2026紫金山暗物质研讨会

Probing 5.5 MeV Solar Axions at Xenon Experiments

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arXiv:2607.xxxxx

Urumqi · July 2026

Part 1

Motivation

Why 5.5 MeV solar axions ?

Why Xenon experiments ?

01

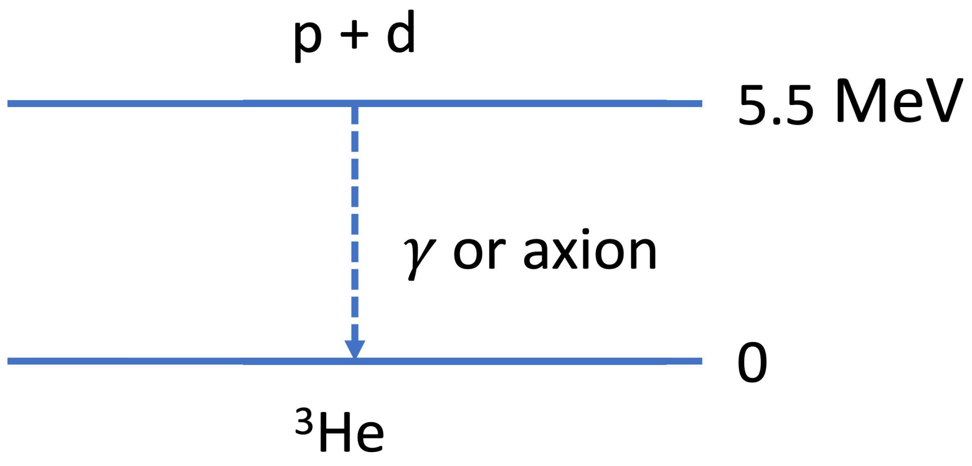
MOTIVATION

What is the 5.5 MeV solar axion ?

The Sun is an intense **axion source** via nuclear reactions

- One possibility in the **proton–proton chain :**
  - $p + p \to d + e^+ + \nu_e$
  - $p + d \to {}^3\mathrm{He} + \boldsymbol{\gamma}\ (\mathbf{5.5\ MeV})$ ⟵ M1 transition
  - …
- Axion could be produced in place of photon:

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



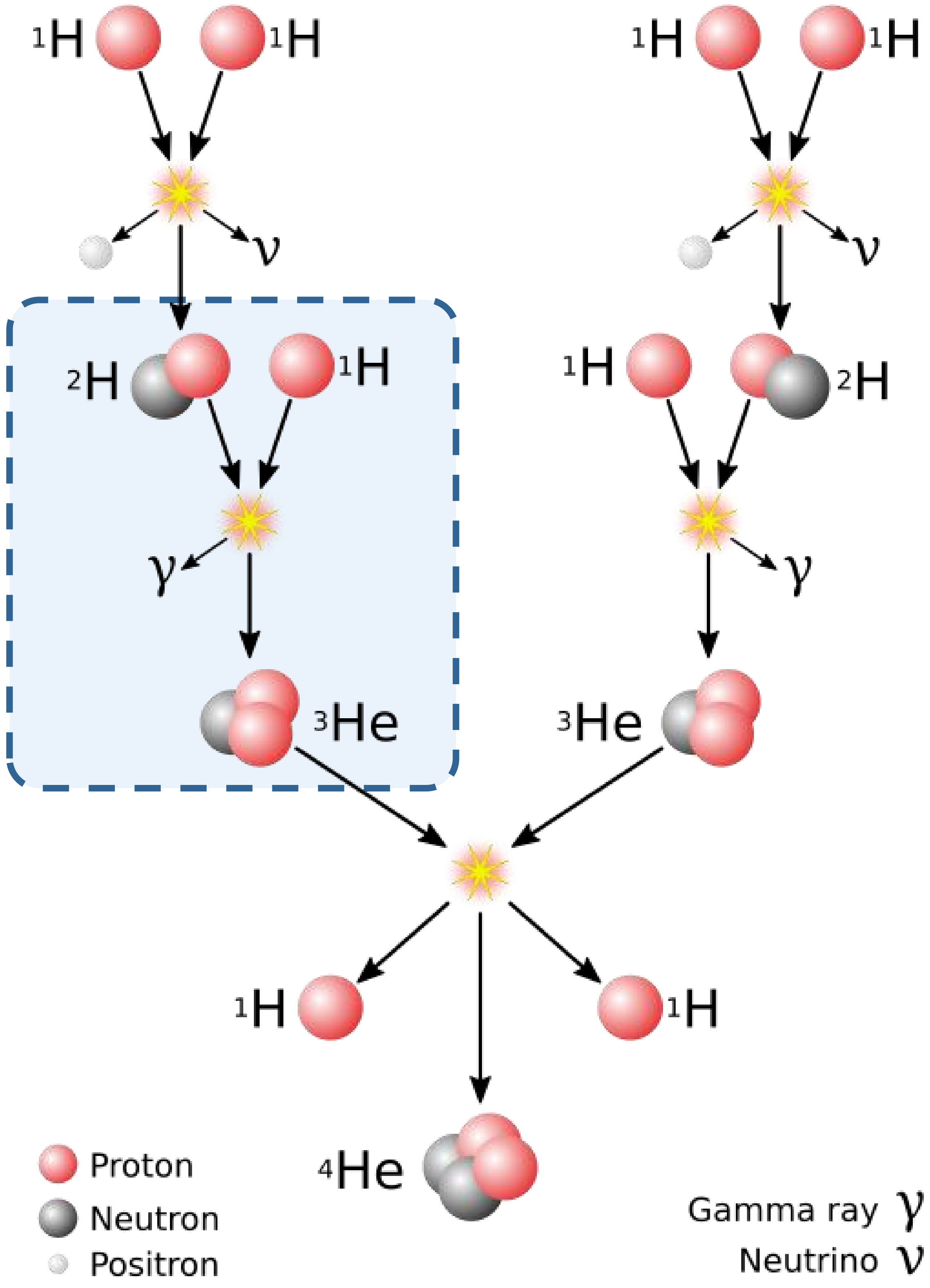
monochromatic axion flux

Why 5.5 MeV Solar Axions ?

Clean signal

Low background

Xenon -- high Z material



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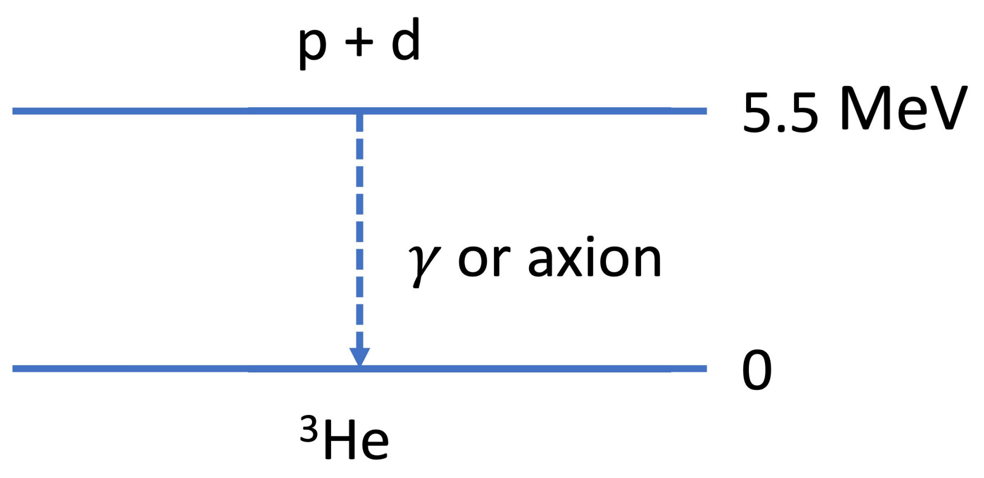

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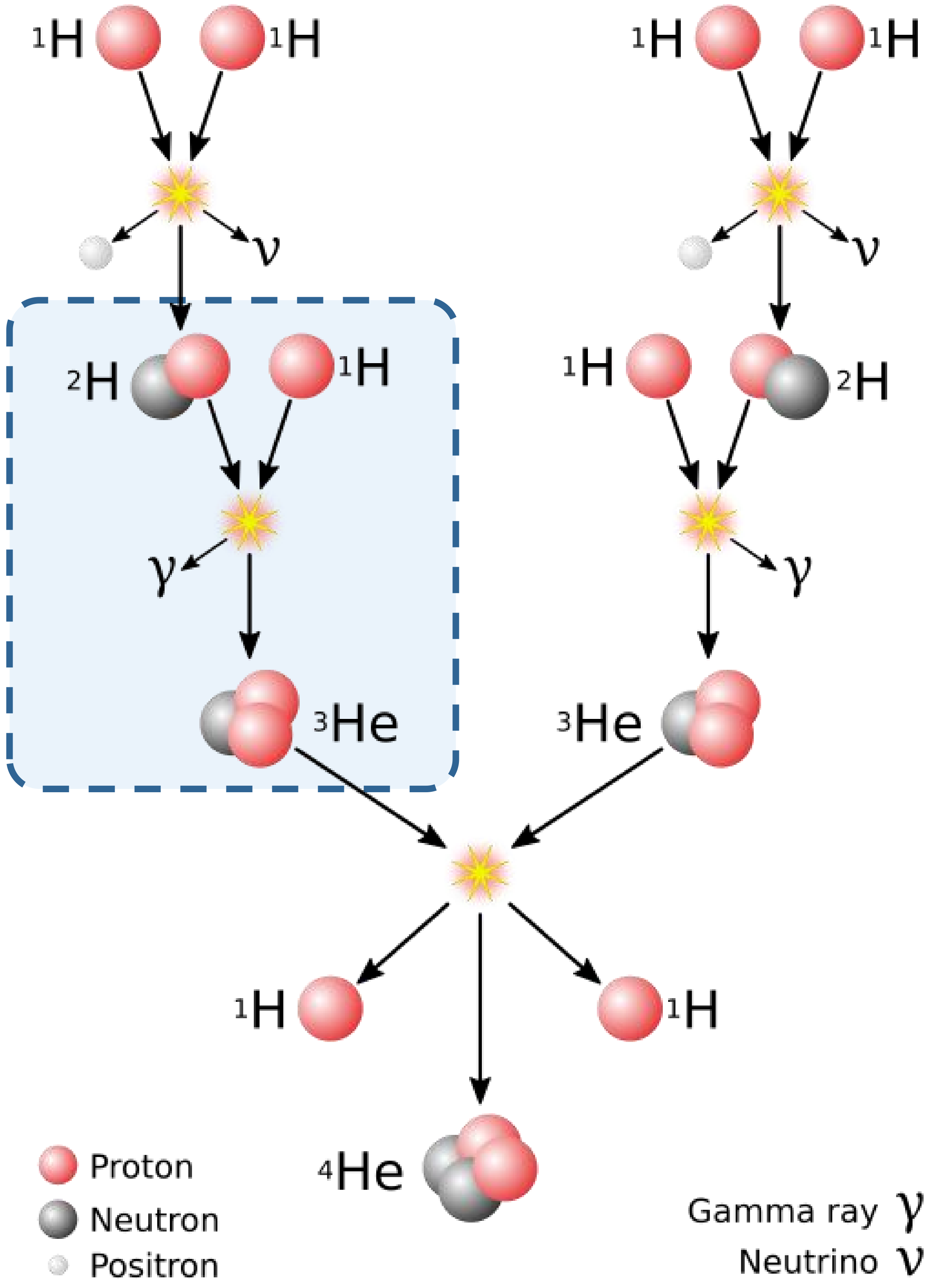
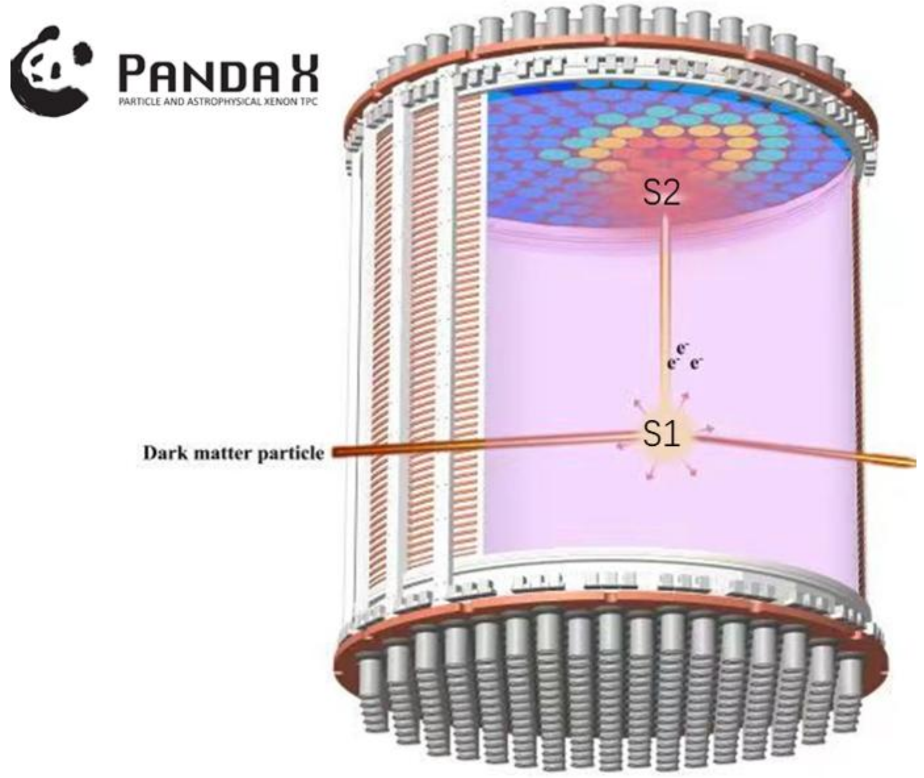


MOTIVATION

01 Detectors

Xenon-based



3.7 tons, Xenon

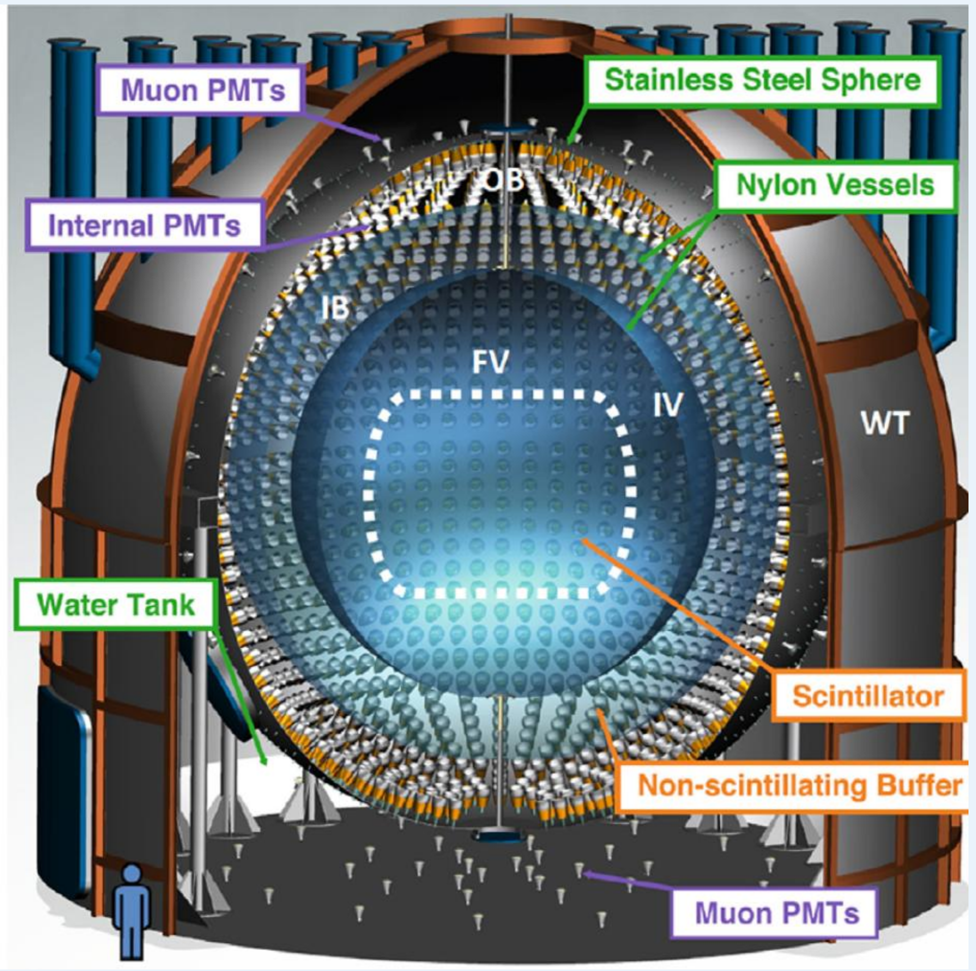
Carbon-based

The Borexino detector @ LNGS

Active volume: 280 tons of liquid scintillator.

Detection principle
$\nu_x + e \rightarrow \nu_x + e$

Elastic scattering off the electrons of the scintillator. Threshold at ~ 60 keV (electron energy)

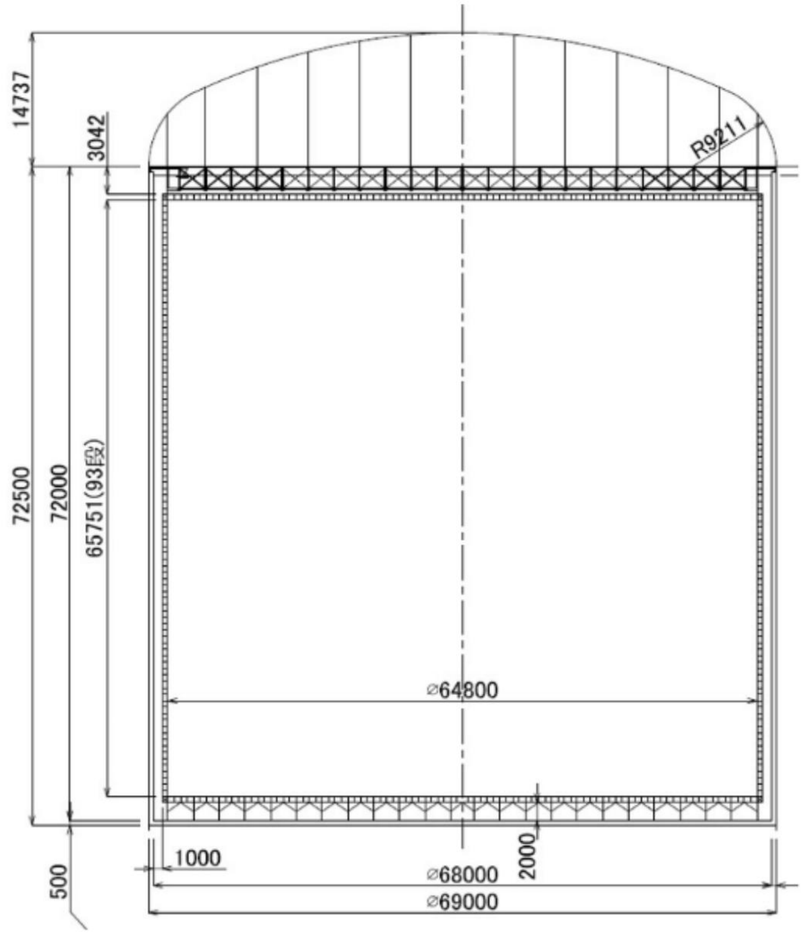


280 tons, liquid scintillator (C_9H_{12})

Oxygen-based

Hyper-Kamiokande

Aiming to start observation in 2028



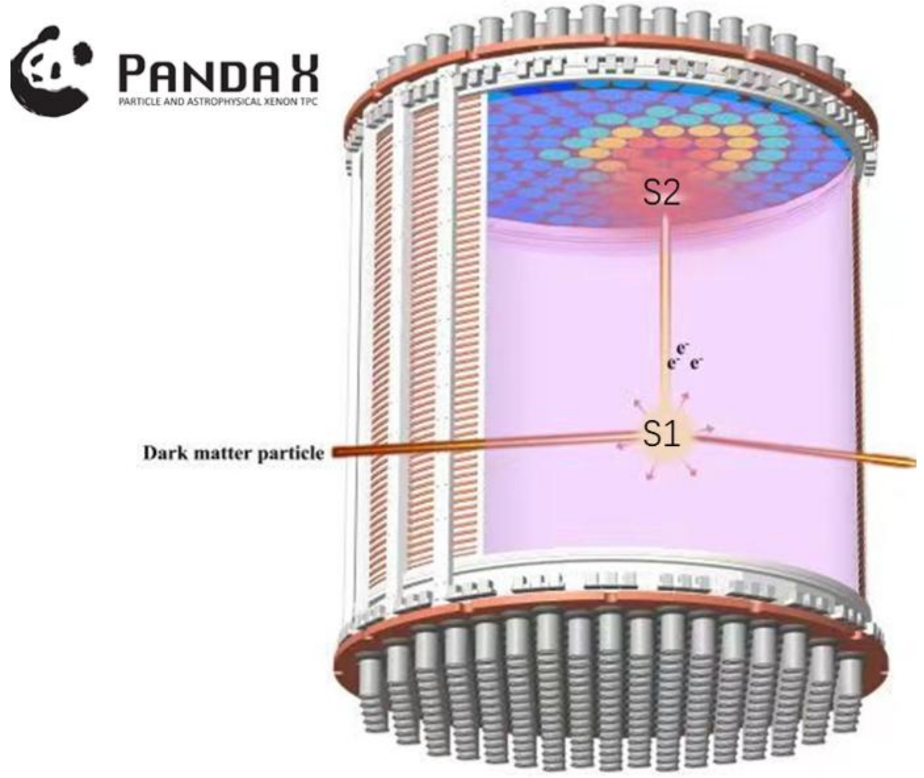
260000 tons, water(H_2O)

01

MOTIVATION

Detectors

Xenon-based



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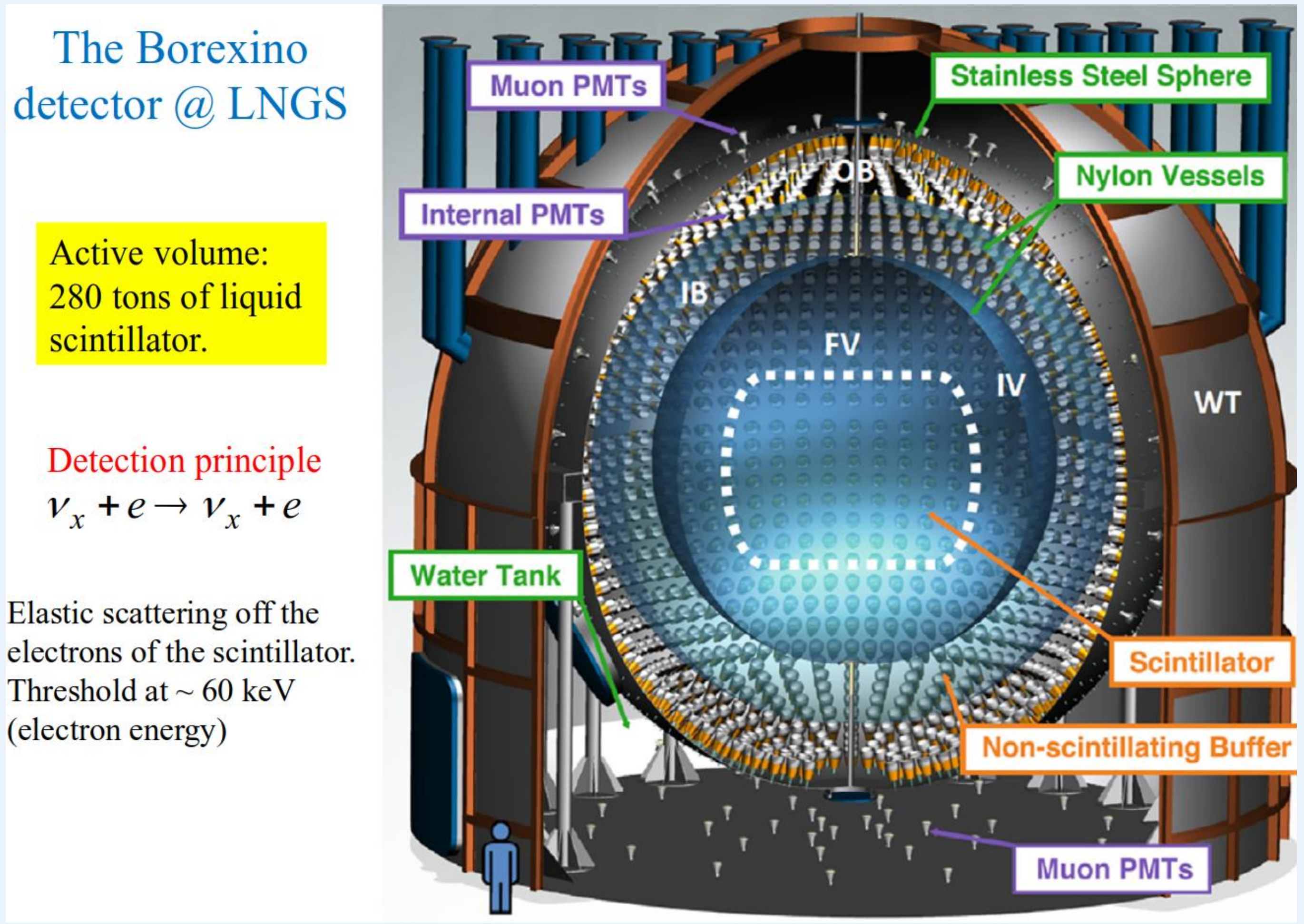
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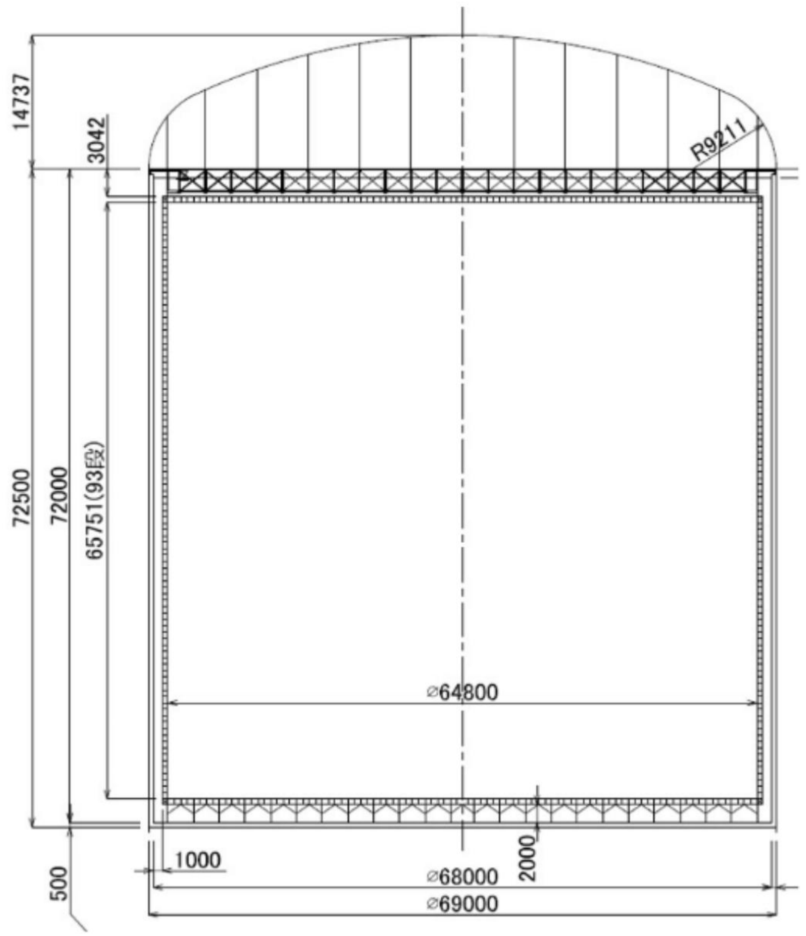


260000 tons, water(H_2O)

Can a smaller detector compete?

Part 2

Direct Detection with Axion–Electron Coupling

Pair production

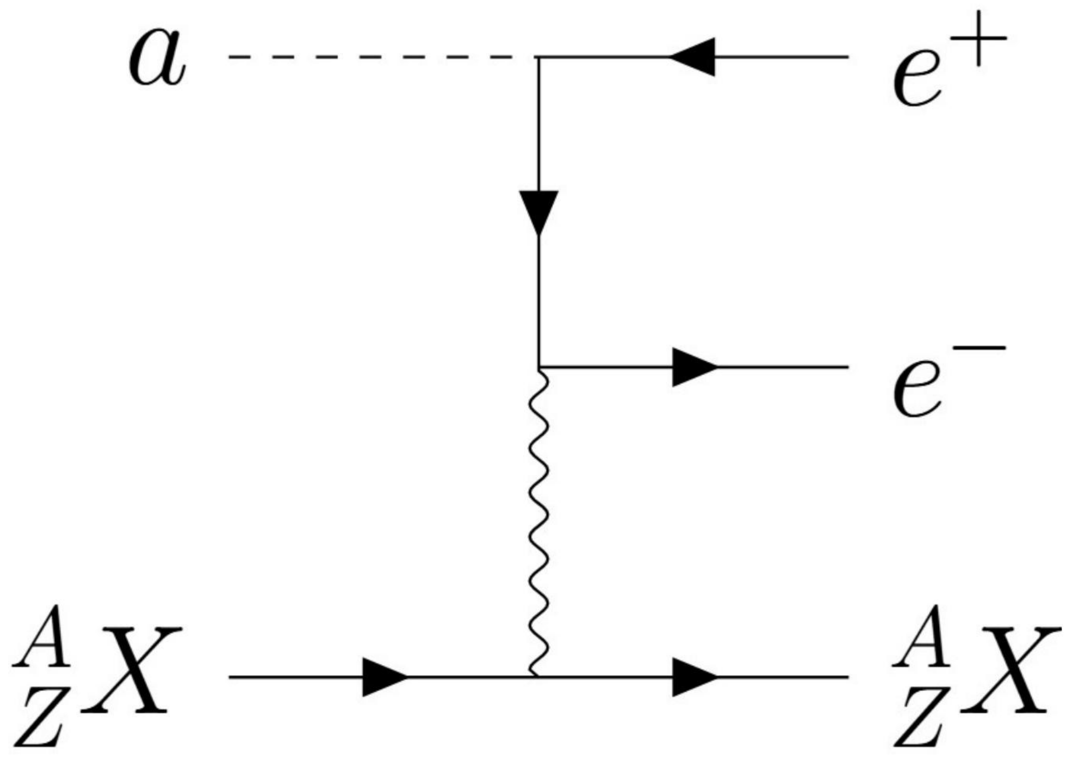
Massless & massive

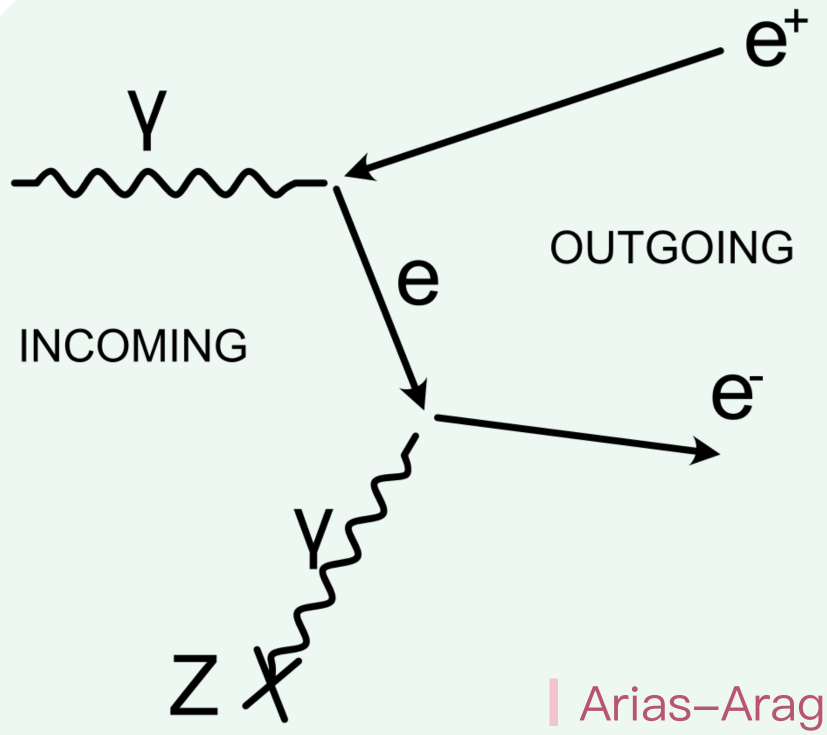
Sensitivity

Detection Channels

$$\mathcal{L}_{\rm int} \supset -ig_{ae}a\bar{e}\gamma_5 e - ia\bar{N}\gamma_5\left(g_{0aN} + \tau_3 g_{3aN}\right)N$$

- axion-induced **pair production** in the Coulomb field of a nucleus $a + {}^A_Z X \to {}^A_Z X + e^+ + e^-$
- inverse Compton scattering $a + e^- \to e^- + \gamma$
- axio-electric effect $a + e^- + Ze \to e^- + Ze$





Bethe–Heitler pair production

$\sigma_{\gamma ee}\left(E_a\right)$ ~ NIST XCOM

Arias–Aragón, M Giannotti, G Cortona, F Mescia, 2411.19327

Detection Channels

$$\mathcal{L}_{\rm int} \supset -i g_{ae} a \bar{e}\gamma_5 e - i a \bar{N}\gamma_5 \left(g_{0aN} + \tau_3 g_{3aN}\right) N$$

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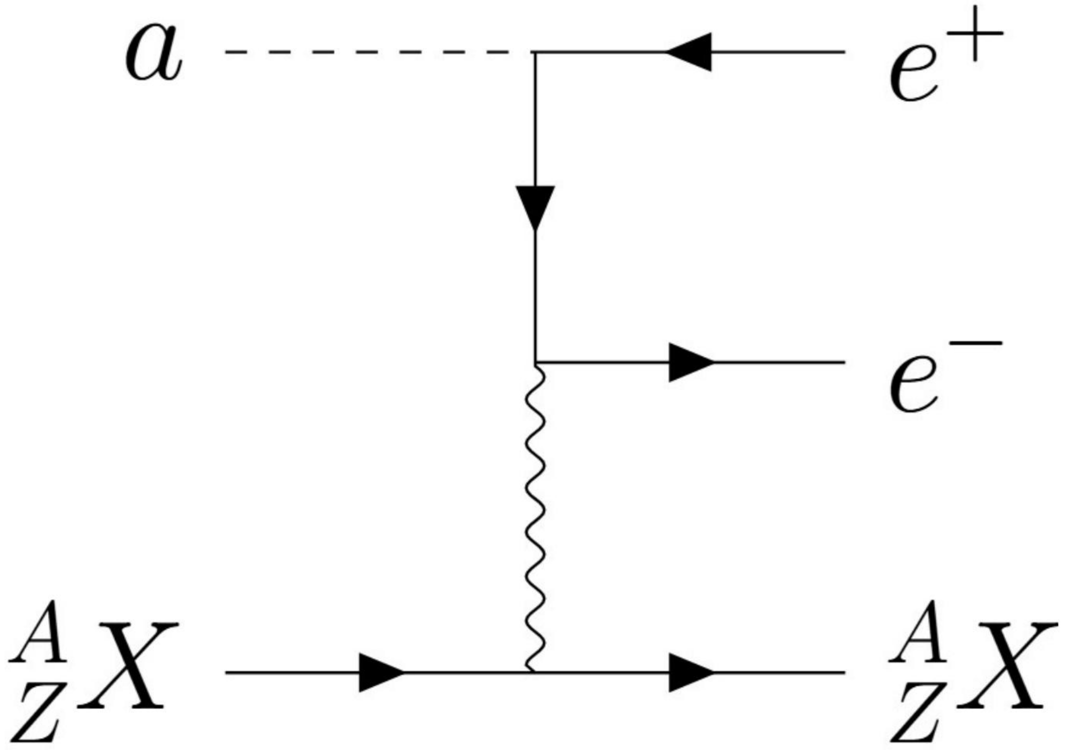
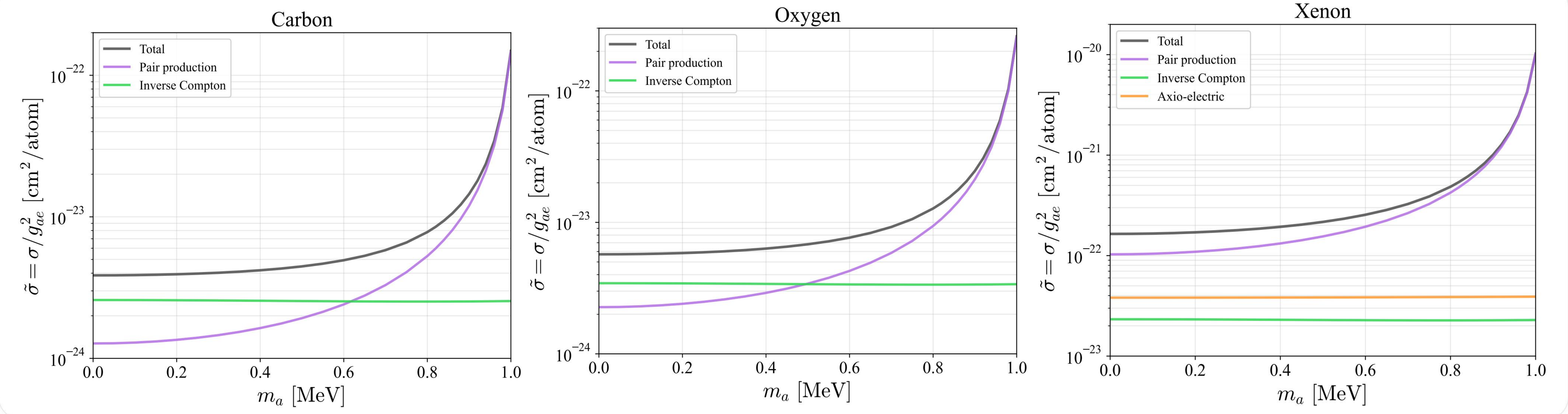


for **massless** axion $m_a \ll m_e$:

$$\sigma_{\rm PP}(E_a) \simeq 2.6 \frac{g_{ae}^2}{4\pi\alpha} \sigma_{\gamma ee}(E_a)$$ ~ NIST XCOM

Arias–Aragón, M Giannotti, G Cortona, F Mescia, 2411.19327

Massive Axion



$$\boxed{m_a \leq 1\ \text{MeV}}$$

$$a \rightarrow \cancel{e^+e^-}$$

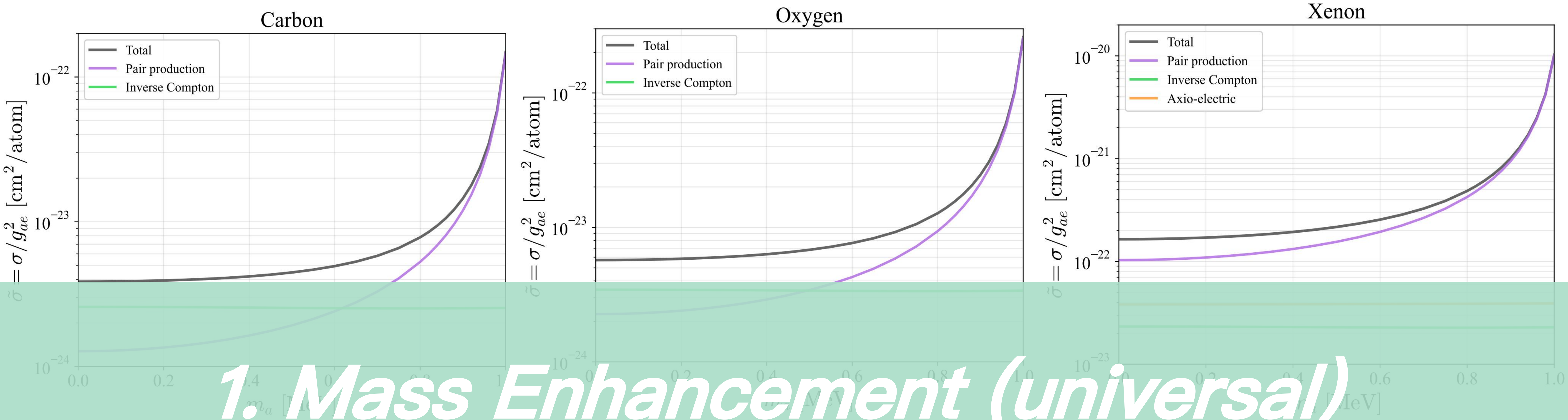
- To quantify the effect of a finite axion mass: **the mass enhancement factor**

$$R_X(m_a) \equiv \frac{\sigma_{\rm PP}(m_a, E_a; X)}{\sigma_{\rm PP}(0, E_a; X)}$$

- Our numerical calculations give:

$$R_{\rm H}(1{\rm MeV}) \simeq 120, R_{\rm C}(1{\rm MeV}) \simeq 115,$$
$$R_{\rm O}(1{\rm MeV}) \simeq 113, R_{\rm Xe}(1{\rm MeV}) \simeq 99.$$

Massive Axion



1. Mass Enhancement (universal)

$m_a \leq 1$ MeV

$\cancel{a \to e^+e^-}$

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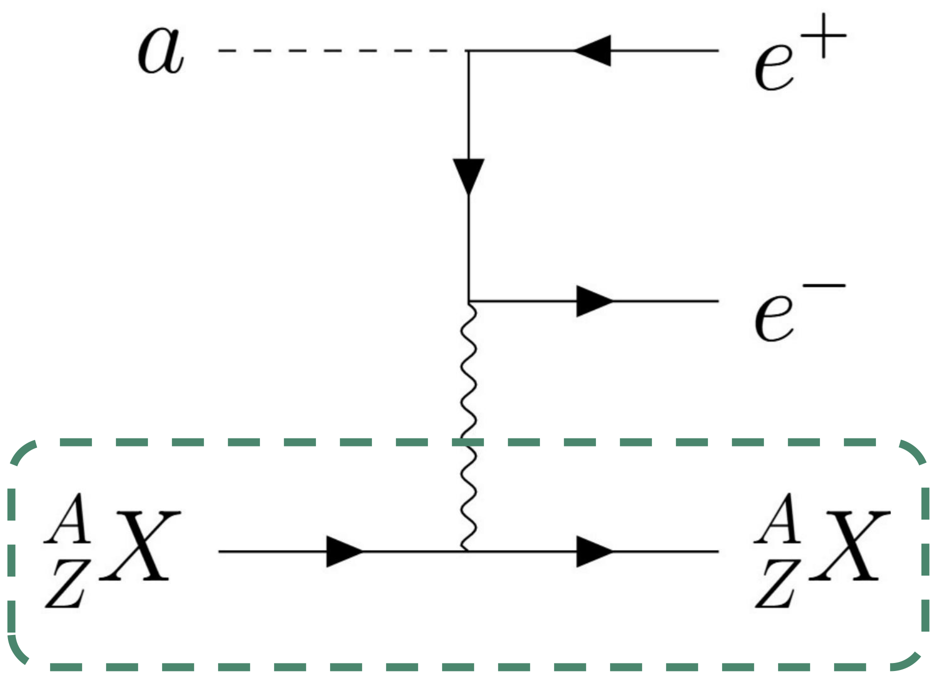
AXION–ELECTRON COUPLING

02

High–Z Enhancement

– axion-induced **pair production** in the Coulomb field of a nucleus



an **important advantage of xenon** (Z = 54) over relatively light nuclei: carbon (Z = 6) and oxygen (Z = 8)

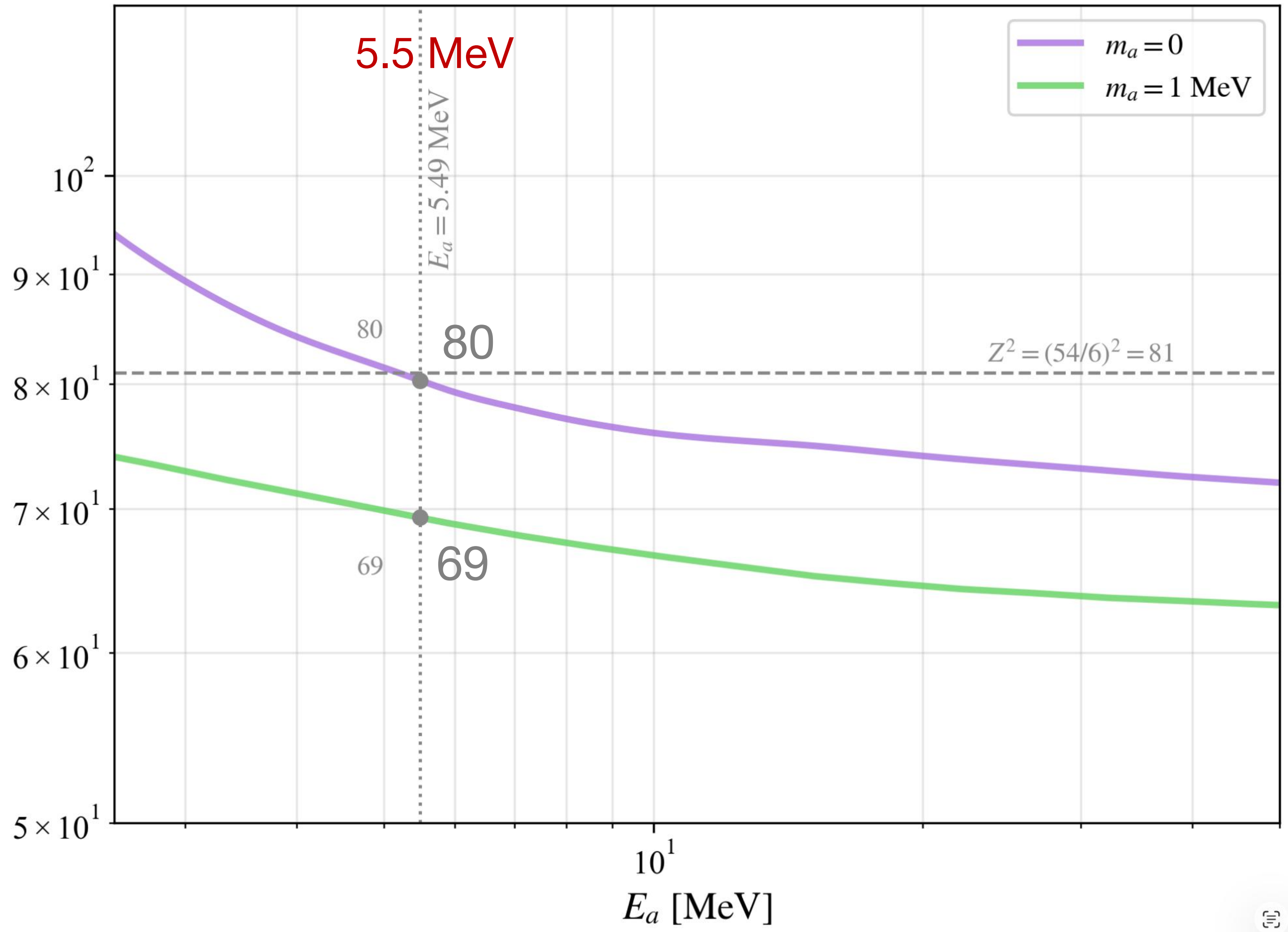
$$\sigma_{\mathrm{PP}} \propto Z^2 g_{ae}^2$$

$$a + {}^A_Z X \rightarrow {}^A_Z X + e^+ + e^-$$

$$\frac{\sigma_{\mathrm{PP}}(0, E_a; \mathrm{Xe})}{\sigma_{\mathrm{PP}}(0, E_a; \mathrm{C})} \simeq 81\,, \qquad \frac{\sigma_{\mathrm{PP}}(0, E_a; \mathrm{Xe})}{\sigma_{\mathrm{PP}}(0, E_a; \mathrm{O})} \simeq 45\,,$$

$$\frac{\sigma_{\mathrm{PP}}(1\,\mathrm{MeV}, E_a; \mathrm{Xe})}{\sigma_{\mathrm{PP}}(1\,\mathrm{MeV}, E_a; \mathrm{C})} \simeq 69\,, \quad \frac{\sigma_{\mathrm{PP}}(1\,\mathrm{MeV}, E_a; \mathrm{Xe})}{\sigma_{\mathrm{PP}}(1\,\mathrm{MeV}, E_a; \mathrm{O})} \simeq 40\,.$$

Ratio of Axion Cross Section: Xe vs C



High–Z Enhancement

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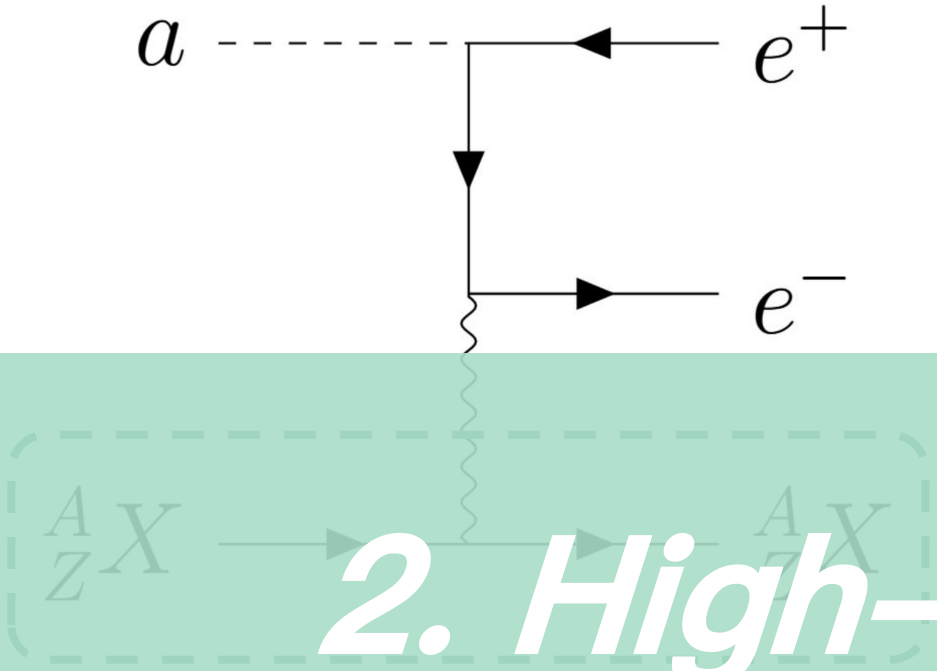

an **important advantage of xenon** (Z = 54) over relatively light nuclei: carbon (Z = 6) and oxygen (Z = 8)

$$\sigma_{\rm PP} \propto Z^2 g_{ae}^2$$

$$a + {}^A_ZX \to {}^A_ZX + e^+ + e^-$$

2. High–Z Enhancement (benefit to Xe)

$$\frac{\sigma_{\rm PP}(0, E_a; {\rm Xe})}{\sigma_{\rm PP}(0, E_a; {\rm C})} \simeq 81\,, \qquad \frac{\sigma_{\rm PP}(0, E_a; {\rm Xe})}{\sigma_{\rm PP}(0, E_a; {\rm O})} \simeq 45\,,$$

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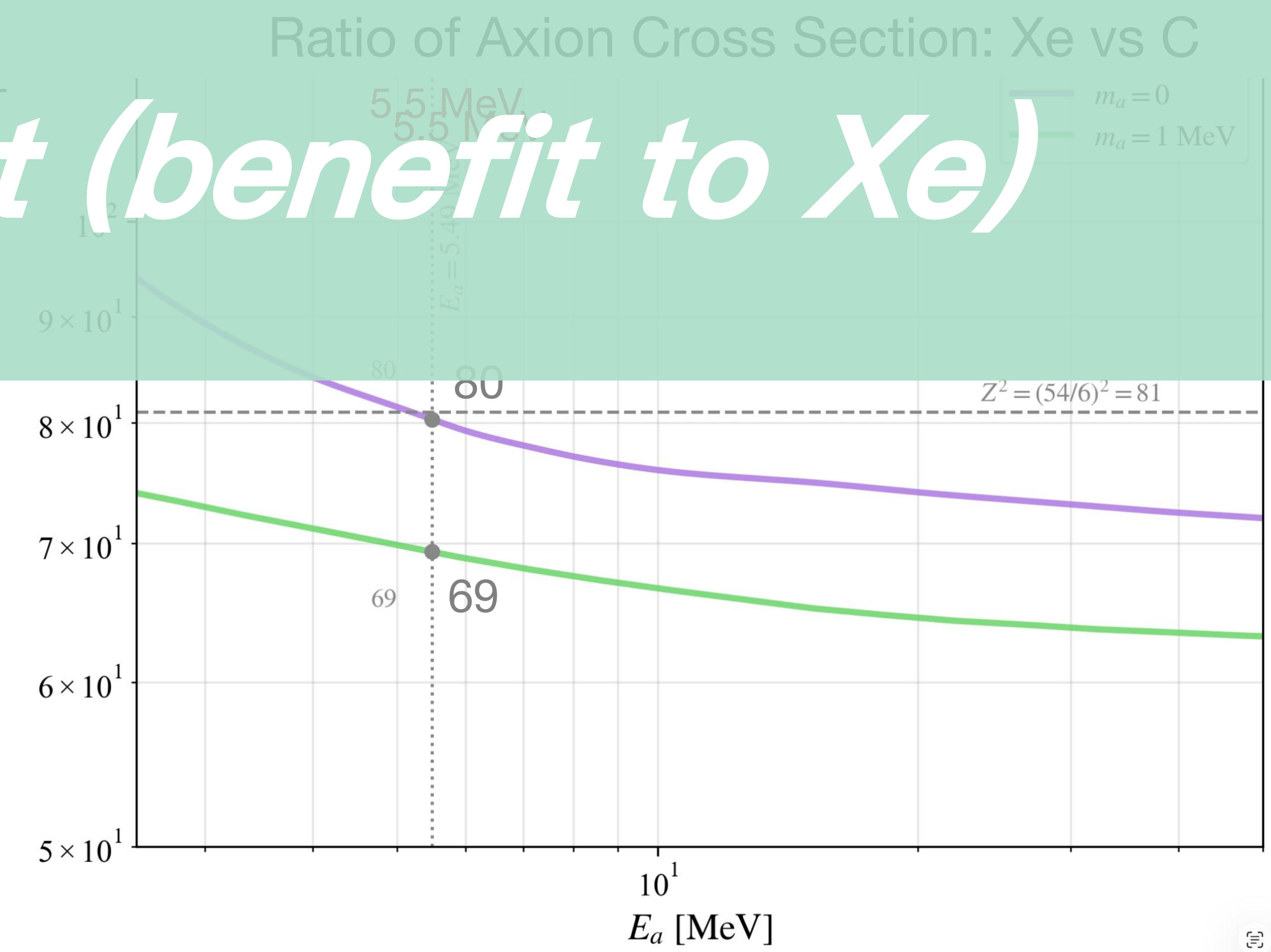
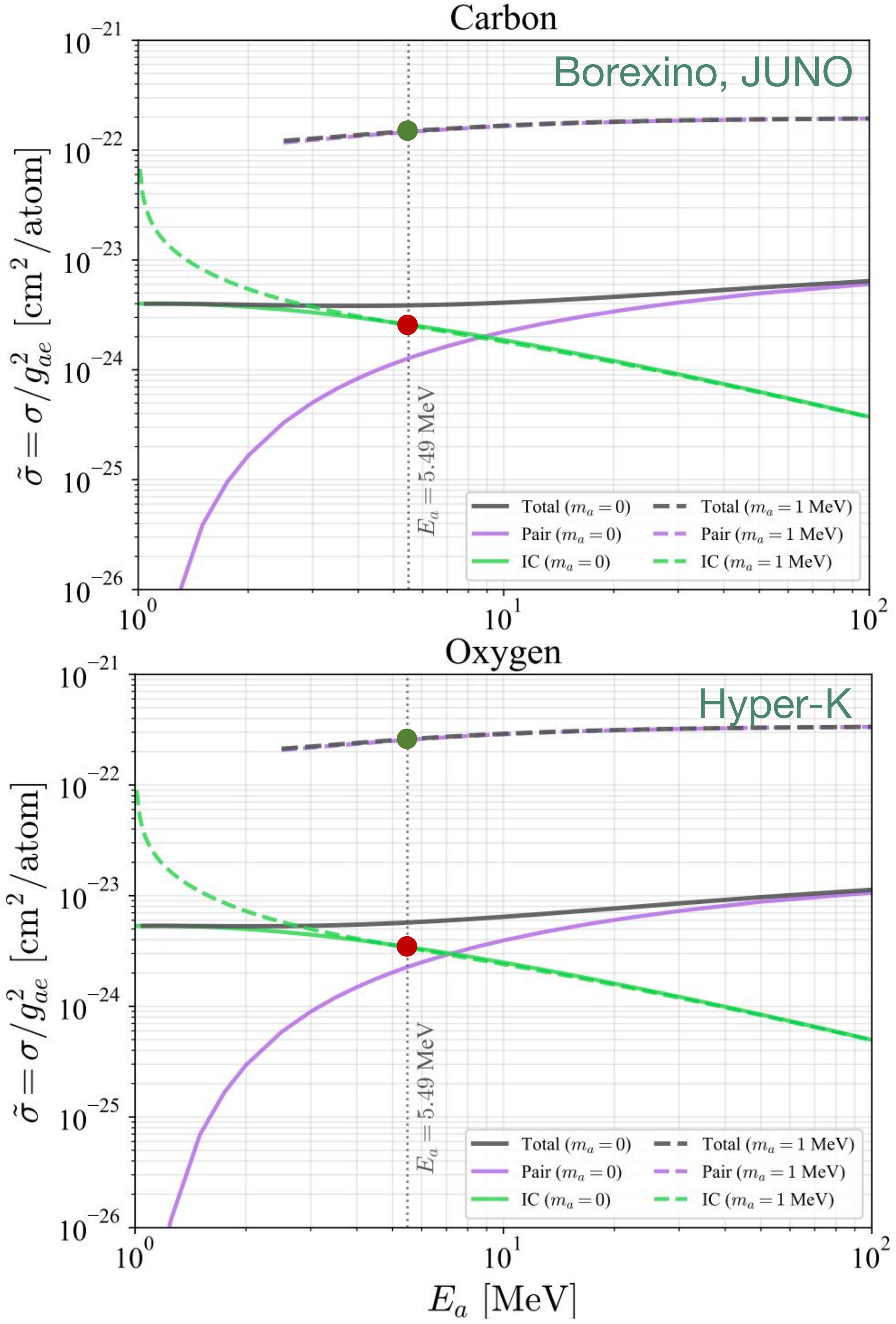
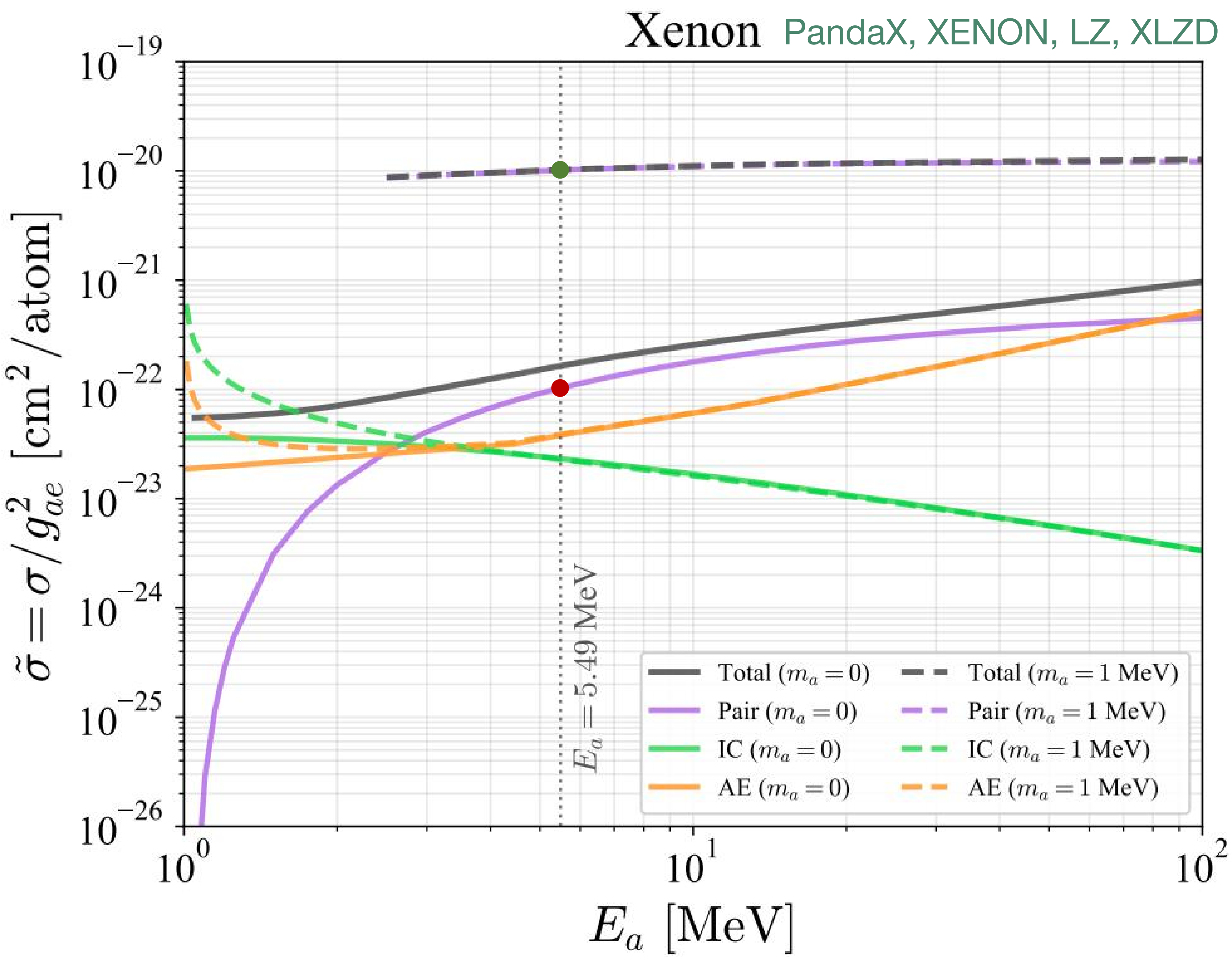


Dominant Channels



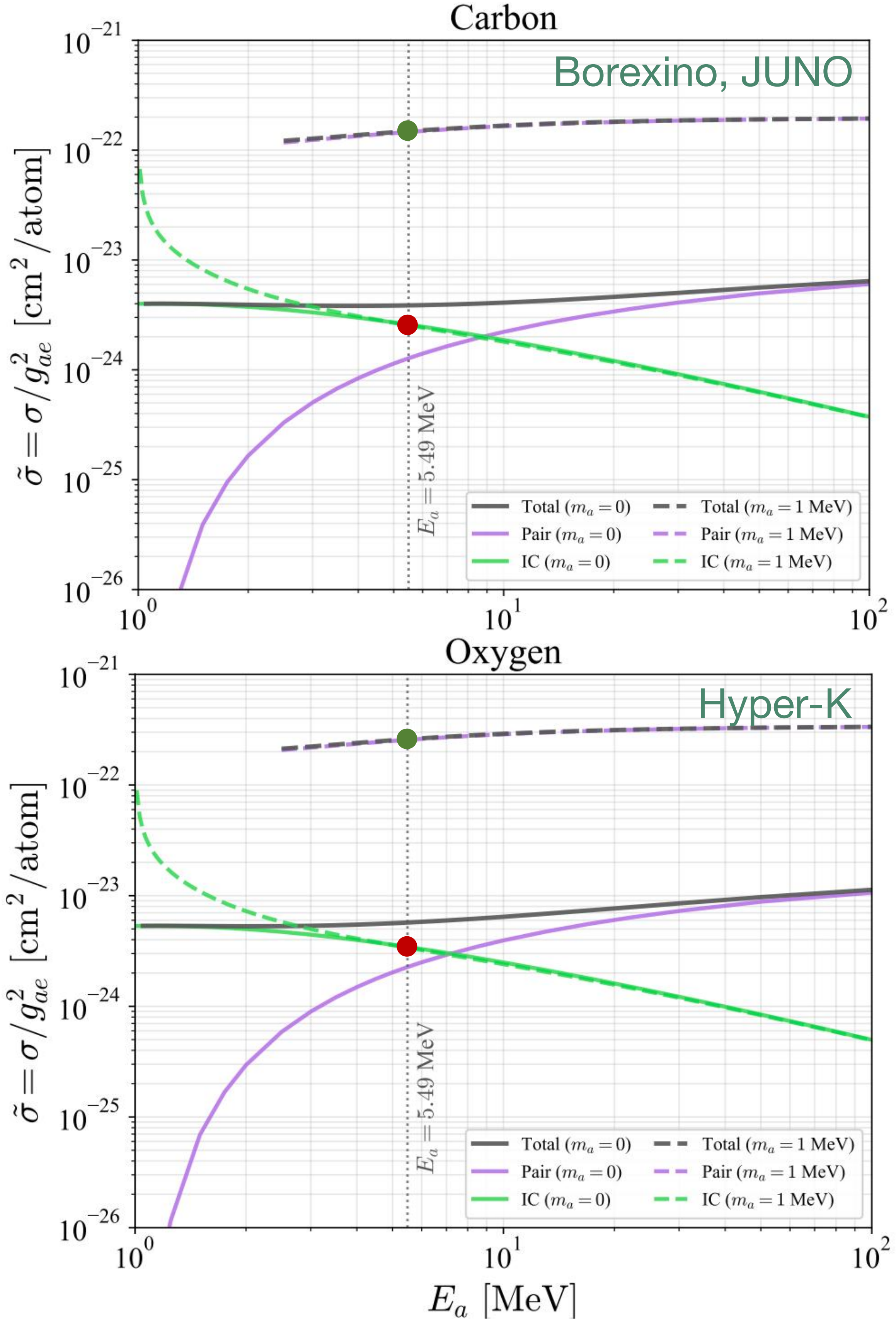


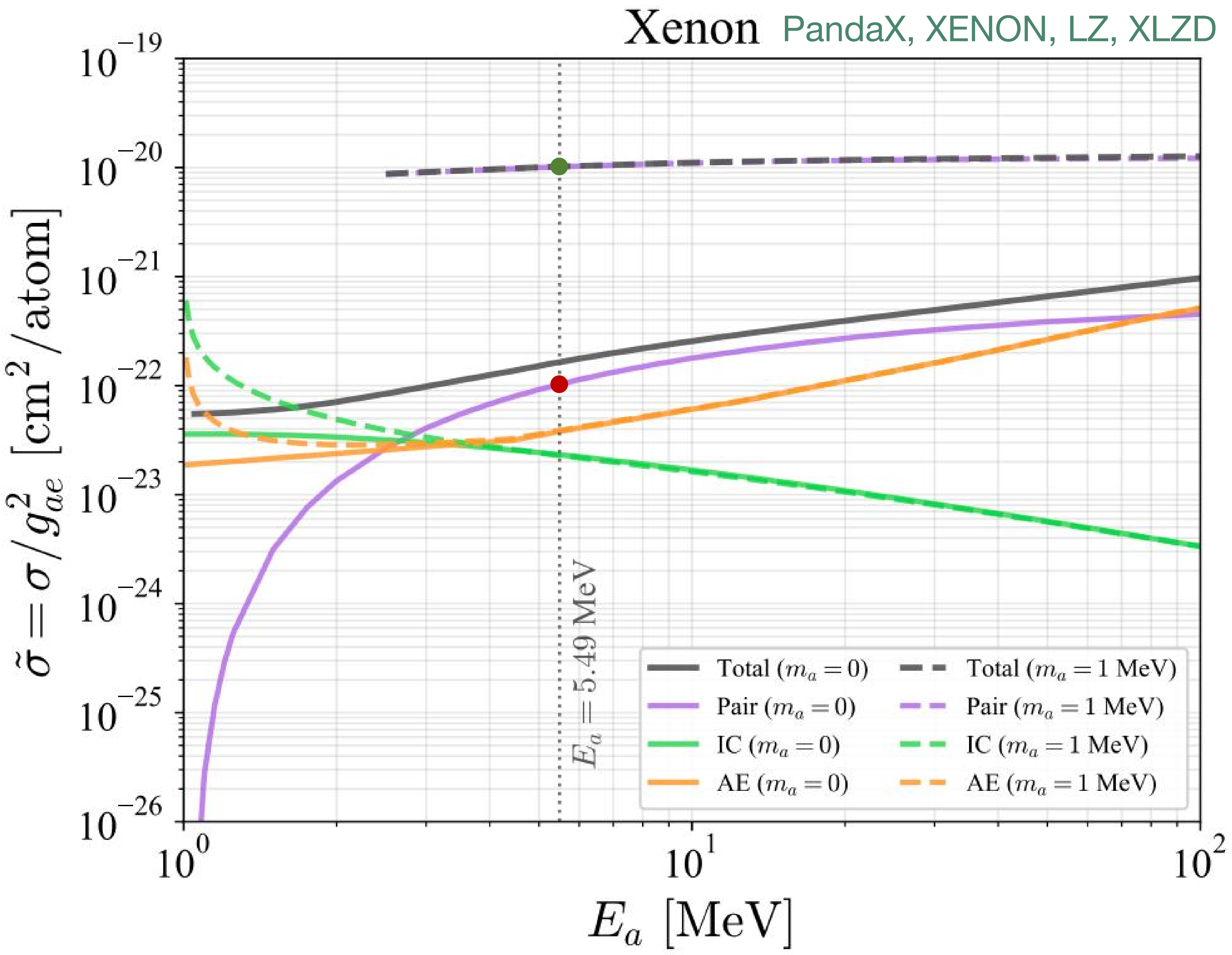
Pair production is the dominant channel
Axio-Electric effect contributes

02

AXION–ELECTRON COUPLING

Dominant Channels





Combine all detection channels

02

AXION–ELECTRON COUPLING

Sensitivity

Refs [73] BOREXINO, 2504.19135, [74] Arias-Aragón, M Giannotti, G Cortona, F Mescia, 2411.19327

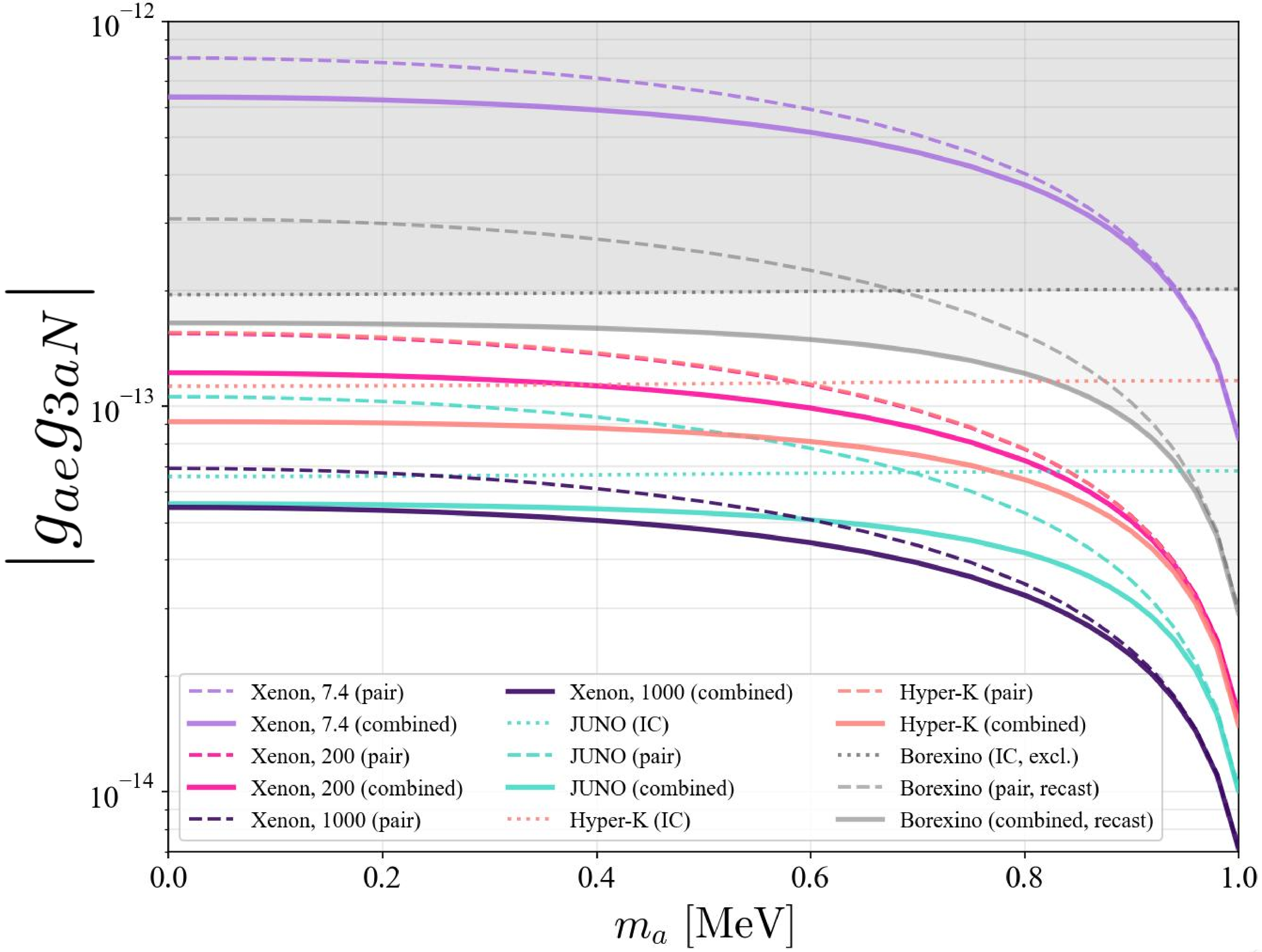
Experiment	Target	Exposure (ton×yr)	Efficiency (%)	Channels	$\lvert g_{ae}g_{3aN}\rvert$ at $m_a = 0$	$\lvert g_{ae}g_{3aN}\rvert$ at $m_a \simeq 1$ MeV
Borexino	C_9H_{12}	1587	22.5–25.1	IC(+PP)	1.90×10^{-13} [73]	2.91×10^{-14}
JUNO	$C_{19}H_{32}$	1.62×10^5	~ 100	PP+IC	5.59×10^{-14} [74]	1.00×10^{-14}
Hyper-K	H_2O	1.87×10^6	~ 100	PP+IC	9.14×10^{-14} [74]	1.49×10^{-14}
xenon experiments	Xe	7.4 PandaX-4T	~ 100	PP+IC+AE	6.90×10^{-13}	8.98×10^{-14}
		200 PandaX-xT, XLZD...			1.33×10^{-13}	1.73×10^{-14}
		1000 XLZD...			5.93×10^{-14}	7.72×10^{-15}

Three **KEY advantages** of Xenon-based experiments

- **Mass** Enhancement
- **High-Z** Enhancement
- **Ultra-low background** at MeV energy range

Sensitivity

- **Current strongest** lab limit: Borexino
- **PandaX-4T** (**7.4** t·yr): still below the recast Borexino limit
- **PandaX-xT** (**200** t·yr): surpasses recast Borexino across 0-1 MeV
- **XLZD** (**1000** t·yr): comparable to JUNO, beats Hyper-K by ×1.5–1.9



Part 3

Direct Detection with Axion–Photon Coupling

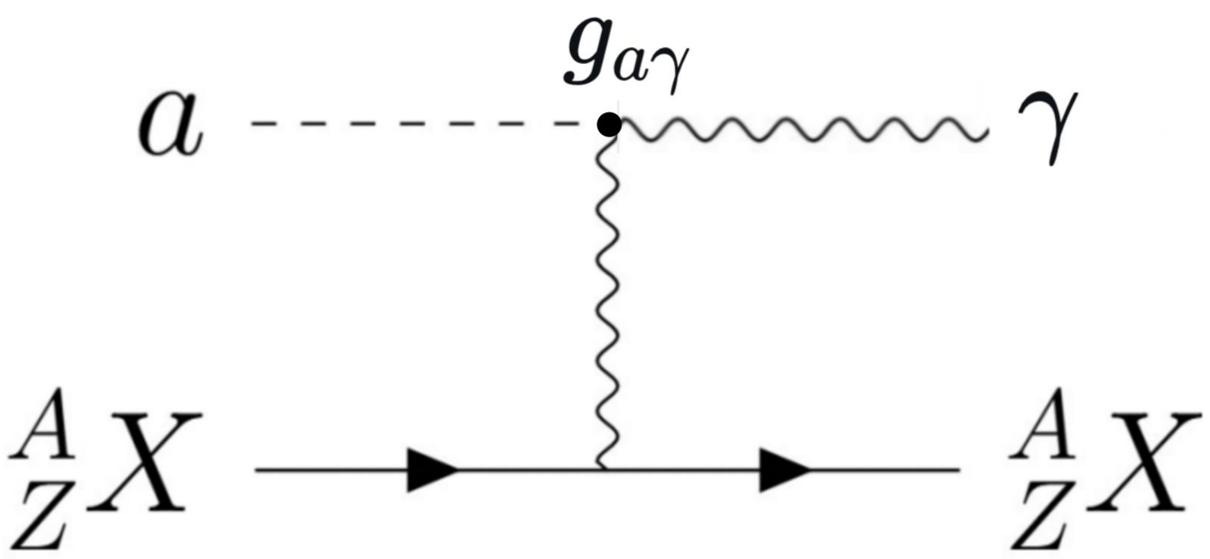
Inverse Primakoff

Sensitivity

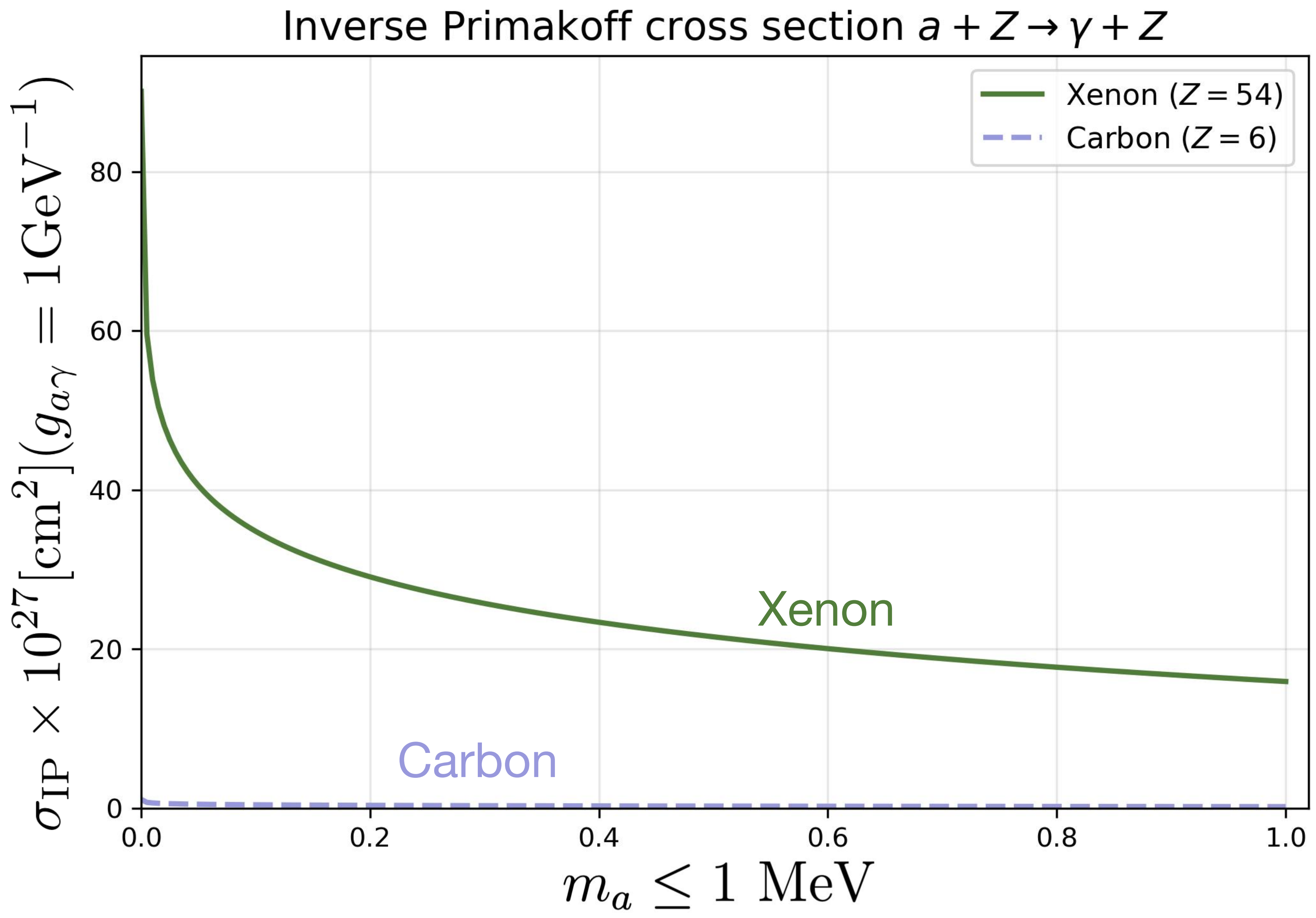
Inverse Primakoff

$$\mathcal{L}_{\rm int} \supset \boxed{-\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}} - i g_{ae} a \bar{e}\gamma_5 e - i a \overline{N}\gamma_5 (g_{0aN} + \tau_3 g_{3aN}) N$$

$$a + Z \to \gamma + Z$$



Inverse Primakoff conversion
enhanced by high-Z

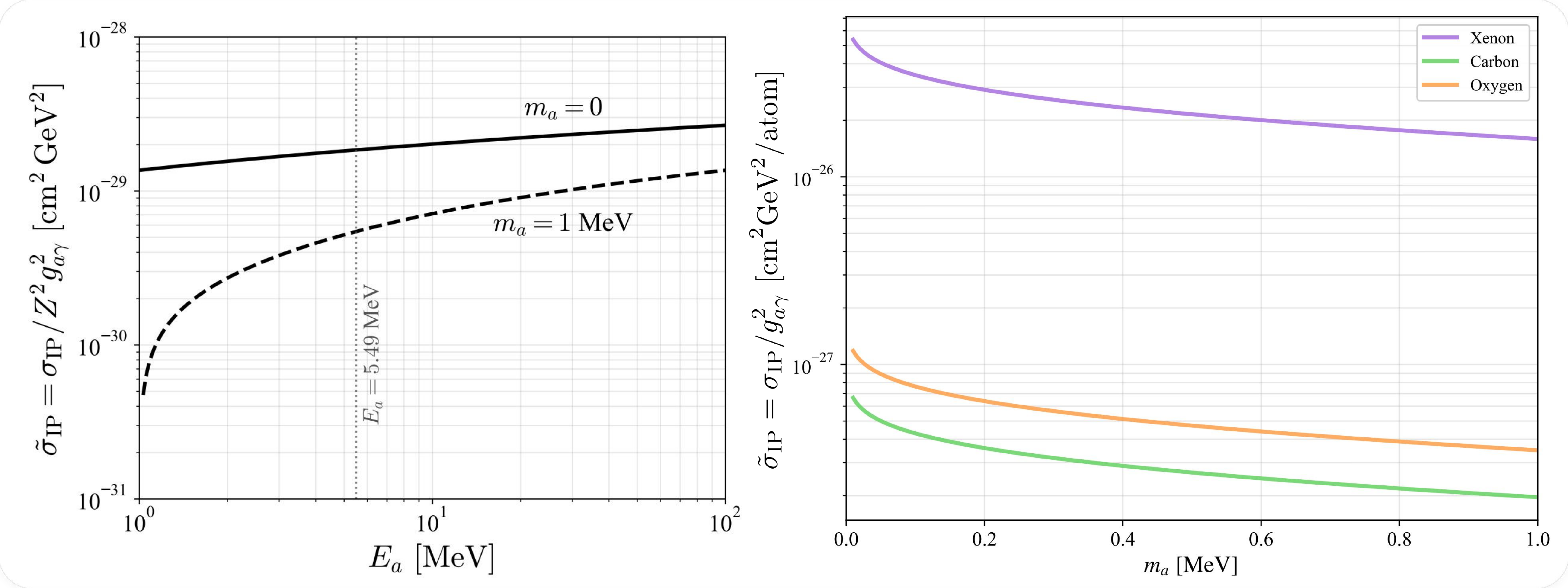


AXION–PHOTON COUPLING

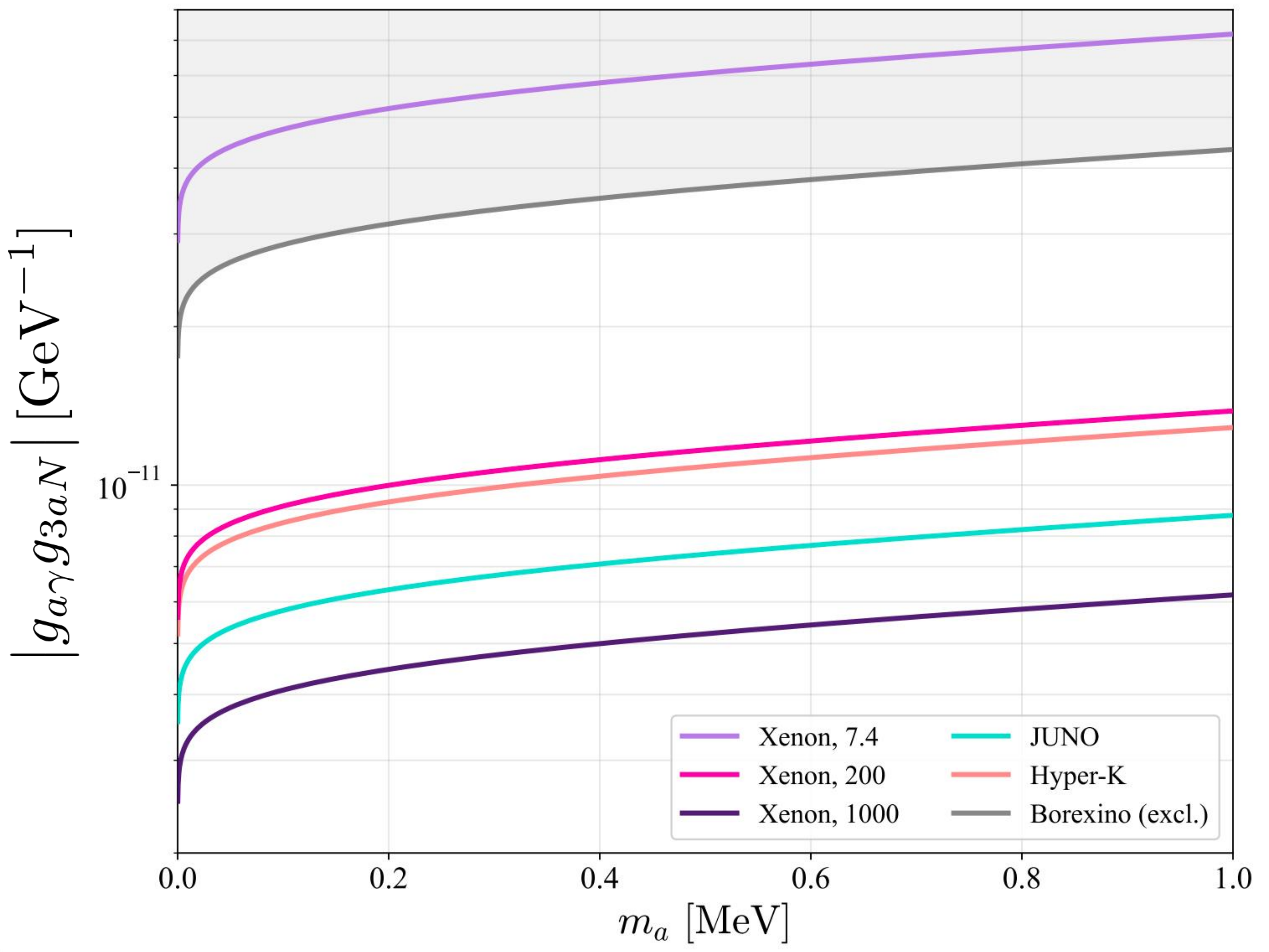
03

Inverse Primakoff

$$\mathcal{L}_{\text{int}} \supset \boxed{-\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}} - i g_{ae} a \bar{e} \gamma_5 e - i a \overline{N} \gamma_5 (g_{0aN} + \tau_3 g_{3aN}) N$$



Sensitivity



Experiment	$\lvert g_{a\gamma}g_{3aN}\rvert$ [GeV^{-1}] at $m_a \simeq 0$	$\lvert g_{a\gamma}g_{3aN}\rvert$ [GeV^{-1}] at $m_a = 1$ MeV
Borexino	2.30×10^{-11} [73]	4.34×10^{-11}
JUNO	4.64×10^{-12}	8.76×10^{-12}
Hyper-K	6.82×10^{-12}	1.29×10^{-11}
xenon experiments	3.81×10^{-11}	7.19×10^{-11}
	7.33×10^{-12}	1.38×10^{-11}
	3.28×10^{-12}	6.19×10^{-12}

the next generation xenon detectors can provide a **complementary and competitive** probe of the MeV-scale solar axions with a **far smaller target mass**

04 Summary

$p + d \rightarrow {}^3\text{He} + \boxed{\boldsymbol{a}\ (\mathbf{5.5\ MeV})}$ monochromatic, clean

- We systematically study axion detection in **xenon experiments** via:

$|g_{ae}g_{3aN}|$ **pair production** inverse Compton **(axio-electric)**

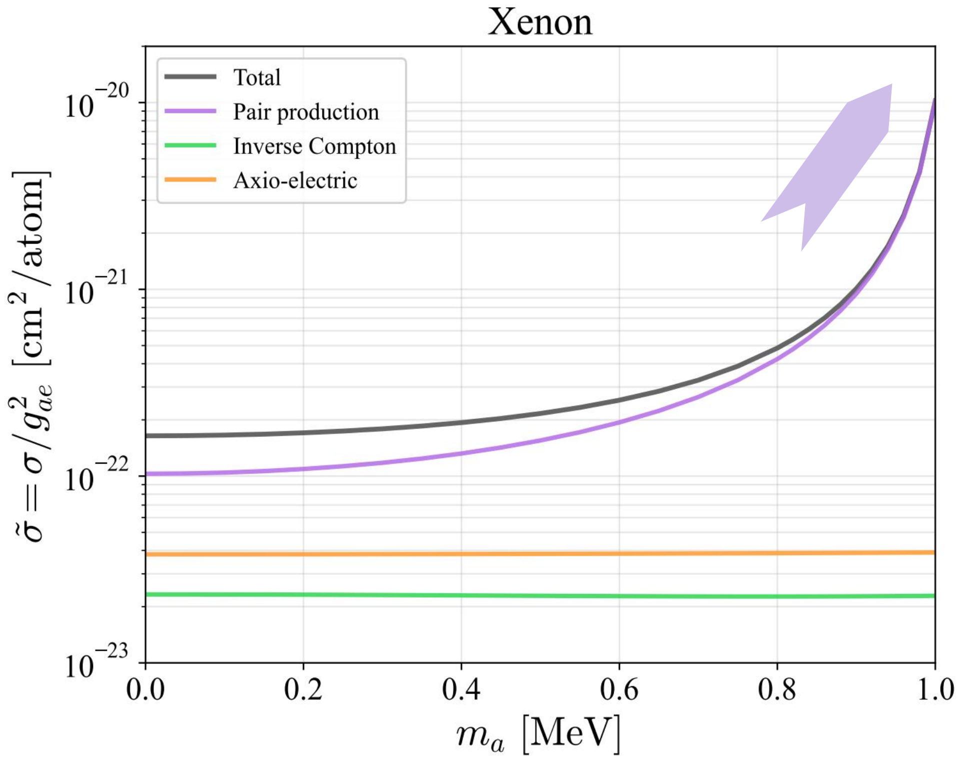
$|g_{a\gamma}g_{3aN}|$ **inverse Primakoff**

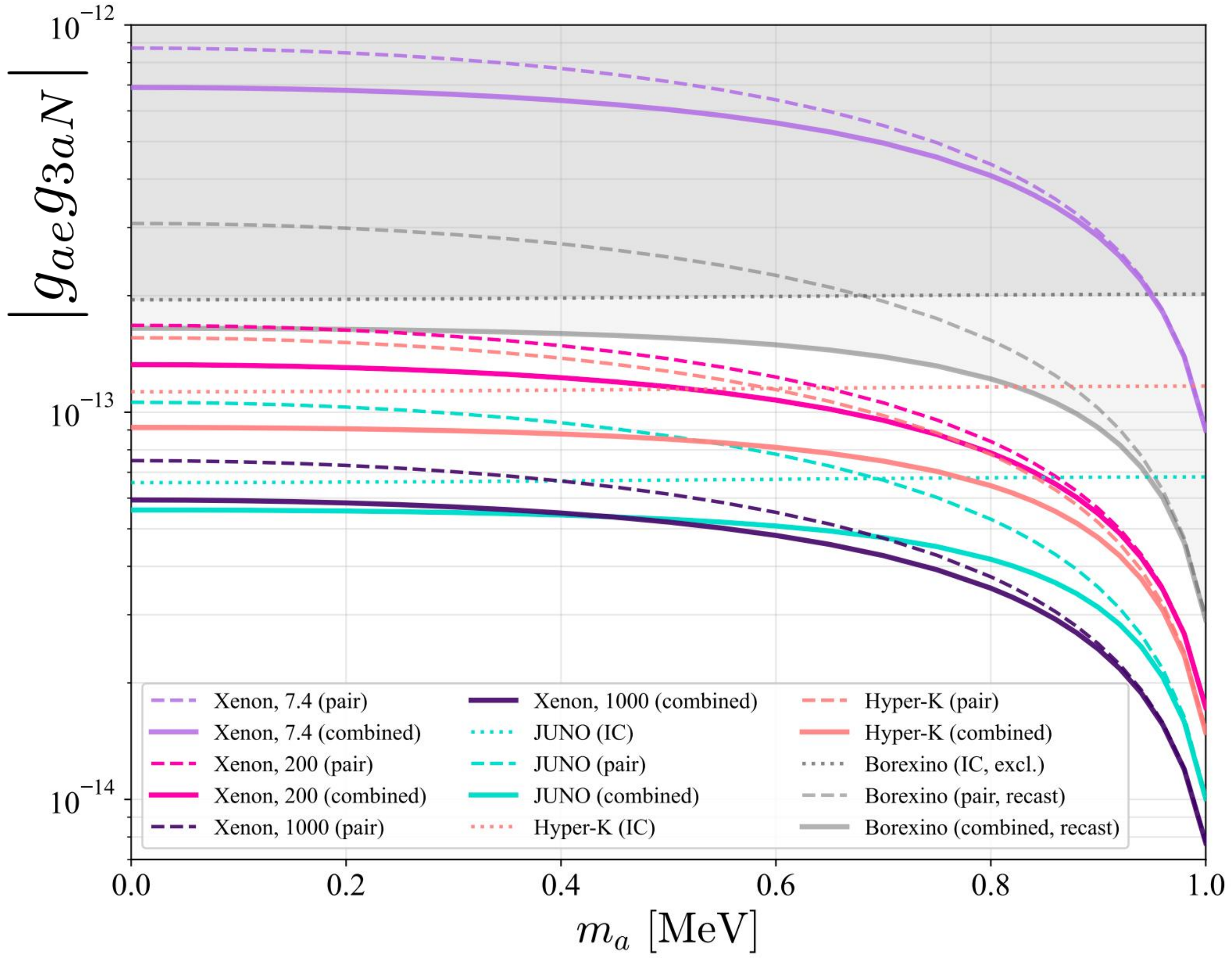
- **Key advantages** of xenon:

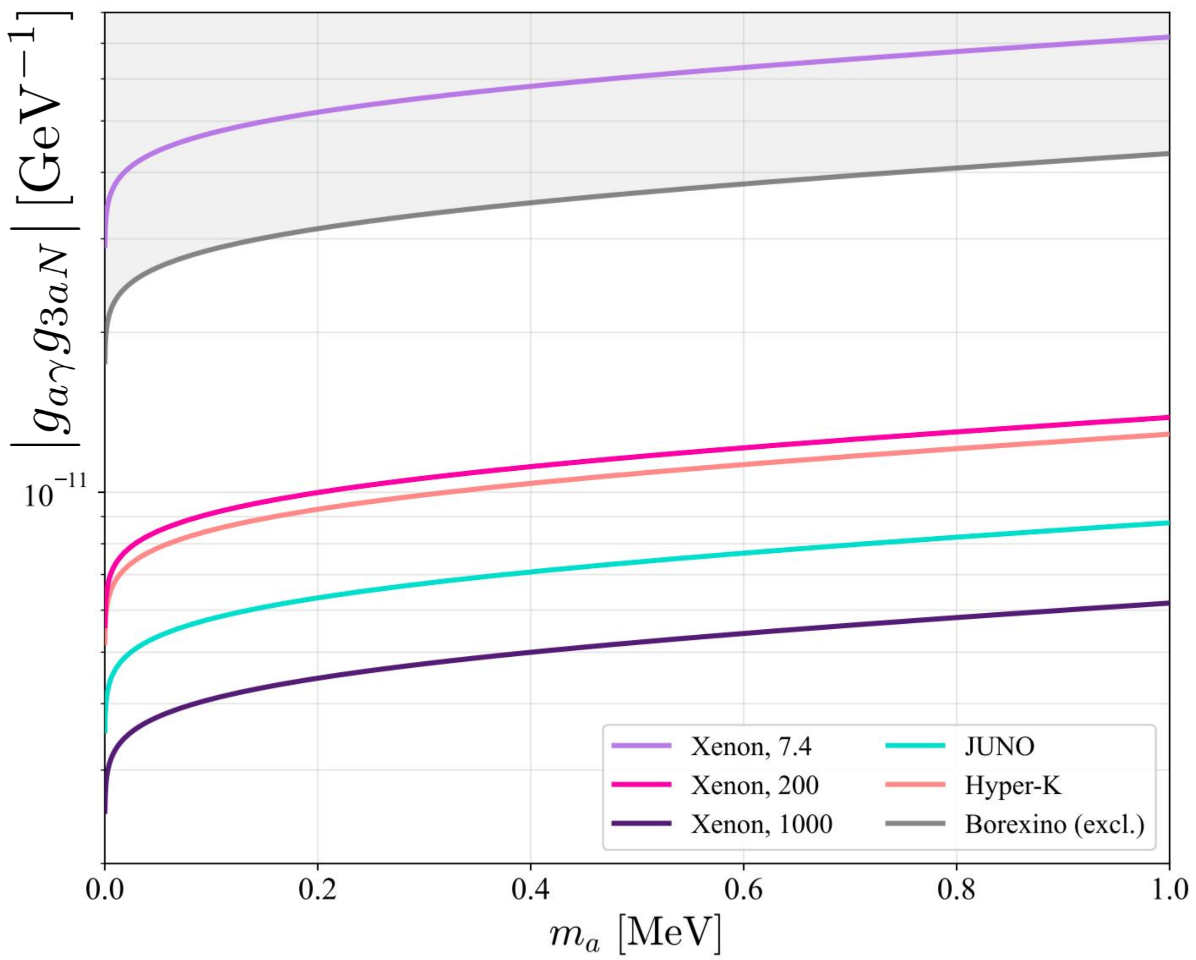
Mass Enhancement (Pair production)

High-Z Enhancement

Ultra-low background







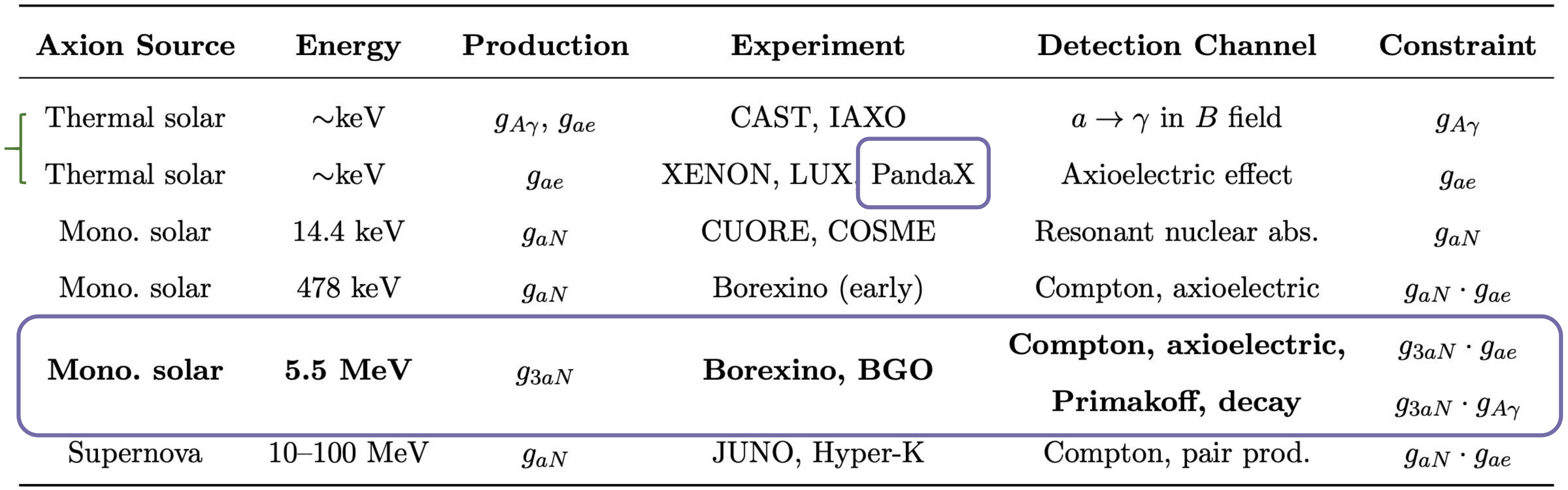
Thank You!

Xenon detectors provide a **complementary and competitive** probe!

Backup–Axion source

Primakoff, ABC...

nuclear reactions...



Axion Source	Energy	Production	Experiment	Detection Channel	Constraint
Thermal solar	~keV	$g_{A\gamma}$, g_{ae}	CAST, IAXO	$a \to \gamma$ in B field	$g_{A\gamma}$
Thermal solar	~keV	g_{ae}	XENON, LUX, PandaX	Axioelectric effect	g_{ae}
Mono. solar	14.4 keV	g_{aN}	CUORE, COSME	Resonant nuclear abs.	g_{aN}
Mono. solar	478 keV	g_{aN}	Borexino (early)	Compton, axioelectric	$g_{aN} \cdot g_{ae}$
Mono. solar	**5.5 MeV**	g_{3aN}	**Borexino, BGO**	**Compton, axioelectric,** **Primakoff, decay**	$g_{3aN} \cdot g_{ae}$ $g_{3aN} \cdot g_{A\gamma}$
Supernova	10–100 MeV	g_{aN}	JUNO, Hyper-K	Compton, pair prod.	$g_{aN} \cdot g_{ae}$

channel	Prod.	Prod. Coupl.	Det	Det. Coupl.	Signal	PandaX-4T	Borexino
thermal axion (~keV)	Primakoff, ABC...	g_ae,g_aA	axio-electric	g_ae	recoil electron	gae<10^-12	thershold is low
5.5 MeV (elec.)	p+d->3He+a	g_3aN	a+Xe->Xe e+ e- (pair prod.)	g_ae	e+ e- (5.5 MeV)	better with mass	|g_ae g_3aN|<1.9 *10^-13
5.5 MeV (elec.)	p+d->3He+a	g_3aN	a+e->Xe e- A (inverse Comp.)	g_ae	e- A (5.5 MeV)	same	|g_ae g_3aN|<1.9 *10^-13
5.5 MeV (photon)	p+d->3He+a	g_3aN	a+Xe->Xe+A (inverse Prima.)	g_aA	A (5.5 MeV)	future better	|g_aA g_3aN|<2.3 *10^-11

04 Backup–Axion flux

- Axions can be produced in the Sun through non-thermal mechanisms involving **nuclear reaction processes** induced by the axion-nucleon couplings.

Monochromatic fluxes

magnetic dipole transitions during the **de–excitation** of nuclei

$$^{57}\mathrm{Fe}^* \rightarrow {}^{57}\mathrm{Fe} + a(14.4\,\mathrm{keV}) \quad {}^{83}\mathrm{Kr}^* \rightarrow {}^{83}\mathrm{Kr} + a(9.4\;\mathrm{keV})$$

axion line from the proton-proton (pp) chain reaction

one of the most efficient production mechanisms induced by the axion-nucleon coupling

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

F Arias-Aragón, M Giannotti, G Cortona, F Mescia, 2411.19327

$$\delta = 0.82 \quad \eta = 0$$

$$\Phi_{a0} = (\Gamma_a/\Gamma_\gamma)\Phi_{\nu pp}$$

magnetic moment $\mu_3 = \mu_p - \mu_n = 4.77$

$$\frac{\Gamma_a}{\Gamma_\gamma} = \frac{1}{2\pi\alpha}\left(\frac{|\vec{k}_a|}{|\vec{k}_\gamma|}\right)^3 \frac{1}{1+\delta^2}\left(\frac{g_{3aN}}{\mu_3-\eta}\right)^2$$

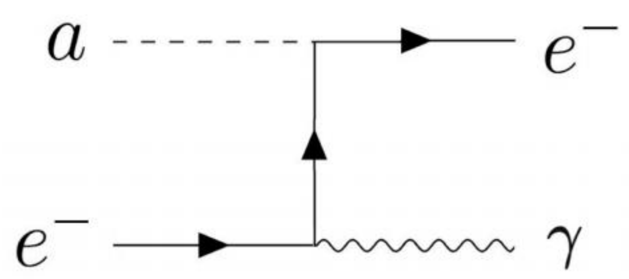
$$\simeq 0.54\, g_{3aN}^2 \left(\frac{|\vec{k}_a|}{|\vec{k}_\gamma|}\right)^3$$

$$\Phi_a = \Phi_{a0}\, e^{-d_\odot/\ell_{\mathrm{tot}}}$$

$$\simeq 3.23 \times 10^{10} g_{3aN}^2 \boxed{\left(\frac{|\vec{k}_a|}{|\vec{k}_\gamma|}\right)^3} e^{-d_\odot/\ell_{\mathrm{tot}}}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

04 Backup–g_ae coupling detection

- Inverse Compton scattering $a + e^- \to e^- + \gamma$

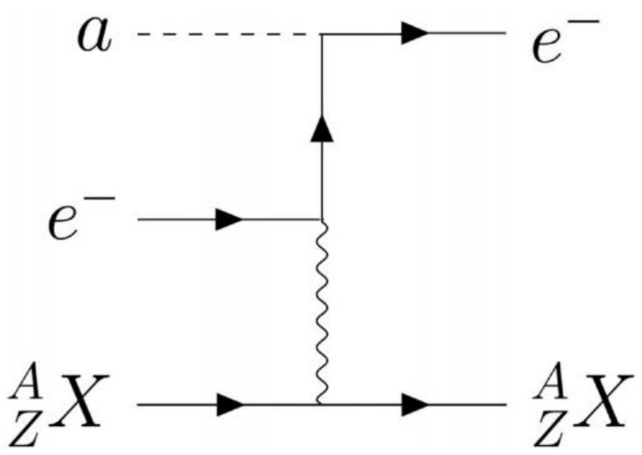


$$\sigma_{IC} = \frac{g_{ae}^2 \alpha}{8m_e^2|\vec{k}_a|}\left[\frac{2m_e^2(m_e+E_a)y}{(m_e^2+y)^2} + \frac{4m_e(m_a^4+2m_a^2m_e^2-4m_e^2E_a^2)}{y(m_e^2+y)} + \frac{4m_e^2|\vec{k}_a|^2+m_a^4}{|\vec{k}_a|y}\ln\frac{m_e+E_a+|\vec{k}_a|}{m_e+E_a-|\vec{k}_a|}\right]$$

for $m_a \lesssim 2$ MeV

$$\sigma_{IC} \simeq 4.3\times 10^{-25}\, g_{ae}^2\ \mathrm{cm}^2$$

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

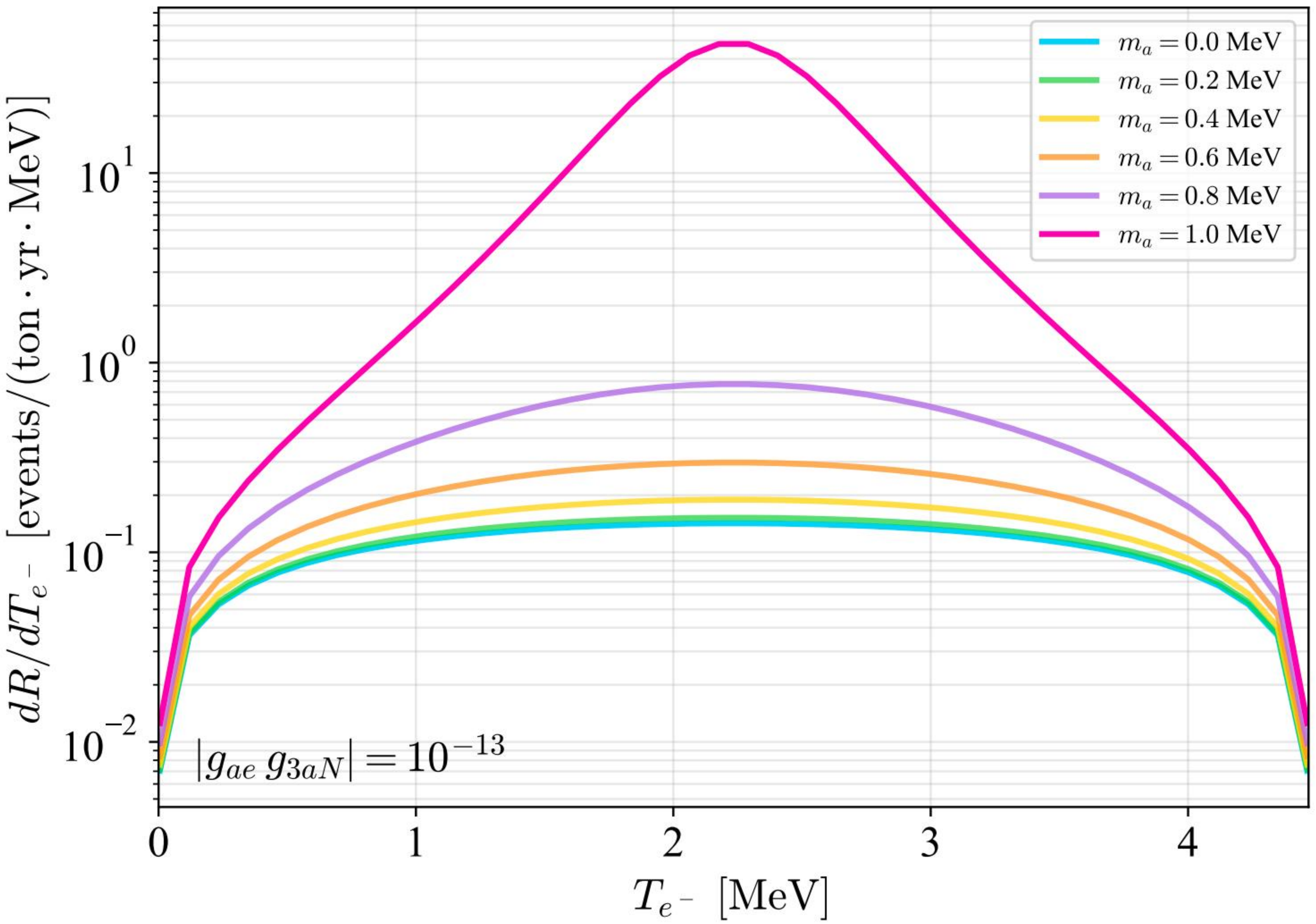


- Axion-induced external pair production $\frac{d\sigma_{aee}}{d\cos\theta_+ d\cos\theta_- dE_- d\phi} = -\frac{|\mathcal{M}|^2\,|\vec{\ell}_+|\,|\vec{\ell}_-|}{512\,\pi^4\,m_X^2\,|\vec{k}_a|}$

F Arias-Aragón, M Giannotti, G Cortona, F Mescia, 2411.19327

04 Backup–pair production

$$
\begin{aligned}
|\mathcal{M}|^2 &= \frac{e^4 g_{ae^2}}{t^2}(|\mathcal{M}_1|^2 + |\mathcal{M}_2|^2 + 2\,\mathcal{M}_{12}) \\
|\mathcal{M}_1|^2 &= \frac{32}{(m_a^2 - 2(k_a\cdot\ell_+))^2}\bigg[2m_X^2(k_a\cdot\ell_-)(k_a\cdot\ell_+) - 2(k_a\cdot\ell_+)(k_a\cdot p_2)(p_1\cdot\ell_-) \\
&\quad - 2(k_a\cdot\ell_+)(k_a\cdot p_1)(p_2\cdot\ell_-) + m_a^2\bigg(-m_X^2(\ell_+\cdot\ell_-) + (p_2\cdot\ell_-)(p_1\cdot\ell_+) \\
&\quad + (p_2\cdot\ell_+)(p_1\cdot\ell_-) + m_e^2((p_1\cdot p_2) - 2m_X^2)\bigg)\bigg] \\
|\mathcal{M}_2|^2 &= \frac{32}{(m_a^2 - 2(k_a\cdot\ell_-))^2}\bigg[2(k_a\cdot\ell_-)\bigg(m_X^2(k_a\cdot\ell_+) - (k_a\cdot p_2)(\ell_+\cdot p_1) \\
&\quad - (k_a\cdot p_1)(\ell_+\cdot p_2)\bigg) + m_a^2\bigg(-m_X^2(\ell_-\cdot\ell_+) + (\ell_-\cdot p_2)(\ell_+\cdot p_1) \\
&\quad + (\ell_-\cdot p_1)(\ell_+\cdot p_2) + m_e^2((p_1\cdot p_2) - 2m_X^2)\bigg)\bigg] \\
\mathcal{M}_{12} &= -\frac{32}{(m_a^2 - 2(k_a\cdot\ell_-))(m_a^2 - 2(k.\ell_+))}\bigg((k_a\cdot\ell_-)\bigg(-2m_X^2(k_a\cdot\ell_+) \\
&\quad + (k_a\cdot p_2)(\ell_+\cdot p_1) + (k_a\cdot p_1)(\ell_+\cdot p_2)\bigg) - 2(k_a\cdot p_1)(k_a\cdot p_2)\bigg((\ell_-\cdot\ell_+) + m_e^2\bigg) \\
&\quad + (k_a\cdot\ell_+)\bigg((k_a\cdot p_2)(\ell_-\cdot p_1) + (k_a\cdot p_1)(\ell_-\cdot p_2)\bigg) - m_a^2\bigg((\ell_-\cdot p_2)(\ell_+\cdot p_1) \\
&\quad + (\ell_-\cdot p_1)(\ell_+\cdot p_2) - (\ell_-\cdot\ell_+)(p_1\cdot p_2)\bigg) + m_X^2 m_a^2 m_e^2\bigg)
\end{aligned}
$$



04 Backup

- the expected number of signal events $S = \epsilon \cdot N_T \cdot T \cdot \Phi_a \cdot \sigma$

$$S_{\text{total}} = \sum_i S_i \,, \qquad \text{with} \qquad S_i = K_i \, g_{ae}^2 g_{3aN}^2$$

- the 90% C.L. upper limit on the number of signal events corresponds to the Poisson probability $e^{-\mu} = 0.1$, giving $S_{\text{lim}} = 2.3$