Axionlike particles searches in nuclear reactor experiments

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Motivation
- ALPs
- Astro+Cosmo limits
- Reactor searches
- Phenomenologically...

γ's at reactors

ALPs production and detection

Sensitivities (selected cases)

Final remarks

Motivation

ALPs

ALPs: Pseudo Nambu-Goldstone bosons of spontaneously broken global symmetries

QCD axion (Weinberg 1978, Wilczek 1978)

Global symmetry: $U(1)_{\text{PQ}}$

$U(1)_{\text{PQ}}$ solves the strong CP problem

Axionlike particles (ALPs)

Global $U(1)$ factors related with:

LNV: Majoron (Y. Chikashige et. al, 1981)

FSB: Familons (Wilczek, 1982)

QCD axion: $m_a f_a \sim m_\pi f_\pi$

Mass and "decay constant" related

$$m_a = 5.7 \left(\frac{10^6\,\text{GeV}}{f_a}\right)\text{eV}$$

ALP mass does not arise from QCD effects

m_a and f_a are not related

Reactor searches (mainly) related with ALPs

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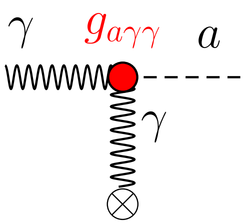
Astro+Cosmo limits

These scenarios are subject to a variety of astrophysical and cosmological limits (laboratory too) in the region of interest $m_a \lesssim 10\,$MeV for reactor searches

Few astrophysical bounds

Primakoff process

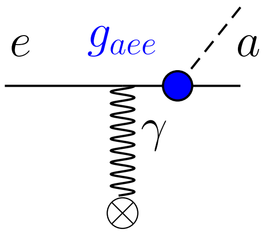


Dicus et. al, PRD 18 (1978)

$\vec{E}$ generated by p and $e \Rightarrow a$

Affects the He-burning lifetime of HB stars

ALP Bremsstrahlung



Krauss et. al, PLB 181 (1984)

Bremsstrahlung ALP emission produces delay of He ignition in low-mass Red Giants

e.g J. Jaeckel et. al, PRD 75, 2007

Can be relaxed (fully evaded [?]) if e.g. $m_a = m_a(T)$ and $g_{aXX} = g_{aXX}(T)$

Lab. limits in those regions welcome!

Reactor searches do so!

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Reactor searches

VOLUME 40, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1978

A New Light Boson?

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 6 December 1977)

It is pointed out that a global U(1) symmetry, that has been introduced in order to preserve the parity and time-reversal invariance of strong interactions despite the effects of instantons, would lead to a neutral pseudoscalar boson, the "axion," with mass roughly of order 100 keV to 1 MeV. Experimental implications are discussed.

PHYSICAL REVIEW D VOLUME 18, NUMBER 5 1 SEPTEMBER 1978

Do axions exist?

T. W. Donnelly, S. J. Freedman, R. S. Lytel, R. D. Peccei, and M. Schwartz
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 21 March 1978)

We critically examine various existing experiments which could provide evidence for the axion. Although our conclusions regarding the existence of this particle are somewhat pessimistic, we discuss other possible experiments which could throw additional light on this question.

First search

Bugey Nuclear power plant (France)

J.F. Cavaignac et.al, PLB 121, 1983

$P \simeq 2$GW, $L = 13.5$ m

Production: $p(n,\gamma)d$ and ^{97}Nb

Detection: ALP decay $a \to 2\gamma$

Most recent search

Kuosheng nuclear power plant (Taiwan)

H. M. Chang et. al, PRD 75, 2007 [TEXONO]

$P \simeq 2$GW, $L = 28$ m

Production: $p(n,\gamma)d$

Detection: Inverse Primakoff+Compton

Phenomenologically...

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J. Dent et. al, PRL 124 (2020)

Production: Primakoff and Compton-like scattering

Detection: Inverse processes plus decays $a \to 2\gamma$ and $a \to e^+e^-$

Goal

Build a comprehensive picture of what reactor experiments can achieve by including

all possible processes with minimal assumptions

Motivation
γ's at reactors
- EM radiation at reactors
- Photon total cross section
ALPs production and detection
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γ's at reactors

EM radiation at reactors

Motivation
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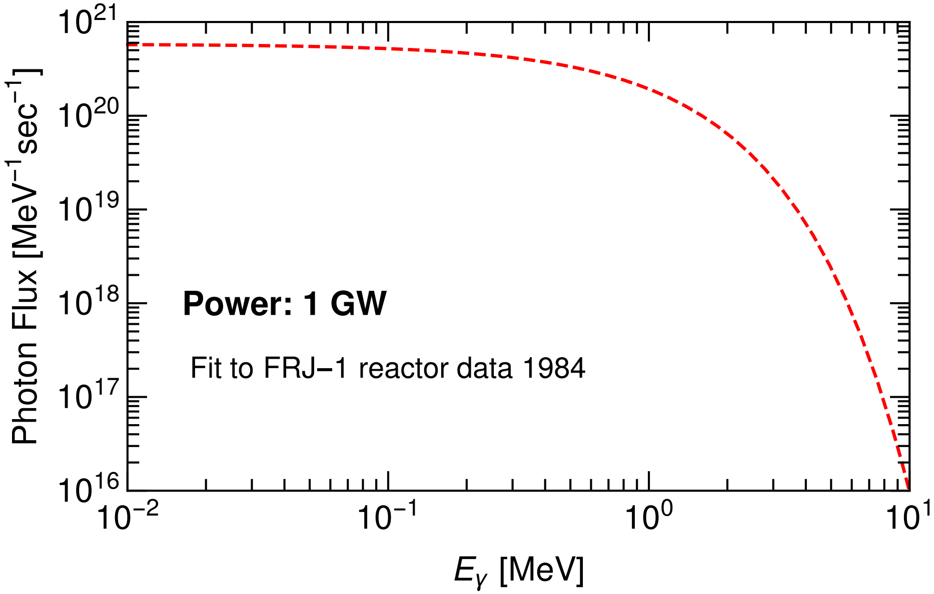
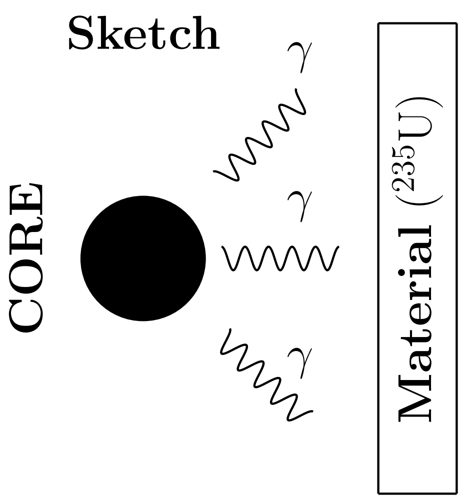
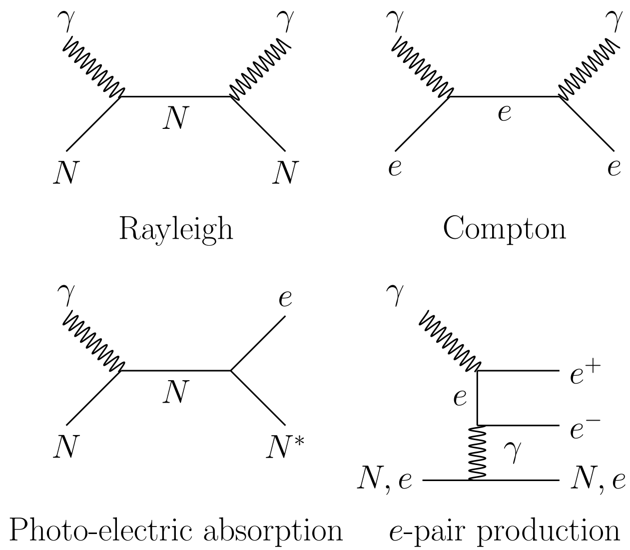
Photons produced via:
Prompt fission
β decay of fission products
Radiative n capture
Inelastic n capture







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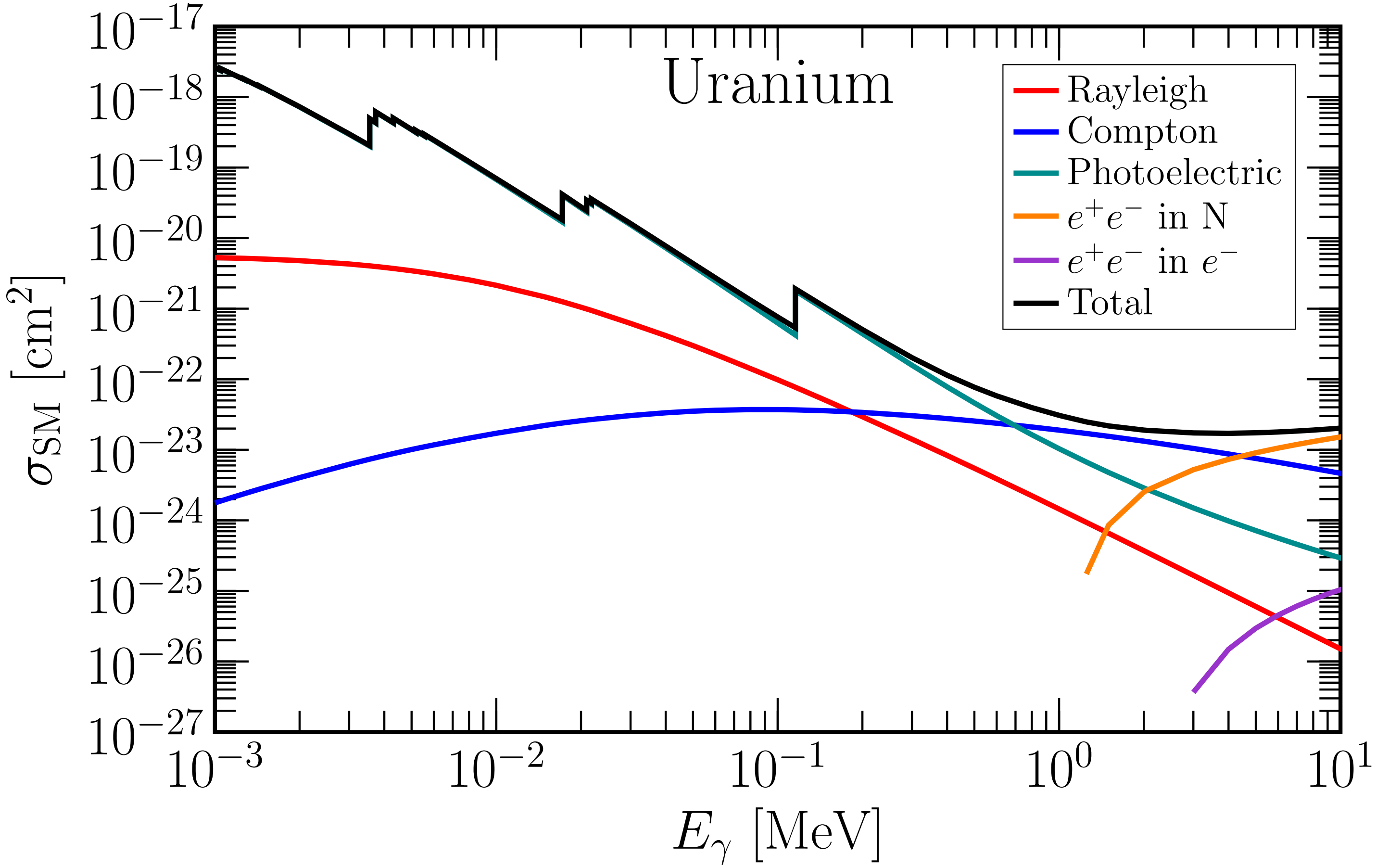
Photon total cross section

XCOM: Photon cross section database



A fraction of these photons can produce ALPs!

Motivation

γ's at reactors

ALPs production and detection

- ALPs production
- Detection
- Relevance of scattering and decay

Sensitivities (selected cases)

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ALPs production and detection

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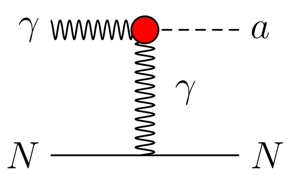
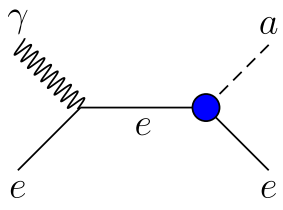
ALPs production

ALPs: Relevant interactions for reactor analysis

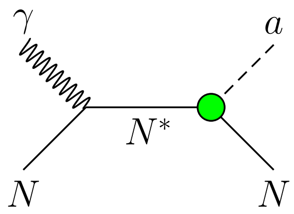
$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma}\, aF_{\mu\nu}\widetilde{F}^{\mu\nu} - i g_{aee} a\,\bar{e}\gamma_5 e - i a\bar{n}\gamma_5 \left(g_{ann}^{(0)} + \tau_3 g_{ann}^{(1)}\right) n$$



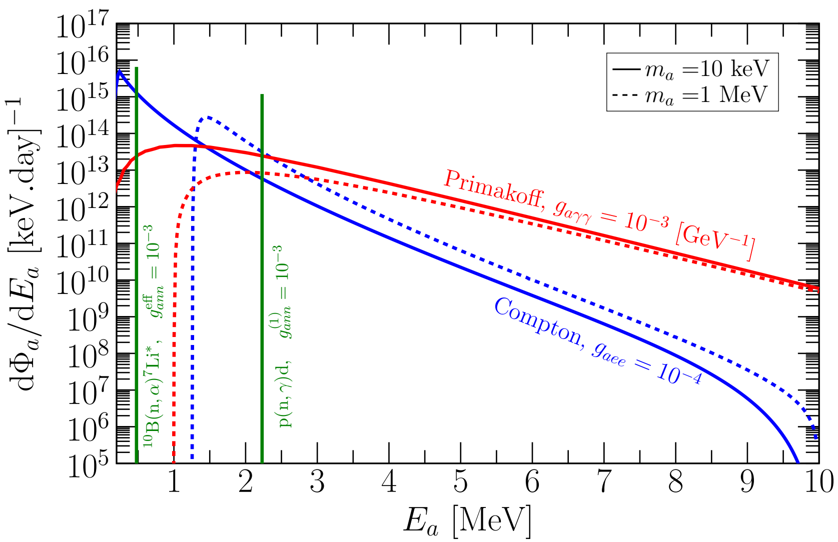
Primakoff



Compton-like



Nuclear de-excitation



A substantial amount of ALPs can be produced!

Detection

Motivation

γ's at reactors

ALPs production and detection
- ALPs production
- Detection
- Relevance of scattering and decay

Sensitivities (selected cases)

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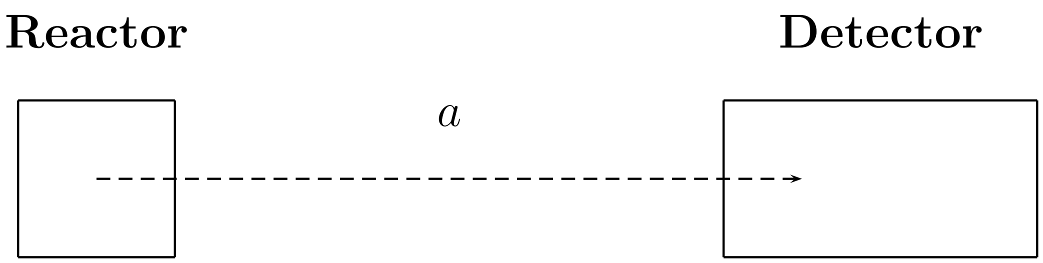

Processes at the detector selected by minimality:

Same coupling at production and detection

Scattering processes				
Process		Coupling	Prod	Det
Primakoff	$\gamma + N \leftrightarrow a + N$	$g_{a\gamma\gamma}$	✔	✔
Compton-like	$\gamma + e^- \leftrightarrow a + e^-$	g_{aee}	✔	✔
Nuclear de-excitation	$\gamma + N \leftrightarrow N^* \to a + N$	g_{ann}	✔	✗
Axio-electric	$a + e^- + Z \to e^- + Z$	g_{aee}	✗	✔
$e-$pair production in N	$a + N \to e^- + e^- + N$	g_{ann}	✗	✗
$e-$pair production in e	$a + e^- \to e^- + e^+ + e^-$	g_{aee}	✗	✔

Decay processes				
Process		Coupling	Prod	Det
γ-pair final state	$a \to \gamma + \gamma$	$g_{a\gamma\gamma}$	✗	✔
e-pair final state	$a \to e^- + e^+$	g_{aee}	✗	✔
n-pair final state	$a \to n + n$	g_{ann}	✗	✗

Relevance of scattering and decay

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- Detection
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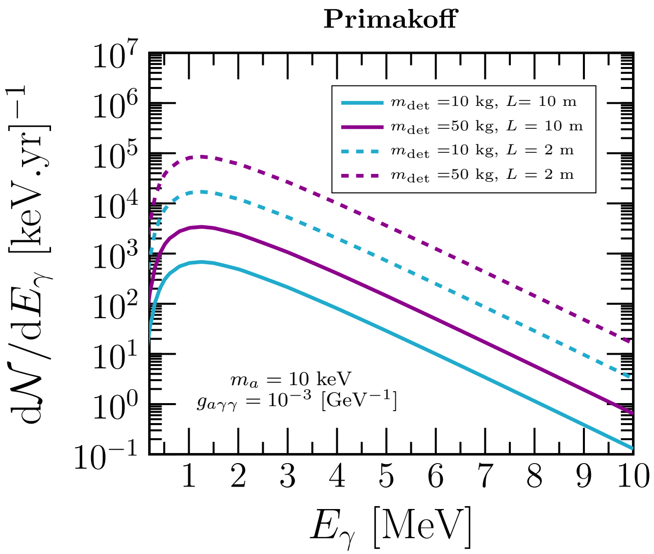

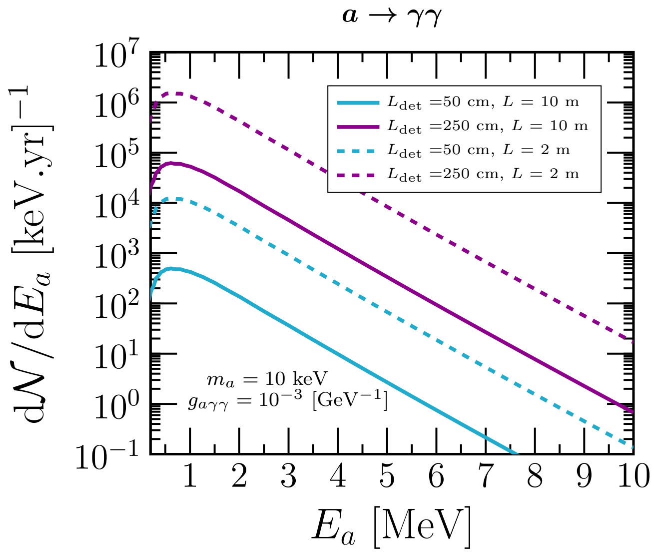

At small (large) ALP mass inverse-Primakoff (decay) dominates

Low (large) ALP mass sensitivities dominated by IP (decay)

Sensitivities

P[GW]	PM	TM	$m_{\rm det}$[kg]	L[m]	$L_{\rm det}$[cm]	bkg [1/keV/day/kg]
4	^{235}U	Ge	10	10	50	10-100
8	^{235}U	Xe	10^3	10	140	1-10

Motivation

γ's at reactors

ALPs production and detection

Sensitivities (selected cases)

- Sensitivities for dominant $g_{a\gamma\gamma}$ scenarios
- Sensitivities for dominant g_{ann} and $g_{a\gamma\gamma}$ scenarios

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Sensitivities (selected cases)

Sensitivities for dominant $g_{a\gamma\gamma}$ scenarios

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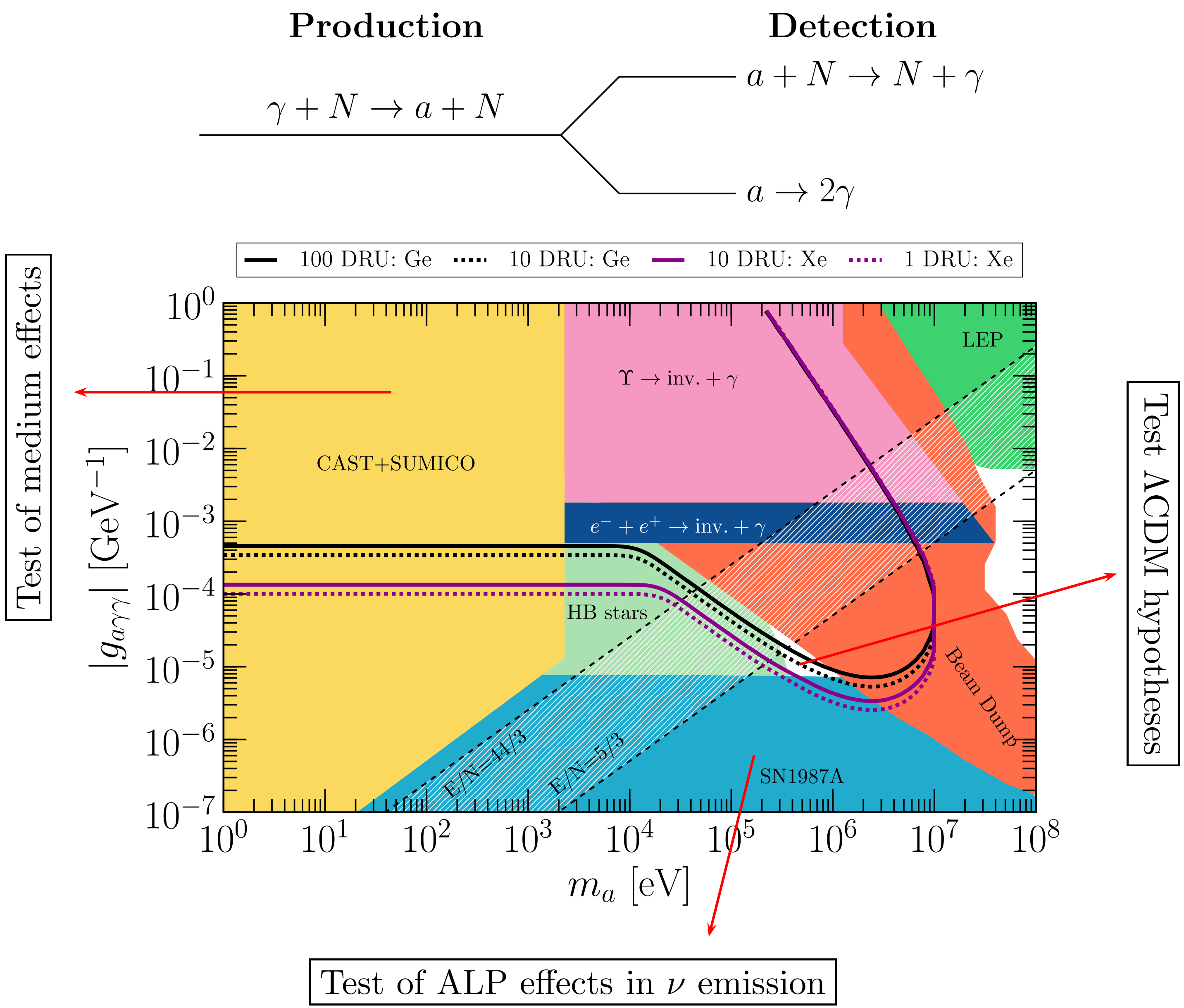

Cosmological triangle fully tested!

Sensitivities for dominant g_{ann} and $g_{a\gamma\gamma}$ scenarios

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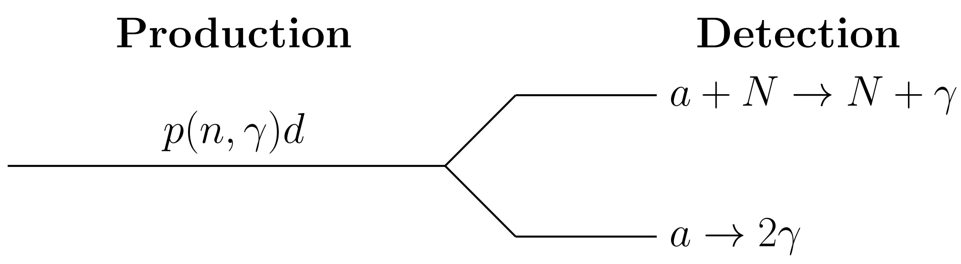

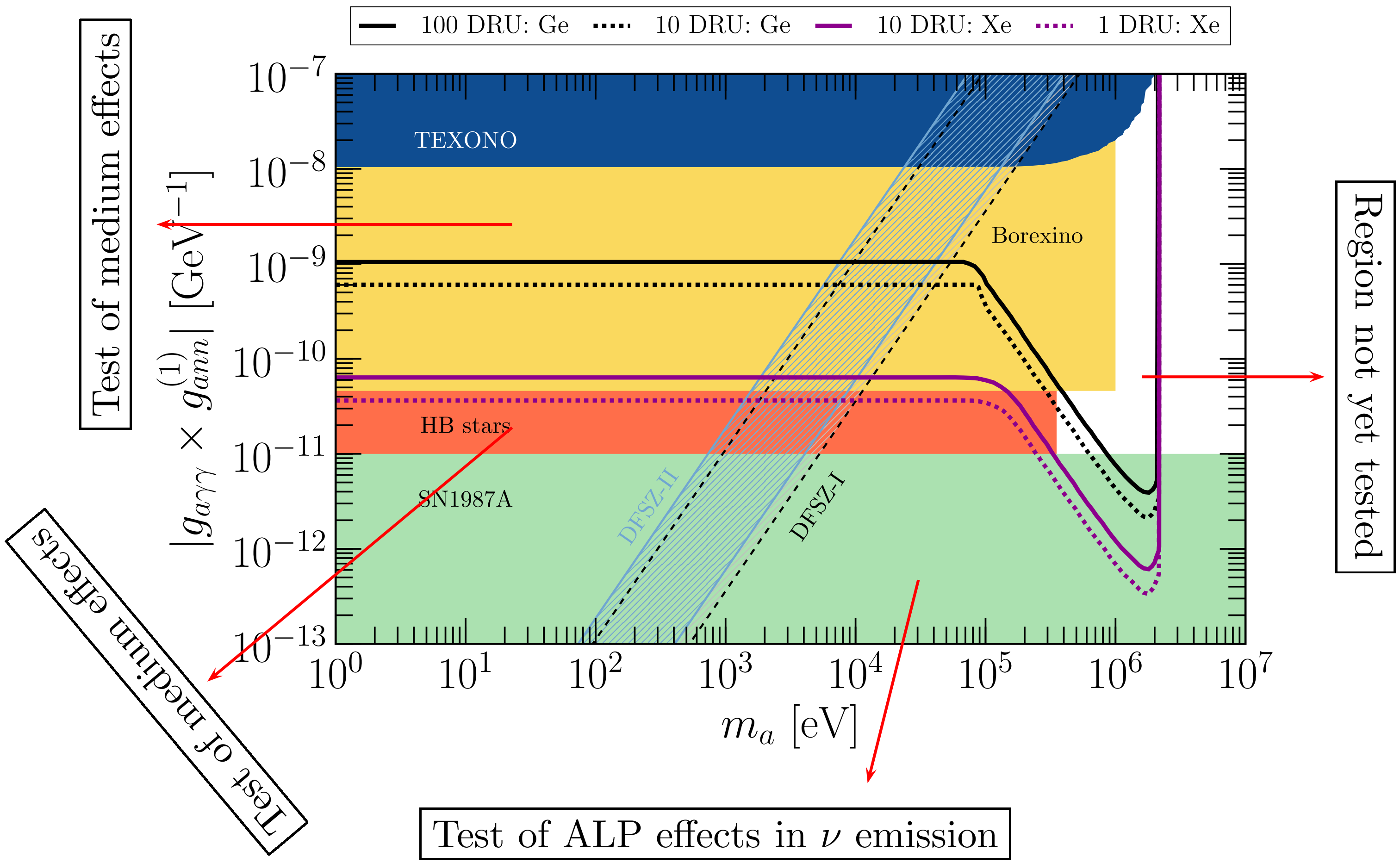

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● Conclusions

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Conclusions

$g_{a\gamma\gamma} - m_a$ sensitivities

☞ $\gamma + \gamma$ signals at reactor neutrino experiments will test ALP environmental effects: stellar environments and SN

☞ The same signal will **fully** test the cosmological triangle

$g_{aee} - m_a$ sensitivities

☞ $e^- + \gamma$, $e^- + e^+$ and e^- (axioelectron) emission signals will test regions not yet explored

Magnetic transition sensitivities

☞ Combined with inverse Primakoff, inverse Compton-like, axio-electric and decays regions not yet explored will be tested