Zuoz -Low energy Particle Physics I.

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Intro / info

Exotic atoms

Beyond SM at Low E

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Antimatter

https://lepp.ethz.ch/

This light summer course is a **short** extract of the - Low Energy Particle Physics & Exotic Atoms courses at ETHZ

With some slides borrowed from Aldo Antognini and others

Includes:

- Simple atoms and exotic atoms
- Spectroscopy methods
- Physics in Penning traps
- Precision decays of the muon and the pion
- Physics using antimatter

Missing:

- UCN physics
- Atomic, neutron and EDM
- Muon g-2
- Electron g-2
- …
- … DETAILS

Standard Model and beyond

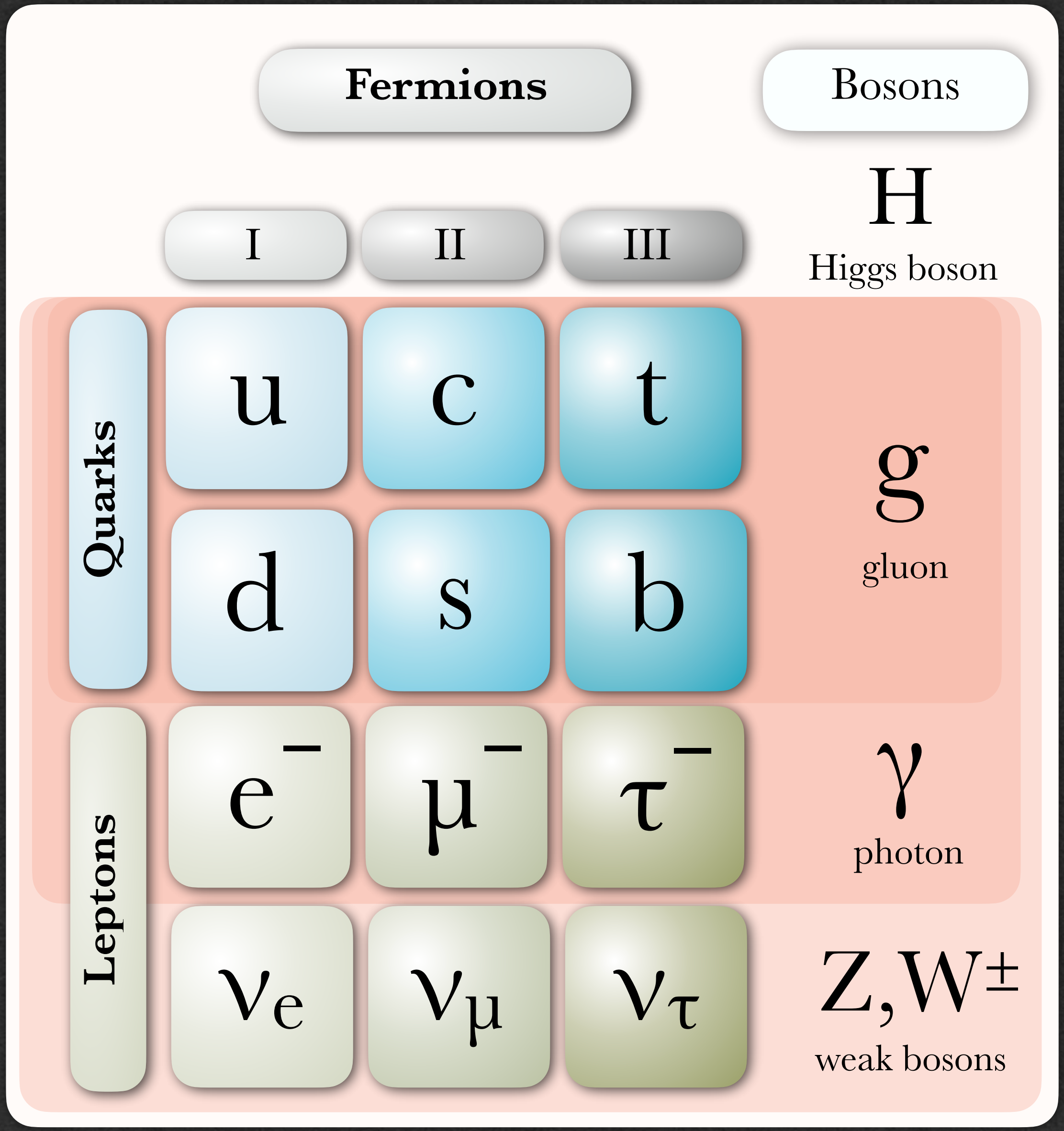
Why three generations?

Mass hierarchy?

Many free parameters

Too light Higgs

cLFV?



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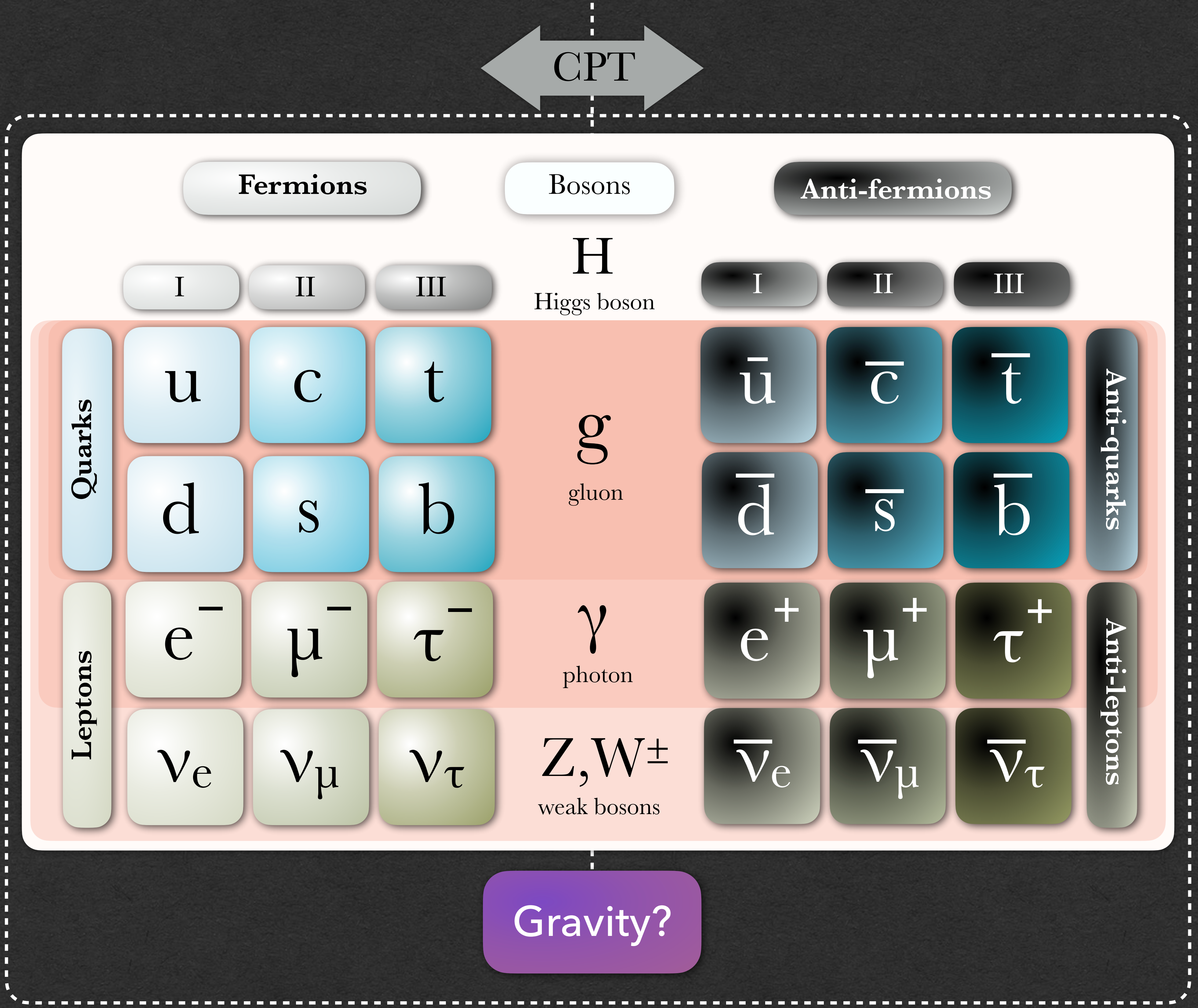
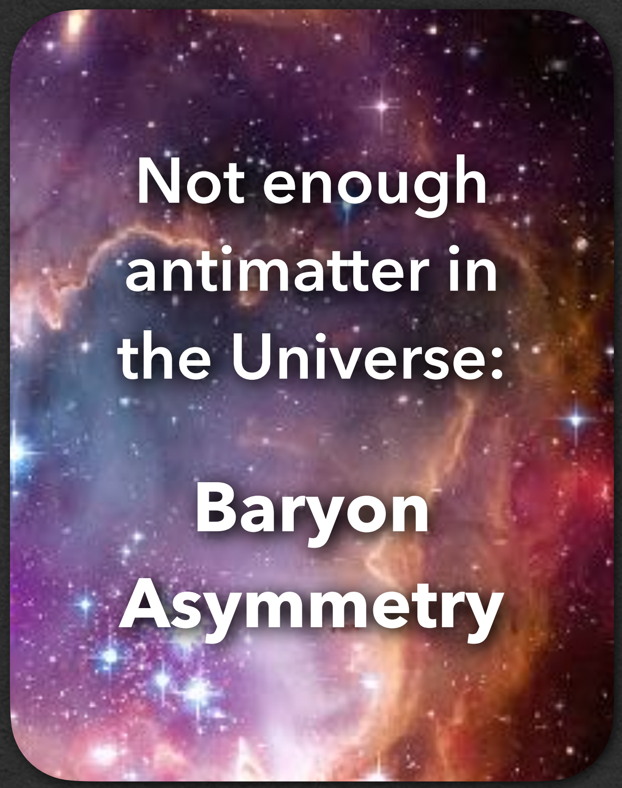


CPT

	Fermions			Bosons	Anti-fermions			
	I	II	III	H Higgs boson	I	II	III	
Quarks	u	c	t	g gluon	$\bar{u}$	$\bar{c}$	$\bar{t}$	Anti-quarks
	d	s	b		$\bar{d}$	$\bar{s}$	$\bar{b}$	
Leptons	e^-	μ^-	τ^-	γ photon	e^+	μ^+	τ^+	Anti-leptons
	ν_e	ν_μ	ν_τ	$Z,W^\pm$ weak bosons	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$	

Gravity?



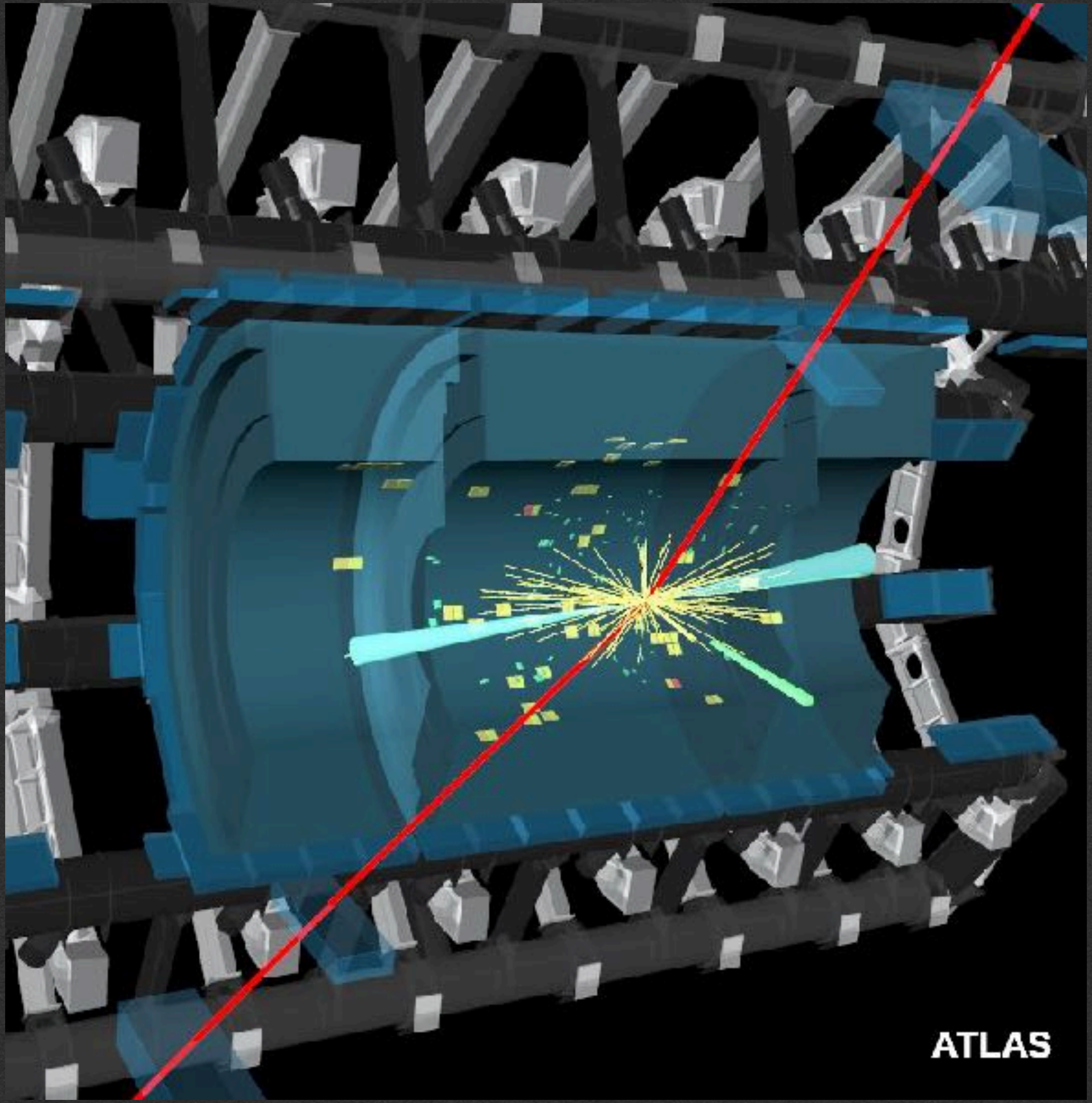
Not enough antimatter in the Universe:

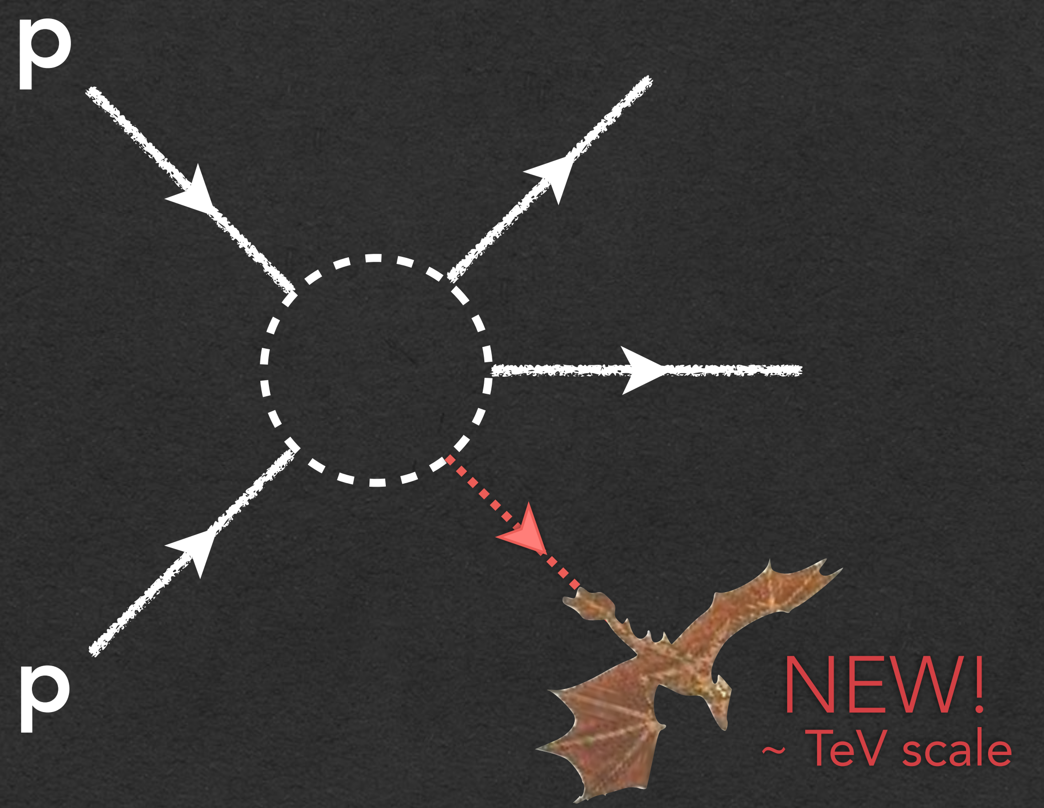
Baryon Asymmetry

Dark Matter?

Dark Energy?

The high energy frontier of particle physics

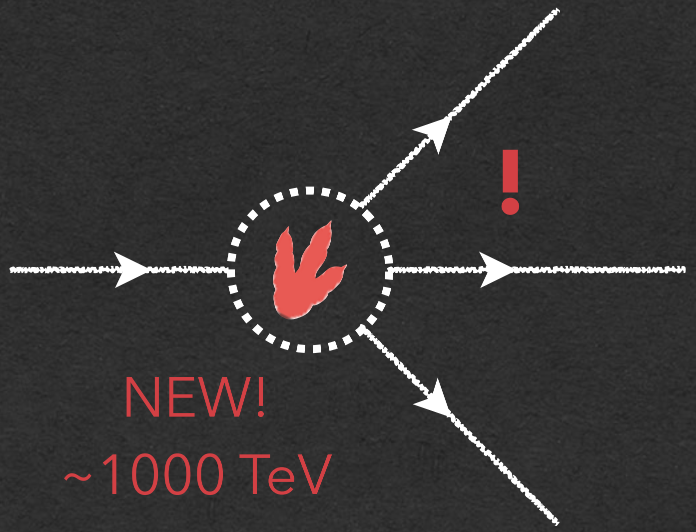




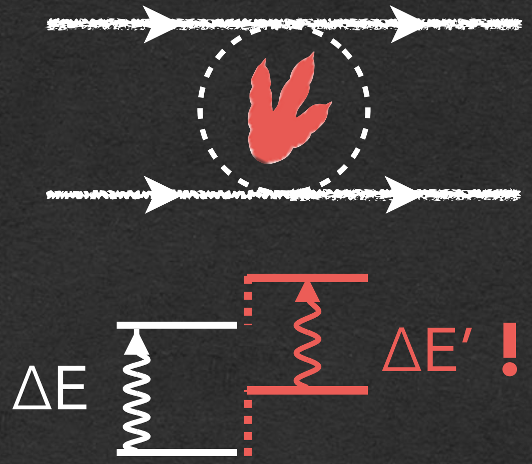
- Collisions at TeV-scale energies
- **Direct** production of new particles
- Limited by the collider energy

The intensity- and precision frontier

- Complementary way to search for new physics
- We are looking for rare events, and small energy shifts
- Indirect search, to see the "footprint" of new physics by precise observation of particles, in forms of:



Forbidden decays / precision decays



Energy shifts in interactions

Ingredients for precision particle physics

Particle accelerators

Antiprotons ($\bar{p}$) at CERN

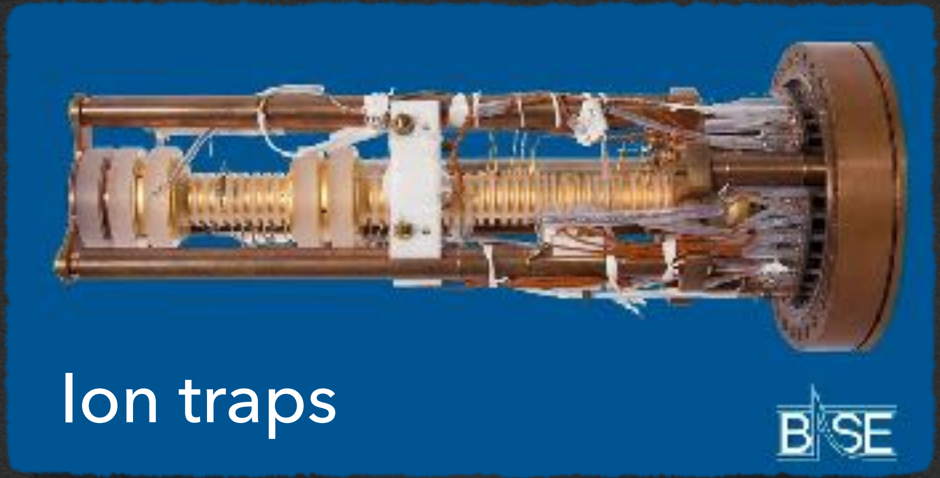
World's only low-energy $\bar{p}$

Muons at PSI

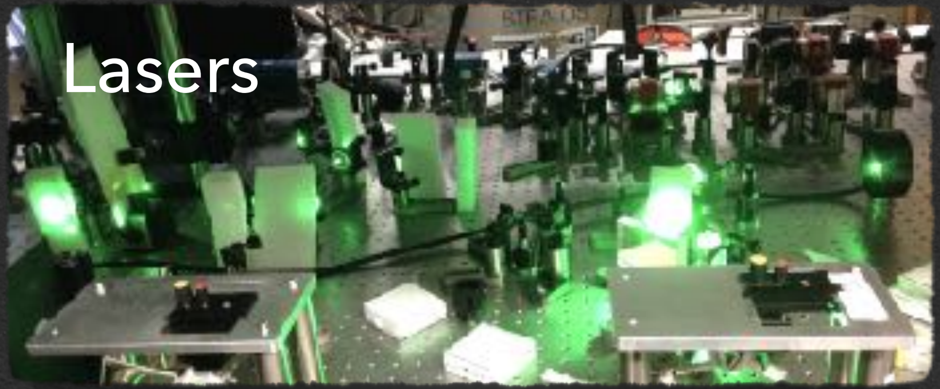
World's highest intensity cw π, μ

+

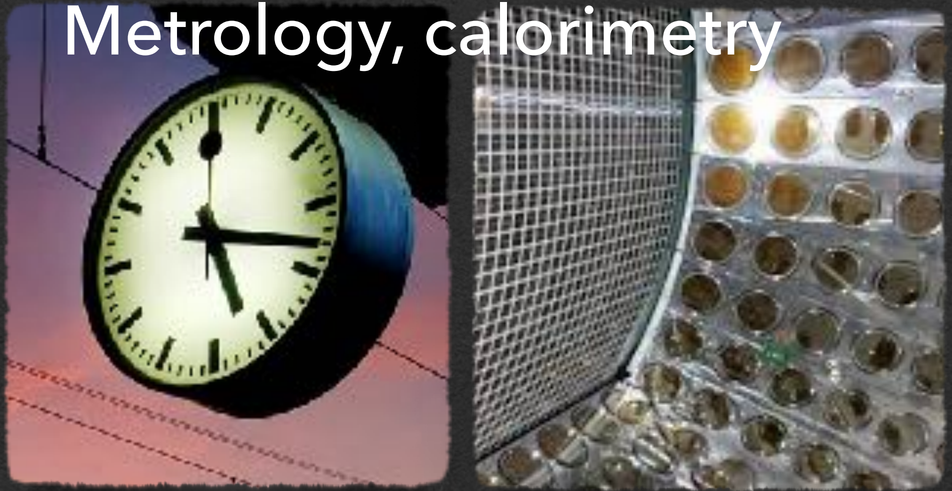
Precision methods



Ion traps



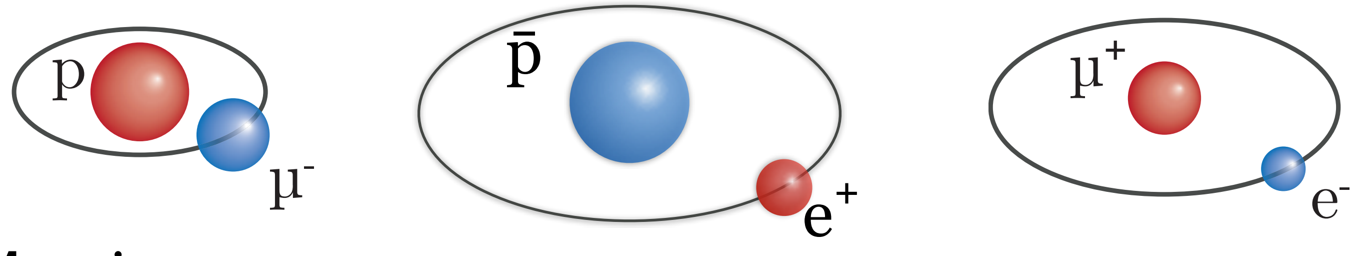
Lasers



Metrology, calorimetry

(Some) subjects of Low Energy Particle Physics

Bound systems I. - Atoms and Exotic atoms

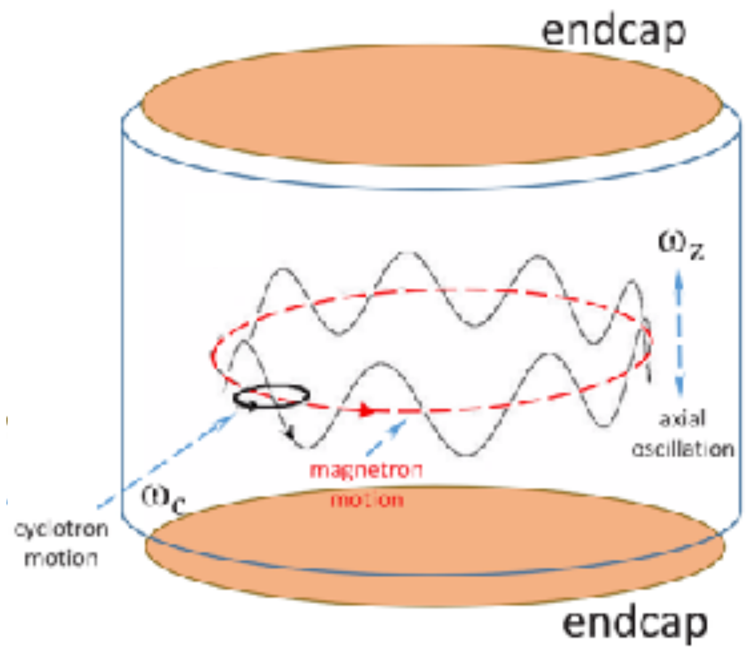


Muonic hydrogen

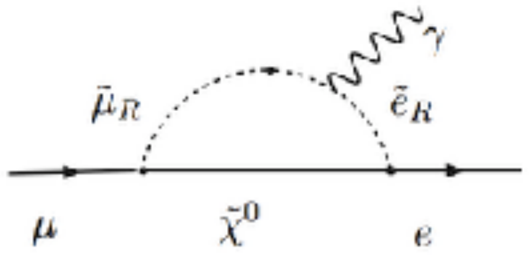
Antihydrogen

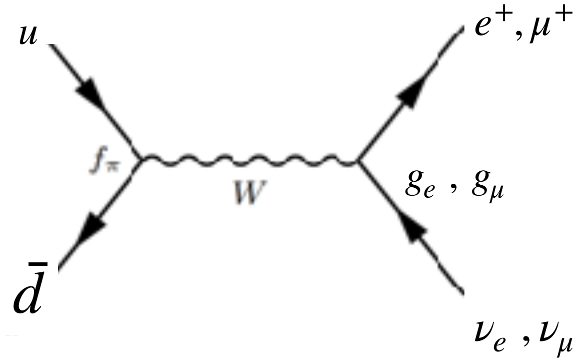
Muonium

Bound systems II. - Precision physics in traps



Precision decays / forbidden decays



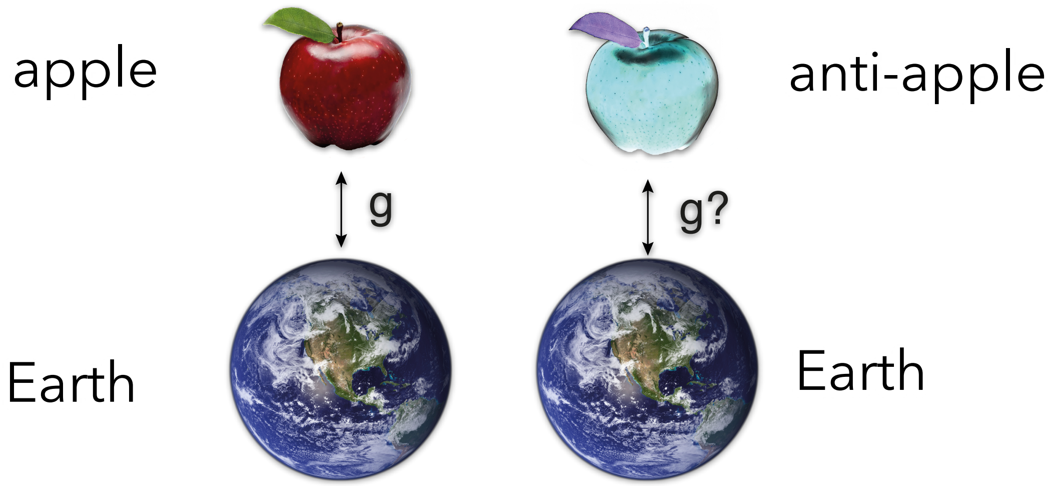


$$\mu^+ \to e^+ + \gamma$$

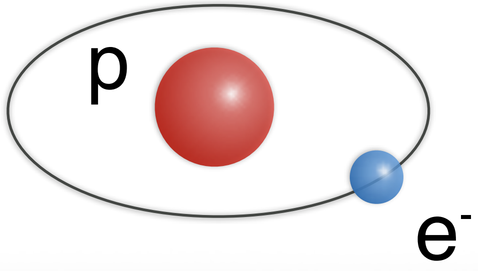
$$R_{e/\mu} = \frac{\pi^+ \to e^+ \nu(\gamma)}{\pi^+ \to \mu^+ \nu(\gamma)}$$

Muon and pion decay experiments

Gravity and the SM



Simple atomic systems as precision probes



Hydrogen atom - theory

$$E_n \simeq \left(1 - \frac{m_e}{m_p}\right) \frac{R_\infty}{n^2}$$

Schrödinger

Precise theory, experiment, and knowledge of fundamental constants

Hydrogen 1s-2s - experiment

Dirac Finite size of *p* ?

$$f_{1s-2s} = \quad 2\ 466\ 061\ 413.187\ 035(10)\ \ \mathrm{MHz}$$

QED proton spin

(Latest result: Parthey *et al.* 2011)

The gross energy levels of the hydrogen atom

Solve Schrödinger equation:

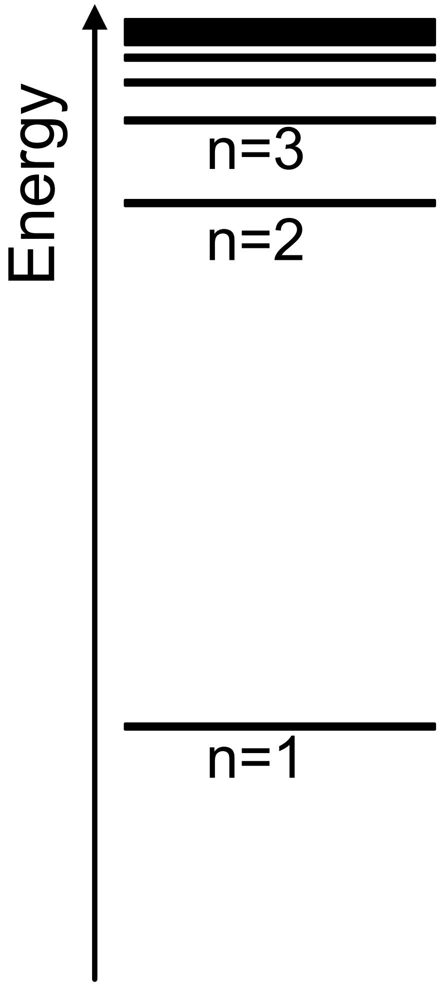
$$\left[\frac{\nabla^2}{2m} + V(r)\right]\Psi_{nlm}(r) = E_{nlm}\Psi_{nlm}(r)$$

in the Coulomb potential: $$V(r) = -\frac{1}{4\pi\epsilon_0}\frac{Ze^2}{r}$$

Reduced mass: $$m = \frac{M_p m_e}{M_p + m_e}$$

Rydberg: $$R_\infty = \frac{\alpha^2 m_e c}{2h}$$

Fine structure: $$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c}$$

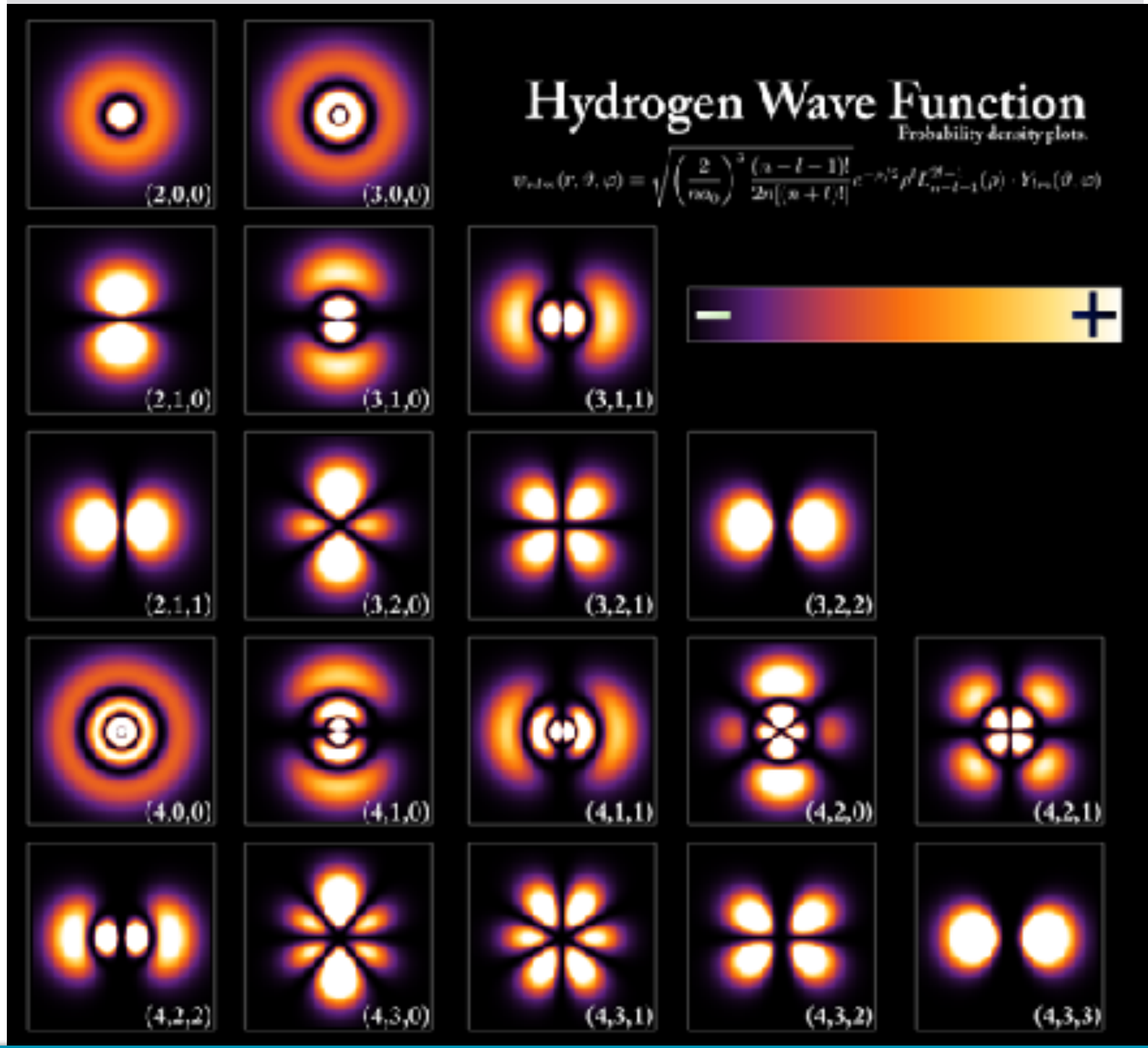


Energy levels (Bohr)

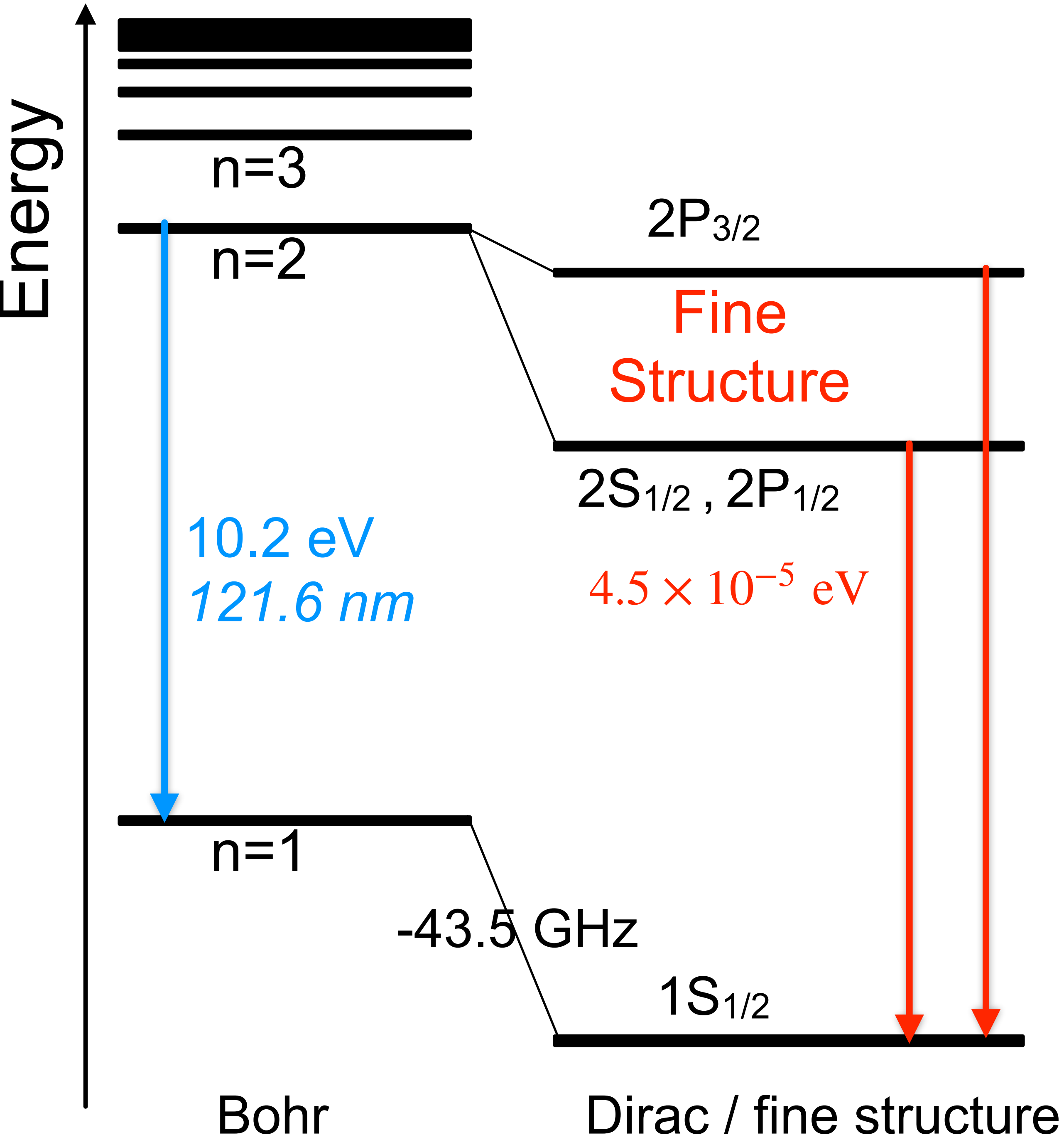
$$E_n = -\frac{(Z\alpha^2)mc^2}{2n^2} = -\frac{m}{m_e}\frac{R_\infty}{n^2}$$

Atomic size

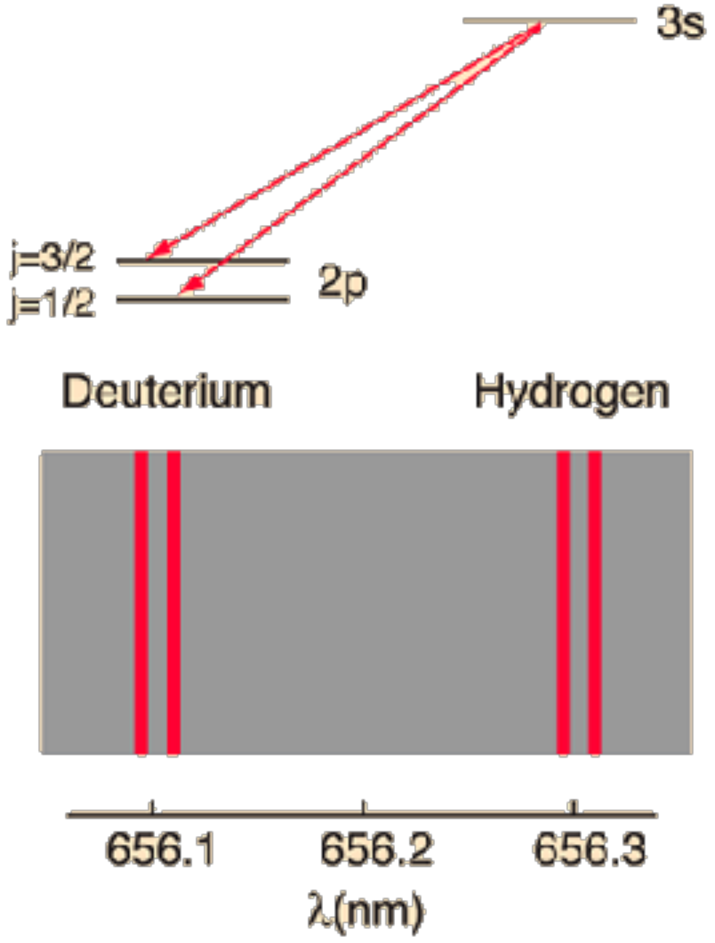
$$\langle r\rangle = \frac{\hbar}{Z\alpha c}\frac{n^2}{m}$$



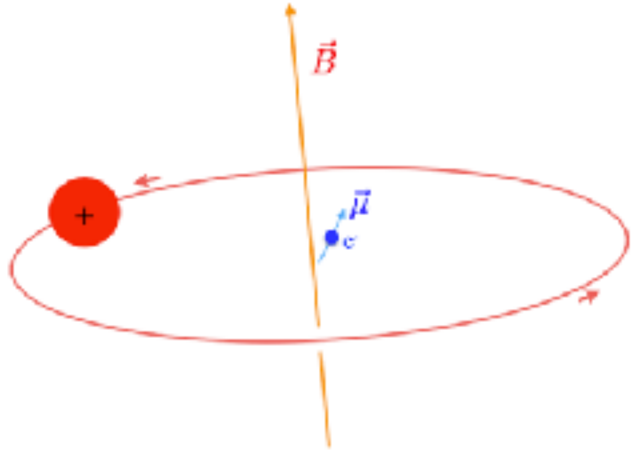
Relativistic effects



History: Balmer doublet, 3s→2p in the H emission spectra



The first terms of the fine structure Hamiltonian



$$H = \underbrace{m_{\mathrm{e}}c^2}_{\text{rest mass}} + \underbrace{\frac{P^2}{2m_{\mathrm{e}}} + V(R)}_{H_0} \underbrace{- \frac{P^4}{8m_{\mathrm{e}}^3c^2}}_{W_{\mathrm{mv}}} + \underbrace{\frac{1}{2m_{\mathrm{e}}^2c^2}\frac{1}{R}\frac{dV(R)}{dR}L\cdot S}_{W_{\mathrm{SO}}} + \quad \cdots$$

Relativistic treatment of electron kinetic energy:

$$E = c\sqrt{p^2 + m_{\mathrm{e}}^2c^2}$$

$$E = m_e c^2 + \frac{p^2}{2m_{\mathrm{e}}} - \frac{p^4}{8m_{\mathrm{e}}^3c^2} + \ldots$$

Spin-orbit interaction

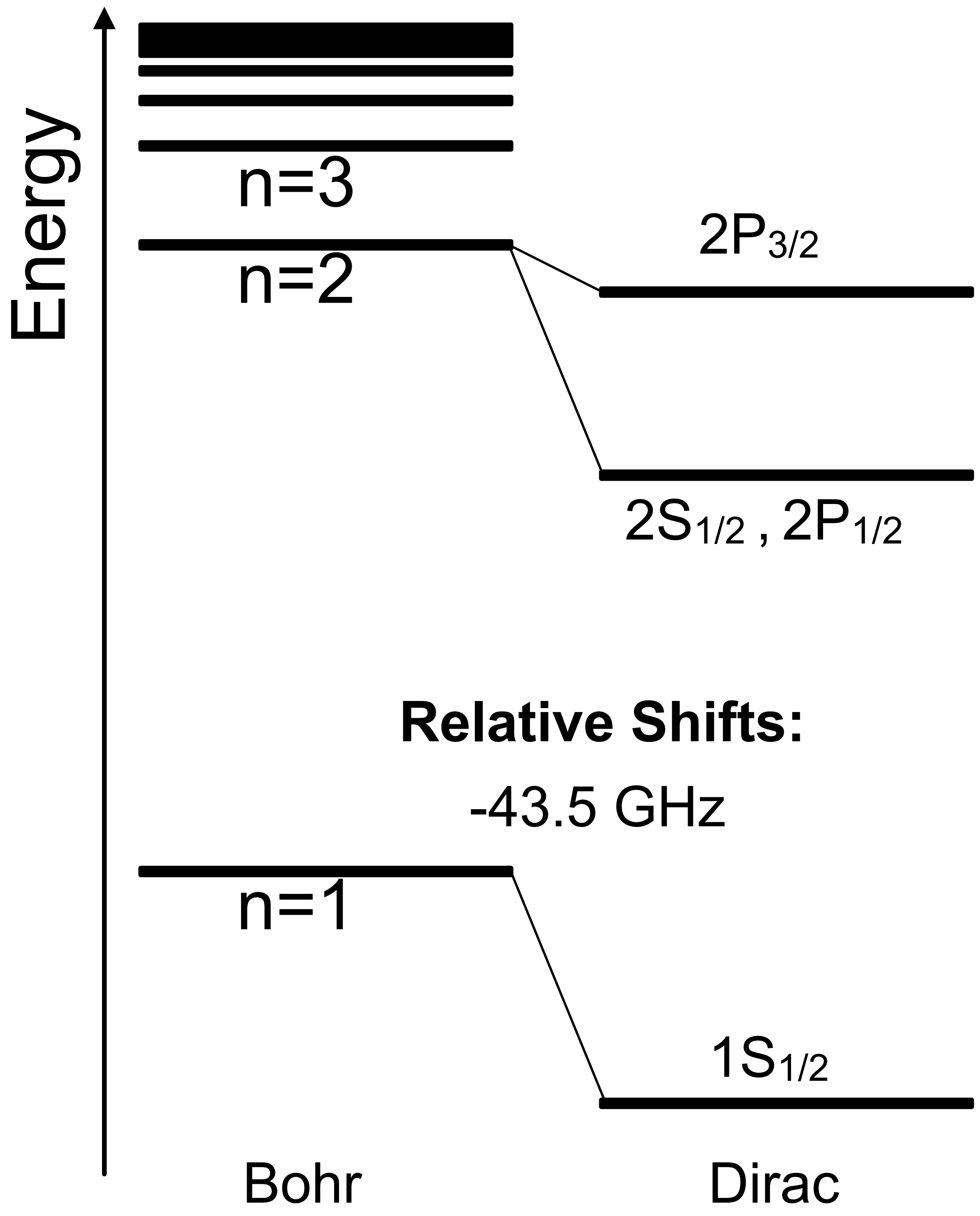
- The moving electron in the Coulomb field induces a magnetic field ***B'*** in the rest frame of the electron:

$$\mathbf{B}' = -\frac{1}{c^2}\mathbf{v}\times\mathbf{E}$$

- The intrinsic magnetic moment of the electron (the spin) M_S interacts with this:

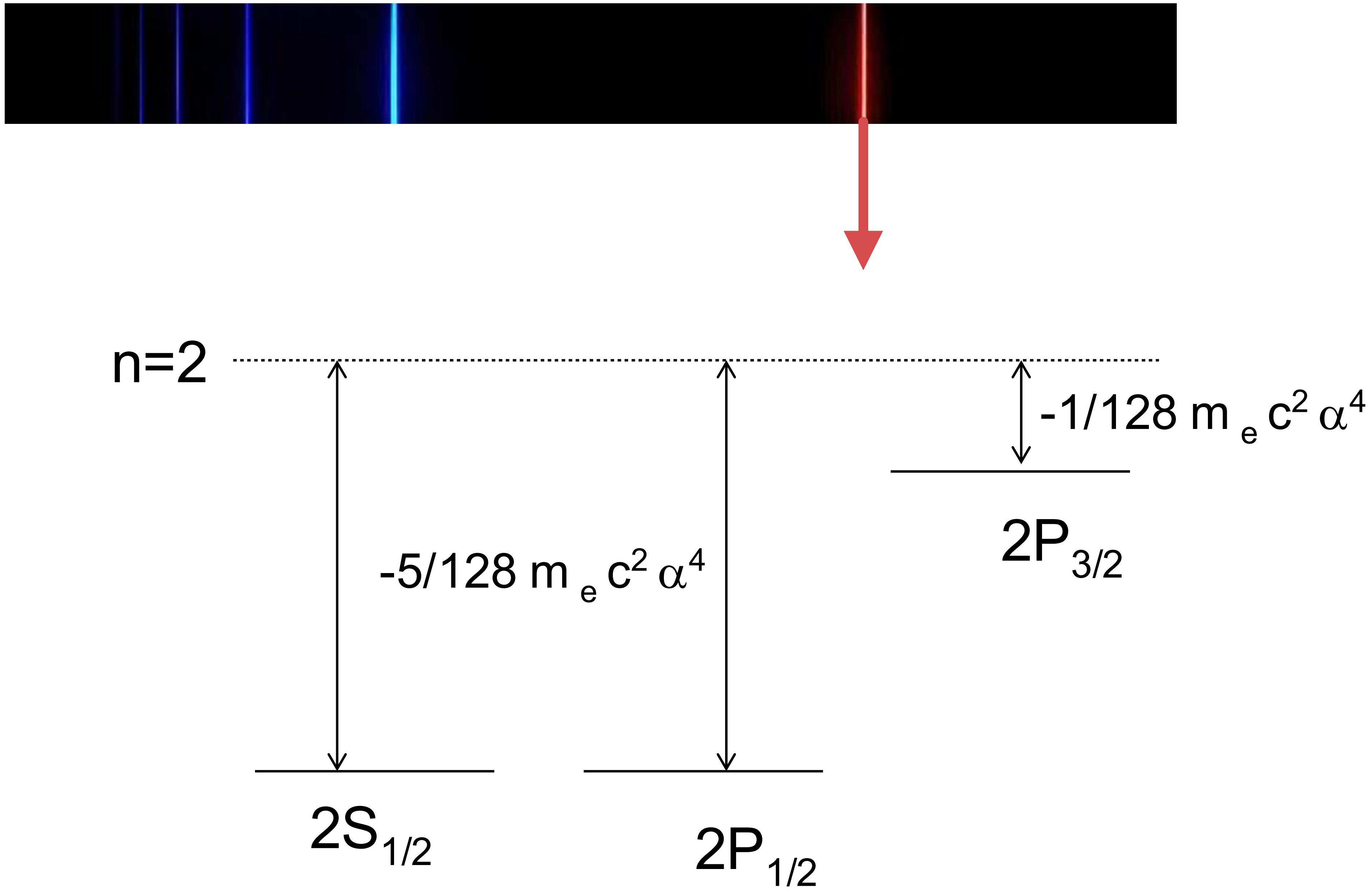
$$W' = -M_S \cdot B'$$

Results of the fine structure corrections at n=2



Relative Shifts:

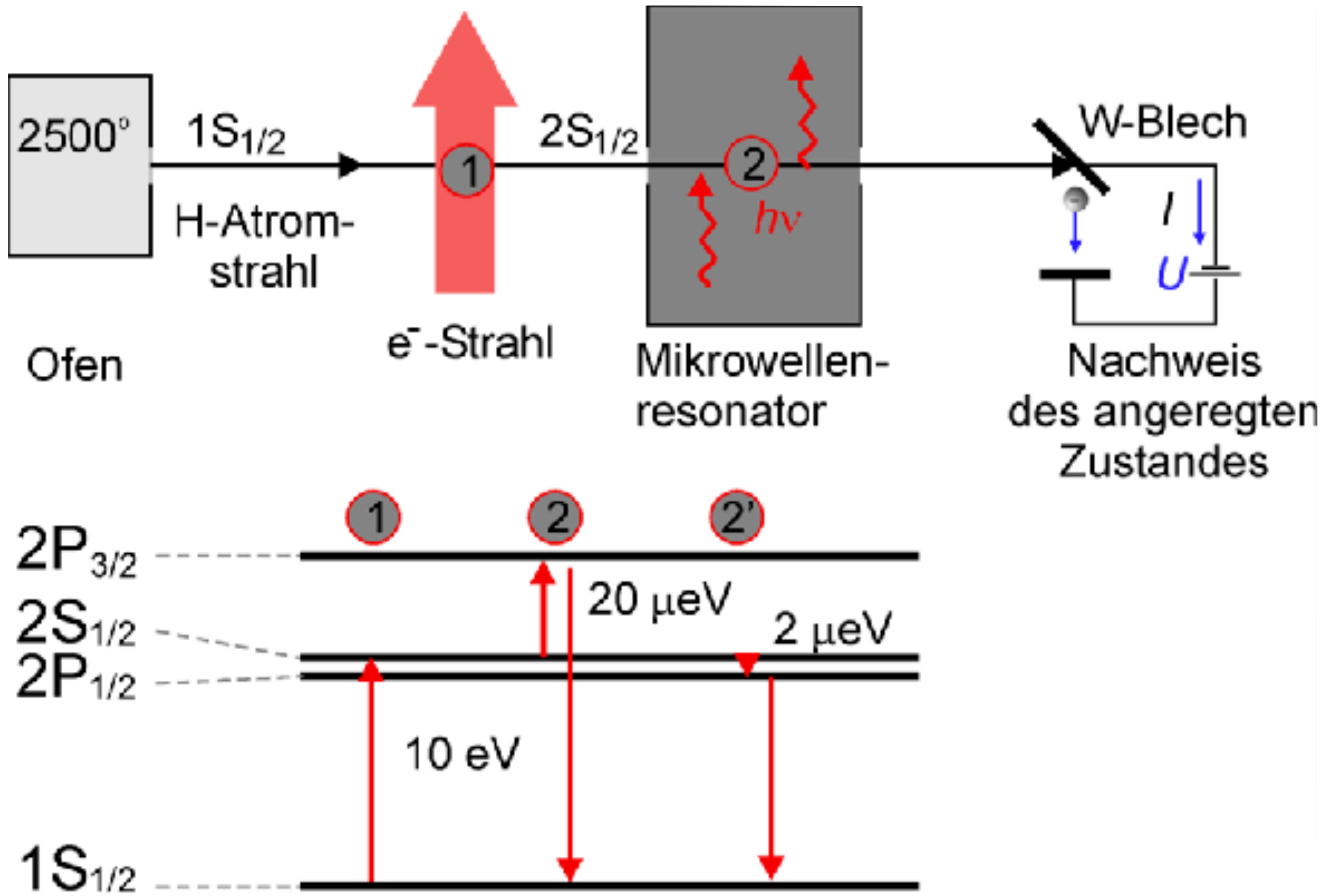
-43.5 GHz



Now we understand everything!*

*for a short time at least…

Unfortunately, Lamb's experiment occured...



- H atoms in $1S$-state are excited into the $2S$-state via electron collisions.

- If frequency of microwave is resonant with transition $\rightarrow$ excitation to the $2P$-state.

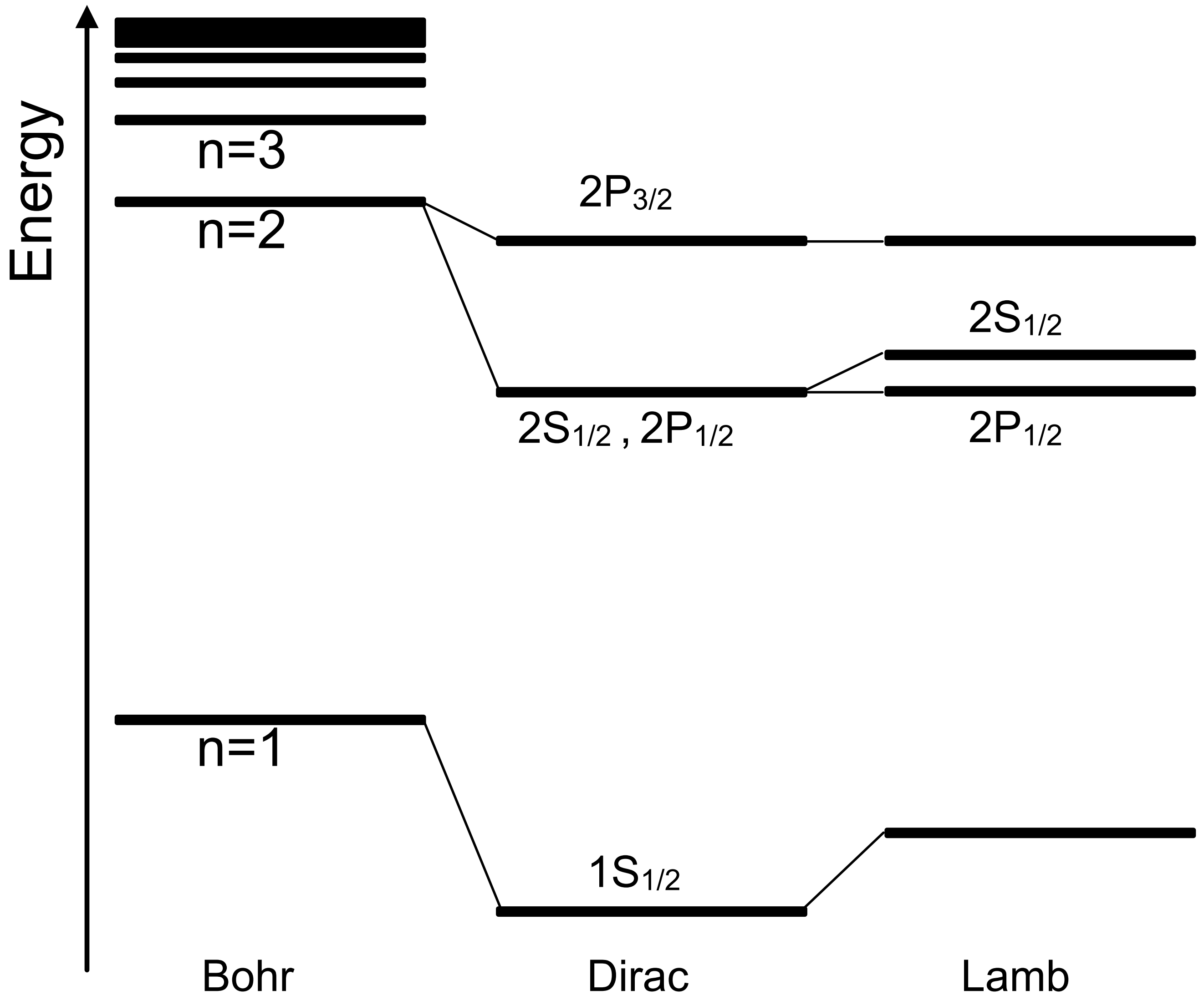
-The 2P state decays immediately to the ground state whereas the $2S$-state is meta-stable

-If $2S$-state reaches the W-plate $\rightarrow$ ejection of electrons

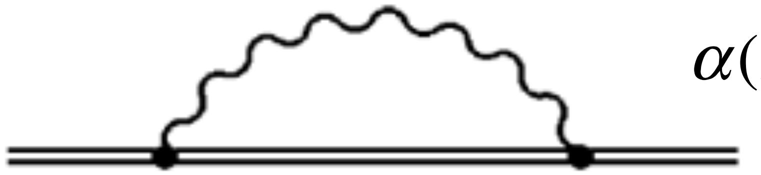
-If $1S$-state reaches the W-plate $\rightarrow$ NO ejection of electrons

- The measured $\Delta E(2P_{3/2} - 2S_{1/2})$ was in disagreement with Dirac prediction
- The measured $\Delta E(2P_{1/2} - 2S_{1/2}) \neq 0$ was in disagreement with Dirac prediction

Lamb's experiment initiated the development of QED



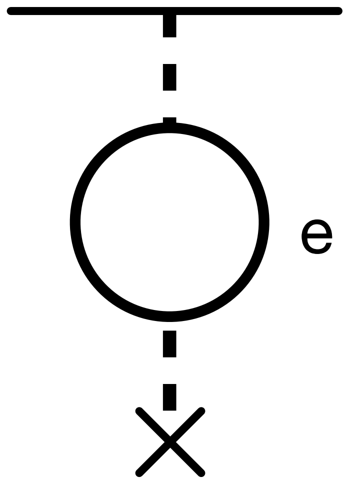
Self energy:



$$\alpha(Z\alpha)^2 \ln\left(\frac{1}{Z\alpha}\right)$$

- Main component of Lamb shift in hydrogen
- Splitting the energy levels with the **same *J* but different *L***

Vacuum polarization:



- In H smaller correction - with large Z and some exotic atoms even level crossing

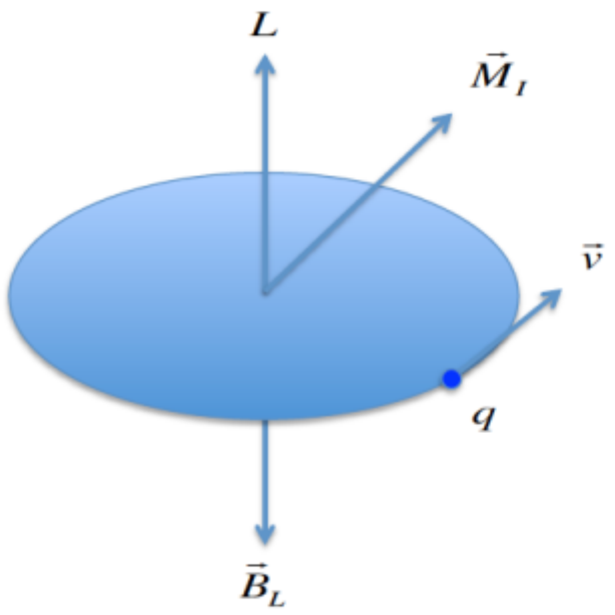
Hyperfine splitting

- Nuclear structure effects appear already in the non-relativistic approximation
- Has its origin in the magnetic effects due to the electron and proton spin interaction
- As for the fine structure we introduce the hyperfine splitting as a perturbation

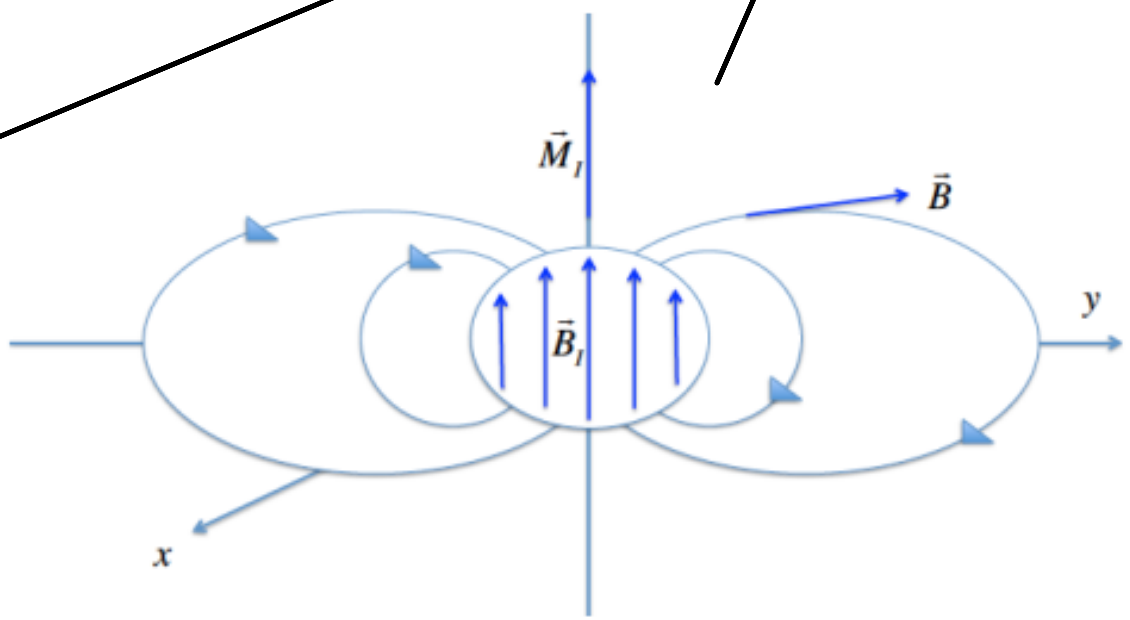
$$H = H_0 + H_{\text{HFS}}$$

- The perturbation arises in three terms: $H_{\text{HFS}} = \cancel{H^{L}_{\text{HFS}}} + \cancel{H^{\text{dip}}_{\text{HFS}}} + H^{\text{c}}_{\text{HFS}}$
- 1S state:

$$\frac{2\mu_0}{3}\frac{\mu_{\text{B}} g_{\text{e}} g_{\text{p}} \mu_{\text{N}}}{\hbar^2}\boldsymbol{I}\cdot\boldsymbol{S}$$

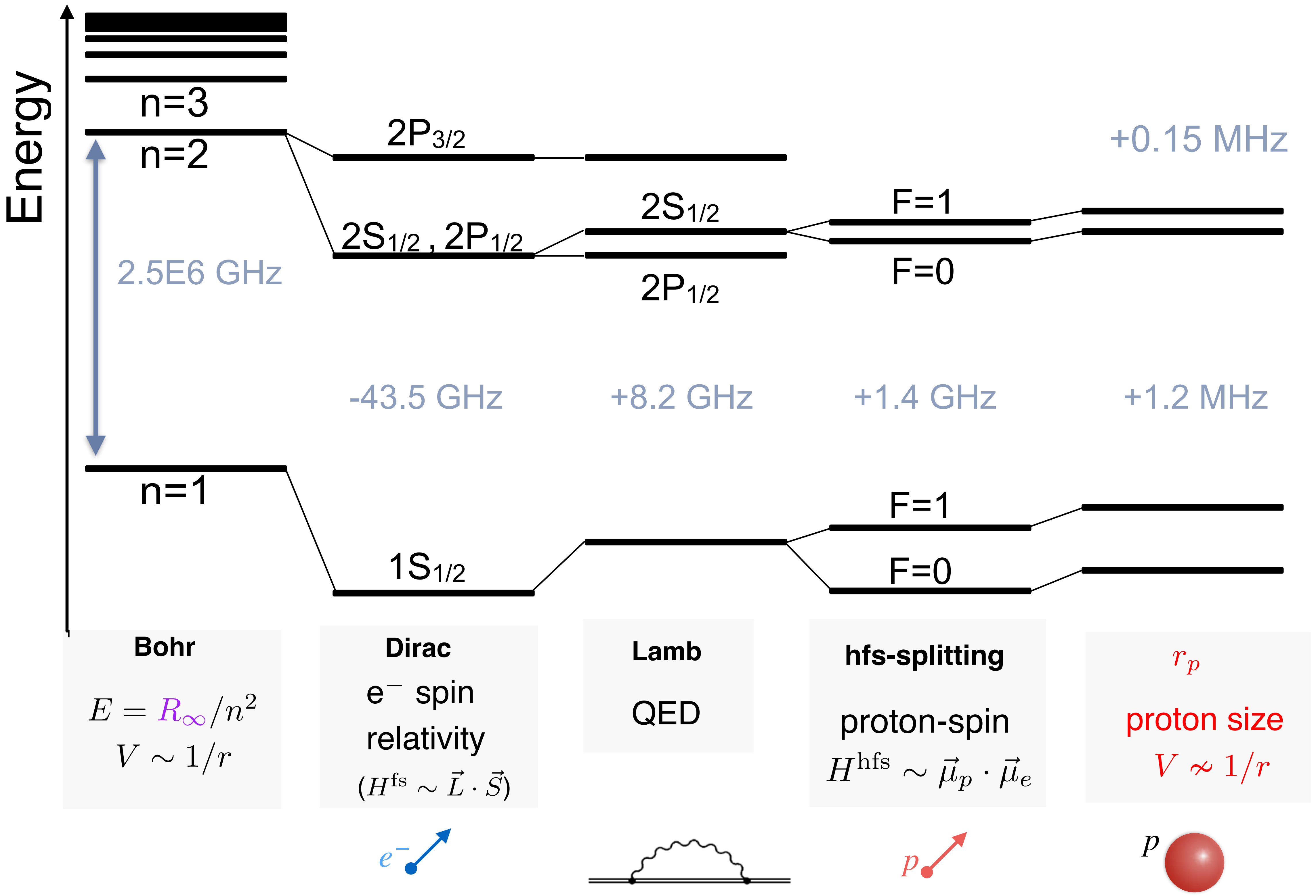


Coupling of the proton magnetic moment to the electron orbital momentum L



Magnetic B-field created by the proton magnetic moment M_I coupling to the electron spin momentum: **Dipole interaction**

The corrected energy spectrum of hydrogen



Bohr

$E = R_\infty/n^2$

$V \sim 1/r$

Dirac

e^- spin

relativity

$(H^{\mathrm{fs}} \sim \vec{L}\cdot\vec{S})$

Lamb

QED

hfs-splitting

proton-spin

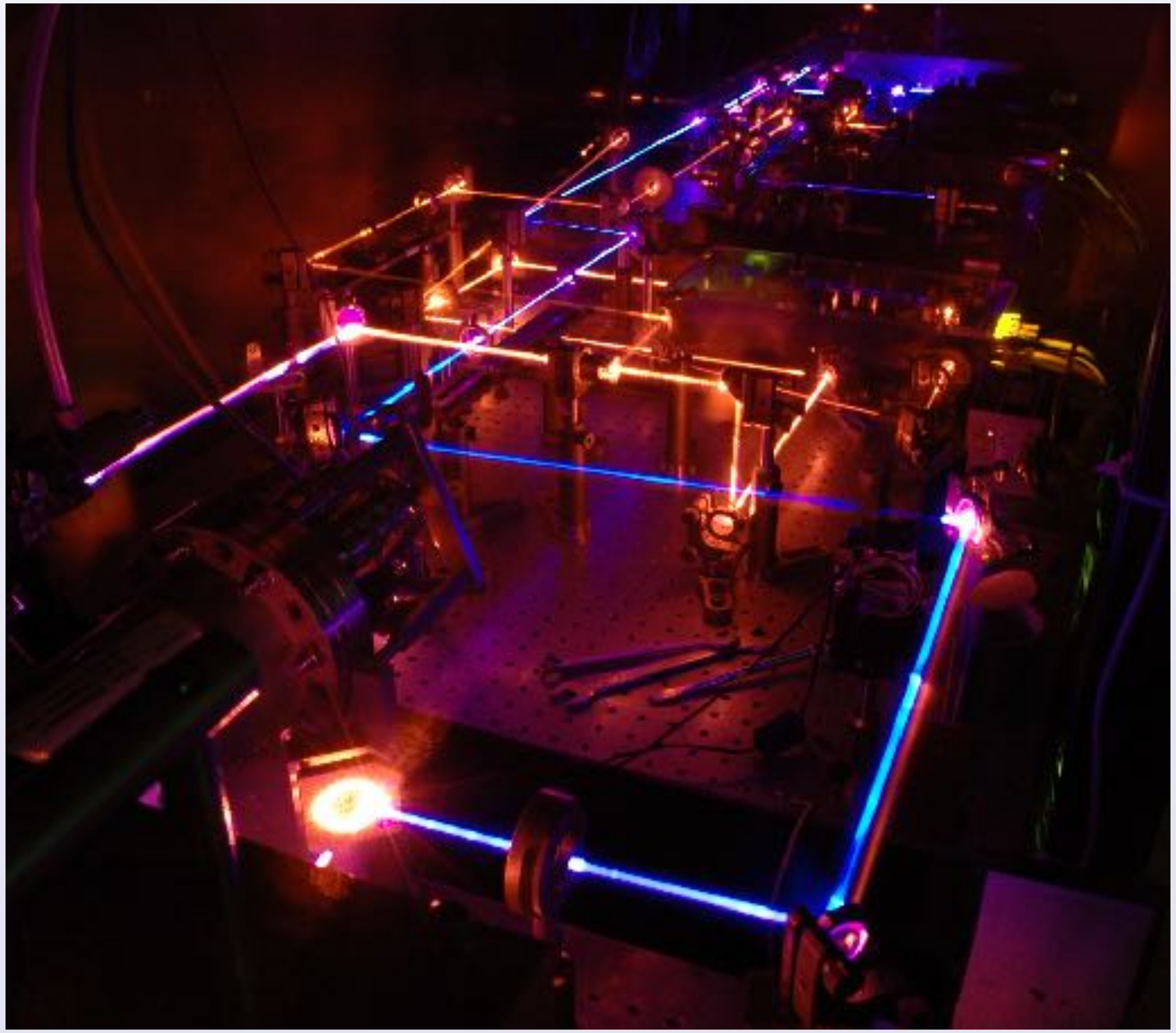
$H^{\mathrm{hfs}} \sim \vec{\mu}_p \cdot \vec{\mu}_e$

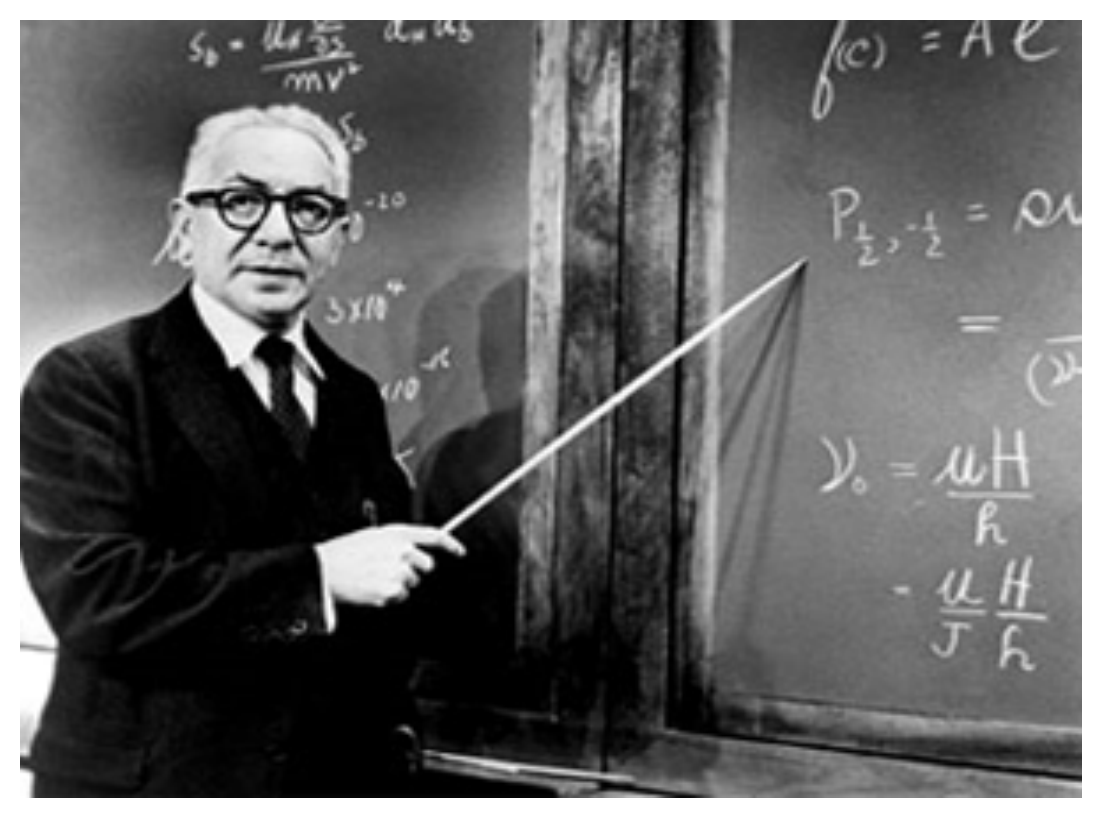
r_p

proton size

$V \nsim 1/r$

Methods: Spectroscopy





"Never measure anything but frequency"

~ Rabi ~

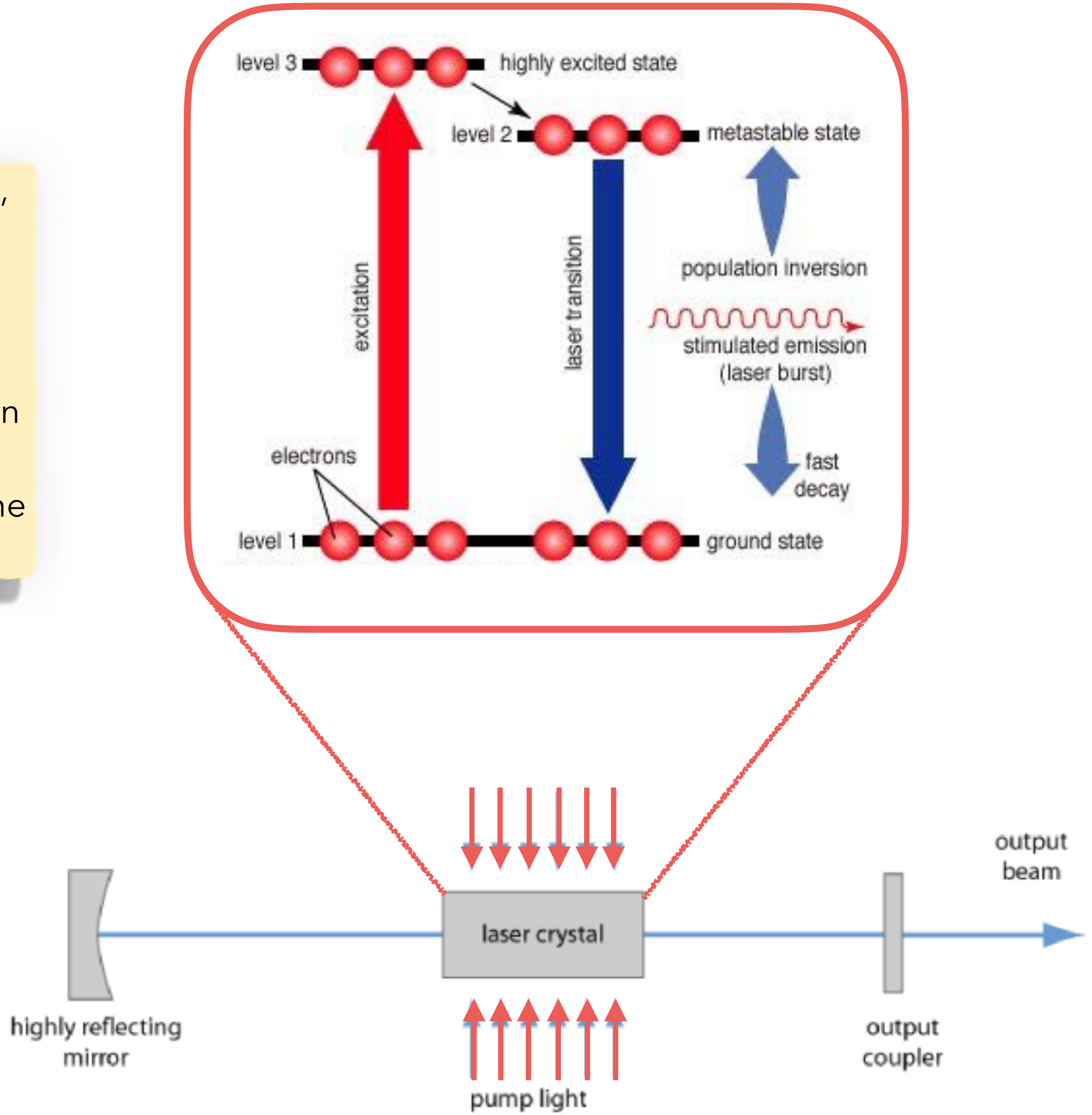
Needed: a coherent light source - lasers

Principles

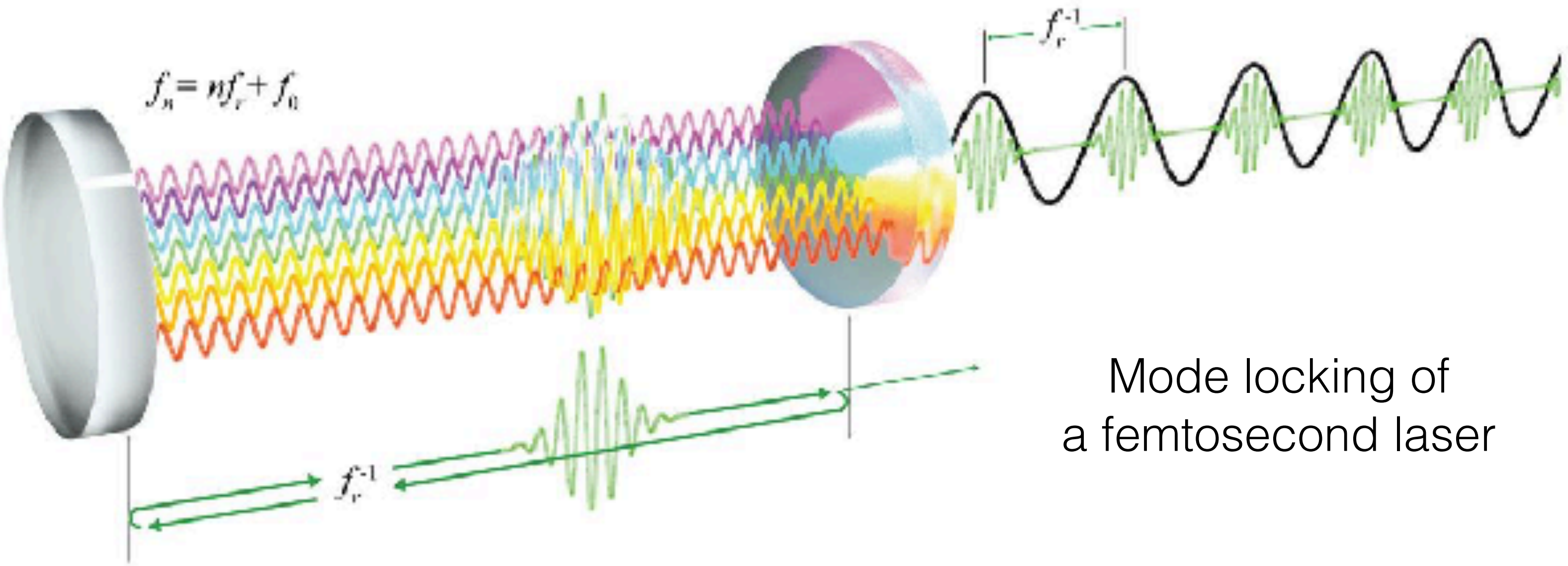
1. Optical pumping (here in the 3-level example: L1-> L3, which spontaneously decays to L2)
2. Pumped state (L2) is a metastable state: spontaneous emission is “slow”.
3. Stimulated emission is triggered by intracavity radiation (photons coupled back by cavity mirrors), which prompts L2 to deexcite to L1 by emitting photons of the same phase and direction.

Features

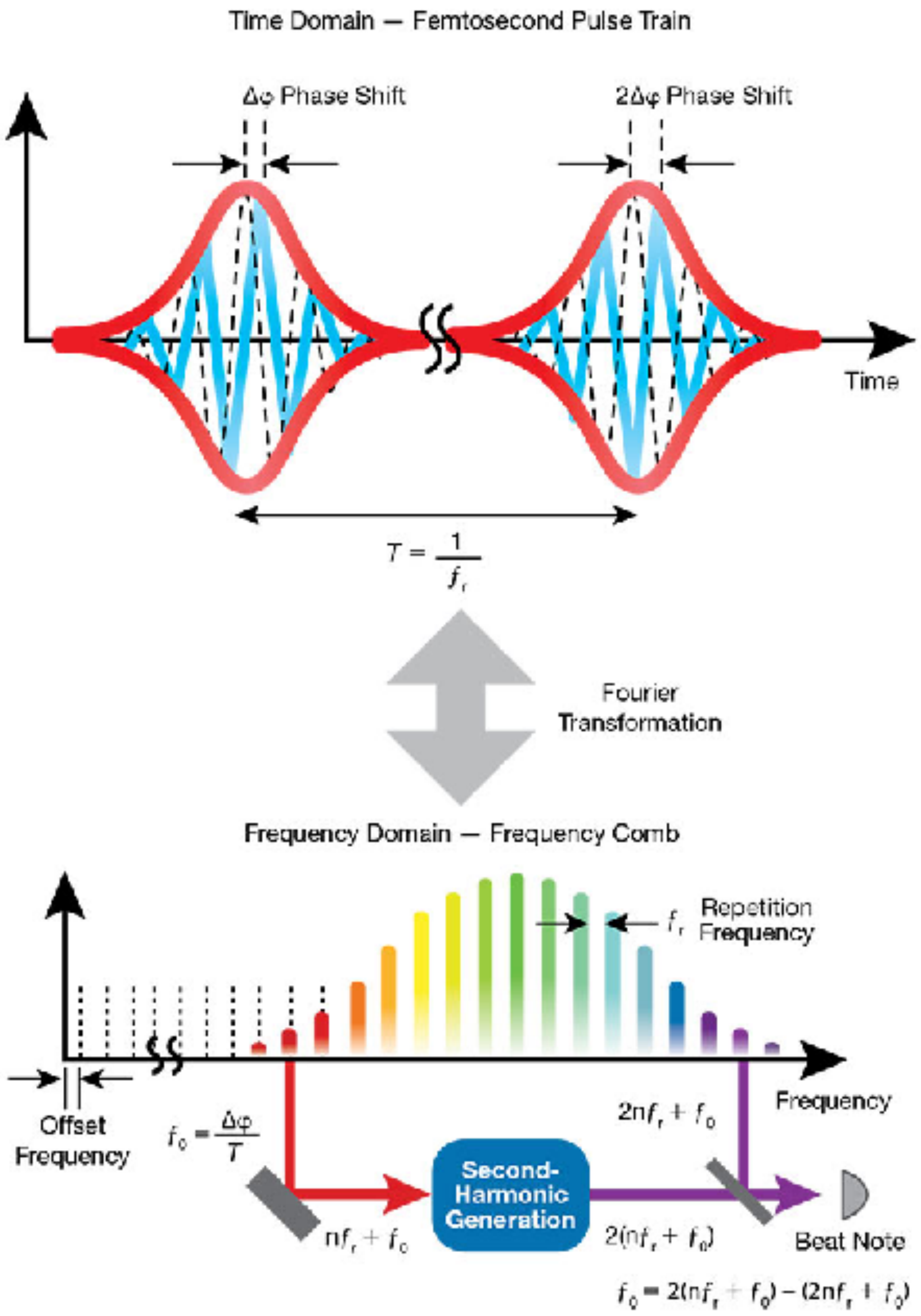
- High spatial coherence: due to point (3) above
- Narrow spectral linewidth lasers exhibit large degree of temporal coherence as well
- These features makes possible to carry out precise measurements on transition energies



Precise frequency measurements - the frequency comb



Mode locking of
a femtosecond laser



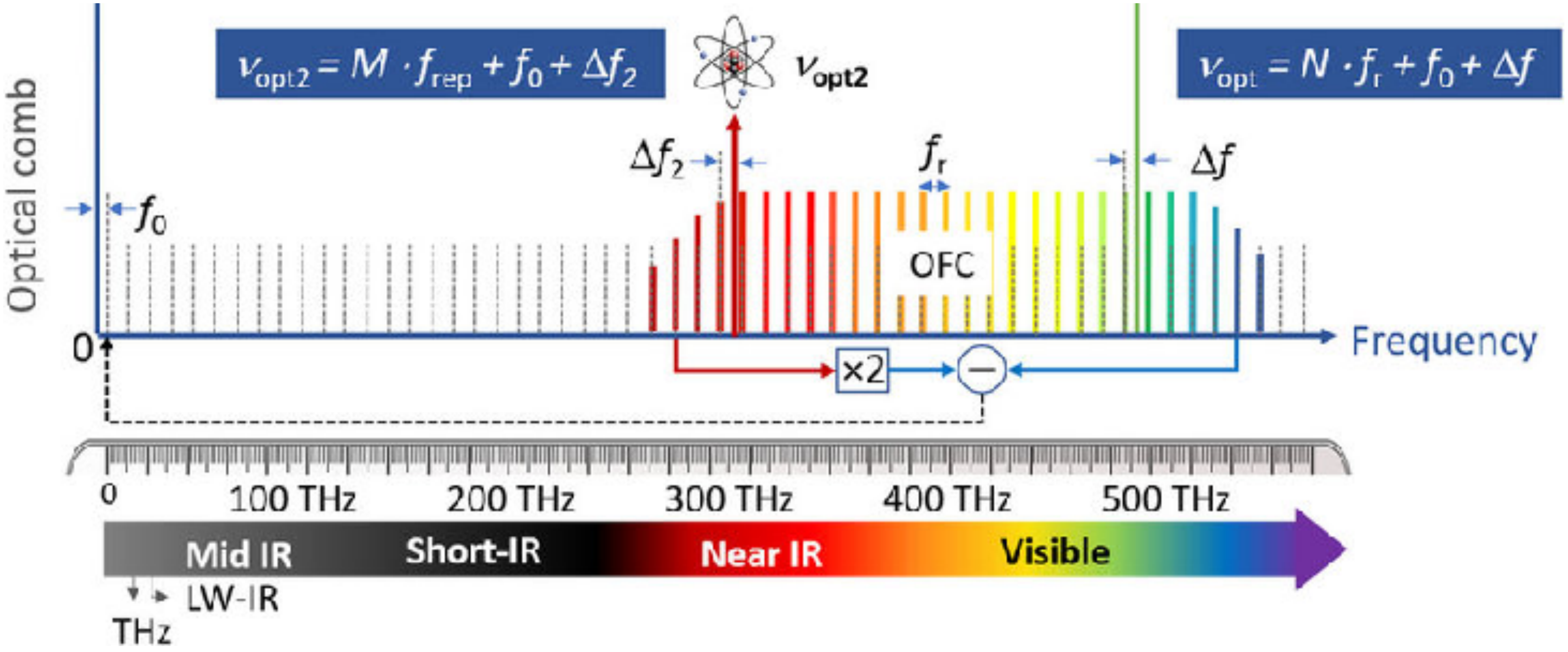
Nth comb line is determined by two parameters

$$f_n = nf_{\text{rep}} + f_{\text{ceo}}$$

- repetition rate via cavity length
- ceo offset via dispersions with error signal from beating:

$$2f_n - f_{2n} = 2(nf_{\text{rep}} + f_{\text{ceo}}) - (2nf_{\text{rep}} + f_{\text{ceo}}) = f_{\text{ceo}}\,.$$

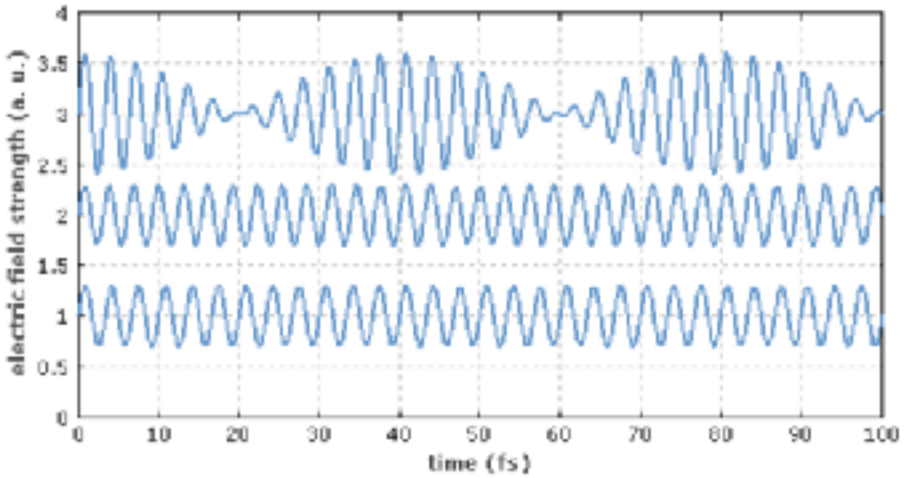
Usage of a frequency comb



Absolute frequency measurement / frequency reference.

Locking Fabry-Perot cavities to comb lines

Beatnote of comb and laser: intensity modulation which is slow enough to measure by a photodiode:



Understanding the interaction of atoms with coherent light

- Analogy with parametrically driven coupled and damped mech osc., see from Frimmer & Novotny:

  http://dx.doi.org/10.1119/1.4878621

- Equation of motions:

$$\ddot{x}_A + \gamma \dot{x}_A + \left[\frac{k+\kappa}{m} - \frac{\Delta k(t)}{m}\right] x_A - \frac{\kappa}{m} x_B = \frac{F(t)}{m},$$

$$\ddot{x}_B + \gamma \dot{x}_B + \left[\frac{k+\kappa}{m} + \frac{\Delta k(t)}{m}\right] x_B - \frac{\kappa}{m} x_A = 0.$$

- Introducing carrier, detuning and coupling frequencies:

$$\Omega_0^2 = \frac{k+\kappa}{m},$$

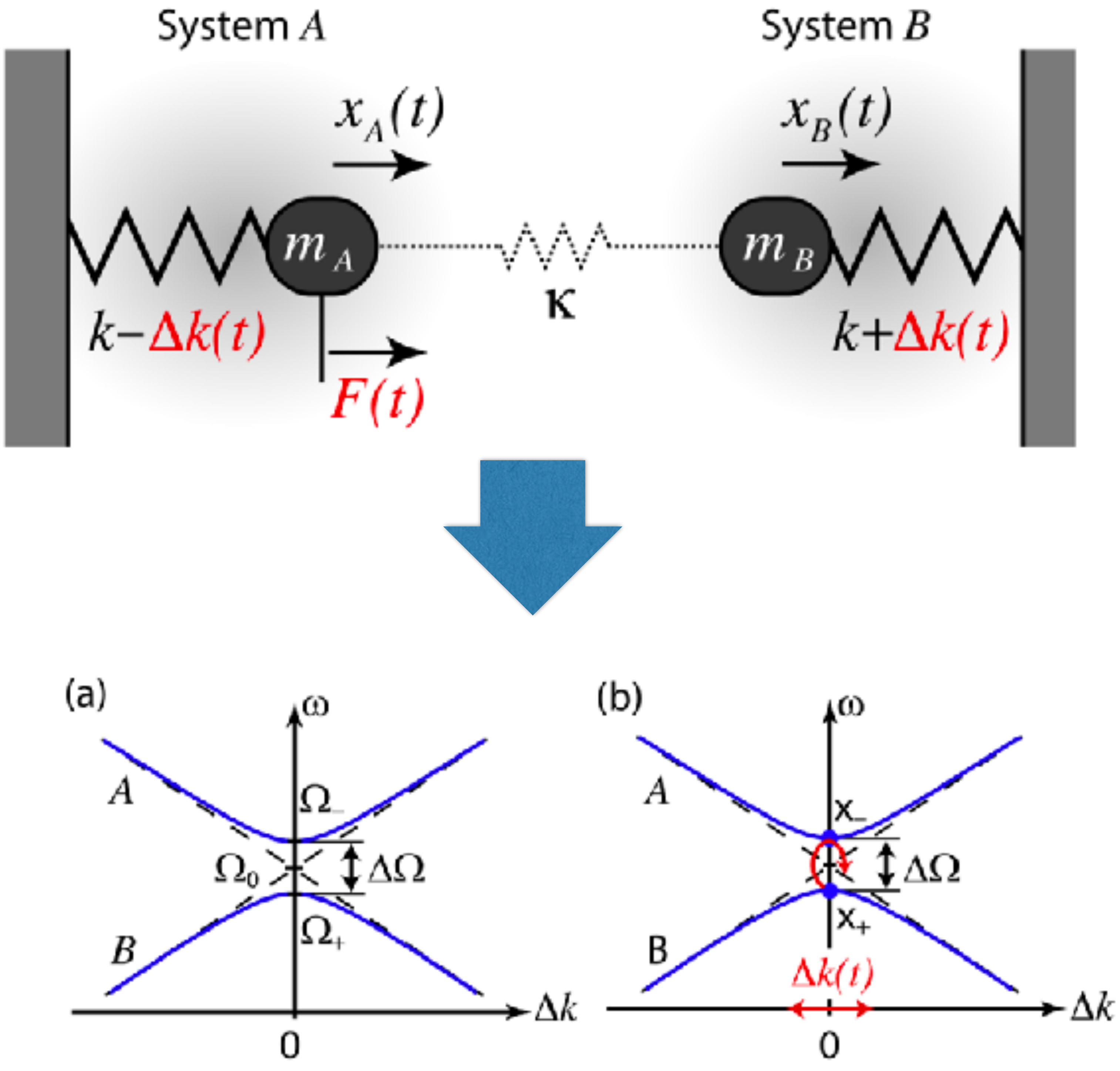
$$\Omega_d^2 = \frac{\Delta k}{m},$$

$$\Omega_c^2 = \frac{\kappa}{m},$$

- Can be made analogous to the time dependent Schrodinger for 2-level systems

$$i\hbar\, \partial_t |\Psi\rangle = \hat{H} |\Psi\rangle \quad \text{with} \quad |\Psi\rangle = a(t)|g\rangle + b(t)|e\rangle$$

where the coupling is: $\langle e|\hat{H}|g\rangle = \hbar\omega_d/2$



$$\Omega_+ = \sqrt{k/m} \qquad \Omega_- = \sqrt{(k+2\kappa)/m}$$

Two level systems: time evolution on a Bloch sphere

The state of the system can be represented with a vector s, and an endpoint at the surface of a sphere:

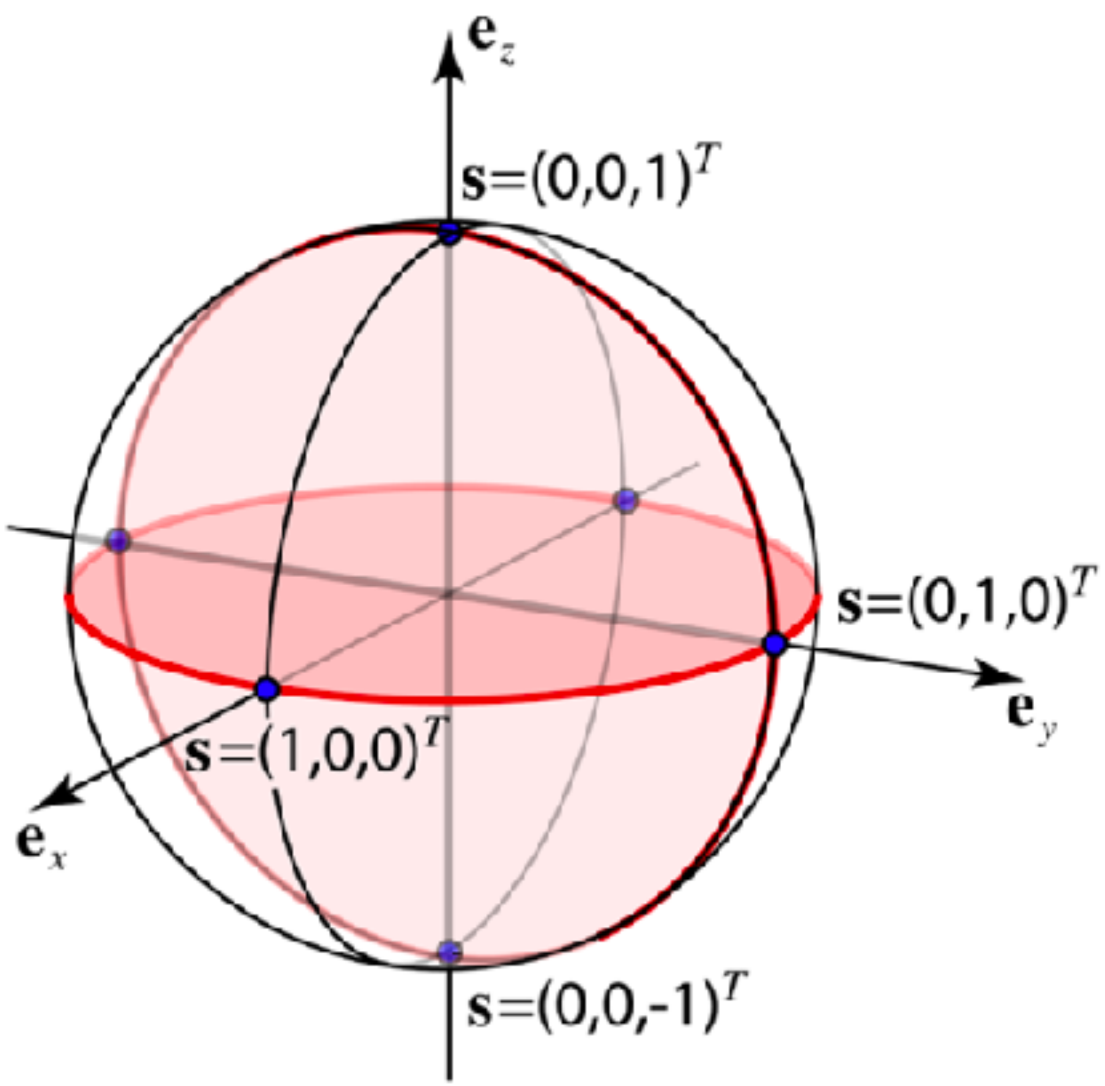
$s_x = 2|\bar{a}||\bar{b}|\cos(\phi)$ - real part

$s_y = -2|\bar{a}||\bar{b}|\sin(\phi)$ - imaginary part

$s_z = |\bar{a}|^2 - |\bar{b}|^2.$ - population inversion

North and south pole: ground state and excited state. With damping , the surface "shrinks". Bloch equations:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} s_x \\ s_y \\ s_z \end{bmatrix} = \begin{bmatrix} -\gamma & -\delta & 0 \\ \delta & -\gamma & A \\ 0 & -A & -\gamma \end{bmatrix} \begin{bmatrix} s_x \\ s_y \\ s_z \end{bmatrix}.$$



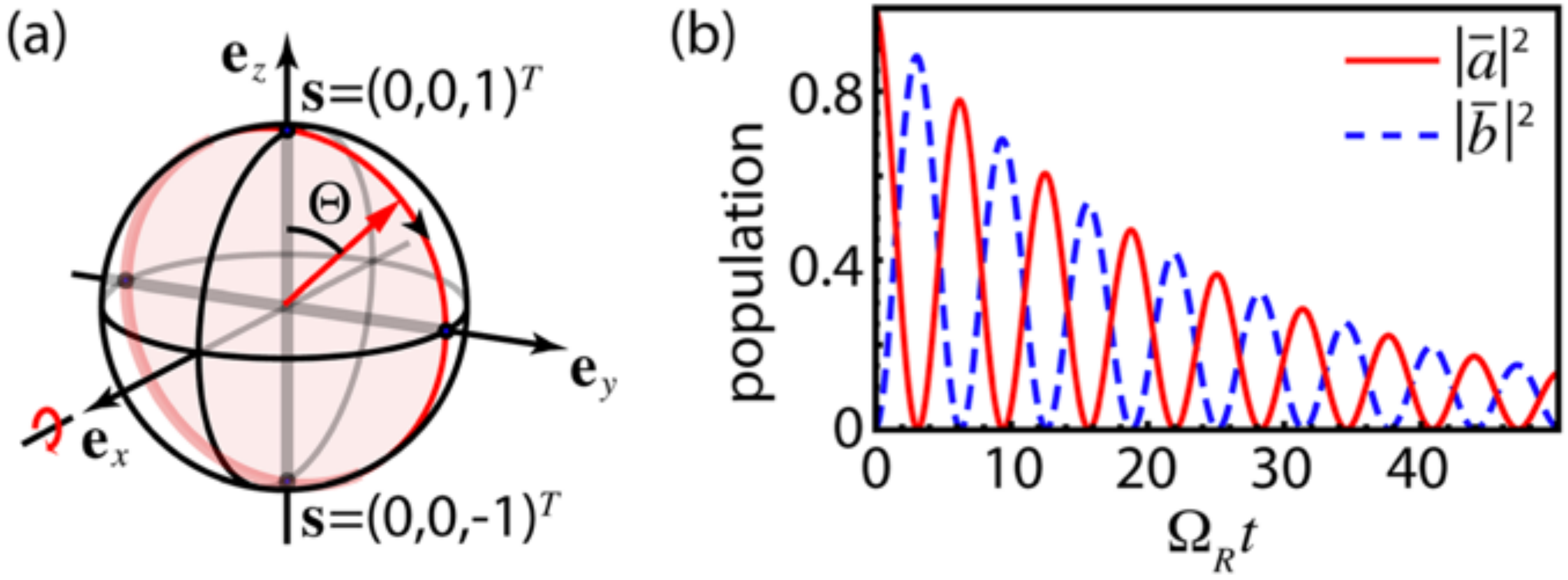
Amplitudes |ā|, |b̄| represent state populations in a 2-level system, ***A*** represents the strength of the drive (of the laser field), $\boldsymbol{\delta}$ the detuning from the energy gap between the 2 states, $\boldsymbol{\gamma}$ is dissipation by decay.

NOTE: only a single decay from this mechanical analogy both damping in contrast to a quantum-mechanical two-level system that can show different decay rates due to spontaneous emission and dephasing processes.

Rabi oscillations

One Rabi-cycle with zero detuning $(\omega_{\text{drive}} = \Delta\Omega)$

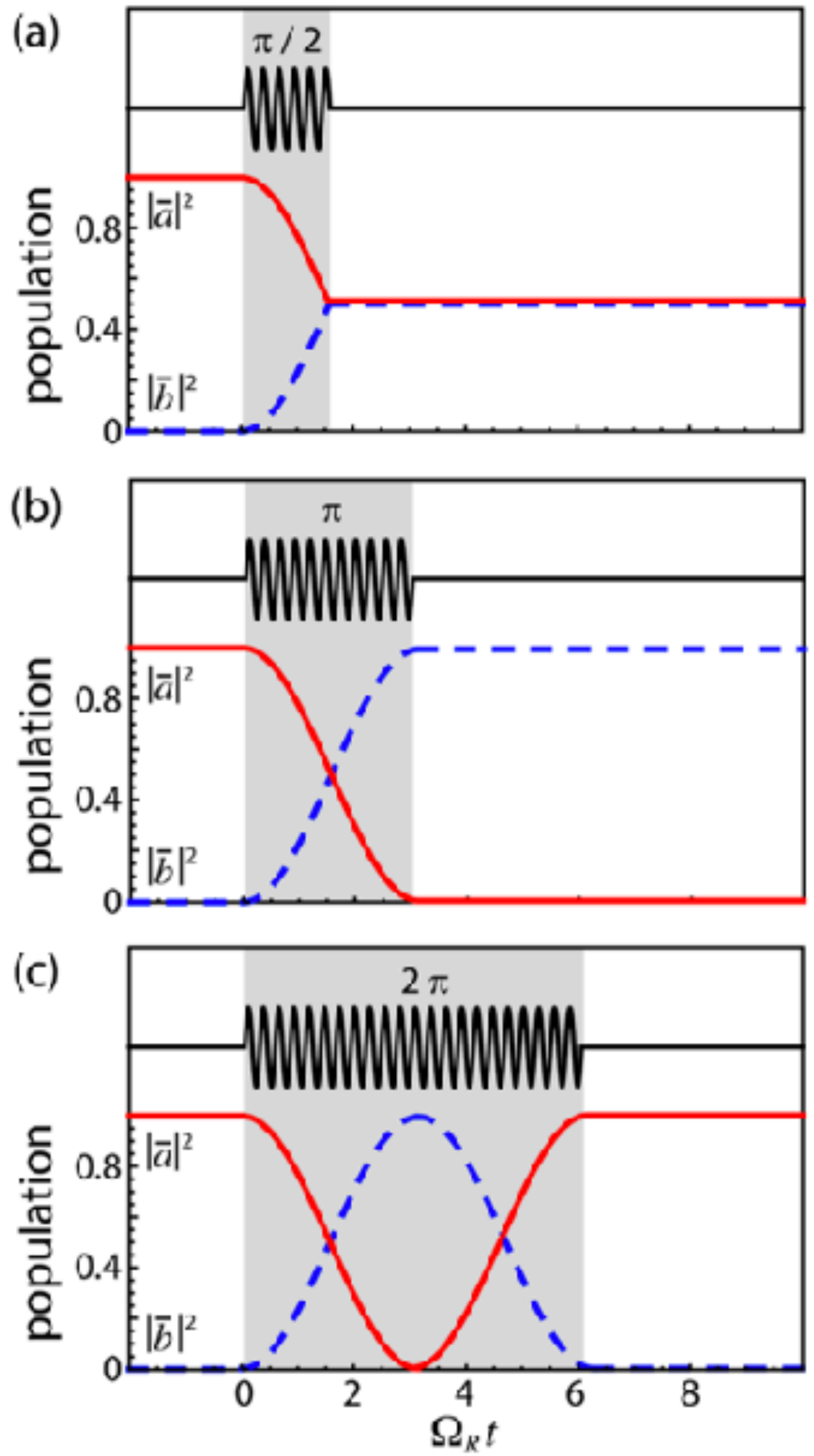
finite damping $\gamma = \Omega_R/25$.



To rotate the Bloch vector by the angle Θ the driving field with amplitude A has to be turned on for a time $t_\Theta = \Theta/A$.

Fig. 5. (a) Bloch sphere with trajectory of Bloch vector during resonant Rabi oscillations marked in gray (red online). Starting from the north pole the Bloch vector rotates around the $\mathbf{e}_x$-axis. To rotate the Bloch vector by the angle Θ the driving field with amplitude A has to be turned on for a time $t_\Theta = \Theta/A$. (b) Rabi oscillations of the populations $|\bar{a}|^2$ and $|\bar{b}|^2$ for zero detuning $(\omega_{\text{drive}} = \Delta\Omega)$ and damping $\gamma = \Omega_R/25$. The energy flops back and forth between the two oscillation modes x_+ and x_-. The Rabi frequency Ω_R defines the flopping rate and is given by the rescaled modulation amplitude A of the detuning Δk.

1/2 and 1 Rabi cycle with no damping

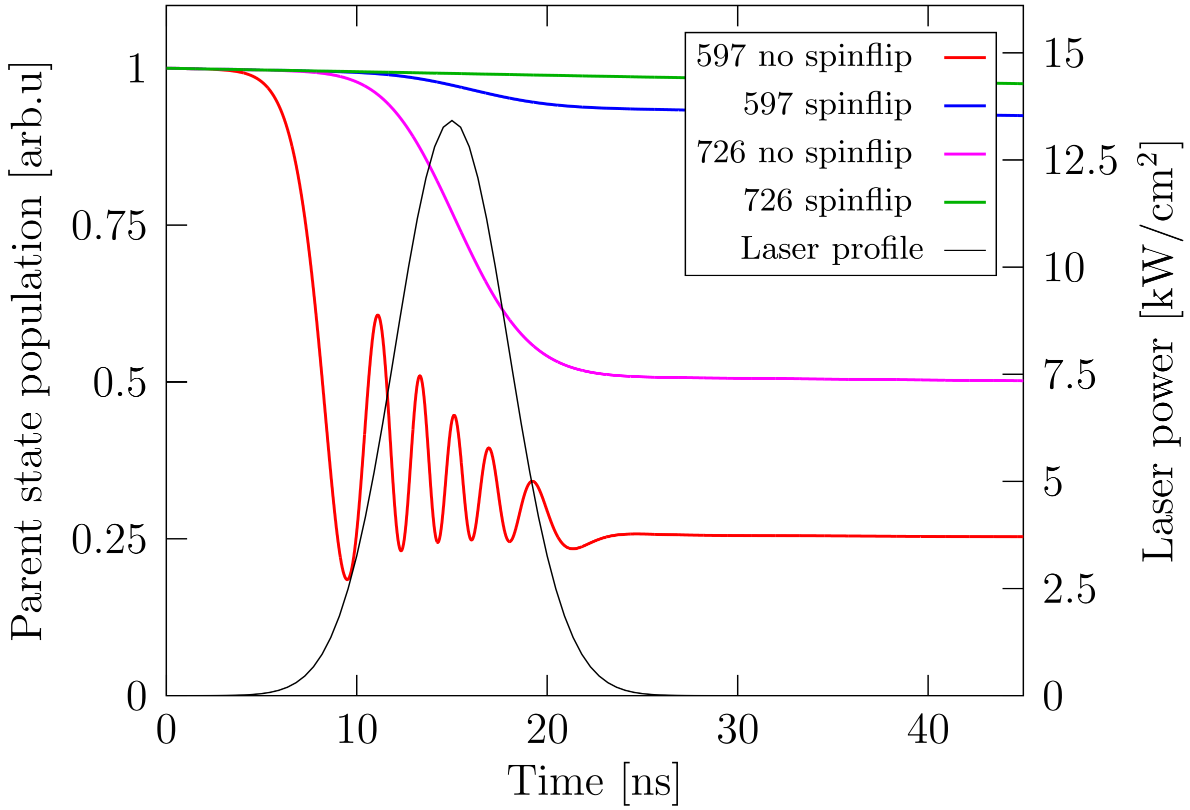


Example of spectroscopy

Dissipations in atoms: due to decays from both states, and dephasing from e.g. collisions

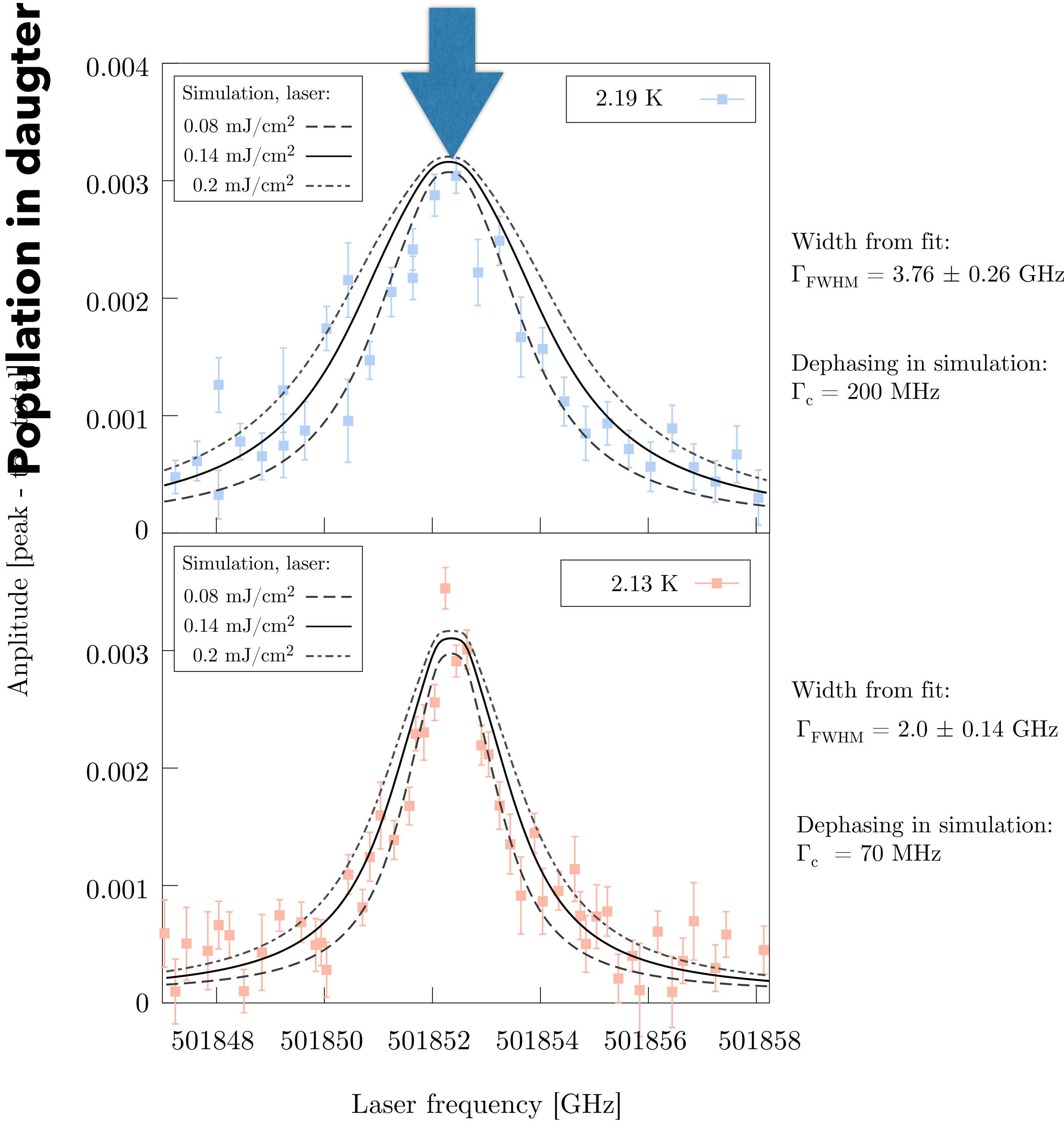
Application: studying the necessary laser power to carry out a transition, and the effects of power broadening on the lineshape

Can be extended to **multiple** levels



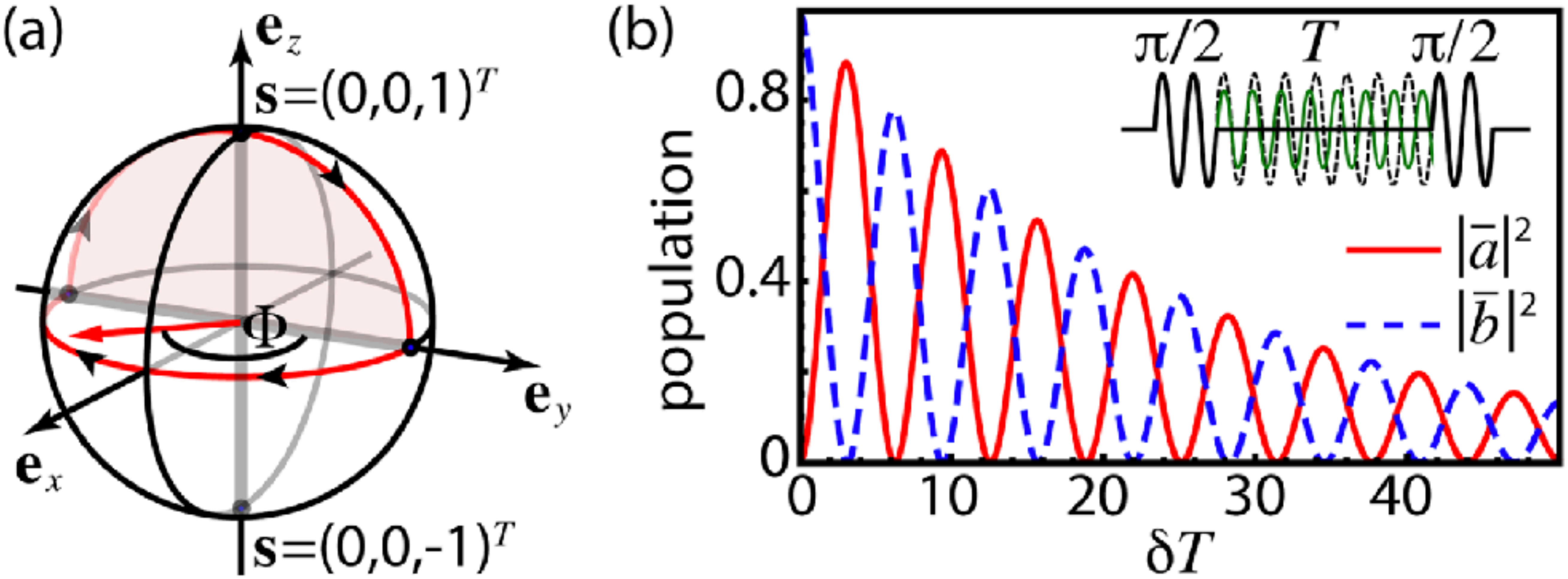
Find centroid (ΔE)

Population in daugter



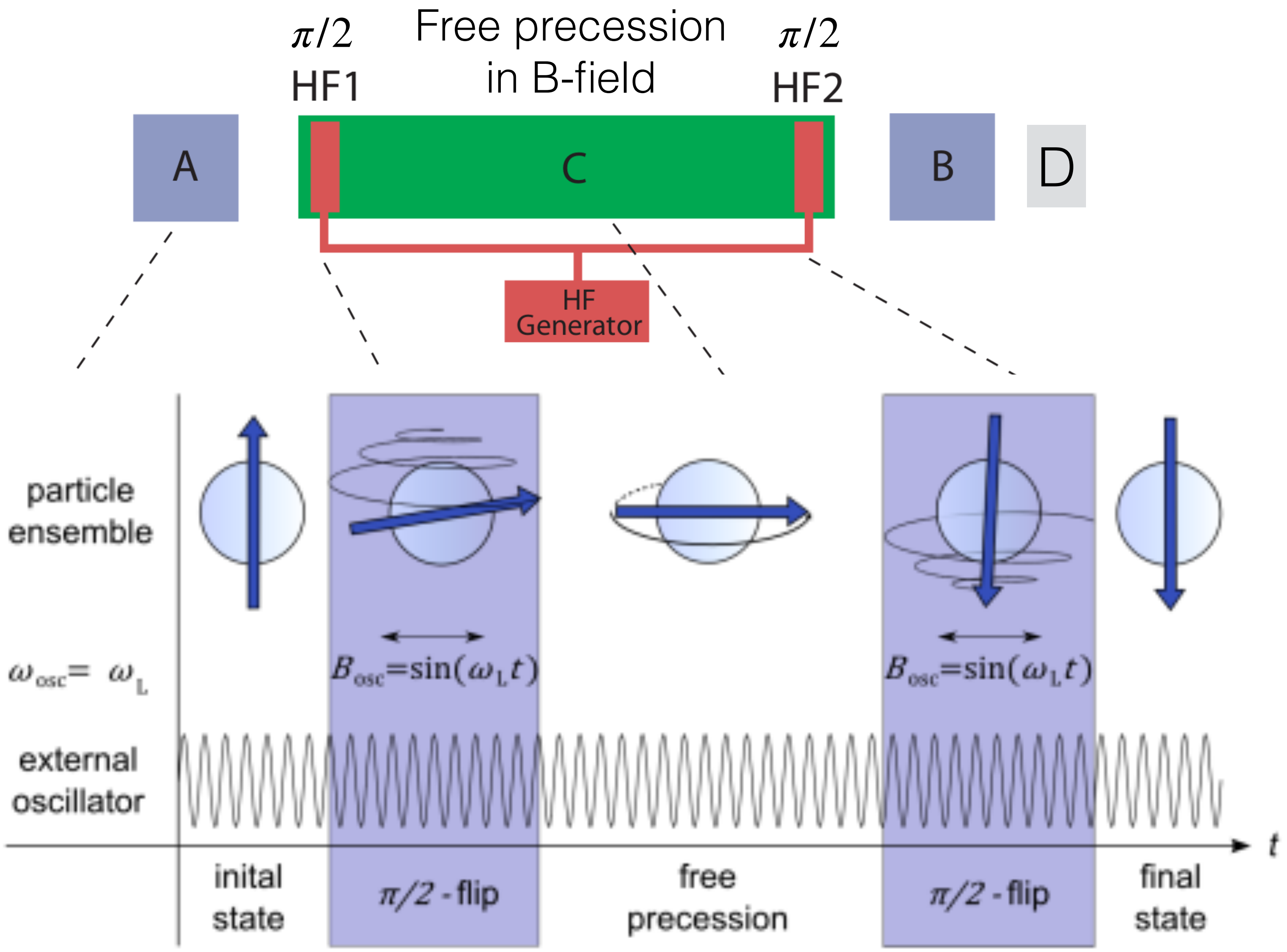
Laser frequency

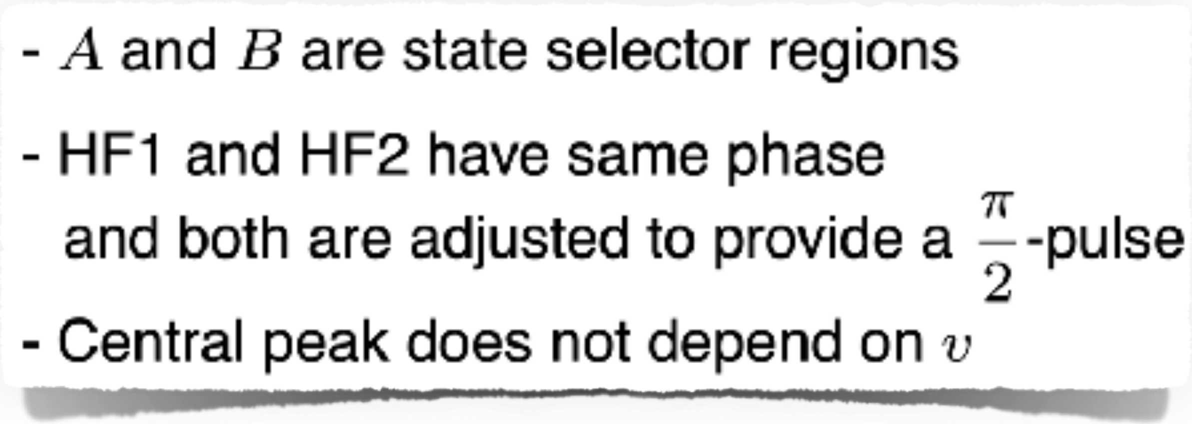
Alternative: Ramsey interferometry



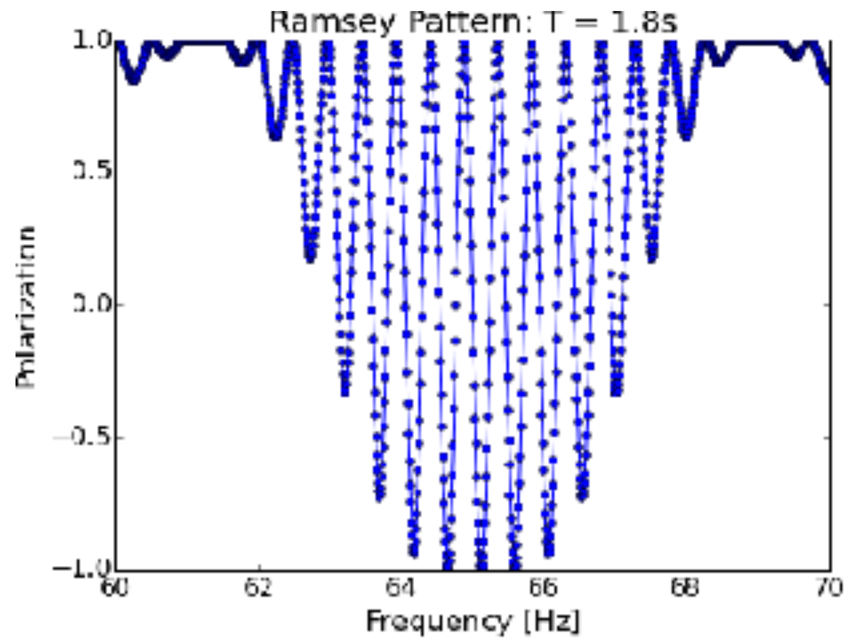
Separated oscillatory fields method

Ramsey interferometry



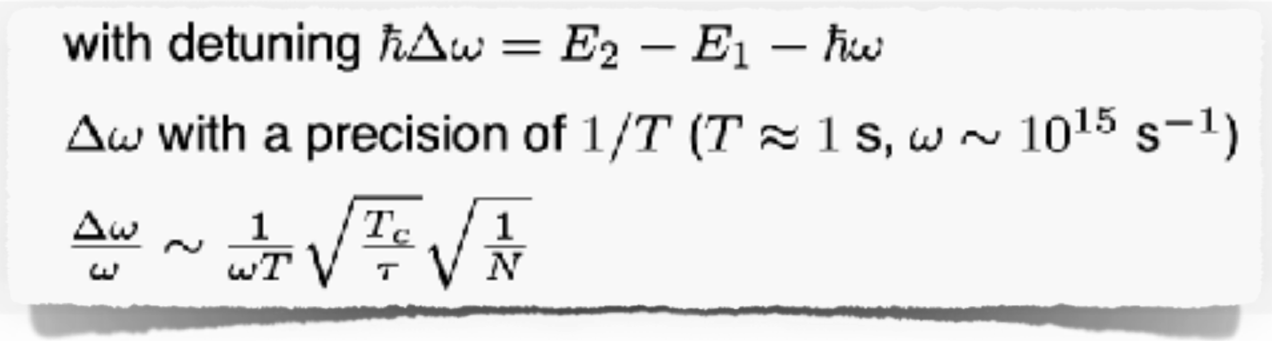


- A and B are state selector regions
- HF1 and HF2 have same phase and both are adjusted to provide a $\frac{\pi}{2}$-pulse
- Central peak does not depend on v



$$P_{\text{up}} - P_{\text{down}} = \cos\Phi = \cos\big((\omega_L - \omega_{HF})T\big)$$

Phases matters:
Coherence between between
the two $\pi/2$ pulse is required



with detuning $\hbar\Delta\omega = E_2 - E_1 - \hbar\omega$

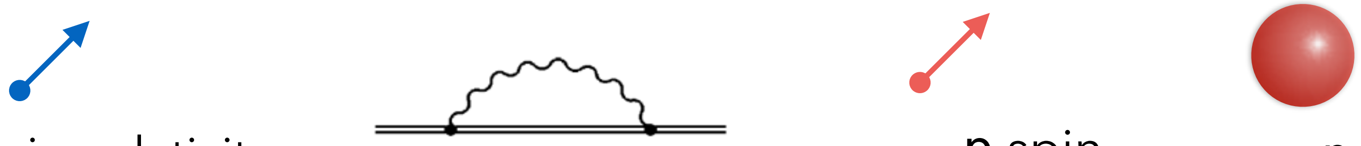
$\Delta\omega$ with a precision of $1/T$ ($T \approx 1$ s, $\omega \sim 10^{15}$ s^{-1})

$$\frac{\Delta\omega}{\omega} \sim \frac{1}{\omega T}\sqrt{\frac{T_c}{\tau}}\sqrt{\frac{1}{N}}$$

Bound systems 1

Atoms and exotic atoms

$$E_n \simeq \left(1-\frac{m_e}{m_p}\right)\frac{R_\infty}{n^2} + \varepsilon_{\text{Dirac}} + \text{QED}(\alpha, m_e\ldots) + \varepsilon_{\text{HFS}} + k m_e^3 R_p^2 + \ldots + \varepsilon_{\text{BSM}}$$



Schrödinger

e$^-$ spin, relativity

p spin

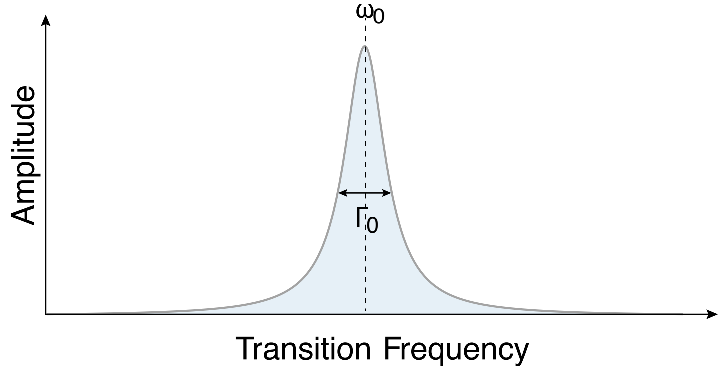
p finite size

Experimental challenges

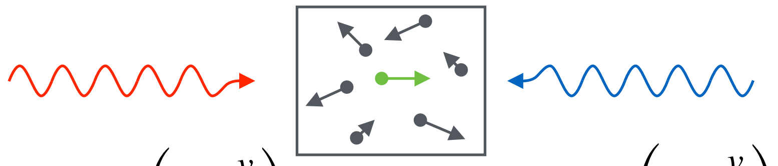
Natural linewidth

Heisenberg uncertainty $\Delta E > \frac{\hbar}{2\tau}$

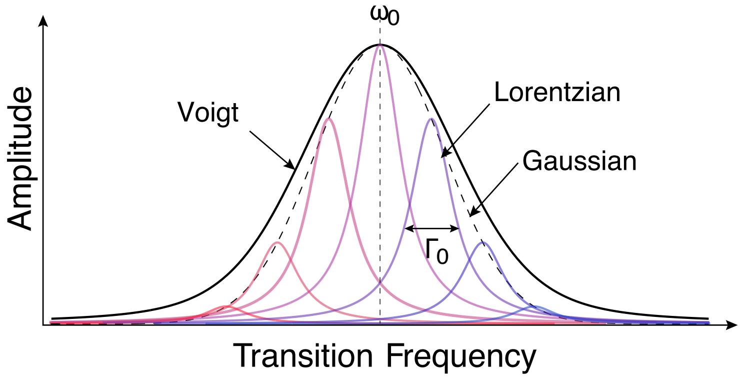
Sometimes limited by exotic particle lifetime!



Doppler broadening

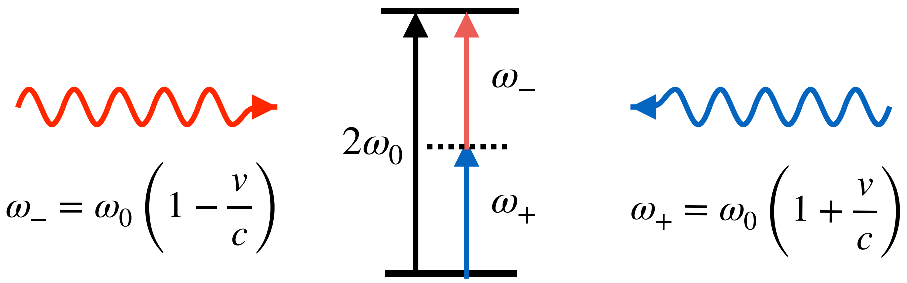


$\omega_- = \omega_0\left(1 - \frac{v}{c}\right)$ $\omega_+ = \omega_0\left(1 + \frac{v}{c}\right)$

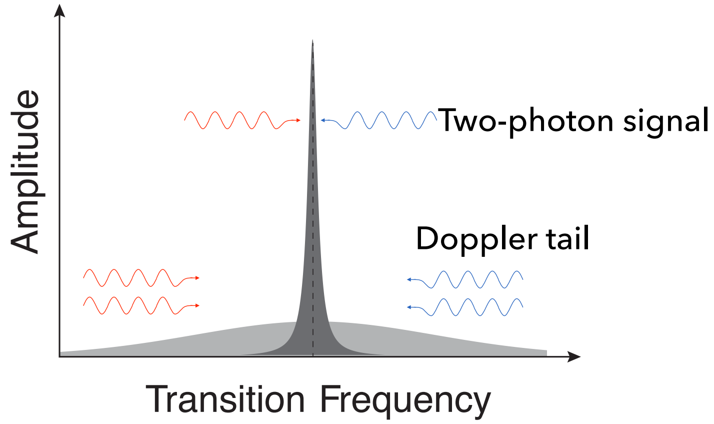


Thermal motion of atoms broadens the spectral lines.

Two-photon spectroscopy

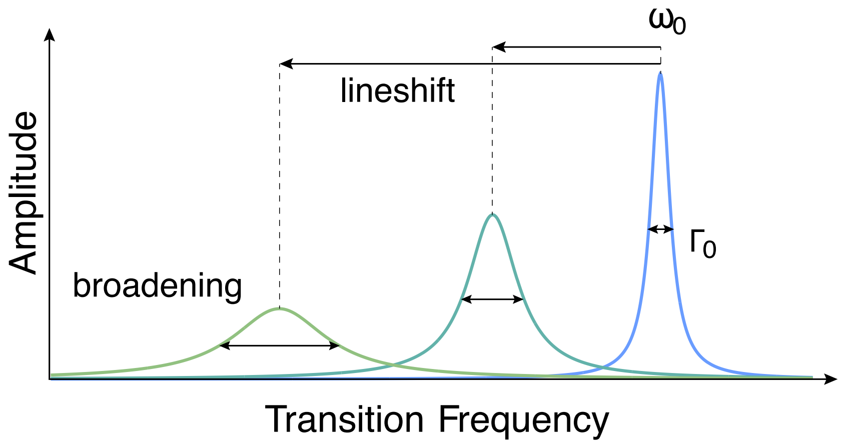


$\omega_- = \omega_0\left(1 - \frac{v}{c}\right)$ $\omega_+ = \omega_0\left(1 + \frac{v}{c}\right)$



Effects of collisions and external fields

Collisions perturb the energy levels: broadening and lineshift



External EM fields: Stark shift,
Strong laser fields: power broadening

Cold atoms, low density

The ultimate spectroscopy in hydrogen

Why 1s-2s spectroscopy?

- Strong Binding

$$E_n = \frac{R_\infty}{n^2}$$

- Smallest wave functions

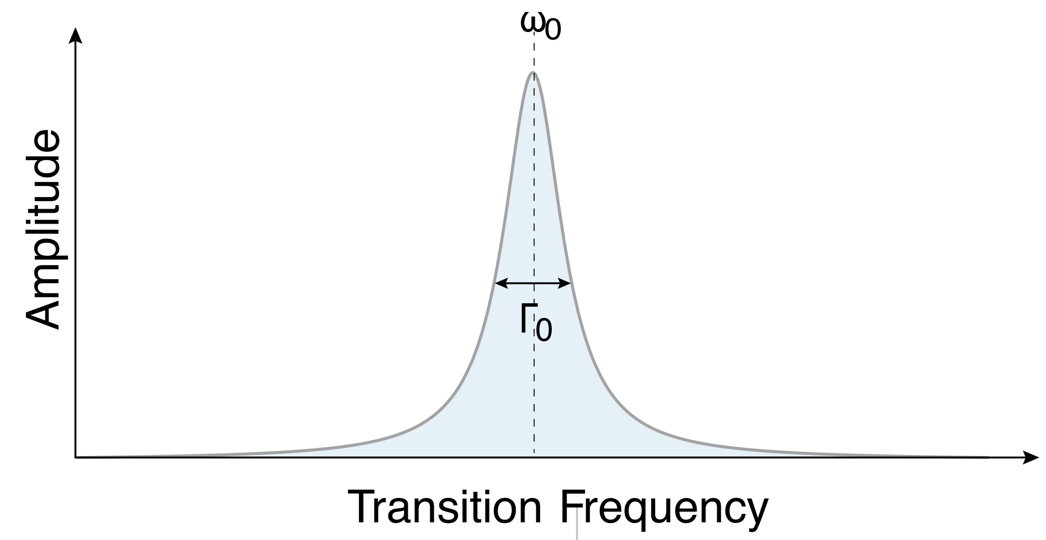
$$\langle r \rangle = \frac{\hbar}{Z\alpha c}\frac{n^2}{m}$$

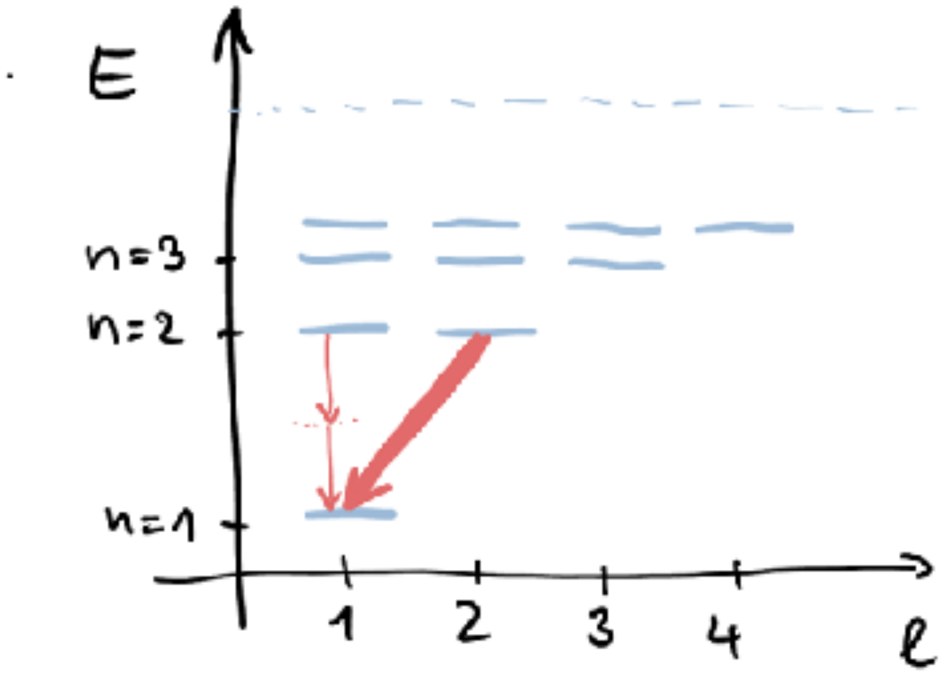
- Long lifetime - narrow linewidth
- Suited for 2-photon spectroscopy (Doppler-free spectroscopy)

Natural linewidth

$$\Delta E > \frac{\hbar}{2\tau}$$

Heisenberg uncertainty

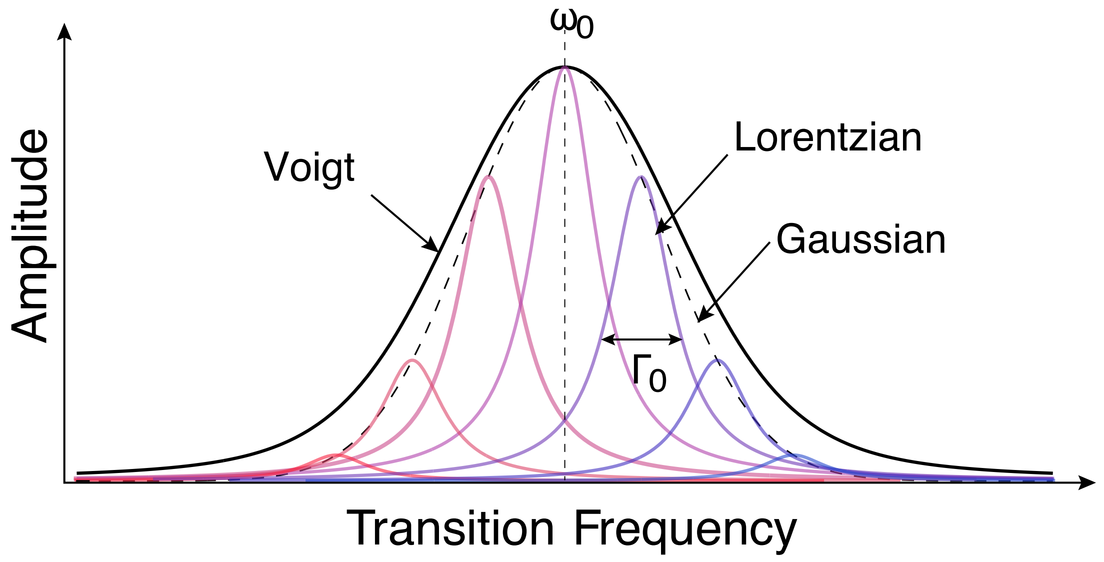


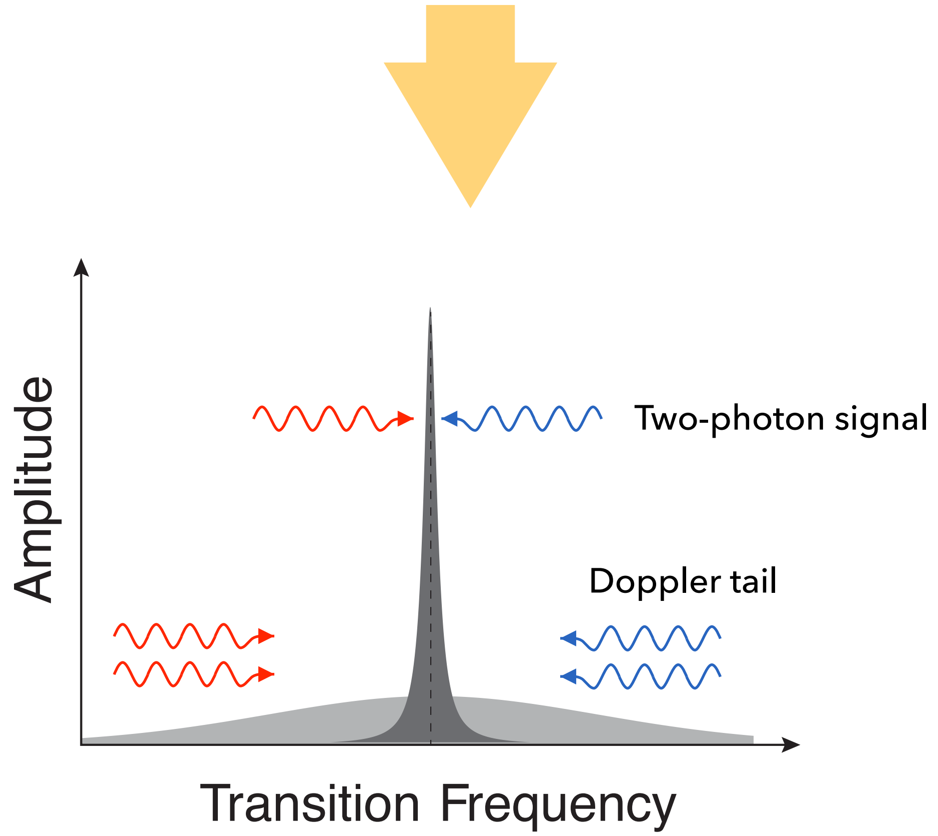


$$\Gamma_{2S} = 1\ \text{Hz}$$

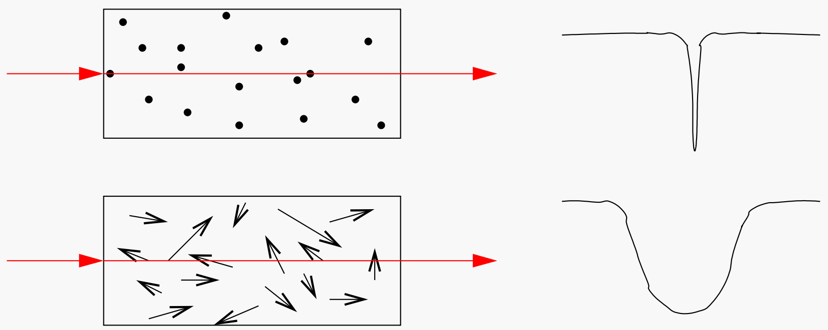
$$\Gamma_{2P} = 3 \cdot 10^9\ \text{Hz}$$

Doppler - free two-photon spectroscopy



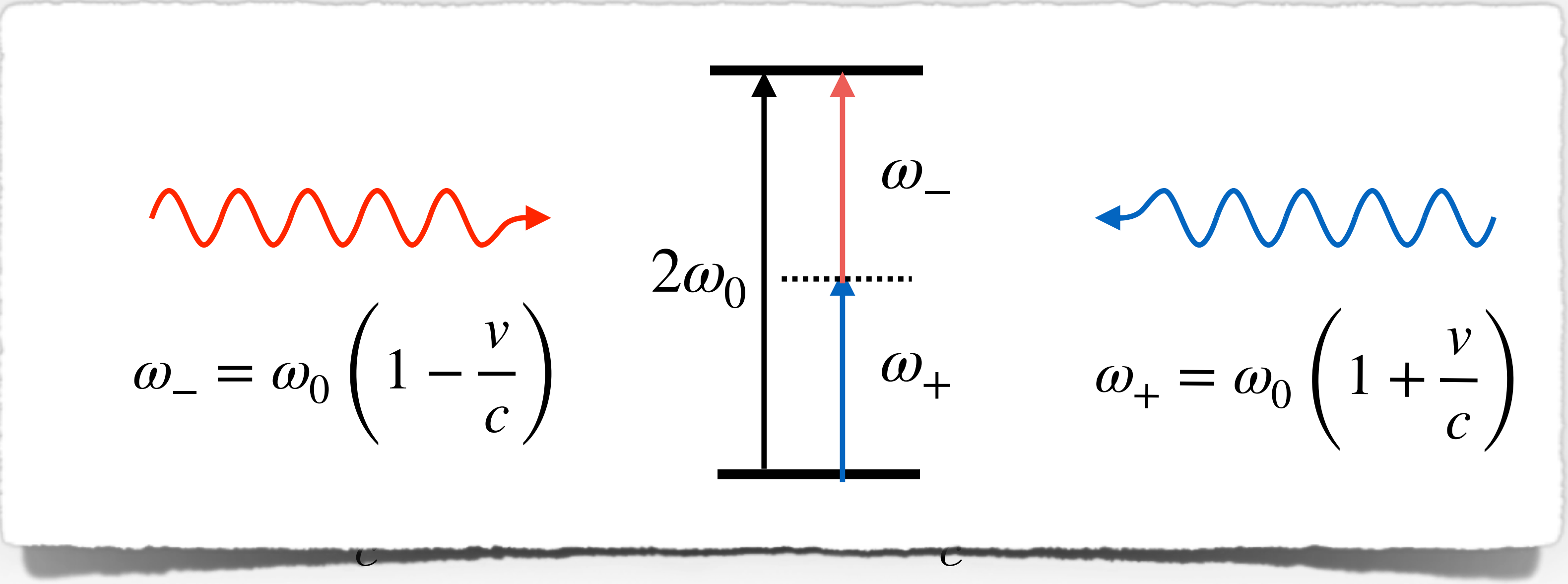


- For one-photon spctroscopy: even though each single atom has small transition width, the measured line is broadened due to Doppler effects because of atoms v-distribution



$$\delta_D = 7 \times 10^{-7} \omega_0 \sqrt{\frac{T}{M}}$$

- Two-photon spectroscopy is Doppler free

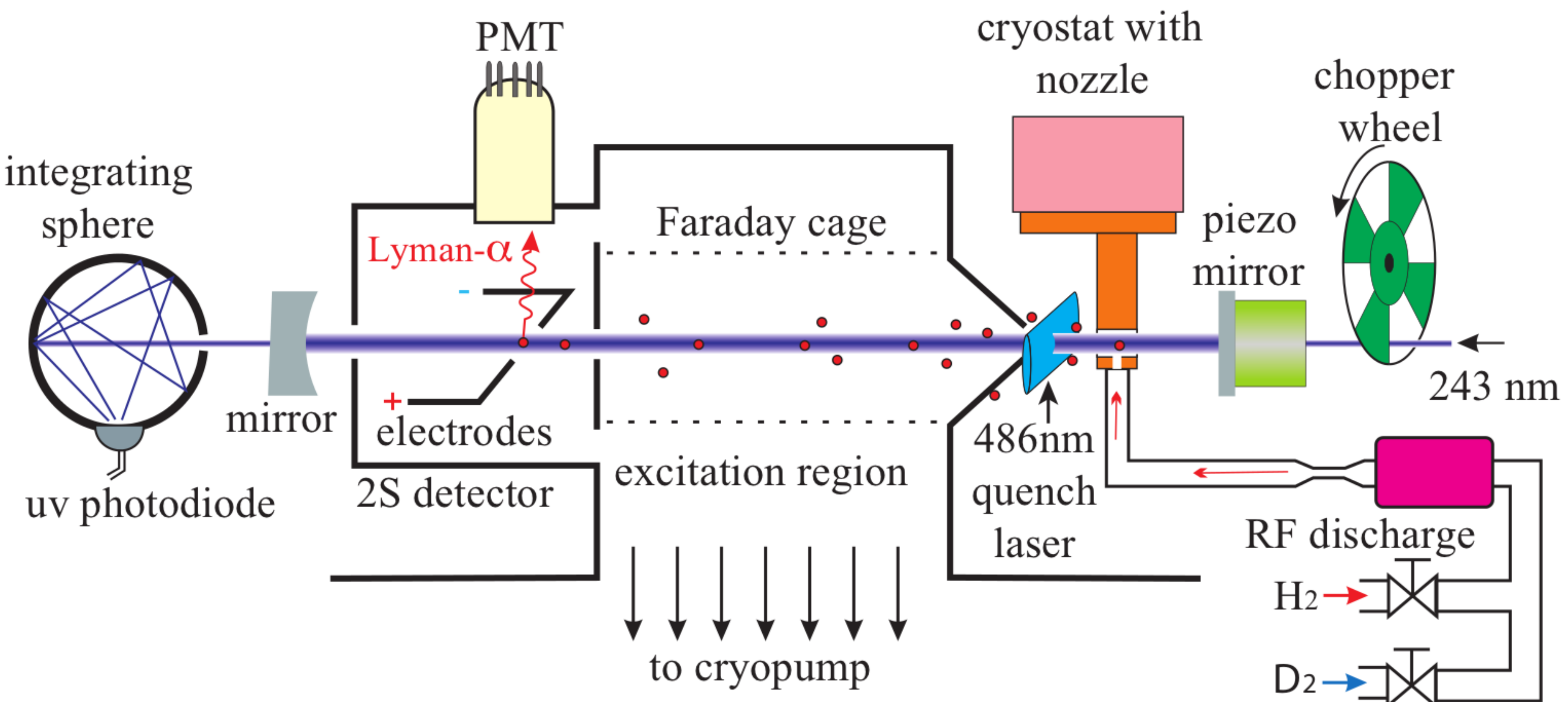


$$\omega_- = \omega_0 \left(1 - \frac{v}{c}\right)$$

$$\omega_+ = \omega_0 \left(1 + \frac{v}{c}\right)$$

But $\omega_L + \omega_R = 2\omega_0$ does not depend on the velocity

Hydrogen 1s-2s measurement at MPQ Garching (DE)



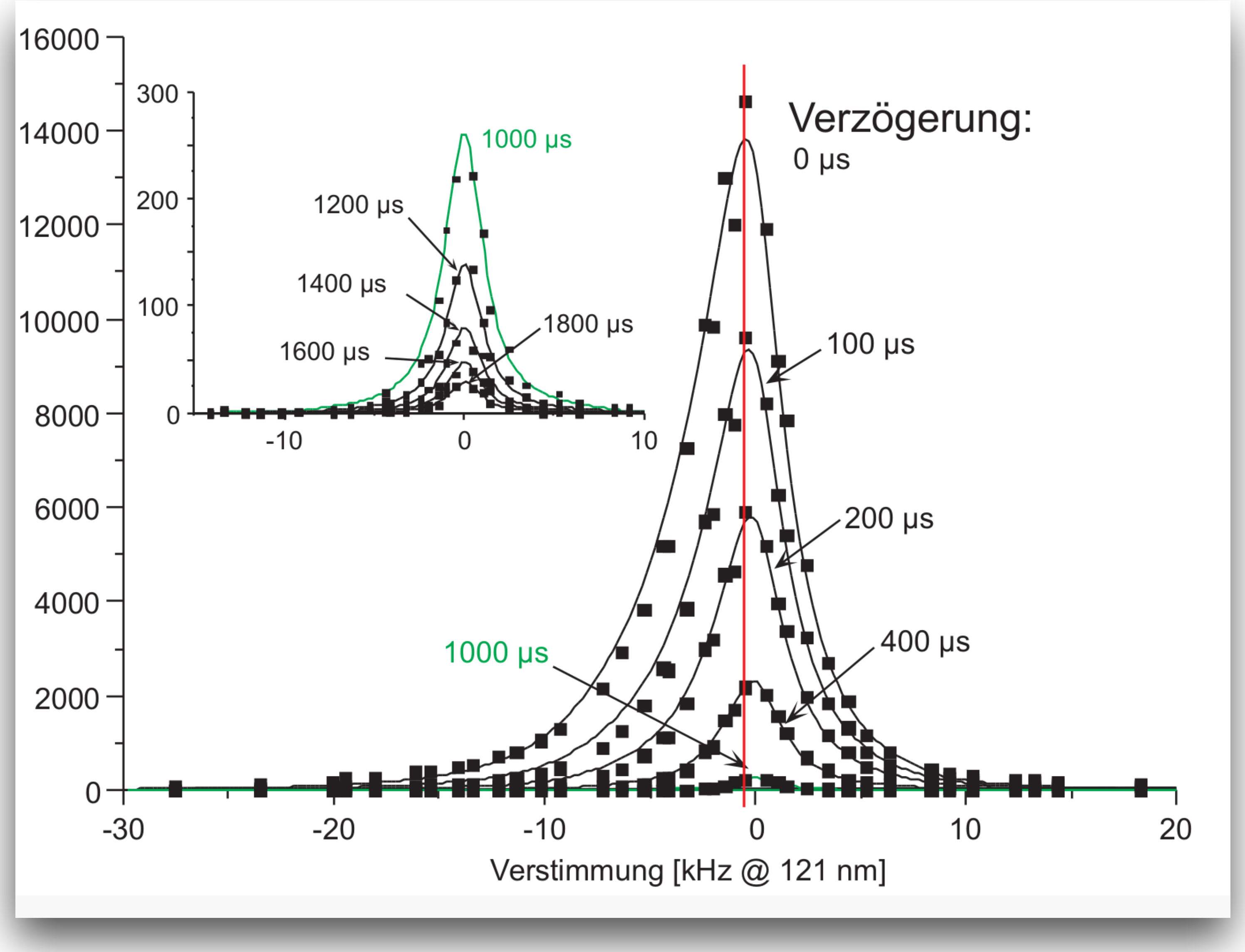
- Produce atomic H(1S) from H2 dissociation in discharge
- Cool down H(1S) cold nozzle
- Excite the 1S-2S transition with 2 x 243 nm photons
- Cut the laser beam to define t=0
- The atoms enter in a region with strong E-field
  - Stark mixing $|2S\rangle \rightarrow \frac{1}{\sqrt{2}}(|2S\rangle + |2P\rangle)$
  - The 2P component decay to 1S emitting Lα photons
- Counts number of Lα photons versus laser frequency

2 466 061 413.187035(10) MHz

(Parthey *et al.* 2011)

Uncertainty due to proton charge radius on these digits

The hydrogen 1S-2S measurement at MPQ



Main systematic:
second-order Doppler effect

$$\omega = \omega_0 \left(1 \pm \frac{v}{c} + \frac{v^2}{2c^2}\right)$$

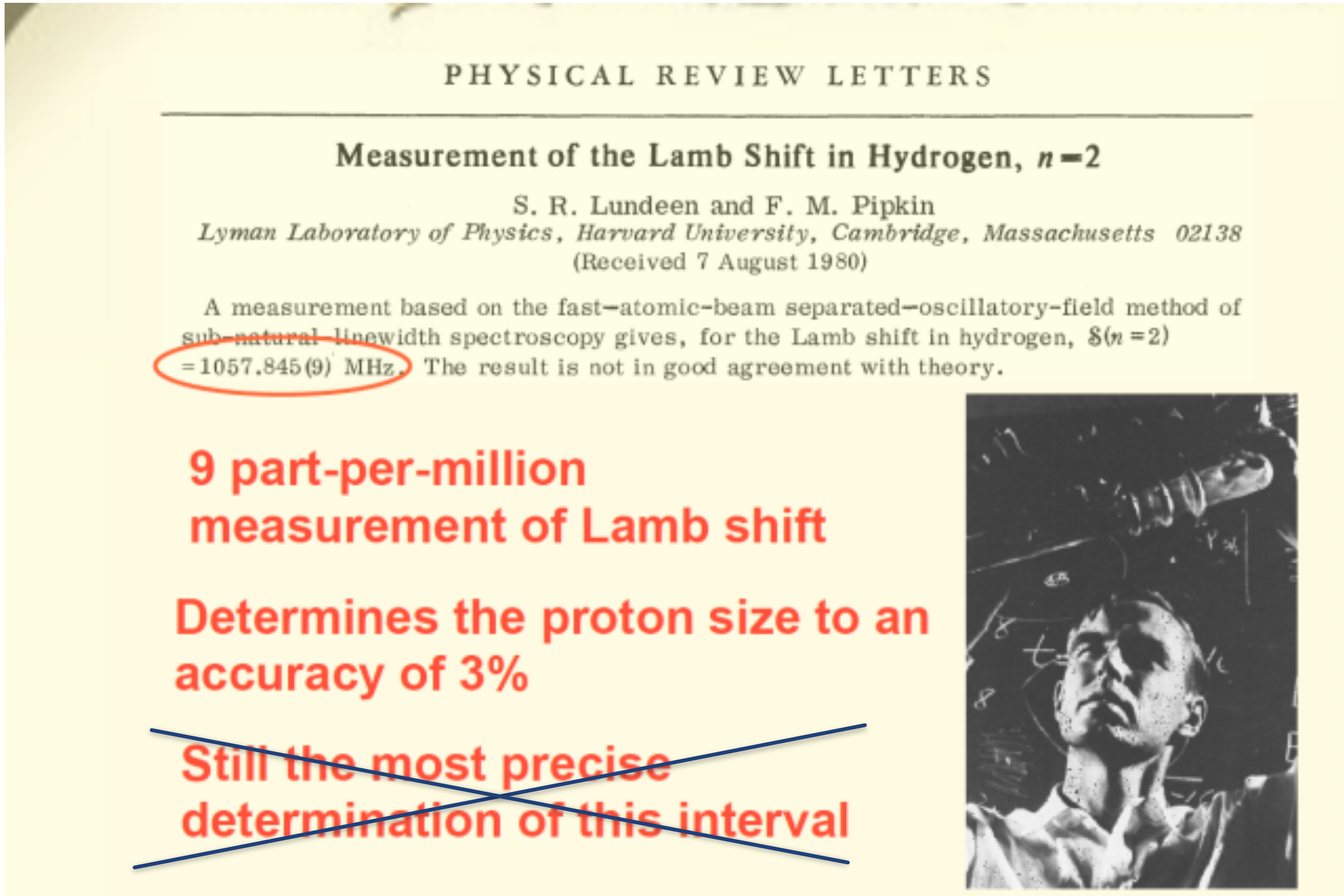
Longer delay:
⇨ select slower atoms
⇨ smaller systematics

$$\nu_{1S-2S} = 2466061413187035(10)\ \mathrm{Hz}$$

PRL107.203001

$$h\nu_{1S-2S} \approx \frac{3}{4} R_\infty + \mathrm{QED} + k R_p$$

Modern experiments on the hydrogen atom II - the Lamb shift



PHYSICAL REVIEW LETTERS

Measurement of the Lamb Shift in Hydrogen, $n=2$

S. R. Lundeen and F. M. Pipkin
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 7 August 1980)

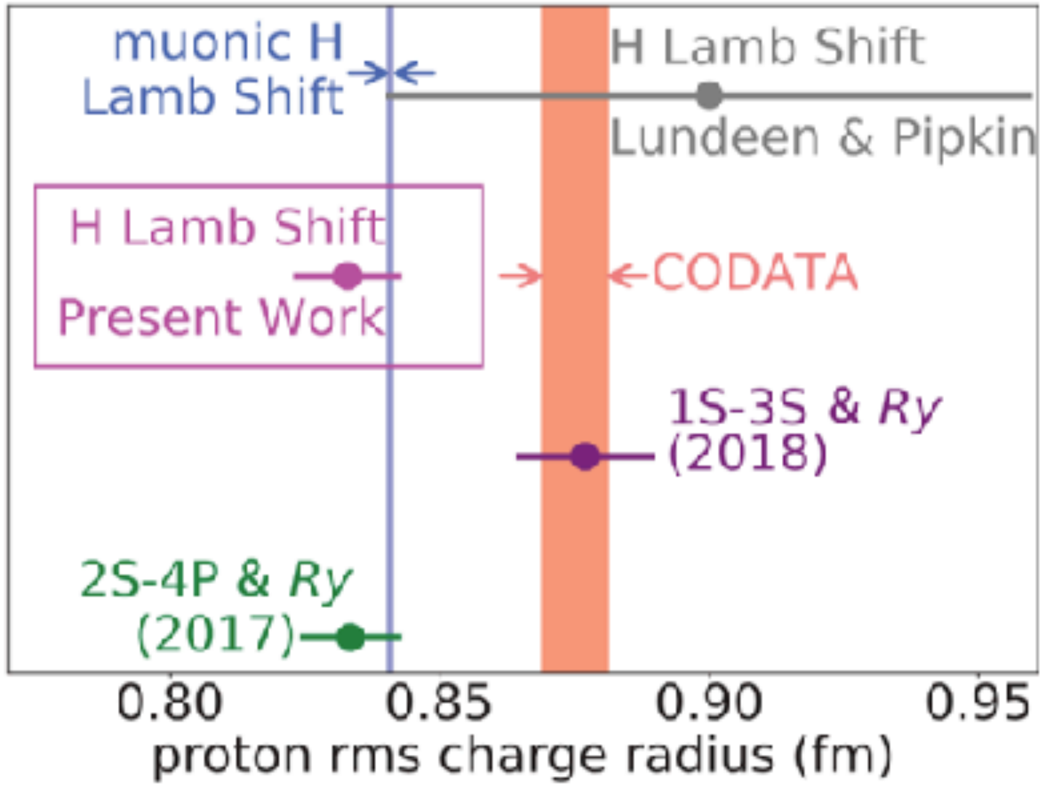
A measurement based on the fast-atomic-beam separated-oscillatory-field method of sub-natural-linewidth spectroscopy gives, for the Lamb shift in hydrogen, $S(n=2)$ $=1057.845(9)$ MHz. The result is not in good agreement with theory.

9 part-per-million measurement of Lamb shift

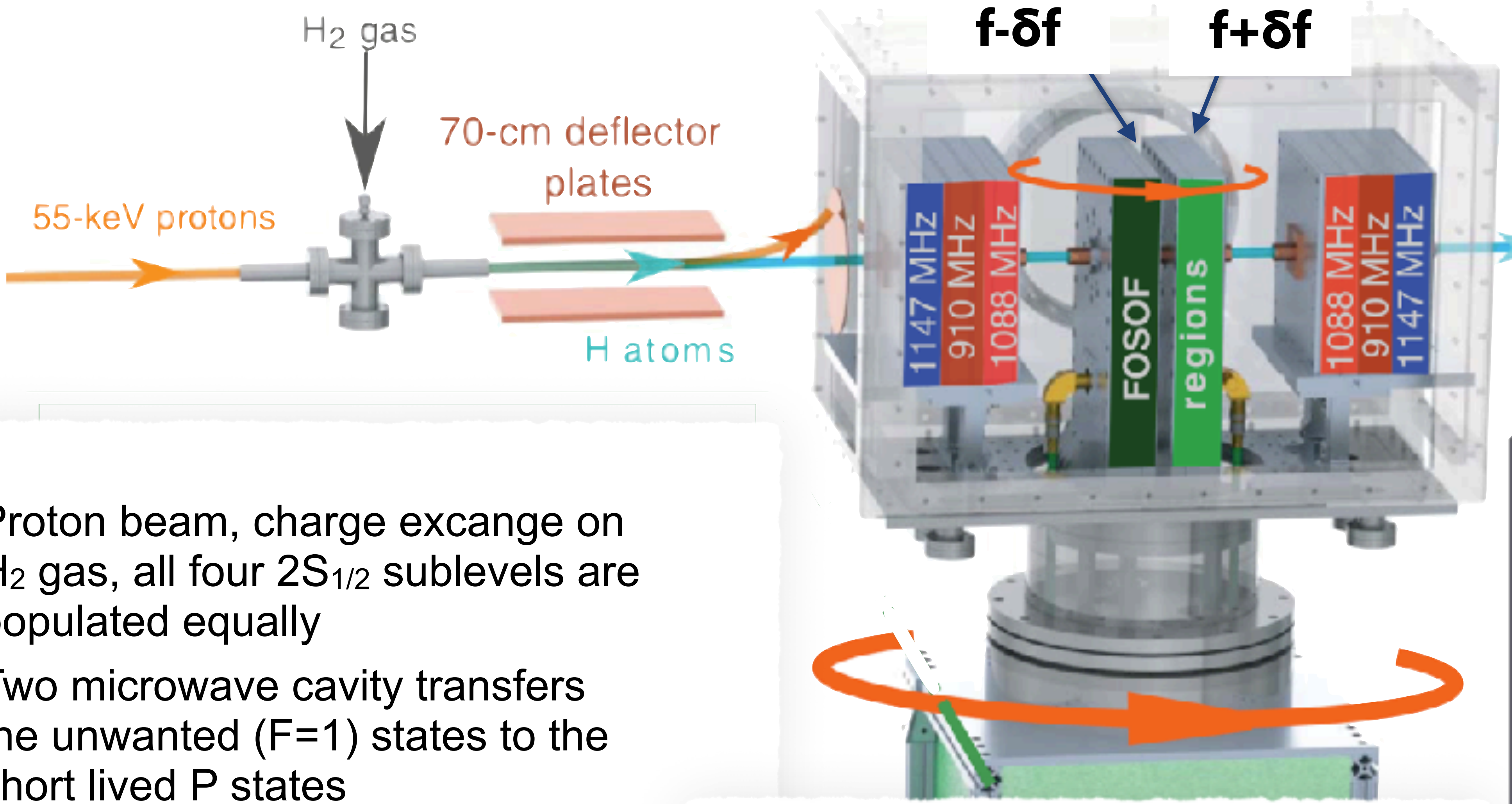
Determines the proton size to an accuracy of 3%

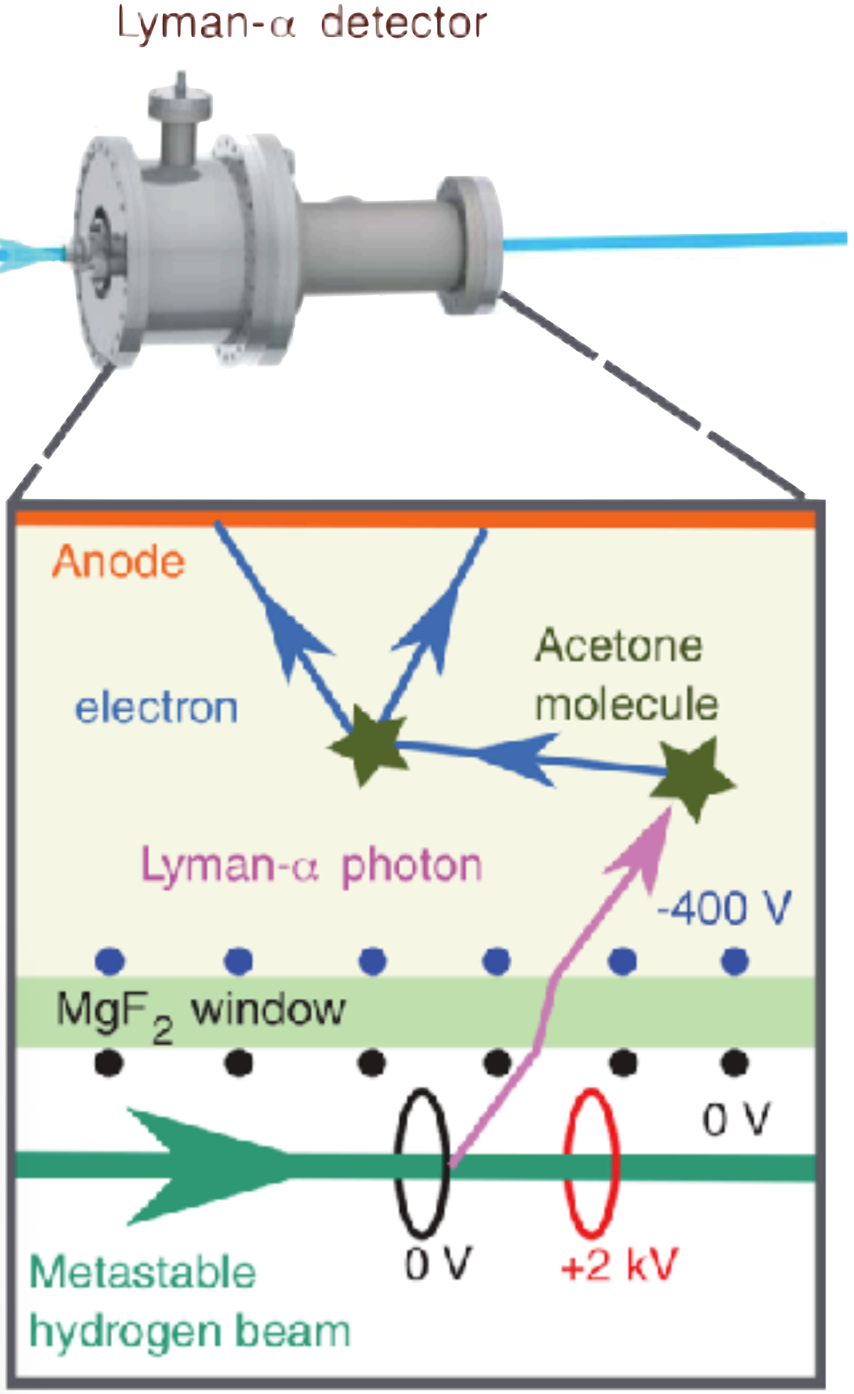
~~Still the most precise determination of this interval~~

N. Bezginov, T. Valdez, M. Horbatsch, A. Marsman, A. C. Vutha, **E. A. Hessels, Science 365, 1007–1012 (2019)**

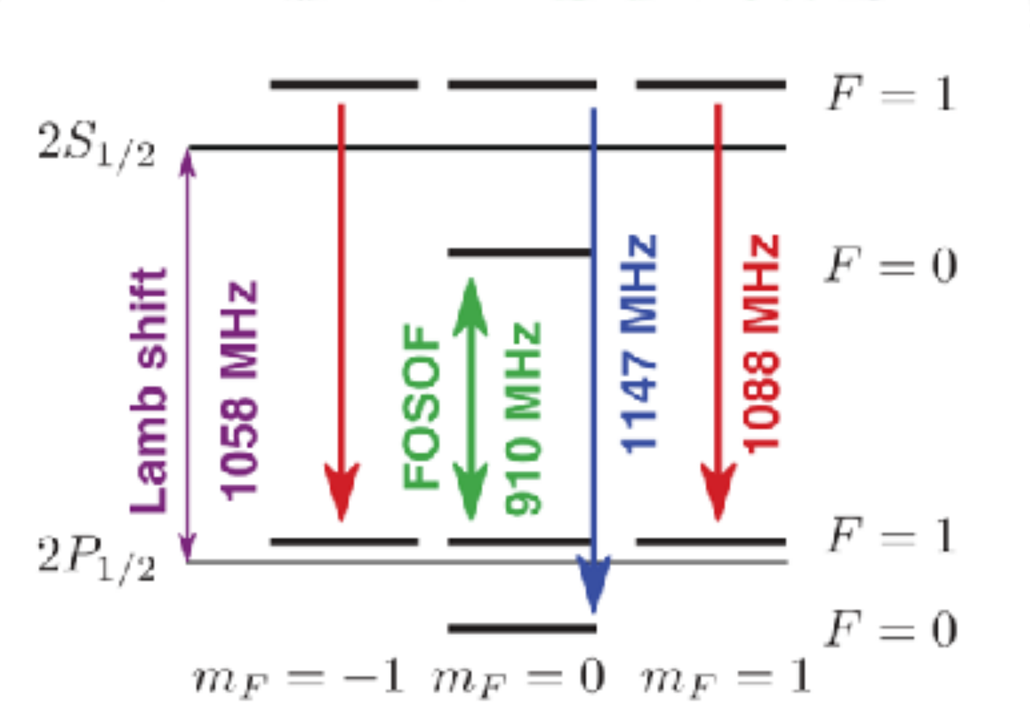


Modern experiments on the hydrogen atom II - the Lamb shift

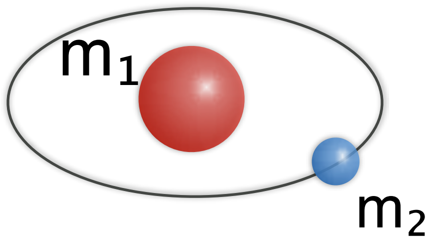




- Proton beam, charge excange on H_2 gas, all four $2S_{1/2}$ sublevels are populated equally
- Two microwave cavity transfers the unwanted (F=1) states to the short lived P states
- The green transitions (910 MHz) can be then probed with separated oscillatory fields (*Ramsey-technique!*), and the 2S atoms measured after mixing 2s-2p states with an e-field in a Lyman-α detector
- Phase offset to the drive field cancelled by rotating the apparatus

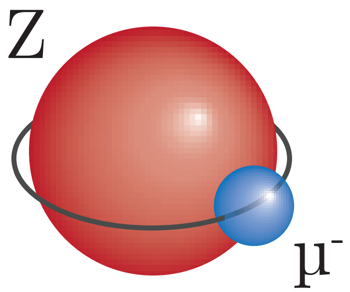


Exotic atoms as simple atomic probes



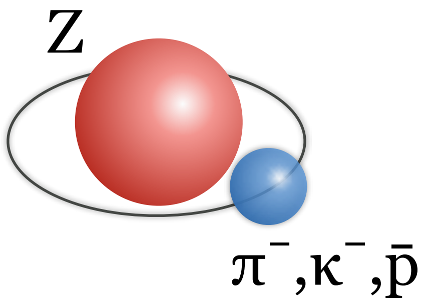
$$E_n \simeq \frac{Z^2 m^*}{m_e}\frac{R_\infty}{n^2} + \mathrm{QED}(\alpha, \ldots) + k m_2^3 R_Z^2 + \varepsilon_{\mathrm{hadronic}} + \varepsilon_{\mathrm{BSM}} \ldots$$

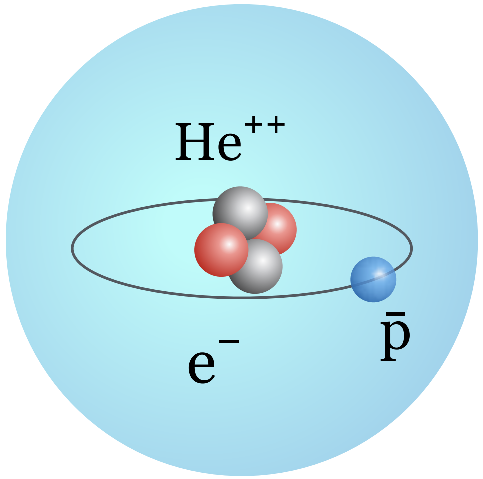
Negative exotic particle



Muonic atoms
Nuclear charge radii

Hadronic atoms
Pions: hadronic effects, kaons strangeness…





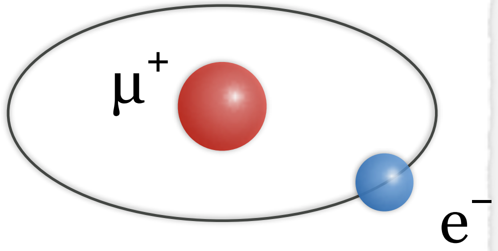
Antiprotonic helium

Mass determination, 3-body QED, CPT test, fifth force

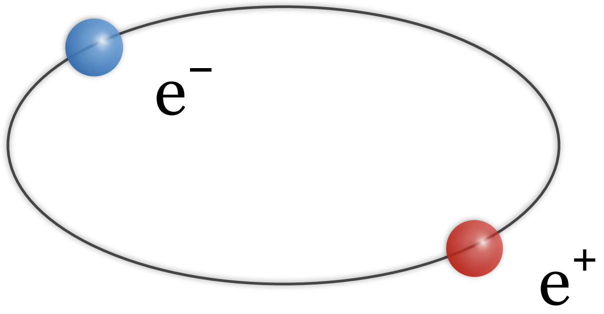
Positive exotic particle

Leptonic atoms

No finite size effects, QED test, symmetry test, μ⁺ mass…



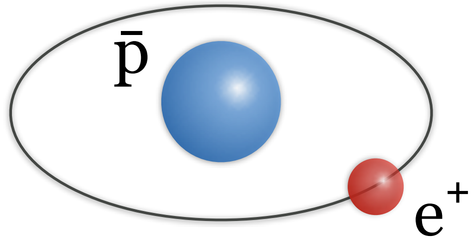
Muonium



Positronium

QED test, large recoil correction matter-antimatter

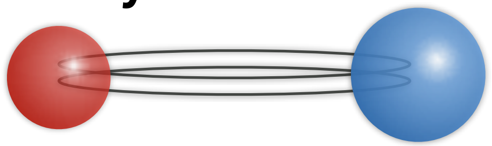
Both exotic



Antihydrogen

Produced and measured in traps
Sensitive CPT probe

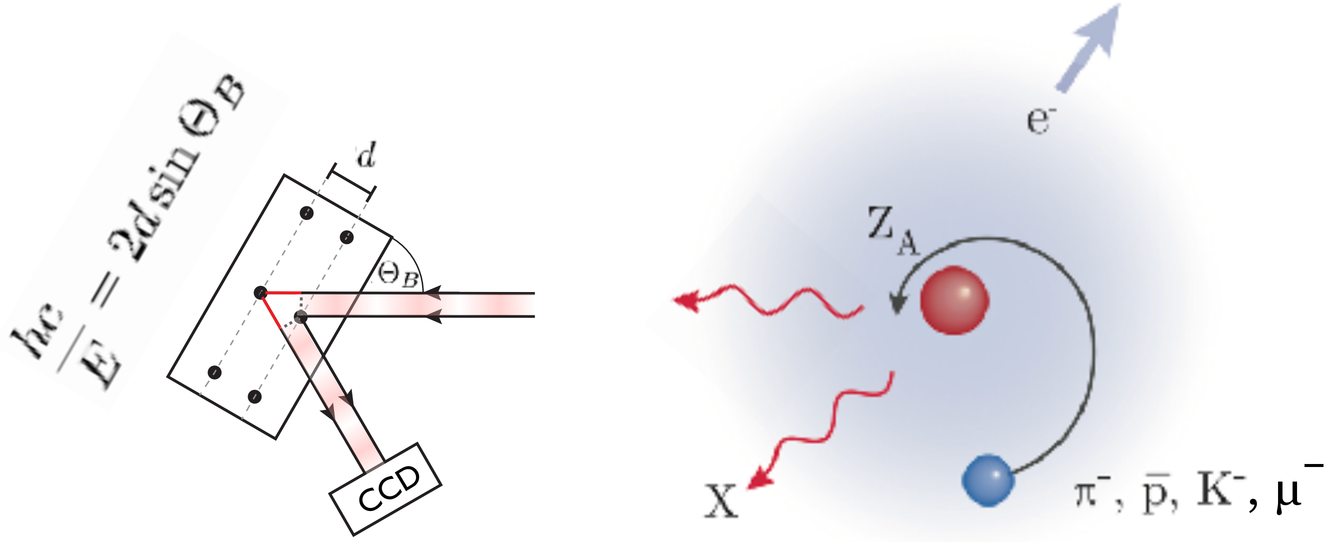
+ many others



E.g. Coulomb- pairs in accelerators (protonium, pion-kaon…)

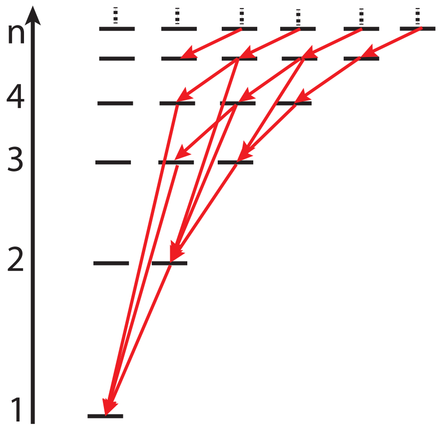
Spectroscopy of exotic atoms

X-ray spectroscopy of atomic cascades

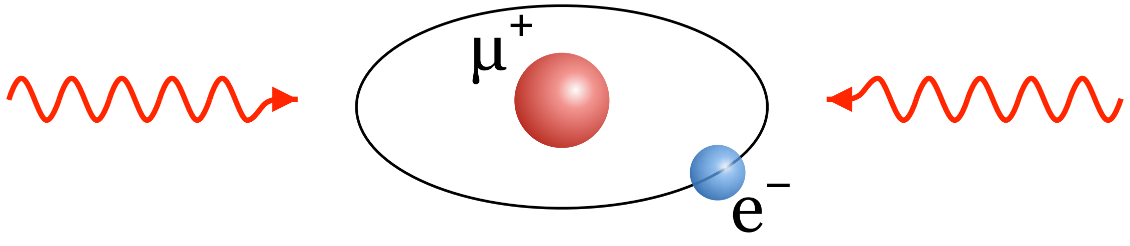


Measuring the energy of characteristic X-rays emitted during cascades

- only negative exotic particles
- MeV-scaled energies with high Z
- broad resonances (short lifetime), low instrument resolution

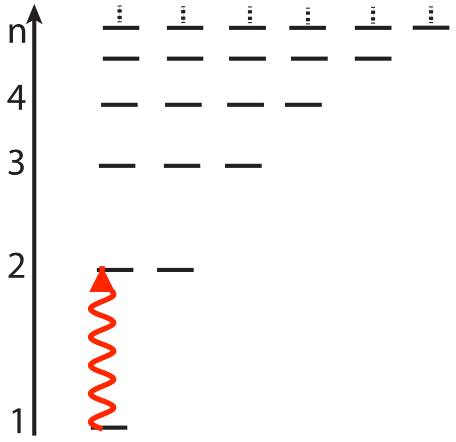


Laser- and microwave spectroscopy



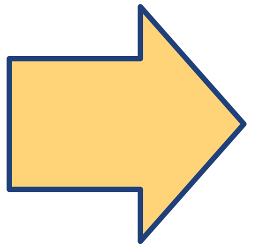
Resonant laser beams or MW radiation transfer the populations between atomic states

- only if state lifetime > ns (ground state or metastable states),
- accessible by lasers
- challenging: only a few atoms are at hand
- can lead to measure the ultimate precision

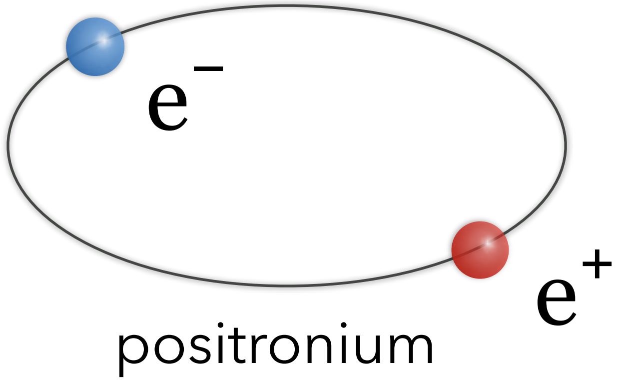


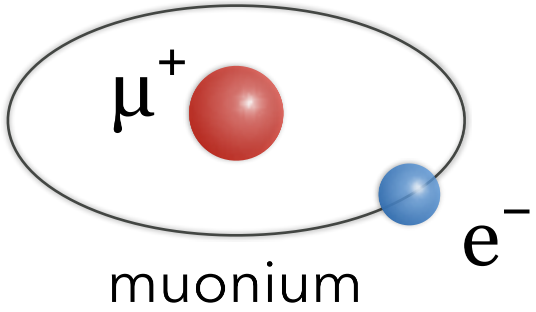
Hadronic and leptonic exotic atoms

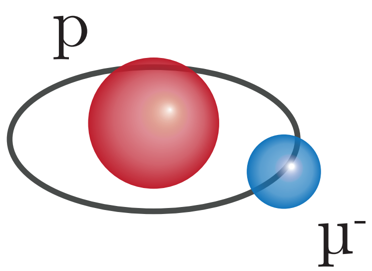
Leptons do not participate in the strong interaction



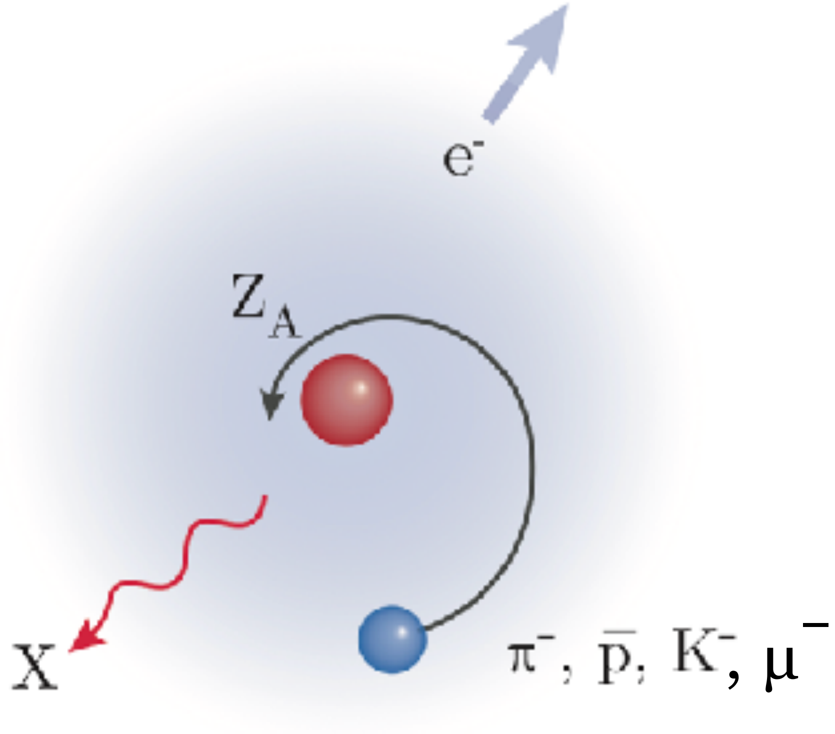
ground states live long enough to be studied by **laser spectroscopy**



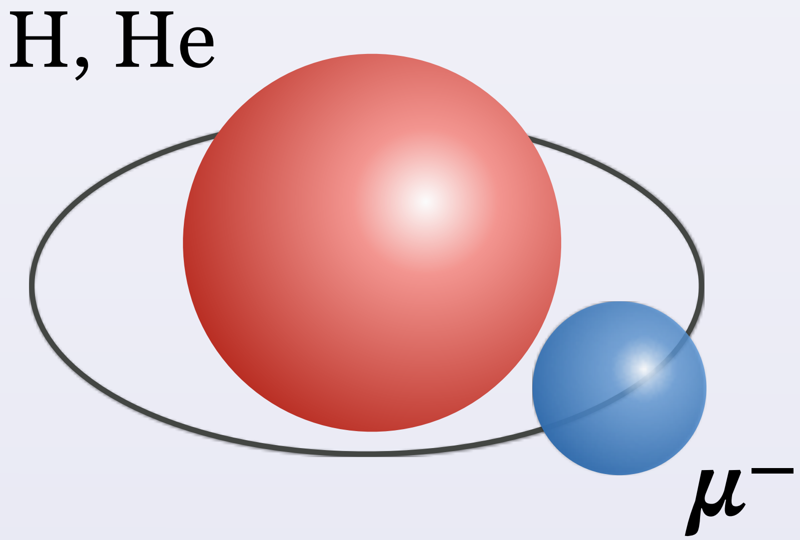




Hadrons, on the other hand interact strongly!
This results in short lifetimes when wave functions of bound states overlap

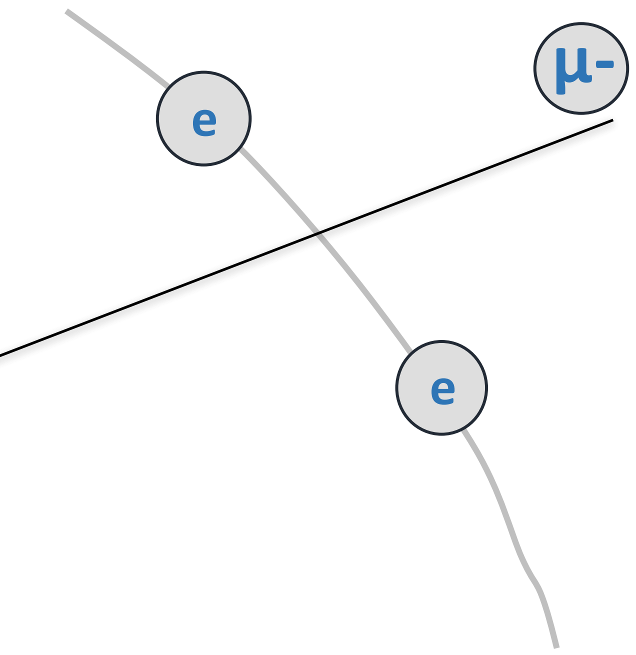


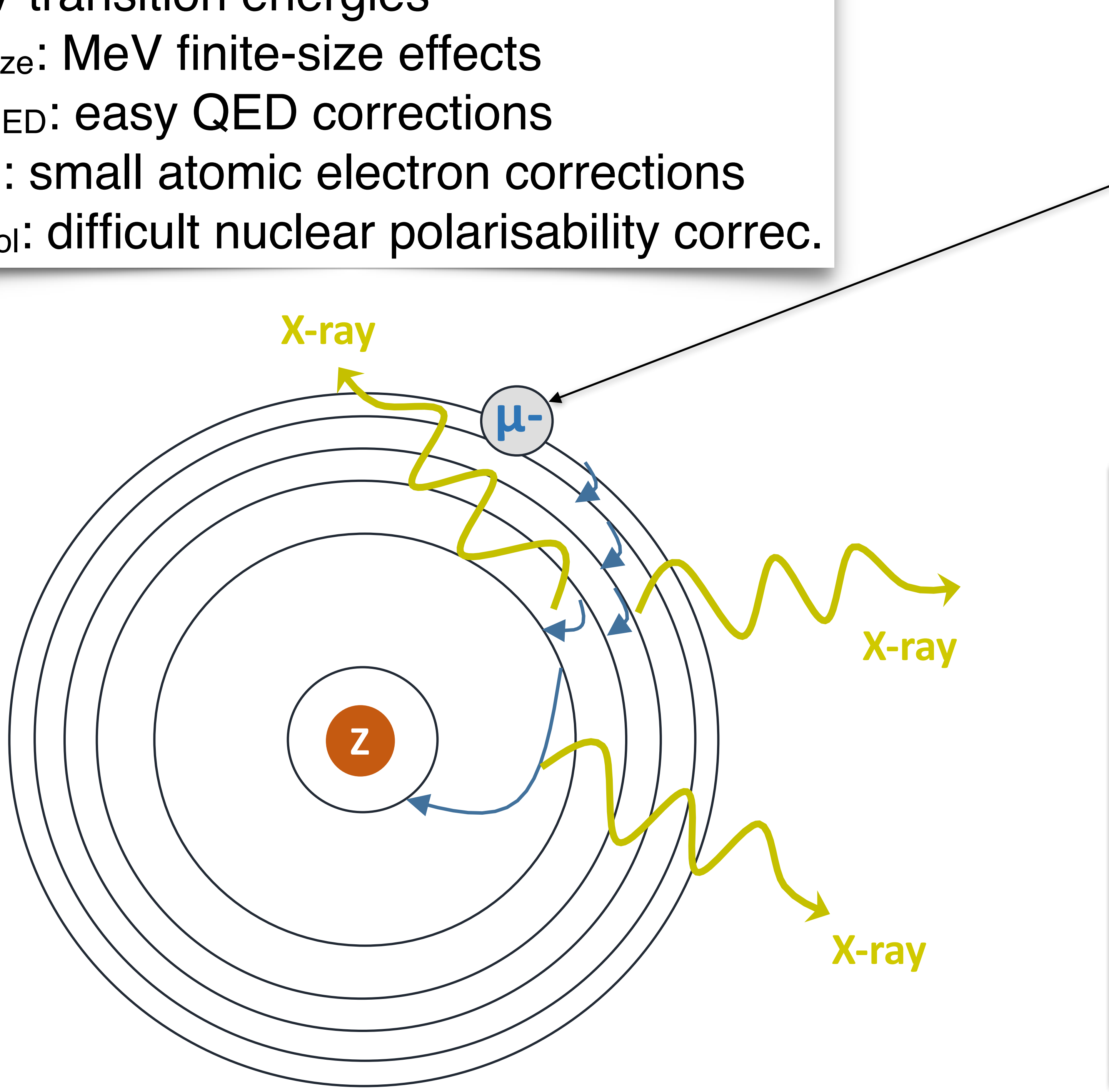
Muonic H, He



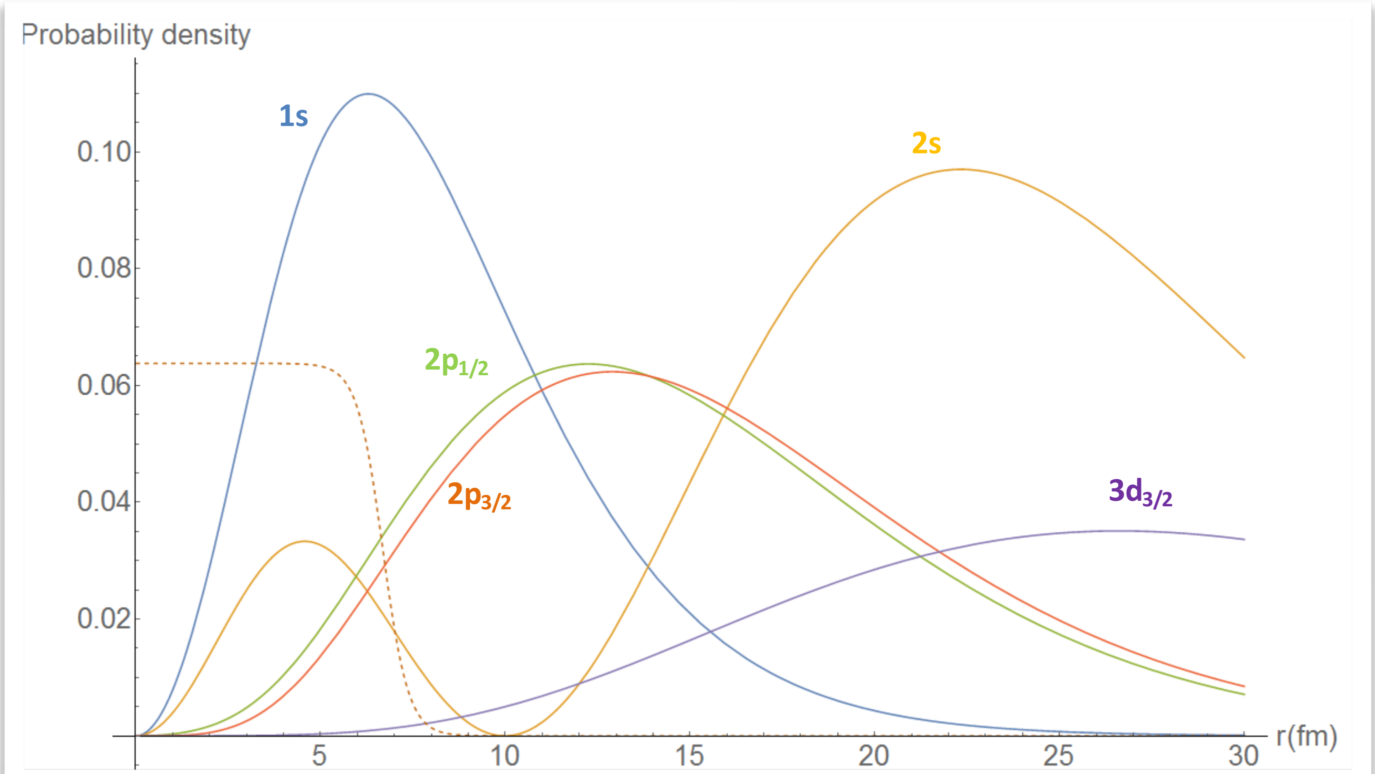
X-ray spectroscopy of high-Z muonic atoms

- H-like atoms
- MeV transition energies
- ΔE_{size}: MeV finite-size effects
- ΔE_{QED}: easy QED corrections
- ΔE_{el}: small atomic electron corrections
- ΔE_{pol}: difficult nuclear polarisability correc.



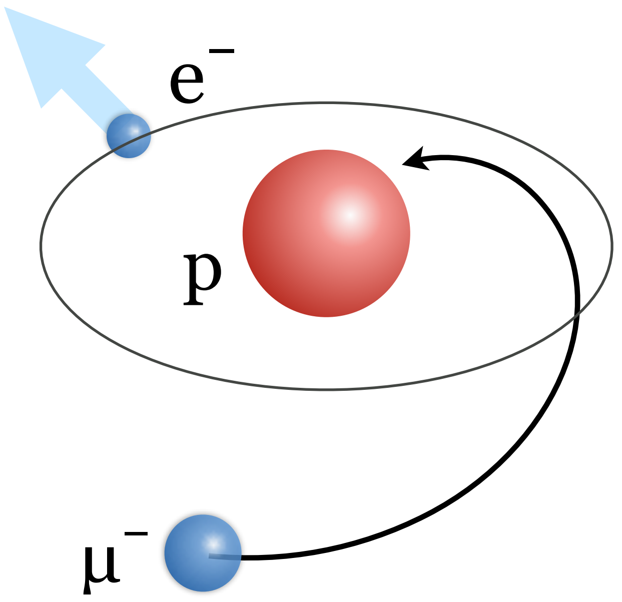


MuX
Knecht,
Wauters



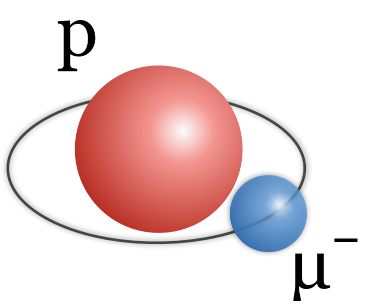
- For the lightest muonic atoms, some transitions are in laser frequencies!

Muonic hydrogen



(1) The stopping μ⁻ replaces the electron of a H atom

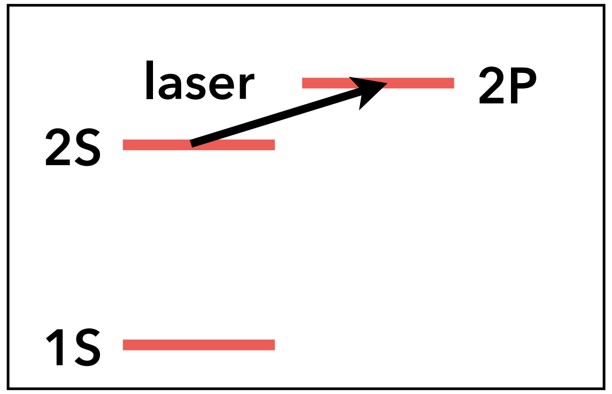
(2) The μ⁻ cascades to orbits ~200-times closer to the proton



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

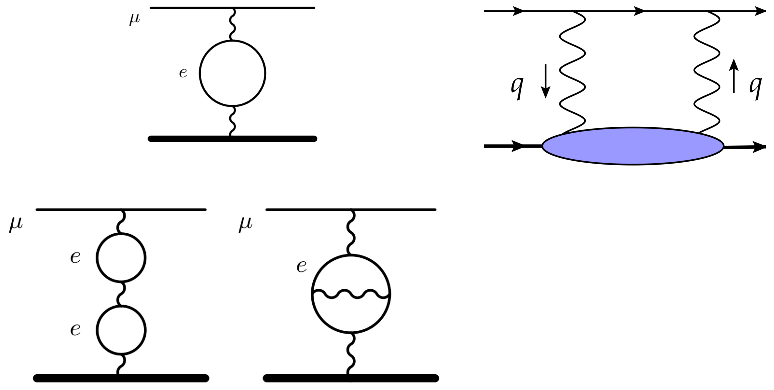
This exotic atom is extremely sensitive to the finite size of the nucleus!

measure transition (10 ppm)



known

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



extract R_p

$$\frac{\delta R_p}{R_p} = 5 \times 10^{-4}$$

Experimental method

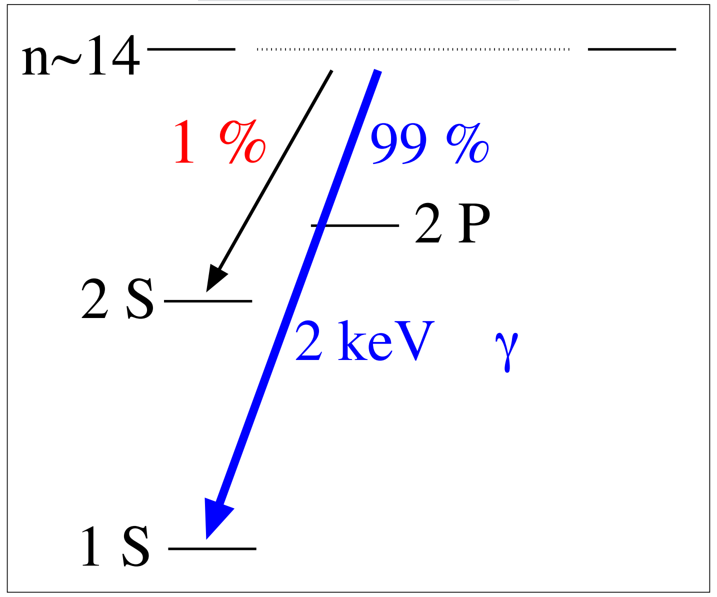
Produce many μ^- at keV energy

Form μp by stopping μ^- in 1 mbar H_2 gas

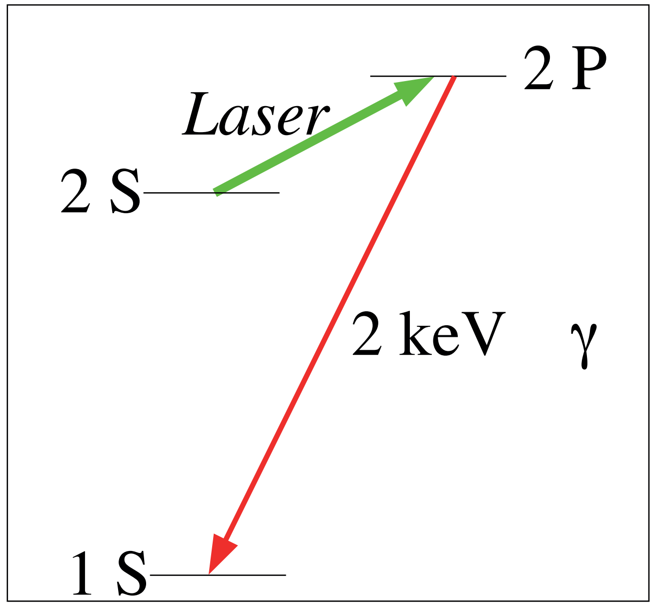
Fire laser to induce the 2S-2P transition

Detect the 2 keV X-rays from 2P-1S decay

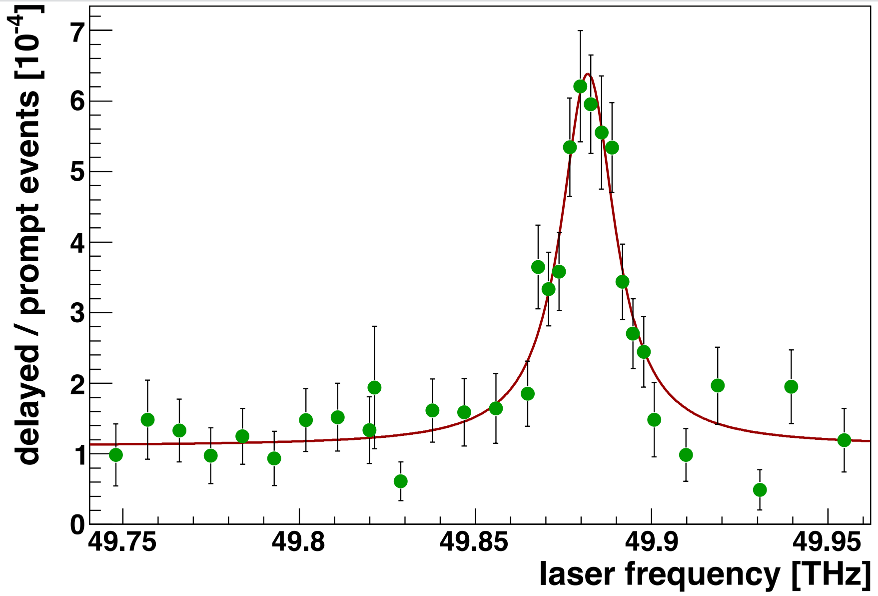
μp formation



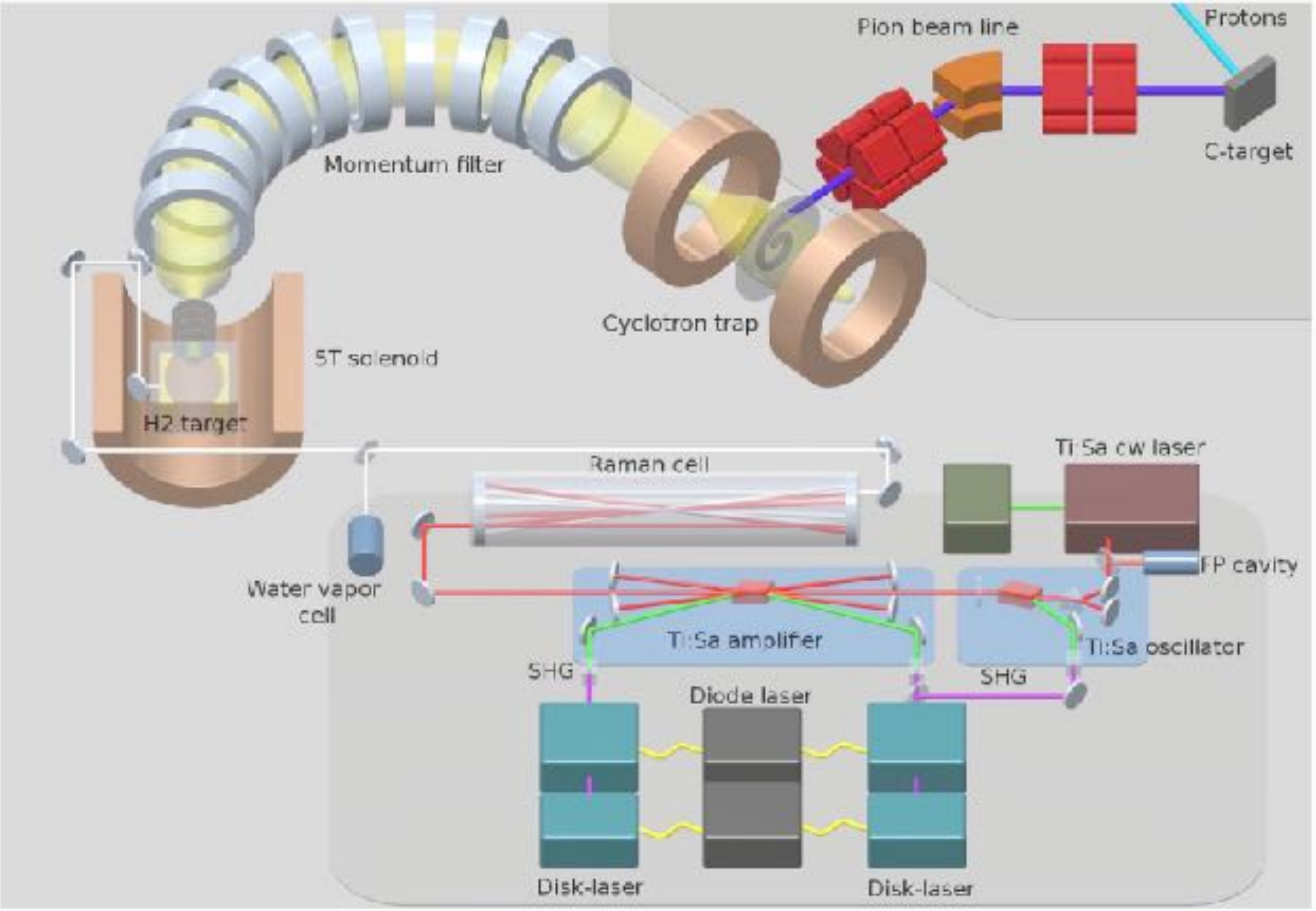
Laser excitation



Plot number of X-rays vs laser frequency

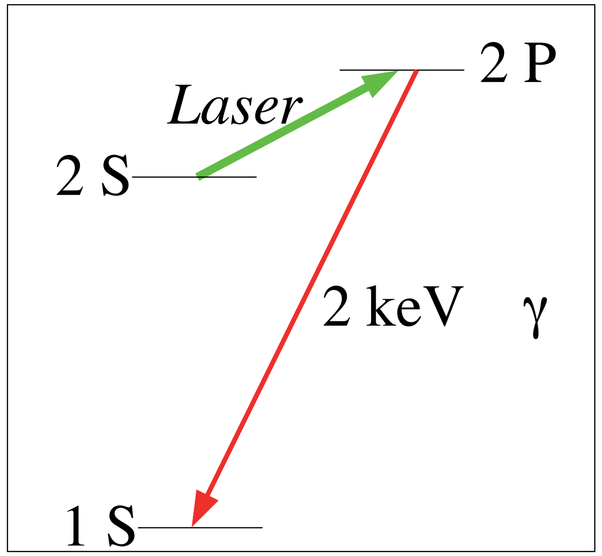


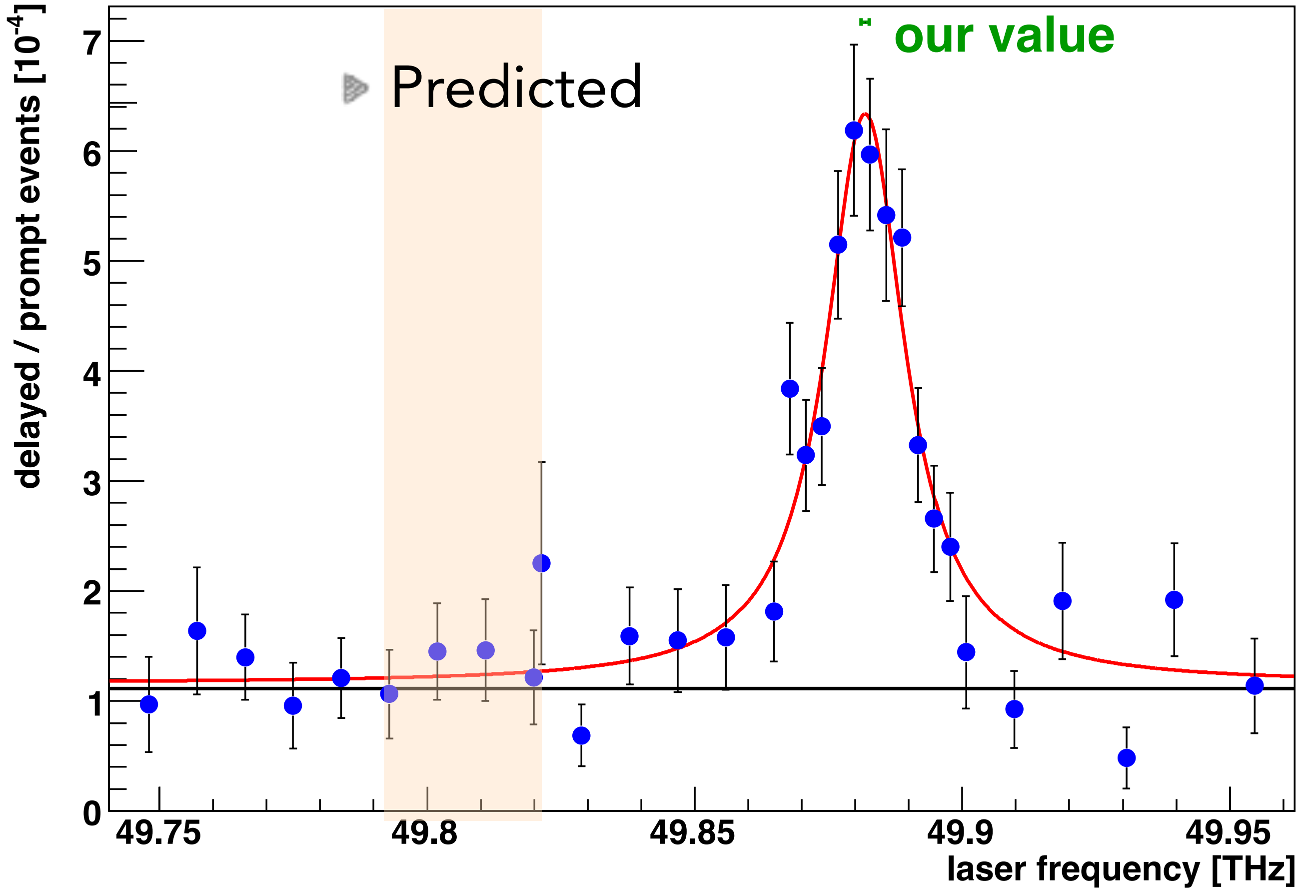
The CREMA experiment at PSI



Pohl et al., Nature 466, 213 (2010)

- Fire laser to induce the 2S-2P transition
- Measure the 2 keV X-rays from 2P-1S decay

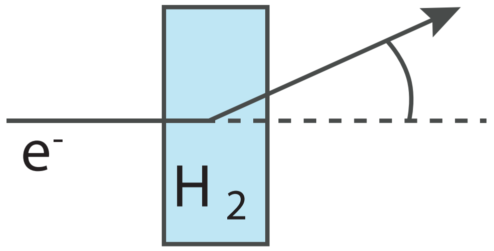




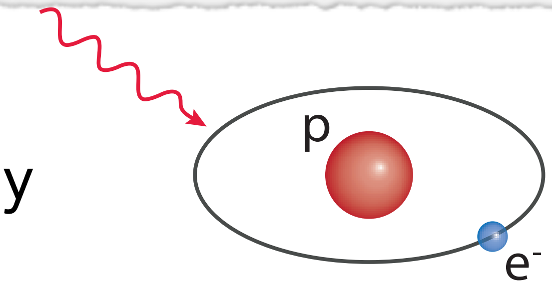
- Produce many μ^- at keV energy
- Form μp by stopping μ^- in 1 mbar H2 gas
- About 1% ends up in metastable 2S state

The proton charge radius puzzle

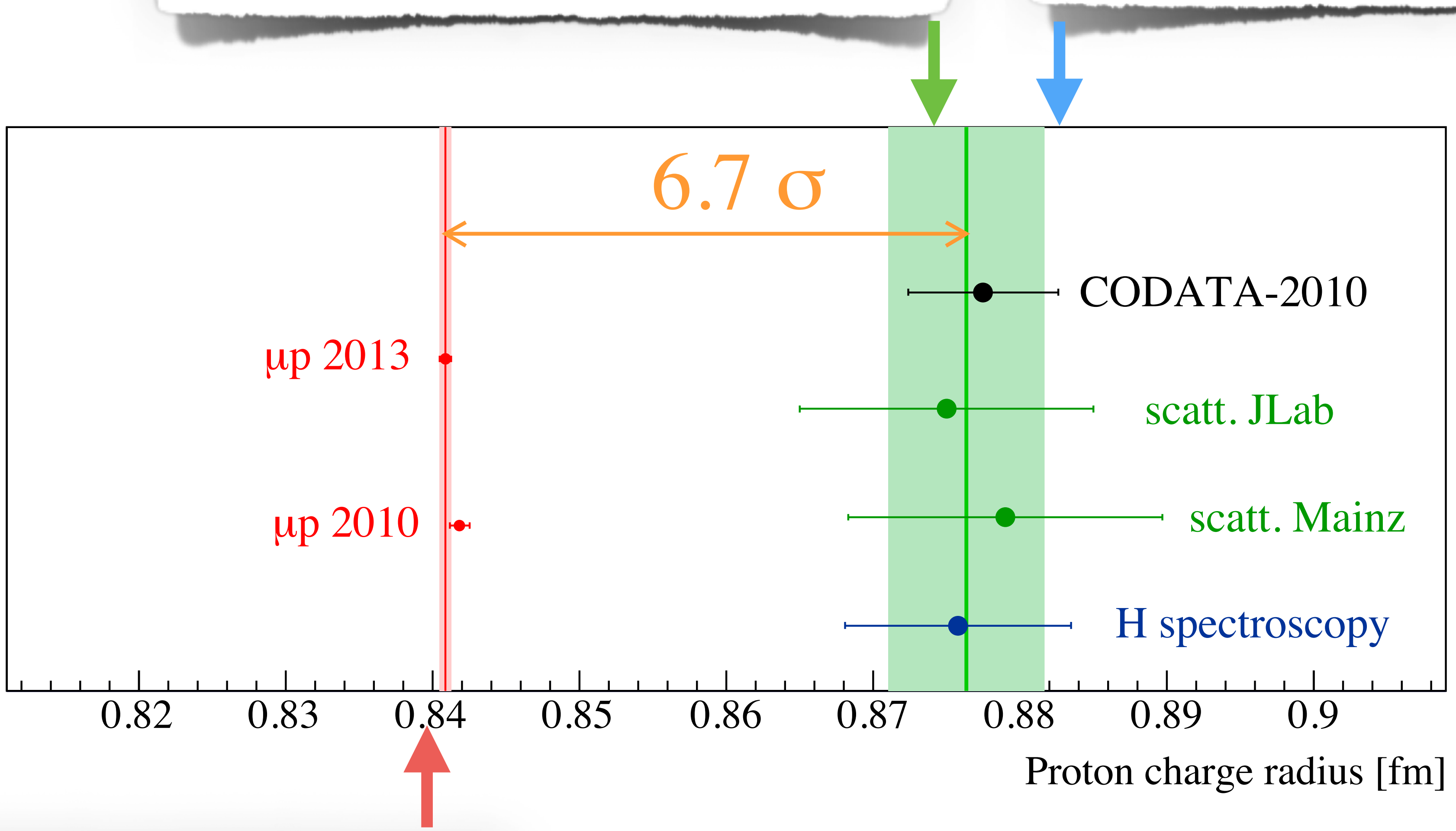
Electron scattering



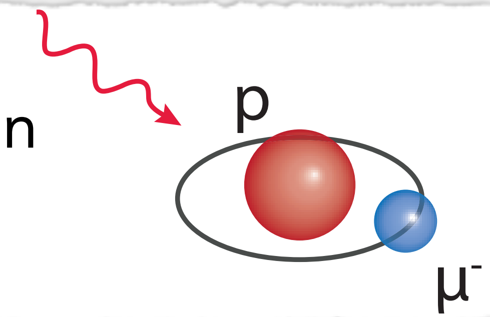
Hydrogen spectroscopy



2010

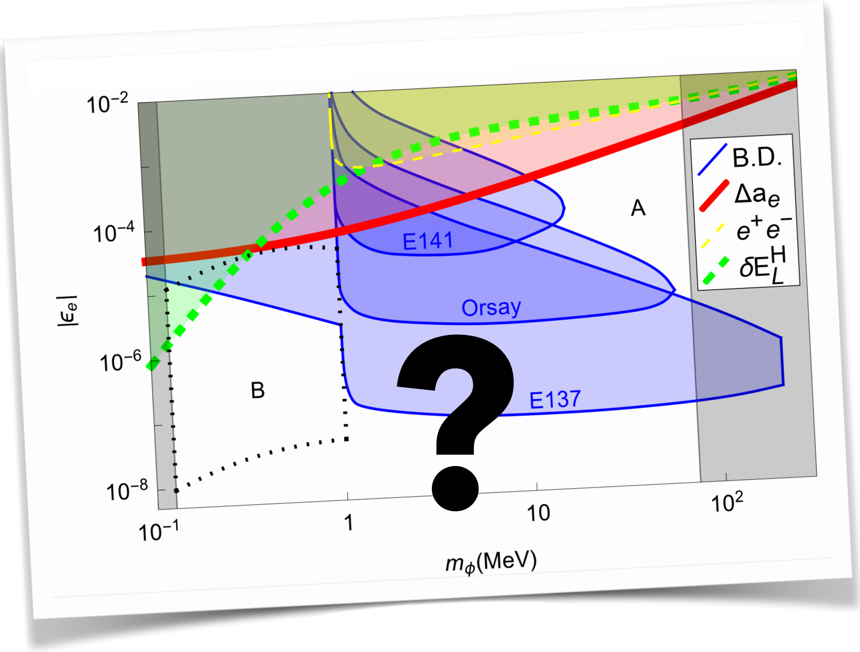


Muonic hydrogen spectroscopy



Whirlwind of new analysis, measurements, theoretical advances

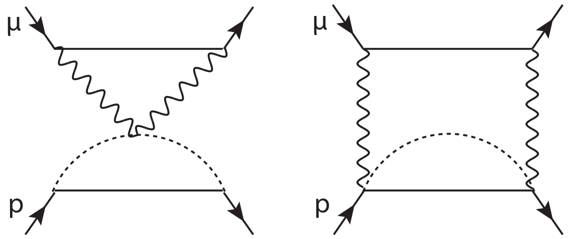
Theory **2016** **Experiments**



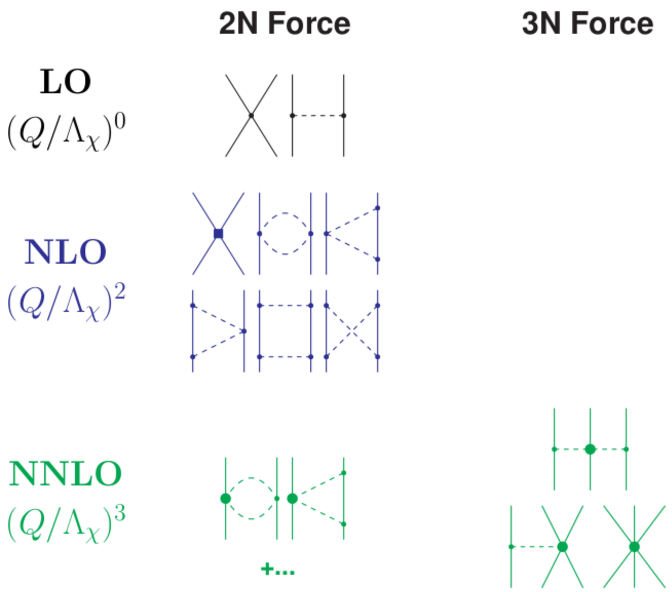
BSM

New force carrier?

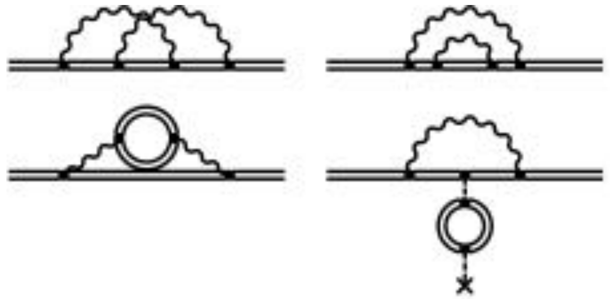
Chiral PT



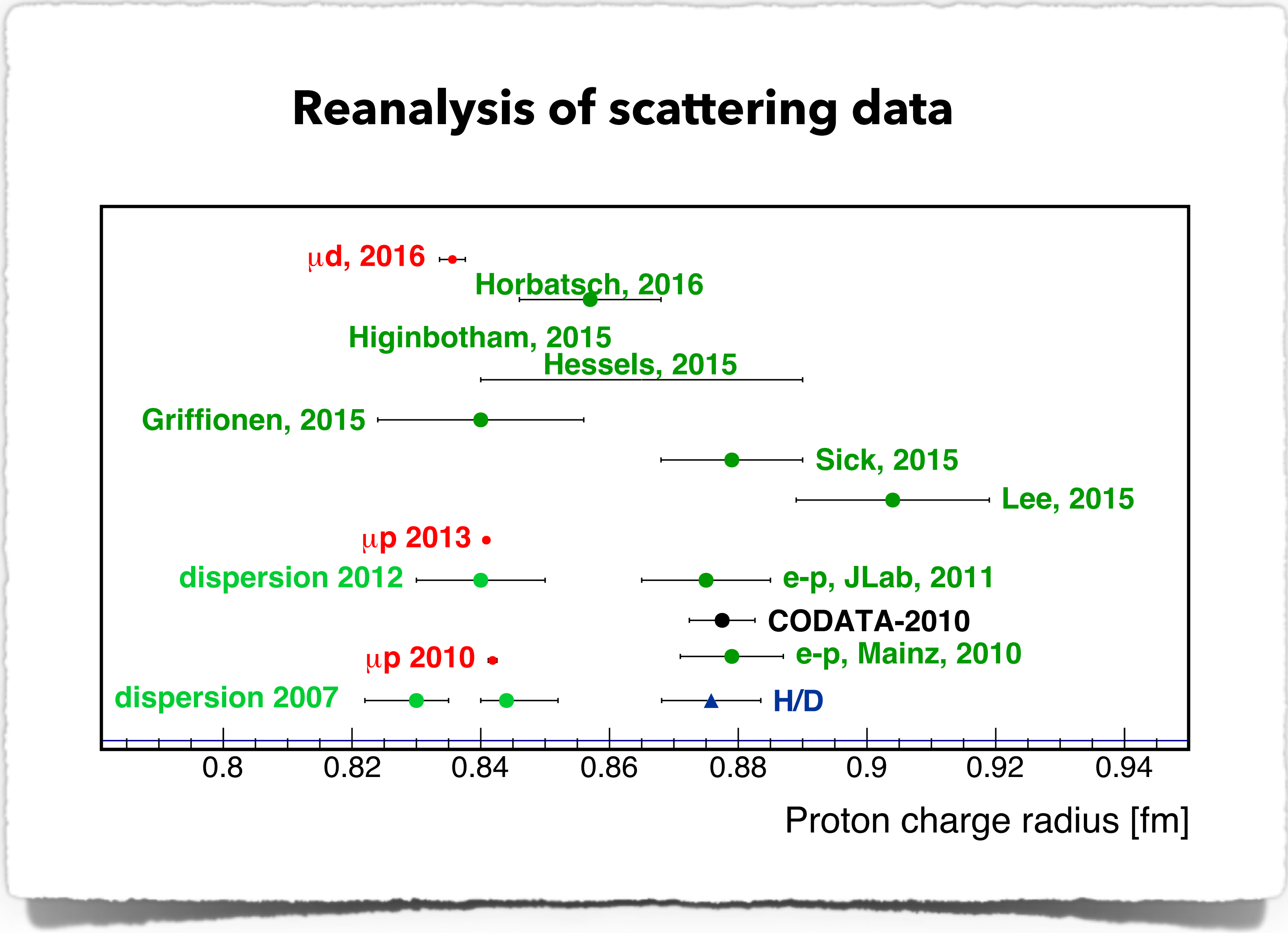
Few-Nucleon EFT



Bound-state QED



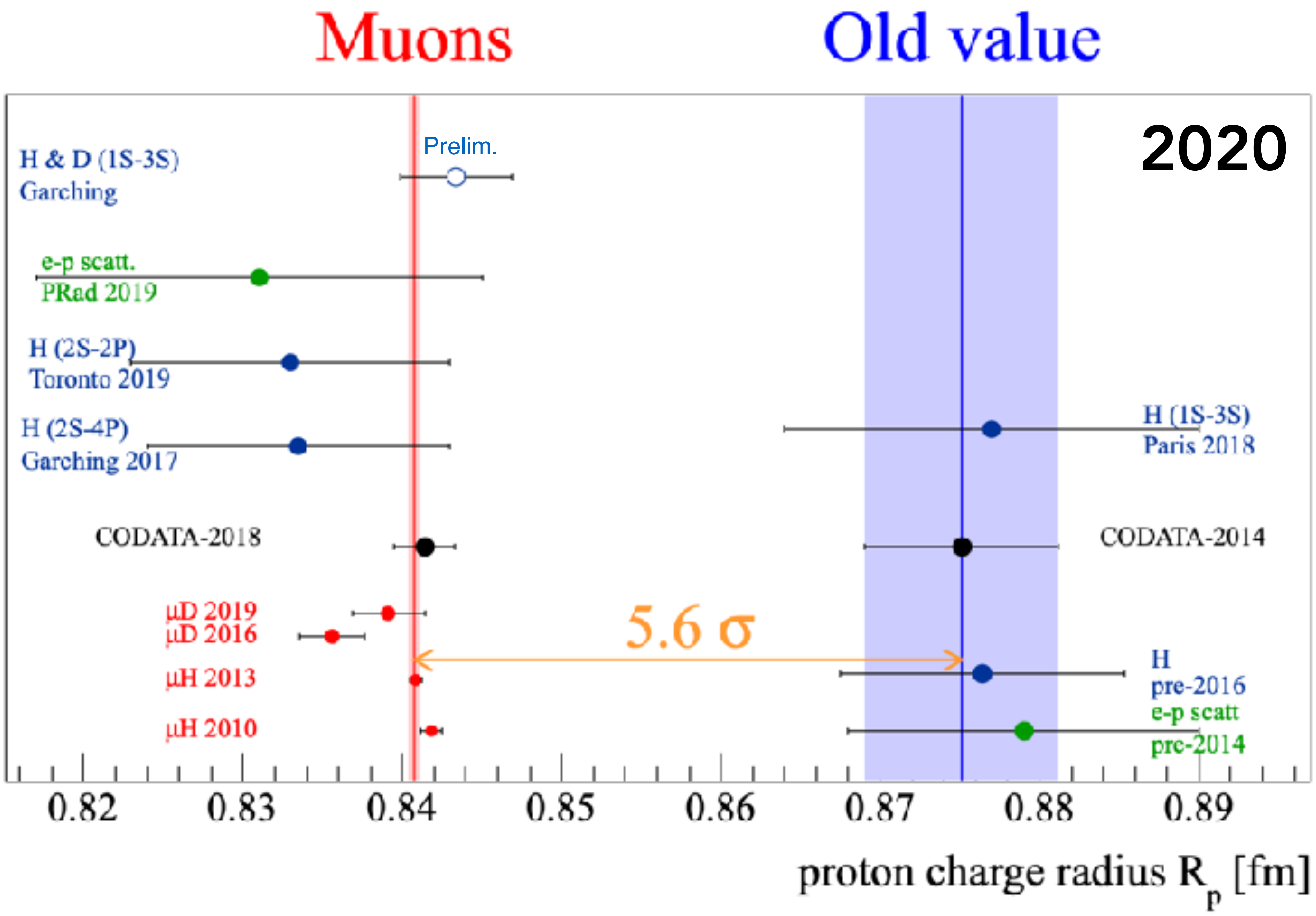
from A. Antognini



Reanalysis of scattering data

- New scattering experiment started to run
- Several spectroscopy experiments taking data (mainly H but also H_2 molecules, Rydberg states)

Present status and outcome



5 new experiments

The ETH/PSI experiment seems to be confirmed

The new Rydberg constant

$$R_\infty = \frac{\alpha^2 m_e c}{2h}$$

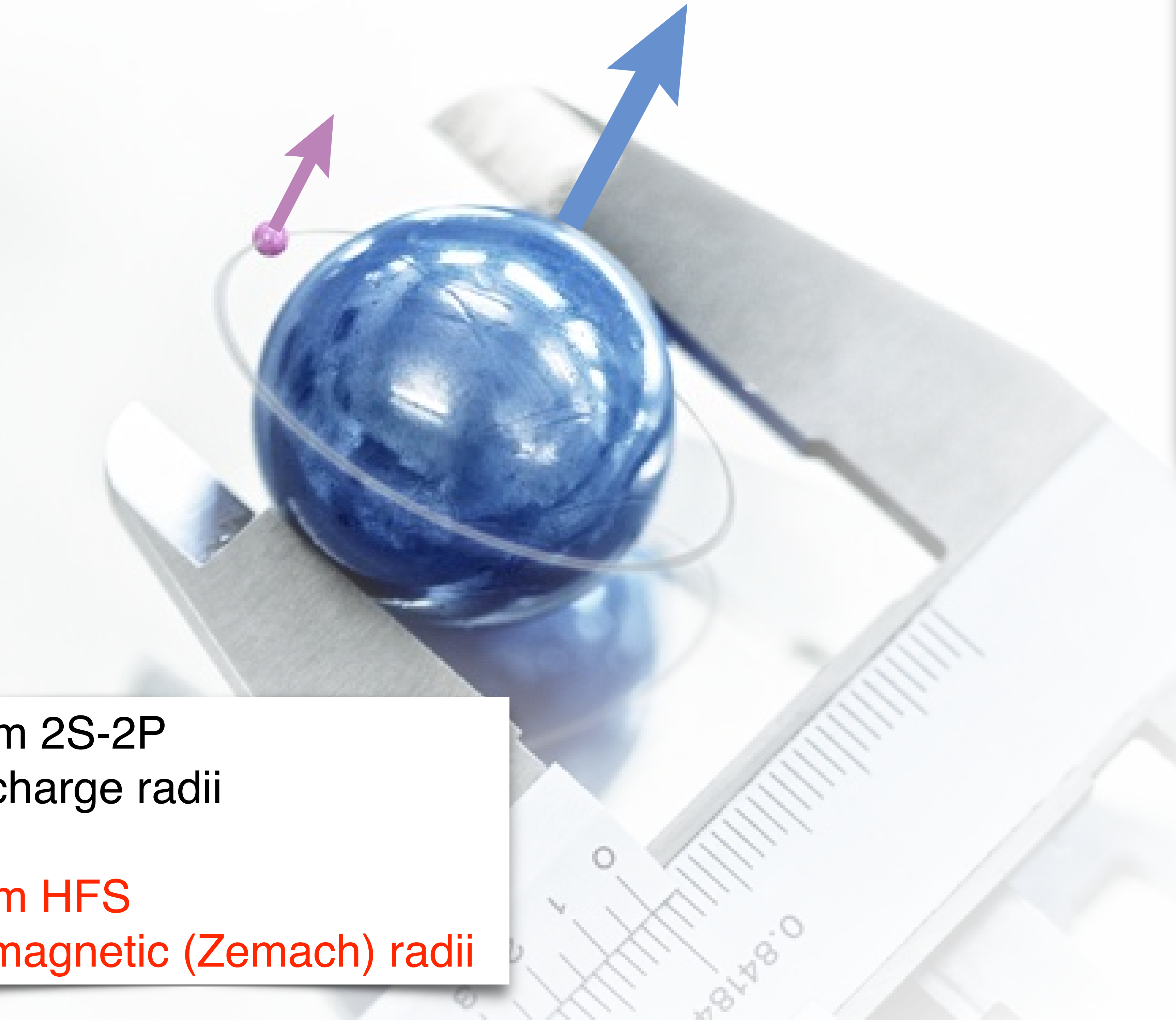
$$\frac{\delta R_\infty}{R_\infty} = 1.9 \times 10^{-12}$$

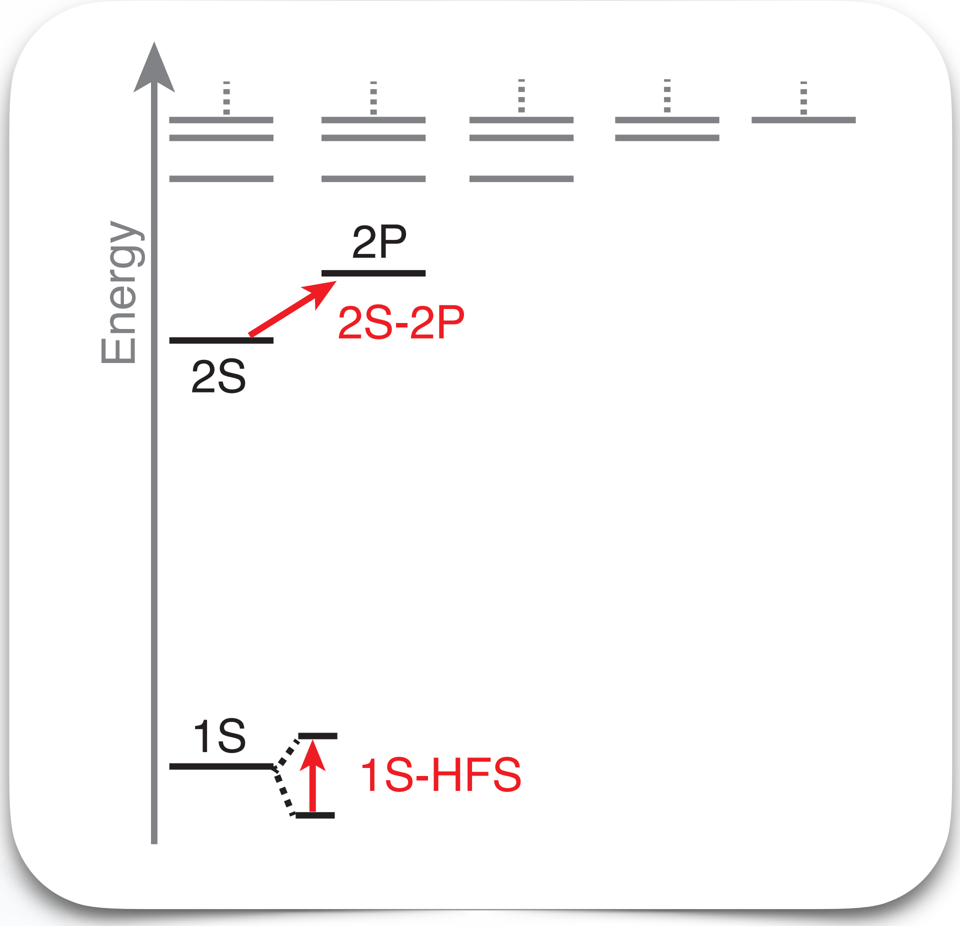
Pohl et al., Nature 466, 213 (2010)
Antognini et al., Science 339, 417 (2013)
Pohl et al., Science 353, 669 (2016)

Beyer et al., Science 358, 79 (2017)
2S-2P N. Bezginov et al., Science 365, 1007-1012 (2019)
Xiong, W., Gasparian, A., Gao, H. *et al.Nature* 575, 147–150 (2019)
Fleurbaey, et al. PRL 120.18 (2018)

Hyperfine splitting of μp - HyperMu experiment

PI: A. Antognini





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

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

Goal of the HFS measurement in muonic hydrogen

Goal:

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

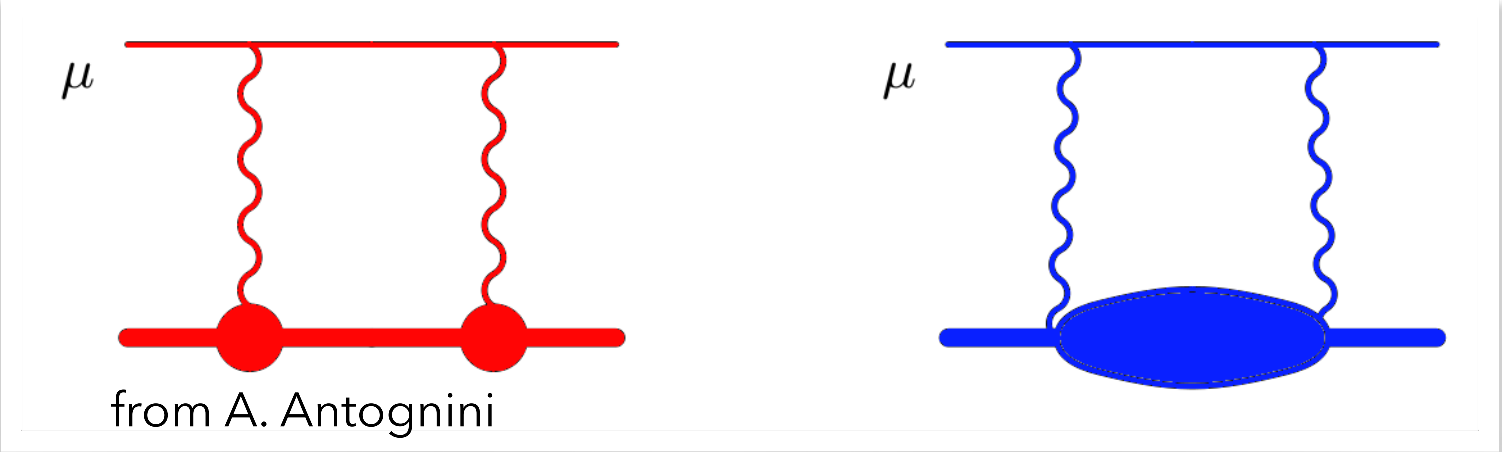
Impact:

- Two-photon-exchange (TPE) with 3x10^{-4} rel. accuracy
- Zemach radius and polarizability contributions

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

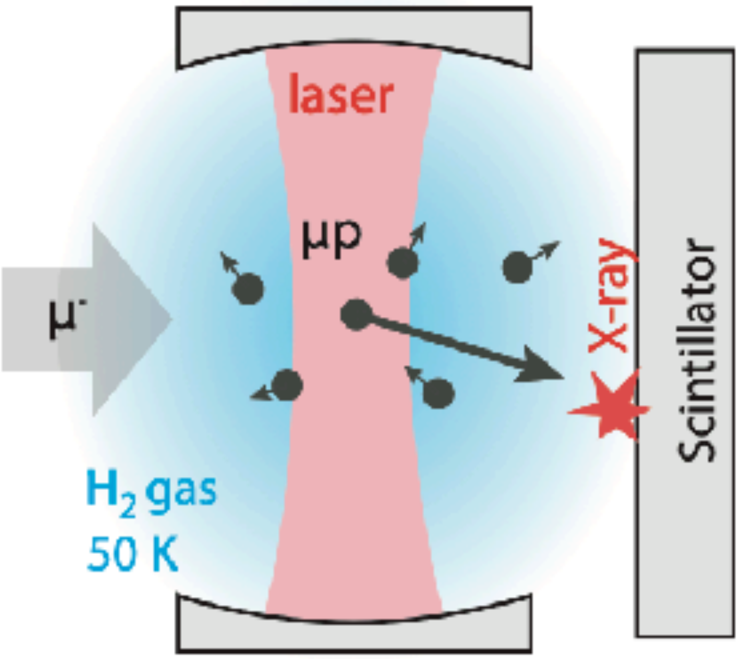
$$R_Z = \int d^3\vec{r}\, |\vec{r}| \int d^3\vec{r'} \rho_E(\vec{r} - \vec{r'}) \rho_M(\vec{r'})$$

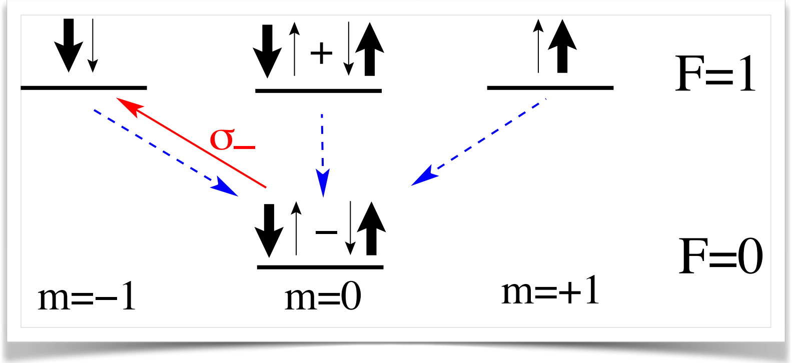
- Zemach radius
- Polarizability



from A. Antognini

The HyperMu experiment at PSI

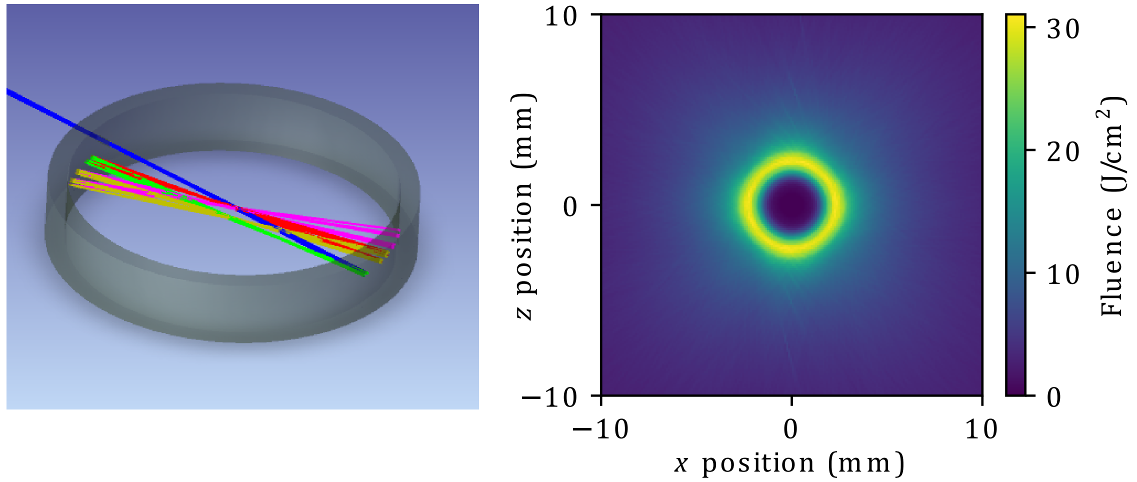




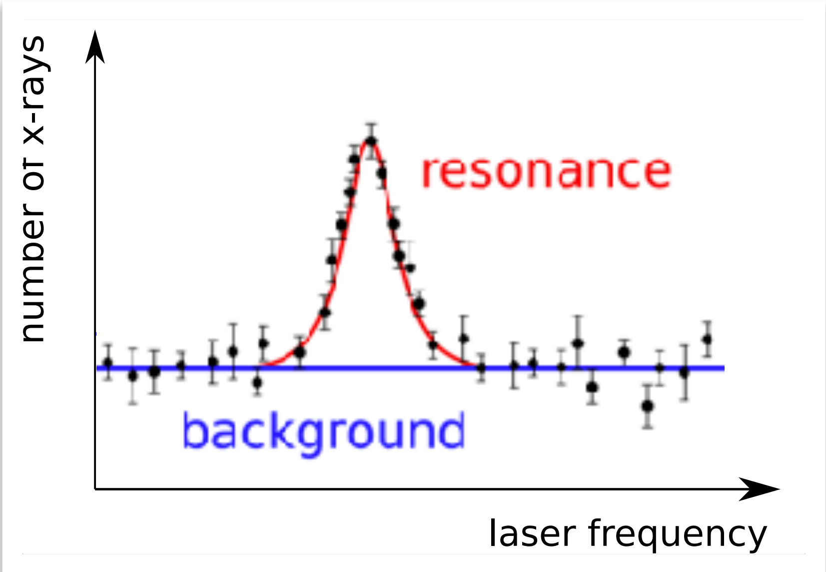
Experimental setup:

- μp atoms thermalises and de-excite to the F=0 level of the ground state
- A laser pulse excite the transition $\mu p(F=0)+\gamma \rightarrow \mu p(F=1)$
- The F=1 state is quenched to F=0 $\mu p(F=1)+H_2 \rightarrow \mu p(F=0)+H_2+E_{kin}$
- The μp having larger kinetic energy reach the target walls and produce X-rays

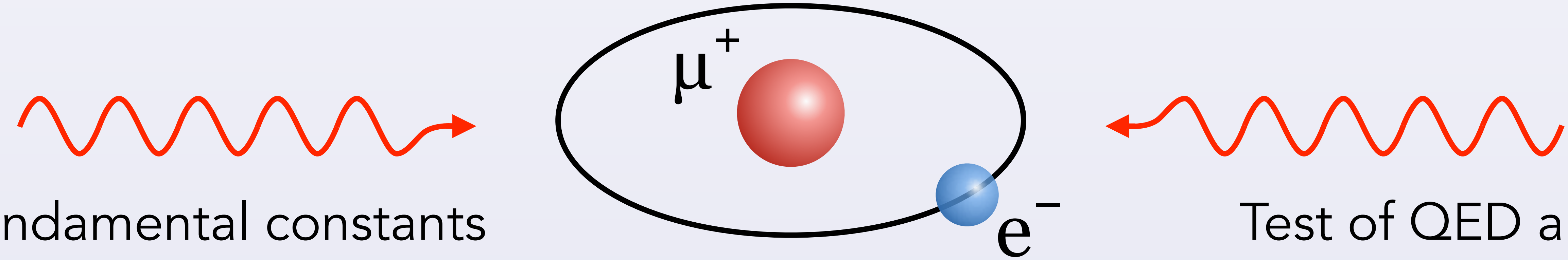
- Cylindrical cavity



- By plotting the number of X-rays versus laser frequency we obtain a resonance



Muonium



Fundamental constants

R_∞, α, m_μ

μ_μ / μ_p

Test of QED and

fundamental symmetries

q_μ / q_e

Physics motivation for Mu spectroscopy

Present

Exp. acc. 4×10^{-9}

H(1S-2S)+μp 6×10^{-13}

Muonium HFS 2×10^{-8}

1s-2s - V. Meyer et al., PRL 84(6) (2000)
HFS - W. Liu et al 82, 711 (1999)

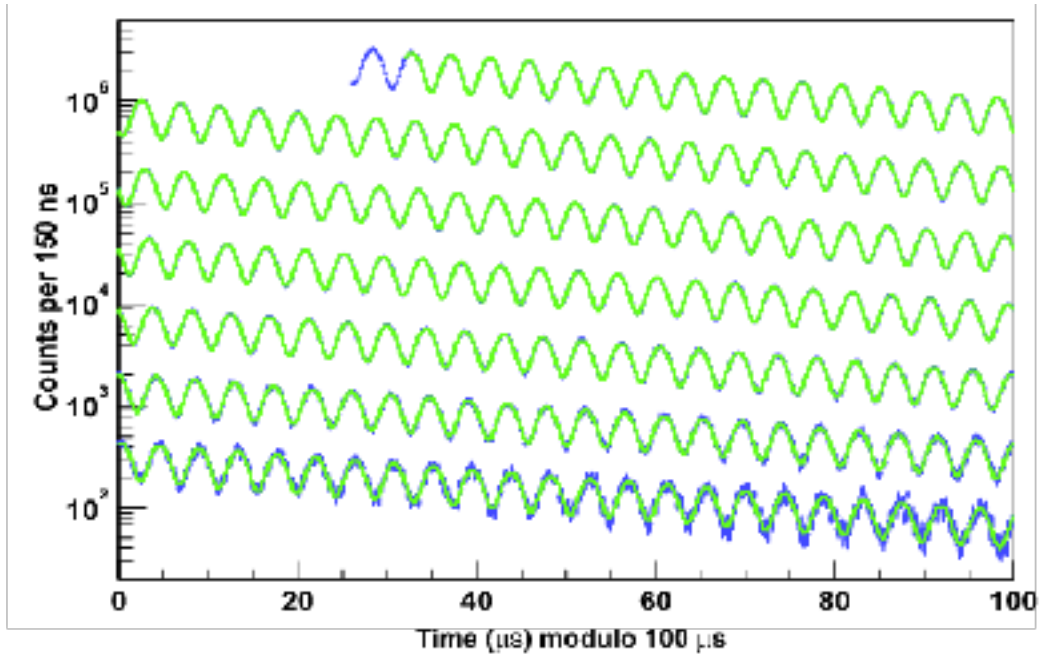
$$E(1s-2s) \simeq \frac{3}{4} R_\infty \left(1 - \frac{m_e}{m_\mu}\right) + \mathrm{QED}(\alpha, \mathrm{m_e} \ldots)$$

Future

Exp. acc. 4×10^{-12}

$\frac{m_\mu}{m_e}$ with 1×10^{-9} rel . acc .

Application in muon g-2 experiments



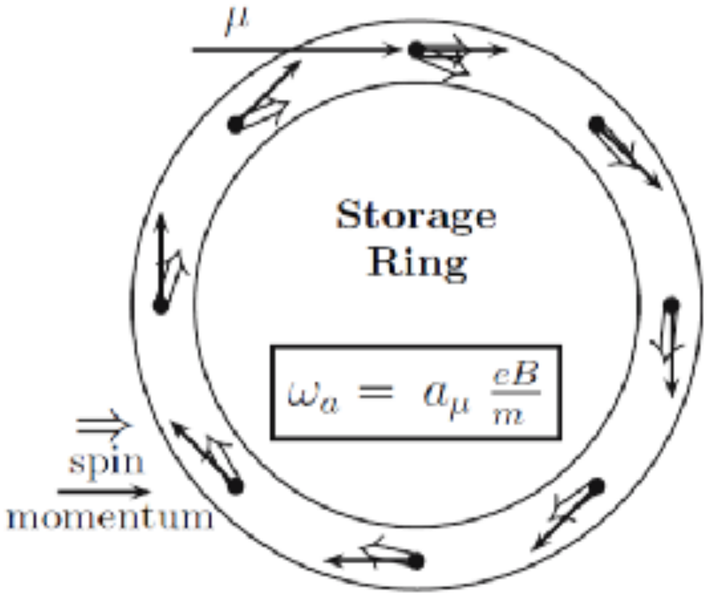
Muonium HFS (22 ppb)
or **future Mu-Mass 1 ppb**

From storage ring
[~200 ppb]

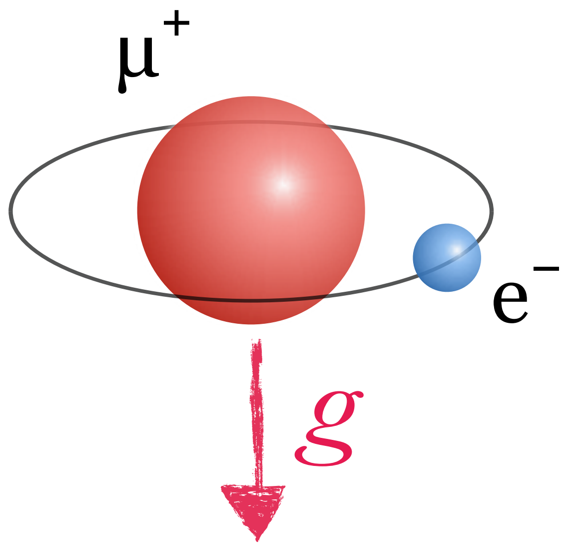
$$\frac{g-2}{2} = \frac{m_\mu}{e}\frac{\omega_a}{B} = \frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}\frac{\omega_a}{\omega_p}$$

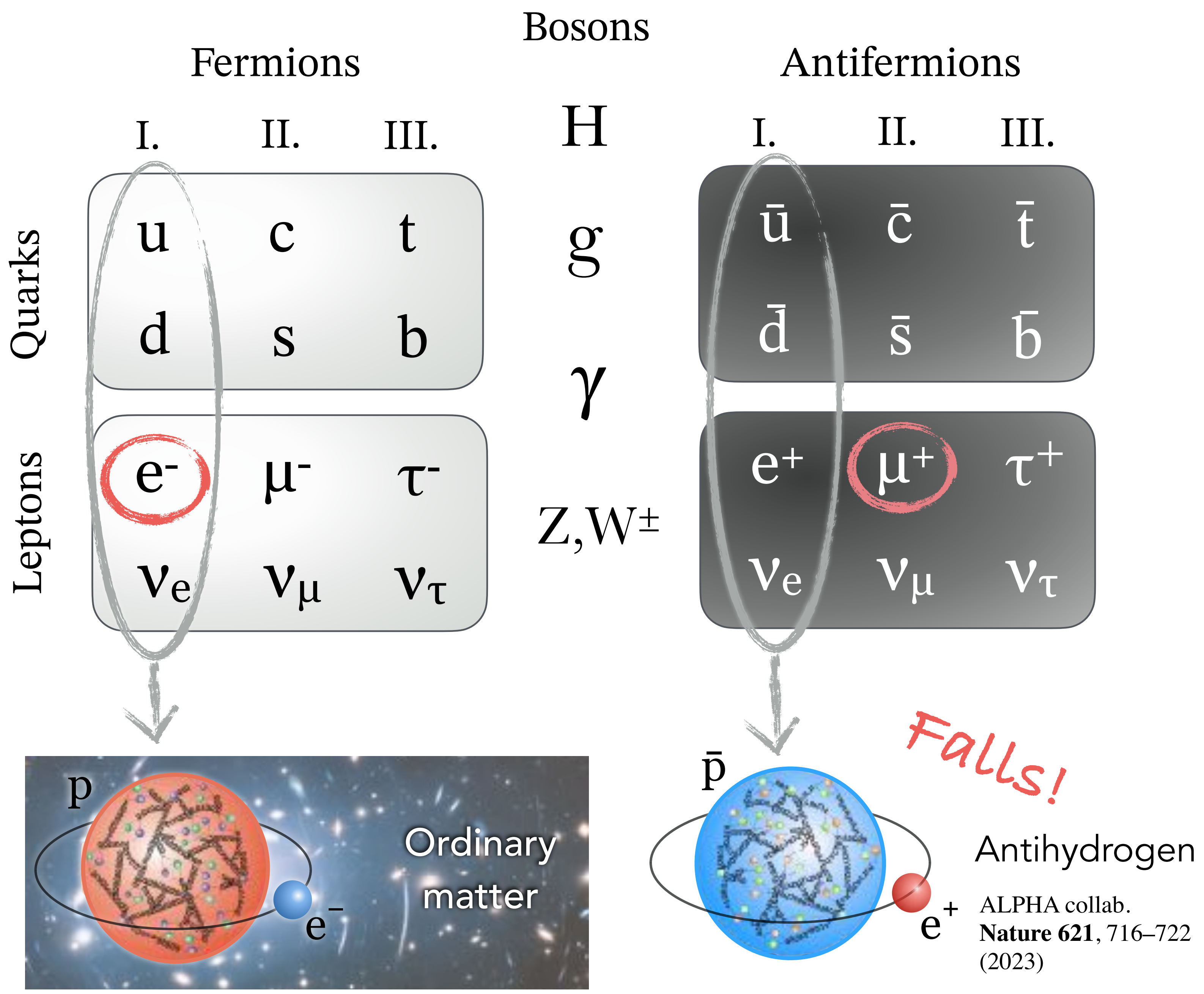
Hydrogen maser
[3 ppb]

Electron g-2 +
QED
[0.26 ppt]



Muonium - probing the SM and beyond





ALPHA collab.
Nature 621, 716–722 (2023)

Free fall of Mu

Test of the Weak Equivalence Principle by measuring the coupling of gravity to:

- **fundamental parameters** of SM, in the absence of masses generated by the strong interaction
- **second generation** (anti)fermions of the SM - only possible probe of this sector

Hadron mass

1% valence quark
99% strong interaction

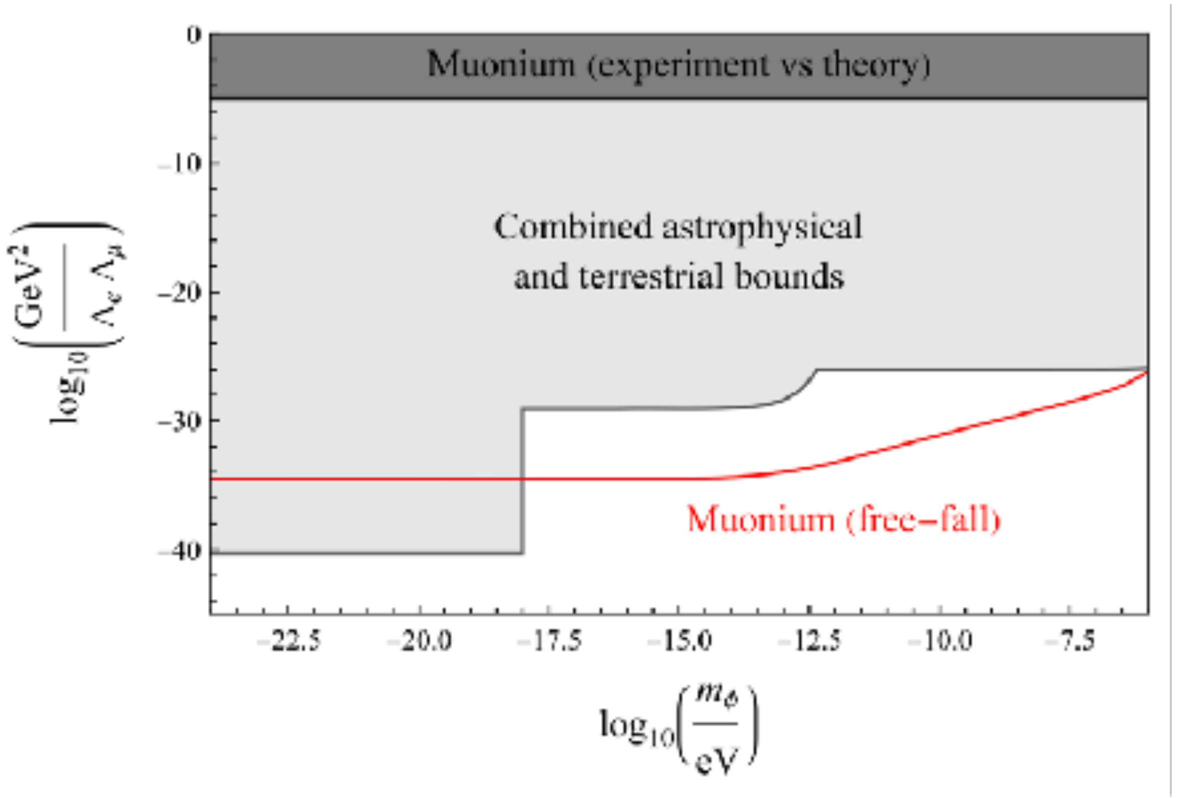
Muonium mass

Binding 13.7 eV

μ^+ mass: 105.6583745(24) MeV/c
e^- mass: 0.5109989461(31) MeV/c

Disclaimer on “exotic gravity”

- Causes more problems than it solves
- Many **indirect constrains** exist on matter/antimatter (kaon oscillations, gravitational redshift) Short summary: SciPost Phys. Proc. 5, 031 (2021)
- **No constrains exist yet with muons** or in general second vs first generation, in the absence of strong binding energies
- Not needed to invent exotic gravity for an anomaly



- Y. Stadnik PRL 131, 011001 (2023)
- assuming 10% precision on g of Mu
- Potential originates from virtual ultralight scalar bosons

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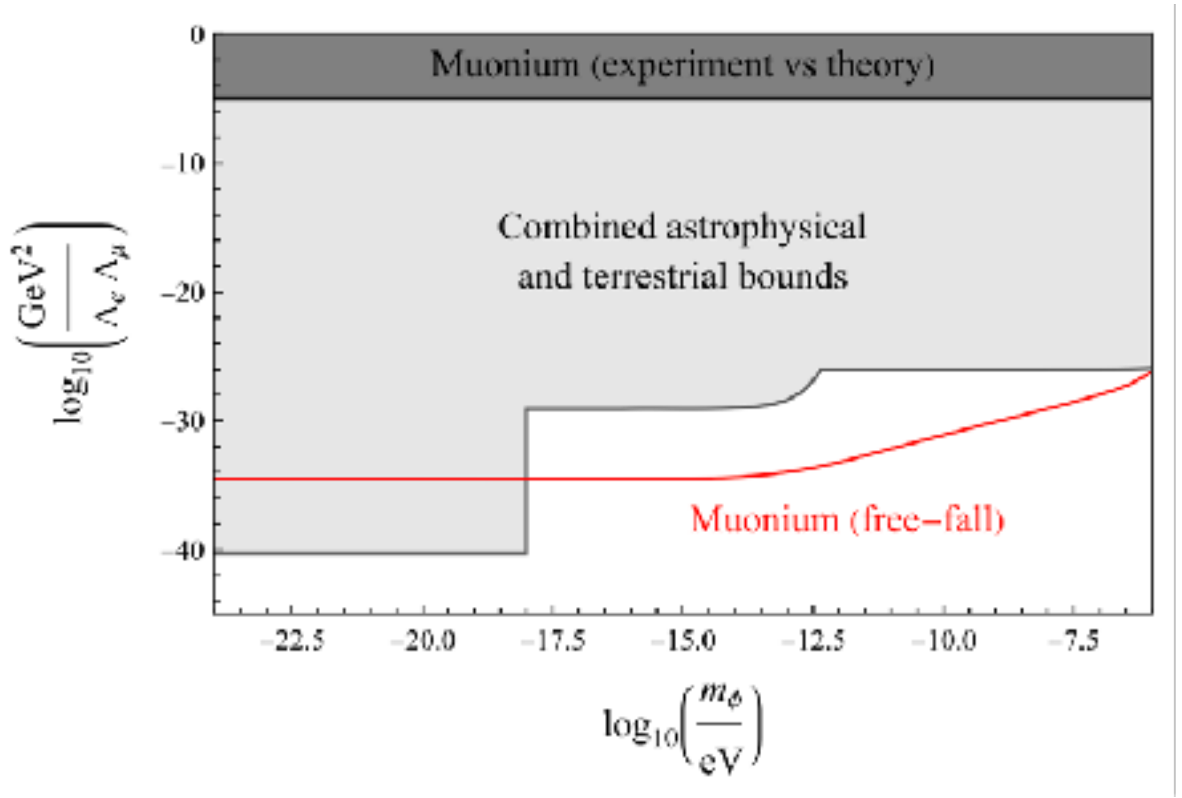


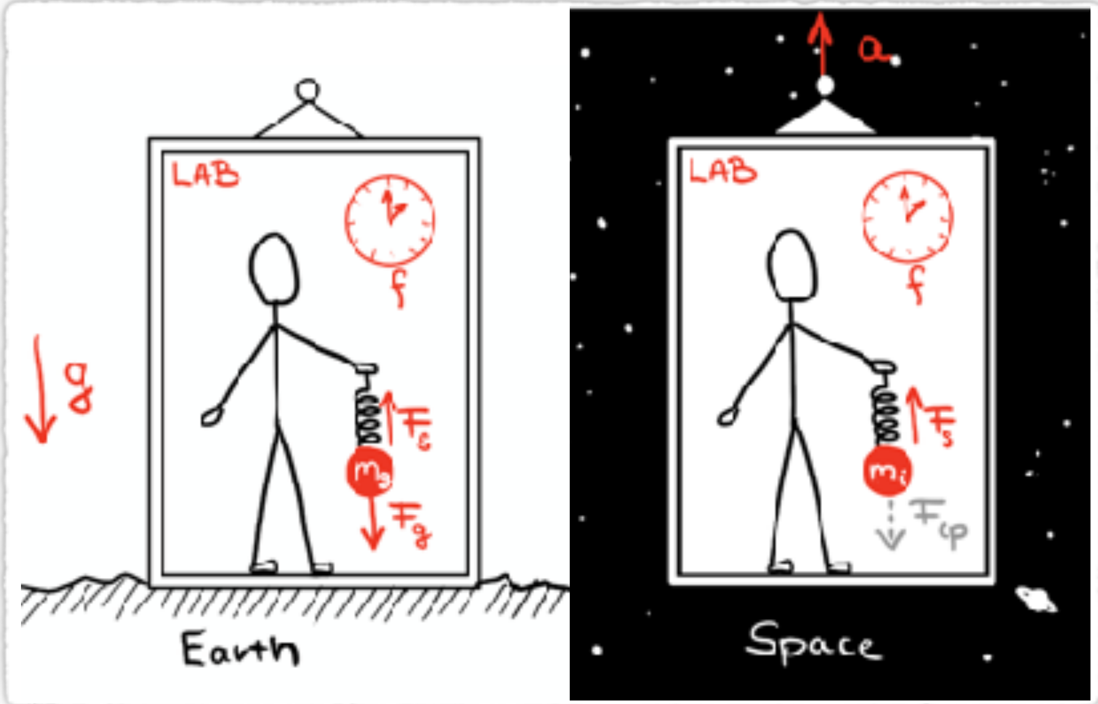
- **How a theorist sees the experimental physicist**

- Y. Stadnik PRL 131, 011001 (2023)
- assuming 10% precision on g of Mu
- Potential originates from virtual ultralight scalar bosons

Tests of the weak equivalence principle (WEP)

Foundation of GR. Many formulations since Galilei:

Usually describing that he outcome of any local experiment conducted in gravitational field (local g acceleration) must be the same than in an accelerating lab, where a=g.



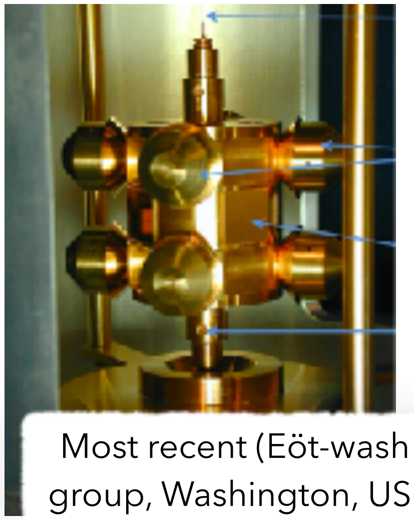
Various experimental consequences:

- Universality of free fall: $\eta(1,2) = 2\frac{|g_1 - g_2|}{|g_1 + g_2|}$
- Local Lorentz invariance
- Local position invariance:
  - universality of clocks,
  - lack of variation of fundamental constants

- *Needs to be tested in different experiments sensitive to one of the above!*

Torsion pendula

Original setup of Eötvös (1910, Hungary)

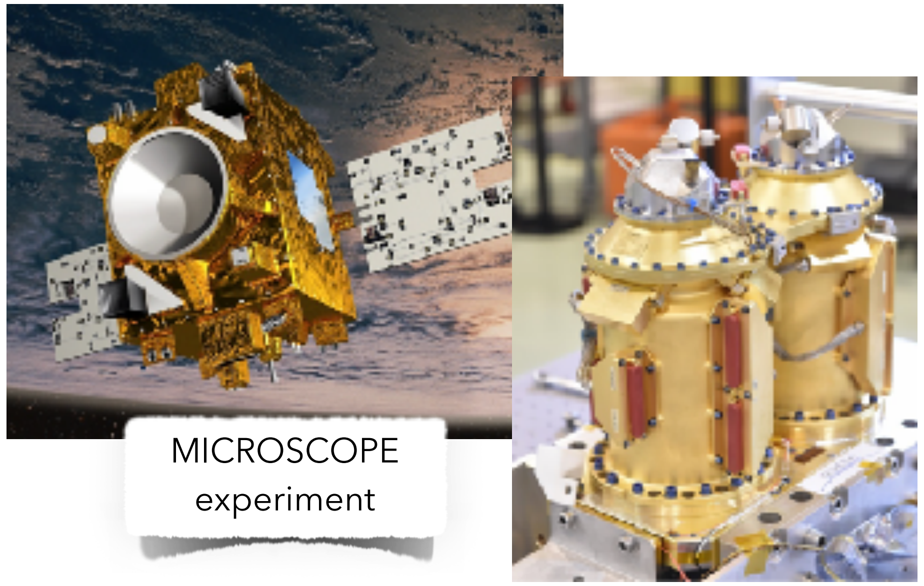


Most recent (Eöt-wash group, Washington, US)

$\eta(\mathrm{Be,Ti}) = [0.3 \pm 1.8] \times 10^{-13}$

Phys. Rev. Lett. **100**, (2008)

Satellite experiments

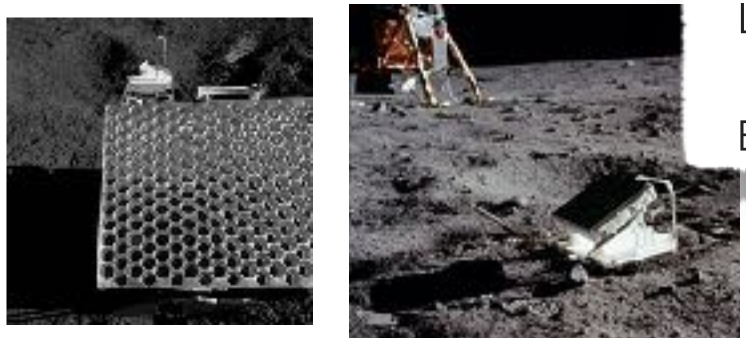


MICROSCOPE experiment

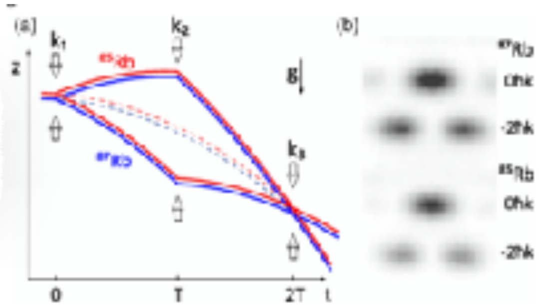
$\eta(\mathrm{Ti,Pt}) = [-1.5 \pm 2.3(\mathrm{stat}) \pm 1.5(\mathrm{syst})] \times 10^{-15}$

Phys. Rev. Lett. **129**, 121102, 2022

Tests on the largest and smallest scales



Lunar Laser Ranging Experiment



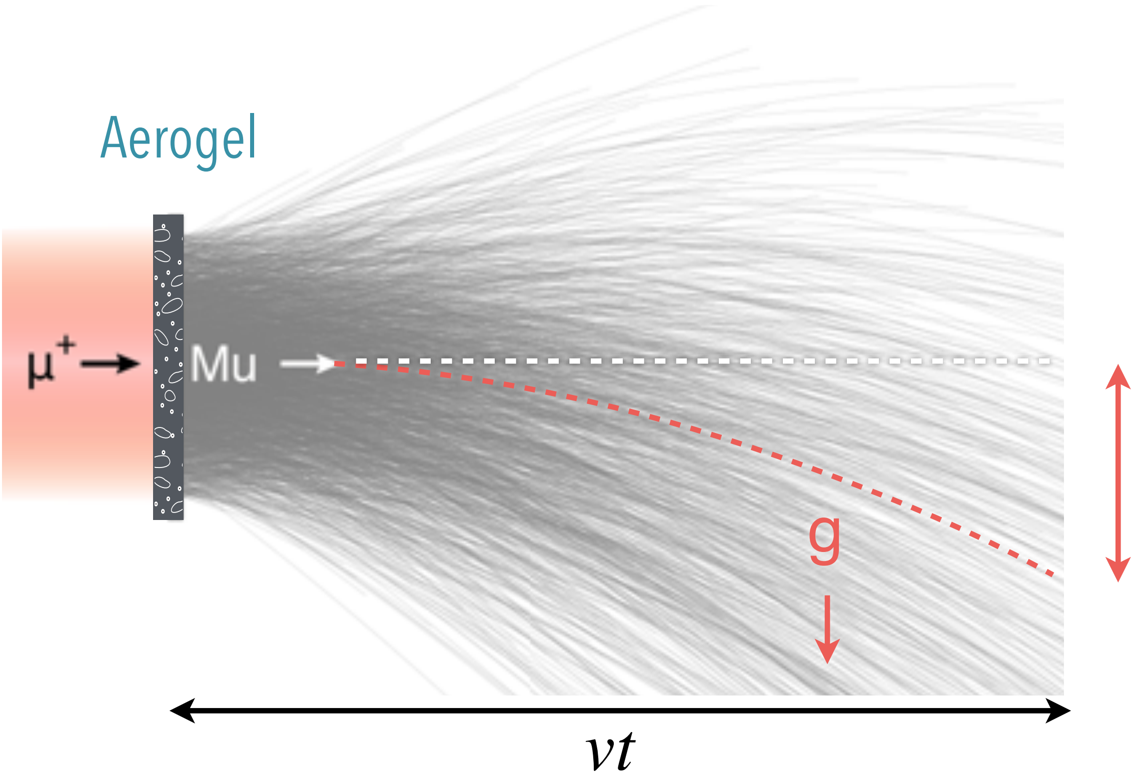
Atom interferometry

$\eta(^{85}\mathrm{Rb}, ^{87}\mathrm{Rb}) = [1.6 \pm 1.8(\mathrm{stat}) \pm 3.4(\mathrm{syst})] \times 10^{-12}$

Phys. Rev. Lett. **125**, 191101, 2020

The challenges of measuring Mu gravity

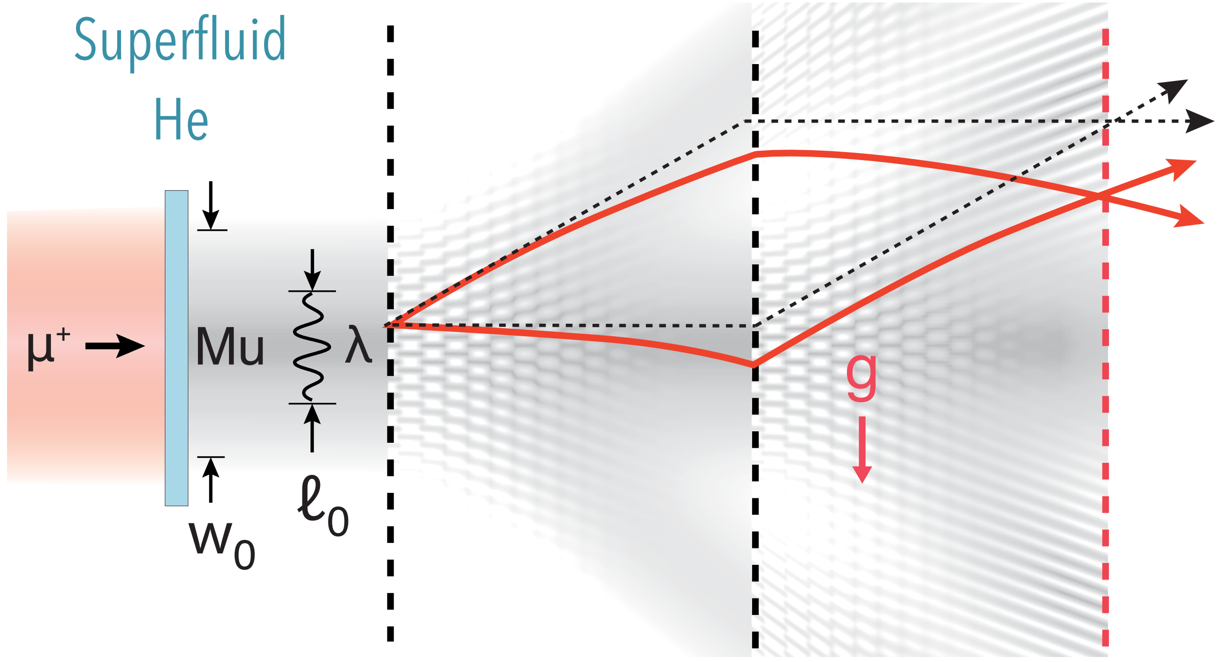
Not possible with existing Mu sources



Mu lifetime of 2.2 μs

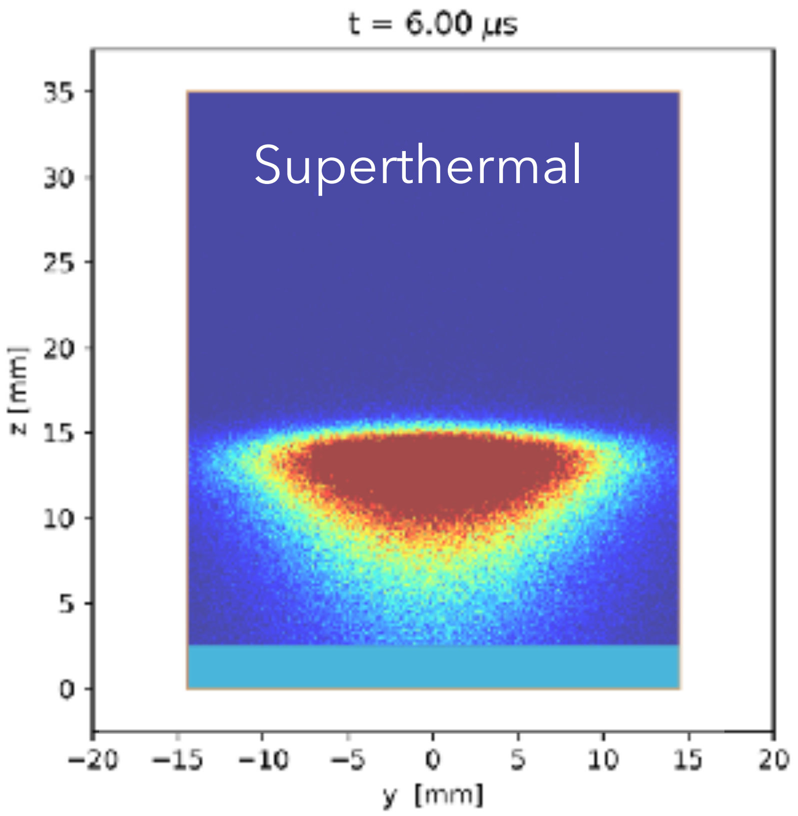
$$\Delta x = \frac{1}{2} g t^2 < 1\ \text{nm}$$

Why it might be possible now

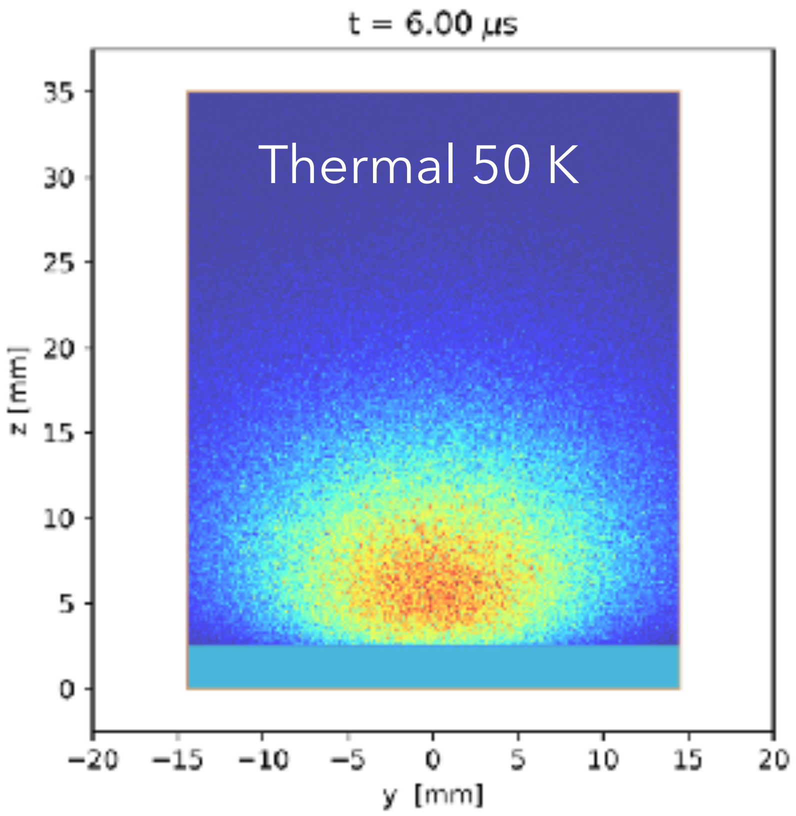


We developed a novel Mu beam amenable to interferometry

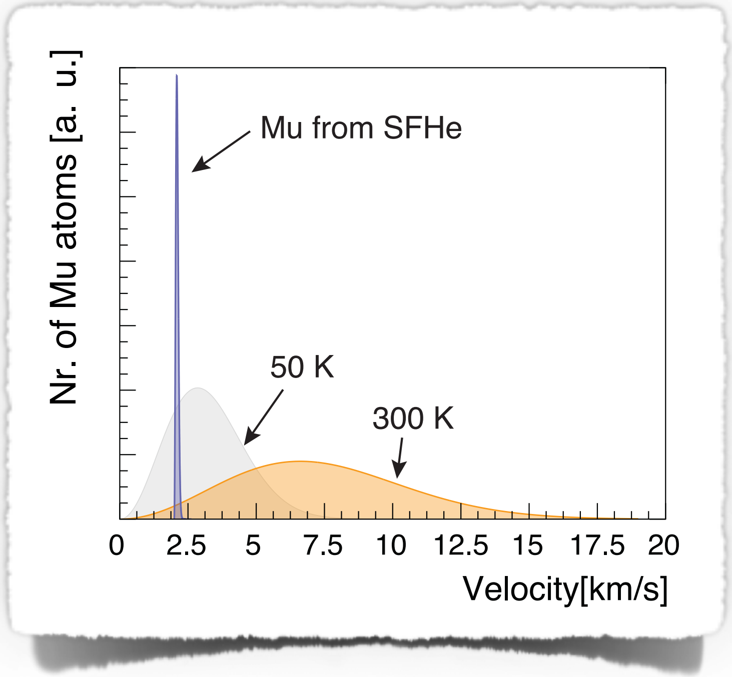
Characterisation of the new superthermal muonium



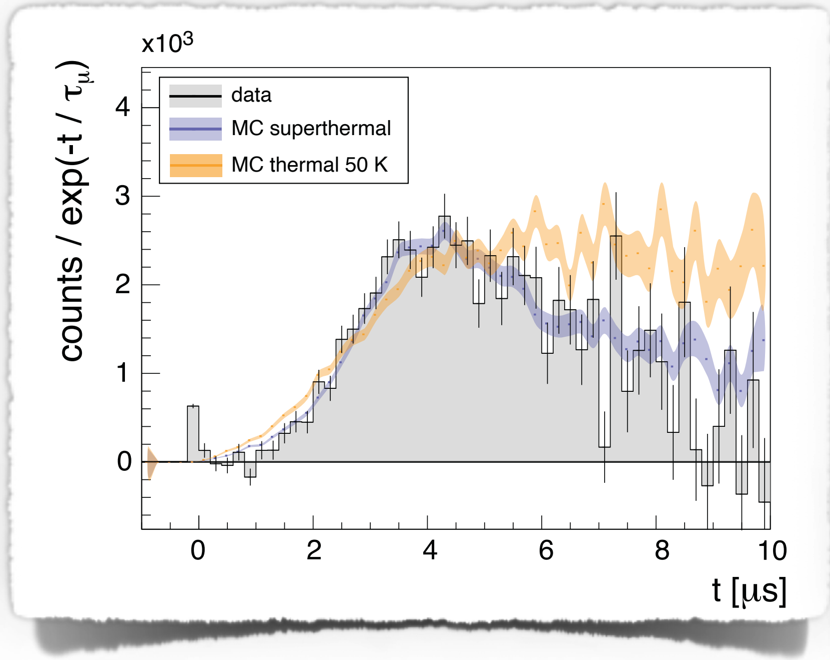
- **Lowest** mean **velocity** muonium source ever made: $v_x \approx 2175\ \mathrm{m/s}$
- Velocity distribution much **narrower** than Maxwell-Boltzmann: $\sigma_{v_x} \approx 70\ \mathrm{m/s}$
- Ballistic diffusion $v_{\mathrm{diff}} \approx 50\ \mathrm{m/s}$
- **Yields similar amounts** to the best 300 K sources $R(\mu^+ \rightarrow \mathrm{Mu}_{\mathrm{vac}}) = 10\,\%$



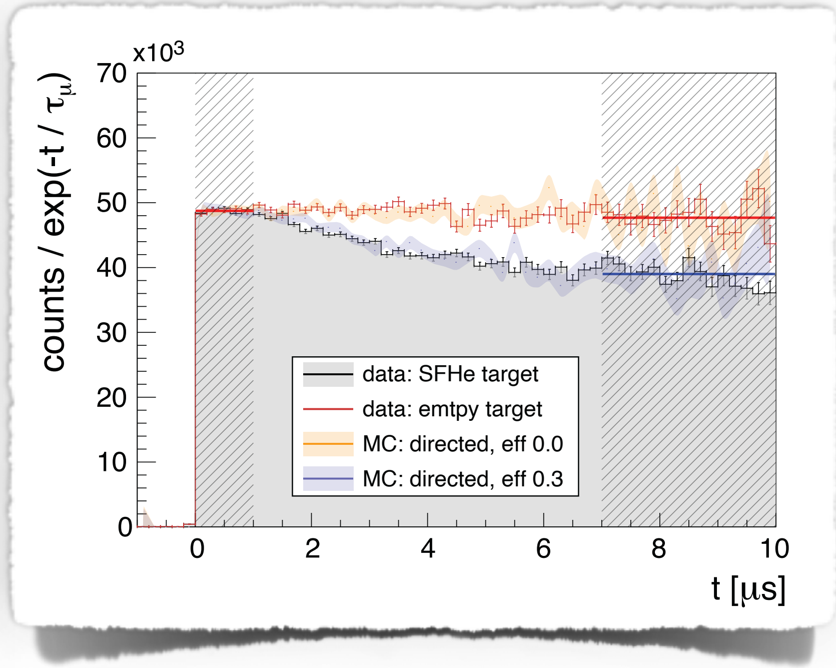
Reconstructed velocity distribution



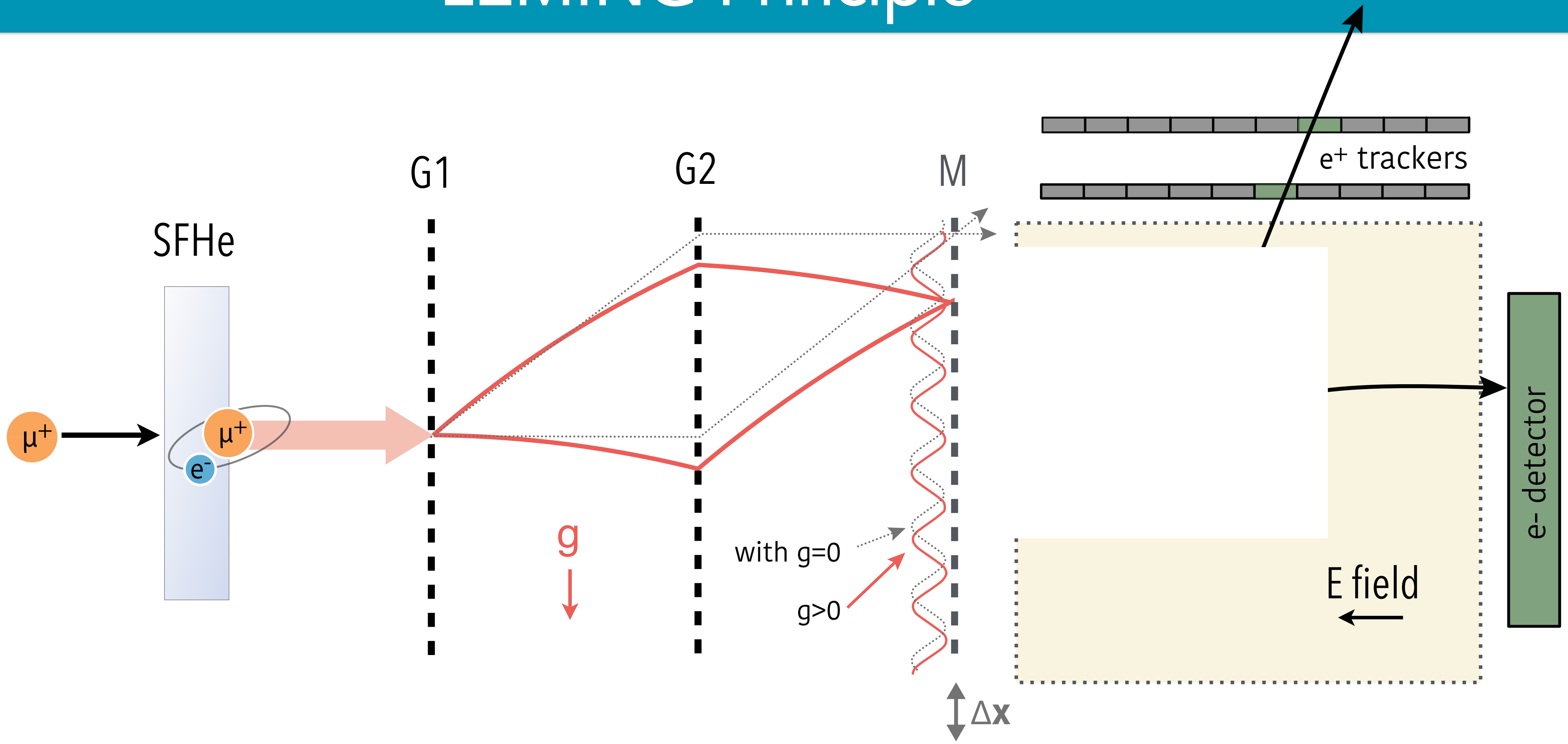
Time spectra of fly-by



Time spectra of target emission



LEMING Principle



Horizontal cold Mu beam

WP1

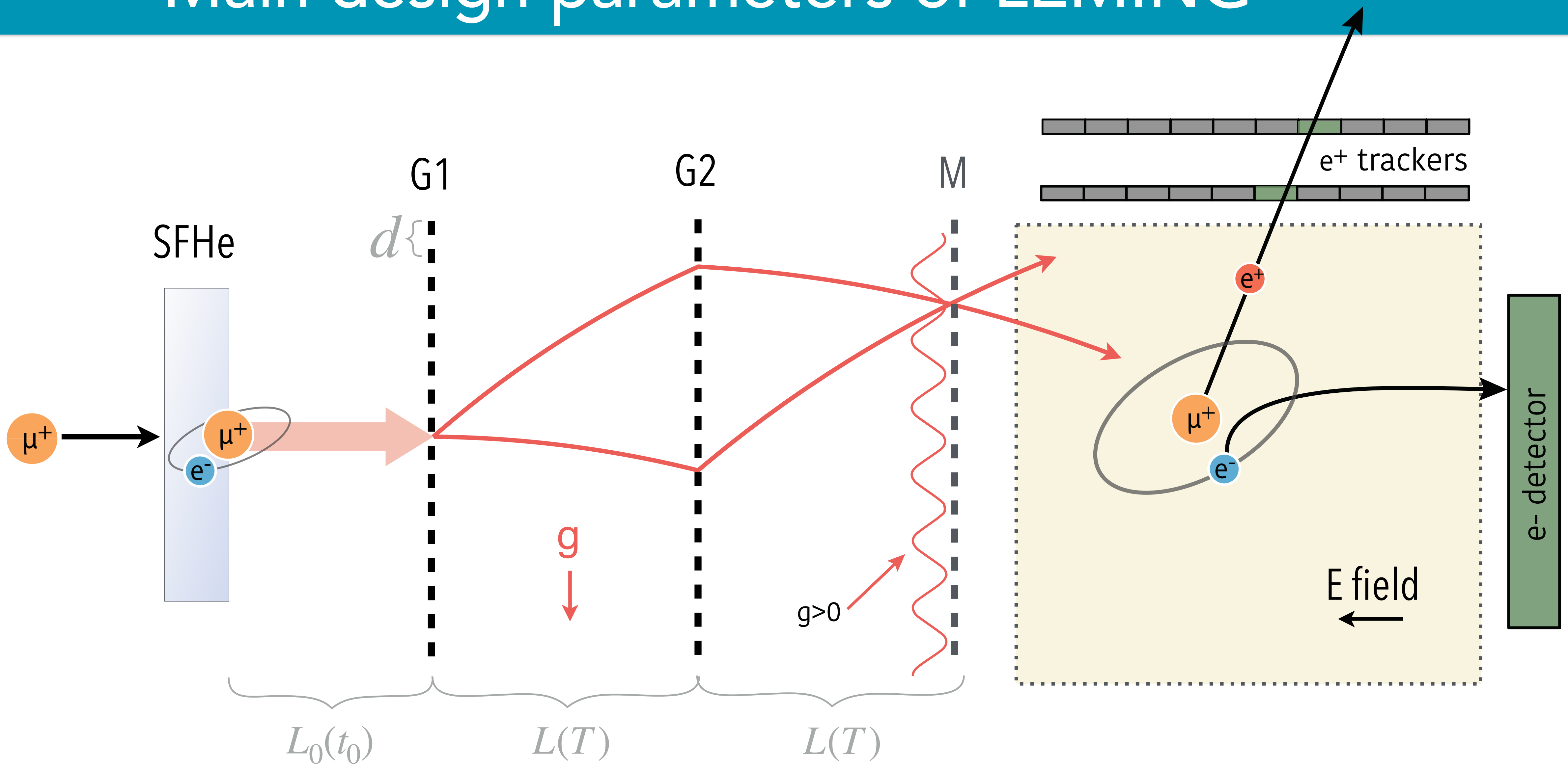
Interferometer

WP3-4

Detection

WP2

Main design parameters of LEMING



Sensitivity

$$\Delta g \approx \frac{1}{2\pi T^2}\,\frac{d}{C\sqrt{N_0\epsilon\eta^3 e^{-(t_0+2T)/\tau}}}$$

Grating period
d~100 nm

Interaction time
~4-5 μs, L~10 mm

Contrast C~0.3

Atom yield $N_0>10^5$/s

Losses

Sign of g in ~1 day
overall 1% sensitivity
@ PSI

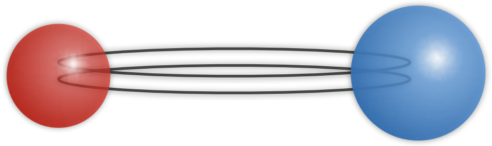
world's highest
intensity cw muons

Hadronic exotic atoms

Experimental methods depends a lot on the lifetime

Coulomb pairs

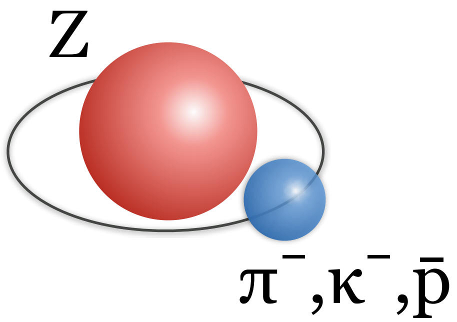
Final state interaction



lifetime: ~fs

Particle detection

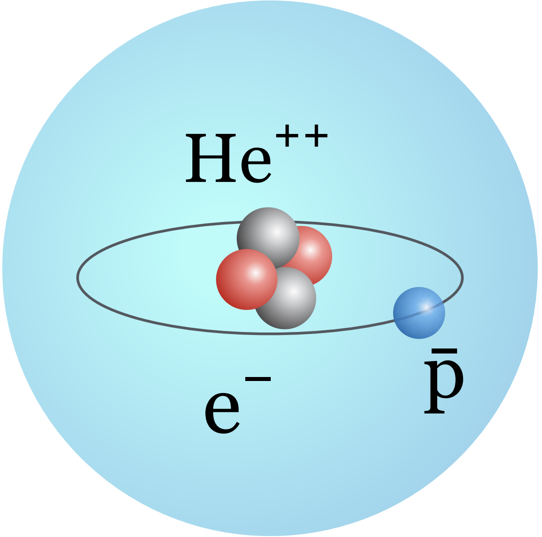
Pionic, kaonic, antiprotonic atoms



~ps → ns

X-ray detection

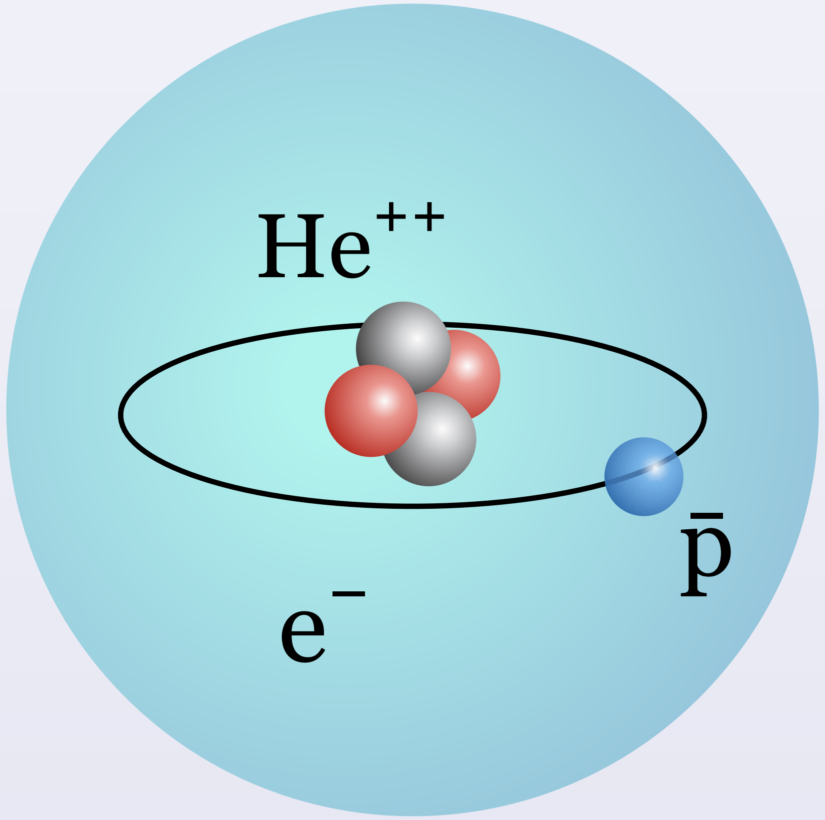
Metastable hadronic helium



~ns → us

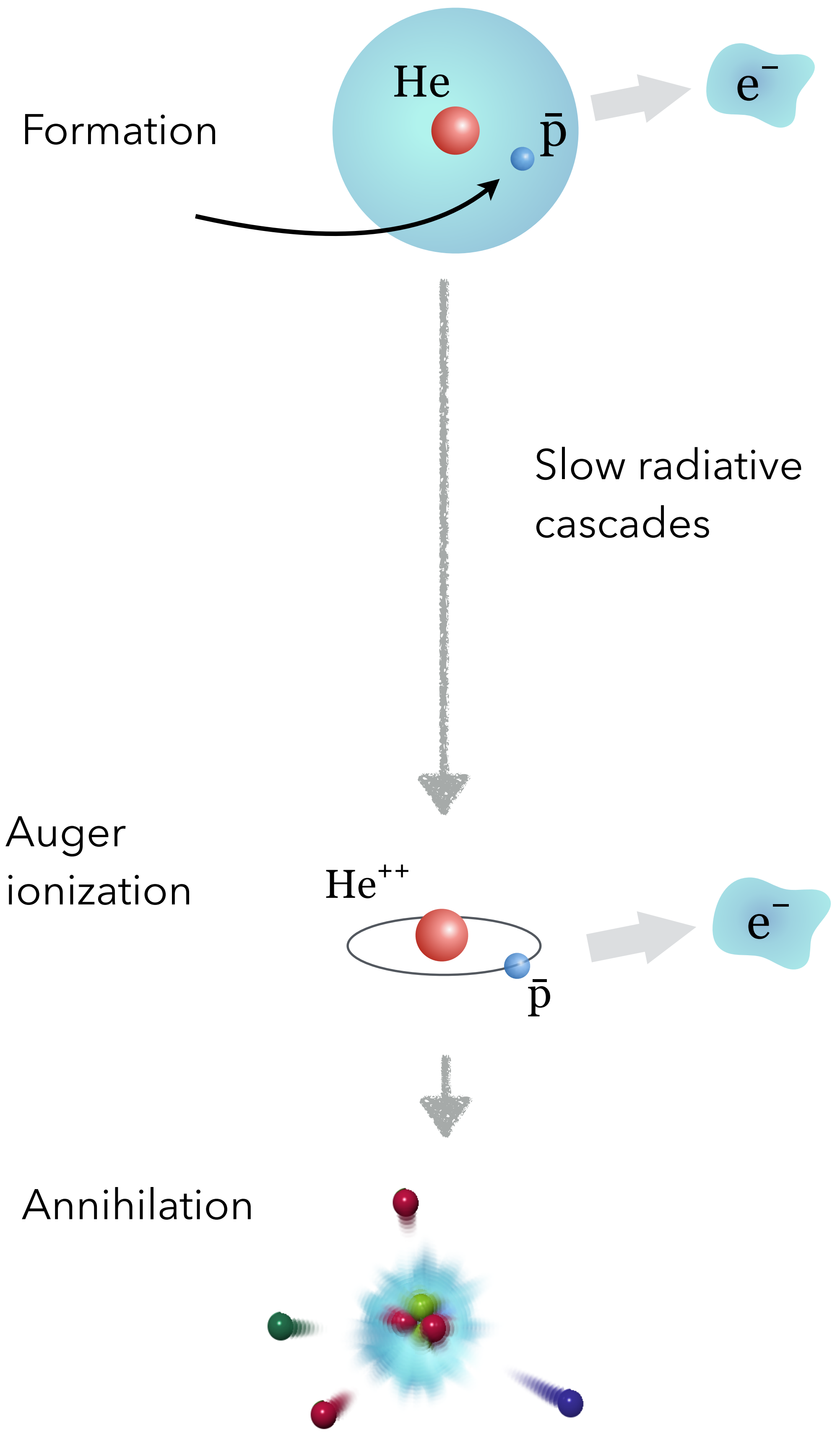
Laser spectroscopy

Antiprotonic helium



$m_{\bar{p}}/m_e$ and CPT test to ~ 8×10^{-10}

Precision laser spectroscopy of antiprotonic helium at CERN

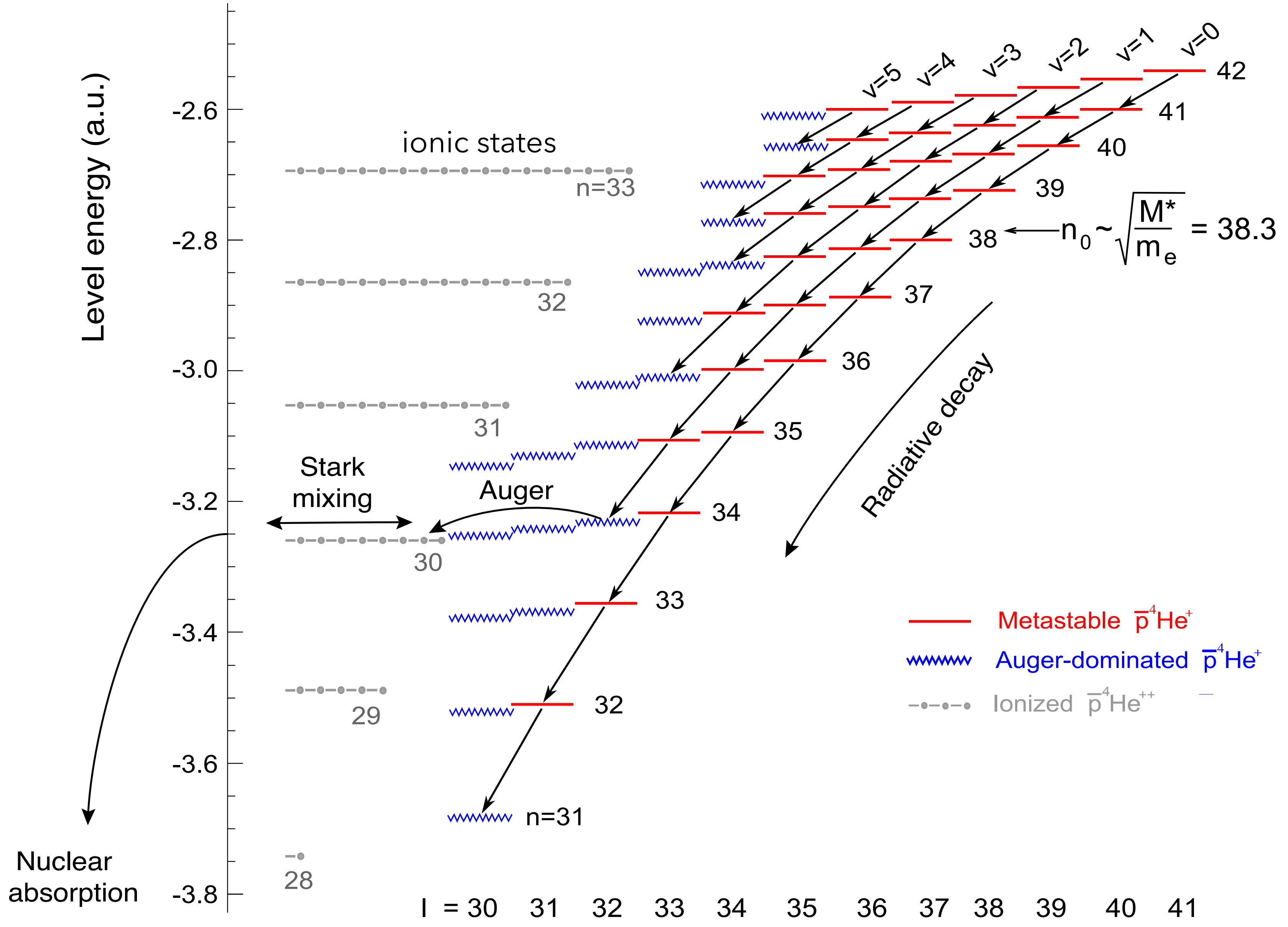


Formation

Slow radiative cascades

Auger ionization

Annihilation



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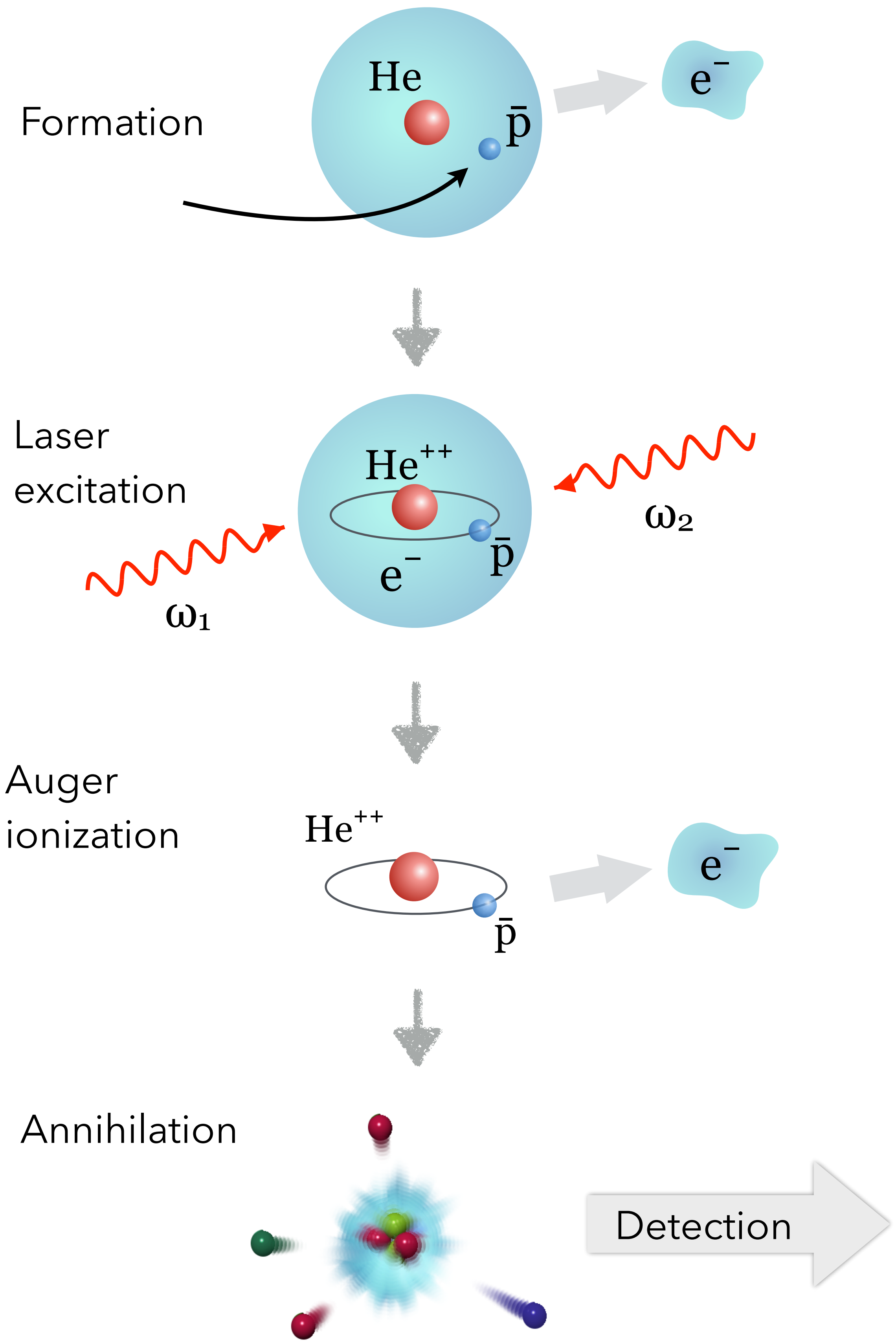
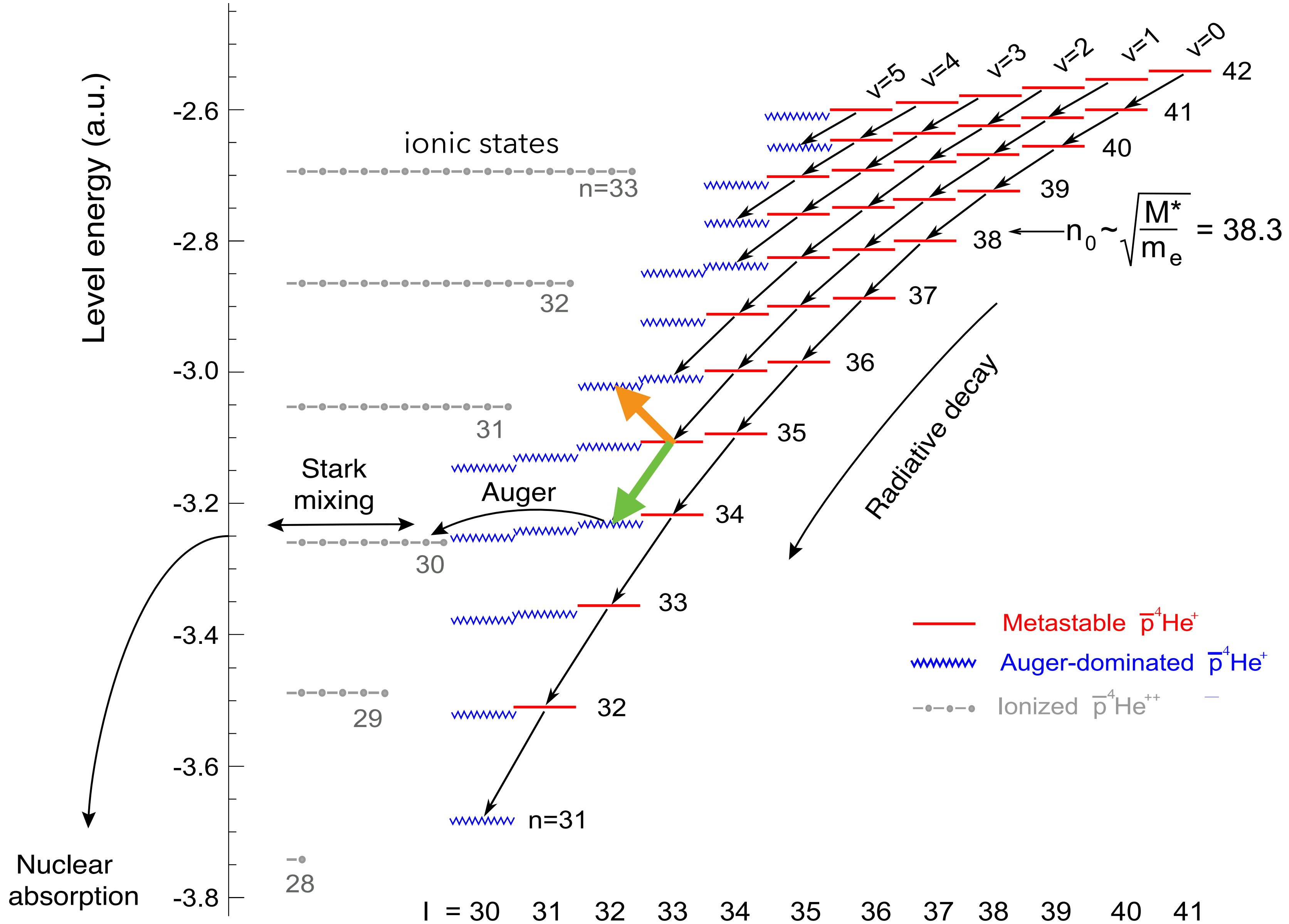

Formation

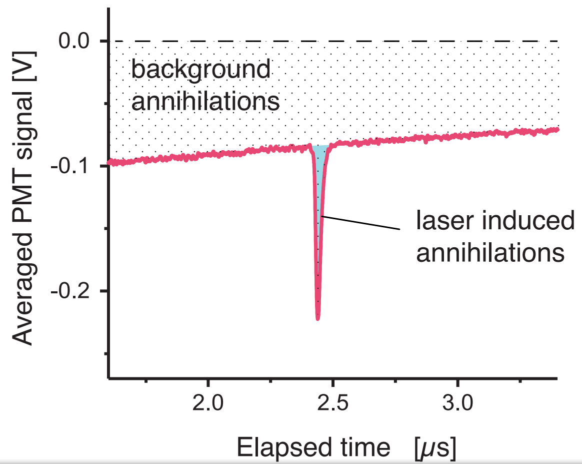
Laser excitation

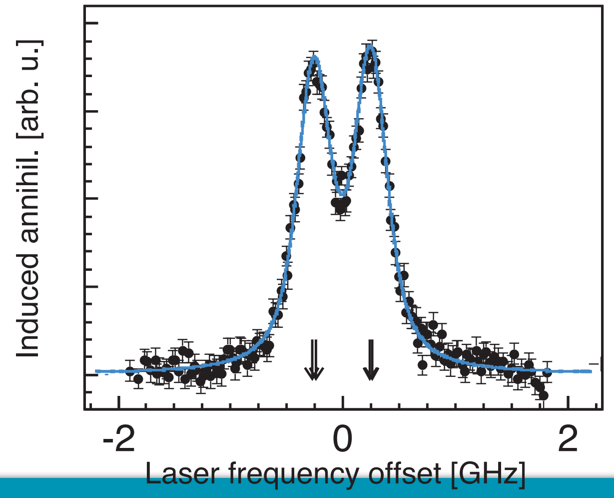
Auger ionization

Annihilation

Detection

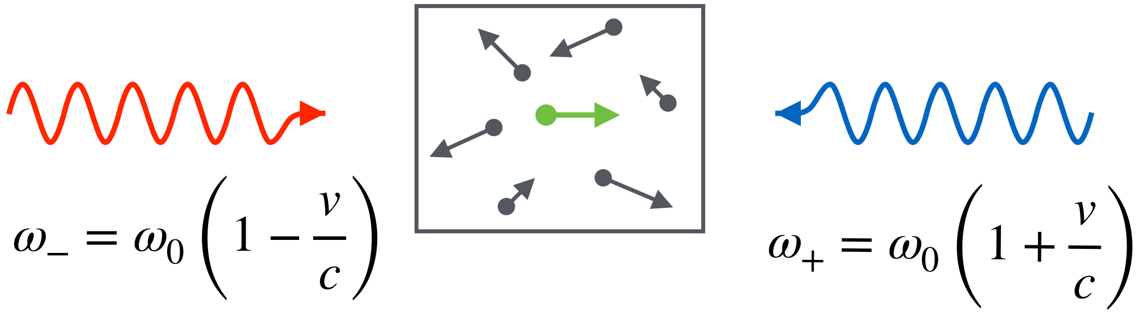




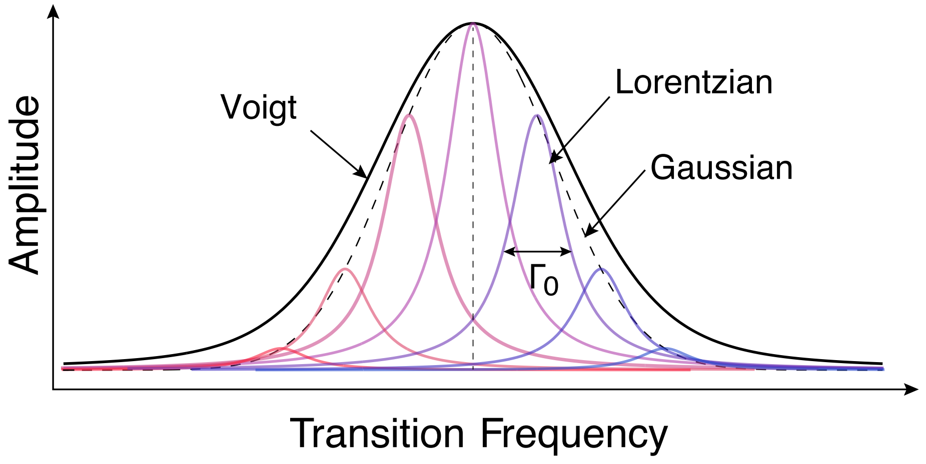


Sub-Doppler 2-photon laser spectroscopy

Doppler broadening

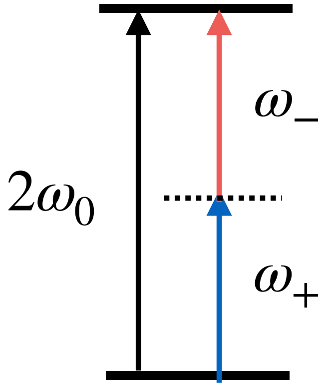


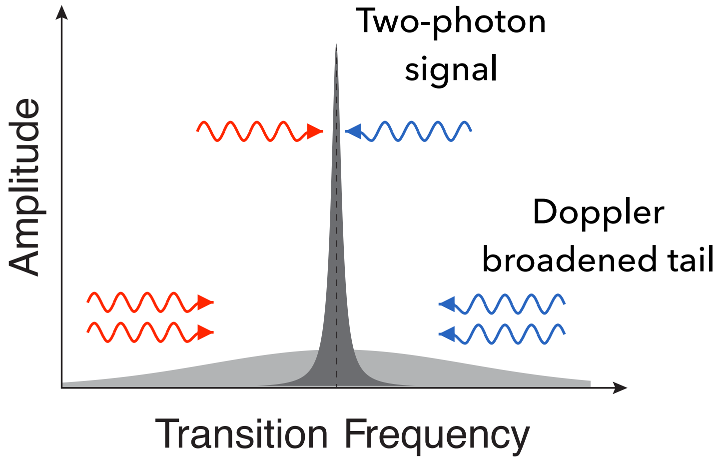
$$\omega_- = \omega_0\left(1 - \frac{v}{c}\right) \qquad \omega_+ = \omega_0\left(1 + \frac{v}{c}\right)$$



Thermal Doppler motion of atoms broadens the spectral lines.

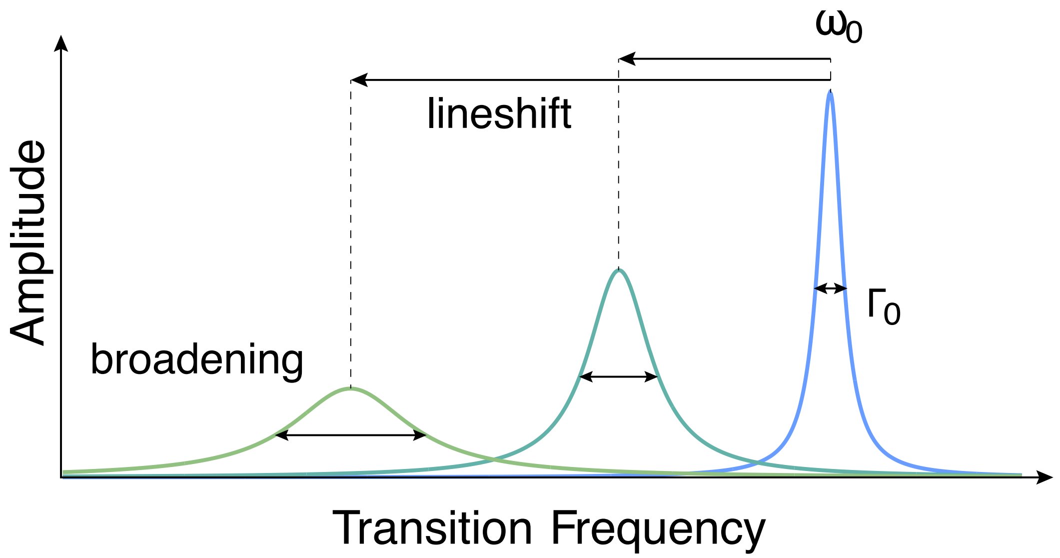
Two-photon spectroscopy





Effects of collisions and external fields

Collisions perturb the energy levels: broadening and lineshift

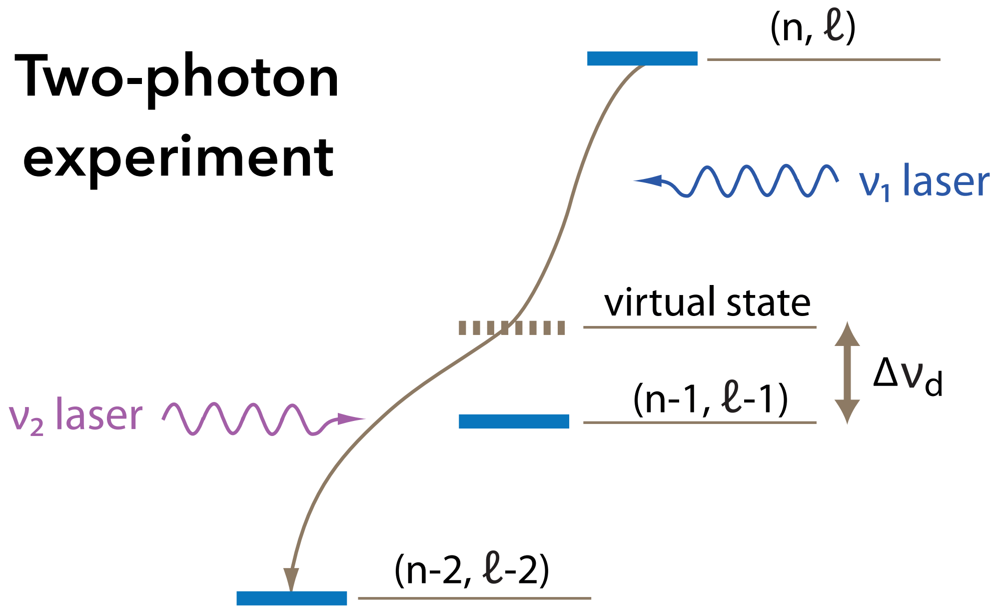


External EM fields: Stark shift,
Strong laser fields: power broadening

- Low temperature, low density
- Doppler-free spectroscopy

Doppler-reduced $\bar{p}$He spectroscopy at CERN

Two-photon experiment

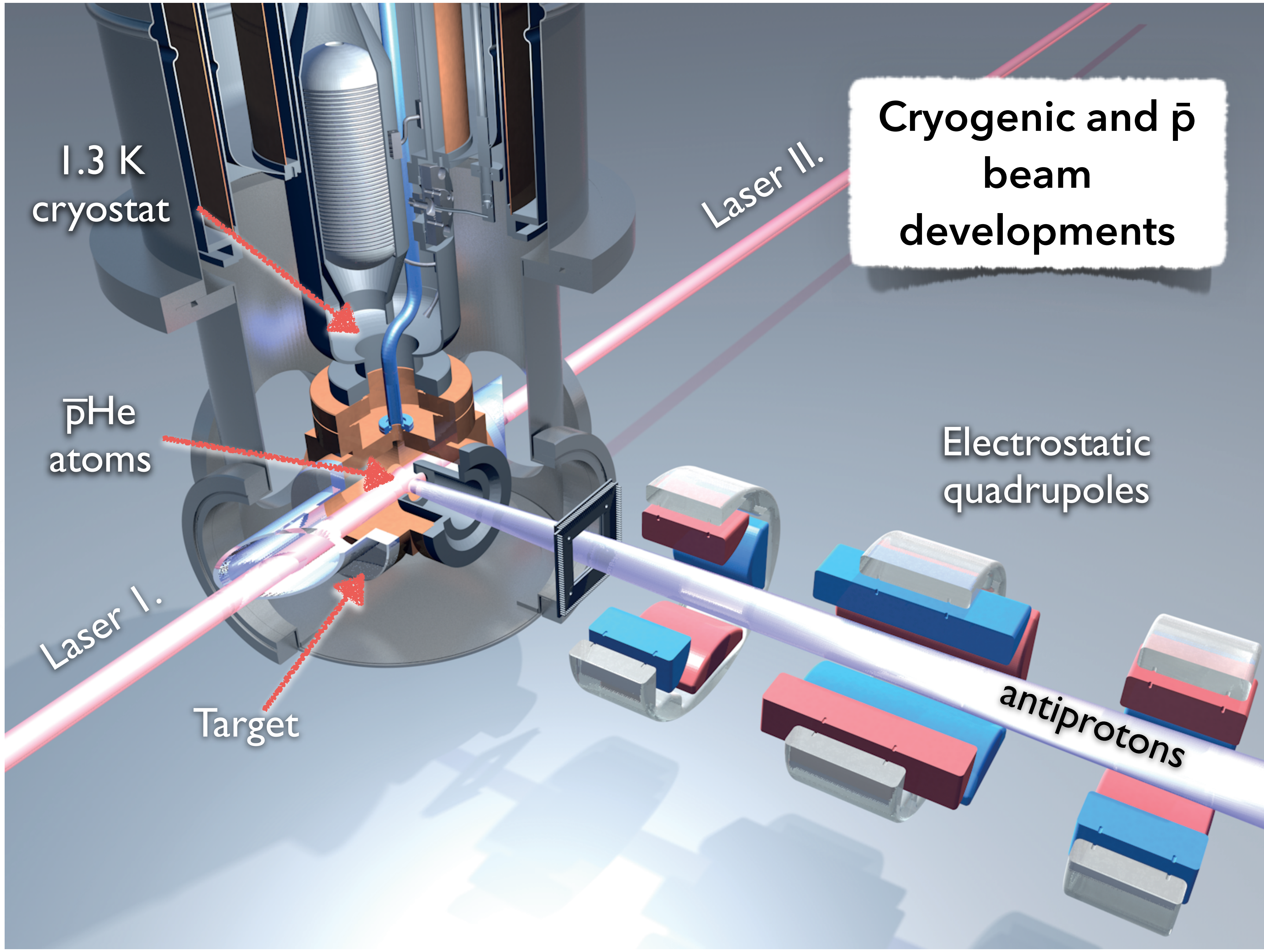


The Doppler width:

$$\Delta\nu_{\rm FWHM} = 2\sqrt{2\ln 2}\;\nu_0\sqrt{\frac{k_BT}{Mc^2}}$$

can be reduced by a factor:

$$\frac{|\nu_1-\nu_2|}{\nu_1+\nu_2}$$

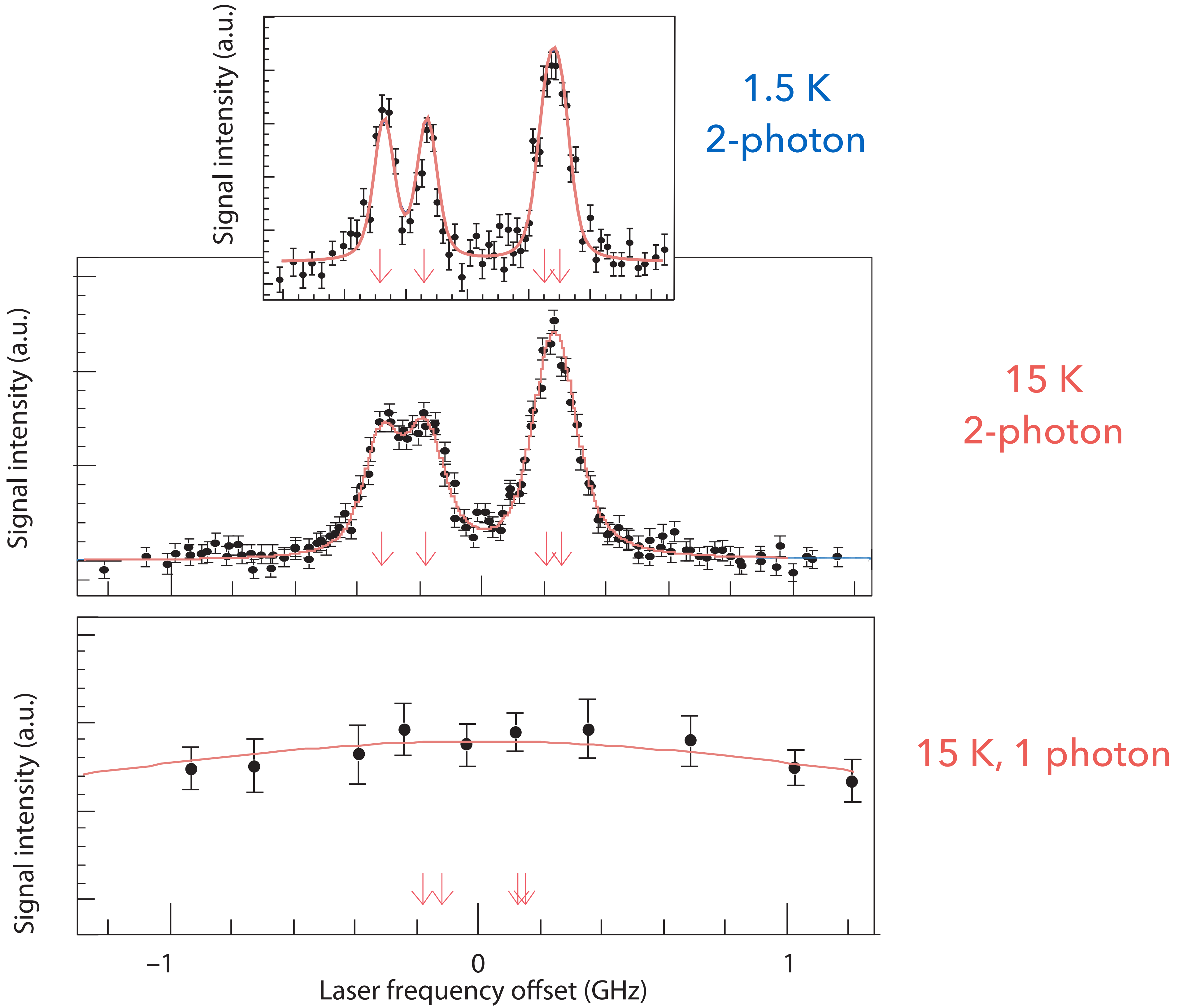


Cryogenic and $\bar{p}$ beam developments

Nature 475, 7357 (2011).

Science 354.6312 (2016).

Improvement in p̄He lineshapes over 7 years



Antiproton mass, CPT test, new phycics

$$\Delta E \approx \frac{m_{\bar{p}}}{m_e} R_\infty Q_p^2 \left(\frac{1}{n'^2} - \frac{1}{n^2}\right) + \text{3-body} + \text{QED} + \cancel{\text{hadronic}}$$

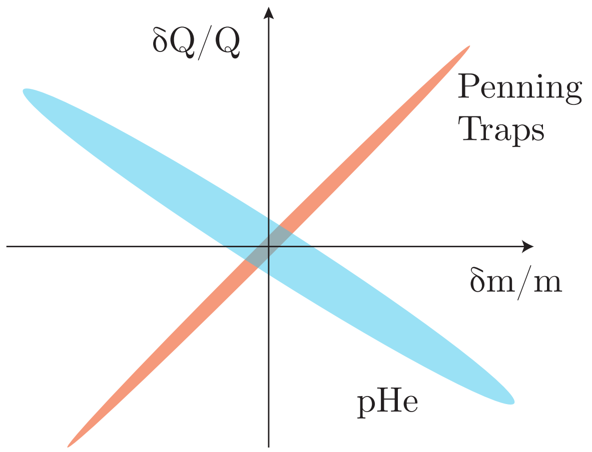
$m_{\bar{p}}/m_e = 1836.1526734\ (15)$

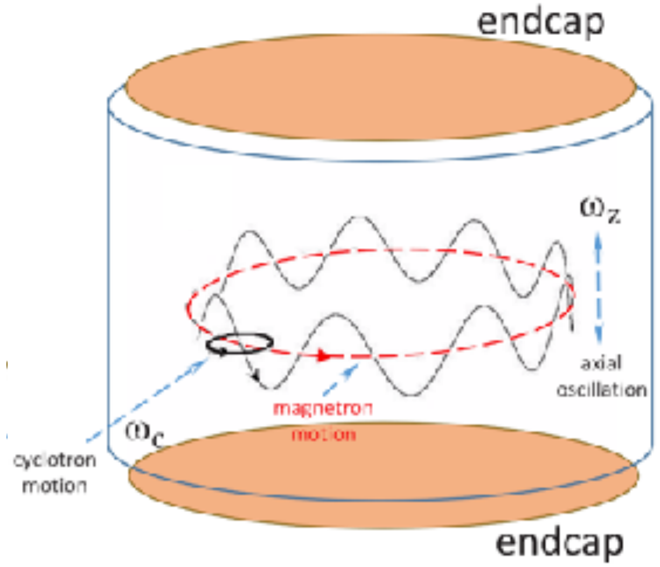
Comparison of p and p̄ mass & charge (**CPT test**) with trap results to 5 × 10^{-10}

p̄He⁺ transiton: $\omega_0 \sim m_{\bar{p}} Q_{\bar{p}}^2$ $\qquad \frac{\delta m_{\bar{p}}}{m_{\bar{p}}} = -2\frac{\delta Q_{\bar{p}}}{Q_{\bar{p}}}$

Penning trap: $\omega_c \sim Q_{\bar{p}}/m_{\bar{p}}$ $\qquad \frac{\delta m_{\bar{p}}}{m_{\bar{p}}} = \frac{\delta Q_{\bar{p}}}{Q_{\bar{p}}}$

S. Ulmer, Nature, 524,(2015)





Assuming CPT, **m_e** to rel. precision 8 × 10^{-10} $\qquad \frac{m_e}{m_{\bar{p}}} \cdot \frac{m_p}{m_C}$

Best result from trap: 3 × 10^{-11} frac. precision

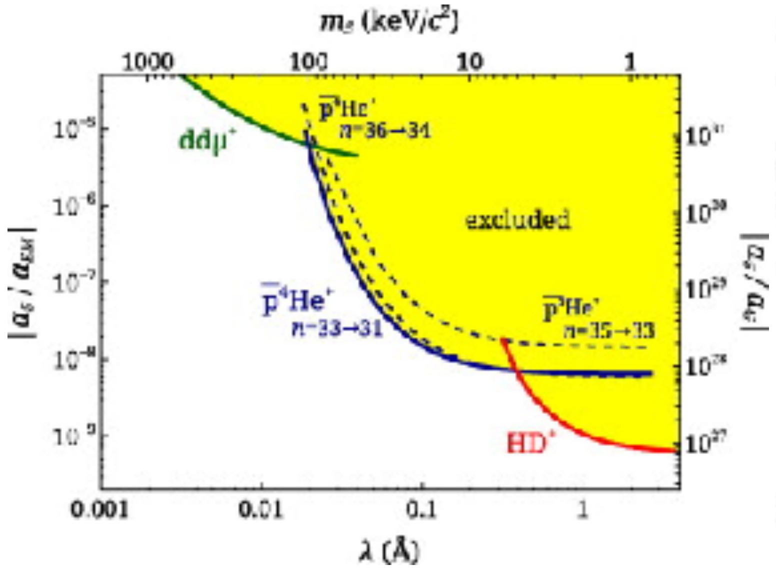
Sturm *et al.* Nature 2014

Constrain on exotic forces

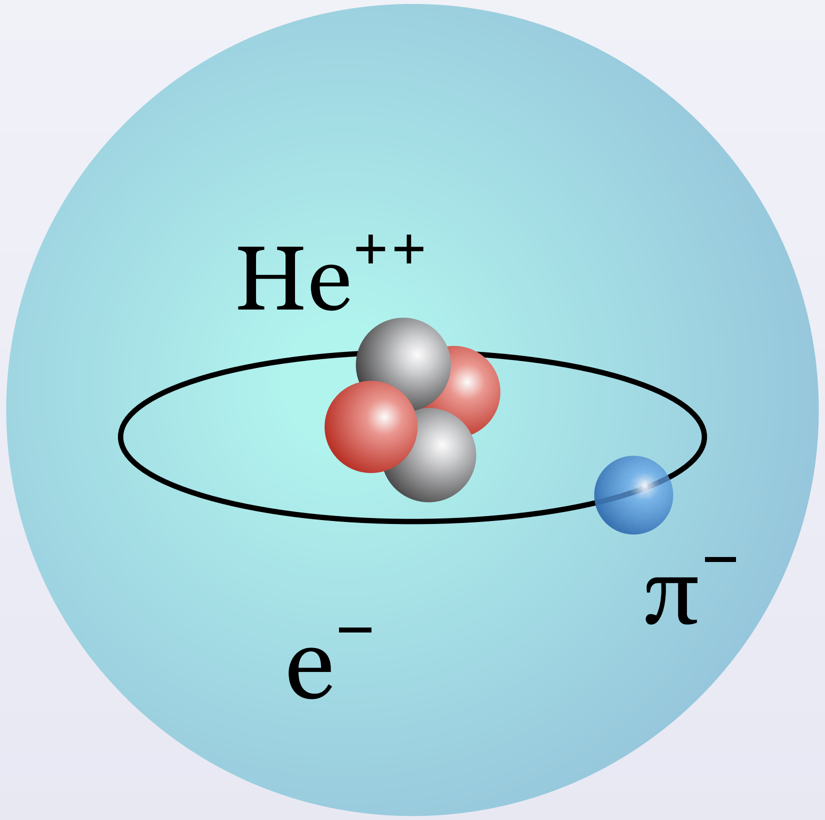
- fifth forces on sub-angstrom length scales

PRL 120, (2018)

J. Mol. Spect. 300, 65 (2014)

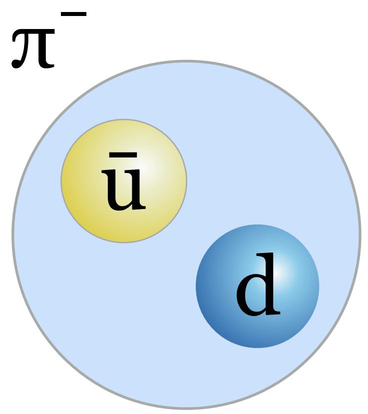


Pionic helium



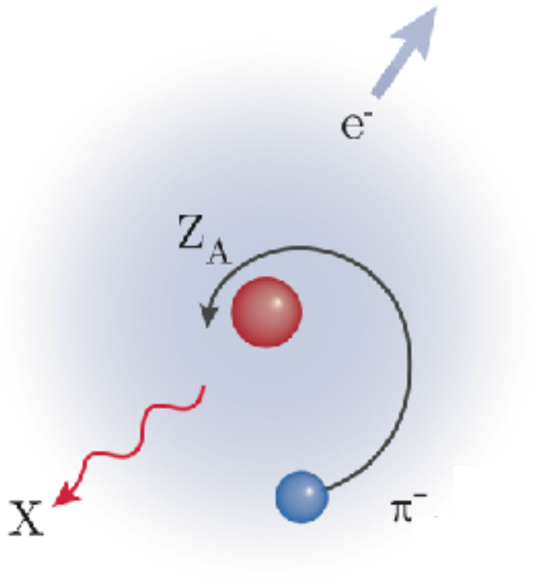
m_π/m_e to 10 ppb

Pionic atoms



Pion: simplest (lightest) hadronic system

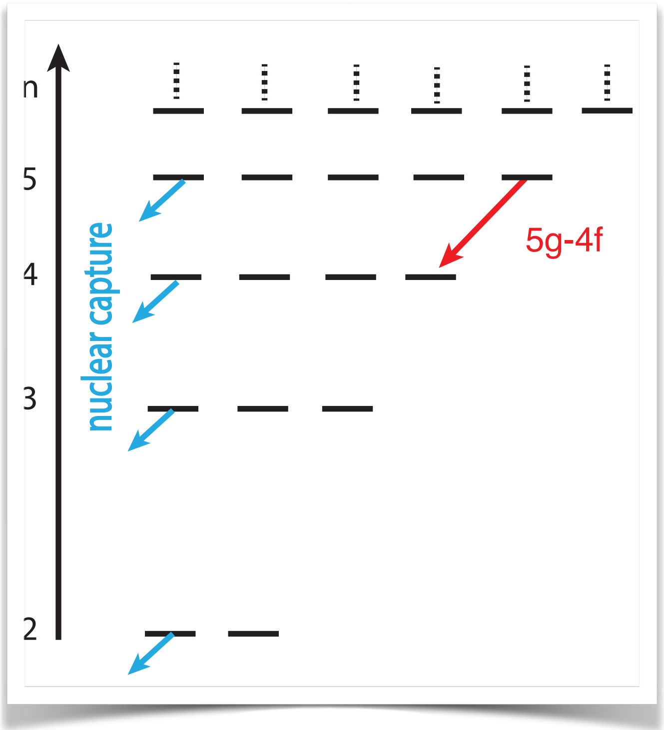
Mediates the nuclear force at low energy



Forms short lived exotic atoms, ending up in the nucleus after fast cascades

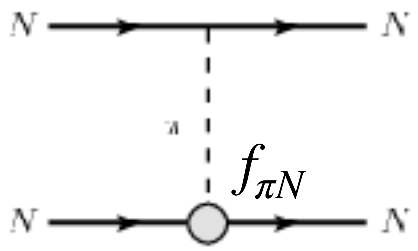
$$E \simeq \frac{m_\pi}{m_e} R_\infty Z^2 \left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) + \mathrm{QED} - c_1 |\Psi_{nl}(0)|^2 a_{\pi A}$$

Medium n, l=n-1

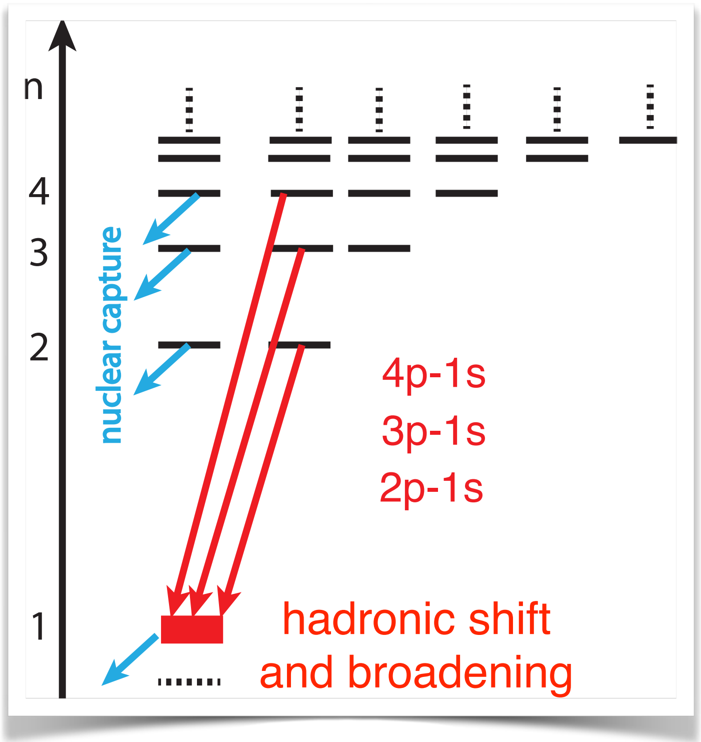


Pion mass determination

Pion-nucleon coupling constant

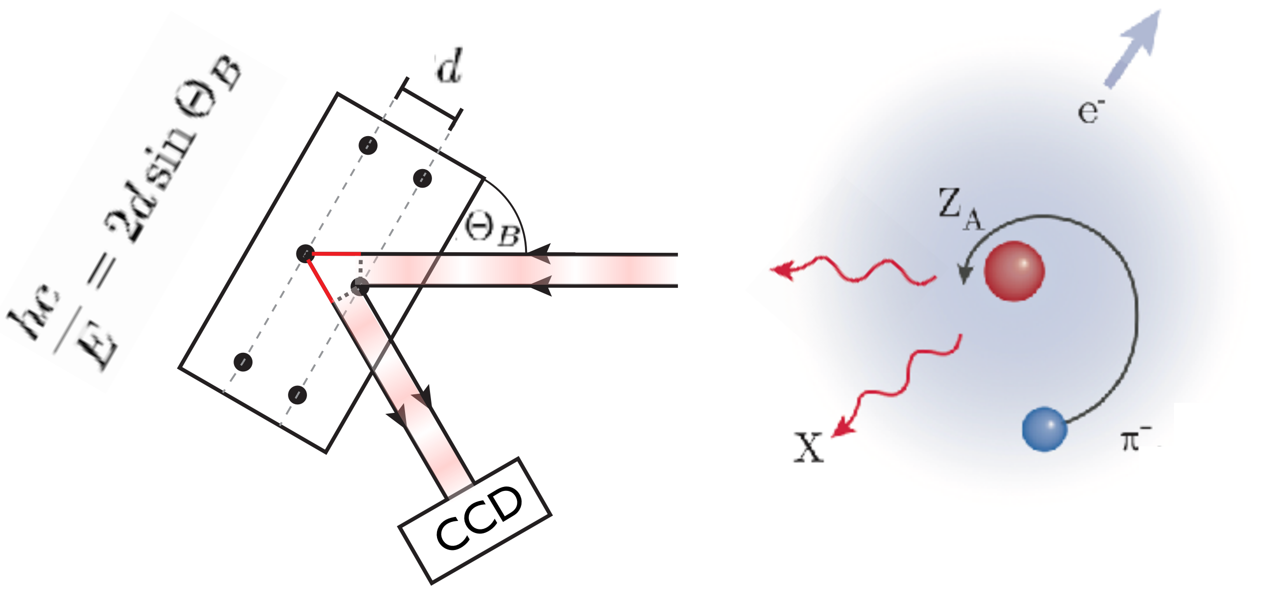


Low n (np to 1s)

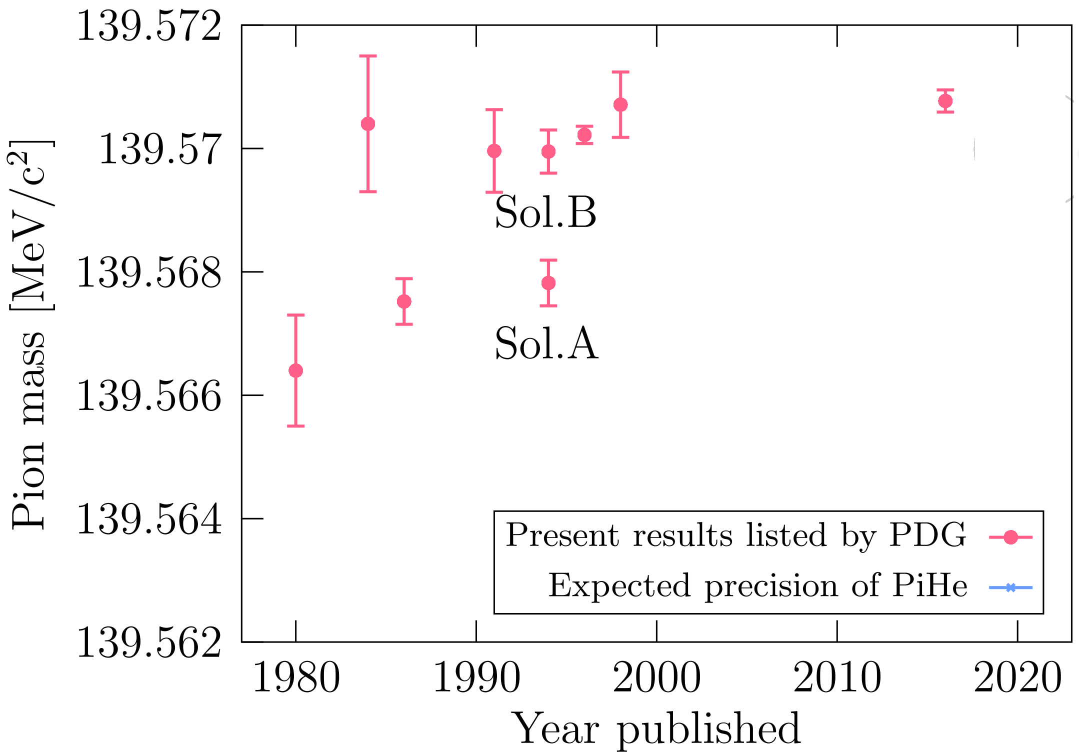


Measurement of the pion mass

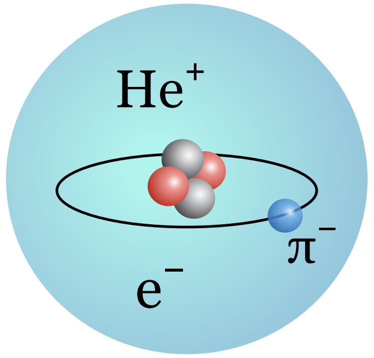
Pion mass from pionic X-rays



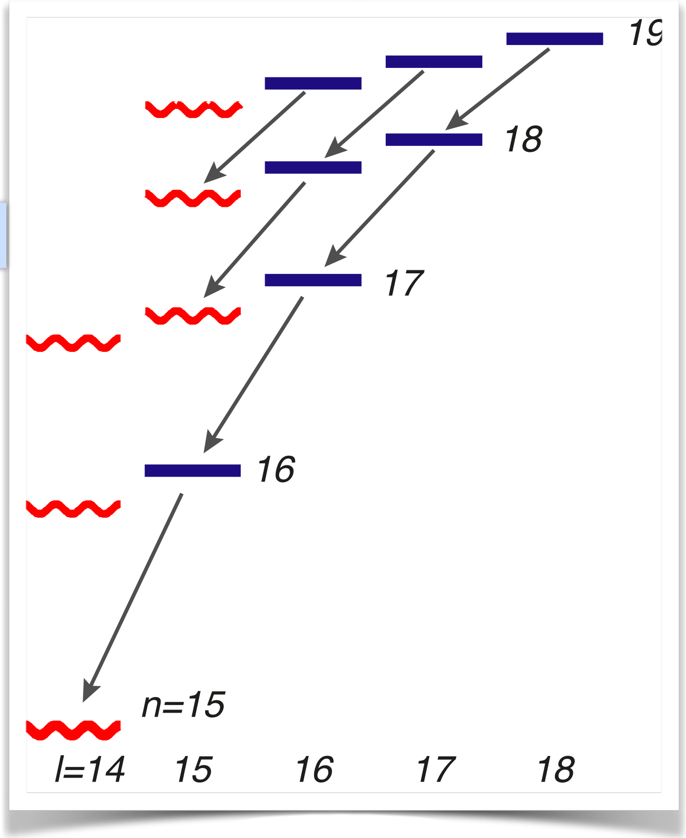
Method: Bragg spectroscopy and calibration with muonic atoms.
Limited to few ppm



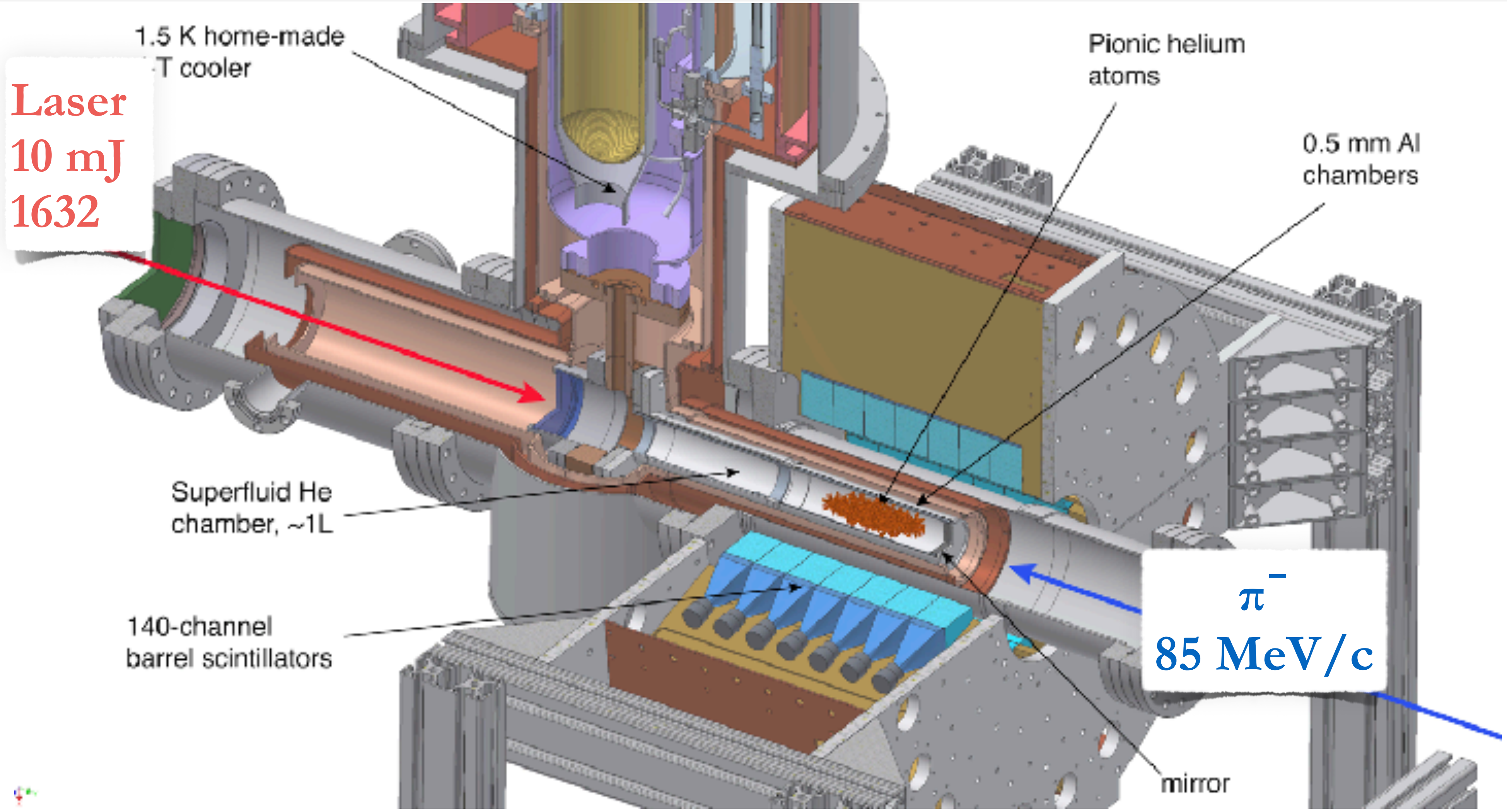
Laser spectroscopy?

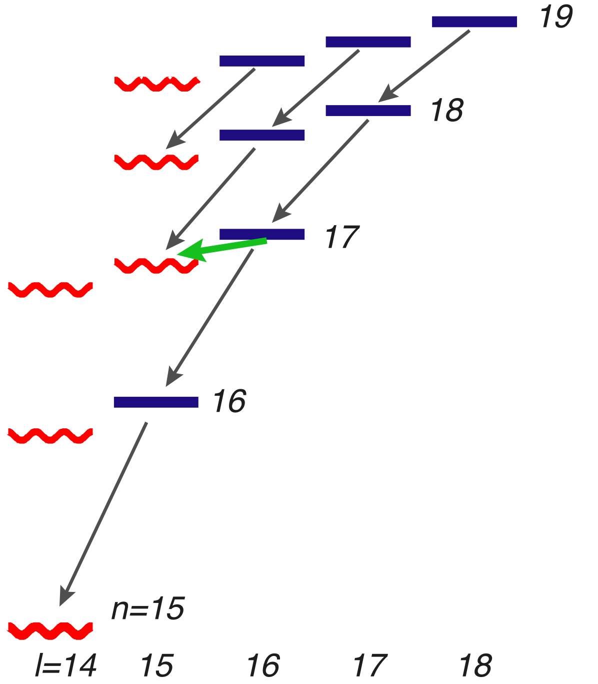


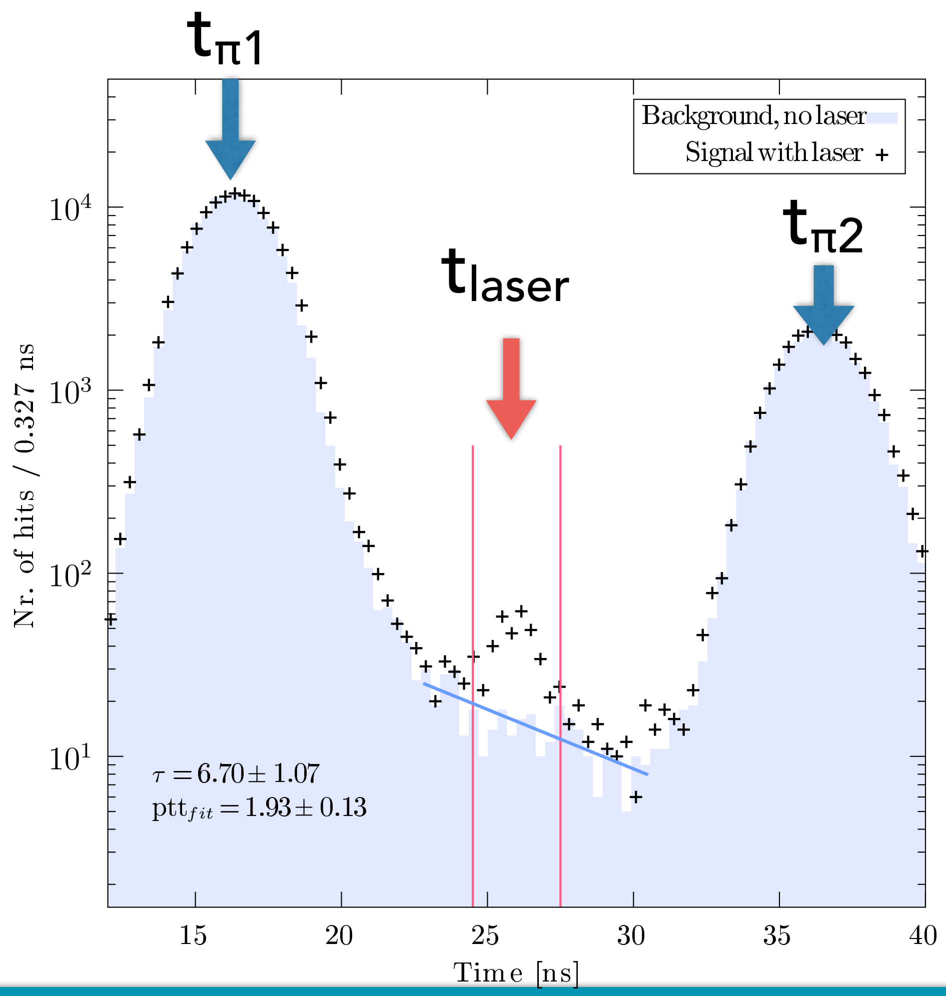
Lifetime already bad (26 ns), and needs the existence of metastable states



Pionic helium spectroscopy experiment at PSI

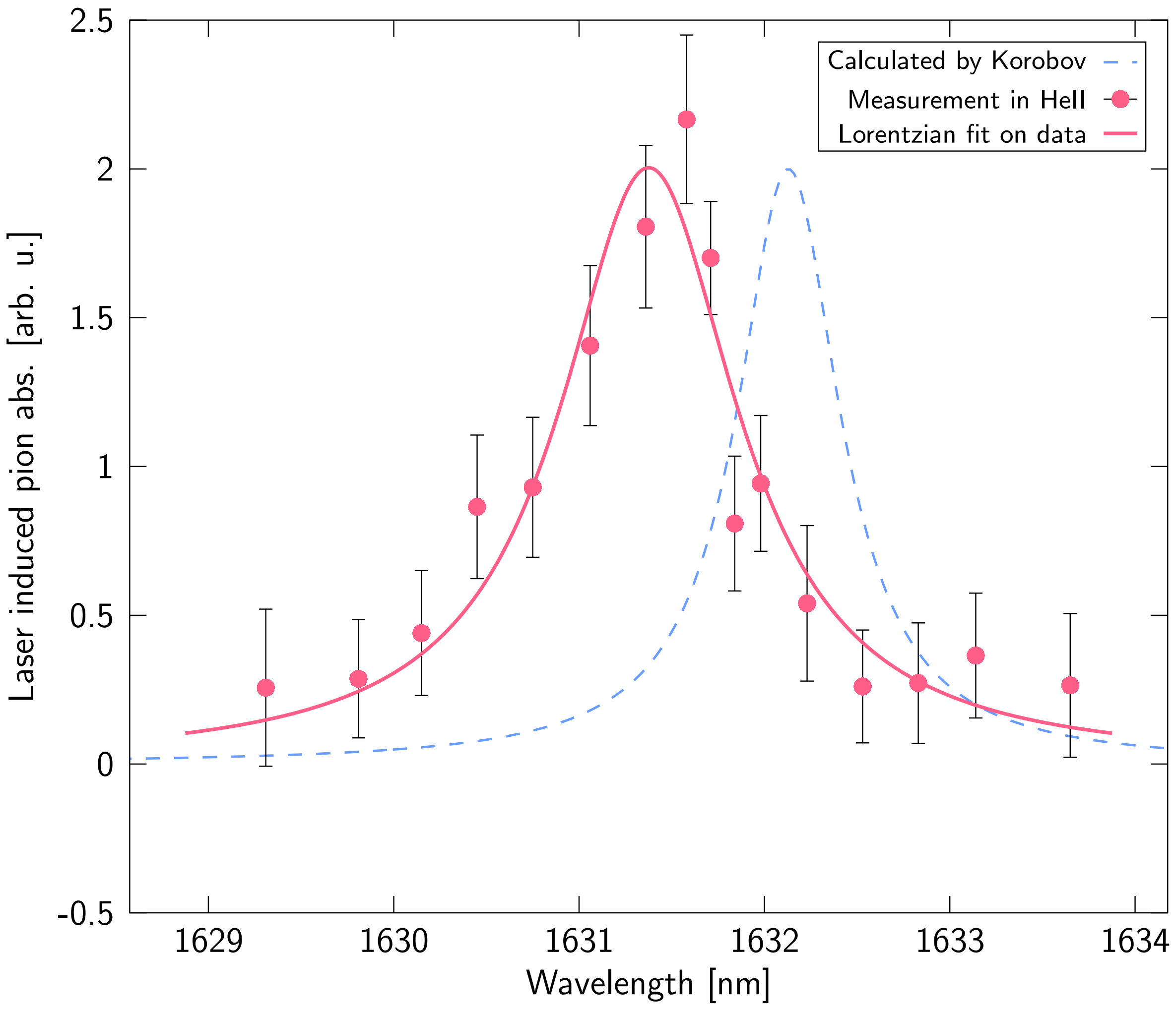


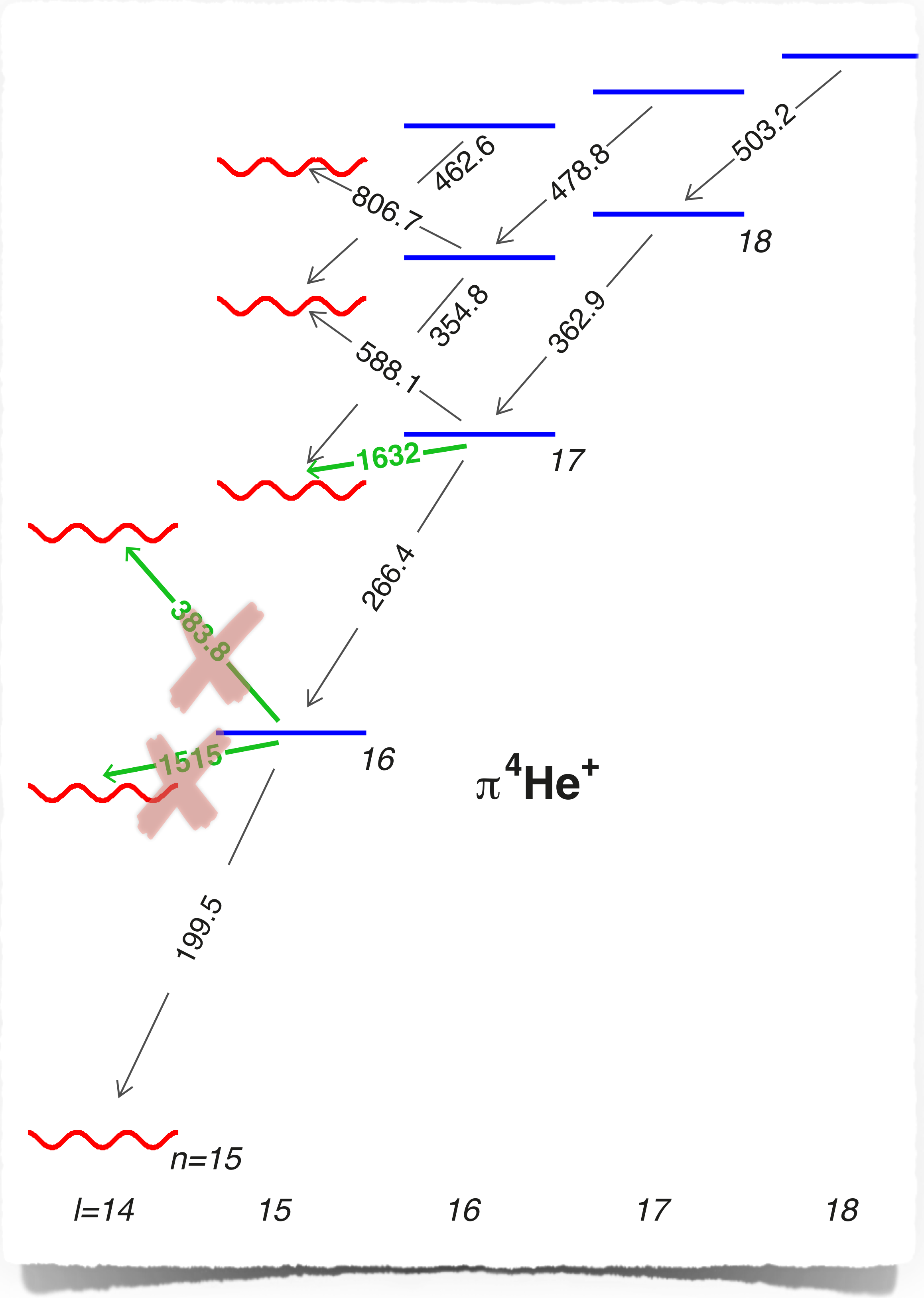




- Bunched pion beam stopped in LHe target
- Drive transition between metastable to short-lived (7 ns)
- Measure laser-induced pion absorption (low energy nuclear fragments, including neutrons)
- Plot number of nuclear absorption events vs laser frequency

First laser excitation of a mesonic atom





- three transitions tried - **one found**! (17, 16)→(17,15)
- Next steps: repeating experiment in low density targets
- find narrow **narrow transition** (17, 16)→(16,15)

(Accepted by Nature)