GGI LECTURES ON THE THEORY OF FUNDAMENTAL INTERACTIONS 2023

TABLETOP EXPERIMENTS: LECTURE 1

GRAND CHALLENGES OF PARTICLE PHYSICS

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https://www.colorado.edu/research/qsense/

https://thoriumclock.eu/

Please ask questions during the lecture!

THE BENEFITS OF ASKING QUESTIONS

You will learn more.

The winter school will be more fun for you.

Great practice for the future.

You will stay awake ☺

1923

100 years ago

We though we knew everything about the Universe

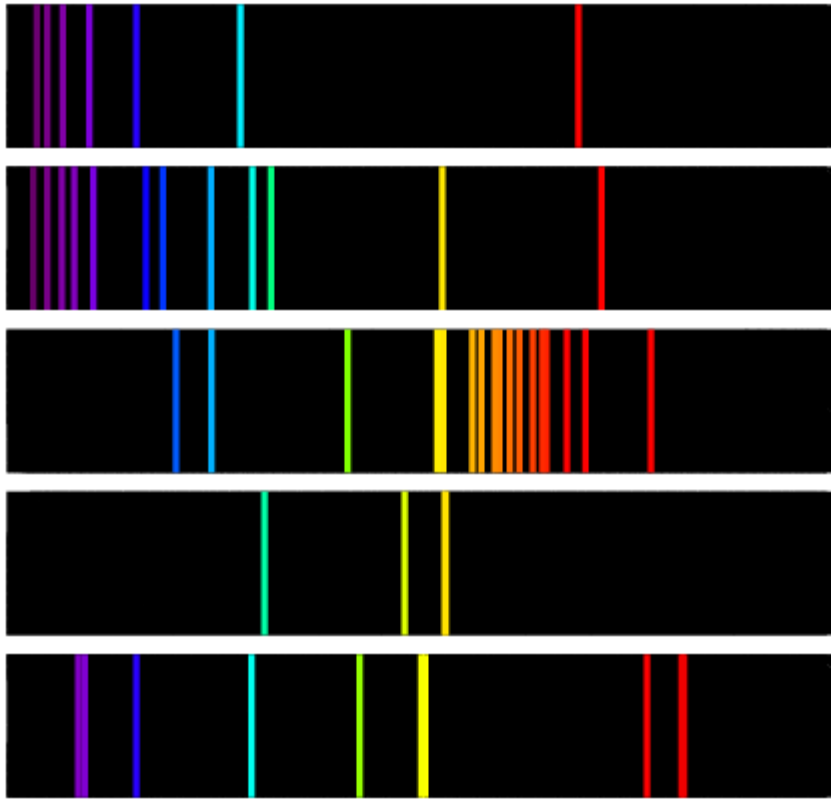
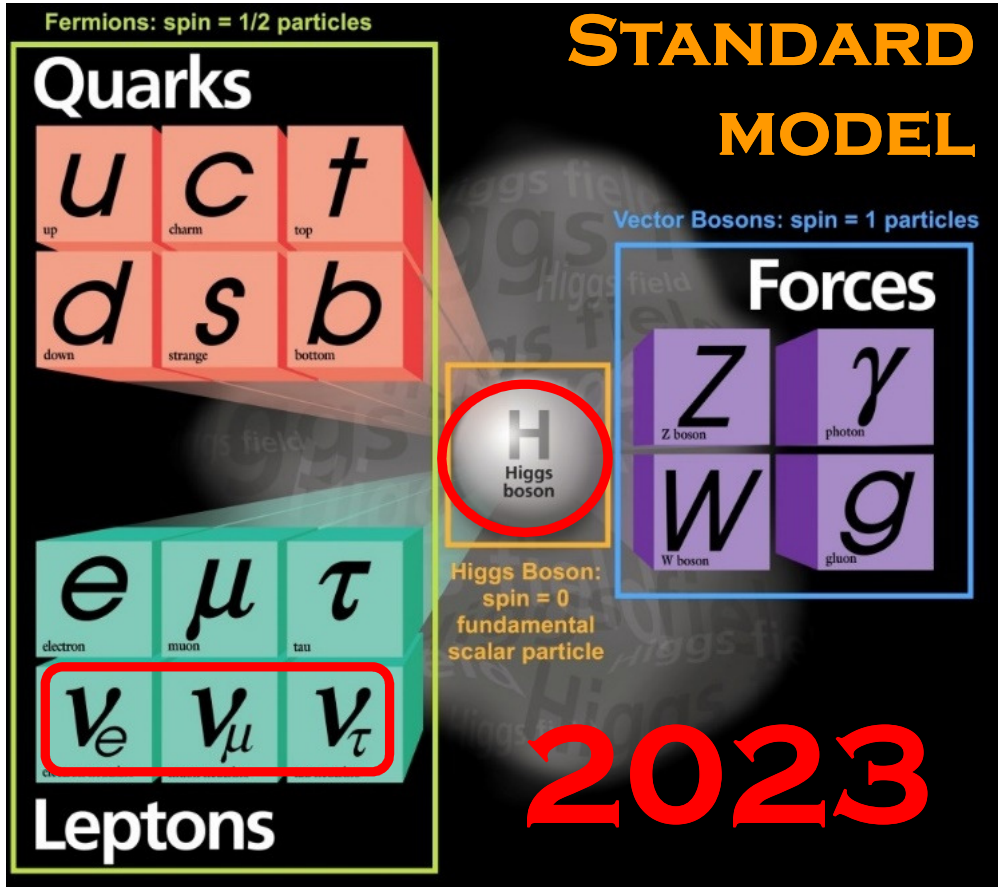


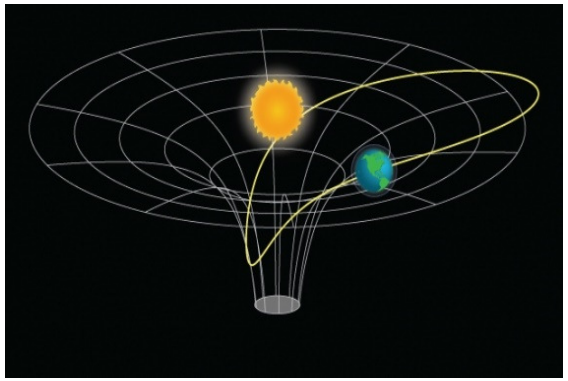
Figure credit: practical-chemistry.com

Fundamental physics: present view of the laws of the Universe

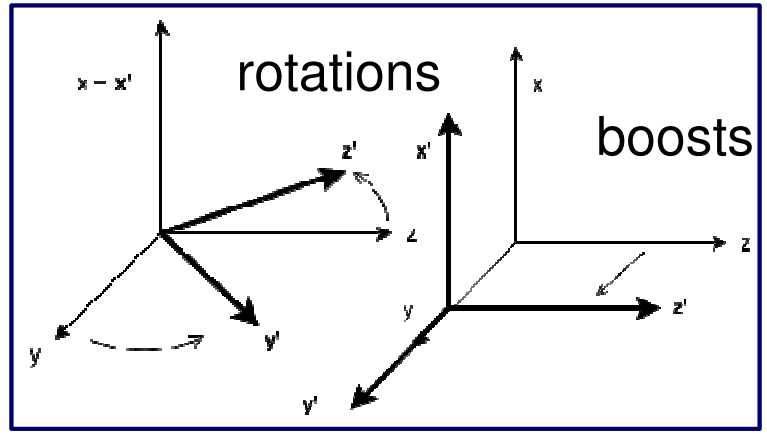


Fundamental physics postulates

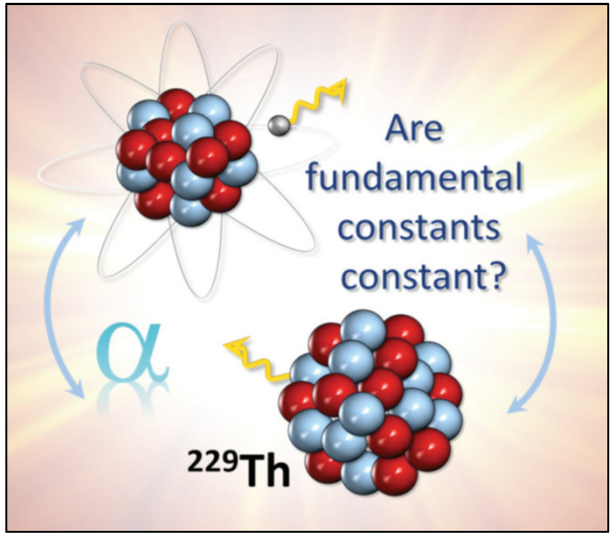
Position invariance



Lorentz invariance



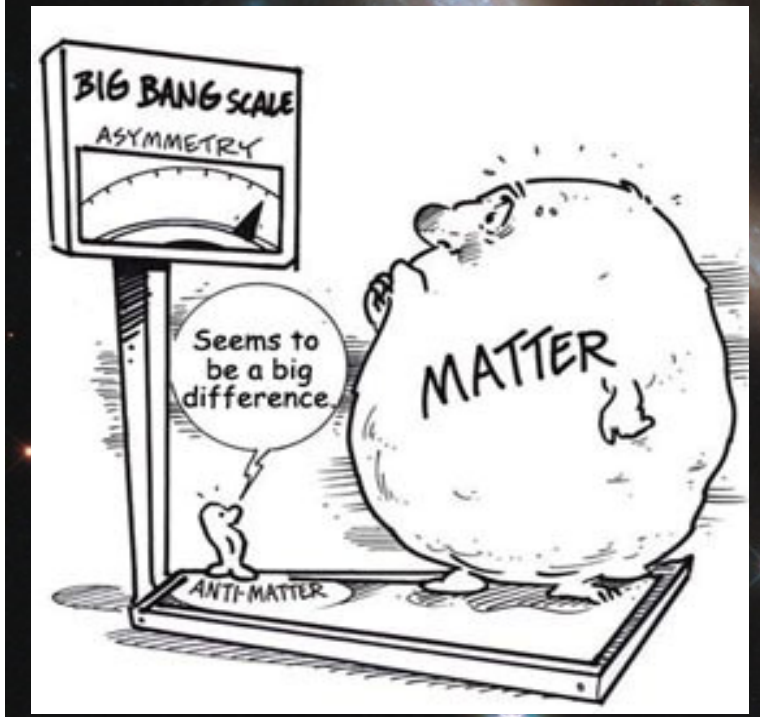
Weak equivalence principle



Quantum mechanics

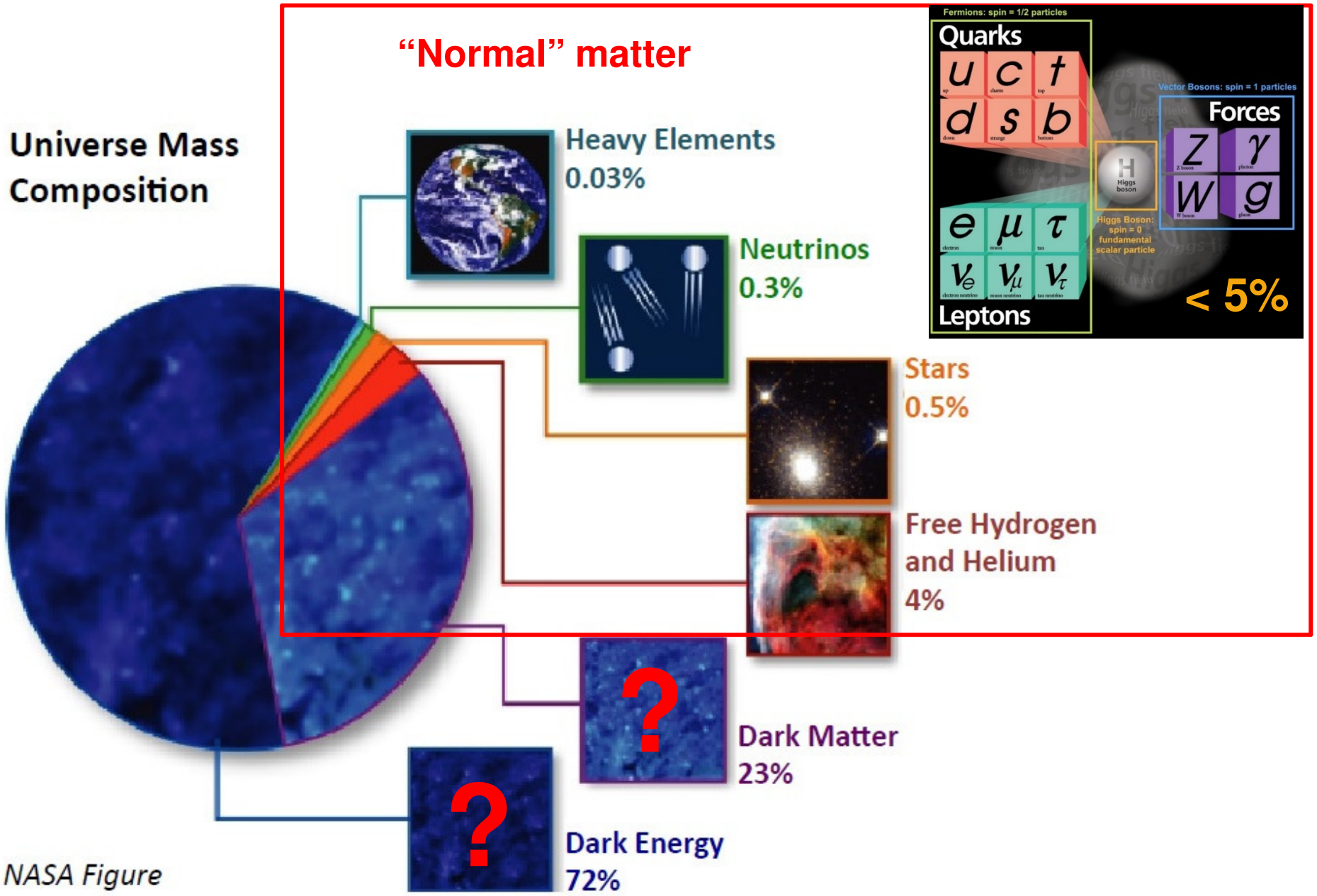
General relativity

According to the Standard Model



Our Universe can not exist !

We don't know what most (95%) of the Universe is!



2023: Unanswered questions in particle physics
What we do not know about fundamental particle and interactions

Why to introduce Beyond the Standard Model (BSM) physics?

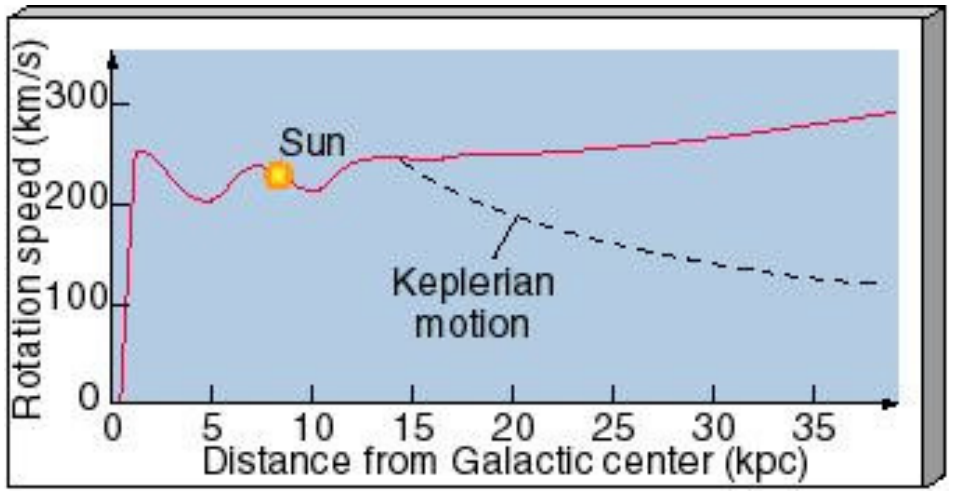
1. **Required by observations: Standard Model can not explain**

   - Dark matter
   - Matter-antimatter asymmetry
   - Accelerate expansion of the Universe (dark energy/cosmological constant?)
   - Neutrino masses

2. **"Unnatural" values of Standard Model parameters**

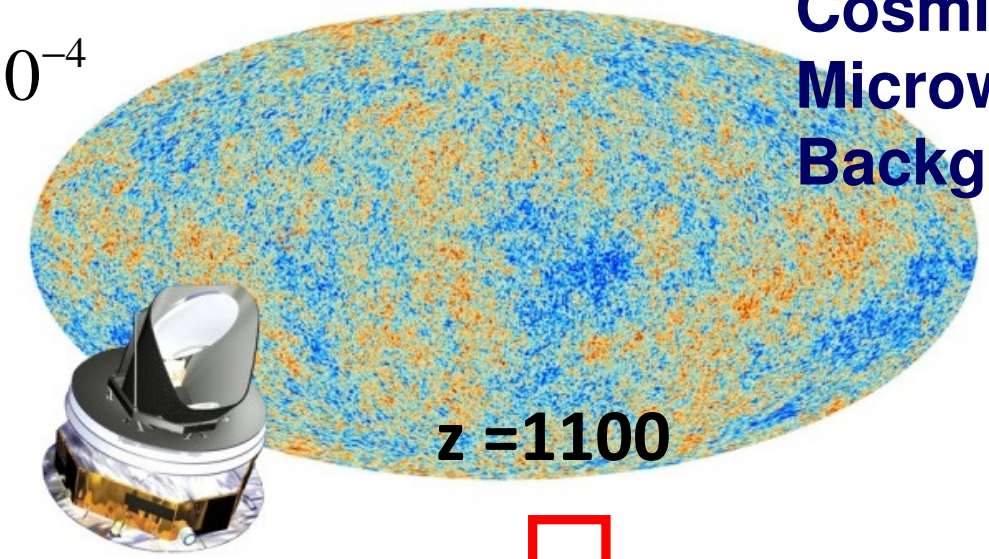
   - Cosmological constant
   - Higgs mass
   - Strong CP angle (from neutron EDM)
   - Masses of quark/leptons & numbers of families
   - Constants of fundamental interactions (fine-structure constant, strong coupling constant)

What is the experimental evidence for dark matter?

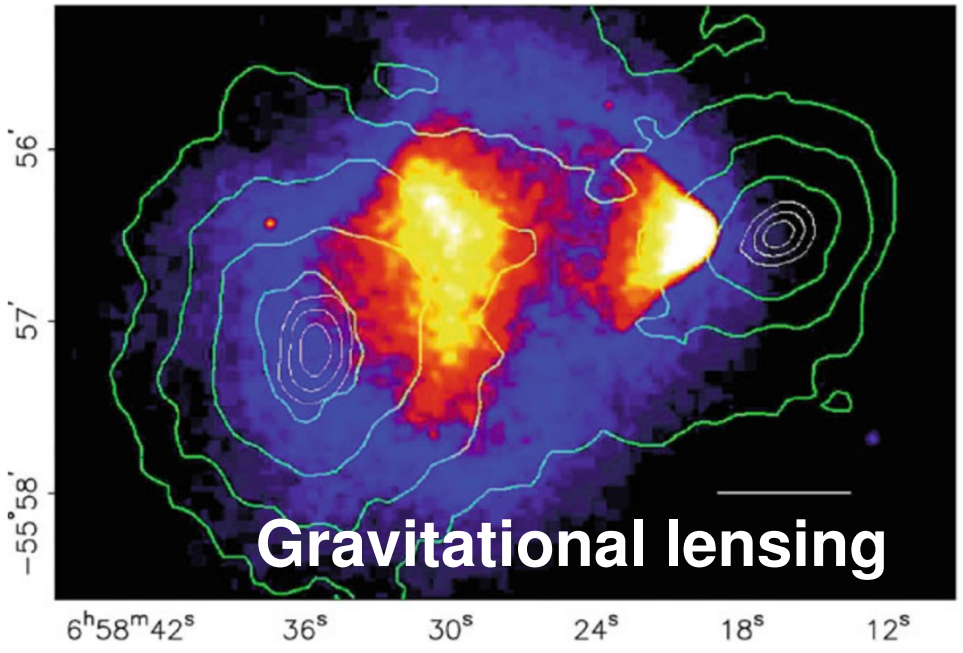


Rotation curves

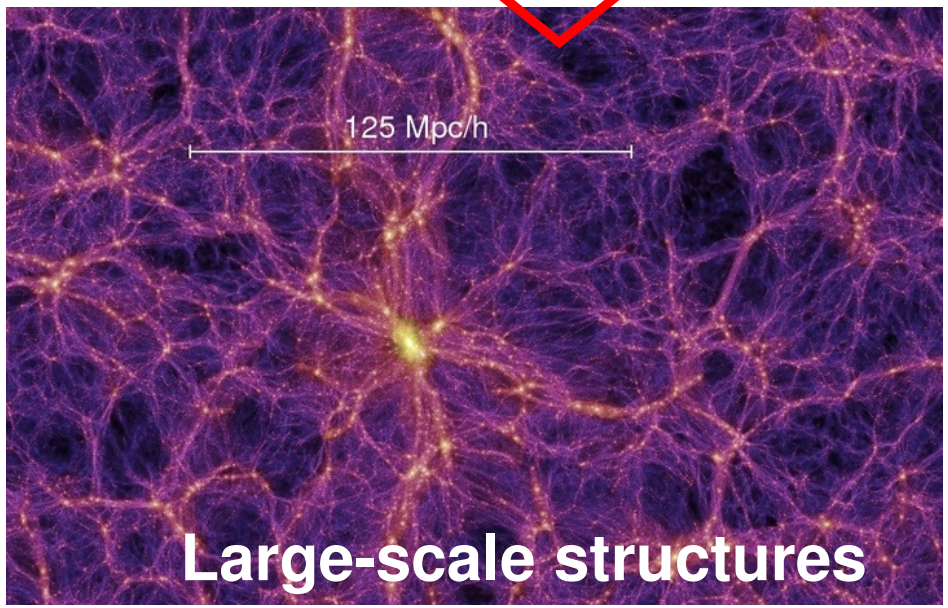
$$\frac{\delta\rho}{\rho} \approx 10^{-4}$$



Cosmic Microwave Background



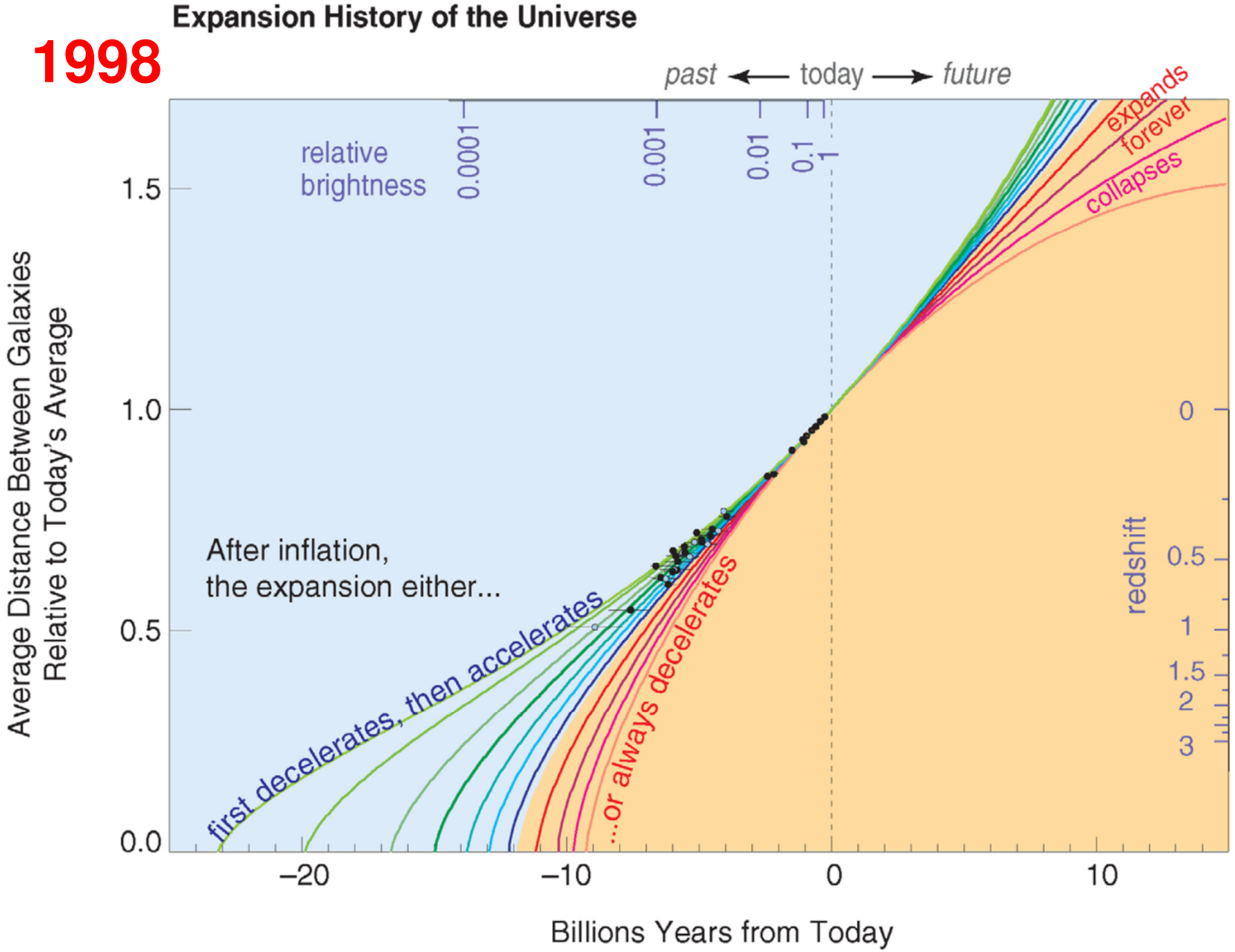
Gravitational lensing



Large-scale structures

1998

Dark energy



Accelerated expansion of the Universe from observations of type Ia supernovae, from Cosmic Microwave Background measurements, and from detailed studies of large-scale structure.

http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/perlmutter-lecture.html

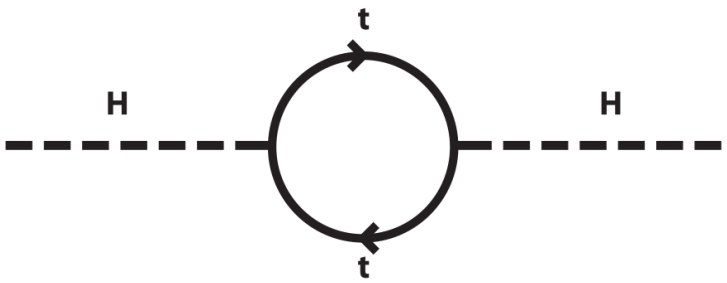
Hierarchy problems: weak scale

Why the Higgs field vacuum expectation value is so small, average value 246 GeV **(really NOT natural).**

Natural: Universes will have the Higgs field “fully on” .Particles at Plank scale masses, turning into black holes.

Natural: Higgs field is “off” - no masses.

The problem is that corrections to Higgs mass from even obvious loop with top quark results in quadratic divergences ($1/k^2$), putting the mass back to Plank scale. The main issue is that there are a lot of corrections which are then very large but all nearly cancel out, which is very puzzling.



Solutions: supersymmetry, dynamical electroweak symmetry breaking (technicolor), little Higgs, twin Higgs, **dynamical explanation (relaxation)**,…

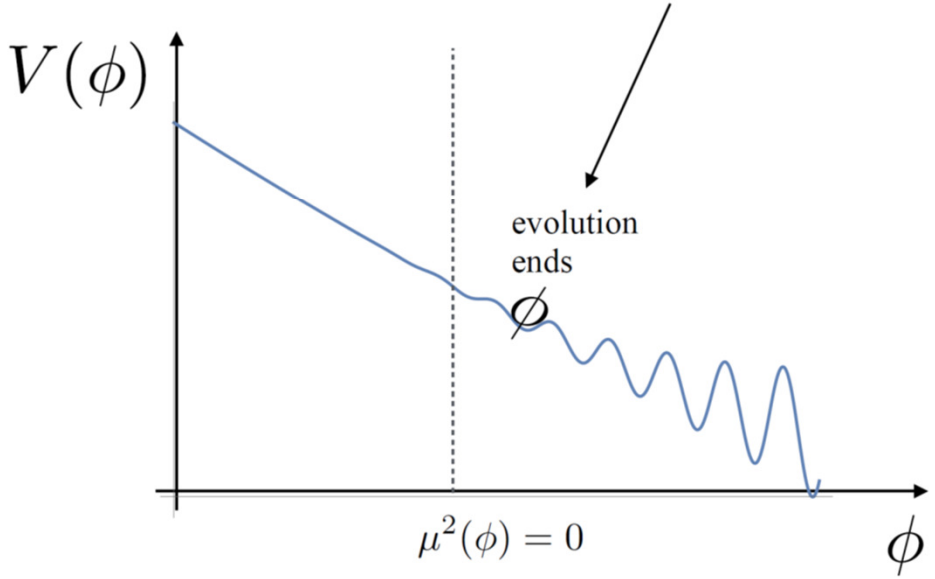
Relaxion's physics

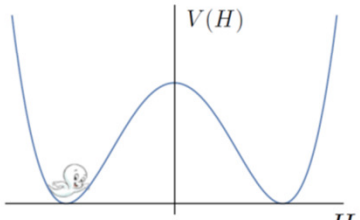
Graham, Kaplan & Rajendran (15)

- A dynamical solution/amelioration of the Higgs fine-tuning problem:

(*i*) Add a scalar (relaxion) Higgs dependent mass: $\overbrace{\left(\Lambda^2 - g^2\phi^2\right)}^{\mu^2(\phi)} H^\dagger H$

(*ii*) ϕ roles till μ^2 changes sign $\Rightarrow \langle H \rangle \neq 0 \Rightarrow$ stops rolling.





$\langle H \rangle = v \neq 0$

Slide credit: Gilad Perez

Dynamical relaxation to solve the hierarchy problem

- Does not required new physics at the TeV scale
- Introduces a relaxion
- It will couple to standard model via the Higgs

- Can not search for it with colliders but can with precision physics including clock and fifth forces
- Relaxion can be ultralight
- It can be dark matter

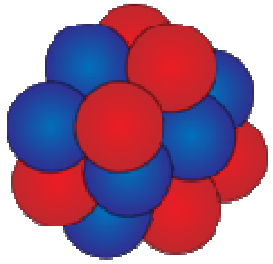
Probing the Relaxed Relaxion at the Luminosity and Precision Frontiers, Abhishek Banerjee, Hyungjin Kim, Oleksii Matsedonskyi, Gilad Perez, Marianna S. Safronova, J. High Energ. Phys. 2020, 153 (2020).

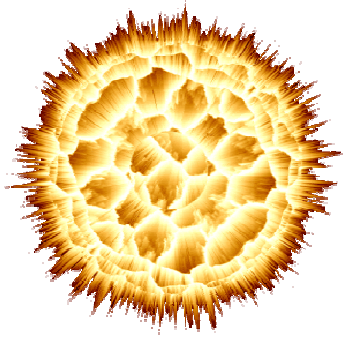
Life needs very specific fundamental constants!

If α is too big $\rightarrow$ small nuclei can not exist

Electric repulsion of the protons **>** strong nuclear binding force

$\alpha \sim 1/137$

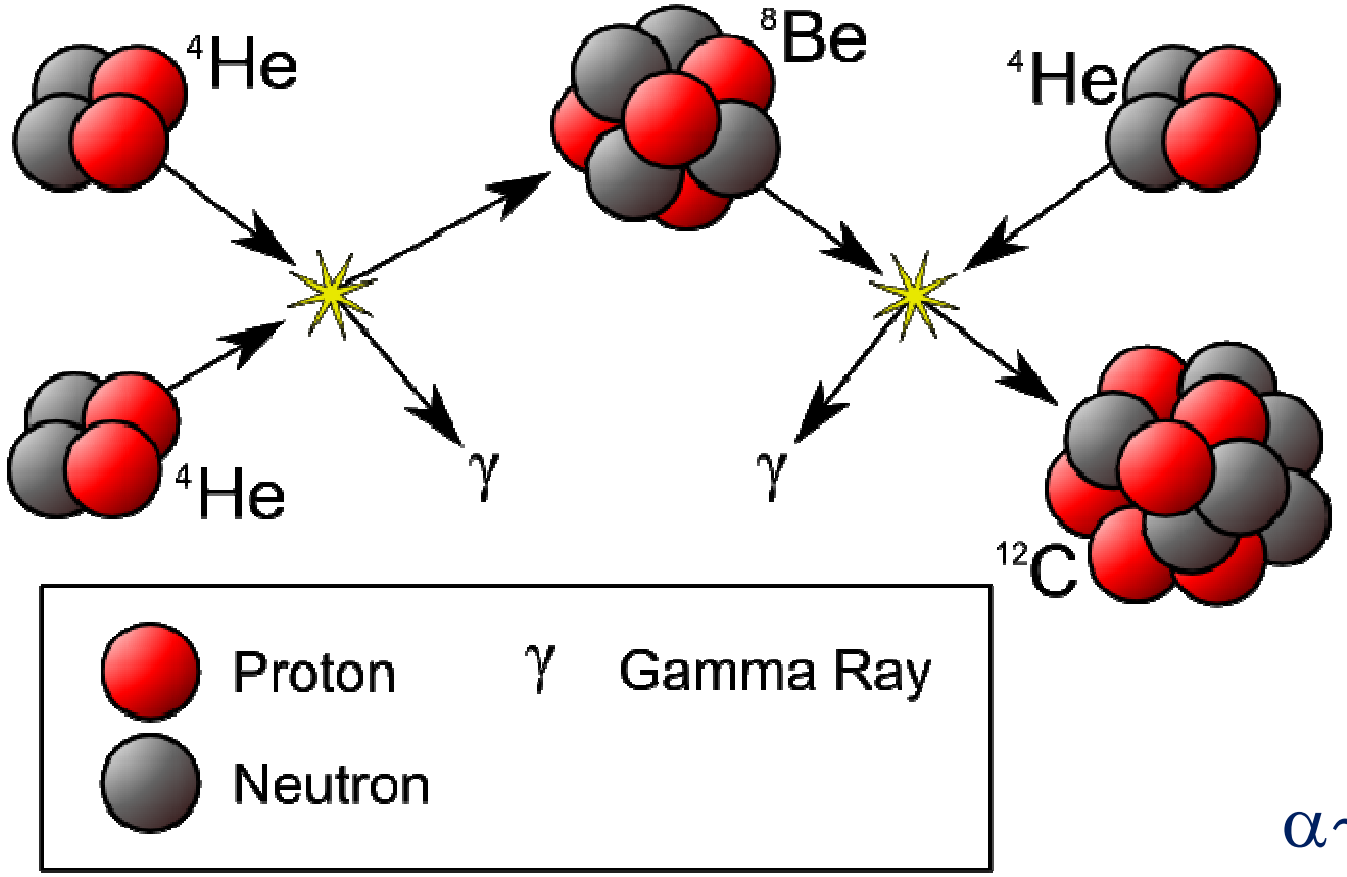




$\alpha \sim 1/10$

will blow carbon apart

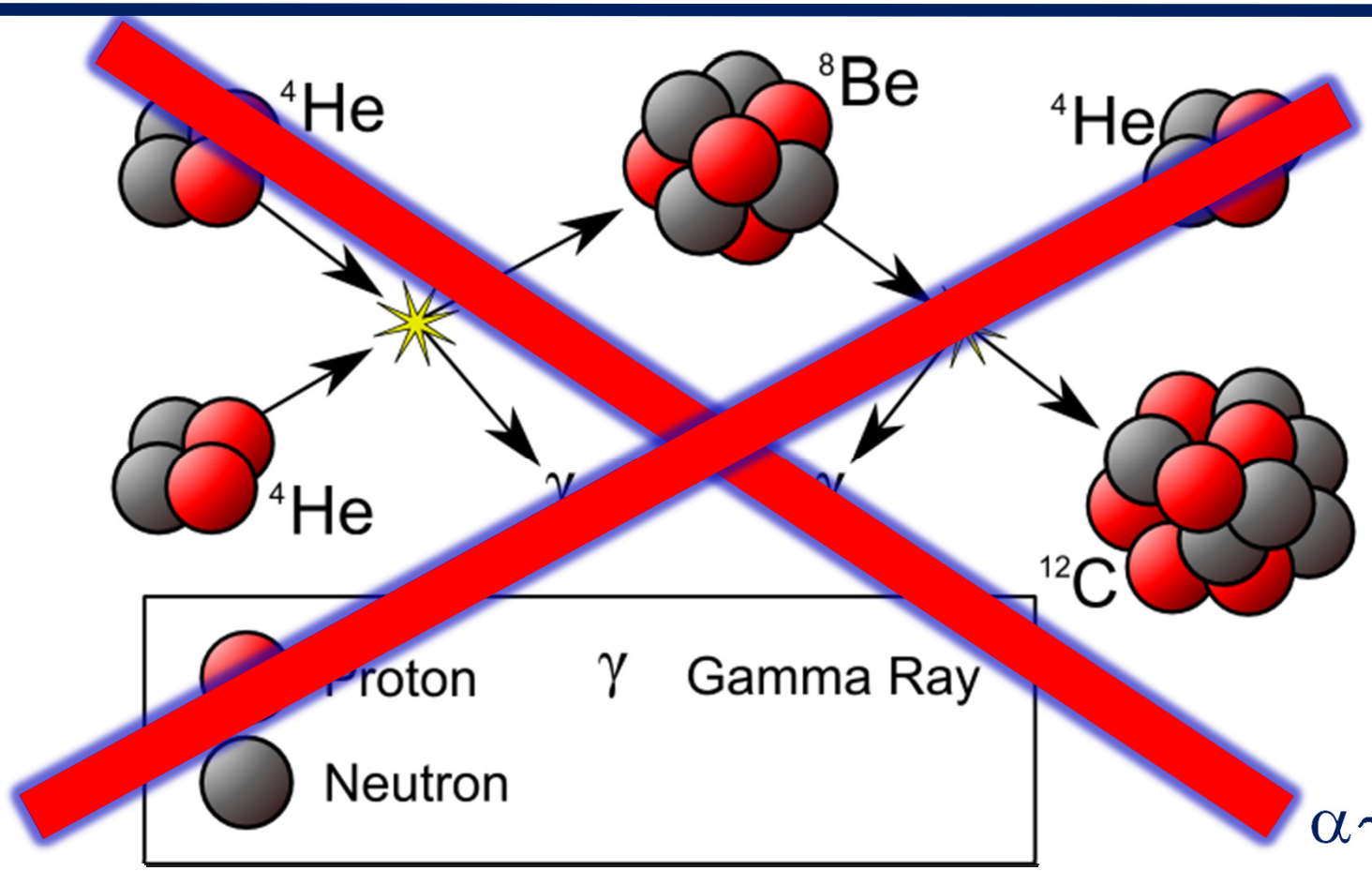
Life needs very specific fundamental constants!



$\alpha \sim 1/137$

Nuclear reaction in stars are particularly sensitive to α.
If α were different by 4%: **no carbon produced by stars**. No life.

Life needs very specific fundamental constants!



$\alpha \sim 1/132$

No carbon produced by stars:
No life in the Universe

2023: Unanswered questions in particle physics

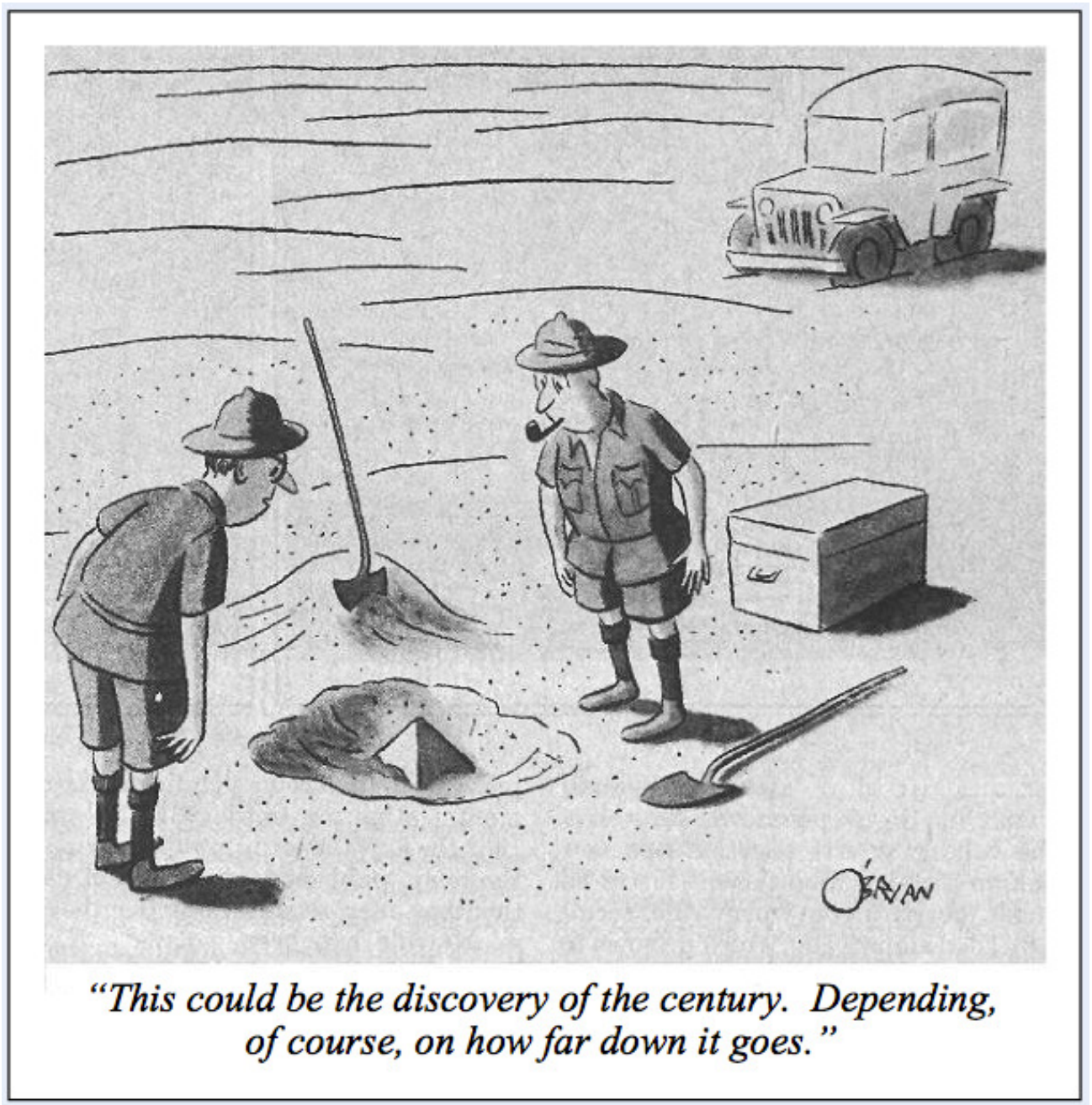
Other open questions

- How to connect gravity and quantum mechanics?
- Is there a limit on macroscopic quantum suppositions? Is quantum mechanics linear?
- Does general relativity hold in extreme regimes?
- Are fundamental constants actually constant?
- Are there violations of Einstein equivalence principle?
  - ✓ Universality of free fall
  - ✓ Position invariance
  - ✓ Local Lorentz invariance
- Are there violations of fundamental symmetries?
  - ✓ CPT (charge, parity, time)
  - ✓ Permutation symmetry for identical particles
  - ✓ The spin-statistics connection

Postulates of modern fundamental physics, experiments verify only to a certain precision

- New particles (many not contribute much for dark matter)?
- New fundamental interactions?
- Experimental/observational anomalies (could be SM): EDGES 21 cm anomaly, Hubble constant, too early quasars, muon g-2, gravitational constant G, neutron lifetime, neutrino experiment anomalies, many others

Experimental/observational anomalies



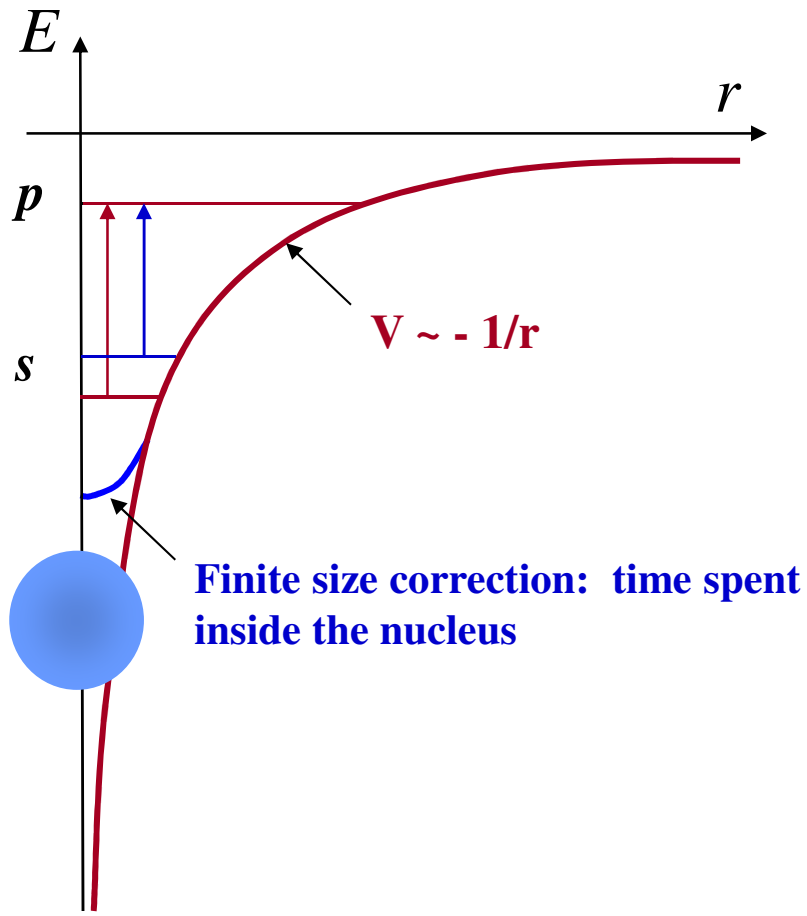
"This could be the discovery of the century. Depending, of course, on how far down it goes."

http://engent.blogspot.com

The proton radius puzzle

Finite radius of the proton → H energy level shifts

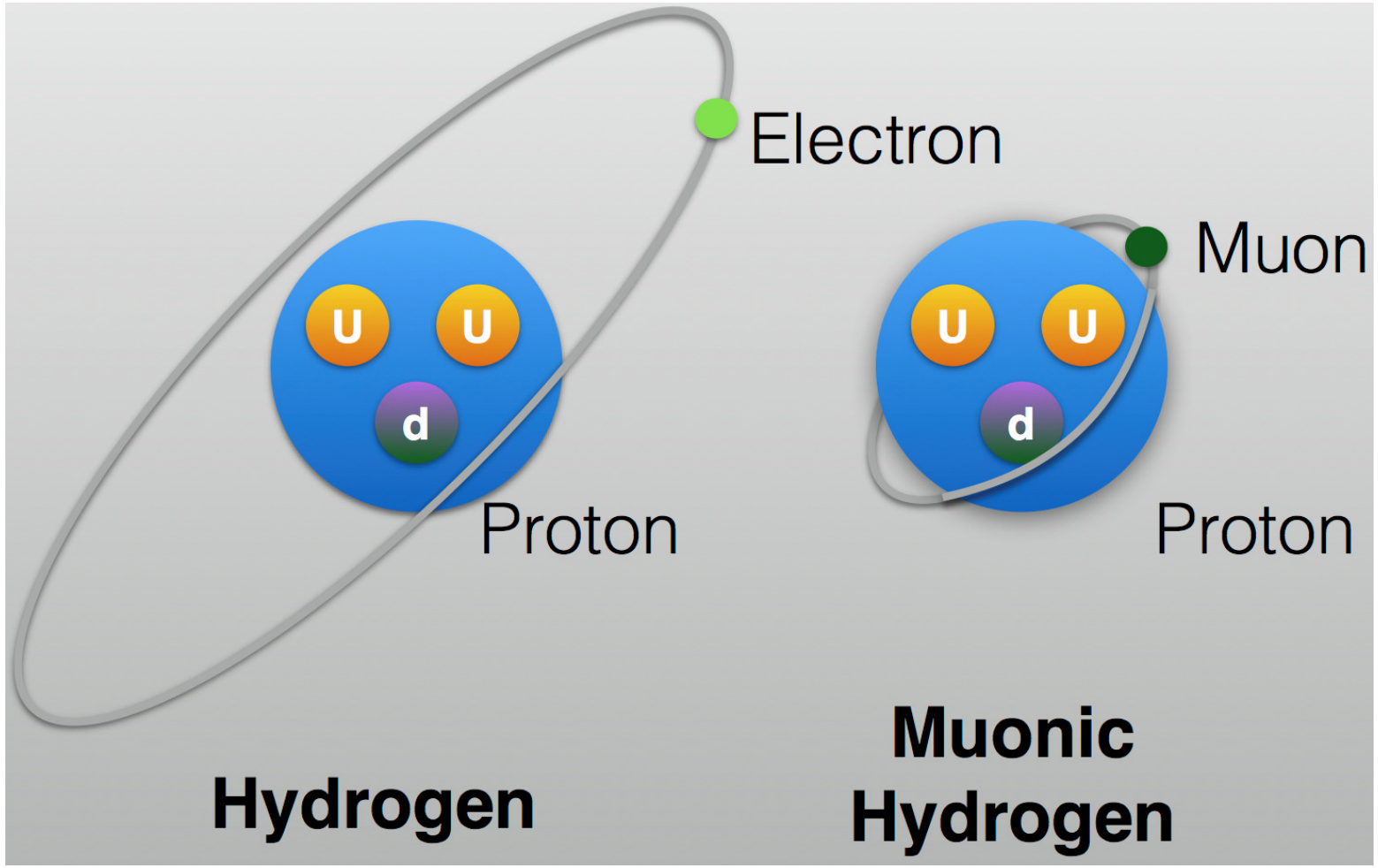
Measurement of transitions → measure nuclear size



1. Measure the transition energies between different levels
2. Calculate all corrections to these energies (need to calculated QED really well)
3. Extract the corrections to the energies due to a proton radius

   $\sim (Z\alpha)\, R_p^2\, |\Psi(0)|^2$
4. Extract the rms radius
5. Repeat for many transitions and average

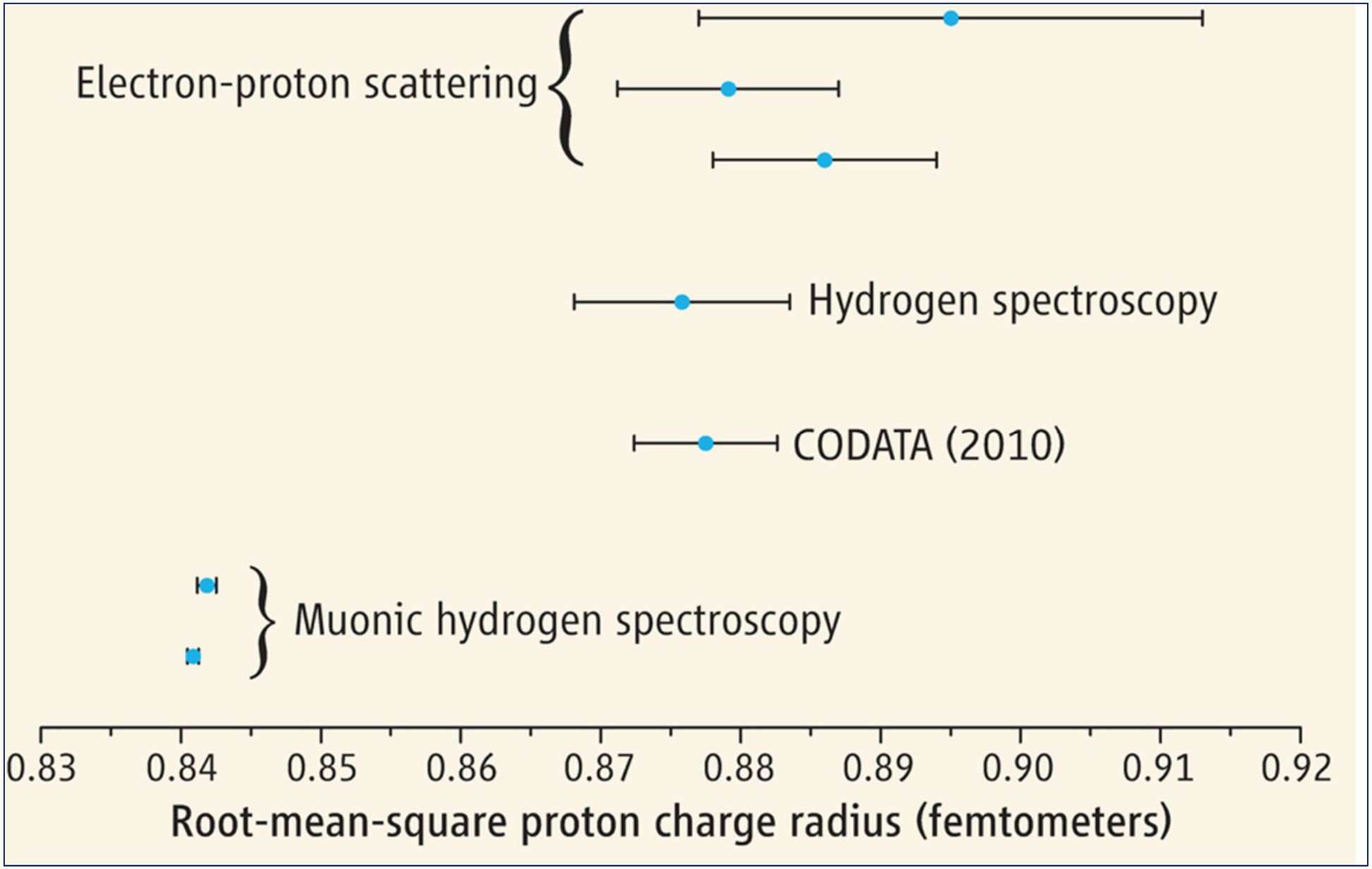
The proton radius puzzle



Probability for a lepton to be inside the proton ∝ to its mass cubed,
$(207)^3 = 8\ 869\ 743$ enhancement for a muon !

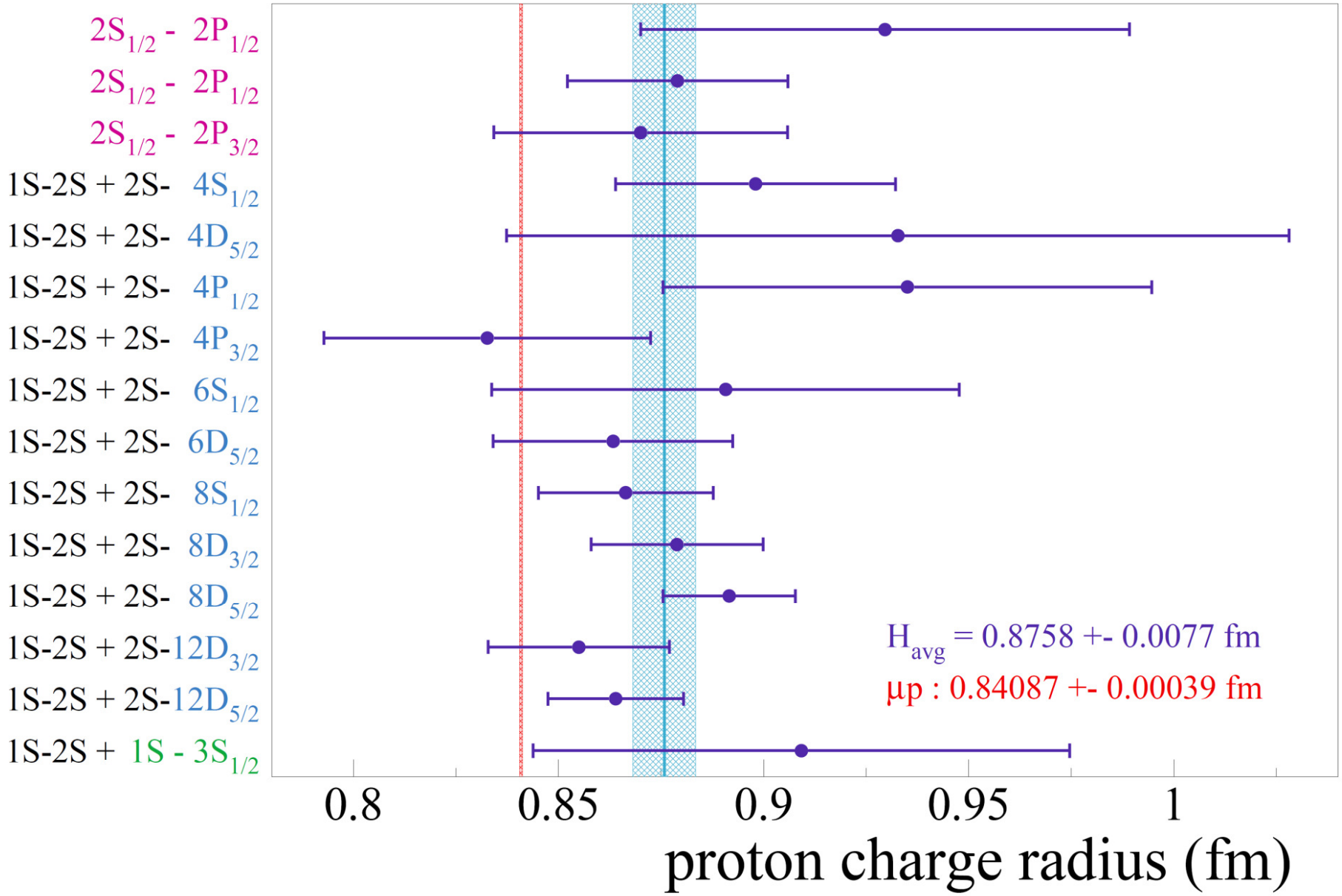
http://www.ust.edu.tw/

Proton radius puzzle



Science 339, 405 (2013)

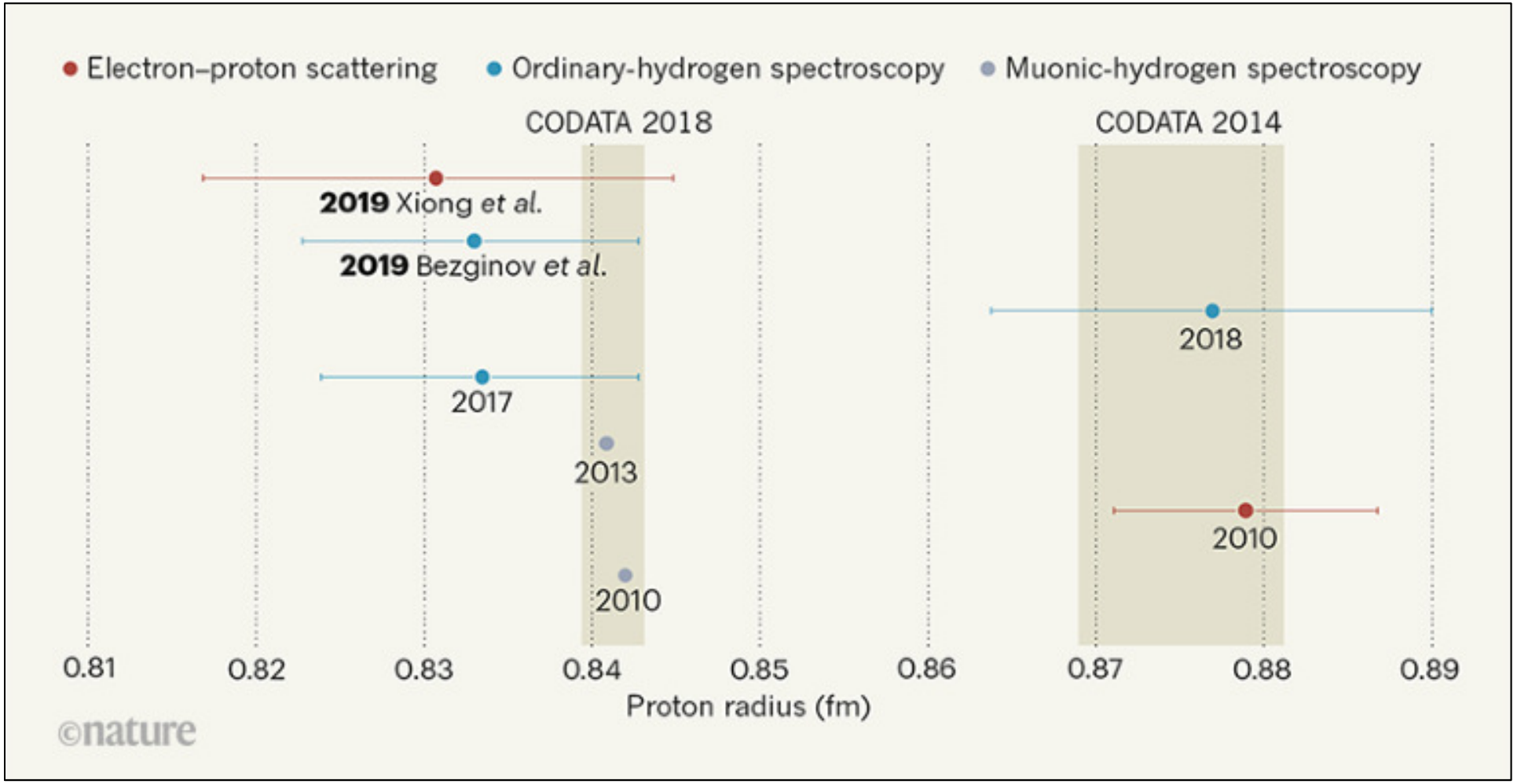
Close up: Hydrogen Spectroscopy



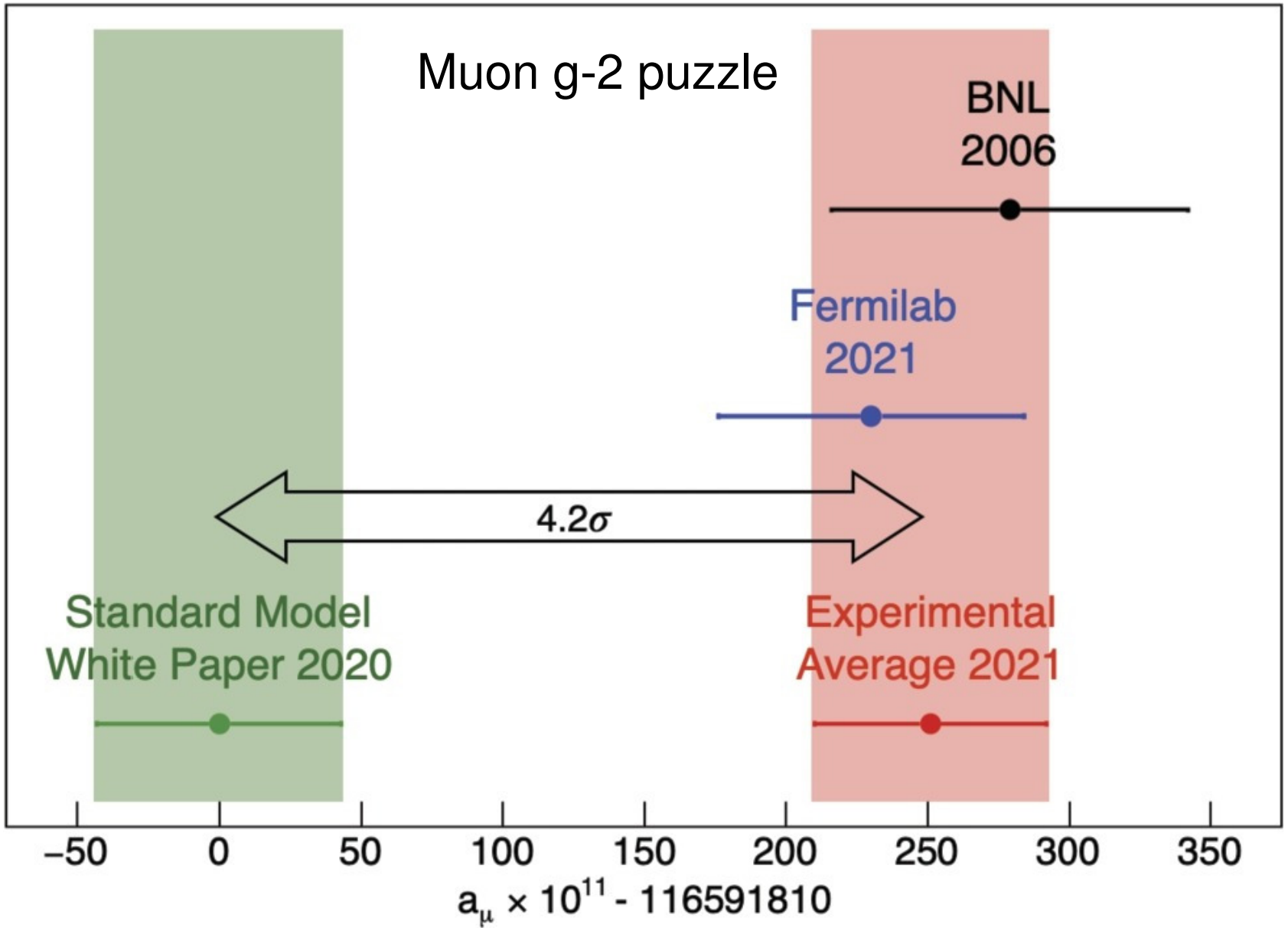
R. Pohl et al., Annu. Rev. Nucl. Part. Sci. 63, 175 (2013)

Proton radius puzzle resolved

New hydrogen measurements redone

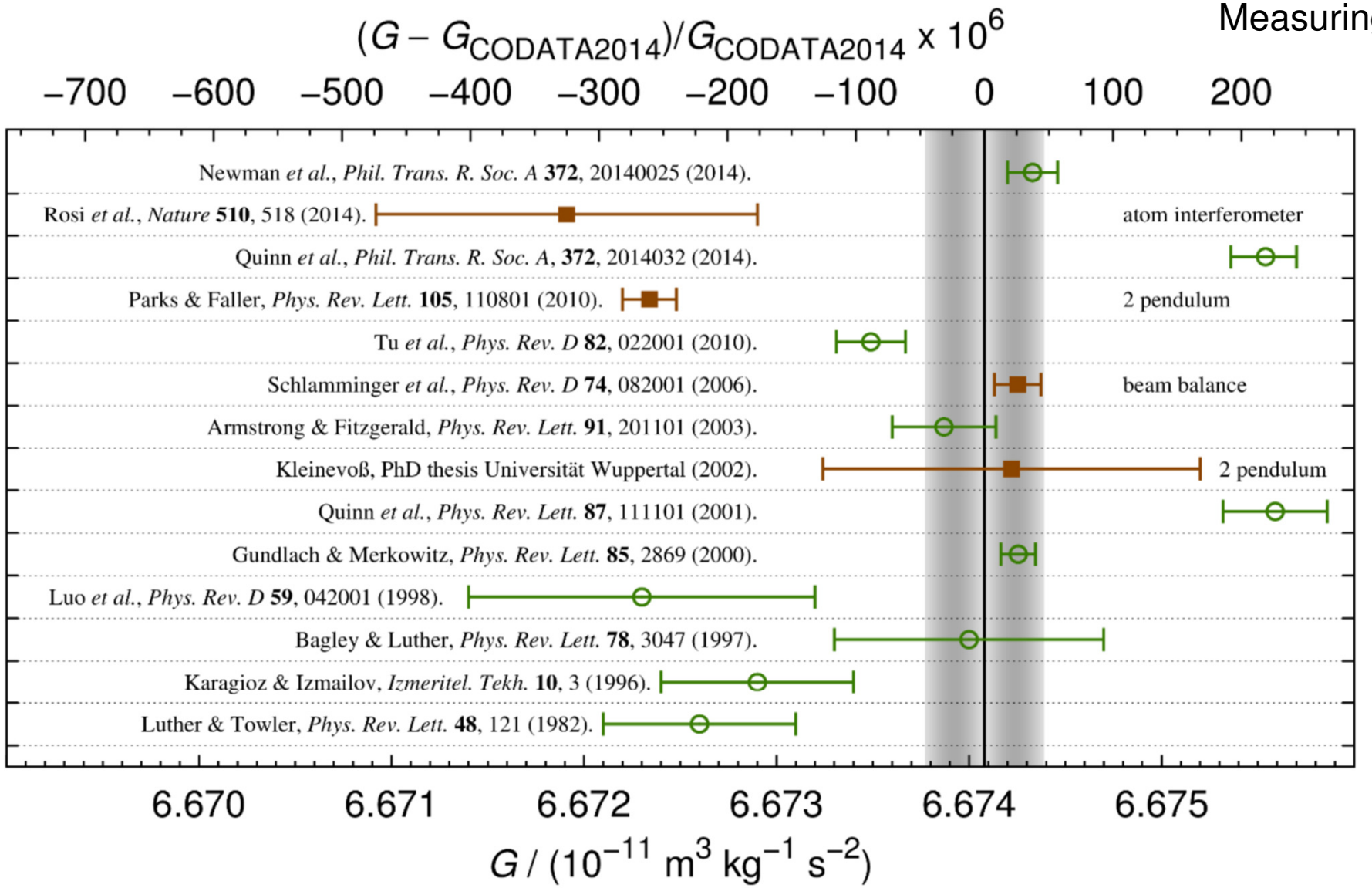


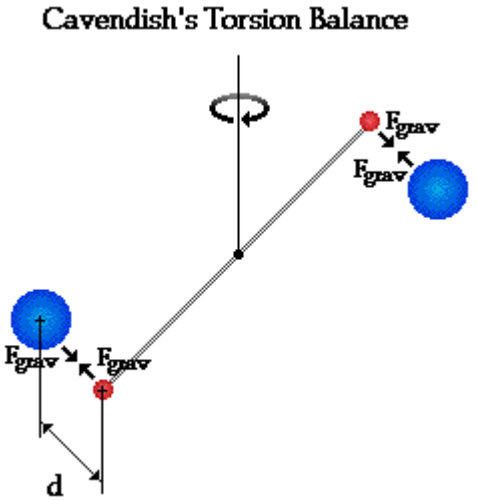
https://www.nature.com/articles/d41586-019-03364-z



Review: Nuclear Physics B 975, 115675, 2022

Measuring gravitational constant G



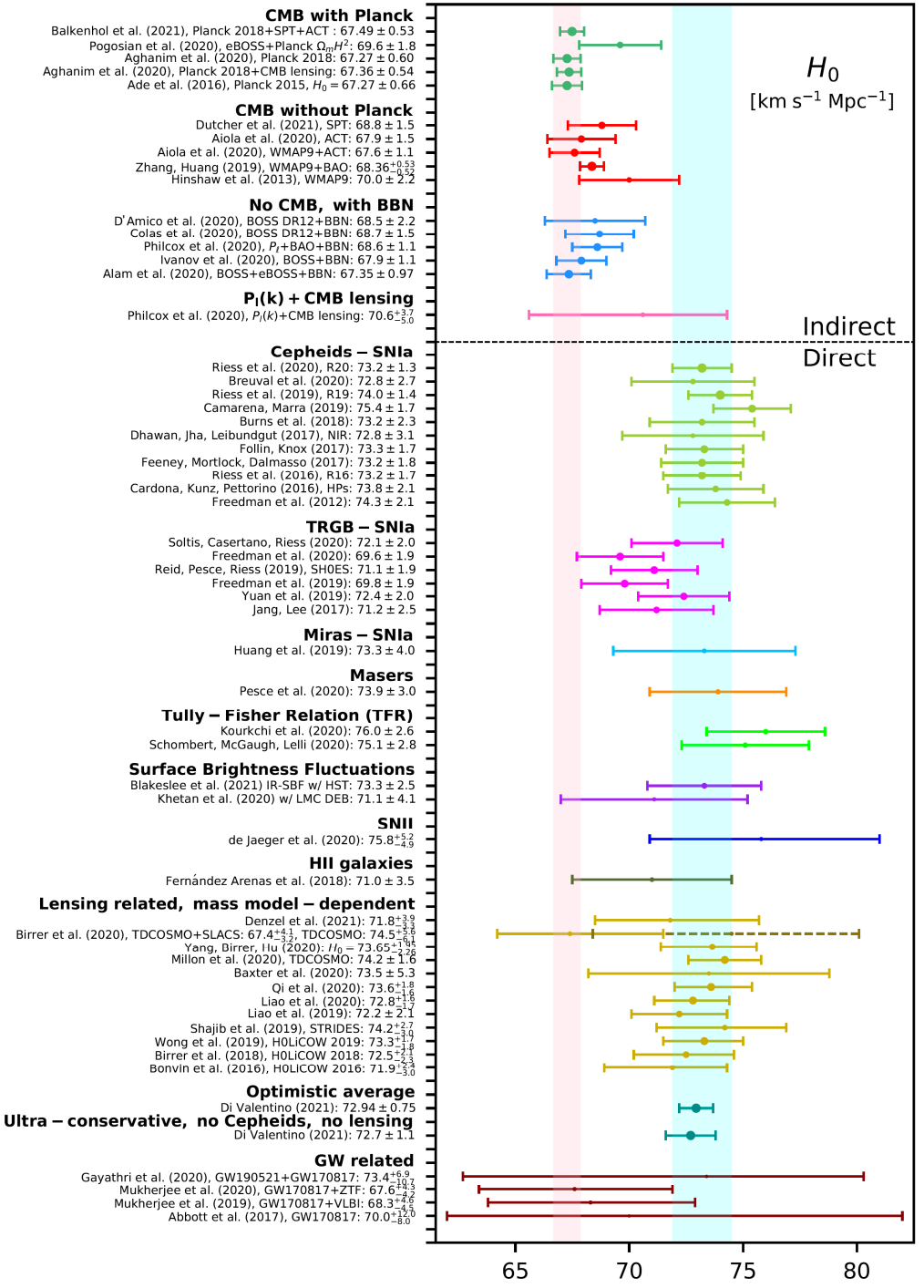


Measurements of the gravitational constant G. The points denoted with open circles were measured using a torsion balance, the solid points by other means. The black vertical line indicates the recommended value by CODATA. The grey area surrounding the black line denotes the 1-sigma uncertainty interval of the recommended value.
https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=921014

In the Realm of the Hubble tension – a Review of Solutions, E. Di Valentino et al., Class. Quantum Grav. 38, 153001 (2021), arXiv:2103.01183

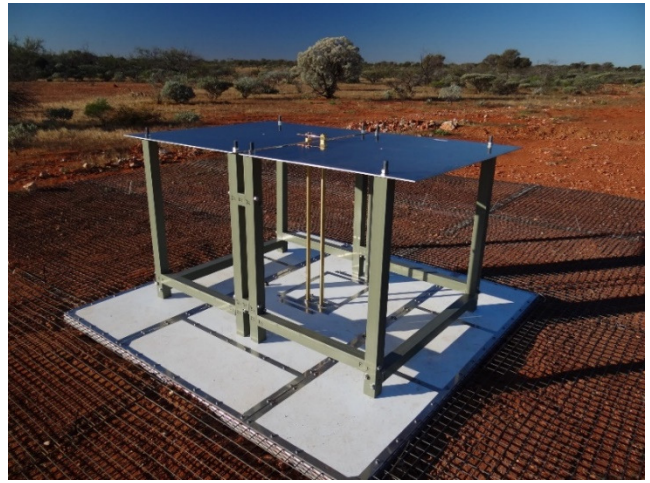
The simplest ΛCDM model provides a good fit to a large span of cosmological data but harbors large areas of phenomenology and ignorance. With the improvement of the number and the accuracy of observations, discrepancies among key cosmological parameters of the model have emerged.

The most statistically significant tension is the 4σ to 6σ disagreement between predictions of the Hubble constant, H_0, made by the early time probes in concert with the "vanilla" ΛCDM Cosmological model, and a number of late time, model-independent determinations of H_0 from local measurements of distances and redshifts.



The EDGES result (H 21cm line anomaly)

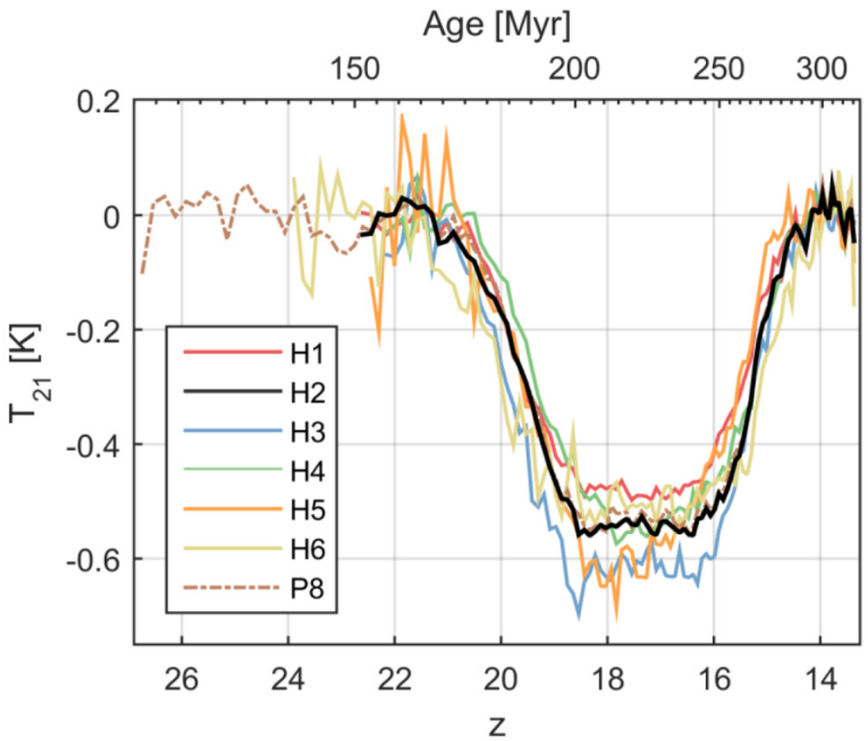
Nature 555, 67 (2018)



After stars formed in the early Universe, their ultraviolet light is expected, eventually, to have penetrated the primordial hydrogen gas and altered the excitation state of its 21-centimetre hyperfine line.

This alteration would cause the gas to absorb photons from the cosmic microwave background, producing a spectral distortion that should be observable today at radio frequencies of less than 200 megahertz.

The best-fitting amplitude of the profile is more than a factor of two greater than the largest predictions, so either the primordial gas was much colder than expected or the background radiation temperature was hotter than expected.



Review: arXiv:1907.13384