New directions EXploring the Unknown beyond the Standard Model (NEXUS 2026)

Novel signature of axion-like particles at neutrino experiments

Ningqiang Song

with Haotian Li, Zuowei Liu, and Jindong Lv

Institute of Theoretical Physics, Chinese Academy of Sciences

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Outline

- Flavor-violating Axion
  - Theory overview of flavor-violating axion
  - Axion production cross section
  - Topologies of flavor-violating axion
  - Sensitivity of flavor-violating axion at LArTPC
- Axion-nucleon coupling
  - Axion production channels
  - Axion detection
  - Constraints on axion-nucleon coupling

Flavor-violating axion

Effective field theory

$$\mathcal{L}_{a\ell\ell} \supset \sum_i \frac{\partial_\mu a}{2f_a}\,\bar{\ell}_i C^A_{\ell_i\ell_i}\gamma^\mu\gamma_5\ell_i + \sum_{i\neq j}\frac{\partial_\mu a}{2f_a}\,\bar{\ell}_i\gamma^\mu\left(C^V_{\ell_i\ell_j}+C^A_{\ell_i\ell_j}\gamma_5\right)\ell_j$$

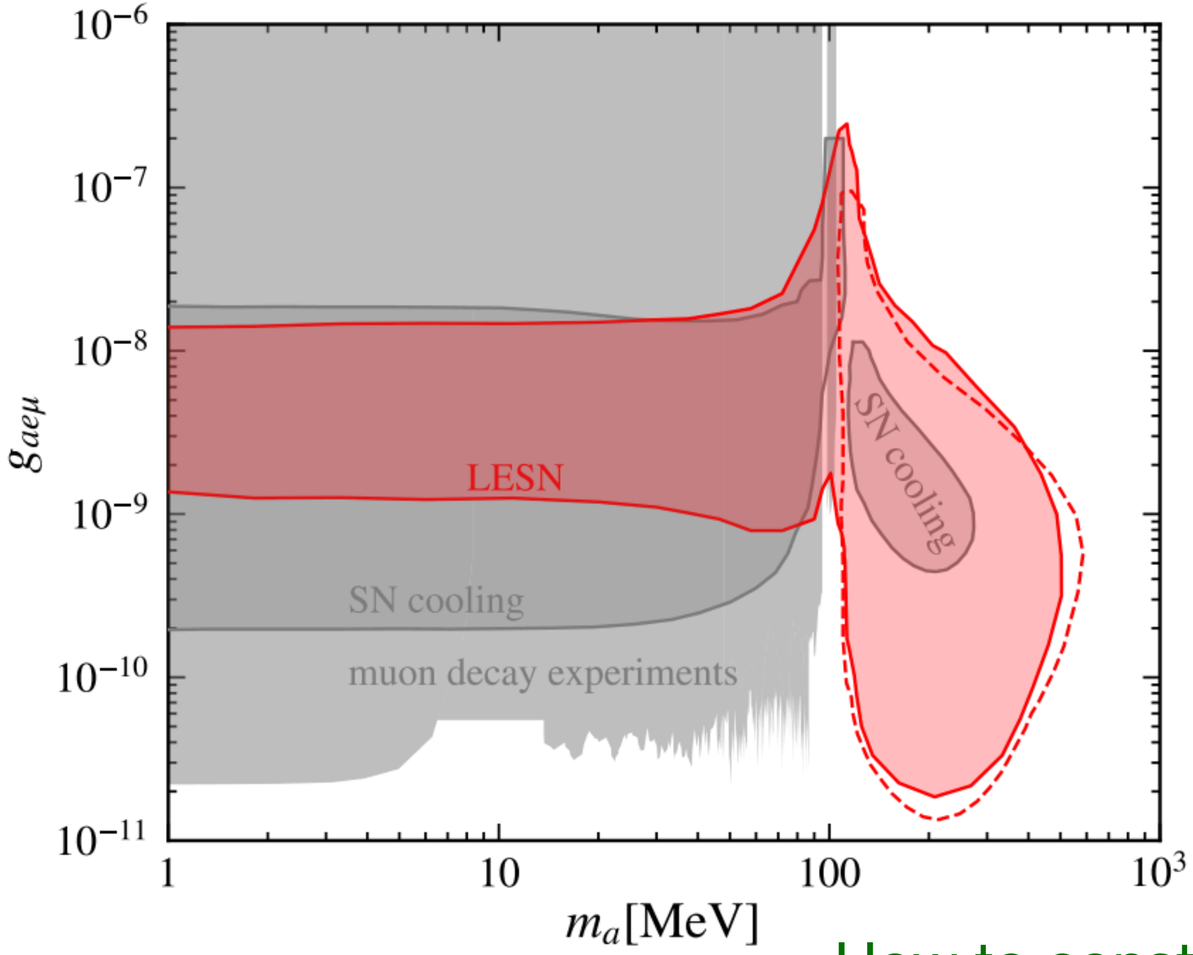
$$\rightarrow\quad \mathcal{L}_{a\ell\ell} \supset -\mathrm{i}\sum_{i,j}\left[\frac{C^V_{\ell_i\ell_j}(m_{\ell_i}-m_{\ell_j})}{2f_a}\,a\bar{\ell}_i\ell_j + \frac{C^A_{\ell_i\ell_j}(m_{\ell_i}+m_{\ell_j})}{2f_a}\,a\bar{\ell}_i\gamma_5\ell_j\right]$$

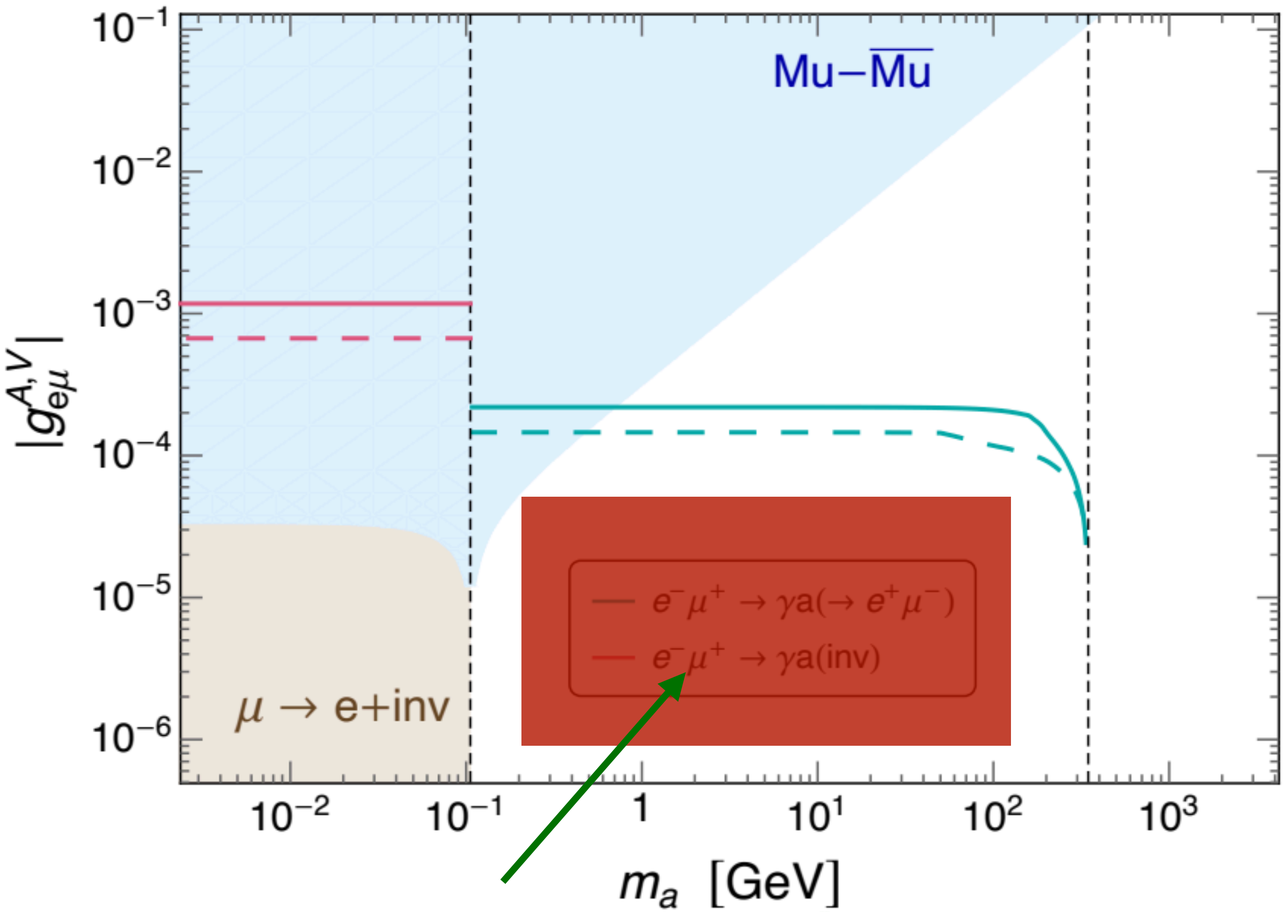
arXiv: 2406.13234

$$g^V_{ij}\equiv\frac{C^V_{\ell_i\ell_j}(m_{\ell_i}-m_{\ell_j})}{2f_a},\qquad g^A_{ij}\equiv\frac{C^A_{\ell_i\ell_j}(m_{\ell_j}+m_{\ell_i})}{2f_a}$$

See also Davidson and Wali 1982, Wilczek 1982, Ema et al 1612.05492, Callibi et al 1612.08040, Bjorkerot et al 1806.00660, Bauer et al 2012.12772

Existing Constraints on Flavor-violating Axion





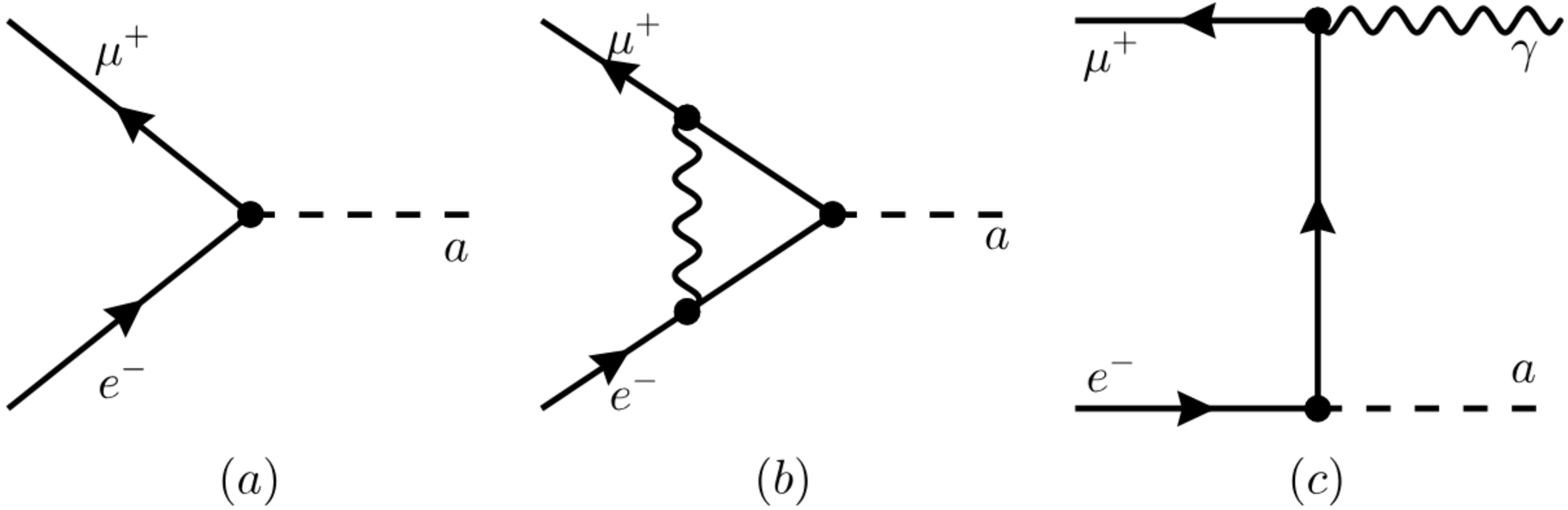
How to constrain the parameter space here?

Huang, Li, Liu, arXiv: 2510.22523

arXiv: 2406.13234

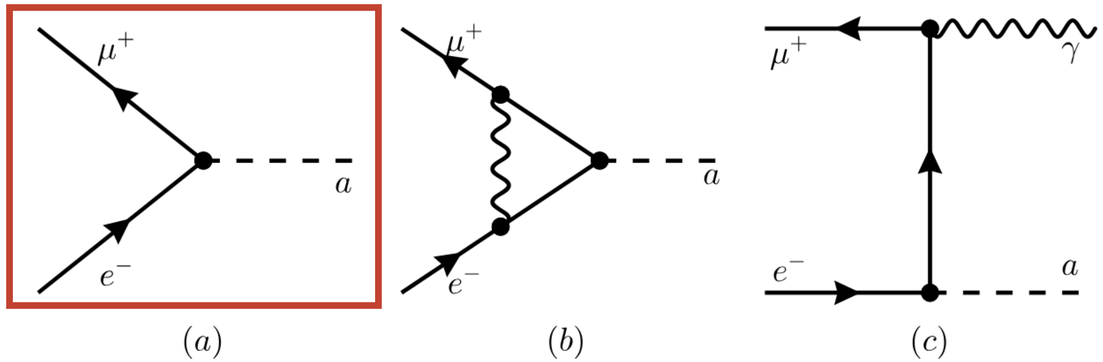
Axion Production in Neutrino Experiments

Advantage of neutrino experiments: large target mass, large atmospheric muon flux, ….



Coalescence Virtual correction Radiative photon emission

Axion Production: Coalescence



$$E_\mu = E_\mu^\star = \frac{m_a^2 - m_\mu^2 - m_e^2}{2m_e}$$

$$\overline{|\mathcal{M}_{\rm coal}|^2} = \frac{1}{2} g_{ae\mu}^2 \left[m_a^2 - (m_\mu - m_e)^2 \right]$$

$$\sigma_{\rm coal}^{(0)} = \frac{\pi g_{ae\mu}^2}{4m_e} \frac{1-(x-y)^2}{\sqrt{\lambda(1,x^2,y^2)}} \delta(E_\mu - E_\mu^*)$$

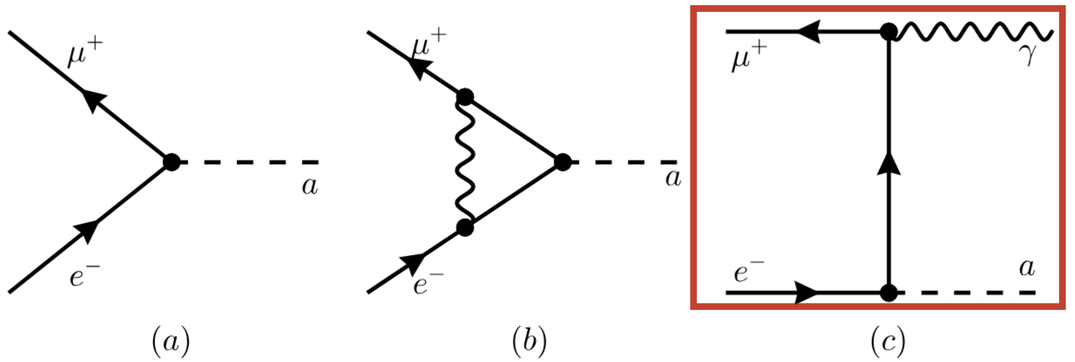
$$x \equiv m_\mu / m_a$$

$$\lambda(a,b,c) = a^2 + b^2 + c^2 - 2ab - 2ac - 2bc$$

$$y \equiv m_e / m_a$$

Axion Production: Radiative Hard Photon Emission

$$\overline{|\mathcal{M}_{\rm h}|^2} = -4\pi\alpha g_{ae\mu}^2 \left[\frac{(\tilde{s}+\Delta^2)^2+\Delta^4}{\tilde{t}(\tilde{s}+\tilde{t})} + \frac{2\Delta^2 m_\mu^2}{\tilde{t}^2} \right]$$



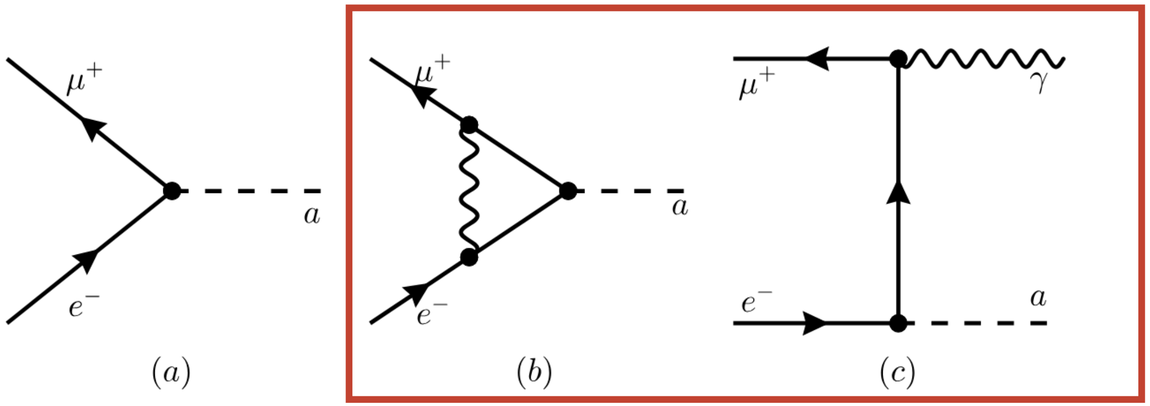
(a) (b) (c)

$$\sigma_{\rm h} = \int_{t_-}^{t_+} dt\, \frac{d\sigma_{\rm rad}}{dt} \Theta\left(E_\gamma^{\rm lab}(t) - E_\gamma^{\rm th}\right)$$

$$t_\pm = -\frac{\widetilde{s}}{2s}\left(s + m_\mu^2 \mp \sqrt{\lambda(s, m_\mu^2, 0)}\right) + m_\mu^2$$

$$\tilde{t} = t - m_\mu^2,\ \tilde{s} = s - m_a^2,\ \text{and}\ \Delta^2 = m_a^2 - m_\mu^2$$

Axion Production: Soft and Virtual Correction



Soft photon

$$\frac{\sigma_{\rm s}}{\sigma^{(0)}_{\rm coal}} = \frac{\alpha}{\pi}\left[B(\beta_{e\mu})\ln\frac{2E^{\rm th}_\gamma}{\lambda_{\rm IR}} + C^{\rm finite}_{\rm real}\right] \qquad B(\beta_{e\mu}) = \frac{1}{\beta_{e\mu}}\ln\frac{1+\beta_{e\mu}}{1-\beta_{e\mu}} - 2$$

Virtual correction

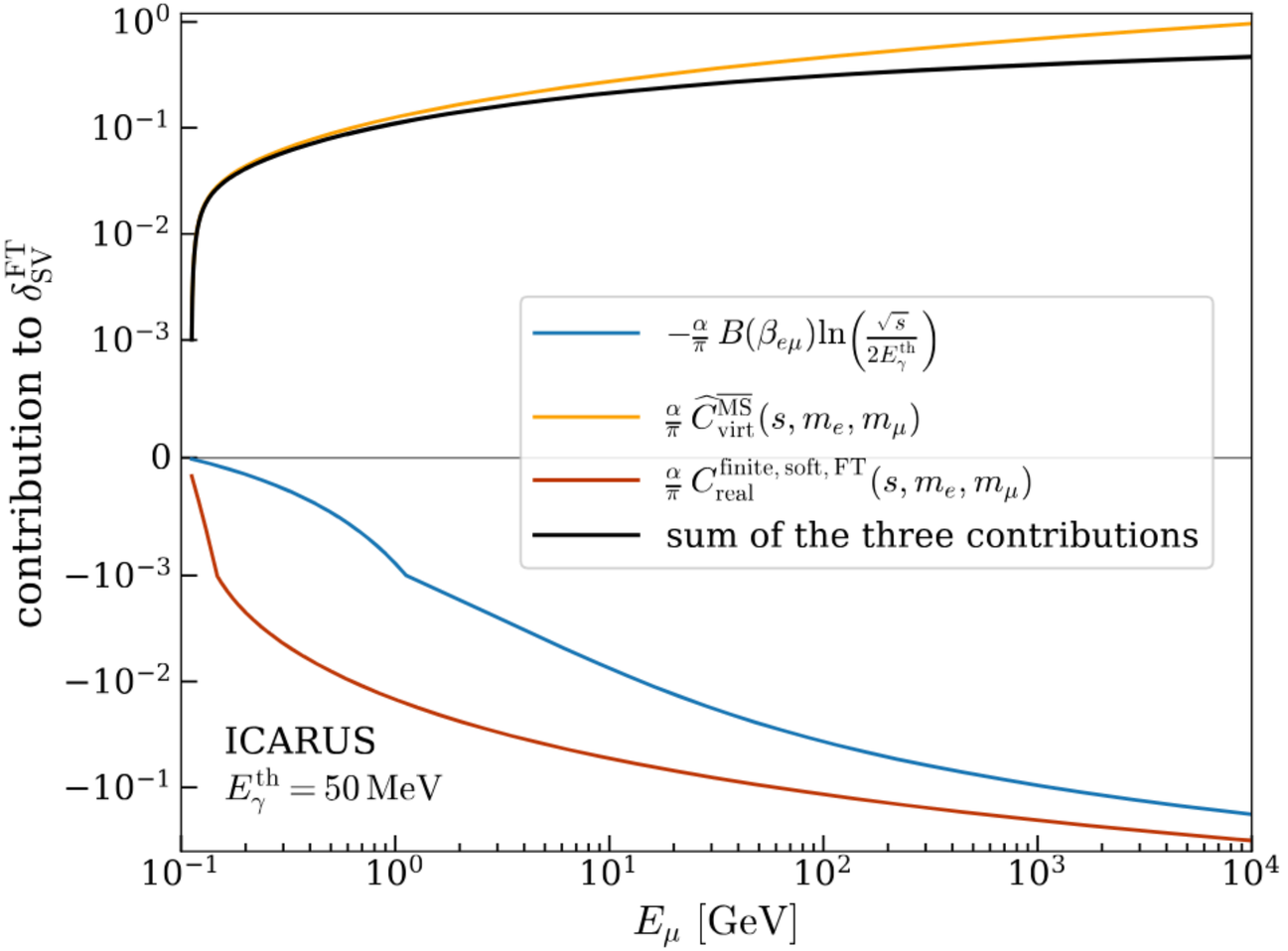
$$\frac{\sigma_{\rm v}}{\sigma^{(0)}_{\rm coal}} = \frac{\alpha}{\pi}\left[B(\beta_{e\mu})\ln\frac{\lambda_{\rm IR}}{\sqrt{s}} + C^{\rm finite,\overline{\rm MS}}_{\rm virt}\right]$$

Soft+virtual

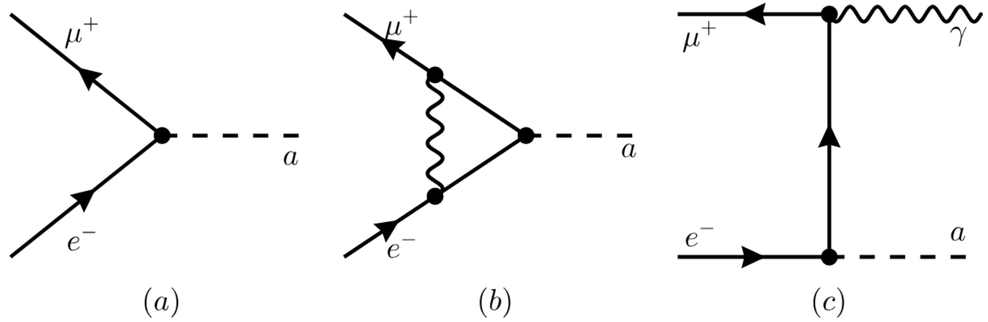
$$\frac{\sigma_{\rm sv}}{\sigma^{(0)}_{\rm coal}} = \frac{\alpha}{\pi}\left[-B(\beta_{e\mu})\ln\frac{\sqrt{s}}{2E^{\rm th}_\gamma} + C^{\rm finite,\overline{\rm MS}}_{\rm virt} + C^{\rm finite}_{\rm real}\right]$$

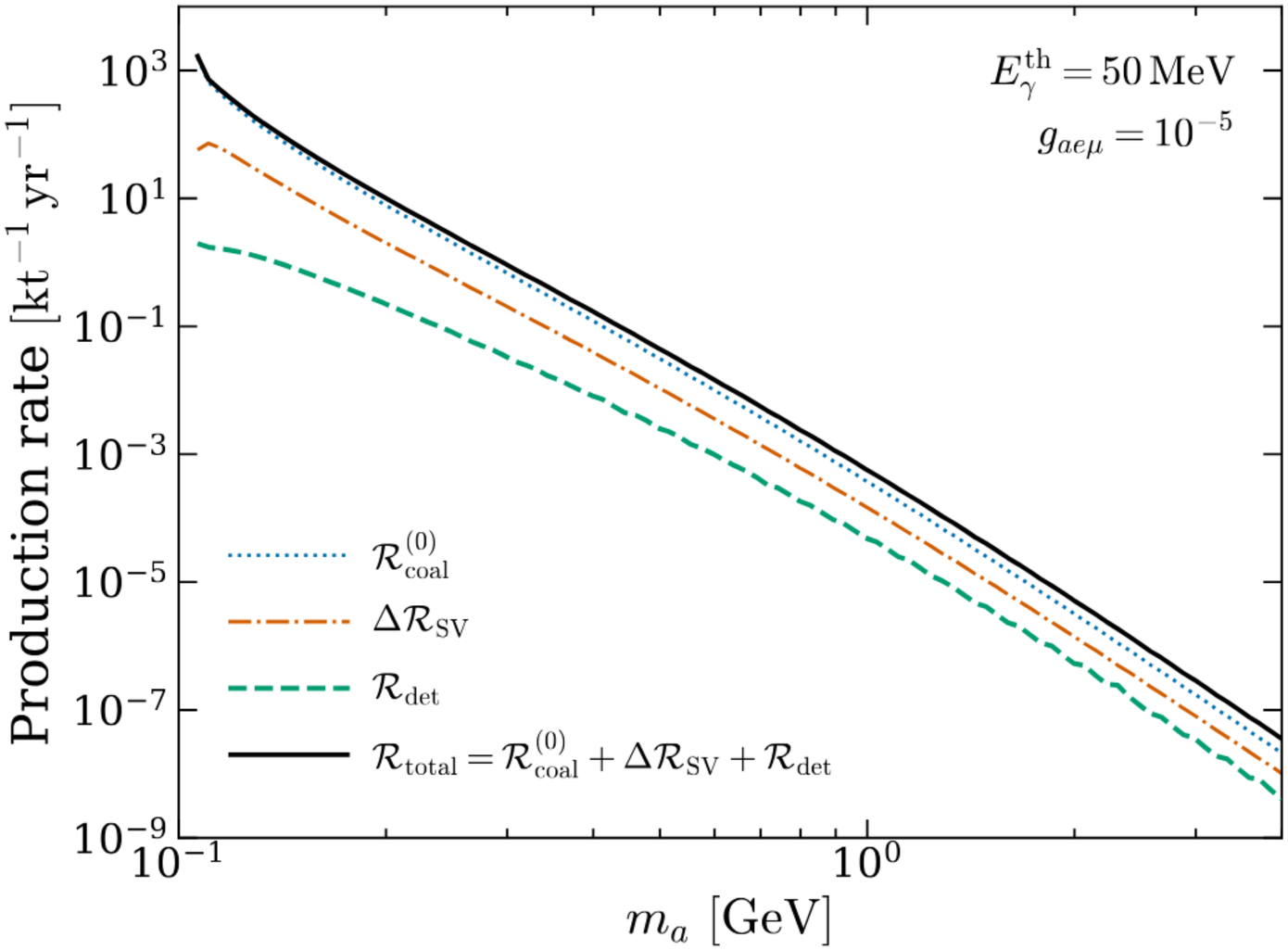
Axion Production: Soft and Virtual Correction

$$\delta_{\rm SV}^{\rm FT}(s;\mu_R,E_\gamma^{\rm th}) = \frac{\alpha}{\pi}\left[- B(\beta_{e\mu})\ln\frac{\sqrt{s}}{2E_\gamma^{\rm th}} + \frac{3}{2}\ln\frac{\mu_R^2}{s} + \widehat{C}_{\rm virt}^{\overline{\rm MS}}(s,m_e,m_\mu) + C_{\rm real}^{\rm finite,soft,FT}(s,m_e,m_\mu)\right]$$



Axion Production Rate





Axion Decay and Displaced Vertex

Decay rate

$$\Gamma_a^{\rm lab} = \frac{g_{ae\mu}^2 \left[m_a^2 - (m_\mu - m_e)^2\right]}{8\pi m_a^2 E_a} \sqrt{\lambda(m_a^2, m_\mu^2, m_e^2)}$$

Average decay length

$$\lambda_a(E_a) = \frac{\beta_a}{2\Gamma_a^{\rm lab}}$$

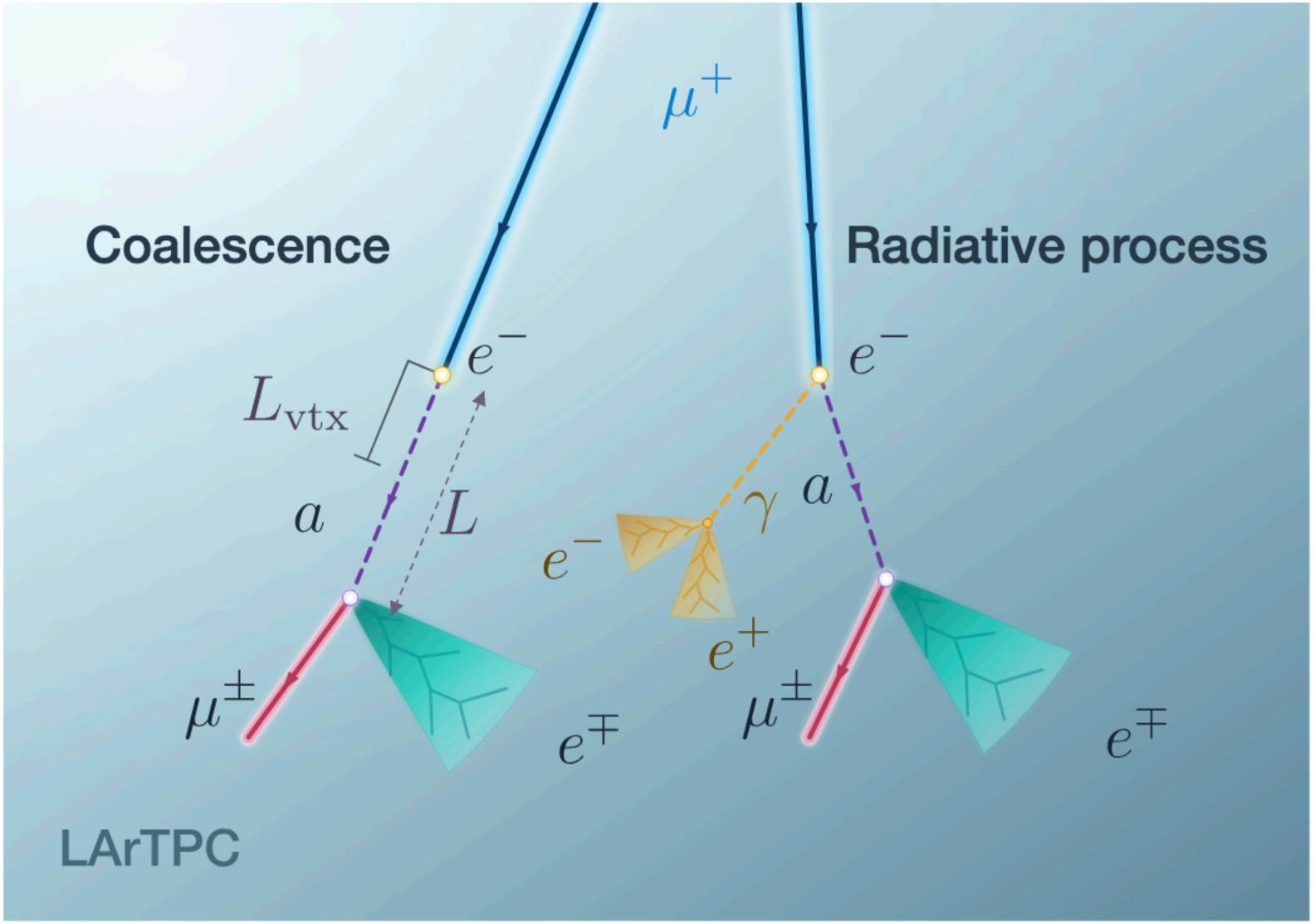
Decay probability for $L > L_{\rm vtx}$

$$P_{\rm vtx}(E_a) = \exp\left[-\frac{L_{\rm vtx}}{\lambda_a(E_a)}\right]$$

Event rate with displaced vertex

$$\begin{aligned}\mathcal{R}_{\rm sig}^{\rm vtx} = &\left[\mathcal{R}_{\rm coal}^{(0)} + \Delta\mathcal{R}_{\rm SV}\right] P_{\rm vtx}\left(E_a^{\rm coal}\right) \\ &+ N_e \int dE_\mu\, \Phi_{\mu^+}(E_\mu) \int_{t_-}^{t_+} dt\, \frac{d\sigma_{\rm rad}}{dt} \\ &\times \Theta\left(E_\gamma^{\rm lab}(t) - E_\gamma^{\rm th}\right) P_{\rm vtx}\left(E_a^{\rm rad}(t)\right)\end{aligned}$$

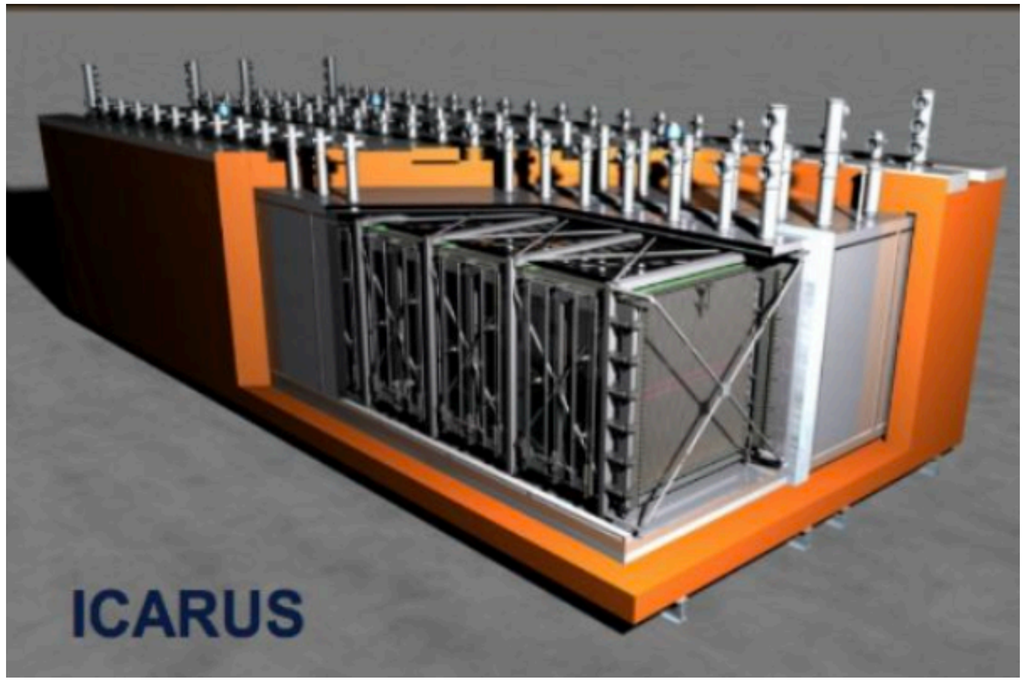
Topologies at LArTPC



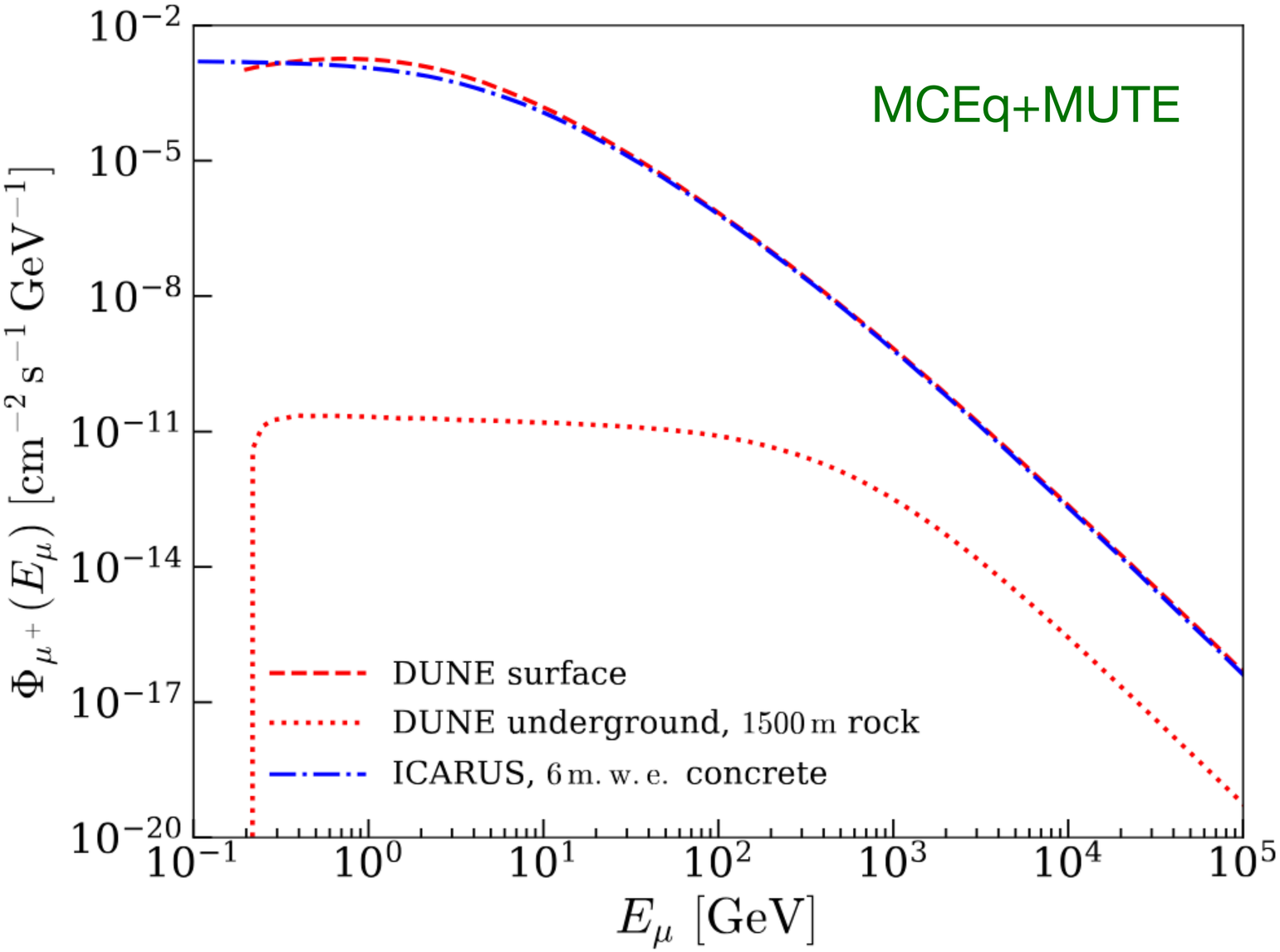
LArTPC Experiments

- ICARUS: Total active mass 476 tons, 3 meters of concrete, mm vertex reconstruction resolution, photon reconstruction threshold 50 MeV

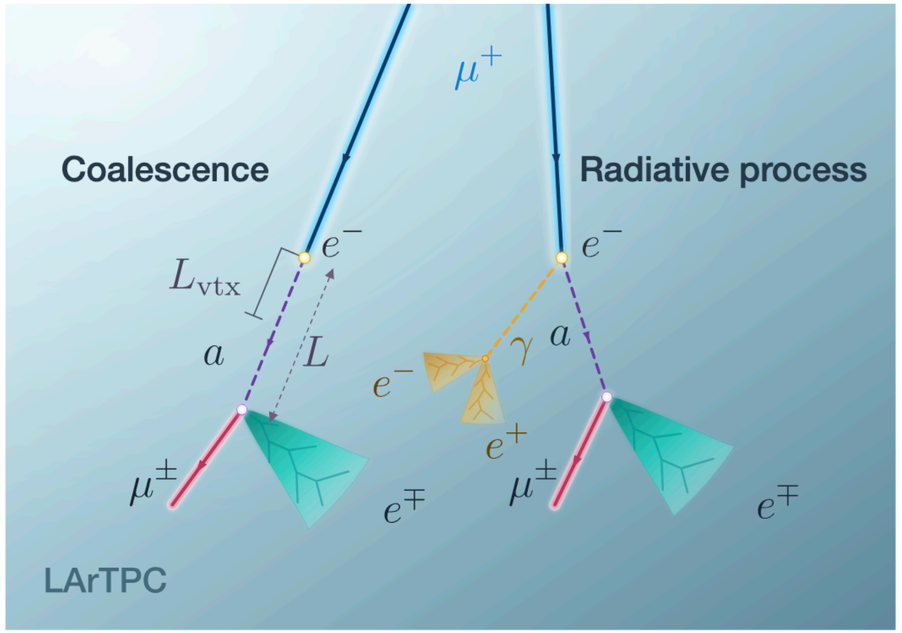
- DUNE far detector: Total active mass 40 kt, 1500 m underground, cm vertex reconstruction resolution, photon reconstruction threshold 5 MeV



Muon Spectrum



Sensitivity on Flavor-violating Axion



Background:

- $\mu^\pm + N \to \mu^\pm + e^\pm + e^- + N$
- Ionization

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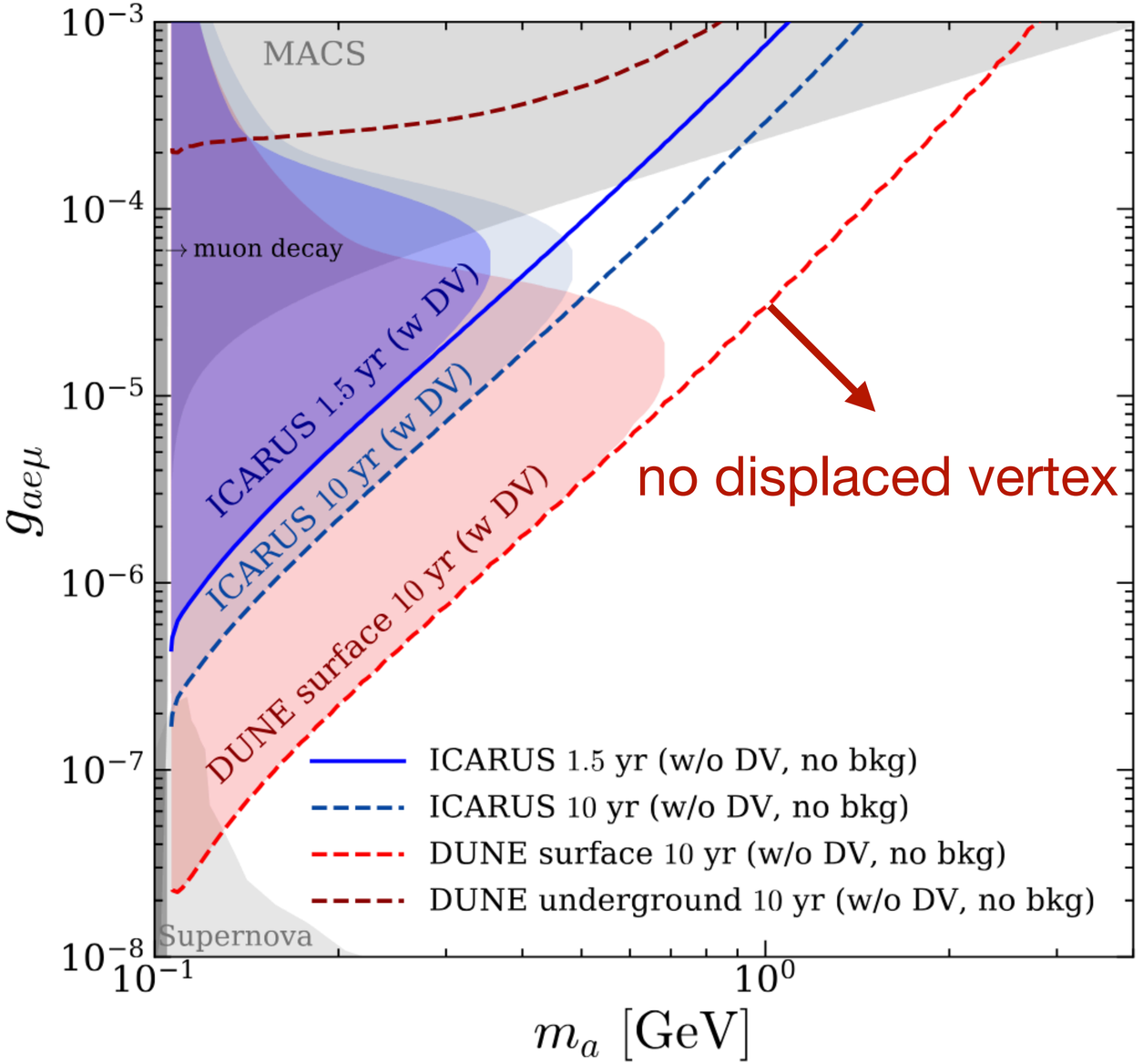
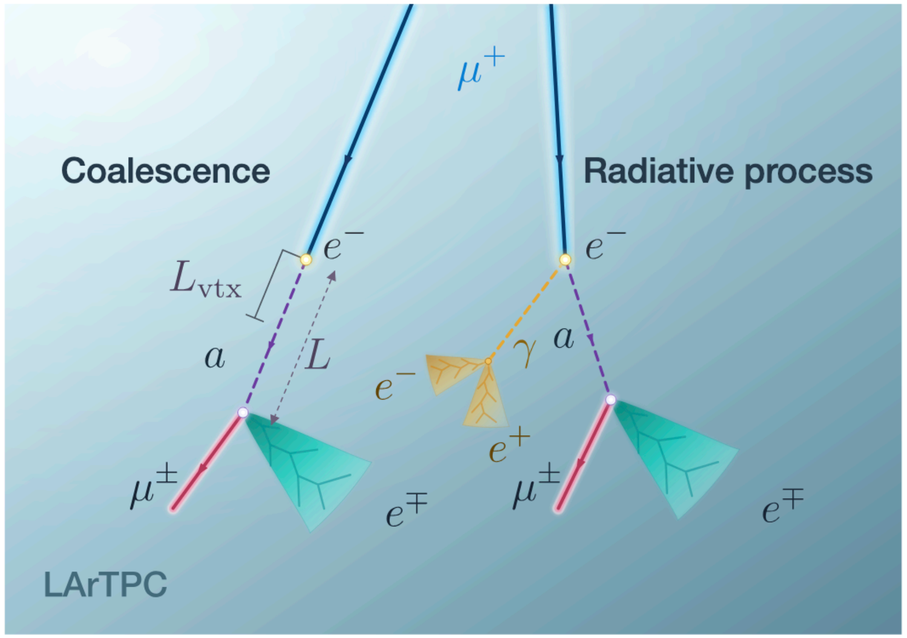
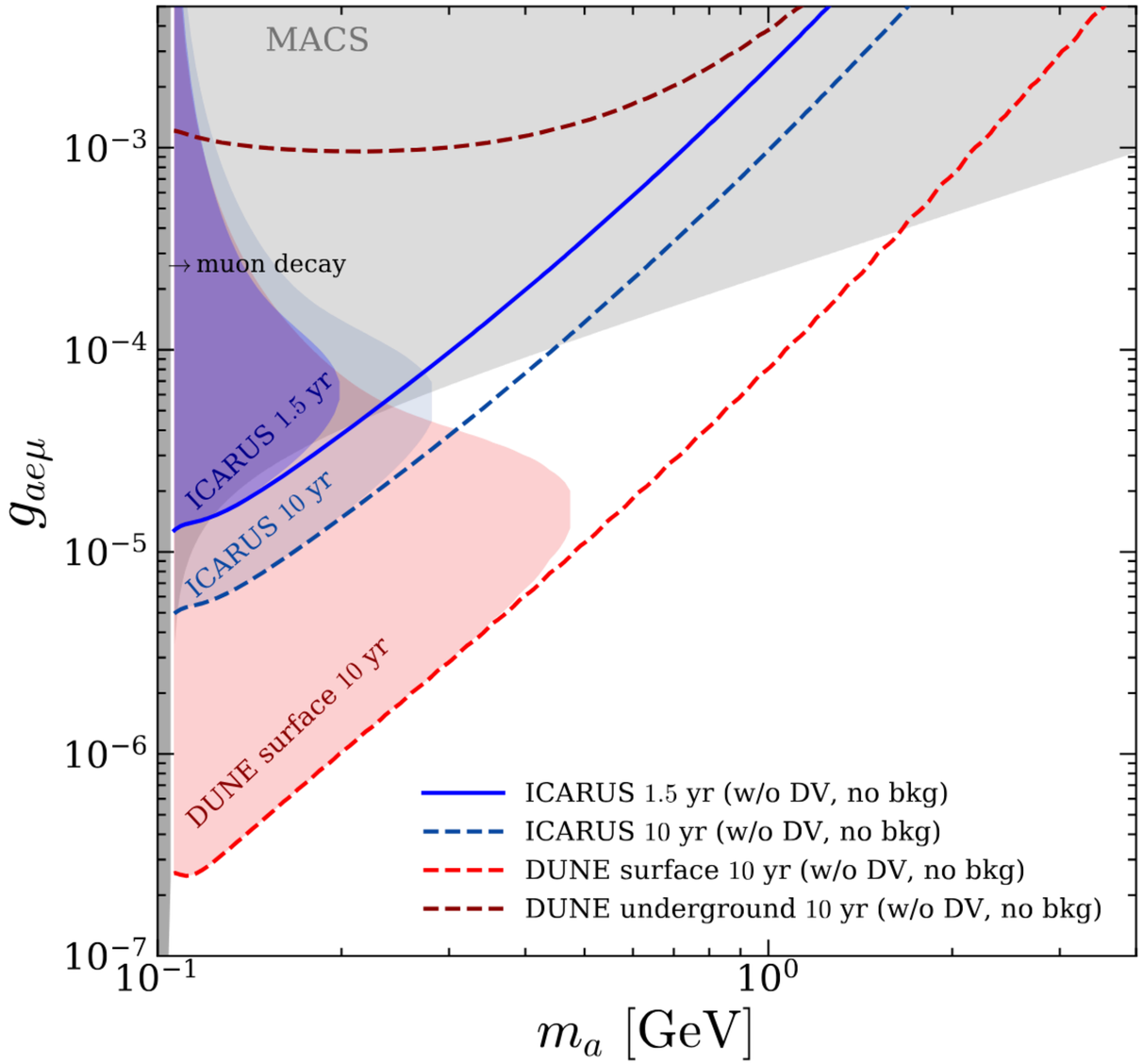


Sensitivity on Flavor-violating Axion from Hard Photon



Background:

- $\mu^\pm + N \to \mu^\pm + e^\mp + e^- + \gamma + N$



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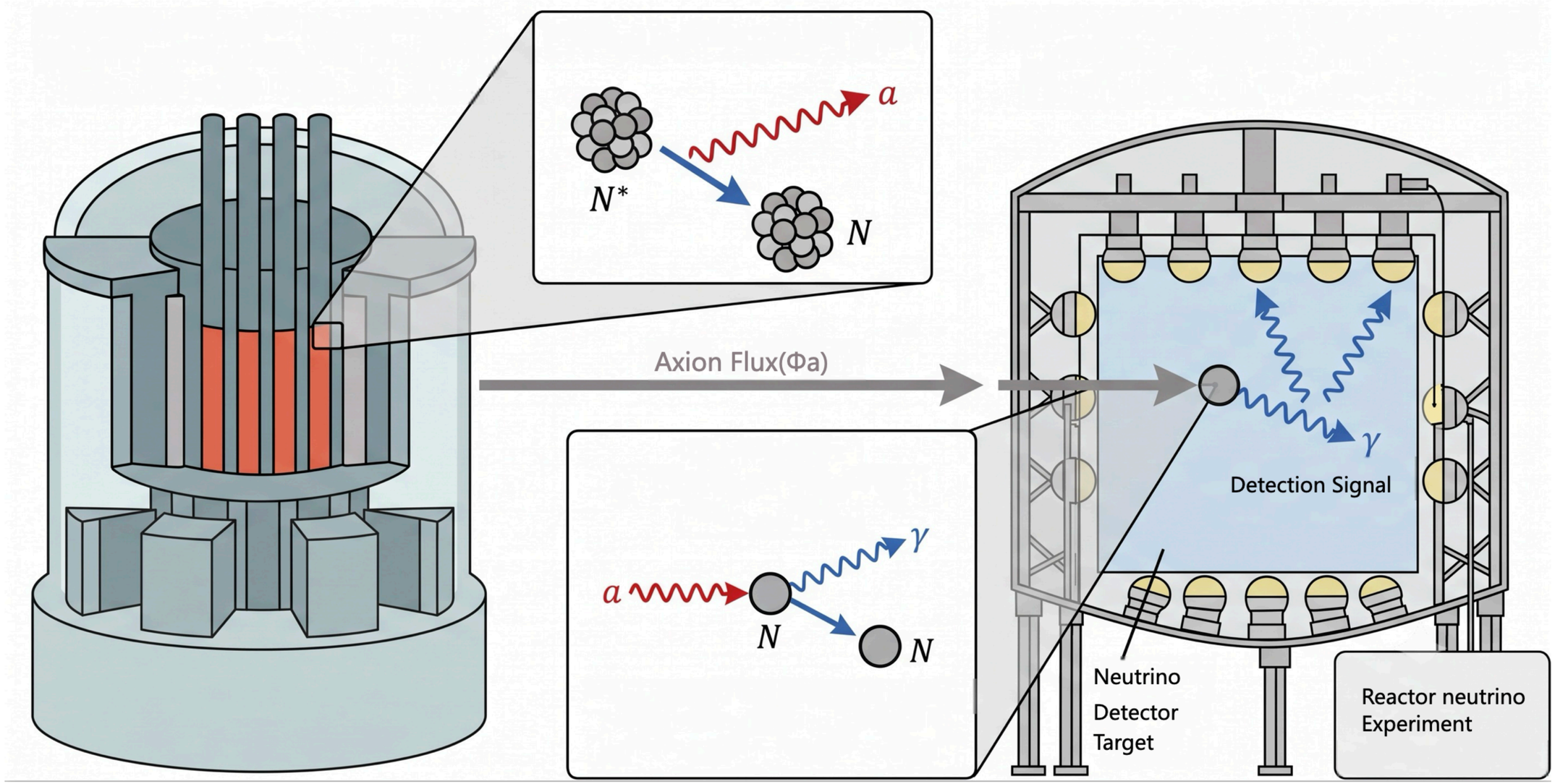
Axion-Nucleon Coupling at Reactor Neutrino Experiments



Axion Production in Nuclear Transitions

The Lagrangian $$\mathcal{L}_{aNN} = C_{ap}\partial_\mu a\bar{p}\gamma^\mu\gamma^5 p + C_{an}\partial_\mu a\bar{n}\gamma^\mu\gamma^5 n$$

Integration by parts $$\mathcal{L}_{aNN} = -ia(g_{ap}\bar{p}\gamma^5 p + g_{an}\bar{n}\gamma^5 n) \qquad g_{aN} = 2m_N C_{aN}$$

$$\mathcal{L}_{\rm int} = -ia\bar{N}\gamma_5(g^0_{aN} + \tau_3 g^1_{aN})N$$

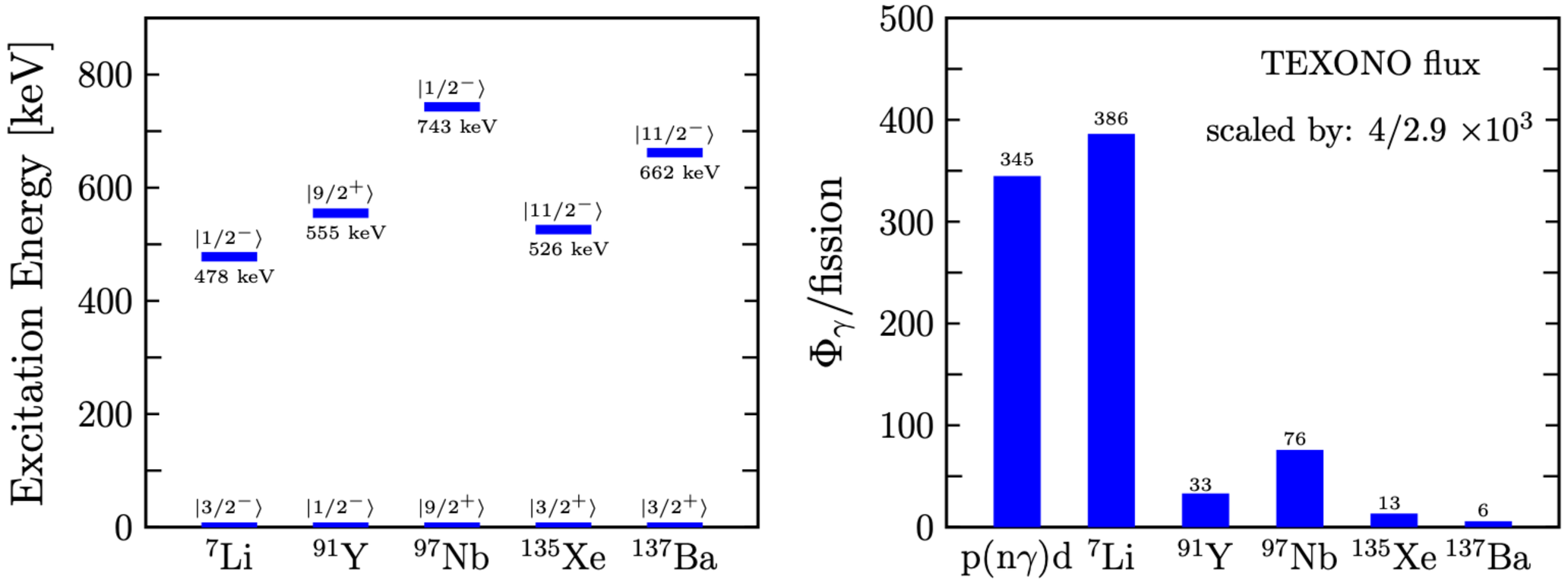
$$g^0_{aN} = (g_{ap} + g_{an})/2 \qquad g^1_{aN} = (g_{ap} - g_{an})/2$$

Axion production rate $$\left(\frac{\Gamma_a}{\Gamma_\gamma}\right)_{MJ} = \frac{1}{\pi\alpha}\left(\frac{1}{1+\delta^2}\right)\left(\frac{J}{J+1}\right)\left(\frac{|\mathbf{k}|}{|\mathbf{q}|}\right)^{2J+1} \times \left(\frac{g^0_{aN}\kappa + g^1_{aN}}{(\mu_0 - 1/2)\kappa + (\mu_1 - \eta)}\right)^2$$

Axion flux $$\left(\frac{d\Phi_a}{dE_a}\right)_i = R_f \Phi^i_\gamma \left(\frac{\Gamma_a}{\Gamma_\gamma}\right)_i \mathcal{P}_{\rm surv}\delta(E_\gamma - E_a)$$

Axion Production in Nuclear Transitions

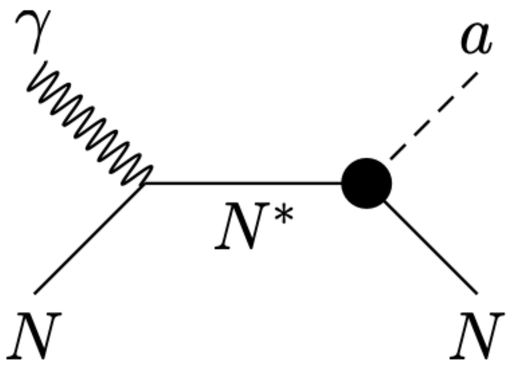
Channel	E_γ [keV]	Transition	$\Phi_\gamma/P_{\rm th}$ [fission^{-1} GW$_{\rm th}^{-1}$]	(δ, η, κ)
$^{10}\mathrm{B}(n,\alpha)^7\mathrm{Li}^* \to {}^7\mathrm{Li} + \gamma/a$	478	$M1 + E2(1/2^- \to 3/2^-)$	0.097	(0, 0.5, 1)
$^{97}\mathrm{Nb}^* \to {}^{97}\mathrm{Nb} + \gamma/a$	743	$M4(1/2^- \to 9/2^+)$	0.019	(0, −3, 1)
$p + n \to d + \gamma/a$	2230	Isovector $M1$	0.086	–



Sierra et al 2010.15712

Axion Detection

Compton-like process $a(k) + A(P) \to A(P') + \gamma(q, \varepsilon)$



Non-relativistic Hamiltonian

$$h_{aN}^{\mathrm{NR}} = -C_{aN}\boldsymbol{\sigma}_N \cdot \nabla a(\mathbf{r}_N) + \mathcal{O}\left(\frac{1}{m_N}\right)$$

$$h_{\gamma N}^{\mathrm{NR}} = eQ_N\Phi - \frac{eQ_N}{2m_N}\{\boldsymbol{p}_N, \boldsymbol{A}\} - \frac{e\mu_N}{2m_N}\boldsymbol{\sigma}_N \cdot \boldsymbol{B} + \frac{e^2Q_N^2}{2m_N}\boldsymbol{A}^2 + \mathcal{O}\left(\frac{1}{m_N^2}\right)$$

Cross section

$$\frac{d\sigma_T}{d\Omega_\gamma} = \frac{\omega^2}{4\pi^2 v_a}\frac{\overline{|\mathcal{M}_{\mathrm{NR}}|^2}}{1 + (\omega - k\cos\theta)/m_T}$$

$$\simeq \frac{\alpha}{3\pi v_a}\frac{J+1}{J}\left[\frac{k^2}{m_N^2}A_m^2(1+\cos^2\theta) + \frac{Z^2}{m_T^2}\frac{k^4}{E_a^2}A_a^2\sin^2\theta\right]$$

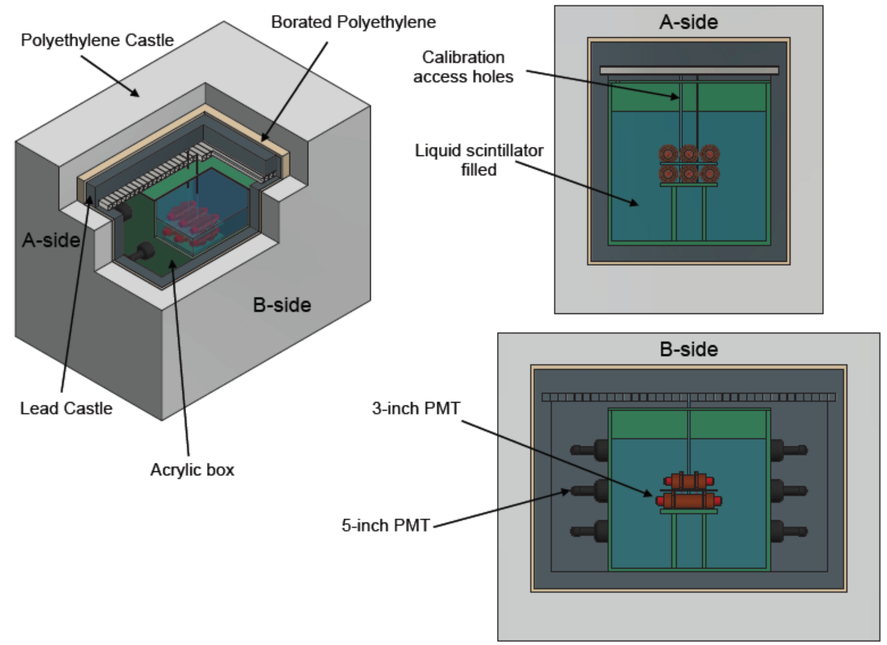
$$\mathcal{A}_a = C_{ap}\langle S_p\rangle + C_{an}\langle S_n\rangle$$

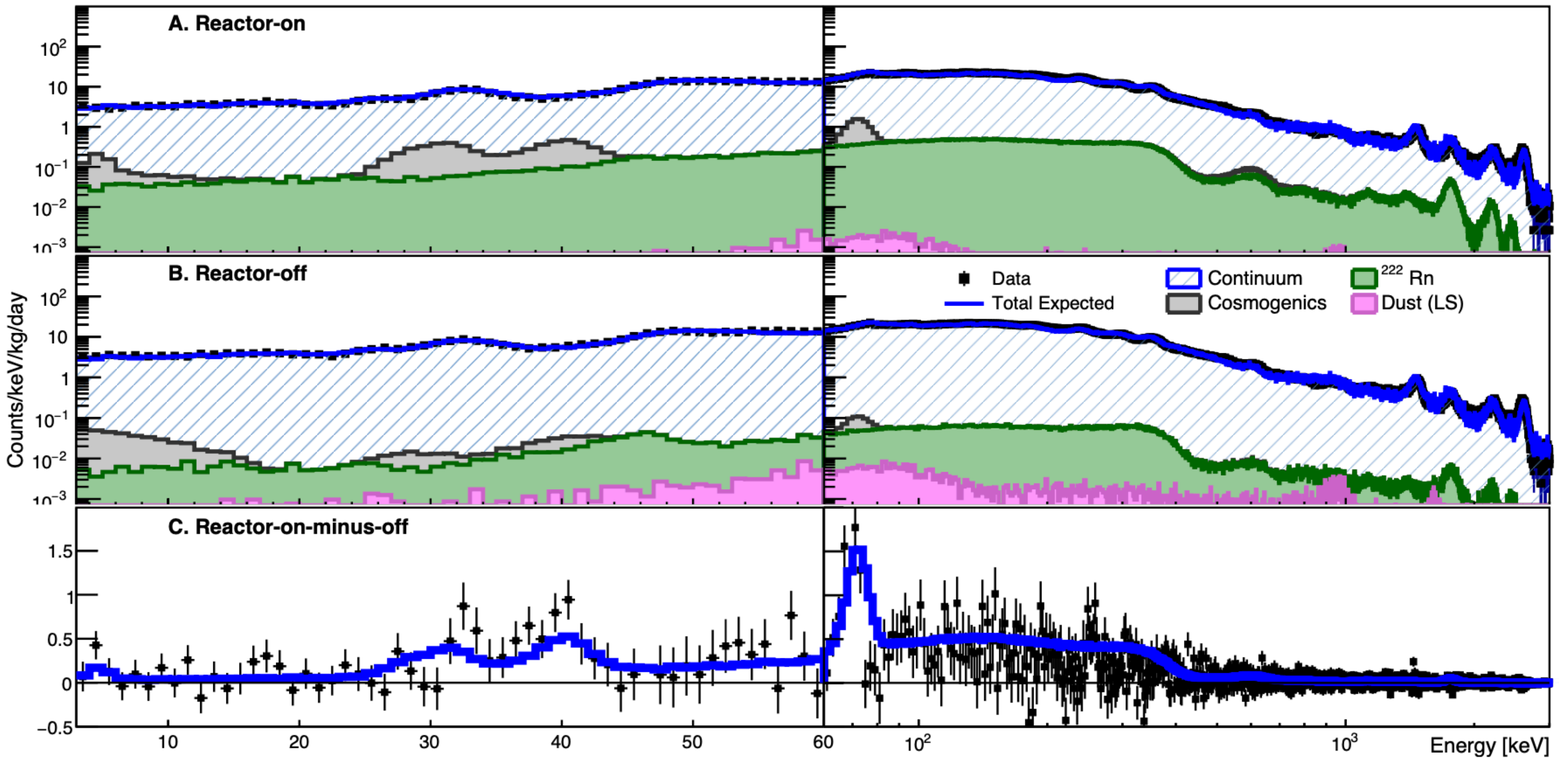
$$\mathcal{A}_m = C_{ap}\mu_p\langle S_p\rangle + C_{an}\mu_n\langle S_n\rangle$$

Detection rate

$$\frac{dR}{dE_\gamma} = \sum_T\sum_i n_T \int dE_a \frac{1}{4\pi L^2}\left(\frac{\mathrm{d}\Phi_a}{\mathrm{d}E_a}\right)_i \frac{d\sigma_T}{dE_\gamma}$$

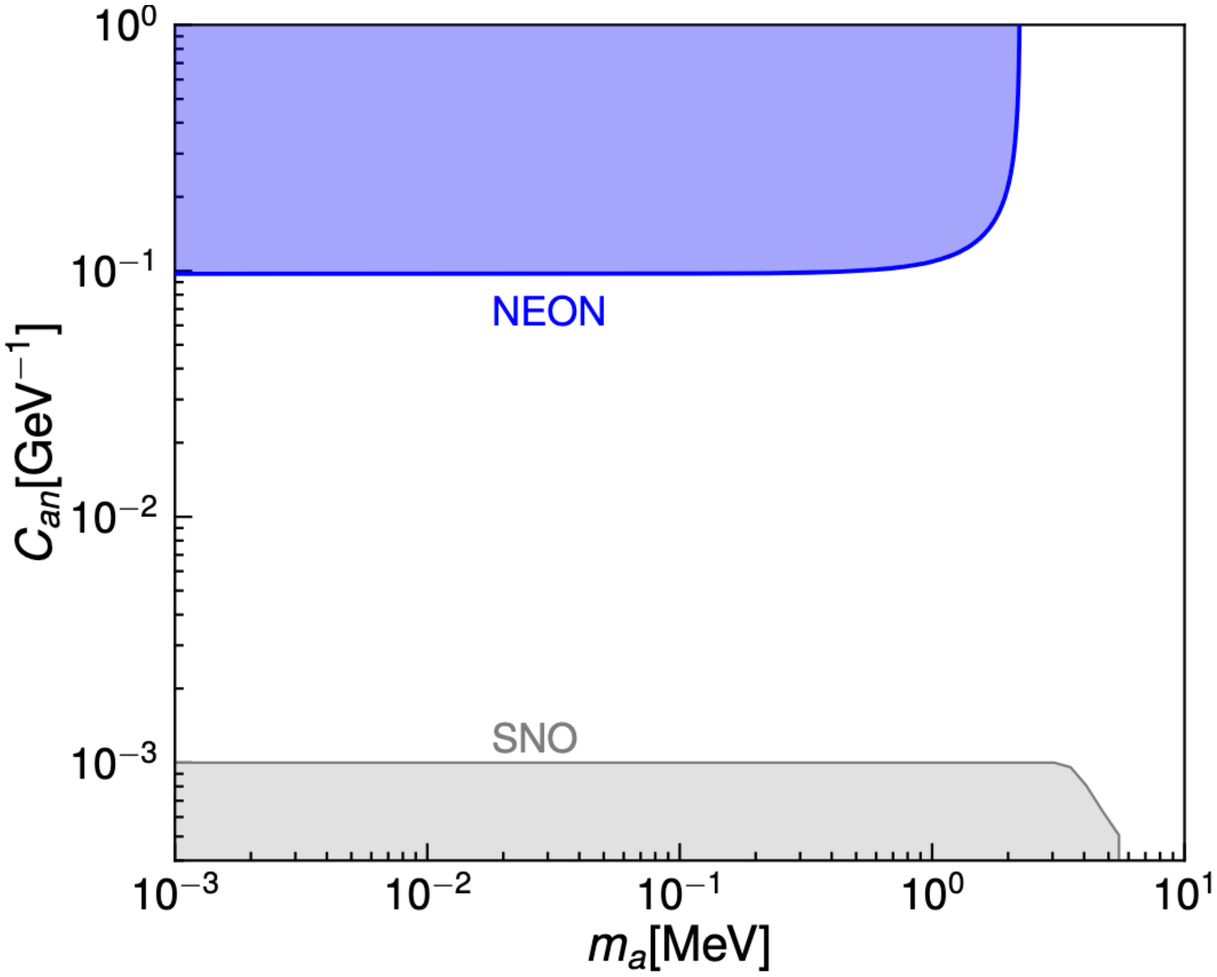
The Neon Experiment

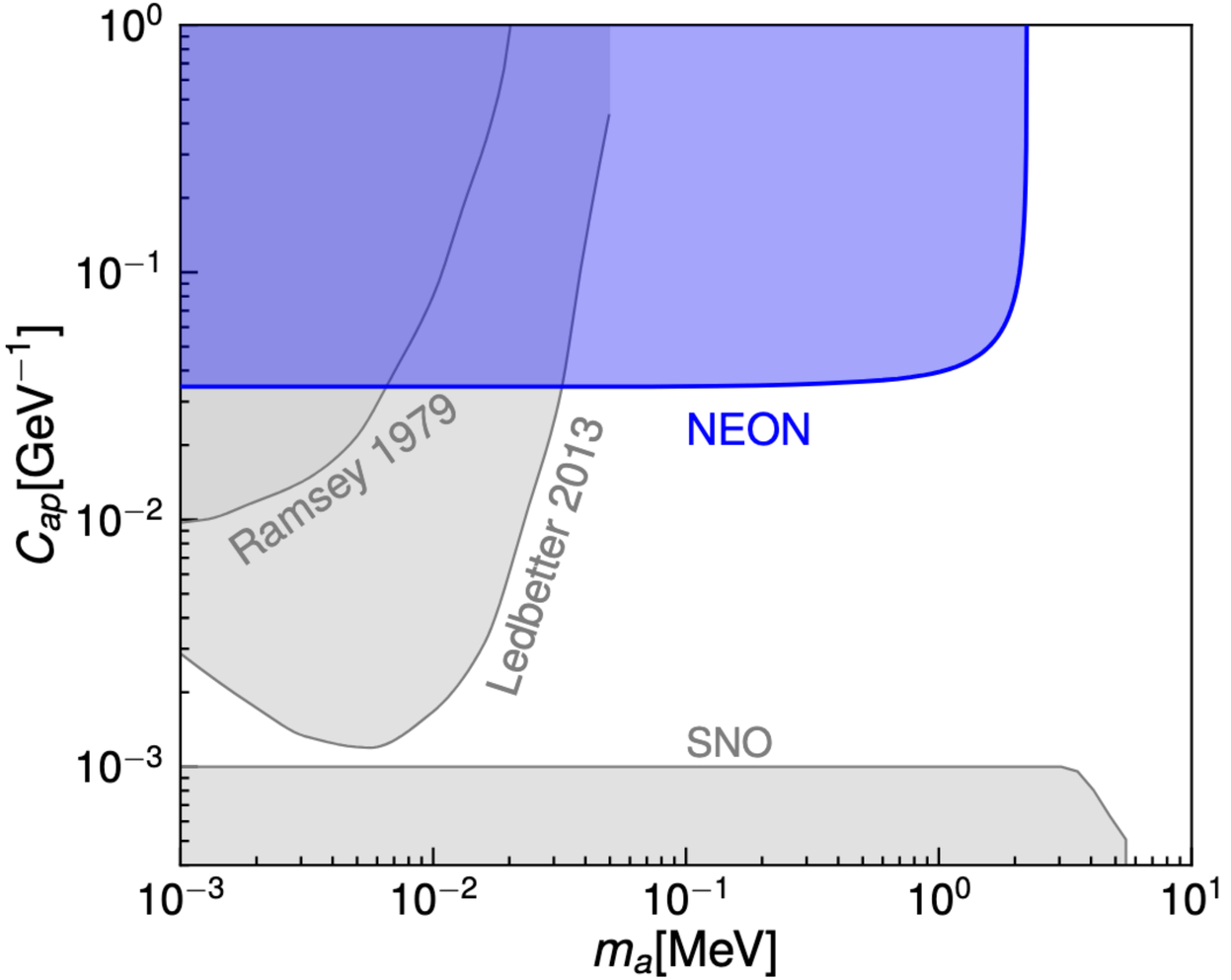




Neon Collaboration, 2406.06117

Constraints on Axion-Nucleon Couplings





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Summary

- Flavor-violating axions can be produced resonantly in neutrino experiments from muon-electron scattering
- The coalescence process dominates the production, while soft photon plus virtual correction gives fractional contribution
- ICARUS and DUNE can surpass the existing constraints by orders of magnitude
- Axions can be resonantly produced in nuclear transitions, and be detected in Compton-like process
- Neutrino experiments provide powerful probes of axion-nucleon couplings

Thanks