Axion Search via Neutrino Experiments

Xiao-Ping Wang（Beihang University）

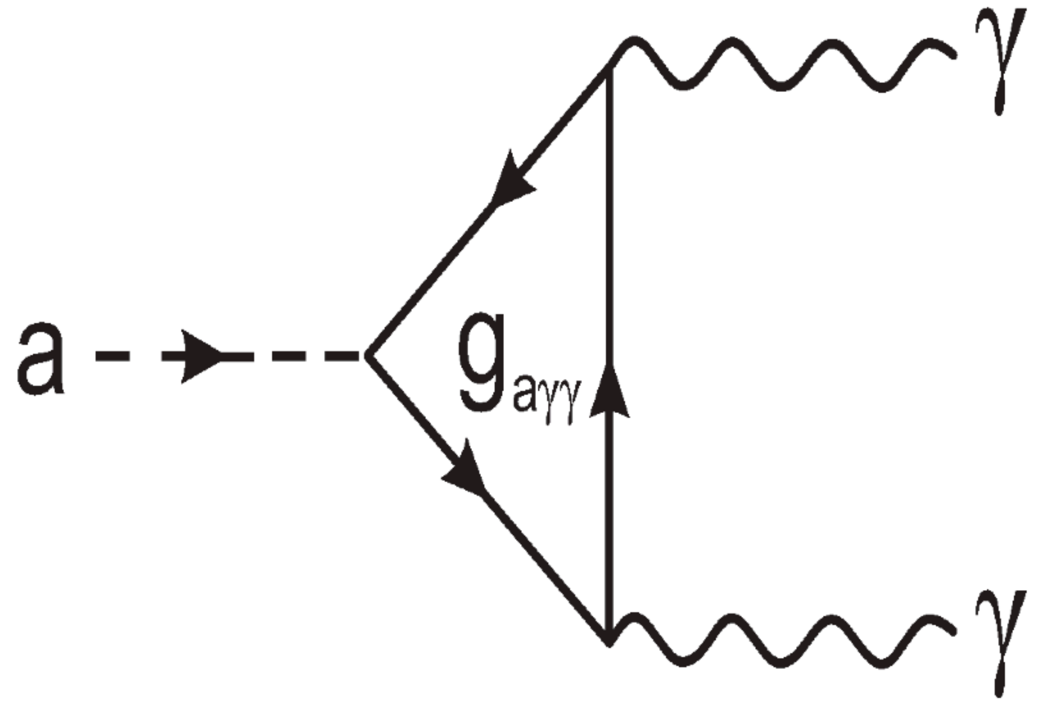
May, 11 @ Qingdao

Base On: Phys.Rev.D 110 (2024) 3, 035037[arXiv:2405.02084]
RELICS Collaboration

Axion and New Physics

- **Particle Physics Motivation**

$$\mathscr{L} \supset \frac{\bar{\theta} g_s^2}{32\pi^2} G\tilde{G} \rightarrow \frac{g_s^2}{32\pi^2}\left(\bar{\theta} + \frac{a}{f_a}\right) G\tilde{G}$$



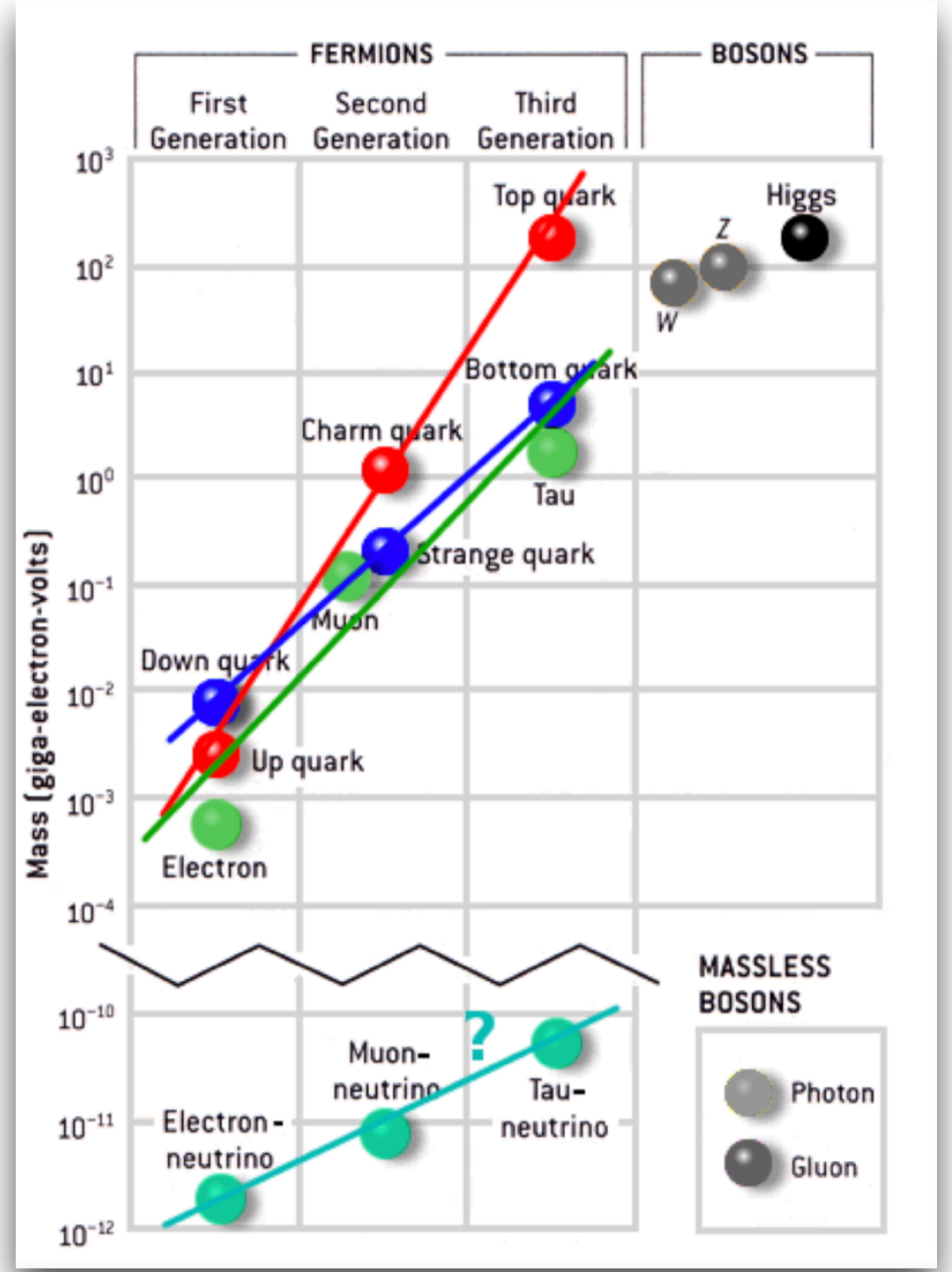
- **Axion Interactions**

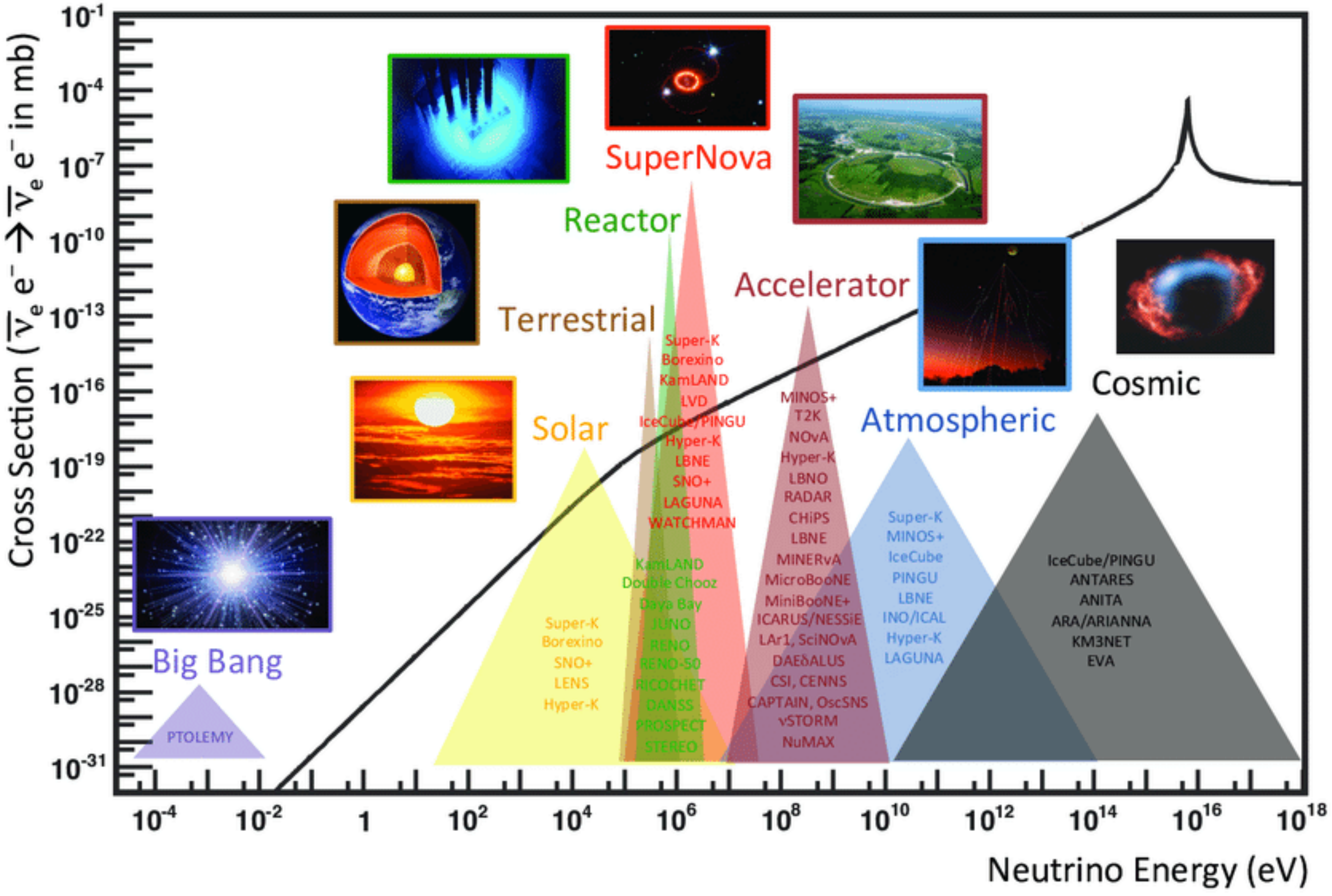
$$\mathscr{L}_a^{\text{int}} \supset \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a} aF\tilde{F} + C_{af}\frac{\partial_\mu a}{2f_a}\bar{f}\gamma^\mu\gamma_5 f + \frac{C_{a\pi}}{f_a f_\pi}\partial_\mu a[\partial\pi\pi\pi]^\mu - \frac{i}{2}\frac{C_{an\gamma}}{m_n}\frac{a}{f_a}\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu}$$

Coupling to photon	Coupling to fermions	Coupling to mesons	Coupling to neutron eDM

Neutrino Physics and Experiments

- **Neutrino Physics related to New Physics**





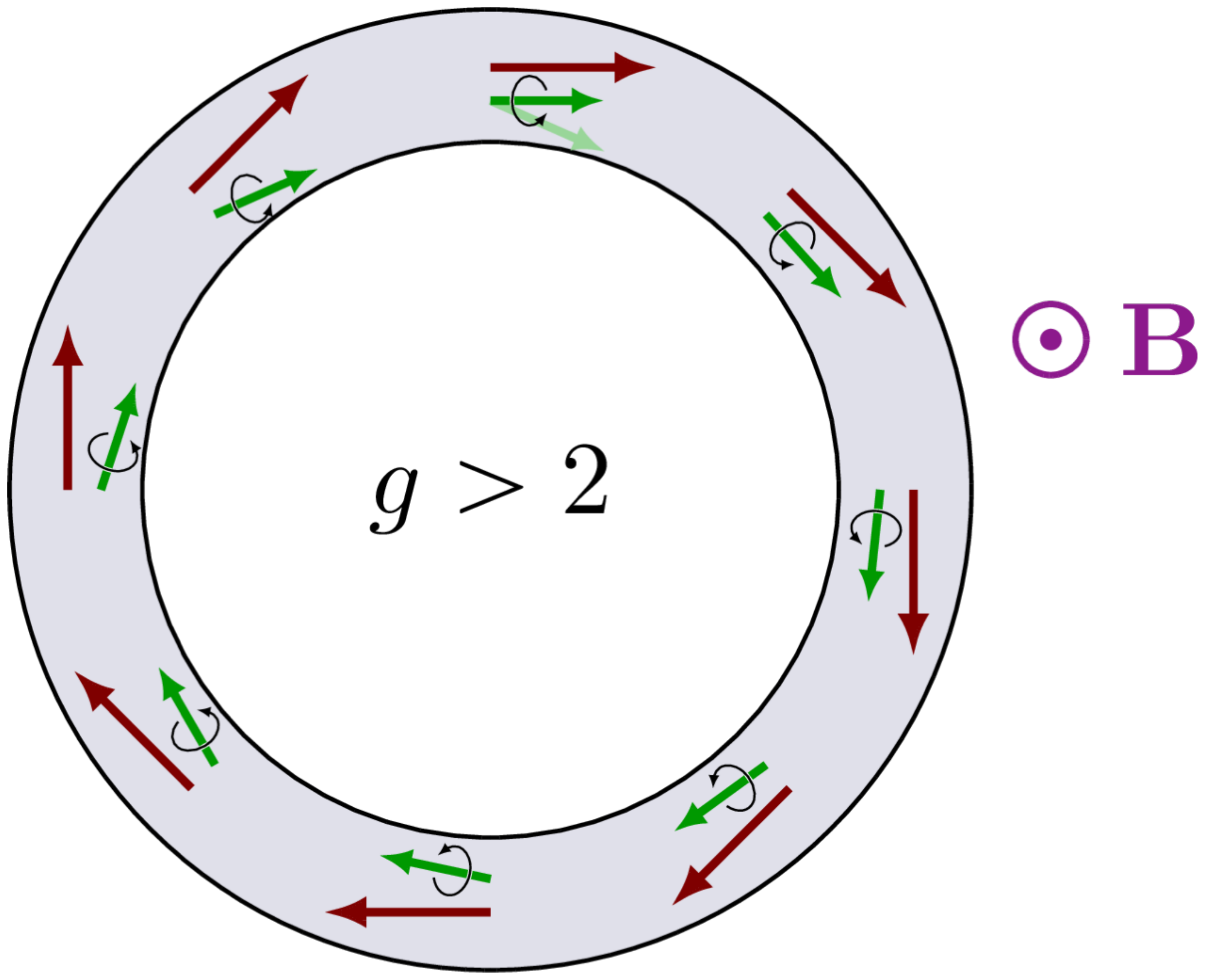
Outline

- **Search long-range axion-ν coupling by ν experiments**
- **Search non-ν axion couplings by reactor ν experiment RELICS**

ALP related to muon g-2

- **Positive value and a 4.2 σ (Fermilab + Brookhaven)**

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm th} = (25.1 \pm 5.9) \times 10^{-10}$$



ω_c: cyclotron frequency

ω_s: spin precession frequency

$\omega_c = \omega_s$ if $g = 2$,

measure $g - 2$ by measuring $\omega_s - \omega_c$

Ultra-light ALP for Muon g-2

- **The Lagrangian for ALP is**

P. Agrawal, et al. PRD 108 (2023), 015017
H. Davoudiasl, et al. PRL 130 (2023), 181802

$$\mathscr{L}_{\rm int} = g_a \partial_\alpha a \bar{\psi}\gamma^\alpha \gamma^5 \psi + g_s a \bar{N} N$$

Non relativistic limit

$$H = -g_a \vec{\nabla} a \cdot \hat{\vec{\sigma}}$$

Earth as source

$$\frac{da(r)}{dr} = -\frac{g_s}{r^2}\int_0^r n_N(\ell)\ell^2 d\ell$$

$$\frac{d\vec{S}}{dt} = \vec{\omega} \times \vec{S}, \quad \frac{d\hat{S}_i}{dt} = i\left[H, \hat{S}_i\right]$$

Muon rest frame

$$\delta\omega_j = -2 g_a \partial_j a,$$

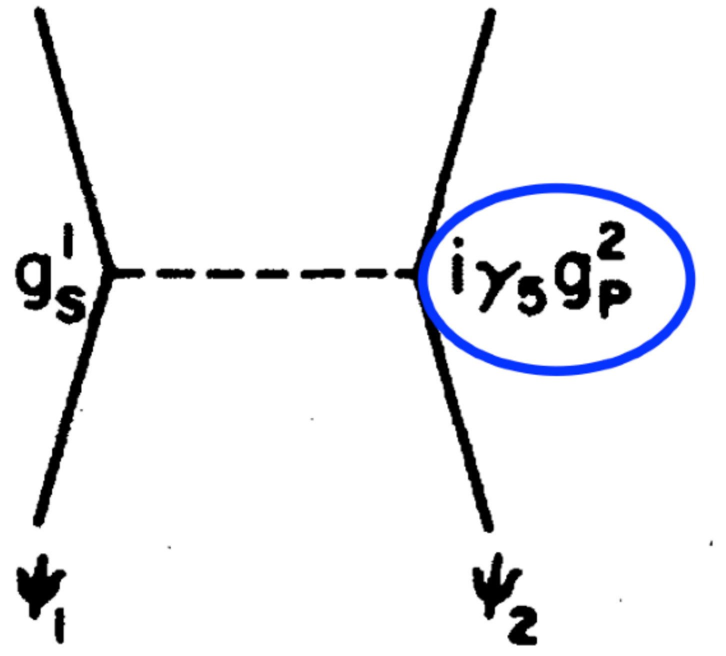
In lab frame:

$$\delta\omega = \frac{g_s g_a N_E}{2\pi\gamma r_E^2}$$

$$g_a g_s \in \left[4.6 \times 10^{-29}, 1.7 \times 10^{-28}\right] \mathrm{GeV}^{-1}$$

H. Davoudiasl, et al. PRL 130 (2023), 181802

Spin dependent Scalar Force



CP violating coupling

$$\mathscr{L} = \partial_\mu a \left(\bar{\nu}_L^i \boldsymbol{\kappa}_\nu^{ij} \nu_L^j + \bar{e}_L^i \boldsymbol{\kappa}_L^{ij} e_L^j + \bar{e}_R^i \kappa_R^{ij} e_R^j \right) + g_s a \bar{N} N$$

$$\boldsymbol{\kappa}_\nu = \boldsymbol{\kappa}_L = -\boldsymbol{\kappa}_R$$

Weak Symmetry

$$\mathscr{L}_{\text{int}} = g_a \partial_\alpha a \bar{\ell} \gamma^\alpha \gamma^5 \ell + g_s a \bar{N} N$$

- **This leads to a gradient interaction between neutrinos and matter**

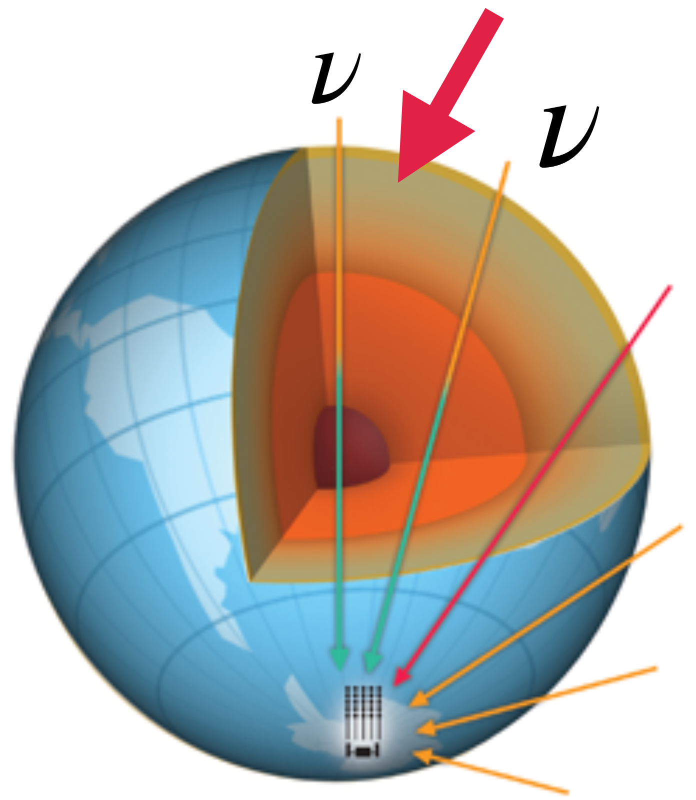
$$\Delta H = \boldsymbol{\kappa}_\nu \nabla a \cdot \vec{p} / |\vec{p}|$$

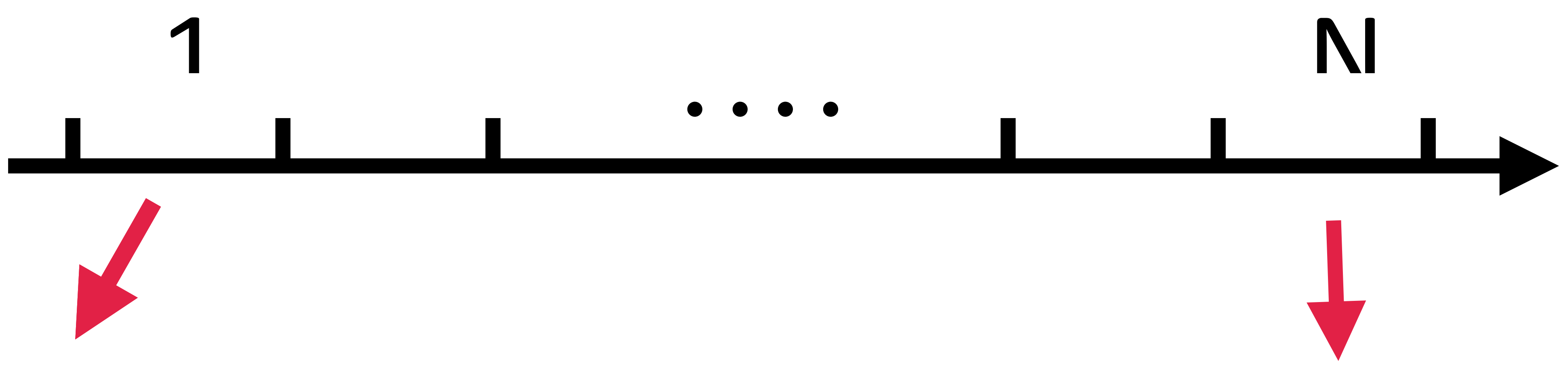
- **The potential for the matter source (Sun/ Earth)**

$$\frac{da(r)}{dr} = -\frac{g_s}{r} \int_0^r n_N(\ell) \ell^2 d\ell$$

Fang, Guo, Liu, XPW, Phys.Rev.D 110 (2024), 035037

Atmospheric Neutrino





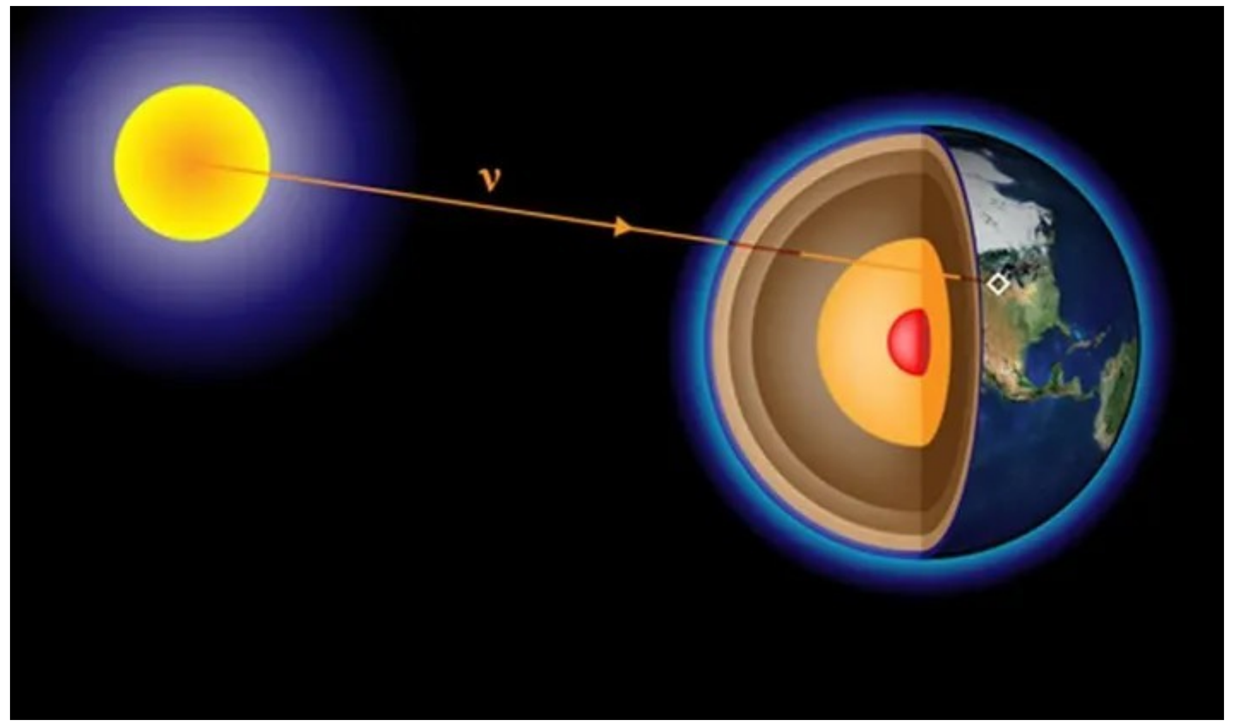
$$A_1 = e^{-i\mathscr{H}_1 L_1} \quad \cdots\cdot \quad A_N = e^{-i\mathscr{H}_N L_N}$$

- **Total time evolution:** $A = A_N \cdots A_1$

- **Oscillation probability:** $P_{\alpha\beta} = |A^{\mathrm{T}}_{\alpha\beta}|^2$

Preliminary reference Earth model (PREM)
Adam M. Dziewonski, et al.

Solar Neutrino



Inside Sun: adiabaticity approximation
each eigenstate evolutes independently.

$$i\frac{d\nu_j}{dx} \approx \mathscr{H}^{\text{diag}}\nu_j$$

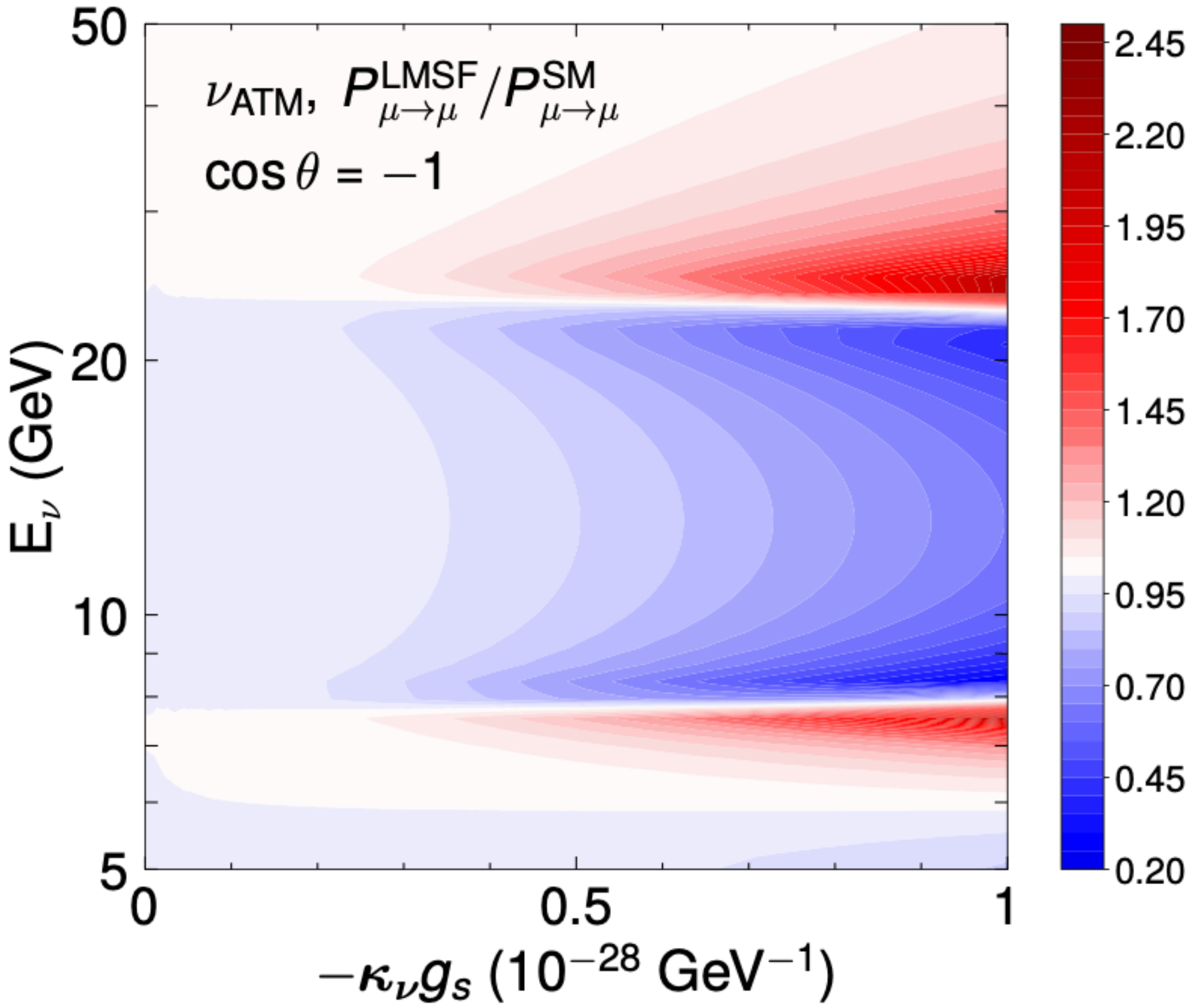
- **From Sun to Earth: very long propagation length**

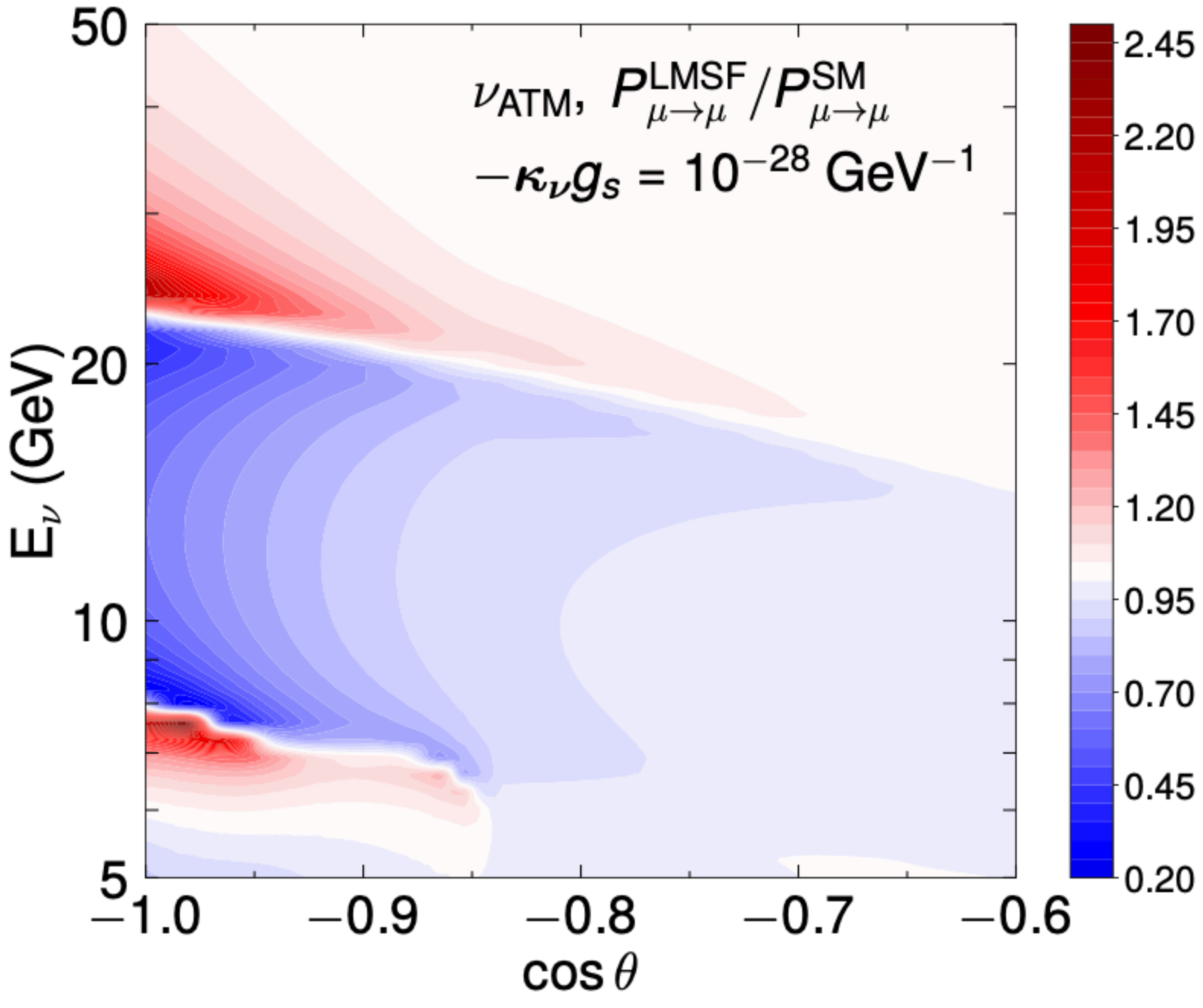
$$P_{\alpha\beta} \approx \sum_{j=1}^{3} \left| U^m_{\alpha j}(r_0) \right|^2 \left| U_{\beta j} \right|^2$$

(U^m: the matrix diagonalizes the total Hamiltonian)

Only depends on production position

The oscillation probability





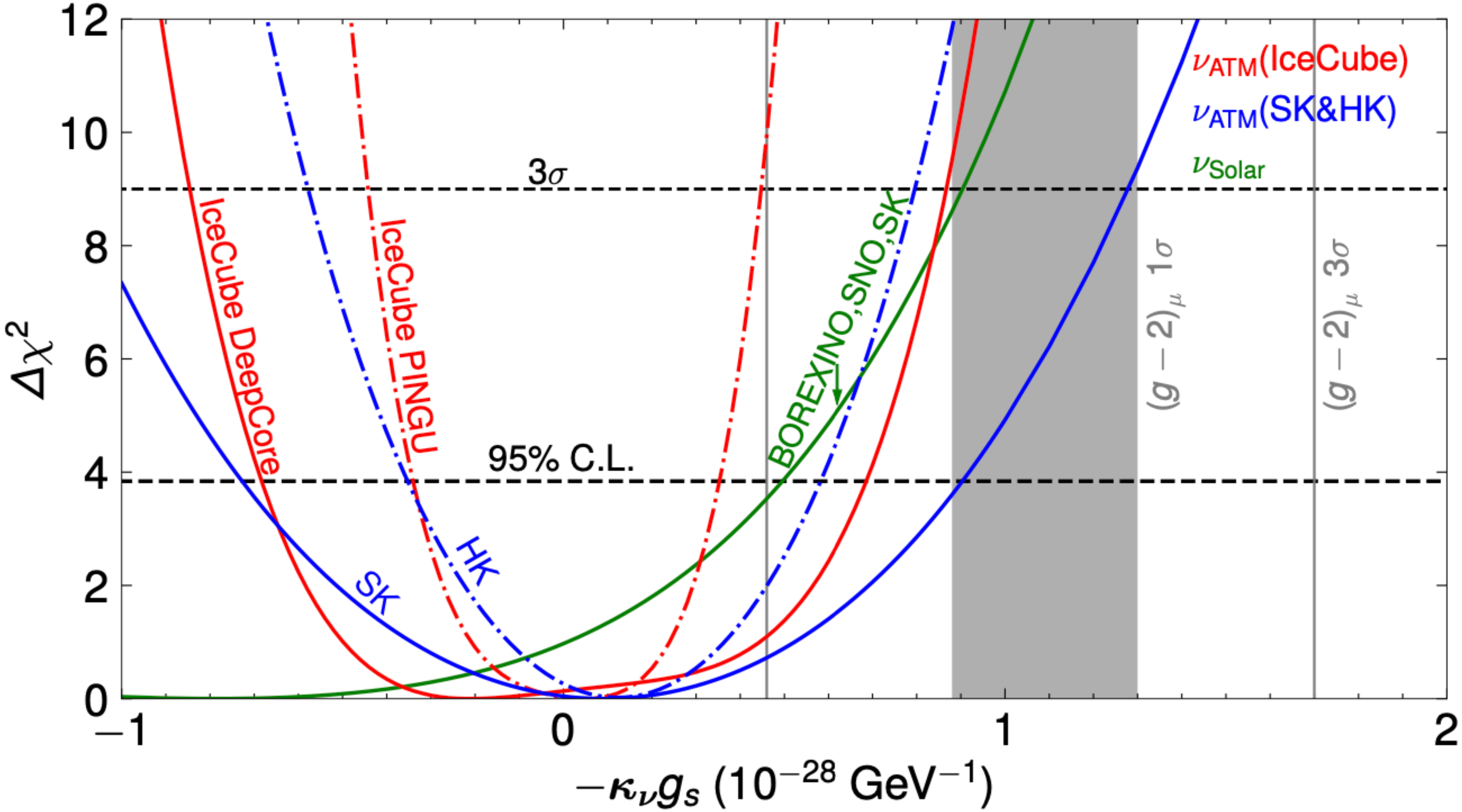
- **χ^2 method for the atmospheric neutrino data**

$$\chi^2(N,O) = 2\sum_{ij\alpha}\left(N_{ij\alpha} - O_{ij\alpha} + O_{ij\alpha}\ln\frac{O_{ij\alpha}}{N_{ij\alpha}}\right)$$

i and j refer to the bin indices for neutrino energy Eν and incoming angle cosθ

Final Results for the Axion-ν Coupling

- **The 95% constraints from neutrino experiments**



- **Solar/ATM ν experiments exclude the 5th force solution to muon g-2 at 1σ**

Outline

- Search long-range axion-ν coupling by ν experiments
- **Search non-ν axion couplings by reactor ν experiment RELICS**

RELICS Collaboration

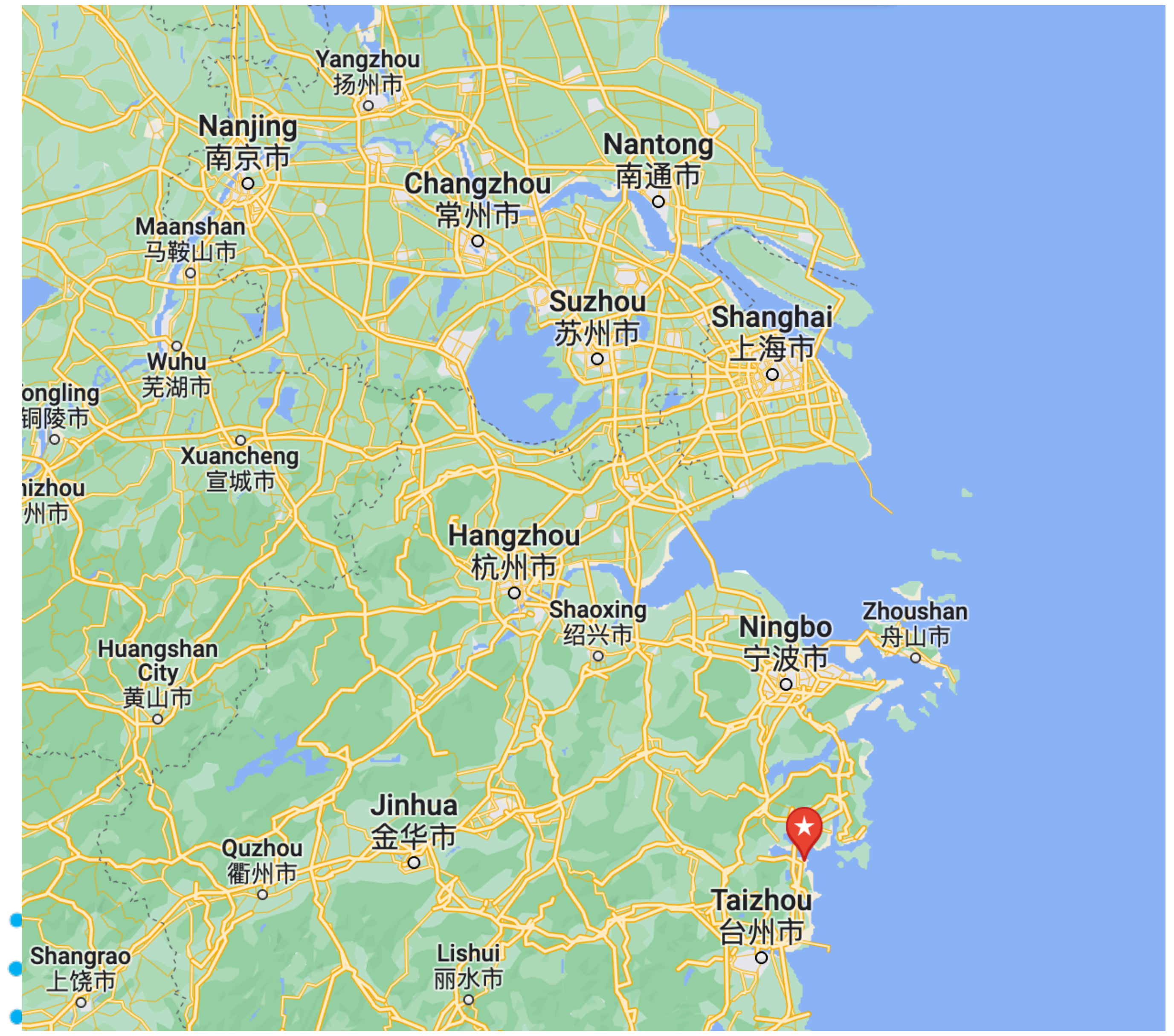
- **6 Institutes, ~40 members.**

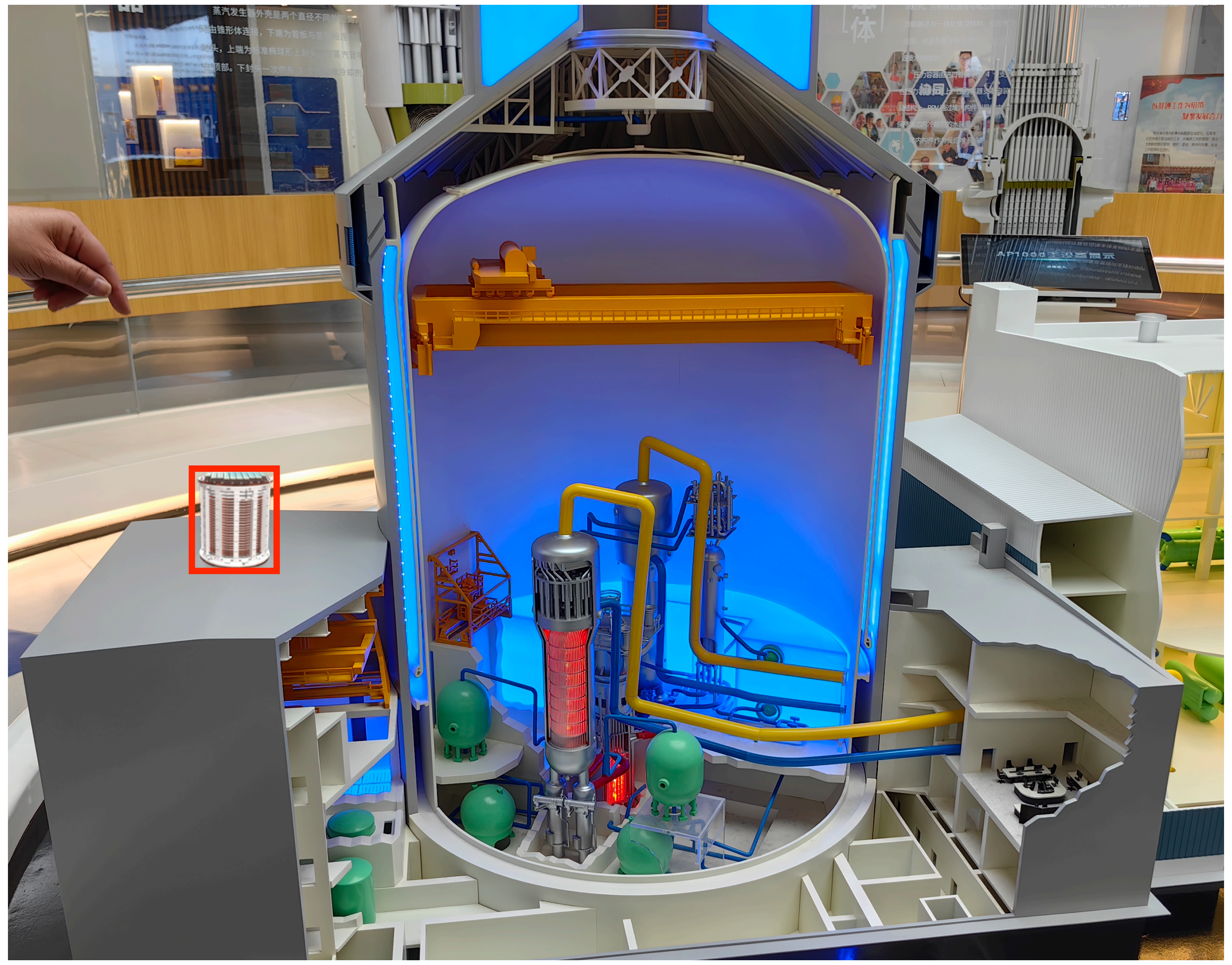
RELICS
REactor neutrino **LI**quid xenon
Coherent elastic **S**cattering

香港中文大學(深圳)
The Chinese University of Hong Kong, Shenzhen

RELICS Experiment

- **Sanmen Nuclear Power Plant, Zhejiang Province**
- **Thermal Power ~3.4GW, baseline ~22m**
- **Neutrino flux ~1e14 ν/cm^2/s**

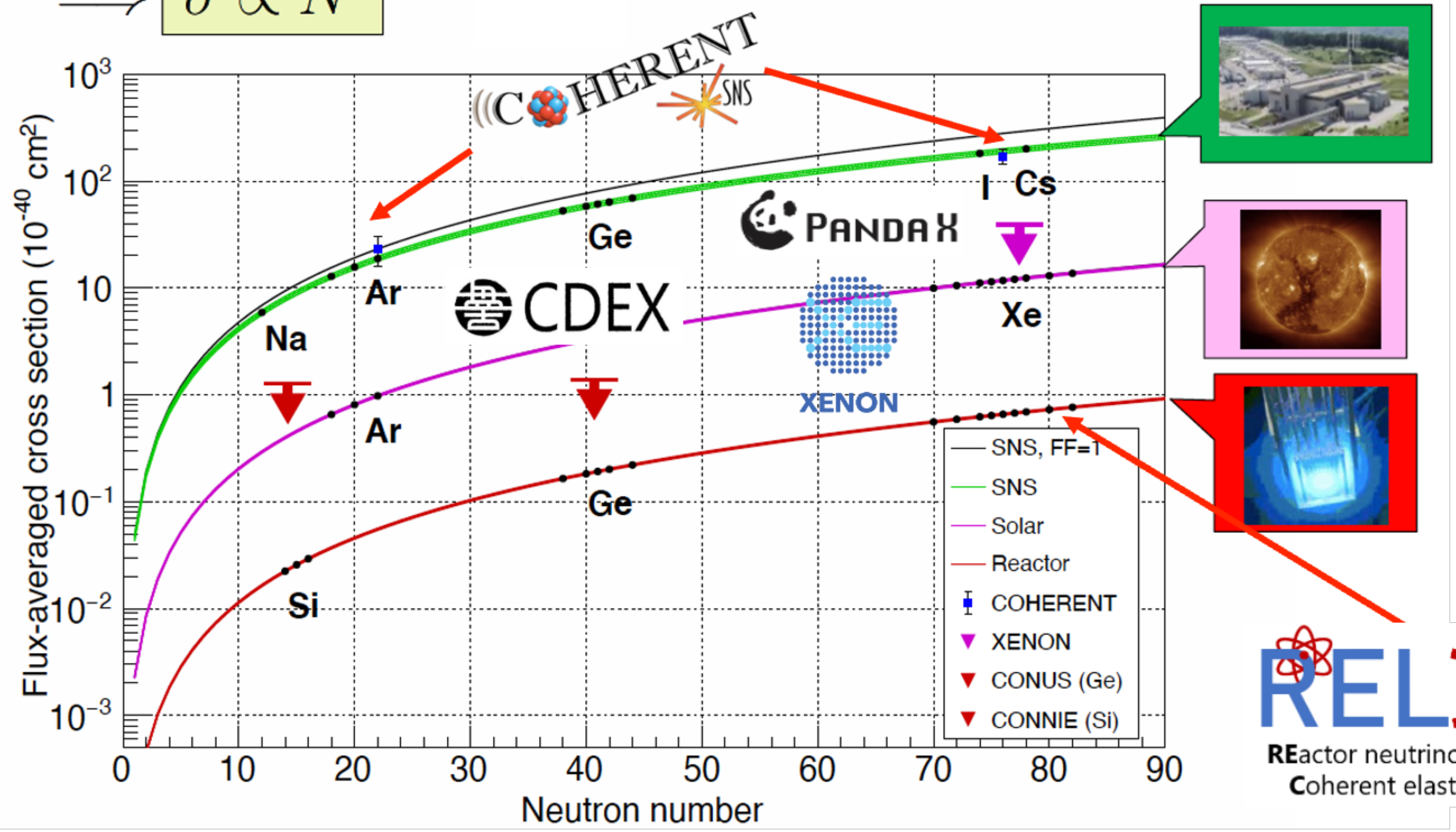




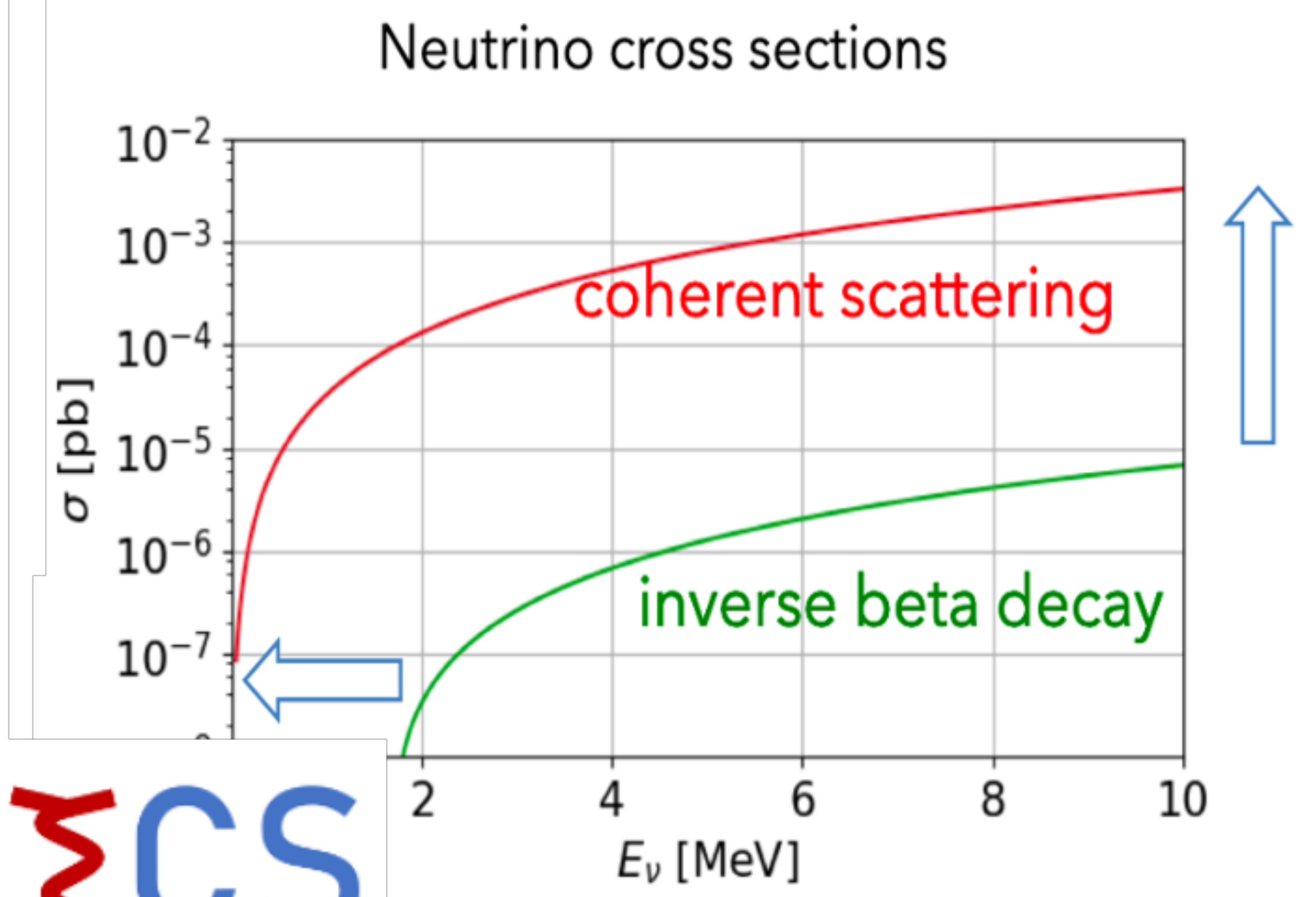
RELICS Experiment

$$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

$$\Longrightarrow \boxed{\sigma \propto N^2}$$



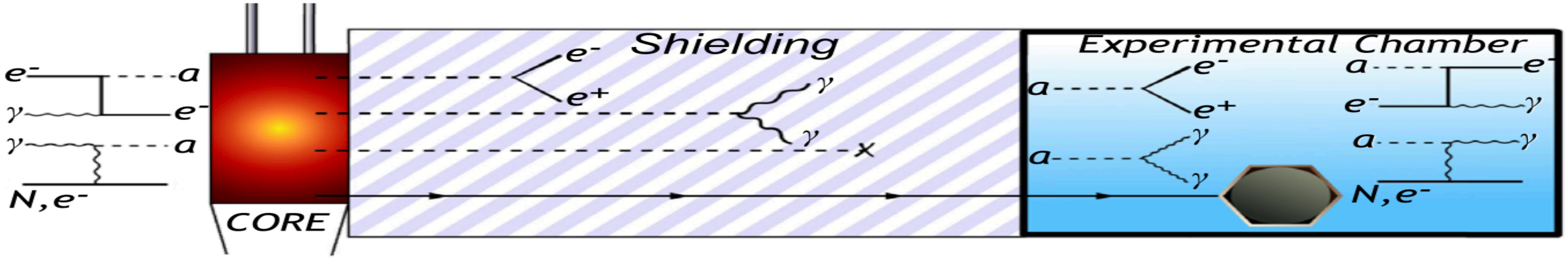
- 极低能量阈值
- 极低本底
- 大探测体积
- 大中微子流强



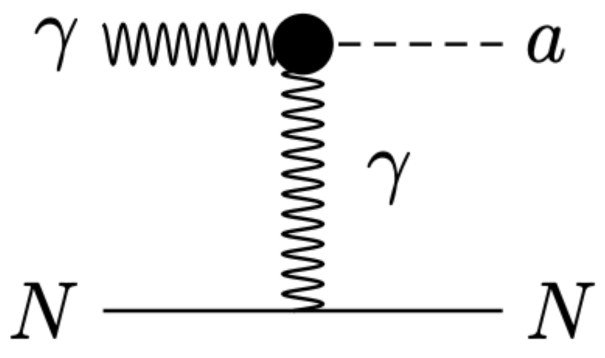
RELICS

REactor neutrino **LI**quid xenon **C**oherent elastic **S**cattering

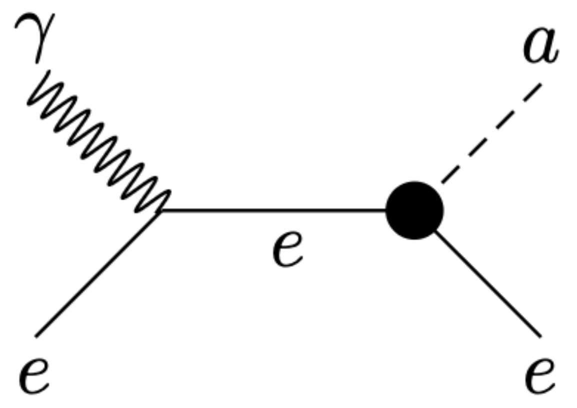
Axion Production from Reactor



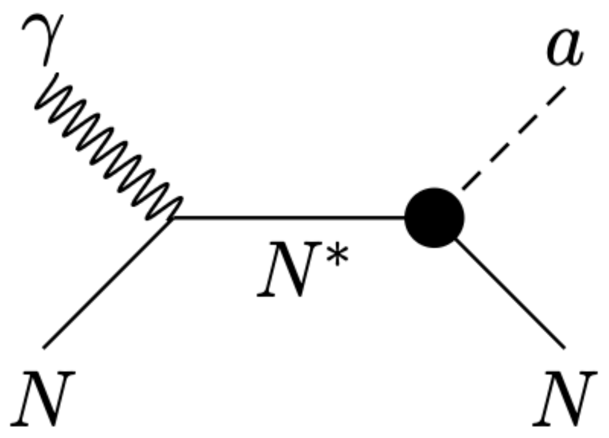
Primakoff



Compton-like



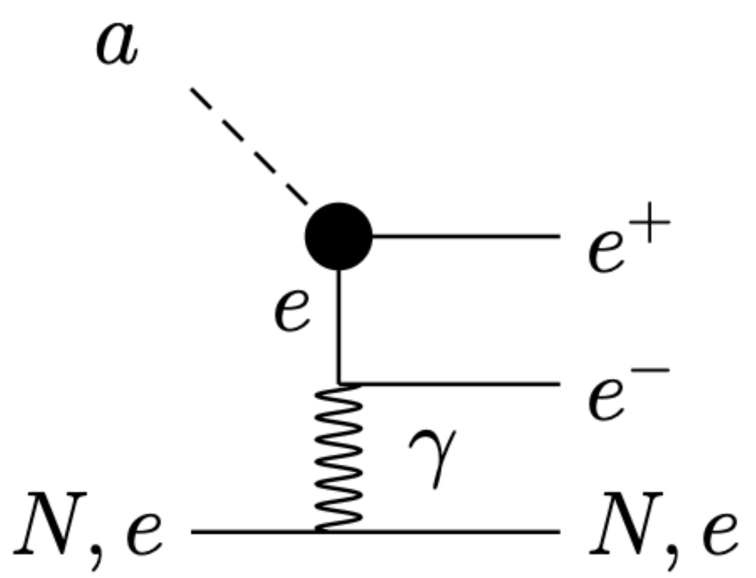
Nuclear de-excitation



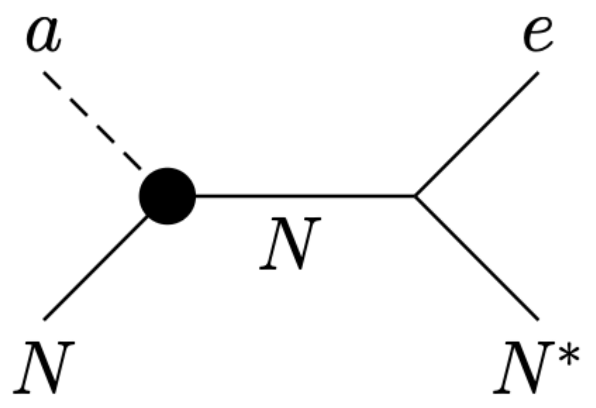
Inverse Primakoff

Inverse Compton-like

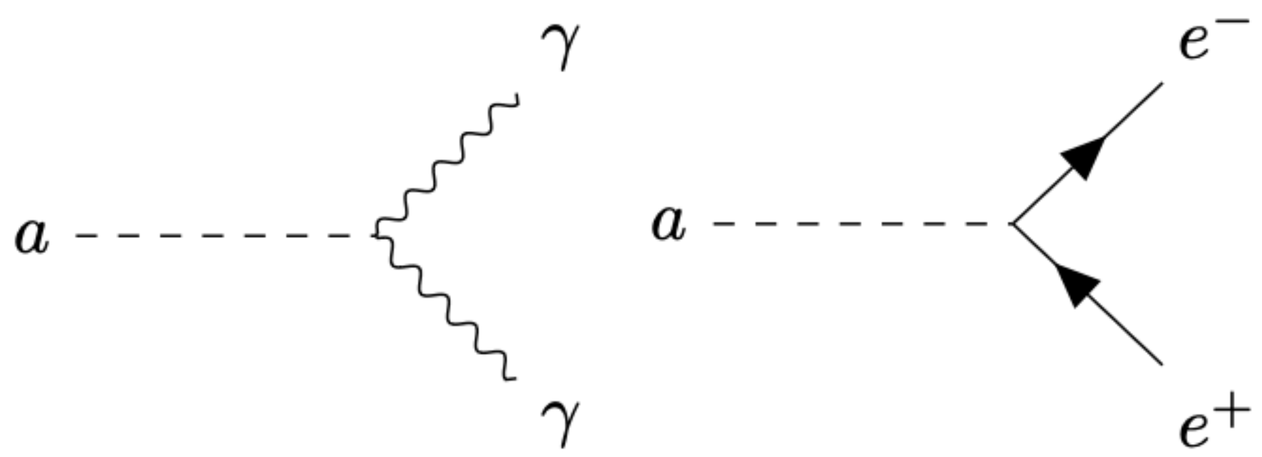
Nuclear excitation



Axio-electric process



Axion decay



Reactor ALP flux at detector

- Photon from fission:

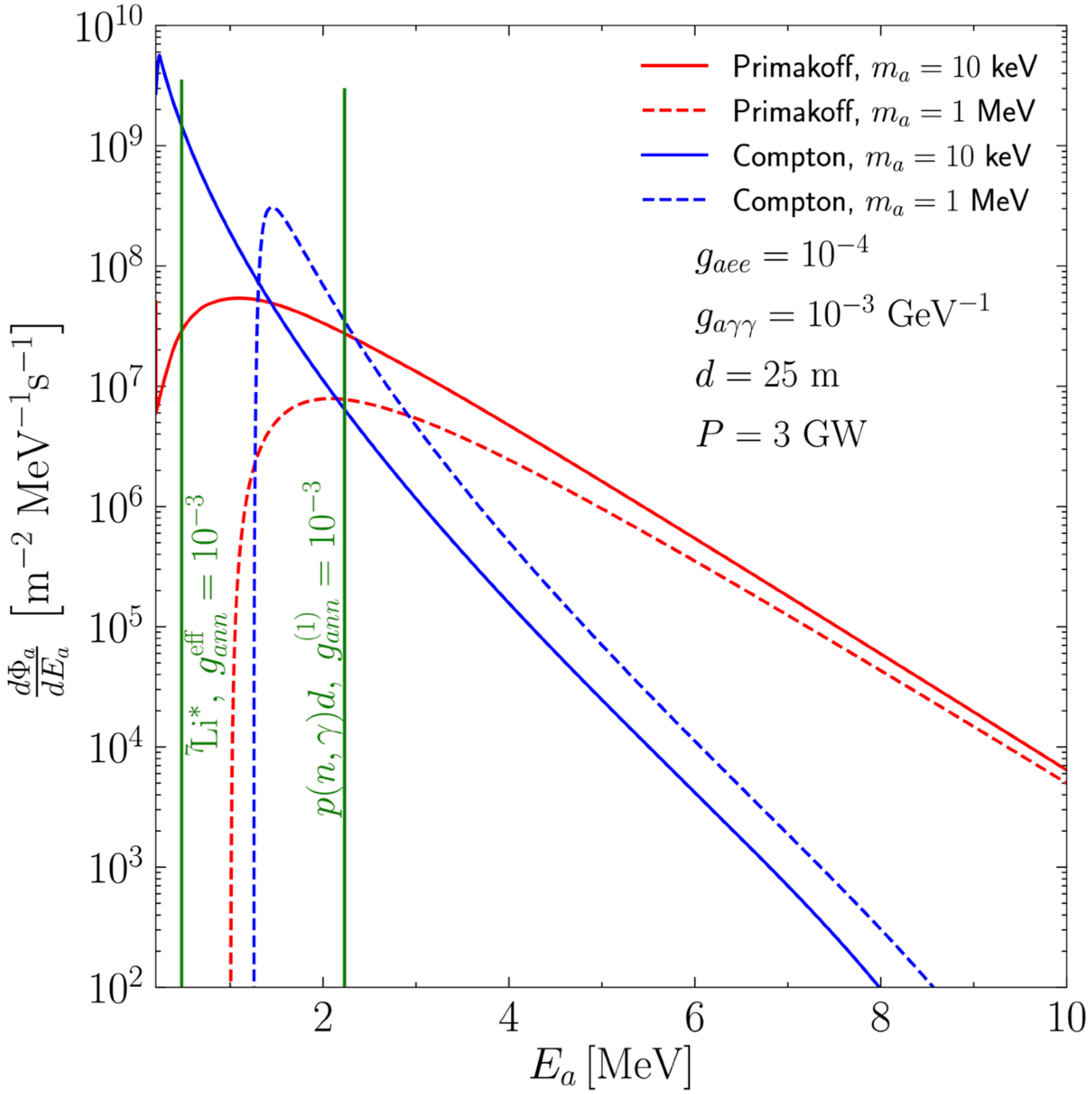
$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{5.8\times 10^{17}}{\text{MeV sec}}\left(\frac{P}{\text{MW}}\right)e^{-\frac{E_\gamma}{0.91\ \text{MeV}}}$$

- ALP from Photon

$$\frac{d\sigma_P^P}{dt} = 2\alpha Z^2 F^2(t) g_{a\gamma\gamma}^2 \frac{M_N^4}{t^2\left(M_N^2 - s\right)^2\left(t-4M_N^2\right)^2}\left\{m_a^2 t\left(M_N^2+s\right) - m_a^4 M_N^2 - t\left[\left(M_N^2-s\right)^2 + st\right]\right\}$$

- ALP from Electron

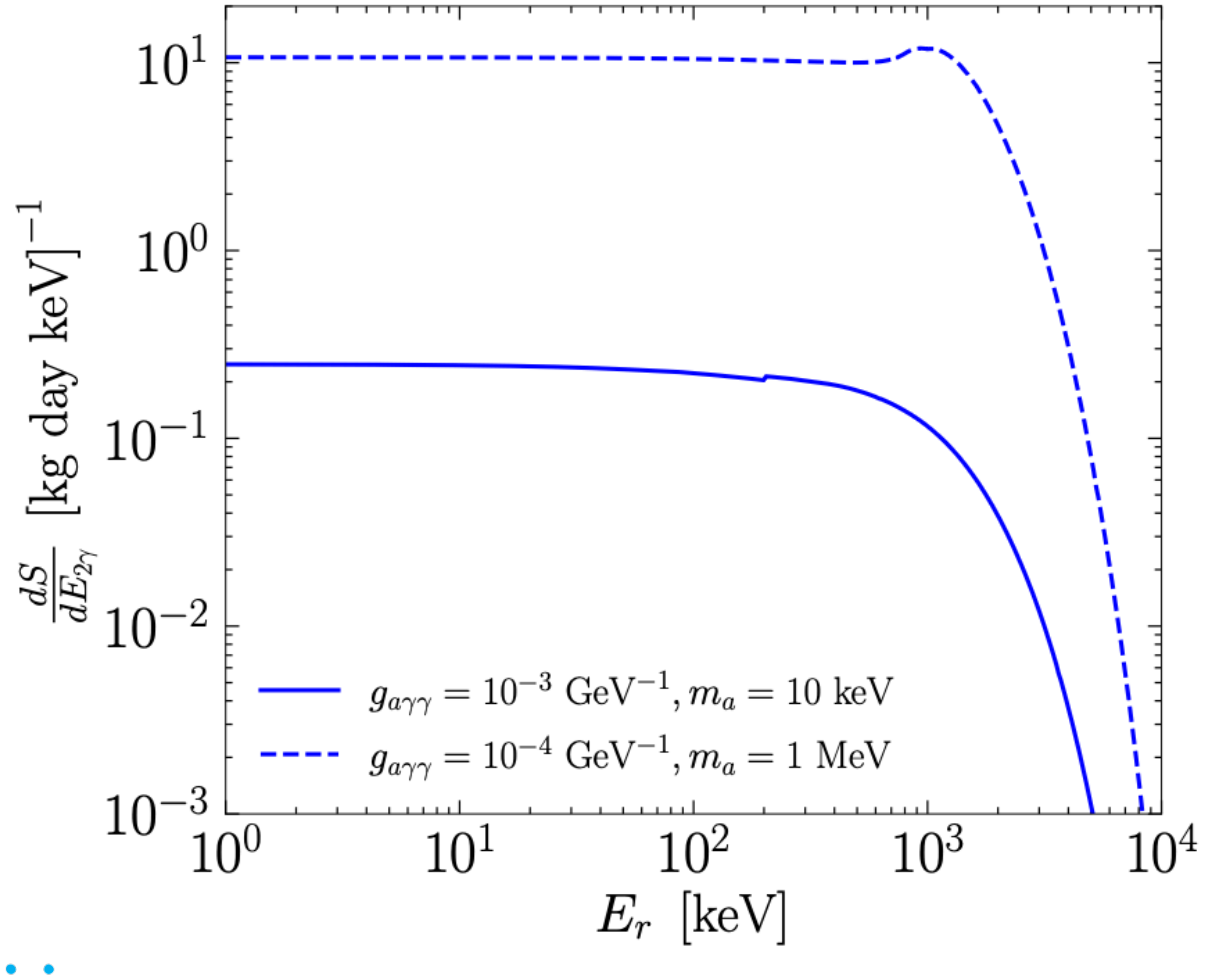
$$\frac{d\sigma_P^C}{dE_a} = \frac{Z\pi g_{aee}^2 \alpha x}{4\pi(s-m_e^2)(1-x)E_{\gamma'}}\left[x - \frac{2m_a^2 s}{\left(s-m_e^2\right)^2} + \frac{2m_a^2}{\left(s-m_e^2\right)^2}\left(\frac{m_e^2}{1-x}+\frac{m_a^2}{x}\right)\right]$$

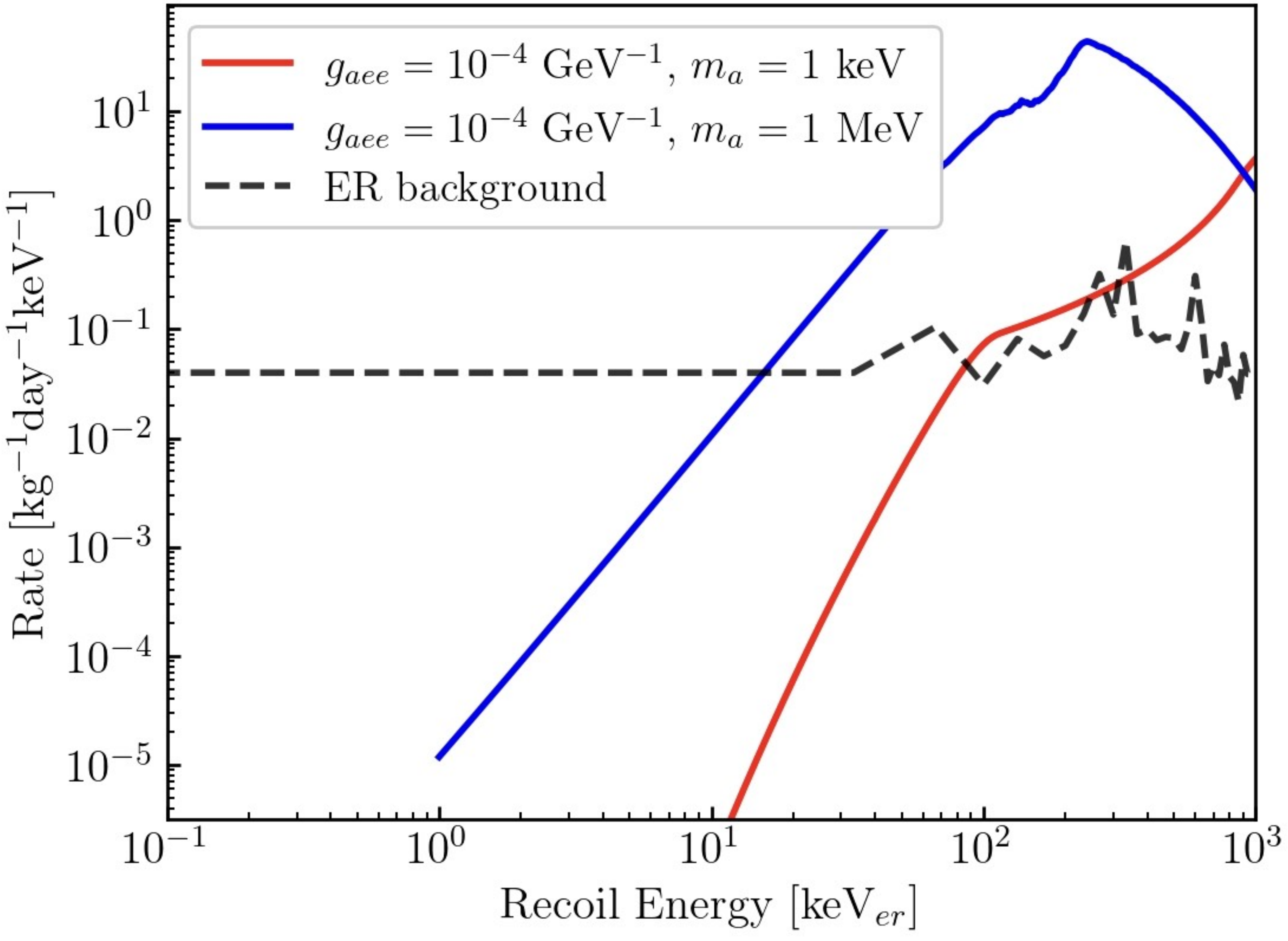


Electronic recoil energy spectrum

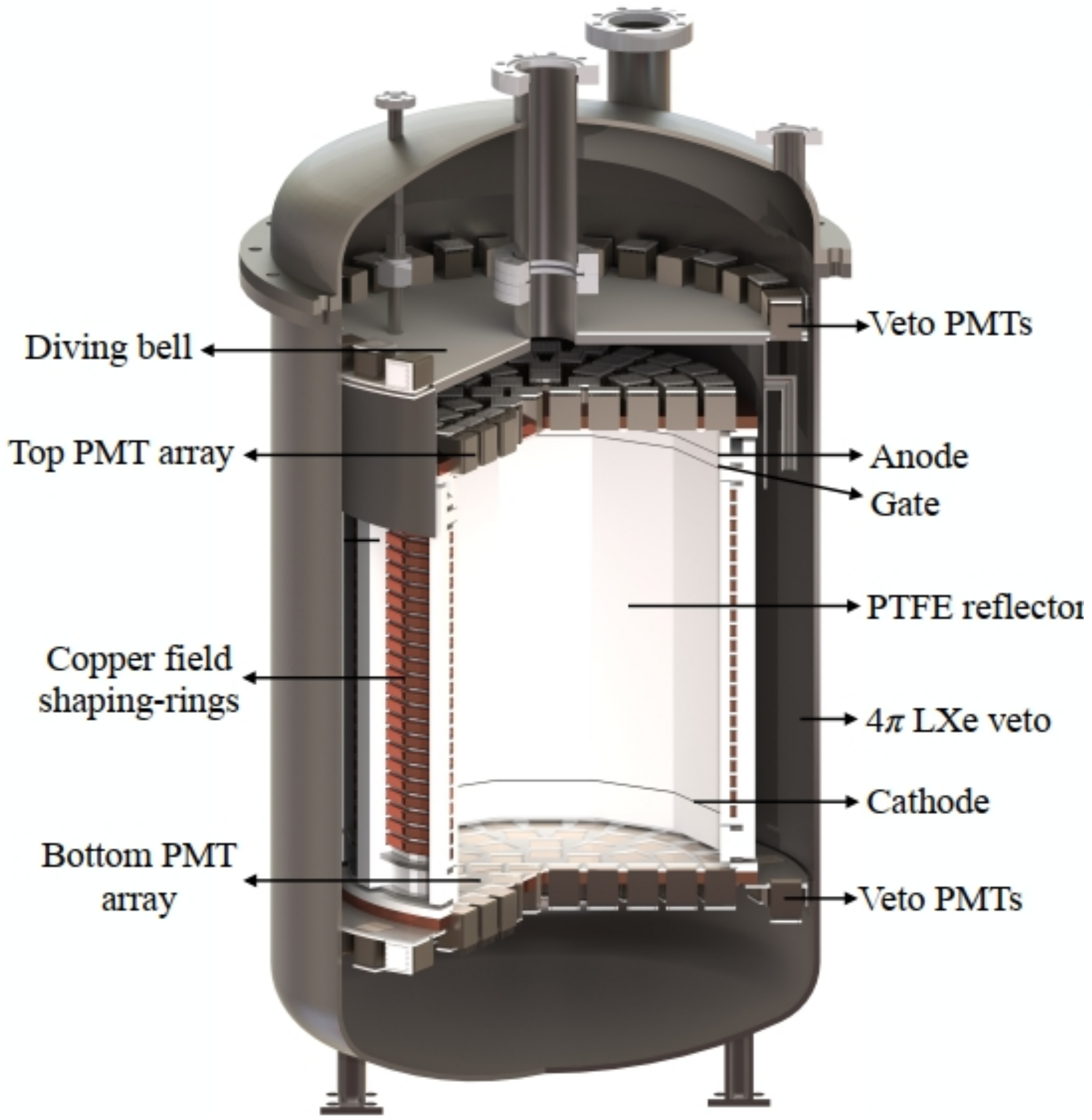
- **The energy spectrum for signal is**

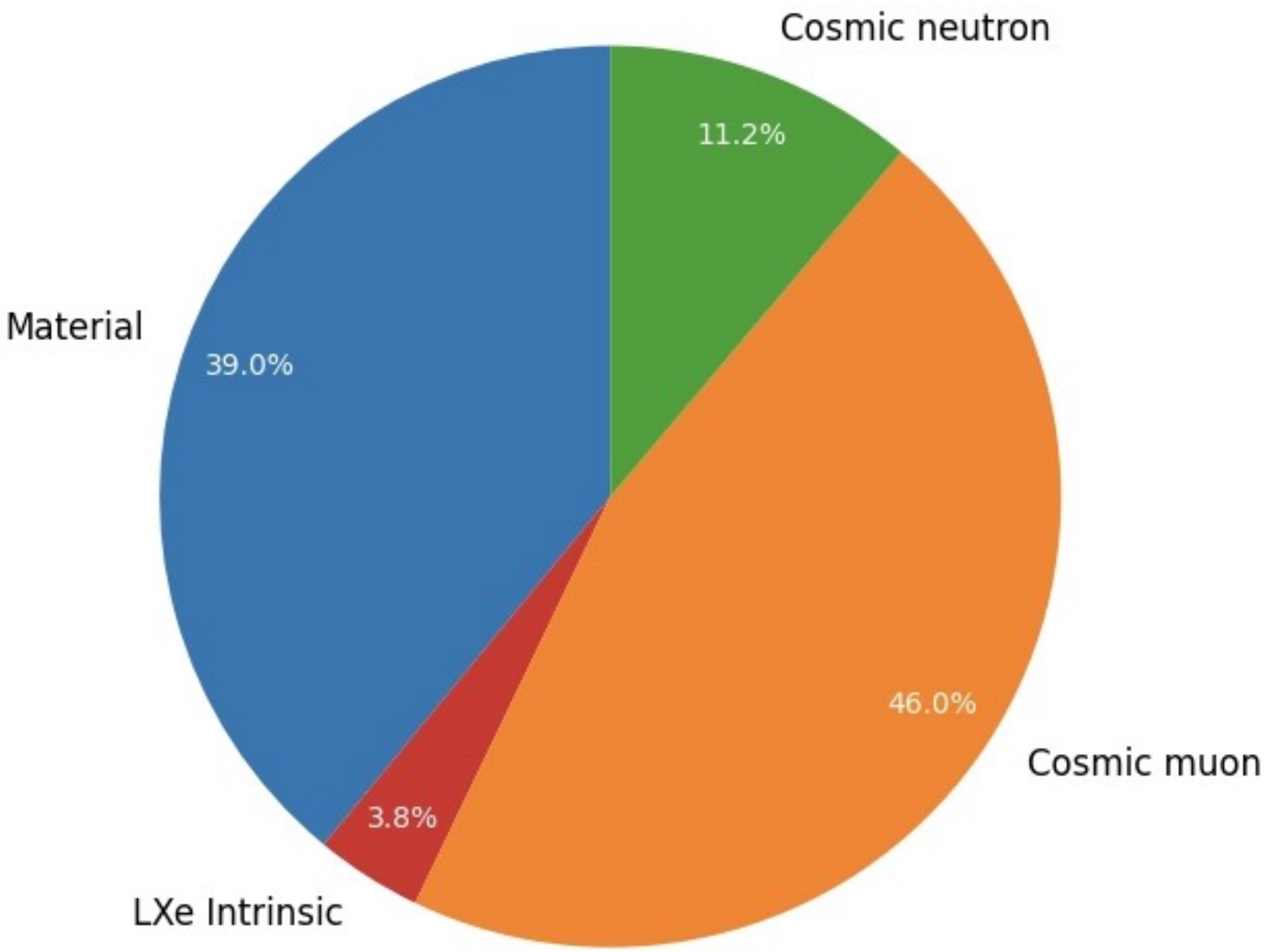
$$\frac{dS}{dE_f} = TN_t \frac{1}{4\pi R^2} \int dE_a \frac{1}{L_D^2} \frac{d\Gamma_a}{\Gamma_a dE_f} \mathscr{P}_a \frac{d\Phi_a}{dE_a} \Theta\left(E_r - E_r^{\min}\left(E_a\right)\right) \Theta\left(E_r^{\max}\left(E_a\right) - E_r\right)$$

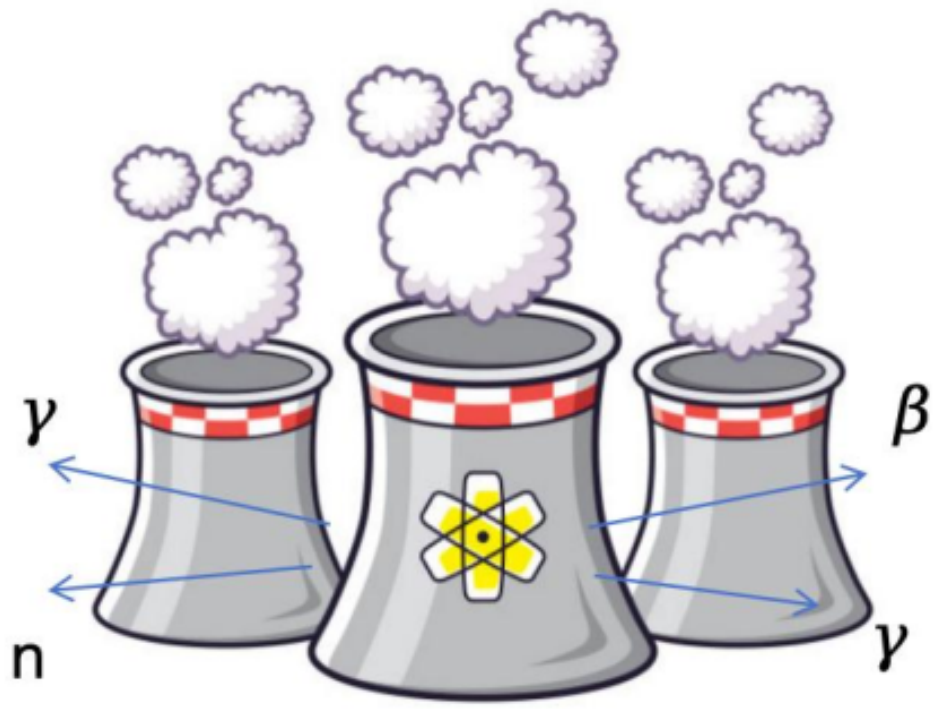




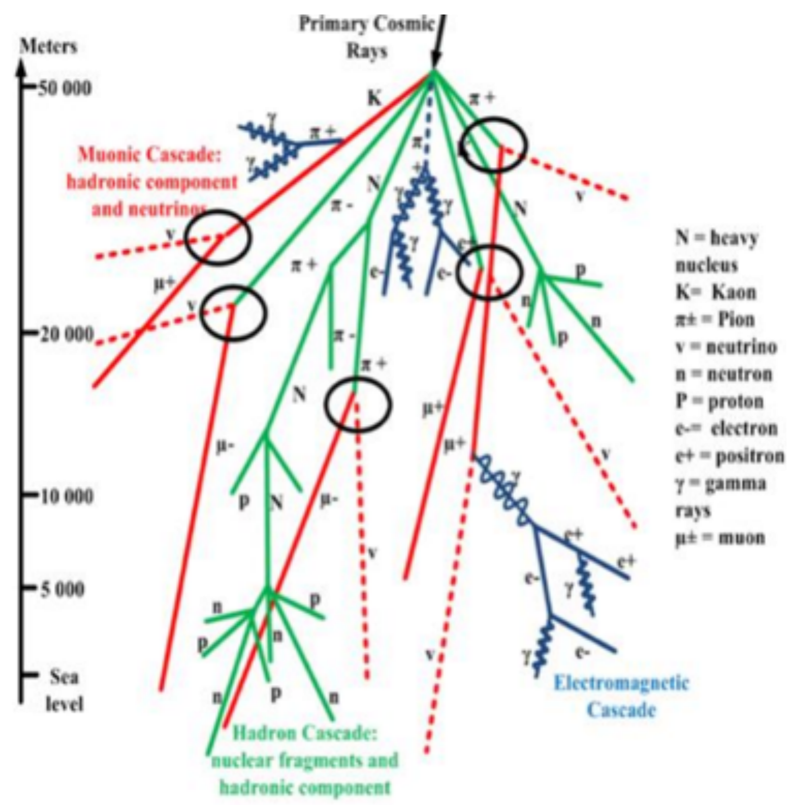
RELICS background







neutron, γ from Reactor, environment

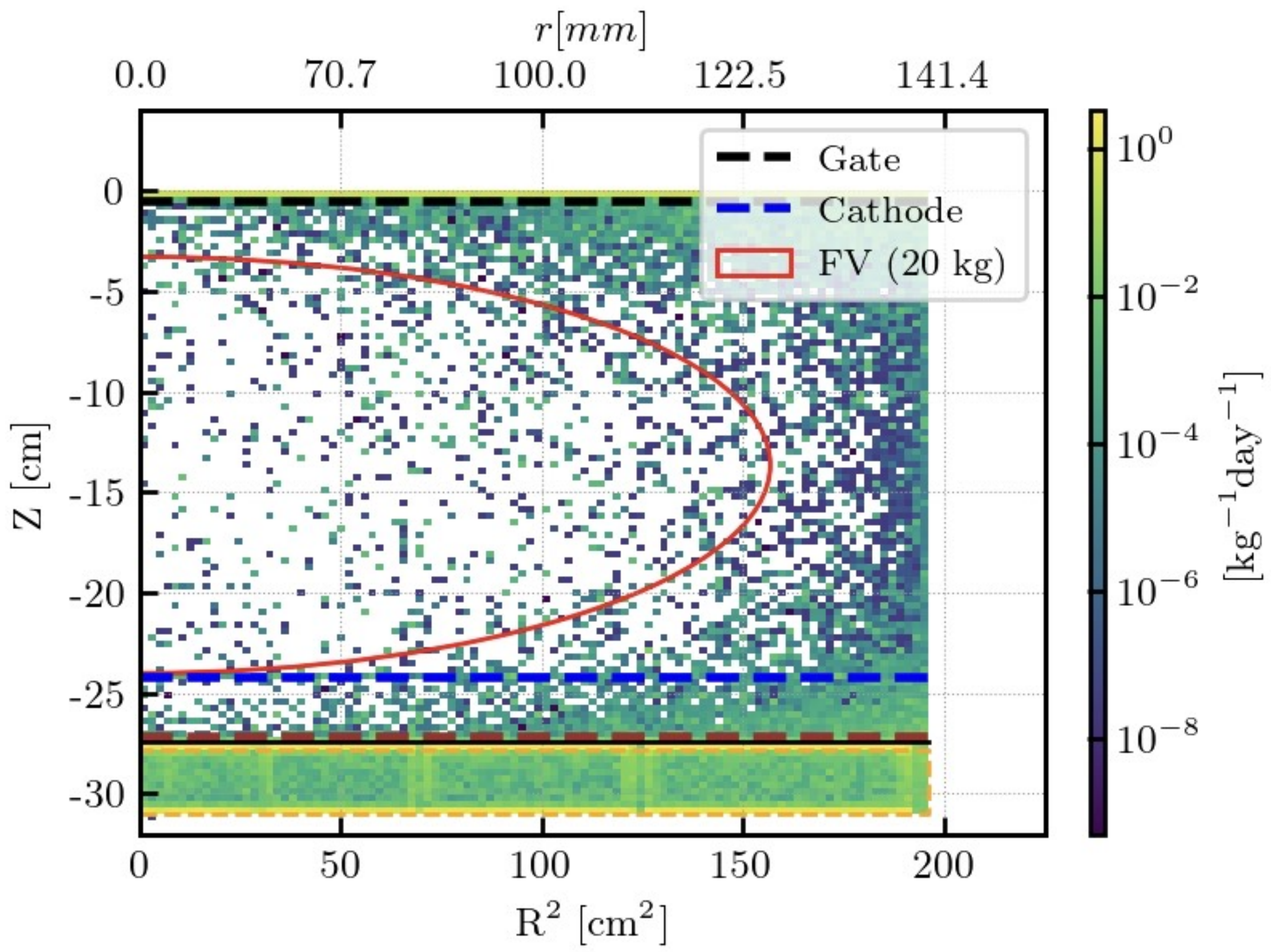


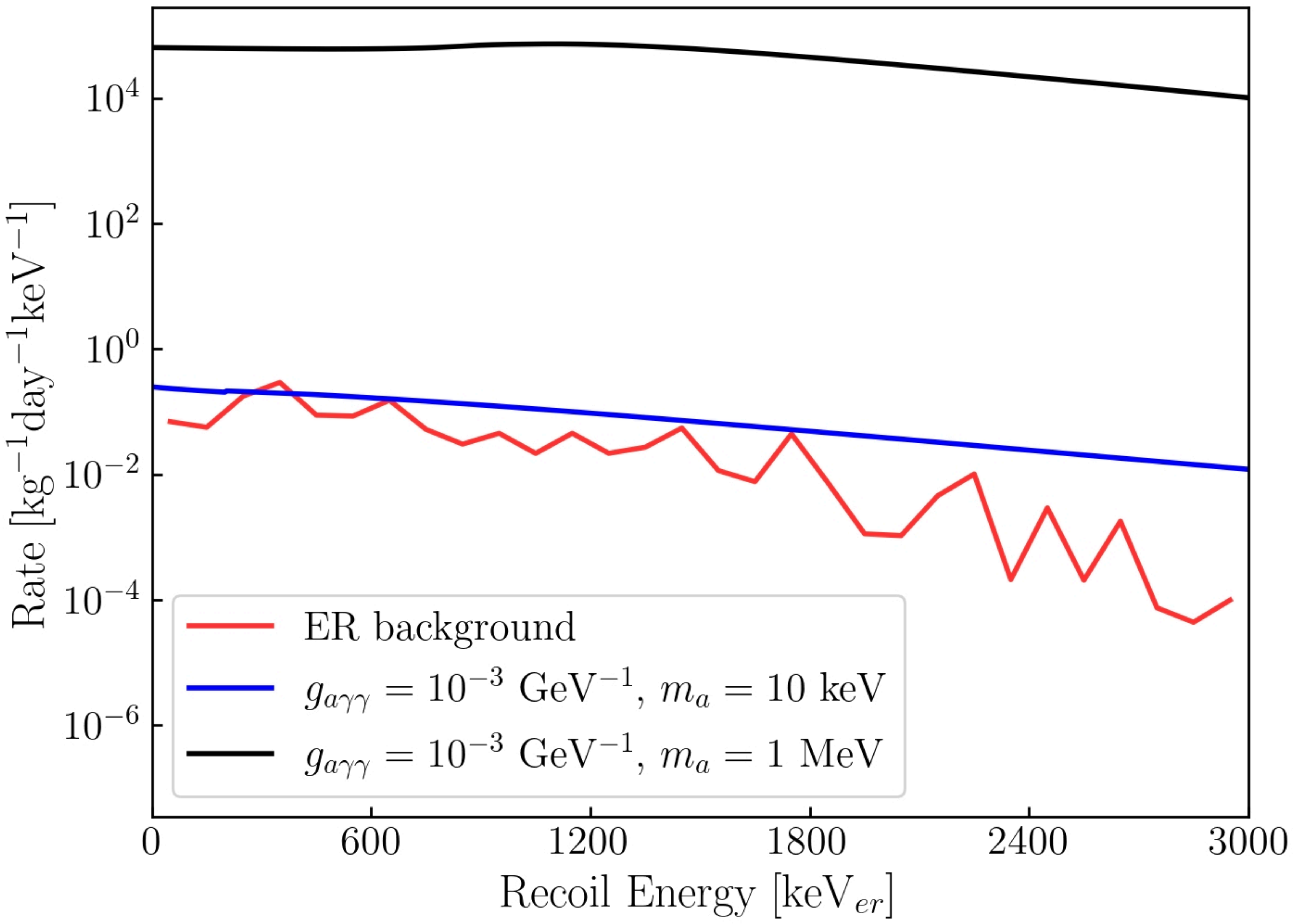
Cosmic muons
Cosmic neutrons

neutron, γ from detector materials

RELICS background

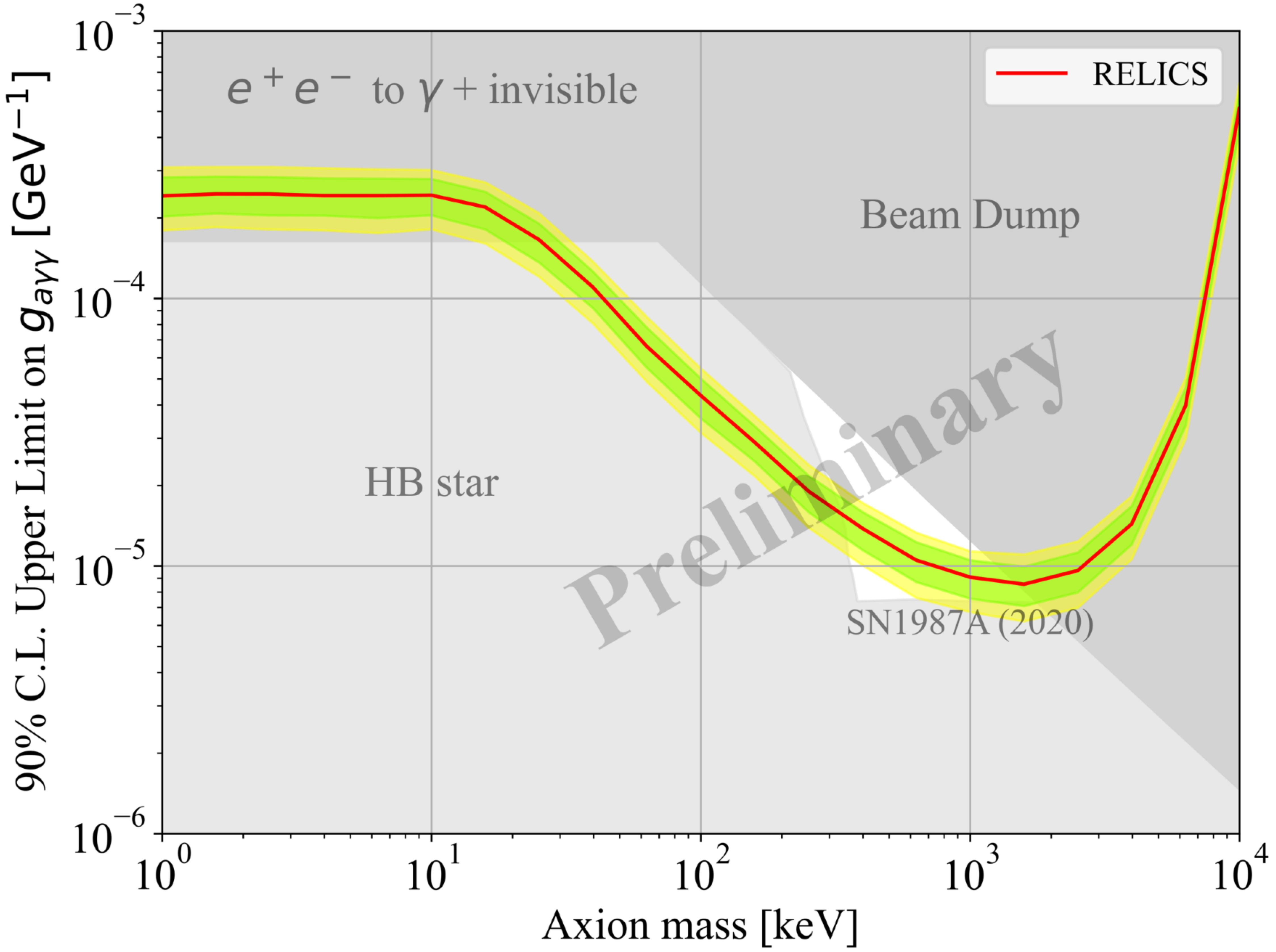
- **We use Geant4 simulations for the background**

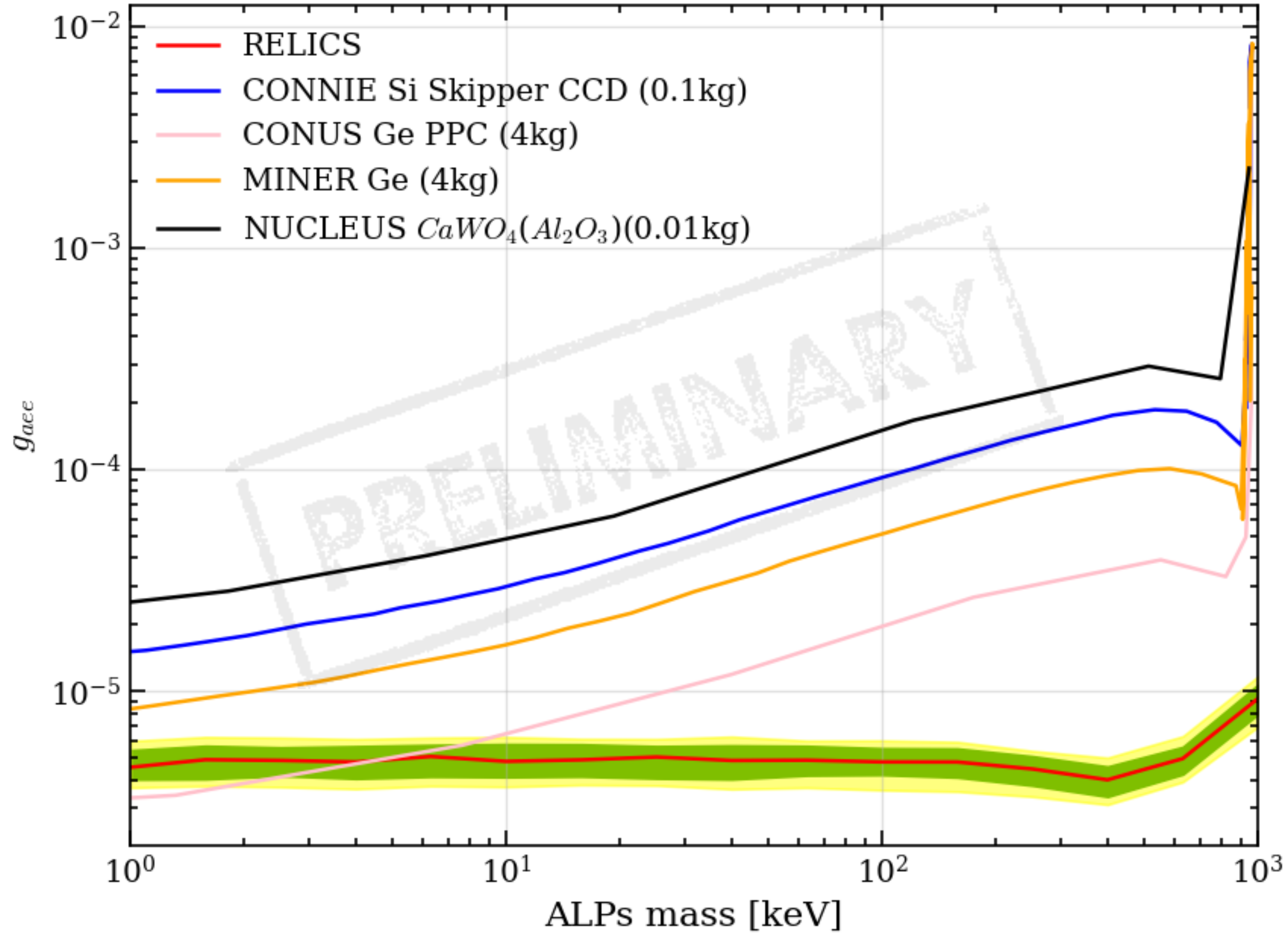




RELICS Sensitivity

- **RELICS sensitivity on ALP coupling with 20 kg·year exposure**





Summary

- Axion have the potential to solve strong CP problem.
- Neutrino oscillation experiments can be used to detect long-range muon spin force via ALP which can explain muon g-2.
- RELICS has rich physics, competitive in the search for axions, which can explore or close the Cosmological Triangle.

Thank you!