New experiments to identify dark matter and solve particle physics riddles

Part 1: the standard model world is not enough

NASA/CXC/SAO/ESA/CSA/STScI

DESY
Summerstudent Lecture 2025

Axel Lindner
Aaron Spector

DESY

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

New experiments to identify dark matter and solve particle physics riddles

Part 2: finding the axion

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Summerstudent Lecture 2025

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DESY

Outline

- Our starting point
- Dark matter in the universe
  - Evidences
  - Consequences and questions
- HERA, QCD and the axion
- Axions and dark matter
- Introduction to axion searches at DESY

Outline

- Our starting point — Axel
- Dark matter in the universe — Aaron
  - Evidences
  - Consequences and questions — Axel
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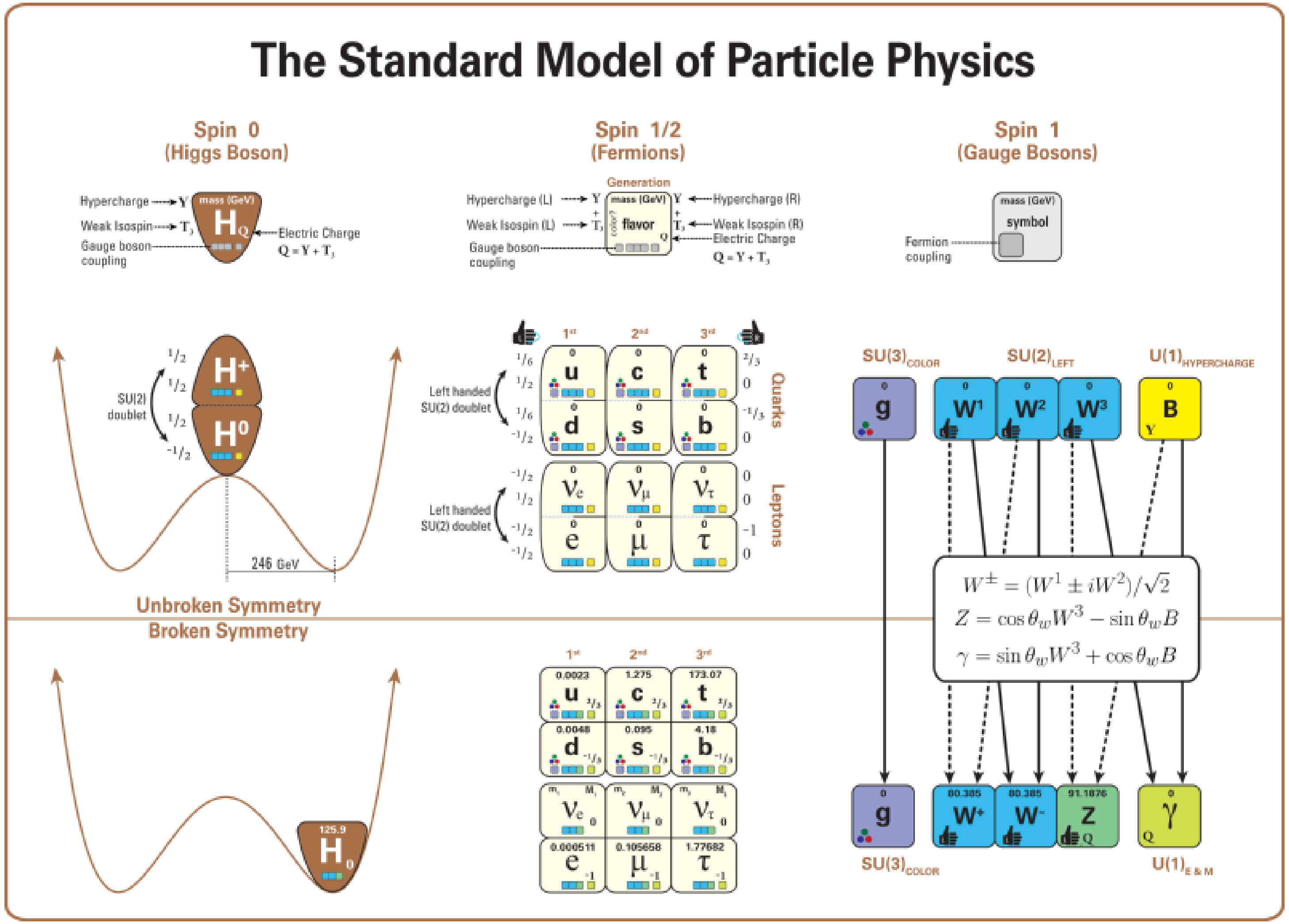
What do we know (I)

A fantastic and consistent model

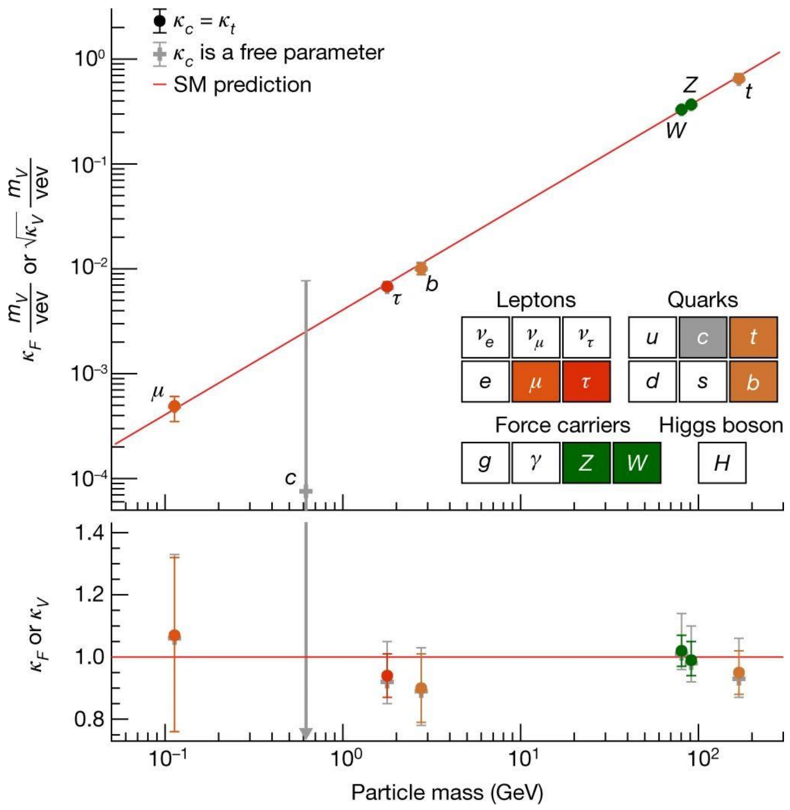


https://en.wikipedia.org/wiki/Standard_Model

All experiments probing the smallest constituents of matter and its interactions perfectly fit to the standard model,

apart from non-zero neutrino masses.

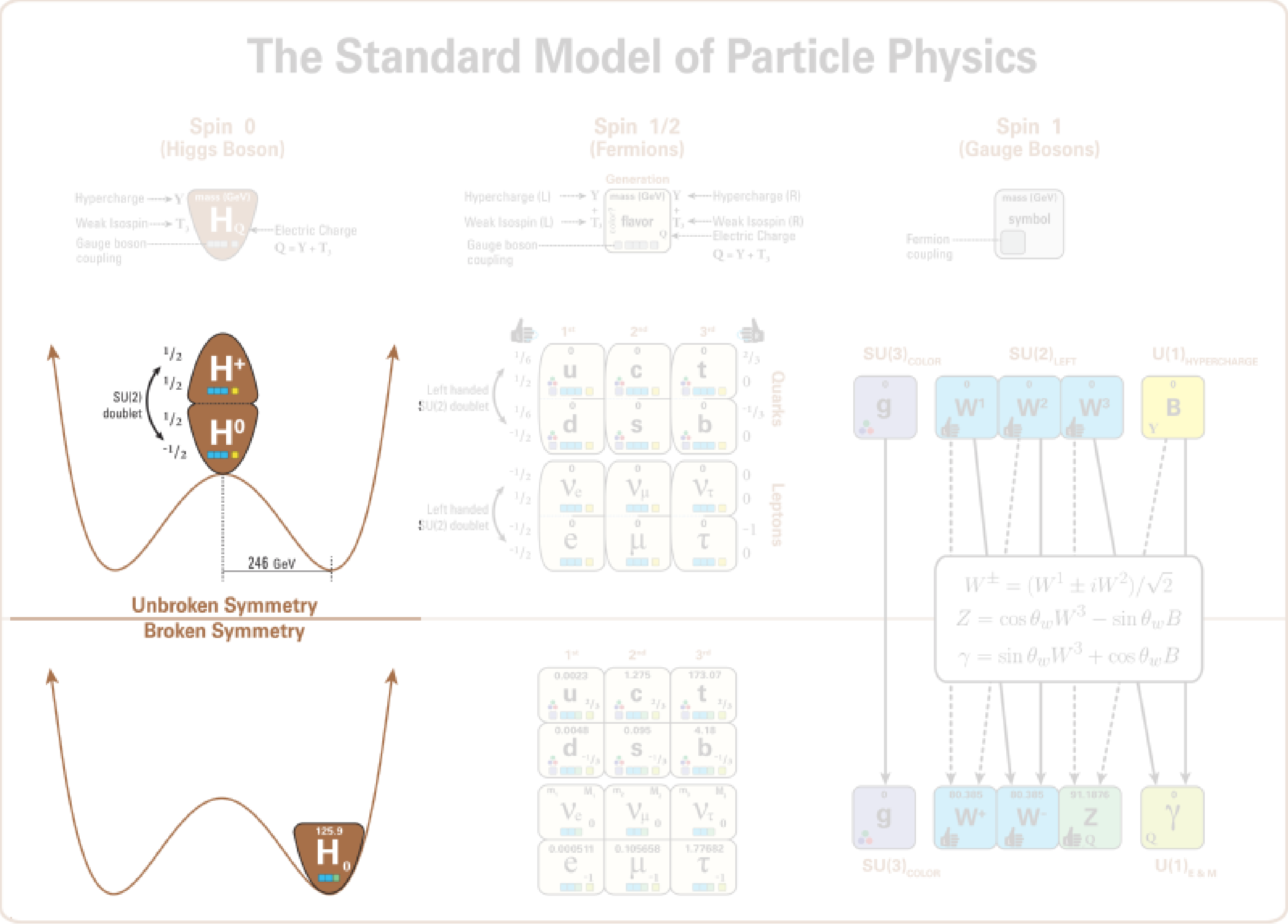
Example: properties of the Higgs.



A detailed map of Higgs boson interactions by the ATLAS experiment. *Nature* **607**, 52–59 (2022)

What do we know (I)

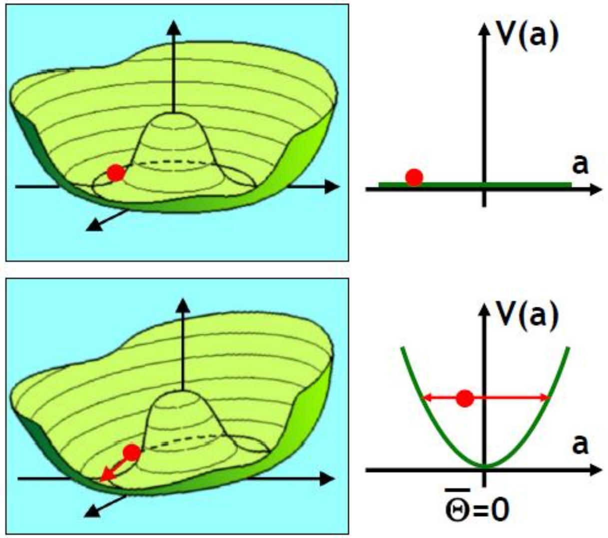
Understanding consituents and forces



https://en.wikipedia.org/wiki/Standard_Model

Symmetries and their breakings are the key to understand particle properties and forces.

The origin of the axion (see later):

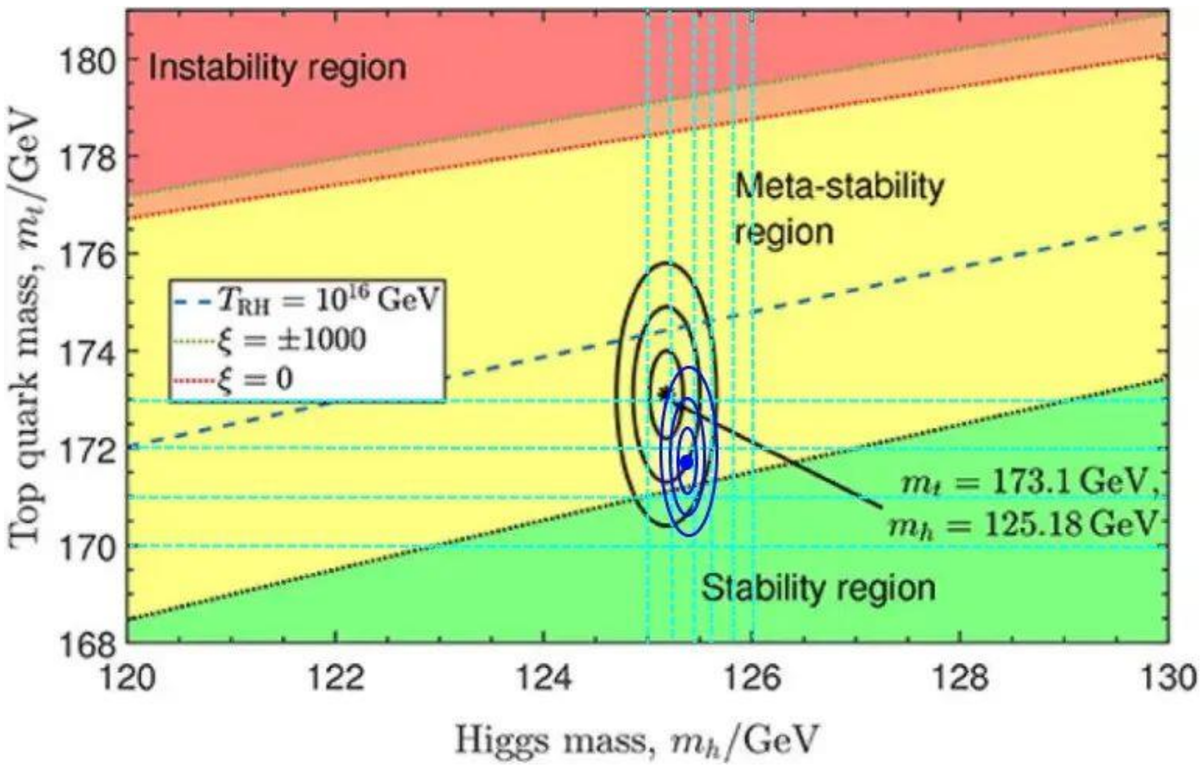


S. Hannestad, presentation at 5th Patras Workshop 2009

What do we know (I)

The next relevant energy scale might be out of reach at accelerators

QCD (1 GeV) ⟶ Electroweak (246 GeV, LHC) ⟶ Planck 10^{19} GeV (10^{15}·LHC)



https://bigthink.com/starts-with-a-bang/universe-fundamentally-unstable/
https://arxiv.org/pdf/1809.06923

There is no hint for a “new physics energy scale”.

A next relevant energy scale might be out of reach for any “thinkable” future accelerator.

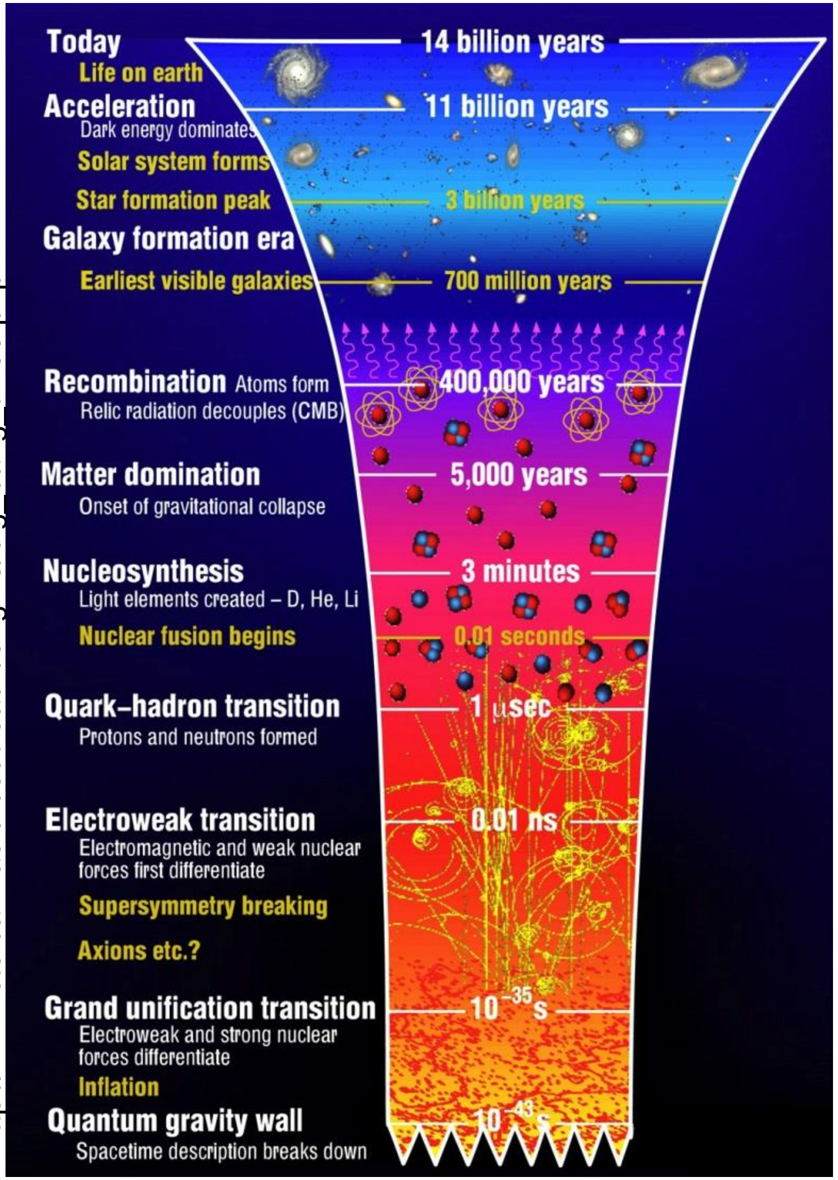
An experimental loophole:
Look for (pseudo) Goldstone bosons originating from spontaneous breaking of continuous symmetries.

- Such symmetries are predicted by many theories.
- Goldstones would be very lightweight,
- but interact extremely weakly with the SM: usually not detectable at colliders.

A prime example is the axion.

From quarks to the cosmos

Particle physics and cosmology



http://www.ctc.cam.ac.uk/outreach/origins/big_bang_three.php

3,000,000,000 years after the Big Bang

Astronomy

400,000 years after BB

3 minutes after BB

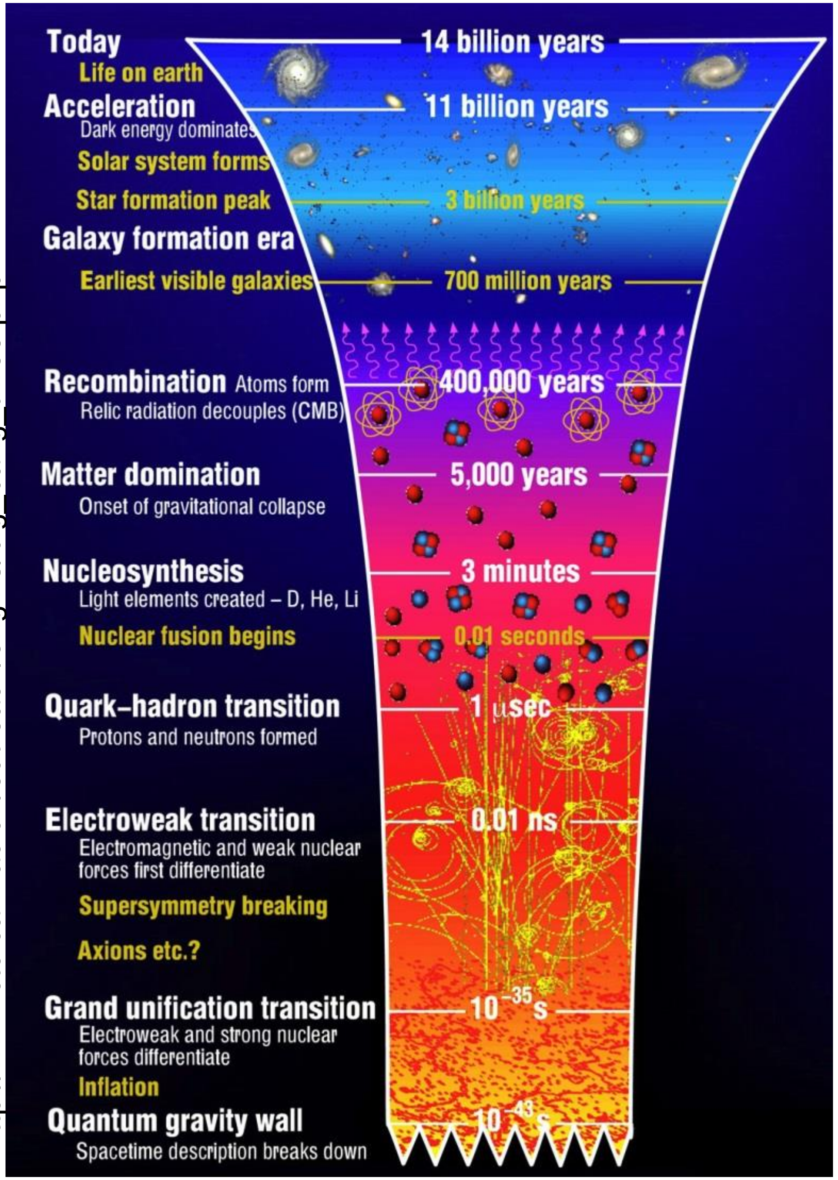
BB in the laboratory: Elementary particle physics

0.000001 seconds after BB

0.00000000001 seconds after BB

From quarks to the cosmos

Particle physics and cosmology



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3,000,000,000 years after the Big Bang

400,000 years after BB

3 minutes after BB

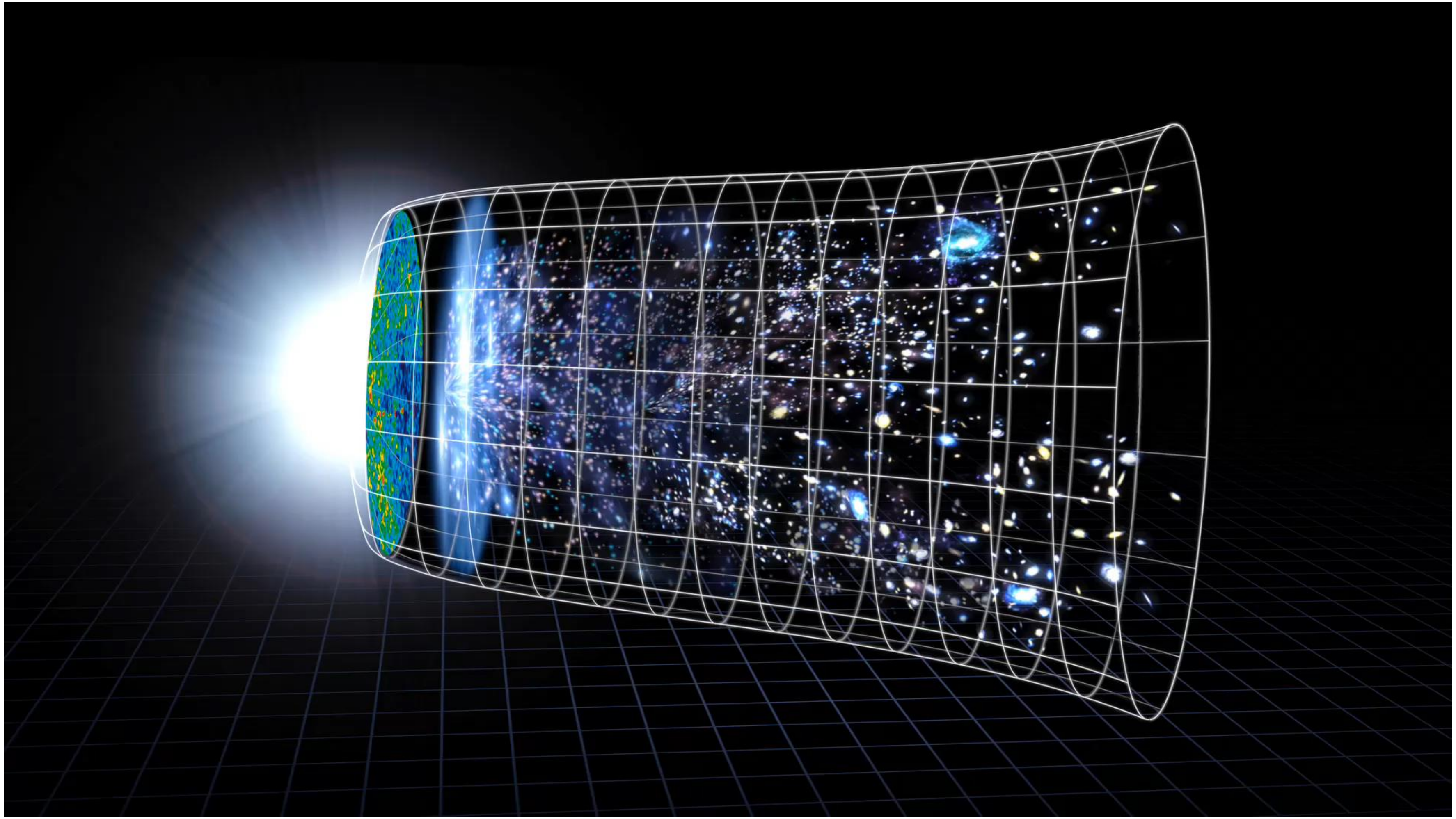
0.000001 seconds after BB

0.00000000001 seconds after BB

Gravitational waves?

A tremendous success story: understanding smallest scales

Enables to understand the largest scales!



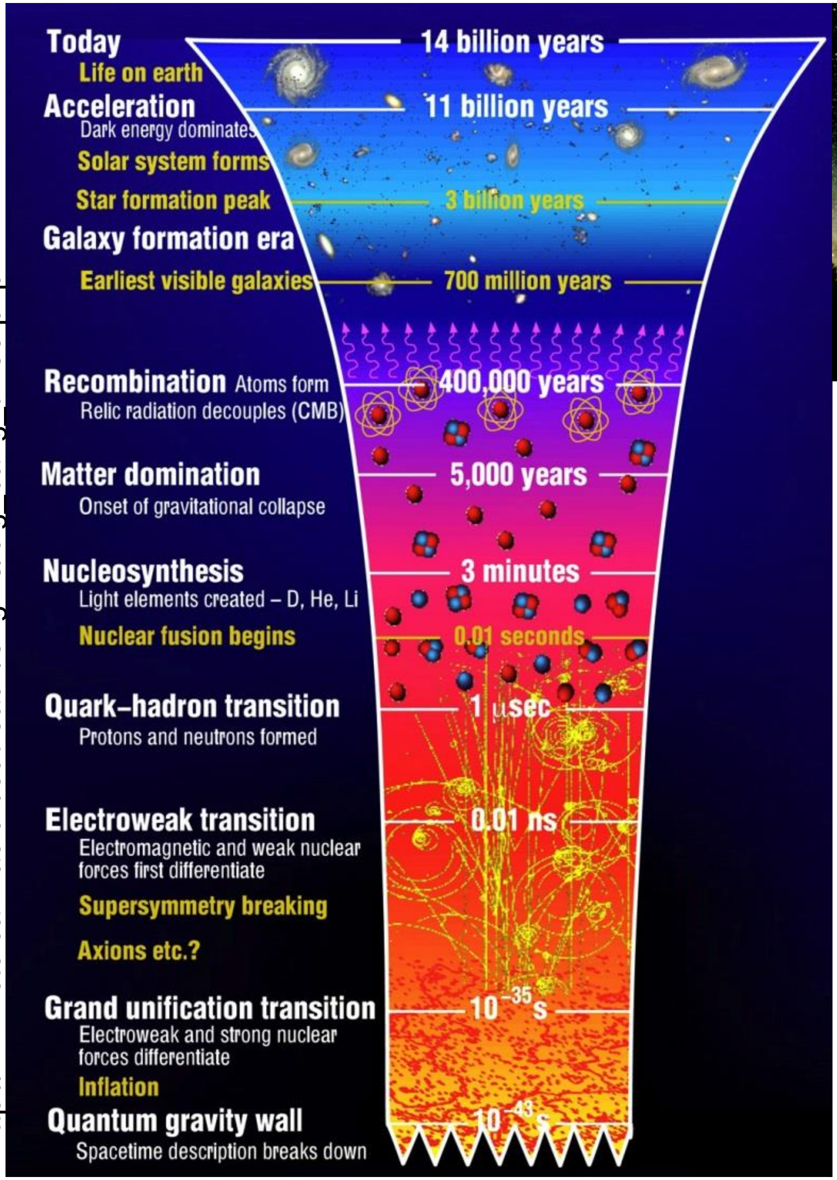
High energy particle colliders simulate the earliest moments of the universe!

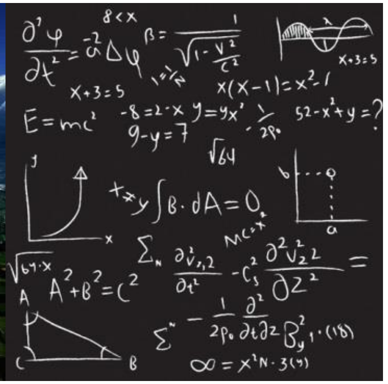
We also have a standard model of cosmology.

What do we know (II)

A very brief status report

http://www.ctc.cam.ac.uk/outreach/origins/big_bang_three.php





Astronomy, particle physics theory

seem to fit perfectly!

Example:
Age of the universe = 13.799 ± 0.021 billion years (0.15% accuracy!)

We seem to understand precisely how the universe evolved.

If we could solve one of the biggest questions in fundamental science …

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Aaron

THE ASTROPHYSICAL JOURNAL, Vol. 159, February 1970

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡
Received 1969 July 7; revised 1969 August 21

ABSTRACT

Spectra of sixty-seven H II regions from 3 to 24 kpc from the nucleus of M31 have been obtained with the DTM image-tube spectrograph at a dispersion of 135 Å mm^{-1}. Radial velocities, principally from Hα, have been determined with an accuracy of ± 10 km sec^{-1} for most regions. Rotational velocities have been calculated under the assumption of circular motions only.

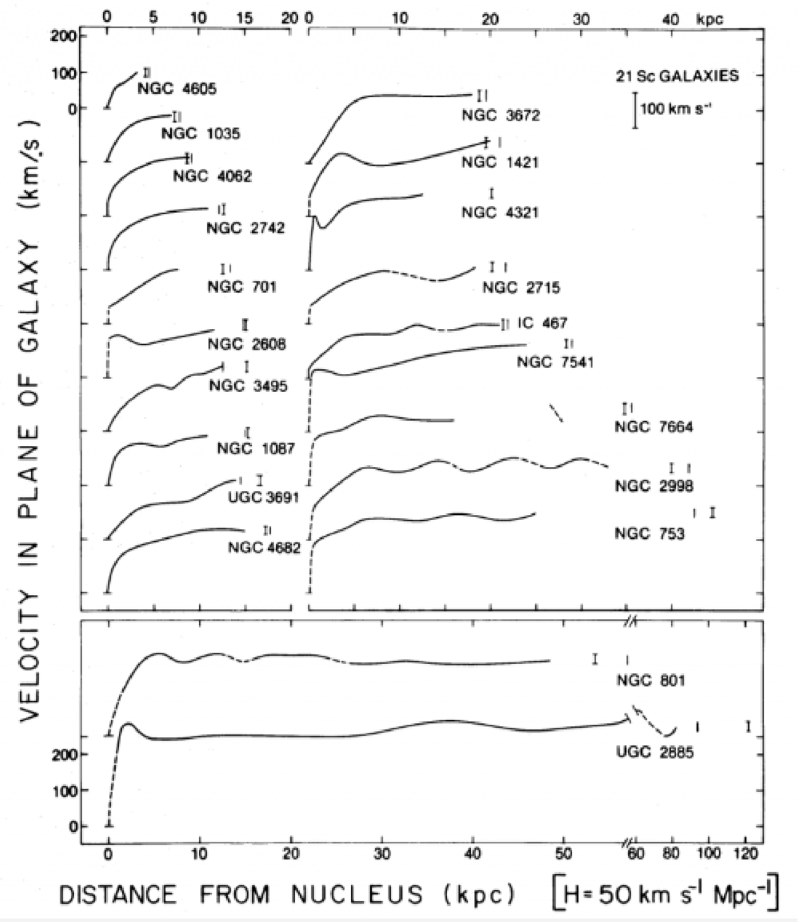
For the region interior to 3 kpc where no emission regions have been identified, a narrow [N II] λ6583 emission line is observed. Velocities from this line indicate a rapid rotation in the nucleus, rising to a maximum circular velocity of $V = 225$ km sec^{-1} at $R = 400$ pc, and falling to a deep minimum near $R = 2$ kpc.

From the rotation curve for $R \leq 24$ kpc, the following disk model of M31 results. There is a dense, rapidly rotating nucleus of mass $M = (6 \pm 1) \times 10^9 M_\odot$. Near $R = 2$ kpc, the density is very low and the rotational motions are very small. In the region from 500 to 1.4 kpc (most notably on the southeast minor axis), gas is observed leaving the nucleus. Beyond $R = 4$ kpc the total mass of the galaxy increases approximately linearly to $R = 14$ kpc, and more slowly thereafter. The total mass to $R = 24$ kpc is $M = (1.85 \pm 0.1) \times 10^{11} M_\odot$; one-half of it is located in the disk interior to $R = 9$ kpc. In many respects this model resembles the model of the disk of our Galaxy. Outside the nuclear region, there is no evidence for noncircular motions.

The optical velocities, $R > 3$ kpc, agree with the 21-cm observations, although the maximum rotational velocity, $V = 270 \pm 10$ km sec^{-1}, is slightly higher than that obtained from 21-cm observations.

Rotation of galaxies

Measurements

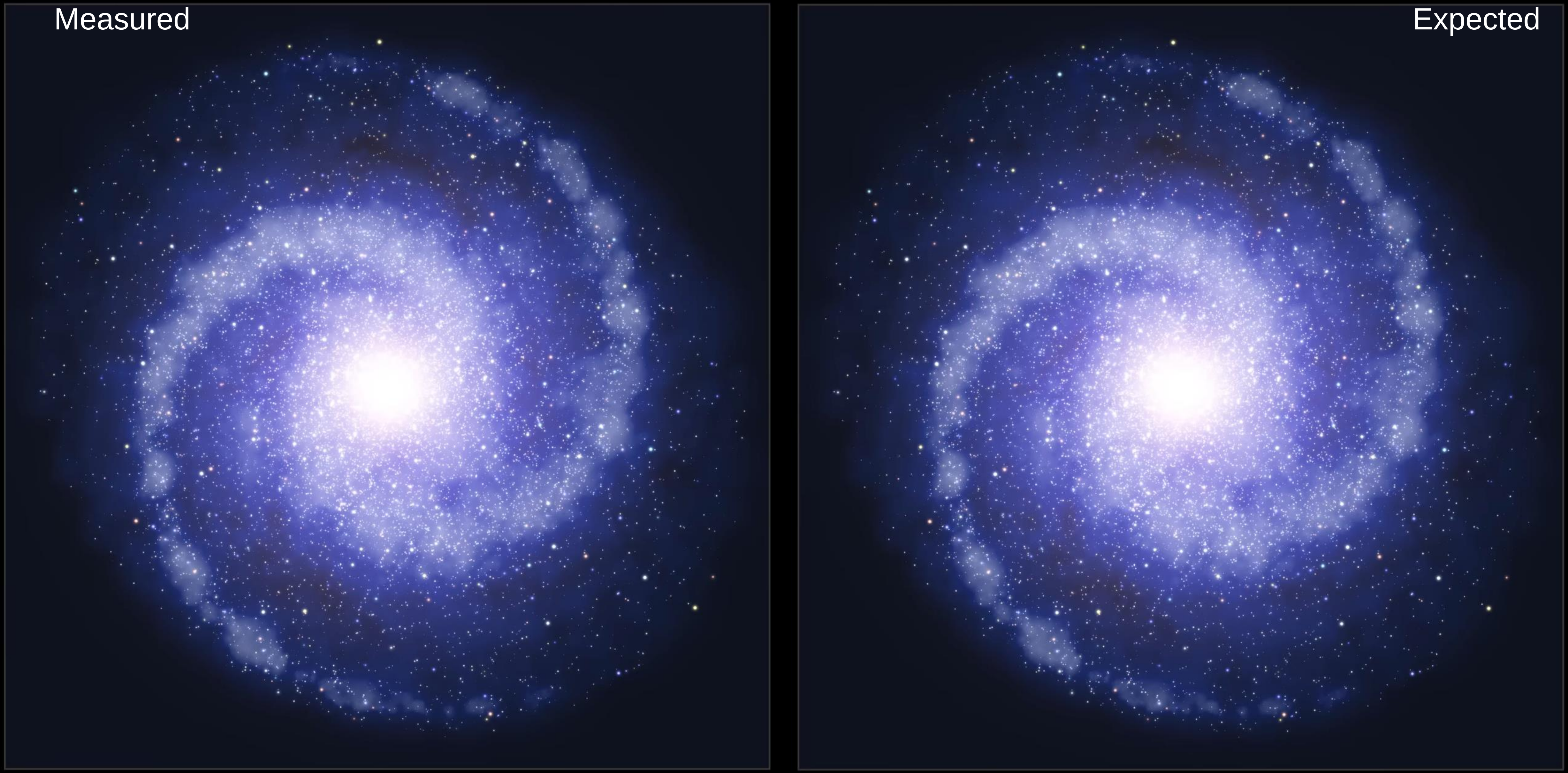


Expectations

Newtonian dynamics: $F_G + F_C = 0$

- $-\frac{GMm}{R^2} + \frac{mv^2}{R} = 0$
- $v^2 = \frac{GMmR}{R^2 m}$
- $v \propto \frac{1}{\sqrt{R}}$ Keplerian decrease

They don‘t match!


Measured
Expected

Structures and dynamics in the universe

Missing mass?

Andromeda Galaxy
(Picture by Hubble Space Telescope)

Component	$M_\odot$
Total	$\sim 10^{12}$
Stellar	$\sim 10^{11}$
Atomic hydrogen	$\sim 10^{8}$
Molecular hydrogen	$\sim 10^{7}$

luminous mass

Tamas Szalay,
Volker Springel,
Gerard Lemson

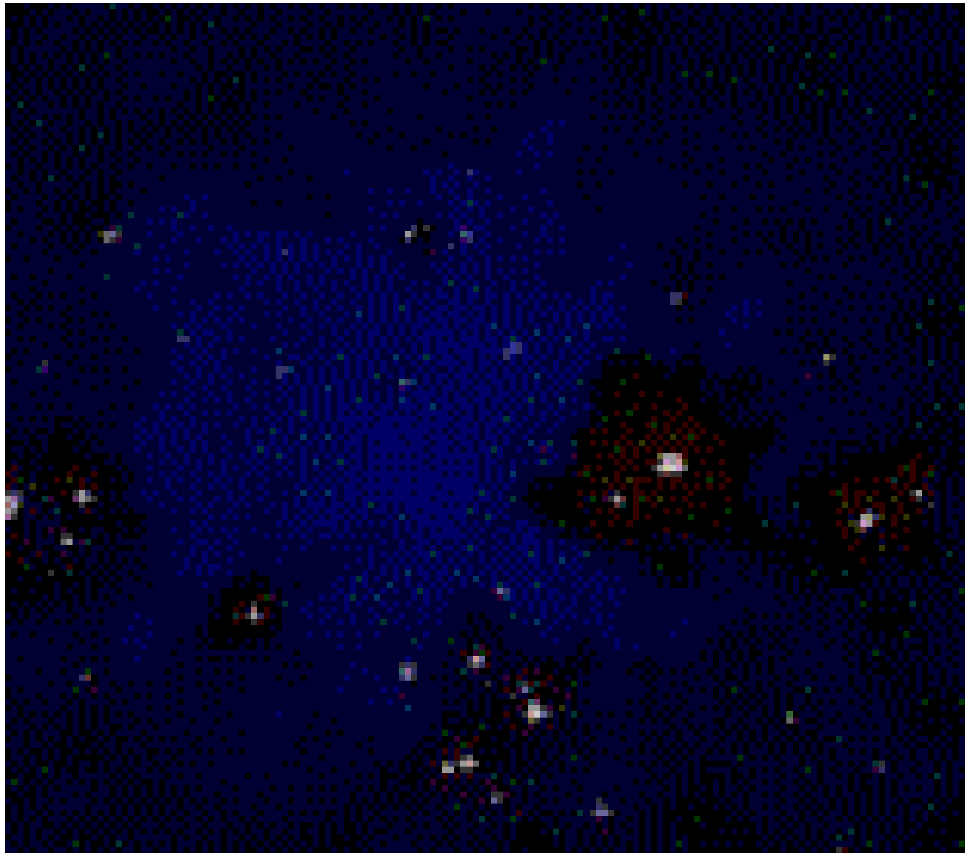
Structures and dynamics in the universe

Clusters

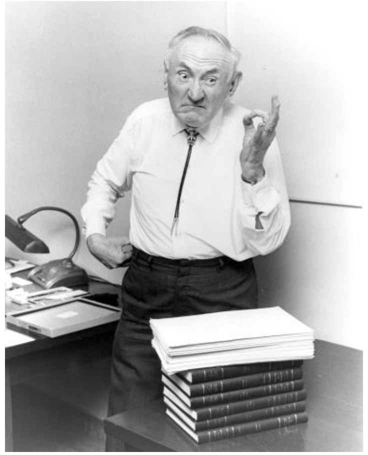
- Galaxies come in groups with typical distances of 100 Million lightyears
- Assumption that clusters are in mechanical equilibrium

  → Virial Theorem $T = -\frac{1}{2}U$
- Clusters at high speed → do not diffuse?
- To keep galaxies gravitationally bound much more mass is required

Dark matter ≈ 30 · visible matter!



http://ircamera.as.arizona.edu/NatSci102/NatSci102/lectures/galaxydist.htm



“Should this turn out to be true, the surprising result would follow that dark matter is present in a much higher density rate than radiating matter.“

http://archiv.ethlife.ethz.ch/articles/news/zwickysmorphologie.html

Gravitational lensing

More dark matter evidence

- Deflection of light rays in “invisible” gravitational fields
- Knowledge of original undistorted image
- Able to determine lens properties e.g. mass density or matter distribution

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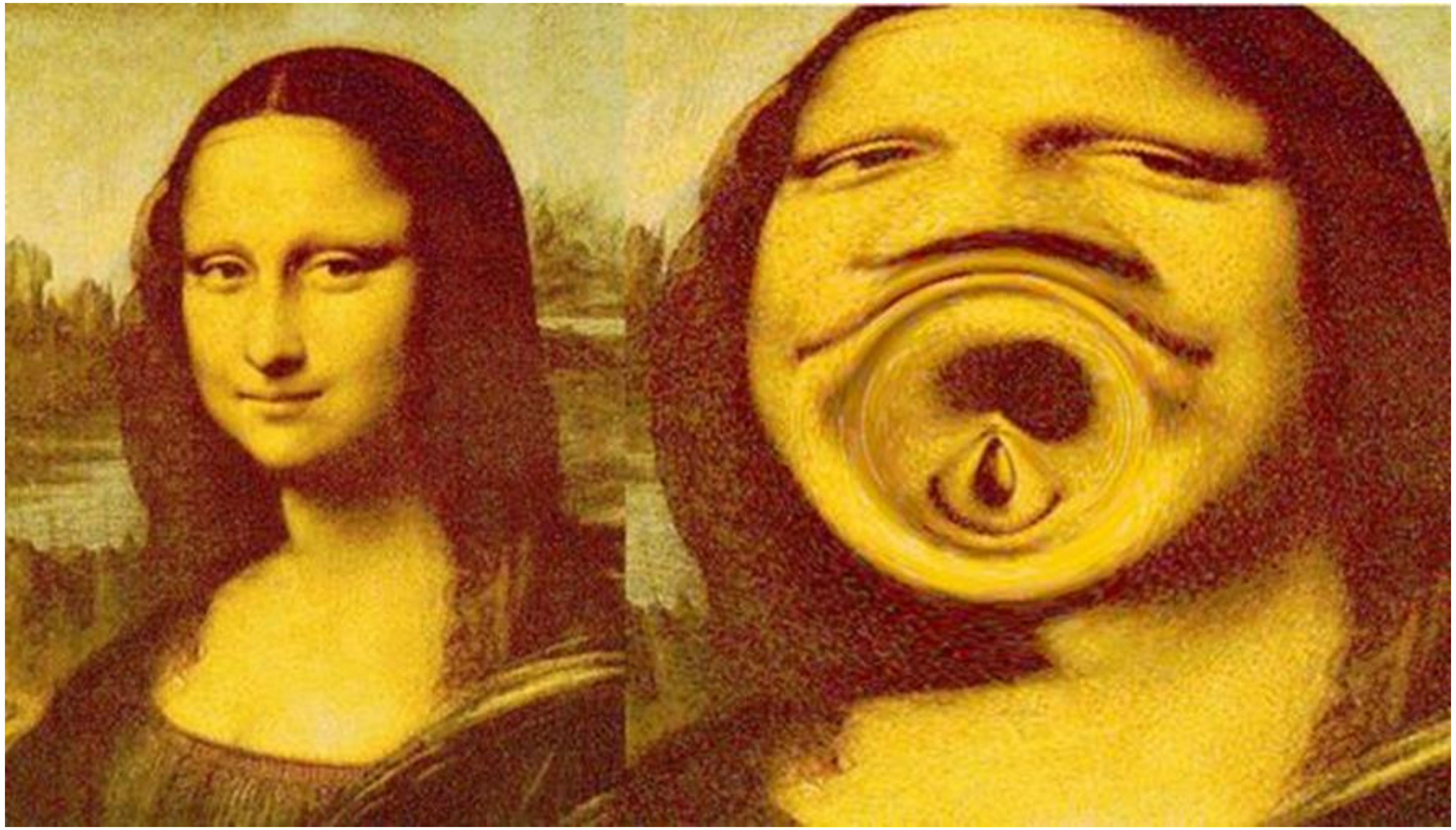
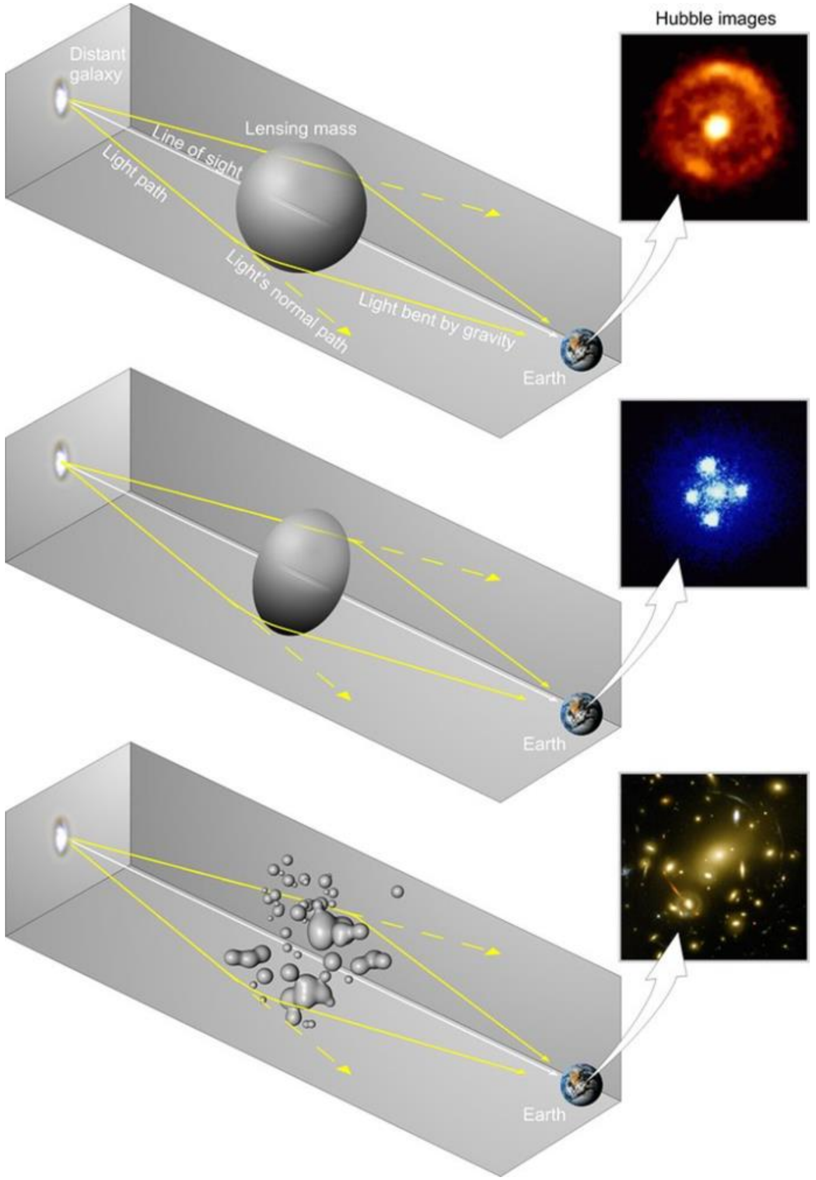


http://astronomyonline.org/Cosmology/GravitationalLensing.asp

Gravitational lensing

More dark matter evidence

- Distorts image of background object
- Magnifies background object
- Stretches image tangentially around foreground mass
- **Reveal objects that are behind galaxy clusters**
- Analysis provides information about e.g. deflector‘s mass

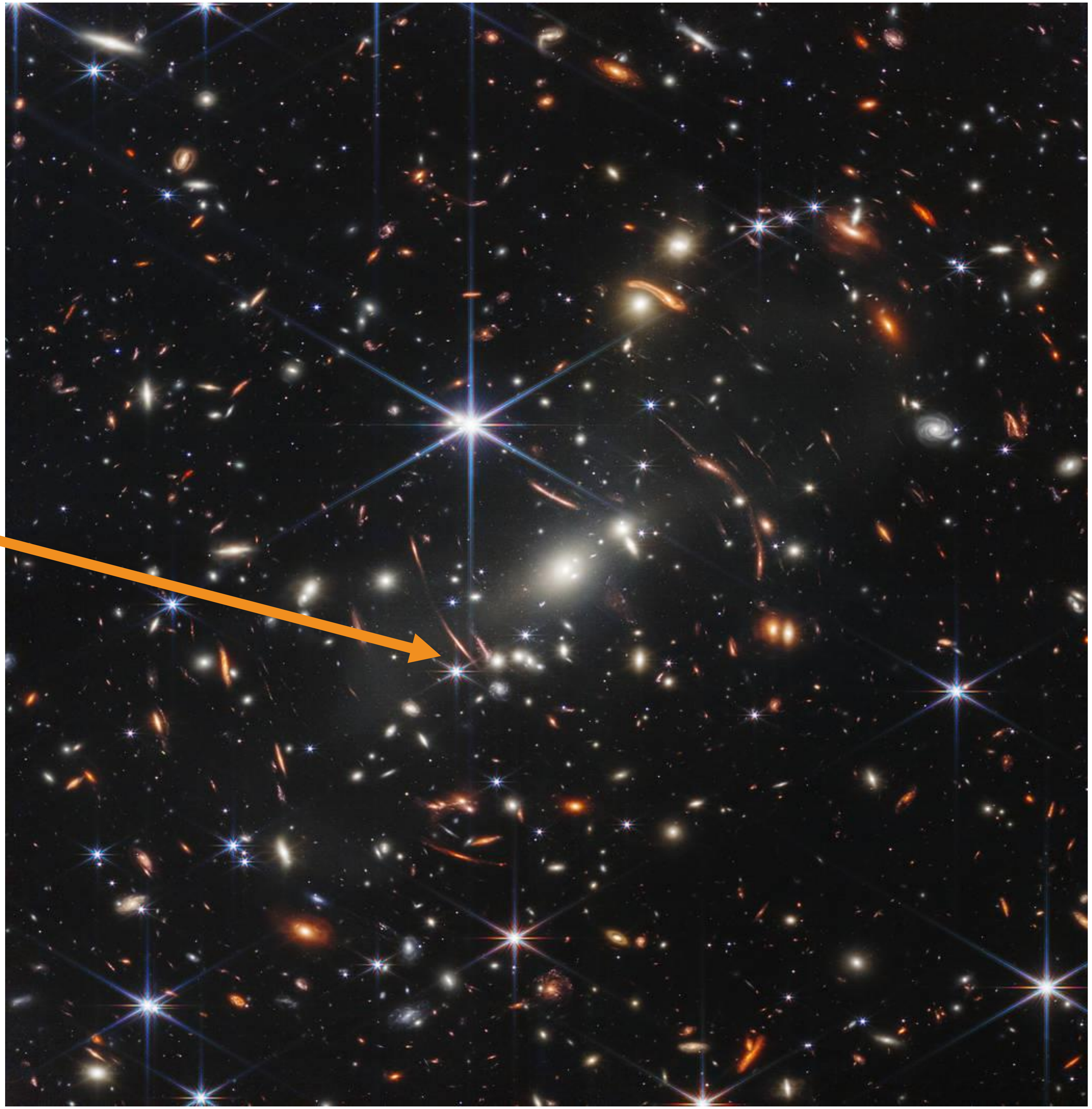


http://spacetelescope.org/images/heic0404b/

Gravitational lensing

More dark matter evidence

Arcs visible in images from
James Webb Space Telescope
picture of the SMACS 0723 Galaxy Cluster



https://www.nasa.gov/image-feature/goddard/2022/nasa-s-webb-delivers-deepest-infrared-image-of-universe-yet

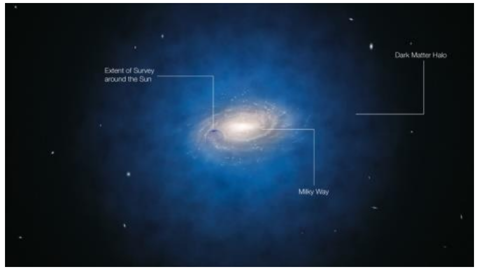
What do we know?

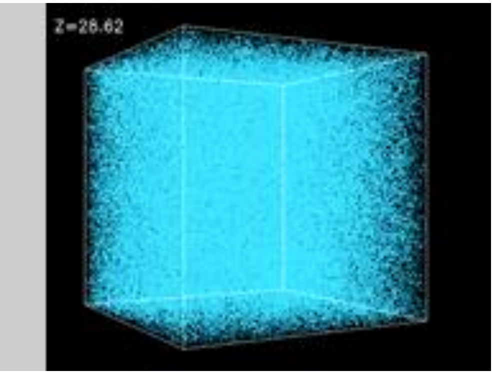
Flaw(s)?

Axel

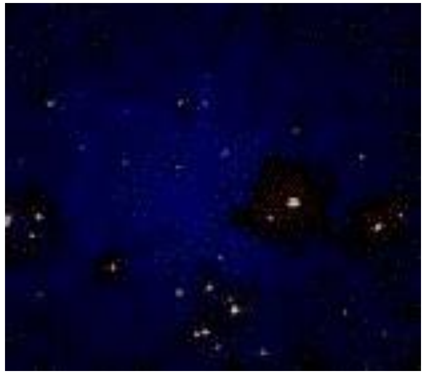
Particle physics and cosmology only fit if a large amount of mass and energy of unknown constituents exist.

Many evidences for dark matter on length scales of 1,000 light-years and beyond.





http://cosmicweb.uchicago.edu/filaments.html



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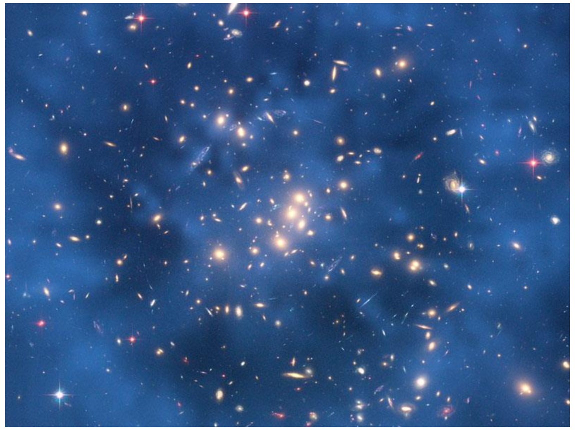
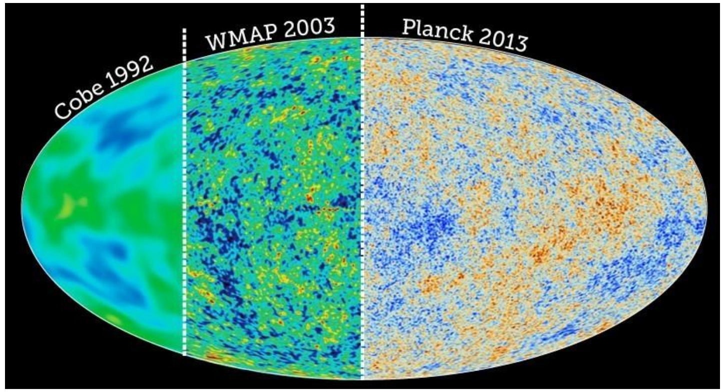


https://www.esa.int/Science_Exploration/Space_Science/Hubble_sees_dark_matter_ring_in_a_galaxy_cluster

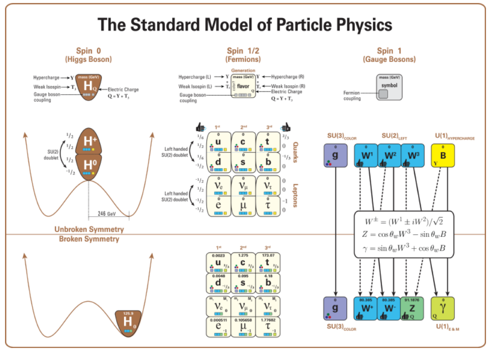
https://www.researchgate.net/figure/Temperature-fluctuations-observed-in-the-CMB-using-COBE-WMAP-Planck-data-Gold-et-al_fig1_328474806

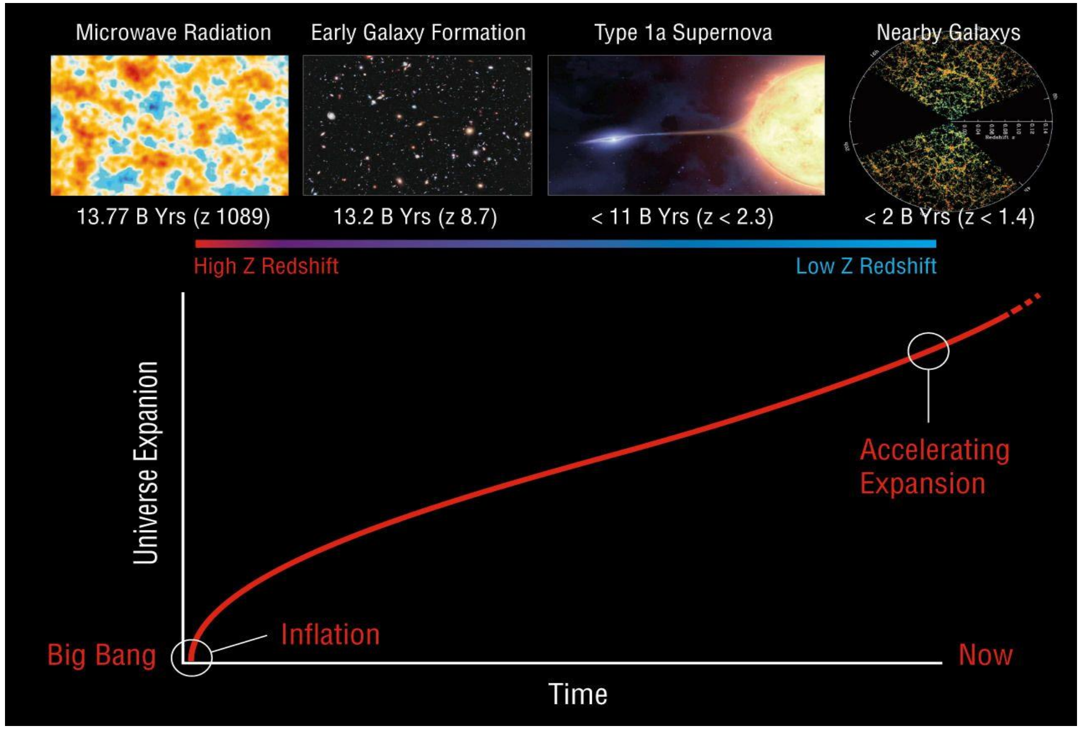


The composition of the Universe

95% waiting for discovery!

stars	gas / dust	dark matter	dark energy
0.4%	4.6%	26%	69%
		additional gravitation (galaxies & beyond)	anti-gravitation on largest scales





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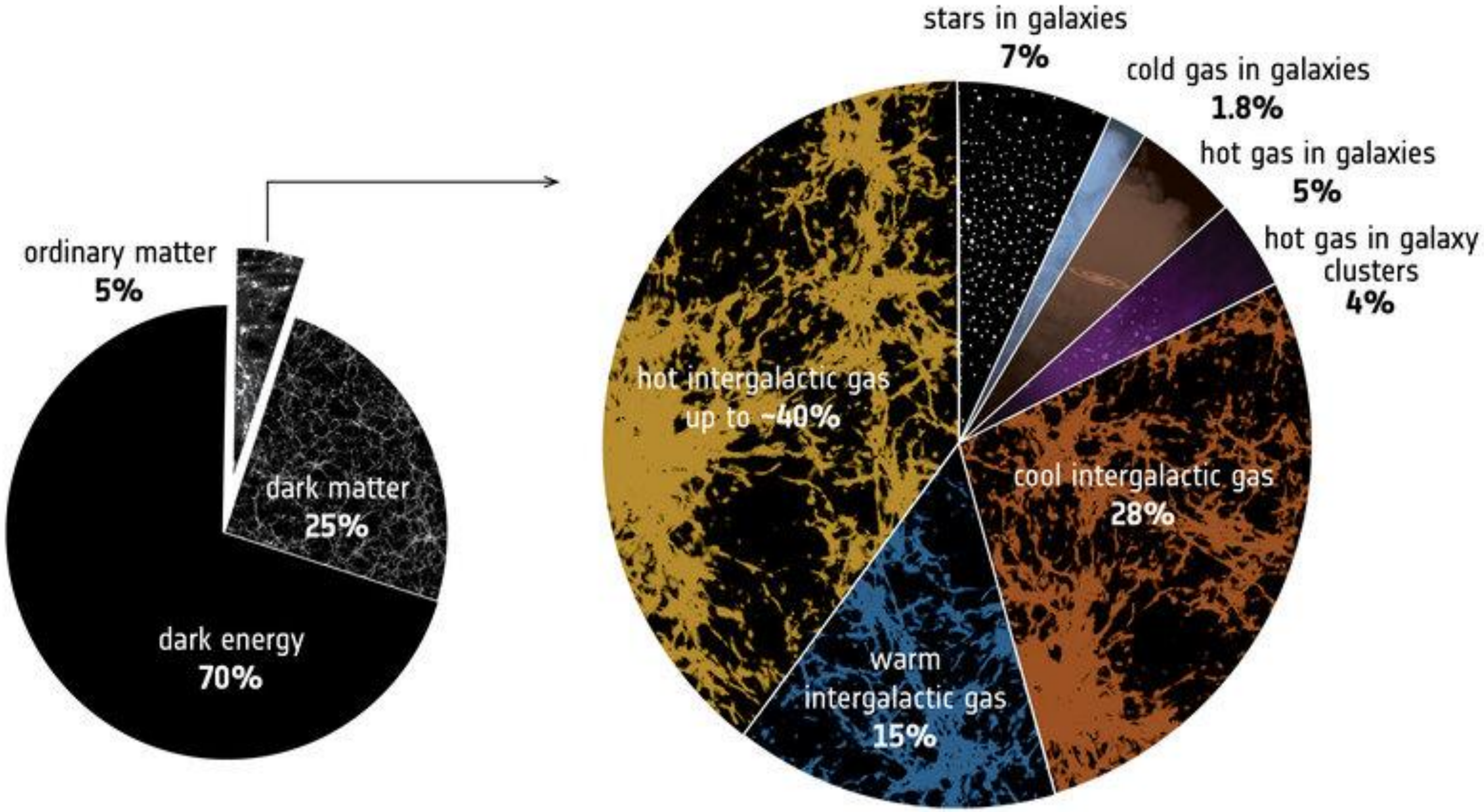


Questions?

New DESI (Dark Energy Spectroscopic Instrument) results

Survey to create largest 3D map of the Universe

Expansion history of the Universe with highest precision by

- Measuring clustering of galaxies.

First results suggests tensions with the standard models of particle physics and cosmology:

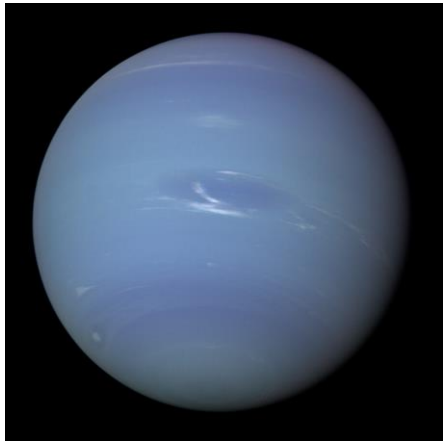
- Negative neutrino masses seem to be preferred.
- Dark energy may evolve with time.

Do we miss something in our understanding?

https://noirlab.edu/public/media/archives/images/wallpaper1/noirlab2408a.jpg

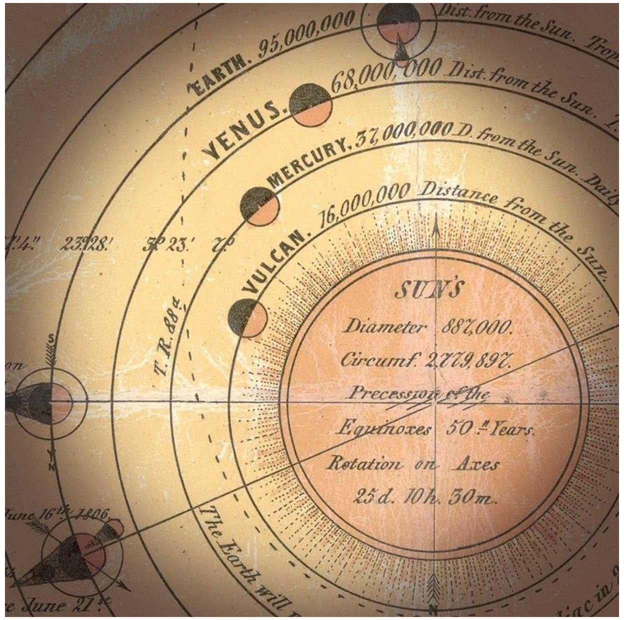
Recap: how to find something previously invisible?

A bit of history



1: Discovery of the planet Neptune:

- The orbit of Uranus did not match calculations (Newtonian forces).
- The differences could be well explained by another gravitating body: Neptune.



2: General relativity:

- The orbit of Mercury did not match calculations (Newtonian forces).
- The differences could not be explained by another gravitating body (Vulcan), but is perfectly explained by general relativity.

You may find either a new form of matter or a new more fundamental theory.

Dark Matter

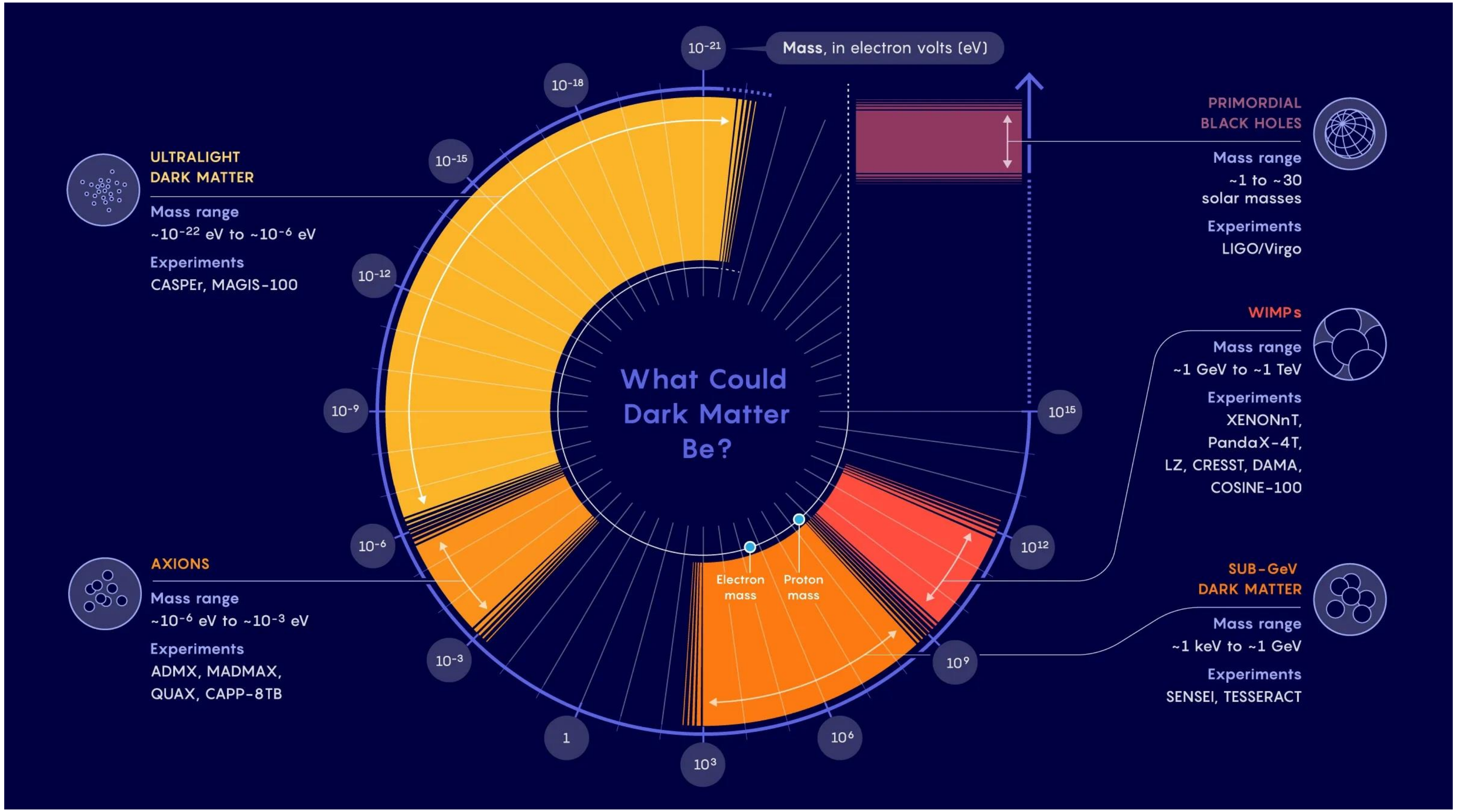
Many candidates, no convincing observation yet

Candidates from

10^{-22} eV to 10^{67} eV !

Many different kinds
of experiments required.

Axions might also be related
to dark energy.



https://www.wired.com/story/the-search-for-dark-matter-is-dramatically-expanding/

Dark Matter

Candidates are expected by theories beyond the standard model

Examples:

- Weakly Interacting Particles (WIMPs)
  are expected by Super-Symmetry to solve the mass hierarchy problem.

- Sterile neutrinos
  could explain neutrino masses and mixing.

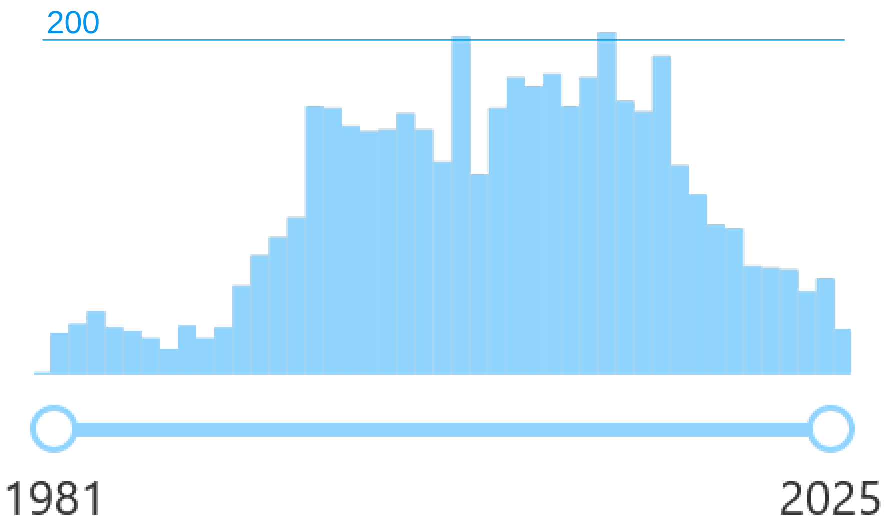
- The QCD axion
  is motivated by the Peccei-Quinn symmetry breaking to explain the vanishing electric dipole moments of neutron and proton.

- The axion and axion-like particles (ALPs)
  are expected in string-theories to combine gravitation and particle physics.

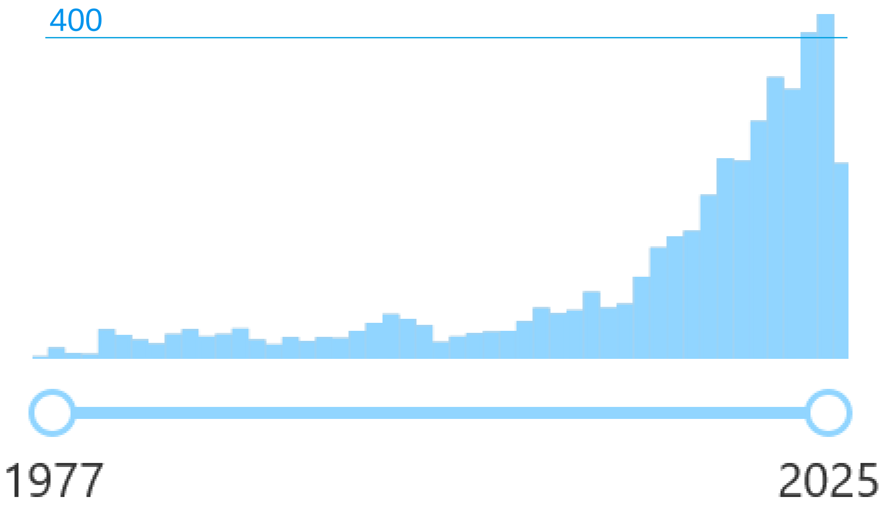
Dark Matter

https://inspirehep.net

find t SUSY



find t axion



Particle physics theory: axions are very fashionable at present!

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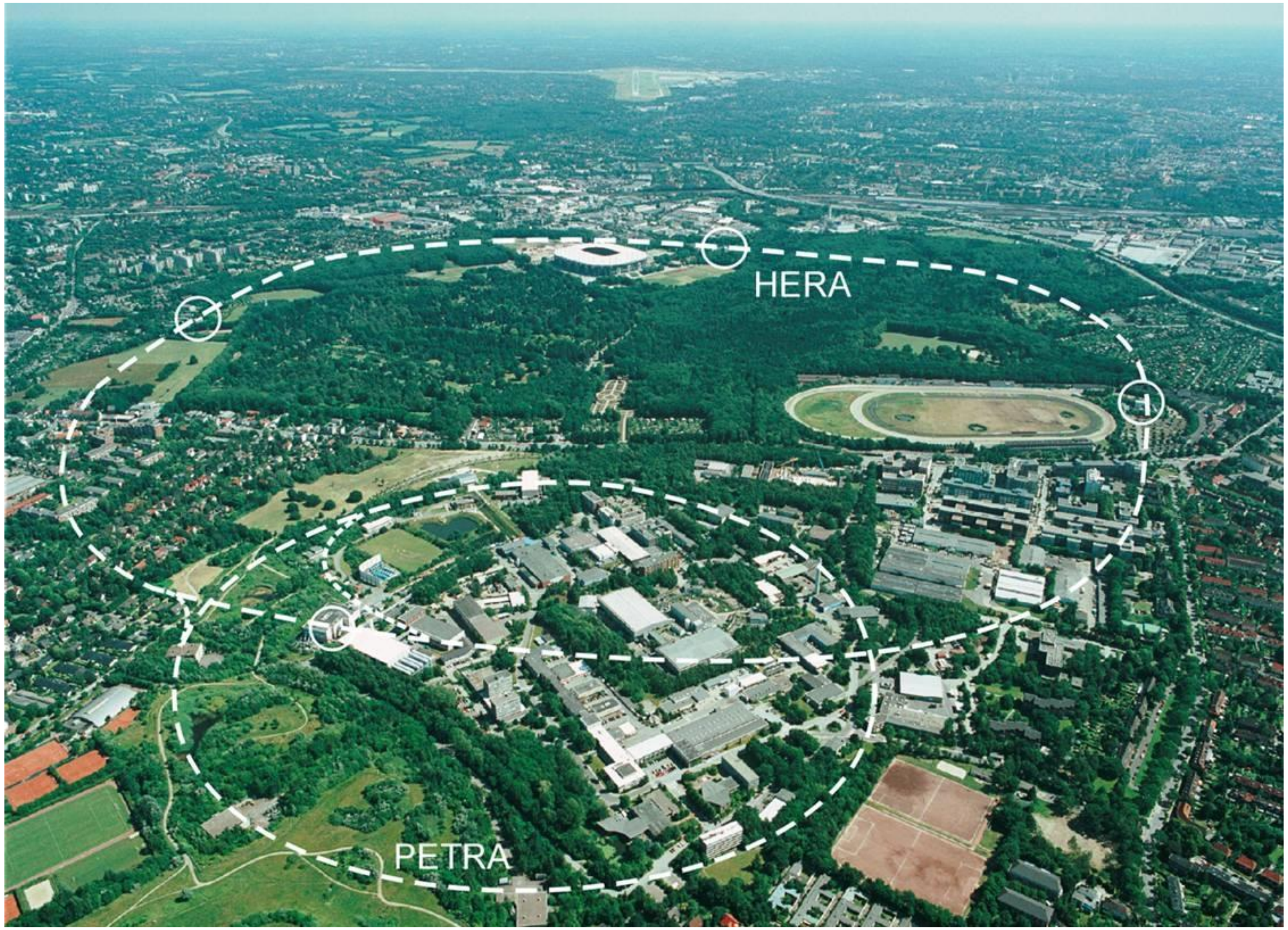
- Summary

DESY in Hamburg around the year 2000

HERA: data taking 1992 - 2007



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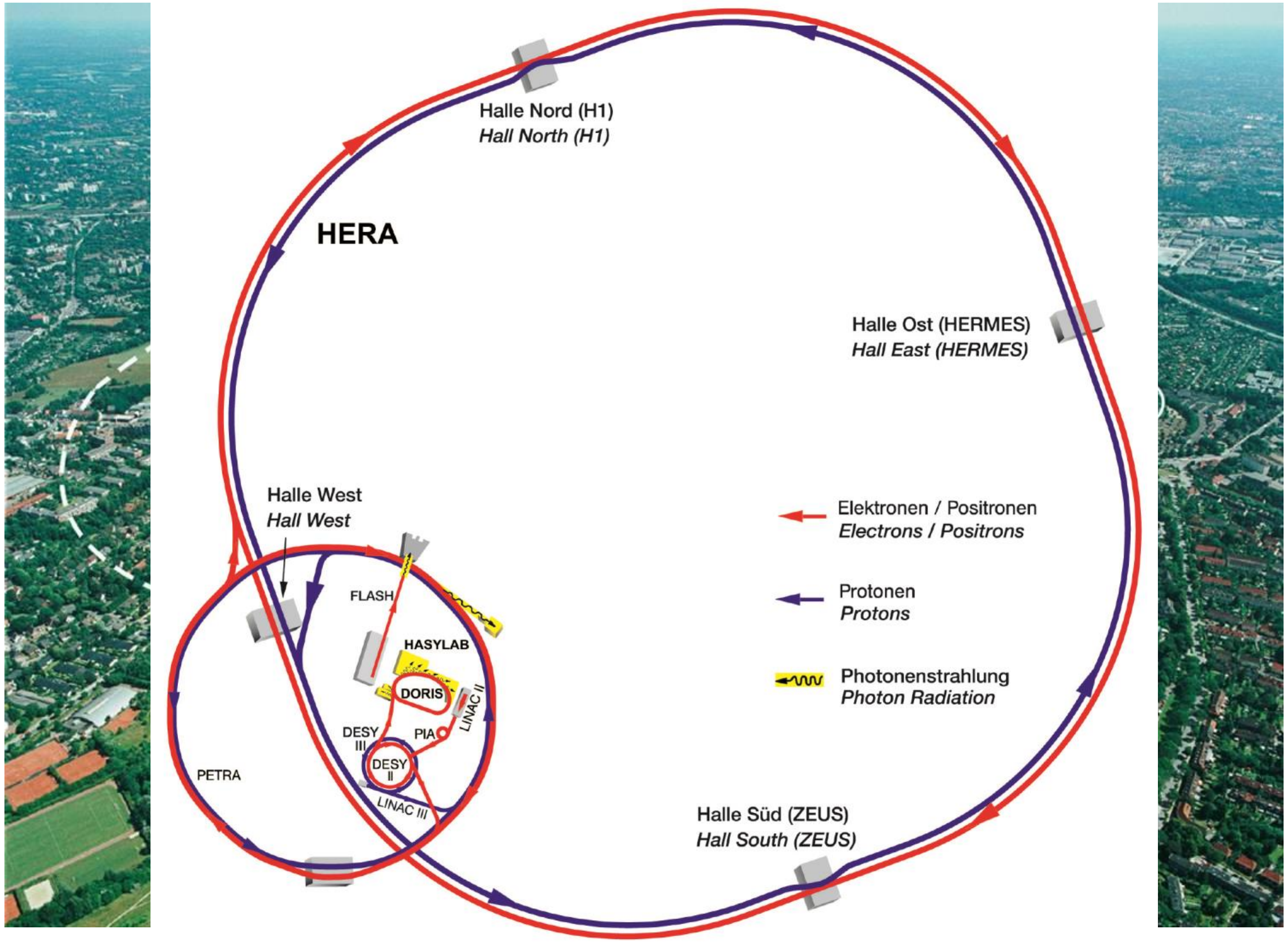

Frank A. Wilczek, Nobel lecture 2004

https://www.nobelprize.org/nobel_prizes/physics/laureates/2004/wilczek-lecture.pdf

*The established symmetries permit a sort of interaction among gluons …
that violates the invariance of the equations of QCD under a change in the direction of time. Experiments provide extremely severe limits on the strength of this interaction, much more severe than might be expected to arise accidentally.*

By postulating a new symmetry, we can explain the absence of the undesired interaction. The required symmetry is called Peccei-Quinn symmetry after the physicists who first proposed it. If it is present, this symmetry has remarkable consequences. It leads us to predict the existence of new very light, very weakly interacting particles, axions. (I named them after a laundry detergent, since they clean up a problem with an axial current.) In principle axions might be observed in a variety of ways, though none is easy. They have interesting implications for cosmology, and they are a leading candidate to provide cosmological dark matter.

Frank A. Wilczek, Nobel lecture 2004

https://www.nobelprize.org/nobel_prizes/physics/laureates/2004/wilczek-lecture.pdf

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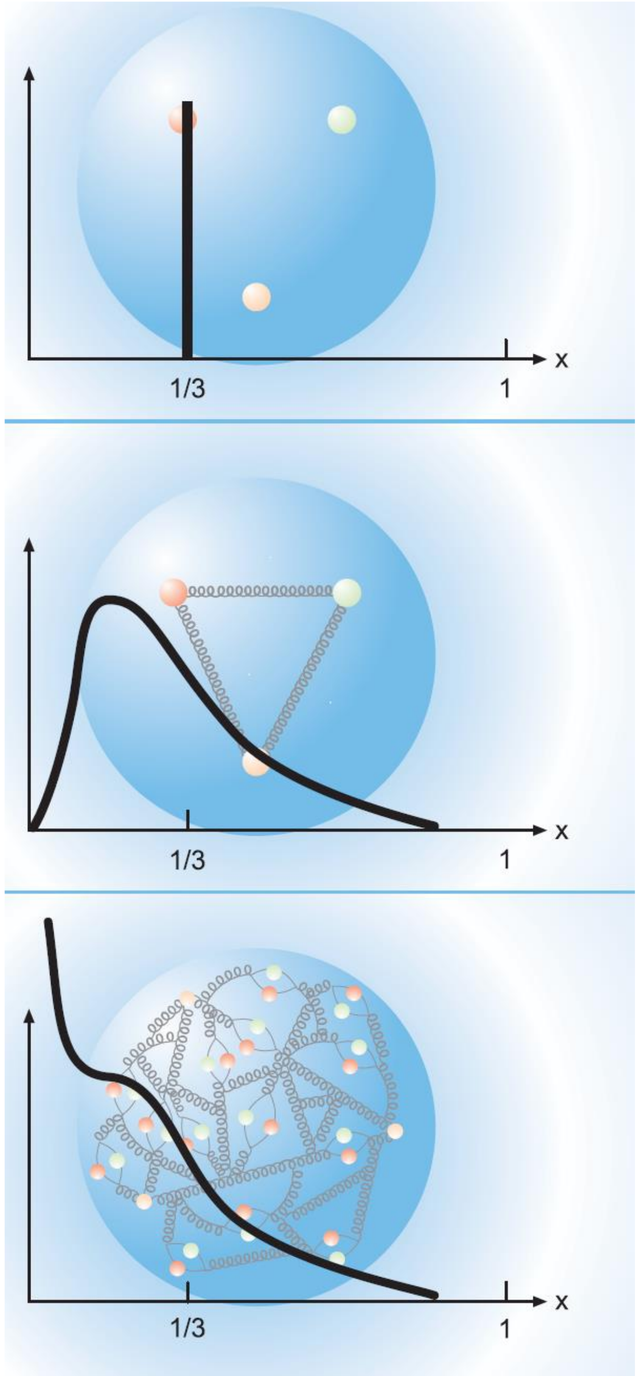
Some axion motivation

…. and some laxness in HERA communication

The proton:

- is, in the static limit, made out of three quarks.
- becomes very complex with increasing time/spatial resolution due to gluon-mediated interactions.

This picture has been confirmed in numerous experiments.

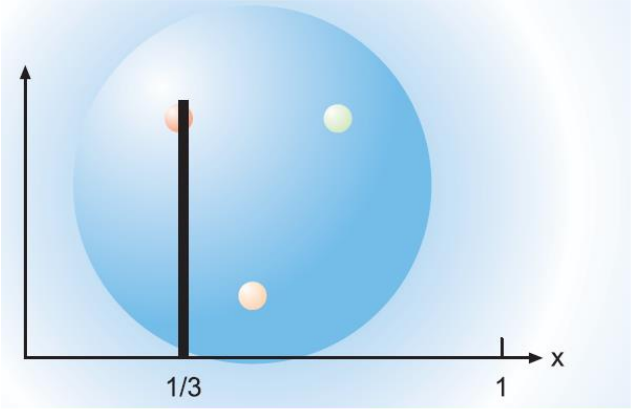


Brochure: "Super Microscope HERA"

Some axion motivation

…. and some laxness in HERA communication

If this is the real picture,



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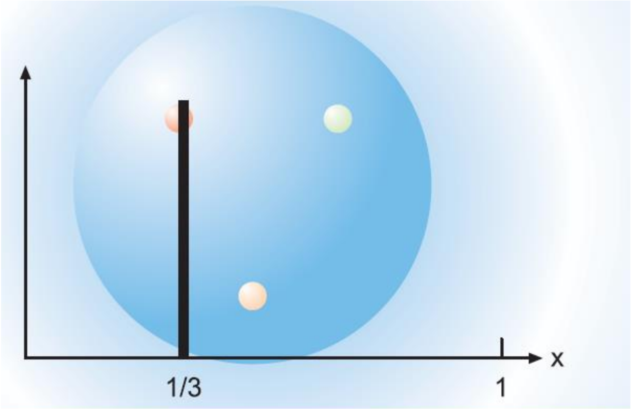
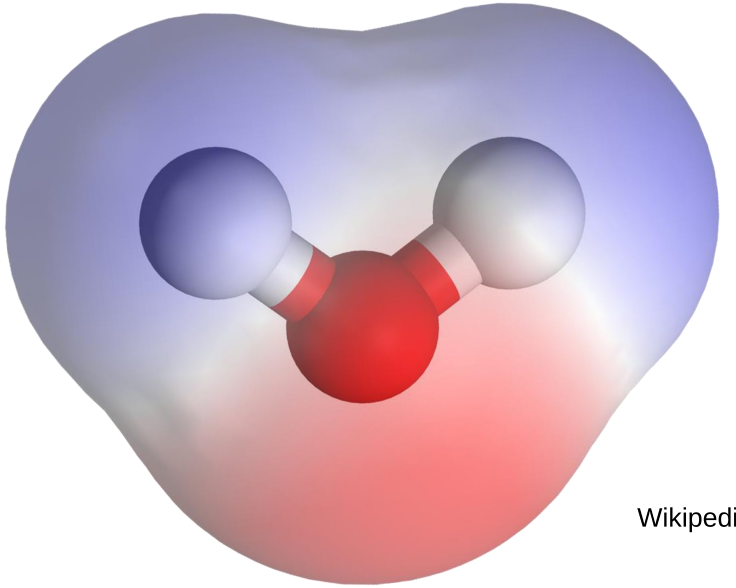


protons and neutrons, in the static limit,
should show an electric dipole moment (EDM)!

Like water molecules for example.



Wikipedia

Some axion motivation

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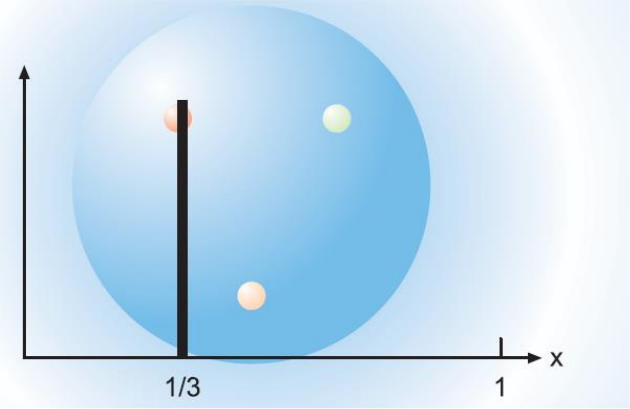
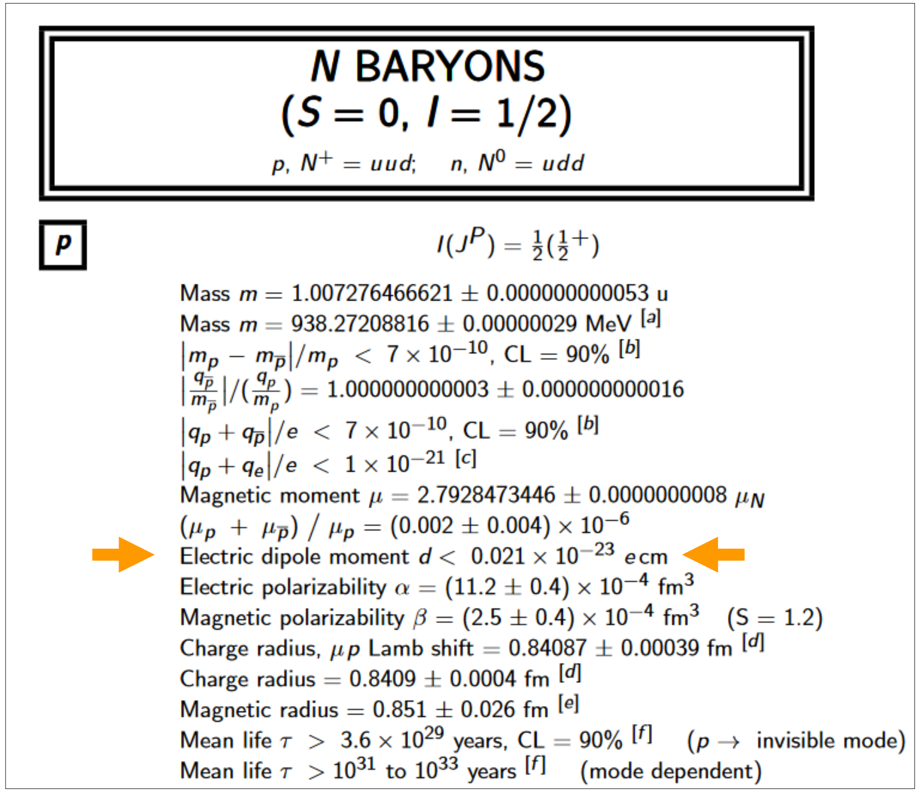
If this is the real picture,



protons and neutrons, in the static limit,
should show an electric dipole moment (EDM)!

Experimentally:
an EDM, if there is any,
would be much smaller than expected!

What is wrong with this picture?



N BARYONS
$(S = 0,\ I = 1/2)$

$p,\ N^+ = uud$; $n,\ N^0 = udd$

p $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

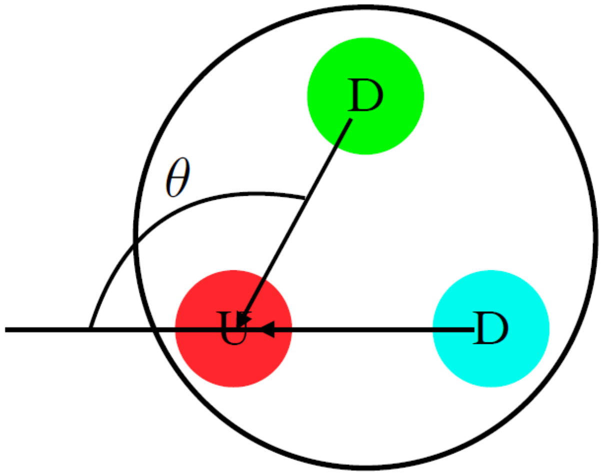
Mass $m = 1.007276466621 \pm 0.000000000053$ u
Mass $m = 938.27208816 \pm 0.00000029$ MeV [a]
$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 1.000000000003 \pm 0.000000000016$
$|q_p + q_{\overline{p}}|/e < 7 \times 10^{-10}$, CL = 90% [b]
$|q_p + q_e|/e < 1 \times 10^{-21}$ [c]
Magnetic moment $\mu = 2.7928473446 \pm 0.0000000008\ \mu_N$
$(\mu_p + \mu_{\overline{p}})\ /\ \mu_p = (0.002 \pm 0.004) \times 10^{-6}$
Electric dipole moment $d < 0.021 \times 10^{-23}$ e cm
Electric polarizability $\alpha = (11.2 \pm 0.4) \times 10^{-4}$ fm^3
Magnetic polarizability $\beta = (2.5 \pm 0.4) \times 10^{-4}$ fm^3 (S = 1.2)
Charge radius, μp Lamb shift $= 0.84087 \pm 0.00039$ fm [d]
Charge radius $= 0.8409 \pm 0.0004$ fm [d]
Magnetic radius $= 0.851 \pm 0.026$ fm [e]
Mean life $\tau > 3.6 \times 10^{29}$ years, CL = 90% [f] ($p \to$ invisible mode)
Mean life $\tau > 10^{31}$ to 10^{33} years [f] (mode dependent)

https://pdg.lbl.gov/2022/

The neutron

QCD and a missing EDM

- QCD predicts an EDM of the neutron: $d_n = \theta \cdot 3 \cdot 10^{-16}$ e cm (from $L_\theta = -\theta(\alpha_s/8\pi)\,\tilde{G}^a_{\mu\nu} G^a_{\mu\nu}$).
  θ is a free parameter



https://arxiv.org/abs/1812.02669

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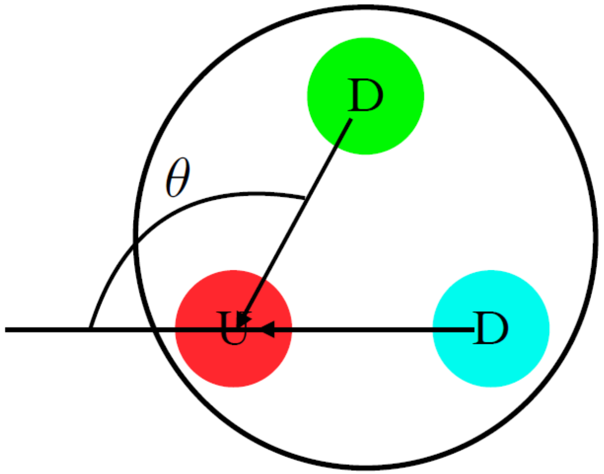

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Experiments: $d_n < 3{\cdot}10^{-26}$ e cm; $\theta < 10^{-10}$

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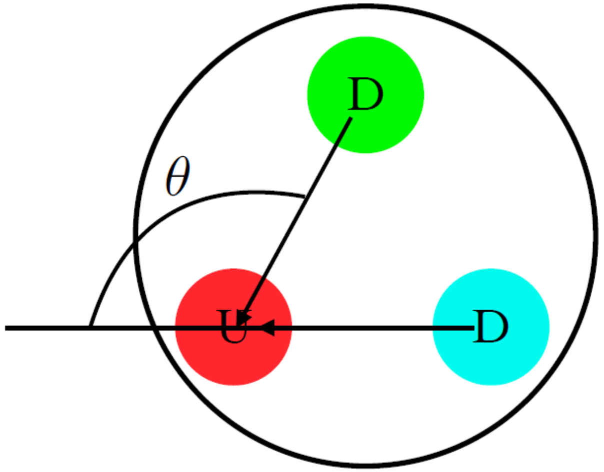

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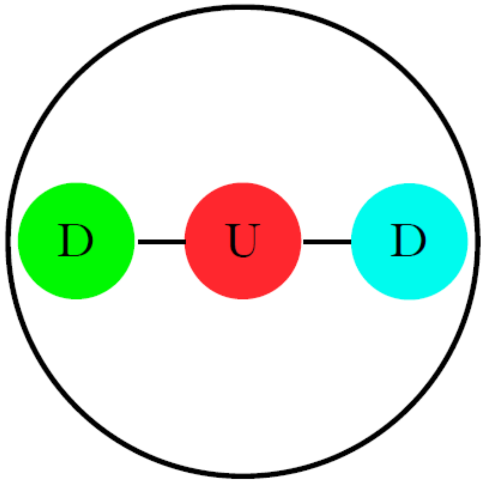

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https://arxiv.org/abs/1812.02669

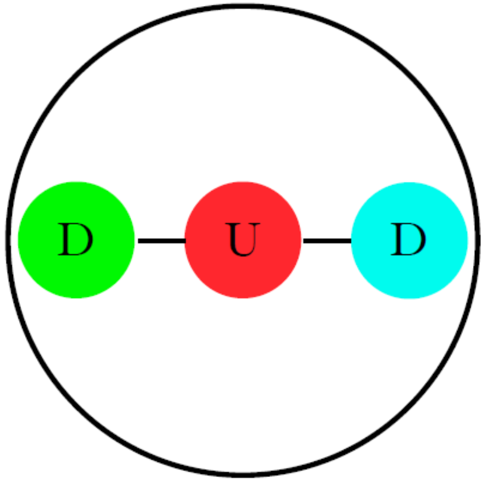
Experiments: $d_n < 3 \cdot 10^{-26}$ e cm; $\theta < 10^{-10}$

This is related to the very fundamental T symmetry!

The three quarks are perfectly aligned!

A “fine-tuning” problem of particle physics.

It might hint at a new elementary particle.



https://arxiv.org/abs/1812.02669

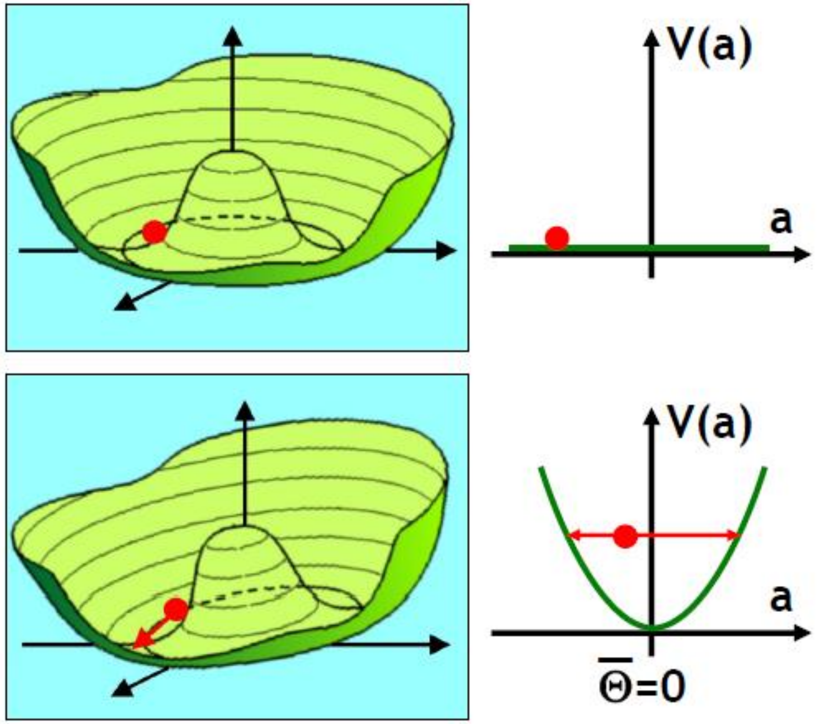
Peccei-Quinn symmetry …

… and a new elementary particle!

Idea: if θ is not a fixed value, but an evolving field, it relaxes to zero by QCD instanton effects.

Peccei-Quinn symmetry:

- Global U(1), complex scalar field.
- Spontaneously broken at very high energies: a massless Goldstone boson should exist. This is the axion.
- QCD instanton effects explicitly break the axion (a) symmetry, so that it becomes inexact at QCD energies. The axion acquires mass.



S. Hannestad, presentation at 5th Patras Workshop 2009

If $\theta = 0$ by the Peccei-Quinn mechanism, an axion should exist!

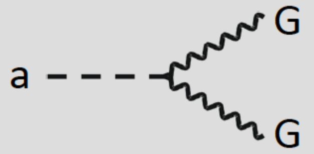
And vice versa.

Axions

Couplings to the SM

Axions are a consequence of the Peccei-Quinn symmetry to explain θ=0.

f_a: energy scale of PQ symmetry breaking

Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$	
Mass (generic)	$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d} \frac{m_\pi}{f_\pi^{-1} f_a} \approx \frac{6\ \mu\text{eV}}{f_a/10^{12}\ \text{GeV}}$	

A. Mirizzi, Next Frontiers in the Search for Dark Matter, 2019

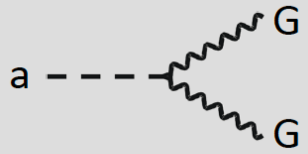
Axions

Couplings to the SM

Axions are a consequence of the Peccei-Quinn symmetry to explain θ=0.

There might be more couplings to Standard Model constituents.

These couplings depend on the BSM models incorporating an "invisible axion".
Also axion-like particles (ALPs) could show photon couplings.

Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$	
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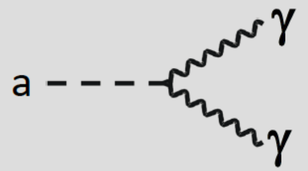
Photon coupling	$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	

A. Mirizzi, Next Frontiers in the Search for Dark Matter, 2019

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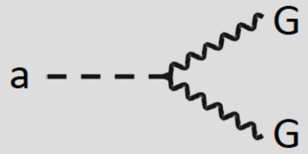
Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$ 
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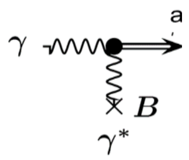
Photon coupling	In a background magnetic field: axion⟺ photon mixing 

Many experiments exploit the axion-photon mixing:

- Axion detection:

  We know how to sense very weak photon signals.

- Axion generation:

  We know how to generate very intense light fields.

A. Mirizzi, Next Frontiers in the Search for Dark Matter, 2019

Axions

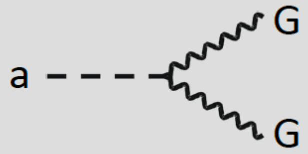
Couplings to the SM

Axions are a consequence of the Peccei-Quinn symmetry to explain θ=0.

There might be more couplings to Standard Model constituents.

These couplings depend on the BSM models incorporating an "invisible axion".
Also axion-like particles (ALPs) could show photon couplings.

Pion, nucleon and/or electron couplings depend on the specific axion models (and might give a handle to discriminate between models).

Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$	
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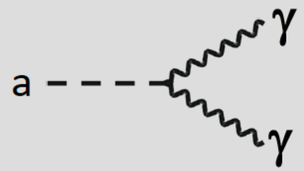
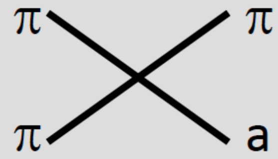
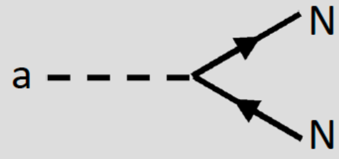
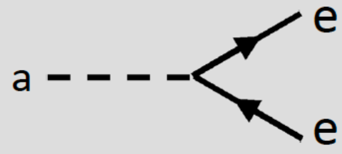
Photon coupling	$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	
Pion coupling	$\mathcal{L}_{a\pi} = \frac{C_{a\pi}}{f_\pi f_a}(\pi^0\pi^+\partial_\mu\pi^- + \cdots)\partial^\mu a$	
Nucleon coupling (axial vector)	$\mathcal{L}_{aN} = \frac{C_N}{2f_a} \bar{\Psi}_N\gamma^\mu\gamma_5\Psi_N\partial_\mu a$	
Electron coupling (optional)	$\mathcal{L}_{ae} = \frac{C_e}{2f_a} \bar{\Psi}_e\gamma^\mu\gamma_5\Psi_e\partial_\mu a$	

A. Mirizzi, Next Frontiers in the Search for Dark Matter, 2019

Disclaimer:

In the following we will not distinguish anymore between the QCD-axion and ALPs, but use both as synonyms.

Unless stated otherwise.

Outline

- Our starting point
- Dark matter in the universe
  - Evidences
  - Consequences and questions
- HERA, QCD and the axion
- Axions and dark matter
- Summary

Axion cosmology in brief

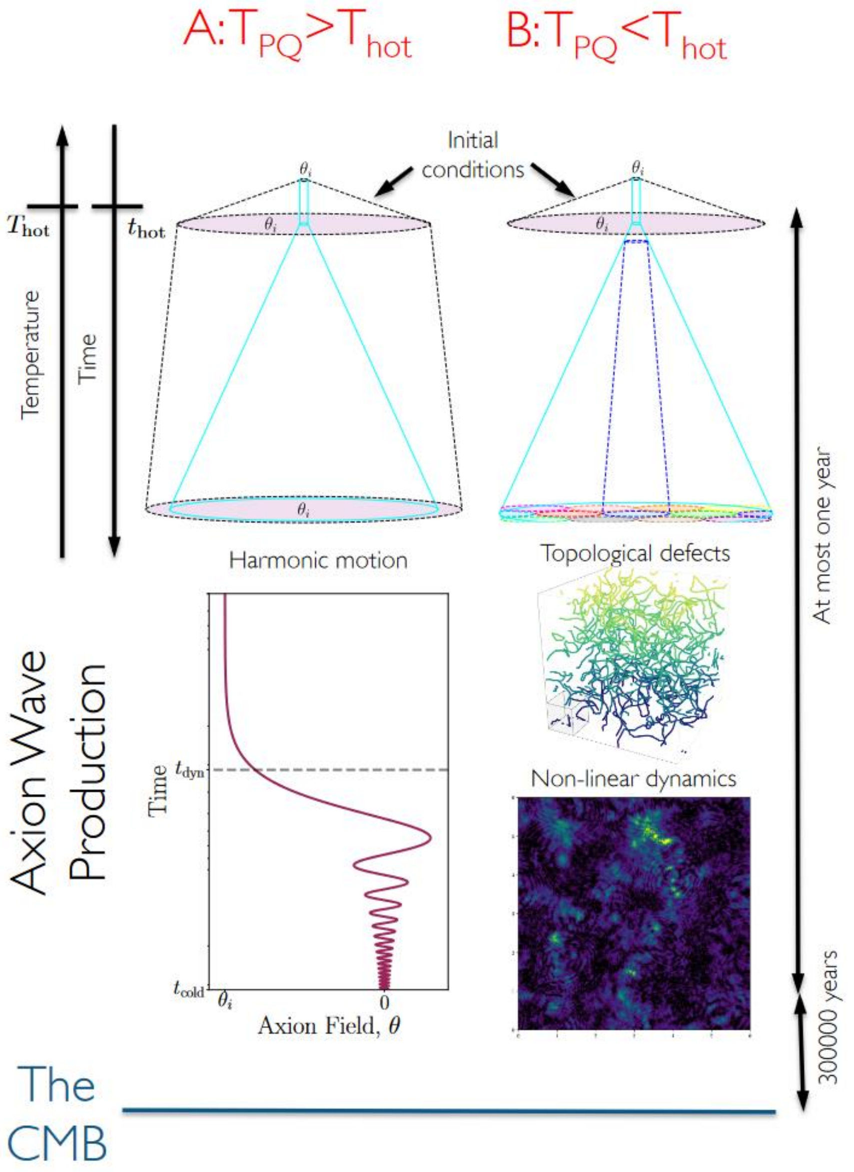
Two different cosmological scenarios

PQ symmetry breaking before inflation:

Our universe is covered by one “patch” of PQ symmetry breaking with random initial conditions.

PQ symmetry breaking after inflation:

Axions in our universe are given by averaging over many PQ symmetry breaking “patches” with random initial conditions.



https://arxiv.org/abs/2105.01406

Axion cosmology in brief

Two different cosmological scenarios

PQ symmetry breaking before inflation:

Our universe is covered by one “patch” of PQ symmetry breaking with random initial conditions:

Initial misalignment angle θ_i.

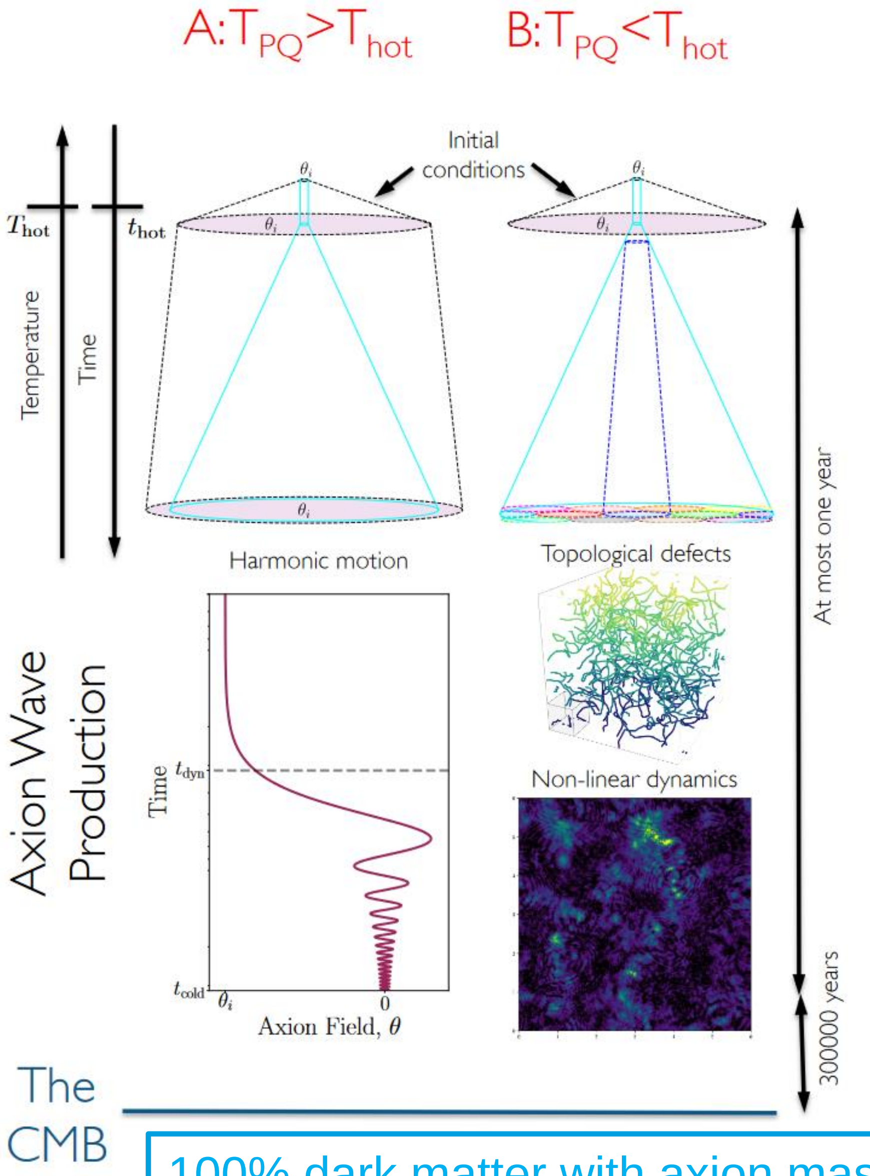
$$\Omega_{A,\mathrm{real}}h^2 \approx 0.35 \left(\frac{\theta_i}{0.001}\right)^2 \times \begin{cases} \left(\frac{f_A}{3\times10^{17}\,\mathrm{GeV}}\right)^{1.17} & \text{for} \quad f_A \lesssim 3\times10^{17}\,\mathrm{GeV}, \\ \left(\frac{f_A}{3\times10^{17}\,\mathrm{GeV}}\right)^{1.54} & \text{for} \quad f_A \gtrsim 3\times10^{17}\,\mathrm{GeV}. \end{cases}$$

WMAP: $\Omega_c h^2$ = 0.1206±0.0021

PQ symmetry breaking after inflation:

$$\Omega_{A,\mathrm{real}}h^2 \approx (3.8\pm0.6)\times10^{-3}\times\left(\frac{f_A}{10^{10}\,\mathrm{GeV}}\right)^{1.165}$$

plus contributions from string and domain wall decays.



https://arxiv.org/abs/2105.01406

https://arxiv.org/pdf/1904.09155

100% dark matter with axion masses around 30 µeV ($f_A \approx 10^8 \cdot$ LHC) !

How to find new elementary particles?

Two approaches

1: Looking for dark matter (DM) in the cosmos:

- Detect local DM around us.
- Identify signatures of DM in the universe (beyond gravitation).

2: Look for DM candidates in the laboratory:

- Experiments at the high energy frontier.
- Precision experiments.
- Understanding extreme conditions in the universe.

How to find new elementary particles?

Two approaches to search for axions

Examples

1: Looking for dark matter (DM) in the cosmos:

- Detect local DM around us. — MADMAX @ DESY
- Identify signatures of DM in the universe (beyond gravitation). — Bose-Einstein condensates of DM? Structures in the universe?

2: Look for DM candidates in the laboratory:

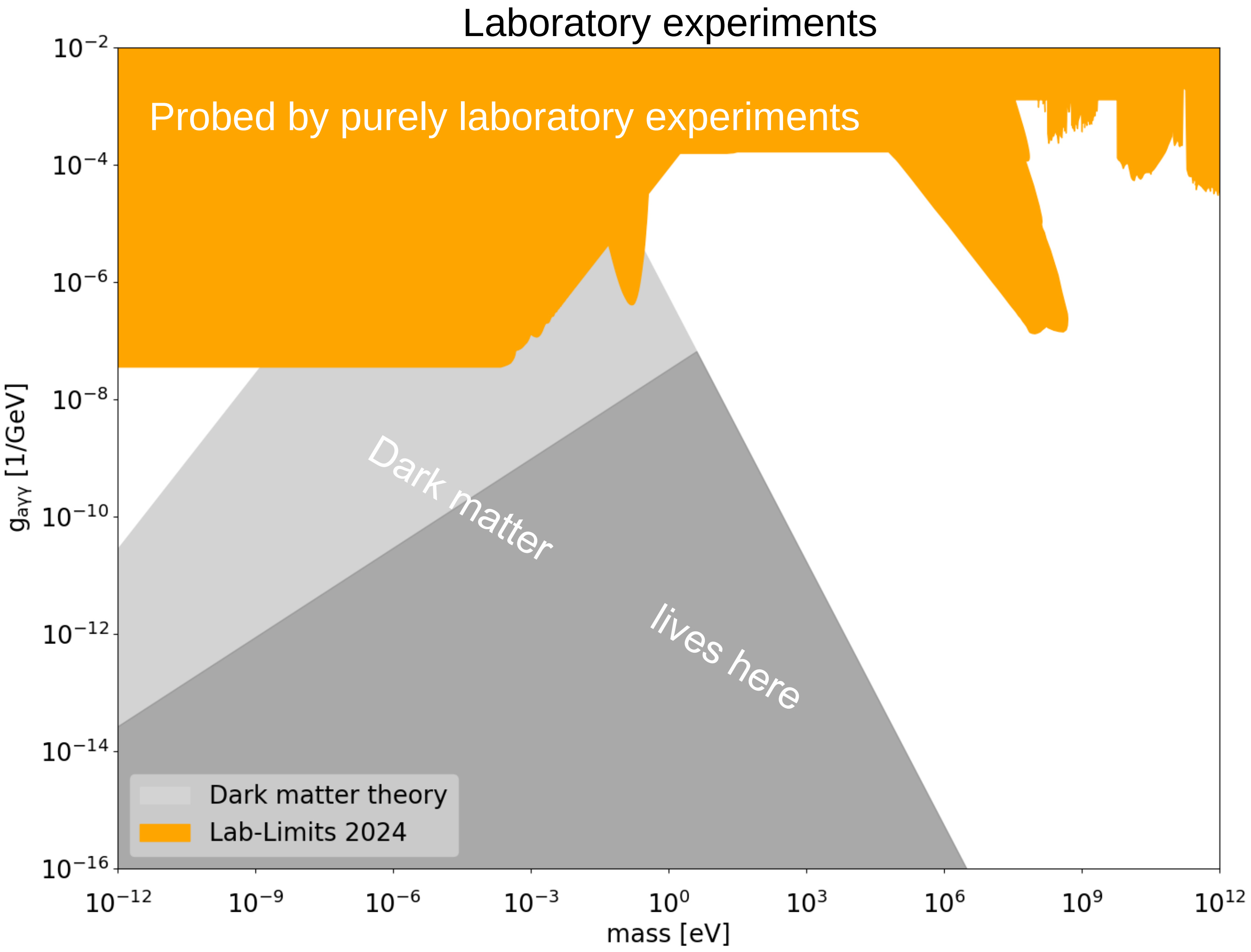
- Experiments at the high energy frontier. — Would need energies > $10^4 \cdot$ LHC
- Precision experiments. — Shining light through walls?
- Understanding extreme conditions in the universe. — Astrophysical hints?

Hypothetical light bosons for BSM physics

Axion and axion-like particle dark matter:

Group G. Servant:
ALP dark matter from kinetic fragmentation
JCAP 10 (2022) 053

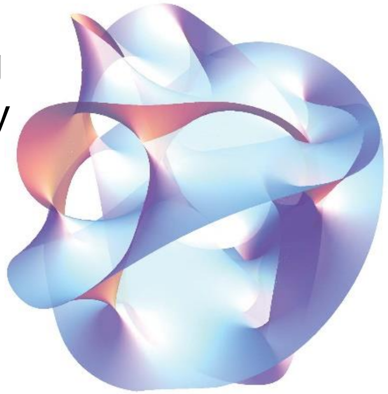
Group A. Ringwald:
WISPy cold dark matter
JCAP 06 (2012) 013

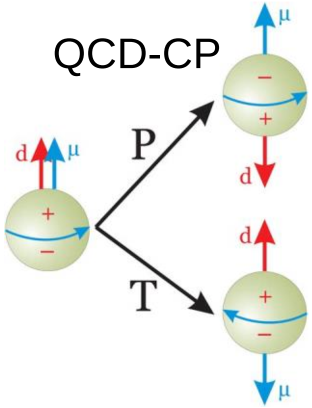


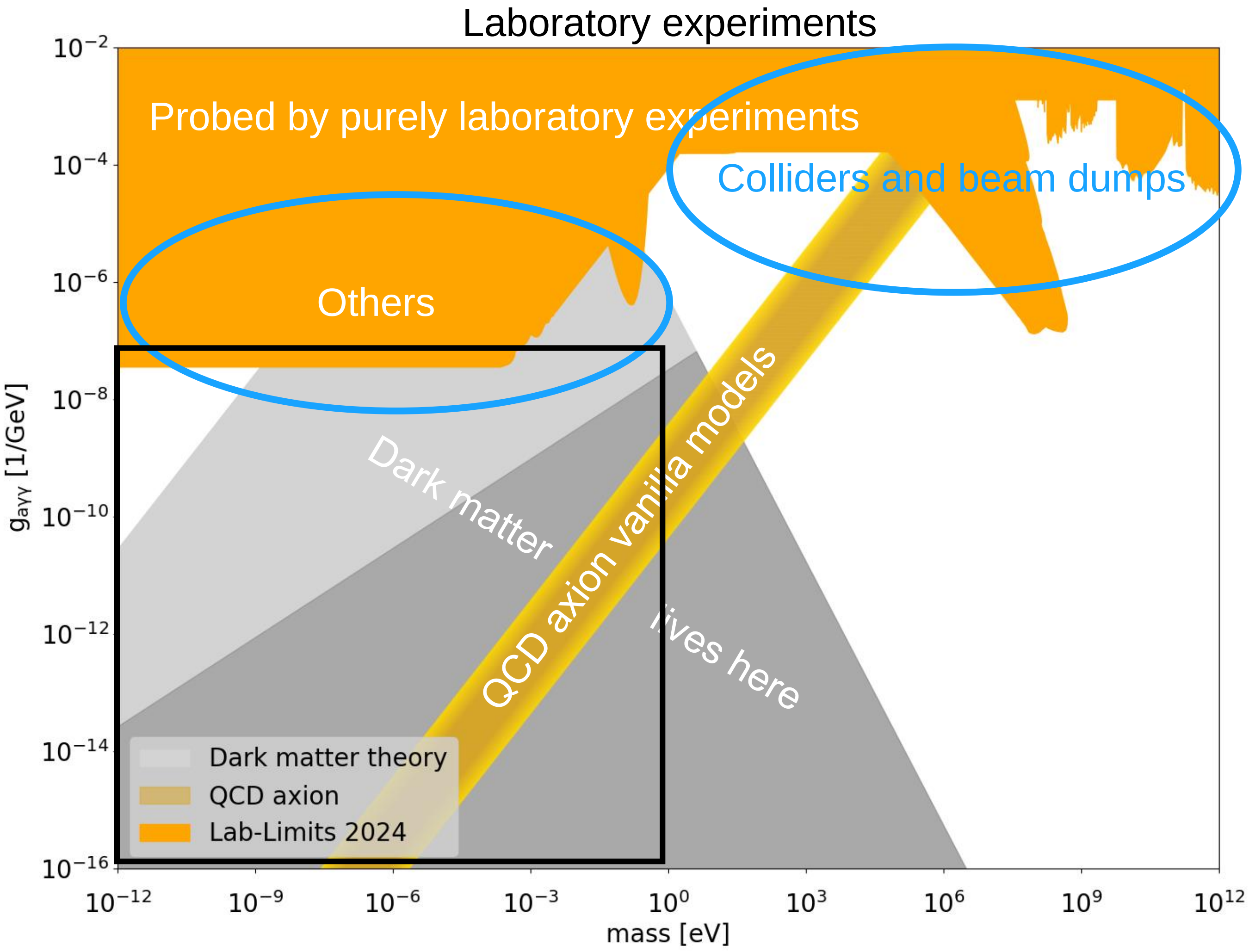
Hypothetical light bosons for BSM physics

Most interesting parameter space out of reach at colliders

String theory







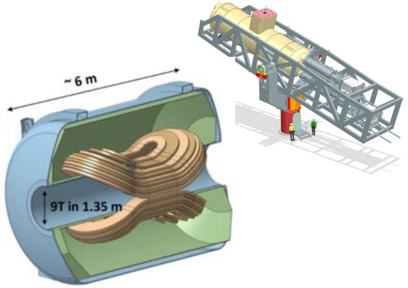
The DESY strategy
Hypothetical light bosons for BSM physics

Mass range < 1 eV.

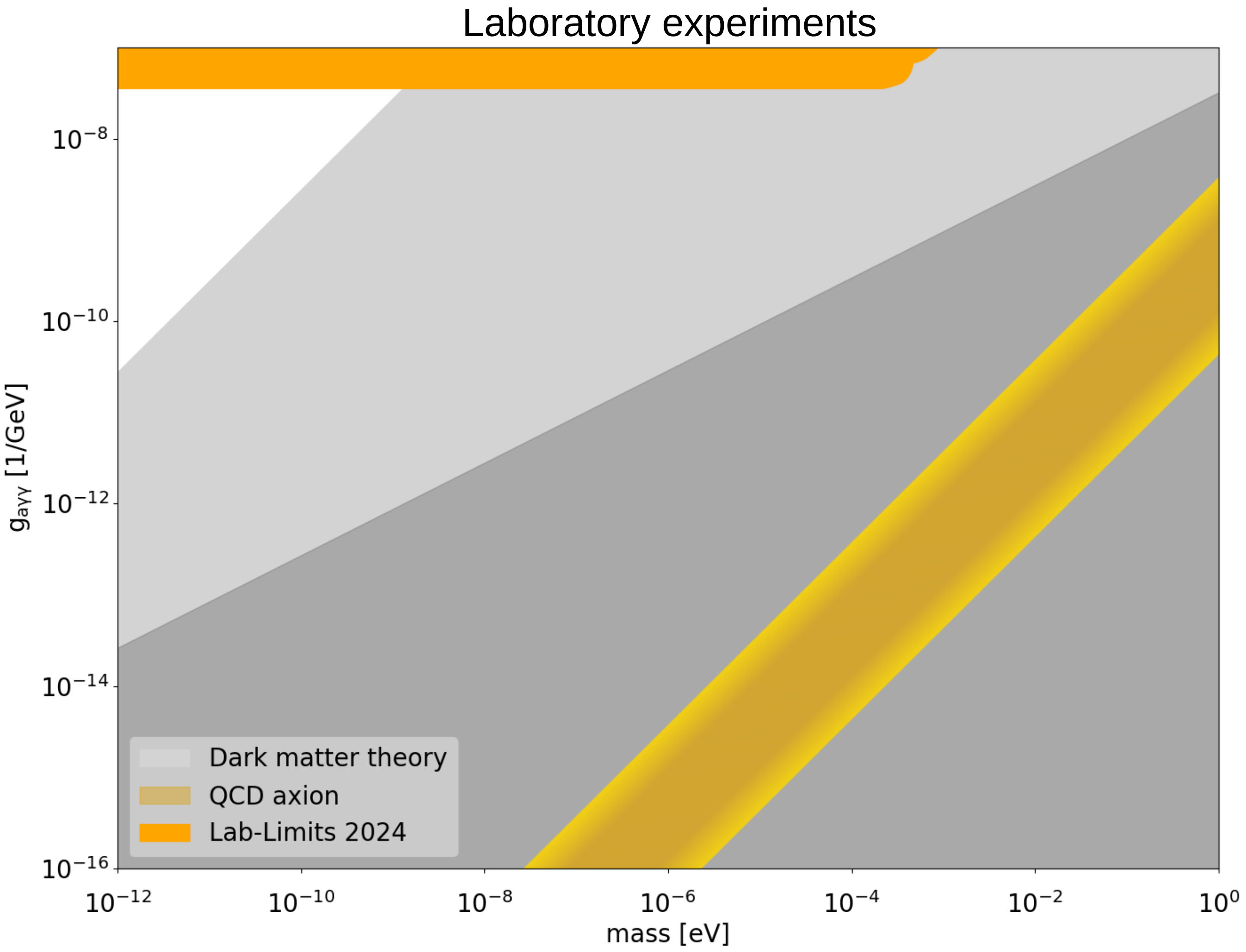
Three different experiments @ DESY:

- ALPS II

- BabyIAXO
- MADMAX



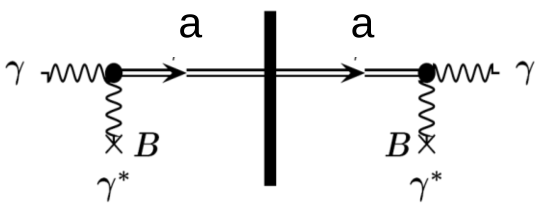
Two new experimental platforms:
- Cryoplatform
- Cryogenic quantum sensing



The DESY strategy

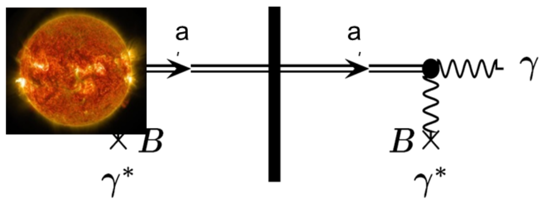
Complementing approaches

1. Probe for axions / ALPs **without additional assumptions**:



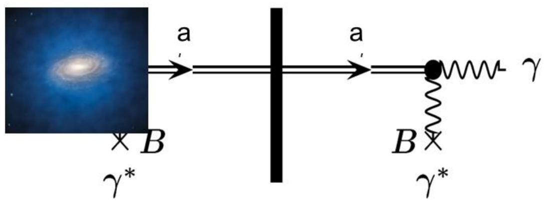
Establish the existence of light bosons beyond the SM, measure $g_{a\gamma\gamma}$.

2. Probe for axions with minimal additional assumptions, **increase the reach**:



Measure the sun‘s axion luminosity (knowing $g_{a\gamma\gamma}$) and narrow done on the BSM theory.

3. Probe for **axions as dark matter constituents** in a mass range not accessible by current experiments:

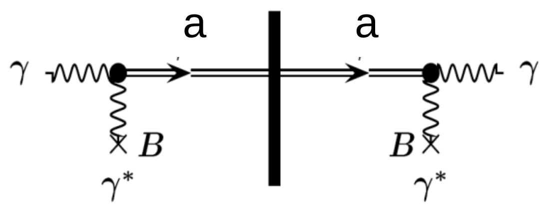


Light bosons make up the dark matter in our galaxy.

The DESY strategy

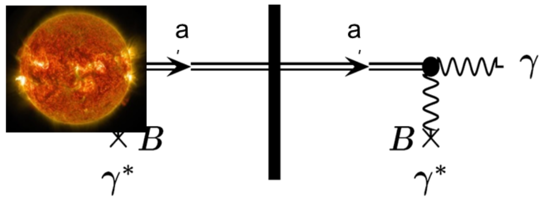
Complementary on-site experiments

1. Probe for axions / ALPs without additional assumptions:

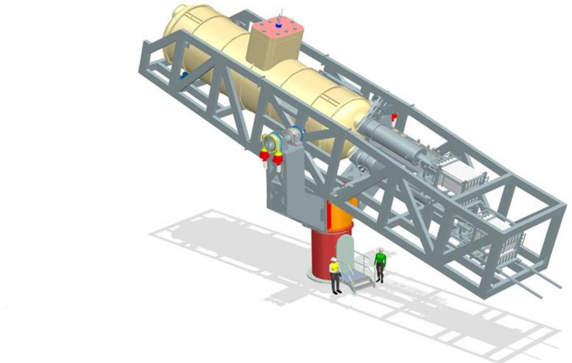


ALPS II
taking data

2. Probe for axions with minimal additional assumptions, increase the reach:



BabyIAXO
(nearly) ready to start construction



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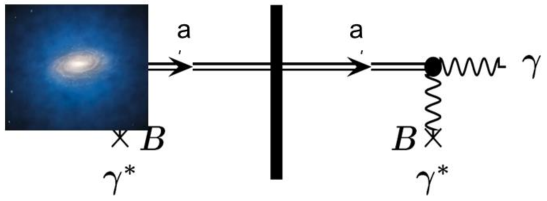
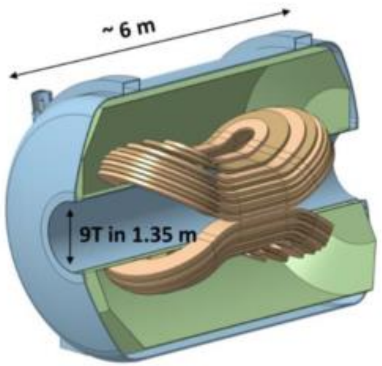
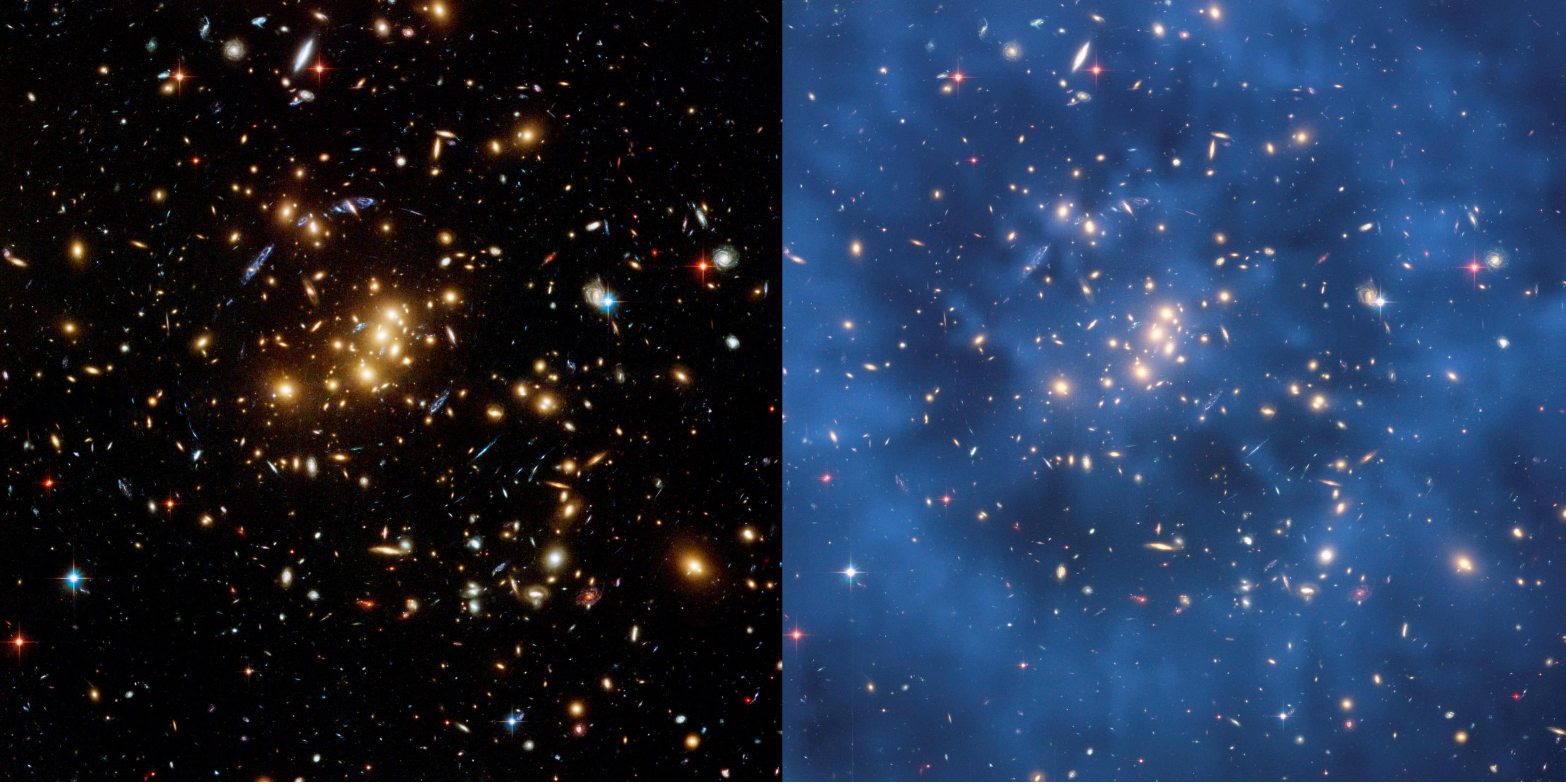


MADMAX
physics results from prototypes





https://www.nasa.gov/sites/default/files/thumbnails/image/galaxy-cluster-cl-0024-17-zwcl-0024-1652.jpg

Summary

<u>Dark matter in the universe</u>

> is very likely to exist (we do not have good alternatives),

> is expected to exist by theories beyond the standard model of particle physics.

<u>Dark matter in the universe</u>

> could by anything from black holes to ultralight bosons,

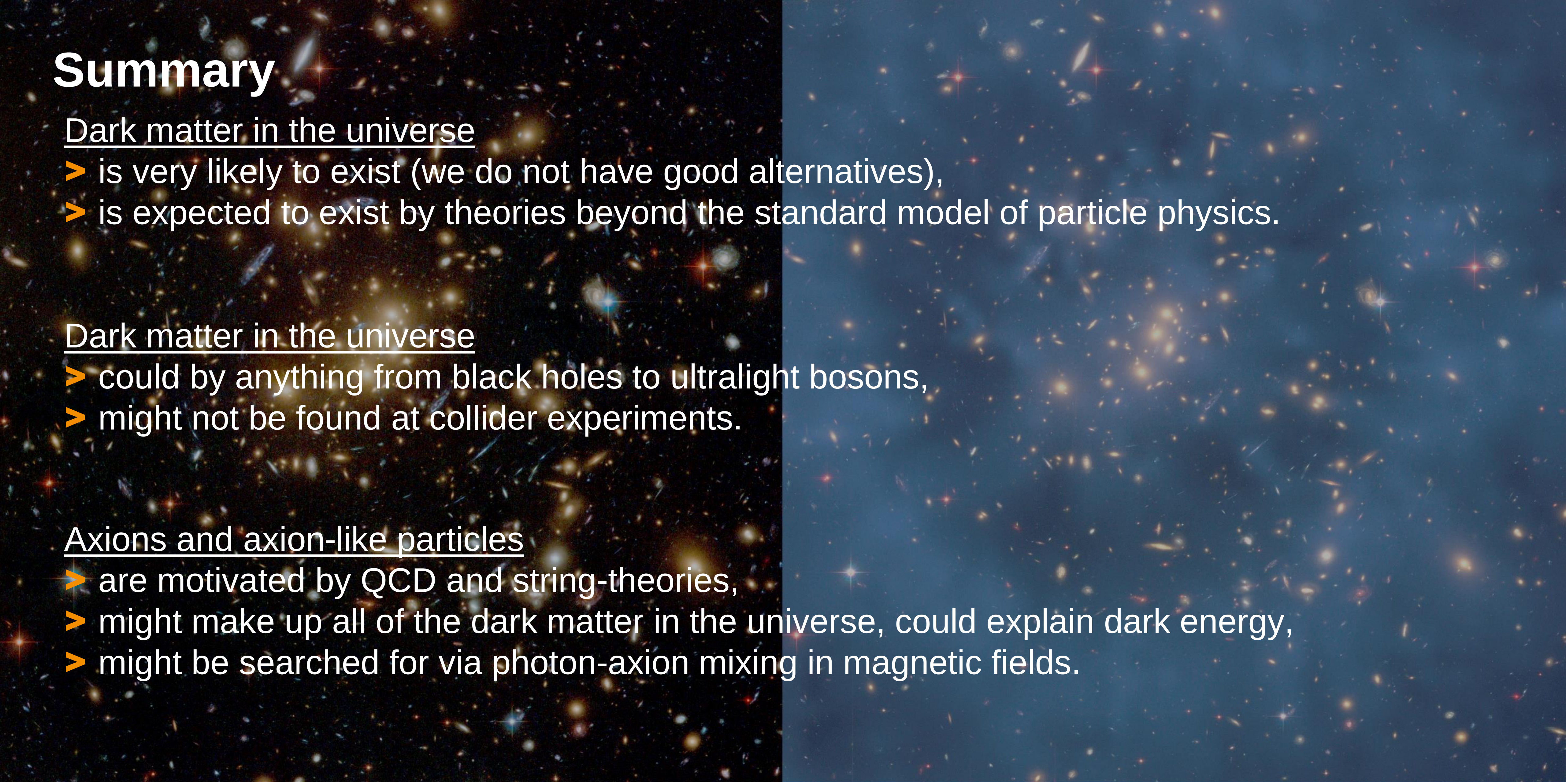
> might not be found at collider experiments.

<u>Axions and axion-like particles</u>

> are motivated by QCD and string-theories,

> might make up all of the dark matter in the universe, could explain dark energy,

> might be searched for via photon-axion mixing in magnetic fields.



https://www.nasa.gov/sites/default/files/thumbnails/image/galaxy-cluster-cl-0024-17-zwcl-0024-1652.jpg