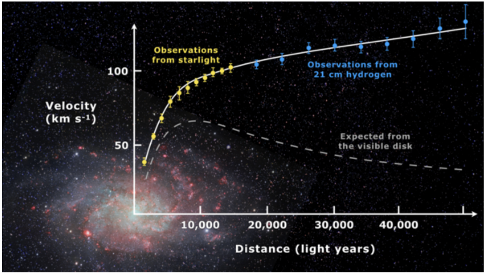
Bari,

19^{th} September 2023

Feebly Interacting Particles: A new paradigm for the dark universe

Pierluca Carenza
OKC, Stockholm University

The dark Universe: dark matter from galaxy rotation curves



SOME PROBLEMS CONCERNING THE STRUCTURE AND DYNAMICS OF THE GALACTIC SYSTEM AND THE ELLIPTICAL NEBULAE NGC 3115 AND 4494[1]

J. H. OORT

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ROTATIONAL PROPERTIES OF 21 Sc GALAXIES WITH A LARGE RANGE OF LUMINOSITIES AND RADII, FROM NGC 4605 ($R = 4$ kpc) TO UGC 2885 ($R = 122$ kpc)

Vera C. Rubin,[1,2] W. Kent Ford, Jr.,[1] and Norbert Thonnard
Department of Terrestrial Magnetism, Carnegie Institution of Washington
Received 1979 October 11; accepted 1979 November 29

Galaxies without DM?

Published: 29 March 2018

A galaxy lacking dark matter

Pieter van Dokkum, Shany Danieli, Yotam Cohen, Allison Merritt, Aaron J. Romanowsky, Roberto Abraham, Jean Brodie, Charlie Conroy, Deborah Lokhorst, Lamiya Mowla, Ewan O'Sullivan & Jielai Zhang

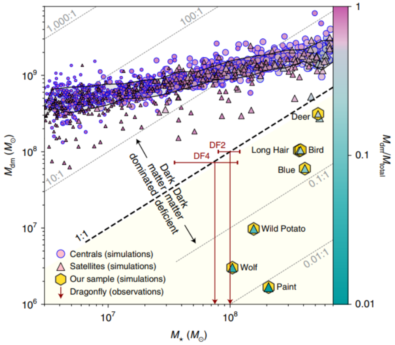
Nature **555**, 629–632 (2018) | Cite this article

Current Velocity Data on Dwarf Galaxy NGC 1052-DF2 do not Constrain it to Lack Dark Matter

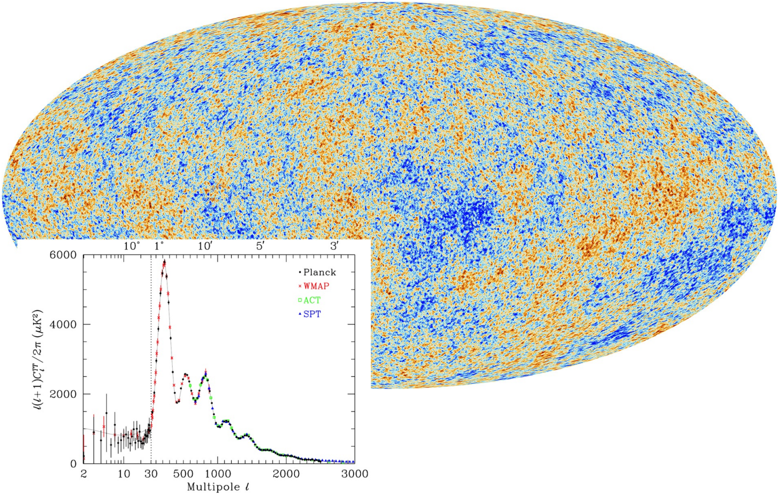
Nicolas F. Martin[1,2], Michelle L. M. Collins[3], Nicolas Longeard[1], and Erik Tollerud[4]

Published 2018 May 17 •

The Astrophysical Journal Letters, Volume 859, Number 1

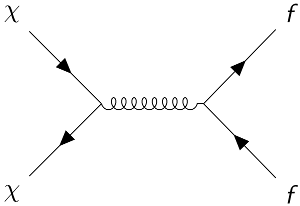


The dark Universe: dark matter from CMB

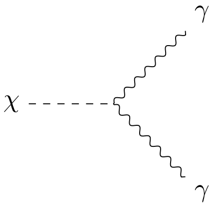


DM properties: Effectively Dark

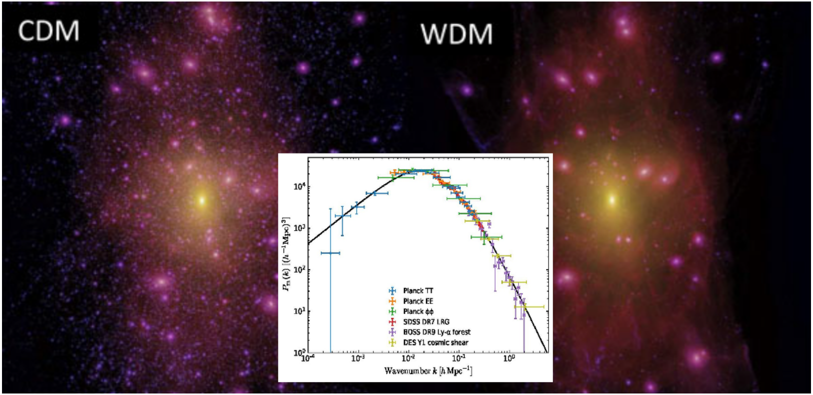
Suppressed interactions with SM particles:
signals in direct detection experiment



Suppressed decay rate:
indirect signatures & life longer than 13.7 Gyr



DM properties: Cold

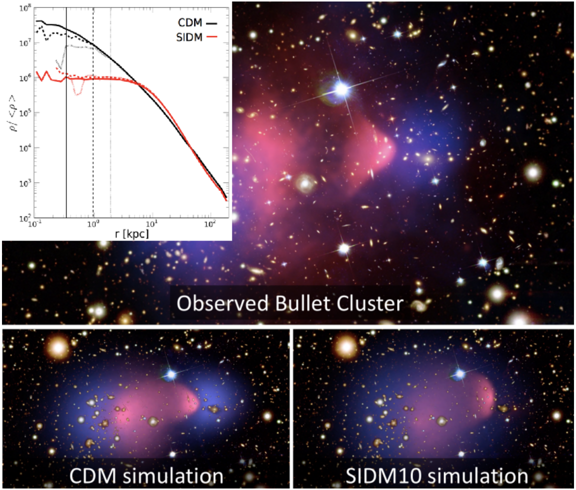


Namely, at the cosmological level DM is pressureless $p = 0$

DM properties: Almost collisionless

S. Adhikari *et al.* [arXiv:2207.10638 [astro-ph.CO]].

Observations require $\sigma/m_{DM} \lesssim 0.1\ \mathrm{cm^2 g^{-1}}$



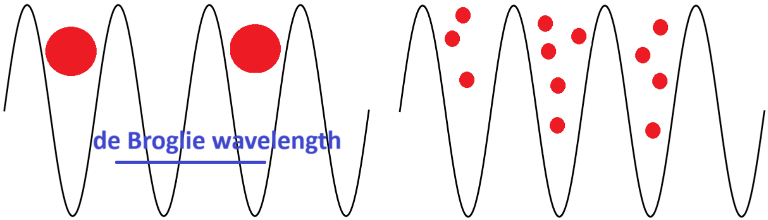
DM unkown properties: Particle or Wave?

Average inter-particle separation is

$$L \simeq 13\ \mu\mathrm{m} \left(\frac{m}{30\ \mathrm{eV}}\right)^{1/3}$$

DM de Broglie wavelength

$$\lambda \simeq 50\ \mu\mathrm{m} \left(\frac{m}{30\ \mathrm{eV}}\right)^{-1} \left(\frac{250\ \mathrm{km\,s^{-1}}}{v}\right)$$



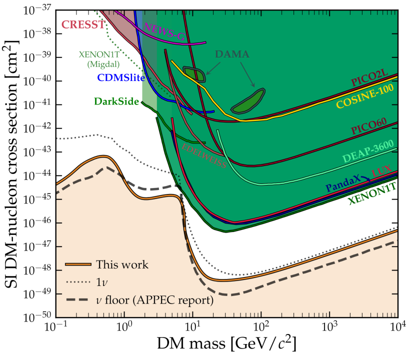
Some DM candidates: WIMPs

C. A. J. O'Hare, Phys. Rev. Lett. **127** (2021) no.25, 251802

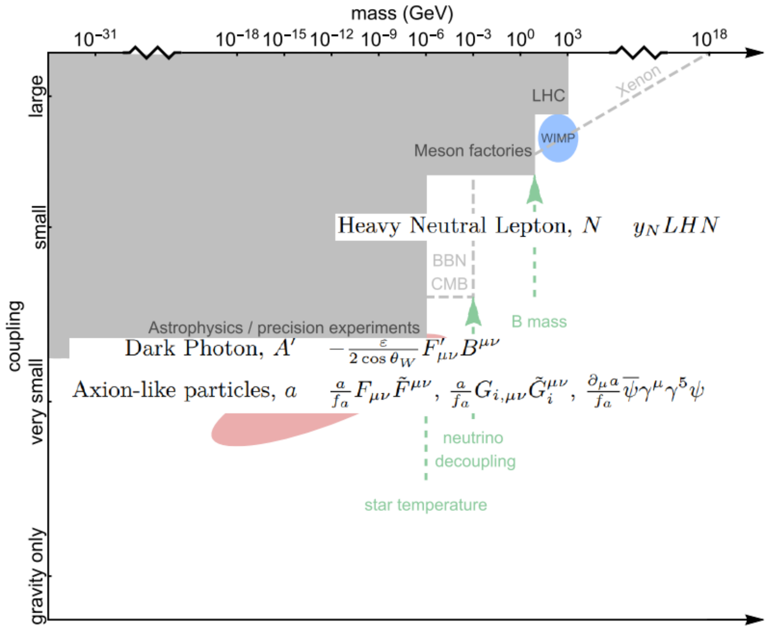
The WIMP miracle...

$$\Omega h^2 \simeq 0.12 \times \left(\frac{3 \times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle \sigma v \rangle} \right)$$

... and the most optimistic status for WIMP searches



An alternative: the FIP paradigm

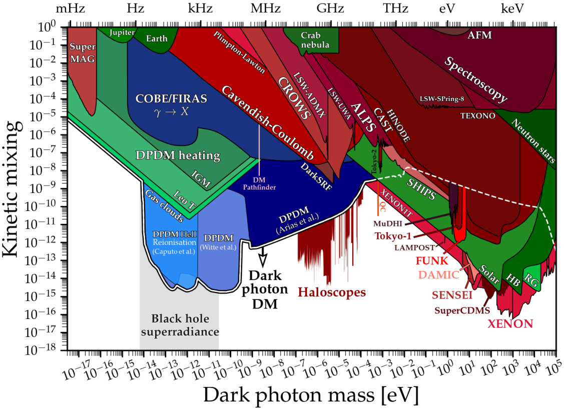


Dark Photons

A. Caputo *et al.*, Phys. Rev. D **104** (2021) no.9, 095029

Kinetic mixing between electromagnetism and an extra $U(1)$

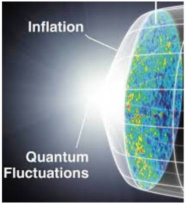
$$\mathcal{L} = -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$



Dark photon DM: production mechanism

P. W. Graham *et al.*, Phys. Rev. D **93** (2016) no.10, 103520

Inflationary production, just like primordial Gravitational Waves



$$S = \int \sqrt{|g|}\, d^3x\, dt \Big(-\frac{1}{4} g^{\mu\kappa} g^{\nu\lambda} F_{\mu\nu} F_{\kappa\lambda} - \frac{1}{2} m^2 g^{\mu\nu} A_\mu A_\nu \Big)$$

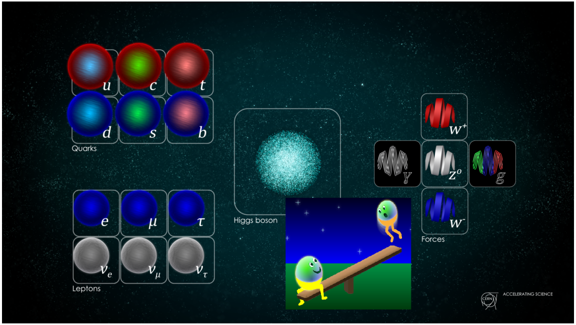
$$\Omega_A = \Omega_{\rm cdm} \times \sqrt{\frac{m}{6 \times 10^{-6}\,{\rm eV}}} \left(\frac{H_I}{10^{14}\,{\rm GeV}} \right)^2$$

Only gravitational interaction is required...

A nightmare scenario

Sterile neutrinos: motivations

Why neutrinos are massive?



$$\mathcal{L}_{mass} = (m_l)_{ij}\,\bar{l}_{iL} l_{jR} + (m_D)_{ij}\,\bar{\nu}_{iL}\nu_{jR} + \frac{1}{2}(M_R)_{ij}\,\nu_{iR}^T C \nu_{jR} + h.c.$$

Dirac mass $m_D \simeq 100$ GeV
Majorana mass for sterile-ν $M_R \simeq 10^{16}$ GeV

Surprisingly $m_\nu \simeq \frac{m_D^2}{M_R} \simeq \mathcal{O}(10^{-3})$ eV!

Sterile neutrino DM: thermal production

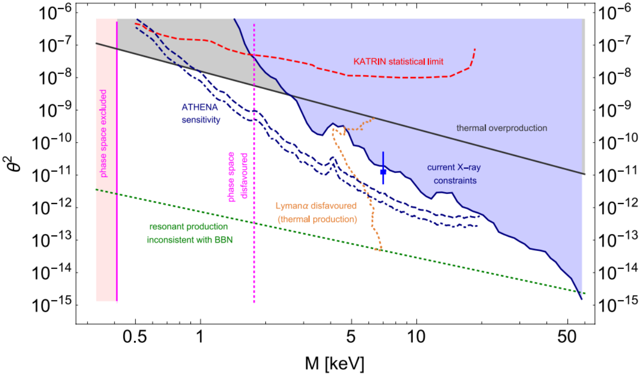
A. Boyarsky *et al.*, Prog. Part. Nucl. Phys. **104** (2019), 1-45

Combination of oscillations

$$|\nu_1\rangle = \cos\theta|\nu_a\rangle + \sin\theta|\nu_s\rangle$$

and thermal production

$$\nu_a e^{\pm} \to \nu_s e^{\pm} \quad \nu_a \nu_a \to \nu_s \nu_a$$



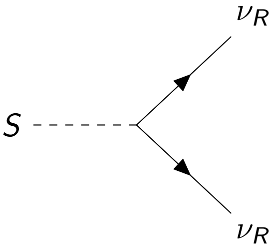
Sterile neutrino DM: non-thermal production

K. N. Abazajian and A. Kusenko, Phys. Rev. D **100** (2019) no.10, 103513

If the Majorana mass is due to a singlet S

$$\mathcal{L} \sim f_{NN}\, S\, \nu_R^T C \nu_R$$

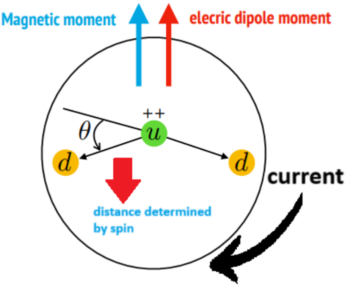
with $f_{NN} \sim 10^{-8}$ and $\langle S \rangle \simeq \mathcal{O}(100)$ GeV

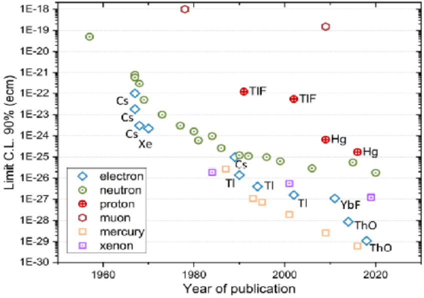


keV Sterile Neutrino Miracle!

Axions and Axion-Like Particles

Pic of a neutron and its Electric Dipole Moment





$$\mathcal{H} \propto \mathbf{d} \cdot \mathbf{E} \xrightarrow{\mathrm{C}} (-\mathbf{d}) \cdot (-\mathbf{E}) \xrightarrow{\mathrm{P}} (-\mathbf{d}) \cdot \mathbf{E}$$

The strong CP problem

The QCD Lagrangian includes a CP-odd term

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{QCD}} - \bar{\theta}_{\mathrm{QCD}} \frac{g^2}{32\pi^2} \mathrm{tr}\, \tilde{G}_{\mu\nu} G^{\mu\nu}$$

where $\tilde{G}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta} G^{\alpha\beta}$ and $\bar{\theta}_{\mathrm{QCD}} = \theta_{\mathrm{QCD}} + \arg\det M_{\mathrm{quark}}$

Prediction of neutron electric dipole moment
$d_n \approx |\bar{\theta}_{\mathrm{QCD}}| \times 10^{-15}\, e\,\mathrm{cm}$
Experimental bound: $|\bar{\theta}_{\mathrm{QCD}}| < 10^{-10}$
Naturalness problem, why $\bar{\theta}_{\mathrm{QCD}}$ is so small?

The Peccei-Quinn mechanism

R. D. Peccei *et al.*, Phys. Rev. Lett. **38** (1977)

PQ symmetry
$U(1)_{PQ}$ is a chiral global symmetry that drives dynamically $\bar{\theta}_{PQ} \to 0$

$U(1)_{PQ}$ is broken at a scale f_a, the **Peccei-Quinn scale**, and the Goldstone boson is the **axion**

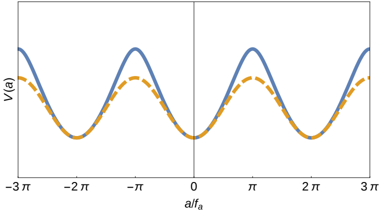
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QCD}} - \zeta \frac{a}{f_a} \frac{g^2}{32\pi^2} \, \text{tr} \, \tilde{G}_{\mu\nu} G^{\mu\nu}$$

The minimum condition removes the CP-odd term: $\bar{\theta}_{\text{QCD}} = 0$

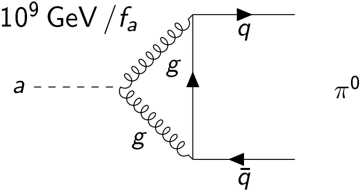
Axion mass

G. Grilli di Cortona *et al.*, JHEP **1601** (2016)

At $T < \Lambda_{\mathrm{QCD}}$ the axion move in a periodic gluon potential, near the minimum the axion acquires a small mass



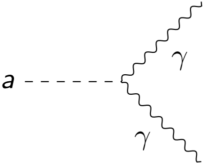
$a - \pi^0$ mixing: $m_a = 5.7\,\mathrm{meV} \times 10^9\ \mathrm{GeV}\,/f_a$



Low-energy axion-SM interactions

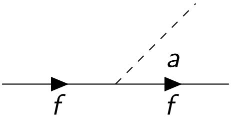
Axion-photon vertex

$$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} a \, F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma} a \, \mathrm{E} \cdot \mathrm{B} \quad g_{a\gamma} = C_\gamma \frac{\alpha}{2\pi f_a}$$



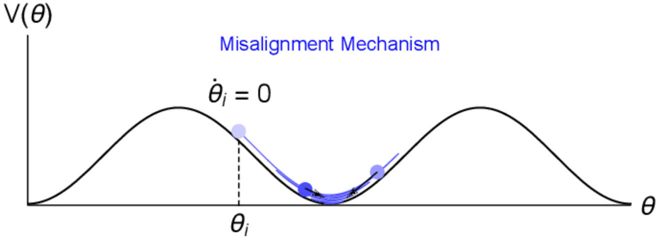
Axion-fermion vertex

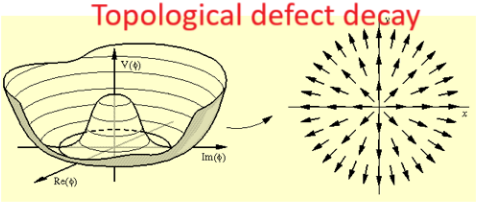
$$\mathcal{L}_{af} = \frac{g_{af}}{2m_f} \bar{\Psi} \gamma^\mu \gamma^5 \Psi \, \partial_\mu a \quad g_{af} = C_f \frac{m_f}{f_a}$$



Axion DM

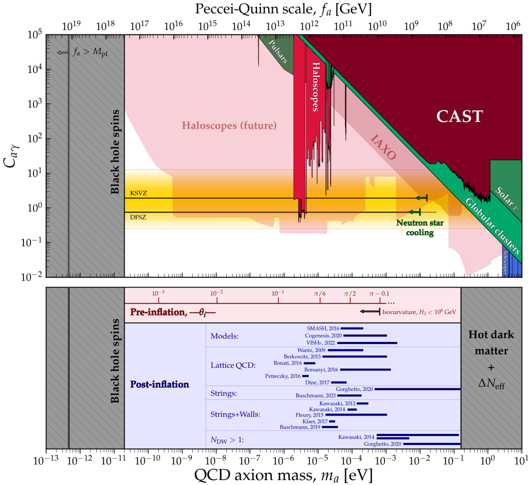
The QCD potential determines the DM production mechanisms





Parameter space of axion DM

F. Chadha-Day *et al.*, Sci. Adv. **8** (2022) no.8, abj3618



Axions and Axion-Like Particles

In any axion model

$$m_a \sim \frac{1}{f_a} \quad g_{a\gamma} \sim \frac{1}{f_a} \quad f_a \gg 246\,\text{GeV}$$

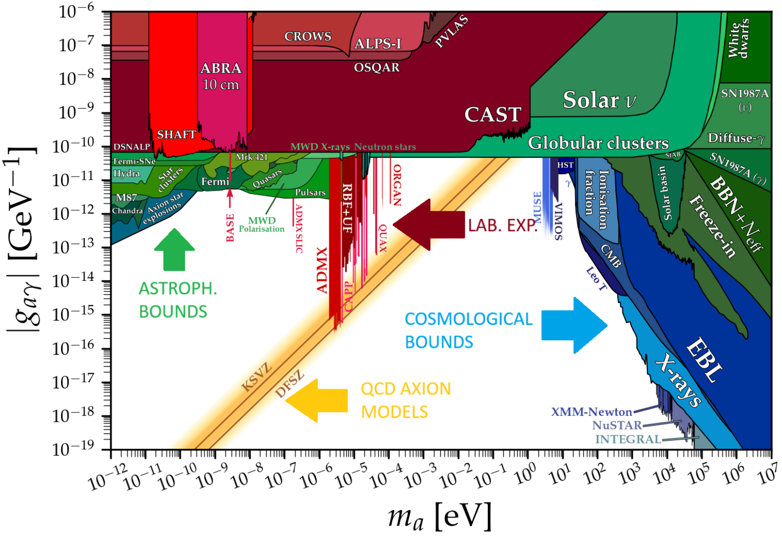
The typical QCD axion is **light** and **weakly interacting**

Axion-Like Particles (ALPs) are a generalization:

- Heavy ALP searches at collider
- Superlight ALPs as fuzzy Dark Matter
- eV-scale ALPs as Warm Dark Matter
- Some ALPs could be the inflaton
- ALPs in flavor-violating processes

Status of axion searches in 2023

https://cajohare.github.io/AxionLimits/



Axion detection

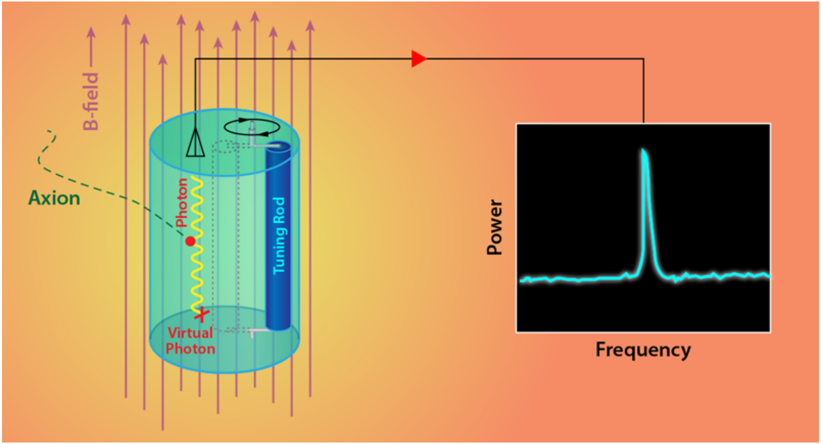
P. Sikivie, Phys. Rev. Lett. **51** (1983)

Axions can be detected by axion-photon conversion in an external magnetic field

- **Haloscopes**: DM axions
  ADMX and MADMAX
- **Helioscopes**: solar axions
  CAST and the future IAXO

Haloscopes

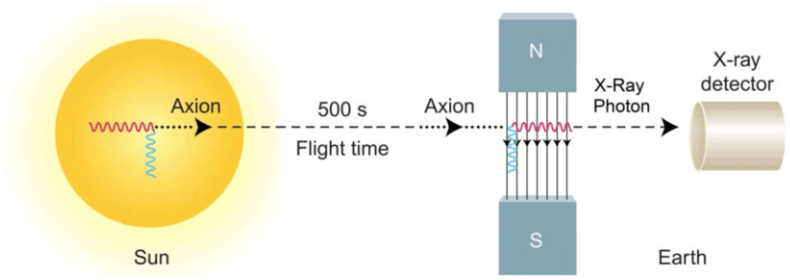
DM axions convert into photons in magnetic fields



ADMX

Helioscopes

Axions are produced in the Sun via Primakoff effect in microscopic magnetic fields...



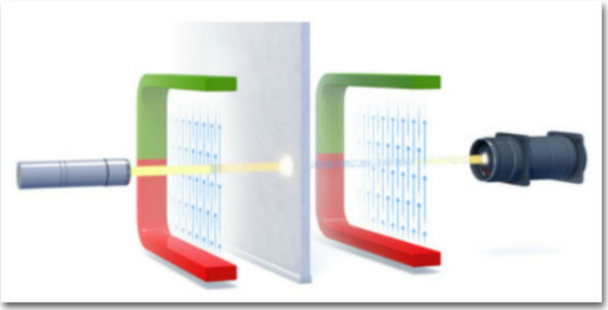
... and they convert into photons in macroscopic magnetic fields

CAST

Light Shining Through the Wall

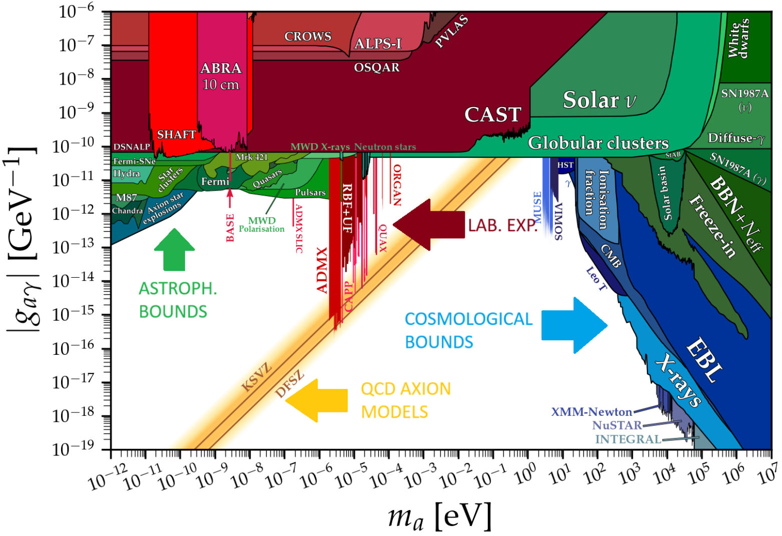
R. Bähre *et al.*, JINST **8** (2013), T09001

Purely lab-based experiment, no assumptions

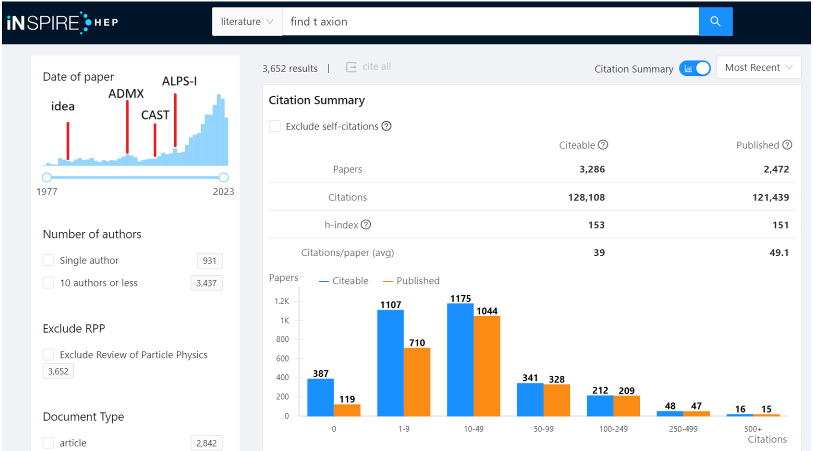


Pushing the development of single-photon detectors

Status of axion searches in 2023: Laboratory searches

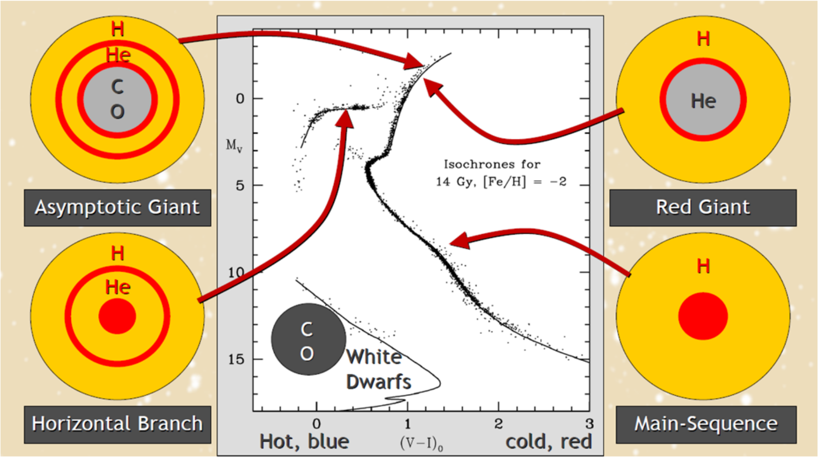


The axion-explosion in 2010-now



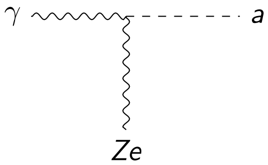
HR diagram

Diagram of stars with the same age and different initial masses

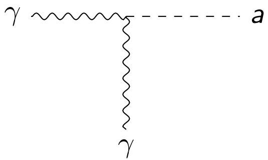


HB stars: axion production

The main processes are Primakoff conversion



and Inverse Decay



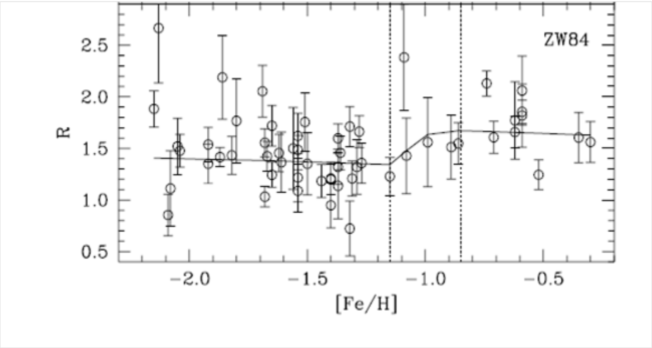
Bound on the R parameter

M. Salaris *et al.*, Astron. Astrophys. **420** (2004), 911-919

Observations on Globular Clusters measure the R parameter

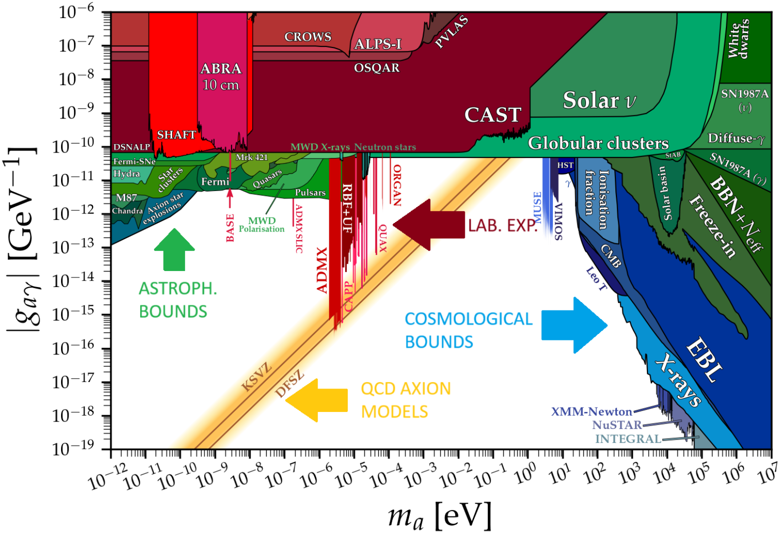
$$R = \frac{N_{\rm HB}}{N_{\rm RGB}} = \frac{\tau_{\rm HB}}{\tau_{\rm RGB}} = 1.39 \pm 0.03$$

The duration of the HB phase can be reduced at most of $\sim 15\%$



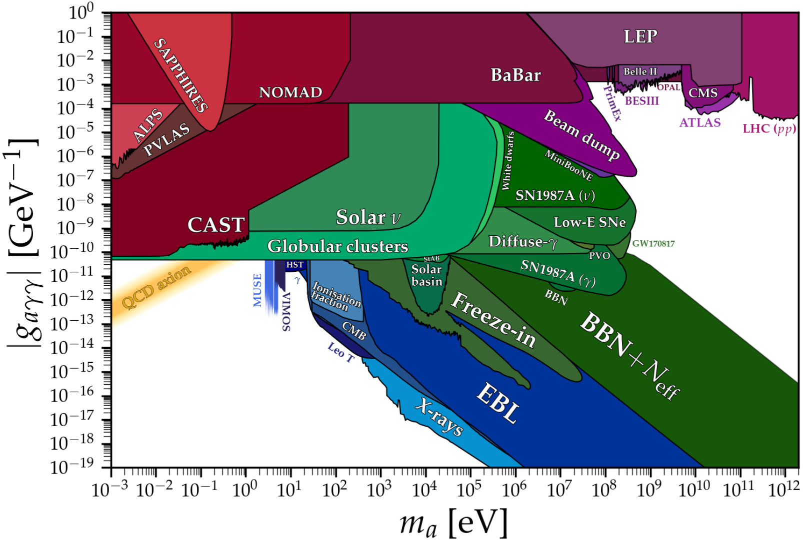
Status of axion searches in 2023:
Globular Cluster bound

A. Ayala *et al.*, Phys. Rev. Lett. **113** (2014) no.19, 191302

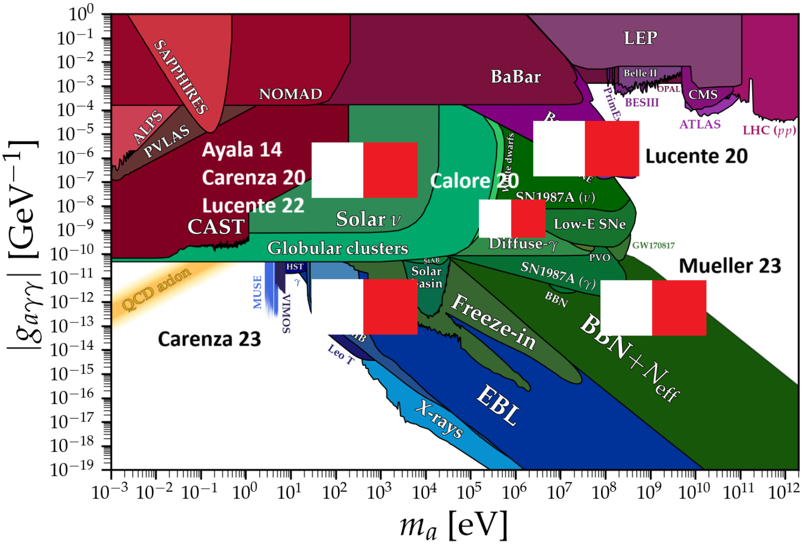


Globular Cluster bound, heavy axions and more...

G. Lucente *et al.*, Phys. Rev. Lett. **129** (2022) no.1, 011101



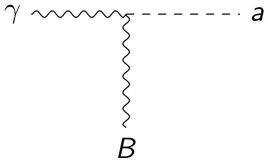
A little Bari in the axion parameter space



Axion-photon oscillations in astrophysics

G. Raffelt and L. Stodolsky, Phys. Rev. D **37** (1988), 1237

Also most of the astro-phenomenology is related to axion-photon conversions

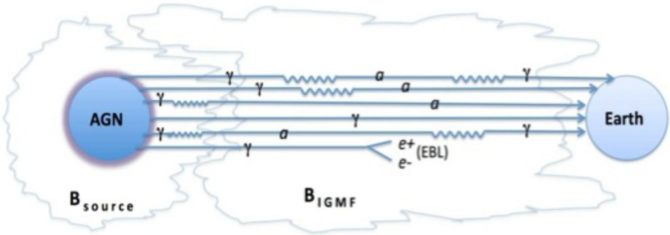


Physics involved here:

- External magnetic field
- Axion mass and plasma frequency
- QED birefringence (high B)
- CMB refraction (high energy)

Galaxy clusters

Hundreds of galaxies held together by gravity

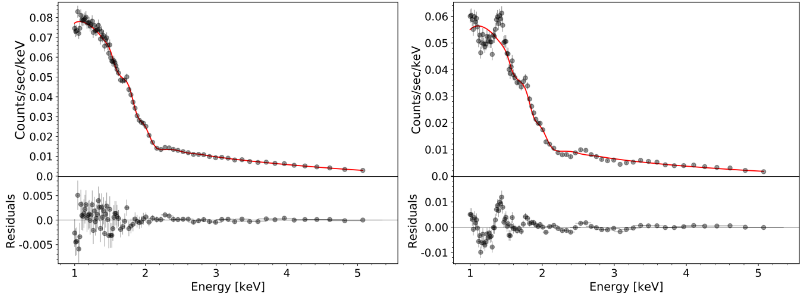


Among the largest structures in the Universe ($\sim$ Mpc) with $B \sim \mu$G

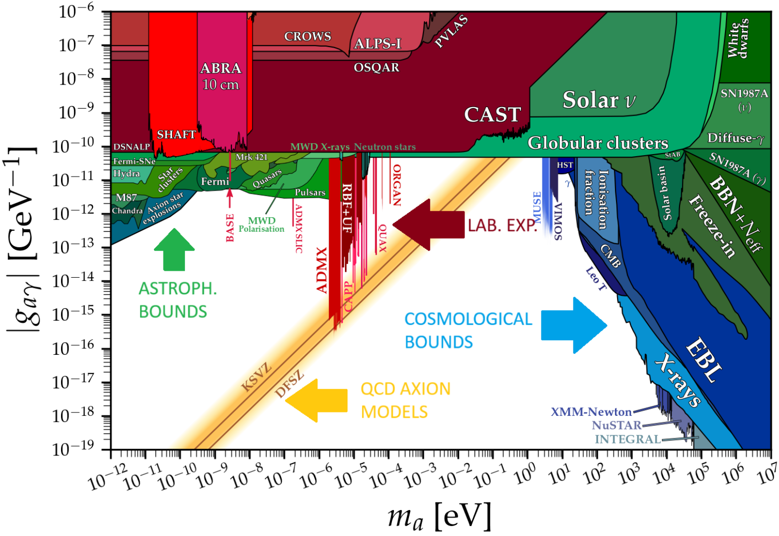
Axion bounds from Galaxy Clusters

S. Schallmoser *et al.*, [arXiv:2108.04827 [astro-ph.CO]].

Comparison: observed spectrum vs fake axion signal
$g_{a\gamma} = 5 \times 10^{-12}\,\mathrm{GeV}^{-1}$

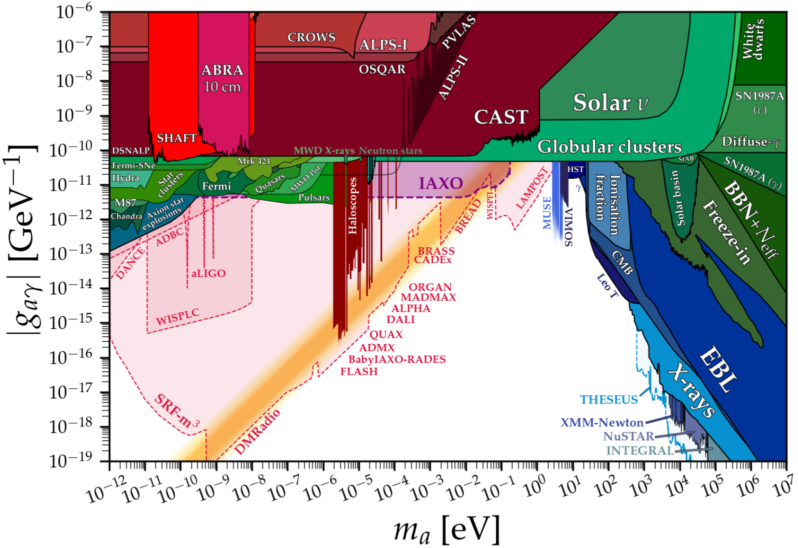


Status of axion searches in 2023: the strongest constraint at low mass



Future of axion searches

https://cajohare.github.io/AxionLimits/

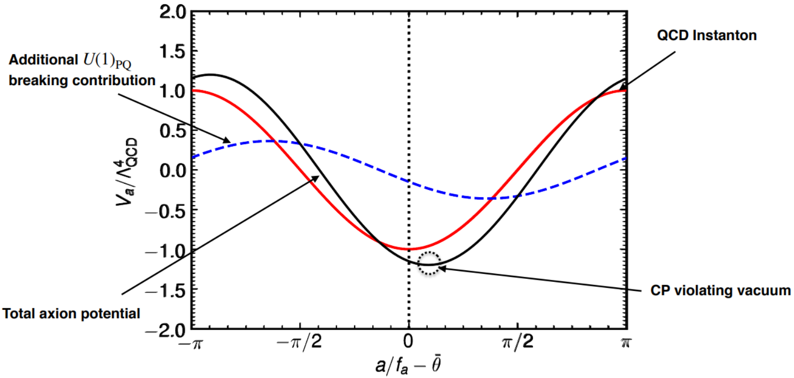


Future implications of axions

Strong-CP problem solved, aka the onslaught of quantum gravity

GRAVITY AND GLOBAL SYMMETRIES

Renata Kallosh[1], Andrei Linde[1], Dmitri Linde[2], and Leonard Susskind[1]



New dark matter candidate, new technologies

The Parties agree that the collaboration shall include as priority activities the following:

1. Development of high quality factor resonant cavities, including superconducting cavities
2. Development of cavity design for high frequencies, including multi-cavity detectors (photonics band gap technique)
3. Development of quantum-limited noise amplifiers
4. Development of single photon counters
5. Development of high-field large-volume superconducting magnets
6. Participation in axion experiments at both bases

Impact on: DNA sequencing, medical imaging, magnetic separation processes

Axion astrophysics: one more messenger

Axion helioscopes as solar magnetometers

Ciaran A. J. O'Hare,[1,a] Andrea Caputo,[2,b] Alexander J. Millar,[3,4,c] and Edoardo Vitagliano[5,d]

Axion Helioscopes as Solar Thermometers

Sebastian Hoof,[a,b] Joerg Jaeckel,[c] and Lennert J. Thormaehlen[c]

Supernova thermometers, magnetic field reconstruction, opacity of the Universe....

No better conclusion than this!

Thanks for your attention!

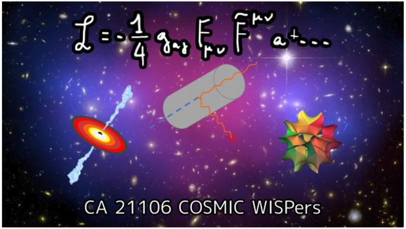
cost
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

COSMIC WISPERS
CA 21106

COST ACTION CA21106

COSMIC WISPers in the Dark Universe:

Theory, astrophysics and experiments



more info at https://www.cost.eu/actions/CA21106/