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COSMIC WISPERS
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EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

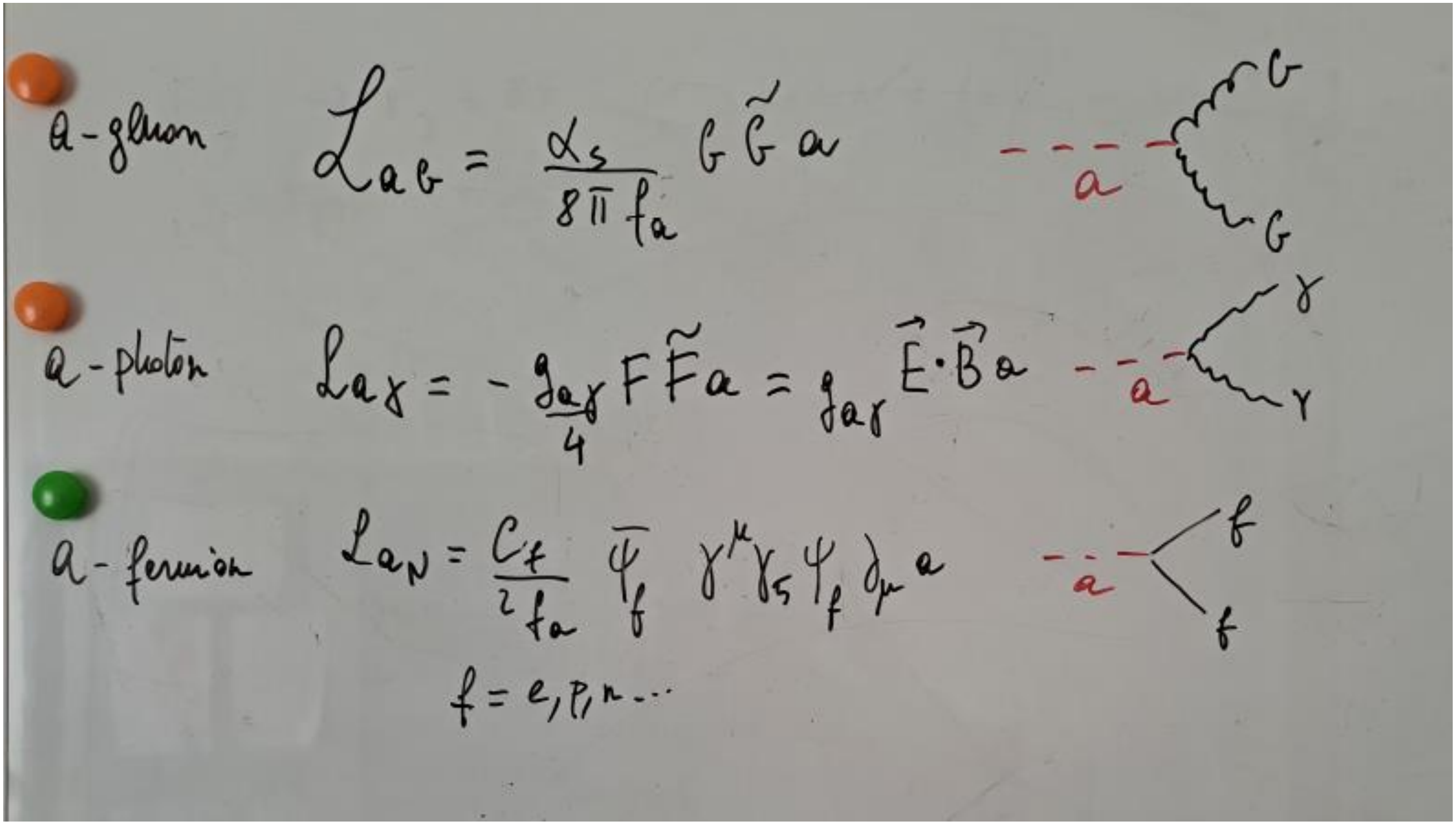
SEARCHING AXIONS FROM STARS: BOUNDS AND DISCOVERY OPPORTUNITIES

ALESSANDRO MIRIZZI
(Deparment of Physics & INFN, Bari,Italy)

OUTLINE

- Axion interactions and models
- Axions and stars: which opportunities?
- Axions and the Sun
- Axions and supergiants
- Axions and supernovae
- Conclusions

AXION PROPERTIES



MAIN AXION MODELS

- DFSZ (Dine, Fischler, Srednicki, Zhitniskii) model

  ✓ Axions coupling to fermions and photons

- KSVZ (Kim, Shifman, Vainshetein, Zakharov) model (hadronic axions)

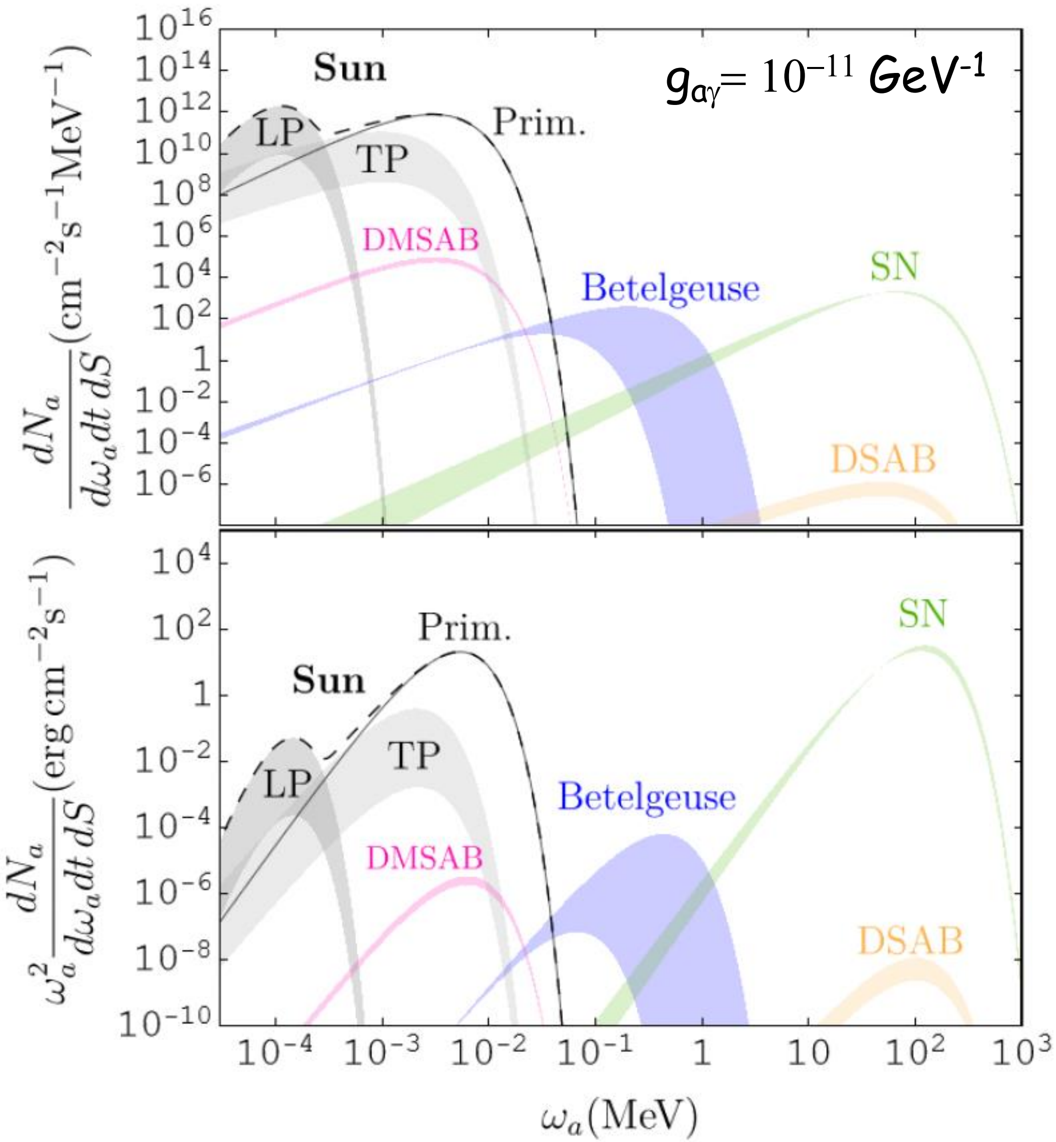
  ✓ tree-level coupling to quarks and leptons suppressed
  ✓ Nucleon and photon couplings still possible
  ✓ Evades bounds of DFSZ model

- Axion-like particles (ALPs)

  ✓ Only coupling with photons by $a\gamma\gamma$ Lagrangian.
  ✓ No relation btw m_a and $g_{a\gamma}$

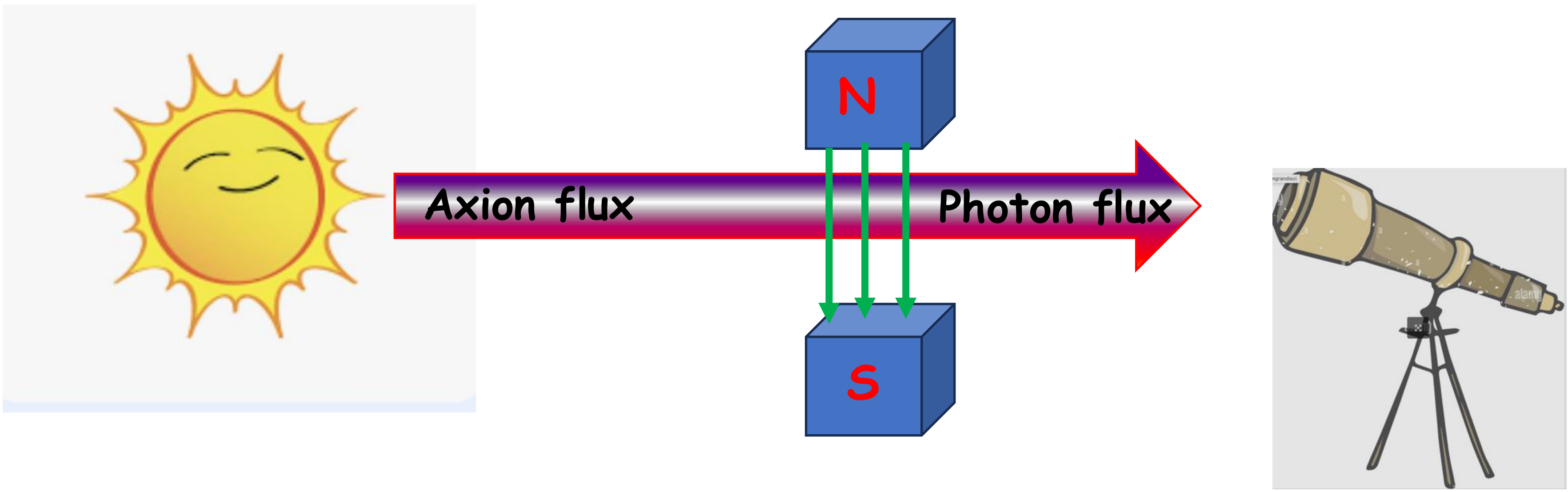
STELLAR AXION FLUXES

[*Carenza, Giannotti,Isern, A.M., Straniero, 2411.02492*]

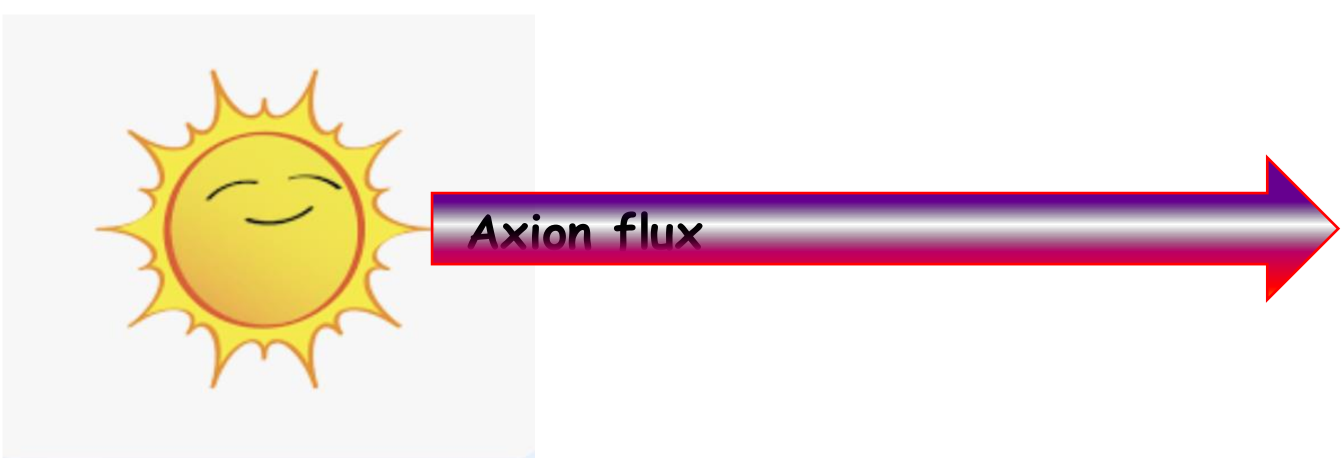


AXIONS AND STARS: HOW TO PROBE THEM?

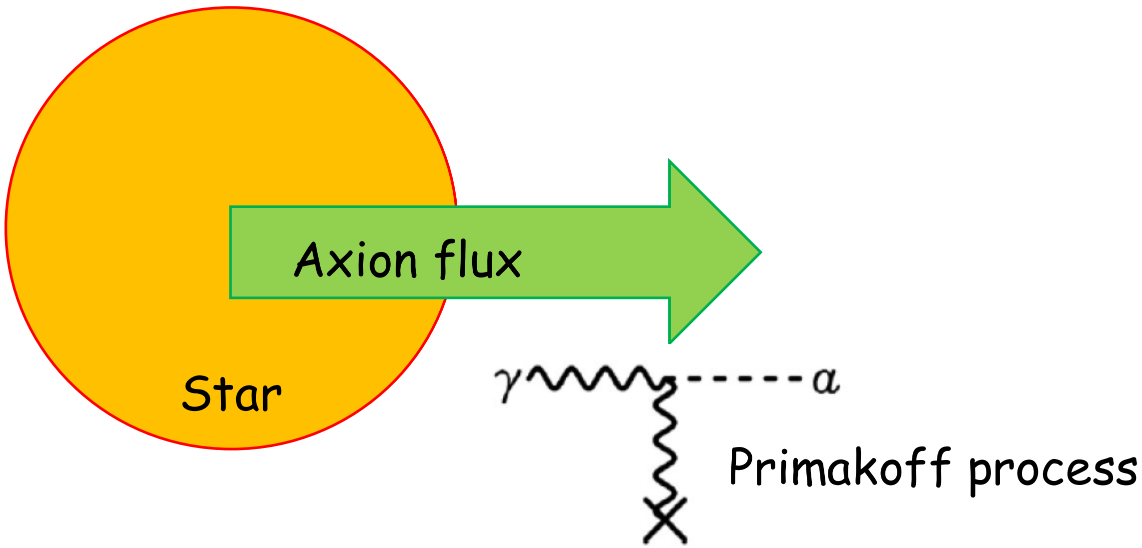
- Direct searches: source, magnetic-field, photon «telescope»



- Indirect searches: energy-loss in stars



ENERGY-LOSS ARGUMENT



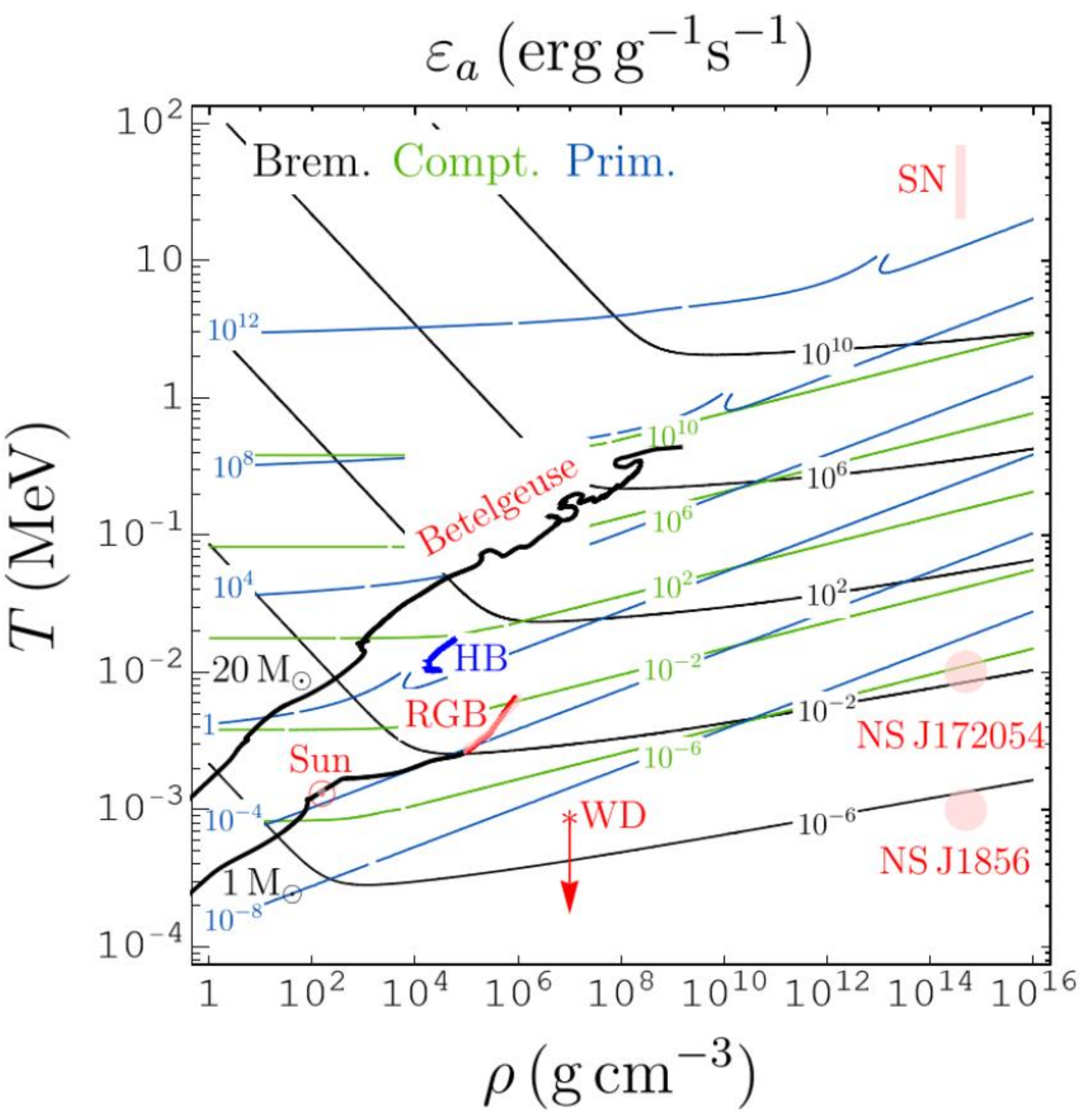
- Axions have very small mass
- Emission from stellar plasma not suppressed by threshold effect
- New energy-loss channel
- Back-reaction on stellar properties and evolution

Additional energy loss ("cooling")

- ➢ Loss of pressure
- ➢ Contraction
- ➢ Heating
- ➢ Increased nuclear burning

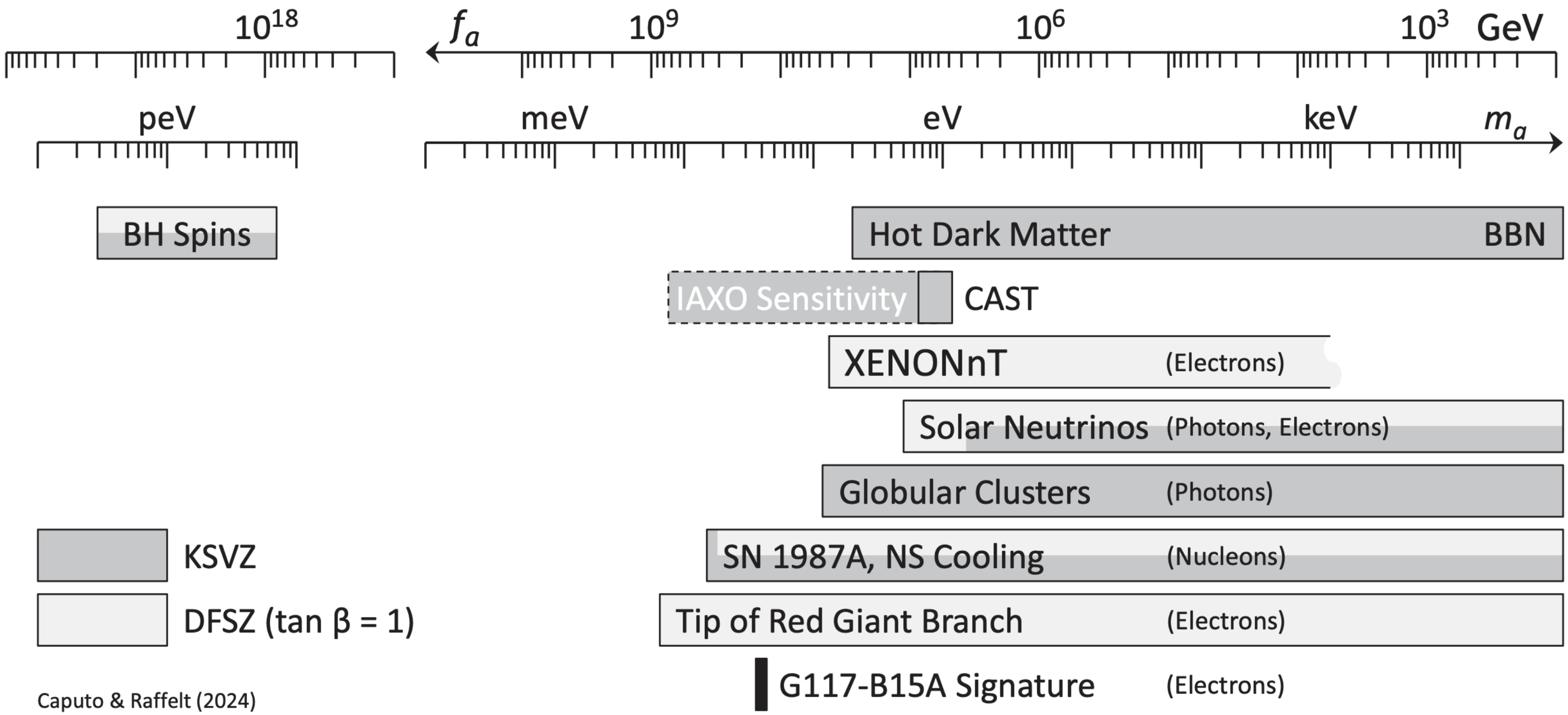
AXION ENERGY-LOSS IN STARS

[*Carenza, Giannotti, Isern, A.M., Straniero, 2411.02492*]

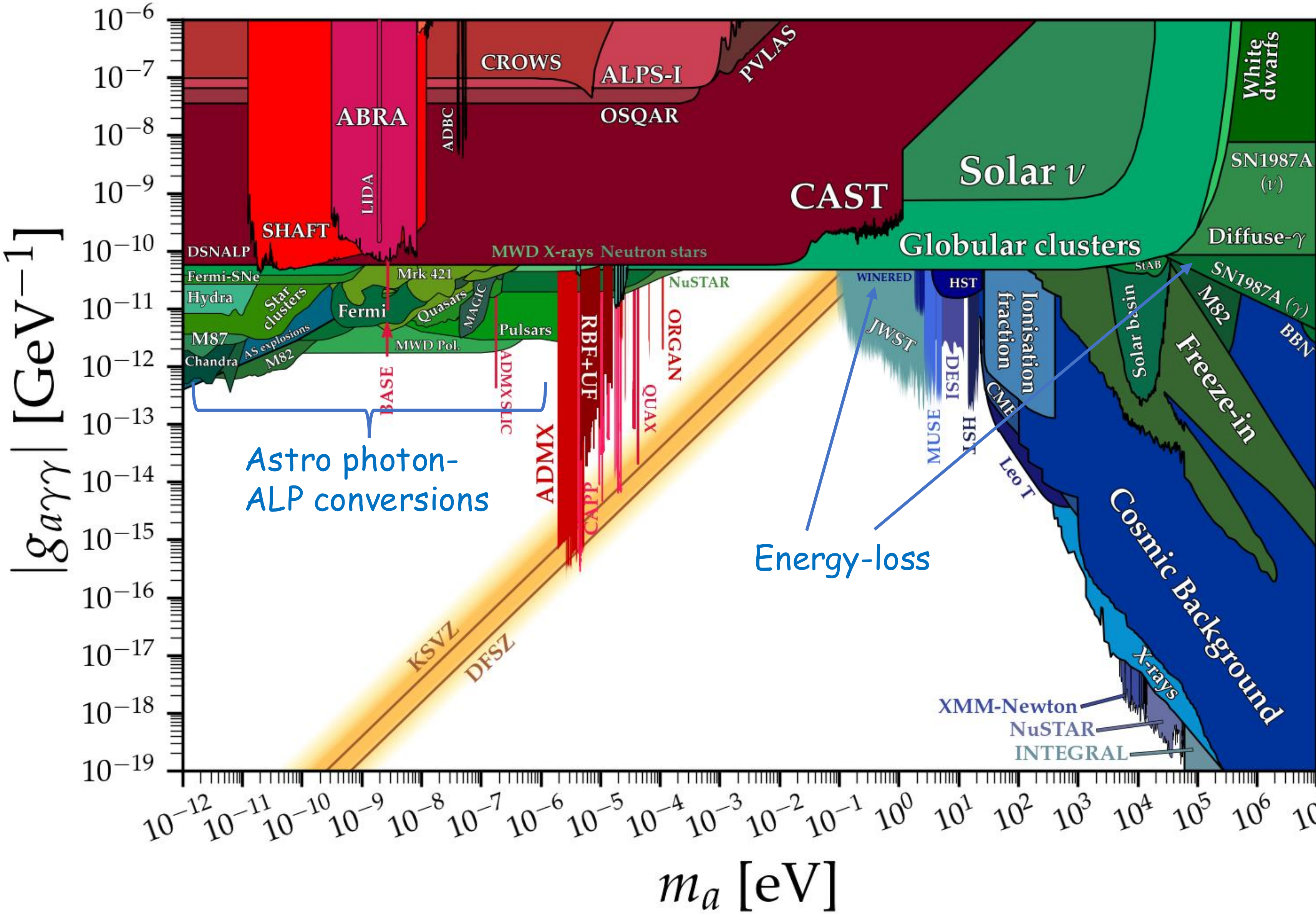


ASTROPHYSICAL AXION BOUNDS

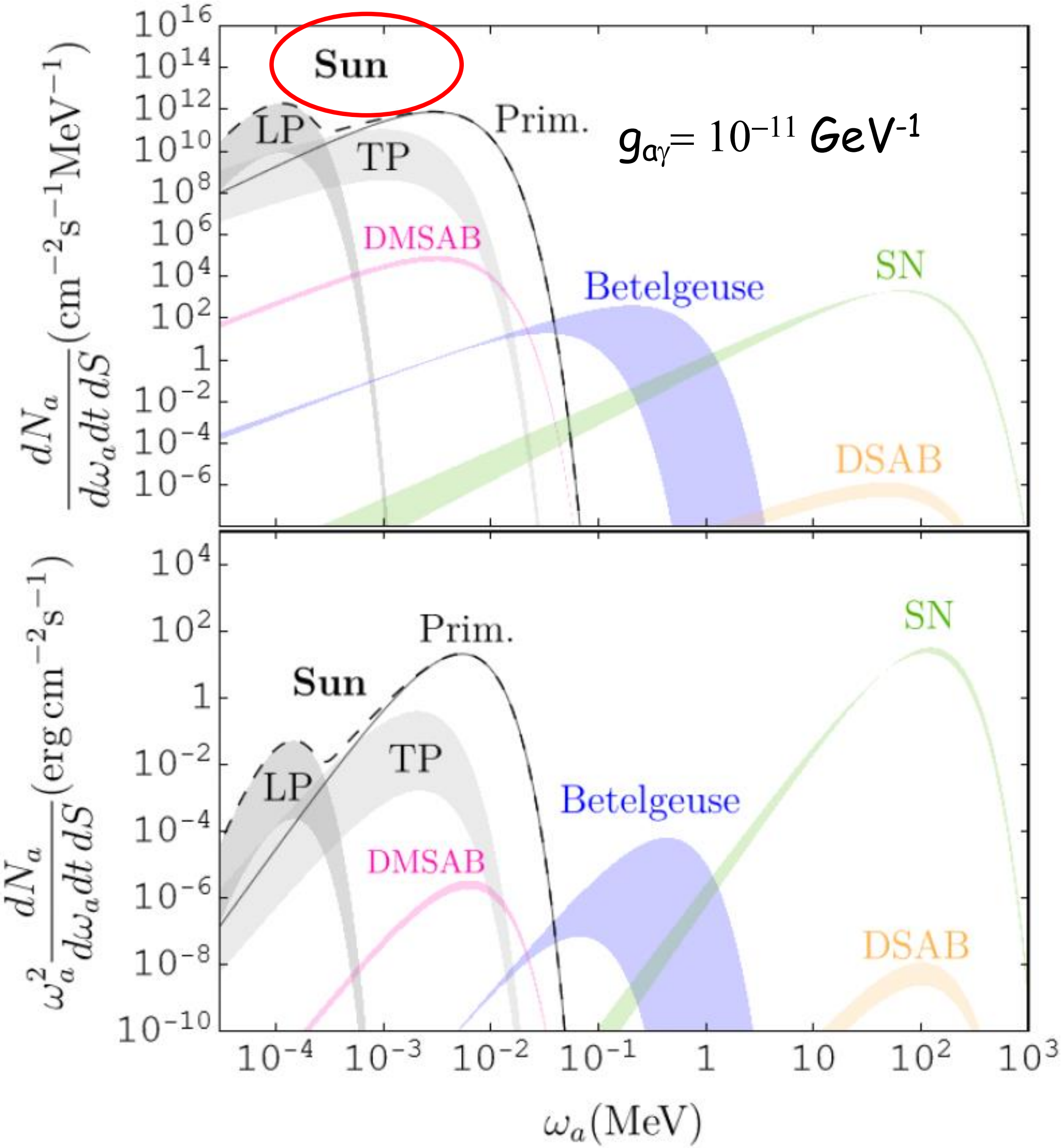
[Caputo and Raffelt, 2401.13728]



BOUNDS ON $g_{a\gamma}$ vs m_a



(plot by Ciaran O'Hare https://cajohare.github.io/AxionLimits/)

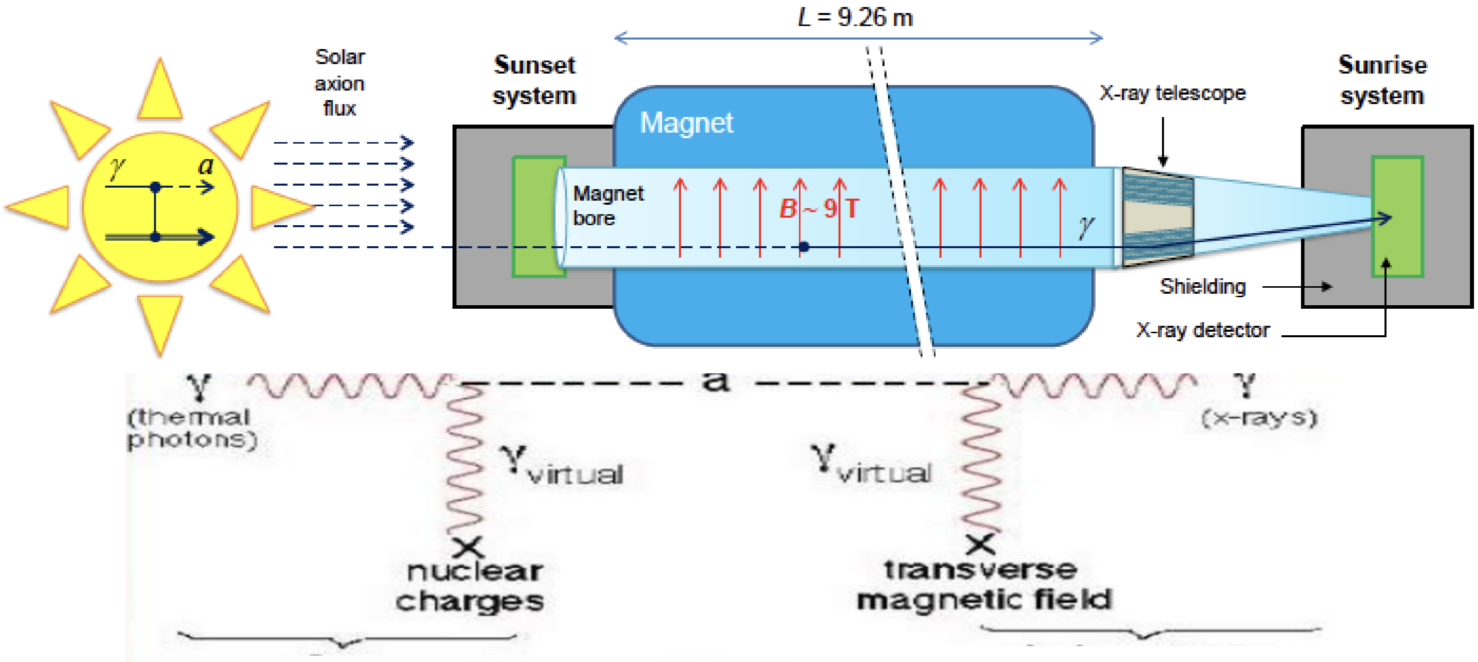


Sun
Prim.
$g_{a\gamma}= 10^{-11}$ GeV^{-1}
LP
TP
DMSAB
Betelgeuse
SN
DSAB
$\frac{dN_a}{d\omega_a dt\, dS}(\mathrm{cm^{-2}s^{-1}MeV^{-1}})$
$\omega_a^2 \frac{dN_a}{d\omega_a dt\, dS}(\mathrm{erg\,cm^{-2}s^{-1}})$
$\omega_a(\mathrm{MeV})$

HELIOSCOPES

Searches for solar axions: Axion helioscopes

Primakoff process **Axion-photon oscillation**

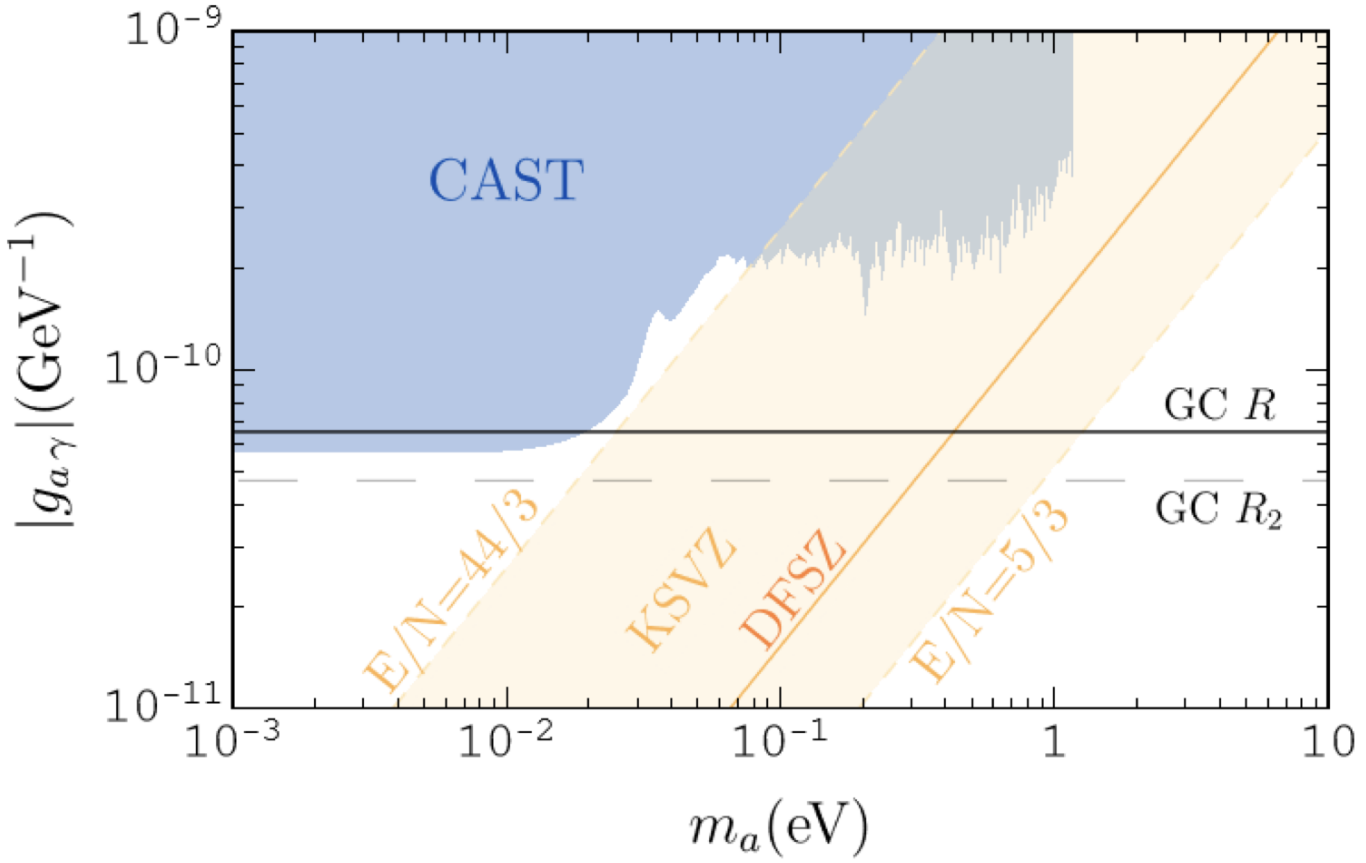


Sun **Laboratory**

- 1° generation: Brookhaven ⟶ 1992. Just a few hours of data
- 2° generation: Tokyo axion helioscope (SUMICO) ⟶ Results since 1998
- 3° generation: CERN Axion Solar Telescope (CAST) ⟶ Data since 2003

AXION BOUND FROM HB vs CAST

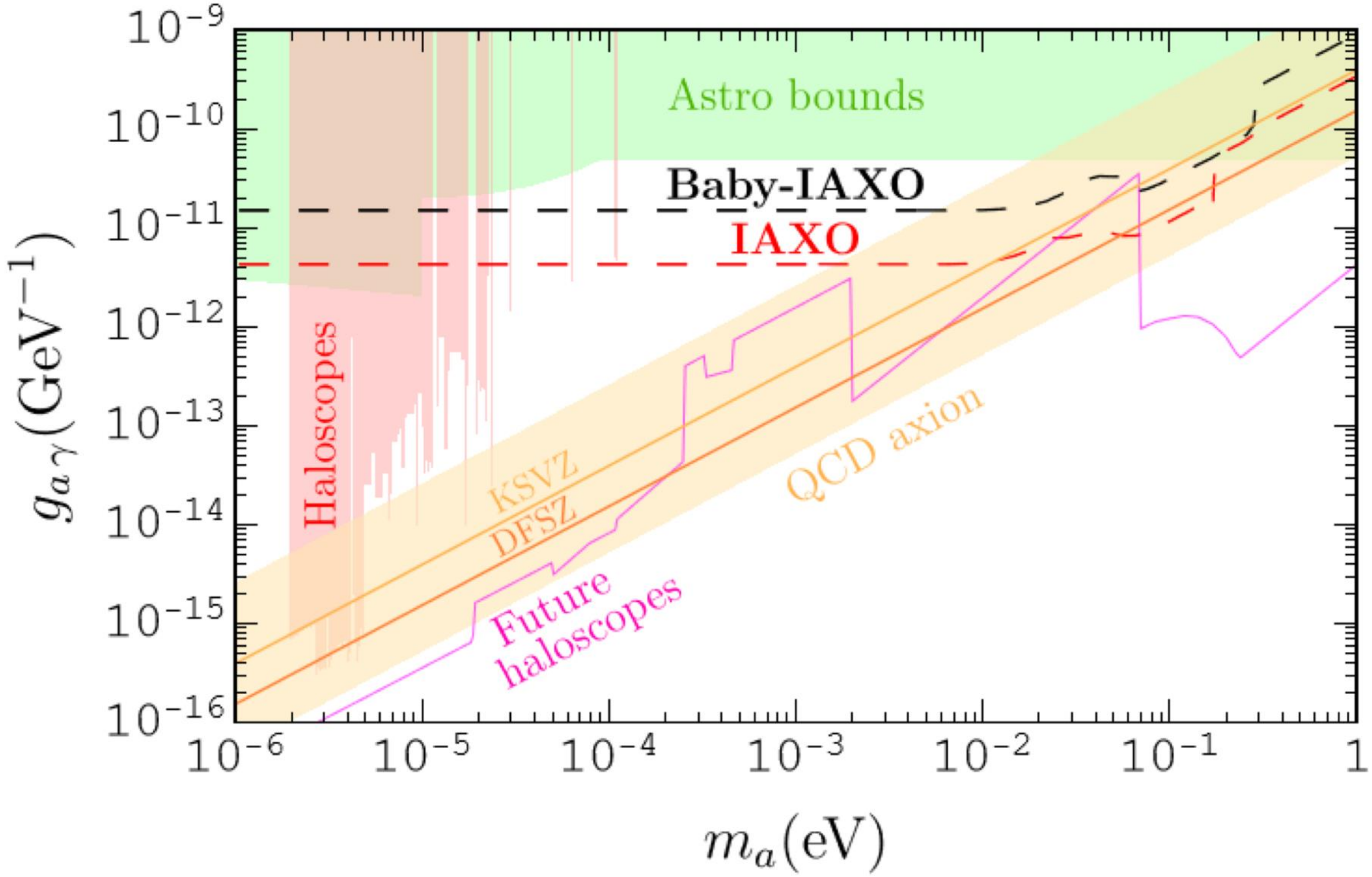
[*Carenza, Giannotti, Isern, A.M., Straniero, 2411.02492*]



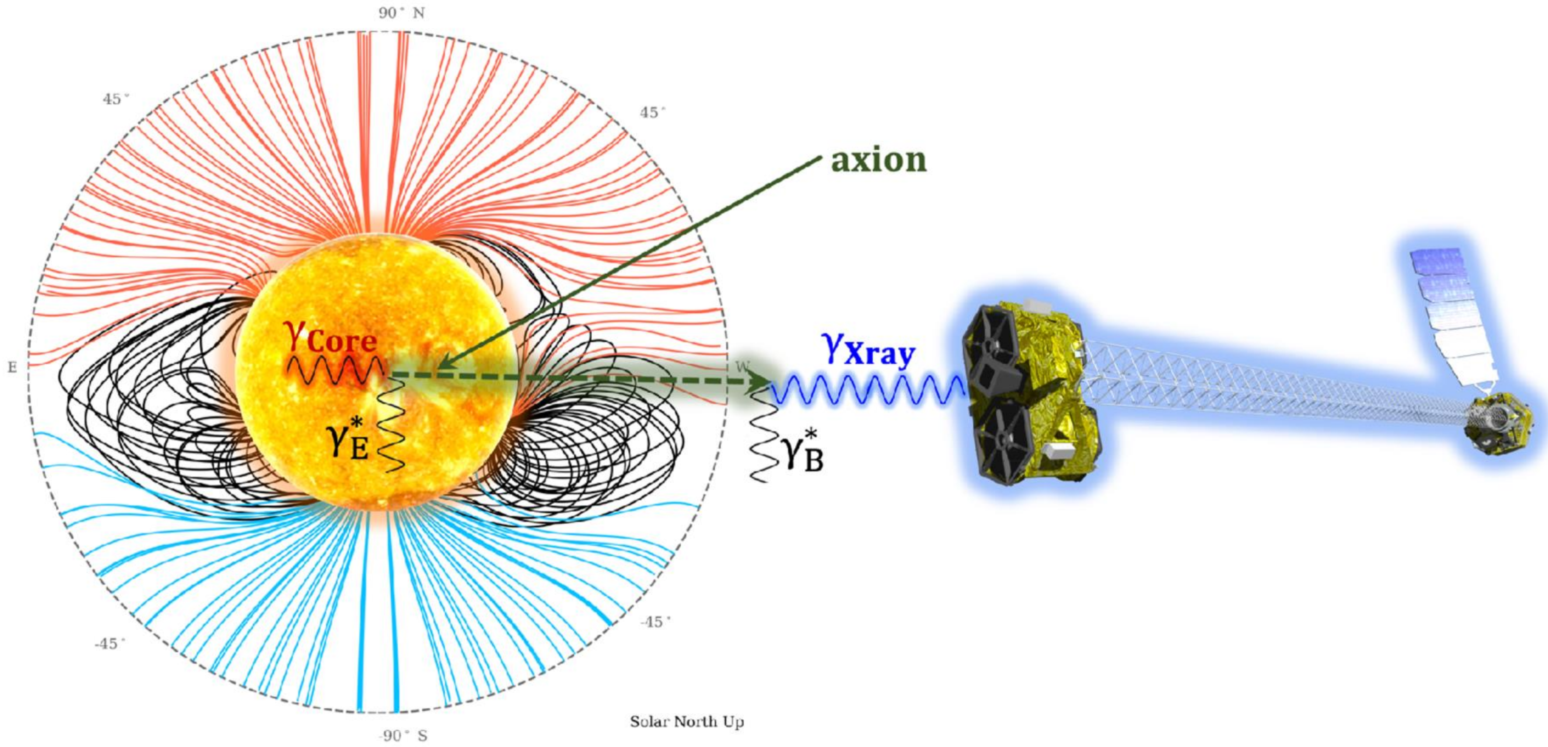
$$g_{a\gamma} < 0.66 \times 10^{-10}\,GeV^{-1} \quad (95\,\%\,CL)$$

HB bound slightly worse than CAST for low-mass ALPs [2406.16840]

BABY-IAXO AND IAXO PHYSICS REACH



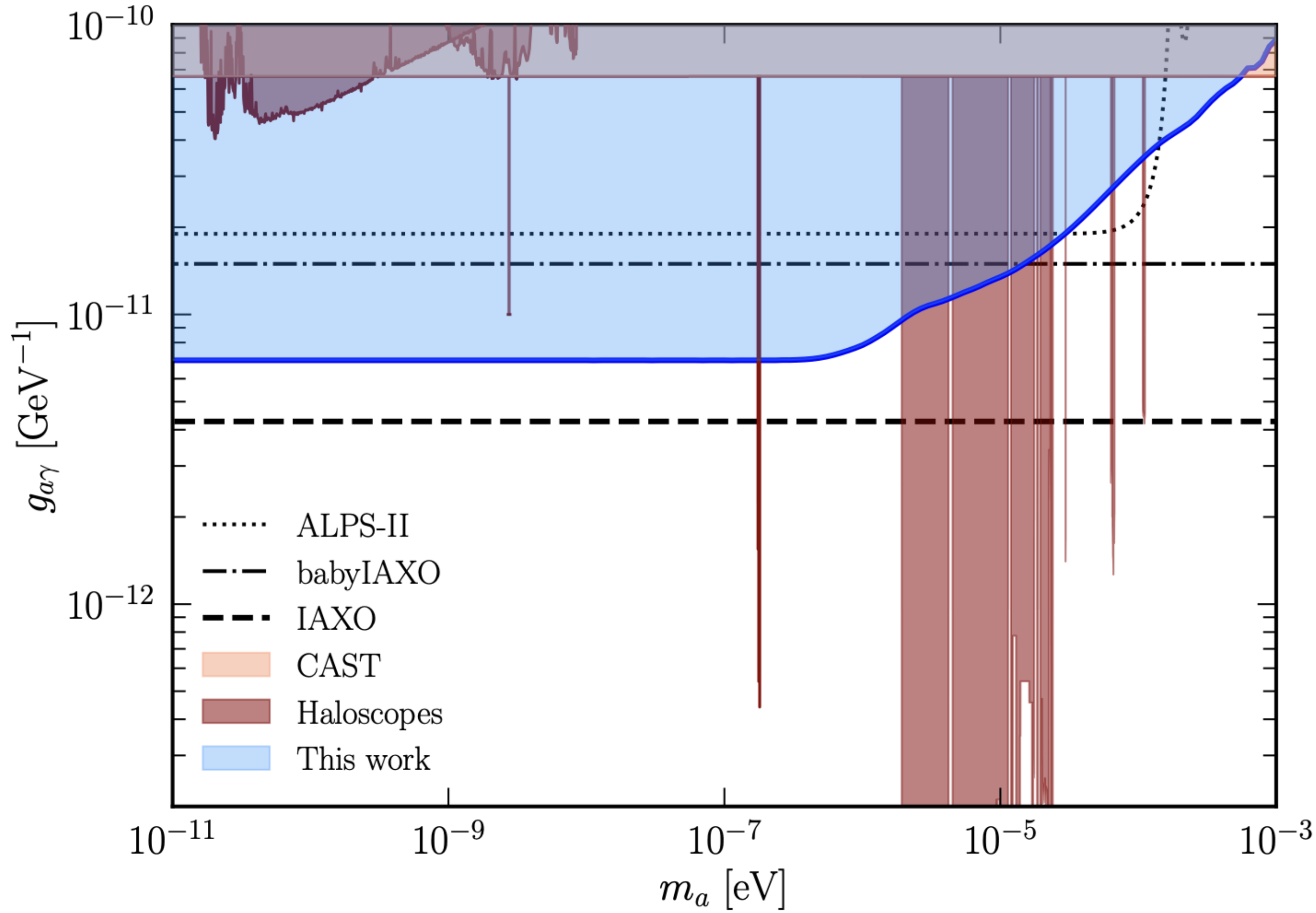
NuSTAR as an Axion Helioscope



Axion-photon conversions in solar atmosphere

[Ruz, Todarello, Vogel, Giannotti, Grefenstette et al., 2407.03828]

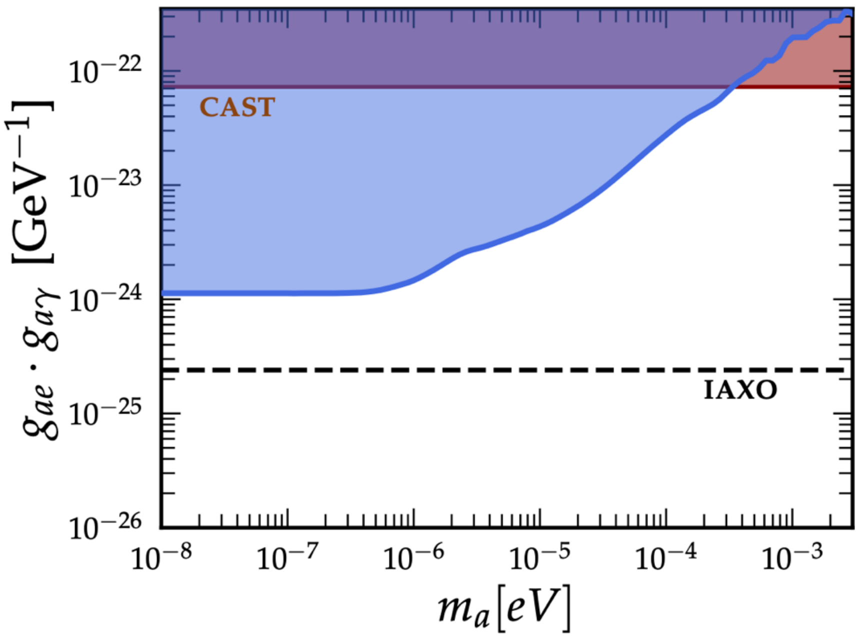
NuSTAR AS AXION HELIOSCOPE

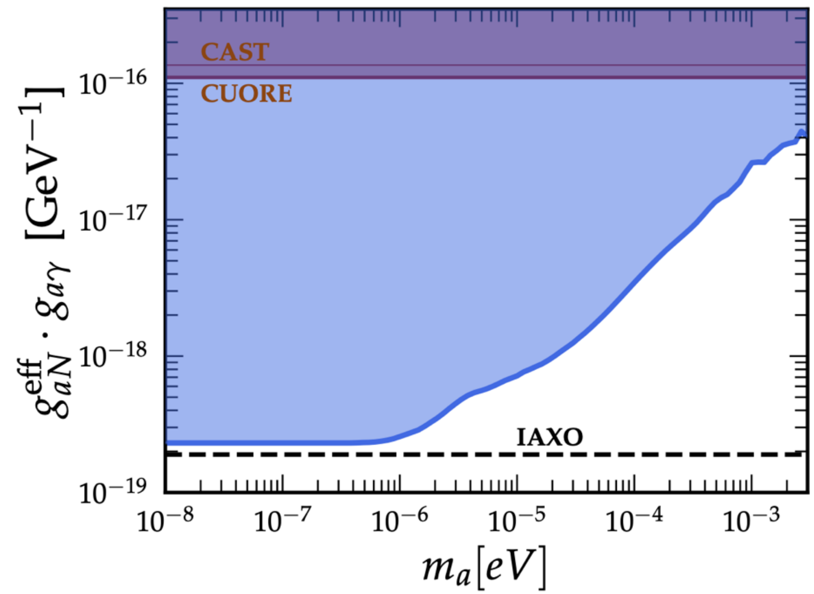


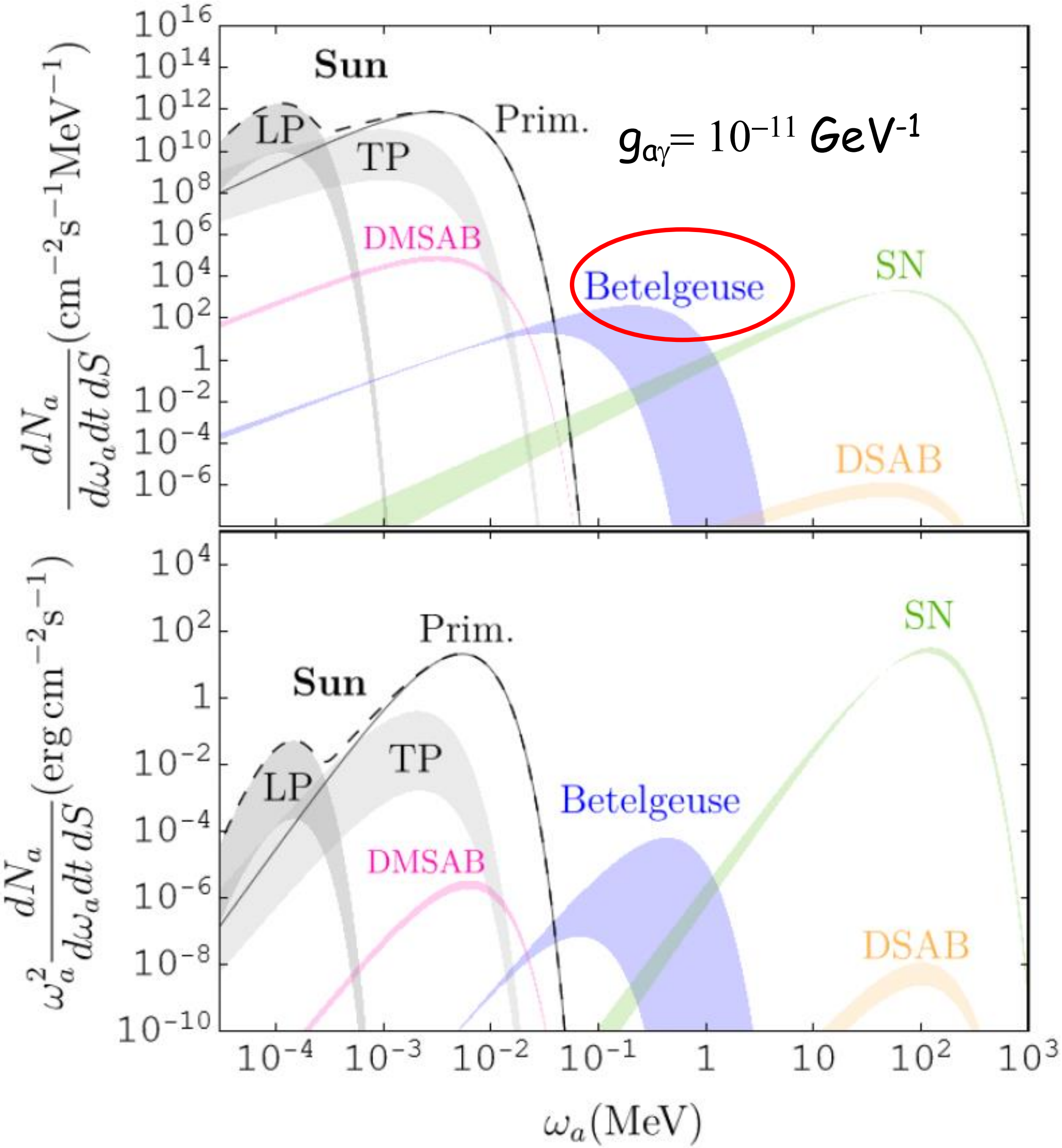
[Ruz, Todarello, Vogel, Giannotti, Grefenstette et al., 2407.03828]

NuSTAR AS AXION HELIOSCOPE (II)

[Zanzarella, Candon, Giannotti et al. Ruz, 2605.26265]







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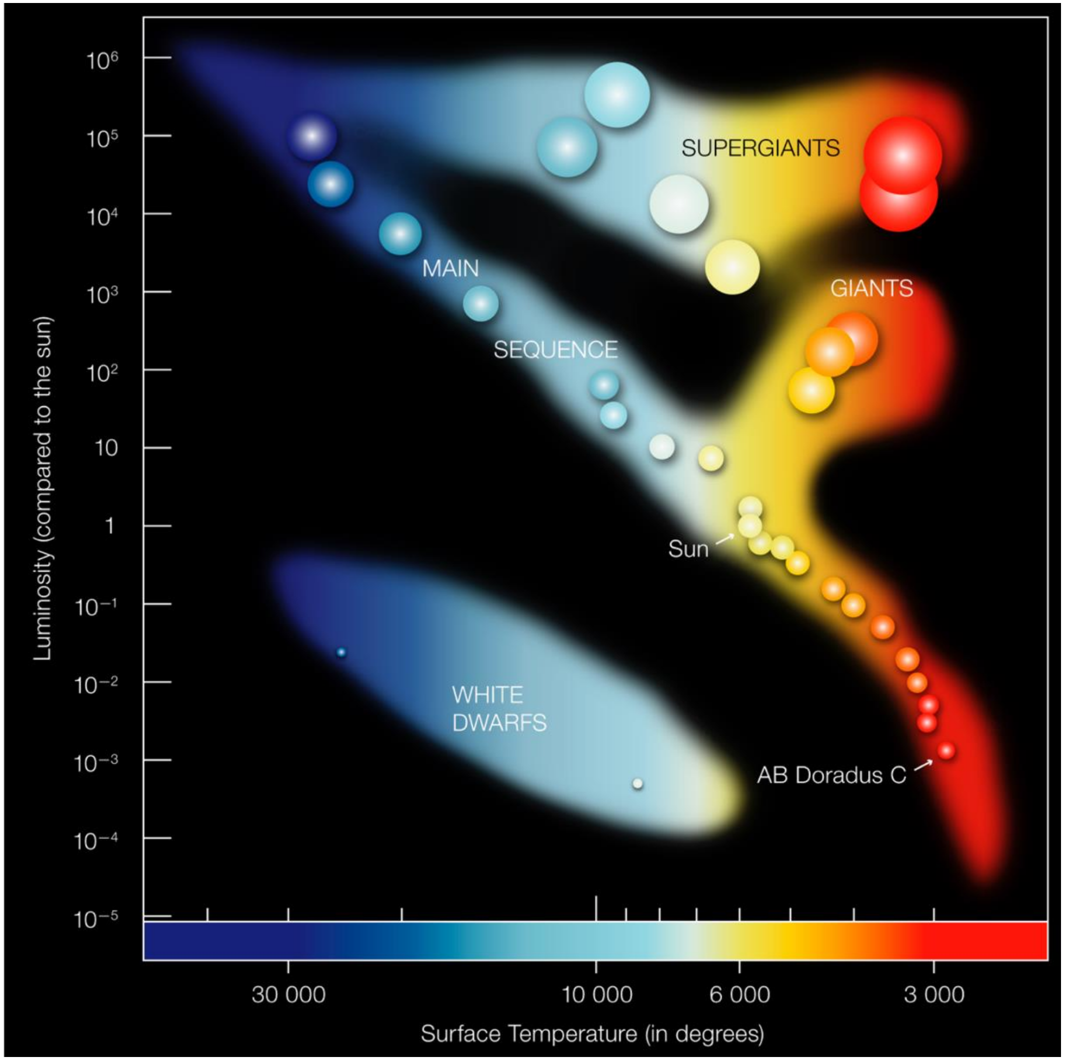
$g_{a\gamma}= 10^{-11}$ GeV^{-1}
$\frac{dN_a}{d\omega_a dt\, dS}(\mathrm{cm^{-2}s^{-1}MeV^{-1}})$
$\omega_a^2\frac{dN_a}{d\omega_a dt\, dS}(\mathrm{erg\, cm^{-2}s^{-1}})$
$\omega_a(\mathrm{MeV})$

SUPERGIANT STARS



Red supergiants are massive, aging stars (8 to 40 solar masses) that have exhausted their core hydrogen and begun fusing helium. They are the largest stars by volume in the universe, but are destined to violently explode as supernovae.

SUPERGIANT STARS

There are 21 supergiants within 1 kpc from the Sun. Some may be in advanced stage and produce a large axion flux. Should we monitor them in hard X-ray?

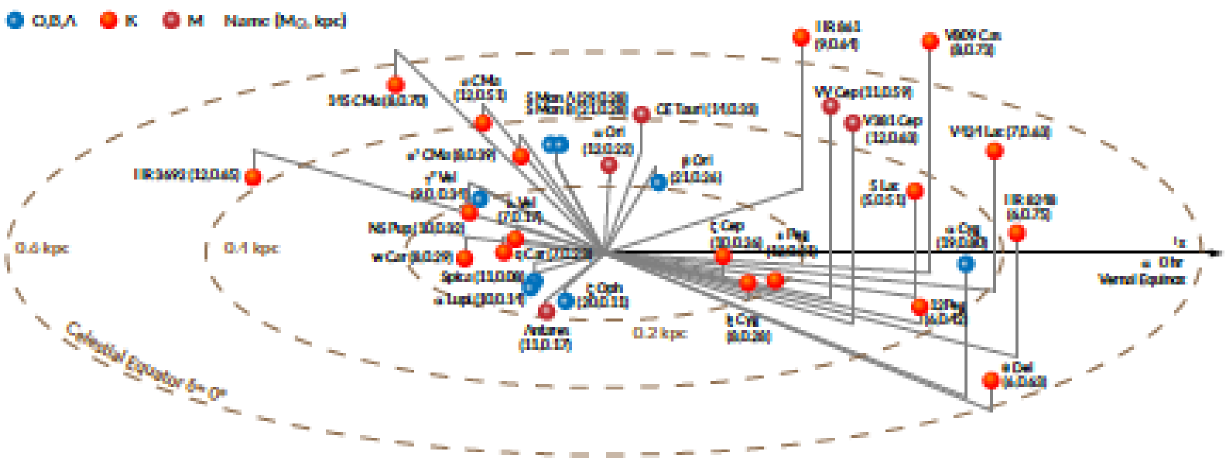
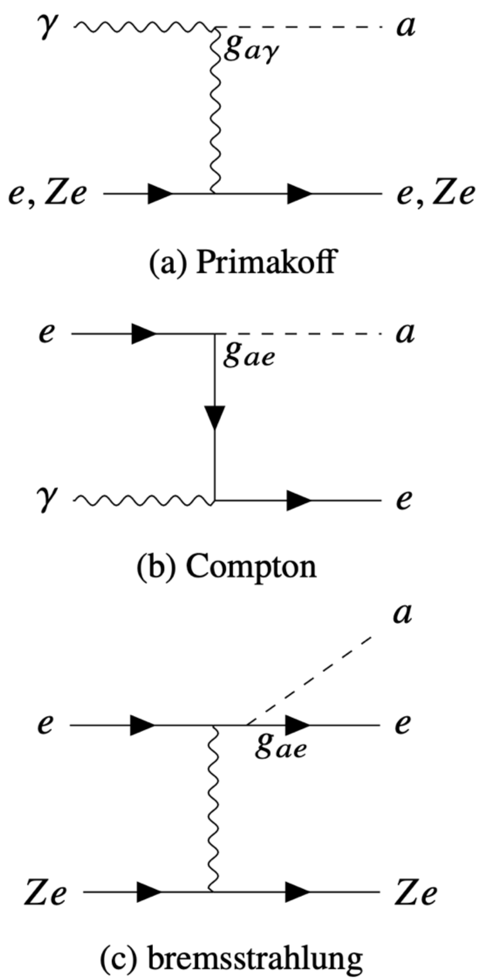


Figure 2. Illustration of nearby ($D \leq 1$ kpc) core collapse supernova candidates. Each star's spectral type, name, mass and distance is shown in labels. See Table A1 for details and references.

[Mukhopadhyay et al., arxiv:2004.02045]

AXIONS FROM SUPERGIANT STARS



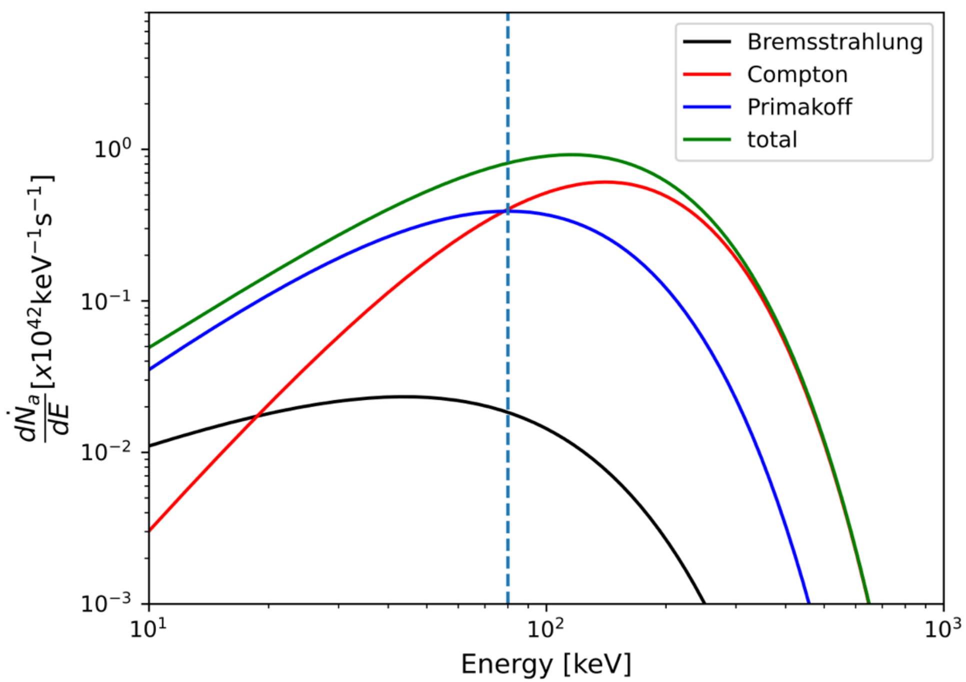
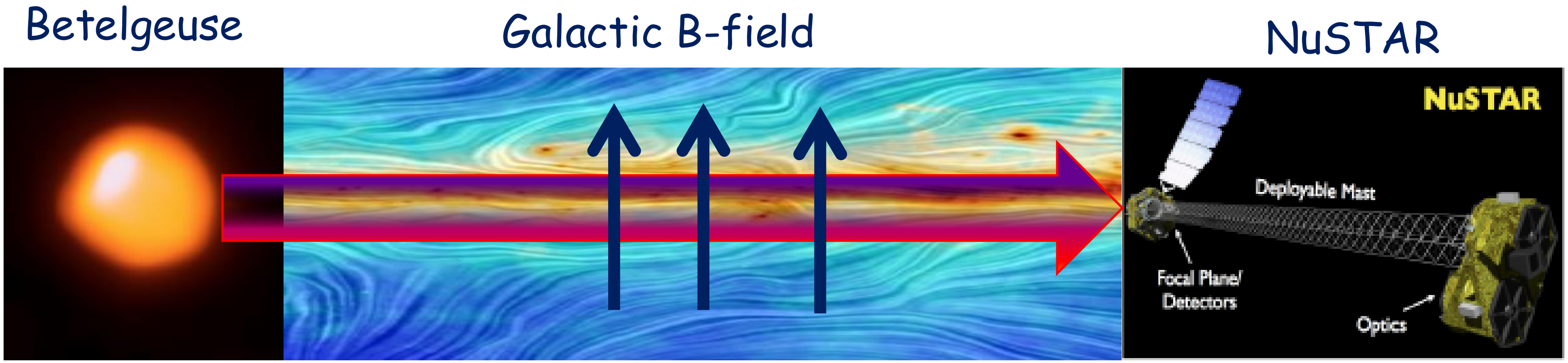


Fig. 3. Expected ALP fluxes from bremsstrahlung (black), Compton (red), Primakoff (blue), and total (green) using $g_{ae} = 10^{-13}$, $g_{a\gamma} = 10^{-11}$ GeV^{-1}, and a time to core collapse of $t_{cc} = 6900$ yr. The dashed blue line shows the energy upper limit of NuSTAR (79 keV).

OBSERVING BETELGEUSE WITH NUSTAR



ALPs produced in Betelgeuse core

ALP-photon conversions in the Galactic B-fields

Search from X-ray flux from Betelgeuse

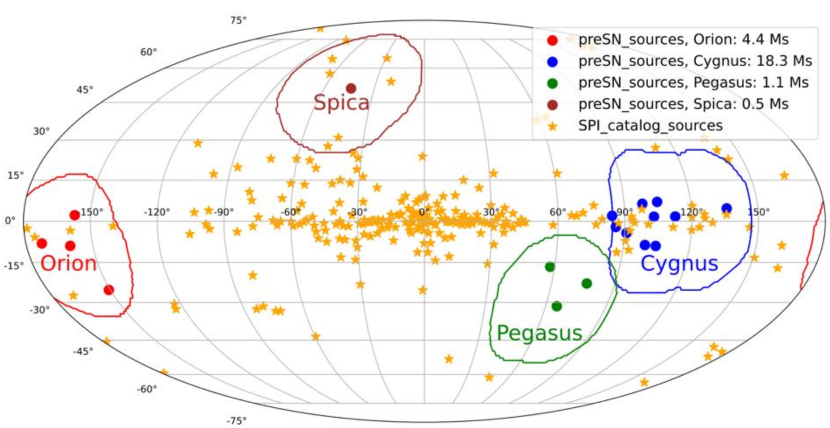
- First hard X-ray observation of Betelgeuse, using Nustar, awarded under NASA Grant No. 80NSSC20K0031 (50 ks observation time, August 2019, ObsID 30501012002)
  Kerstin Perez, Maurizio Giannotti, Brian Grefenstette, Oscar Straniero, Alessandro Mirizzi
- Data analysis in M.Xiao, K. Perez, M. Giannotti, O. Straniero, A. M., B. Grefenstette, B. Roach, N. Nynka, arXiv: 2009.09059. PRL 126, 3, 031101 (2021), Xiao, Carenza, Giannotti, A.M., Perez, Straniero, Grefenstette, 2204.03121

SEARCH WITH 18 STARS WITH INTEGRAL DATA

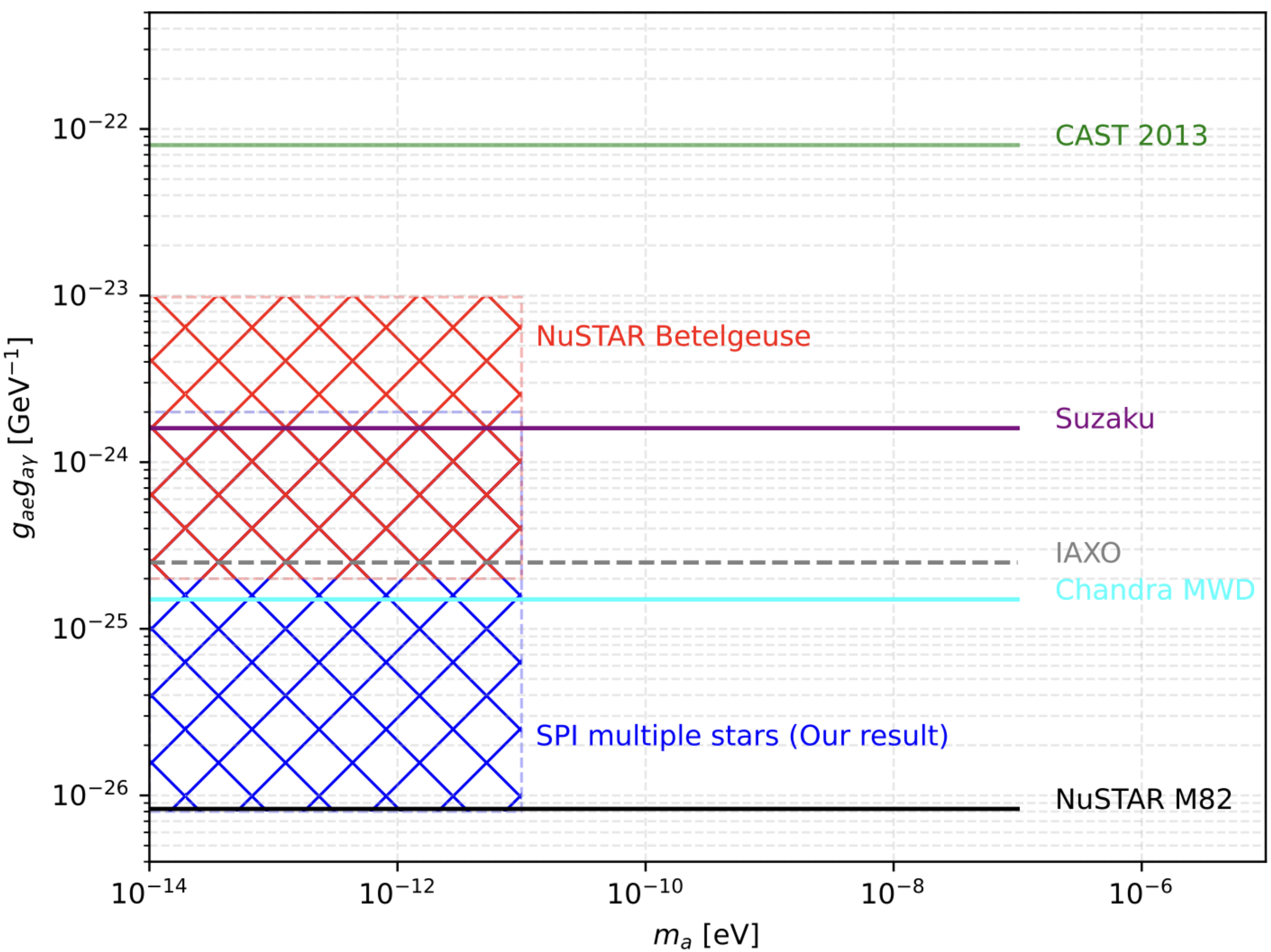
[Mittal et al., 2512.19298]

Table 1. Pre-supernovae candidates within 1 kpc.

Common Name	Gal. long [deg]	Gal. lat [deg]	Distance [kpc]	Mass [$M_\odot$]	$g_{ae} \times g_{a\gamma}$ 2σ UL	$g_{a\gamma}$ 2σ UL	511 keV 3σ UL	1.8 MeV 3σ UL	M_{Al} [$M_\odot$] 3σ UL
Spica	316.11	50.84	0.077 ± 0.004	$11.43^{+1.15}_{-1.15}$	27.7	4.36	35.6	11.8	6
ϵ Pegasi	65.57	−31.45	0.211 ± 0.006	$11.7^{+0.8}_{-0.8}$	13.5	3.26	30.3	9.7	37
Betelgeuse	199.78	−8.95	0.222 ± 0.040	$11.6^{+5.0}_{-3.9}$	8.1	2.15	11.1	4.4	19
ζ Cephei	103.06	1.66	0.256 ± 0.006	$10.1^{+0.1}_{-0.1}$	3.3	1.97	1.1	0.4	2
Rigel	209.24	−25.24	0.264 ± 0.024	$21.0^{+3.0}_{-3.0}$	11.7	3.31	5.7	1.8	11
ξ Cygni	71.01	3.36	0.278 ± 0.029	8.0	25.1	5.69	13.4	4.6	30
S Monocerotis A	202.93	2.19	0.282 ± 0.040	29.1	41.8	5.51	45.9	13.3	90
CE Tauri	187.17	−8.07	0.326 ± 0.070	$14.37^{+2.00}_{-2.00}$	50.8	5.86	289.0	41.4	375
12 Pegasi	76.64	−22.82	0.415 ± 0.031	$6.3^{+0.7}_{-0.7}$	56.4	6.68	100.0	17.0	250
5 Lacertae	99.66	−8.65	0.505 ± 0.046	$5.11^{+0.18}_{-0.18}$	17.2	3.60	1.9	0.7	15
VV Cephei	104.92	7.04	0.599 ± 0.083	$10.6^{+1.0}_{-1.0}$	4.7	3.11	1.1	0.4	13
θ Delphini	57.94	−16.60	0.629 ± 0.029	$5.60^{+3.0}_{-3.0}$	22.5	4.98	45.8	14.9	503
V381 Cephei	98.18	6.35	0.631 ± 0.086	12.0	5.1	2.01	2.3	0.9	31
V424 Lacertae	104.58	−8.99	0.634 ± 0.075	$6.8^{+1.0}_{-1.0}$	4.2	4.93	1.2	0.5	16
HR 861	135.95	4.66	0.639 ± 0.039	$9.2^{+0.5}_{-0.5}$	14.4	2.30	1.9	0.7	25
V809 Cassiopeia	112.61	1.72	0.730 ± 0.074	$8.3^{+0.5}_{-0.5}$	2.0	1.19	0.7	0.3	13
HR 8248	90.83	−4.30	0.746 ± 0.039	$6.3^{+0.7}_{-0.7}$	4.6	1.66	4.7	1.8	85
α Cygni	84.28	1.99	0.802 ± 0.066	$19.0^{+4.0}_{-4.0}$	11.5	3.58	11.5	3.9	213
combined:					1.9	1.26			



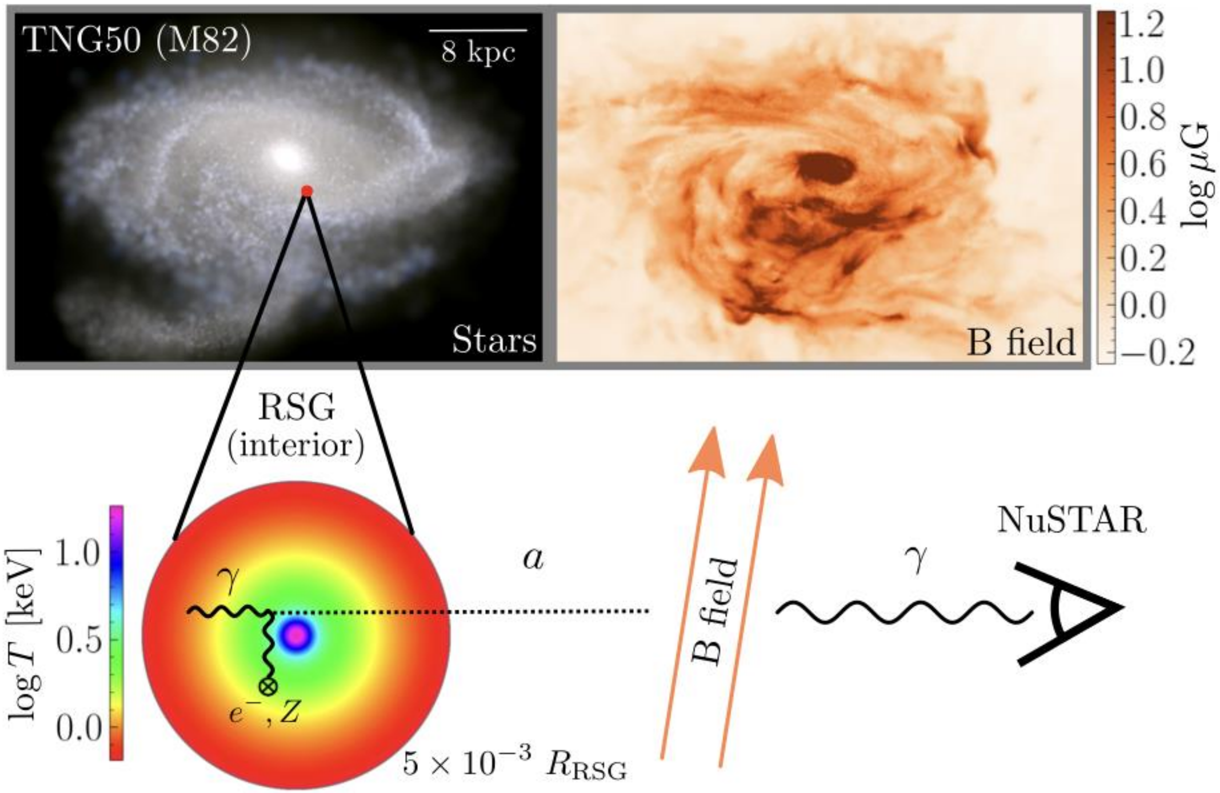
full public INTEGRAL/SPI 22-year database


CAST 2013
NuSTAR Betelgeuse
Suzaku
IAXO
Chandra MWD
SPI multiple stars (Our result)
NuSTAR M82
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
$g_{ae}g_{a\gamma}$ [GeV^{-1}]
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
m_a [eV]

AXION FLUX FROM RSG IN CLOSE-BY GALAXIES

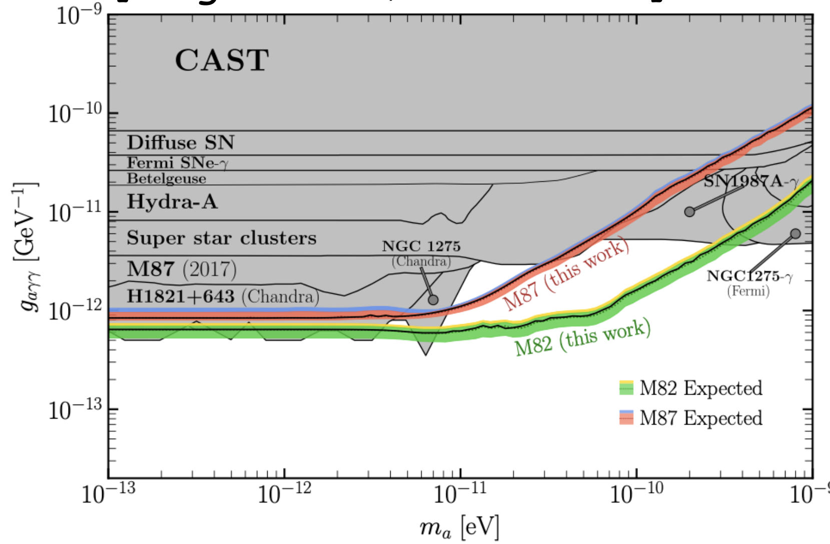
[Ning & Safdi, 2404.14476]

Stellar axion production in the M82 starburst galaxy (d=3.5 Mpc) and the M87 central galaxy (d=17 Mpc) of the Virgo cluster

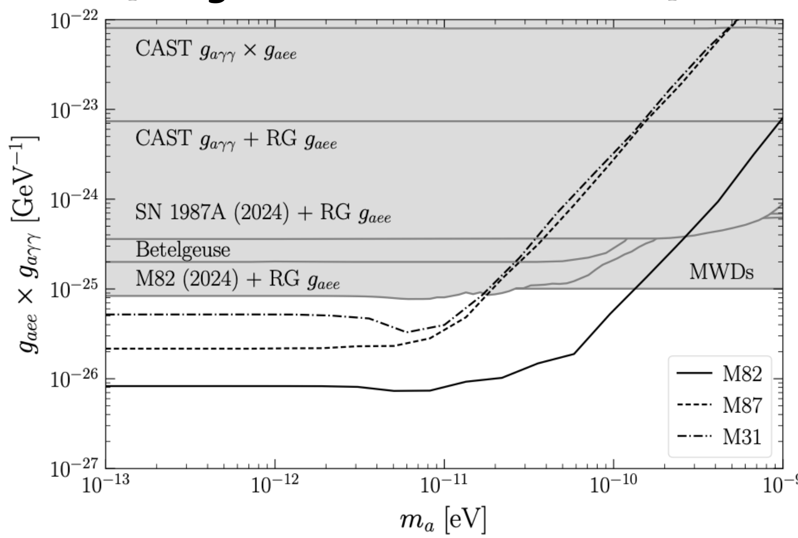


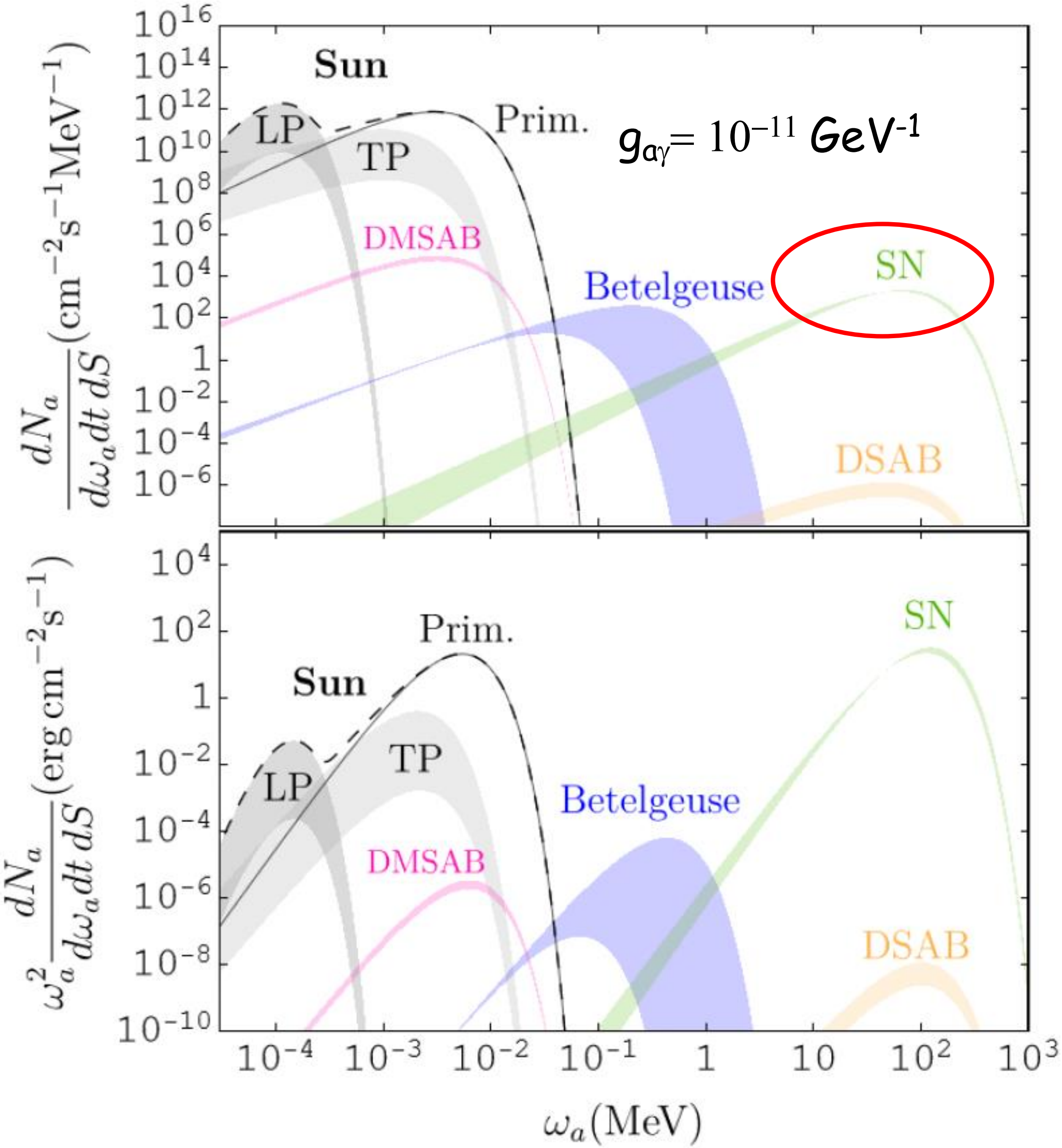
AXION BOUNDS FROM M82 AND M87

[Ning & Safdi, 2404.14476]



[Ning & Safdi, 2503.09682]





Sun
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$g_{a\gamma} = 10^{-11}$ GeV^{-1}
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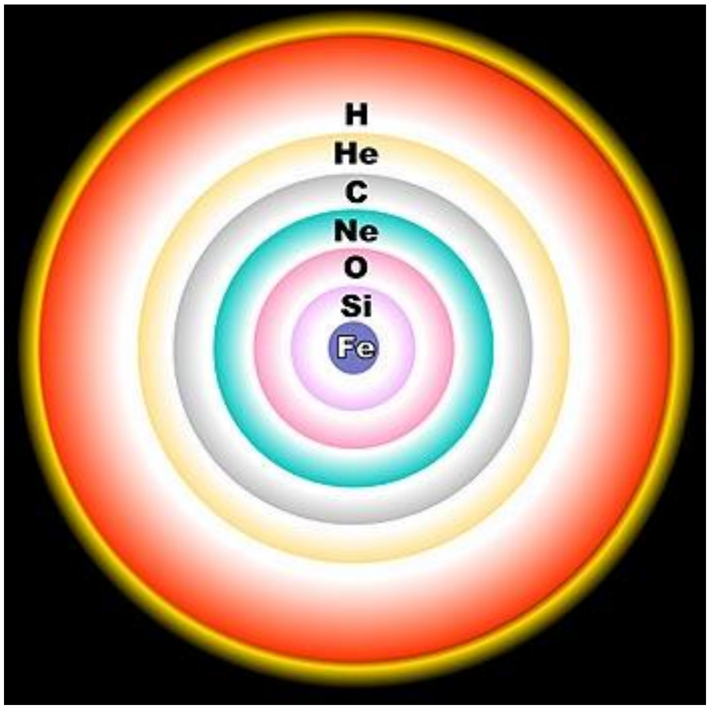
$\omega_a^2 \frac{dN_a}{d\omega_a dt\, dS}(\mathrm{erg\, cm^{-2} s^{-1}})$
ω_a(MeV)

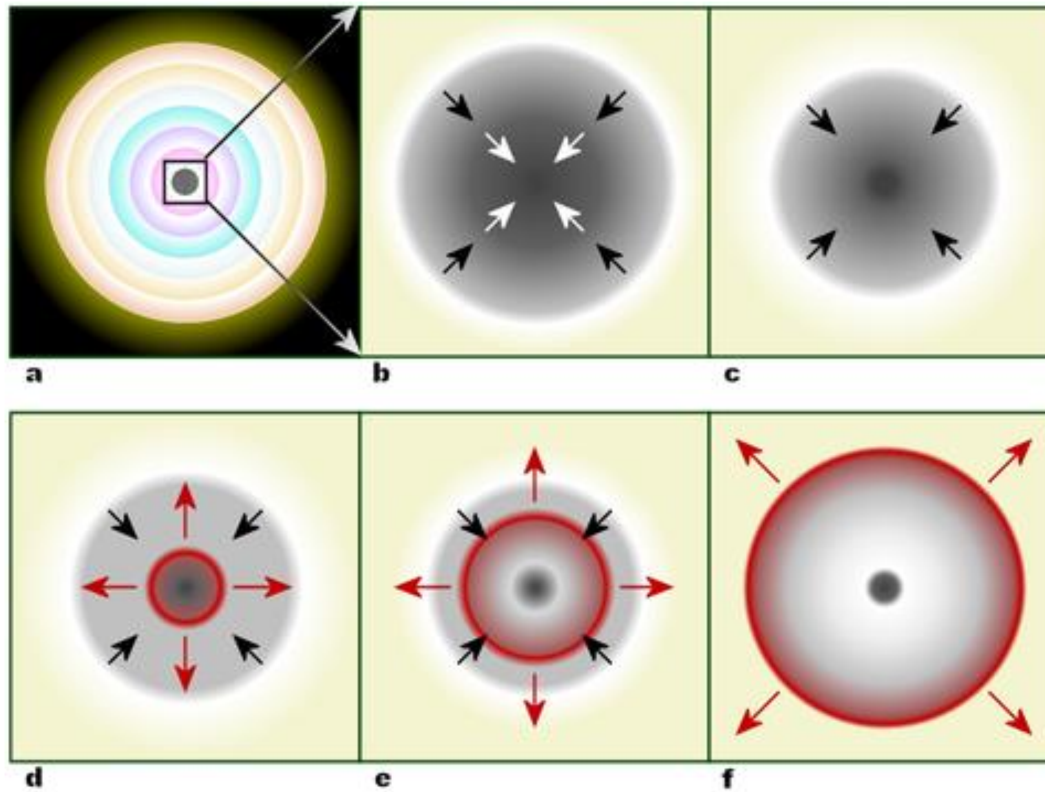
LIFE AND DEATH OF A MASSIVE STAR

Onion-like layers of a massive, evolved star just before core collapse.



Collapse

Nuclear density



Core-bounce & shock wave

shock-wave stalling

Shock revival

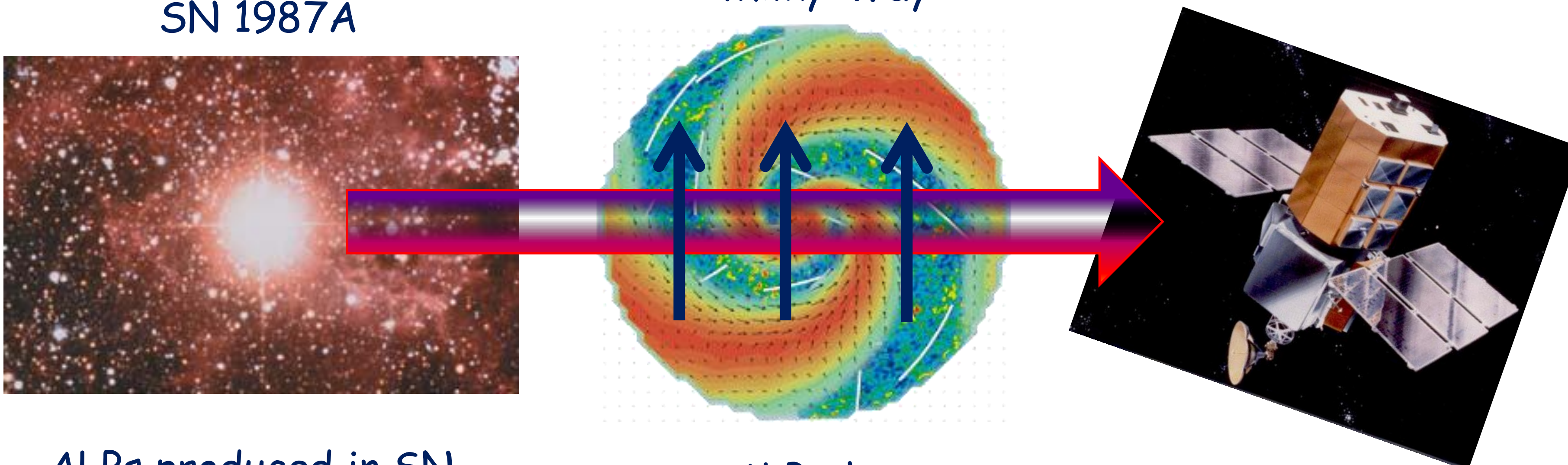
ALPs CONVERSIONS FOR SN 1987A

[*Brockway, Carlson, Raffelt, astro-ph/9605197, Masso and Toldra, astro-ph/9606028, Payez et al., 1410.3747*]

SN 1987A

Milky-Way

SMM Satellite



ALPs produced in SN core by Primakoff process

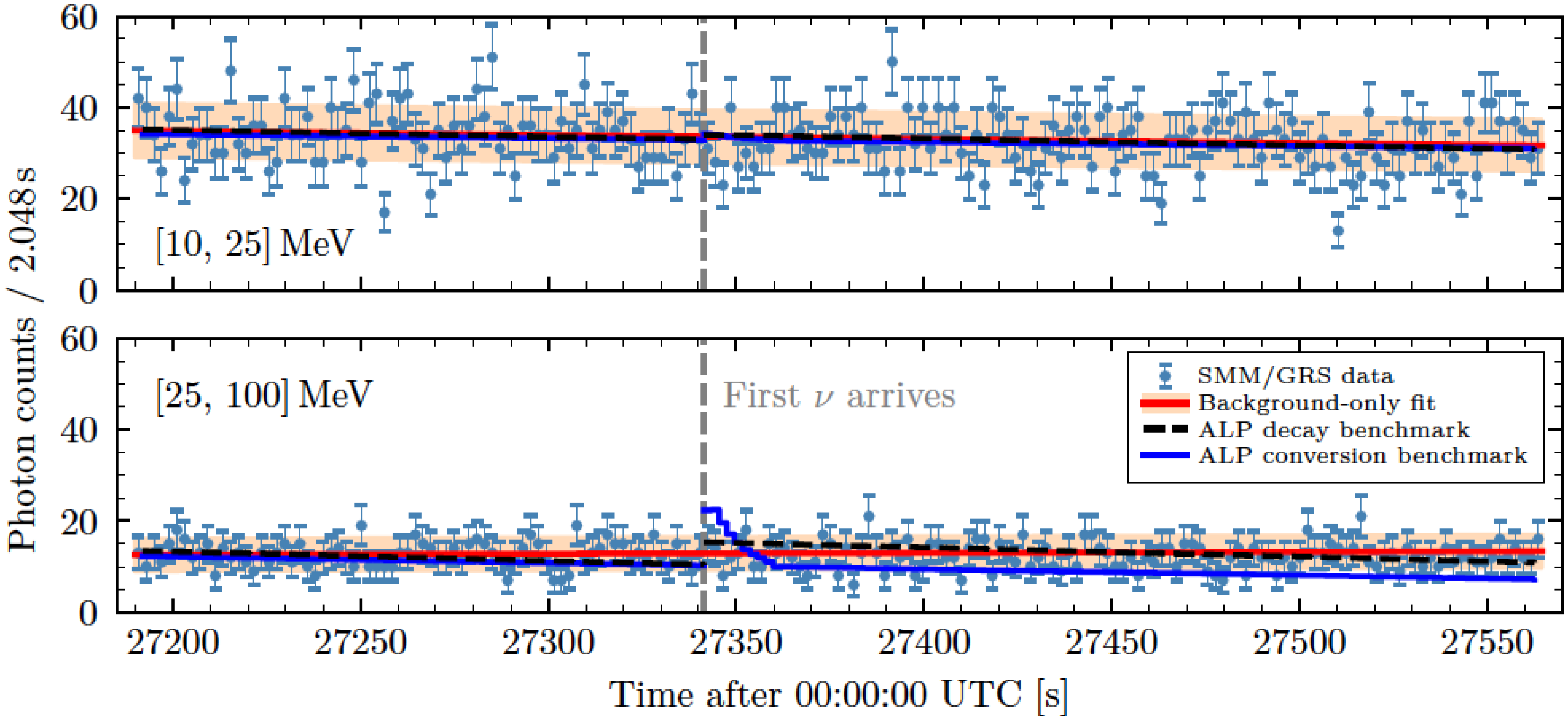
ALP-photon conversions in the Galactic B-fields

No excess gamma-rays in coincidence with SN 1987A

GAMMA-RAY OBSERVATION FROM SMM SATELLITE

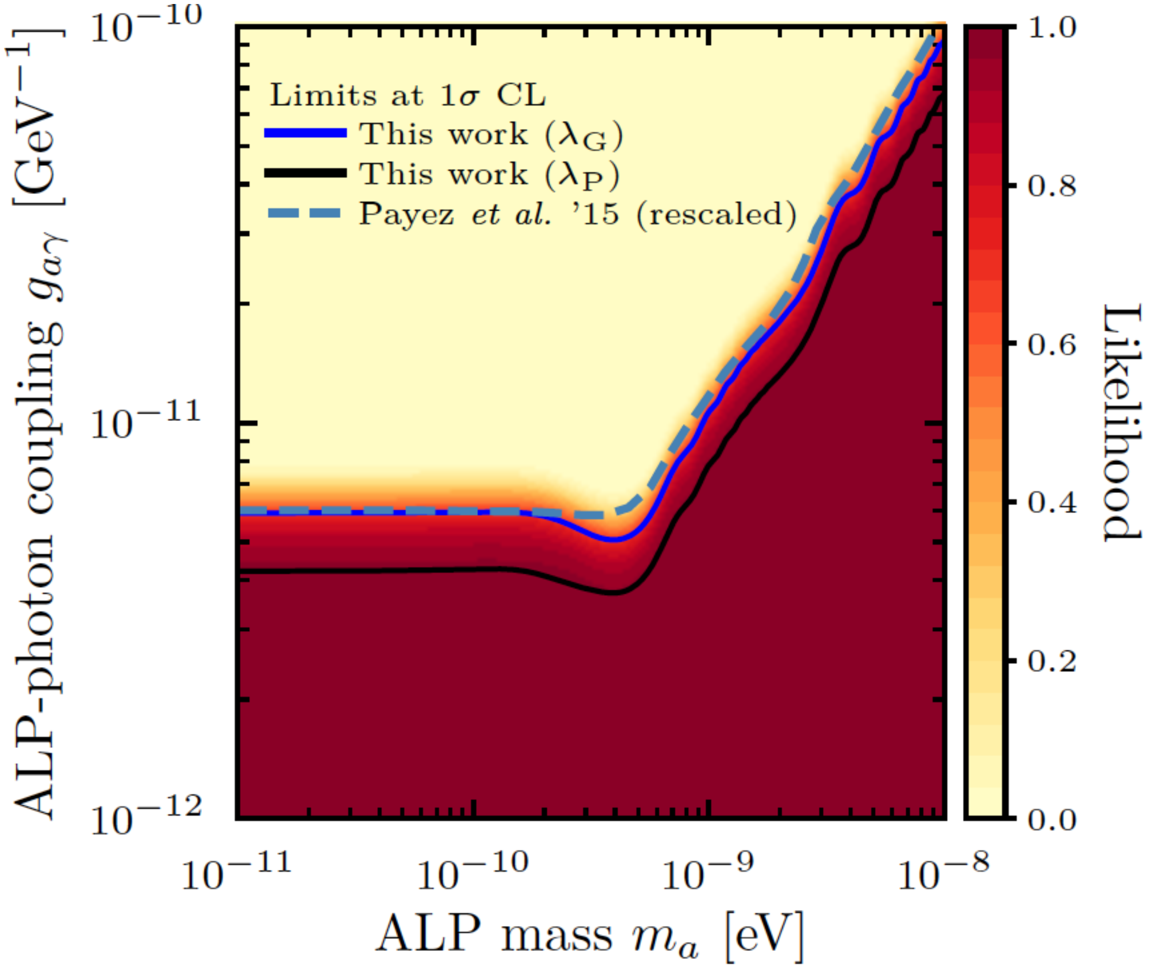
Counts in the GRS instrument on the Solar Maximum Mission Satellite

[Hoof & Schulz, 2212.09764]



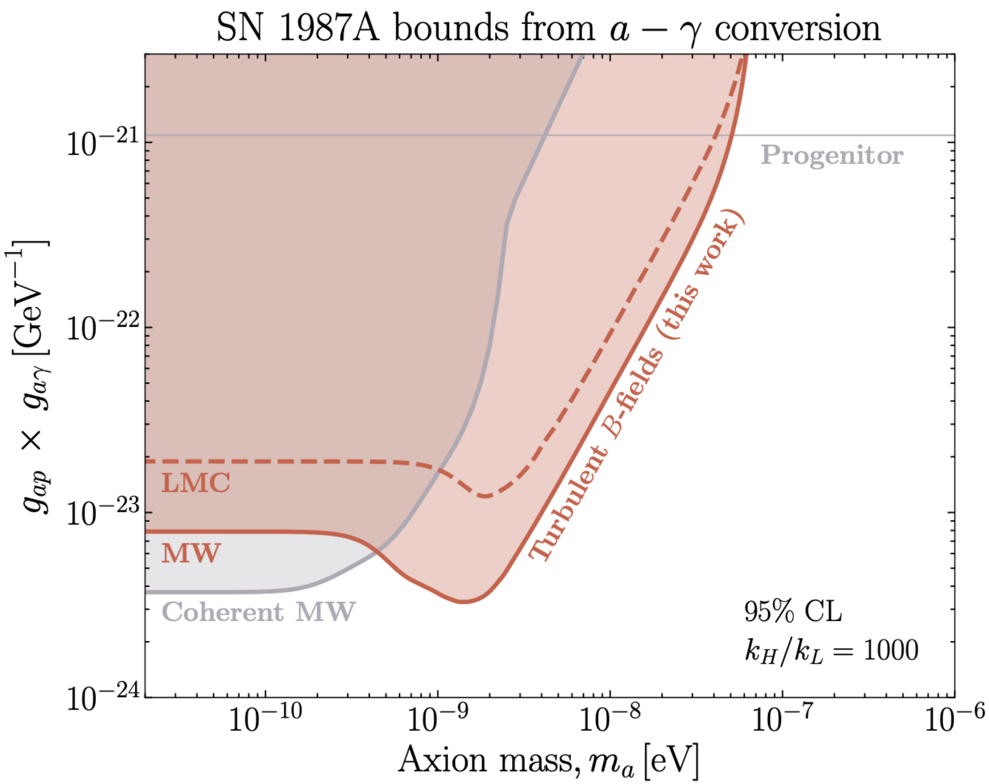
BOUND ON ALPs FROM SN 1987A

[Hoof & Schulz, 2212.09764] updated bounds using the temporal information of the signal



MAGNETIC TURBULENCE BOOST ON ALPs BOUNDS FROM SN 1987A

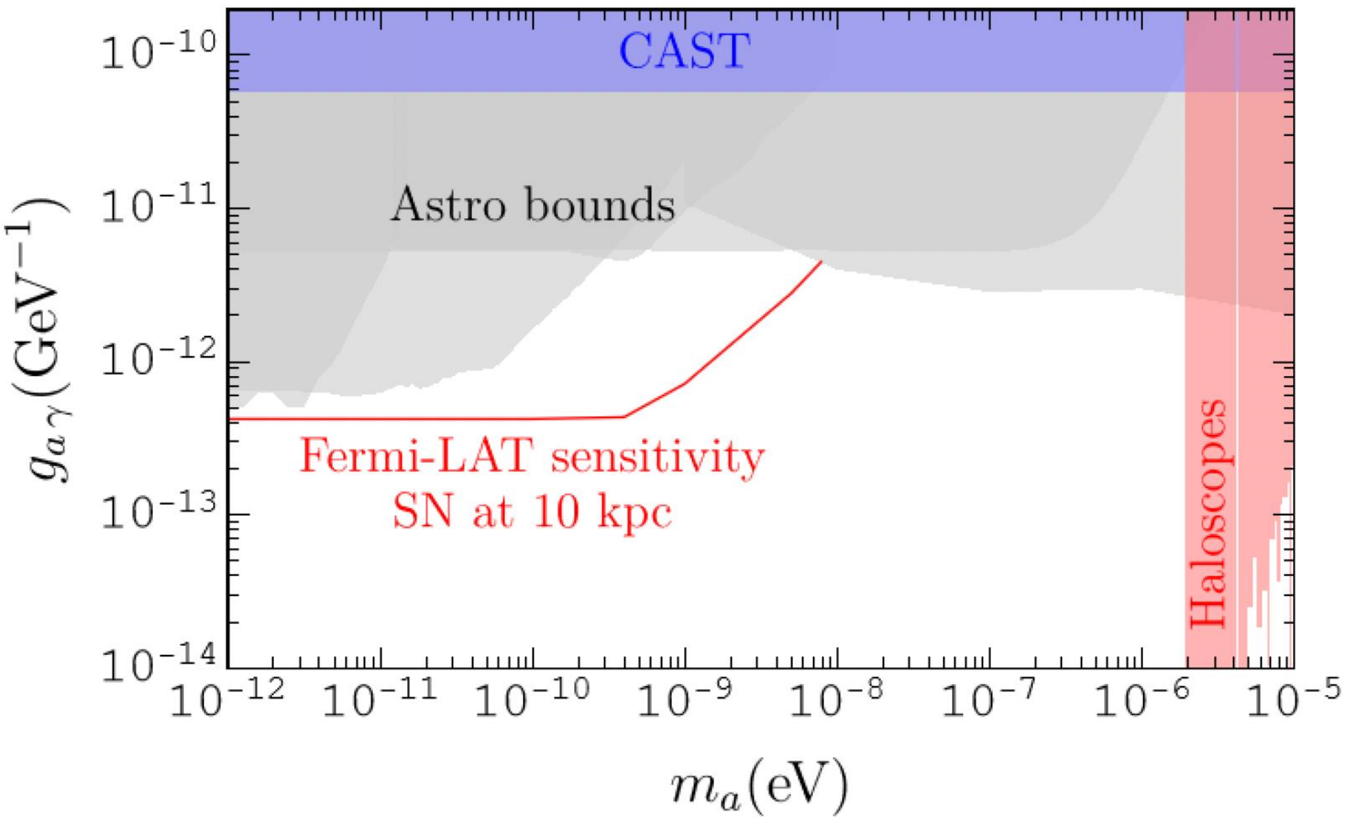
[Fiorillo et al, 2605.15261]



Small-scale power of the turbulent magnetic field component boosts axion-photon conversion and, crucially, extends sensitivity to larger masses.

FERMI-LAT SENSITIVITY TO A GALACTIC SN

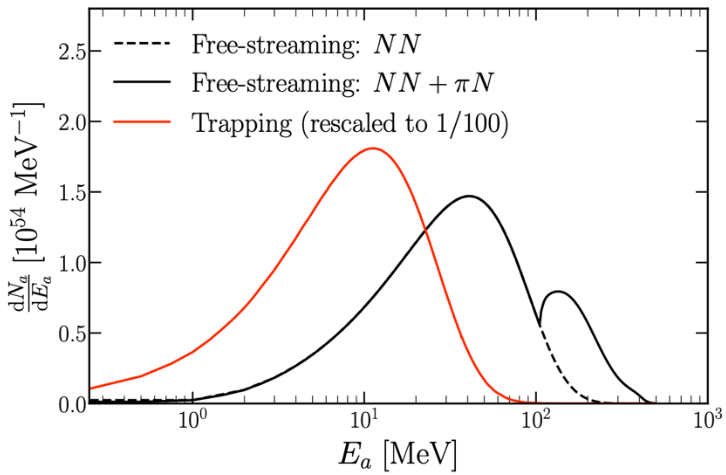
[Meyer, Giannotti, A.M., Conrad & Sanchez-Conde, arXiV:1609.02350, Calore, Carenza, Eckhner, Giannotti, Lucente, A.M., Sivo, arXiV:2306.03925]



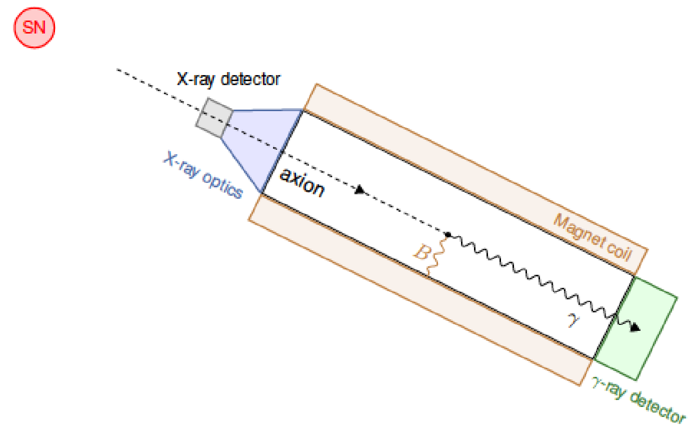
SN AXION SCOPE

[Shao-Feng Ge et al., 2008.03924 [hep-ph], Carenza et al., 2502.19476]

SN axion flux

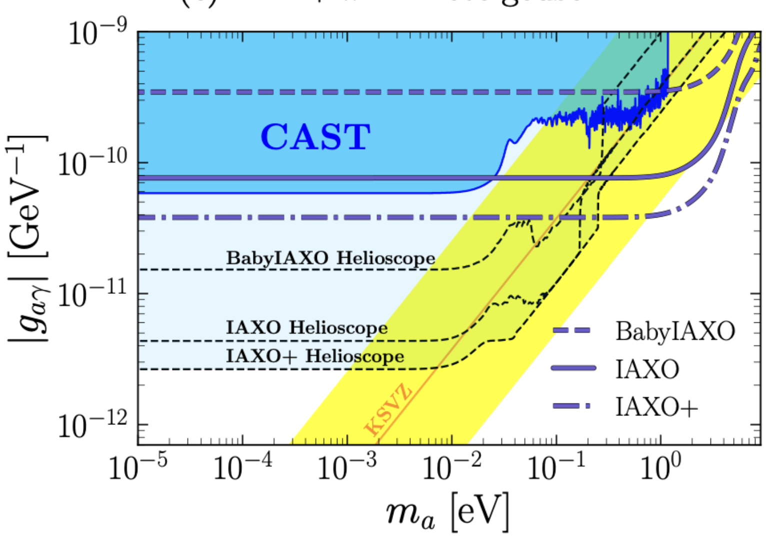


SN axion scope



(b) Axion SNscope

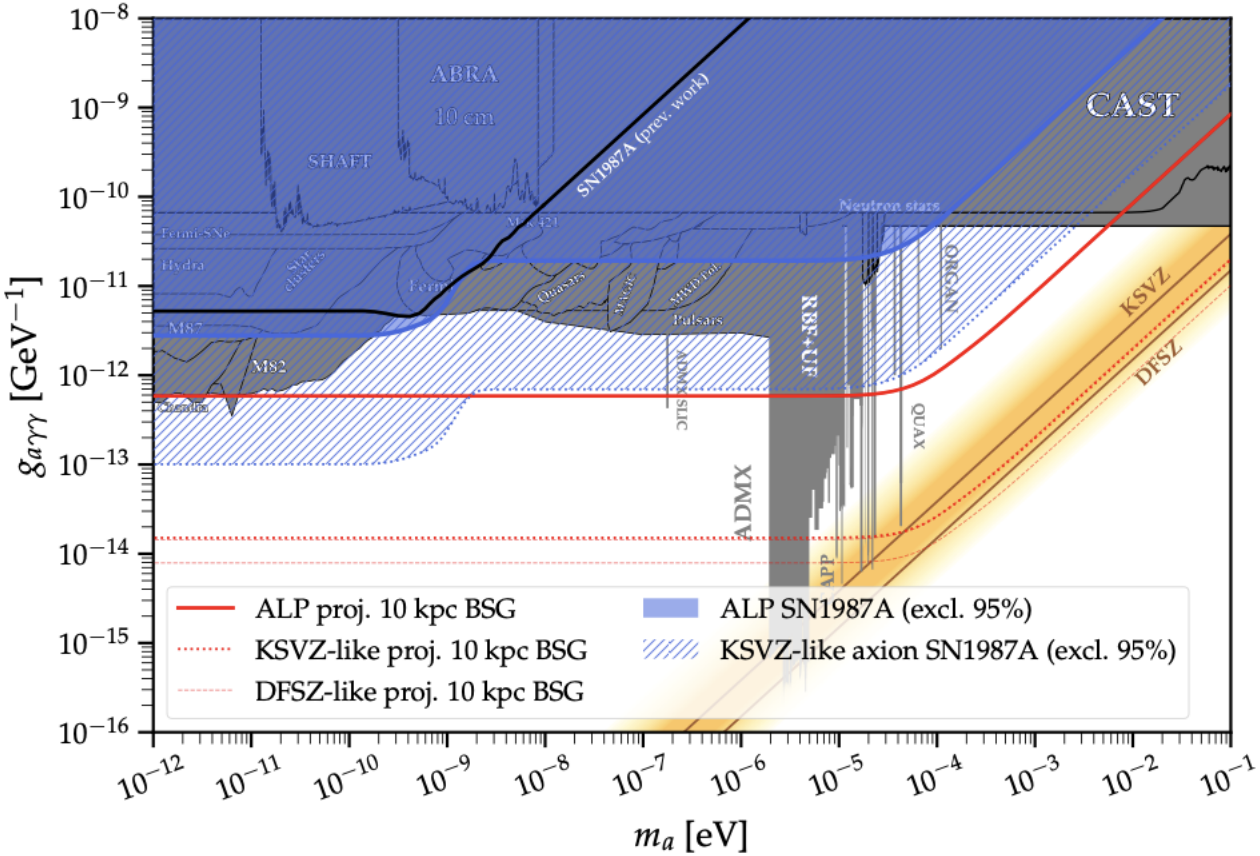
(c) $NN + \pi N$: Betelgeuse



- A close-by SN (d < few hundreds pcs) can be pointed with a neutrino SN pre-alert system
- SN axions can be detected by a gamma-ray detector installed at the end of an helioscope
- It can extend IAXO sensitivity towards higer masses

SN ALP CONVERSIONS IN ENVELOPE B-FIELD

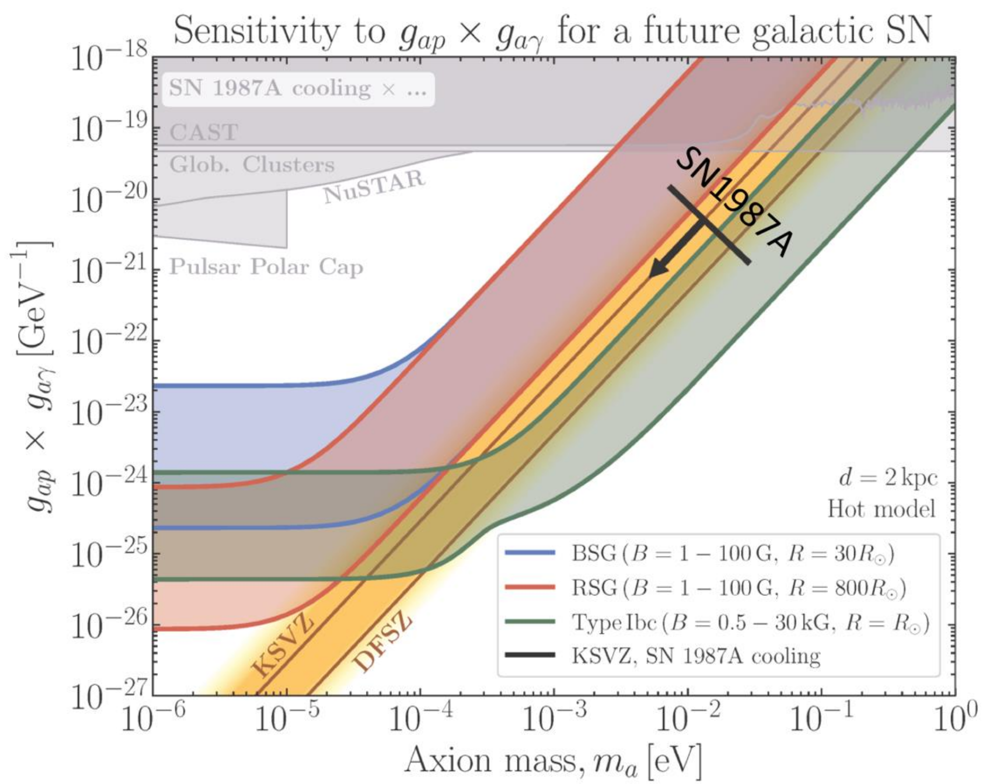
[Manzari, Park, Safdi, Savoray, 2405.19393]



Assume B-field on SN surface O(100) G. SN argument can probe the QCD axion band

STRIPPED ENVELOPE SNe

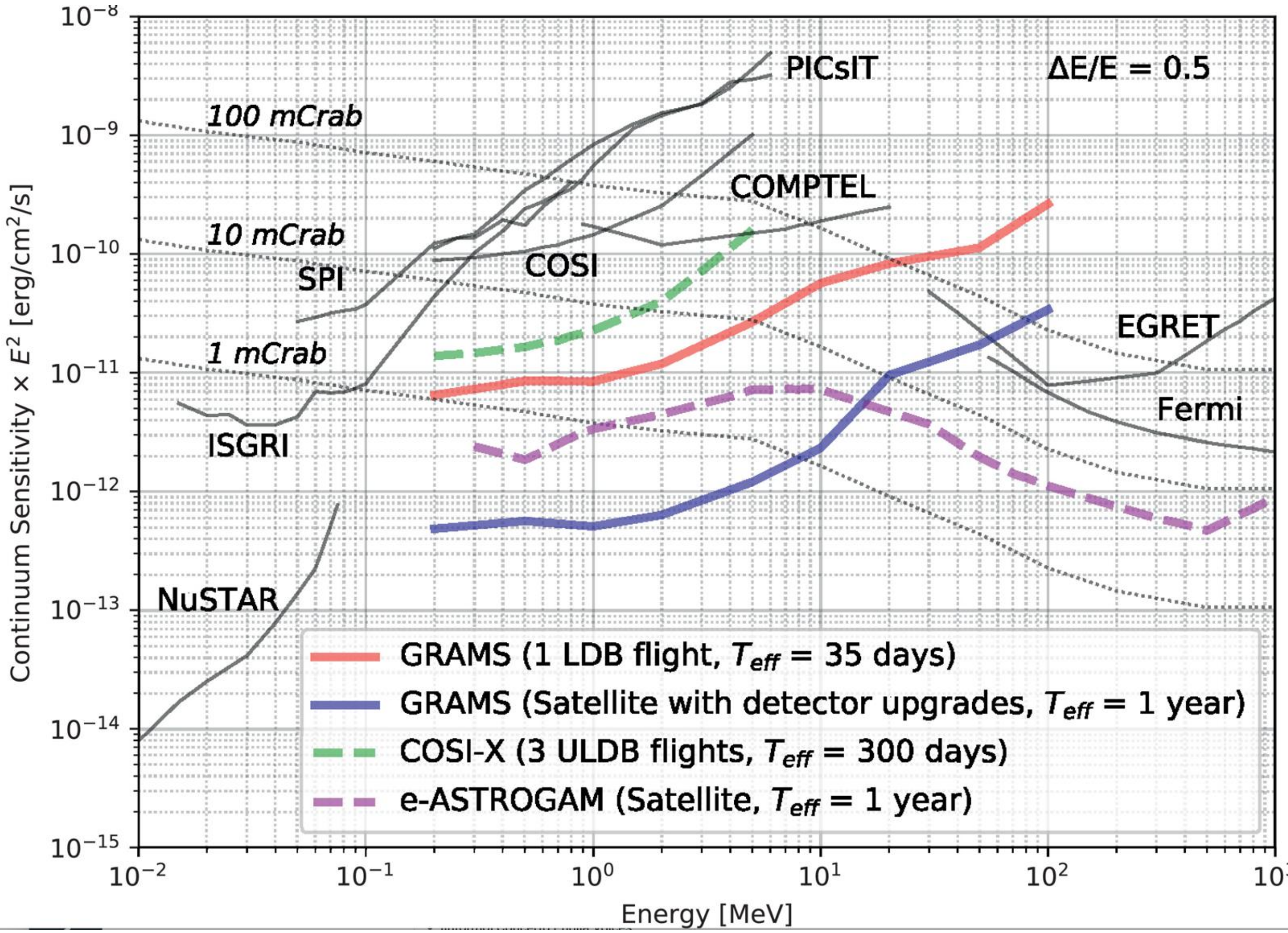
Candón, Fiorillo, Gil Muyor, Janka, Raffelt, Vitagliano 2511.13815



Type Ibc SNe—whose progenitors have lost their hydrogen or even helium envelopes—are the optimal targets for this search. The stripped progenitors are much more compact, and they show larger magnetic fields than both red and blue supergiants, the progenitors of Type IIP/L SNe.

MeV GAP IN GAMMA-RAY ASTROPHYSICS

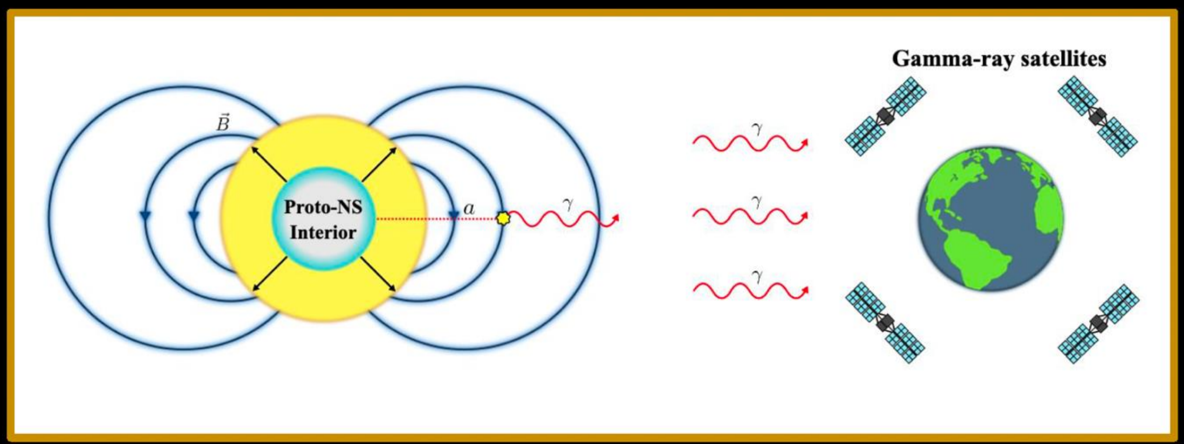
[Aramaki et al., 1901.03430]



A NEW PROPOSAL: GALAXIES

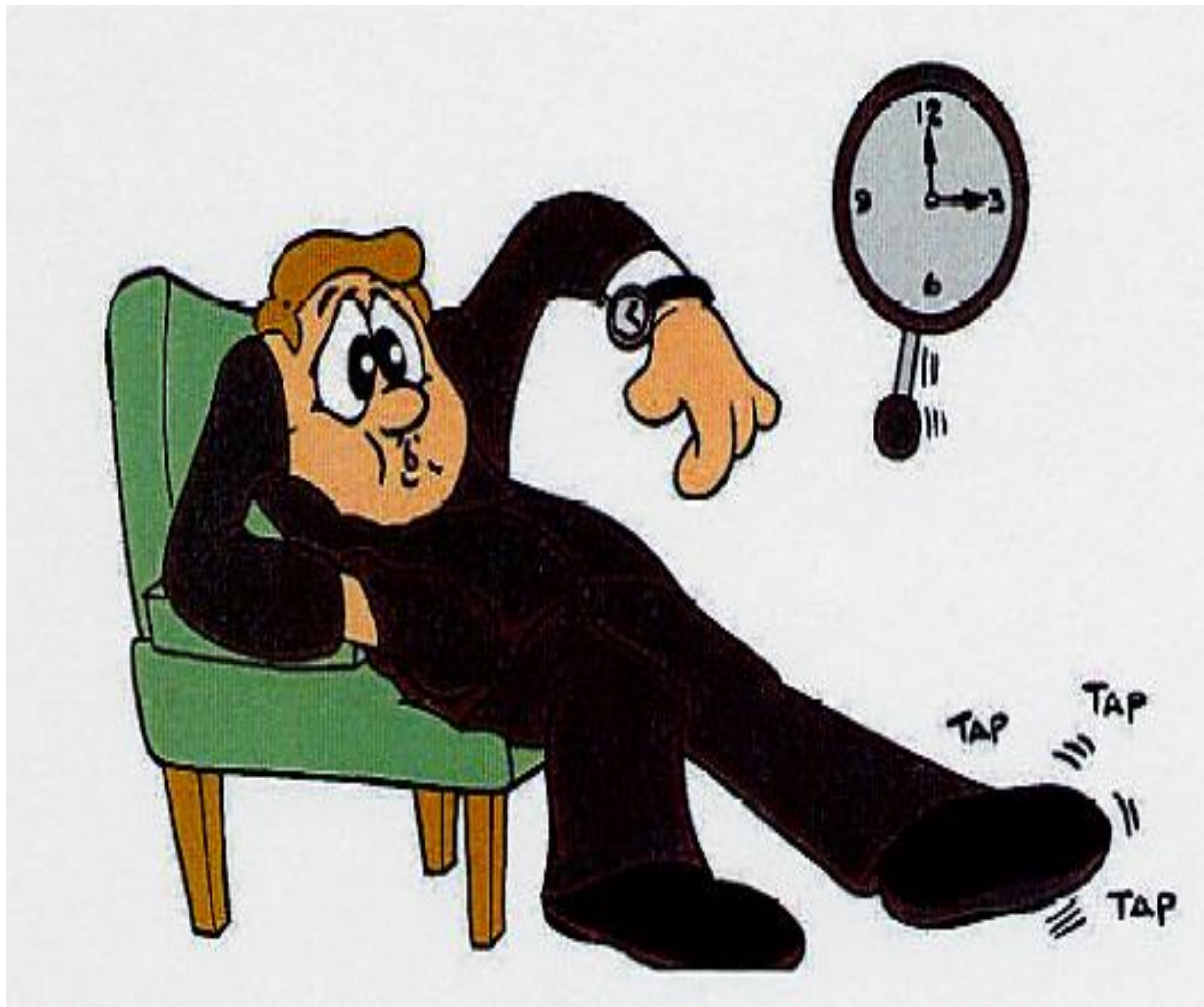
A Modest Proposal

- Prospects of catching axions from the next galactic SN demanded an MeV gamma-ray telescope with full-sky coverage and continuous monitoring
- GALAXIS: GALactic AXion Instrument for Supernova



Orion Ning - COST WG3 Meeting - April 30, 2026

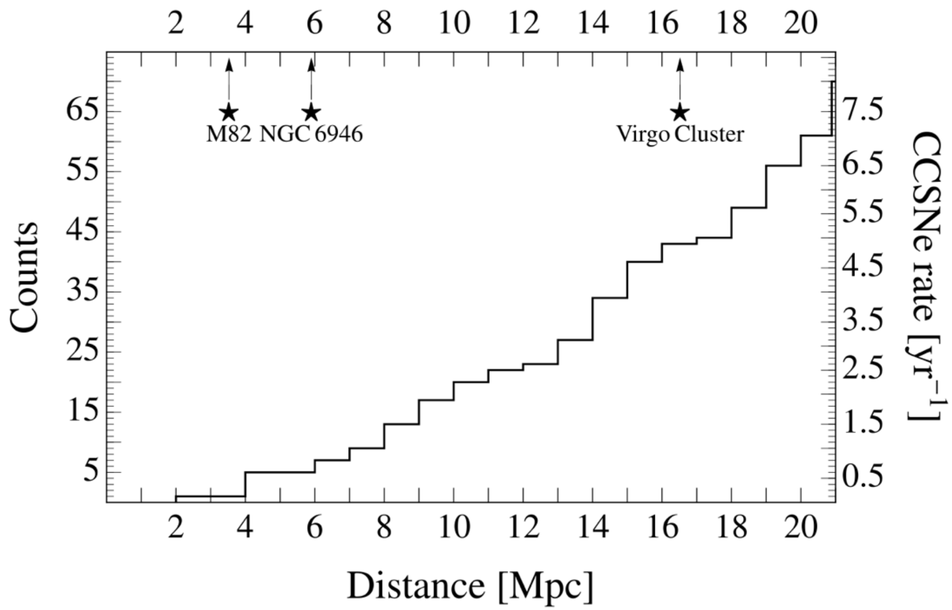
A galactic SN explosion is a spectacular event which might produce an enormous number of axions, but it is a rare event (~ 3/century) …



AXIONS FROM EXTRAGALACTIC SNe

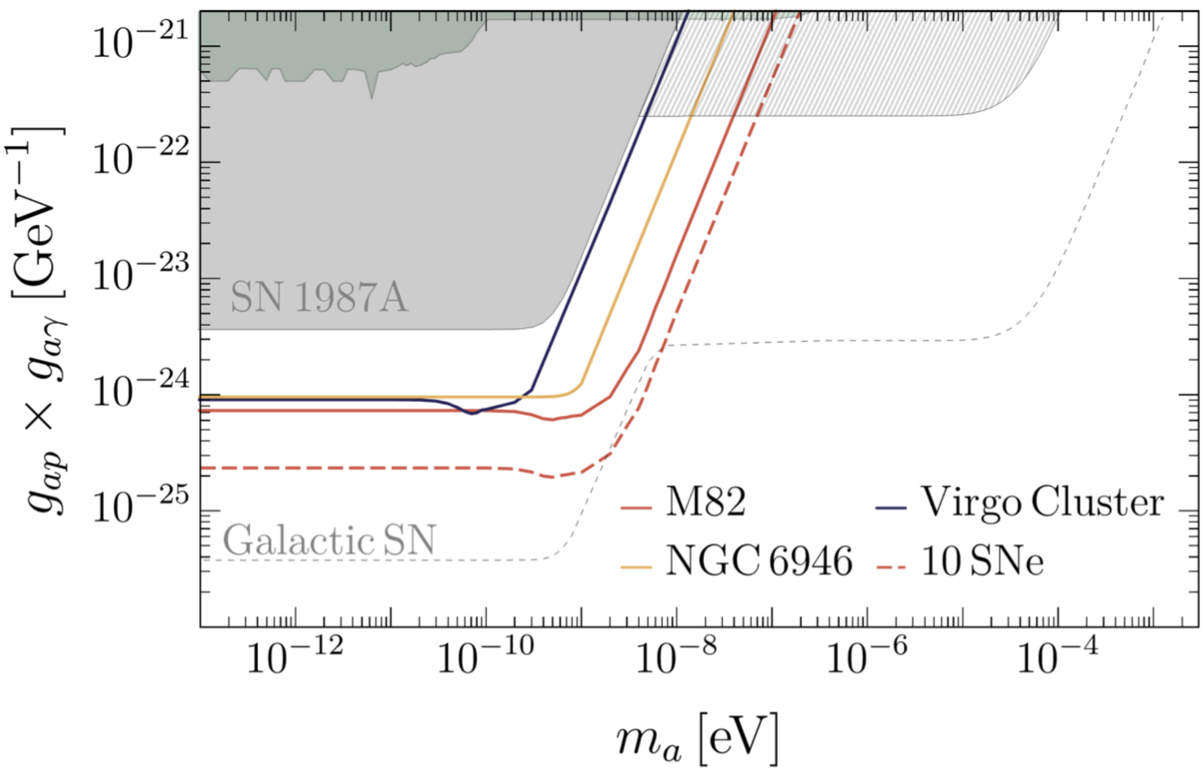
[Lecce, Lella, Lucente, Giannotti, Mirizzi, 2512.04185]

See talk by Francesca Lecce



....In contrast, a few SNe per year are expected in nearby galaxies within ~ O(10) Mpc, where strong magnetic fields can enable more efficient ALP-photon conversions than in the Milky Way.

Full-sky gamma-ray monitoring, ideally combined with deci-hertz gravitational-wave detectors (e.g. DECIGO) to enable time-triggered searches from nearby galaxies.



Host Environment	Observed SNe (2008-2025)	$\langle B_T \rangle$ (μG)	L (kpc)	d (Mpc)	$P_{a\gamma}$	$g_{ap} \times g_{a\gamma}$ ($\times 10^{-25}$ GeV^{-1})
M82	SN 2008iz	2.9	20	3.5	7.7×10^{-3}	7.3
NGC 6946	SN 2008S,SN 2017eaw	8.3	9	5.9	1.2×10^{-2}	9.5
Virgo Cluster	SN 2012cc, SN 2014L, SN 2020oi, SN 2019ehk	0.2	10^3	16.4	1.1×10^{-1}	9.1

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PREPARED FOR SUBMISSION TO JCAP

Axions at the meV Crossroads: Theory, Cosmology, Astrophysics, and Experiments

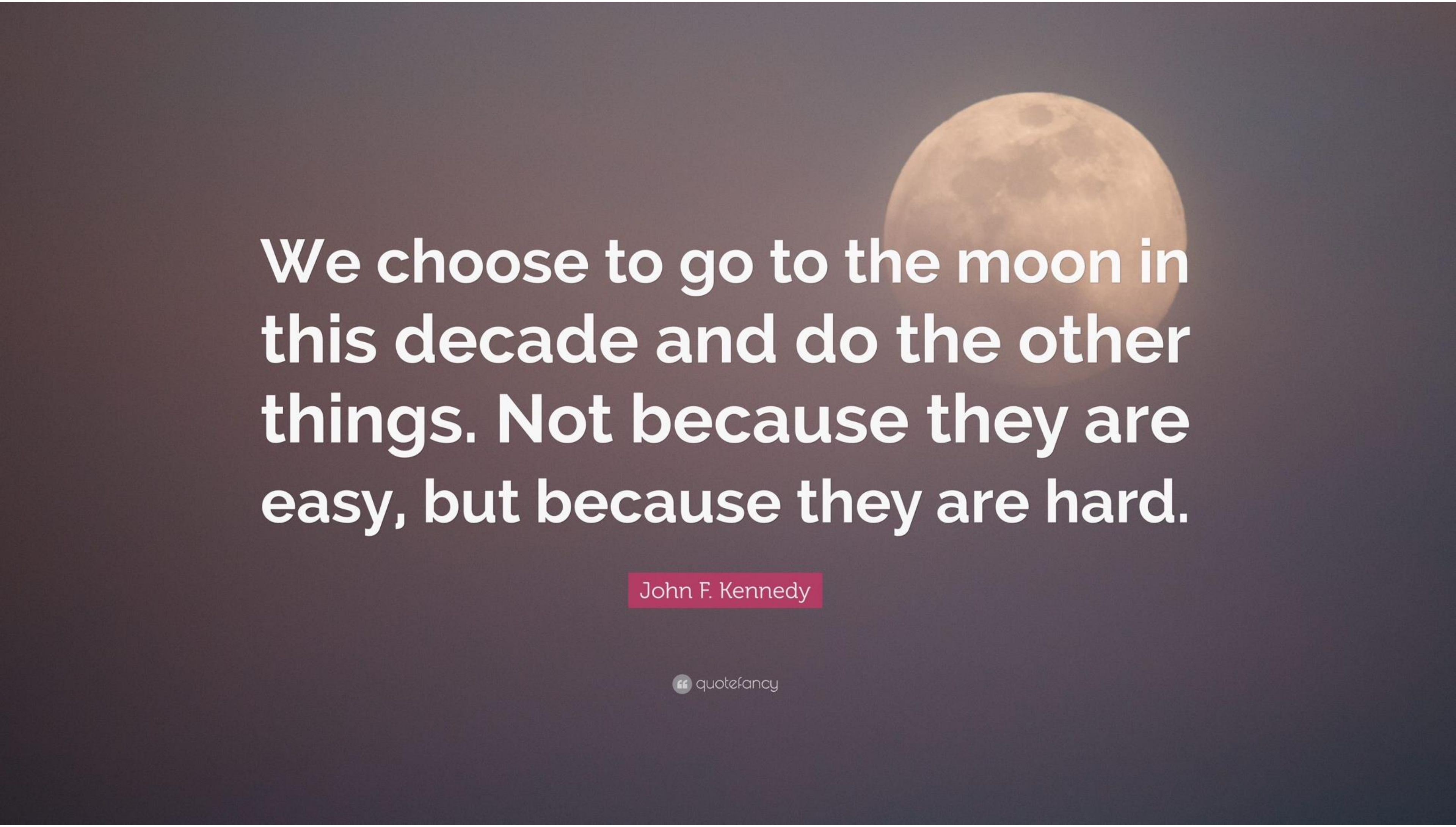
CONCLUSIONS

- Astrophysics offers valuable opportunities to probe axions and axion-like particles

- Impressive advances in modelling stellar systems (GCs, SNe..) and cosmic magnetic fields allow to improve the robusteness of astro bounds and allow to point out signatures for X and gamma-ray observations

- It is crucial to guarantee sky observations in X and gamma-rays

- Future astro observations and lab experiments (e.g. IAXO, ALPS II) would be crucial to probe the axion parameter space and may lead to a potential discovery


We choose to go to the moon in this decade and do the other things. Not because they are easy, but because they are hard.
John F. Kennedy
quotefancy