New experimental approaches towards finding dark matter

Part 1: the standard model world is not enough

DESY
Summerstudent Lecture 2022

Axel Lindner
Jose Alejandro Rubiera Gimeno
Christina Schwemmbauer

DESY

https://www.darkmatterday.com/educational-resources-dark-matter-day/

New experimental approaches towards finding dark matter

Part 2: experiments @ DESY in Hamburg

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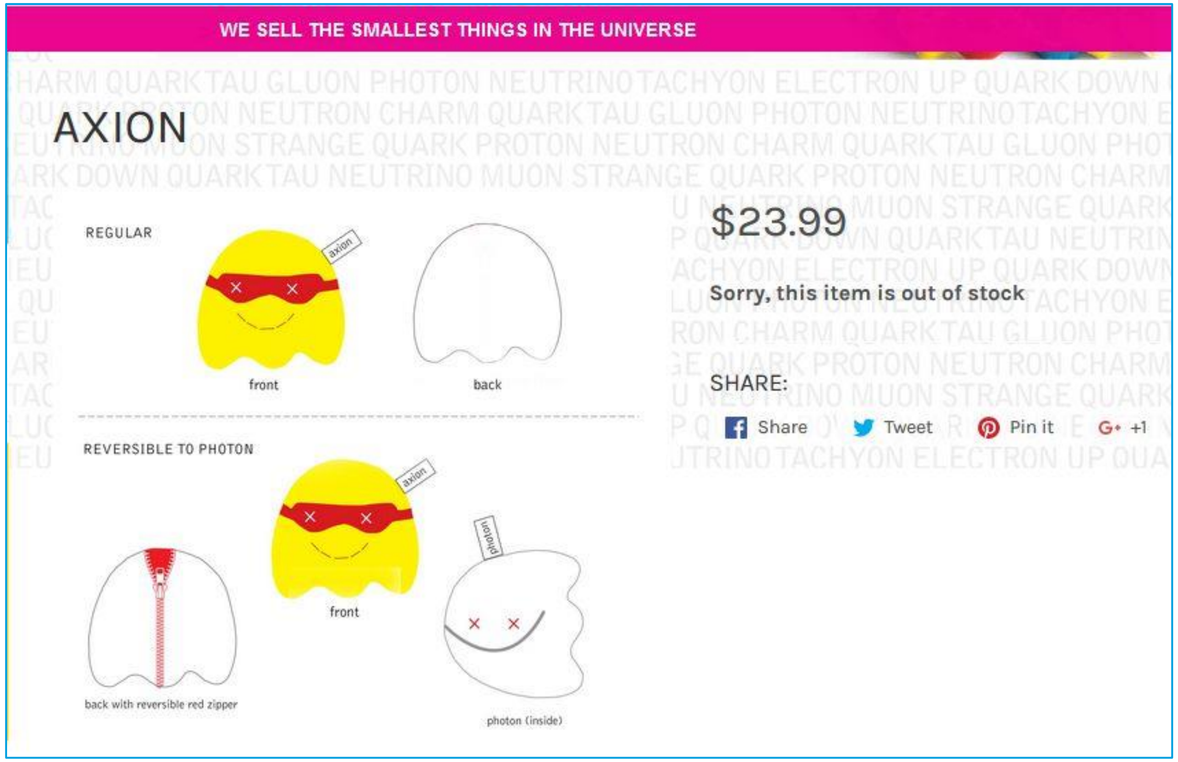


https://www.particlezoo.net

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Outline

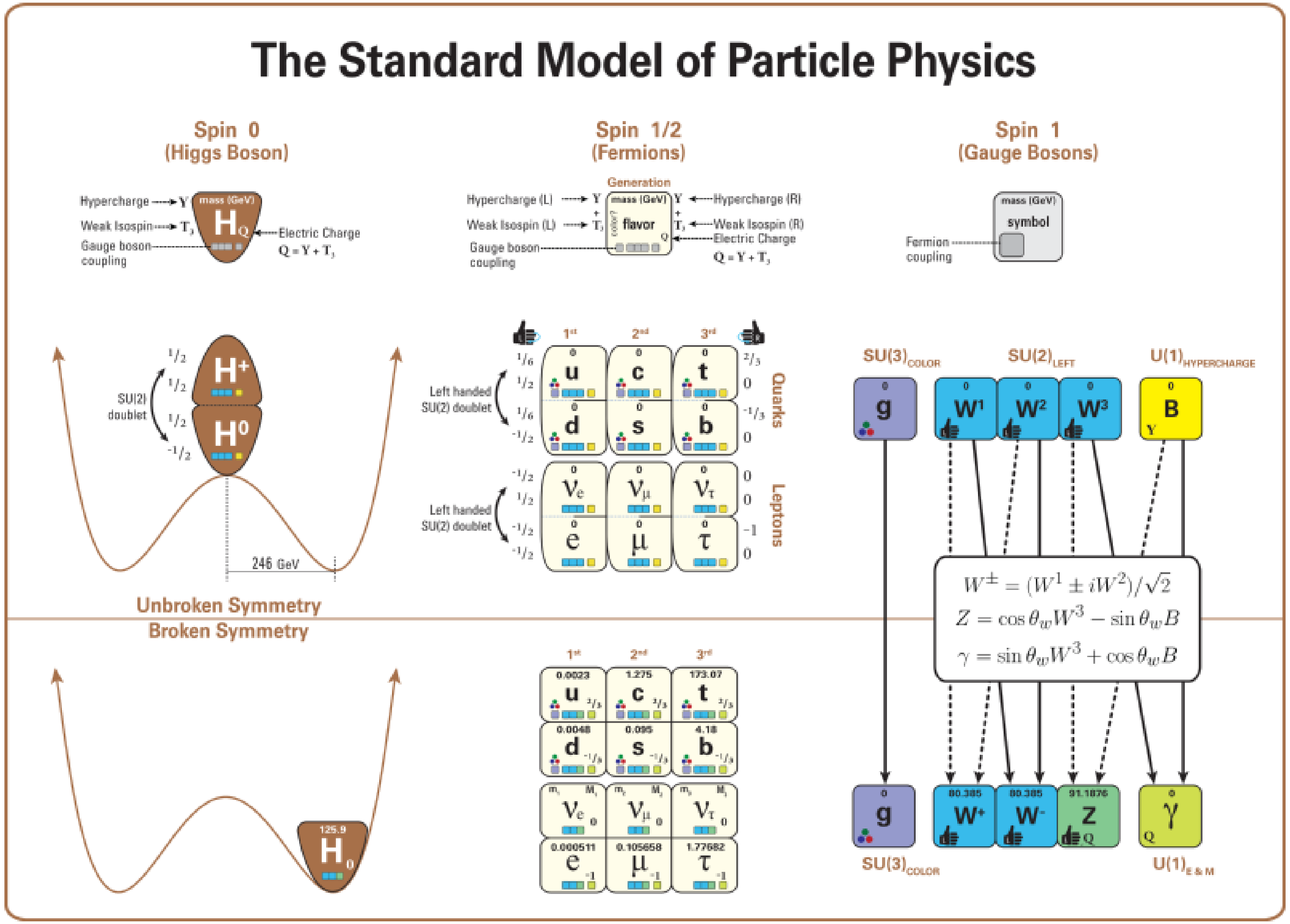
- Our starting point
- Dark matter in the universe
  - Alternatives to dark matter?
  - Dark matter candidates
- HERA, QCD and the axion
- Astrophysical motivations for axions and ALPs
- Summary

Outline

- Our starting point — Axel
- Dark matter in the universe — Christina
  - Alternatives to dark matter? — Axel
  - Dark matter candidates — Axel
- HERA, QCD and the axion — Axel
- Astrophysical motivations for axions and ALPs — Jose
- Summary — Axel

What do we know (I)

A very brief status report

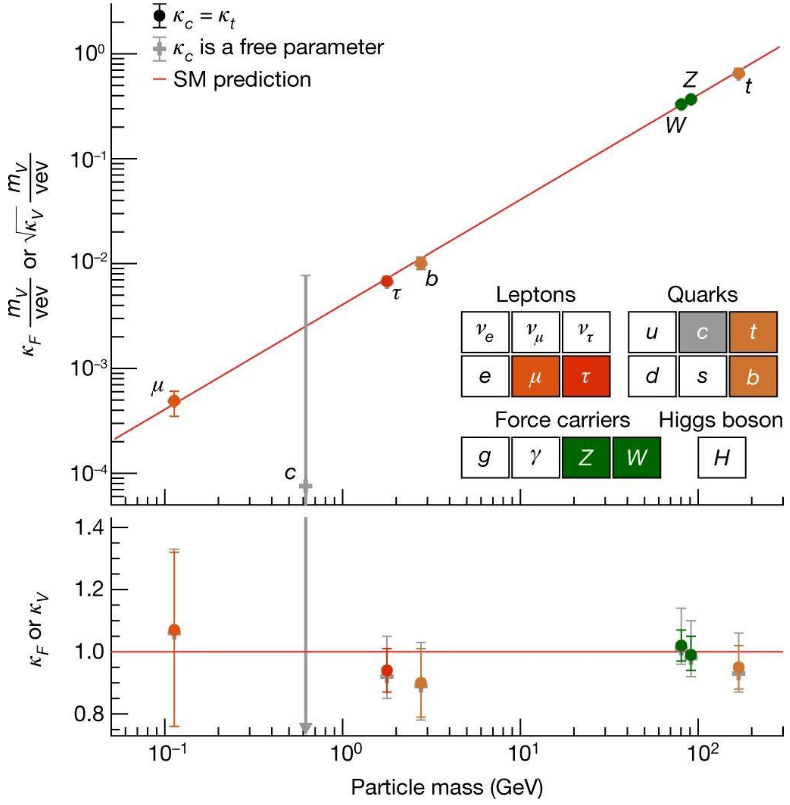


https://en.wikipedia.org/wiki/Standard_Model

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

apart from non-zero neutrino masses.

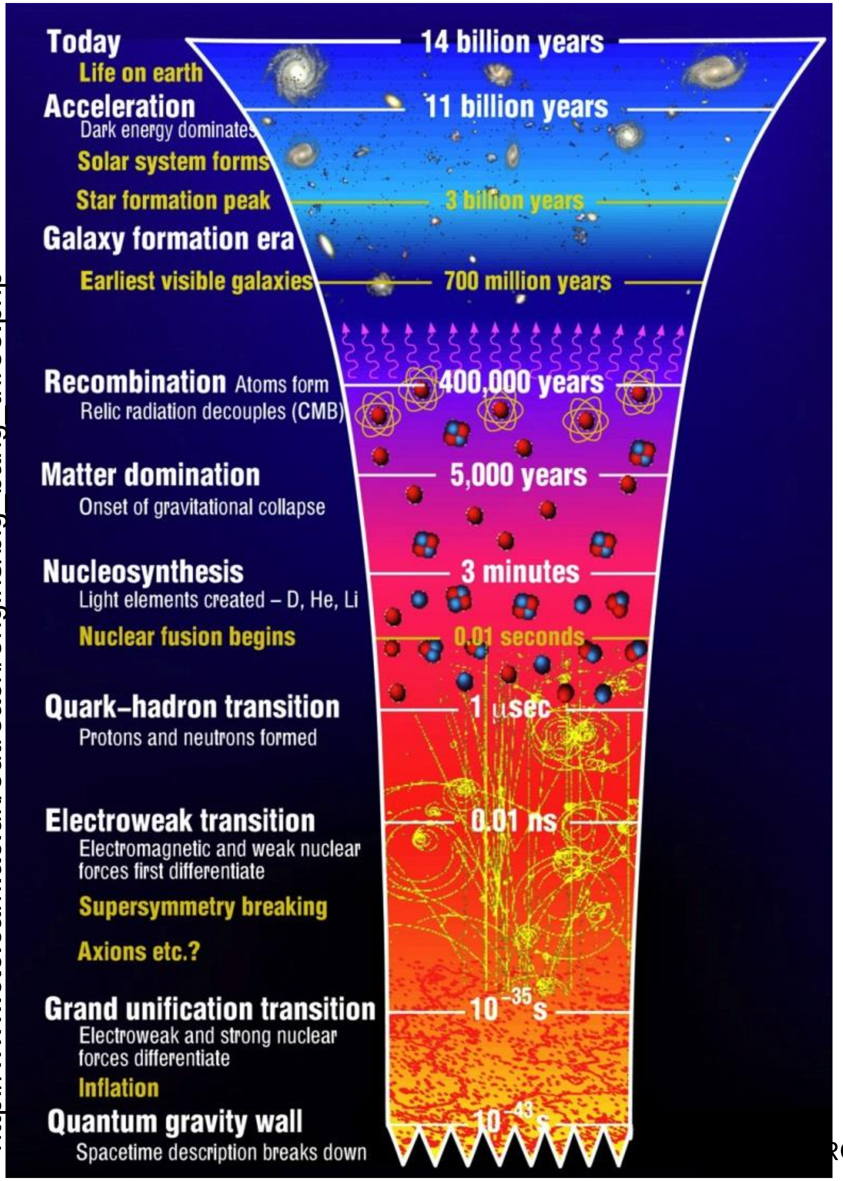
Example: properties of the Higgs.



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

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

400,000 years after BB

3 minutes after BB

0.000001 seconds after BB

0.0000000001 seconds after BB

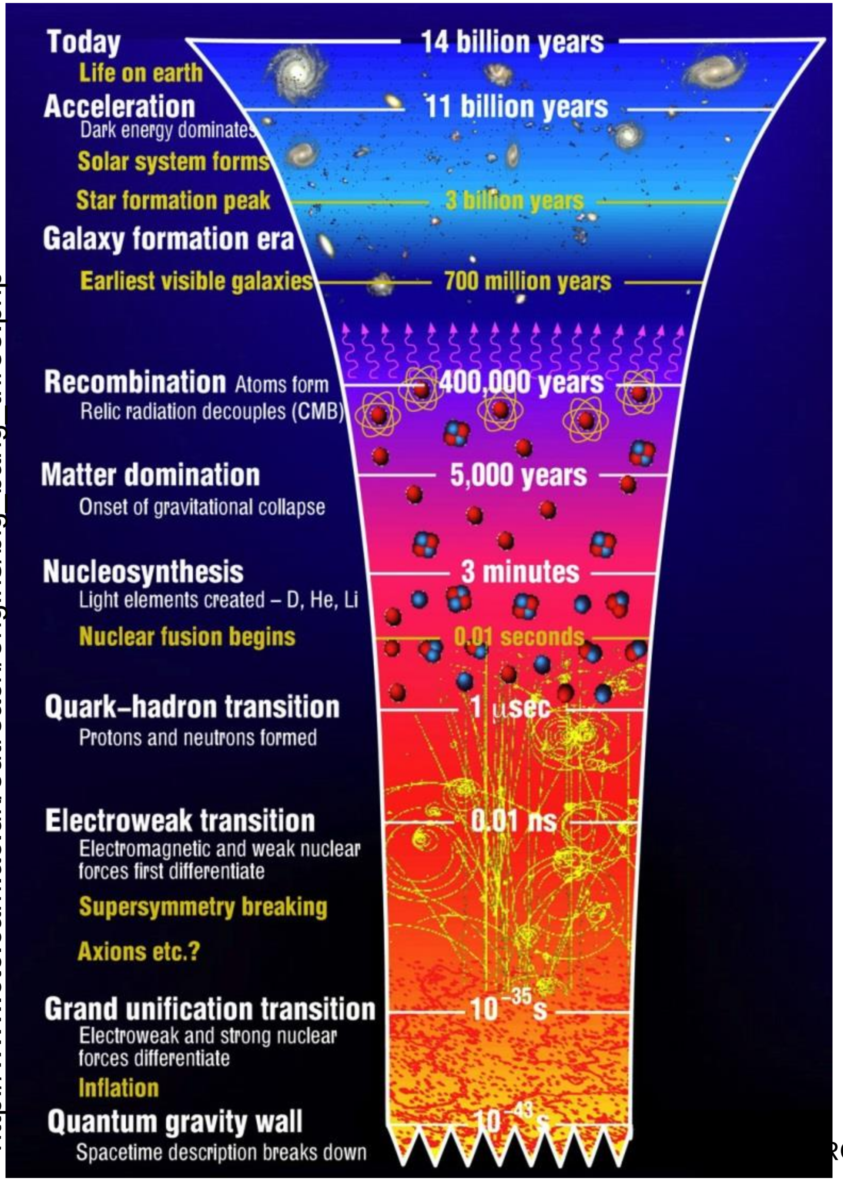
Astronomy

BB in the laboratory:

Elementary particle physics

From quarks to the cosmos

Particle physics and cosmology



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

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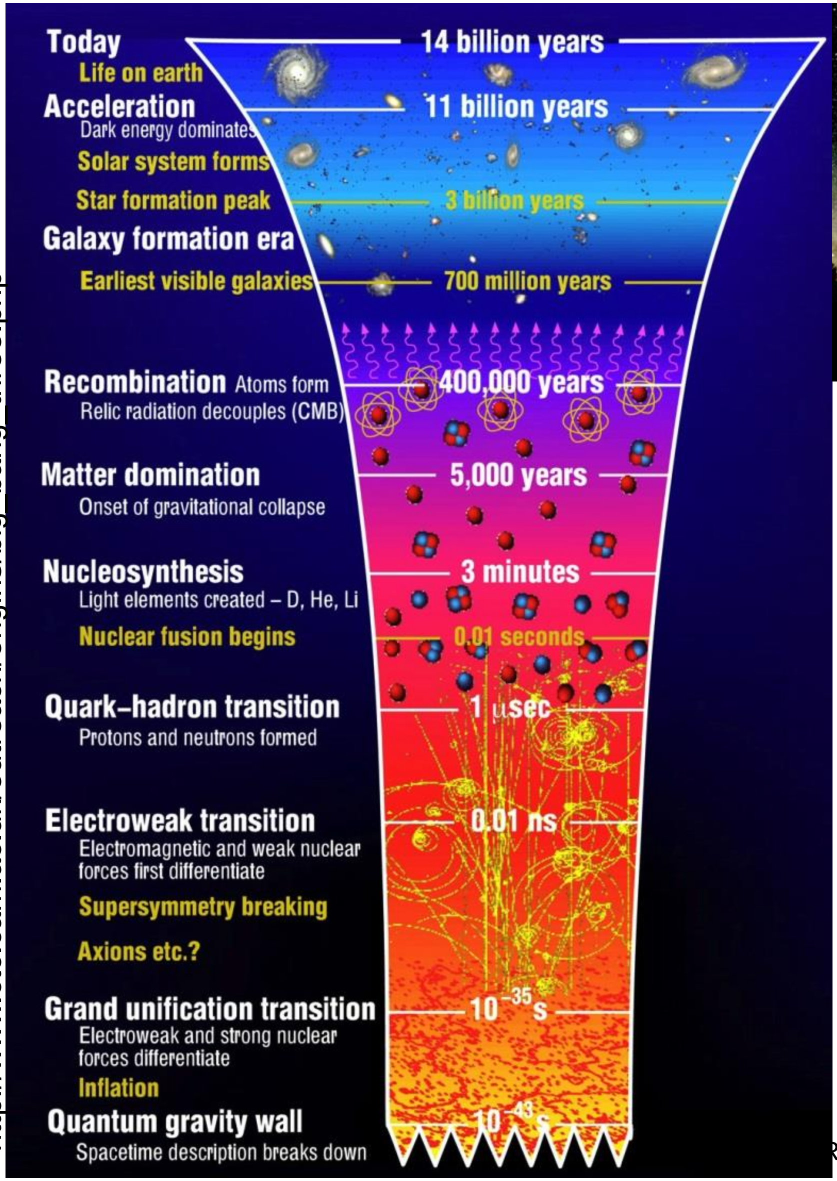
0.00000000001 seconds after BB

Gravitational waves?

What do we know (II)

A very brief status report



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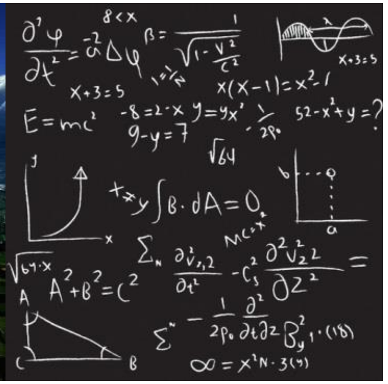

Astronomy, particle physics theory

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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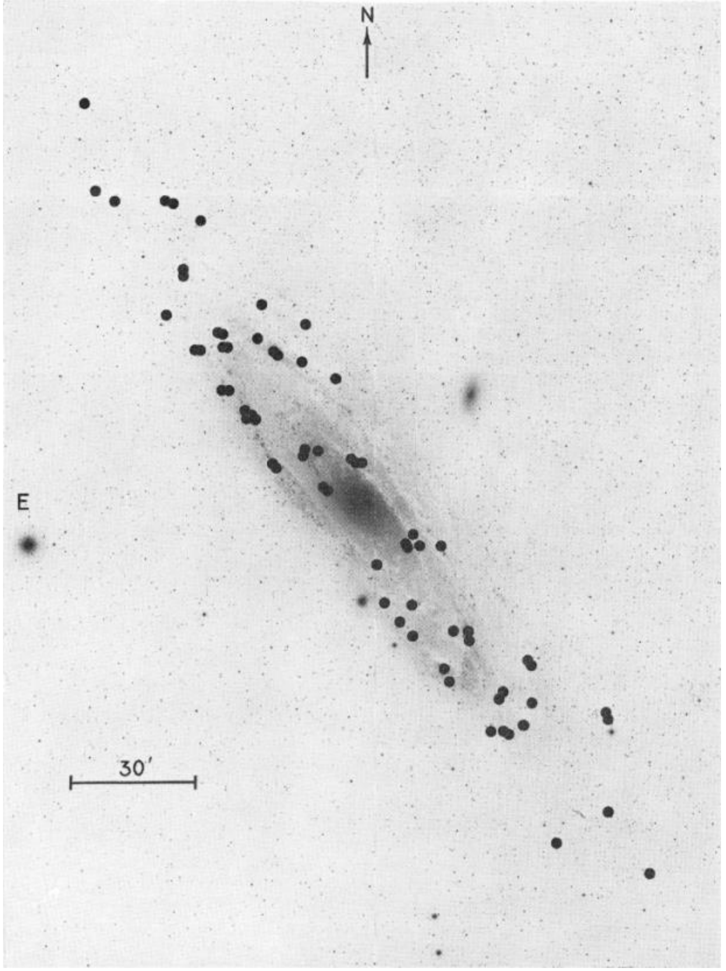
Structure and dynamics in the universe

Galaxies

Distant galaxies allow to map their mass distribution by measuring the rotation velocity of stars as a function of their distance to the galaxies' centers.

Andromeda (M31): things get weird.
Vera Rubin, 1972

Birthday on 23rd July!



Rubin & Ford 1970, ApJ 159, 379

Structure and dynamics in the universe

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Distance: 2.5 Million LY

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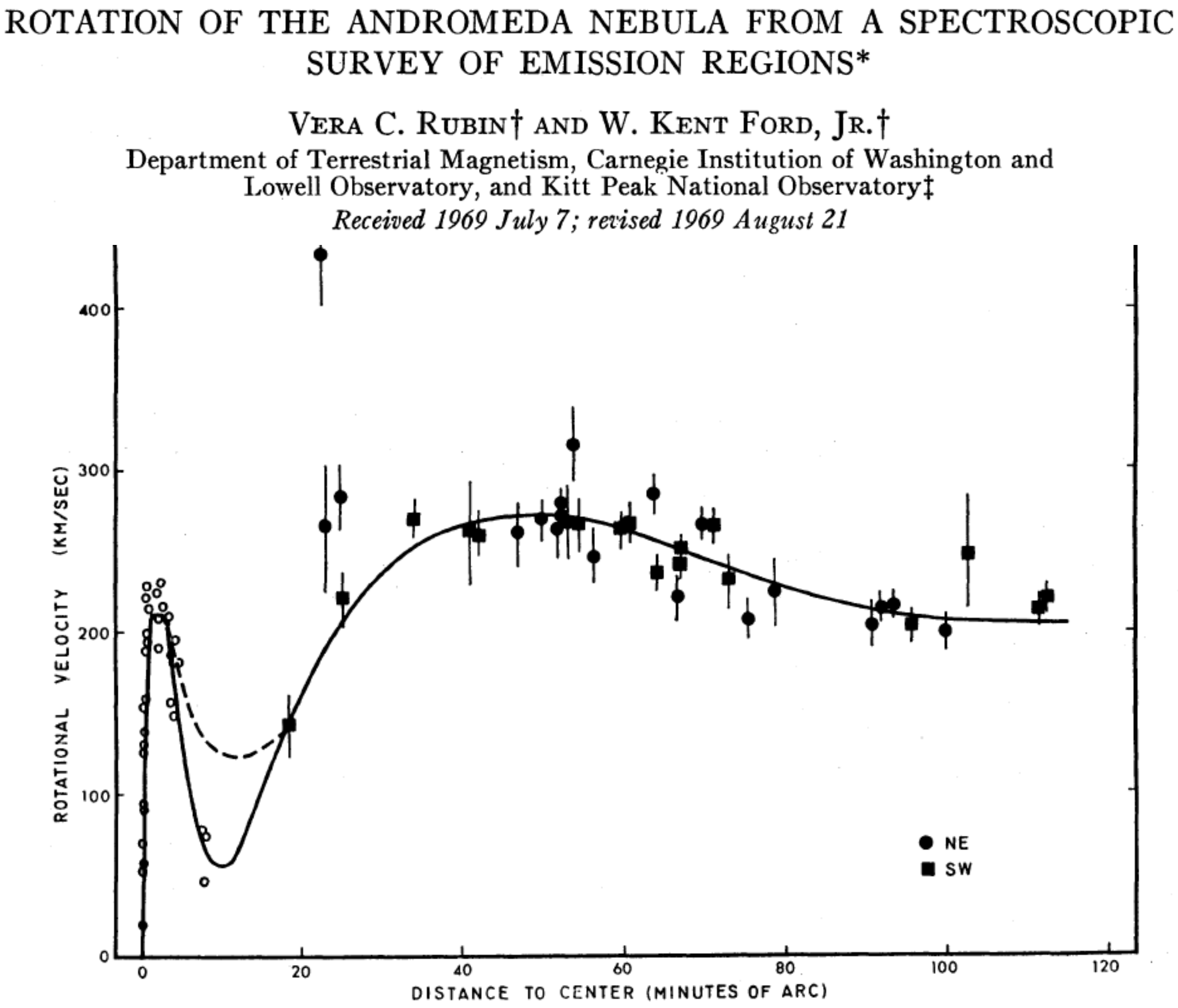


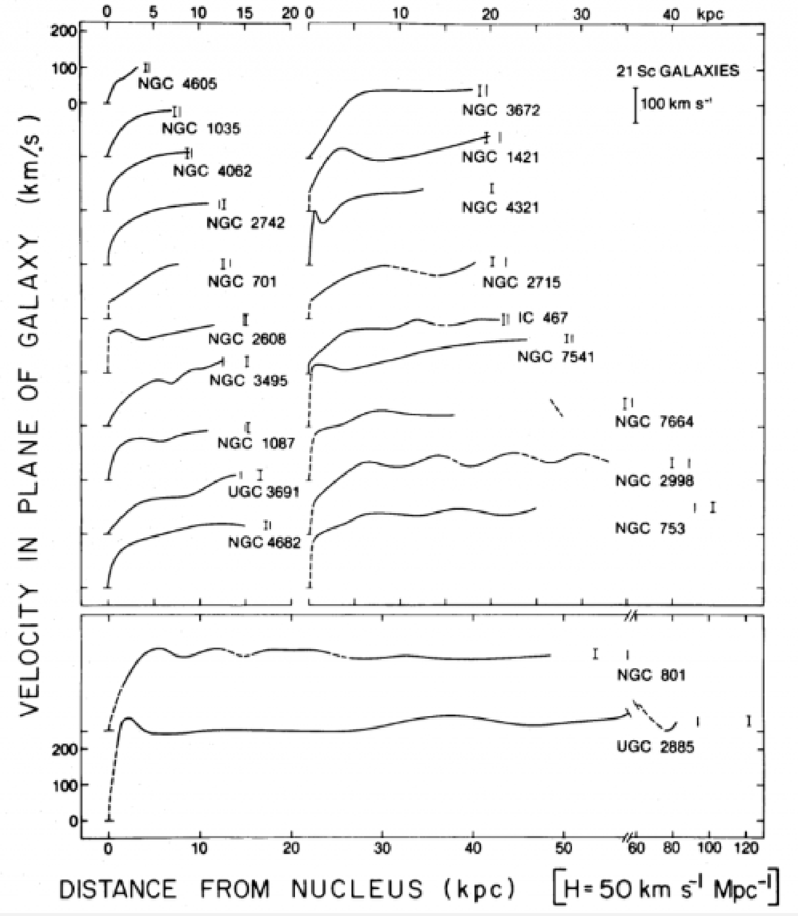
Vera Rubin

The astronomer who made the discovery

Vera Rubin at
Carnegie Institution
(Washington)

Structures and dynamics in the universe

Expectation vs reality



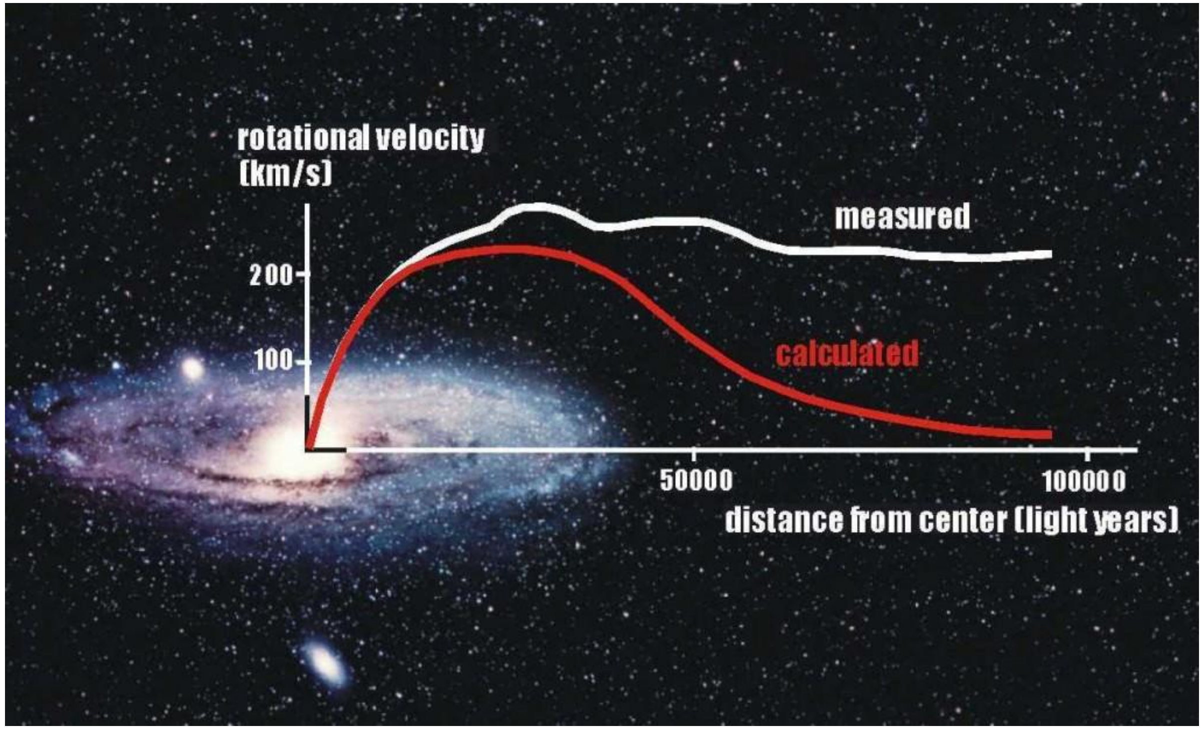
Assumption: $F_R = 0$

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

Structures and dynamics in the universe

Expectation vs reality

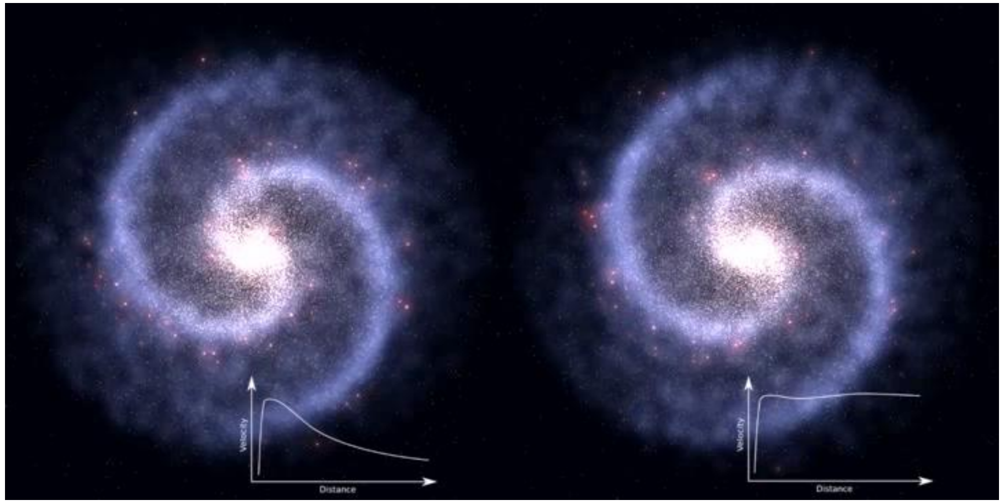


https://cdms.phy.queensu.ca/Public_Docs/DM_Intro.html

Most rotation curves approximately flat!

Velocities remain high for high *R*

- Mass must increase for high *R*
- *„Is the luminous matter only a minor component of the total galaxy mass?“*

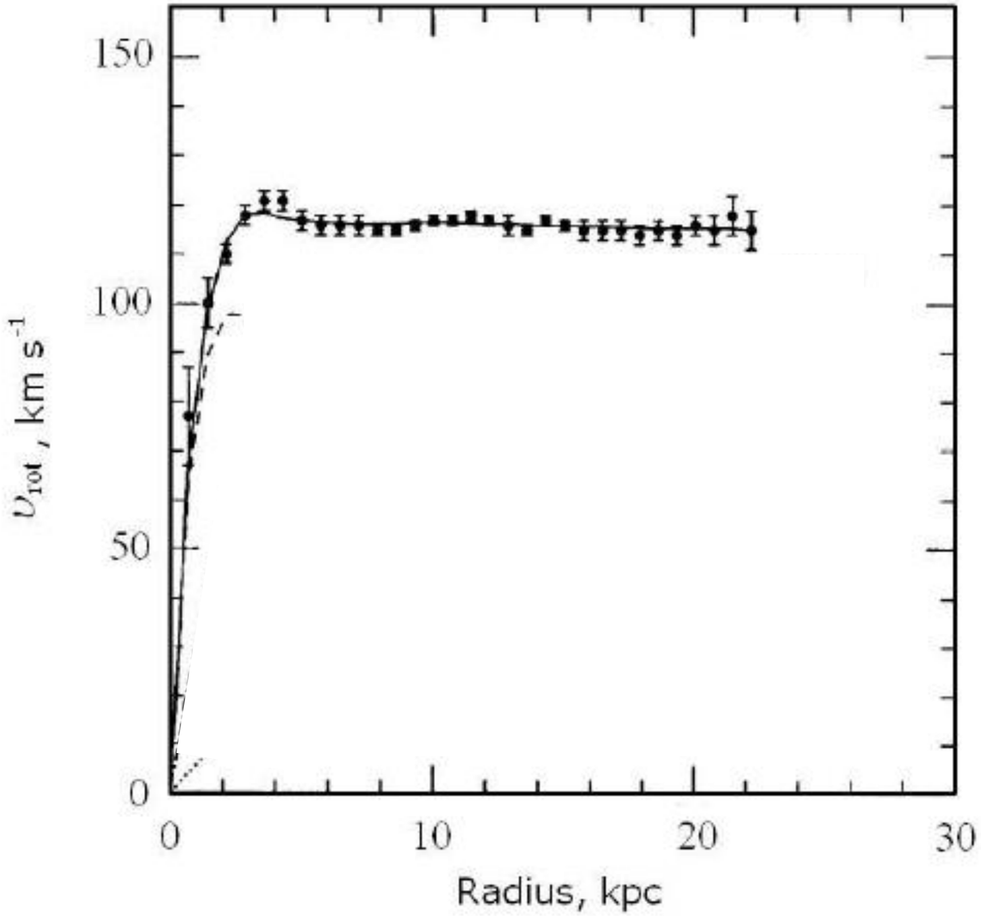


http://beltoforion.de/article.php?a=spiral_galaxy_renderer

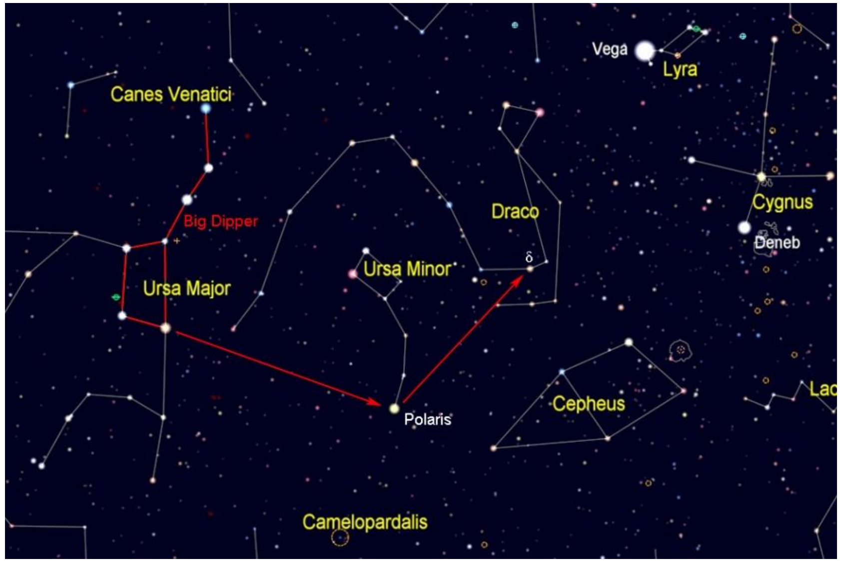
Rotational velocities

Expectation vs reality

Young, Bing-Lin (2017): A survey of dark matter and related topics in cosmology.



Data and theoretical predictions for galaxy NGC 6503 (17 Million LY away)



Rotational velocities

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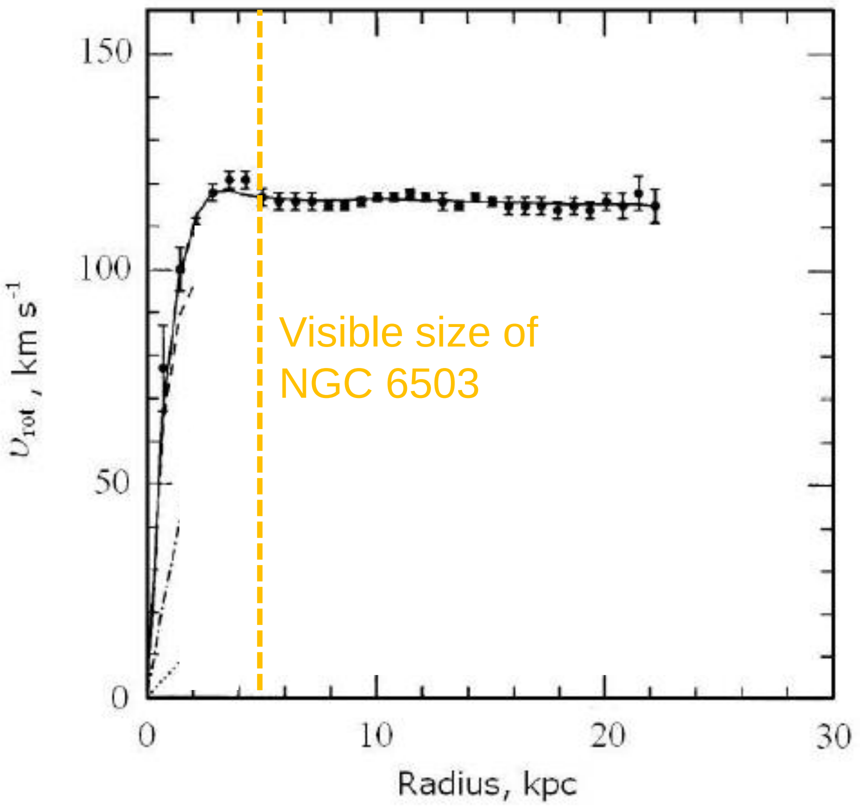

Rotational velocities

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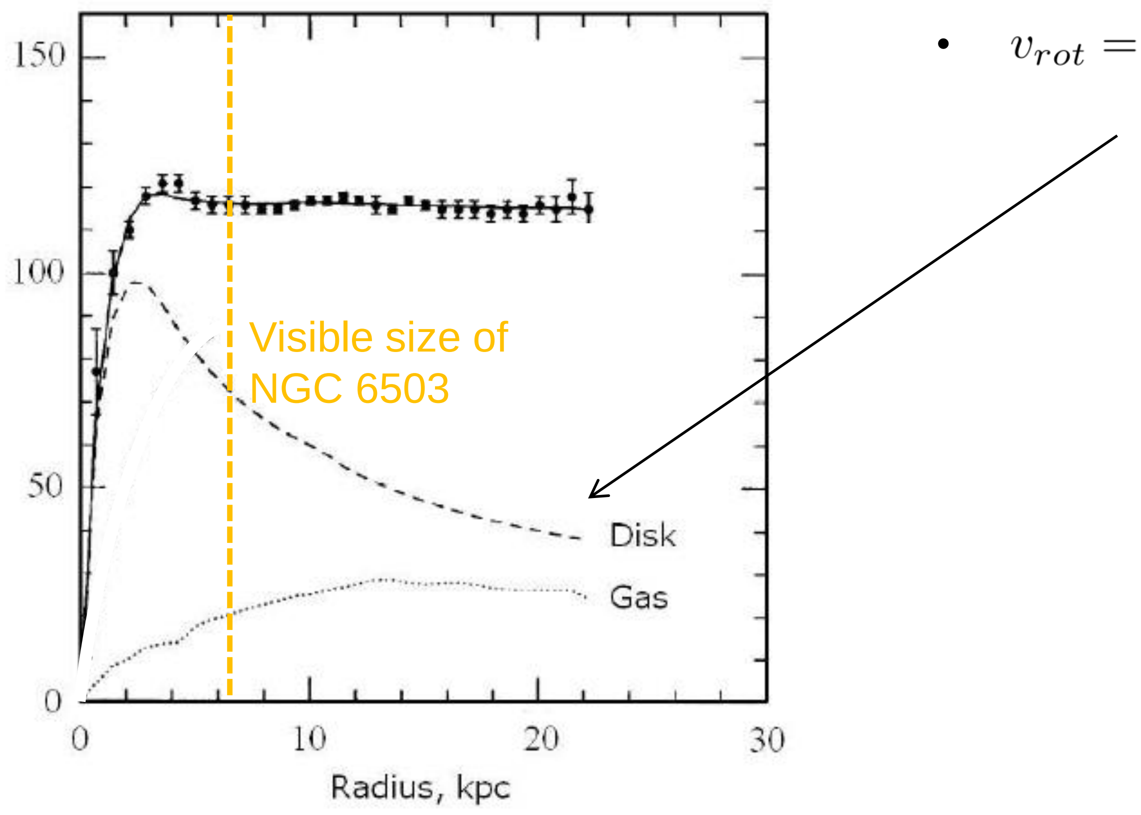

- $v_{rot} = \sqrt{\frac{GM}{r}}$ decreases with $\sim \sqrt{\frac{1}{r}}$

Rotational velocities

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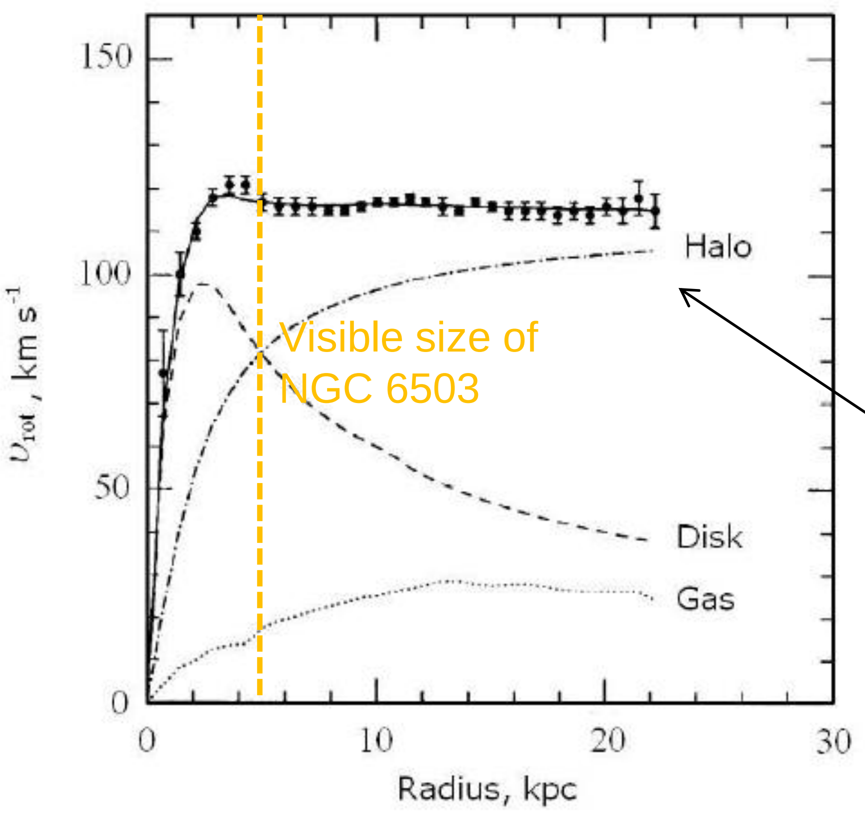


- $v_{rot} = \sqrt{\frac{GM}{r}}$ decreases with $\sim \sqrt{\frac{1}{r}}$
- Observation:

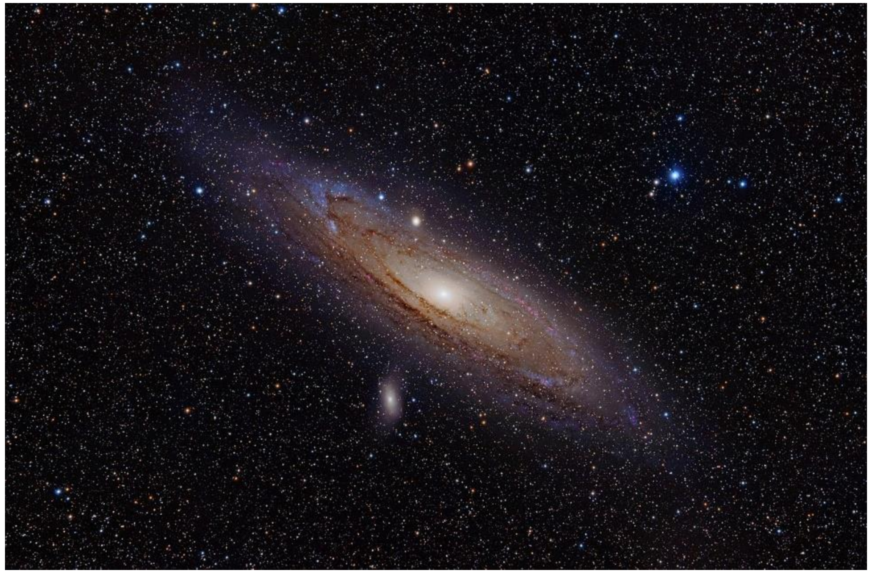
$$v_{\text{obs}} = \sqrt{\frac{GM(r)}{r}} = \text{const}$$

$$\Rightarrow \boxed{M(r) = \text{const} \cdot r}$$

- There must be a halo of invisible mass!

Structures and dynamics in the universe

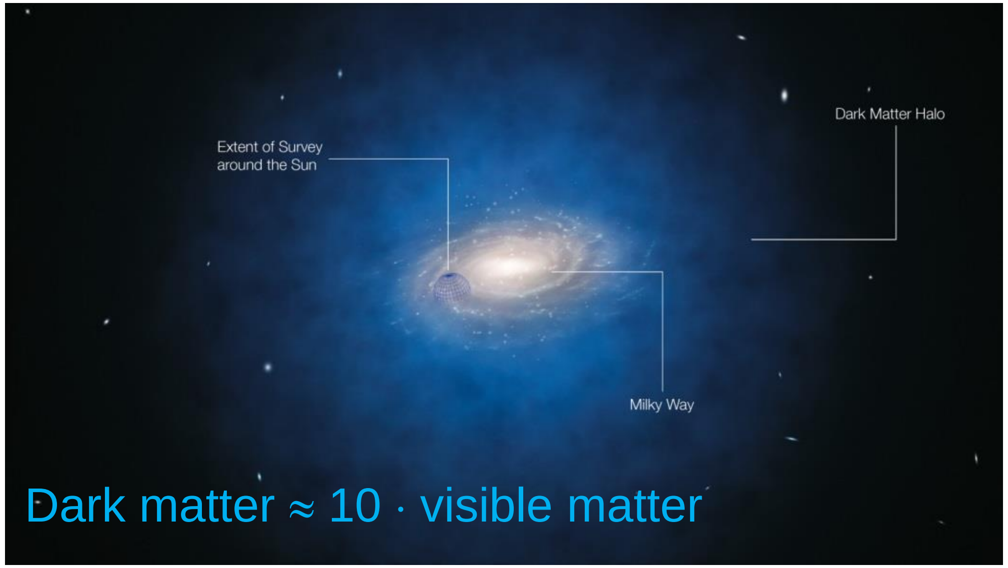
Missing mass?



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	$\sim 10^{7}$

→ There's **a lot** of mass missing!



Structures and dynamics in the universe

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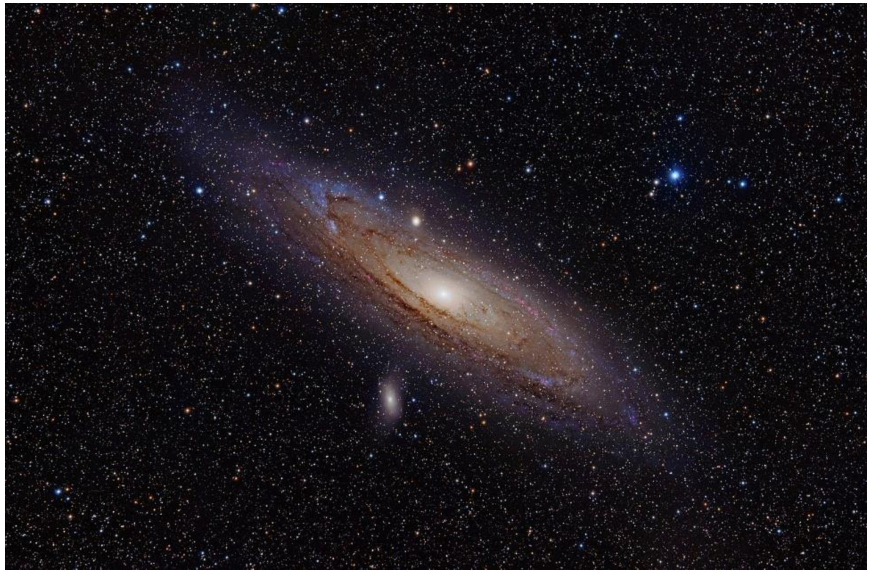

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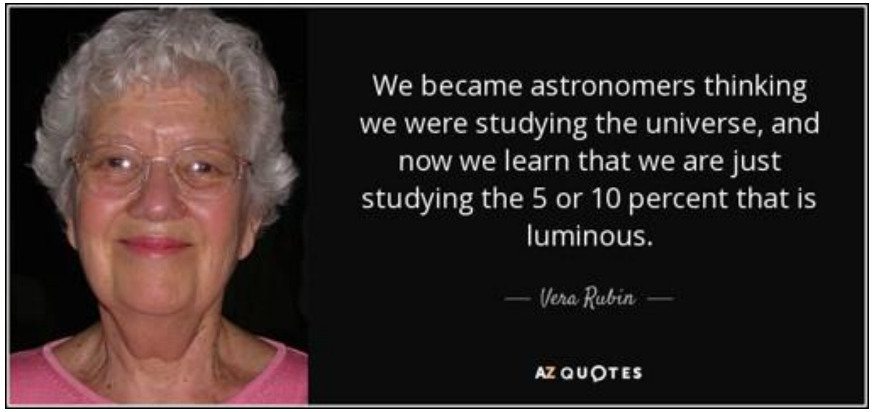

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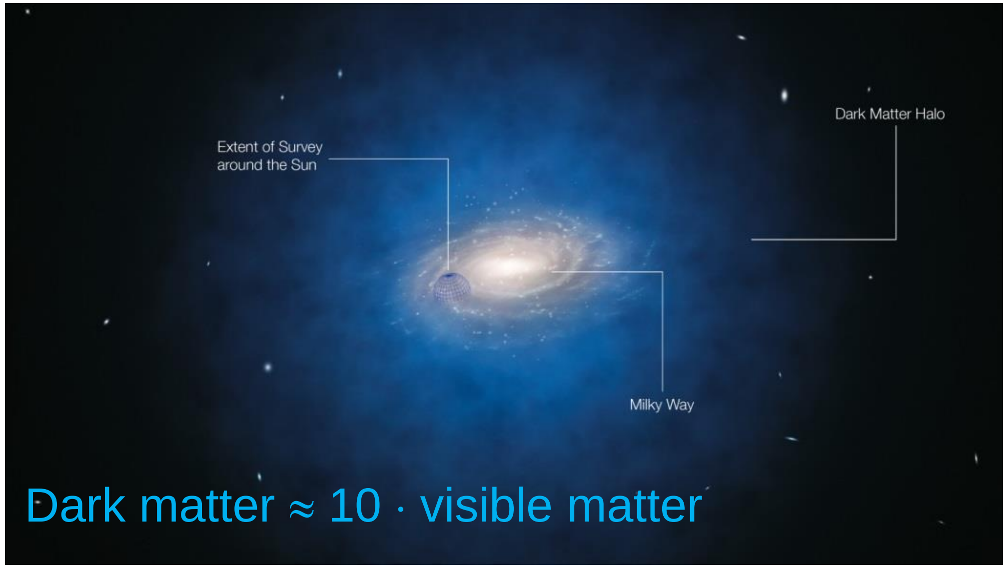
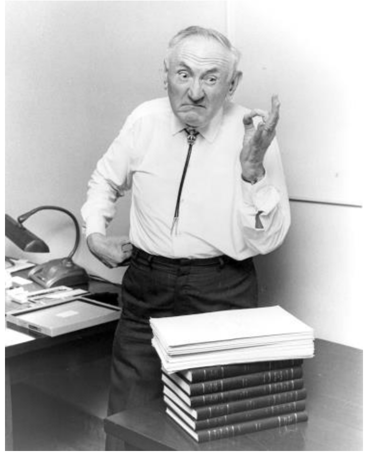


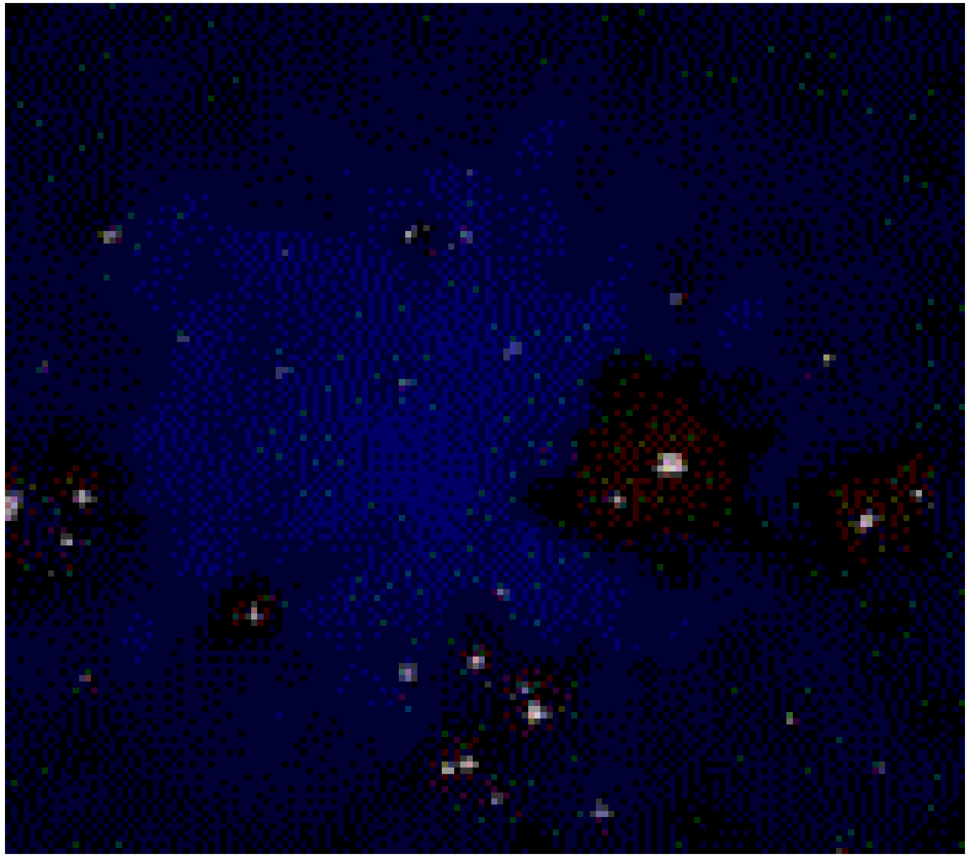
Structures and dynamics in the universe
Clusters

- 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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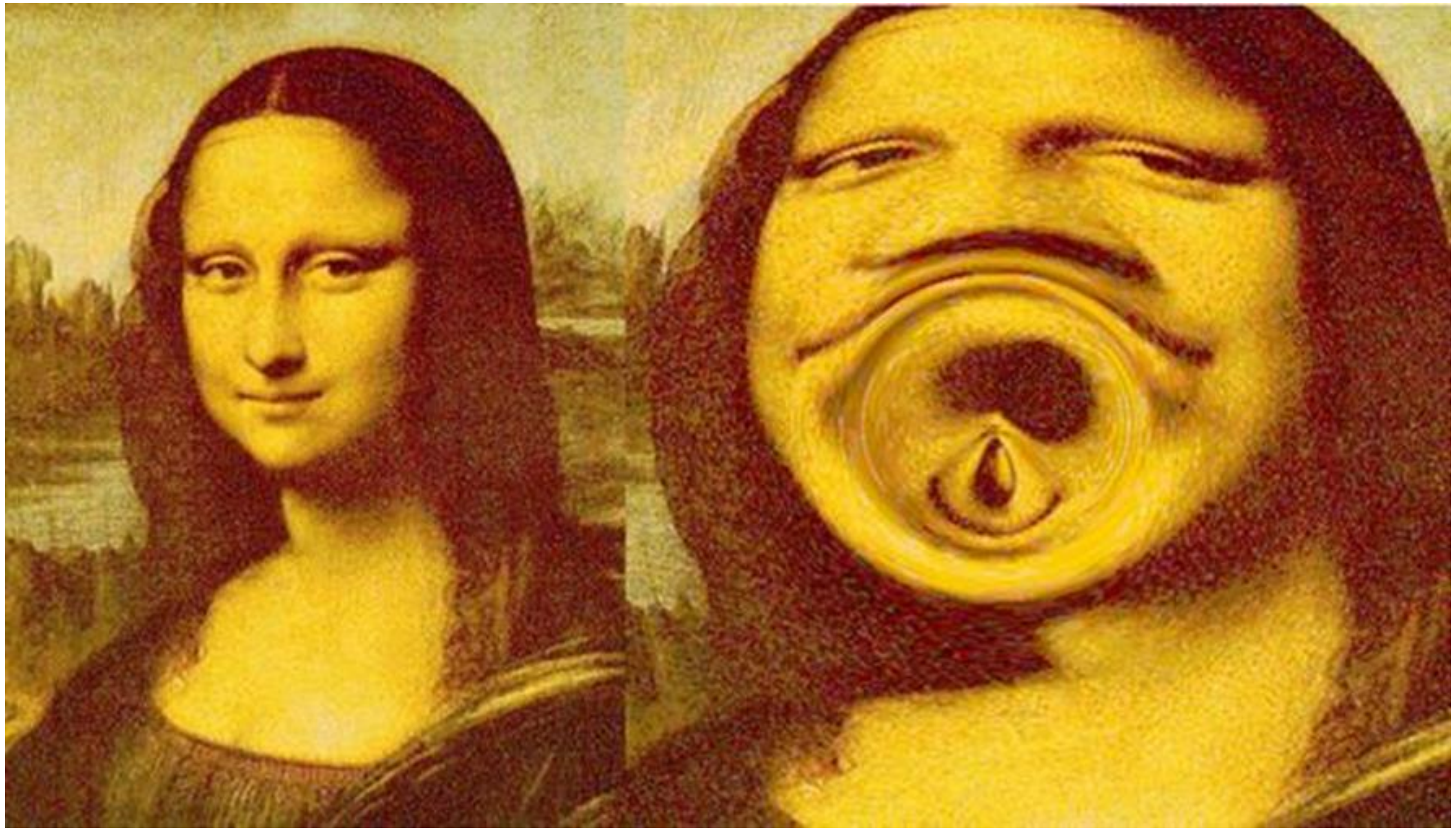
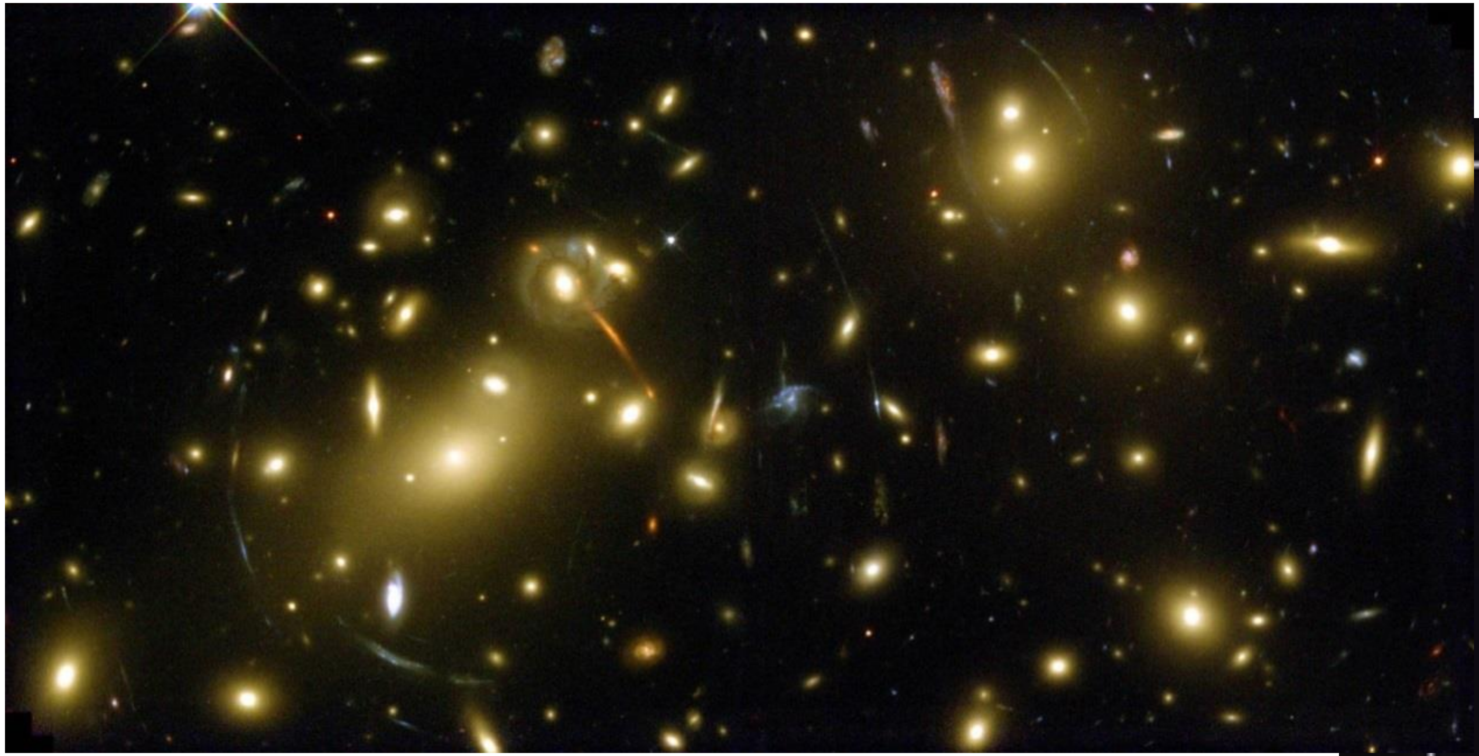


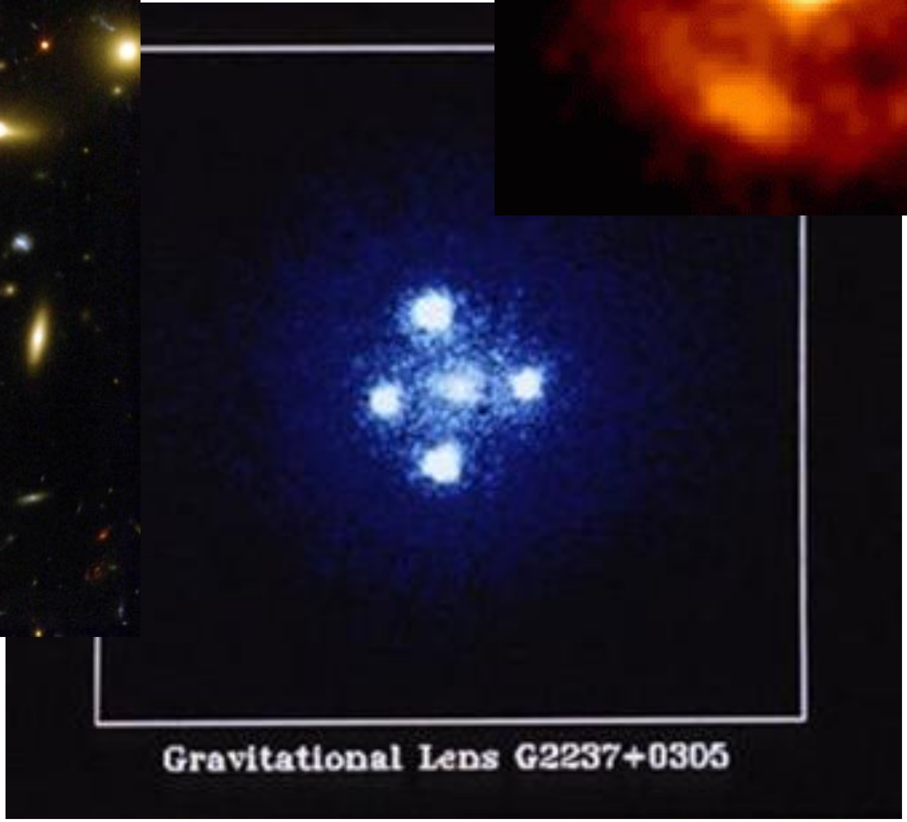
http://astronomyonline.org/Cosmology/GravitationalLensing.asp

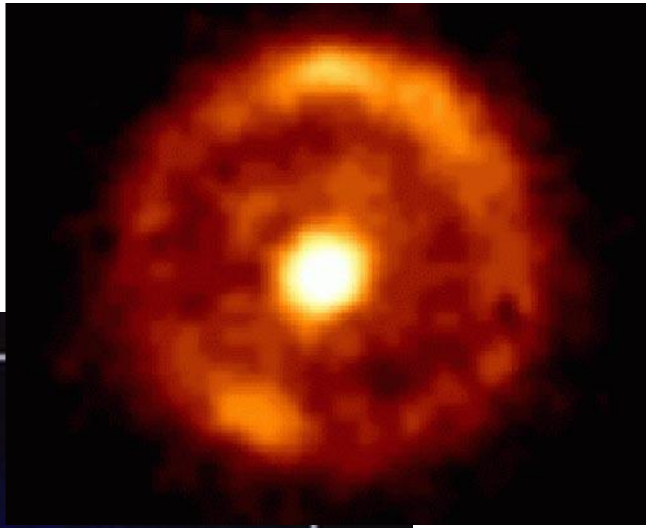
Gravitational lensing

More dark matter evidence

Gravitational lensing is real:



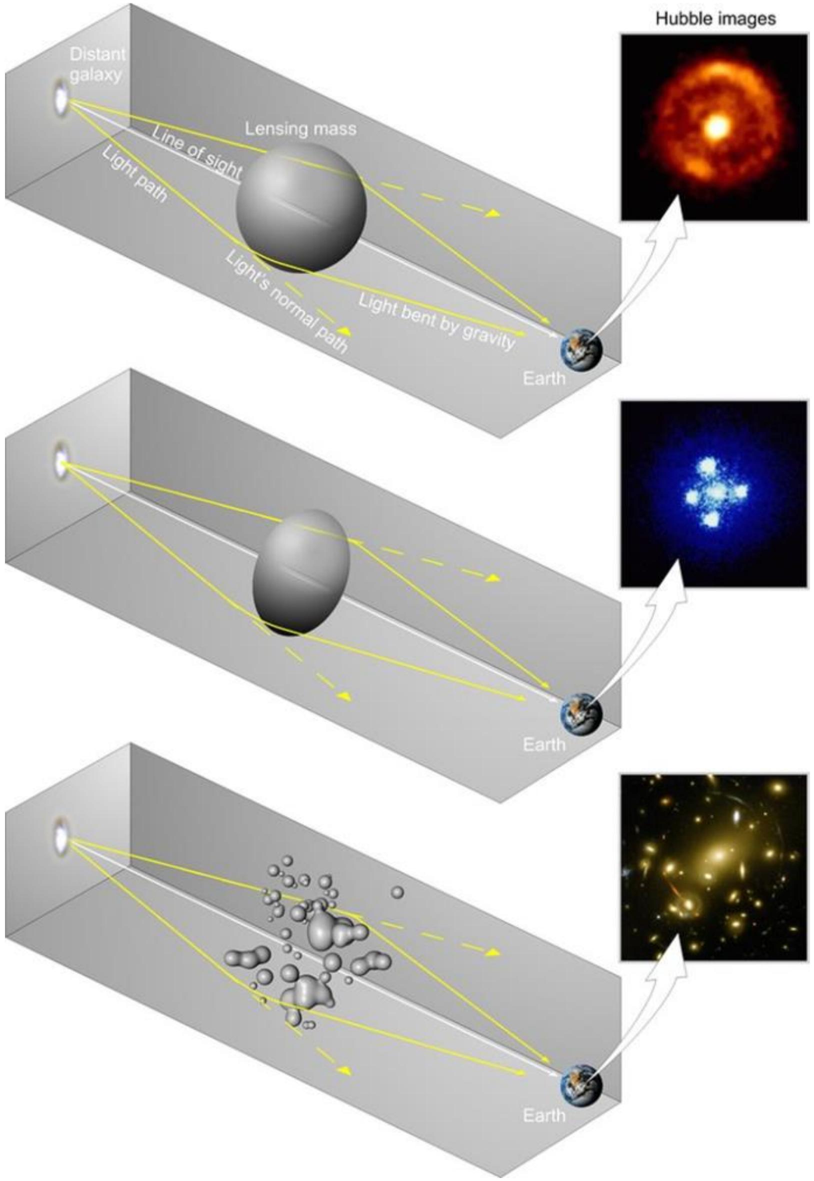




Gravitational lensing

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

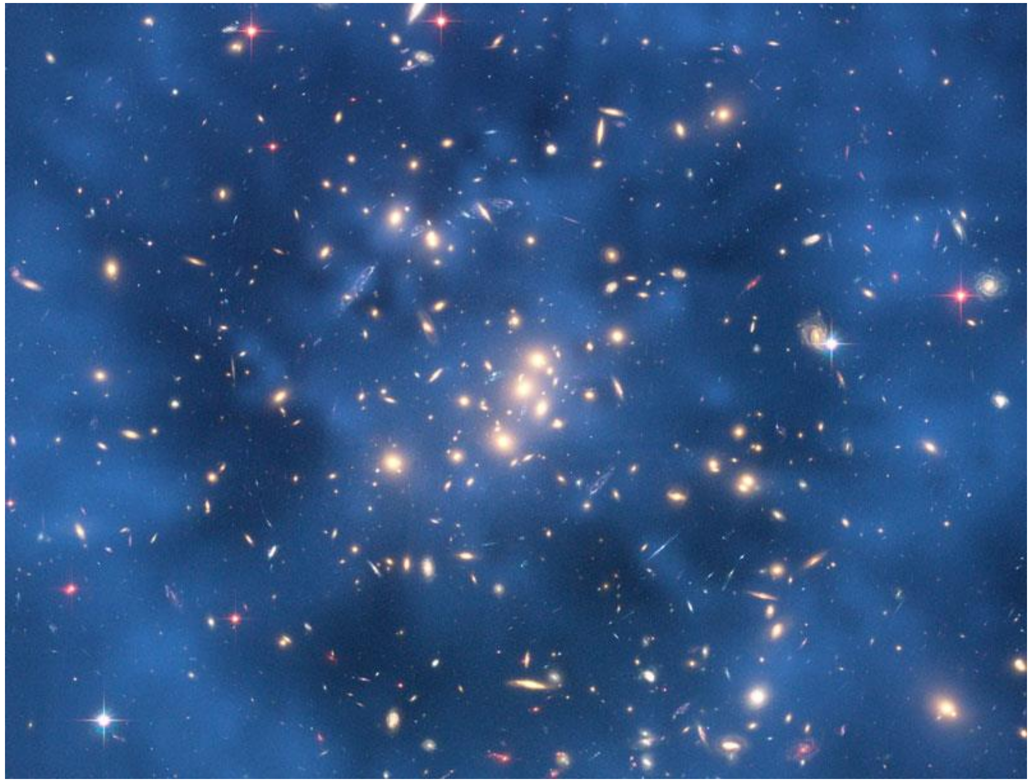


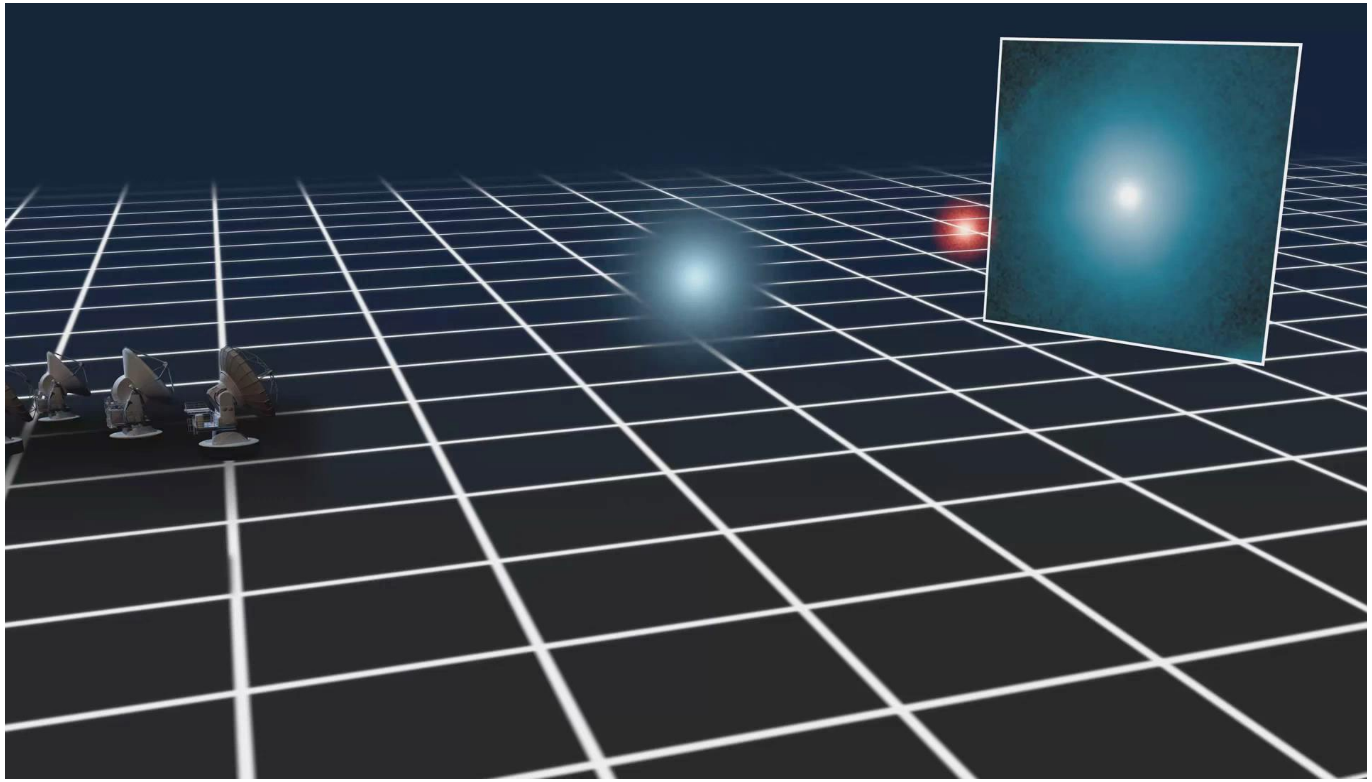
http://spacetelescope.org/images/heic0404b/

Gravitational lensing

More dark matter evidence

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



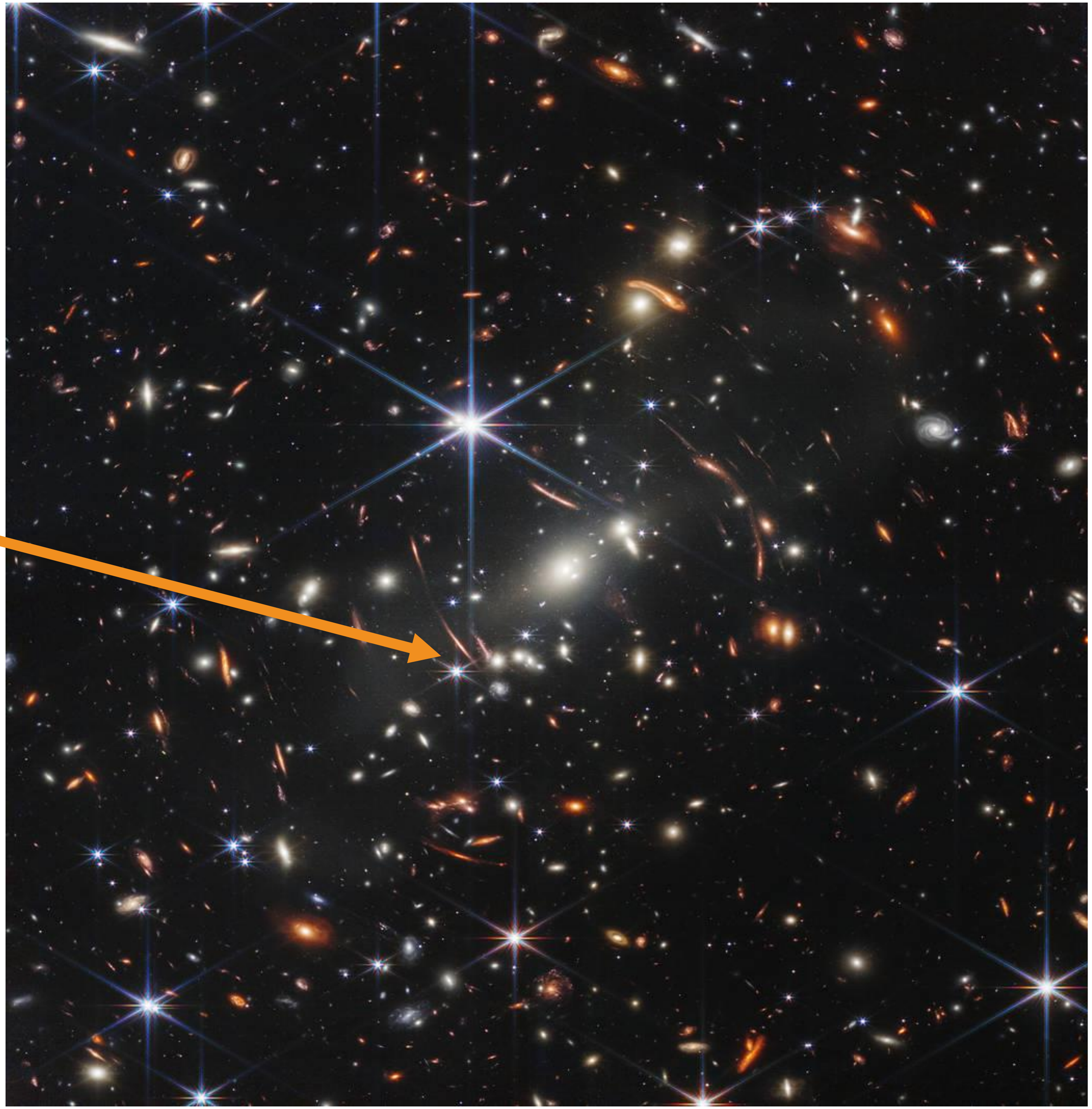


Dark matter $\approx$ 30 · visible matter!

Gravitational lensing

More dark matter evidence

Also visible in the
brand new James Webb Telescope
picture of the SMACS 0723 Galaxy Cluster

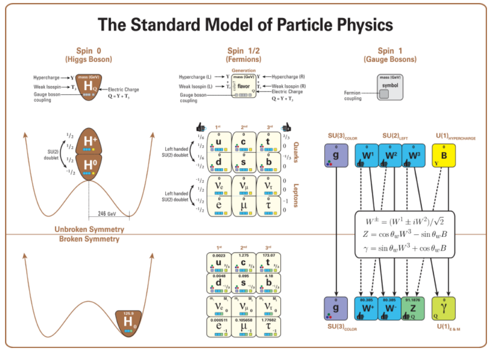


https://www.nasa.gov/image-feature/goddard/2022/nasa-s-webb-delivers-deepest-infrared-image-of-universe-yet

What do we know

Composition of the universe

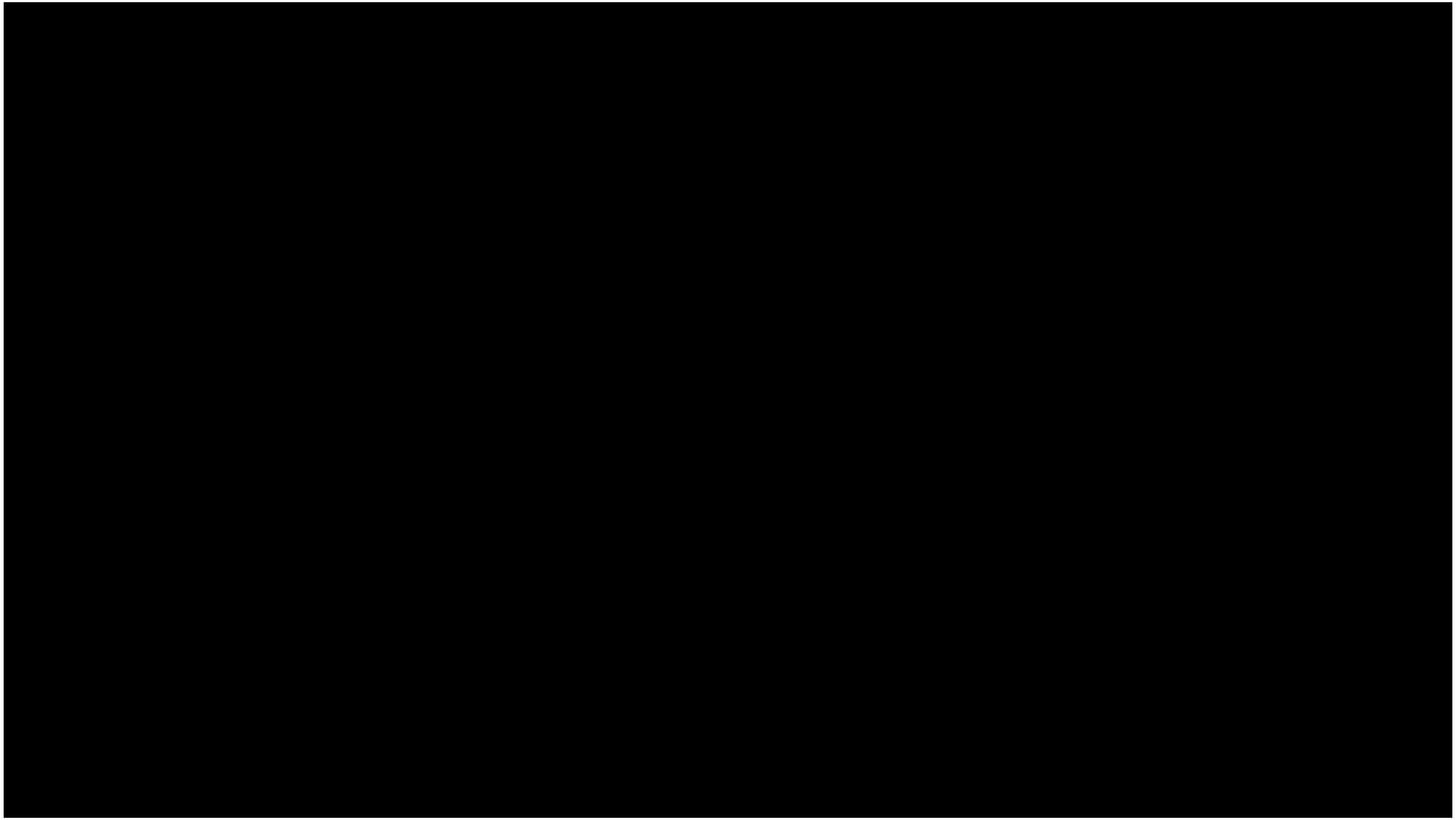
stars	gas / dust	dark matter	dark energy
0.5%	4.5%	26%	69%



dark matter: additional gravitation (galaxies & beyond)

dark energy: anti-gravitation on largest scales

Switching off dark matter



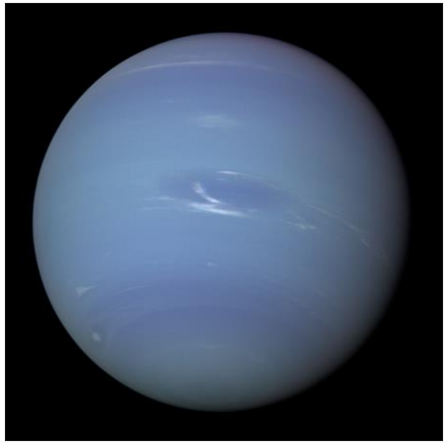
Tamas Szalay,
Volker Springel,
Gerard Lemson

Recap: how to find something previously invisible?

A bit of history

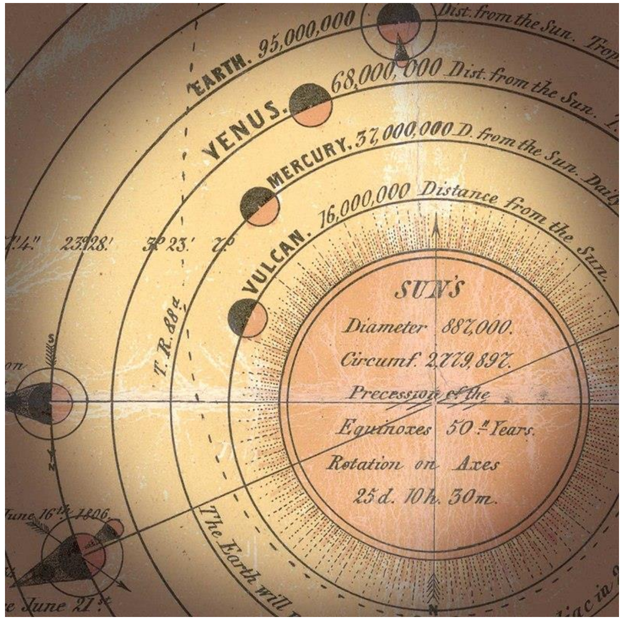
1: Discovery of the planet Neptune:

- 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.

NGC 1052–DF2 and NGC 1052–DF4

No dark matter as strong evidence for dark matter

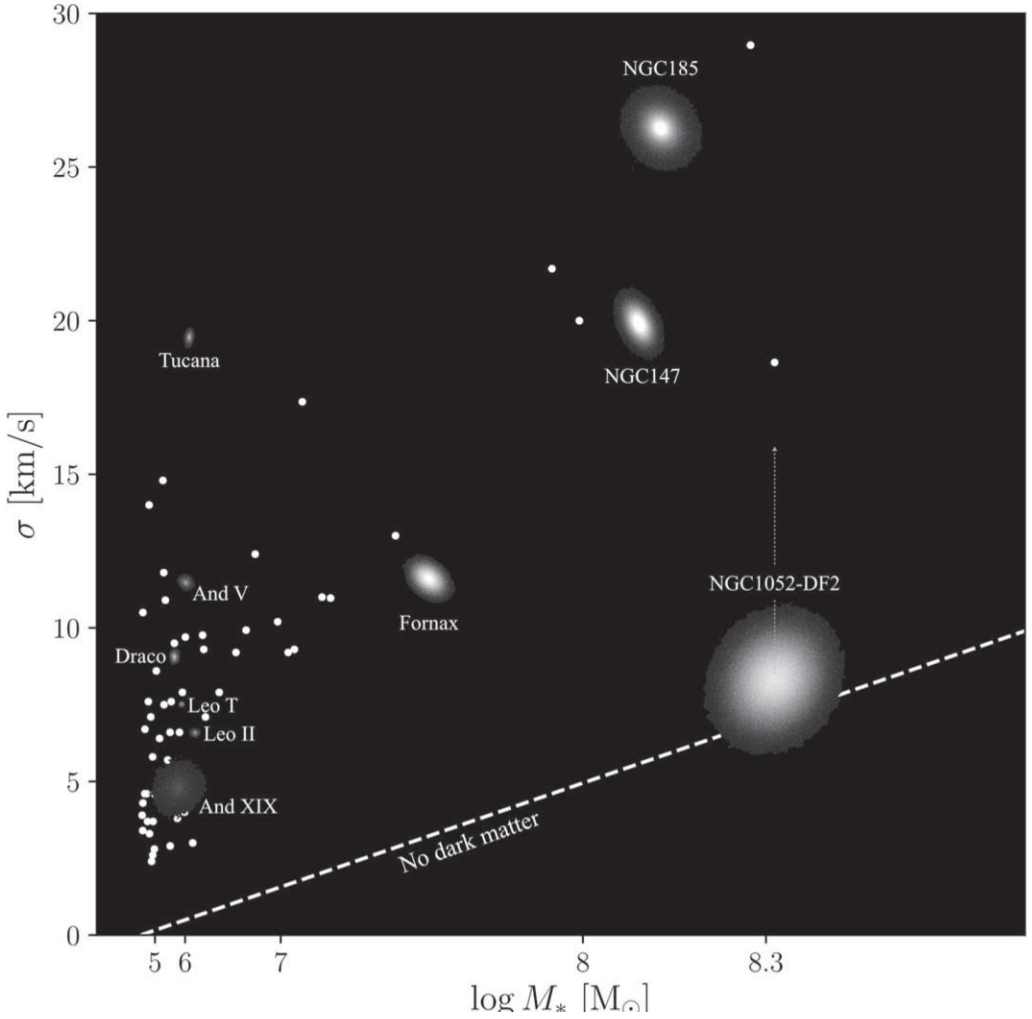
The dynamics in both galaxies does not require any dark matter component.

This strongly excludes a modification of gravity as an alternative to dark matter.

Both galaxies show more unusual properties hinting at special evolutions so that a lack of dark matter is not suprising:
van Dokkum, P., Shen, Z., Keim, M.A. *et al.* A trail of dark-matter-free galaxies from a bullet-dwarf collision. *Nature* **605,** 435–439 (2022).

Let's stick to dark matter searches!

The Astrophysical Journal Letters, 874:L12 (8pp), 2019 April 1



Dark Matter

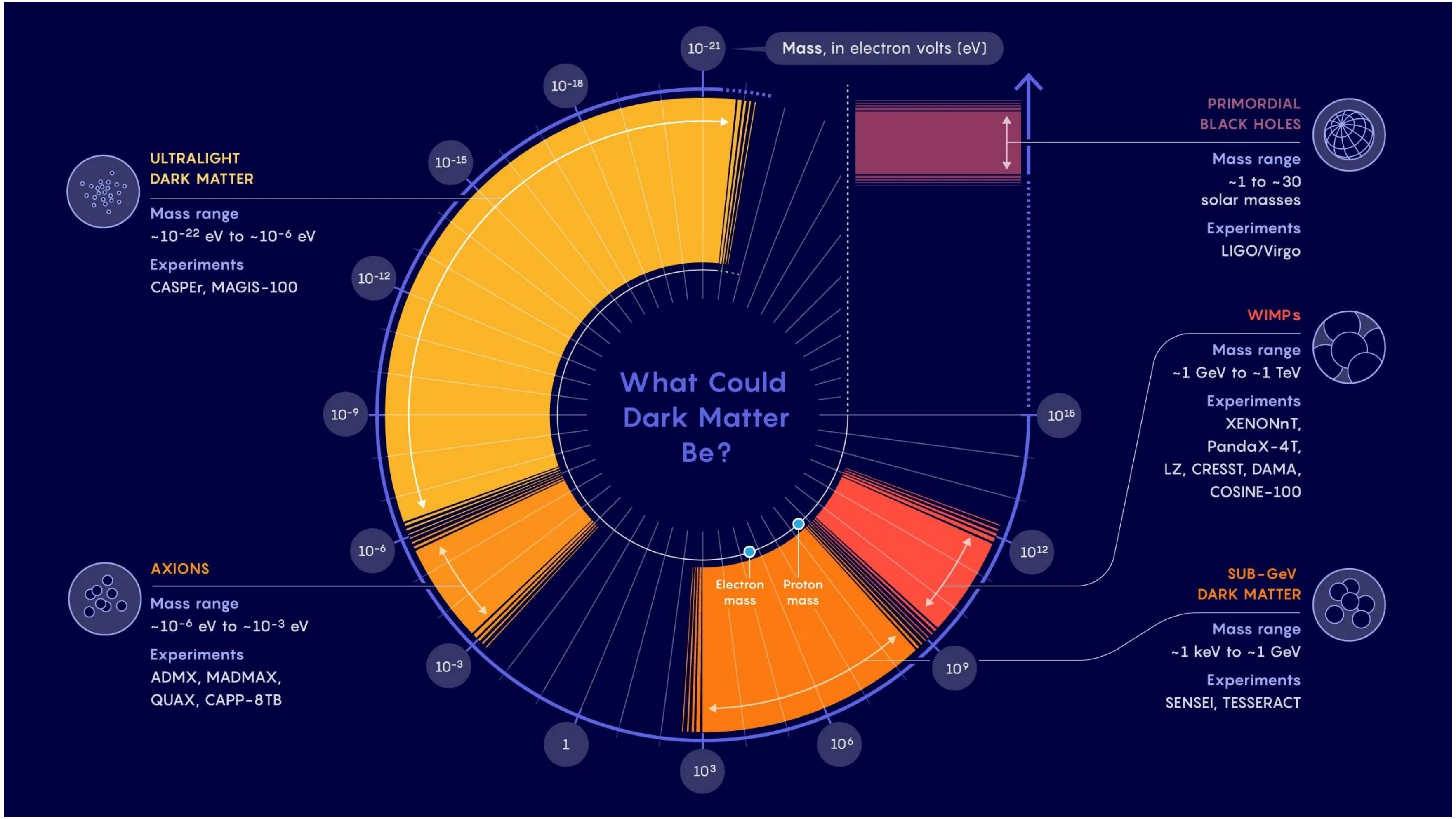
Many candidates, no convincing observation yet

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/

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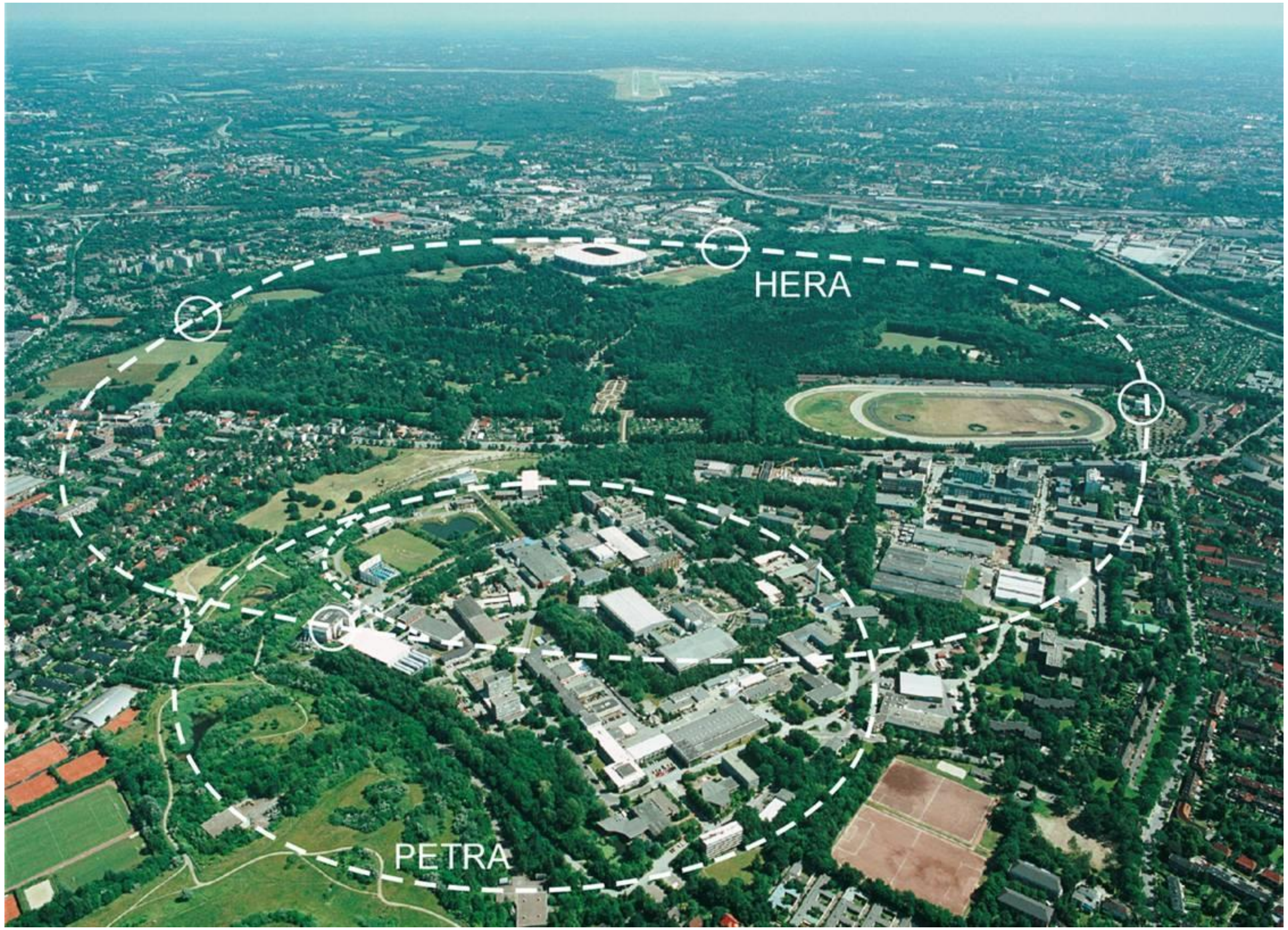
DESY in Hamburg around the year 2000

HERA: data taking 1992 - 2007



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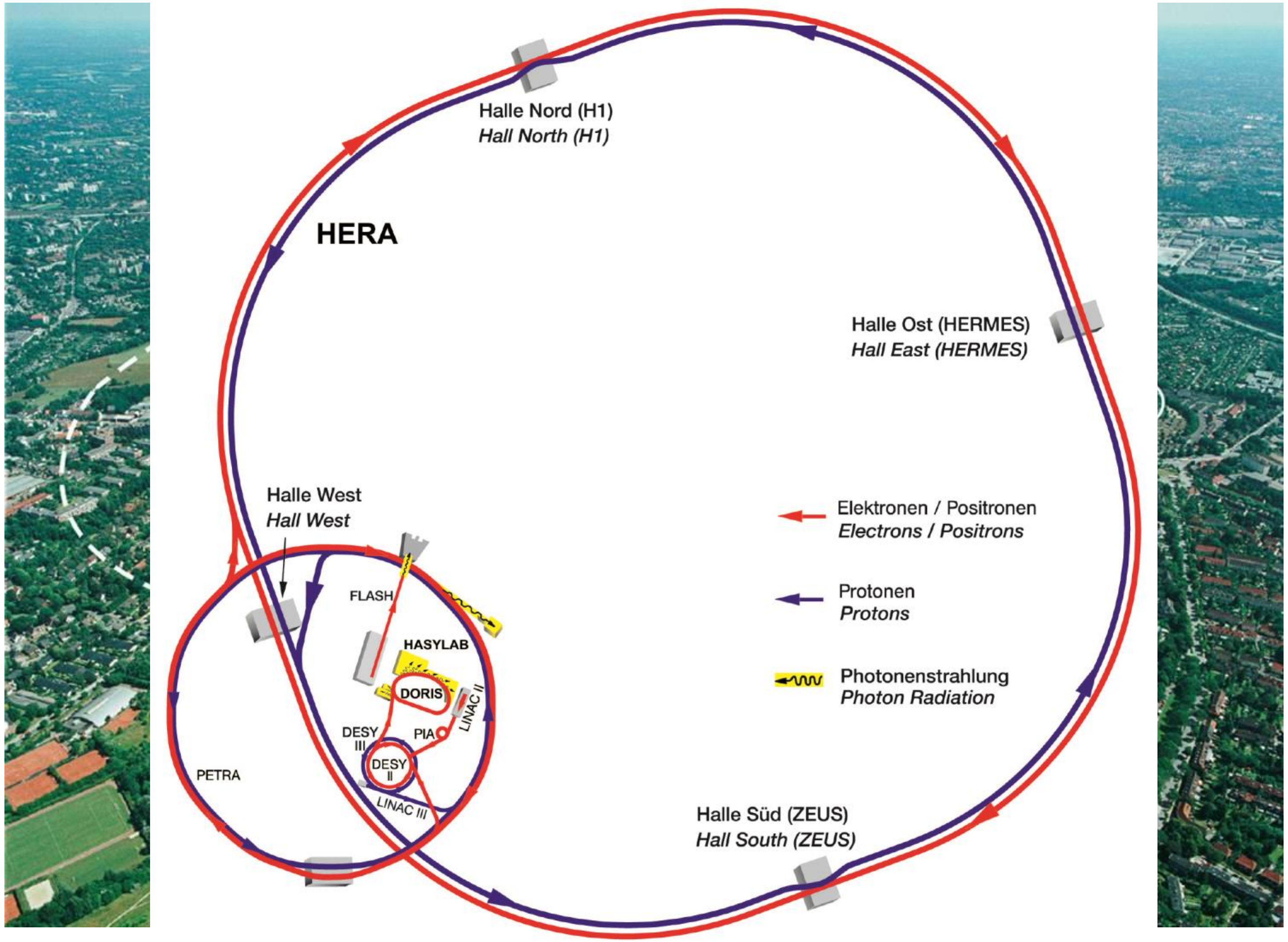

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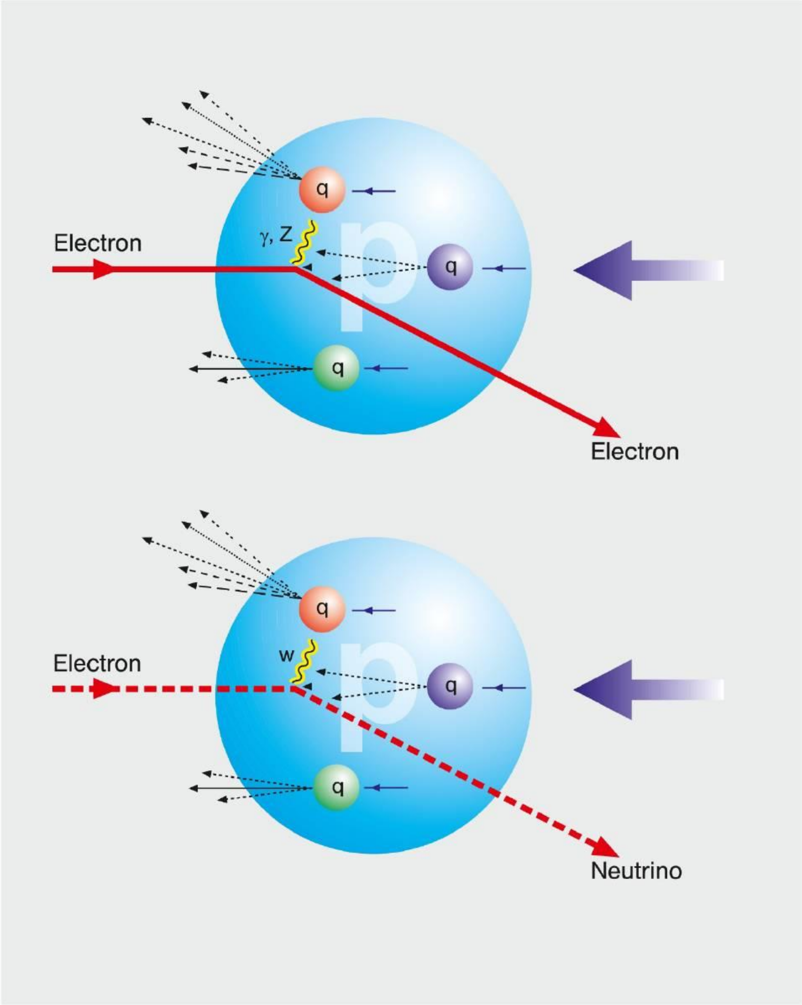

HERA in 2022

Still publishing 15 years after shutdown

PHYSICAL REVIEW LETTERS **128,** 132002 (2022)

Measurement of Lepton-Jet Correlation in Deep-Inelastic Scattering with the H1 Detector Using Machine Learning for Unfolding

V. Andreev,[23] M. Arratia,[35] A. Baghdasaryan,[46] A. Baty,[16] K. Begzsuren,[39] A. Belousov,[23,*] A. Bolz,[14] V. Boudry,[31] G. Brandt,[13] D. Britzger,[26] A. Buniatyan,[6] L. Bystritskaya,[22] A. J. Campbell,[14] K. B. Cantun Avila,[47] K. Cerny,[28] V. Chekelian,[26] Z. Chen,[37] J. G. Contreras,[47] L. Cunqueiro Mendez,[27] J. Cvach,[33] J. B. Dainton,[19] K. Daum,[45] A. Deshpande,[38] C. Diaconu,[21] G. Eckerlin,[14] S. Egli,[43] E. Elsen,[14] L. Favart,[4] A. Fedotov,[22] J. Feltesse,[12] M. Fleischer,[14] A. Fomenko,[23] C. Gal,[38] J. Gayler,[14] L. Goerlich,[17] N. Gogitidze,[23] M. Gouzevitch,[42] C. Grab,[49] T. Greenshaw,[19] G. Grindhammer,[26] D. Haidt,[14] R. C. W. Henderson,[18] J. Hessler,[26] J. Hladký,[33] D. Hoffmann,[21] R. Horisberger,[43] T. Hreus,[50] F. Huber,[15] P. M. Jacobs,[5] M. Jacquet,[29] T. Janssen,[4] A. W. Jung,[44] H. Jung,[14] M. Kapichine,[10] J. Katzy,[14] C. Kiesling,[26] M. Klein,[19] C. Kleinwort,[14] H. T. Klest,[38] R. Kogler,[14] P. Kostka,[19] J. Kretzschmar,[19] D. Krücker,[14] K. Krüger,[14] M. P. J. Landon,[20] W. Lange,[48] P. Laycock,[41] S. H. Lee,[3] S. Levonian,[14] W. Li,[16] J. Lin,[16] K. Lipka,[14] B. List,[14] J. List,[14] B. Lobodzinski,[26] E. Malinovski,[23] H.-U. Martyn,[1] S. J. Maxfield,[19] A. Mehta,[19] A. B. Meyer,[14] J. Meyer,[14] S. Mikocki,[17] M. M. Mondal,[38] A. Morozov,[10] K. Müller,[50] B. Nachman,[5] Th. Naumann,[48] P. R. Newman,[6] C. Niebuhr,[14] G. Nowak,[17] J. E. Olsson,[14] D. Ozerov,[43] S. Park,[38] C. Pascaud,[29] G. D. Patel,[19] E. Perez,[11] A. Petrukhin,[42] I. Picuric,[32] D. Pitzl,[14] R. Polifka,[34] S. Preins,[35] V. Radescu,[30] N. Raicevic,[32] T. Ravdandorj,[39] P. Reimer,[33] E. Rizvi,[20] P. Robmann,[50] R. Roosen,[4] A. Rostovtsev,[25] M. Rotaru,[7] D. P. C. Sankey,[8] M. Sauter,[15] E. Sauvan,[21,2] S. Schmitt,[14] B. A. Schmookler,[38] L. Schoeffel,[12] A. Schöning,[15] F. Sefkow,[14] S. Shushkevich,[24] Y. Soloviev,[23] P. Sopicki,[17] D. South,[14] V. Spaskov,[10] A. Specka,[31] M. Steder,[14] B. Stella,[36] U. Straumann,[50] C. Sun,[37] T. Sykora,[34] P. D. Thompson,[6] D. Traynor,[20] B. Tseepeldorj,[39,40] Z. Tu,[41] A. Valkárová,[34] C. Vallée,[21] P. Van Mechelen,[4] D. Wegener,[9] E. Wünsch,[14] J. Žáček,[34] J. Zhang,[37] Z. Zhang,[29] R. Žlebčík,[34] H. Zohrabyan,[46] and F. Zomer[29]

(H1 Collaboration)

PHYSICAL REVIEW D **101,** 112009 (2020)

Study of proton parton distribution functions at high *x* using ZEUS data

I. Abt,[19] L. Adamczyk,[7] R. Aggarwal,[3,b] V. Aushev,[17] O. Behnke,[9] U. Behrens,[9] A. Bertolin,[21] I. Bloch,[10] I. Brock,[2] N. H. Brook,[28,m] R. Brugnera,[22] A. Bruni,[1] P. J. Bussey,[11] A. Caldwell,[19] M. Capua,[4] C. D. Catterall,[32] J. Chwastowski,[6] J. Ciborowski,[29,n] R. Ciesielski,[9,d] A. M. Cooper-Sarkar,[20] M. Corradi,[1,a] R. K. Dementiev,[18] S. Dusini,[21] J. Ferrando,[9] B. Foster,[20,j] E. Gallo,[13,k] D. Gangadharan,[14] A. Garfagnini,[22] A. Geiser,[9] L. K. Gladilin,[18] Yu. A. Golubkov,[18] G. Grzelak,[29] C. Gwenlan,[20] D. Hochman,[31] N. Z. Jomhari,[9] I. Kadenko,[17] S. Kananov,[23] U. Karshon,[31] P. Kaur,[3,c] R. Klanner,[13] U. Klein,[9,e] I. A. Korzhavina,[18] N. Kovalchuk,[13] H. Kowalski,[9] O. Kuprash,[9,f] M. Kuze,[25] B. B. Levchenko,[18] A. Levy,[23] B. Löhr,[9] A. Longhin,[22] O. Yu. Lukina,[18] I. Makarenko,[9] J. Malka,[9,g] S. Masciocchi,[12,i] K. Nagano,[15] J. D. Nam,[24] J. Onderwaater,[14,l] Yu. Onishchuk,[17] E. Paul,[2] I. Pidhurskyi,[17] A. Polini,[1] M. Przybycień,[7] A. Quintero,[24] M. Ruspa,[27] D. H. Saxon,[11] U. Schneekloth,[9] T. Schörner-Sadenius,[9] I. Selyuzhenkov,[12] M. Shchedrolosiev,[17] L. M. Shcheglova,[18] I. O. Skillicorn,[11] W. Słomiński,[8] A. Solano,[26] L. Stanco,[21] N. Stefaniuk,[9] P. Stopa,[6] B. Surrow,[24] J. Sztuk-Dambietz,[13,g] E. Tassi,[4] K. Tokushuku,[15] M. Turcato,[13,g] O. Turkot,[9] T. Tymieniecka,[30] A. Verbytskyi,[19] W. A. T. Wan Abdullah,[5] K. Wichmann,[9] M. Wing,[28] S. Yamada,[15] Y. Yamazaki,[16] A. F. Żarnecki,[29] L. Zawiejski,[6] and O. Zenaiev[9,h]

(ZEUS Collaboration)

HERA: indispensable for particle physics today, no “new physics” found.

Nobel prize in physics 2004

David Gross, David Politzer and Frank Wilczek

"… for the discovery of asymptotic freedom in the theory of the strong interaction …"

"HERA measurements confirmed the nature of the strong force as it was predicted by physicists Davis Gross, David Politzer and Frank Wilczek for which they received the 2004 Nobel Prize."
(End of an era at HERA accelerator, https://phys.org/news/2007-07-era-hera.html)

HERA changed our understanding of QCD and of the proton structure.

DESY.

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Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

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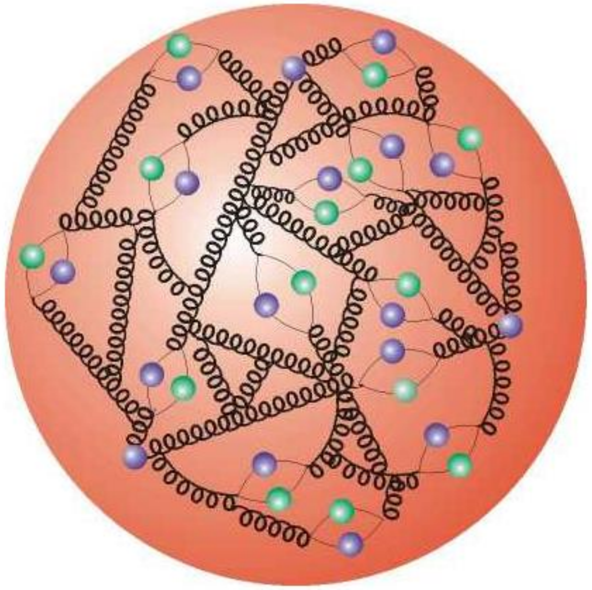
"The DESY physics community congratulates the winners of this year's Nobel Prize, David Gross, David Politzer and Frank Wilczek, on their award", said Robert Klanner, Research Director at DESY." The Nobel Prize recognizes a pioneering discovery on the way towards the comprehensive theory of the strong force. This is particularly gratifying for DESY, since scientists at the Laboratory's accelerators PETRA and HERA were not only able to experimentally confirm the predictions made by Gross, Politzer and Wilczek, they also discovered unexpected new properties of the strong force," he adds.
Indeed, **Frank Wilczek** begins his internet list of "selected publications, with brief comments" with the three papers on the theory of the strong force that were published in 1973 and 1974. One comment reads: **"… The most dramatic of these [tests], that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later".**



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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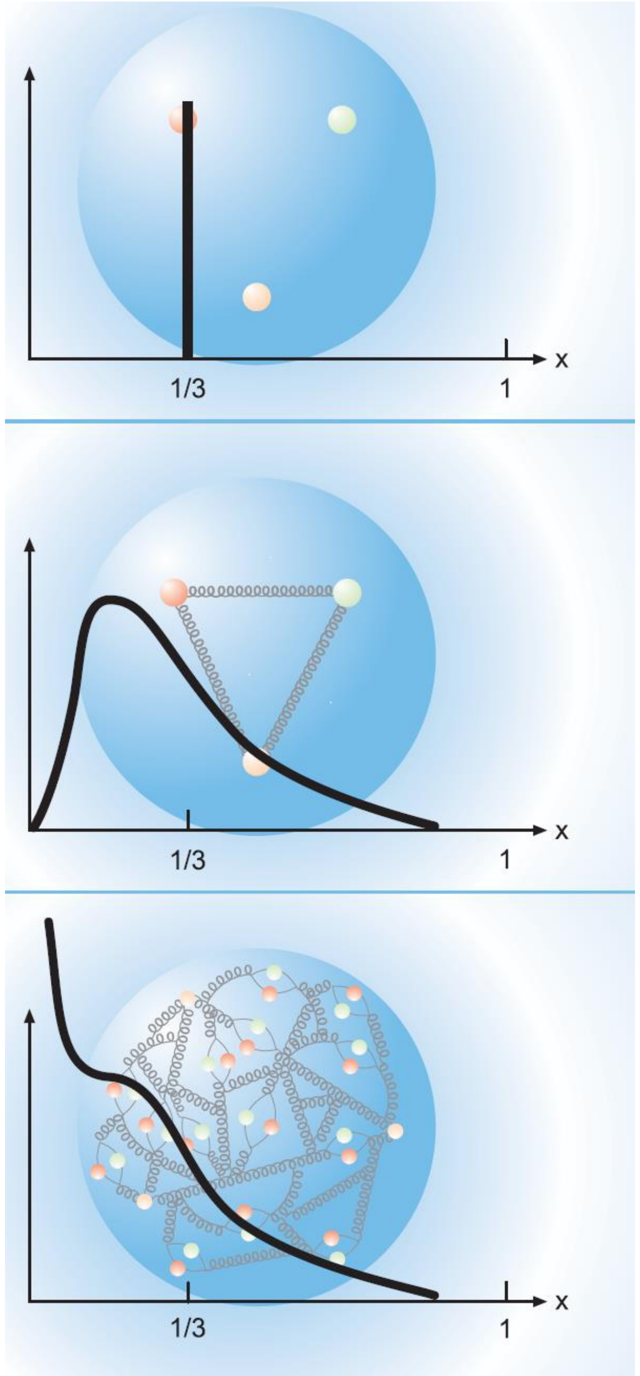
Some axion motivation

…. 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.

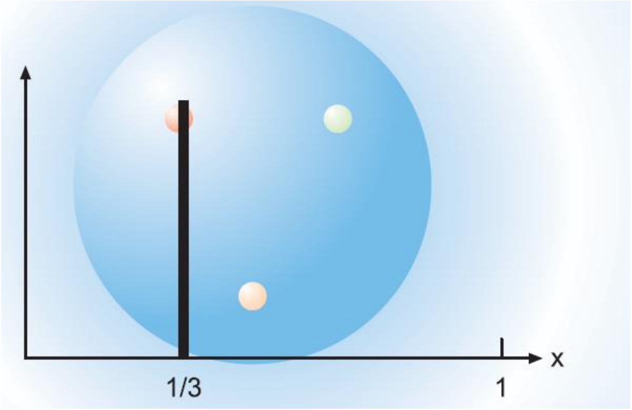


Brochure: “Super Microscope HERA”

Some axion motivation

…. and some laxness in HERA communication

If this is the real picture,



Some axion motivation

…. and some laxness in HERA communication

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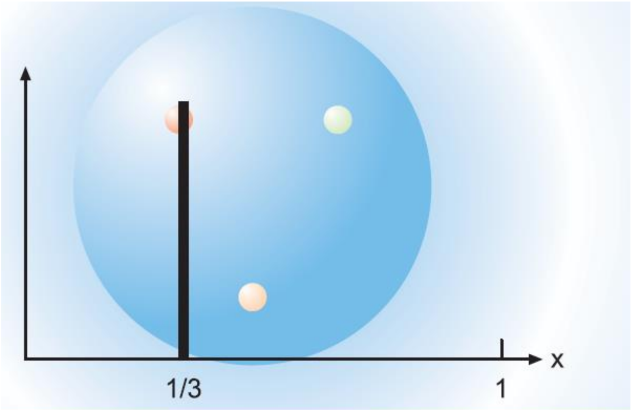
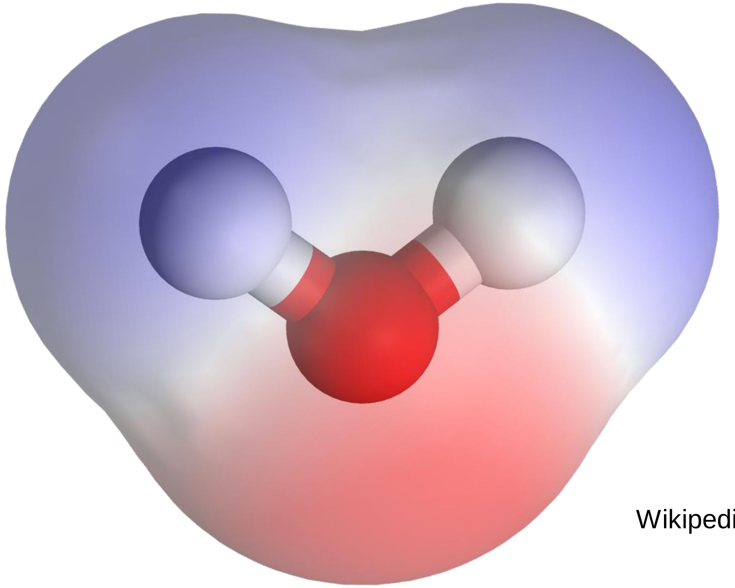


protons and neutrons, in the static limit,
should show an electric dipole moment (EDM)!

Like water molecules for example.



Wikipedia

Some axion motivation

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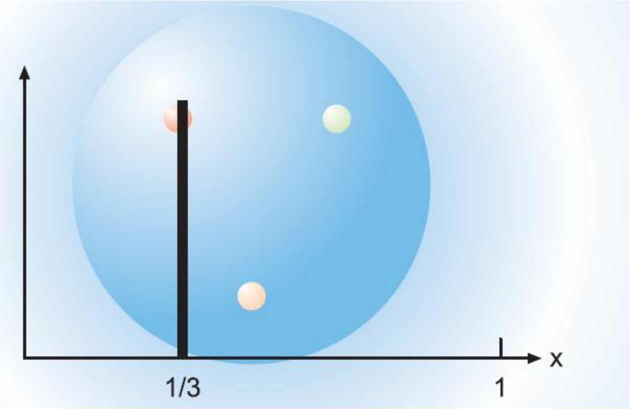


protons and neutrons, in the static limit,
should show an electric dipole moment (EDM)!

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)

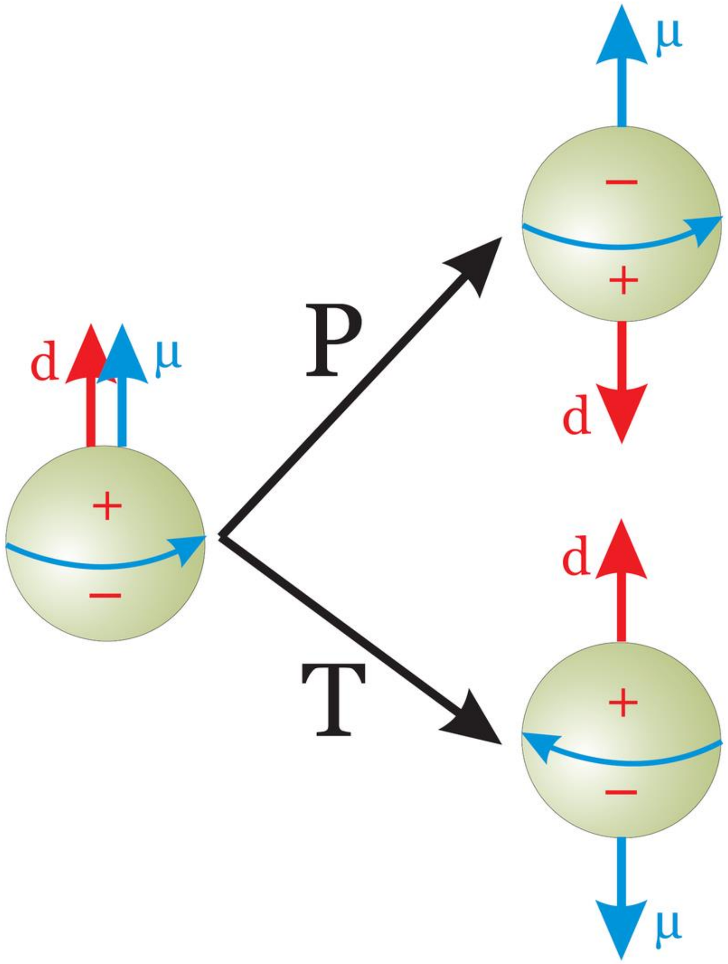
https://pdg.lbl.gov/2022/

The neutron

QCD, EDM and symmetries

An electric dipole moment of the neutron would violate:

- parity (P) symmetry,
- time reversal (T) symmetry (hence also CP symmetry).



Magnetic dipole moment (existing)

Electric dipole moment (hypothetical)

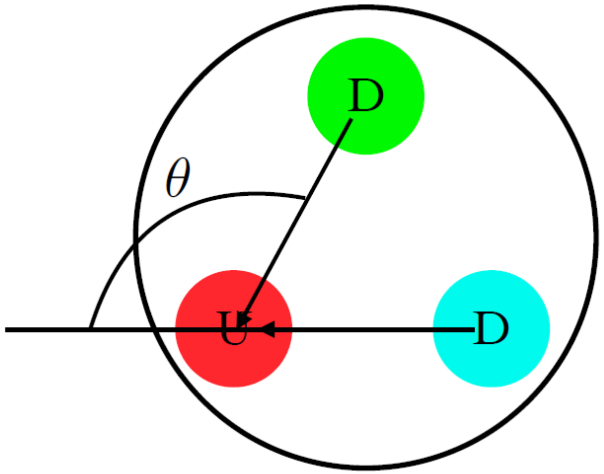
Wikipedia

The neutron

QCD and a missing EDM

T symmetry violation in strong interactions ?

- QCD predicts an EDM of the neutron: $d_n = \theta \cdot 3{\cdot}10^{-16}$ e·cm.
  θ is a free parameter



https://arxiv.org/abs/1812.02669

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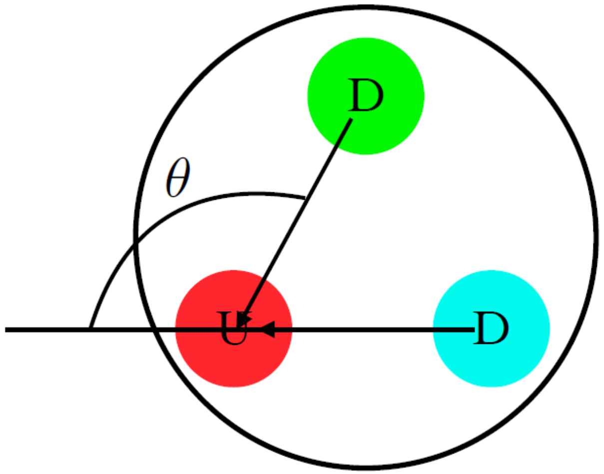

https://arxiv.org/abs/1812.02669

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

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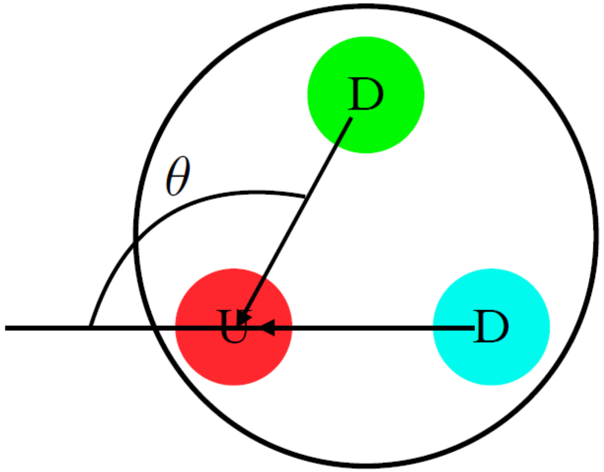

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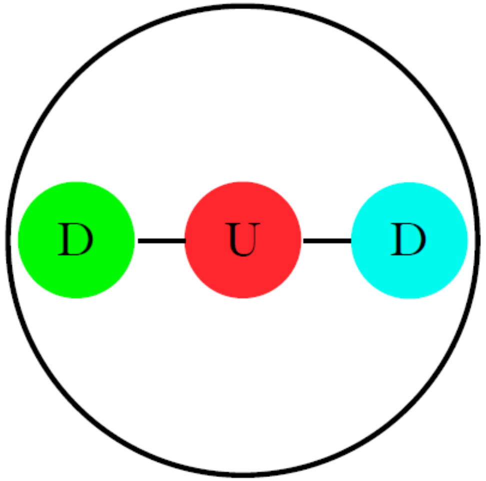

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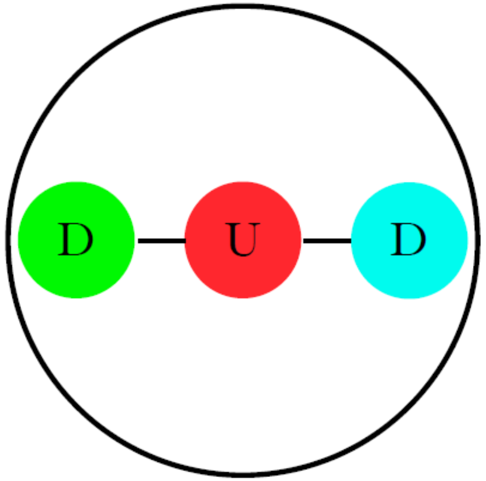
Experiments: $d_n < 3{\cdot}10^{-26}$ e·cm; $\theta < 10^{-10}$

QCD conserves 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!

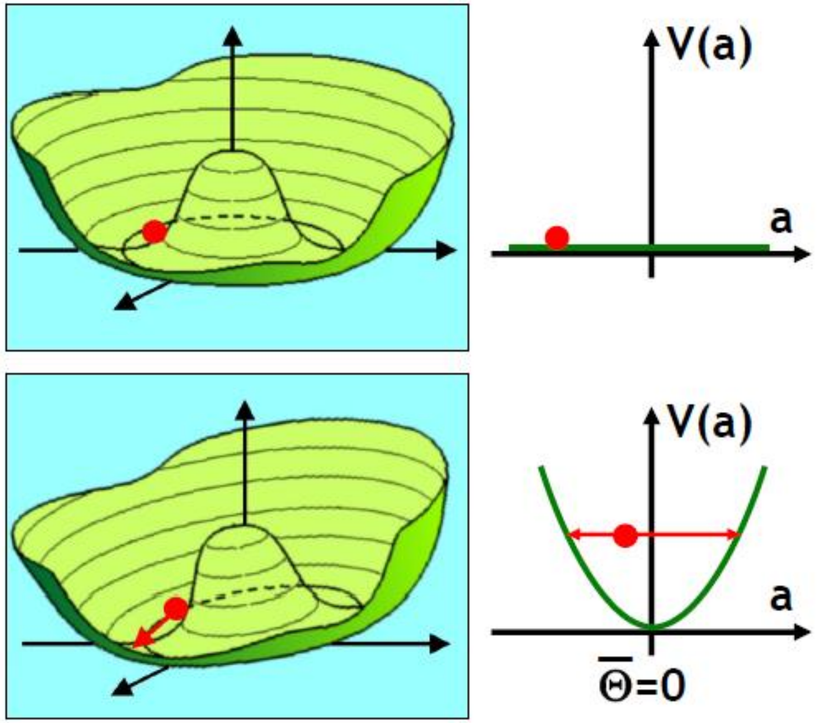
Idea: if θ is not a fixed value, but an evolving field, it relaxes to zero by QCD instanton effects.

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.

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

And vice versa.



S. Hannestad, presentation at 5th Patras Workshop 2009

Peccei-Quinn symmetry, Weinberg and Wilczek

Axions!

VOLUME 40, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1978

A New Light Boson?

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 6 December 1977)

It is pointed out that a global U(1) symmetry, that has been introduced in order to preserve the parity and time-reversal invariance of strong interactions despite the effects of instantons, would lead to a neutral pseudoscalar boson, the "axion," with mass roughly of order 100 keV to 1 MeV. Experimental implications are discussed.

VOLUME 40, NUMBER 5 PHYSICAL REVIEW LETTERS 30 JANUARY 1978

Problem of Strong *P* and *T* Invariance in the Presence of Instantons

F. Wilczek[a]
Columbia University, New York, New York 10027, and The Institute for Advanced Studies, Princeton, New Jersey 08540[b]
(Received 29 November 1977)

The requirement that *P* and *T* be approximately conserved in the color gauge theory of strong interactions without arbitrary adjustment of parameters is analyzed. Several possibilities are identified, including one which would give a remarkable new kind of very light, long-lived pseudoscalar boson.

Peccei-Quinn symmetry, Weinberg and Wilczek

Axions!

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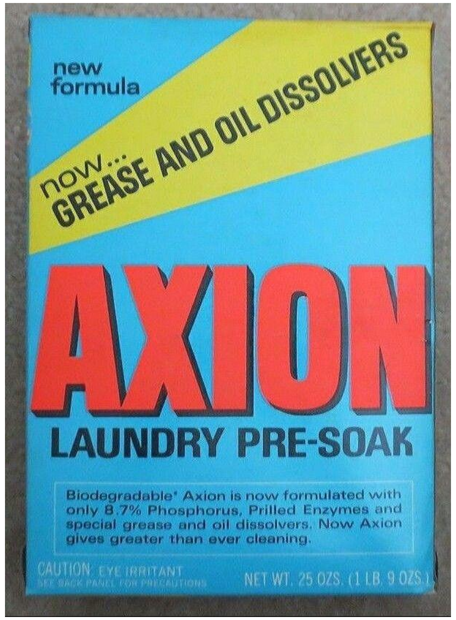

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Peccei and Quinn[7] have made the ingenious observation that instead of a quark of bare mass zero, we might also consider a chiral symmetry. This leads to a special kind of Higgs boson (which we are calling the *axion*) with zero bare mass.[10] This proposal has some remarkable physical implications.

Axions

BSM physics, dark matter and more

Mass and couplings of the axion are determined by one energy scale f_a.

Experimentally, f_a >> TeV.

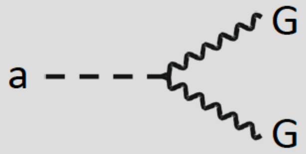
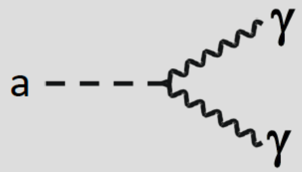
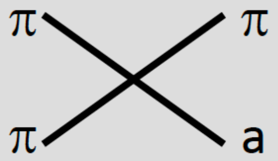
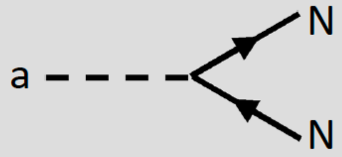
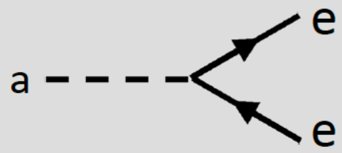
Axion couplings (beyond gluons) depend on the BSM models incorporating an "invisible axion".

For f_a beyond about 10^6 TeV the axion might explain all of the dark matter.

For f_a around 10^5 TeV the axion might explain astrophysical anomalies.

There might be an "axiverse" with many kinds of axion-like particles.

- Not related to CP-QCD
- Mass and couplings not correlated.

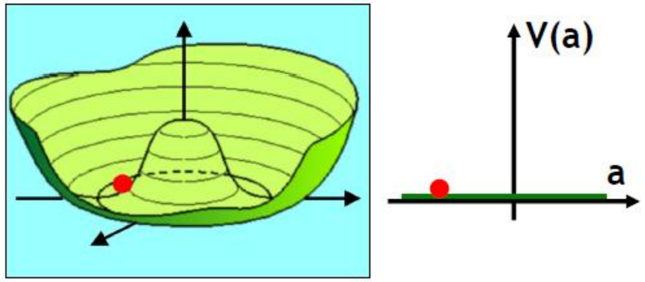
Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$	
Mass (generic)	$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d} \frac{m_\pi}{f_\pi f_a} \approx \frac{6\ \mu\text{eV}}{f_a/10^{12}\,\text{GeV}}$	
Photon coupling	$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\,\mathbf{E}\cdot\mathbf{B}\,a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	
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

Axion cosmology in brief

Two different cosmological scenarios

PQ symmetry breaking before of after inflation:



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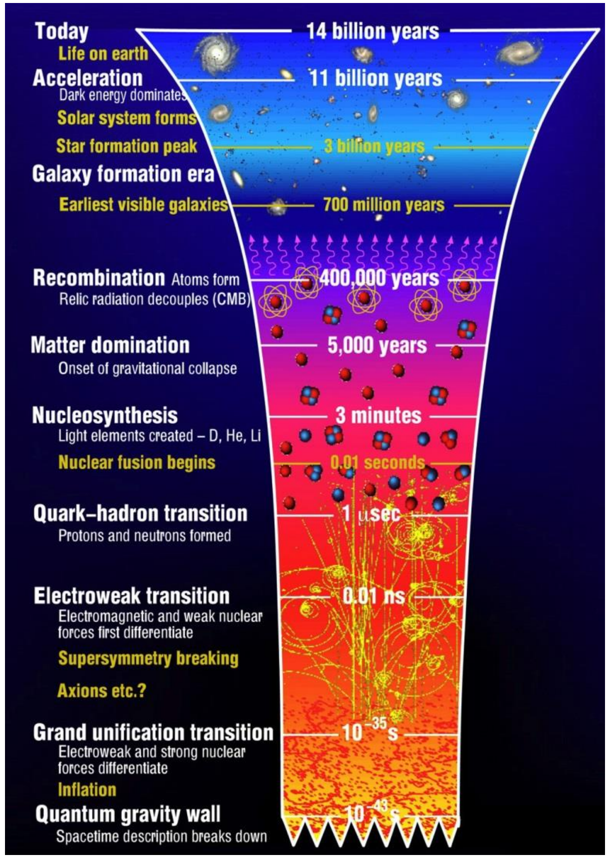
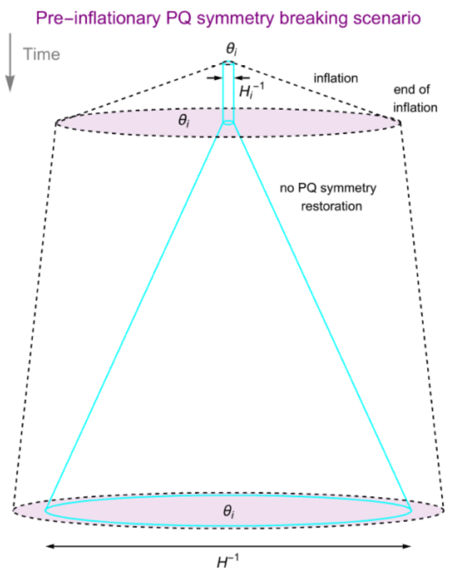


Axion cosmology in brief

Two different cosmological scenarios

PQ symmetry breaking before inflation:

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



Axion cosmology in brief

Two different cosmological scenarios

PQ symmetry breaking before inflation:

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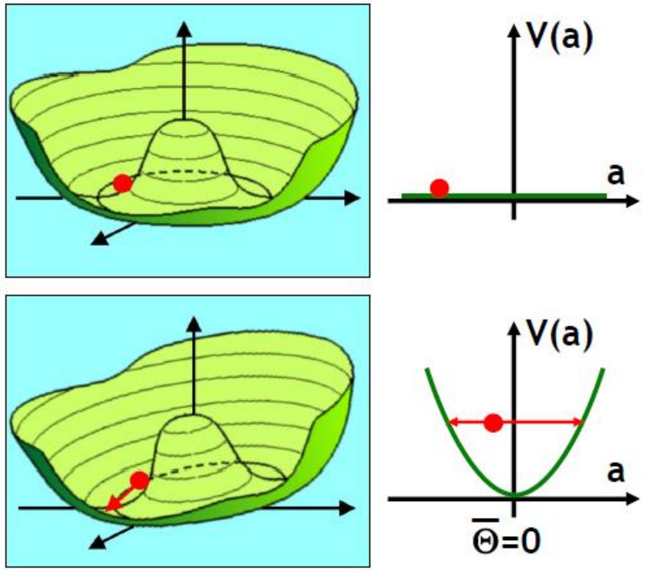
Initial misalignment angle θ_i ($L_\theta = -\theta(\alpha_s/8\pi)\,\tilde{G}^a_{\mu\nu}G^a_{\mu\nu}$).



S. Hannestad, presentation at 5th Patras Workshop 2009

Axion cosmology in brief

Two different cosmological scenarios

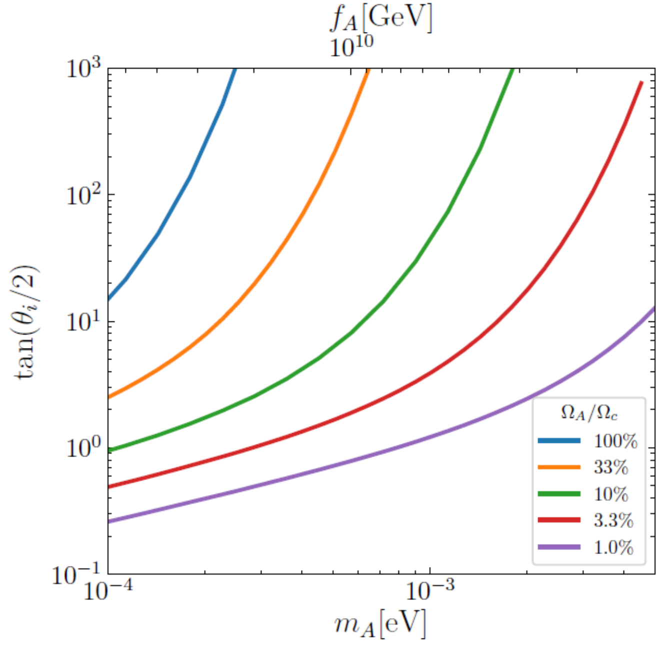
PQ symmetry breaking before inflation:

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



Physics potential of the International Axion Observatory (IAXO), JCAP 1906 (2019) 047

Axion cosmology in brief

Two different cosmological scenarios

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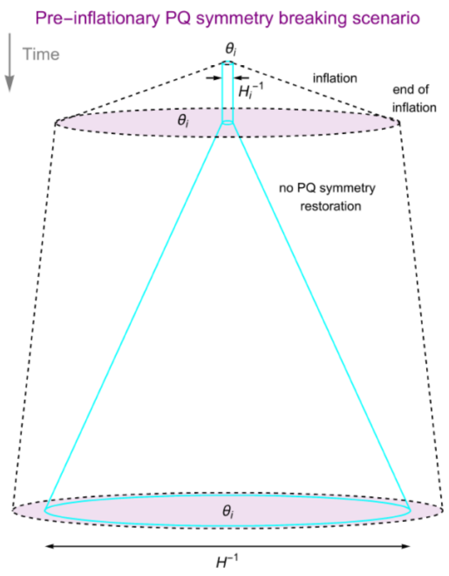
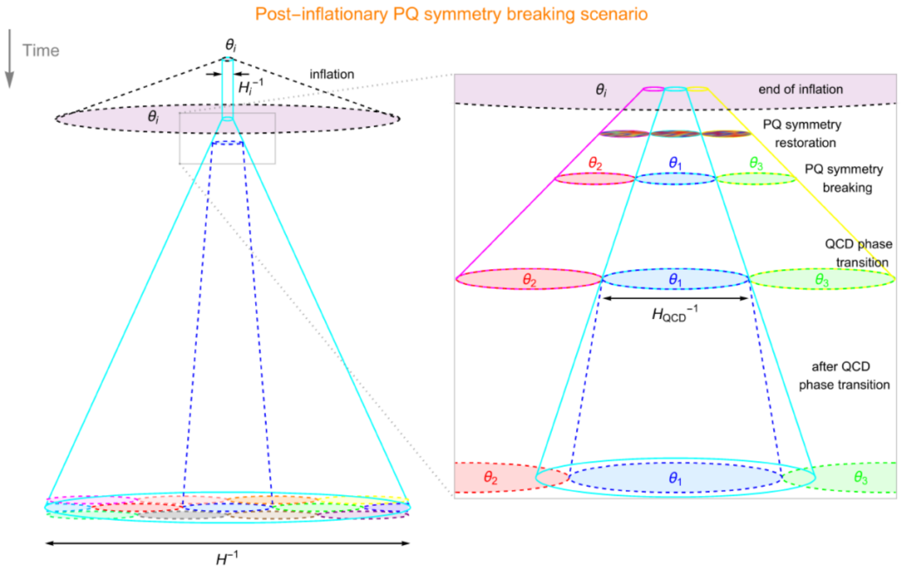


PQ symmetry breaking after inflation:

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



Physics potential of the International Axion Observatory (IAXO), JCAP 1906 (2019) 047

Axion cosmology in brief

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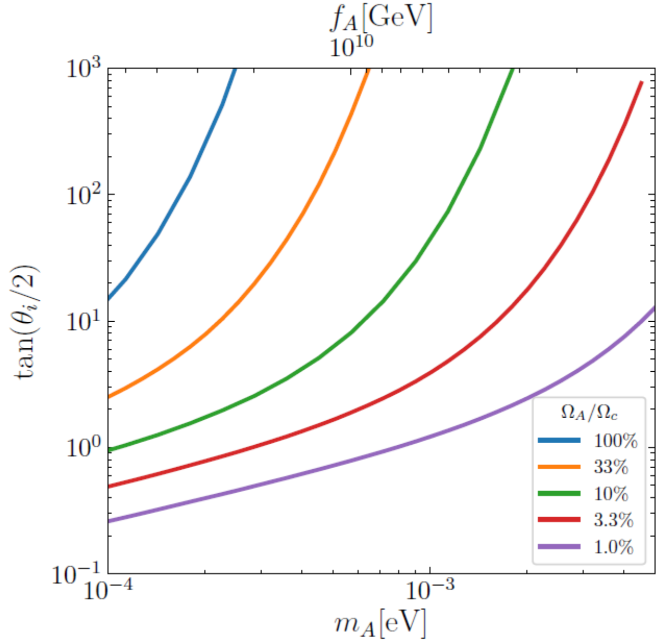
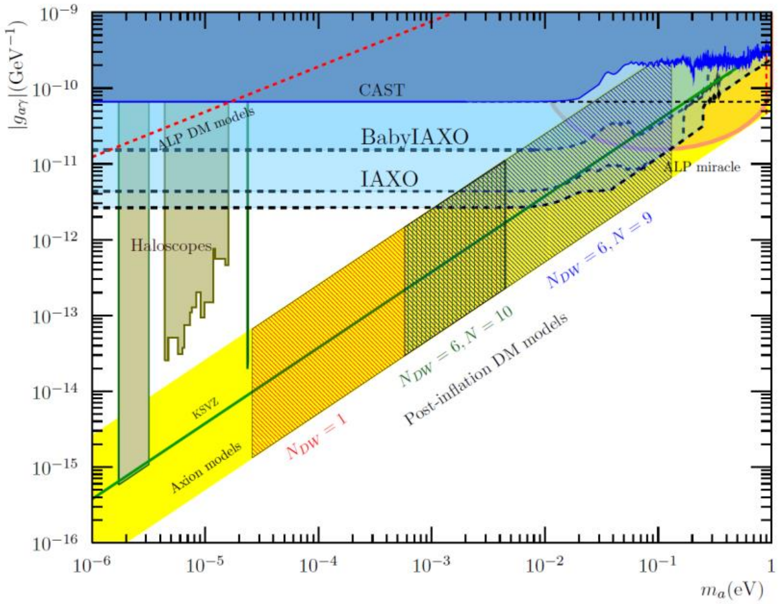
WMAP: $\Omega_c h^2$ = 0.1206±0.0021

PQ symmetry breaking after inflation:

$$\Omega_{A,\mathrm{real}}h^2 \approx (3.8 \pm 0.6) \times 10^{-3} \times \left(\frac{f_A}{10^{10}\,\mathrm{GeV}}\right)^{1.165}$$

plus contributions from string and domain wall decays.





Physics potential of the International Axion Observatory (IAXO), JCAP 1906 (2019) 047

Disclaimer:

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

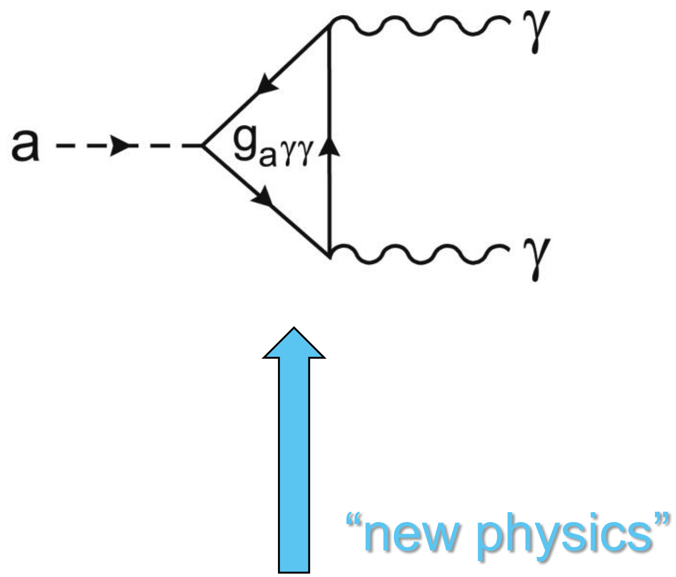
Unless stated otherwise.

Axions

Photon coupling

Exploited by many experiments as relatively "simple".

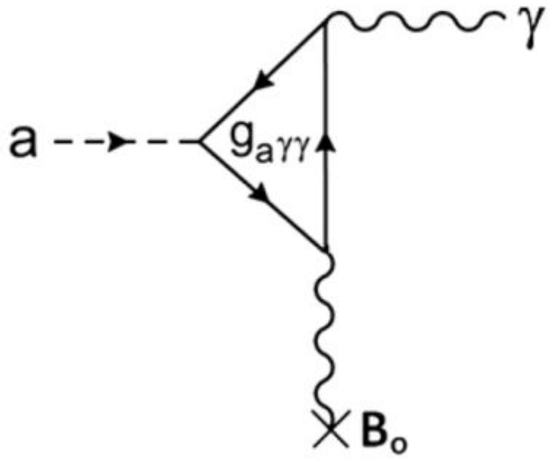
Decay time: larger than (10^{21} · age of the universe). **The "invisible axion".**



Axions

Photon coupling and Maxwell 1864

Exploited by many experiments as relatively “simple”.



Axions

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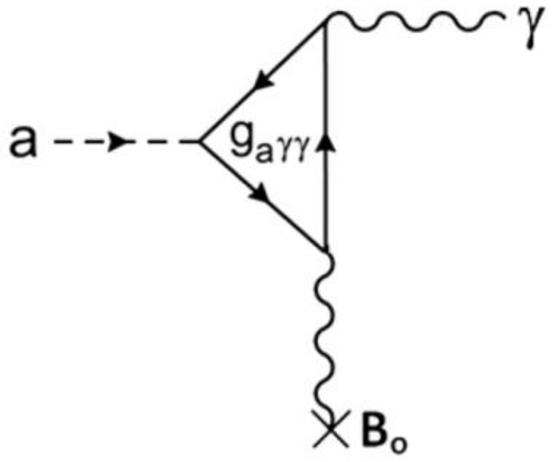
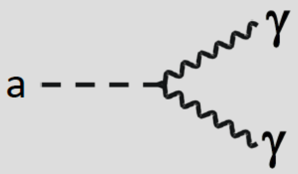


Photon coupling	$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\,\mathbf{E}\cdot\mathbf{B}\,a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$



Photon-axion mixing in a background magnetic dipole field.
Works also with a background electric field.

How to find dark matter?

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 dark matter?

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?
2: Look for DM candidates in the laboratory:	
• Experiments at the high energy frontier.	Not possible for the time being
• Precision experiments.	Shining light through walls
• Understanding extreme conditions in the universe.	Astrophysical hints

How to find dark matter?

Two approaches to search for axions

Examples

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- Precision experiments. — Shining light through walls: next lecture
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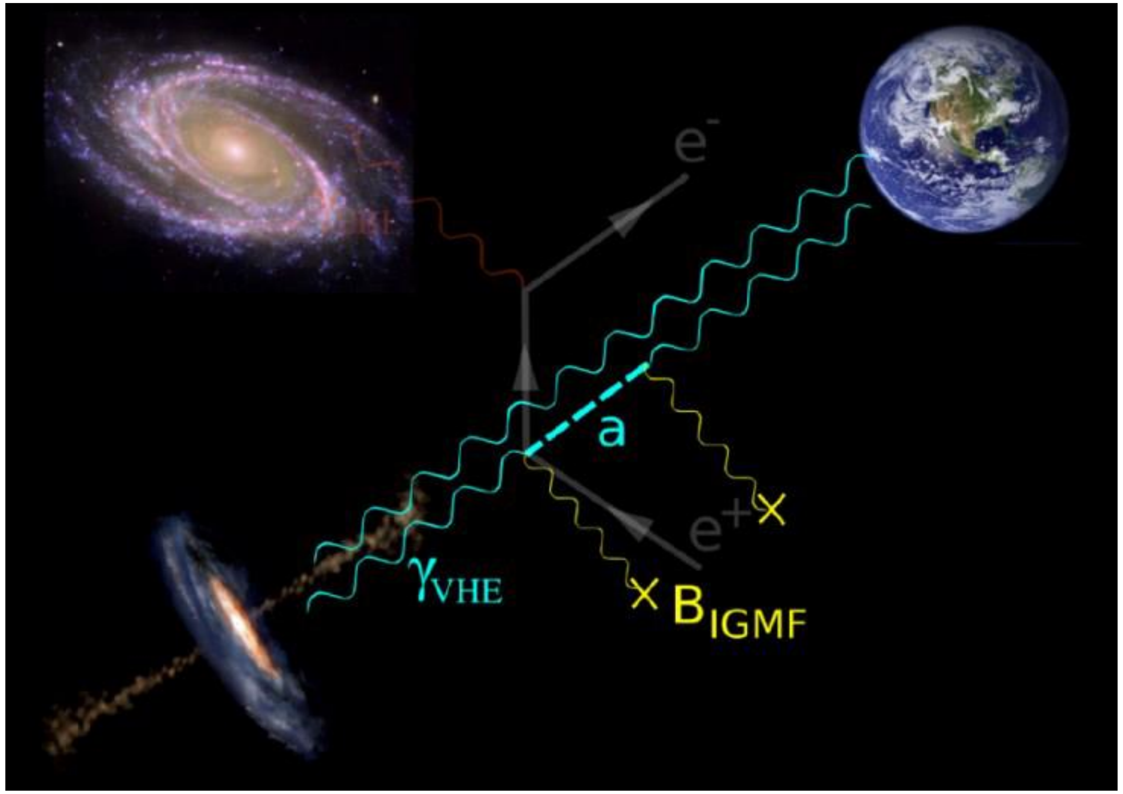
Outline

- Our starting point
- Dark matter in the universe
  - Alternatives to dark matter?
  - Dark matter candidates
- HERA, QCD and the axion
- Astrophysical motivations for axions and ALPs
- Summary

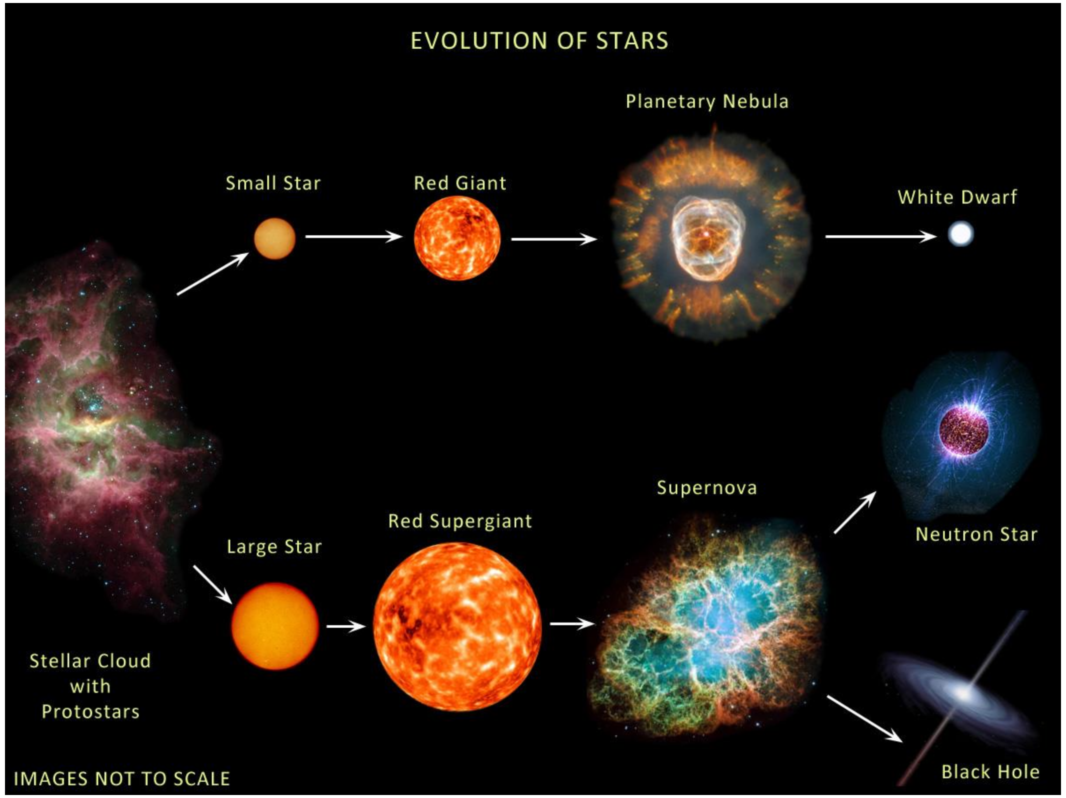
Astrophysical motivations for axions

TeV transparency



Universe's transparency to gamma-rays, Dieter Horns

Stellar evolution

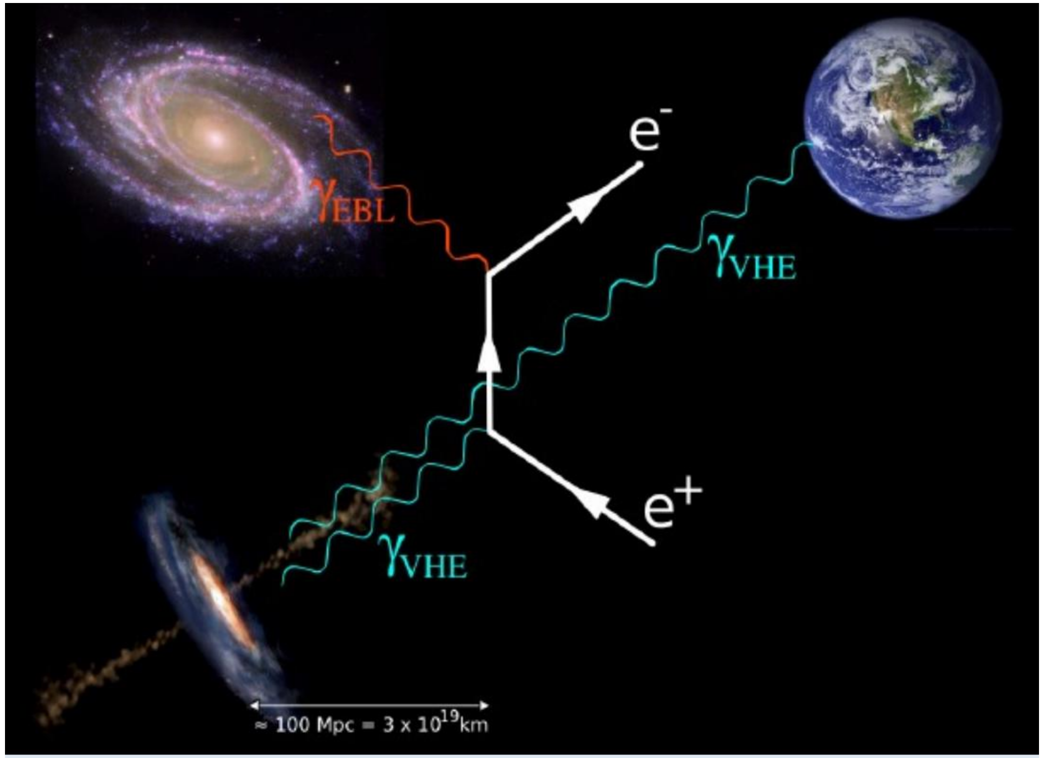


http://earthspacecircle.blogspot.com/2013/07/stellarevolution.html

Astrophysical motivations for axions

TeV transparency

High energy (> TeV) photons



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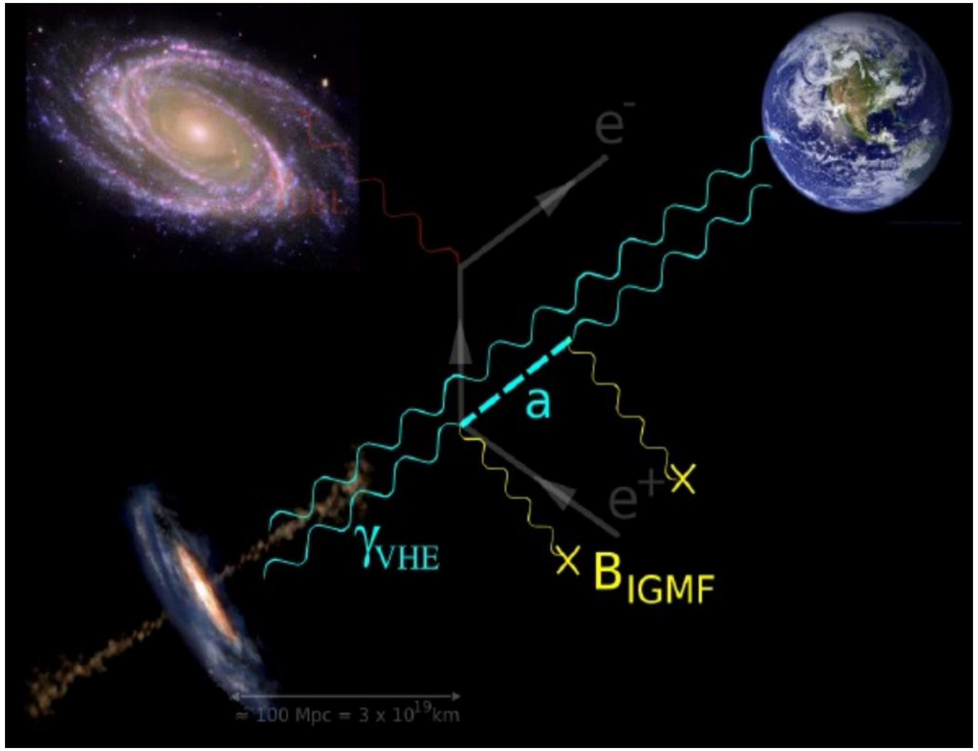


Universe's transparency to gamma-rays, Dieter Horns

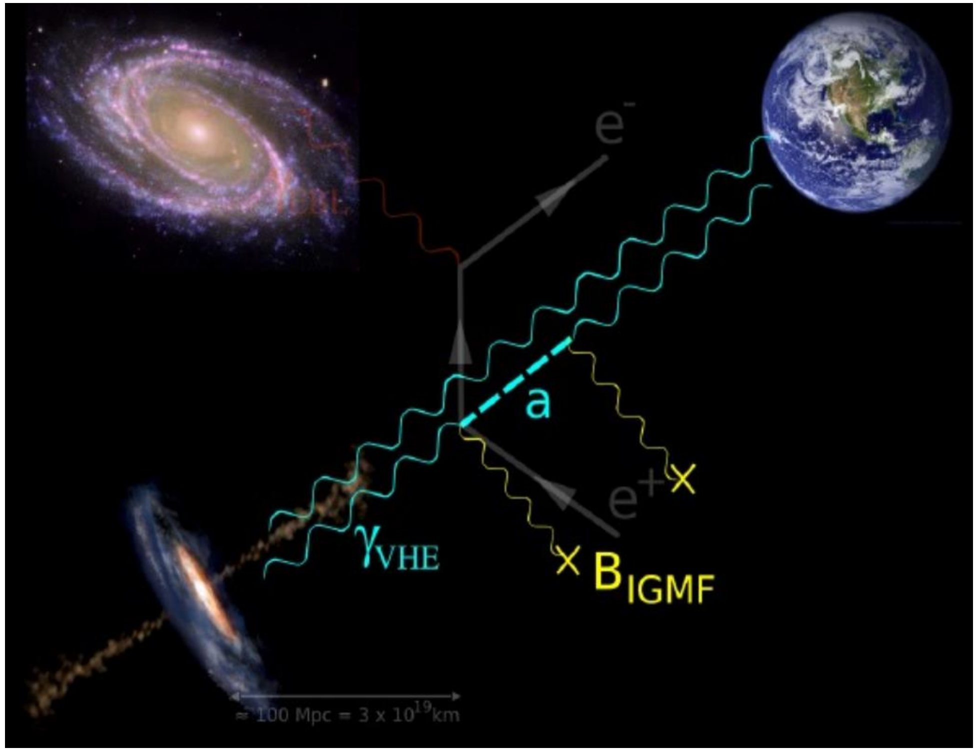
- Excessive transparency of the universe.
- May be explained by photon to axion conversion.

$$m_a \sim 10^{-7} \text{eV}, \qquad g_{a\gamma} \sim 10^{-11} \text{GeV}^{-1}$$

Astrophysical motivations for axions

TeV transparency

High energy (> TeV) photons



Universe's transparency to gamma-rays, Dieter Horns

- Excessive transparency of the universe.
- May be explained by photon to axion conversion.

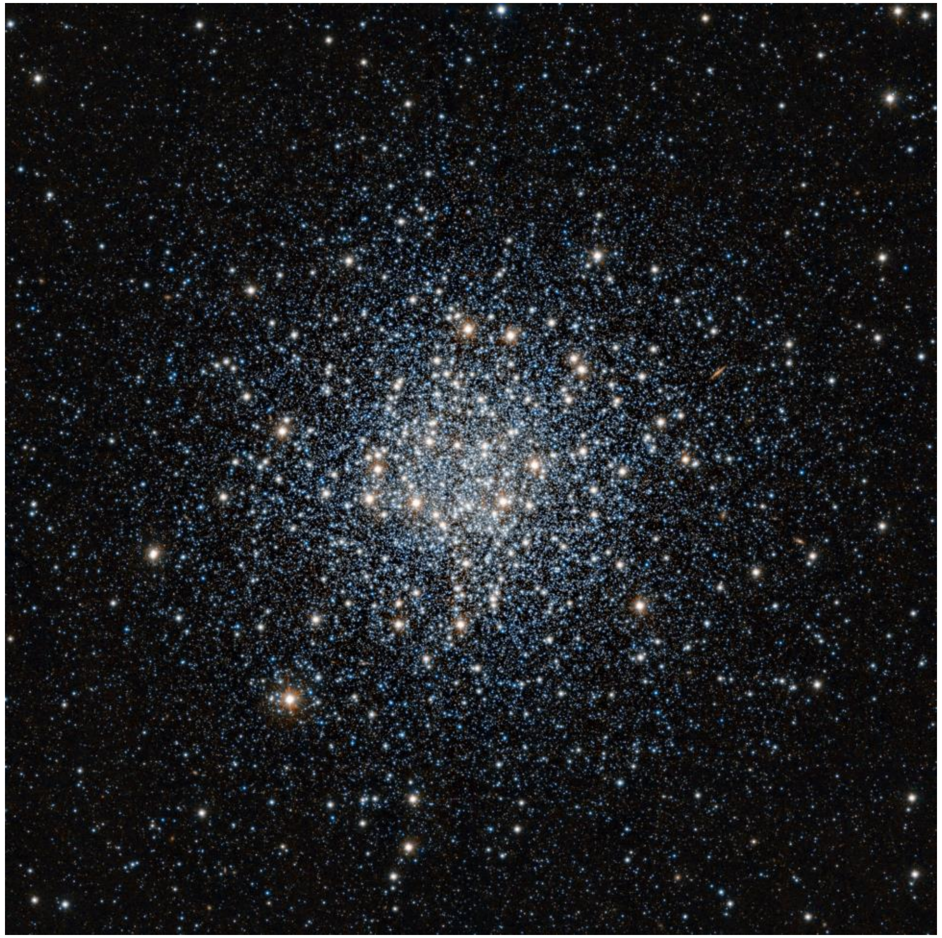
$$m_a \sim 10^{-7} eV, \qquad g_{a\gamma} \sim 10^{-11} GeV^{-1}$$

BUT

- Controversy about whether the effect exist.
- Other interpretations based on standard physics have been proposed.

Astrophysical motivations for axions

Stellar evolution



http://www.eso.org/public/images/eso1220a/

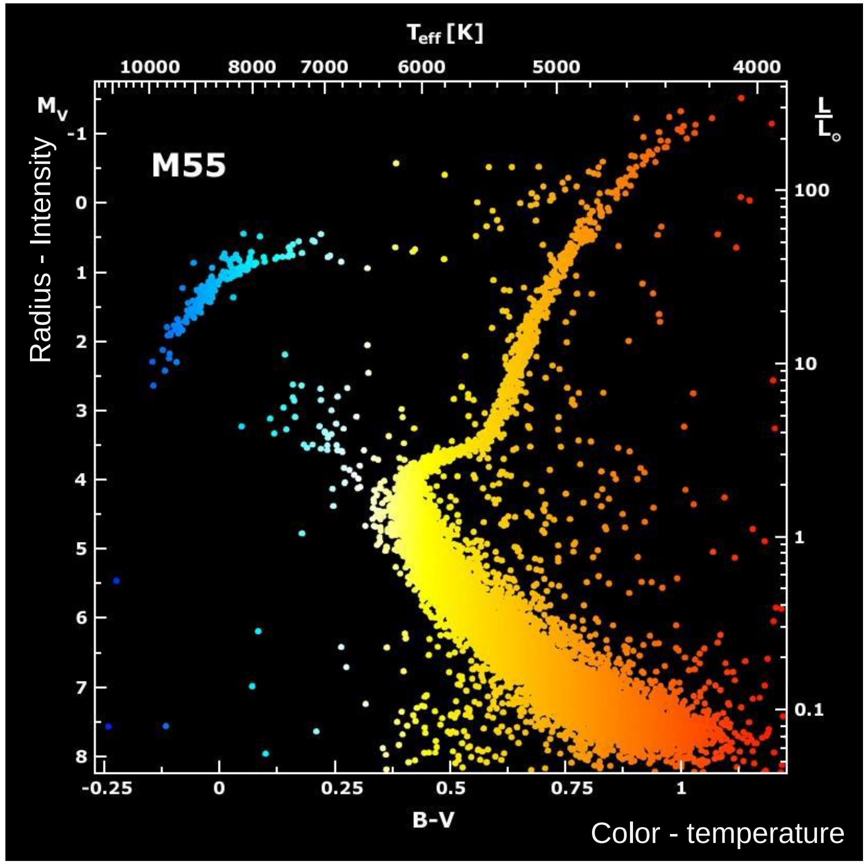
Globular cluster:

- Star population from a single cloud of gas.
- Uniform age.
- Not known active star formation.

Astrophysical motivations for axions

Stellar evolution

Hertzsprung–Russell diagram



Particle Physics Constraints from Stars, Georg G. Raffelt

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Astrophysical motivations for axions

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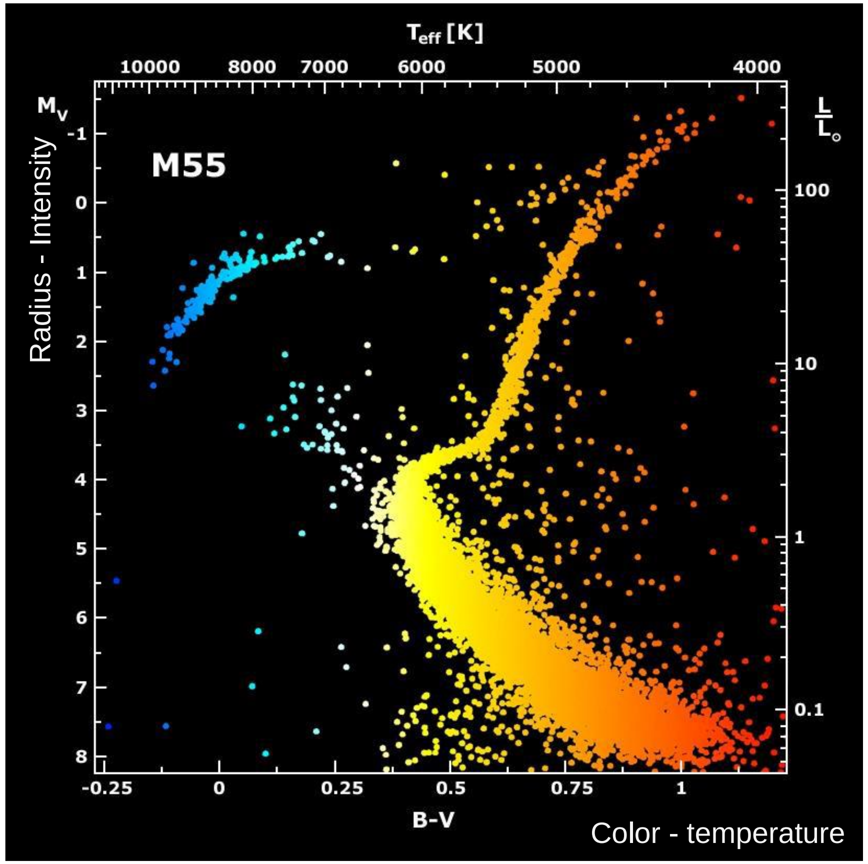

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⇓

Reflect age and initial mass

Astrophysical motivations for axions

Stellar evolution

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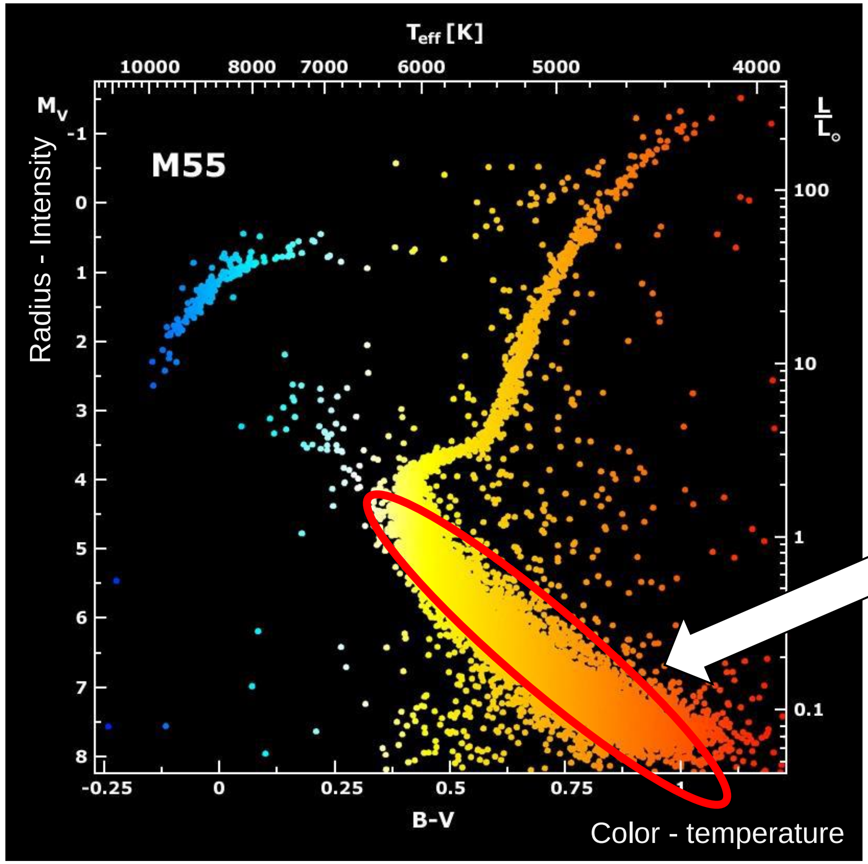
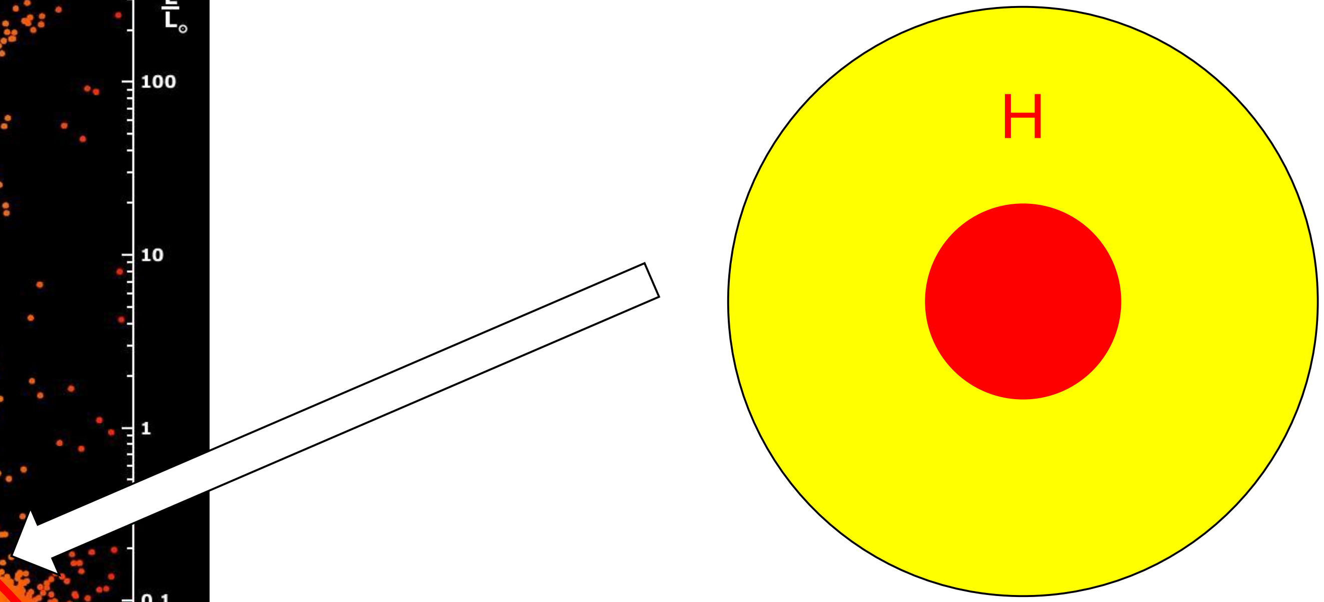


Particle Physics Constraints from Stars, Georg G. Raffelt

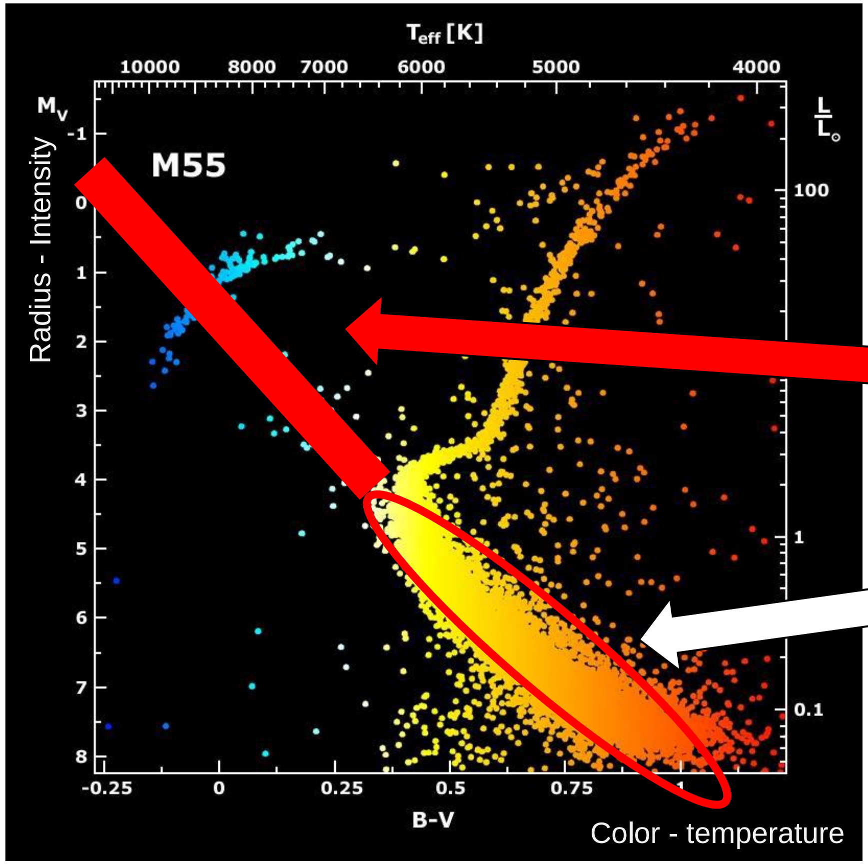
Main sequence



Astrophysical motivations for axions

Stellar evolution

Hertzsprung–Russell diagram



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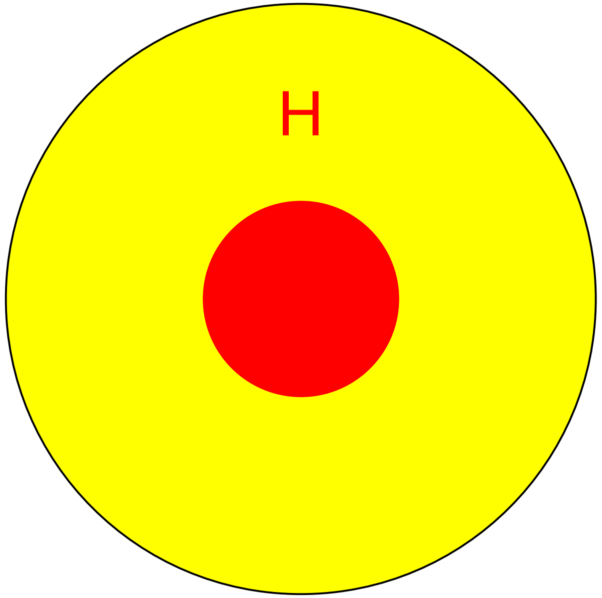
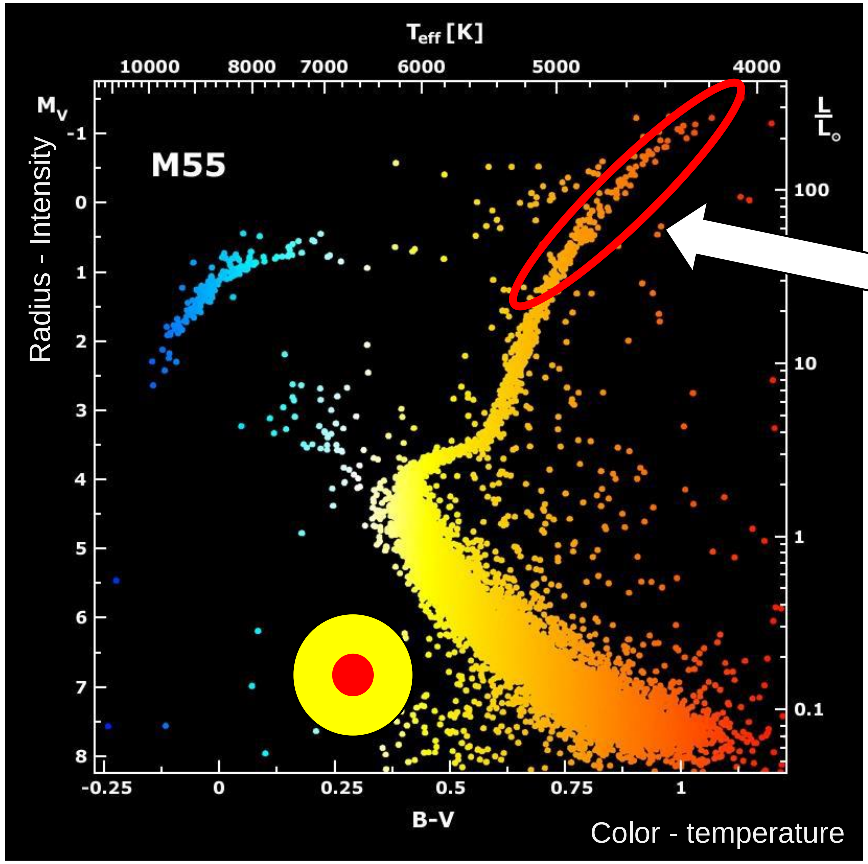


Massive stars live “only” millions of years

Astrophysical motivations for axions

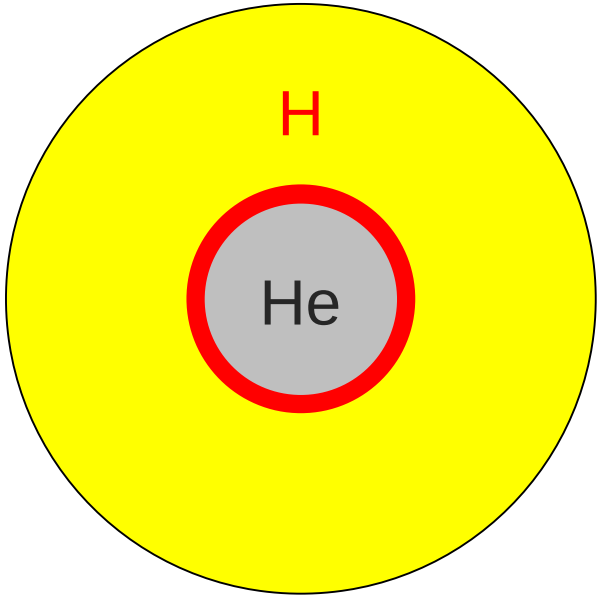
Stellar evolution

Hertzsprung–Russell diagram



Particle Physics Constraints from Stars, Georg G. Raffelt

Red Giant Branch (RGB)



Astrophysical motivations for axions

Stellar evolution

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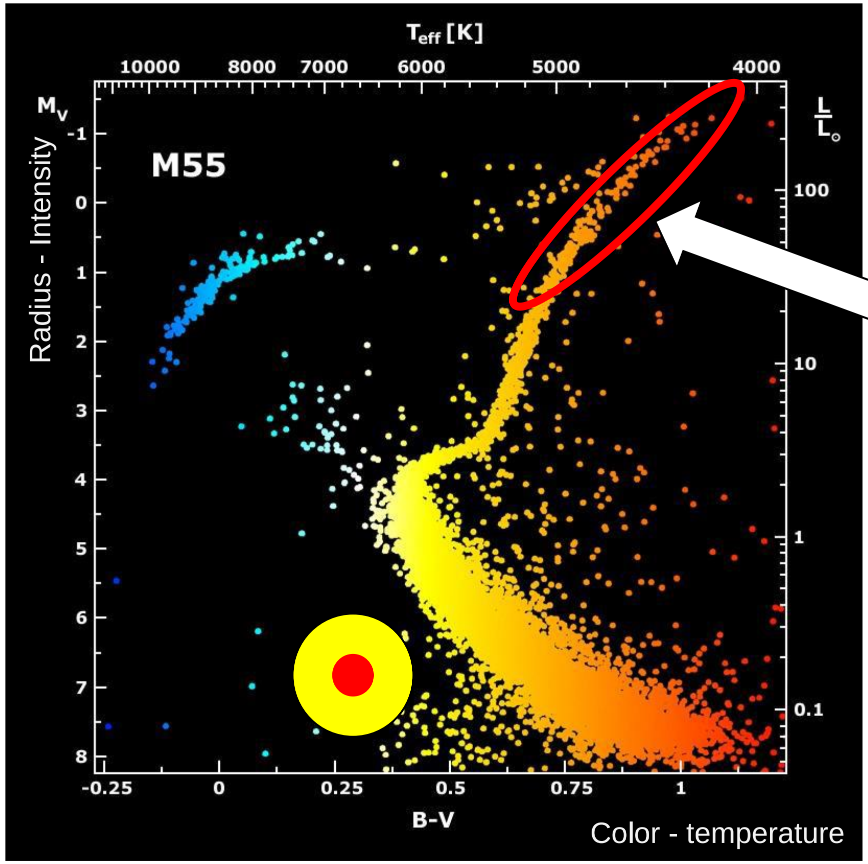

Particle Physics Constraints from Stars, Georg G. Raffelt

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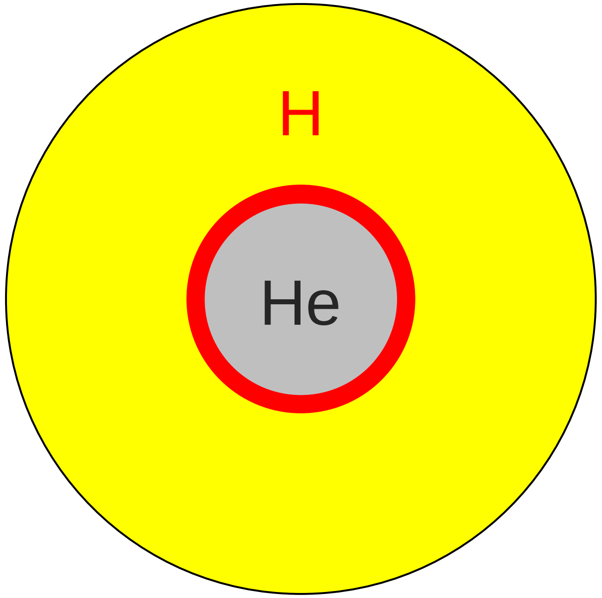
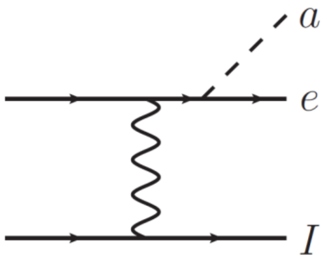


Particle emission delays He ignition (cooling).



In dense stellar interiors

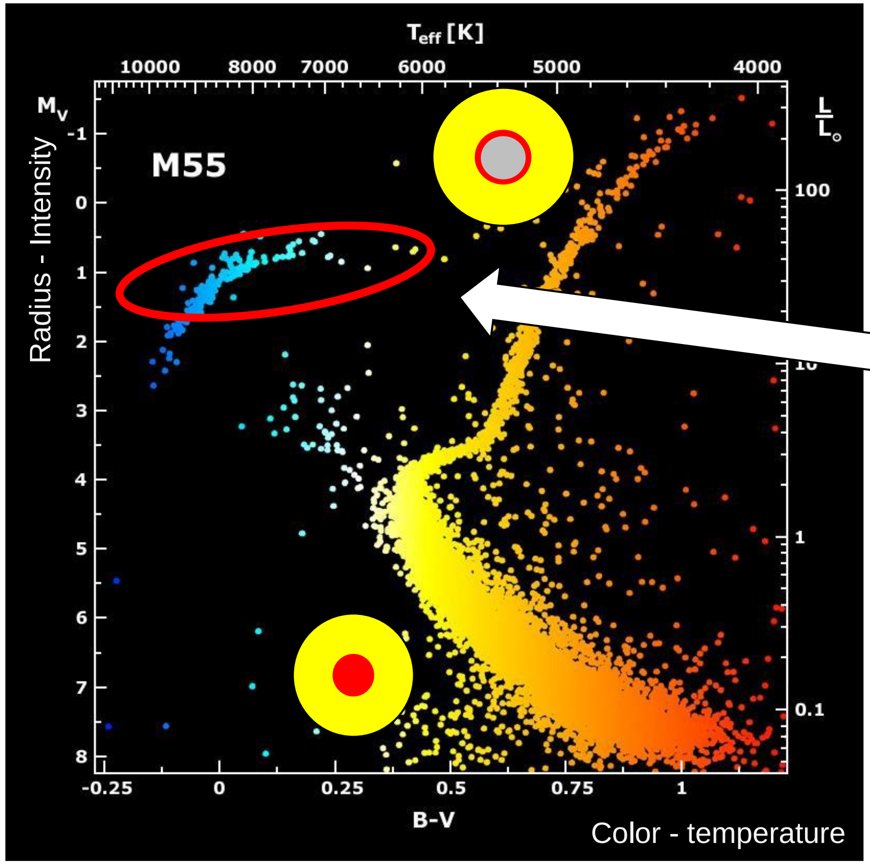
$$g_{ae} \neq 0$$

$$g_{ae} < 1.6 \times 10^{-13}\ \mathrm{GeV}^{-1}$$

Astrophysical motivations for axions

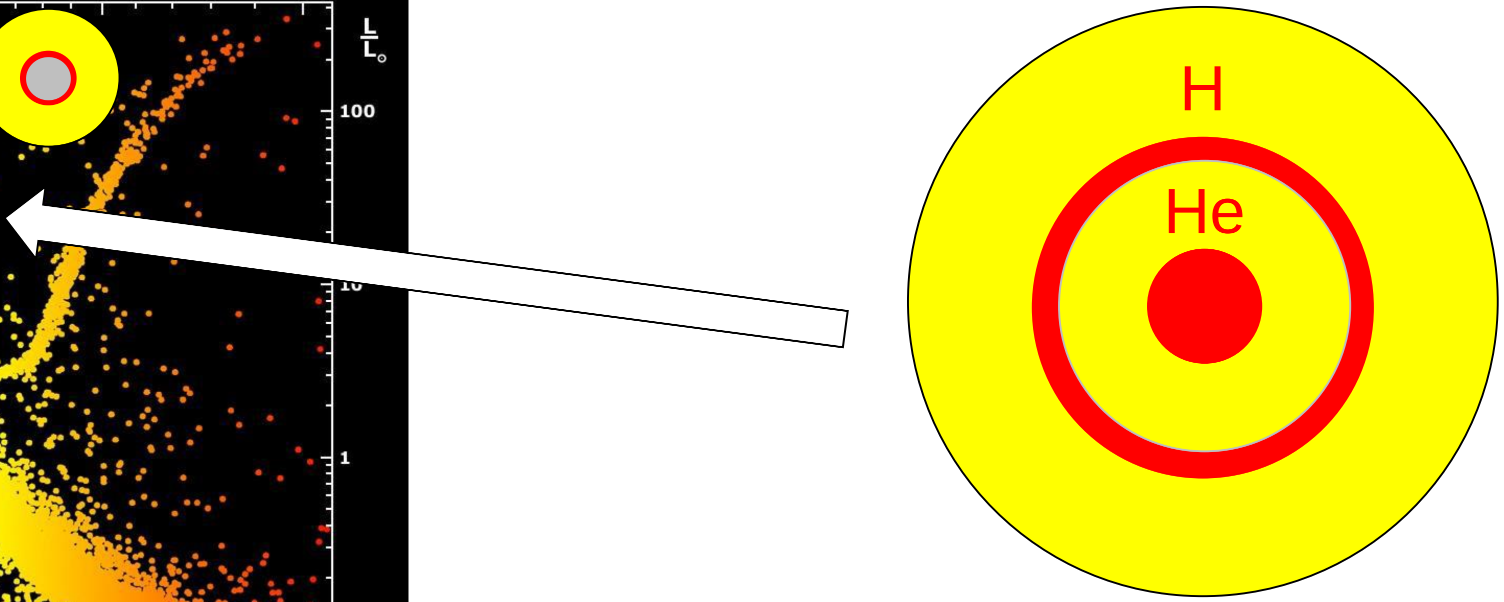
Stellar evolution

Hertzsprung–Russell diagram



Particle Physics Constraints from Stars, Georg G. Raffelt

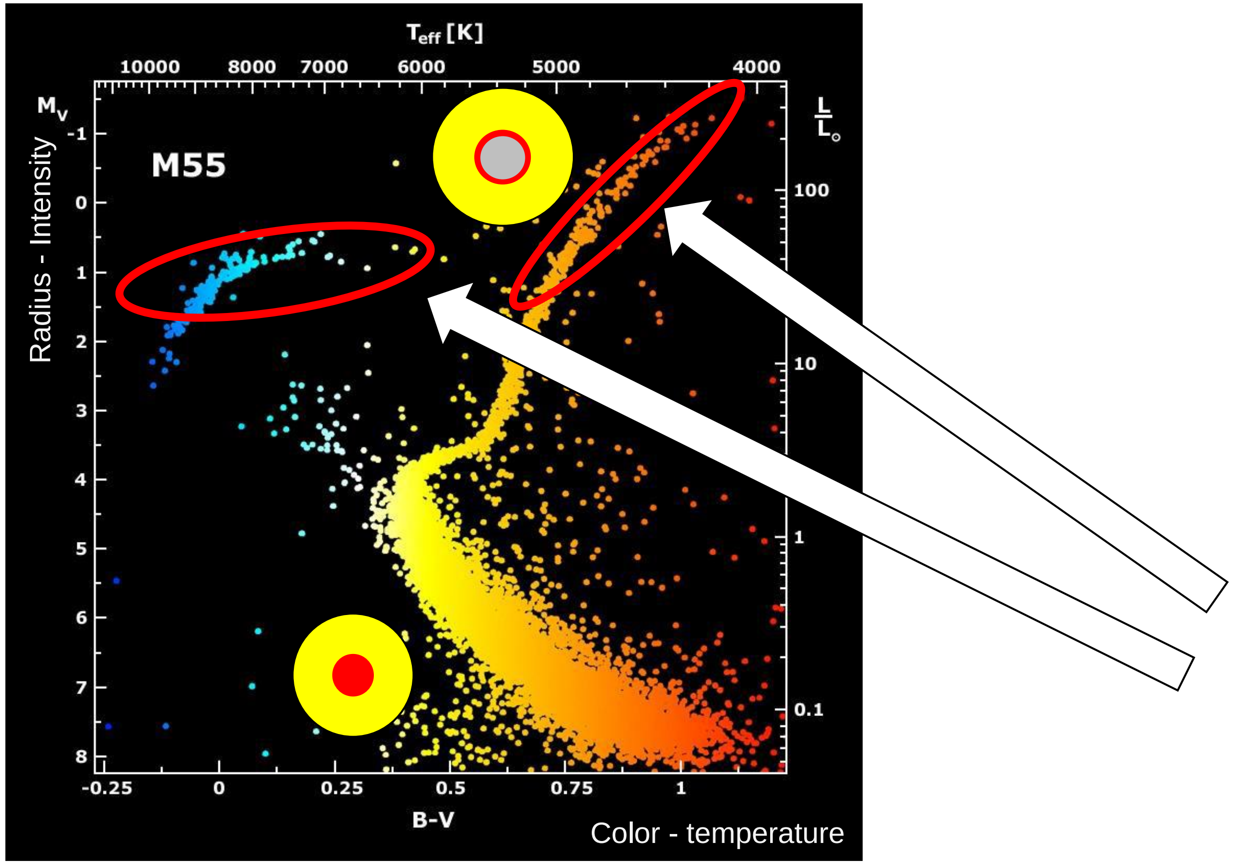
Horizontal Branch (HB)



Astrophysical motivations for axions

Stellar evolution

Hertzsprung–Russell diagram



Particle Physics Constraints from Stars, Georg G. Raffelt

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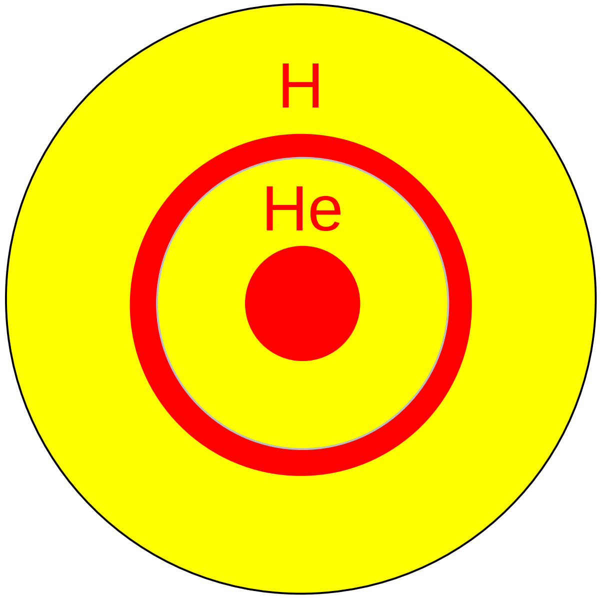


Particle emission reduces He burning time. (cooling)

$$R = N_{HB}/N_{RGB}$$

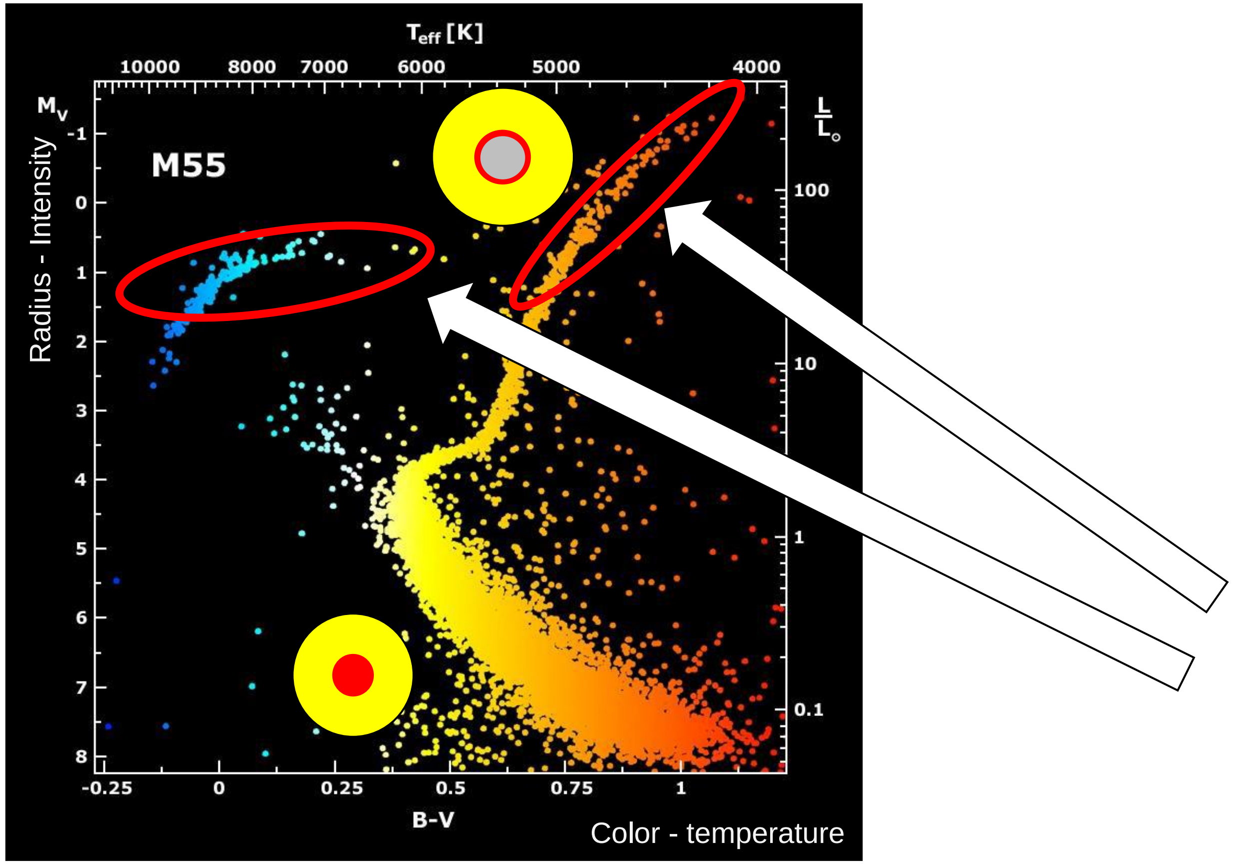
Expected: $1.44 < R < 1.50$

Measured: $R = 1.39 \pm 0.03$

Astrophysical motivations for axions

Stellar evolution

Hertzsprung–Russell diagram



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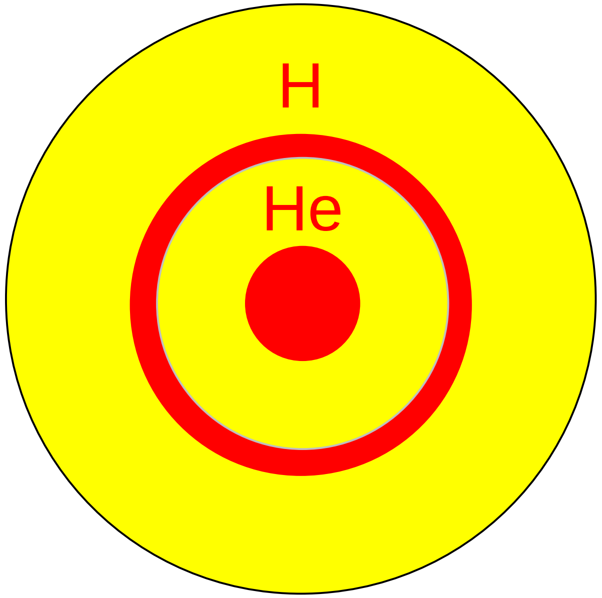
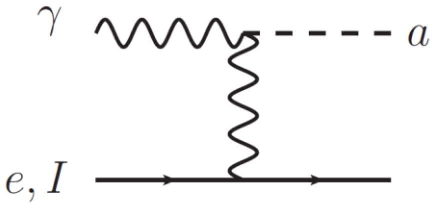


Particle emission reduces He burning time. (cooling)

$R = N_{HB}/N_{RGB}$

High number of thermal photons

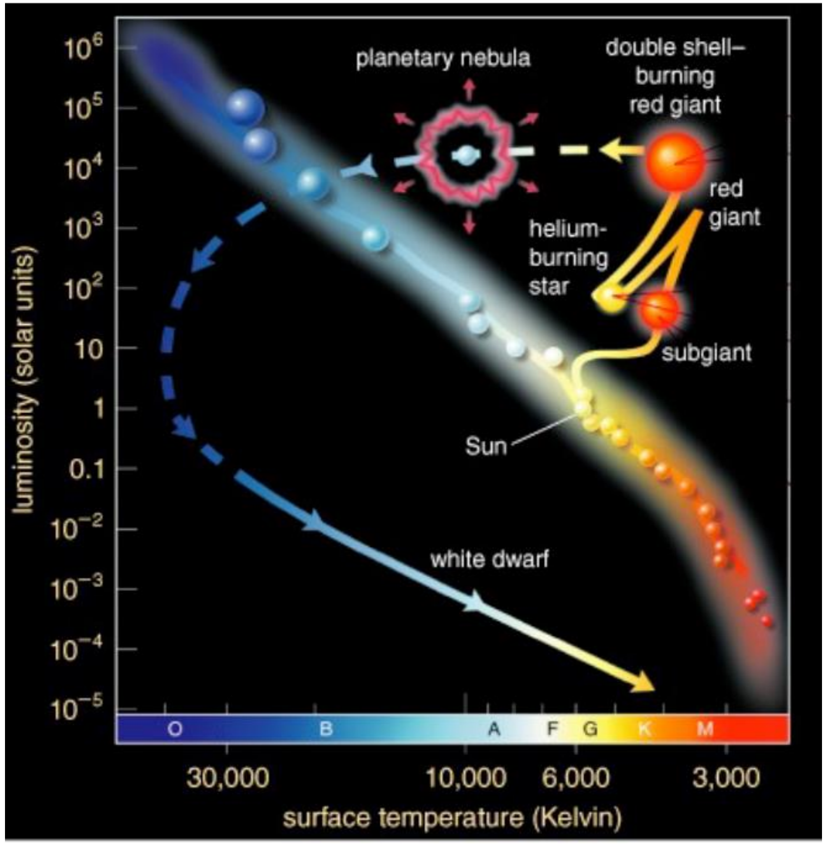


$$g_{a\gamma} = (0.29 \pm 0.18) \times 10^{-10}\ \text{GeV}^{-1}$$

Astrophysical motivations for axions

Stellar evolution

Hertzsprung–Russell diagram

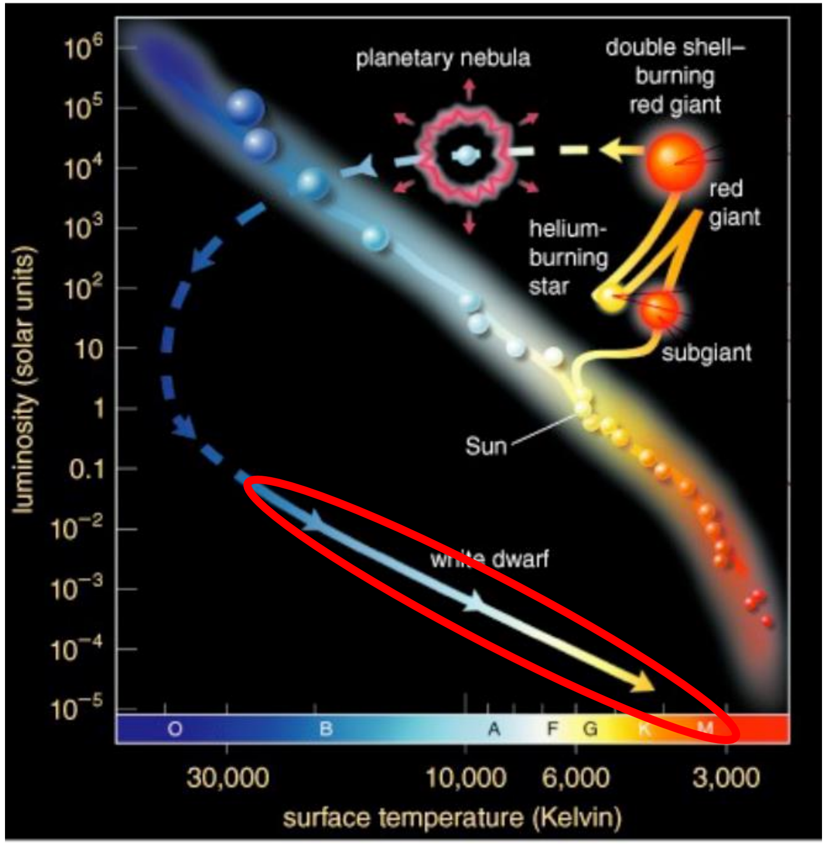


Astrophysical motivations for axions

Stellar evolution

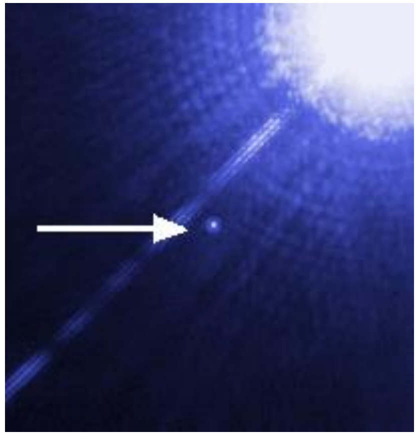
http://www.spacetelescope.org/images/heic0516a/

Hertzsprung–Russell diagram



[Copyright Addison Wesley]

White dwarf



- Luminosity changes with slowly changing period.

$$\frac{\dot{P}}{P} \propto \frac{\dot{T}}{T}$$

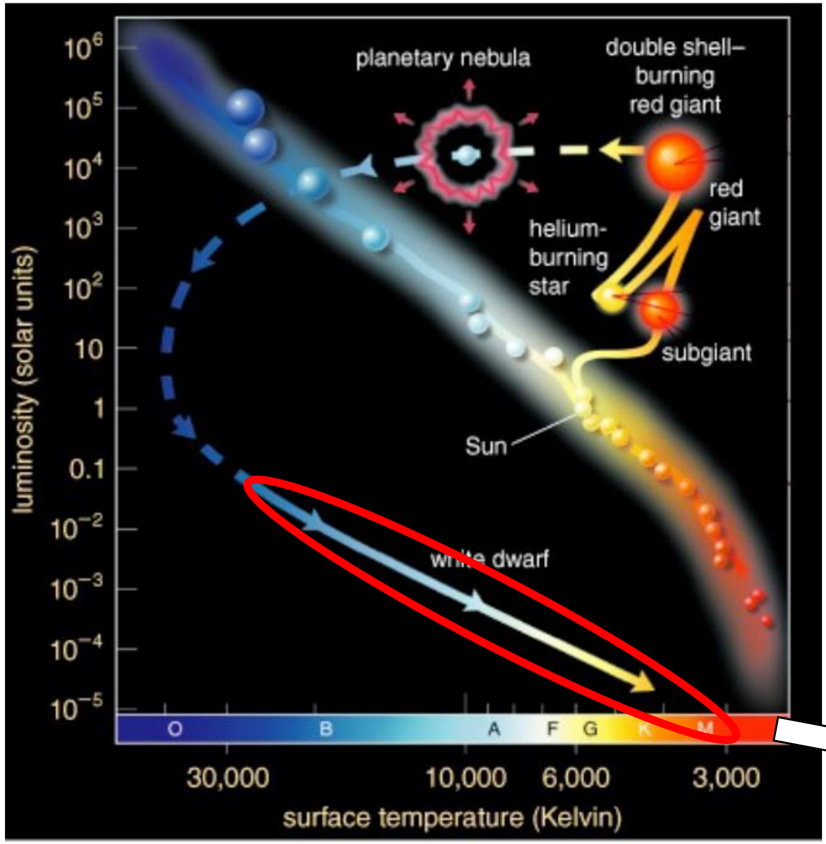
- Proportional to cooling rate.

Astrophysical motivations for axions

Stellar evolution

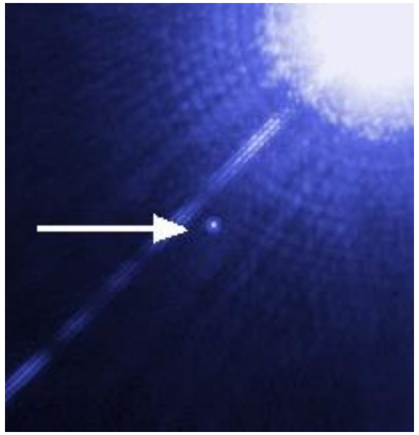
http://www.spacetelescope.org/images/heic0516a/

Hertzsprung–Russell diagram



[Copyright Addison Wesley]

White dwarf



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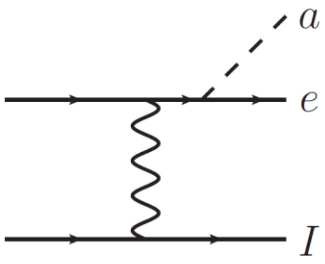


Dense core

Anomalous cooling

$$g_{ae} \sim 10^{-13}\ \text{GeV}^{-1}$$

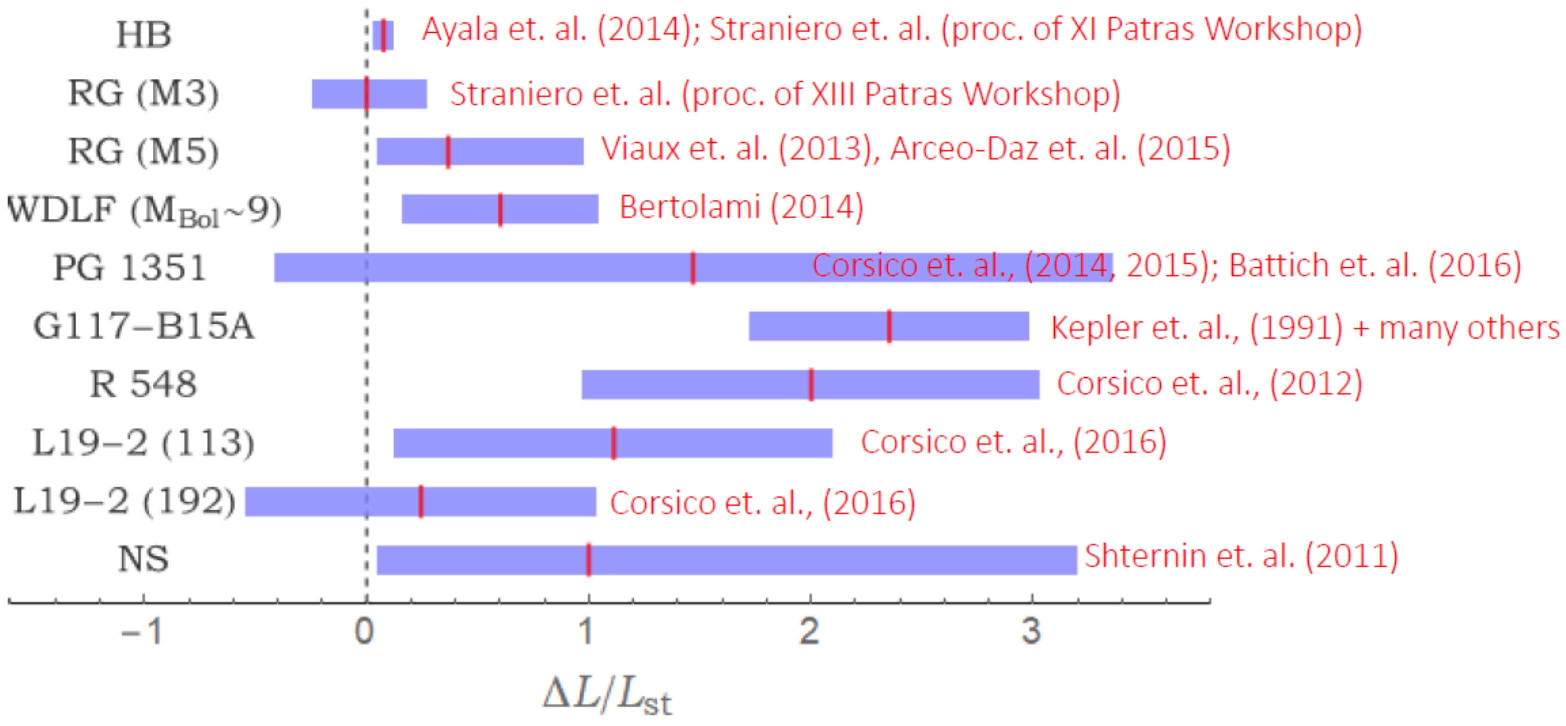
RGB + white dwarf hints:

$$g_{ae} = (1.6^{+0.29}_{-0.34}) \times\ 10^{-13}\text{GeV}^{-1}$$

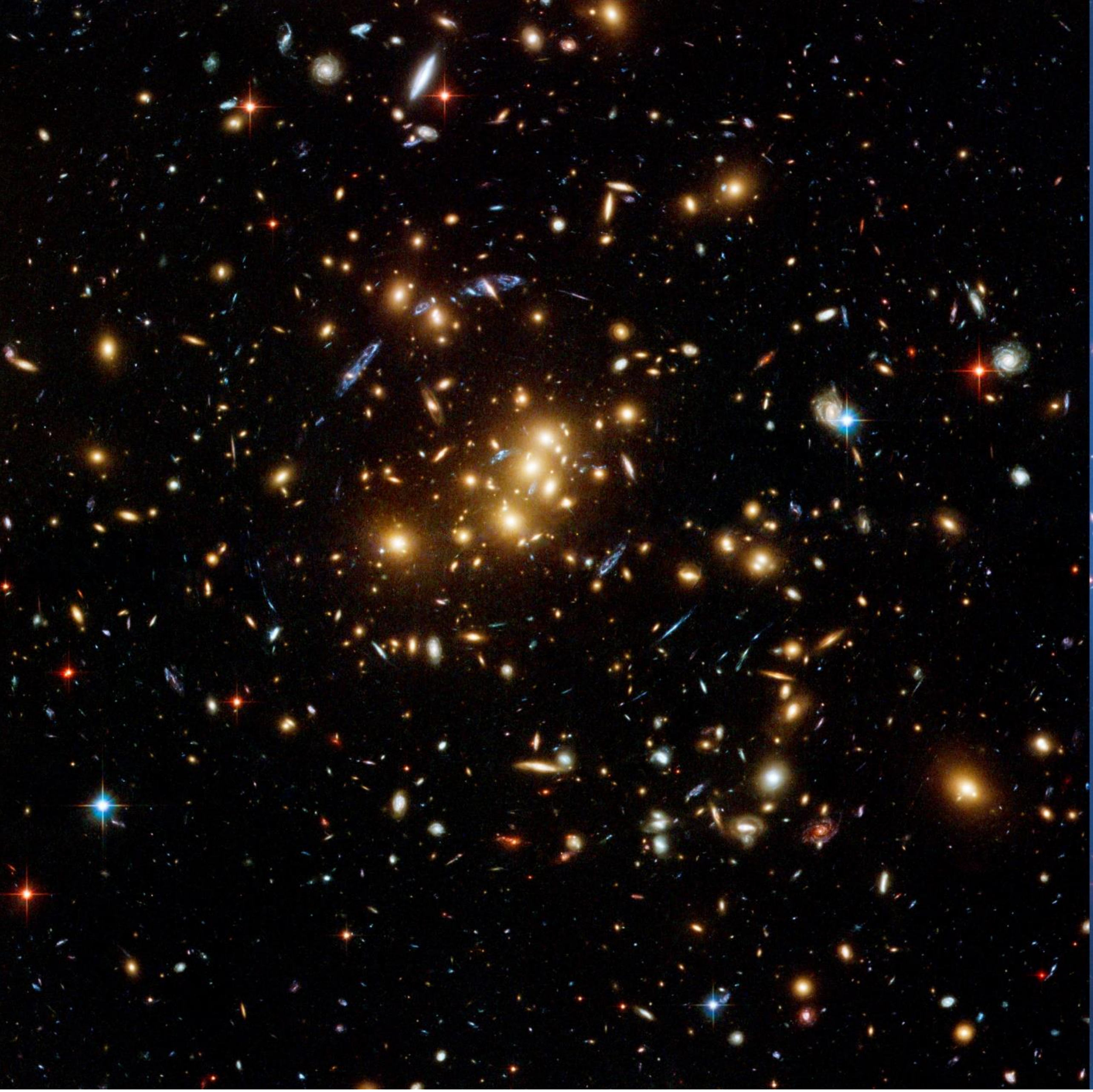
Astrophysical motivations for axions

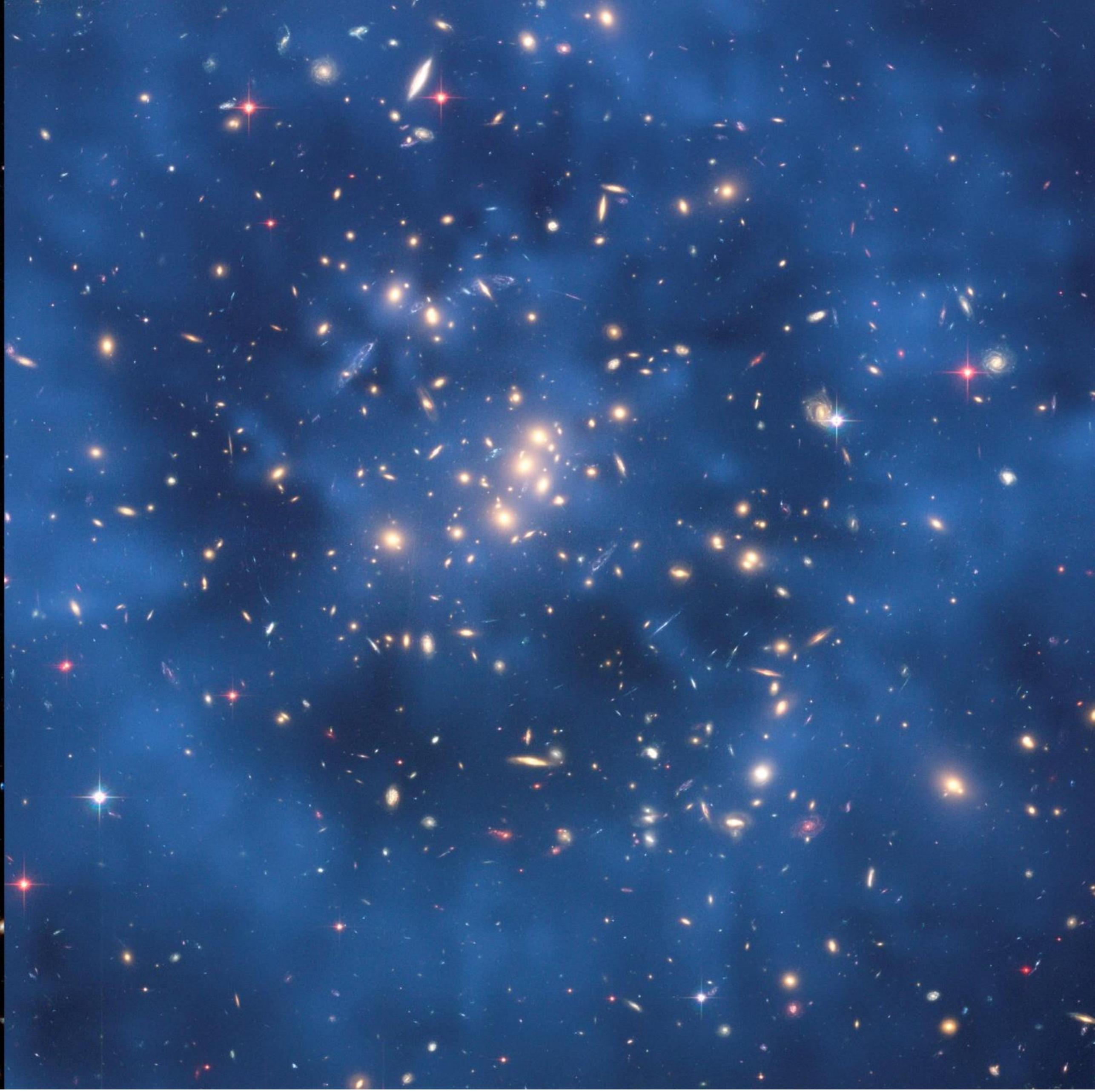
Stellar evolution

- Stellar systems seem to be cooling faster than predicted.
- Hints for new physics.



Axions/ALPs could provide a simple explanation to all of them!





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

Summary

Dark matter in the universe

- is very likely to exist (we do not have good alternatives),
- is expected to exist by theories beyond the standard model of particle physics.

Axions and axion-like particles

- are motivated by the time reversal symmetry of QCD and string-theories,
- might make up all of the dark matter in the universe,
- might be searched for via photon-axion mixing in magnetic fields.

The existence of axions is hinted at by

- the propagation of high energy photons in the universe,
- the evolution of stars.

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