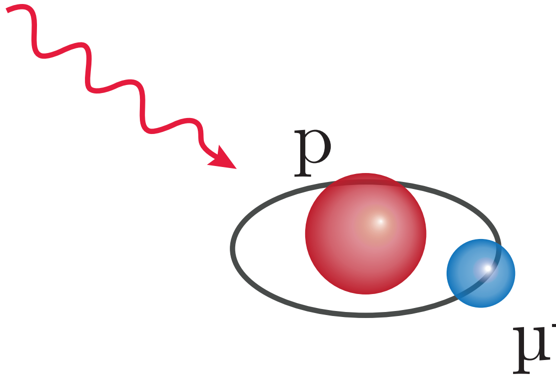
Proton radius puzzle



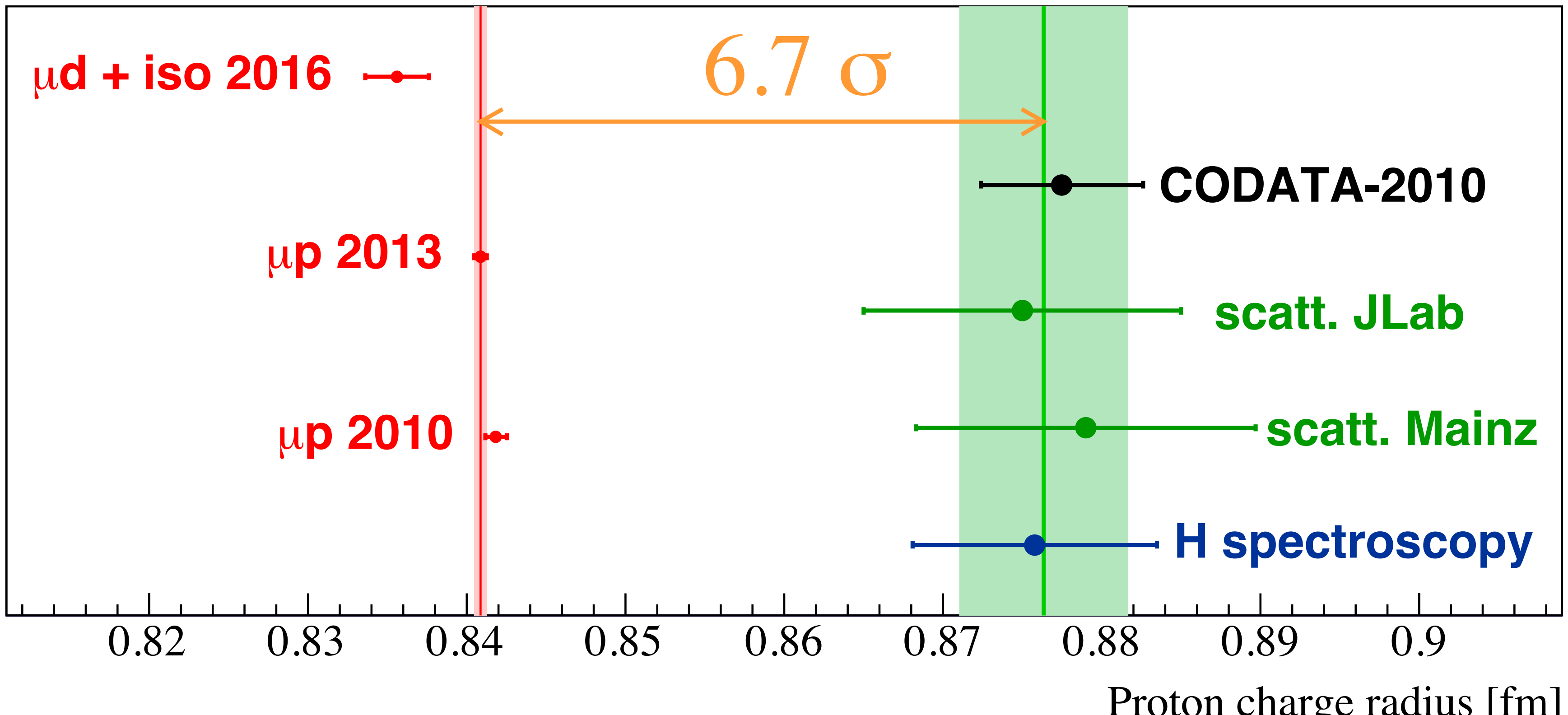
e⁻-p scattering



H spectroscopy



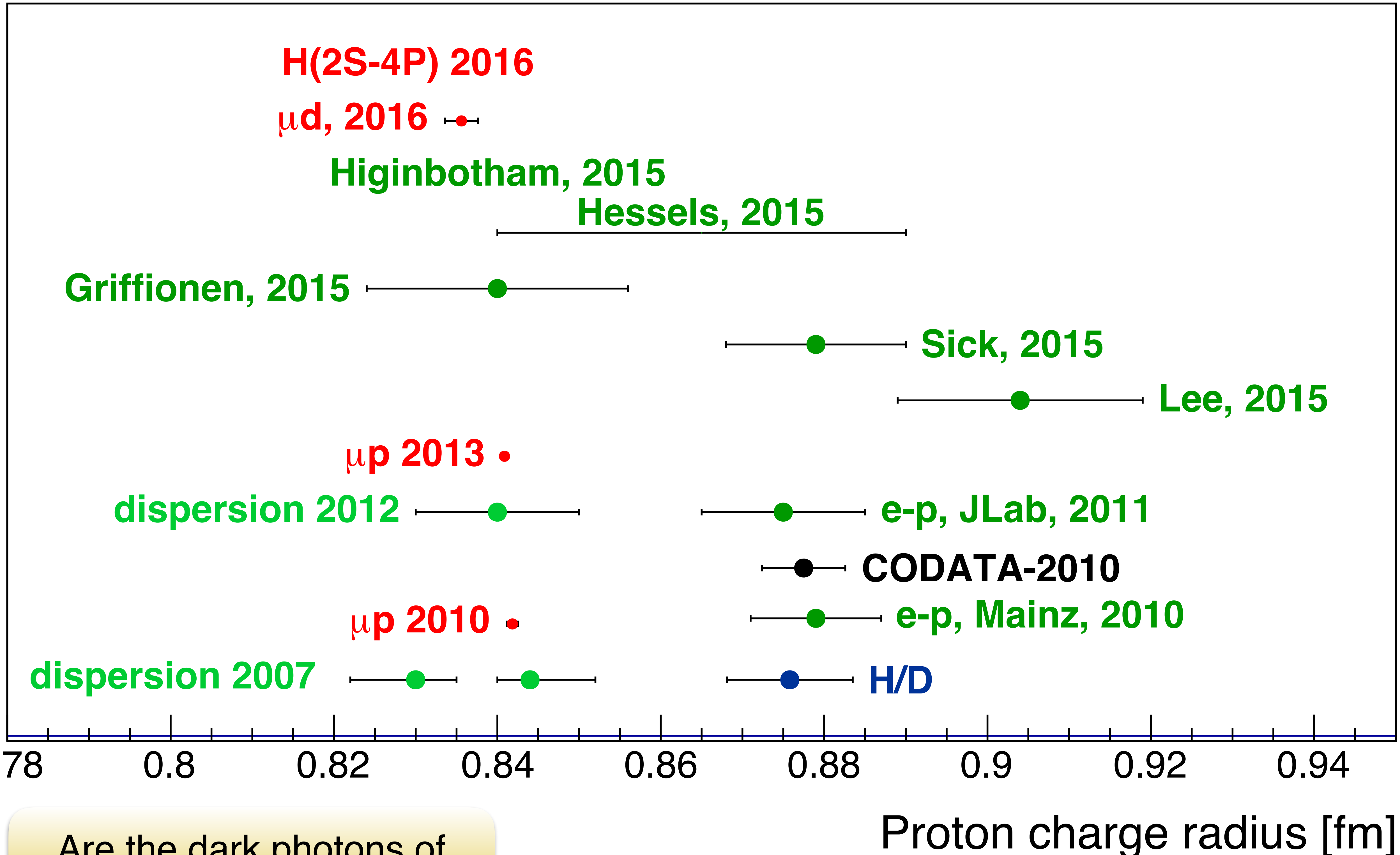
μp spectroscopy



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

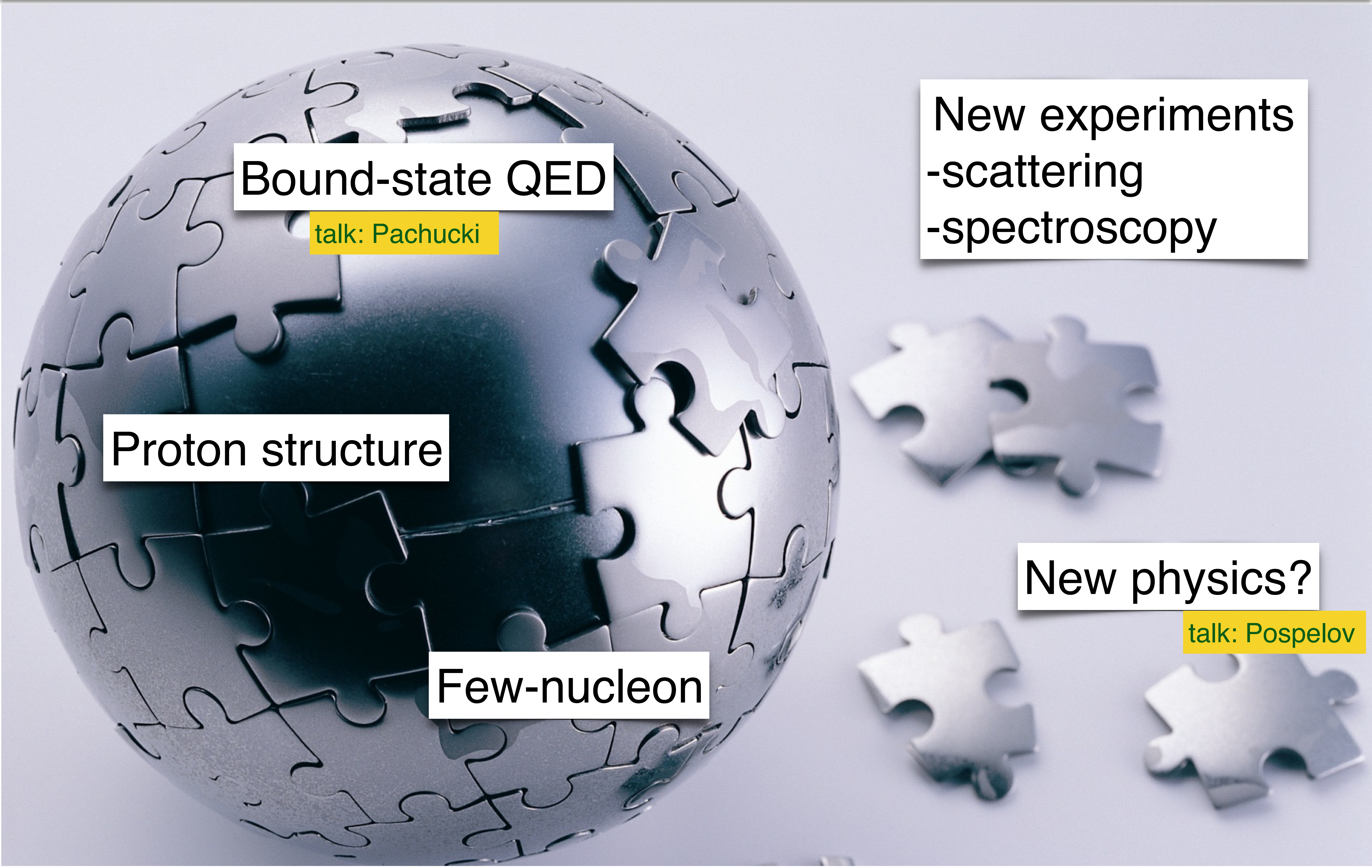
talk: Krauth

Towards resolution of the proton radius puzzle?

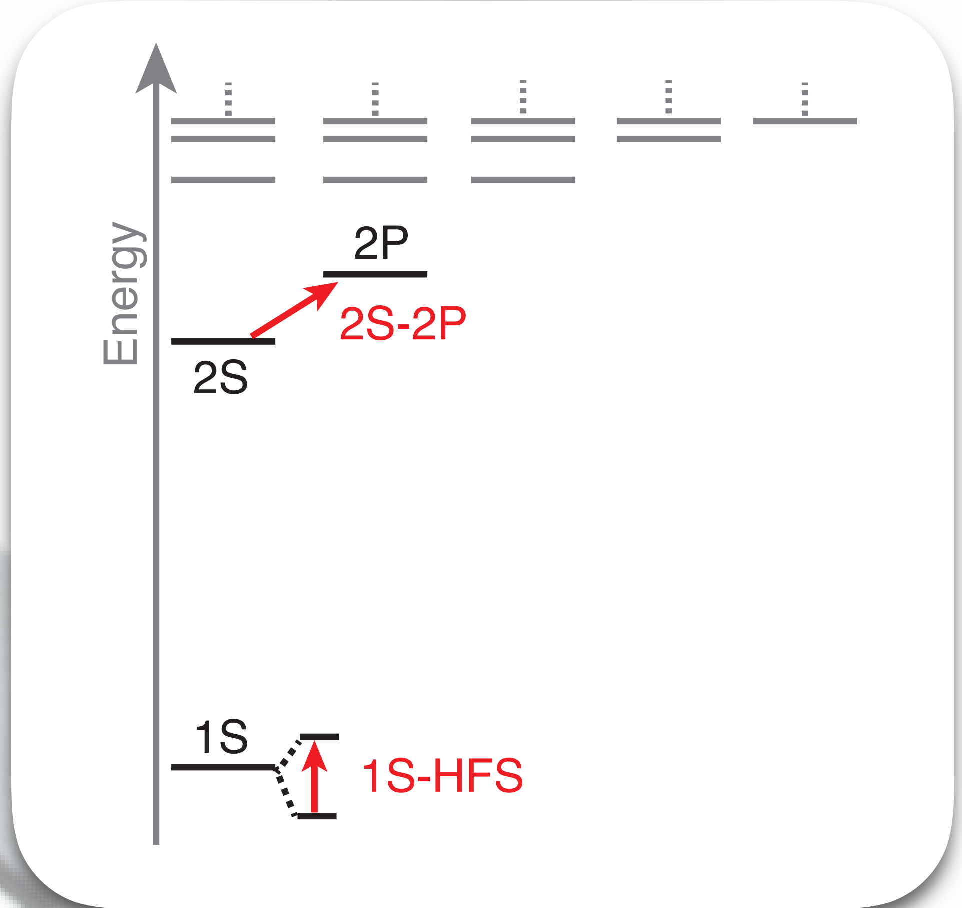


Are the dark photons of Maxim back to business?

The r_p puzzle has triggered many activities



Next generation experiments: HFS



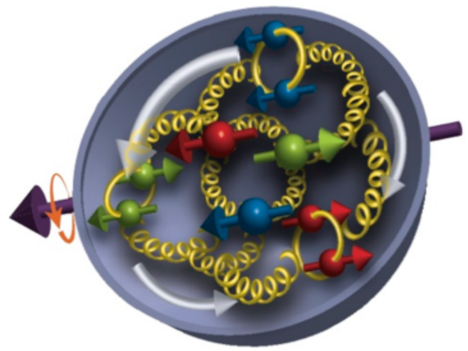
- 2S-2P μp
- 2S-2P μd
- 2S-2P μ^{3}He, μ^{4}He
- 1S-HFS μp
- 1S-HFS μ^{3}He

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

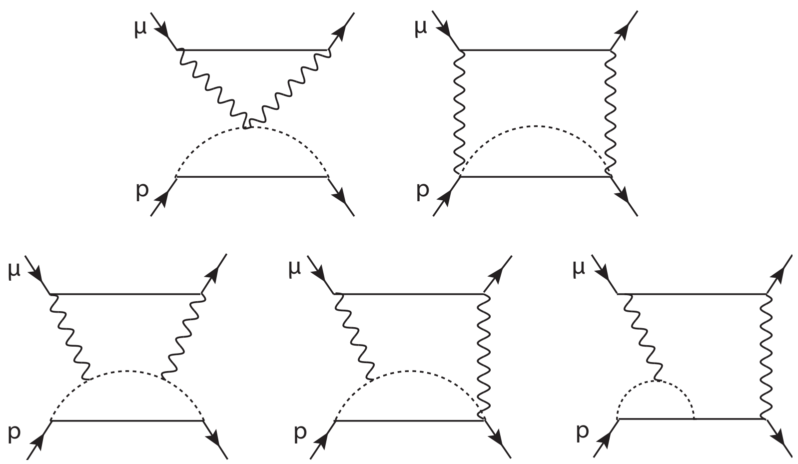
Vacchi et al.

talk: Iwasaki

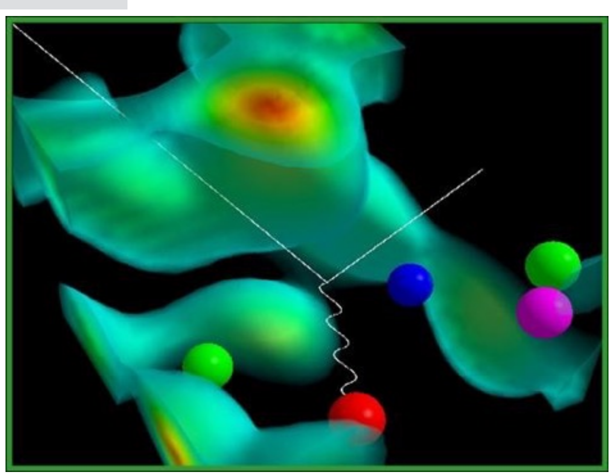
Impact: radii, polarizabilities contributions and R_∞

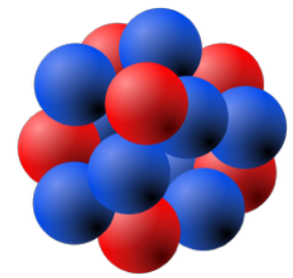


Chiral PT

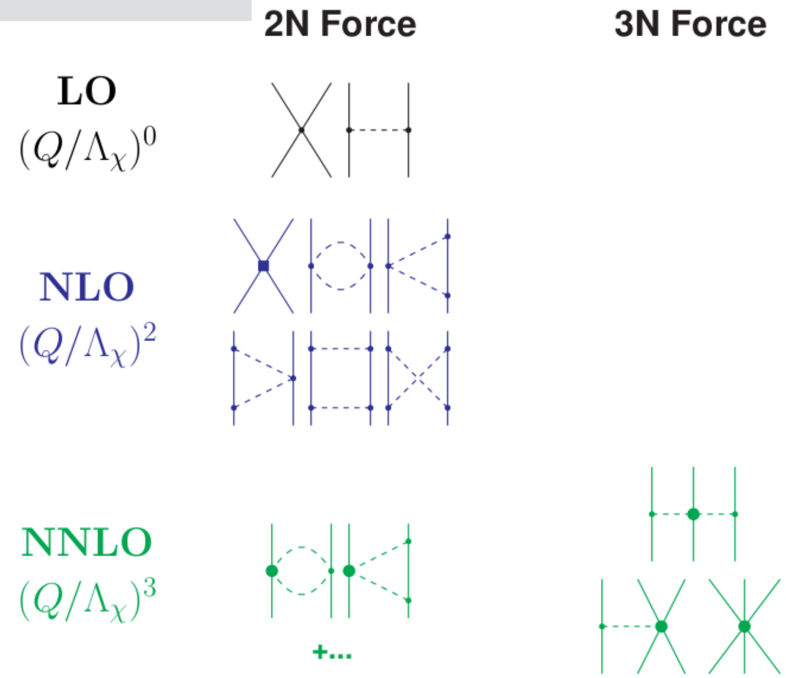


Lattice

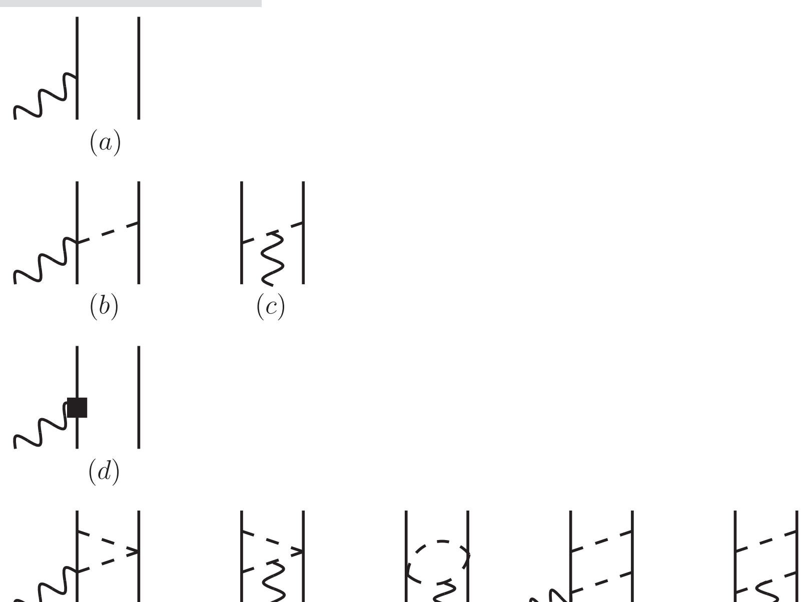


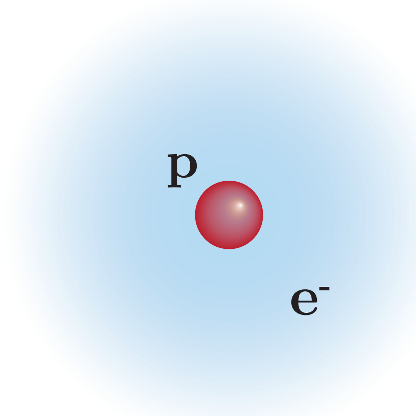


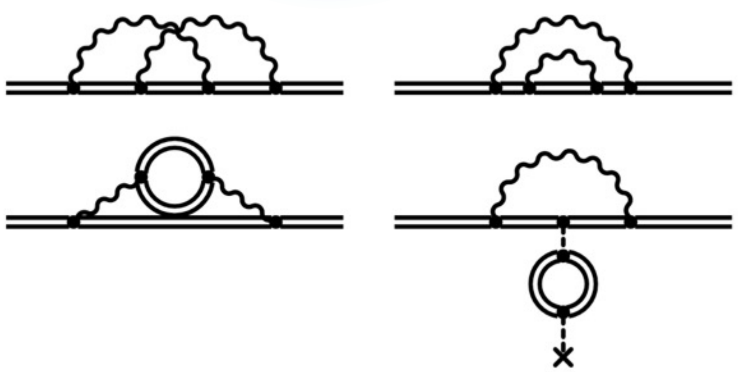
Potential



Currents

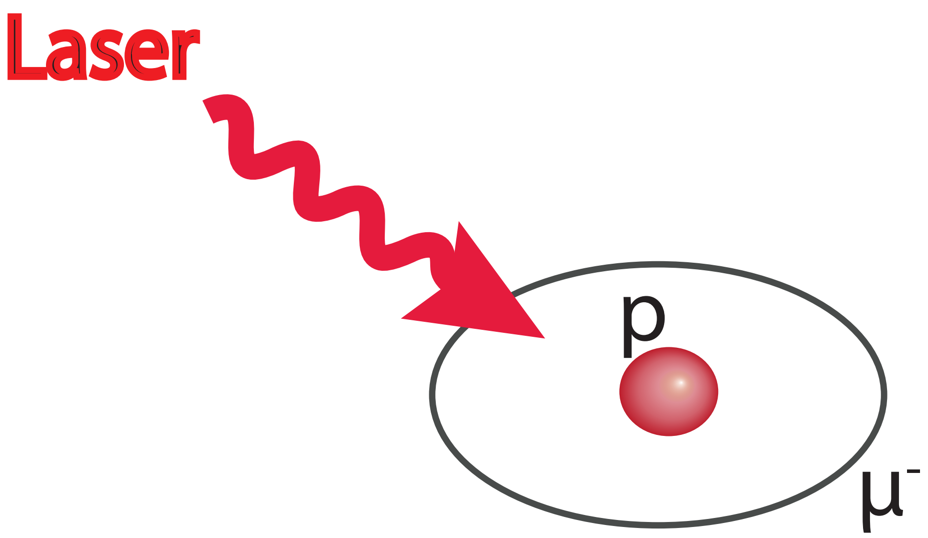


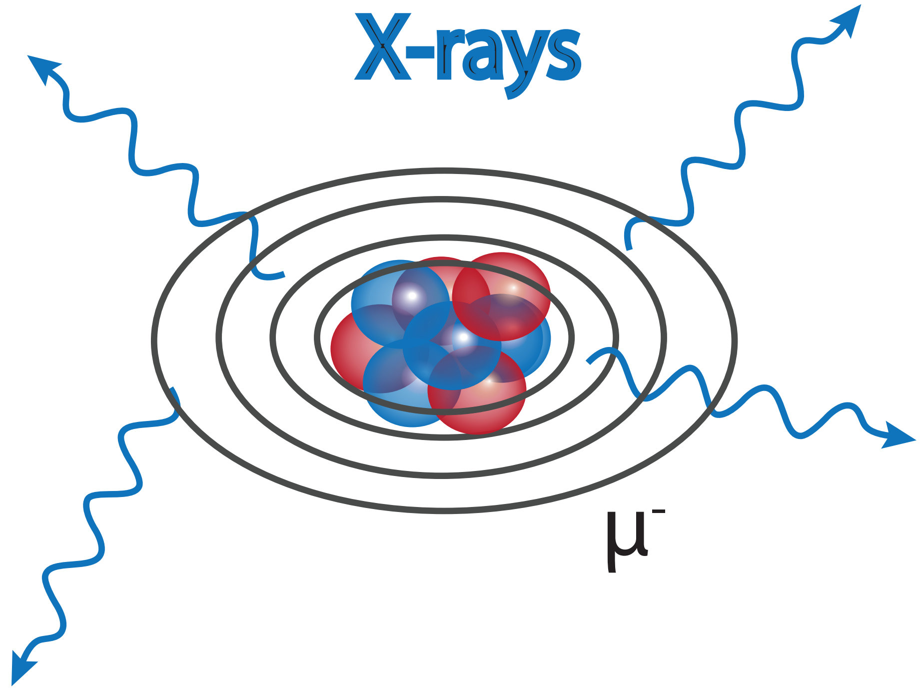




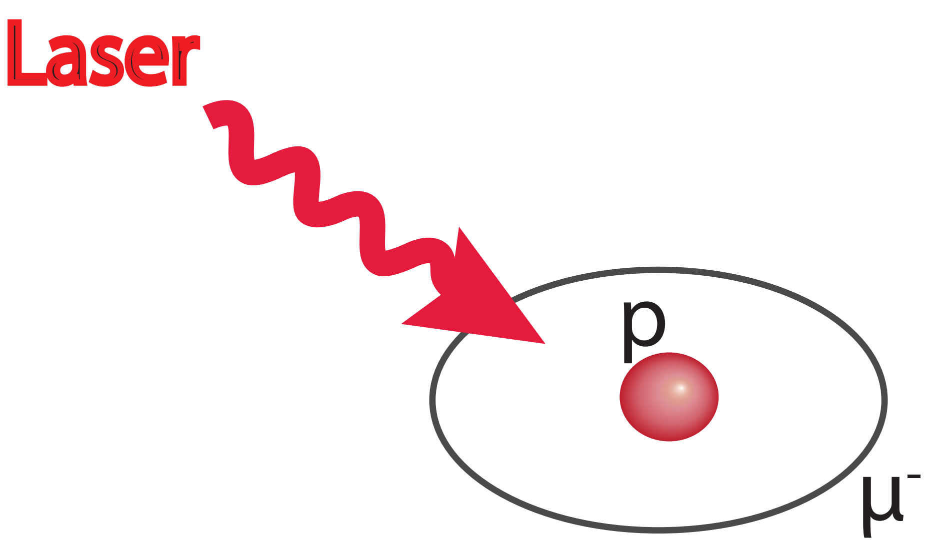
- Chiral pert. th.
- Lattice
- Dispersion relations
- Few-nucleon th.
- bound-state QED
- distribution functions
- spin structure
- currents
- ....

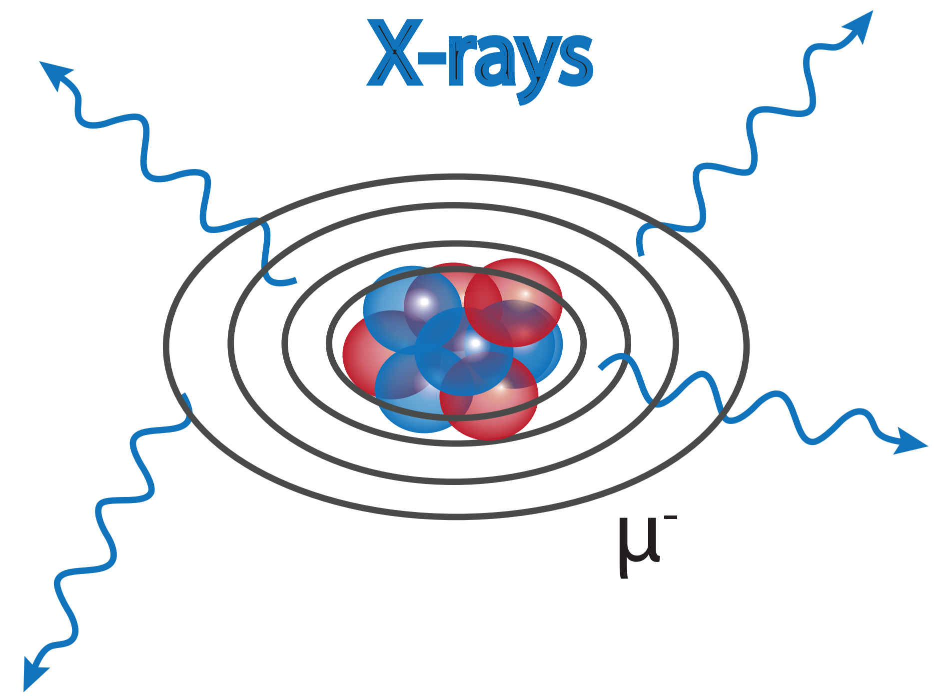
X-ray spectroscopy of high-Z muonic ions (μZ)





X-ray spectroscopy of high-Z muonic ions (μZ)

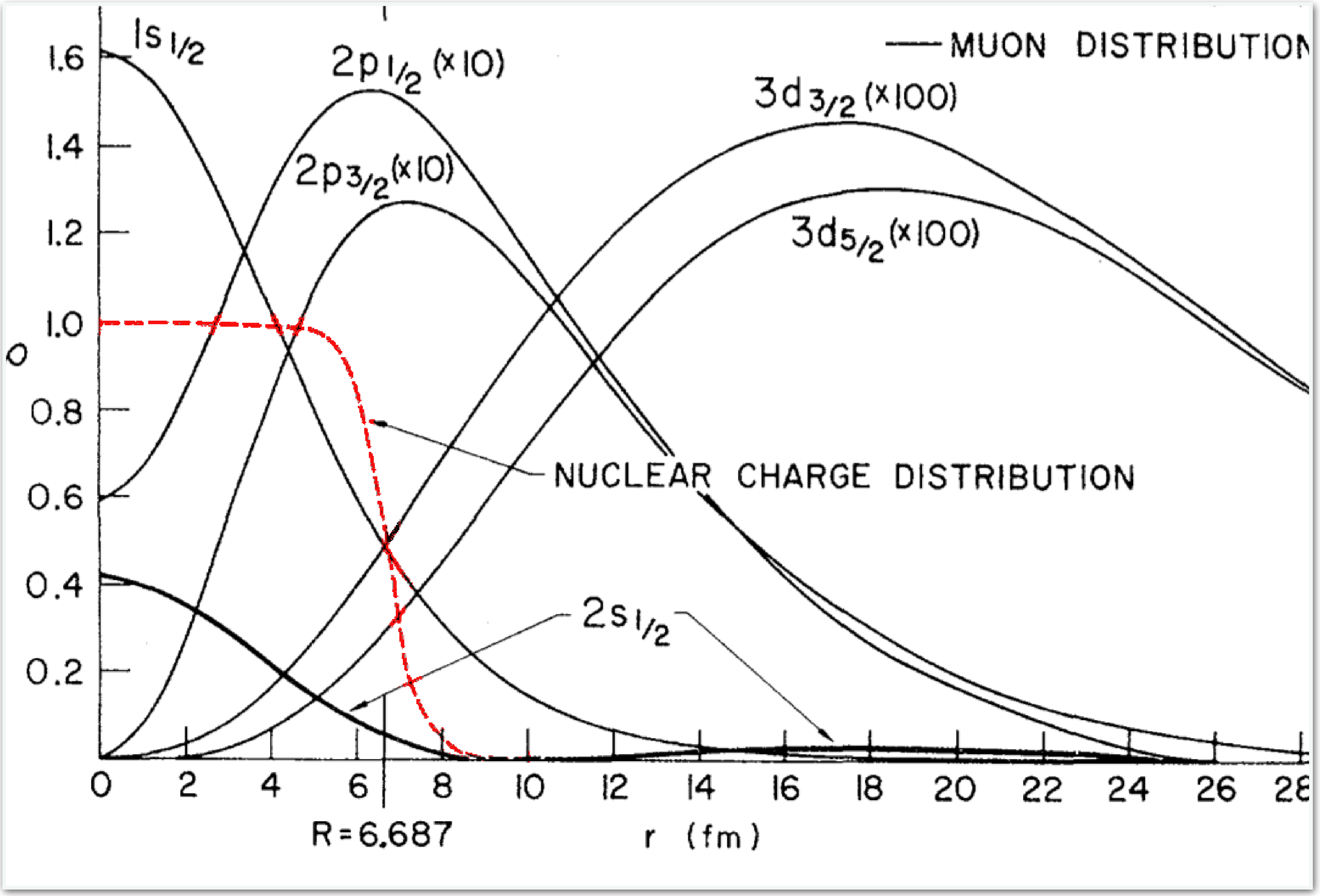




Muonic atoms are formed
in highly excited states n∼14

Measure the X-rays
emitted during the de-excitation

Huge overlap of μ-wave function with nucleus



Finite-size effects can not be treated perturbatively

High-Z muonic ions (μZ)

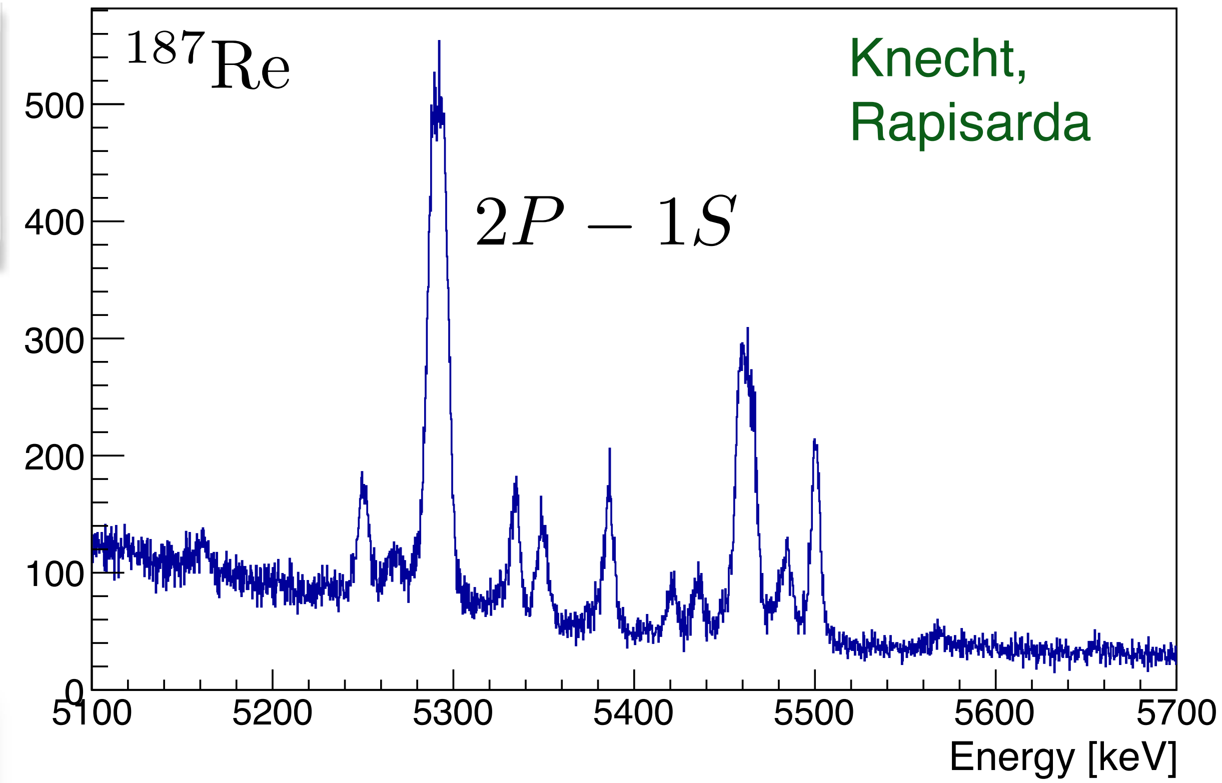
$$E \simeq \frac{m_\mu}{m_e} R_\infty Z^2 \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right) - \Delta E_{\text{size}}$$

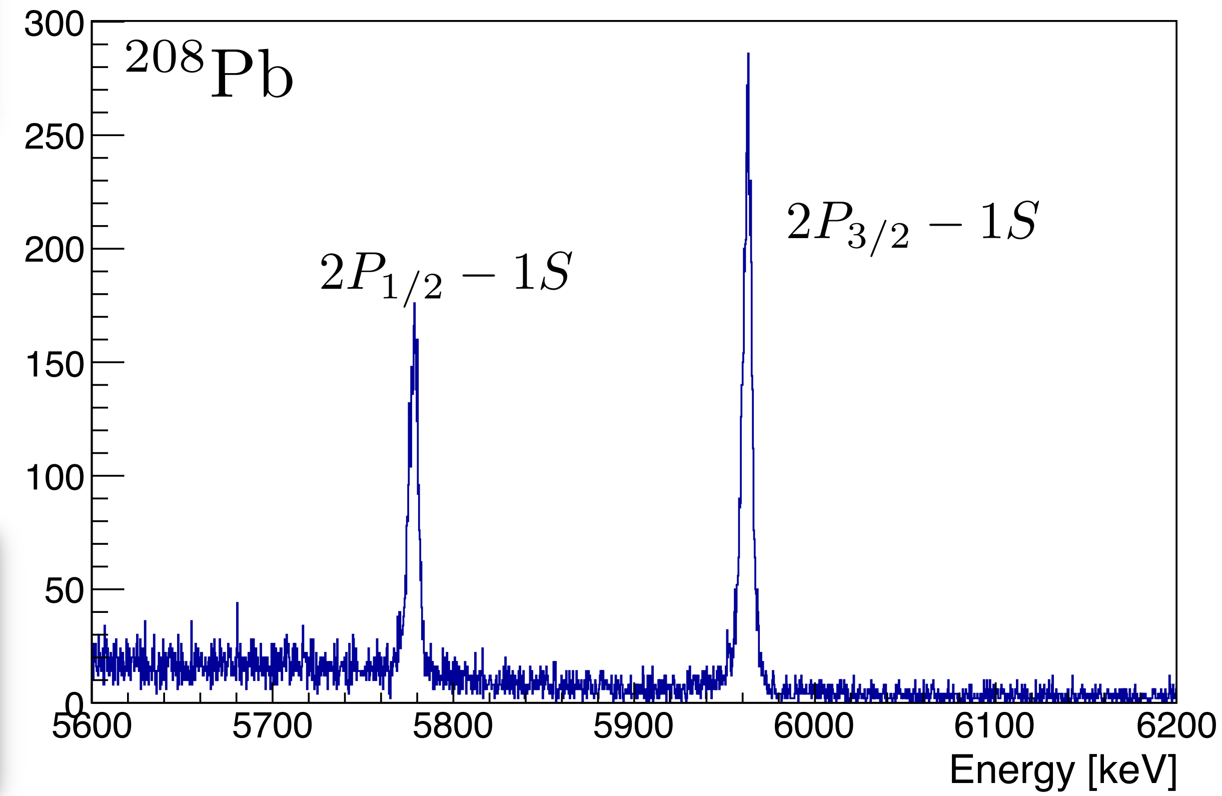
- H-like atoms
- MeV transition energies
- MeV finite-size effects

Measure
- Cascade X-rays
- with Ge detectors (0.1 keV acc.)

Extract
- charge radii via Barrets moments
- quadrupole moments

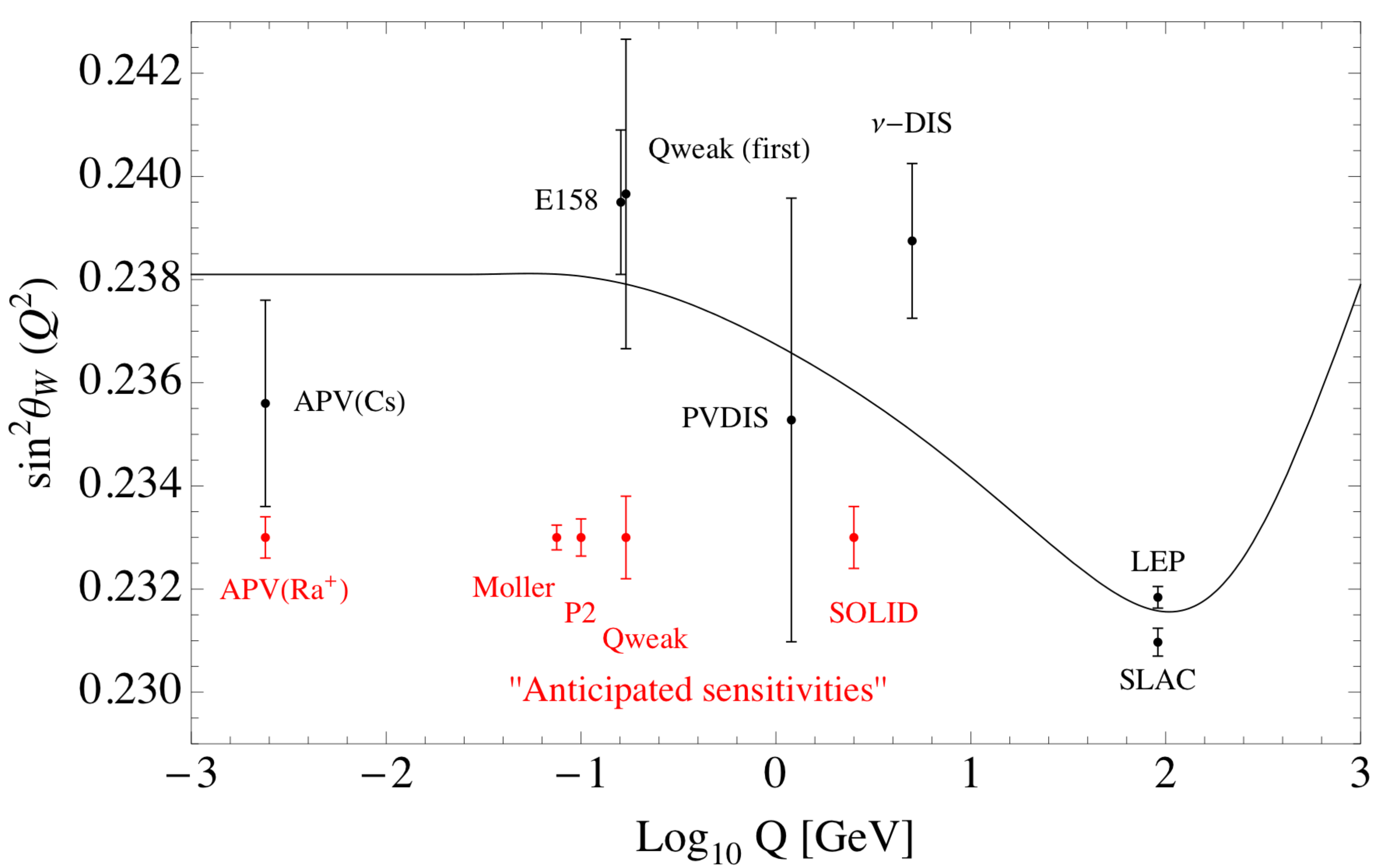
Complications
- nuclear polarisability
- nuclear excitation in final state





Impact of μZ ions

There is a renewed interest at PSI (muX collaboration)
to perform spectroscopy of μZ ions



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

Focus given to charge radii of radioactive nuclei: Radium, …

poster: Wauters

talk: Willmann

Workshop on Muonic Atom Spectroscopy

21 October 2016 *Paul Scherrer Institut*

Europe/Zurich timezone

Overview

Scientific Programme

Timetable

Call for Abstracts

- View my abstracts
- Submit a new abstract

Registration

- Registration Form

Key Dates

Venue

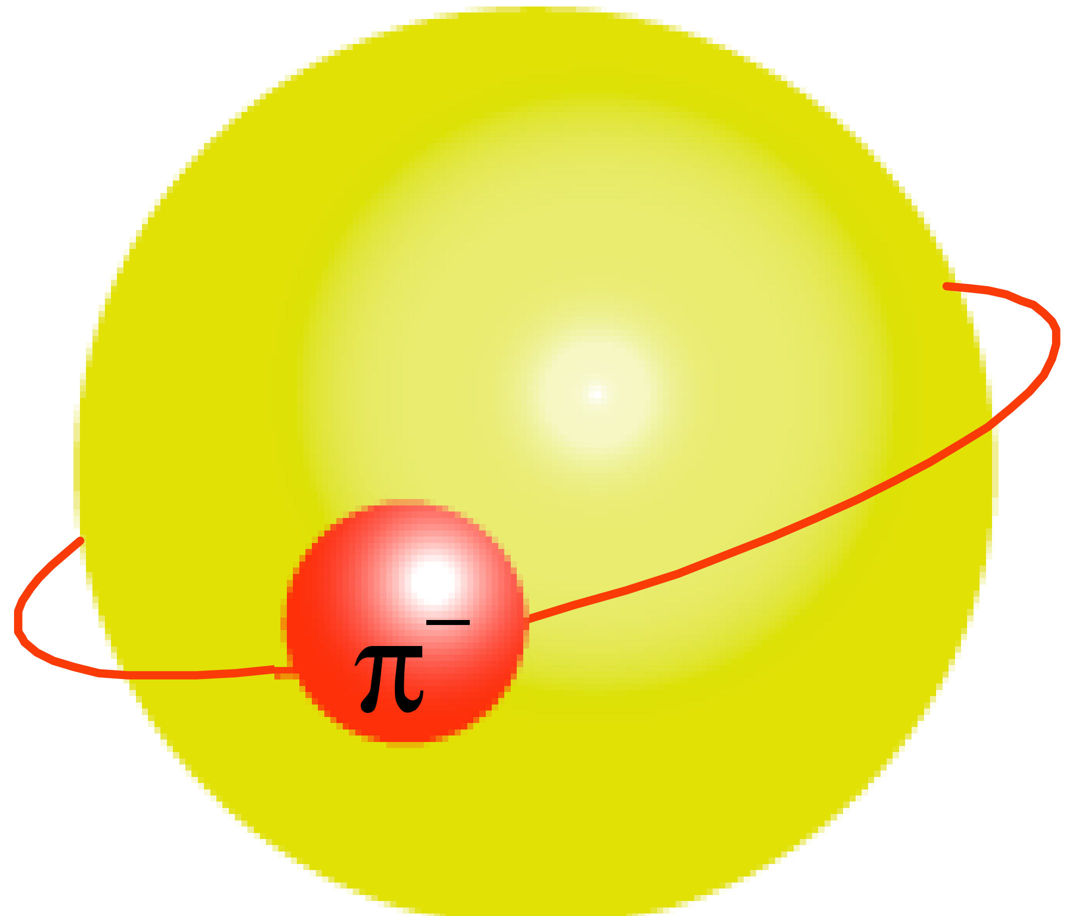
Accommodation

List of registrants

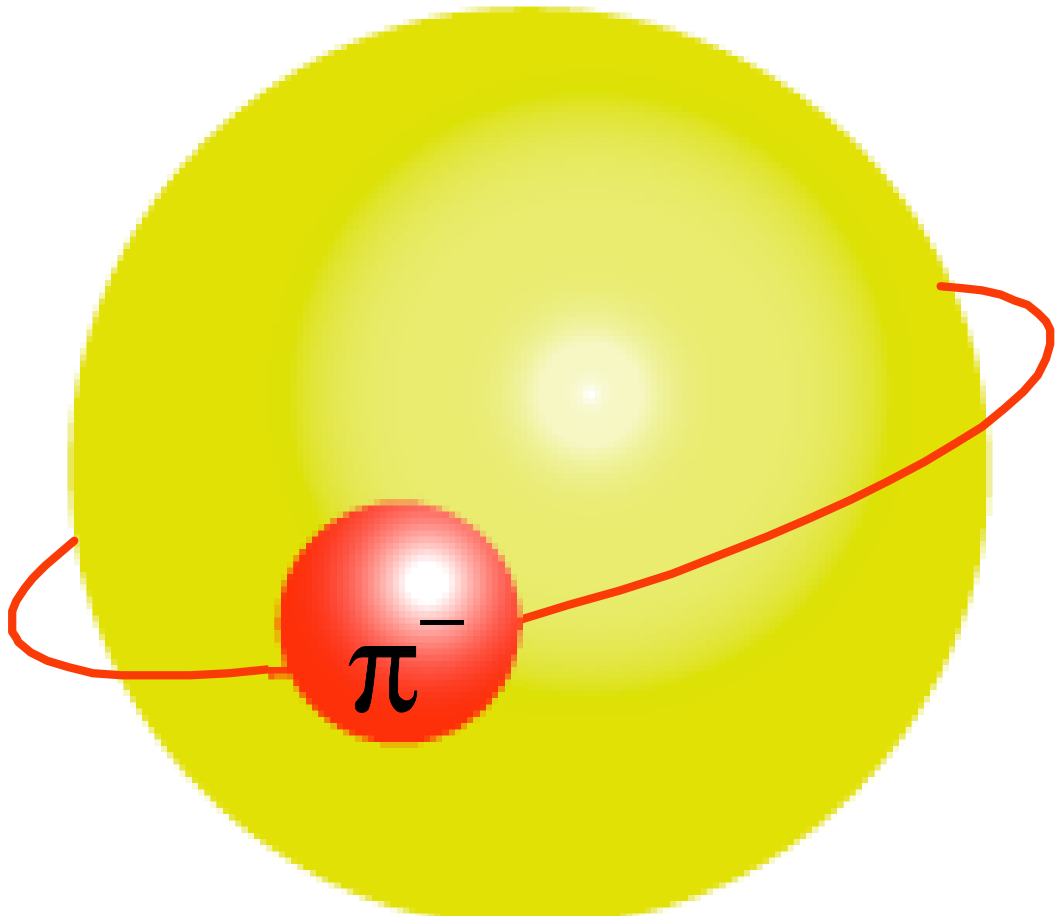
The workshop aims to bring together the physics community interested in performing high resolution muonic X-ray spectroscopy of medium and high-Z elements. While muon beam intensities and quality have been improved in recent years at PSI, still muonic X-rays have never been studied with highly efficient multi-Ge-detector arrays covering large solid angles. Such advancements open the way to the measurements of nuclear charge radii in radioactive elements and of atomic parity violation effects in muonic atoms. From the fruitful exchange between participants, the workshop aims to strengthen the physics case of these measurements and to discuss future plans and ideas.

Dates:	21 October 2016 (09:00-18:10)
Timezone:	Europe/Zurich
Location:	*Paul Scherrer Institut* CH-5232 Villigen Room: Auditorium / WHGA001
Additional info:	Organizers: K. Kirch, A. Knecht, B. Lauss, E. Rapisarda, A. Govaerts Van Loon

Pionic atoms



Pionic atoms

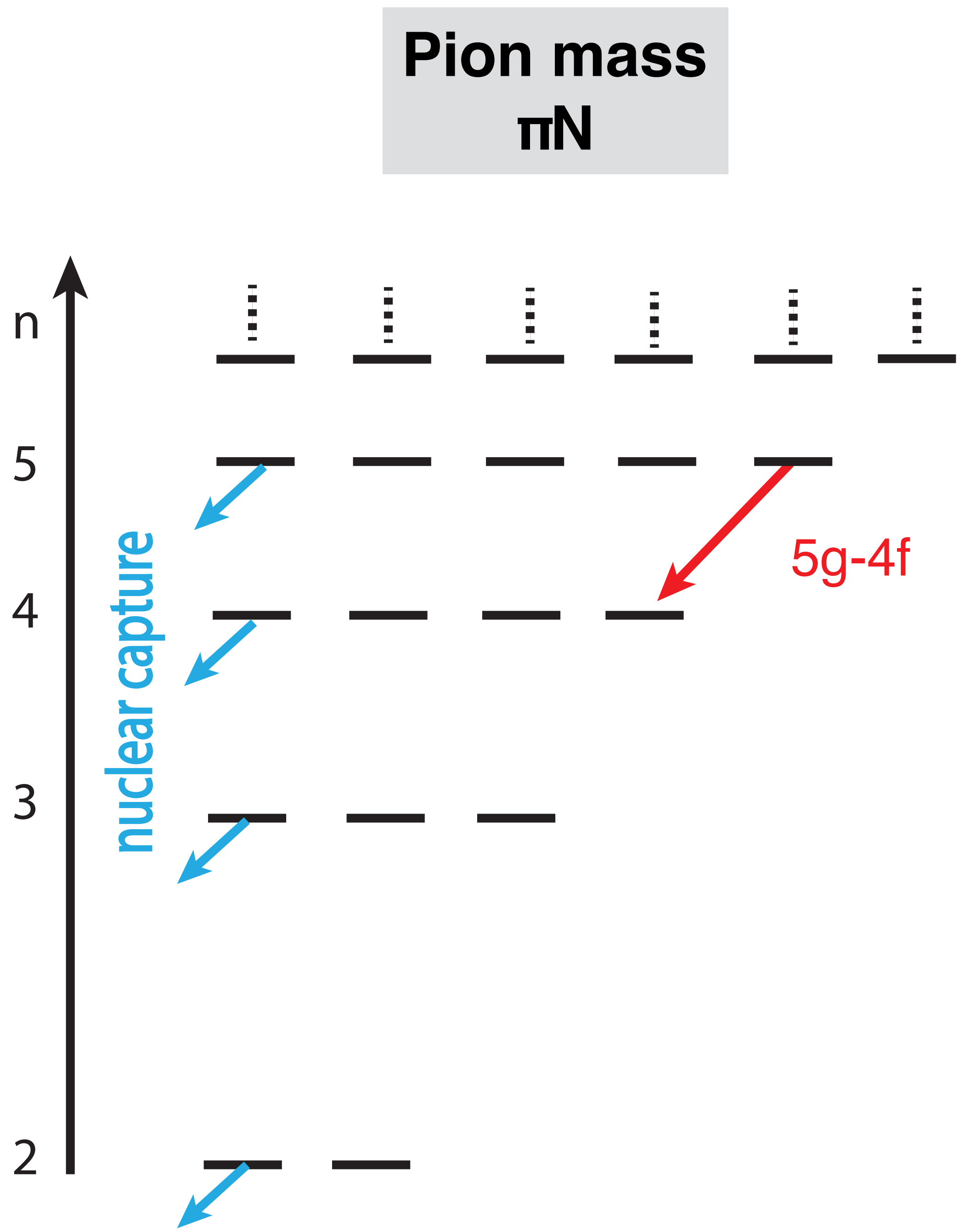


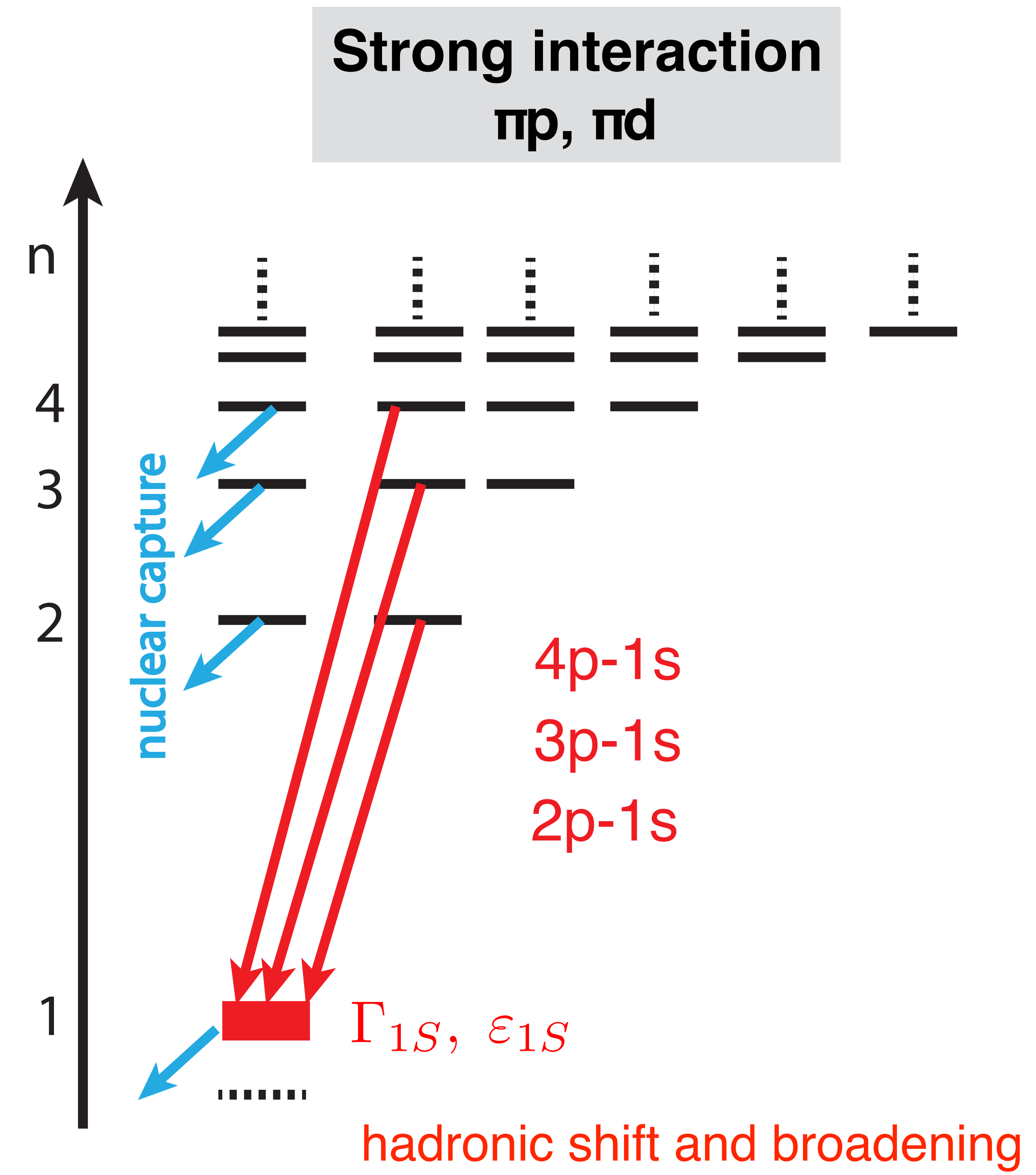
Strong interaction

- energy level shifts
- energy level broadenings

$$
\begin{aligned}
\pi^- + p &\rightarrow \pi^0 + n \\
&\rightarrow \gamma + n \\
\\
\pi^- + d &\rightarrow n + n \\
&\rightarrow \gamma + n + n
\end{aligned}
$$

X-ray spectroscopy of light pionic atoms





$$E \simeq \frac{m_\pi}{m_e} R_\infty Z^2 \left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) - c_1 |\Psi_{nl}(0)|^2 a_{\pi A}$$

The setup (πp, πd, πN)

Cold CCD
resolution similar to Ge(Li)
2D: structure and BG studies

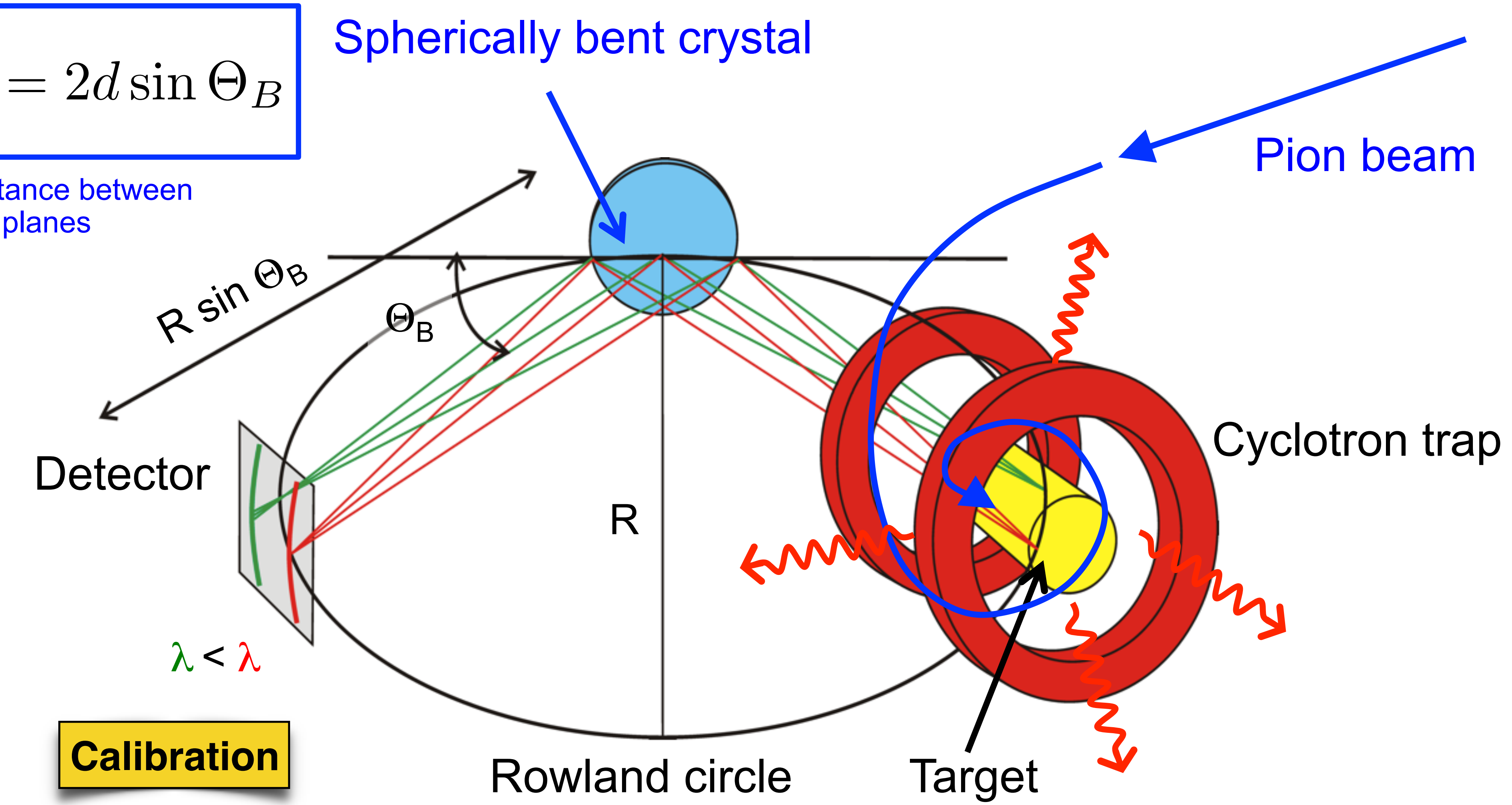
Bragg spectrometer
ECRIT used to study response function

Cyclotron trap
stop pions and muons
π: 0.5% stop at 1 bar, 300 K
μ: 10% of π stops

Gotta, Prog. Part. Nucl. Phys. Rep. 52, 133 (2004)

$$\frac{hc}{E} = 2d\sin\Theta_B$$

d = distance between crystal planes



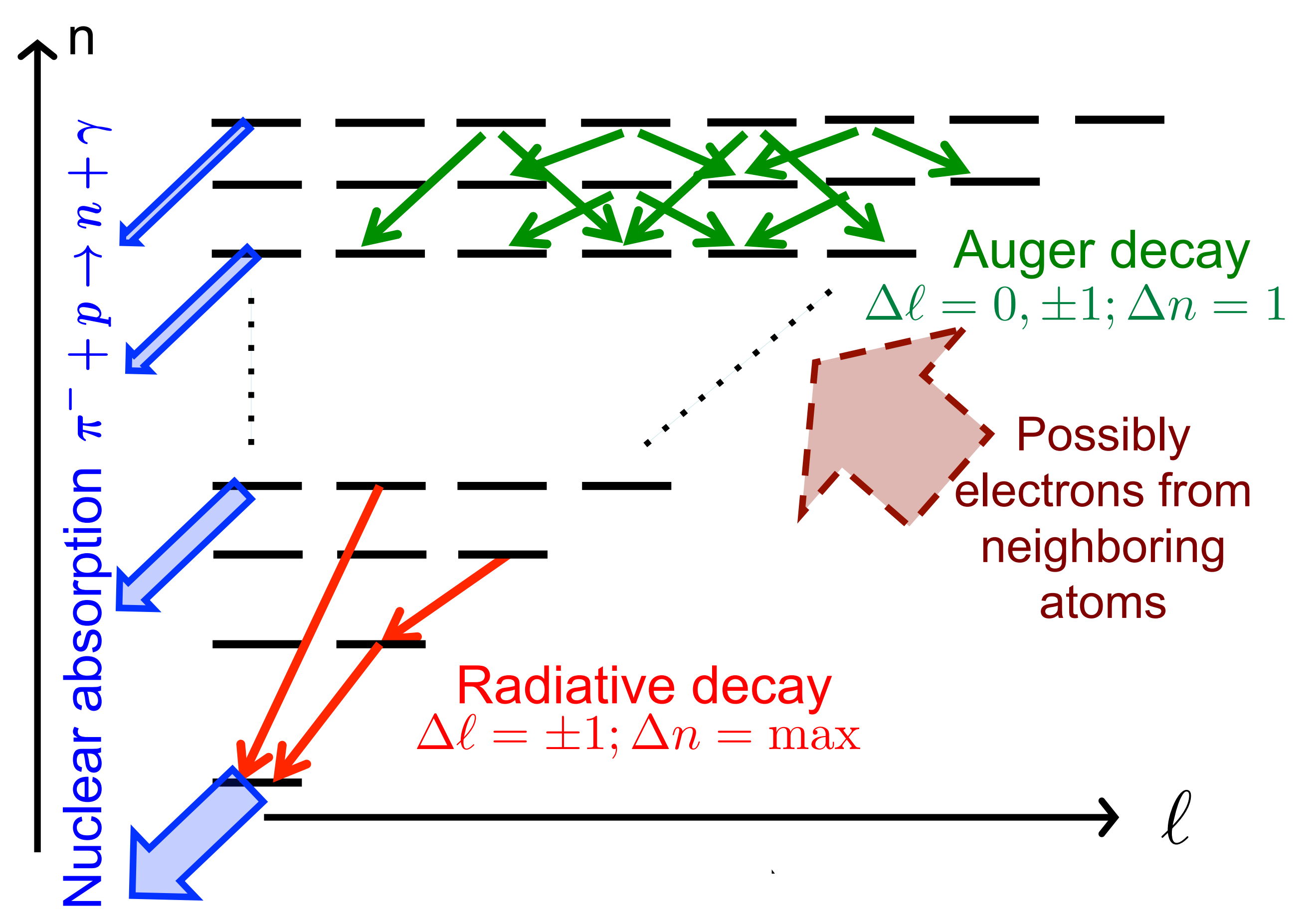
Pion mass from πN

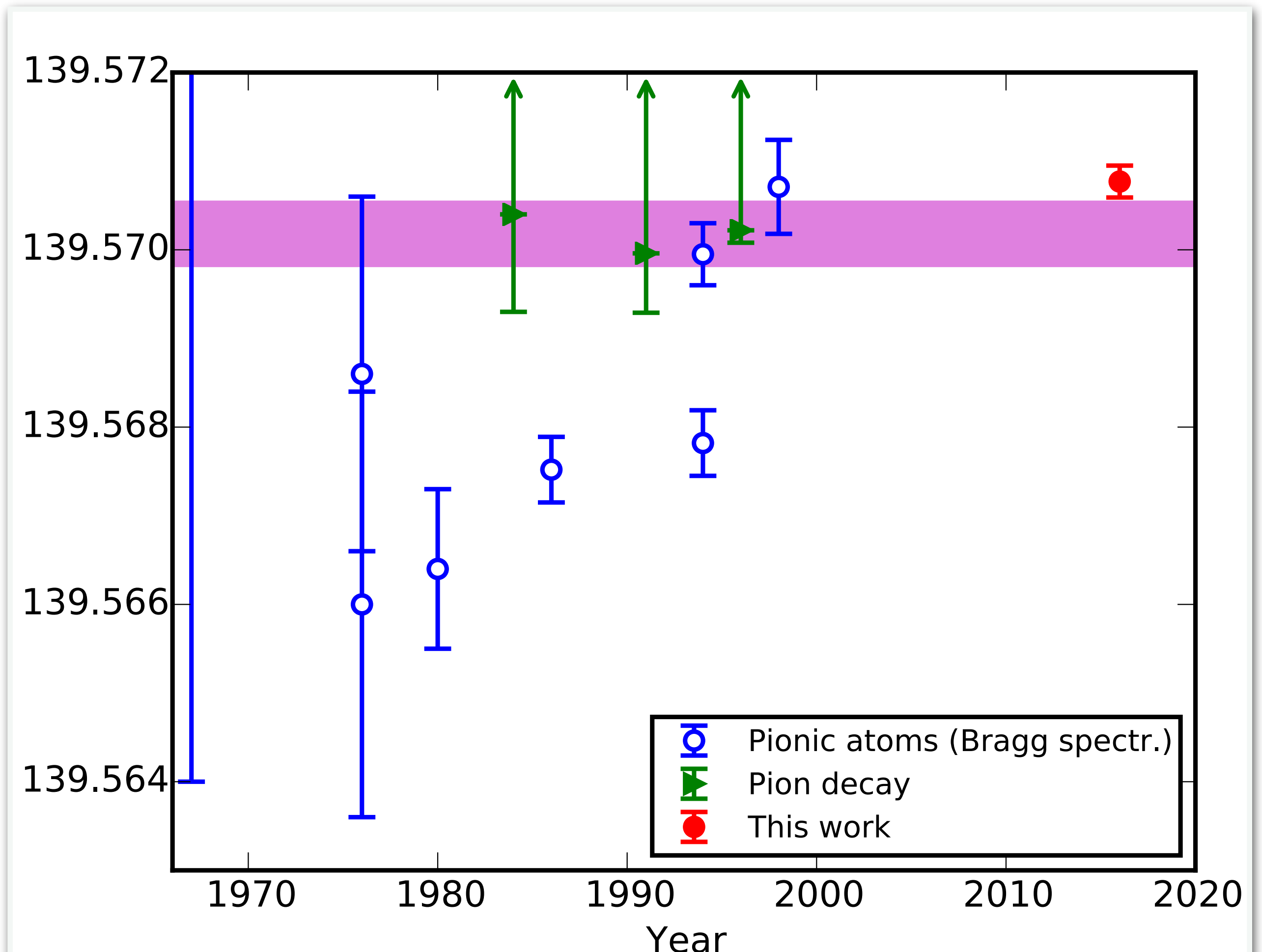
$$E^{\pi N}(5g-4f) = 4055.397(5)\ \text{eV} \qquad (u_r = 1\times 10^{-6})$$

$$m_\pi = 139.57077(18)\ \text{MeV/c}^2 \qquad (u_r = 1\times 10^{-6})$$

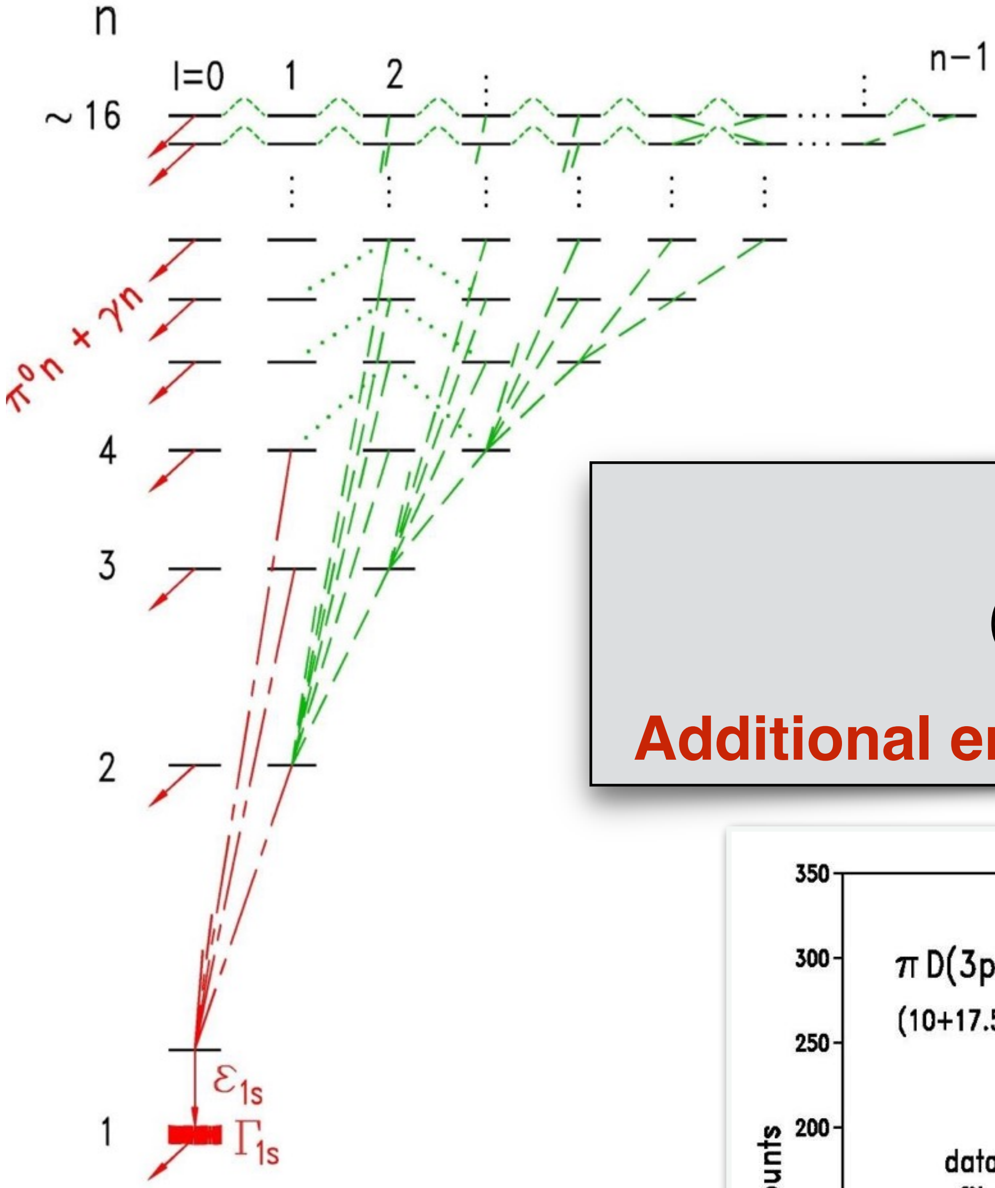
$$\Longrightarrow m_{\nu_\mu} = 183^{+62}_{-83}\ \text{keV/c}^2 (90\%\ \text{C.L.}) \qquad [\text{cosmological limit } 11\ \text{eV/c}^2]$$

Trassinelli et al., arXiv:1605.03300





Pionic hydrogen (πp, πd): the challenges



Coulomb explosion

$$(\pi p)_{nl} + H_2 \rightarrow (\pi p)_{n'l'} + H + H + \text{kinetic energy}$$

Doppler broadening

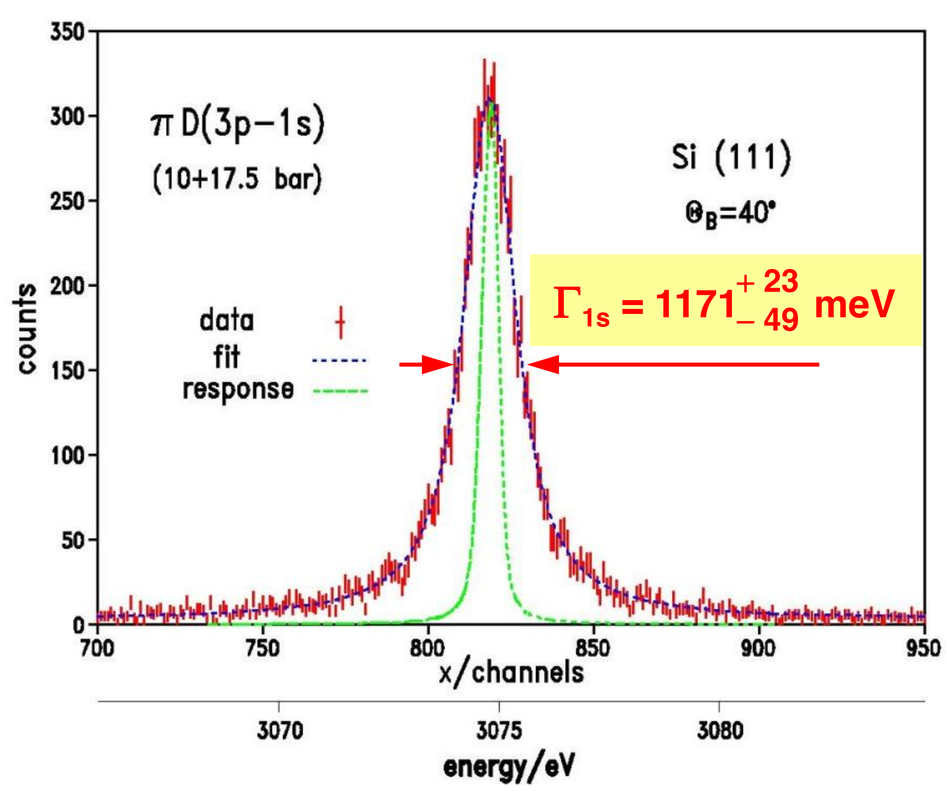
Molecular formation

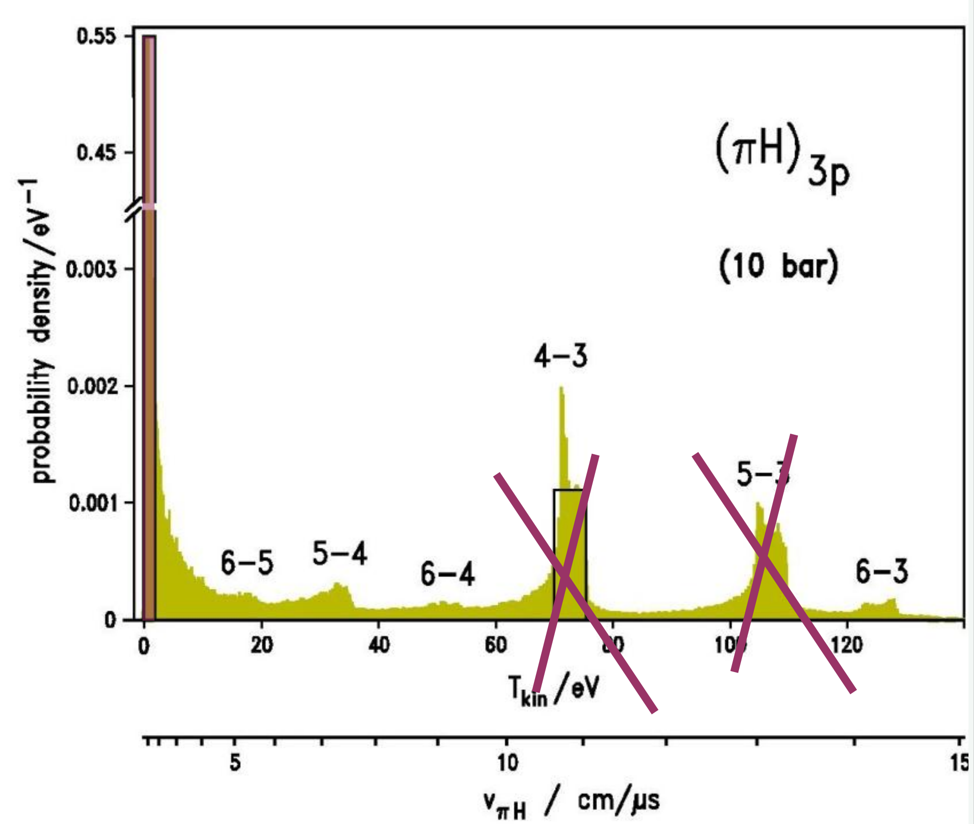
$$(\pi p) + H_2 \rightarrow [(\pi pp)\cdot p]ee$$

Additional energy shift if radiative decay of molecule

Line shape

- Strong interaction
- Crystal response
- Doppler broadening

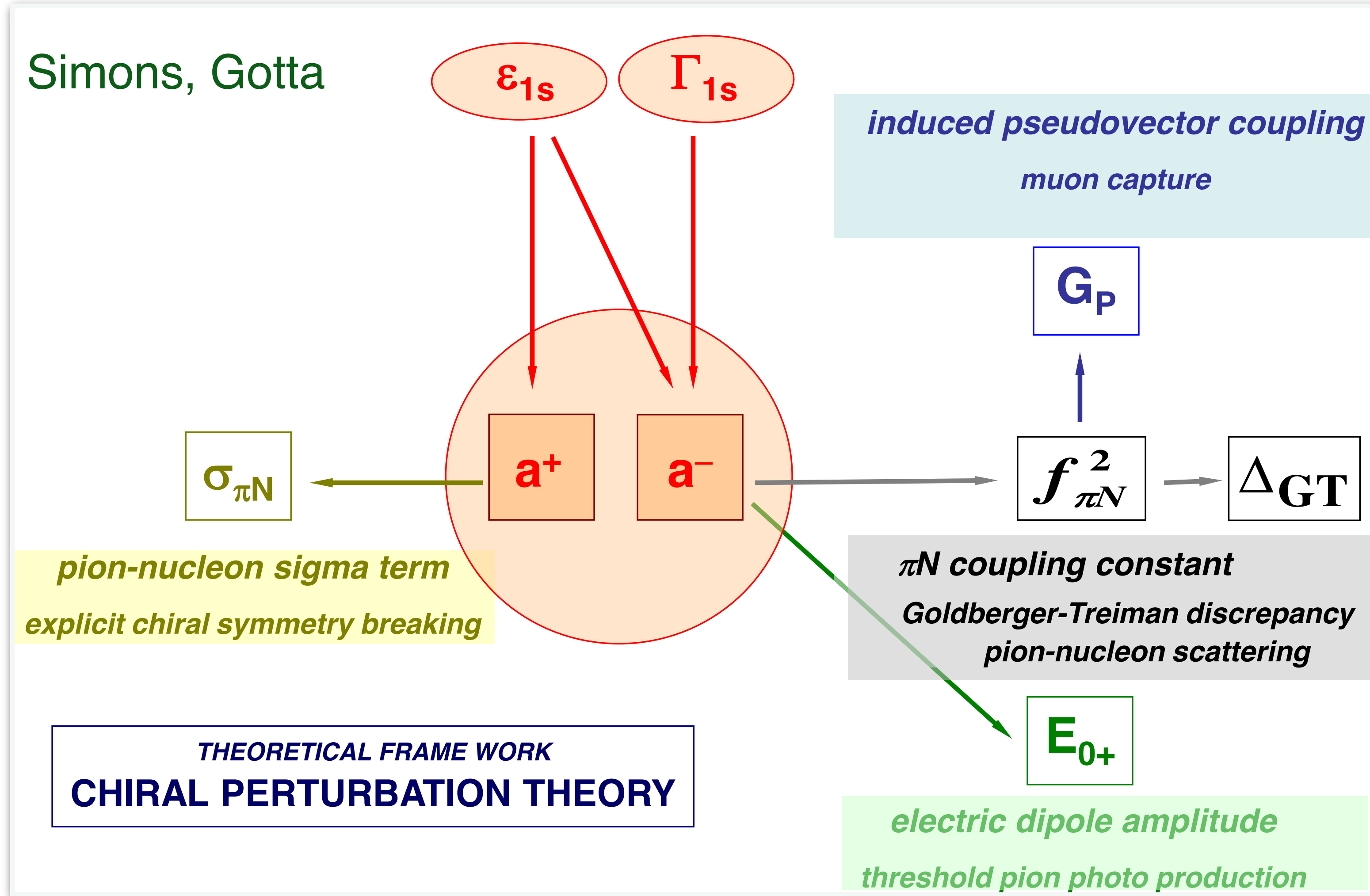




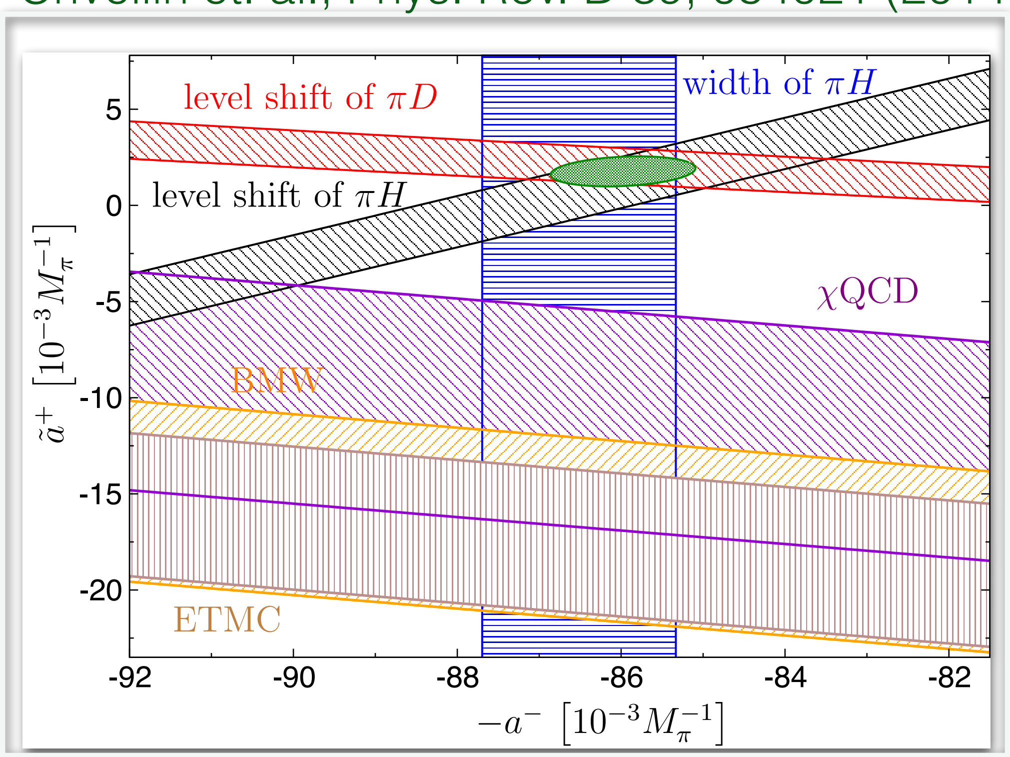
Impact of πp and πd measurements

$\varepsilon_{1S}^{\pi H}$	$= +7.087(9)$ eV
$a_{\pi^- p}$	$= 85.26(12) \cdot 10^{-3} m_{\pi^{-1}}$
$\Gamma_{1S}^{\pi H}$	$= 0.85(5)$ eV
$a_{\pi^- p}$	$= 124(3) \cdot 10^{-3} m_{\pi^{-1}}$
$\varepsilon_{1S}^{\pi D}$	$= -2.356(31)$ eV
$\mathrm{Re}(a_{\pi^- d})$	$= 25.0(3) \cdot 10^{-3} m_{\pi^{-1}}$
$\Gamma_{1S}^{\pi D}$	$= 1.17(4)$ eV
$\mathrm{Im}(a_{\pi^- d})$	$= 124(3) \cdot 10^{-3} m_{\pi^{-1}}$

Hennebach., Eur. Rhys. J. A 50, 190 (2014)
Strauch et al., , Eur. Rhys. J. A 47, 88 (2011)



Hofericher et al., arXiv 1602.07688
Crivellin et. al., Phys. Rev. D 89, 054021 (2014)



Gasser et al., Phys. Rep. 456 167 (2008)
Colangelo, Leutwyler, Meissner etc.

The scalar coupling of the nucleon is a key quantity in:

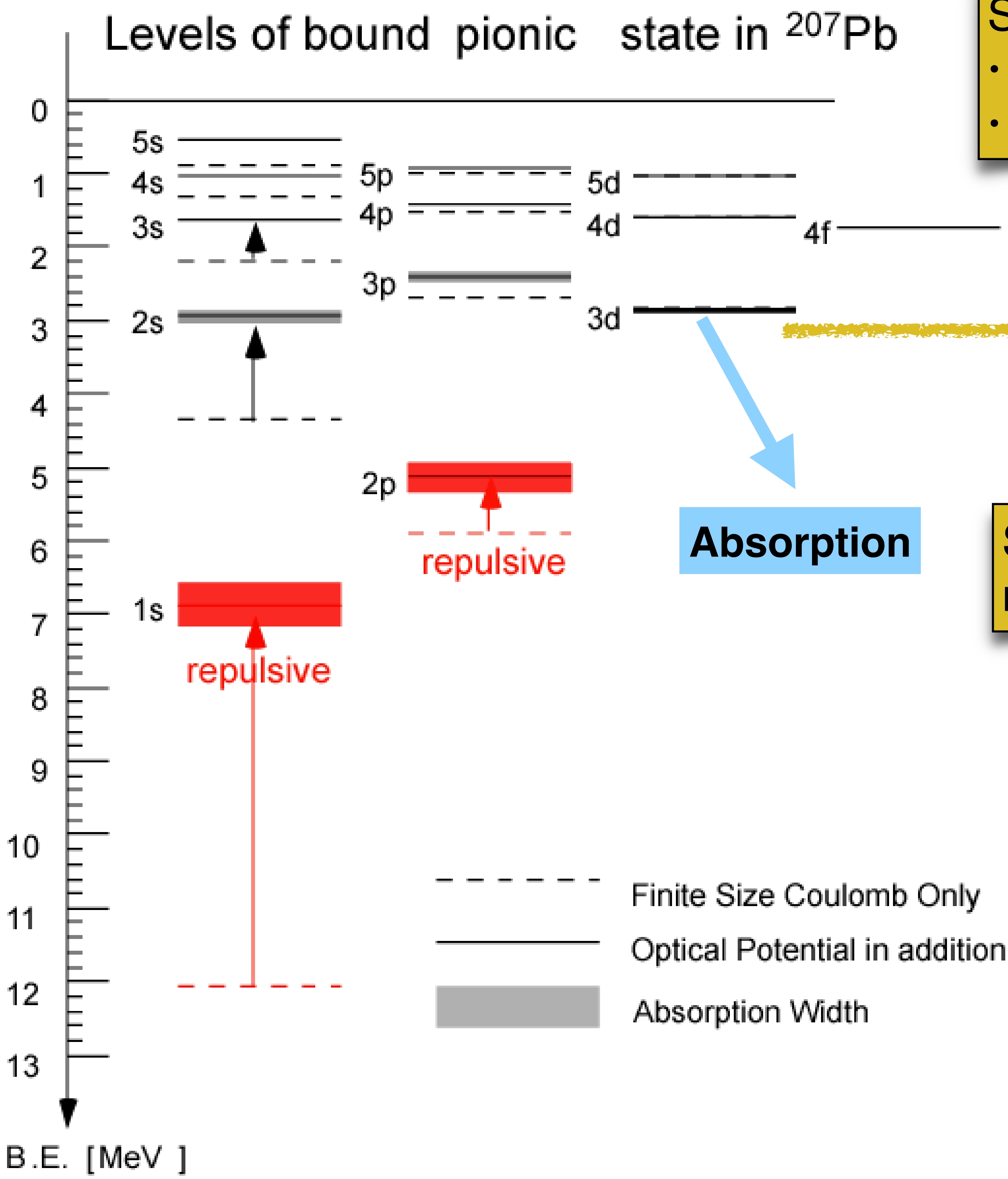
- Dark matter detection [Ellis et al., PRD77 (2008)]
- Strangeness content of nucleon [Ericson]
- CP violation [de Vries et al., PRC92 (2015)]
- Nuclear thermodynamics [Holt et al., Phys. Rep. 621 (2016)]
- Higgs-nucleon coupling
- Lepton flavour violation in μ-e conversion

$$\sigma_{\pi N} = \frac{m}{2M} \langle N | \bar{u}u + \bar{d}d | N \rangle$$

Alarcon

Deeply bound pionic atoms (πSn, πPb…)

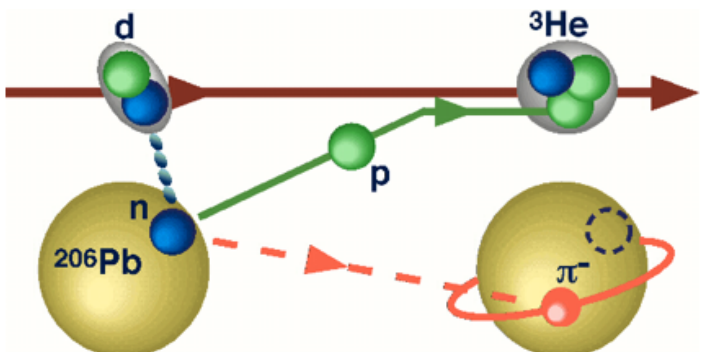
Ken Suzuki

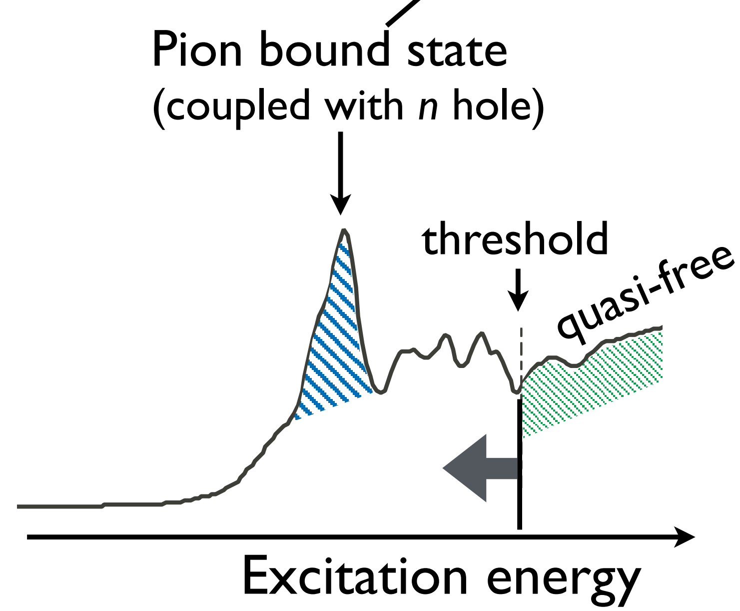


States formed from:
- stopped pions
- cascade

Absorption

States formed via reaction process



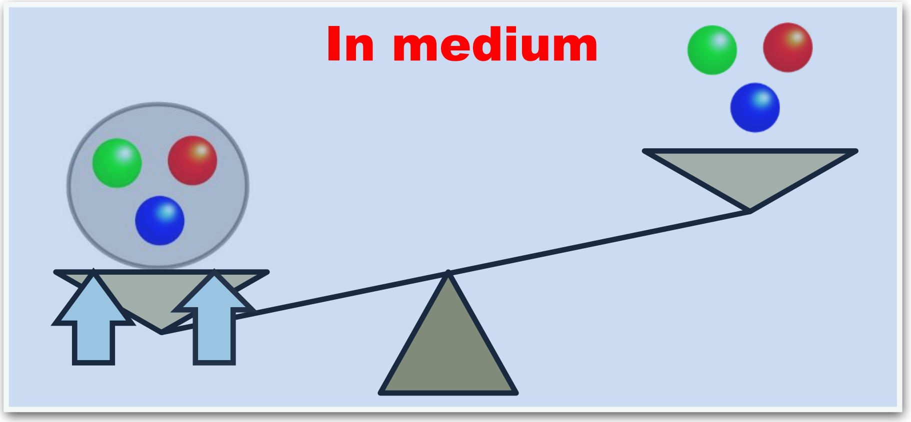


N. Ikeno et al., PTEP(2013) 063D01

Impact of deeply-bound pionic atoms

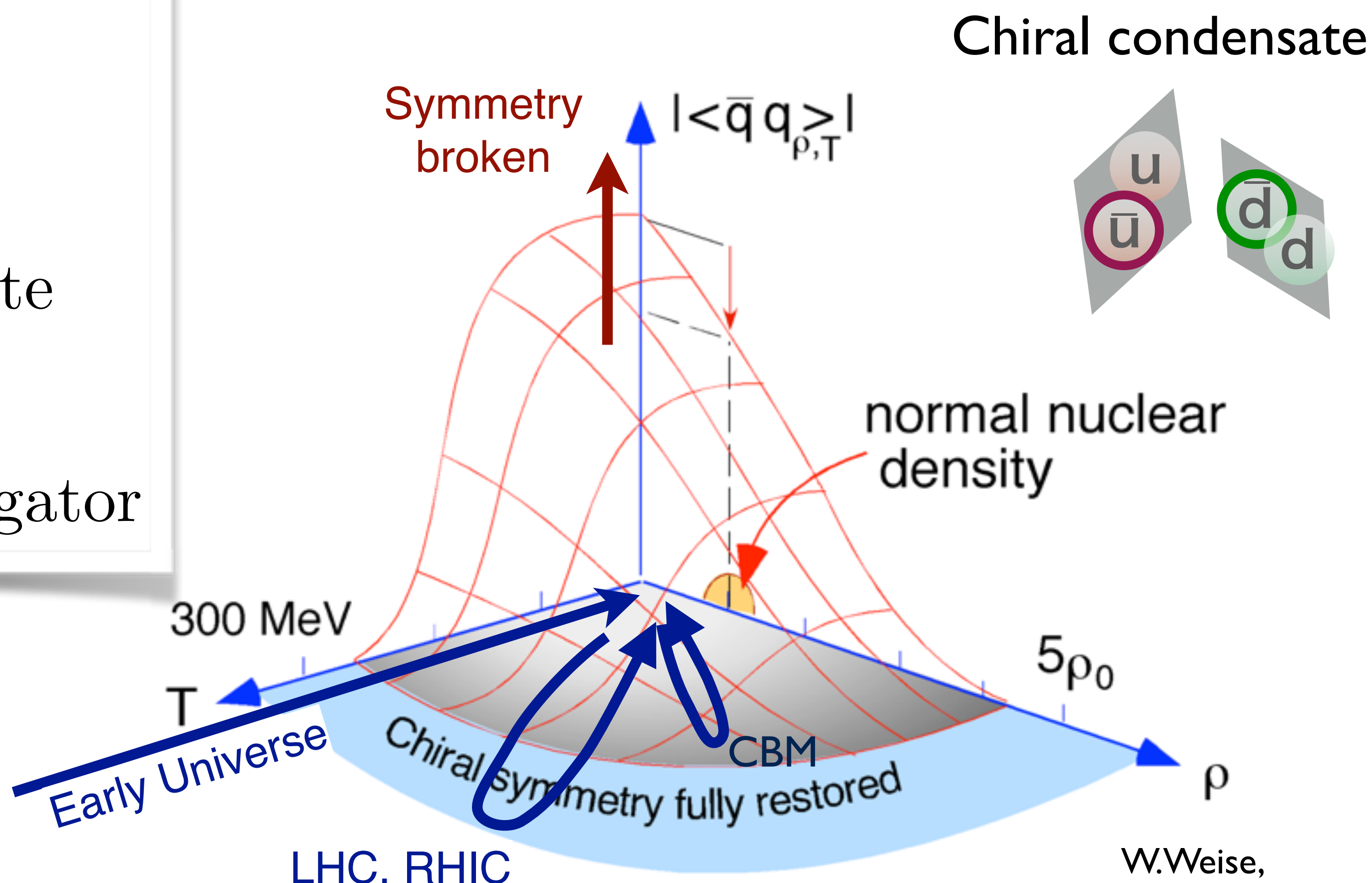
- Pion-nucleous interaction
  $V_{\rm opt} = b_0\rho + {\color{red}b_1}(\rho_n - \rho_p) + B_0\rho^2$
- Gell-Mann-Oakes-Renner relation
  $f_\pi^2 m_\pi^2 = -2m_q\langle q\bar{q}\rangle$
- In-medium vs. vacuum value
  ${\color{red}\frac{\langle q\bar{q}\rangle_\rho}{\langle q\bar{q}\rangle_0} \approx \frac{b_1^{\rm free}}{b_1^\rho}}$
- Partial restoration of chiral symmetry
  (reduction of $|\langle q\bar{q}\rangle|$)
- In-medium pionic observable $(m_\pi,\ f_\pi \ldots)$
  are related to in-medium chiral condensate
- In-medium chiral perturbation th.
  Nucleon propagator $\rightarrow$ in-medium propagator

Soichiro Goda, Kenta Itahashi



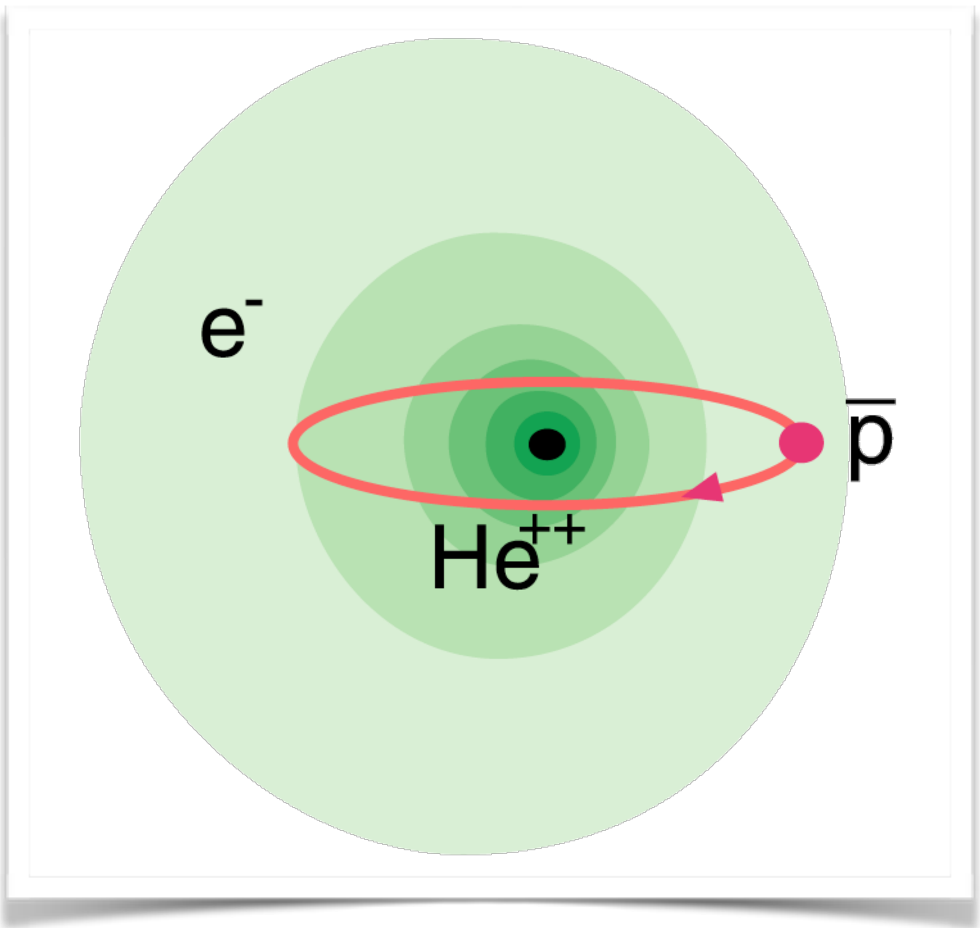
Structure of vacuum

chiral symmetry and order parameter



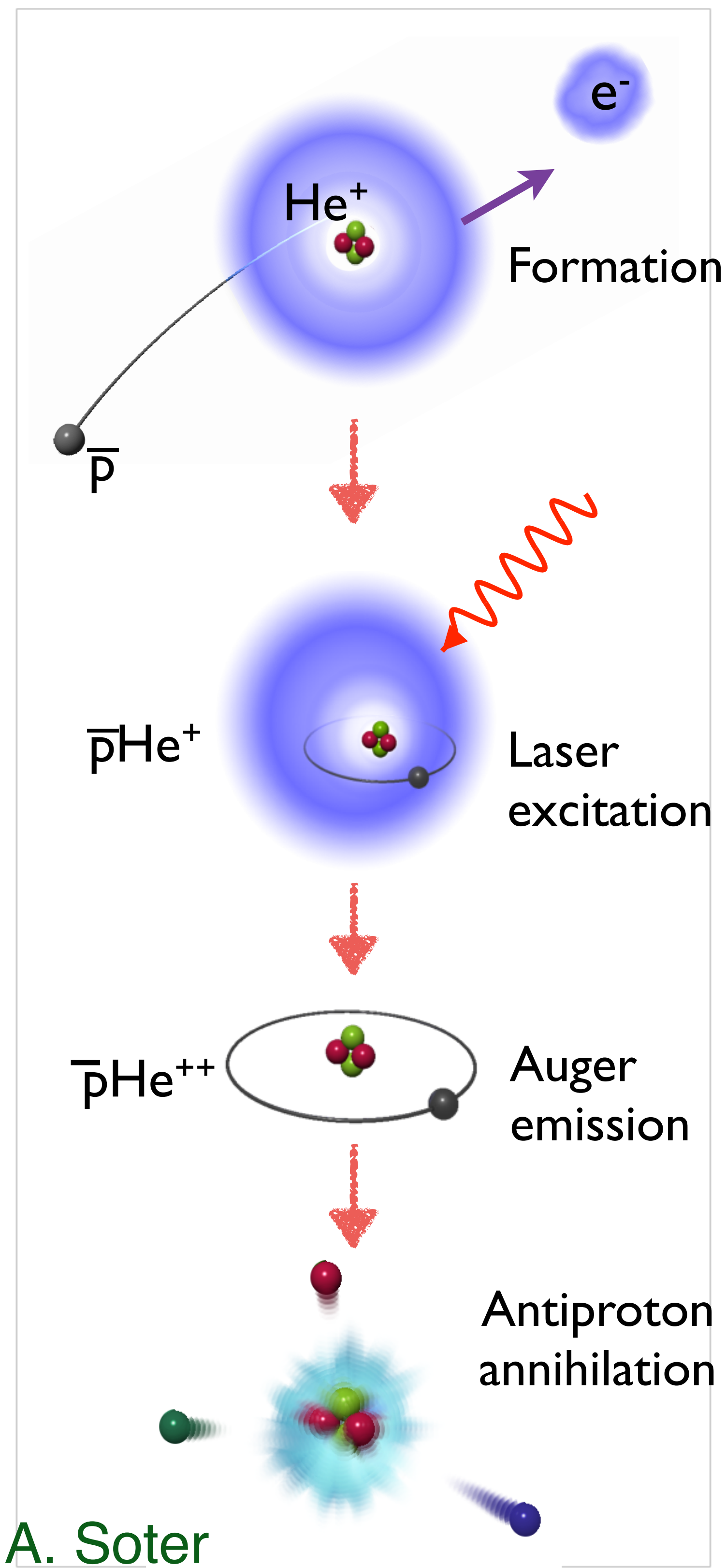
W.Weise, NPA553(93)59.

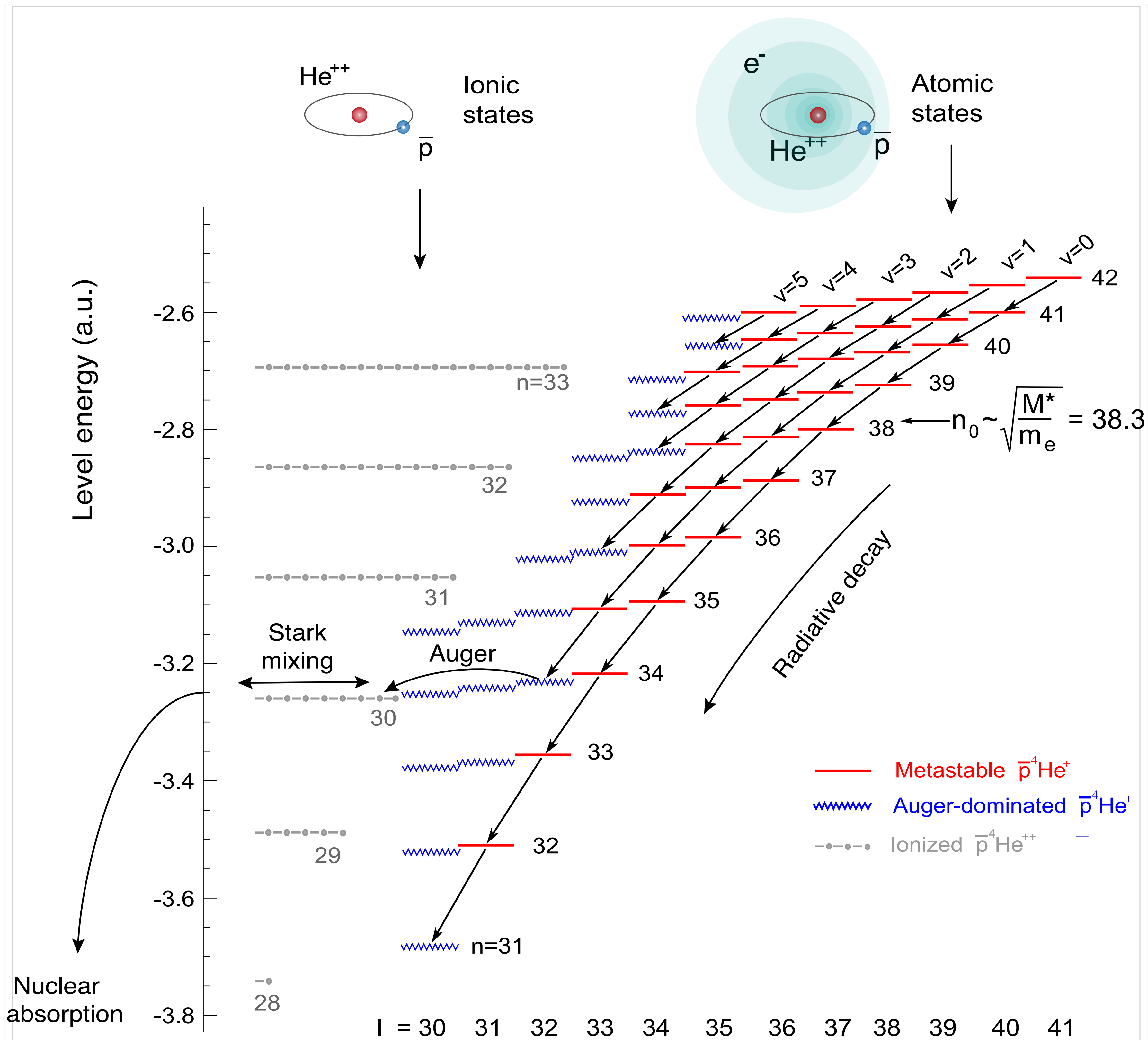
Antiprotonic He ($\bar{p}$He)



ASACUSA collaboration

Laser spectroscopy of antiprotonic He (p̄He)





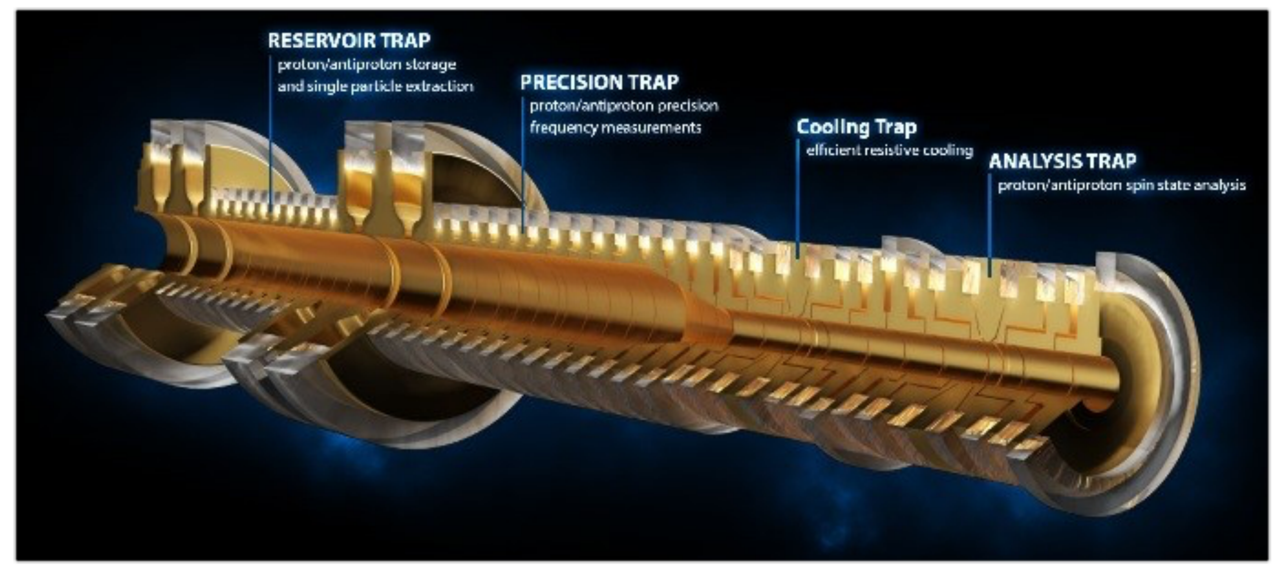
Impact of p̄He spectroscopy

$$h\nu^{\rm th} = h\nu^{\rm th}\left(\frac{m_{\bar p}}{m_e}, \frac{m_{\bar p}}{m_{\rm He}}, \frac{m_{\rm He}}{m_e}, Q_{\bar p}, R_\infty, \alpha\right)$$

$$\approx \frac{m_{\bar p}}{m_e} R_\infty Z_{\rm eff}^2 \left(\frac{1}{n'^2} - \frac{1}{n^2}\right)(\text{3-body, QED, } \cancel{\text{hadronic}})$$

3-body, QED test (1 x 10^{-9})

Theory	1 522 107 060.3(2)	MHz
Experiment	1 522 107 062(4)	MHz



Electron mass (8 x 10^{-10})

talk: Blaum

$$\frac{m_e}{m_C} = \frac{m_e}{m_p} \cdot \frac{m_p}{m_C} \overset{\rm CPT}{=} \frac{m_e}{m_{\bar p}} \cdot \frac{m_p}{m_C}$$

talk: Smorra

CPT test (5 x 10^{-10})

p̄He⁺ transition frequencies:

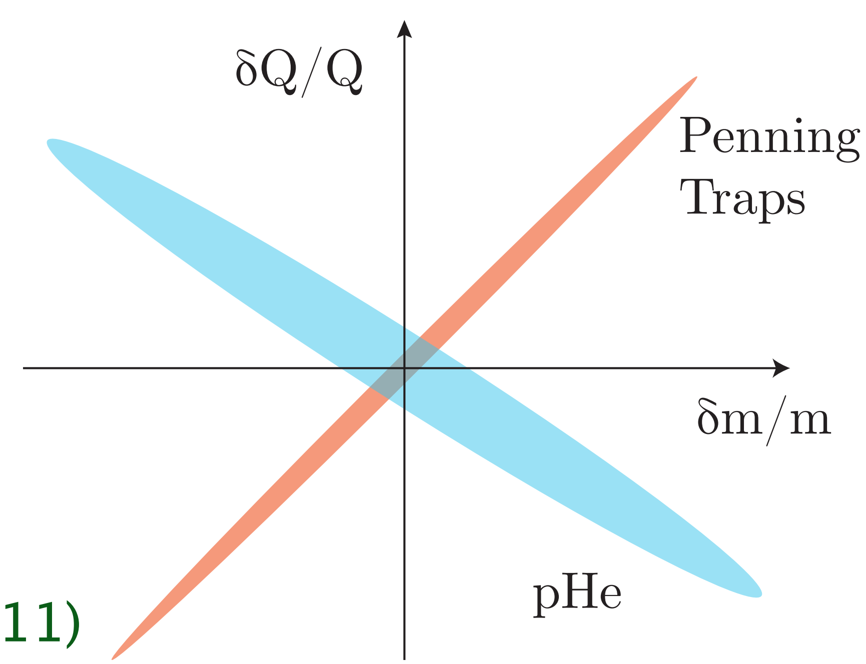
$$\nu \sim m_{\bar p} Q_{\bar p}^2$$

$$\frac{\delta m_{\bar p}}{m_{\bar p}} = -2\frac{\delta Q_{\bar p}}{Q_{\bar p}}$$

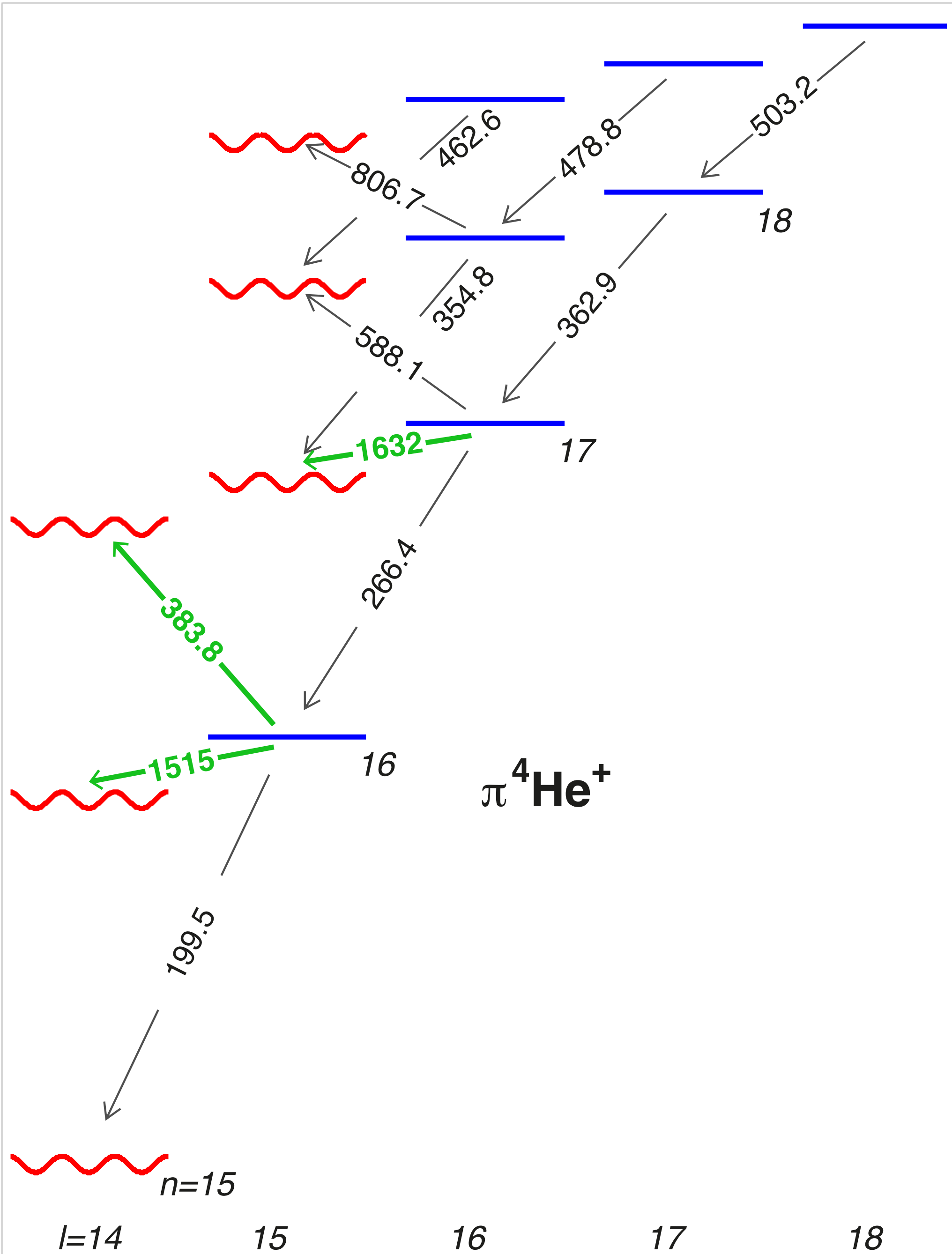
Penning trap frequencies:

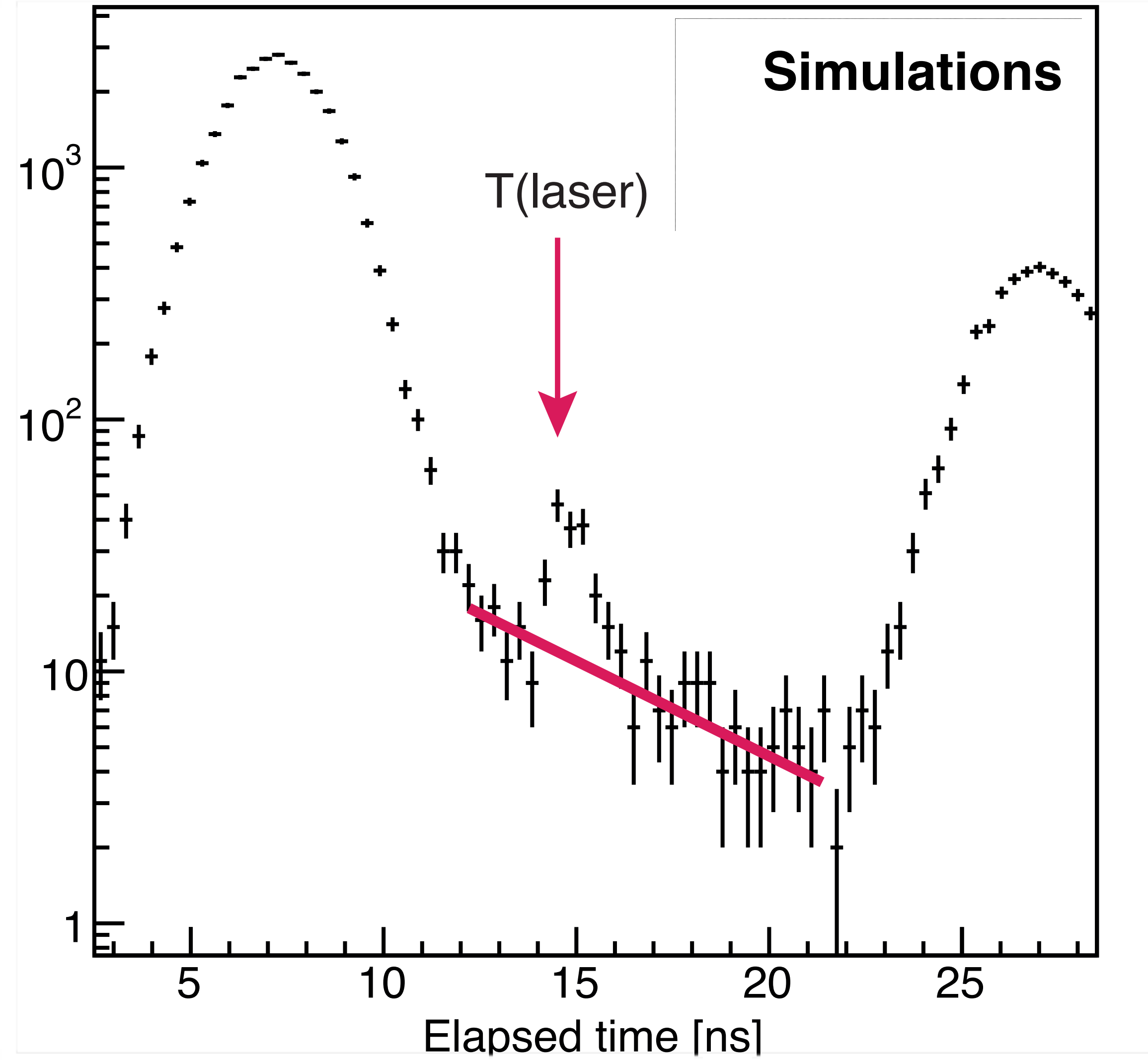
$$\omega \sim Q_{\bar p}/m_{\bar p}$$

Hori, et al., Nature 475, 484 (2011)



Pionic Helium (πHe)





p̄He: 5 x10⁷ p̄ per pulse every 2 minutes
πHe: 1 π per RF cycle (laser rep. rate = 80 Hz)

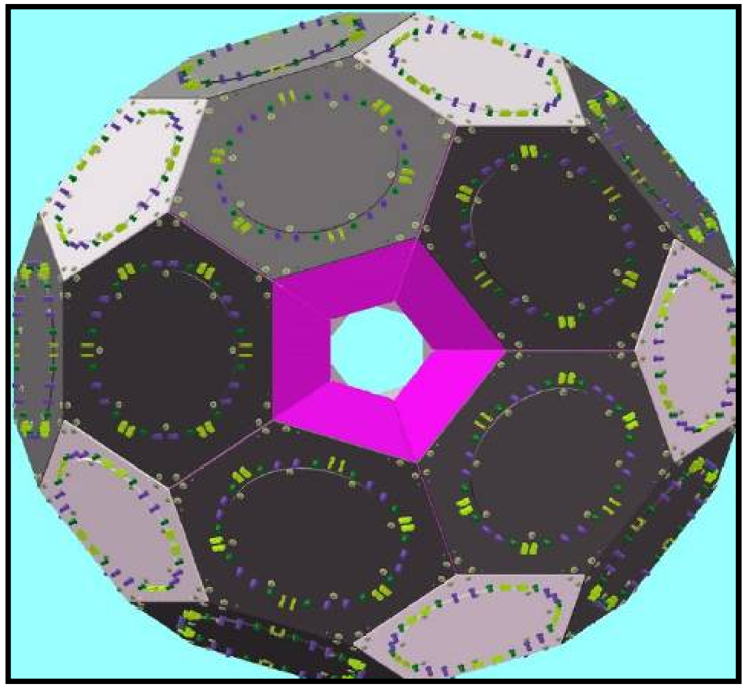
Timing resolution of < 1 ns !

Goal: improve pion mass to 10 ppb
- needs a "long lived" state
- needs low pressure

Hori, Soter

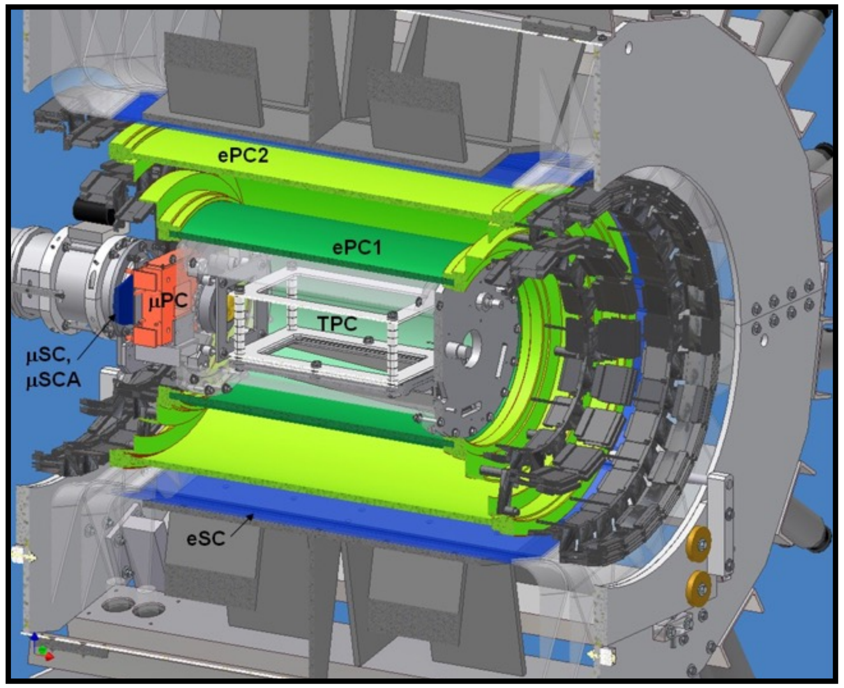
- Three lines searched
- One line found (2015)

From muon lifetimes to weak and strong interactions

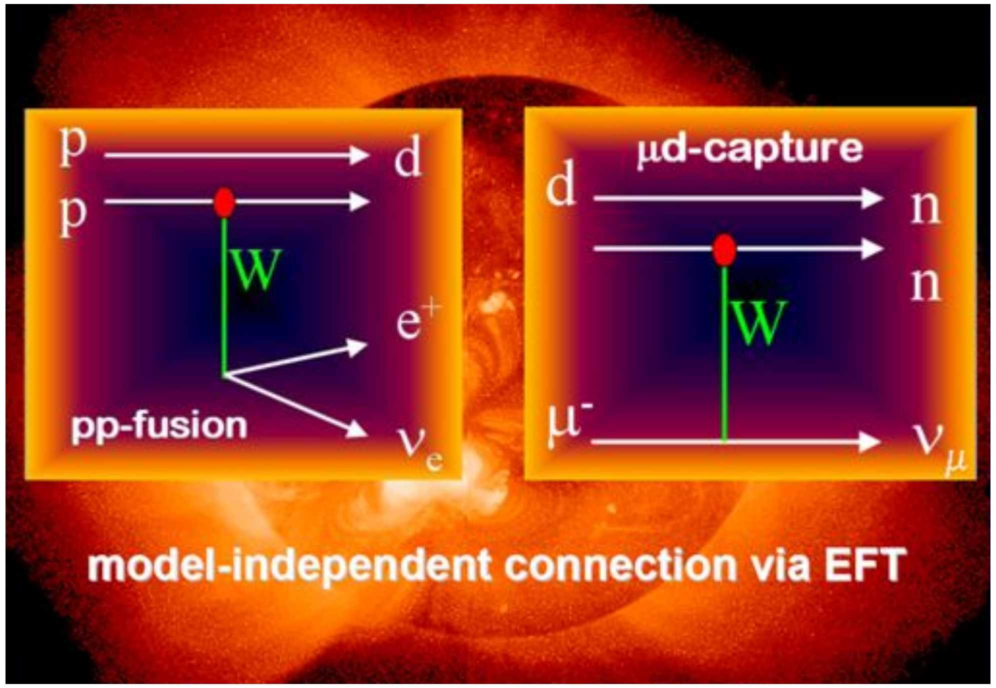


MuLan G_F

MuCap g_p



MuSun L_{1A}



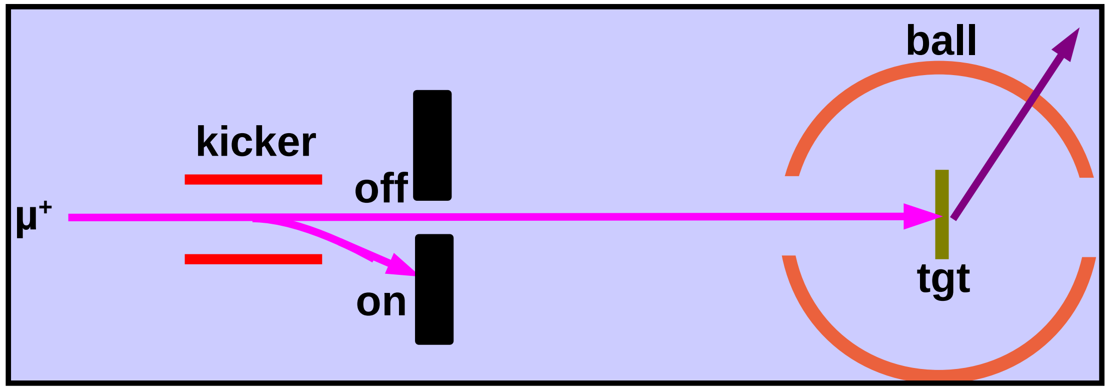
talk: Ryan

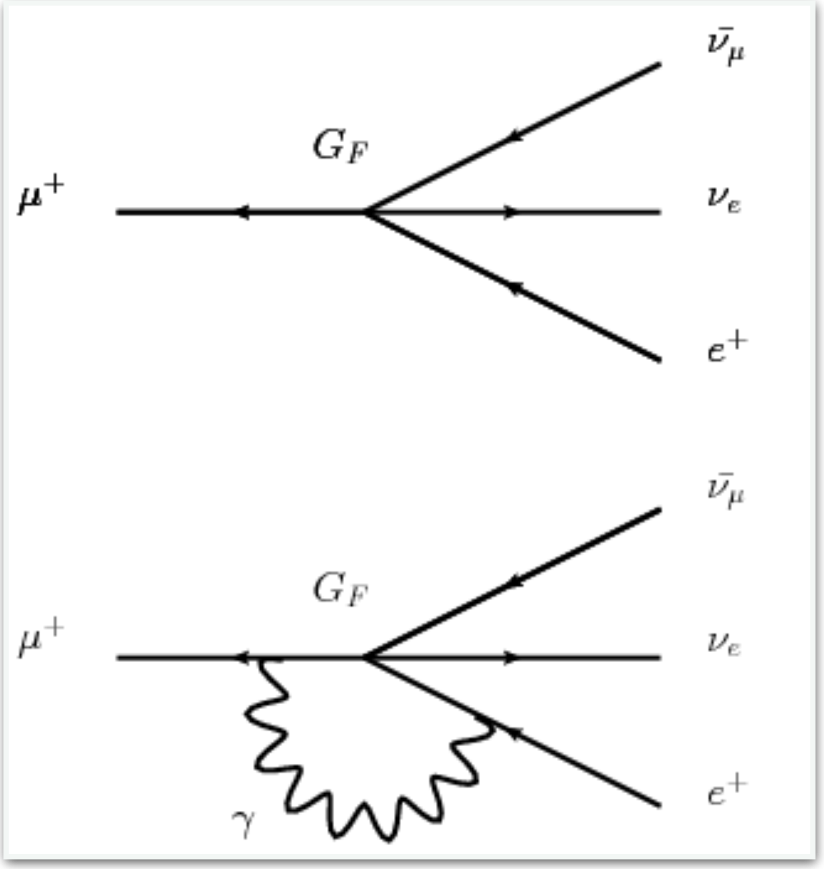
MuLan, μ^+ lifetime

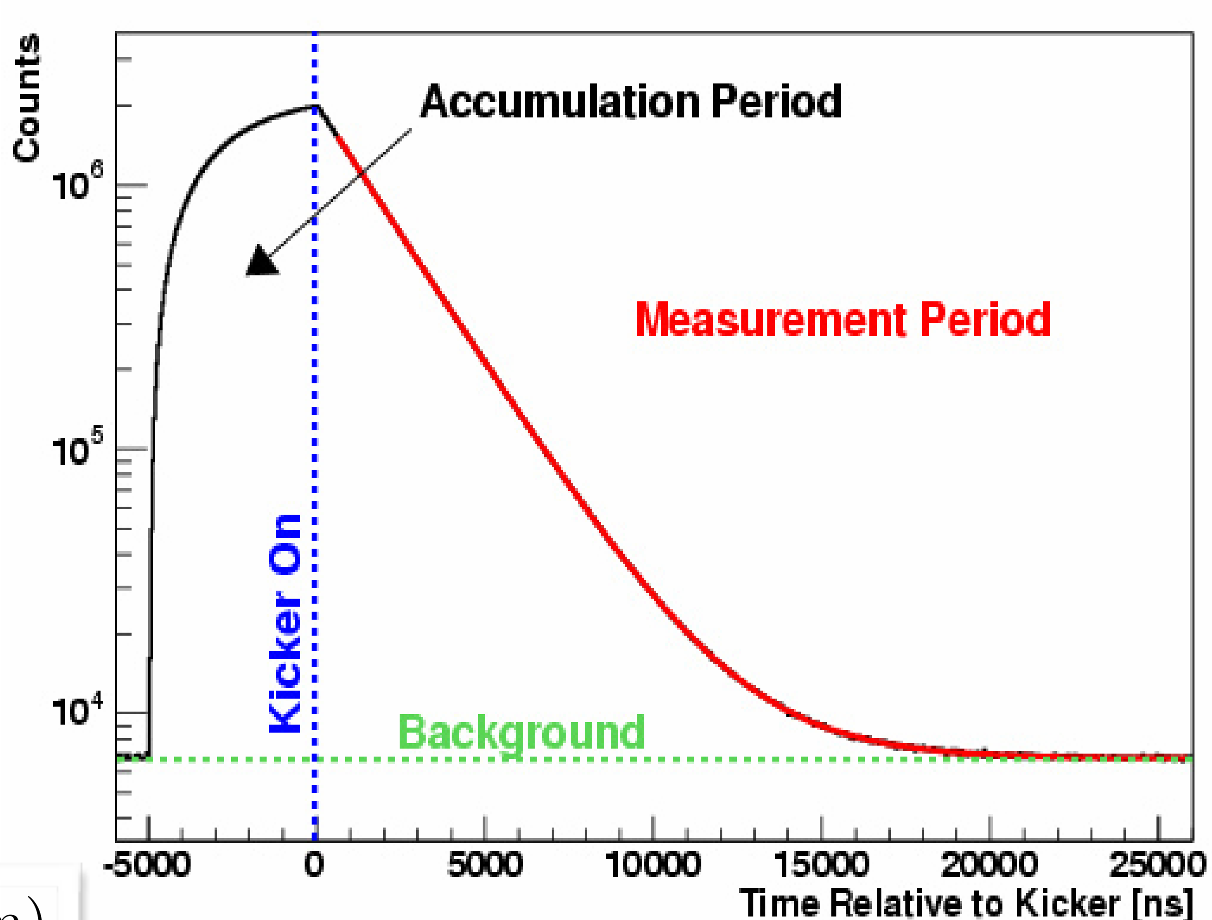
Muon lifetime $\rightarrow$ Fermi coupling constant
τ_μ (1 ppm) $\rightarrow$ G_F (0.6 ppm)

$$\frac{1}{\tau_\mu^+} = \frac{G_F^2 m_\mu^5}{192\pi^2}(1+\Delta q)$$

D. Hertzog







Knowledge of α (0.2 ppb), G_F (0.6 ppm), M_Z (23 ppm)
$\rightarrow$ precision SM test via measurements of θ_W, M_W etc.

PhysRevLett.106.079901

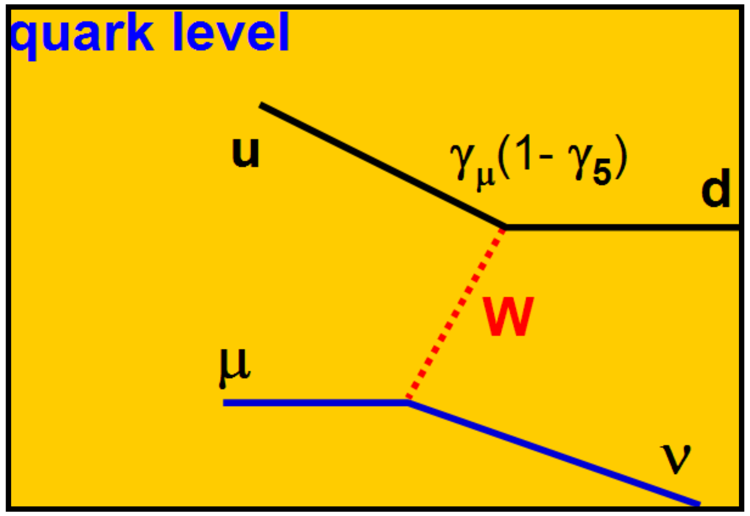
MuCap and MuSun goals and method

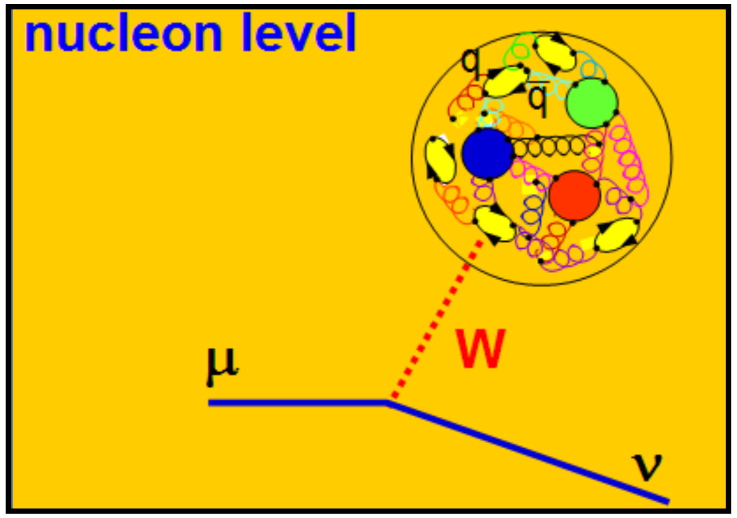
MuCap

$$(\mu^- p): \qquad \mu^- + p \to \nu_\mu + n \qquad \longrightarrow \qquad \Lambda_S$$

MuSun

$$(\mu^- d): \qquad \mu^- + d \to \nu_\mu + n + n \qquad \longrightarrow \qquad \Lambda_d$$



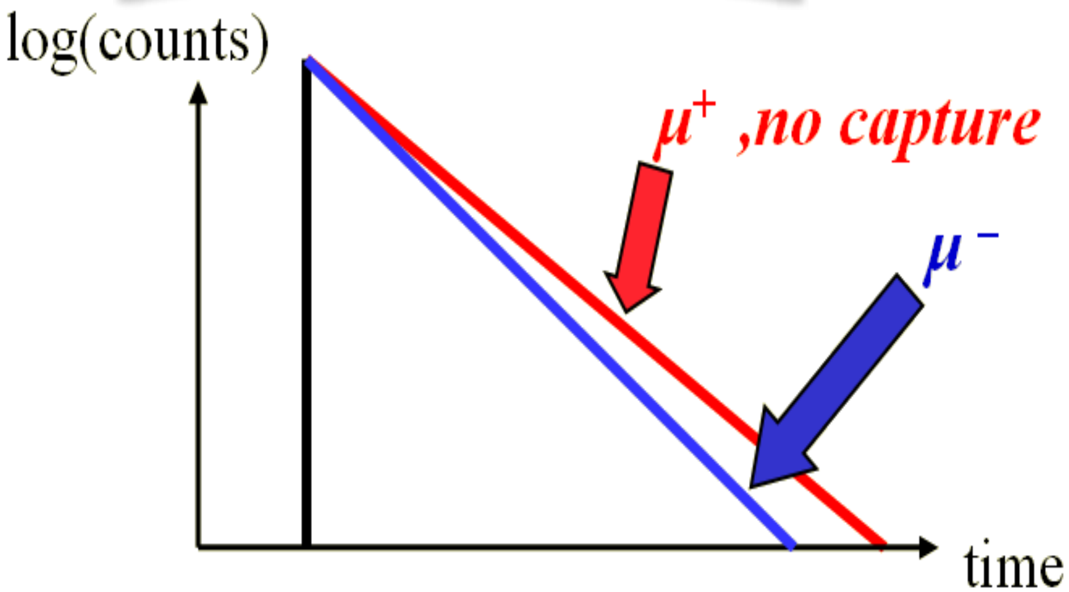


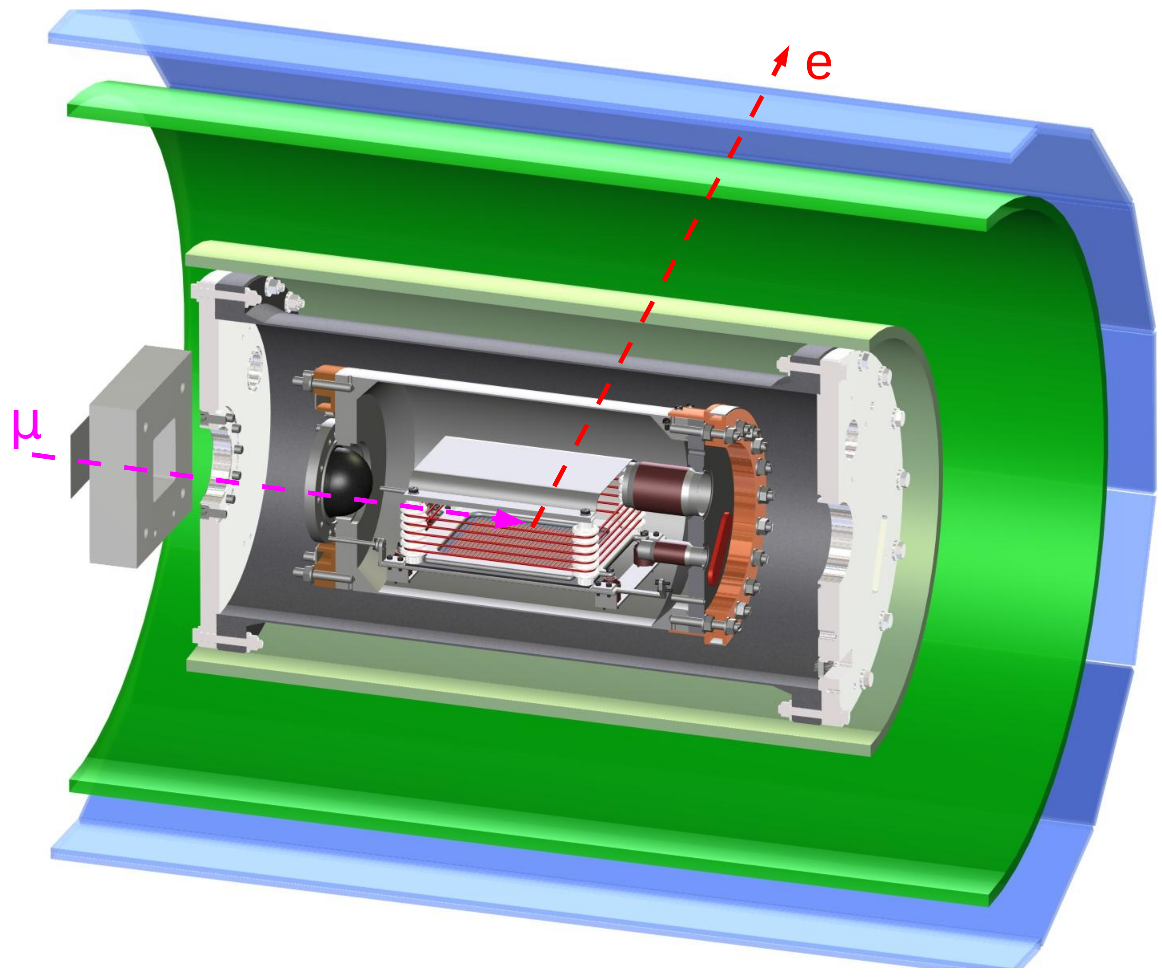
P. Kammel

Method

$$\Lambda_S = \frac{1}{\tau_{\mu^-}} - \frac{1}{\tau_{\mu^+}}$$

(measure τ_μ with 10 ppm)





MuCap

$$\mu^- + p \to \nu_\mu + n \quad \longrightarrow \quad \Lambda_S$$

Matrix element and form factors

$$M = \frac{-iG_F V_{ud}}{\sqrt{2}} \bar{u}(p_\nu)\gamma_\alpha(1-\gamma^5)u(p_\mu)\bar{u}(p_f\tau_-[V_\alpha - A_\alpha])u(p_i)$$

$$V_\alpha = g_V(q^2)\gamma_\alpha + \frac{ig_M(q^2)}{2m_N}\sigma_{\alpha\beta}q^\beta$$

$$A_\alpha = g_A(q^2)\gamma_\alpha\gamma_5 + \frac{g_p(q^2)}{m_\mu}q_\alpha\gamma_5$$

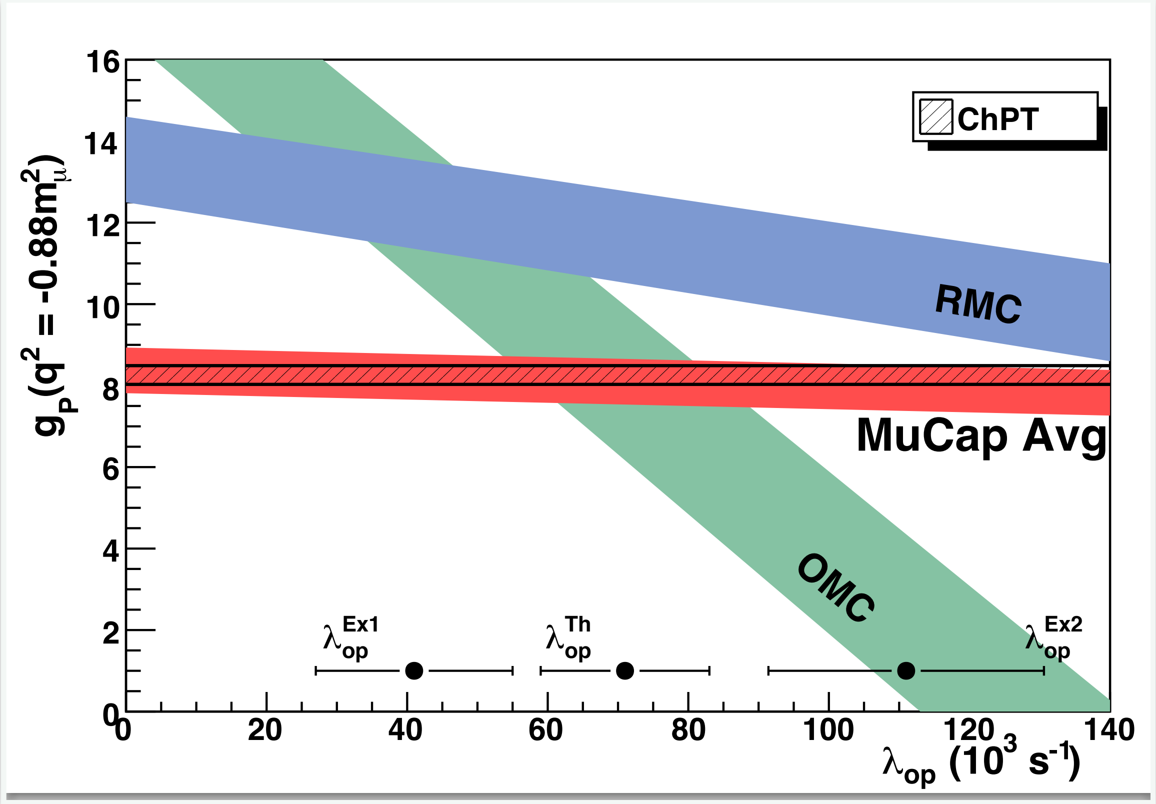
Chiral PT

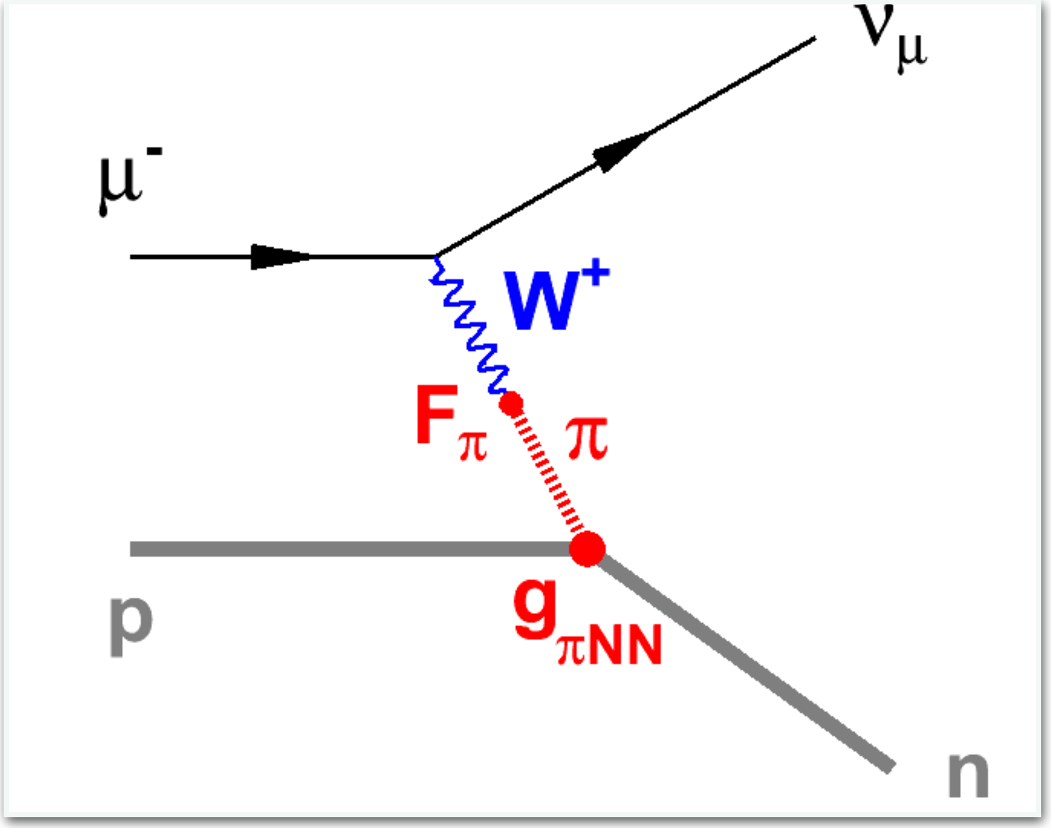
$$g_p(q^2) = \frac{2m_\mu g_{\pi NN(q^2)}F_\pi}{m_{\pi^2 - q^2}} - \frac{1}{3}g_a(0)m_\mu m_N r_A^2 + (\text{one loop}) + (\text{two loop}) + \cdots$$

Results

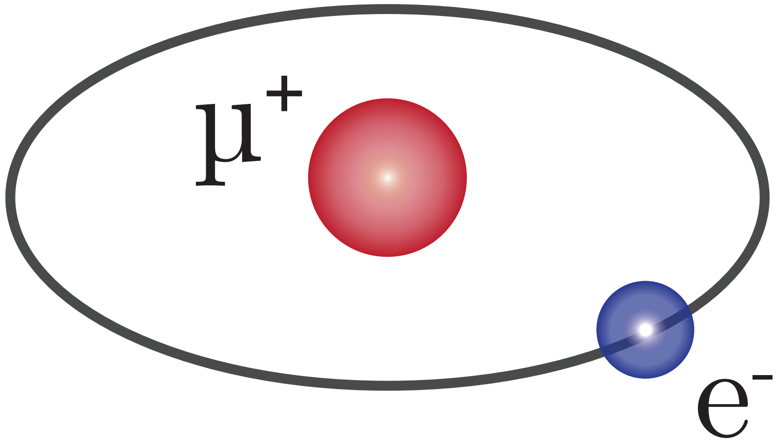
$$\Lambda_S = 714.9(7)\ \mathrm{s}^{-1}$$
$$\to g_p(q_0^2 = -0.88m_\mu^2) = 8.06(55)$$

Andreev, Phys. Rev. Lett. 110 012504 (2013)

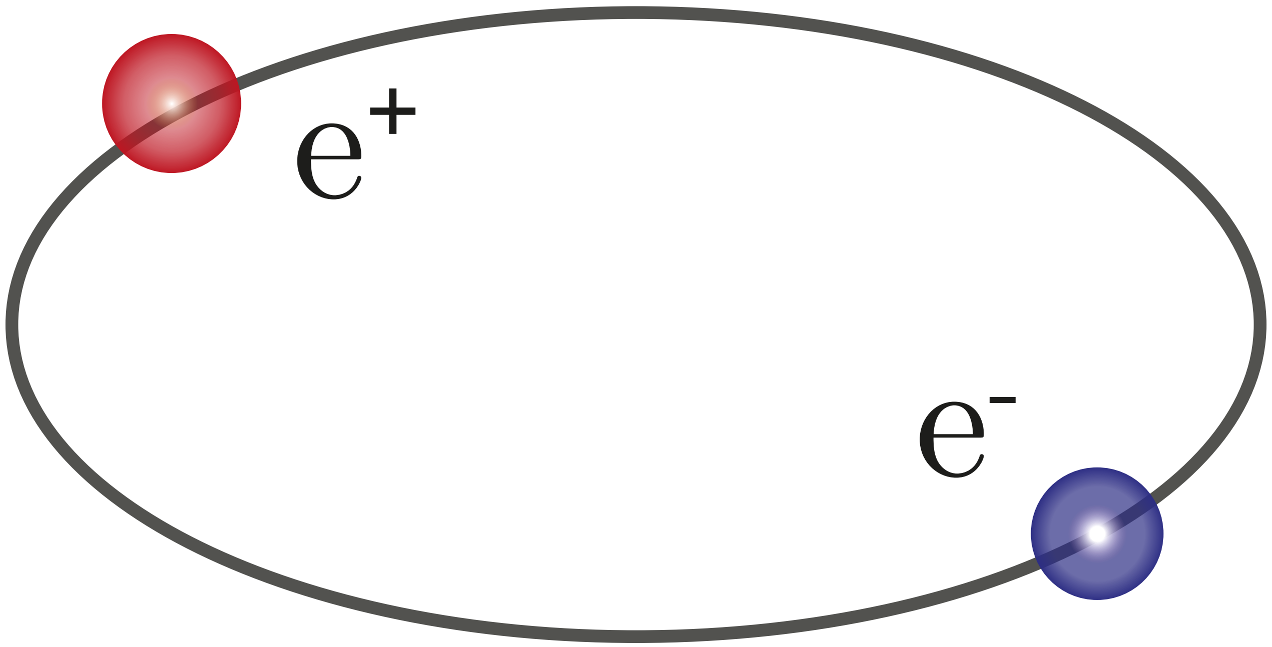




Muonium & Positronium



Pure leptonic systems free of finite-size effects



talk: Crivelli

Excellent platform to
- test bound-state QED
- determine fundamental constants $m_\mu,\ \mu_\mu/\mu_p,\ m_e^+/m_e^-,\ q_e^+/q_e^-$
- tests of fundamental symmetries, BSM searches (mirror world, Mu to anti-Mu)
- anti-particles gravity (PSI-ETH project)

Muonium, the muon mass and $(g\text{-}2)_\mu$

4×10^{-9} 6×10^{-13} 2×10^{-8}

$$E(1S-2S) \simeq \frac{3}{4} R_\infty \left(1 - \frac{m_e}{m_\mu}\right) + \text{QED}$$

PSI future
10^{-10}

1×10^{-8} 2×10^{-10} 6×10^{-13}

$$E(\text{HFS}) \simeq \frac{16}{3} \alpha^2 R_\infty c \left(\frac{m_e}{m_\mu}\right) + \text{QED}'$$

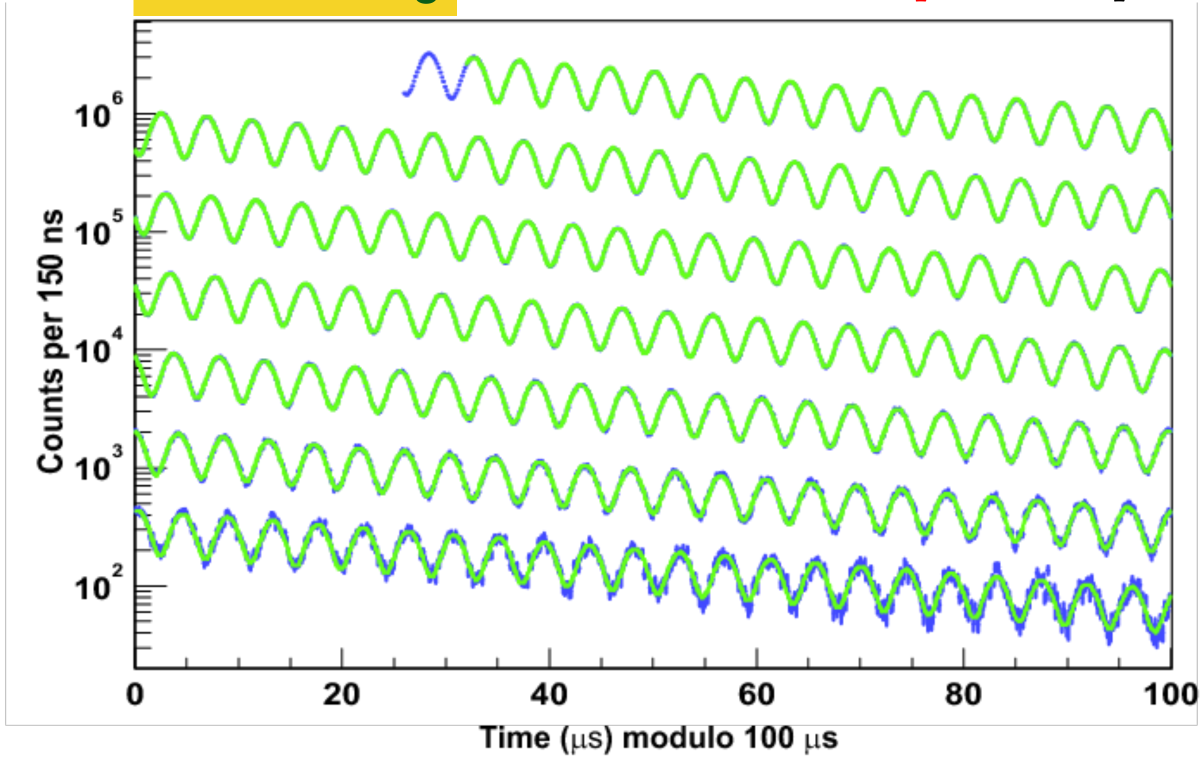
2×10^{-8}

Proposed J-PARK
1×10^{-9}

poster: Ueno

$$a_\mu = \frac{\frac{\omega_p}{\omega_a}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$

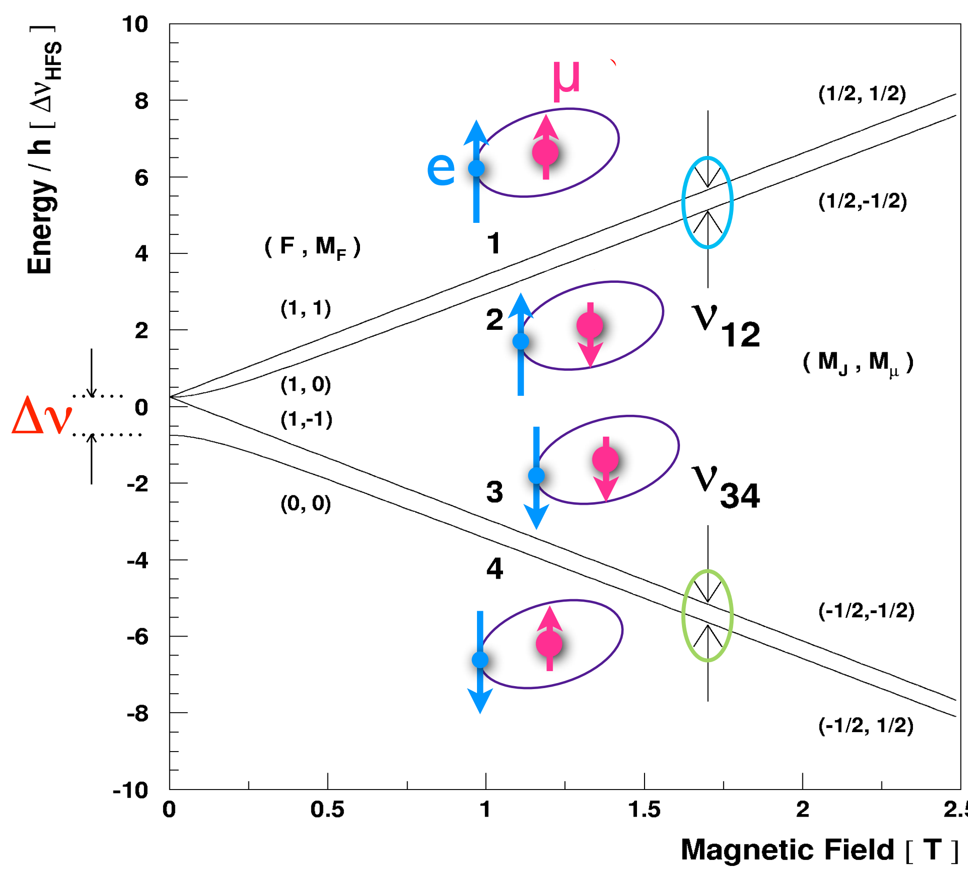
talk: Hertzog



$$\Delta\nu = \nu_{12} + \nu_{34}$$

$$\frac{\mu_\mu}{\mu_p} \sim \nu_{12} - \nu_{34}$$

K. Jungmann



Conclusions