# Stellar evolution and axions

Maurizio Giannotti,
Barry University

International workshop on Axion physics and dark matter cosmology

Osaka University, December 20, 2017

# Stars as ALPs Laboratories

What can we learn about axions/ALPs from stars?

Pioneered in M. Fukugita, S. Watamura, and M. Yoshimura, Phys. Rev. Lett. **48**, 1522 and M. Fukugita, S. Watamura, and M. Yoshimura, Phys. Rev. D **26**, 1840

PHYSICAL REVIEW D VOLUME 26, NUMBER 8 15 OCTOBER 1982

**Astrophysical constraints on a new light axion and other weakly interacting particles**

M. Fukugita, S. Watamura,* and M. Yoshimura
*National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki, 305 Japan*

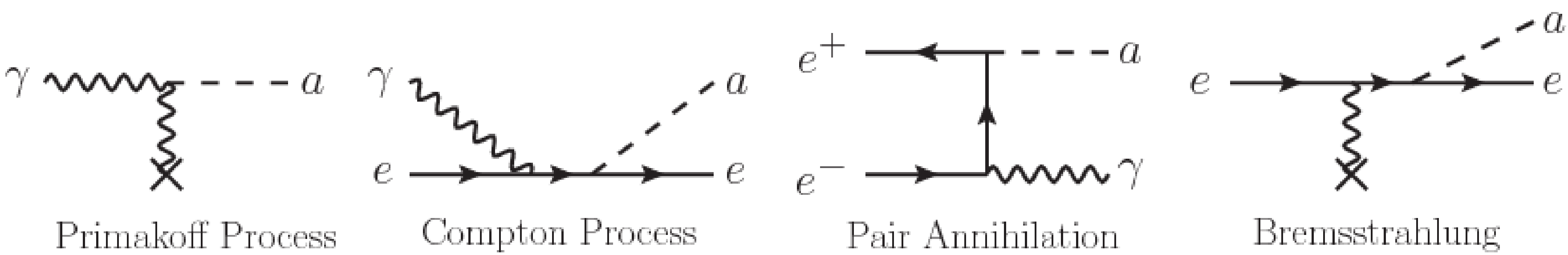
(Received 24 May 1982)

Constraints on the light axion of Dine, Fischler, and Srednicki are critically reexamined and upper bounds on its mass are derived from stars at various stages of evolution. A conservative upper bound for the axion mass is about 1 eV, while a model-dependent argument gives a better upper bound of mass $\sim$0.07 eV. The same argument also applies to coupling of any massless pseudoscalar particle to electrons giving an upper bound of $|g_e| < 1\times 10^{-11}$.

# Stars as ALPs Laboratories

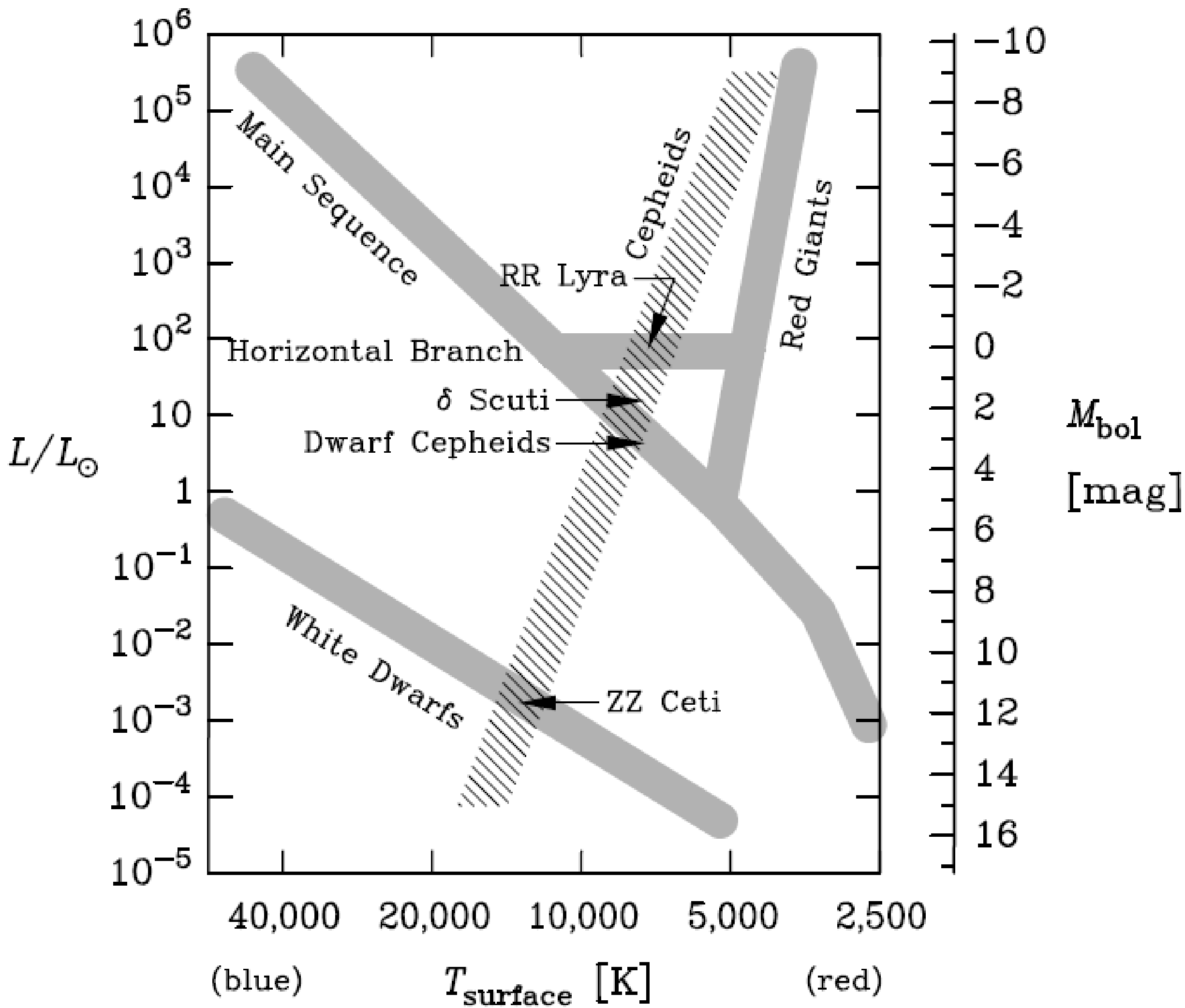
What can we learn about axions/ALPs from stars?

If light enough, axions-ALPs can be created in the stellar core




... and escape the star, contributing to the cooling!

# Stars as Laboratories

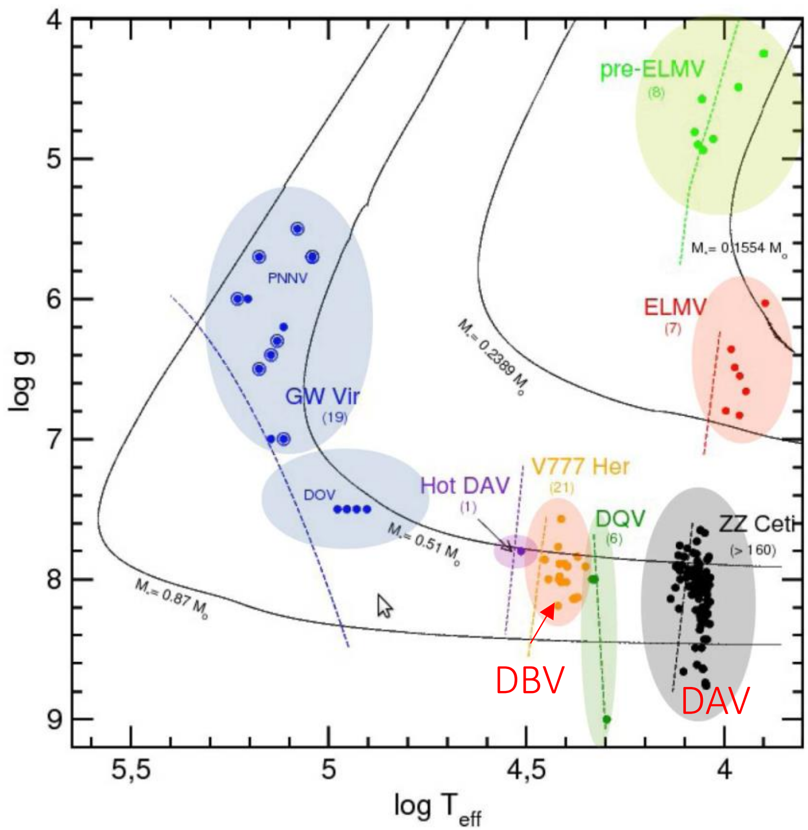



G. Raffelt, "Stars as laboratories for fundamental physics" (1996)

# White Dwarf Variables

Luminosity changes periodically with a slowly changing period.

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




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

Additional cooling source:

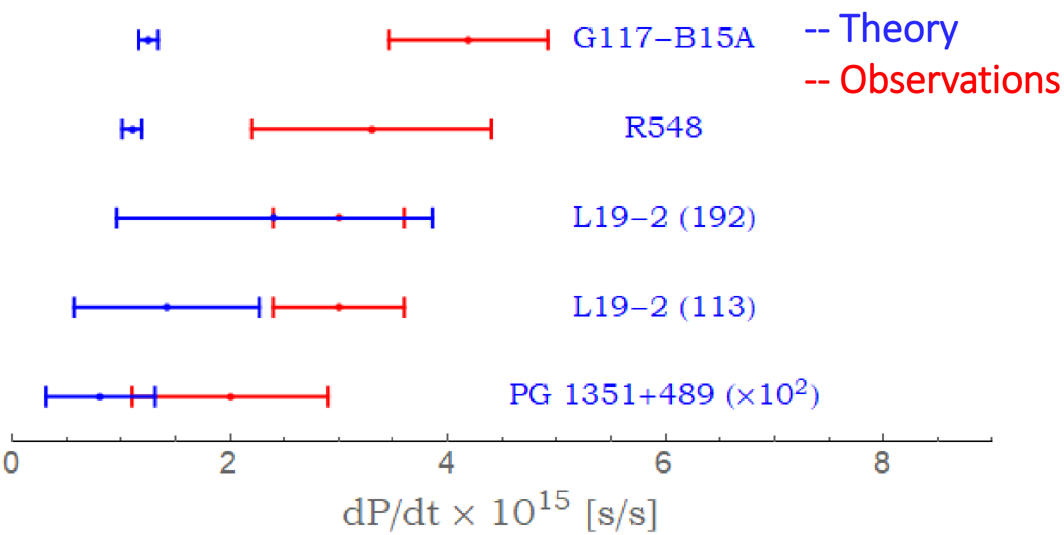
$\dot{T}/T \Uparrow \Rightarrow \dot{P}/P \Uparrow$

# White Dwarf Variables

Observations and models show some discrepancy

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

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



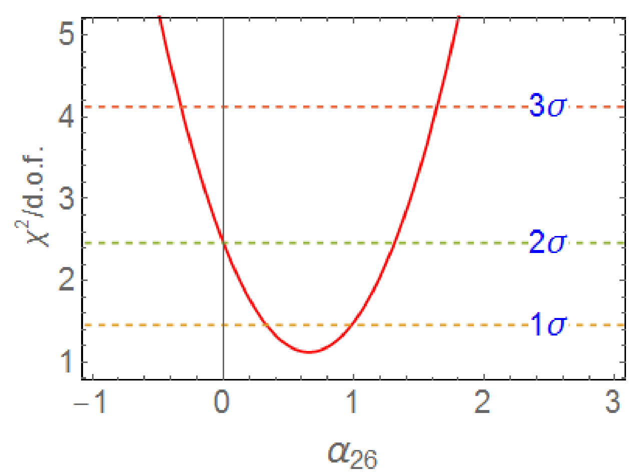

*The discrepancies run from 0.4 to 4 $\sigma$*

$2\sigma$ hint for $\alpha_{26} > 0$,

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

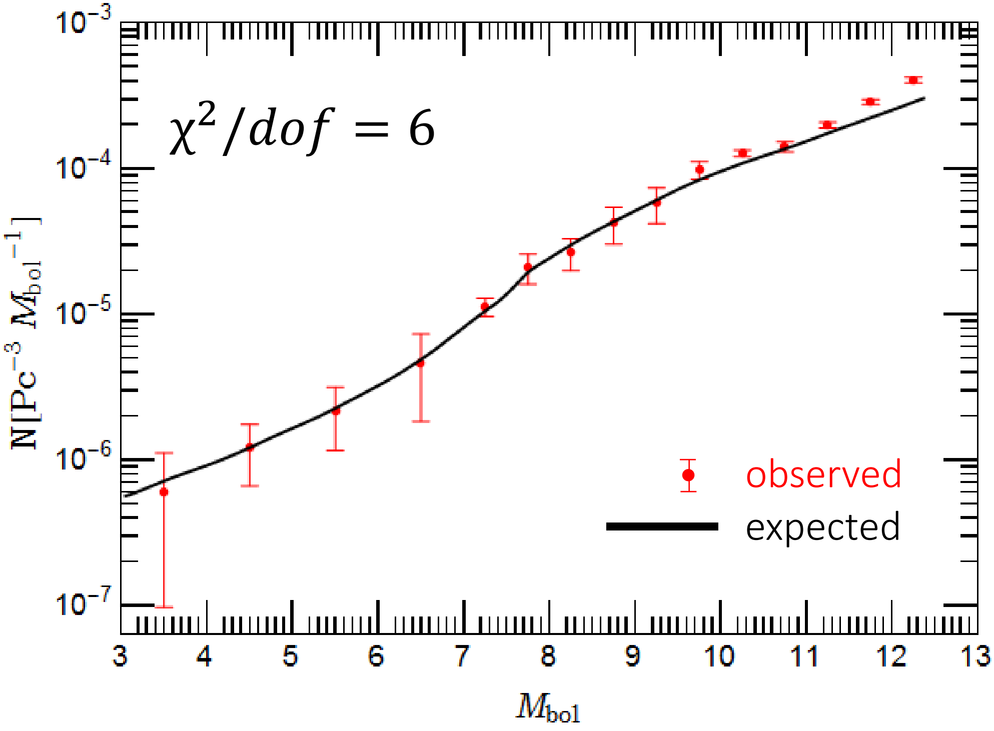
$\chi^2_{min}$/d.o.f. = 1.1

<u>bound</u> ($2\sigma$): $\alpha_{26} < 1.3$ ($g_{13} < 4.1$)



# White Dwarfs Luminosity Function

White Dwarfs Luminosity Function:




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

Sensitive to WD cooling efficiency

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

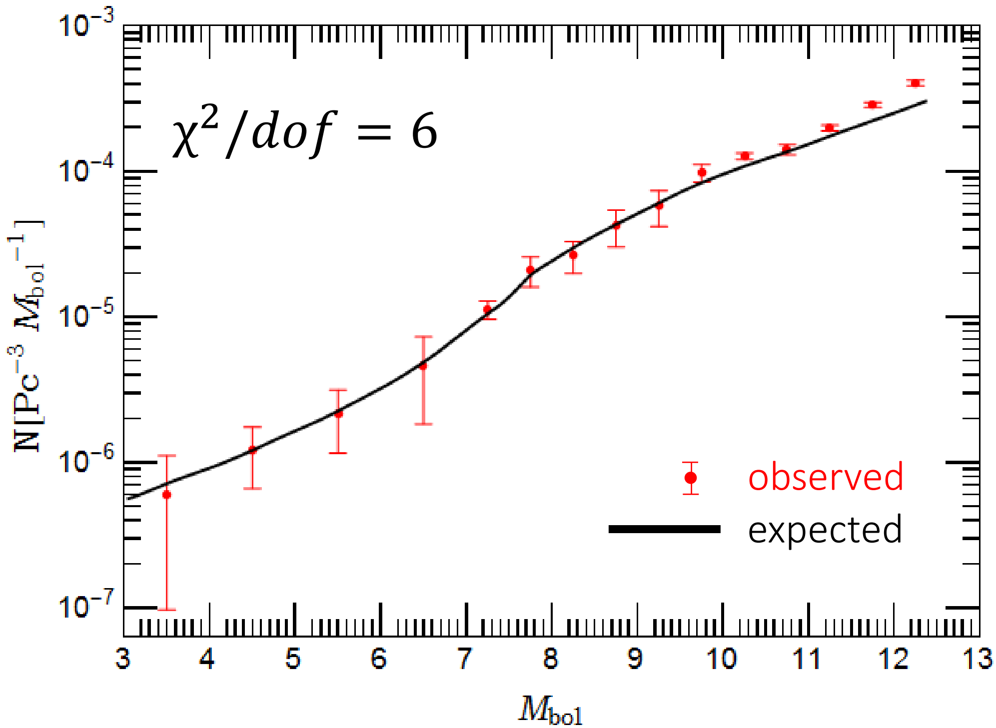
$L_x$= anomalous cooling, e.g. axions

The fit is not accurate, especially in the colder section.

Several systematics are not well understood and errors have been enlarged by hand

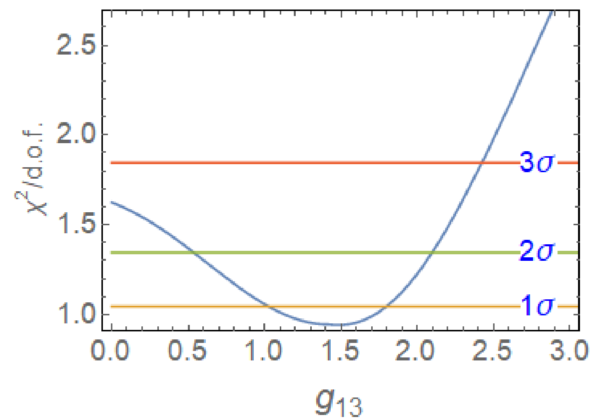
# White Dwarfs Luminosity Function

White Dwarfs Luminosity Function:




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

ALPs analysis
(1-parameter, 11 points)



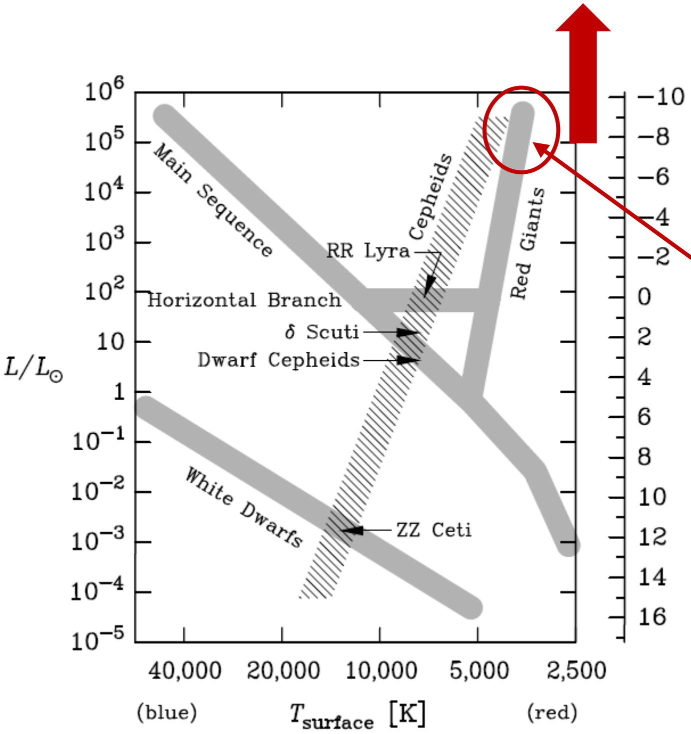

Best fit value: $g_{13}$=1.4

Bound (2σ): $g_{13}$<2.1

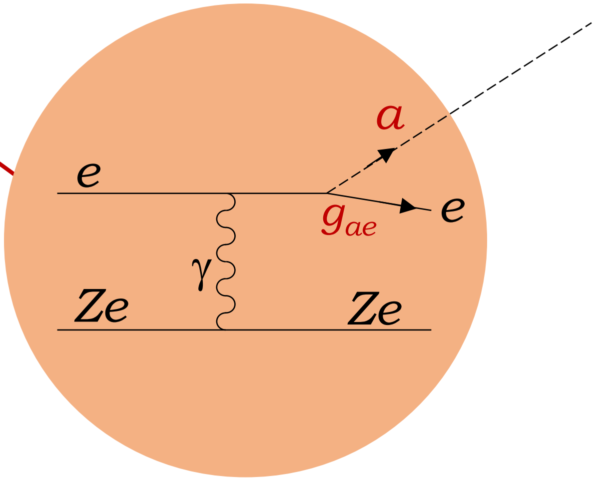
$\chi^2_{min}$/d.o.f. = 0.94

# RG Cooling

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




Additional cooling would give rise to a brighter RGB tip.



# RG Cooling

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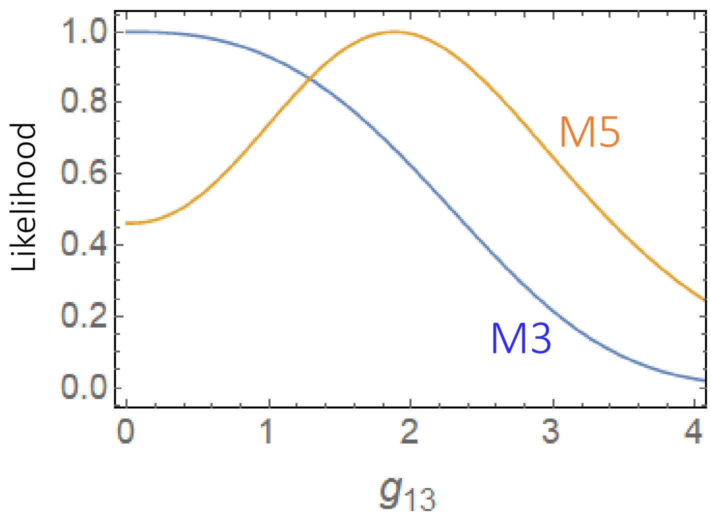
Additional cooling would give rise to a brighter RGB tip.

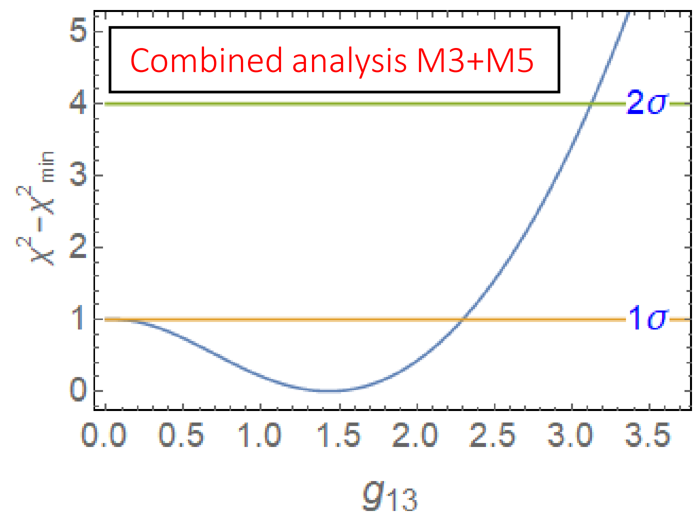
| Cluster | Results |
|---|---|
| **M5:** (analysis of $g_{ae}$ and $\mu_\nu$)<br>Viaux et. al., Phys.Rev.Lett. 111 (2013); Viaux et. al. Astron.Astrophys. 558 (2013) A12; | Shows a slightly brighter tip |
| **$\omega$-Centauri:** (analysis of $\mu_\nu$)<br>Arceo-Daz et. al. (2015) | Shows a slightly brighter tip |
| **M3:** (analysis of $g_{ae}$)<br>O. Straniero et. al. (2017) | Compatible with observations |

# RG Cooling

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

Additional cooling would give rise to a brighter RGB tip.



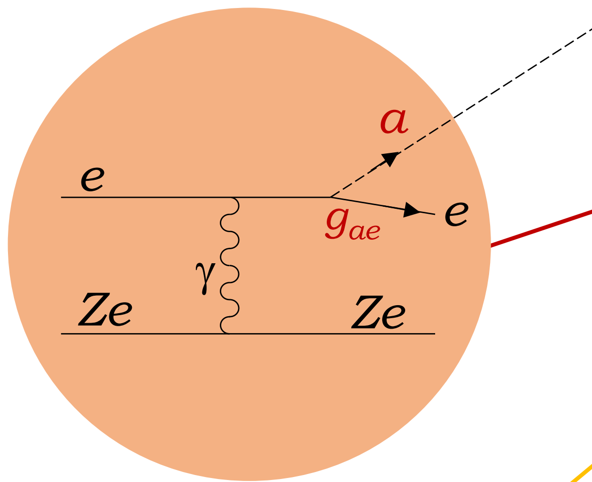

*A study of many more clusters is underway…*

Best fit value: $g_{13}$=1.4

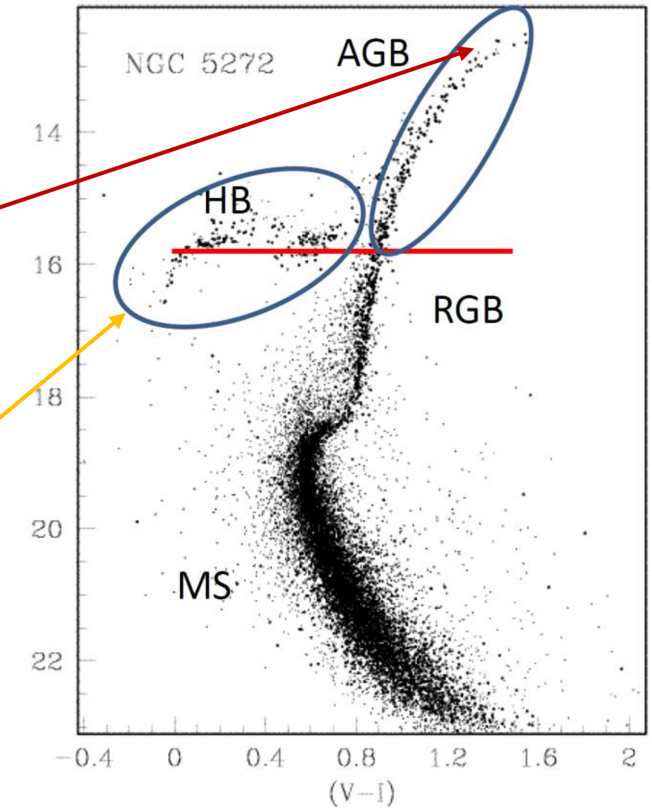
Bound ($2\sigma$): $g_{13}$<3.1

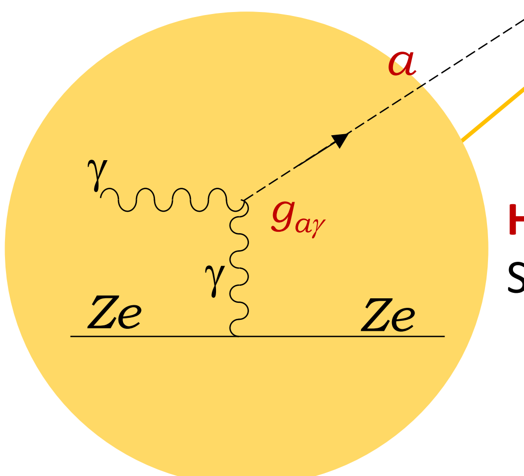
# HB stars and the R-parameter

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




**RGB**: Very dense.
Sensitive to $g_{ae}$




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

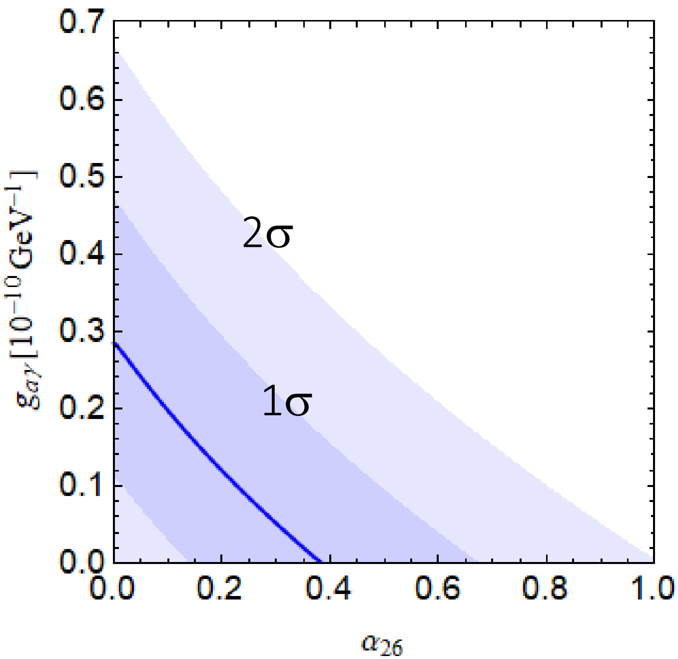
Ayala, Dominguez, M.G., Mirizzi, Straniero, (2014)

Straniero (proc. of XI Patras Workshop, 2015)

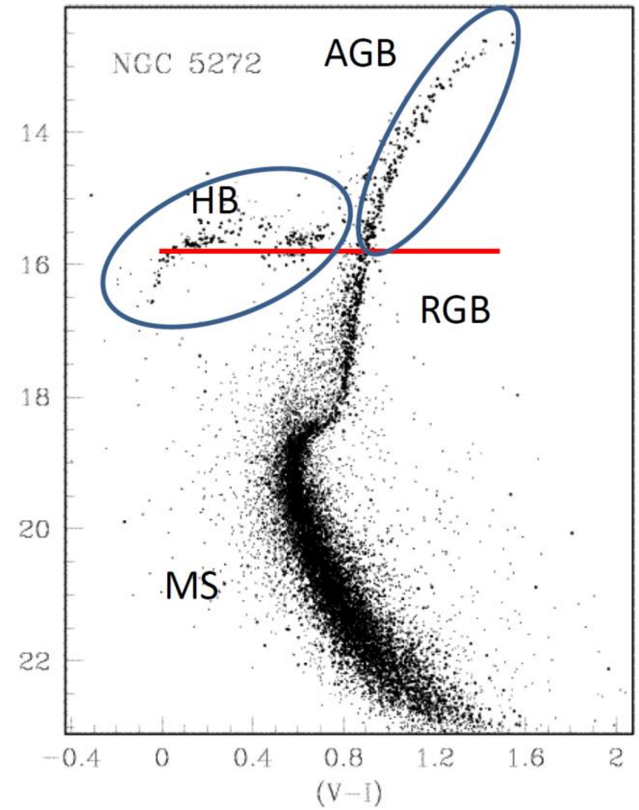
M.G., Irastorza, Redondo, Ringwald (2015)

# HB stars and the R-parameter

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




M.G., Irastorza, Redondo, Ringwald, **JCAP** 1605 (2016)




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

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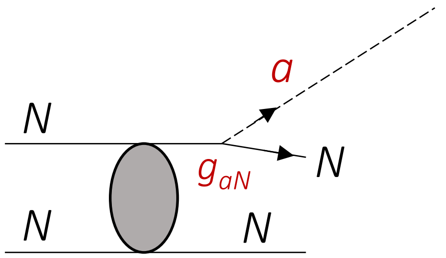
M.G., Irastorza, Redondo, Ringwald (2015)

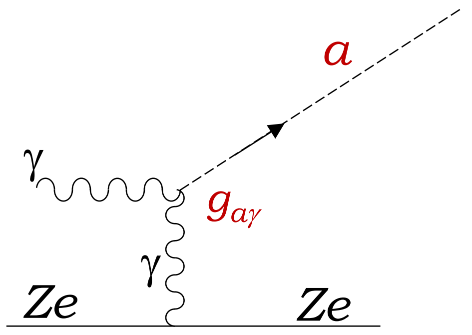
# Supernovae and Neutron Stars

SN and NS are very dense and much hotter than regular stars

$\rho \approx$ a few $10^{14}$g cm$^{-3}$ and $T \approx$ a few 10 MeV

ALP production: Bremsstrahlung or Primakoff.




Strong bounds from cooling considerations or from missing gamma rays from ALP decay/conversion in external B

# Supernovae and Neutron Stars

SN and NS are very dense and much hotter than regular stars

$\rho \approx$a few $10^{14}$g cm$^{-3}$ and T≈a few 10 MeV

Additional *axion induced* cooling would affect the observed neutrino signal from SN1987A

This leads to:

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

for KSVZ

T. Fischer, S. Chakraborty, M. G., A. Mirizzi, A. Payez, A. Ringwald, Phys.Rev. D94 (2016)

$$g_{ap}^2 + g_{an}^2 < 3.6 \times 10^{-19}$$

for DFSZ

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

However, not a very solid bound: very few data and the interaction is difficult to model. With a complete error budget, the bound should relax

Very recent "astrophobic" models could not suffer from this bound.

Di Luzio, Mescia, Nardi, Panci, Ziegler (2017)

# Hints of new physics?

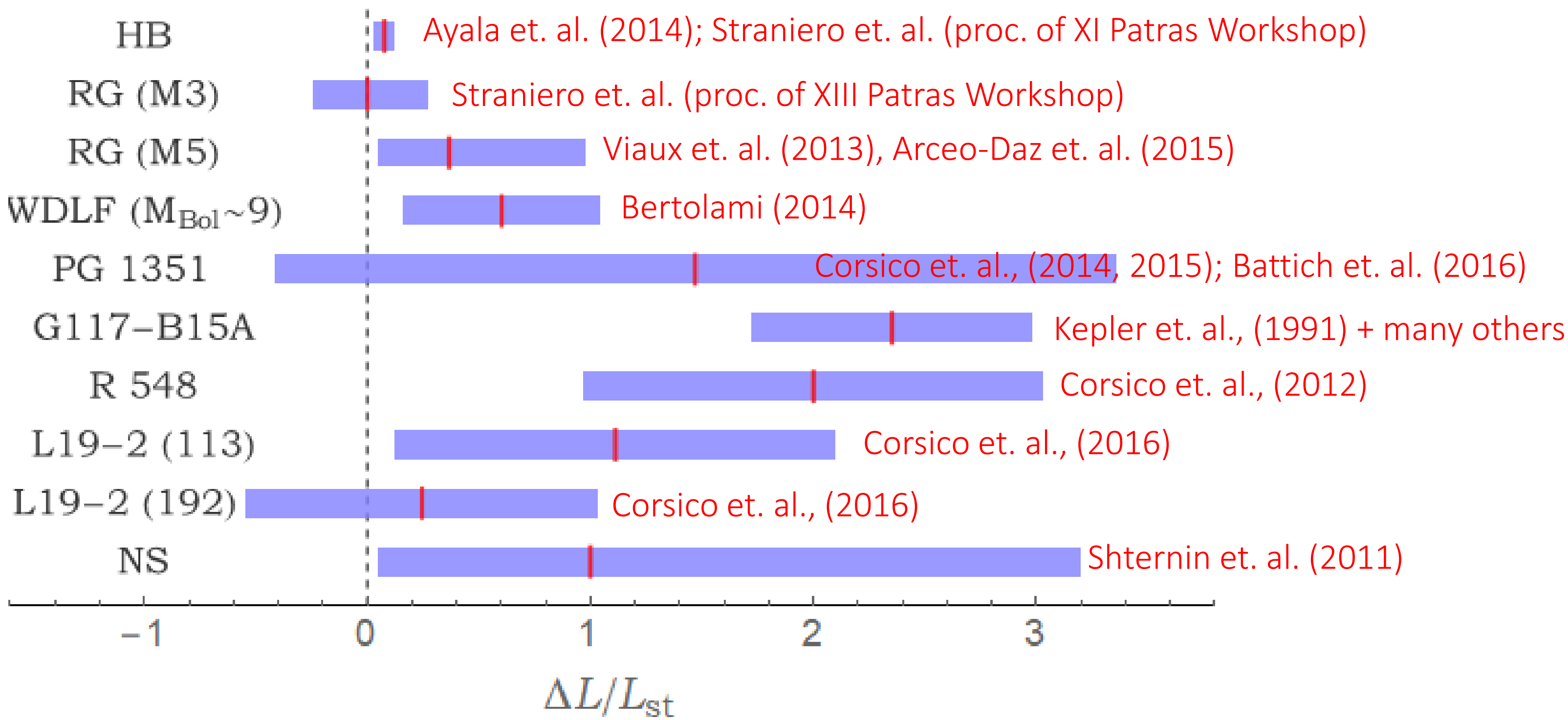
As seen, several stellar systems seem to be cooling faster than predicted by the models, perhaps hinting to new physics.

Though these hints should be taken carefully, they could show a systematic problem in our understanding of stellar evolution.

Axions/ALPs could provide a simple explanation of all of them.

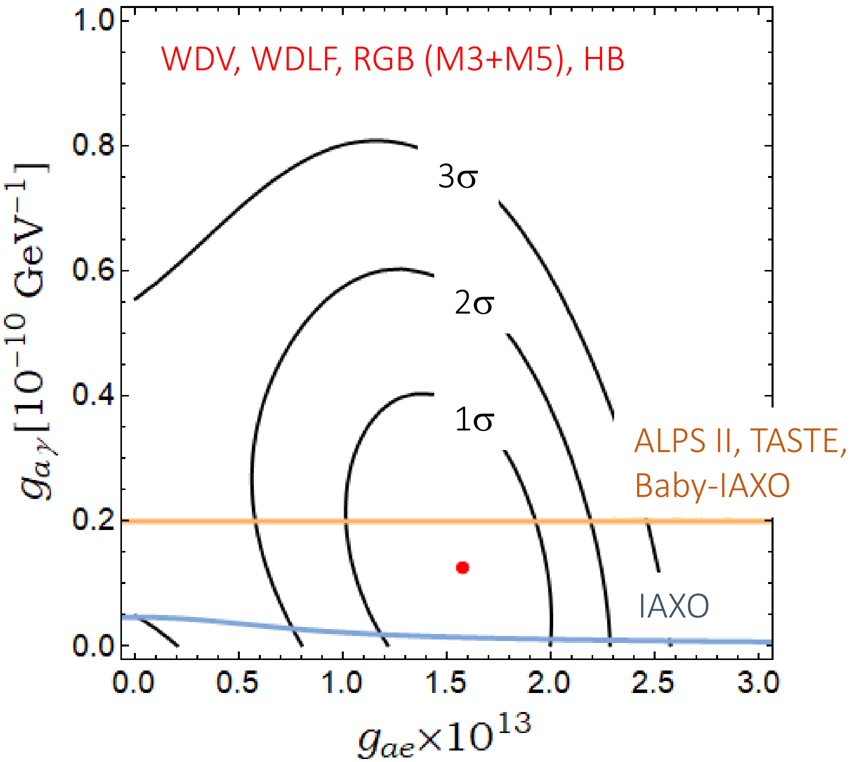
M.G., I. Irastorza, J. Redondo, A. Ringwald, JCAP 1605 (2016)

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



# ALP/Axion interpretation

*Stellar cooling shows a mild preference for a small coupling to photons and electrons*




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

Best fit

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

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

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

best fit corresponds to:

$$\frac{C_{ae}}{C_{a\gamma}} \approx 2.7\times 10^{-2}$$

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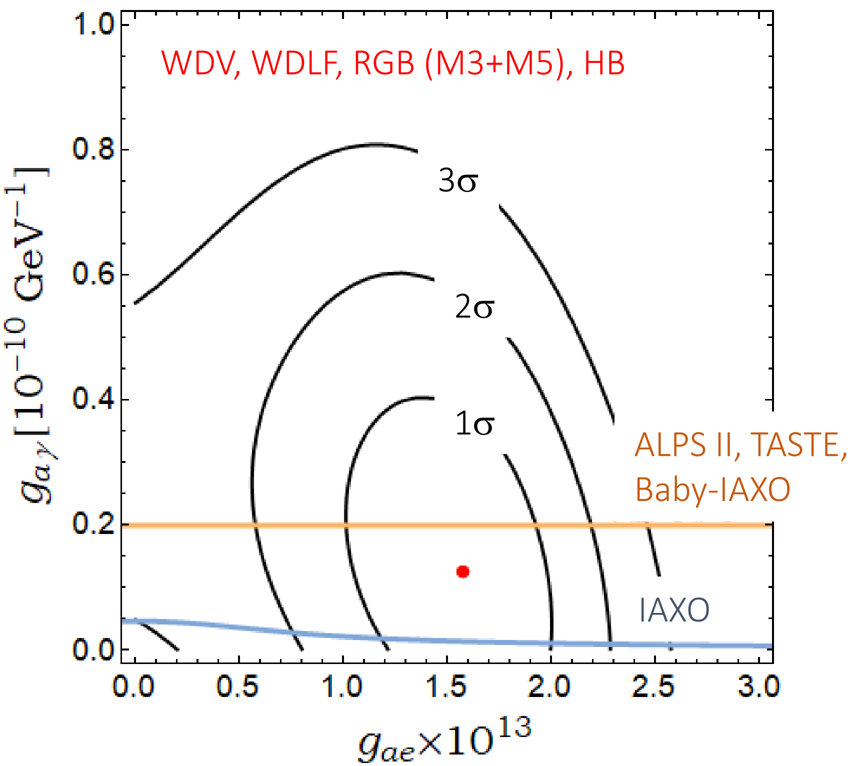
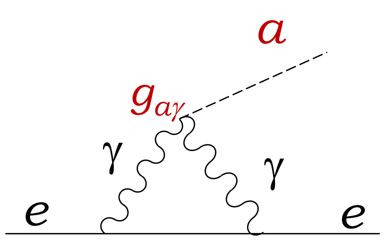



M.G., I. Irastorza, J. Redondo, A. Ringwald, K. Saikawa, JCAP **1710** (2017)

In the KSVZ model, coupling to electrons naturally small




In fact, too small!

$$C_{ae} / C_{a\gamma} \approx 10^{-3}$$

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

# ALP/Axion interpretation

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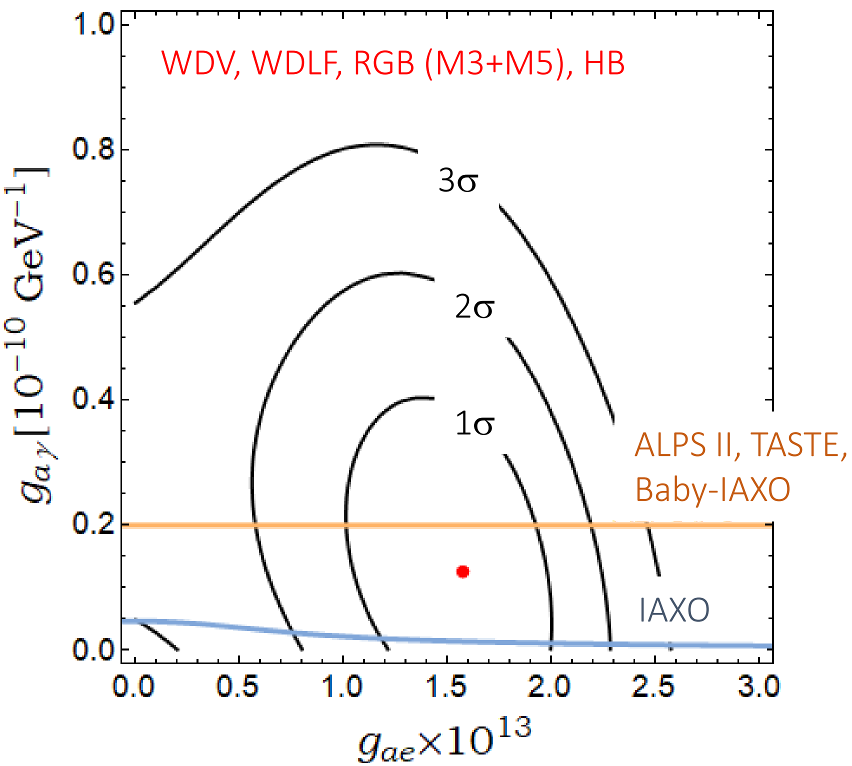



M.G., I. Irastorza, J. Redondo, A. Ringwald, K. Saikawa, JCAP **1710** (2017)

For the DFSZ I (II) model, this means a preference for a small (large) tan β

DFSZ I: $C_e = \dfrac{\mathrm{Sin}^2\beta}{3}$; $C_{a\gamma} = \dfrac{2}{3} - 1.92$

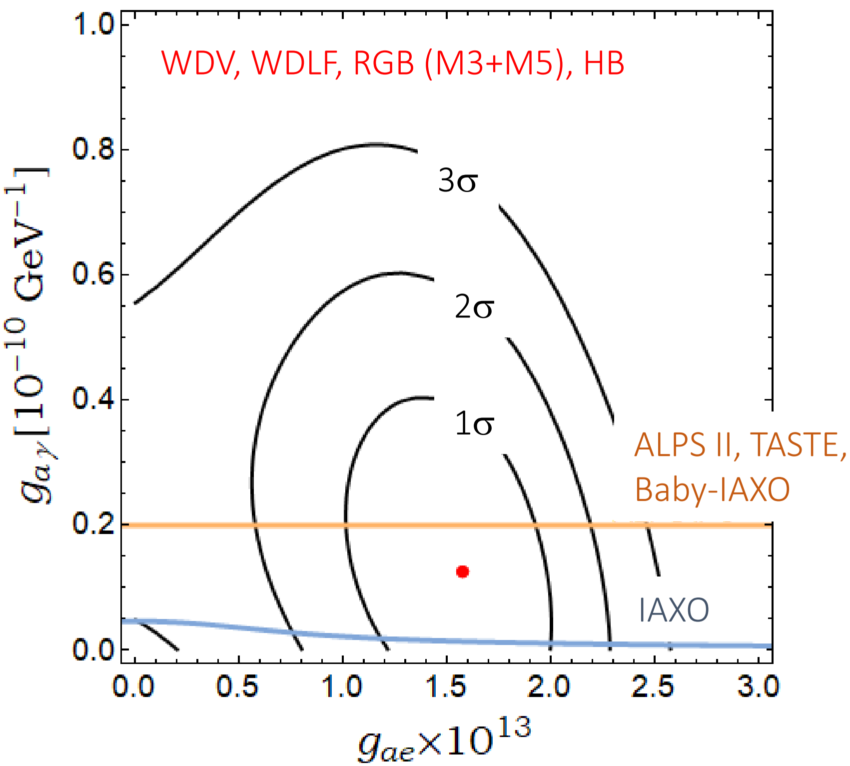
DFSZ II: $C_e = \dfrac{\mathrm{Cos}^2\beta}{3}$; $C_{a\gamma} = \dfrac{8}{3} - 1.92$

Both DFSZ I and II explain fairly well the combined observations

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

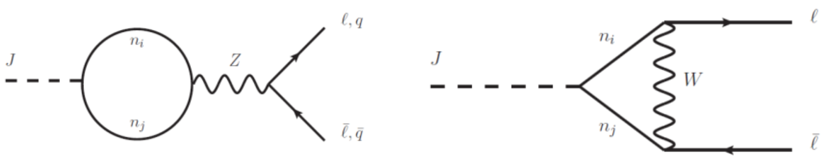
# ALP/Axion interpretation

*Stellar cooling shows a mild preference for a small coupling to photons and electrons*




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

In the KSVZ-type axi-majoron (a/J) models, the one-loop induced axion-electron coupling gets extra contributions from neutrinos



In this case the fit can improve considerably

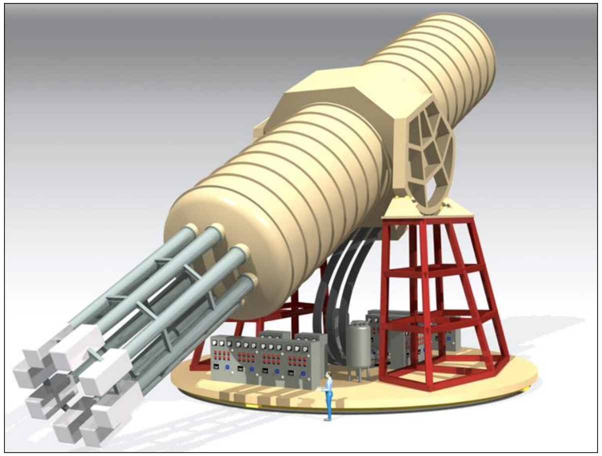
$\chi^2_{min}$/d.o.f. ≈ 1

G. Ballesteros, J. Redondo, A. Ringwald and C. Tamarit, PRL **118** (2017); JCAP **1708** (2017)

# Experimental Probes

How do we probe the parameter space hinted by the cooling anomalies?

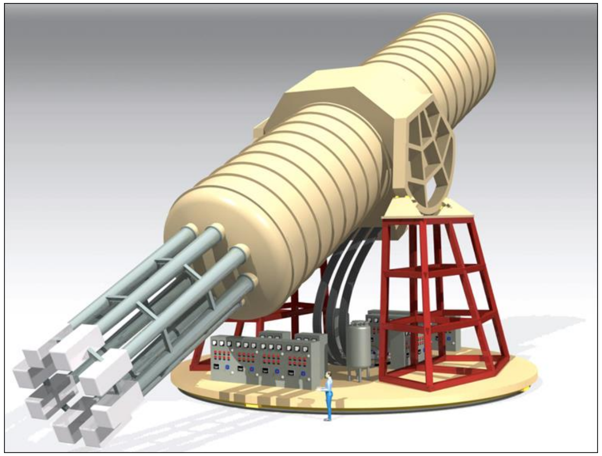
# Experimental Probes



How do we probe the hinted parameter space?

The best option is in the next generation axion helioscope IAXO

# Experimental Probes



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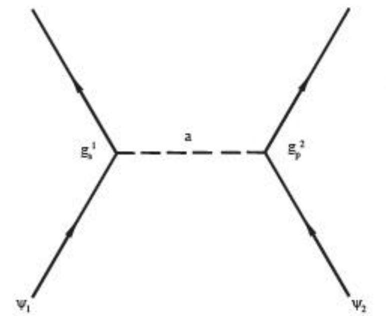
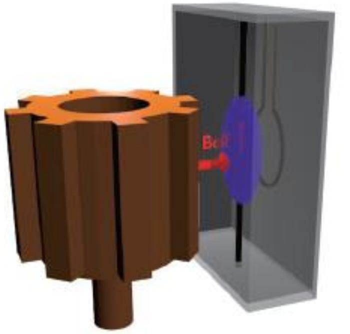
The long range force experiments. Particularly, ARIADNE shows potential to probe the hinted axion parameter space



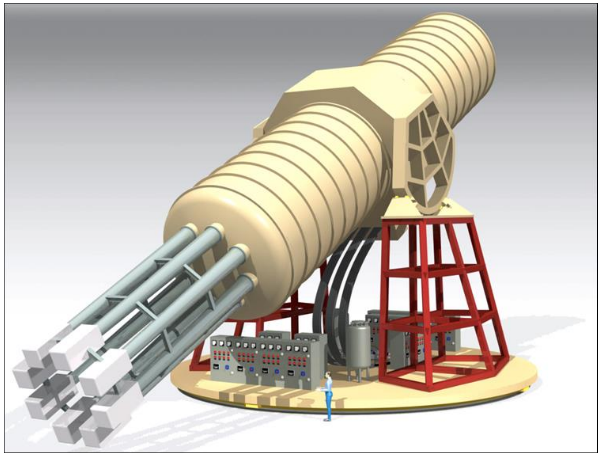

Feynman diagram for monopole-dipole interaction



ARIADNE experimental schematic for monopole-dipole interaction [3]

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

# Experimental Probes



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The <u>long range force experiments</u>.
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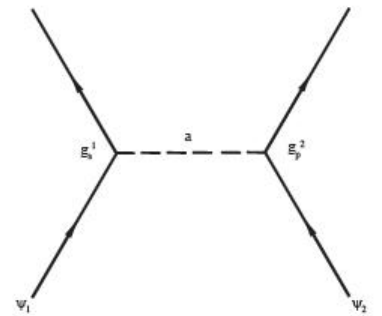


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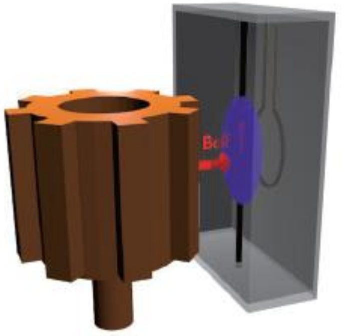

ARIADNE experimental schematic for mono-pole-dipole interaction [3]

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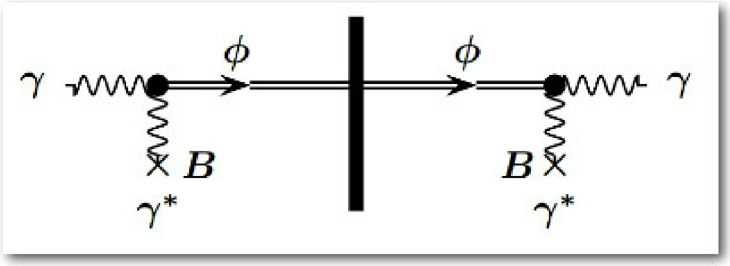
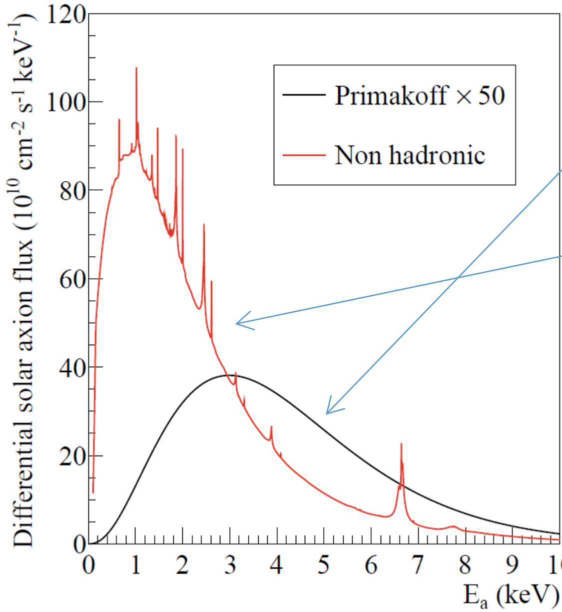



The hinted parameter space for very light ALPs could be probed by ALPS II or by space-born X- and Gamma-ray detectors such as Fermi and NuSTAR

# Axion Helioscope

**Axion helioscope concept**
**P. Sikivie, 1983**
**+ K. van Bibber, G. Raffelt, et al. (1989)**
**(use of buffer gas)**

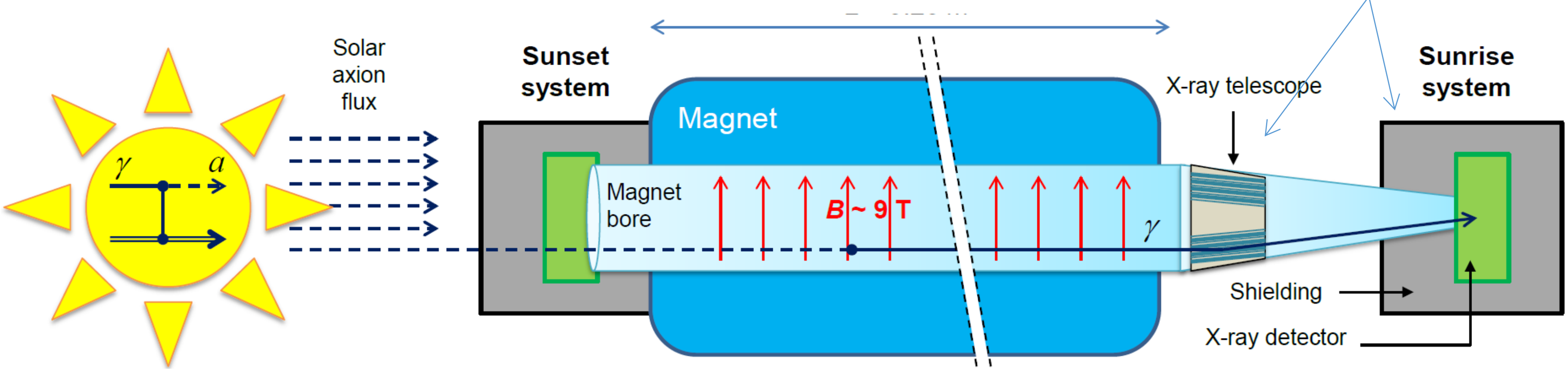
- Relatively strong sensitivity
- Little dependence on the mass.
- Minimal model dependence




**Standard Primakoff spectrum**

**Non-hadronic "ABC" Solar axion flux at Earth**
*JCAP 1312 008*
**(only if axion couples to electron)**

**X-ray Focussing & low-background Innovations of CAST**




Slide from Igor G. Irastorza, Axion-WIMP, Thessaloniki, May 2017

# Axion Helioscope

CAST (CERN Axion Solar Telescope).

3rd gen helioscope. Very successful in constraining the axion-photon coupling for a wide mass range.

nature physics

ARTICLES

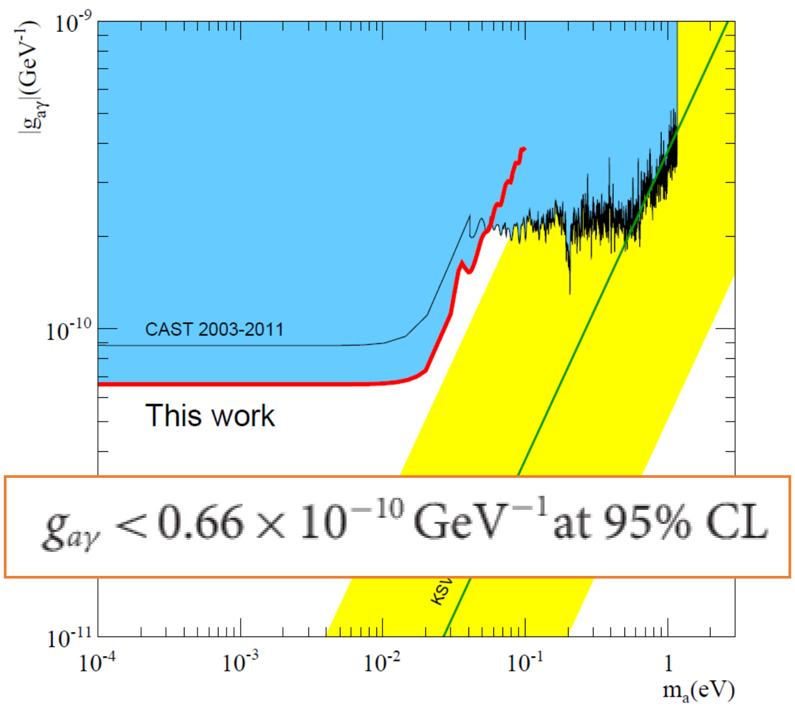
PUBLISHED ONLINE: 1 MAY 2017 | DOI: 10.1038/NPHYS4109

OPEN

## New CAST limit on the axion–photon interaction

CAST Collaboration†

Hypothetical low-mass particles, such as axions, provide a compelling explanation for the dark matter in the universe. Such particles are expected to emerge abundantly from the hot interior of stars. To test this prediction, the CERN Axion Solar Telescope (CAST) uses a 9 T refurbished Large Hadron Collider test magnet directed towards the Sun. In the strong magnetic field, solar axions can be converted to X-ray photons which can be recorded by X-ray detectors. In the 2013–2015 run, thanks to low-background detectors and a new X-ray telescope, the signal-to-noise ratio was increased by about a factor of three. Here, we report the best limit on the axion–photon coupling strength (0.66 × $10^{-10}$ $\mathrm{GeV}^{-1}$ at 95% confidence level) set by CAST, which now reaches similar levels to the most restrictive astrophysical bounds.



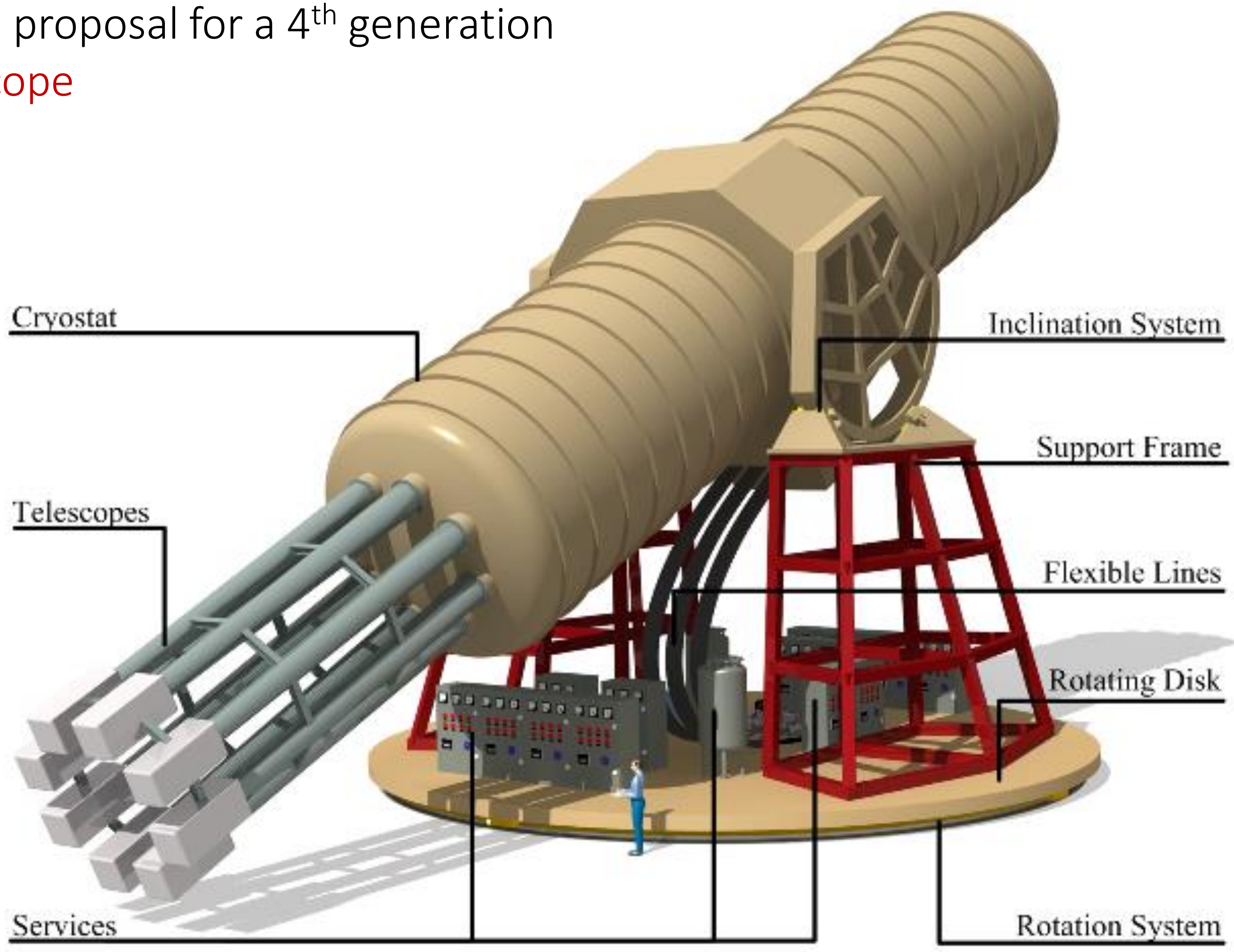

$$g_{a\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1} \text{at } 95\%\ \mathrm{CL}$$

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

# IAXO: The International Axion Observatory

4th generation axion helioscope

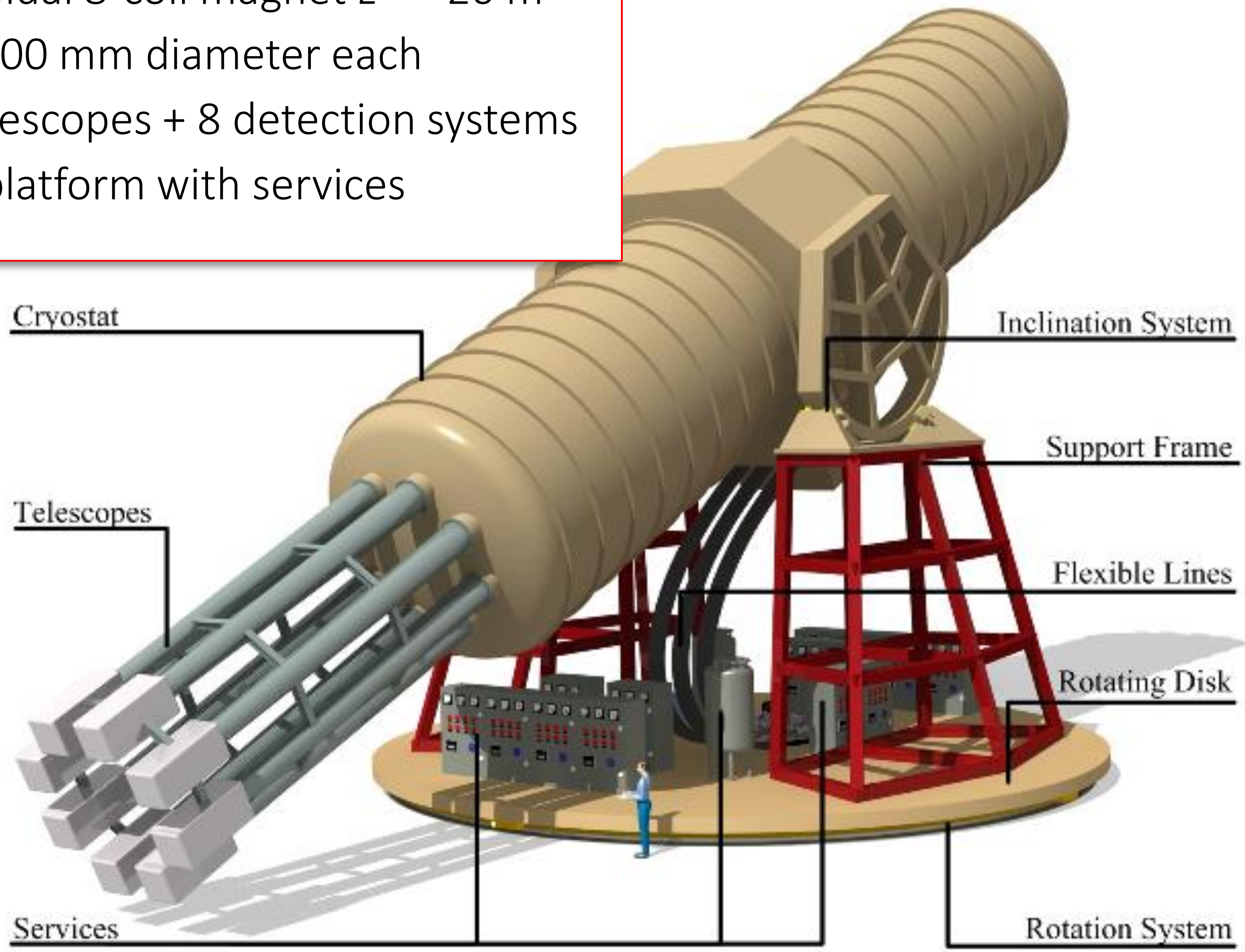
International proposal for a 4th generation axion helioscope



# IAXO: The International Axion Observatory

4th generation axion helioscope

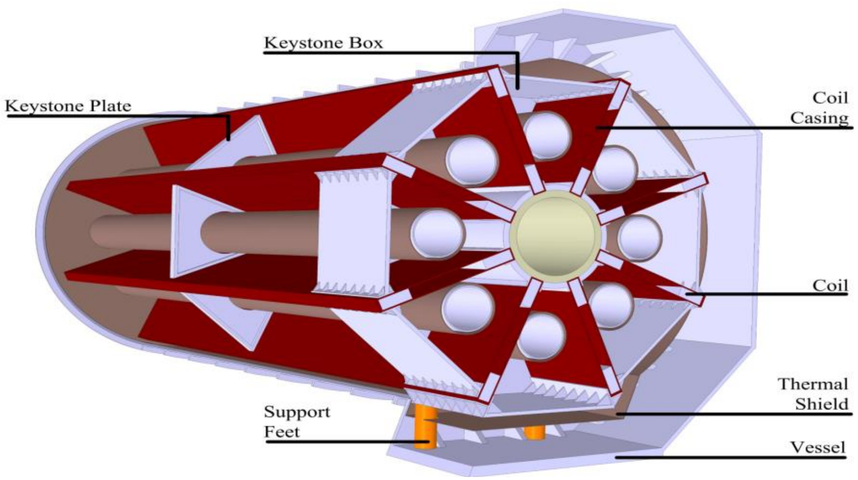
- Large toroidal 8-coil magnet *L* = ~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services



# IAXO: The International Axion Observatory

## IAXO magnet

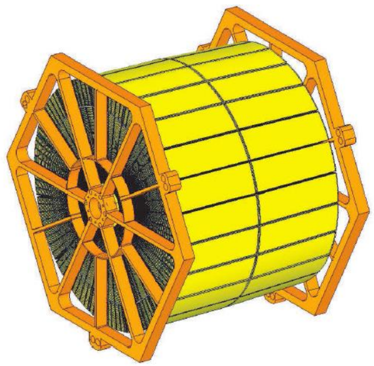
- Superconducting “detector” magnet
- Toroidal geometry (8 coils)
- Based on ATLAS toroid technical solutions
- 8 bores| 20m long| 60cm ⌀ per bore|5.4/2.5 T




**IAXO Letter of Intent: CERN-SPSC-2013-022**
**IAXO Conceptual Design: JINST 9 (2014), T05002, [arXiv::1401.3233]**

## IAXO telescopes

- Slumped glass technology with multilayers
- Cost-effective to cover large areas
- Based on NuSTAR technology



- Focal length ≃ 5m
- 8 optics with 123 layers each
- 60-70% efficiency

## IAXO detectors

- Micromegas gaseous detectors
- Radiopure components+ shielding
- Event topology in gas for discrimination
- Bgrd ≤$10^{-7}$/(keV×cm$^2$×s) through fabrication, radiopurity, shielding and simulations

# Improving the sensitivity

$$g_{ag}^{4} \propto \underbrace{b^{1/2} e^{-1}}_{\textbf{detectors}} \times \underbrace{s^{1/2} \varepsilon_0^{-1}}_{\textbf{optics}} \times \underbrace{(BL)^{-2} A^{-1}}_{\textbf{magnet}} \times \underbrace{t^{-1/2}}_{\textbf{exposure}}$$

**detectors**

$b$ = background

$\varepsilon$ = efficiency

**optics**

$s$ = spot size

$\varepsilon_0$= efficiency

**magnet**

$B$ = magnetic field

$L$ = magnet length

$A$ = cross-sectional area

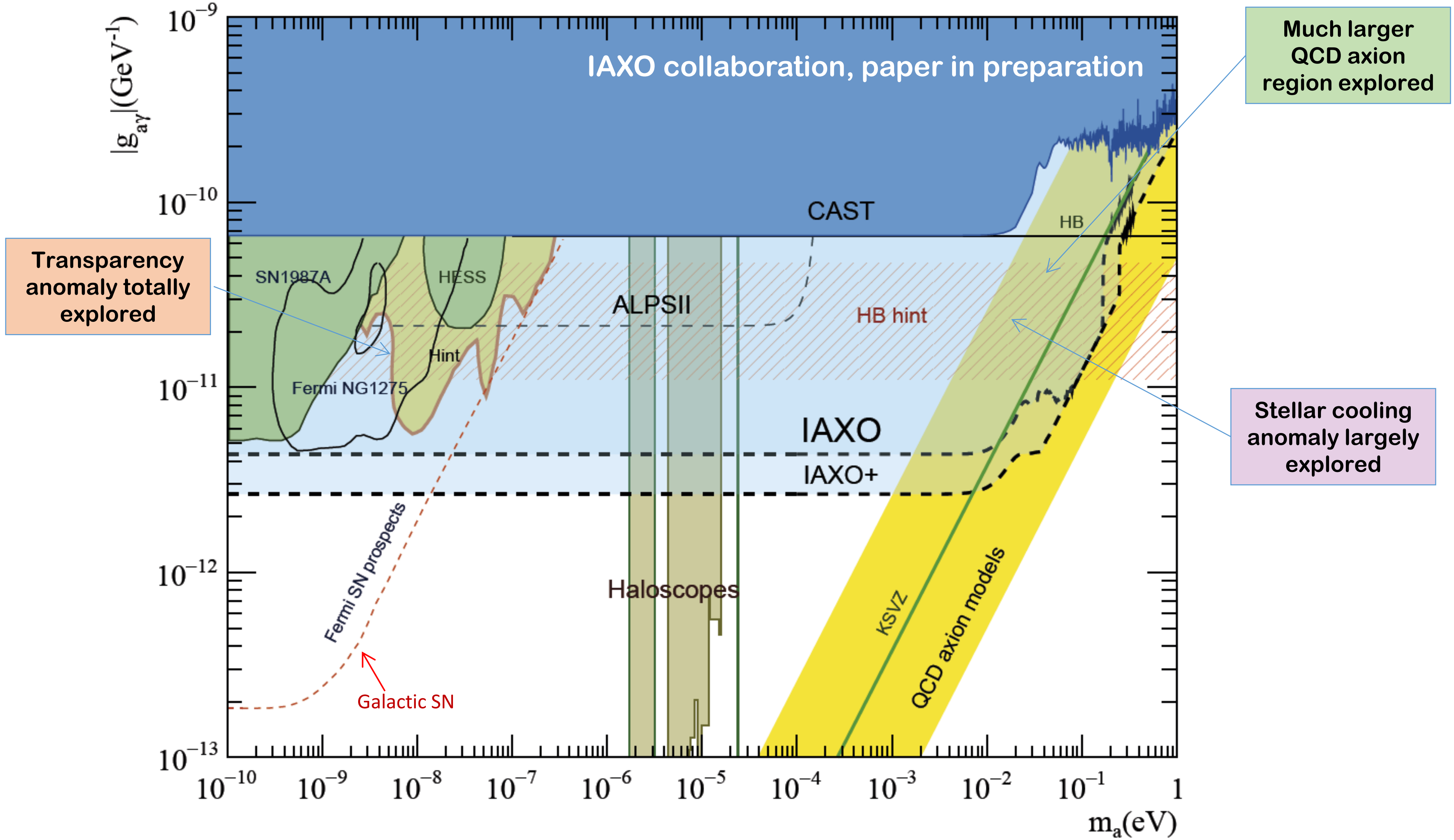
**exposure**

$t$ = time

IAXO is expected to improve on the CAST sensitivity to $g_{a\gamma}$ by a factor of 20

IAXO Letter of Intent: CERN-SPSC-2013-022;
IAXO Conceptual Design: JINST 9 (2014), T05002 [arXiv::1401.3233]

# IAXO sensitivity prospects




Slide from Igor G. Irastorza, Axion-WIMP, Thessaloniki, May 2017

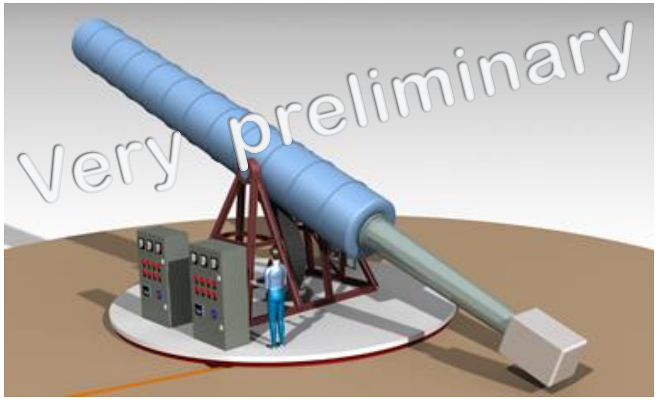
# mini-IAXO (aka babyIAXO)

- **Goal: full intermediate experimental stage**
  - Test magnet design at relevant scale (only 1 bore full diameter)
  - Test bench for optics + detector
  - Will deliver relevant physics (at intermediate level). Under work

- Will better mobilize community into experimental activity & increase interest
- Better (more staged) access to funding
- Detail concept and effect on near-term planning under intense study at the moment in the collaboration.

**Detailed conceptual design under preparation:**

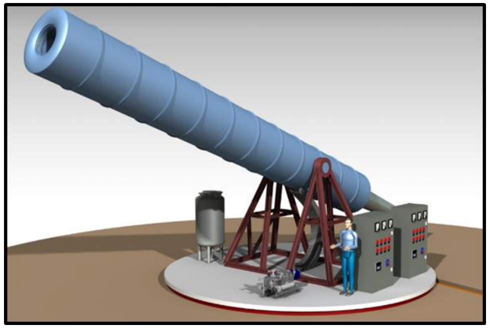
**Presumably:**
**1-bore magnet with relevant dimensions.**
**1 optics+detector system of specs close to final ones.**

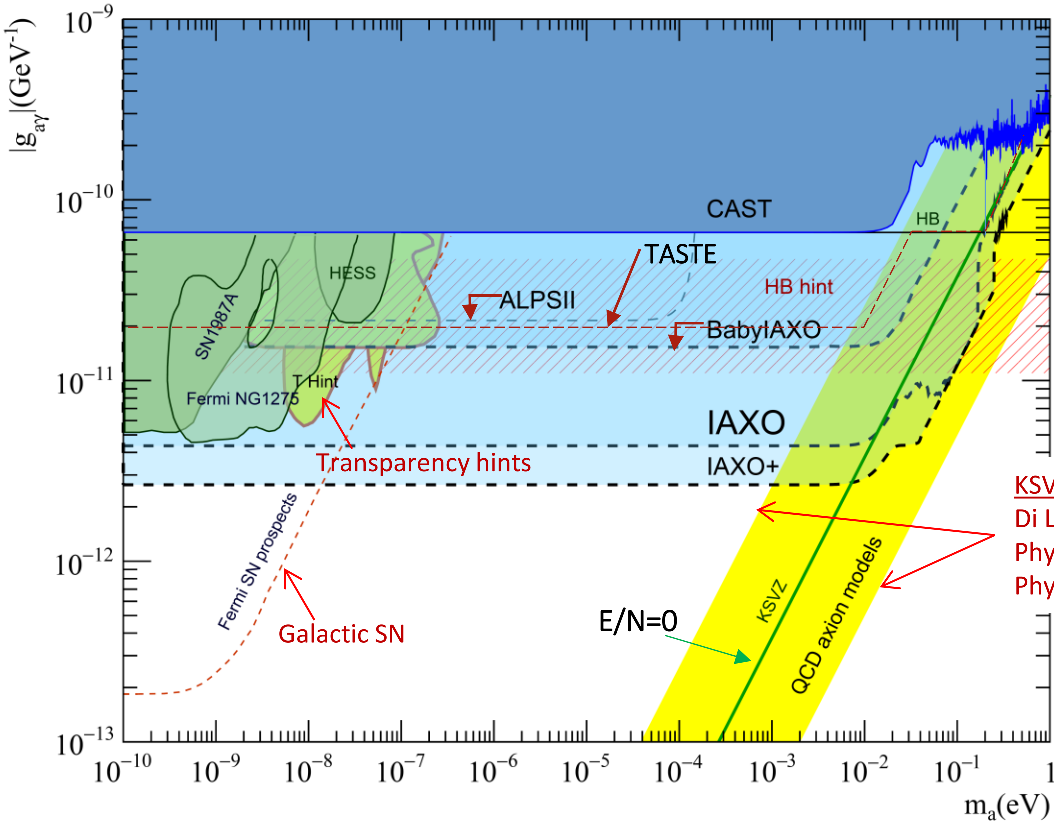



From Igor G. Irastorza, Axion-WIMP, Thessaloniki, May 2017

# Experimental Potential

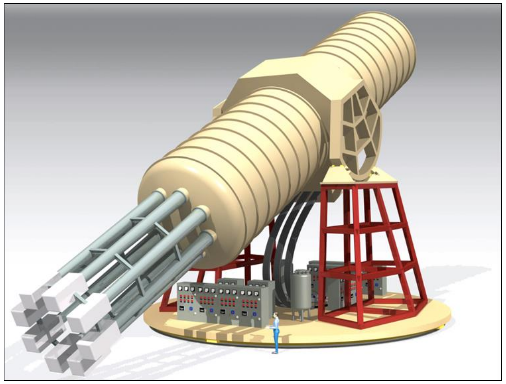
Medium Size next generation Helioscopes (MSH) such as BabyIAXO or TASTE can probe ALPs - but not easily QCD axions – in the regions of interest for astrophysics






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

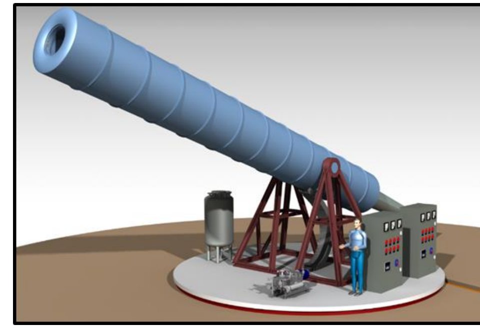
KSVZ axion band: Di Luzio, Mescia, Nardi, Phys.Rev.Lett. 118 (2017), Phys.Rev. D96 (2017)

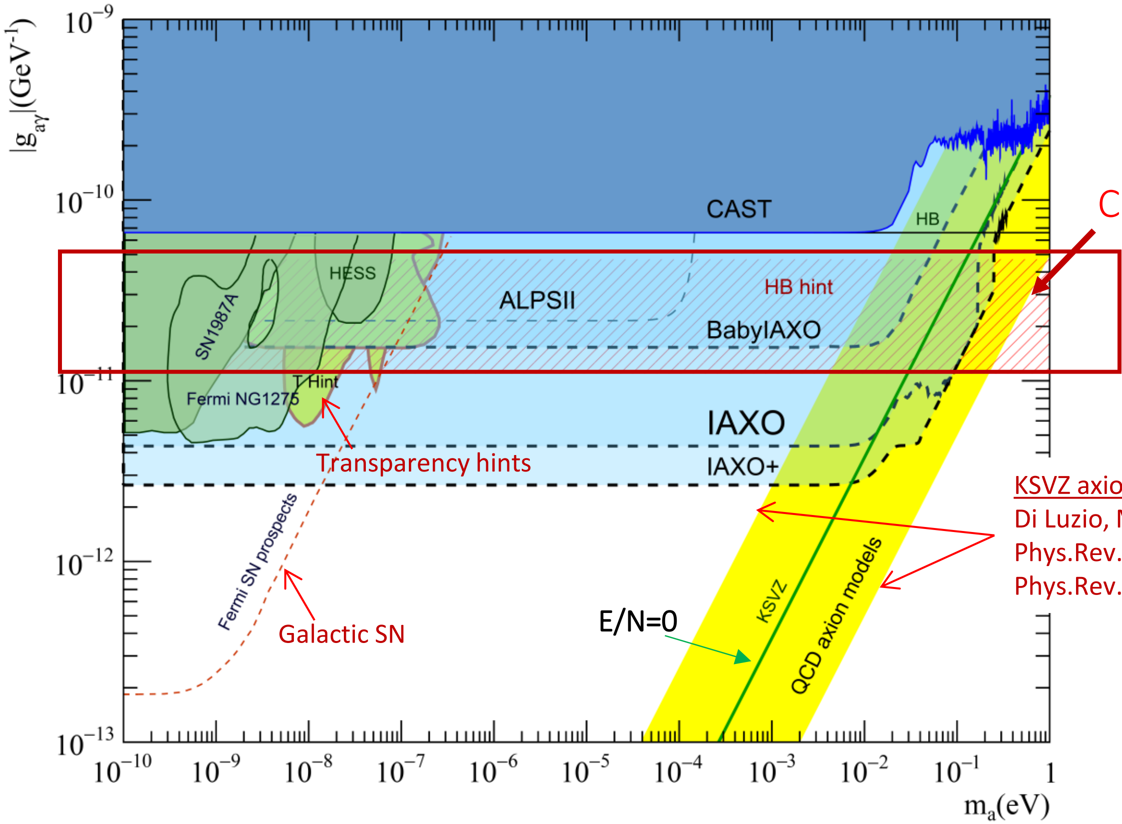


IAXO collaboration, in preparation

# Experimental Potential

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

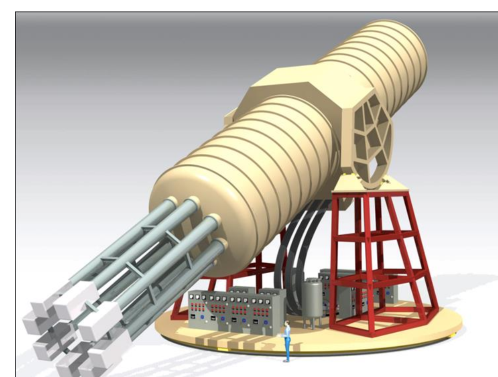





Cooling hints

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

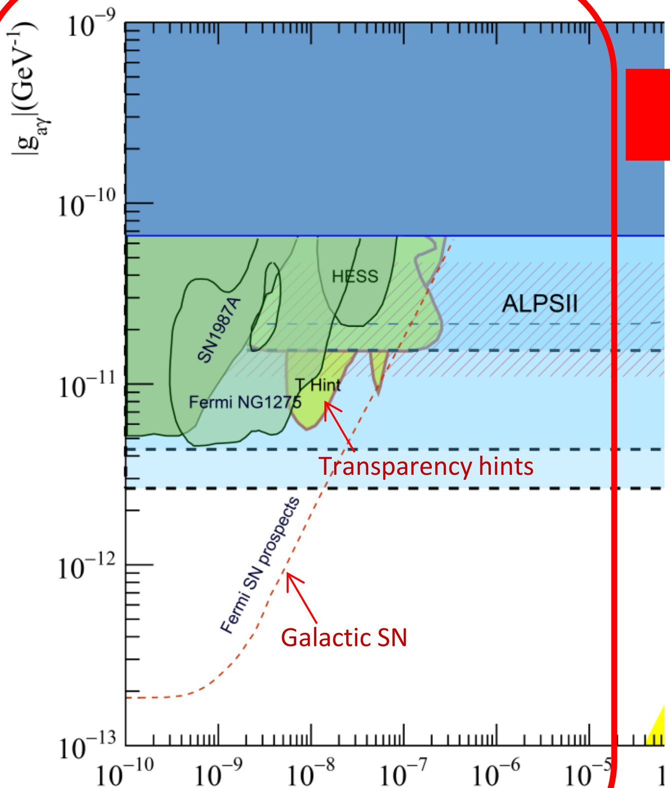
IAXO has the greatest potential in the regions of interest for astrophysics

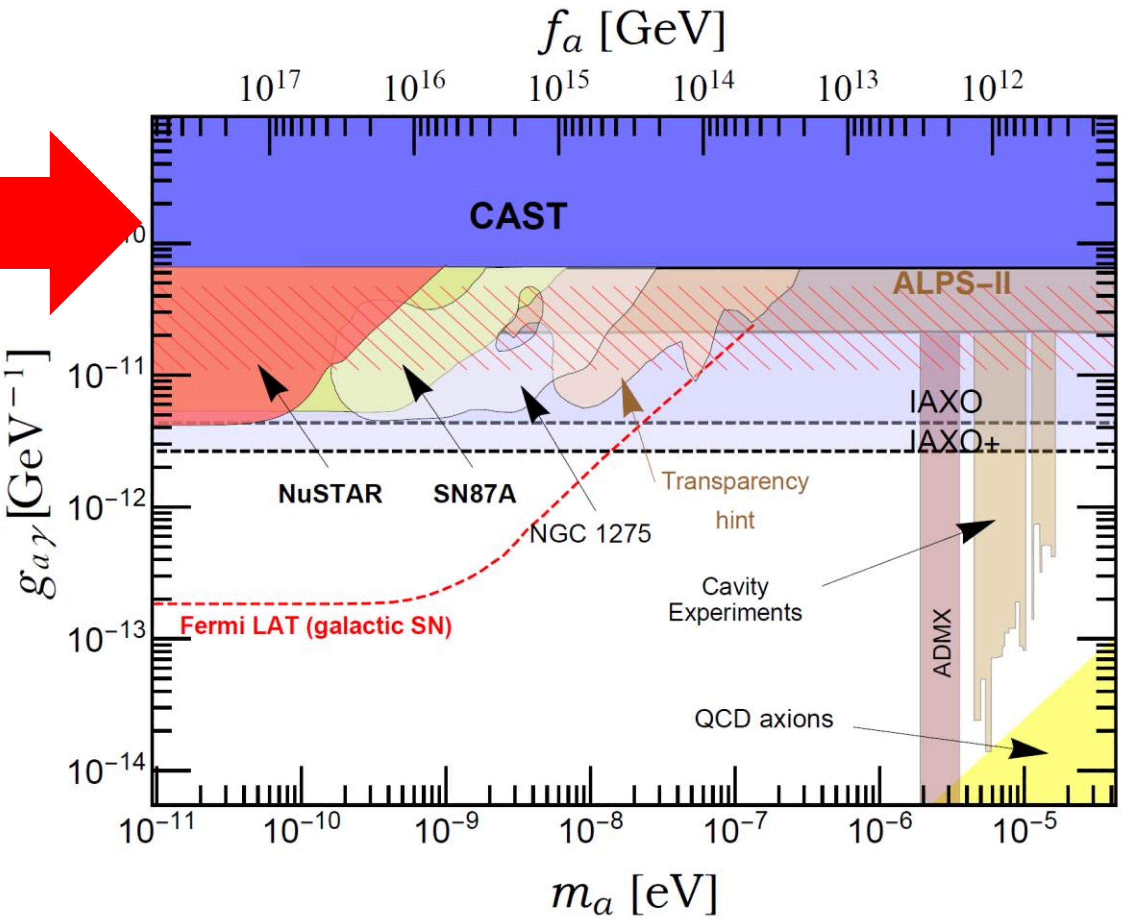


IAXO collaboration, in preparation

# Experimental Potential

The low mass region can be probed extremely well with gamma and X-ray detectors

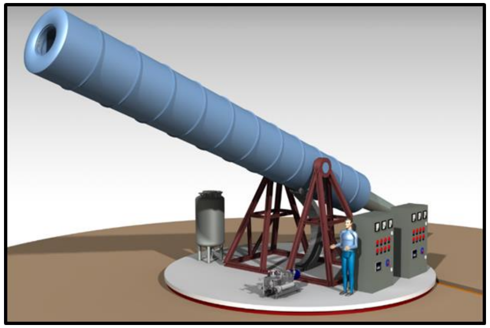


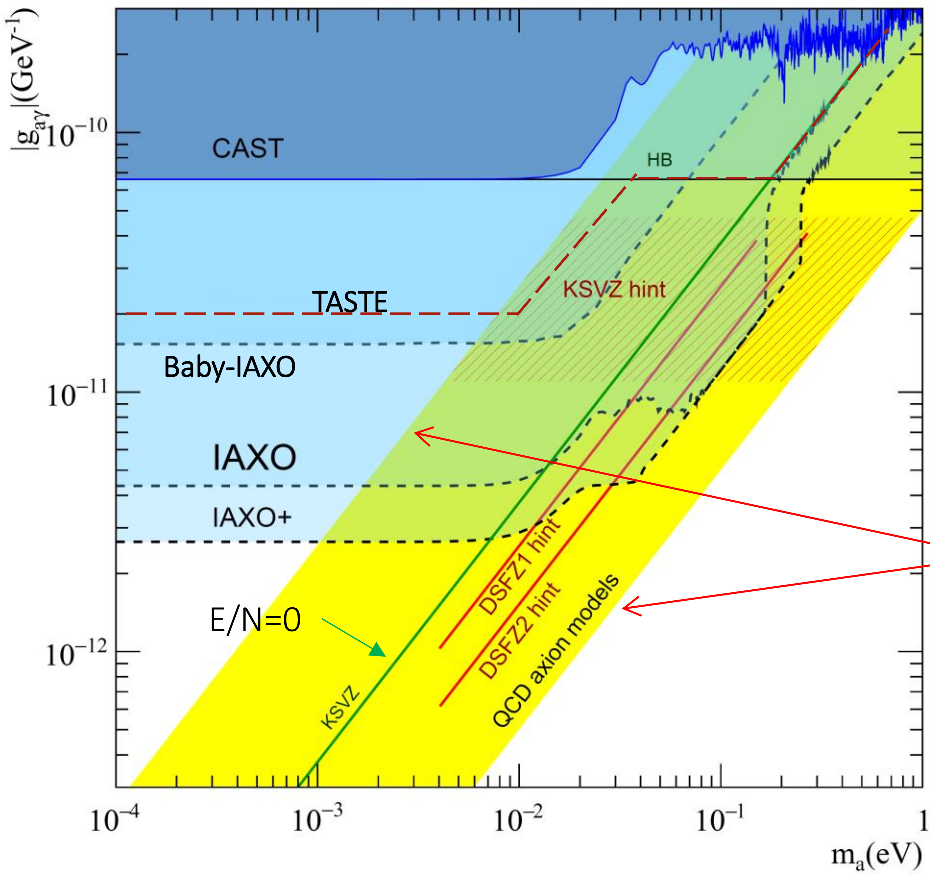




M.G., Axion-WIMP, Thessaloniki, May 2017

# Experimental Potential: QCD axions

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

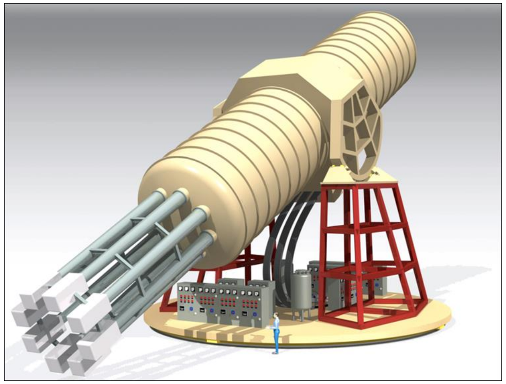




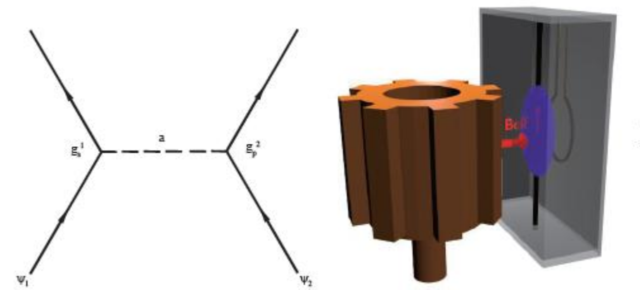

KSVZ axion band:
Di Luzio, Mescia, Nardi,
Phys.Rev.Lett. 118 (2017),
Phys.Rev. D96 (2017)

IAXO collaboration, in preparation

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



# Experimental Potential: DFSZ axions



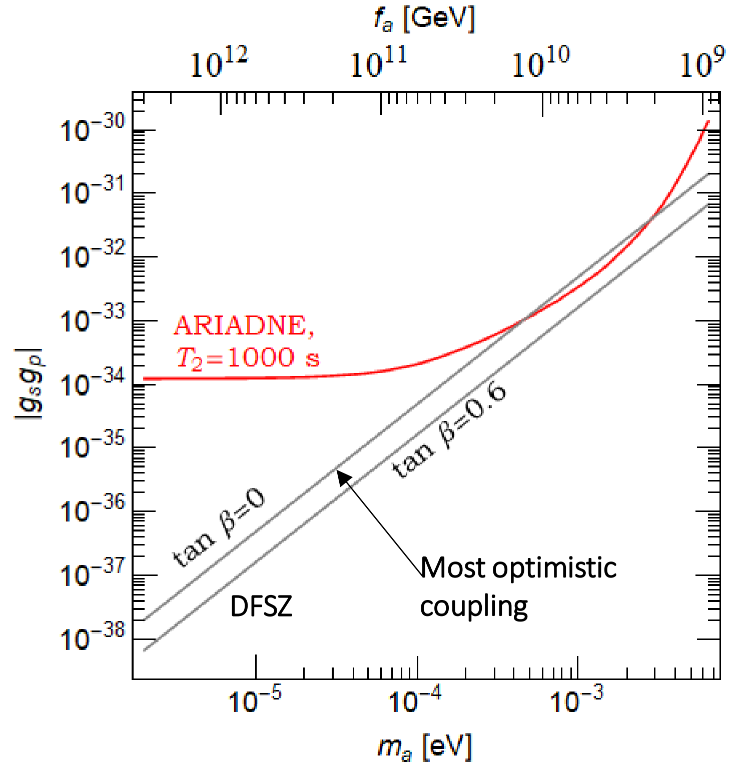
Feynman diagram for monopole-dipole interaction ARIADNE experimental schematic for monopole-dipole interaction [3]

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

ARIADNE searches for long range forces mediated by axions.

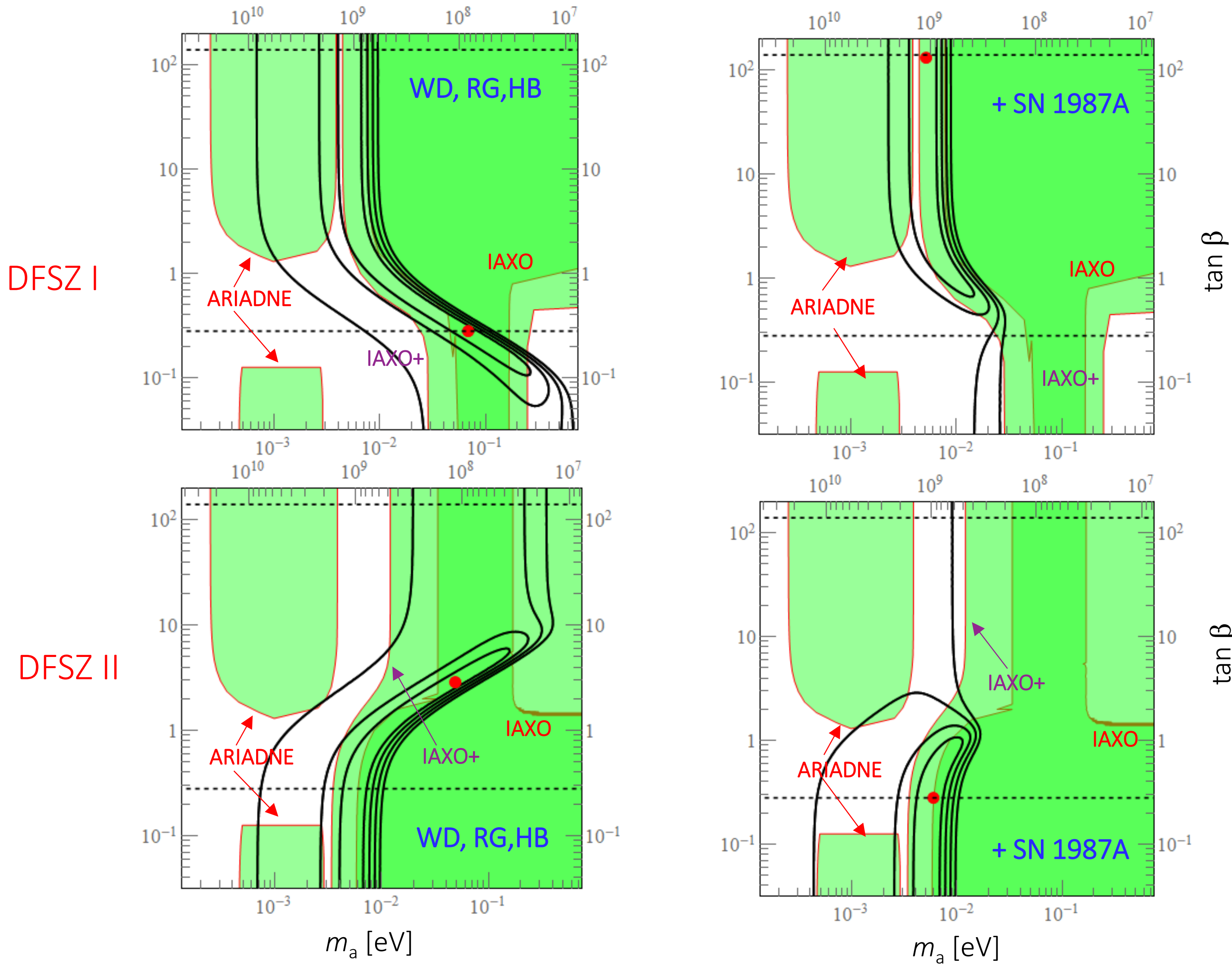
The experiment would probe the coupling of axions to neutrons

J. E. Moody and F. Wilczek, Phys. Rev. D 30, 130 (1984).
A. Arvanitaki and A. A. Geraci, Phys. Rev. Lett. 113 (2014)




ARIADNE can probe sections of the DFSZ parameter space and is <u>more sensitive than IAXO at low masses</u>

# Experimental Potential: DFSZ axions




M.G., Irastorza, Redondo, Ringwald, Saikawa, JCAP 1710 (2017)

# Conclusion

- Astrophysical bounds on axion/ALPs are improving and terrestrial experiments are catching up! It is an exciting period!

-Hints from several stellar systems. ALPs and DFSZ axions are the best candidates to explain the hints. Axi-majoron models are also good candidates while KSVZ are not as good.

- IAXO will be capable to find the hinted QCD axions in a sizeable part of the parameter space, although it is with the upgraded IAXO configuration that most of the parameter space will be covered.

- Medium size helioscopes would likely miss the most interesting regions for DFSZ axions but could probe KSVZ and ALPs.