Axions and anomalies in stellar cooling

Maurizio Giannotti, Barry University

XIIIth Quark Confinement and the Hadron Spectrum

Axion round table – status, prospects and challenges

Maynooth University, 3 August 2018

Stellar evolution in a nutshell

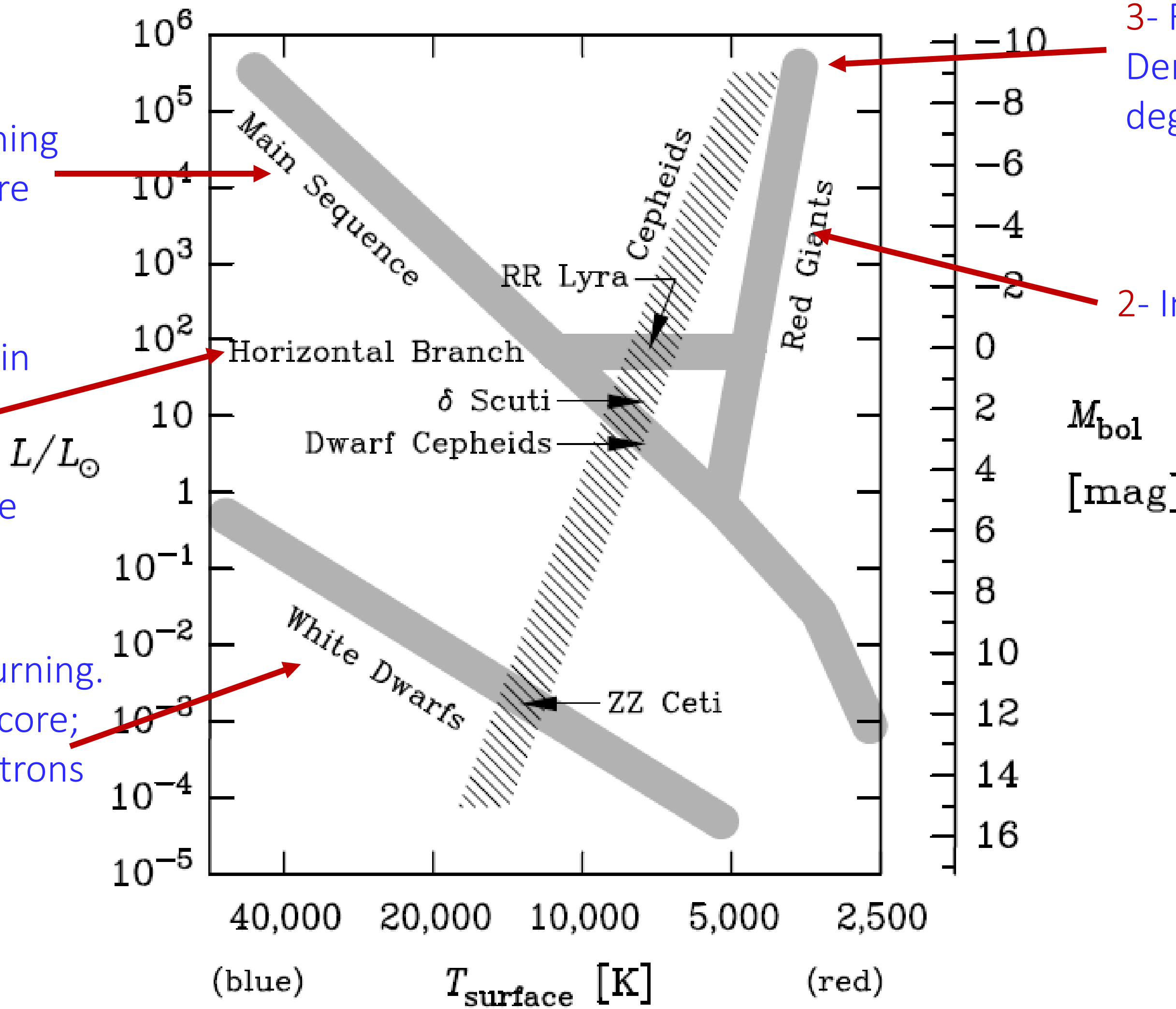
1- H burning in the core

2- Inactive He core.

3- RG tip. He ignition. Dense and hot core; degenerate electrons

4- He burning in the core. Hot core; nondegenerate electrons

5- No nuclear burning. Dense and cold core; degenerate electrons

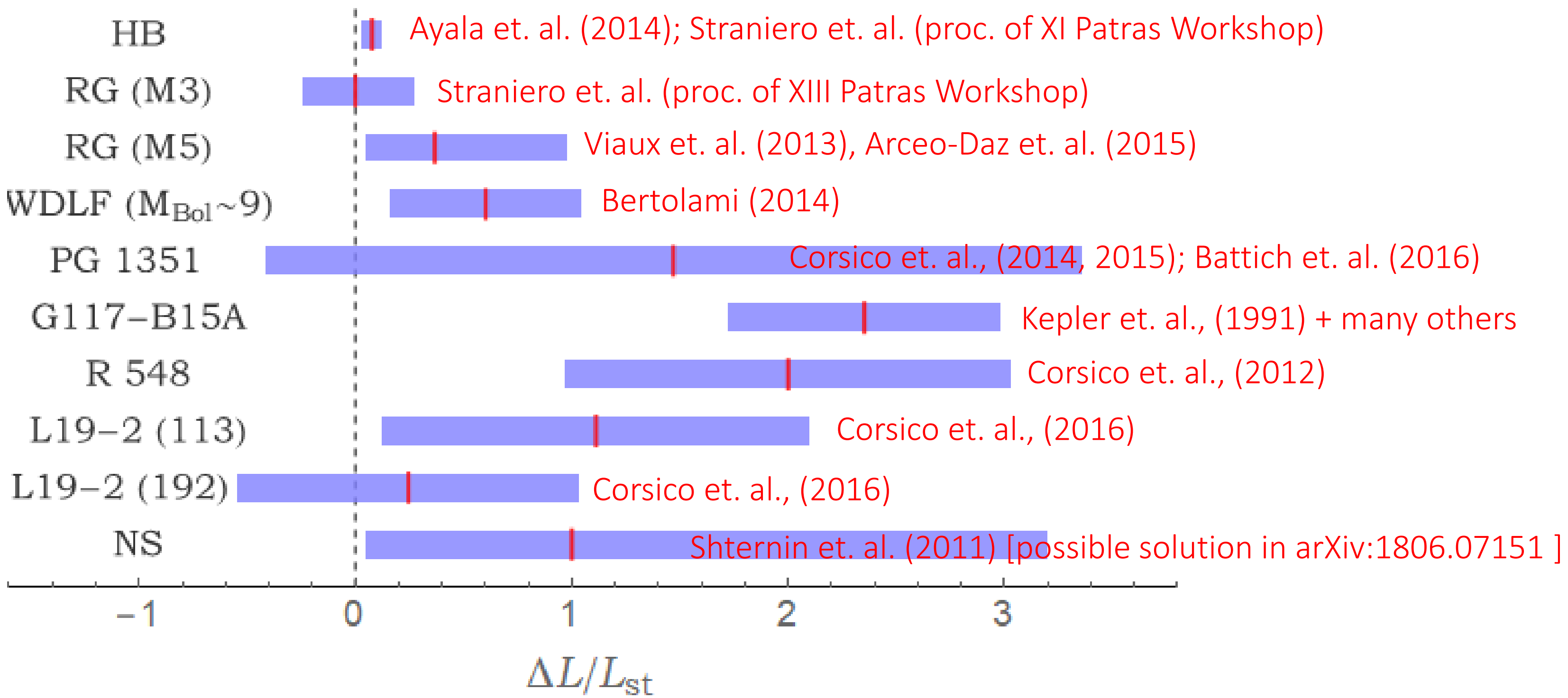


G. Raffelt, “Stars as laboratories for fundamental physics” (1996)

Hints of new physics?

Many stellar system indicate a faster cooling than predicted: Cooling anomalies!!
Systematic problem in our understanding of stellar evolution. Hint to new physics?

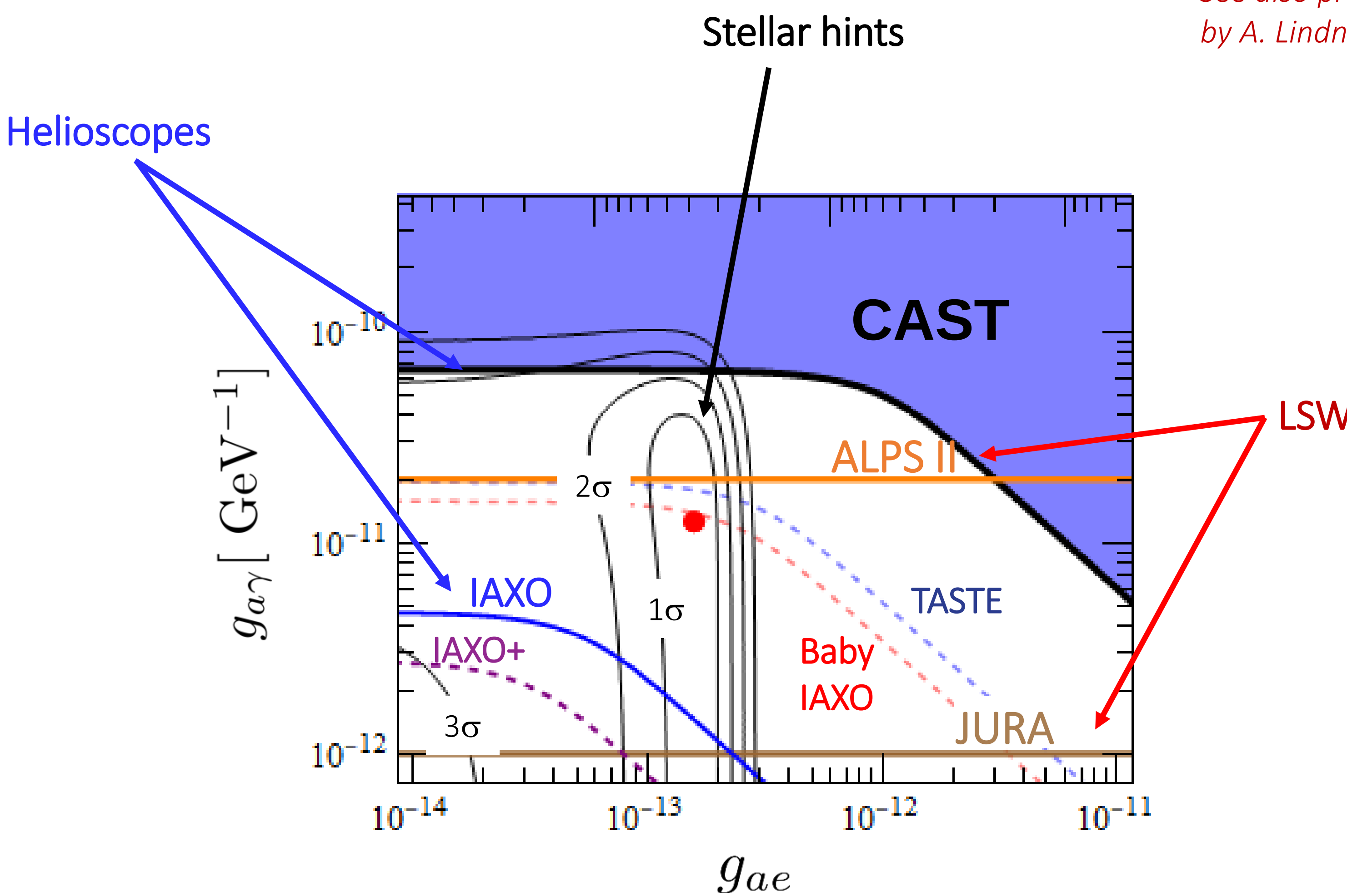
If so, ALPs are the best solution to this problem



The ALP solution

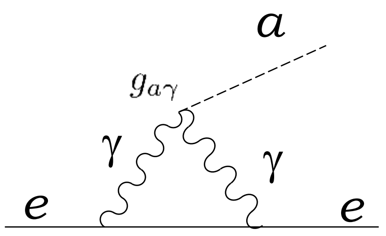
The stellar fast cooling hints at a well defined, experimentally accessible, region in the ALP parameter space

See also presentation by A. Lindner



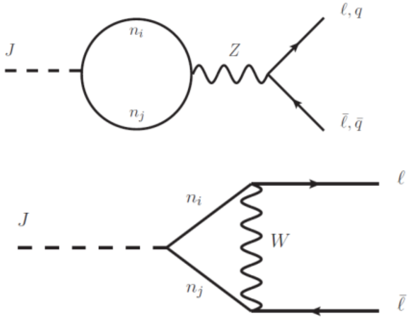
QCD Axion Models and Cooling Hints

KSVZ models predict a coupling to electrons which is about an order of magnitude smaller than what needed for the best fit.



χ^2_{min}/d.o.f. > 2

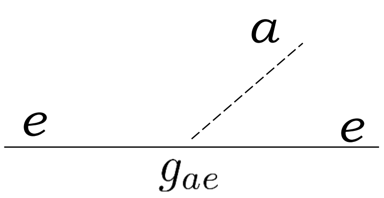
Extended hadronic models, such as SMASH can improve the case by increasing the contribution to the axion-electron coupling



χ^2_{min}/d.o.f. ≈ 1

DFSZ 1: $C_e = \frac{\sin^2\beta}{3}$ $\quad C_{a\gamma} = \frac{8}{3} - 1.92$ requires tan β=0.27

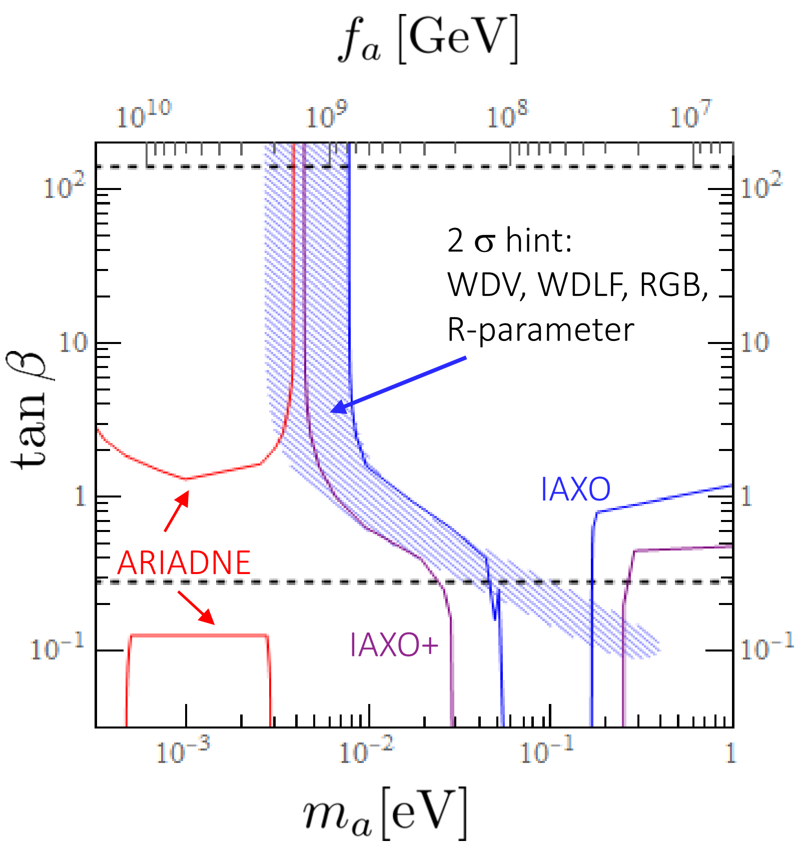
DFSZ 2: $C_e = \frac{\cos^2\beta}{3}$ $\quad C_{a\gamma} = \frac{2}{3} - 1.92$ requires tan β=2.8.

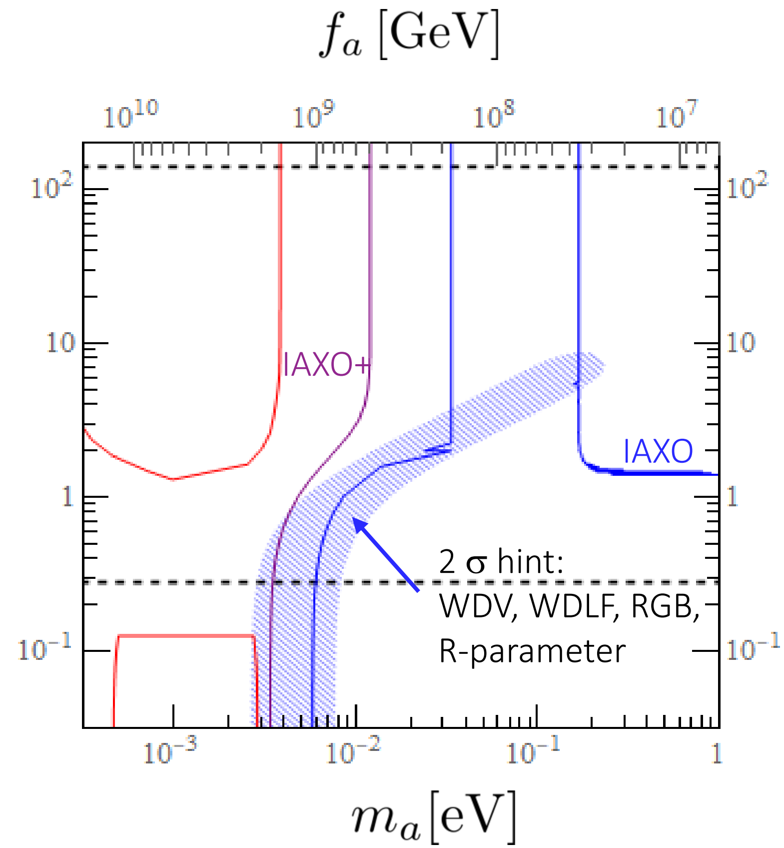


χ^2_{min}/d.o.f. ≈ 1

QCD Axion Models and Cooling Hints

The hinted region for DFSZ 2 is easier to probe with IAXO but harder to probe by ARIADNE





Other axion models are discussed in:
M.G., I. Irastorza, J. Redondo, A. Ringwald, k. Saikawa, JCAP 1710 (2017)

The future on the astrophysics front!

1- GAIA, TESS, LSST,... Confirm cooling anomalies?

Pancino et al., MNRAS.467 (2017); A. Corsico, Terceras Jornadas de Astrofisica Estelar (2017)

2- SN ALPs: resolving the SN-1987A nightmare?

Chang, Essig, McDermott, arXiv:1803.00993

3- ALP-photon oscillations. TeV transparency hints + Gamma-ray spectral modulations of galactic pulsars hint at photon-ALPs mixing with a rather large coupling (tension with CAST), accessible to ALPS II. Agreement with the Fermi-LAT observations of bright supernova remnants.

Majumdar, Calore, Horns, JCAP 1804 (2018)

Xia, Zhang, Liang, Feng, Qiang Yuan, Fan, Wu, Phys.Rev. D97 (2018)

3- Ultralight axions from extra dim. compactification (example, string theory, see P. di Vecchia talk). Observable cosmological and astrophysical consequences accessible to next gen. probes?

Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell, Phys.Rev. D81 (2010);
Arvanitaki, Dubovsky, Phys.Rev. D83 (2011);

Recent evidence of the central motion of bulge stars in the Milky Way compatible with ultralight axions

De Martino, Broadhurst, Tye, Chiueh, Schive: arXiv:1807.08153;

$$m_a \simeq 10^{-22}\,\mathrm{eV}$$

in tension with the recent EDGES observation of the 21 cm absorption line. More experimental tests? Imprint on CMB? BH superadiance? Gravitational waves?

Lidz, Hui, Phys.Rev. D98 (2018)

Additional Slides

Three astro-experiments with an indirect impact on ALPs

The largest systematic error in the axion bound from GC is the distance. A considerable improvement of roughly a factor of 10 on the uncertainty in the distance will follow the final GAIA data release (2022-2023)

Pancino et al., (2017) [arXiv:1701.03003]

Transiting Exoplanet Survey Satellite (TESS), designed to search for exoplanets using the transit method in an area 400 times larger than that covered by the Kepler mission. Considerable improvement for WDVs.

https://tess.gsfc.nasa.gov

Large Synoptic Survey Telescope (LSST), will measure SN rates much more accurately and will identify SN progenitors. These observations will be useful to understand the mass range of SN progenitors, which are affected by axion cooling. Additionally, it will improve significantly the statistics of galactic WDs. Full science operation starting from 2023

https://www.lsst.org

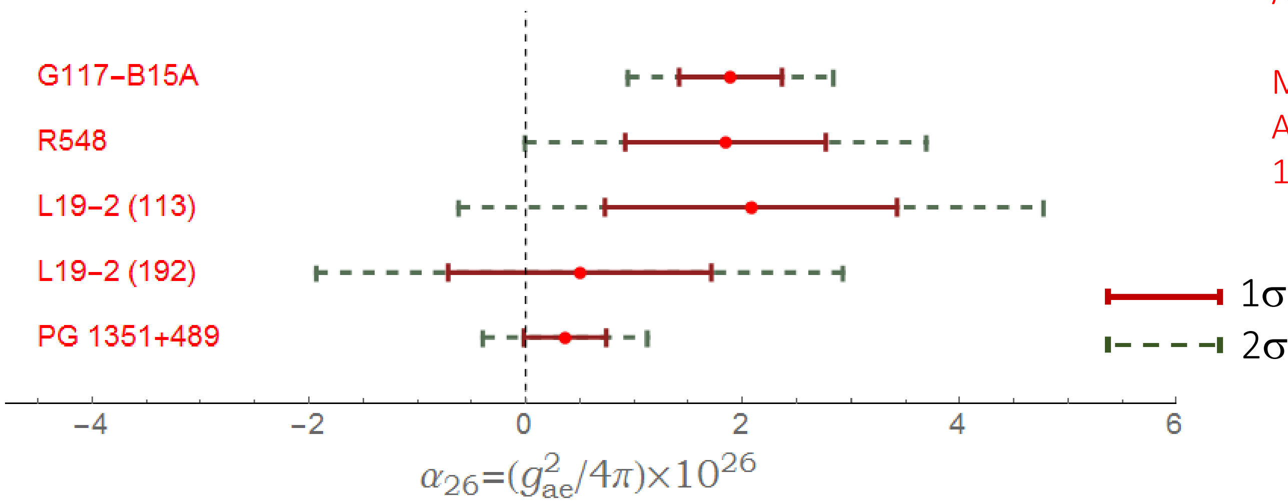
White Dwarf Variables

The discrepancy can be interpreted in terms of axions/ALPs

ALP solution:

M.G., I. Irastorza, J. Redondo, A. Ringwald, JCAP 1605 (2016)

M.G., I. Irastorza, J. Redondo, A. Ringwald, K. Saikawa, JCAP 1710 (2017)

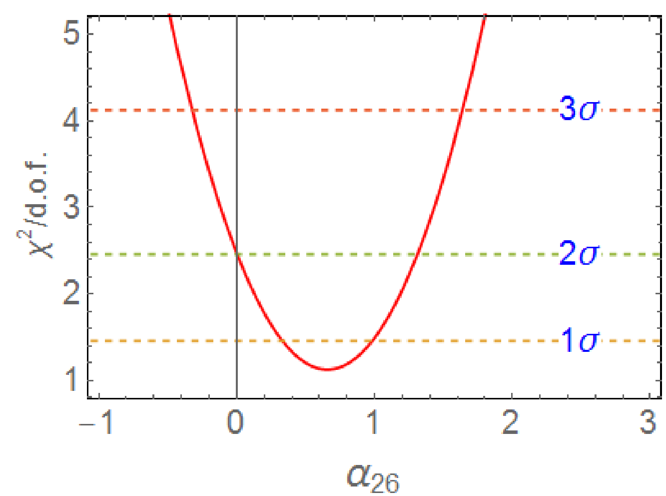


2σ hint for $\alpha_{26}>0$,

best fit: $\alpha_{26} = 0.66$ ($g_{13} = 2.9$)

χ^2_{min}/d.o.f. = 1.1

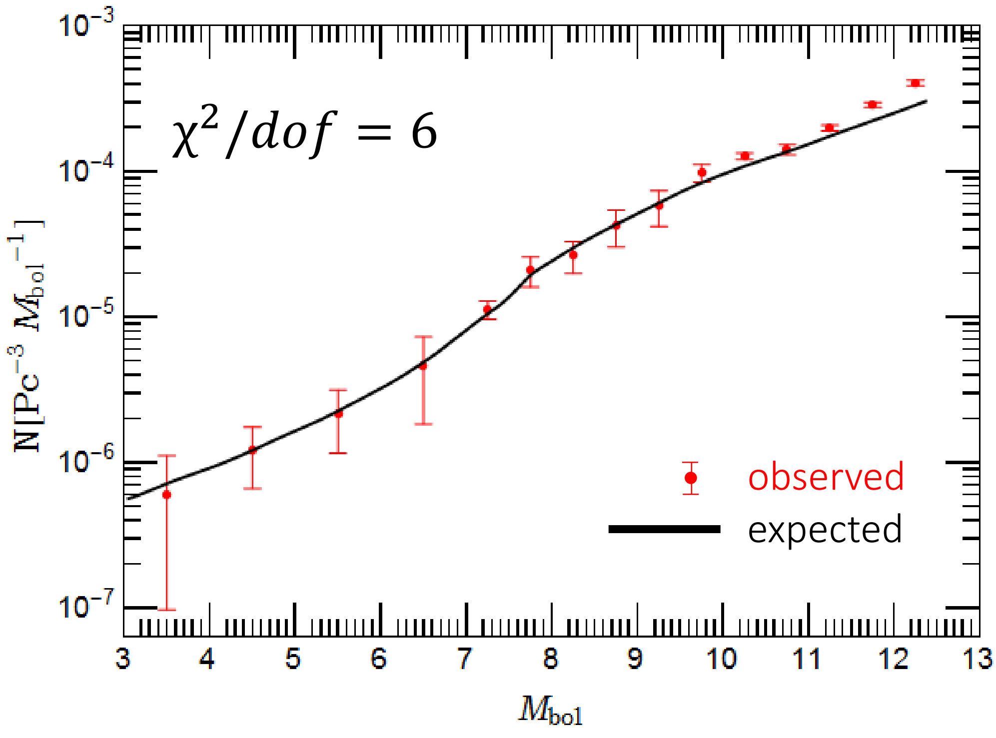
bound (2σ): $\alpha_{26} < 1.3$ ($g_{13} < 4.1$)



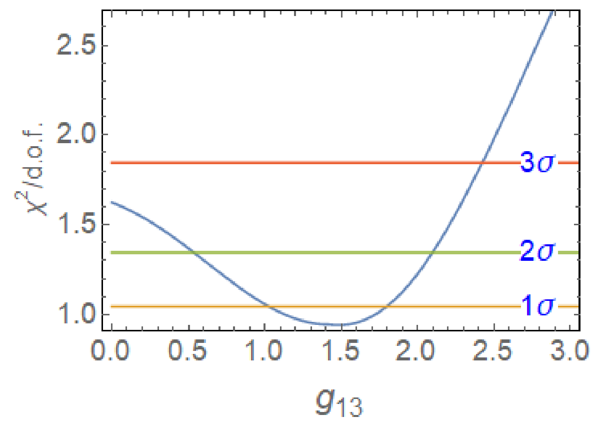
White Dwarfs Luminosity Function

See also talk by J. Isern

White Dwarfs Luminosity Function:



ALPs analysis
(1-parameter, 11 points)



Best fit value: g_{13}=1.4

Bound (2σ): g_{13}<2.1

χ^2_{min}/d.o.f. = 0.94

Data from: M. Bertolami et. al. (2014)

ALP propagation in the universe

Gamma rays are expected to scatter with the EBL.

The VHE photon luminosity of distant objects, such as active galactic nuclei, should be severely reduced. Observations, however, report VHE photon detection from AGN as distant as Gpc scales

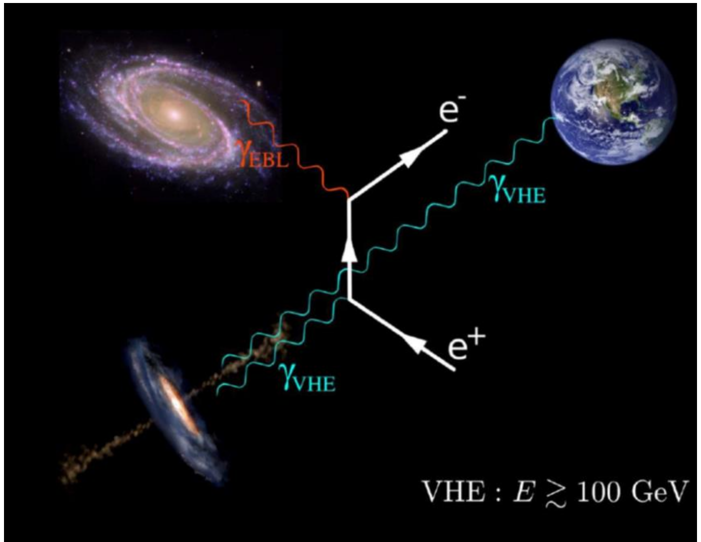


Figure from a talk by Manuel Meyer (Univ. Hamburg)

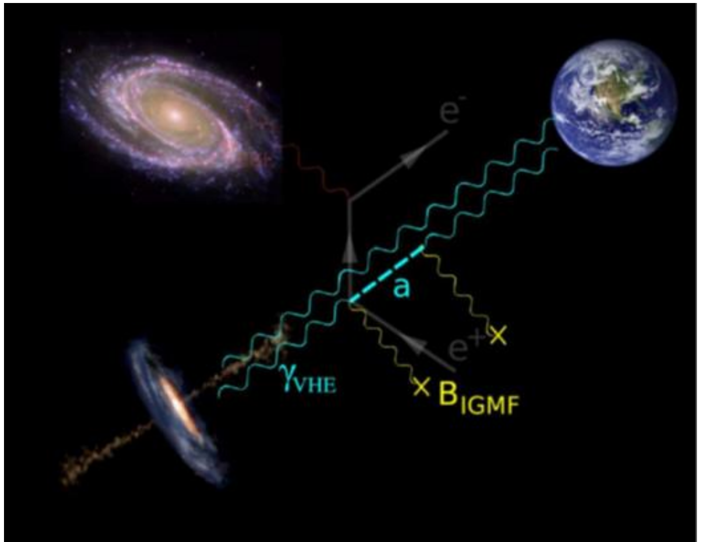
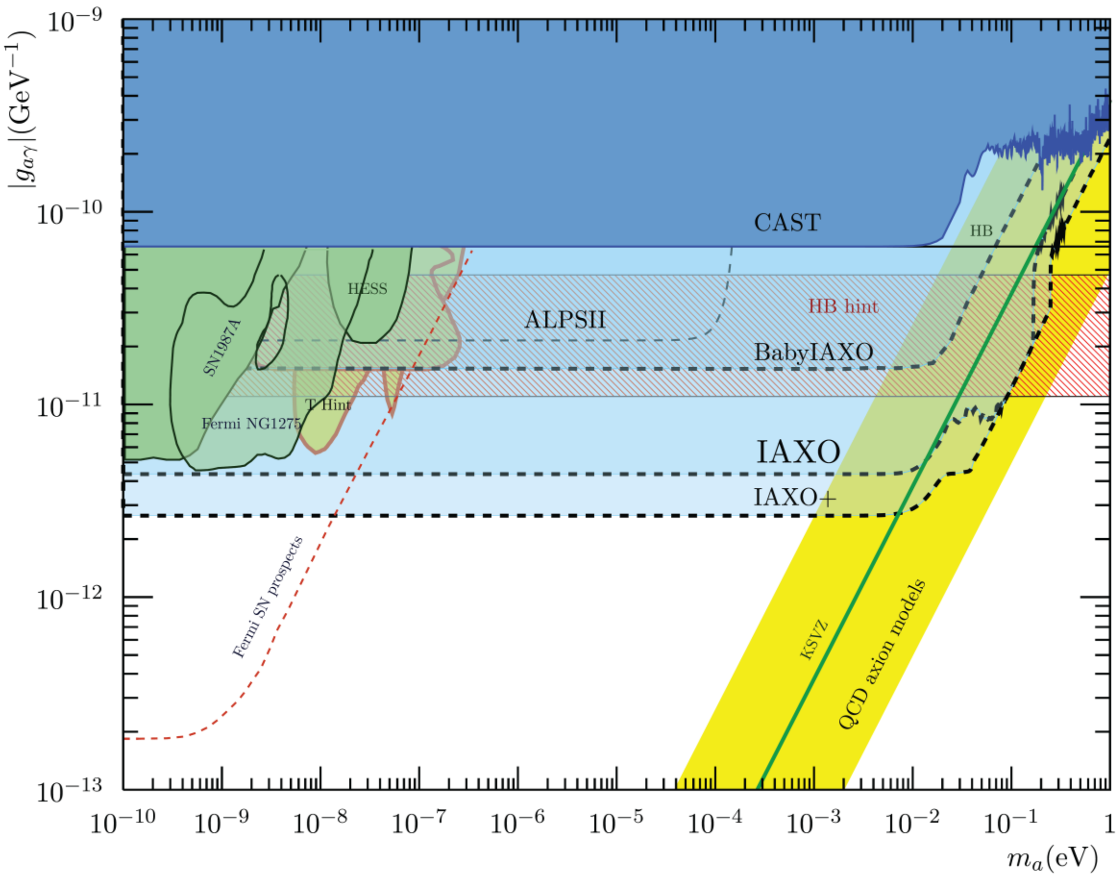


Figure from a talk by Manuel Meyer (Univ. Hamburg)

ALP propagation in the universe



Light ALPs explain the hints.

The hints are supported by recent results from CIBER.

The hinted region is partially constraint by non-observation of gamma rays from SN 1987A and by the search for spectral irregularities in the gamma ray spectrum of NGC 1275, and by HESS.

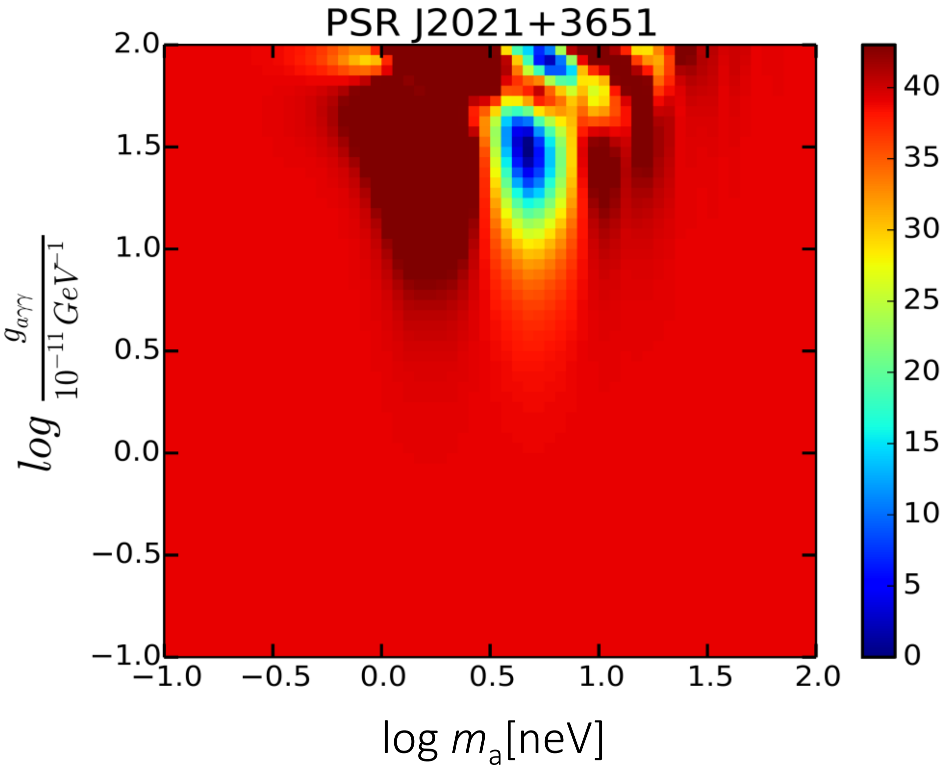
M. Meyer, D. Horns, M. Raue, **PRD87** (2013) no.3, 035027

K. Kohri, H. Kodama, arXiv:1704.05189

Gamma-ray spectral modulations in Galactic pulsars

Recenty, Jhilik Majumdar, Francesca Calore and Dieter Horns reported that the data recorded with the Fermi-LAT from selected Galactic pulsars show a preference for a sizable photon-ALP mixing oscillation with a combined statistical significance of 5.5 σ.

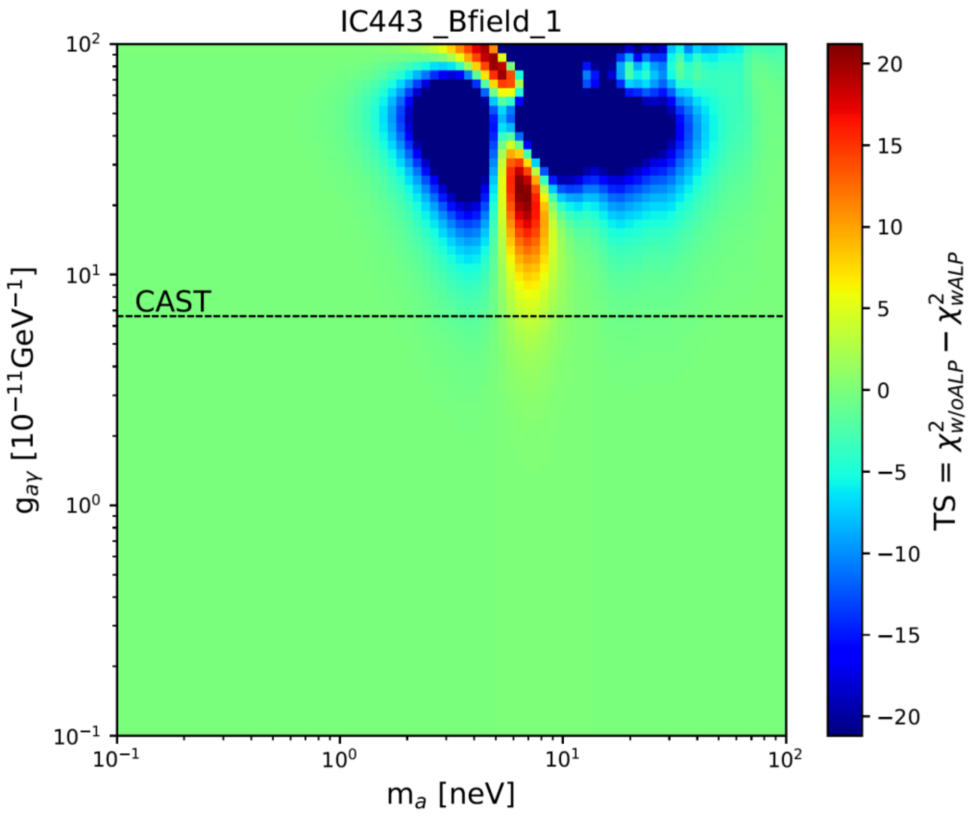
JCAP 1804 (2018)
[arXiv:1801.08813]



Gamma-ray spectral modulations from bright supernova remnants

The pulsar result is also consistent with the observed effects in the spectra of some bright supernova remnants, with a statistical significance of 4.2 σ.

Phys.Rev. D97 (2018)



In both cases, the hinted region is in tension with the CAST result and with observations of HB stars.

The explanation would require a mechanism which suppresses the ALP production in stars.

Updates on Gamma-ray propagation

From Sergey Troitsky, private communication

The anomalous transparency is confirmed in a new analysis (with new EBL models, new data, new redshifts etc.)

The NGC 1275 studies could be too optimistic in the exclusion, given the large uncertainties in the magnetic field. The magnetic-field models they all use are not supported by observations: there exists only one measurement of the field, in one point close to the very central galaxy, and only theoretical models on how it behaves in the cluster. In particular, the addition of a regular field to the purely turbulent one (which they all use) may change drastically the picture, and large-scale regular fields are common around radio galaxies.

The results of Dieter Horns (indications to ALPs with a coupling in the CAST excluded region) from a similar analysis of Galactic sources - look more robust because in the Milky Way, we have at least some scarce observational information about the field. And of course the uncertainty of the field model may be responsible for the strange value of the coupling (and for the source-to-source discrepancies in the coupling values).

Latest results to be presented in the TeVPA conference in Berlin, in the end of August

The 3.5 keV Line

The line was found originally in observations of stacked samples of galaxy clusters and is not at an energy that corresponds to a known atomic line.

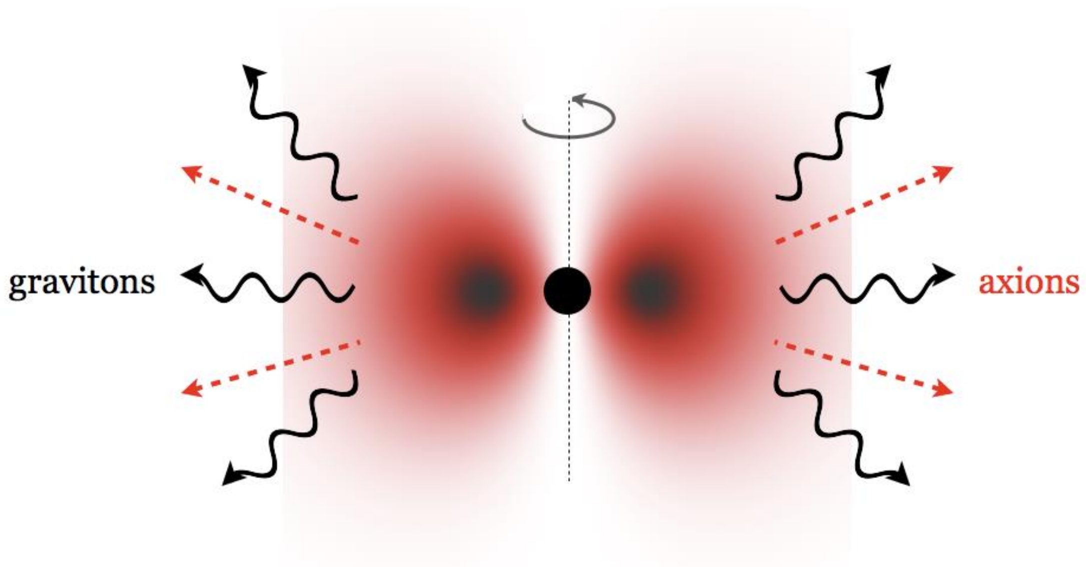
The difficulty with the standard DM interpretations is that the line is much stronger in clusters than in galaxies, and in particular is much stronger at the center of the Perseus cluster than at any other location. This implies that the line is not sensitive only to the dark matter content, but also to some aspects of the astrophysical environment.

One way this can arise is in models where the dark matter decays originally to a relativistic ALP with energy E = 3.5 keV, and the observed photon signal comes from conversion of this ALP in the magnetic field of the cluster.

The line signal can be reproduced for axion-photon couplings of order
10^{-15} GeV^{-1} < $g_{a\gamma}$ < 10^{-12} GeV^{-1} for ALP masses $m_a < 10^{-12}$ eV.

The stronger signal in clusters would then arise from the larger and more extended magnetic fields present in clusters compared to galaxies.

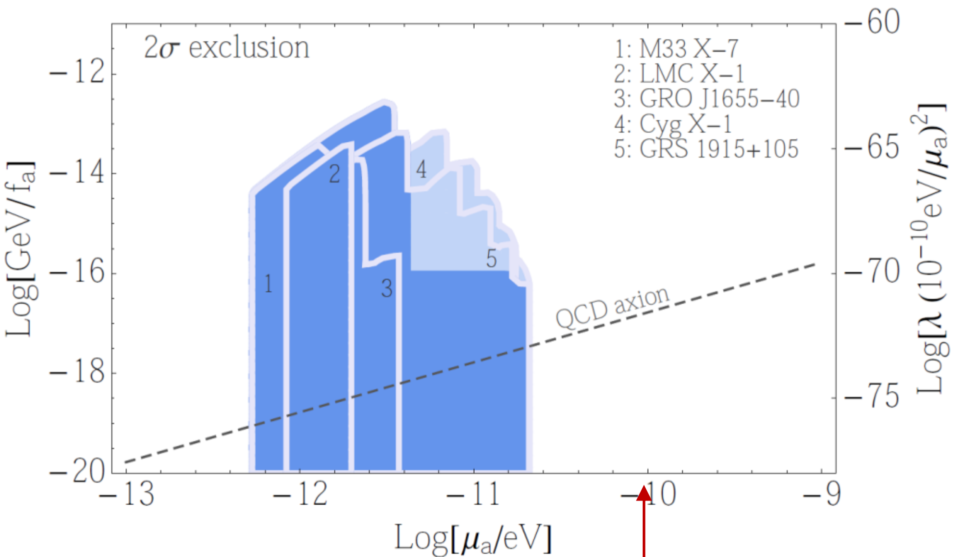
Black Hole superadiance as a probe for ALPs



Arvanitaki, Dubovsky, Phys.Rev. D83 (2011)

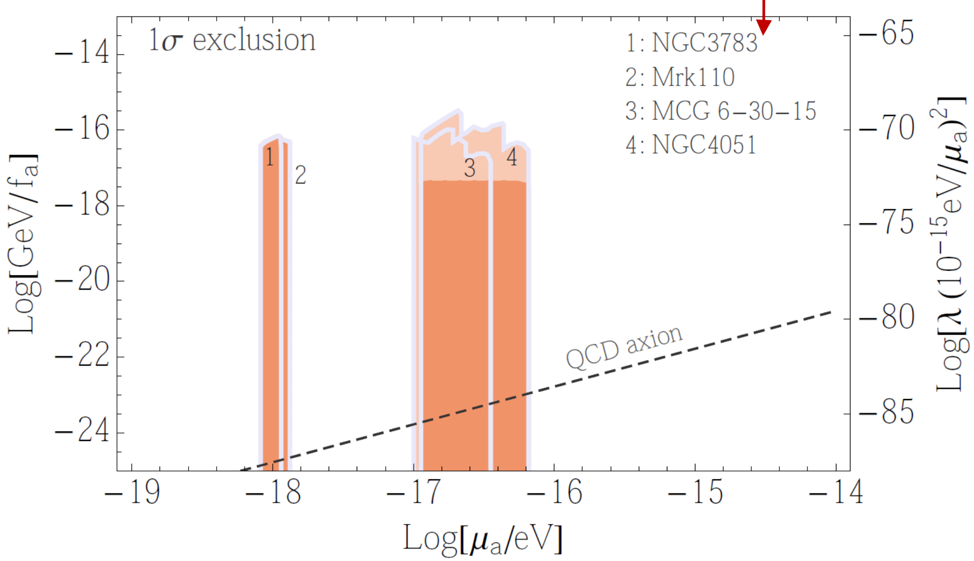
Massive axions, have bound levels in the gravitational field of a black hole. The black hole releases its spin by populating axion levels and creating an axionic BEC cloud rotating around the black hole.

Transitions and annihilations within the axion cloud predict the emission of monochromatic gravitational waves which could be observed in advanced LIGO and eLISA.



M_{BH} of a few solar masses

Supermassive BHs (less accurate)



The spinning BHs would be spun-down in the presence of a light boson. Therefore, the observation of mass and spin of black holes constraints the ALPs.

Note that ALPs do not need to be present initially (i.e. they do not have to be the DM) for this process to occur: superradiance can start from a quantum mechanical fluctuation.

Excludes light axion masses but not superlight masses necessary for Fuzzy DM.

David J. E. Marsh, Phys. Rep. (2016);

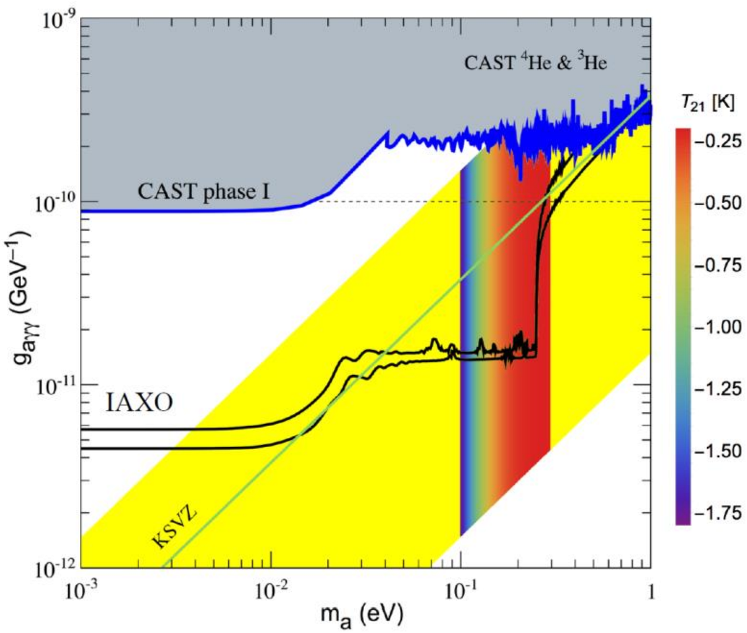
A. Arvanitaki, M. Baryakhtar, and X. Huang, Phys. Rev. D91, 084011 (2015), 1411.2263.

EDGES observation of 21 cm absorption line

Fuzzy DM can instead be constrained by the EDGES observation of the 21 cm absorption line, which indicates star formation very early on while Fuzzy DM could indicate later formation unless

Lidz, Hui, Phys.Rev. D98 (2018); Schneider, arXiv:1805.00021

$$m_a > 5 \times 10^{-21}\ \text{eV}$$



21 cm brightness temperature at z ~17 (from arXiv:1805.04426)

The observation also hints ad axions since the BEC of axion CDM could explain the cooling of the plasma [Houston, Li, Li, Yang, Zhang, arXiv:1805.04426; Sikivie: arXiv:1805.05577]

The 99% confidence limits presented imply the range $0.12 < m_a/\text{eV} < 0.18$, with the best fit value corresponding to $m_a = 0.15$ eV.

See also
Lambiase, Mohanty, arXiv:1804.05318;

Finally, notice the very recent result: [arXiv:1807.11482, Tighter Limits on Dark Matter Explanations of the Anomalous EDGES 21cm Signal, Kovetz, Poulin, Gluscevic, Boddy, Barkana, Kamionkowski

Additional astrophysical prospects?

Prospects for axion searches with Advanced LIGO through binary mergers

Junwu Huang, Matthew C. Johnson, Laura Sagunski , Mairi Sakellariadou, Jun Zhang, arXiv:1807.02133

X-Ray Polarization Signals from Magnetars with Axion-Like-Particles

Jean-François Fortin, Kuver Sinha. arXiv:1807.10773