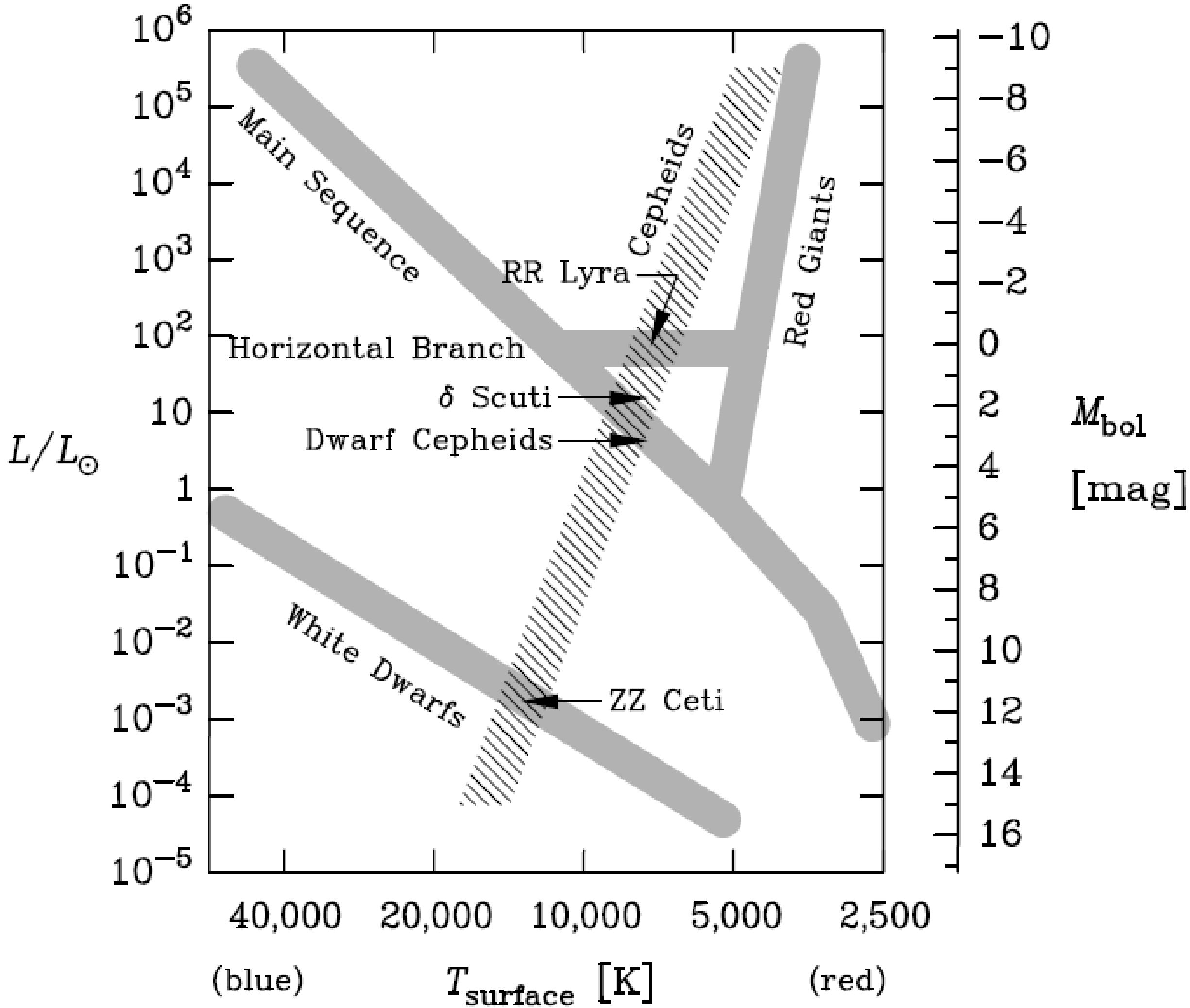
Axions and Stellar Physics

Maurizio Giannotti,
Barry University (FL)

IAXO international meeting,
April 18, 2016
Laboratori Nazionali di Frascati, Italy

Stars as Laboratories

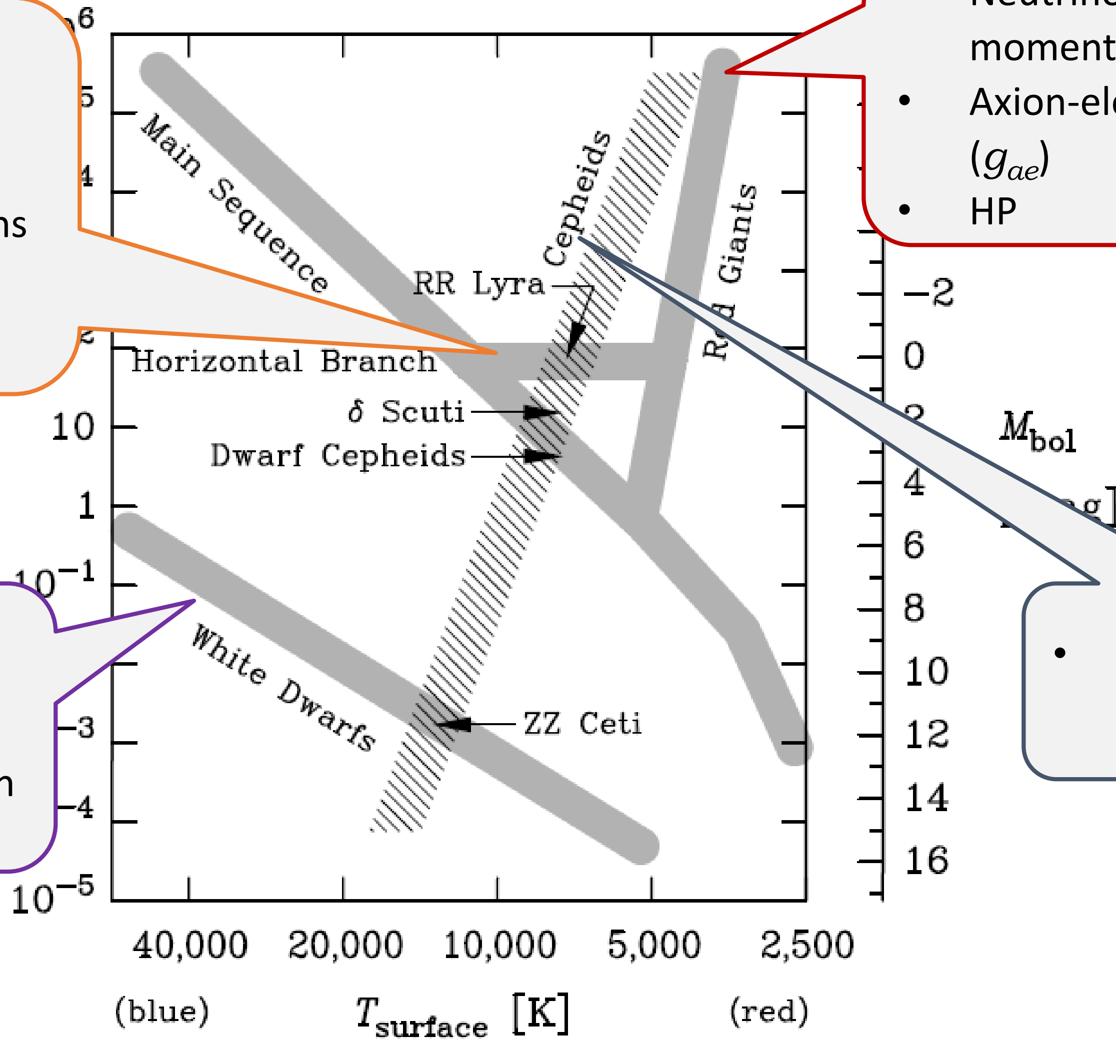


G. Raffelt, “Stars as laboratories for fundamental physics” (1996)

Stars as Laboratories

- minicharged fermions
- HP
- Extradimensions
- Axion-photon coupling ($g_{a\gamma}$)

- Neutrino magnetic moment (μ_ν)
- Axion-electron coupling (g_{ae})
- HP



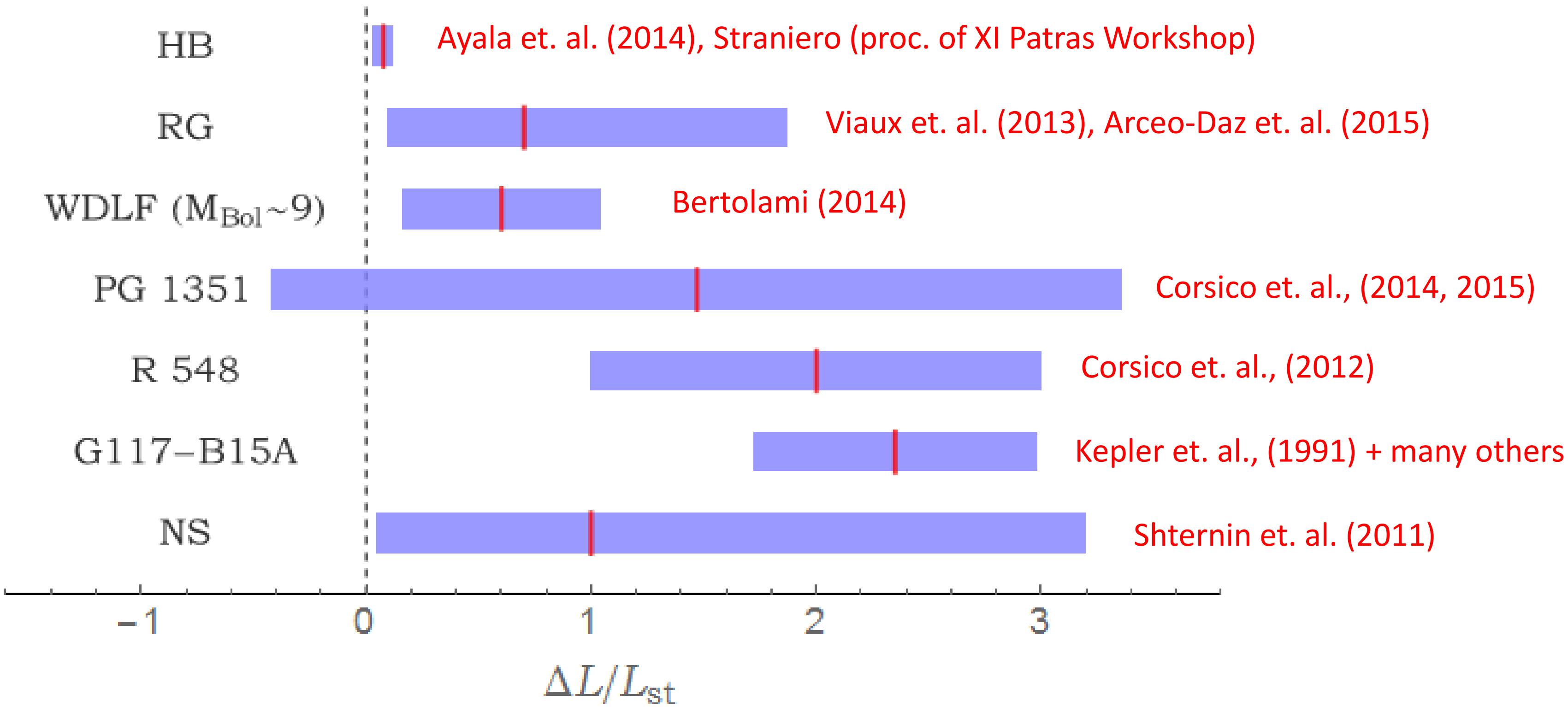
- Neutrino magnetic moment (μ_ν)
- Axion-electron coupling (g_{ae})

- Axion-photon coupling ($g_{a\gamma}$)

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

Cooling Anomalies

Practically every stellar system seems to be cooling faster than predicted by the models.



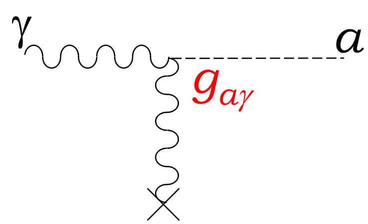
[M.G., Irastorza, Redondo, Ringwald (2015)]

Axions and Stellar Evolution

Light axions can be produced in stars through various mechanisms, e.g.

Primakoff conversion

$$\gamma + Ze \rightarrow a + Ze$$



Relevant in He-burning stars

Compton scattering/ bremsstrahlung

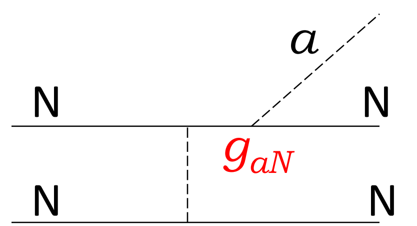
$$\gamma + e \rightarrow a + e$$

$$\gamma + (Z, A) \rightarrow (Z, A) + e + a$$

Relevant in RG and WD

Nucleon Bremsstrahlung

$$N + N \rightarrow N + N + a$$



Relevant in SN and neutron stars

The emission of axions could lead to an *overly efficient energy drain*, inconsistent with observations. This leads to bounds on the axion couplings with photons, electrons and nuclei.

KSVZ and DSFZ axion couplings

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

$$g_{ai} = m_i \frac{C_{ai}}{f_a}$$

$$g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a} \quad \text{with} \quad C_{a\gamma} = \frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_d + m_u}$$

- J.E. Kim (1979);
- M. Shifman, A. Vainshtein, V. Zakharov (1980);
- A.R. Zhitnitskii (1980);
- M. Dine, W. Fischler, M. Srednicki (1980)

Most known example of QCD axion : DSVZ and KSVZ (hadronic) axions.

Mass and coupling have a peculiar dependence on the PQ constant.

“The QCD axion Precisely”

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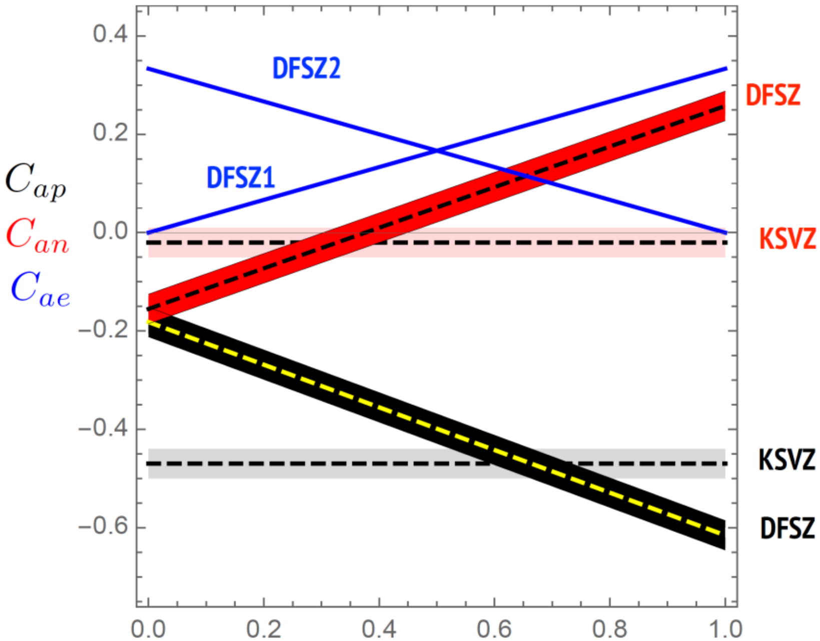
New results from recent NLO chiral perturbation theory and lattice

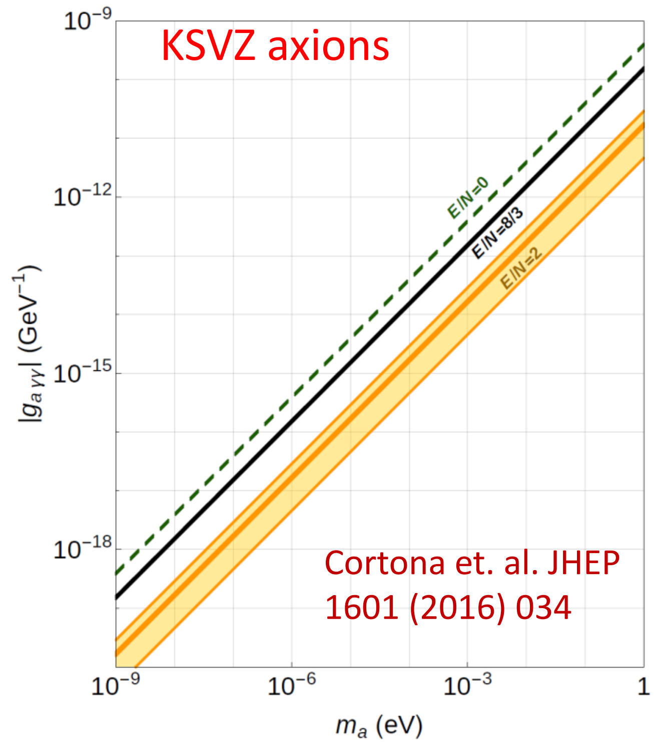
G. G. di Cortona, E.Hardy, J.P.Vega, G.Villadoro, JHEP 1601 (2016) 034

	KSVZ	DFSZ I	DFSZ II
C_{ae}	zero (at tree level)	$\frac{\cos^2\beta}{3}$	$\frac{\sin^2\beta}{3}$
C_{ap}	-0.47 ± 0.03	-0.182(25) - 0.435 $\cos^2\beta$	-0.182(25) + 0.435 $\cos^2\beta$
C_{an}	-0.02 ± 0.03	-0.160(25) + 0.414 $\cos^2\beta$	-0.160(25) + 0.414 $\cos^2\beta$
$C_{a\gamma}$	$\frac{E}{N} - 1.92(4)$	$\frac{8}{3} - 1.92(4)$	$\frac{2}{3} - 1.92(4)$

KSVZ and DSFZ axion couplings

J.Redondo (talk at the Axion Forum, Bonn, march 2016)





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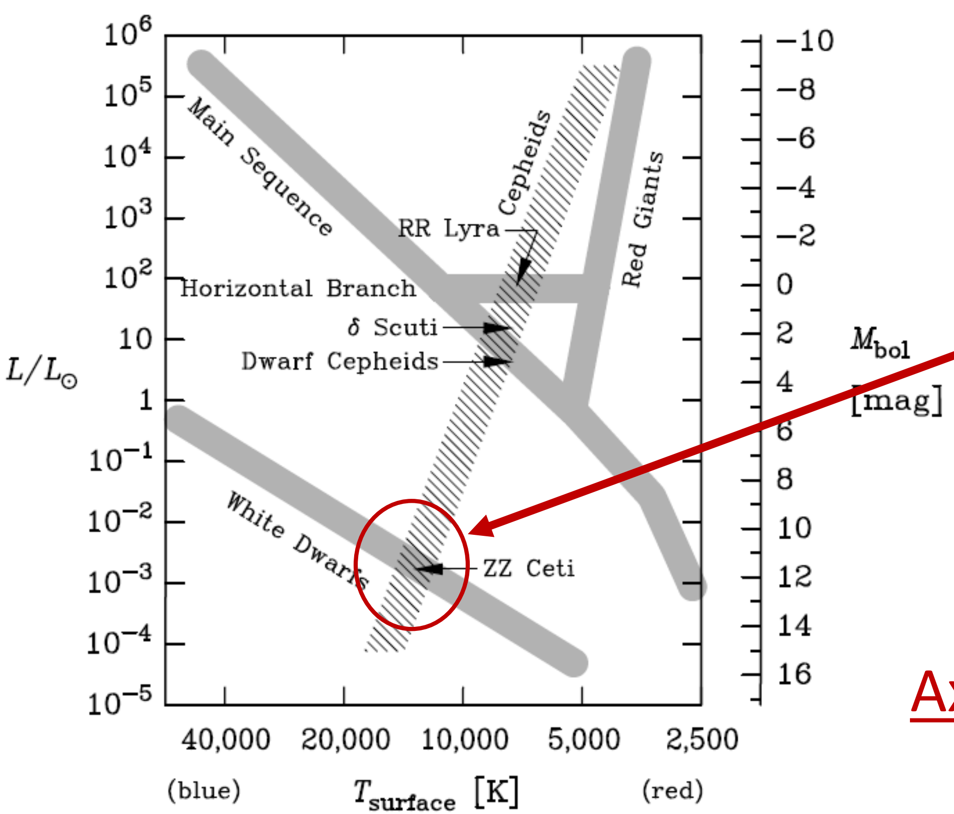
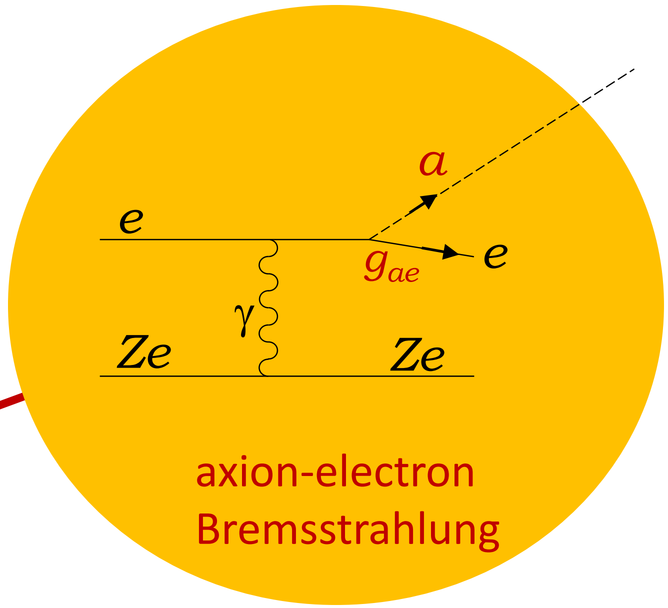
White Dwarf Variables

Luminosity changes periodically with a slowly increasing period.

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

TESTs axion-electron coupling





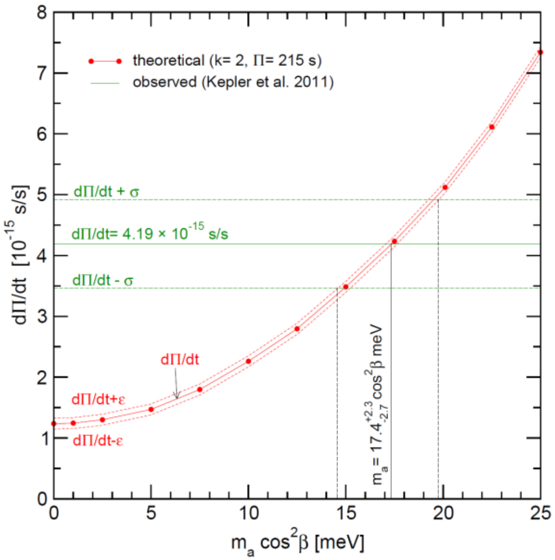
Axion: $\dot{T}/T$ $\dot{P}/P$

White Dwarf Variables

Observations:

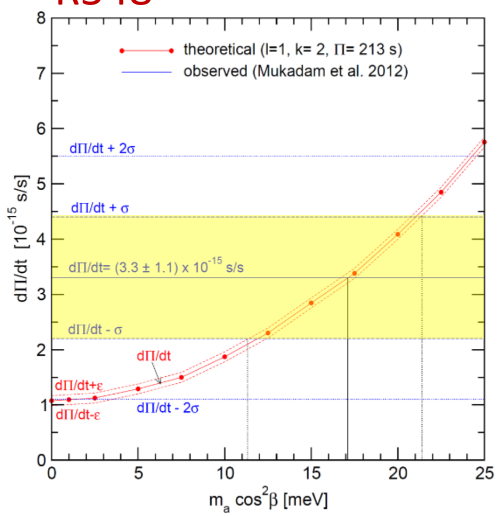
WD	class	$\dot{P}_{\rm obs}$[s/s]	$\dot{P}_{\rm th}$[s/s]
G117 - B15A	DA	$(4.19 \pm 0.73) \times 10^{-15}$	$(1.25 \pm 0.09) \times 10^{-15}$
R548	DA	$(3.33 \pm 1.1) \times 10^{-15}$	$(1.1 \pm 0.09) \times 10^{-15}$
PG 1351+489	DB	$(2.0 \pm 0.9) \times 10^{-13}$	$(0.81 \pm 0.5) \times 10^{-13}$

G117-B15A



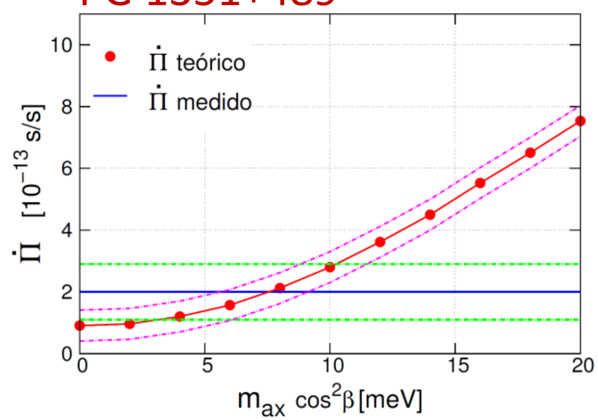
Corsico et. al., Mon. Not. R. Astron. Soc. 424, 2792–2799 (2012)

R548



Corsico et. al., JCAP 1212 (2012).

PG 1351+489



Battich et. al., proceeding of the Argentinian Annual Meeting of Astronomy (2016)

Bounds: $g_{ae} < 5.5 \times 10^{-13}$ $g_{ae} < 6.0 \times 10^{-13}$ $g_{ae} < 3.2 \times 10^{-13}$

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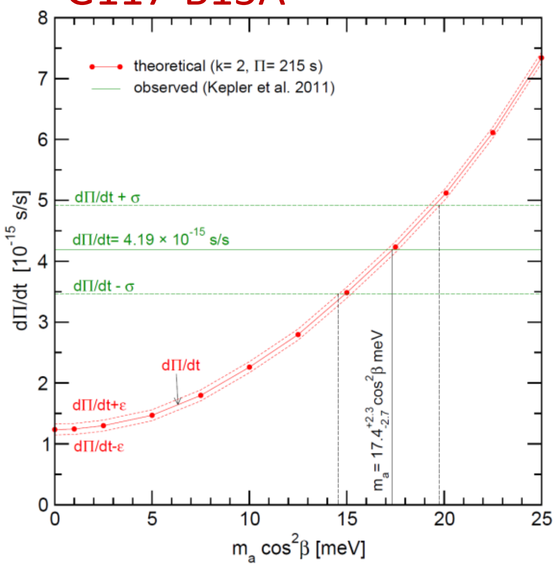

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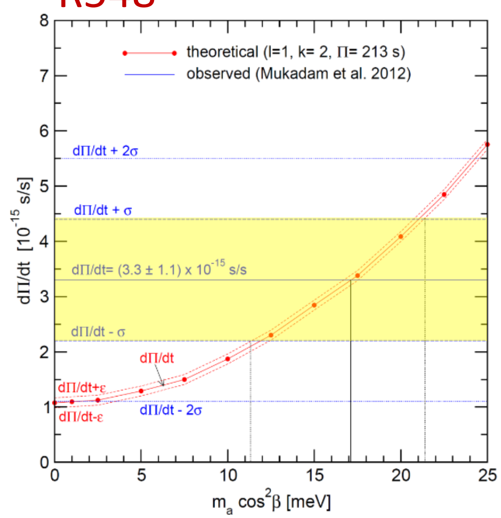

Corsico et. al., JCAP 1212 (2012).

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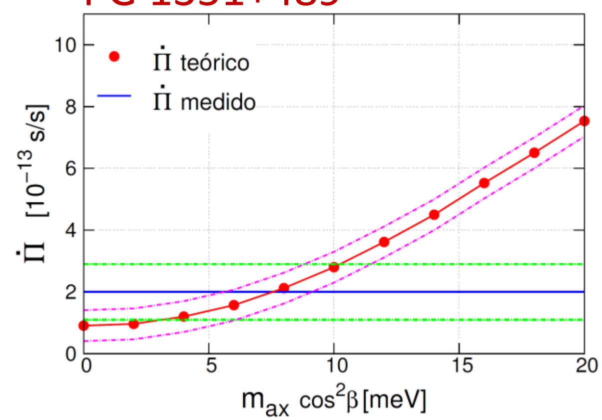

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Hints: $g_{ae} = 4.85 \times 10^{-13}$ $\quad$ $g_{ae} = 4.78 \times 10^{-13}$ $\quad$ $g_{ae} = 2.13 \times 10^{-13}$

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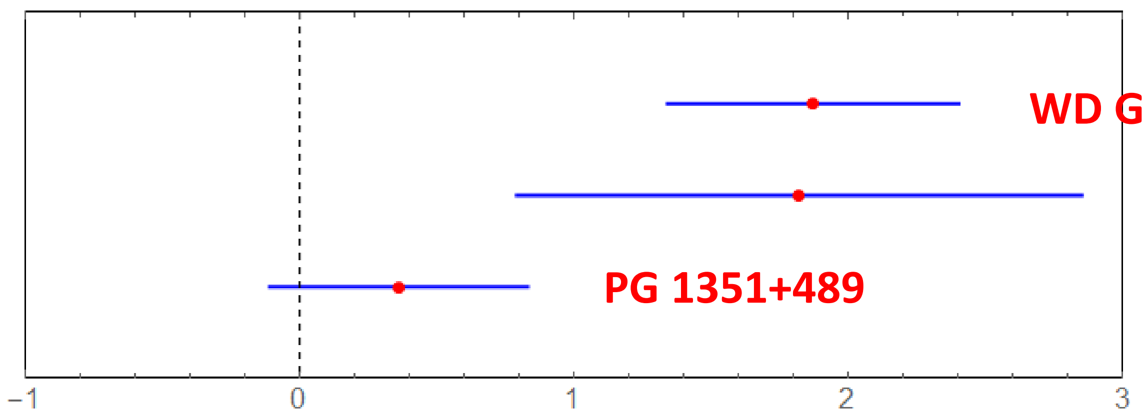

$$\alpha_{26} = \left(g_{ae}^2 / 4\pi\right) \times 10^{26}$$

Corsico et. al., Mon. N... Astron. Soc. 424, 2792–279... (2012)

... et al., JCAP 1212 (2012).

... Meeting of Astronomy (2016)

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White Dwarfs Luminosity Function

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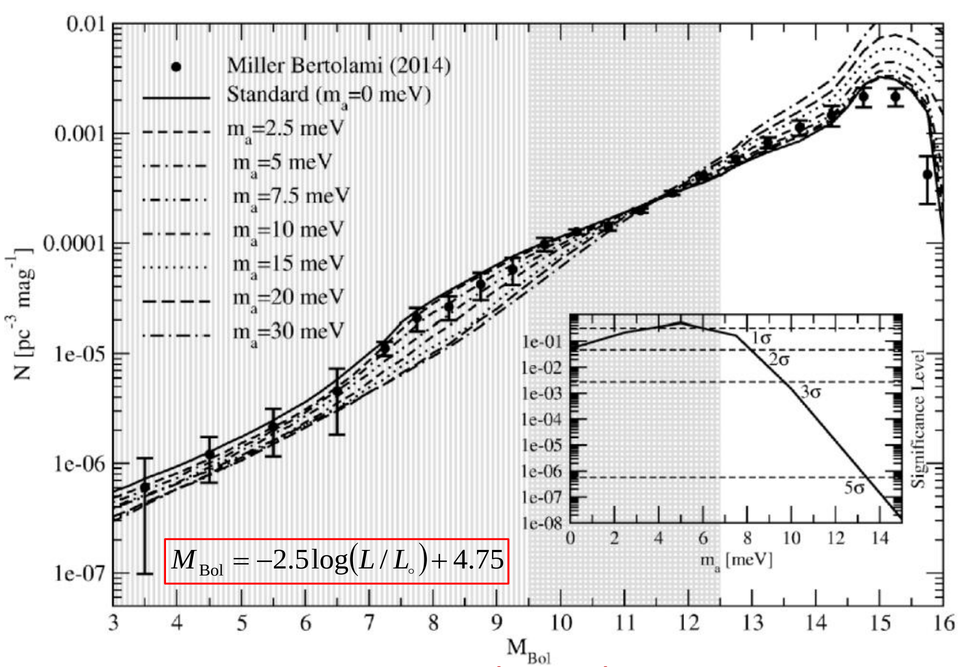
$$\frac{dN_{WD}}{dV\ dL} \propto \frac{1}{L_\gamma + L_\nu + L_x}$$

L_x= anomalous cooling, e.g. axions



M. Bertolami et. al. (2014)

Axion bound: $g_{ae} < 2.4 \times 10^{-13}$

Bertolami, Melendez, Althaus, Isernd, JCAP **1410** (2014)

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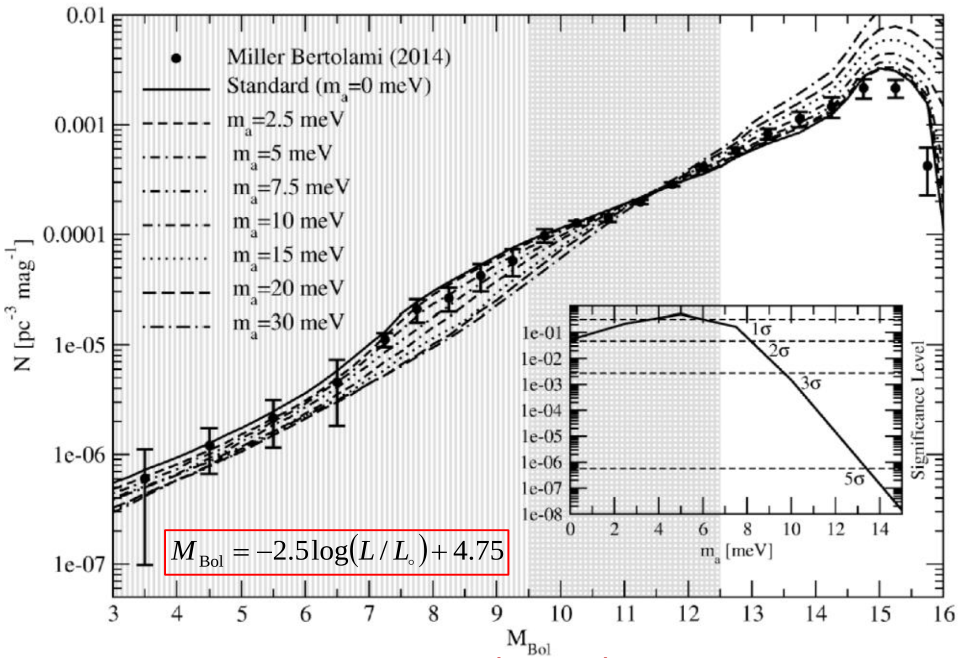

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Axion Hint: $g_{ae} = 1.4\times10^{-13}$

Bertolami, Melendez, Althaus, Isernd, JCAP **1410** (2014)

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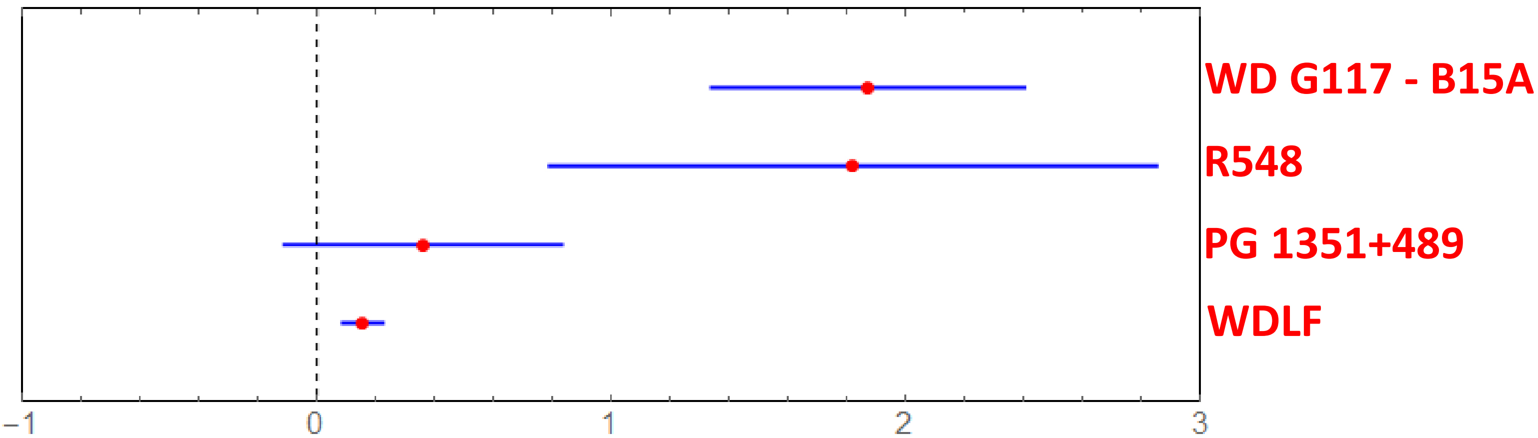

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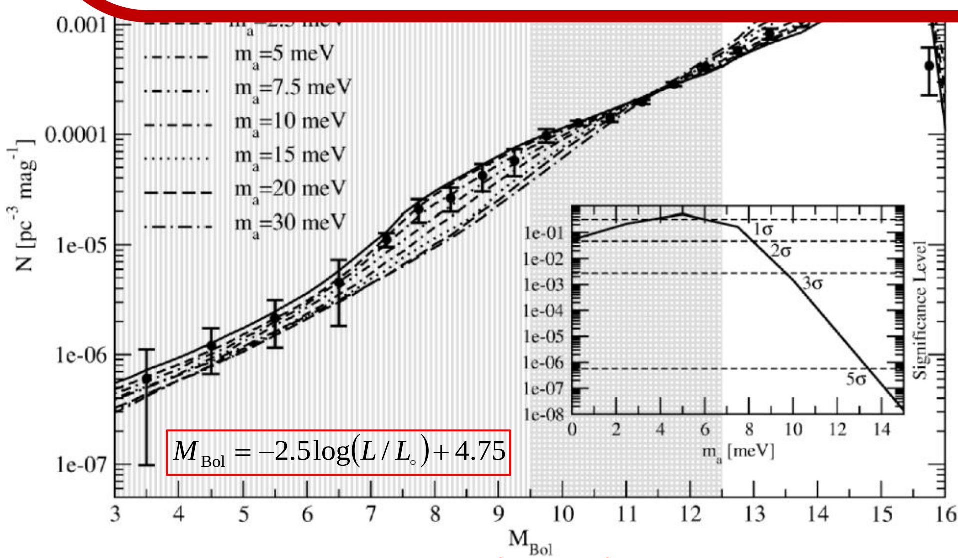

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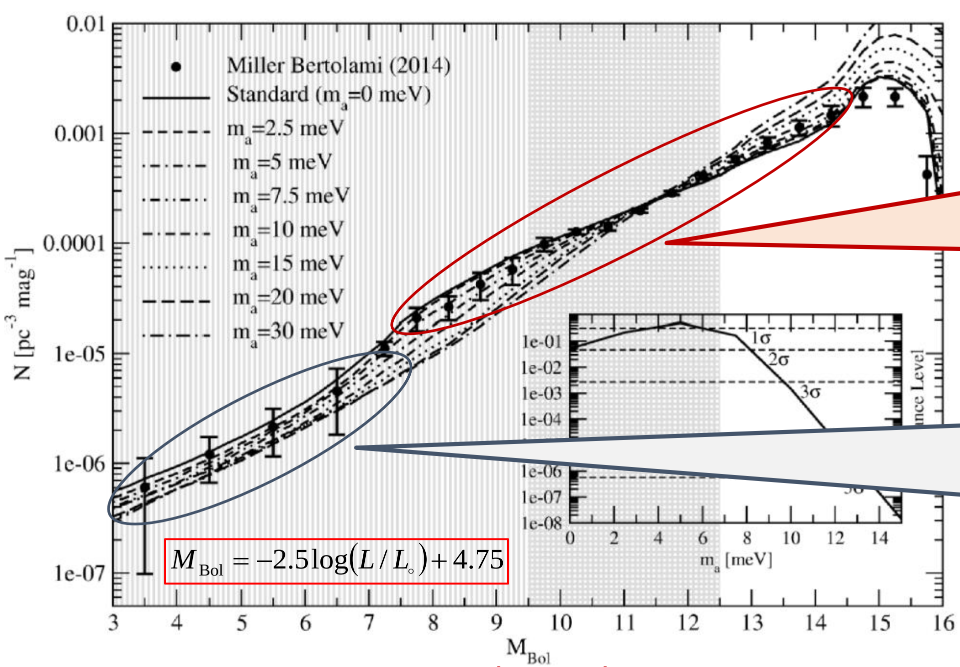
White Dwarfs Luminosity Function

- ✓ The WDLF offers a unique way to test the functional dependence of the additional cooling rather than just its amplitude.
- ✓ The addition of axions coupled to electrons showed improvement of the fits.
- ✓ The addition of an anomalous neutrino magnetic moment showed no improvement.



M. Bertolami et. al. (2014)

Cold.
ν cooling unimportant.
Linear behavior (Mestel Law).
Small uncertainties

Hot;
ν cooling becomes important.
Nonlinear behavior.
Large uncertainties

White Dwarfs Luminosity Function

The WDLF is expected to be approximately linear in the range between $8<M_{bol}<14$

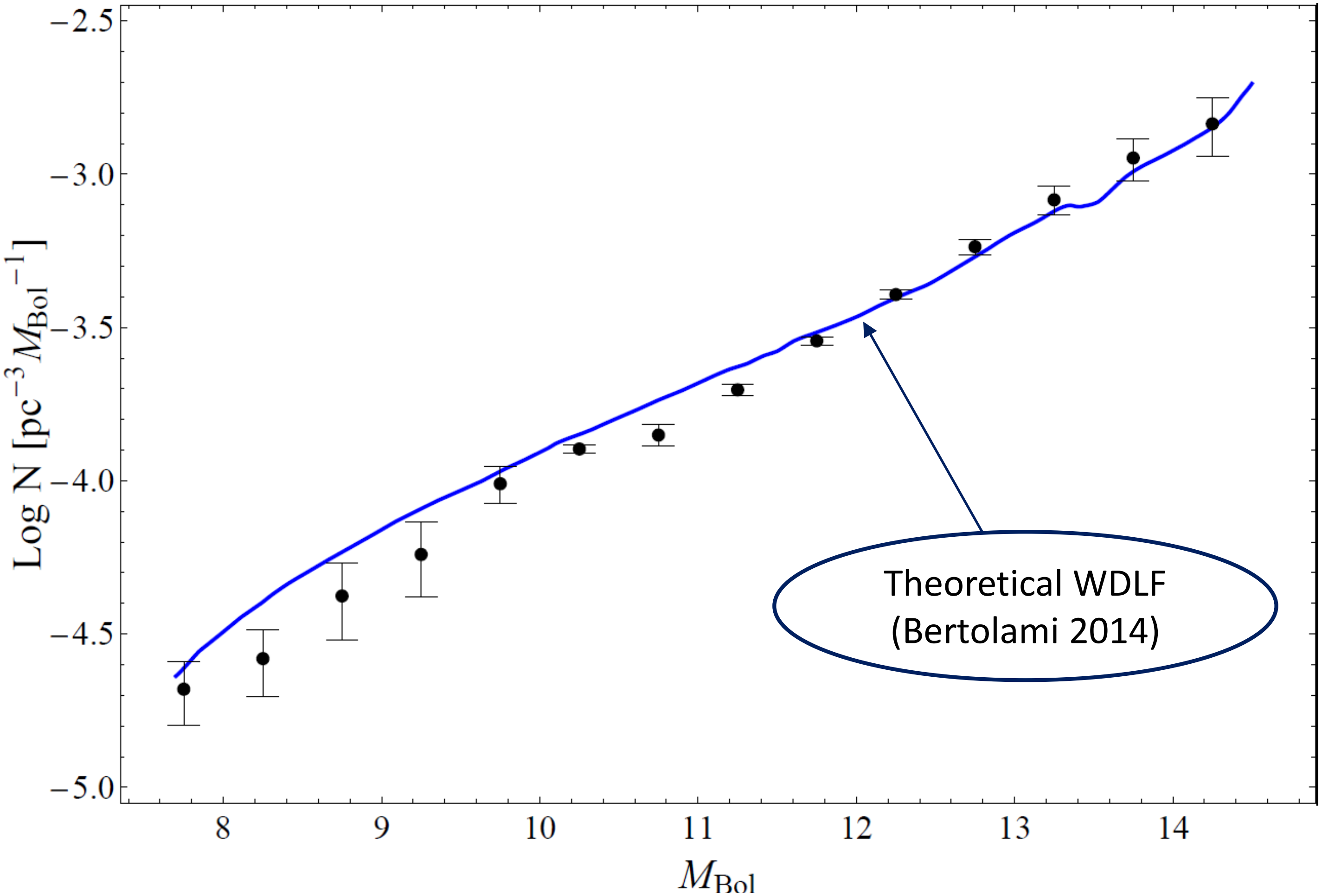


Figure reproduced using data from Bertolami (2014)

$$M_{Bol} = -2.5\log(L/L_{\circ}) + 4.75$$

White Dwarfs Luminosity Function

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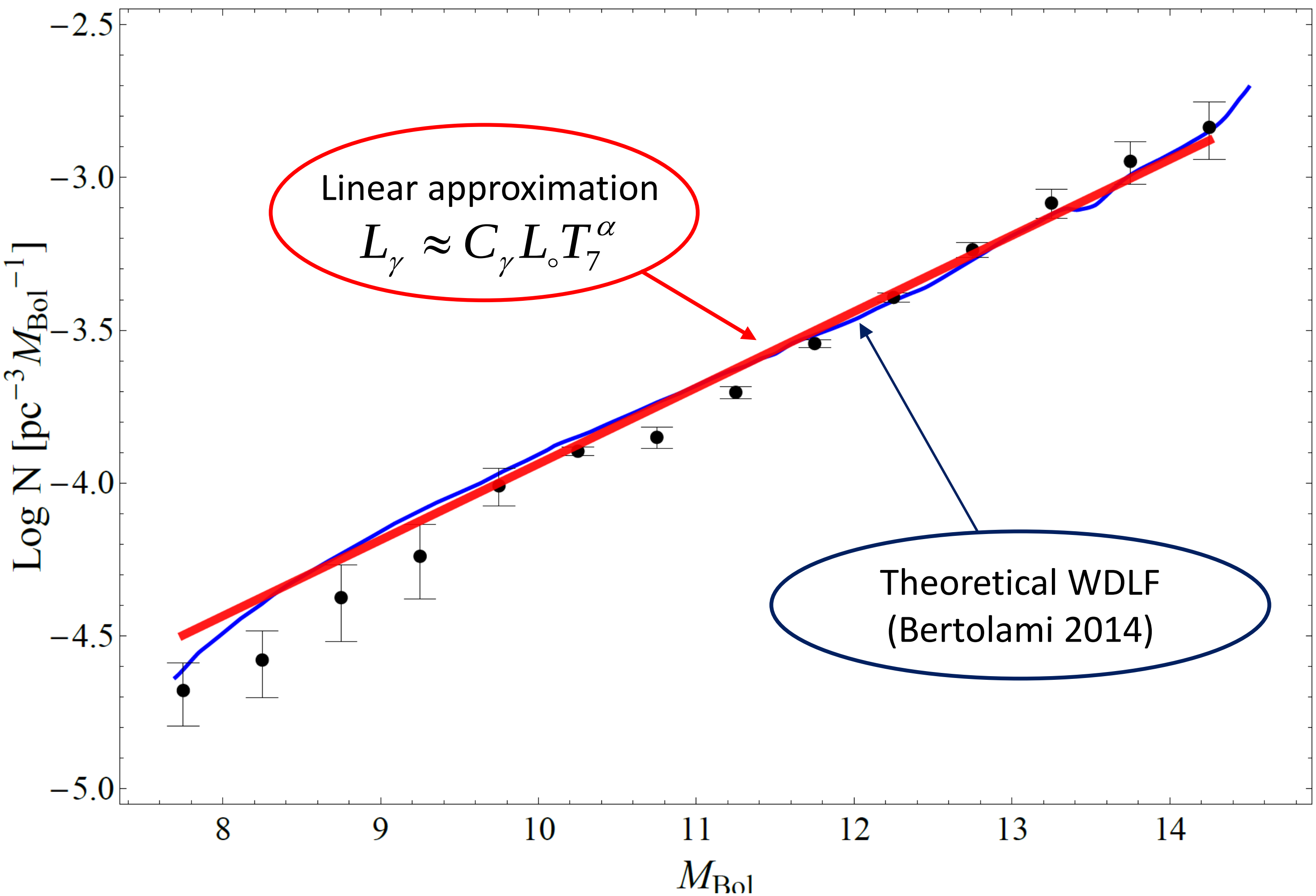

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$$M_{Bol} = -2.5\log\left(L/L_\circ\right) + 4.75$$

WDLF and new physics

Consider the linear approximation before and add theoretical errors large enough to account for the difference between the actual theoretical prediction;

Several new physics models, including axions/ALPs, predict an additional energy loss of the form

$$\boxed{L_x = C_x T_7^n}$$

This form gives testable predictions for

$$\boxed{\frac{N_{\rm exp} - N_{\rm obs}}{N_{\rm exp}}}$$

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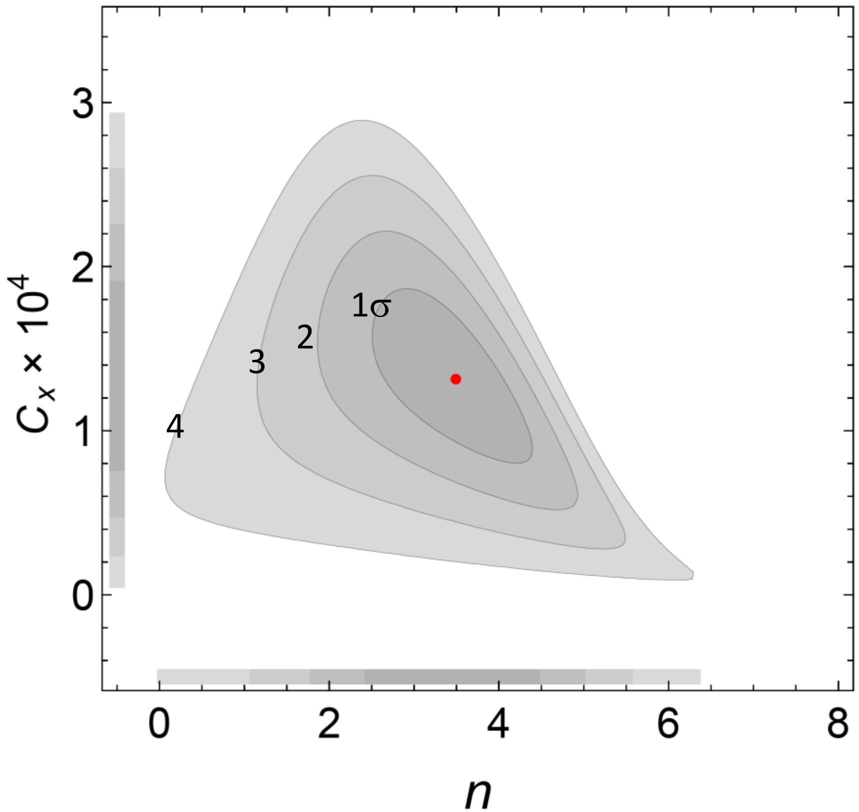
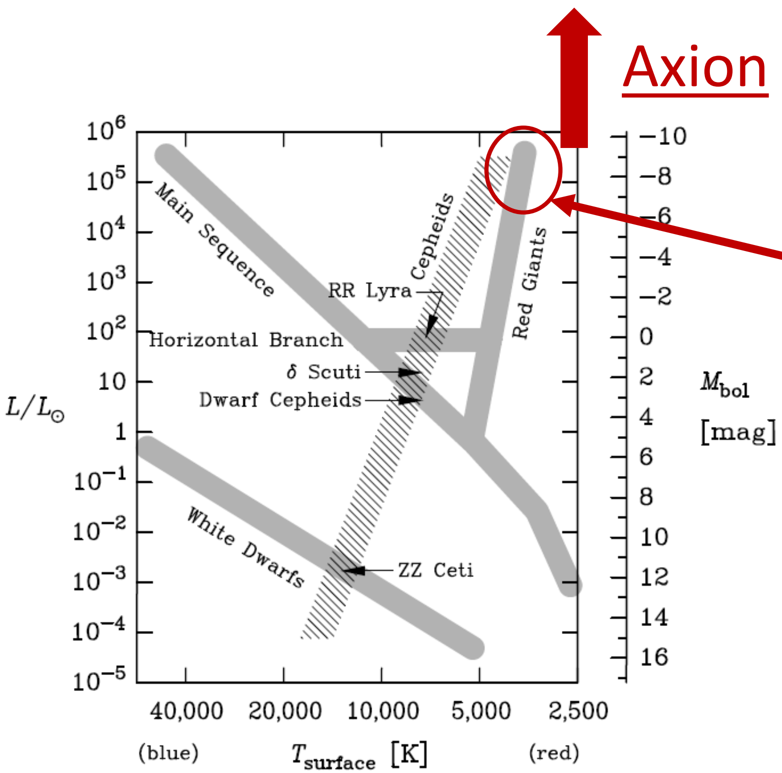
The results (1 to 4σ) are shown to the side

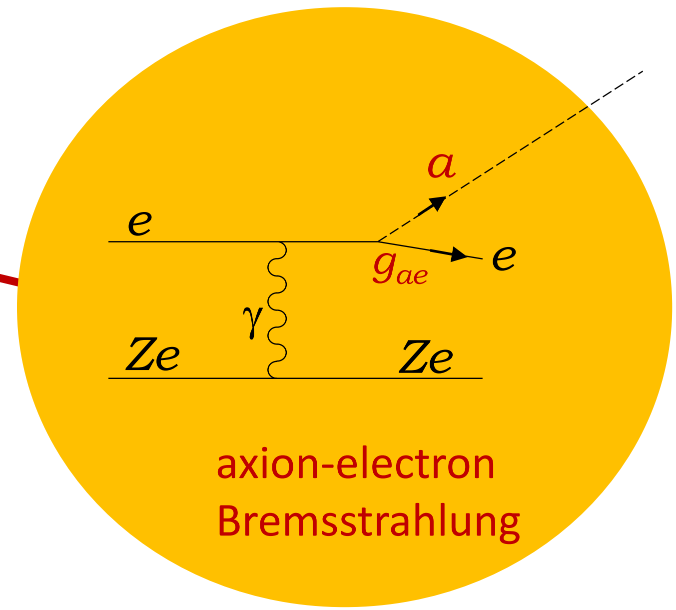


[M.G., Irastorza, Redondo, Ringwald (2015)]

RG Cooling

A particularly useful observable in the CMD is the brightness of the tip of the RG branch.





Additional cooling would give rise to a brighter RGB tip.

Strong axion bound on the axion-electron coupling:

$$g_{ae} < 2.6\,(4.3)\times 10^{-13}$$

at 1 (2) σ

[Viaux et. al., Phys.Rev.Lett. 111 (2013)]

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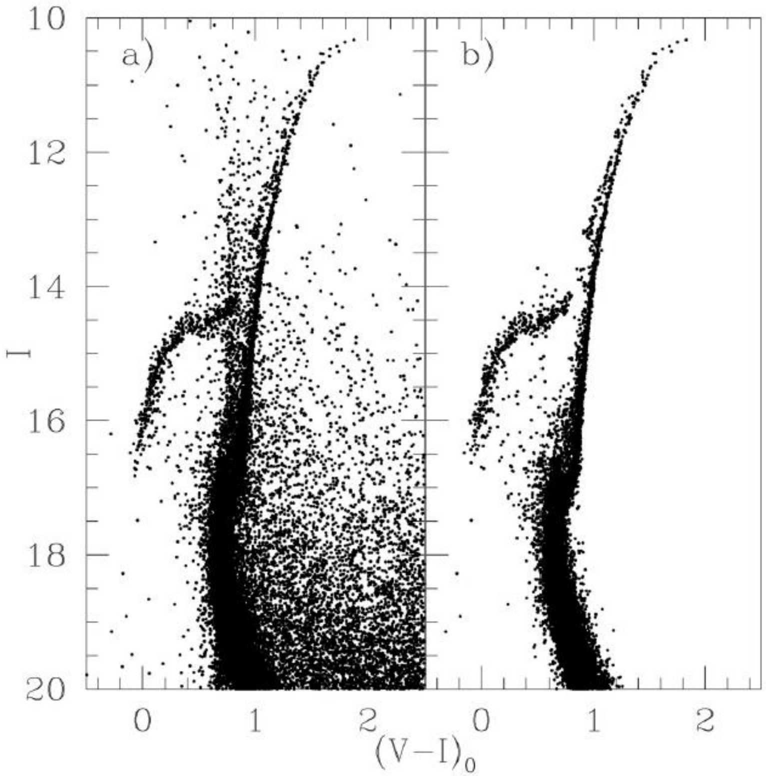

Viaux et. al. Astron.Astrophys. 558 (2013) A12
Color-magnitude diagram of M5. Left: Original. Right: After field star decontamination.

Additional cooling would give rise to a brighter RGB tip.

Recent papers showed a tip slightly more luminous than expected

M5: (analysis of g_{ae} and μ_ν)
Viaux et. al., Phys.Rev.Lett. 111 (2013); Viaux et. al. Astron.Astrophys. 558 (2013) A12; for M5

ω-Centauri: (analysis of μ_ν)
Arceo-Daz et. al. (2015)

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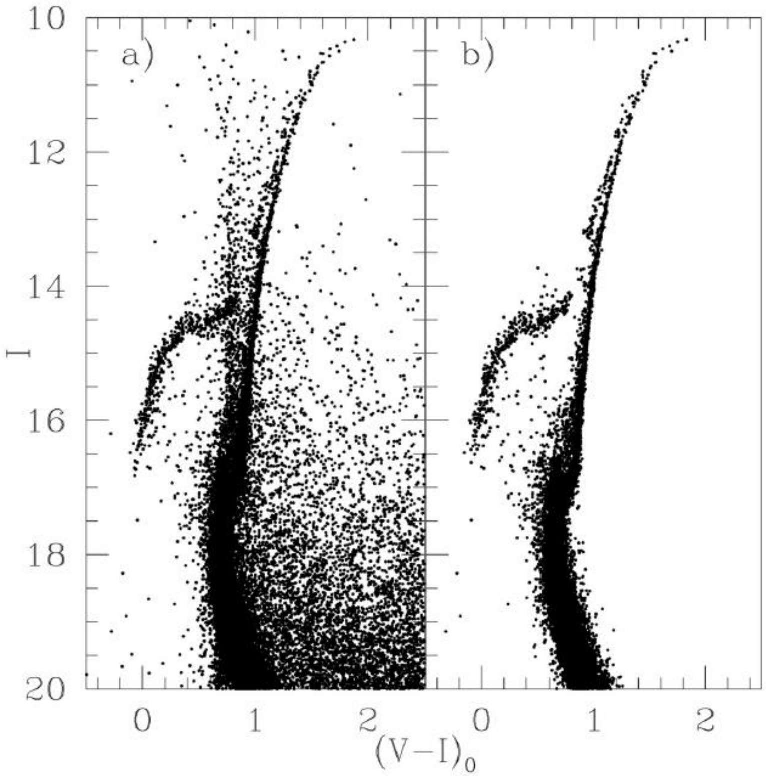

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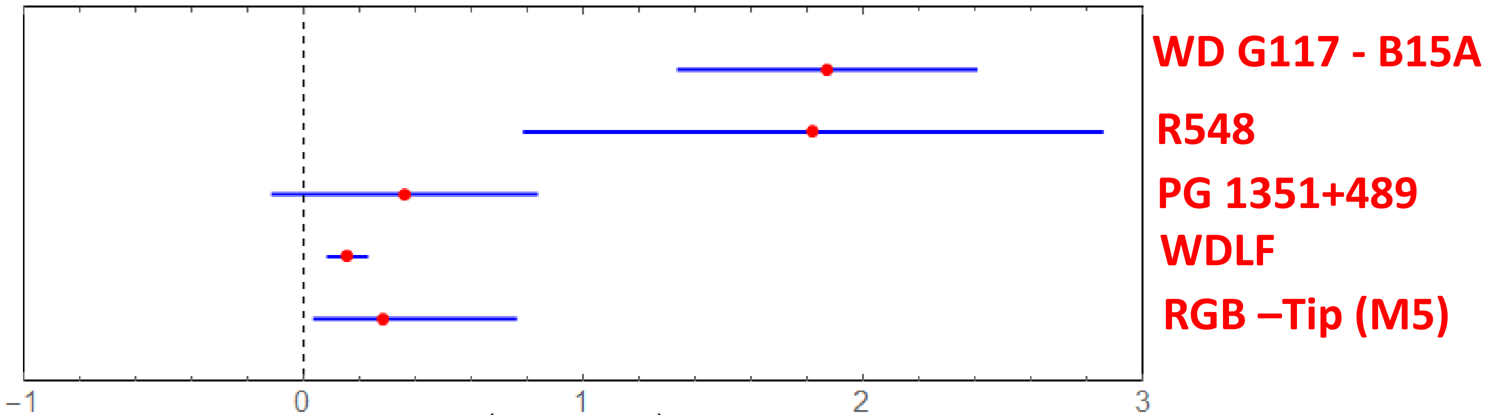
Hint: $g_{ae} = 1.88^{1.20}_{-1.18} \times 10^{-13}$

Viaux et. al., Phys.Rev.Lett. 111 (2013)

Putting all together

Hints on the axion- electron coupling



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Putting all together

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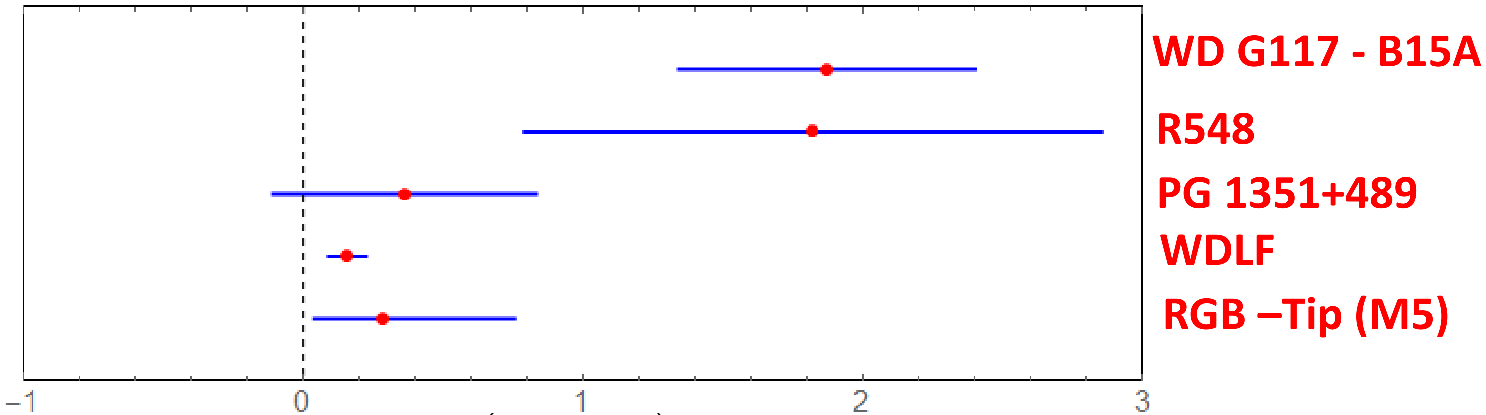

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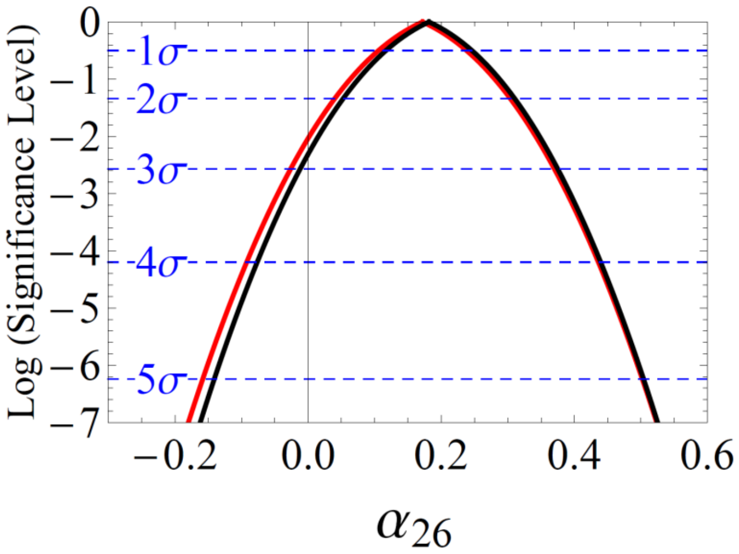


Global Analysis of the cooling hints

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

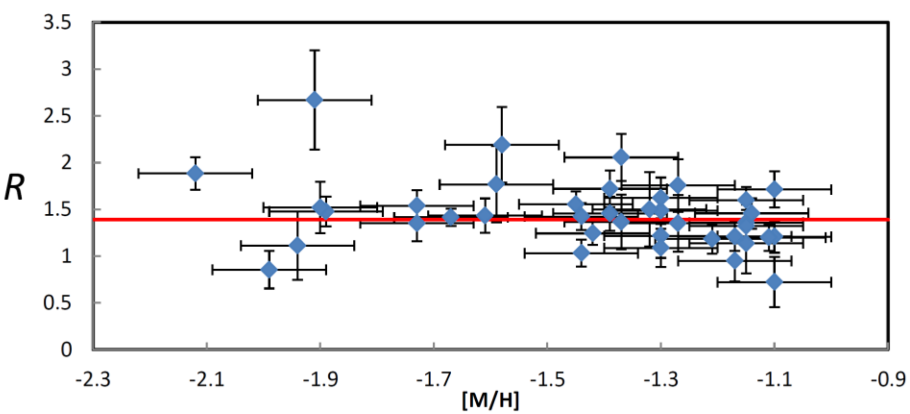
HB (R-parameter)

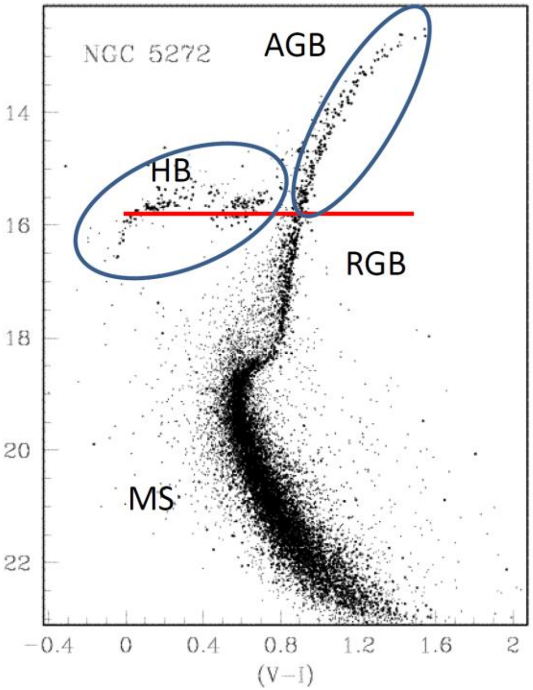
The R-parameter:

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

compares the number of stars in the HB (N_{HB}) and in the upper portion of the RGB (N_{RG}).

39 GCs (from the Salaris et al 2004 catalog)





Straniero (proc. of XI Patras Workshop)

$\langle R \rangle = 1.39 \pm 0.03$

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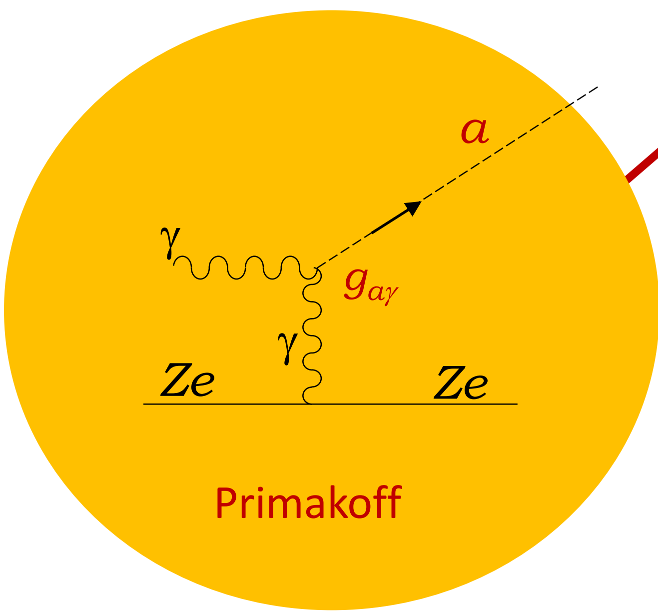

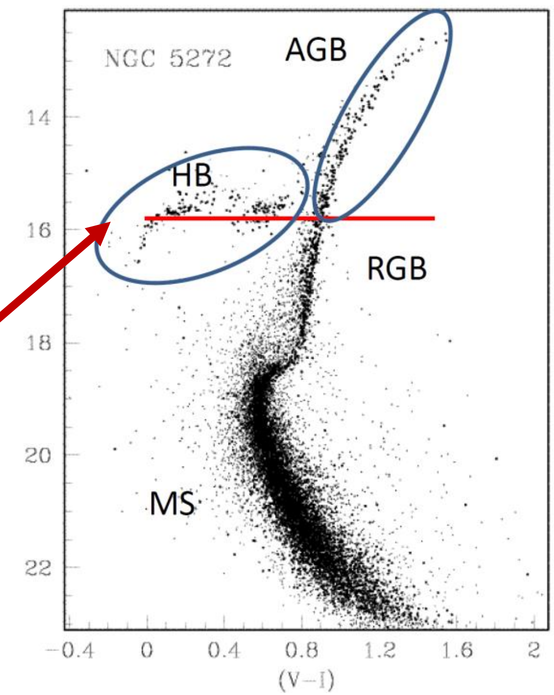

- Ayala, Dominguez, M.G., Mirizzi, Straniero (PRL 113 (2014))
- Straniero (proc. of XI Patras Workshop);
- Straniero, Ayala, M.G., Mirizzi, Dominguez (in preparation)

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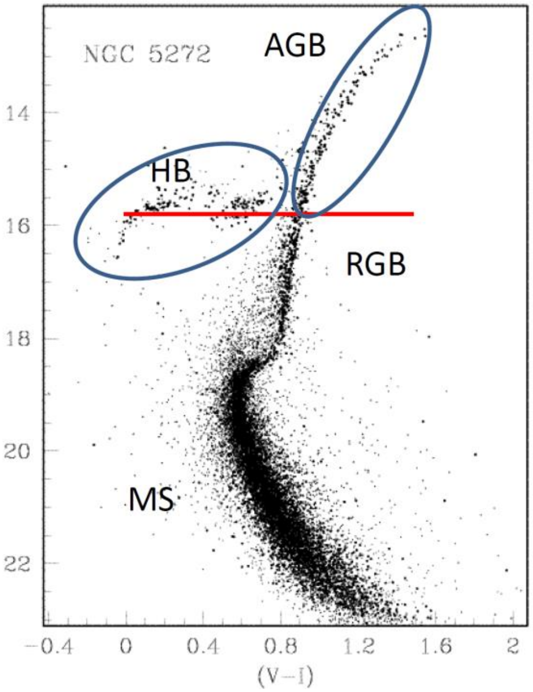
A recent analysis using the 39 GC from Salaris et. al. gave

$$g_{a\gamma} = (0.29 \pm 0.18) \times 10^{-10}\,\text{GeV}^{-1}$$ 68% C.L.

and the upper bound on the axion-photon coupling

$$g_{a\gamma} < 0.65 \times 10^{-10}\,\text{GeV}^{-1}$$ 95% C.L.



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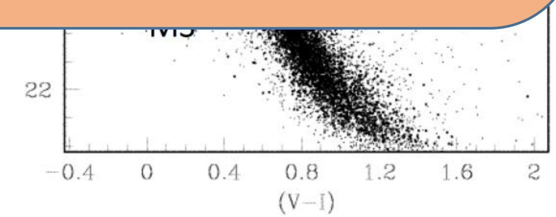
(N_{HB}) and in the upp

RGB (N_{RG}).

The apparent need for additional cooling may be a consequence of an incomplete understanding of the $^{12}C(\alpha,\beta)^{16}O$ reaction rate. This reaction is among the main scientific cases of LUNA MV, a new nuclear astrophysics facility under construction at the Gran Sasso underground laboratory of INFN (LNGS).
[Straniero (proc. of XI Patras Workshop)]



A recent analysis using the 39

Salaris et. al. gave

$$g_{a\gamma} = (0.29 \pm 0.18) \times 10^{-10}\,\mathrm{GeV}^{-1}$$ 68% C.L.

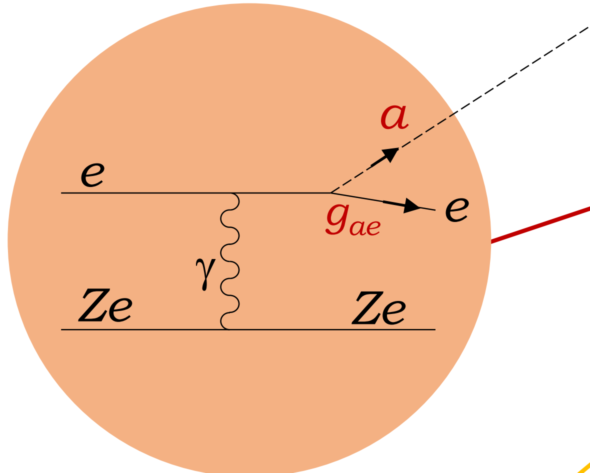
and the upper bound on the axion-photon coupling

$$g_{a\gamma} < 0.65 \times 10^{-10}\,\mathrm{GeV}^{-1}$$ 95% C.L.

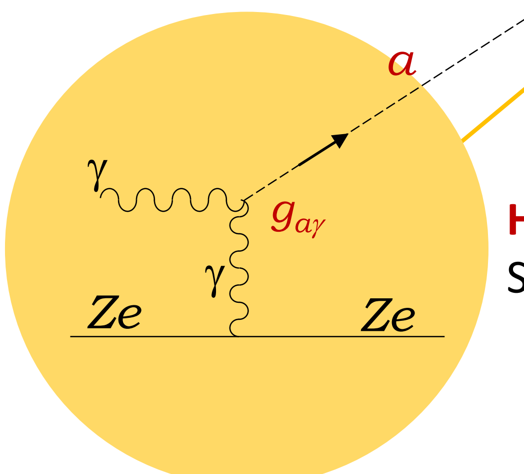
- Ayala, Dominguez, M.G., Mirizzi, Straniero (PRL 113 (2014))
- Straniero (proc. of XI Patras Workshop);
- Straniero, Ayala, M.G., Mirizzi, Dominguez (in preparation)

R-parameter: a new look

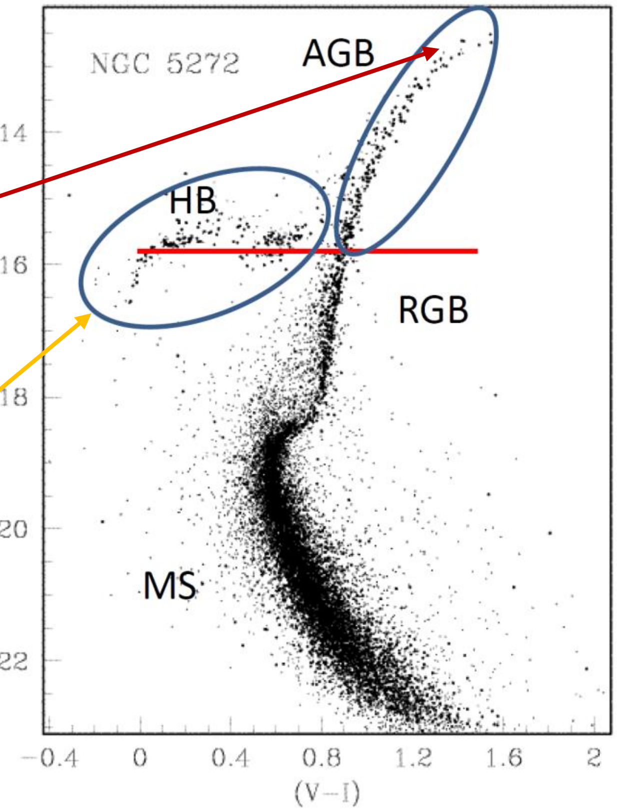
$R = N_{HB}/N_{RG}$



RGB: Very dense.
Sensitive to g_{ae}



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



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

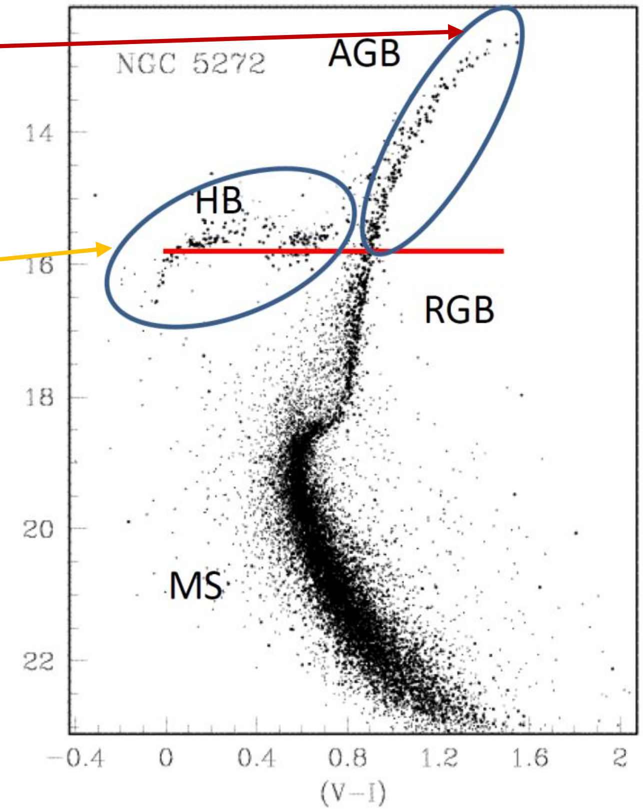
Straniero, Mirizzi, M.G., in preparation

R-parameter: a new look

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

Very dense. Sensitive to g_{ae}

Not very dense. Sensitive to $g_{a\gamma}$



The R-parameter may be modified also by processes efficient in the RGB stage, particularly by the axion bremsstrahlung process:

$$R = 7.33Y + 0.02 - 0.095\sqrt{21.86 + 21.08 g_{10}} - 1.61\delta\mathcal{M}_c - 0.067\alpha_{26}$$

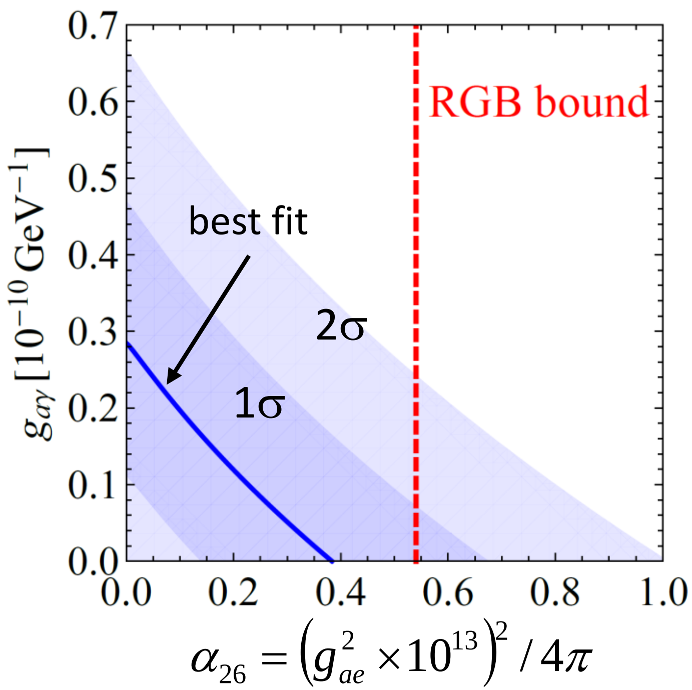
where

$$\delta\mathcal{M}_c = 0.024 M_\odot \left(\sqrt{4\pi\alpha_{26} + (1.23)^2} - 1.23 - 0.921\,\alpha_{26}^{0.75}\right)$$ and $$\alpha_{26} = \frac{\left(g_{ae}\times 10^{13}\right)^2}{4\pi}$$

R-parameter: a new look

R=N_{HB}/N_{RG}

$$R = 7.33Y + 0.02 - 0.095\sqrt{21.86 + 21.08 g_{10}} - 1.61\delta\mathcal{M}_c - 0.067\alpha_{26}$$



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

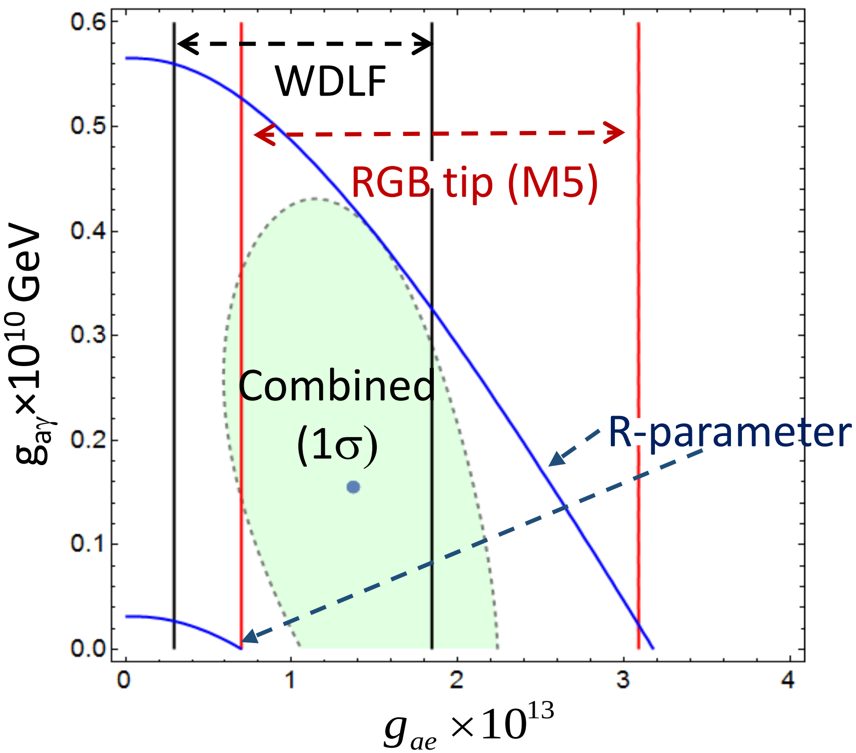
The R-parameter is a function of both g_{ae} and $g_{a\gamma}$.

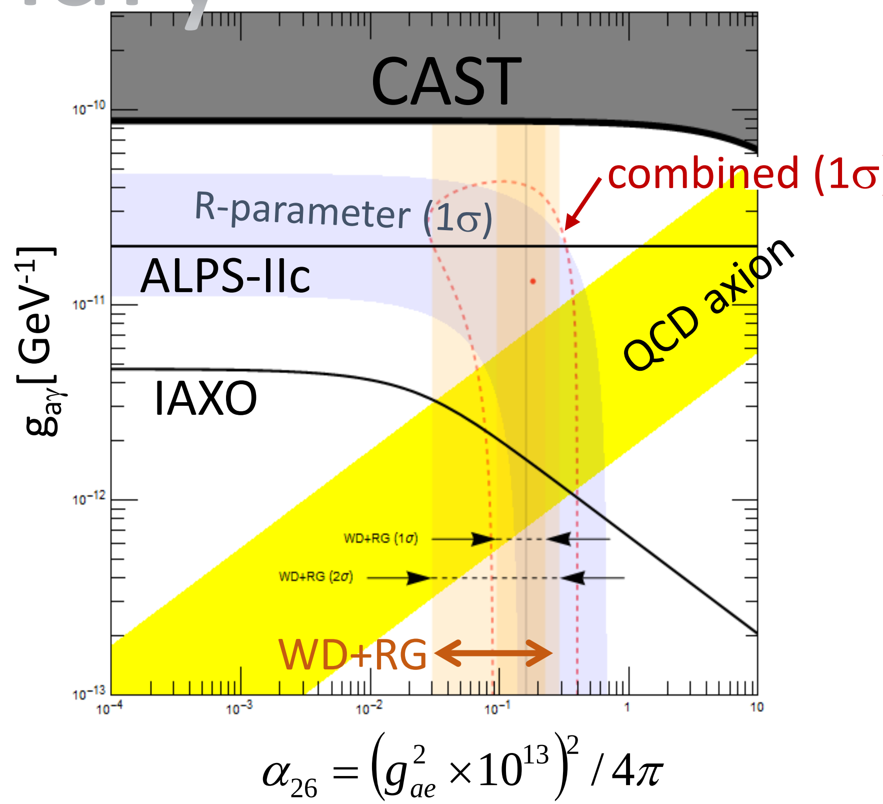
Therefore, the hint could be explained by a combination of these couplings or even only by g_{ae}

ALP parameters region

M.G., Irastorza, Redondo, Ringwald, In preparation

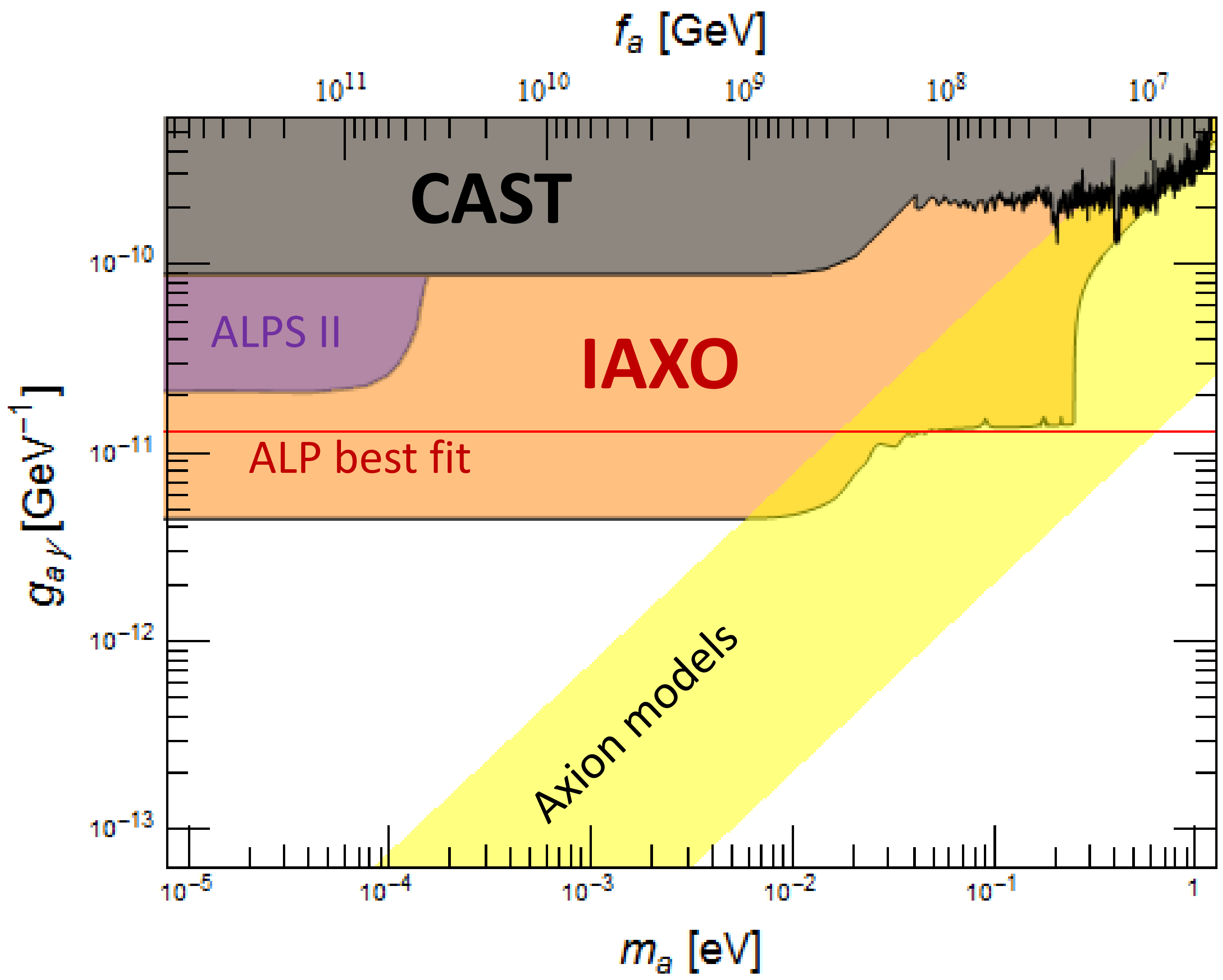
Preliminary



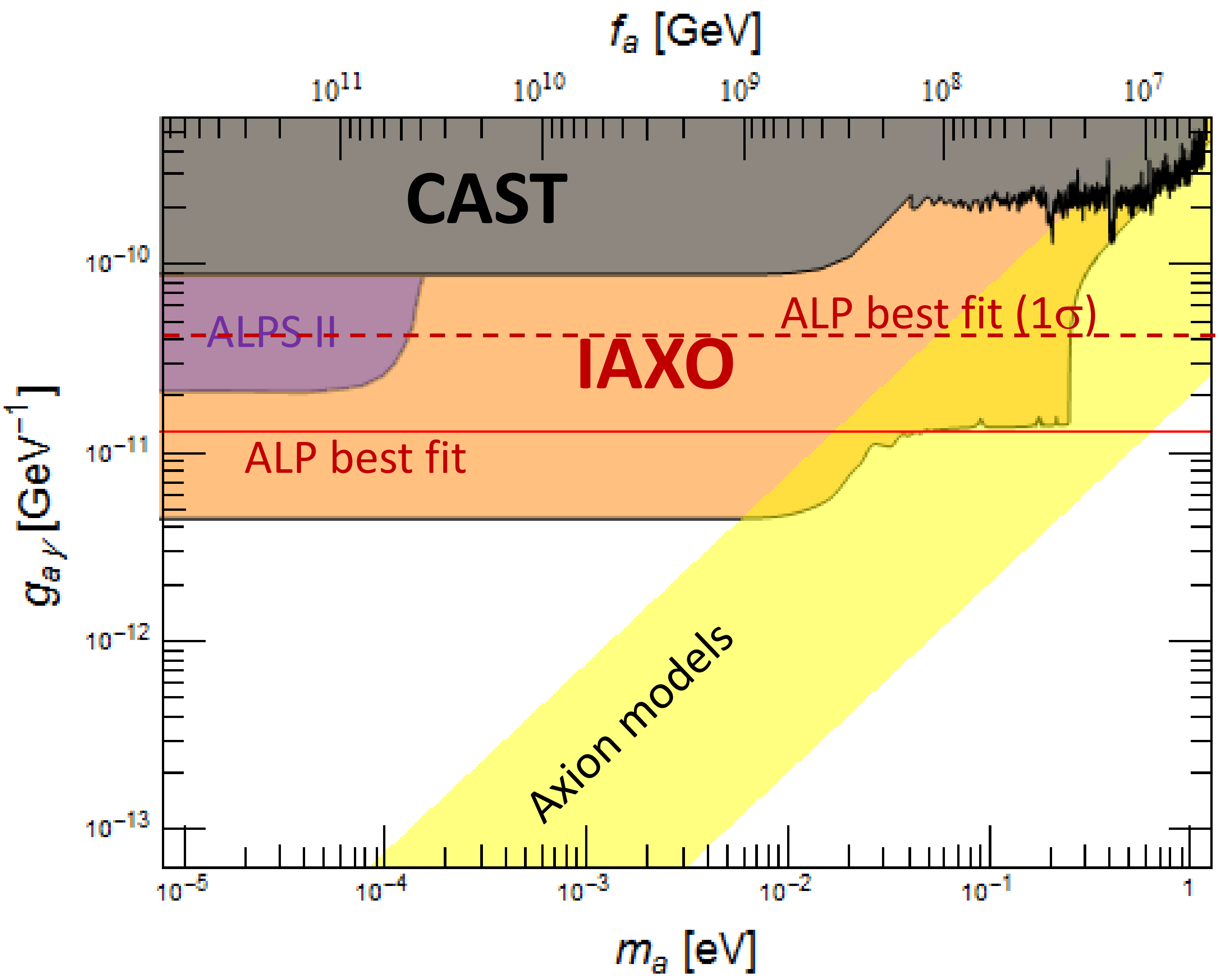


best fit: $g_{ae}=1.5\times10^{-13}$, $g_{a\gamma}=0.13\times10^{-10}\,\mathrm{GeV}^{-1}$

ALP parameters region



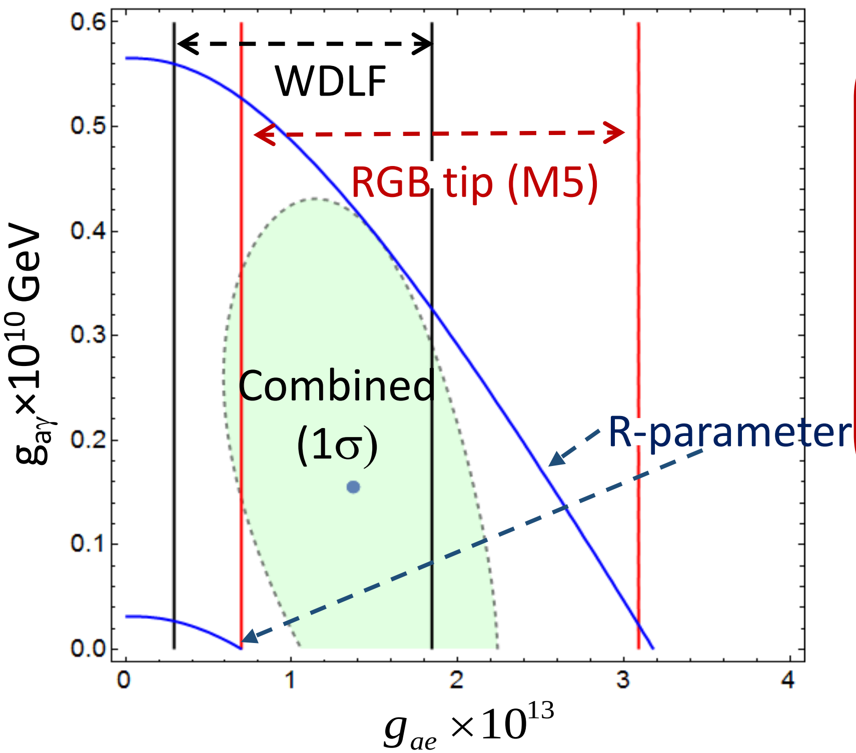
ALP parameters region



Axion parameters region

Preliminary

M.G., Irastorza, Redondo, Ringwald, In preparation



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

best fit corresponds to:

$$\frac{C_{ae}}{C_{a\gamma}} = 2.6 \times 10^{-2}$$

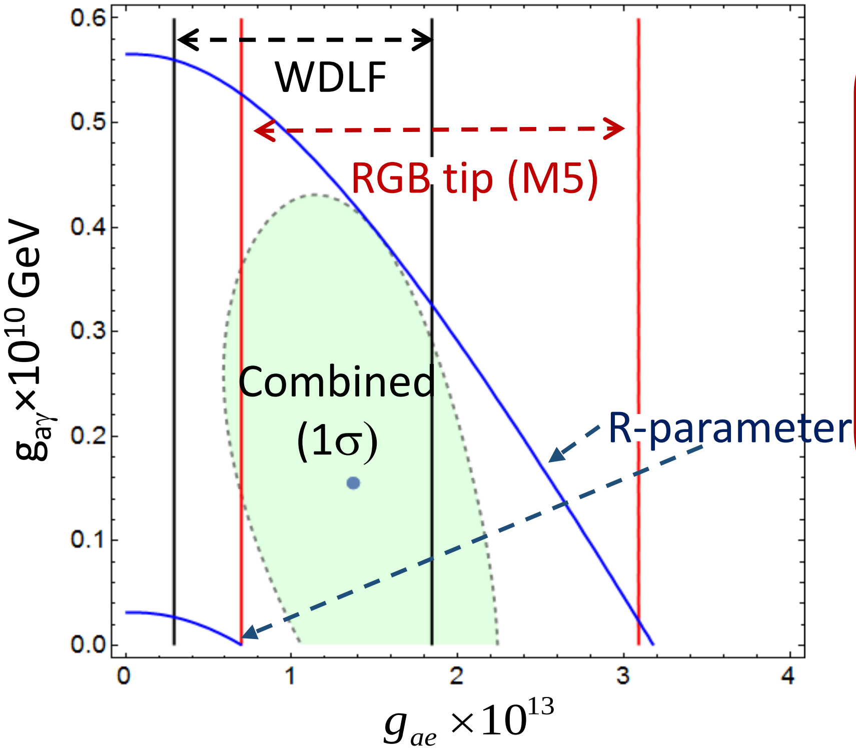
DSVZ 1:

$$\left\{ \begin{aligned} C_{a\gamma} &= \frac{8}{3} - 1.92 \\ C_{ae} &= \frac{1}{3}\cos^2\beta \end{aligned} \right. \quad \Rightarrow \quad \left\{ \begin{aligned} \cos^2\beta &= 0.06 \\ f_a &= 6.7 \times 10^7 \text{ GeV} \end{aligned} \right.$$

Axion parameters region

M.G., Irastorza, Redondo, Ringwald, In preparation

Preliminary



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

best fit corresponds to:

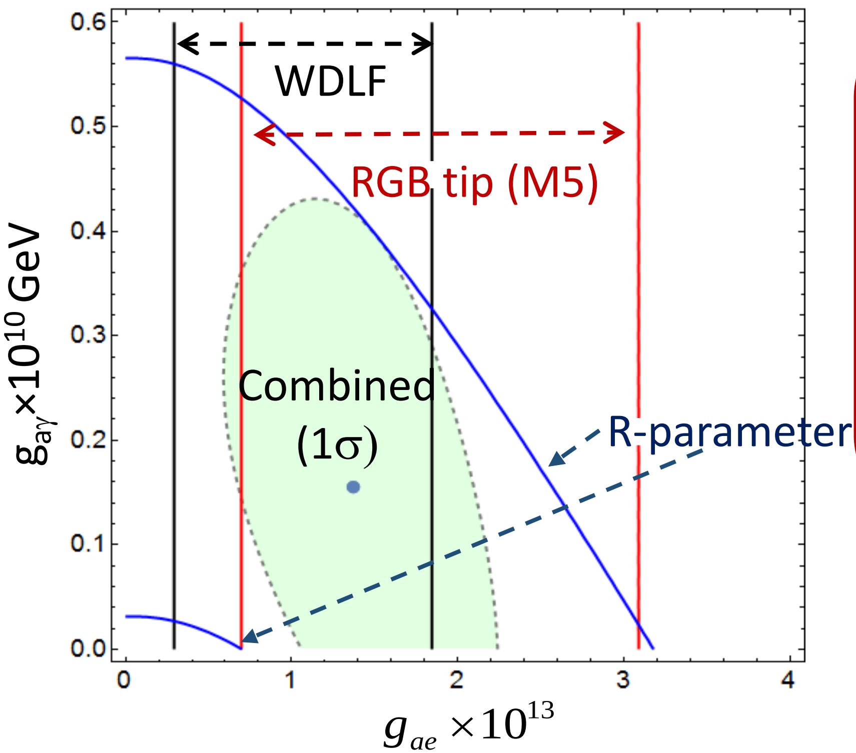
$$\frac{C_{ae}}{C_{a\gamma}} = 2.6\times10^{-2}$$

DSVZ 2: $\begin{cases} C_{a\gamma} = \frac{2}{3} - 1.92 \\ C_{ae} = \frac{1}{3}\sin^2\beta \end{cases}$ ⇒ $\begin{cases} \cos^2\beta = 0.9 \\ f_a = 1.1\times10^{8}\ \text{GeV} \end{cases}$

Axion parameters region

Preliminary

M.G., Irastorza, Redondo, Ringwald, In preparation

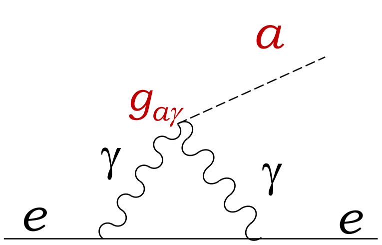


$$g_{ae} = m_e \frac{C_{ae}}{f_a} \qquad g_{a\gamma} = \frac{\alpha}{2\pi} \frac{C_{a\gamma}}{f_a}$$

best fit corresponds to:

$$\frac{C_{ae}}{C_{a\gamma}} = 2.6 \times 10^{-2}$$

KSVZ: coupling to electrons naturally small

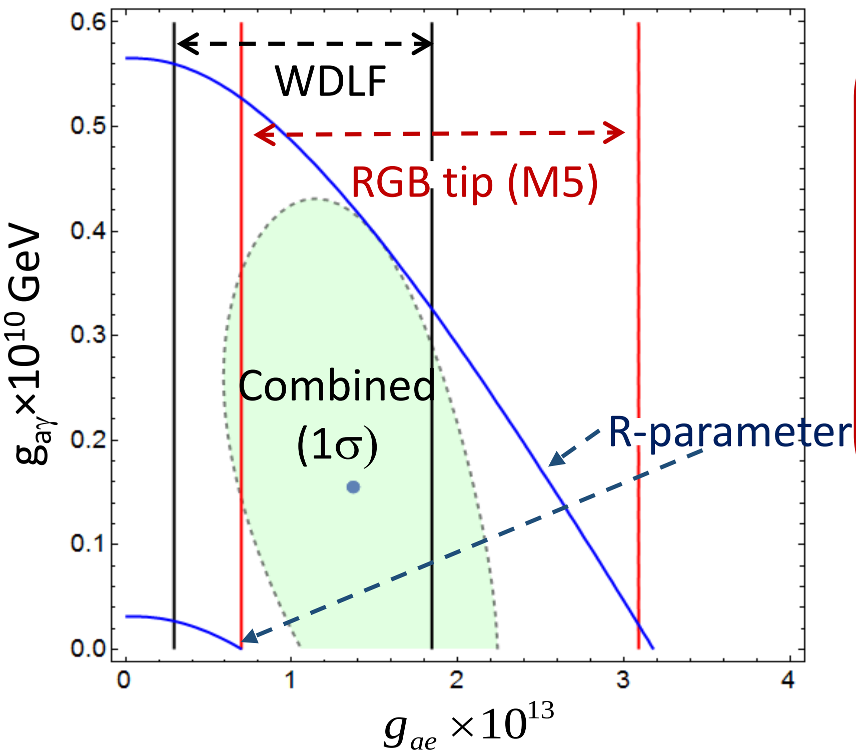


$$\left\{ \begin{aligned} \frac{E}{N} &= 1.9 \\ f_a &= 1.4 \times 10^6 \text{ GeV} \end{aligned} \right.$$

Axion parameters region

M.G., Irastorza, Redondo, Ringwald, In preparation

Preliminary

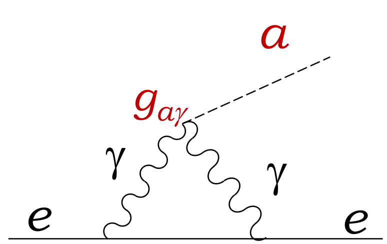


$$g_{ae} = m_e \frac{C_{ae}}{f_a} \qquad g_{a\gamma} = \frac{\alpha}{2\pi} \frac{C_{a\gamma}}{f_a}$$

best fit corresponds to:

$$\frac{C_{ae}}{C_{a\gamma}} = 2.6 \times 10^{-2}$$

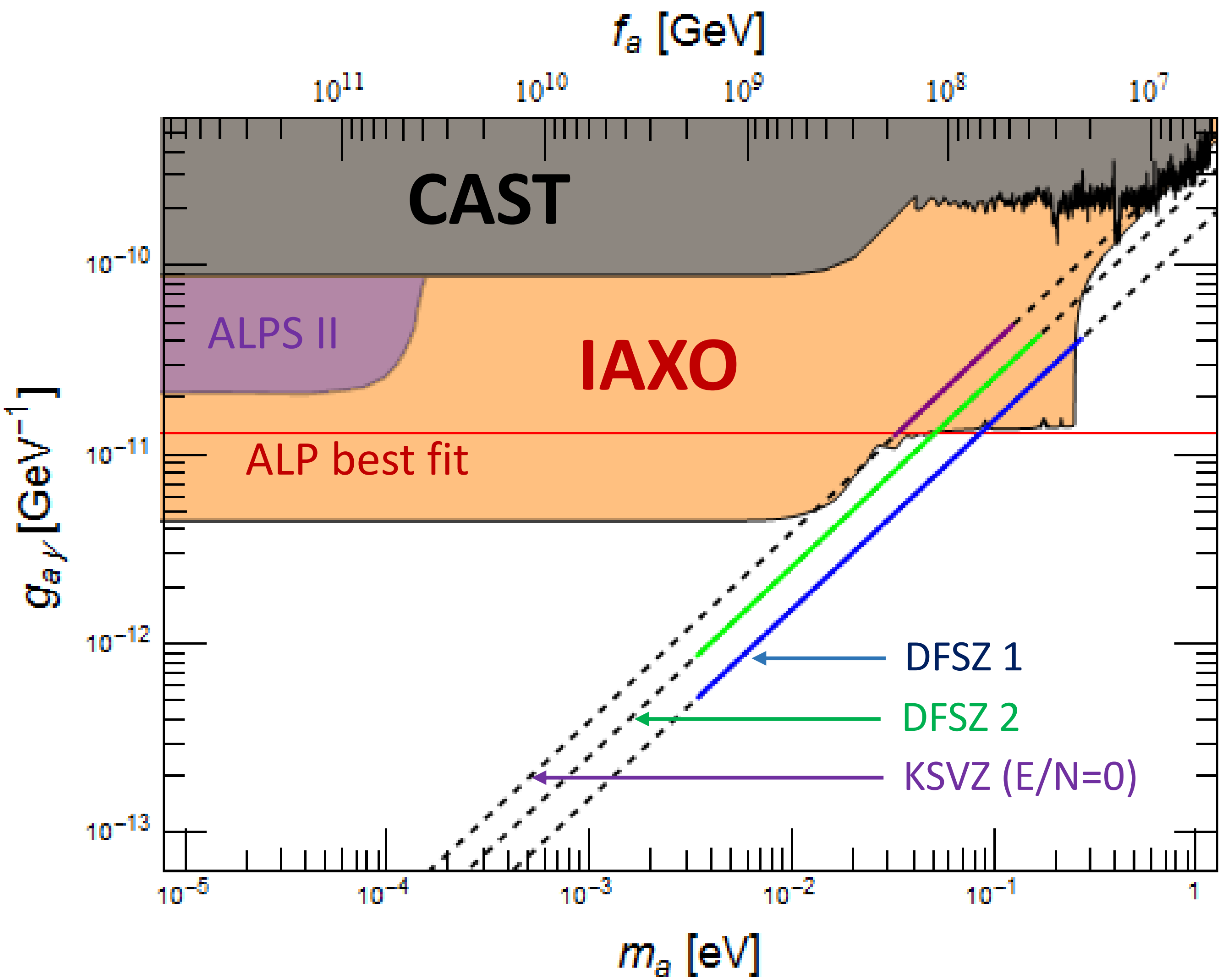
KSVZ: coupling to electrons naturally small



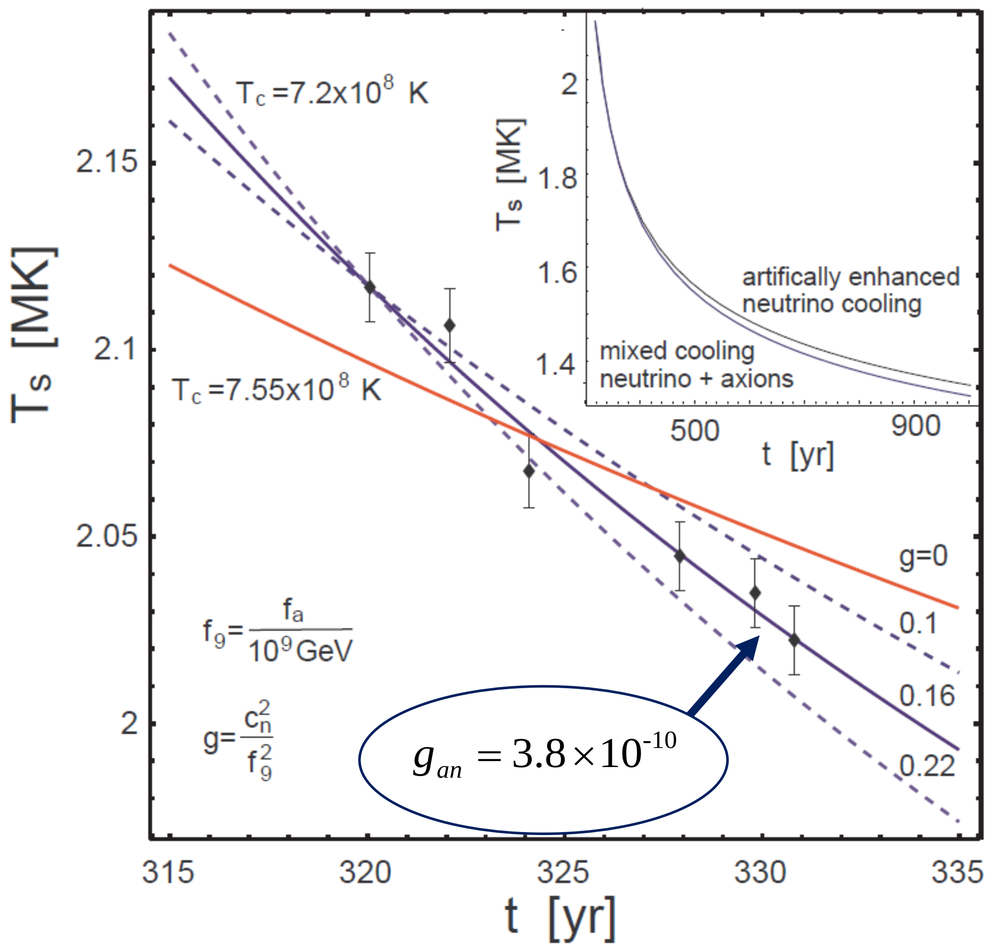
forcing $\frac{E}{N} = 0$

$f_a = (1.4 - 4.64) \times 10^{8}$ GeV

Axion parameters region



Axion-Nucleons Couplings

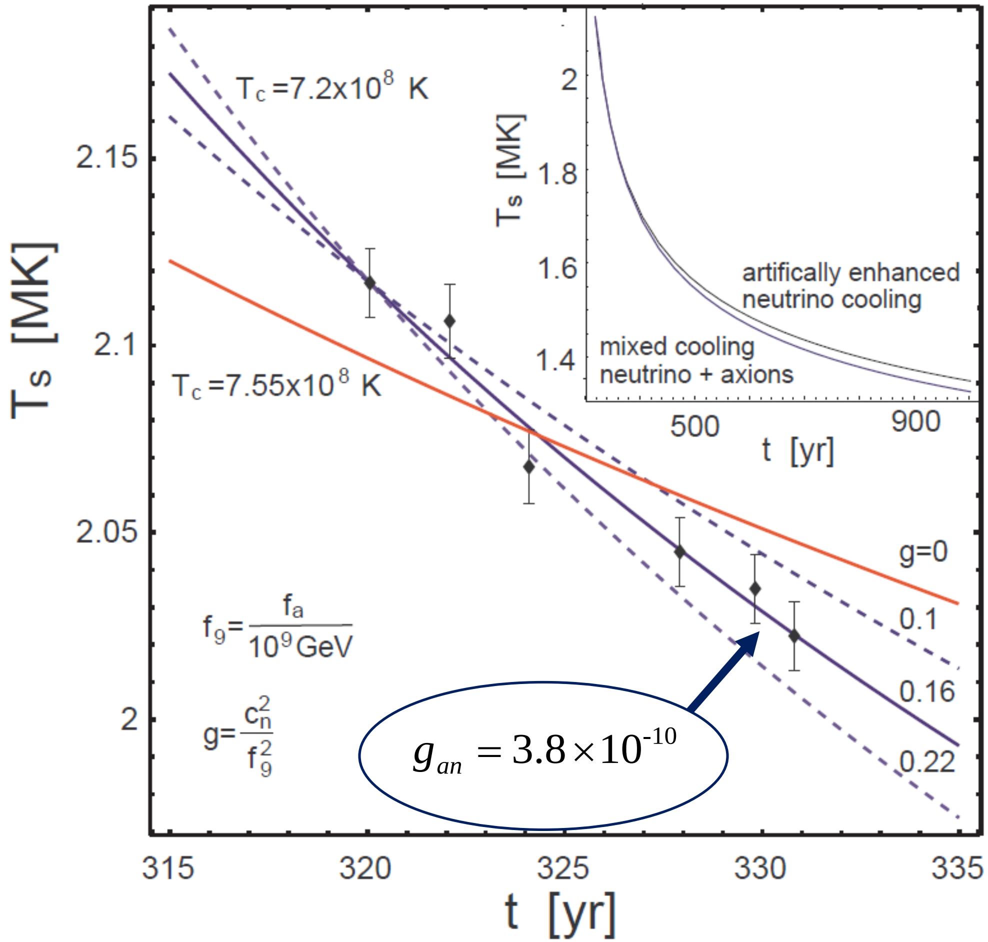


Leinson, JCAP 1408 (2014)

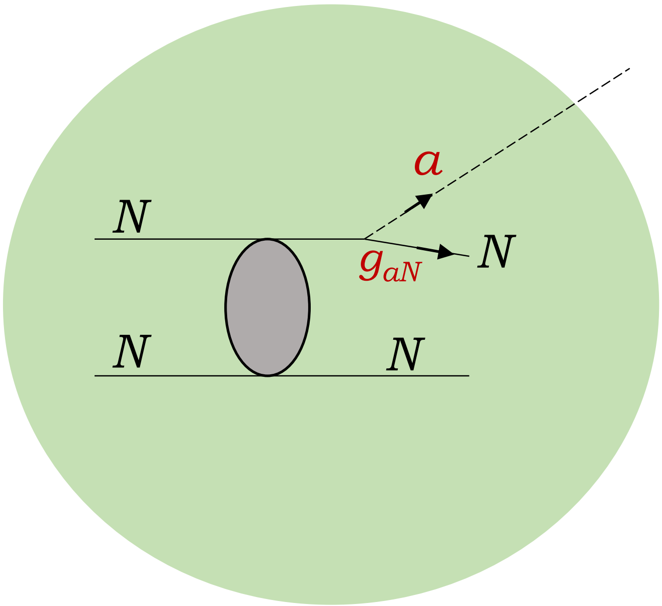
Measured surface temperature over 10 years of the NS in Cas A reveals unusually fast cooling rate.

The thermal energy losses are approximately twice more intensive than it can be explained by the neutrino emission.
[Shternin et. al., Mon. Not. R. Astron. Soc. 412 (2011)]

Axion-Nucleons Couplings



Leinson, JCAP 1408 (2014)



could be explained by introducing an ALP coupled to nucleons [Leinson, JCAP 1408 (2014)]

The effect could have a different origin, for example as a phase transition of the neutron condensate into a multicomponent state [Leinson, Phys. Lett. B 741, (2015)]

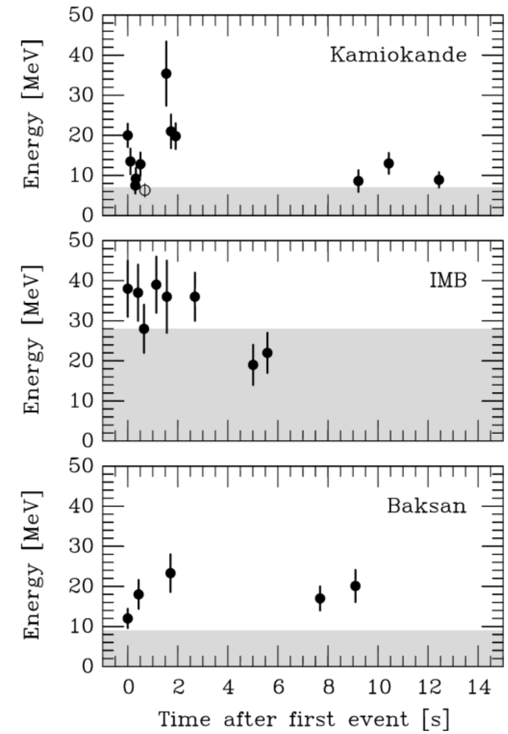
Supernova 1987A

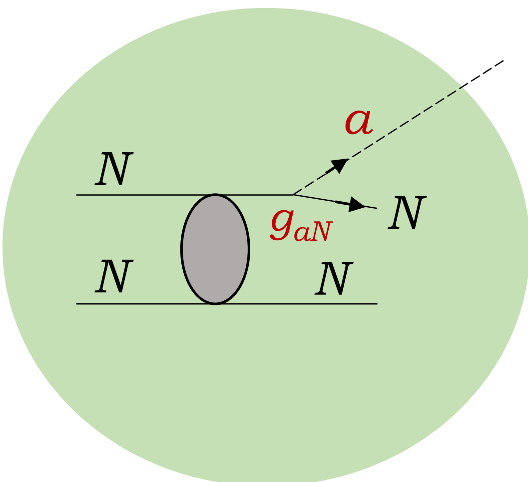
Enormous amount of neutrinos expected from core collapse SN.

If weakly coupled, axions escape from the core without interactions.

Neutrino events observed from SN1987 A restrict how much energy can be lost in ALPs.

See Alessandro Mirizzi's talk





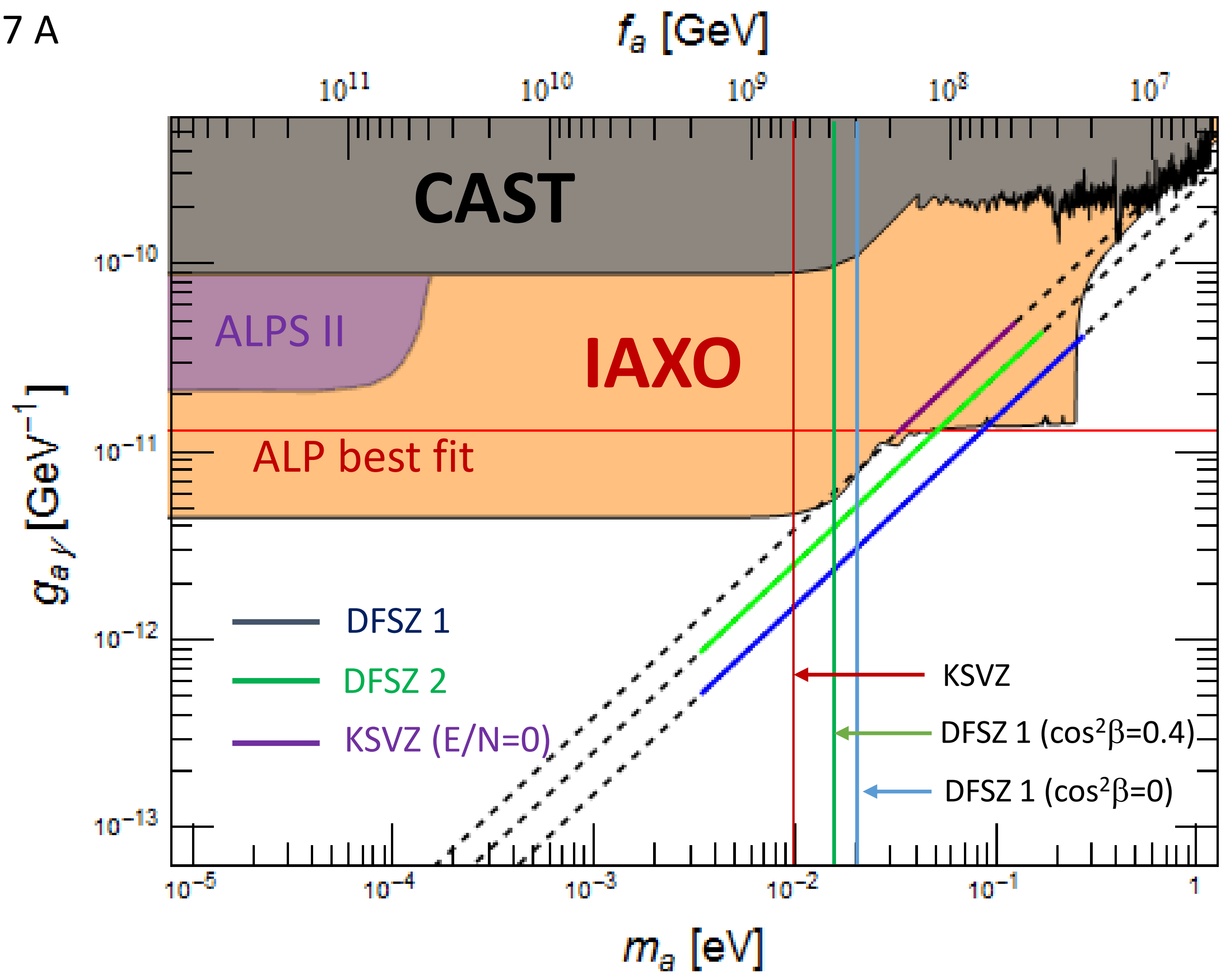
PDG bound: $g_{ap} < 9 \times 10^{-10}$

This is compatible with the NS hint.

However, not a very solid bound: very few data and the interaction is difficult to model.

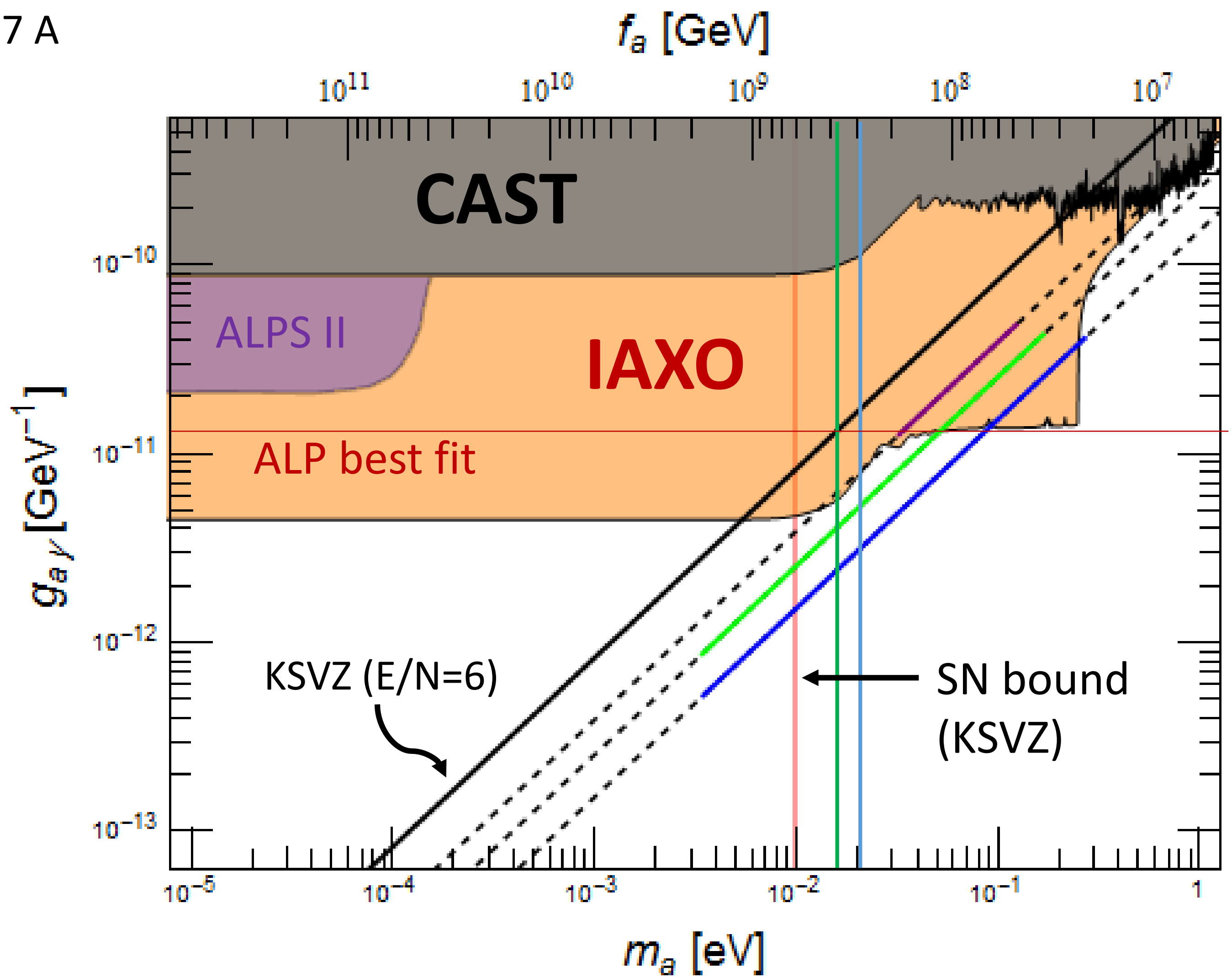
Supernova 1987A

Estimates on the axion bounds from SN 1987 A



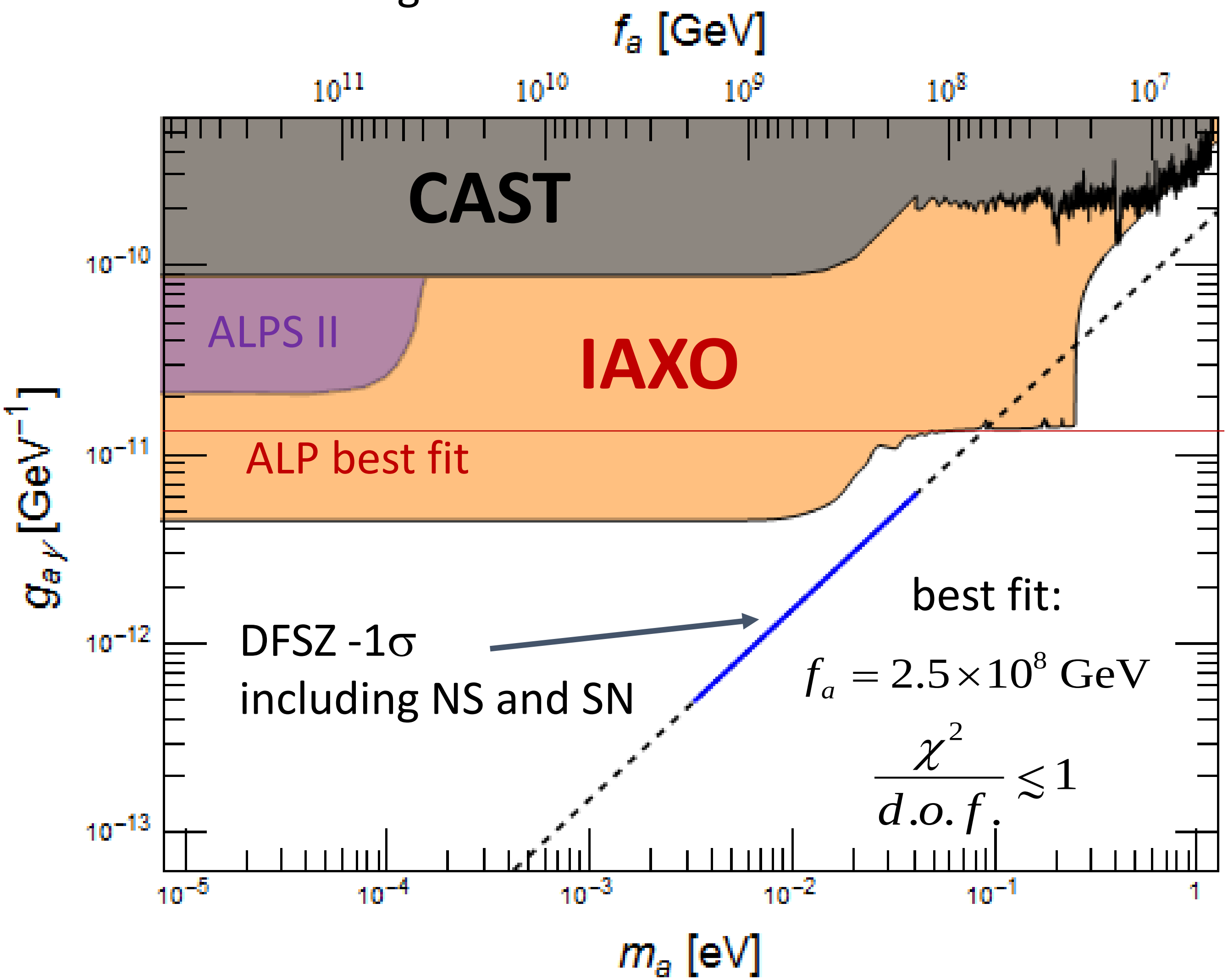
Supernova 1987A

Estimates on the axion bounds from SN 1987 A



SN 1987A and NS in Cas A

The fit for the DFSZ axion is good.



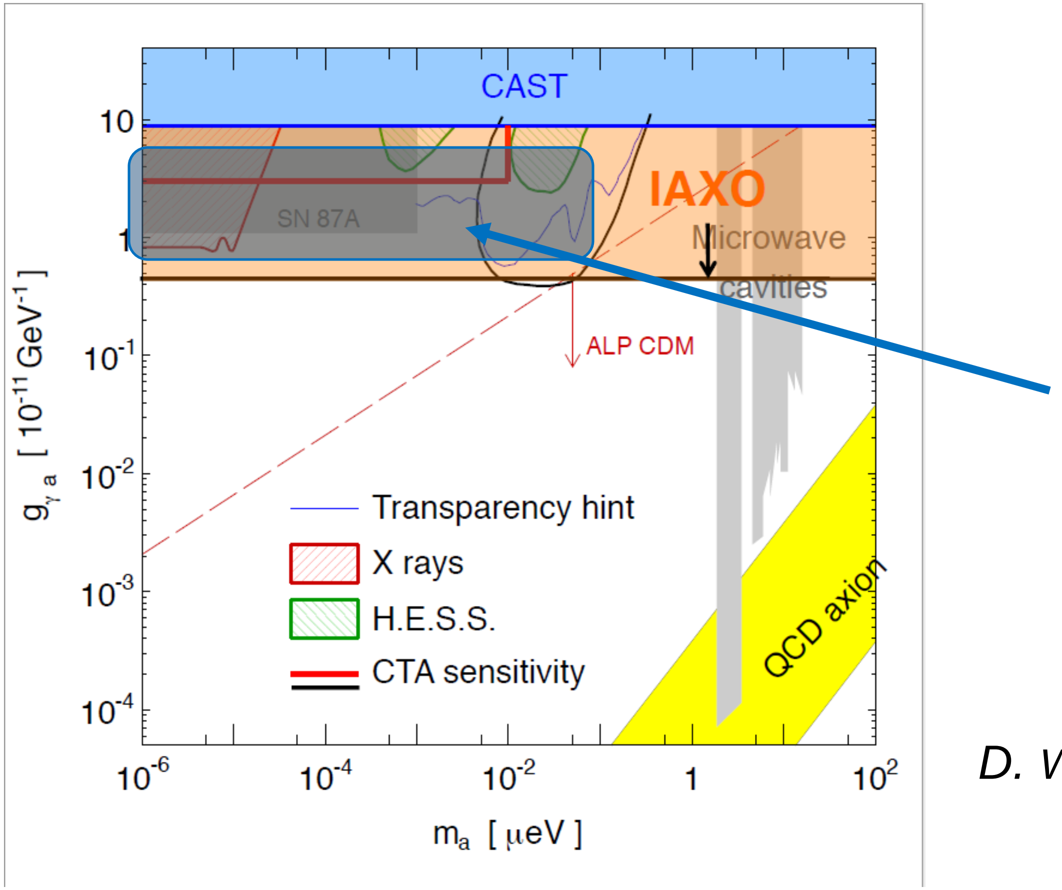
IAXO and

Astrophysical hints (including the transparency hints) can be explained by an ALP with

A. Ringwald, Karlsruhe colloquium, 2014

A. Ringwald, XVI International Workshop on Neutrino Telescopes, 2015

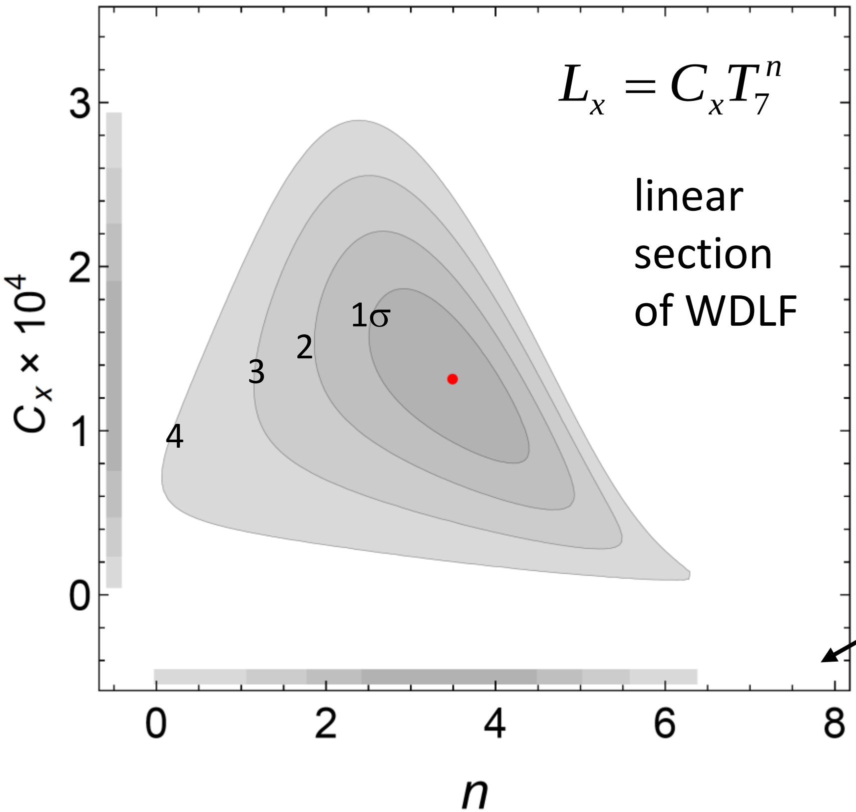
$$f_a \approx 10^8 \mathrm{GeV}, C_{a\gamma} \approx 1, C_{ae} \approx C_{an} \approx 10^{-2} \text{ and } m_a \leq 0.1 \mu\mathrm{eV}$$



This region is completely accessible to IAXO

D. Wouters & P.B., JCAP 2014

Cooling anomalies and new physics

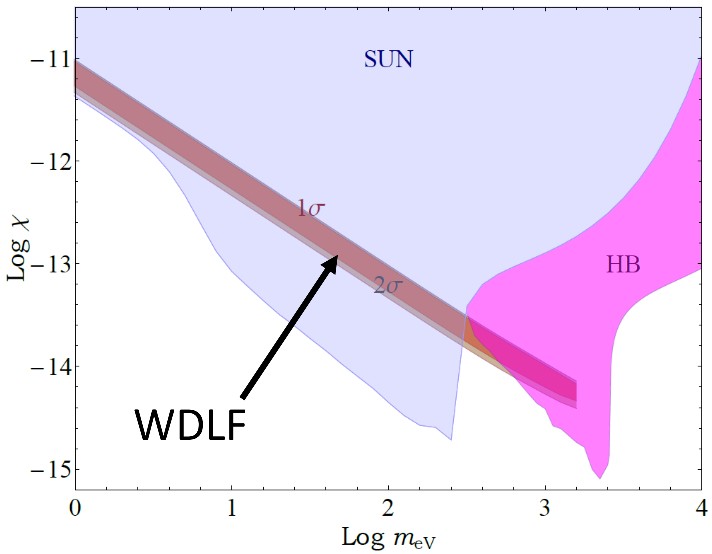


[M.G., Irastorza, Redondo, Ringwald (2015)]

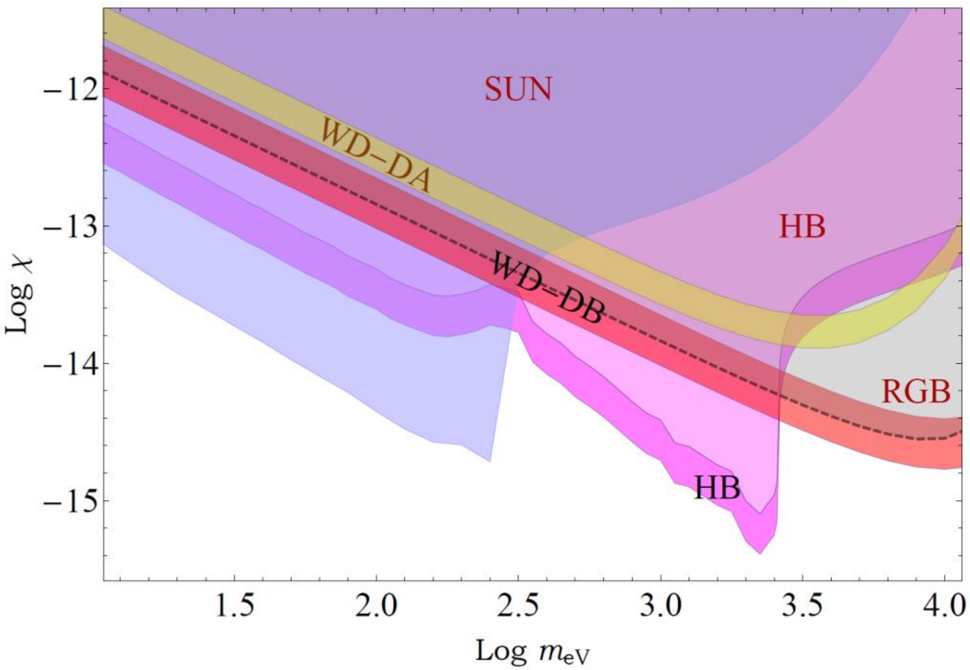
Analysis of the linear portion of the WDLF reveals preference for ALPs and HP while strongly rejects anomalous neutrino electromagnetic factors.

Neutrino anomalous magnetic moment

Cooling anomalies and new physics



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



Massive HP can explain the WDLF and other hints but not all of them simultaneously.

Leaves only ALPs and massless HP. ALPs are slightly preferred since can cool HB stars

Conclusions

- ✓ Stars are excellent tools to study the properties of light, weakly interacting particles, particularly axions.
- ✓ Several anomalies seem to indicate the need for additional cooling and require further investigation.
- ✓ ALPs (together with massless HPs) are the best candidate among WISPs. Astrophysical hints (including the transparency hints) can be explained by an ALP with

$$f_a \approx 10^8\,\mathrm{GeV}, C_{a\gamma} \approx 1, C_{ae} \approx C_{an} \approx 10^{-2} \text{ and } m_a \leq 0.1\,\mu\mathrm{eV}$$

- ✓ The ALP hinted region is accessible to IAXO and partially to APS II.
- ✓ The KSVZ and DFSZ may be harder to probe.

What to do next

The hints are not very strong and the uncertainties are still not well known.

1. Investigate stellar cooling, systematics and uncertainties, and see if the cooling anomalies are actually a hint to new physics

2. Build IAXO.

Additional material

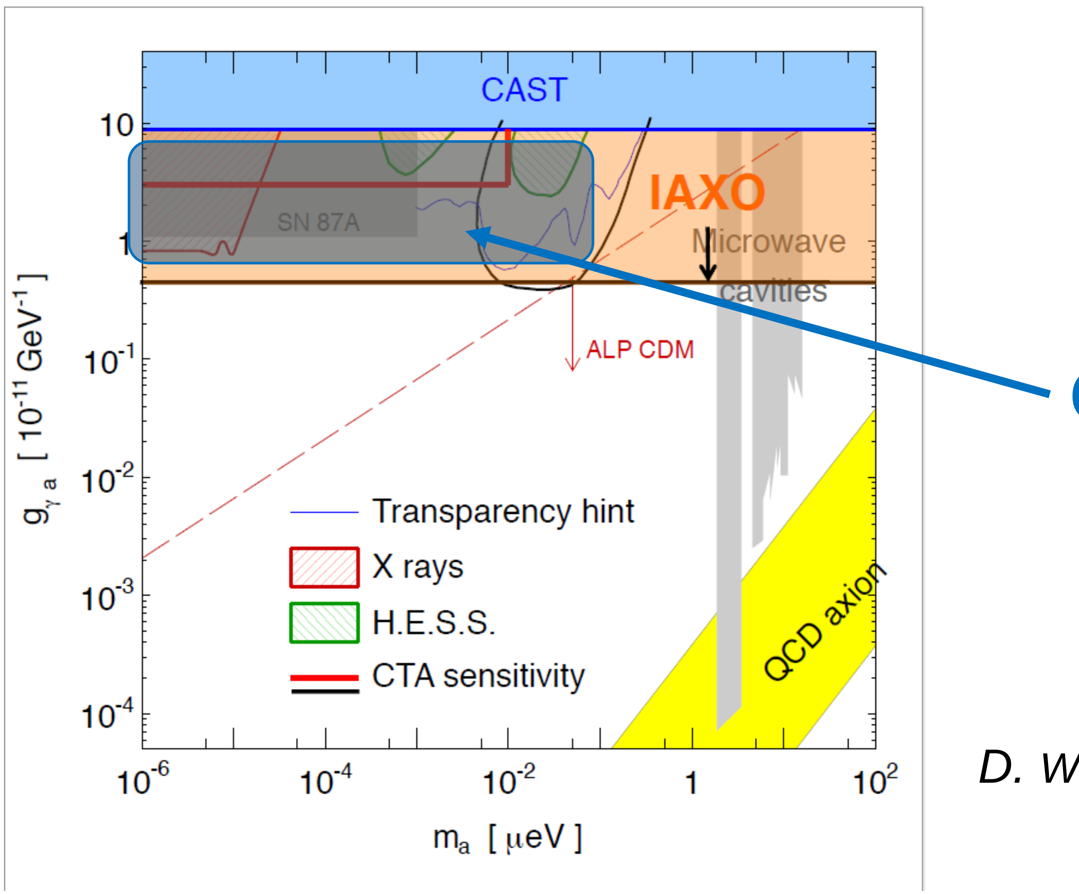
Discussion

Astrophysical hints (including the transparency hints) can be explained by an ALP with

$f_a \approx 10^8\,\mathrm{GeV}, C_{a\gamma} \approx 1, C_{ae} \approx C_{an} \approx 10^{-2}$ and $m_a \le 0.1\,\mu\mathrm{eV}$

A. Ringwald, Karlsruhe colloquium, 2014

A. Ringwald, XVI International Workshop on Neutrino Telescopes, 2015



This region is completely accessible to IAXO

D. Wouters & P.B., JCAP 2014

Stars as Laboratories

Observable	Comments	USE
Sun	Best known star.	• Low mass HP • Minicharges
RGB-tip	Sensitive to processes efficient at high densities.	• Neutrino magnetic moment (μ_ν) • Axion-electron coupling (g_{ae}) • Massive HP
WD pulsation		
WDLF		
AGB (?)	"very bright and so their photometric and spectroscopic properties are well known" [I. Dominguez, O. Straniero, J. Isern (1999)]. So far not used often for particle physics	
R-parameter	$R=N_{HB}/N_{RGB}$ can probe processes efficient at low density and high temperature.	• g_{ae}, μ_ν • Fermion minicharges • Axion-photon coupling ($g_{a\gamma}$)
Blue loop	Not very numerous. Have a blue loop which is observable. The microphysics is difficult to model	
SN progenitor	Can be probed from SN light curves, SN remnant, nucleosynthesis… [Heger et. al. 2008; Aoyama & Suzuki, 2015)]	• μ_ν , g_{ae} , $g_{a\gamma}$
SN	Unique environment but rare. Probes interactions with nuclei (See A. Mirizzi Talk later today)	• Couplings to nuclei • Extra dim.
NS cooling	Colder than SN but hotter and denser than standard stars	

KSVZ and DSFZ axions

Most known example of QCD axion : DSVZ and KSVZ (hadronic) axions

- J.E. Kim (1979);
- M. Shifman, A. Vainshtein, V. Zakharov (1980);
- A.R. Zhitnitskii (1980);
- M. Dine, W. Fischler, M. Srednicki

The QCD axion, precisely

Giovanni Grilli di Cortona[a], Edward Hardy[b],
Javier Pardo Vega[a,b] and Giovanni Villadoro[b]

[a] *SISSA International School for Advanced Studies and INFN Trieste, Via Bonomea 265, 34136, Trieste, Italy*

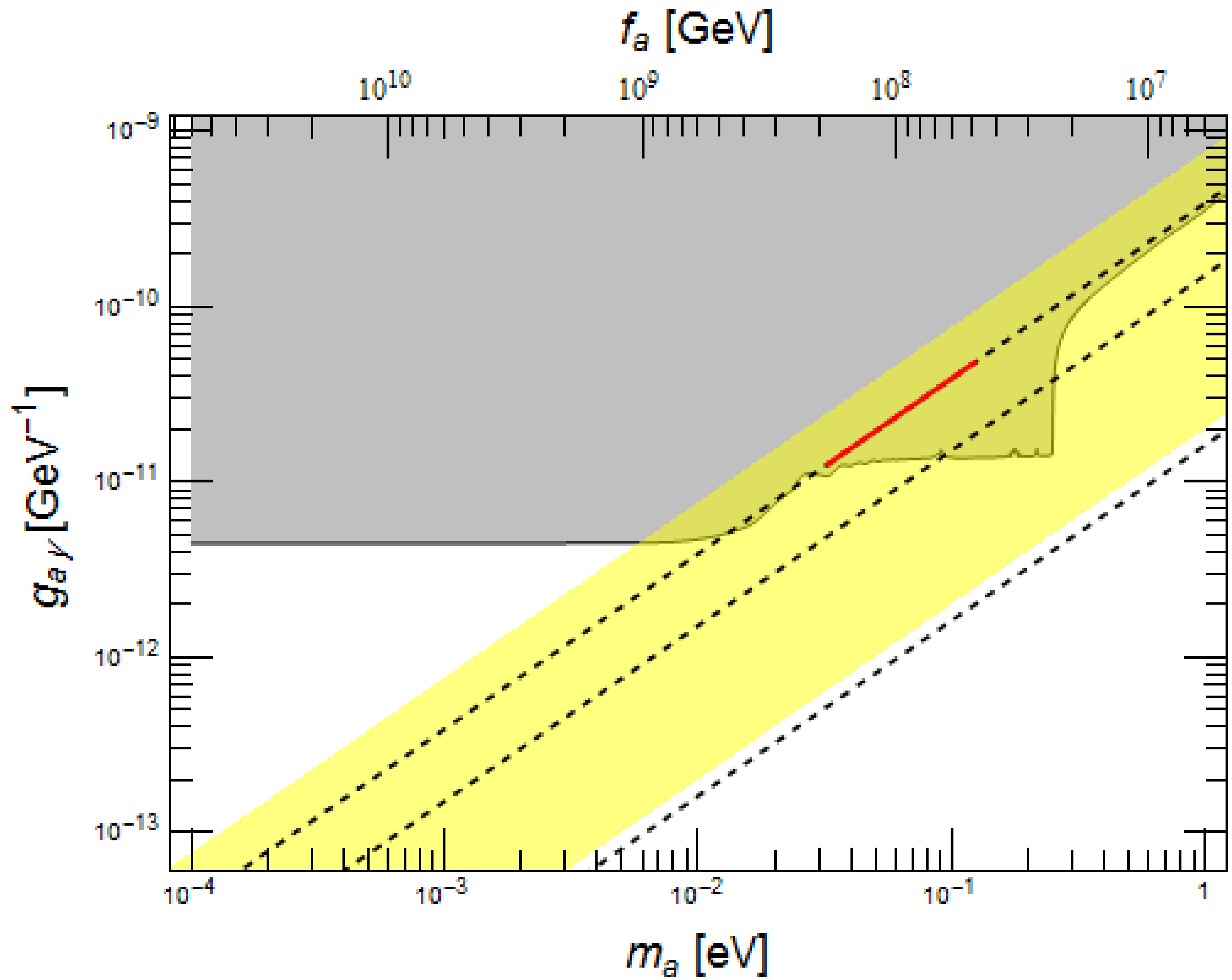
[b] *Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, 34151, Trieste, Italy*

Abstract

We show how several properties of the QCD axion can be extracted at high precision using only first principle QCD computations. By combining NLO results obtained in chiral perturbation theory with recent Lattice QCD results the full axion potential, its mass and the coupling to photons can be reconstructed with percent precision. Axion couplings to nucleons can also be derived reliably, with uncertainties smaller than ten percent. The approach presented here allows the precision to be further improved as uncertainties on the light quark masses and the effective theory couplings are reduced. We also compute the finite temperature dependence of the axion potential and its mass up to the crossover region. For higher temperature we point out the unreliability of the conventional instanton approach and study its impact on the computation of the axion relic abundance.

Mass and coupling have a peculiar dependence on the PQ constant. New results from recent NLO chiral perturbation theory and lattice

G. G. di Cortona, E.Hardy, J.P.Vega, G.Villadoro, JHEP 1601 (2016) 034



f_a [GeV]
10^{10}
10^{9}
10^{8}
10^{7}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$g_{a\gamma}$ [GeV^{-1}]
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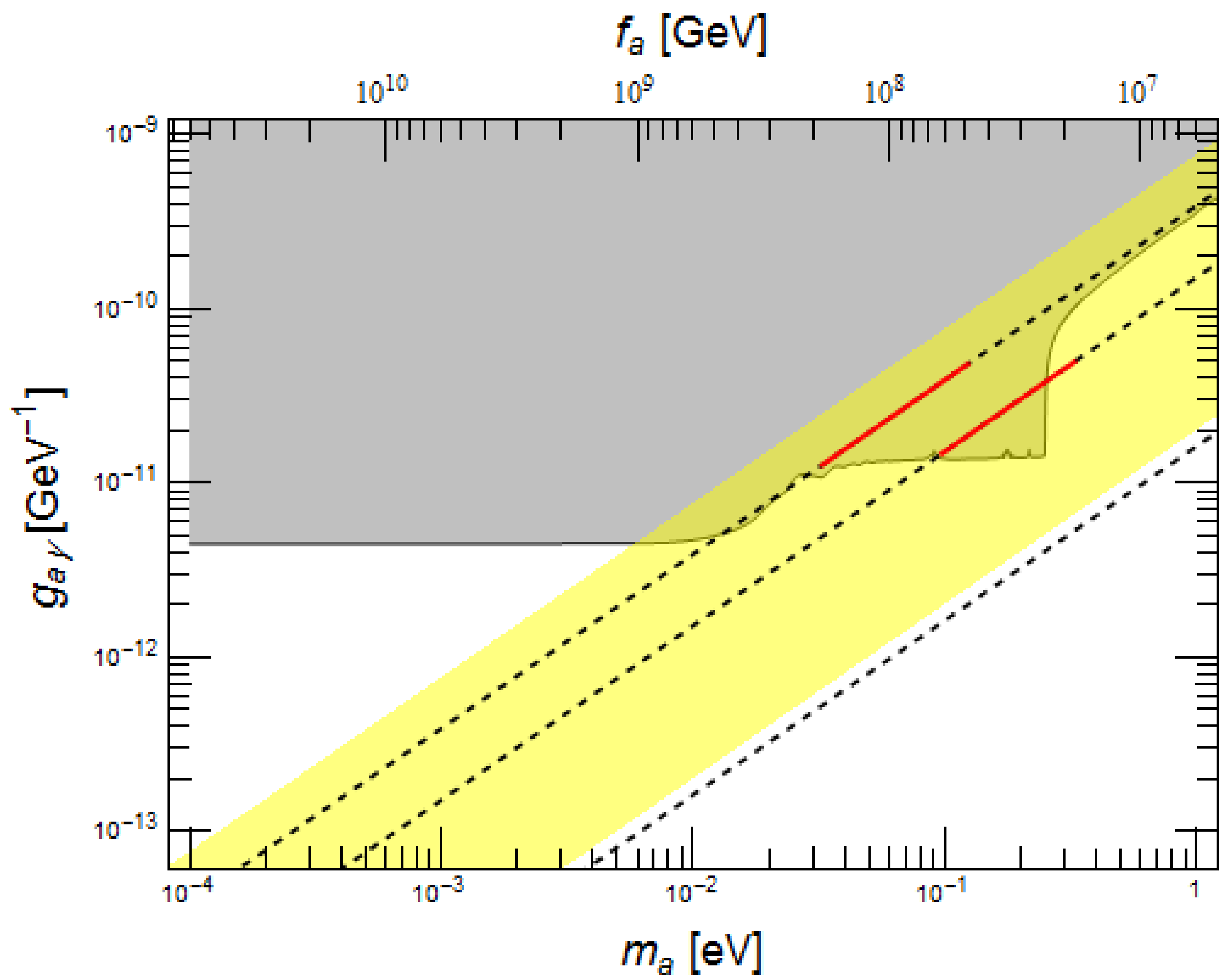
10^{-3}
10^{-2}
10^{-1}
1
m_a [eV]



f_a [GeV]
10^{10}
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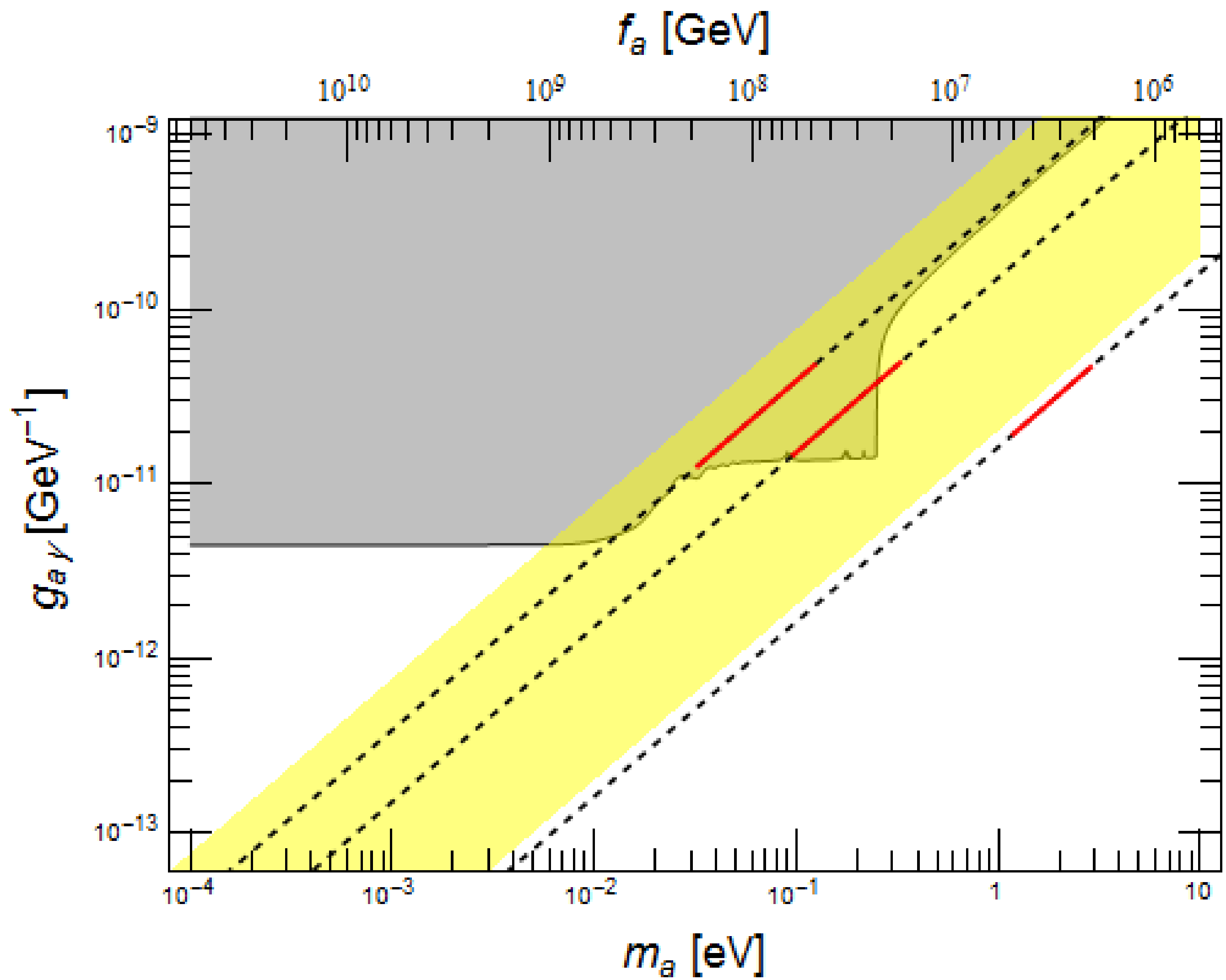
$g_{a\gamma}$ [GeV^{-1}]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
m_a [eV]



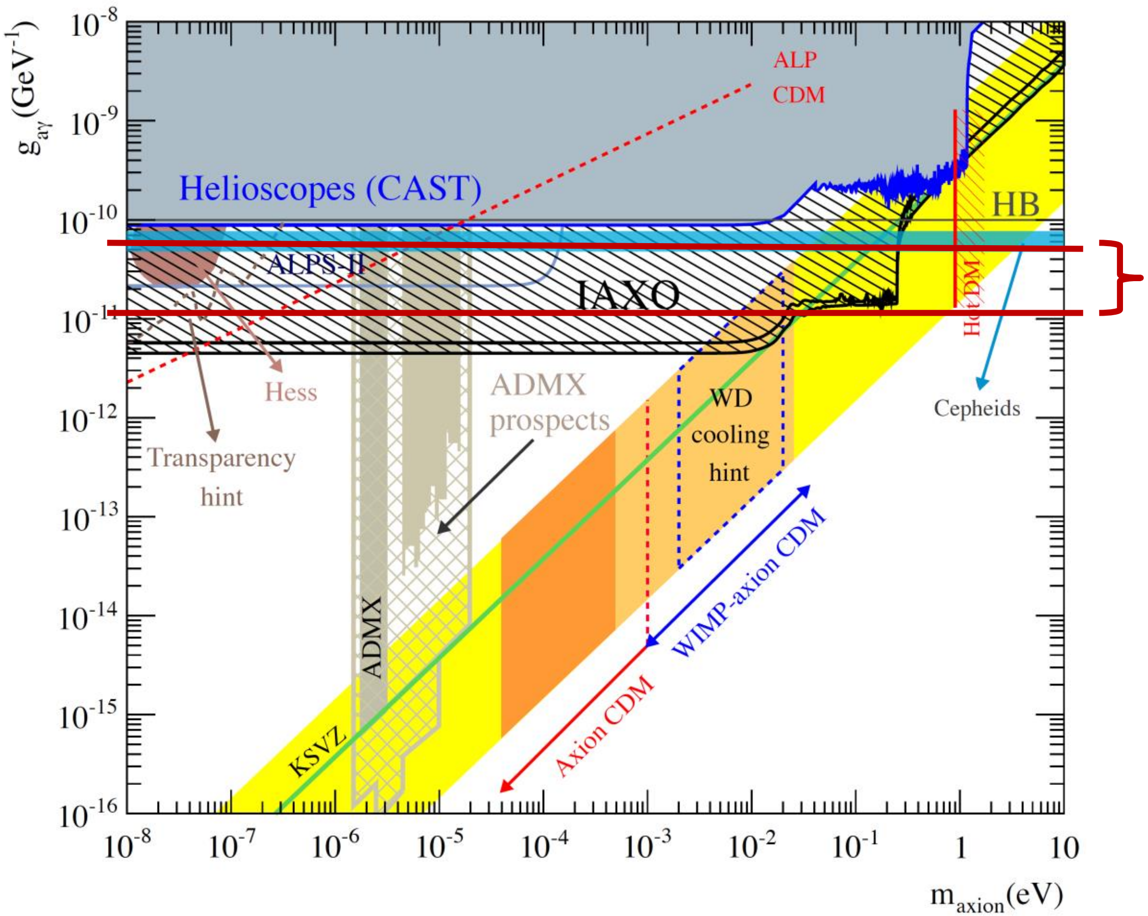
f_a [GeV]
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$g_{a\gamma}$ [GeV^{-1}]
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
m_a [eV]

Stars bounds on axions

Observable	Upper bound	observable
Axion-electron coupling g_{ae}	$2.6\ (4.3) \times 10^{-13}$ at 1 (2) σ	RGB tip in M5 [Viaux et. al. (2013)] Axion *e*-bremsstrahlung → additional cooling →brighter tip
Axion-photon coupling $g_{a\gamma}$	0.66×10^{-10} GeV^{-1} at 2 σ	R-parameter $=N_{HB}/N_{RGB}$ from analysis of 39 GC [Ayala et. al. (2014), Straniero, proceedings of the 2015 Patras Workshop] Axion Primakoff production accelerate HB evolution. Also, *e*-bremsstrahlung modifies RGB evolution [Giannotti et. al. (2016)]
Axion-nucleon coupling g_{aN}	$\sim 9 \times 10^{-10}$	See A Mirizzi's talk later

Discussion

Some particularly interesting areas can be identified in the ALP parameter space



Interesting area from analysis of HB and massive stars

ALPS II and especially IAXO have potential to explore large portions of these areas

Stars as Laboratories