Low energy precision physics - future opportunities

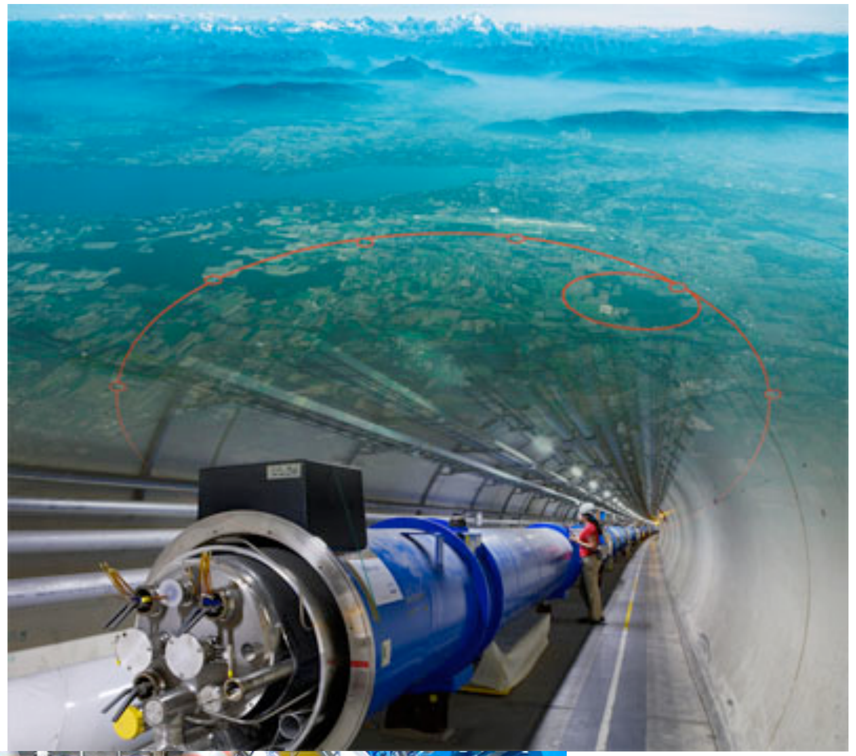
E. Widmann

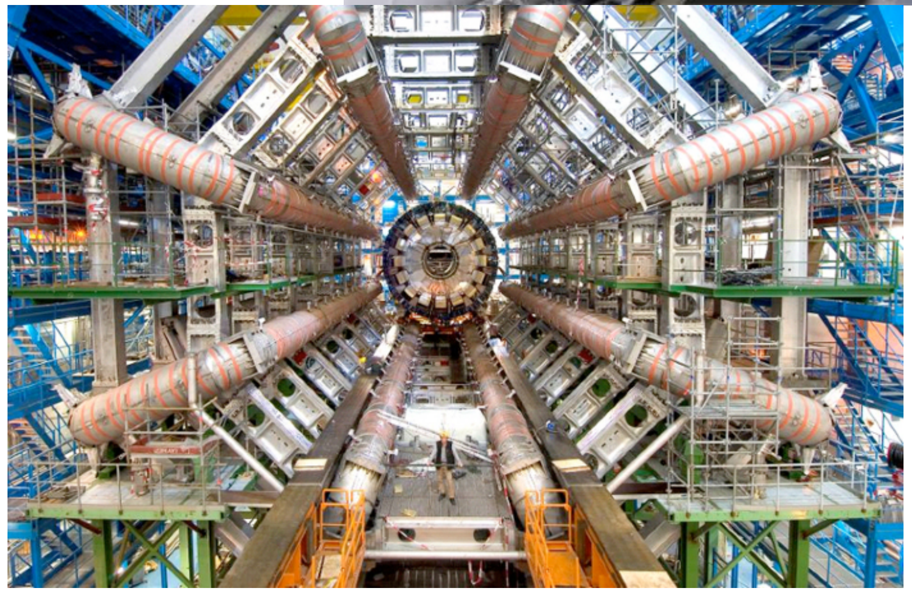
Stefan Meyer Institute for subatomic Physics, Vienna

Early Career Researchers in Particle Physics in Austria
HEPHY, 23 May 2024

New knowledge in subatomic physics

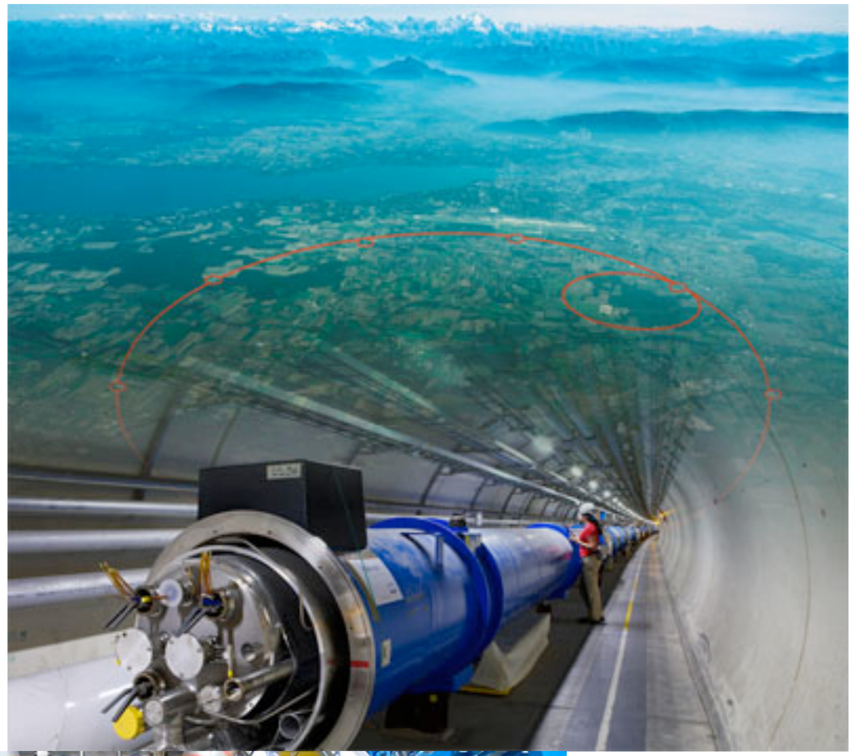
- High energies
  - *Direct observation*

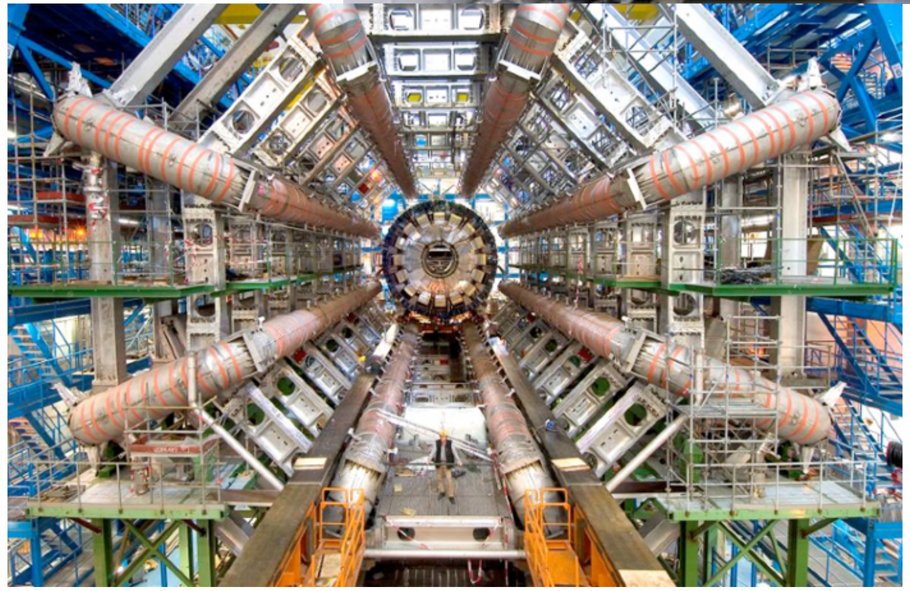




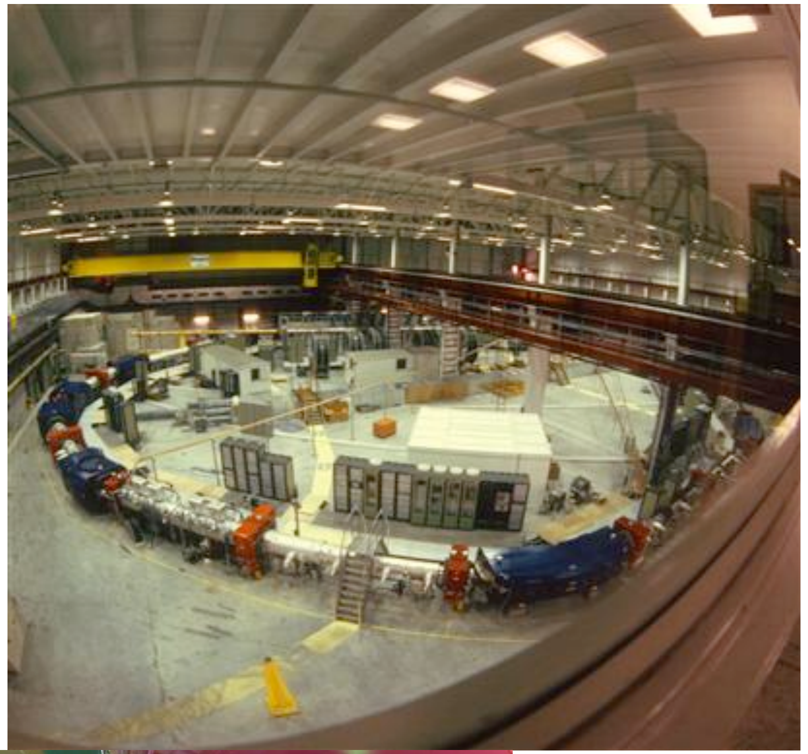
New knowledge in subatomic physics

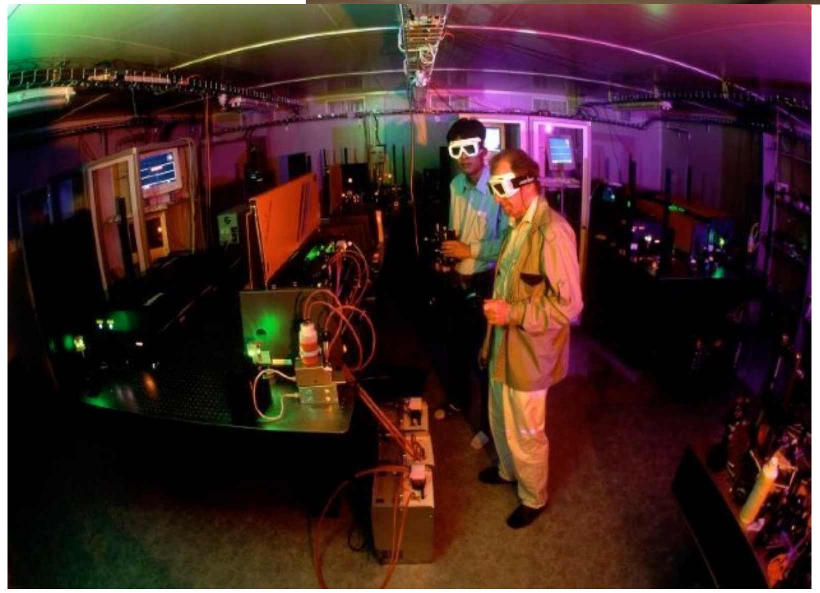
- High energies
  - *Direct observation*





- Low energies
  - *Precision experiments*





Low energy precision experiments to study SM

- Selected topics from LRP www.nupecc.org
  - CP
    - EDMs: P, T (*CP assuming CPT is conserved*)
      - n: θ-*term*, e: *SM CP, SUSY*, p, μ
    - Radioactive molecules (ISOLDE)
    - Beta decay
  - CPT and Lorentz invariance
    - CERN-AD/ELENA
    - Thorium clock (*stability of fund. constants*)
  - Neutrinoless double ß decay
  - Particle masses: π^{-}He, K^{-}He

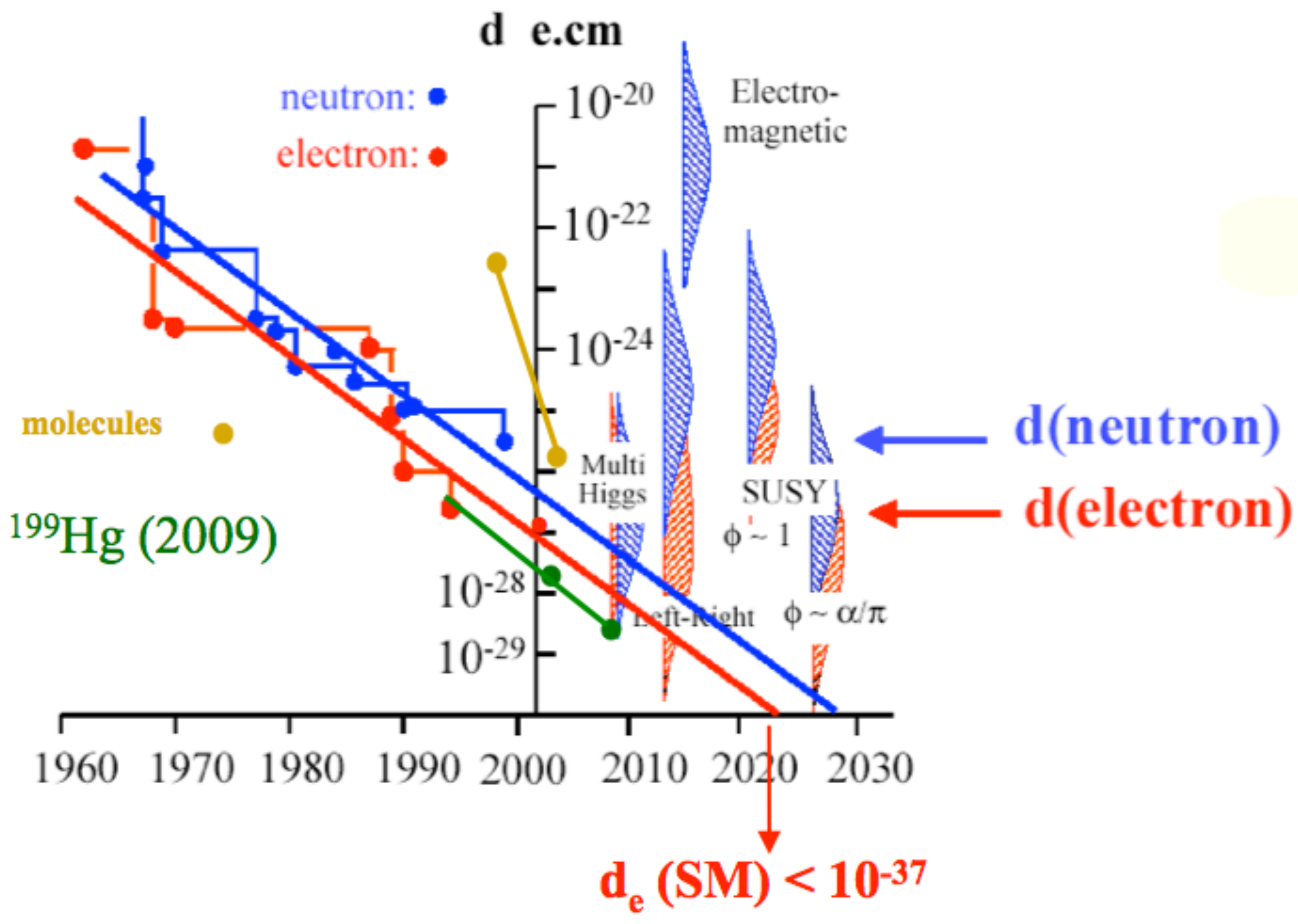
Low energy precision experiments to study SM

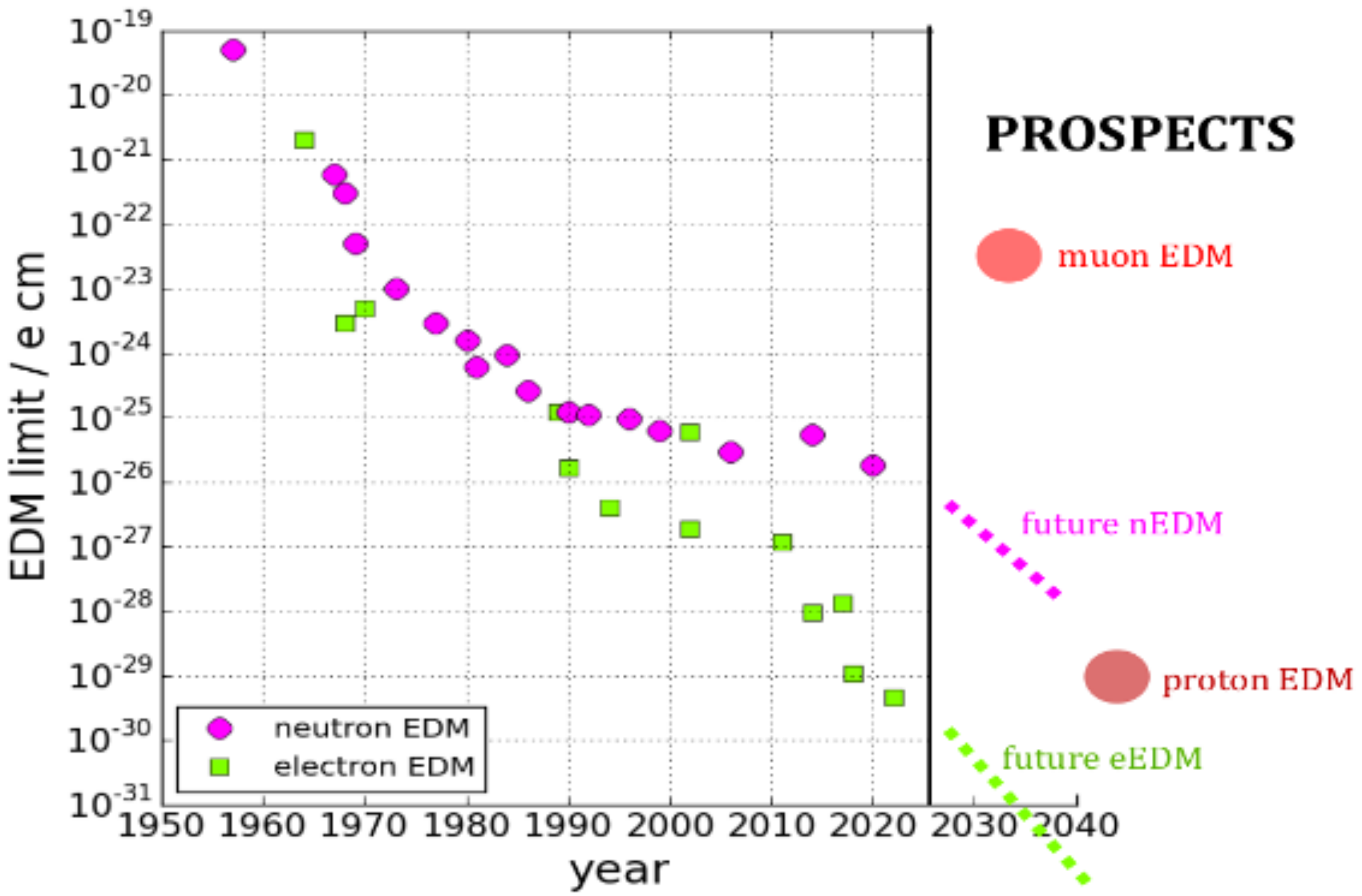
- Broad variety of experiments: NuPECC Long Range Plan, to appear in fall 2024
- Tools (**AT**)
  - Exotic atoms:
    - $\overline{\text{H}}$, Mu, Ps: QED and fundamental symmetries, gravity of antimatter
    - Hadronic atoms: low-energy QCD
  - Ordinary atoms **H, D**:
    - LIV → CPT
    - Short-range forces
  - Cold and ultra-cold **neutrons** (H. Abele ATI)
    - weak interaction, CKM, modified gravity

- Selected topics from LRP www.nupecc.org
  - CP
    - EDMs: P, T (*CP assuming CPT is conserved*)
      - n: *θ-term*, e: *SM CP, SUSY*, p, μ
    - Radioactive molecules (ISOLDE)
    - Beta decay
  - CPT and Lorentz invariance
    - CERN-AD/ELENA
    - Thorium clock (*stability of fund. constants*)
  - Neutrinoless double ß decay
  - Particle masses: π^{-}He, K^{-}He

Electric dipole moments

NuPECC LRP 2024 ch. 5
Fundamental interactions
and symmetries
(preliminary)

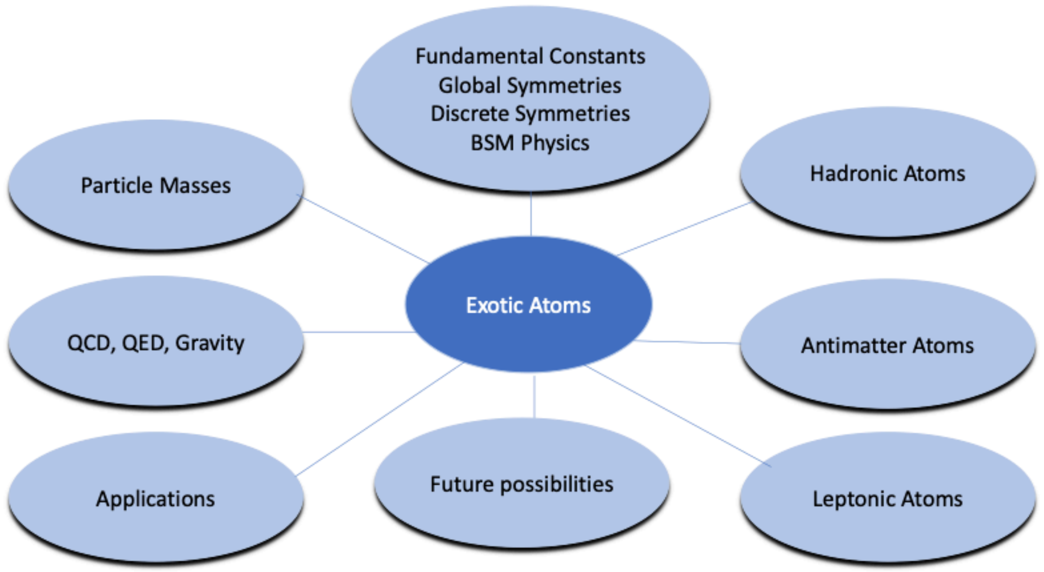




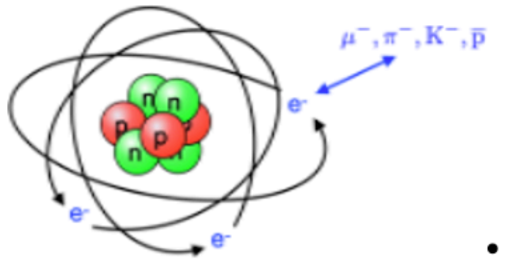
Box 2: Exotic Atoms: unique probes of the Standard Model and Beyond

NuPECC LRP 2024 ch. 5 Fundamental interactions and symmetries (preliminary)

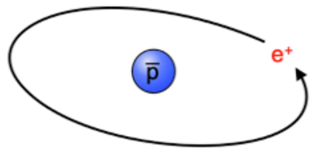
Exotic atoms offer a unique and complementary approach to extracting fundamental constants, testing all known interactions including the validity of the weak equivalence principle for antimatter, searching for new physics while probing fundamental symmetries. Recent years have witnessed an impressive progress in the field of exotic atoms driven by the development of improved beamlines and trapping techniques, manipulation of the constituent particles, quantum logic spectroscopy, and tremendous advancement of technology (e.g. lasers, microcalorimeters, etc.). The next decade promises great prospects for this multidisciplinary research area, which merges different fields such as nuclear, atomic, particle, laser, quantum information and plasma physics.



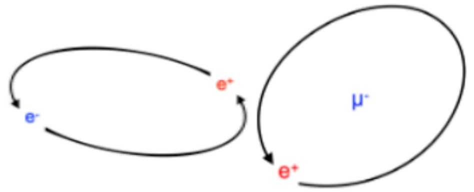
What are exotic atoms? Ordinary atoms: positive nucleus which interacts electromagnetically with e^-
Exotic Atoms: replace at least one of the two



- an e^- replaced by any **negatively** charged particle (muonic, pionic, kaonic and anti- proton atoms)



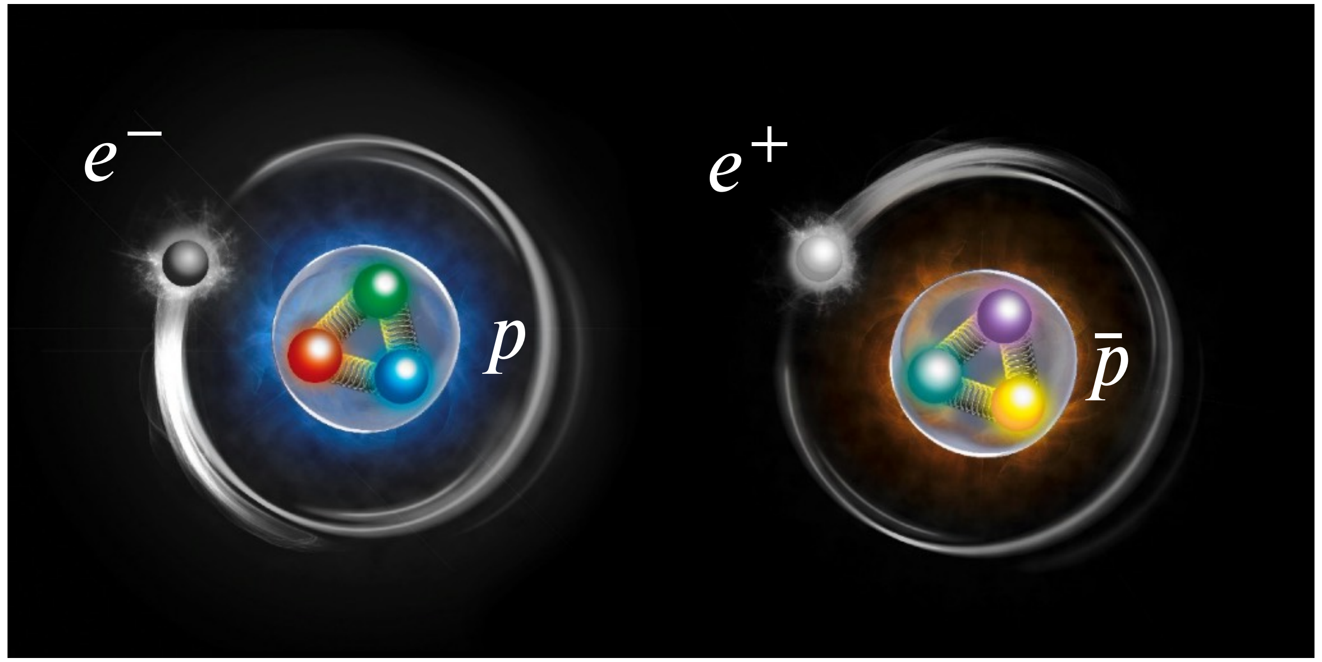
- **negative nucleus** and positive orbiting particle (anti-hydrogen)



nucleus replaced by a **positive** particle (e^+e^- positronium (Ps), μ^+e^- muonium

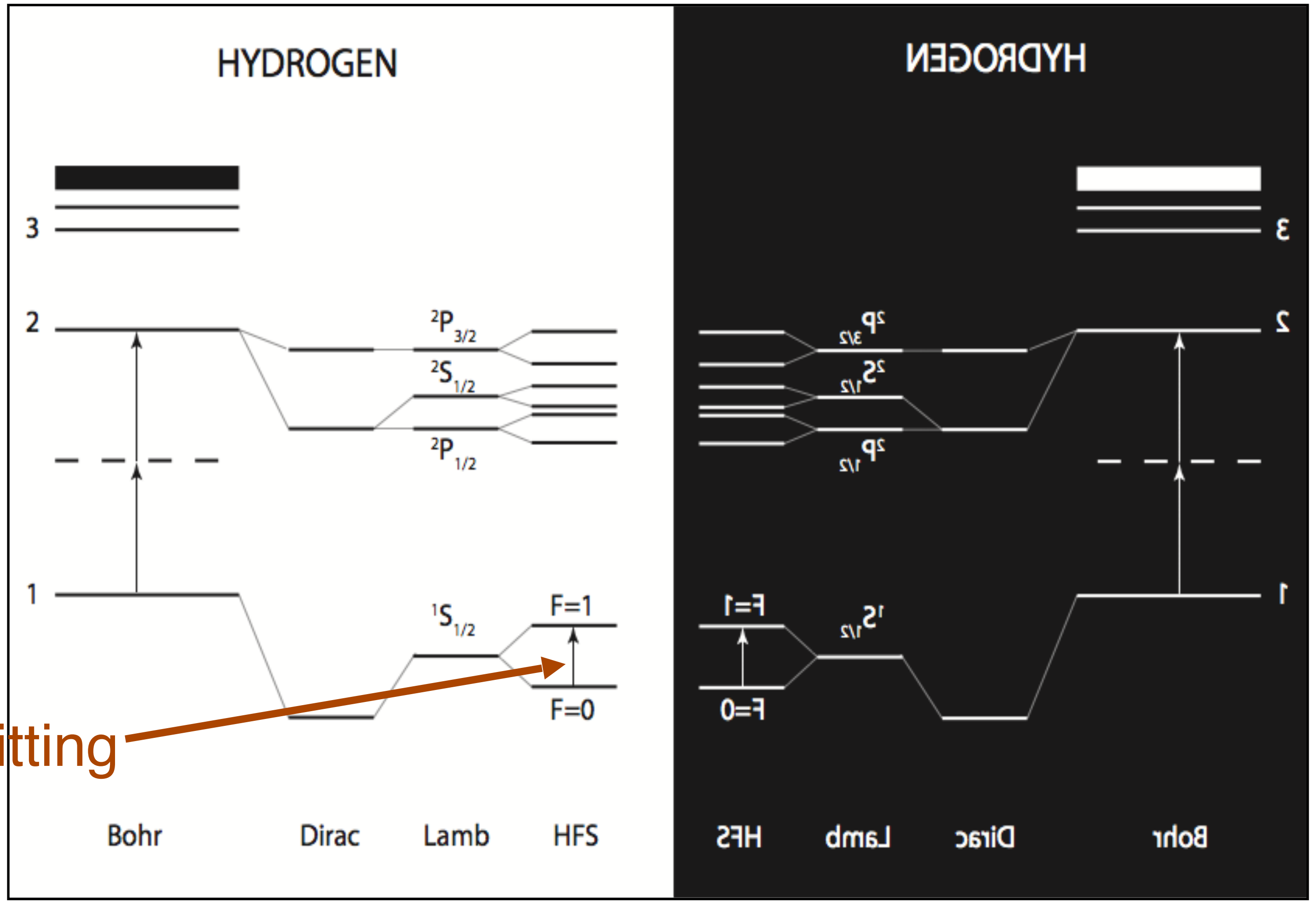
Antihydrogen experiments motivation

- Matter-Antimatter Symmetry
  - Charge conjugation-Parity-Time reversal: CPT
  - CPTV points to BSM physics



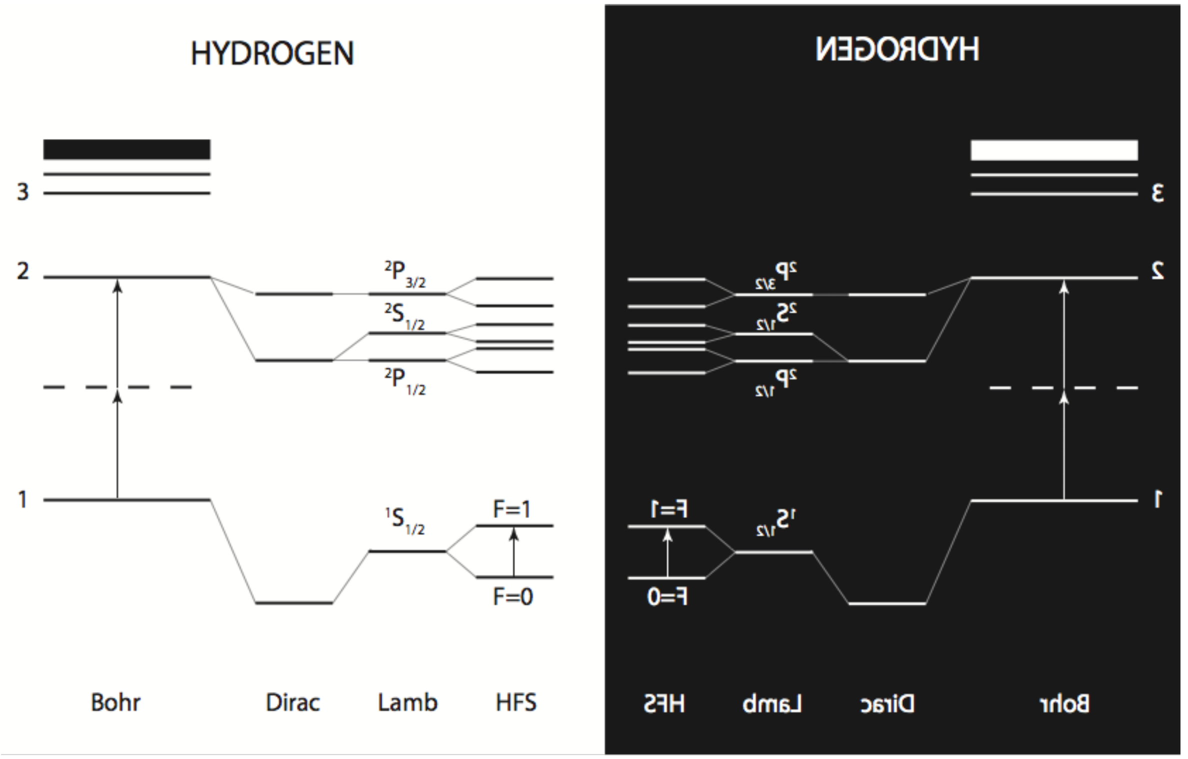
1s-2s
2 photon
λ=243 nm
Δf/f=10⁻¹⁴

Ground state hyperfine splitting
f = 1.4 GHz
Δf/f=10⁻¹²



Antihydrogen experiments

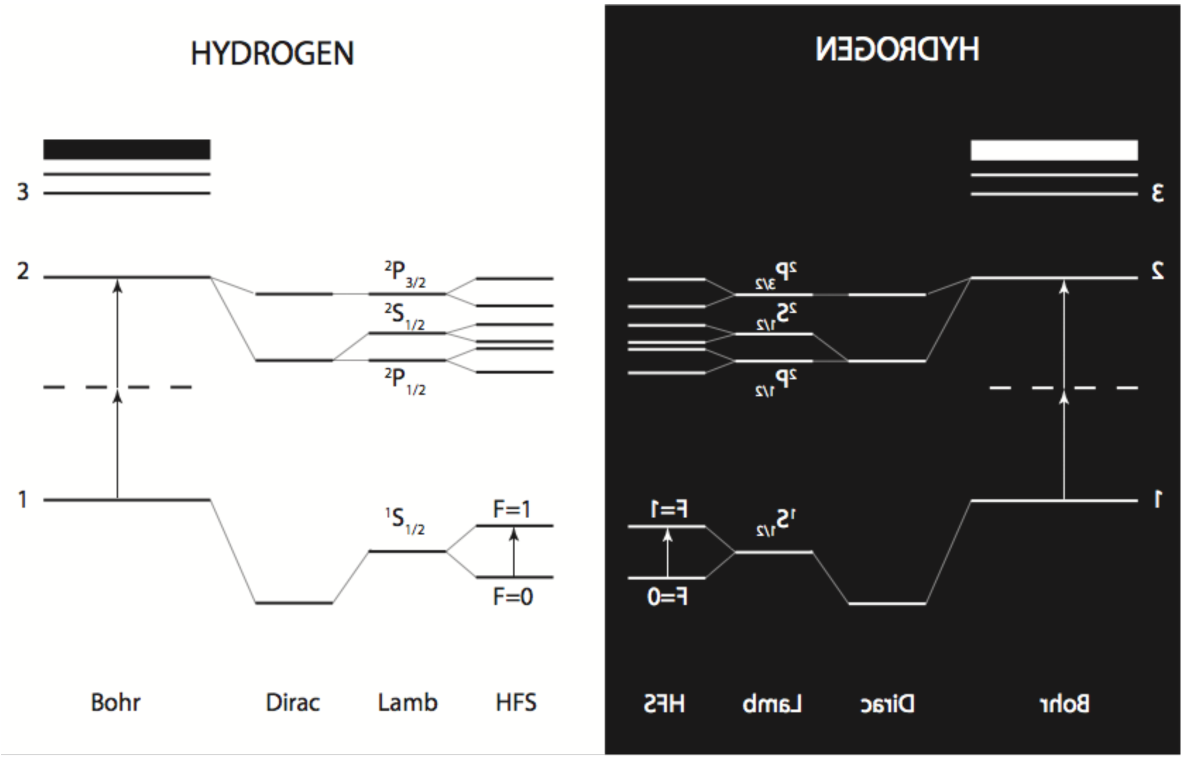
- Matter-Antimatter Symmetry
  - Charge conjugation-Parity-Time reversal: CPT
- Antimatter gravity
  - Weak Equivalence principle: WEP

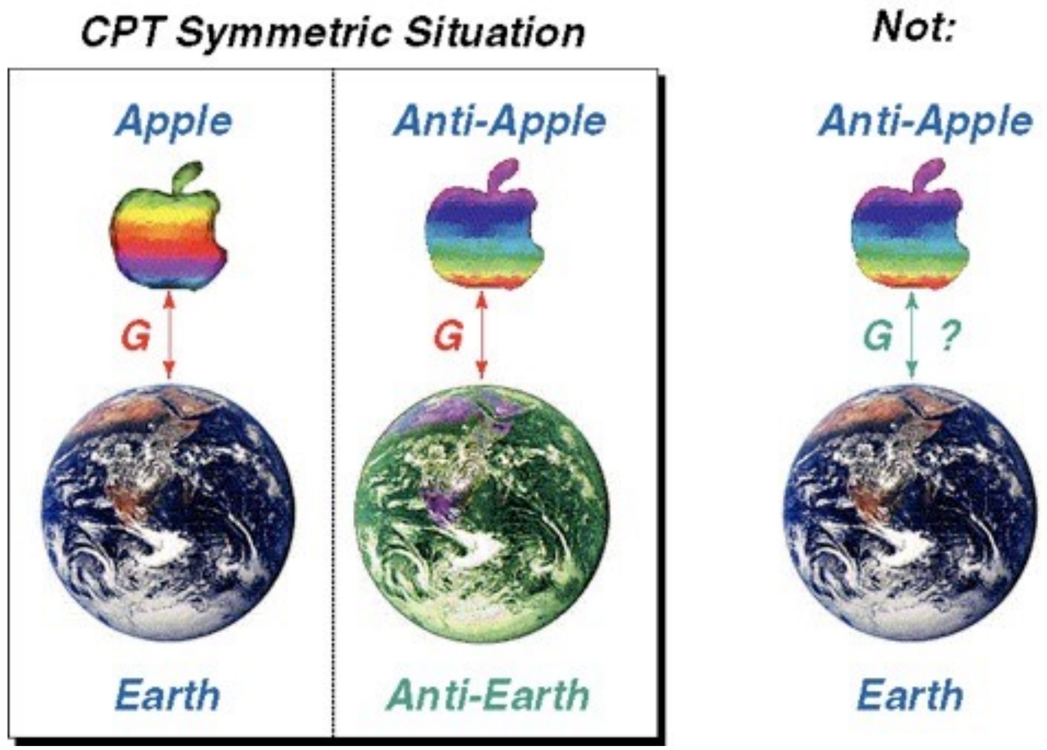


Antihydrogen experiments

- Matter-Antimatter Symmetry
  - Charge conjugation-Parity-Time reversal: CPT

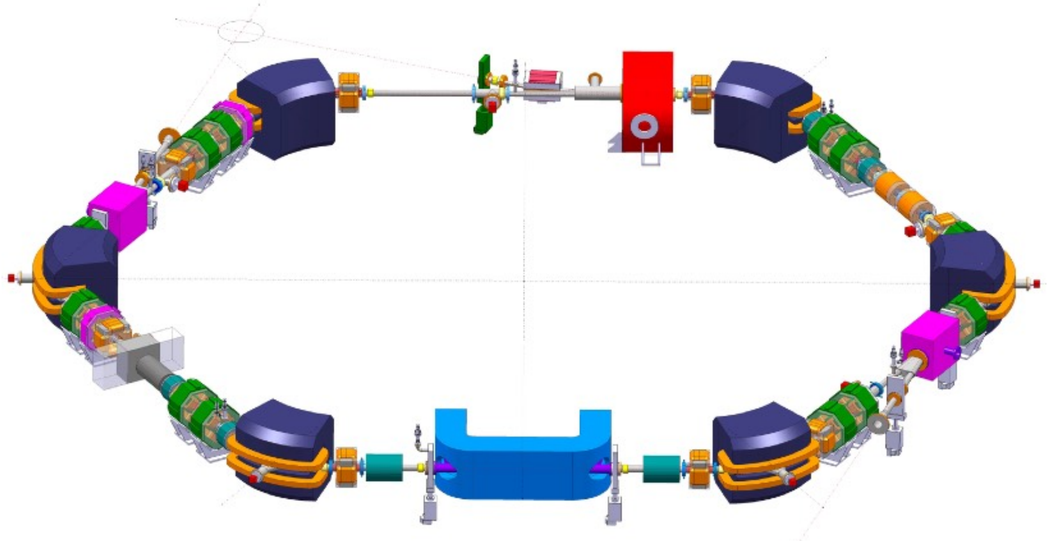
- Antimatter gravity
  - Weak Equivalence principle: WEP





AD/ELENA @ CERN

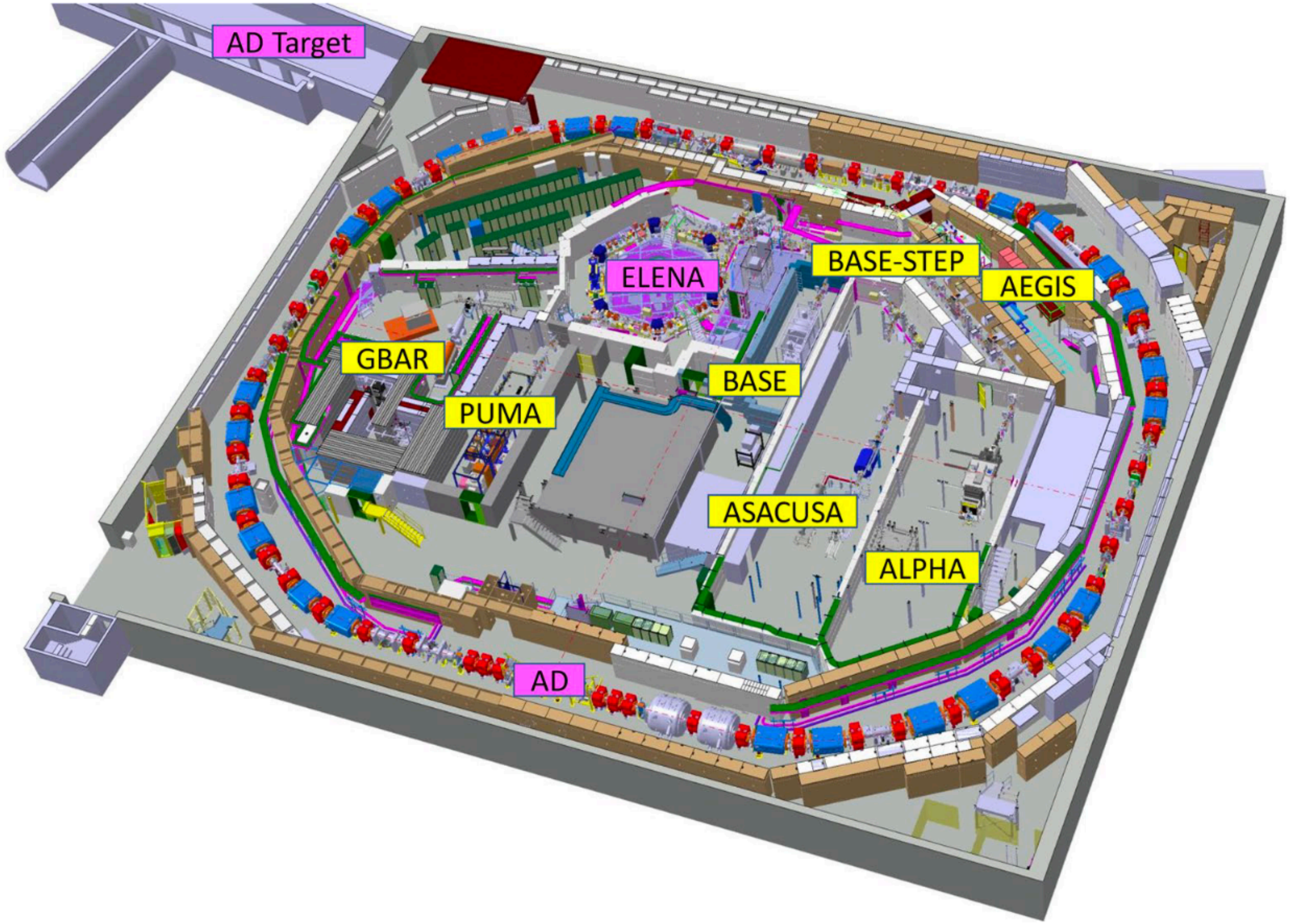
ELENA



CERN

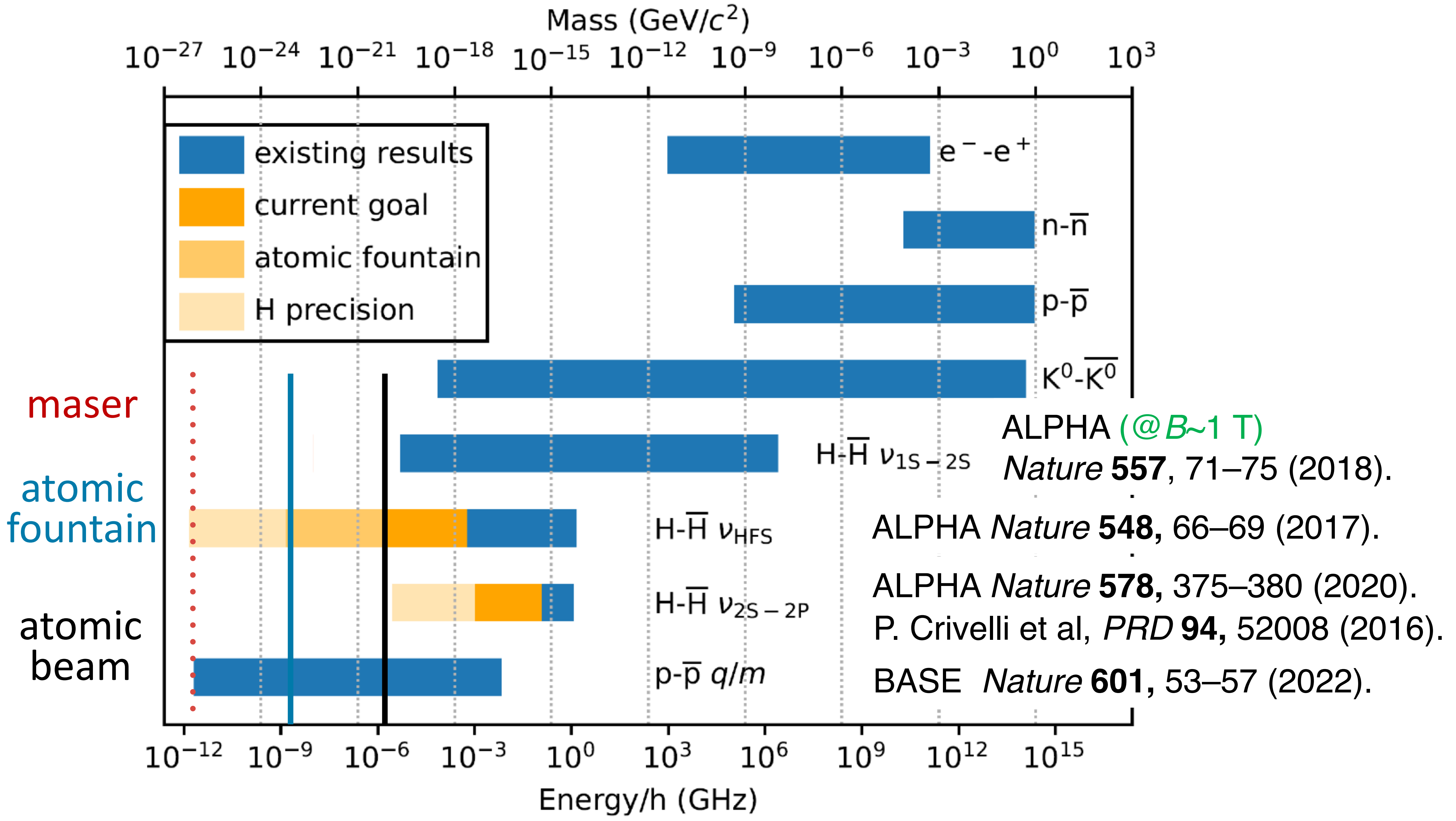
Energy range, MeV	5.3 - 0.1
Intensity of ejected beam	1.8×10^7
$\varepsilon_{x,y}$ of extracted beam, $\pi\cdot$mm$\cdot$mrad, [95%], standard	4 / 4
$\Delta p/p$ of extracted beam, [95%], standard	$8\cdot10^{-3}$

ELENA operation started Aug. 2021
Currently being discussed:
program after LS3



Comparison of CPT tests

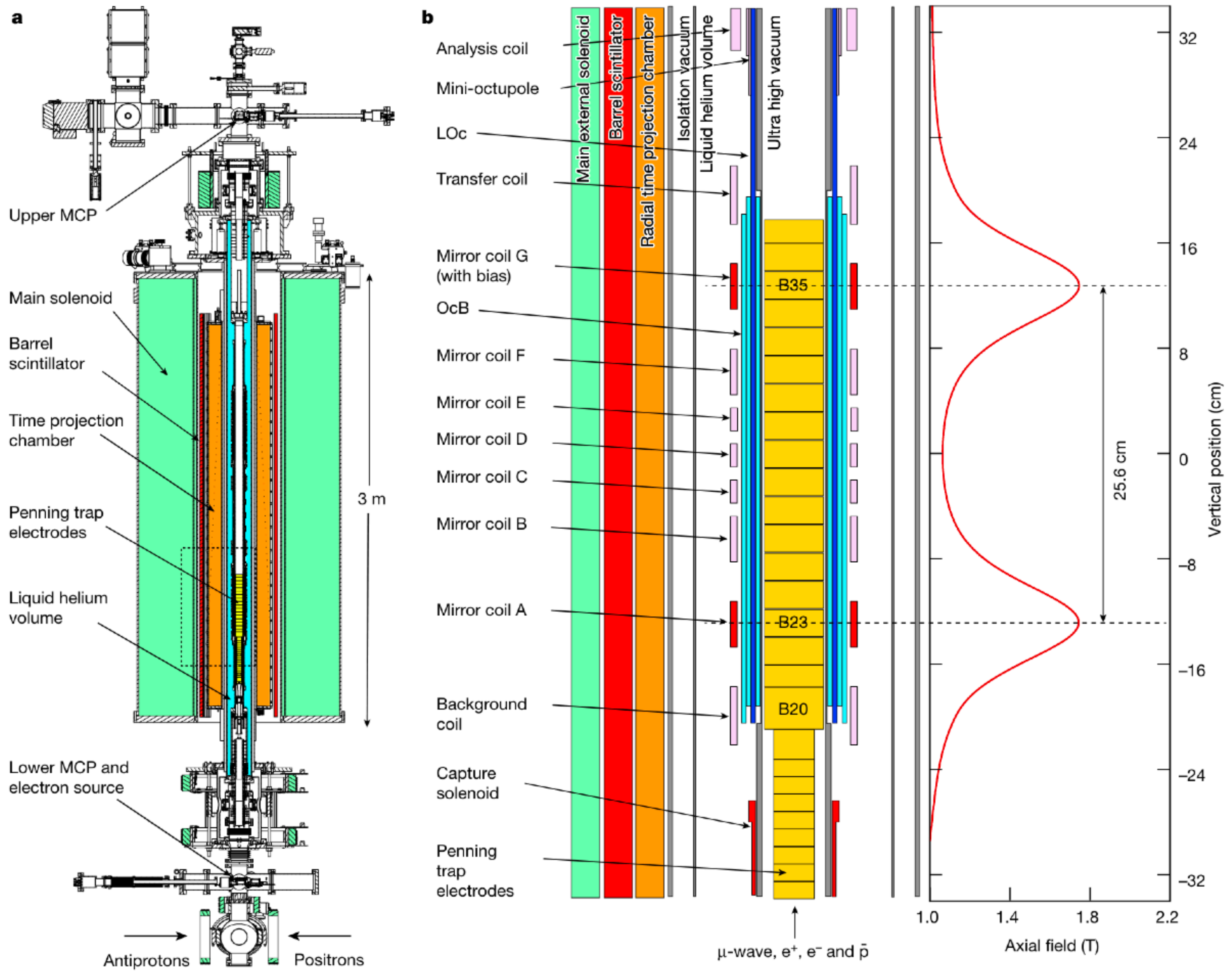
- Mass & frequency



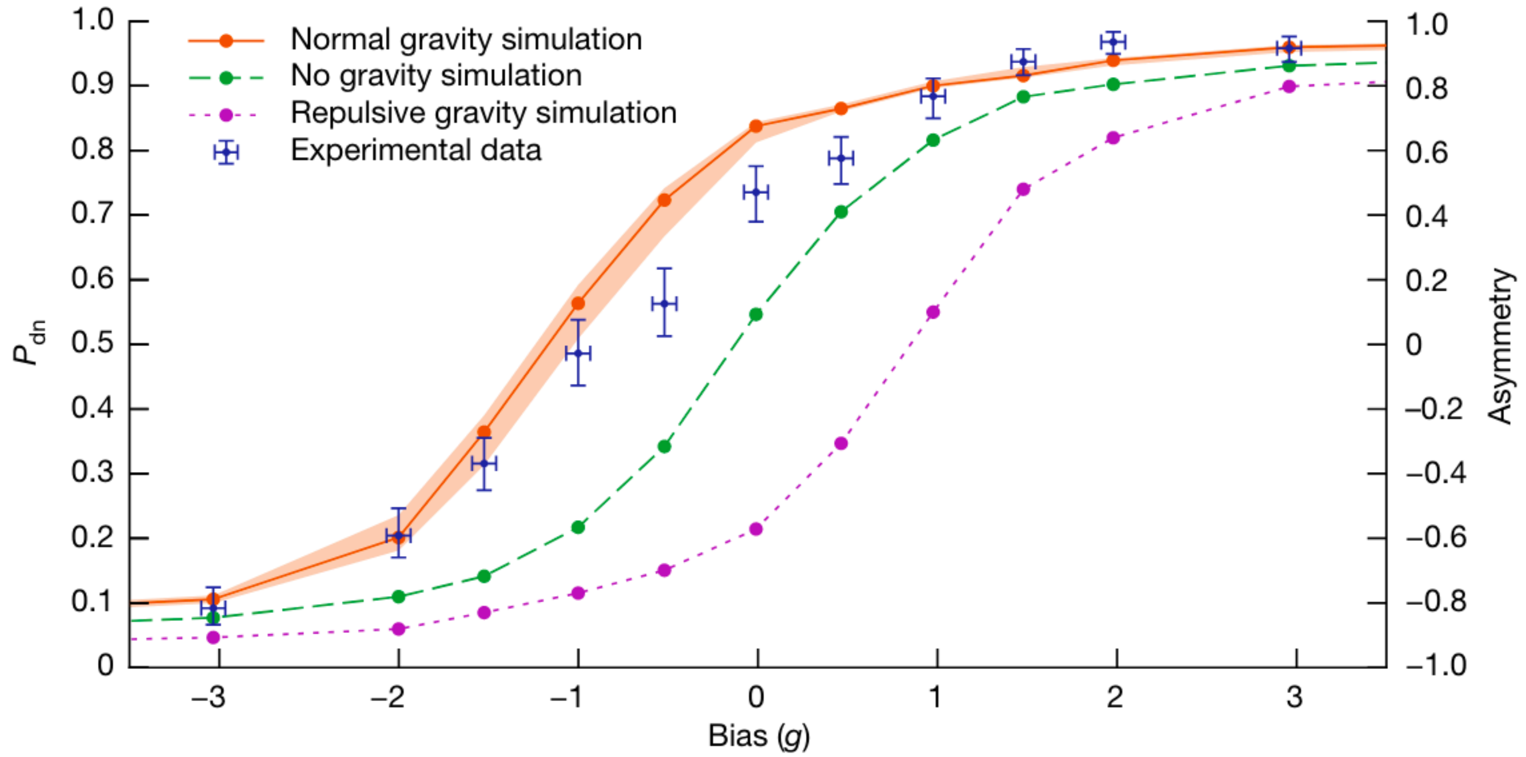
- Synopsis: CPT violating interaction appears at the level of Lagrangian
  - Relevant scale: absolute energy
- Right edge: value
- Bar length: relative precision
- Left edge: absolute sensitivity
  - Source: PDG

EW, Phys. Part. Nuclei **53**, 790–794 (2022).
arXiv:2111.04056 [hep-ex]

Gravity matter - antimatter (hadron)



$\bar{g} = (0.75 \pm 0.13\ (\text{stat.+syst.}) \pm 0.16\ (\text{sim}))\ g$

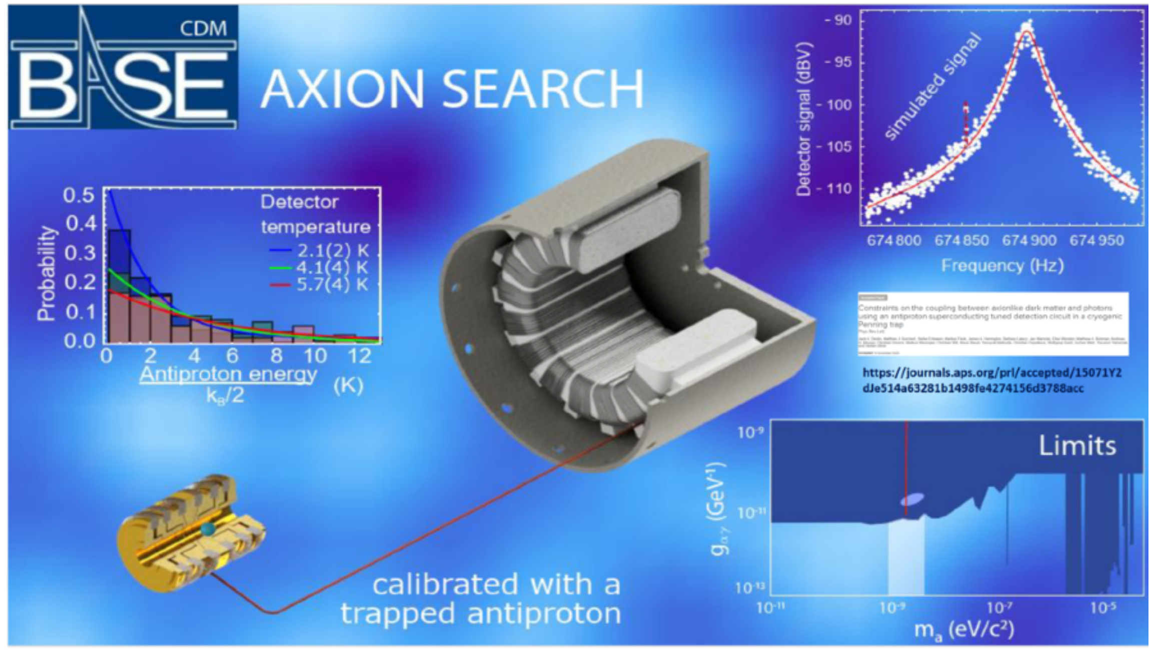


Anderson, E. K. *et al.* Observation of the effect of gravity on the motion of antimatter. *Nature* **621**, 716–722 (2023).

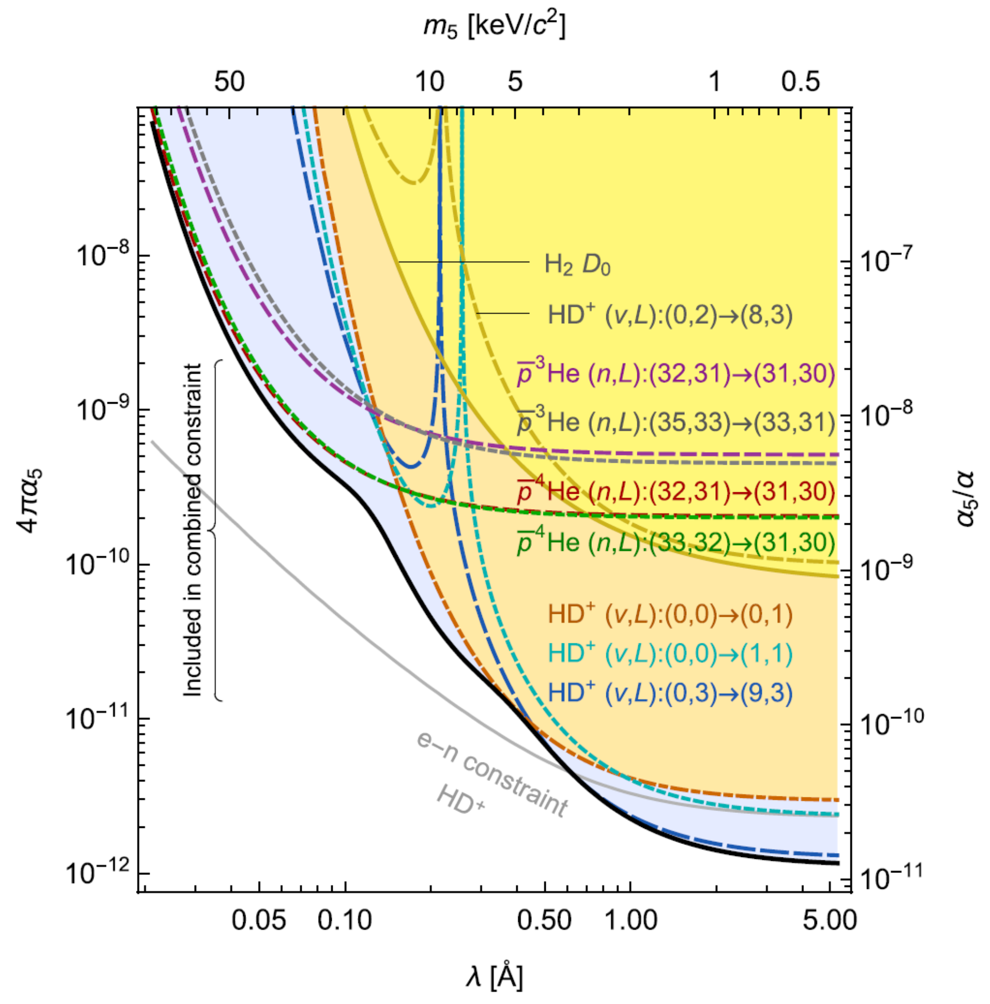
Future program

- Laser cooling of $\overline{\mathrm{H}}$
  - Higher precision for spectroscopy & gravity
  - Gravity: interferometry 20 % → < 10^{-6}
- New species
  - $\overline{\mathrm{H}}_2^+ = \bar{p}\bar{p}e^+$: trapping, cooling, laser spectroscopy
    - Key: formation
- Antideuteron & Antideuterium
  - Low yield, not so interesting (EW)

Featured in EXA/LEAP2024 conference
SMI/Vienna 25-30 Aug 2024



5th force search in $\bar{p}He^+$



Spectroscopic signatures in SME

$$\mathcal{L} \supset \frac{1}{2}\overline{\Psi}_w(\gamma^\mu i\partial_\mu - m_w + \hat{Q}_w)\Psi_w + \text{h.c.}$$

$\hat{Q}_w$: sum of all Lorentz invariance and CPT violating terms compatible with QFT: low-energy manifestation of unknown theory at M_{Pl}

V.A. Kostelecký and M. Mewes, PRD 88 096006 (2013)

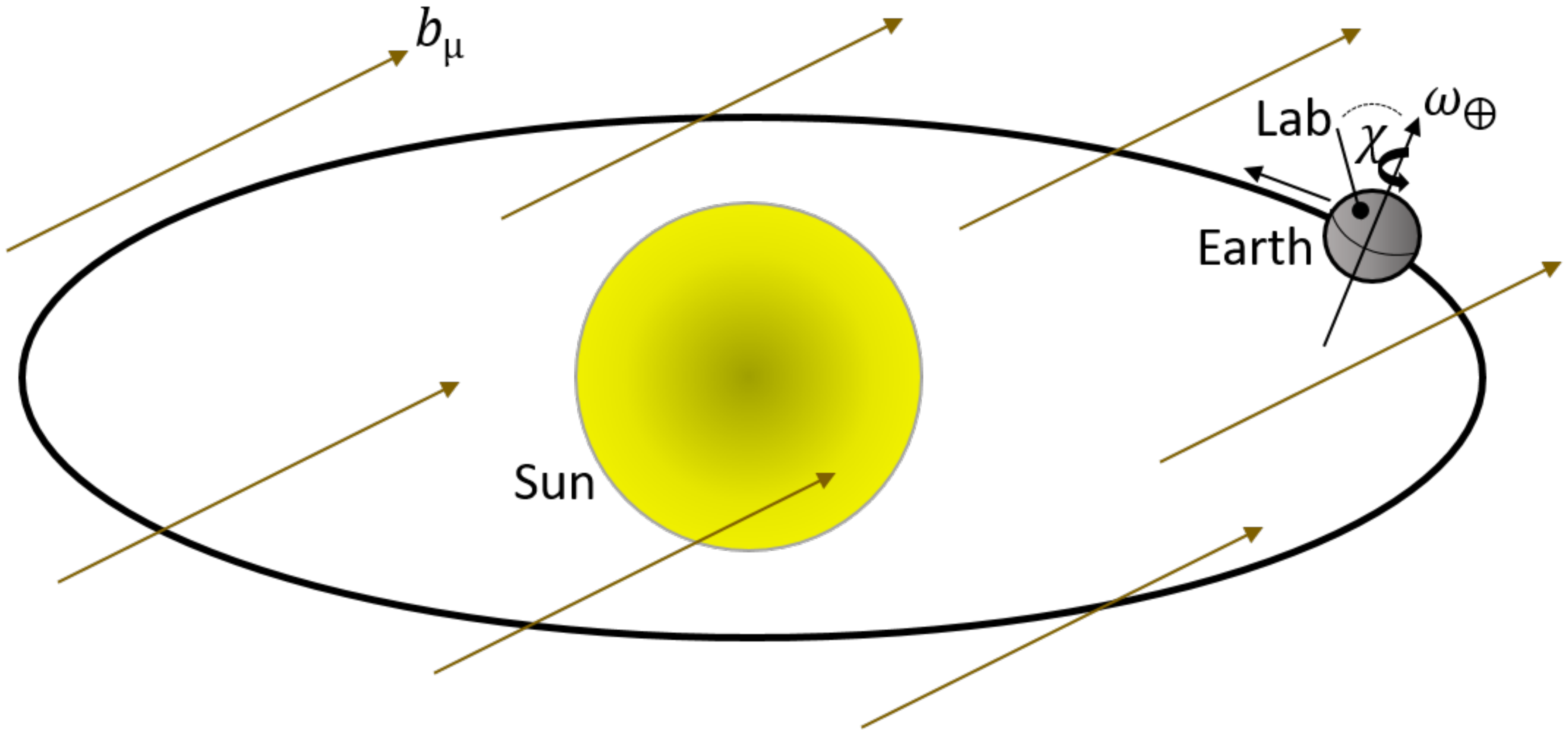
$$\mathcal{H}^0_{\mathrm{w}} = -\sum_{kjm} |\boldsymbol{p}|^k\, {}_0Y_{jm}(\hat{\boldsymbol{p}})\, \mathcal{V}^{\mathrm{NR}}_{w\,jkm}$$

$$\mathcal{H}_{\mathrm{wr}} = -\sum_{kjm} |\boldsymbol{p}|^k\, {}_0Y_{jm}(\hat{\boldsymbol{p}})\, \mathcal{T}^{\mathrm{NR(0B)}}_{w\,jkm},$$

$$\mathcal{H}_{\mathrm{w}\pm} = -\sum_{kjm} |\boldsymbol{p}|^k\, {}_{\pm1}Y_{jm}(\hat{\boldsymbol{p}})\, (i\mathcal{T}^{\mathrm{NR(1E)}}_{w\,jkm} \pm \mathcal{T}^{\mathrm{NR(1B)}}_{w\,jkm})$$

$$\mathcal{V}^{\mathrm{NR}}_{wkjm} = c^{\mathrm{NR}}_{wkjm} - a^{\mathrm{NR}}_{wkjm},$$

$$\mathcal{T}^{\mathrm{NR(qP)}}_{wkjm} = g^{\mathrm{NR(qP)}}_{wkjm} - H^{\mathrm{NR(qP)}}_{wkjm}.$$



$$\begin{aligned}\mathcal{K}^{\mathrm{NR,lab}}_{wk10} = {} & \mathcal{K}^{\mathrm{NR,sun}}_{wk10}\cos\vartheta \\ & - \sqrt{2}\mathrm{Re}\mathcal{K}^{\mathrm{NR,sun}}_{wk11}\sin\vartheta\cos\omega_\oplus T_\oplus \\ & + \sqrt{2}\mathrm{Im}\mathcal{K}^{\mathrm{NR,sun}}_{wk11}\sin\vartheta\sin\omega_\oplus T_\oplus,\end{aligned}$$

Spectroscopic signatures in SME

$$\mathcal{L} \supset \frac{1}{2}\overline{\Psi}_w(\gamma^\mu i\partial_\mu - m_w + \hat{Q}_w)\Psi_w + \text{h.c.}$$ w=e,p,n

$\hat{Q}_w$: sum of all Lorentz invariance and CPT violating terms compatible with QFT: low-energy manifestation of unknown theory at M_{Pl}

V.A. Kostelecký and M. Mewes, PRD 88 096006 (2013)

$$\mathcal{H}^0_{\text{w}} = -\sum_{kjm} |\boldsymbol{p}|^k\, {}_0Y_{jm}(\hat{\boldsymbol{p}})\, \mathcal{V}^{\text{NR}}_{w\,jkm}$$ p: particle momentum

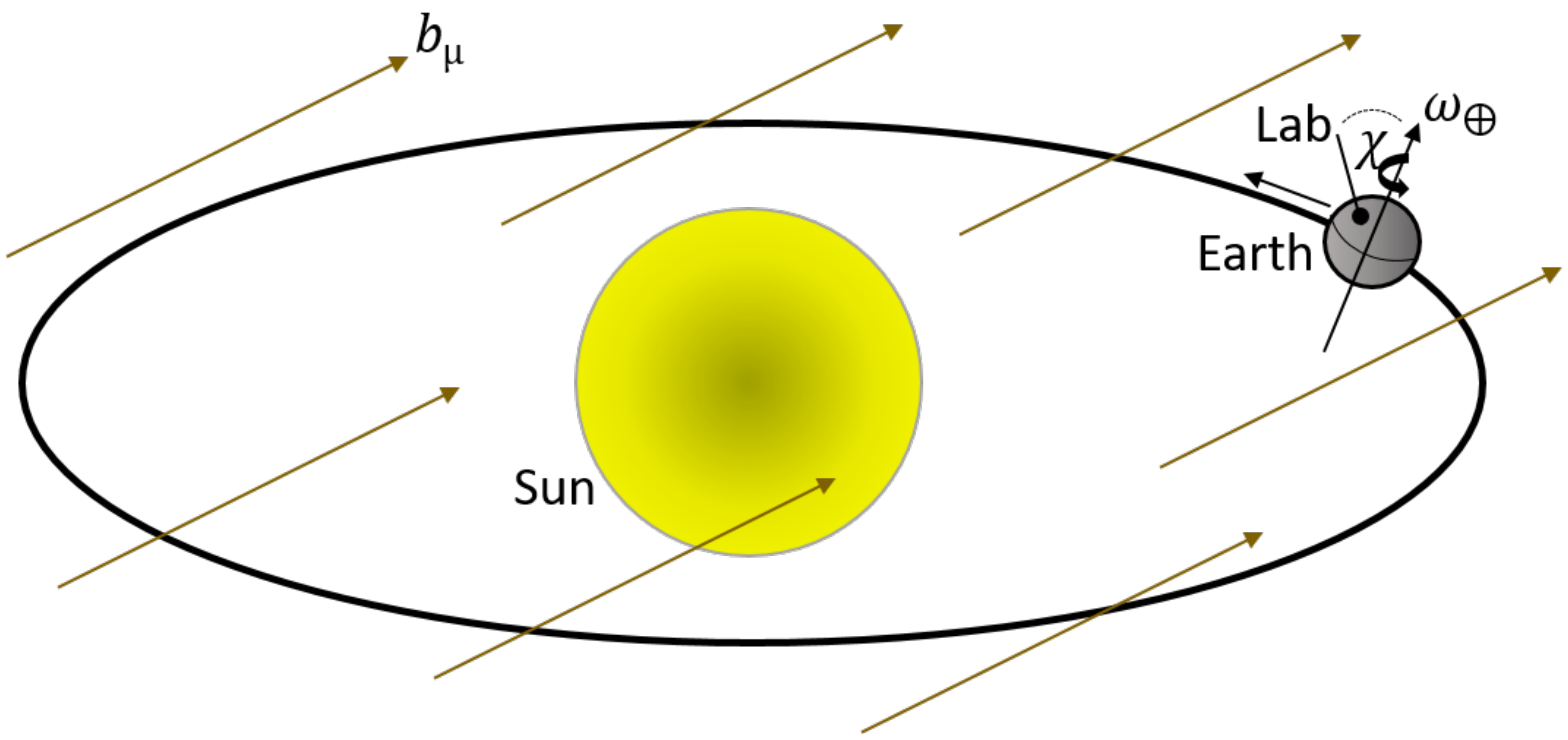
$$\mathcal{H}_{\text{wr}} = -\sum_{kjm} |\boldsymbol{p}|^k\, {}_0Y_{jm}(\hat{\boldsymbol{p}})\, \mathcal{T}^{\text{NR(0B)}}_{w\,jkm},$$

$$\mathcal{H}_{\text{w}\pm} = -\sum_{kjm} |\boldsymbol{p}|^k\, {}_{\pm1}Y_{jm}(\hat{\boldsymbol{p}})\, (i\mathcal{T}^{\text{NR(1E)}}_{w\,jkm} \pm \mathcal{T}^{\text{NR(1B)}}_{w\,jkm})$$

$$\mathcal{V}^{\text{NR}}_{wkjm} = c^{\text{NR}}_{wkjm} - a^{\text{NR}}_{wkjm},$$ Isotropic (spin-independent)

$$\mathcal{T}^{\text{NR(qP)}}_{wkjm} = g^{\text{NR(qP)}}_{wkjm} - H^{\text{NR(qP)}}_{wkjm}.$$ Anisotropic (spin-dependent)

a, g: CPT odd
c, H: CPT even



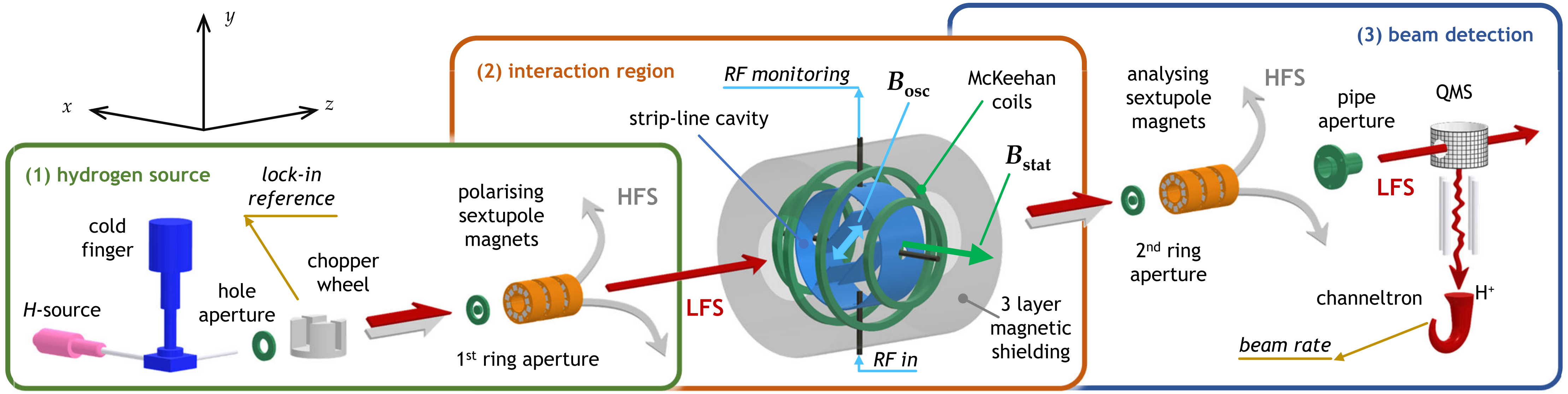
$$\mathcal{K}^{\text{NR,lab}}_{wk10} = \mathcal{K}^{\text{NR,sun}}_{wk10}\cos\vartheta - \sqrt{2}\text{Re}\mathcal{K}^{\text{NR,sun}}_{wk11}\sin\vartheta\cos\omega_\oplus T_\oplus + \sqrt{2}\text{Im}\mathcal{K}^{\text{NR,sun}}_{wk11}\sin\vartheta\sin\omega_\oplus T_\oplus,$$

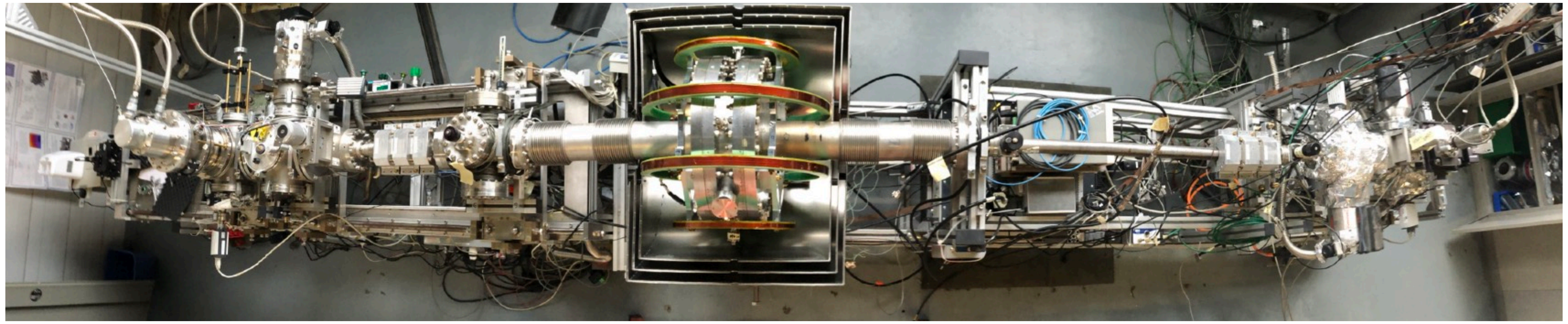
Orientation dependence
ϑ: *B* field - Earth rotation axis

Sidereal variations

Simultaneous measurement of σ and π_1 transition in H

- Atom optics to create same trajectories for HF states involved in σ and π_1 transitions
- New sextuples made of permantent magnets
- $T \sim 50$ K, $v \sim 900$ m/s
- Cavity $L = 10.5$ cm ($\lambda/2$)
- Line width
  - $\Delta\nu \sim 1/t_L \sim 8$ kHz





Hydrogen beam @Bat 275 CERN

Results of *B*-direction dependence

Results of B-direction dependence

- Series of measurements in Jan – Mar 2022
  - Sequence $\nu_\sigma(+\boldsymbol{B}), \nu_\pi(+\boldsymbol{B}), \nu_\sigma(-\boldsymbol{B}), \nu_\pi(-\boldsymbol{B})$

Results of B-direction dependence

- Series of measurements in Jan – Mar 2022
  - Sequence $\nu_\sigma(+\boldsymbol{B}), \nu_\pi(+\boldsymbol{B}), \nu_\sigma(-\boldsymbol{B}), \nu_\pi(-\boldsymbol{B})$
- Result of blind analysis

Results of B-direction dependence

- Series of measurements in Jan – Mar 2022
  - Sequence $\nu_\sigma(+\boldsymbol{B}), \nu_\pi(+\boldsymbol{B}), \nu_\sigma(-\boldsymbol{B}), \nu_\pi(-\boldsymbol{B})$
- Result of blind analysis

$$\boxed{\Delta\nu_\pi^+ - \Delta\nu_\pi^- = (19 \pm 51)\,\mathrm{Hz}}$$

Results of B-direction dependence

- Series of measurements in Jan – Mar 2022
  - Sequence $\nu_\sigma(+\boldsymbol{B}), \nu_\pi(+\boldsymbol{B}), \nu_\sigma(-\boldsymbol{B}), \nu_\pi(-\boldsymbol{B})$
- Result of blind analysis

$$\boxed{\Delta\nu_\pi^+ - \Delta\nu_\pi^- = (19 \pm 51)\,\mathrm{Hz}}$$

$$\boxed{|\, h(\Delta\nu_\pi^+ - \Delta\nu_\pi^-)\,| \frac{\sqrt{3\pi}}{\cos\theta} = (0.9 \pm 2.3) \times 10^{-21}\ \mathrm{GeV}}$$

Results of B-direction dependence

- Series of measurements in Jan – Mar 2022
  - Sequence $\nu_\sigma(+\boldsymbol{B}), \nu_\pi(+\boldsymbol{B}), \nu_\sigma(-\boldsymbol{B}), \nu_\pi(-\boldsymbol{B})$
- Result of blind analysis

$$\boxed{\Delta\nu_\pi^+ - \Delta\nu_\pi^- = (19 \pm 51)\,\mathrm{Hz}}$$

$$\boxed{|\,h(\Delta\nu_\pi^+ - \Delta\nu_\pi^-)\,|\,\frac{\sqrt{3\pi}}{\cos\theta} = (0.9 \pm 2.3) \times 10^{-21}\,\mathrm{GeV}}$$

- @CERN: $\cos\theta = -0.26$ (angle $\boldsymbol{B}$, earth axis)

$$\begin{aligned}\Delta(2\pi\nu_\pi) &\equiv 2\pi\nu_\pi(\boldsymbol{B}) - 2\pi\nu_\pi(-\boldsymbol{B}) \\ &= -\frac{\cos\vartheta}{\sqrt{3\pi}}\sum_{q=0}^{2}(\alpha m_r)^{2q}(1+4\delta_{q2})\sum_w\Big[g_{w(2q)10}^{\mathrm{NR,Sun}(0B)} - H_{w(2q)10}^{\mathrm{NR,Sun}(0B)} \\ &\qquad + 2g_{w(2q)10}^{\mathrm{NR,Sun}(1B)} - 2H_{w(2q)10}^{\mathrm{NR,Sun}(1B)}\Big]\end{aligned}$$

Results of *B*-direction dependence

- Series of measurements in Jan – Mar 2022
  - Sequence $\nu_\sigma(+\boldsymbol{B}), \nu_\pi(+\boldsymbol{B}), \nu_\sigma(-\boldsymbol{B}), \nu_\pi(-\boldsymbol{B})$
- Result of blind analysis

$$\Delta\nu_\pi^+ - \Delta\nu_\pi^- = (19 \pm 51)\,\mathrm{Hz}$$

$$|\, h(\Delta\nu_\pi^+ - \Delta\nu_\pi^-)\,| \frac{\sqrt{3\pi}}{\cos\theta} = (0.9 \pm 2.3) \times 10^{-21}\,\mathrm{GeV}$$

Natural units

- @CERN: $\cos\theta = -0.26$ (angle $\boldsymbol{B}$, earth axis)

$$\Delta(2\pi\nu_\pi) \equiv 2\pi\nu_\pi(\boldsymbol{B}) - 2\pi\nu_\pi(-\boldsymbol{B})$$
$$= -\frac{\cos\vartheta}{\sqrt{3\pi}} \sum_{q=0}^{2} (\alpha m_r)^{2q} (1 + 4\delta_{q2}) \sum_w \left[g_{w(2q)10}^{\mathrm{NR,Sun}(0B)} - H_{w(2q)10}^{\mathrm{NR,Sun}(0B)} + 2g_{w(2q)10}^{\mathrm{NR,Sun}(1B)} - 2H_{w(2q)10}^{\mathrm{NR,Sun}(1B)} \right]$$

Results of *B*-direction dependence

- Series of measurements in Jan – Mar 2022
  - Sequence $\nu_\sigma(+\boldsymbol{B}), \nu_\pi(+\boldsymbol{B}), \nu_\sigma(-\boldsymbol{B}), \nu_\pi(-\boldsymbol{B})$
- Result of blind analysis

$$\Delta\nu_\pi^+ - \Delta\nu_\pi^- = (19 \pm 51)\,\mathrm{Hz}$$

Natural units

$$|\,h(\Delta\nu_\pi^+ - \Delta\nu_\pi^-)\,|\,\frac{\sqrt{3\pi}}{\cos\theta} = (0.9 \pm 2.3)\times 10^{-21}\,\mathrm{GeV}$$

- @CERN: $\cos\theta = -0.26$ (angle $\boldsymbol{B}$, earth axis)

$$\begin{aligned}\Delta(2\pi\nu_\pi) &\equiv 2\pi\nu_\pi(\boldsymbol{B}) - 2\pi\nu_\pi(-\boldsymbol{B}) \\ &= -\frac{\cos\vartheta}{\sqrt{3\pi}}\sum_{q=0}^{2}(\alpha m_{\mathrm{r}})^{2q}(1+4\delta_{q2})\sum_w \left[g_{w(2q)10}^{\mathrm{NR,Sun}(0B)} - H_{w(2q)10}^{\mathrm{NR,Sun}(0B)}\right. \\ &\left.\quad + 2g_{w(2q)10}^{\mathrm{NR,Sun}(1B)} - 2H_{w(2q)10}^{\mathrm{NR,Sun}(1B)}\right]\end{aligned}$$

Results of *B*-direction dependence

- Series of measurements in Jan – Mar 2022
  - Sequence $\nu_\sigma(+\boldsymbol{B}), \nu_\pi(+\boldsymbol{B}), \nu_\sigma(-\boldsymbol{B}), \nu_\pi(-\boldsymbol{B})$
- Result of blind analysis

$$\Delta\nu_\pi^+ - \Delta\nu_\pi^- = (19 \pm 51)\,\text{Hz}$$

$$|\,h(\Delta\nu_\pi^+ - \Delta\nu_\pi^-)\,|\,\frac{\sqrt{3\pi}}{\cos\theta} = (0.9 \pm 2.3)\times 10^{-21}\,\text{GeV}$$

Natural units

- @CERN: $\cos\theta = -0.26$ (angle $\boldsymbol{B}$, earth axis)

$$\Delta(2\pi\nu_\pi) \equiv 2\pi\nu_\pi(\boldsymbol{B}) - 2\pi\nu_\pi(-\boldsymbol{B})$$
$$= -\frac{\cos\vartheta}{\sqrt{3\pi}}\sum_{q=0}^{2}(\alpha m_r)^{2q}(1+4\delta_{q2})\sum_w \Big[g_{w(2q)10}^{\text{NR,Sun}(0B)} - H_{w(2q)10}^{\text{NR,Sun}(0B)} + 2g_{w(2q)10}^{\text{NR,Sun}(1B)} - 2H_{w(2q)10}^{\text{NR,Sun}(1B)}\Big]$$

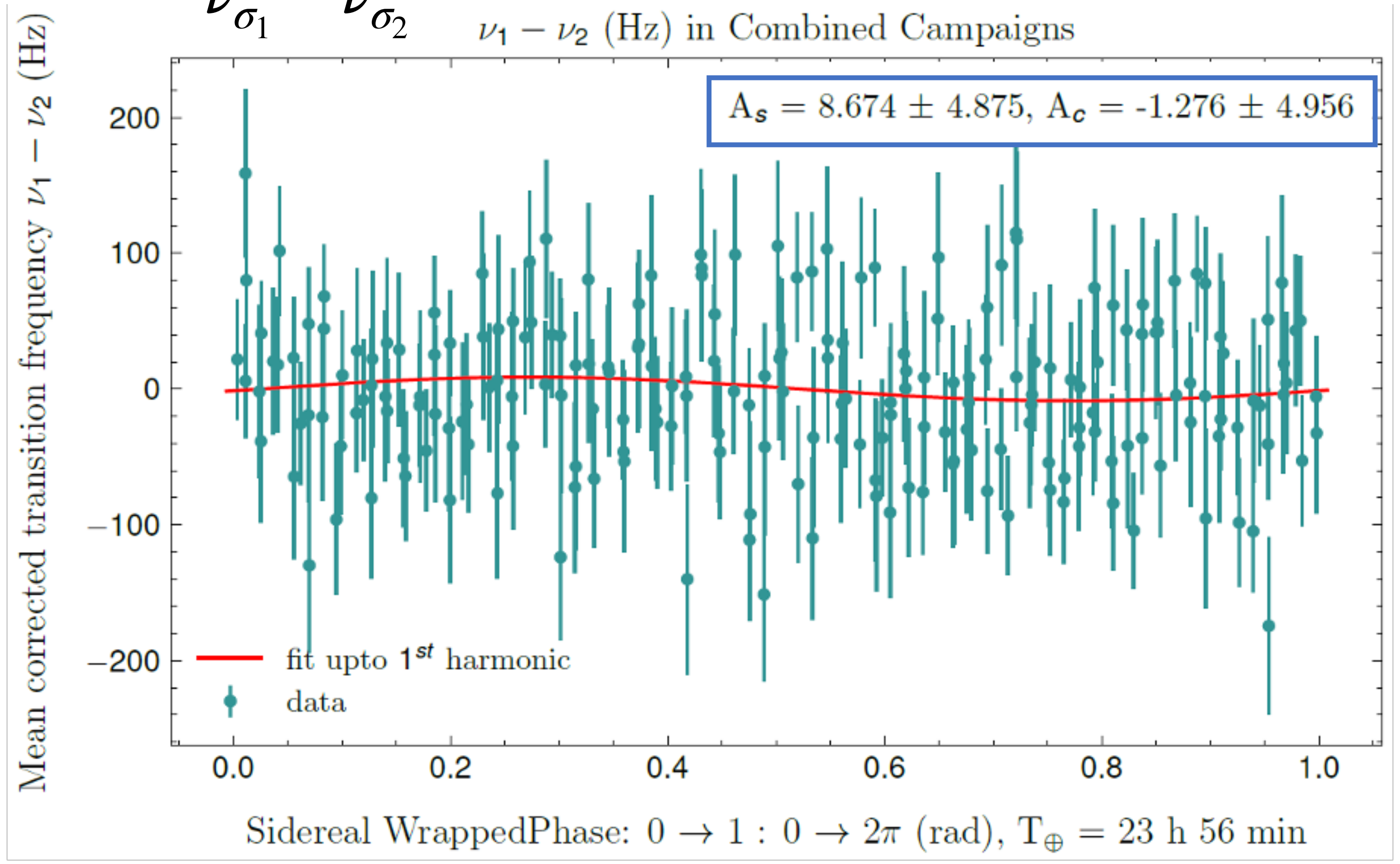
Kostelecký, V. A., & Vargas, A. J. *PRD*, *92*, 056002 (2015).

Coefficient $\mathcal{K}$	Constraint on $\lvert\mathcal{K}\rvert$
proton	
$H_{p010}^{\text{NR(0B),Sun}}, g_{p010}^{\text{NR(0B),Sun}}$	$< 1.2\times10^{-21}$ GeV
$H_{p010}^{\text{NR(1B),Sun}}, g_{p010}^{\text{NR(1B),Sun}}$	$< 5.8\times10^{-22}$ GeV
$H_{p210}^{\text{NR(0B),Sun}}, g_{p210}^{\text{NR(0B),Sun}}$	$< 8.4\times10^{-11}$ GeV^{-1}
$H_{p210}^{\text{NR(1B),Sun}}, g_{p210}^{\text{NR(1B),Sun}}$	$< 4.2\times10^{-11}$ GeV^{-1}
$H_{p410}^{\text{NR(0B),Sun}}, g_{p410}^{\text{NR(0B),Sun}}$	< 1.2 GeV^{-3}
$H_{p410}^{\text{NR(1B),Sun}}, g_{p410}^{\text{NR(1B),Sun}}$	< 0.6 GeV^{-3}
electron	
$H_{e010}^{\text{NR(0B),Sun}}, g_{e010}^{\text{NR(0B),Sun}}$	$< 7.7\times10^{-19}$ GeV
$H_{e010}^{\text{NR(1B),Sun}}, g_{e010}^{\text{NR(1B),Sun}}$	$< 3.8\times10^{-19}$ GeV
$H_{e210}^{\text{NR(0B),Sun}}, g_{e210}^{\text{NR(0B),Sun}}$	$< 5.5\times10^{-8}$ GeV^{-1}
$H_{e210}^{\text{NR(1B),Sun}}, g_{e210}^{\text{NR(1B),Sun}}$	$< 2.8\times10^{-8}$ GeV^{-1}
$H_{e410}^{\text{NR(0B),Sun}}, g_{e410}^{\text{NR(0B),Sun}}$	$< 8.0\times10^{2}$ GeV^{-3}
$H_{e410}^{\text{NR(1B),Sun}}, g_{e410}^{\text{NR(1B),Sun}}$	$< 4.0\times10^{2}$ GeV^{-3}

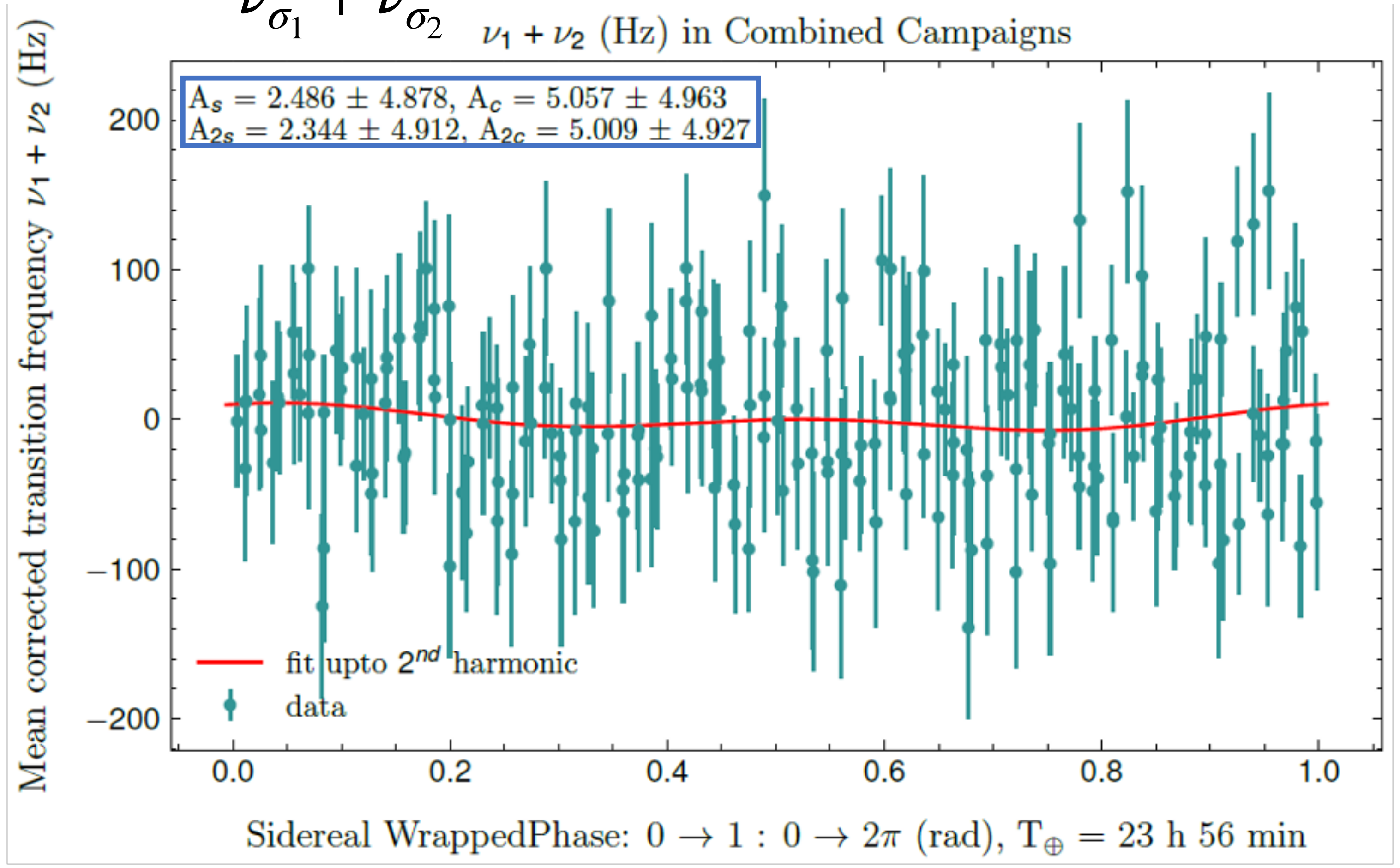
First limits on this type of coefficients
Nowak, L. et al. arXiv.2403.17763

Results: data wrapped into one sidereal period

$\nu_{\sigma_1} - \nu_{\sigma_2}$



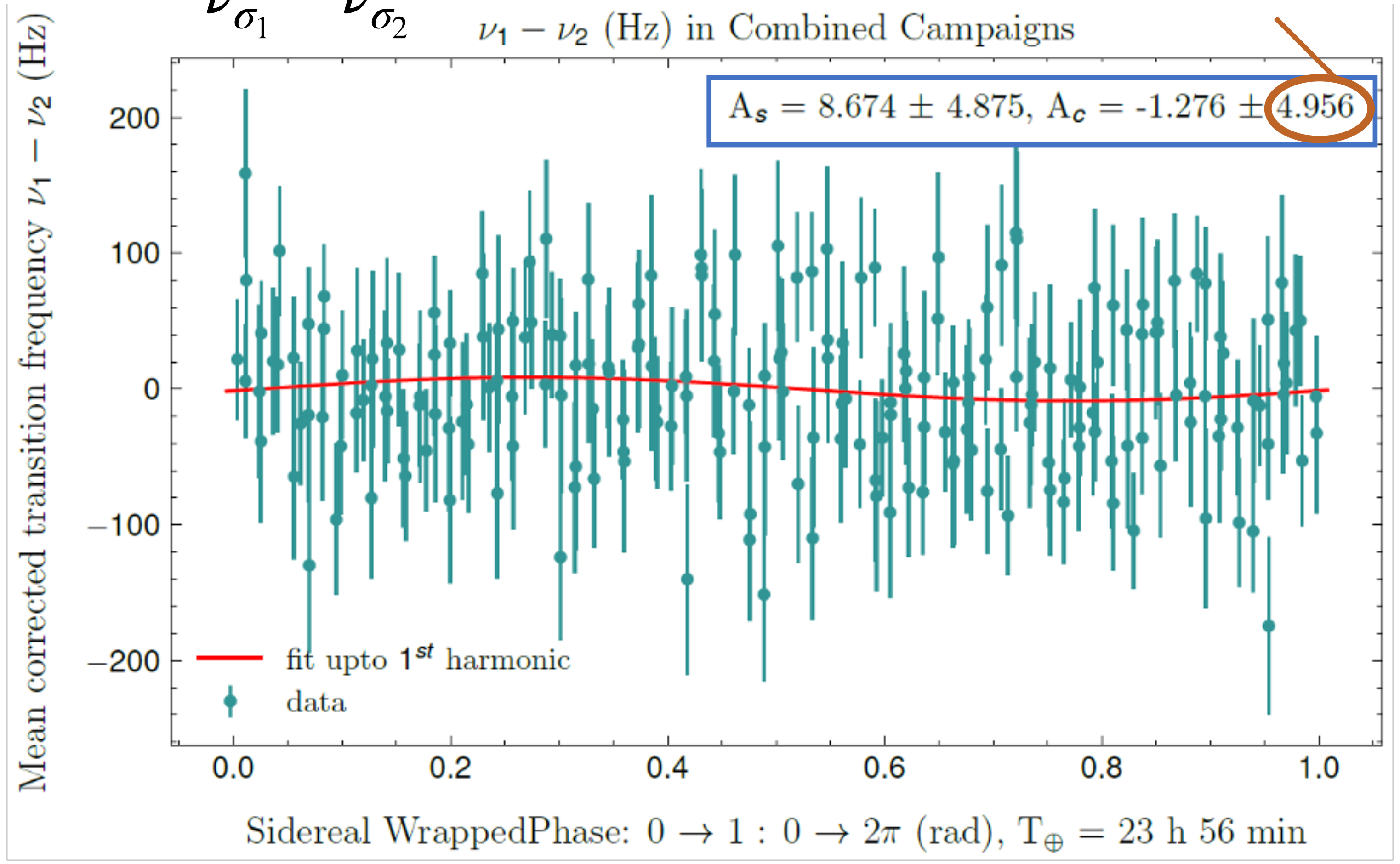
$\nu_{\sigma_1} + \nu_{\sigma_2}$



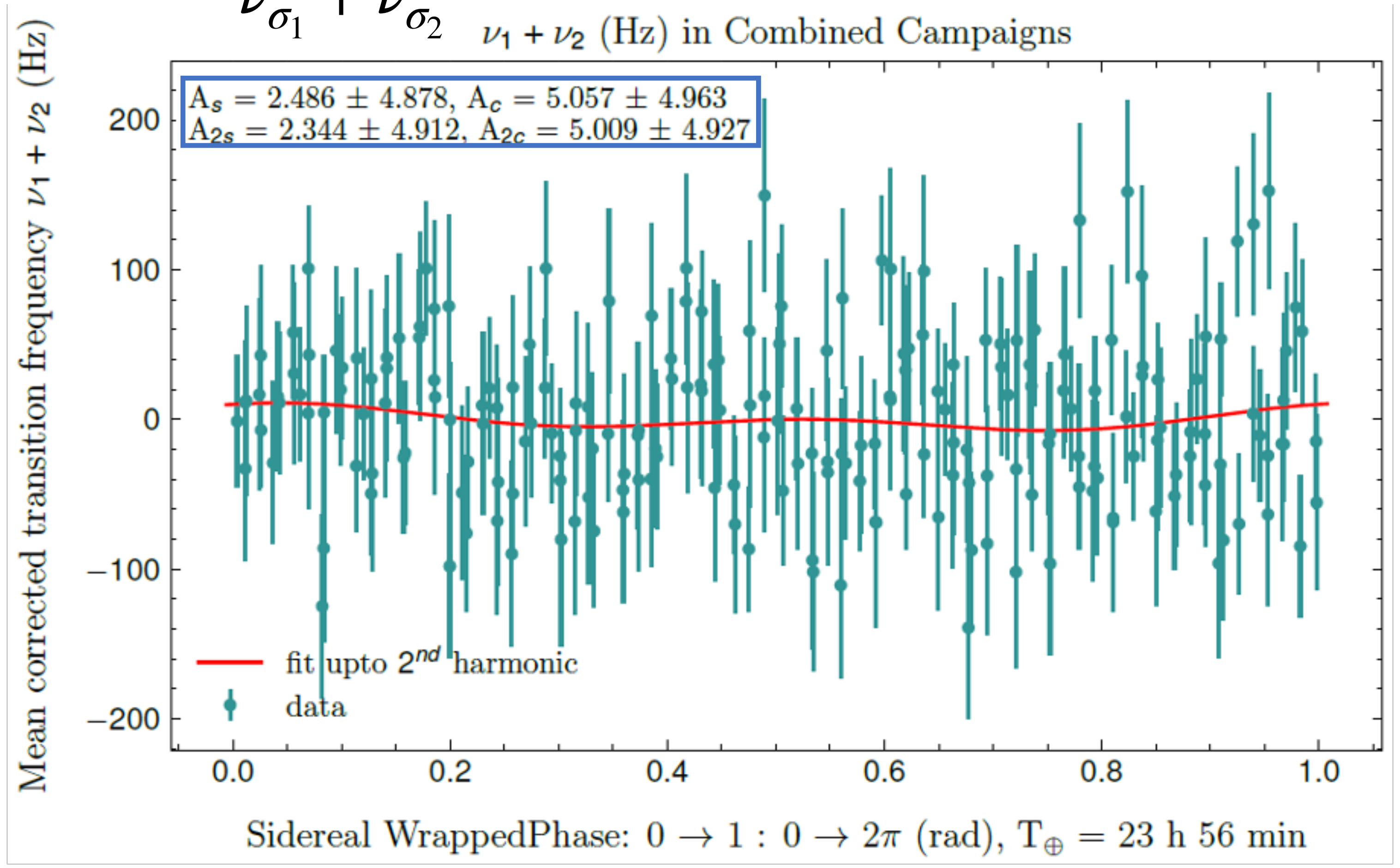
Results: data wrapped into one sidereal period

$\Delta\nu_{stat} \sim 5\,\text{Hz}$

$\nu_{\sigma_1} - \nu_{\sigma_2}$



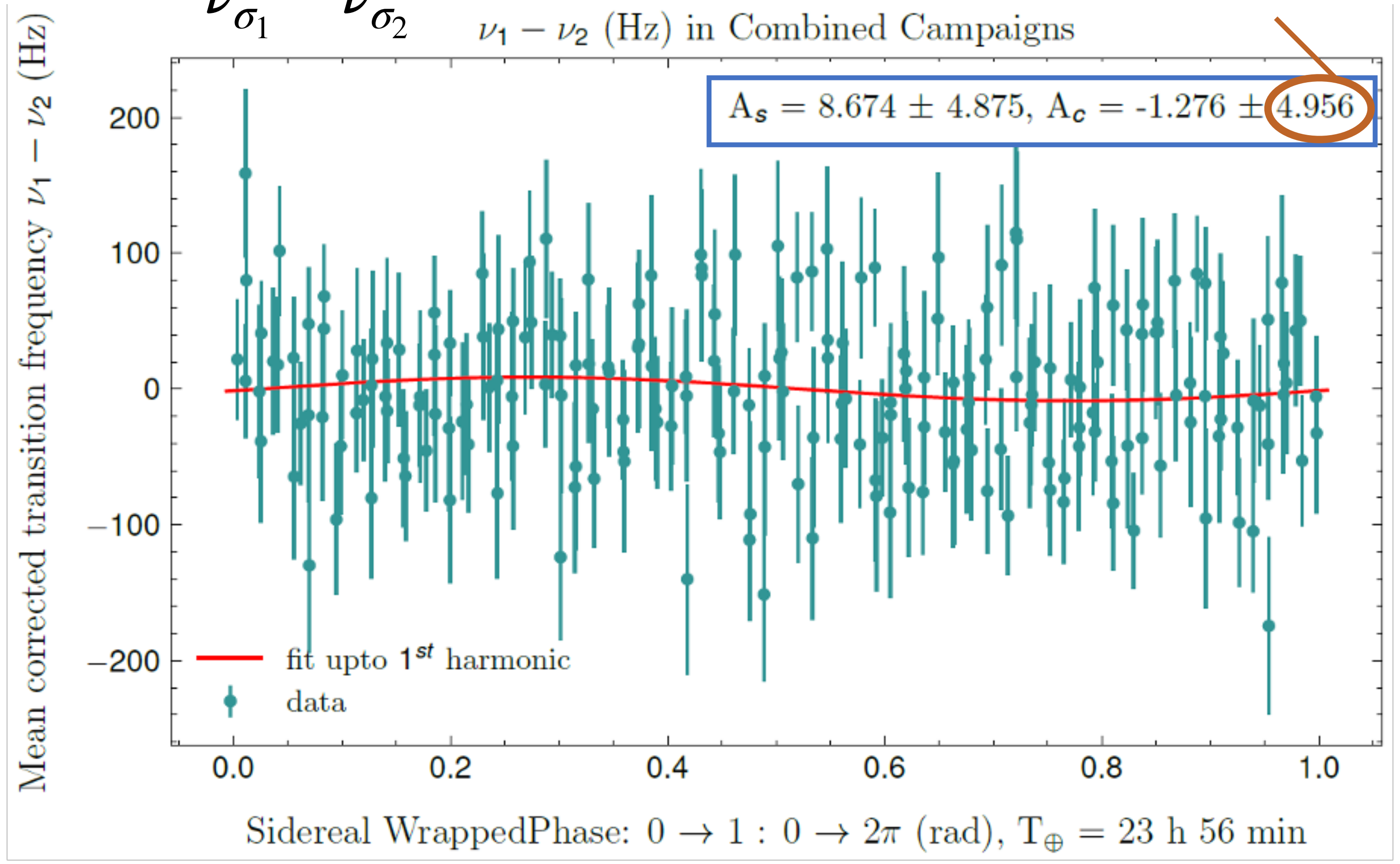
$\nu_{\sigma_1} + \nu_{\sigma_2}$



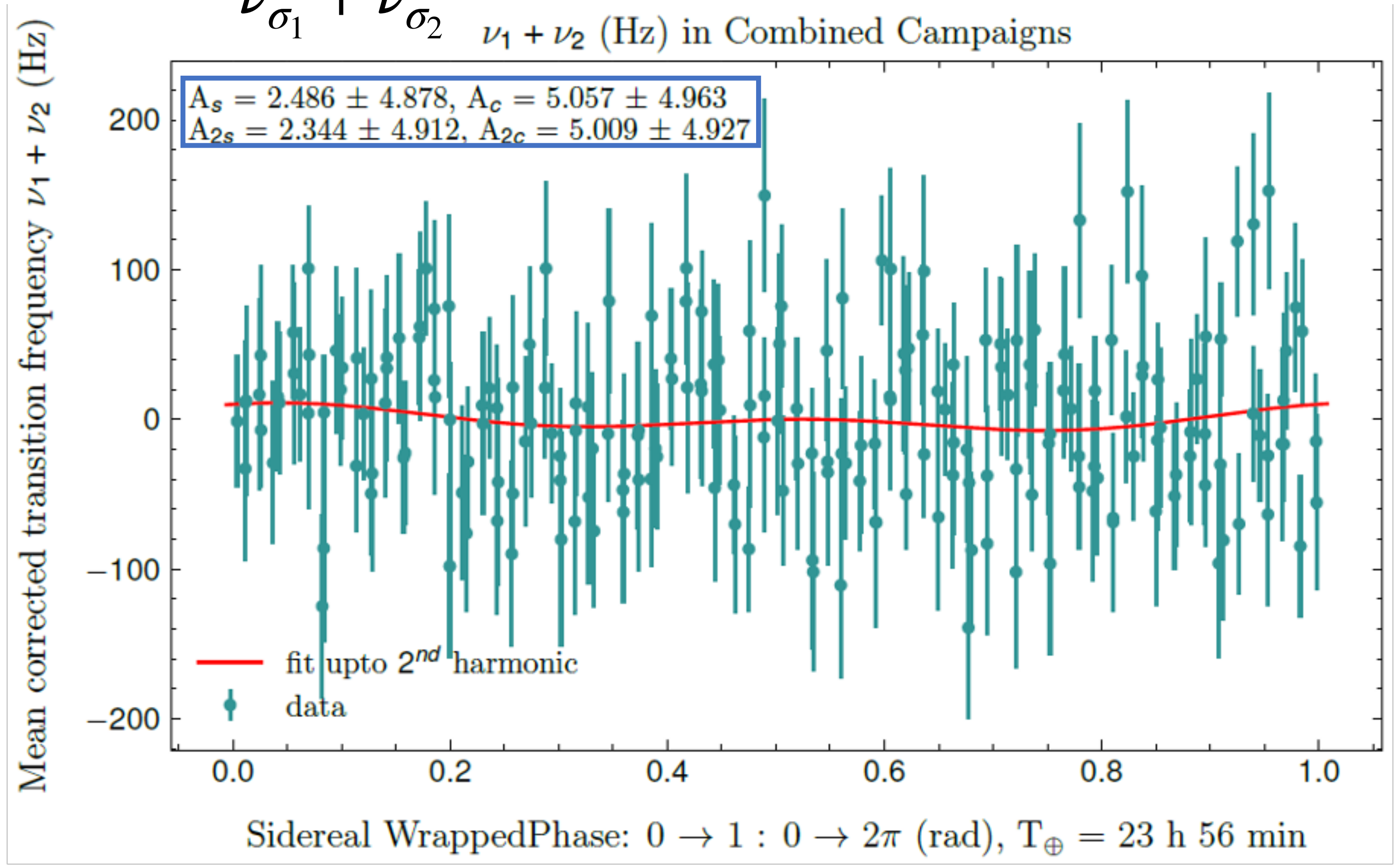
Results: data wrapped into one sidereal period

$\Delta\nu_{\text{stat}} \sim 5\,\text{Hz}$

$\nu_{\sigma_1} - \nu_{\sigma_2}$



$\nu_{\sigma_1} + \nu_{\sigma_2}$



$A_0^0 = 0$: data normalised to mean since B_{ext} was
Different for two campaigns

$$2\pi\delta\nu^{(0)} = A_0^0 + A_c^{(0)}\cos(\omega_\oplus T_L) + A_s^{(0)}\sin(\omega_\oplus T_L) + A_{2c}^{(0)}\cos(2\omega_\oplus T_L) + A_{2s}^{(0)}\sin(2\omega_\oplus T_L)$$

Vargas, A. J. *Phys. Rev. D* **109**, 055001 (2024).

Results for SME coefficients

- Results for p coefficients
  - e, n: better limits exist from other experiments (*except in linear boost*)

Preliminary: systematic error evaluation ongoing

Coefficient	|Re $\mathcal{K}$|	Error | Re $\mathcal{K}$|	|Im $\mathcal{K}$|	Error | Im $\mathcal{K}$|	Units
$H_{w011}^{\text{NR(0B),Sun}}, g_{w011}^{\text{NR(0B),Sun}}$	7.1×10^{-23}	2.76×10^{-22}	4.83×10^{-22}	2.71×10^{-22}	GeV
$H_{w011}^{\text{NR(1B),Sun}}, g_{w011}^{\text{NR(1B),Sun}}$	3.18×10^{-23}	1.23×10^{-22}	2.16×10^{-22}	1.21×10^{-22}	GeV
$H_{w211}^{\text{NR(0B),Sun}}, g_{w211}^{\text{NR(0B),Sun}}$	4.31×10^{-21}	1.67×10^{-20}	2.93×10^{-20}	1.65×10^{-20}	GeV^{-1}
$H_{w211}^{\text{NR(1B),Sun}}, g_{w211}^{\text{NR(1B),Sun}}$	1.01×10^{-20}	3.91×10^{-20}	6.84×10^{-20}	3.84×10^{-20}	GeV^{-1}
$H_{w411}^{\text{NR(0B),Sun}}, g_{w411}^{\text{NR(0B),Sun}}$	1.24×10^{-20}	4.83×10^{-20}	8.46×10^{-20}	4.75×10^{-20}	GeV^{-3}
$H_{w411}^{\text{NR(1B),Sun}}, g_{w411}^{\text{NR(1B),Sun}}$	3.09×10^{-20}	1.20×10^{-19}	2.10×10^{-19}	1.18×10^{-19}	GeV^{-3}
$c_{w221}^{\text{NR,Sun}}, a_{w221}^{\text{NR,Sun}}$	1.75×10^{-20}	1.72×10^{-20}	8.62×10^{-21}	1.69×10^{-20}	GeV^{-1}
$c_{w222}^{\text{NR,Sun}}, a_{w222}^{\text{NR,Sun}}$	3.02×10^{-20}	2.97×10^{-20}	1.41×10^{-20}	2.96×10^{-20}	GeV^{-1}
$c_{w421}^{\text{NR,Sun}}, a_{w421}^{\text{NR,Sun}}$	9.76×10^{-20}	9.58×10^{-20}	4.8×10^{-20}	9.42×10^{-20}	GeV^{-3}
$c_{w422}^{\text{NR,Sun}}, a_{w422}^{\text{NR,Sun}}$	1.68×10^{-19}	1.65×10^{-19}	7.86×10^{-20}	1.64×10^{-19}	GeV^{-3}

Inferior to H maser results

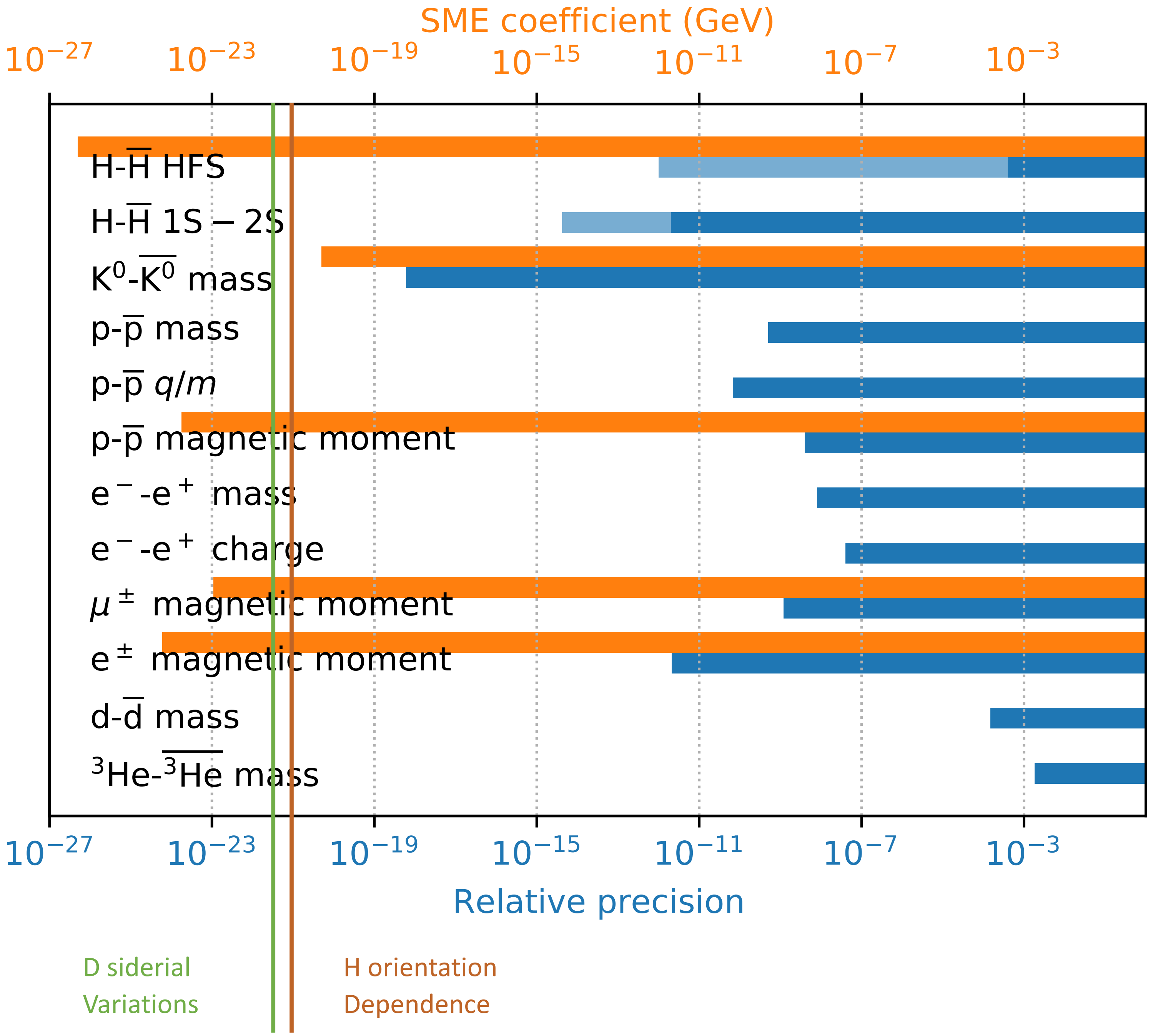
By 4 O.M.

Improvement over limits set by H-Maser results

By 14 O.M.

New results for proton coefficients

Comparison of CPT tests

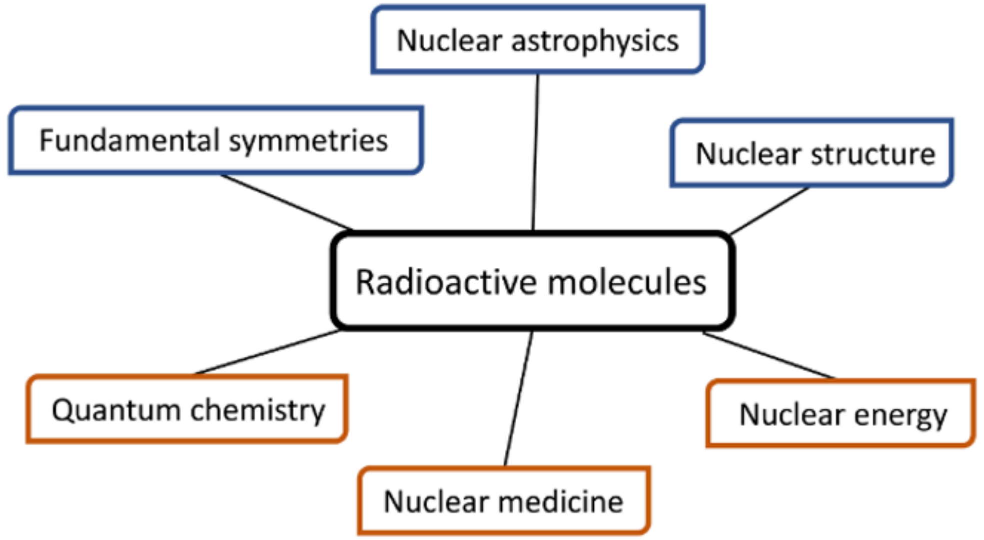


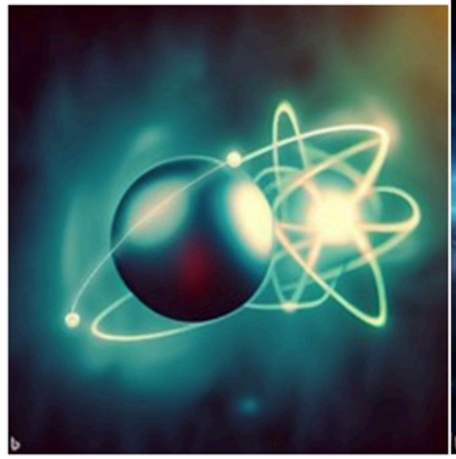
E. Widmann, Phys. Part. Nucl. 53, 790 (2022)
Source: PDG & arXiv:0801.0287v17

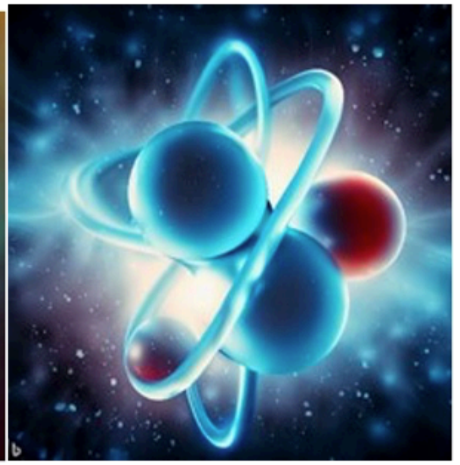
Box 1: Radioactive molecules: powerful tool and unique laboratory

The production and study of radioactive molecules is quickly acquiring momentum at radioactive ion beam facilities across Europe and beyond. The motivation for studying the structure and dynamics of molecules containing short-lived radioactive nuclei is multi-faceted and covers areas of both fundamental and applied science in regions of the nuclear chart where molecular studies have so far been too challenging.

For heavy species, gas-phase spectroscopy provides powerful benchmarks of the predictions of ab initio quantum chemistry in regions where relativistic effects are crucial, the chemistry of 5*f*-electrons is not fully understood, and experimental data is scarce. Meanwhile, producing isotopically pure compounds of the early actinides is important for understanding the isolated molecular dynamics of relevance to nuclear engineering and radioactive waste management. Simultaneously, the optimization of the ISOL production of molecular beams that are purer and more intense than the constituent atomic beams is also of direct importance for the future of ISOL as a production plan for medical radioisotopes. Finally, some of those radioactive molecules may prove ideal laboratories for searches of physics beyond the Standard Model.

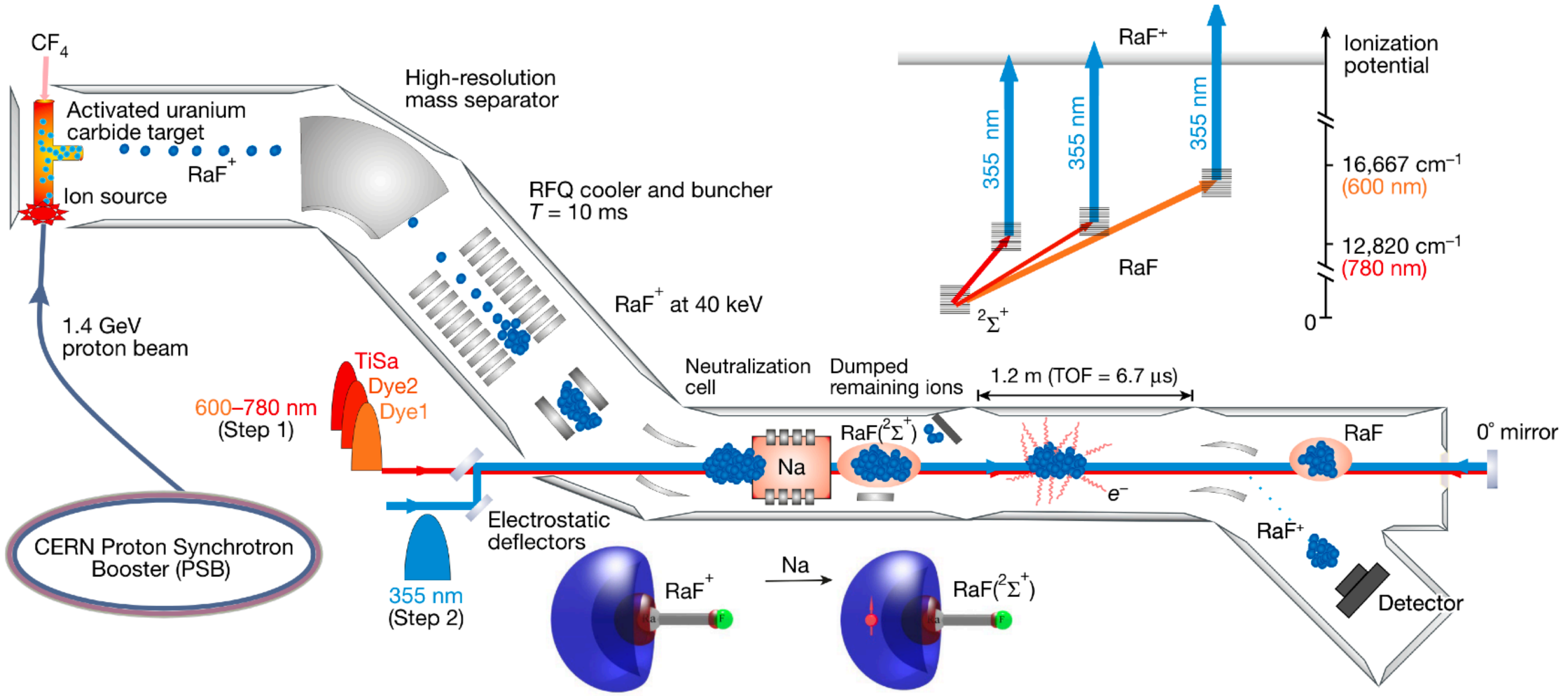


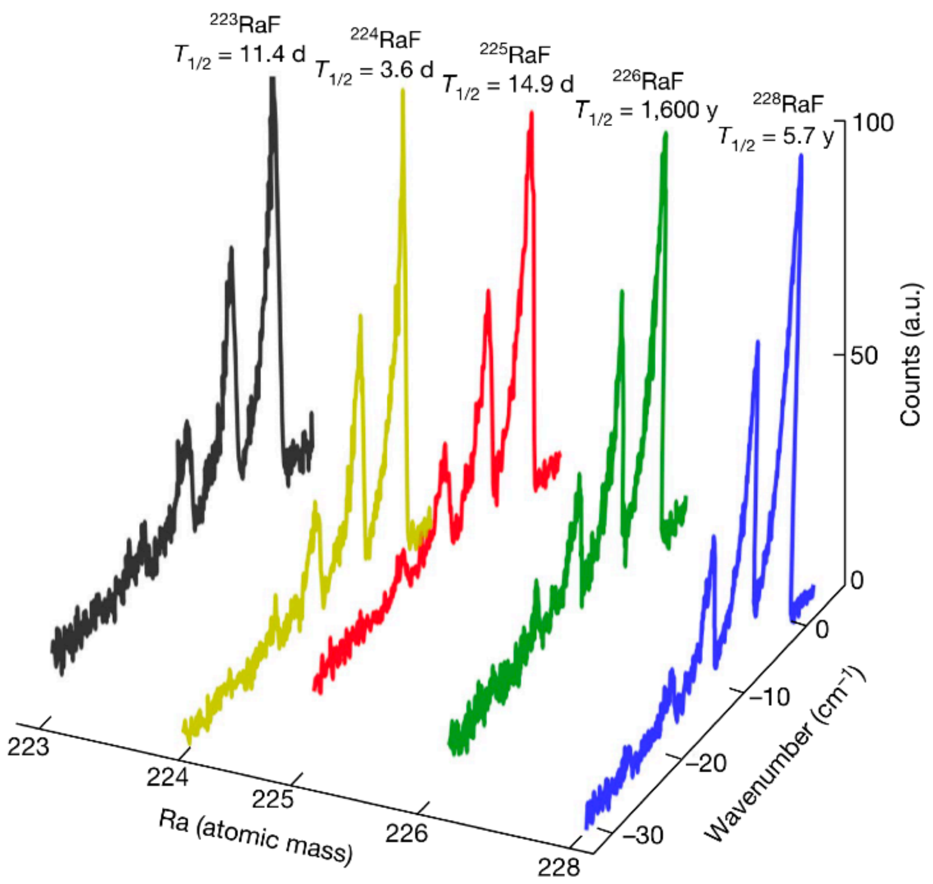




NuPECC LRP 2024 ch. 5 Fundamental interactions and symmetries (preliminary)

1st spectroscopy of radioactive molecules

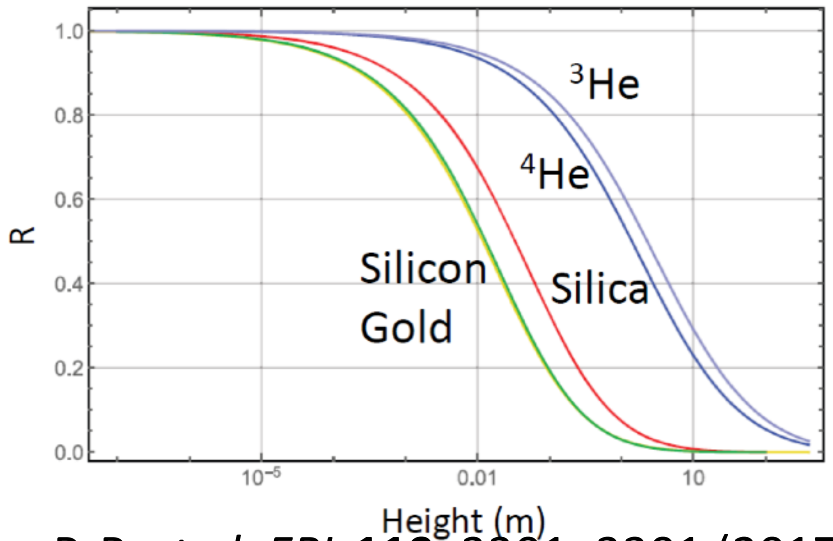




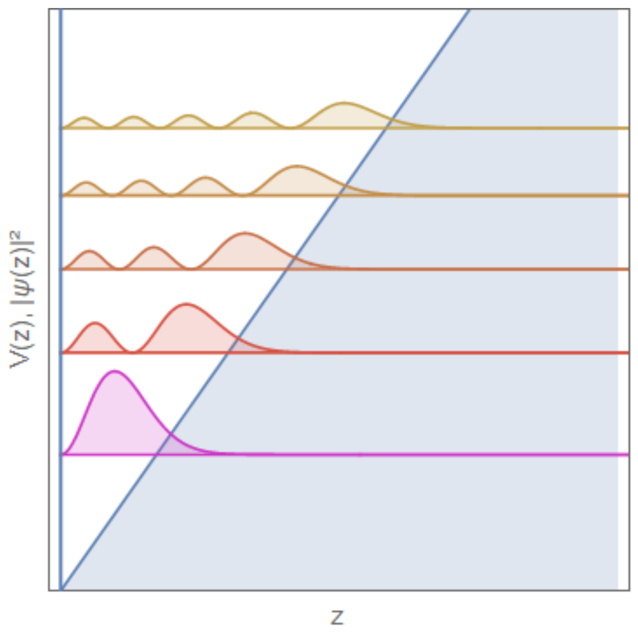
Garcia Ruiz, R., Berger, R., Billowes, J. *et al.* Spectroscopy of short-lived radioactive molecules. *Nature* **581**, 396–400 (2020). https://doi.org/10.1038/s41586-020-2299-4

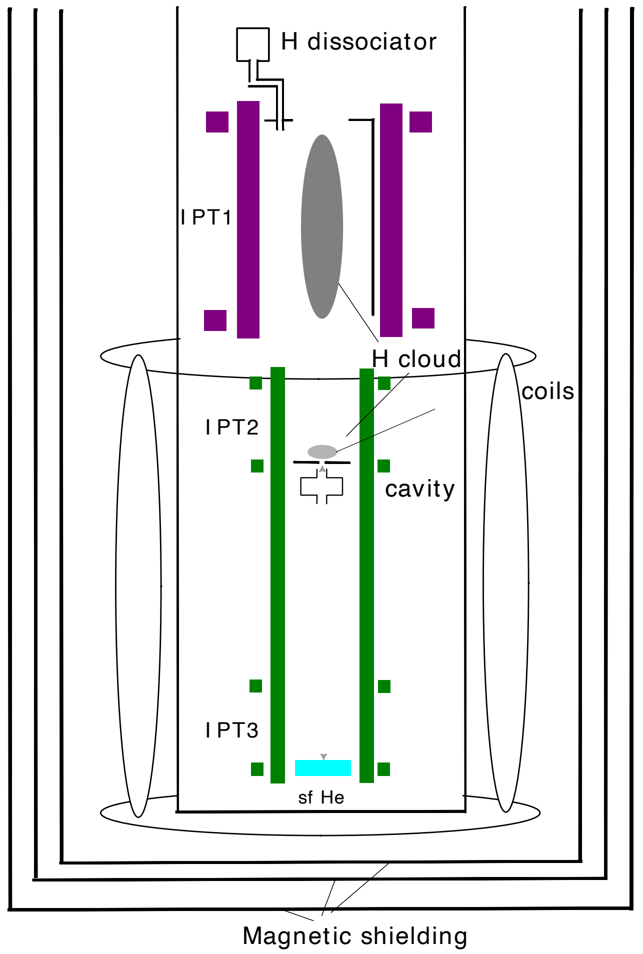
GRASIAN *GRAvity, Spectroscopy and Interferometry with ultra-cold Atoms and Neutrons*

- Quest for coldest hydrogen source
  - Longer interaction time → higher precision in laser or microwave spectroscopy
  - Lowest energies: gravitational quantum states (analogy neutrons): *v~cm/s*
  - Quantum reflection from van der Waals/Casimir-Polder potential
  - Highest reflectivity: superfluid He
  - Bouncing H: Ramsey hyperfine spectroscopy, 1s-2s laser spectroscopy
  - Also possible for antihydrogen
  - Other applications: short-range forces



Crépin, P. P. *et al. EPL* **119**, 3301–3301 (2017).





Comparat, D., Malbrunot, C., Malbrunot-Ettenauer, S., Widmann, E. & Yzombard, P. *Phil. Trans. R. Soc. A.38220230089*

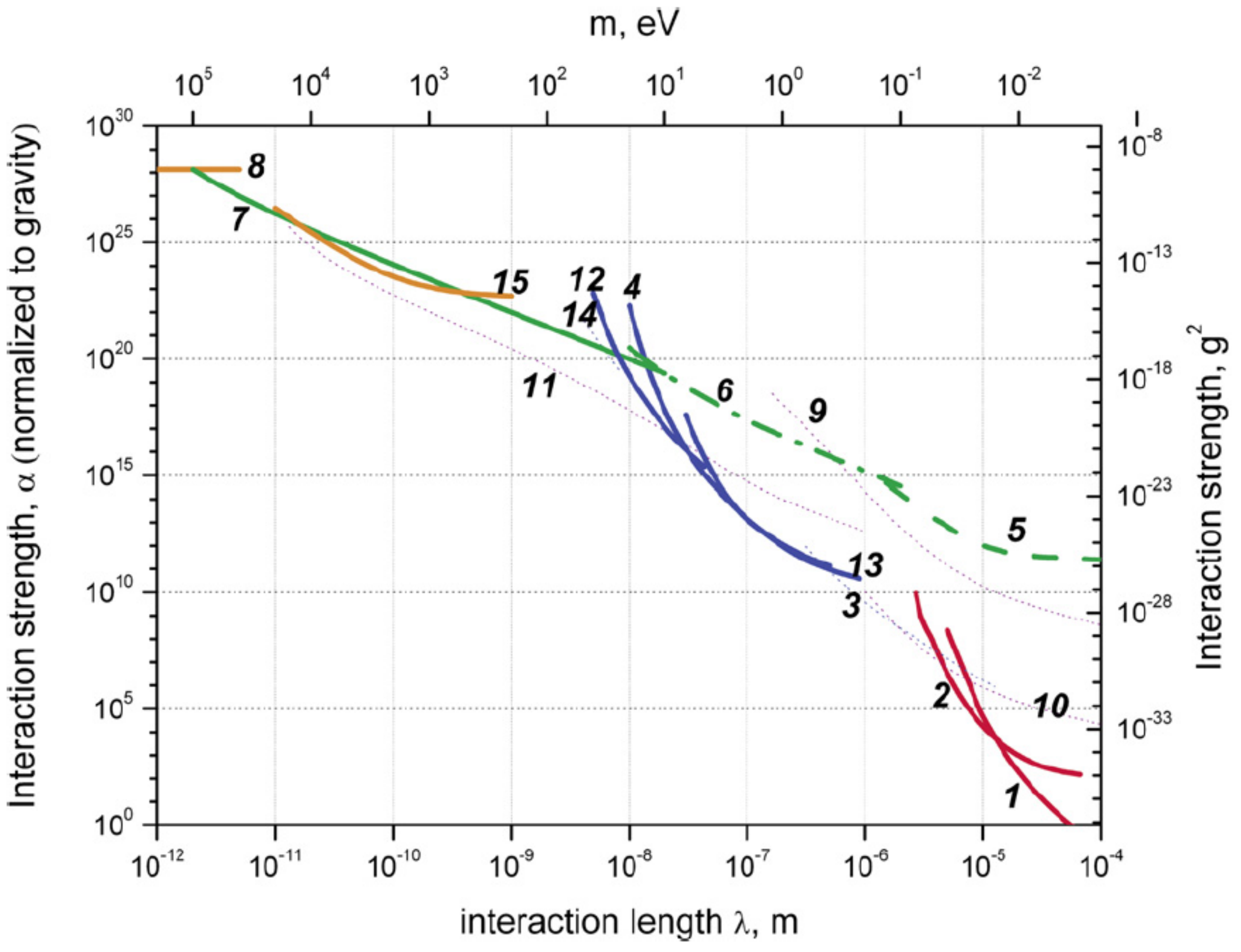
GRASIAN https://grasian.eu/

Short-range forces

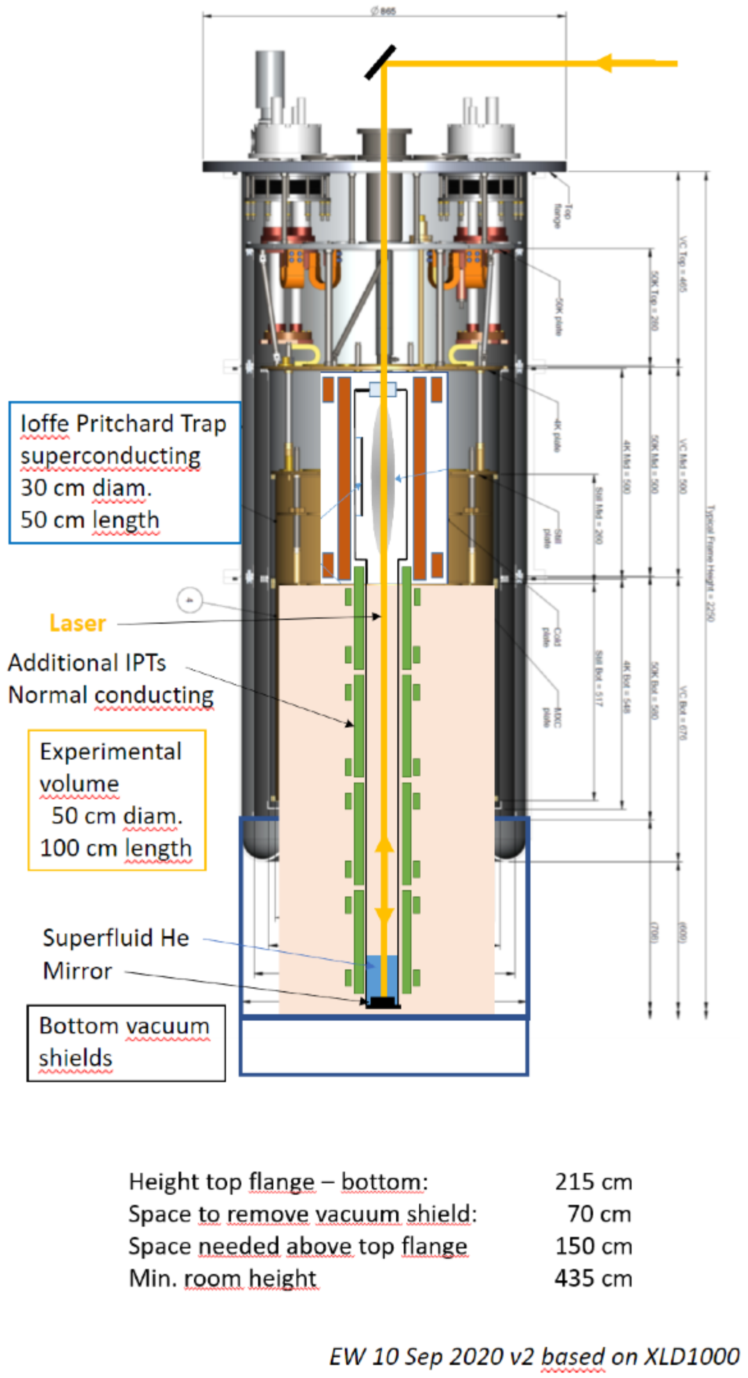
$$V(r) = \alpha G \frac{m_1 m_2}{r} e^{-\frac{r}{\lambda}}$$

- n,H: compare GQS transition frequencies to theory
- 5: n gravitational quantum states
- 9,10,11: future n experiments

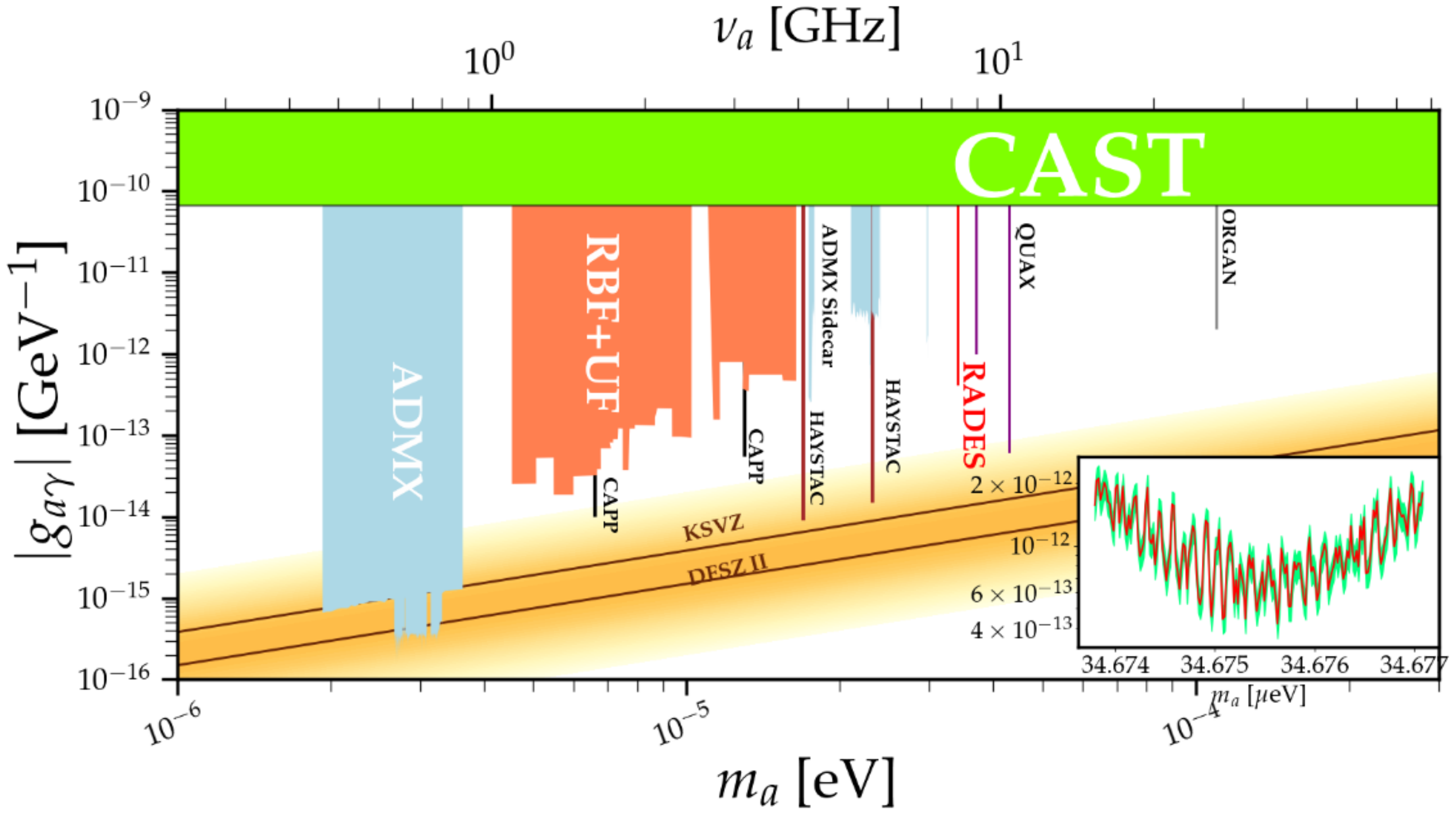
I. Antoniadis et al. / C. R. Physique 12 (2011) 755–778



Experiments in dilution cryostat



- Insert cryogenic solenoid magnet
  - 9T, ID 150 mm, 500 mm length
- Álvarez Melcón, A., Arguedas Cuendis, S., Baier, J. et al.

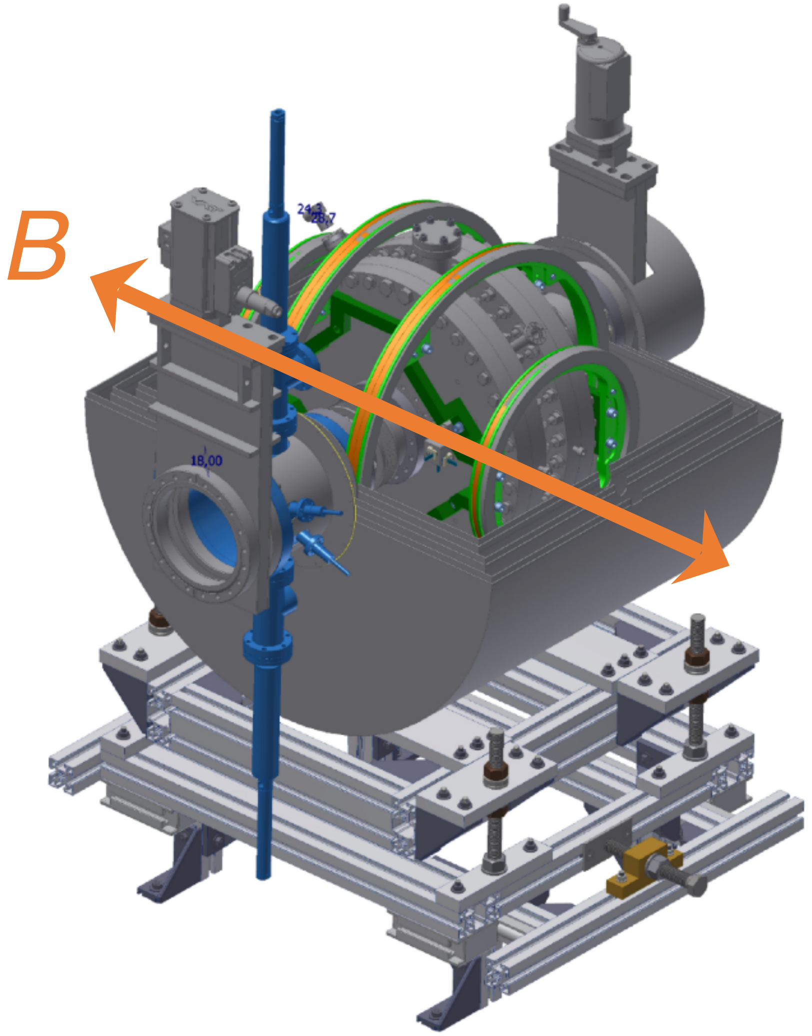


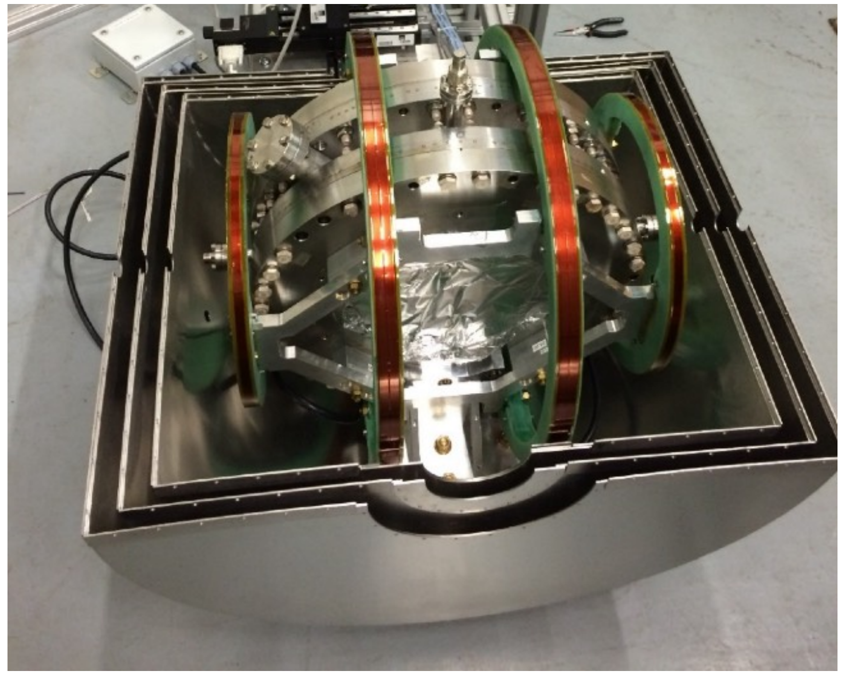
RADES: Álvarez Melcón, A. *et al*. *J. High Energ. Phys.* **2021**, 75 (2021).

The end

H-beam and non-minimal SME

- π_1 transition
  - Better field homogeneity needed
    - Inproved coils, shielding
  - SME: effect only in π_1
  - Non-minimal SME: direction dependent coefficients accessible by beam experiments
- Conditions
  - Invert direction of B-field – data taken
  - Rotate B-field – not yet
  - Measure σ_1 (no CPTV) as reference





Spectroscopy with bouncing H ($\bar{H}$?)

- Needs big $^3He/^4He$ dilution fridge
- Trap H, evaporative cooling
  - T1 superconducting trap
  - T2 normal conducting: turn off fast
- Velocity ~ cm/s, 10^7-10^8 atoms
- Height 20 cm
  - time per bounce O(0.1s)
  - Up to 100 bounces (theory)
    - Need to worry about lateral drift
- HFS: Precision may reach **mHz**

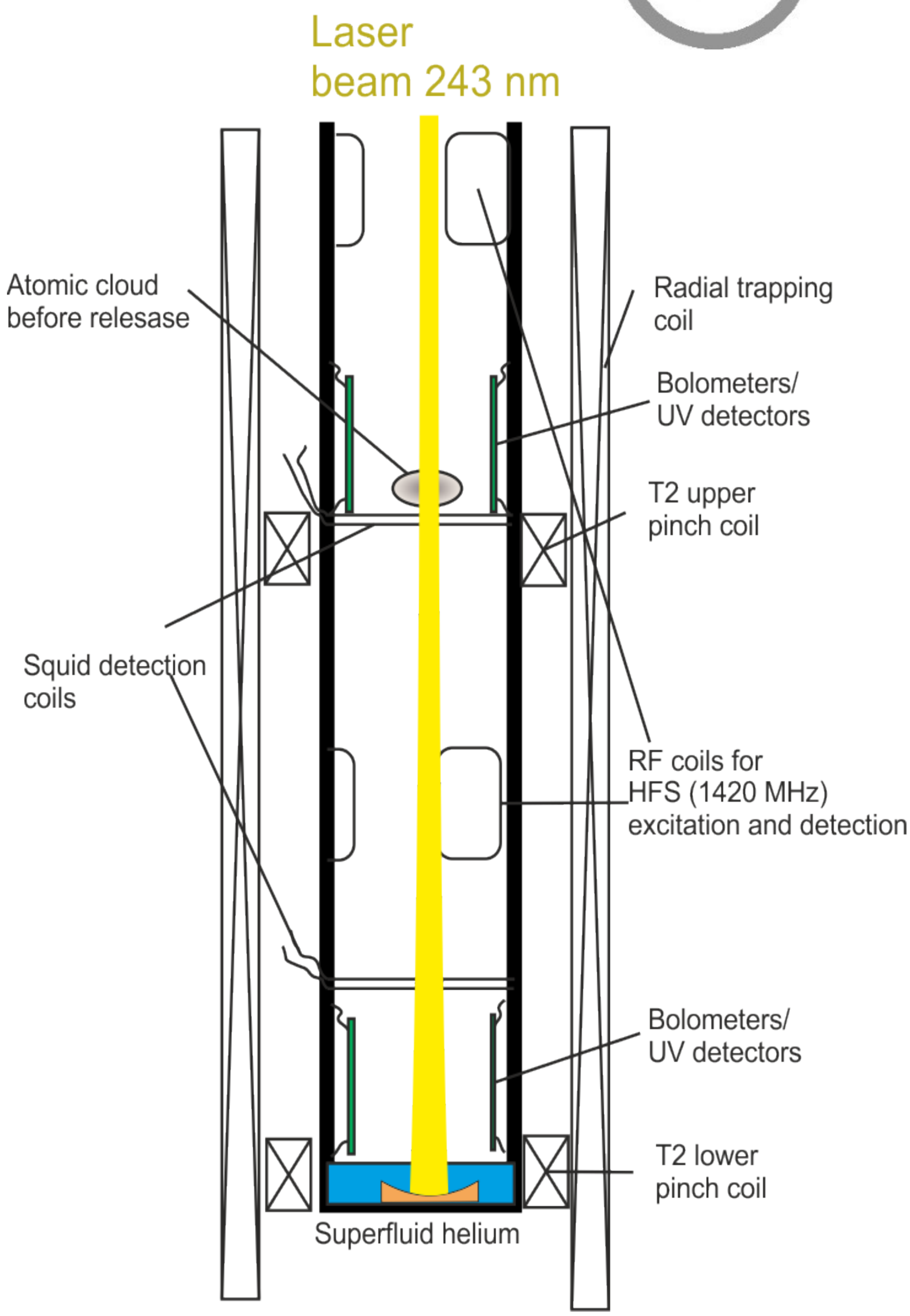


Figure 4. HFS spectroscopy experiment at ultra-low energies of H(D)

CPT symmetry & cosmology

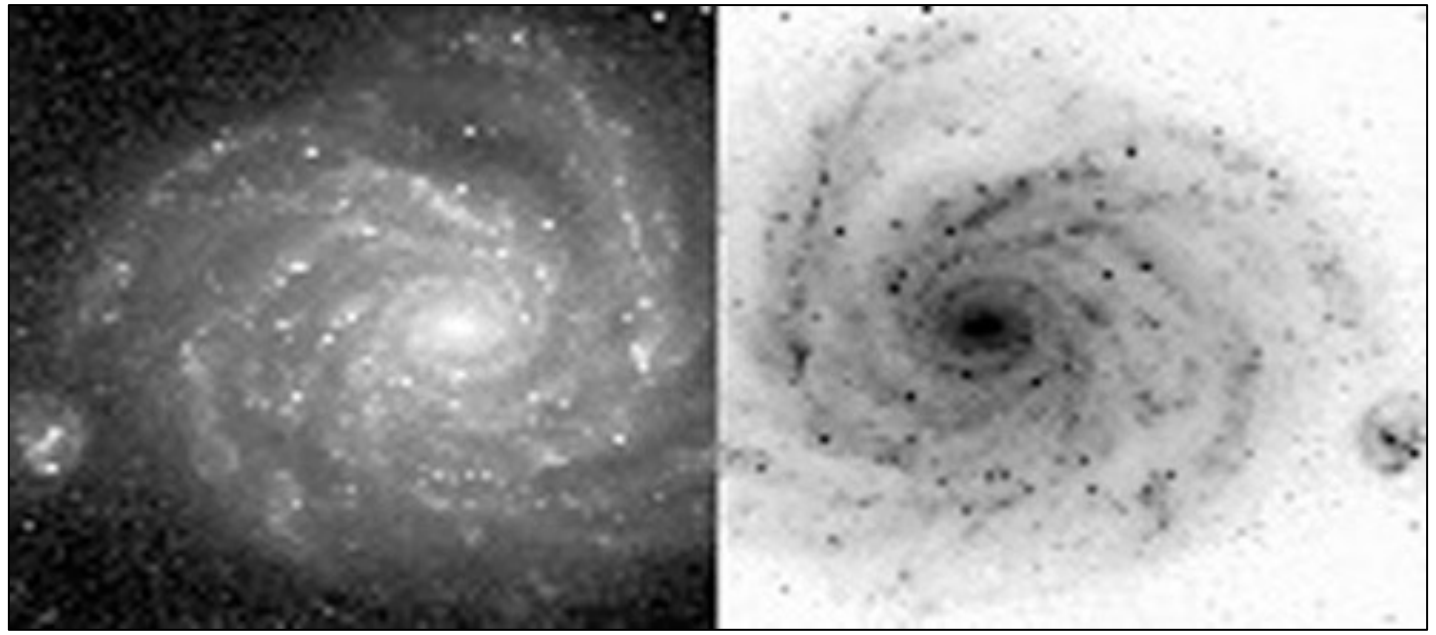
CPT symmetry & cosmology

- Mathematical theorem
  - not valid e.g. in string theory, quantum gravity

CPT symmetry & cosmology

- Mathematical theorem
  - not valid e.g. in string theory, quantum gravity
- Problem: antimatter absence in the universe

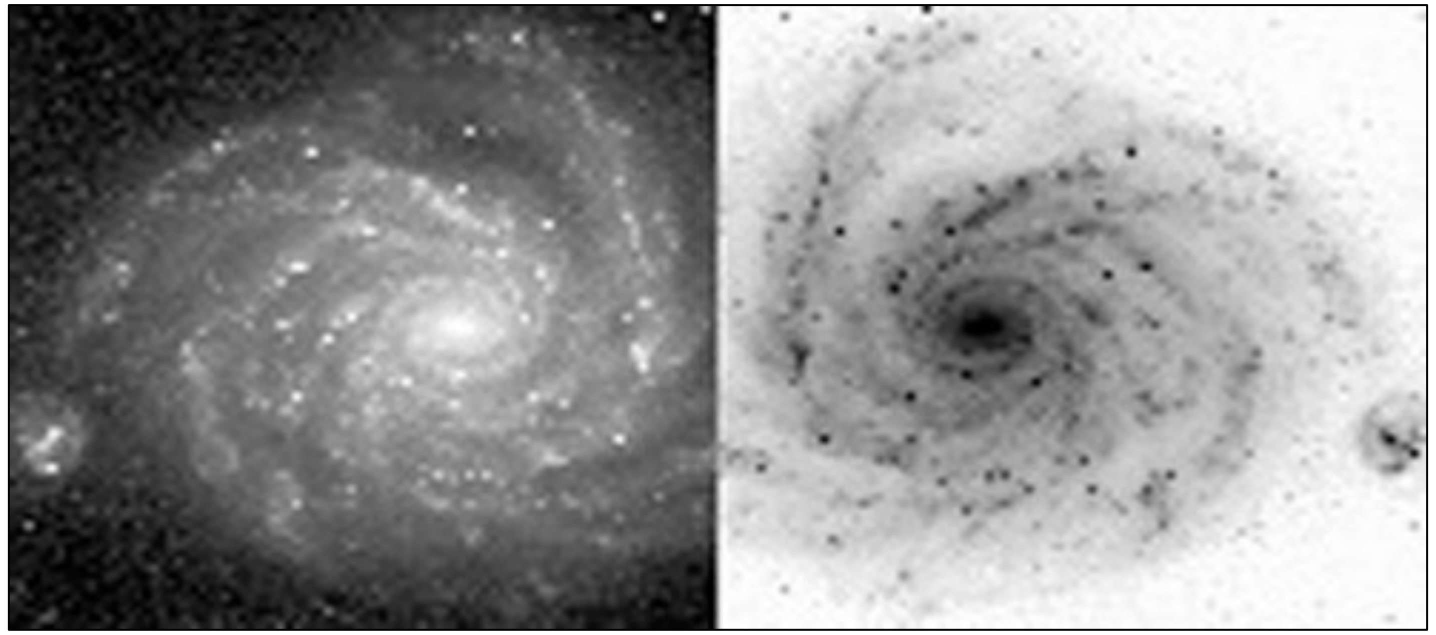
$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6.1 \ x \ 10^{-10}$$ WMAP



CPT symmetry & cosmology

- Mathematical theorem
  - not valid e.g. in string theory, quantum gravity
- Problem: antimatter absence in the universe
- Big Bang -> if CPT holds: equal amounts of matter / antimatter
  - Standard scenario for Baryogenesis (Sakharov 1967)
    - *Baryon-number non-conservation*
    - *C and CP violation*
    - *Deviation from thermal equilibrium*
  - Generate Baryon asymmetry during evolution

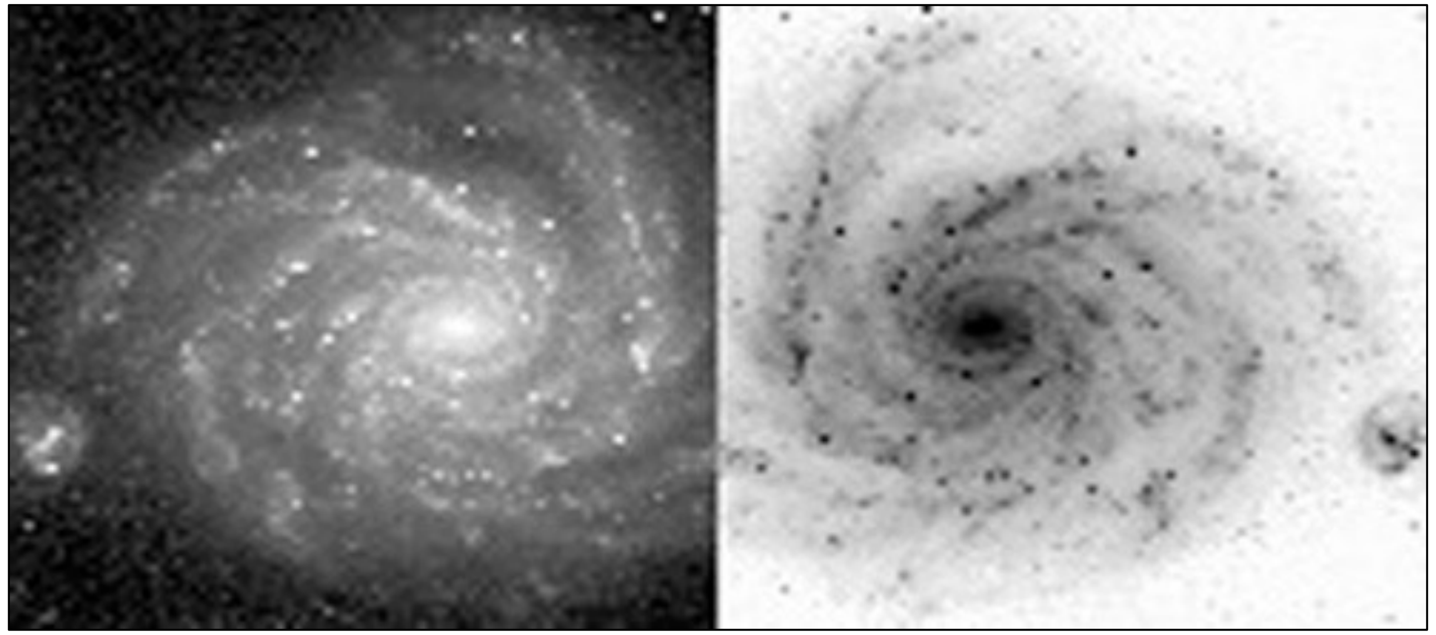
$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6.1 \; x \; 10^{-10} \quad \text{WMAP}$$



CPT symmetry & cosmology

- Mathematical theorem
  - not valid e.g. in string theory, quantum gravity
- Problem: antimatter absence in the universe
- Big Bang -> if CPT holds: equal amounts of matter / antimatter
  - Standard scenario for Baryogenesis (Sakharov 1967)
    - *Baryon-number non-conservation*
    - *C and CP violation*
    - *Deviation from thermal equilibrium*
  - Generate Baryon asymmetry during evolution
- Currently known CPV not large enough
  - Other source of baryon asymmetry?

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6.1 \, x \, 10^{-10}$$ WMAP



Bertolami, O., Colladay, D., Kostelecký, V. A. & Potting, R.
CPT violation and baryogenesis. *Physics Letters B* **395**, 178–183 (1997).

Comparison of CPT tests particle-antiparticle: SME

- Standard Model Extension SME

CPT & LORENTZ VIOLATION

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \tfrac{1}{2} H^e_{\mu\nu} \sigma^{\mu\nu} + i c^e_{\mu\nu} \gamma^\mu D^\nu + i d^e_{\mu\nu} \gamma_5 \gamma^\mu D^\nu)\psi = 0\,.$$

LORENTZ VIOLATION

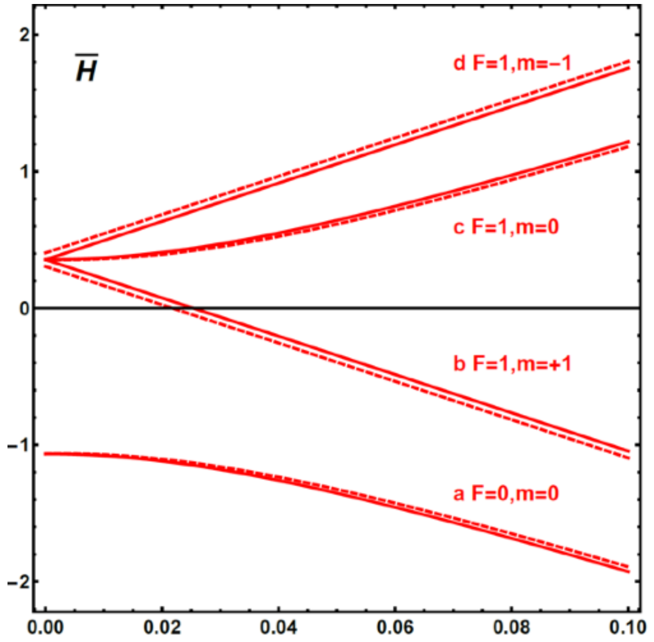
D. Colladay and V.A. Kostelecky, PRD 55, 6760 (1997)

- Minimal SME: only HFS

Bluhm, R., Kostelecky, V., & Russell, N., PRL *82*, 2254–2257 (1999).

- Non-minimal SME: 1S-2S shows higher-order CPTV

Kostelecký, V. A. & Vargas, A. J. PRD 056002 (2015).



Comparison of CPT tests particle-antiparticle: SME

- Standard Model Extension SME

CPT & LORENTZ VIOLATION

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \frac{1}{2} H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^\mu D^\nu + id^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0 .$$

LORENTZ VIOLATION

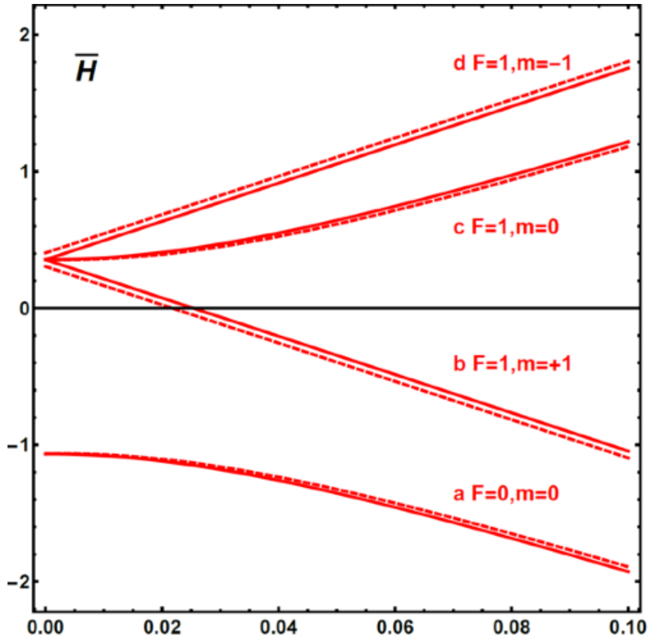
D. Colladay and V.A. Kostelecky, PRD 55, 6760 (1997)

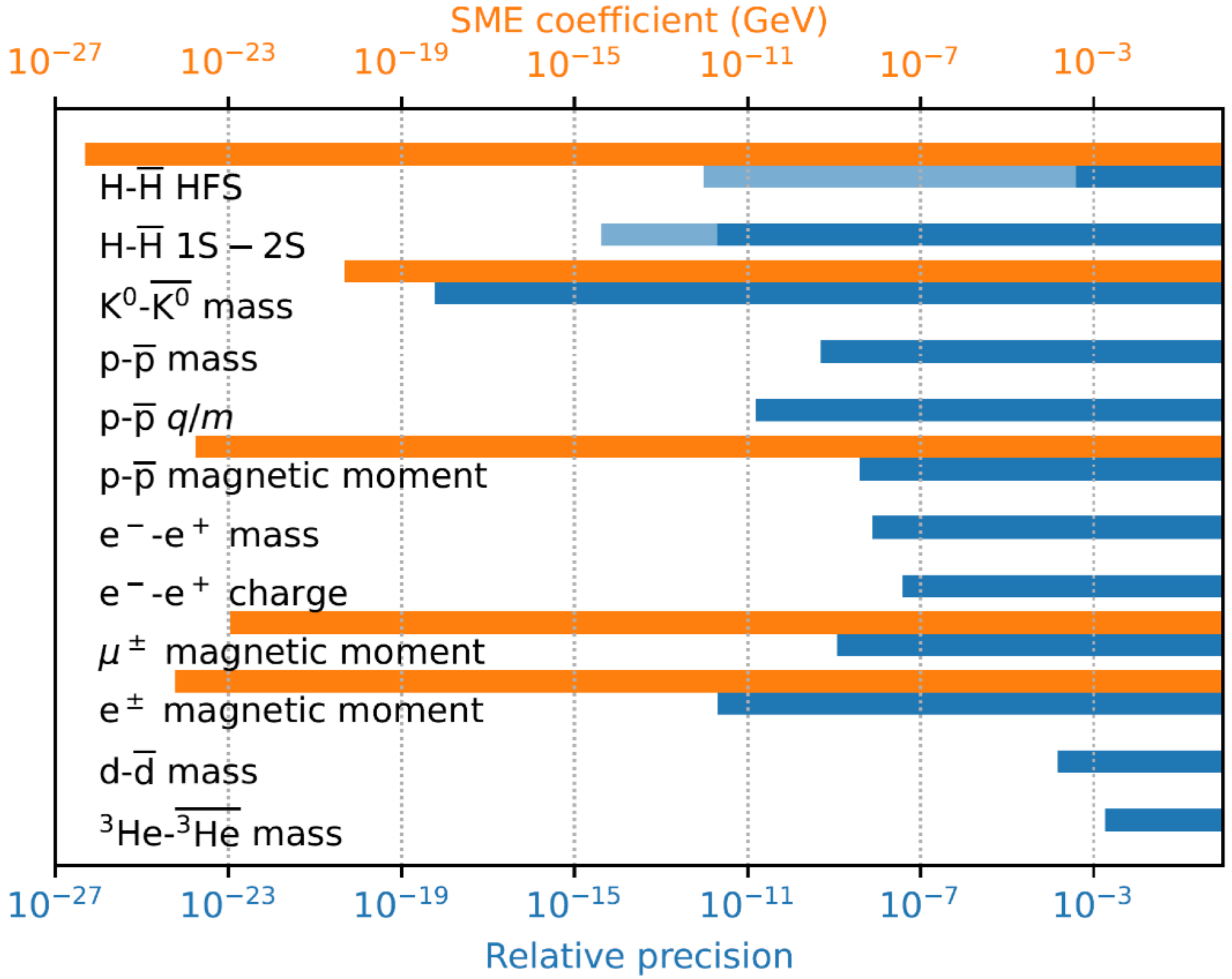
- Minimal SME: only HFS

Bluhm, R., Kostelecky, V., & Russell, N., PRL *82*, 2254–2257 (1999).

- Non-minimal SME: 1S-2S shows higher-order CPTV

Kostelecký, V. A. & Vargas, A. J. PRD 056002 (2015).





Source: PDG, Kostelecky & Bluhm arXiv:0801.0287 (updated annually)
EW, Phys. Part. Nuclei **53**, 790–794 (2022). arXiv:2111.04056 [hep-ex]