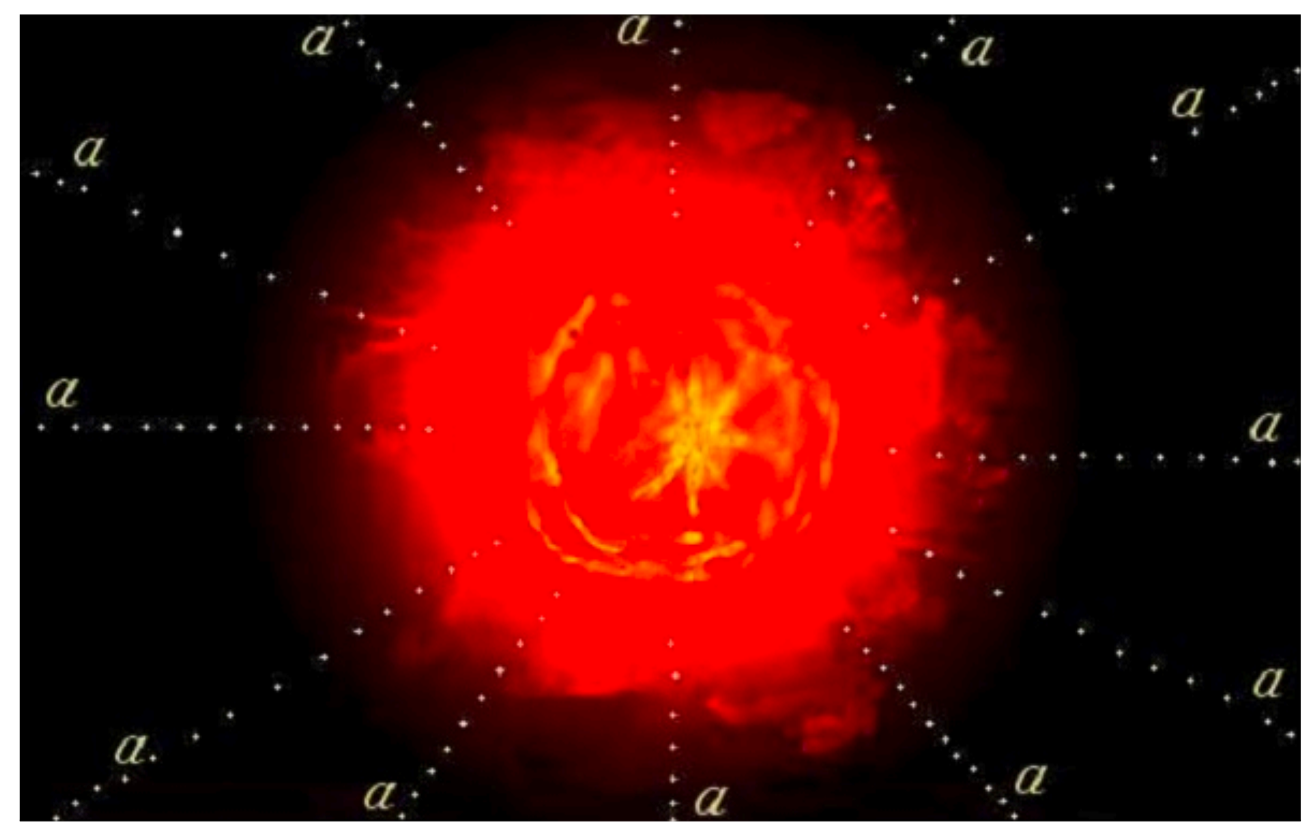
Axions from Monster Stars

Maurizio Giannotti
University of Zaragoza, CAPA

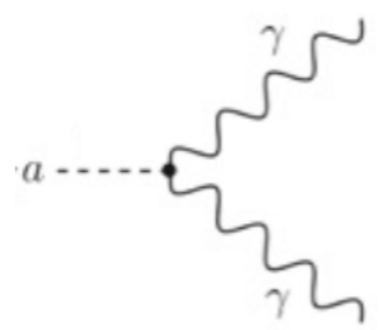
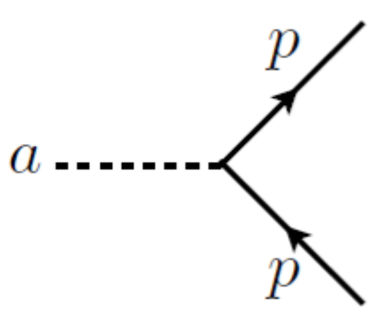
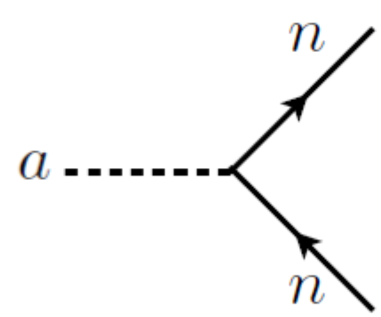
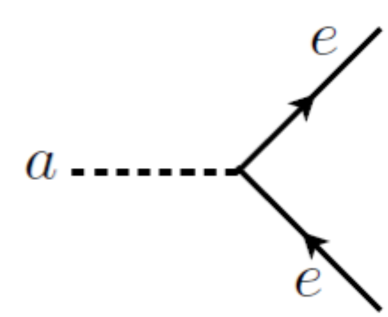


Contact →
mgiannotti@unizar.es

Saturnalia,
Universidad de Zaragoza, 19 December, 2023

Axions and ALPs

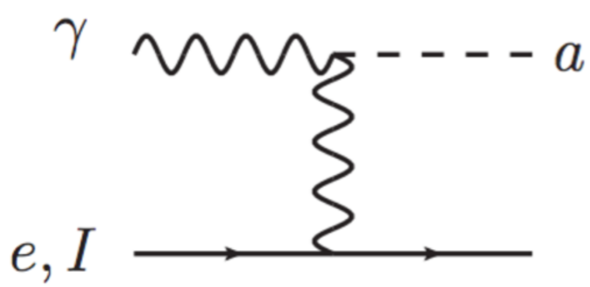
Axions (and ALPs) interact with SM fields. This allow for a rich and interesting phenomenology, and for their possible detection

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

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

Axions and ALPs

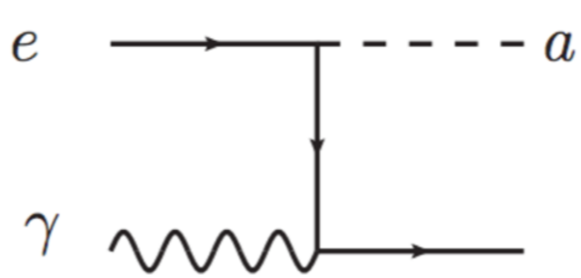
Most relevant axion channels



Primakoff

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

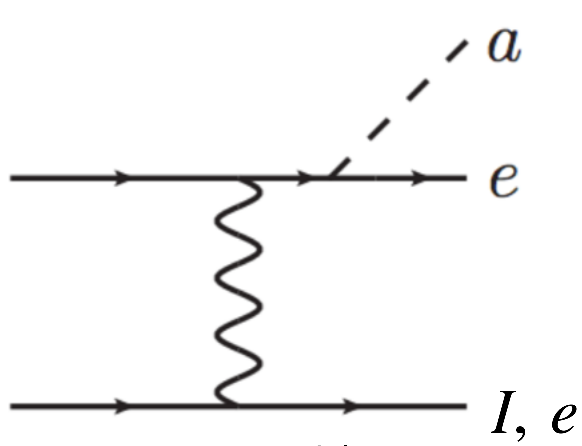
with T in K and ρ in $\mathrm{g\,cm^{-3}}$, and $F(\xi)$ is $\mathcal{O}(1)$. Valid in nondegeneratae plasma



Compton

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

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



Bremsstrahlung

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

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

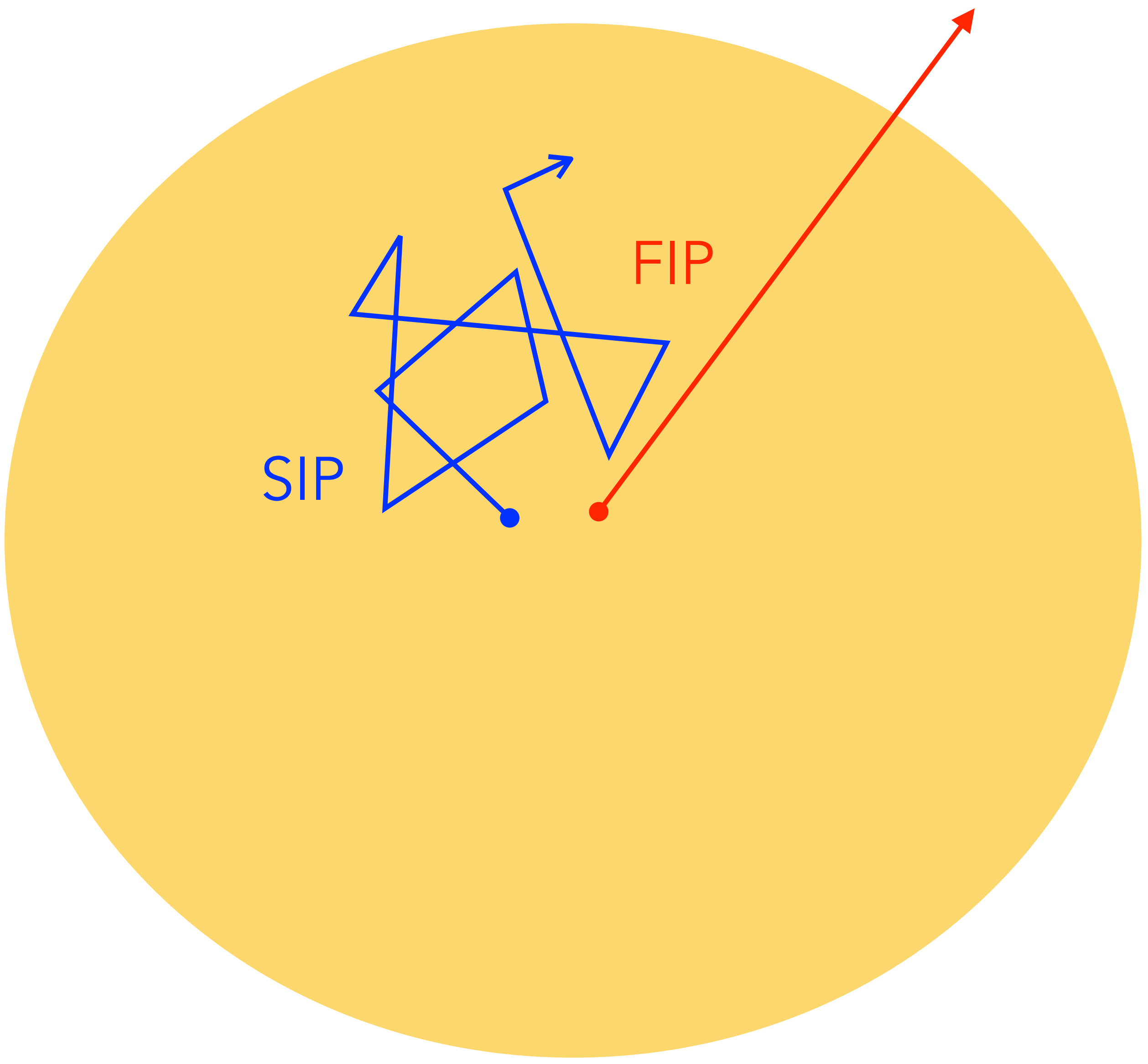
Di Luzio, Fedele, M.G., Mescia, Nardi, JCAP 02 (2022) 02, 035

Stars as FIPs Factories

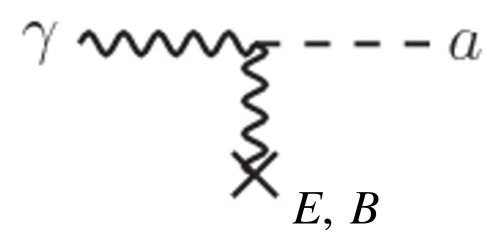
FIPs can escape stars, once produced.

Volume production.

Large flux!

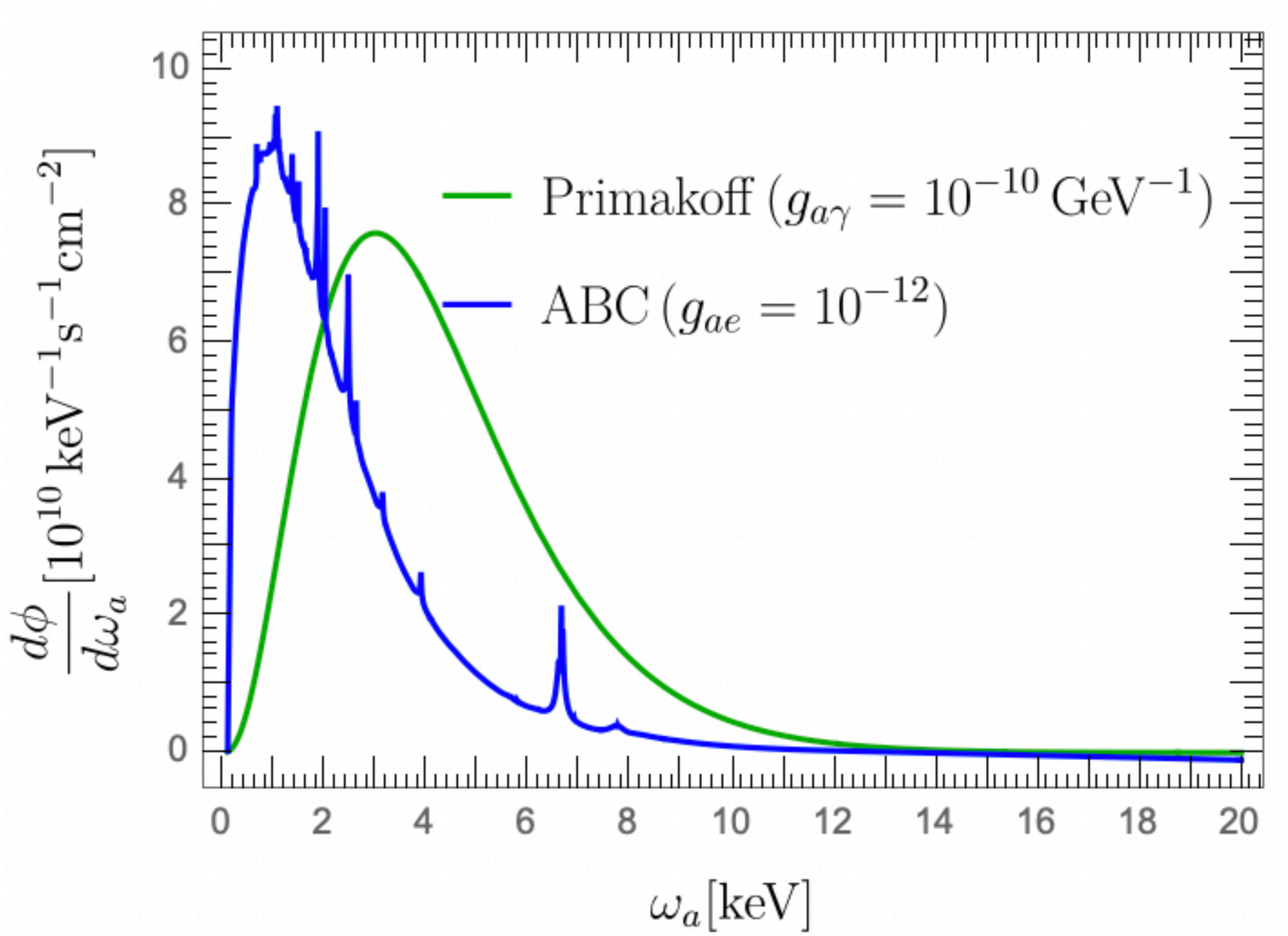


The Sun as Axion Factory

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

The Sun as Axion Factory

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



J. Redondo, JCAP 1312 (2013)

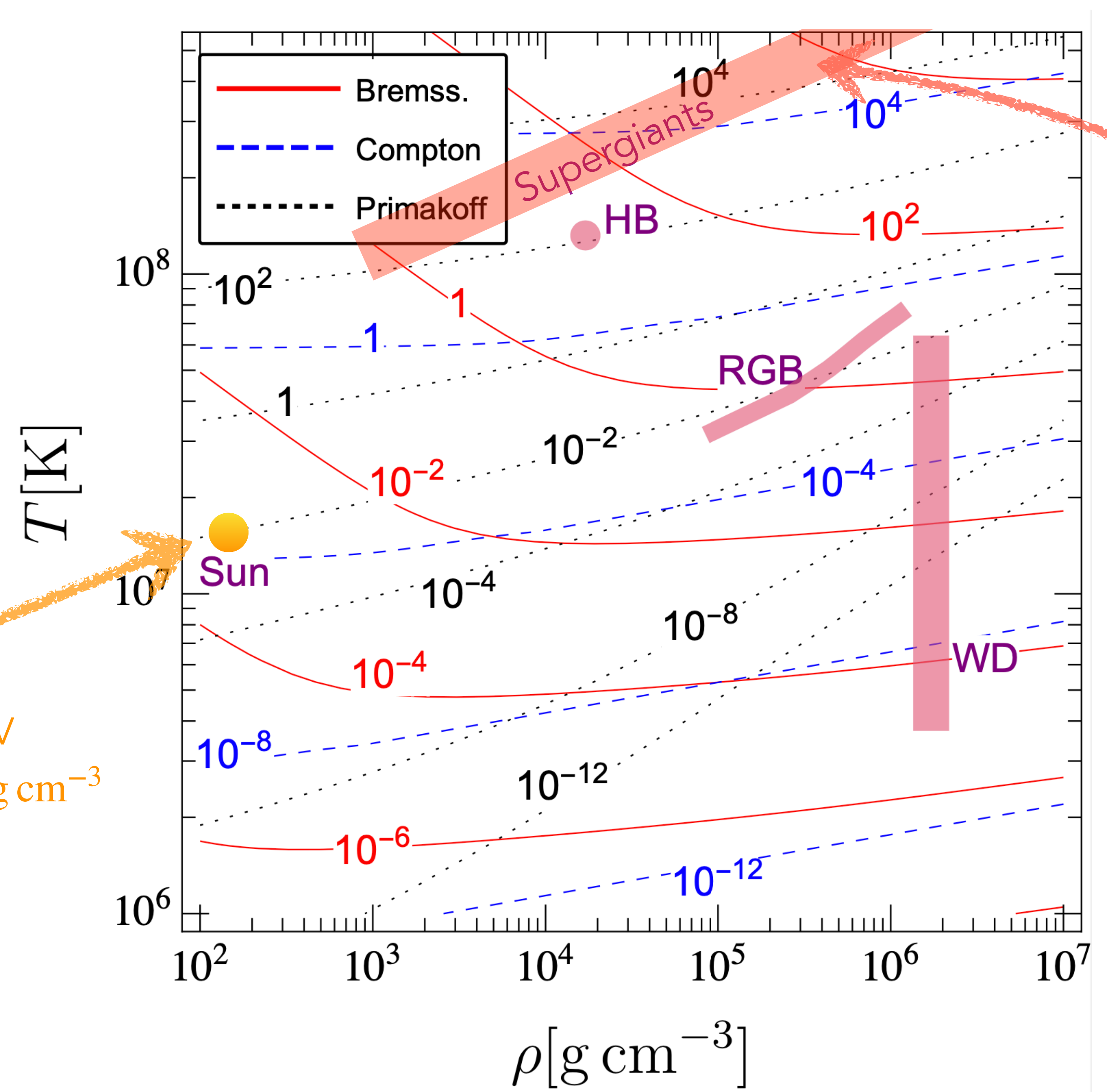
up to $\sim 10^{39}$ axions/s
($\Rightarrow 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ axions on Earth), peaked at $\sim$ keV

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

→ See Julia's talk

Plus, the additional axion flux from the other processes

Monster Stars



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

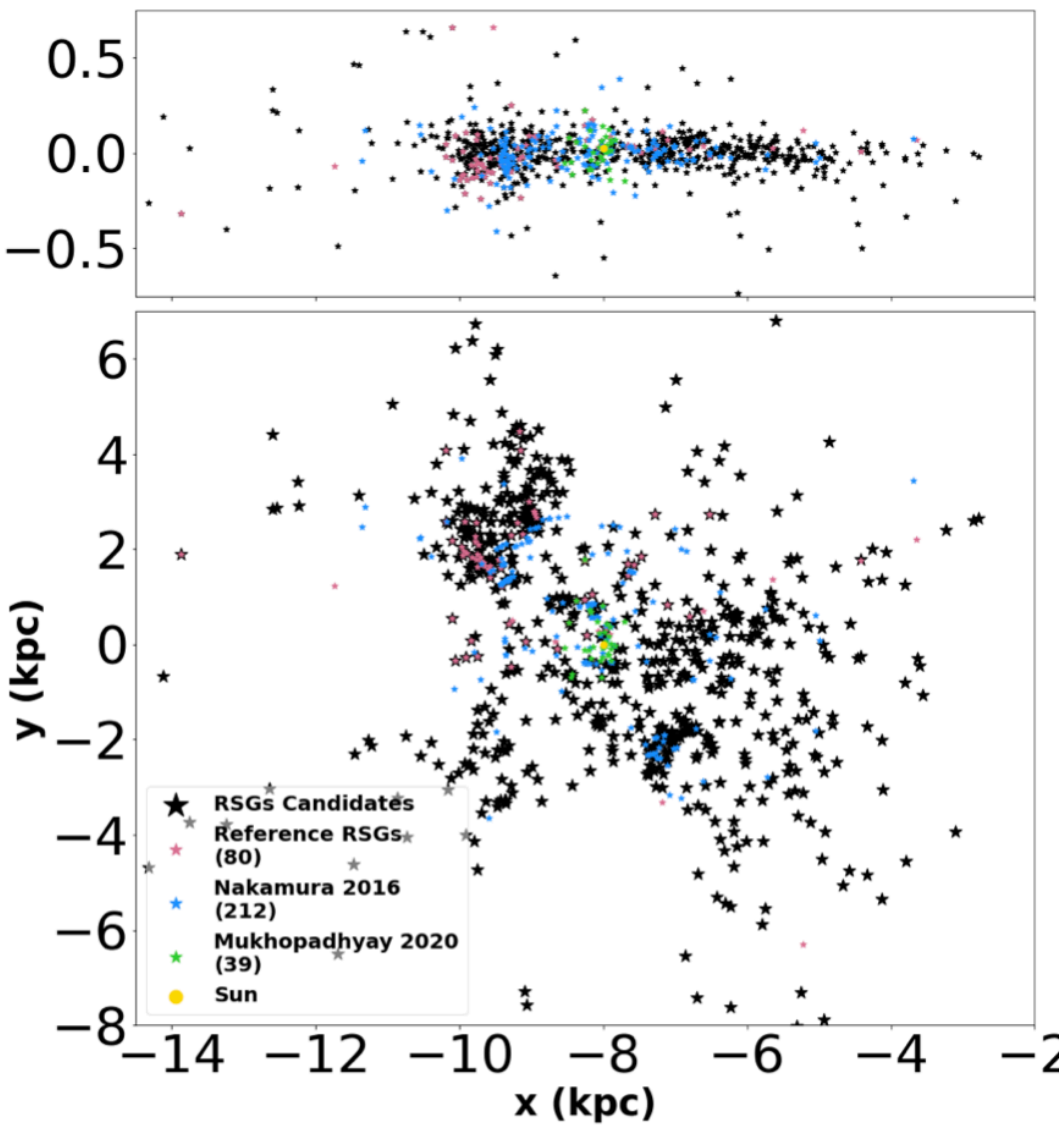
supergiants: T_c and ρ_c depend on mass and evolutionary stage

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 at d<200 pc

Table 1: List of SN progenitor candidates with having a mass $\gtrsim 10\ M_\odot$ and within 250 pc from the Earth. We basically use the values listed in the Hipparcos catalogue [78]; otherwise, we show the reference for the source.

HIP	Common Name	Distance (pc)	Mass ($M_\odot$)	RA (J2000)	Dec (J2000)
65474	Spica/α Virginis	77(4)	11.43 ± 1.15 [79]	13:25:11.58	-11:09:40.8
81377	ζ Ophiuchi	112(3)	20.0 [80]	16:37:09.54	-10:34:01.5
71860	α Lupi	142(3)	10.1 ± 1.0 [81]	14:41:55.76	-47:23:17.5
80763	Antares/α Scorpii	170(30)	11–14.3 [82]	16:29:24.46	-26:25:55.2
107315	Enif/ϵ Pegasi	211(8)	11.7(8) [81]	21:44:11.16	+09:52:30.0
27989	Betelgeuse/α Orionis	222^{+48}_{-34} [83]	$11.6^{+5.0}_{-3.9}$ [84]	05:55:10.31	+07:24:25.4

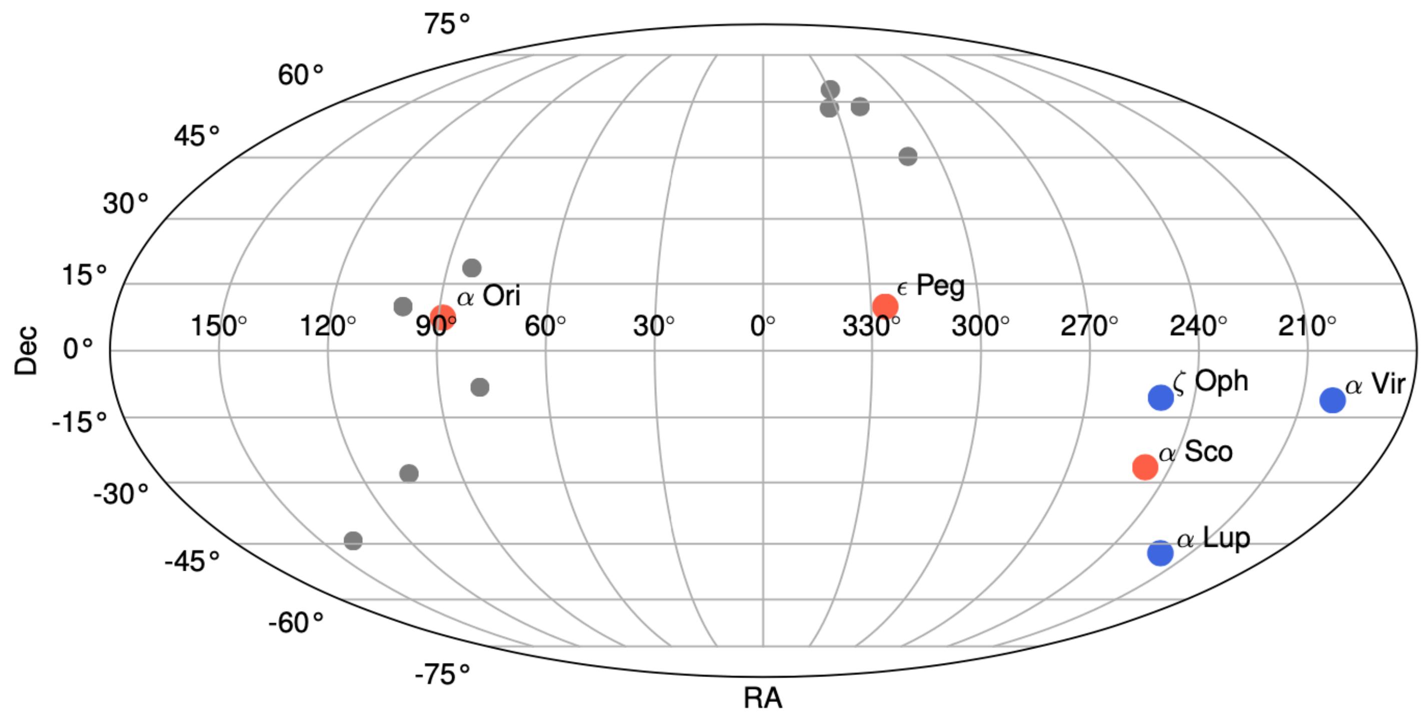
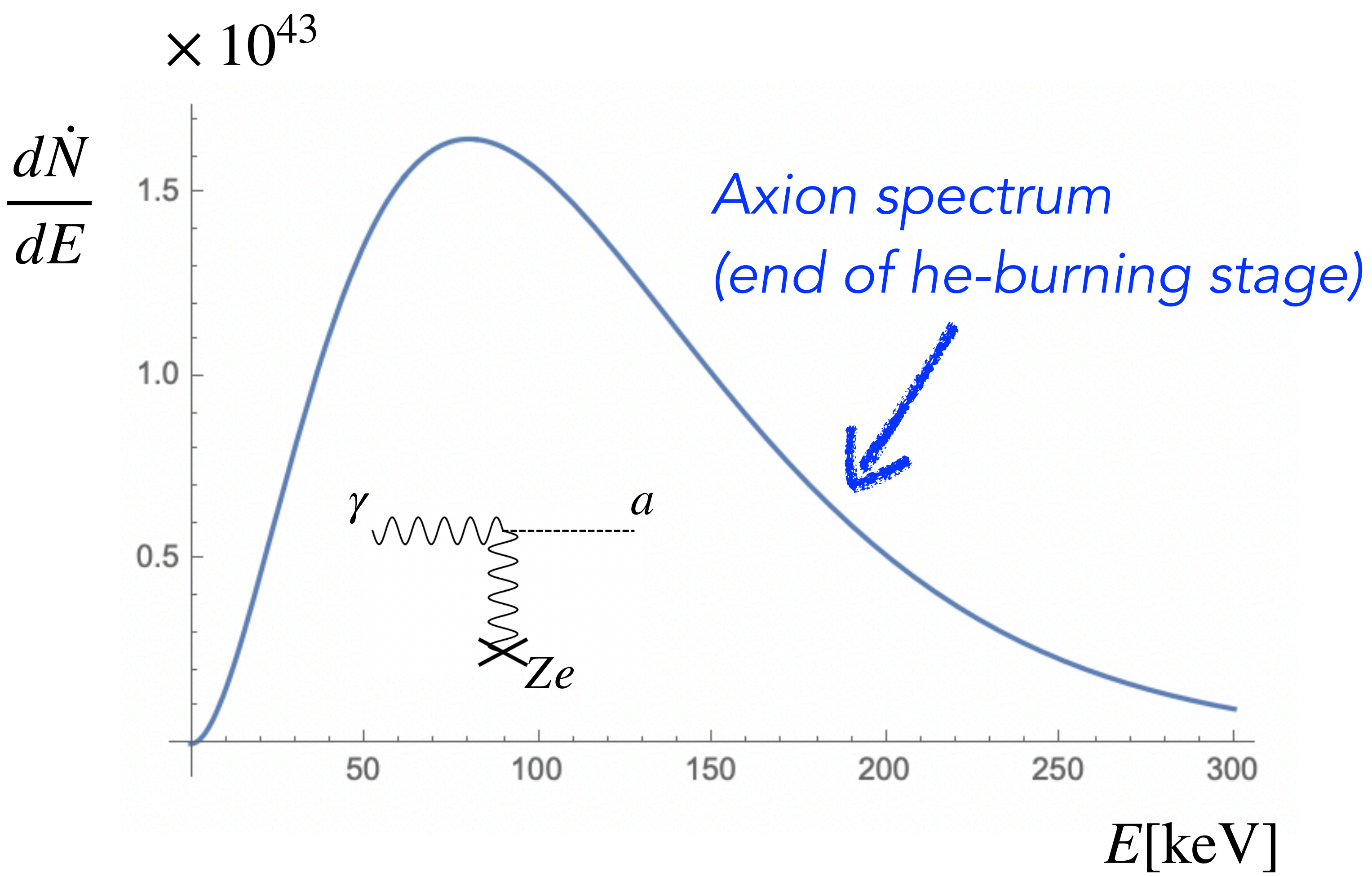


Figure 1: The position of the SN progenitors in Table 1 on the Mollweide projection of the celestial sphere, where the red and blue dots correspond to the spectral types of K/M and O/B, respectively. We also show by the gray dots the progenitors with $d > 250$ pc and $M \gtrsim 10\ M_\odot$ listed in Table A1 in Ref. [87].

From S. F. Ge et al., IAXO as SN-scope JCAP 11 (2020) 059

Supergiant Axions



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

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

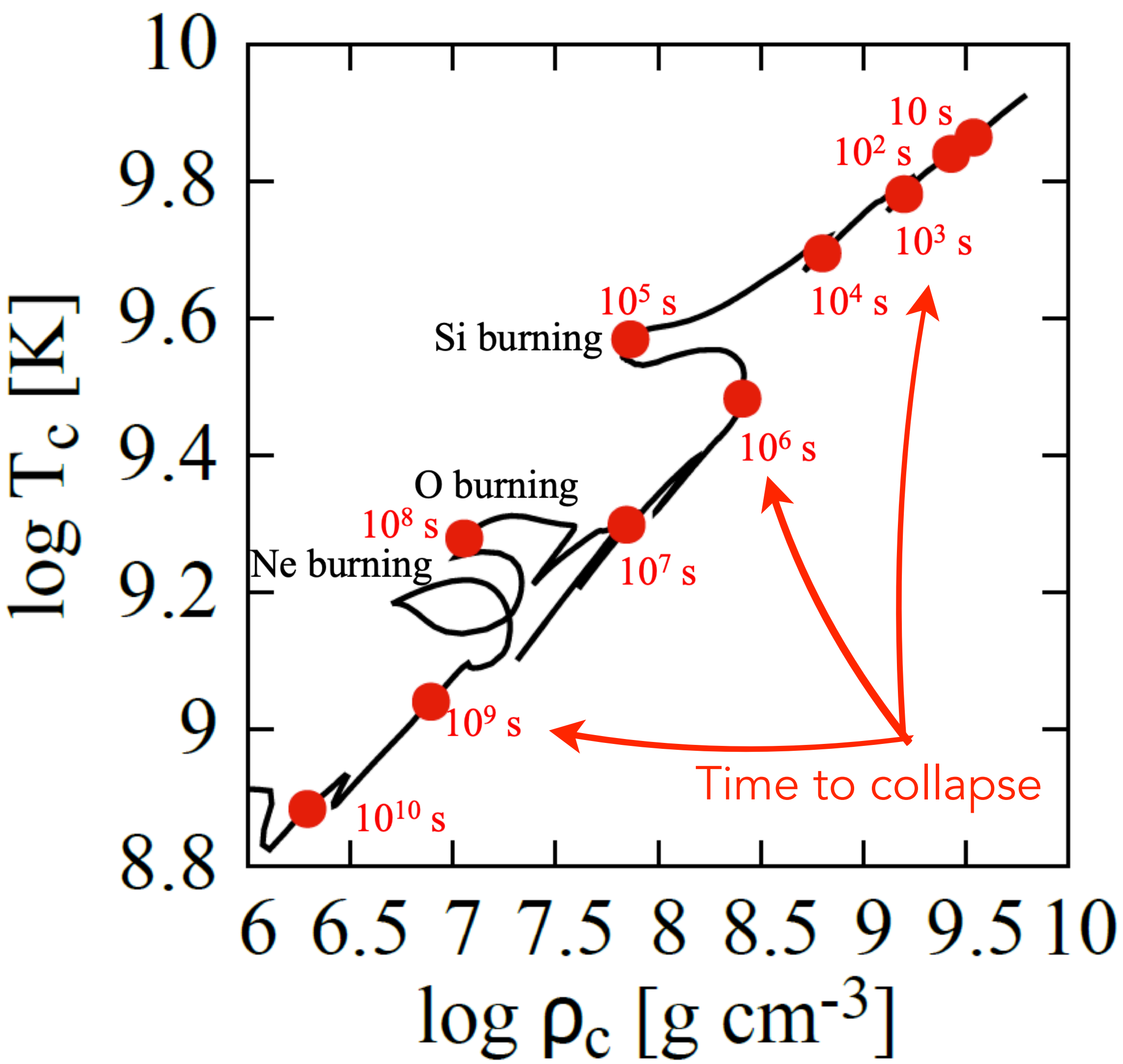
Flux increases adding g_{ae} coupling

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

The Very Last Stages of a Monster Star

$t_{\mathrm{collpase}} - t$ [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



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

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

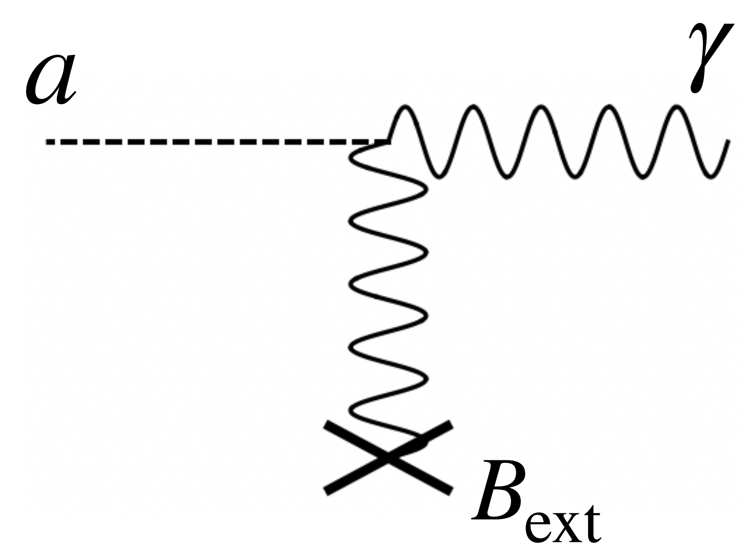
Supergiant Axions

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

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

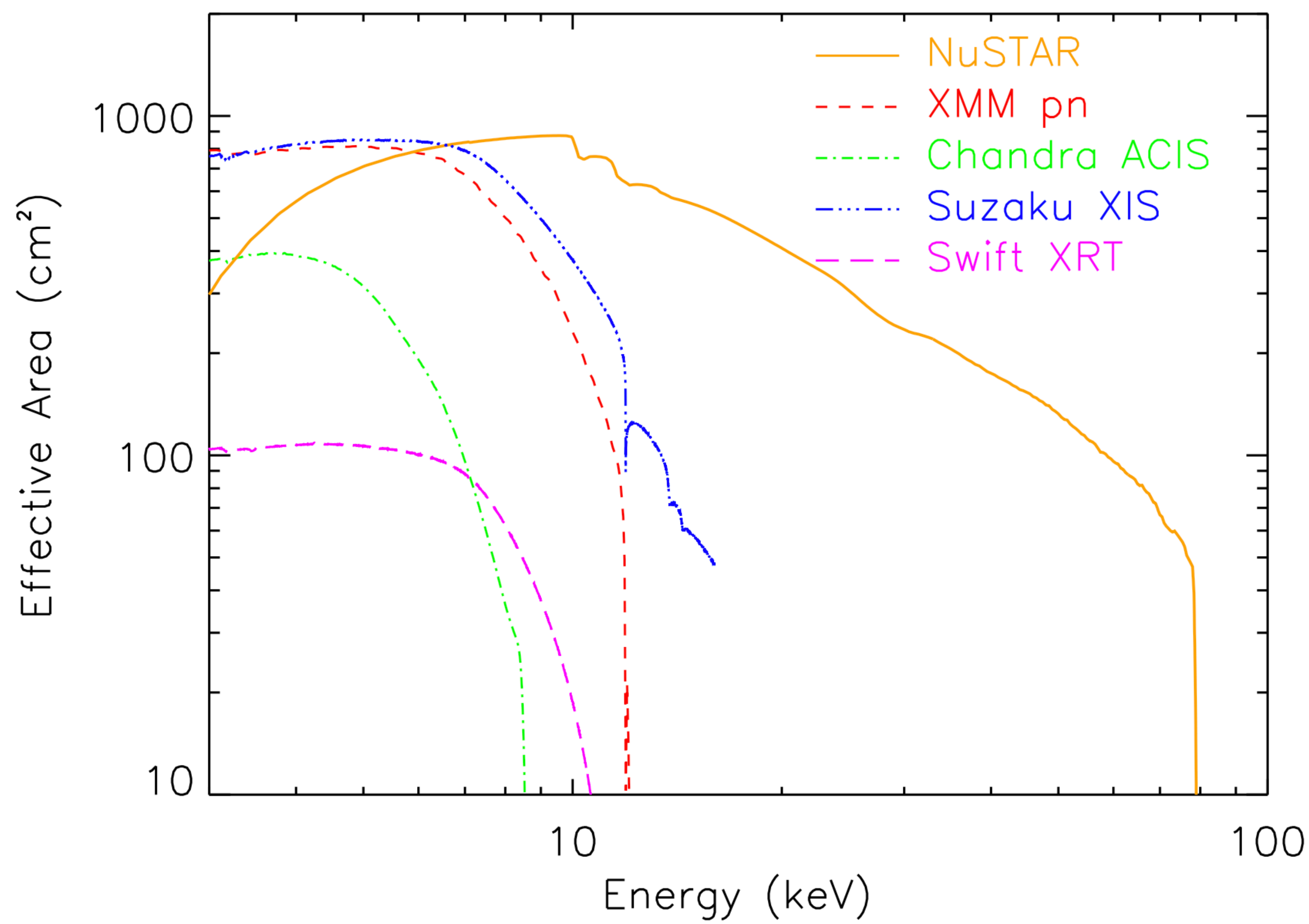
(Assuming B uniform)

$g_{11} \leq 6.5$ 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)

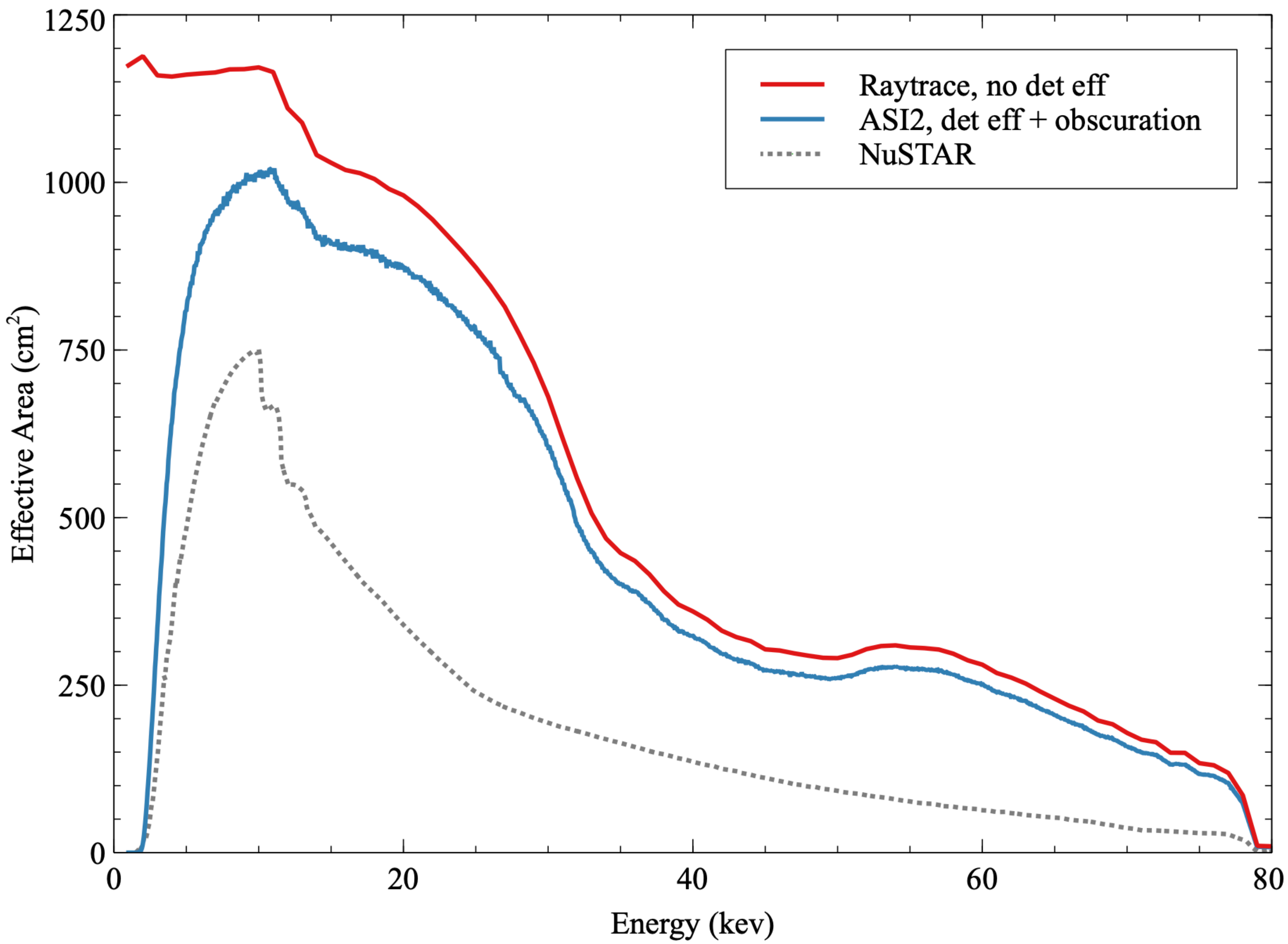


Gamma-ray detectors in MeV range → GECCO, COSI, AMEGO…

X-Ray Detectors

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

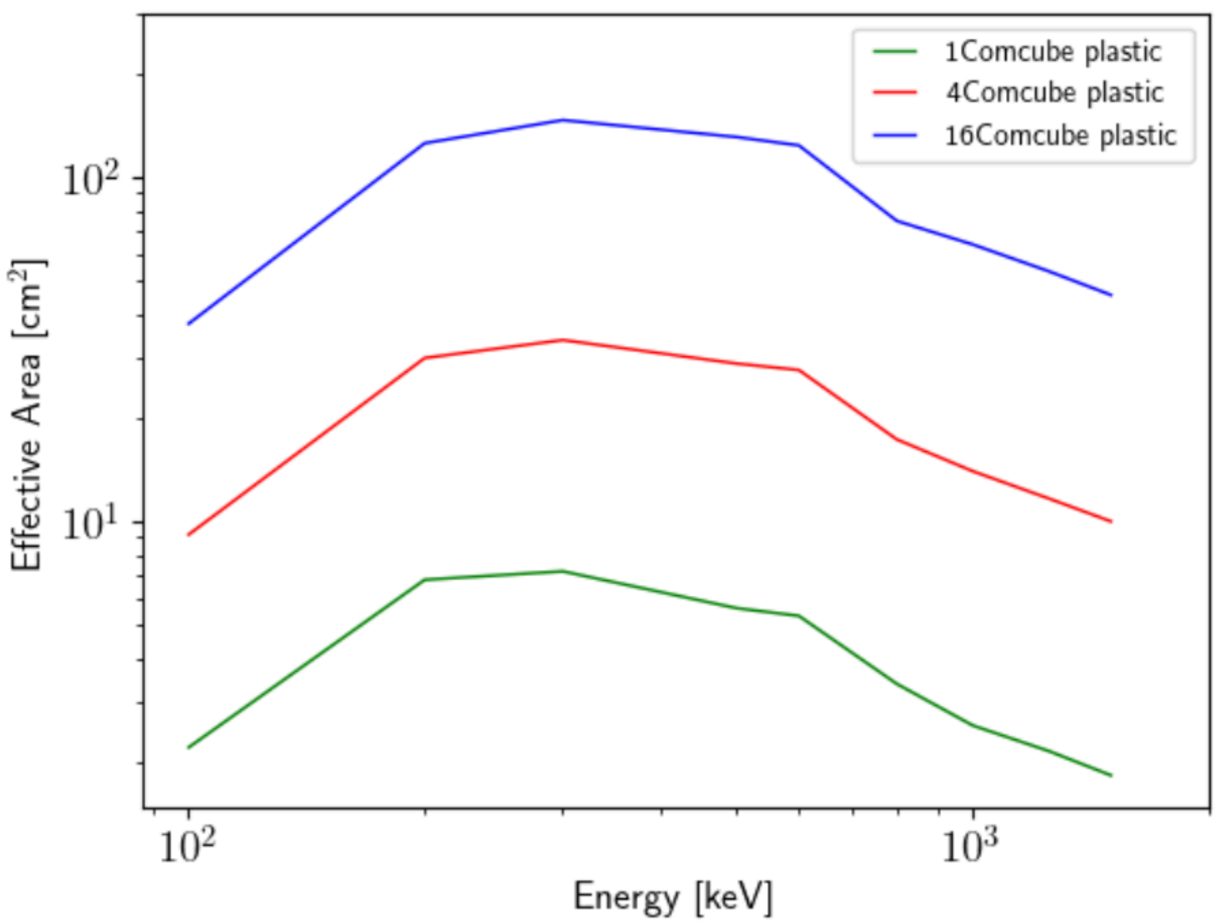
Instrument and Mission Profile paper last week (on Dec 7)

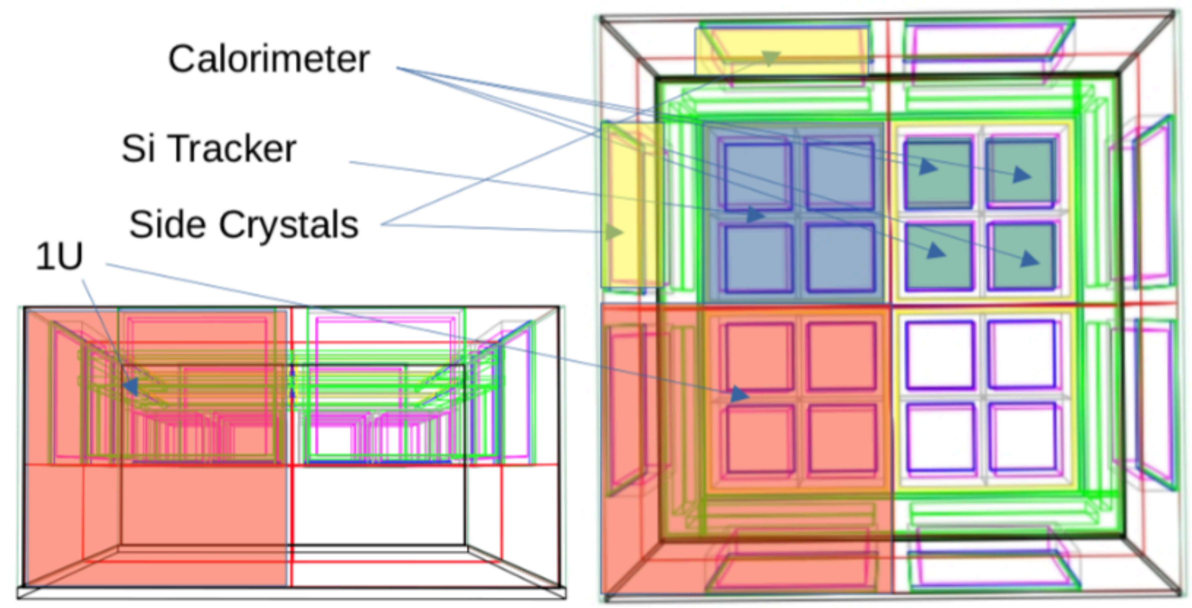


Same target energy as NuSTAR.

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

Soft Gamma-Ray Telescopes?

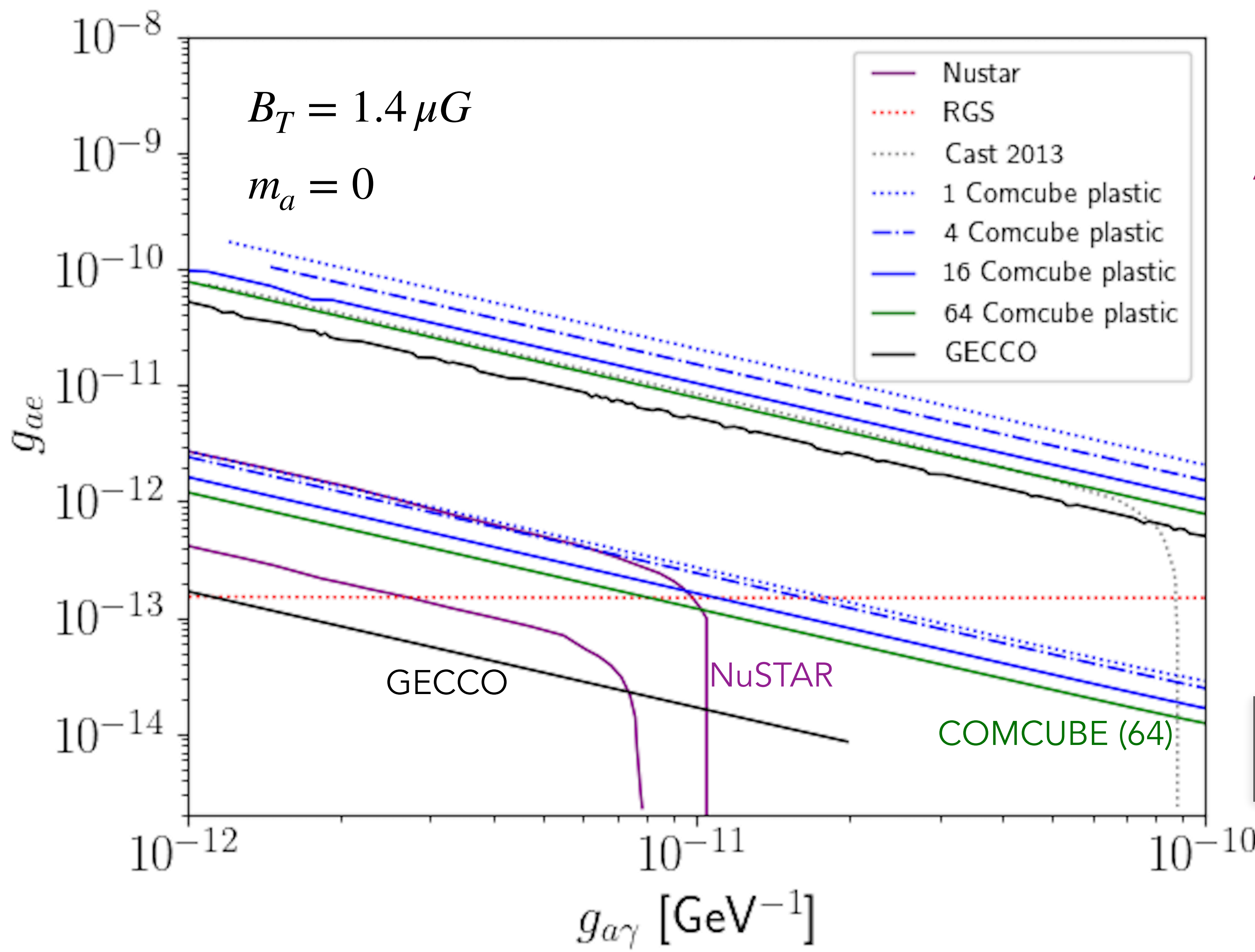




The CubeSat units (U), defined as $10 \times 10 \times 10\,\mathrm{cm}^3$ in volume and 1.3 kg in mass, can be combined to form larger spacecrafts.

COMCUBE is a project of the European programme AHEAD2020 for a Compton polarimeter CubeSat mission to measure the polarization of bright gamma-ray bursts, and transient events in general. Presented at the Journées de la SF2A Société française d'astronomie et d'astrophysiques (2021) → [communication from Aldo Morselli]

Soft Gamma-Ray Telescopes?

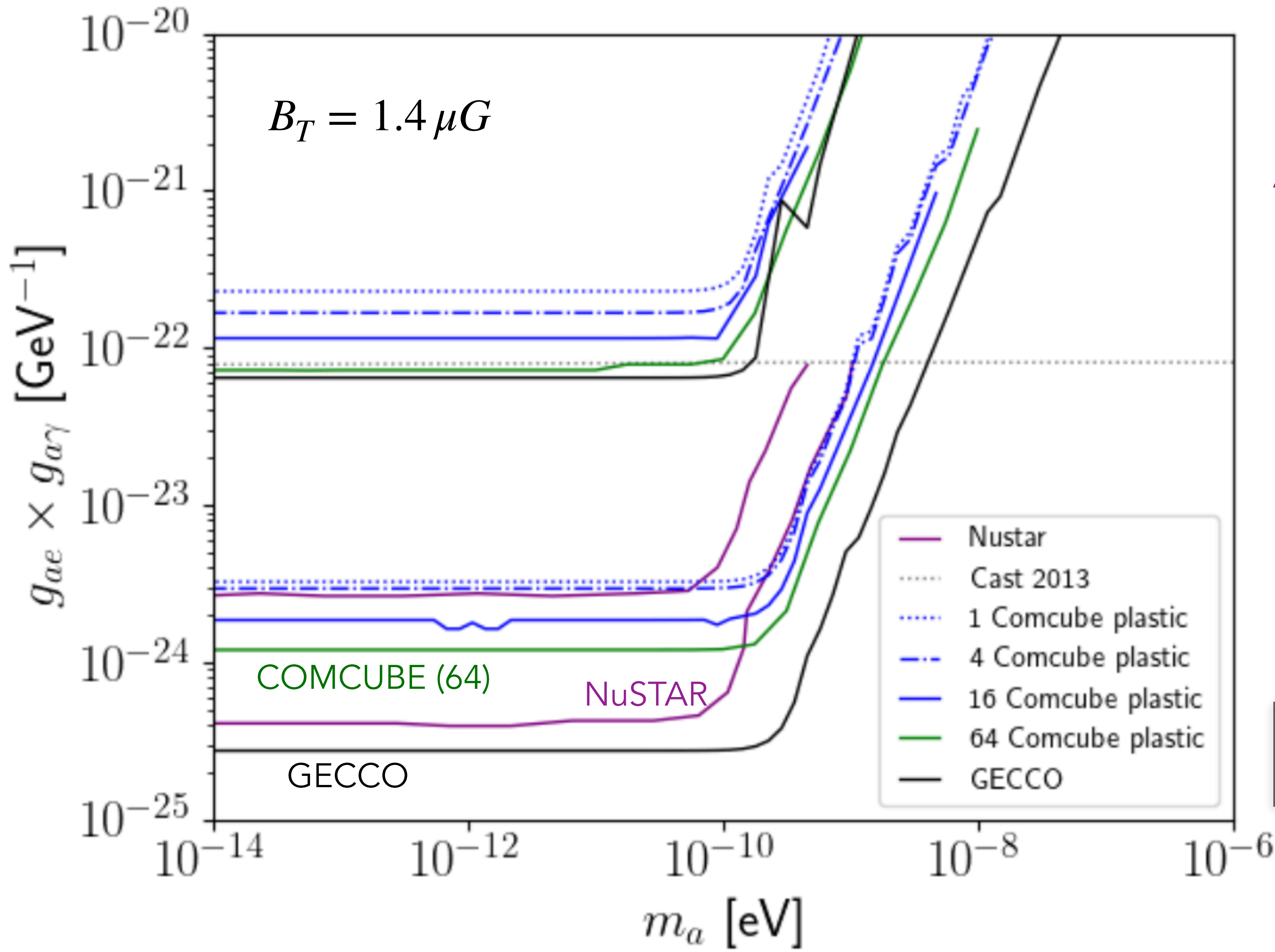


Best options → NuSTAR, GECCO, COSI, AMEGO

PRELIMINARY

Aldo Morselli, F. Calore, MG, et al. (in preparation)

Soft Gamma-Ray Telescopes?



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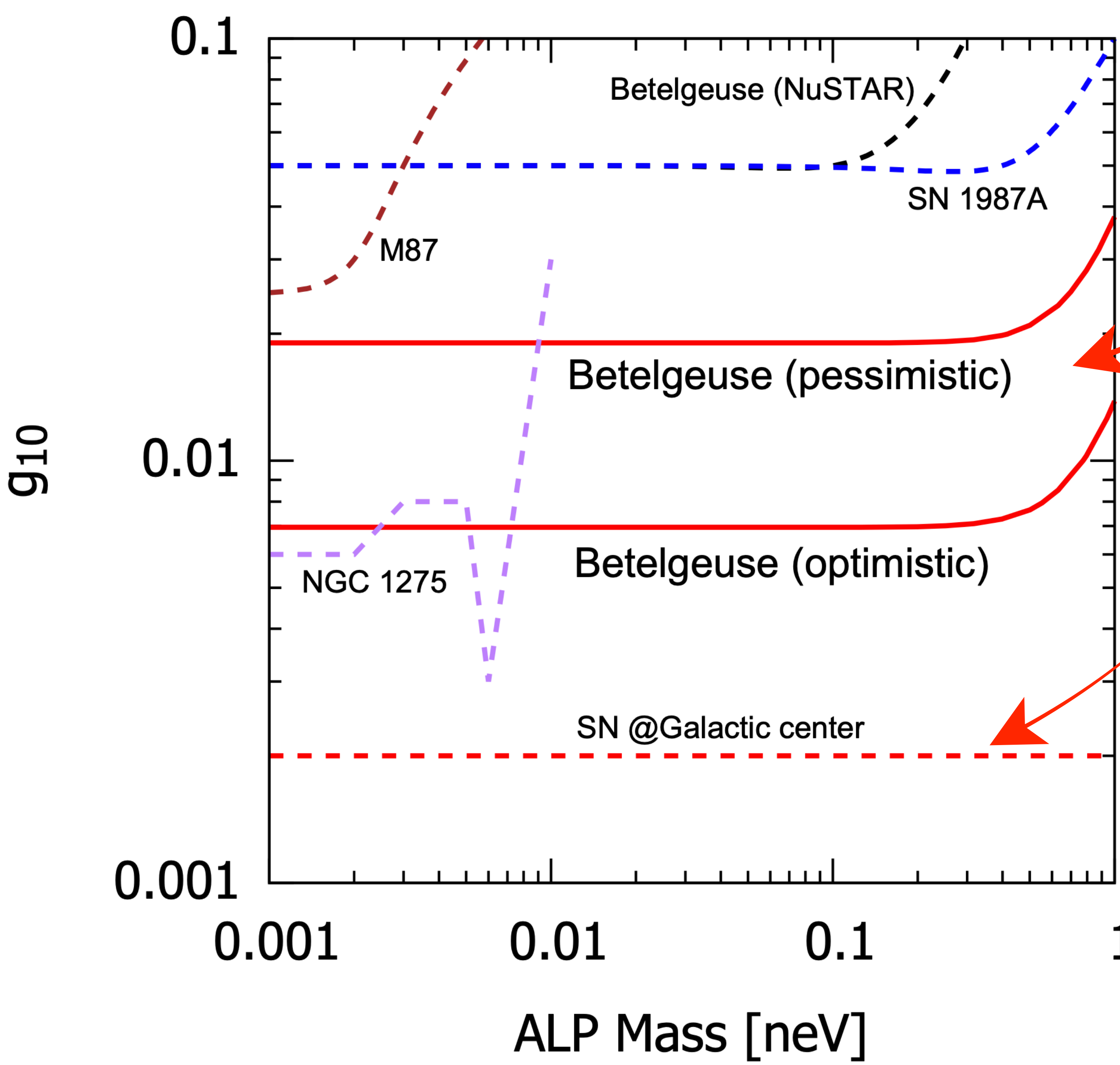
PRELIMINARY

Aldo Morselli, F. Calore, MG, et al. (in preparation)

The Very Last Stages of a Monster Star



Sensitivity: Assuming AMEGO 100 ks observation before collapse.

Sensitivity: Fermi LAT, SN-explosion

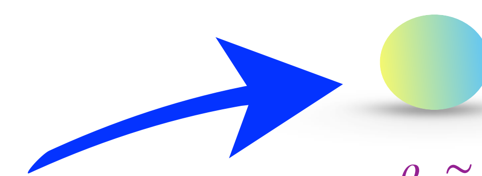
M. Meyer , M. G., A. Mirizzi, J. Conrad, M. A. Sánchez-Conde, Phys.Rev.Lett. 118 (2017)

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

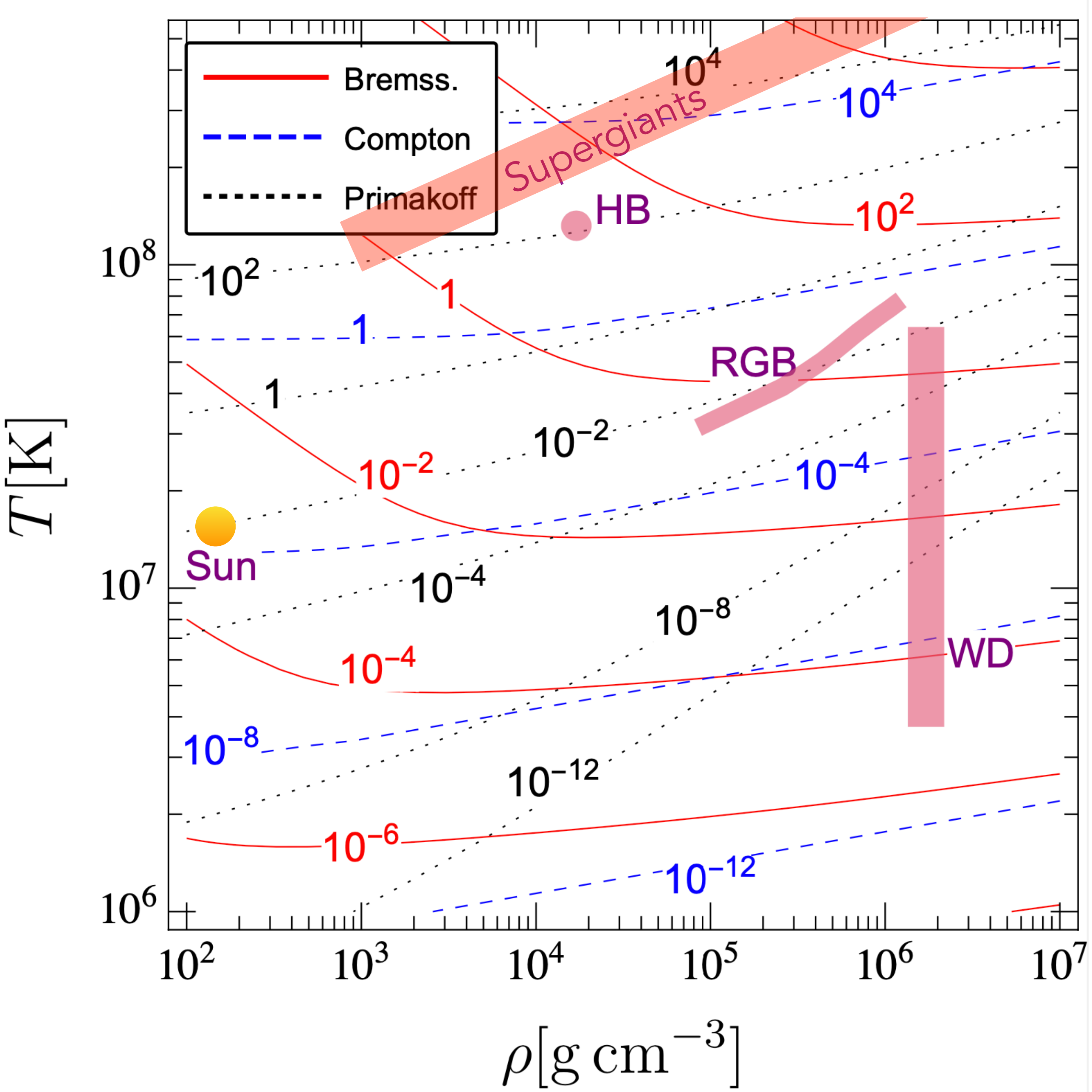


SN

The truly monster stars

$T_c \simeq 30$ MeV

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



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

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

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

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

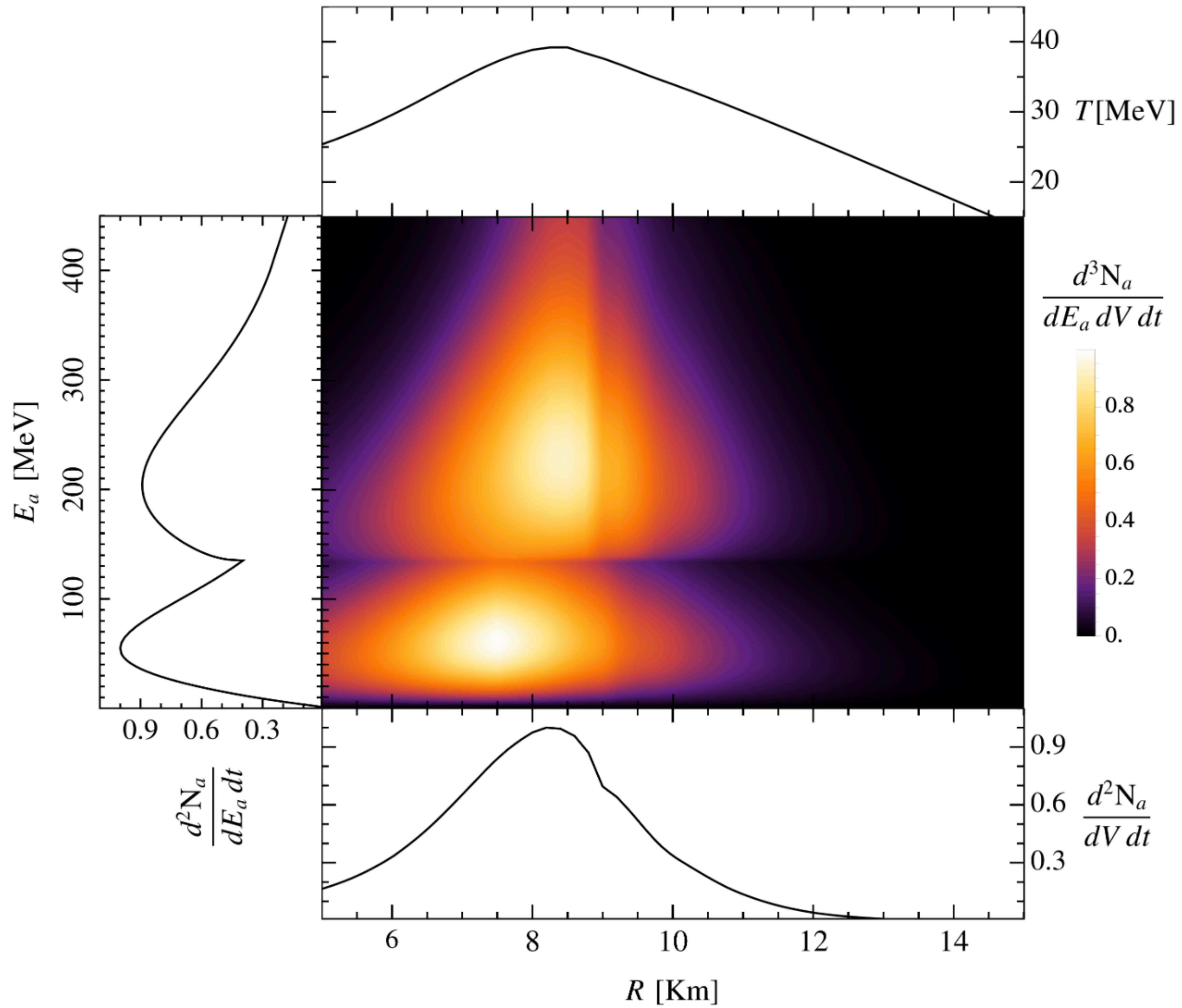
About $\sim 10^{13}\,\mathrm{cm^{-2}\,s^{-1}}$ axions on Earth from Betelgeuse

Huge flux… but short!

Supernova axions

Contributions from pion processes and from nucleon bremsstrahlung

Very significant progress in the last 3 years but still many uncertainties (See backup slides)



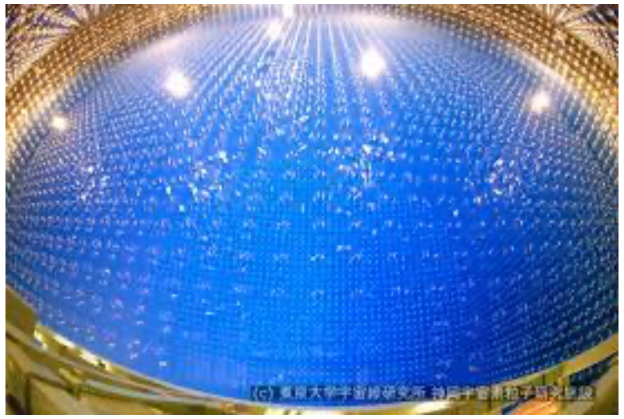
Alessandro Lella et al., in preparation

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

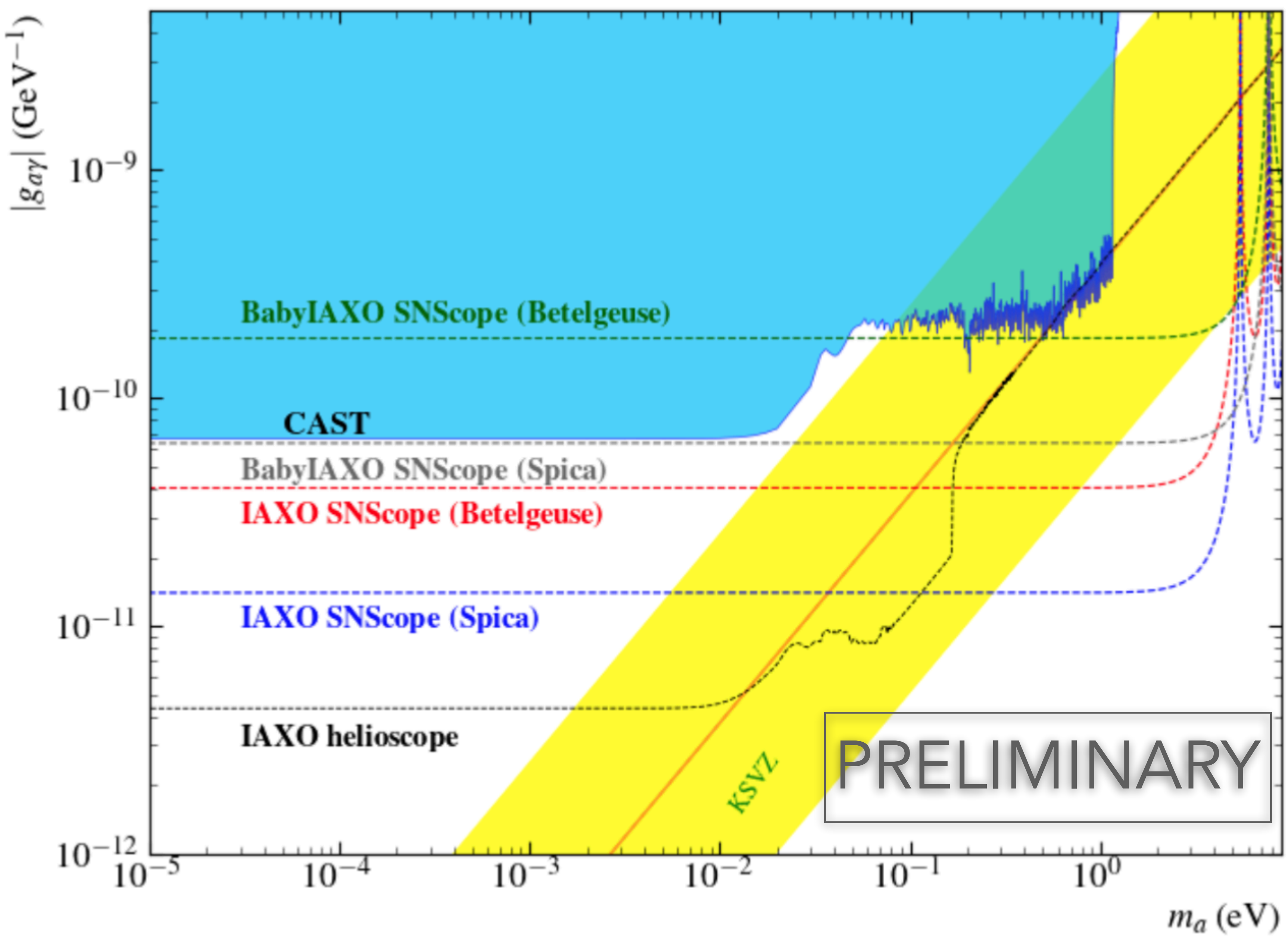
Through photon oscillations in B_{ext}

- 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 @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 • Higher masses may be accessed through g_{aN}, but in large part in 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 we need JuanAn's new detector • 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

- Other stars besides the Sun may be very good ALP factories

- New interesting ideas are popping out and many things are still unexplored

- Come talk to me if you are interested in learning more about some of these aspects.

→ Opportunities for students

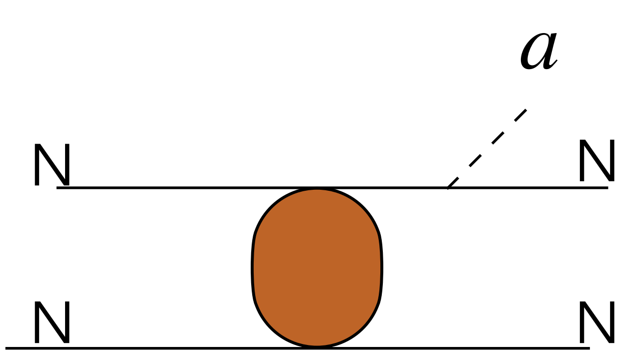
Backup Slides

Supernova axions

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

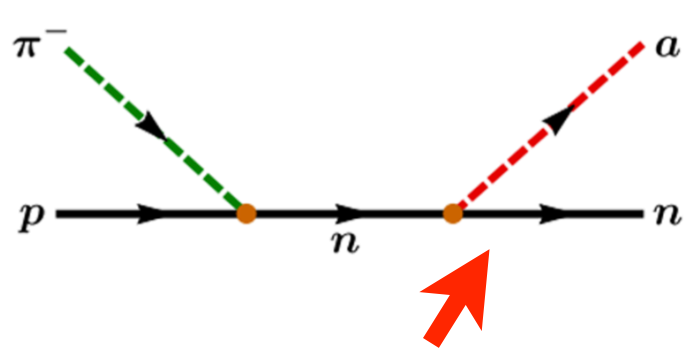
Relevant interaction Lagrangian

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

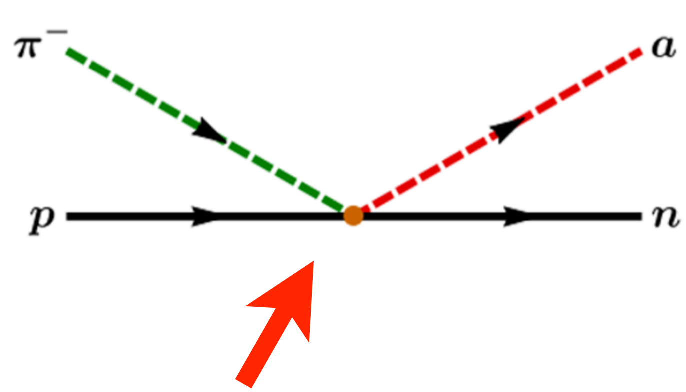


P. Carenza et al., JCAP 10 (2019) 10, 016

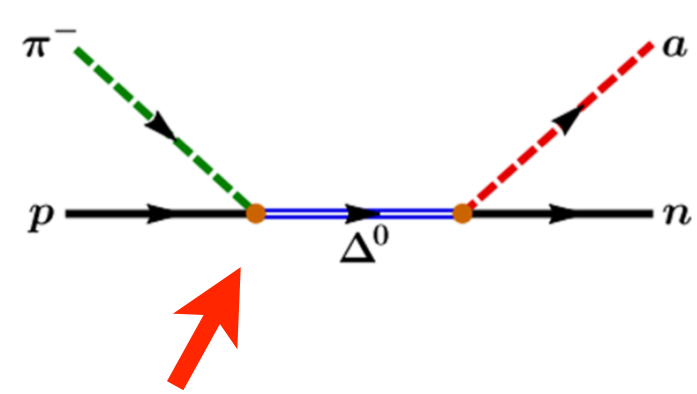
Leads to a variety of processes, studied very recently



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



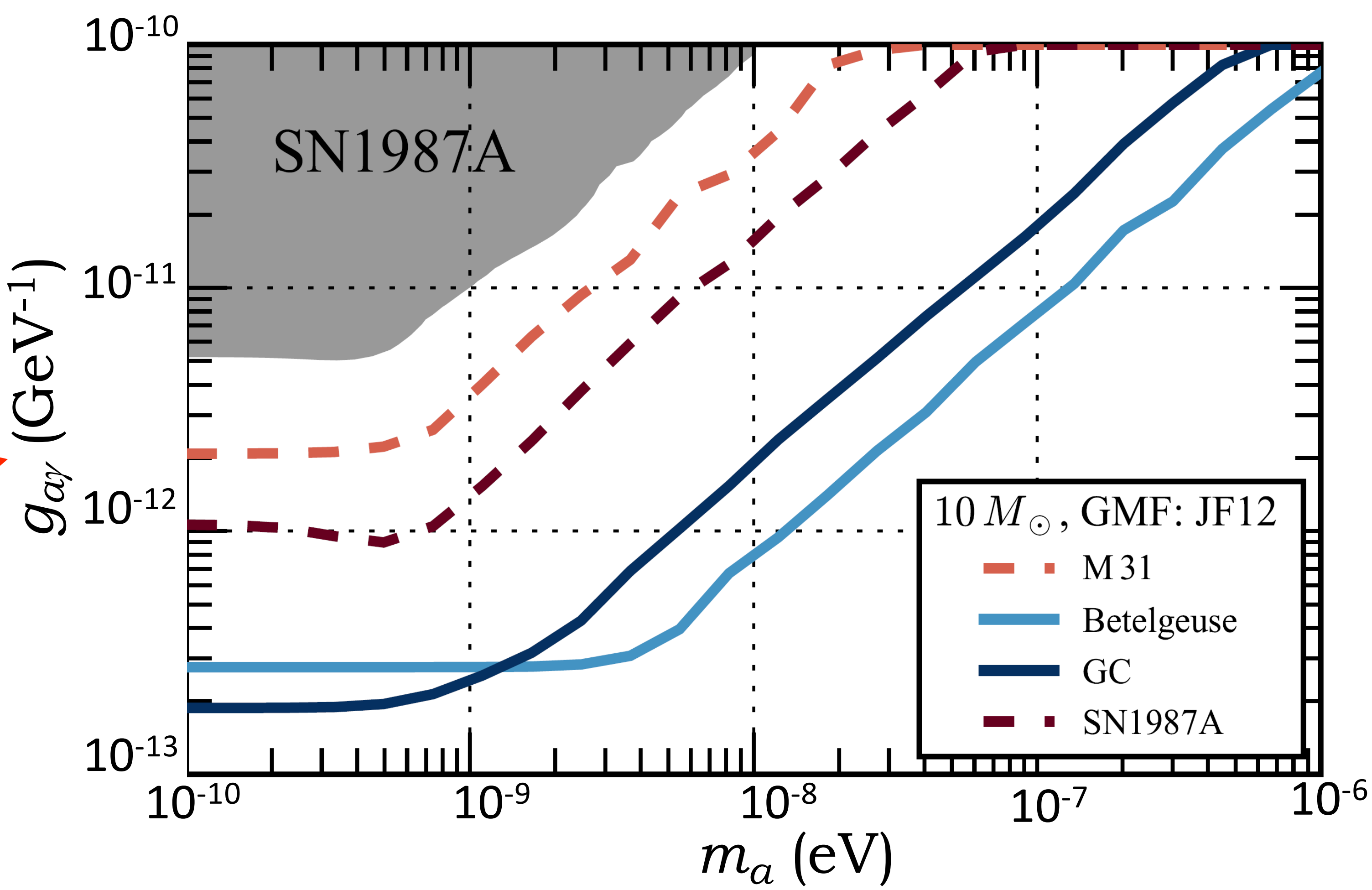
K. Choi et al., *JHEP* 02 (2022) 143



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

Detecting SN axions

Observations may reveal a lot about the SN interior

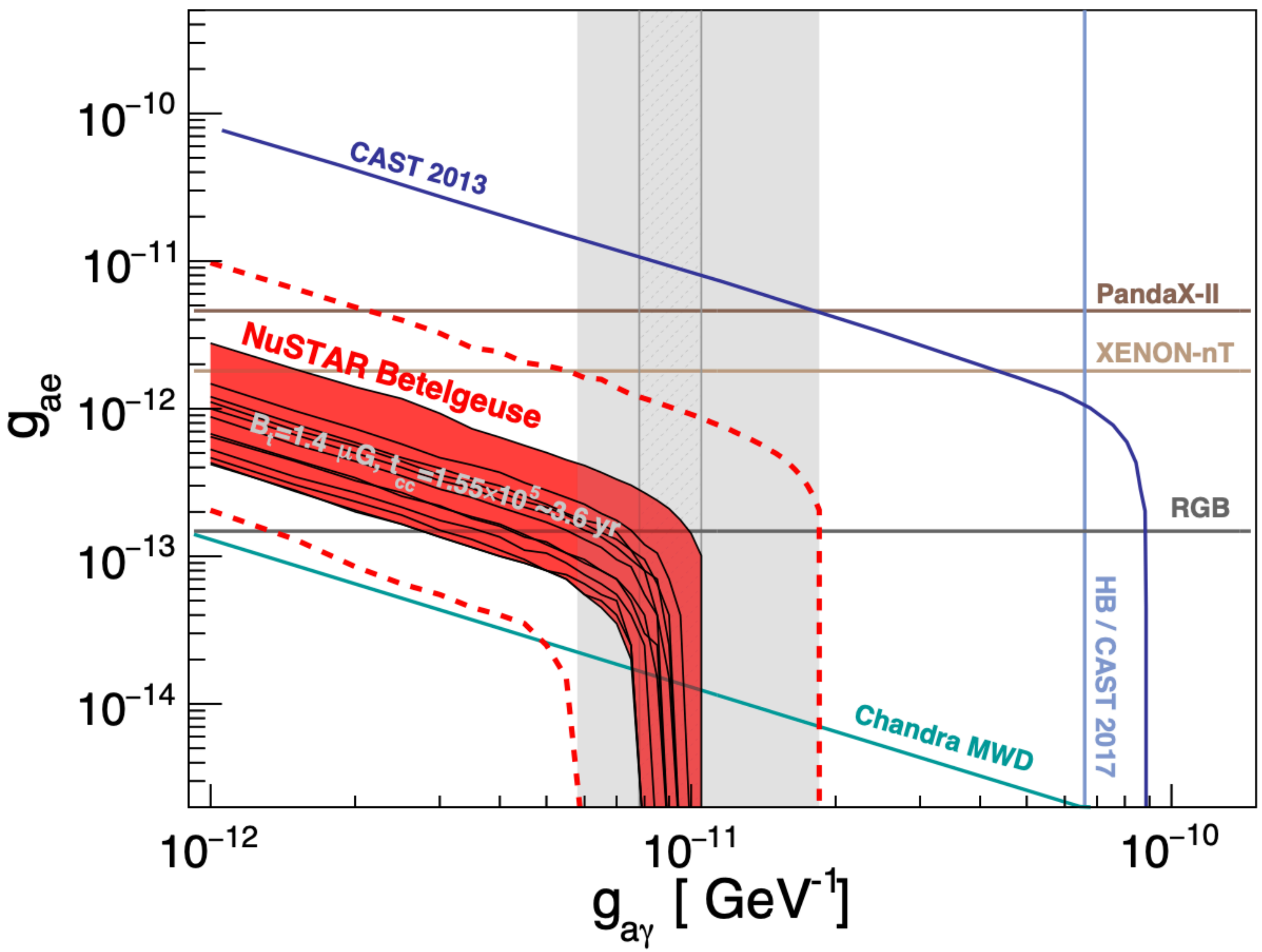


Indirect detection

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

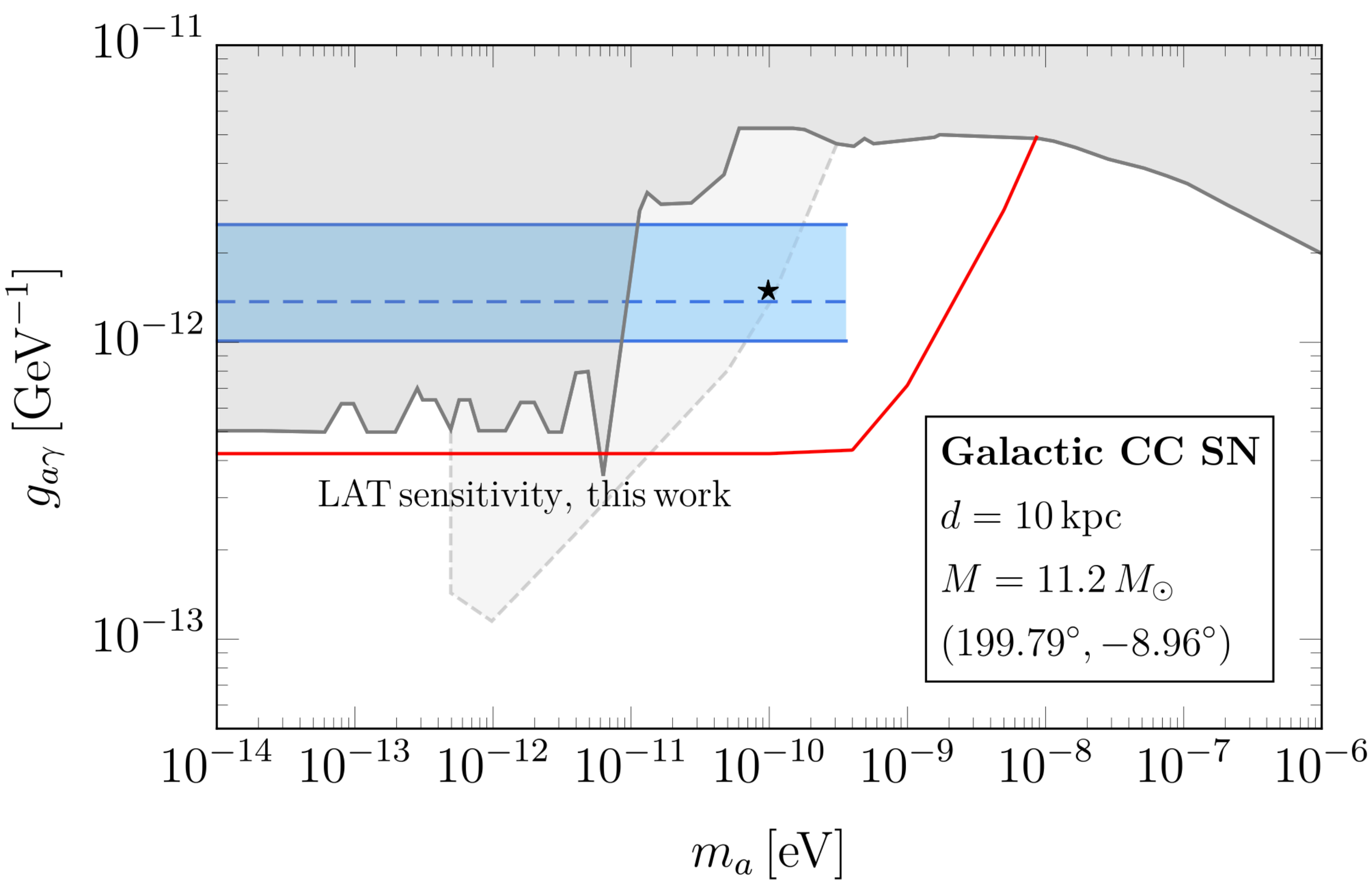
- F. Calore et al. e-Print: 2306.03925
- A. Lella et al. In preparation
- Meyer et al. Phys.Rev.Lett. 118 (2017)

Observing Betelgeuse in hard X-rays



Dedicated NuSTAR observations did not find evidence for ALPs.

Fermi LAT as Axion SN-Scope

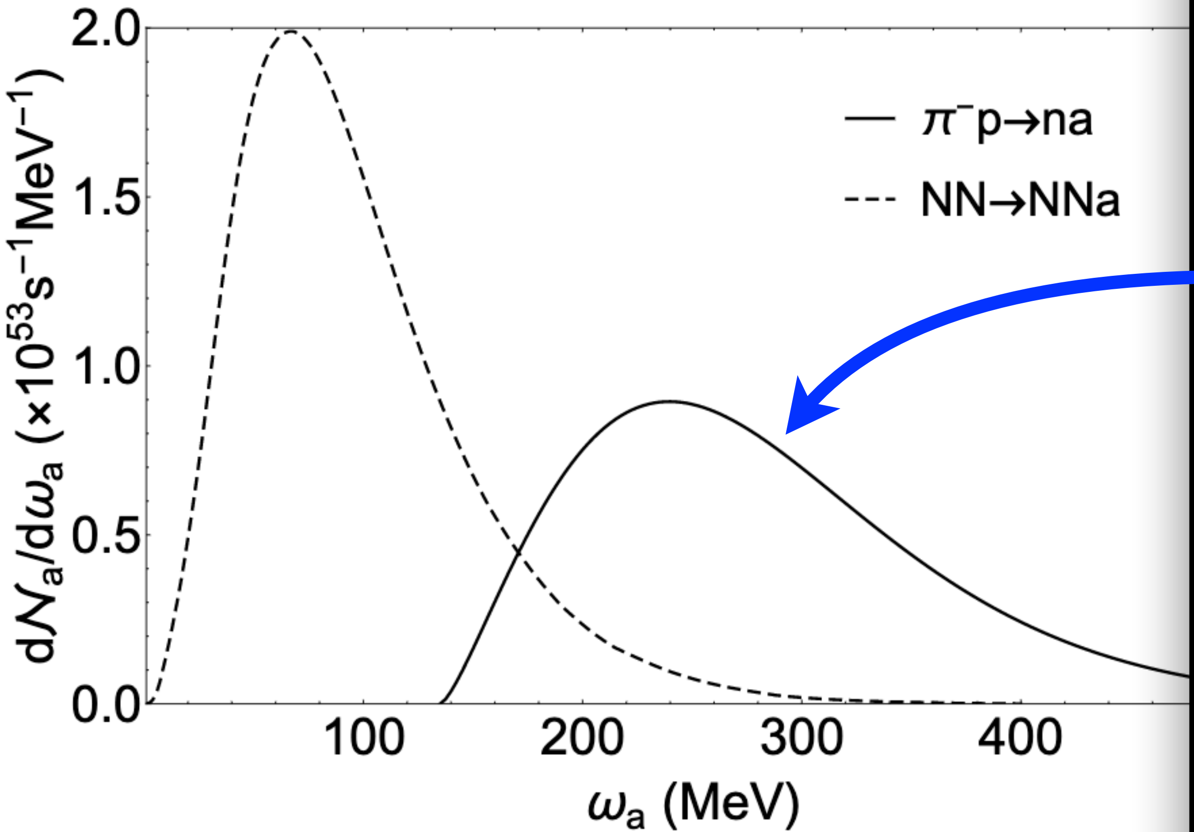


Calore, Carenza, Eckner, M. G., Lucente, Mirizzi, Sivo et al. arXiv:2306.03925

New analysis
→ slightly reduced sensitivity.
But…

Significant opportunities to study axions and the SN itself if $g_{a\gamma} \gtrsim 10^{-12}\,\mathrm{GeV}^{-1}$

Supernova axions



- Pions in SN: Larger than expected fraction of π^-
  B. Fore and S. Reddy, Phys.Rev.C 101 (2020);
  B. Fore et al., arXiv:2301.07226 (2023)

- Significance of the $\pi + N \to N + a$ processes. Dominates the axion emission rate. Harder spectrum.
  P. Carenza et al., Phys.Rev.Lett. 126 (2021);
  A. Lella et al, *Phys.Rev.D* 107 (2023) 10

- Inclusion of the axion-pion contact interaction. Significant contribution to $\pi + N \to N + a$. Irrelevant contribution to $N + N \to N + N + a$
  K. Choi et al., *JHEP* 02 (2022) 143

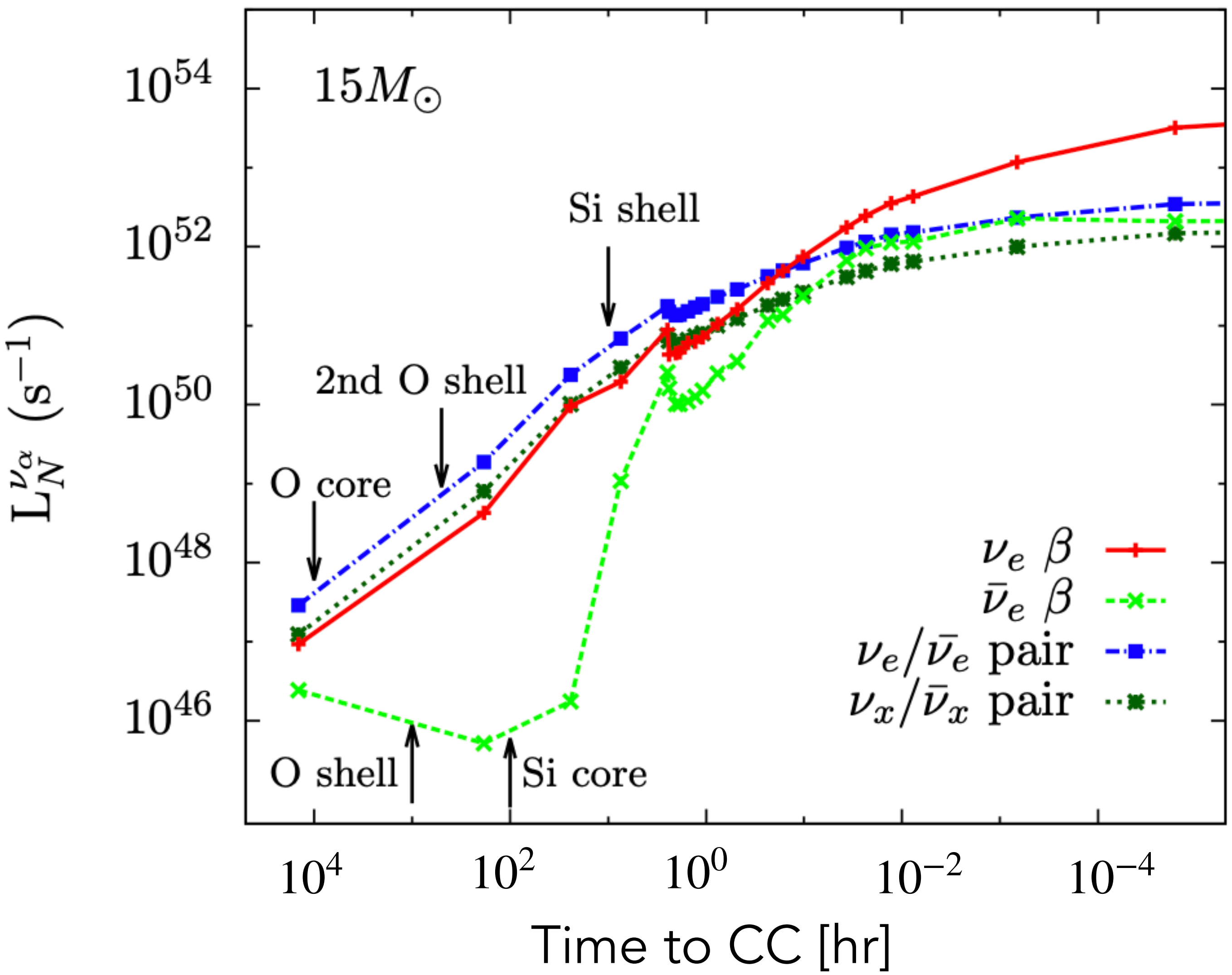
- Inclusion of the Δ resonance contribution in pion process
  Ho, Kim, Ko, Park, *Phys.Rev.D* 107 (2023) 7

- Direct detection of SN axions
  Ge, Hamaguchi, Ichimura, Ishidoshiro, Kanazawa, JCAP 11 (2
  Vonk, Guo, Meißner, *Phys.Rev.D 105 (2022)*

Significant theoretical progress in last 2 years

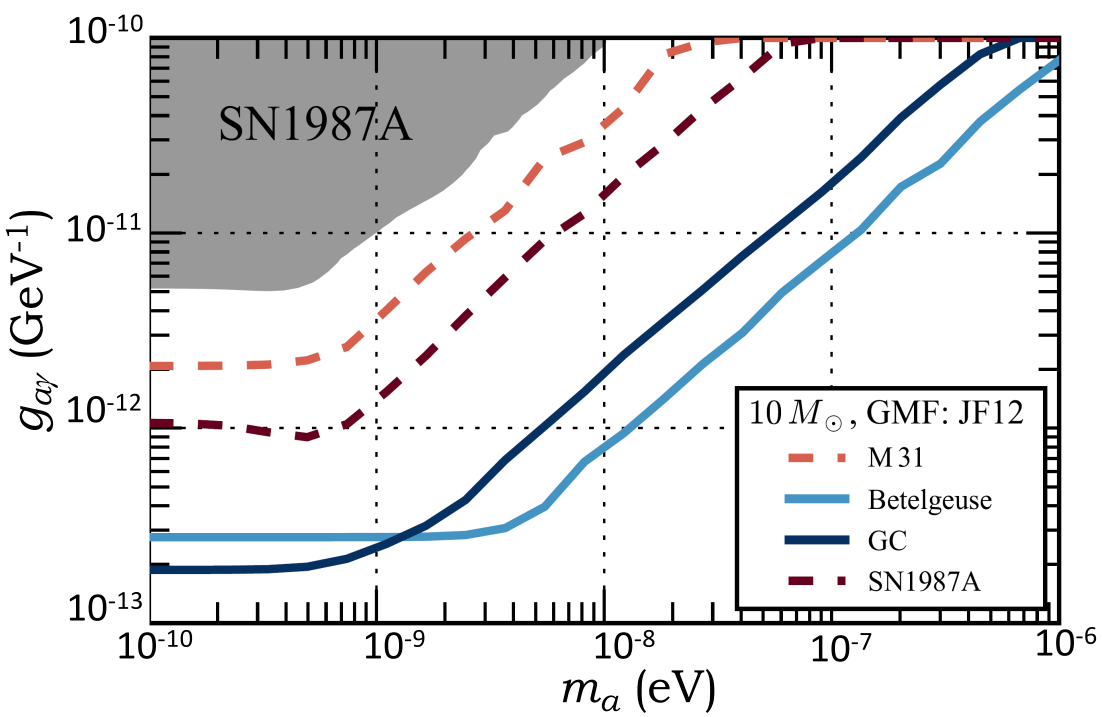
Pre-SN signal

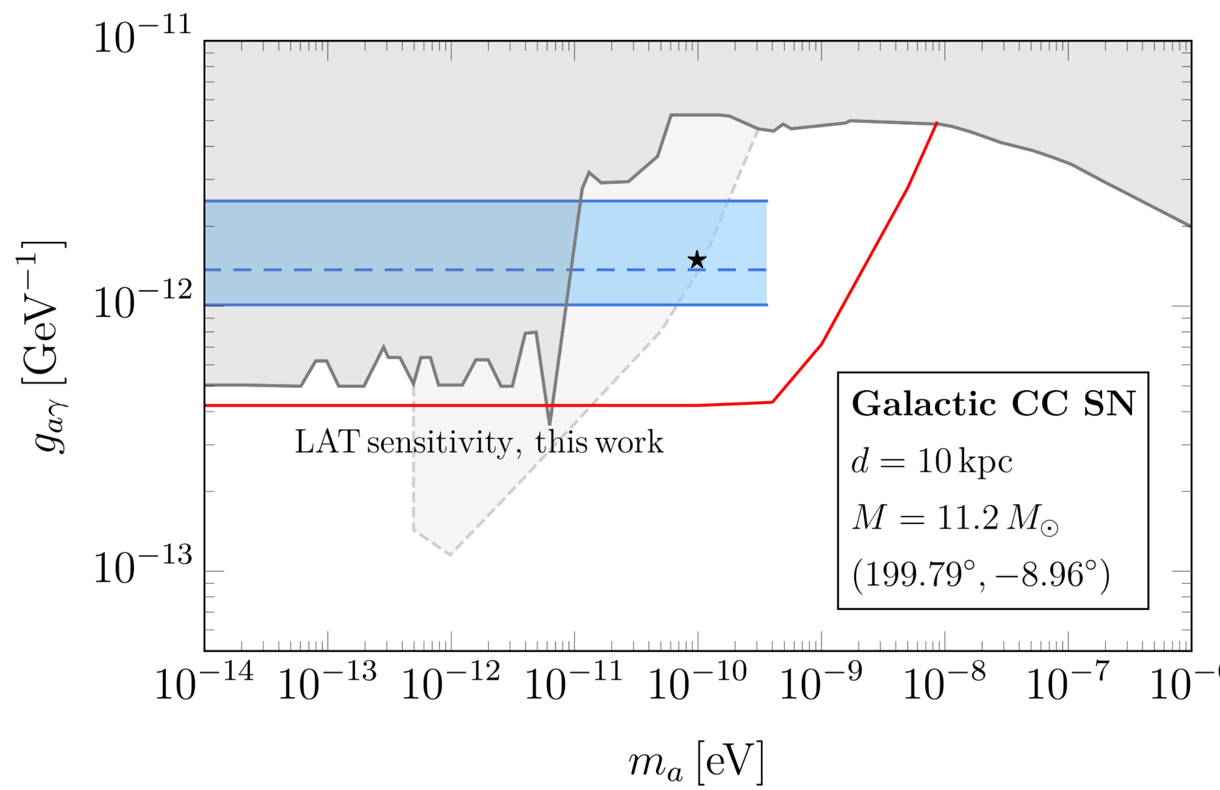
Neutrinos are produced from thermal and beta processes.



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

Fermi LAT as Axion SN-Scope





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

Calore, Carenza, Eckner, M. G., Lucente, Mirizzi, Sivo et al. arXiv:2306.03925

New analysis
→ slightly reduced sensitivity. But…

Significant opportunities to study axions and the SN itself if $g_{a\gamma} \gtrsim 10^{-12}\,\mathrm{GeV}^{-1}$

Pre-SN signal

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

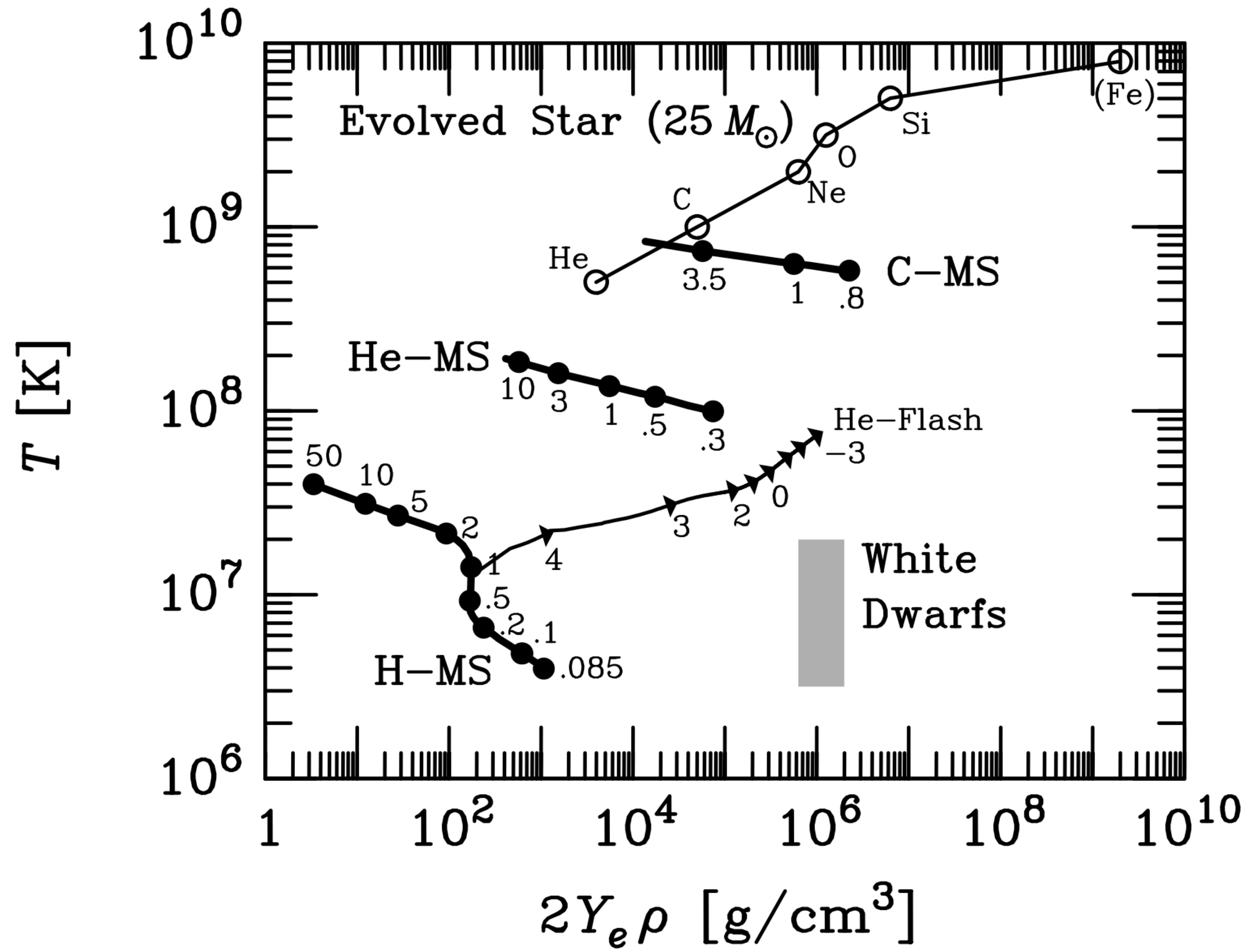
Tanaka & Watanabe (2014)

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)

Stellar Evolution in a snapshot



Stellar core conditions

The rear ends of the arrows mark the indicated values of the absolute surface brightness in magnitudes ($0.8M_\odot$ star).

From G. Raffelt: *Stars as Laboratories for Fundamental Physics*, (1996)

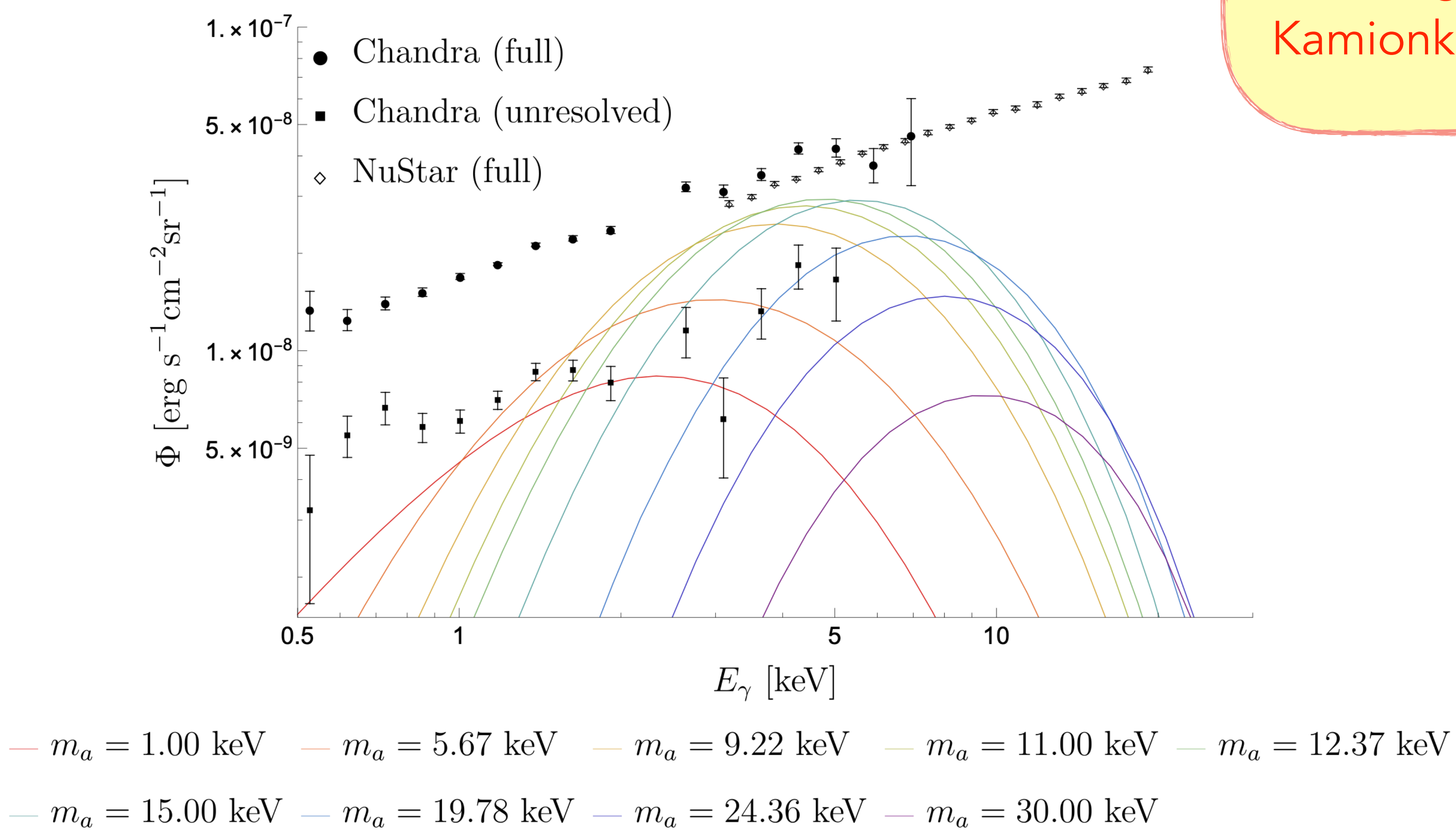
Other stars?

Other MS have solar-like properties but are much further away. Less interesting.

Yet, there are many of them.

Diffuse axion flux recently calculated

If ALPs are sufficiently heavy, their decay produces an x-ray diffuse background:
N. H. Nguyen, E. H. Tanin, M. Kamionkowski arXiv:2307.11216



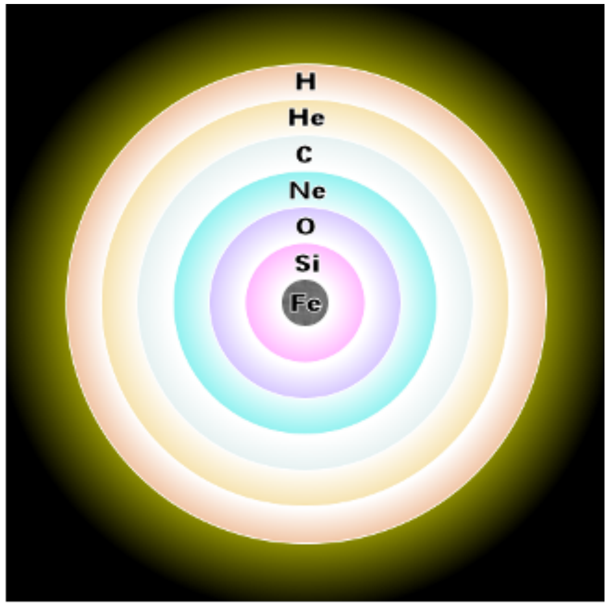
Stellar Evolution in a snapshot

Stages of nucleosynthesis for a star of mass $\sim 25 M_{\odot}$

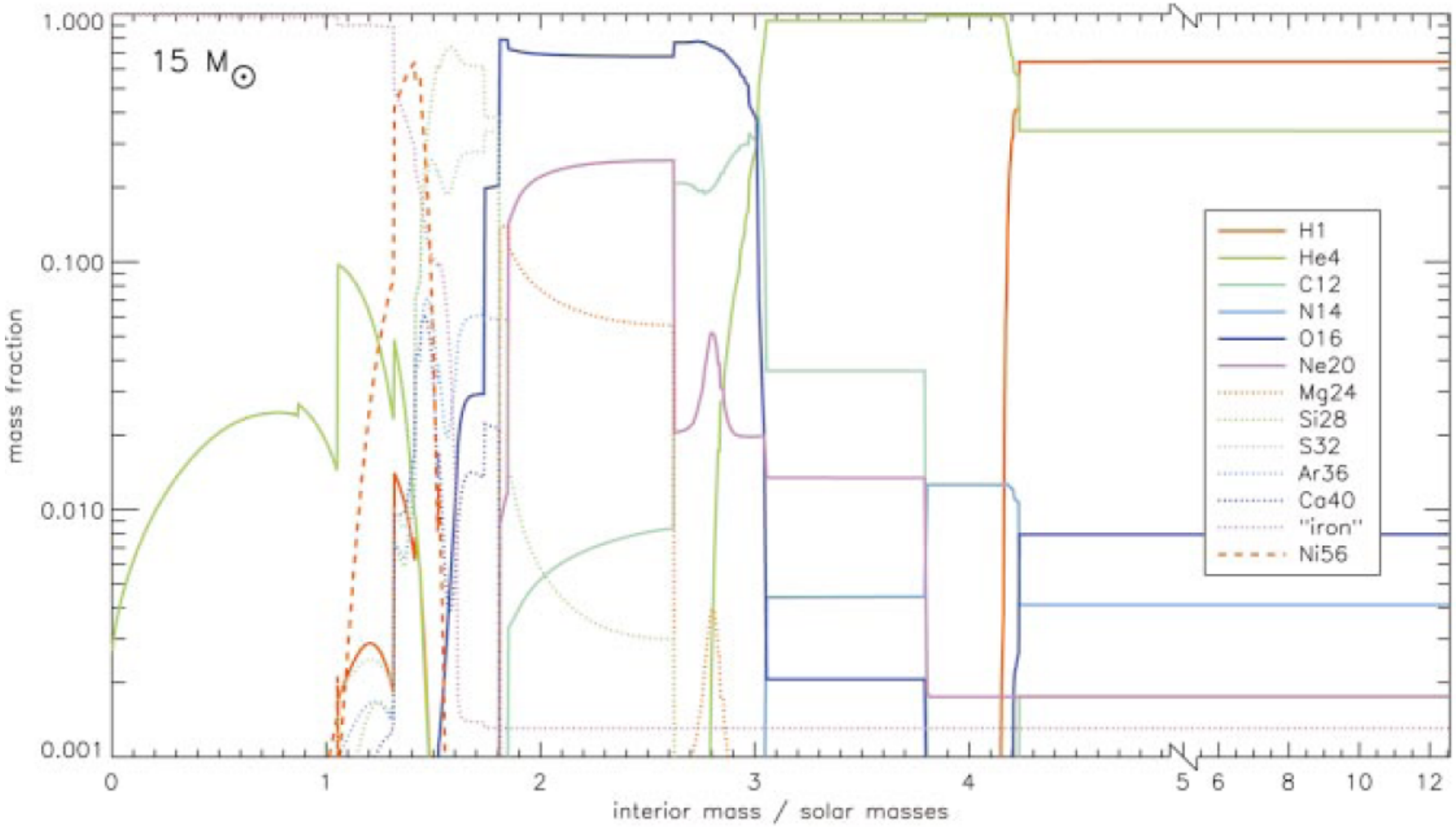
Nuclear fuel	Main products	Temperature (K)	Density (g cm^{-3})	Duration (yrs)
H	He	3.81×10^7	3.81	6.70×10^6
He	C, O	1.96×10^8	762	8.39×10^5
C	O, Ne, Mg	8.41×10^8	1.29×10^5	522
Ne	O, Mg, Si	1.57×10^9	3.95×10^6	0.891
O	Si, S	2.09×10^9	3.60×10^6	0.402
Si	Fe	3.65×10^9	3.01×10^7	0.002

From Omar Benhar, Structure and Dynamics, of Compact Stars, Springer (2023).
Data from Woosley, Heger, Weaver, Rev Mod Phys, 74, 1015 (2002)

Later Evolutionary Stages



Stars with $M \gtrsim 8\,M_\odot$ go on burning until they develop a iron core



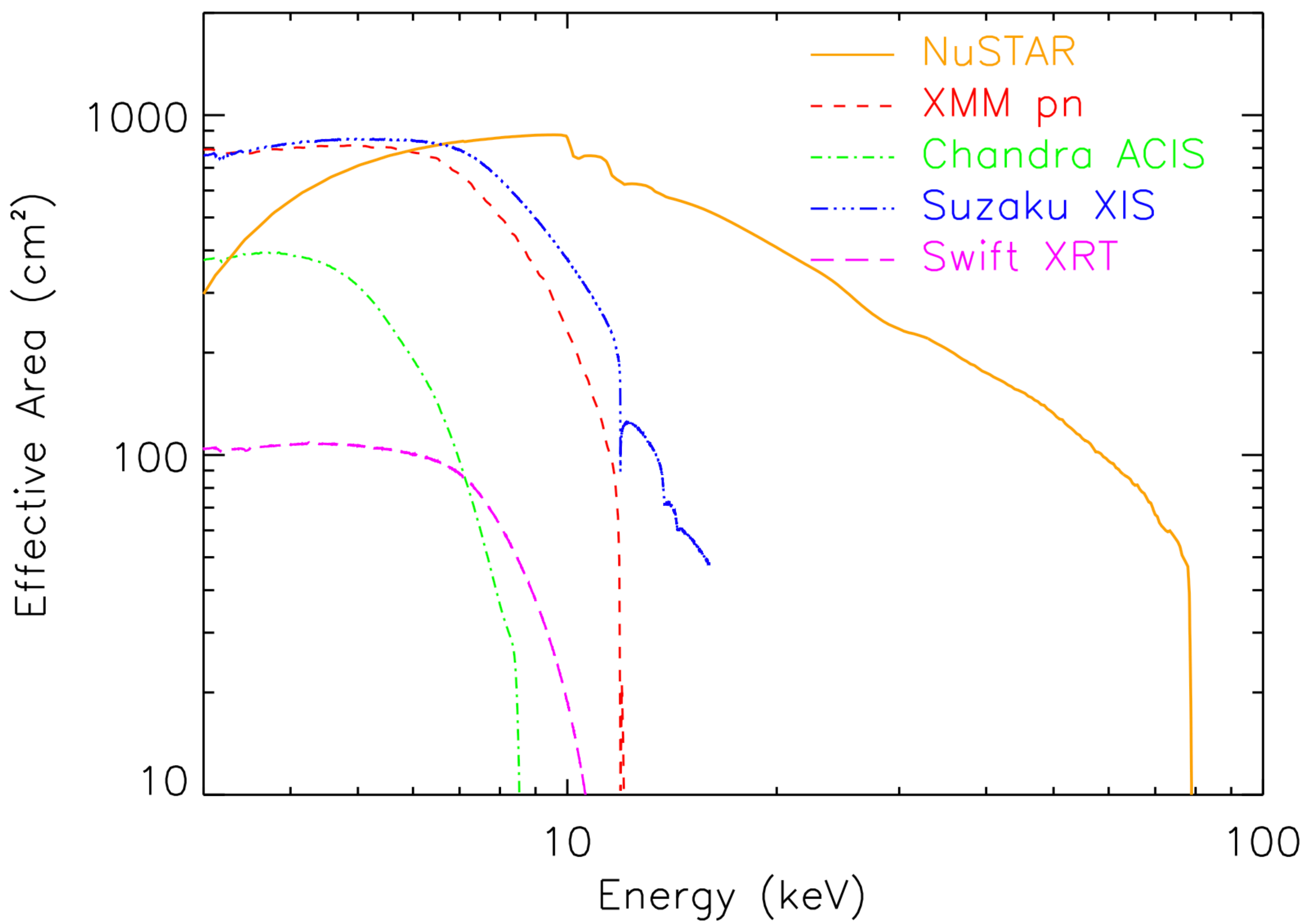
From Woosley, Heger, Weaver, Rev Mod Phys, 74, 1015 (2002)

Observing Betelgeuse in hard X-rays

NuSTAR: NUclear Spectroscopic Telescope ARray

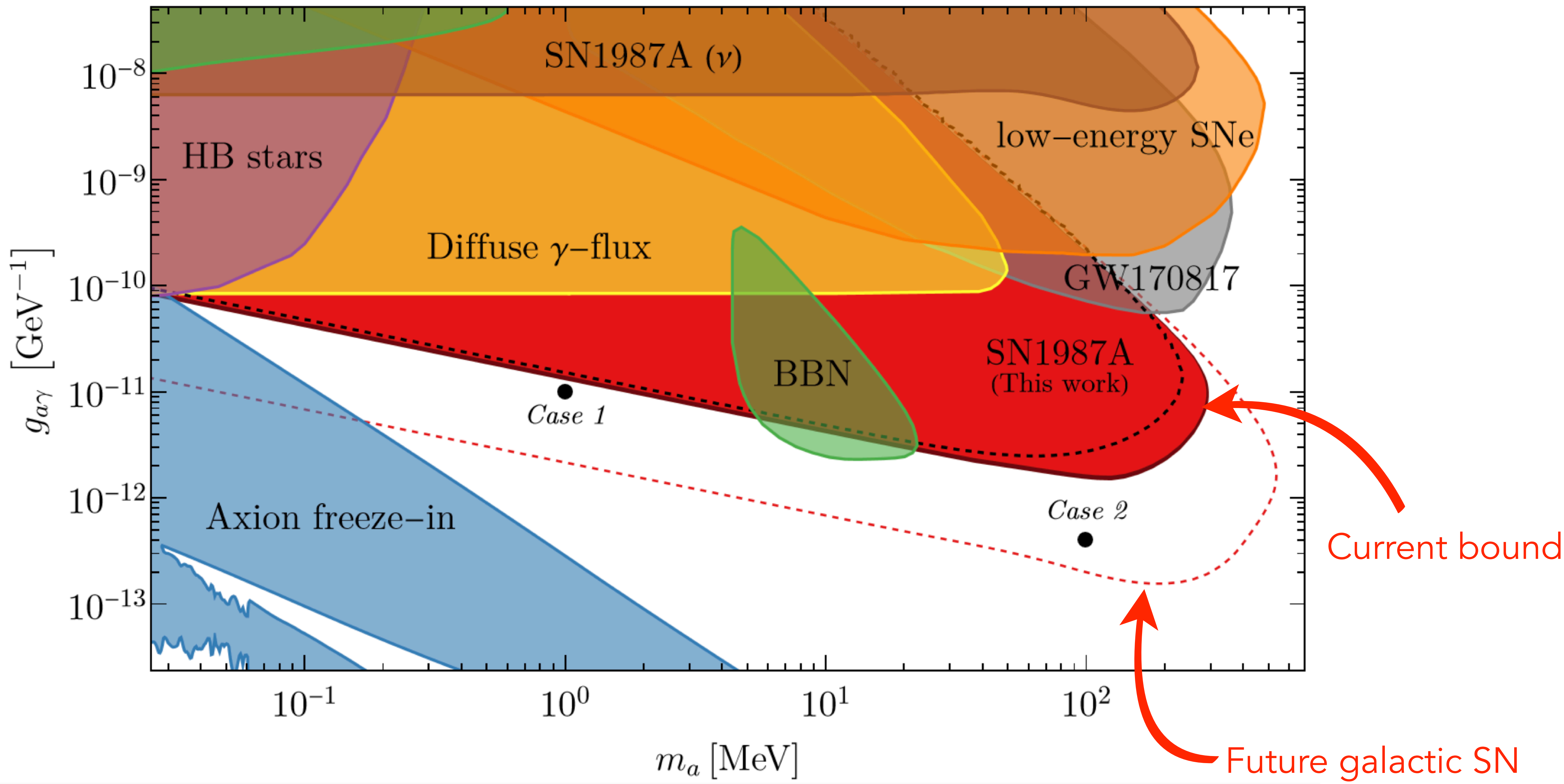
Is it really the best option?

First focusing high-energy X-ray (3–79 keV) telescope in orbit.
Has two identical telescopes, each with an independent optic and focal-plane detector
Each FOV ~ 13′ ×13′, with a half-power diameter of ~60′′ for a point source near the optical axis.



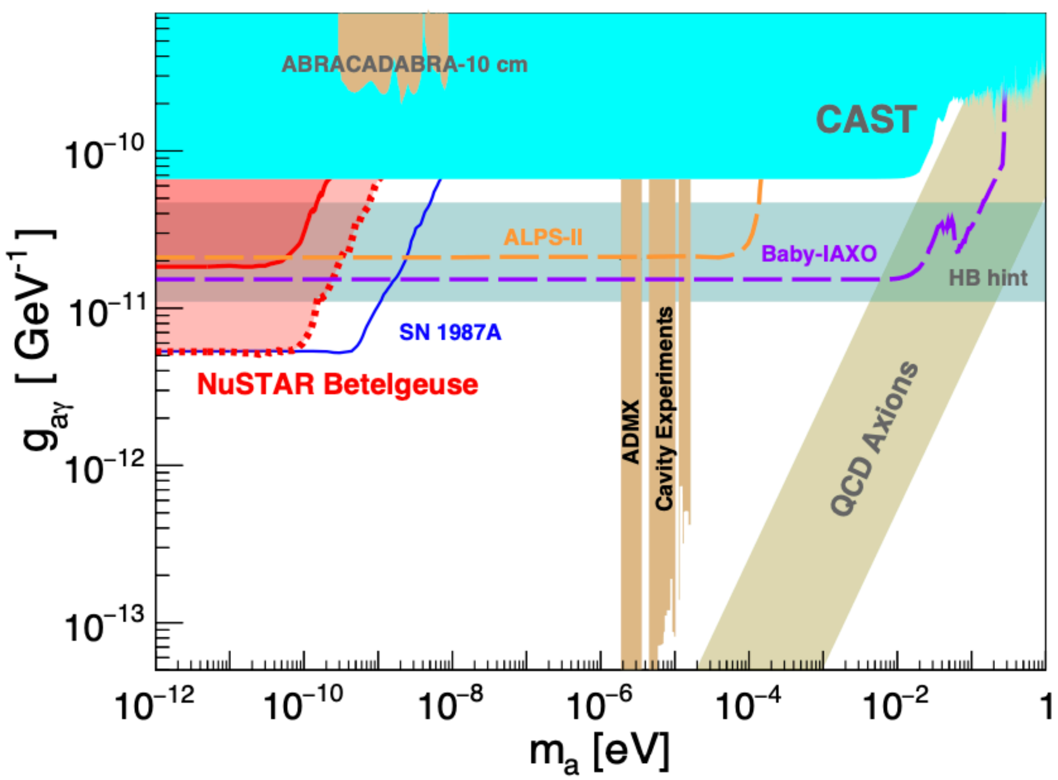
From: F.A. Harrison et al. ApJ, 770, 103 (2013)

High Mass SN ALPs @ Fermi LAT



Eike Müller, Francesca Calore, Pierluca Carenza,
Christopher Eckner, M.C. David Marsh, arXiv:2304.01060

… and Super Star Clusters

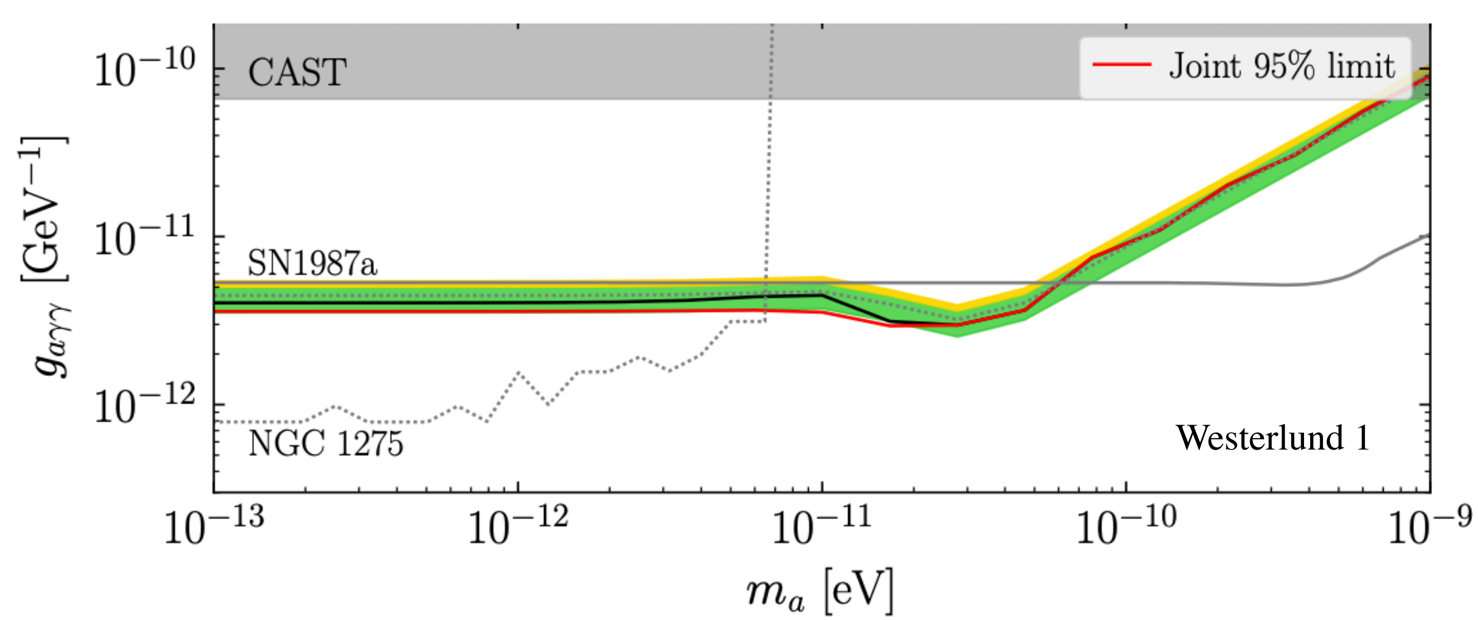


First hard X-ray observations of Betelgeuse (with NuSTAR)… no trace of Axions

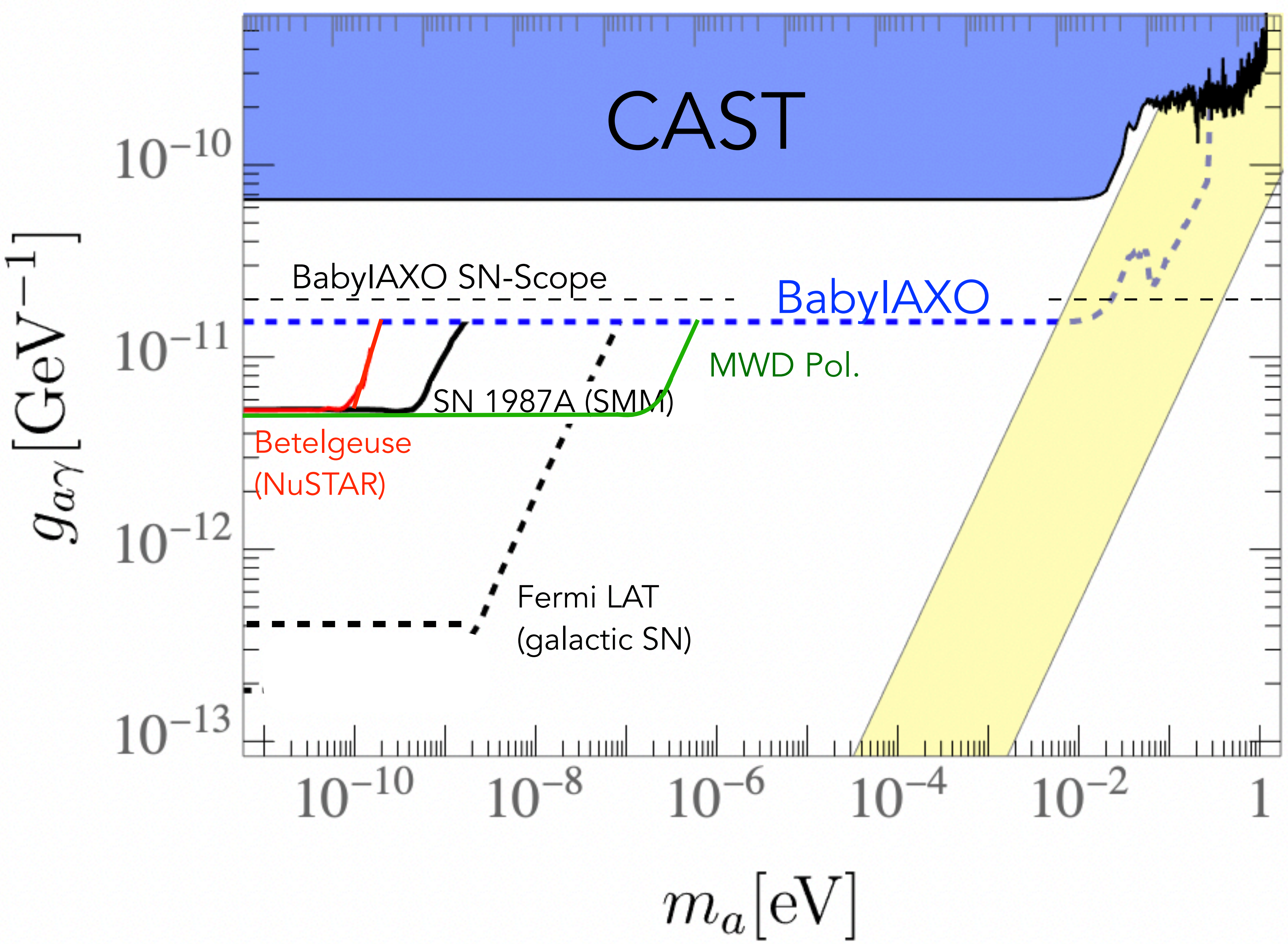
- *Xiao, Perez, M.G., Straniero, Mirizzi, Grefenstette, Roach, Nynka, Phys.Rev.Lett. 126 (2021)*
- *Xiao, Carenza, M.G., Mirizzi, Perez, Straniero, Grefenstette Phys.Rev.D 106 (2022)*

Similar result from observations of Super Star Clusters

Dessert, Foster, Safdy, Phys.Rev.Lett. 125 (2020)



Summary: Detecting Stellar Axions



Legend:

Solar Axion

Pre-SN Axions

SN Axions

Current bounds

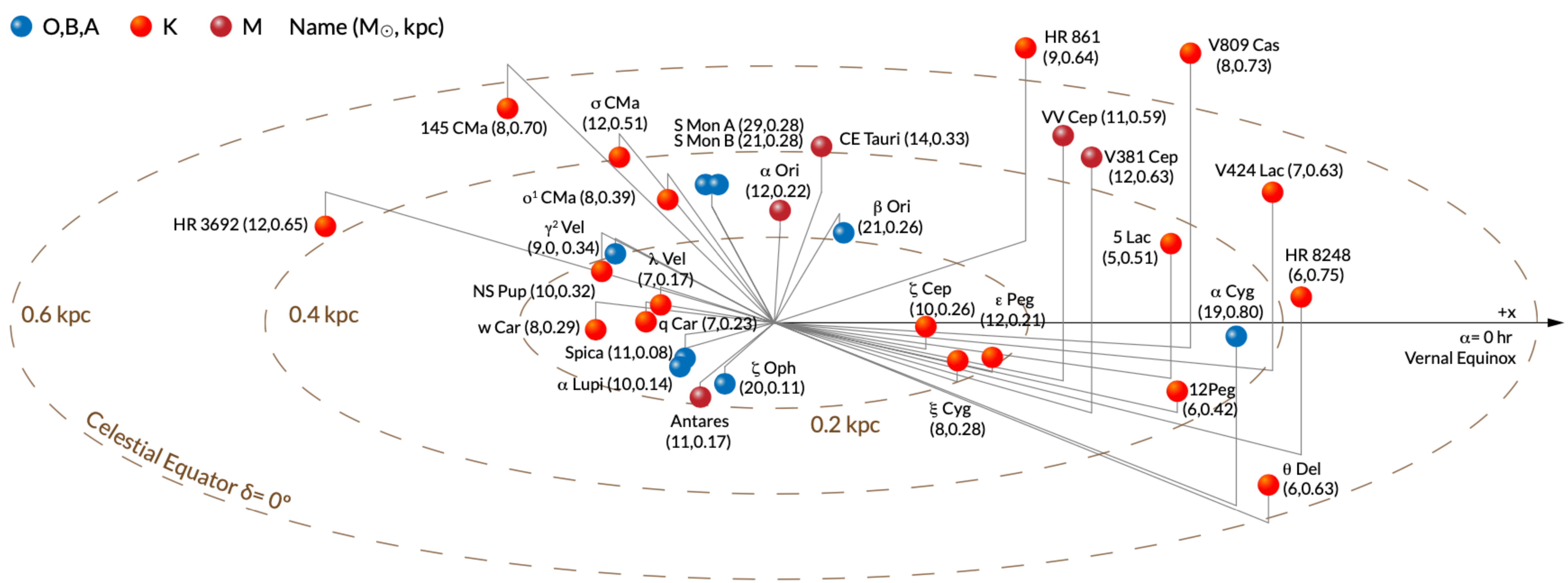
Estimated sensitivities

Benchmark QCD models

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.

Summary

- *Stellar axions*

- *Why Monster Stars?*

- *Are we going to detect stellar axions in the next n-years? ($\log_{10} n < 2$, hopefully !)*