The Hunt for Stellar Axions: Current Status and Future Prospectives.

YOUNGST@RS,
Mainz Institute for Theoretical Physics, Johannes Gutenberg University,

Oct 4 – 7, 2022

Maurizio Giannotti, Barry University

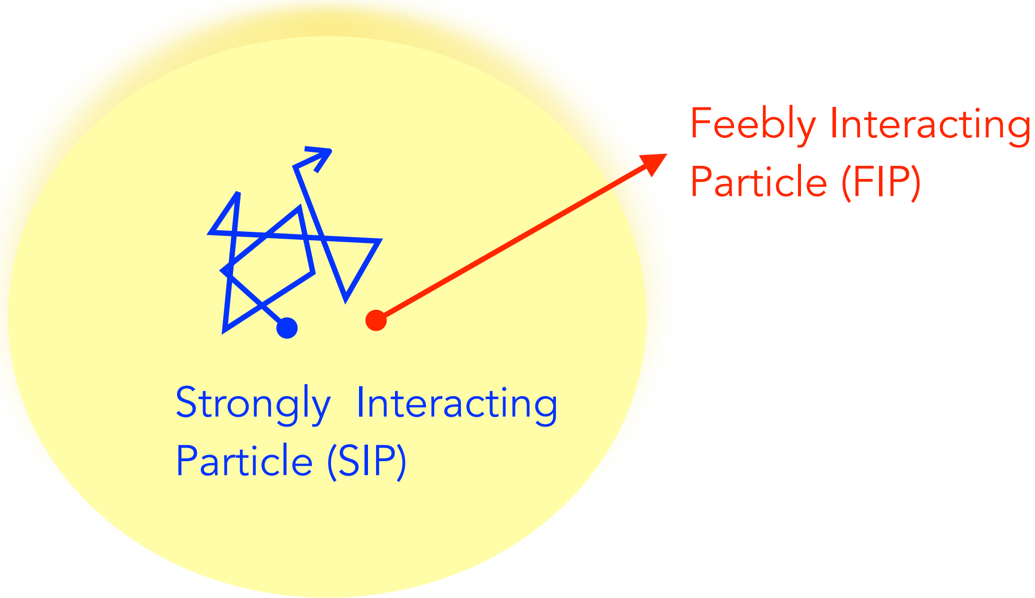
Outline

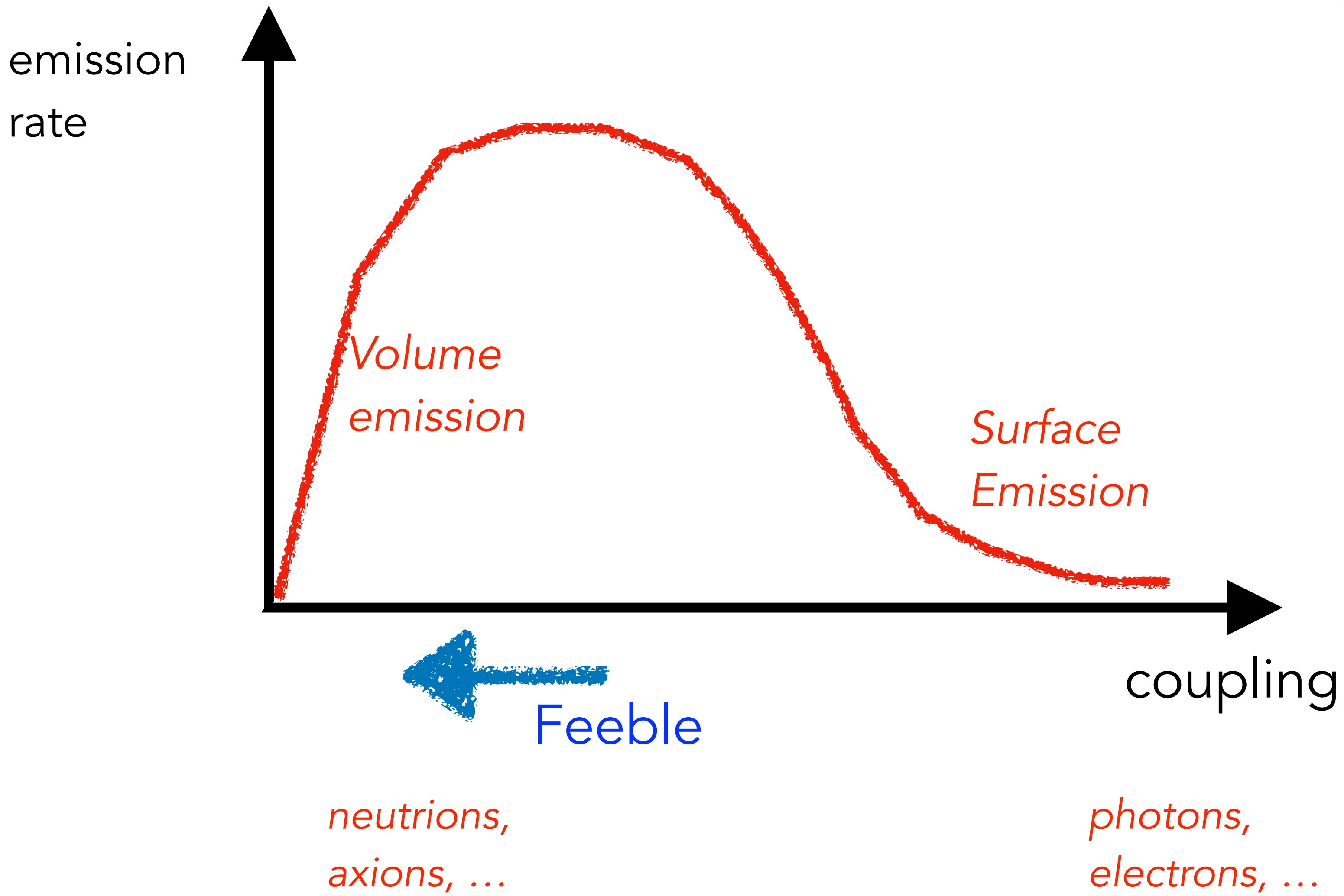
- *Mostly, Solar axions and helioscopes*
- *Brief overview of stellar axions*

(A lot more in backup slides)

Feeble is good!

Light particles, $m \lesssim T$, can be efficiently thermally produced in stellar cores





Efficient production:

1) energy loss ⇒ modified evolution

(See talks by G. Raffelt and O. Straniero)

2) large flux

Where should we look?

The Sun average distance from Earth is

$$d_\odot = 1.5 \times 10^8\,\mathrm{km}\ \text{(=1 AU).}$$

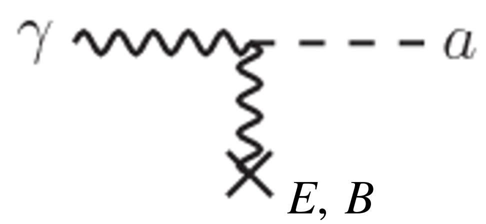
The closest known star to the sun is Proxima Centauri, at

$$d = 4.25\,\mathrm{ly} = 2.7 \times 10^5\,\text{AU}$$

The axion flux scales as d^{-2}.

$\longrightarrow$ *The sun is certainly a good place to start hunting for axions*

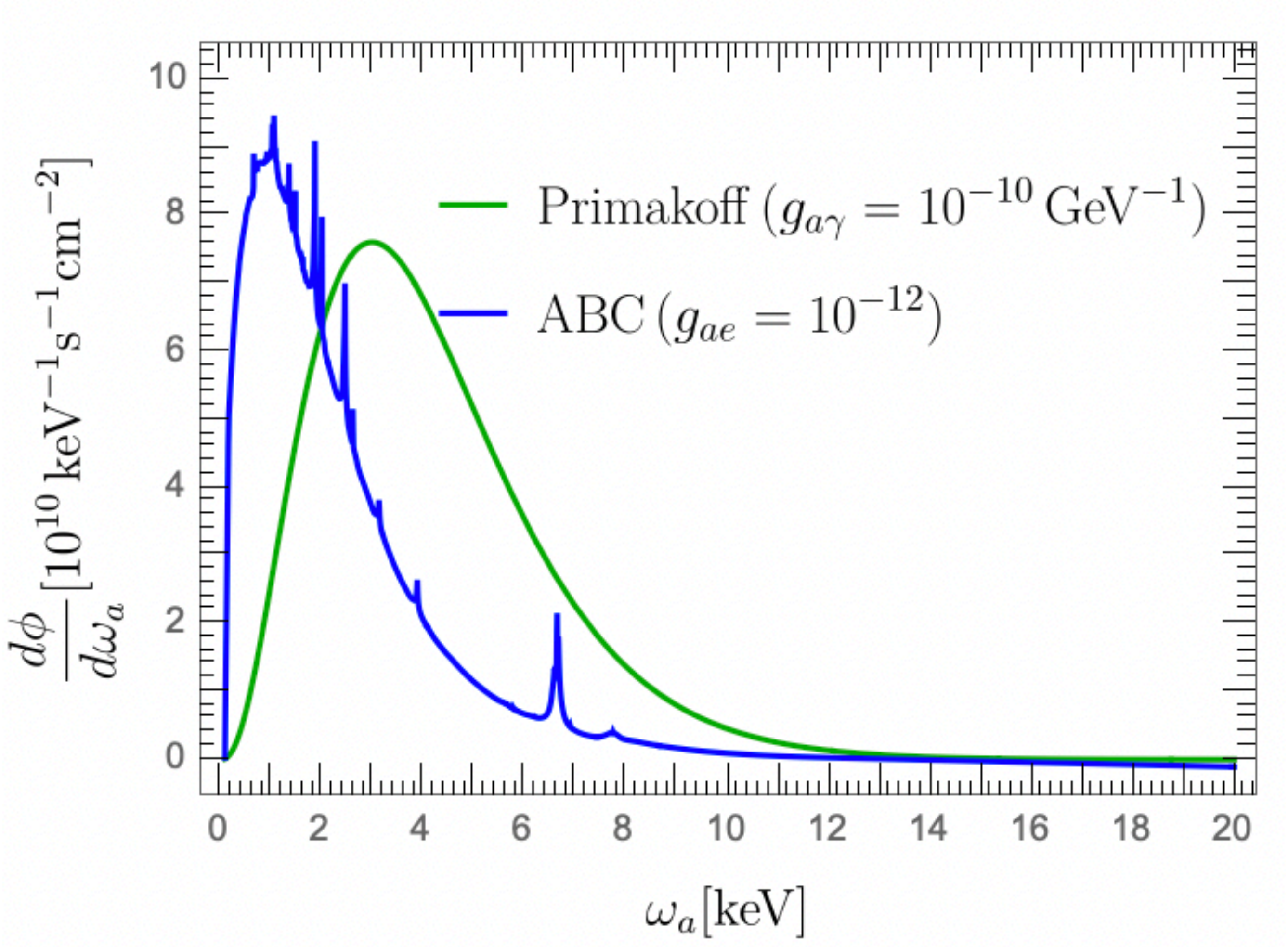
Solar axions

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., $e + Z_e \to Ze + e + a$	$\sim 1\,\mathrm{keV}$
g_{aN}	nuclear reactions $p + d \to {}^3\mathrm{He} + a$ Nuclear de-excitation ${}^{57}\mathrm{Fe}^* \to {}^{57}\mathrm{Fe} + a$ ${}^{7}\mathrm{Li}^* \to {}^{7}\mathrm{Li} + a$ ${}^{83}\mathrm{Kr}^* \to {}^{83}\mathrm{Kr} + a$	$5.5\,\mathrm{MeV}$ $14.4\,\mathrm{keV}$ $478\,\mathrm{keV}$ $9.4\,\mathrm{keV}$

Primakoff (E) + ABC processes

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

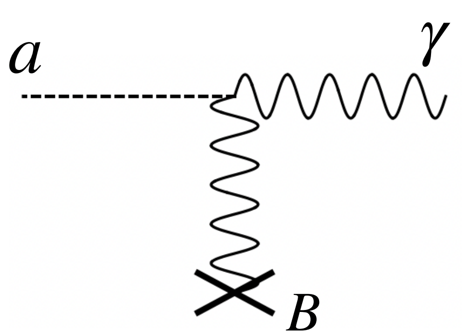
up to $\sim 10^{39}$ axions/s ($\Rightarrow 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ axions on Earth), peaked at $\sim$ keV

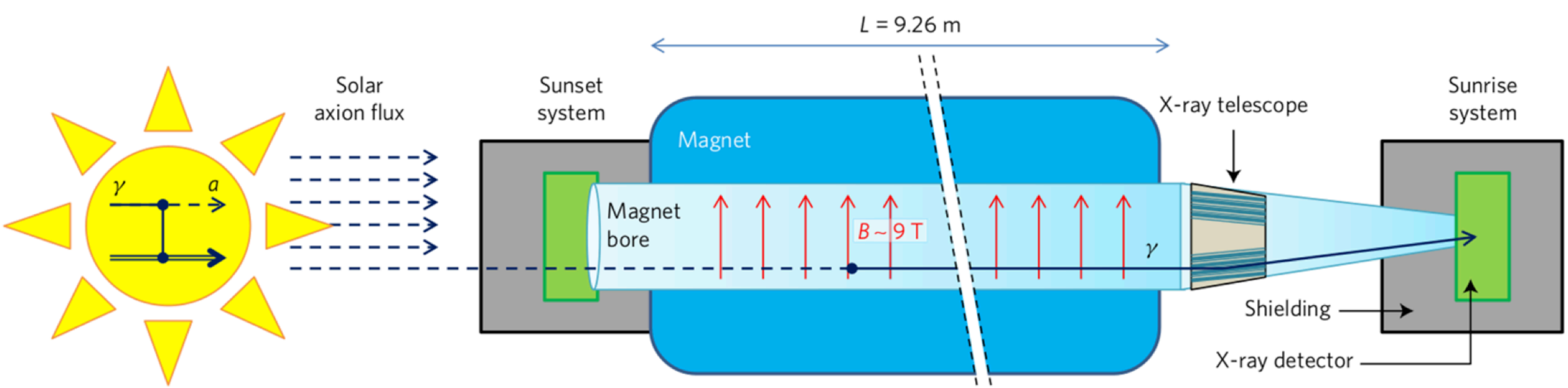


J. Redondo, JCAP 1312 (2013); S. Hoof, J. Jaeckel, L. J. Thormaehlen, JCAP 09 (2021)

Hunting for solar axions

Sikivie Helioscope: $a \rightarrow \gamma$ in lab B-field: CAST, IAXO, …





The CERN Axion Solar Telescope (CAST)

Sensitivity

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

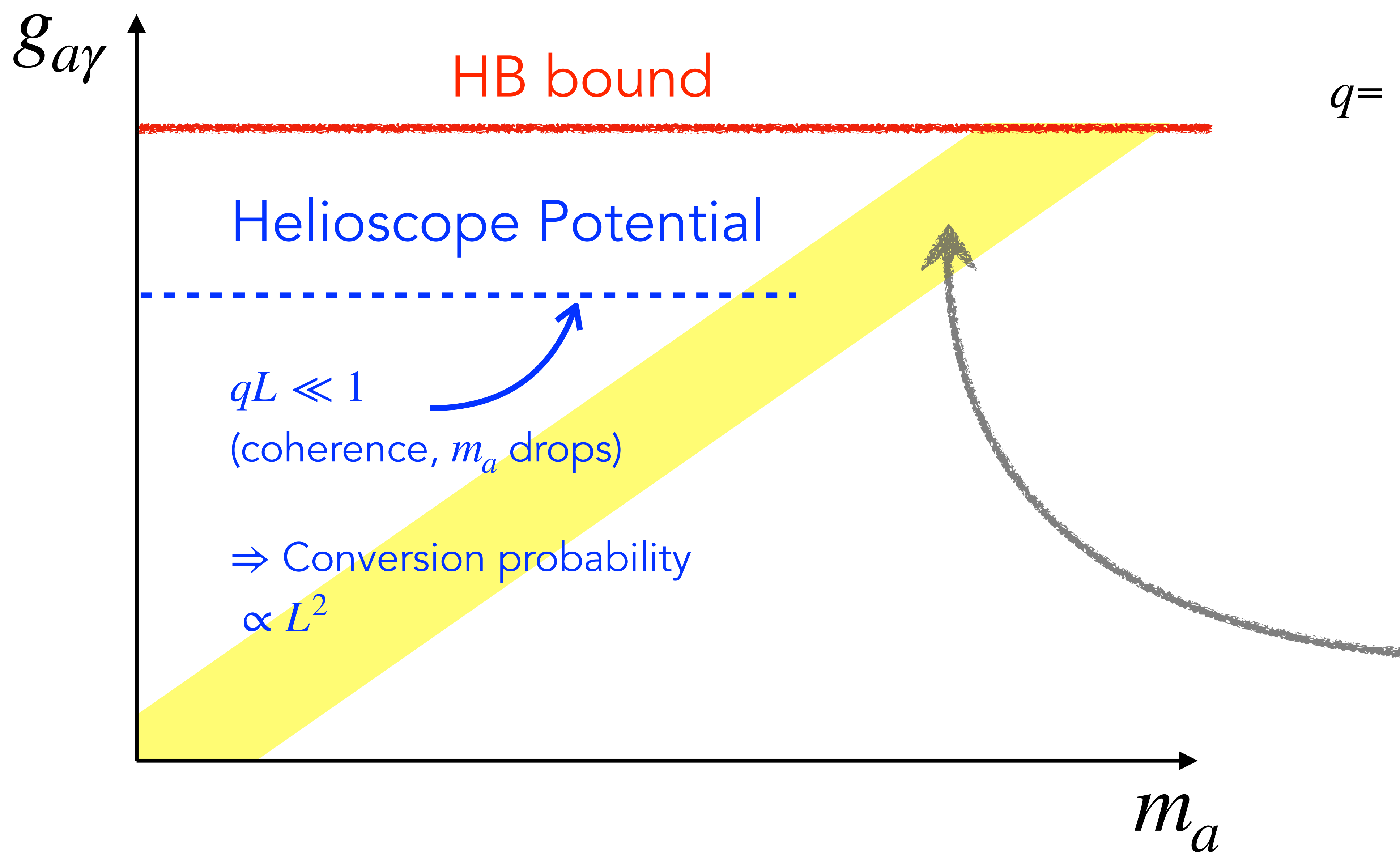
G. Raffelt, L. Stodolsky, Phys.Rev.D 37 (1988)

B= magnetic field

L= magnet length

q= momentum transfer

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



QCD axion band

(see L. Di Luzio talk)

Sensitivity

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

G. Raffelt, L. Stodolsky, Phys.Rev.D_ 37 (1988)

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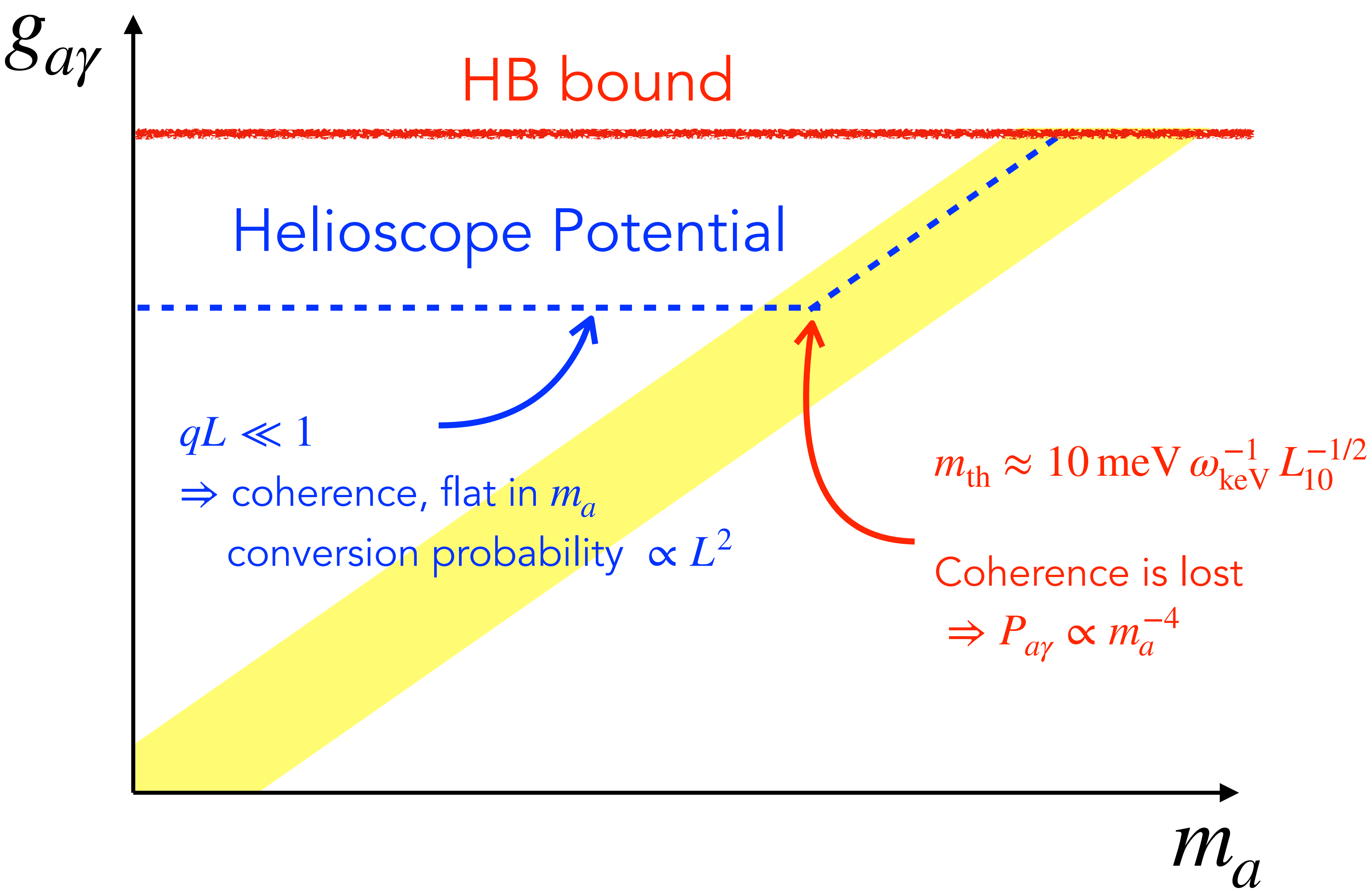

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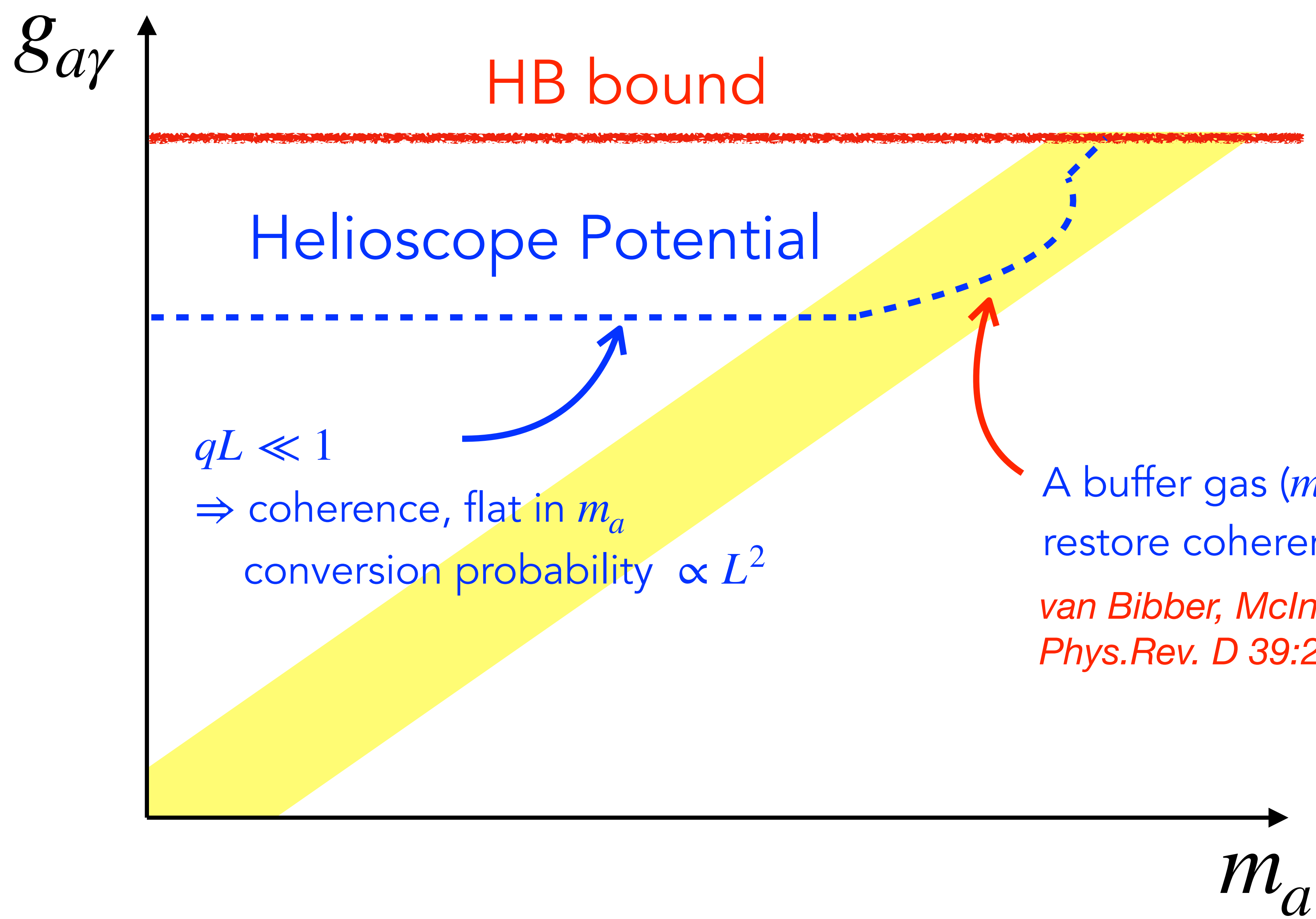
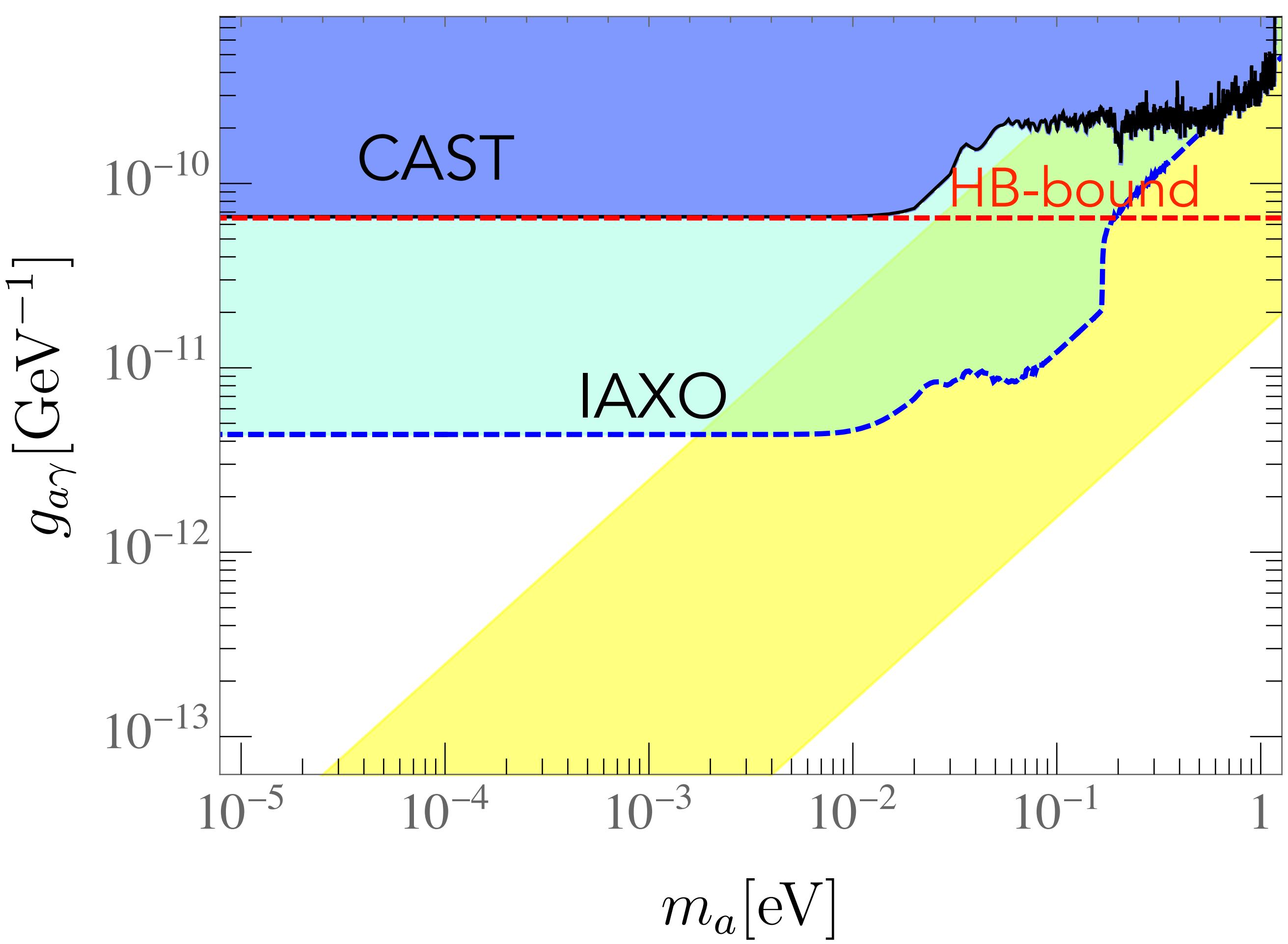


A buffer gas ($m_\gamma \simeq m_a$) can restore coherence

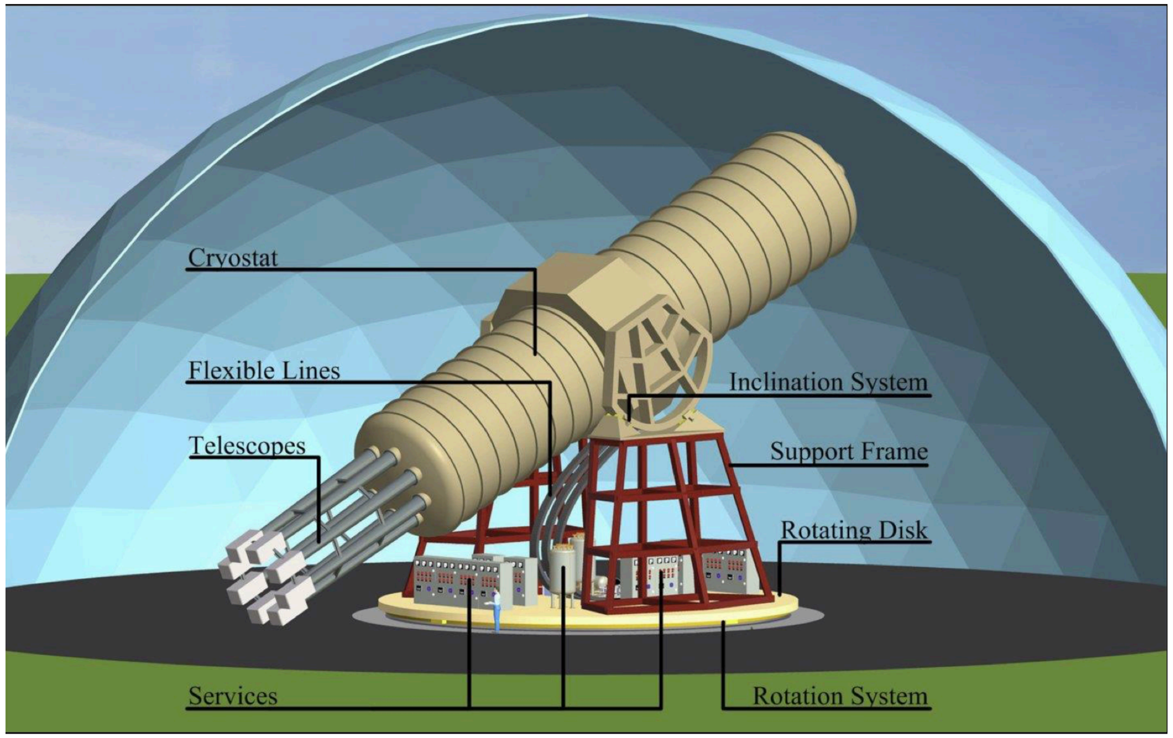
van Bibber, McIntyre, Morris, Raffelt, Phys.Rev. D 39:2089 (1989)

Next generation helioscopes:

IAXO
(International AXion Observatory)



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



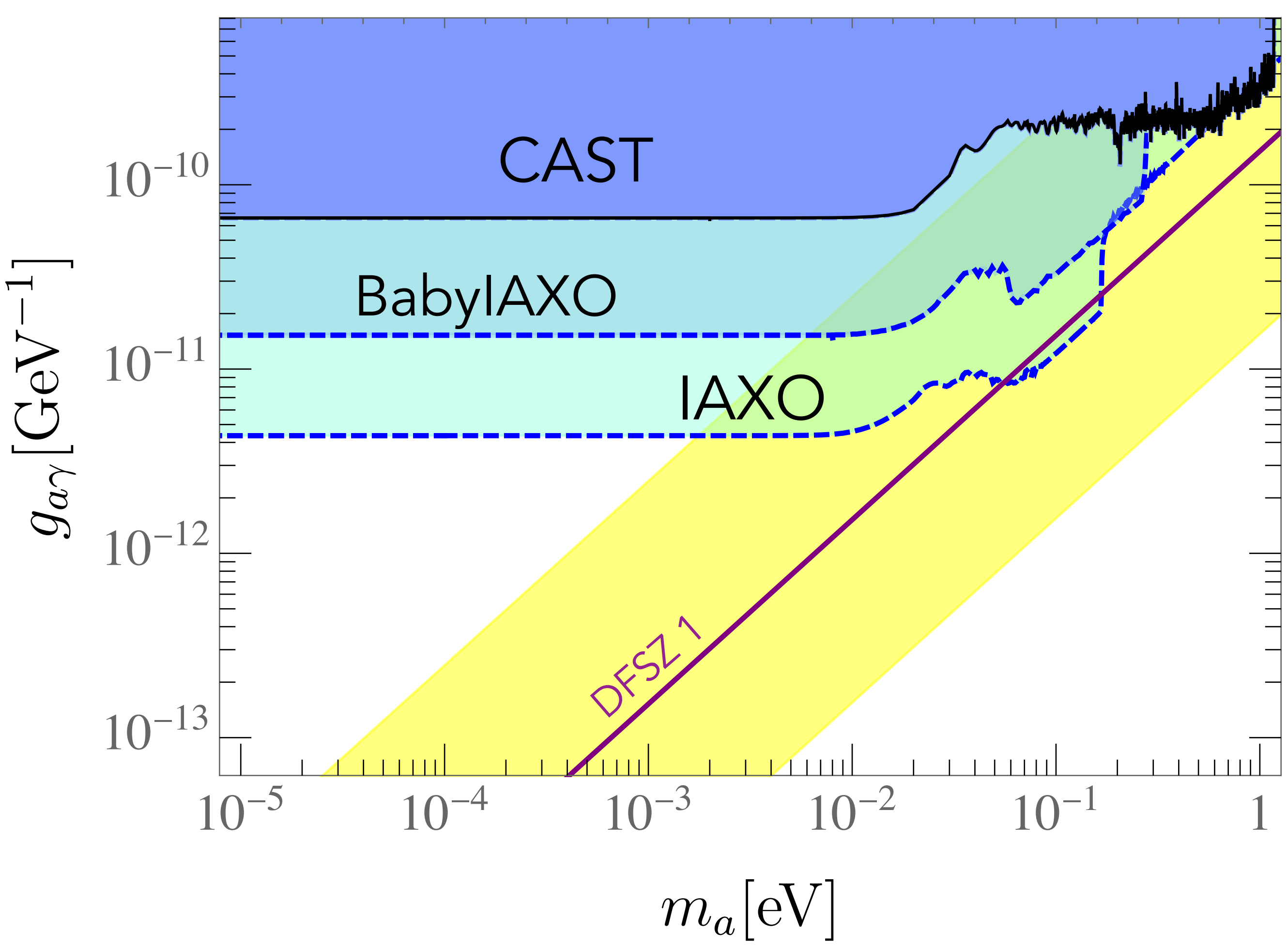
Large area: 2.3 m^2 total area (8 bores)

Each bore equipped with X-ray telescope

20 m long magnet, ~ 2.5 T

Next generation helioscopes:

Scale down version (BabyIAXO)
@ DESY.
Commissioning expected in 2026



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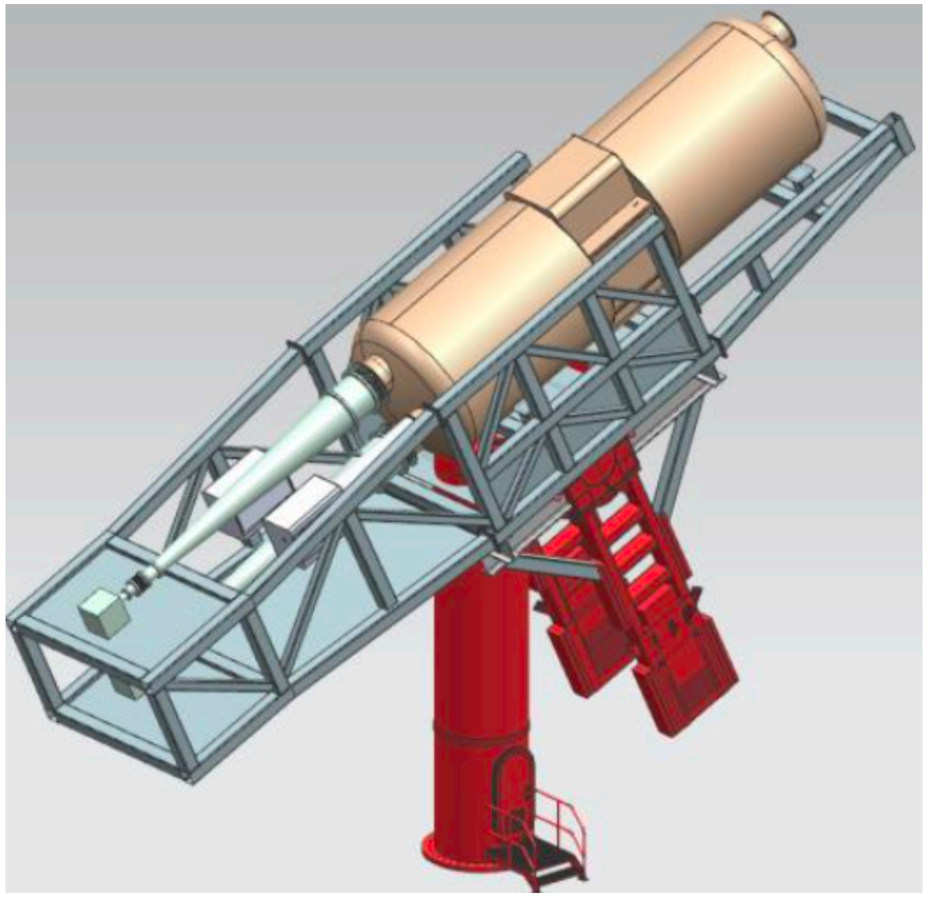


0.77 m^2 total area (2 bores)

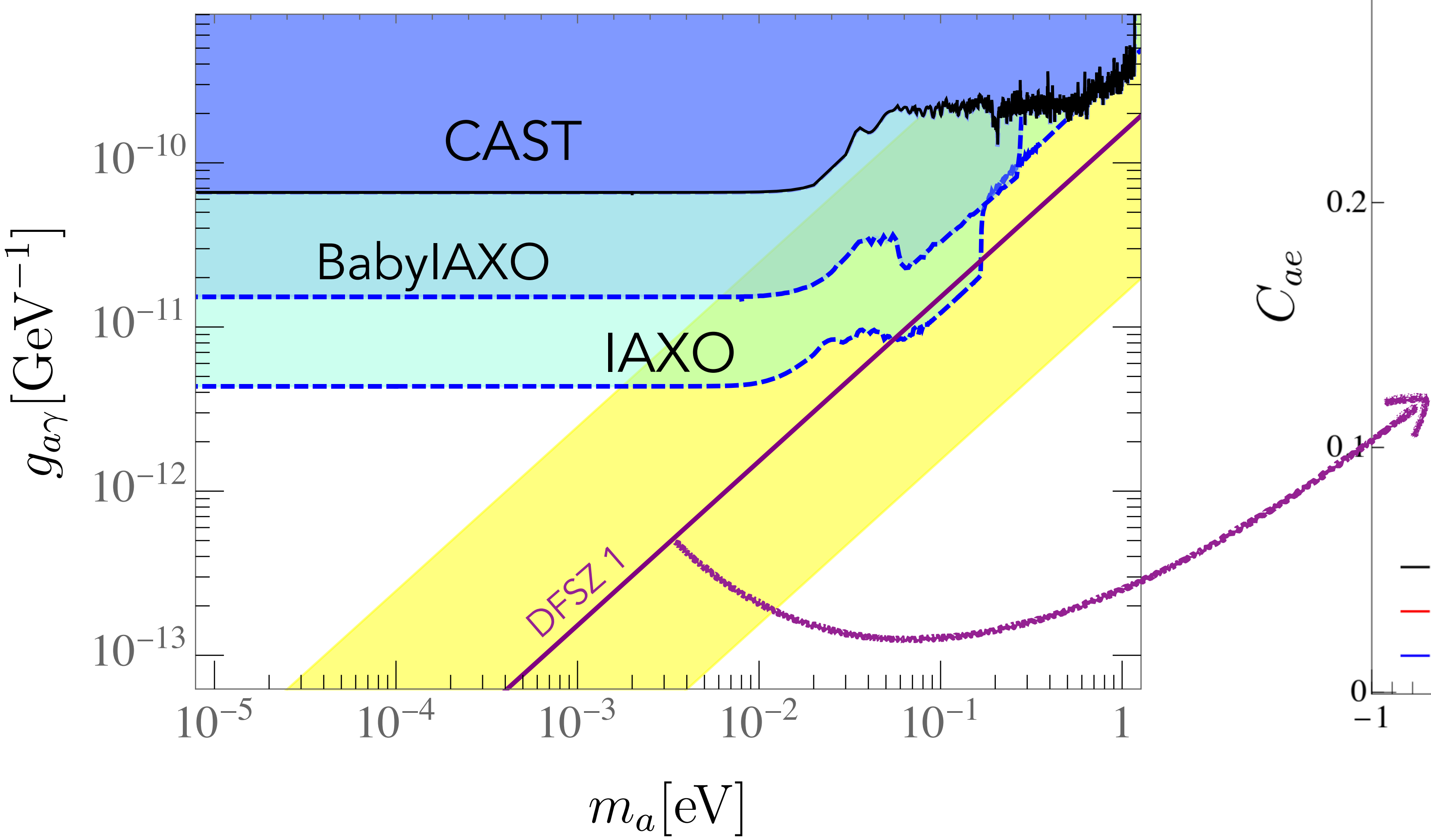
10 m long magnet, ~ 2 T

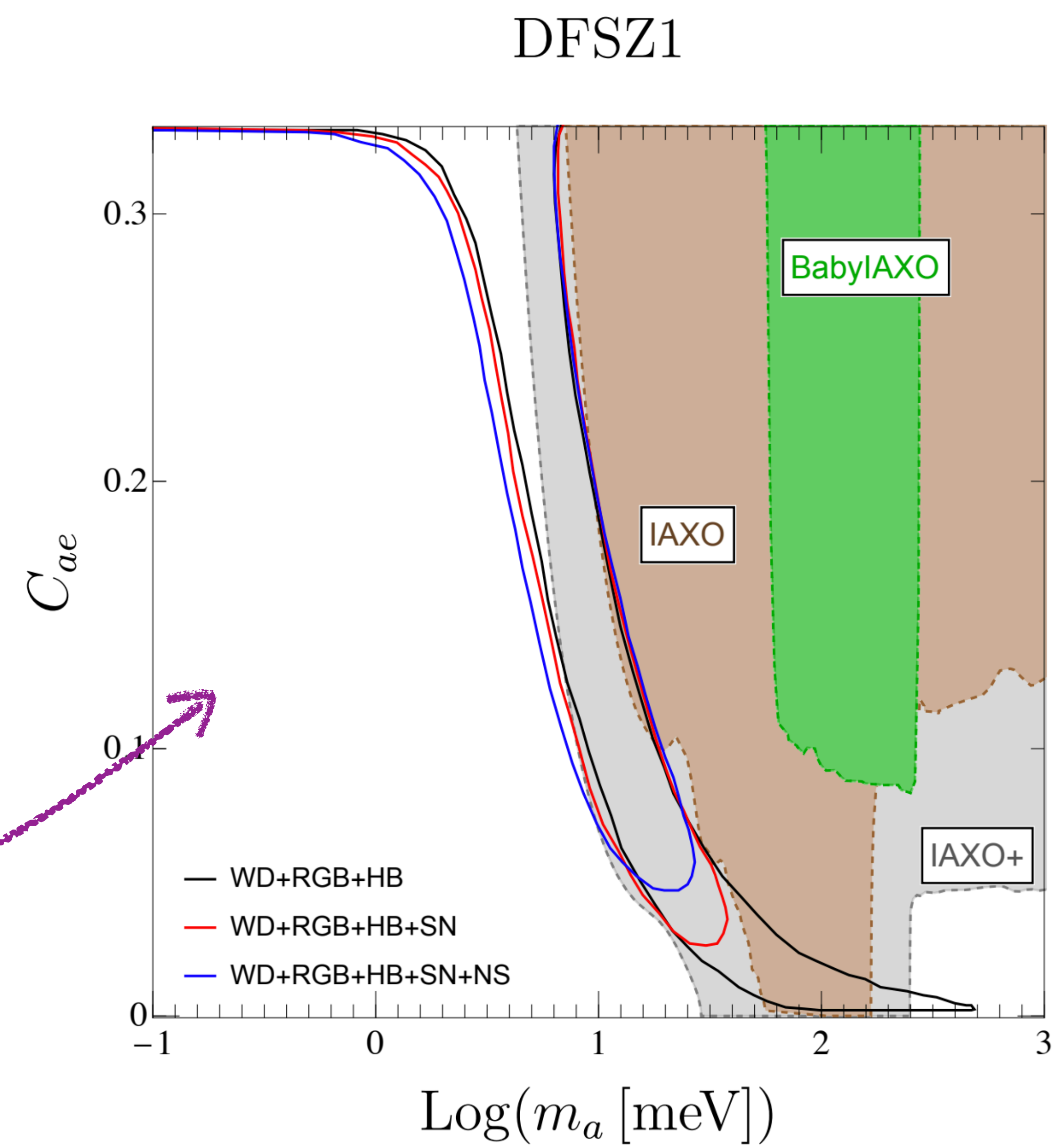
Conceptual Design of BabyIAXO, arXiv:2010.12076 (2020)

Next generation helioscopes

Scale down version (BabyIAXO)
@ DESY.
Commissioning expected in 2026

Example with a specific DFSZ model.
Includes also very stringent bounds
from SN and NS





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

Di Luzio, Fedele, M.G., Mescia, Nardi (2021), arXiv:2109.10368

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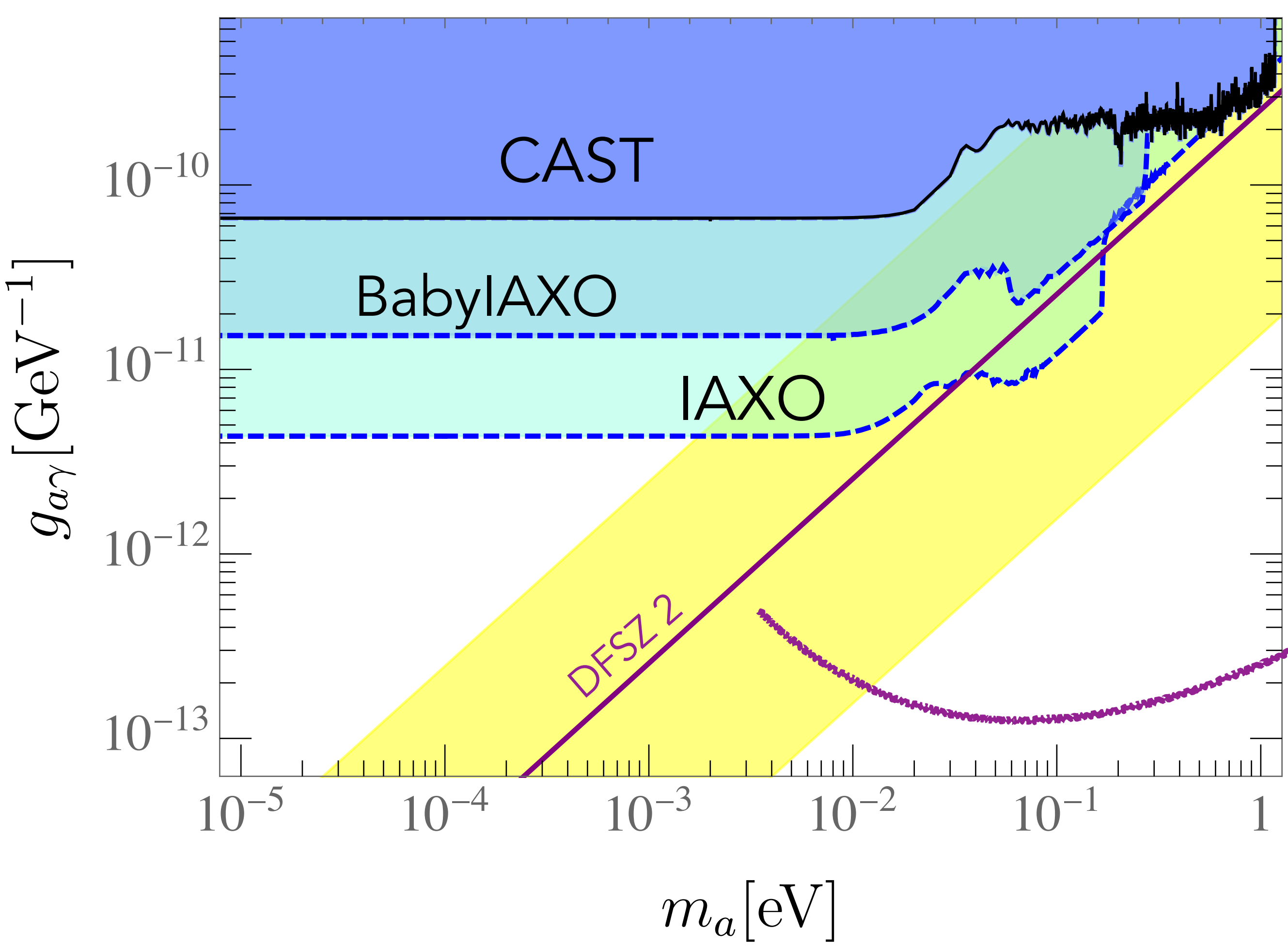

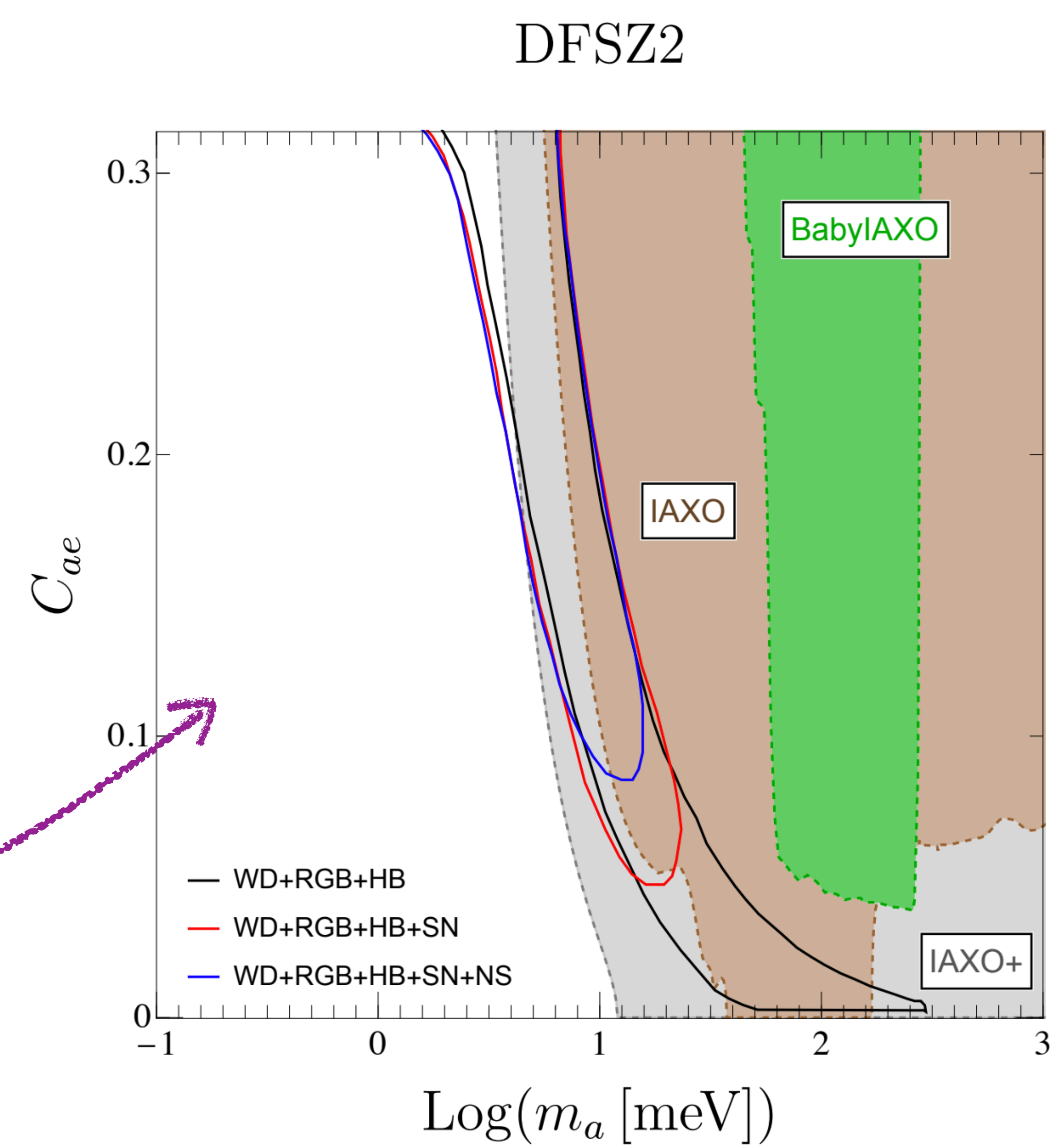

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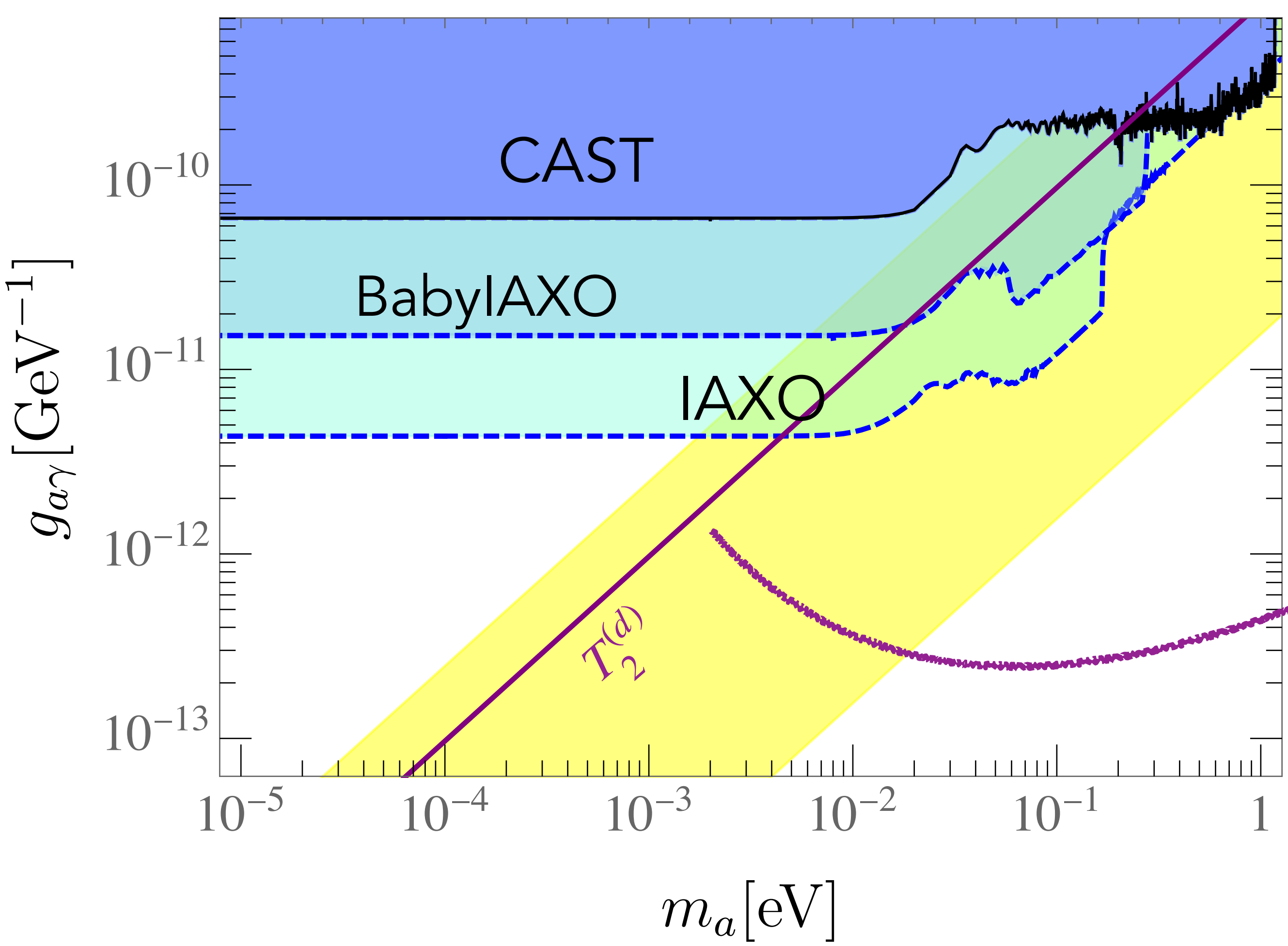

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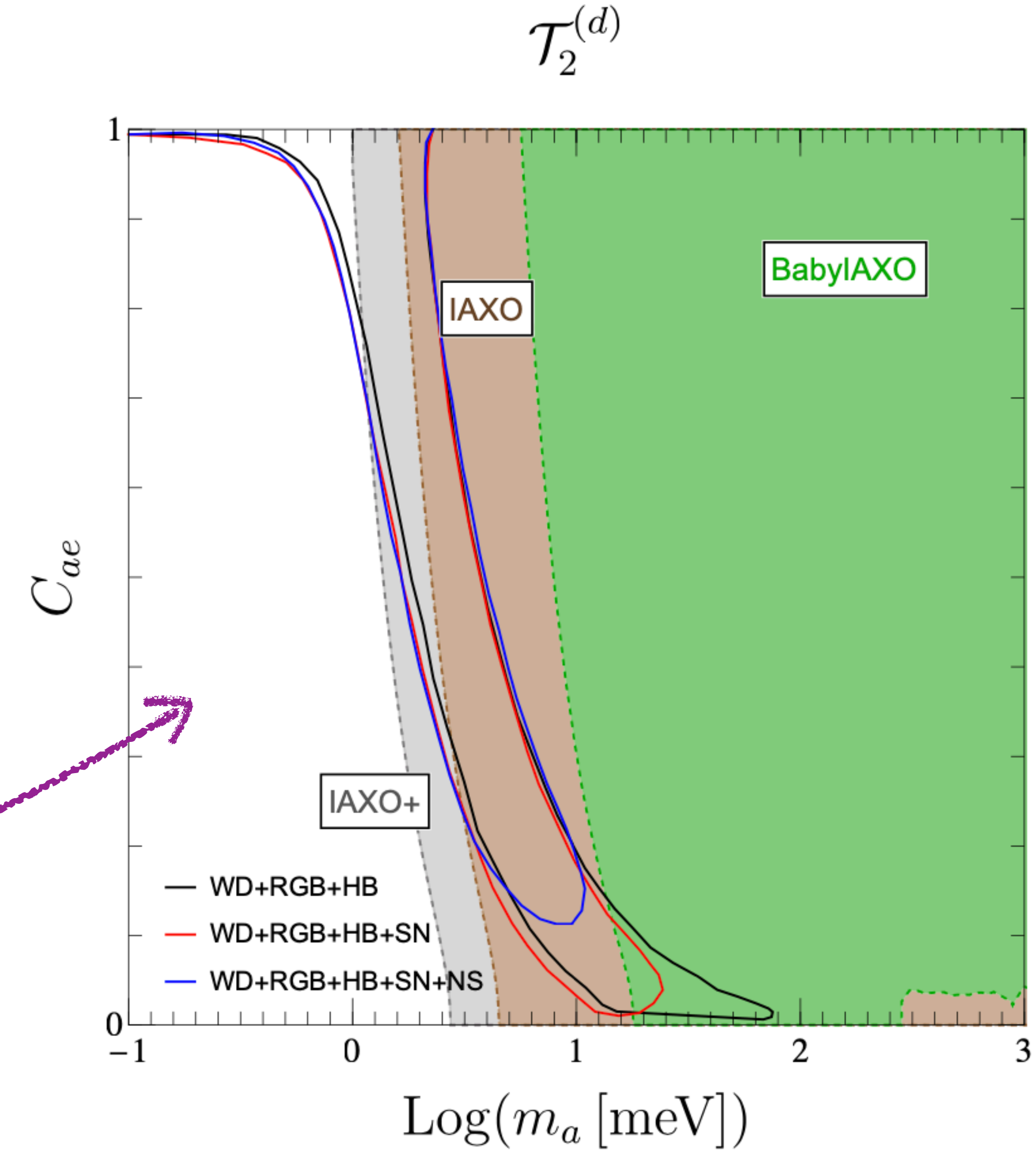


Di Luzio, Fedele, M.G., Mescia, Nardi (2021), arXiv:2109.10368

Other detection strategies for solar axions

Helioscopes based on Axioelectric effect: LUX, XENON1T, …

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

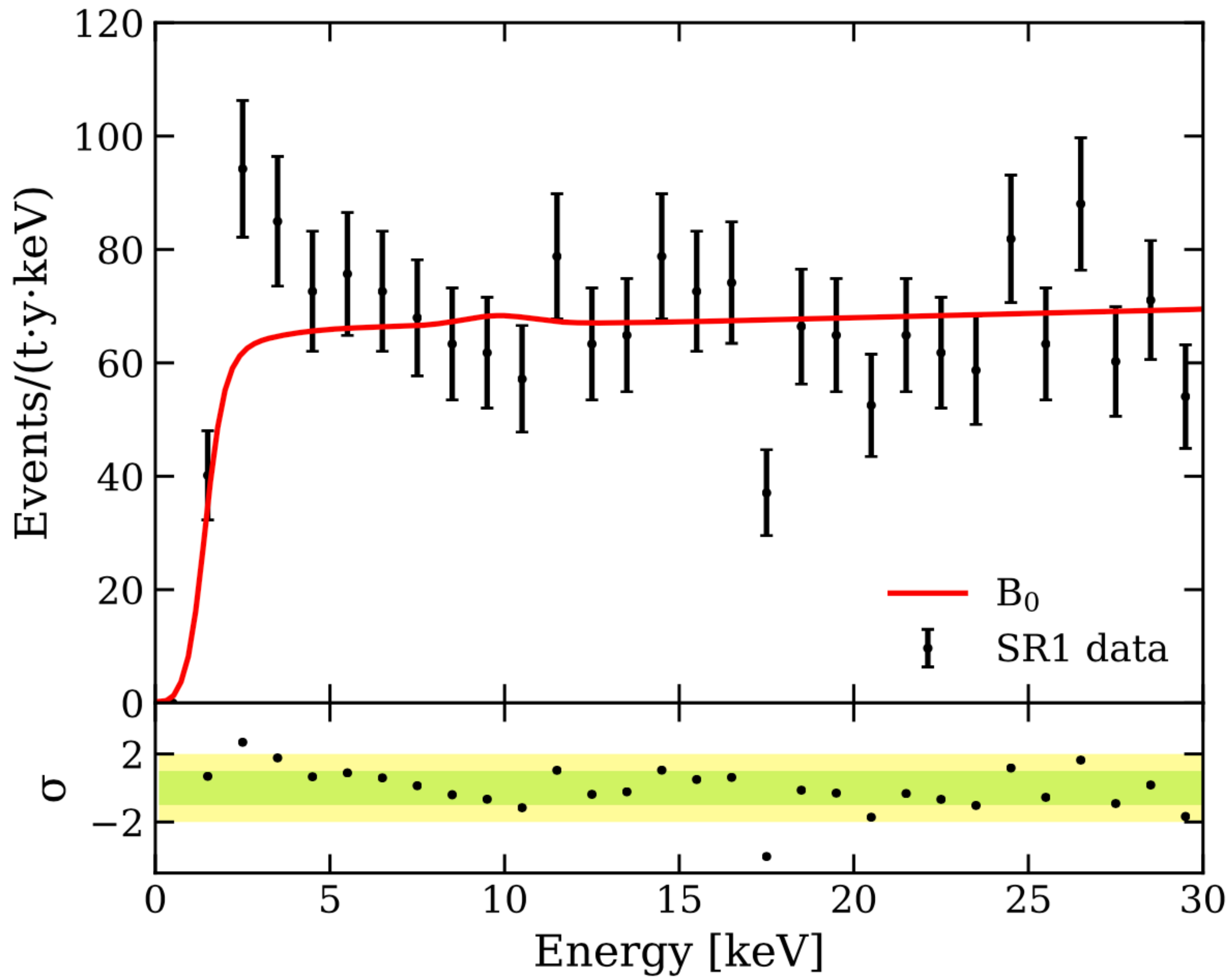
$$\sigma_{ae} = \sigma_{pe} \frac{g_{ae}^2}{\beta} \frac{3E_a^2}{16\pi\alpha m_e^2}\left(1 - \frac{\beta^{2/3}}{3}\right)$$

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

However, they can reach higher masses

Excess Electronic Recoil Events in XENON1T

Solar axions?



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

Stimulated a lot of interesting work on the low energy frontier

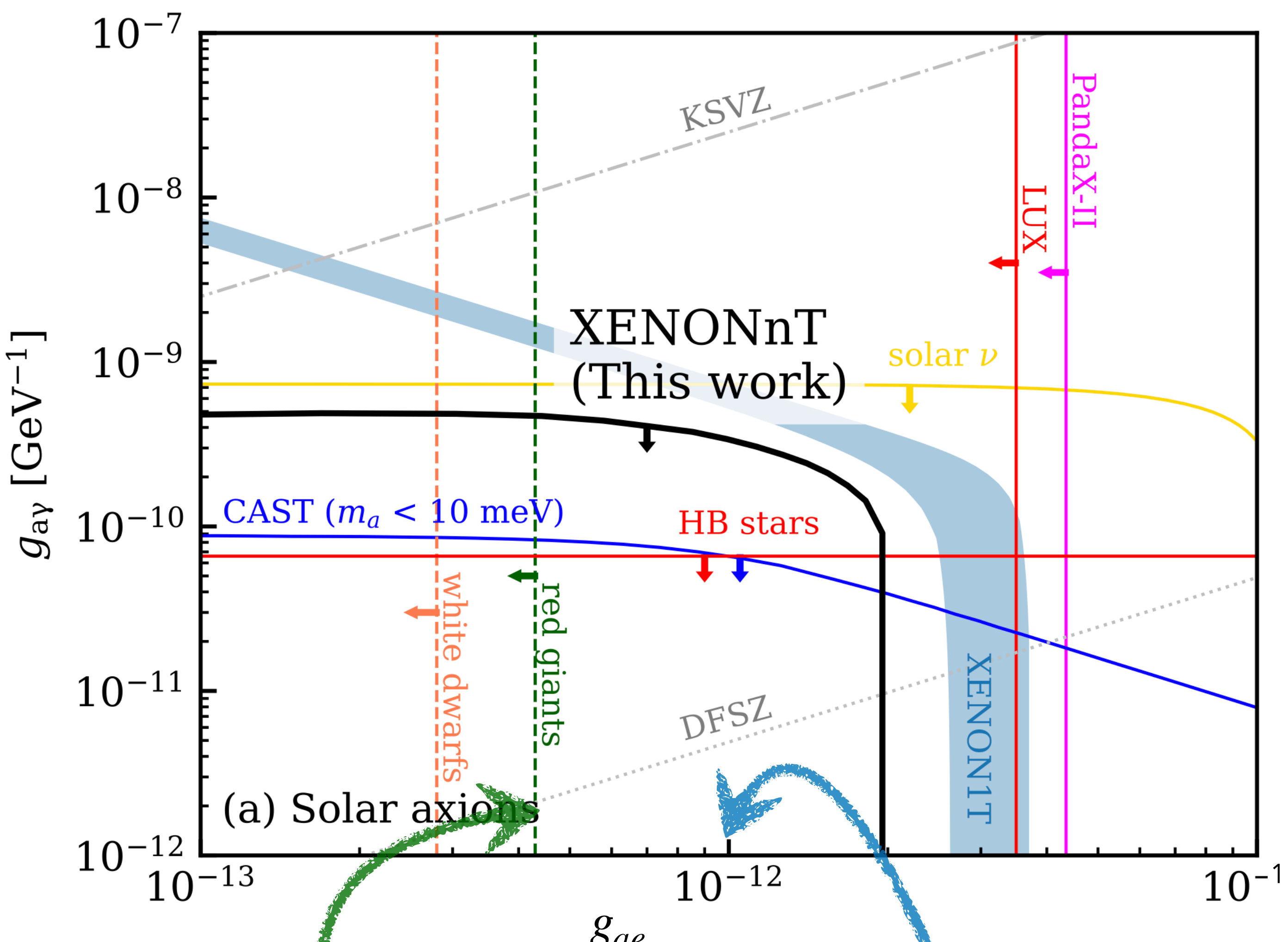
E.g., axions with $g_{ae} \sim 3 \times 10^{-12}$

The value is very large and in tension with stellar evolution

(see talk by O. Straniero)

New results: XENONnT

Solar axions?



RGB bound has been updated
(see talk by O. Straniero)

DARWIN
(Expected potential)

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

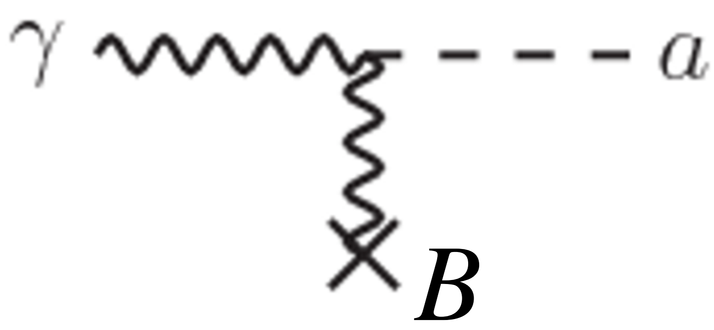
$$g_{ae} \lesssim 2 \times 10^{-12}$$

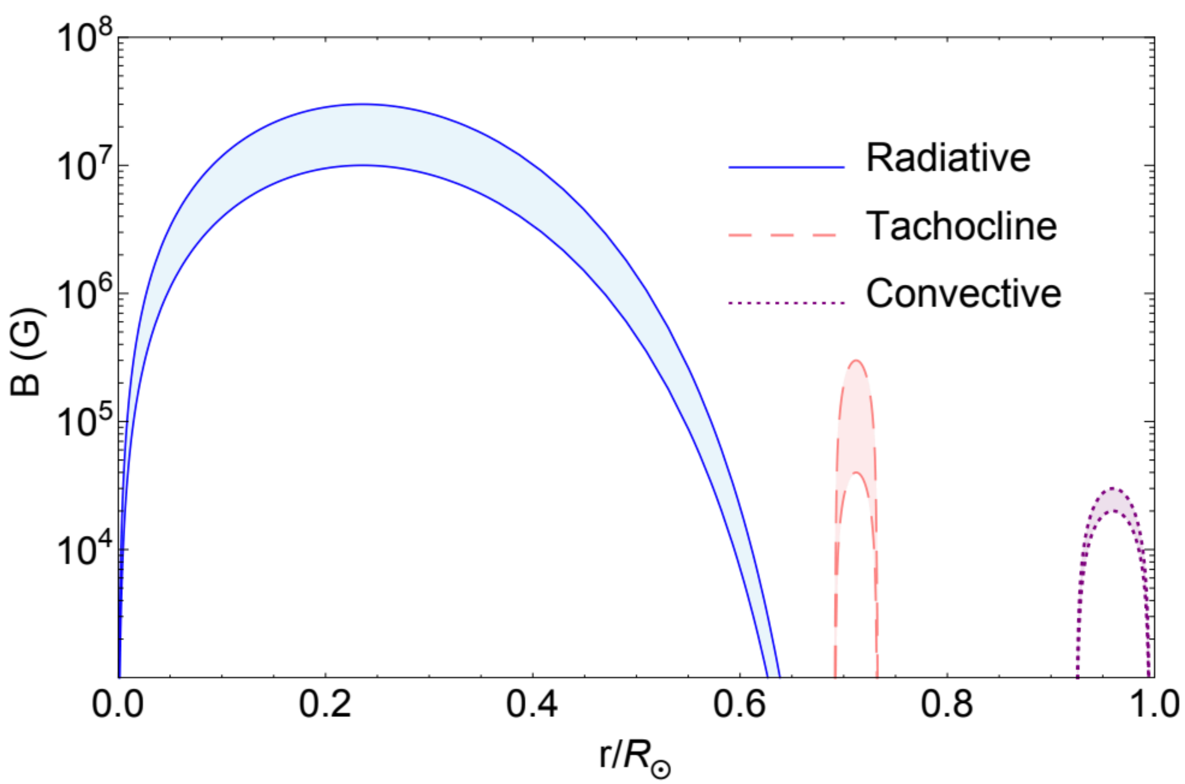
E. Aprile et al., e-Print: 2207.11330 [hep-ex] (2022)

Axions from solar magnetic field?

(More in Backup Slides)

The production in B can take contribution from transverse and longitudinal modes





E. Guarini, P. Carenza, J. Galan, M. G., A. Mirizzi, Phys.Rev.D 102 (2020)

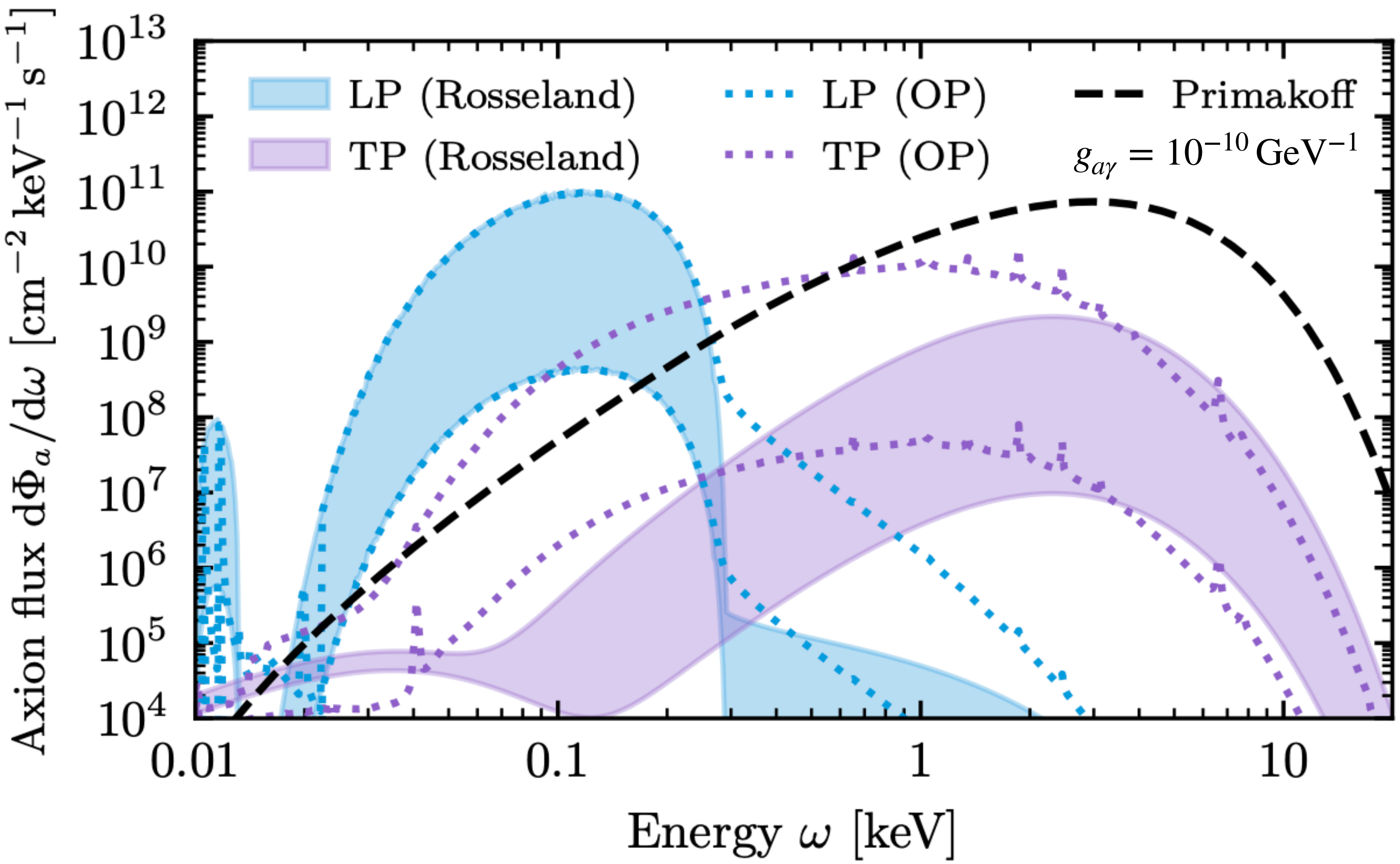
Interior Solar B-field highly uncertain.

Saclay seismic model:
solid benchmark that satisfies observational bounds

S. Couvidat, et al., Astrophys.J. 599 (2003)

Axions from solar magnetic field

(More in Backup Slides)



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

E. Guarini, P. Carenza, J. Galan, M. G., A. Mirizzi, Phys.Rev.D 102 (2020)

A. Caputo, A. J. Millar, E. Vitagliano, Phys.Rev.D 101 (2020)

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

Perhaps accessible in IAXO but requires low-threshold detectors

Some options available:

Metallic magnetic calorimeters (**MMC**) could do the job. Threshold and resolution ~ eV.

Another option is **GridPix** (U. Bonn) with threshold ~tens of eV.

Solar axions from Nuclear Reactions

Recent progress in the search for axions from nuclear reactions in the sun.
Important examples:

$p + d \rightarrow {}^3\mathrm{He} + a$

- Searched by CAST *JCAP* 03 (2010)
- Borexino *Phys.Rev.D* 85 (2012)
- and using previous SNO data Phys.Rev.Lett. 126 (2021)
- Recent analysis of the JUNO sensitivity shows potential to search in unexplored regions G. Lucente, N. Nath, F. Capozzi, MG, A. Mirizzi (2022)

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

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

${}^7\mathrm{Li}^* \rightarrow {}^7\mathrm{Li} + a$

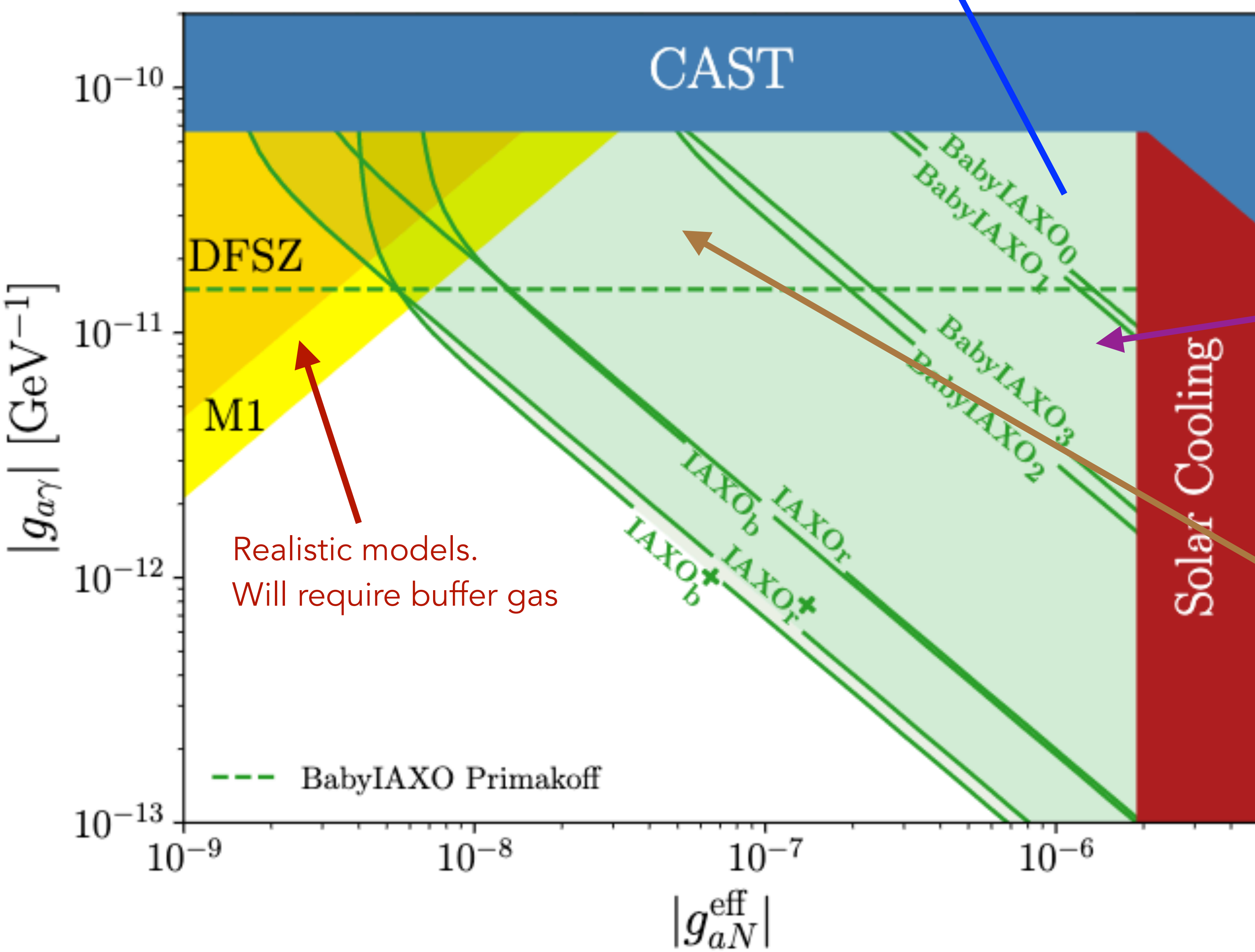
- Searched by Borexino *Eur.Phys.J.C 54 (2008)*
- CAST *JCAP* 03 (2010)

Comprehensive discussion in R. Massarczyk, P.H. Chu, S.R. Elliott, Phys.Rev.D 105 (2022)

Detection of axions from $^{57}\mathrm{Fe}^* \rightarrow {}^{57}\mathrm{Fe} + a\,(14.4\,\mathrm{keV})$

Discovery through both ^{57}Fe and Primakoff. Possibility of understanding couplings relations

Parameter region for massless axions



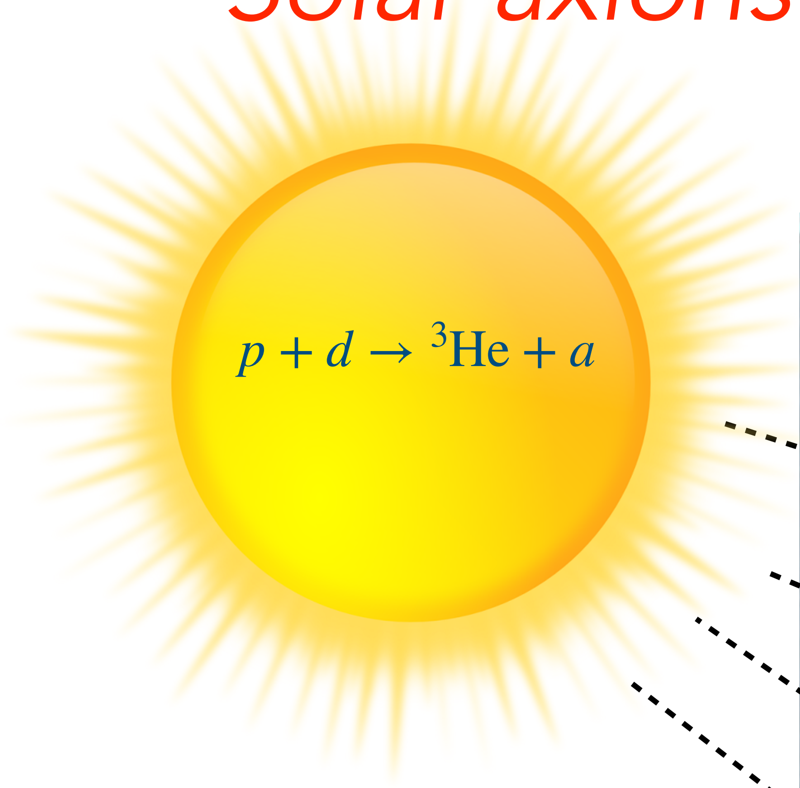
Realistic models.
Will require buffer gas

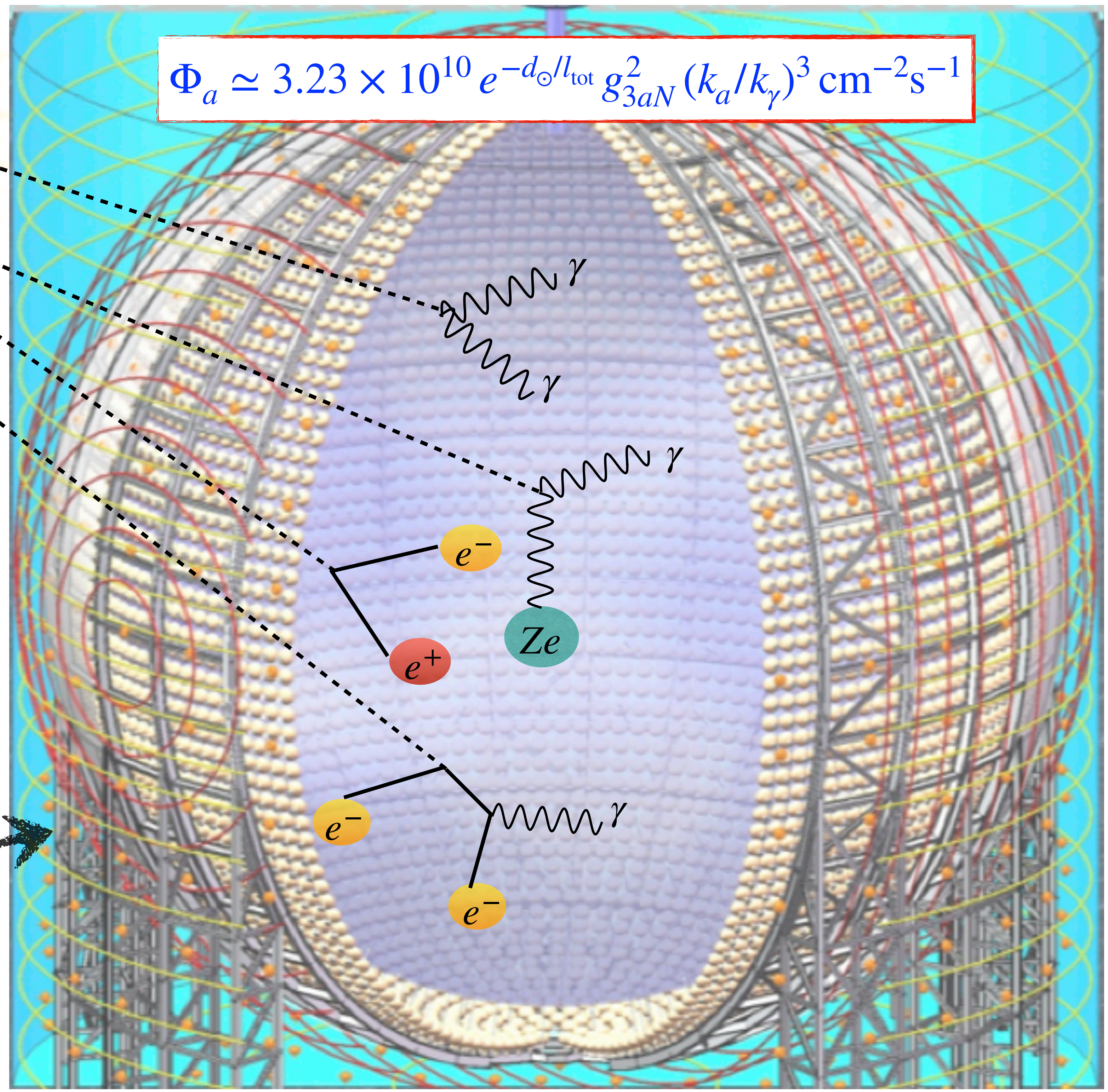
BabyIAXO discovery of axions through ^{57}Fe before Primakoff

BabyIAXO discovery through Primakoff and IAXO detection of ^{57}Fe flux

Di Luzio, Galan, MG, Irastorza, Jaeckel, Lindner, Ruz, Schneekloth, Sohl, Lennert J. Thormaehlen, Vogel Eur.Phys.J.C 82 (2022)

Solar axions with scintillation neutrino detectors





Borexino analysis in 2012
Phys.Rev.D 85 (2012)

Considerable improvement expected with JUNO
G. Lucente et al. (2022)

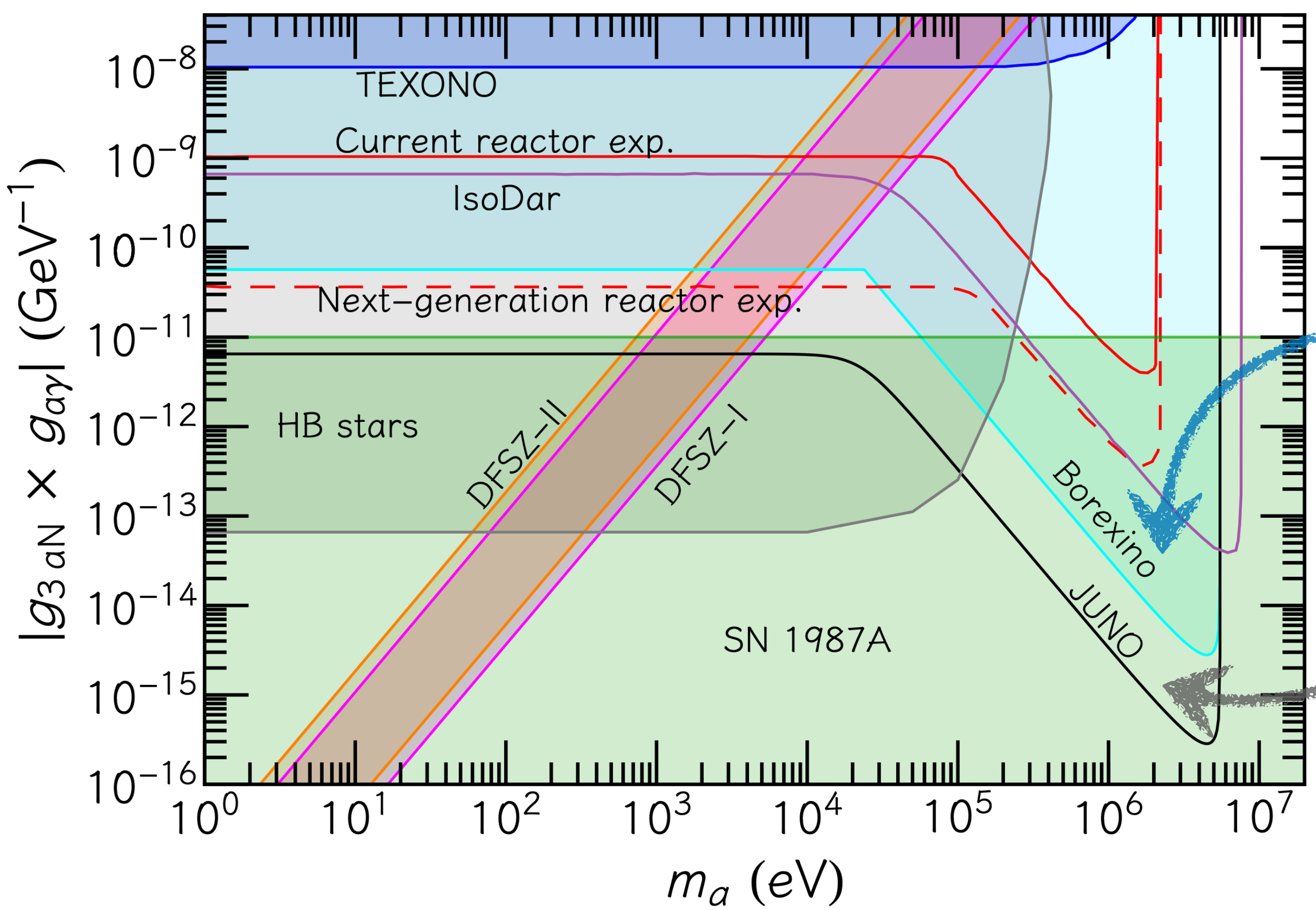
Solar axions with scintillation neutrino detectors

JUNO potential for solar axions

$p + d \rightarrow {}^3\mathrm{He} + a$

$$\Phi_a \simeq 3.23 \times 10^{10}\, e^{-d_\odot/l_{\rm tot}}\, g_{3aN}^2\, (k_a/k_\gamma)^3\, \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Access the MeV mass region! Complementary to SN and Beam Dump Experiments.



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Phys.Rev.D 85 (2012)

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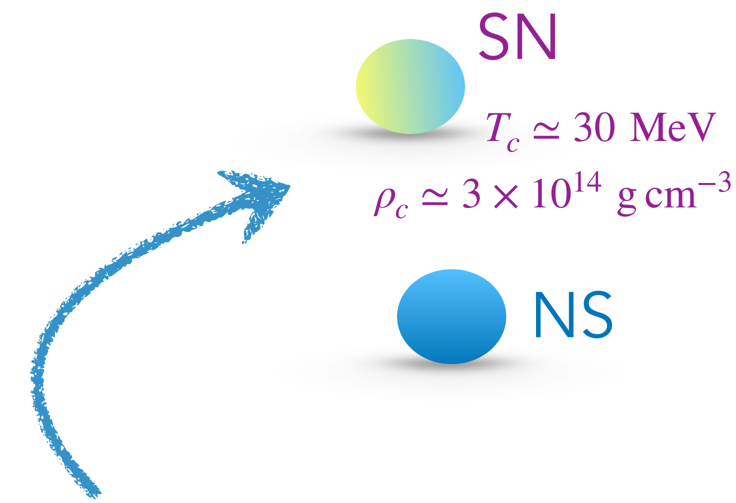
G. Lucente et al. (2022)

G. Lucente, N. Newton, F. Capozzi, MG, A. Mirizzi, e-Print: 2209.11780 [hep-ph] (2022)

Analogous bounds on $|g_{3aN} \times g_{ae}|$ vs m_a

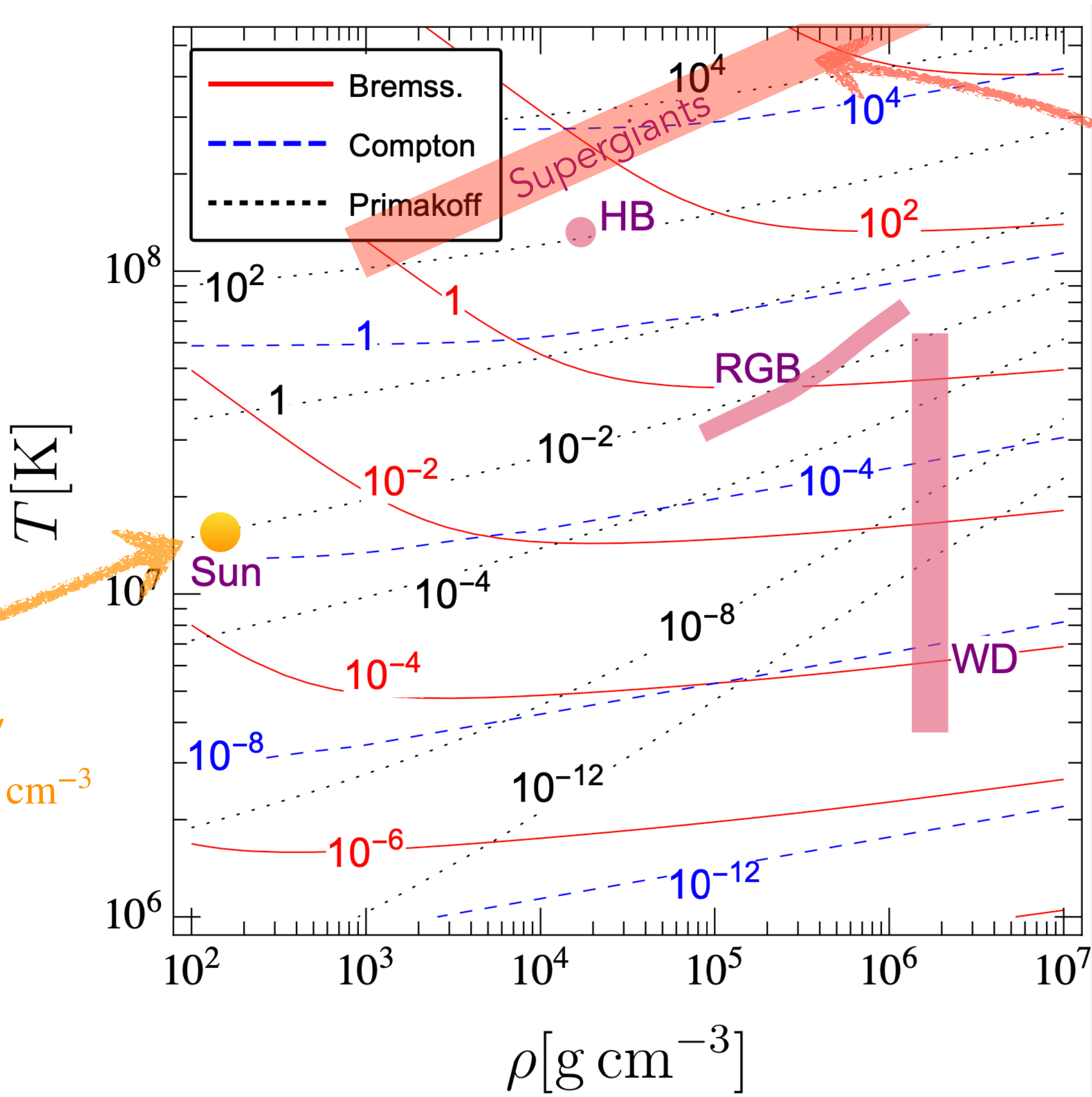
(See backup slides)

Other stars?



Monster Stars

(See talks by G. Raffelt and A. Lella)



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

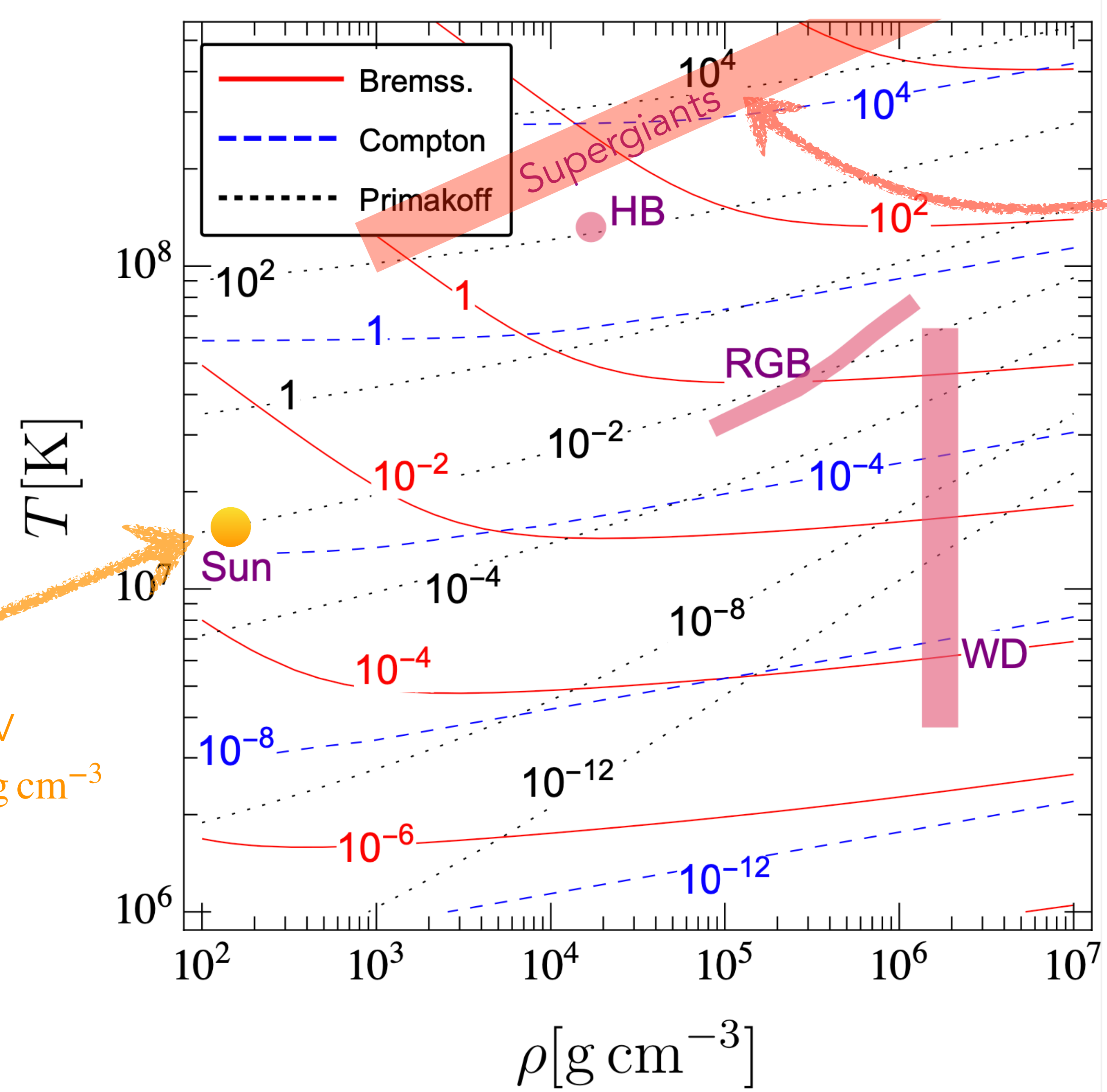
Supergiants:
T_c and ρ_c depend on mass and evolutionary stage

The sun is quite an unremarkable star… but yet, likely, our best bet

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

Supergiant Stars

Axion production is very sensitive to temperature



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

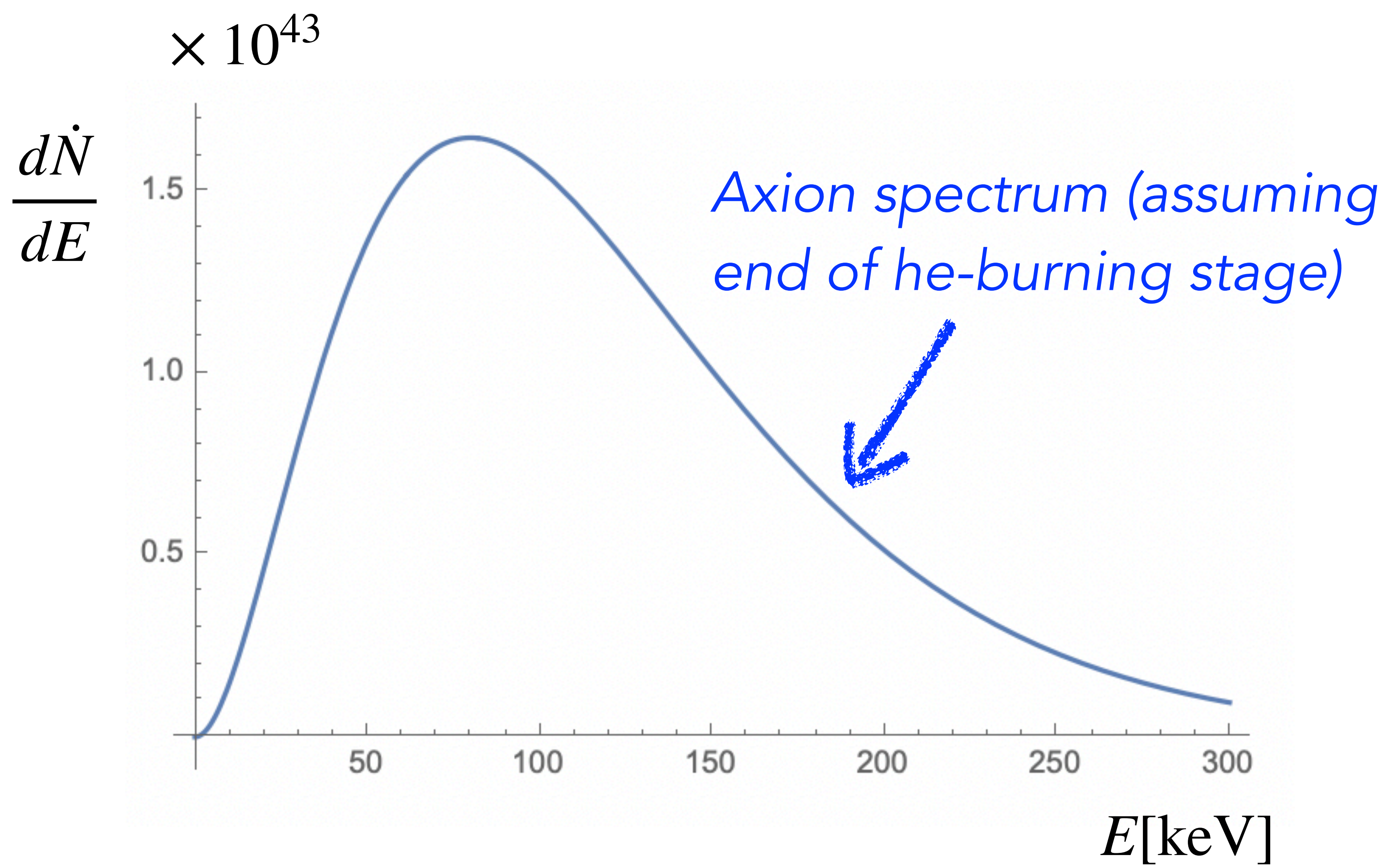
Supergiant stars are much hotter than the sun, especially in late evolutionary stages
→ efficient axion production.

The axion spectrum would offer a very precise map of the supergiant evolution
→ Excellent telescope for supergiant

(More info in backup slides)

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

Betelgeuse, a case study



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

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

Too little for current experiments!

Betelgeuse, a case study

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

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

(Assuming B uniform)

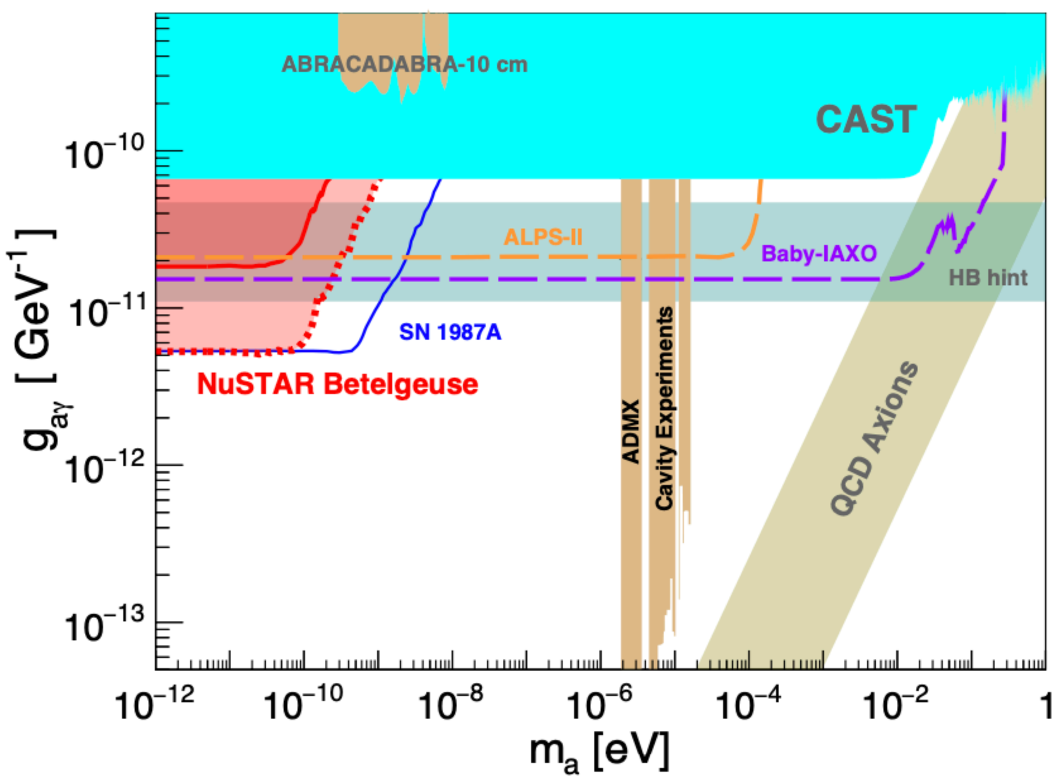
$g_{11} \leq 6.5$ from helioscope (CAST) bound

The distance drops!

However, there is a very high price to pay!

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

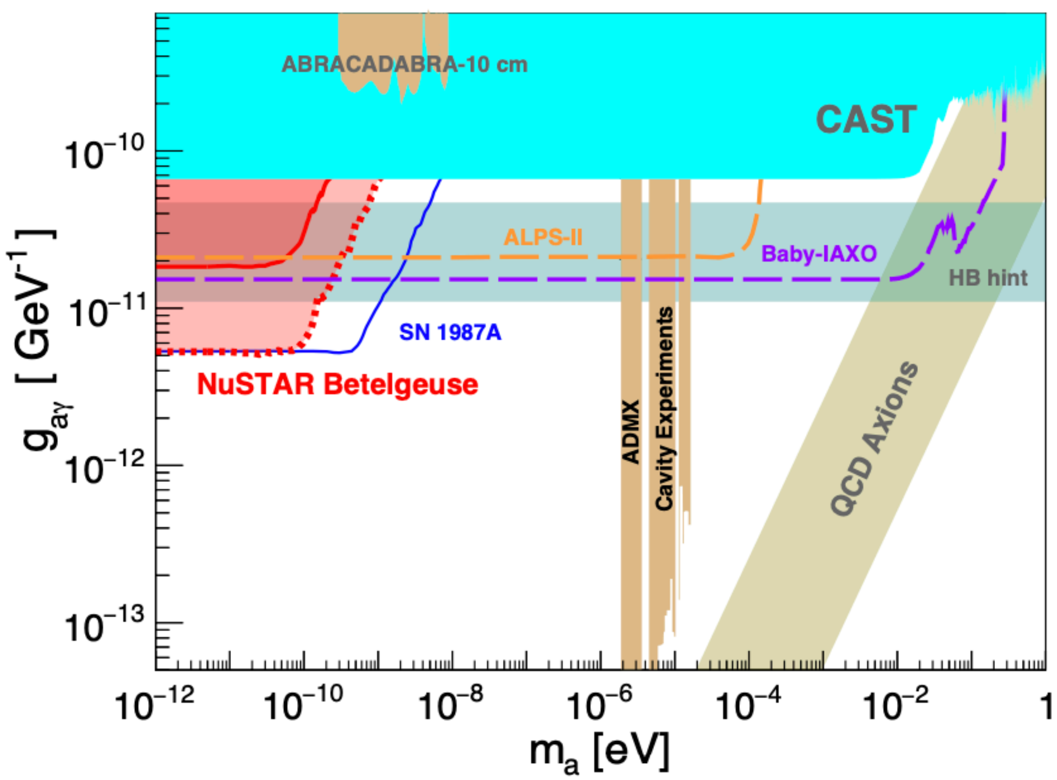
Betelgeuse, a case study



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 (2022) [e-Print: 2204.03121]*

… and Super Star Clusters



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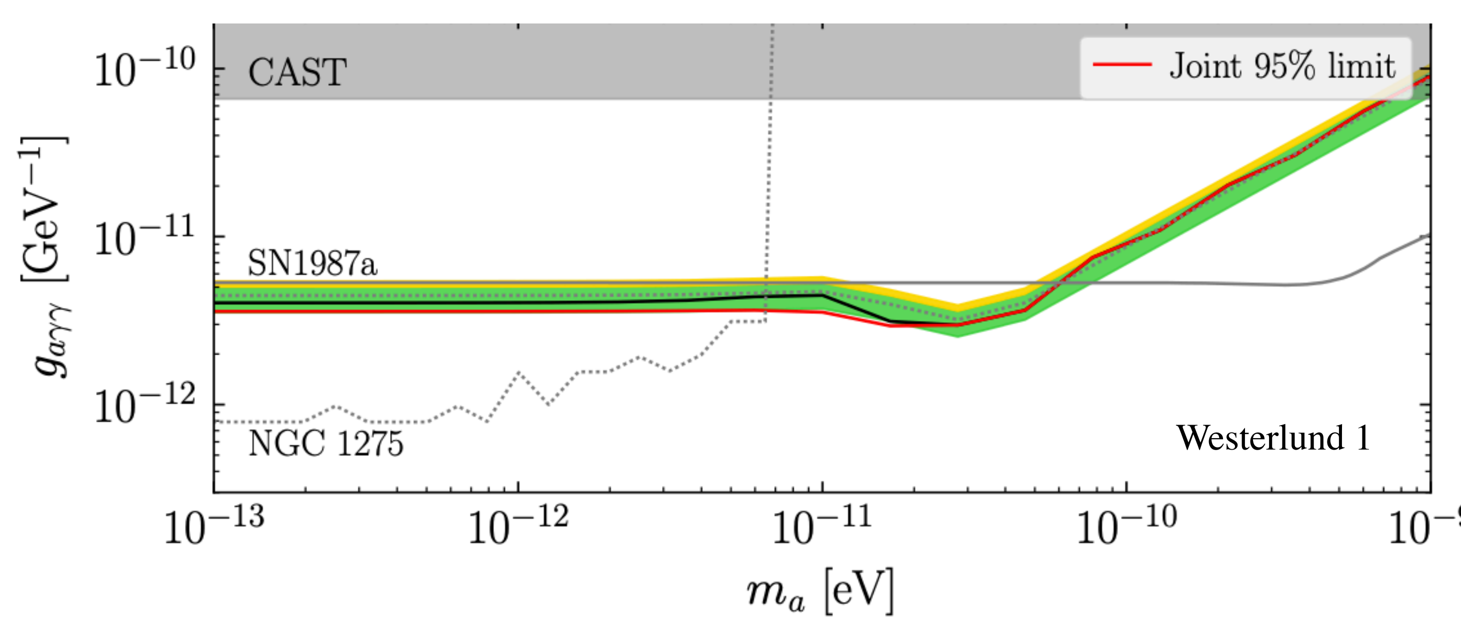
- *Xiao, Carenza, M.G., Mirizzi, Perez, Straniero, Grefenstette (2022) [e-Print: 2204.03121]*

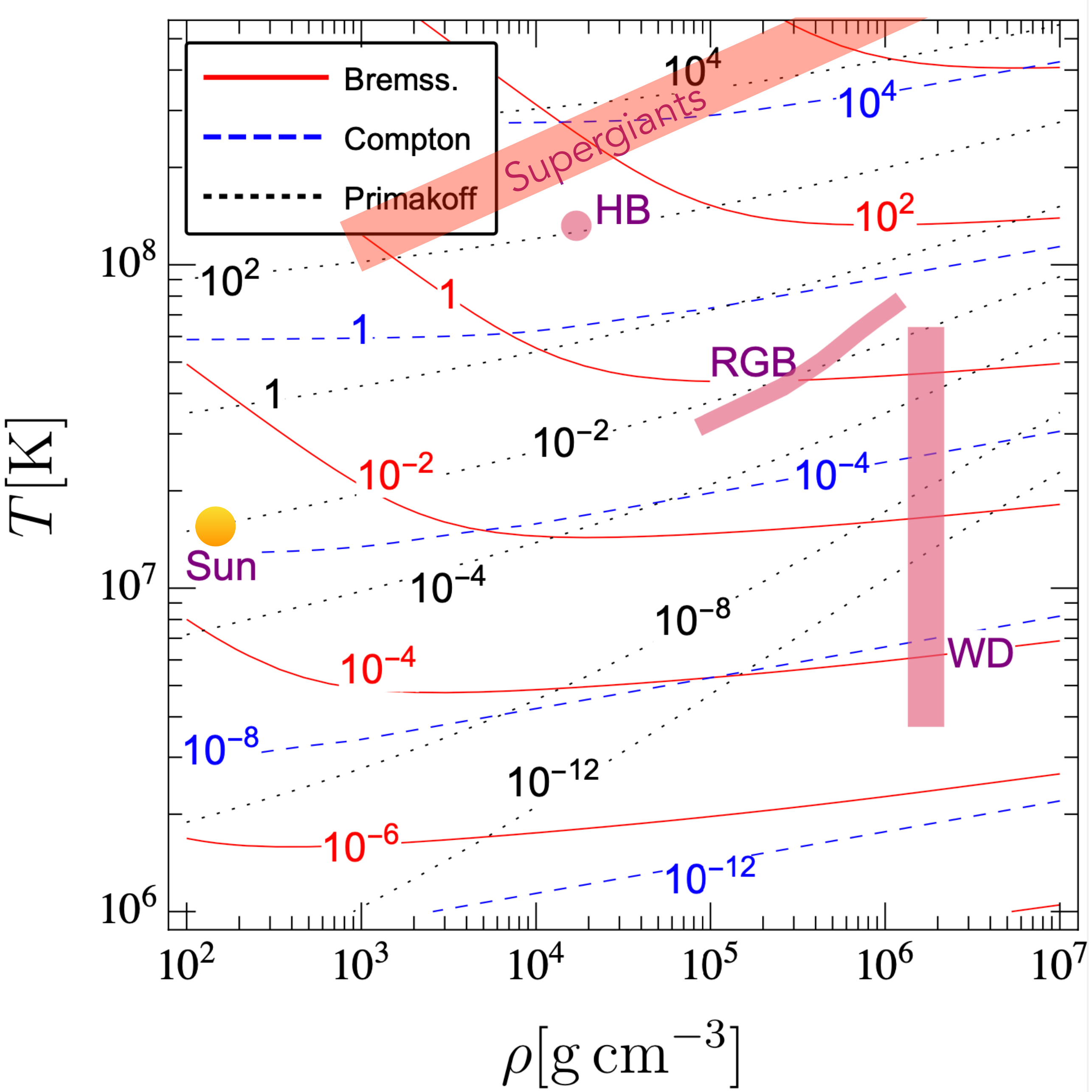
Similar result from observations of Super Star Clusters

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



Supernova axions

(See G. Raffelt Talk)



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

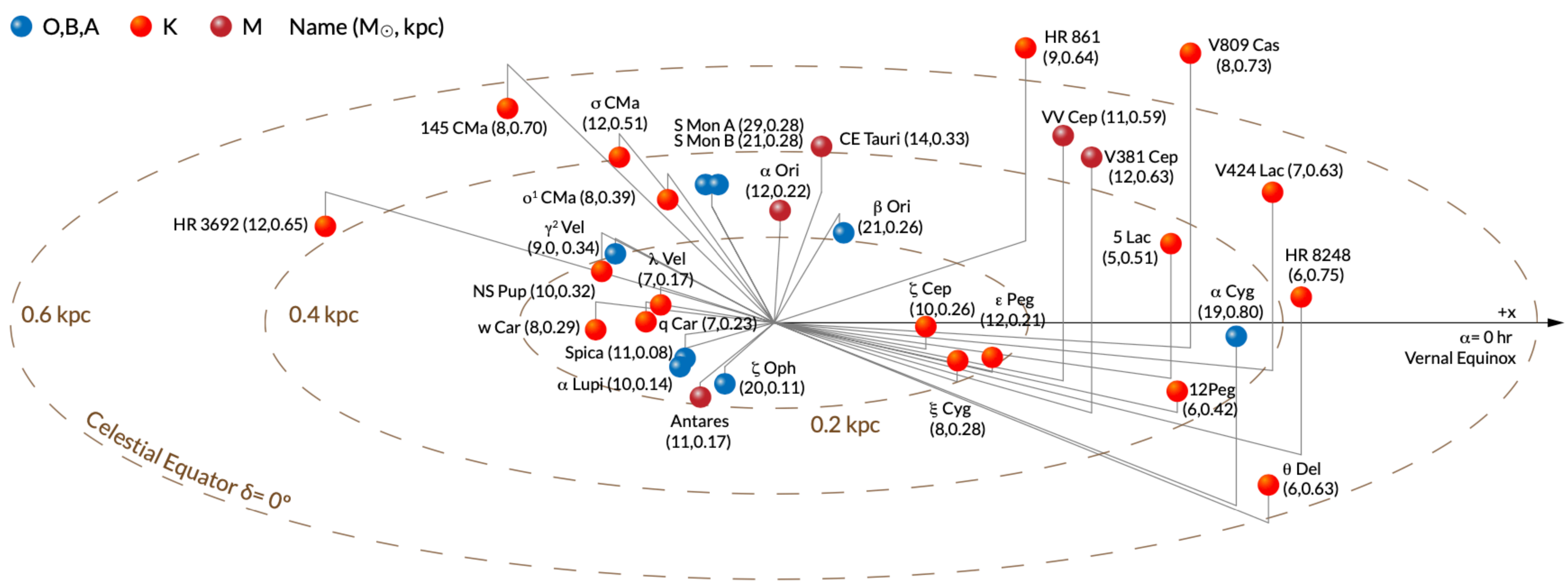
About $\sim 10^{13}\,\mathrm{cm^{-2}\,s^{-1}}$ axions on Earth from Betelgeuse

Huge flux… but short!

Where should we look ?

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

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



31 candidates within 1 kpc from the sun.

SN Axions

There are studies on detection of SN axions.
Among the proposals:

- $a \rightarrow \gamma$ *in galactic magnetic field* $\longrightarrow$ *e.g., Fermi LAT*

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

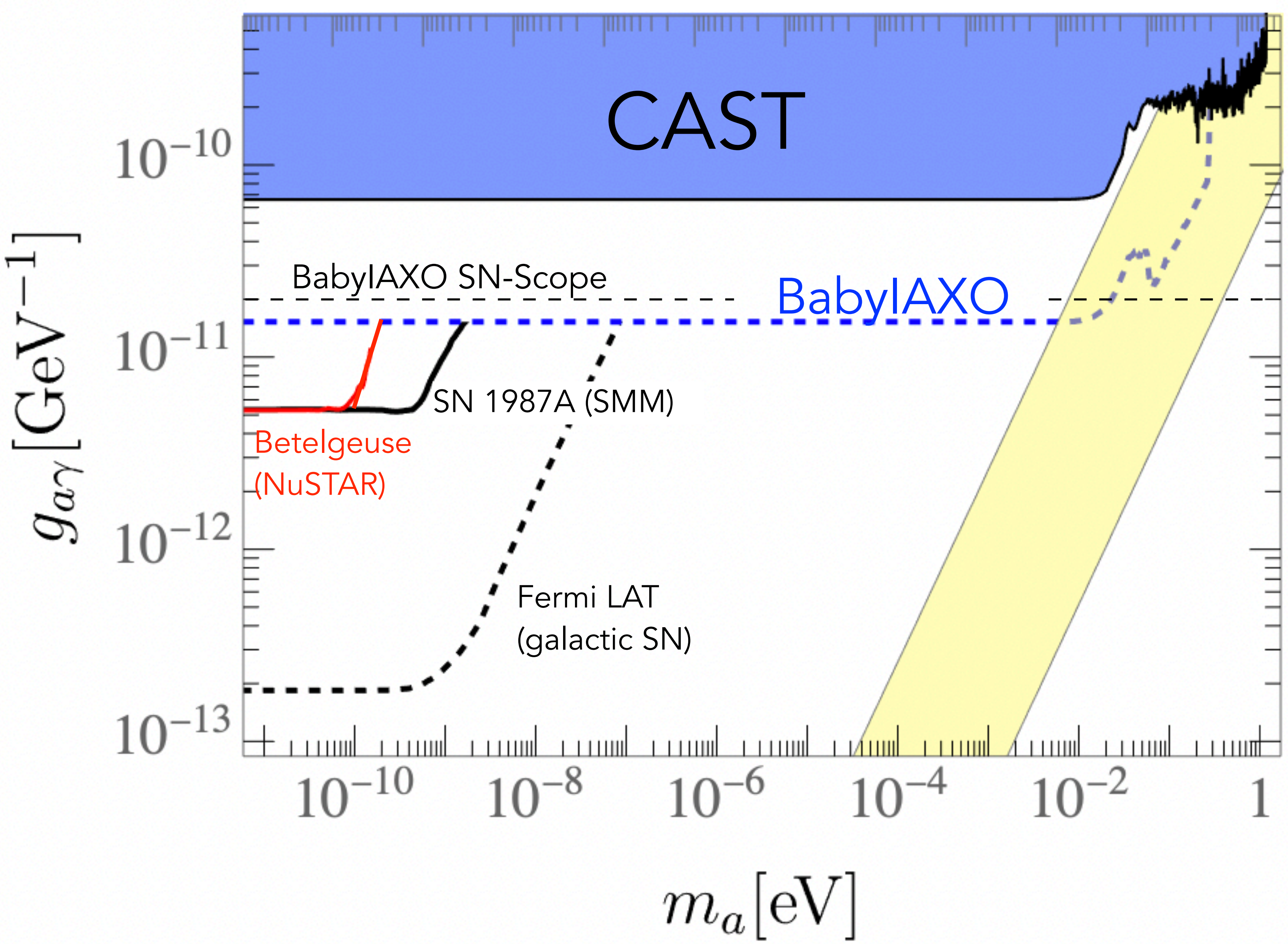
- *Direct detection with IAXO*

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

… but there is still a lot of work to do in this direction

(More in Backup Slides)

Overview



Solar Axion

Supergiant Axions

SN Axions

Current bounds

Estimated sensitivities

Benchmark QCD models

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 close by candidates • Direct detection may be possible but more studies are required • At very low mass, strong potential for detection with γ-ray observatories (e.g., Fermi LAT) • At high mass, possible detection of decay products *(see talk by Eike Mueller)*

Conclusions and final considerations

- The sun is an excellent source of axions. Detection can occur with different ways and through various channels.
- Detection of axions from stars other than the sun is also possible and could be efficient in some regions of the parameter space.
- Personal opinion: We need good ideas for next generation instruments to probe the ~100 keV (post NuSTAR) and the ~100 MeV (post Fermi-LAT) photon spectrum.
- *Exiting time. A lot of work and many new results since 2020*

Backup Slides

Comments

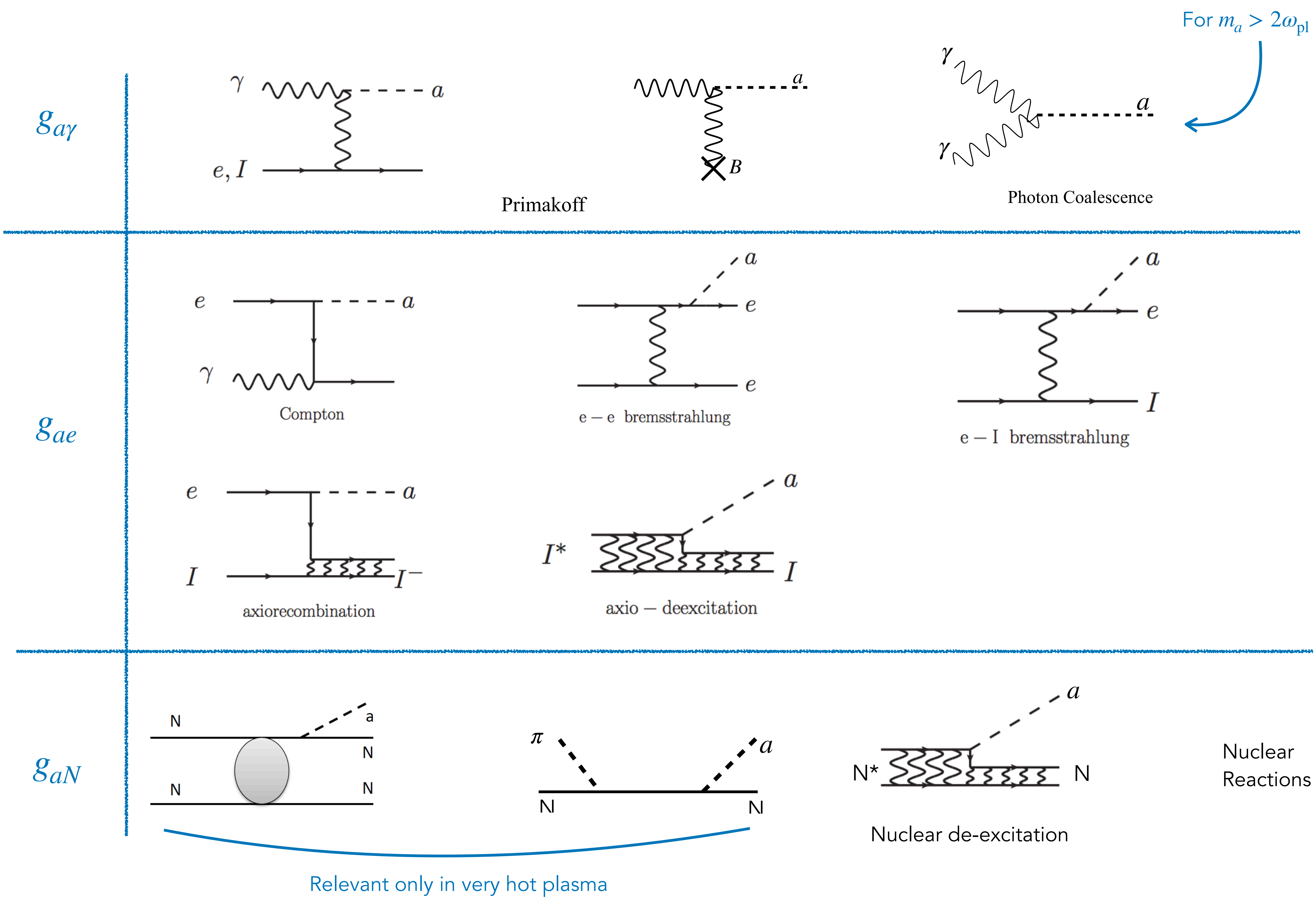
Besides the sun, the only chance to detect stellar axions is from supergiants of SNe, at energies of ~100 keV or ~100 MeV. In my opinion we are missing proposals to follow up on NuSTAR and Fermi LAT in that energy range.

NuSTAR: unique position in X-Ray astronomy as it operates at high energy (3-79 keV). It is very difficult to focus down the E>10 keV X-rays. Even near future telescopes may not be as efficient at energies above ~ 10 keV or so.

A new mission concept in the Astro2020 decadal survey called HEX-P (the High-Energy X-ray Probe), would expand the NuSTAR bandpass in both directions, with more sensitivity (as well as finer angular resolution). However, still just a concept. [*private communication from Brian Grefenstette*]

Very important. We need a better understanding of the local magnetic field.

Stellar axions



Axion Telescopes for Supergiant Stars

Axion telescopes for massive stars

Model	Phase	t_{cc} [yr]	$\log_{10}(L_{\rm eff}/L_\odot)$ (Photons)	$\log_{10}(T_{\rm eff}/{\rm K})$ (Photons)	C (Axions)	E_0 [keV] (Axions)	β (Axions)
0	He burning	155000	4.90	3.572	1.36	50	1.95
1	before C burning	23000	5.06	3.552	4.0	80	2.0
2	before C burning	13000	5.06	3.552	5.2	99	2.0
3	before C burning	10000	5.09	3.549	5.7	110	2.0
4	before C burning	6900	5.12	3.546	6.5	120	2.0
5	in C burning	3700	5.14	3.544	7.9	130	2.0
6	in C burning	730	5.16	3.542	12	170	2.0
7	in C burning	480	5.16	3.542	13	180	2.0
8	in C burning	110	5.16	3.542	16	210	2.0
9	in C burning	34	5.16	3.542	21	240	2.0
10	between C/Ne burning	7.2	5.16	3.542	28	280	2.0
11	in Ne burning	3.6	5.16	3.542	26	320	1.8
12	beginning of O burning	1.4	5.16	3.542	27	370	1.8

Axions are sensitive to the evolution and can pin down t_{cc} from $\sim 10^{-5}$ yr

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

$$\frac{d\dot{N}_a}{dE} = \frac{10^{42} C g_{11}^2}{\text{keV s}} \left(\frac{E}{E_0}\right)^{\beta} e^{-(\beta+1)E/E_0}$$

Axion spectrum

Axions are sensitive to all late evolutionary stages. Surface photons are not.

Observing Betelgeuse with NuSTAR

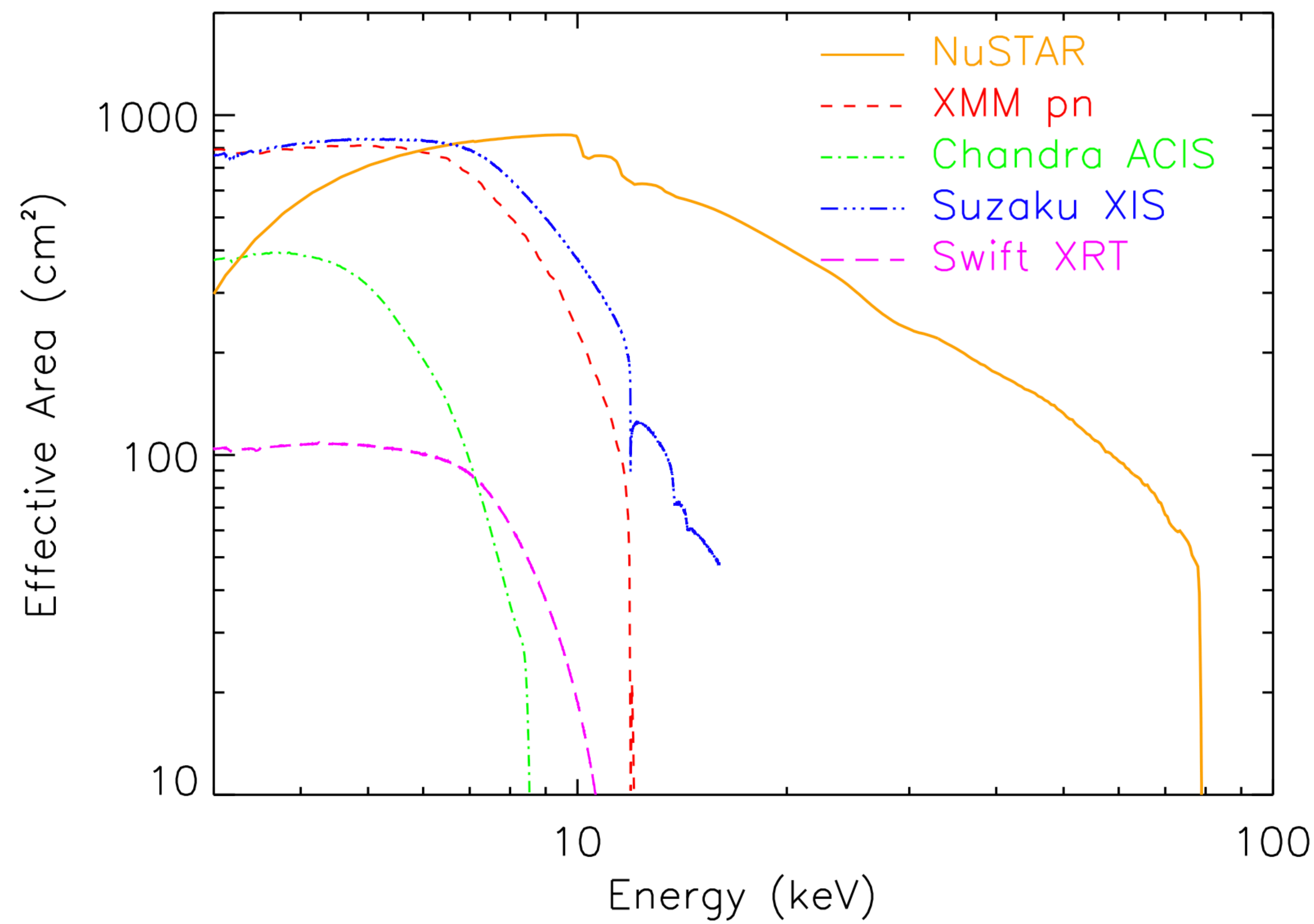
NuSTAR: NUclear Spectroscopic Telescope ARray

Best existing instrument to detect the expected X-ray flux.

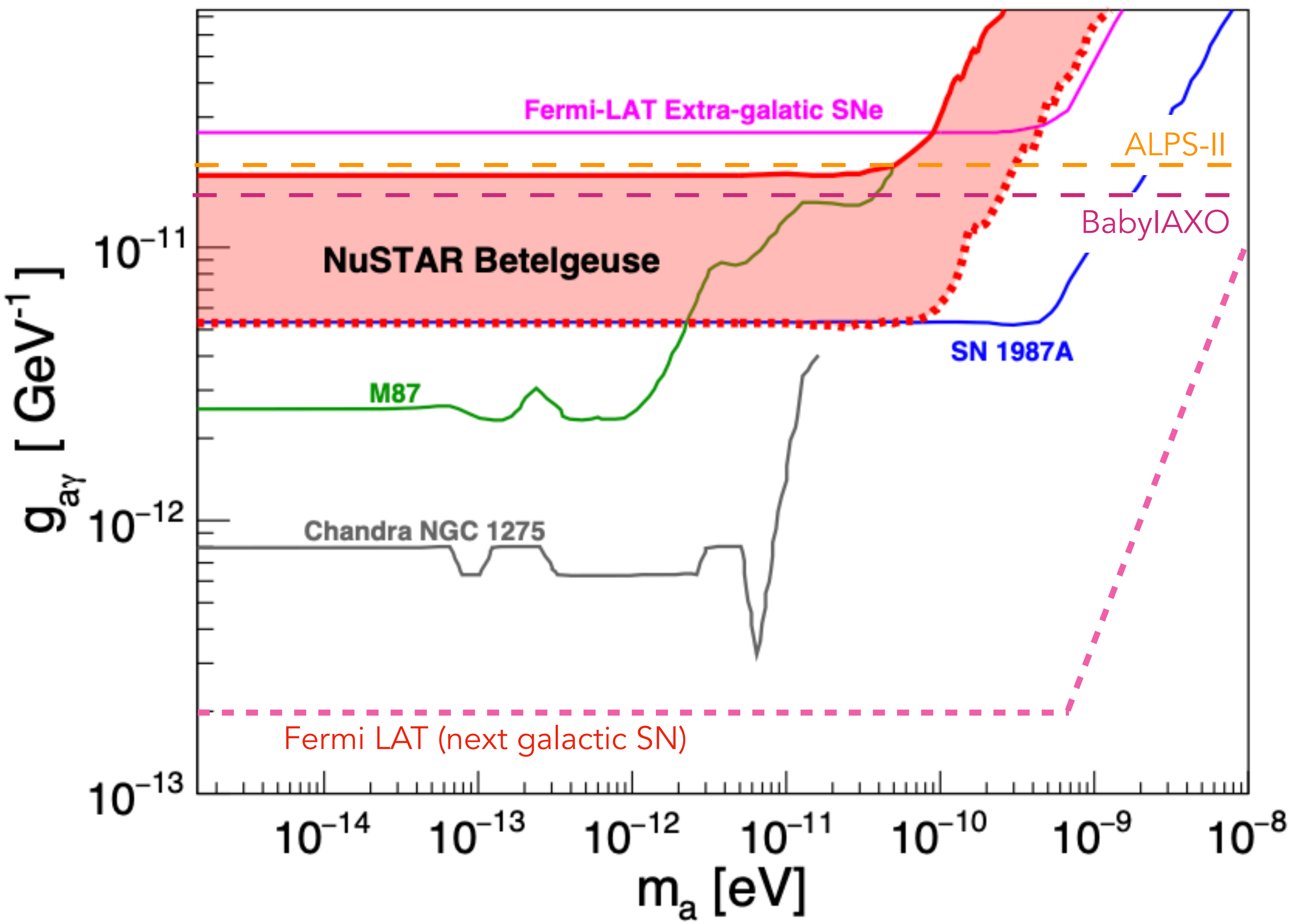
First focusing high-energy X-ray (3–79 keV) telescope in orbit.

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)



Meyer et al., Phys. Rev. Lett. 124, 231101 (2020),

Xiao et al, to appear in PRL (2020)

Dessert, Foster, Safdi, (2020), to appear in PRL (exclusion region similar to Xiao et al.)

Payez et al., J. Cosm 02, 006 (2015).

M.C. D. Marsh et al., J. Cosmol. Astropart. Phys. 12, 036 (2017),

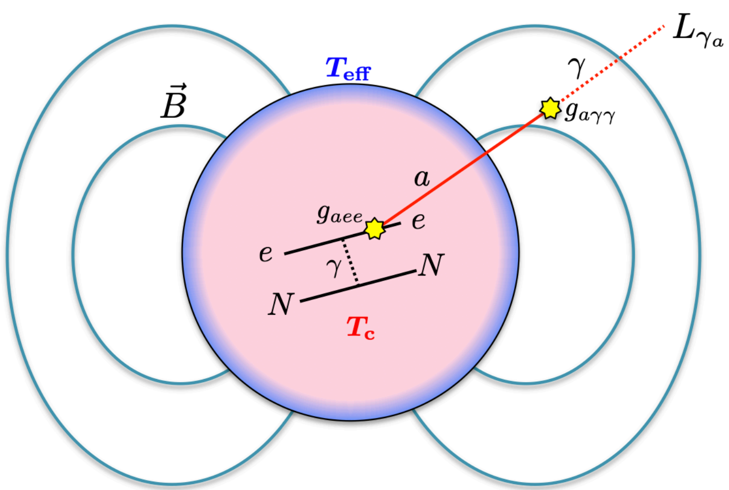
Reynolds et al., Astrophys. J. 890, 59 (2019),

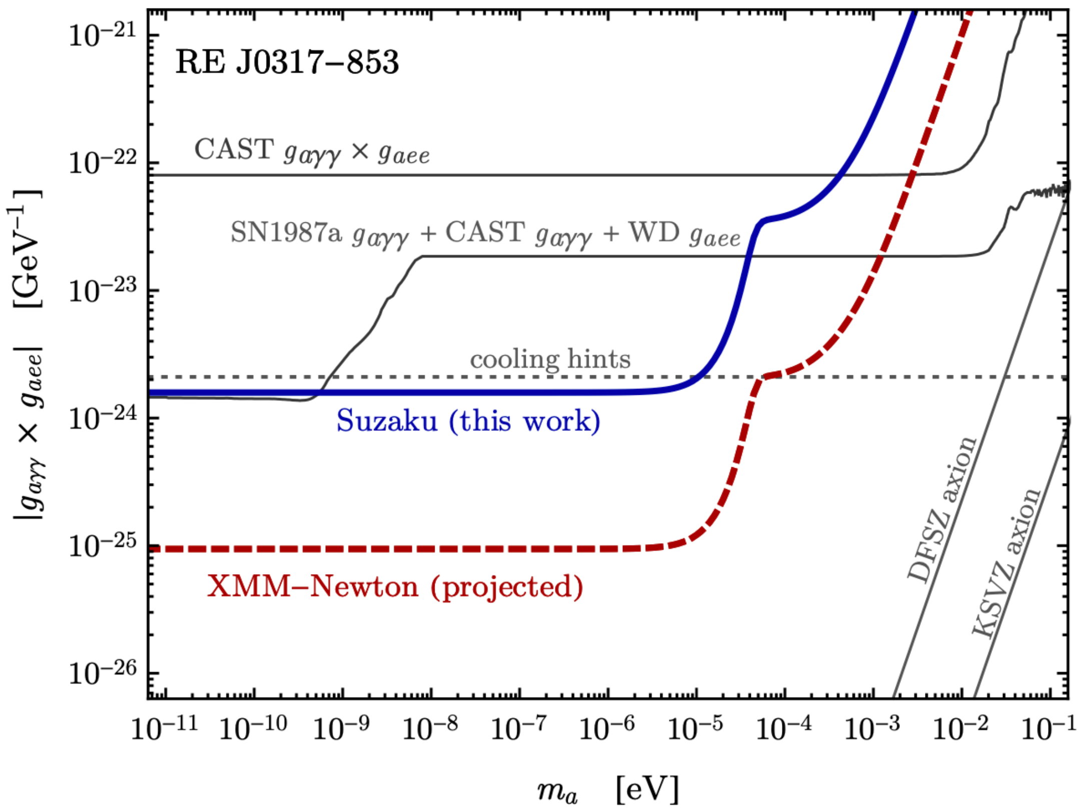
Meyer et al., Phys.Rev.Lett. 118 (2017)

Xiao, Perez, M.G., Straniero, Mirizzi, Grefenstette, Roach, Nynka [arXiv:2009.09059]

What can be see through B-fields

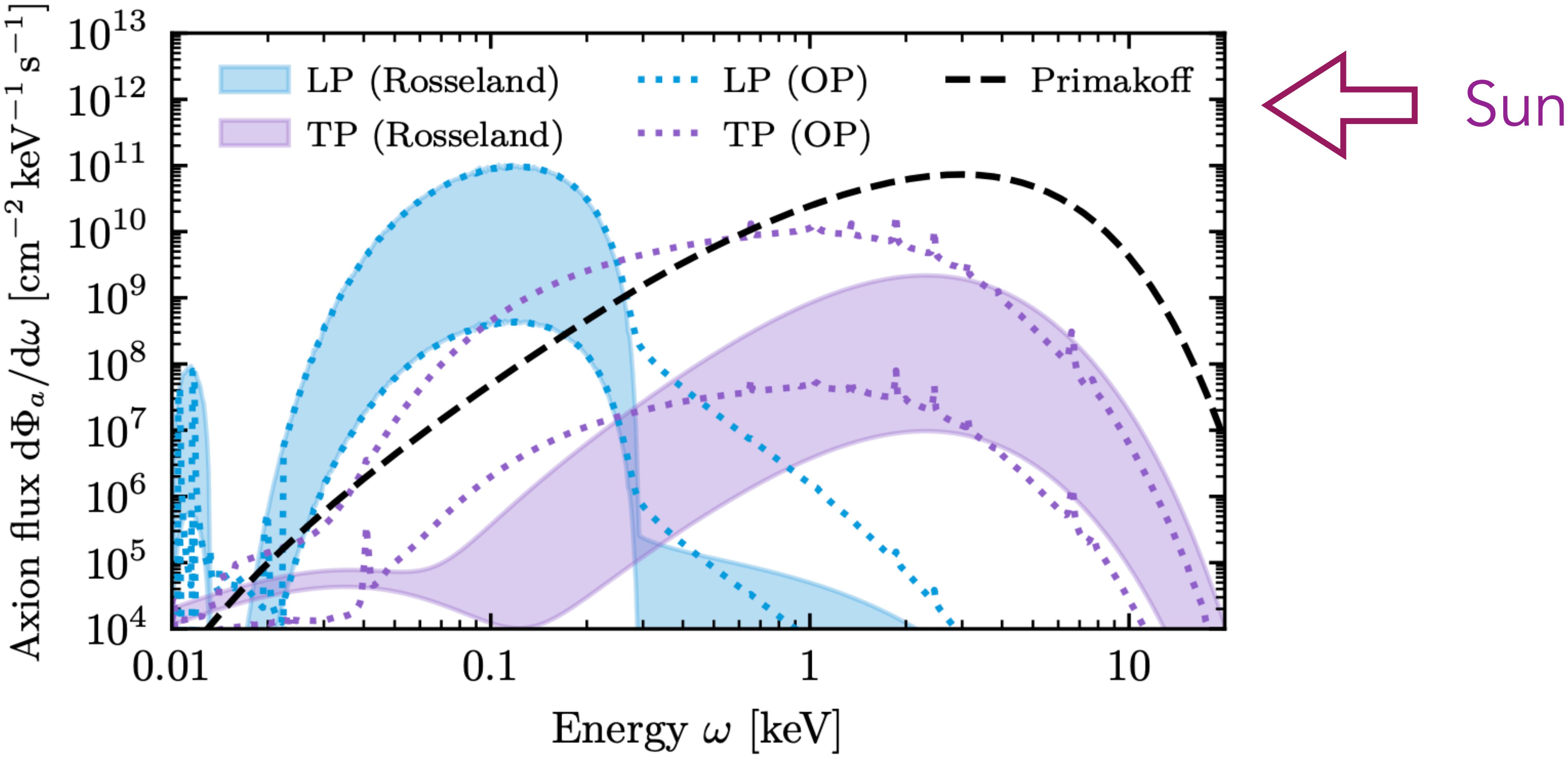
Rather than converting in the galactic magnetic field, the conversion could happen directly in the stellar magnetosphere





C. Dessert, A J. Long, B. R. Safdi, Phys.Rev.Lett. 123 (2019)

Axions from Solar Magnetic Field



S. Hoof, J. Jaeckel, L. J. Thormaehlen, arXiv:2101.08789 (2021)

SN analysis in preparation,

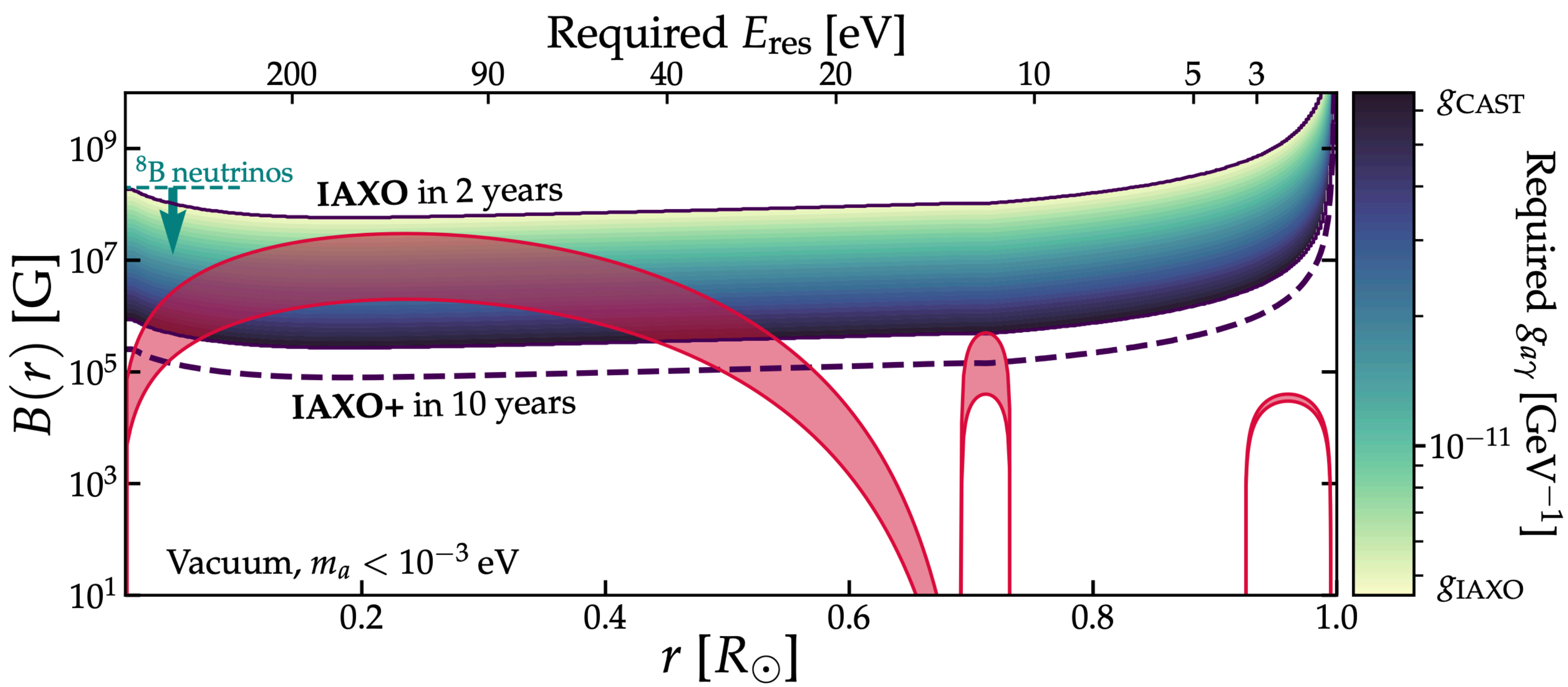
Caputo, Carenza, MG, Kotake, Lucente, Mirizzi, Vitagliano

New available SN simulations which include B:

J. Matsumoto, T. Takiwaki, K. Kotake, Y. Asahina, H. R. Takahashi, arXiv:2008.08984 (2021)

Axion helioscopes as solar magnetometers

Axions carry information about the structure of the magnetic field in the sun



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

LP axions produced resonantly when $\omega_a = \omega_{pl}$

With enough energy resolution one can map the axion energy to the radius.
The better the resolution, the more accurate that magnetic map.

Nuclear Axions

Axion from nuclear transitions

Ratio photon/axion decay

→ Universal

→ Specific

$$\beta = \frac{\langle J_f || \sum_{i=1}^{A} \boldsymbol{\sigma}(i) || J_i \rangle}{\langle J_f || \sum_{i=1}^{A} \boldsymbol{\sigma}(i) \tau_3 || J_i \rangle}$$

In general, $2L+1$ for M(L) transition

$$\frac{\Gamma_{\rm a}}{\Gamma_\gamma} = \left(\frac{k_{\rm a}}{k_\gamma}\right)^3 \frac{1}{2\pi\alpha} \frac{1}{1+\delta^2} \left[\frac{g_{\rm aN}^0 \beta + g_{\rm aN}^3}{(\mu_0 - 1/2)\beta + \mu_3 - \eta}\right]^2$$

~ 1

(ultra relativistic axions)

$E2/M1$

(quadrupole transition contribution)

$\mu_p + \mu_n$

$\mu_p - \mu_n$

$$\eta = -\frac{\langle J_f || \sum_{i=1}^{A} \boldsymbol{l}(i) \tau_3(i) || J_i \rangle}{\langle J_f || \sum_{i=1}^{A} \boldsymbol{\sigma}(i) \tau_3(i) || J_i \rangle}$$

F. T. Avignone, III, et aL, Phys. Rev. D 37, 618 (1988)

Most parameters are not universal and need to be calculated in specific nuclear models

Axion from Nuclear Processes in the Sun

$$\mathcal{N}_a = \mathcal{N}\omega_1 \frac{1}{\tau_0} \frac{1}{1+\alpha} \frac{\Gamma_a}{\Gamma_\gamma}$$

Fe-57 is by far the most efficient channel

	^{57}Fe	^{83}Kr	^{169}Tm	^{187}Os	^{201}Hg
E^* [keV]	14.4	9.4	8.4	9.7	1.6
J_0	1/2	9/2	1/2	1/2	3/2
J_1	3/2	7/2	3/2	3/2	1/2
τ_0 [ns]	141	212	5.9	3.4	144
α	8.56	17.09	285	264	47000
$\epsilon = N_X/N_H$	$10^{-4.5}$	$10^{-8.75}$	$10^{-11.9}$	$10^{-10.6}$	$10^{-10.83}$
a [%]	2.14	11.55	100	1.6	13.2
$\mathcal{N}_a(r=0)$ [relative to ^{57}Fe]	1	1.8×10^{-3}	1.3×10^{-4}	3.0×10^{-5}	1.9×10^{-6}

Compiled by Lennert J. Thormaehlen

Solar flux from ^{57}Fe

$$\Phi_a = 5 \times 10^{23} \left(g_{aN}^{\text{eff}}\right)^2 \text{cm}^{-2}\,\text{s}^{-1}$$

Saturating the solar bound gives

$$\boxed{\Phi_a = 1.8 \times 10^{12}\,\text{cm}^{-2}\,\text{s}^{-1}}$$

Very Large!

Very narrow line $\quad \sigma \simeq E^* \sqrt{\frac{kT}{M}} \simeq 2\,\text{eV} \quad$ (Doppler)

Width at half maximum of the Doppler broadened iron peak = 5 eV

Detecting ^{57}Fe axions: BabyIAXO

	BabyIAXO			
	baseline	no optics	optimized optics	high energy resolution
Label	BabyIAXO_0	BabyIAXO_1	BabyIAXO_2	BabyIAXO_3
B [T]	2	2	2	2
L [m]	10	10	10	10
A [m^2]	0.77	0.38	0.38	0.38
t [year]	0.75	0.75	0.75	0.75
b $[\frac{1}{\text{keV cm}^2\text{s}}]$	10^{-7}	10^{-6}	10^{-7}	10^{-5}
ϵ_d	0.15	0.9	0.5	0.99
ϵ_0	0.013	1	0.3	0.3
a [cm^2]	0.6	3800	0.3	0.3
$r_\omega = \frac{\Delta E_d}{14.4\,\text{keV}}$	0.12	0.12	0.12	0.02
Detector	Micromegas	Micromegas	SDD	CZT

Requires either optimized optics or large detectors that can operate without optics

$\epsilon_{o,d}$ optics and detector efficiencies

ΔE_d energy resolution of the detector,

b spectral background rate per area,

a focal spot area on the detector.

*L. Di Luzio, J. Galan, M.G., I. G. Irastorza, J. Jaeckel, A. Lindner, J. Ruz, U. Schneekloth, L. Sohl, L. J. Thormaehlen, J. K. Vogel [**arXiv:2111.06407**]*

Detecting ^{57}Fe axions: IAXO

	BabyIAXO				IAXO		IAXO+	
	baseline	no optics	optimized optics	high energy resolution	low background	high energy resolution	low background	high energy resolution
Label	BabyIAXO_0	BabyIAXO_1	BabyIAXO_2	BabyIAXO_3	IAXO_b	IAXO_r	IAXO_b^+	IAXO_r^+
B [T]	2	2	2	2	2.5	2.5	3.5	3.5
L [m]	10	10	10	10	20	20	22	22
A [m^2]	0.77	0.38	0.38	0.38	2.3	2.3	3.9	3.9
t [year]	0.75	0.75	0.75	0.75	1.5	1.5	2.5	2.5
$b\ [\frac{1}{\text{keV cm}^2 \text{s}}]$	10^{-7}	10^{-6}	10^{-7}	10^{-5}	10^{-8}	10^{-6}	10^{-9}	10^{-6}
ϵ_d	0.15	0.9	0.5	0.99	0.99	0.99	0.99	0.99
ϵ_0	0.013	1	0.3	0.3	0.3	0.3	0.3	0.3
a [cm^2]	0.6	3800	0.3	0.3	1.2	1.2	1.2	1.2
$r_\omega = \frac{\Delta E_d}{14.4\,\text{keV}}$	0.12	0.12	0.12	0.02	0.02	$\frac{5}{14400}$	0.02	$\frac{5}{14400}$

Two setups studied for IAXO: Low background and High energy resolution

Optimized optics in all bores.

*L. Di Luzio, J. Galan, M.G., I. G. Irastorza, J. Jaeckel, A. Lindner, J. Ruz, U. Schneekloth, L. Sohl, L. J. Thormaehlen, J. K. Vogel [**arXiv:2111.06407**]*

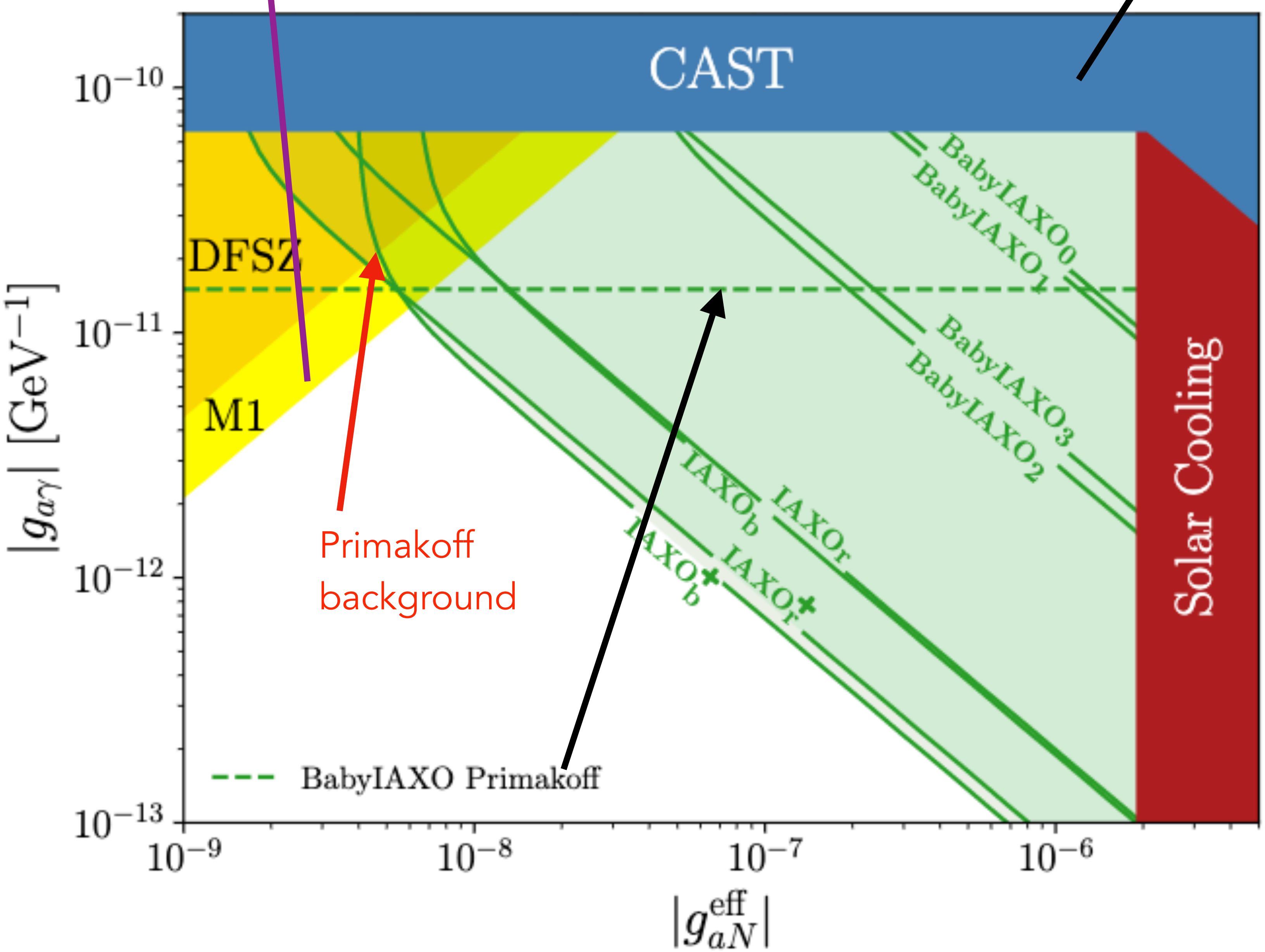
Results (massless axions)

Realistic QCD models

Requires efficiency at high mass (buffer gas filling)

CAST (2009)

JCAP 12 (2009) 002



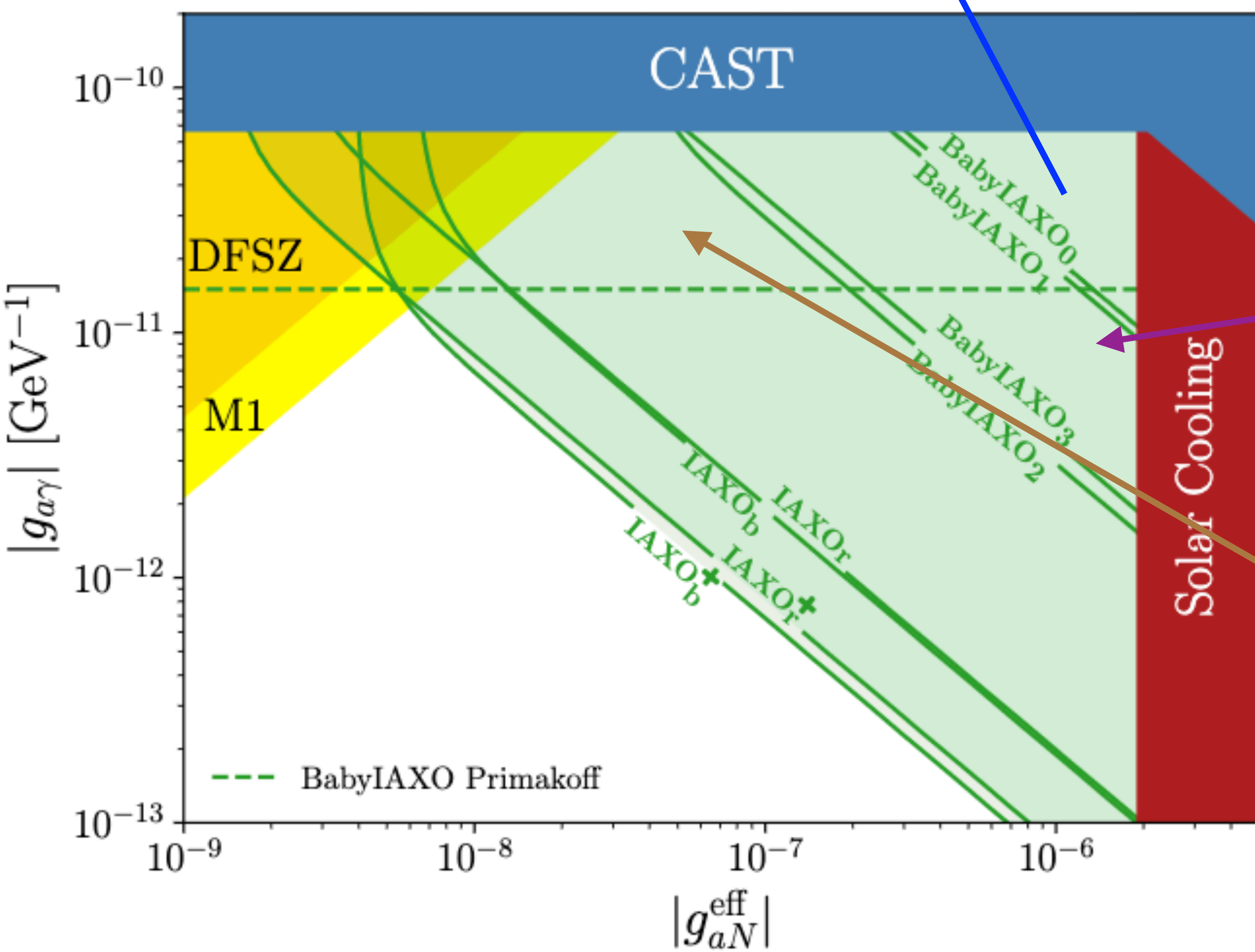
The next generation of helioscopes will cover a considerable larger area in the parameter space

Assumption of low axion mass

M.G. et al, arXiv:2111.06407

Results (massless axions)

Discovery through both ^{57}Fe and Primakoff.
Possibility of understanding couplings relations



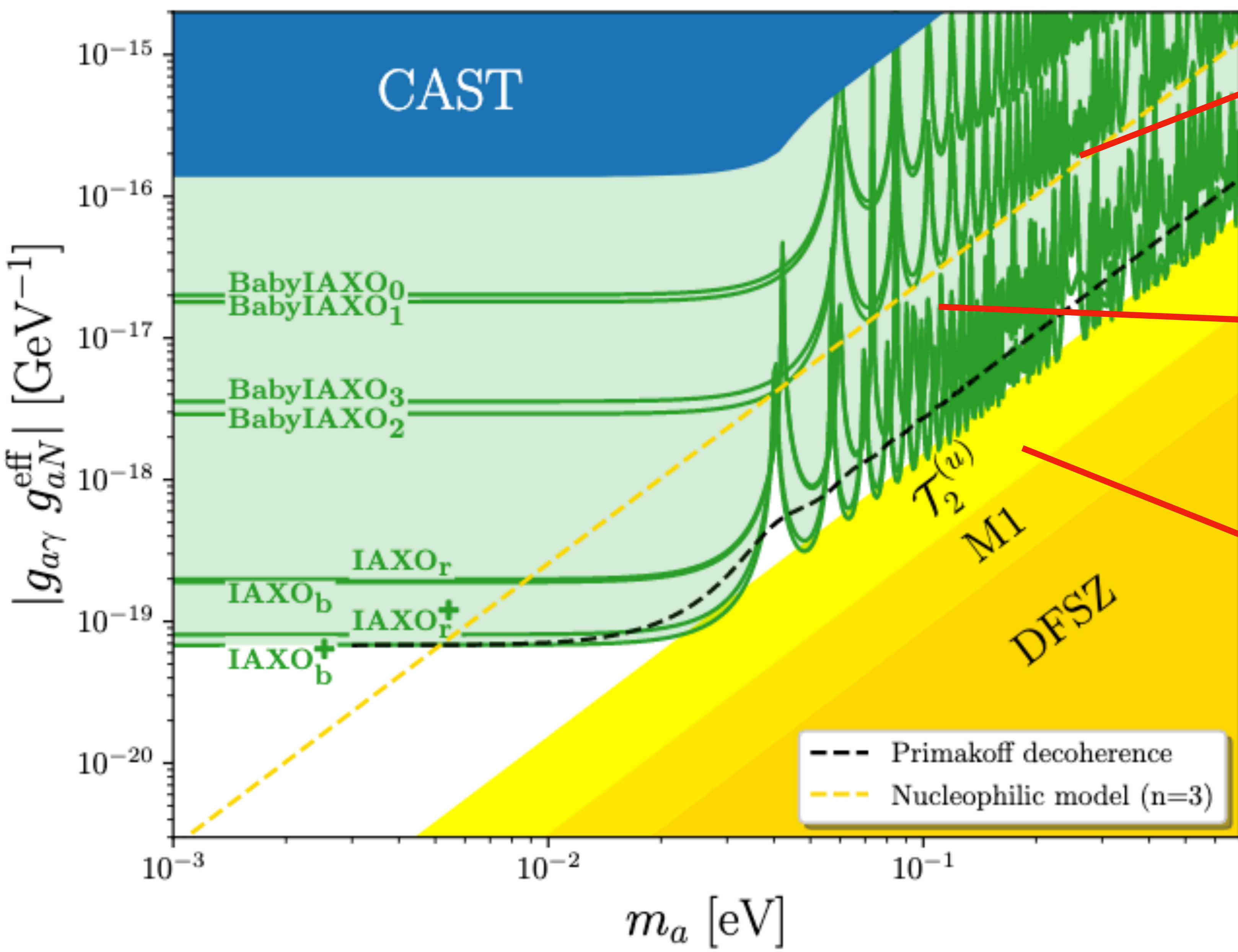
BabyIAXO discovery of axions through ^{57}Fe before Primakoff

BabyIAXO discovery through Primakoff and IAXO detection of 57Fe flux

M.G. et al, arXiv:2111.06407

Axions from deexitation of Fe-57

Detection of axions from $^{57}\mathrm{Fe}^* \rightarrow ^{57}\mathrm{Fe} + a\,(14.4\,\mathrm{keV})$



Nucleophilic model

Darme, di Luzio, M.G., Nardi, Phys.Rev.D 103 (2021)

Only vacuum analysis, for the moment

Region spanned by generalized DFSZ (2 Higgs) models

Possibility to reach realistic models with buffer gas

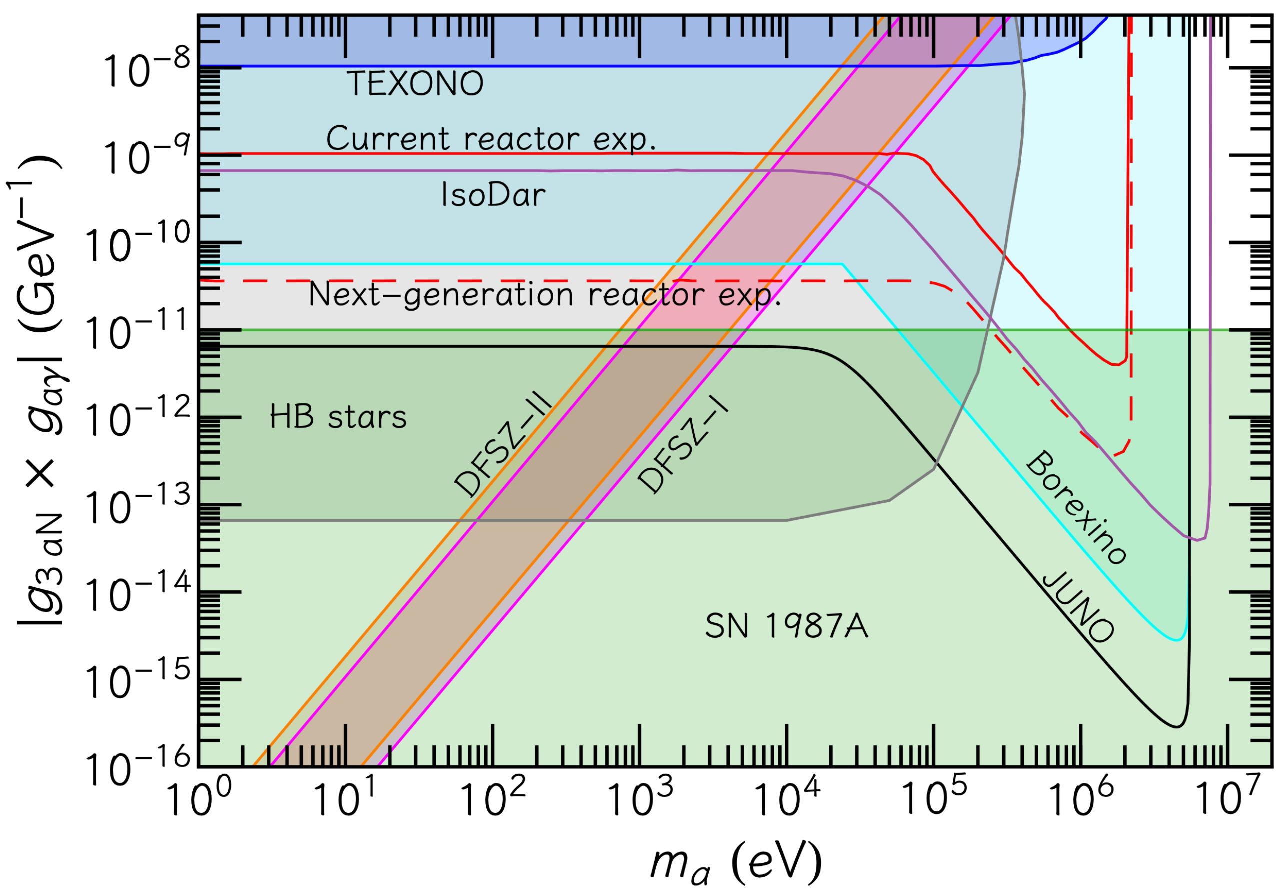
Di Luzio, Galan, MG, Irastorza, Jaeckel, Lindner, Ruz, Schneekloth, Sohl, Lennert J. Thormaehlen, Vogel Eur.Phys.J.C 82 (2022)

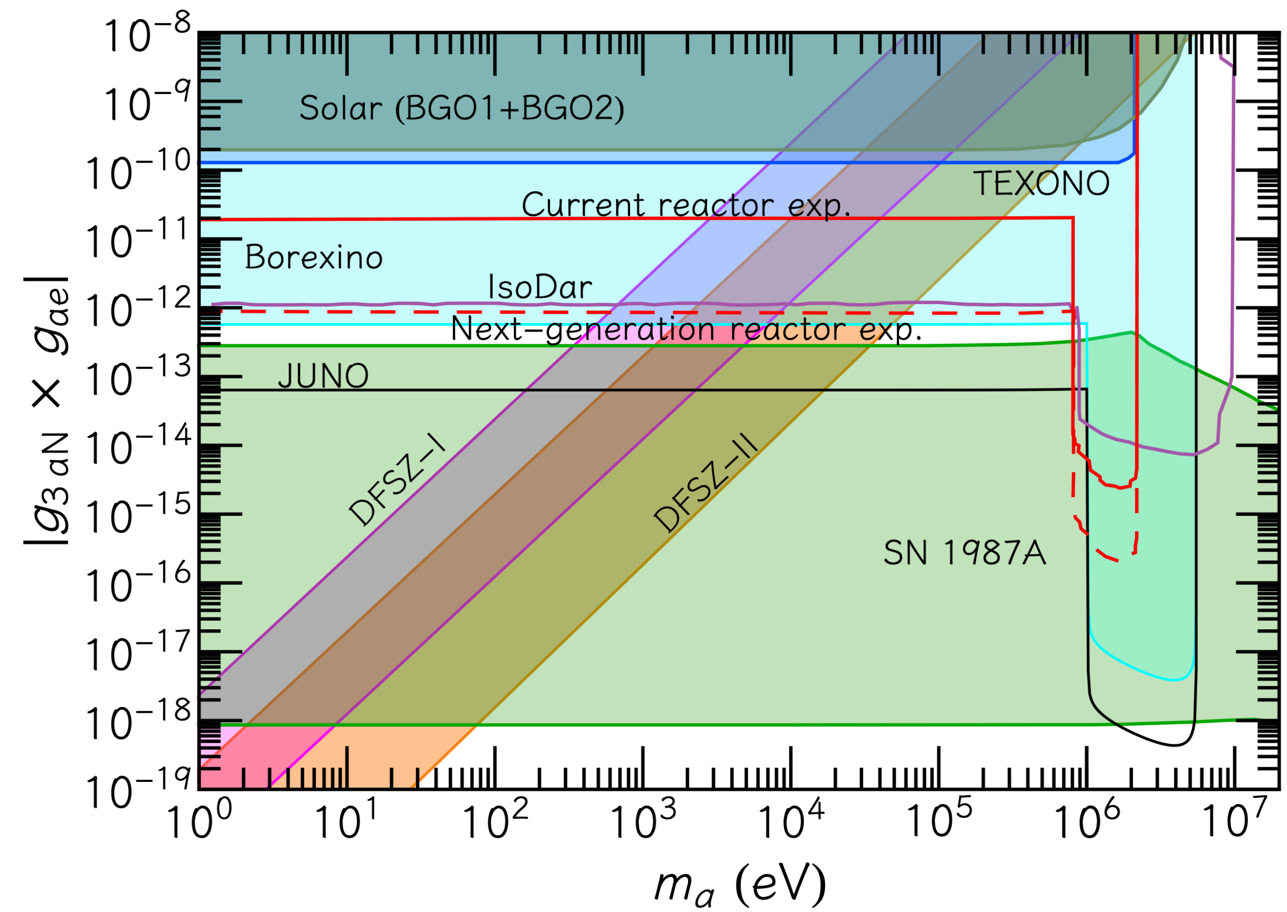
Solar axions with scintillation neutrino detectors

$$\Phi_a \simeq 3.23 \times 10^{10}\, e^{-d_\odot/l_{\rm tot}}\, g_{3aN}^2\, (k_a/k_\gamma)^3\ {\rm cm^{-2}s^{-1}}$$

JUNO potential for solar axions

$$p + d \rightarrow {}^3\mathrm{He} + a$$



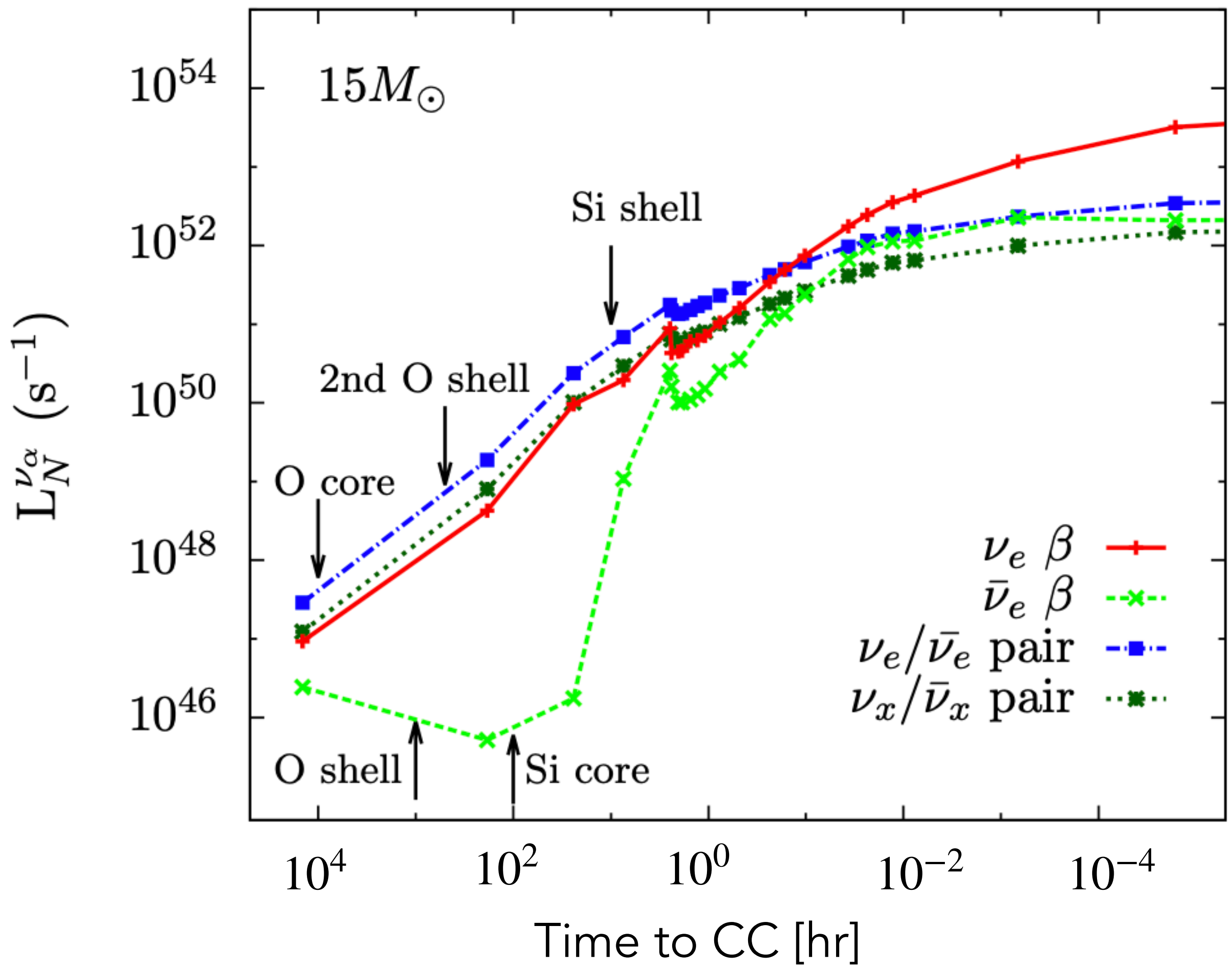


G. Lucente, N. Newton, F. Capozzi, MG, A. Mirizzi, e-Print: 2209.11780 [hep-ph] (2022)

SN Axions and their detection

Pre-SN signal

Neutrinos are produced from thermal and beta processes.



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

Pre-SN signal

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

Tanaka & Watanabe (2014)

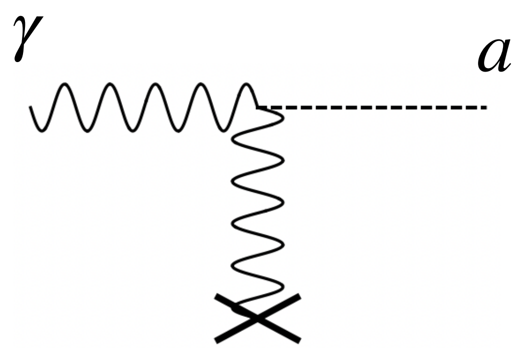
Betelgeuse				LS		LS-Li	
Time to CC	N_{Total}	N_{Signal}	N_{Bkg}	68% C.L.	90% C.L.	68% C.L.	90% C.L.
4.0 hr	93	78	15	78.43°	116.17°	23.24°	33.98°
1.0 hr	193	170	23	63.92°	98.42°	15.47°	22.26°
2 min	314	289	25	52.72°	81.79°	11.63°	16.67°

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

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

Supernova axions

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

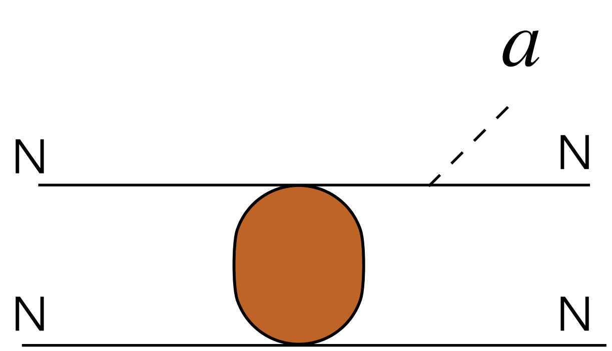


Primakoff requires $\propto g_{a\gamma}^2$

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

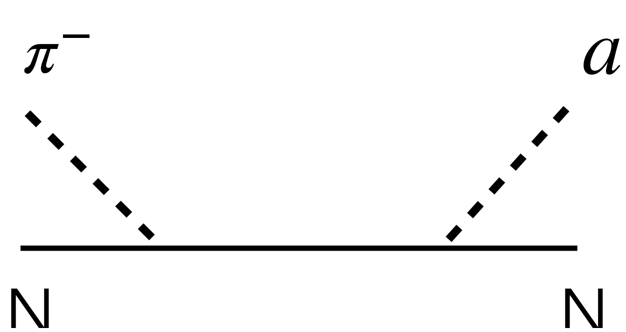
J. Grifols, E. Masso, R. Toldra, Phys. Rev. Lett. 77, 2372 (1996)

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



Bremsstrahlung $\propto g_{aN}^2$

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



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

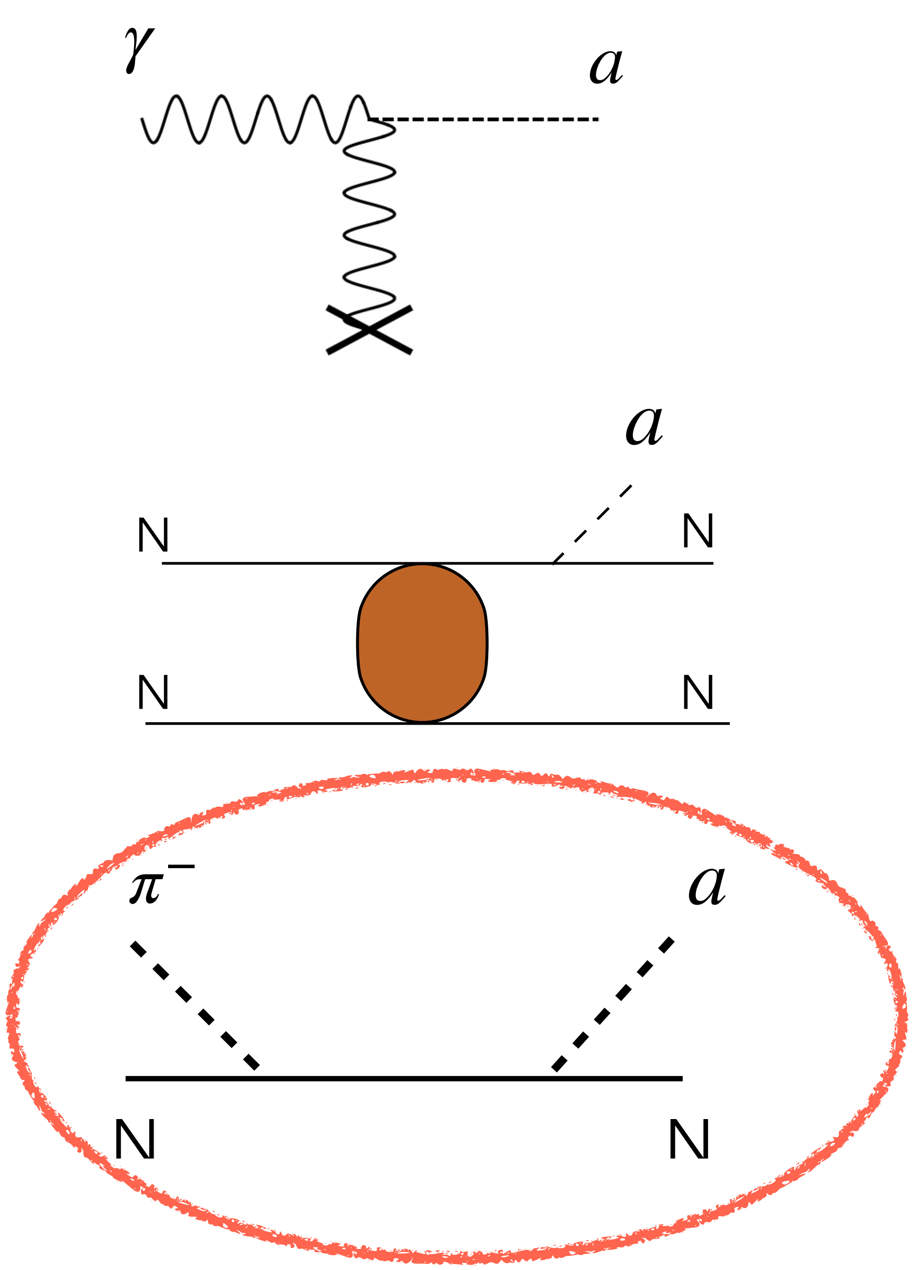
P. Carenza, B. Fore, M.G., A. Mirizzi, S. Reddy, (2020) [arXiv:2010.02943]

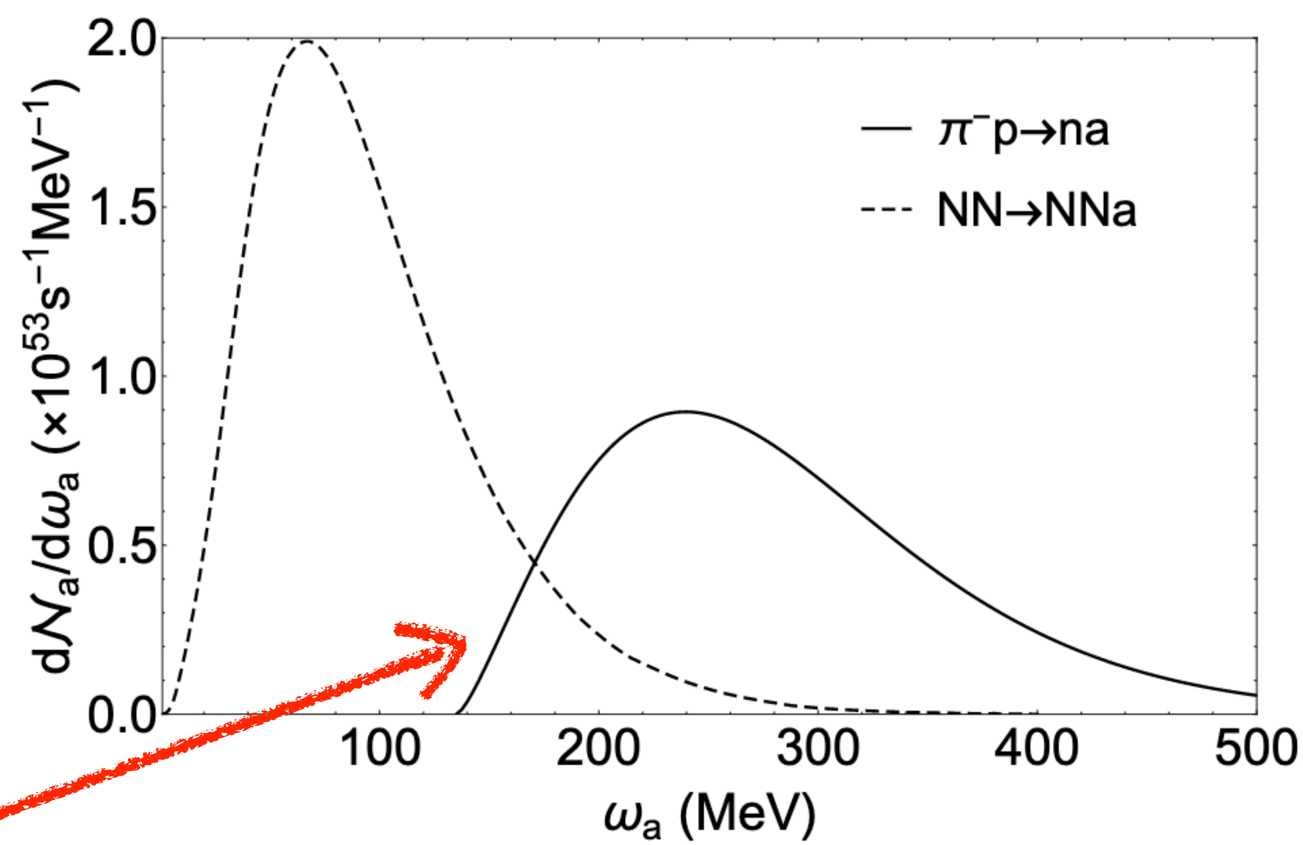
Pion abundance was underestimated. Breakthrough result in

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

Supernova axions

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

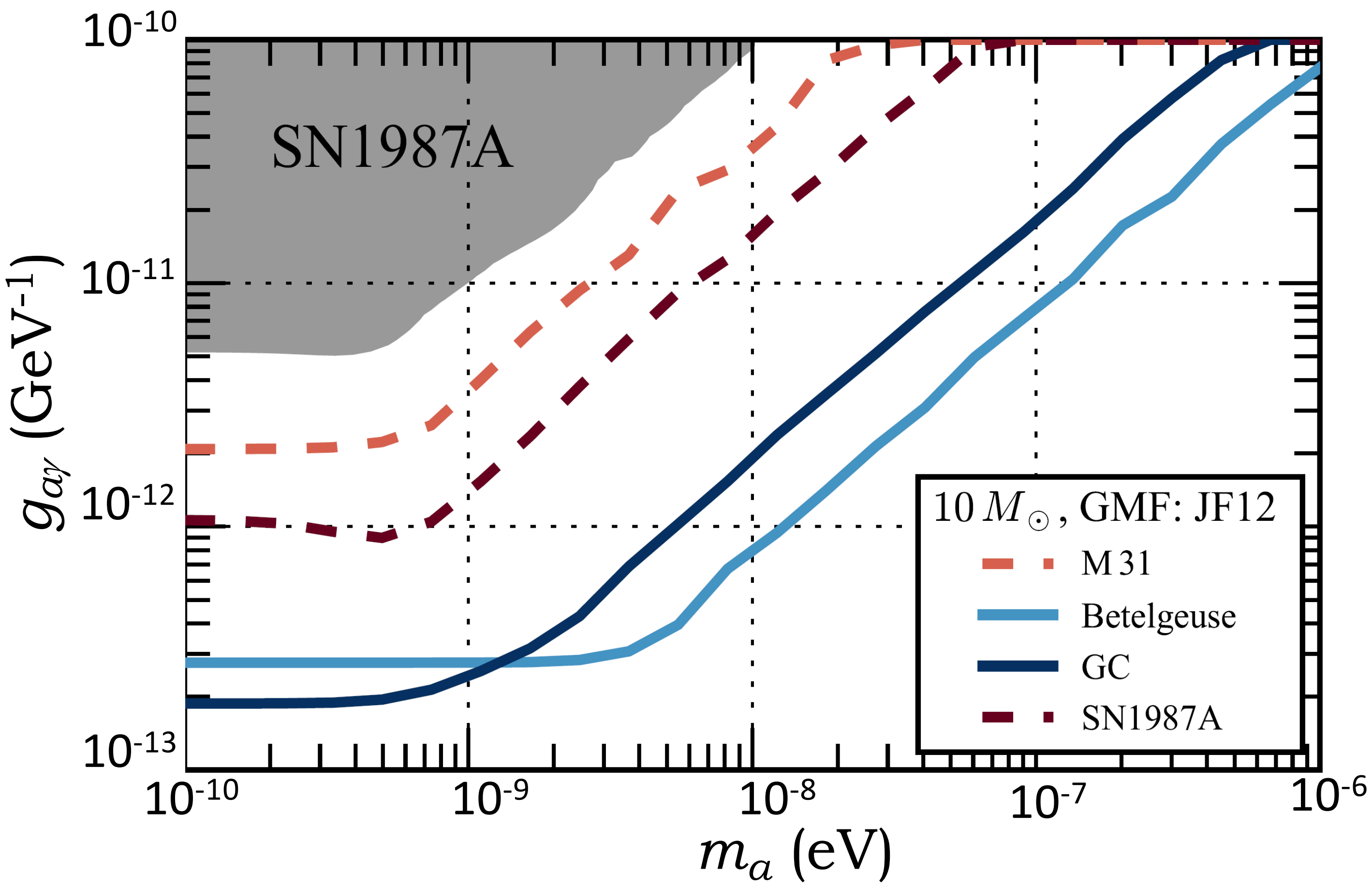




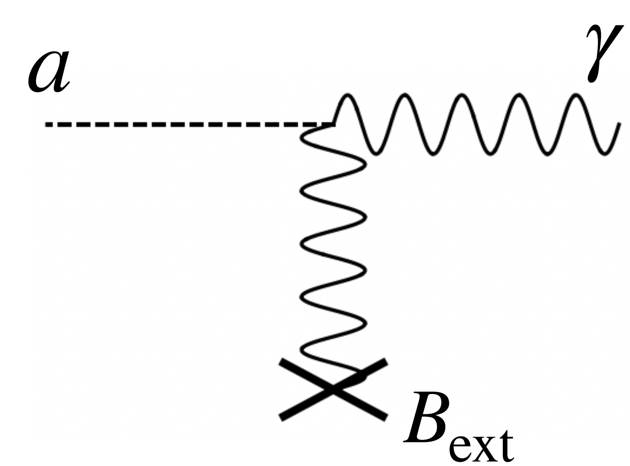
Harder spectrum: opens possible detection channel through pions in water Cherenkov detectors

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

Fermi LAT as Axion SN-Scope



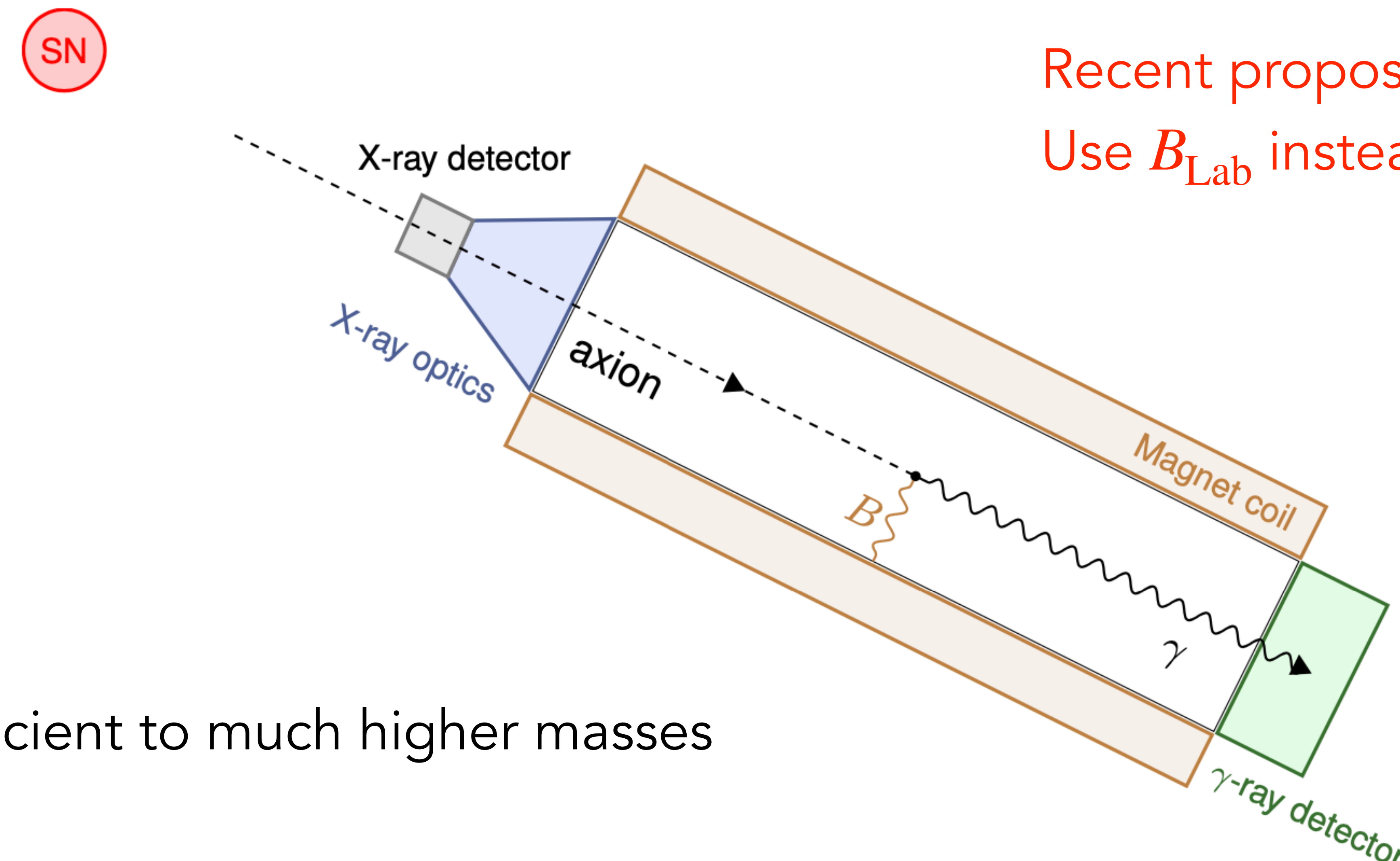
SN axions → photons in galactic B



Very efficient at low mass

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

Helioscopes as Axion SN-Scopes



Recent proposal.

Use $B_{\rm Lab}$ instead of $B_{\rm galactic}$

Axion helioscope turned around

Efficient to much higher masses

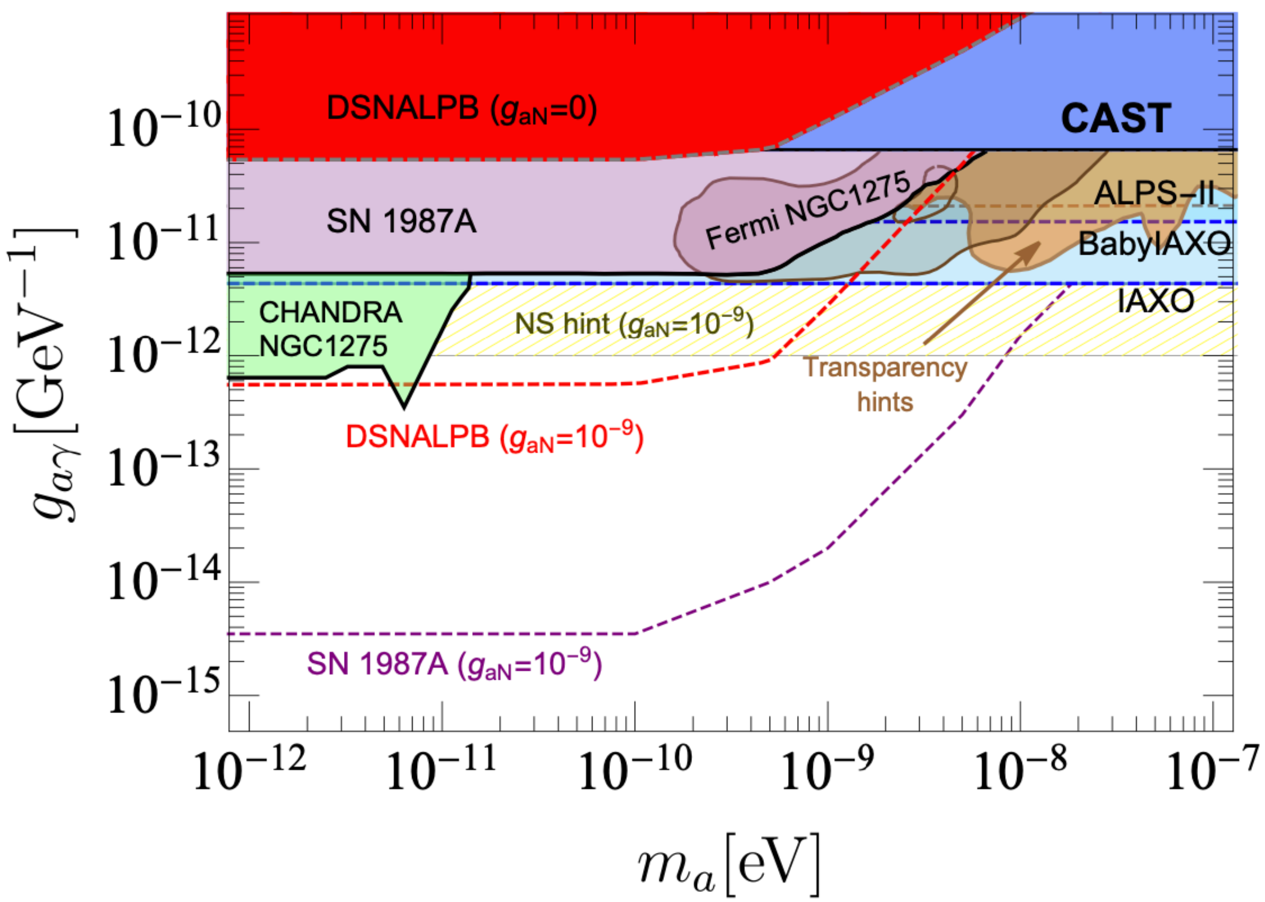
Up to ~12 events (Spica), 2 events (Betelgeuse) with BabyIAXO setup

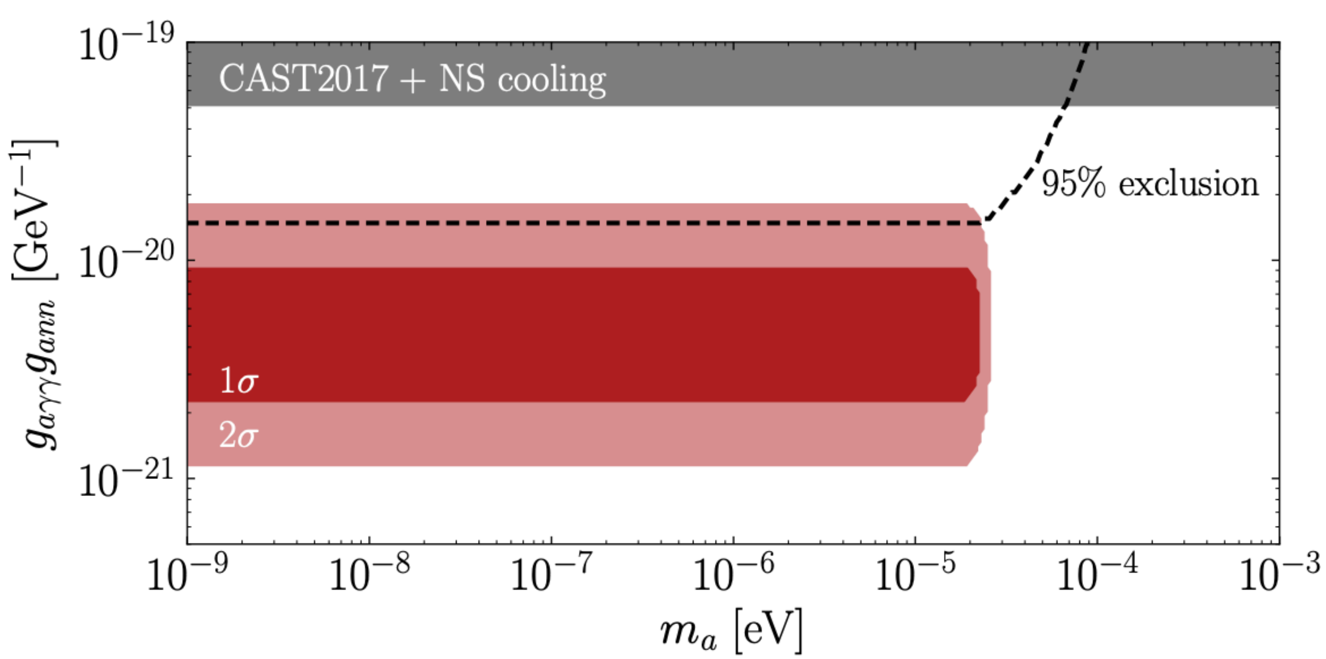
Ge, Hamaguchi, Ichimura, Ishidoshiro, Kanazawa JCAP 11 (2020)

Epilogue: some other promising possibilities

The hinted region is partially excluded by a study of SNe diffuse flux and SN 1987A

Calore, Carenza, M.G., Jaeckel, Mirizzi, Phys.Rev.D 102 (2020) 12



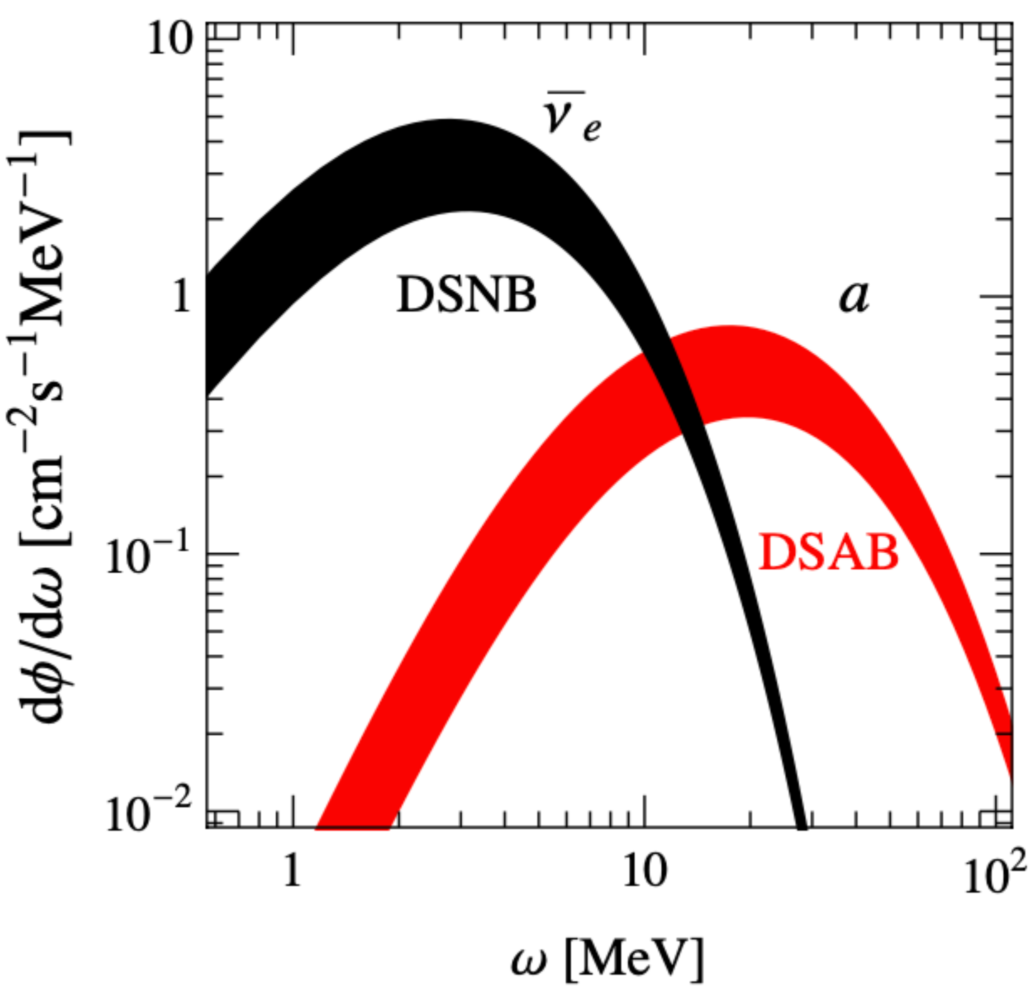


A few NS, observed by XMM- Newton and Chandra, exhibit an unexplainable excess. Is it due to $a \to \gamma$?

M. Buschmann, R. T. Co, C. Dessert, B. R. Safdi, Phys.Rev.Lett. 126 (2021)

Diffuse Supernova axions

SNe: $\sim 10^{52}\,\mathrm{erg/s}$ in ν and up to the same in axions

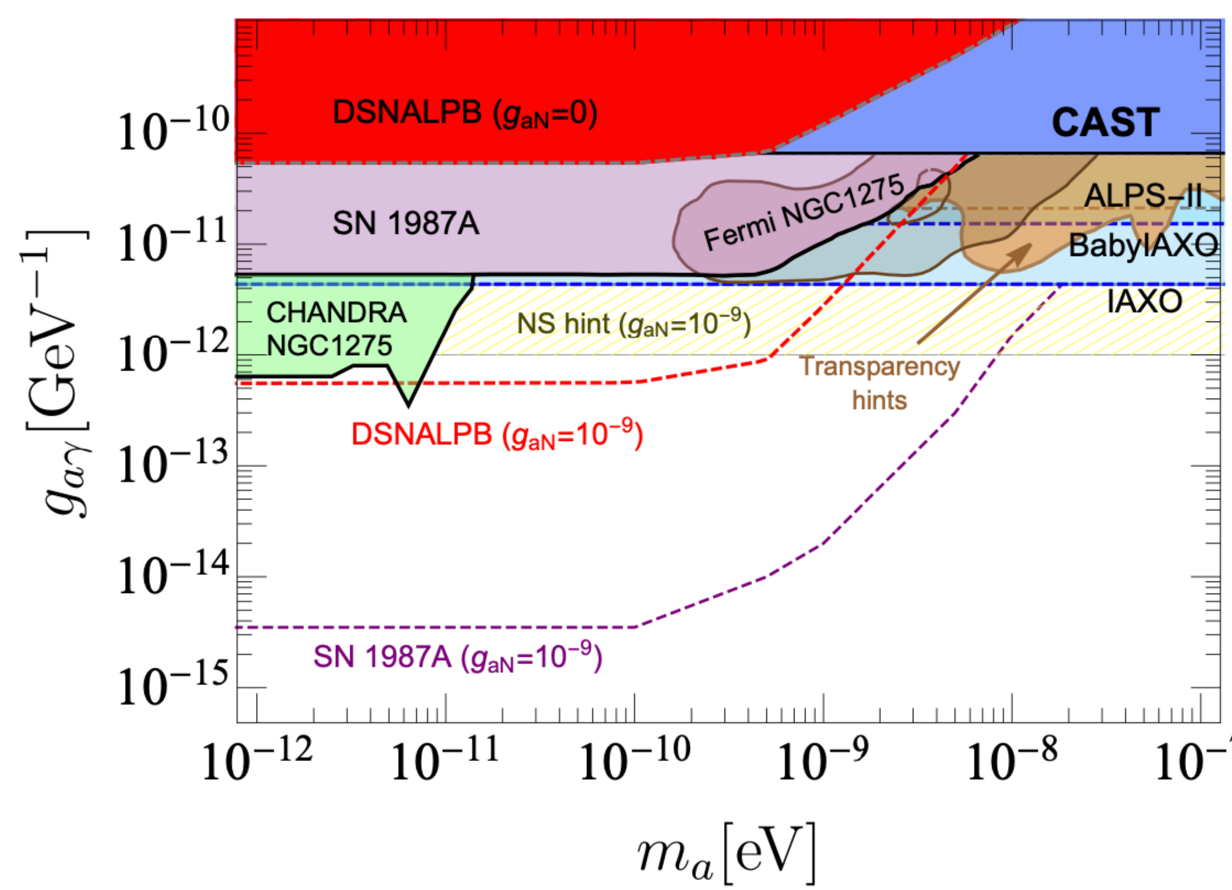


SN diffuse axion background?

Accessible through $a \to \gamma$ in galactic B

Raffelt, Redondo, Viaux, Phys.Rev.D 84 (2011) 103008

Calore, Carenza, M.G., Jaeckel, Mirizzi, Phys.Rev.D 102 (2020) 12



Supernova 1987A

SN1987A: SNe cannot cool too fast (ν-signal).
Roughly, $L_a \lesssim L_\nu$

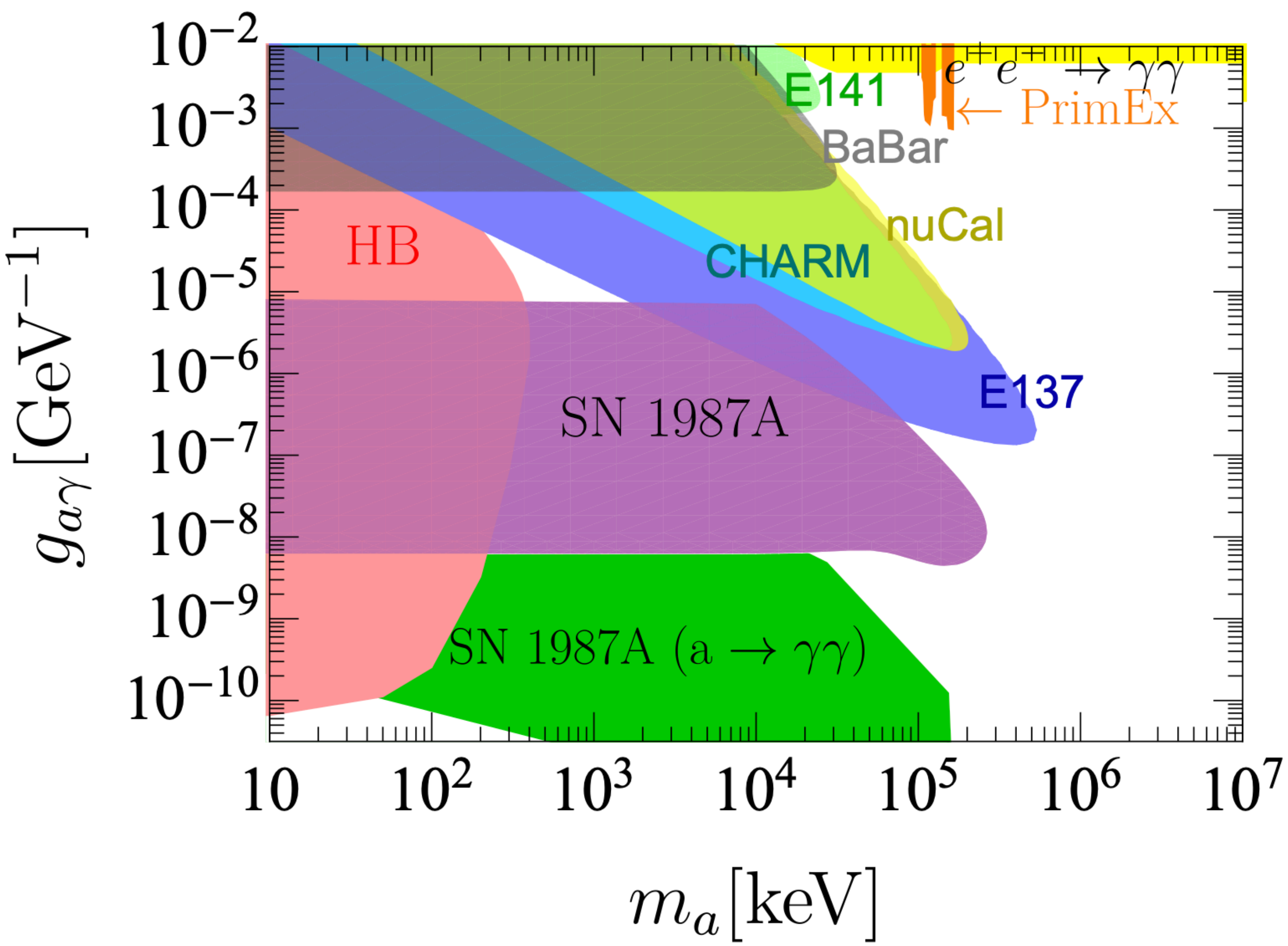
Very old bounds however:

- Emission rate is hard to calculate
- Very few data

Several recent revisitations

- *C. Hanhart, D. R. Phillips, S. Reddy (2001)*
- *Chang, Essig, McDermott (2018);*
- *Chang, Essig, McDermott (2019);*
- *P. Carenza et al. (2019);*
- *Ertas and Kahlhoefer (2020)*
- *G. Lucente et al. (2020)*
- *...*

Axion-like particles ($g_{a\gamma}$)



- *Jaeckel, Malta, Redondo (2017);*
- *Ertas and Kahlhoefer (2020);*
- *G. Lucente et al. (2020);*

Stars as FIP Factories: heavy axions

Stars may produce FIPs copiously.

- Solar ALPs and HP are searched by terrestrial experiments.
- SNe can produce enormous quantities of FIPs ($\sim 10^{52}$ erg/s).
- Very strong limits from SN 1987A

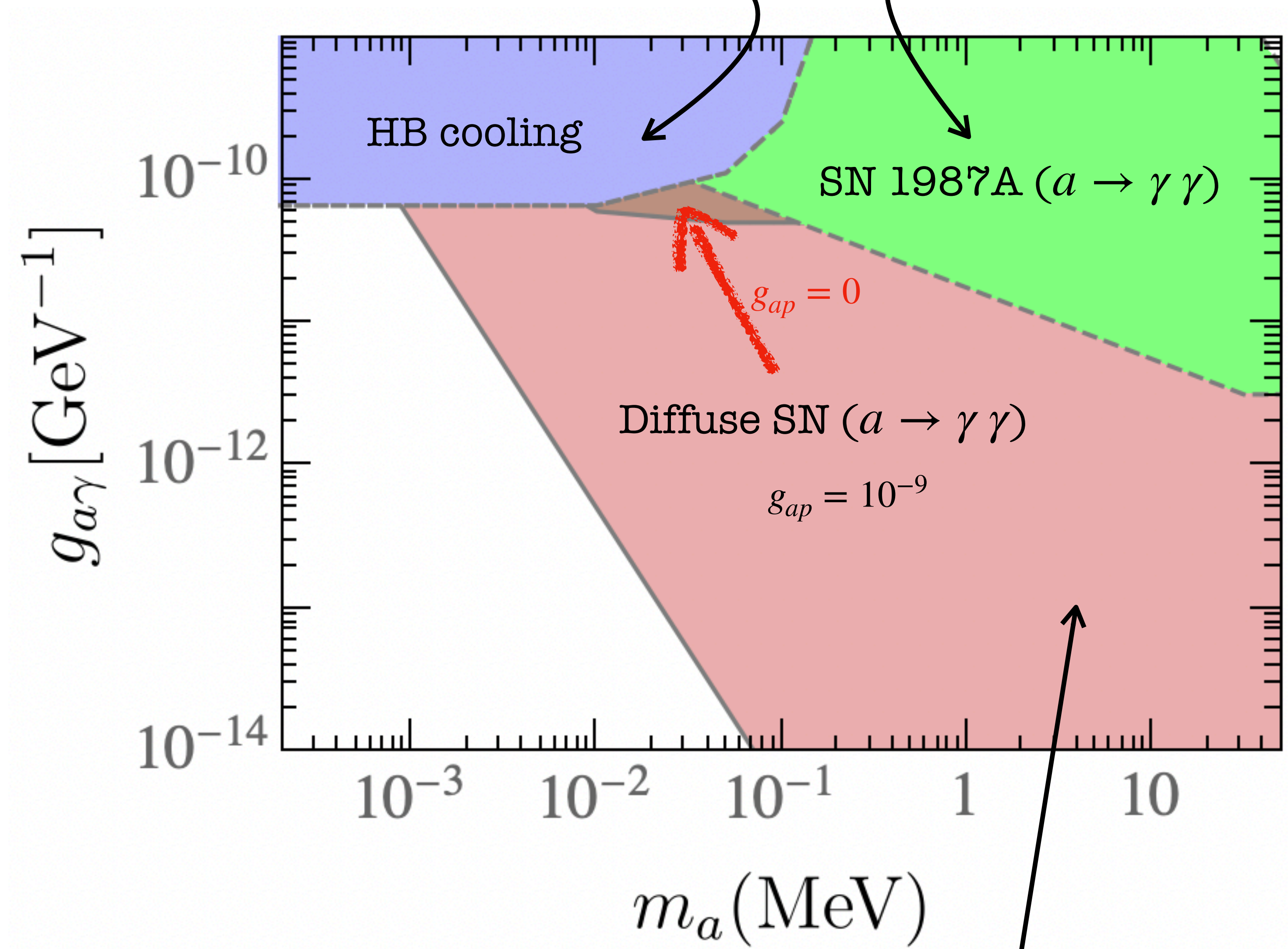
[Payez et al. (2015), De Rocco et al. (2020)]

- and from diffuse gamma ray from all past SNe

[Calore et al. (2020), De Rocco et al. (2020)]

Carenza, Dobrich, Lucente, M.G., Mirizzi, Straniero (2020)

Jaeckel, Malta, Redondo (2017)

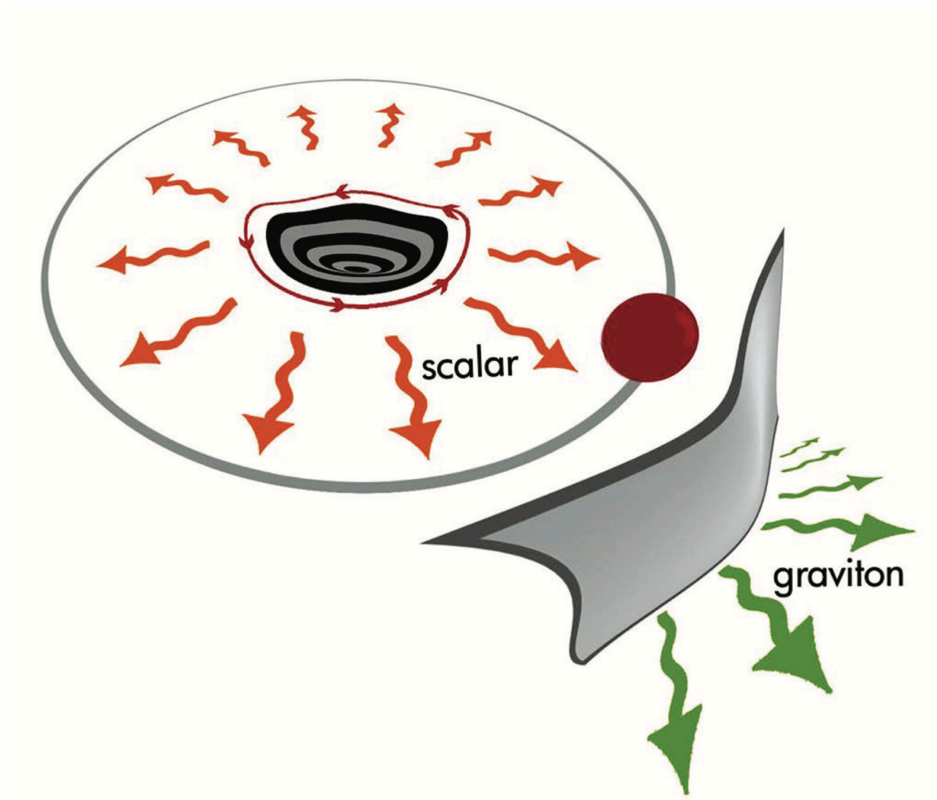


- Calore, Carenza, M.G., Jaeckel, Mirizzi (2020)
- DeRocco, Graham, Kasen, Marques-Tavares, Rajendran (2020)

BH Superradiance

Epilogue: some other promising possibilities

BH as axion factories?



Brito, Cardoso, Pani, arXiv:1501.06570

Black hole superradiance.
Detectable GW from axion cloud around a BH.

Axion Factory! No need for an initial axion

Advanced Ligo as axion telescope

Active searches going on

- C. Palomba et al. Phys.Rev.Lett. 123 (2019)
- L. Sun, R. Brito, M. Isi, Phys.Rev.D 101 (2020)

Limitations: geometrical factor limit the boson mass to very small values:
axion Compton wavelength ~ BH size $\Rightarrow m_a < 10^{-11}\,\mathrm{eV}$

Black holes as axion factories

Boson fields form bound states around a rotating BH, with occupation number exponentially increasing through the Penrose superradiance mechanism.

Amplification continues until

$$\omega_a < m\,\Omega_{BH}$$

(with m=magnetic quantum number) at expense of BH angular momentum.

Axion Factory! No need for an initial axion (no need for DM axions).

Advanced LIGO as a BH Axionscope

Axion transition between levels and axion annihilation produce GW.

Discovering the QCD Axion with Black Holes and Gravitational Waves

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Masha Baryakhtar,[†] and Xinlu Huang,[‡]
Stanford Institute for Theoretical Physics, Department of Physics,
Stanford University, Stanford, CA 94305, USA
(Dated: March 25, 2015)

Advanced LIGO may be the first experiment to detect gravitational waves. Through superradiance of stellar black holes, it may also be the first experiment to discover the QCD axion with decay constant above the GUT scale. When an axion's Compton wavelength is comparable to the size of a black hole, the axion binds to the black hole, forming a "gravitational atom." Through the superradiance process, the number of axions occupying the bound levels grows exponentially, extracting energy and angular momentum from the black hole. Axions transitioning between levels of the gravitational atom and axions annihilating to gravitons can produce observable gravitational wave signals. The signals are long-lasting, monochromatic, and can be distinguished from ordinary astrophysical sources. We estimate up to $\mathcal{O}(1)$ transition events at aLIGO for an axion between 10^{-11} and 10^{-10} eV and up to 10^4 annihilation events for an axion between 10^{-13} and 10^{-11} eV. In the event of a null search, aLIGO can constrain the axion mass for a range of rapidly spinning black hole formation rates. Axion annihilations are also promising for much lighter masses at future lower-frequency gravitational wave observatories; the rates have large uncertainties, dominated by supermassive black hole spin distributions. Our projections for aLIGO are robust against perturbations from the black hole environment and account for our updated exclusion on the QCD axion of $6 \times 10^{-13}\,\text{eV} < \mu_a < 2 \times 10^{-11}\,\text{eV}$ suggested by stellar black hole spin measurements.

Asimina Arvanitaki, Masha Baryakhtar, and Xinlu Huang, Phys. Rev. D 91, 084011 (2015)

Advanced LIGO as a BH Axionscope

C. Palomba et al. Phys.Rev.Lett. 123 (2019) [arXiv:1909.08854]

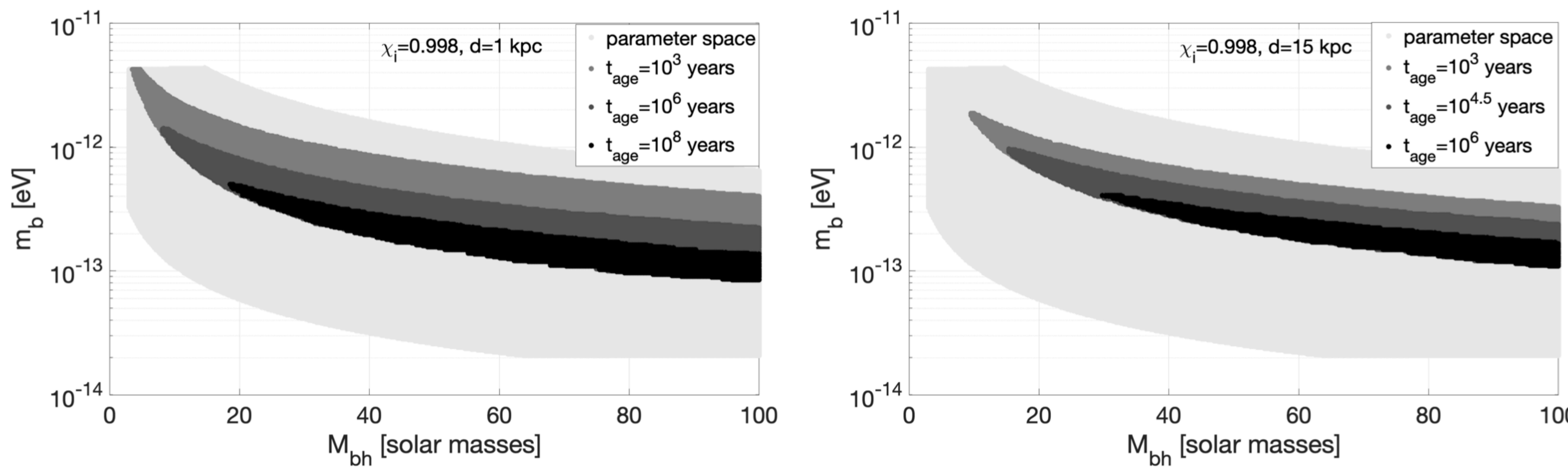
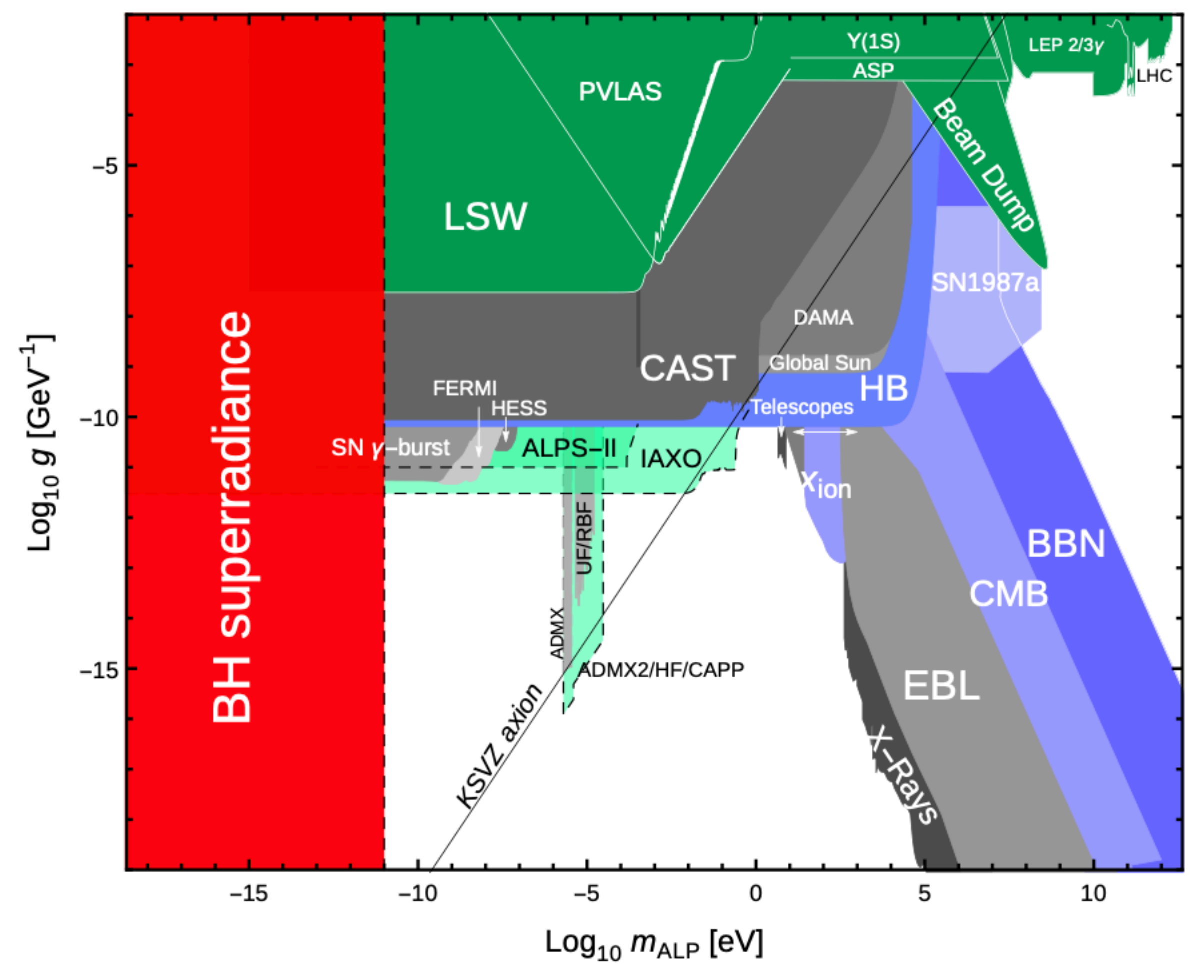


FIG. 2: 95% C.L. exclusion regions in the plane $m_b - M_{bh}$ assuming a maximum distance $d = 1$ kpc (left plot) and $d = 15$ kpc (right plot), a black hole initial a-dimensional spin $\chi_i = 0.998$, and three possible values for t_{age}: 10^3, 10^6, 10^8 years (left plot) and 10^3, $10^{4.5}$, 10^6 years (right plot). The larger light gray area is the accessible parameter space. As expected, the extension of the excluded region decreases for increasing t_{age} (corresponding to darker color).

Limitations: geometrical factor limit the boson mass to very small values:
axion Compton wavelength ~ BH size $\Rightarrow m_a < 10^{-11}\,\mathrm{eV}$

BH superradiance

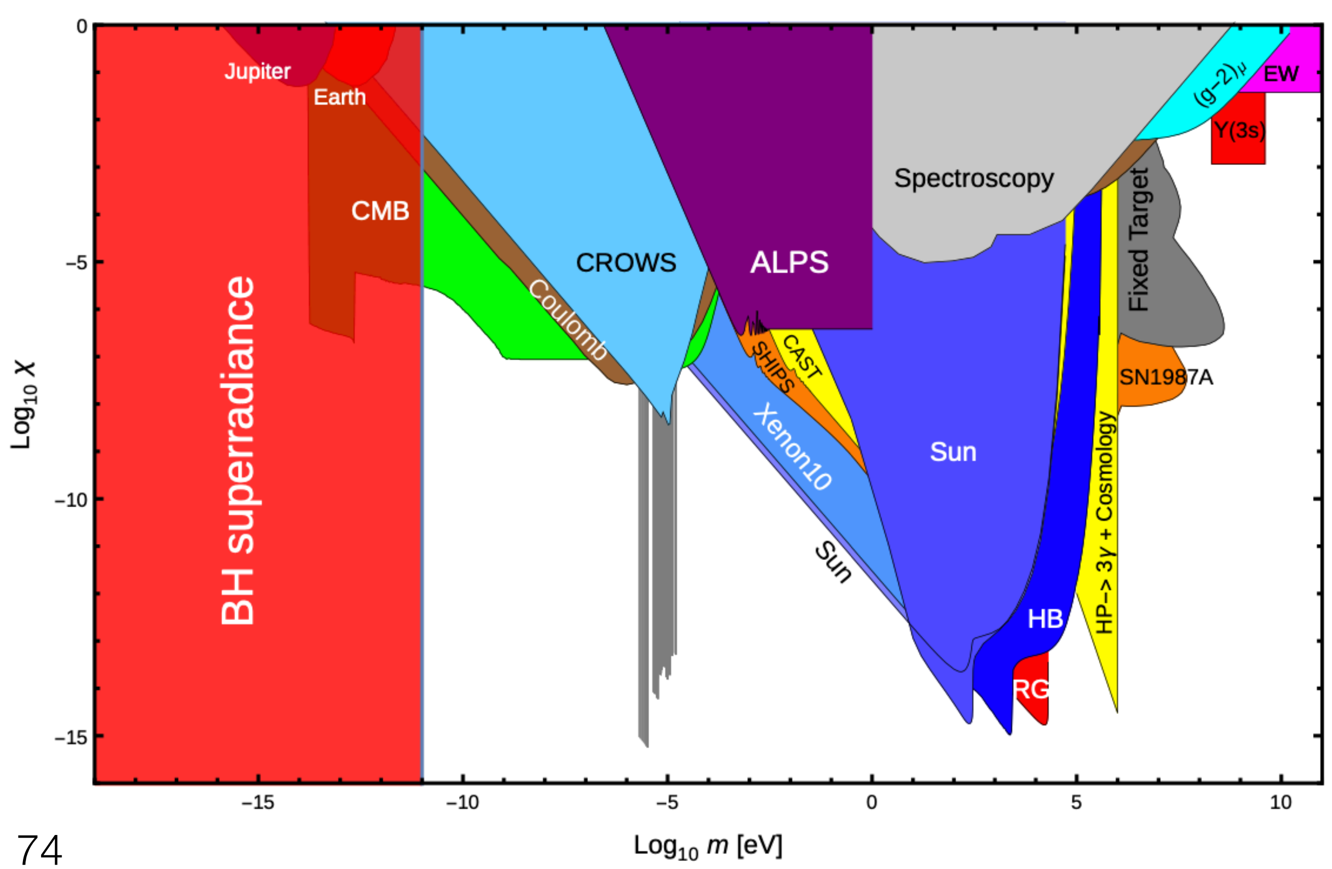
Tests coupling to gravity. No assumption that the boson is initially present, i.e. there is no requirement for the boson to be the DM.



A. Arvanitaki, S. Dubovsky, PhysRevD.83.044026 (2011);

A. Arvanitaki, M. Baryakhtar, X. Huang, PhysRevD.91.084011 (2015)

V. Cardoso et al. JCAP 1803 (03) (2018)



Figures form V. Cardoso et al. JCAP 1803 (03) (2018)