Astrophysics of Axions and Axion-Like Particles

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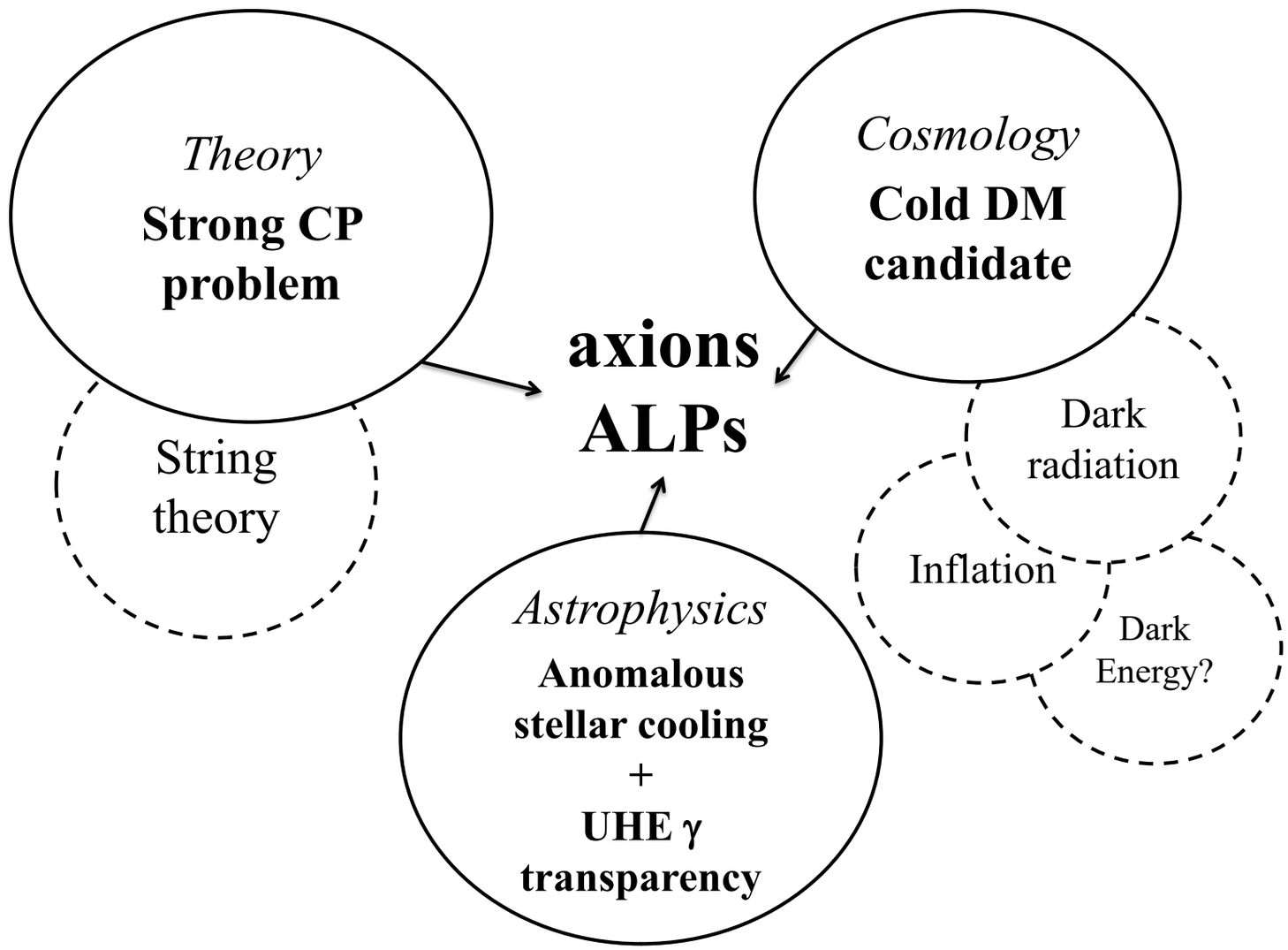
Barry University

LSST Dark Matter Workshop,
KICP, August 5-7 2019, Chicago

Axions Overview



Axions Overview

Most compelling solution of the Strong CP problem of the SM

The QCD Lagrangian admits a CP violating term

$$L = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + i\bar{\Psi}\gamma^\mu D_\mu \Psi - \bar{\psi}M\psi - \bar{\theta}\frac{1}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Observable consequence: neutron electric dipole moment which, however, is not observed

Crewther, Vecchia, Veneziano, Witten (1979)

J. M. Pendlebury et al., Phys.Rev. D92 (2015)

Peccei and Quinn solution: $\bar{\theta}$ is dynamical:

$$\bar{\theta} \to a/f_a$$

Peccei and Quinn (1977)

a is the axion field!

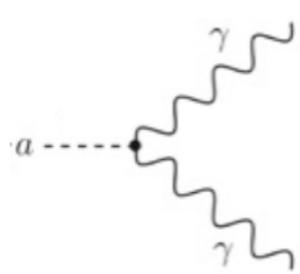
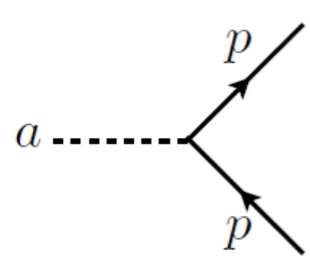
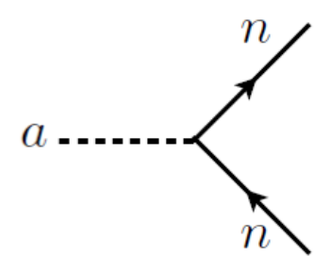
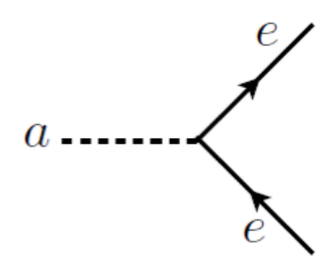
Weinberg (1978)
Wilczek (1978)

The potential of a has a minimum in zero (Vafa-Witten theorem)

Axions Overview

Rich phenomenology!!

Axions interact with matter and photons.

2 photon	proton	neutron	electron
$\frac{\alpha C_{a\gamma}}{2\pi}\frac{a}{f_a}\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4}$	$C_{ap}m_p\frac{a}{f_a}[i\bar{p}\gamma_5 p]$	$C_{an}m_n\frac{a}{f_a}[i\bar{n}\gamma_5 n]$	$C_{ae}m_e\frac{a}{f_a}[i\bar{e}\gamma_5 e]$
			

$$g_{a\gamma} = \frac{C_{a\gamma}\alpha}{2\pi f_a} \qquad g_{ap} = C_{ap}\frac{m_p}{f_a} \qquad g_{ap} = C_{an}\frac{m_n}{f_a} \qquad g_{ap} = C_{ae}\frac{m_e}{f_a}$$

Axion mass

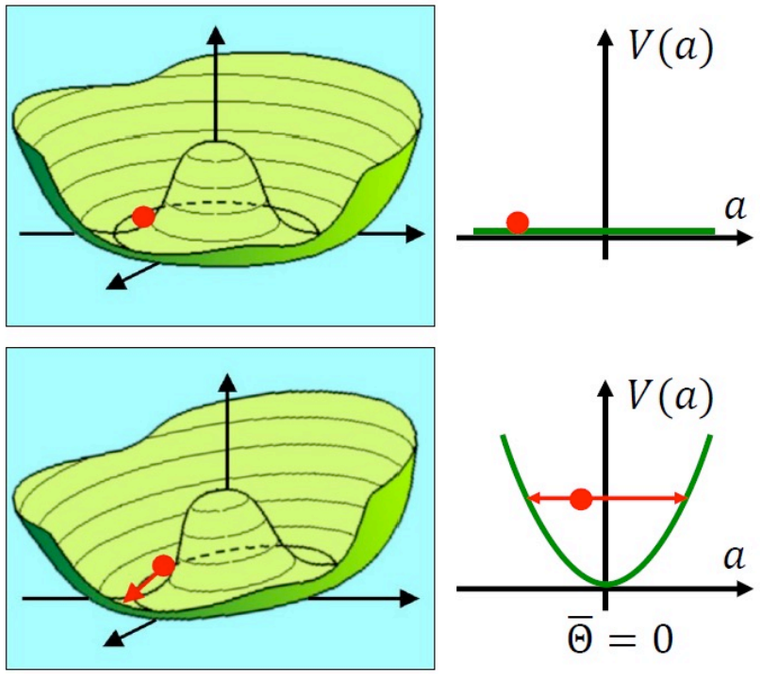
$$m_a = \frac{(5.70 \pm 0.07)\,\mu\text{eV}}{f_a/10^{12}\,\text{GeV}}$$

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

Axions Overview

Most compelling solution of the Strong CP problem of the SM

May account for the totality or part of the DM in the universe



Misalignment production
(non thermal)

$$\ddot{\theta} + 3H(T)\dot{\theta} + m_a(T)^2 \sin(\theta) = 0$$

Preskill, Wise and Wilczek (1983)
Abbott and Sikivie (1983)
Dine and Fischler (1983)

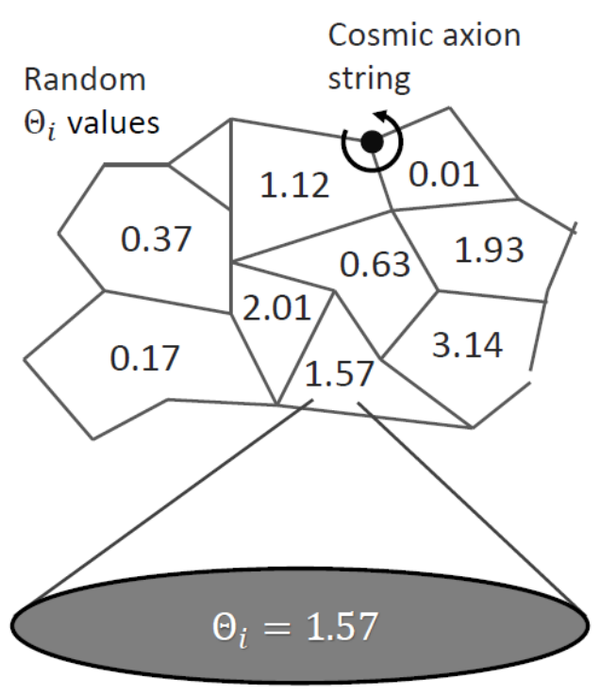
If axions exist and are weakly interacting, a little axion DM is inevitable.

Axions Overview

Most compelling solution of the Strong CP problem of the SM

May account for the totality or part of the DM in the universe

Problem with initial condition (unknown)



Fromm G. Raffelt, NSF (2014)

If PQ symmetry broken after inflation:
the problem with the initial conditions is removed
but axion production from topological defects
becomes important and has large uncertainties
(*Gorghetto, Hardy, Villadoro (2018)*)

The preferred mass region for axion DM is still not well known!

Axions Overview

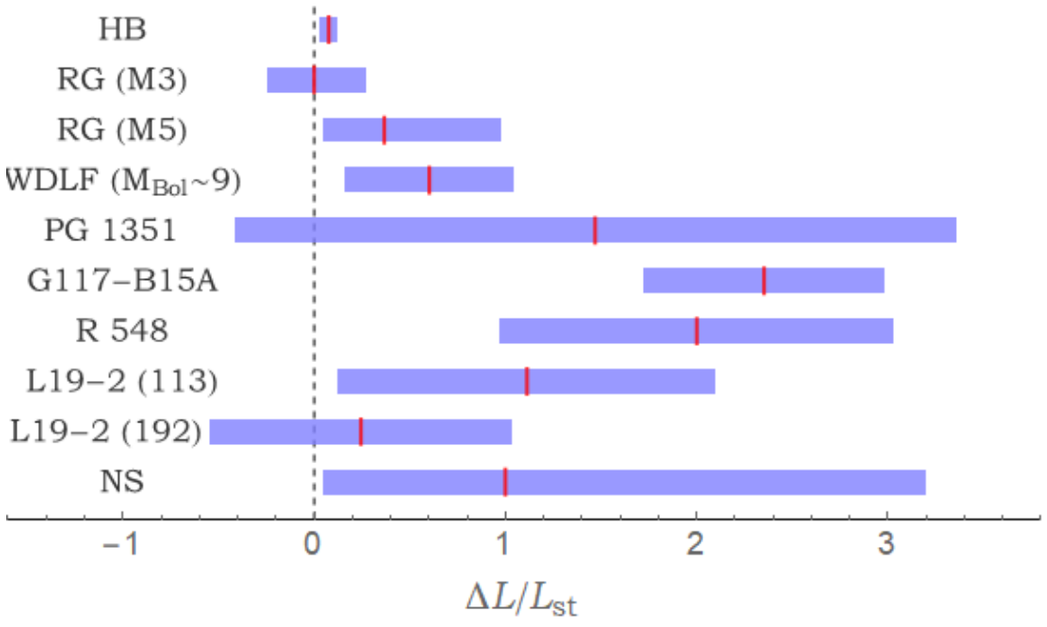
Most compelling solution of the Strong CP problem of the SM

May solve the DM problem

Axions would account for the excessive energy loss in stars

…Observed in WDs, RGB and HB stars

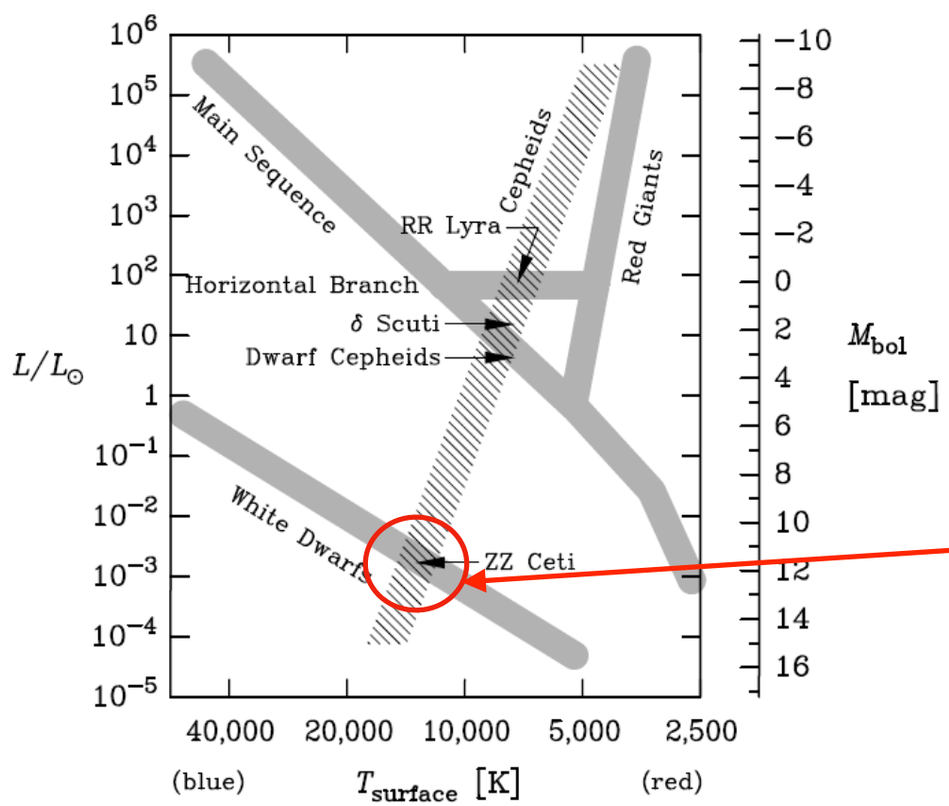
In general, axions may affect stellar evolution in a significant way!



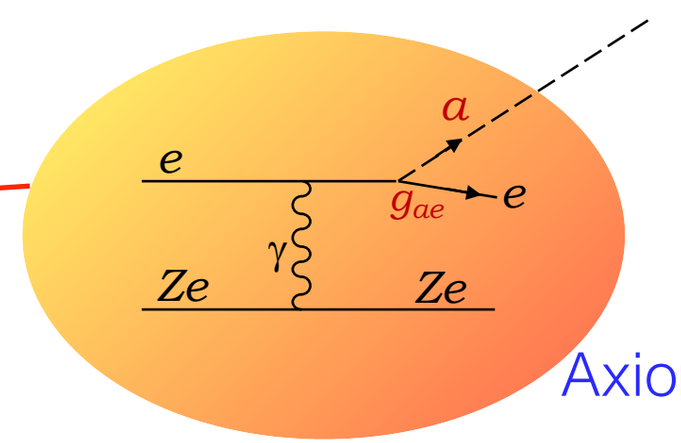
M.G., Irastorza, Redondo, Ringwald (2015)
M.G., Irastorza, Redondo, Ringwald, Saikawa (2017)

Axions & Stars: WD variables

WD	class	P[s]	$\dot{P}_{\rm obs}$[s/s]	$\dot{P}_{\rm th}$[s/s]
G117 - B15A	DA	215	$(4.19 \pm 0.73) \times 10^{-15}$	$(1.25 \pm 0.09) \times 10^{-15}$
R548	DA	213	$(3.3 \pm 1.1) \times 10^{-15}$	$(1.1 \pm 0.09) \times 10^{-15}$
PG 1351+489	DB	489	$(2.0 \pm 0.9) \times 10^{-13}$	$(0.81 \pm 0.5) \times 10^{-13}$
L 19-2 (113)	DA	113	$(3.0 \pm 0.6) \times 10^{-15}$	$(1.42 \pm 0.85) \times 10^{-15}$
L 19-2 (192)	DA	192	$(3.0 \pm 0.6) \times 10^{-15}$	$(2.41 \pm 1.45) \times 10^{-15}$



Notice that $\dot{P}/P$ is practically proportional to $\dot{T}/T$



Axion Bremsstrahlung

Figure from G. Raffelt, *Stars as laboratories for fundamental physics*

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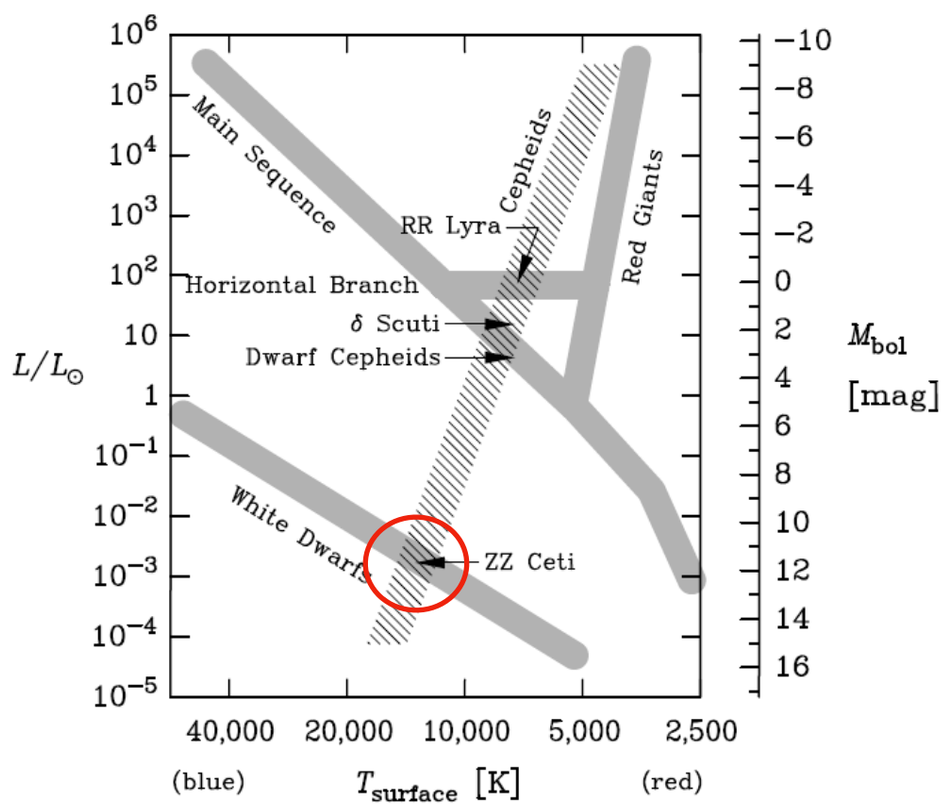


Figure from G. Raffelt, *Stars as laboratories for fundamental physics*

Notice that $\dot{P}/P$ is practically proportional to $\dot{T}/T$

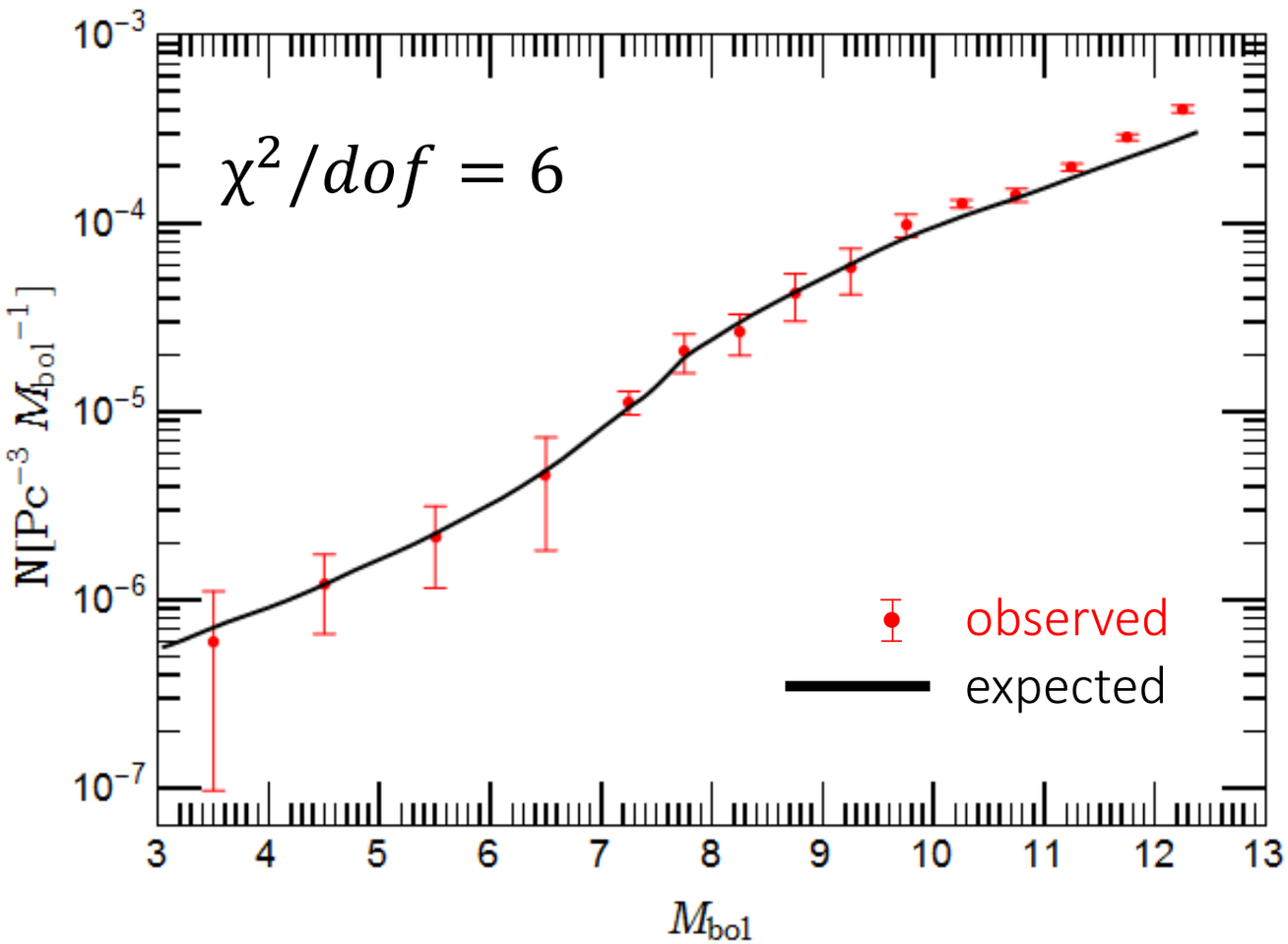
2 σ hint for $g_{ae} > 0$,

<u>Best fit</u>: $g_{ae} = 2.9 \times 10^{-13}$

<u>Bound</u> (2σ) : $g_{ae} \leq 4.1 \times 10^{-13}$

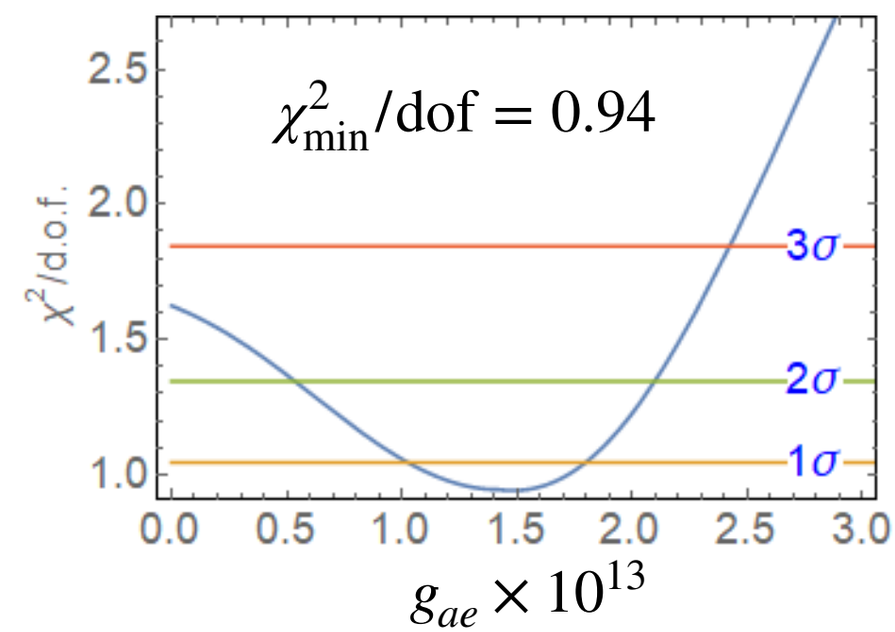
Córsico, Althaus, Miller Bertolami (2019)

Axions & Stars: WD Luminosity Function



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

Axion analysis



Best fit: $g_{ae} = 1.4 \times 10^{-13}$

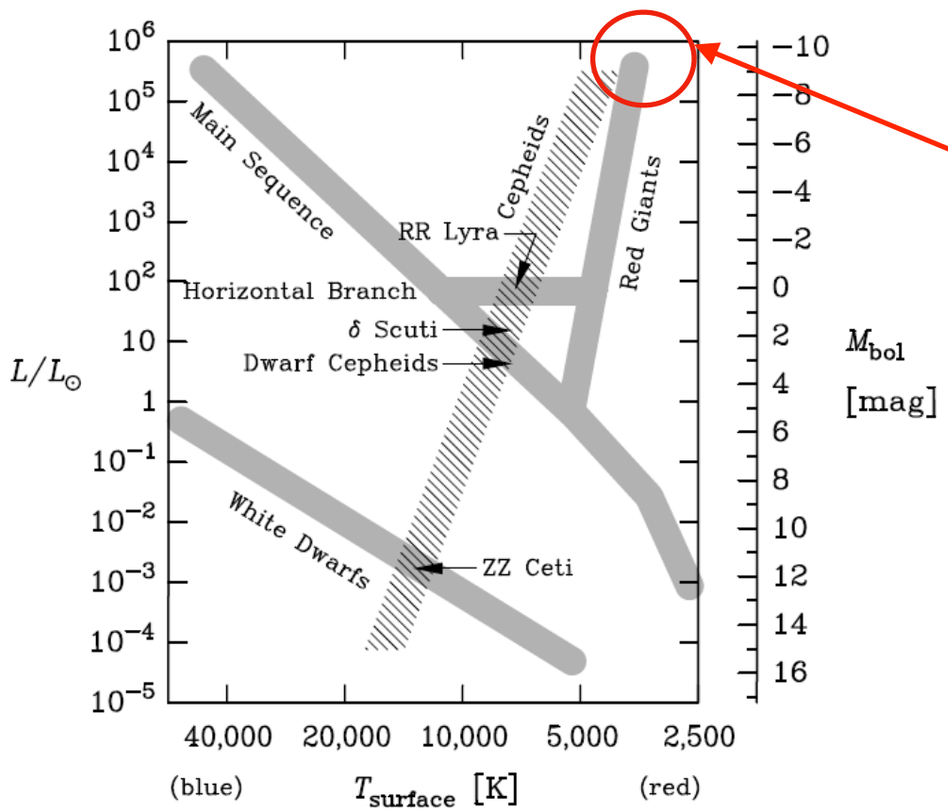
Bound: $g_{ae} \leq 2.1 \times 10^{-13}$

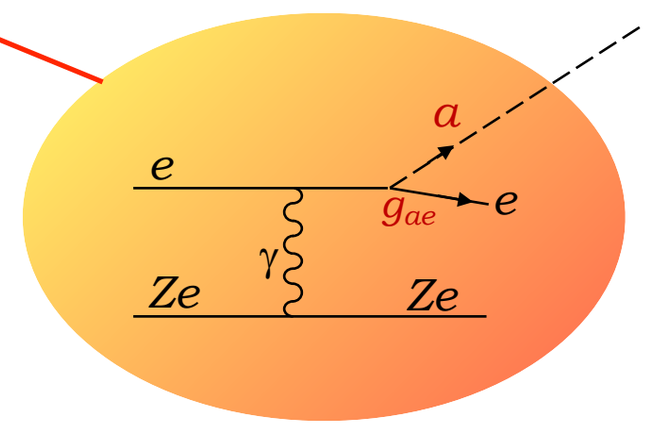
Tremendous improvement expected with LSST!

A. Drlica-Wagner et al. (LSST DM Group), "Probing the Fundamental Nature of Dark Matter with the Large Synoptic Survey Telescope "(2019)

Axions & Stars: RGB-Tip

Additional cooling increases the luminosity of the RGB tip





Axion Bremsstrahlung

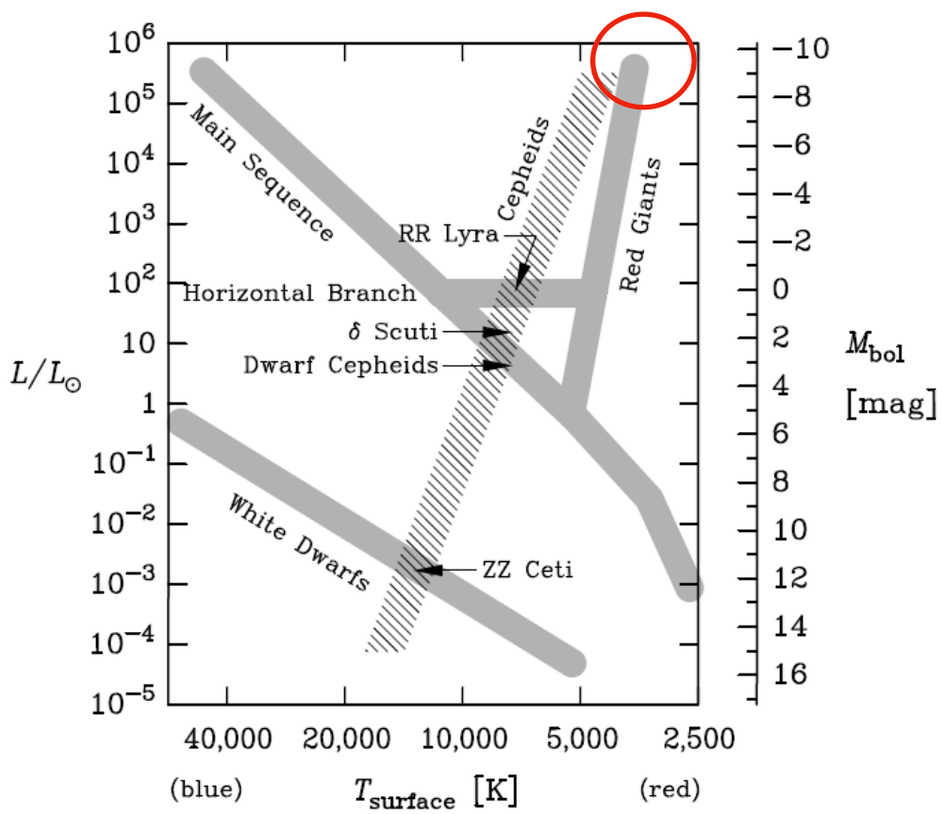
Best fit: $g_{ae} = 1.4 \times 10^{-13}$

Bound: $g_{ae} < 3.1 \times 10^{-13}$ (2σ)

- Viaux et. al., Phys.Rev.Lett. 111 (2013);
- Viaux et. al. Astron.Astrophys. 558 (2013) A12;
- Arceo-Daz et. al. (2015)
- O. Straniero et. al. (2017)

Axions & Stars: RGB-Tip

Additional cooling raises the luminosity of the RGB tip



Best fit: $g_{ae} = 1.4 \times 10^{-13}$

Bound: $g_{ae} < 3.1 \times 10^{-13}$ (2σ)

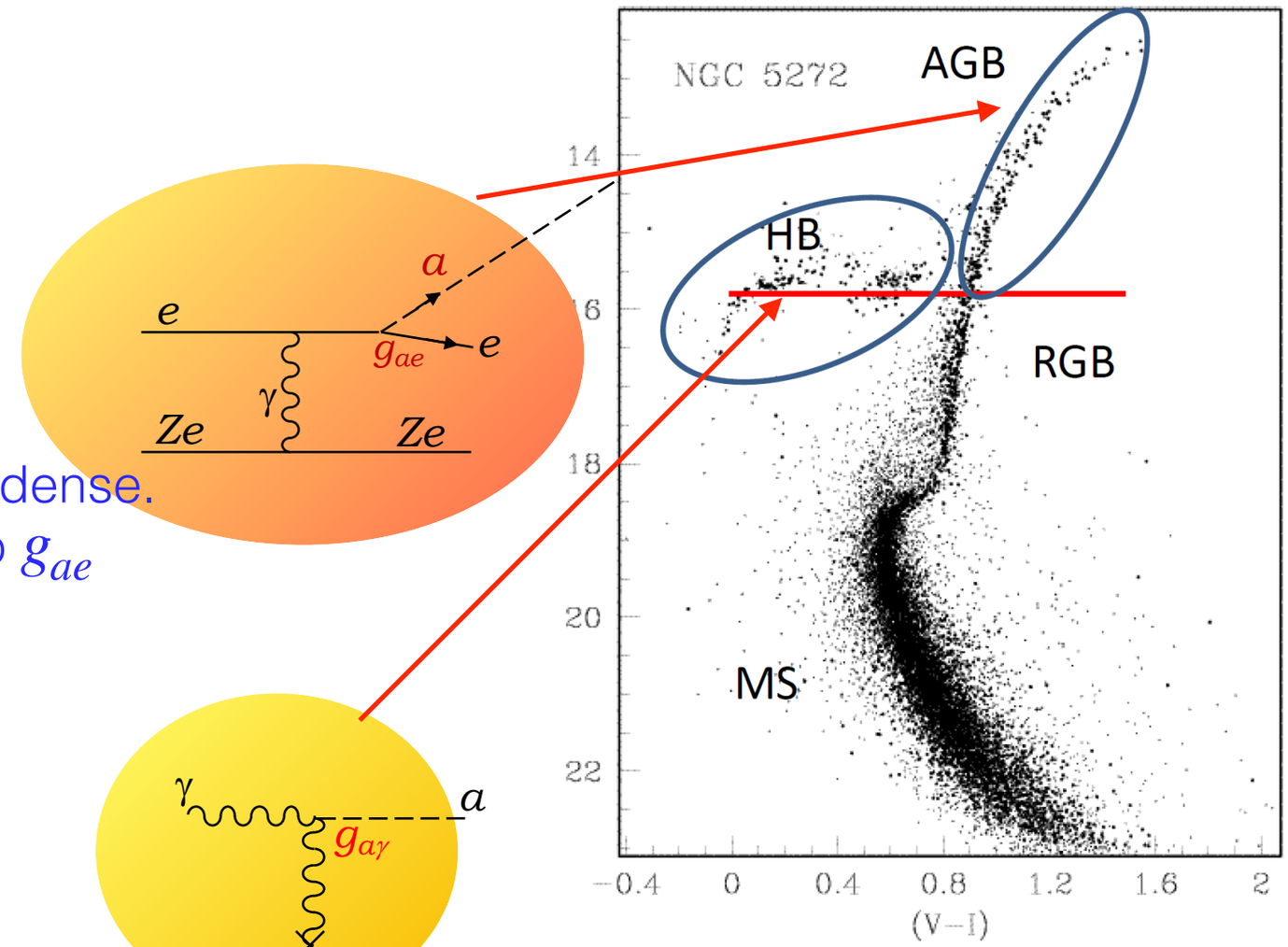
The largest systematic error is the distance.

The final GAIA data release (2022-2023) will provide an improvement of roughly a factor of 10 on the uncertainty in the distance.

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

Axions & Stars: R-parameter

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



RGB: very dense.
Sensitive to g_{ae}

Sensitive to both <u>axion-electron</u> and <u>axion-photon</u> coupling.

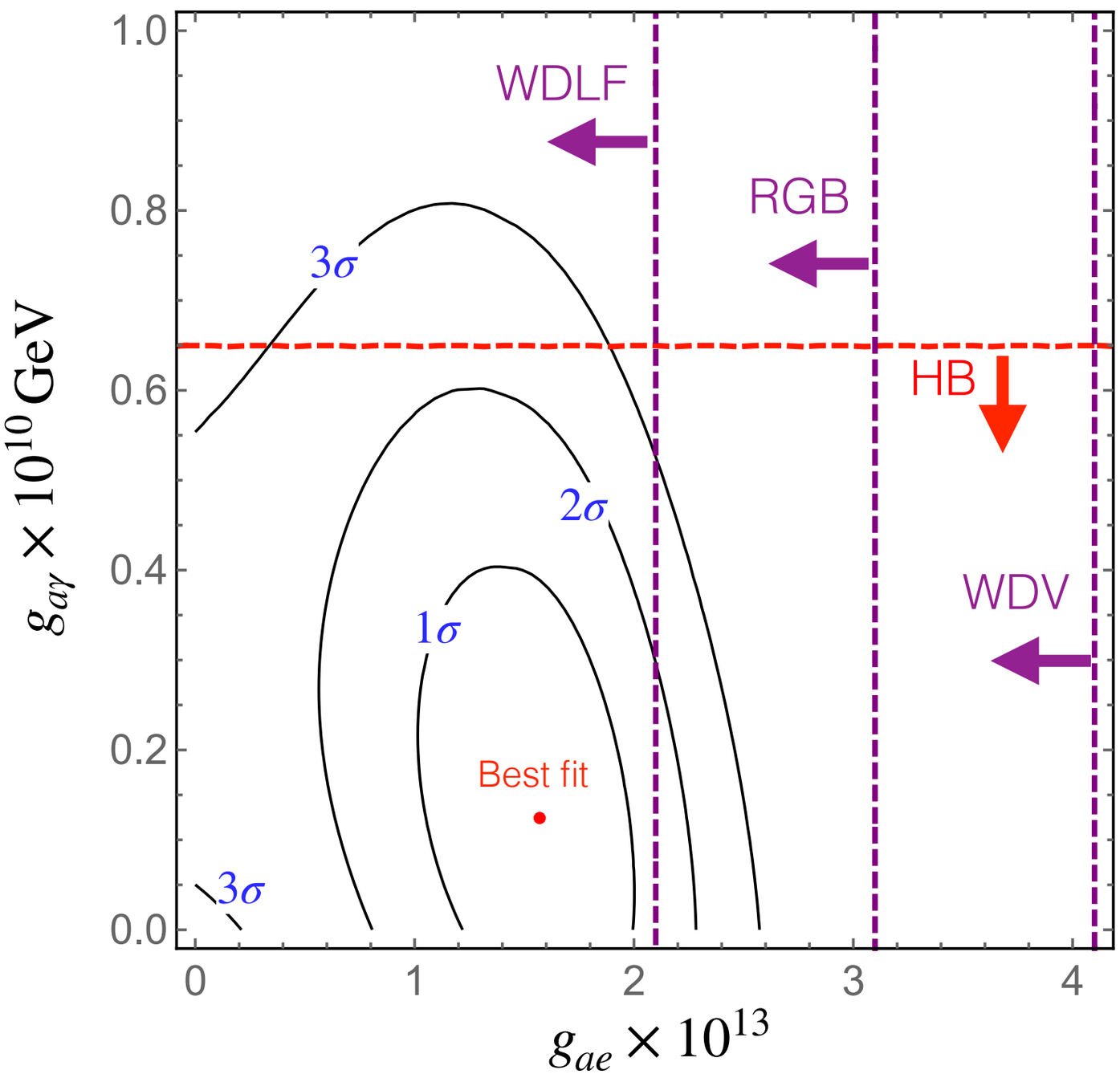
HB: not very dense.
Sensitive to $g_{a\gamma}$

In the case of $g_{ae} = 0$ the R-parameter bound is known as the

<u>HB bound:</u> $g_{a\gamma} \leq 0.65 \times 10^{-10}\,\mathrm{GeV}^{-1}\ (2\sigma)$

- Ayala, Dominguez, M.G., Mirizzi, Straniero, (2014)
- Straniero (proc. of XI Patras Workshop, 2015)
- M.G., Irastorza, Redondo, Ringwald (2015)

Axions & Stars: Global analysis



Best fit:

$$g_{a\gamma} = 1.2 \times 10^{-11}\,\mathrm{GeV}^{-1}$$

$$g_{ae} = 1.6 \times 10^{-13}$$

ALPs are the best candidates to explain the excessive energy loss

Cooling anomalies point to specific region of the ALP parameter space

M.G., Irastorza, Redondo, Ringwald, Saikawa (2017)

A Bright Future?

Observations from the Gaia satellite $\Longrightarrow$ catalog of WDs increased by an order of magnitude with respect to SDSS. However, the Gaia sample is limited to WDs within 100 pc. LSST may detect WDs 5 to 6 magnitudes fainter, bringing the census of WDs to tens of millions.

Kilic et al., 2018;
Jiménez-Esteban et al., 2018;
Gentile Fusillo et al., 2019

A. Drlica-Wagner et al.
(LSST DM Group), (2019)

Expected a large growing sample of the WD Variable sample (LSST + TESS).

Accurate astrometry from the Gaia satellite $\Longrightarrow$ Precise determination of cluster distances. LSST will enable independent measurements of GC distances, providing a valuable handle on systematic uncertainties of Gaia observations.

Pancino et al., 2017

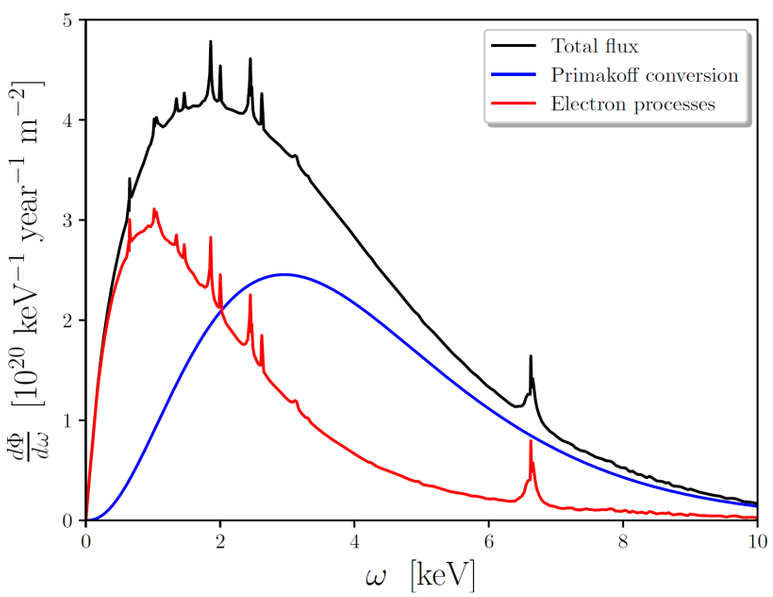
LSST is expected to discover $\sim$ a few 10^5 CCSNe per year, and will be able to resolve massive progenitor stars in pre-explosion imaging in the case of nearby SNe. This may ultimately also constraint/reveal new-physics of light particles

Lien & Fields, 2009

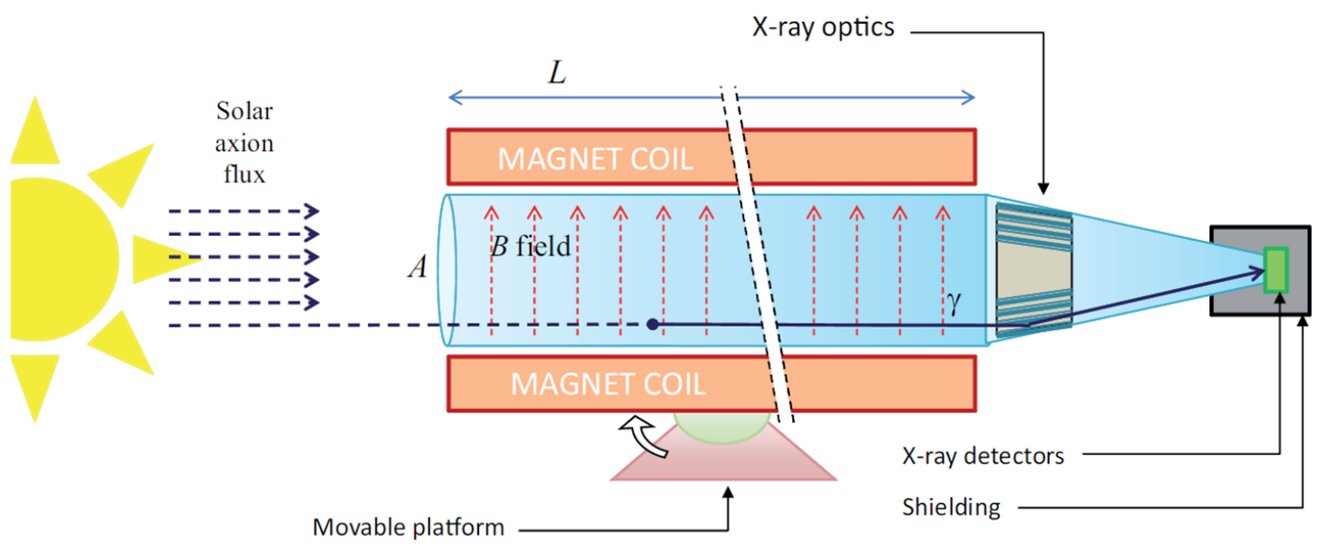
Straniero, Dominguez,
Piersanti, M. G., Mirizzi (2019).

A Bright Future?

Our best option for the astro-region are the new generation of axion Helioscopes.



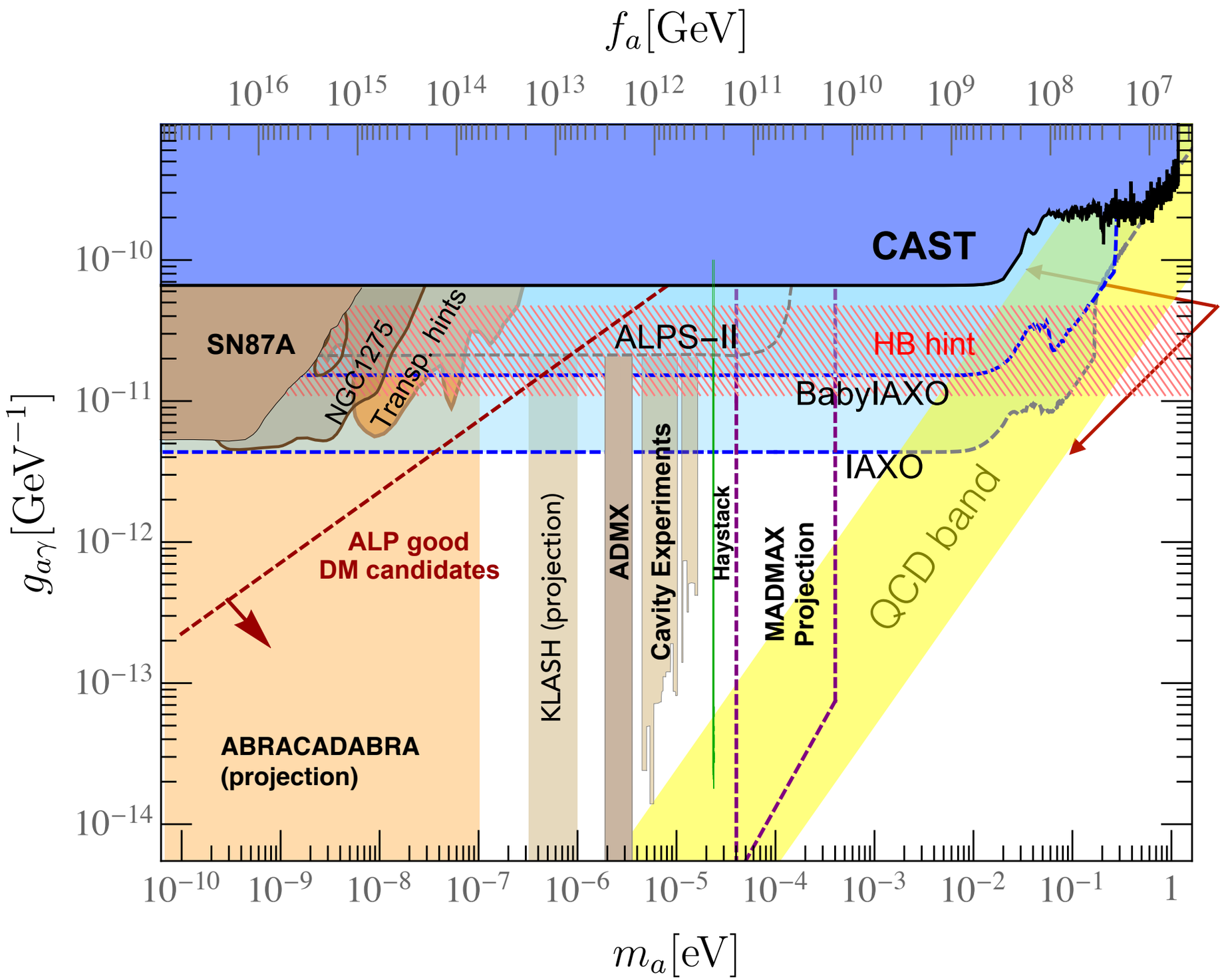
J. Redondo, JCAP 1312 008



CAST (CERN Axion Solar Telescope) is the currently most powerful helioscope.

BabyIAXO improves on the CAST sensitivity by a factor of ~ 100 (to be built in DESY).
IAXO, by a factor of $>10^4$

A bright Future?



QCD band:
Di Luzio, Mescia, Nardi,
Phys.Rev.Lett. 118 (2017),
Phys.Rev. D96 (2017)

Tremendous experimental effort!!

Many other experiments testing other couplings

Summary and conclusions

1. Growing interest in axions with many new proposals and experiments.
2. Stellar evolution constraints the axion properties and hints at well defined regions of the axion parameter space.
3. These regions are accessible to the next generation of axion-scopes
4. The next generation of astrophysical probes, particularly LSST, will provide much information to test the axion hypothesis in astrophysics
5. *Lots to be expected in the early 2020s…stay tuned!*