Axion Telescopes: detecting stellar axions

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Premises: Stars and ALPs

Stars → Very efficient ALP factories

→ Stars as ALP labs
(old and successful idea)

→ *Stars as ALP sources*
Direct detect stellar ALPs
(only recently there is potential for that)

↓

Many new strategies and proposals in the last few years.

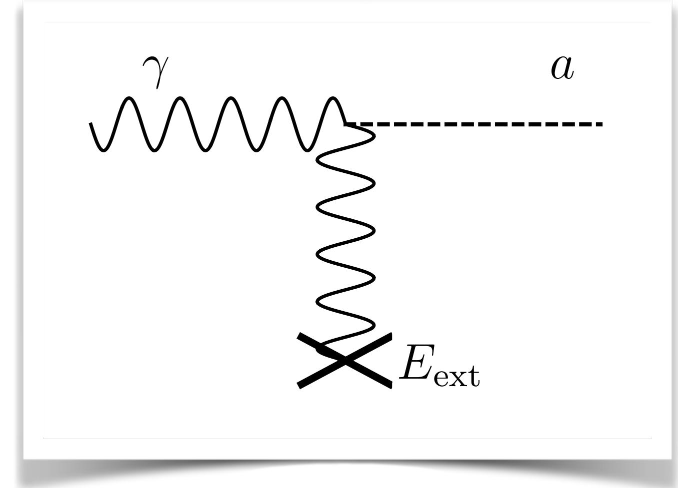
Focus of this talk: Sun, Supergiant Stars, SNe.

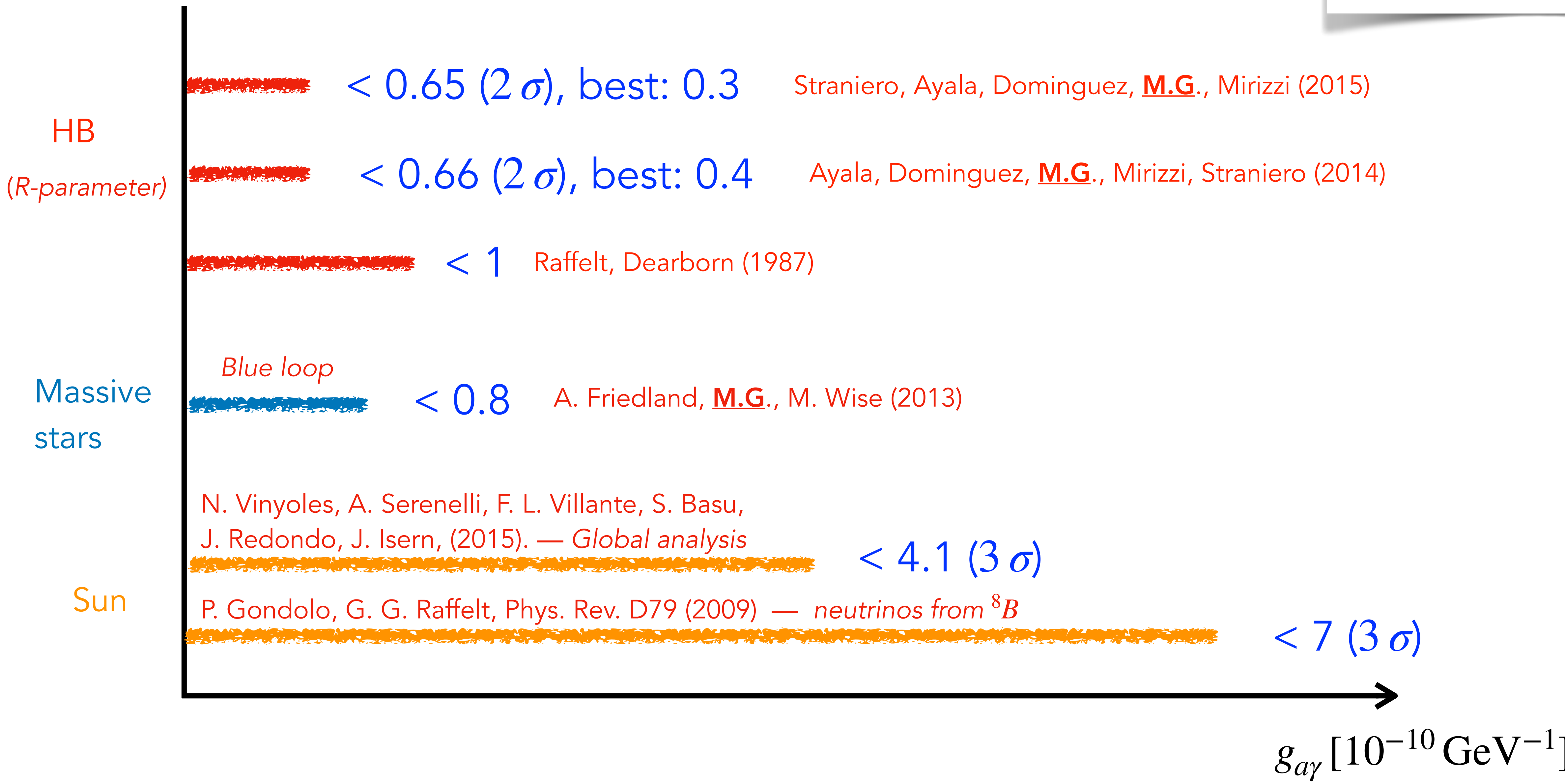
I will not be able to discuss some very relevant new ideas and results (apologies)

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

$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma}\, aF\tilde{F}$$

Most relevant process in stars:
Primakoff

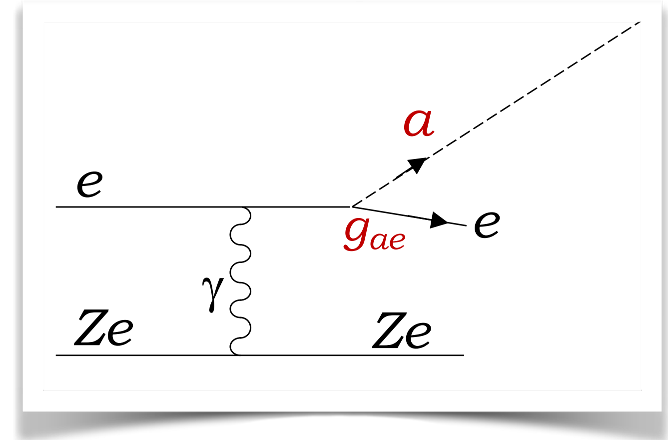




Axion-electron coupling (g_{ae})

$$L_{ae} = -\, i g_{ae}\, a\, \bar{e}\, \gamma_5\, e$$

Most relevant process in stars:
bremsstrahlung



RGBT

22 GC — < 1.4 ($2\,\sigma$), best 0.6 — O. Straniero et al., Astron.Astrophys. 644 (2020)

NGC 4258 — < 1.6 ($2\,\sigma$) — F. Capozzi, G. Raffelt, *Phys.Rev.D* 102 (2020)

} Gaia DR2 data

WDV

< 4.1 ($2\,\sigma$), best: 2.9 — Córsico, Althaus, Miller Bertolami, Kepler, Astron. Astrophys. Rev. 27 (1) (2019)

WDLF

0.5-2.1 ($2\,\sigma$), best: 1.4 — M. Bertolami, E. Melendez, L. G. Althaus, J. Isern (2014)

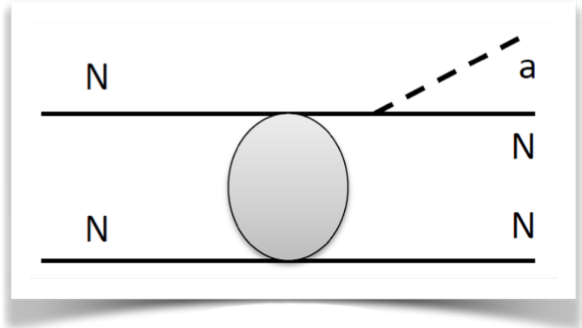
< 3.5 — Raffelt (1986)

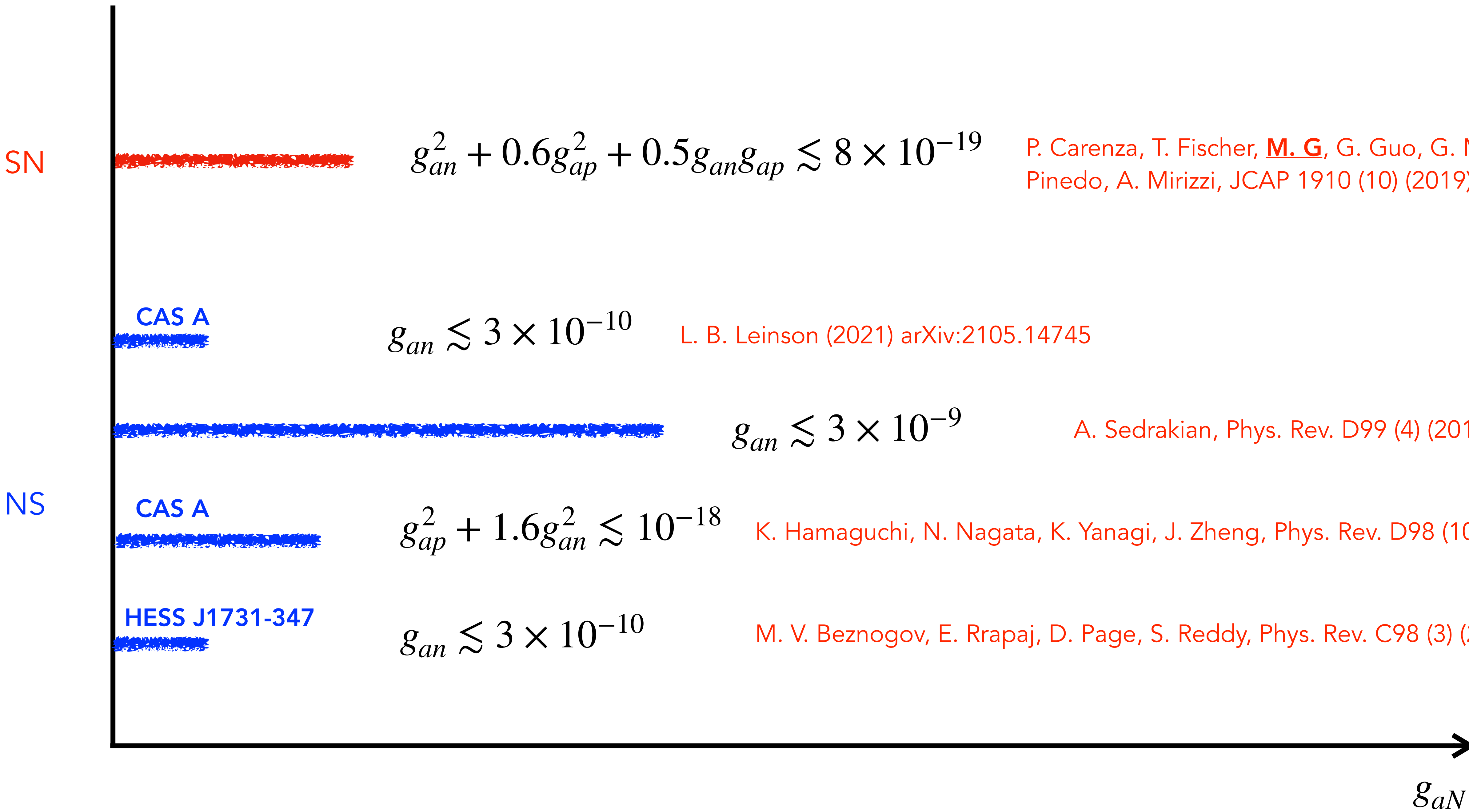
$g_{ae}\,[10^{-13}]$

Axion-nucleon coupling (g_{aN})

$$L_{aN} = -\,i g_{aN}\, a\, \bar{N} \gamma_5 N$$

Most relevant process in stars: bremsstrahlung





SN: $g_{an}^2 + 0.6 g_{ap}^2 + 0.5 g_{an} g_{ap} \lesssim 8 \times 10^{-19}$ — P. Carenza, T. Fischer, **M. G**, G. Guo, G. Martinez-Pinedo, A. Mirizzi, JCAP 1910 (10) (2019)

CAS A: $g_{an} \lesssim 3 \times 10^{-10}$ — L. B. Leinson (2021) arXiv:2105.14745

$g_{an} \lesssim 3 \times 10^{-9}$ — A. Sedrakian, Phys. Rev. D99 (4) (2019)

CAS A: $g_{ap}^2 + 1.6 g_{an}^2 \lesssim 10^{-18}$ — K. Hamaguchi, N. Nagata, K. Yanagi, J. Zheng, Phys. Rev. D98 (10) (2018)

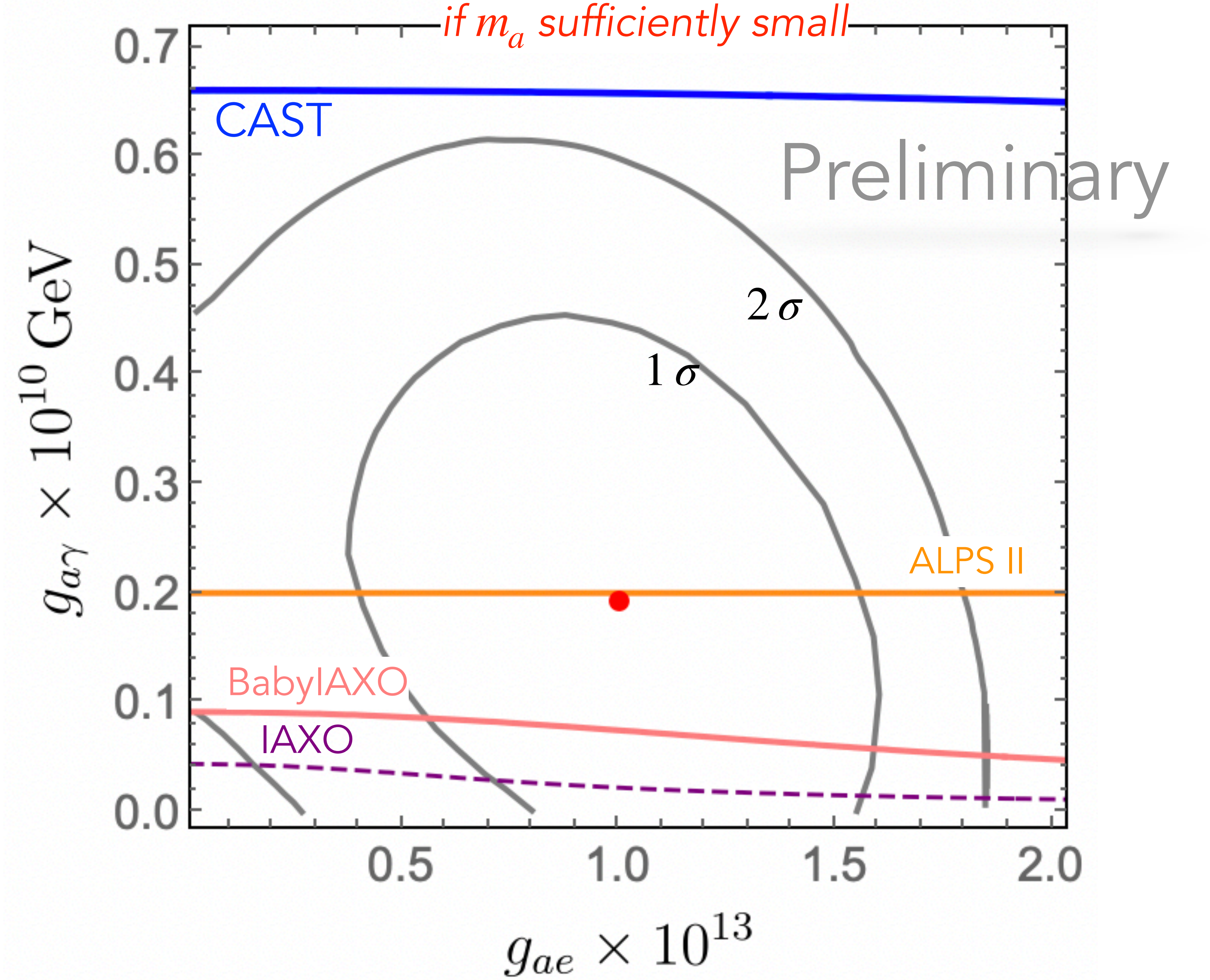
HESS J1731-347: $g_{an} \lesssim 3 \times 10^{-10}$ — M. V. Beznogov, E. Rrapaj, D. Page, S. Reddy, Phys. Rev. C98 (3) (2018)

Global fits on axion couplings (g_{ae}, $g_{a\gamma}$)

A global analysis of RGB, WDLF, WDV and R-parameter gives a preference to some energy loss unaccounted in the SM and explainable by axions coupled to photons and electrons.

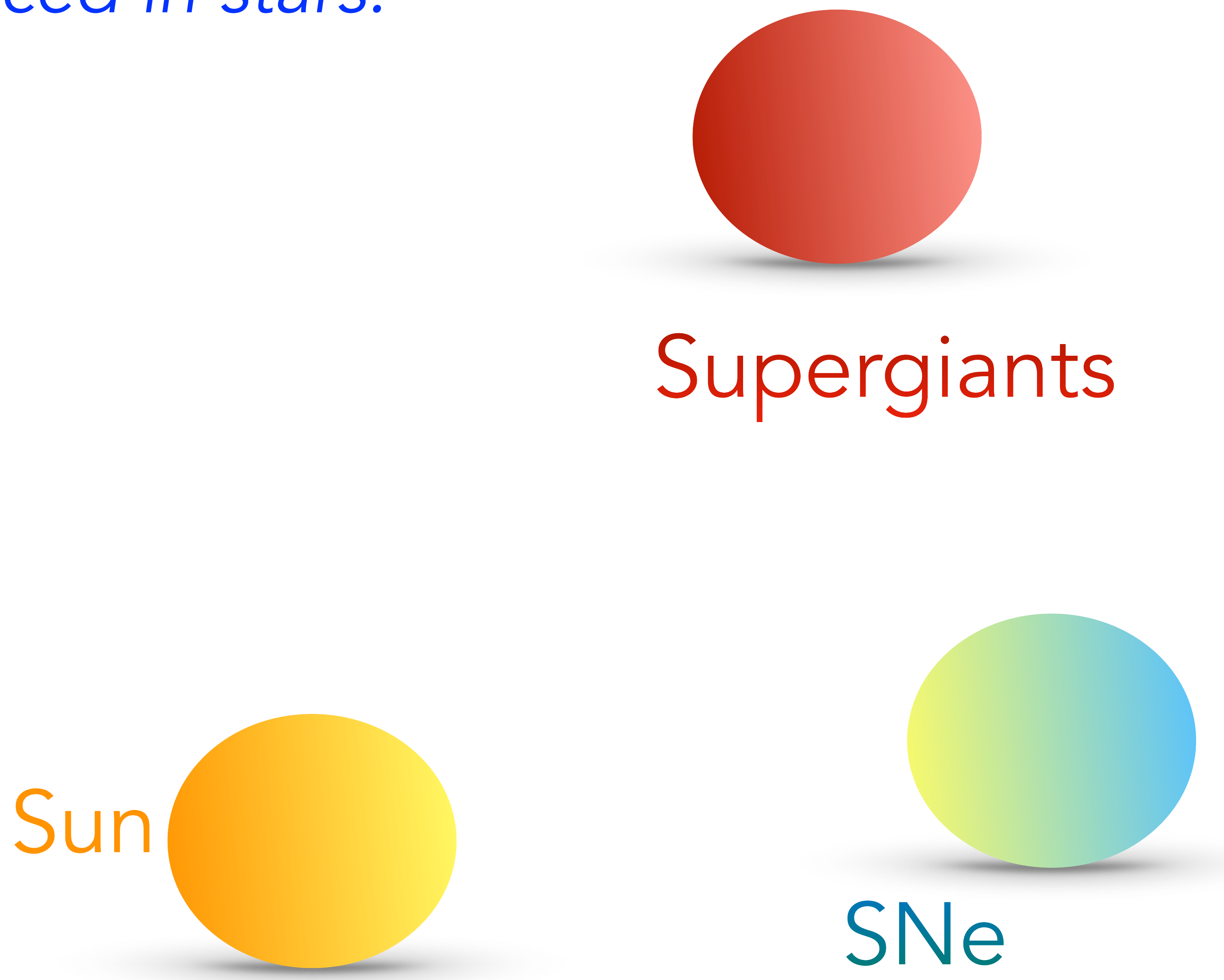
- *M.G., Irastorza, Redondo, Ringwald, Saikawa, (2017)*
- *Di Luzio, Fedele, M.G., Mescia, Nardi (in preparation)*

Couplings accessible to next gen. experiments (ALPS II, BabyIAXO), if m_a sufficiently small



Detecting stellar axions!

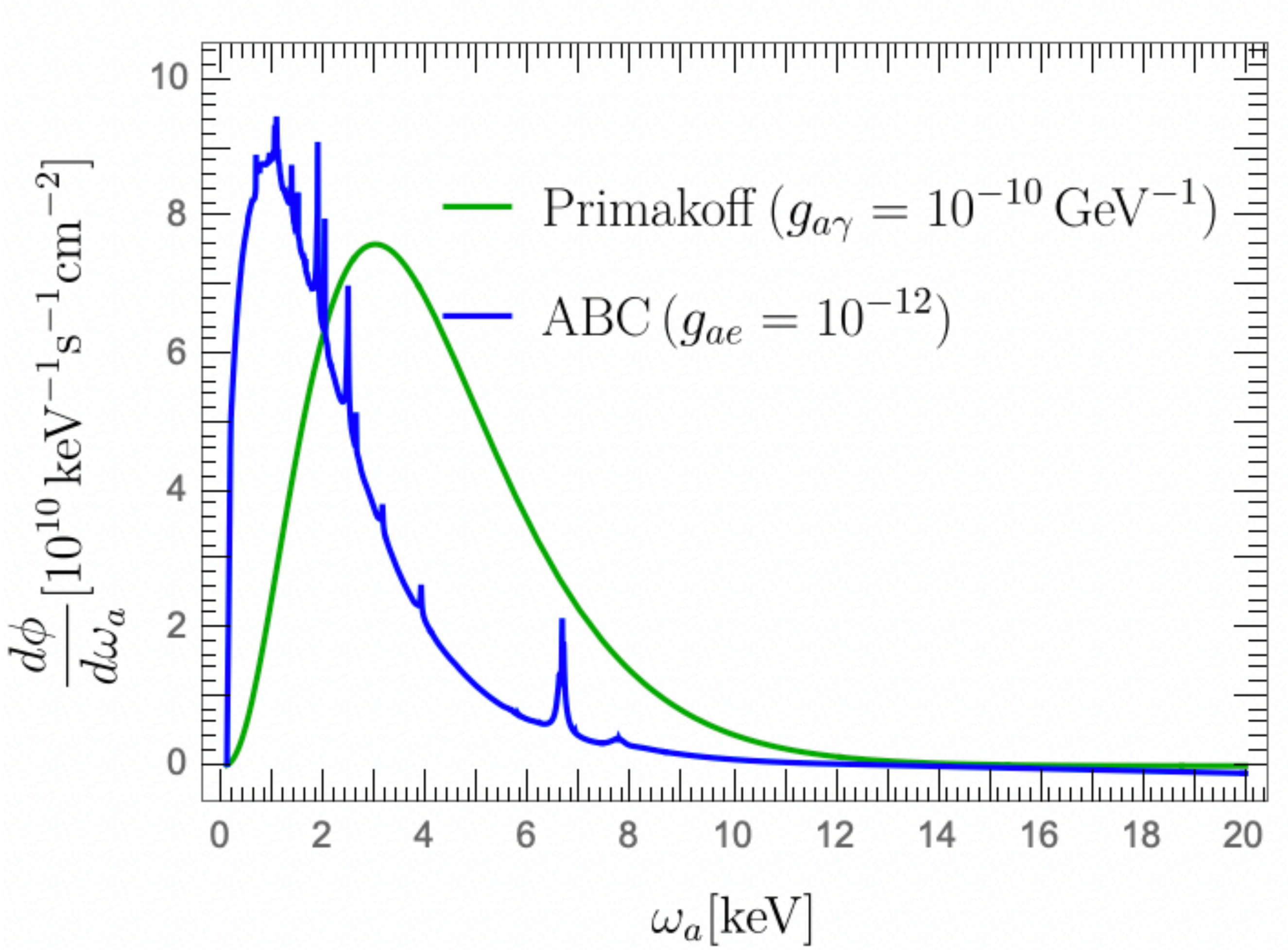
Axions are copiously produced in stars.
Can we detect them?



Solar axions

Thermal flux from $g_{a\gamma}$, g_{ae}

$$\frac{dN_a}{dt} = 1.1 \times 10^{39} \left[\left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}} \right)^2 + 0.7 \left(\frac{g_{ae}}{10^{-12}} \right)^2 \right] \mathrm{s}^{-1}$$



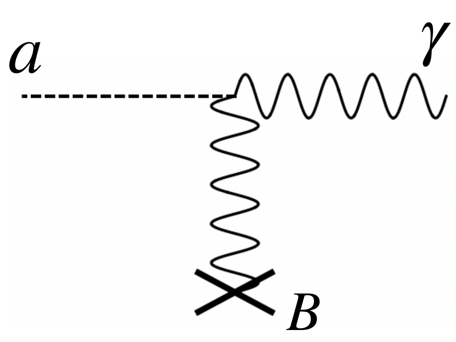
J. Redondo, JCAP 1312 (2013)

up to $\sim 10^{39}$ axions/s ($\Rightarrow 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ axions on Earth), peaked at $\sim$ keV

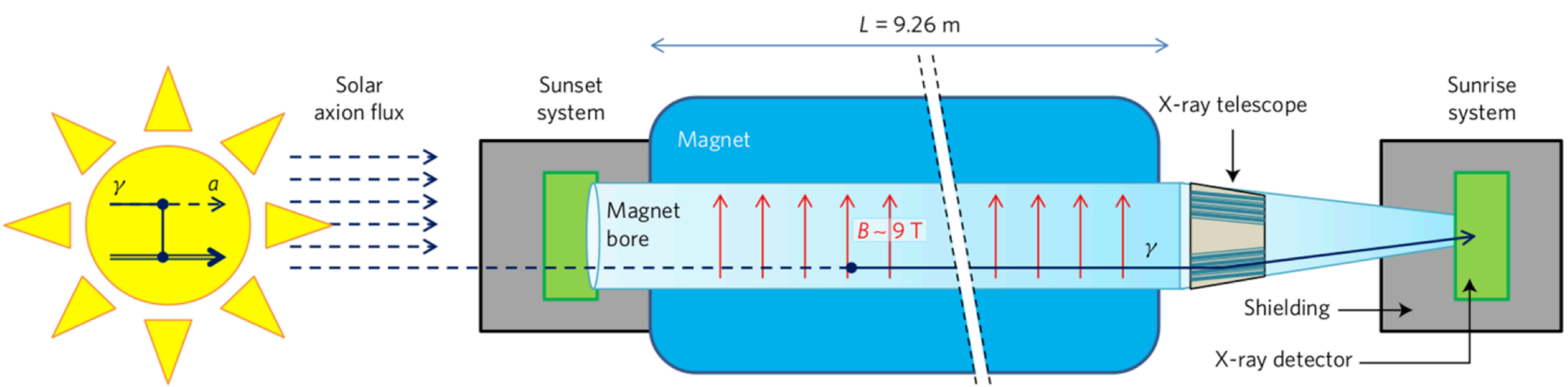
Can we observe this flux?

Hunting for solar axions

Option 1: $a \to \gamma$ in lab B-field (*Sikivie Helioscope*): CAST, IAXO, …



Coherent conversion for $m_a \lesssim 10\,\mathrm{meV}$ or so

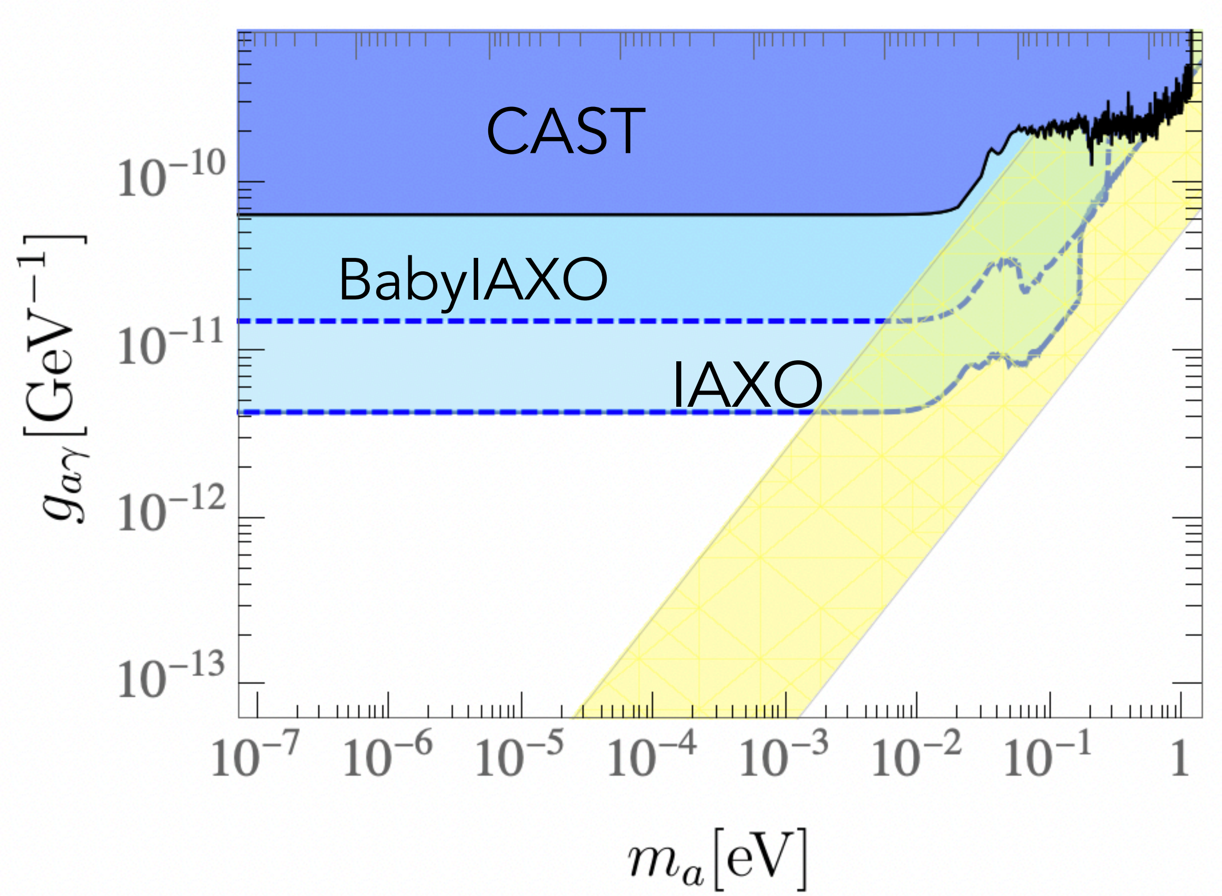


The CERN Axion Solar Telescope (CAST)

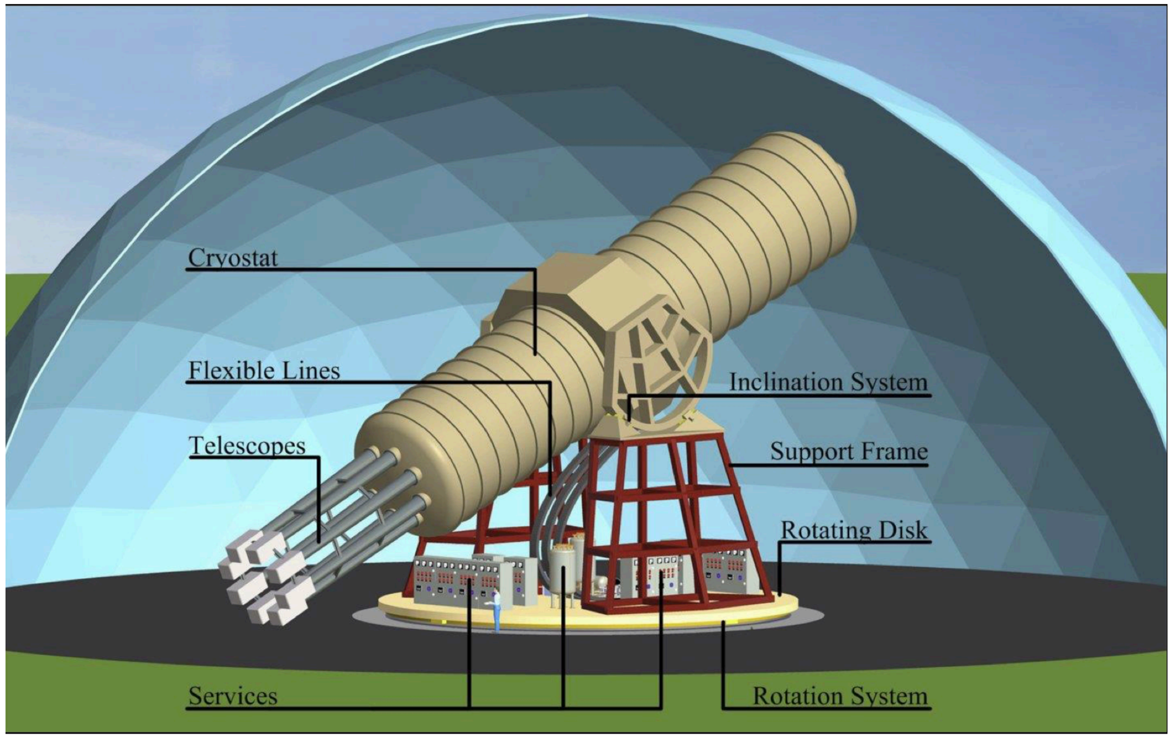
Next generation helioscopes:

IAXO

(International AXion Observatory)



Physics potential of the International Axion Observatory (IAXO) JCAP 1906 (2019) 047



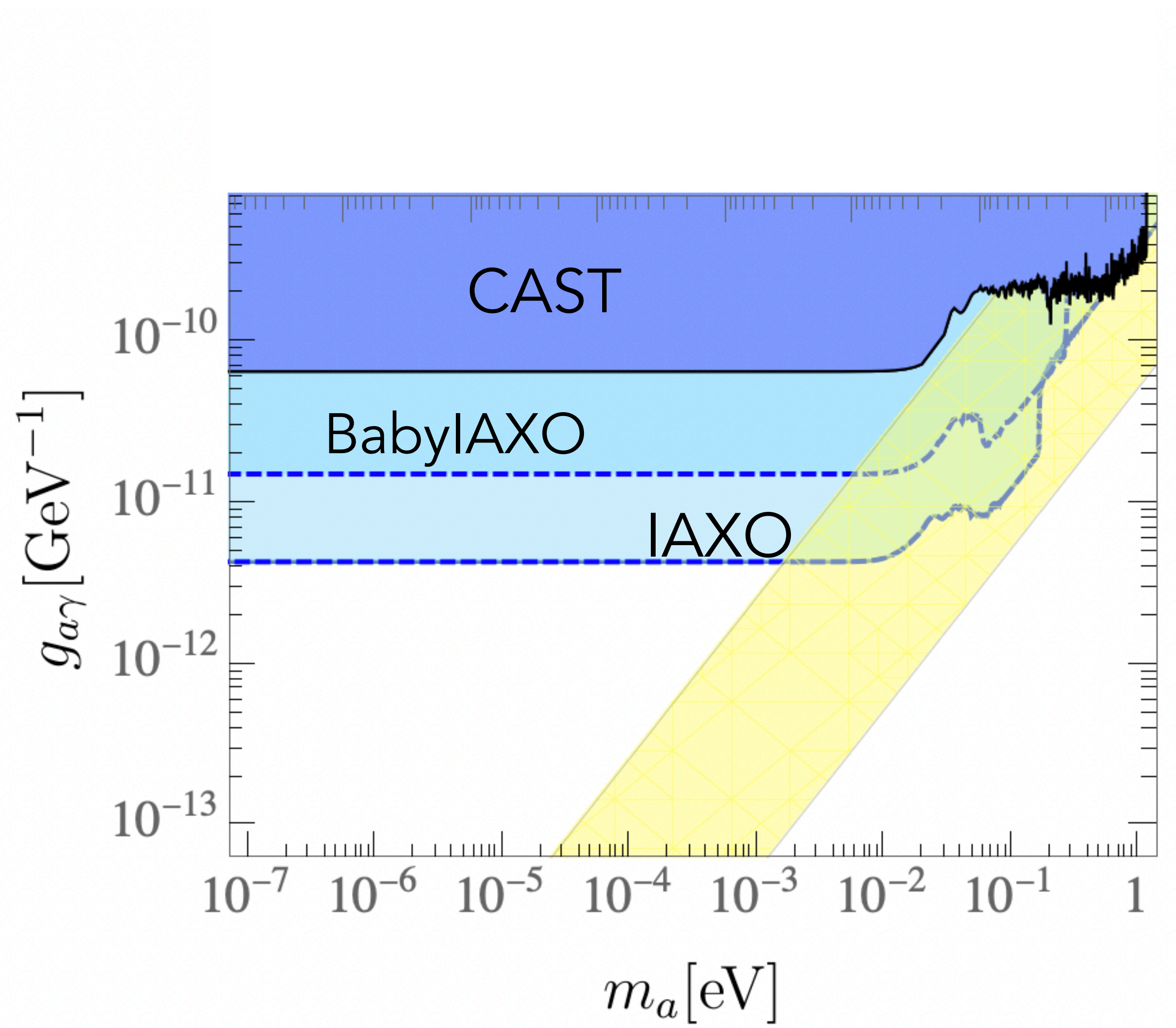
Large area: 2.3 m^2 total area (8 bores)

Each bore equipped with X-ray telescope

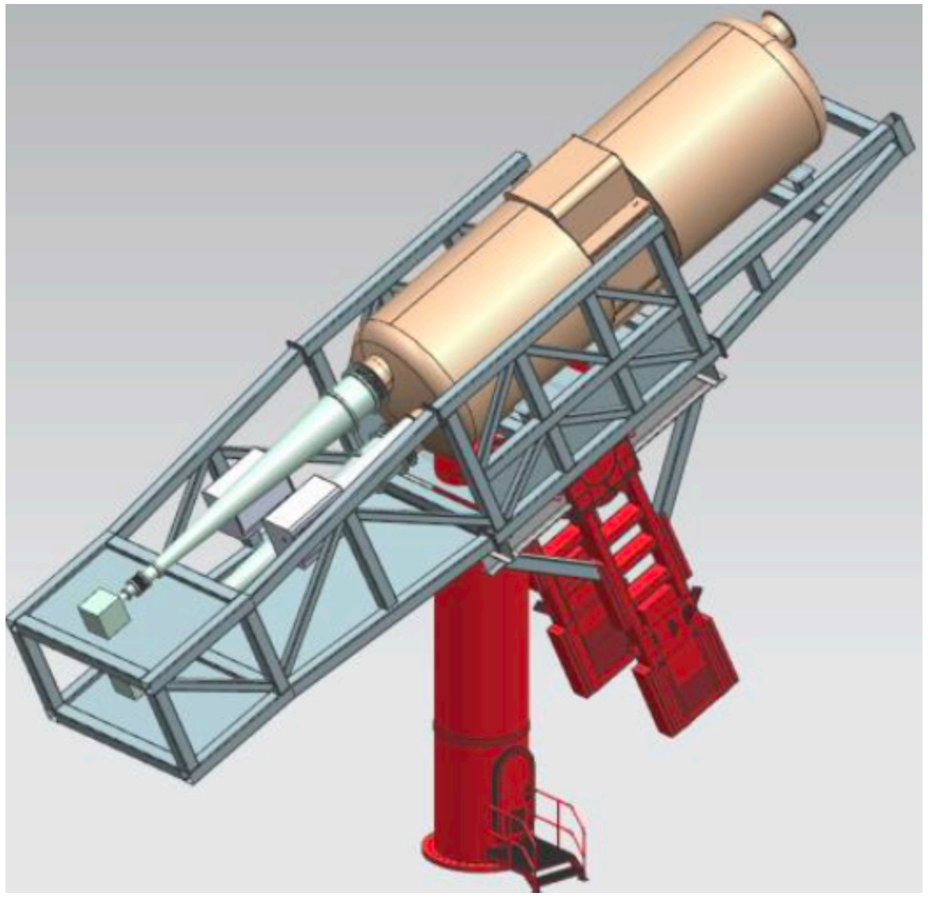
20 m long magnet, ~ 2.5 T

Next generation helioscopes:

Scale down version (BabyIAXO)
@ DESY. Data taking in 2024



Physics potential of the International Axion Observatory (IAXO) JCAP 1906 (2019) 047



0.77 m^2 total area (2 bores)

10 m long magnet, ~ 2 T

Conceptual Design of BabyIAXO, arXiv:2010.12076 (2020)

Hunting for solar axions

Option 2: Axioelectric effect: LUX, XENON1T, …

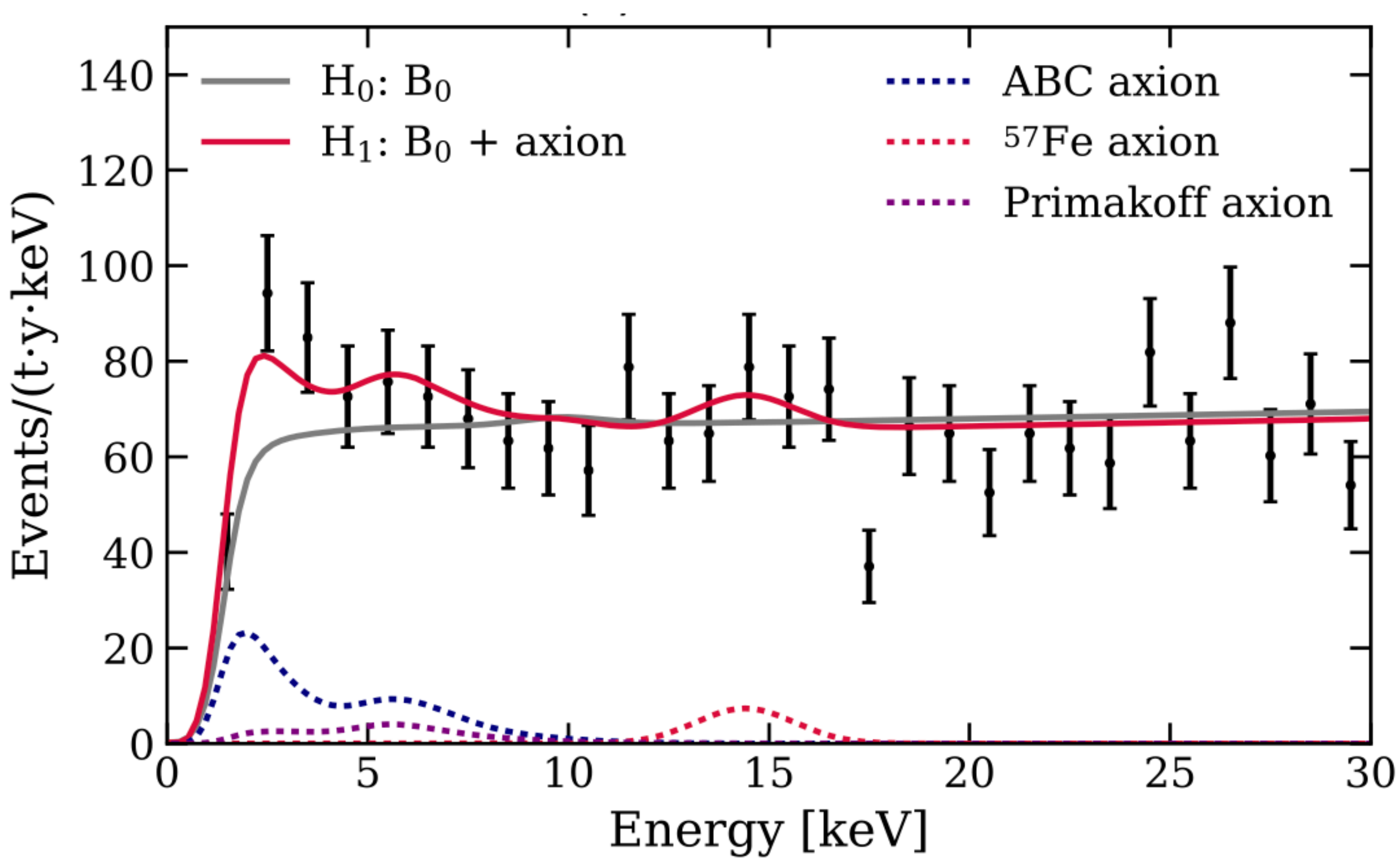
Large underground DM detectors.
Axioelectric = axion analog to the photoelectric (pe) effect

$$\sigma_{\mathrm{ae}} = \sigma_{\mathrm{pe}} \frac{g_{\mathrm{ae}}^2}{\beta} \frac{3E_{\mathrm{a}}^2}{16\pi\alpha m_{\mathrm{e}}^2} \left(1 - \frac{\beta^{2/3}}{3}\right)$$

Low energy suppression $(E_a/m_e)^2$

Excess Electronic Recoil Events in XENON1T

Solar axions?



The solar axion model has a 3.5 σ significance

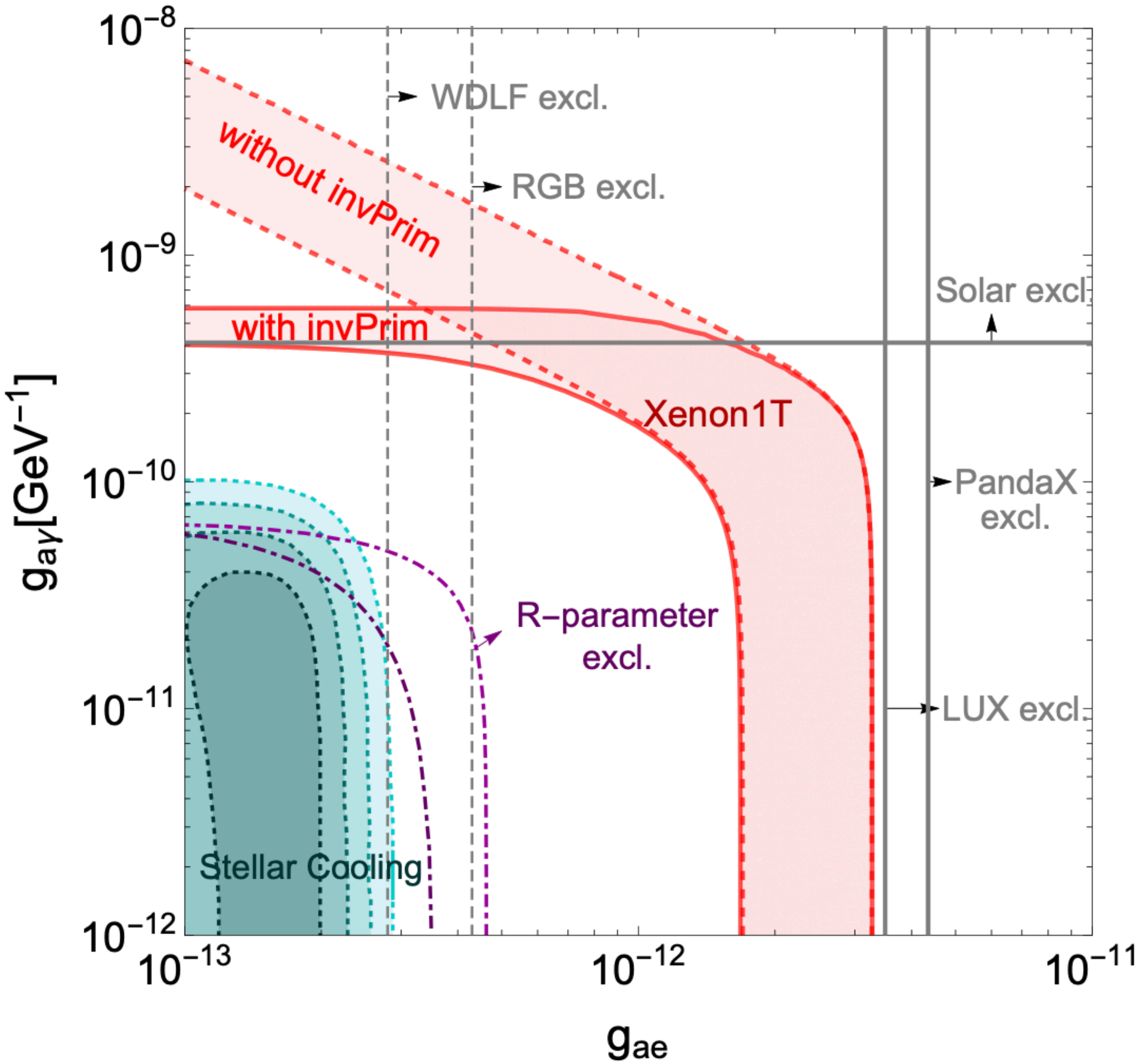
Requires $g_{ae} \sim 3 \times 10^{-12}$

… or a large coupling with photons plus a coupling with electrons

See Gao et al. Phys.Rev.Lett. 125 (2020)

E. Aprile et al., PHYSICAL REVIEW D 102, 072004 (2020)

XENON1T did not observe solar ALPs…



Gao et al. Phys.Rev.Lett. 125 (2020)

Xe1T hint ~30

Strong conflict with stars

*di Luzio, Fedele, **M.G.**, Mescia, Nardi (2020)*
Phys.Rev.Lett. 125 (2020) 13

… but we cannot exclude that it observed non-solar ALPs (e.g. DM ALPs)

Takahashi, Yamada, Yin, Phys.Rev.Lett. 125 (2020).

See also talk by Oscar Manuel Vives Garcia

Option 3: Non-Thermal solar axions. ALPs from nuclear processes

Axion nuclear interactions allow for production in nuclear fusion and nuclear de-excitation processes

Donnelly, Freedman, Lytel, Peccei, Schwartz (1978)
Barroso, Mukhopadhyay (1981)
Avignone et al. (1988)

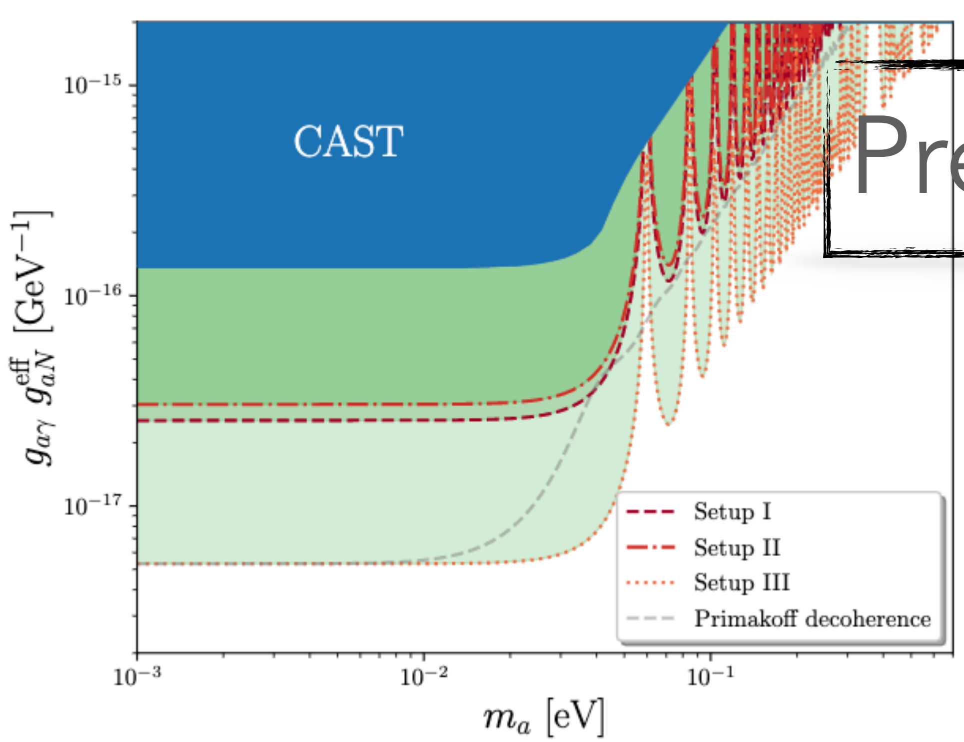
$$\mathcal{L}_{aN} = ia\overline{N}\gamma_5 \left(g^0_{aN}\mathbb{1} + g^3_{aN}\tau^3\right) N$$

Very interesting recent proposal to search for axions in SNO

Bhusal, Houston, Li, Phys.Rev.Lett. 126 (2021)

$p + n \to d + a$ ➡ $a + d \to p + n$

See talk by Nick Houston



Preliminary

Physics potential of BabyIAXO for ^{57}Fe transition currently under investigation.
Promises to probe unexplored parameter space.

Other stars?

Most stars are MS, burning H in their core, just like our sun.

Produce axions with a solar-like spectrum

Ilídio Lopes (2021) arXiv:2108.00888

In general, however, MS stars other than the sun may be not the best place to look at.

They have properties similar to our sun and the closest stars are $\gtrsim 4$ lyr.

Other stars?

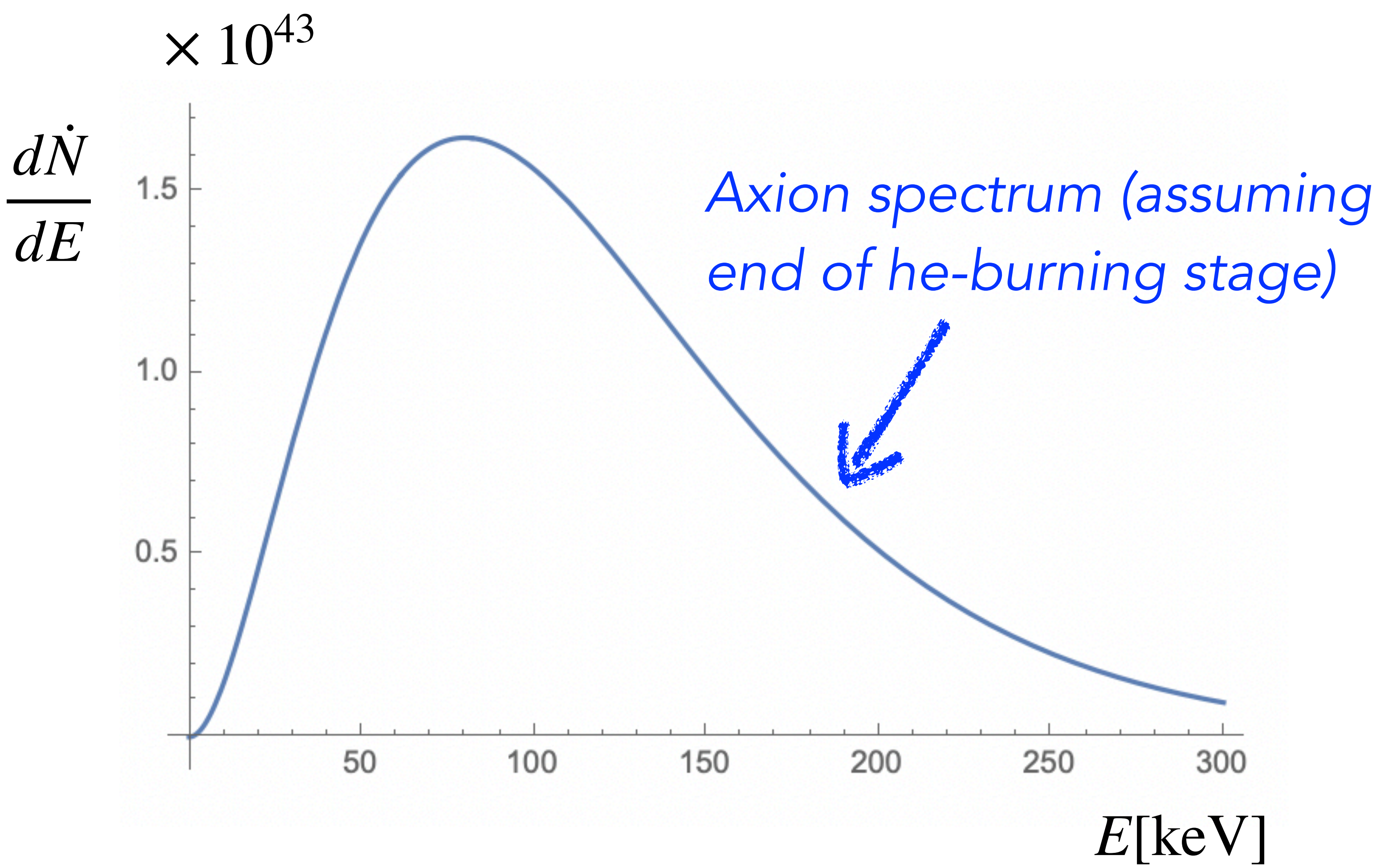
What about supergiants?

There are ~30 massive stars in advanced evolutionary stage at distance ~0.1 — 1 kpc

Massive stars in post a H-burning stage are much hotter than the sun

→ *efficient axion production*

An Example: Betelgeuse



Total: $\sim 10^{45}$ axions/s, (many more than from the sun) peaked at $\sim 100\,\mathrm{keV}$

… however, in the case of Betelgeuse (~200 pc from us) ⇒ $0(10^3)$ axions $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Too little for current experiments!

Axion telescopes for massive stars. Is it feasible?

However, axions can convert into photons in the magnetic field between us and the star

$$P_{a\gamma} = 8.7 \times 10^{-6} g_{11}^2 \left(\frac{B_T}{1\ \mu\mathrm{G}}\right)^2 \left(\frac{d}{197\,\mathrm{pc}}\right)^2 \frac{\sin^2 q}{q^2}$$

(Assuming B uniform)

$g_{11} \lesssim 6.5$ from helioscope (CAST) bound

There is a very high price to pay!

This term effetely limits to $m_a \lesssim 10^{-10}\,\mathrm{eV}$

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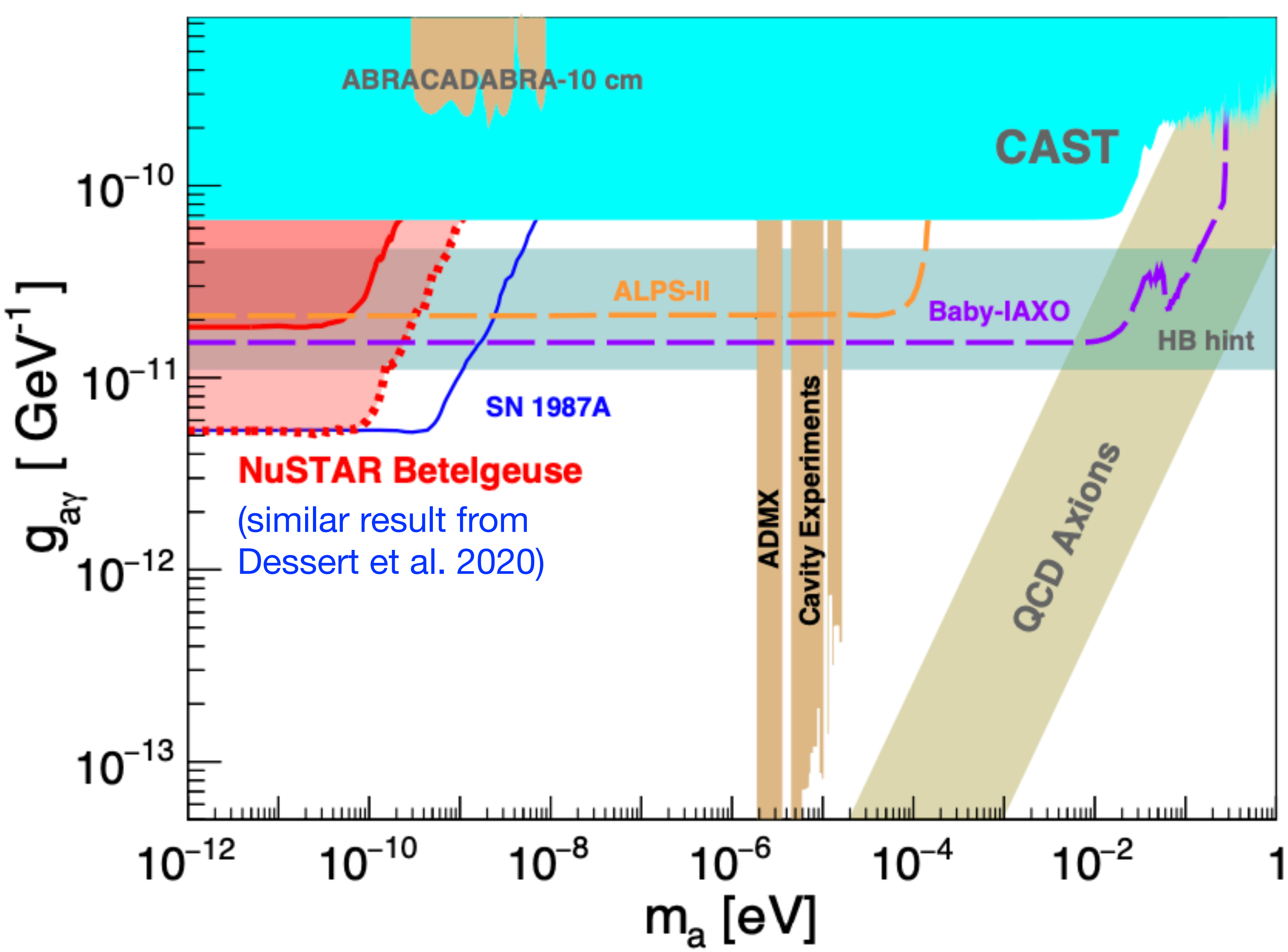
However, if we limit ourselves to $m_a \lesssim 10^{-10}\,\mathrm{eV}$, then $q \ll 1$ and the distance (practically) drops from the flux! We may get a very large flux ~ 100 keV X-rays.

Can we see massive stars with an axion telescope?

Axions from supergiants

Negative results from a dedicated NuSTAR observation of Betelgeuse



Another recent analysis searched for X-ray axion signatures from Super Star Clusters, leading to similar results

C. Dessert, J. Foster, B. Safdi, Phys.Rev.Lett. 125 (2020)

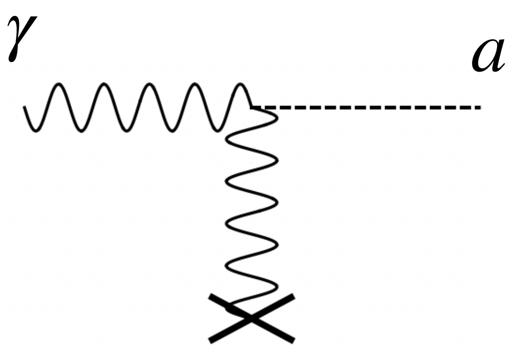
Quite remarkable results. The bound is at least 3 times stronger than CAST

*Xiao, Perez, **M.G.**, Straniero, Mirizzi, Grefenstette, Roach, Nynka, Phys.Rev.Lett. 126 (2021)*

NASA Grant No. 80NSSC20K0031

Supernova axions

Extreme environment $\rho \sim 3 \times 10^{14}\,\mathrm{g\,cm^{-3}}$, $T \sim 30$ MeV.

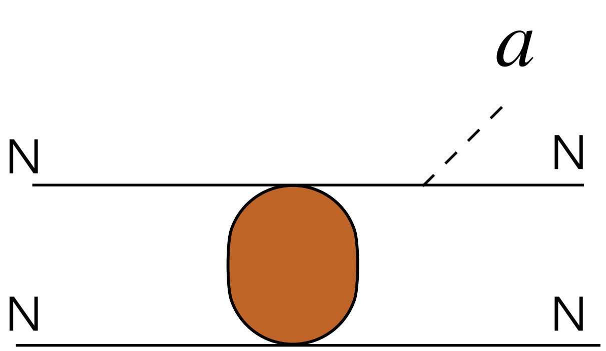


Primakoff requires $\propto g_{a\gamma}^2$

J. Brockway, E. Carlson, G. Raffelt, Phys. Lett. B 383, 439 (1996);

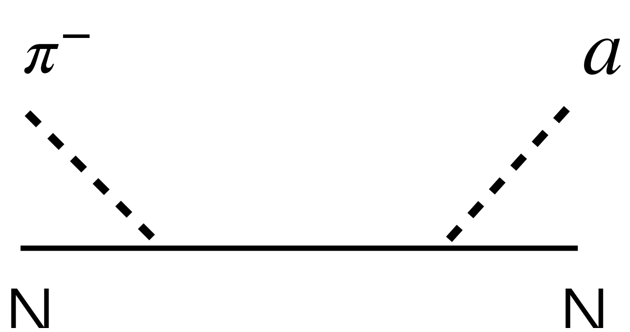
J. Grifols, E. Masso, R. Toldra, Phys. Rev. Lett. 77, 2372 (1996)

*A. Payez, C. Evoli, T. Fischer, **M.G.**, A. Mirizzi, A. Ringwald, JCAP 1502 (2015).*



Bremsstrahlung $\propto g_{aN}^2$

*P. Carenza, T. Fischer, **M.G.**, G. Guo, G. Martinez-Pinedo, A. Mirizzi, JCAP 10 (2019) 10, 016*



Pion induced $\propto g_{aN}^2$

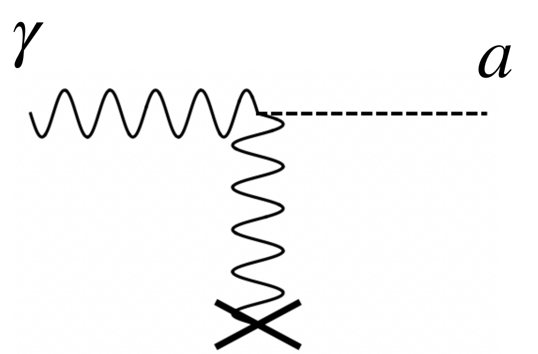
*P. Carenza, B. Fore, **M.G.**, A. Mirizzi, S. Reddy, (2020) [arXiv:2010.02943]*

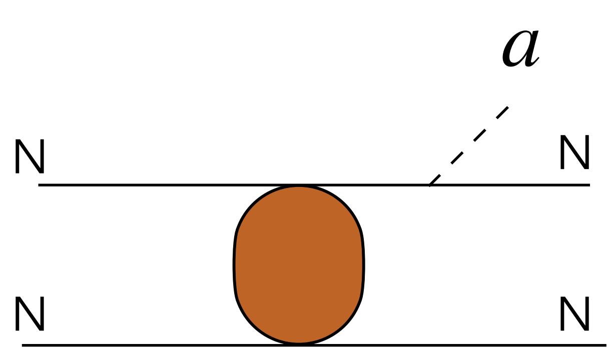
Pion abundance was underestimated. Breakthrough result in

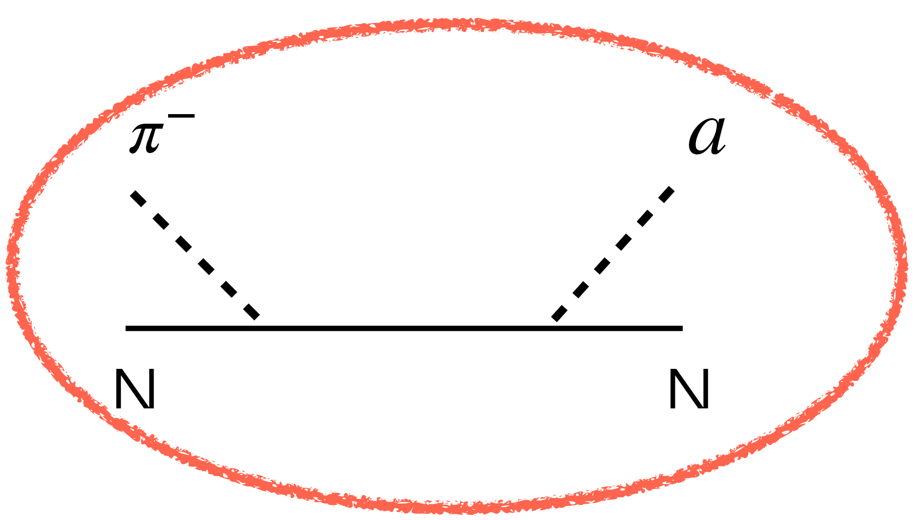
B. Fore and S. Reddy, Phys. Rev. C 101, 035809 (2020)

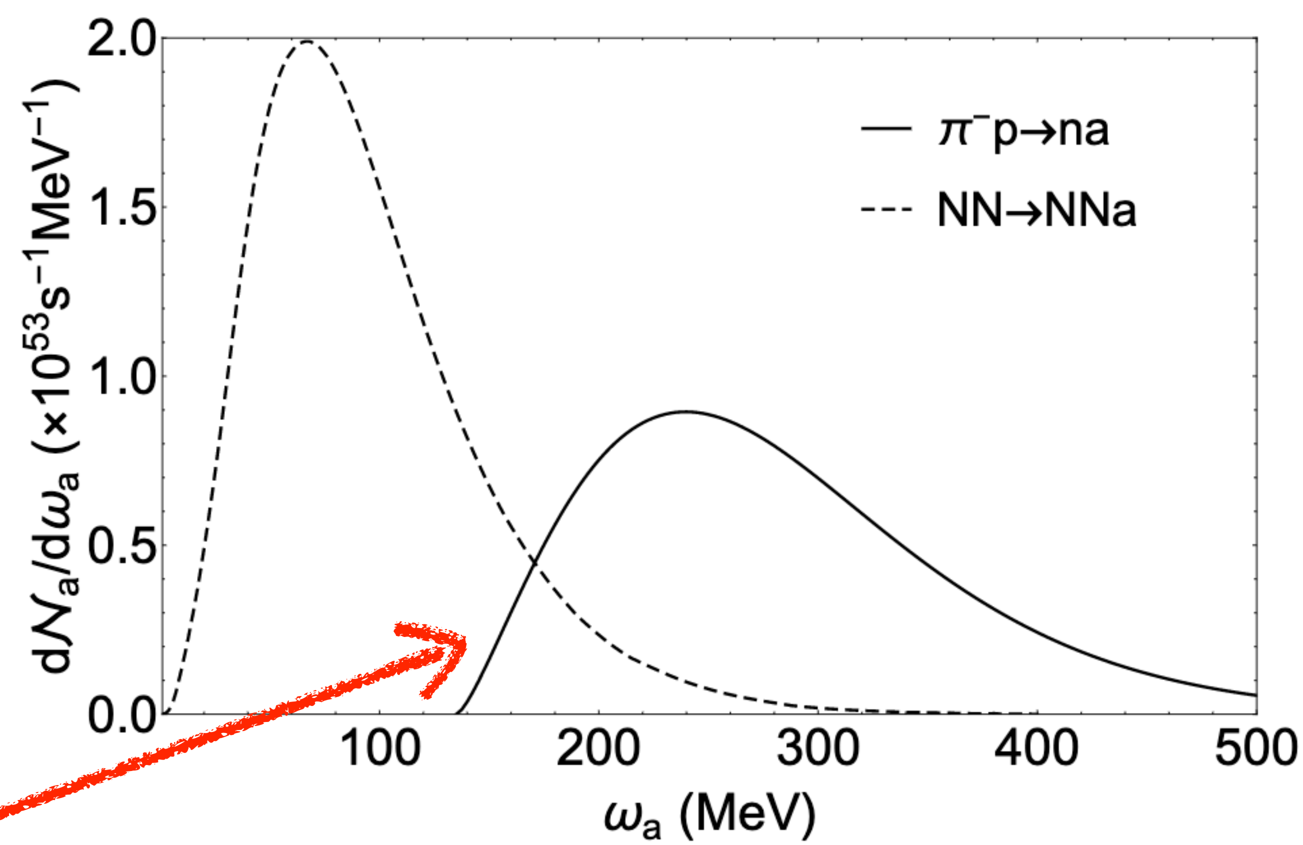
Supernova axions

Extreme environment $\rho \sim 3 \times 10^{14}\,\mathrm{g\,cm^{-3}}$, $T \sim 30$ MeV.









Harder spectrum: opens possible detection channel through pions in water Cherenkov detectors

- *P. Carenza, B. Fore, **M.G.**, A. Mirizzi, S. Reddy, Phys.Rev.Lett. 126 (2021)*
- *Fisher, Carenza, Fore, **M.G.**, Lucente, Mirizzi, Reddy, (submitted to PRD, 2021)*

Detecting Supernova axions

General criterion (Raffelt) from observed ν-signal form SN 1987A:

$$\varepsilon_x \lesssim 10^{19}\,\mathrm{erg\,g^{-1}s^{-1}} \qquad @ \qquad \rho = 3\times10^{14}\,\mathrm{g\,cm^{-3}},\ T = 30\,\mathrm{MeV}$$

$\Rightarrow \sim 10^{52}\,\mathrm{erg/s}$ for ~10 s in axions

Corresponds to $\sim 10^{56}\,\mathrm{axions/\,s}$.

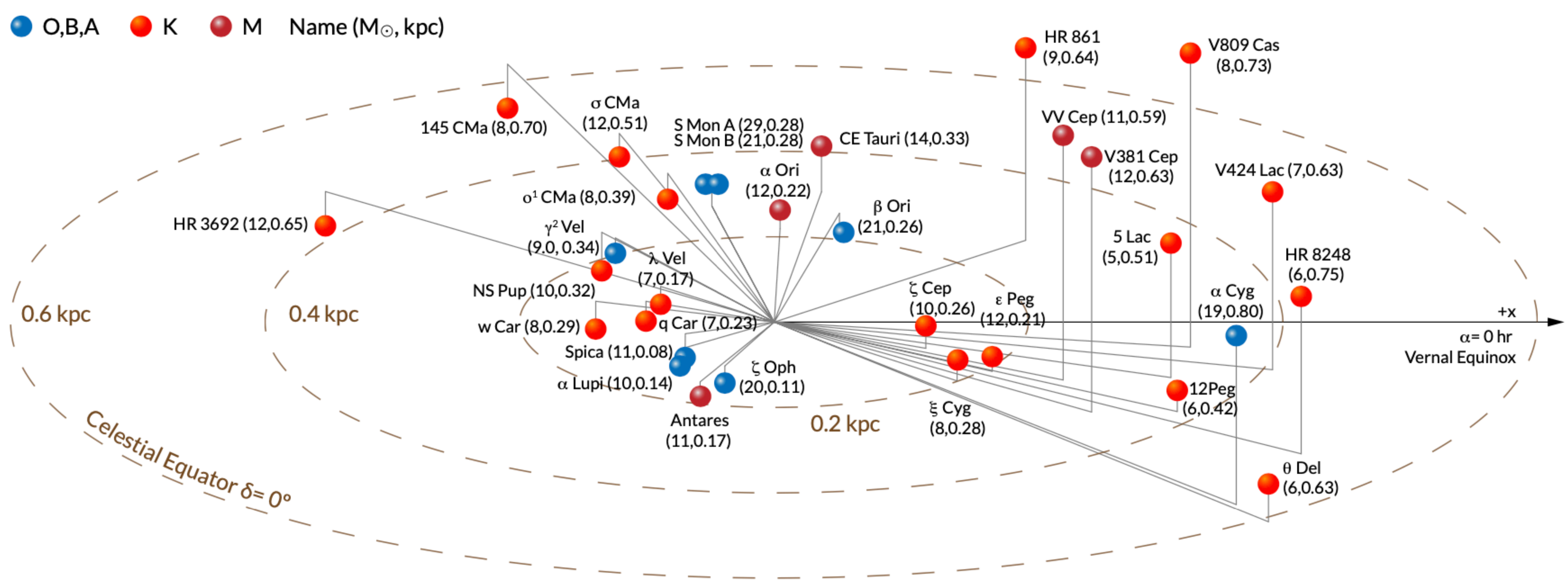
About $\sim 10^{13}\,\mathrm{cm^{-2}\,s^{-1}}$ axions on Earth from Betelgeuse

Huge flux… but short!

Where should we look ?

Very comprehensive recent analysis on identification of (near) SN from pre-SN neutrinos

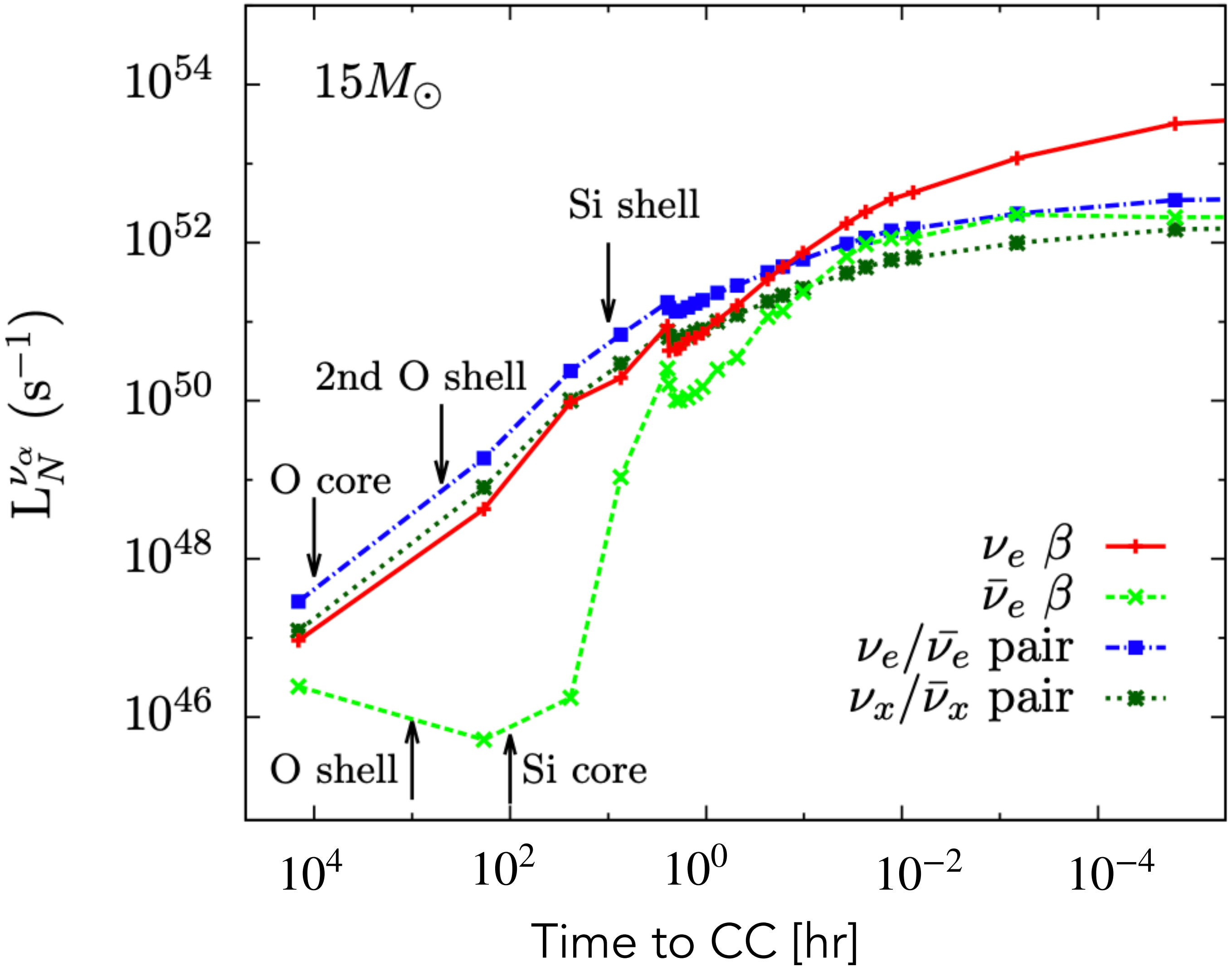
M. Mukhopadhyay, C. Lunardini, F.X. Timmes, K. Zuber, Astrophys.J. 899 (2020)



31 candidates within 1 kpc from the sun.

Pre-SN signal

Neutrinos are produced from thermal and beta processes.



K .M. Patton. C. Lunardini, R. Farmer and F. X. Timmes, ApJ 851 (2017)

Pre-SN signal

Major difficulty: angular resolution.
Improves with use of Liquid Scintillator (LS) detector with a Lithium compound dissolved (LS-Li)

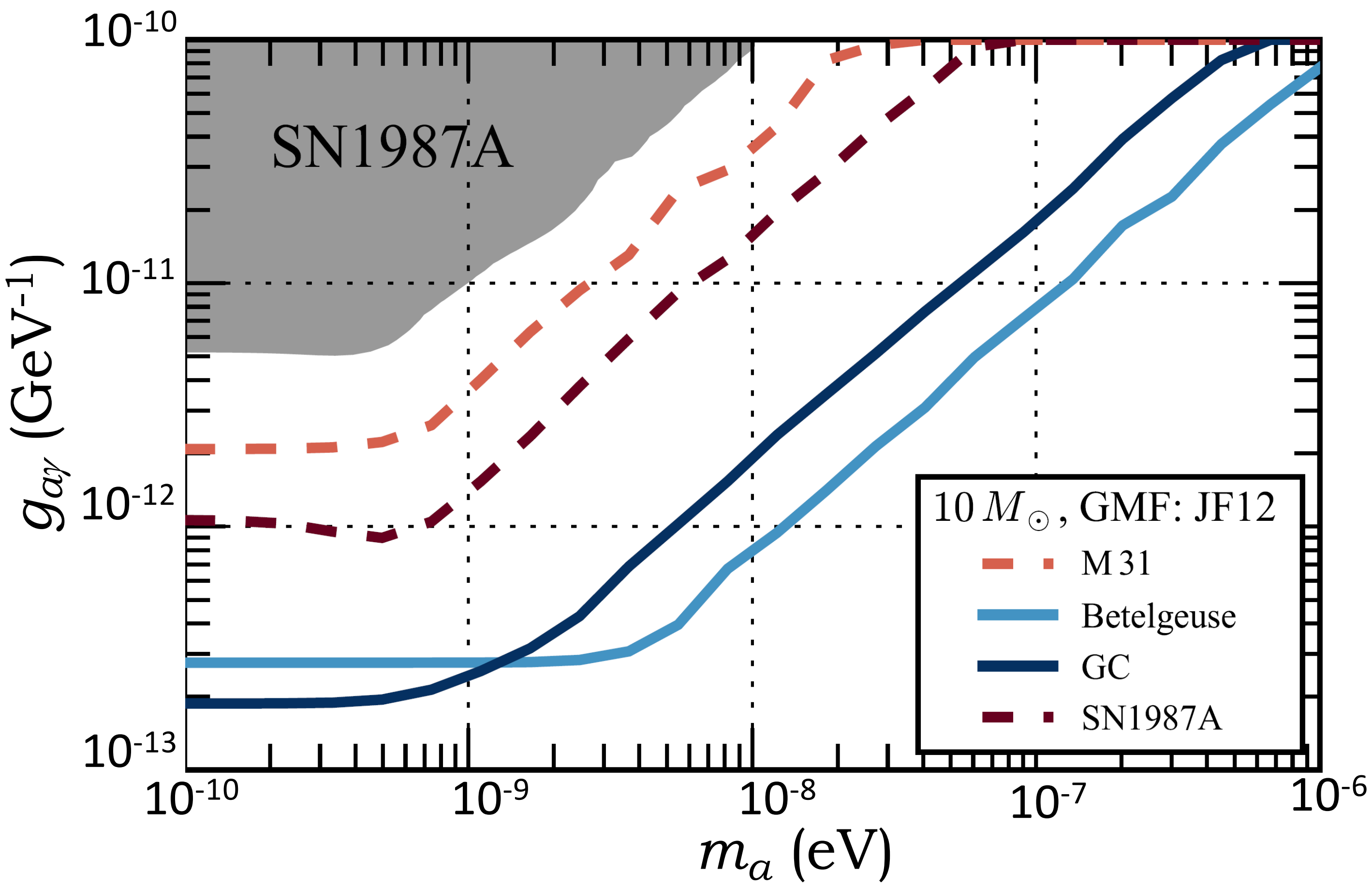
Tanaka & Watanabe (2014)

Betelgeuse				LS		LS-Li	
Time to CC	N_{Total}	N_{Signal}	N_{Bkg}	68% C.L.	90% C.L.	68% C.L.	90% C.L.
4.0 hr	93	78	15	78.43°	116.17°	23.24°	33.98°
1.0 hr	193	170	23	63.92°	98.42°	15.47°	22.26°
2 min	314	289	25	52.72°	81.79°	11.63°	16.67°

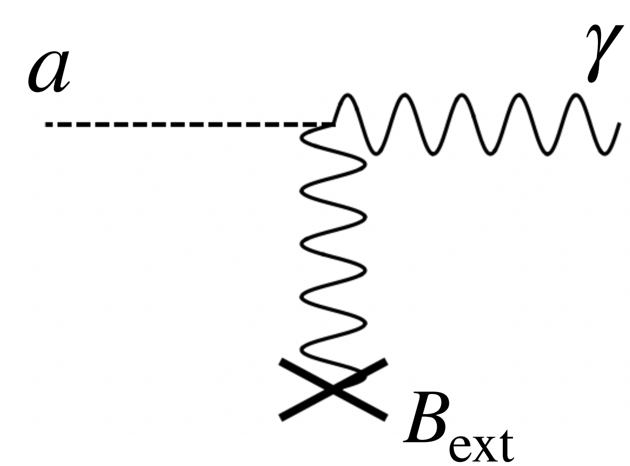
Adapted from: M. Mukhopadhyay, C. Lunardini, F.X. Timmes, K. Zuber, Astrophys.J. 899 (2020)

- Betelgeuse is 11.6° from S Monoceros A, B (~280 pc)

Fermi LAT as Axion SN-Scope



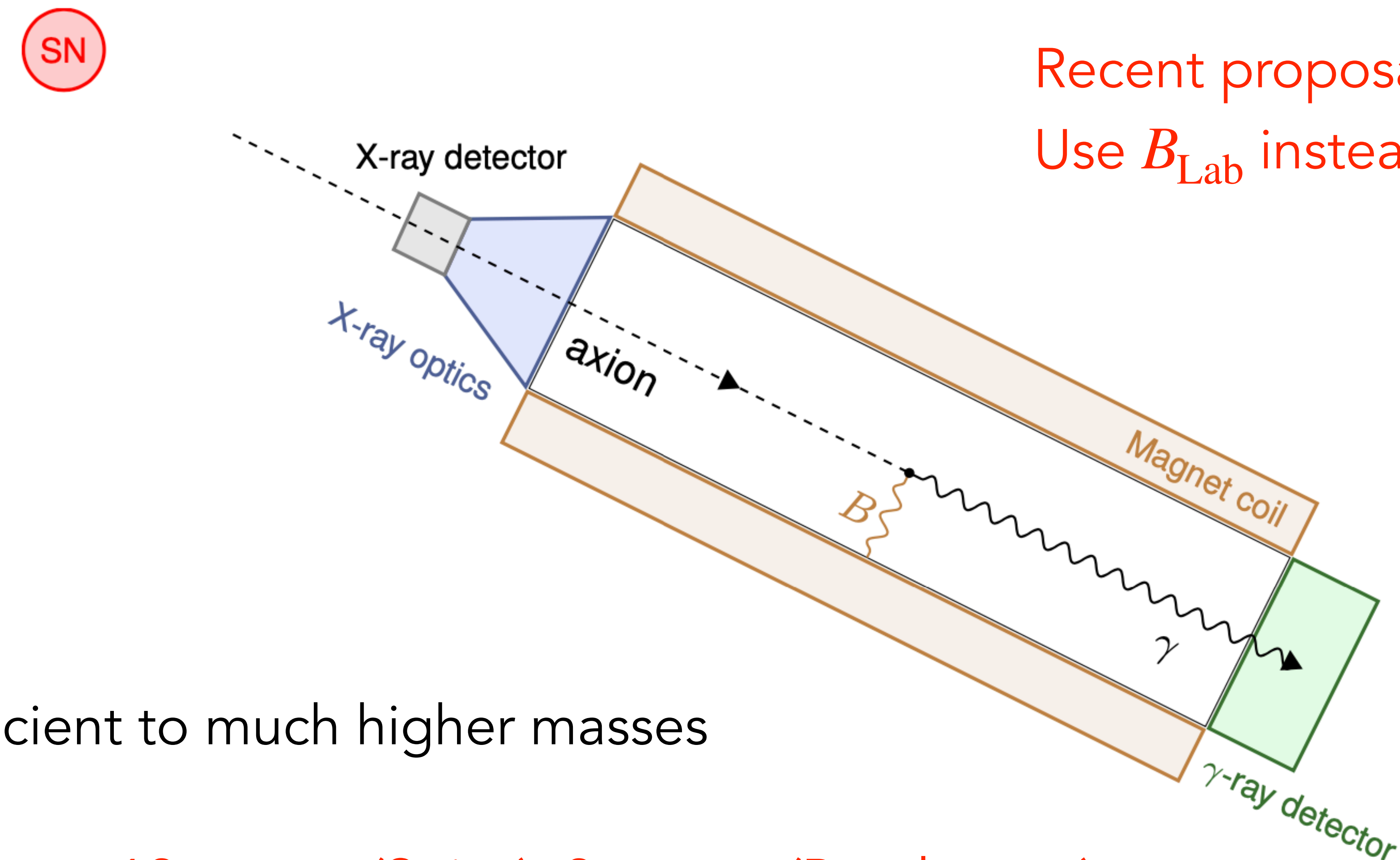
SN axions → photons in galactic B



Very efficient at low mass

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

Helioscopes as Axion SN-Scopes



Recent proposal.
Use $B_{\rm Lab}$ instead of $B_{\rm galactic}$

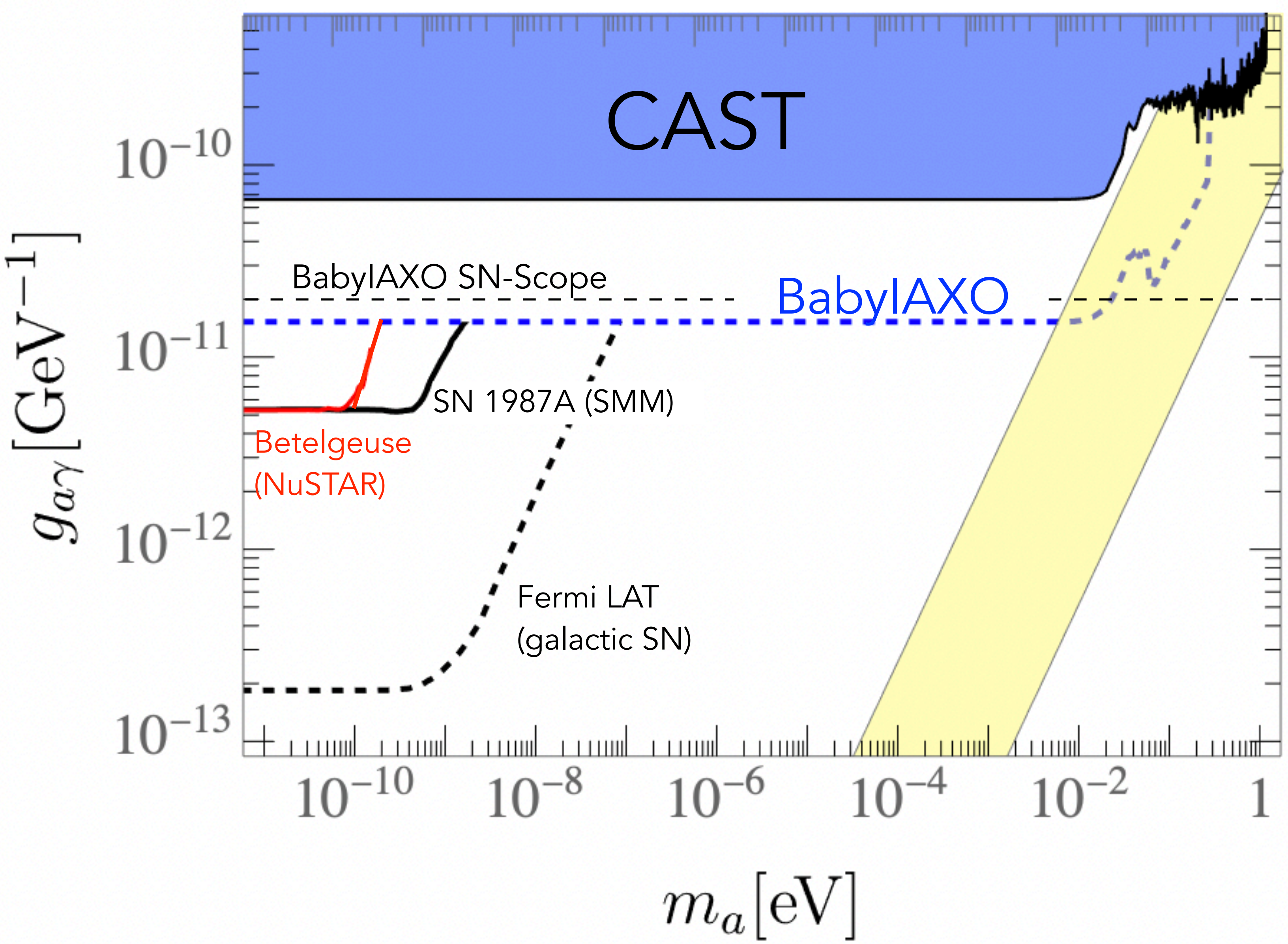
Axion helioscope
turned around

Efficient to much higher masses

Up to ~12 events (Spica), 2 events (Betelgeuse)
with BabyIAXO setup

Ge, Hamaguchi, Ichimura, Ishidoshiro, Kanazawa, JCAP 11 (2020)

Summary: Detecting stellar axions



Legend:

Solar Axion

Pre-SN Axions

SN Axions

Current bounds

Estimated sensitivities

Benchmark QCD models

Conclusions and final considerations

- Strong axion bounds from stellar evolution. Great advancements thanks to Gaia. More to expect from future probes, e.g. the Vera Rubin (former LSST) telescope

- Combined analysis of stellar evolution indicates some hints in regions accessible to next generation axionscopes

- Observations of solar and non-solar axions help explore new parameter space and perhaps detect axions/ALPs.

- *Exiting time. Many new results and ideas in 2020/2021*