# Precise atomic physics utilising antimatter

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Ministry of Education and Science
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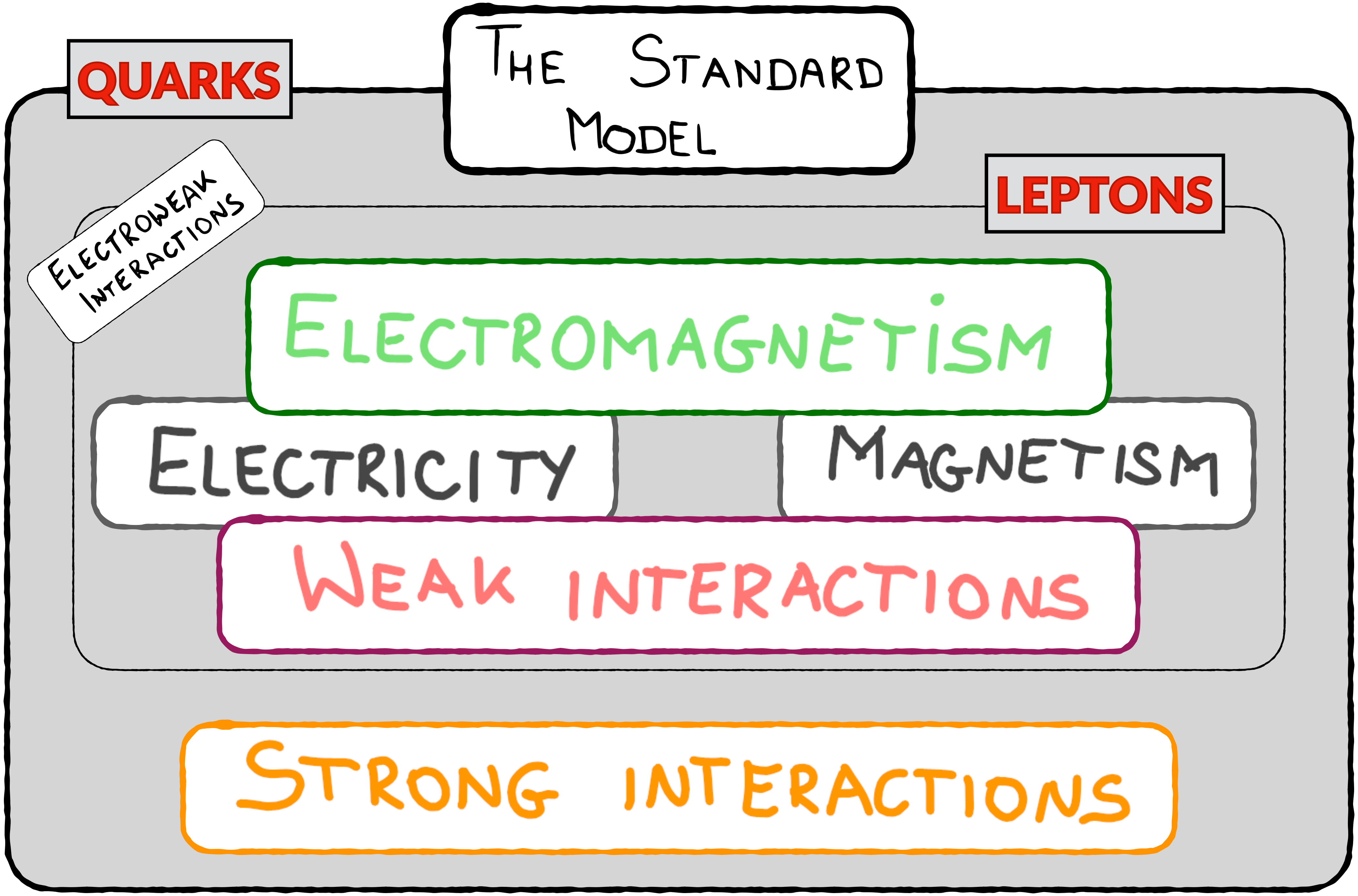
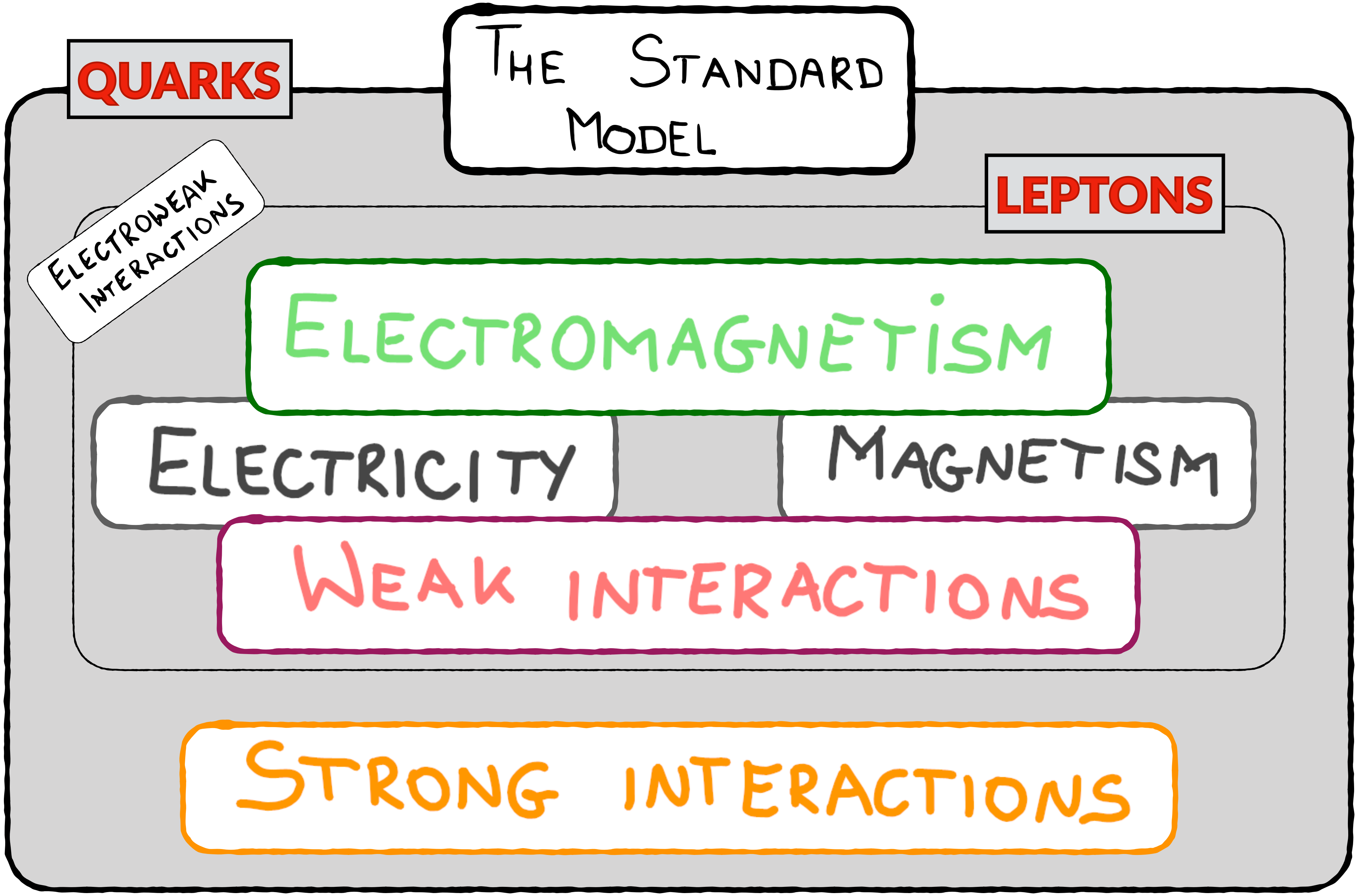
# the Standard Model




**in HEP experiments, no visible deviations from the Standard Model predictions**

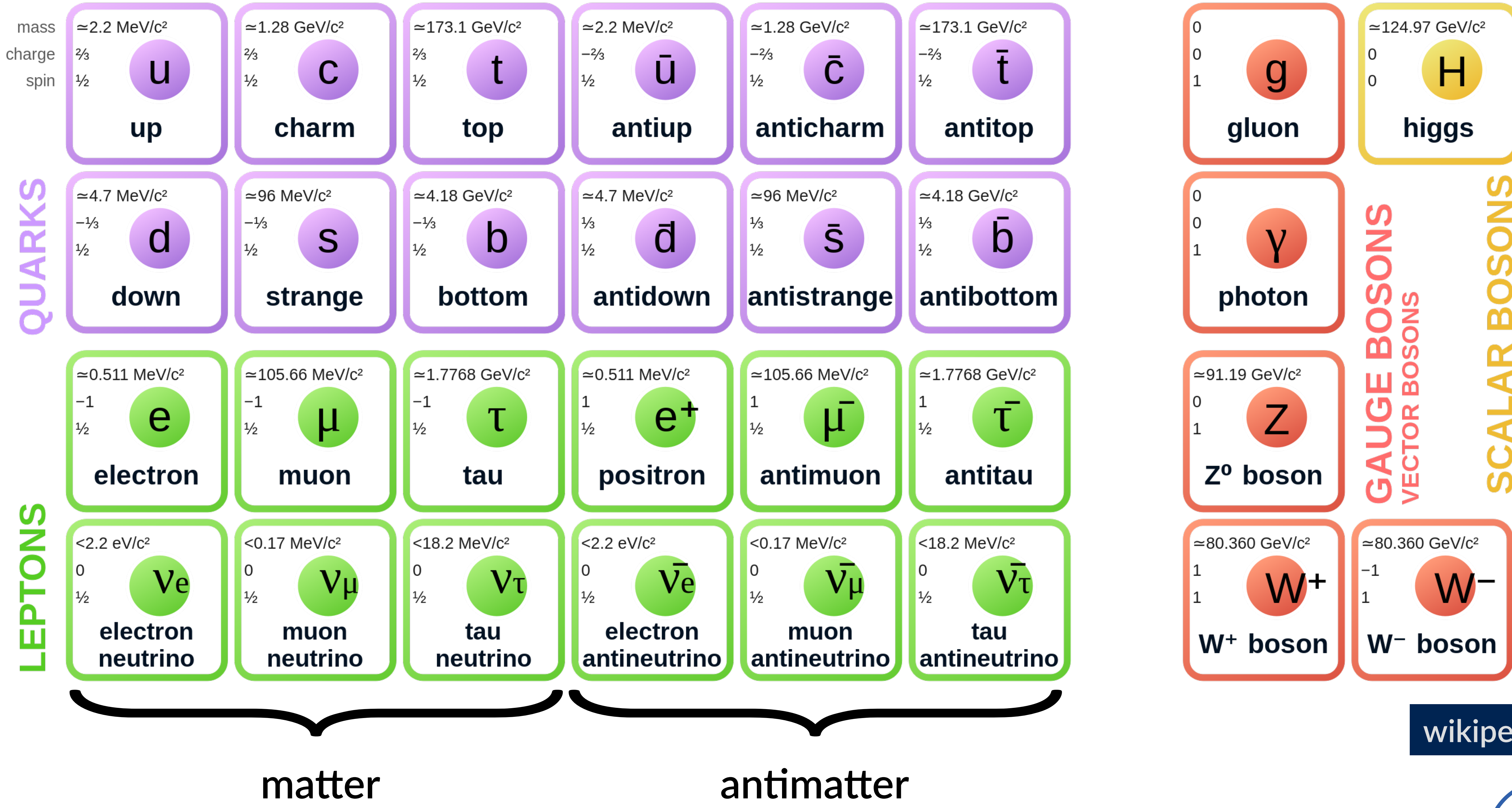
# the Standard Model




**in HEP experiments, no visible deviations from the Standard Model predictions**

**... almost true ... ☞ Muon g-2 experiment**

# the Standard Model




wikipedia.org

# … full symmetry in the theory

## matter and antimatter
## ARE ALWAYS
## produced in equal amounts

- conservation of the barion number

$$\tau(p \to e^+\pi^0) > 10^{33}\,\mathrm{yrs}$$

- conservation of the leptonic number

$$\tau(^{76}\mathrm{Ge} \to ^{76}\mathrm{Se} + \bar{\nu} + e^- + e^-) > 10^{26}\,\mathrm{yrs}$$

- conservation of the electric charge

$$\tau(n \to p\nu_e\bar{\nu}_e) > 10^{18}\,\mathrm{yrs}$$

D. H. Perkins: *Introduction to High Energy Physics*, Cambridge University Press, 2000

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... almost true ...

interested ??

"sphaleron"

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D. H. Perkins: *Introduction to High Energy Physics*, Cambridge University Press, 2000

# ... clear disproportion in Nature!

- In the visible part of the Universe matter significantly dominates antimatter

$$\frac{N_B - N_{\bar{B}}}{N_\gamma} \approx 6 \times 10^{-10} \qquad N_\gamma \approx 400\,\mathrm{cm}^{-3}$$

- Assuming that just after the Big Bang only radiation was present the Standard Model fails to explain such a huge disproportion

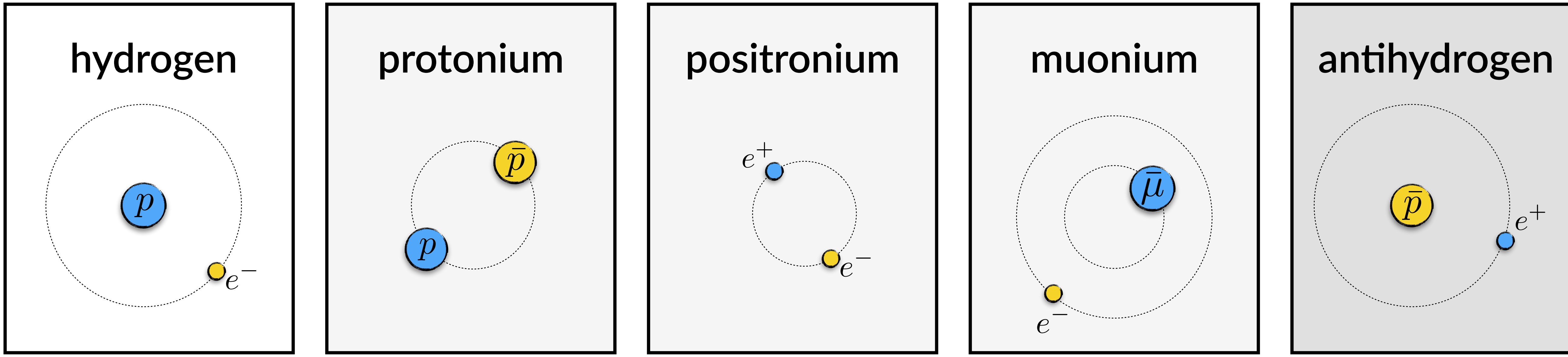
$$\frac{N_B}{N_\gamma} = \frac{N_{\bar{B}}}{N_\gamma} \approx 10^{-20}$$

**More details needed ?? ☞ check Sakharov conditions (1967) ...**

J. M. Cline: *Baryogenesis*, hep-ph/0609145
(lectures at Les Houches Summer School, 2006)

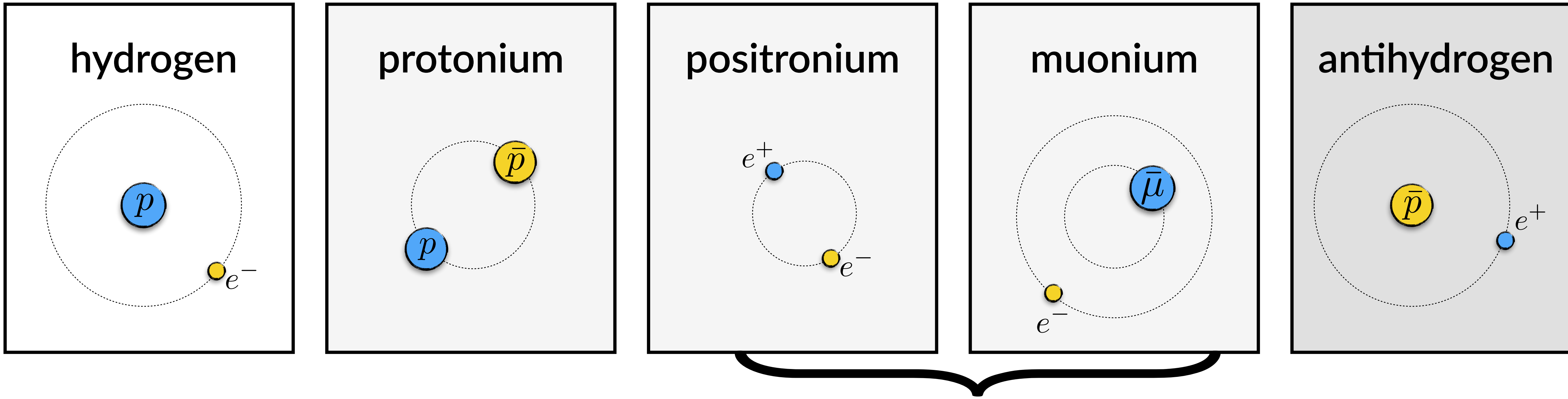
# exotic atoms with antimatter...

## hydrogen-like atoms



# exotic atoms with antimatter...

## hydrogen-like atoms

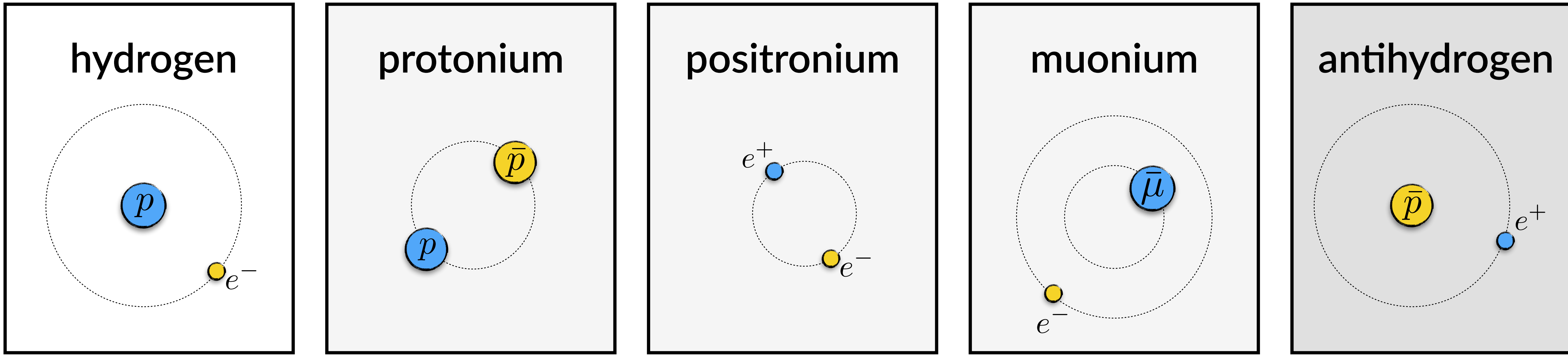



purely leptonic systems

precise tests of the electroweak sector!

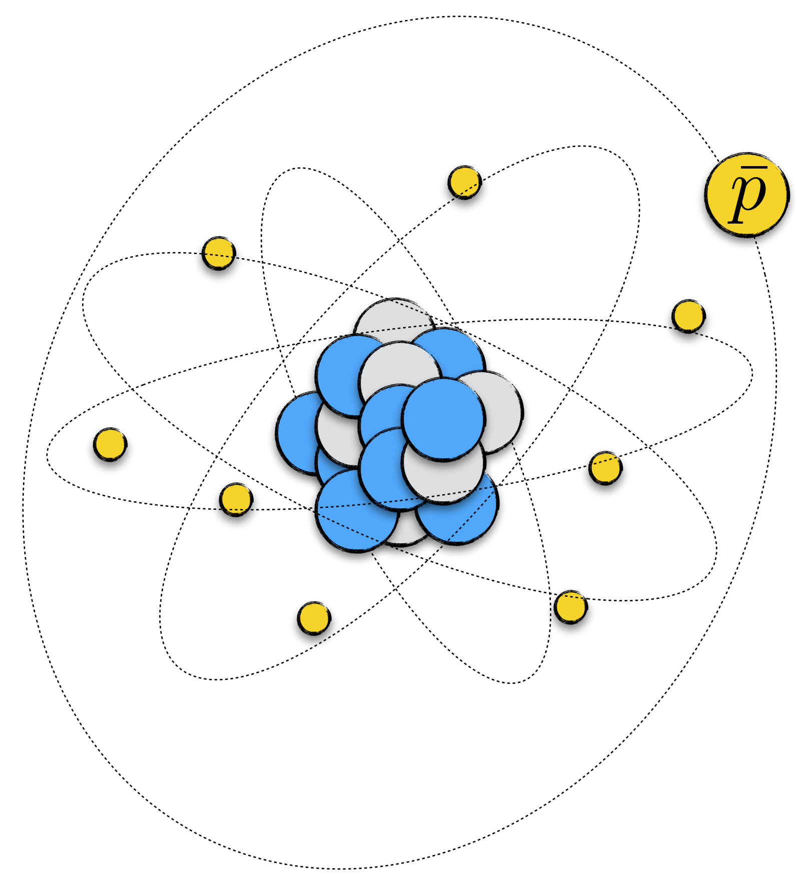
# exotic atoms with antimatter...

## hydrogen-like atoms

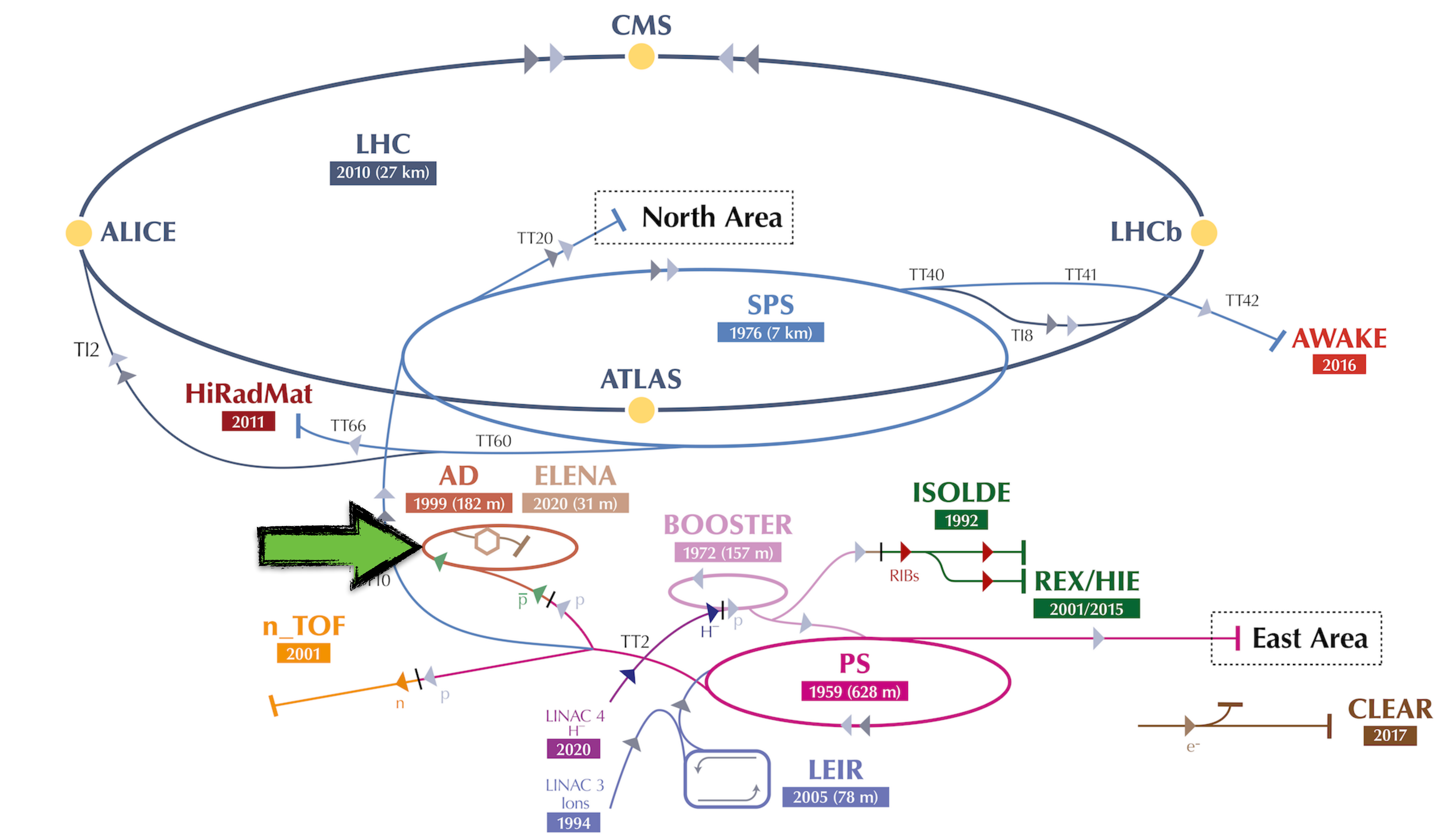



## neutral antiprotonic atoms

- heavier atoms with one (or more) electron substituted by antiproton
- their properties are purely explored
- may server as excellent platform for testing the Standard Model on the intersection of electroweak and strong interactions



# The CERN accelerator complex
# *Complexe des accélérateurs du CERN*




▶ $H^-$ (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ $\bar{p}$ (antiprotons) ▶ $e^-$ (electrons)

**LHC** - Large Hadron Collider // **SPS** - Super Proton Synchrotron // **PS** - Proton Synchrotron // **AD** - Antiproton Decelerator // **CLEAR** - CERN Linear Electron Accelerator for Research // **AWAKE** - Advanced WAKefield Experiment // **ISOLDE** - Isotope Separator OnLine // **REX/HIE** - Radioactive EXperiment/High Intensity and Energy ISOLDE // **LEIR** - Low Energy Ion Ring // **LINAC** - LINear ACcelerator // **n_TOF** - Neutrons Time Of Flight // **HiRadMat** - High-Radiation to Materials

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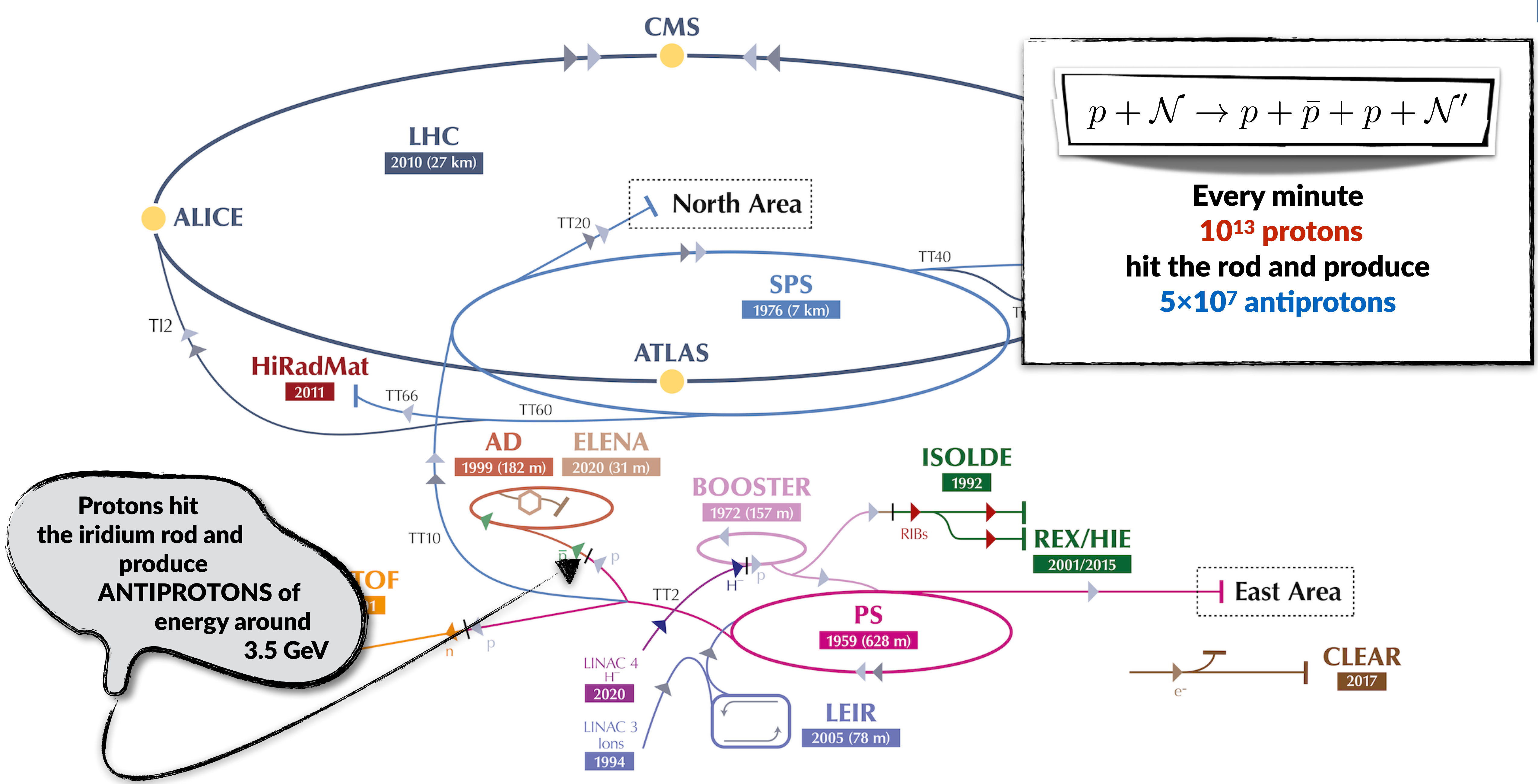
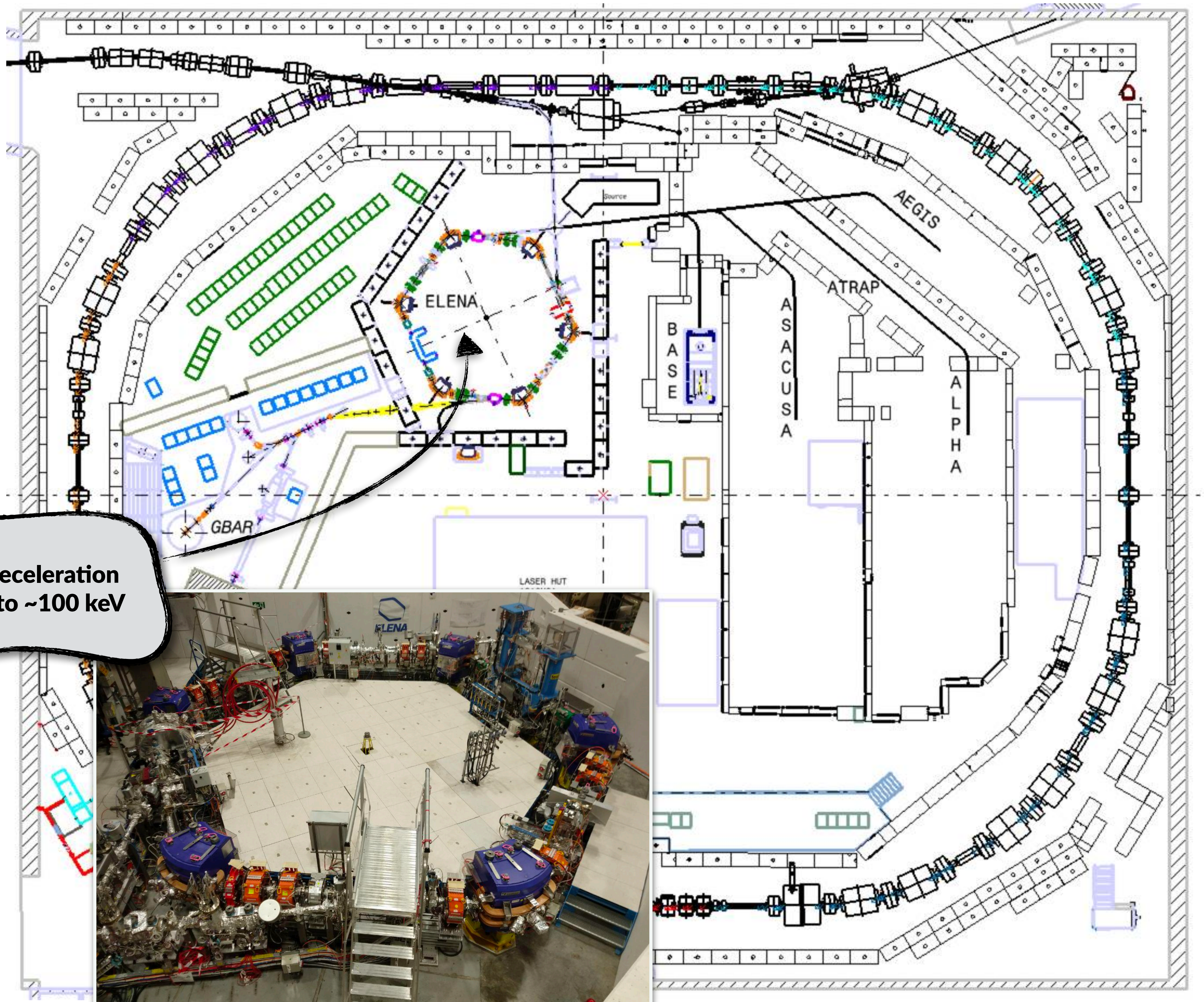



▶ H⁻ (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ p̄ (antiprotons) ▶ e⁻ (electrons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials

ELENA
Extra Low ENergy Antiprotons




Further deceleration down to ~100 keV

**delivery of about 5 millions of antiprotons every 2 minutes**

# atomic precision with antimatter

$$\mu_{\bar{p}} = 2.792\,847\,344\,1(42)\mu_N$$
$$\mu_p = 2.792\,847\,344\,62(82)\mu_N$$

BASE Coll.: Nature 550, 371 (2017)

$$\frac{(q/m)_{\bar{p}}}{(q/m)_p} - 1 = 1(69) \times 10^{-12}$$

BASE Coll.: Nature 524, 196 (2015)

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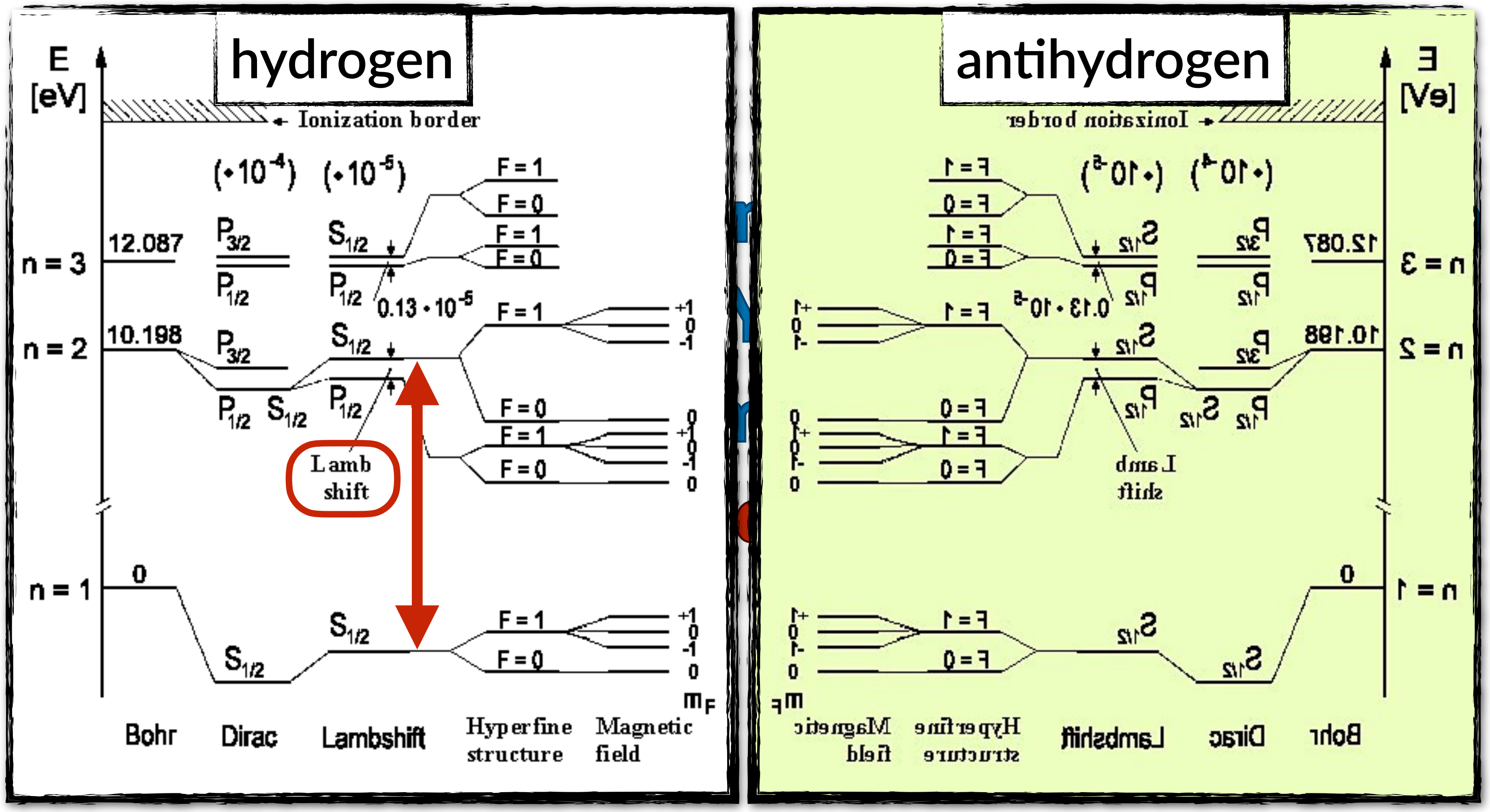



**1S ↔ 2S (magnetic field ~1T)**

**antihydrogen: 2 466 061 103 079.4(5.4)kHz**

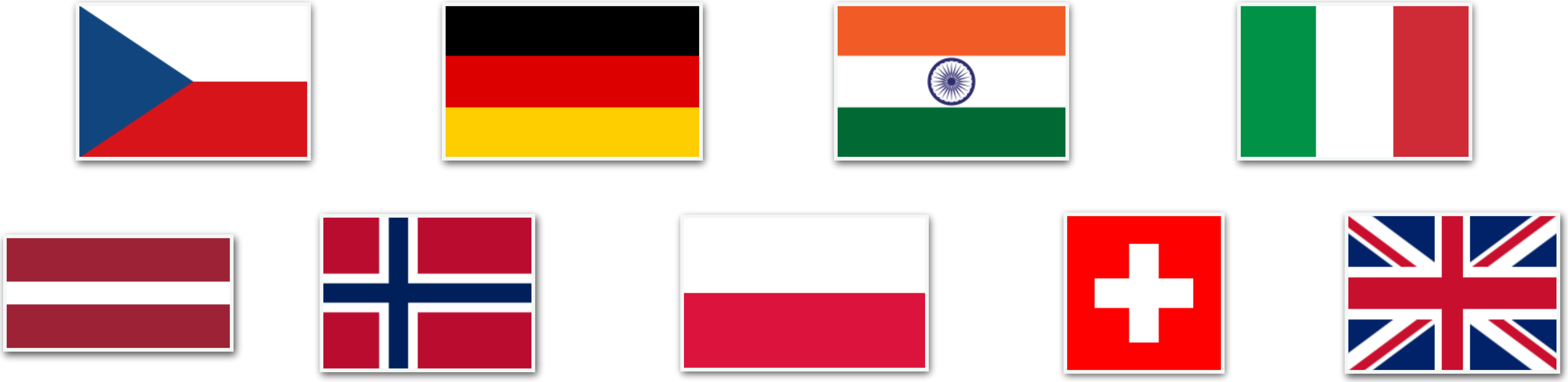
**hydrogen: 2 466 061 103 080.3(0.6)kHz**

Alpha Coll.: Nature 557, 71 (2018)

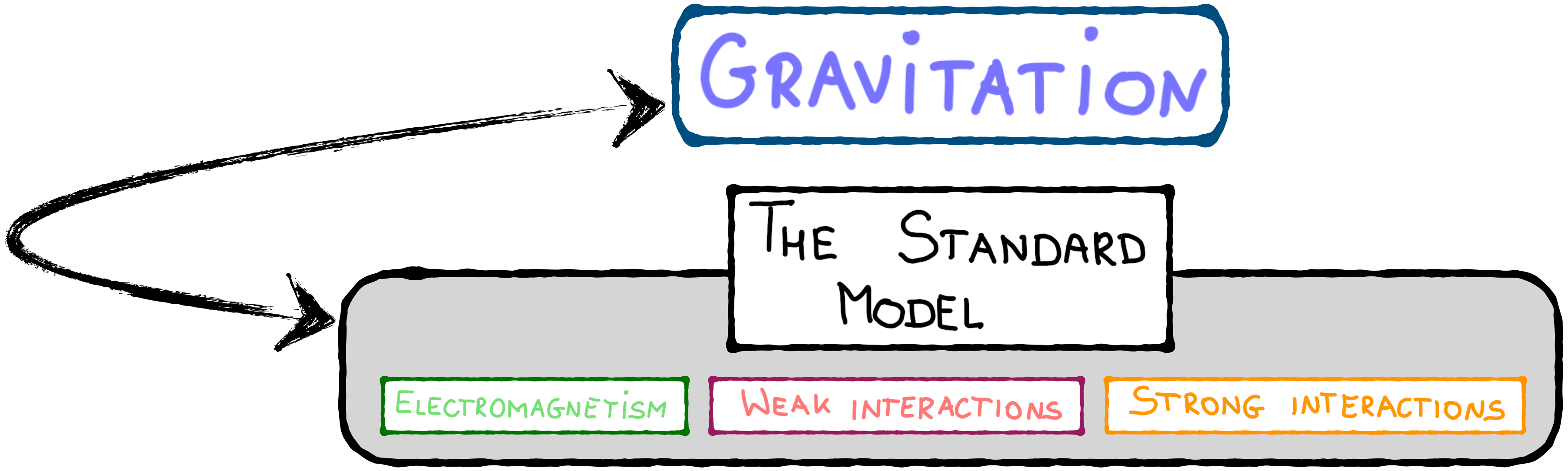
Alpha Coll.: Nature 578, 375 (2020)

## Antihydrogen Experiment Gravity, Interferometry, Spectroscopy

*AEgIS Collaboration Meeting, Warsaw, 2023*



# ... the main goal

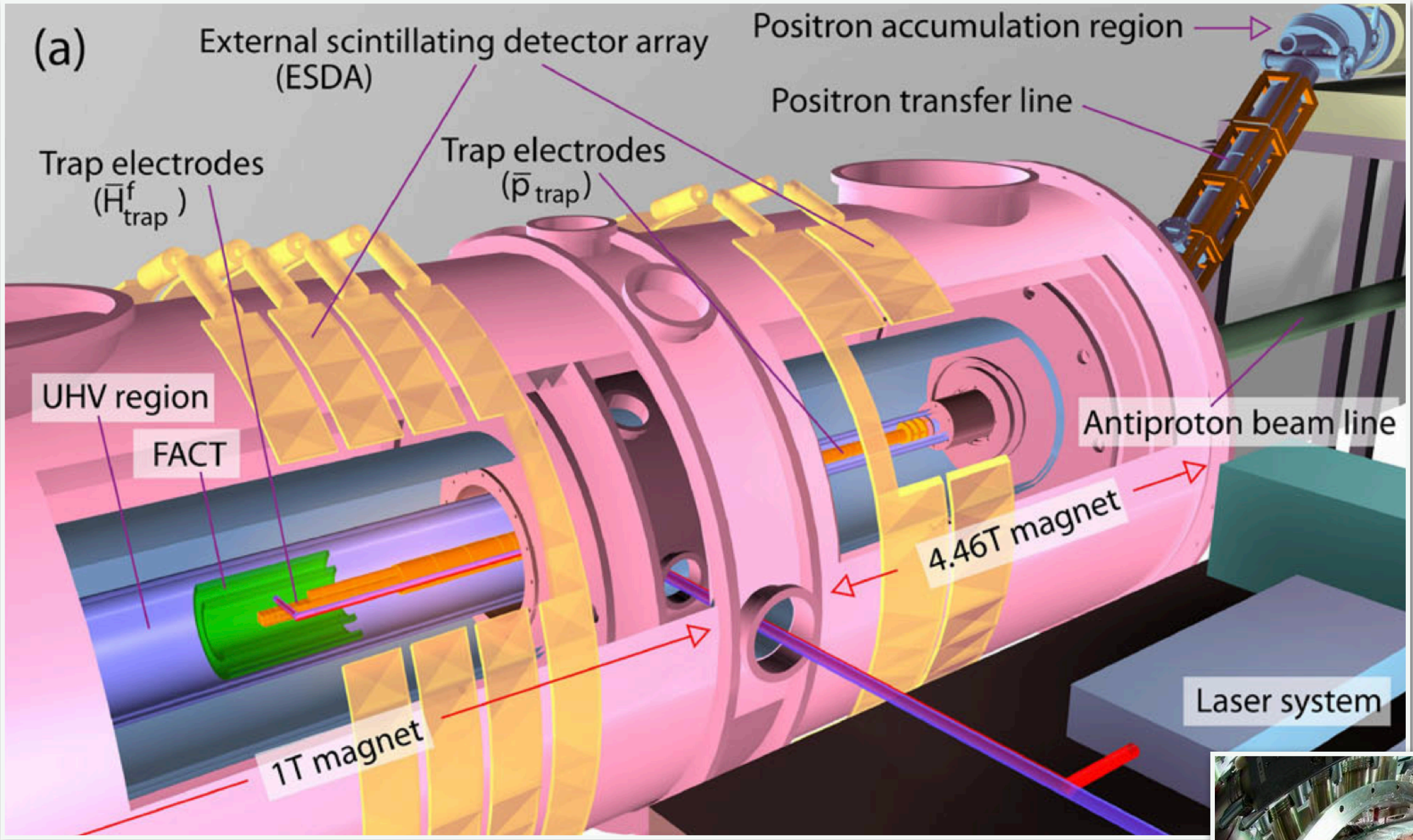


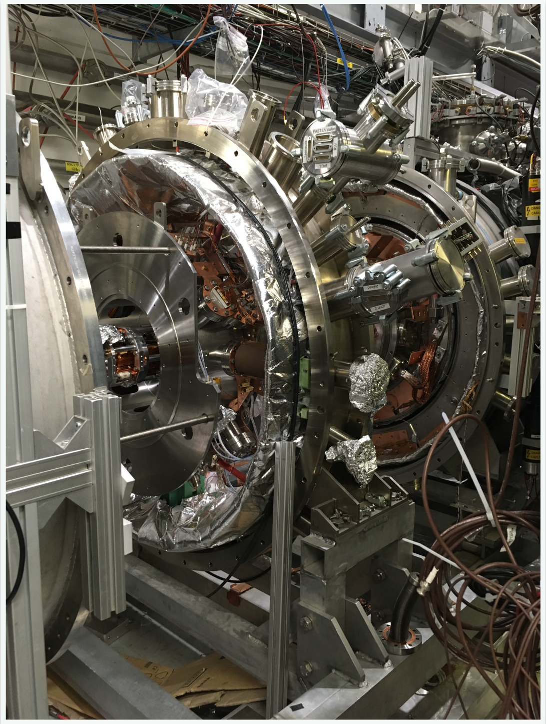

## Weak Equivalence Principle

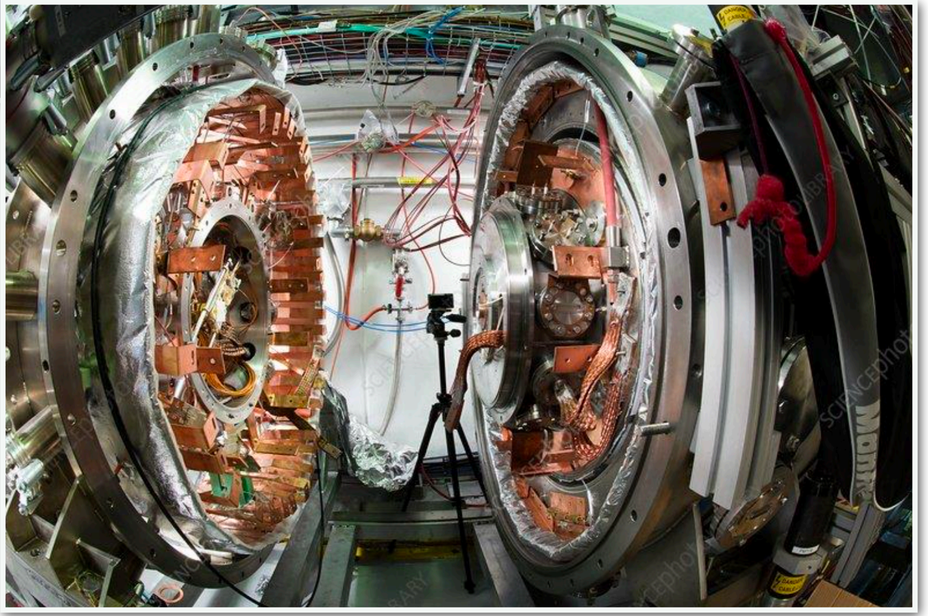
**Free fall of material objects**
**IS COMPLETELY INDEPENDENT**
**from their mass and internal structure**

**Experimentally verified for material objects**
**on all possible scales**

# AEgIS experiment



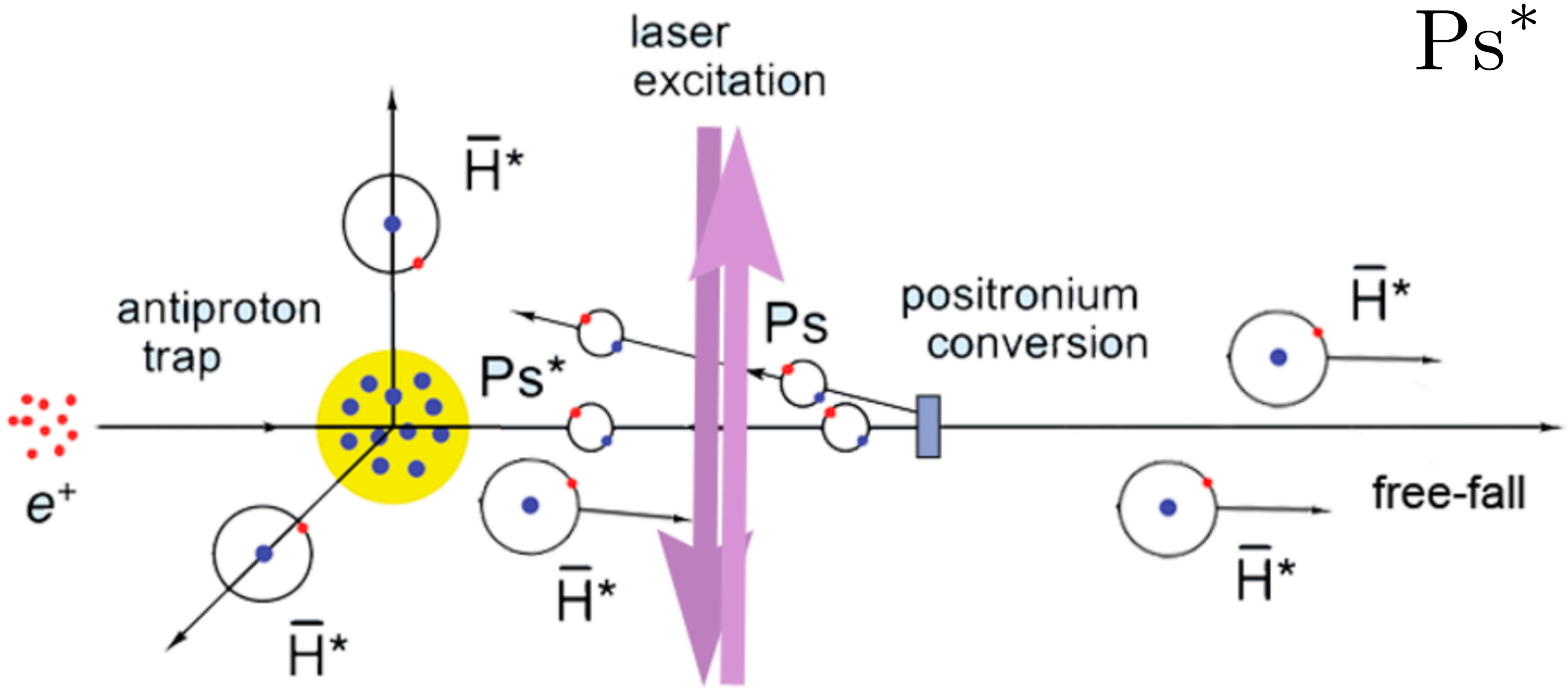



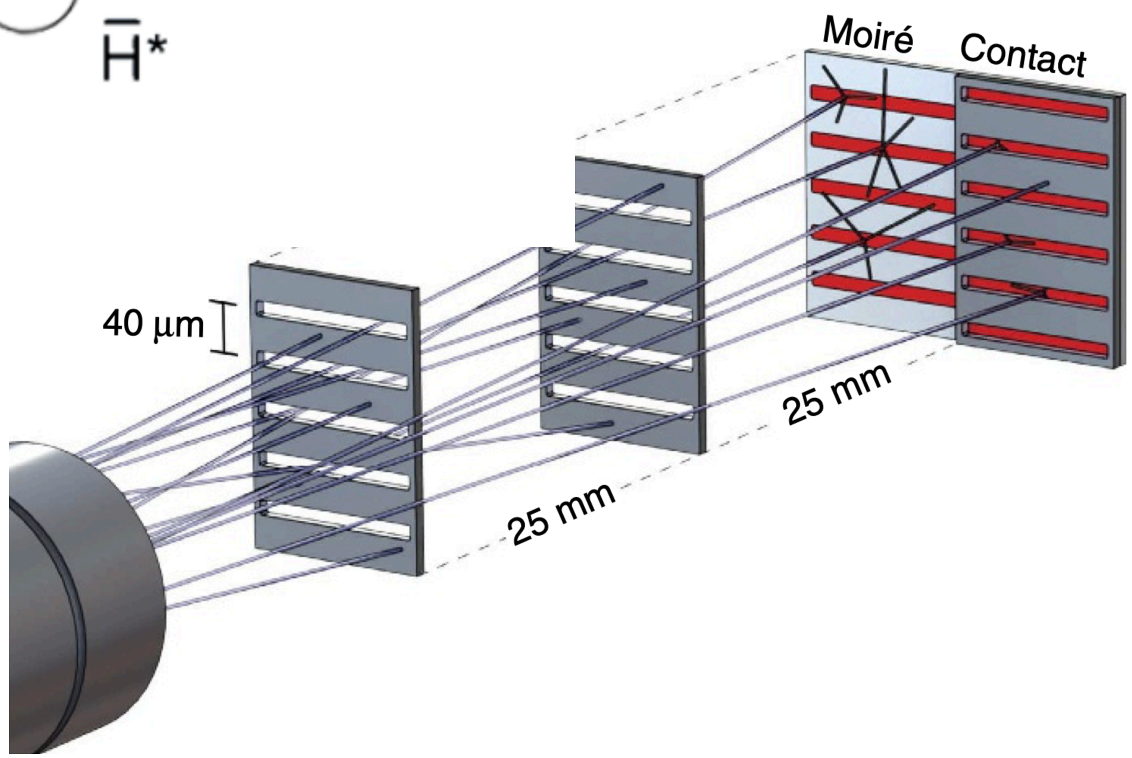


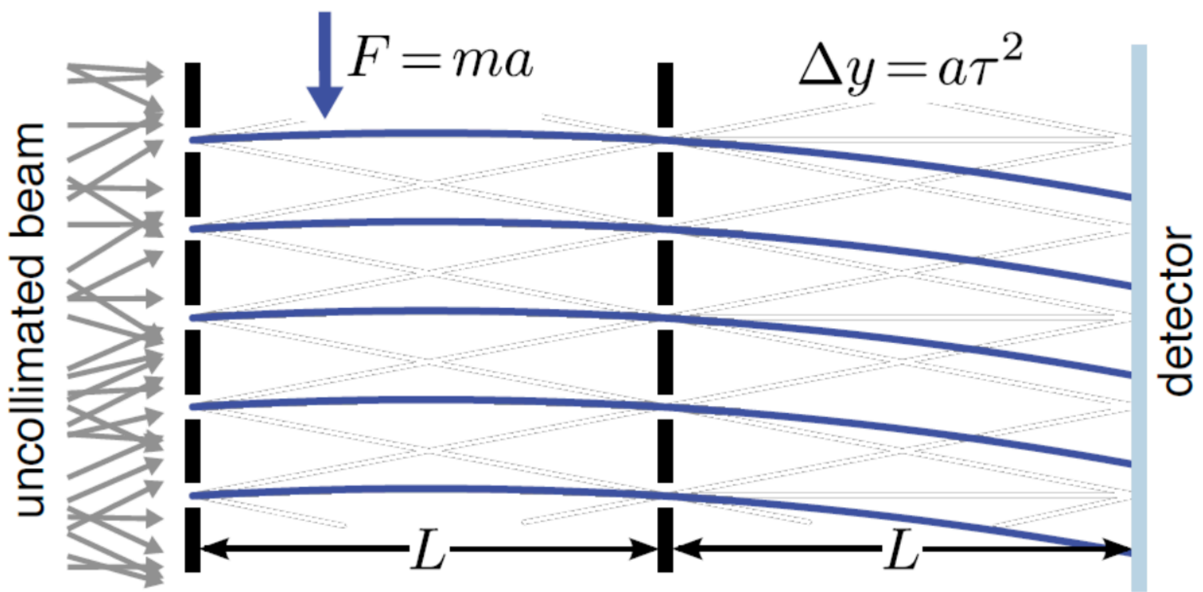
AEgIS Coll.: Comm. Phys. 4, 19 (2021)

# antihydrogen free-fall experiment

$$\mathrm{Ps}^* + \bar{p} \rightarrow \bar{\mathrm{H}}^* + e^-$$



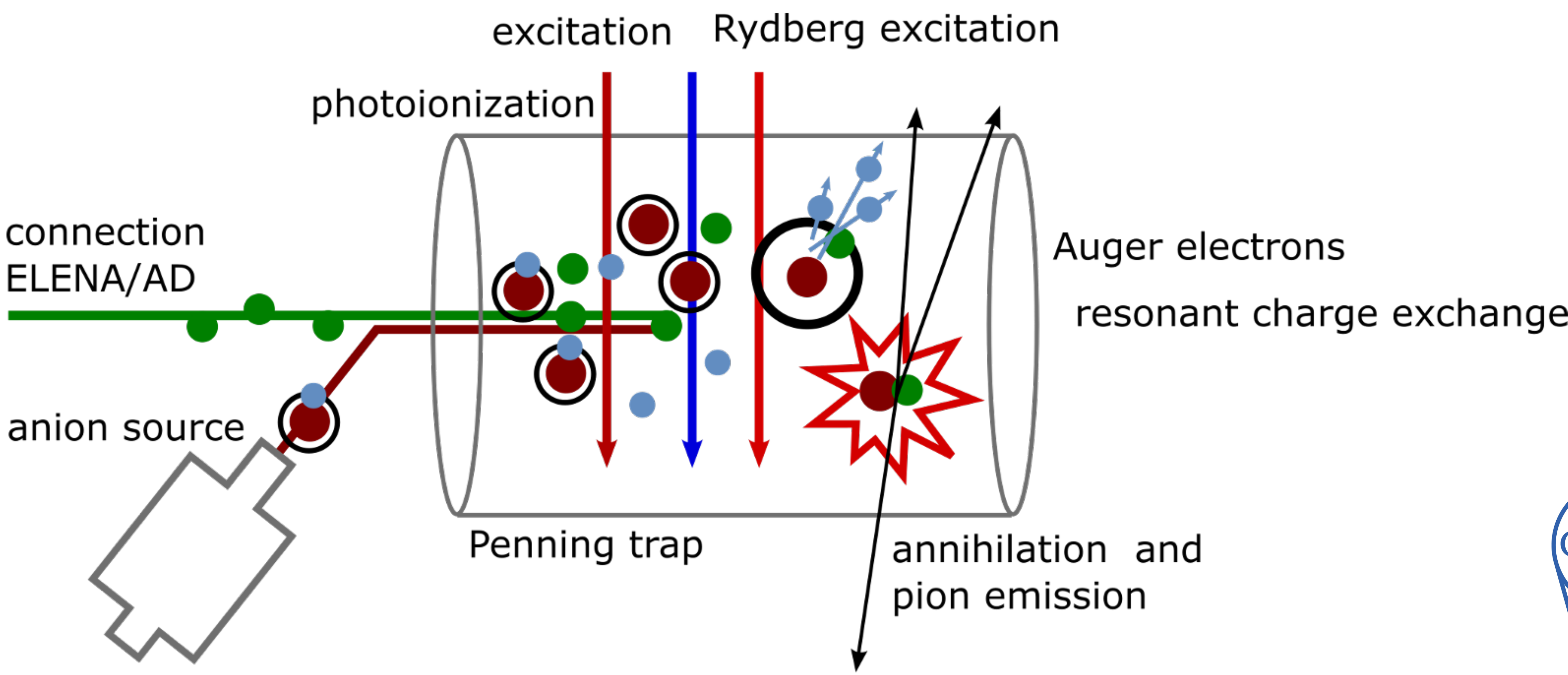

AEgIS Coll.: Nature Comm. 5, 4538 (2014)

# towards antiprotonic atoms

$$\mathrm{Ps}^* + \bar{p} \rightarrow \bar{\mathrm{H}}^* + e^-$$

$$\mathrm{Cs}^- + \bar{p} \rightarrow \bar{p}\mathrm{Cs}^* + e^- + e^- \qquad \mathrm{I}^- + \bar{p} \rightarrow \bar{p}\mathrm{I}^* + e^- + e^-$$

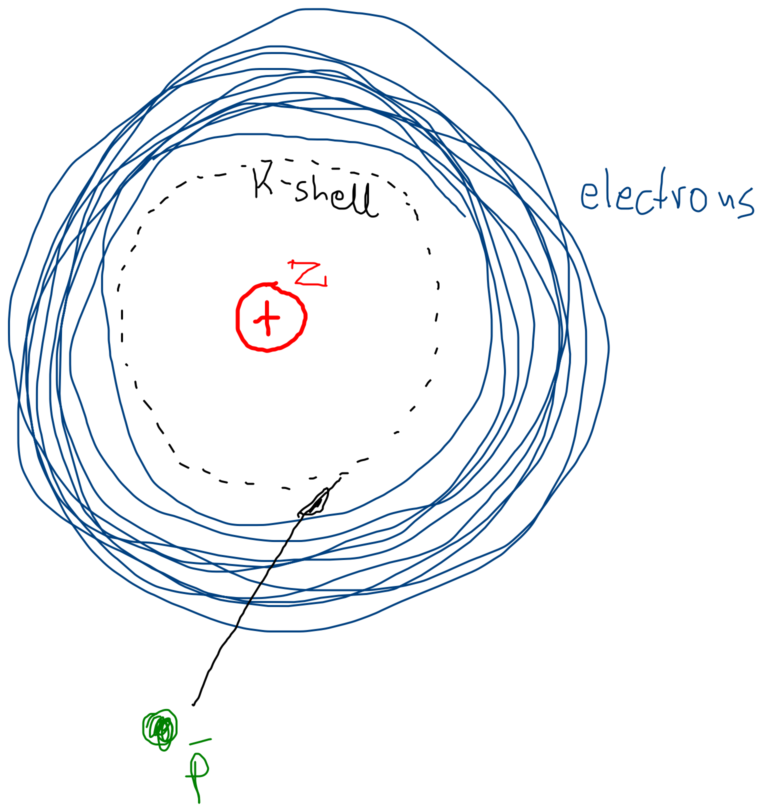
**AEgIS setup can be "quite easily" upgraded for this purposes**



# the simplest scenario

1) antiproton substitutes the inner-most electron (the largest probability) and enters an almost circular orbit

$$n_{\bar{p}} \sim \sqrt{\frac{m_{\bar{p}}}{m_e}} n_e \sim 40\, n_e \qquad \ell \approx n_{\bar{p}} - 1$$




$$E_{\bar{p}} \sim \frac{m_{\bar{p}}}{m_e} E_e \qquad 13.6\,\mathrm{eV} \;\rightarrow\; 25\,\mathrm{keV}$$

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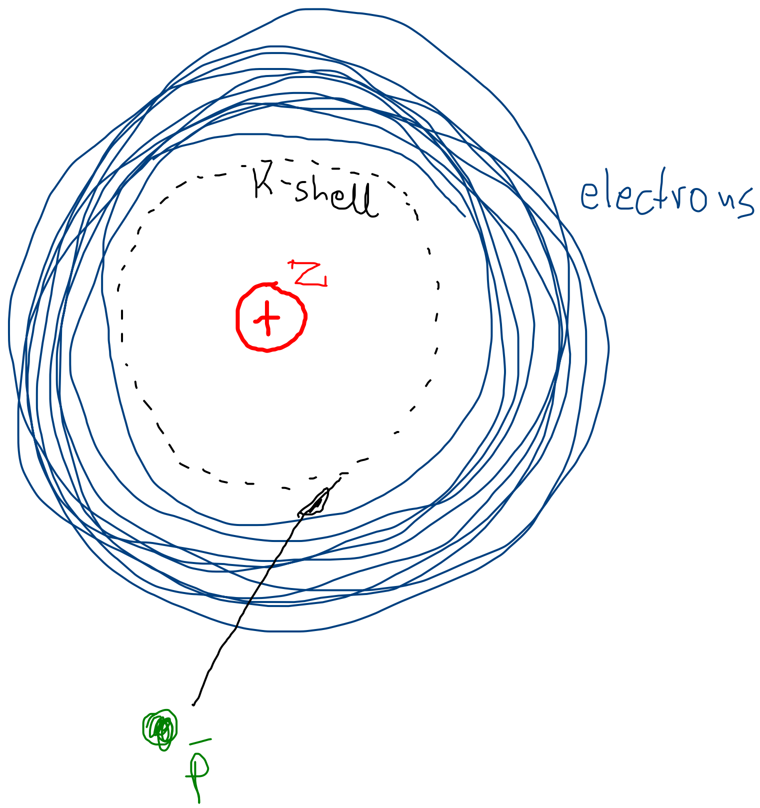


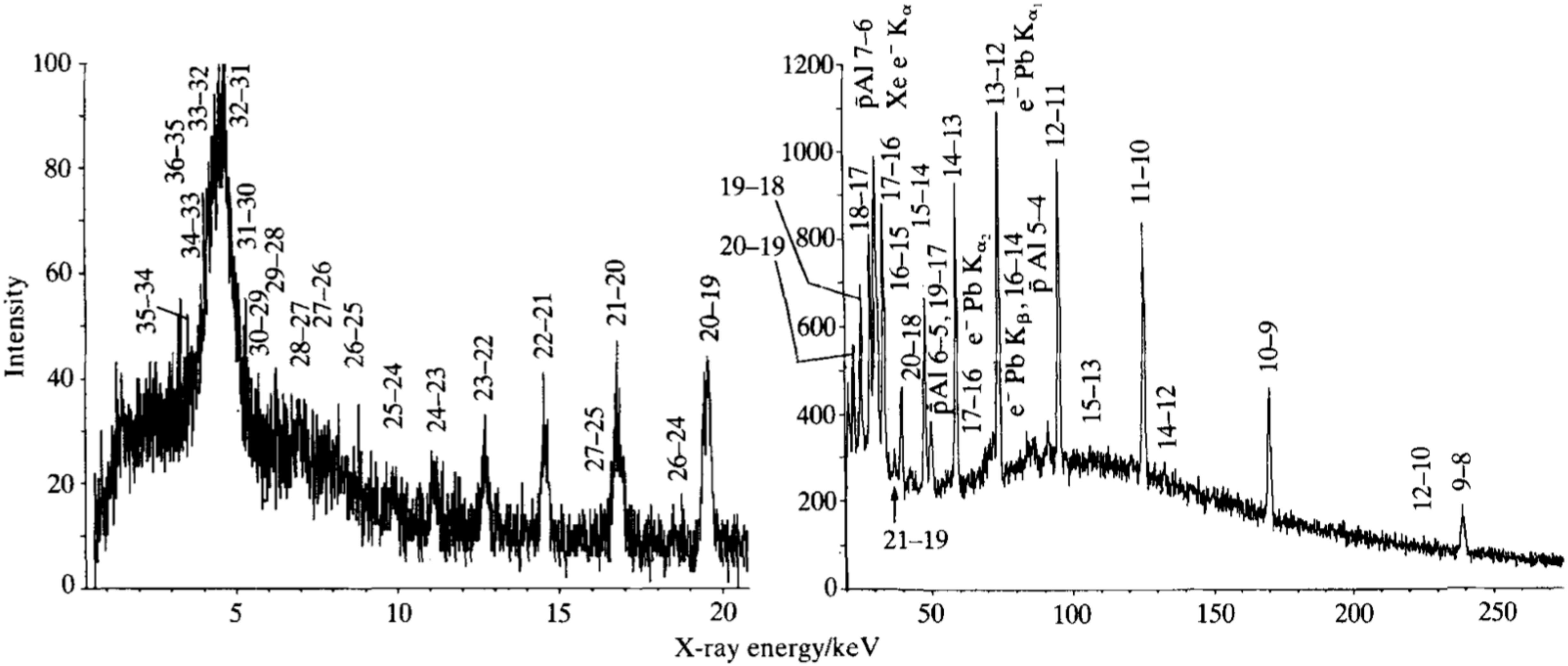

$$E_{\bar{p}} \sim \frac{m_{\bar{p}}}{m_e} E_e \qquad 13.6\,\mathrm{eV} \;\rightarrow\; 25\,\mathrm{keV}$$

2) undergoes slow, spontaneous deexcitation and emits X-ray photons

3) at the final stage, the antiproton is very close to the nucleus surface; its electronic transitions are substantially affected by strong interactions

4) annihilation with surface nucleon (proton or neutron); open possibility for measuring differences between distributions

# the simplest scenario




**Perfect agreement with hydrogen-like Rydberg model**

experimental data from: L. M. Simons, Proceedings 2nd LEAR Workshop on Physics with Low energy Cooled Antiprotons, Erice 1982, edited by U. Gastaldi and R. Klapisch (New York: Plenum), p. 155

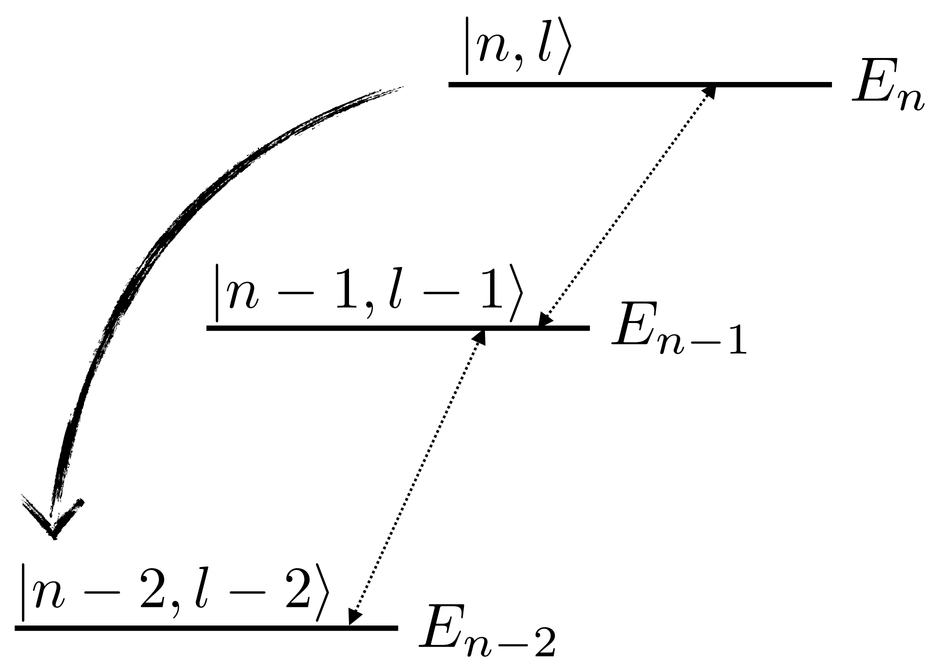
# quadrupole coupling...

$$\mathcal{Q}_\mu = \sqrt{\frac{16\pi}{5}} \int \mathrm{d}^3\boldsymbol{R}\ \rho(\boldsymbol{R}) R^2 \mathrm{Y}_2^\mu(\boldsymbol{\Theta})$$

**quadrupole charge distribution** → **quadrupole coupling**

$$\langle n, \ell | \mathcal{H}_Q | n-2, \ell-2 \rangle$$

**antiproton**




$$\Delta\ell = 2$$

# quadrupole resonance...

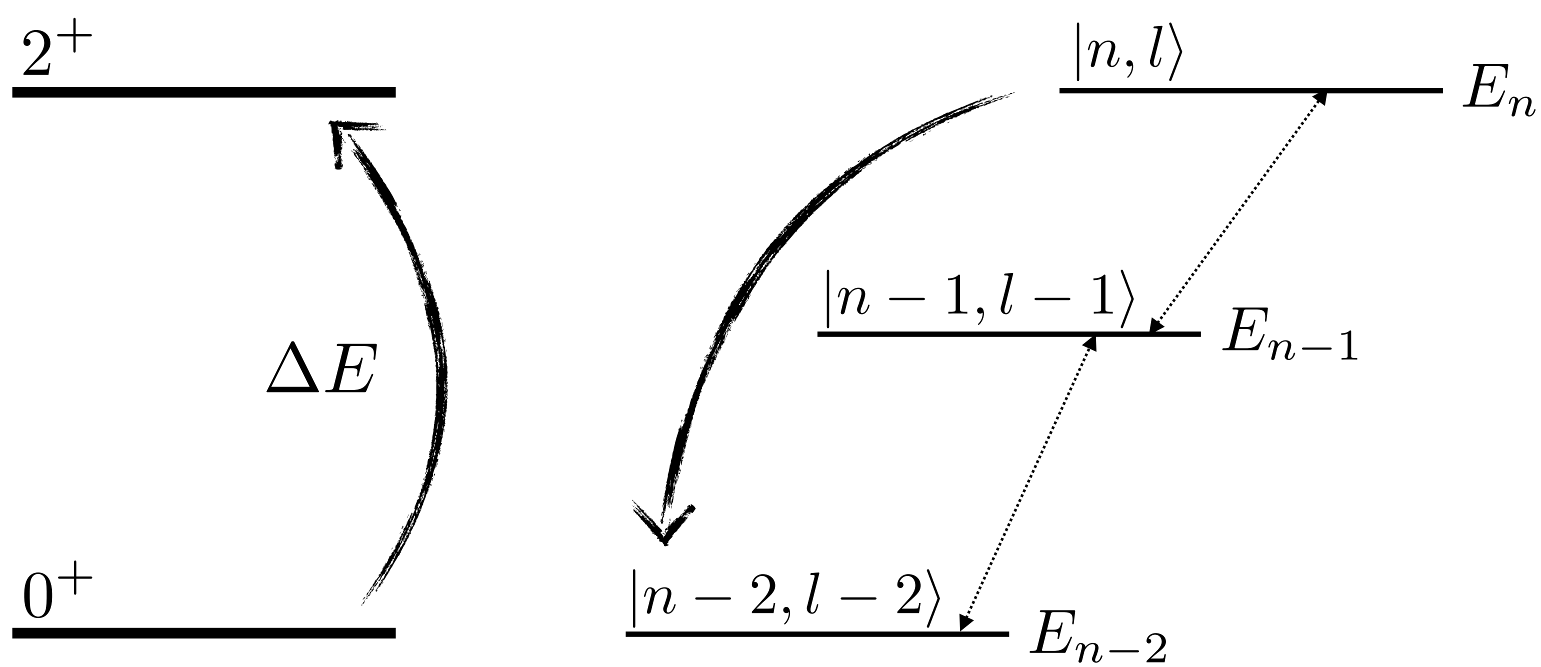
## huge deexcitation energy of the antiproton

## RESONANCE POSSIBLE

M. Leon: Nucl. Phys. A260, 461 (1976)

$$\mathcal{H}_Q = -\sqrt{\frac{\pi}{5}}\, Z\, Q_0\, \mathrm{Y}_2^0(\boldsymbol{\Theta})\, r^{-3}\, \mathrm{Y}_2^0(\boldsymbol{n})$$

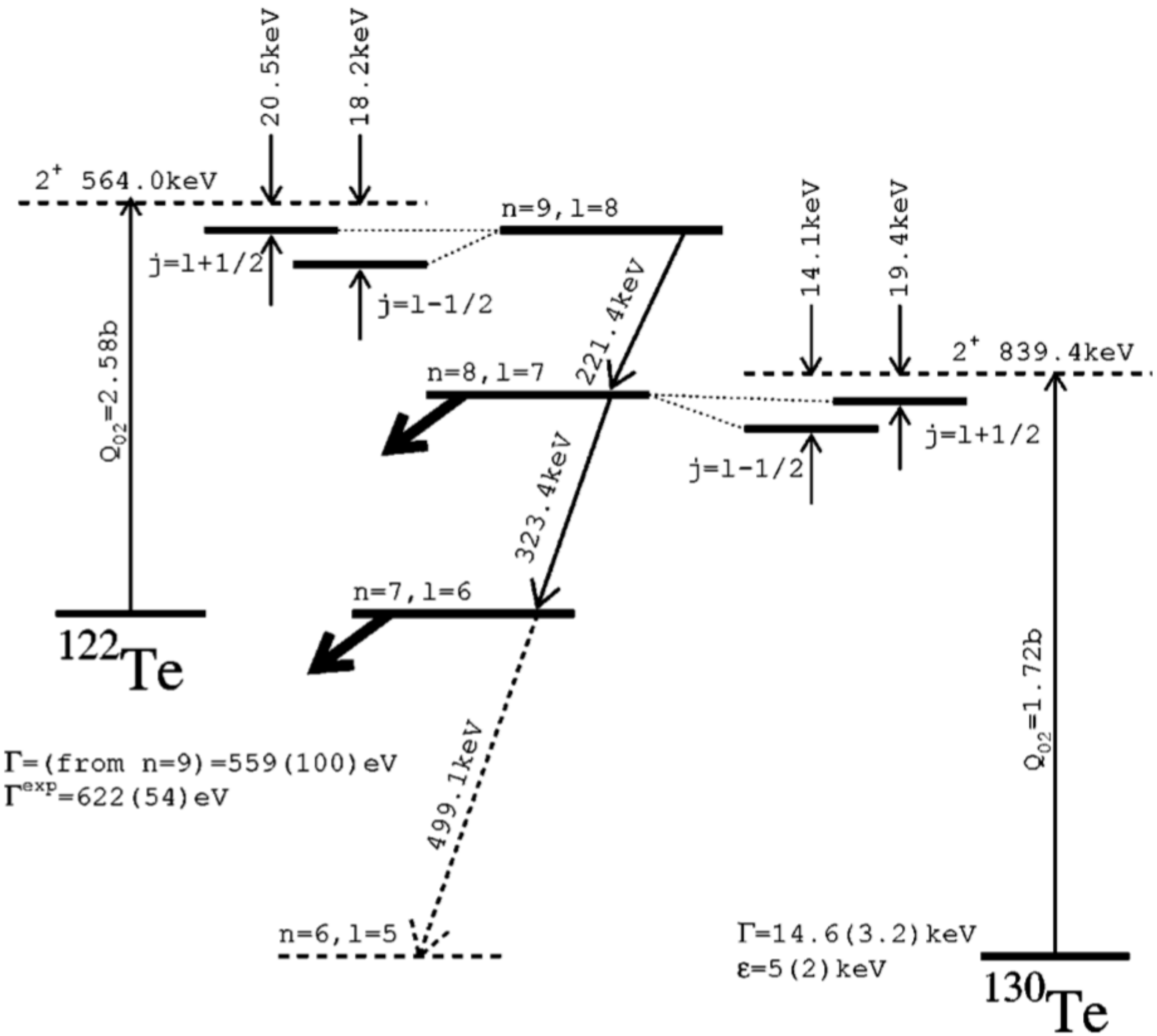
**nucleus** **antiproton**




$$\Delta \ell = 2$$

... energy gained by antiproton deexcitation is close to the excitation energy of nucleus ...

# quadrupole resonance...

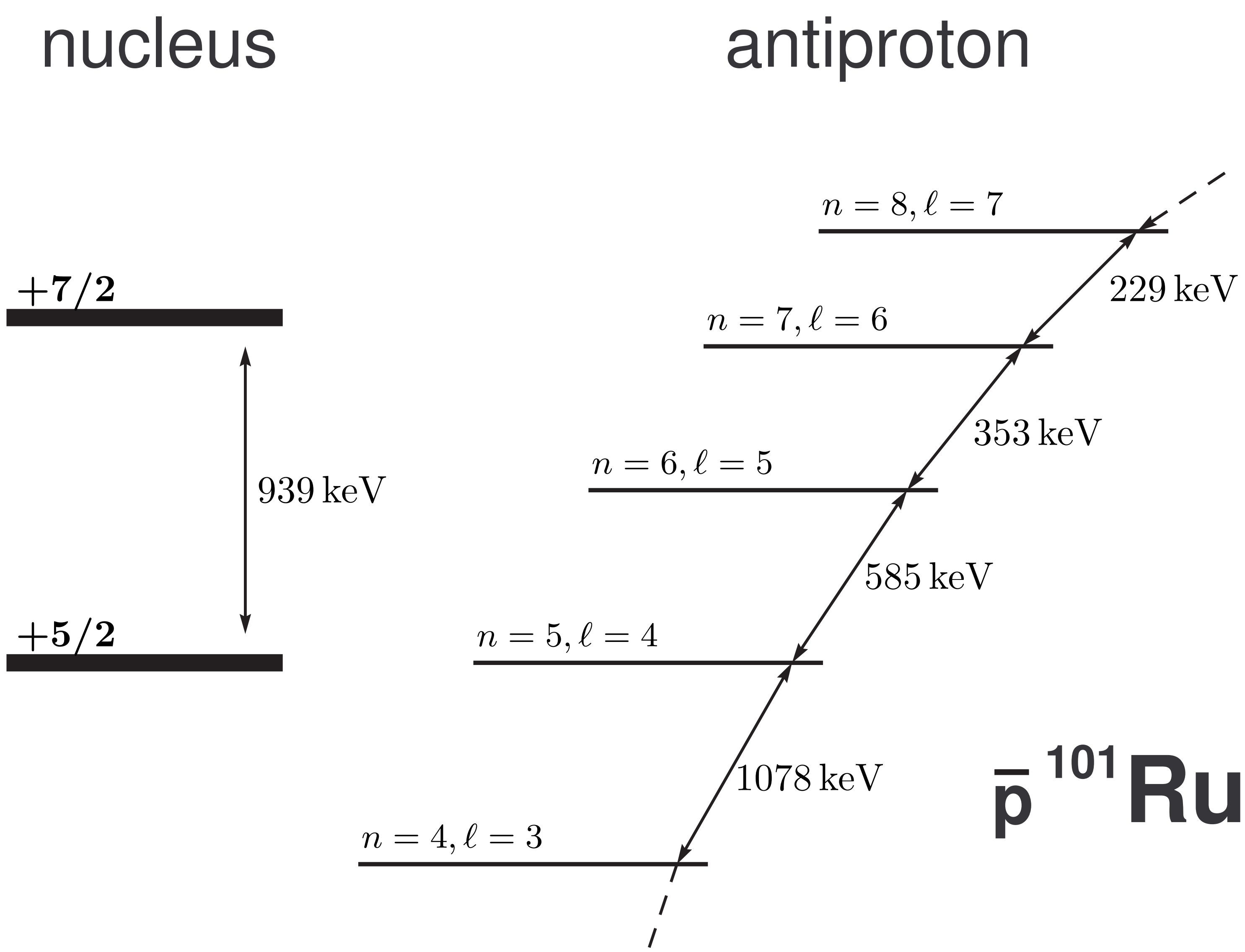



$$\langle n,\ell;\mathtt{G}|\mathcal{H}_Q|n-2,\ell-2,\mathtt{E}\rangle$$

B. Kłos et al.:Phys. Rev. C 69, 044311 (2004)

# what about odd-A nuclei?

**from purely energetic arguments the list of possible candidates is NOT EMPTY ...**



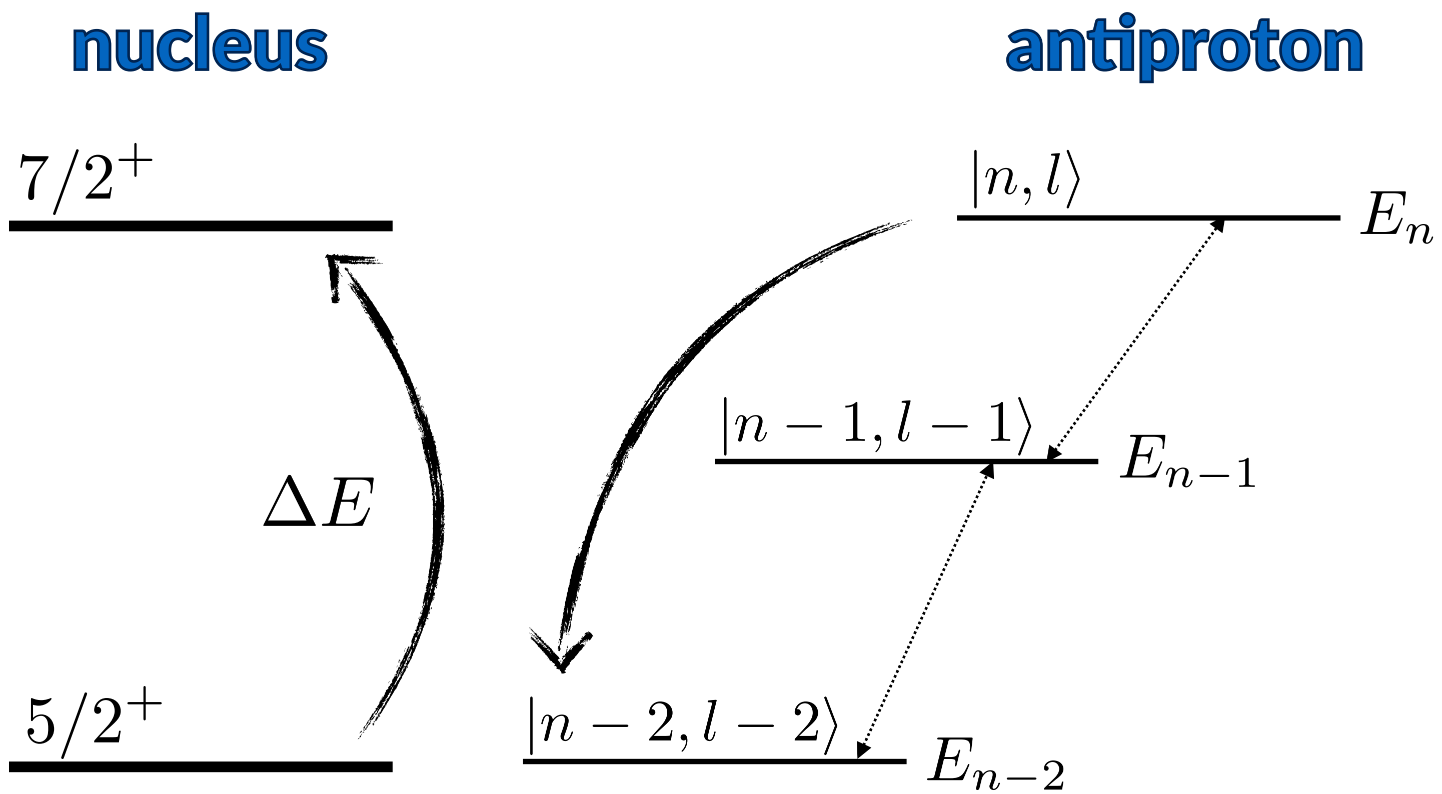

**Almost perfect matching:**

$$\Delta E_{\text{nucl}} = 938.65\,\text{keV}$$
$$E_7 - E_5 = 939.40\,\text{keV}$$

# is it possible for odd-A nuclei?

**... but (!) what about the conservation of total angular momentum?**

$$\mathcal{H}_Q = -\sqrt{\frac{\pi}{5}} Z Q_0 \mathrm{Y}_2^0(\boldsymbol{\Theta})\, r^{-3}\, \mathrm{Y}_2^0(\boldsymbol{n})$$



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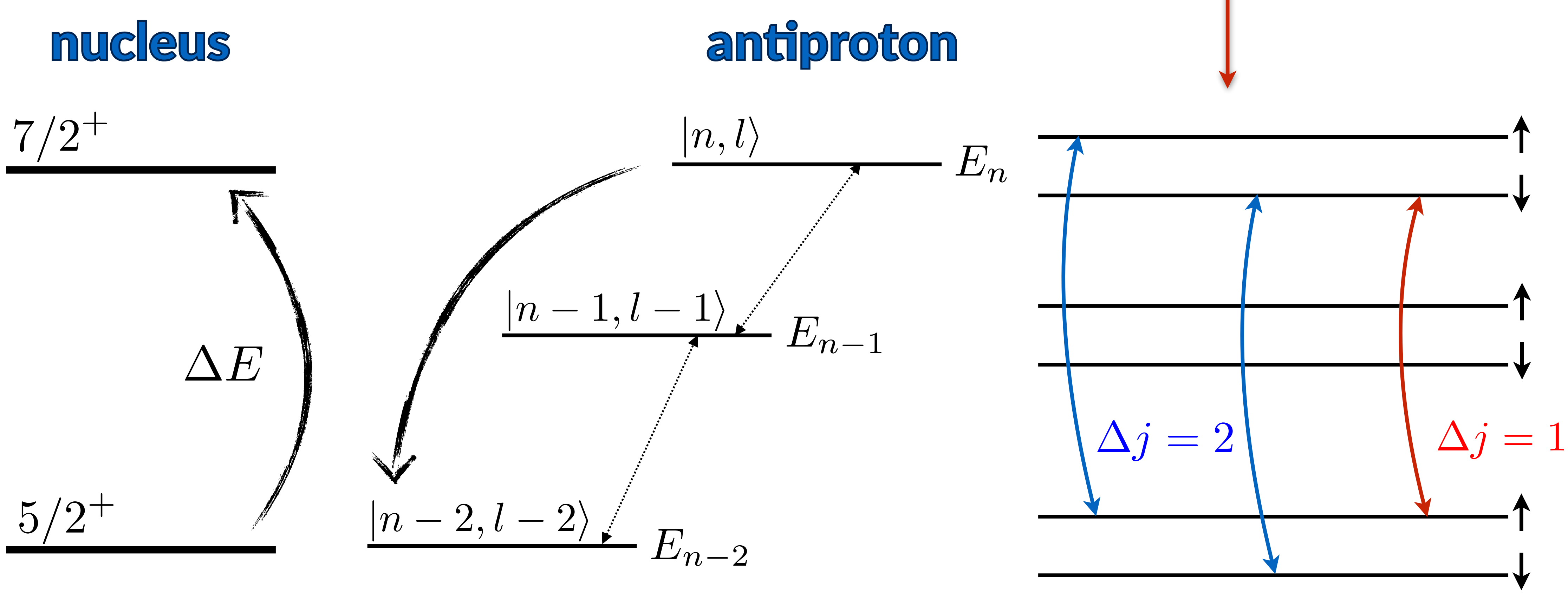


- only the ORBITAL angular momentum has to change by 2 quanta!

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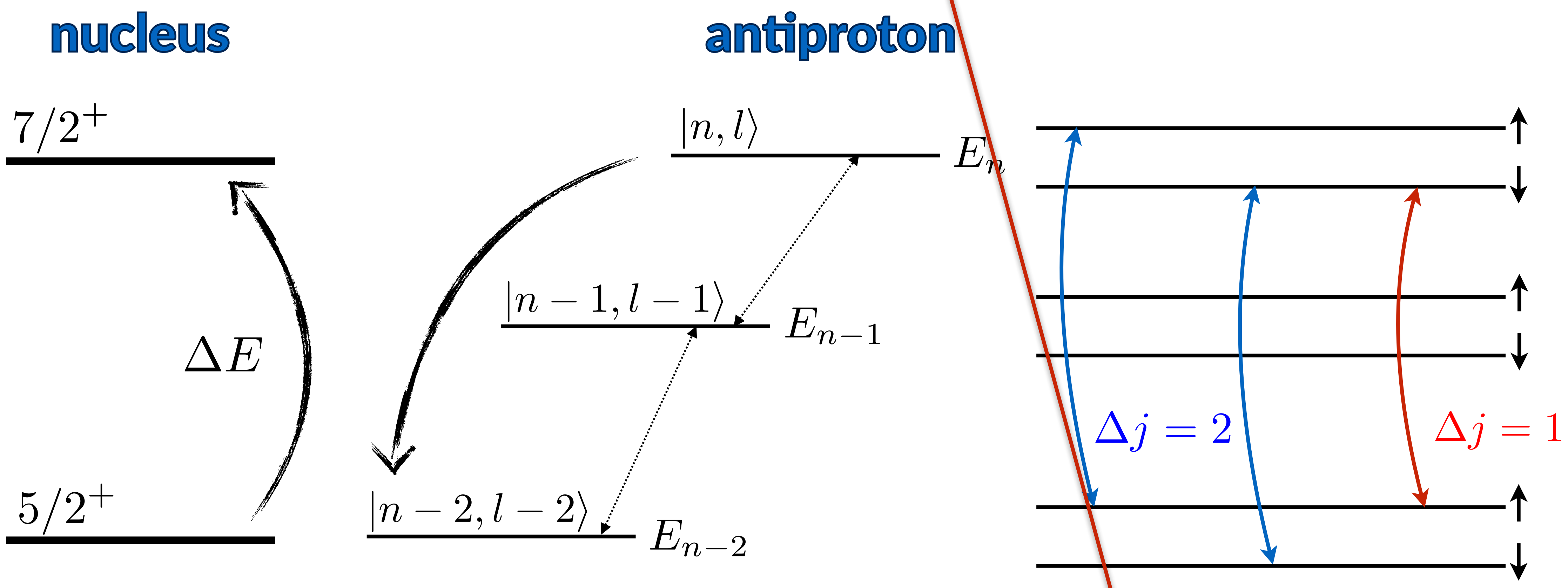


- only the ORBITAL angular momentum has to change by 2 quanta!
- for half-integer spins ΔJ=1 possible!

$$\langle 7/2^+ | \mathrm{Y}_2^0 | 5/2^+ \rangle \neq 0$$

# is it possible for odd-A nuclei?

$$\mathcal{H}_Q = -\sqrt{\frac{\pi}{5}} Z \mathcal{Q}_0 \mathrm{Y}_2^0(\boldsymbol{\Theta})\, r^{-3}\, \mathrm{Y}_2^0(\boldsymbol{n})$$

## what about intensity of the resonance?

# is it possible for odd-A nuclei?

$$\mathcal{H}_Q = -\sqrt{\frac{\pi}{5}} Z \mathcal{Q}_0 \mathrm{Y}_2^0(\boldsymbol{\Theta})\, r^{-3}\, \mathrm{Y}_2^0(\boldsymbol{n})$$

## what about intensity of the resonance?

- obviously, spin-conserving processes have higher amplitudes
- they are forbidden due to the nuclear spin conservation!
- amplitudes may be large when related to the energy gap

$\bar{p}\,{}^{101}$Ru

$$\Delta E_{\text{nucl}} = 938.65\,\text{keV}$$
$$E_7 - E_5 = 939.40\,\text{keV}$$

$$\Delta E \approx 750\,\text{eV}$$
$$\langle \mathtt{E} | \hat{\mathcal{Q}} | \mathtt{G} \rangle \approx 190\,\text{eV}$$

# … take-home message …

**high-precision atomic spectroscopy of**
**exotic matter-antimatter atoms**
**may shed new light**
**on the Standard Model**

**… thank You for your attention…**