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Constraints on axions from neutrino experiments

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Outline

- Theory overview of flavor-violating axion
- Axion production cross section
- Topologies of flavor-violating axion
- Sensitivity of flavor-violating axion at LArTPC

Flavor-violating axion

Effective field theory

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

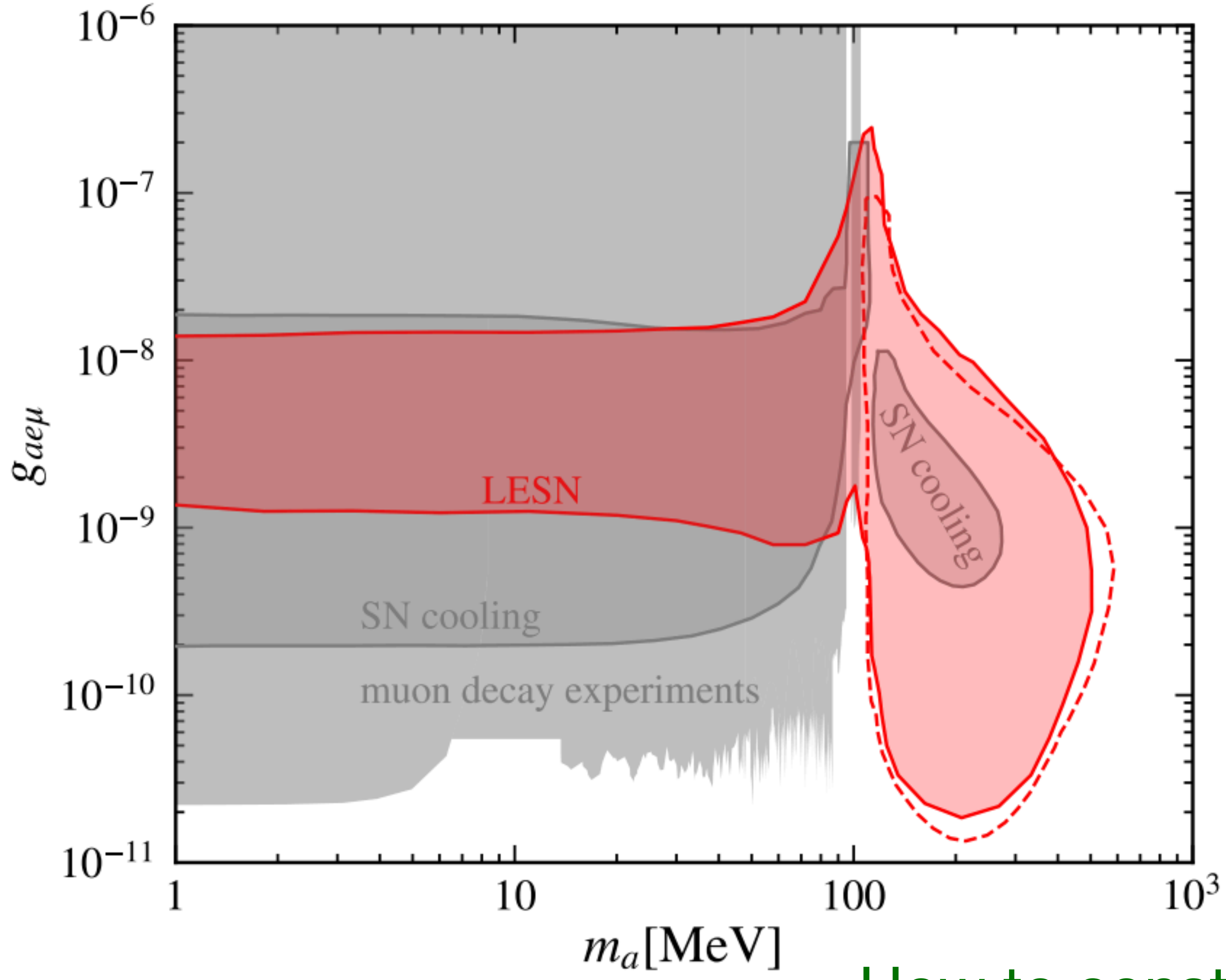
$$\Rightarrow \quad \mathcal{L}_{a\ell\ell} \supset -\mathrm{i} \sum_{i,j} \left[\underbrace{\frac{C^V_{\ell_i\ell_j}(m_{\ell_i} - m_{\ell_j})}{2f_a}}_{\downarrow} a\bar{\ell}_i \ell_j + \underbrace{\frac{C^A_{\ell_i\ell_j}(m_{\ell_i} + m_{\ell_j})}{2f_a}}_{\downarrow} a\bar{\ell}_i \gamma_5 \ell_j \right]$$

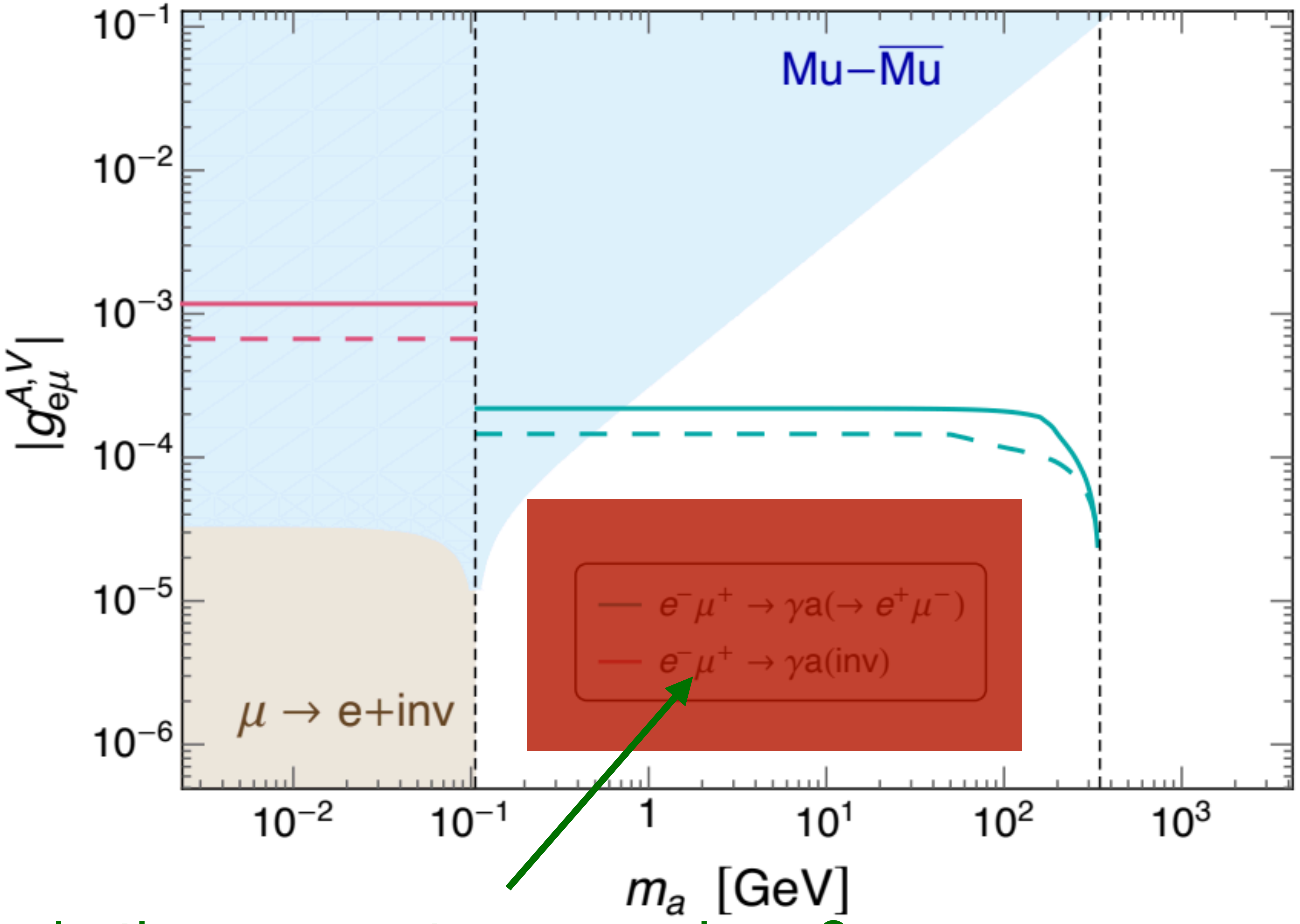
arXiv: 2406.13234

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

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





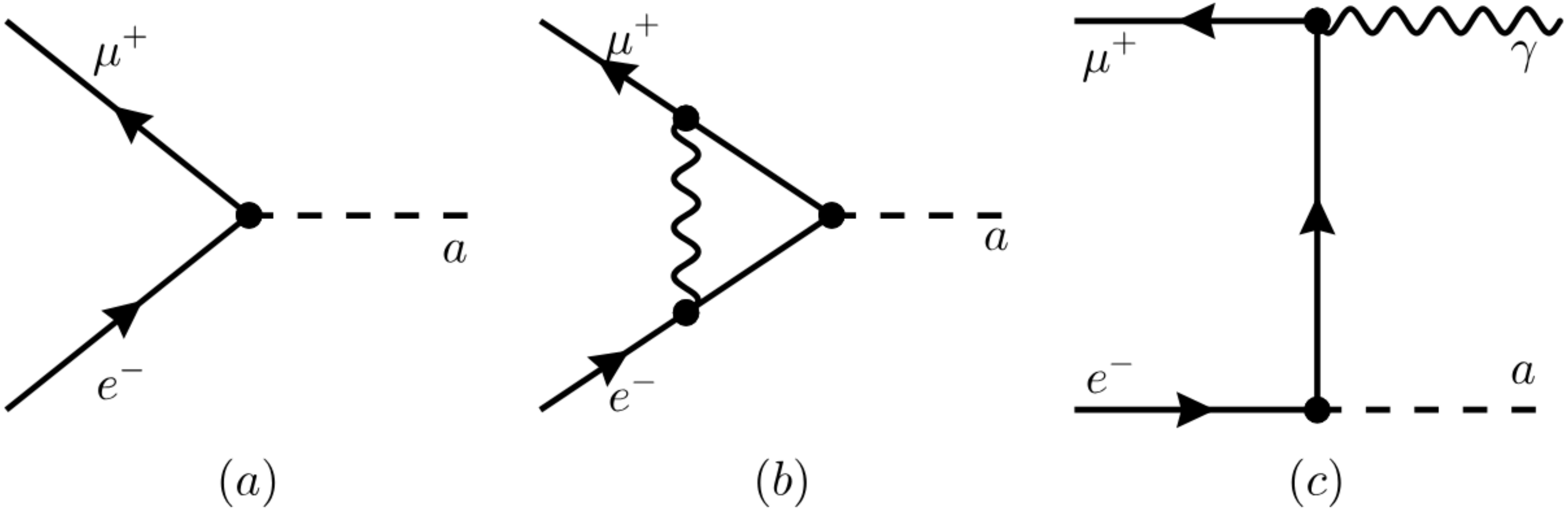
How to constrain the parameter space here?

Huang, Li, Liu, arXiv: 2510.22523

arXiv: 2406.13234

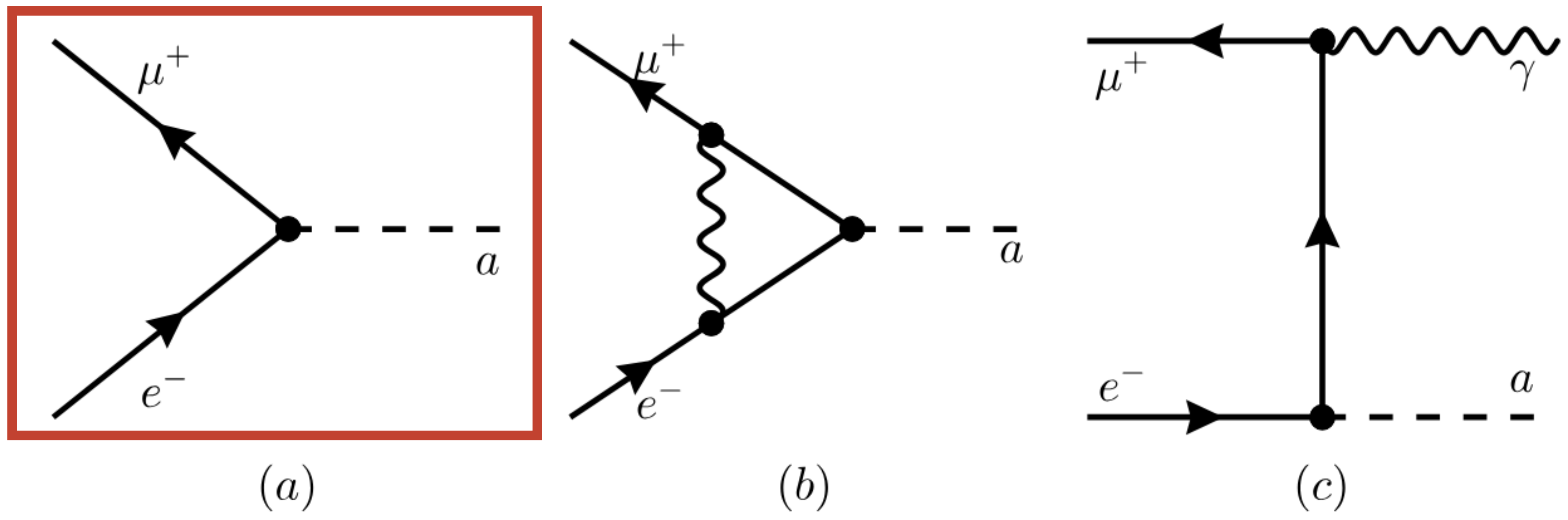
Axion Production in Neutrino Experiments

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



Coalescence | Virtual correction | Radiative photon emission

Axion Production: Coalescence



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

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

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

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

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

$$y \equiv m_e/m_a;$$

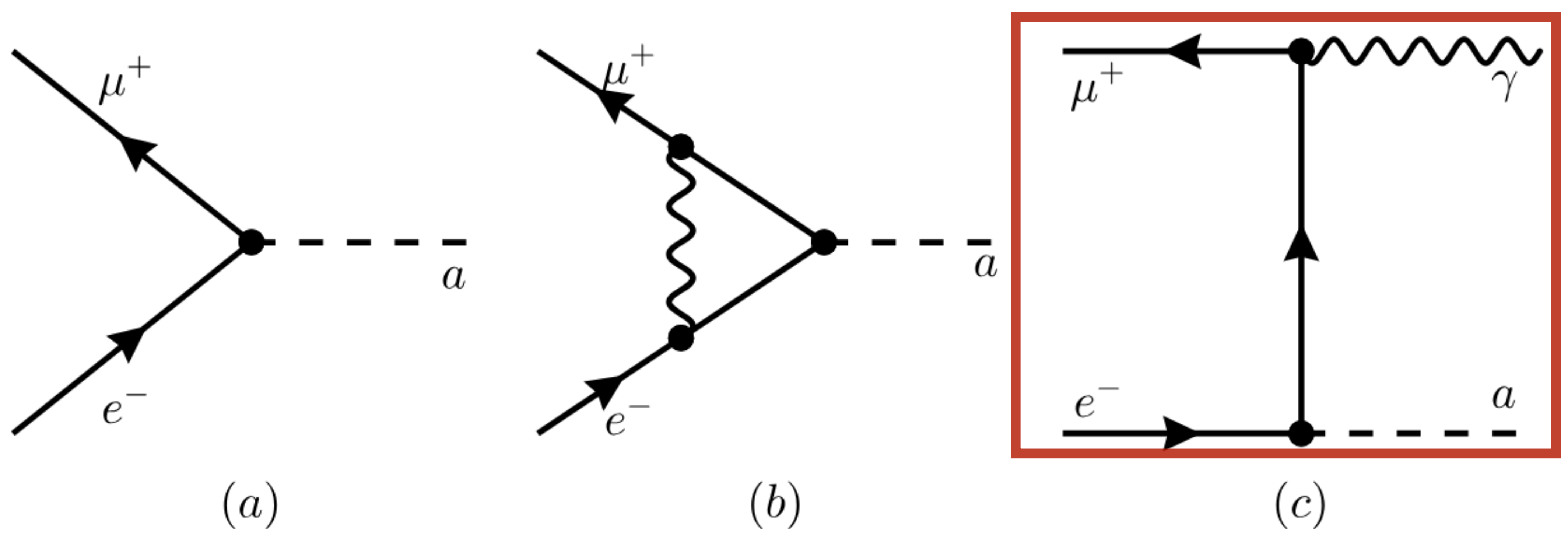
Axion Production: Radiative Hard Photon Emission

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

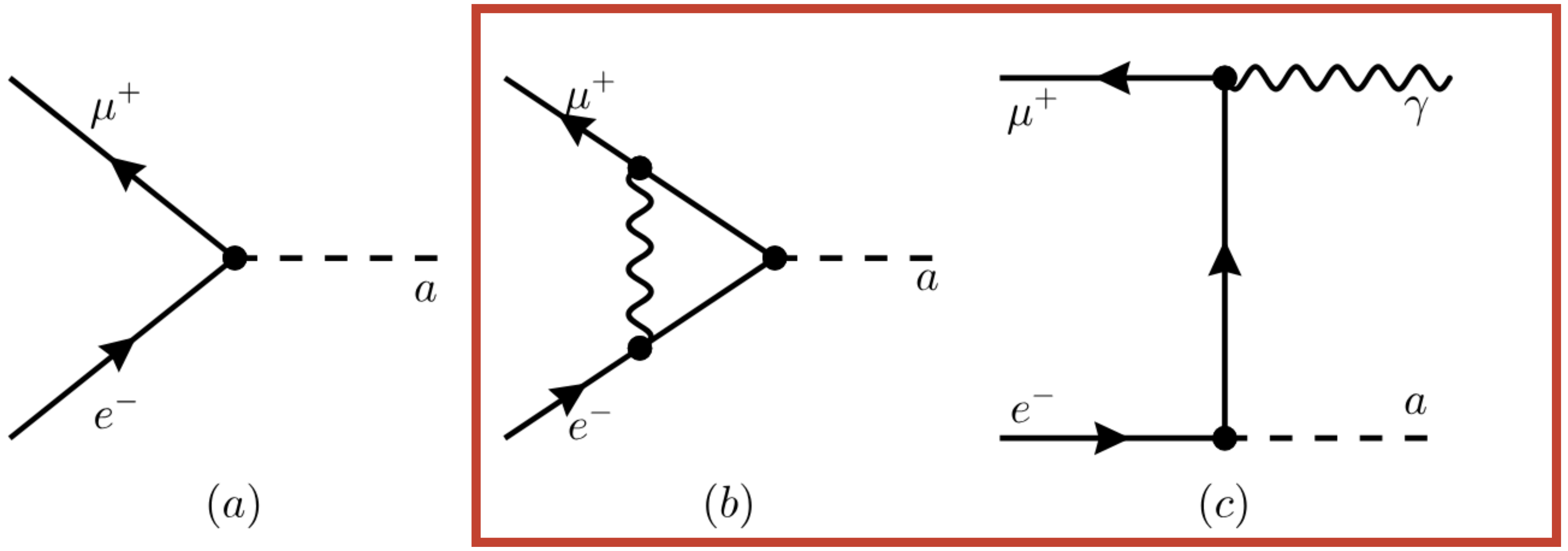
$$\sigma_{\mathrm{h}} = \int_{t_-}^{t_+} dt\, \frac{d\sigma_{\mathrm{rad}}}{dt} \Theta\left(E_\gamma^{\mathrm{lab}}(t) - E_\gamma^{\mathrm{th}}\right)$$

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

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



Axion Production: Soft and Virtual Correction



$$B(\beta_{e\mu}) = \frac{1}{\beta_{e\mu}} \ln \frac{1+\beta_{e\mu}}{1-\beta_{e\mu}} - 2$$

Soft photon

$$\frac{\sigma_{\mathrm{s}}}{\sigma^{(0)}_{\mathrm{coal}}} = \frac{\alpha}{\pi}\left[B(\beta_{e\mu}) \ln \frac{2E_\gamma^{\mathrm{th}}}{\lambda_{\mathrm{IR}}} + C_{\mathrm{real}}^{\mathrm{finite}}\right]$$

Virtual correction

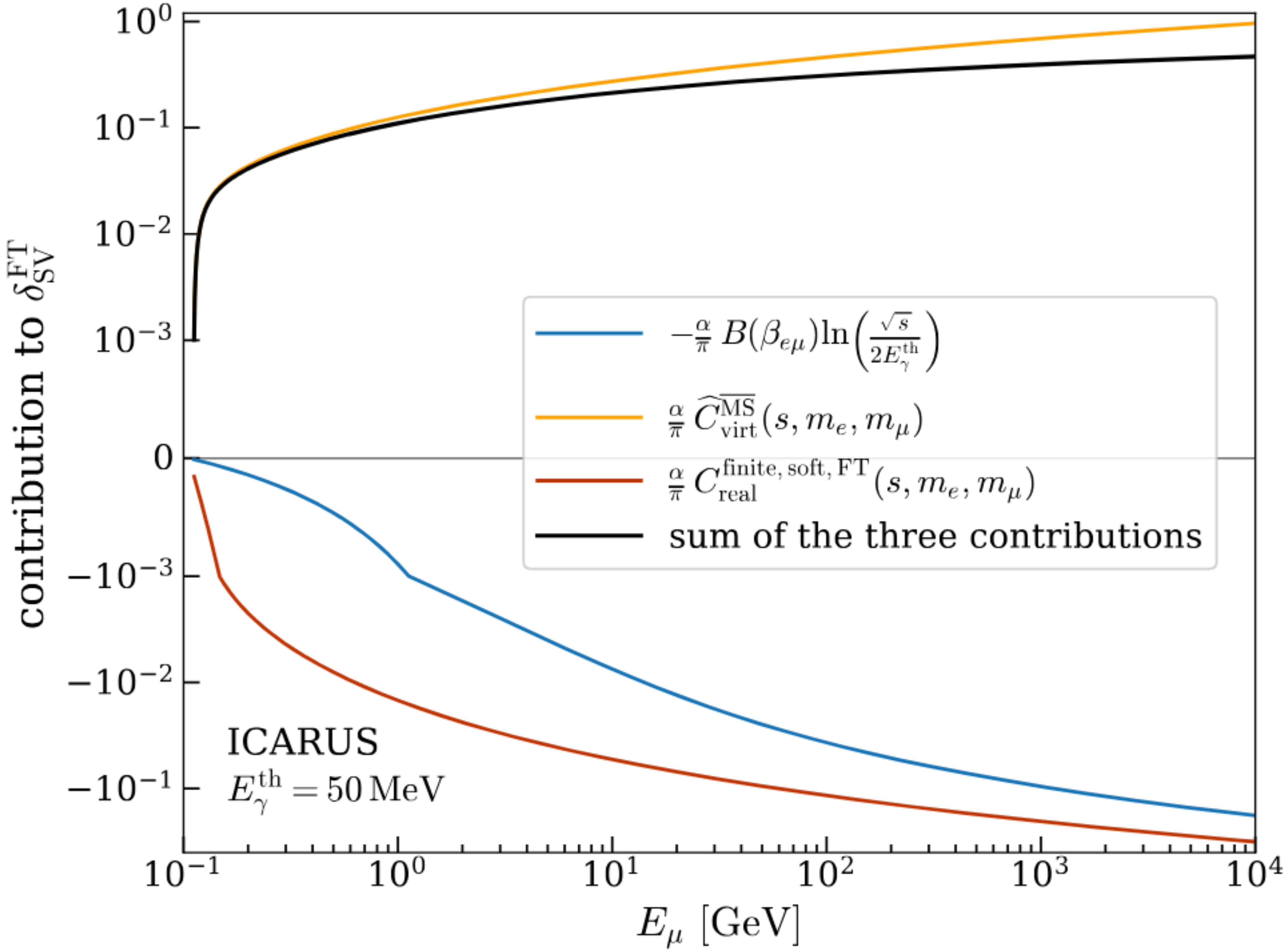
$$\frac{\sigma_{\mathrm{v}}}{\sigma^{(0)}_{\mathrm{coal}}} = \frac{\alpha}{\pi}\left[B(\beta_{e\mu}) \ln \frac{\lambda_{\mathrm{IR}}}{\sqrt{s}} + C_{\mathrm{virt}}^{\mathrm{finite},\overline{\mathrm{MS}}}\right]$$

Soft+virtual

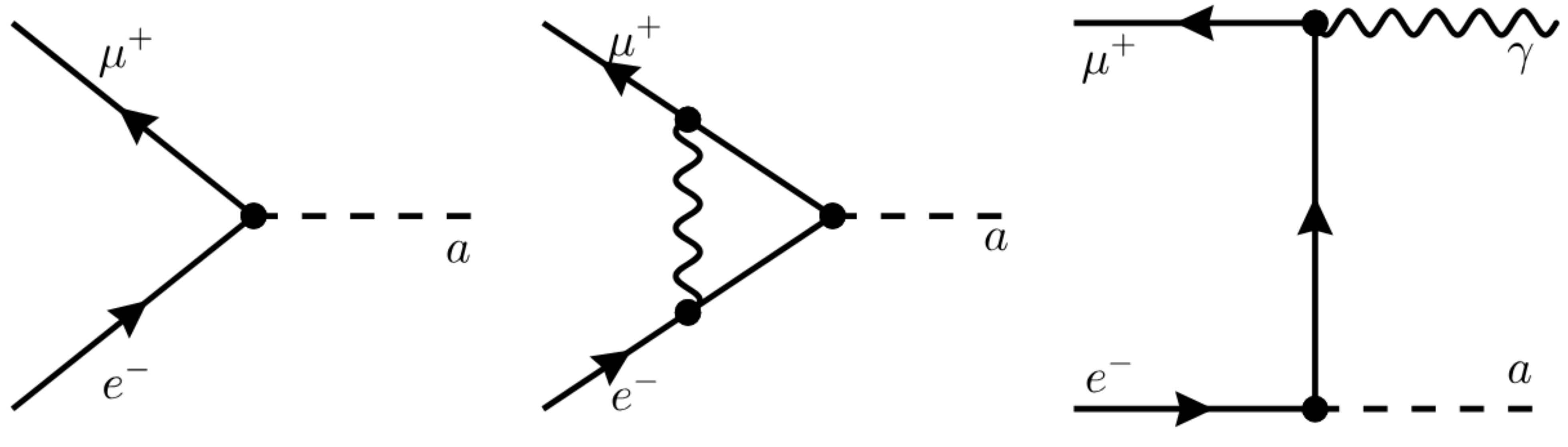
$$\frac{\sigma_{\mathrm{sv}}}{\sigma^{(0)}_{\mathrm{coal}}} = \frac{\alpha}{\pi}\left[-B(\beta_{e\mu}) \ln \frac{\sqrt{s}}{2E_\gamma^{\mathrm{th}}} + C_{\mathrm{virt}}^{\mathrm{finite},\overline{\mathrm{MS}}} + C_{\mathrm{real}}^{\mathrm{finite}}\right]$$

Axion Production: Soft and Virtual Correction

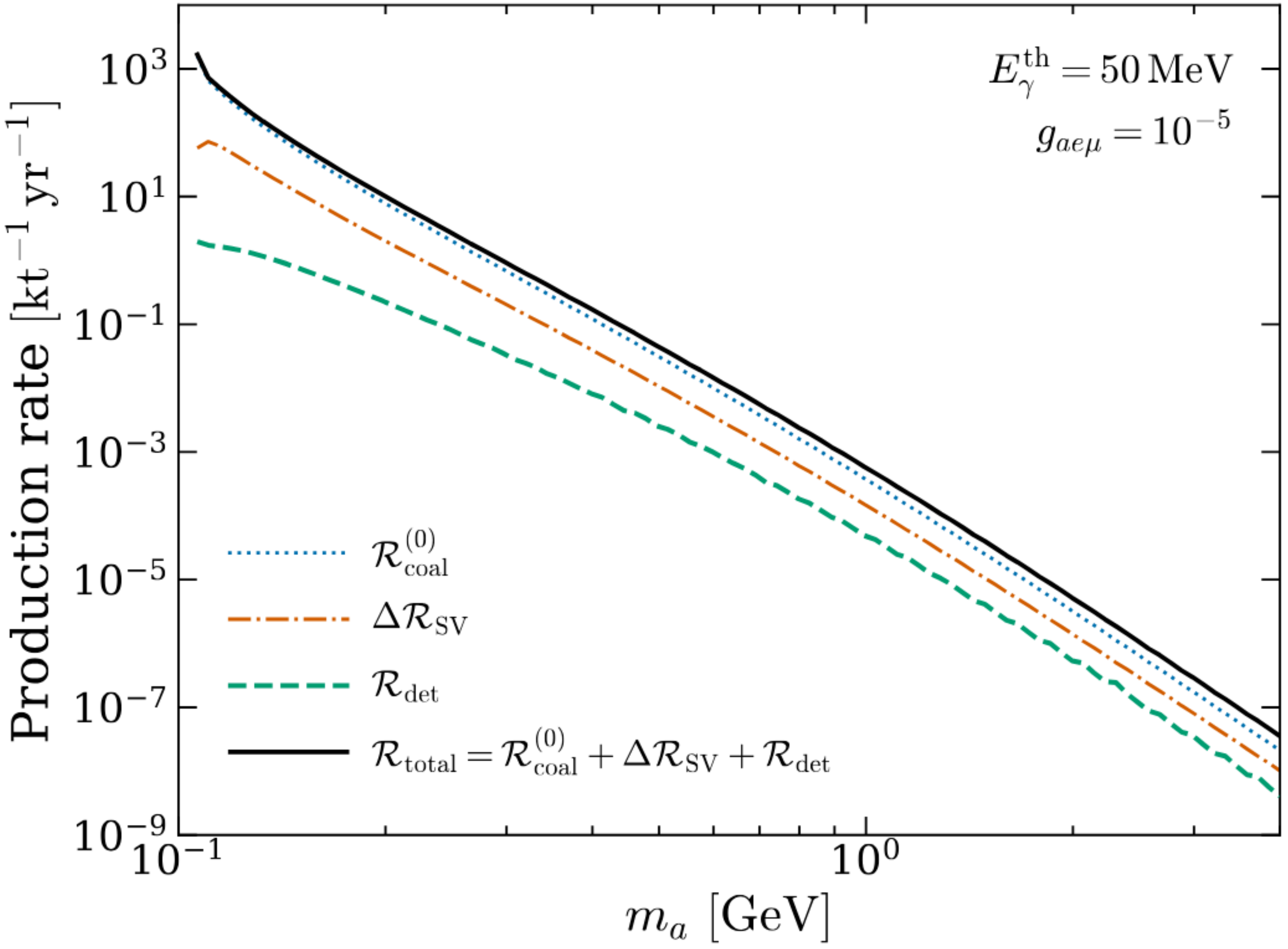
$$\delta_{\rm SV}^{\rm FT}(s;\mu_R,E_\gamma^{\rm th}) = \frac{\alpha}{\pi}\left[-B(\beta_{e\mu})\ln\frac{\sqrt{s}}{2E_\gamma^{\rm th}} + \frac{3}{2}\ln\frac{\mu_R^2}{s} + \widehat{C}_{\rm virt}^{\overline{\rm MS}}(s,m_e,m_\mu) + C_{\rm real}^{\rm finite,soft,FT}(s,m_e,m_\mu)\right]$$



Axion Production Rate



(a) (b) (c)



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

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

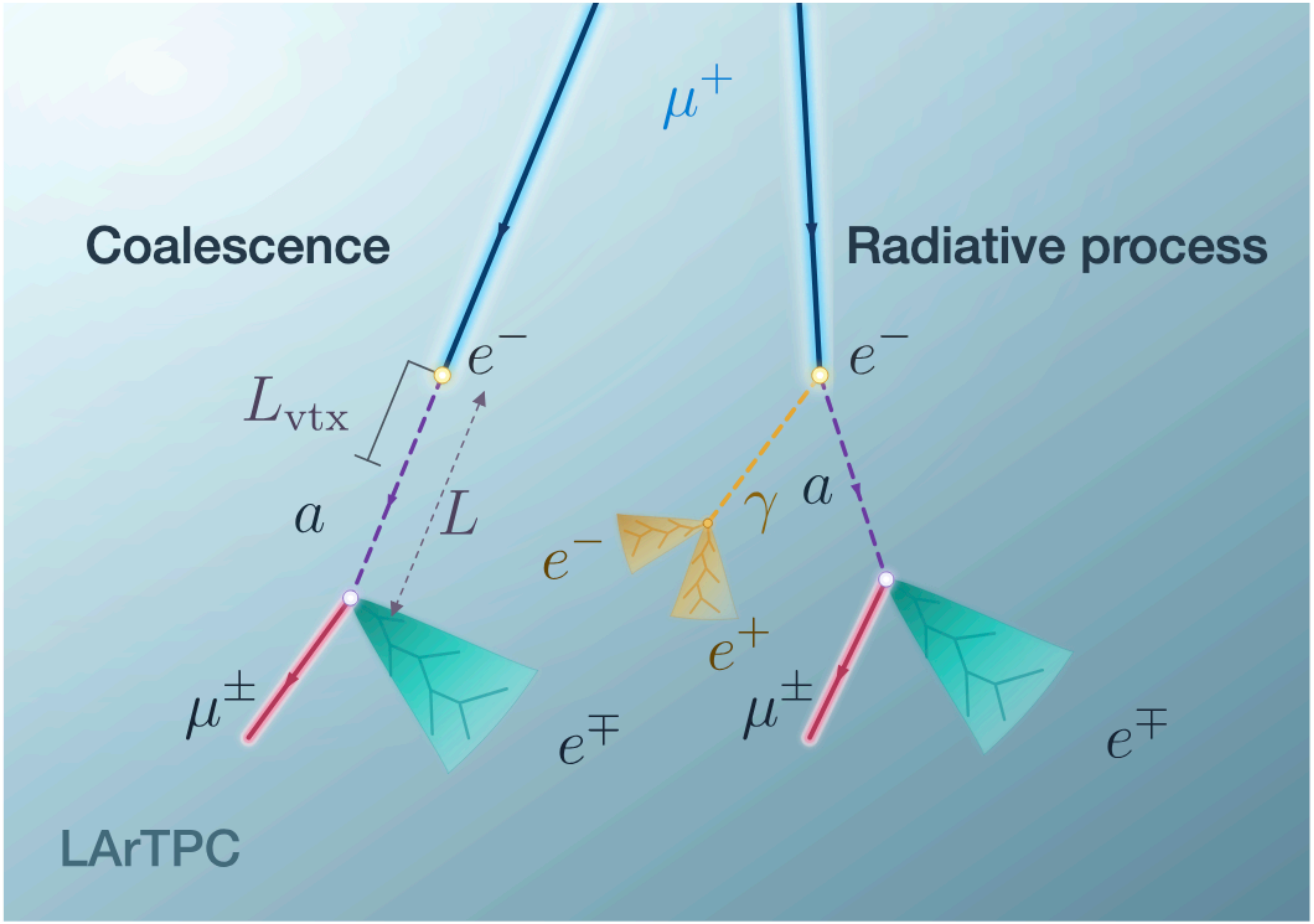
Decay probability for $L > L_{\rm vtx}$

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

Event rate with displaced vertex

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

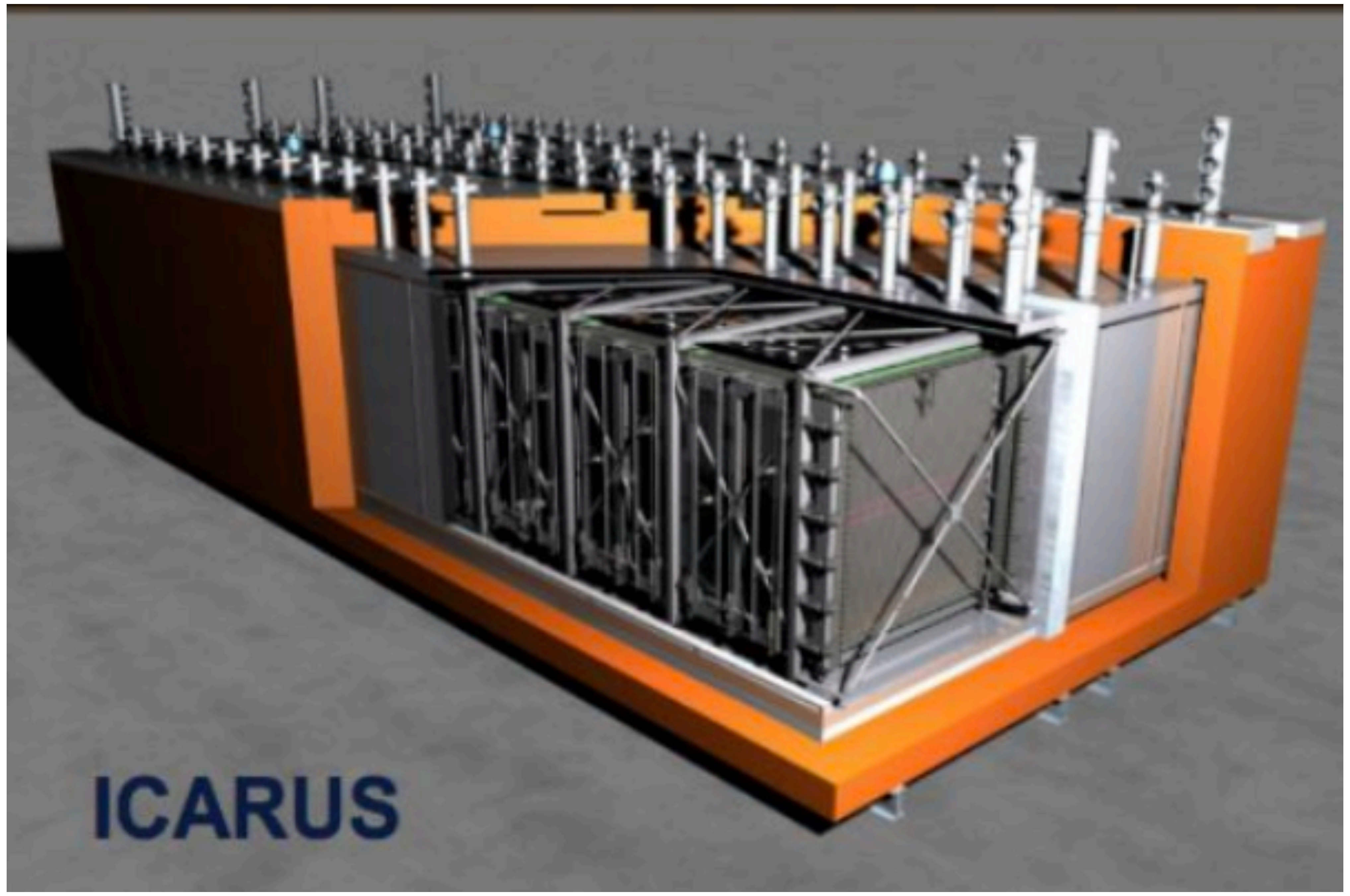
Topologies at LArTPC



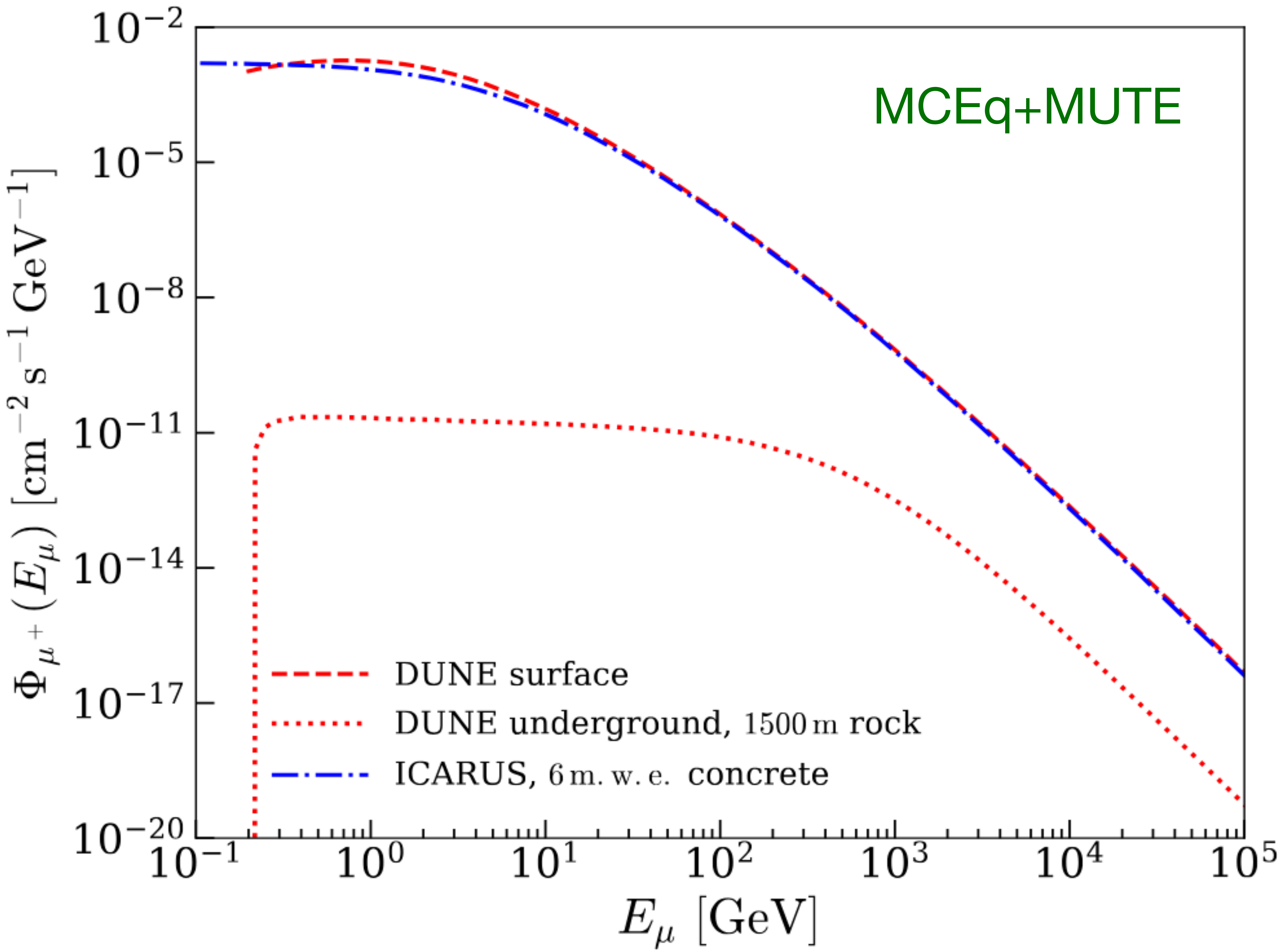
LArTPC Experiments

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

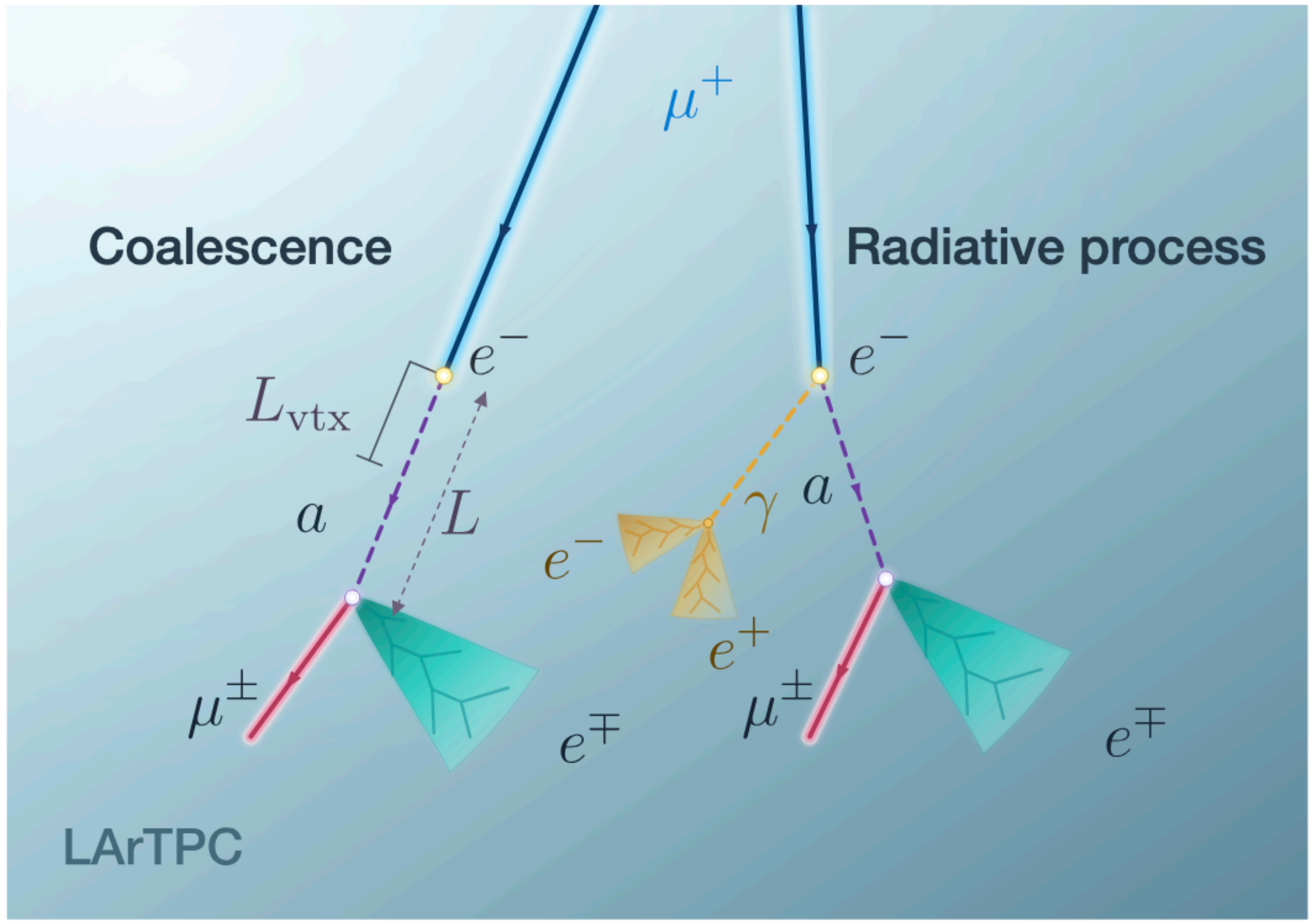
- DUNE far detector: Total active mass 40 kt, 1500 m underground, cm vertex reconstruction resolution, photon reconstruction threshold 5 MeV

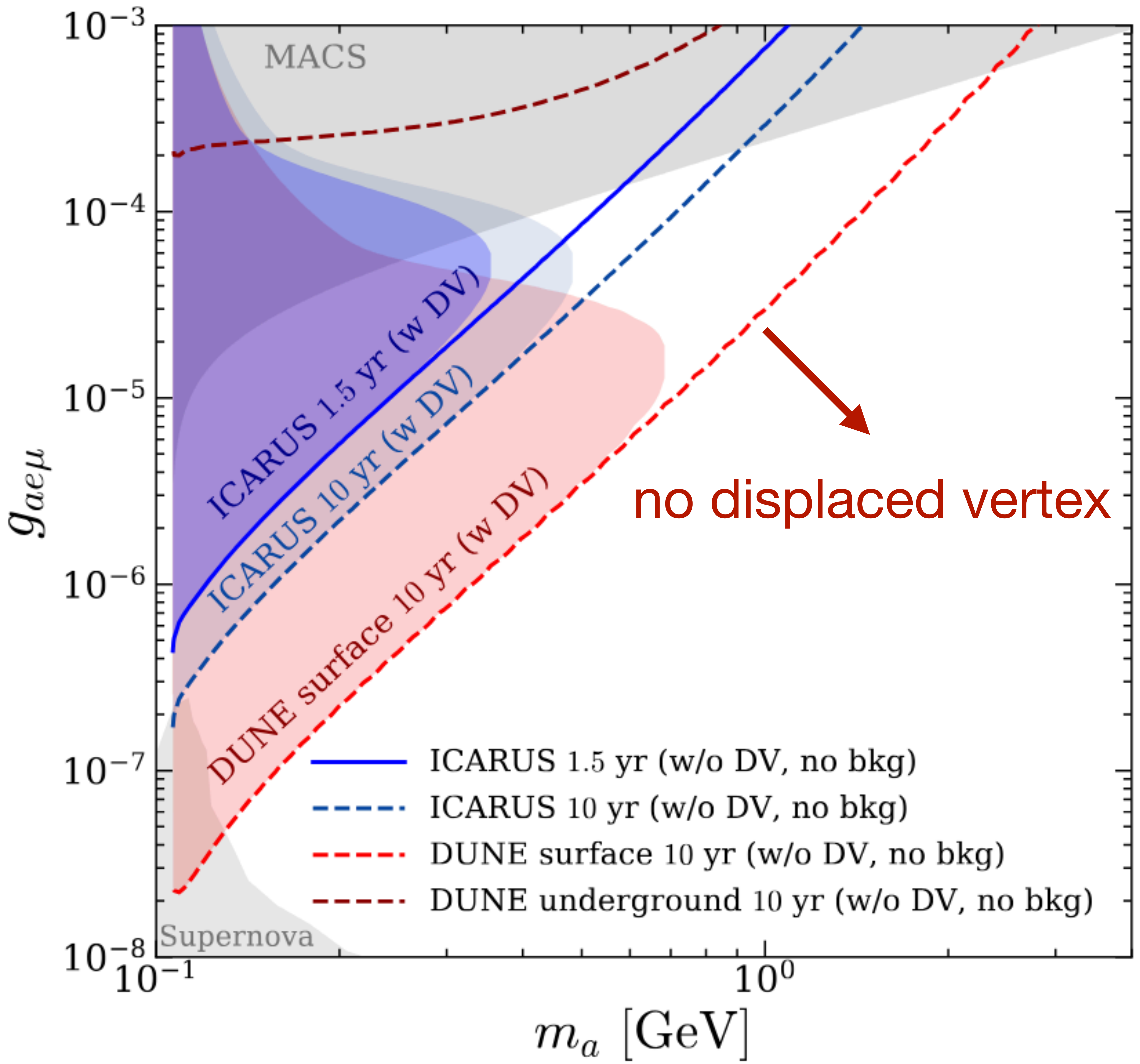


Muon Spectrum



Sensitivity on Flavor-violating Axion





Backgound:

- $\mu^\pm + N \to \mu^\pm + \cancel{e^+} + e^- + N$
- Ionization

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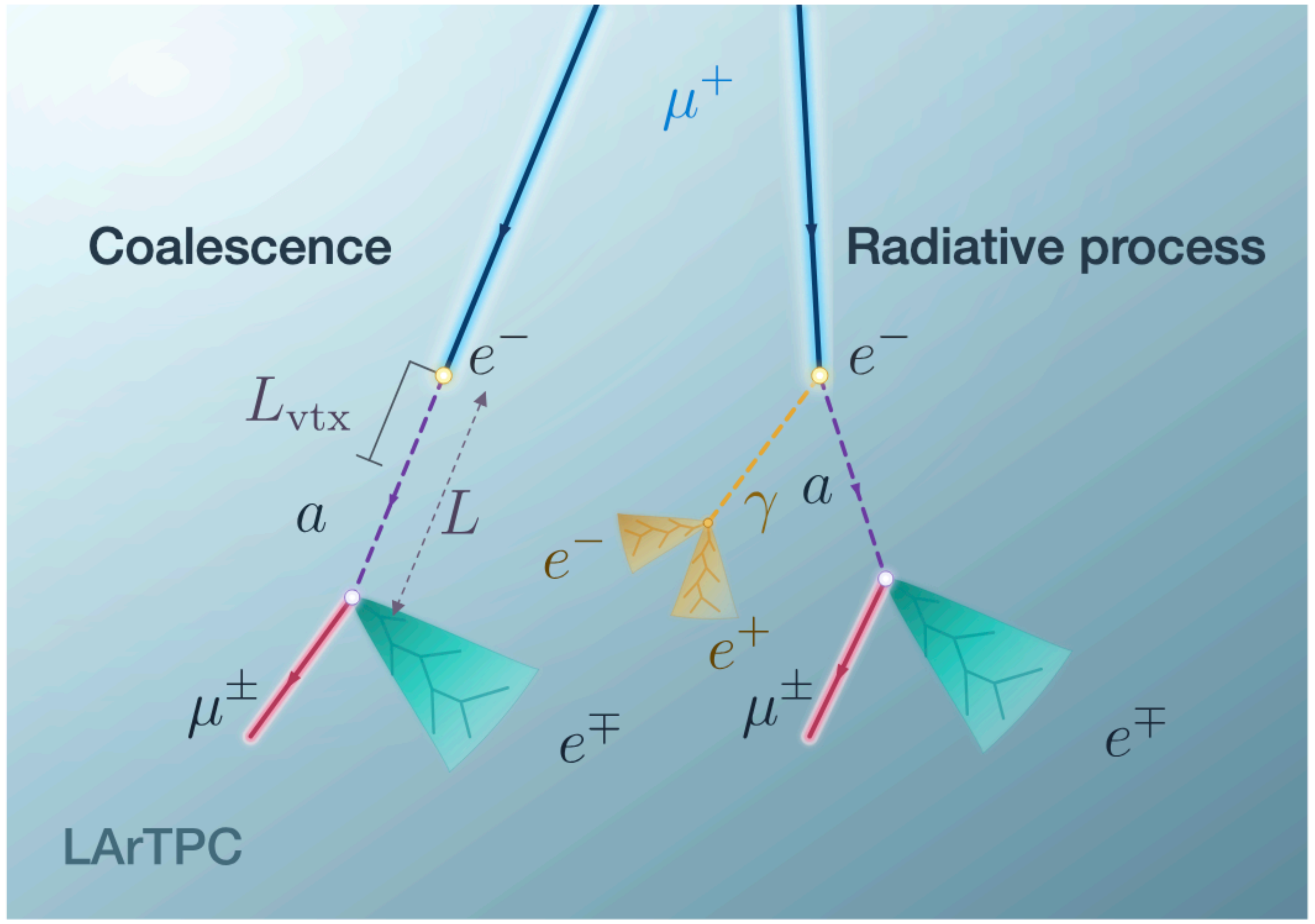
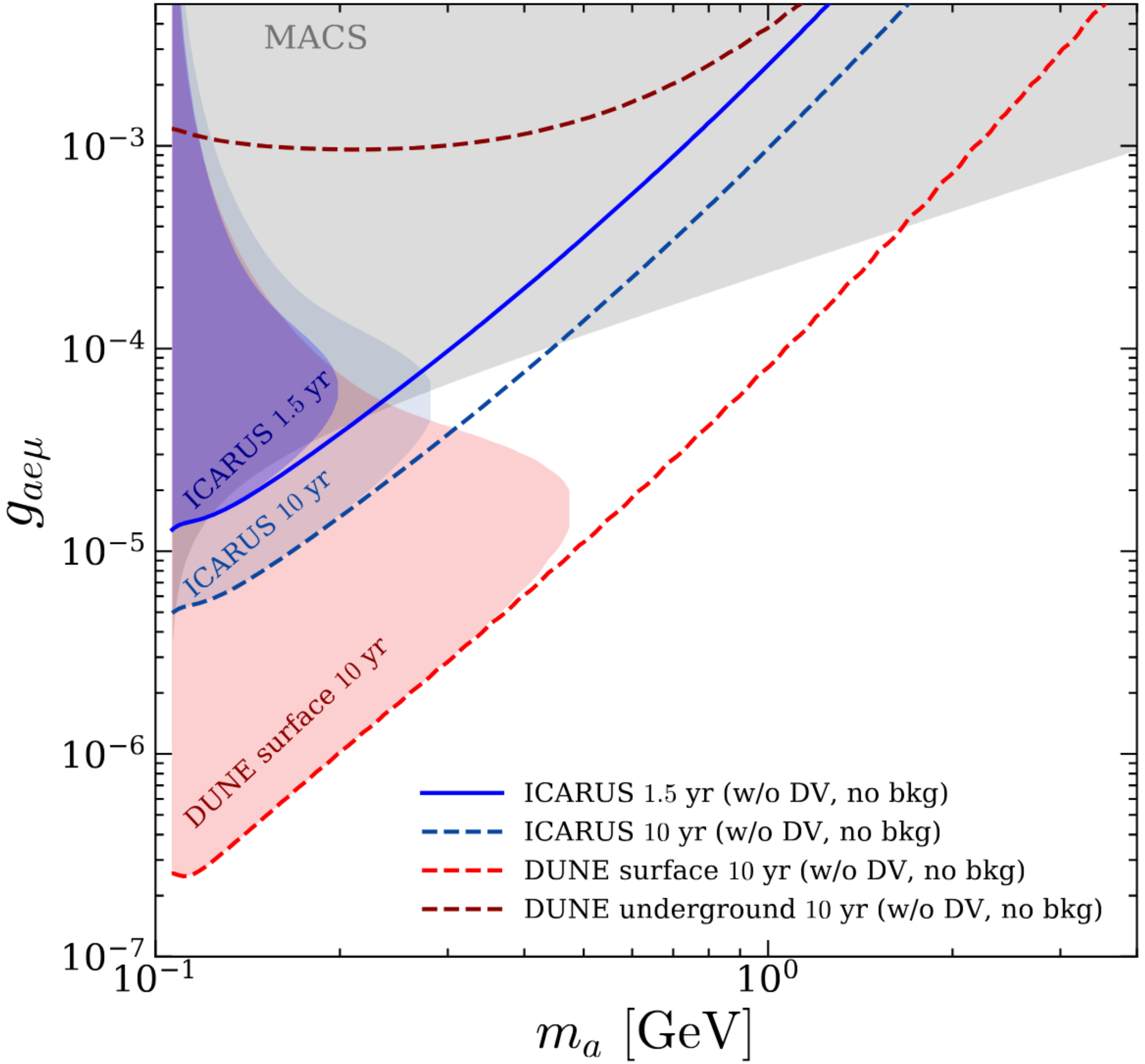
Sensitivity on Flavor-violating Axion from Hard Photon



Backgound:

- $\mu^\pm + N \to \mu^\pm + \cancel{e^+} + e^- + \gamma + N$

Zuowei Liu, Jindong Lv, NS, to appear



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
- Such process has unique topology at LArTPC
- ICARUS and DUNE can surpass the existing constraints by orders of magnitude

Thanks