Bad Honnef Physics School, May 11, 2025

Frontiers of Quantum Metrology for New Physics Searches

Why to search for new physics?

Marianna Safronova

Q-SEnSE
An NSF Quantum Leap Challenge Institute
https://www.colorado.edu/research/qsense/

University of Delaware

thorium nuclear clock
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.

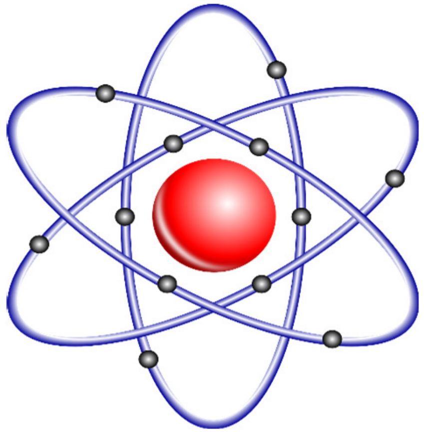
Great practice for the future.

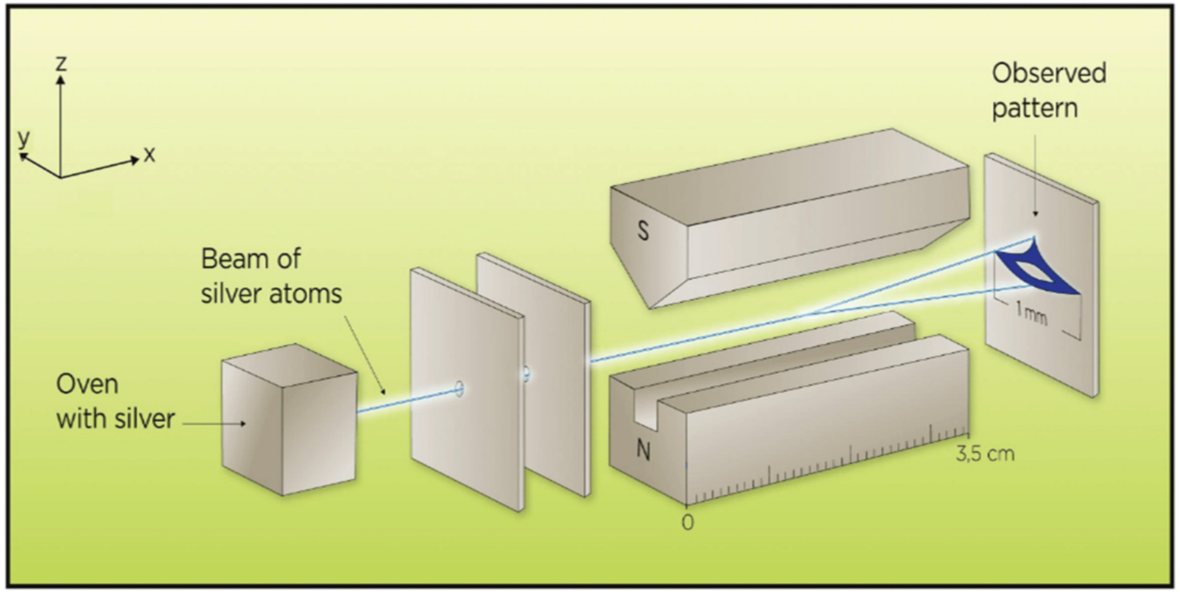
You will stay awake ☺

1925

100 YEARS AGO

WE DID NOT KNOW WHAT ATOMS ARE MADE OF





Puzzles of atomic spectra

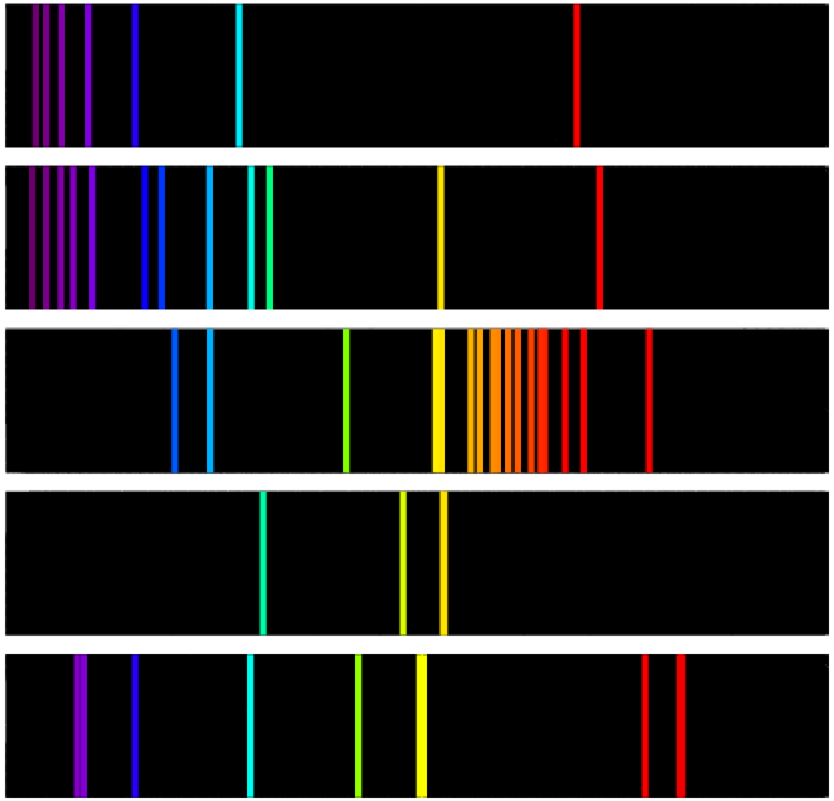
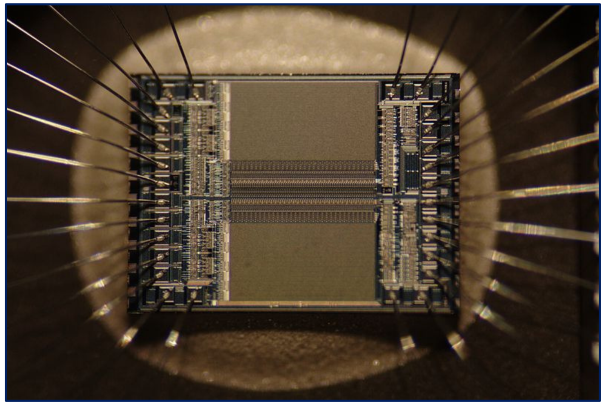


Figure credits: Entropy 2017, 19, 186, practical-chemistry.com

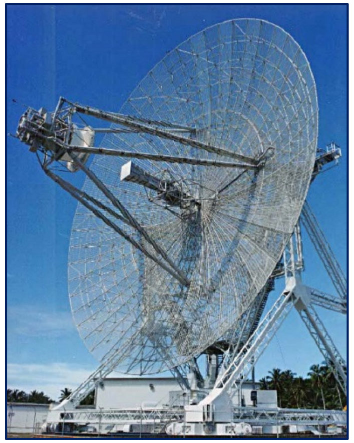
Solving physics puzzles: quantum mechanics



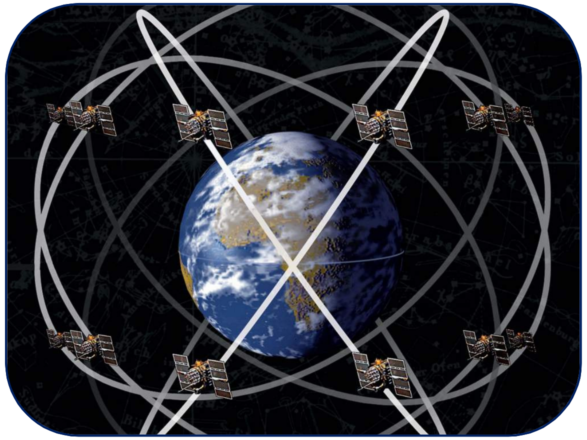
Computer technologies

Lasers

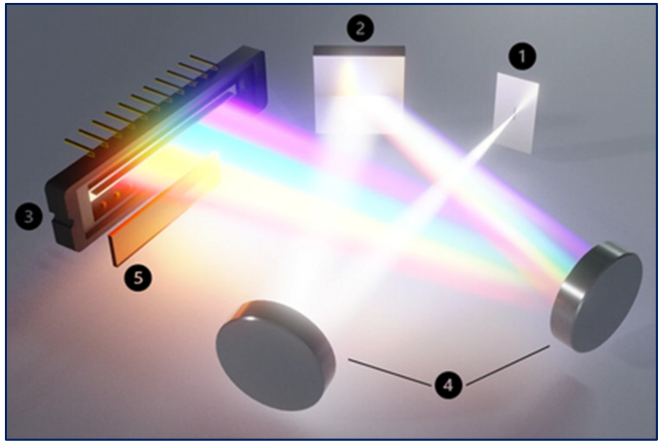
Solar cells



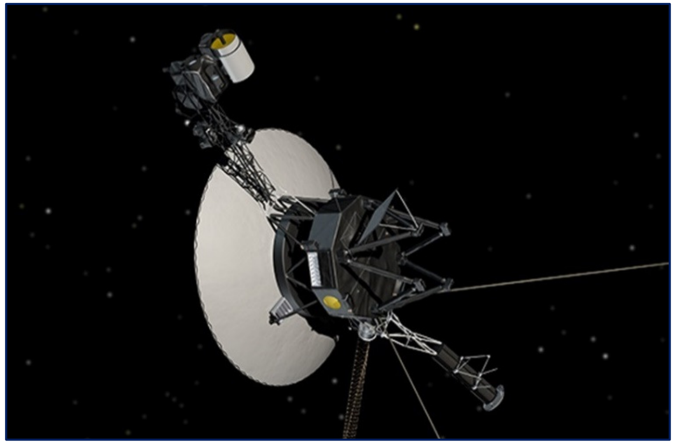
Radars



Navigation



Spectrometers, other detectors



Nuclear technologies

Image credits: Wiki, NASA, National Air and Space Museum

Revolution in atomic physics: the path to quantum sensors

1997 Nobel Prize
Laser cooling and trapping

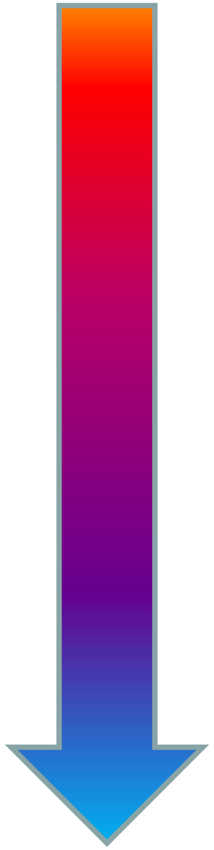
2001 Nobel Prize
Bose-Einstein Condensation

2005 Nobel Prize
Frequency combs

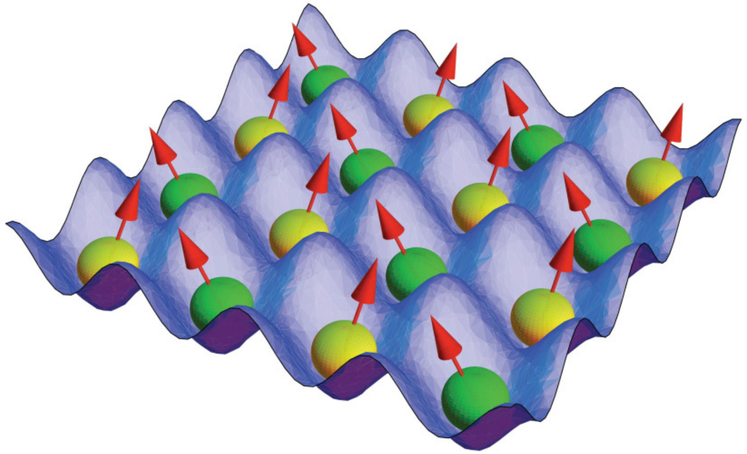
2012 Nobel prize
Quantum control

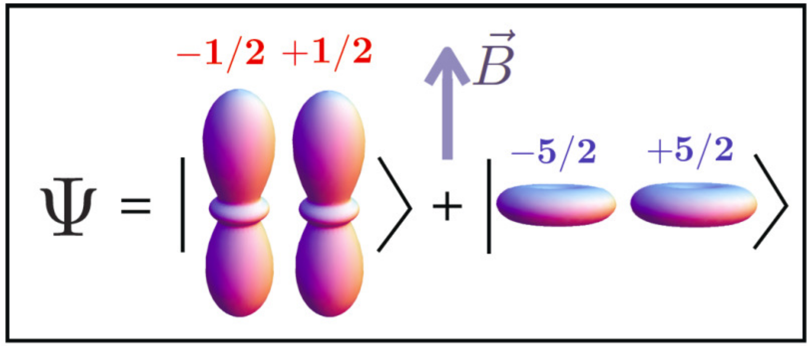
2022 Nobel prize
Bell inequalities, quantum information science

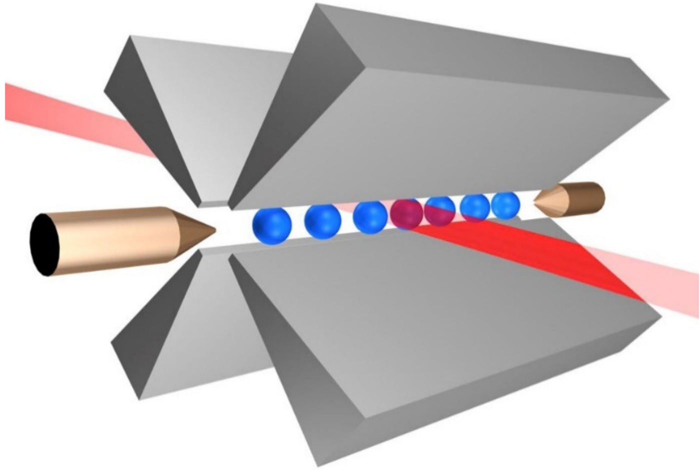
300K

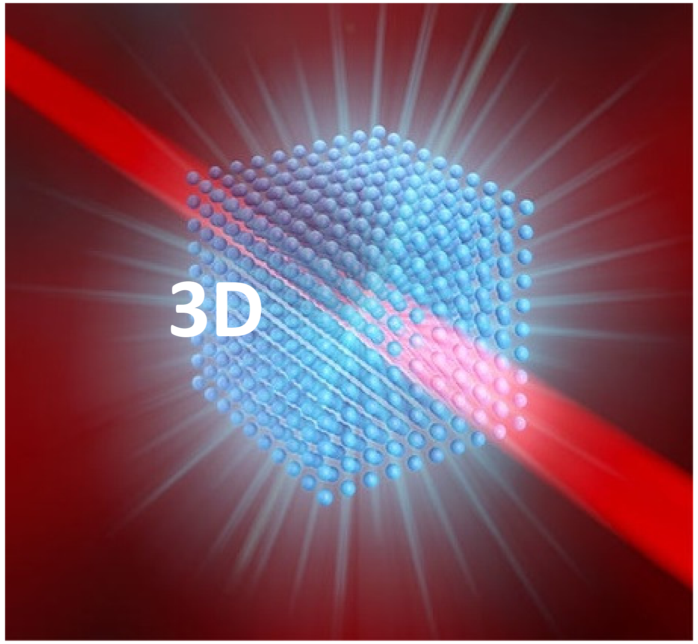


pK









Atoms are now: **Ultracold** **Trapped** **Precisely controlled**

What is a quantum sensor?

Focus Issue in Quantum Science and Technology (20 papers)

Quantum Sensors for New-Physics Discoveries

Editors: Marianna Safronova and Dmitry Budker

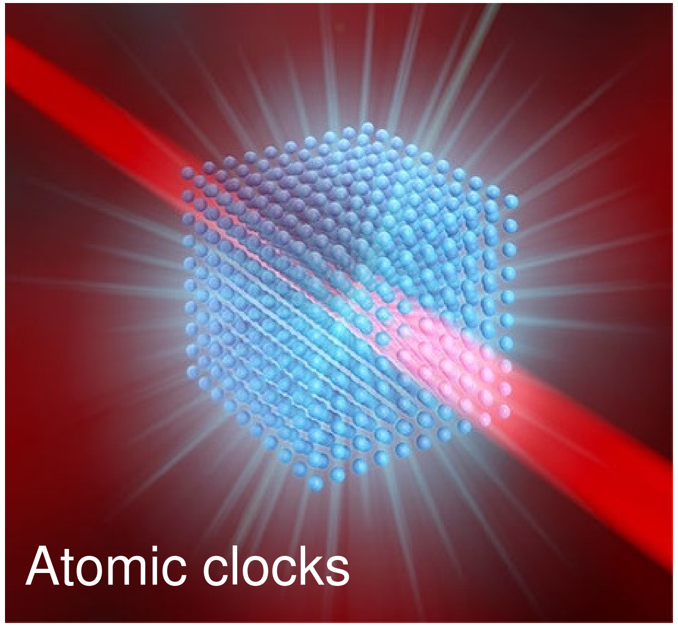
https://iopscience.iop.org/journal/2058-9565/page/Focus-on-Quantum-Sensors-for-New-Physics-Discoveries

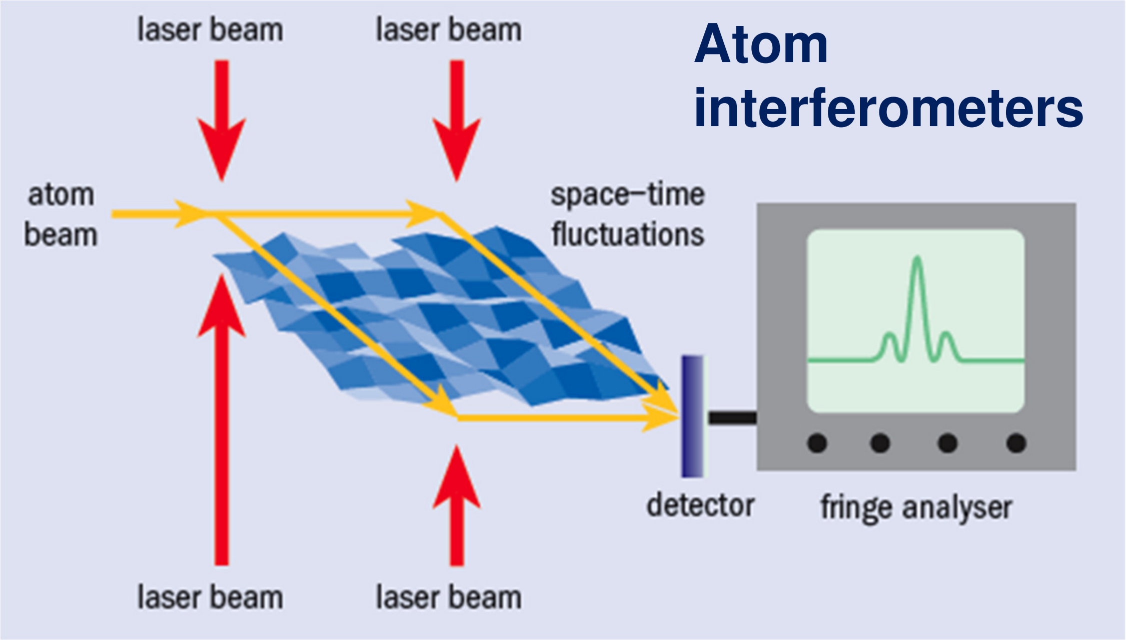
Editorial:

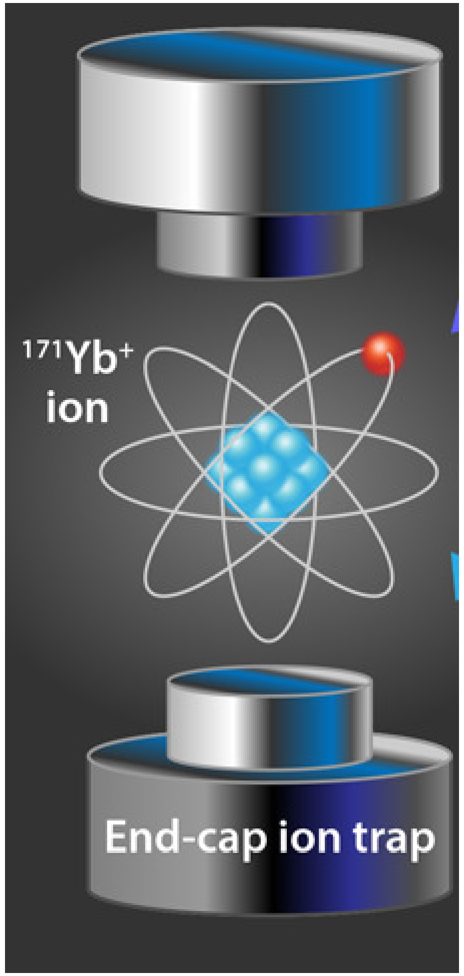
Quantum technologies and the elephants, M. S Safronova and Dmitry Budker, Quantum Sci. Technol. 6, 040401 (2021).

"We take a broad view where any technology or device that is naturally described by quantum mechanics is considered ``quantum''. Then, ***a "quantum sensor" is a device, the measurement (sensing) capabilities of which are enabled by our ability to manipulate and read out its quantum states***. "

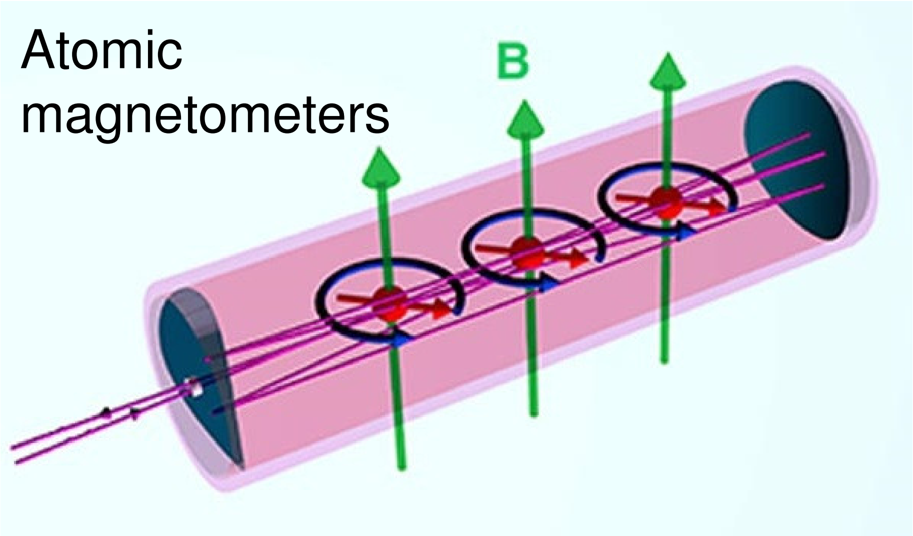
2025 100 YEARS LATER: QUANTUM SENSORS







Trapped ions



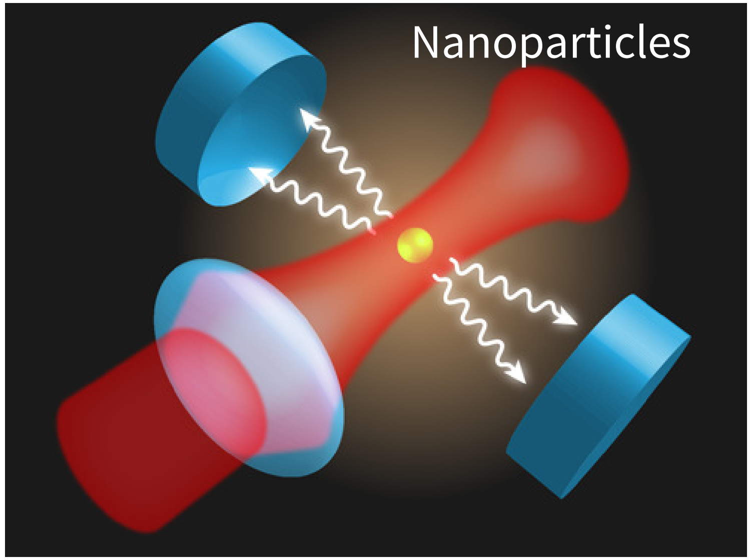
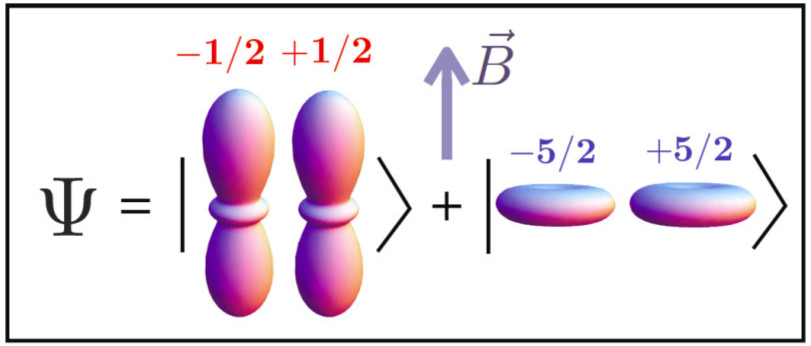
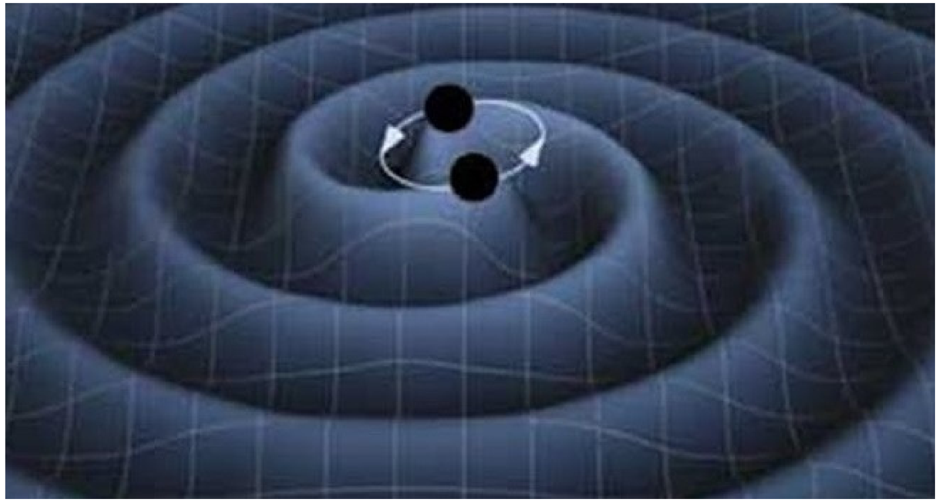


Image credit: JILA, APS/Alan Stonebraker, https://cerncourier.com/a/can-experiment-access-planck-scale-physics/, http://physicsworld.com/cws/article/news/2013/apr/24

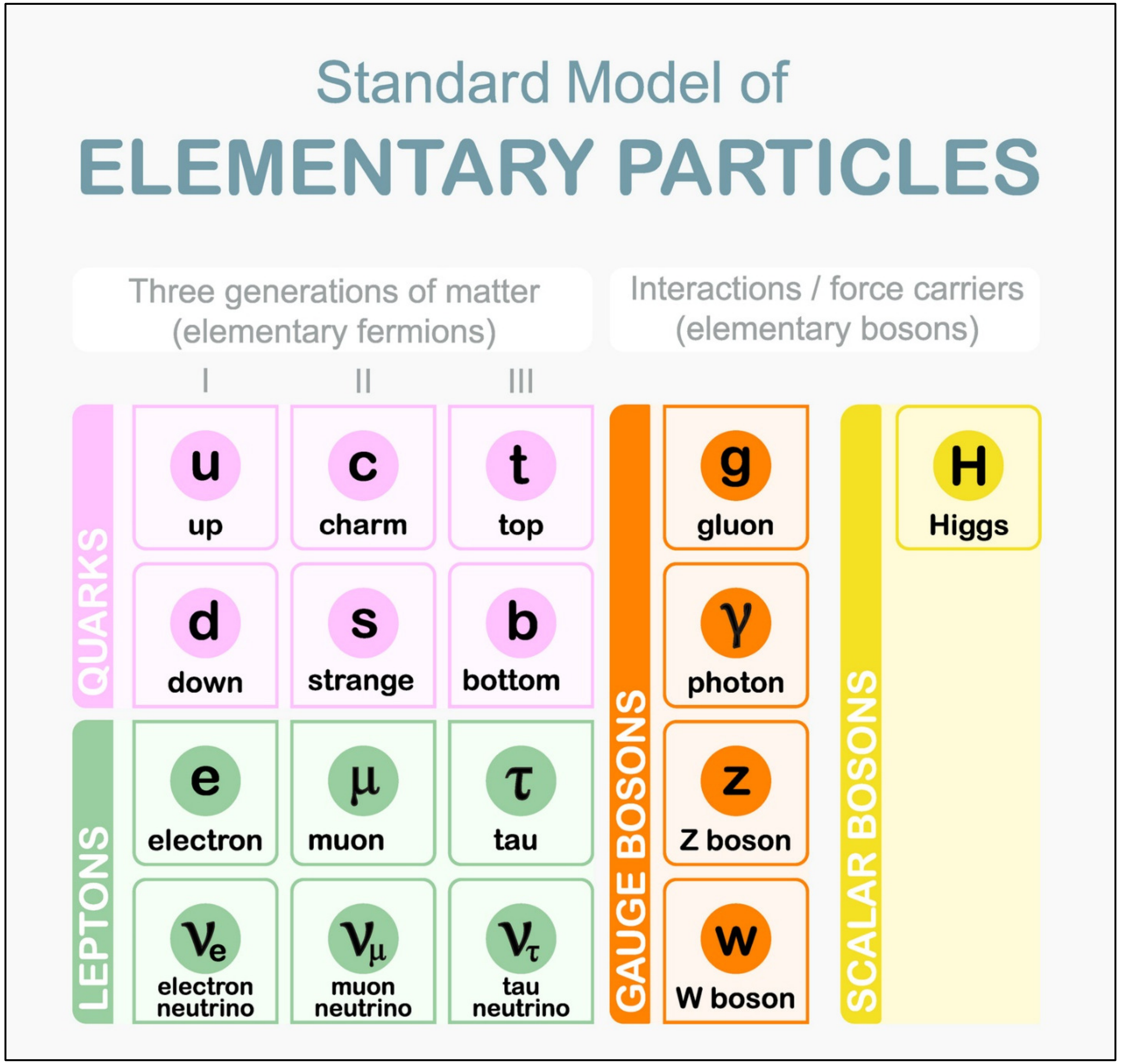
2025

Quantum mechanics





General relativity



iStock,credit:HatchCR

2025: Problems with the standard model

New physics is required due to observations: no Standard Model explanation

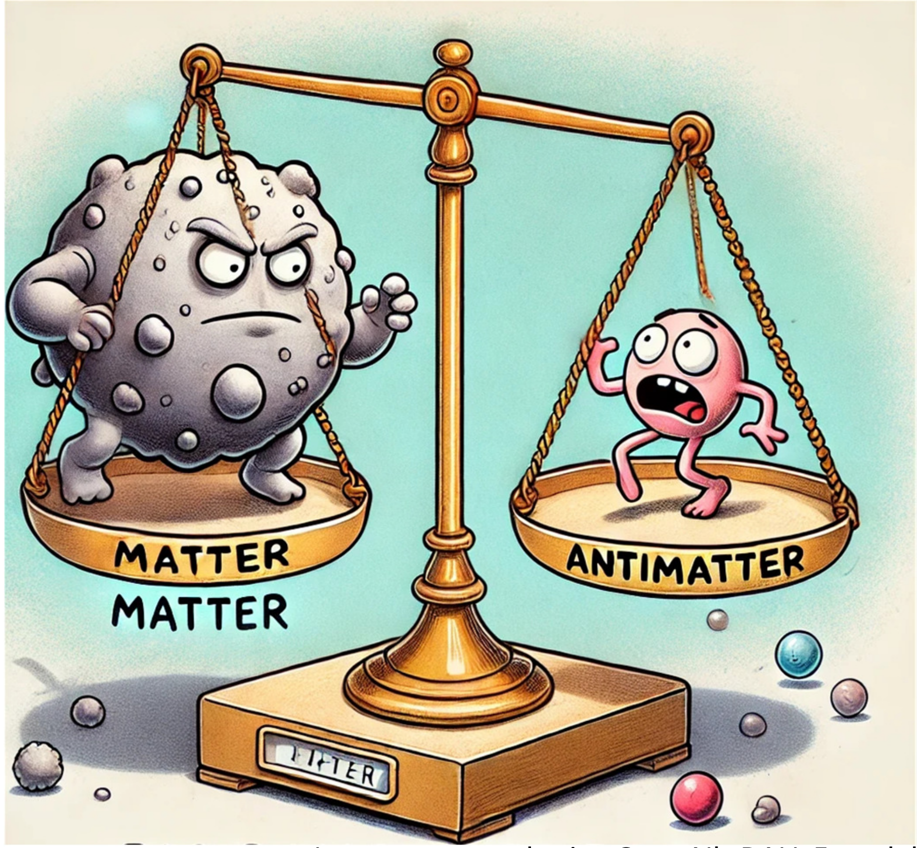
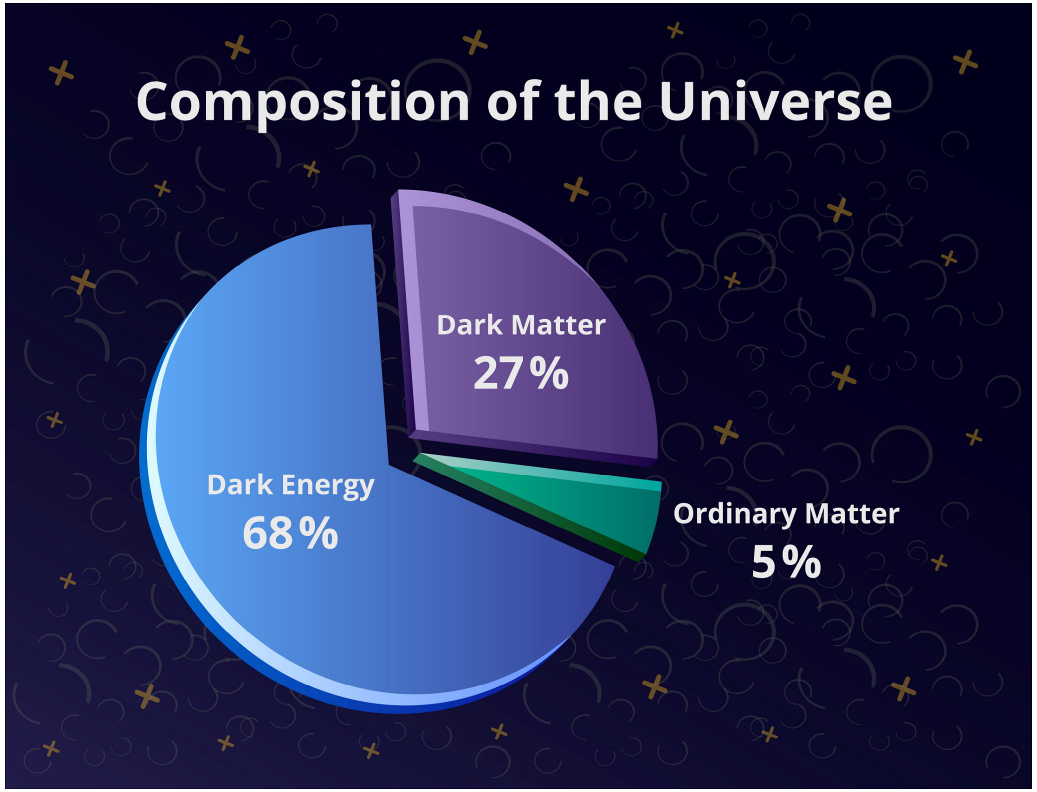


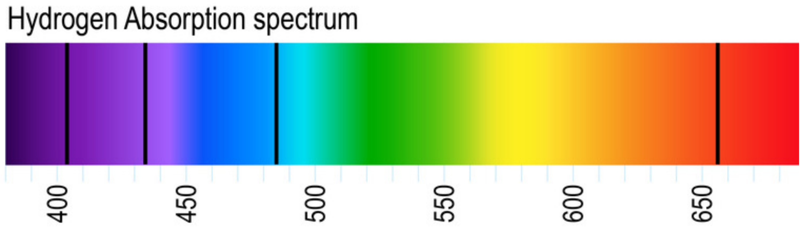
Image generated using OpenAI's DALL·E model

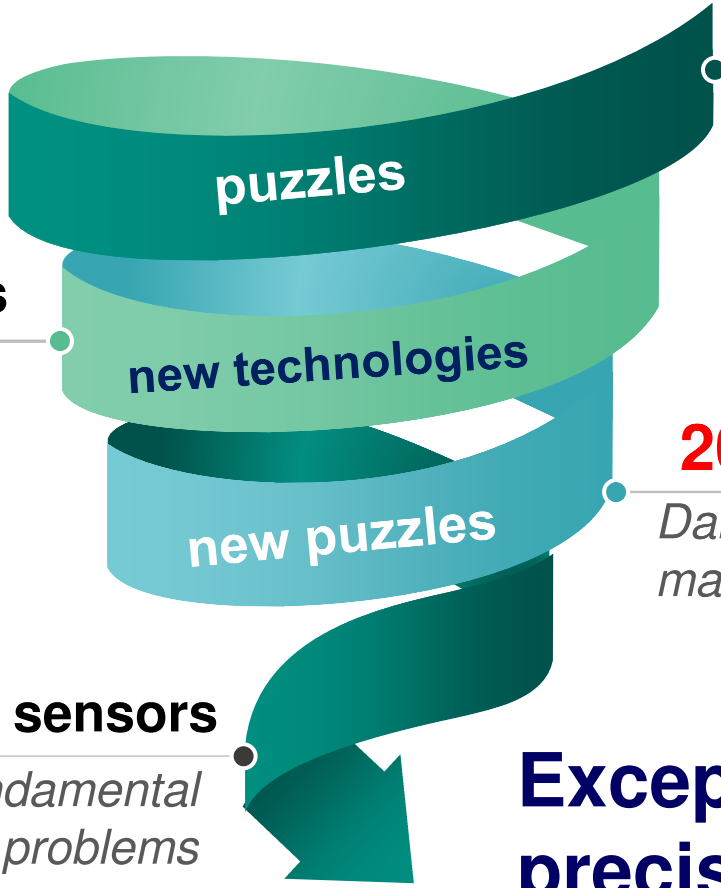


- Dark matter
- Matter-antimatter asymmetry
- Neutrino masses
- Accelerate expansion of the Universe (dark energy/cosmological constant?)

We do not know what the universe is made of

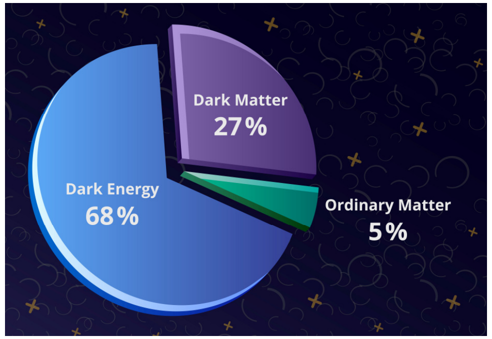
From atomic spectra to dark matter



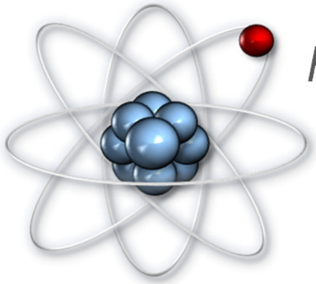


1925

Fundamental physics puzzles: atomic spectra, Stern-Gerlach experiment, etc., …



Quantum mechanics



Result of solving 1925 fundamental physics problems

2025

Dark matter, dark energy, matter-antimatter asymmetry

Quantum sensors

To solve 2025 fundamental physics problems

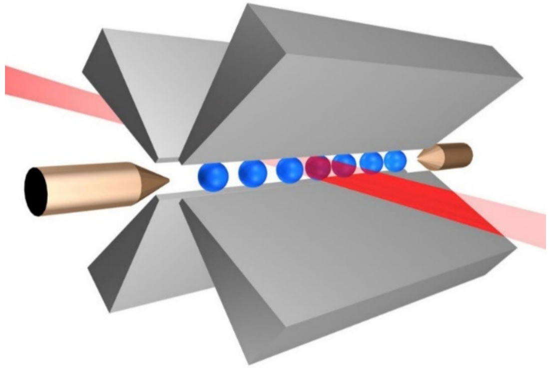


Image courtesy of Timo Koerber

Exceptional improvement in precision of Atomic and Molecular quantum technologies opens new ways to solve the puzzles of the Universe

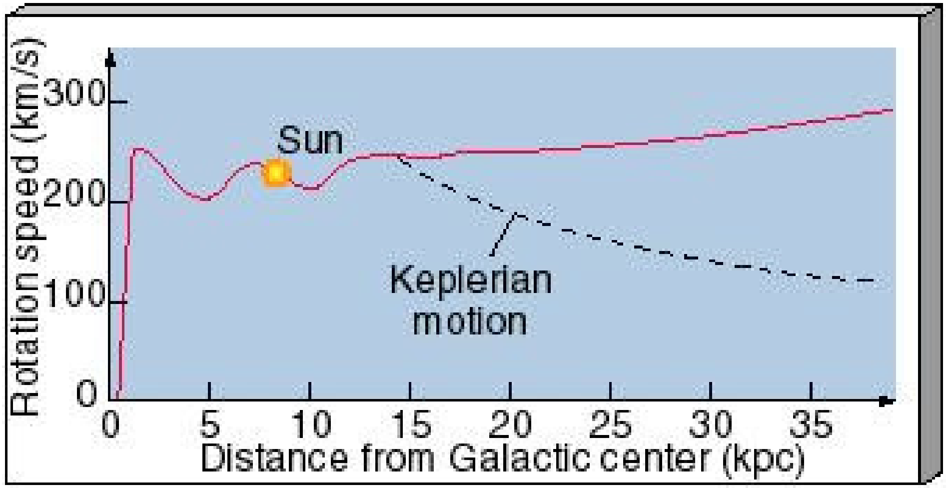
2025: Unanswered questions in particle physics
What we do not know about fundamental particle and interactions

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

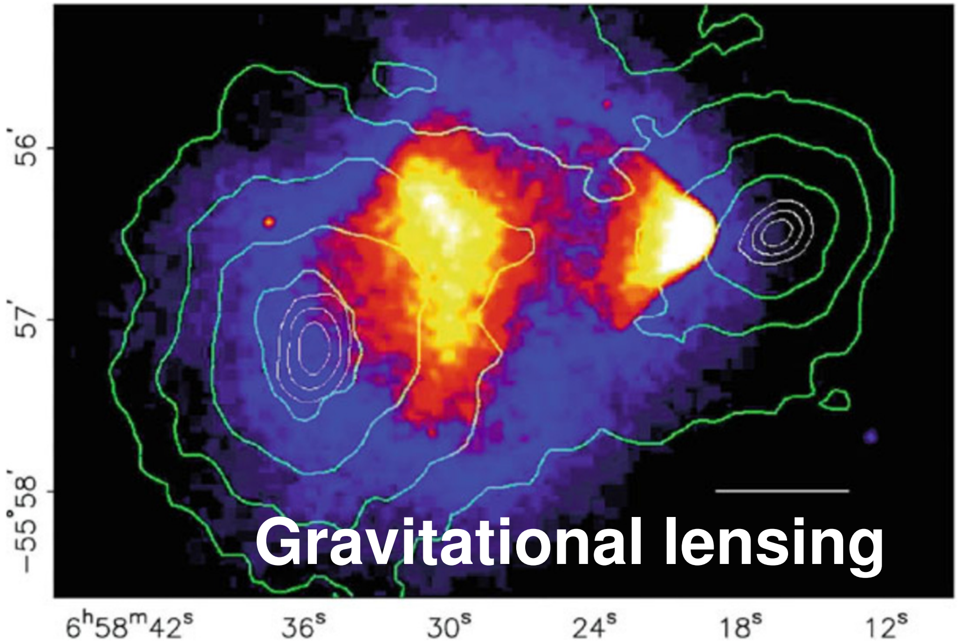
1. **Required by observations: Standard Model can not explain**
   - Dark matter
   - Matter-antimatter asymmetry
   - Accelerate expansion of the Universe (dark energy/cosmological constant?)
   - Neutrino masses

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)

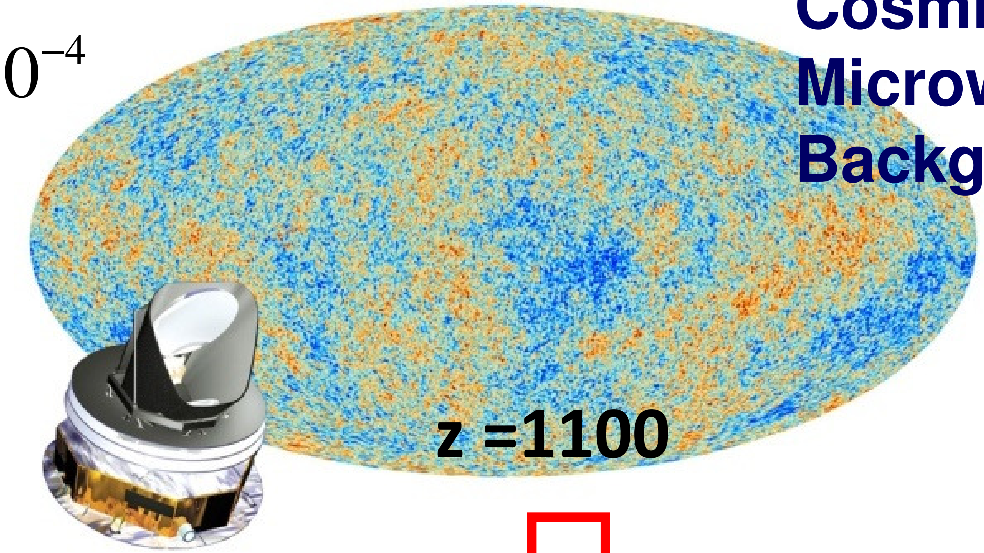
WHAT IS THE EXPERIMENTAL EVIDENCE FOR DARK MATTER?



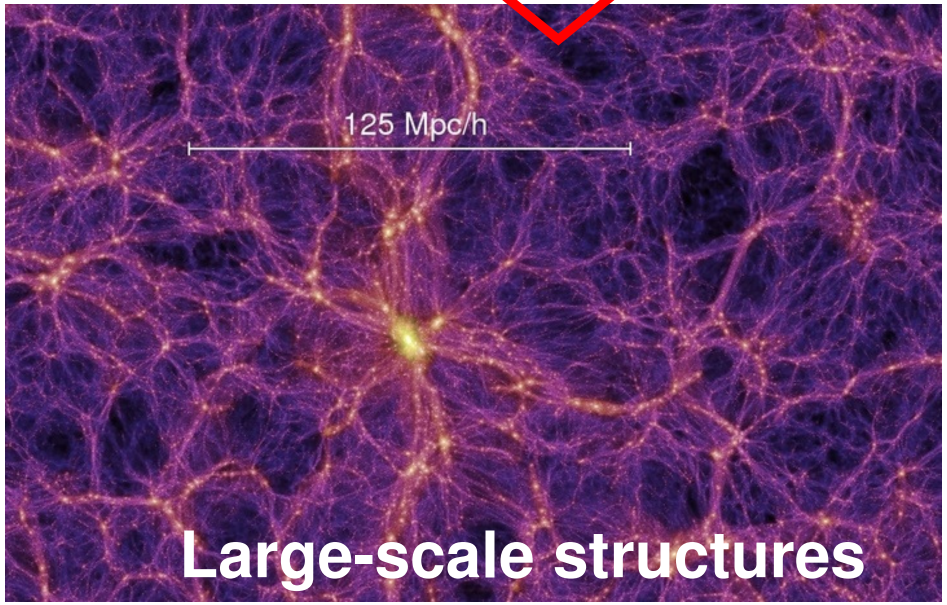
Rotation curves



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

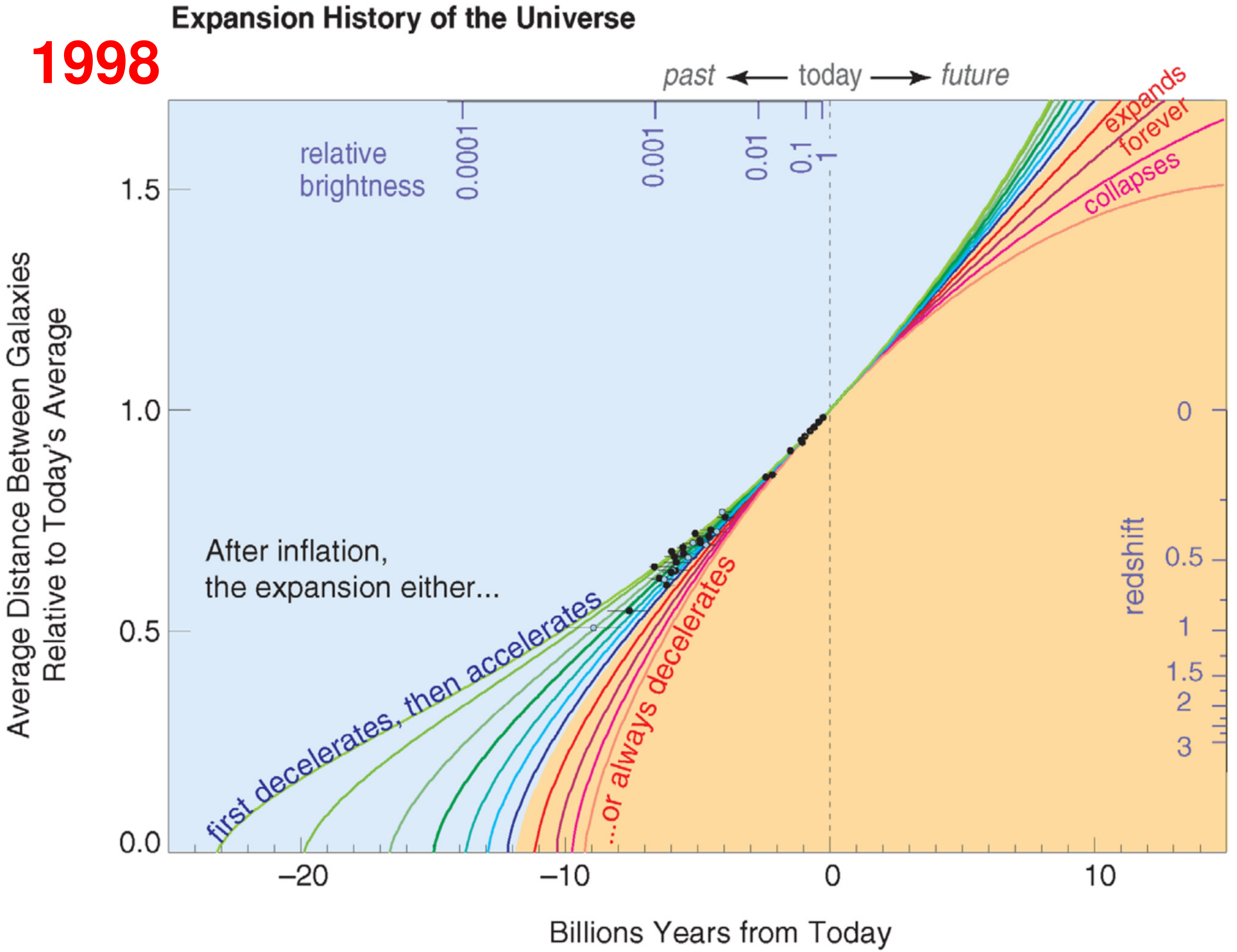


Cosmic Microwave Background



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

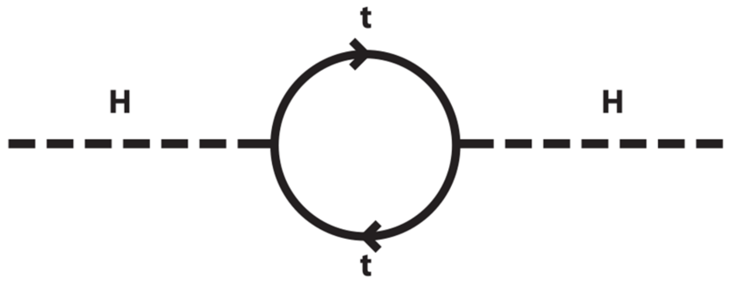
Hierarchy problems: weak scale

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.



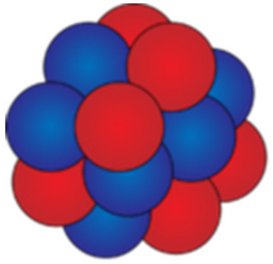
Solutions: supersymmetry, dynamical electroweak symmetry breaking (technicolor), little Higgs, twin Higgs, **dynamical explanation (relaxation)**,…

Life needs very specific fundamental constants!

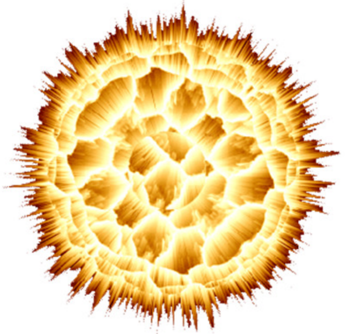
If α is too big $\rightarrow$ small nuclei can not exist

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

$\alpha \sim 1/137$



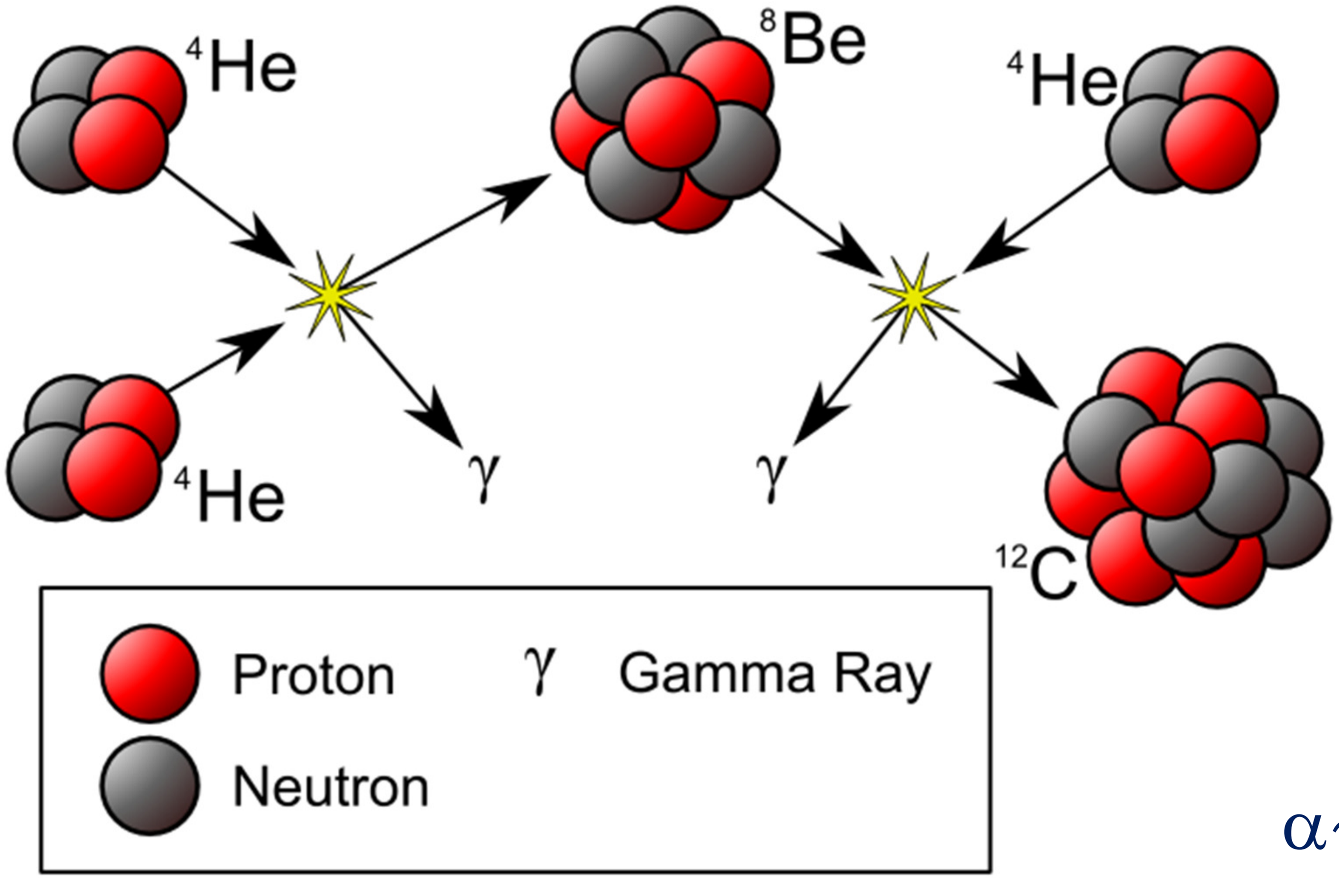
Carbon-12



$\alpha \sim 1/10$

will blow carbon apart

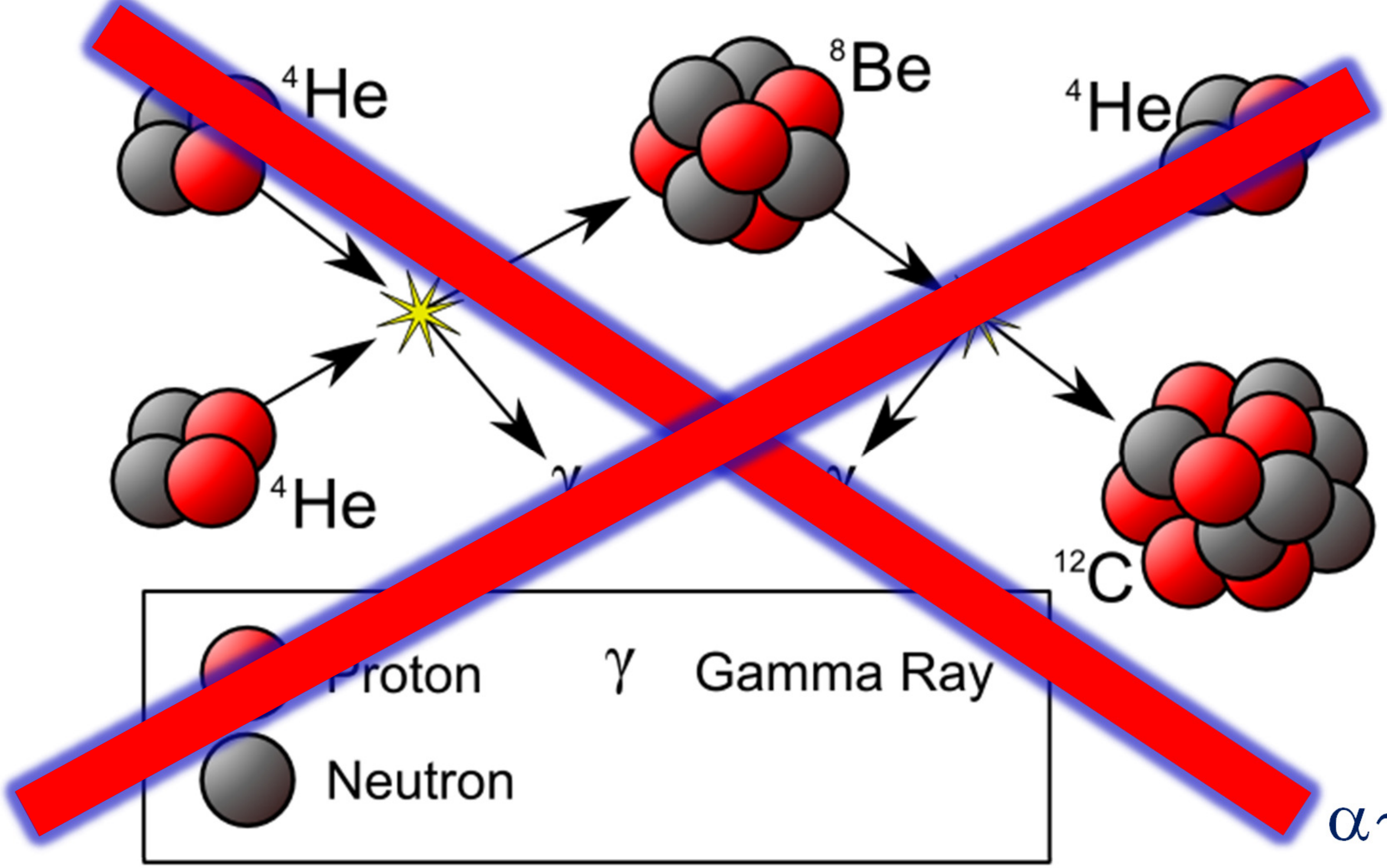
Life needs very specific fundamental constants!



$\alpha \sim 1/137$

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

2025: Unanswered questions in particle physics

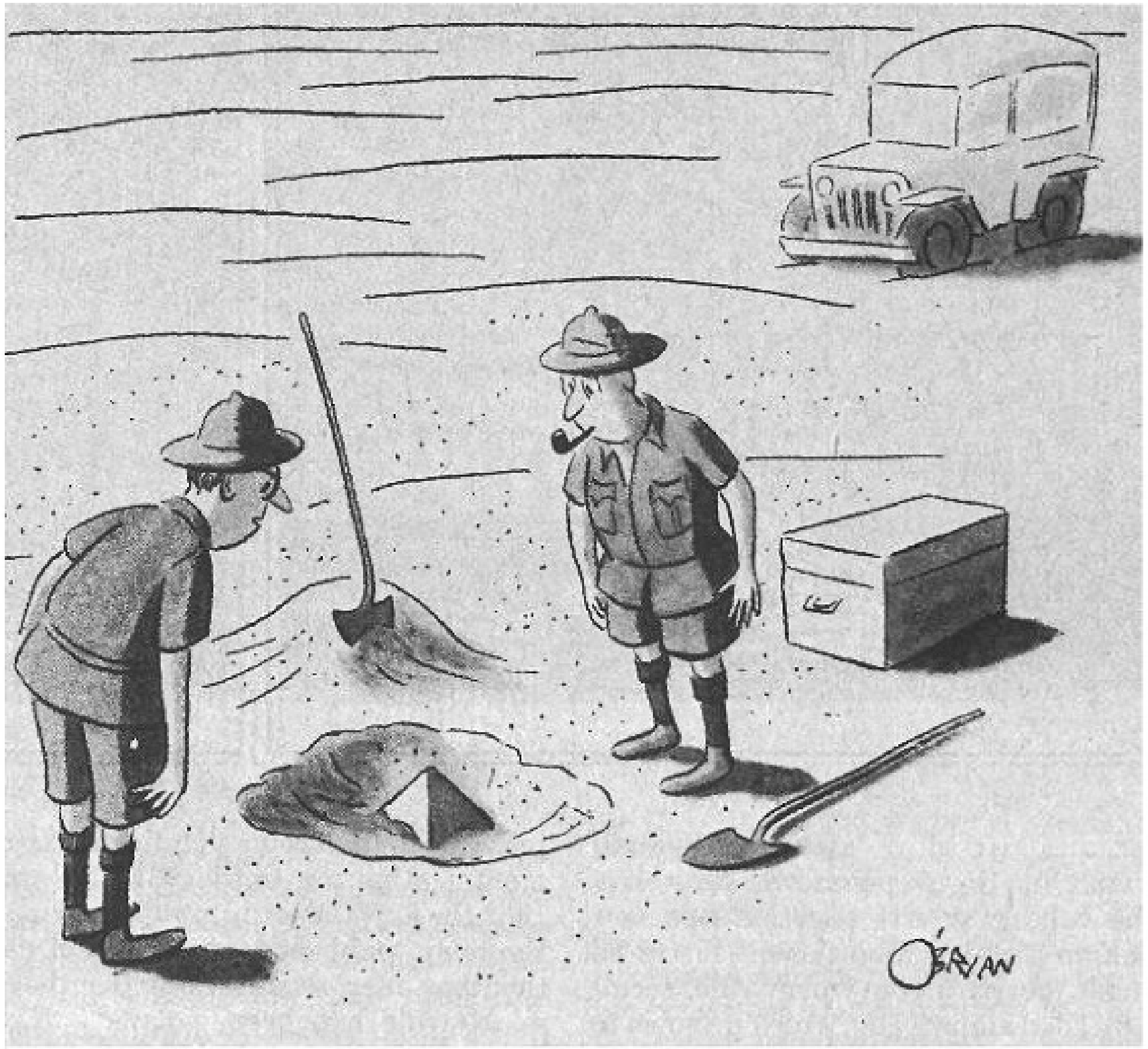
Other open questions

- 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

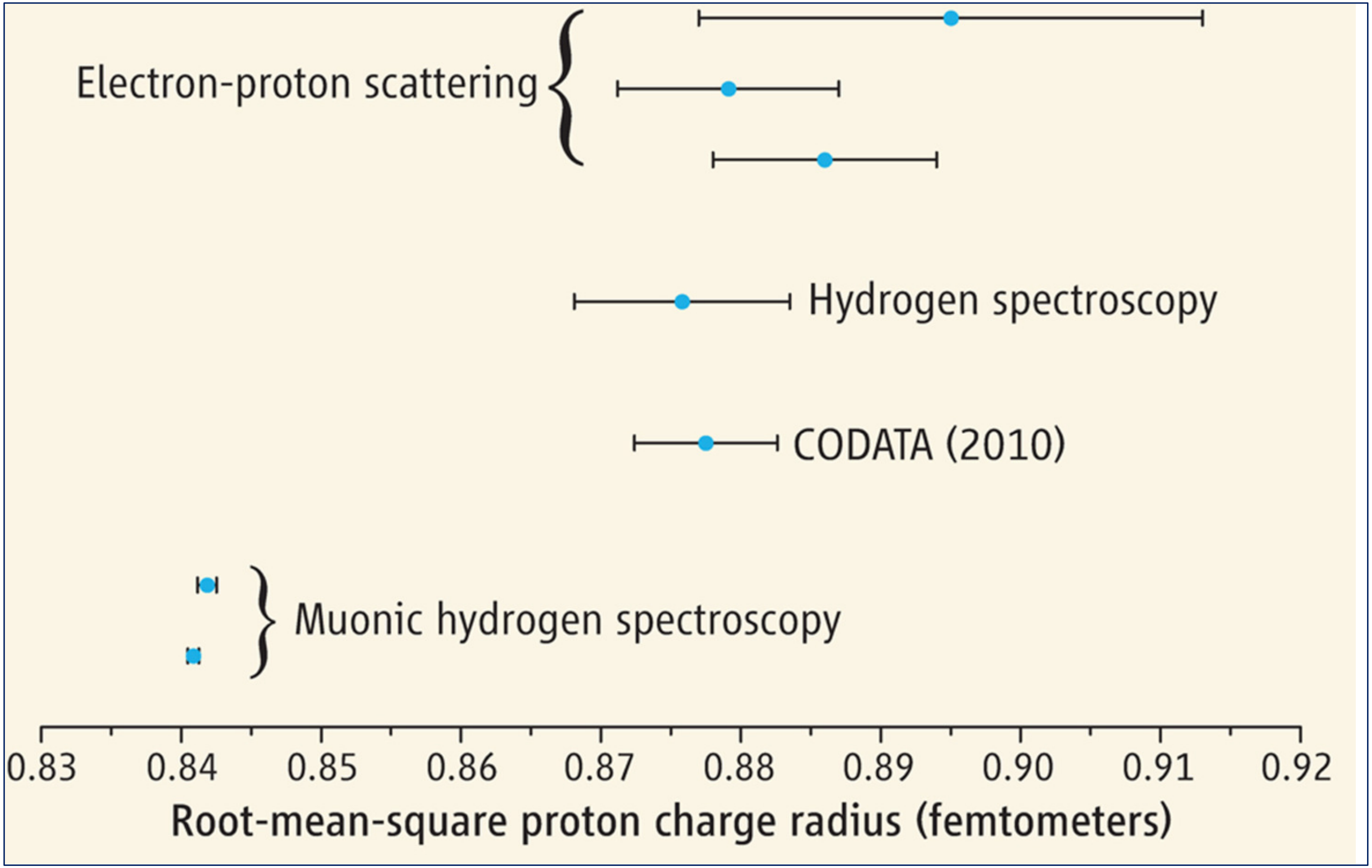
Experimental/observational anomalies



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

http://engent.blogspot.com

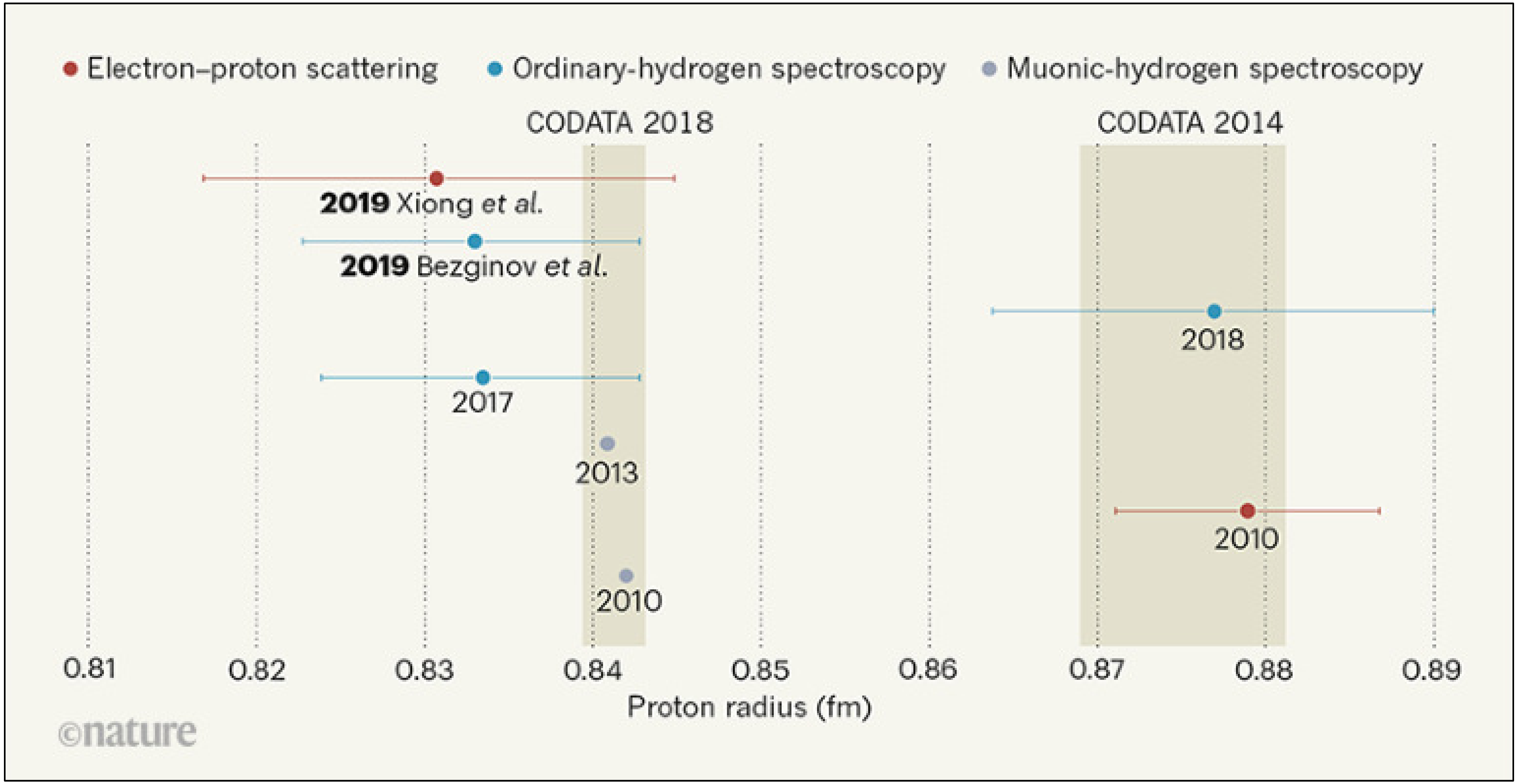
Proton radius puzzle



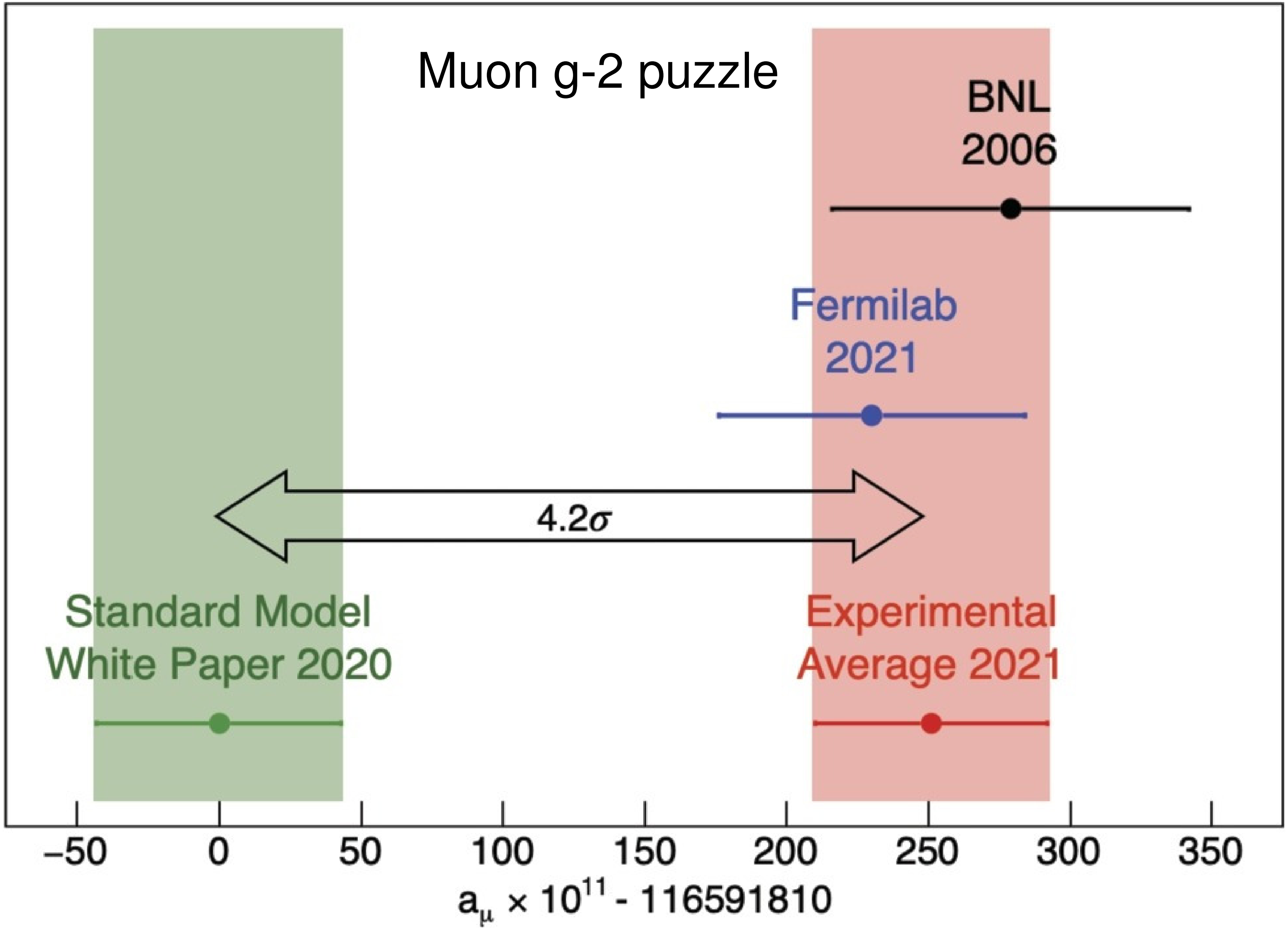
Science 339, 405 (2013)

Proton radius puzzle resolved

New hydrogen measurements redone

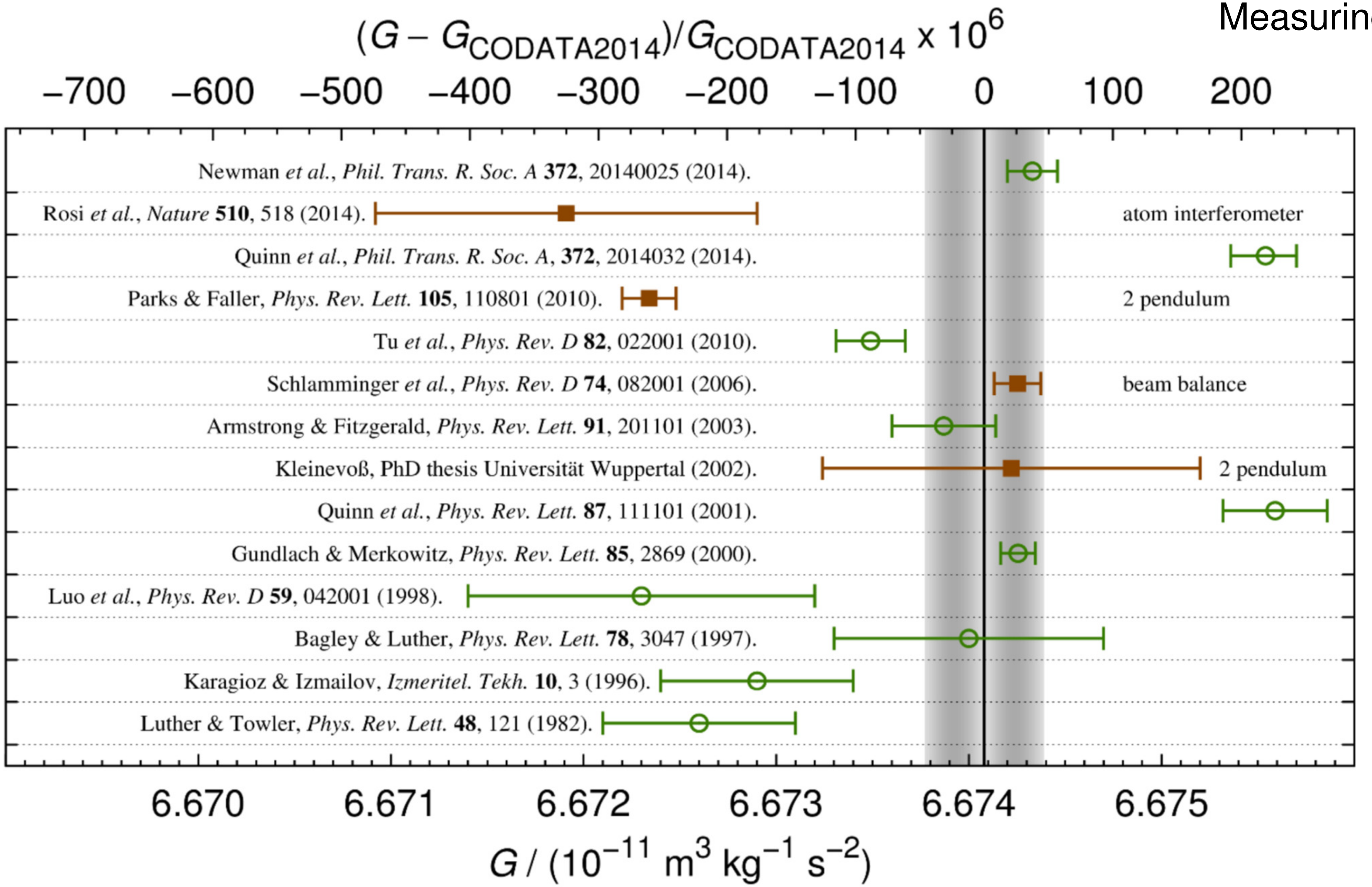


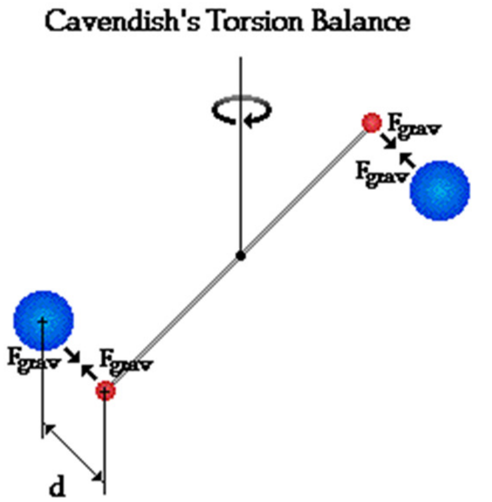
https://www.nature.com/articles/d41586-019-03364-z



Review: Nuclear Physics B 975, 115675, 2022

Measuring gravitational constant G



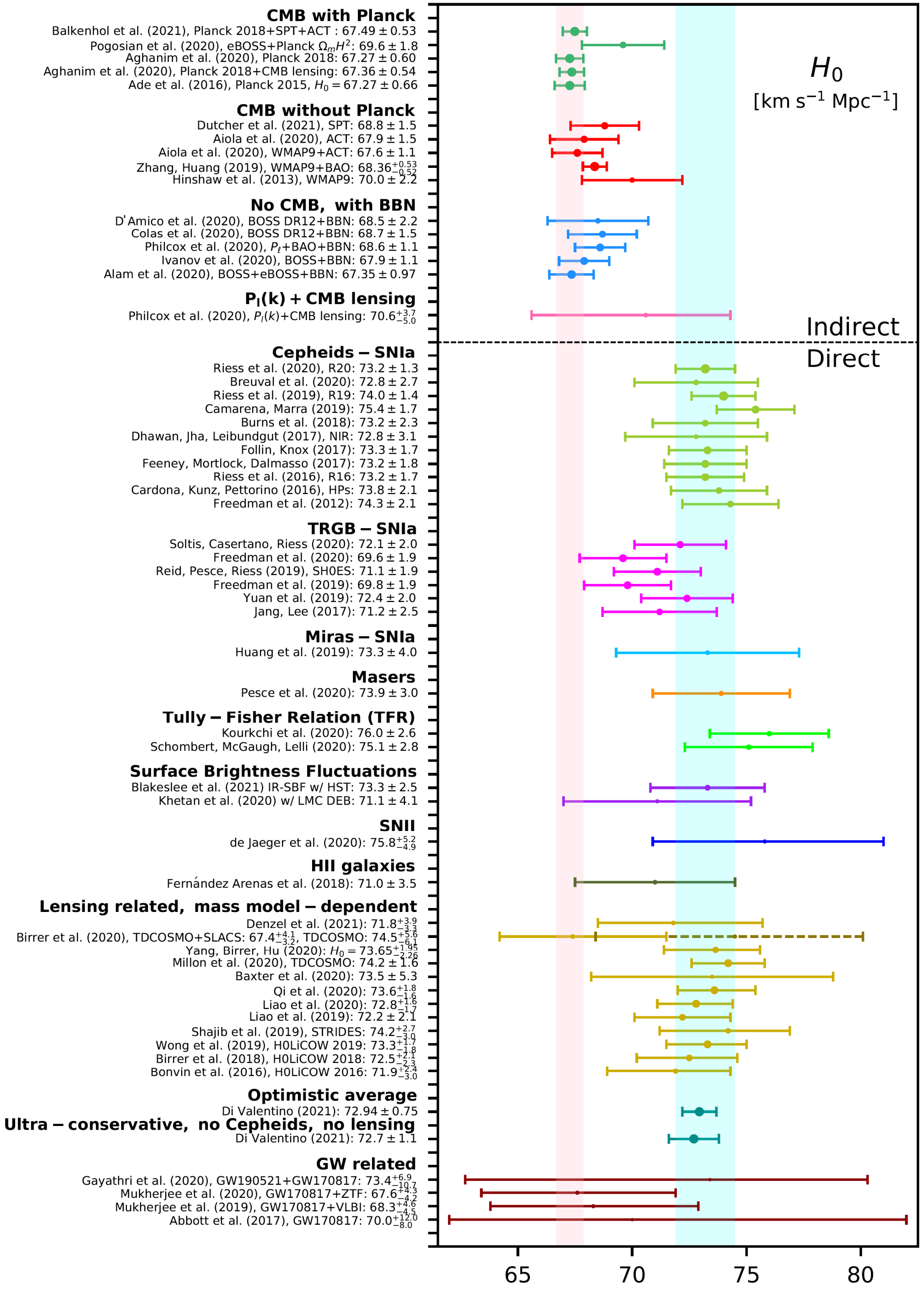


Measurements of the gravitational constant G. The points denoted with open circles were measured using a torsion balance, the solid points by other means. The black vertical line indicates the recommended value by CODATA. The grey area surrounding the black line denotes the 1-sigma uncertainty interval 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.



NEW PHYSICS SEARCHES WITH AMO QUANTUM SENSORS

Focus Issue in Quantum Science and Technology (20 papers)

Quantum Sensors for New-Physics Discoveries

Editors: Marianna Safronova and Dmitry Budker

https://iopscience.iop.org/journal/2058-9565/page/Focus-on-Quantum-Sensors-for-New-Physics-Discoveries

REVIEWS OF MODERN PHYSICS, VOLUME 90, APRIL–JUNE 2018

Search for New Physics with Atoms and Molecules

M.S. Safronova[1,2], D. Budker[3,4,5], D. DeMille[6], Derek F. Jackson Kimball[7], A. Derevianko[8] and C. W. Clark[2]

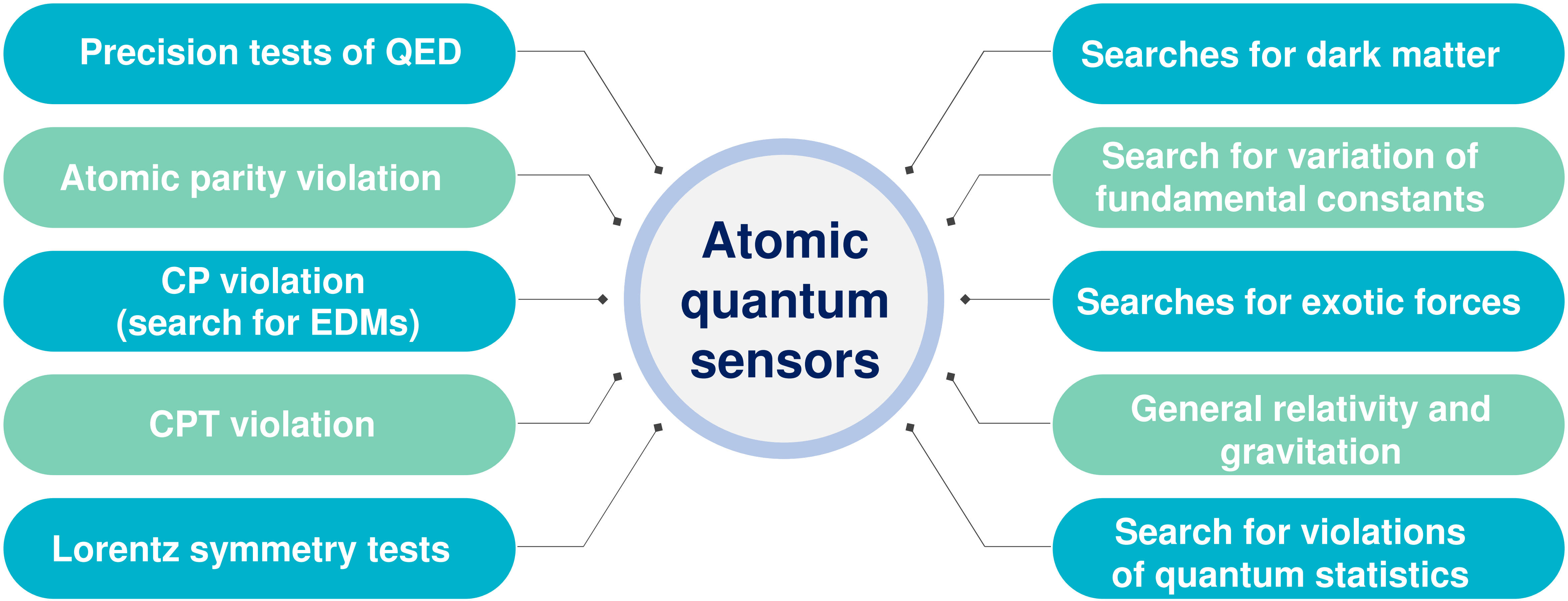
[1]University of Delaware, Newark, Delaware, USA,
[2]Joint Quantum Institute, National Institute of Standards and Technology and the University of Maryland, College Park, Maryland, USA,
[3]Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany,
[4]University of California, Berkeley, California, USA,
[5]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA
[6]Yale University, New Haven, Connecticut, USA,
[7]California State University, East Bay, Hayward, California, USA,
[8]University of Nevada, Reno, Nevada, USA

This article reviews recent developments in tests of fundamental physics using atoms and molecules, including the subjects of parity violation, searches for permanent electric dipole moments, tests of the CPT theorem and Lorentz symmetry, searches for spatiotemporal variation of fundamental constants, tests of quantum electrodynamics, tests of general relativity and the equivalence principle, searches for dark matter, dark energy and extra forces, and tests of the spin-statistics theorem. Key results are presented in the context of potential new physics and in the broader context of similar investigations in other fields. Ongoing and future experiments of the next decade are discussed.

RMP 90, 025008 (2018)

Very wide scope of AMO new physics searches

AMO: atomic, molecular, and optical



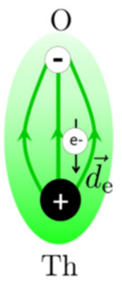
Search for new physics with atoms and molecules, M. S. Safronova, D. Budker, D. DeMille, Derek F. Jackson-Kimball, A. Derevianko, and Charles W. Clark, Rev. Mod. Phys. 90, 025008 (2018).

Searches for BSM physics with Atomic, Molecular, and Optical Physics

Fundamental symmetries with quantum science techniques

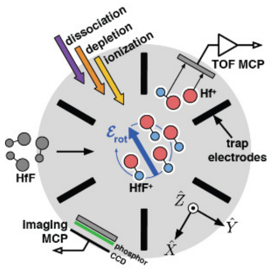
Searches for electron electric-dipole moment (eEDM)

Advanced ACME



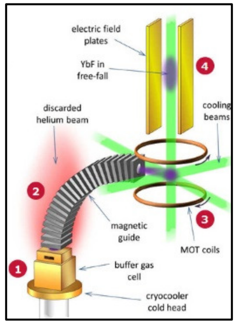
ThO

JILA eEDM



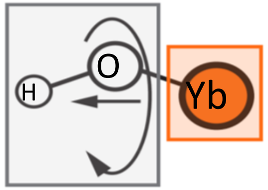
HfF^+, ThF^+

Imperial College



YbF

PolyEDM

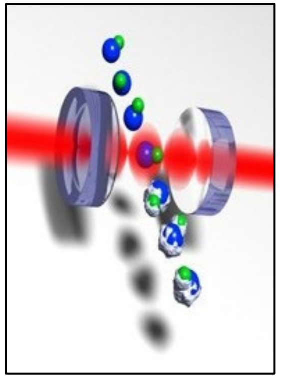


Also NMQM search

YbOH, …

Searches for hadronic EDMs

CeNTREX

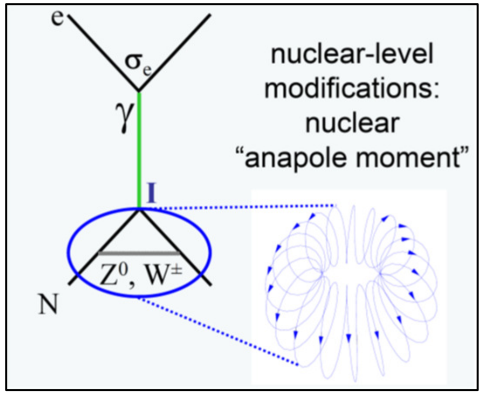


Hg
Xe
Ra
EDMs

TlF (proton EDM)

Enhanced parity violation

ZOMBIES



Also Yb (Mainz), Fr (FRIUMF & Japan)

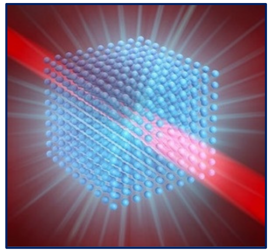
Rapid advances in ultracold molecule cooling and trapping; polyatomic molecules; future: molecules with Ra & "spin squeezed" entangled states

Atomic and Nuclear Clocks & Cavities

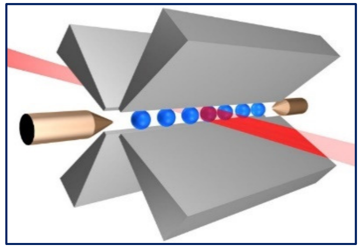
Major clock & cavities R&D efforts below, also molecular clocks, portable clocks and optical links

BSM searches with clocks

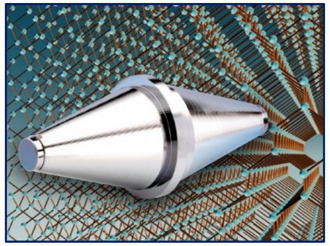
- Searches for variations of fundamental constants
- Ultralight scalar dark matter & relaxion searches
- Tests of general relativity
- Searches for violation of the equivalence principle
- Searches for the Lorentz violation



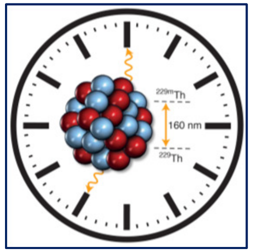
3D lattice clocks



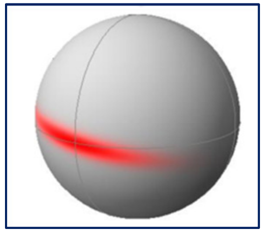
Multi-ion & entangled clocks



Ultrastable optical cavities



Nuclear & highly charge ion clocks



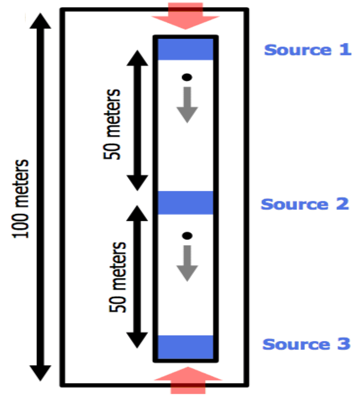
Measurements beyond the quantum limit

Atom interferometry

BSM searches:
Variation of fundamental constants
Ultralight scalar DM & relaxion searches
Violation of the equivalence principle

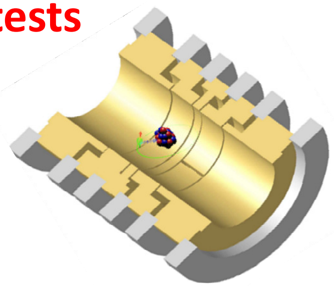
Prototype gravitational wave detectors

MAGIS-100 Fermilab



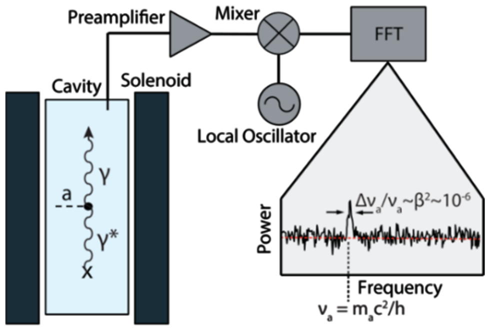
MIGA , AION, ZIGA

QED tests



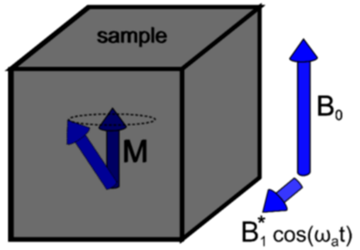
Highly charged ions and simple systems (H, D, $^3He^+$, He, Li, HD, …)

Axion and ALPs searches



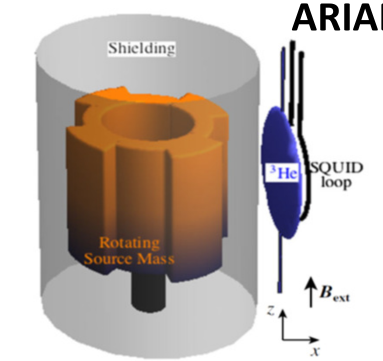
Microwave cavities: HAYSTAC
AMO: measurements beyond quantum limits

CASPEr-electric, solids
(coupling to gluons)



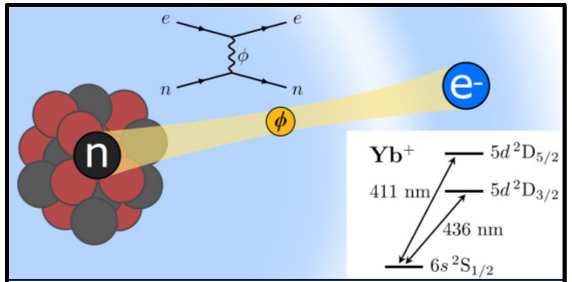
CASPEr-wind, Xe
(coupling to fermions)

ARIADNE

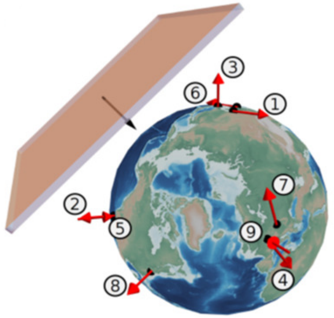


Resonantly detecting axion-mediated forces with NMR

Other dark matter & new force searches

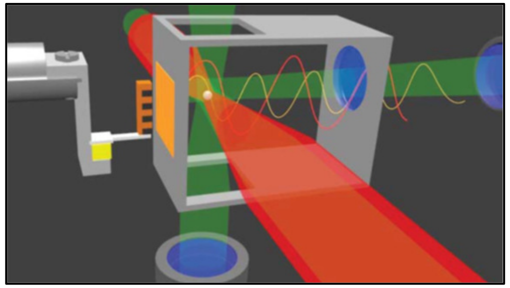


Fifth force searches with precision spectroscopy with atoms and ions



GNOME: network of optical magnetometers for exotic physics

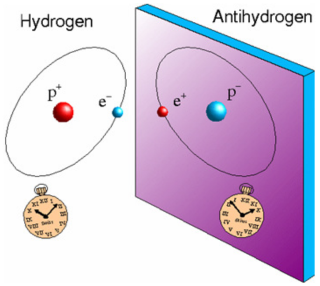
Levitated optomechanics



Also: GW detection and testing the Newtonian inverse square law

CPT tests

$\bar{p}, \bar{H}$



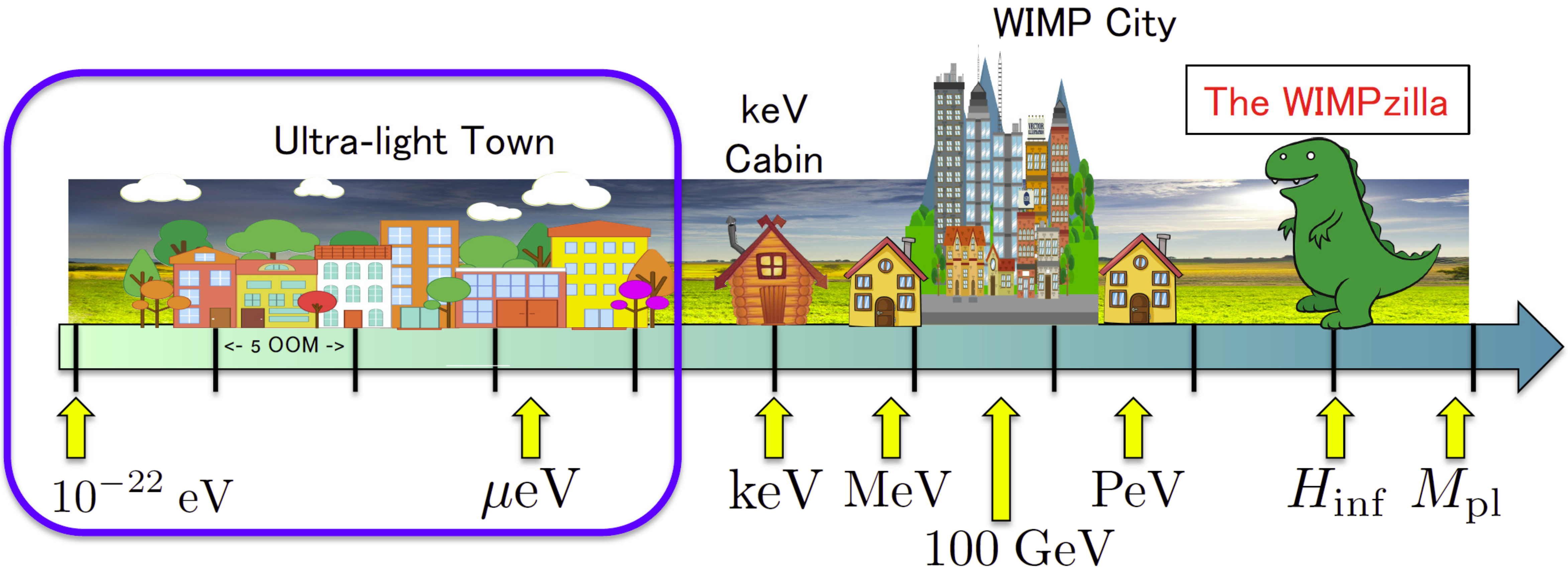
Many other current & future experiments: tests of the gravity-quantum interface, and HUNTER, SHAFT, ORGAN & UPLOAD (axions), solid-state directional detection with NV centers (WIMPs), doped cryocrystals for EDMs, Rydberg atoms, …

Why Search for Dark Matter?


"Because it's there."
–George Mallory

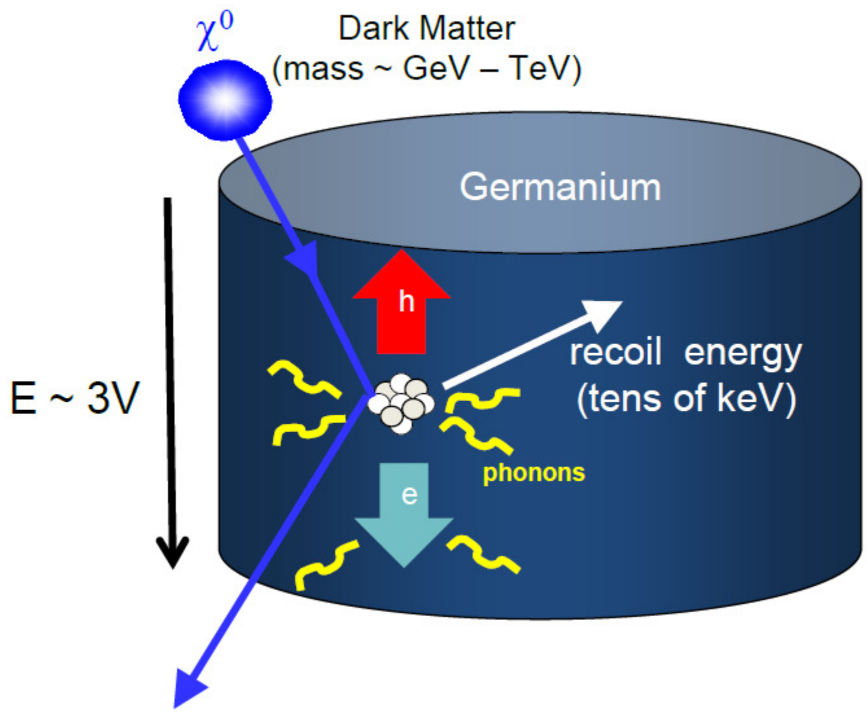
Slide from Andrew Long's 2018 LDW talk

The landscape of dark matter masses

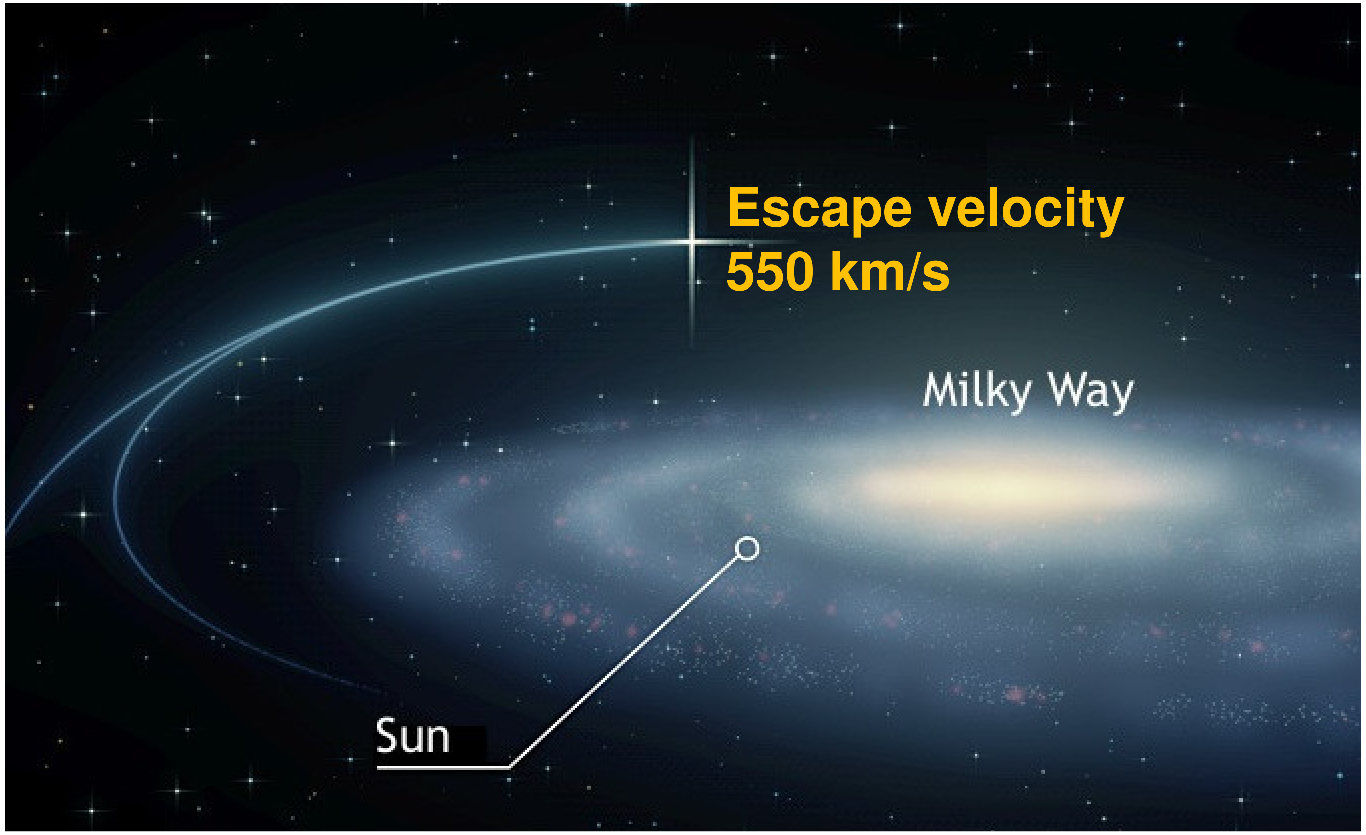


DARK MATTER DETECTION

Particle dark matter detection:
DM particle scatters and deposits energy
We detect this energy



Fermi velocity for DM with mass <10 eV is higher than our Galaxy escape velocity.



Ultralight dark matter has to be bosonic.

Image credits: CDMS: https://www.slac.stanford.edu/exp/cdms/
https://astronomynow.com/2016/04/14/speeding-binary-star-discovered-approaching-galactic-escape-velocity/

ULTRALIGHT DARK MATTER DETECTION

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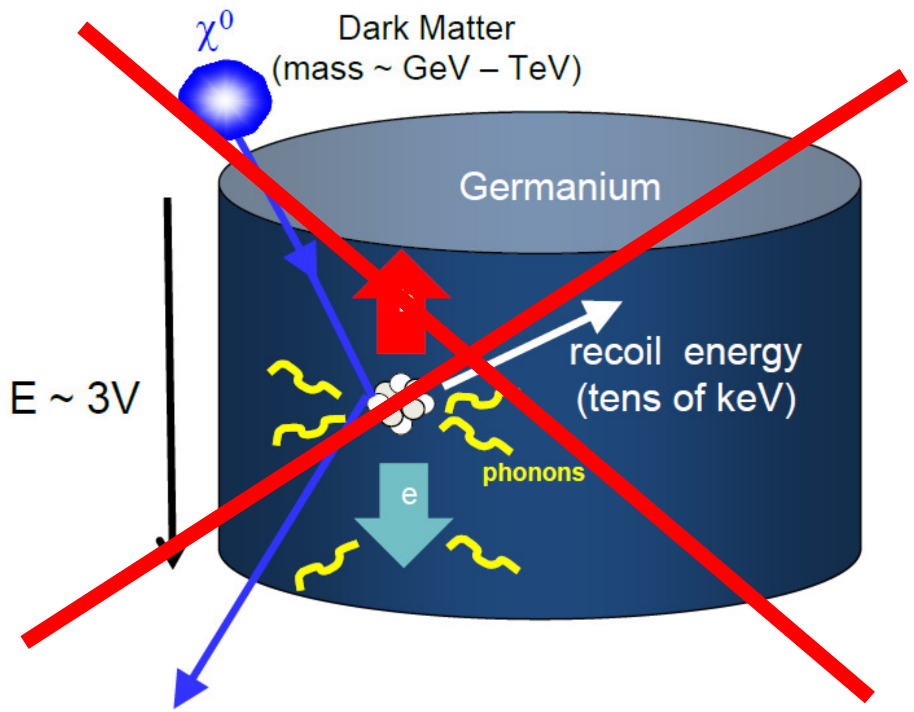

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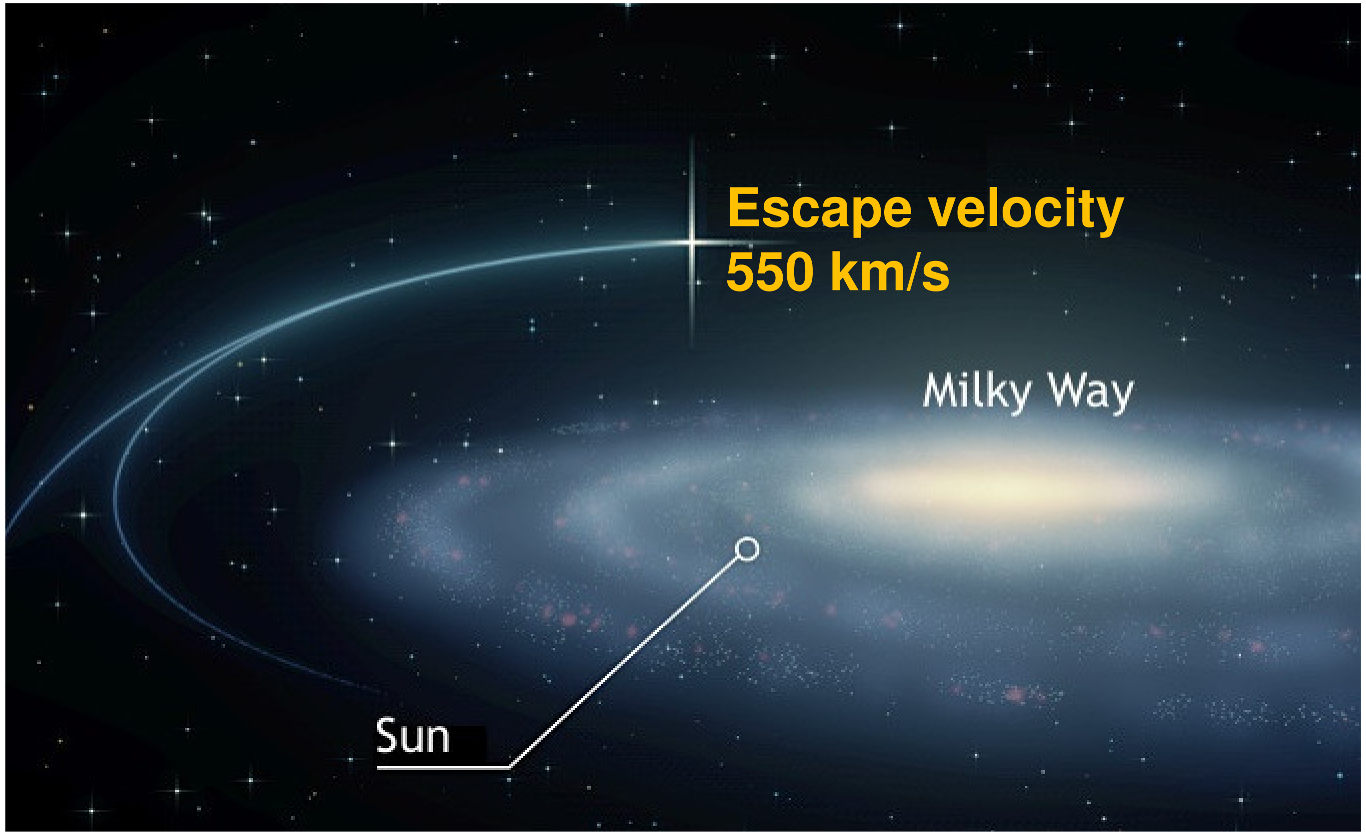

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https://astronomynow.com/2016/04/14/speeding-binary-star-discovered-approaching-galactic-escape-velocity/

Ultralight dark matter $(m_\phi \lesssim 10 \ \text{eV})$

The key idea: ultralight dark matter (UDM) particles behave in a "wave-like" manner.

UDM: coherent on the scale of detectors or networks of detectors.

Need different detection strategies from particle dark matter.

$$\phi(t) \approx \phi_0 \cos(m_\phi t)$$

$$\lambda_{\text{coh}} \sim 10^3 (2\pi / m_\phi c)$$

$$N_{\text{dB}} = n_\phi \lambda_{\text{coh}}^3 \gg 1$$

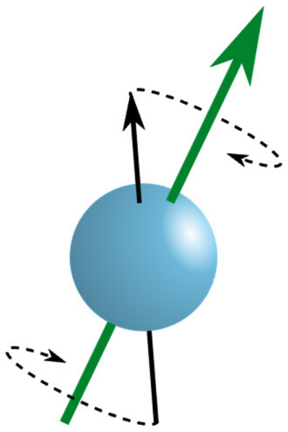
$$\phi_0 \sim \sqrt{2\rho_{\text{DM}}}/m_\phi$$

Dark matter field amplitude

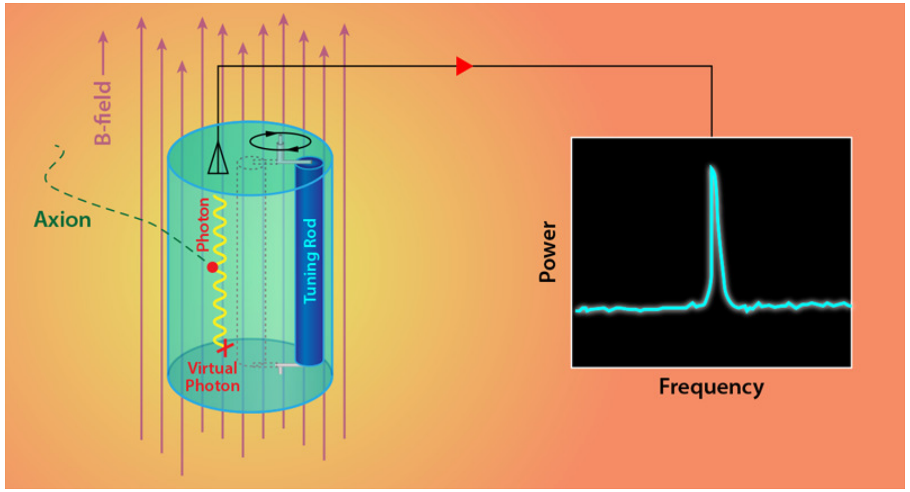
Dark matter density

Dark matter mass

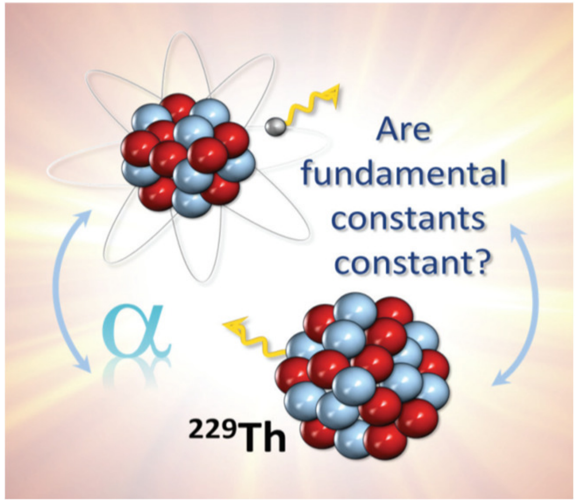
Observable effects of ultralight dark matter



Precession of nuclear or electron spins



Driving currents in electromagnetic systems, produce photons



Modulate the values of the fundamental "constants"

Induced equivalence principle-violating accelerations of matter

Detectors: Magnetometers, Microwave cavities, Trapped ions & other qubits, Atom interferometers, Laser interferometers (includes GW detectors), Optical cavities, Atomic, molecular, and nuclear clocks, Other precision spectroscopy

RMP 90, 025008 (2018)

Picture sources and credits: Wikipedia, Physics 11, 34 C. Boutan/Pacific Northwest National Laboratory; adapted by APS/Alan Stonebraker, modulate the values of the fundamental "constants" of nature

School project: how to solve any of these open questions?

A private foundation decided to contribute to understanding of fundamental physics and allocated 200 billion dollars.

They formed committees of scientists and gave each 10 billion dollars with 100 billion kept in reserve fund.

Each committee can decide to allocate the funds in any way they want with the only goal is to maximum the chance of discovery new physics and /or solving at least one open problem of particle physics.

You are these committees. Make a *specific* plan – what will you do? You can pick one problem or all of them. You can build whatever you decide, send things to space, organize universities, theory institutes, etc. You can decide to invest in one solutions or many.

School project: how to solve any of these open questions?

(1) Form groups of about six, designate a Chair of the committee

(2) Chair emails title & list of members to msafrono@udel.edu by 9 am on Wednesday morning

(3) Each committee will prepare a brief presentation by Thursday discussion section (use slides).
5 min + 5 min for questions.

School project: how to solve any of these open questions?

For each item on the list describe:

A. What you are building/organizing and order of magnitude cost.
   If 10 billion is not enough apply for all or part of the reserve fund of 100 billion, explain why you need it.

B. What problem can it potentially solve?

C. How will it solve this problem?

D. For experiments and space missions, mark rough “technology readiness” level

1: We know how build it and just need the money.

2. There are prototypes and we need 5-10 years of R&D to get to full design before construction.

3. There is a design with a number of problems to solve but should be possible to do so in 10-15 years.

4. There is an idea. We do not really know how to build it but this should not be impossible at the present level of technology (20 year timeline).

5. Theorists wrote a paper with a great idea. Not sure exactly how exactly will this work but somebody will figure this out in the next 30 years, let start now.

6. Not sure what experiment will do this, but here is what we need to measure.

7. Higher levels are considered science fiction (avoid for the purposes of this assignment).

Do not worry too much about the cost estimate, just be aware of the approximate order of magnitude, i.e. is it in millions, hundreds of millions or billions. Use euros or USD. Here are some examples.

US major experiment definition start from ½ billion USD. This includes collider upgrades, future CMB experiments, neutrino detectors, telescopes, gravitational wave detectors.
LHC cost: 4.75 billion. LIGO: 1 billion. 2022 CERN budget 1.5 billion (in a year).
Dark matter detectors. Light DM to WIMPs 10 – 100 million (LZ seems to be 67 million).
More if you need to dig new huge caverns 2 miles underground ☺
Axion detectors a few million to 50 million for an axion facility,
IceCube neutrino detector at South Pole construction cost 279 million.
Hyper-Kamiokande 700 million construction cost.
Muon g-2 , proton EDM 100 million scale.
Molecular EDMs – 5-10 million, atomic clock 1-2 million, nuclear clock 10-15 million to build prototypes.
For smaller experiments these include full operational cost for several years rather than construction cost.
Sending things to space is expensive for now.
Webb telescope 10 billion.
MicroSCOPE satellite mission (EEP test) 140 million euro.
Cold atom lab on ISS 50 million, high-precision clock with link to optical frequency Earth on a satellite in GEO orbit 400 million estimate.

Institutes: 25 million for 5 years for institute with 30 PIs only gives extra 100k/PI/year.