Axions and Stars

Bounds, Hints and Experimental Potential

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Barry University

14TH PATRAS WORKSHOP ON AXIONS, WIMPS AND WISPS

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Axions and Stars

A few preliminary comments:

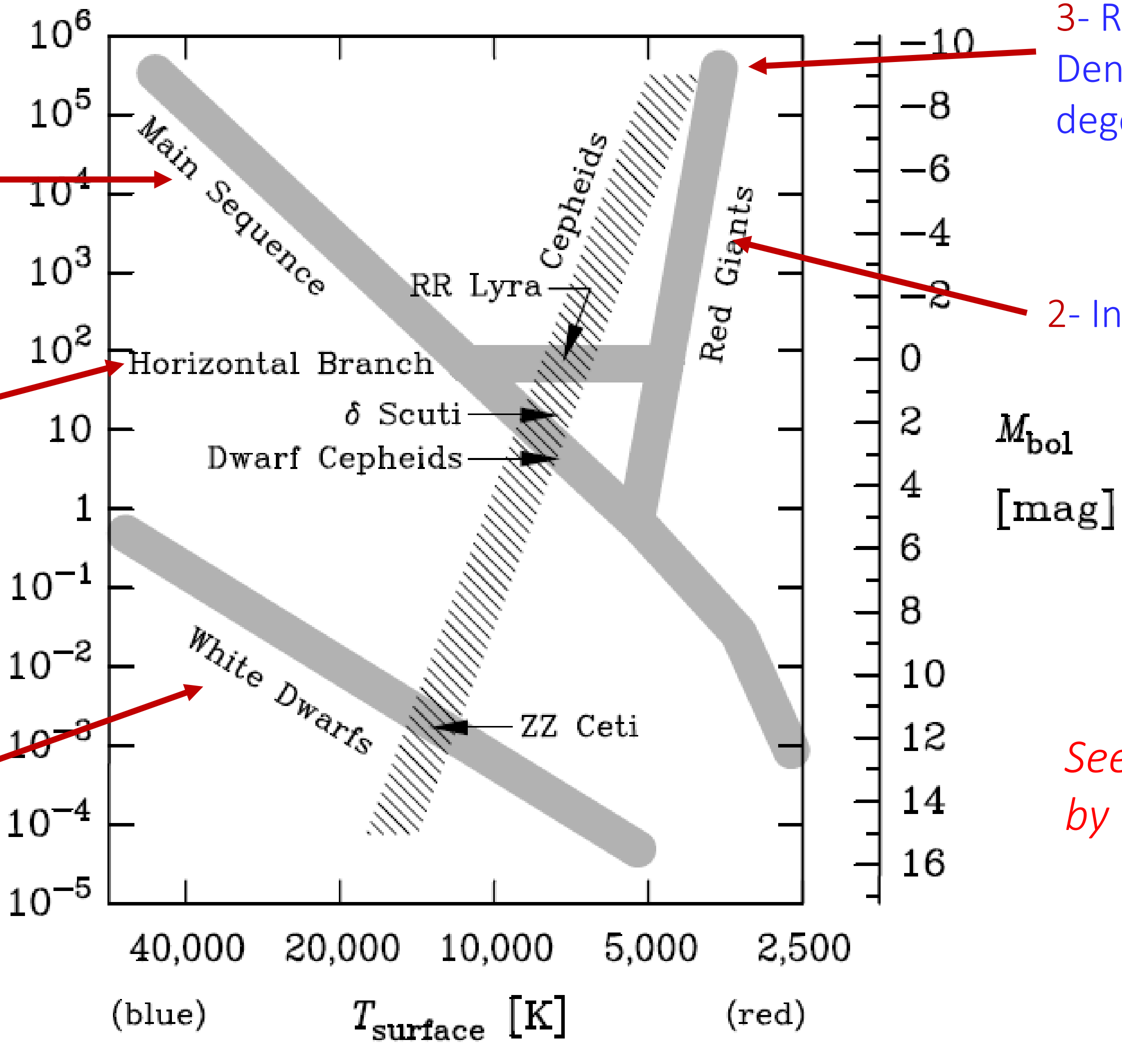
1. Axions coupled with couplings accessible to modern terrestrial experiments can have a substantial (observable) impact on stellar evolution. This is an extremely fortunate situation.

2. Stellar bounds on axions have improved substantially in the last decades. However, in recent years many bounds have saturated and instead we seem to observe hints to nonzero axion couplings (cooling anomalies).

3. Cooling anomalies indicate a systematic problem in our understanding of stellar evolution. Several stellar systems (but not Main Sequence stars) show some anomalous behavior, always indicating the need for additional cooling. All these observations are compatible with the ALP solution

4. Many other astrophysics observations have recently called for an axion solution: transparency hints (*see talk by A. KOROCHKIN*), pulsars (*see talk by J. MAJUMDAR*), the EDGES anomalous observation of the 21 cm signal, etc.

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

See also presentation by I. Dominguez

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

Stars as ALPs Laboratories

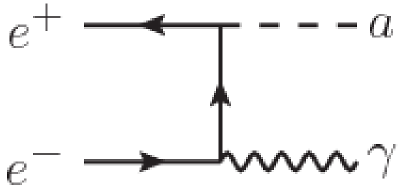
Light, weakly interactive particles (WISPs) can be created in the stellar core and then escape, carrying energy away, therefore contributing to the stellar cooling.

The argument applies to the axion, one of the best studied WISPs.

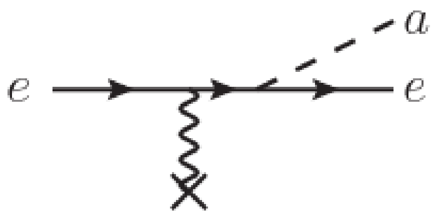
There are many observables which can be used to constrain them.

Primakoff Process

Compton Process



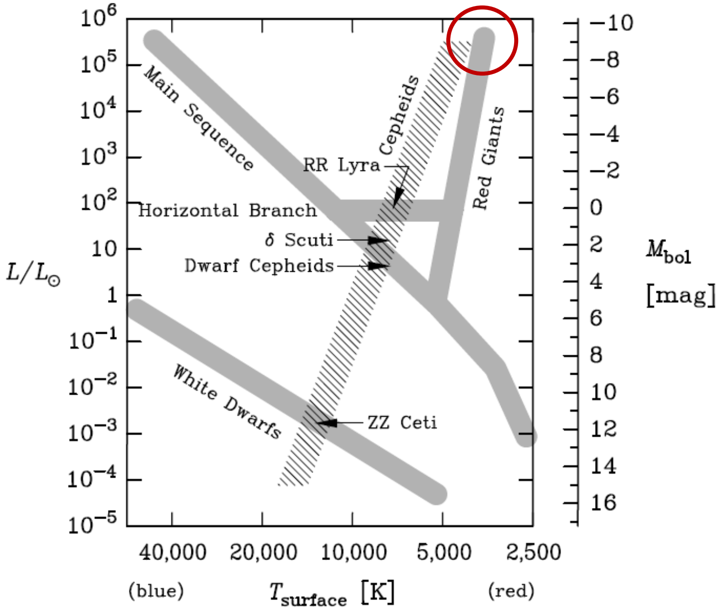
Pair Annihilation



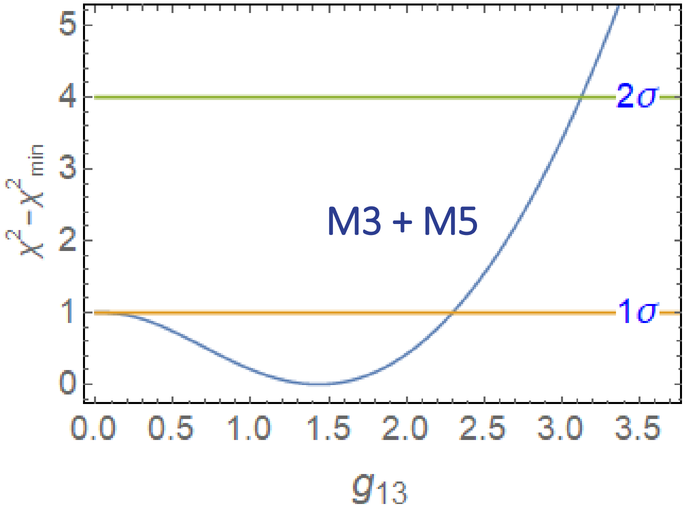
Bremsstrahlung

Red Giant (RG) Stars

Additional cooling would give rise to a brighter RGB tip.



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)



Best fit value: g_{13}=1.4

Bound (2σ): g_{13}<3.1

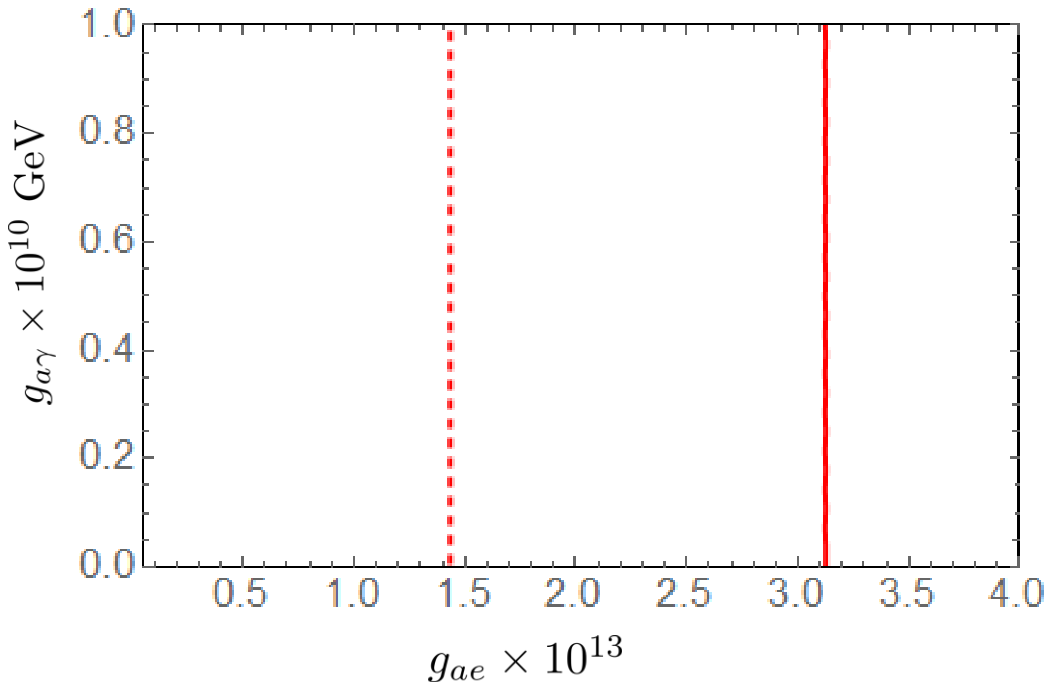
A study of many more clusters is underway…

Red Giant (RG) Stars

The study of many globular clusters is necessary to reduce the uncertainties in the determination of the tip luminosity.

The largest systematic error is the distance. We should wait for the final GAIA data release (2022-2023) to have an improvement of roughly a factor of 10 on the uncertainty in the distance.

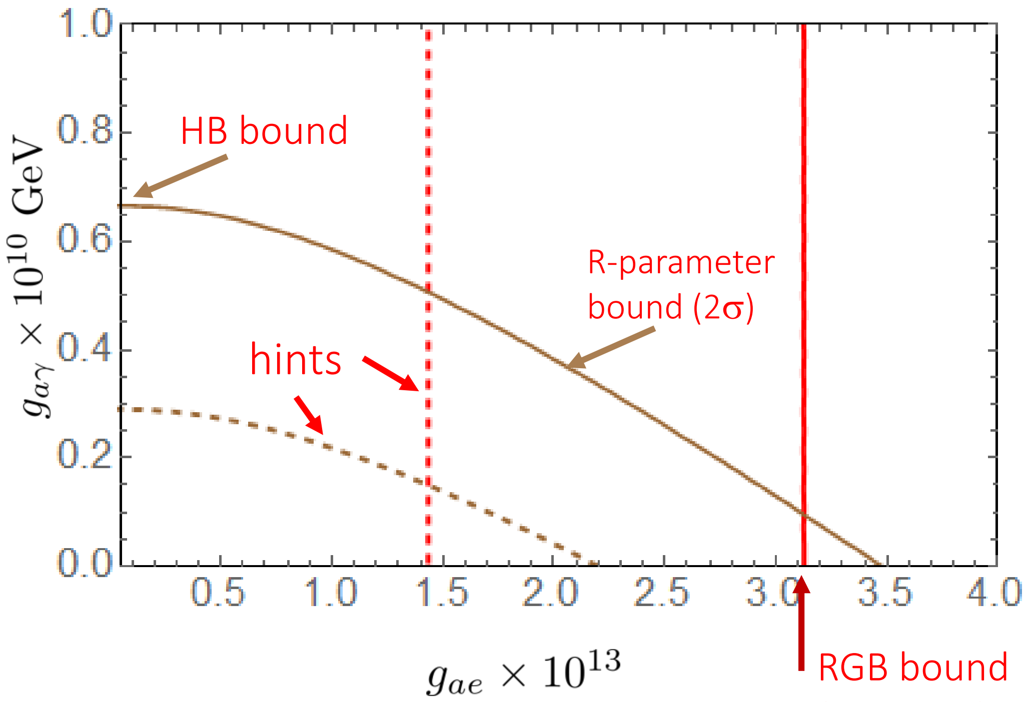
Pancino et al., (2017) [arXiv:1701.03003]



HB stars and the R-parameter

R-parameter $R = N_{HB}/N_{RG}$

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

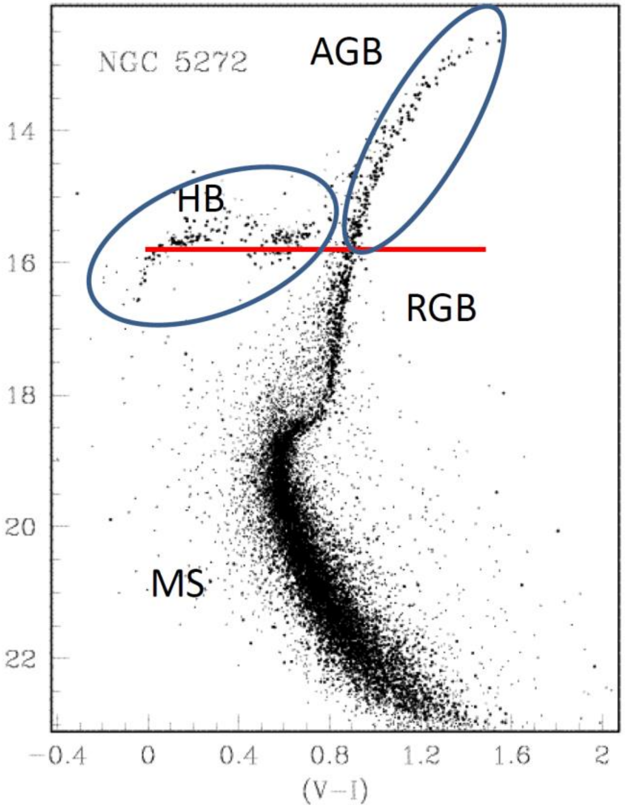


HB bound

R-parameter bound (2σ)

hints

RGB bound (M3+ M5)



Ayala, Dominguez, M.G., Mirizzi, Straniero, (2014)

Straniero (proc. of XI Patras Workshop, 2015)

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

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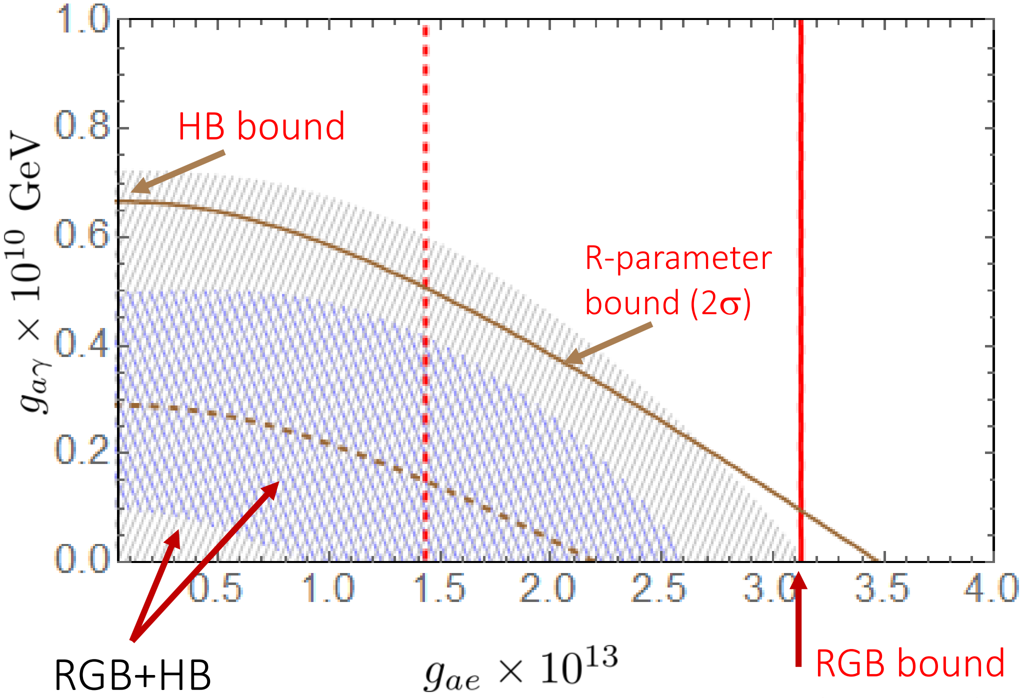
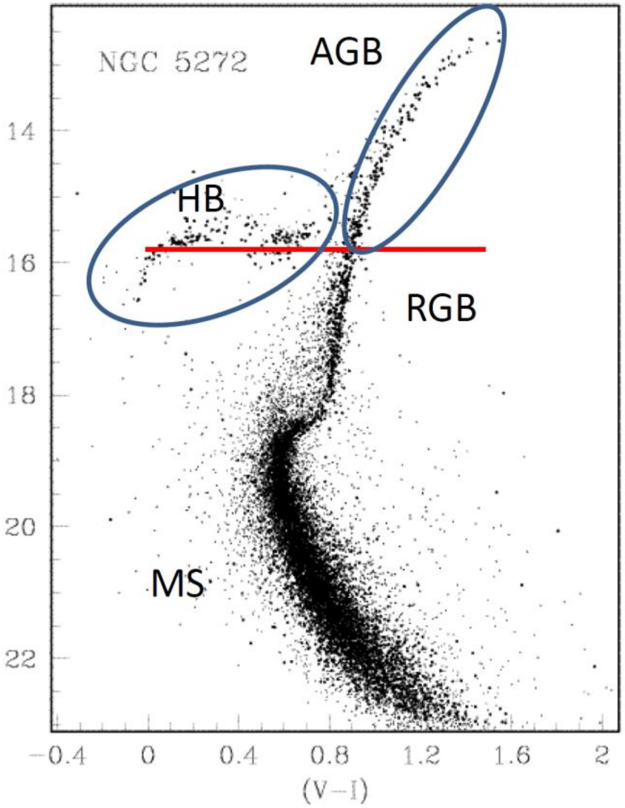


HB bound

R-parameter bound (2σ)

RGB+HB (1 and 2 σ)

RGB bound (M3+ M5)



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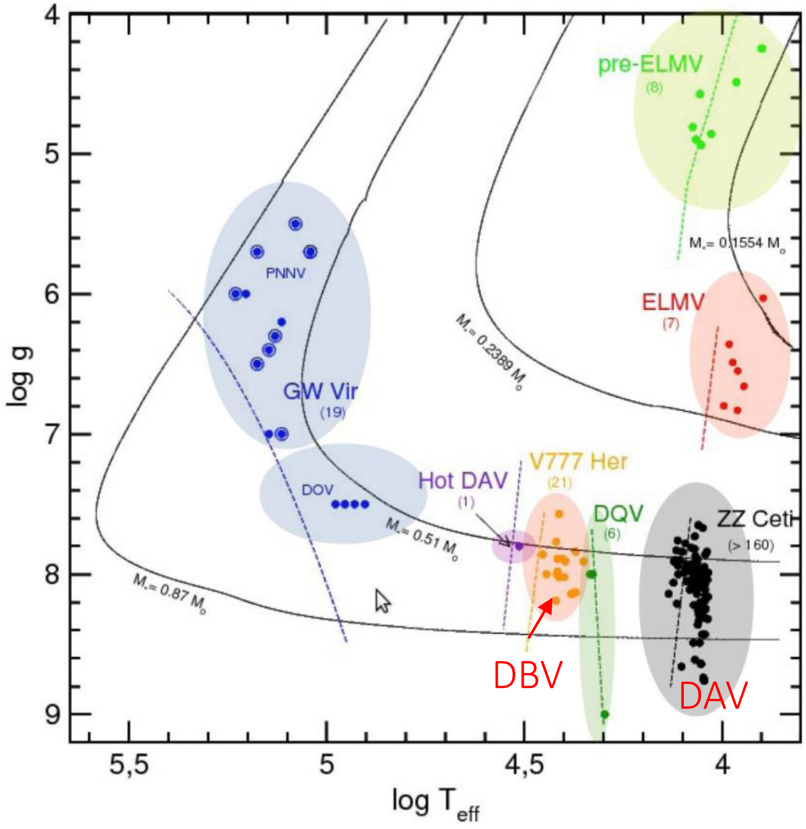
White Dwarf Variables

Luminosity changes periodically with a slowly changing period.

$\dot{P}/P$ is practically proportional to the cooling rate $\dot{T}/T$



Measured period changes of four DAV and one DBV don't agree with the predictions!

First case discussed in
Kepler et. al. (1991),
Isern et. al. (1992)

Discrepancies in the rates of period change run from 0.4 to 4 σ, indicating in all cases additional cooling

A. Corsico, Terceras Jornadas de Astrofisica Estelar (2017)

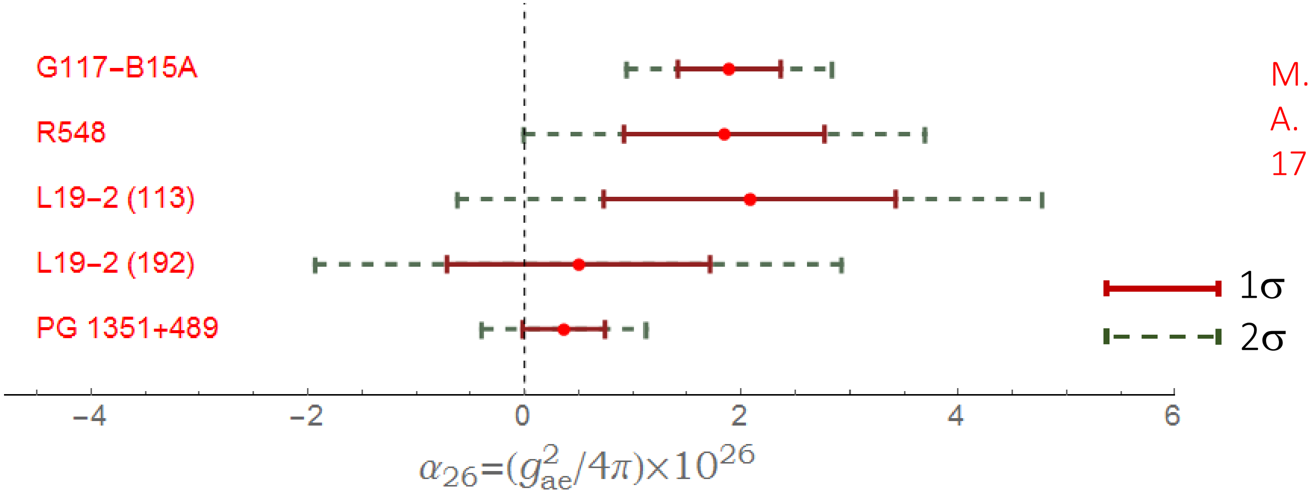
White Dwarf Variables

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)

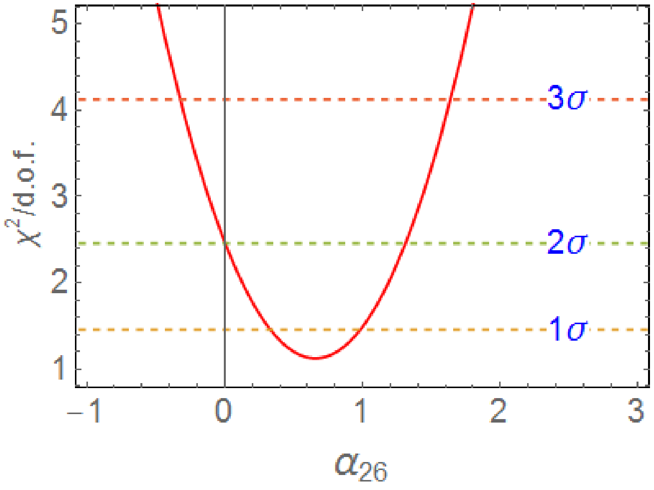


2σ hint for $\alpha_{26} > 0$,

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

χ^2_{min}/d.o.f. = 1.1

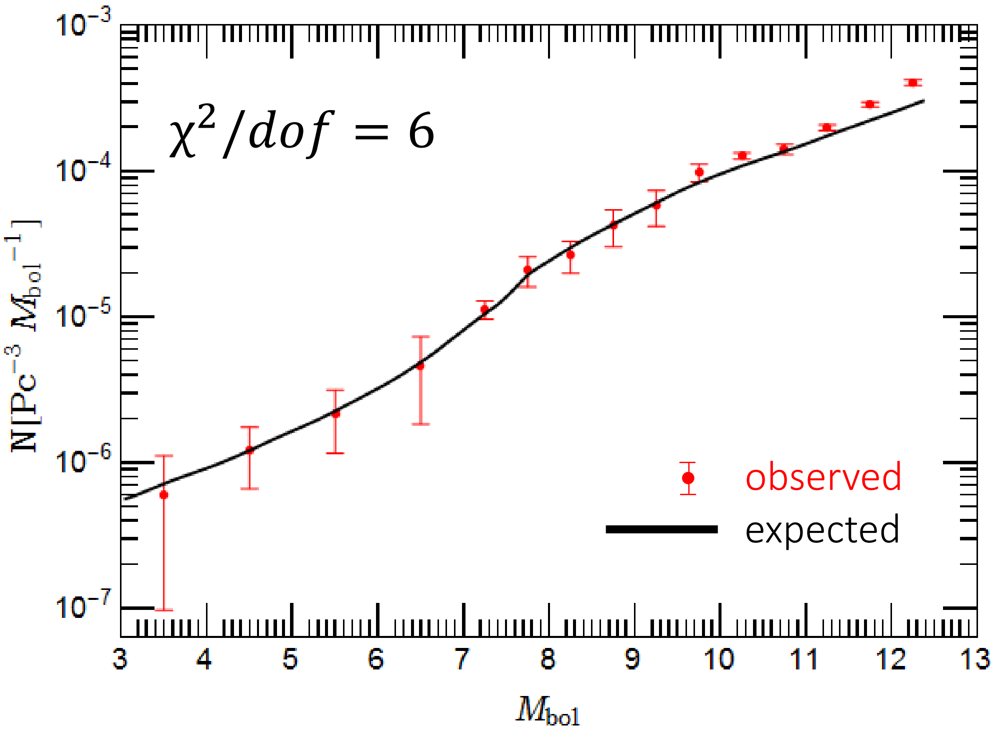
bound (2σ): $\alpha_{26} < 1.3$ ($g_{13} < 4.1$)



White Dwarfs Luminosity Function

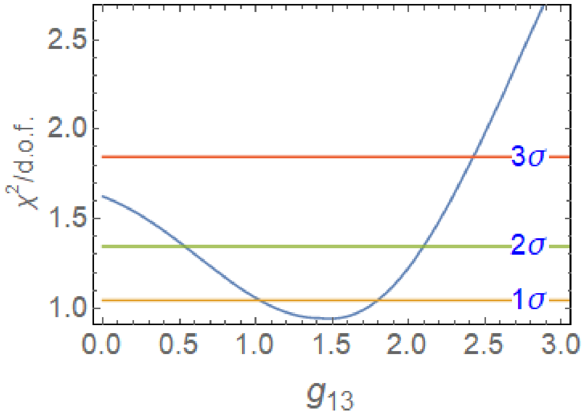
See also talk by J. Isern

White Dwarfs Luminosity Function:



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

ALPs analysis
(1-parameter, 11 points)



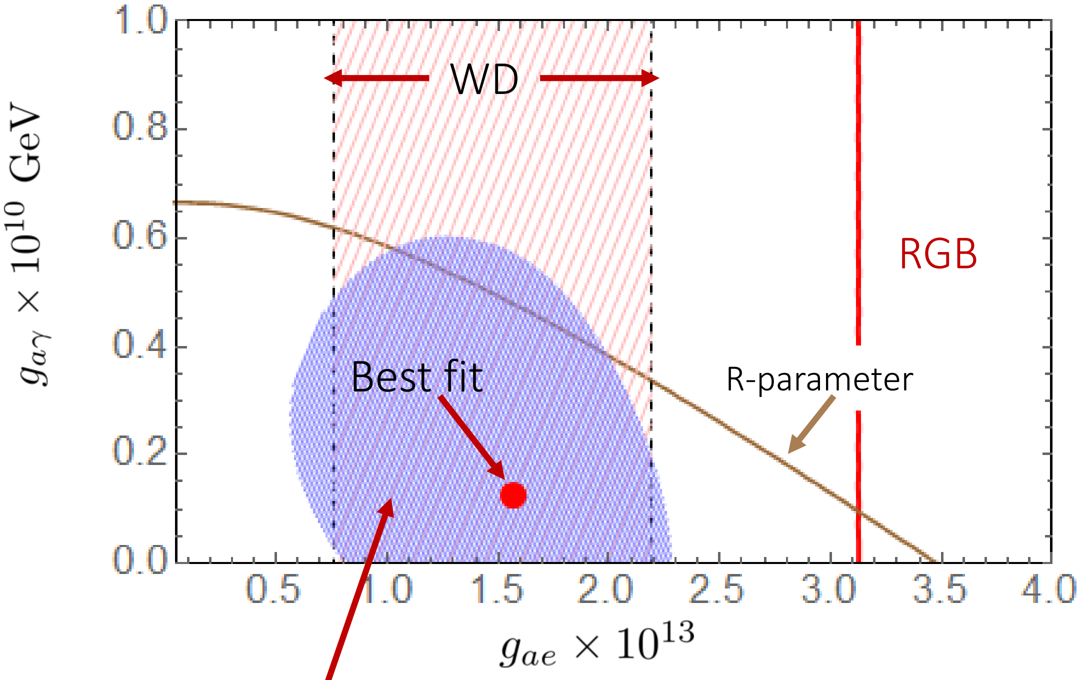
Best fit value: g_{13}=1.4

Bound (2σ): g_{13}<2.1

χ^2_{min}/d.o.f. = 0.94

What do we learn from WDs?

WDs have shown for many years a preference for a nonvanishing axion-electron coupling.



Combined hints (2σ)

The hints allow a vanishing coupling to photons but disfavor (at about 3 σ) a vanishing coupling to electrons

Best fit:

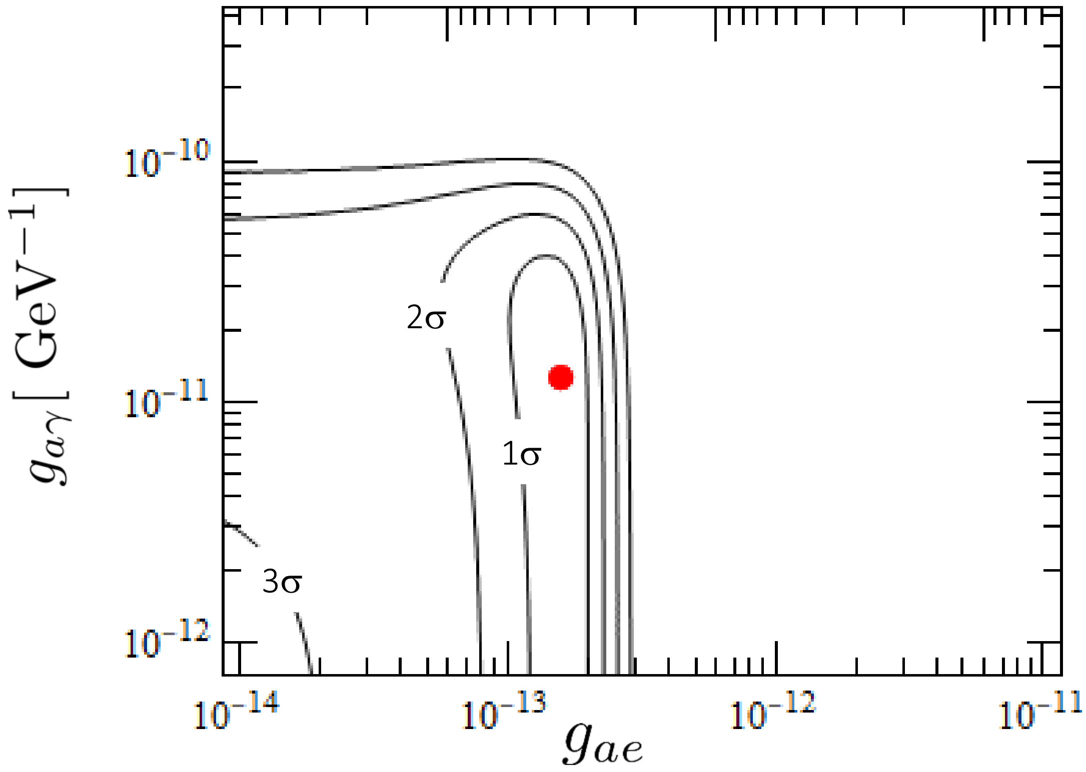
$$g_{a\gamma} = 0.12 \times 10^{-10}\mathrm{GeV}^{-1}$$

$$g_{ae} = 1.57 \times 10^{-13}$$

$$\chi^2_{\mathrm{min}}/\mathrm{d.o.f.} = 0.96$$

ALP interpretation of cooling hints

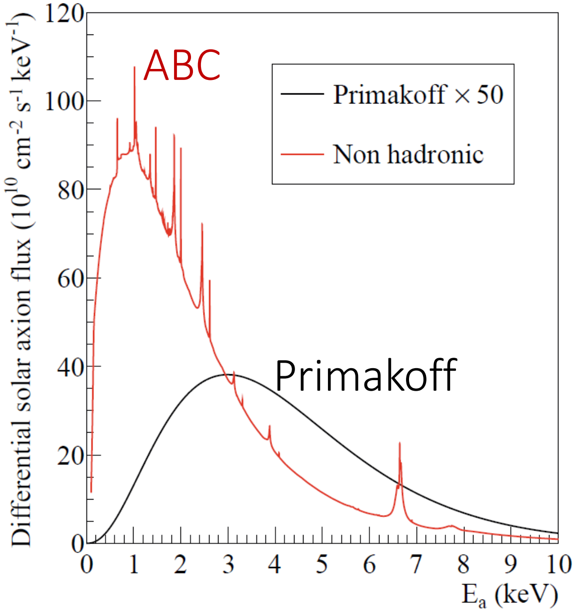
The cooling anomalies points to a well defined area in the axion/ALP g_{ae}-$g_{a\gamma}$ parameter space.



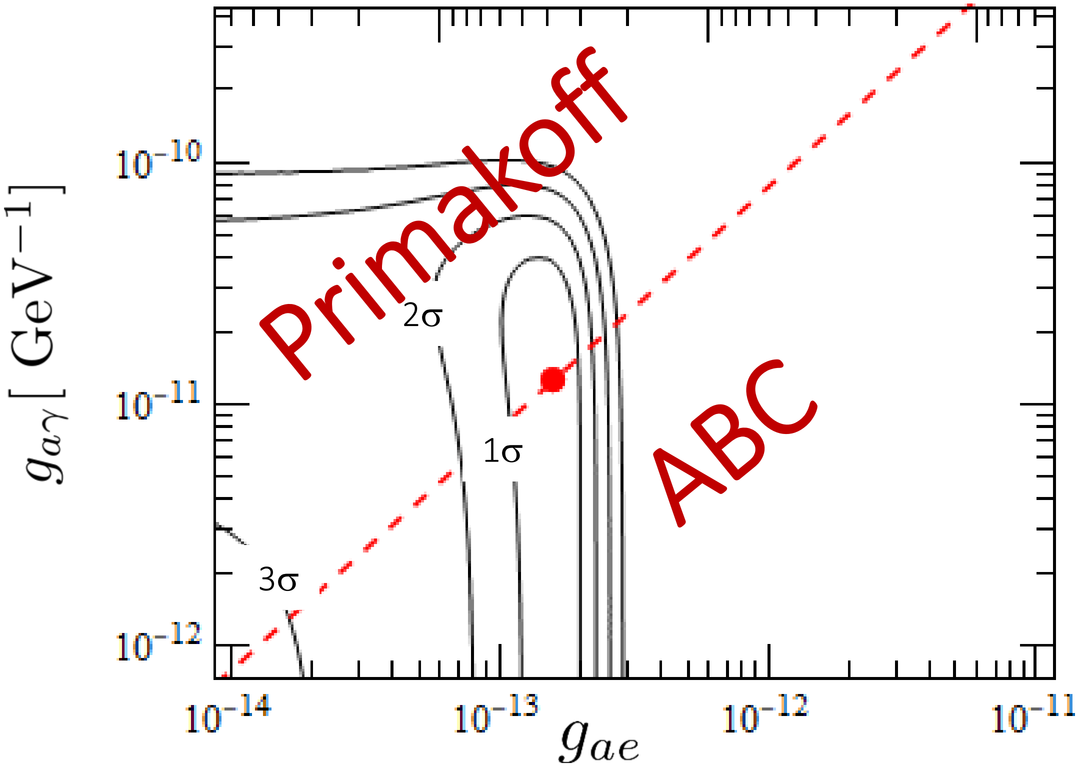
- Since the axion is the simplest (new physics) solution, if experiments exclude the hinted parameters we may also have to rethink our description of stellar cooling!
- The top part of this region may be probed with Mup (*see talk by I. Dominguez*)
- Large parts of this area are accessible to future terrestrial experiments

The sun as an axion source

Solar axions can be produced in the sun through mechanisms which involve the coupling to electrons (ABC) and to photons (Primakoff)

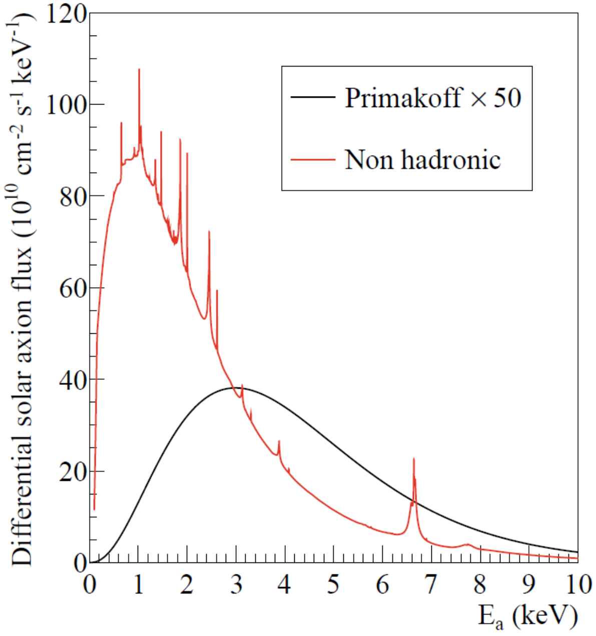


J. Redondo, JCAP 1312 008



Both productions are equally important for the cooling hint region

“Axioelectric Helioscopes”



$$\boxed{\sigma_{\rm ae} = \frac{\alpha_a}{2\alpha_{\rm em}}\left(\frac{E_a}{m_e}\right)^2 \sigma_{\rm pe}}$$

Solar axions can be detected through an axioelectric effect.

The axioelectric cross section is proportional to the photoelectric cross section

Dimopoulos, Starkman, and Lynn, Phys. Lett. B 168, 145 (1986)

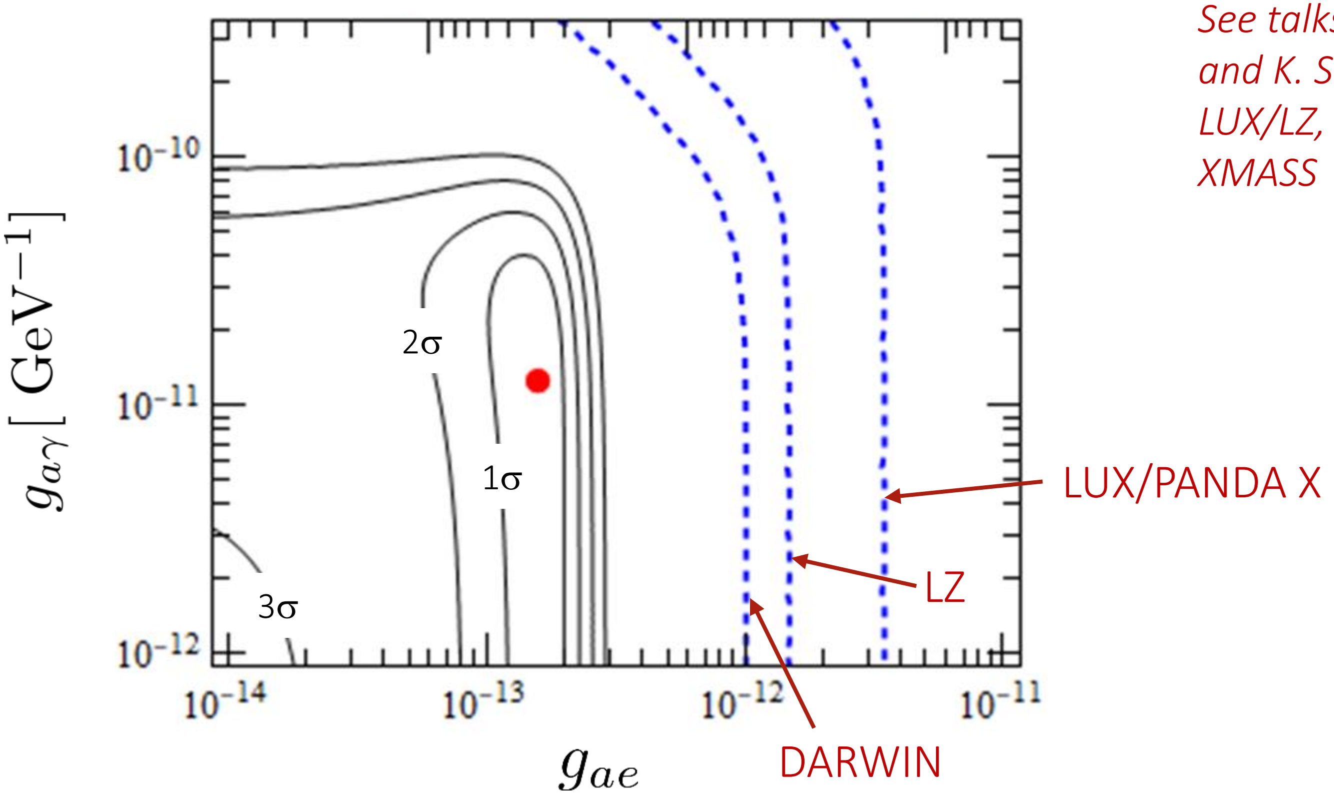
Pospelov, Ritz, and Voloshin, Phys. Rev. D 78, 115012 (2008).

Derevianko, Dzuba, Flambaum, and Pospelov, Phys. Rev. D 82 (2010)

“Axioelectric Helioscopes”

The potential of these experiments is still far from reaching the hinted regions, even with next generation detectors such as LZ or Darwin

See talks by F. Neves, P. Xie, and K. Sato for updates on LUX/LZ, PANDA X, and XMASS



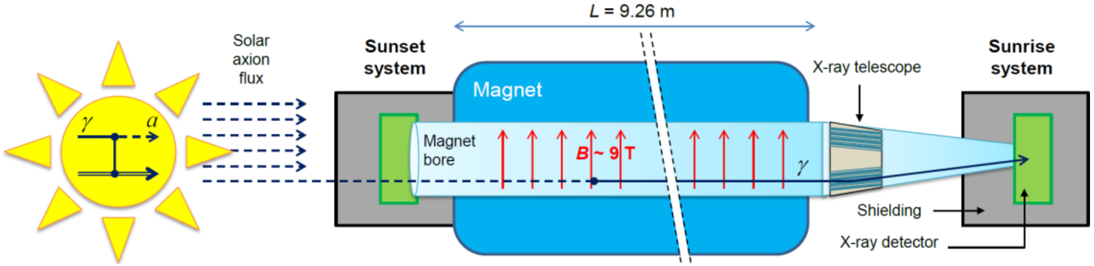
LUX/PANDA X

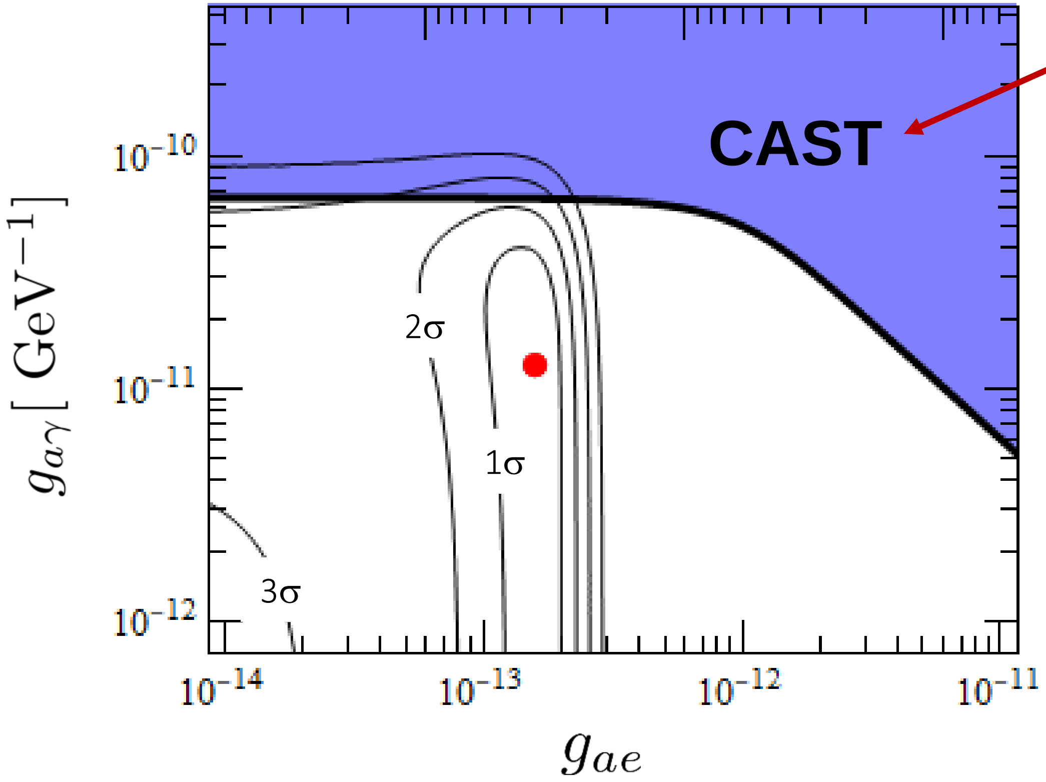
LZ

DARWIN

Axion Helioscopes

Standard helioscope: convert solar axions into x-ray photons in a magnetic field.





Excluded by the **C**ERN **A**xion **S**olar **T**elescope (CAST)

CAST coll., Nature Phys. 13 (2017) 584-590

Axion Helioscopes

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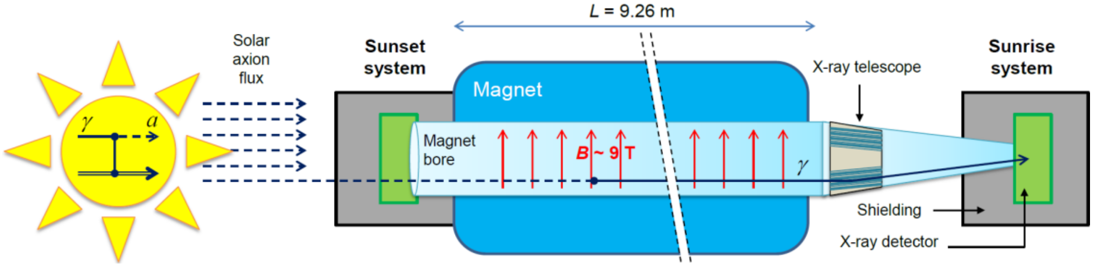
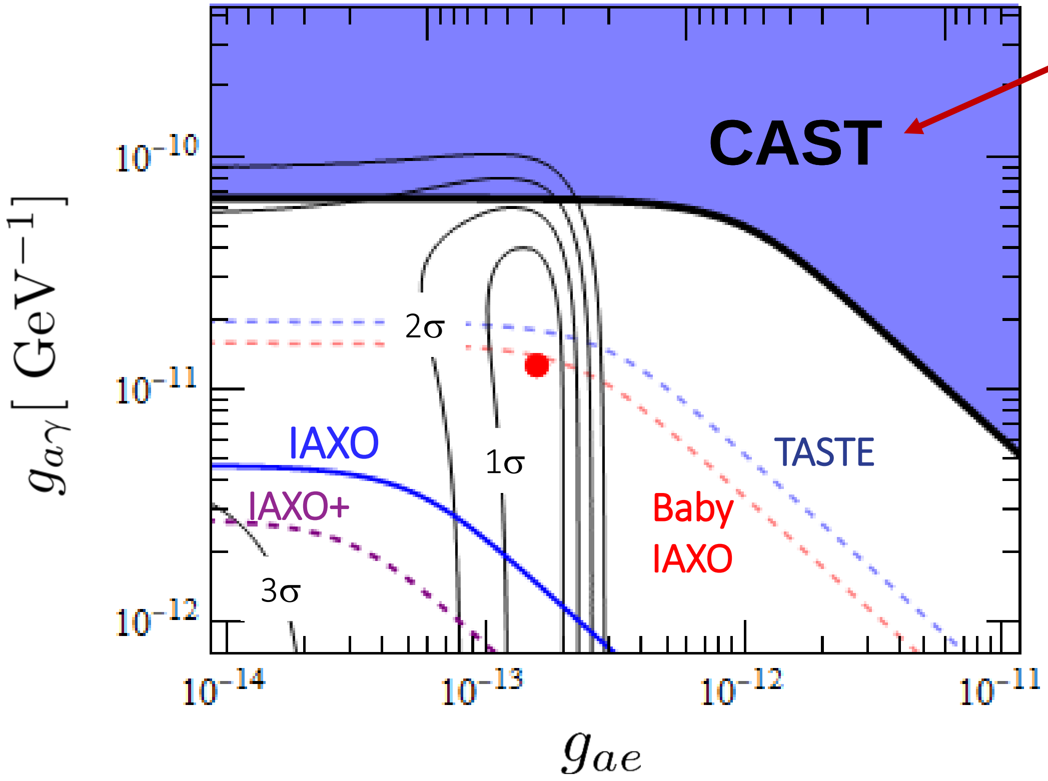




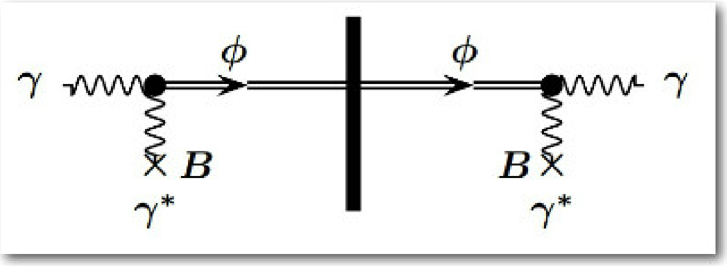
Excluded by the **C**ERN **A**xion **S**olar **T**elescope (CAST)

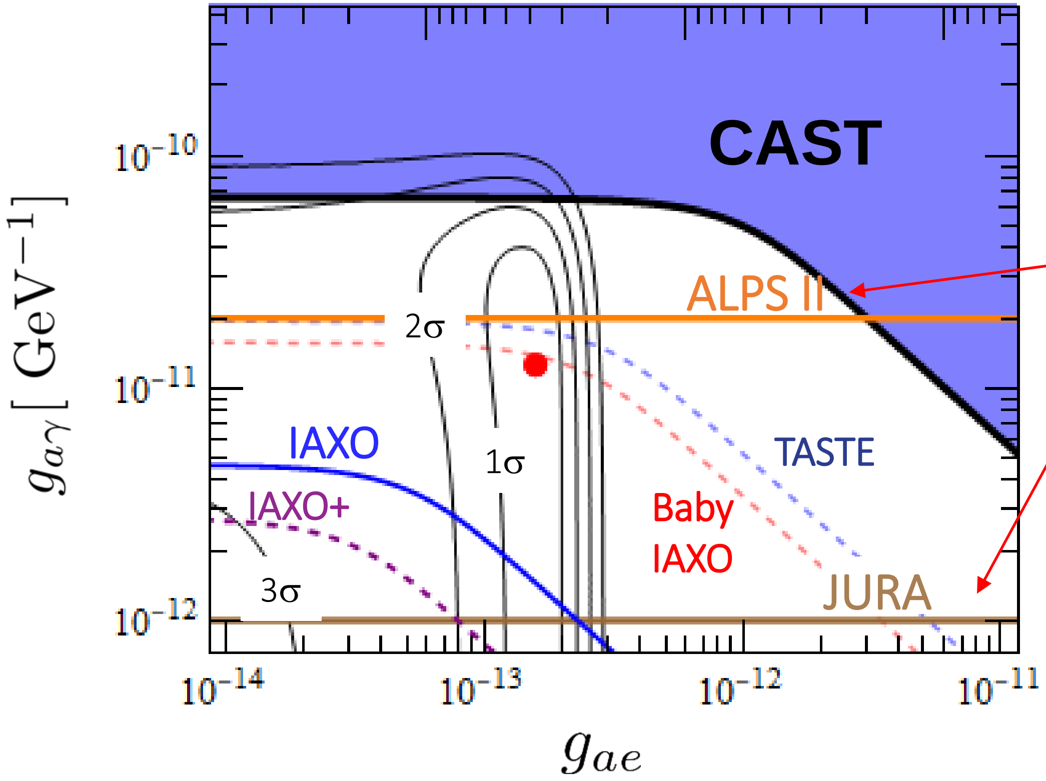
CAST coll., Nature Phys. 13 (2017) 584-590

CAST successors, particularly IAXO (*see talk by I. Irastorza*), could probe a large portion of the hinted region

Light Shining Through a Wall

Light Shining Through a Wall experiments have also the potential to probe the hinted region





No model dependence

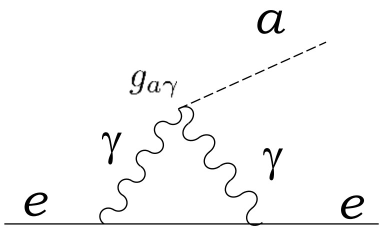
Can be improved

See *D. SCHMELZER talk*

QCD Axion Models and Cooling Hints

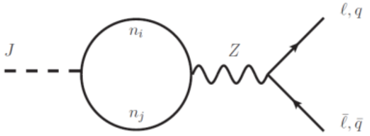
KSVZ models predict a coupling to electrons which is about an order of magnitude smaller than what needed for the best fit.

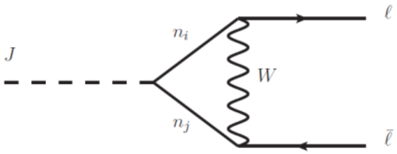
$\chi^2_{\min}/\mathrm{d.o.f.} > 2$



Extended hadronic models, such as SMASH (*see talk by C. R. DAS*), can improve the case by increasing the contribution to the axion-electron coupling

$\chi^2_{\min}/\mathrm{d.o.f.} \approx 1$

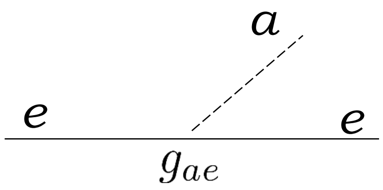




DFSZ 1: $C_e = \frac{\sin^2\beta}{3}$ $\quad C_{a\gamma} = \frac{8}{3} - 1.92$ requires tan β=0.27

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

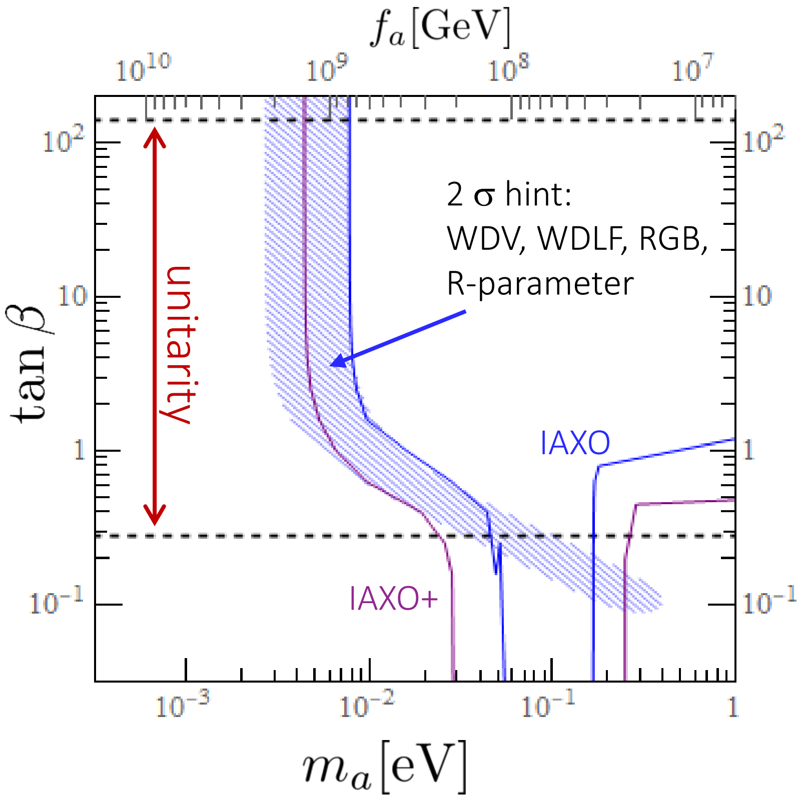
Unitarity bounds require 0.28<tan β<2.8. $\chi^2_{\min}/\mathrm{d.o.f.} \approx 1$

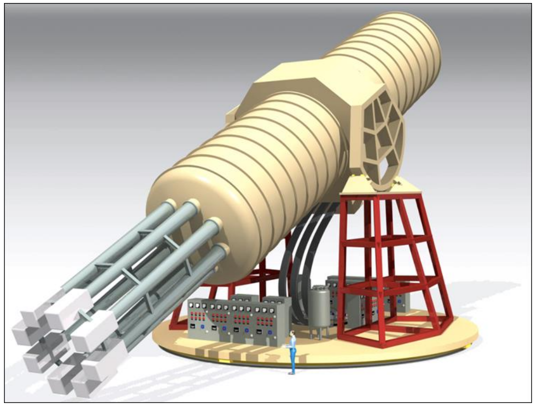


QCD Axion Models and Cooling Hints

Example: DFSZ 1 axions

$\chi^2_{\rm min}/{\rm dof} = 15.4/16$





See talk by I. Irastorza

IAXO can probe only a small region allowed by the unitarity bound. That is where the best fit is.

IAXO+ can probe a much larger region

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

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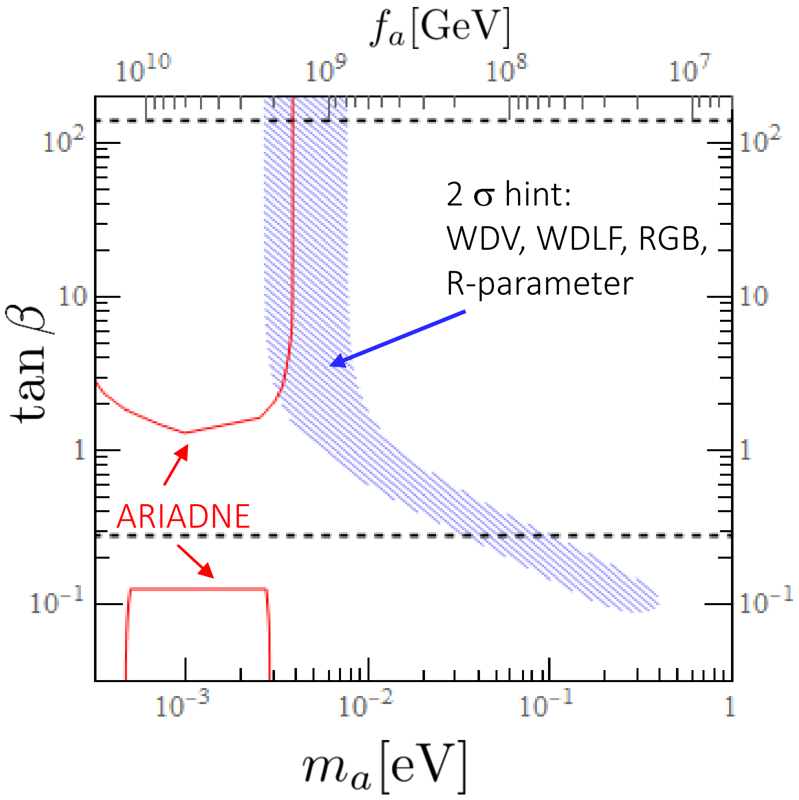


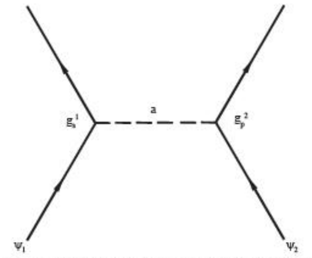
2 σ hint:
WDV, WDLF, RGB,
R-parameter

ARIADNE

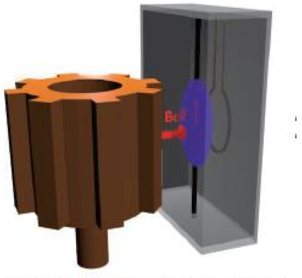
ARIADNE searches for long range forces mediated by axions.

J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984).

A. Arvanitaki and A. A. Geraci, Phys. Rev. Lett. 113 (2014)



Feynman diagram for monopole-dipole interaction



ARIADNE experimental schematic for monopole-dipole interaction [3]

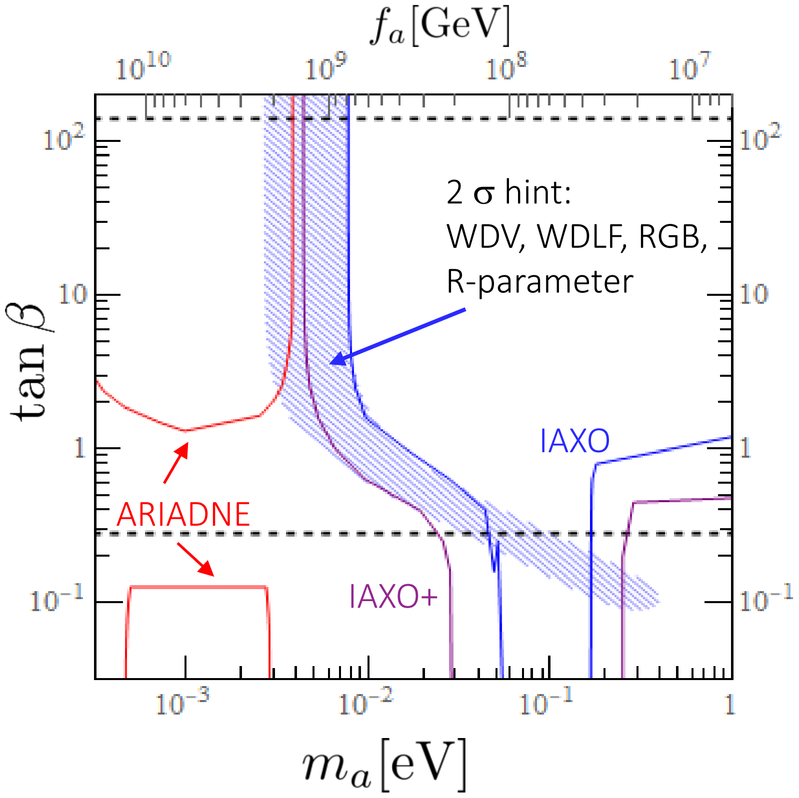
From Kim, Kim, Shin, Semertzidis, Patras workshop 2016

It can probe sections of the DFSZ parameter space and is more sensitive than IAXO at low masses

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

QCD Axion Models and Cooling Hints

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

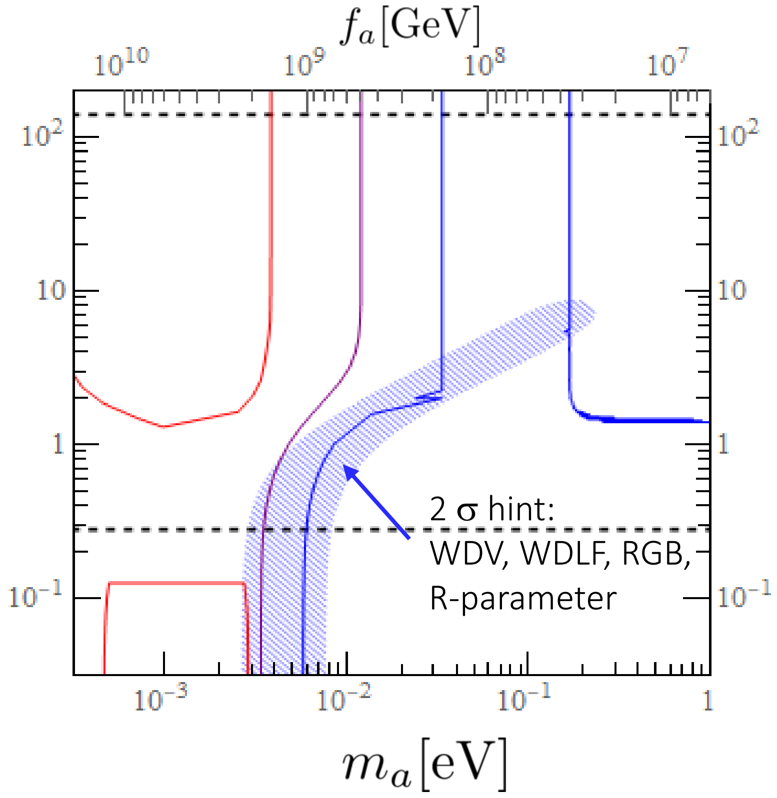


2 σ hint: WDV, WDLF, RGB, R-parameter

IAXO

ARIADNE

IAXO+



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The SN 1987A Nightmare

RGB and WD stars point to a very small values of the axion-electron coupling.

However, this does not imply necessarily that all the other couplings are small! It is easy to accommodate a small axion-electron coupling in QCD axion models.

The SN 1987A Nightmare

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However, this does not imply necessarily that all the other couplings are small! It is easy to accommodate a small axion-electron coupling in QCD axion models.

The analysis of SN 1987A implies that the coupling to nucleons is small. This is hard to explain without requiring all other couplings to be also small.

Difficult but not impossible. Models with generation dependent PQ charges can have small nucleon couplings while keeping large couplings with photons (astrophobic axion models).

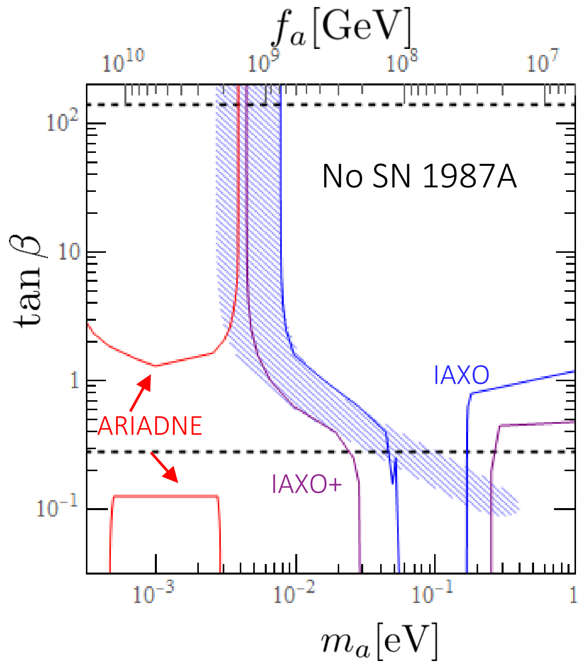
Di Luzio, Mescia, Nardi, Panci, Ziegler (2018)

The SN 1987A Nightmare

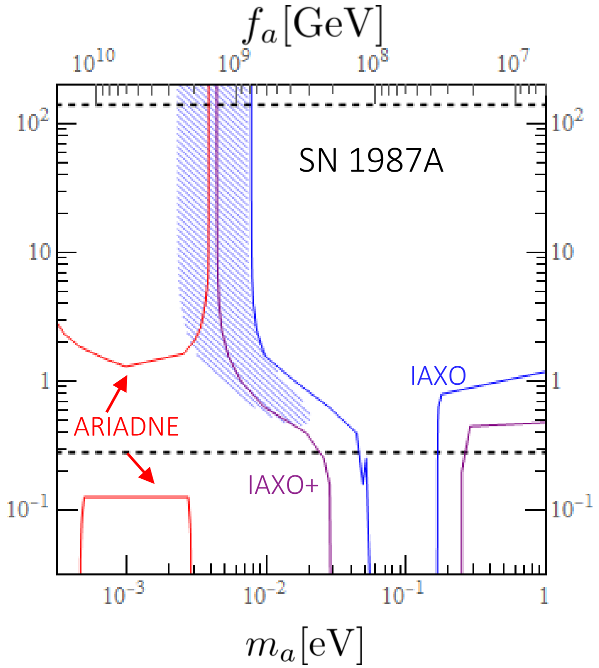
The accepted axion bound from SN 1987A is

$$\boxed{g_{an}^2 + 0.6\, g_{ap}^2 + 0.03\, g_{an} \cdot g_{ap} \leq 3.6 \times 10^{-19}}$$

DFSZ 1



$\chi^2_{\rm min}/\mathrm{dof} = 15.4/16$



$\Delta\chi^2 = 1.3$

The SN 1987A bound is a serious problem for experiments such as IAXO (less so for ARIADNE).

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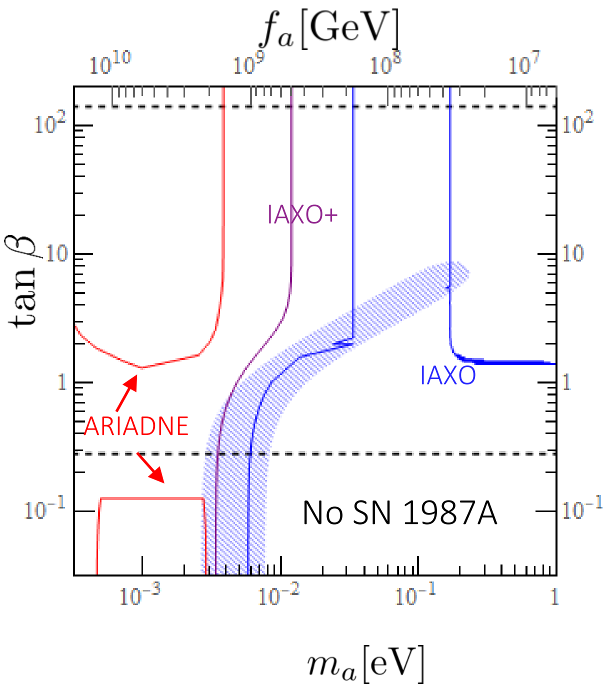
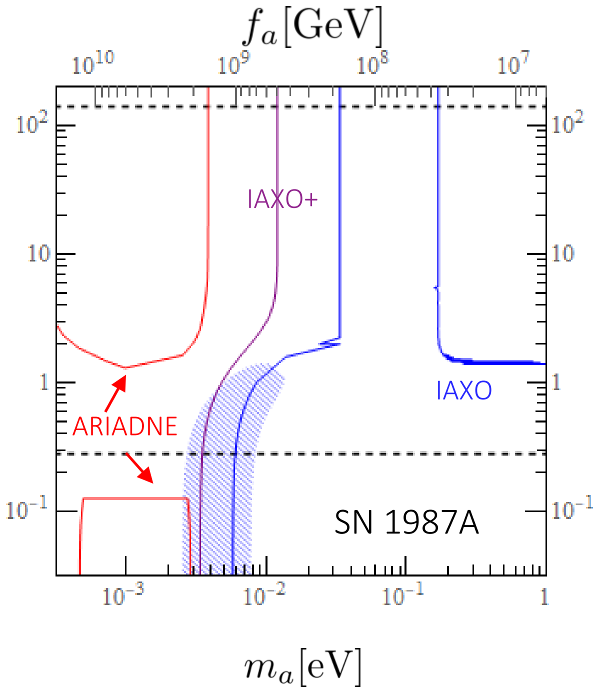
DFSZ 2



$\chi^2_{\rm min}/{\rm dof} = 15.4/16$



$\Delta\chi^2 = 0.5$

The SN 1987A bound is a serious problem for experiments such as IAXO (less so for ARIADNE).

The SN 1987A Nightmare

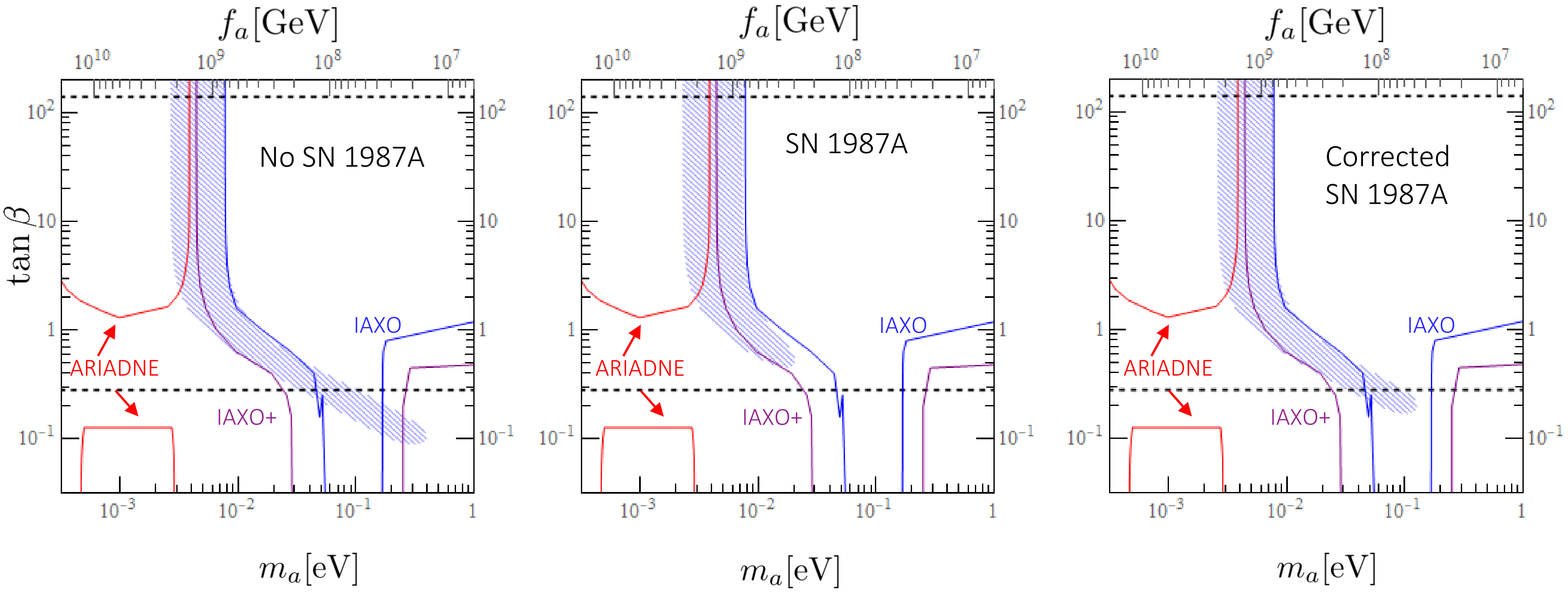
A recent study has indicated that the axion emission from SN 1987A rate was overestimated by a factor of 25 or so. Consequently, the bound on the axion nucleon coupling can be relaxed by a factor of 5 or so. The result is due to the correction of the emission rate by including medium effects, vertex corrections, and a finite pion mass.

Chang, Essig, McDermott (2018)

The claim has not been verified by a self-consistent simulation yet (*see talk by a. Mirizzi*)

The SN 1987A Nightmare

DFSZ 1



$\chi^2_{\rm min}/{\rm dof} = 15.4/16$

$\Delta\chi^2 = 1.3$

$\Delta\chi^2 = 0.2$

Considerable improvement in the fit and IAXO potential with the corrected emission rate

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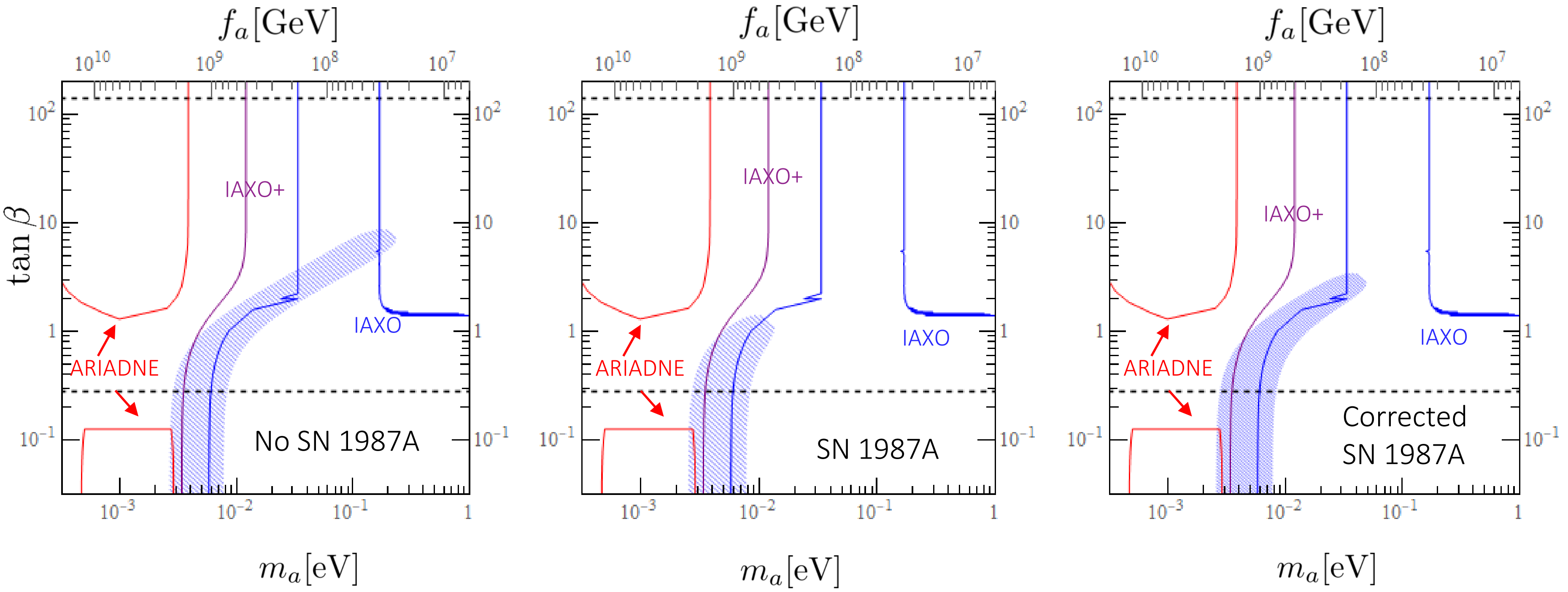
DFSZ 2



$\chi^2_{\min}/\mathrm{dof} = 15.4/16$

$\Delta\chi^2 = 0.5$

$\Delta\chi^2 = 0.3$

Minimal improvement in the fit and IAXO potential with the corrected emission rate

Conclusion

- Astrophysical bounds on axion/ALPs are improving slowly and saturating on finite axion couplings.

- Currently, we observe some hints from several stellar systems. They all indicate the need for additional cooling. The possibility that this is a random effect is less than 1%.

- Terrestrial experiments are catching up with stars! It is an exciting period!

- Next generation axion experiments will be able to probe sizeable regions of the ALP and QCD axions parameter space hinted by the cooling anomalies.

Back up slides

Cooling Anomalies

Observable	**Stellar system**	**Significance**	**Solutions**	**comments**
rate of period change $\dot{P}/P$ of WD variables	G117-B15A	4 σ	g_{ae} ν_{μ}	May depends on some uncertain assumptions on the oscillating modes
	R548	2 σ		
	L19-2 (113)	1.5 σ		
	L19-2 (192)	0.4 σ		
	PG 1351+489	1.1 σ		
Shape of WDLF	WD	2.3 σ	g_{ae}	Based on axion solution in Bertolami et. al., JCAP 1410 (2014). See talk by Isern
Lum. RGB-tip	Globular cluster M5	1.24 σ	g_{ae} ; ν_{μ}	
	Globular cluster ω-Centauri	0.5-0.7 σ	g_{ae} ; ν_{μ}	Approximate estimate based on the data presented
HB stars ($R=N_{HB}/N_{RGB}$)	Globular cluster	2 σ	$g_{a\gamma}$	Y from Aver et. al. (2013); $g_{ae}=0$
Supergiants (B/R)	Open Clusters	??	$g_{a\gamma}$	Systematics in the modeling are largely unknown
NS	CAS A	??	g_{aN}	

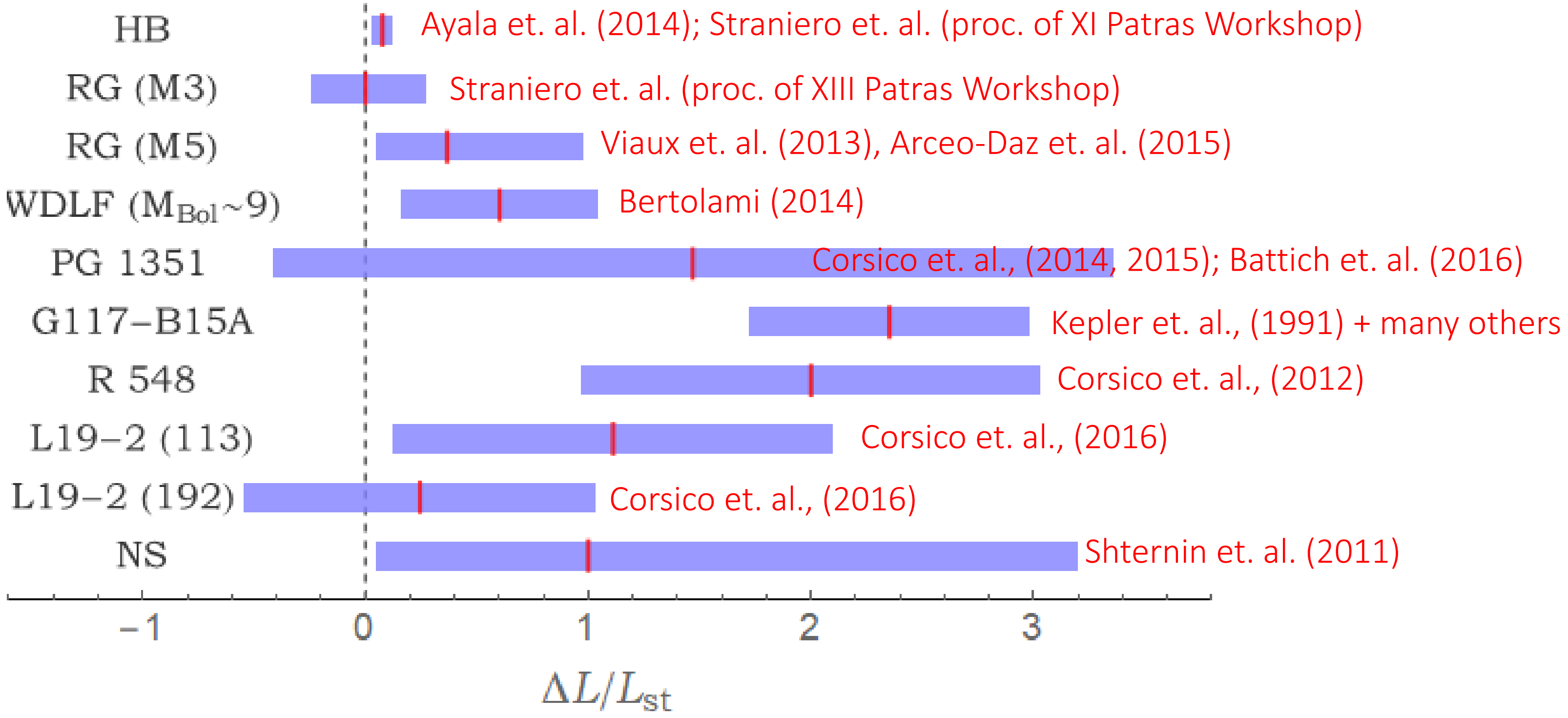
Hints of new physics?

The cooling anomalies show a systematic problem in our understanding of stellar evolution.

Axions/ALPs provide the simplest solution among all new physics candidates

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

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



Ayala et. al. (2014); Straniero et. al. (proc. of XI Patras Workshop)

Straniero et. al. (proc. of XIII Patras Workshop)

Viaux et. al. (2013), Arceo-Daz et. al. (2015)

Bertolami (2014)

Corsico et. al., (2014, 2015); Battich et. al. (2016)

Kepler et. al., (1991) + many others

Corsico et. al., (2012)

Corsico et. al., (2016)

Corsico et. al., (2016)

Shternin et. al. (2011)

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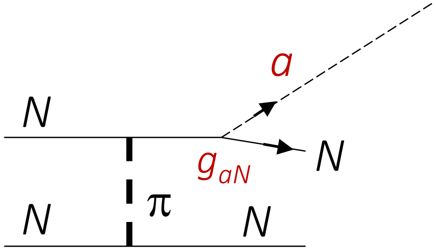
The axion production rate can be calculated in the OPE approximation.

Using a state of the art SN model we find:

$$L_a \propto g_{an}^2 + 0.6\, g_{ap}^2 + 0.03\, g_{an} \cdot g_{ap}$$

$$N_a \propto g_{an}^2 + 0.6\, g_{ap}^2 + 0.07\, g_{an} \cdot g_{ap}$$

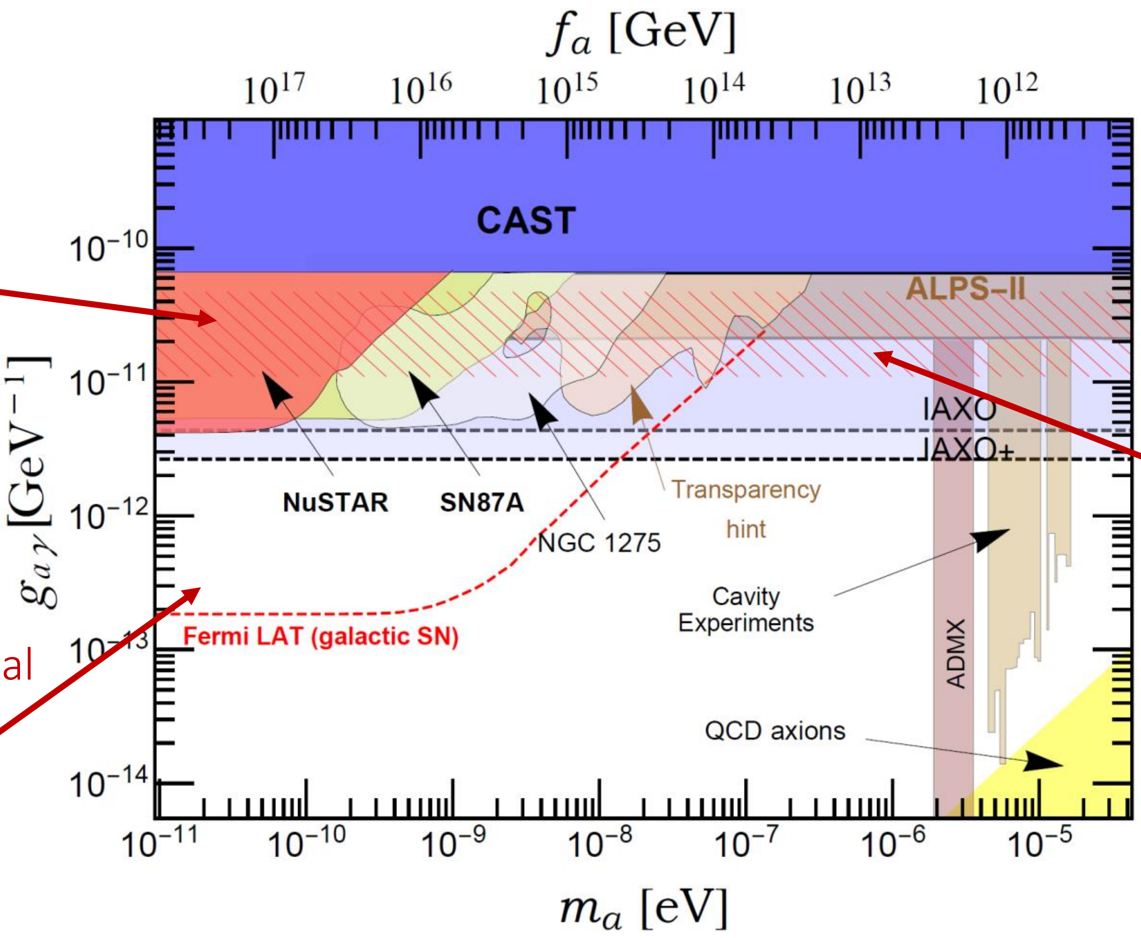


The result is fairly independent from the progenitor mass and is not affected by the axion feedback on the star, since the axion interactions don't change the relative abundance of neutrons and protons.

Additionally, the expression should hold valid if the corrections to OPE do not depend on the relative abundance of neutrons and protons.

Supernovae and Supergiants Axionscopes

The low mass region of the hints can be probed with space born photon detectors



Betelgeuse

Expected NuStar sensitivity

Fermi potential in case of a galactic SN

Cooling Hints

M.G., proceeding of the 13th Patras workshop (2017)