Axions from the sky: perspectives on the detection of solar and other stellar axions

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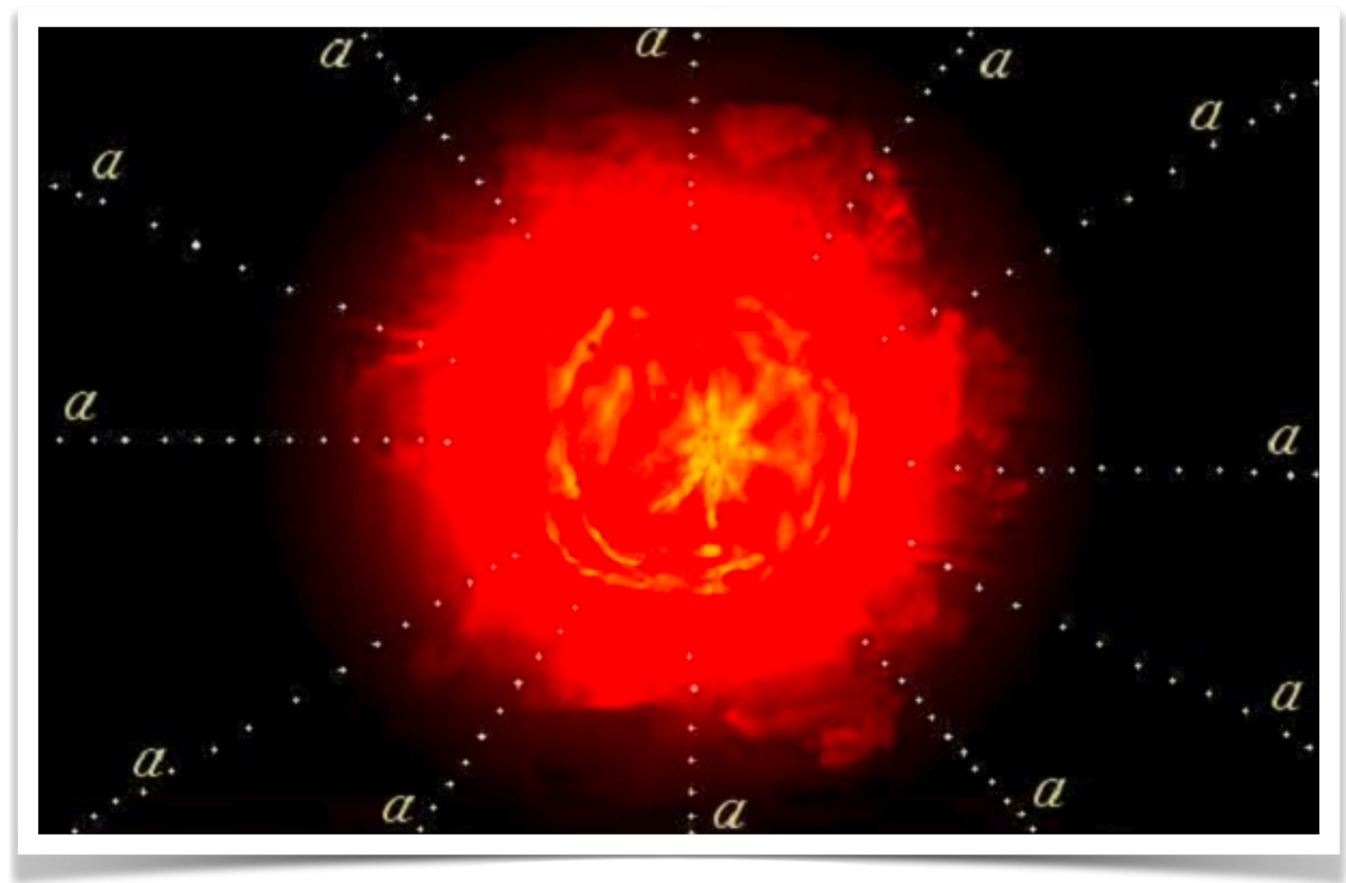
University of Zaragoza, CAPA



COSMIC WISPERS
CA21106

Neutrino Frontiers,
Galileo Galilei Institute, 26 July 2024

Axions and ALPs

Cosmology

Dark Matter

Particle Physics

Strong-CP problem

Astrophysics

Stellar evolution; Cooling anomalies; astro messangers; Transparency hints

We may detect them soon!

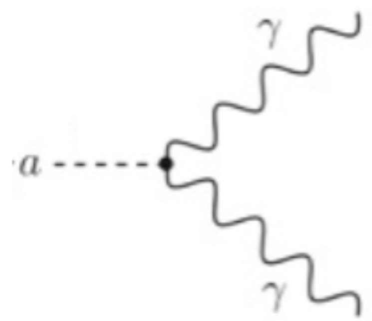
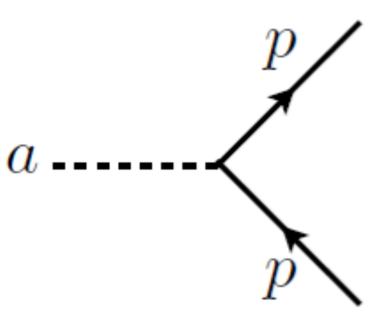
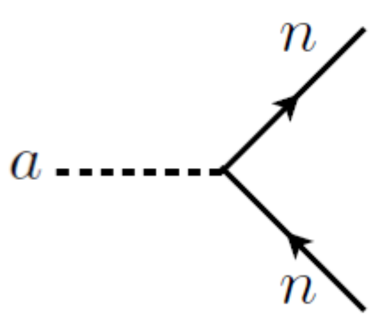
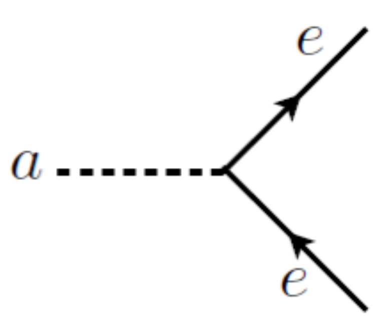
Experimental capabilities to search in well motivated regions of the parameters …

Axions and ALPs

Recent Reviews

- I. Irastorza, J. Redondo, *New experimental approaches in the search for axion-like particles*", Prog.Part.Nucl.Phys. 102 (2018)
- L. Di Luzio et al, *The landscape of QCD axion models*, Phys.Rept. 870 (2020)
- P. Sikivie, *Invisible Axion Search Methods*, Rev.Mod.Phys. 93 (2021)
- A. Caputo, G. Raffelt, *Astrophysical Axion Bounds*, PoS COSMICWISPers (2024)
- …

Axions and ALP Interact with SM Fields

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

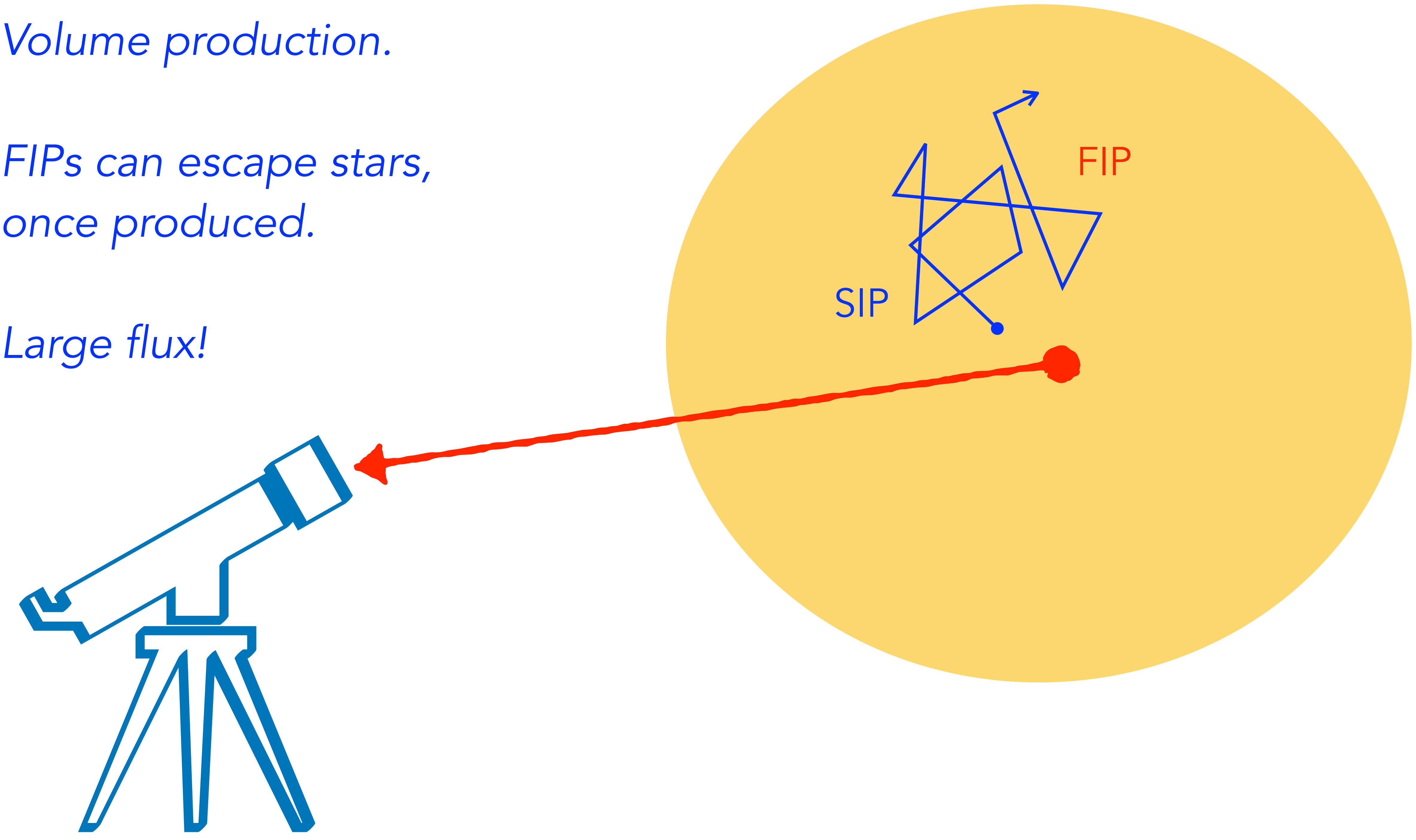
$g_{a\gamma} = \frac{C_{a\gamma}\alpha}{2\pi f_a}$ $g_{ap} = C_{ap}\frac{m_p}{f_a}$ $g_{ap} = C_{an}\frac{m_n}{f_a}$ $g_{ap} = C_{ae}\frac{m_e}{f_a}$

Stars as FIPs Factories

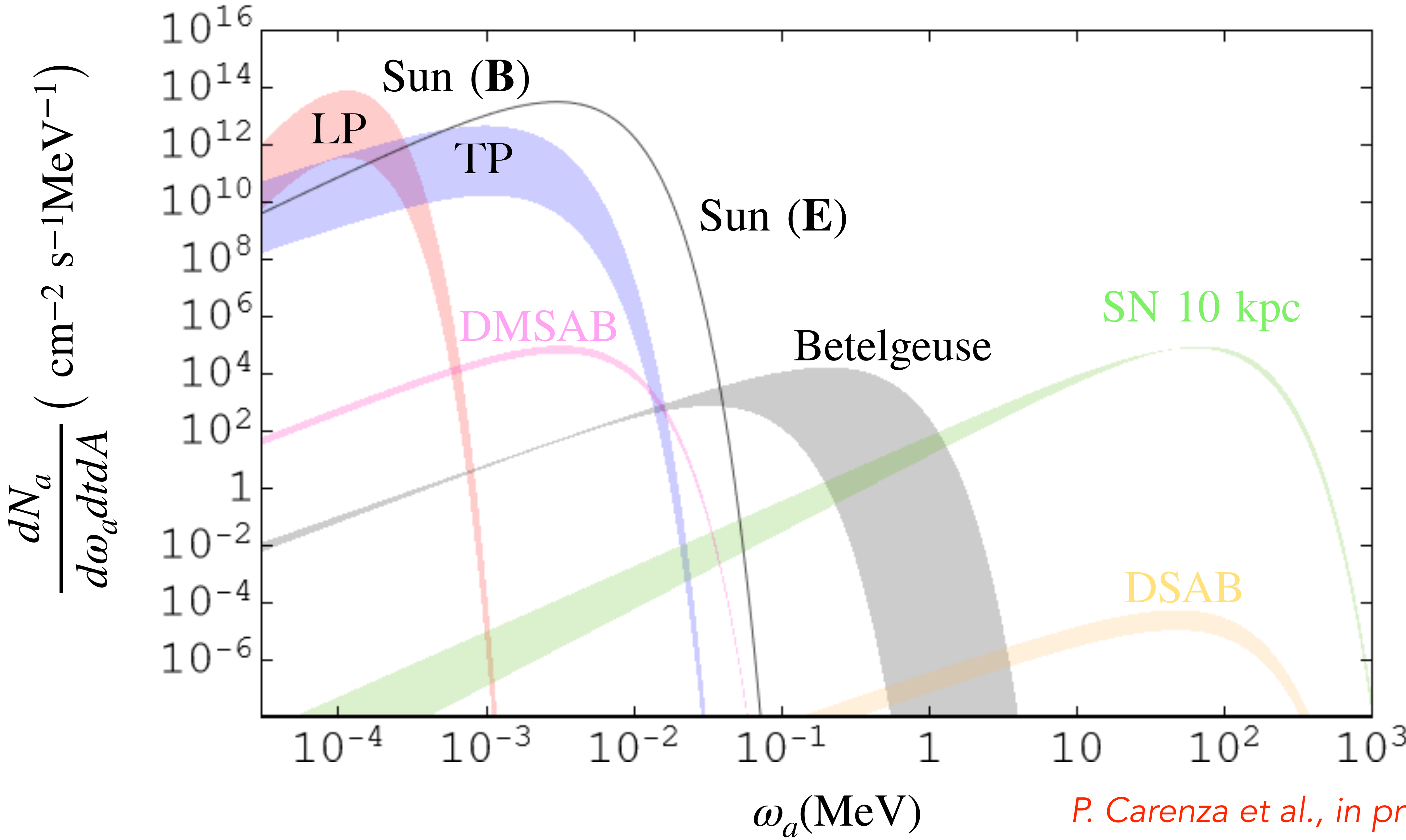
Volume production.

FIPs can escape stars, once produced.

Large flux!



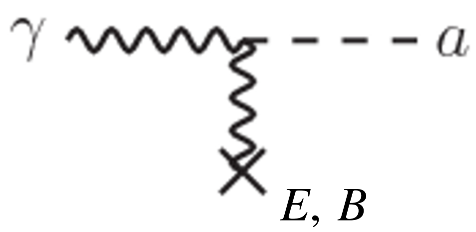
Stellar Axion Flux



P. Carenza et al., in preparation

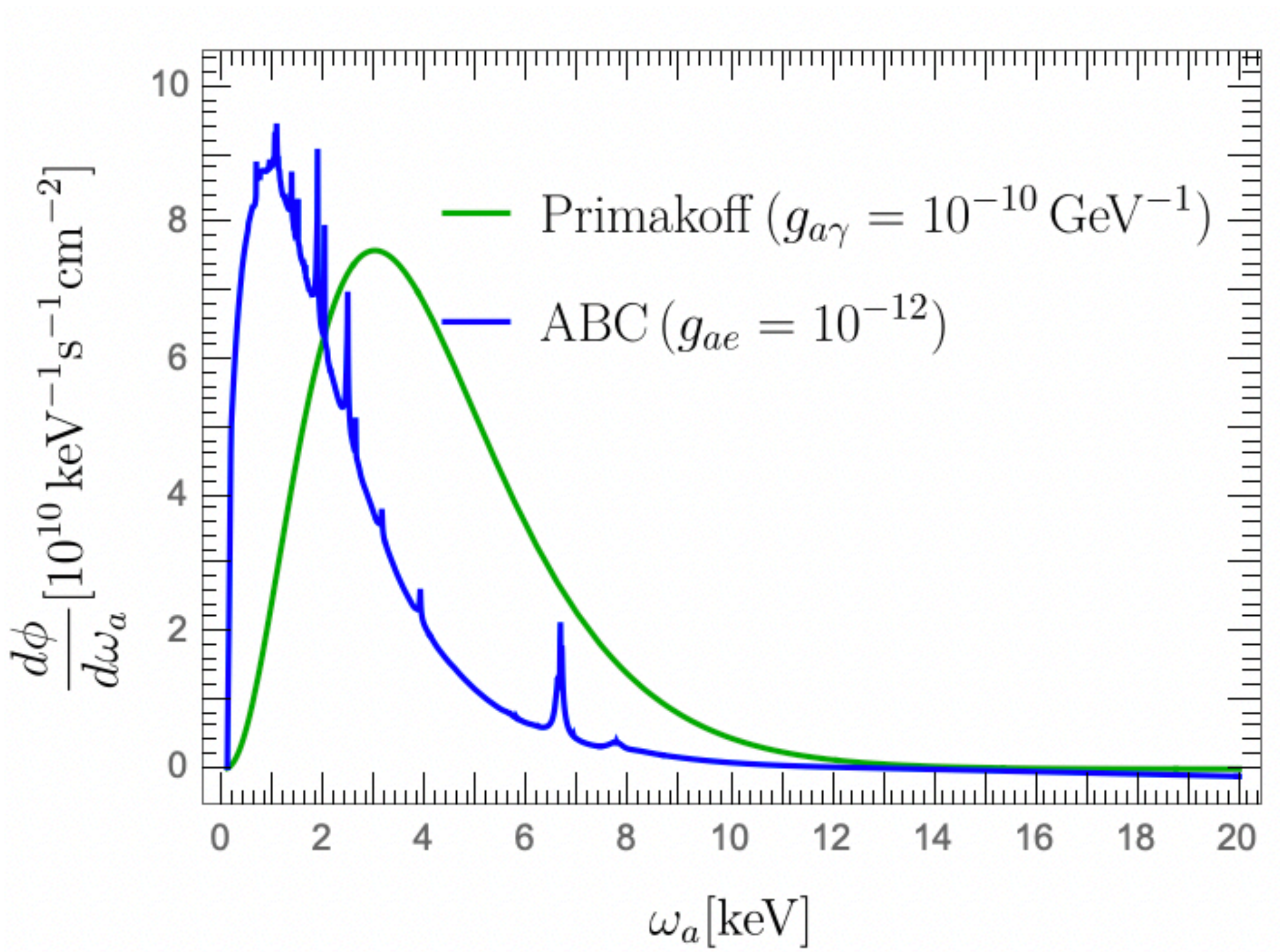
Stellar Axion Flux,
$g_{a\gamma} = 0.6 \times 10^{-10}\,\mathrm{GeV}^{-1}$, $g_{ai} = 0$, $m_a = 0$

The Sun as Axion Factory

Coupling	Process	Energy
$g_{a\gamma}$	Primakoff (E) Primakoff (B) 	$\sim (3-4)\,\mathrm{keV}$ $\sim (10-200)\,\mathrm{eV}$ (LP) $\lesssim 1\,\mathrm{keV}$ (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 ${}^{57}\mathrm{Fe}^* \to {}^{57}\mathrm{Fe} + a$ ${}^{7}\mathrm{Li}^* \to {}^{7}\mathrm{Li} + a$ ${}^{83}\mathrm{Kr}^* \to {}^{83}\mathrm{Kr} + a$ ${}^{169}\mathrm{Tm}^* \to {}^{169}\mathrm{Tm} + a$	5.5 MeV 14.4 keV 0.478 MeV 9.4 keV 8.4 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)

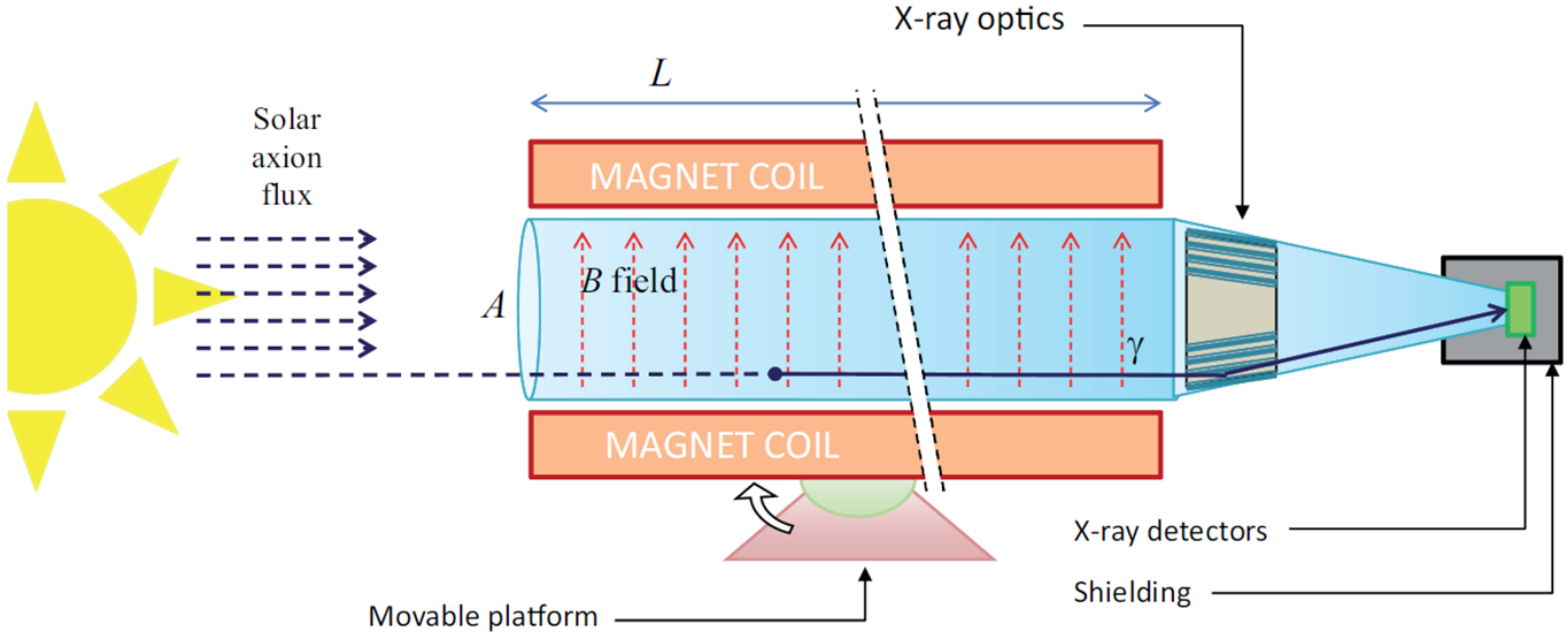
up to $\sim 10^{39}$ axions/s
($\Rightarrow 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ axions on Earth), peaked at $\sim$ keV

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)



Rescalable: increasing collecting area, length, and B.

Sensitivity

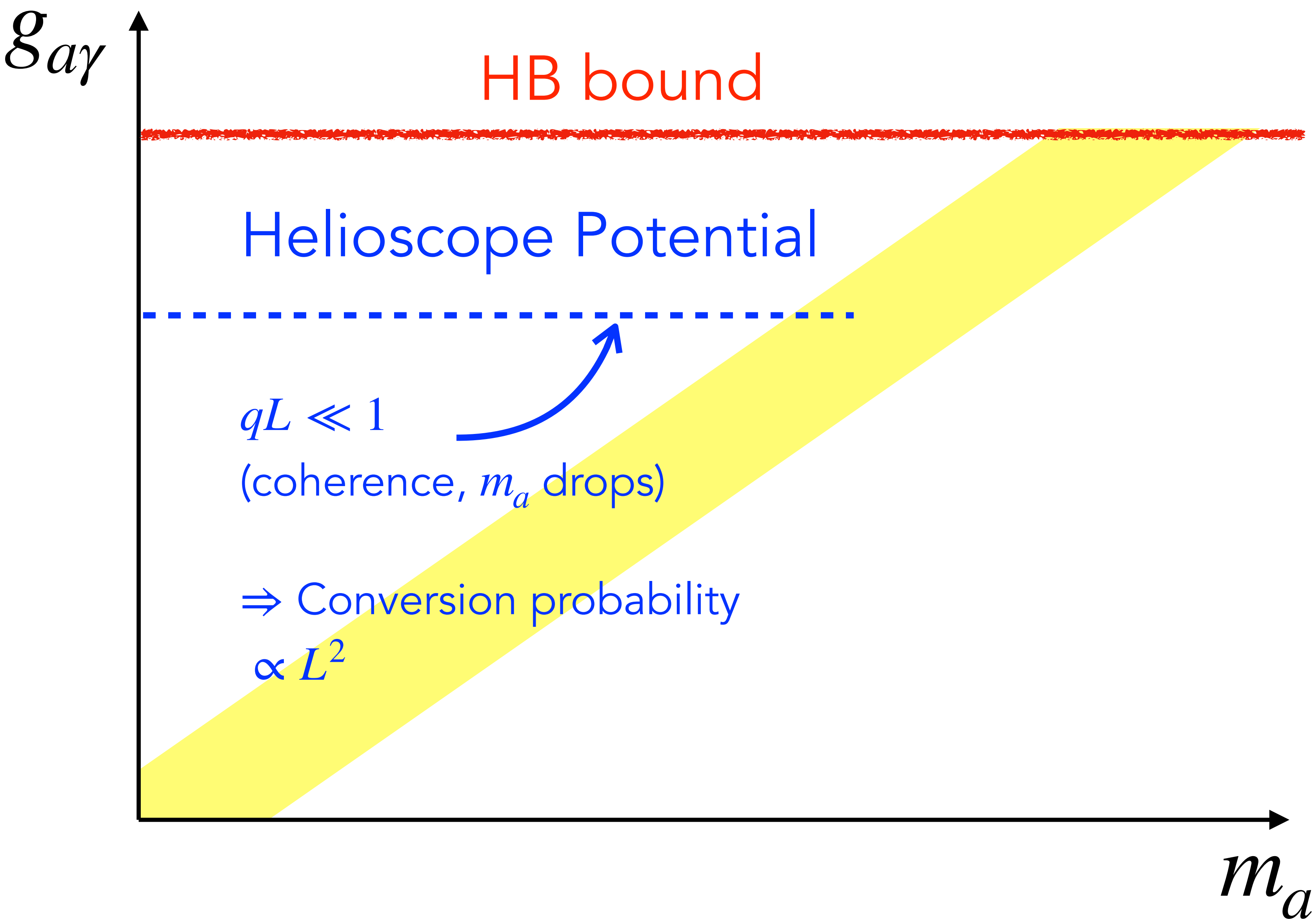
$$P_{a\gamma} = \left(\frac{g_{a\gamma} B L}{2}\right)^2 \frac{\sin^2(qL/2)}{(qL/2)^2}$$

B= magnetic field

L= magnet length

q= momentum transfer

$$q \simeq \frac{m_a^2 - m_\gamma^2}{2\omega}$$



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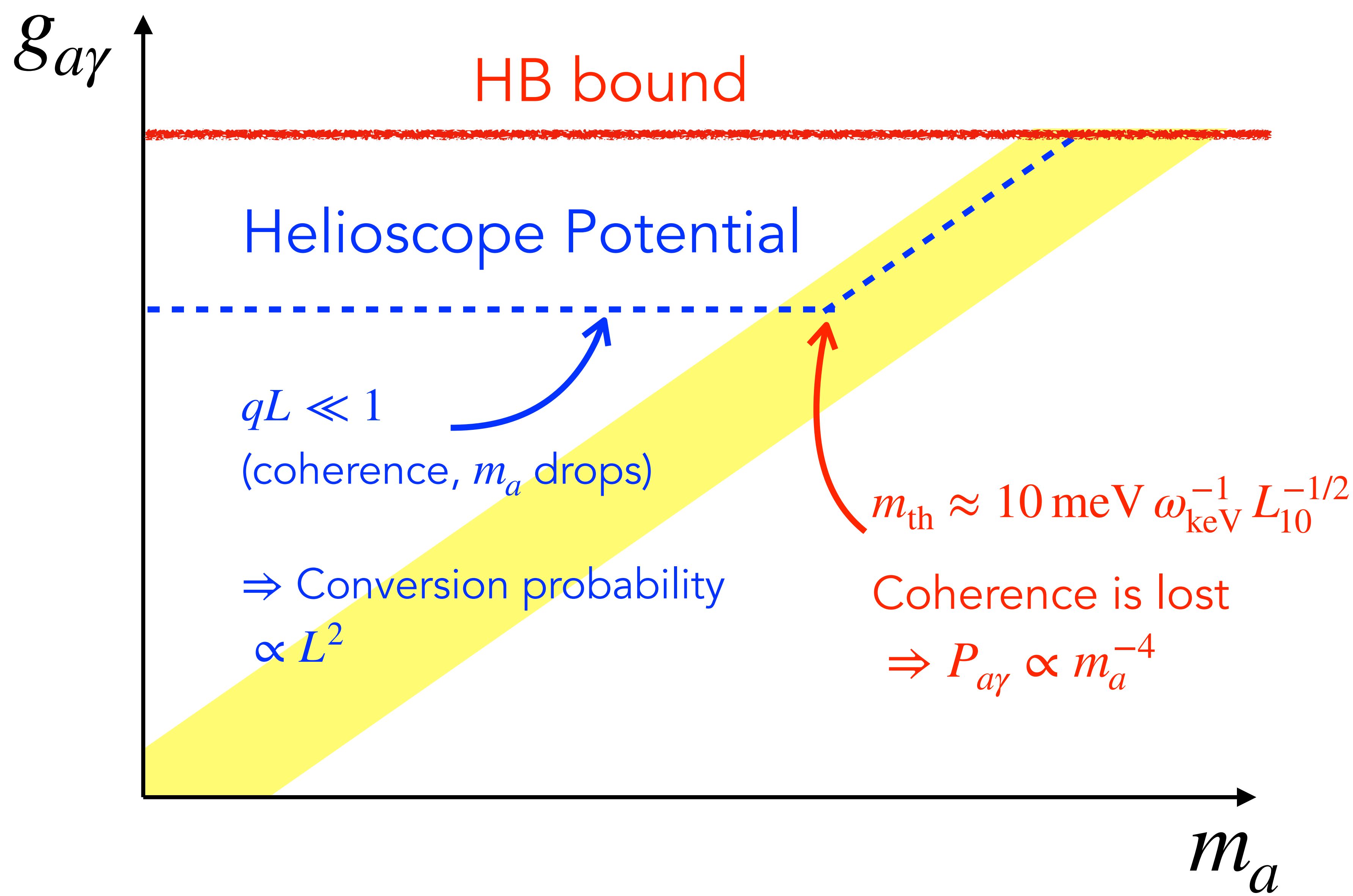

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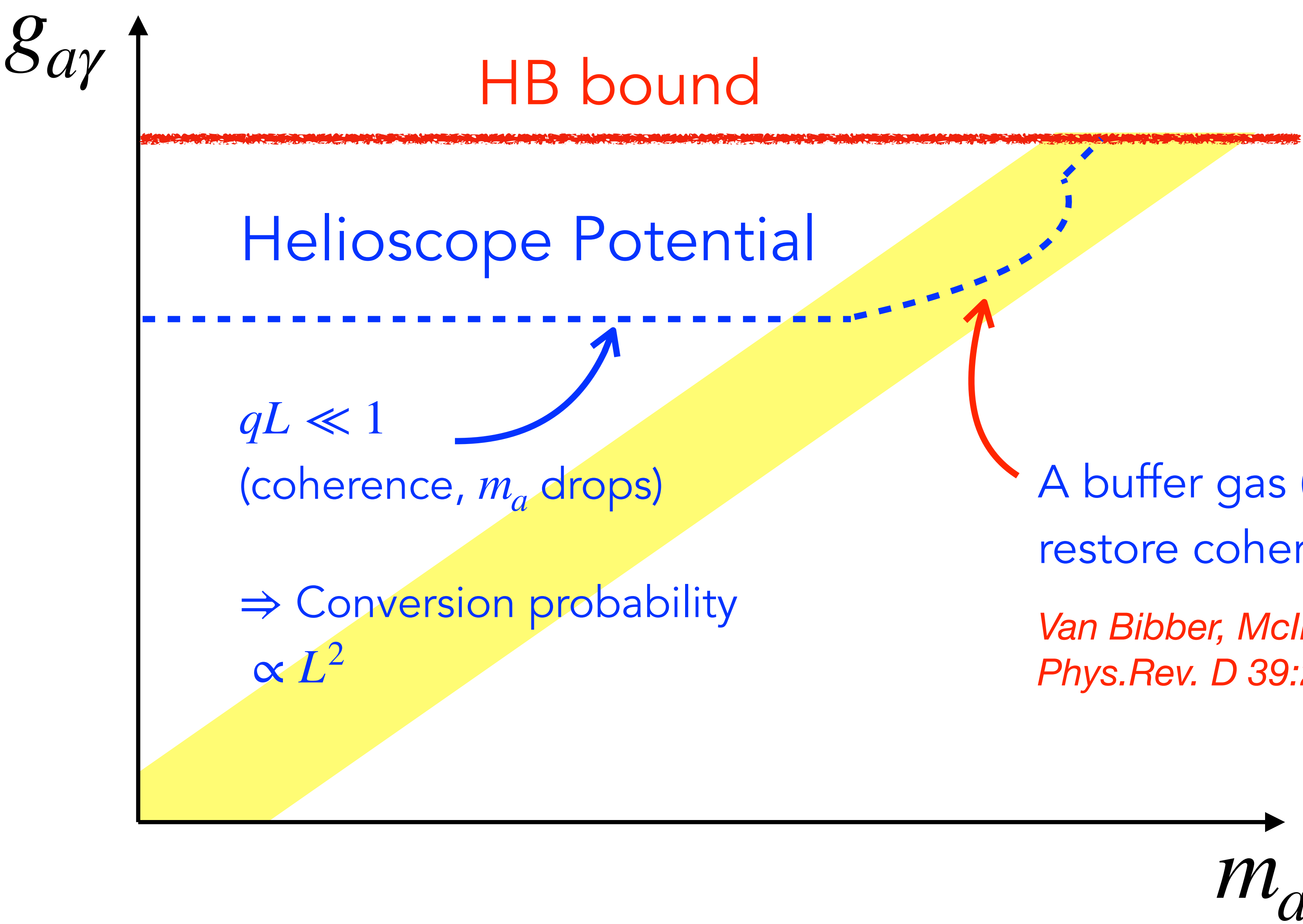


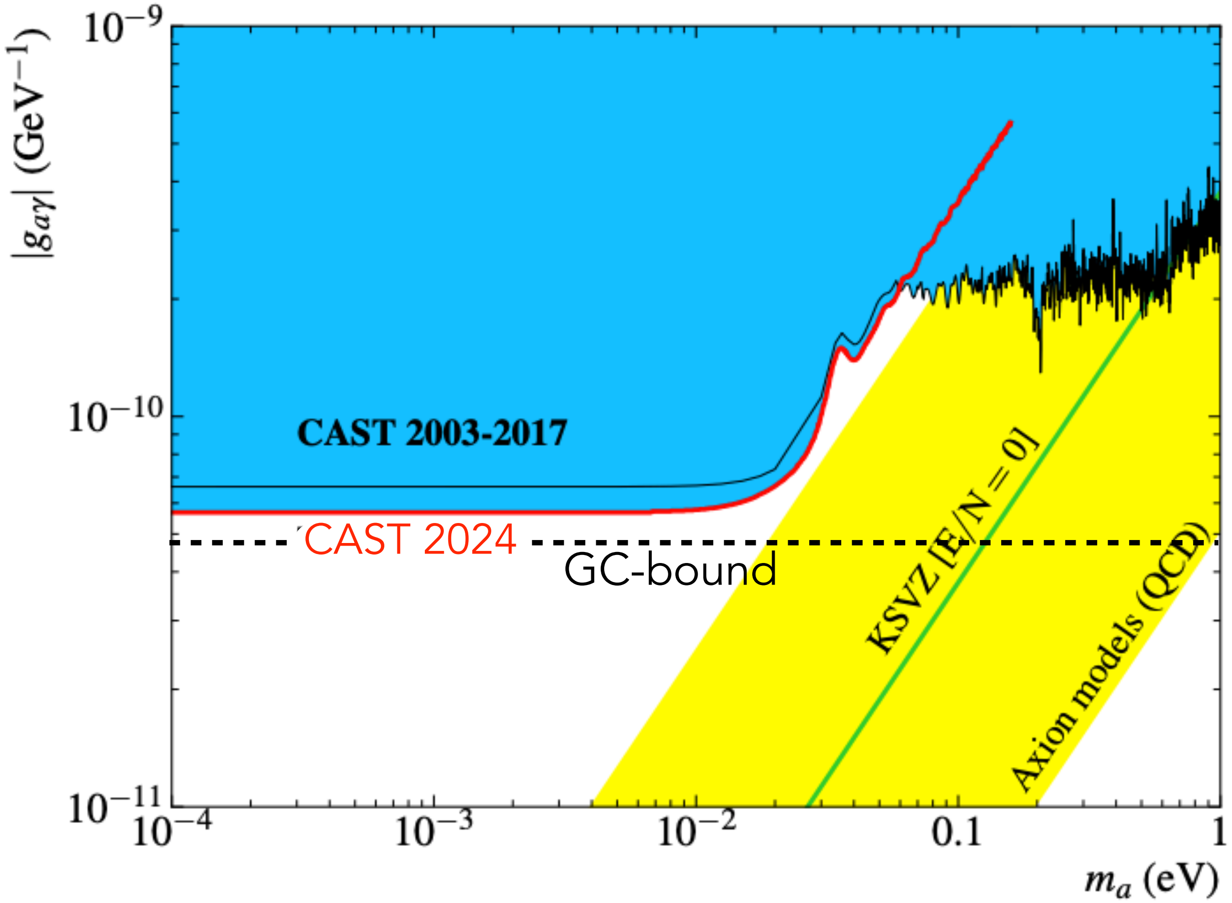
A buffer gas ($m_\gamma \simeq m_a$) can restore coherence

Van Bibber, McIntyre, Raffelt, Phys.Rev. D 39:2089 (1989)

The CERN Axion Solar Telescope (CAST)

Reached the HB bound for the first time

K. Altenmuller, et al., arXiv:2406.16840 (2024)



Brand New !

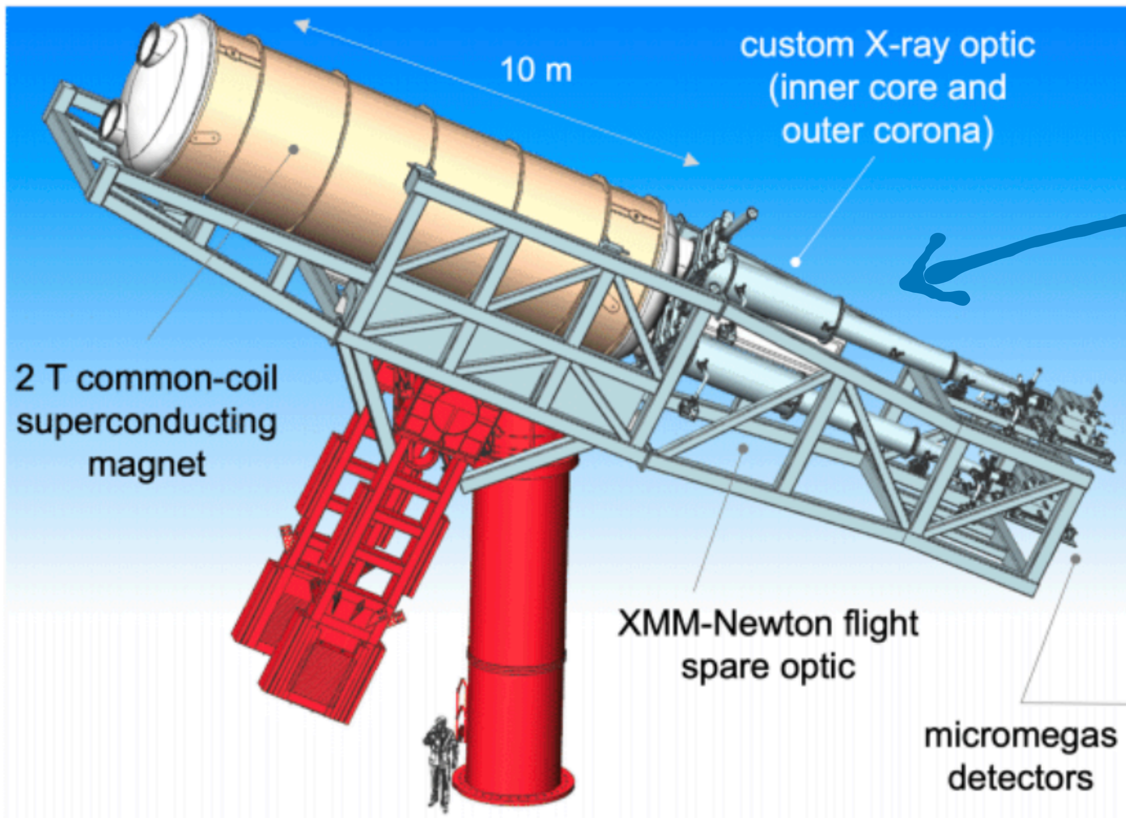
Decommissioned LHC test magnet,
B=9T, D=43 mm, L= 9.3 m

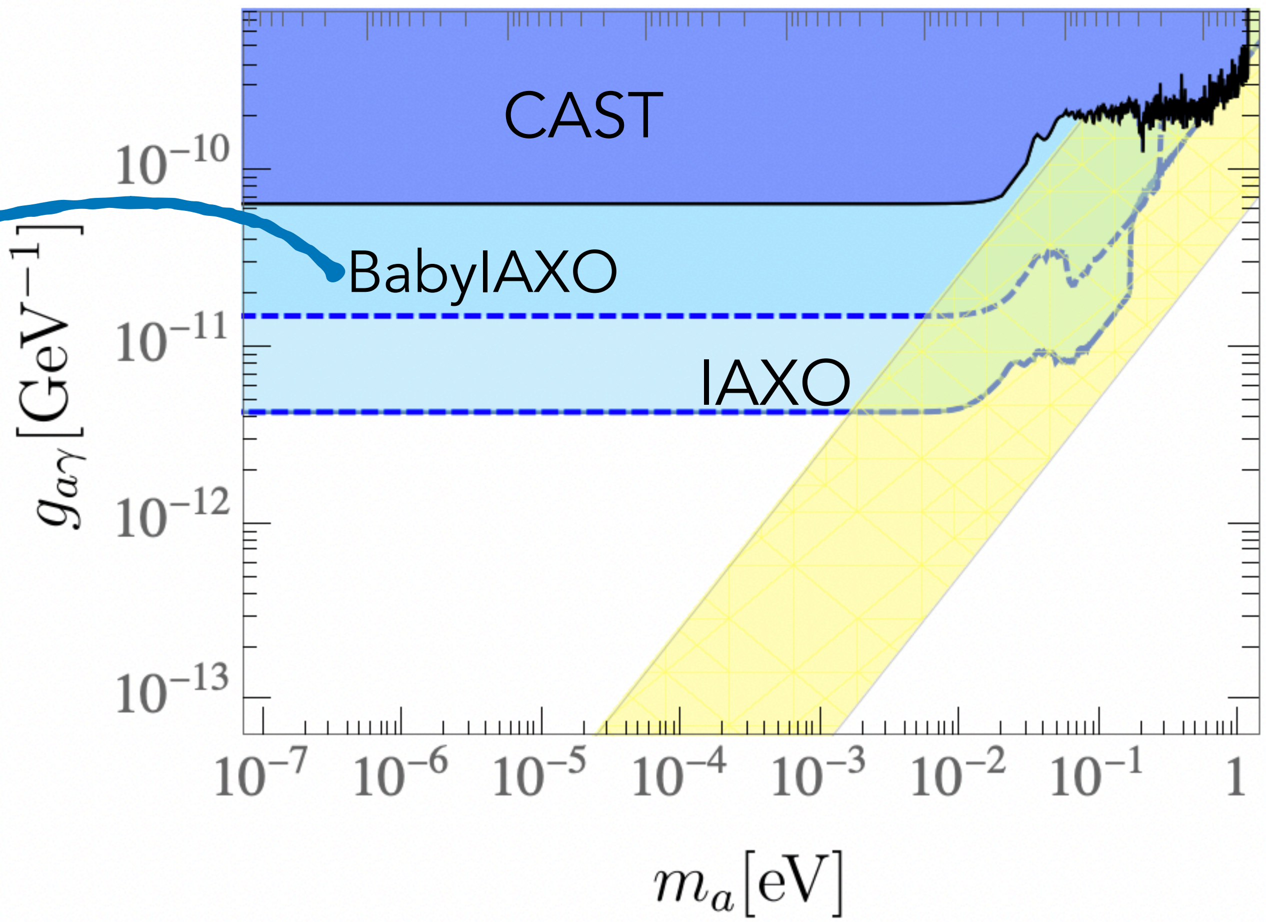
~2 h tracking/day

X-ray optics

Hunting Solar Axions: Sikivie Helioscope

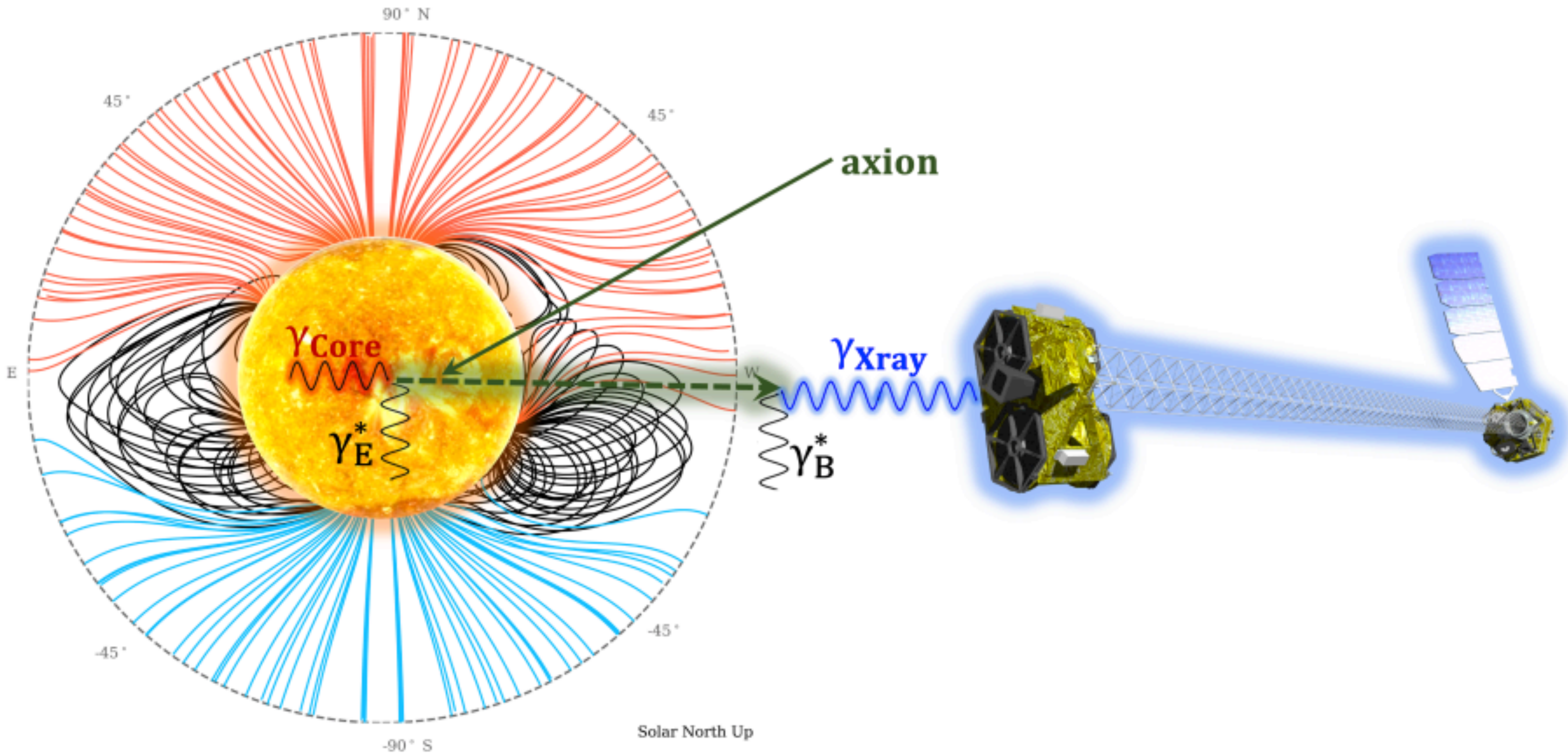
P. Sikivie PRL 51:1415 (1983)





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

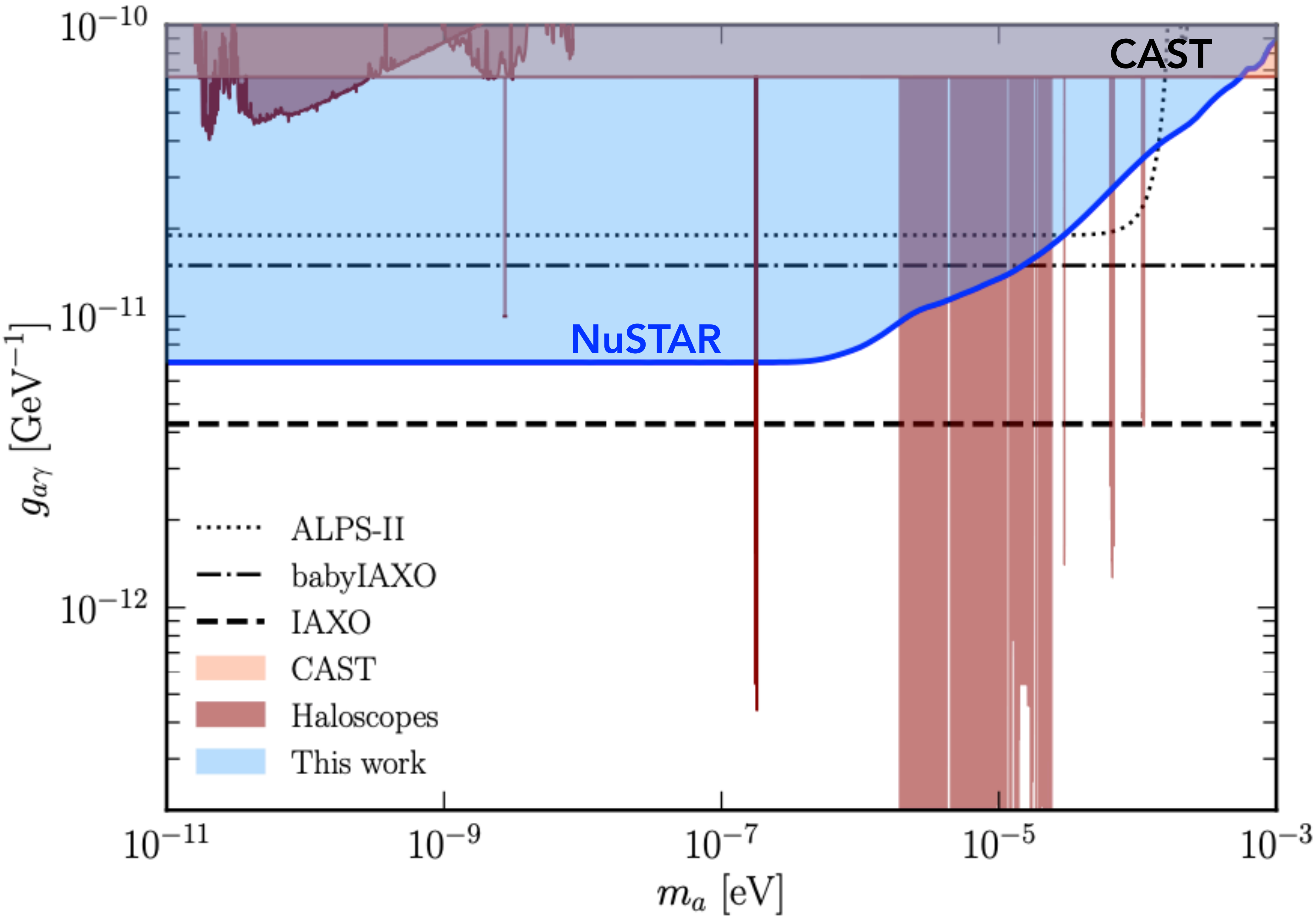
Hunting Solar Axions: NuSTAR



- J. Ruz, E. Todarello et al. arXiv:2407.03828

  (With Jiri Stepan for solar magnetic field modeling)

Hunting Solar Axions: NuSTAR

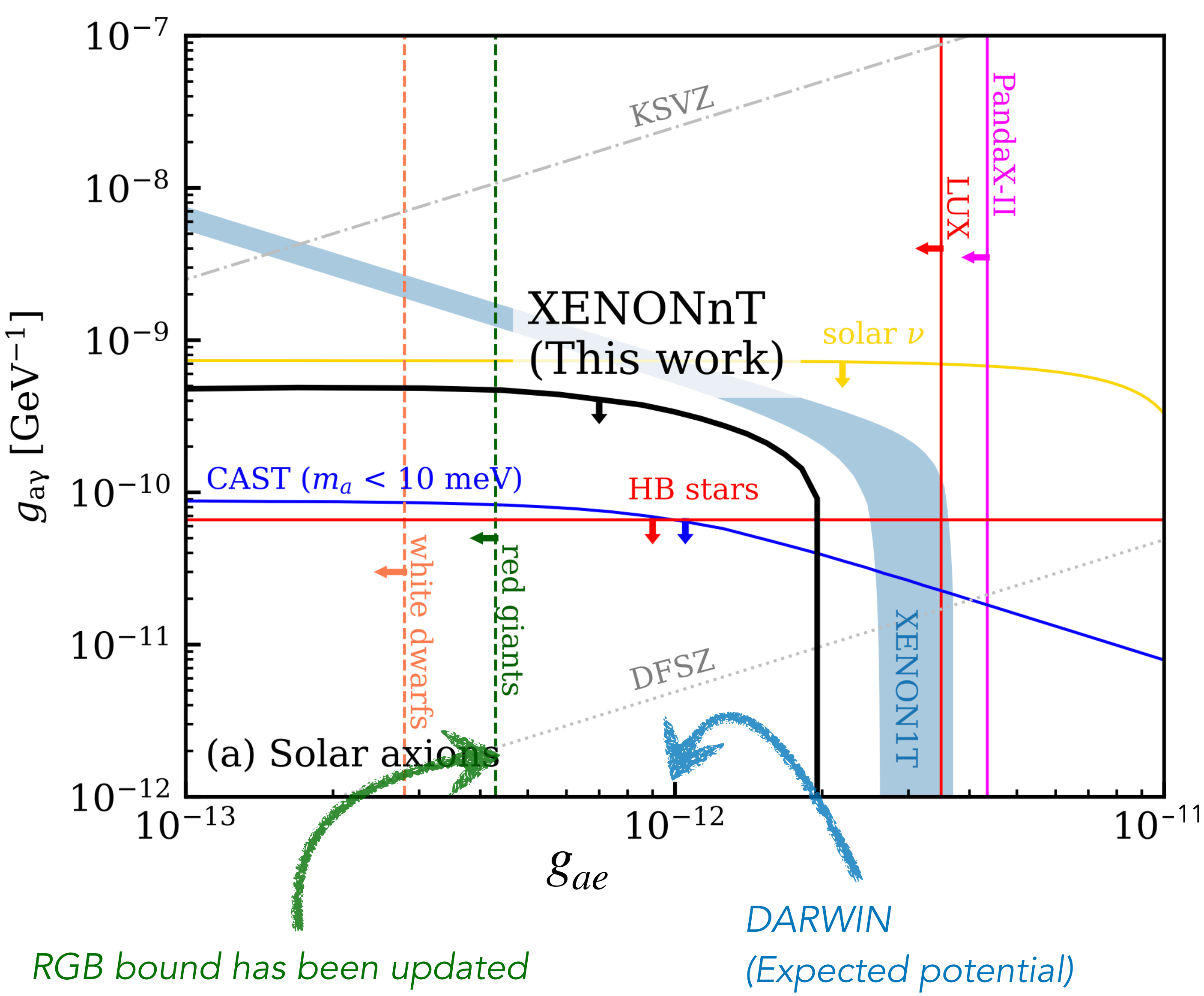


J. Ruz, E. Todarello et al. arXiv:2407.03828

Axioelectric Helioscopes

Large underground DM detectors.

Axioelectric = axion analog to the photoelectric effect $\sigma_{ae} \propto \left(\frac{E_a}{m_e}\right)^2$



Previous hint conclusively dismissed by the first science run of the XENONnT

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

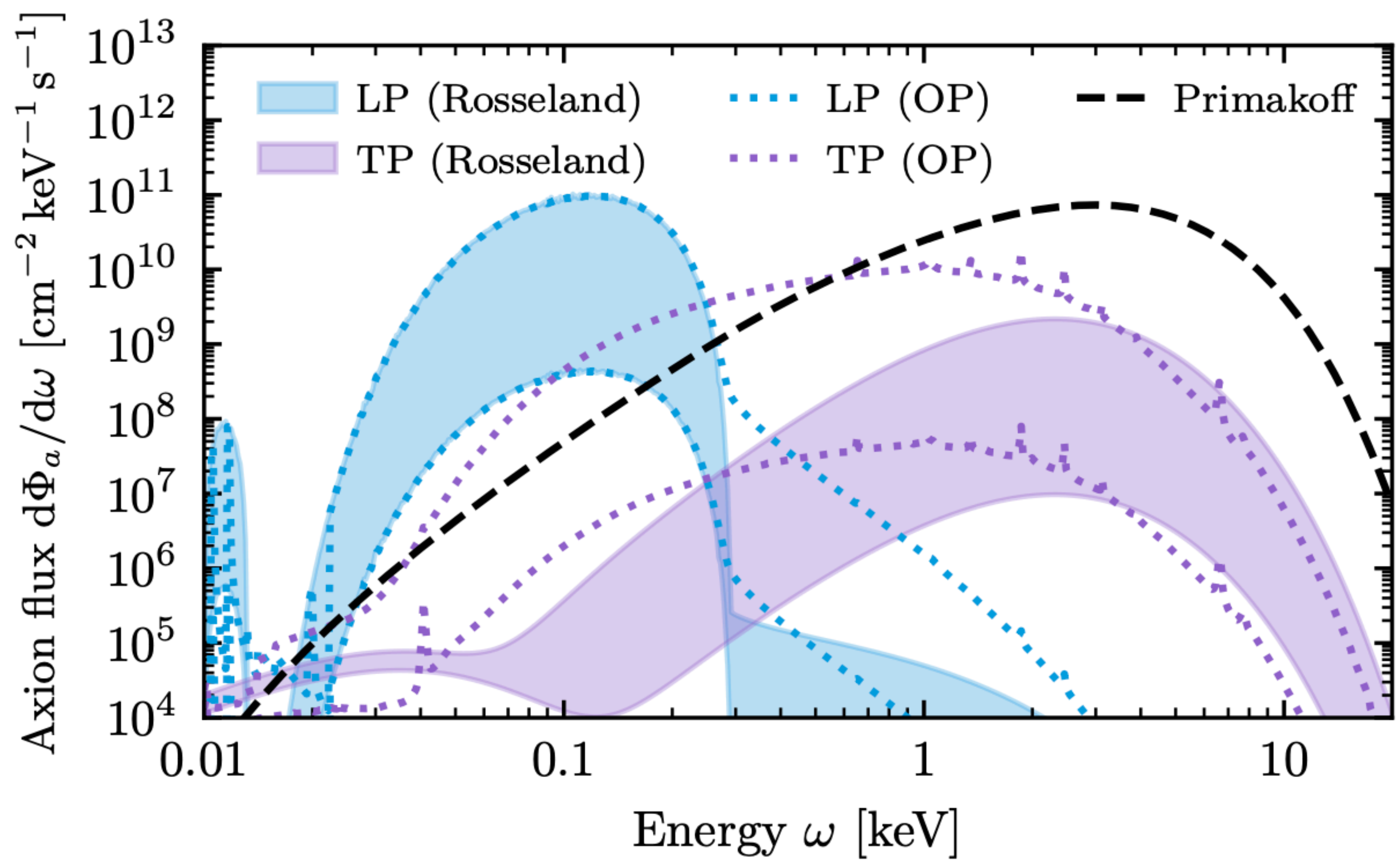
E. Aprile et al., Phys.Rev.Lett. 129 (2022)

Solar axions from Magnetic Field

Axions from photon conversion in the solar magnetic field

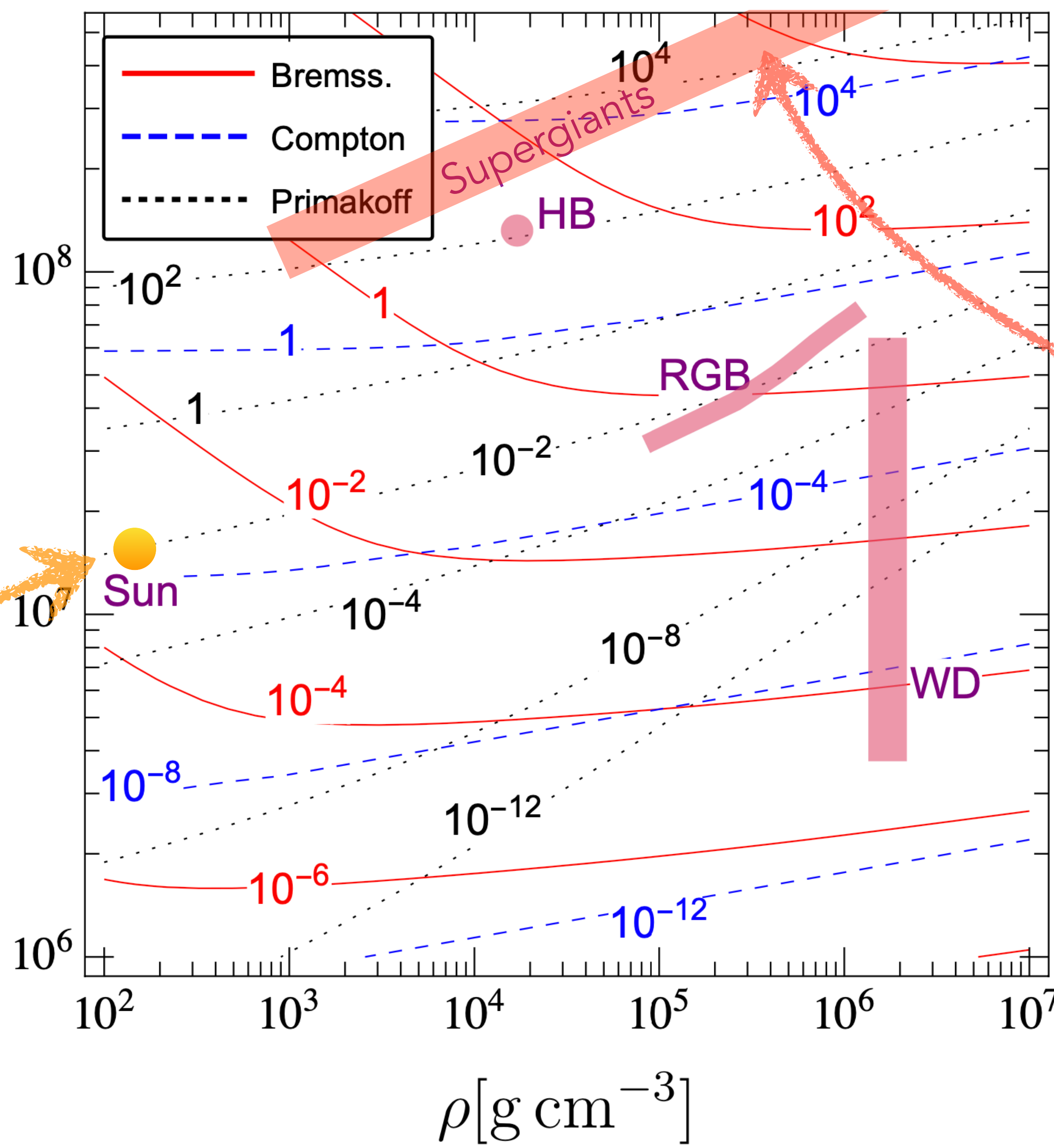
Issues:

- require low threshold. Detector technology exists but the optics may be challenging.
- Very difficult coherent conversions in B_{LAB} for mass above a few meV.
- Perhaps accessible with IAXO beyond baseline



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

Supergiants Axions



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

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

The sun is quite an unremarkable star…

supergiants: T_c and ρ_c depend on mass and evolutionary stage

Brand new SG catalog, Sarah Healy et al., Mon.Not.Roy.Astron.Soc. 529 (2024)

Supergiant Axions

Model	Phase	t_{cc} [yr]	$\log_{10}\frac{L_{eff}}{L_\odot}$	$\log_{10}\frac{T_{eff}}{K}$	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

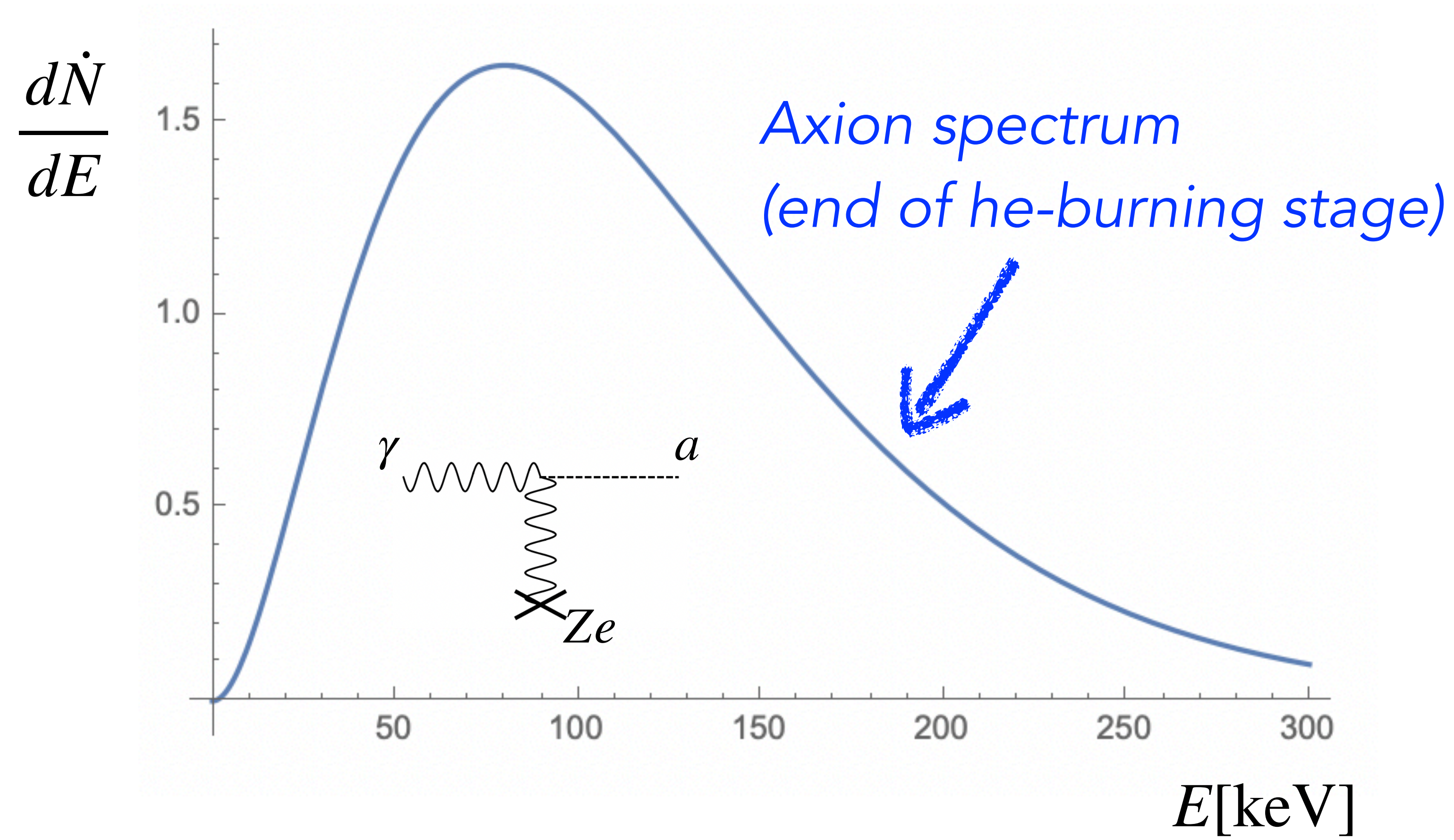
$$\frac{d\dot{N}_a}{dE} = \frac{10^{42}}{\mathrm{keVs}}\left[C^P g_{11}^2 \left(\frac{E}{E_0^P}\right)^{\beta^P} e^{-(\beta^P+1)E/E_0^P} + (P \to B, C; g_{11} \to g_{13})\right]$$

Flux increases adding g_{ae} coupling

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

Supergiant Axions

$\times 10^{43}$



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!

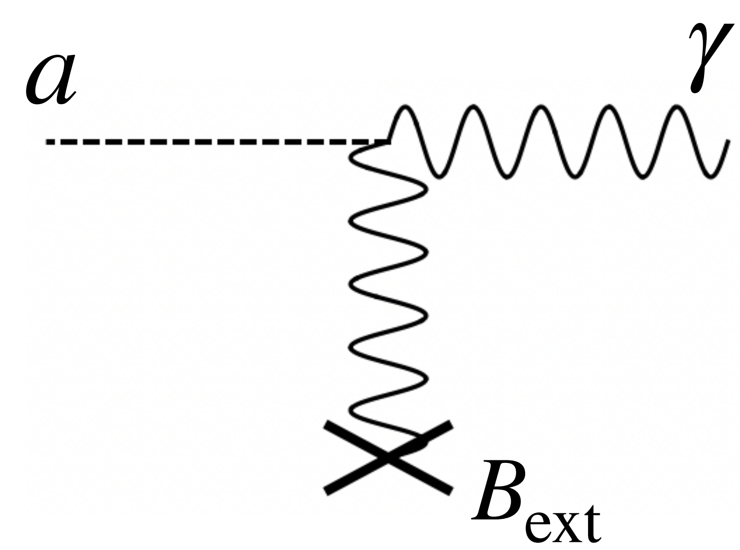
Supergiant Axions

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

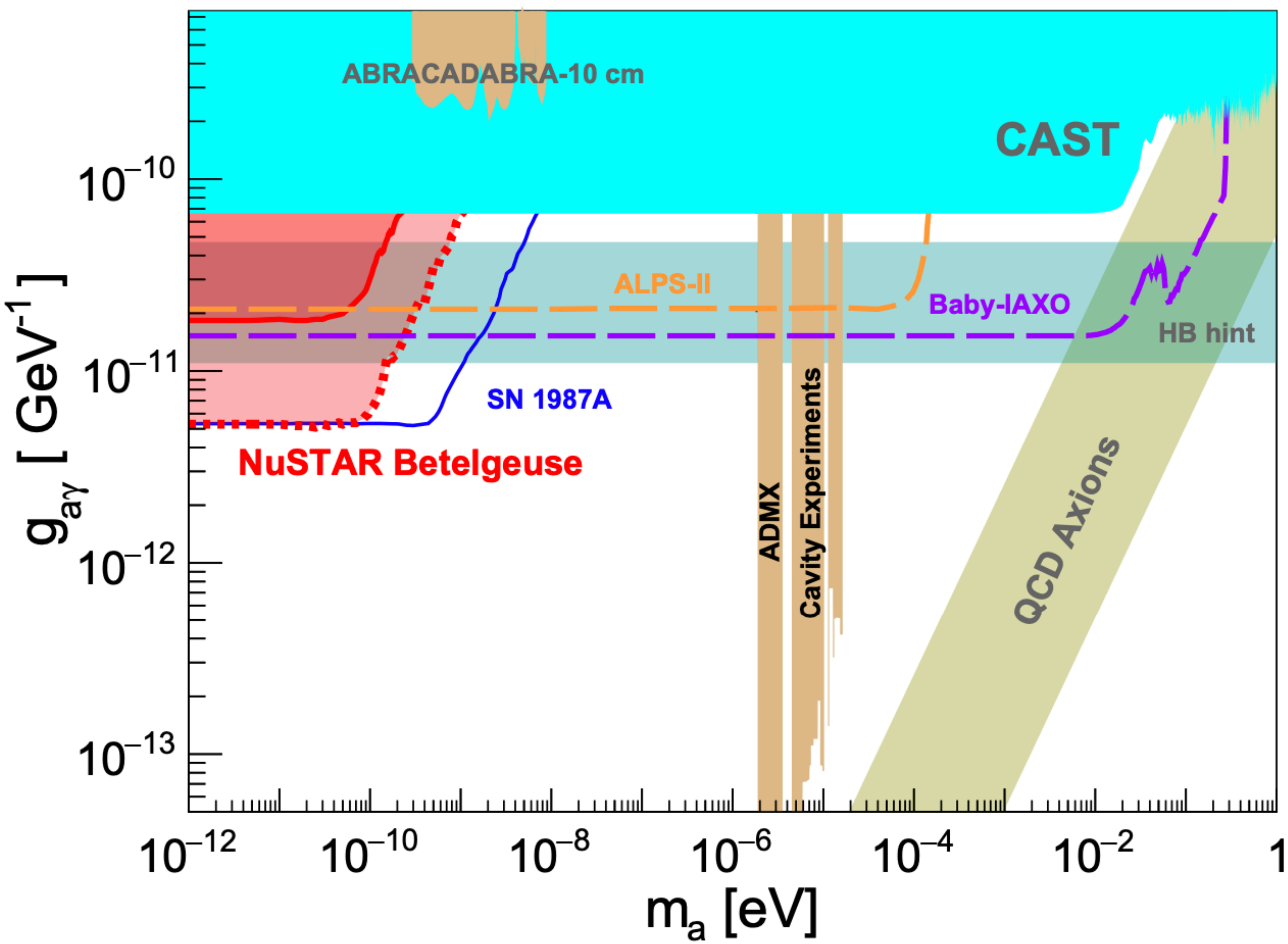
$$P_{a\gamma} = 8.7 \times 10^{-6} g_{11}^2 \left(\frac{B_T}{1\ \mu G} \right)^2 \left(\frac{d}{197\,\mathrm{pc}} \right)^2 \frac{\sin^2(qd)}{(qd)^2}$$

(Assuming B uniform)

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

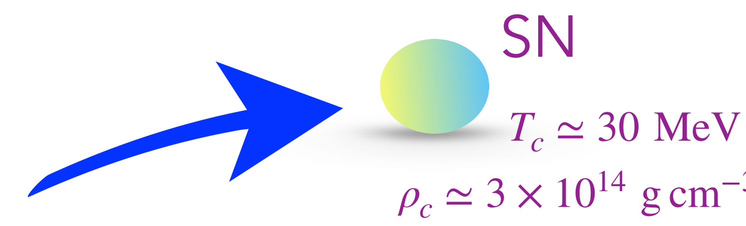


Supergiant Axions

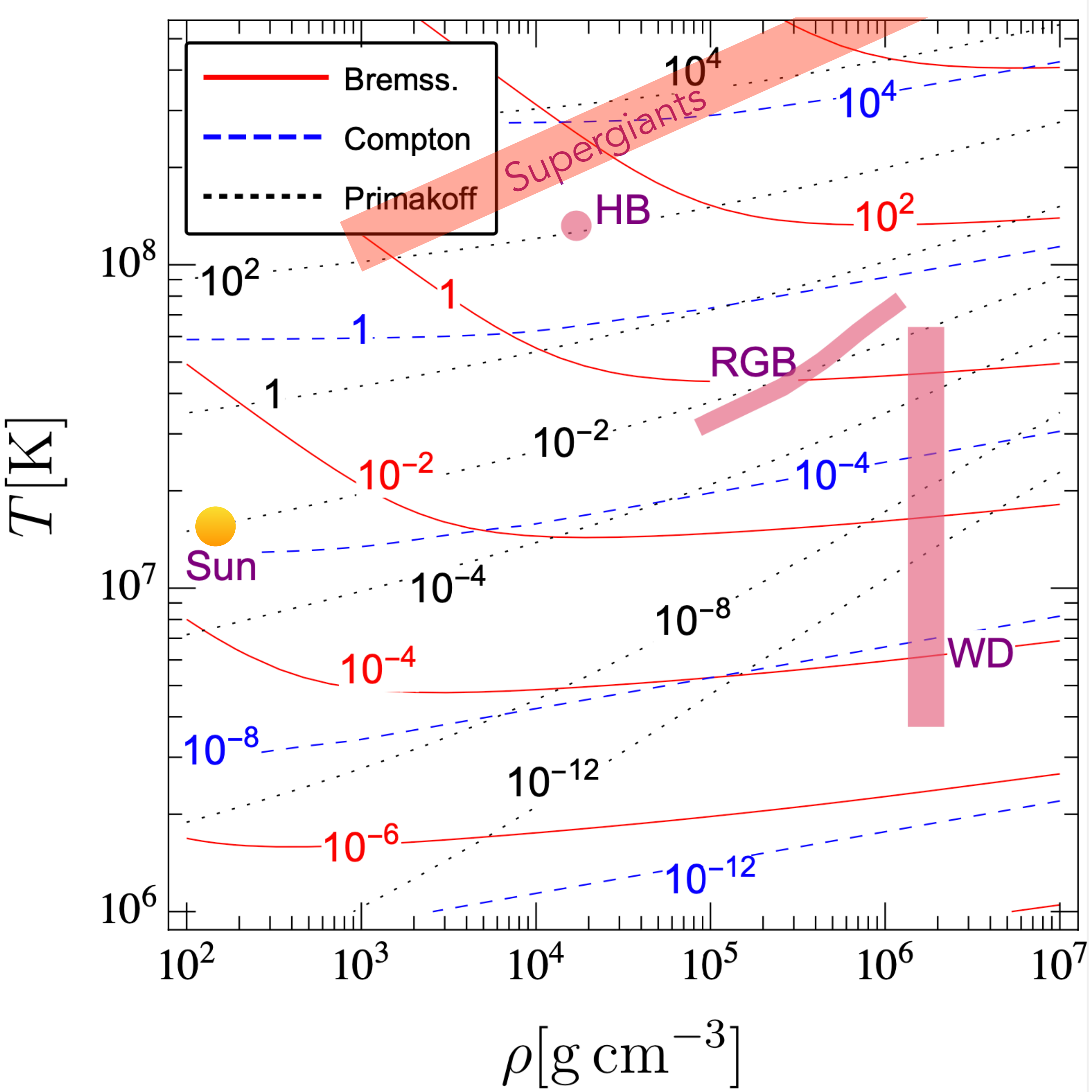


Xiao et al. Phys.Rev.Lett. 126 (2021)

Supernova axions



The monsters

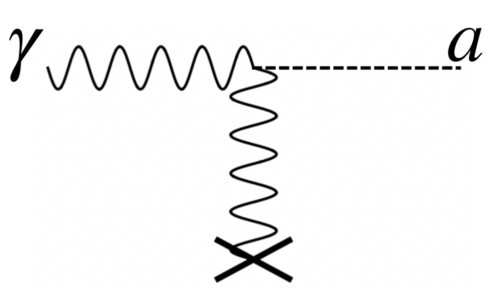


SN may produce up to $\sim 10^{56}$ axions/ s.

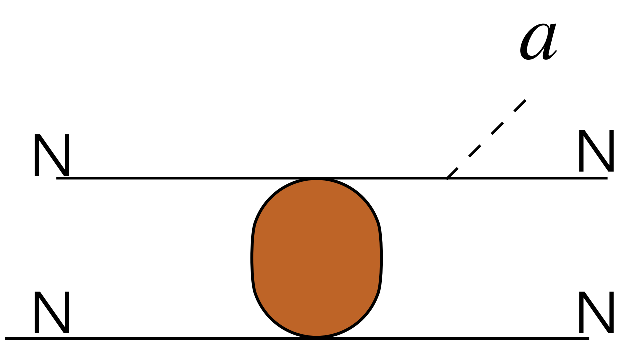
About $\sim 10^{13}\,\mathrm{cm^{-2}\,s^{-1}}$ axions on Earth from Betelgeuse

Huge flux… but short!

Supernova axions



Primakoff



Bremsstrahlung

Pion processes may dominate

$$\pi^- + N \to N + a$$

Harder Spectrum

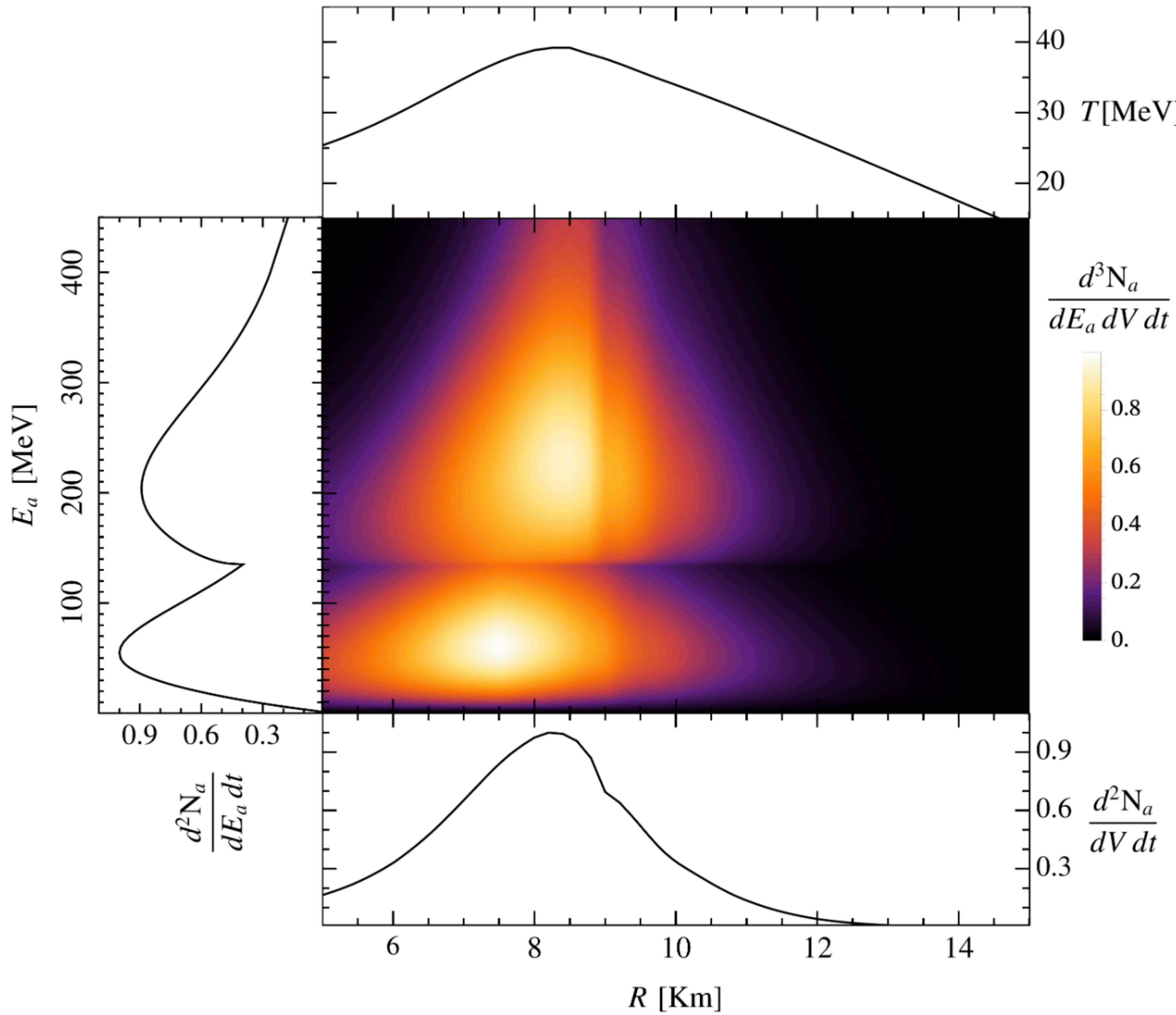
- P. Carenza et al., JCAP 10 (2019) 10, 016
- B. Fore and S. Reddy, Phys.Rev.C 101 (2020);
- A. Lella et al, *Phys.Rev.D* 107 (2023) 10
- K. Choi et al., *JHEP* 02 (2022) 143
- P. Carenza et al., Phys.Rev.Lett. 126 (2021);
- Fischer et al. Phys.Rev.D 104 (2021)
- Ho, Kim, Ko, Park, *Phys.Rev.D* 107 (2023) 7

Supernova axions

Harder spectrum from pion processes

Large uncertainties:

- *T, ρ profiles*
- *Pion properties in medium*
- *Pion condensation*
- *…*



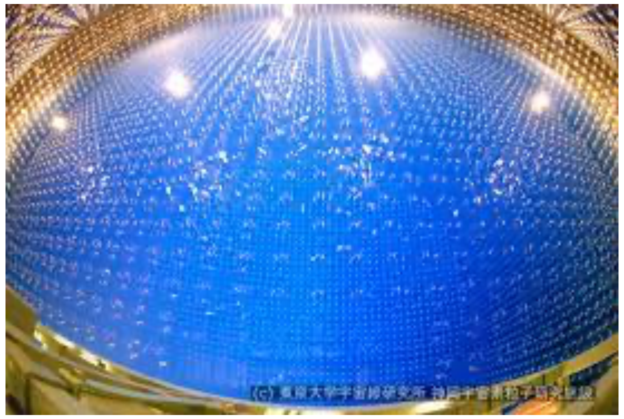
Alessandro Lella et al., arXiv:2405.02395

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
(UNIZAR/CAPA)

Indirect detection

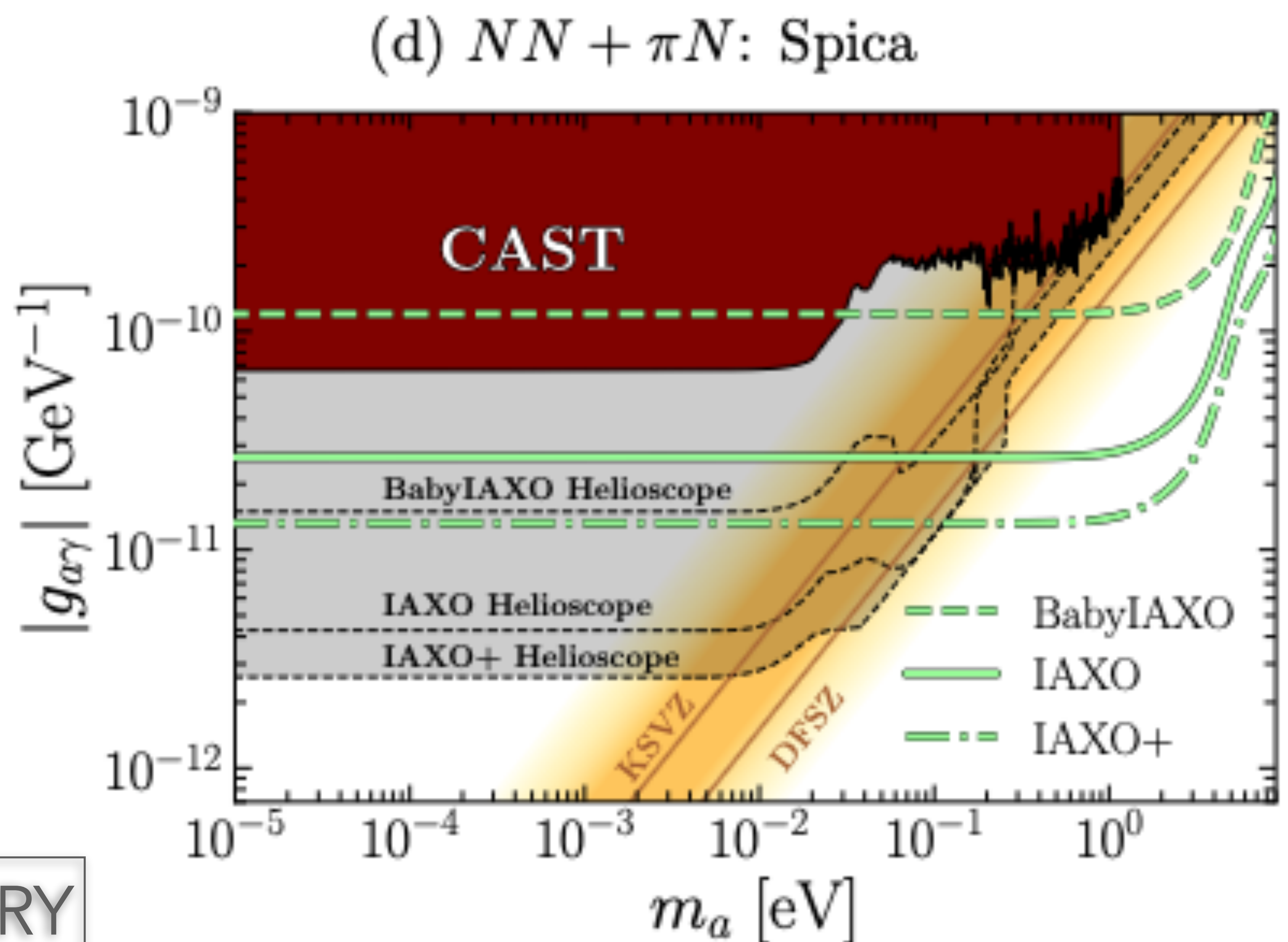
Through photon oscillations in $B_{\rm ext}$

- F. Calore et al. e-Print: Phys.Rev.D 109 (2024)
- A. Lella et al., arXiv:2405.02395
- Meyer et al. Phys.Rev.Lett. 118 (2017)

Detecting SN axions

Direct Detection:

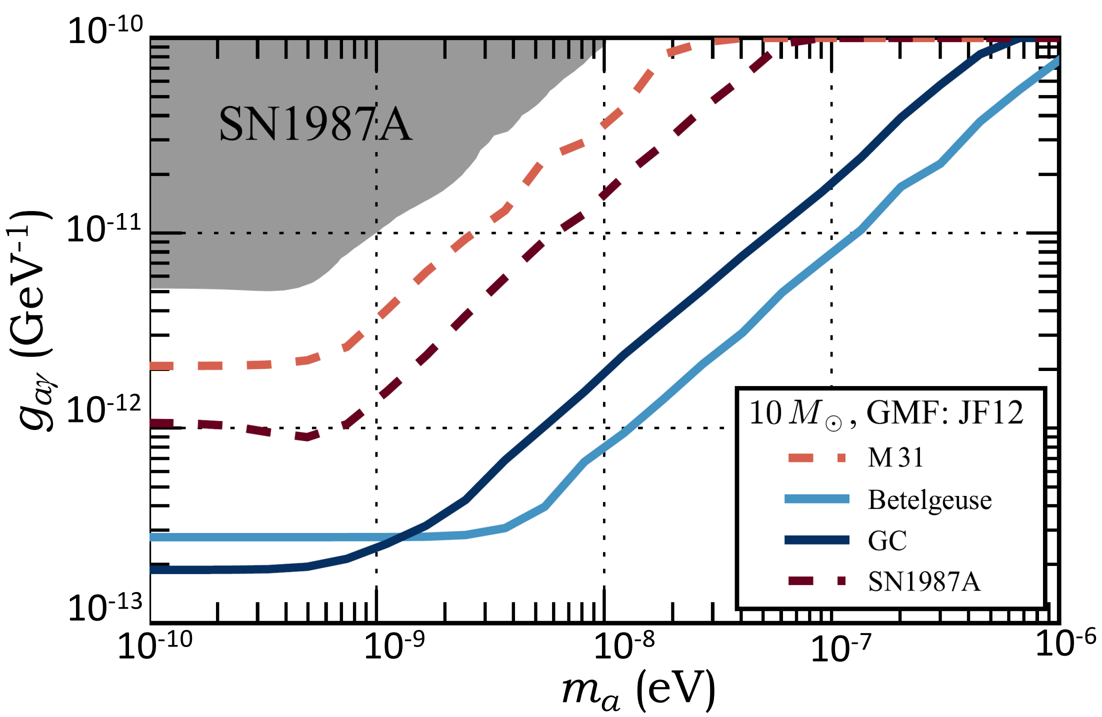
→ **Heliscopes**

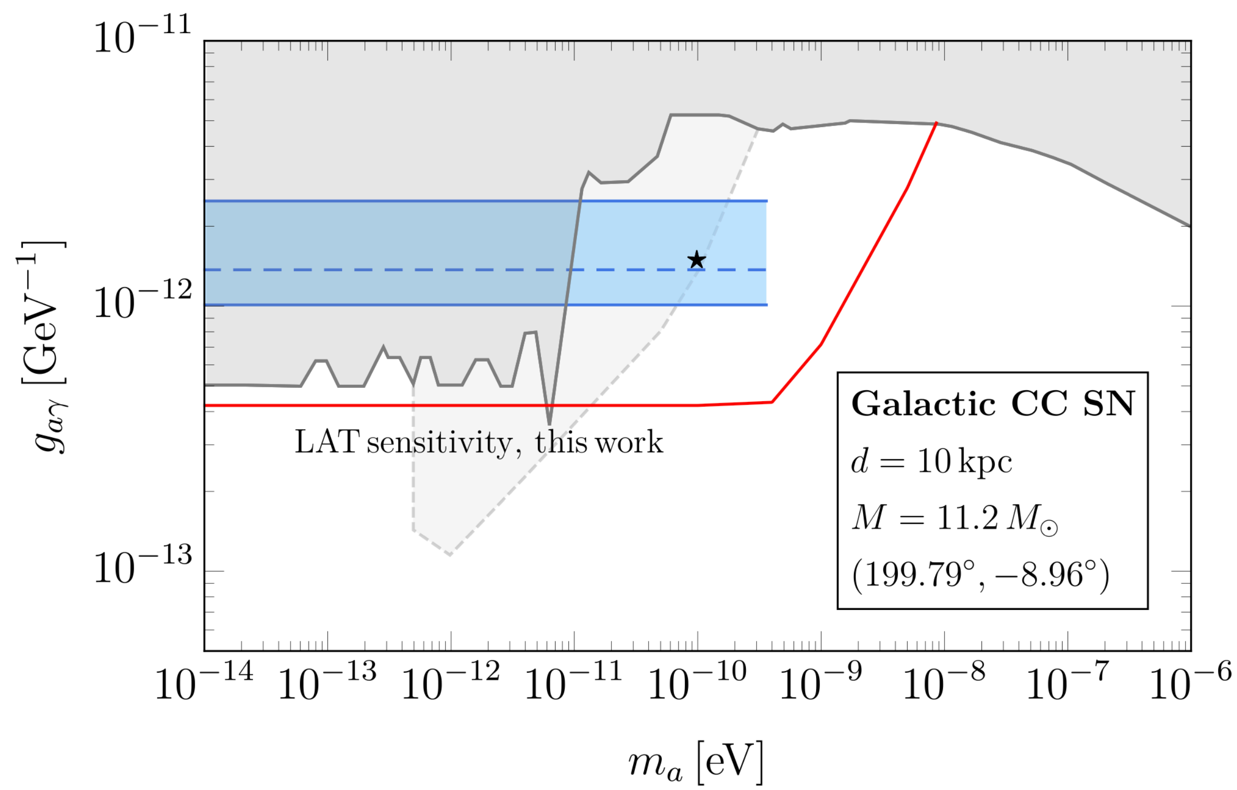


PRELIMINARY

Fermi LAT as Axion SN-Scope

Pure photon coupling





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

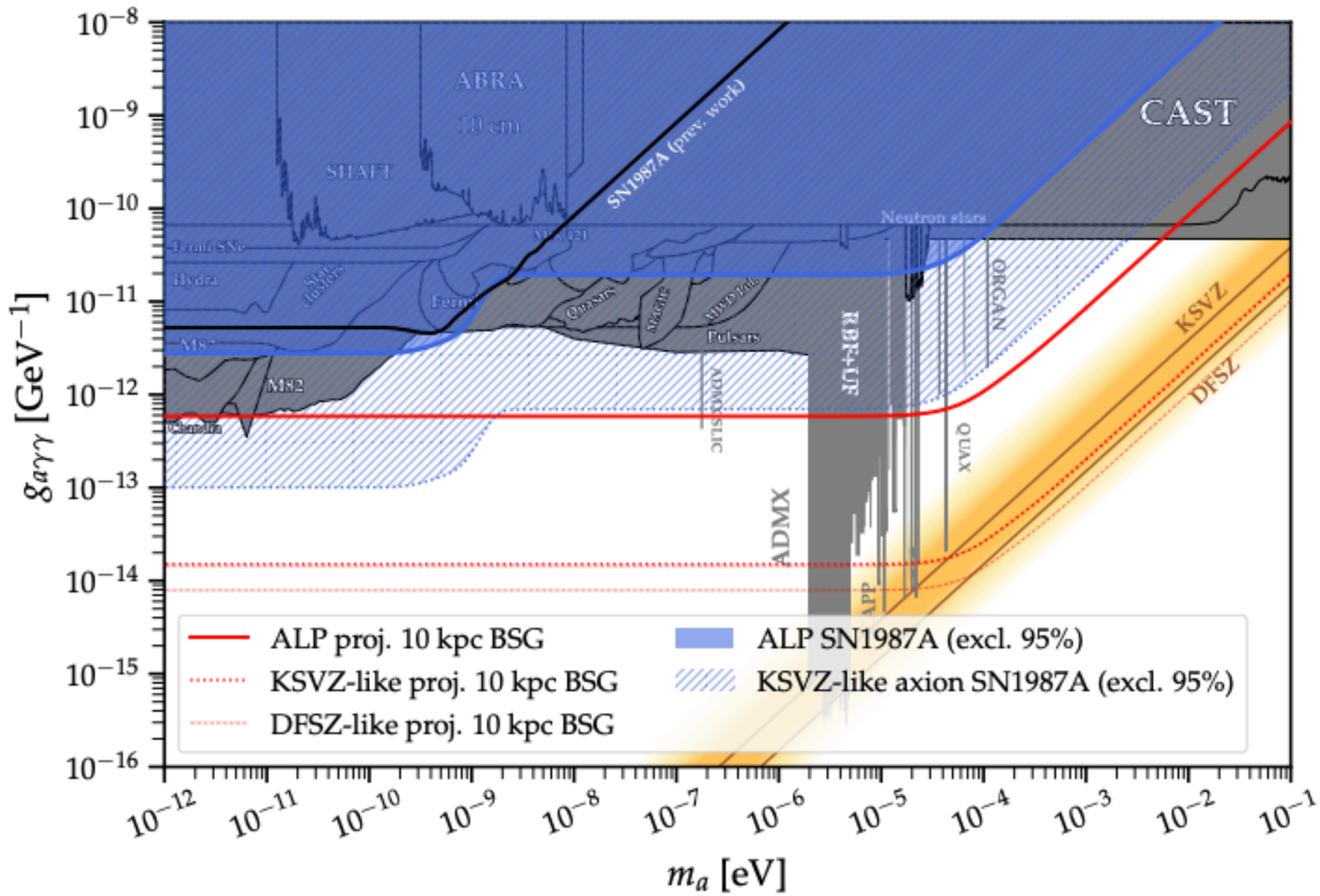
Calore, Carenza, Eckner, M. G., Lucente, Mirizzi, Sivo et al. arXiv:2306.03925

New analysis
→ slightly reduced sensitivity. But…

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

Fermi LAT as Axion SN-Scope

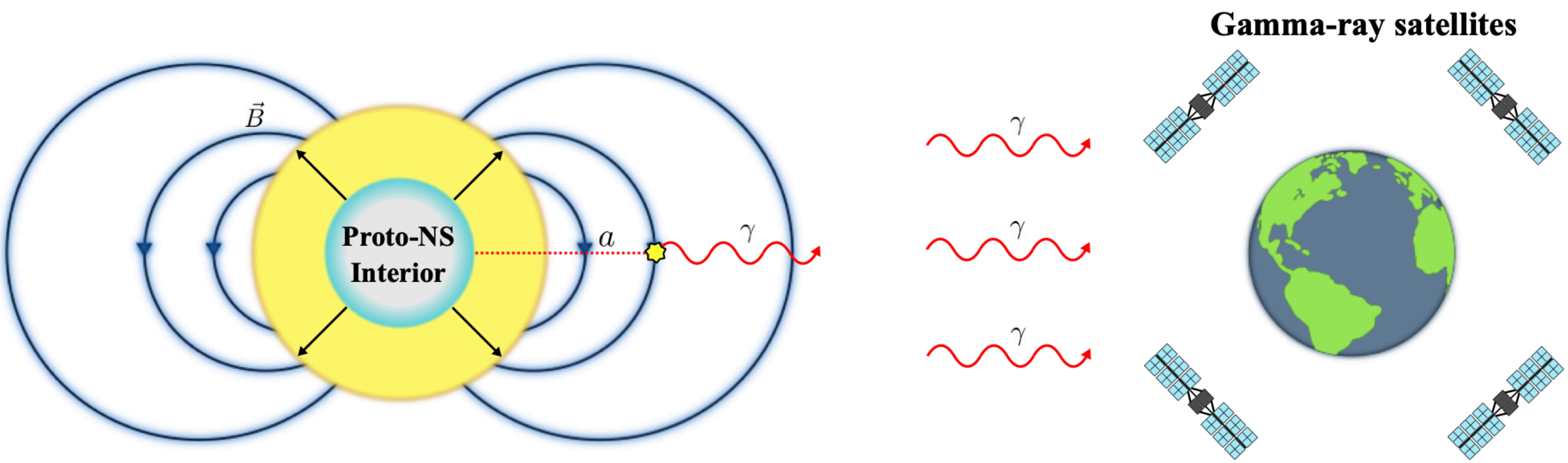
Accounting for possible progenitor magnetic field



Manzari, Park, Safdi, Savoray arXiv: 2405.19393

Detecting SN axions

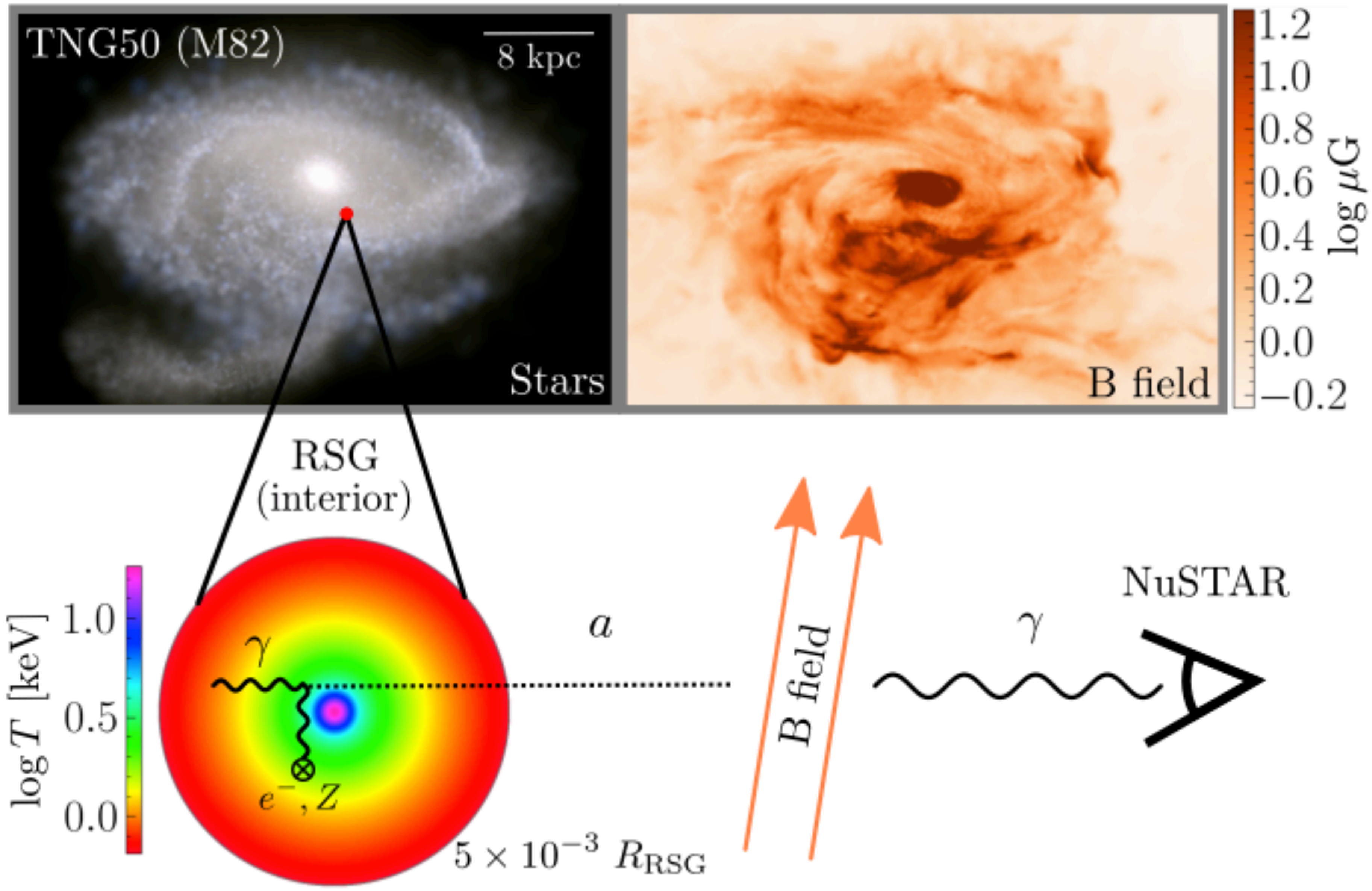
GALactic AXion Instrument for Supernova (GALAXIS)



4π coverage of the gamma-ray sky between ~100 MeV and ~1 GeV

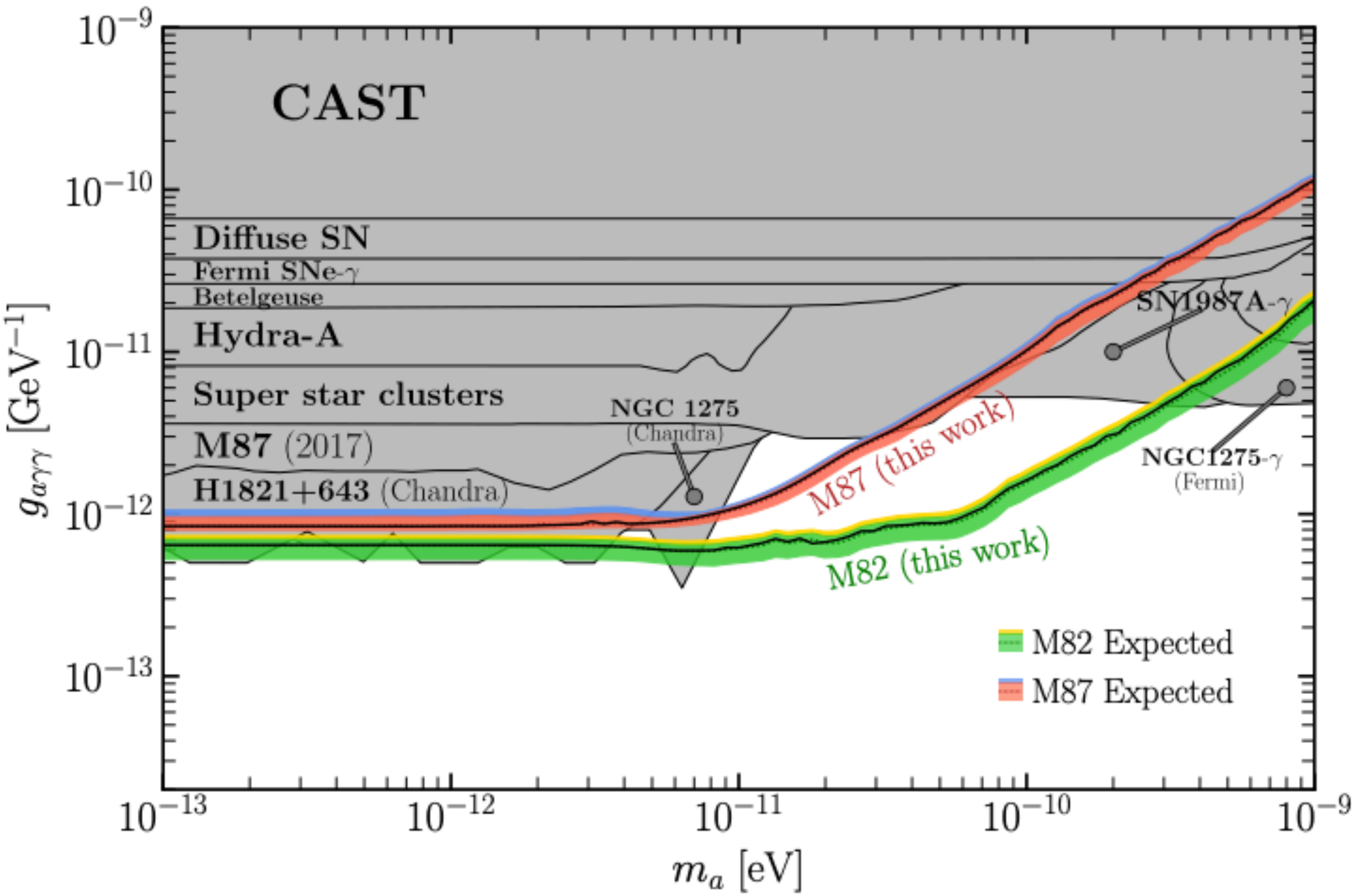
Manzari, Park, Safdi, Savoray arXiv: 2405.19393

Extra-Galactic Axions?



O. Ning, B. R. Safdi arXiv: 2404.14476

Extra-Galactic Axions?



O. Ning, B. R. Safdi arXiv: 2404.14476

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)

- ....

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
Super-Giants	• 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)

Cosmic WISPERs

[COSMIC WISPers in the Dark Universe: Theory, astrophysics and experiments]

COSMIC WISPERS

CA21106

… exhaustive study of WISPs from their theoretical underpinning, to astrophysics, to their searches.

Backup Slides

Solar ALPs coupled to Nucleons

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

Search using previous SNO data → Phys.Rev.Lett. 126 (2021)

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

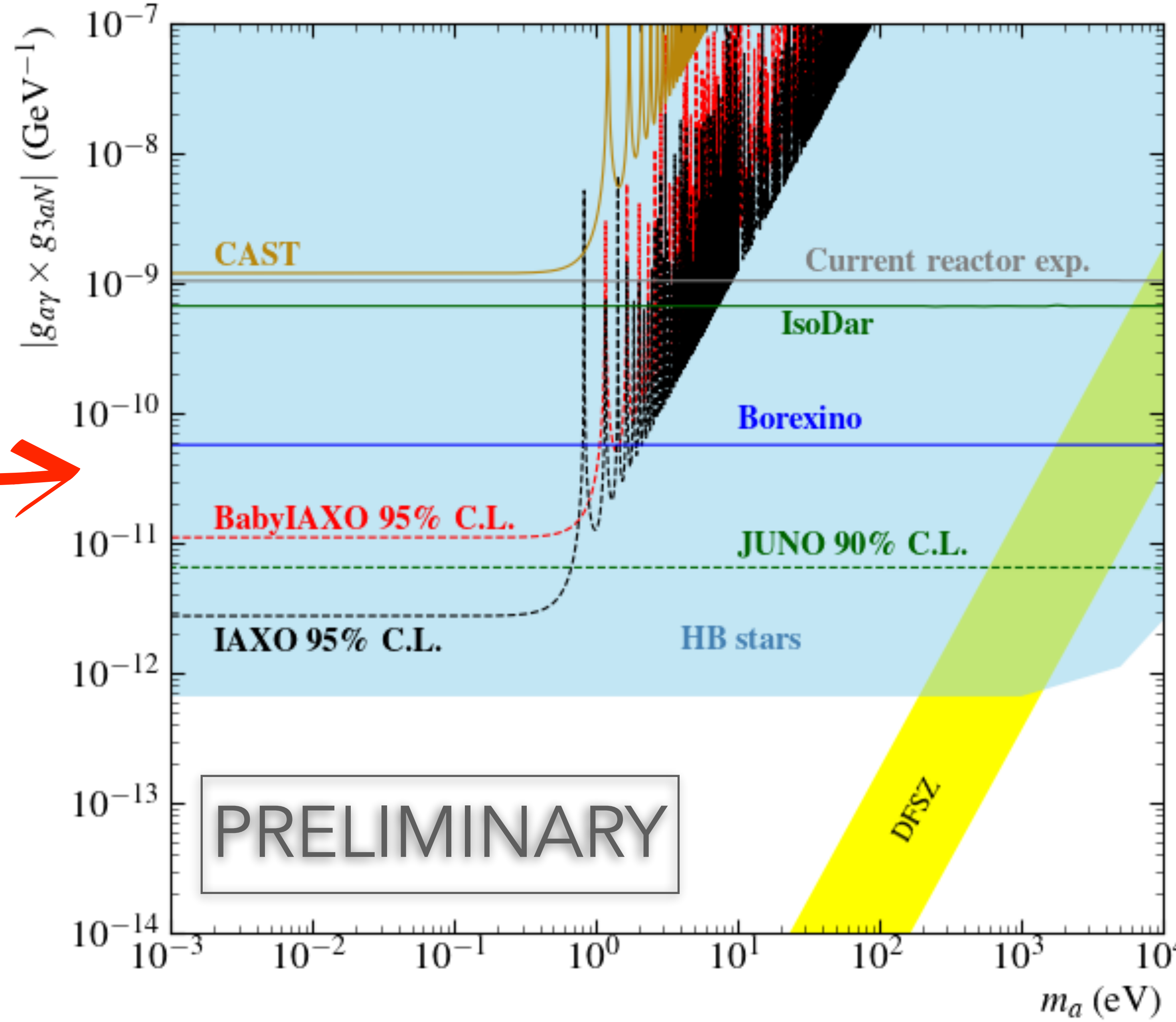
Also

- CAST *JCAP* 03 (2010)
- Borexino *Phys.Rev.D* 85 (2012)
- JUNO sensitivity G. Lucente et al., Phys.Rev.D 106 (2022) 12

Solar ALPs coupled to Nucleons

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

Current proposal for direct detection in IAXO



Solar ALPs coupled to Nucleons

Nuclear de-excitations. Axion production in M1 transitions

$$X^* \to X + a, \quad \Rightarrow \quad a + X \to X^* \to X + \gamma$$

${}^{57}\mathrm{Fe}^* \to {}^{57}\mathrm{Fe} + a(14.4\ \mathrm{keV})$	$g_{aN}^{\mathrm{eff}} = 0.16 g_{ap} + 1.16 g_{an}$ New dedicated project under commissioning → ISAI (Investigating Solar Axion by Iron-57),	
${}^{83}\mathrm{Kr} + a(9.4\,\mathrm{keV})$	$g_{aN}^{\mathrm{eff}} \simeq g_{an}$	→ Gavrilyuk et al. (2015) and Akhmatov et al. (2018).
${}^{169}\mathrm{Tm} + a(8.4\,\mathrm{keV})$	$g_{aN}^{\mathrm{eff}} \simeq g_{ap}$	→ Derbin et al. (2023)

Pre-SN signal

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

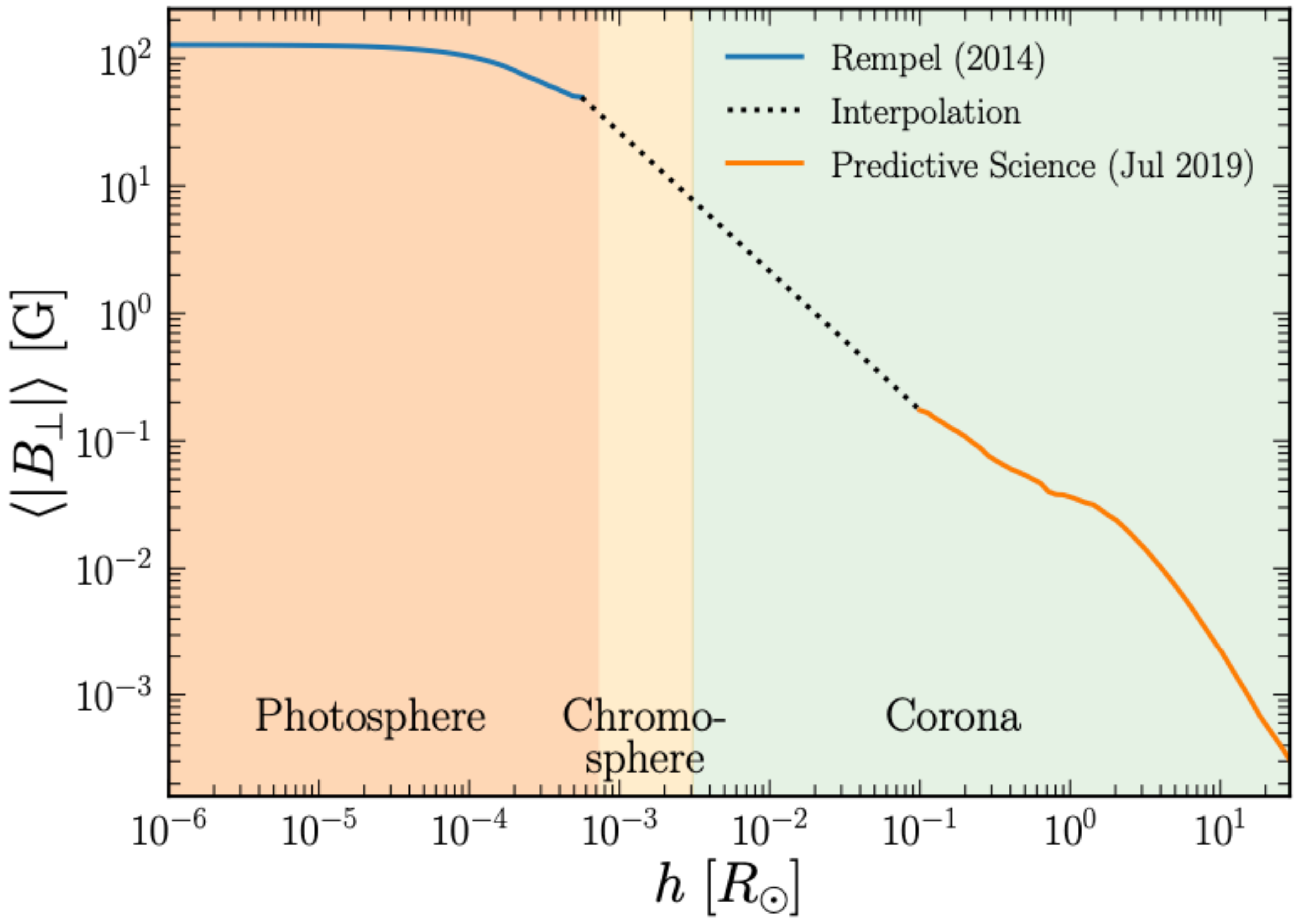
Tanaka & Watanabe (2014)

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)

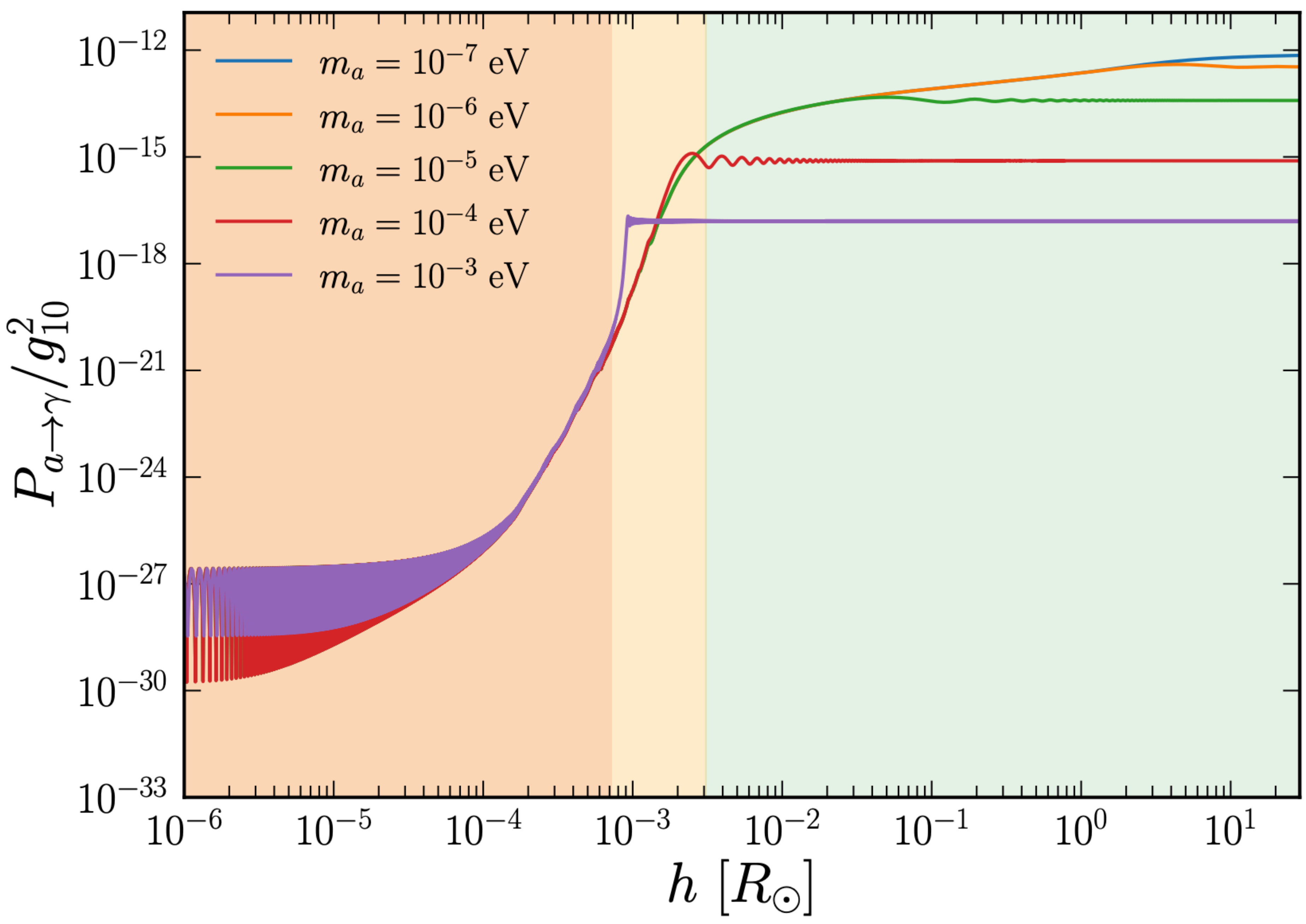
Hunting Solar Axions: NuSTAR



- J. Ruz, E. Todarello et al. arXiv:2407.03828

(With Jiri Stepan for solar magnetic field modeling)

Hunting Solar Axions: NuSTAR



- J. Ruz, E. Todarello et al. arXiv:2407.03828

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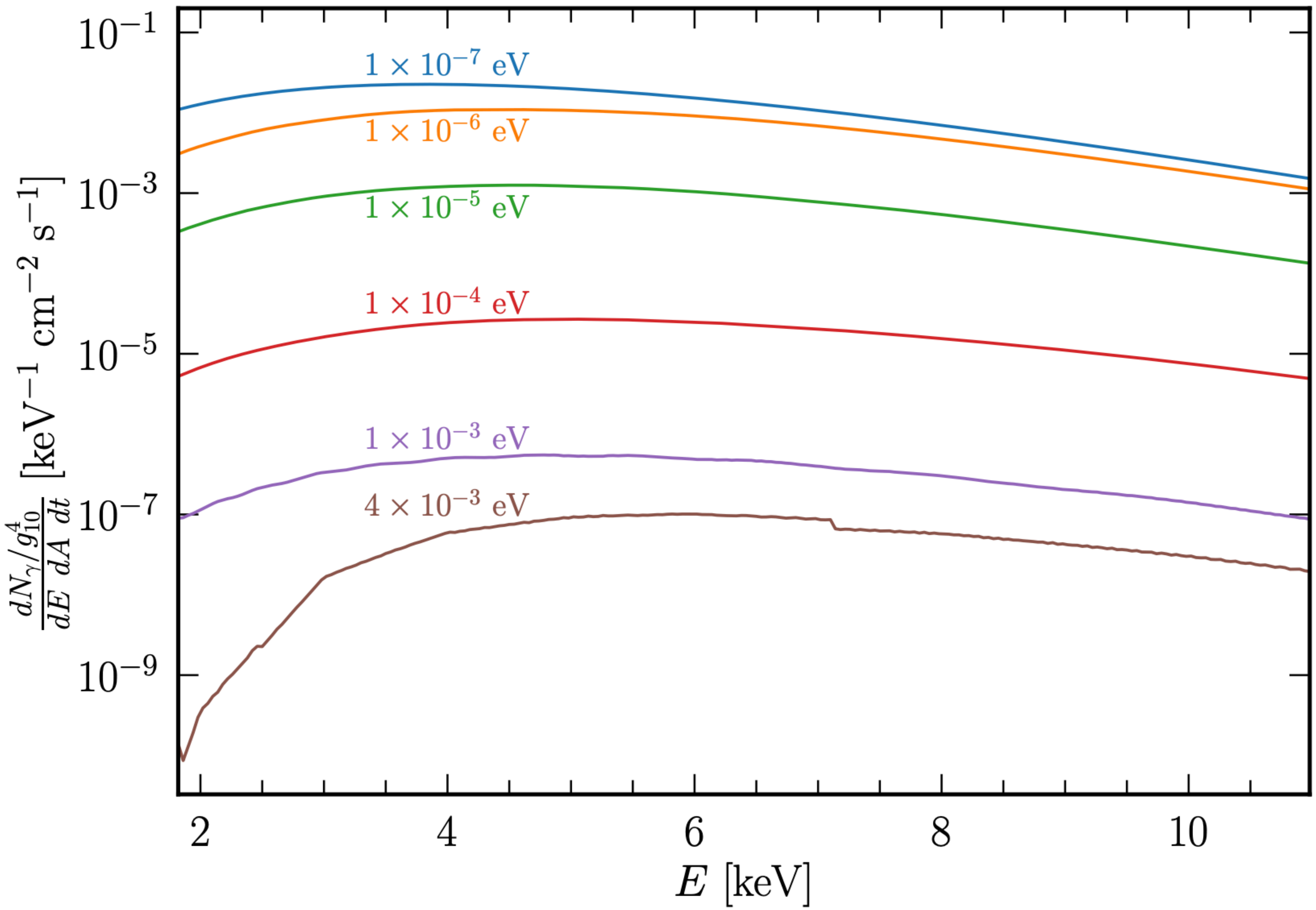
Hunting Solar Axions: NuSTAR



- J. Ruz, E. Todarello et al. arXiv:2407.03828

(With Jirı Stepan for solar magnetic field modeling)

Solar axions from Nuclear Reactions

Axions from Li-7

$$^{7}\mathrm{Be} + e \rightarrow {}^{7}\mathrm{Li}^{*} + \nu_e$$

$$\downarrow$$

$$^{7}\mathrm{Li}^{*} \rightarrow {}^{7}\mathrm{Li} + a(477.6\,\mathrm{keV})$$

Pure proton coupling $g_{aN}^{\mathrm{eff}} = g_{ap}$

→ Krcmar et al (2001)

→ CAST (2009)

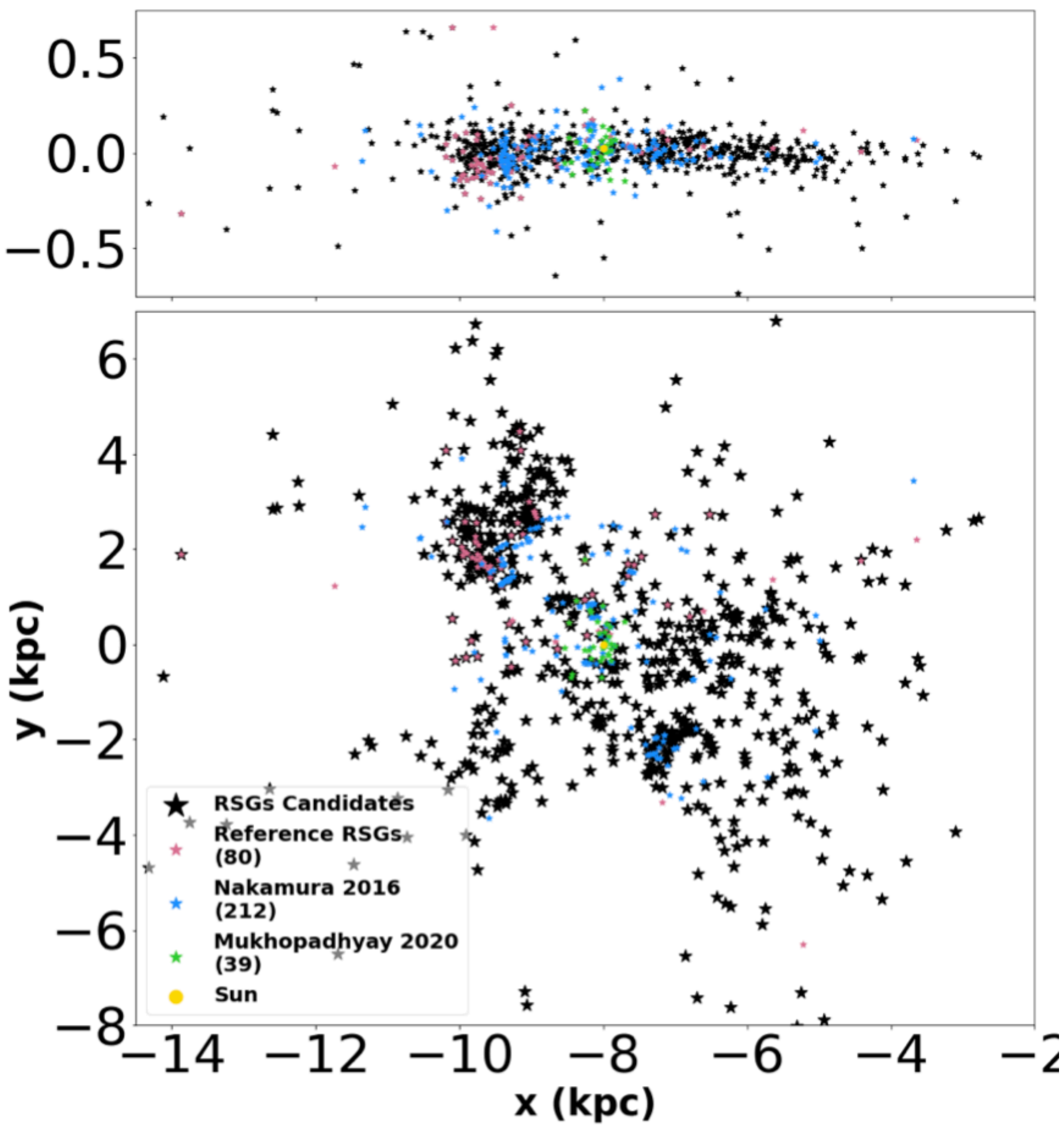
Most restrictive limit (2011): $m_a < 8.6\mathrm{keV}$ (assuming QCD axion with $C_p = 0.4$)

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

No recent analysis (to the best of my knowledge)

Supergiants

Brand new catalog of Red SG, Sarah Healy et al., [Mon.Not.Roy.Astron.Soc. 529 (2024)]

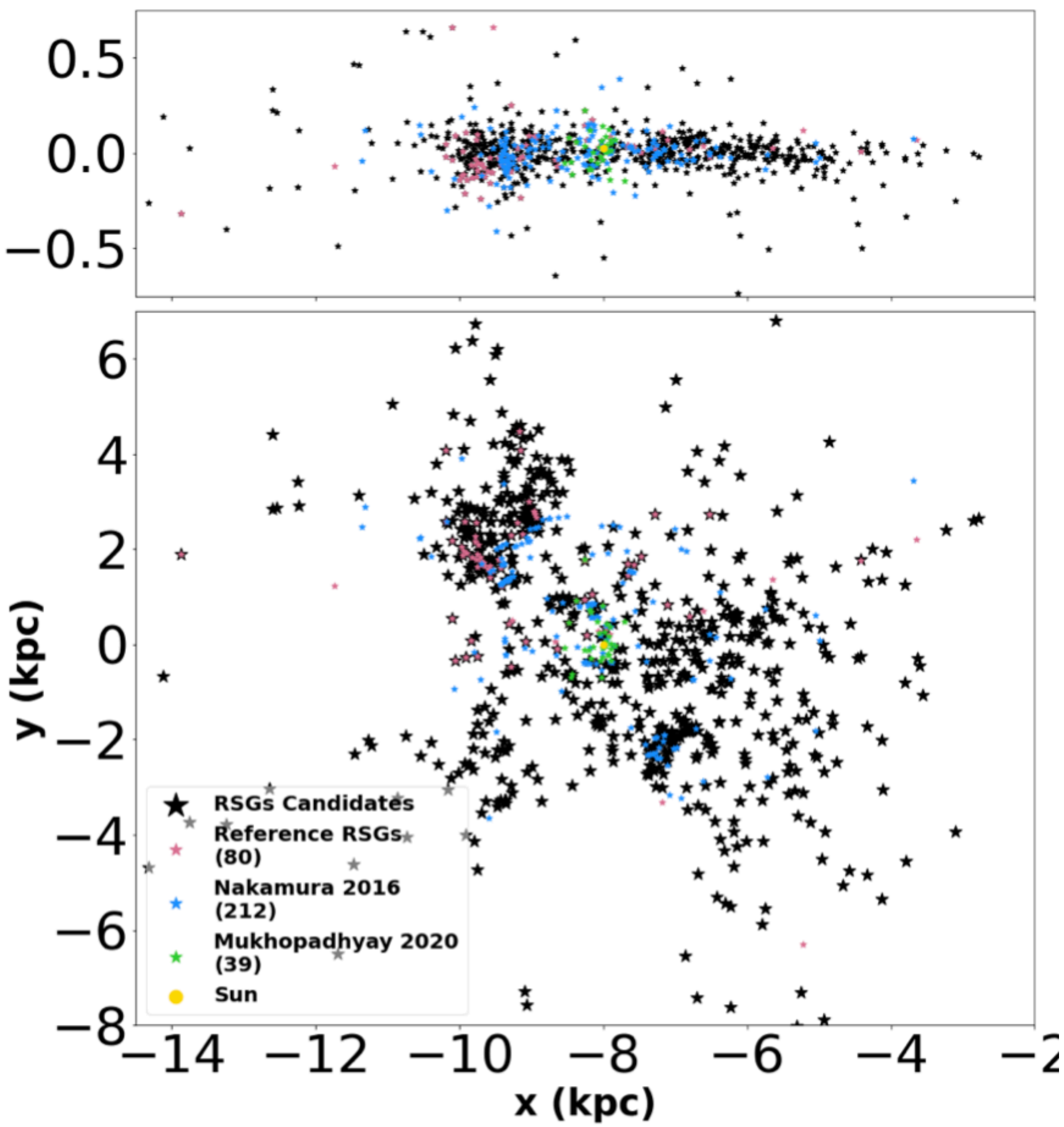


Many candidates at a few kpc from the Sun.

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)

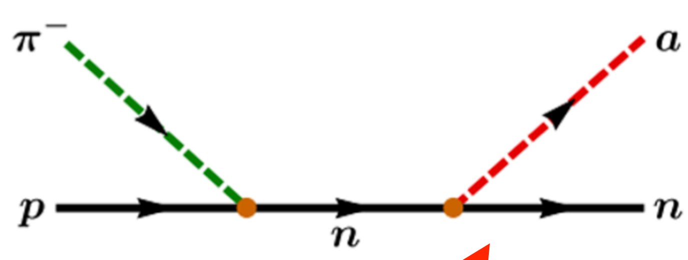
Supernova axions

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

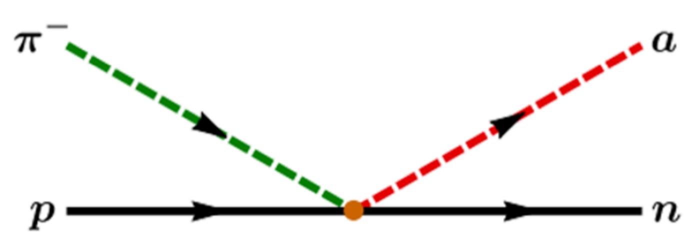
Relevant interaction Lagrangian

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

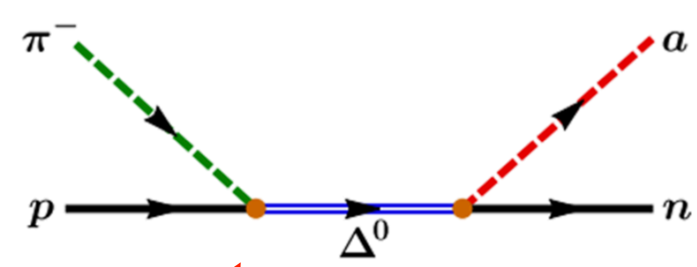
Leads to a variety of processes, studied very recently



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



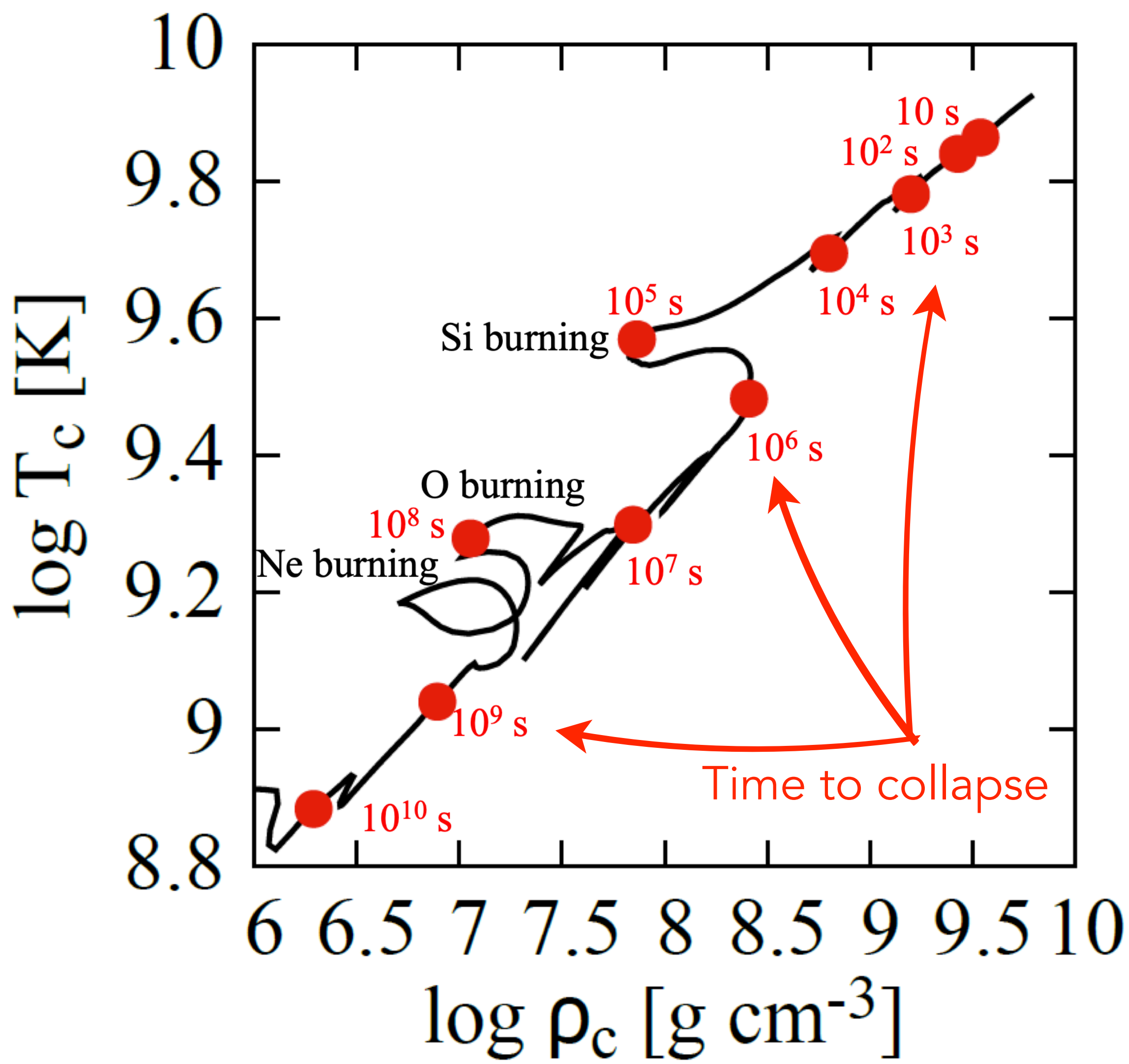
Ho, Kim, Ko, Park, *Phys.Rev.D* 107 (2023) 7

See also Cavan-Piton et al. arXiv:2401.10979

The Very Last Stages of a Monster Star

$t_{\rm collpase} - t$ [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

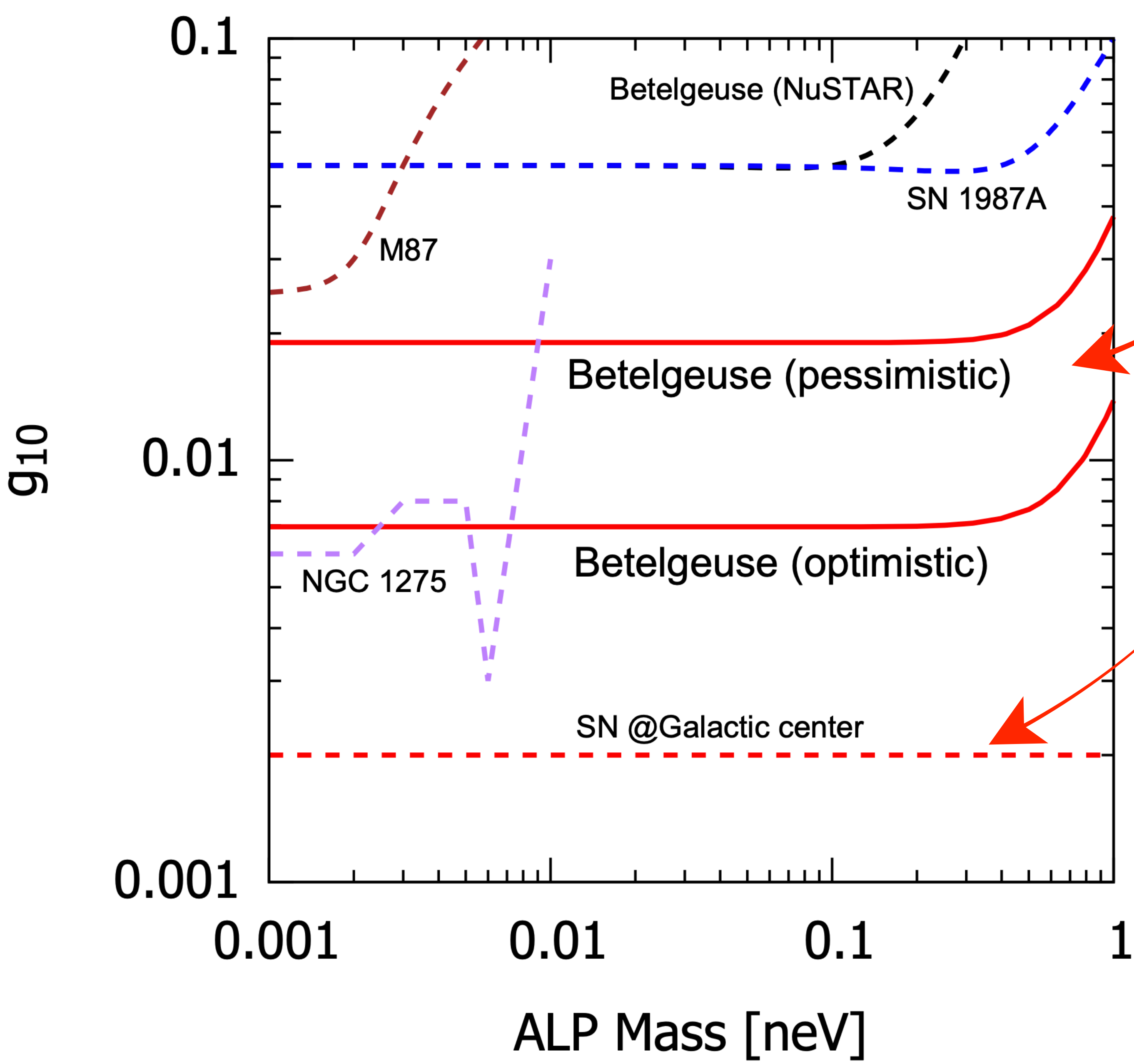
Flux grows substantially in last seconds



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

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

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)

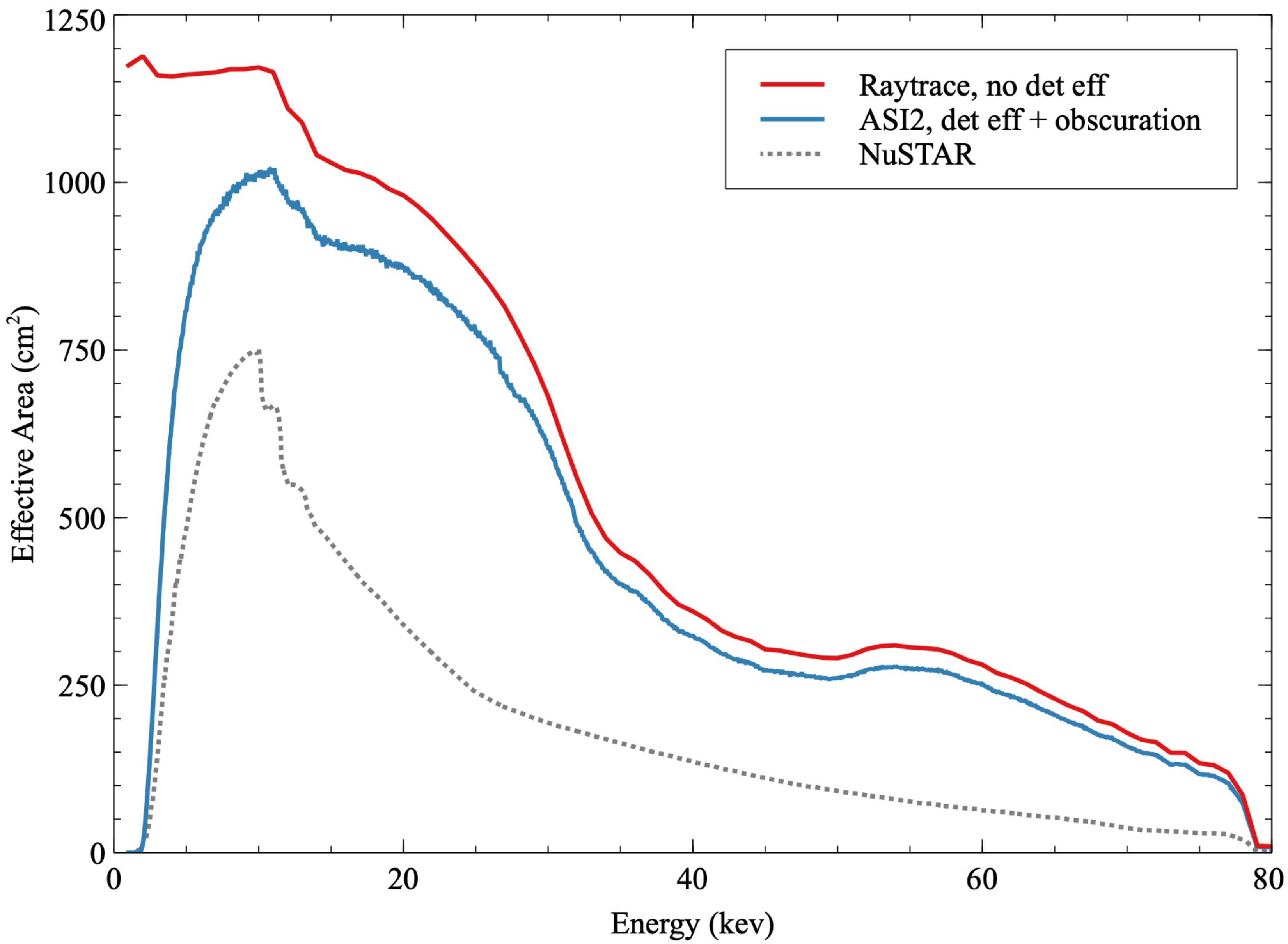
Mori, Takiwaki and Kotake, Phys.Rev.D 105 (2022)

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.

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