Axion Beyond Discoveries:

Measuring Axion Couplings

A very brief overview

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Wish List

→ *Getting the couplings*

→ *Getting info on the Universe*

→ *Getting info on the model*

Measuring the Couplings

Best option: Axion-Photon Coupling

ALPS II

Observed Flux $\sim \left|g_{a\gamma\gamma}\right|^4$

Calculable

Heliscopes

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

Model dependent

Unknown

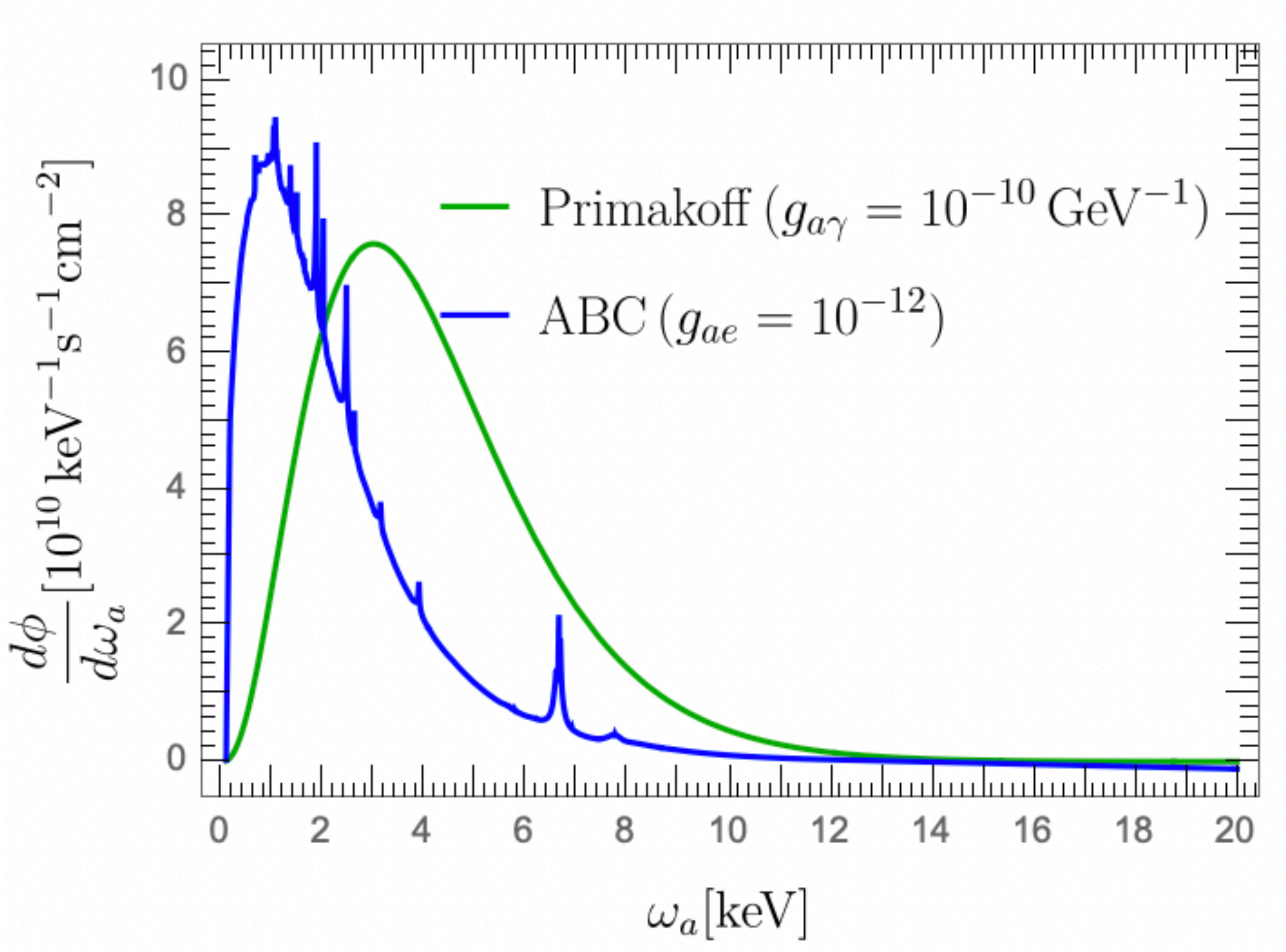
Haloscopes

Observed Flux $\sim \eta_{\mathrm{DM}}\left|g_{a\gamma\gamma}\right|^2$

+ Infer the mass in case of resonant detection

Solar Axions

Best option (for now) → BabyIAXO



→ *J. Redondo, JCAP 1312 (2013)*

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

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

Example: Threshold at 0.3 keV

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

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

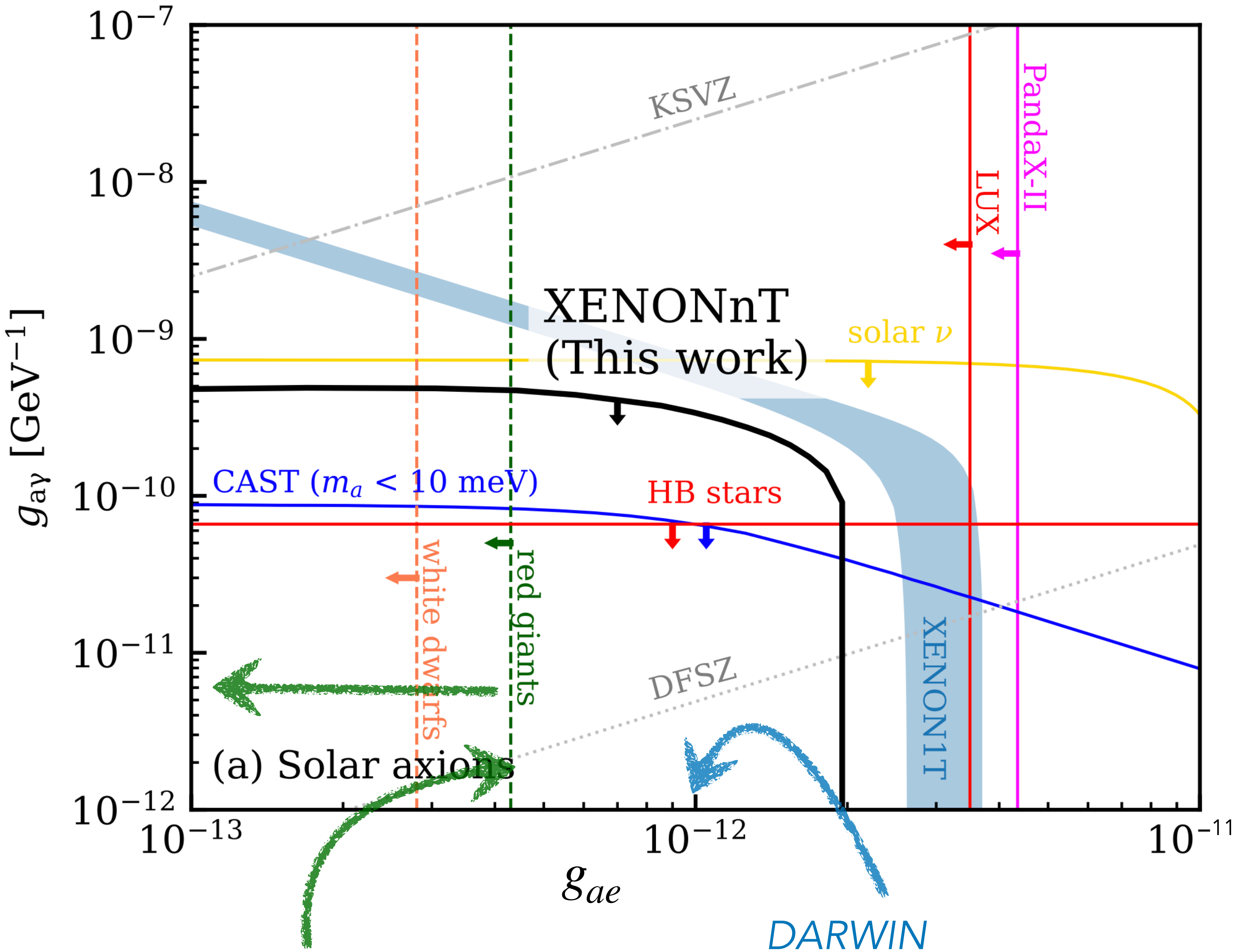
DFSZ with typical couplings
$g_{ae}/g_{a\gamma} = 5 \times 10^{-2}$ GeV,

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

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

No significant improvement in going down to 0.1 keV.

Direct detection of g_{ae}



RGB bound has been updated

DARWIN
(Expected potential)

Inferring g_{ae} directly not likely in near future because of strong astro bounds

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

Axion Nucleon Couplings

The Sun …

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

- 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, Phys.Rev.D 106 (2022) 12
- Maybe accessible to IAXO (work in progress)

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

- Searched by CAST *JCAP 12 (2009)* + BabyIAXO *Eur.Phys.J.C 82 (2022)*
- New dedicated project under commissioning → ISAI (Investigating Solar Axion by Iron-57),

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

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

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

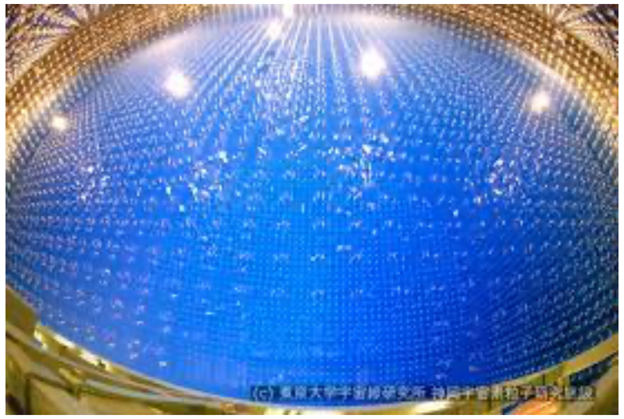
- Thulium garnet crystal as a bolometric detector, Derbin et al., (2023) JETP Letters, Volume 118, Issue 3, p.160-164

… + Supernovae

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)

Post-Discovery: Axion Telescopes

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

- ....

See → talk by
Sebastian Hoof

Post-Discovery: Axion Telescopes

Model	Phase	$t_{\rm cc}$ [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

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

Axion Flux very sensitive to evolutionary stage

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

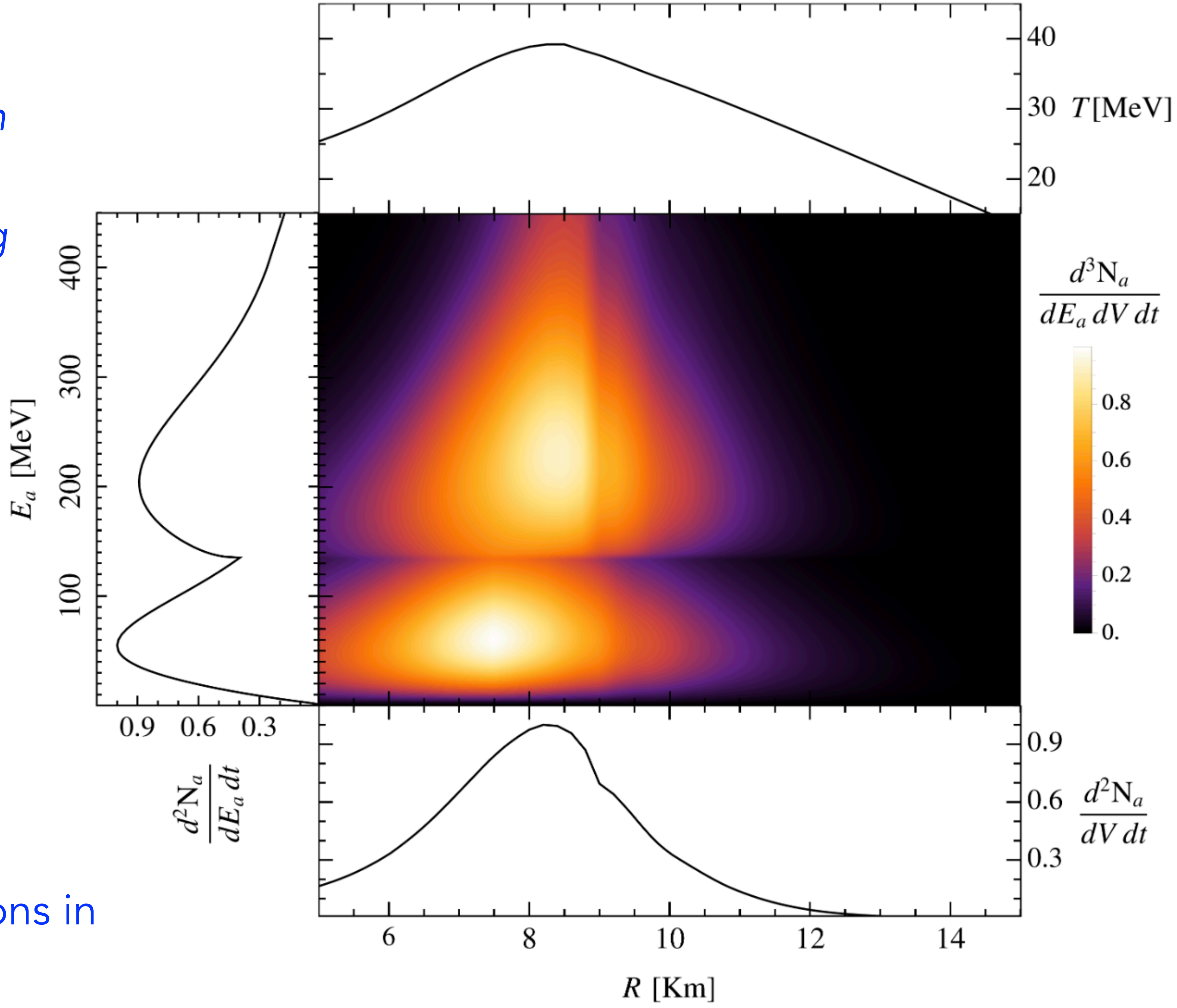
Post-Discovery: Axion Telescopes

Looking into the SN Core

Contributions from pion processes and from nucleon bremsstrahlung

- Maybe accessible to IAXO (work in progress)

Can we distinguish the fluxes?
→ reveal the role of pions in SN

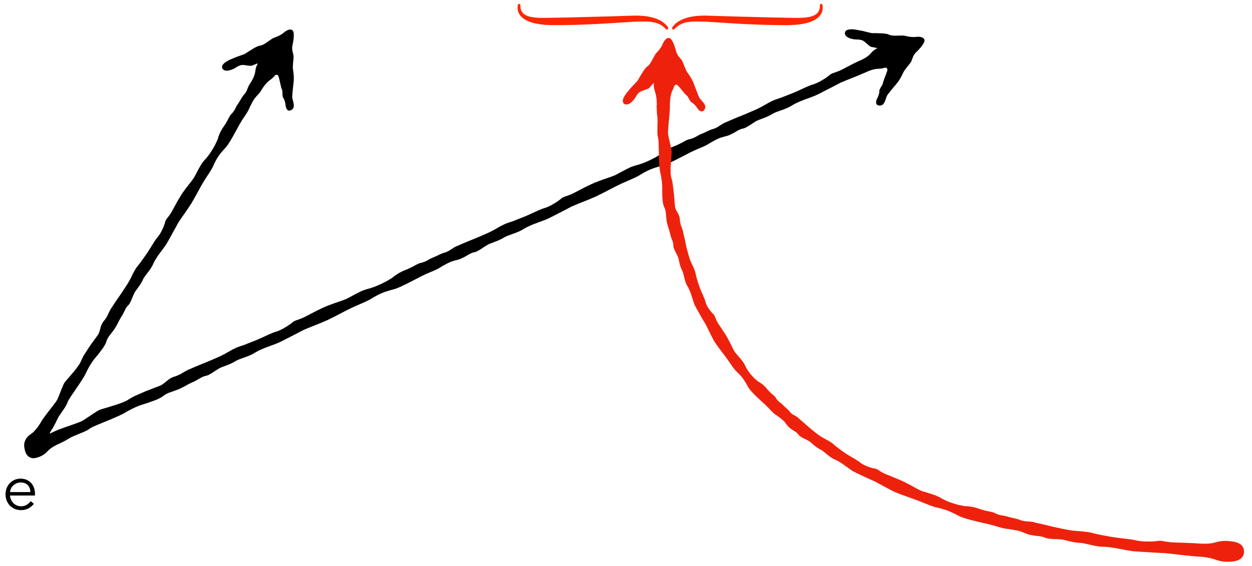


Alessandro Lella et al., in preparation

Inferring the UV completion?

The leading contribution to the running axion couplings arises from top loop diagrams induced by the axion-top coupling C_t

$$C_\Psi(2\mathrm{GeV}) \simeq C_\Psi(f_a) + \underbrace{r^t_\Psi(m_{\mathrm{BSM}})}_{}\, C_t(f_a) \qquad (\Psi = u, d, e)$$



Calculable

Depends on unknown high energy physics

⇒ *unavoidable additional uncertainty*

→ Choi et al. [JHEP 08 (2021) 058]

→ Di Luzio et al. [Phys.Rev.D 108 (2023)]

UV Corrections to Couplings

$$C_\Psi(2\text{GeV}) \simeq C_\Psi(f_a) + r^t_\Psi(m_\text{BSM})\; C_t(f_a)$$

Analytical Approximations

$$\left.\begin{aligned}
r^t_3(m_\text{BSM}) &= r^t_u - r^t_d \simeq -0.54\ln\left(\sqrt{x} - 0.52\right)\\
r^t_0(m_\text{BSM}) &= r^t_u + r^t_d \simeq 3.8\times 10^{-4}\ln^2\left(x - 1.25\right) \approx 0\\
r^t_e(m_\text{BSM}) &\simeq -\frac{1}{2}\, r^t_3
\end{aligned}\right\} \qquad \text{with } x = \log_{10}\left(\frac{m_\text{BSM}}{\text{GeV}}\right)$$

→ Di Luzio et al. Phys.Rev.D 108 (2023)

Less Uncertainty in Nuclear Couplings?

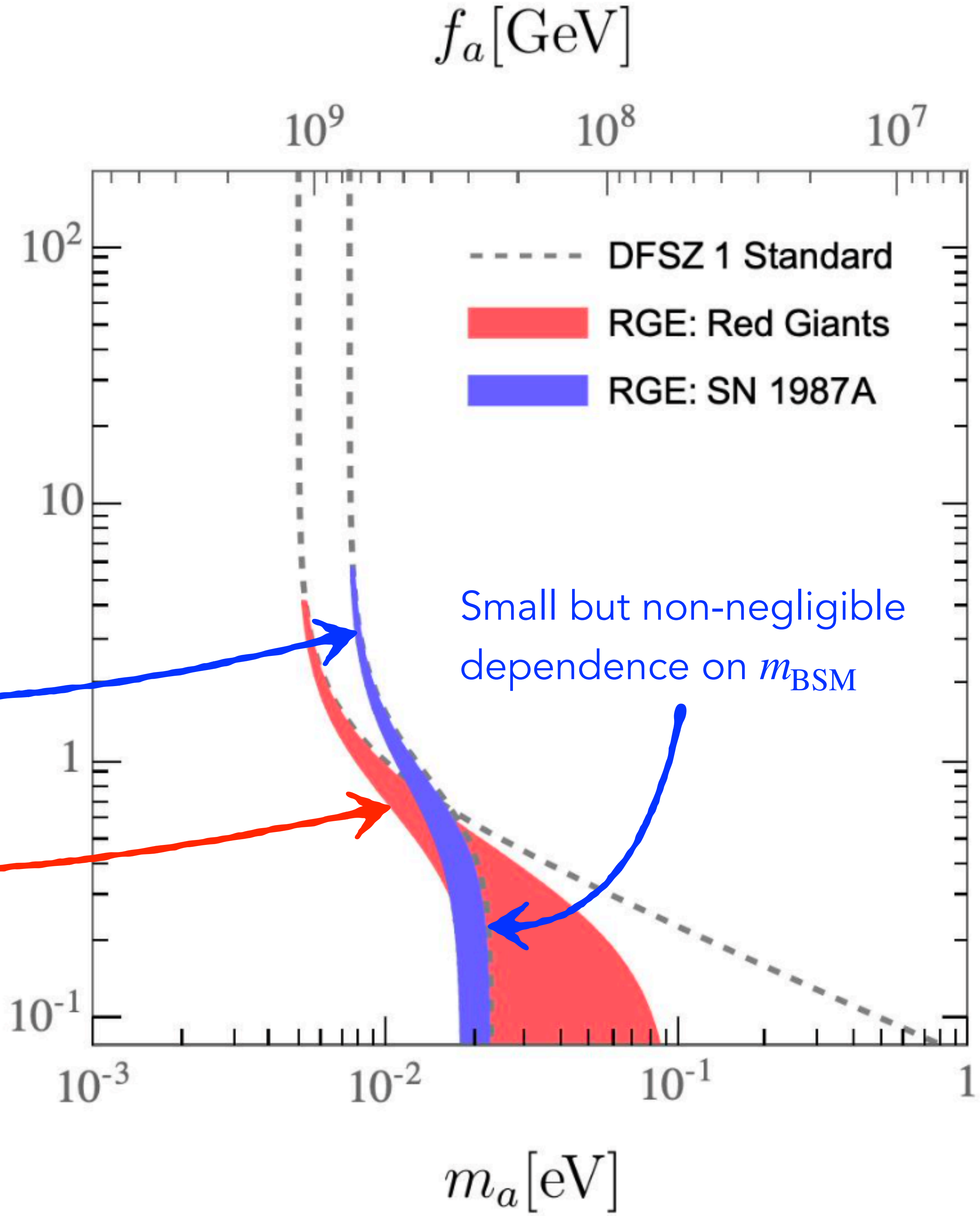
$$C_{\rm SN} \simeq 1.4\left(C_0^2 + 0.11\,C_0C_3 + 1.3\,C_3^2\right)^{1/2}$$

This translates in the bound

$$m_a \leq \frac{\bar{m}}{C_{\rm SN}}\,, \quad \text{with} \quad \bar{m} \sim 5\,\text{meV}$$

$$|C_e| \lesssim 1.65 \times 10^{-3}\left(\frac{m_a}{\text{eV}}\right)^{-1}$$

The C_3 dependence comes mostly (not exclusively) from pion interactions.



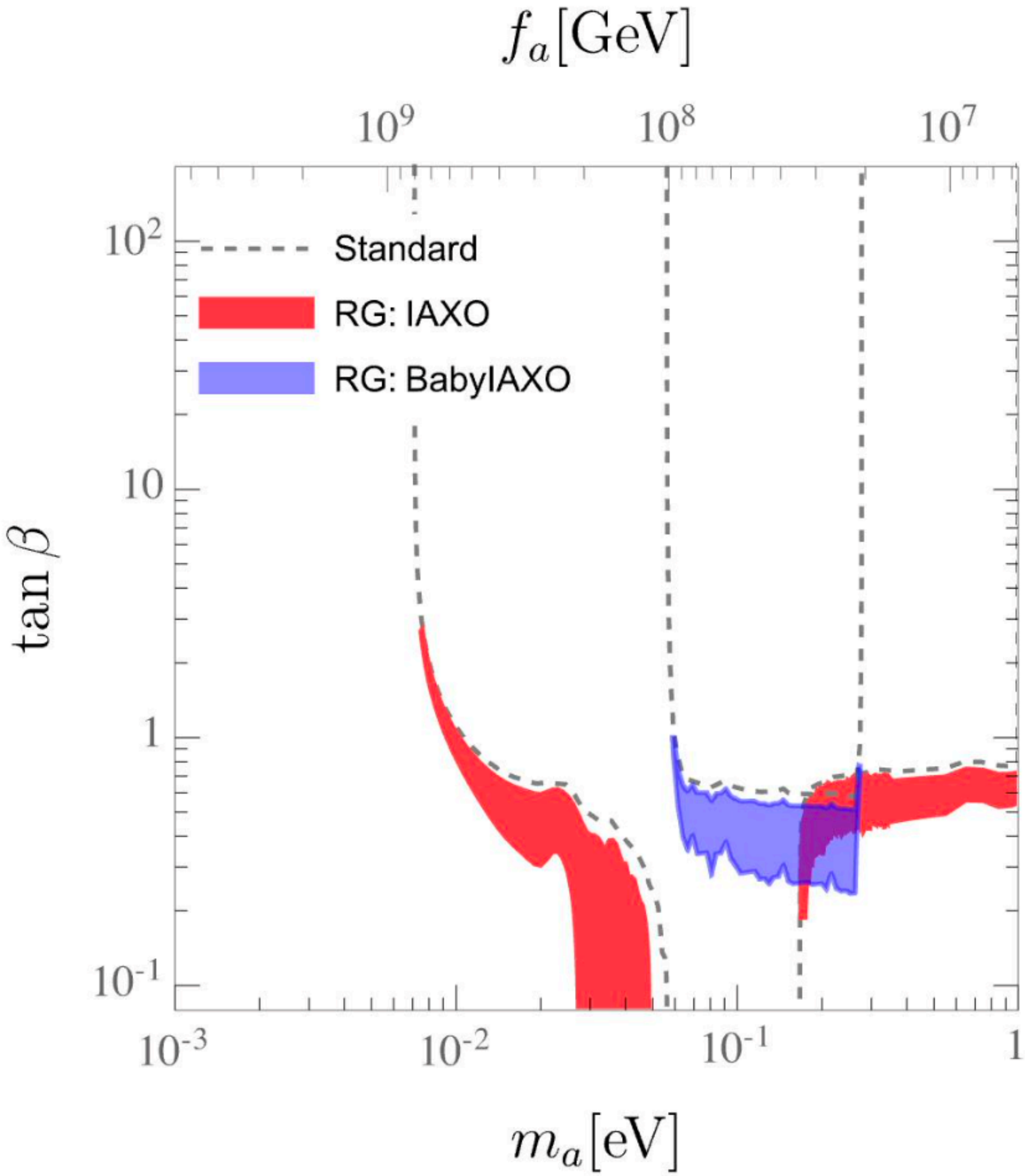
Small but non-negligible dependence on $m_{\rm BSM}$

Detection Perspectives for DFSZ axions

The solar flux of DFSZ axions has *always* a g_{ae} component.

The IAXO potential for DFSZ parameter space is higher than naively expected.

However, post-discovery uncertainties



Conclusions

- Realistic options to find $g_{a\gamma}$ and perhaps $g_{a\gamma}/g_{ae}$.
- Several options also for some *effective* nuclear coupling g_{aN}^{eff}
- The door to the UV may be the axion-photon coupling or isoscalar nuclear couplings.
- After we find the axions, we can use them to study the sun and other stars. → That will be truly fun!! (See Sebastian talk and ask us questions)