Bounds and Hints on Axions from Stars

Maurizio Giannotti,
Barry University

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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.

3. These 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, pulsars, the EDGES anomalous observation of the 21 cm signal, etc.

Stellar evolution in a nutshell

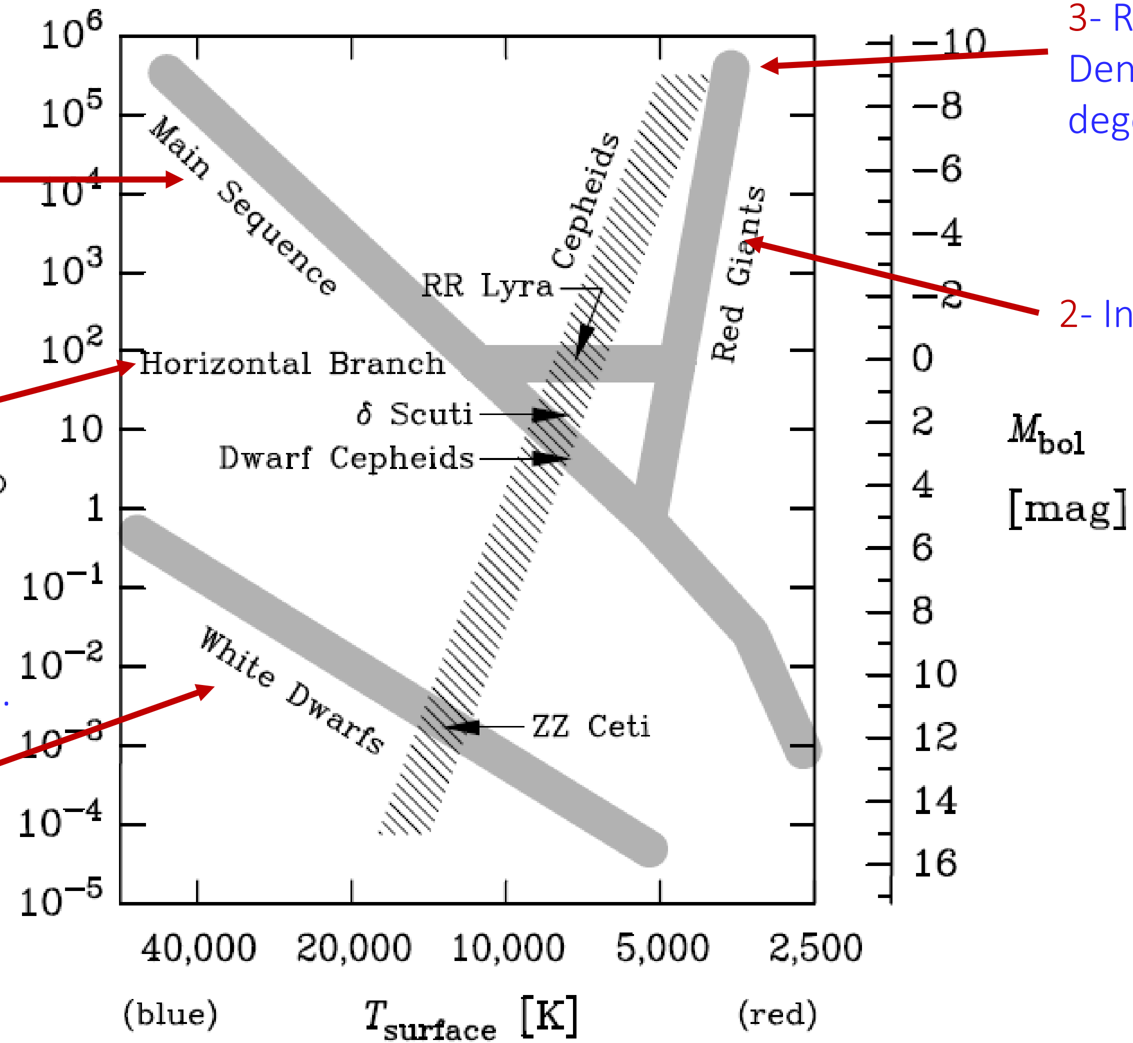
1- H burning in the core

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

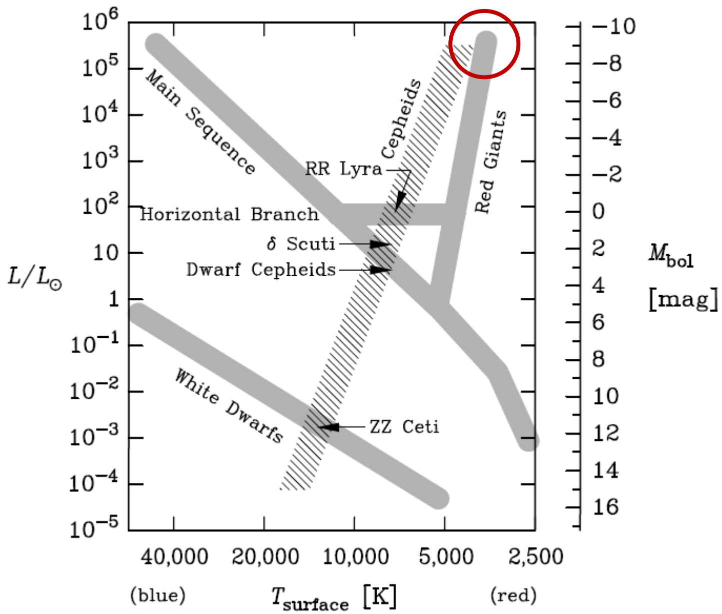
5- No nuclear burning. Dense and cold core; degenerate electrons



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

Red Giant (RG) Stars

Additional cooling would give rise to a brighter RGB tip.



The most recent studies report a slightly brighter tips, particularly in M5.

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)

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]

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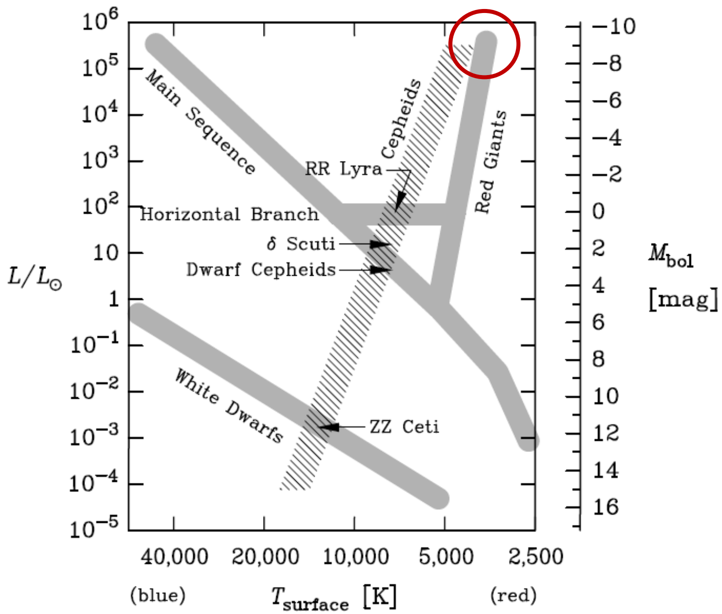

The anomaly can be explained by

- ✓ *Neutrino magnetic moment:*
  $\nu_\mu \approx 2 \times 10^{-12} \mu_B$
- ✓ *Axion-electron coupling*
  $g_{ae} = 1.88^{1.20}_{-1.18} \times 10^{-13}$
- ✓ *HP*

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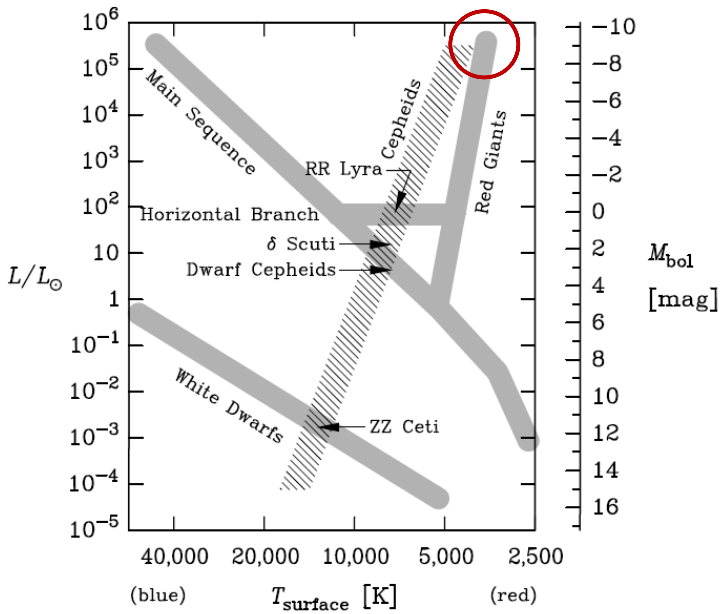

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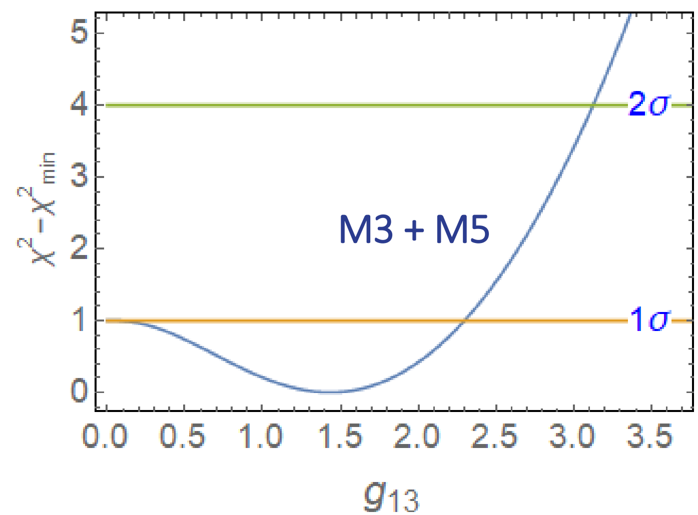

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Bound (2σ): g_{13}<3.1

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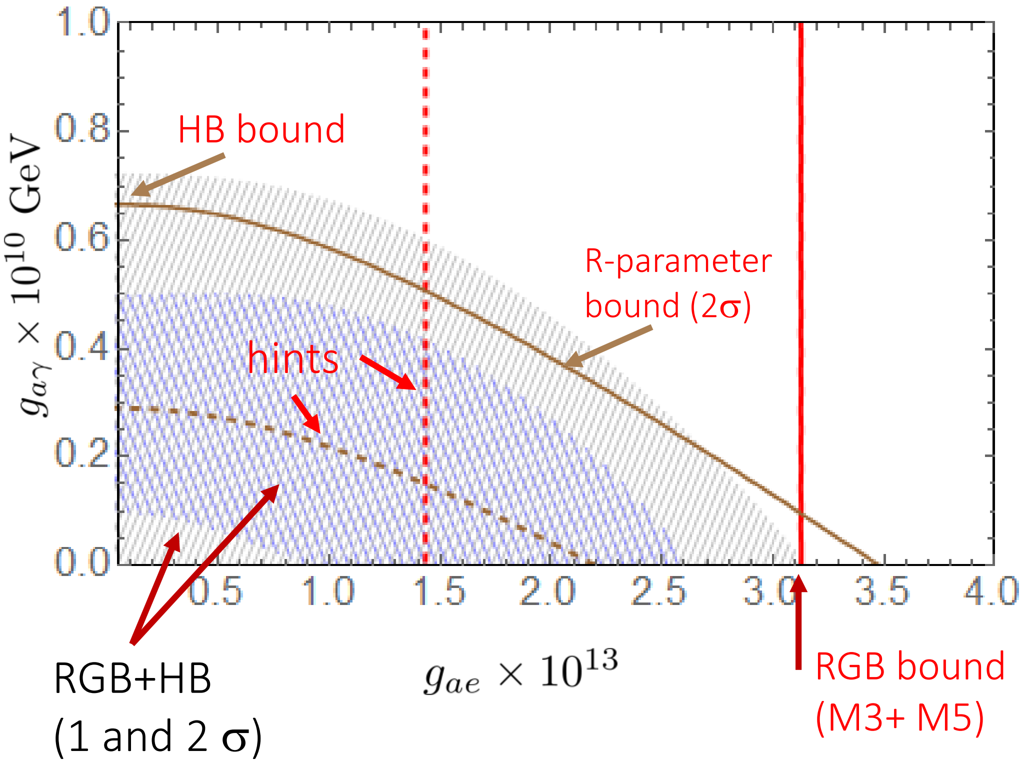
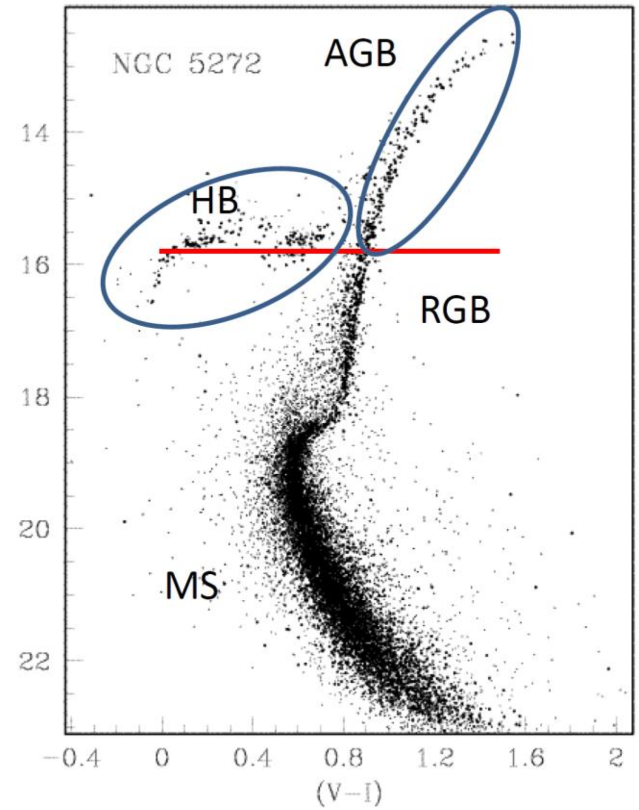
HB stars and the R-parameter

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

Sensitive to both axion-electron and axion-photon coupling.





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

Straniero (proc. of XI Patras Workshop, 2015)

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

White Dwarfs

There are two ways to study the cooling of a WD.

1- From the <u>secular drift of their period of pulsation</u>:
$\dot{P}/P$ is practically proportional to the cooling rate $\dot{T}/T$

2- From their <u>luminosity function</u>
Fast cooling stars are less numerous

Both methods indicate anomalous cooling

White Dwarf Variables

Several new studies of WD periods appeared recently. However, the new results are not presenting measurements of the period change but simply of the period

"The Sloan Digital Sky Survey has allowed us to increase the number of known white dwarfs by a factor of five and consequently the number of known pulsating white dwarfs also by a factor of five."

Table 1. Number of known pulsating white dwarfs.

Class	Number
DAVs	181
DBVs	23
DOVs[1]	22
ELMVs	11
pre-ELMVs	5
DQVs	3

[1] Pulsating PG 1159 stars.

S. O. Kepler and Alejandra D. Romero, European Physical Journal Web of Conferences, 152, 01011 (2017)

White Dwarfs Variables

Observations:

WD	class	P[s]	$\dot{P}_{\rm obs}$[s/s]	$\dot{P}_{\rm th}$[s/s]	discrepancy
G117 - B15A	DA	215	$(4.19 \pm 0.73) \times 10^{-15}$	$(1.25 \pm 0.09) \times 10^{-15}$	$4\,\sigma$
R548	DA	213	$(3.3 \pm 1.1) \times 10^{-15}$	$(1.1 \pm 0.09) \times 10^{-15}$	$2\,\sigma$
PG 1351+489	DB	489	$(2.0 \pm 0.9) \times 10^{-13}$	$(0.81 \pm 0.5) \times 10^{-13}$	$1.1\,\sigma$
L 19-2 (113)	DA	113	$(3.0 \pm 0.6) \times 10^{-15}$	$(1.42 \pm 0.85) \times 10^{-15}$	$1.5\,\sigma$
L 19-2 (192)	DA	192	$(3.0 \pm 0.6) \times 10^{-15}$	$(2.41 \pm 1.45) \times 10^{-15}$	$0.4\,\sigma$

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

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Neutrino magnetic moment:

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

A non-zero μ_ν could explain individually the hints from the WDV but not the DA and DB simultaneously, because of the temperature difference between them and of the strong temperature dependence of the μ_ν induced rate.

A minicharged neutrino would suffer the same problem.

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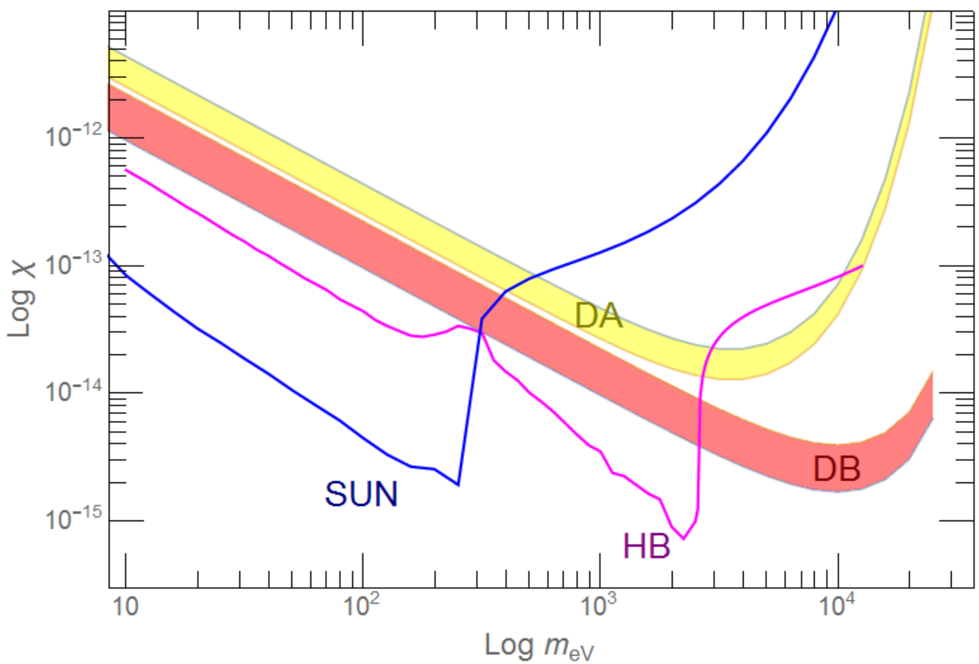

M.G., I. Irastorza, J. Redondo, A. Ringwald, JCAP 1605 (2016)

Hidden Photons:

HP could explain the additional cooling for certain values of mass and coupling.

Sun and HB exclude most of the hinted region.

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ALP solution

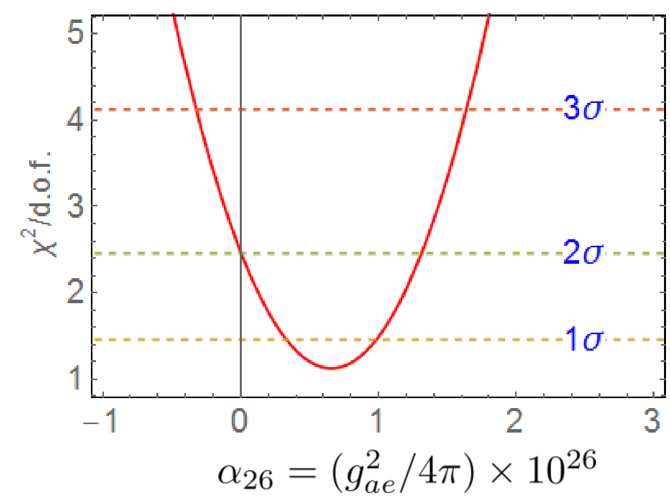
M.G., I. Irastorza, J. Redondo, A. Ringwald, JCAP 1605 (2016)

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

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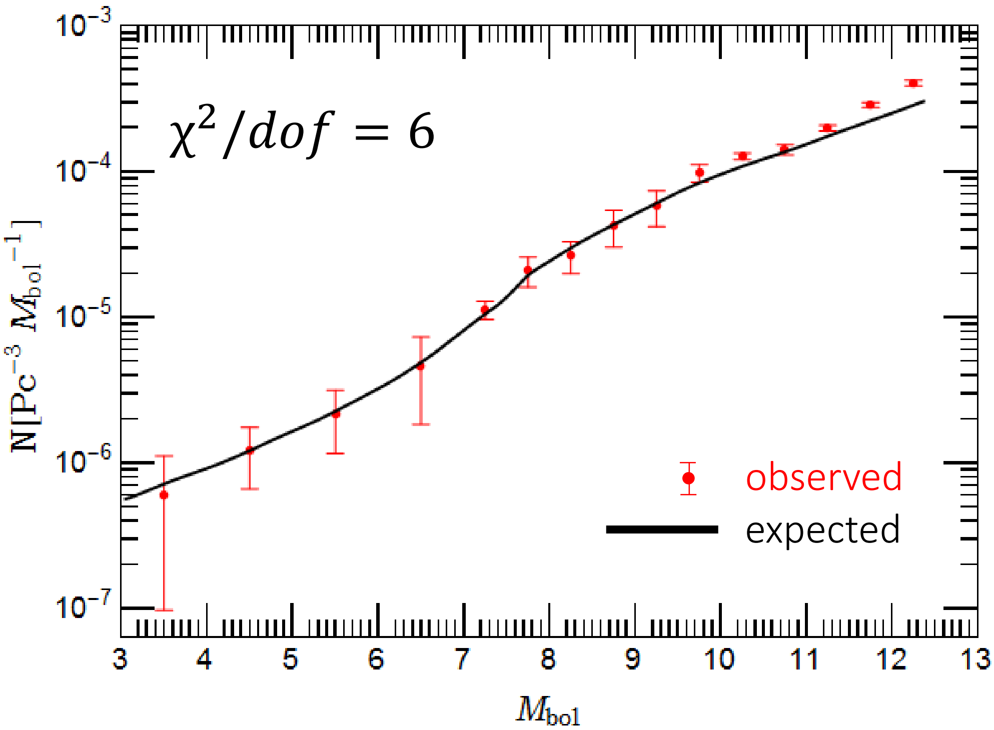
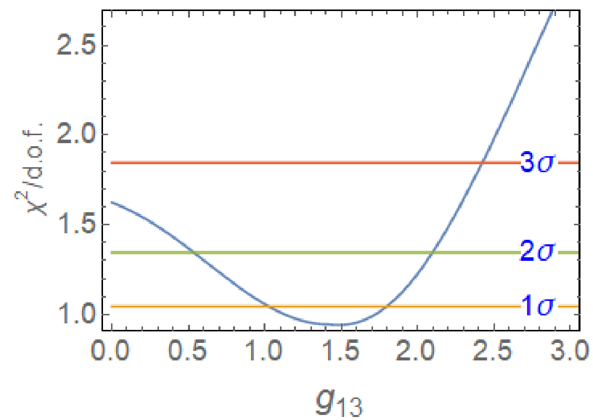


Data from: M. Bertolami et. al. (2014)

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

White Dwarfs Luminosity Function

Axions and the luminosity function of white dwarfs. The thin and thick disks, and the halo

J. Isern[1,2], E. García-Berro[3,2,†], S. Torres[3,2], R. Cojocaru[3,2], S. Catalán[4,2]

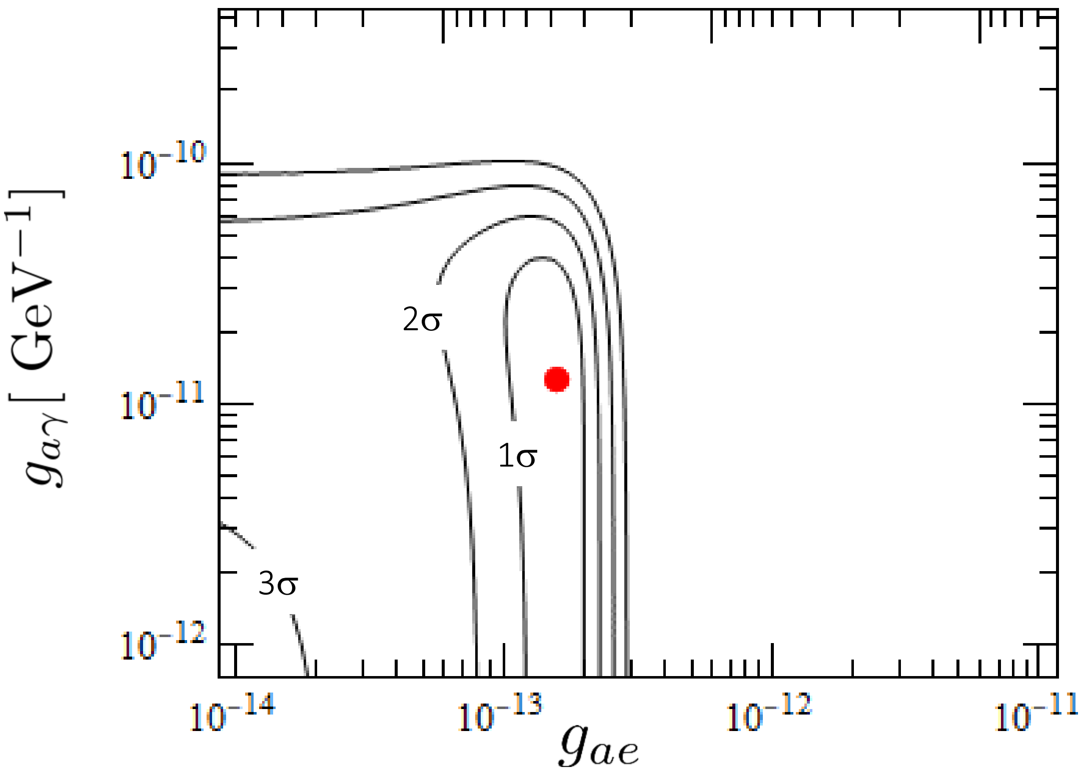
ABSTRACT
The evolution of white dwarfs is a simple gravothermal process of cooling. Since the shape of their luminosity function is sensitive to the characteristic cooling time, it is possible to use its slope to test the existence of additional sources or sinks of energy, such as those predicted by alternative physical theories. The aim of this paper is to study if the changes in the slope of the white dwarf luminosity function around bolometric magnitudes ranging from 8 to 10 and previously attributed to axion emission are, effectively, a consequence of the existence of axions and not an artifact introduced by the star formation rate. We compute theoretical luminosity functions of the thin and thick disk, and of the stellar halo including axion emission and we compare them with the existing observed luminosity functions. Since these stellar populations have different star formation histories, the slope change should be present in all of them at the same place if it is due to axions or any other intrinsic cooling mechanism. The signature of an unexpected cooling seems to be present in the luminosity functions of the thin and thick disks, as well as in the halo luminosity function. This additional cooling is compatible with axion emission, thus supporting to the idea that DFSZ axions, with a mass in the range of 4 to 10 meV, could exist. If this were the case, these axions could be detected by the future solar axioscope IAXO.

This very recent (2018) study confirmed the preference for axions also when comparing different populations, in order to remove the uncertainty of the star formation rate.

ALP interpretation of cooling hints

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

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



Best fit:

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

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

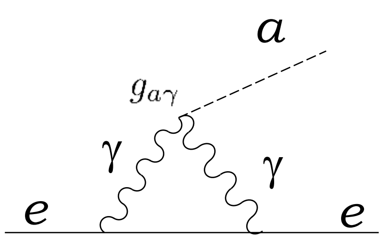
$\chi^2_{\mathrm{min}}/\mathrm{d.o.f.} = 0.96$

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!

QCD Axion Models and Cooling Hints

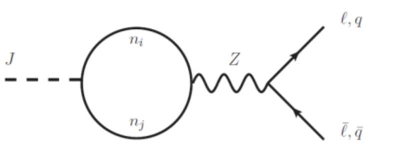
The stellar anomalies require $C_e/C_\gamma \simeq 0.03$

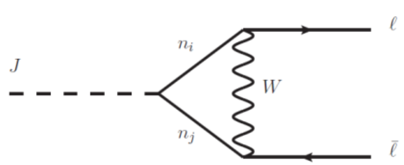
KSVZ models predict a coupling to electrons which is about an order of magnitude smaller than what needed for the best fit.



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



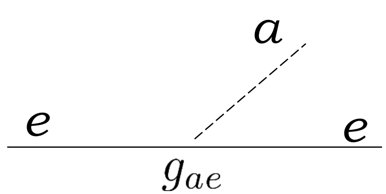


χ^2_{min}/d.o.f. ≈ 1

QCD Axion Models and Cooling Hints

The stellar anomalies require $C_e/C_\gamma \simeq 0.03$

DFSZ 1: $C_e = \frac{\sin^2\beta}{3}$ $C_{a\gamma} = \frac{8}{3} - 1.92$
requires tan β=0.18.
Unitarity bounds require 0.28<tan β<140… so, not too good.

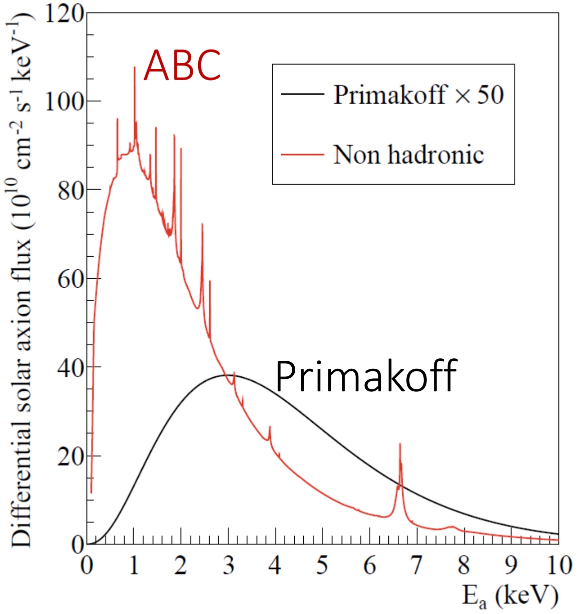


Astrophobic Axions
can naturally reduces coupling to electrons even for $\tan\beta \sim 1$
(nucleophobia)
Reduce problems with SN/NS

DFSZ 2: $C_e = \frac{\cos^2\beta}{3}$ $C_{a\gamma} = \frac{2}{3} - 1.92$
requires tan β=2.8.
Explains reasoneably well cooling anomalies. $\chi^2_{min}/\text{d.o.f.} \approx 1$

Axion Sources: The sun

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

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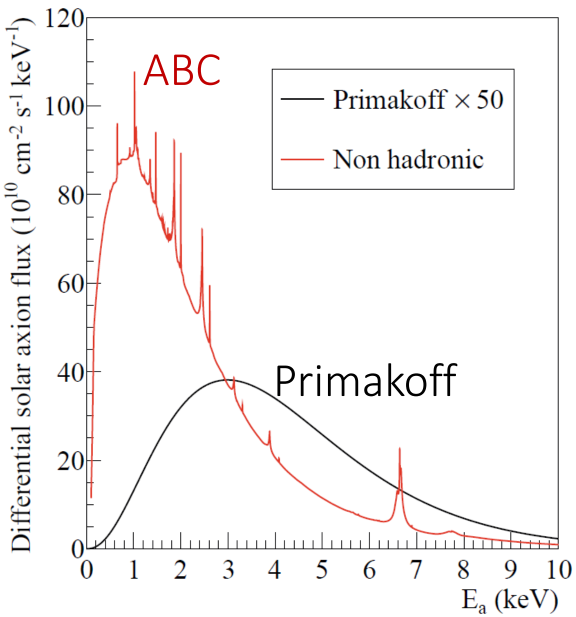

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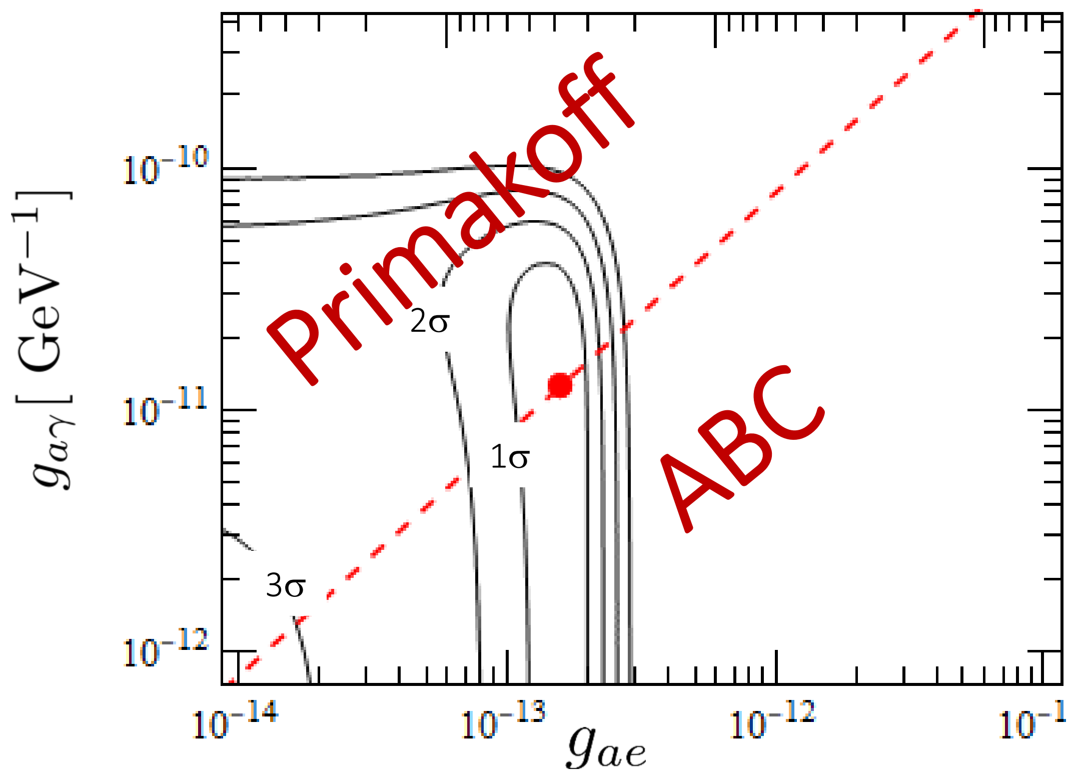

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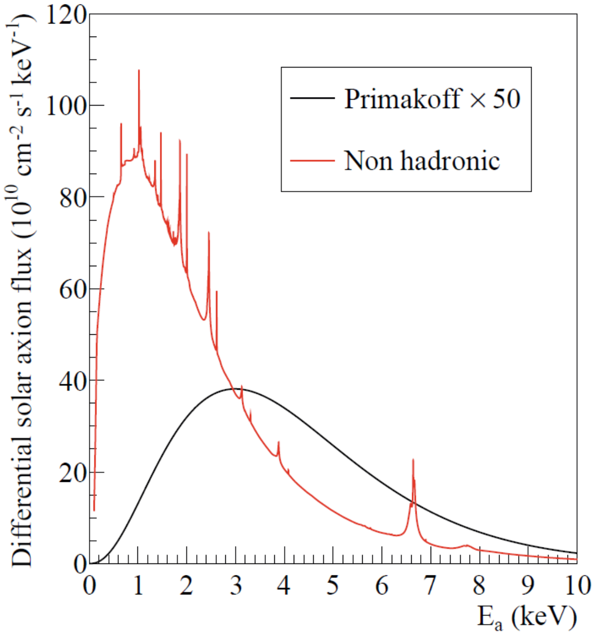
“Axioelectric Helioscopes”



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

Solar axions can be detected through an axioelectric effect.

The axioelectric cross section is proportional to the photoelectric cross section

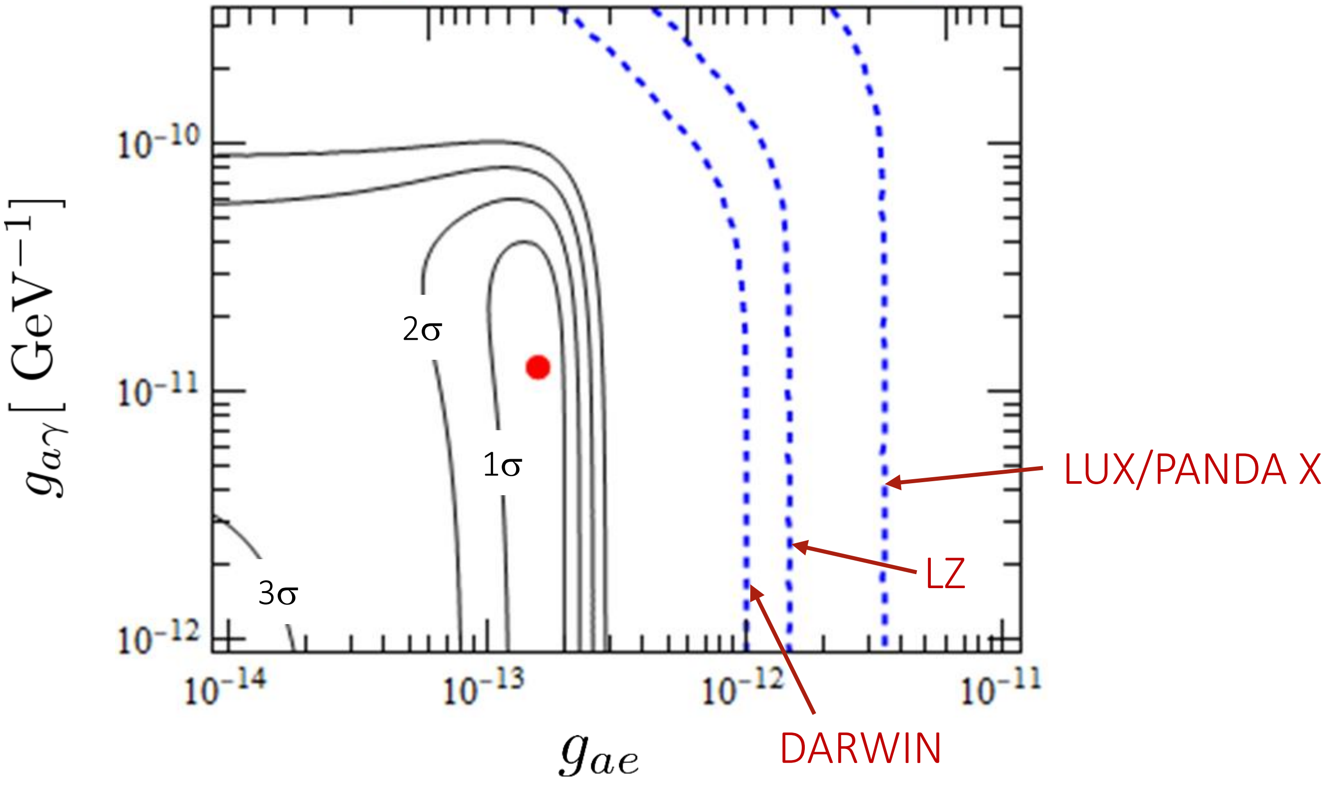
Dimopoulos, Starkman, and Lynn, Phys. Lett. B 168, 145 (1986)

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

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

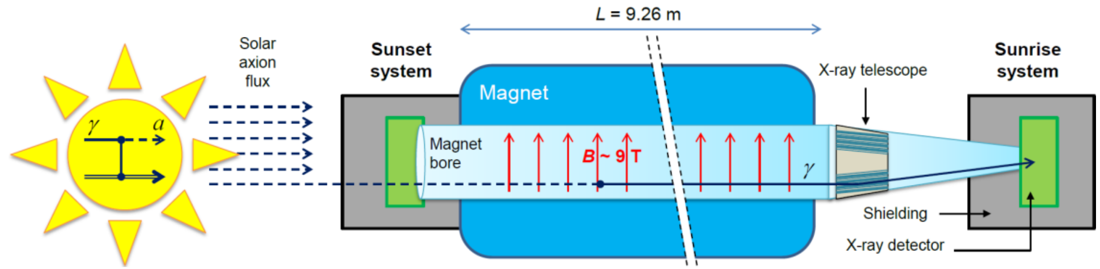
“Axioelectric Helioscopes”

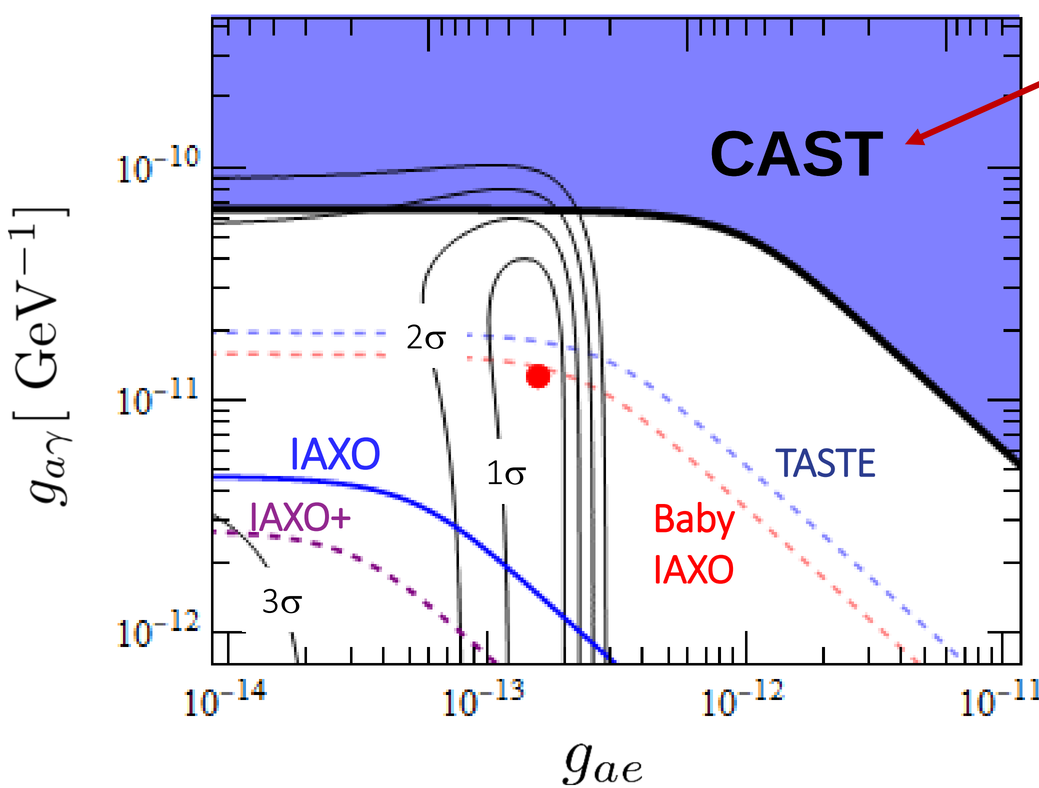
The potential of these experiments is still far from reaching the hinted regions, even with next generation detectors such as LZ or Darwin



Axion Helioscopes

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





Excluded by the CERN Axion Solar Telescope (CAST)

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

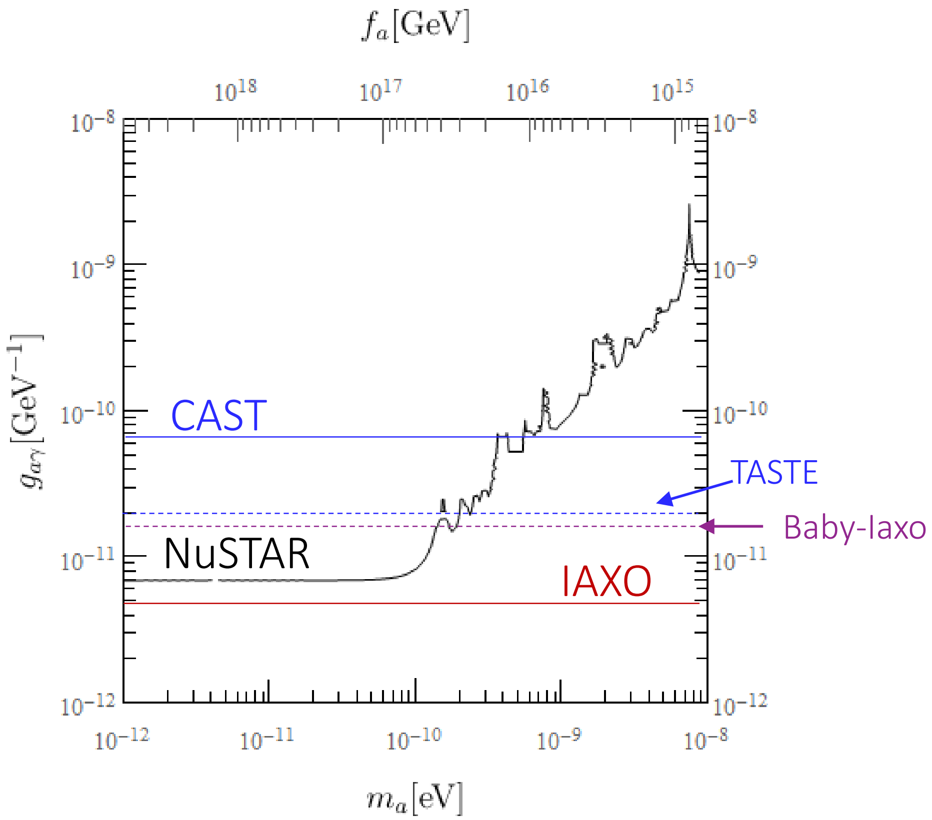
CAST successors, particularly IAXO, could probe a large portion of the hinted region

Other stellar sources?

Red Supergiant Stars have a hotter core than the sun and so produce ALPs much more efficiently.

ALPs from SG stars could be converted in B and become x-rays.

Betelgeuse is a Red Supergiant close enough to possibly give an observable ALP-photon flux. Could explore low mass ALP region.

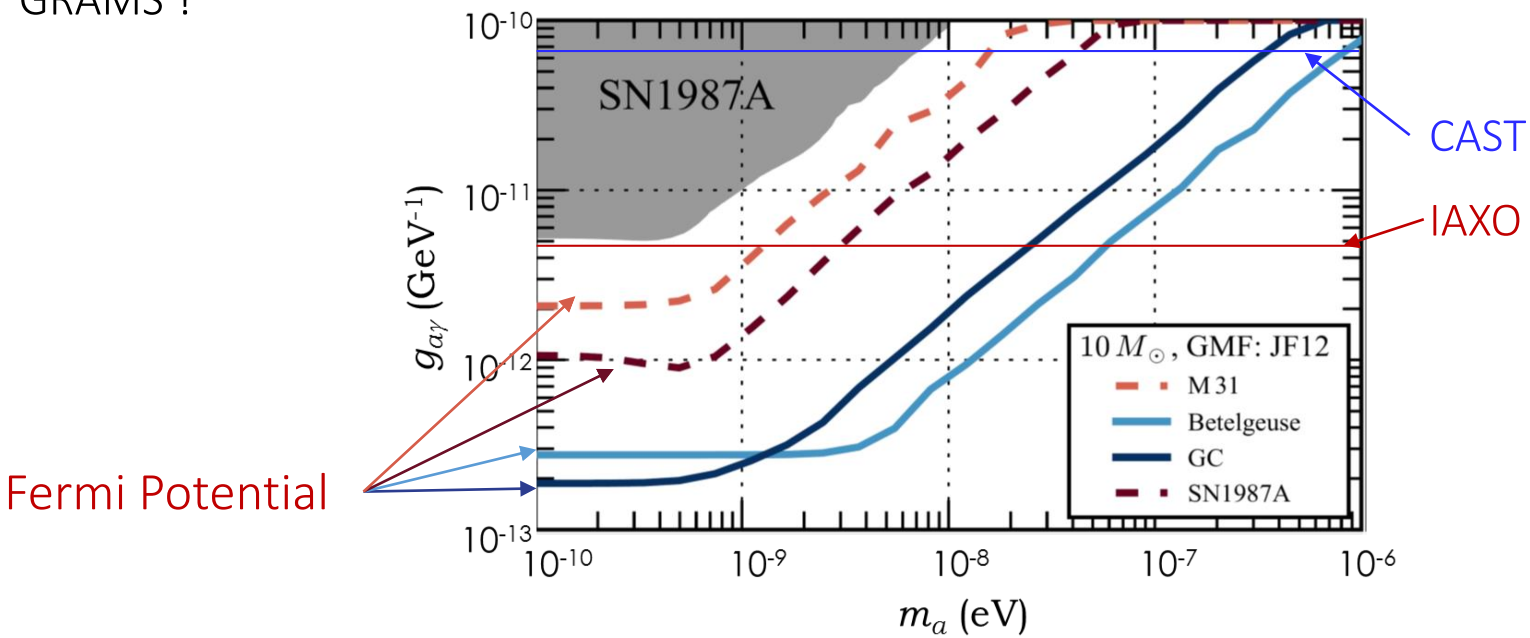


Preliminary estimate of NuSTAR potential for a 50ks observation (with *NuSTAR collaboration*)

Other stellar sources?

An excellent source of ALPs are Supernovae. The extremely hot and dense core produces very energetic ALPs, that can convert into photons in external B and be detected by gamma ray detectors:

Fermi LAT;
e-Astrogam ?
GRAMS ?



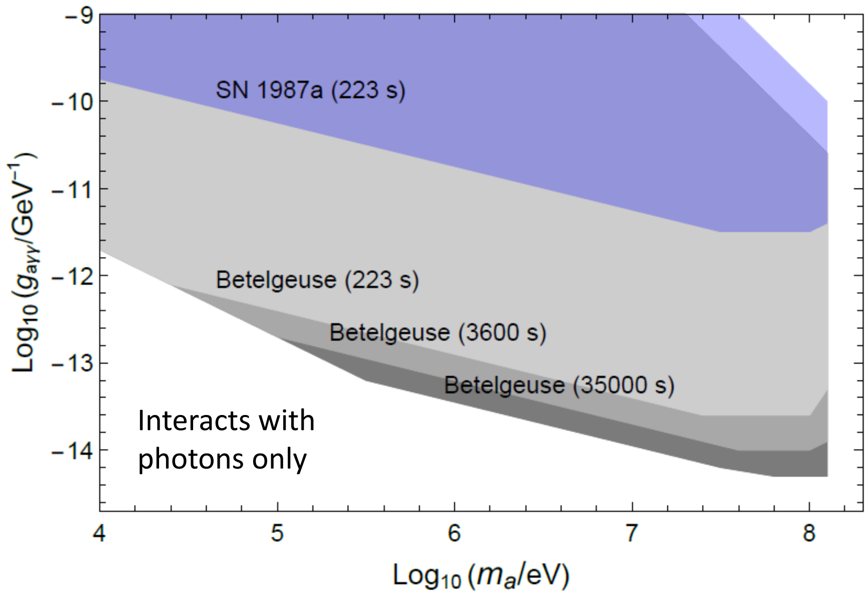
M. Meyer , M. G., A. Mirizzi, J. Conrad, M. A. Sánchez-Conde, Phys.Rev.Lett. 118 (2017)

Massive ALPs from SN and NS

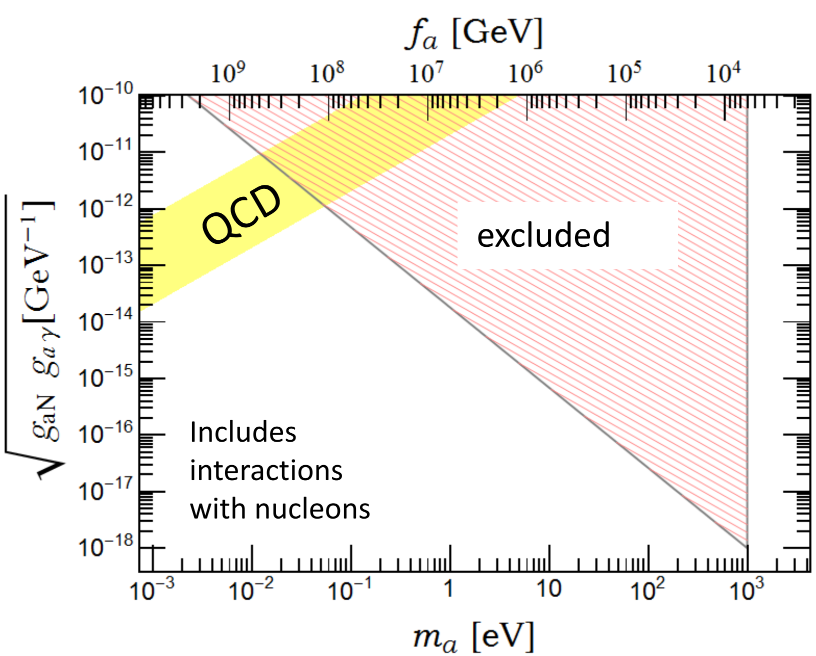
Analysis carried out for SN
- interaction with photons only
- full angular analysis
- complete analysis of time delay

and NS
- nuclear bremsstrahlung, for $m_a<2m_e$
- forward decay only (relativistic)

J. Jaeckel, P.C. Malta, J. Redondo (2017)

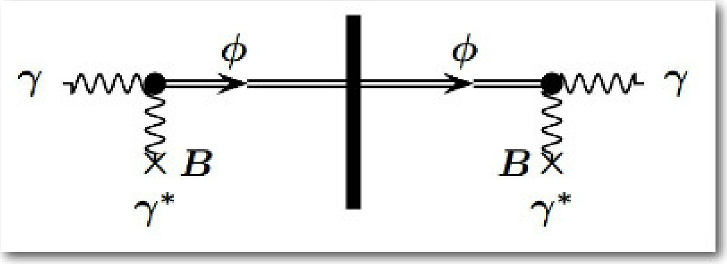


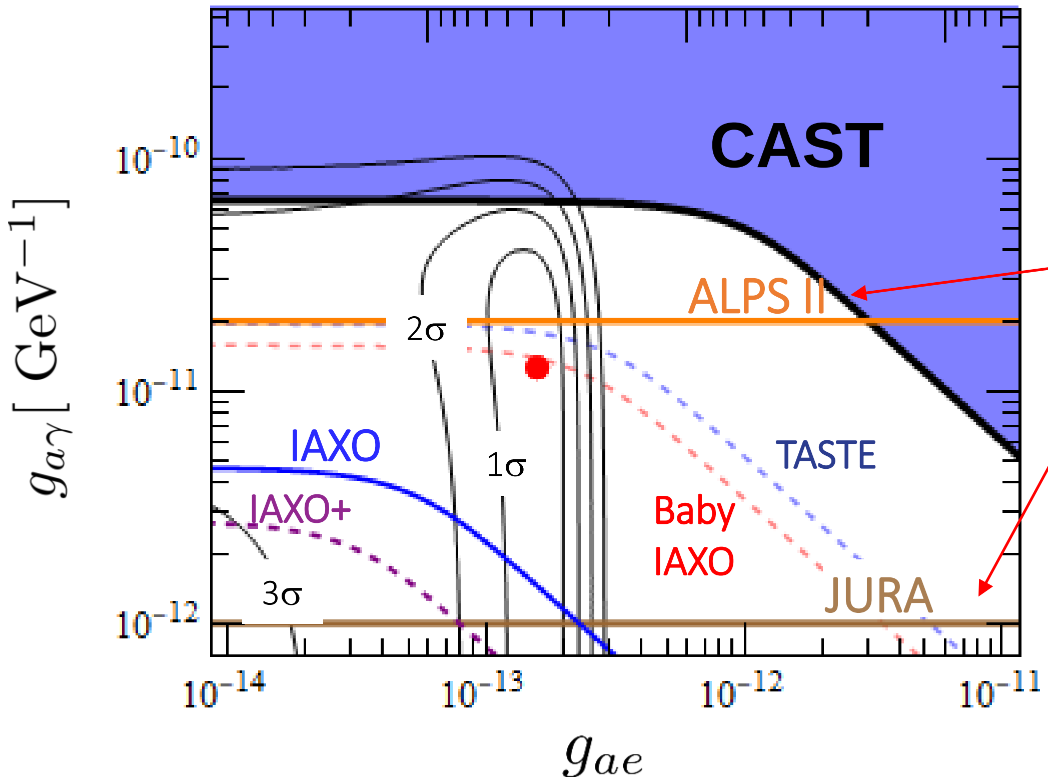
B. Berenji, J. Gaskins, M. Meyer Phys.Rev. D93 (2016)



Lab ALPs

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



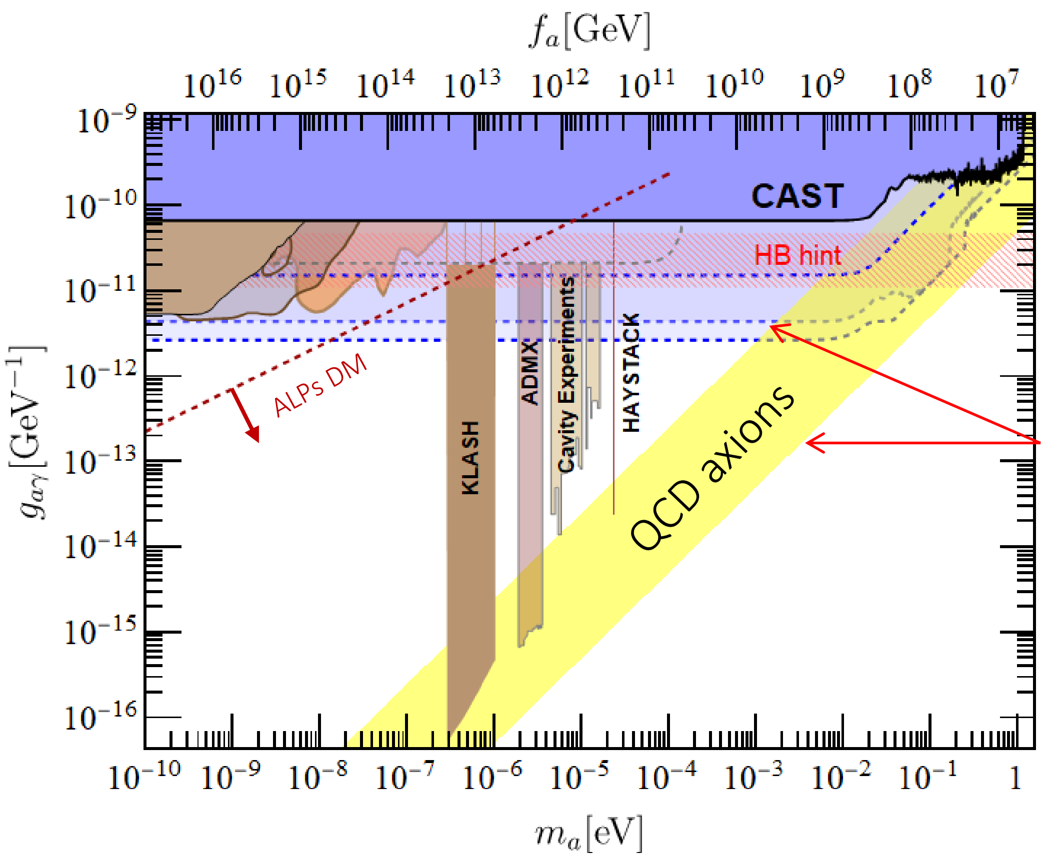


No model dependence

Can be improved

Dark Matter Axions

Haloscopes: detect DM axions. Can be extremely sensitive, though sensitivity depends on DM fraction



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

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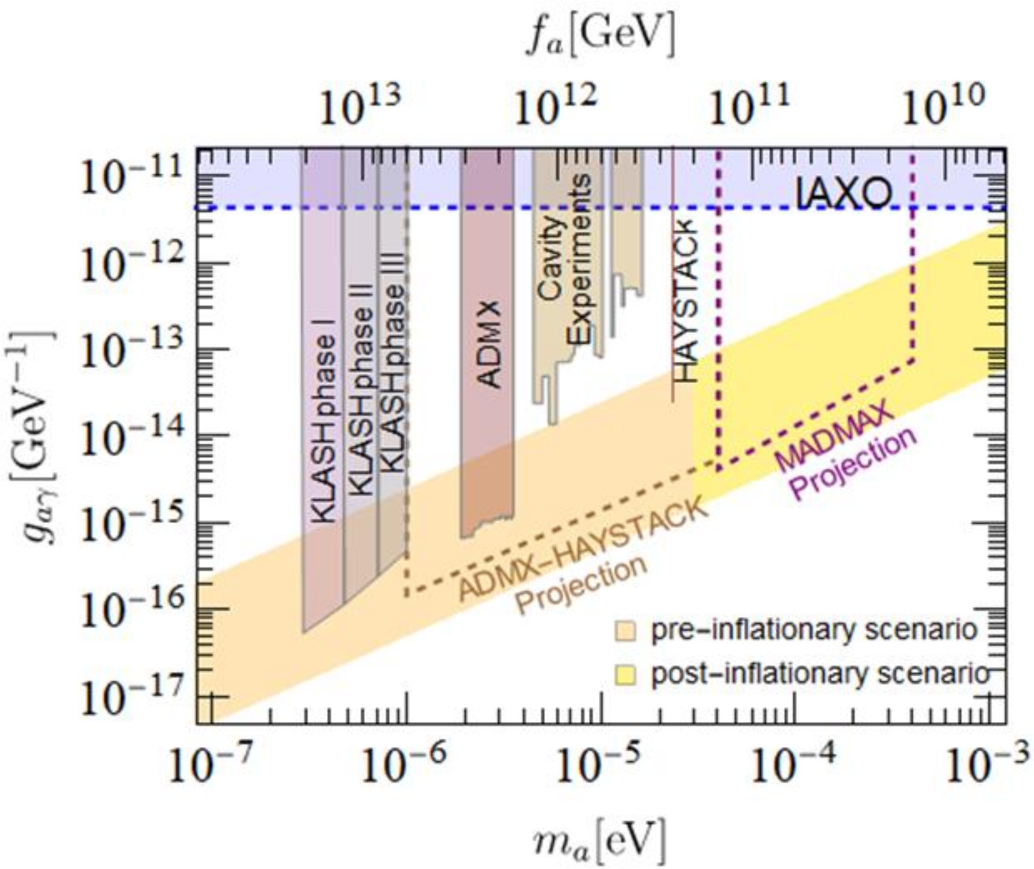

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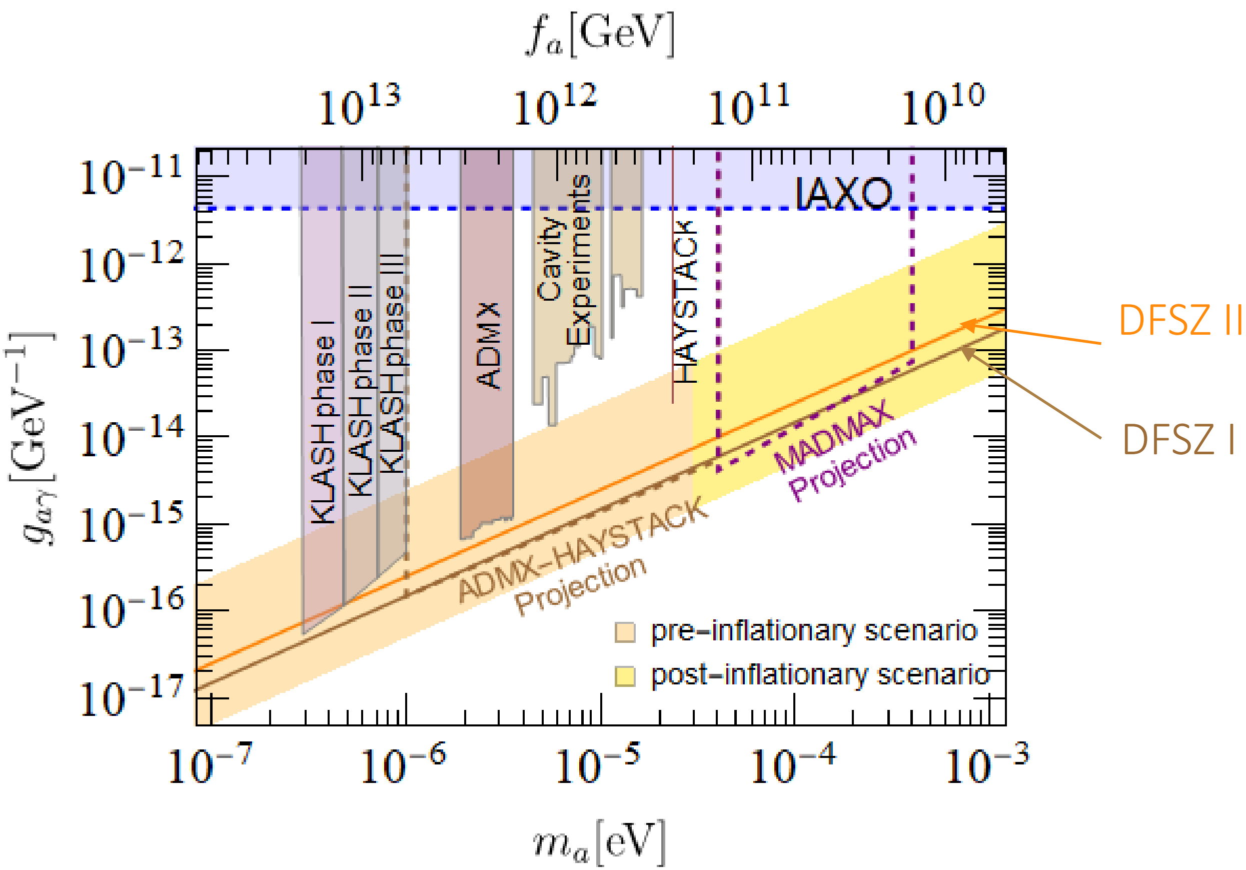
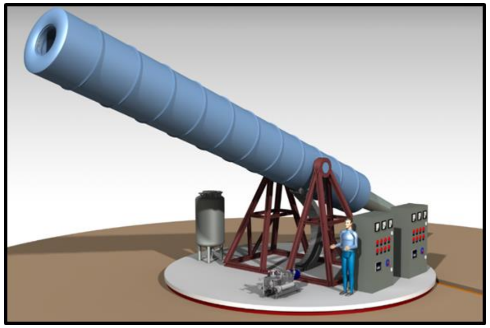
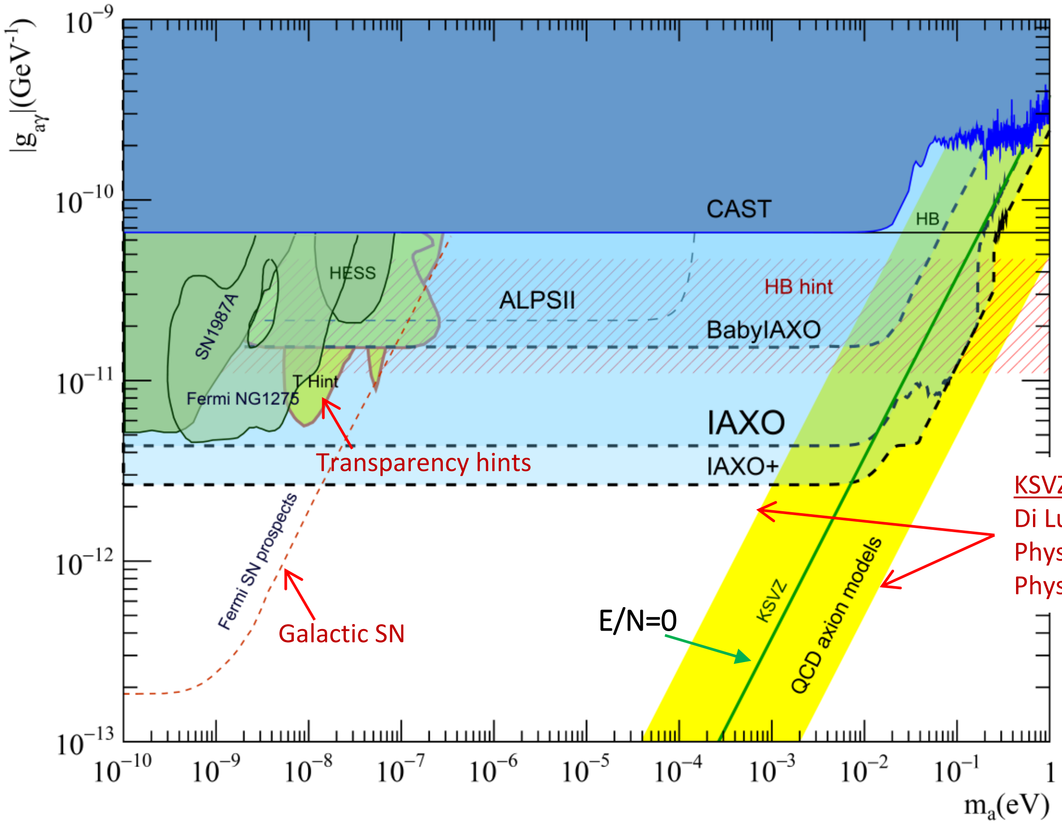


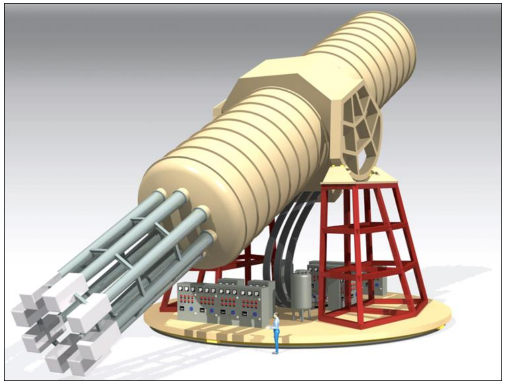
Experimental Landscape

Medium Size next generation Helioscopes (MSH) such as BabyIAXO or TASTE can probe ALPs - but not easily QCD axions – in the regions of interest for astrophysics





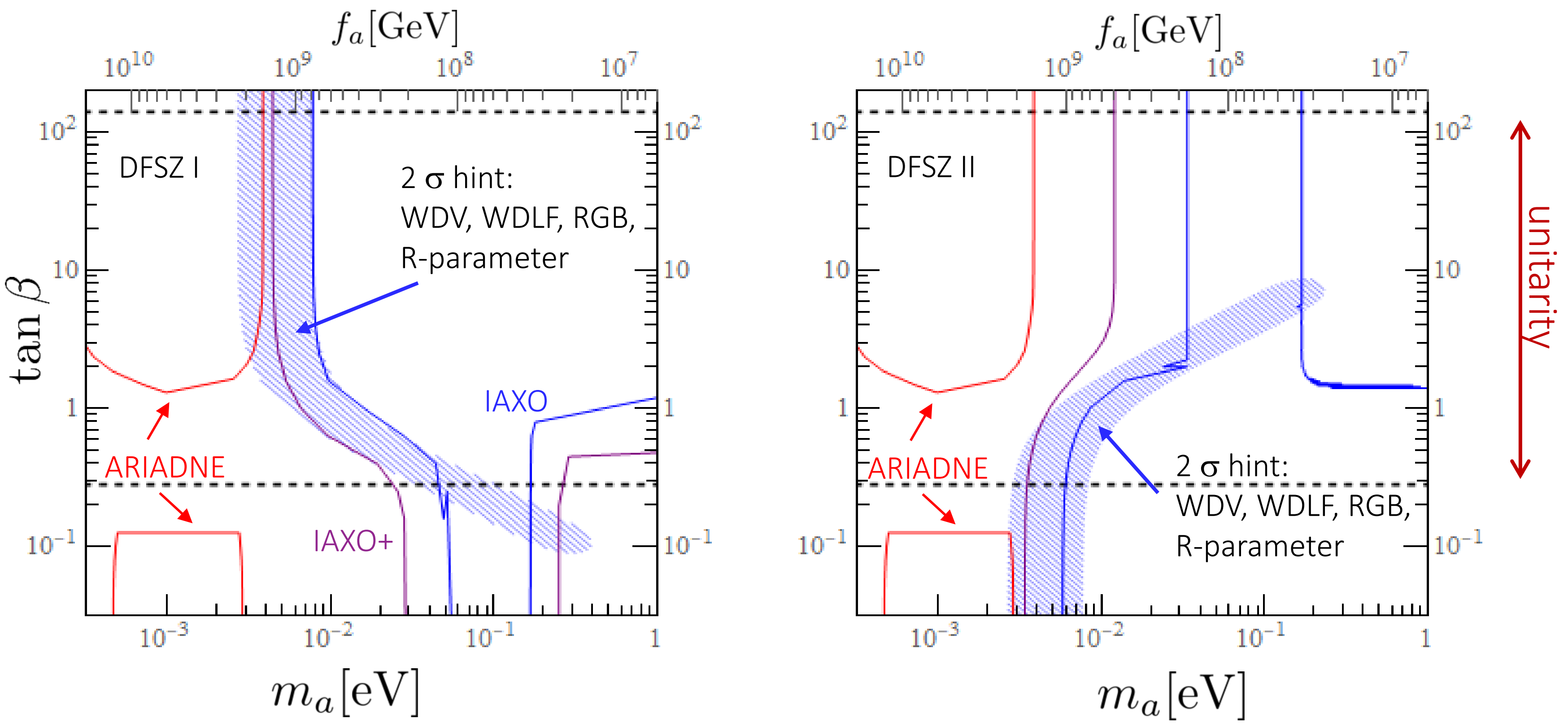
IAXO has the greatest potential in the regions of interest for astrophysics



IAXO collaboration, in preparation

QCD Axion Models and Cooling Hints

- IAXO can probe part of the hinted region.
- IAXO+ can probe a much larger region, especially for DFSZ I
- Baby-IAXO or TASTE would not be able to probe the DFSZ regions relevant to the cooling anomalies



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

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 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.

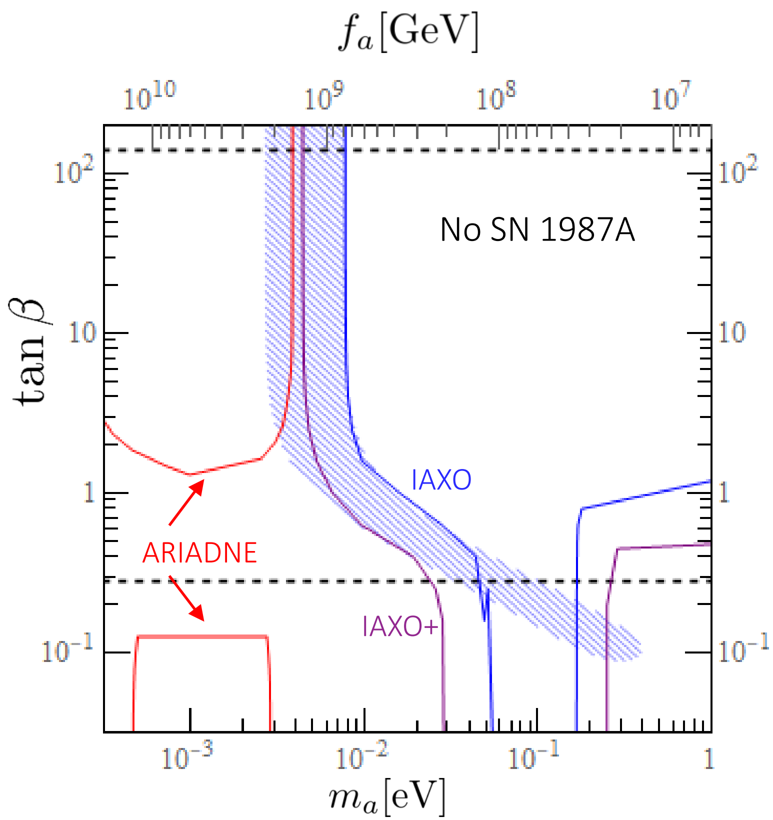
Difficult but not impossible. Models with generation dependent PQ charges can have small nucleon couplings while keeping large couplings with photons (astrophobic axion models).

Di Luzio, Mescia, Nardi, Panci, Ziegler **Phys.Rev.Lett**. 120 (2018) no.26

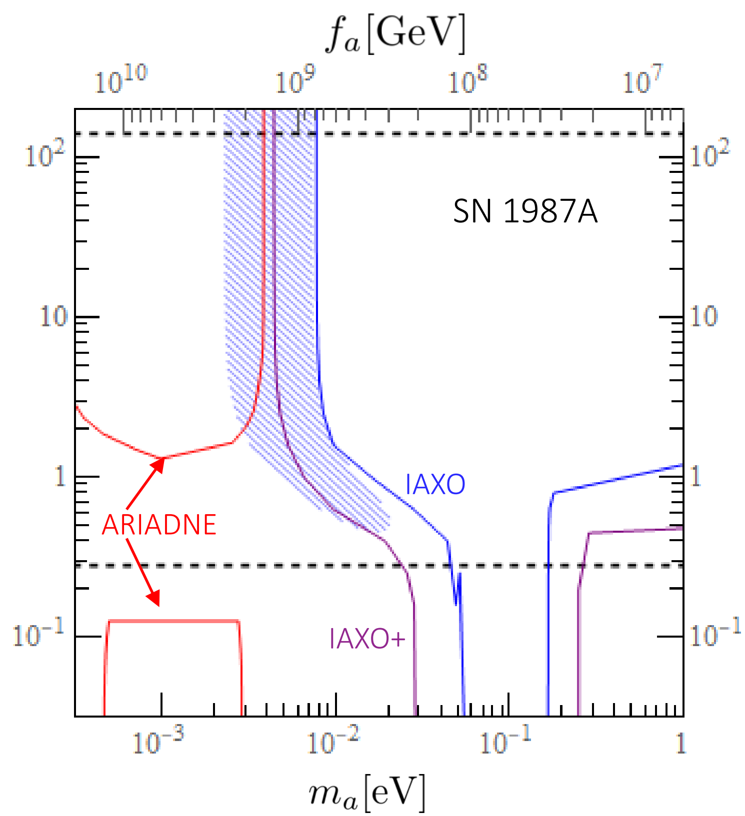
The SN 1987A Nightmare

DFSZ I axions

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



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

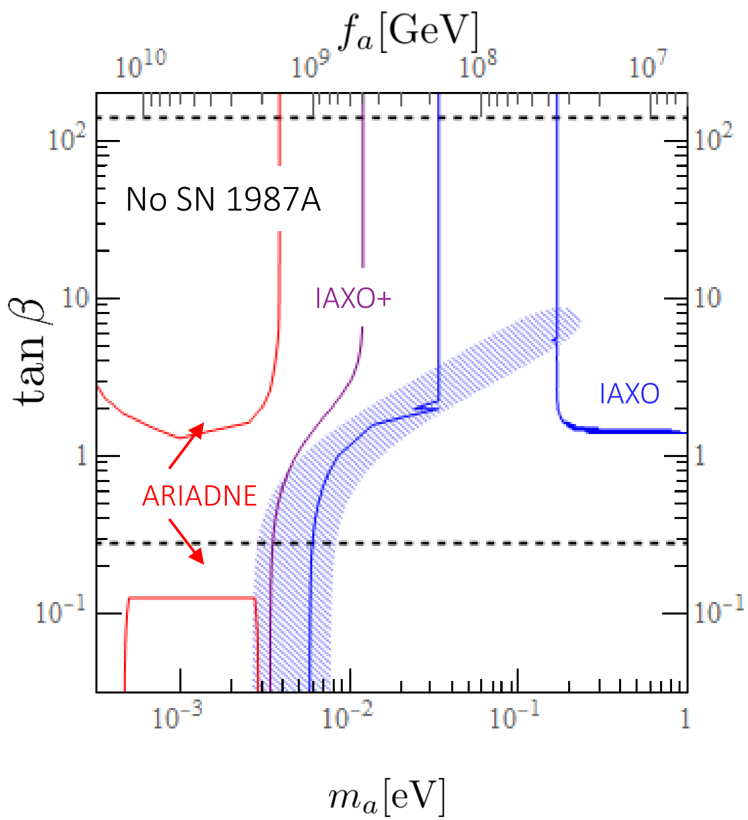


$\Delta\chi^2 = 1.3$

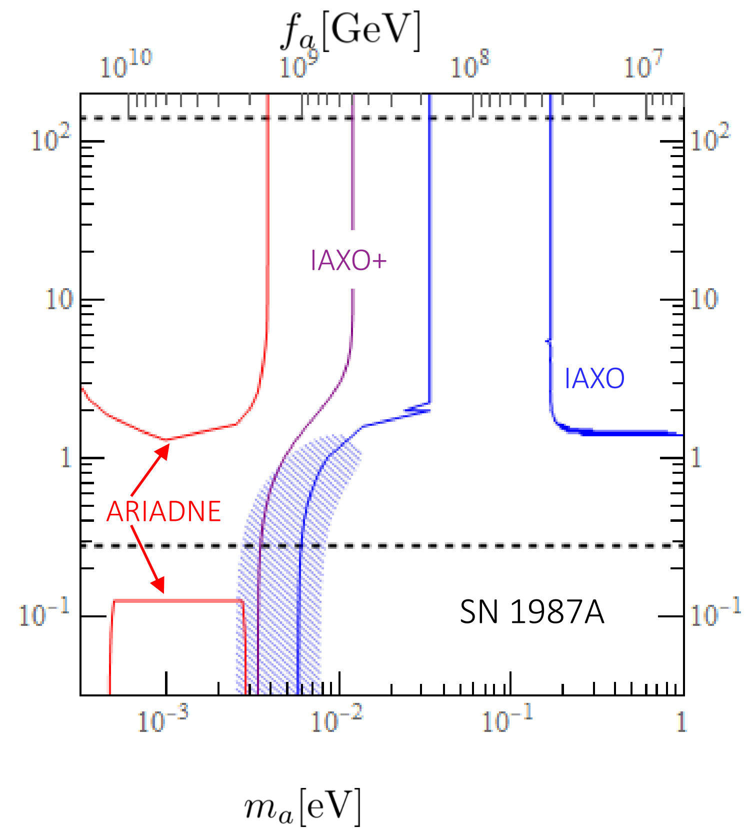
The SN 1987A Nightmare

DFSZ II axions

The SN 1987A bound is less of a problem for DFSZ II. ARIADNE is not efficient.



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



$\Delta\chi^2 = 0.5$

The SN 1987A Nightmare

A recent study claims that the axion bound from SN 1987A was overestimated by a factor of 5 or so.

The correct result can be found after including medium effects, vertex corrections, and a finite pion mass.

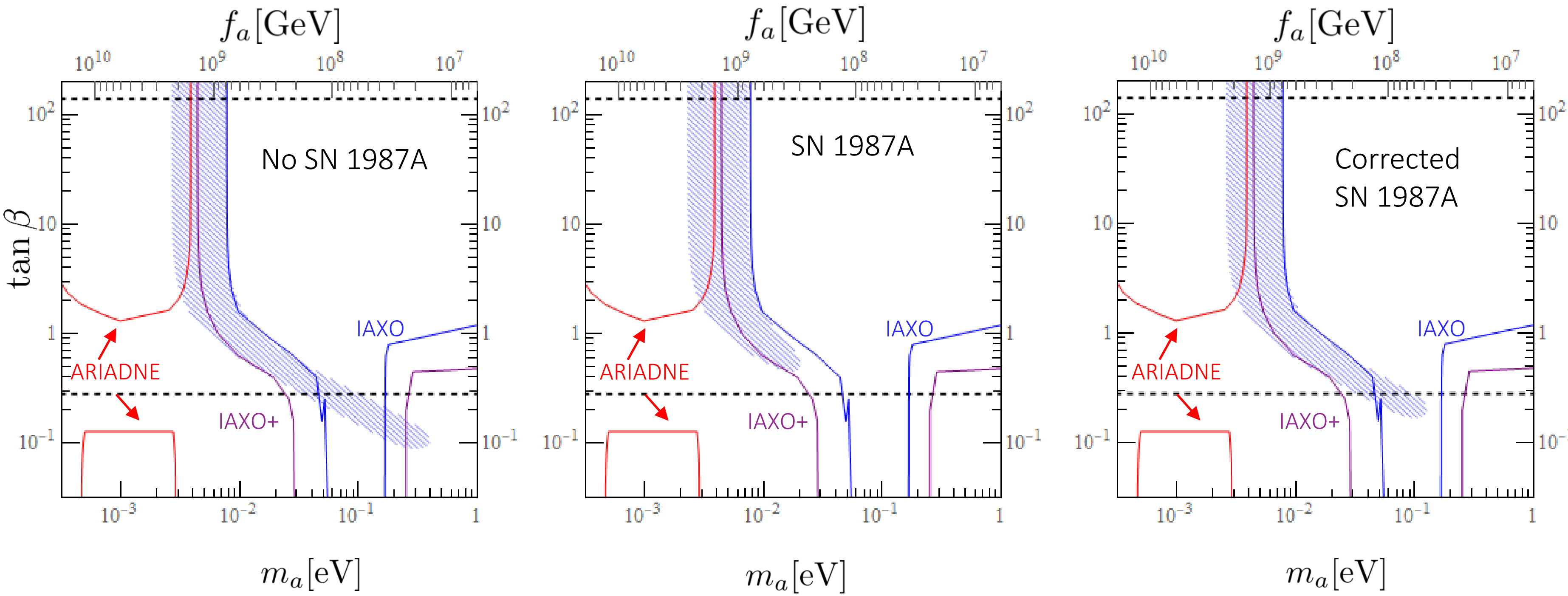
The claim has not been verified by a self-consistent simulation yet

Chang, Essig, McDermott, arXiv:1803.00993 (accepted yesterday for publication in JHEP)

Jun Seok Lee, arXiv:1808.10136

The SN 1987A Nightmare

DFSZ 1

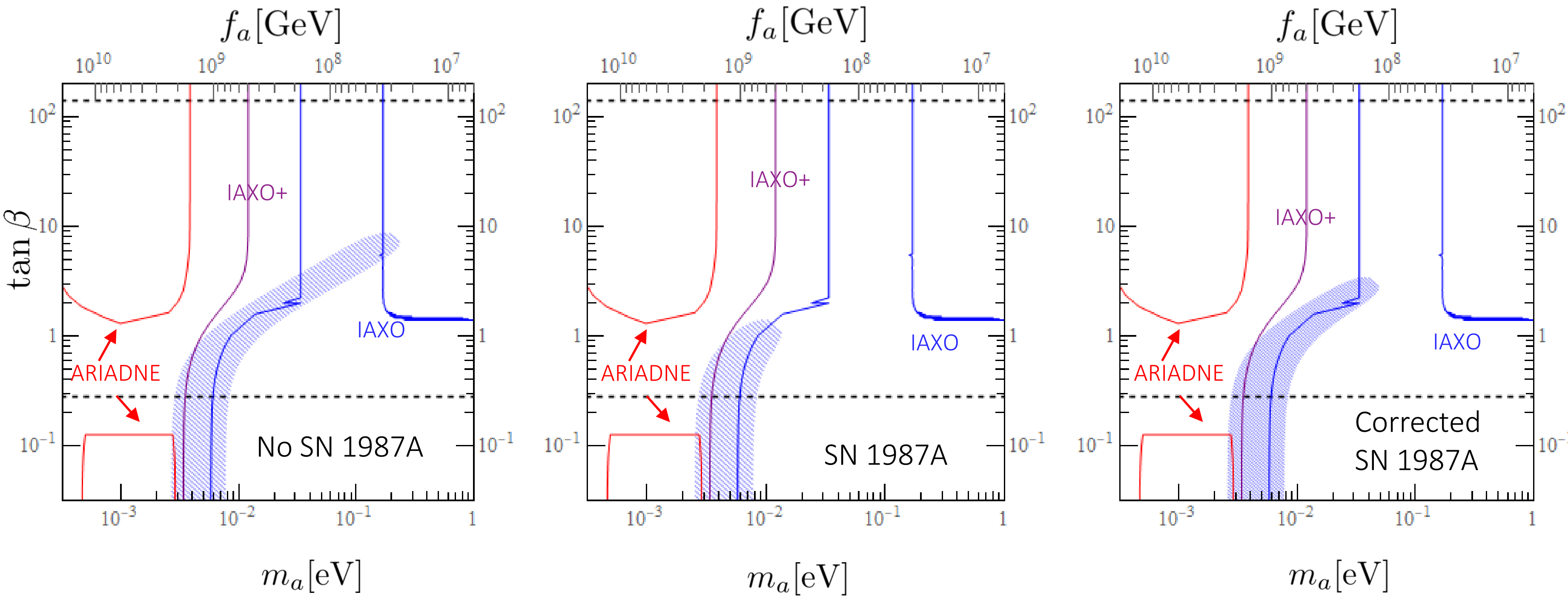


$\chi^2_{\mathrm{min}}/\mathrm{dof} = 15.4/16$ $\Delta\chi^2 = 1.3$ $\Delta\chi^2 = 0.2$

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

The SN 1987A Nightmare

DFSZ 2



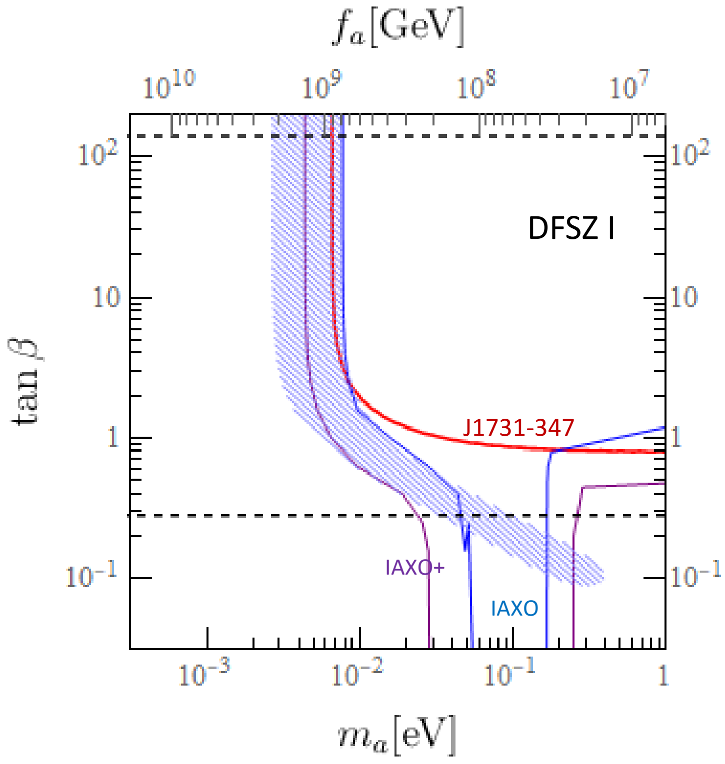
$\chi^2_{\rm min}/{\rm dof} = 15.4/16$ $\Delta\chi^2 = 0.5$ $\Delta\chi^2 = 0.3$

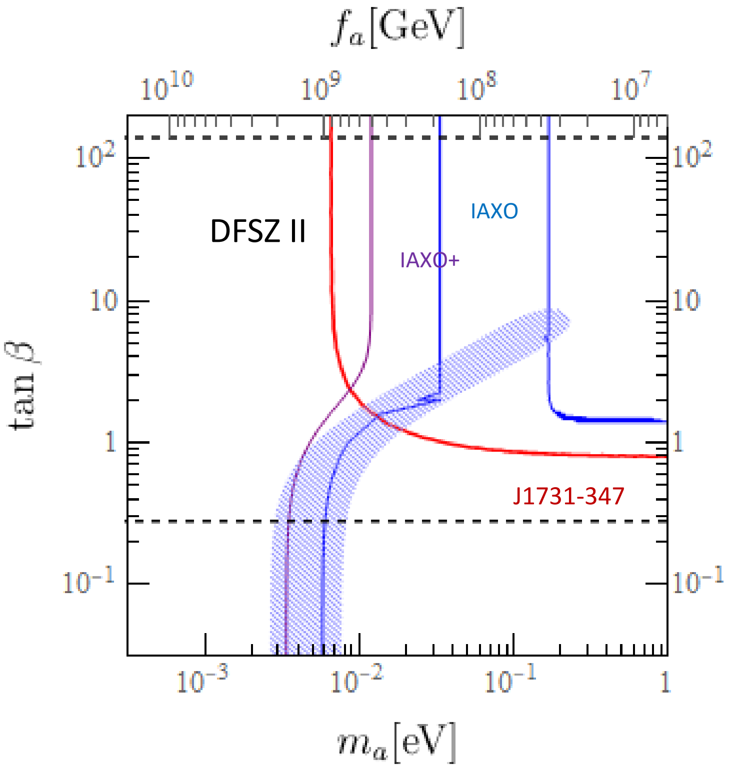
Minimal improvement in the fit and IAXO potential with the corrected emission rate

More Nightmares

Two recent studies of the NS CAS A and J1731-347 hint at very strong bounds on the axion-nucleon couplings

M. V. Beznogov, E. Rrapaj, D. Page, S. Reddy, arXiv:1806.07991.

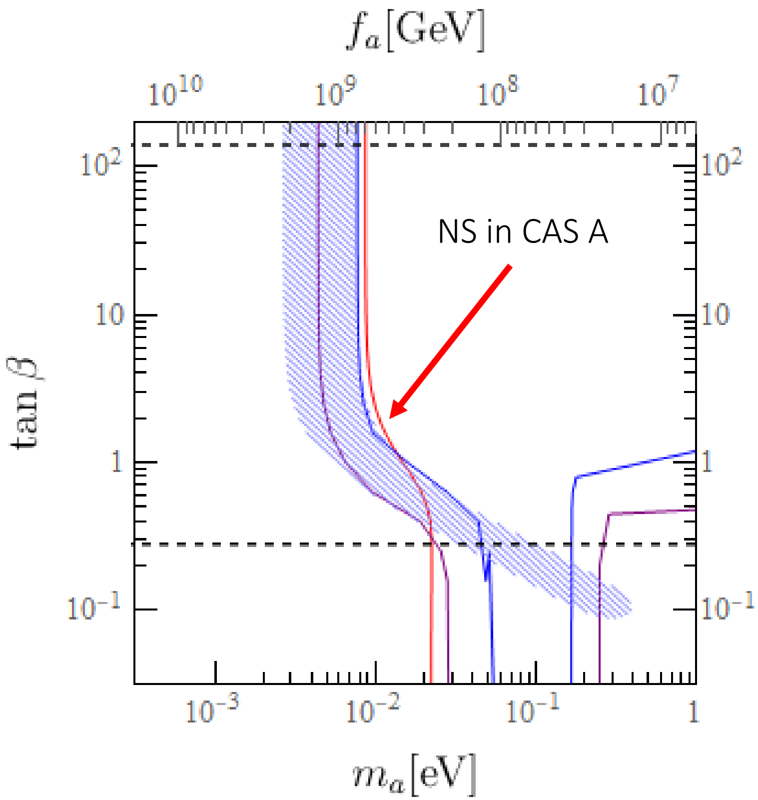


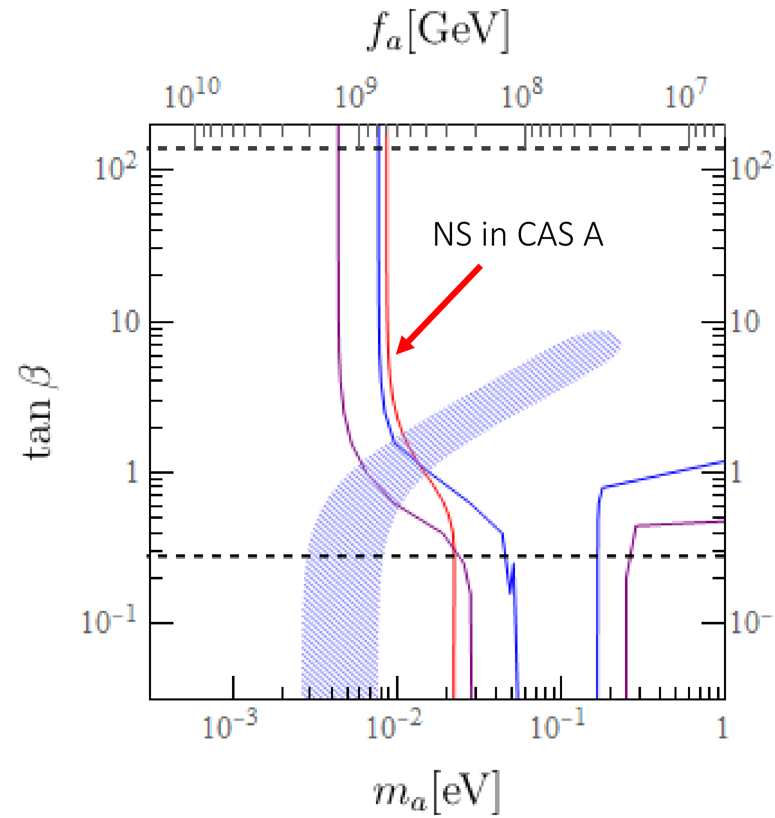


More Nightmares

Two recent studies of the NS CAS A and J1731-347 hint at very strong bounds on the axion-nucleon couplings

K. Hamaguchi, N. Nagata, K. Yanagi, J. Zheng, arXiv:1806.07151





The future may be bright:
New 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

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.

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

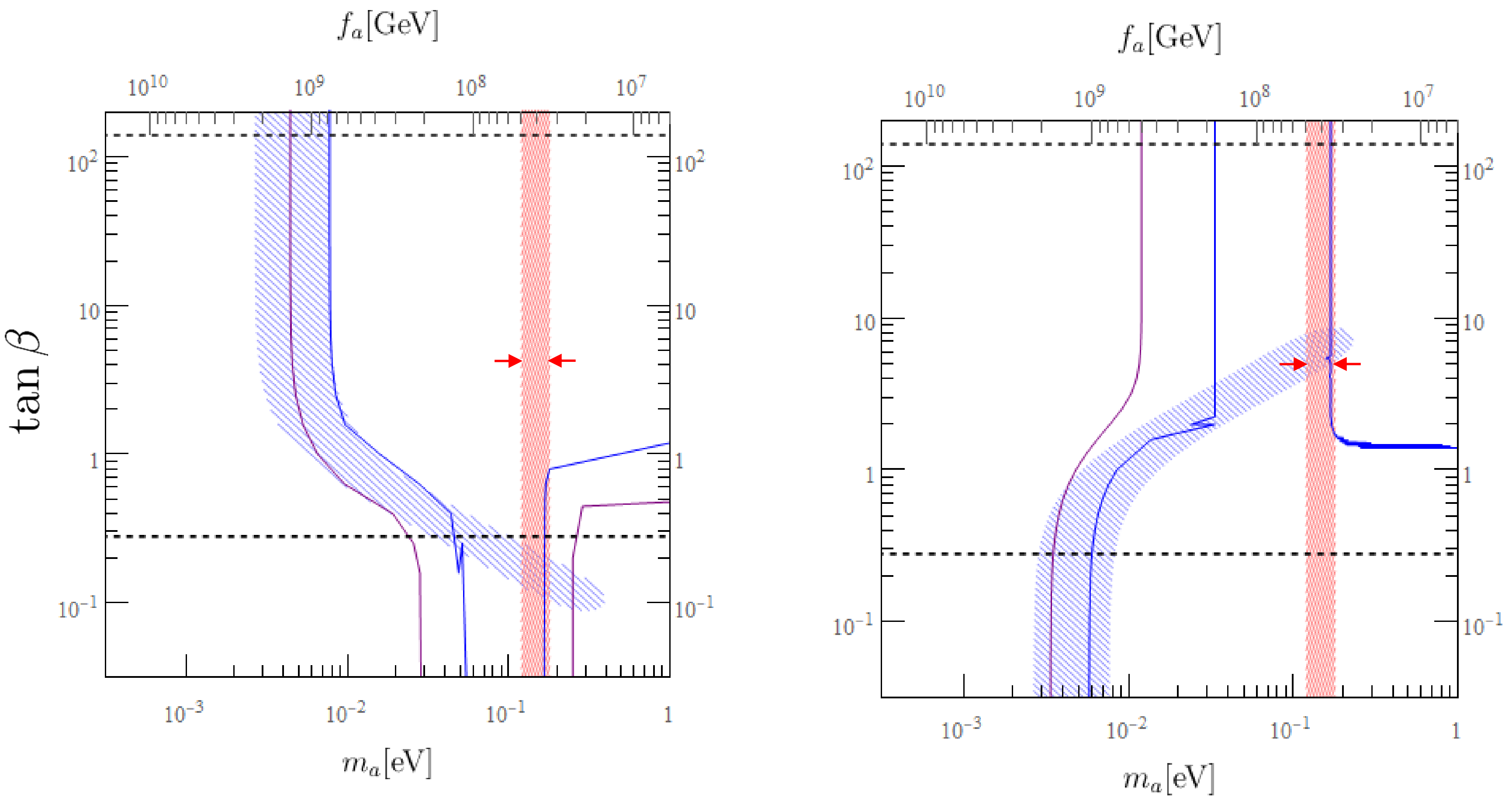
-IAXO (and partially ARIADNE) is the only planned instrument that can detect a DFSZ axion if the anomaly hints are correct

Back up slides

QCD Axion Models and Cooling Hints

It's been recently pointed out that axions could explain the EDGES observation of 21 cm absorption line in a region which happens to be in IAXO reach and that superimposes with the cooling anomalies.

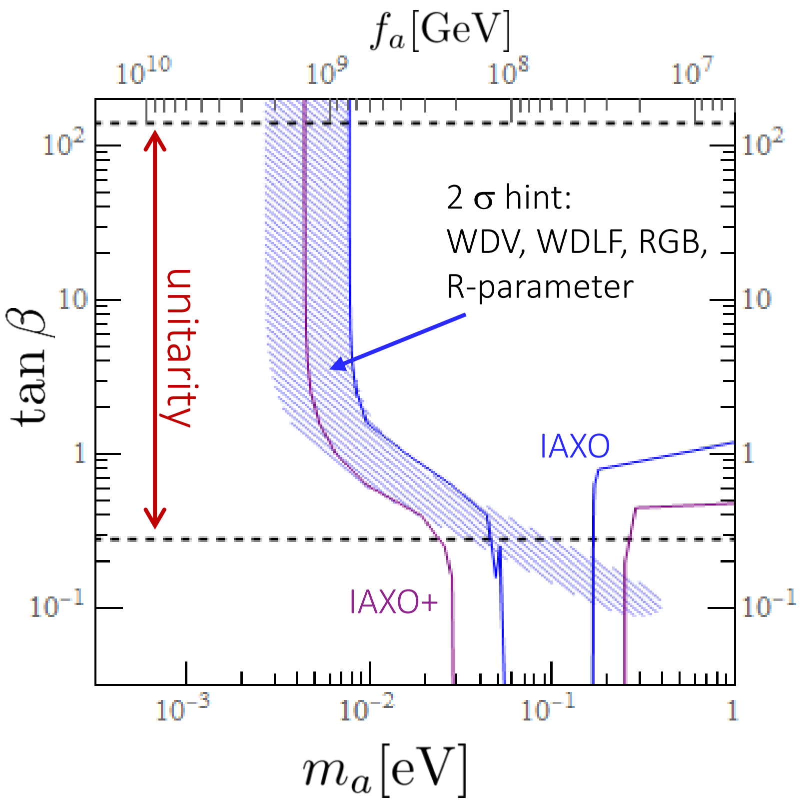
Nick Houston, Chuang Li, Tianjun Li, Qiaoli Yang and Xin Zhang, **Phys. Rev. Lett**. 121, 111301

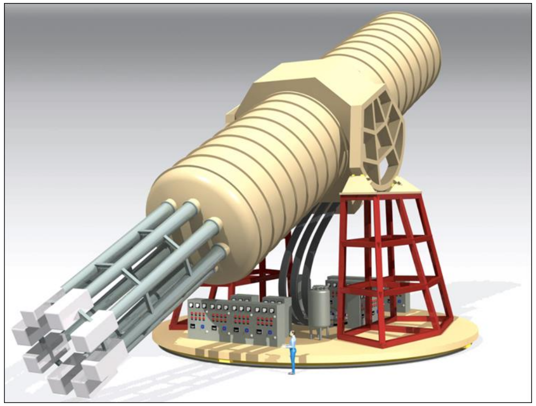


QCD Axion Models and Cooling Hints

Example: DFSZ 1 axions

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





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

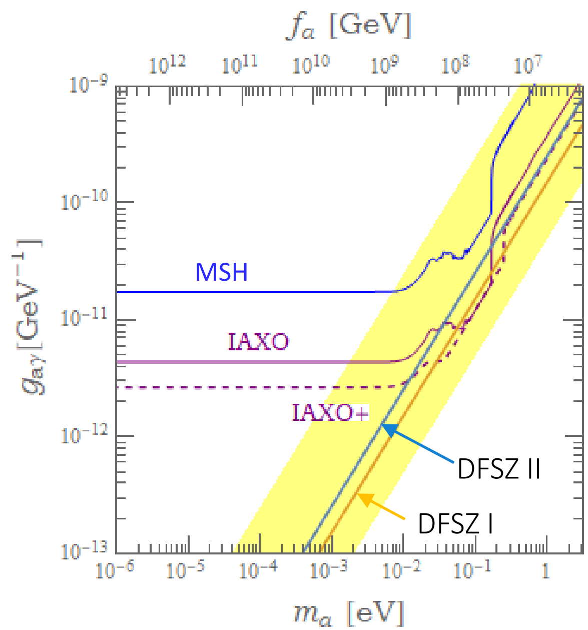
IAXO+ can probe a much larger region

Baby-IAXO or TASTE would not be able to probe the DFSZ region relevant to the cooling anomalies

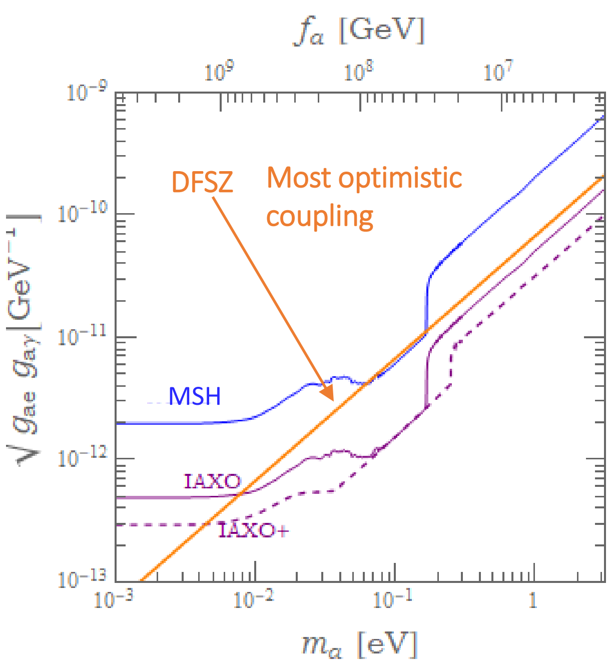
Other axion models are discussed in:
M.G., I. Irastorza, J. Redondo, A. Ringwald, k. Saikawa, JCAP 1710 (2017)

Experimental Potential: DFSZ axions

Define MSH as the Medium Scale Helioscope, defined to have sensitivity exactly ¼ that of IAXO.



IAXO can see DFSZ axions produced through Primakoff. MSH cannot.



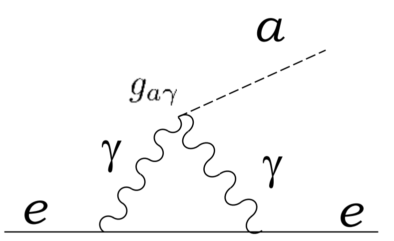
A sensitivity on the coupling of about ¼ that of IAXO is roughly the threshold to probe DFSZ axions produced in the sun through bremsstrahlung!

Baby IAXO and TASTE are expected to have roughly that sensitivity

QCD Axion Models and Cooling Hints

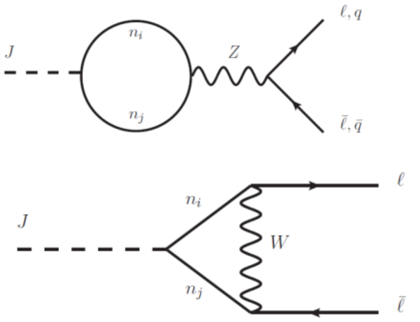
KSVZ models predict a coupling to electrons which is about an order of magnitude smaller than what needed for the best fit.

χ^2_{min}/d.o.f. > 2



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

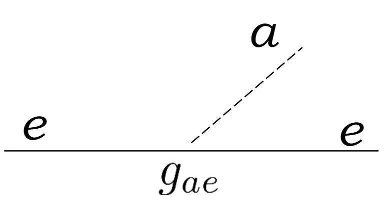
χ^2_{min}/d.o.f. ≈ 1



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.

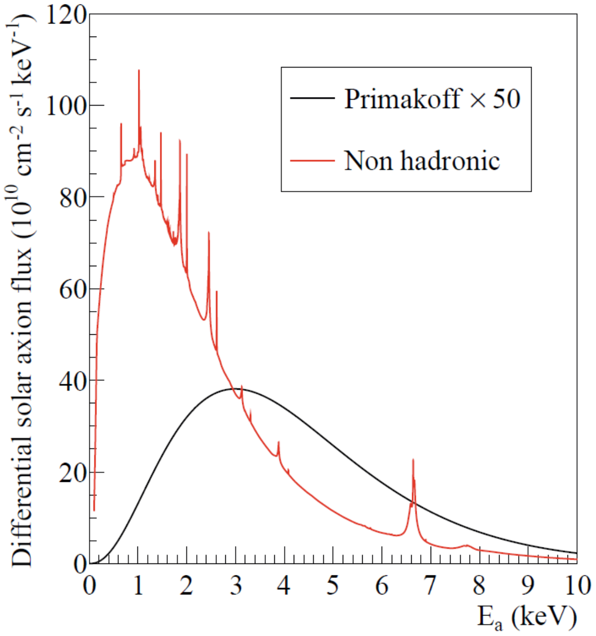
Unitarity bounds require 0.28<tan β<2.8. χ^2_{min}/d.o.f. ≈ 1



IAXO

Parameter	Units	BabyIAXO	IAXO baseline	IAXO upgraded
B	T	2.5	2.5	3.5
L	m	10	20	22
A	m^2	0.28	2.3	3.9
f_M^*		10	300	1200
b	$keV^{-1}\,cm^{-2}\,s^{-1}$	5×10^{-8}	10^{-8}	10^{-9}
ϵ_d		0.7	0.8	0.8
ϵ_o		0.5	0.7	0.7
a	cm^2	8×0.2	8×0.15	8×0.15
ϵ_t		0.5	0.5	0.5
t	year	3	3	5

Axioelectric Helioscopes

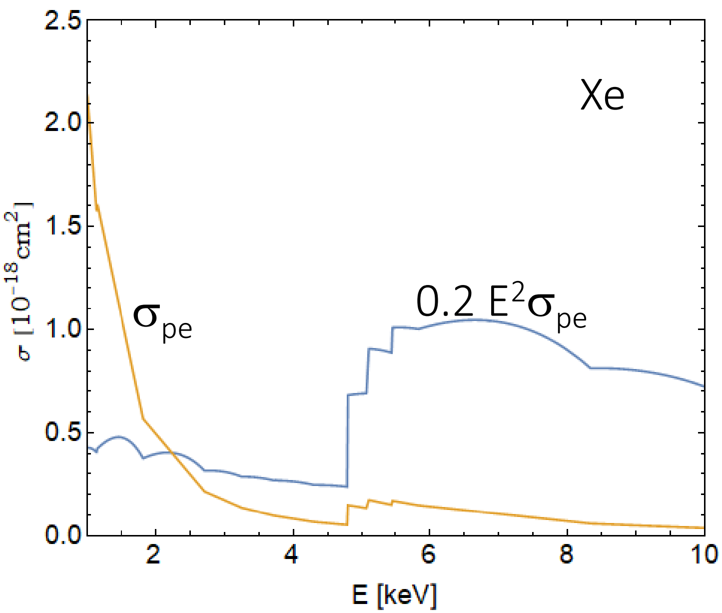


σ_{pe} increases strongly with Z and decreases with the energy.

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

However, $E^2\sigma_{pe}$ is much less sensitive to energy and is large also for Primakoff photons

Therefore, Primakoff axions shouldn't be neglected.



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}	

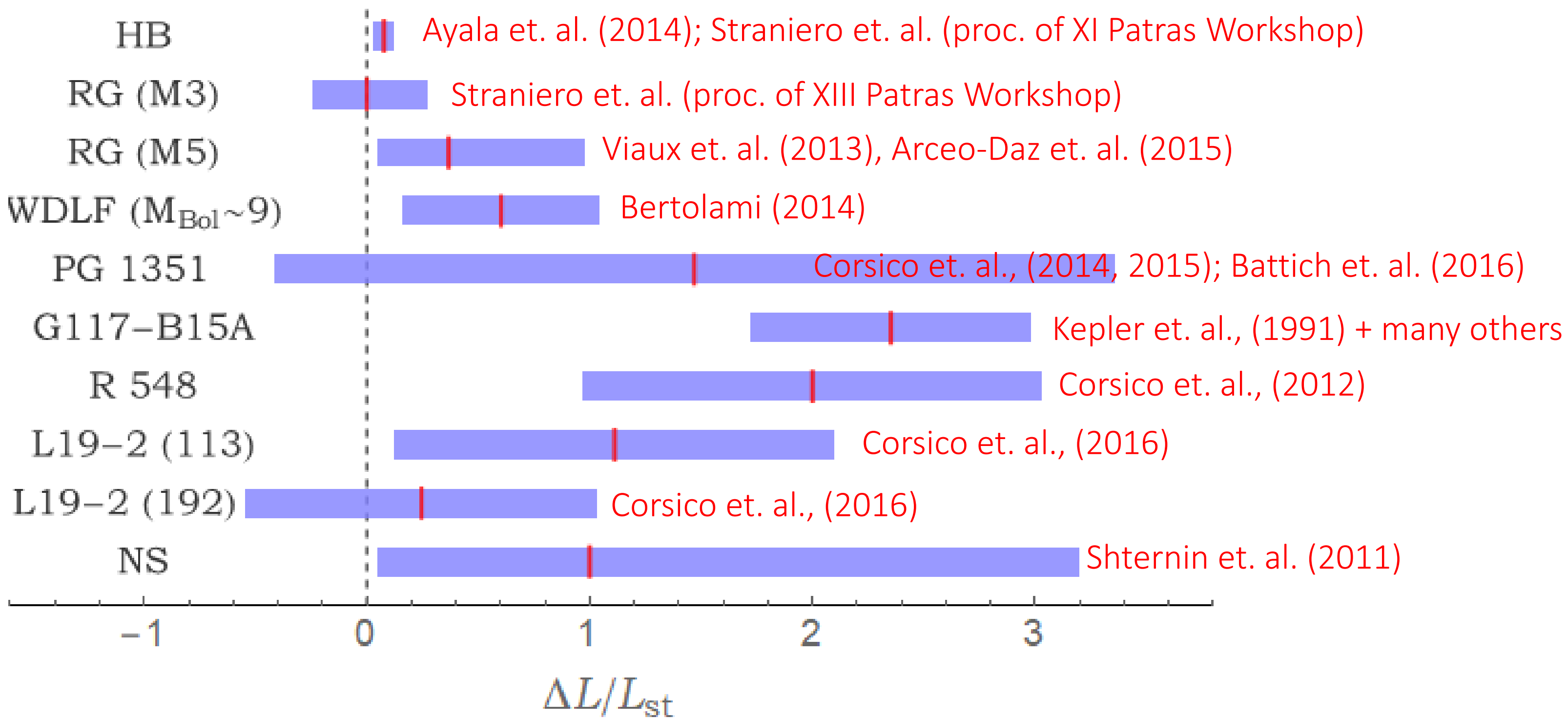
Hints of new physics?

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)



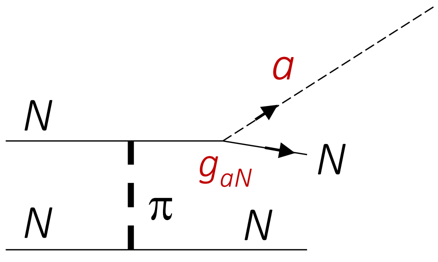
The SN 1987A Nightmare

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

Using a state of the art SN model we find:

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

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

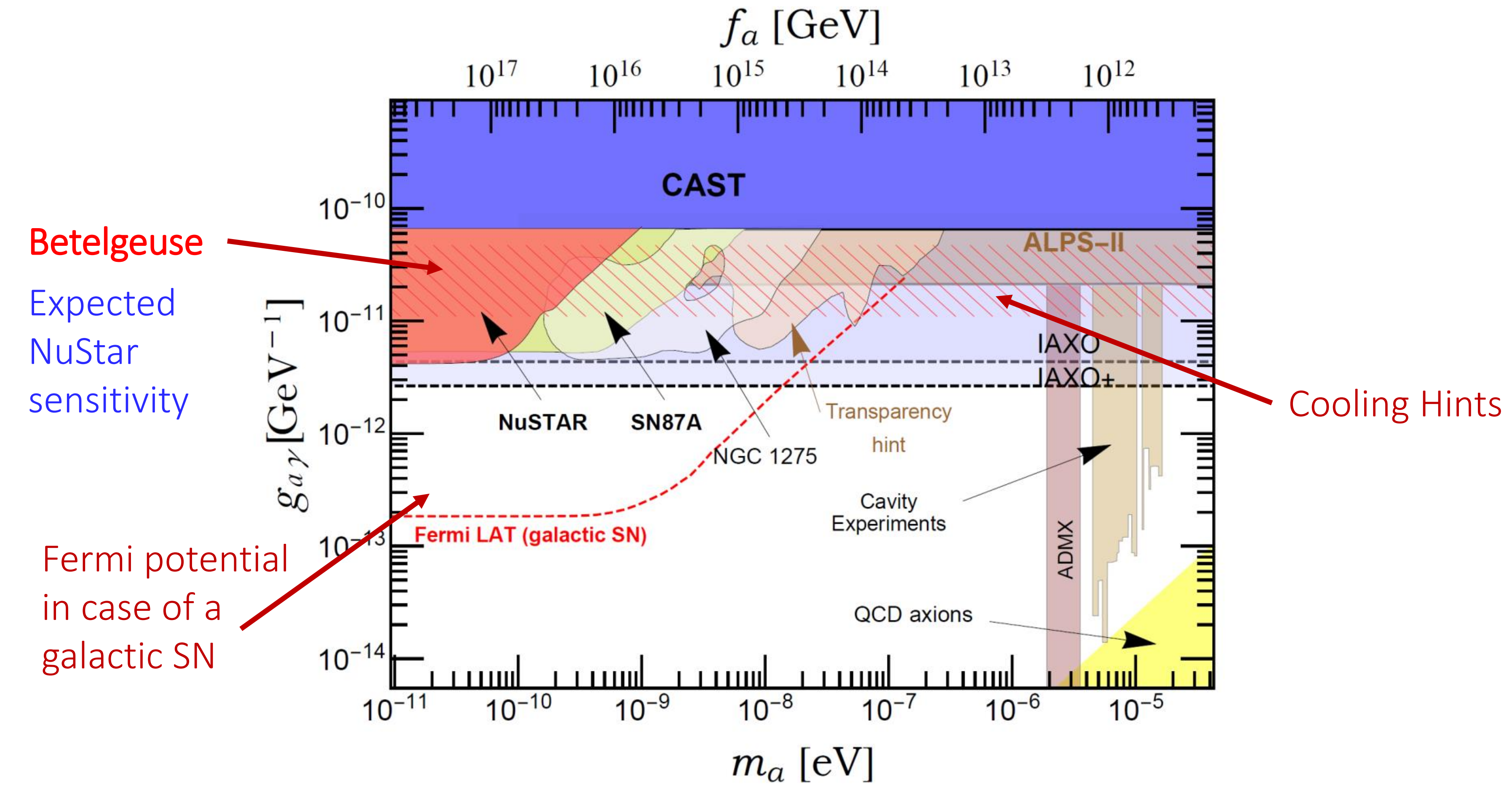


The result is fairly independent from the progenitor mass and is not affected by the axion feedback on the star, since the axion interactions don't change the relative abundance of neutrons and protons.

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

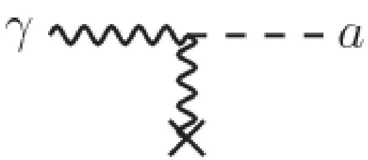
Supernovae and Supergiants Axionscopes

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



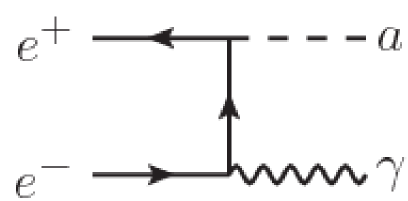
M.G., proceeding of the 13th Patras workshop (2017)

ALP production in Stars

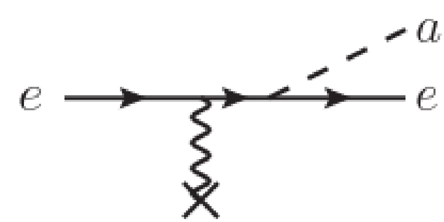


Primakoff Process

Compton Process



Pair Annihilation



Bremsstrahlung