Personal view on the current status of theoretical particle physics

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KSHEP-2022, Nov. 18, 2022

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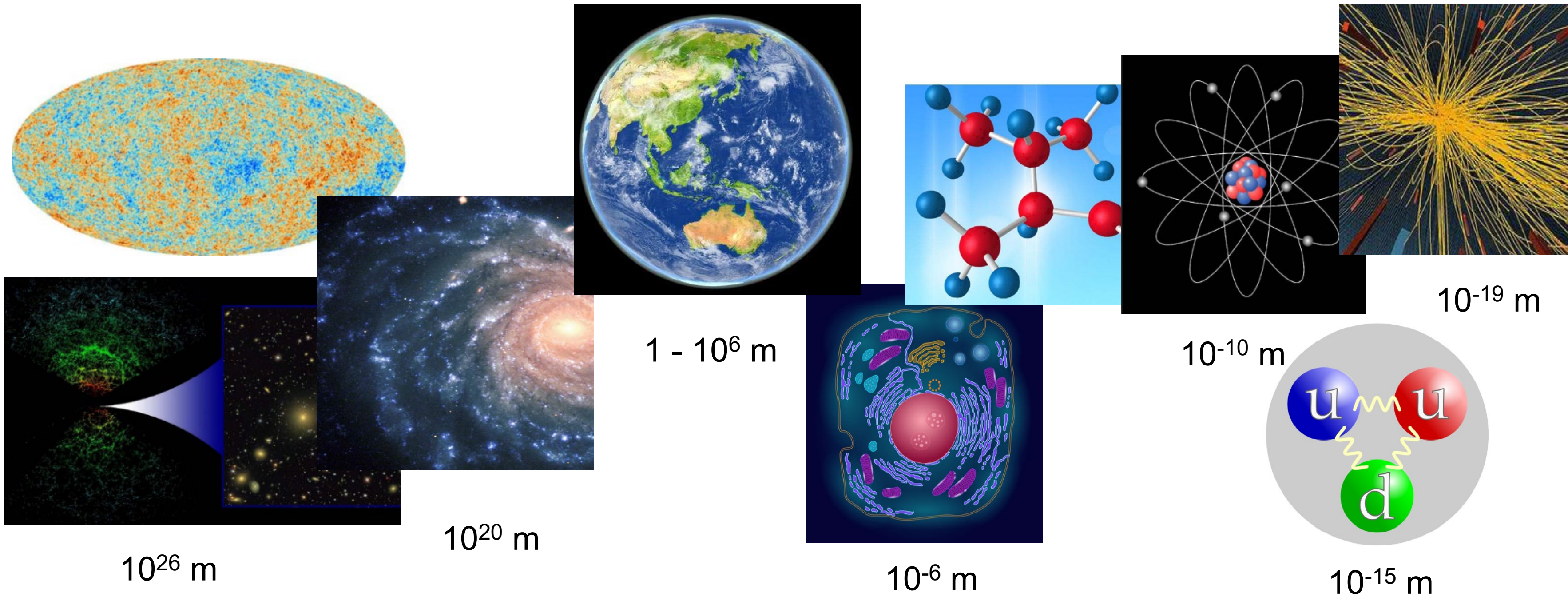
There exist a variety of objects or structures with different size in our Universe.



* CMB anisotropy, Large scale structure, Dark energy near the horizon scale ~ 10^{26} m

* Galaxies, Dark matter at ~ 10^{20} m

* Stars (~10^{9} m) made of plasma, solid, fluid, gas, …

* Life made of cells (~10^{-6} m) and molecules (~10^{-8} m)

* Atoms (~10^{-10} m) made of electrons (<10^{-19} m) and nucleons (~10^{-15} m)

* Nucleons made of quarks and qluons (<10^{-19} m)

Phenomena at different length scales are the subjects of different disciplines of science, and each of those disciplines has its own effective ways to understand the phenomena at its characteristic length scales:

Cosmology (~ 10^{26} m)

Astrophysics (~ 10^{20} m)

…

Biology

Chemistry

Condensed Matter Physics

Atomic physics

Nuclear Physics (~ 10^{-15} m)

Particle Physics ($<$ 10^{-18} m)

Endless journey or ultimate length scale, e.g. the scale of quantum gravity where the conventional concept of spacetime needs to be revised (String Theory?)

The expanding Universe indicates that there has been a continuous evolution from physics at smaller scales to those at bigger scales.

This means that different disciplines of science are interconnected with one another through the question:

"How the phenomena at bigger scales emerge as a consequence of the phenomena at smaller scales?"

Particle physics and early Universe cosmology are mainly concerned with physics at the smallest length scale (highest energy scale) that can be probed either at present or in the future.

The currently established theory in this field of fundamental physics is

* **the Standard Model (SM) of particle physics for the strong, weak, and EM forces**
* **Einstein's General Relativity (GR) for the gravitational force**

and one of the prime concerns of the community is

"What would be there beyond the SM + GR?"

which will be the main topic of this talk.

cf: Many interesting developments for better understanding of the SM+GR, e.g. in computational theory & collider phenomenology (lattice, amplitudes, machine learning, artificial intelligence, jet substructures, …)

SM + GR

Relativistic and quantum mechanical effective theory for point-like degrees of freedom in 4D spacetime, which are either apparently massless or have a well-defined massless limit.

With the tiny strength of the gravitational force & the small dark energy density, the theory admits large scale separations, which is one of the biggest mysteries about our Universe:

Planck length $\leq$ cutoff length $\ll$ propagation length $\leq$ horizon length

$\ell_{\rm Planck} = \sqrt{8\pi G_N} \sim 10^{-34}{\rm m}$ $(\hbar = c = 1)$

Scale where the theory needs to be revised, which looks point-like at longer distances

Dynamical scale of the known light degrees of freedom in SM+GR

$\ell_{\rm horizon} \sim 1/\sqrt{G_N \Lambda_{\rm DE}^4} \sim 10^{27}{\rm m}$

Compared to other disciplines of science (including other areas in physics), physics of relativistic & quantum mechanical light point-like degrees of freedom with a large scale separation is less sensitive to the change of length (or energy) scales, making theoretical understanding relatively easier, but experimental progress a lot more difficult.

Having an interacting massless degree of freedom in relativistic & quantum mechanical theory is non-trivial.

Quantum states with a fixed 4-momentum and spin s:

<u>Massive (rest frame)</u>

(2**s**+1) states interconnected with one another by 3D rotation

$$\begin{bmatrix} |S_z = s\rangle \\ |S_z = s-1\rangle \\ \cdot \\ \cdot \\ |S_z = -s\rangle \end{bmatrix}$$

<u>Massless (no rest frame)</u>

Split into states with different helicity since only the 2D rotation around the momentum axis is allowed

$$\left[\, |\hat{p}\cdot\vec{S} = s\rangle \,\right]$$

$$\left[\, |\hat{p}\cdot\vec{S} = s-1\rangle \,\right]$$

$$\left[\, \cdot \,\right]$$

$$\left[\, \cdot \,\right]$$

$$\left[\, |\hat{p}\cdot\vec{S} = -s\rangle \,\right]$$

(2s+1)-2 extra states

State with helicity = s & its CPT conjugate with helicity = -s

* Taking a massless limit for **s** = 0 does not make any difference.

* For s ≥ 1, (2s+1)-2 extra states need to be properly separated from the states with helicity = ± **s** in a manner consistent with QM and relativity.

With this fundamental difference between massive and massless states, an interacting massless state with $s \neq 0$ is well-protected from quantum fluctuations at short distance scales.

(No such protection for $s = 0$ except for special type of spinless states.)

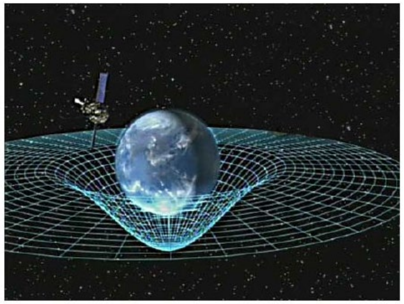
For massless states with $s \geq 1$, we need to deal with the difference $(2s+1) - 2 \neq 0$ in a manner consistent with QM & relativity.

This results in constraints (in the form of symmetry) on the interactions of massless states with helicity $= \pm s$, which are stronger for bigger s.

* **s > 2**: too much constrained, so no such an interacting massless object

* **s = 2**: the unique graviton mediating
  the gravitational force

GR:

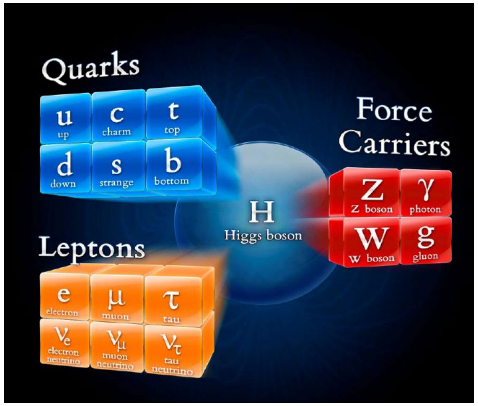


* **s = 3/2**: gravitinos associated with the
  spacetime supersymmetry ($N \leq 8$)

* **s = 1**: gauge bosons associated with compact gauge symmetry
  (SU(3)xSU(2)xU(1) for the strong, weak, and electromagnetic forces)

* **s = 1/2**: anomaly-free chiral fermions
  (quarks & leptons)

SM:



* **s = 0**: the least constrained
  (Electroweak Goldstone bosons (W_L & Z_L)
  and the Higgs boson)

At the moment, only s = 3/2 (SUSY) is missing!

In which directions can we proceed toward beyond the SM + GR?

Data-driven:

* Extension of the SM to explain not yet understood observed phenomena

Neutrino masses, Dark matter, Matter-antimatter asymmetry, Large scale structure and CMB anisotropy, Dark energy

* Experimental anomalies (not convincing yet)

$(g\text{-}2)_\mu$, B-meson decays, H_0-tension, M_W, ...

Good experimental prospect with some theory motivation:

* Light hidden sector

Axions & axion-like particles, Dark photon (vector portal),
Extra Higgs (Higgs portal), Sterile neutrinos (neutrino portal), ….

Theory-driven:

* Understanding of the theoretical structure of the SM + GR

Scale hierarchies (e.g. protection mechanism for the light Higgs boson),
Quark and lepton mass & mixing structure, Strong CP problem, …

* Theoretical completeness

Unification, Quantum gravity, …

Where are they?

Before the running of the CERN Large Hadron Collider (LHC), we always had a map clearly indicating where would be the next scale of new physics.

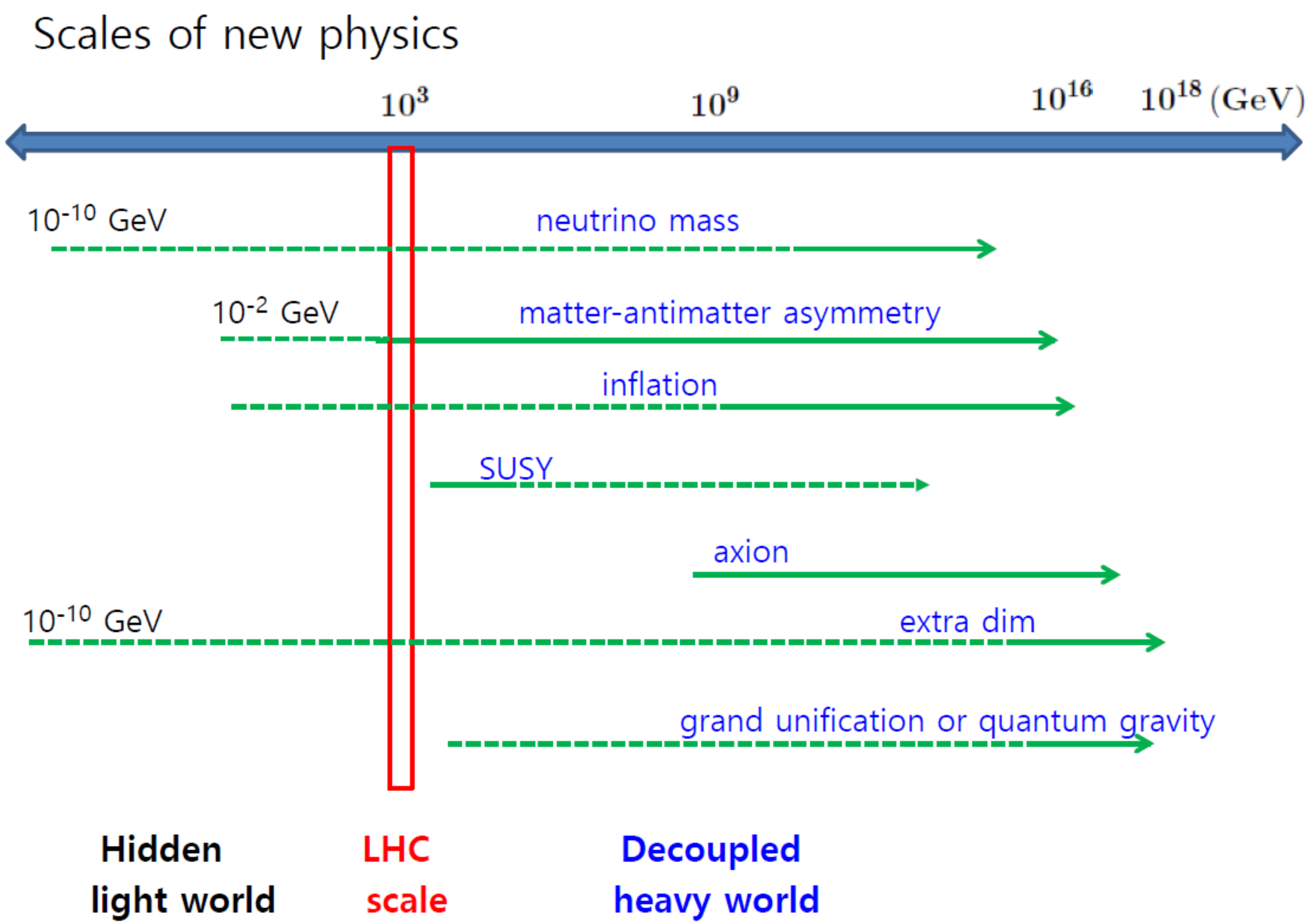
For more than three decades since the establishment of the SM, it has been thought that the so-called **gauge hierarchy problem** implies that there exist **new physics near the weak scale ~ 10^2 GeV,** protecting the weak scale from the quantum fluctuations at higher energy scales:

Protecting $m_{Higgs} \sim 10^2$ GeV from $M_{Planck} = 1/\sqrt{8\pi G_N} \sim 10^{18}$ GeV

➔ supersymmetry, extra dimension, composite Higgs, little Higgs, twin Higgs, relaxion, N-naturalness, ……

In fact, one of the main goals of the LHC experiments was to discover such a new physics.

It turns out that this is not taken by the nature, and now we are in a situation without having any reliable hint on where new physics is.



So now we need **broader and more model-independent approaches** to explore new physics.

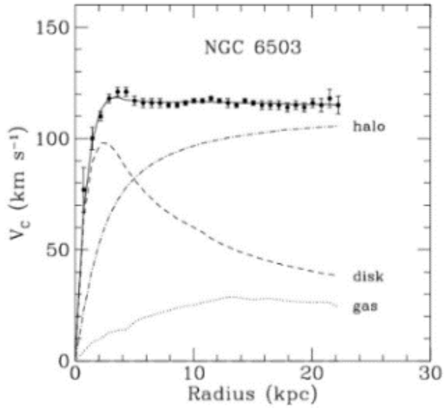
Still the effort to identify the dark matter is one of the prime activities in our field.

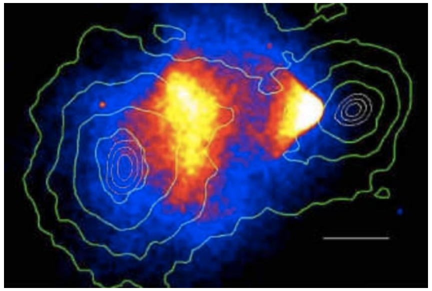
Axions or axion-like particles have been postulated in many well-motivated models for new physics beyond the SM & GR.

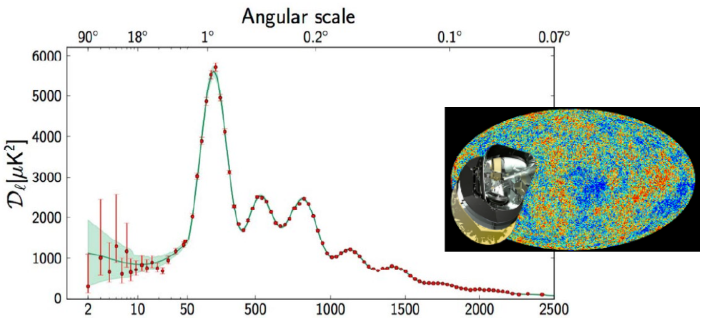
(strong CP problem, dark matter, hierarchy problem, string theory, …)

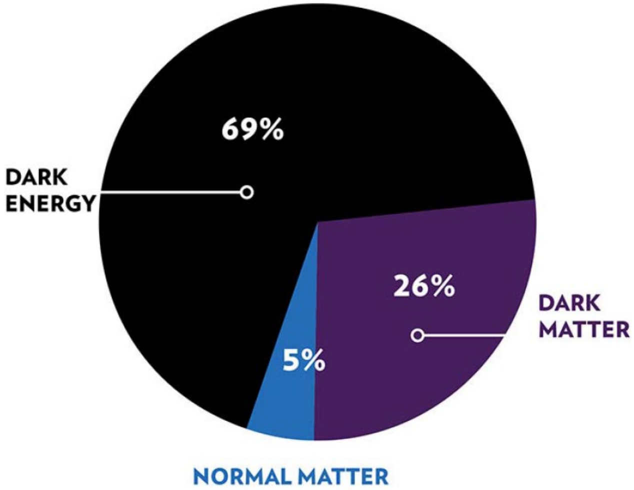
So I will briefly report the current status of the research on **dark matter** and **axions** in the remaining time.

There exist a variety of evidences for dark matter in the sky over a wide range of scales:









For a while, we have had two outstanding candidates for the dark matter:

* **Weakly Interacting Massive Particle (WIMP)** predicted by many models to protect the weak scale from the Planck scale:

$$m_{Higgs} \sim 10^2 \text{ GeV} \quad \ll \quad M_{planck} = 1/\sqrt{8\pi G_N} \sim 10^{18} \text{ GeV}$$

* **QCD axions** proposed to solve the strong CP problem about

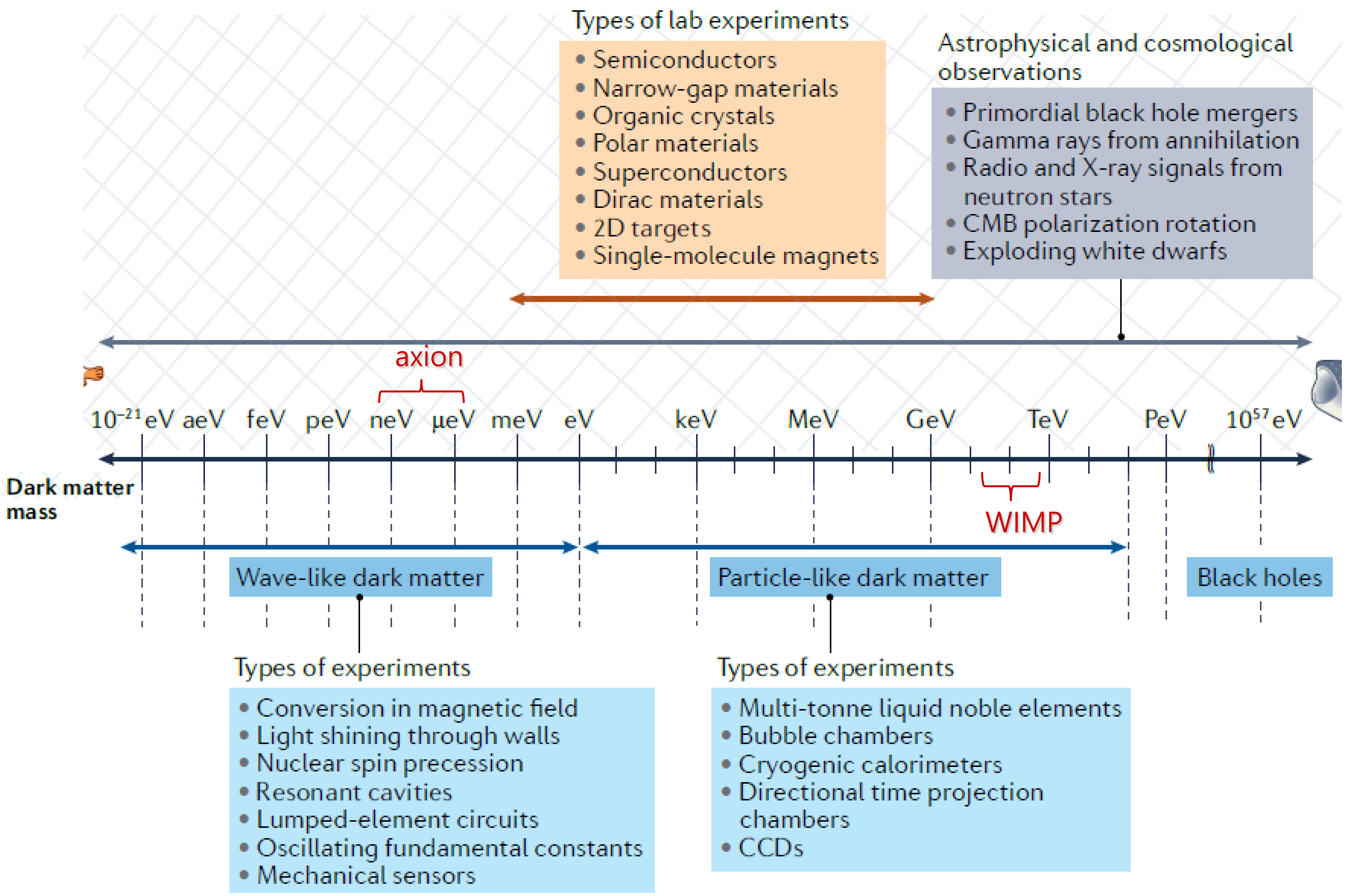
$$|\theta_{QCD}| < 10^{-9} \quad \ll \quad \delta_{KM} \sim 1$$

In these days, we are contemplating much more diverse possibilities for dark matter:

* No discovery of new physics at the TeV scale, so WIMP lost a certain amount of its motivation.

* Many new ideas have been proposed during the last decade on experimental search for different dark matter candidates.

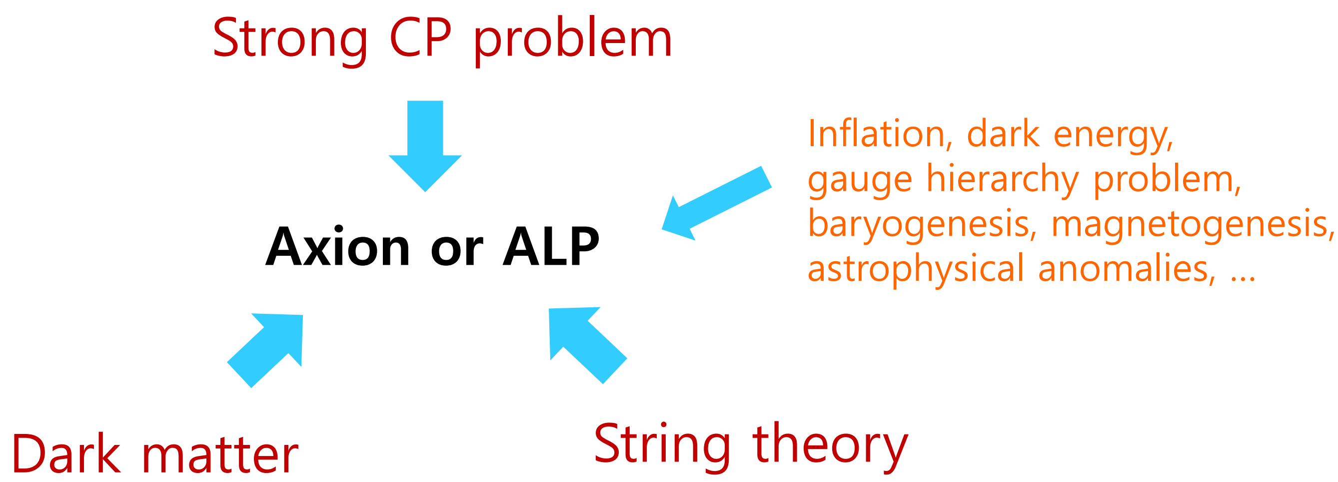
A map of dark matter hunting (from Hochberg et. al. Nature Rev. Phys. 4 (2022) 10)



Axion is a light spin = 0 boson which is initially postulated to solve the strong CP problem, and later turned out to be an appealing candidate for dark matter.

Different type of axions (ALP=axion-like particles) were also proposed to explain other issues in particle physics and cosmology.
(inflation, dark energy, gauge hierarchy problem, baryogenesis, magnetogenesis, astrophysical anomalies, …)

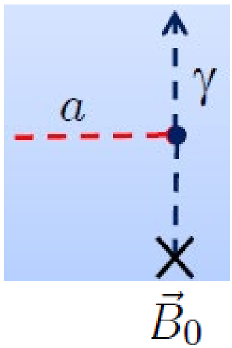
Axions & axion-like particles are generic prediction of string theory which is at the moment the most promising candidate for the theory of quantum gravity.



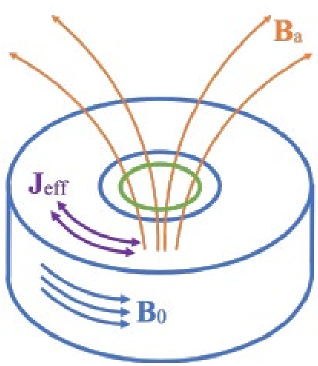
How to discover light (sub-eV) axion or ALP experimentally?

Axion couplings for experimental search:

$$\frac{1}{2} g_{a\gamma} a(x) \vec{E} \cdot \vec{B} + g_{a\Psi} \nabla a(x) \cdot \vec{S}_\Psi \quad (\vec{S}_\Psi = \text{spin density of } \Psi = n, p, e)$$

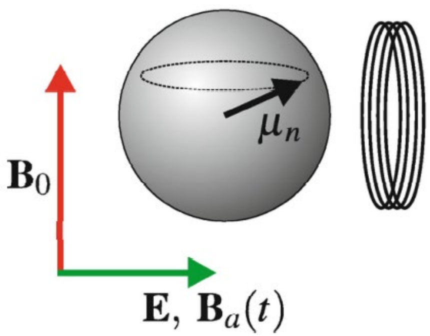


axion → photon
or photon → axion
in external B-field



Effective current induced by oscillating axions in external B-field:

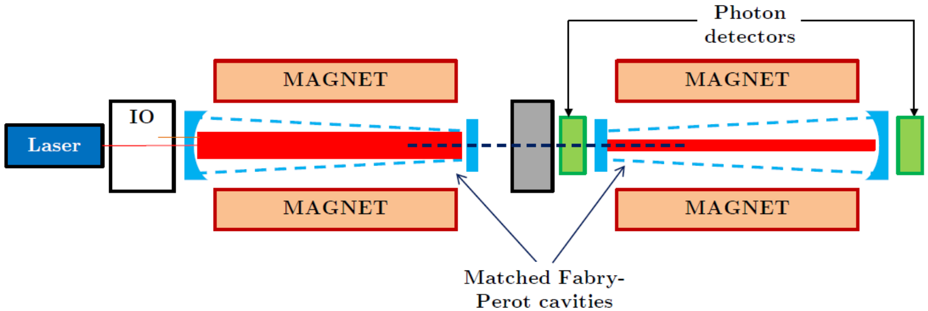
$$\vec{J}_{\rm eff} = g_{a\gamma} \frac{\partial a(t)}{\partial t} \vec{B}_0$$



Effective B-field induced by "axion wind":

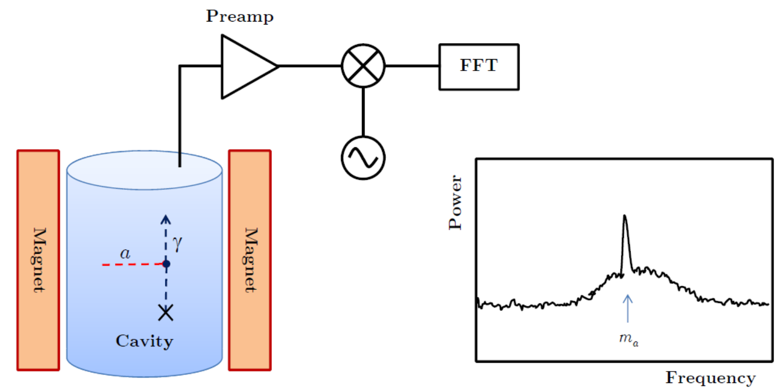
$$\vec{B}_a = g_{a\Psi} m_\Psi \nabla a$$

Figures from
Redondo, Irastorza (2018)

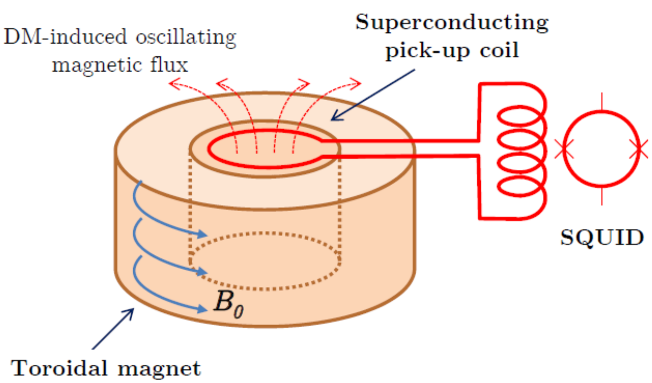


Light shining through the wall

light → axion → light

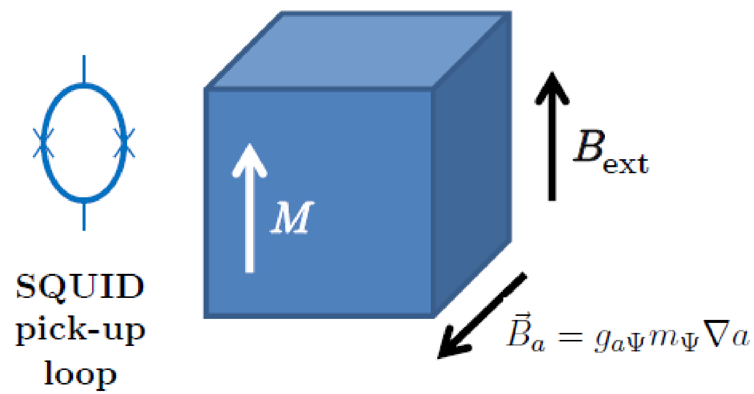


Dark matter axions → EM waves
in resonant cavity



Oscillating magnetic flux
from the dark matter
axion-induced current

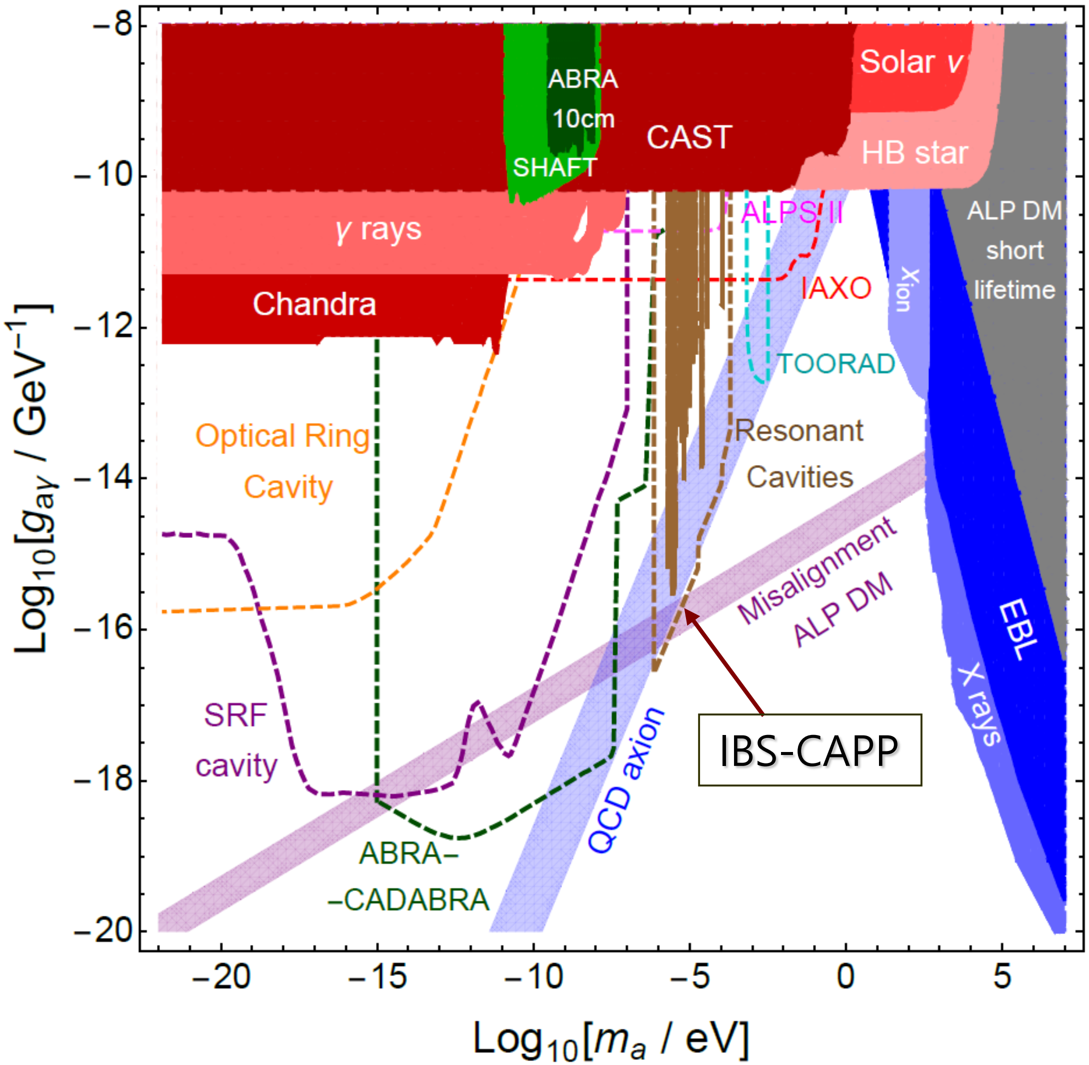
$$\vec{J}_{\rm eff} = g_{a\gamma}\frac{\partial a(t)}{\partial t}\vec{B}_0$$



Precessing magnetization due to
the effective B-field induced by
the dark matter axion "wind"

Observational bounds and the sensitivities of planned experiments

Axion coupling to the photon helicity



Resonant cavity:
Sikivie '83,
Semertzidis et al '09

ABRACADABRA:
Kahn et al '16

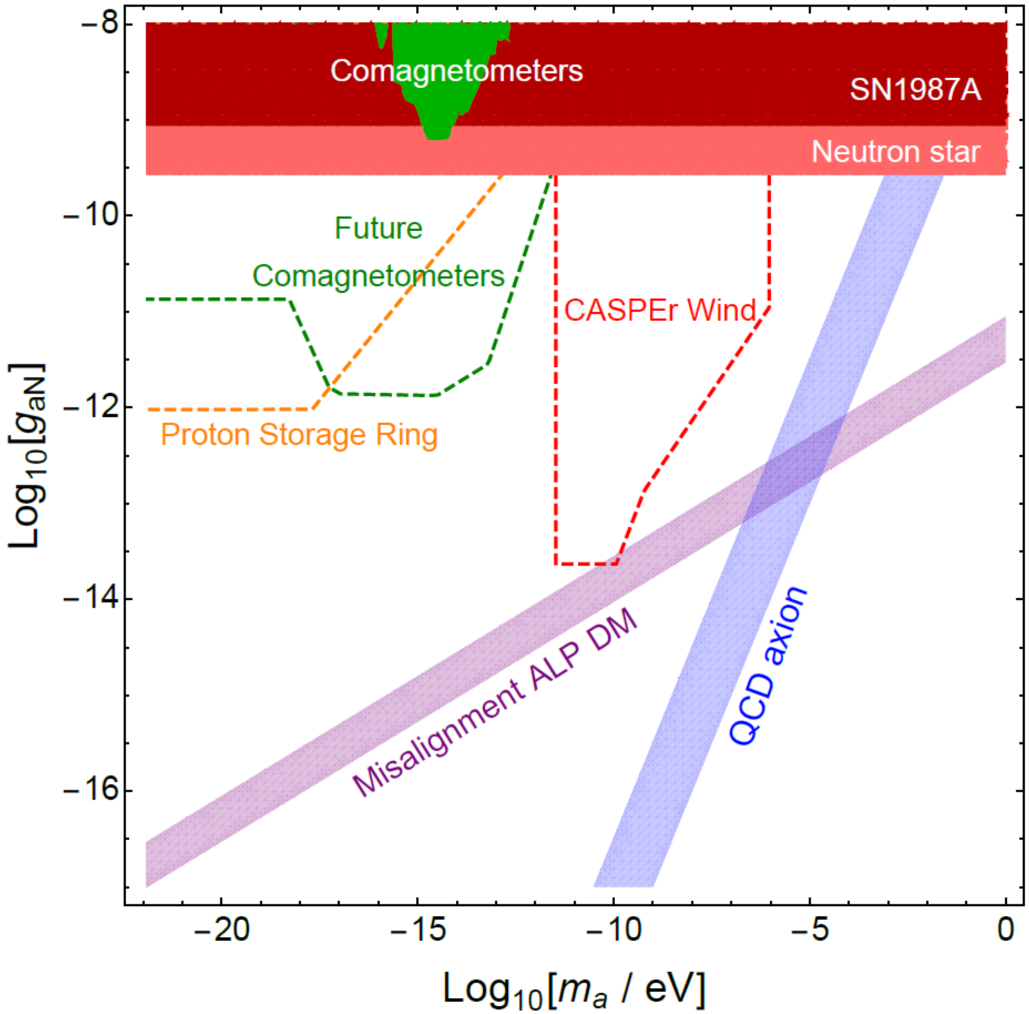
Optical ring cavity:
Obata et al '18

TOORAD:
Marsh et al '19

SRF cavity:
Berlin et al '20

Figures from
KC, Im and Shin (2021)

Axion coupling to the nucleon spin



Figures from
KC, Im and Shin (2021)

Gravitational probe of ultralight ALP dark matter

Through the gravitational interaction, ultralight ALP dark matter can affect various cosmic observables (CMB, density perturbation, pulsar timing array, galactic rotation, shape of dwarf galaxy, rotating blackhole, …) with the characteristic scales determined by ALP mass (de Broglie & Compton wavelength, oscillation frequency, time to start oscillation in the early universe, …) and the strength depending on its energy density.

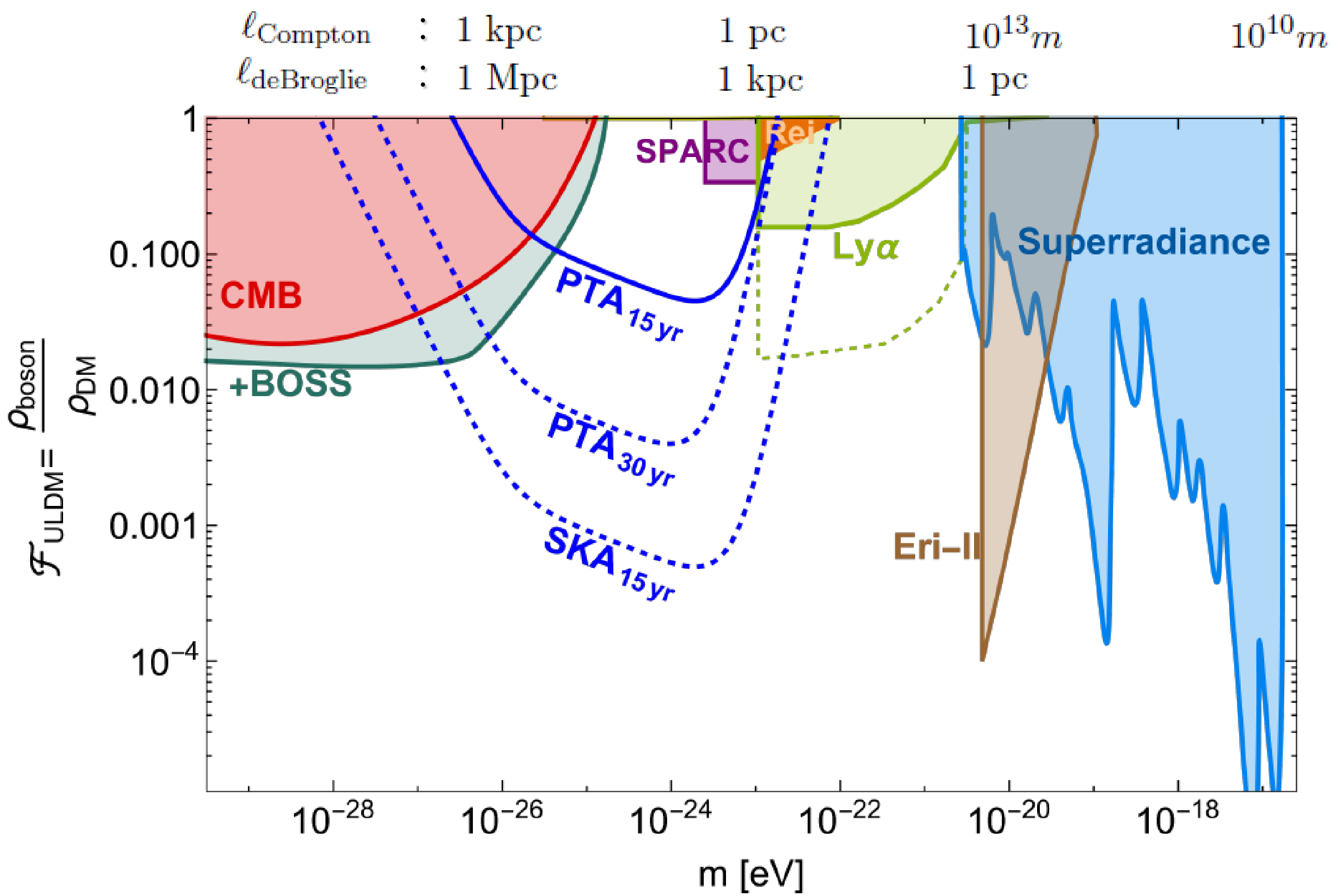


Figure from arXiv:2209.02741

Summary

Particle physics is in a unprecedented situation without having any reliable hint on the scale of new physics.

So we need **broader and more model-independent approaches** to search for new physics.

There can be many different directions with different motivations:

Not yet understood observed phenomena, Experimental anomalies,
Light hidden sector, (Unnatural) Structure of the SM + GR,
Theoretical completeness, …

Over the last decade, much broader and more model-independent ideas & methods have been proposed for the theoretical and experimental search for the dark matter.

Axions or axion-like particles are particularly interesting as they are well motivated in many respects and also have a bright prospect for experimental discovery in the future.

Thanks for your attention!