

Constraining axion couplings with the JUNO detector

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Why axions?

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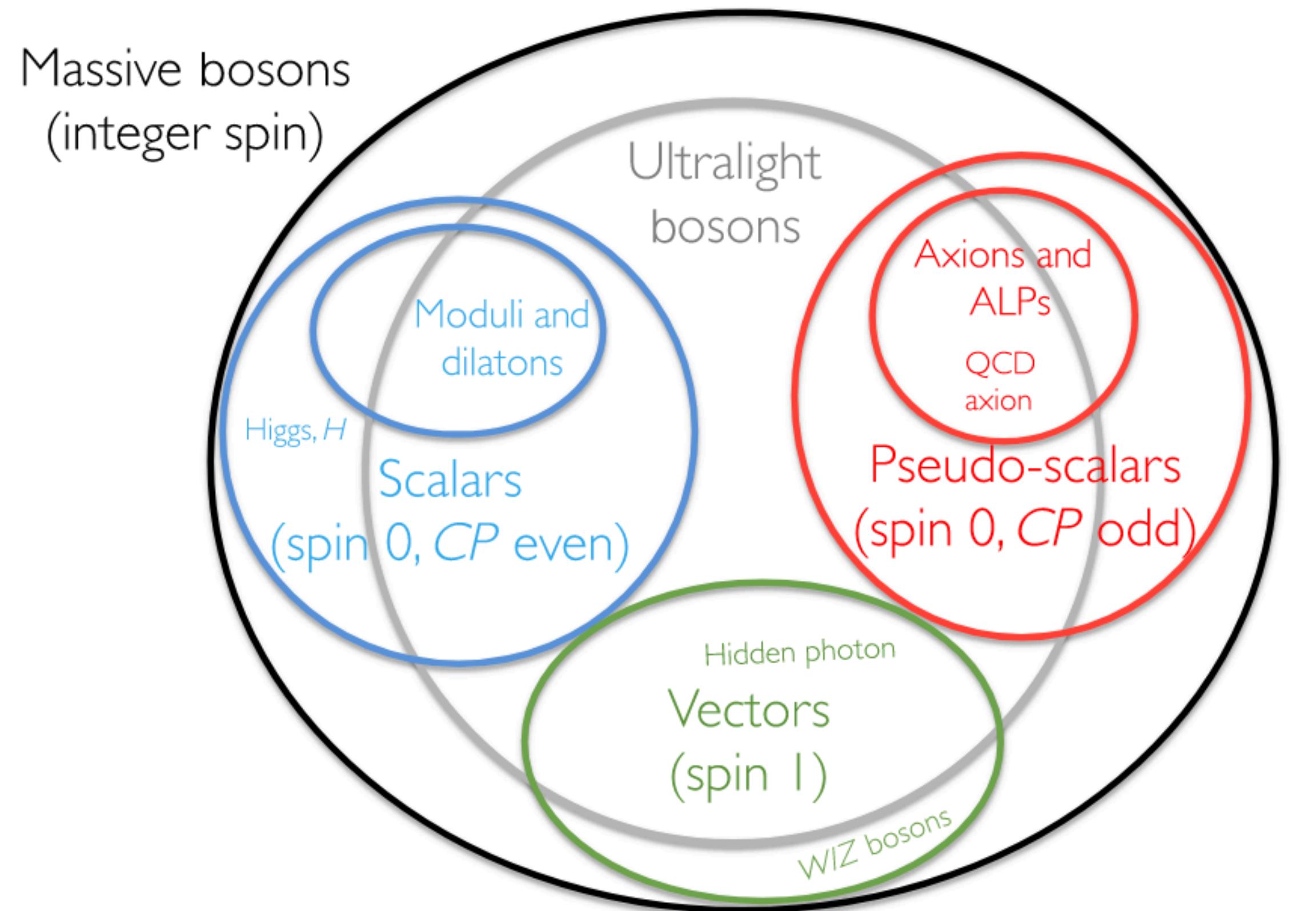


Fig. 1. Many extensions of the Standard Model predict additional massive bosons, beyond the W , Z , and Higgs bosons of the Standard Model. They

[Chadha-Day, Ellis, Marsh, *Sci.Adv.* 8 (2022)]

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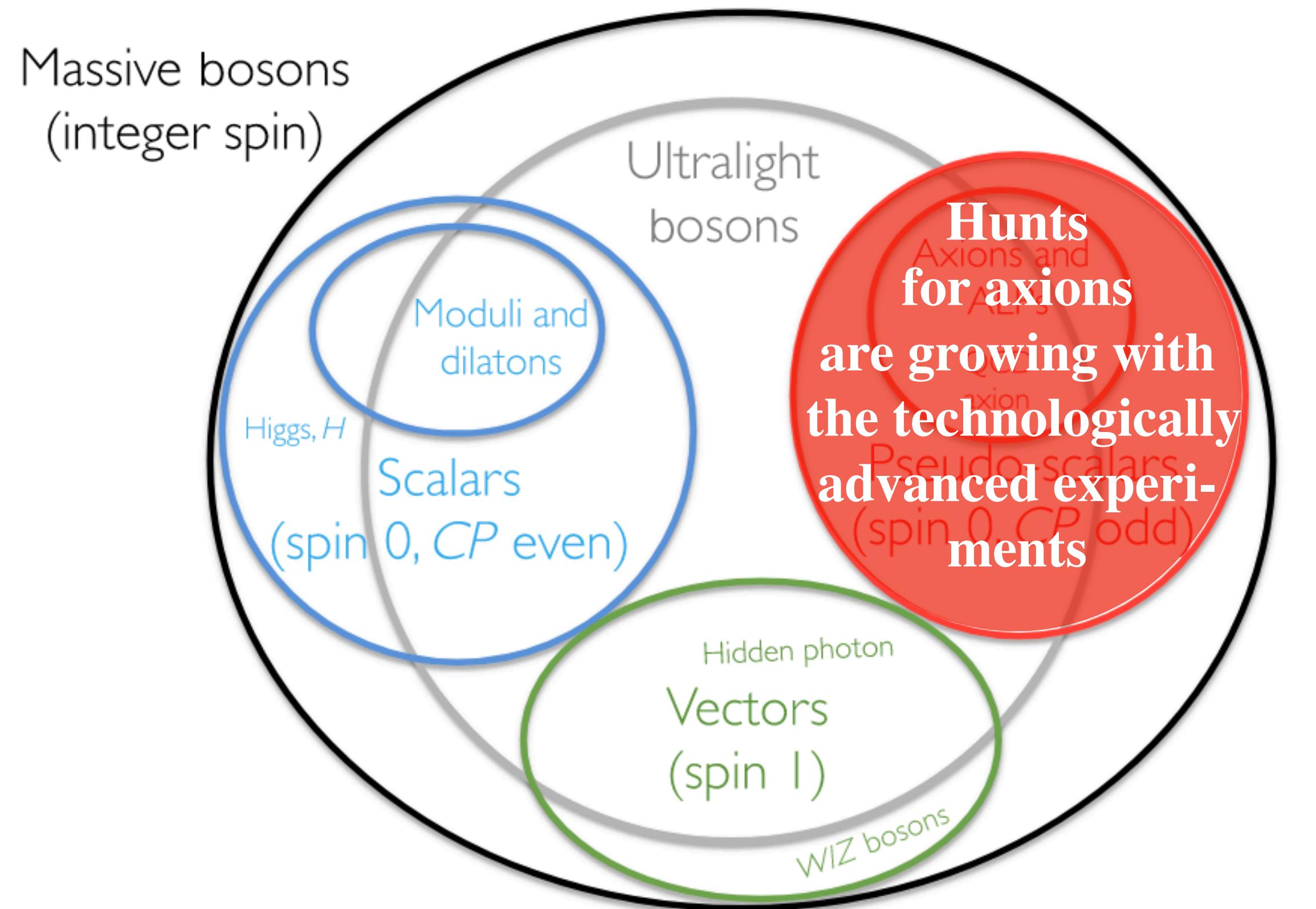


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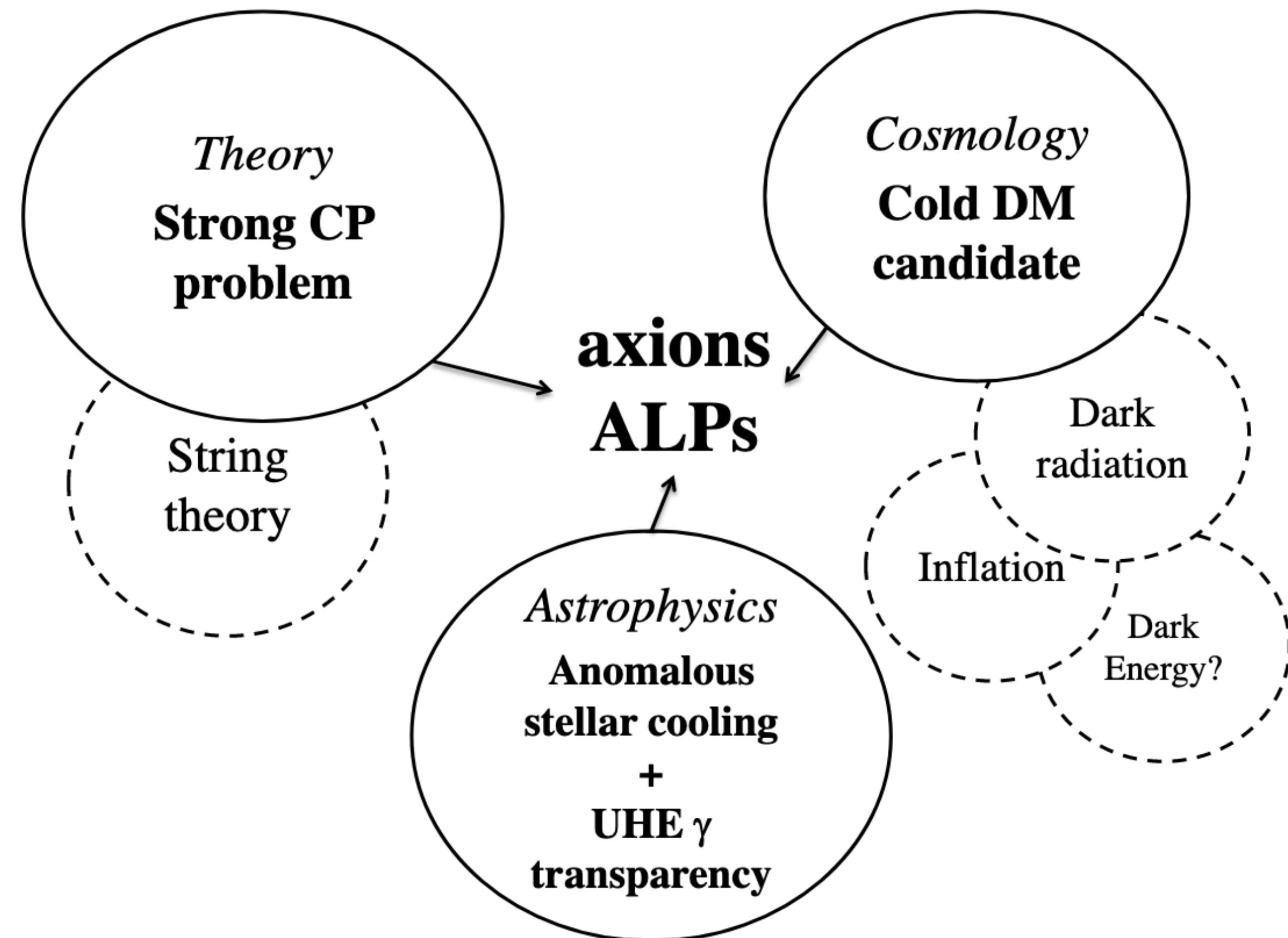
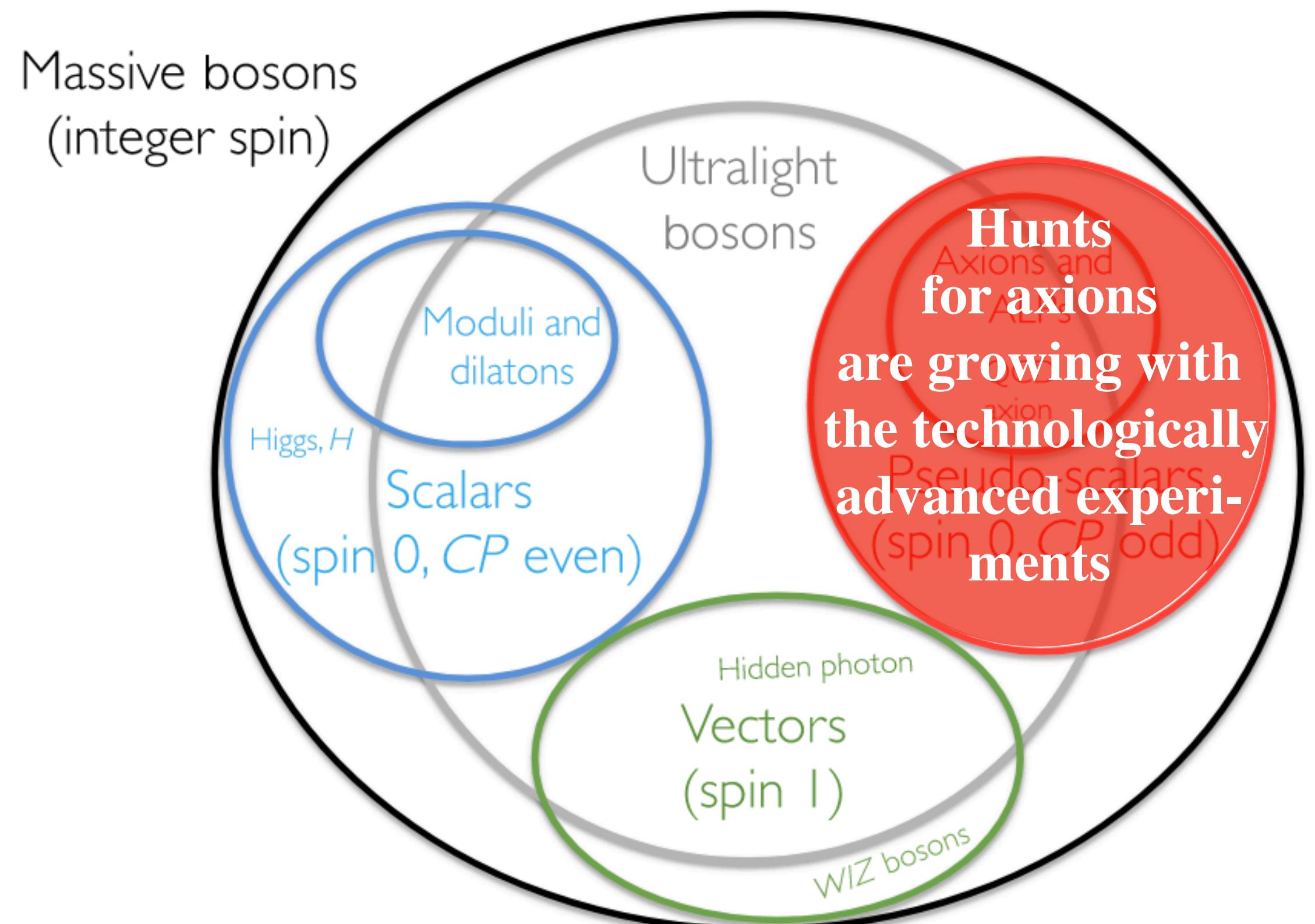


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[Chadha-Day, Ellis, Marsh, *Sci.Adv.* 8 (2022)]

Credits: I. G. Irastorza

Strong CP problem

- The QCD Lagrangian:

$$\mathcal{L}_{\text{QCD}} = \sum_q \bar{q} (iD - m_q e^{i\theta_q \gamma_5}) q - \frac{1}{4} G^{a\mu\nu} G_{\mu\nu}^a + \theta \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \tilde{G}_{\mu\nu}^a$$

$\rightarrow \propto E_a \cdot B^a$

- θ -term is a total derivative and does not affect the classical EoM.
But, it has important effects on the quantum theory.
- It is the difference $\bar{\theta} = \theta - \theta_q$ has physical meaning
- Non-zero $\bar{\theta}$ -term has observational consequences to the neutron electric dipole moment

$$d_n = (2.4 \pm 1.0) \bar{\theta} \times 10^{-3} e \text{ fm}$$

- At present d_n is constrained to $|d_n| < 1.8 \times 10^{-13} \text{ e fm}$ (at 90% C.L.)

$$\Rightarrow |\bar{\theta}| < 10^{-10}$$

Strong CP problem: “*Experimentally $\bar{\theta} \lesssim 10^{-10}$, why is CP-violation so much suppressed in strong interactions?*”

The axion

- To solve the problem, Peccei Quinn introduced a global $U(1)_{PQ}$ symmetry to the QCD
- This $U(1)_{PQ}$ symmetry would be spontaneously broken at a high energy scale f_a
[Peccei, Quinn (1977),
Weinberg (1978), Wilczek (1978)]
- Such an spontaneously broken symmetry implied a new pNG boson, “**Axion**”
- Under the symmetry axion field transform additively as $a \rightarrow a + \alpha f_a$
- The axion Lagrangian: $\mathcal{L}_{\text{eff}} = \left(\bar{\theta} + \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a - \frac{1}{2} \partial^\mu a \partial_\mu a + \mathcal{L}(\partial_\mu a, \psi)$

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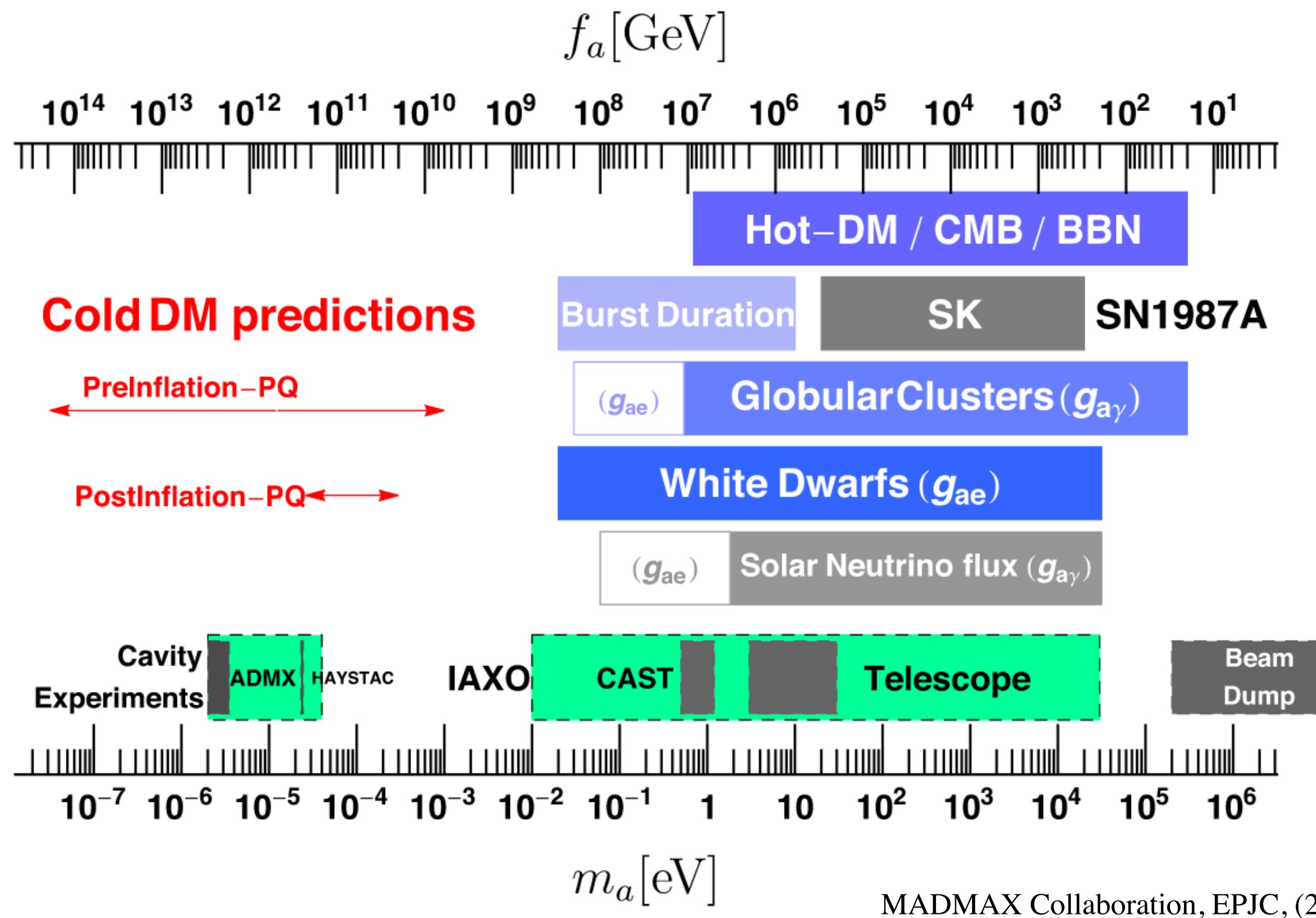
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Axion Landscape

- Axion mass $\sim 1/f_a$;

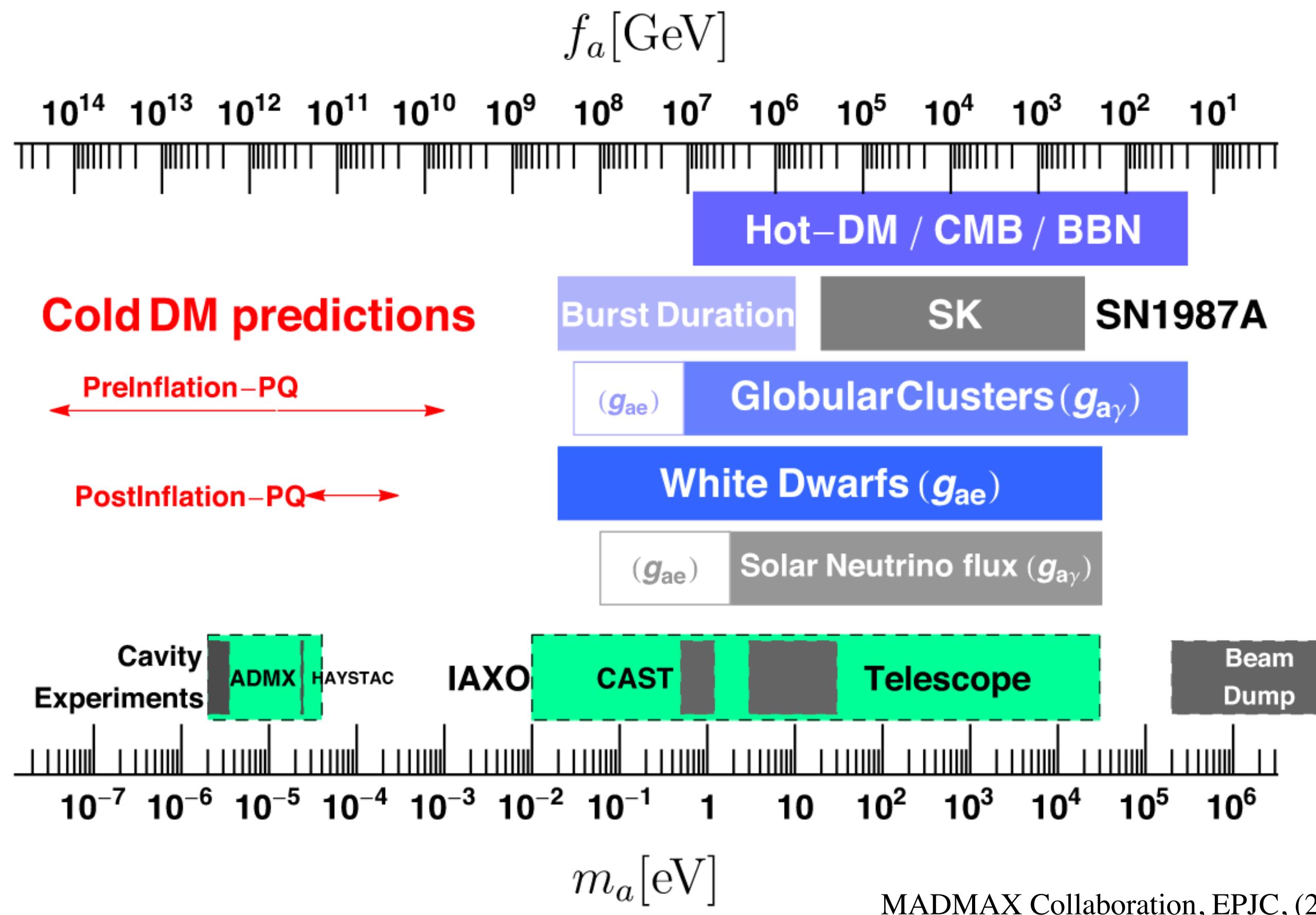
$$m_a \simeq m_\pi \frac{f_\pi}{f_a} \simeq 6 \text{ meV} \frac{10^9 \text{ GeV}}{f_a}$$



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Accessible couplings for experimental detection

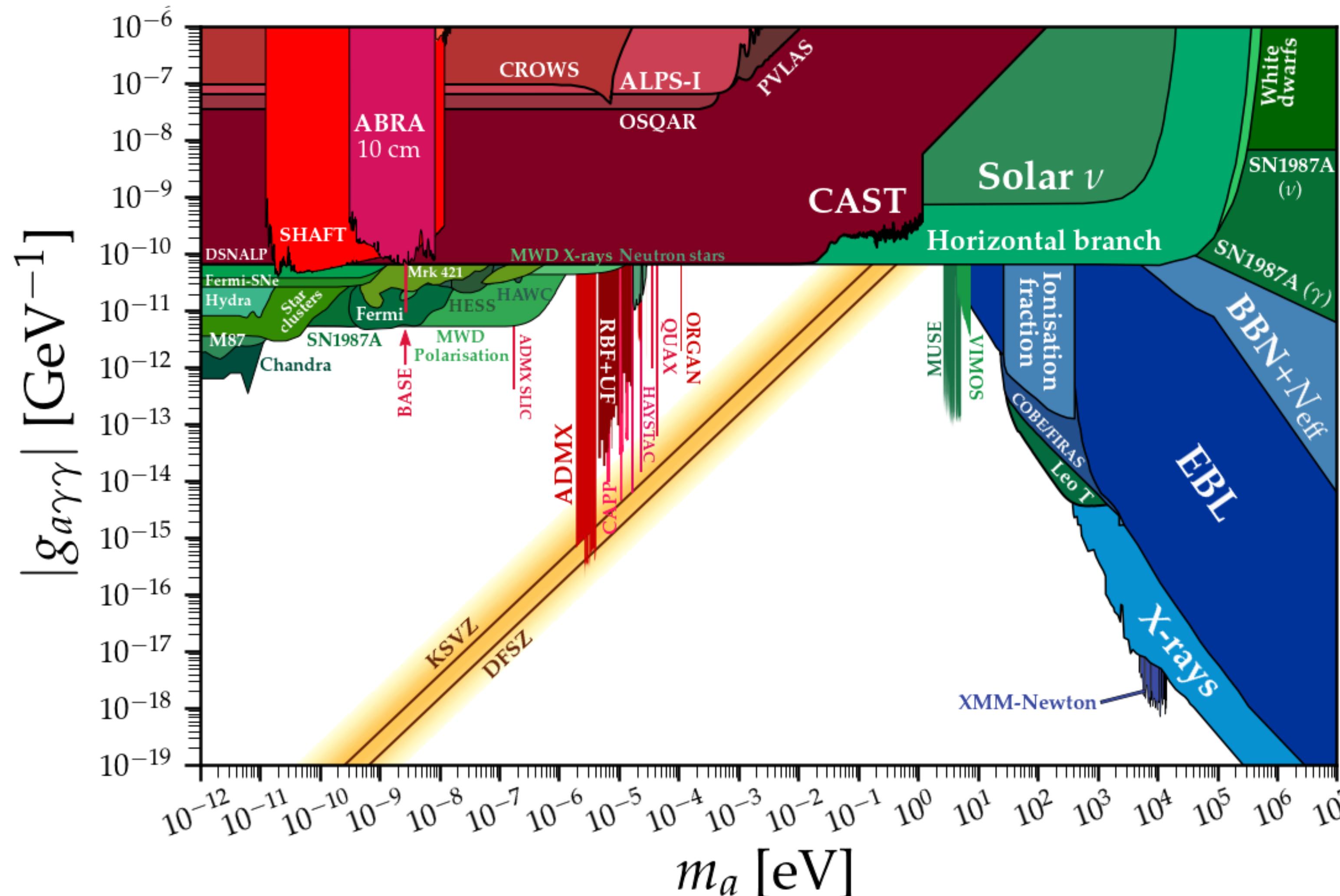
- The effective low energy axion-Lagrangian

$$\mathcal{L} = \frac{1}{2} \left(\partial_\mu a \right)^2 - m_a^2 a^2 - \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \widetilde{F}^{\mu\nu} - i g_{ae} a \bar{e} \gamma_5 e - i a \bar{N} \gamma_5 (g_{0aN} + \tau_3 g_{3aN}) N$$

All axion couplings $\sim 1/f_a$;

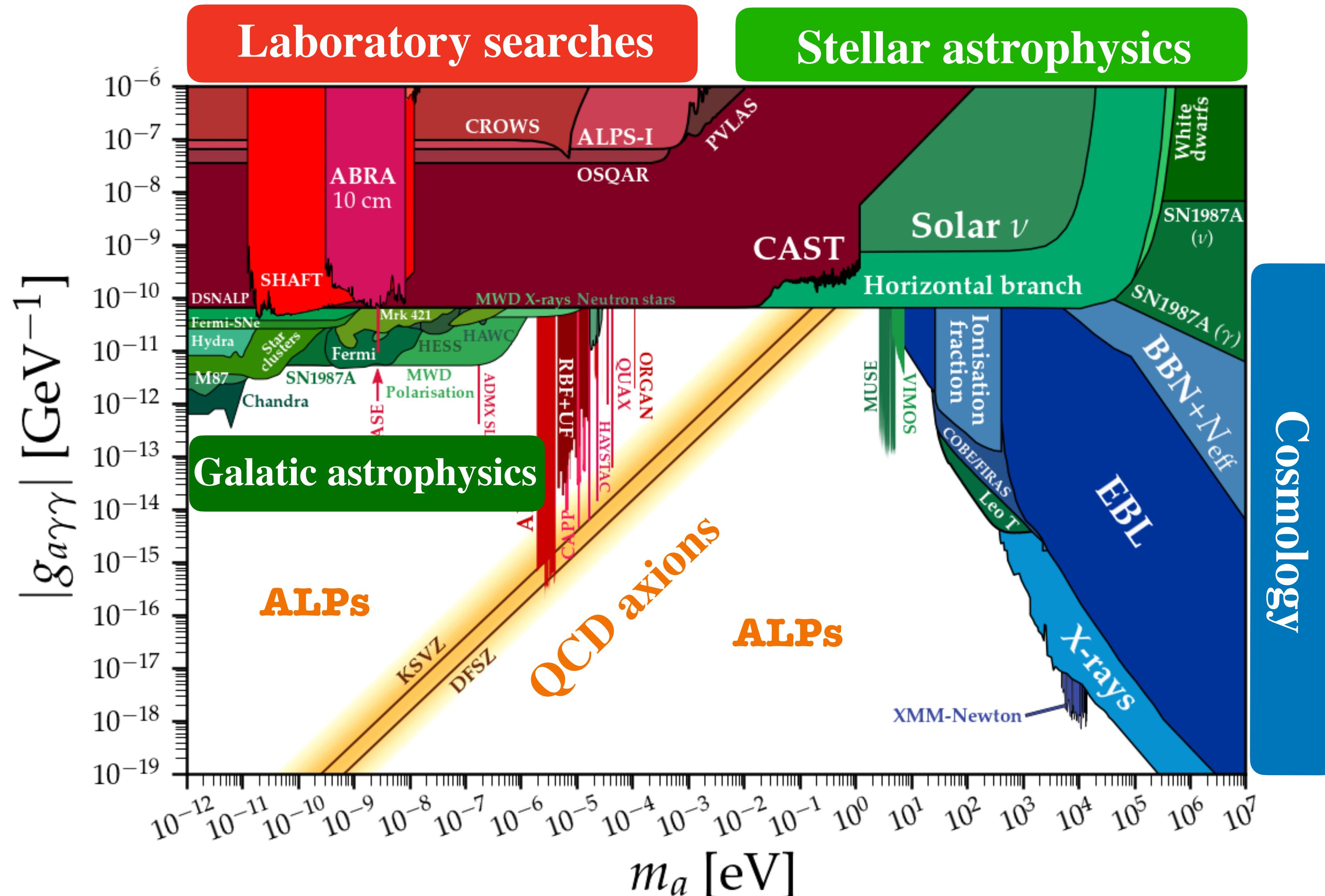
Experimental efforts

Current constraint on axion-photon couplings



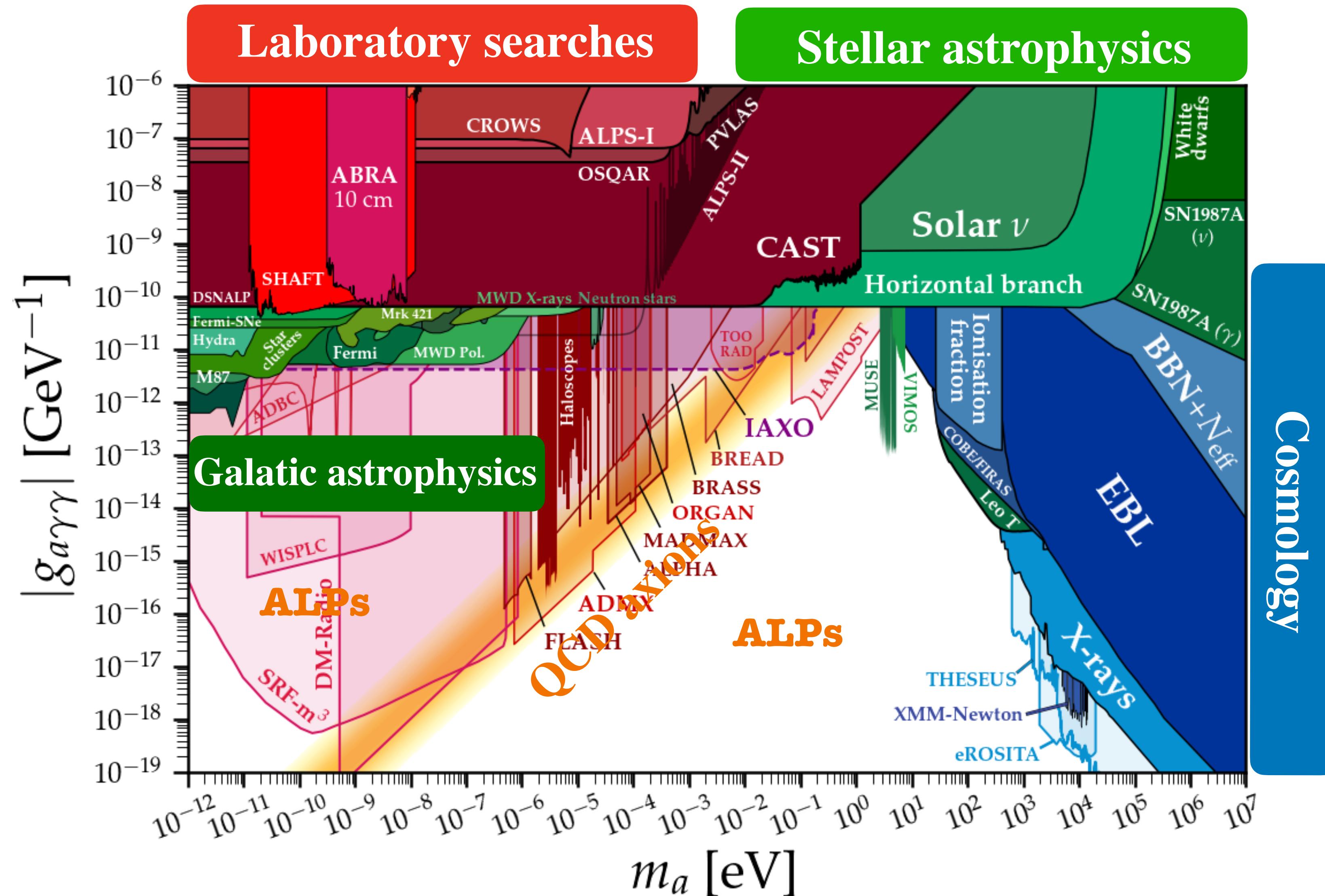
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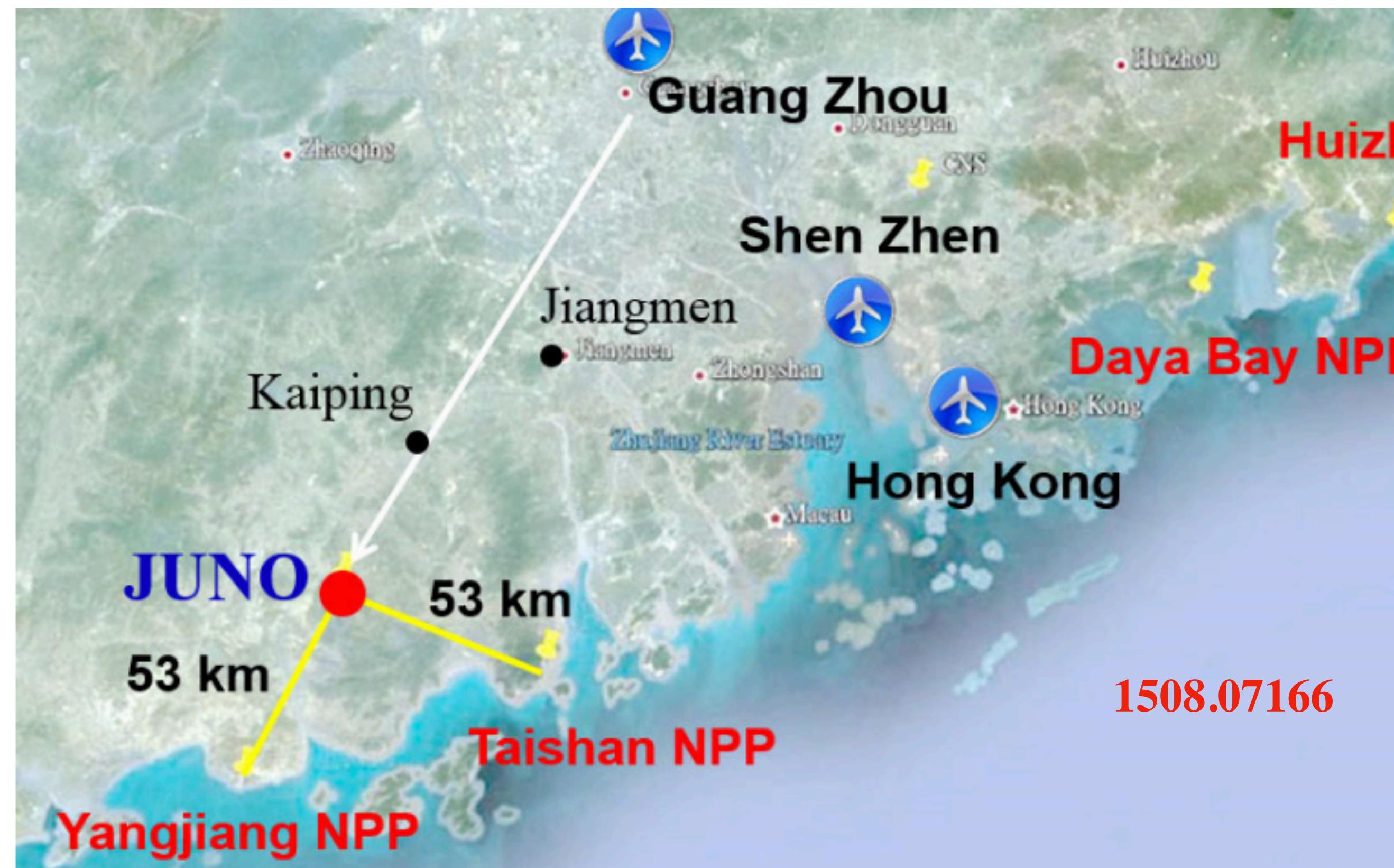
Experimental efforts

Projected constraint on axion-photon couplings



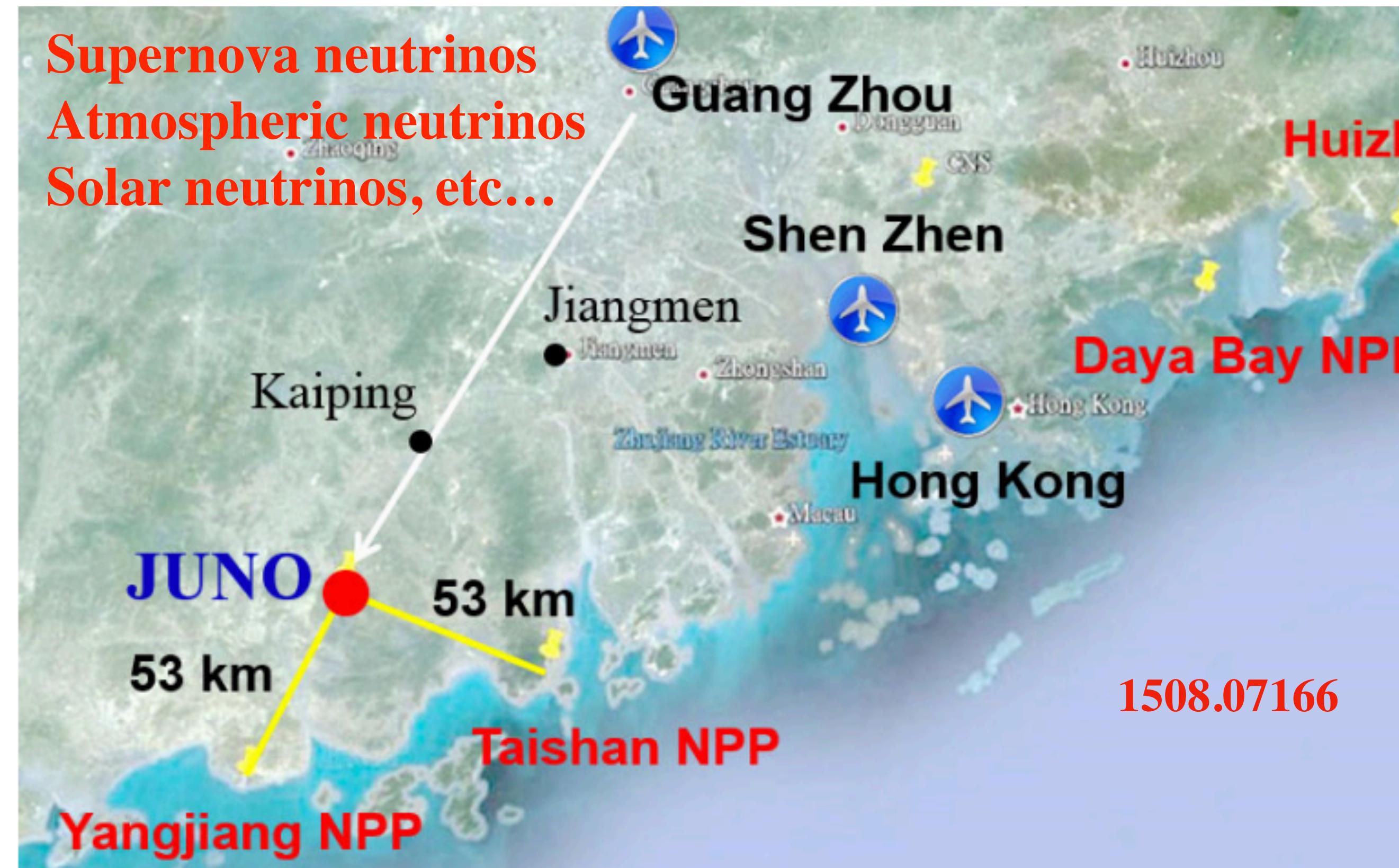
JUNO: Jiangmen Underground Neutrino Observatory

- It is a medium-baseline (53km) **reactor neutrino experiment** located in China, under construction
- JUNO features a 20 kton multi-purpose underground liquid scintillator detector
- Aims to determine neutrino mass ordering and precision measurement of PMNS parameters



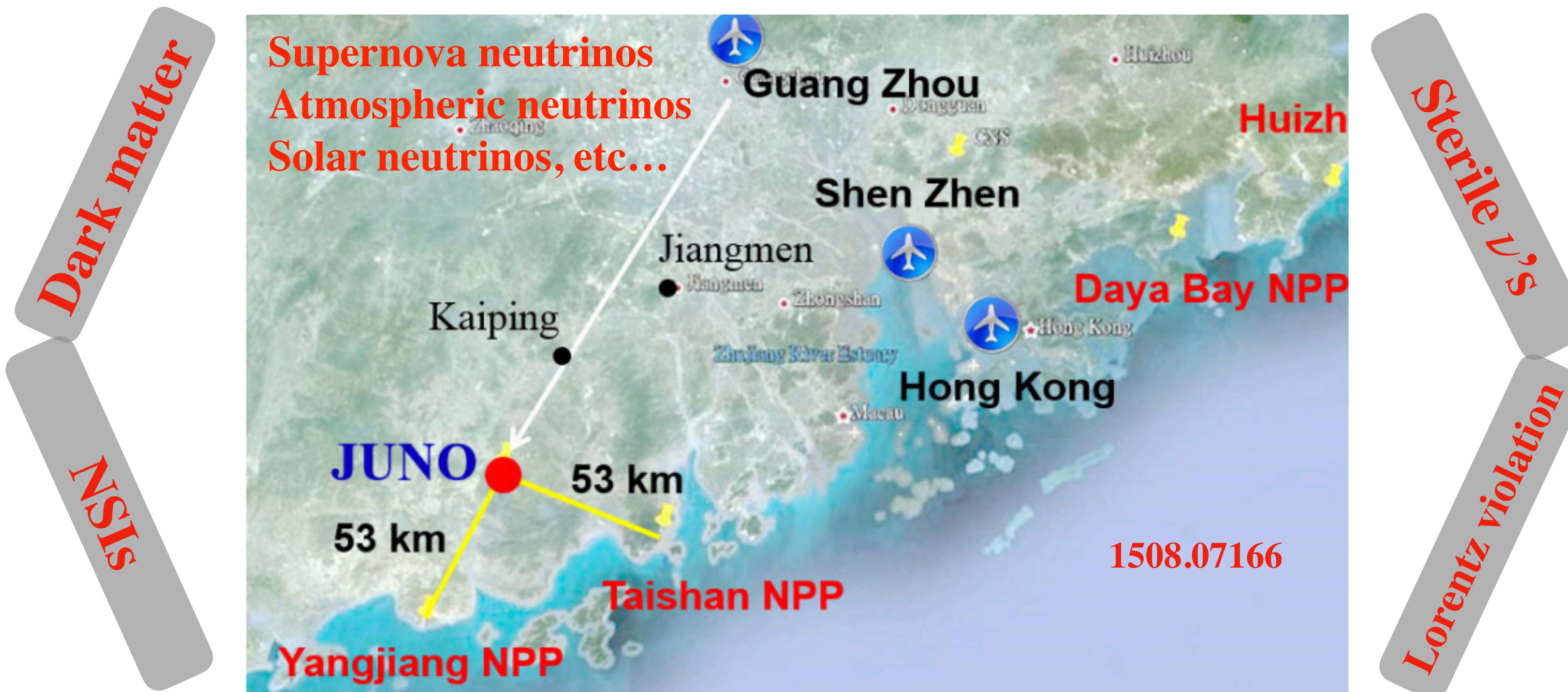
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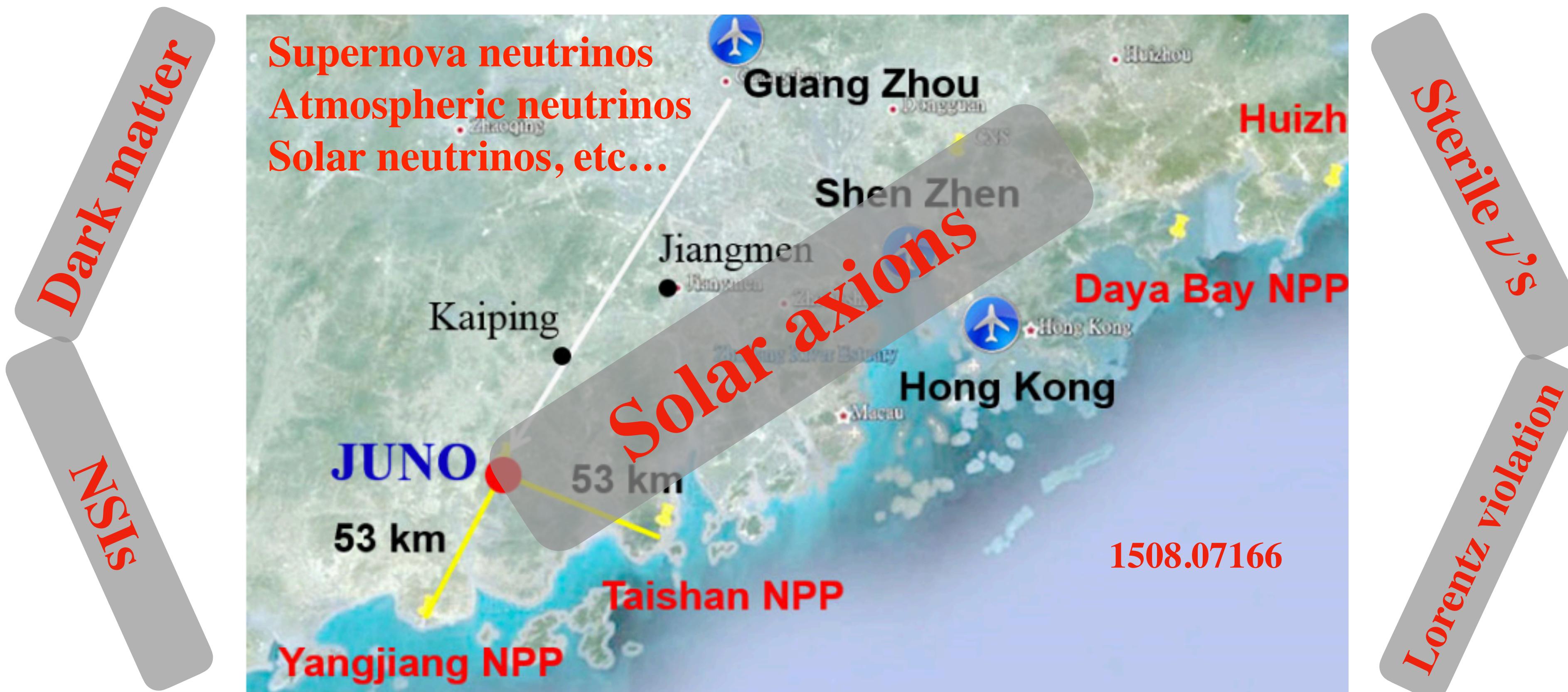
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Solar axion

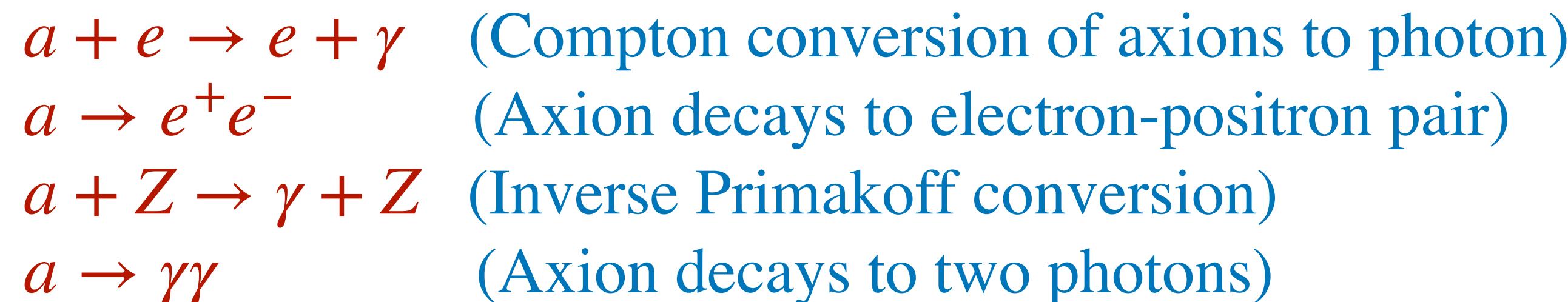
Axion production

- Sun provides an ideal platform to study solar axions by producing very intense flux.
- We consider solar axion produced in the $p + d \rightarrow {}^3\text{He} + a$ (5.49 MeV) reaction
- Axion flux $\propto pp$ neutrino flux and is known with a high accuracy
[Serenelli, W. C. Haxton, and C. Pena-Garay, Astr. J. 743 (2011) 24,
Bellini et. al. PRL 107 (2011) 141302]
- Solar axions flux on the Earth's surface:

$$\Phi_{a0} = 3.23 \times 10^{10} (g_{3aN})^2 (p_a/p_\gamma)^3 \quad \text{where } p_\gamma \text{ and } p_a \text{ are the photon and axion momenta}$$

Axion detection

- We consider



Numerical Procedure: χ^2 is defined as

$$\chi^2 = 2 \times \sum_{i=1}^{240} \left(N_{pre}^i - N_{obs}^i + N_{obs}^i \times \log \frac{N_{obs}^i}{N_{pre}^i} \right) + \left(\frac{\varepsilon_s}{\sigma_s} \right)^2 + \left(\frac{\varepsilon_b}{\sigma_b} \right)^2,$$

$$N_{pre}^i = (1 + \varepsilon_s) \times T_i + (1 + \varepsilon_b) \times B_i + \frac{S}{\sqrt{2\pi}\sigma} \times e^{-\frac{(E_{5.5} - E_i)^2}{2\sigma^2}},$$

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Total signal

Total
Background

Axion peak
Intensity

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Nuisance parameters

Signal and background
Uncertainties, 5% & 15 %

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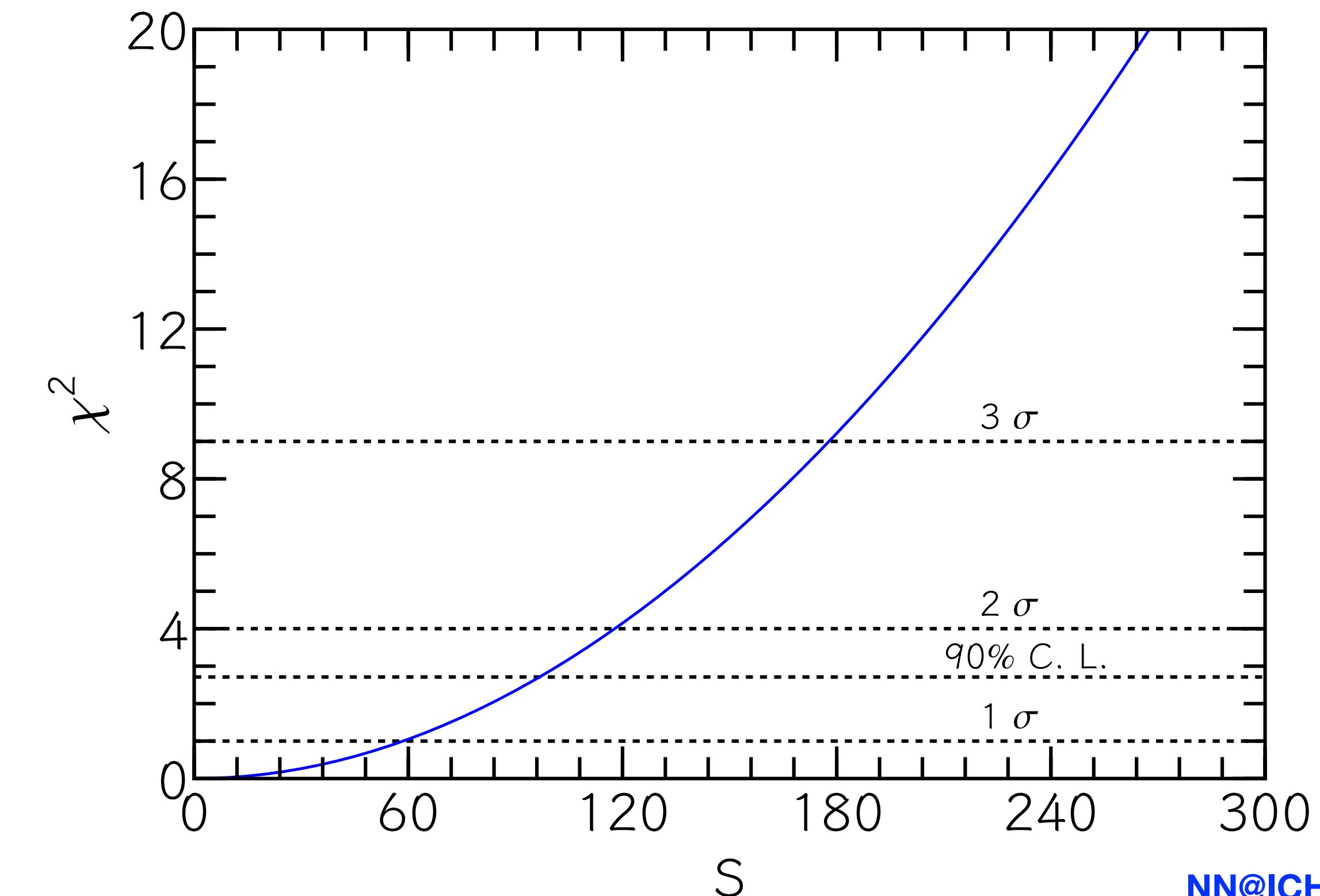
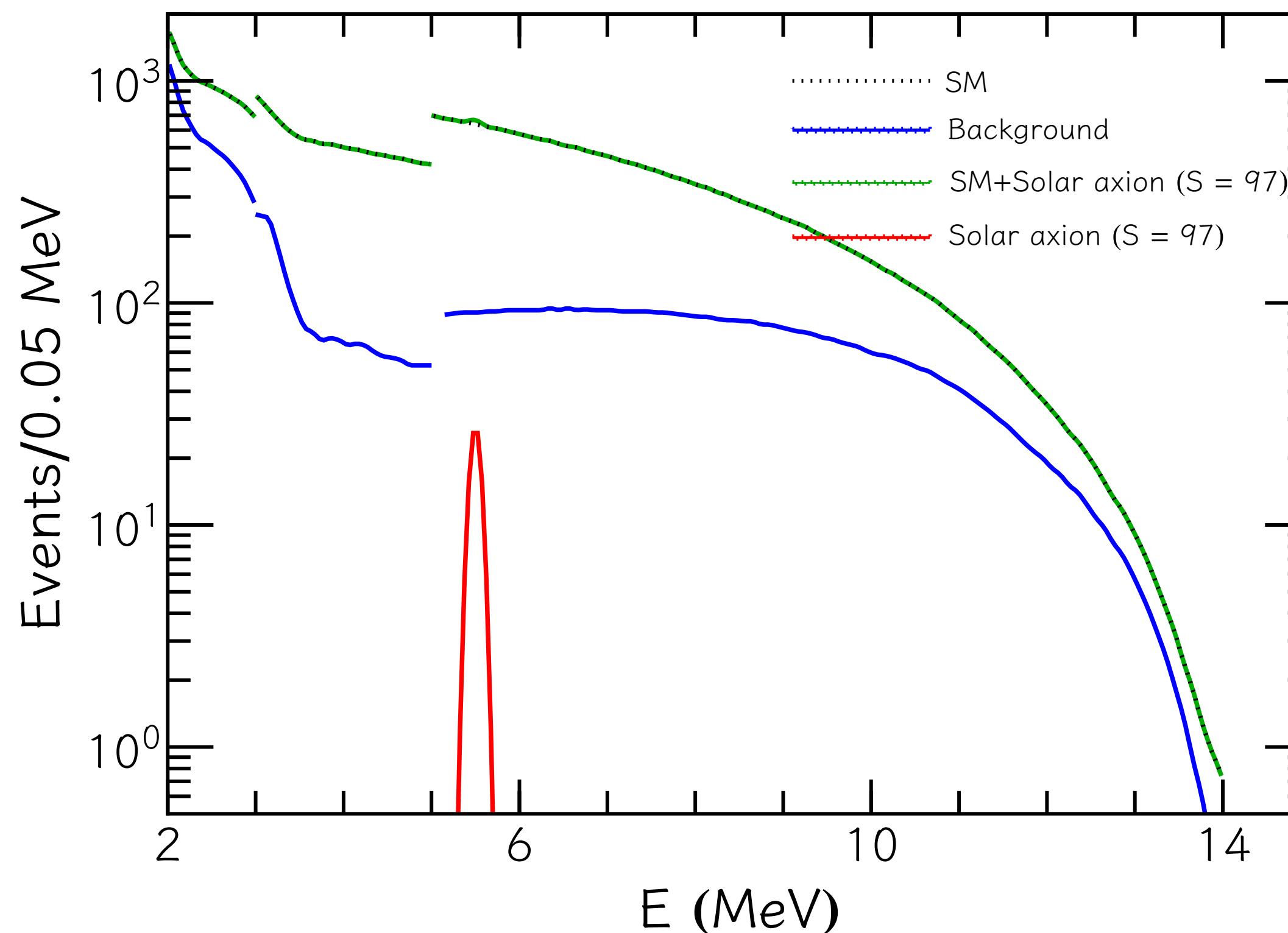
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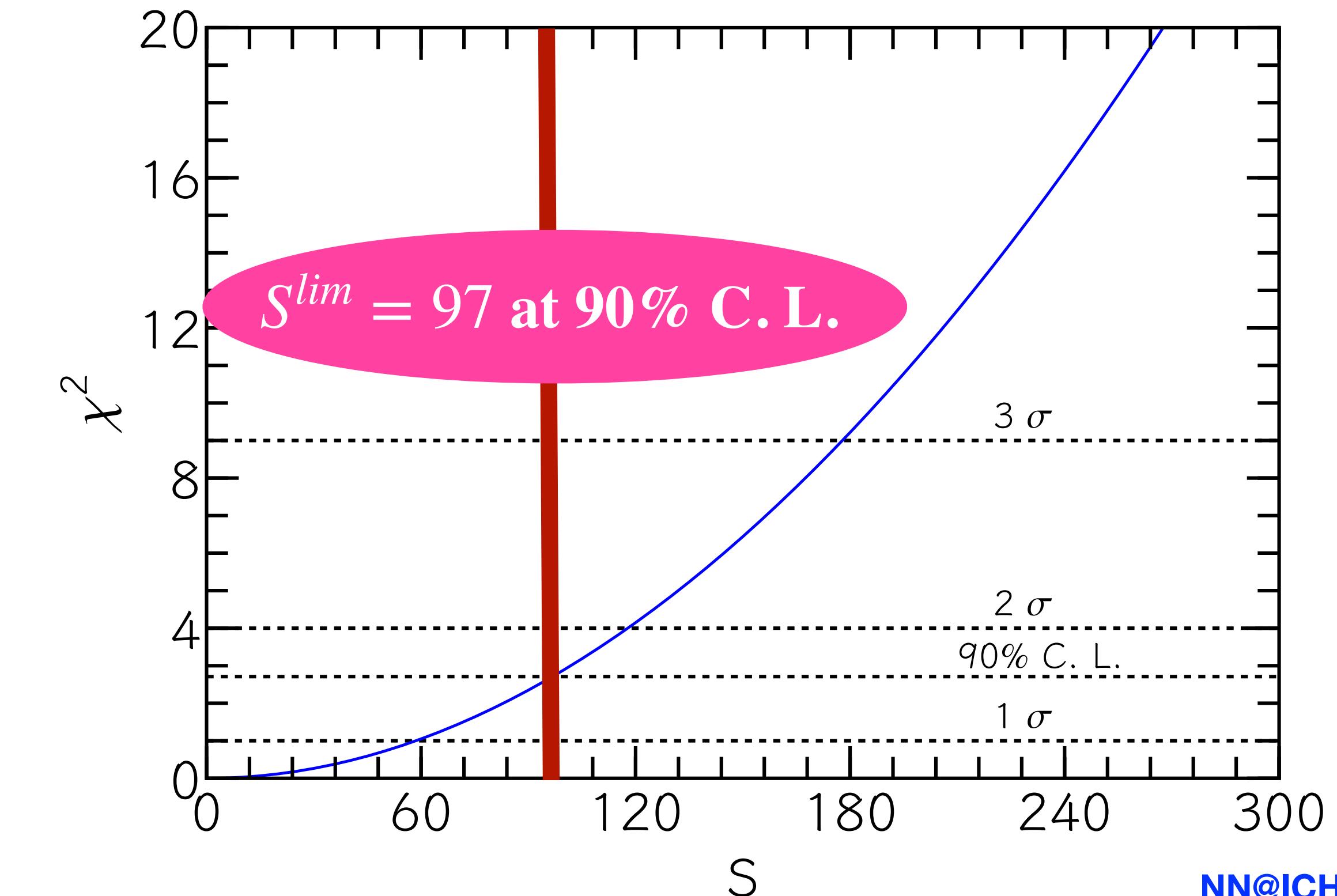
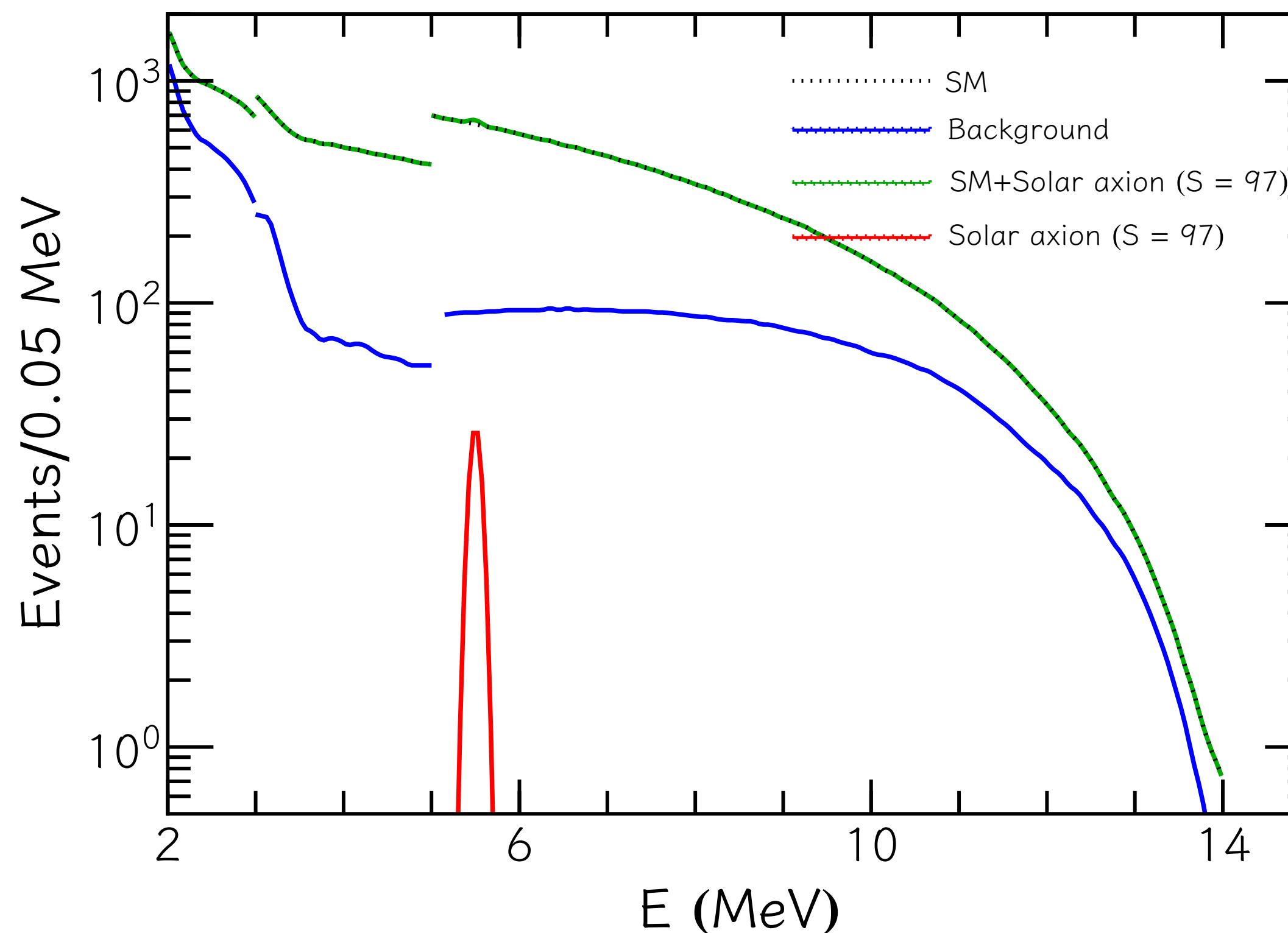
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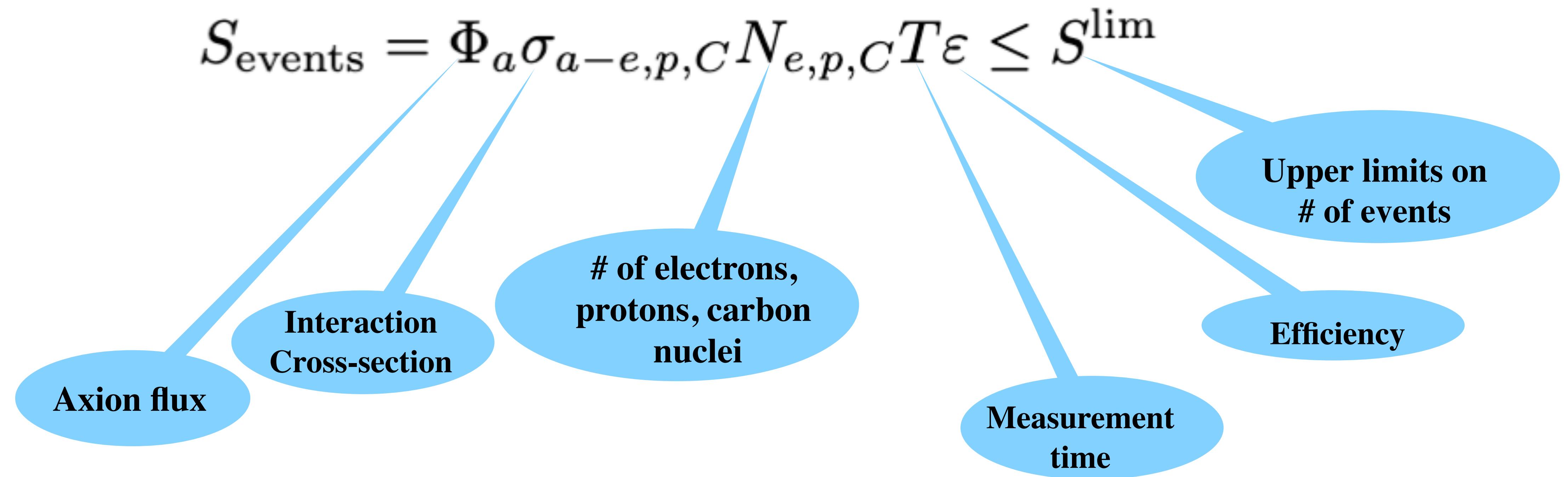
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Cont...

Borexino Collaboration, Bellini, et. al. PRD 85 (2012) 092003

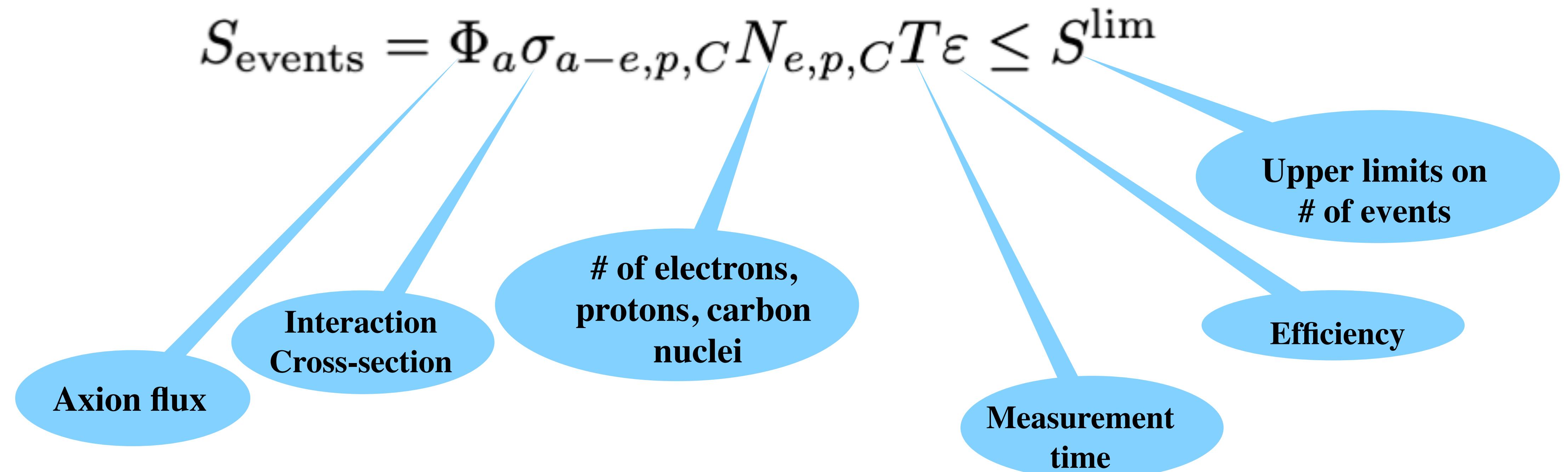
- Expected number of events in presence of solar axion:



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$$S^{\lim} = 97 \text{ at } 90\% \text{ C. L.}$$

Axion detection

- Compton conversion of axions to photons: $a + e \rightarrow e + \gamma$

Cross-section is given by $\sigma_{CC} \approx g_{ae}^2 \times 4.3 \times 10^{-25}$

for $m_a < 1 \text{ MeV}$

- We obtain at 90% c.l.

$$|g_{3aN} \times g_{ae}| \leq 6.33 \times 10^{-14} \text{ for JUNO}$$

$$|g_{3aN} \times g_{ae}| \leq 5.5 \times 10^{-13} \text{ for Borexino}$$

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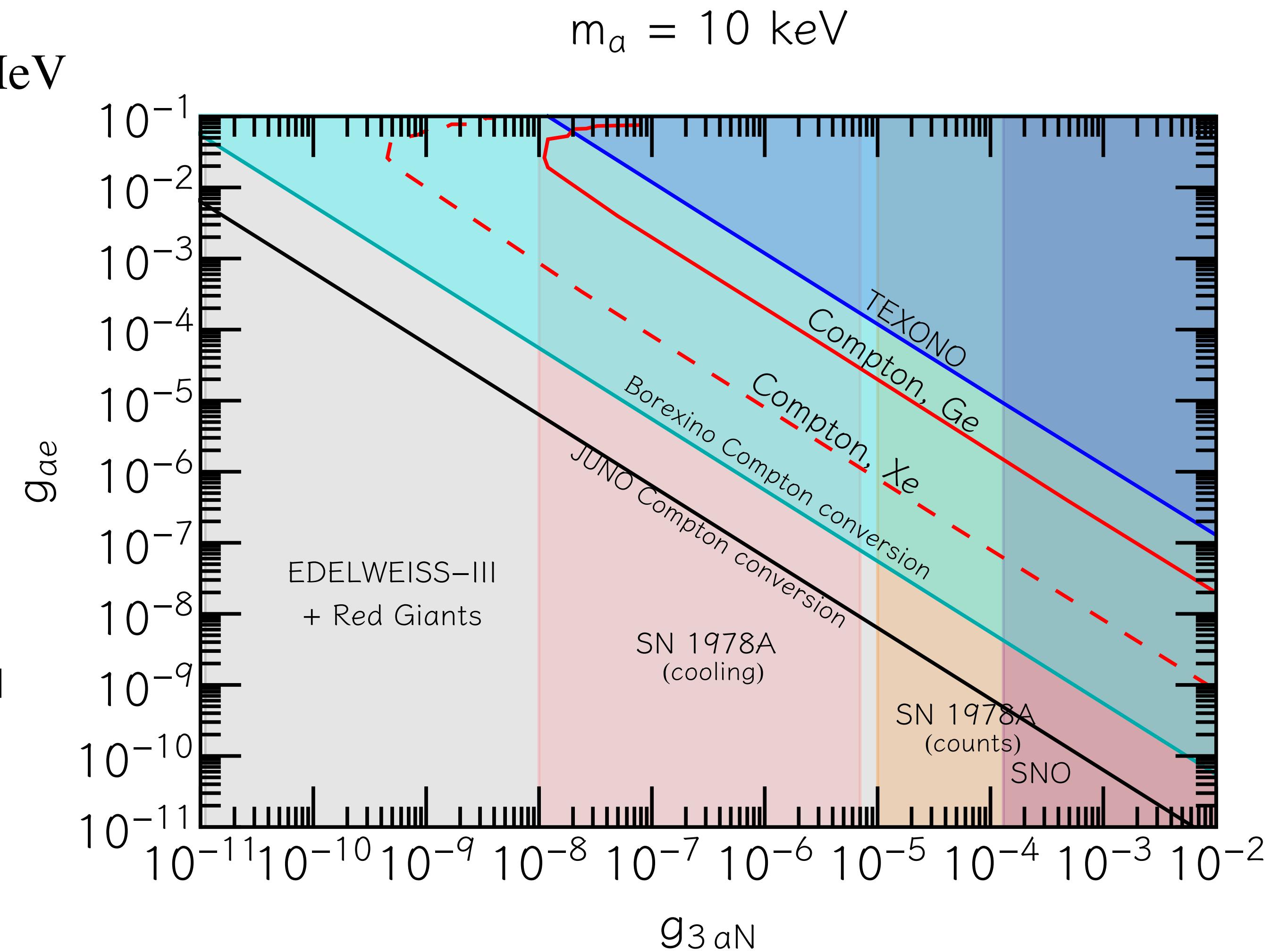
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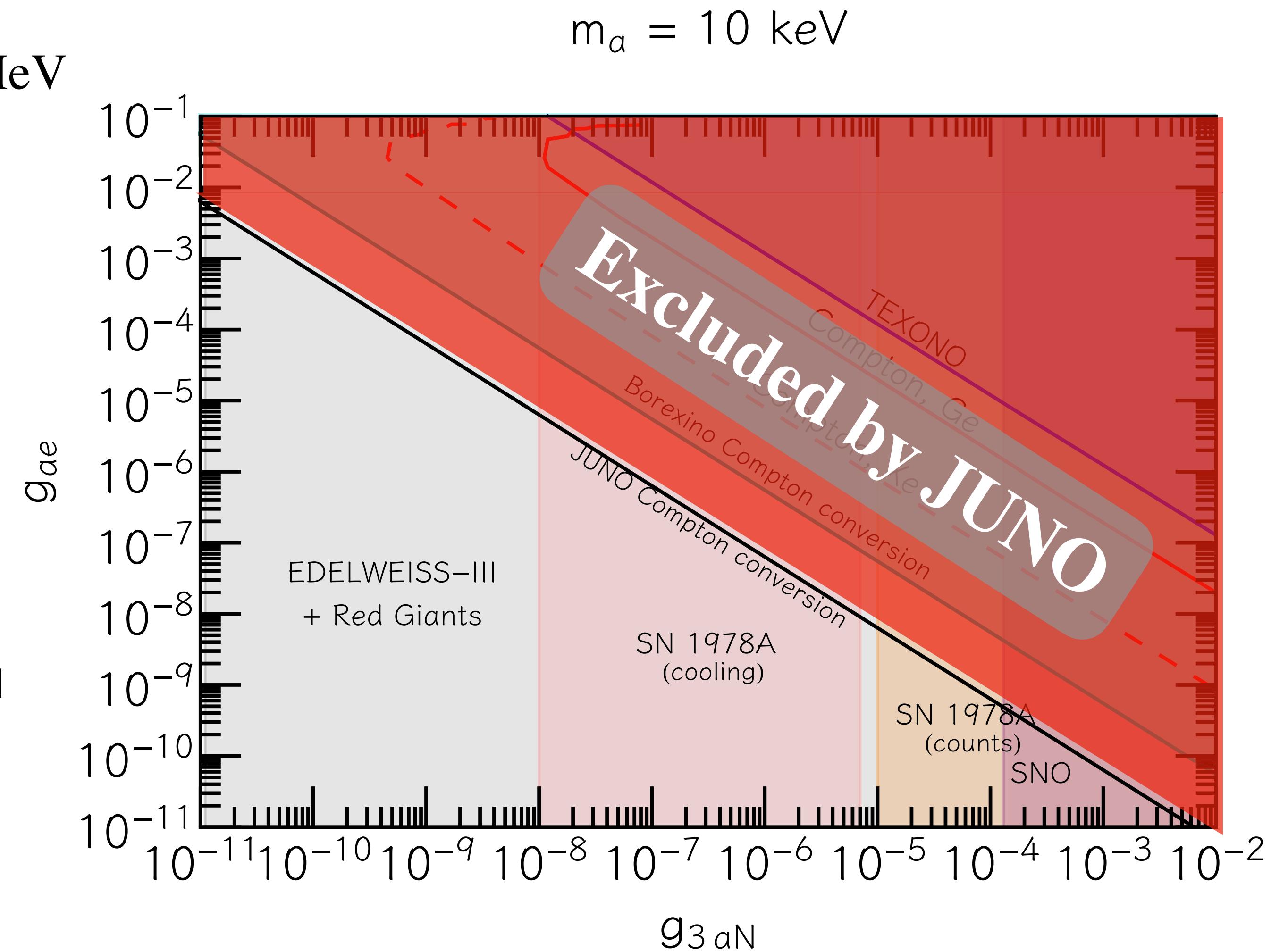
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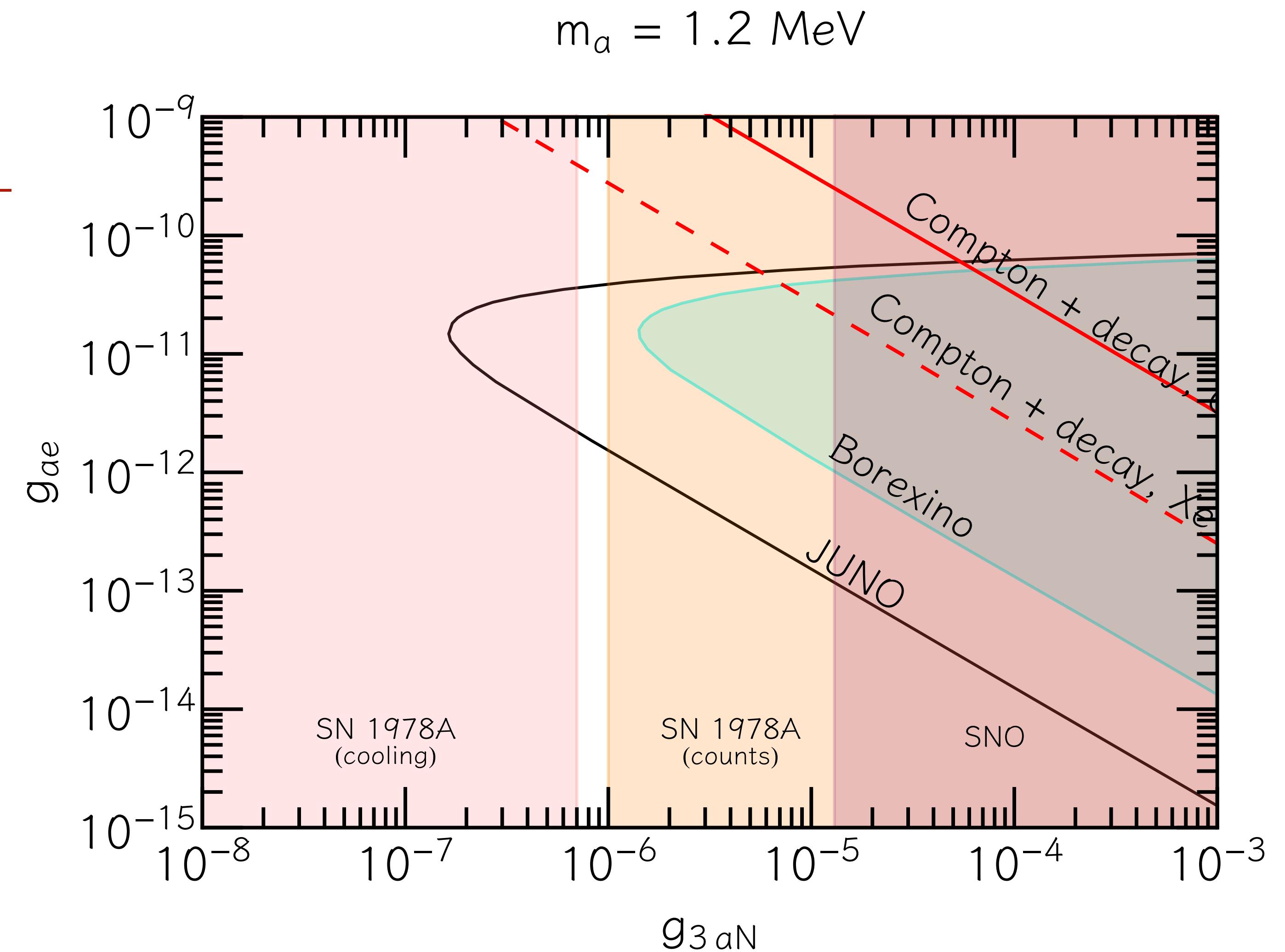
- Axion decays to electron-positron pair

Expected number of events for $a \rightarrow e^+e^-$

$$S_{e^+e^-} = N_{e^+e^-} T$$

where $N_{e^+e^-} = \Phi_a \frac{Vm_a}{\beta E_a \tau_{e^+e^-}}$

$$\propto (g_{3aN}, g_{ae})$$



Cont...

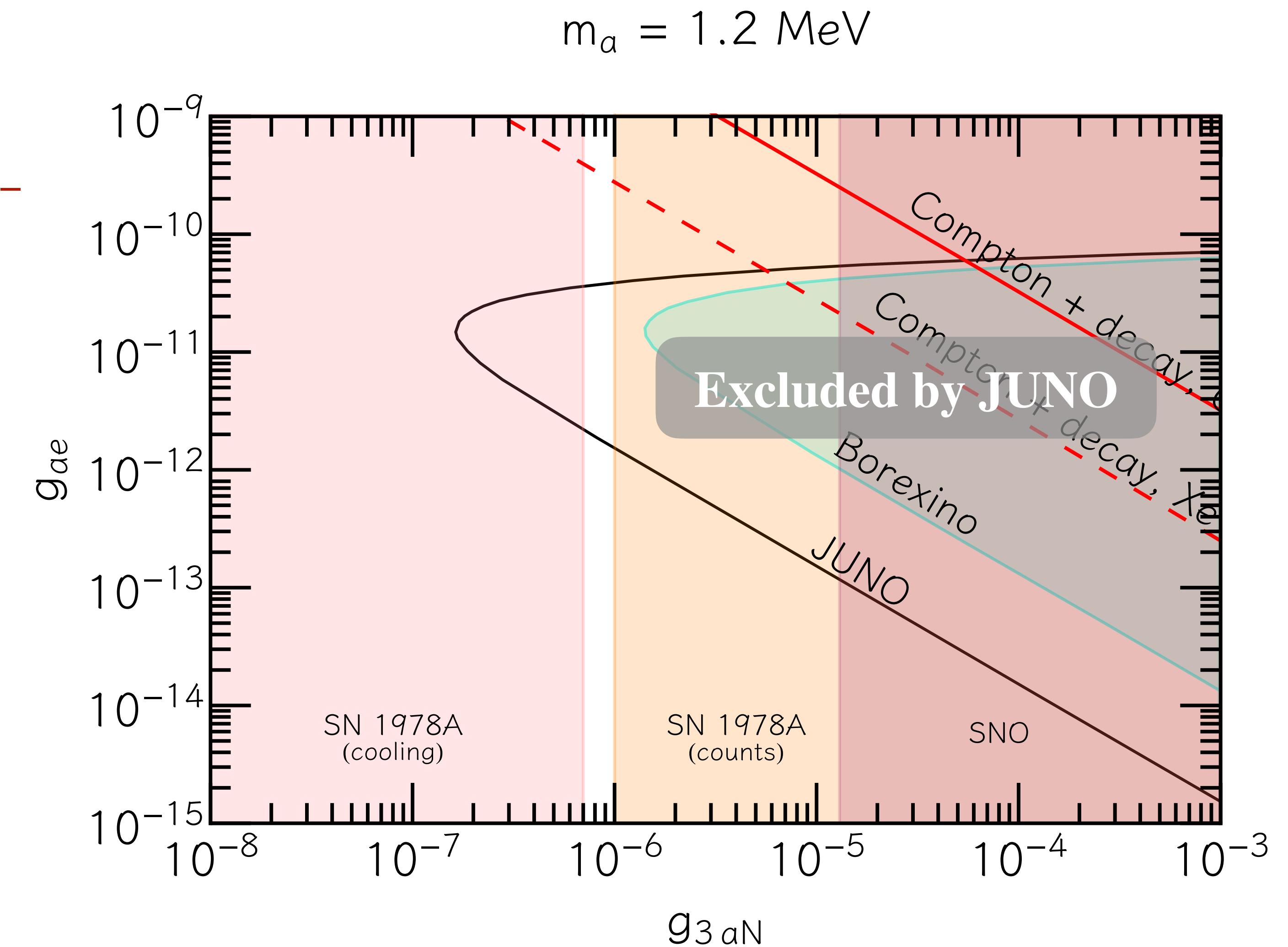
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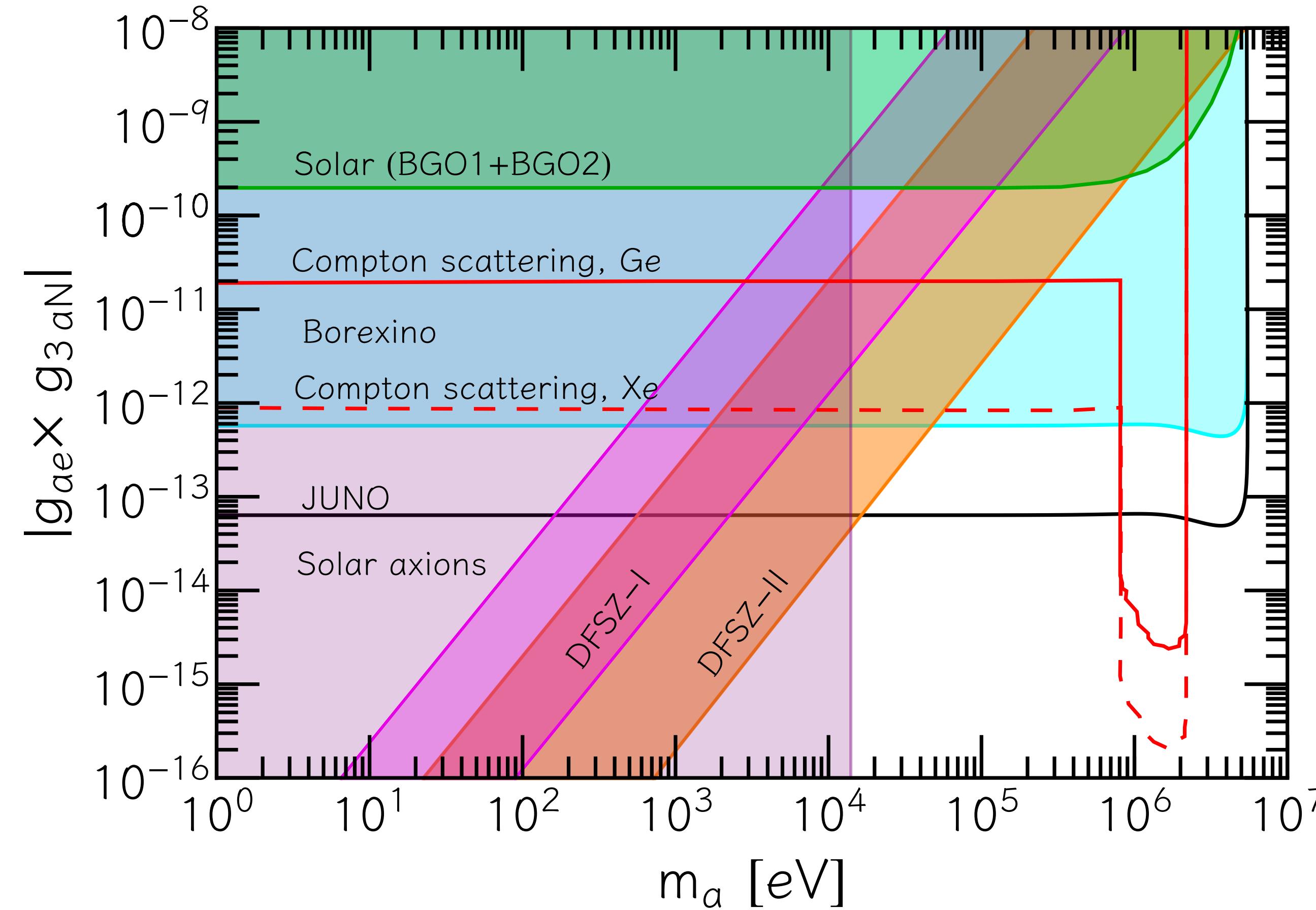
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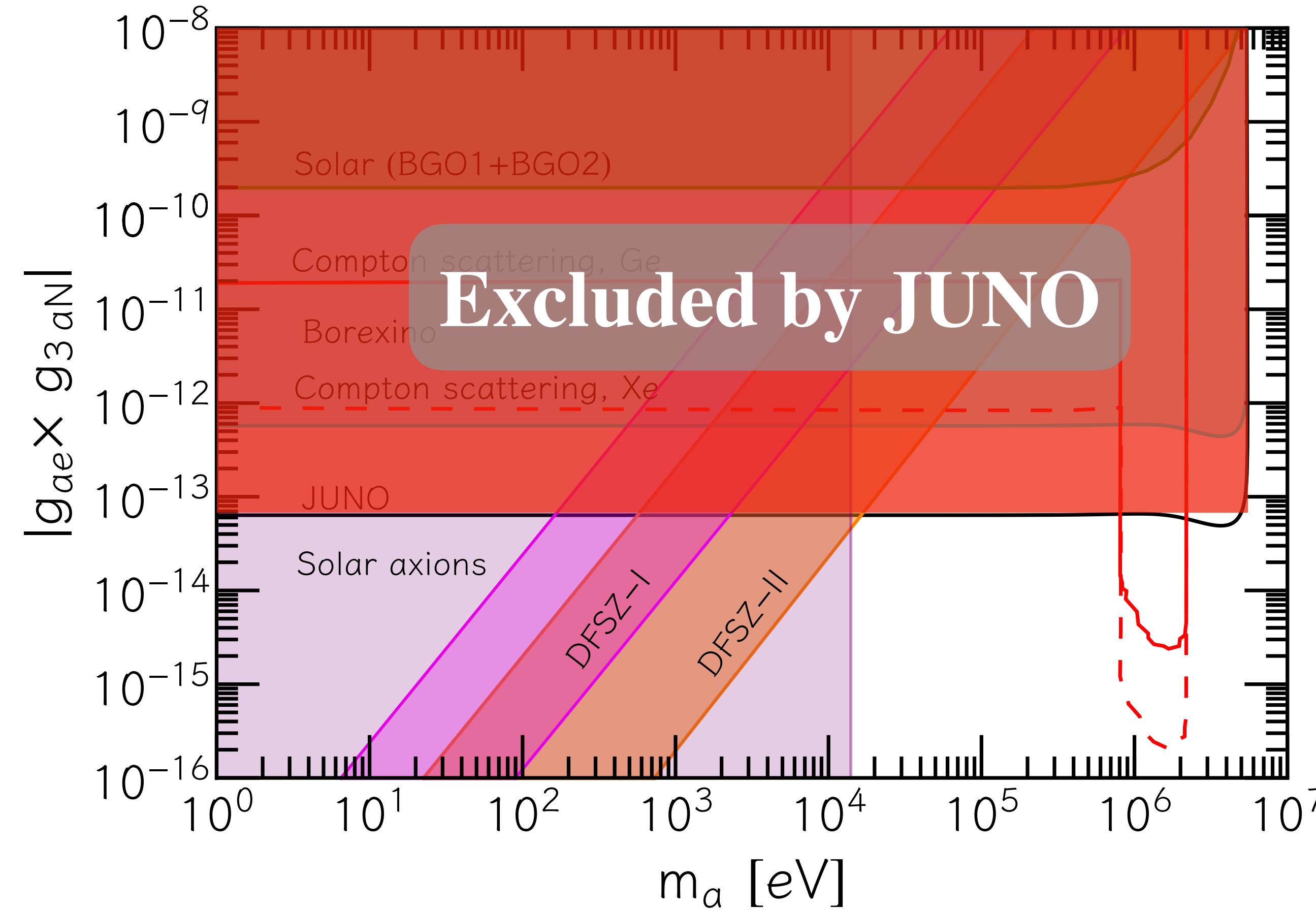
Axion electron and axion nucleon couplings

- For varying axion mass: $S_{\text{events}} = \Phi_a \sigma_{a-e,p,C} N_{e,p,C} T \varepsilon \leq S^{\text{lim}}$



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- JUNO can provide the most stringent bound around sub-MeV axion mass

Axion photon and axion nucleon couplings

- Inverse Primakoff conversion $a + Z \rightarrow \gamma + Z$

$$S_{PC} = \Phi_a \sigma_{PC} N_C T \epsilon_{PC}$$

for $m_a < 1 \text{ MeV}$

\downarrow

$\propto g_{a\gamma}$

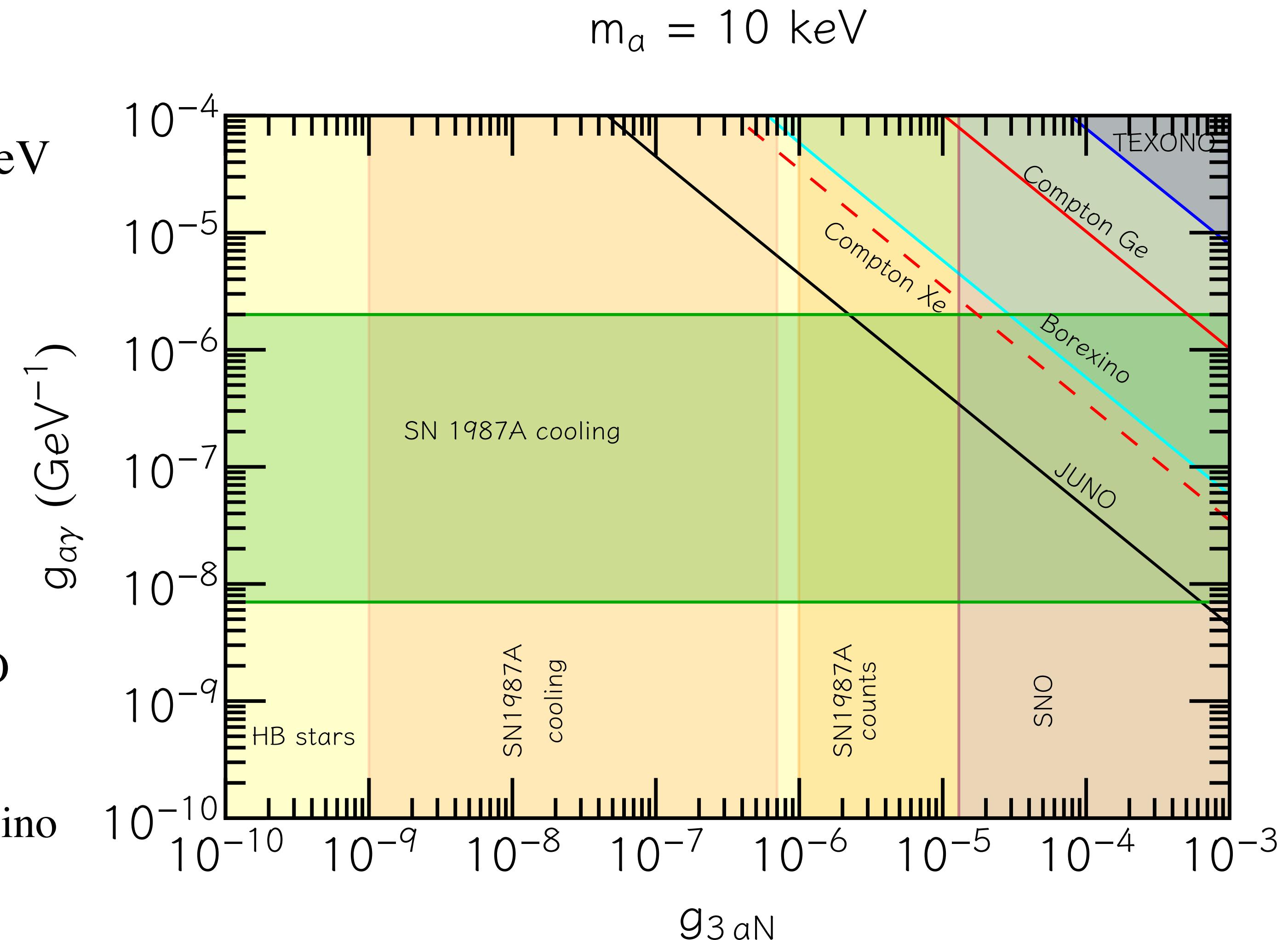
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$\propto g_{3aN}$

- We obtain at 90% c.l.

$$|g_{3aN} \times g_{a\gamma}| \leq 2.0 \times 10^{-12} \text{ GeV}^{-1} \text{ for JUNO}$$

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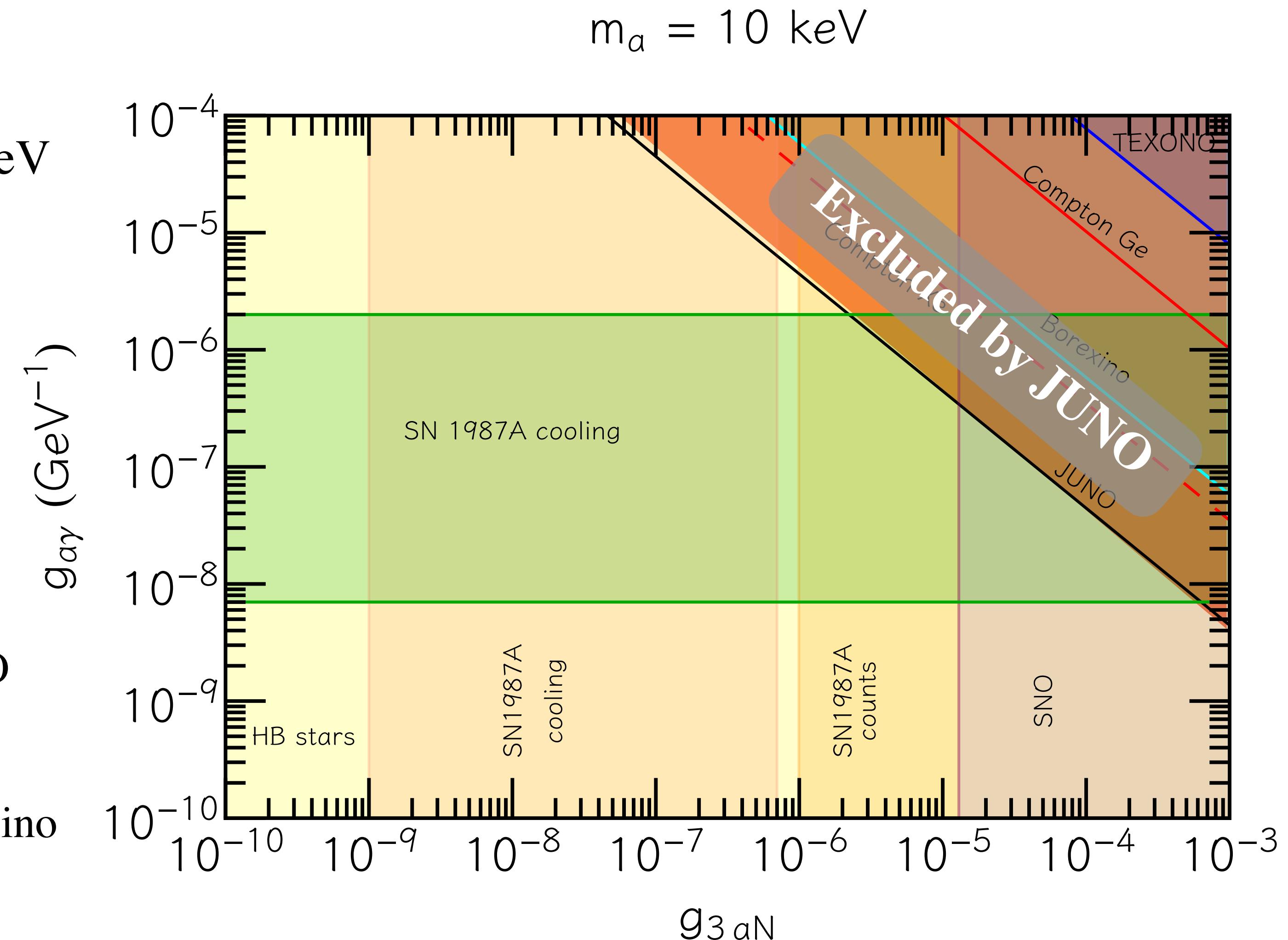
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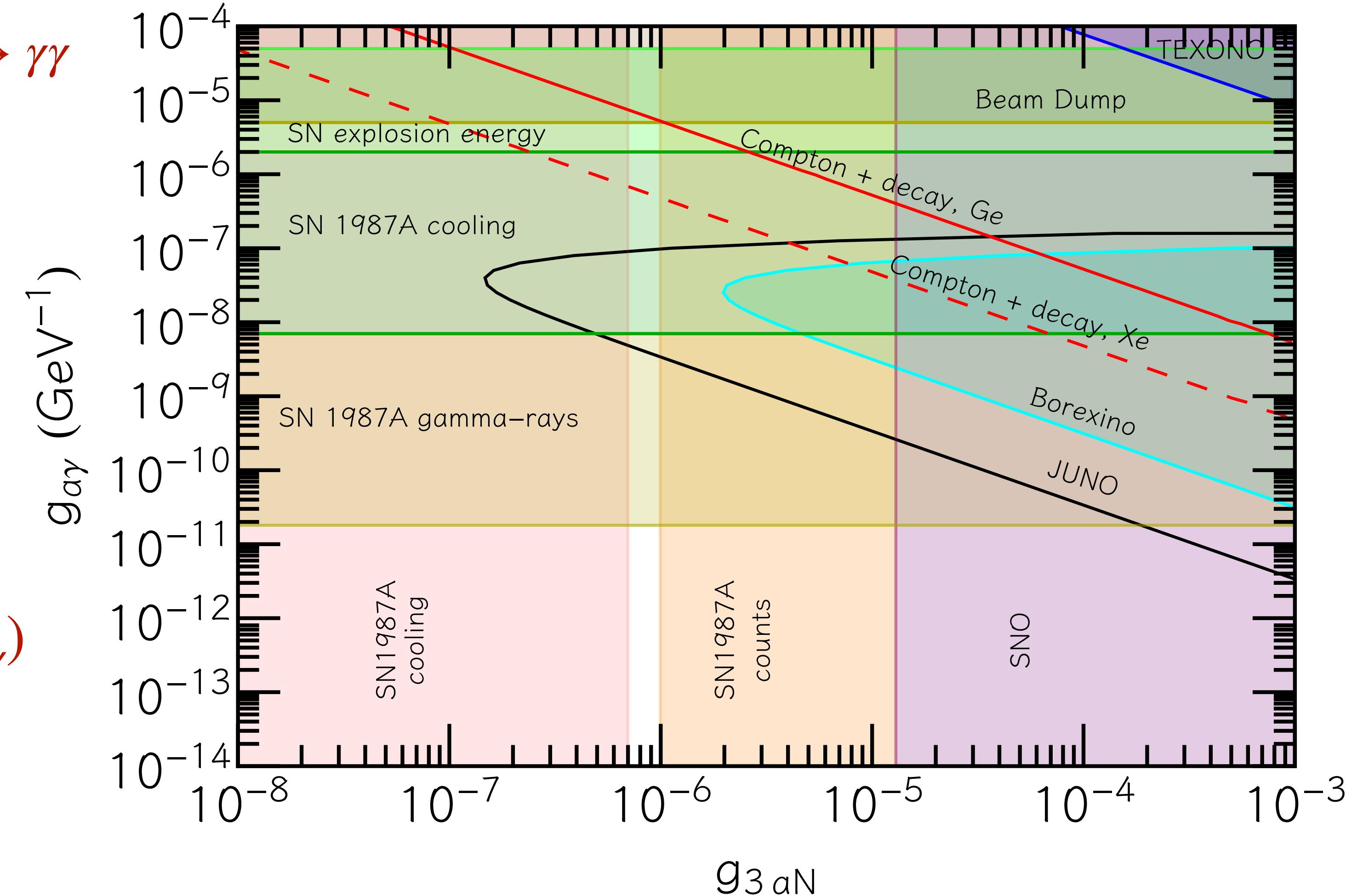
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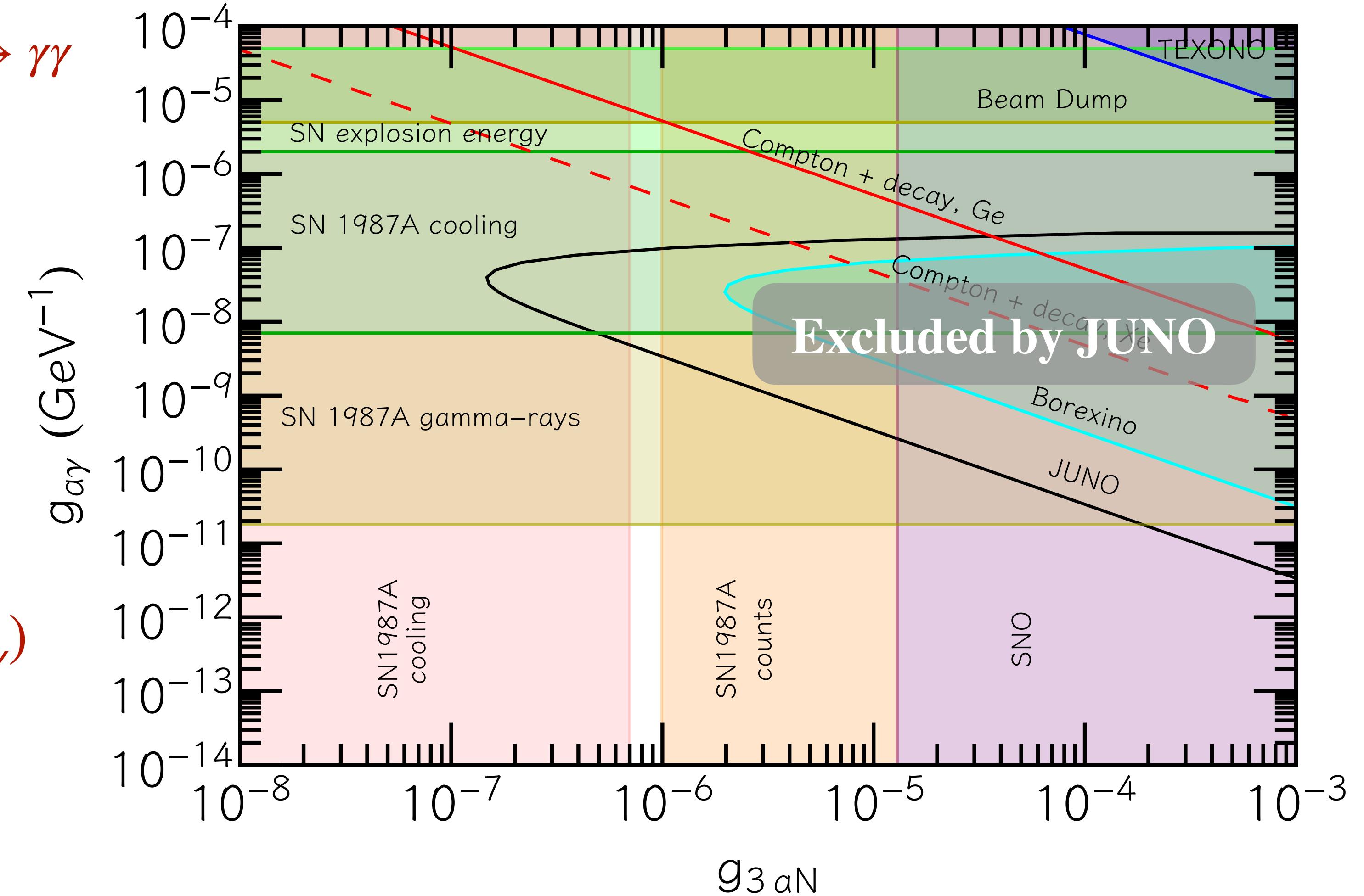
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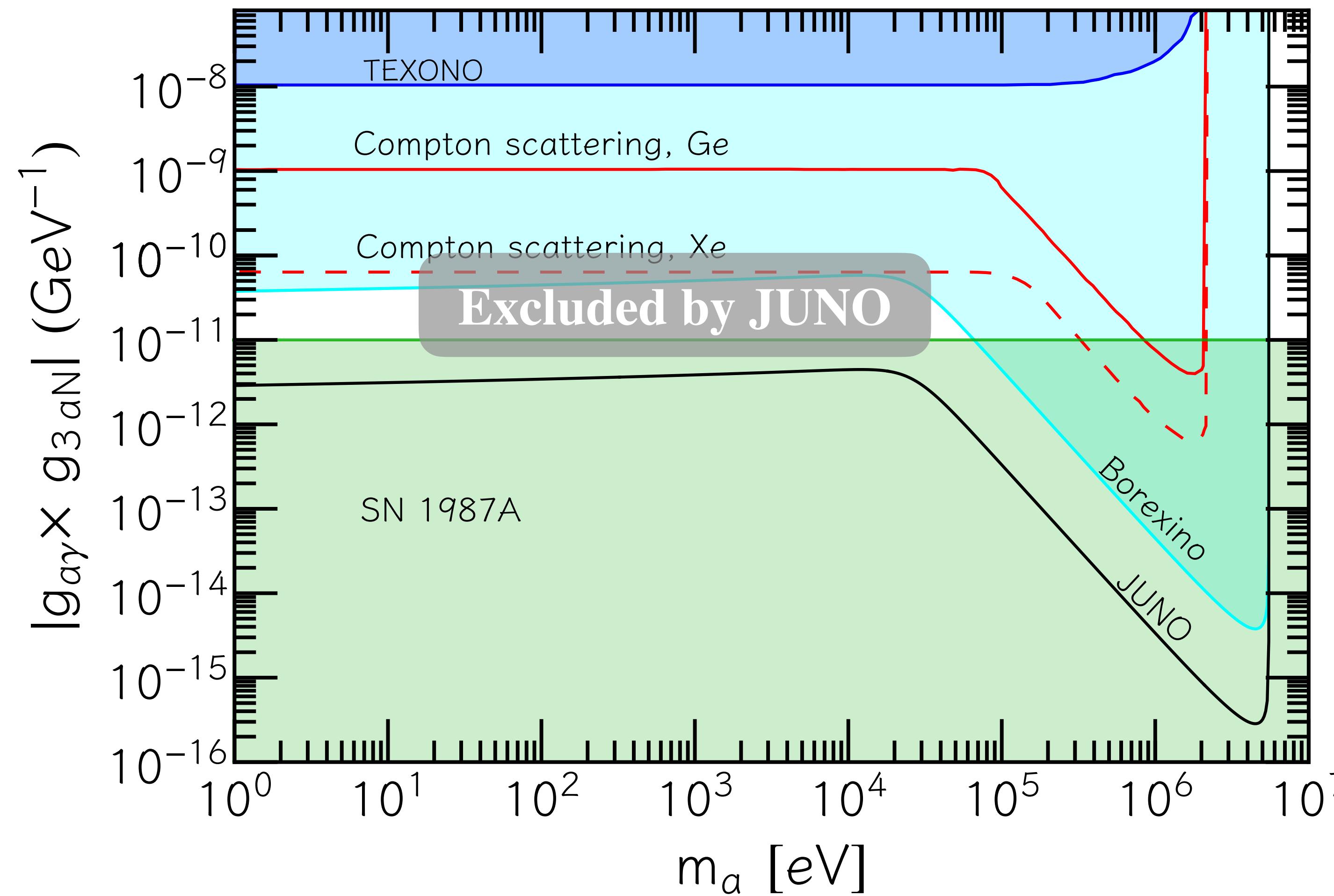
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Final remarks:

- Aimed to search for 5.5 MeV solar axions for the JUNO detector
- The processes that are examined:

$$\begin{aligned}a + e &\rightarrow e + \gamma \\a &\rightarrow e^+ e^- \\a + Z &\rightarrow \gamma + Z \text{ and} \\a &\rightarrow \gamma\gamma\end{aligned}$$

- Bounds obtained for JUNO:

$$|g_{3aN} \times g_{ae}| \leq 6.33 \times 10^{-14}$$

$$|g_{3aN} \times g_{a\gamma}| \leq 2.0 \times 10^{-12} GeV^{-1}$$

- JUNO can provide the most stringent bound around sub-MeV axion mass for the axion electron times axion nucleon plane.

grazie 谢谢 ຂອບຄົມ
merci Σας ευχαριστώ tack bedankt
tack Спасибо thank you ありがとう
gracias terima kasih
teşekkür ederim شکرای danke 고마워요
kiitos köszönjük