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Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

INFN

Missione 4 Istruzione e Ricerca

Maurizio Giannotti

(University of Zaragoza)

Perspectives on the Detection of Solar and Other Stellar Axions

25/01/2024

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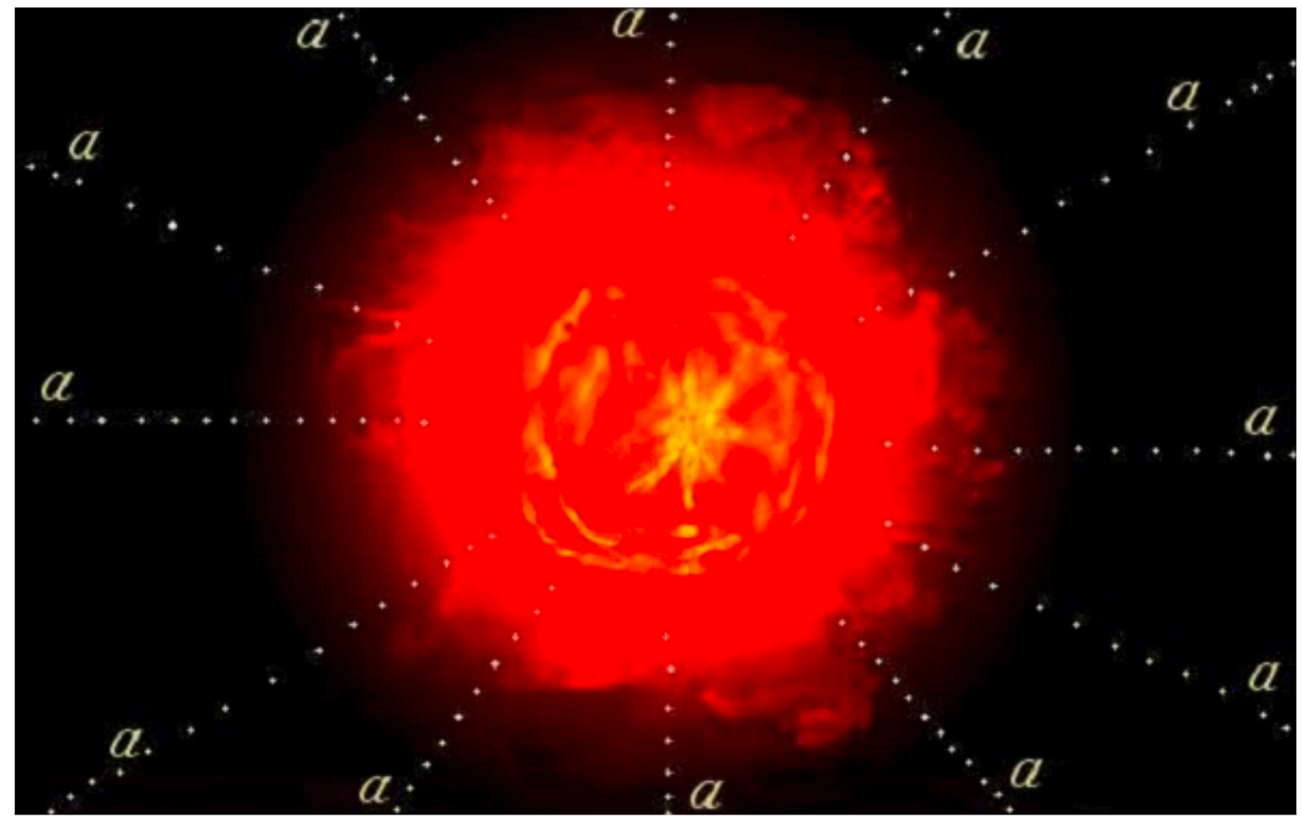
Perspectives on the Detection of Solar and Other Stellar Axions

Maurizio Giannotti
University of Zaragoza, CAPA



AxionOrigins Kickoff Meeting,
INFN-LNF, 25–26 January 2024

Summary

- *Axions from the Sun: News and prospectives*
- *Axions as telescopes for supergiants*
- *SN axions*

Axions

Cosmology

Dark Matter

Particle Physics

Strong-CP problem

Astrophysics

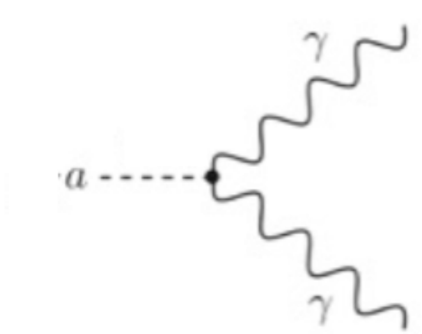
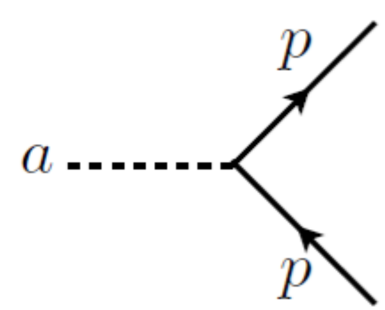
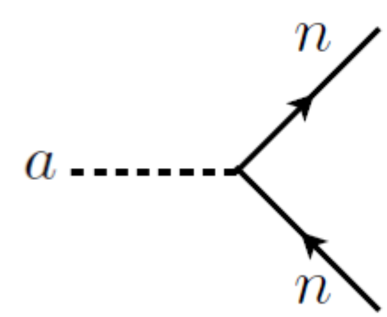
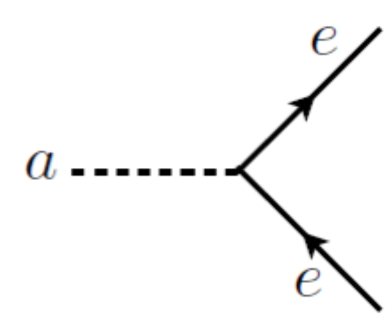
Stellar evolution; Cooling anomalies;
Transparency hints (ALPS)

We may detect them soon!
Experimental capabilities to search in well motivated regions of the parameters …

World-wide effort to detect it.

Axions and ALPs

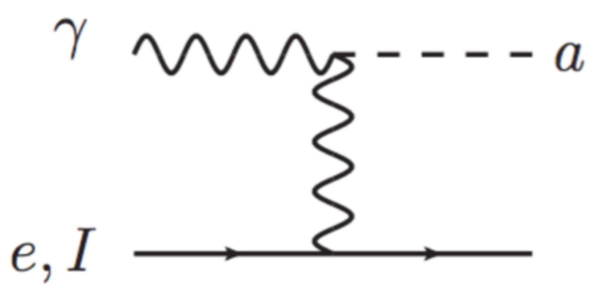
Axions (and ALPs) interact with SM fields. This allow for a rich and interesting phenomenology, and for their possible detection

2 photon	proton	neutron	electron
$\frac{\alpha C_{a\gamma}}{2\pi}\frac{a}{f_a}\frac{F_{\mu\nu}\widetilde{F}^{\mu\nu}}{4} +$	$C_{ap} m_p \frac{a}{f_a}[i\bar{p}\gamma_5 p] +$	$C_{an} m_n \frac{a}{f_a}[i\bar{n}\gamma_5 n] +$	$C_{ae} m_e \frac{a}{f_a}[i\bar{e}\gamma_5 e] +$
			

$g_{a\gamma} = \frac{C_{a\gamma}\alpha}{2\pi f_a}$ $\quad g_{ap} = C_{ap}\frac{m_p}{f_a}$ $\quad g_{ap} = C_{an}\frac{m_n}{f_a}$ $\quad g_{ap} = C_{ae}\frac{m_e}{f_a}$

Axions and ALPs

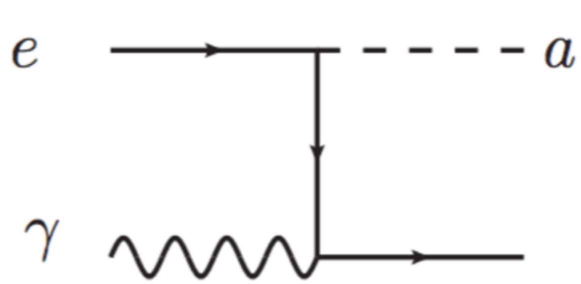
Most relevant axion channels



Primakoff

$$\rightarrow \varepsilon_P \simeq 2.8 \times 10^{-31} F(\xi) \left(\frac{g_{a\gamma}}{\mathrm{GeV}^{-1}} \right)^2 \frac{T^7}{\rho} \,\mathrm{erg\ g^{-1}\ \ s^{-1}}$$

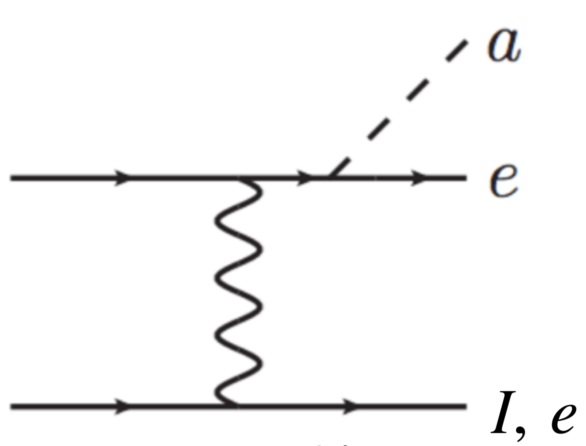
with T in K and ρ in $\mathrm{g\,cm^{-3}}$, and $F(\xi)$ is $\mathcal{O}(1)$. Valid in nondegeneratae plasma



Compton

$$\rightarrow \varepsilon_C \simeq 2.7 \times 10^{-22} g_{ae}^2 \frac{1}{\mu_e} \left(\frac{n_e^{\mathrm{eff}}}{n_e} \right) T^6 \,\mathrm{erg\ g^{-1}\ \ s^{-1}}$$

where n^{eff} takes into account degeneracy effects. Competitive with bremsstrahlung at low ρ and high T



Bremsstrahlung

$$\rightarrow \varepsilon_B \simeq 8.6 \times 10^{-7} F_B g_{ae}^2 T^4 \left(\sum \frac{X_j Z_j^2}{A_j} \right) \mathrm{erg\,g^{-1}\ \ s^{-1}}$$

valid in degenerate plasma conditions. The function F_B takes into account the mild density dependence of the degenerate rate

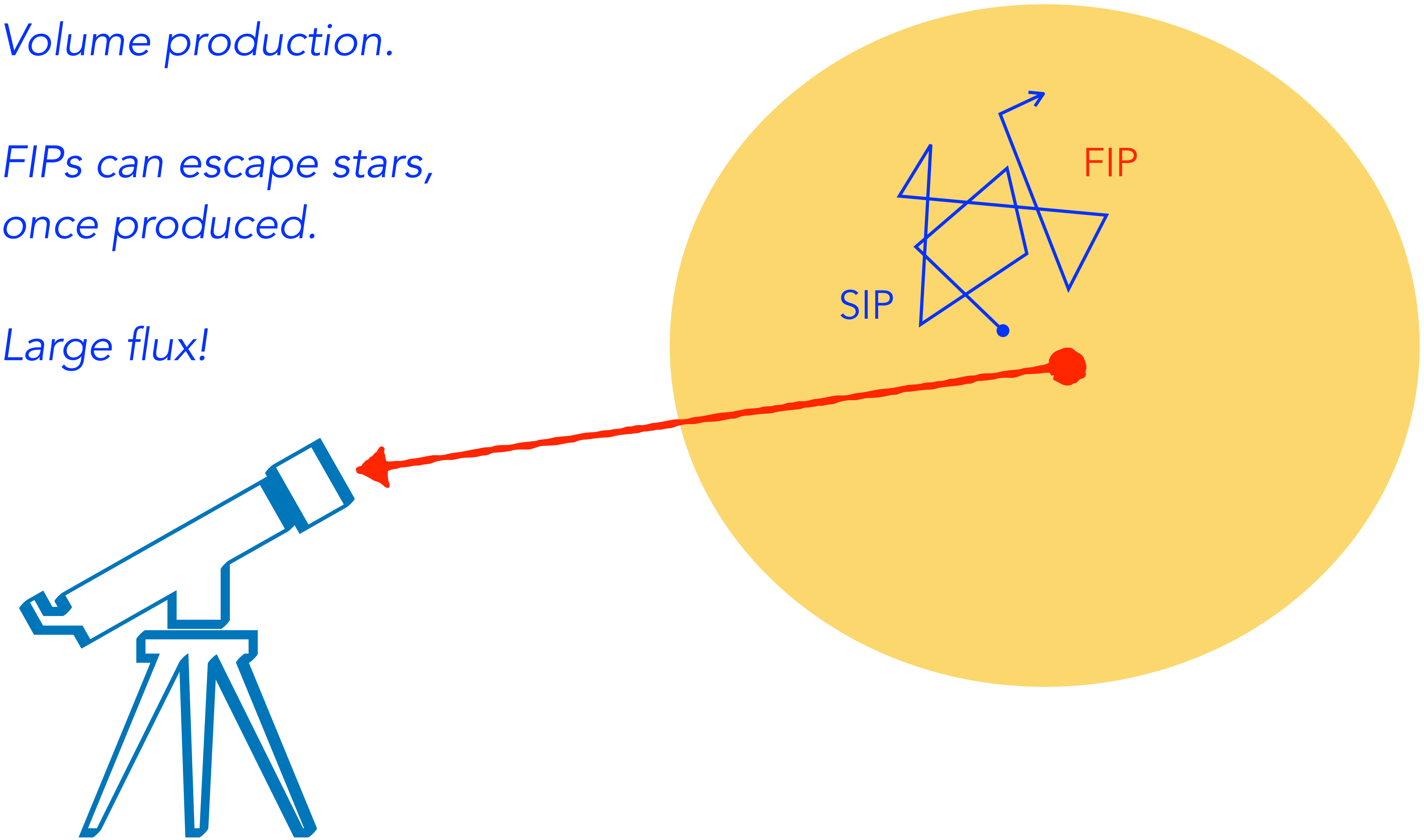
Di Luzio, Fedele, M.G., Mescia, Nardi, JCAP 02 (2022) 02, 035

Stars as FIPs Factories

Volume production.

FIPs can escape stars, once produced.

Large flux!



Axions as Astro Messengers

Detecting stellar axions would allow to understand a lot about stars.

- Solar magnetic field

C. A. J. O'Hare, A. Caputo, A. J. Millar, E. Vitagliano Phys.Rev.D 102 (2020) 4

- Solar temperature profile

S. Hoof, J. Jaeckel, L. J. Thormaehlen, arXiv:2306.00077

- Solar chemical composition

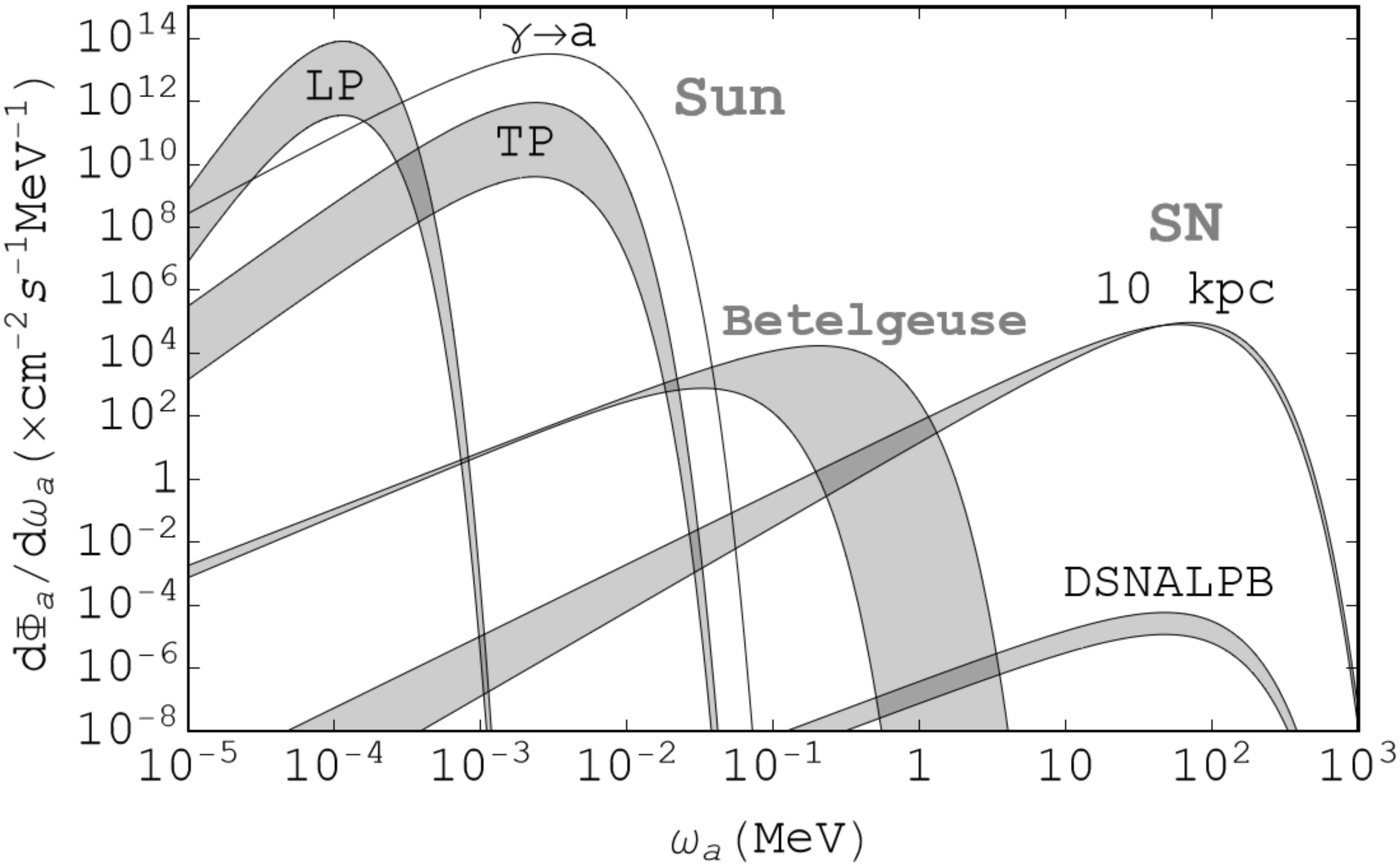
J. Jaeckel, L. J. Thormaehlen, Phys.Rev.D 100 (2019) 12

- Supergiant evolution

M. Xiao, et al., Phys. Rev. D 106 (2022)

- ....

Stellar Axion Flux



P. Carenza et al., in preparation

Stellar Axion Flux,

$g_{a\gamma} = 0.6 \times 10^{-10}\,\mathrm{GeV}^{-1}$, $g_{ai} = 0$, $m_a = 0$

The Sun as Axion Laboratory

We know the sun quite well from **neutrino detection** and **helioseismology**.

Currently, great consistency between the two.
→ **Solar abundance problem** appears to be resolved → Ekaterina Magg et al. (2022).

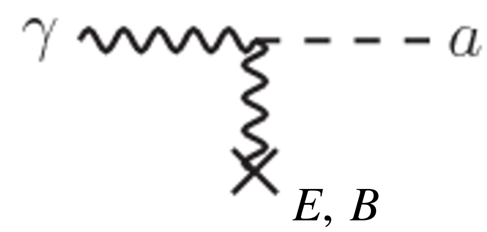
CNO neutrinos measured by the Borexino Collaboration

→ (2020) Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun
and
→ (2023) Final results of Borexino on CNO solar neutrinos

and **pp-neutrinos** by PandaX-4T

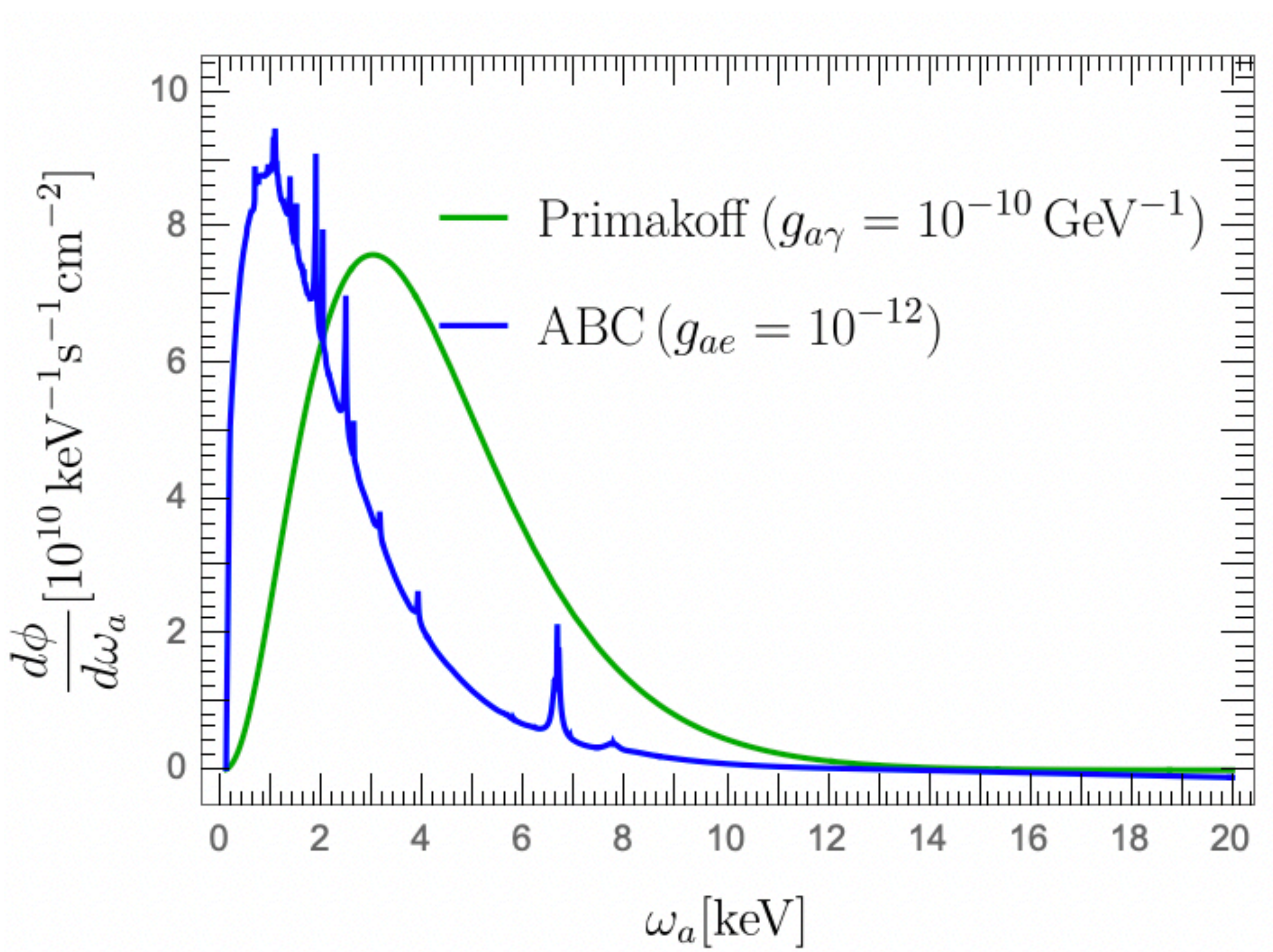
Xiaoying Lu et al. (submitted Jan 13, 2024),
→ A Measurement of Solar pp Neutrino Flux using PandaX-4T Electron Recoil Data

The Sun as Axion Factory

Coupling	Process	Energy
$g_{a\gamma}$	Primakoff (E) 	$\sim (3-4)\,\mathrm{keV}$
	Primakoff (B)	$\sim (10-200)\,\mathrm{eV}\ \ (\mathrm{LP})$ $\lesssim 1\,\mathrm{keV}\ \ (\mathrm{TP})$
g_{ae}	ABC e.g., $e + Ze \to Ze + e + a$	$\sim 1\,\mathrm{keV}$
g_{aN}	nuclear reactions $p + d \to {}^{3}\mathrm{He} + a$	$5.5\,\mathrm{MeV}$
	Nuclear de-excitation ${}^{57}\mathrm{Fe}^{*} \to {}^{57}\mathrm{Fe} + a$	$14.4\,\mathrm{keV}$
	${}^{7}\mathrm{Li}^{*} \to {}^{7}\mathrm{Li} + a$	$0.478\,\mathrm{MeV}$
	${}^{83}\mathrm{Kr}^{*} \to {}^{83}\mathrm{Kr} + a$	$9.4\,\mathrm{keV}$
	${}^{169}\mathrm{Tm}^{*} \to {}^{169}\mathrm{Tm} + a$	$8.4\,\mathrm{keV}$

Solar Axions: photon and electron coupling

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



J. Redondo, JCAP 1312 (2013)

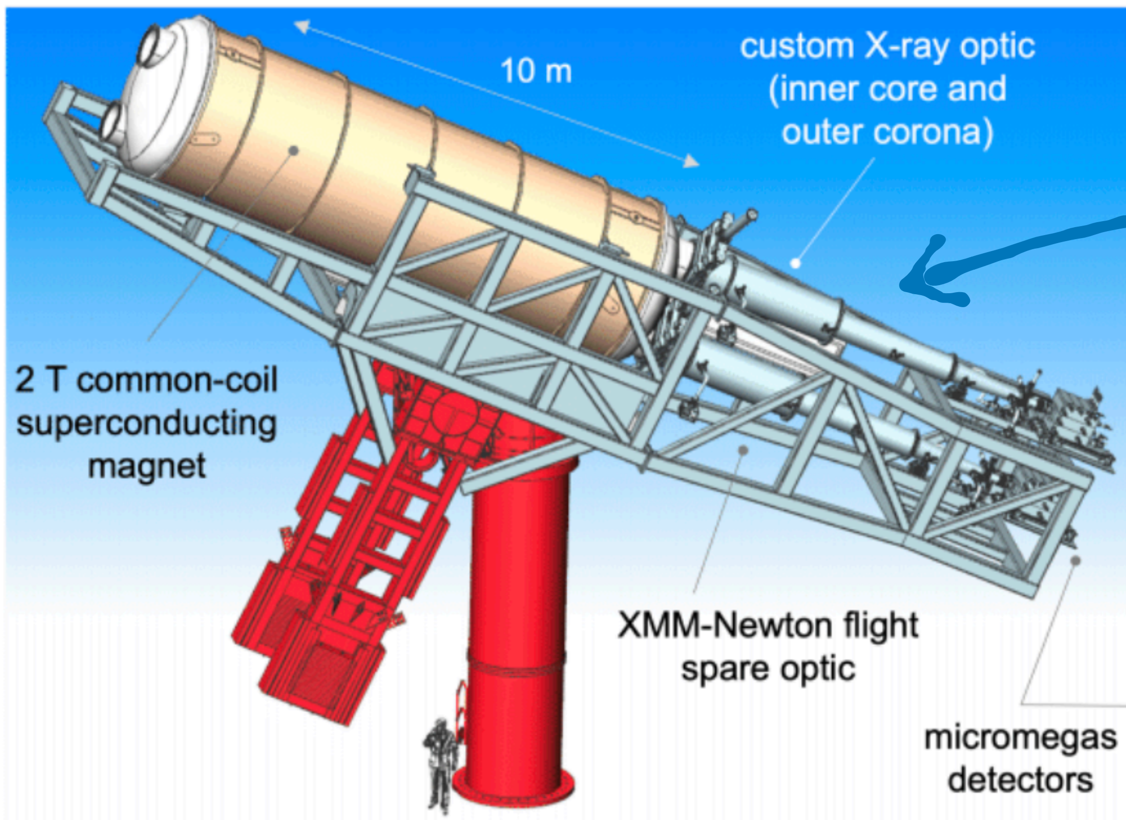
up to $\sim 10^{39}$ axions/s ($\Rightarrow 10^{11}\,\mathrm{cm^{-2}\,s^{-1}}$ axions on Earth), peaked at $\sim$ keV

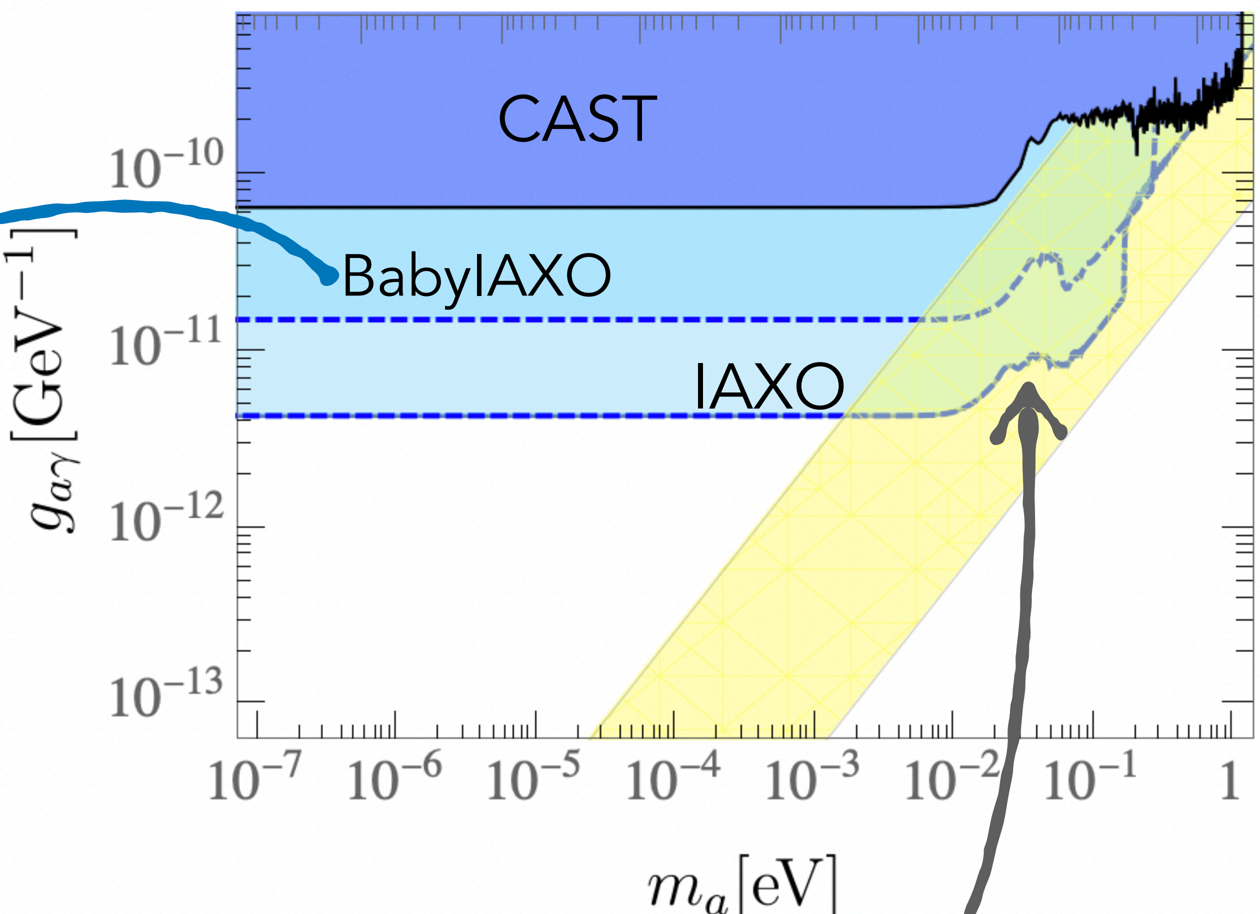
We can observe this flux with the Next Gen. Axion Helioscopes

Plus, the additional axion flux from the other processes

Hunting Solar Axions: Sikivie Helioscope

P. Sikivie PRL 51:1415 (1983)





$$P_{a\gamma} = \left(\frac{g_{a\gamma}BL}{2}\right)^2 \frac{\sin^2(qL/2)}{(qL/2)^2}, \qquad \text{with} \qquad q \simeq \frac{m_a^2 - m_\gamma^2}{2\omega}$$

What can we learn from helioscope Detection?

Degeneracy (g_{ae}, $g_{a\gamma}$) in flux observation.

Calculable from solar model and from instrument characteristics (thresholds, etc).

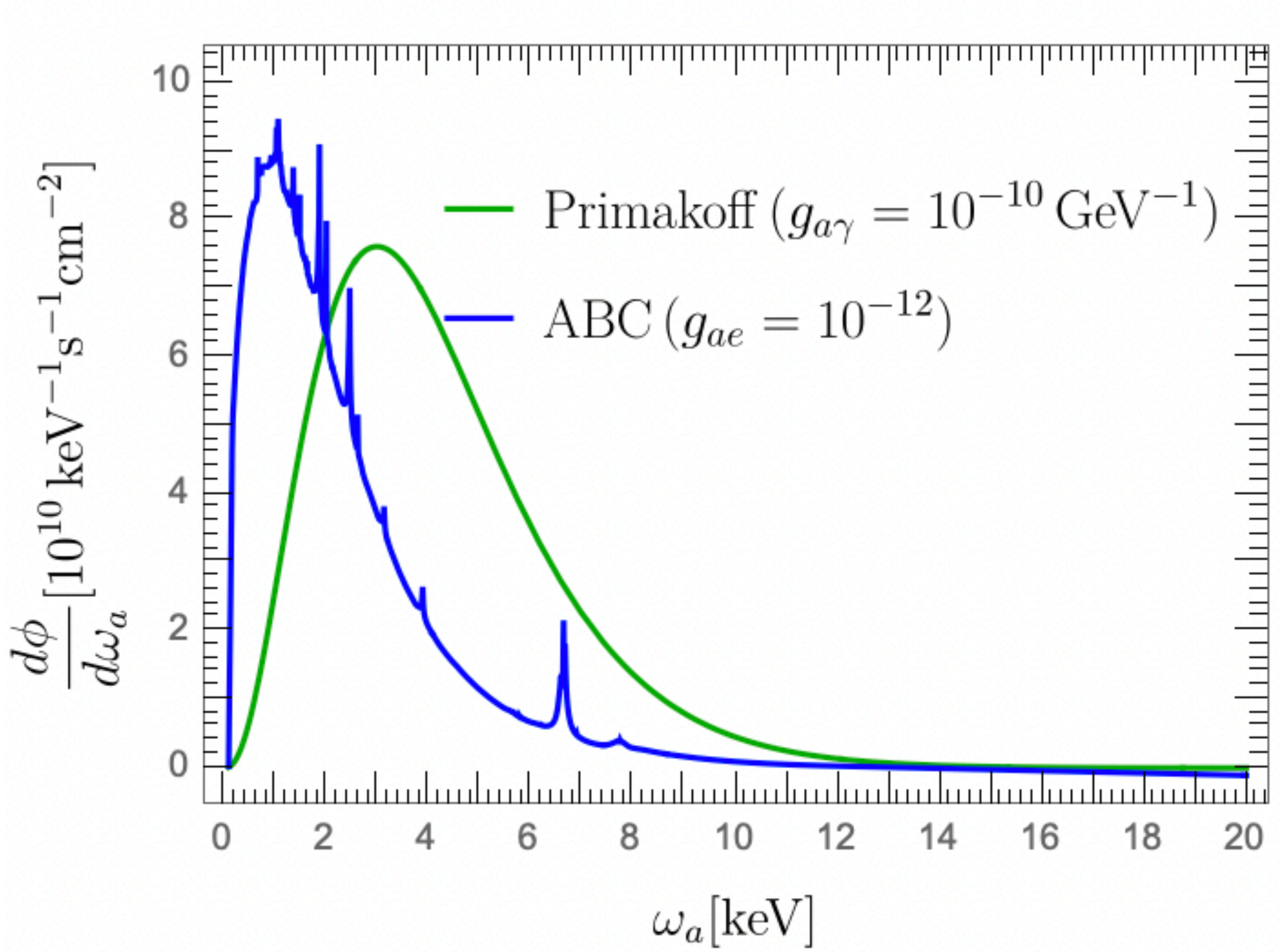
IAXO

$$\text{Observed Flux} \sim \left(1 + C\frac{|g_{ae}|^2}{|g_{a\gamma}|^2}\right)|g_{a\gamma}|^4$$

Degeneracy can be broken in combination with pure terrestrial searches (e.g., ALPS II)

Recommendation:

→ Heliscopes should lower the threshold to 0.3 keV



J. Redondo, JCAP 1312 (2013)

→ *can find $g_{ae}/g_{a\gamma}$ from spectra?*

Example:

$$\frac{\Phi_{(0.3-1)\mathrm{keV}}}{\Phi_{\mathrm{tot}}} \simeq 2.4\,\% \qquad \text{(KSVZ)}$$

where $\Phi_{\mathrm{tot}} = \Phi_{(0.3-10)\mathrm{keV}}$.

DFSZ with typical couplings $g_{ae}/g_{a\gamma} = 5 \times 10^{-2}$ GeV,

$$\frac{\Phi_{(0.3-1)\mathrm{keV}}}{\Phi_{\mathrm{tot}}} \simeq 22\,\% \qquad \text{(DFSZ)}$$

Using other bins (e.g., 1-2 keV) is much less efficient .

No significant improvement in going down to 0.1 keV.

Axioelectric Helioscopes

Helioscopes based on Axioelectric effect: LUX, XENON1T, …

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

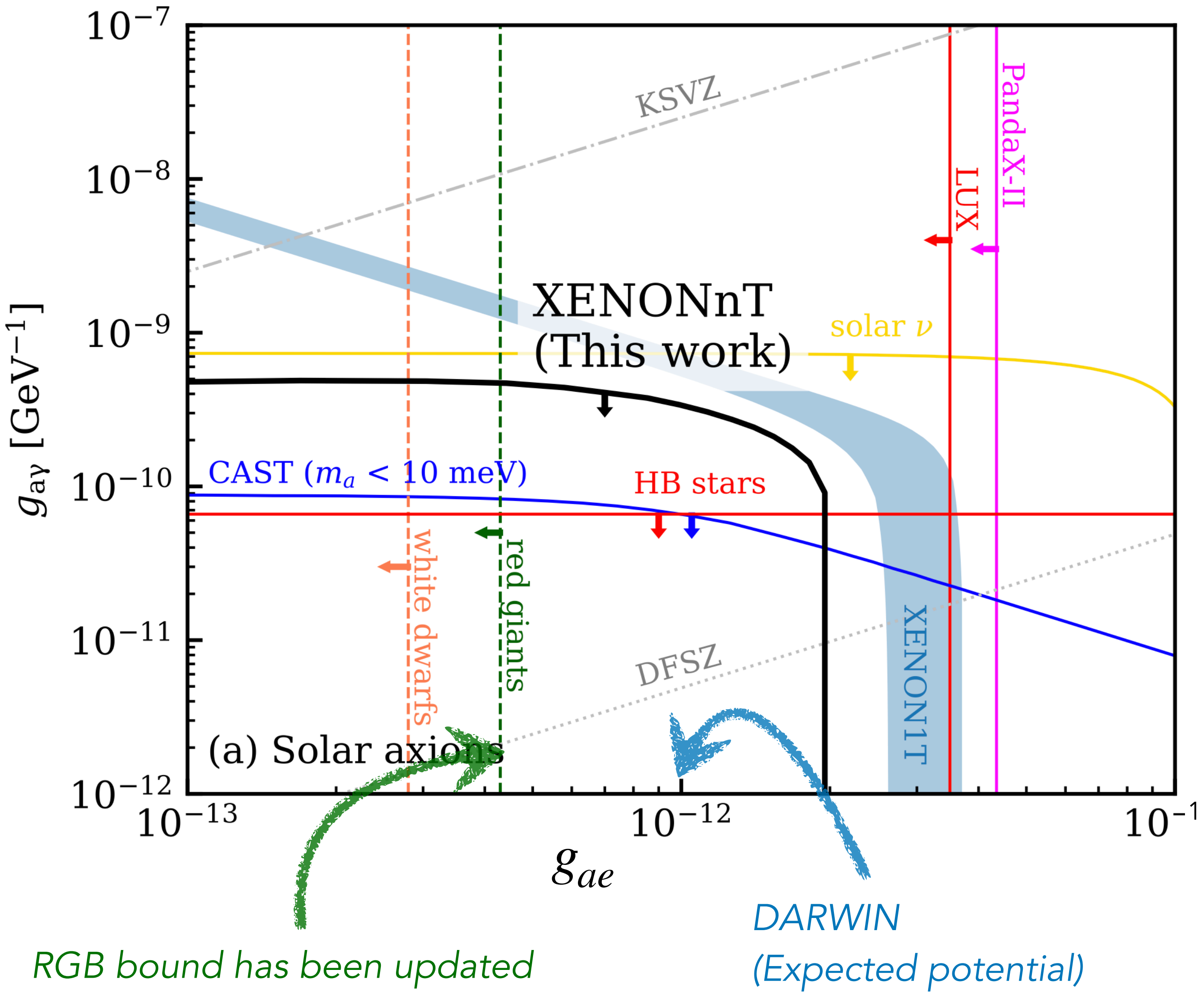
$$\sigma_{\rm ae} = \sigma_{\rm ph.e} \frac{g_{\rm ae}^2}{\beta} \frac{3E_{\rm a}^2}{16\pi\alpha m_{\rm e}^2} \left(1 - \frac{\beta^{2/3}}{3}\right)$$

Low energy suppression $\left(E_a/m_e\right)^2$

However, they can reach higher masses

Axioelectric Helioscopes

Solar axions?



Previous hint conclusively dismissed by the first science run of the XENONnT dark matter experiment (Jul 22, 2022), which confirmed the origin as decays from trace amounts of tritium

$$g_{ae} \lesssim 2 \times 10^{-12}$$

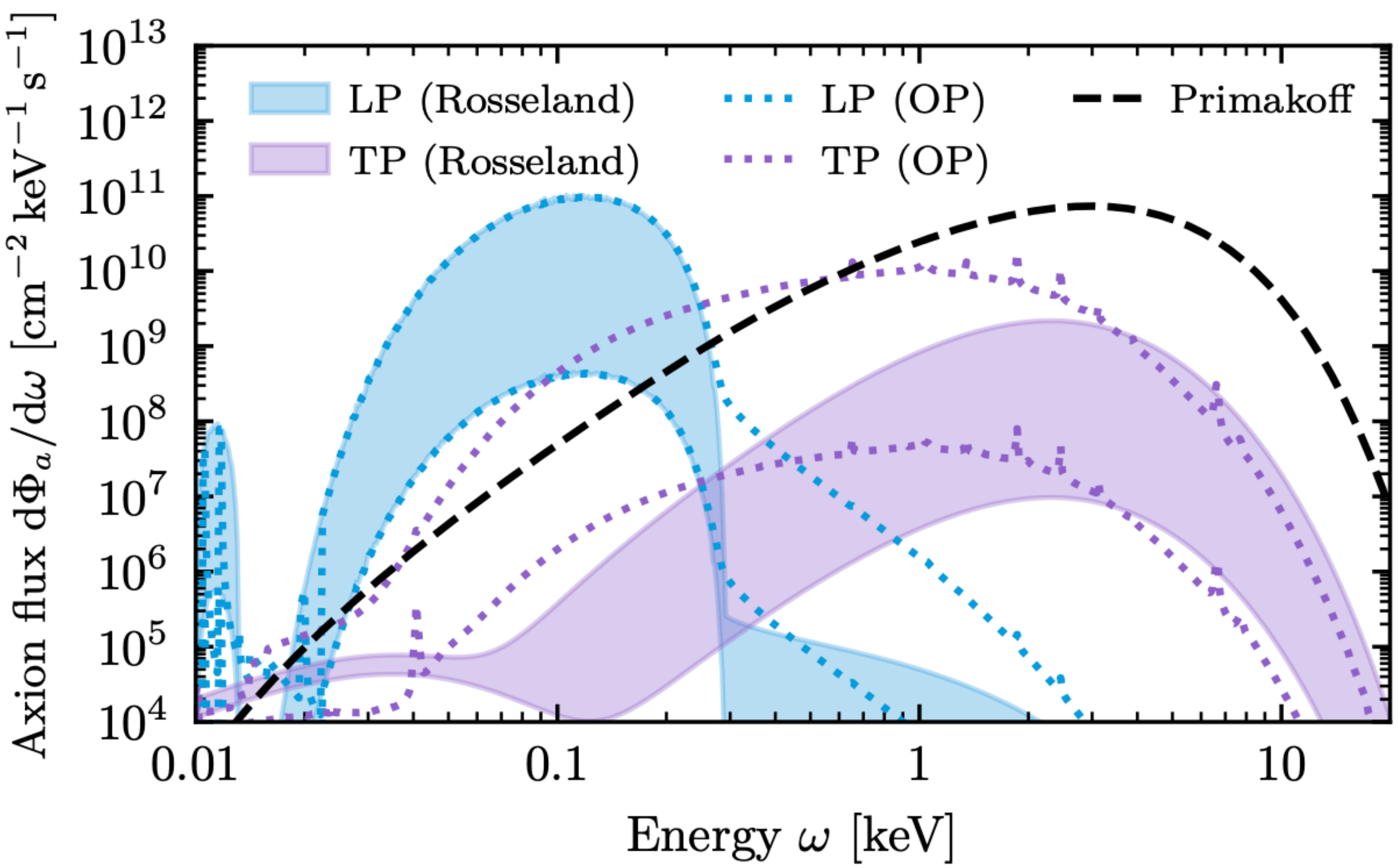
E. Aprile et al., Phys.Rev.Lett. 129 (2022)

Solar axions from Magnetic Field

Axions from photon conversion in the solar magnetic field

Issues:

- require low threshold. Detector technology exists but the optics may be challenging.
- Very difficult coherent conversions in $B_{\rm LAB}$ for mass above a few meV.



→ S. Hoof, J. Jaeckel, L. J. Thormaehlen, JCAP 09 (2021) 006

Solar axions from Nuclear Reactions

Low-lying (thermally excited) nuclear levels. Axion production in M1 transitions

$^{57}\mathrm{Fe}^* \rightarrow {}^{57}\mathrm{Fe} + a$(14.4 keV)

$g_{aN}^{\mathrm{eff}} = 0.16 g_{ap} + 1.16 g_{an}$ Almost entirely neutron coupling

- Searched by CAST *JCAP 12 (2009)*
- BabyIAXO potential studied in *Eur.Phys.J.C 82 (2022)*
  (See backup slides)

→ Sensitive to $|g_{aN}^{\mathrm{eff}} \cdot g_{a\gamma}|^2$

New dedicated project under commissioning → ISAI (Investigating Solar Axion by Iron-57), to constrain only the effective nuclear coupling through the inverse process:

$a + {}^{57}\mathrm{Fe} \rightarrow {}^{57}\mathrm{Fe}^* \rightarrow {}^{57}\mathrm{Fe} + \gamma$

Solar axions from Nuclear Reactions

Low-lying (thermally excited) nuclear levels. Axion production in M1 transitions

$^{83}\mathrm{Kr} + a(9.4\,\mathrm{keV})$ Kripton

Also essentially a neutron M1 transition $g_{aN}^{\mathrm{eff}} \simeq g_{an}$

Experimentally, can be searched through the resonance absorption reaction

$a + {}^{83}\mathrm{Kr} \to {}^{83}\mathrm{Kr}* \to {}^{83}\mathrm{Kr} + \gamma(9.4\,\mathrm{keV})$,

using a proportional gas chamber filled with krypton and placed in a low-background

→ Gavrilyuk et al. (2015) and Akhmatov et al. (2018).

Result: $\left| g_{AN}^{3} - g_{AN}^{0} \right| \leqslant 8.4 \times 10^{-7}$

Solar axions from Nuclear Reactions

Low-lying (thermally excited) nuclear levels. Axion production in M1 transitions

$^{169}\mathrm{Tm} + a(8.4\,\mathrm{keV})$ Thulium

Proton M1 transition

Experimental search using $\mathrm{Tm_3Al_5O_{12}}$ thulium garnet crystal as a bolometric detector for

$$a + {}^{169}\mathrm{Tm} \rightarrow {}^{169}\mathrm{Tm}^* \rightarrow {}^{169}\mathrm{Tm} + \gamma(8.4\mathrm{keV})$$

$$\Rightarrow \quad \left| g_{app} \right| < 8.89 \times 10^{-6} \quad (90\,\% \text{ C.L. })$$

see → Derbin et al. (2023)

Solar axions from Nuclear Reactions

$$p + d \rightarrow {}^3\text{He} + a(5.5\,\text{MeV})$$

Second step of pp-chain

Effective coupling $g_{aN}^{\text{eff}} = \left| \frac{g_{app} - g_{ann}}{2} \right|$

- Searched by CAST *JCAP* 03 (2010)
- Borexino *Phys.Rev.D* 85 (2012)
- Recent analysis of the JUNO sensitivity G. Lucente, N. Nath, F. Capozzi, MG, A. Mirizzi, Phys.Rev.D 106 (2022) 12

⇒ Sensitive to $g_{aN}^{\text{eff}} \cdot g_{a\gamma}$

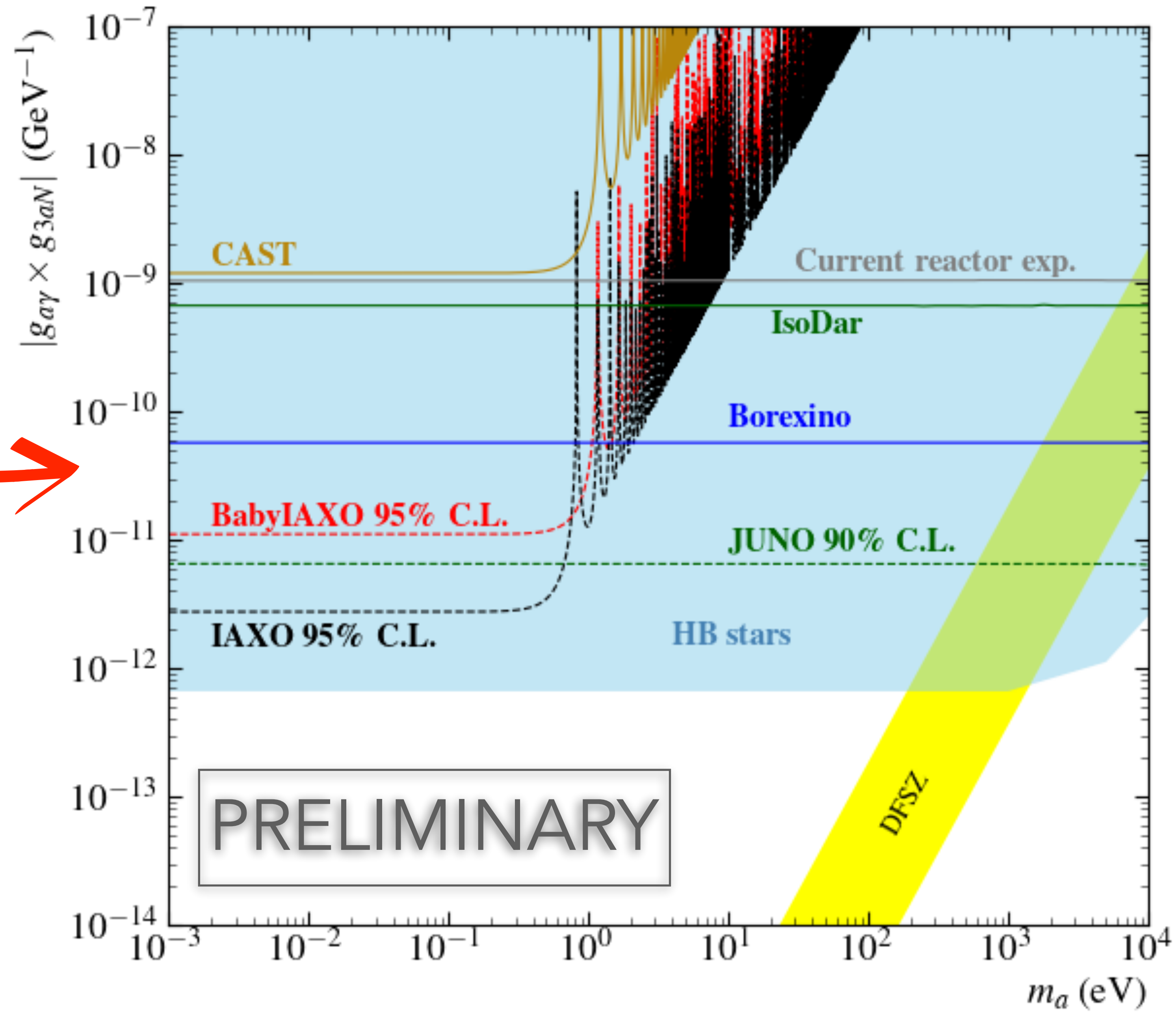
Search for nuclear coupling only, using previous SNO data → Phys.Rev.Lett. 126 (2021)

$$\left| \frac{g_{app} - g_{ann}}{2} \right| < 2 \times 10^{-5} \quad (95\,\%\ \text{C.L.})$$

Solar axions from Nuclear Reactions

$p + d \to {}^3\text{He} + a(5.5\,\text{MeV})$

Current proposal for direct detection in IAXO



Solar axions from Nuclear Reactions

Axions from Li-7

$$^7\text{Be} + e \to {}^7\text{Li}^* + \nu_e$$

$$\downarrow$$

$$^7\text{Li}^* \to {}^7\text{Li} + a(477.6\,\text{keV})$$

Pure proton coupling $g_{aN}^{\text{eff}} = g_p$

→ Krcmar (2001)

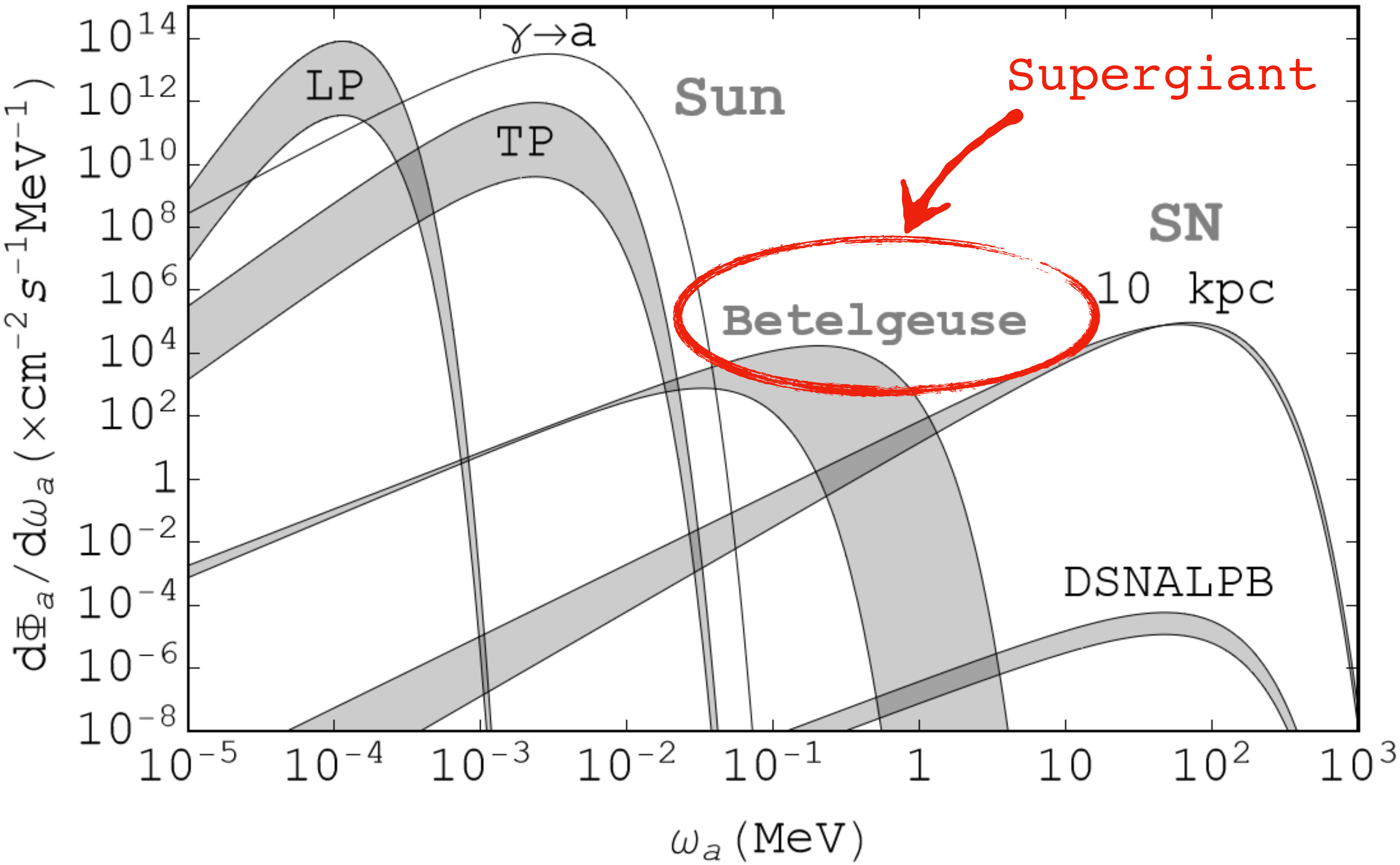
→ CAST (2009)

Most restrictive limit (2011): $m_a < 8.6\text{keV}$ (assuming QCD axion with $C_p = 1$)

→ searches using LiF Crystals (@ Gran Sasso National Laboratories)

No recent analysis (to the best of my knowledge)

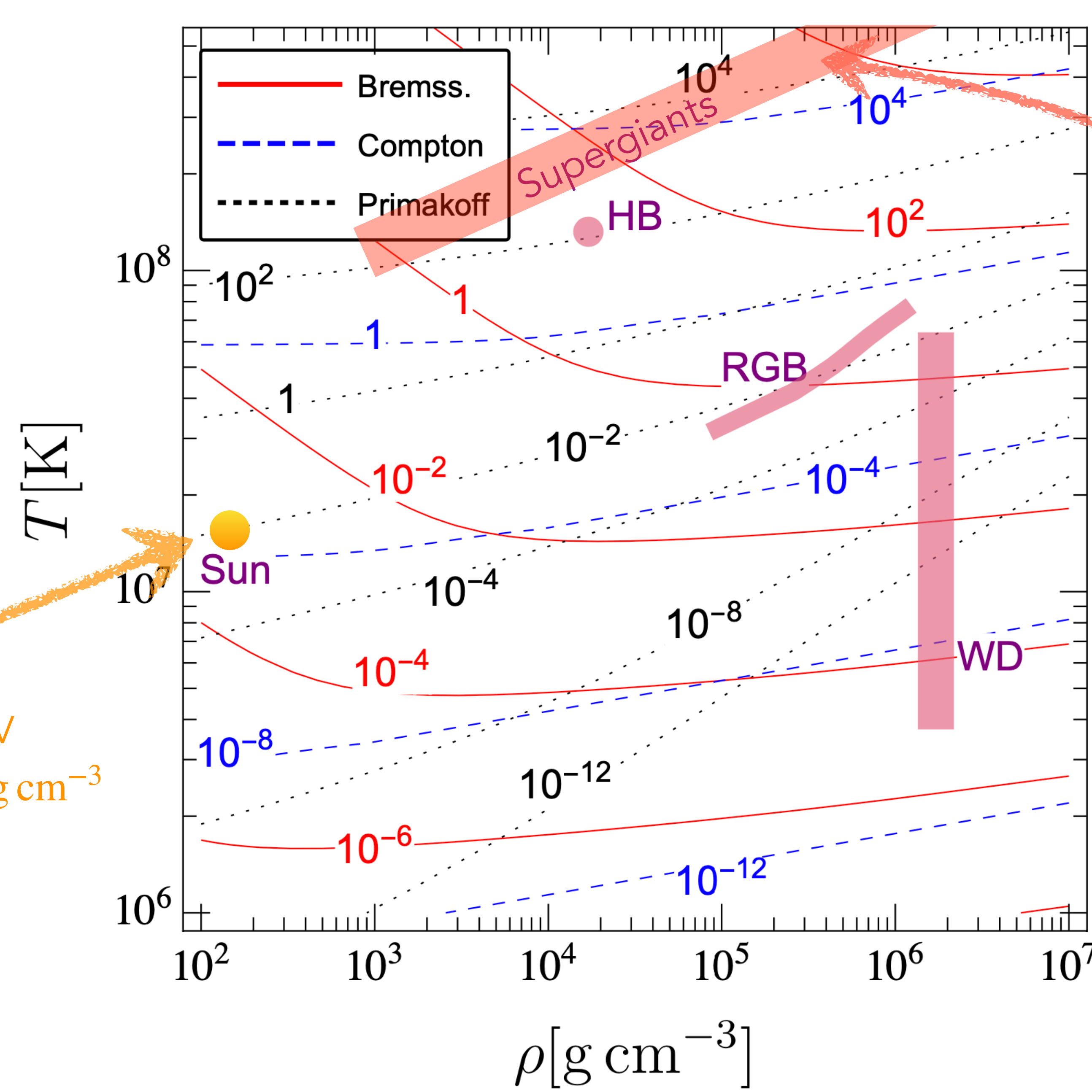
Supergiants Axions



P. Carenza et al., in preparation

Stellar Axion Flux,
$g_{a\gamma} = 0.6 \times 10^{-10}\,\mathrm{GeV}^{-1}$, $m_a = 0$

Supergiants Axions



Sun:
$T_c \sim 1$ keV
$\rho_c \sim 10^2$ g cm^{-3}

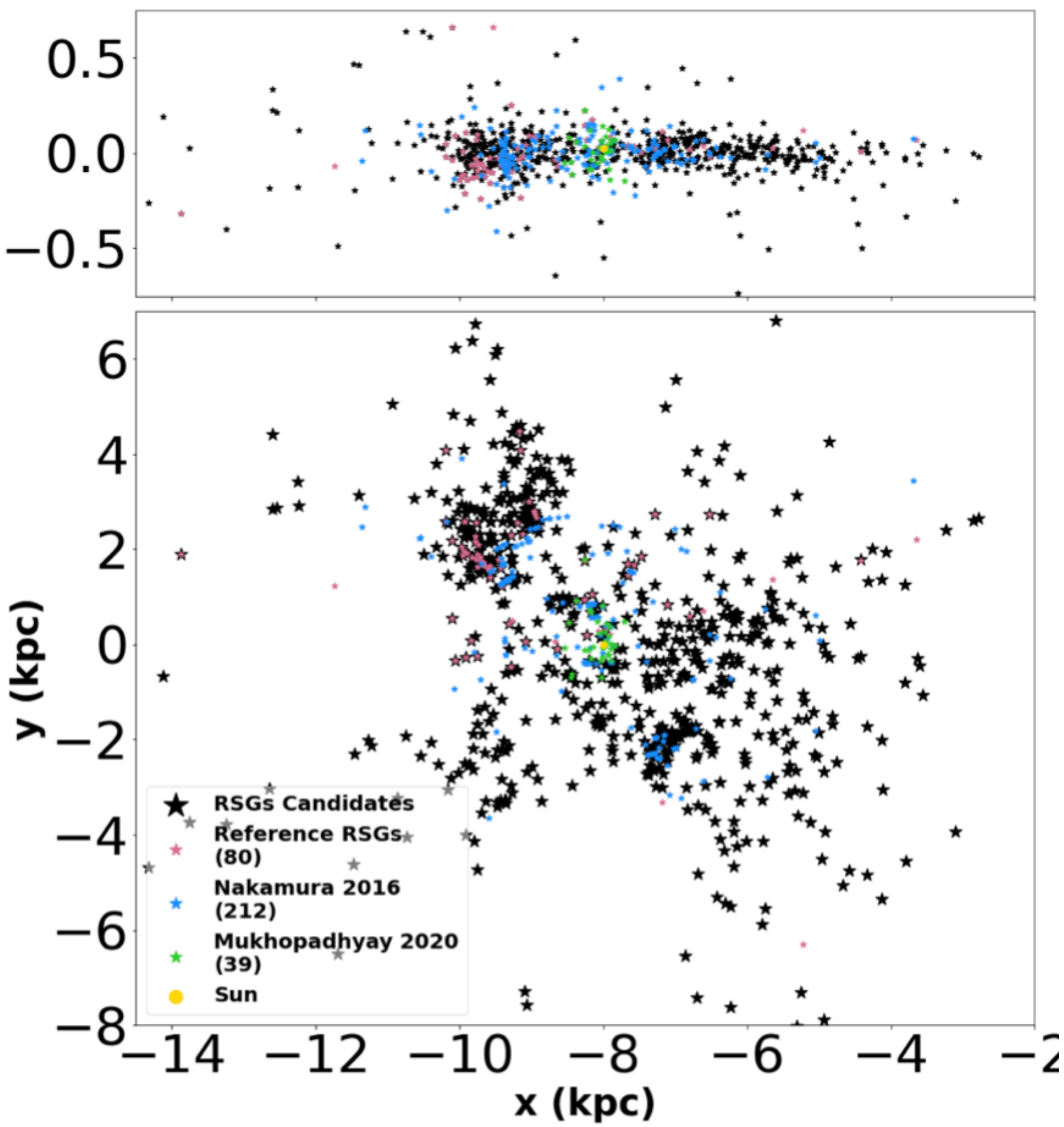
supergiants: T_c and ρ_c depend on mass and evolutionary stage

The sun is quite an unremarkable star…

Di Luzio, MG, Nardi, Visinelli, Phys.Rept. 870 (2020)

Supergiants

Brand new catalog of Red SG, Sarah Healy et al., arXiv:2307.08785

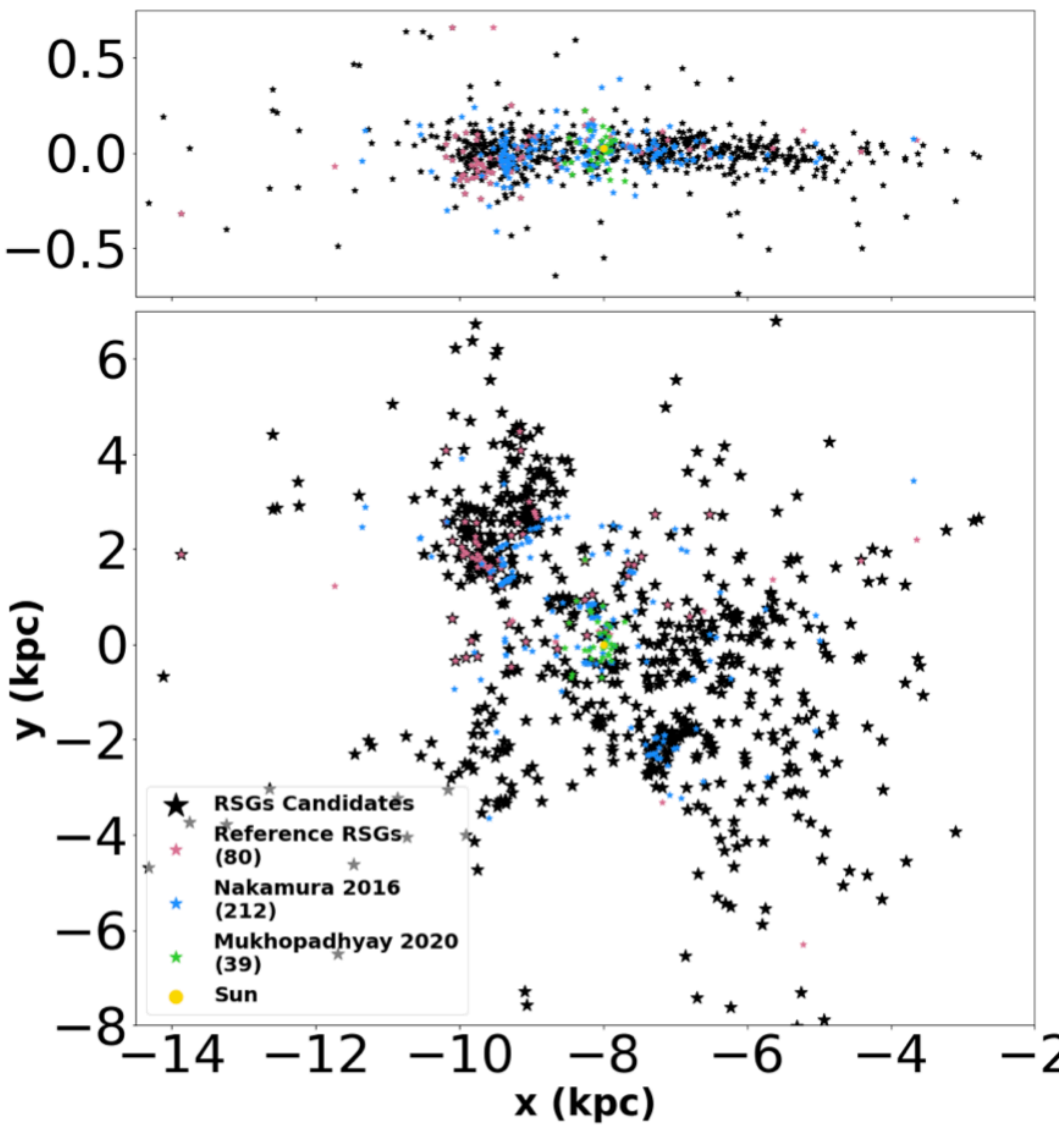


Many candidates at a few kpc from the Sun.

See also
→ M. Mukhopadhyay et al., Astrophys.J. 899 (2020)

Supergiants

Brand new catalog of Red SG, Sarah Healy et al., [arXiv:2307.08785]

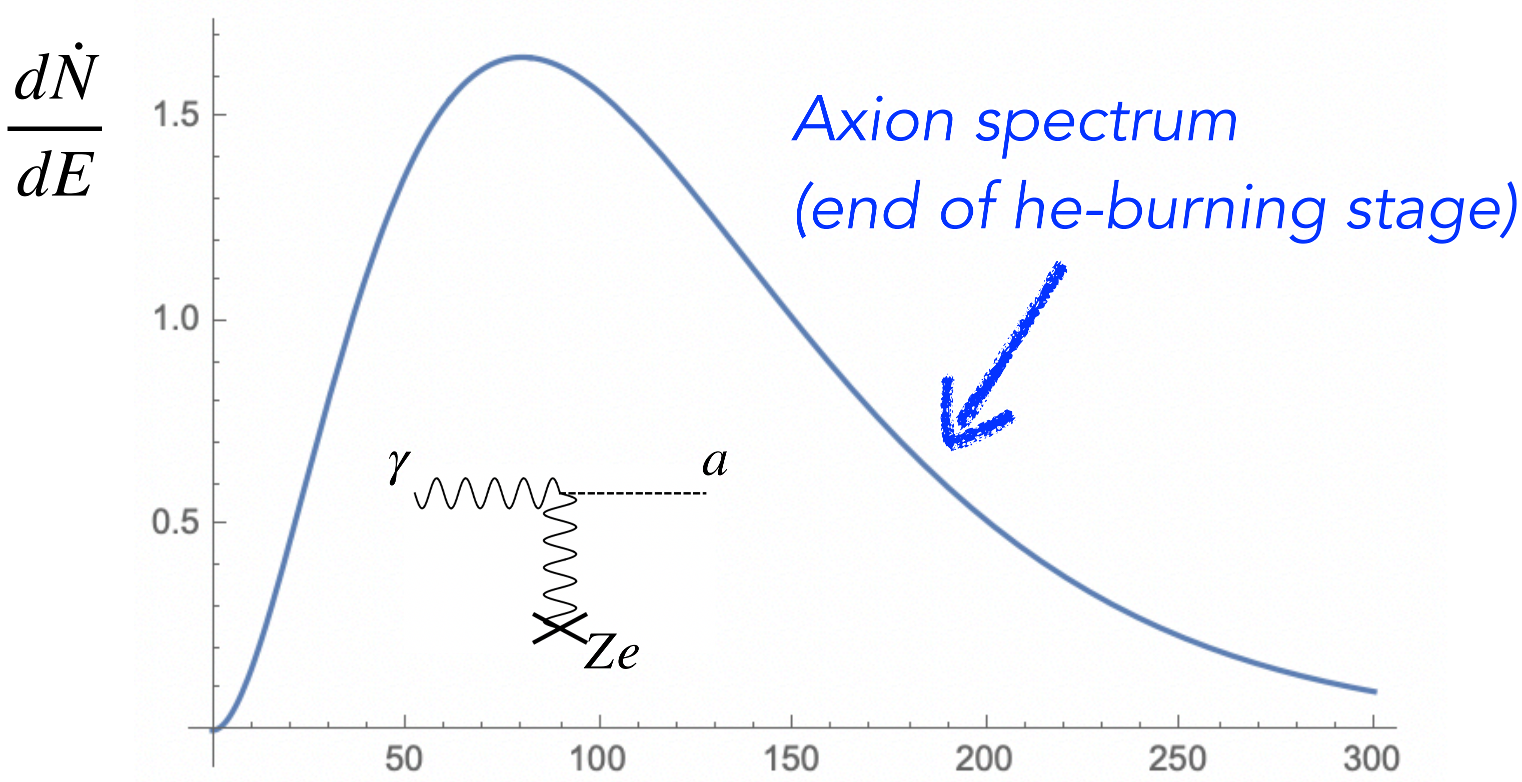


Common Name	Distance (pc)
Spica / α Virginis	77(4)
ζ Ophiuchi	112(2)
α Lupi	143(3)
Antares / α Scorpii	169(30)
Enif / ϵ Pegasi	211(6)
Betelgeuse / α Orionis	222^{+48}_{-34}
ζ Cephei	256(6)
Rigel / β Orionis	264(24)
S Monocetotis A(B)	282(40)
CE Tauri / 119 Tauri	326(70)

Data for table from → M. Mukhopadhyay et al., Astrophys.J. 899 (2020)

Supergiant Axions

$\times 10^{43}$



$E[\mathrm{keV}]$

Sun:
$\sim 10^{39}$ axions/s,
peaked at $\sim$ 4 keV

Betelgeuse:
$\sim 10^{45}$ axions/s,
peaked at $\sim 80\,\mathrm{keV}$

… 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!

Supergiant Axions

Model	Phase	t_{cc} [yr]	$\log_{10}\frac{L_{\rm eff}}{L_\odot}$	$\log_{10}\frac{T_{\rm eff}}{\rm K}$	Primakoff			Bremsstrahlung			Compton		
					C^P	E_0^P [keV]	β^P	C^B	E_0^B [keV]	β^B	C^C	E_0^C [keV]	β^C
0	He burning	155000	4.90	3.572	1.36	50	1.95	1.3E-3	35.26	1.16	1.39	77.86	3.15
1	before C burning	23000	5.06	3.552	4.0	80	2.0	2.3E-2	56.57	1.16	8.55	125.8	3.12
2	before C burning	13000	5.06	3.552	5.2	99	2.0	6.4E-2	70.77	1.09	17.39	156.9	3.09
3	before C burning	10000	5.09	3.549	5.7	110	2.0	8.9E-2	76.65	1.08	22.49	169.2	3.09
4	before C burning	6900	5.12	3.546	6.5	120	2.0	0.136	85.15	1.06	31.81	186.4	3.09
5	in C burning	3700	5.14	3.544	7.9	130	2.0	0.249	97.44	1.04	50.62	210.4	3.11
6	in C burning	730	5.16	3.542	12	170	2.0	0.827	129.17	1.02	138.6	269.1	3.17
7	in C burning	480	5.16	3.542	13	180	2.0	0.789	134.54	1.02	153.2	279.9	3.15
8	in C burning	110	5.16	3.542	16	210	2.0	1.79	151.46	1.02	252.7	316.8	3.17
9	in C burning	34	5.16	3.542	21	240	2.0	2.82	181.74	1.00	447.5	363.3	3.22
10	between C/Ne burning	7.2	5.16	3.542	28	280	2.0	3.77	207.84	0.99	729.2	415.7	3.23
11	in Ne burning	3.6	5.16	3.542	26	320	1.8	3.86	224.45	0.98	856.4	481.2	3.11

$$\frac{d\dot{N}_a}{dE} = \frac{10^{42}}{\rm keV s}\left[C^P g_{11}^2 \left(\frac{E}{E_0^P}\right)^{\beta^P} e^{-(\beta^P+1)E/E_0^P} + (P \to B, C; g_{11} \to g_{13})\right]$$

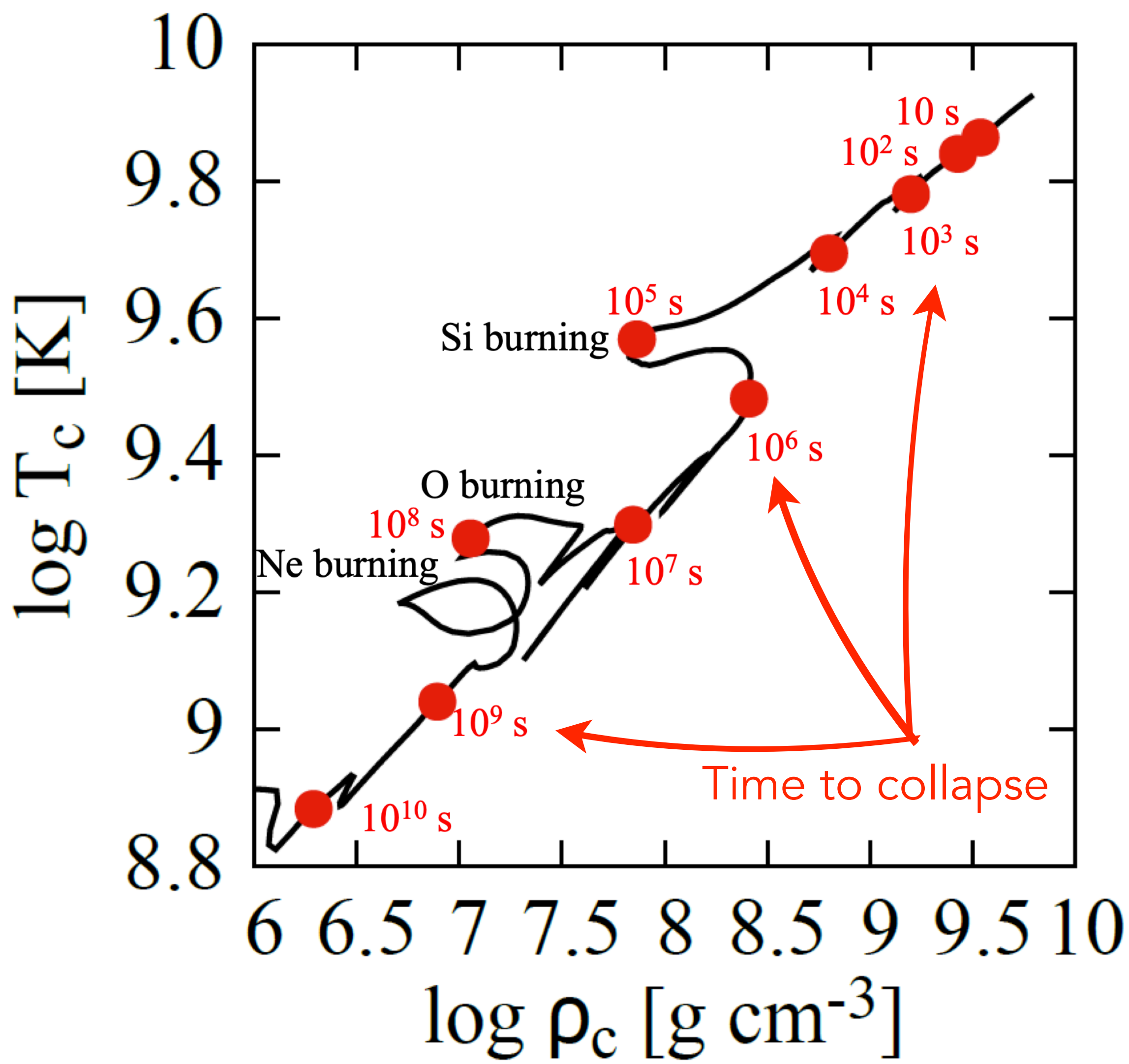
Flux increases adding g_{ae} coupling

M. Xiao, MG, et al., Phys. Rev. D 106 (2022)

The Very Last Stages of a Monster Star

$t_{\text{collpase}} - t$ [s]	C	E_0 [MeV]	β
0	1.68×10^3	2.54	2.50
10^2	1.19×10^3	2.08	2.49
10^3	9.33×10^2	1.77	2.50
10^4	5.98×10^2	1.57	2.47
10^5	1.63×10^2	1.13	2.10
10^6	2.15×10^2	0.85	2.39
10^7	7.31×10^1	0.61	2.10

Flux grows substantially in last seconds



$$\frac{d^2 n_\gamma}{dt dE} = \frac{10^{47} C g_{10}^2 P_{a\gamma}}{4\pi d^2} \left(\frac{E}{E_0}\right)^{\beta} e^{-(\beta+1)\frac{E}{E_0}} \text{ cm}^{-2} \text{ s}^{-1}\text{MeV}^{-1}$$

Mori, Takiwaki and Kotake, Phys.Rev.D 105 (2022)

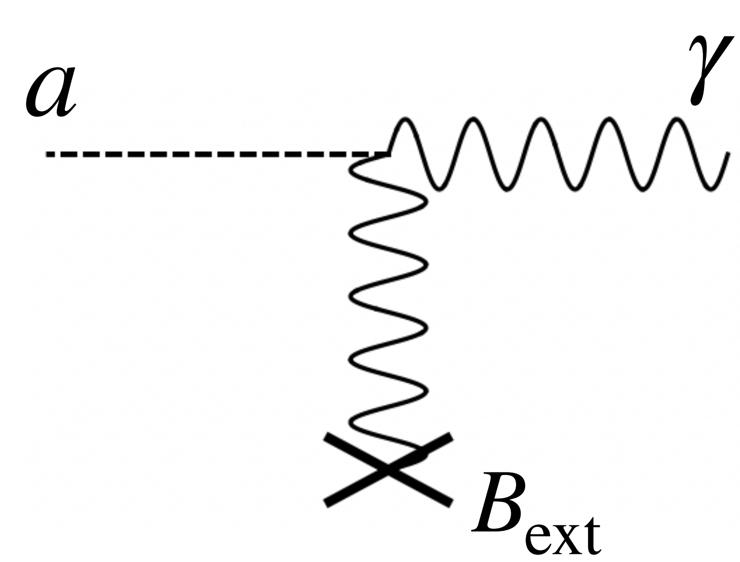
Supergiant Axions

Axions can convert into photons in the magnetic field between us and the star

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

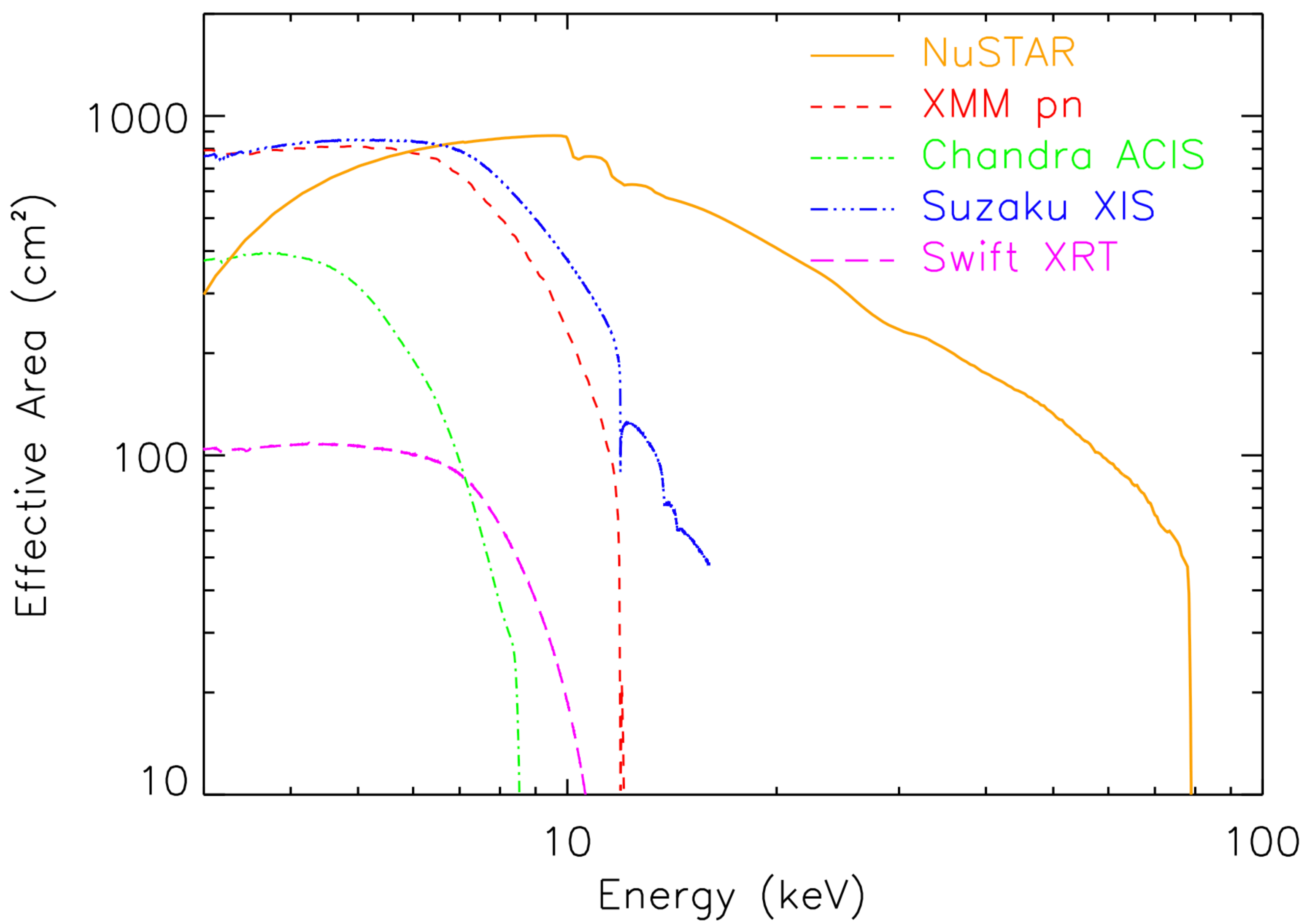
(Assuming B uniform)

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

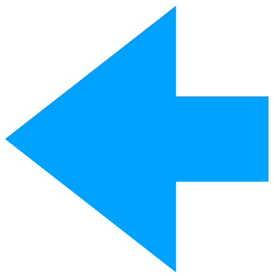


Hard X-ray to Soft gamma-Ray detectors

Huge interest in the low MeV region (see, e.g., ICRC talk by Andreas Zoglauer (2021)



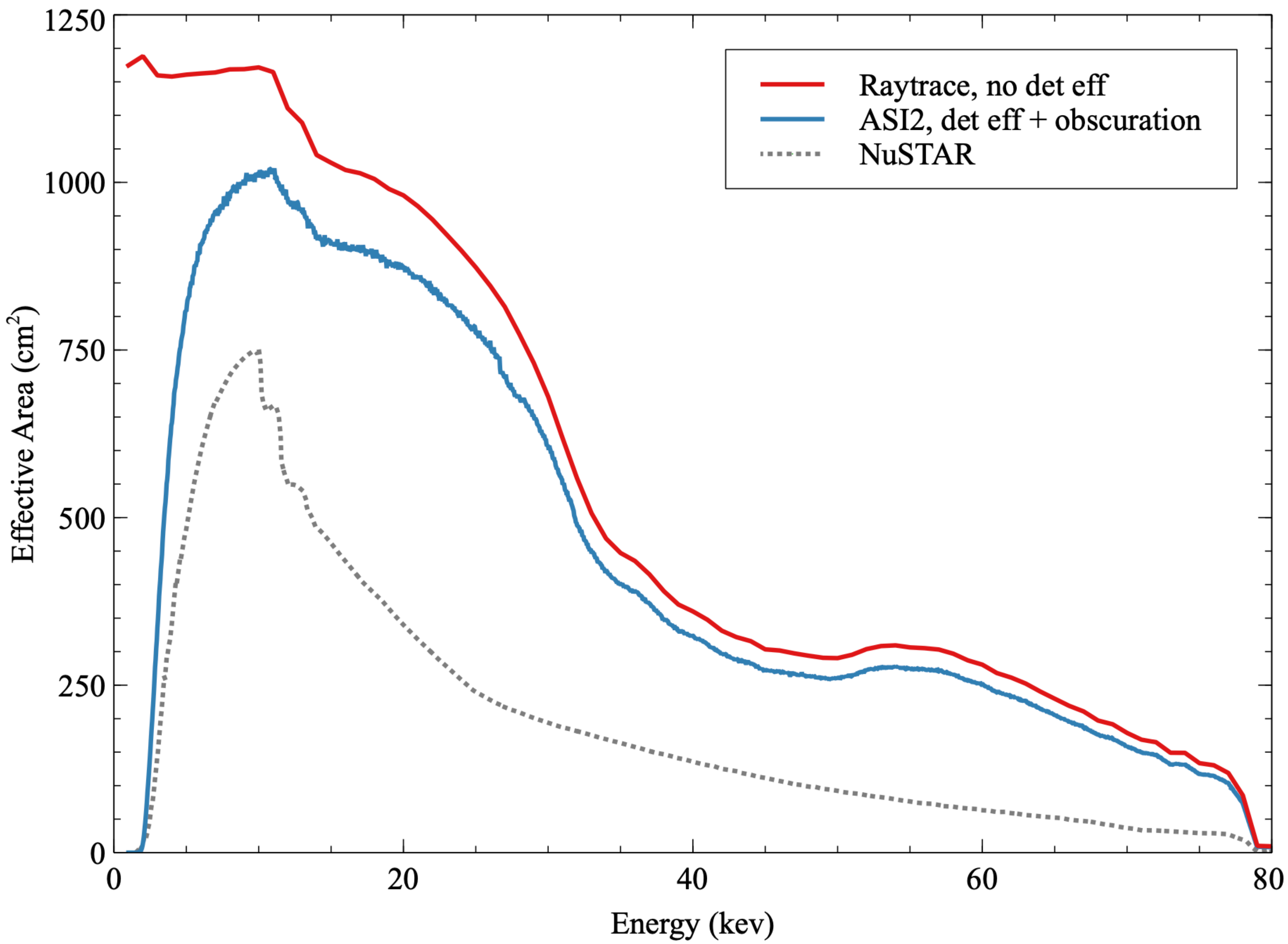
Gamma-ray detectors in MeV range → GECCO, COSI, AMEGO…



X-Ray Detectors

The High Energy X-ray Probe (HEX-P)

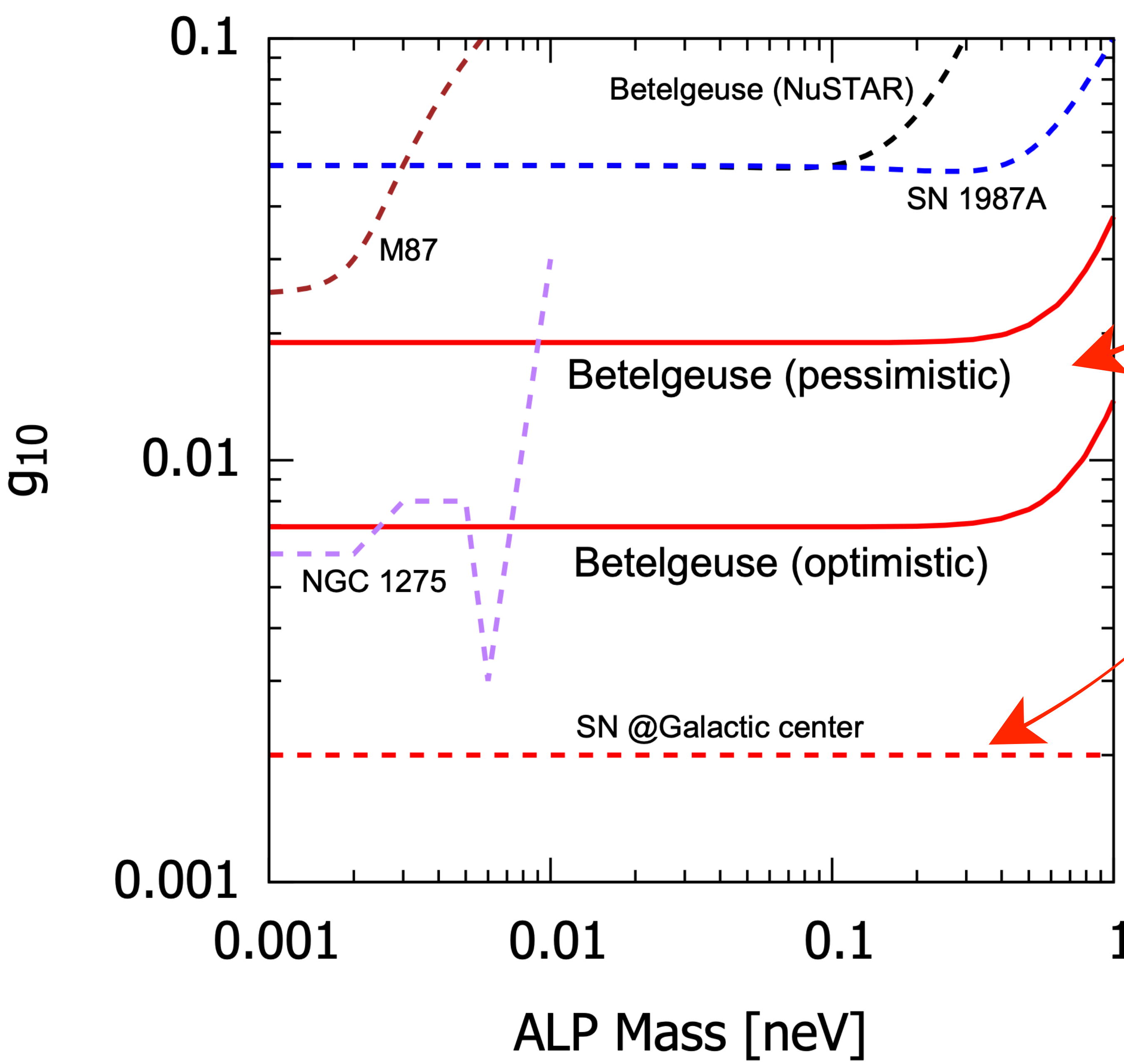
Instrument and Mission Profile paper last week (on Dec 7)



Same target energy as NuSTAR.

3 co-aligned X-ray telescopes designed to cover the 0.2 – 80 keV bandpass

The Very Last Stages of a Monster Star



Sensitivity: Assuming AMEGO 100 ks observation before collapse.

Sensitivity: Fermi LAT, SN-explosion

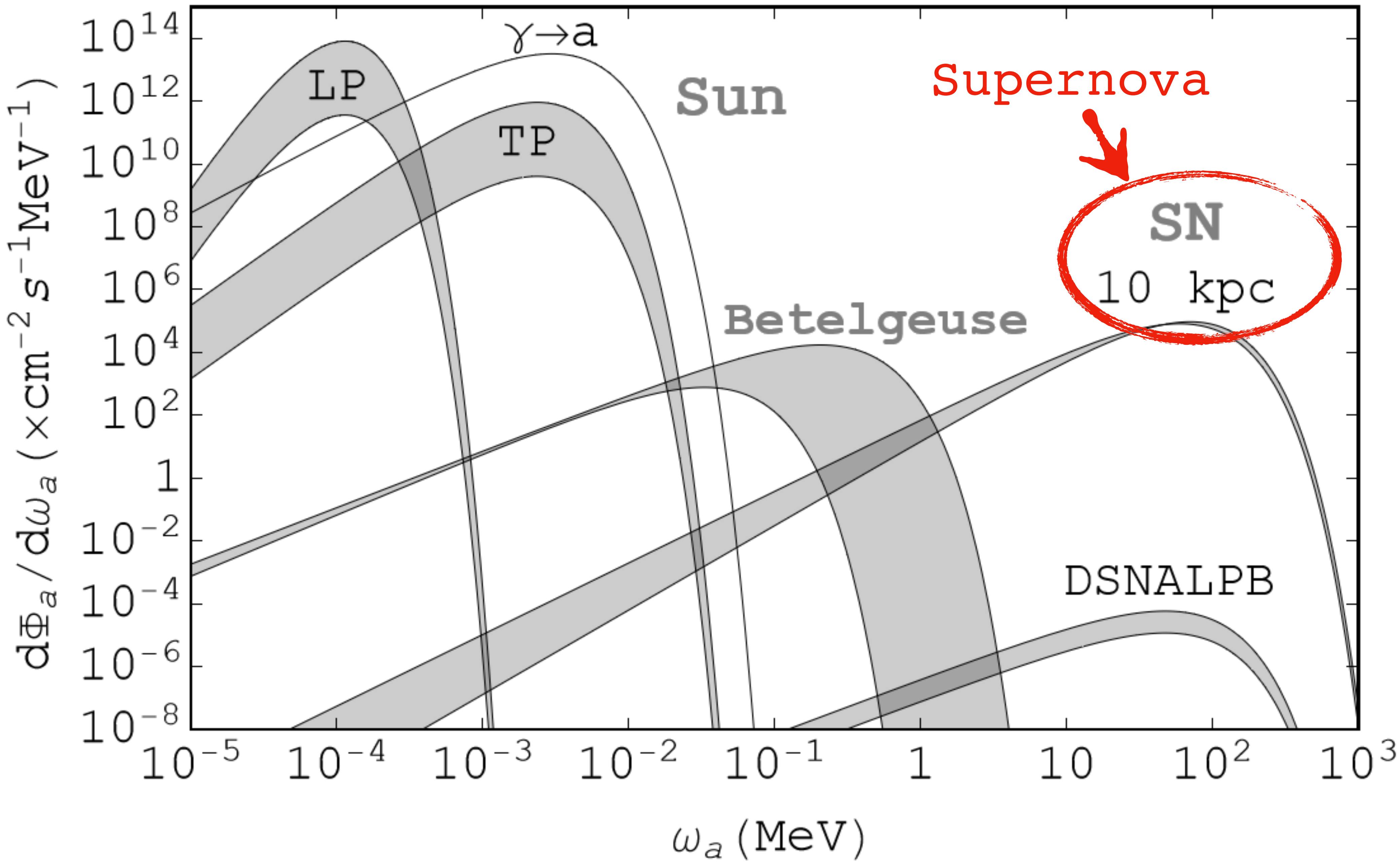
M. Meyer , M. G., A. Mirizzi, J. Conrad, M. A. Sánchez-Conde, Phys.Rev.Lett. 118 (2017)

Mori, Takiwaki and Kotake, Phys.Rev.D 105 (2022)

AMEGO would detect signatures of ALPs even without directional information since it plans all-sky surveys with the field of view of 2.5 sr and the cadence of 3 hours.

Other γ ray telescopes such as INTEGRAL are not performing surveys.

Supernova Axions

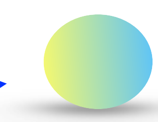


P. Carenza et al., in preparation

Stellar Axion Flux,

$g_{a\gamma} = 0.6 \times 10^{-10}\,\mathrm{GeV}^{-1}$, $m_a = 0$

Supernova axions

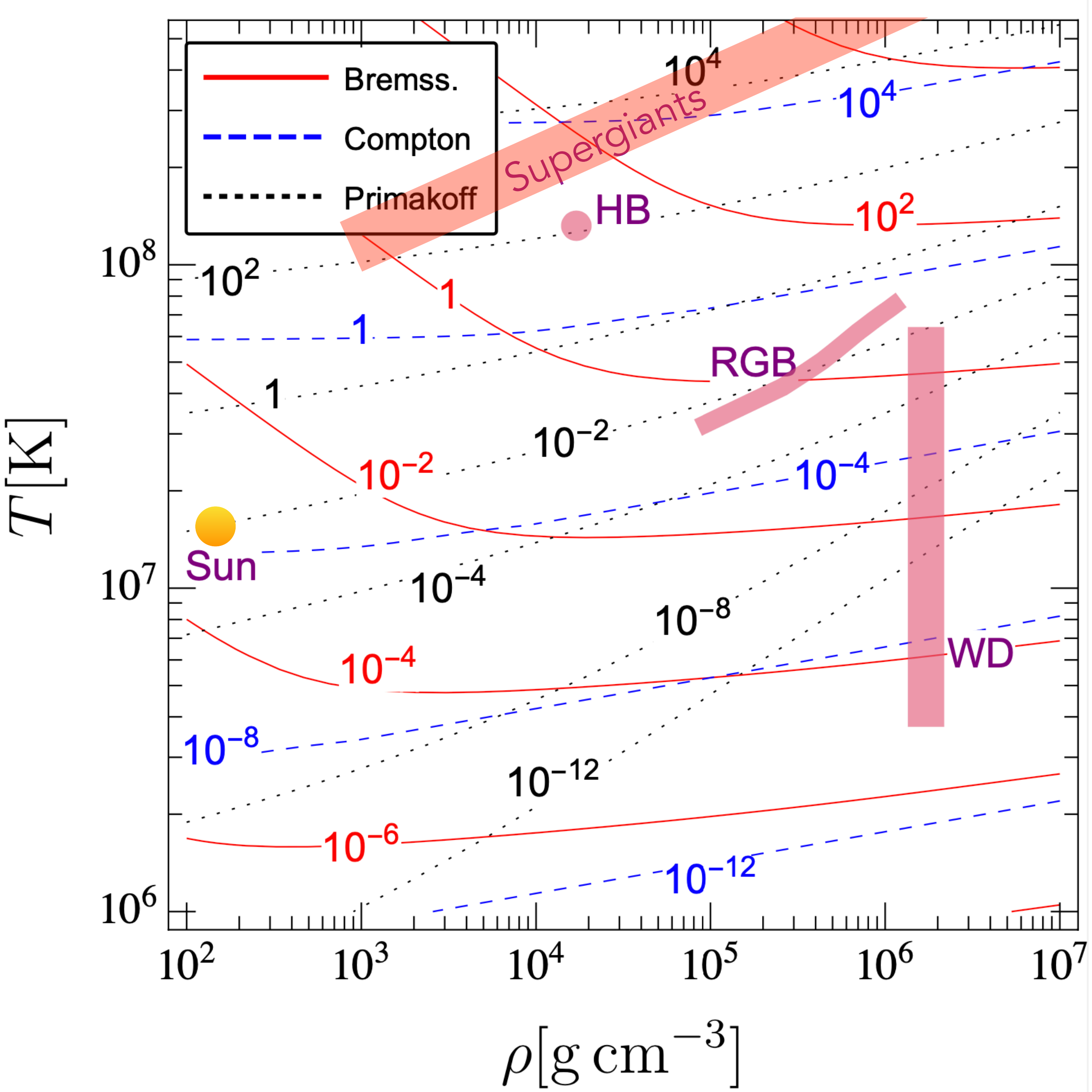


SN

$T_c \simeq 30$ MeV

$\rho_c \simeq 3 \times 10^{14}$ g cm^{-3}

The truly monster stars



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

$$\varepsilon_x \lesssim 10^{19}\,\mathrm{erg\,g^{-1}s^{-1}}$$

$$@ \quad \rho = 3 \times 10^{14}\,\mathrm{g\,cm^{-3}},\ T = 30\,\mathrm{MeV}$$

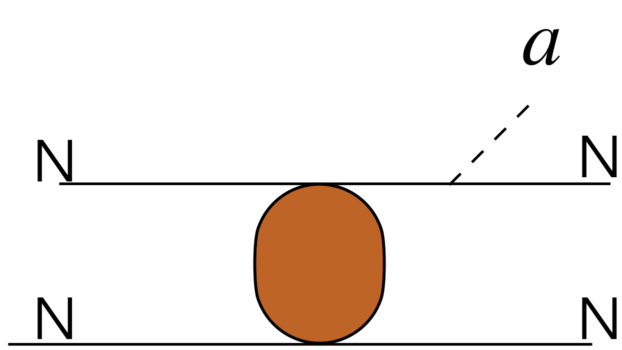
Corresponds to $\sim 10^{56}$ axions/ s.

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

Huge flux… but short!

Supernova axions

Traditional axion production
Nuclear Bremsstrahlung



P. Carenza et al., JCAP 10 (2019) 10, 016

Most significant recent event: a new estimate of the **pion abundance in SN environment**

$Y_{\pi^-} \gg Y_{\pi^0} \gg Y_{\pi^+}$ since pions participate in the **equilibrium** between nucleons $\mu_\pi = \mu_n - \mu_p$ plus ***beyond-ideal-gas*** corrections

$\Rightarrow \quad Y_{\pi^-} \approx$ 1-3%

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

Pion processes $\pi^- + N \to N + a$ may dominate

P. Carenza et al., Phys.Rev.Lett. 126 (2021);
A. Lella et al, *Phys.Rev.D* 107 (2023) 10

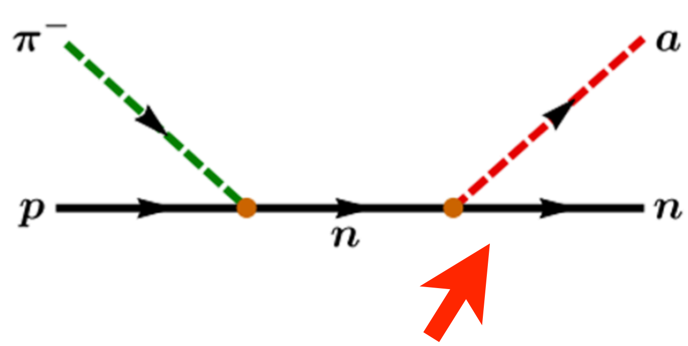
Supernova axions

$$\mathcal{L}_{\rm int} = g_a \frac{\partial_\mu a}{2m_N}\Big[C_{ap}\bar{p}\gamma^\mu\gamma_5 p + C_{an}\bar{n}\gamma^\mu\gamma_5 n + \frac{C_{a\pi N}}{f_\pi}\left(i\pi^+\bar{p}\gamma^\mu n - i\pi^-\bar{n}\gamma^\mu p\right) + C_{aN\Delta}\left(\bar{p}\,\Delta^+_\mu + \overline{\Delta^+_\mu}\,p + \bar{n}\,\Delta^0_\mu + \overline{\Delta^0_\mu}\,n\right)\Big]$$

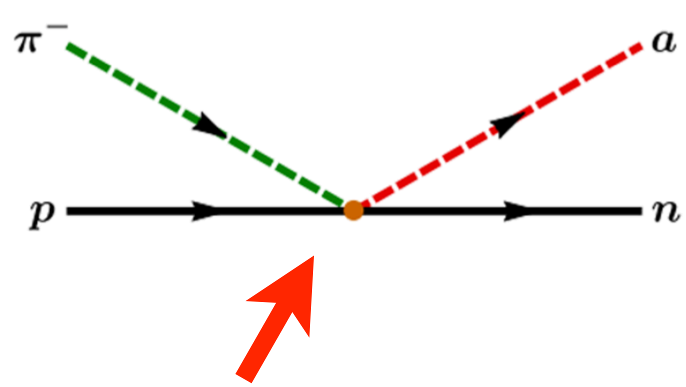
Relevant interaction Lagrangian

A. Lella et al., Phys.Rev.D 107 (2023)

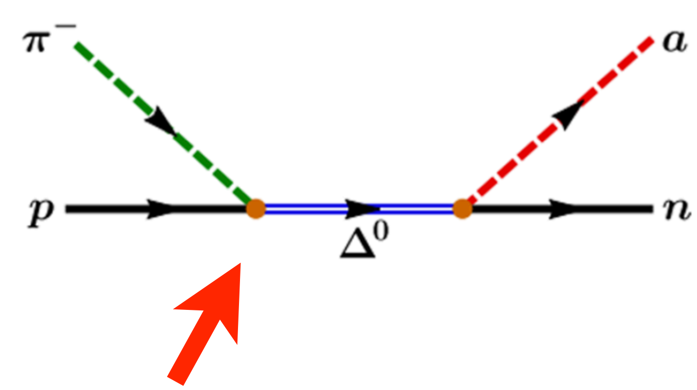
Leads to a variety of processes, studied very recently



P. Carenza et al., Phys.Rev.Lett. 126 (2021);
A. Lella et al, *Phys.Rev.D* 107 (2023) 10



K. Choi et al., *JHEP* 02 (2022) 143



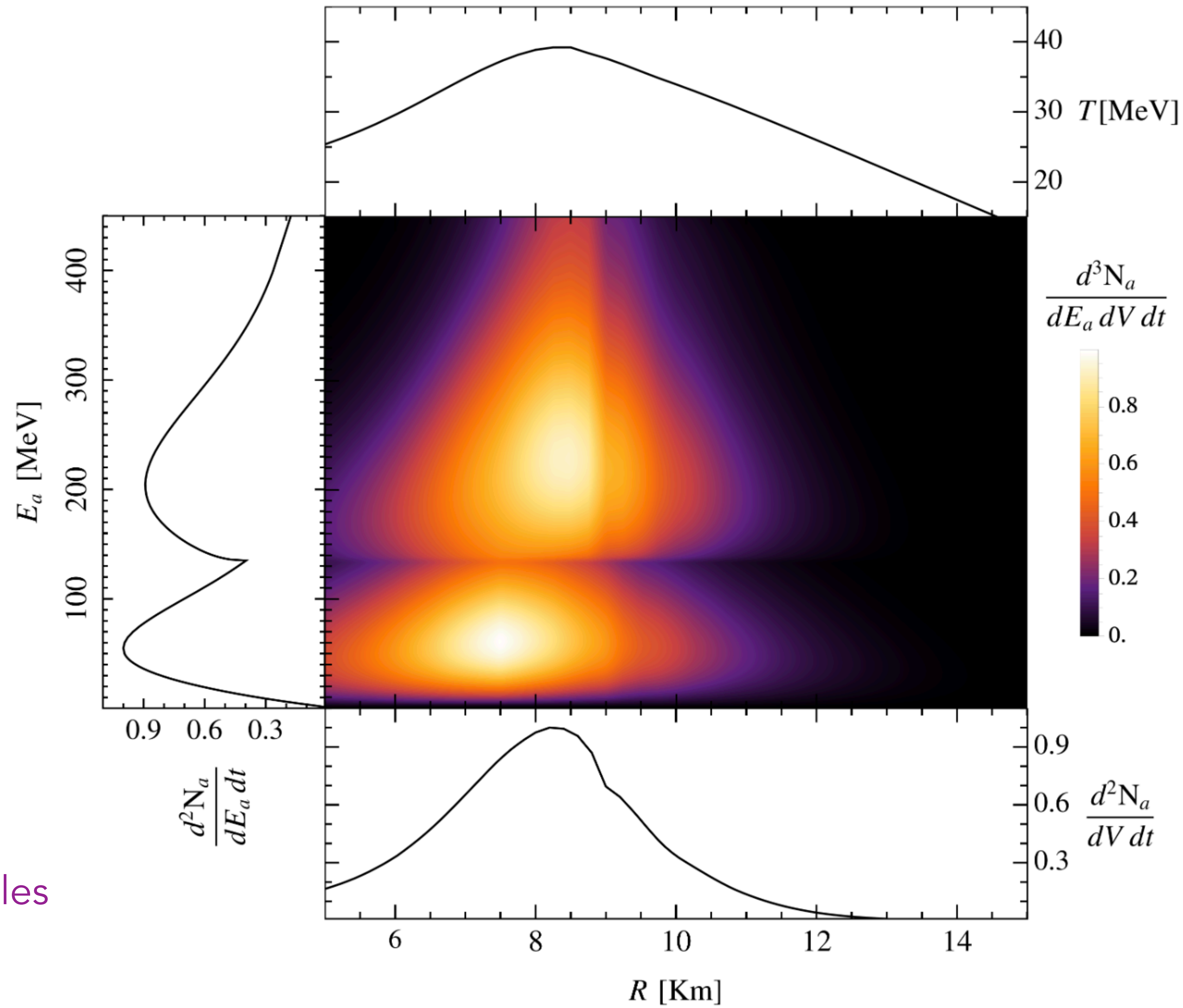
Ho, Kim, Ko, Park, *Phys.Rev.D* 107 (2023) 7

See also Cavan-Piton et al. arXiv:2401.10979

Supernova axions

*Precise **fits exist** in terms of a few parameters.*

Still large uncertainties on the parameters



Uncertainties

- Thermal and density profiles
- Pion mass in medium
- Pion condensate
- …

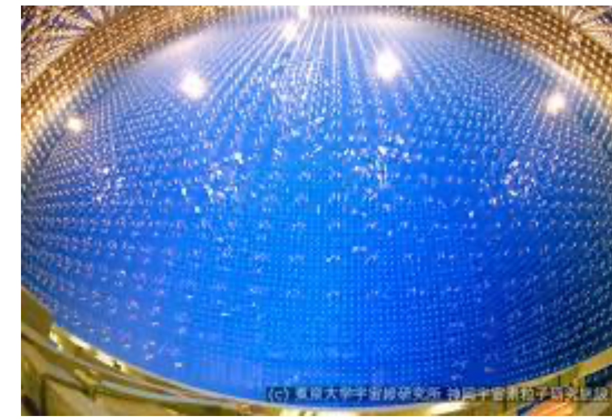
Alessandro Lella et al., in preparation

Detecting SN axions

Direct Detection

→ **Cherenkov**

- A. Lella et al., arXiv:2306.01048;
- Vonk, Guo, Meißner, Phys.Rev.D 105 (2022)
- Li, Hu, Guo, Meißner, 2312.02564
- P. Carenza et al., arXiv:2306.17055



→ **Colliders**

- S. Asai, Y. Kanazawa, T. Moroi, T. Sichanugrist Phys.Lett.B 829 (2022)

→ **Heliscopes**

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

new proposal by Juan Anton Garcia Pascual (UNIZAR/CAPA)

Indirect detection

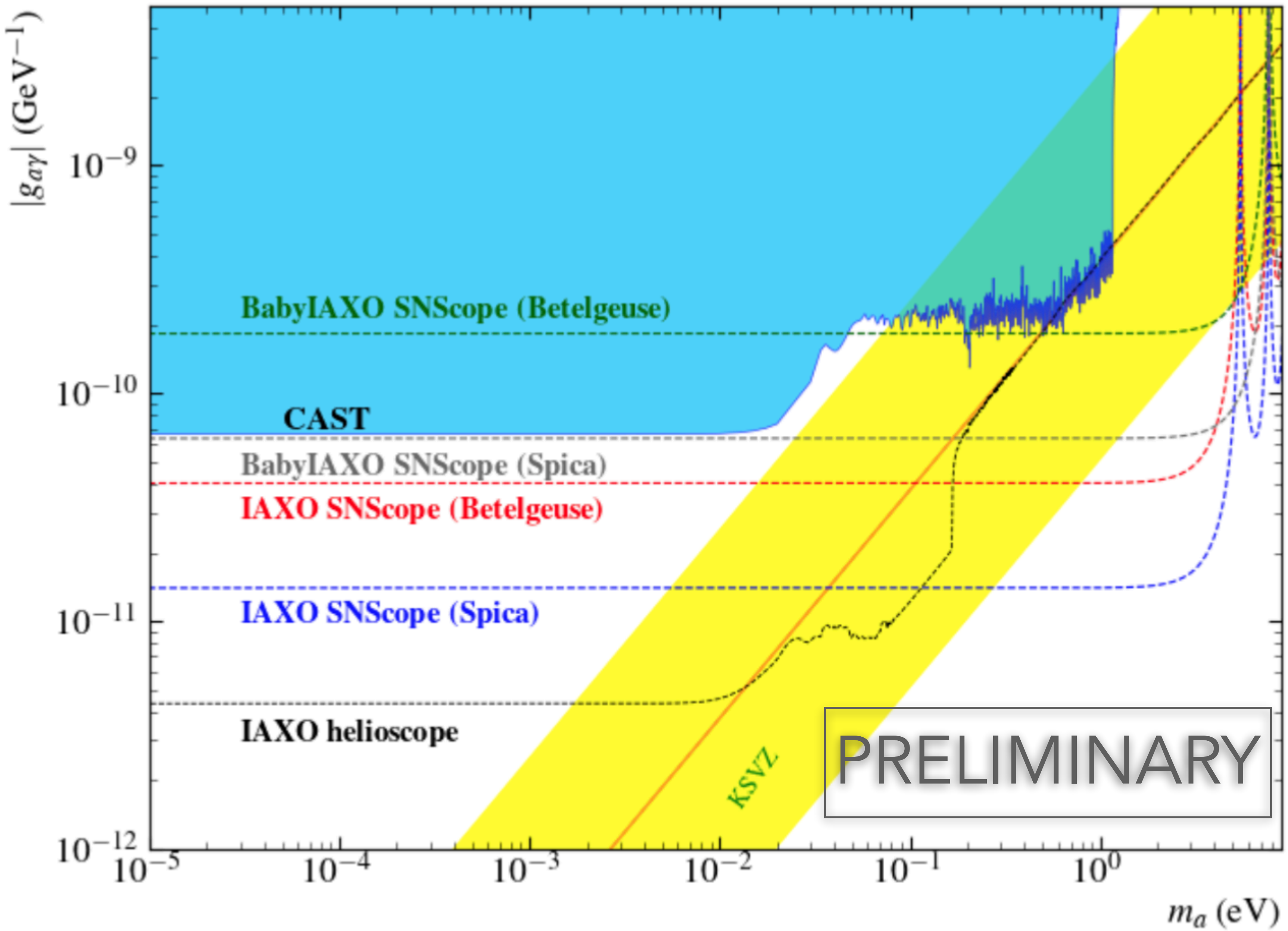
Through photon oscillations in $B_{\rm ext}$

- F. Calore et al. e-Print: 2306.03925
- A. Lella et al. In preparation
- Meyer et al. Phys.Rev.Lett. 118 (2017)

Detecting SN axions

Direct Detection:

→ **Heliscopes**



New research proposal @UNIZAR, lead by Juan Anton Garcia Pascual, for the construction of the appropriate detector for these high energies

Will we detect Stellar Axions with Next Gen. Experiments?

Sun	• High potential to detect ALPs (including QCD axions) if $m_a \lesssim 100\,\mathrm{meV}$ and $g_{a\gamma} \sim$ stellar bounds • Possibility to explore solar magnetic field through $g_{a\gamma}$ but likely not in next generation experiments • Unlikely axions discover through g_{ae} in the near future • Several channels through g_{aN}. Some tension with SN1987A
Other stars	• Production can be much larger than in the Sun • Require magnetic fields to compensate for large distance $\Longrightarrow$ Explore mostly very low mass region but sensitive to very small couplings
SN	• Huge production but for short time. Several nearby candidates • Direct detection may be possible but difficult • At very low mass, strong potential for detection with γ-ray observatories (e.g., Fermi LAT) • At high mass, possible detection of decay products (e.g., Fermi LAT)

Conclusions and final comments

- Important progress in last years in the attempts to detect the stellar axion flux

- Axions with couplings at the current thresholds would excellent astrophysical messengers.