Search for axion with polarization measurement and beam dumps

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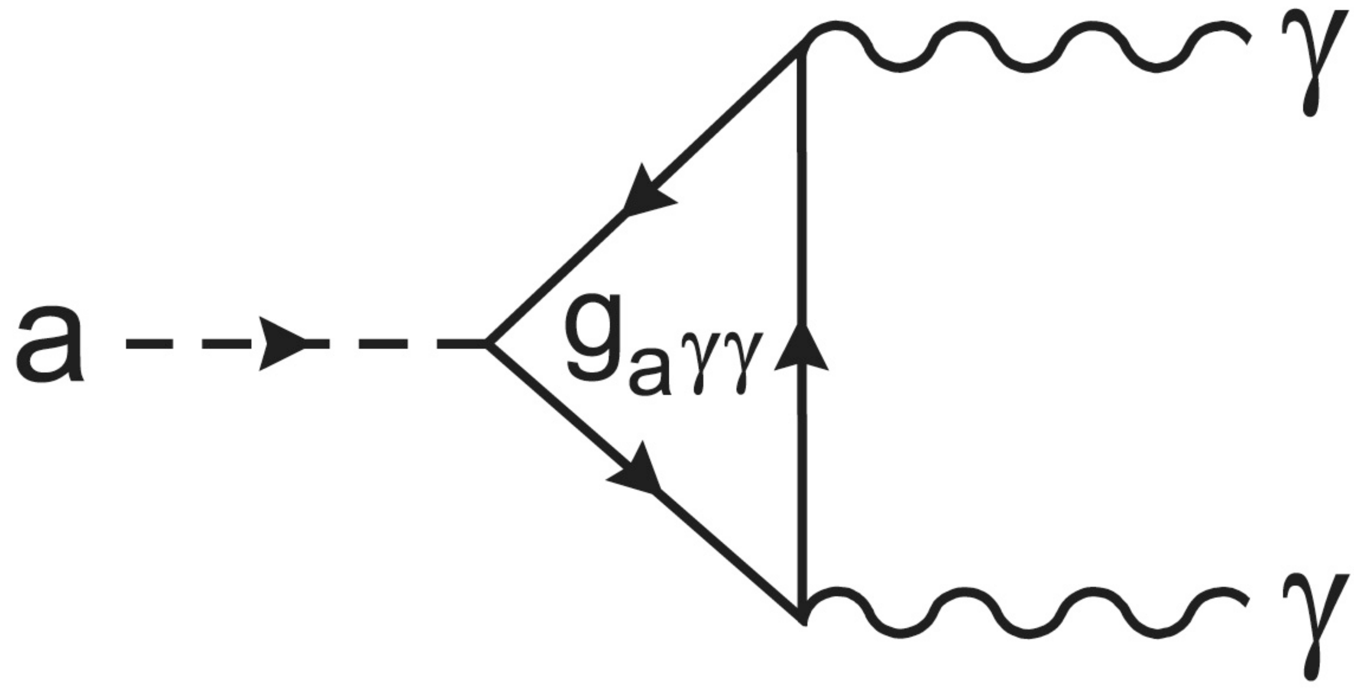
“Light” Axions from Polarization Measurements

with LiangLiang Su and Lei Wu

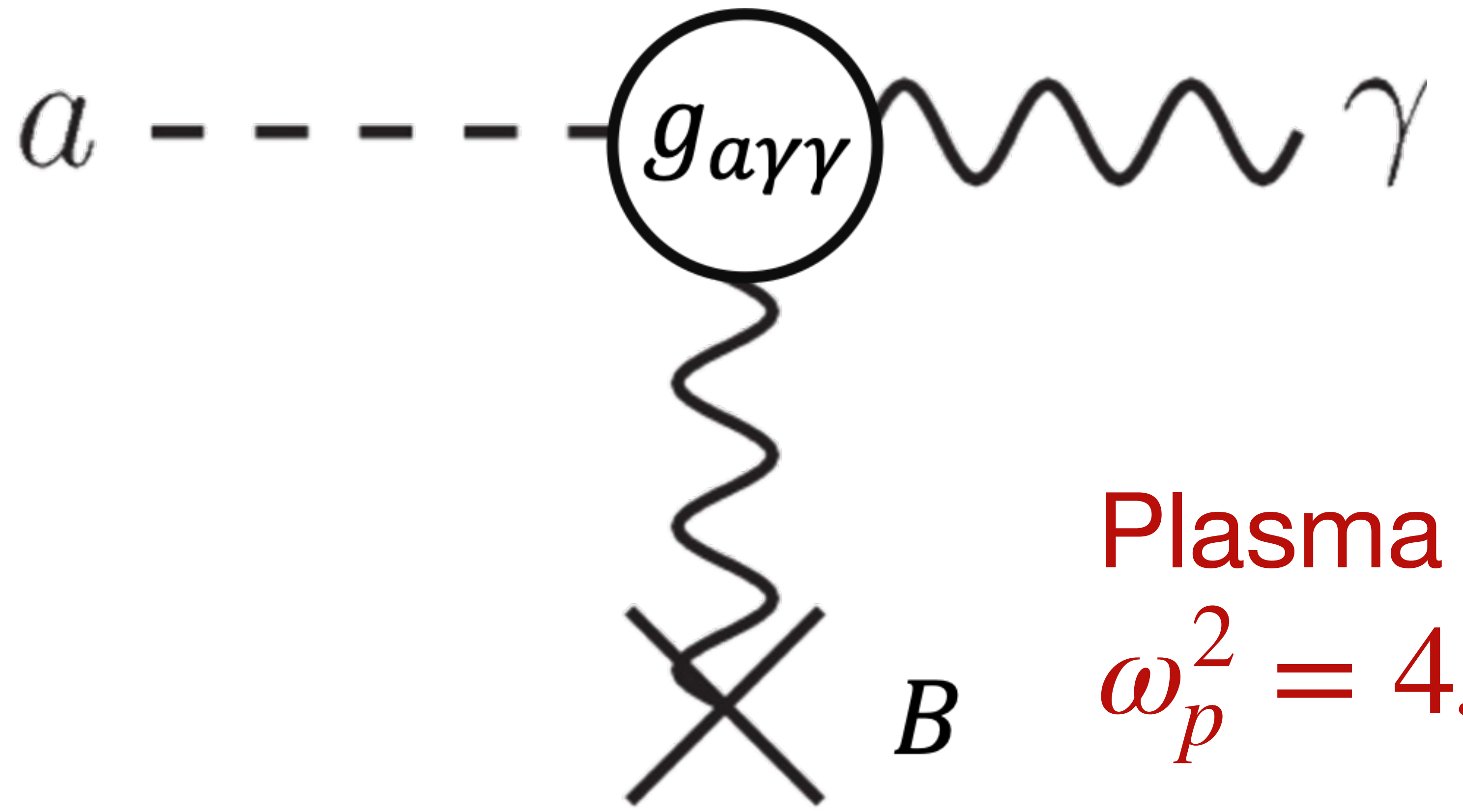
Axion-Photon Conversion

- CP conserved in QCD ⇒ axion
- $\mathscr{L}_{a\gamma\gamma} = \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$
- Resonant conversion from axion to photon in plasma when $m_a \sim \omega_p$



$\omega^2 = k^2 + m_a^2$

$\omega^2 \sim k^2 + \omega_p^2$



Plasma frequency

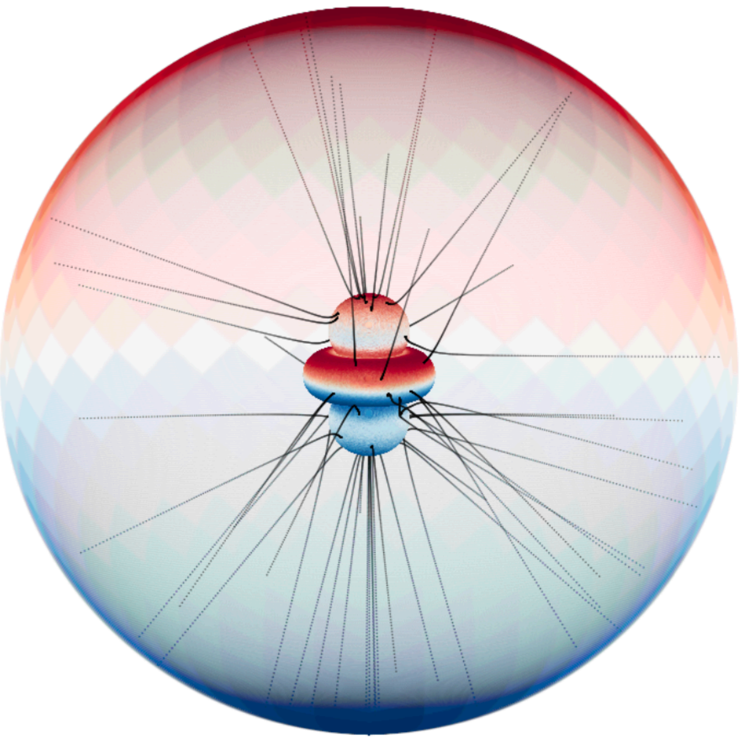
$\omega_p^2 = 4\pi\alpha n_e / m_e$

Radio Observation Constraint

Hook et al 1804.03145

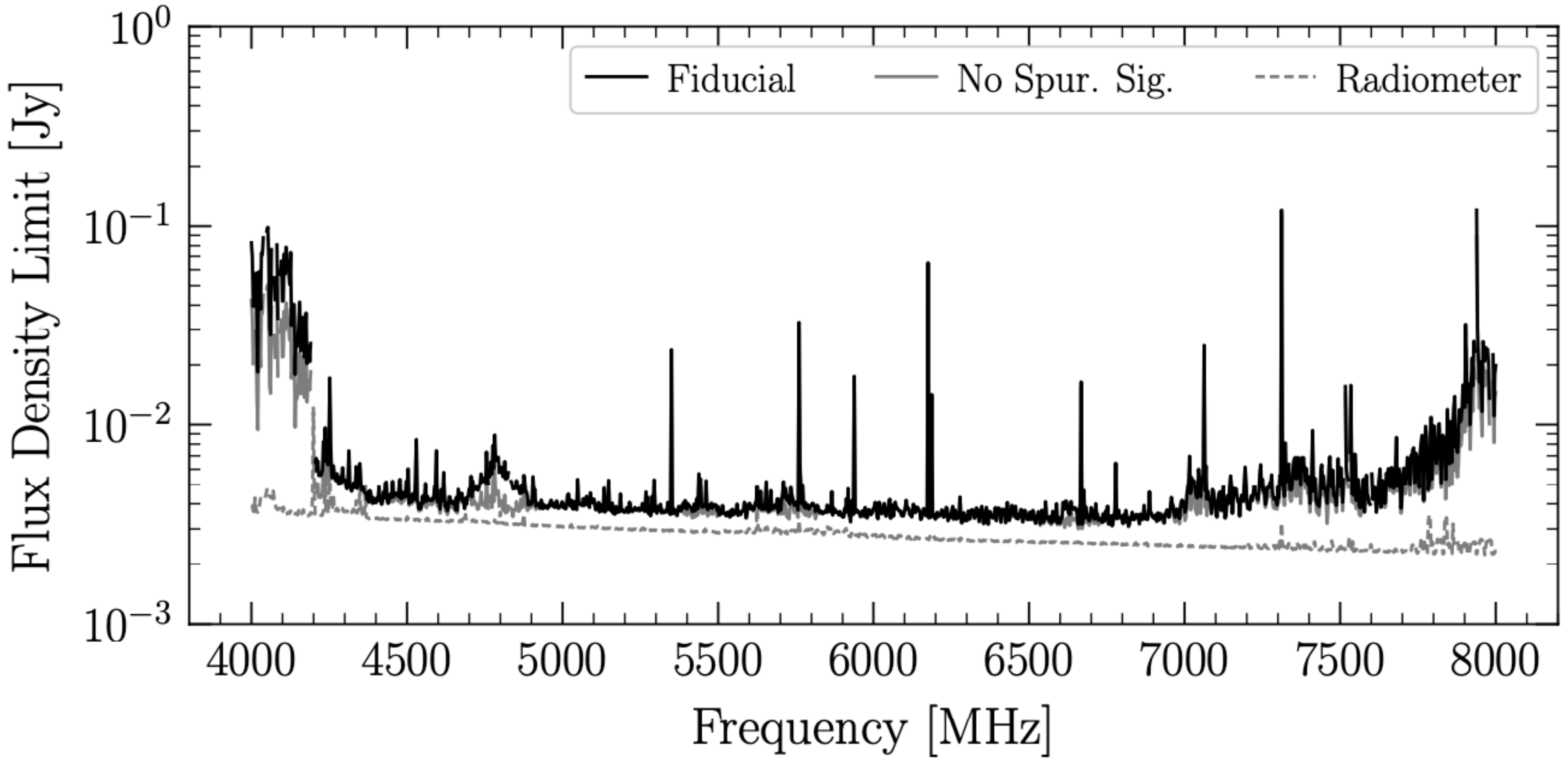
Neutron star magnetosphere

Millar et al 2107.07399

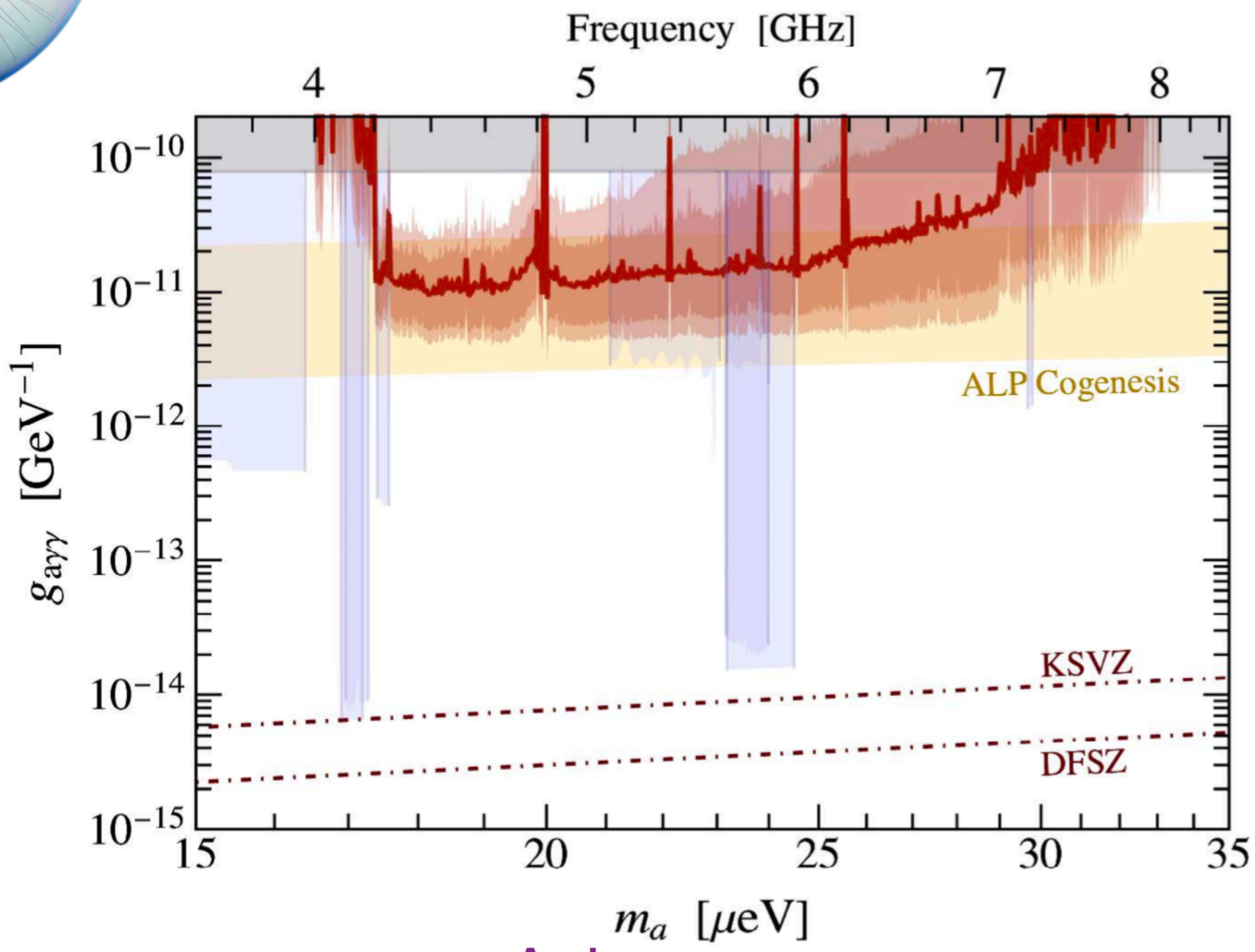


$$p = \frac{g_{a\gamma\gamma}^2 B^2}{2k\,|\,\omega_p'\,|}\frac{\pi m_a^5}{(k^2 + m_a^2 \sin^2\theta)^2}\sin^2\theta$$

Observation of radio from Galactic Center

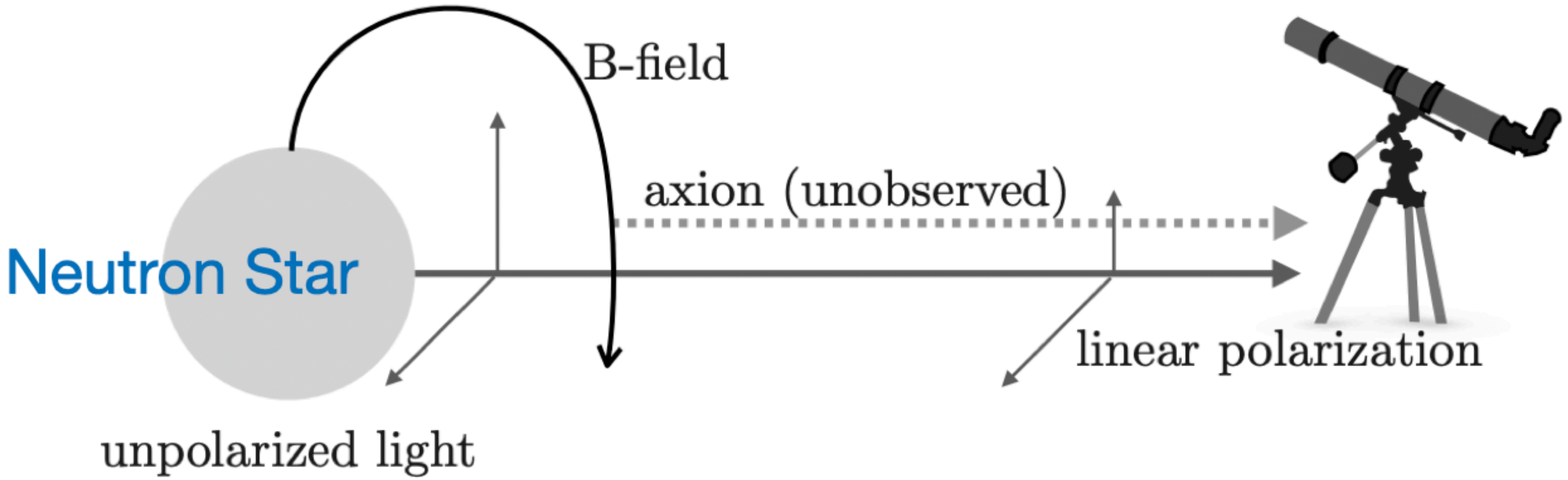


Foster et al 2202.08274



Axion mass

Polarization Signal



- Photon only converts to axion in the direction parallel to magnetic field, inducing polarization signals

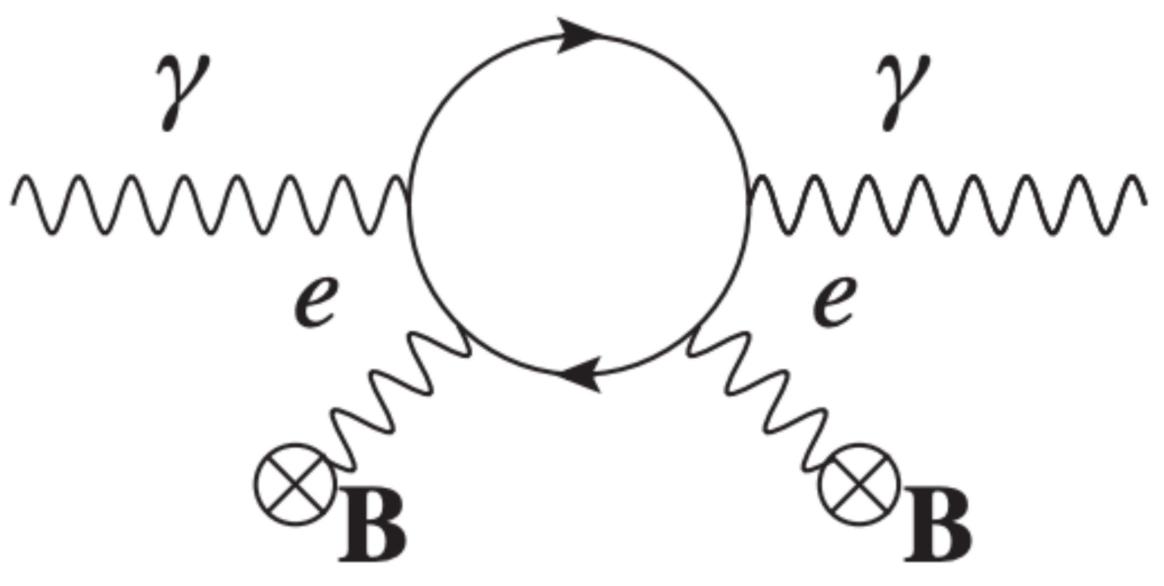
The Euler–Heisenberg Lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\left(\partial_\mu a \partial^\mu a - m_a^2 a^2\right) - \frac{g_{a\gamma}}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}a$$
$$+ \frac{\alpha^2}{90 m_e^4}\left[(F_{\mu\nu}F^{\mu\nu})^2 + \frac{7}{4}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)^2\right],$$

axion-photon coupling

Euler-Heisenberg Lagrangian

- The Euler-Heisenberg Lagrangian is significant when $B \gtrsim B_{\mathrm{QED}} = m_e^2/e \simeq 4.41 \times 10^{13}$ G



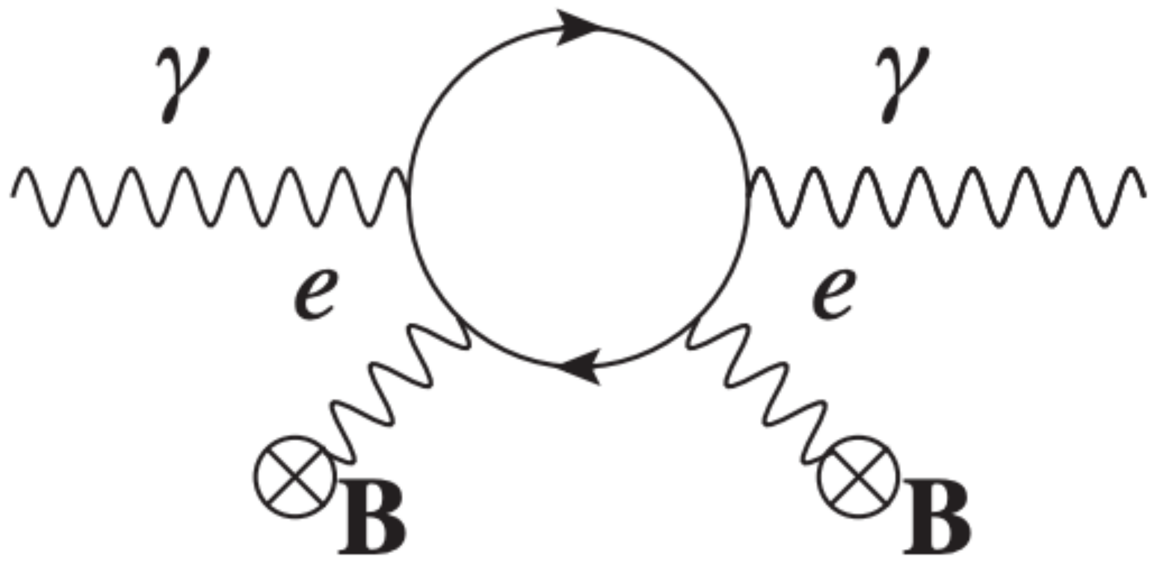
The Equation of Motion

axion-photon mixing

$$\left[i\partial_z + \begin{pmatrix} \Delta_a & \Delta_\mathrm{M} & 0 \\ \Delta_\mathrm{M} & \Delta_\parallel + \Delta_\mathrm{pl} & 0 \\ 0 & 0 & \Delta_\perp \end{pmatrix} \right] \begin{pmatrix} a \\ A_\parallel \\ A_\perp \end{pmatrix} = 0$$

vacuum polarization

plasma effect



$$\Delta_\mathrm{M} = \frac{1}{2} g_{a\gamma} B \sin\Theta, \quad \Delta_a = -\frac{m_a^2}{2\omega}, \quad \Delta_\mathrm{pl} = -\frac{\omega_\mathrm{pl}^2}{2\omega},$$

$$\Delta_\parallel = \frac{7}{2}\omega\xi \sin^2\Theta, \quad \Delta_\perp = \frac{4}{2}\omega\xi\sin^2\Theta,$$

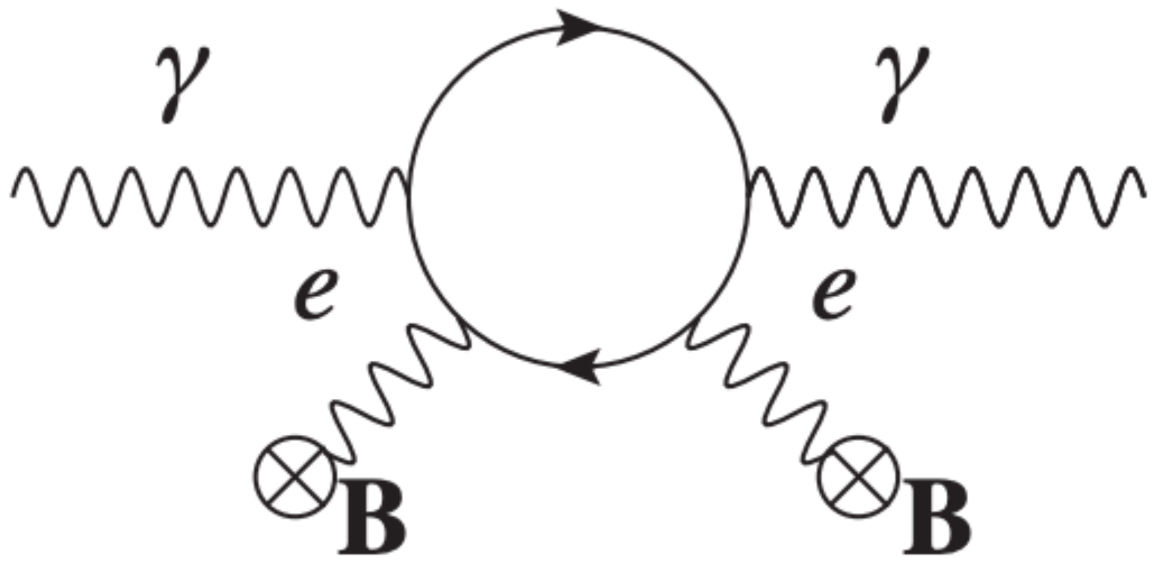
$$\xi = (\alpha/45\pi)(B/B_\mathrm{QED})^2;$$

$$\omega_\mathrm{pl} = \sqrt{4\pi\alpha n_e/m_e}$$

The Equation of Motion

axion-photon mixing

$$\left[i\partial_z + \begin{pmatrix} \Delta_a & \Delta_\mathrm{M} & 0 \\ \Delta_\mathrm{M} & \Delta_\| + \Delta_\mathrm{pl} & 0 \\ 0 & 0 & \Delta_\perp \end{pmatrix}\right]\begin{pmatrix} a \\ A_\| \\ A_\perp \end{pmatrix} = 0$$



vacuum polarization

plasma effect

Effective axion-photon mixing

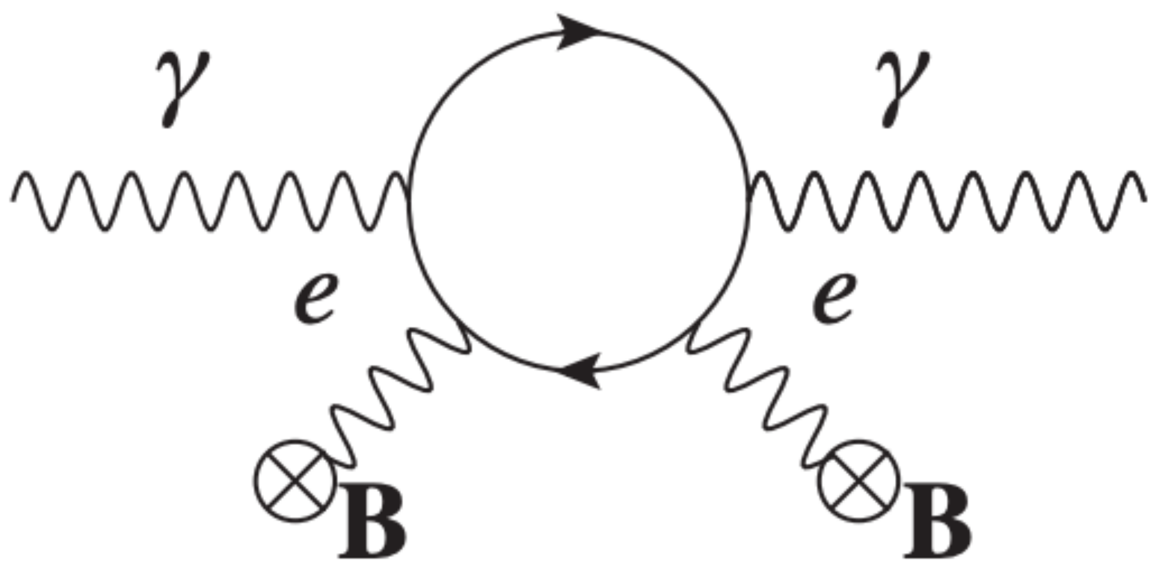
$$\tan 2\beta_m = \frac{2\Delta_\mathrm{M}}{\Delta_\| + \Delta_\mathrm{pl} - \Delta_a}.$$

Resonant conversion condition

$$\Delta_\| + \Delta_\mathrm{pl} - \Delta_a = 0$$

Resonant Conversion Probability

$$\left[i\partial_z + \begin{pmatrix} \Delta_a & \Delta_{\rm M} & 0 \\ \Delta_{\rm M} & \Delta_{\parallel} + \Delta_{\rm pl} & 0 \\ 0 & 0 & \Delta_{\perp} \end{pmatrix}\right] \begin{pmatrix} a \\ A_{\parallel} \\ A_{\perp} \end{pmatrix} = 0$$



Effective axion-photon mixing

$$\tan 2\beta_m = \frac{2\Delta_{\rm M}}{\Delta_{\parallel} + \Delta_{\rm pl} - \Delta_a}.$$

Resonant conversion condition

$$\Delta_{\parallel} + \Delta_{\rm pl} - \Delta_a = 0$$

Resonant conversion probability

$$P_{\gamma\to a} = 1 - P_{\rm jump}$$

$$H = n_e/|n_e'| \qquad \gamma_{\rm res} = \frac{4\Delta_M^2 H}{|\Delta_a + \Delta_{\parallel}|} \qquad P_{\rm jump} = e^{-\pi\gamma_{\rm res}/2}$$

Resonant Conversion Conditions

Resonant conversion condition

$$\Delta_{||} + \Delta_{\rm pl} - \Delta_a = 0$$

Resonant conversion probability

$$P_{\gamma\to a} = 1 - P_{\rm jump} \qquad P_{\rm jump} = e^{-\pi\gamma_{\rm res}/2}$$

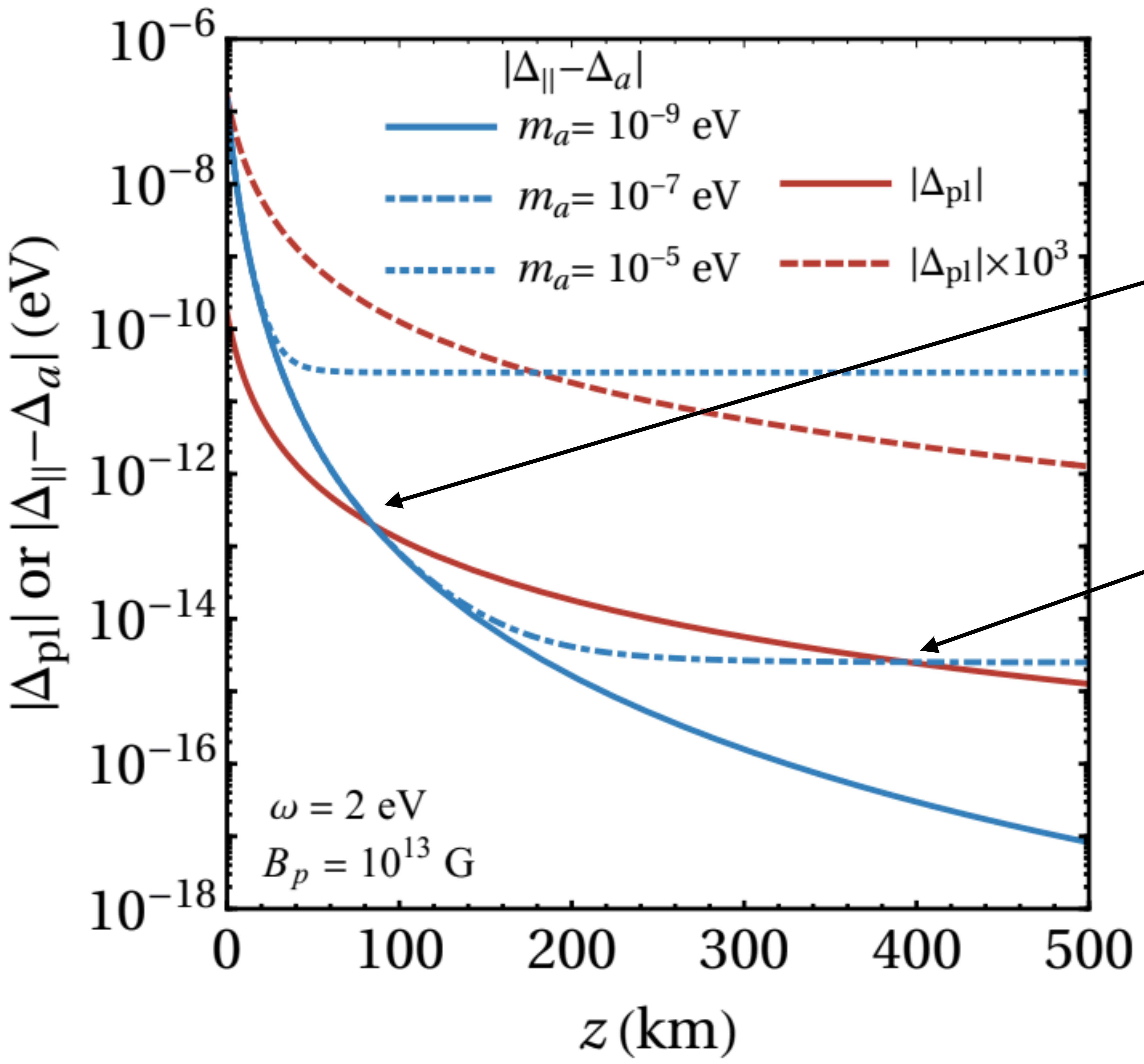
Plasma-vacuum resonance $|\Delta_a| \ll \Delta_{||} \approx -\Delta_{\rm pl}$

$$\gamma_{\rm res} = \frac{4\Delta_{\rm M}^2 H}{\Delta_{||}} \propto \frac{g_{a\gamma}^2 H}{\omega} \approx g_{a\gamma}^2 \frac{r_{\rm NS} + z_{\rm res}}{3\omega},$$

Plasma-mass resonance $\Delta_{||} \ll |\Delta_{\rm pl}| \approx |\Delta_a|$

$$\gamma_{\rm res} = \frac{4\Delta_{\rm M}^2 H}{|\Delta_a|} \propto \frac{g_{a\gamma}^2 B_{\rm res}^2 \omega H}{m_a^2} \approx g_{a\gamma}^2 B_{\rm res}\omega H$$

Resonant Conversion Conditions



NS, Liangliang Su, Lei Wu, PRD/2402.15144

$$\Delta_{\parallel} + \Delta_{\rm pl} - \Delta_a = 0$$

Plasma-vacuum resonance

Plasma-mass resonance

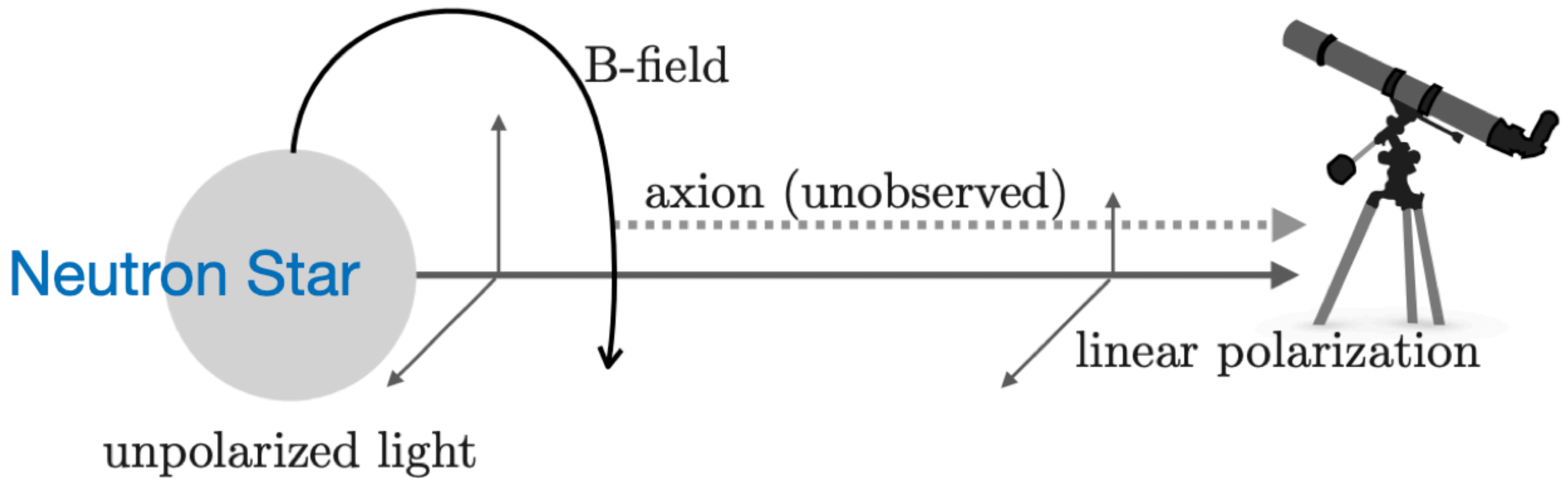
$$\Delta_{\rm M} = \frac{1}{2} g_{a\gamma} B \sin\Theta, \quad \Delta_a = -\frac{m_a^2}{2\omega}, \quad \Delta_{\rm pl} = -\frac{\omega_{\rm pl}^2}{2\omega},$$

$$\Delta_{\parallel} = \frac{7}{2}\omega\xi\sin^2\Theta, \quad \Delta_{\perp} = \frac{4}{2}\omega\xi\sin^2\Theta,$$

$$\Delta_{\parallel} \propto B^2 \qquad \Delta_{pl} \propto n_e \propto B$$

GJ model $$n_c = \frac{2\mathbf{\Omega}\cdot\mathbf{B}}{e}\frac{1}{1-\Omega^2 r^2 \sin^2\theta}$$

Polarization from photon-axion conversion



$$\Pi_L(z) = \frac{I_\perp(z) - (1 - P^{\rm res}_{\gamma\to a}) I_\parallel^{\rm nonres}(z)}{I_\perp(z) + (1 - P^{\rm res}_{\gamma\to a}) I_\parallel^{\rm nonres}(z)}$$

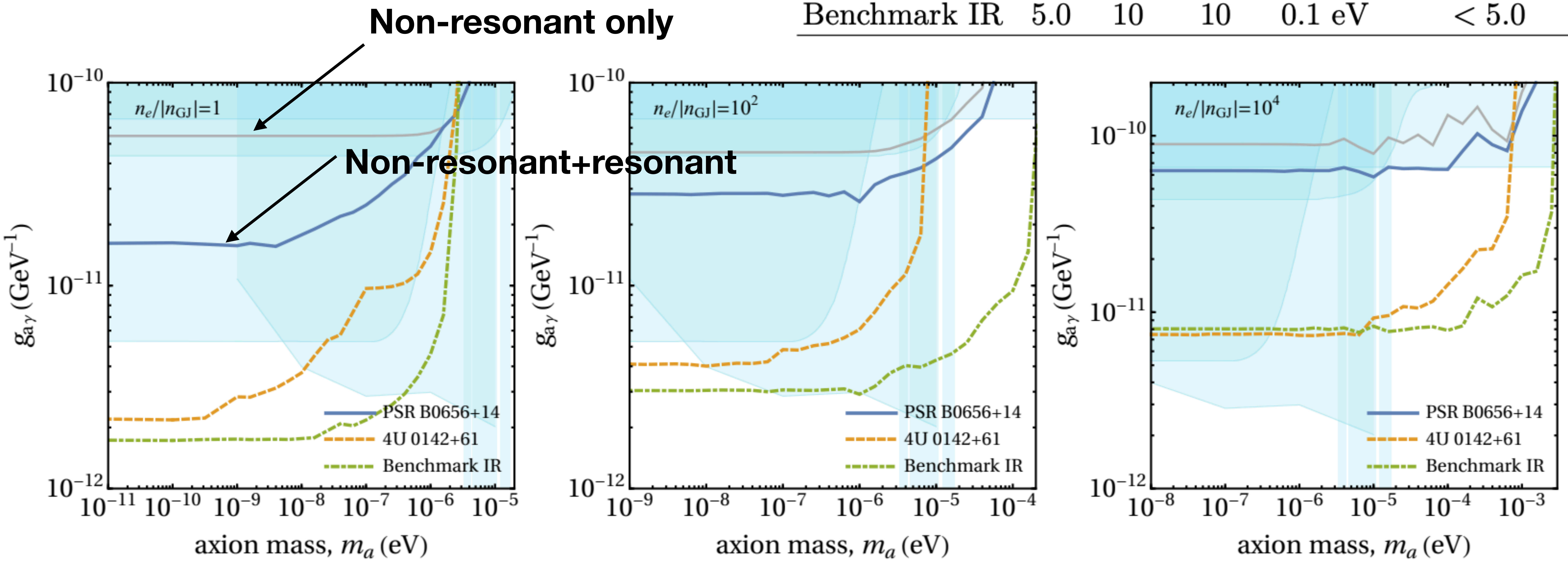
$$\approx \frac{P^{\rm res}_{\gamma\to a} + 2|{\rm Re}(A_{\parallel,2})|}{2 - (P^{\rm res}_{\gamma\to a} + 2|{\rm Re}(A_{\parallel,2})|)},$$

$$A_{\parallel,2}(z) = \int_0^z {\rm d}z' \Delta_{\rm M}(z') \int_0^{z'} {\rm d}z'' \Delta_{\rm M}(z'') e^{-i\int_{z''}^{z'} {\rm d}z''' \Delta_{\rm tr}(z''')}$$

- Photon only converts to axion in the direction parallel to magnetic field, inducing polarization signals

Optical Polarization Signal

Star	T (s)	$r_{\rm NS}$ (km)	B_p (10^{13}G)	ω or λ	PD (%)
B0656+14	0.384	9.3	0.47	555 nm	11.9 ± 5.5 [64]
4U 0142+61	8.689	16.1	13	I-band	< 5.6 [65]
Benchmark IR	5.0	10	10	0.1 eV	< 5.0



- Optical polarization signals from neutron stars could place the most stringent limits

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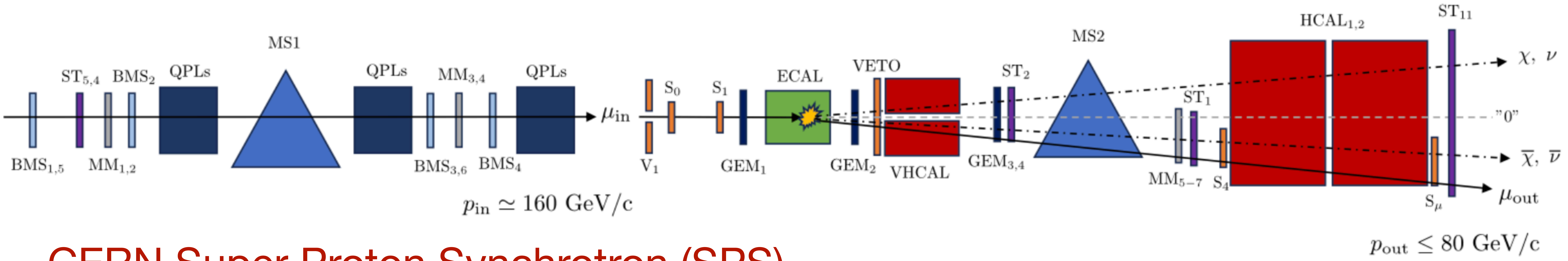
“Heavy” Axions at Beam Dump

with Haotian Li and Zuowei Liu

The NA64μ Experiment

2022 pilot run



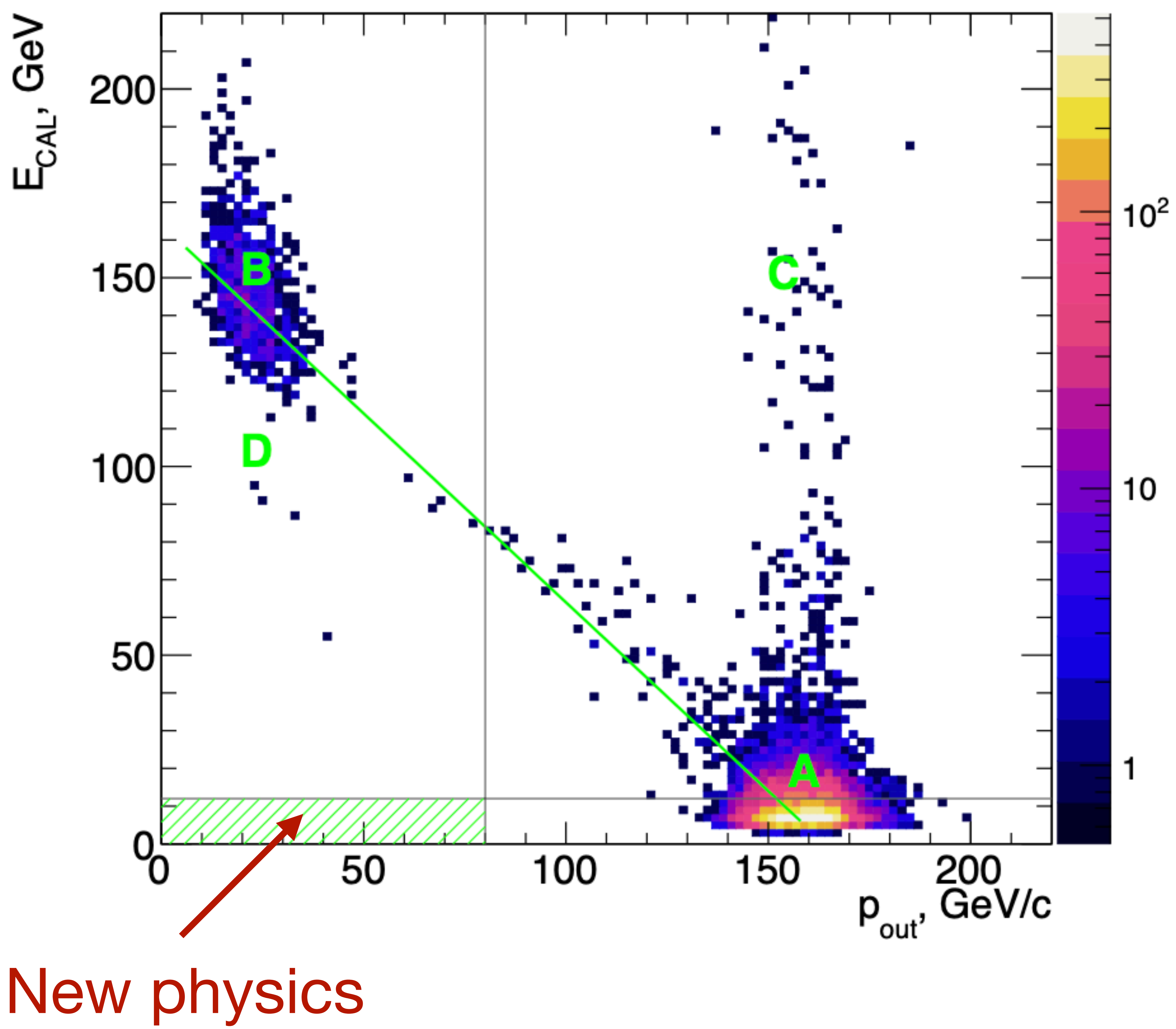
CERN Super Proton Synchrotron (SPS)

NA64 collaboration, PRL/2401.01708

160 GeV muon beam

1.98×10^{10} muon on target

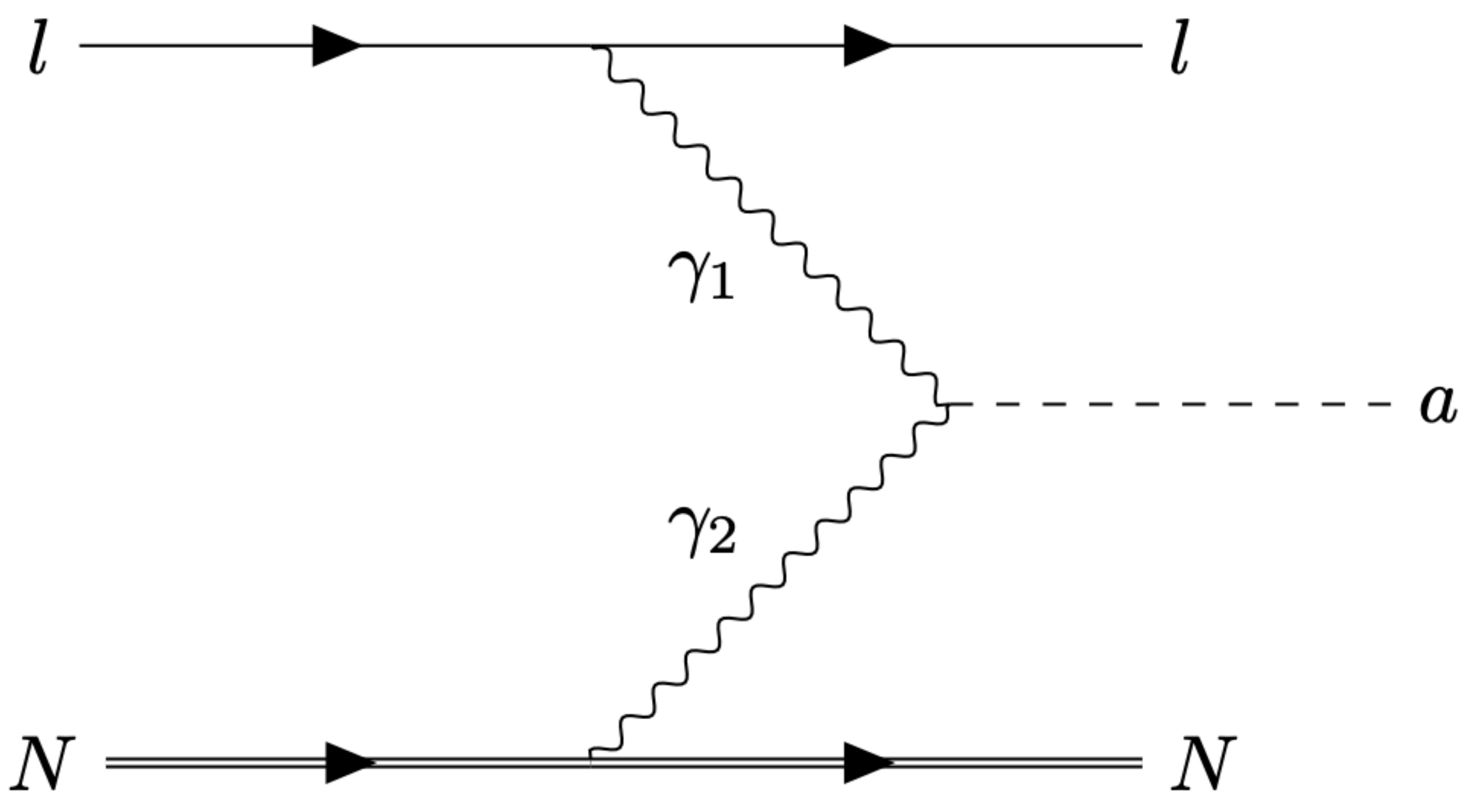
Events at NA64μ

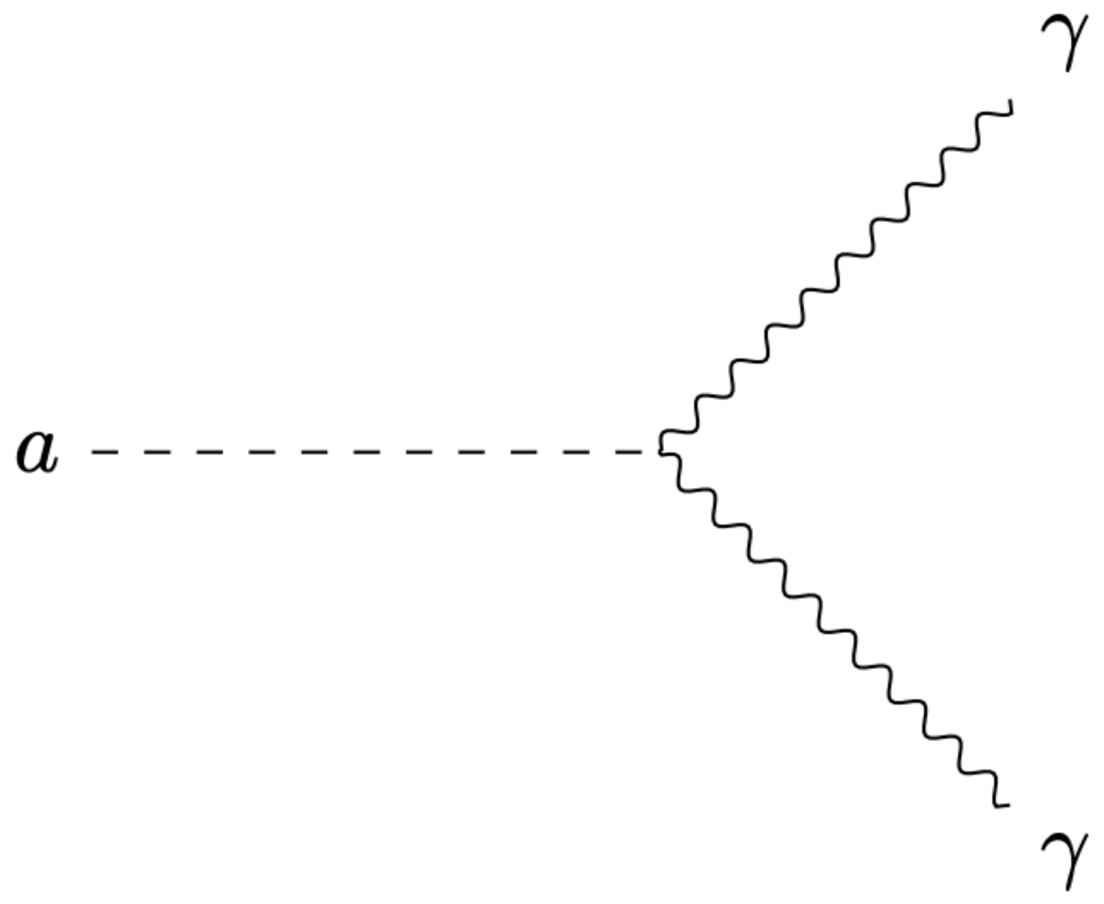


- Region A: soft muon scattering with small energy deposition
- Region B: hard scattering and large energy deposition in the target
- Region C: soft scattering and large energy deposition in the last calorimeter
- Region D: Hard scattering in the target with hadrons left out

Axion-Photon Interaction

$$\mathcal{L}_{\text{ALP}} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$





Axion production through photon-photon fusion

Production Rate

Target length

Decay probability

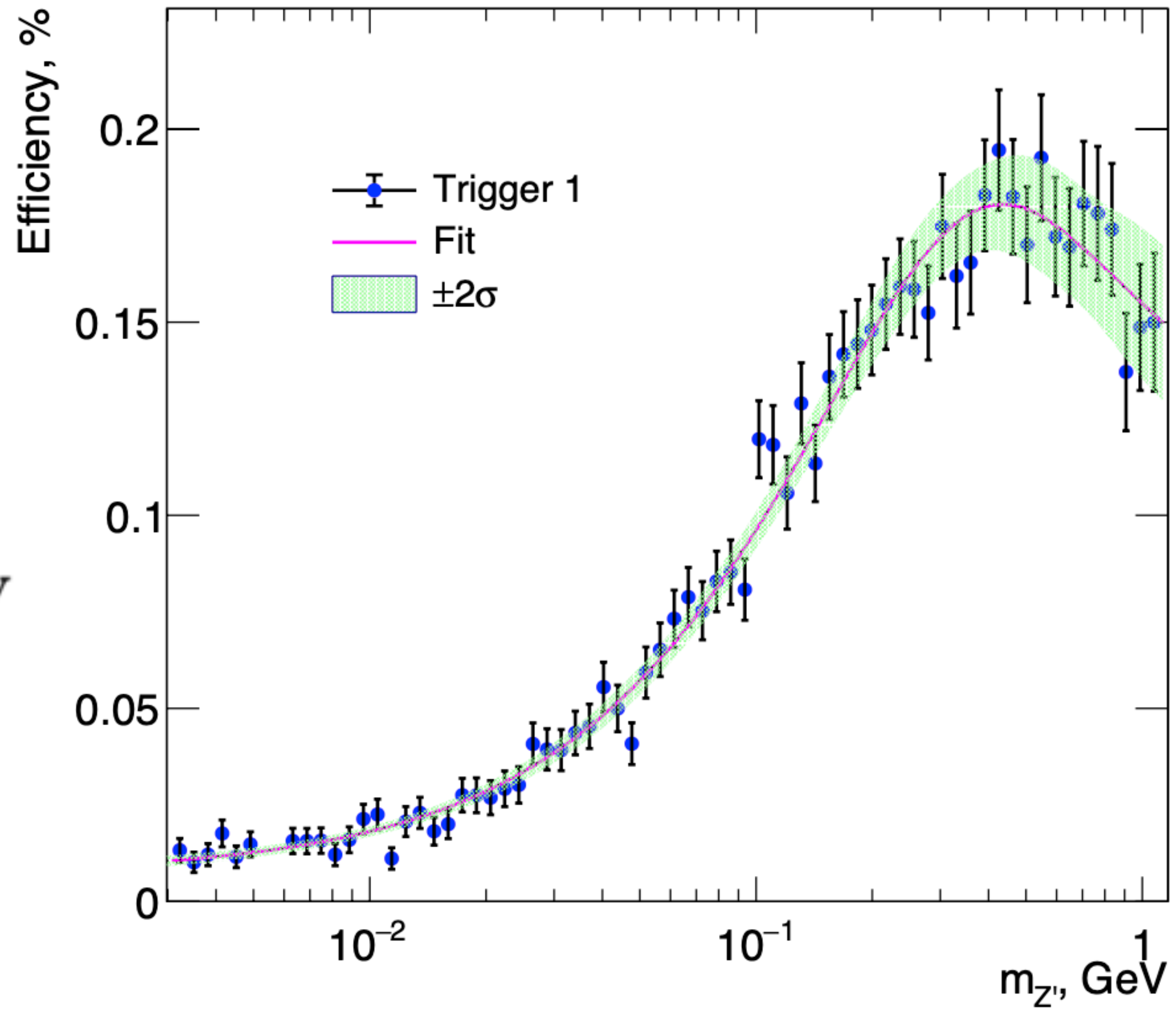
$$N_{\mathrm{signal}} = N_{\mathrm{MOT}} n_{\mathrm{Pb}} L_{\mathrm{tar}} \int d\sigma(\mu N \to \mu N X) \epsilon P_{\mathrm{inv}}$$

Muon on target
1.98×10^{10}

Pb target density

Scattering cross section

Efficiency



NA64 collaboration, 2409.10128

Cross Section

$$N_{\text{signal}} = N_{\text{MOT}} n_{\text{Pb}} L_{\text{tar}} \int d\sigma(\mu N \to \mu N X) \epsilon P_{\text{inv}}$$

Weizsacker-William approxmation

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = \frac{\alpha}{8\pi^2} \sqrt{E_a^2 - m_a^2} E_\mu (1-x) \int \mathrm{d}\cos\theta \frac{\chi}{\tilde{u}^2} \mathcal{A}$$

effective photon flux

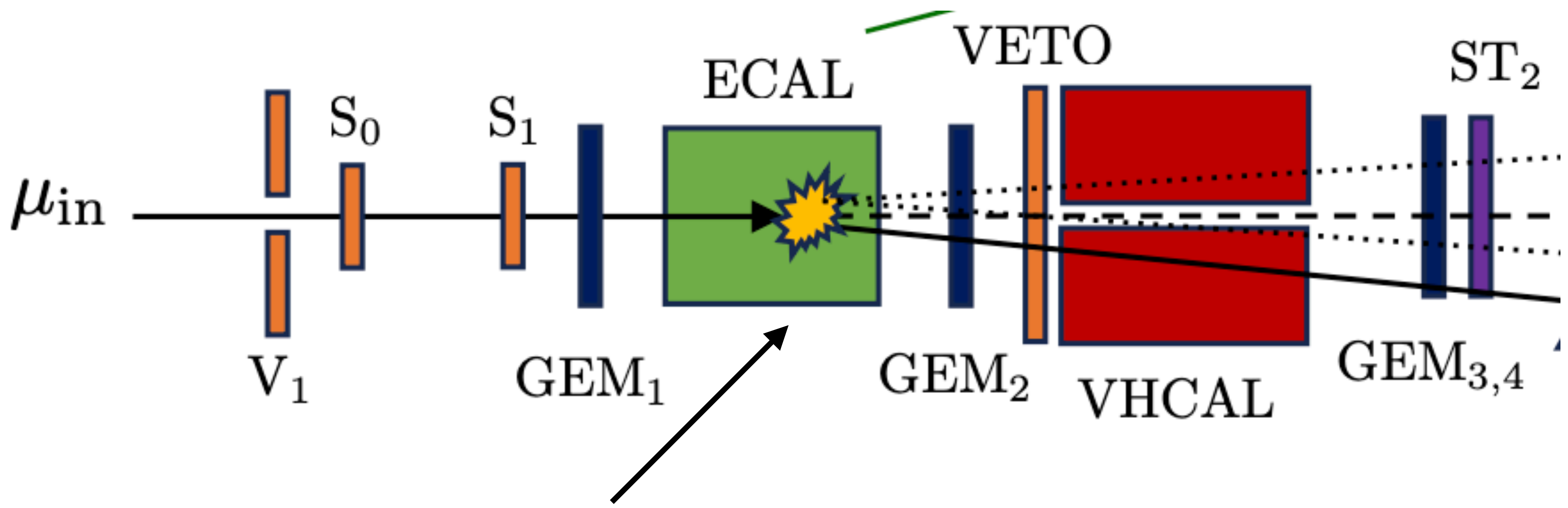
$$\chi = \int_{t_{\min}}^{t_{\max}} \mathrm{d}t \frac{t - t_{\min}}{t^2} F^2(t)$$

Nucleus elastic form factor

$$F(t) \simeq Z\left(\frac{b^2 t}{1 + b^2 t}\right)\left(\frac{1}{1 + t/d}\right)$$

$$\mathcal{A}_{a-\gamma} = -e^2 g_{a\gamma\gamma}^2 \tilde{u}^2 \frac{\tilde{u}x(2-x) + 2m_\mu^2 x^2 + m_a^2(1-x)(2-x)}{(m_a^2(1-x) + x\tilde{u})^2}$$

Decay Probability



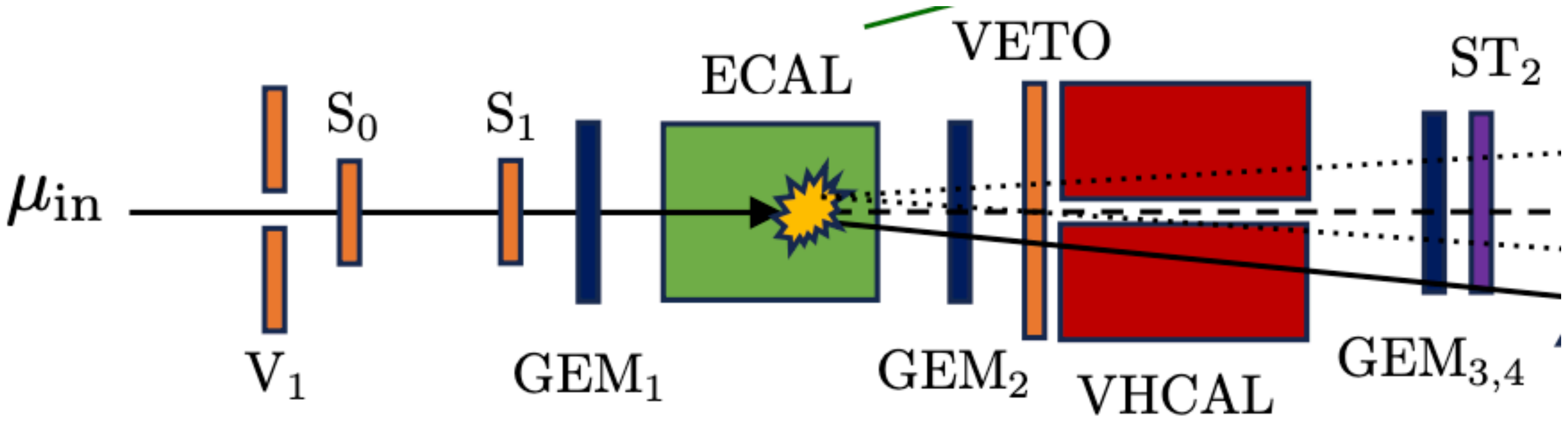
The target ECAL consists of 150 layers of Pb

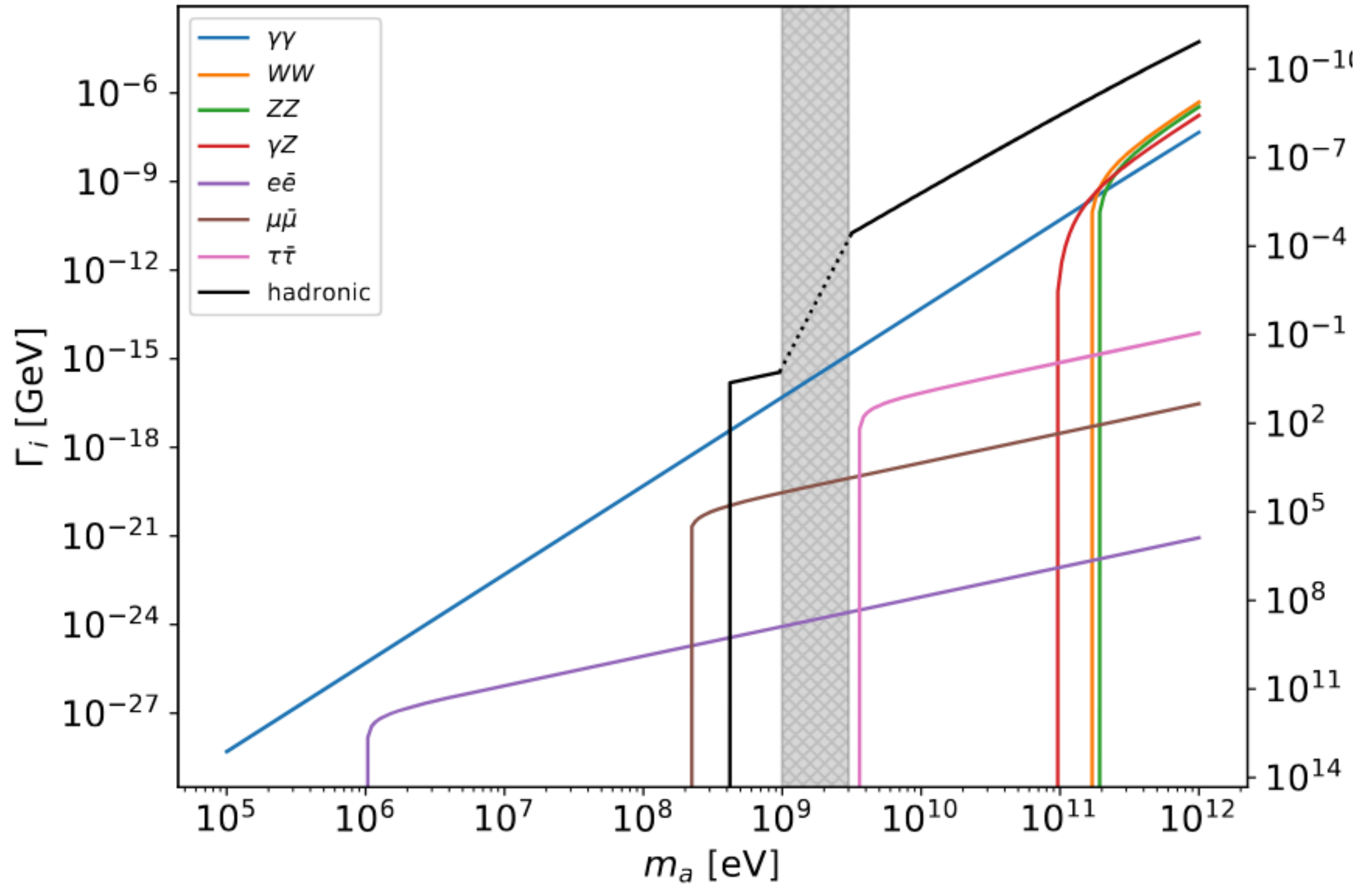
$$P_{\text{invisible}} = (\mathrm{e}^{-L_{\text{ECAL}}/l_a} - \mathrm{e}^{-L_V/l_a}) + (\mathrm{e}^{-(L_V+L_{\text{VHCAL}})/l_a} - \mathrm{e}^{-L_H/l_a}) + \mathrm{e}^{-(L_H+2L_{\text{HCAL}})/l_a}$$

$$\bar{P}_{\text{inv}} = \frac{1}{N}\sum_{i=0}^{N} P_i$$

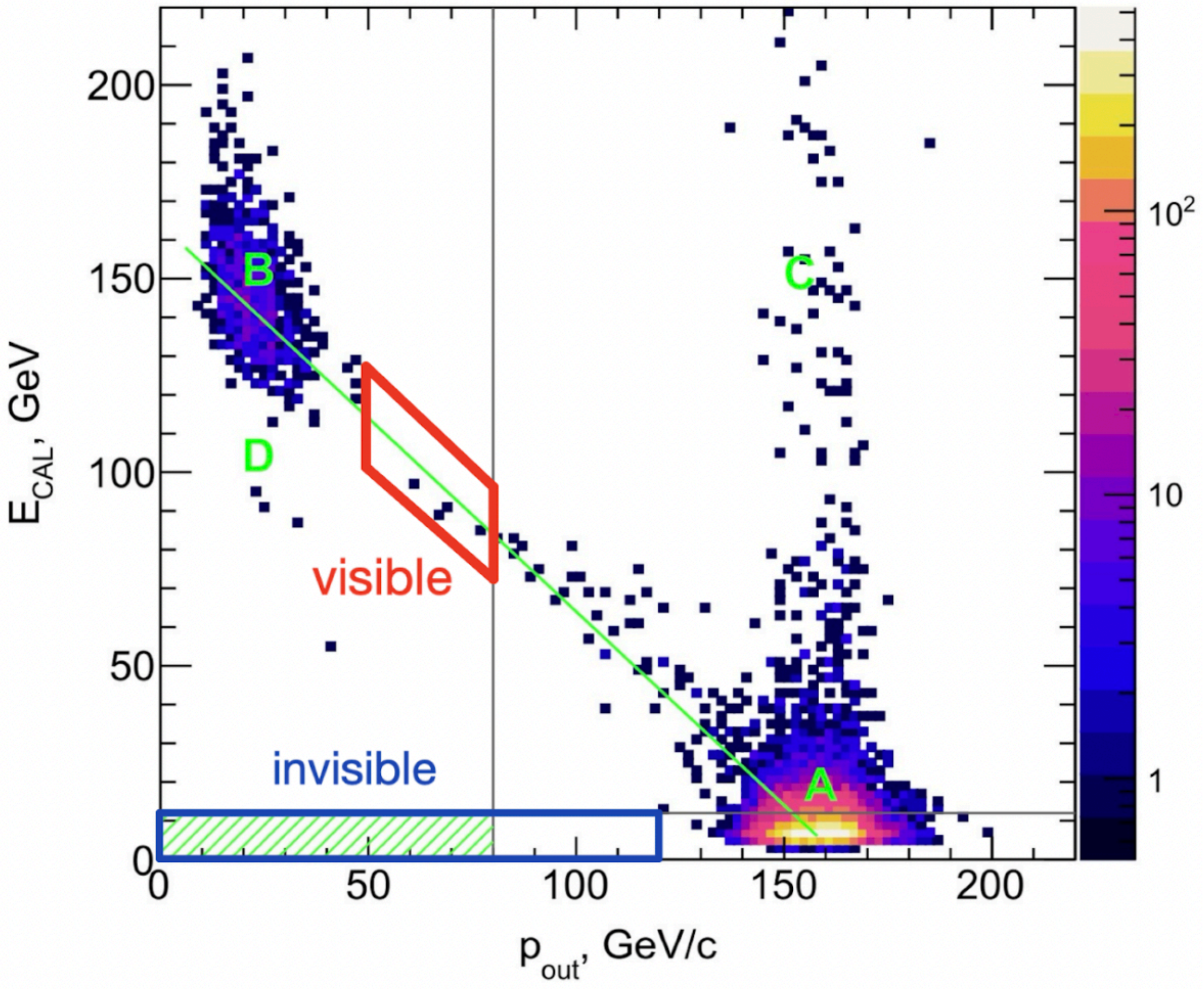
Average over the decay probability from axion production in each ECAL layer

Visible vs Invisible

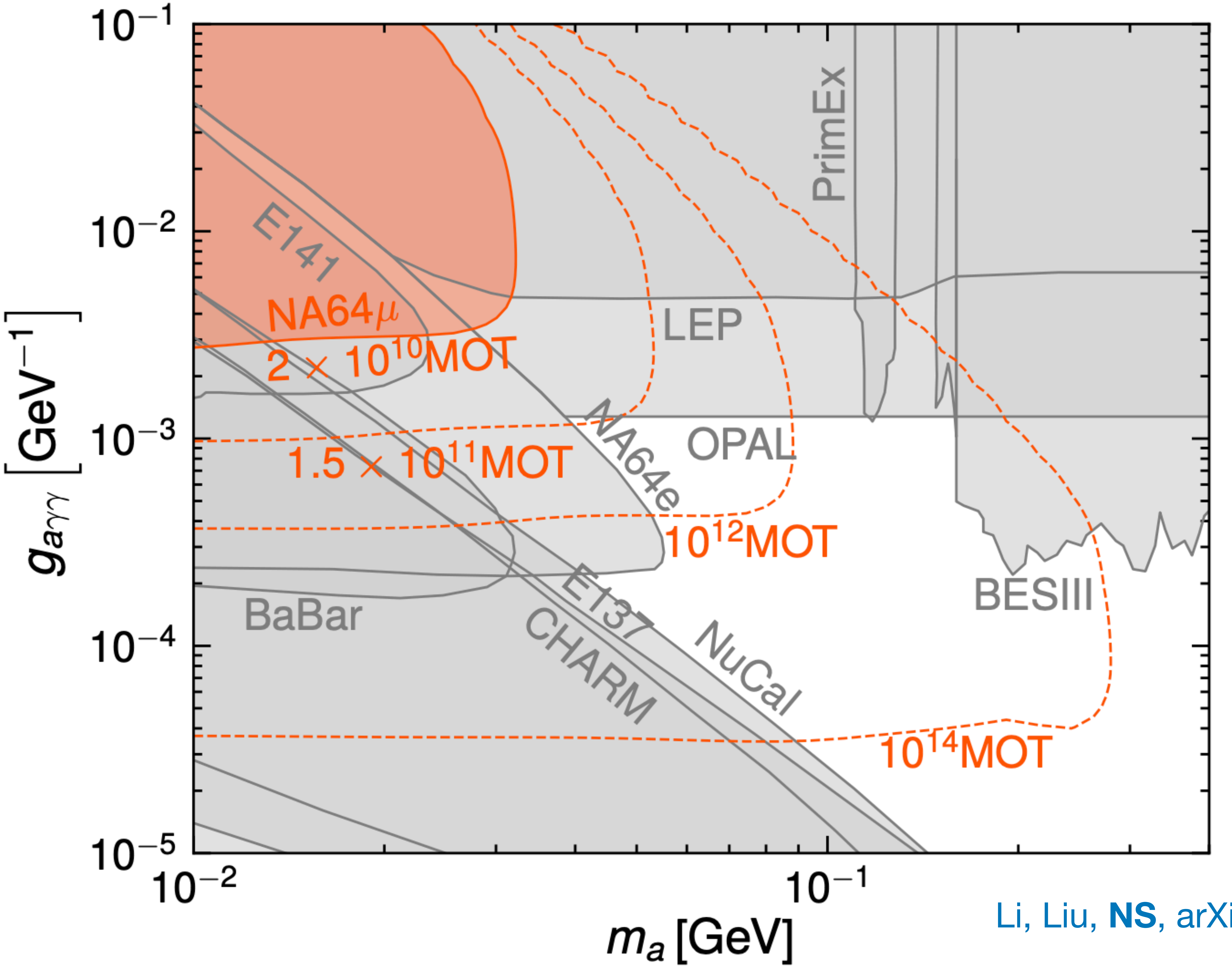




Alonso-Álvarez et al, EPJC/1811.05466



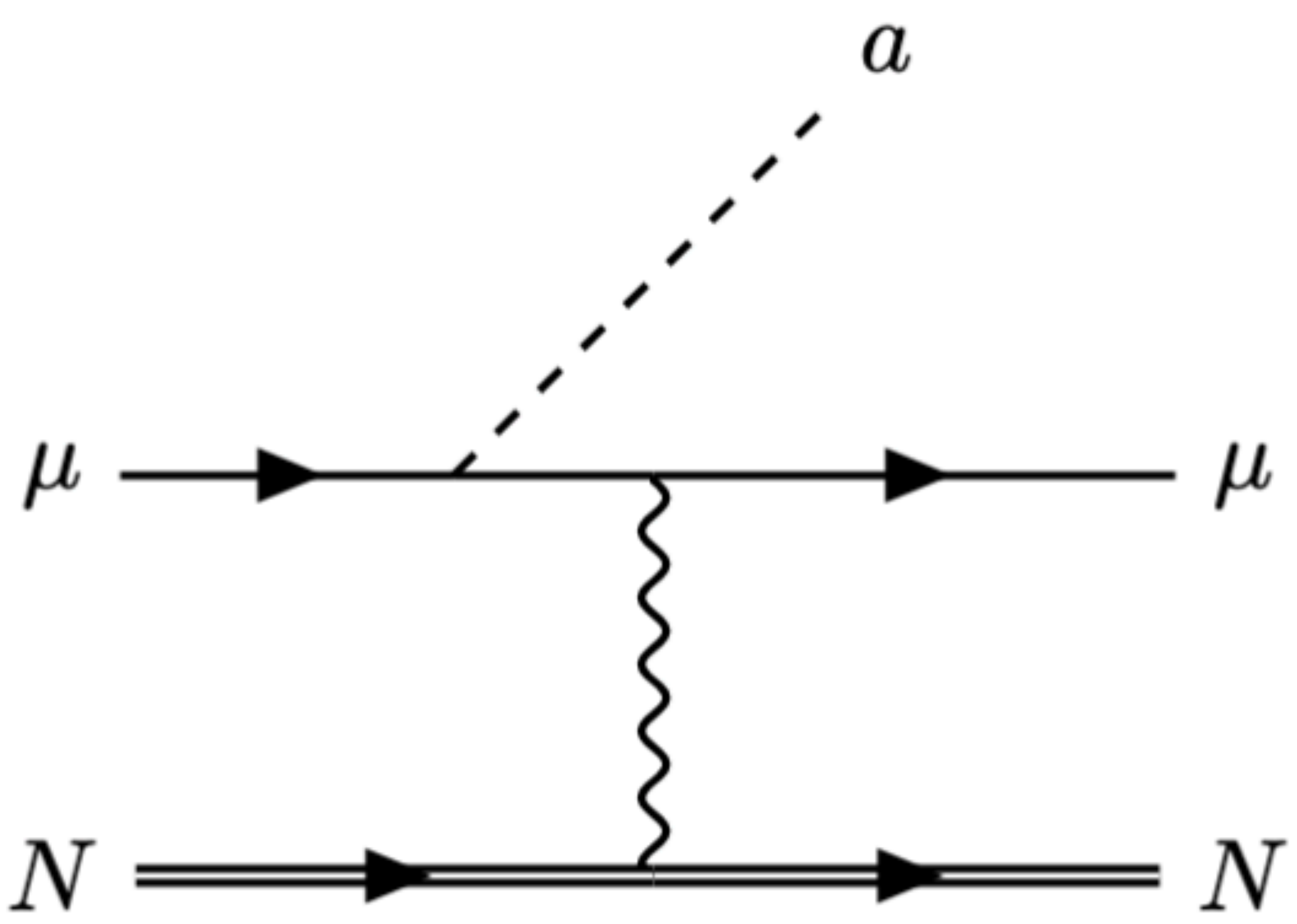
Constraints on Axion-Photon Interaction



Li, Liu, **NS**, arXiv: 2501.06294

Axion-Muon Interaction

$$\mathcal{L} \supset \frac{1}{2}(\partial_\sigma a)^2 - \frac{1}{2}m_a^2 a^2 + g_{a\mu\mu}(\partial_\sigma a)\bar{\mu}\gamma^\sigma\gamma_5\mu$$



Axion production through muon bremsstrahlung

Cross Section

$$N_{\text{signal}} = N_{\text{MOT}} n_{\text{Pb}} L_{\text{tar}} \int d\sigma(\mu N \to \mu N X) \epsilon P_{\text{inv}}$$

Weizsacker-William approxmation

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = \frac{\alpha}{8\pi^2}\sqrt{E_a^2 - m_a^2} E_\mu (1-x) \int \mathrm{d}\cos\theta \frac{\chi}{\tilde{u}^2} \mathcal{A}$$

effective photon flux

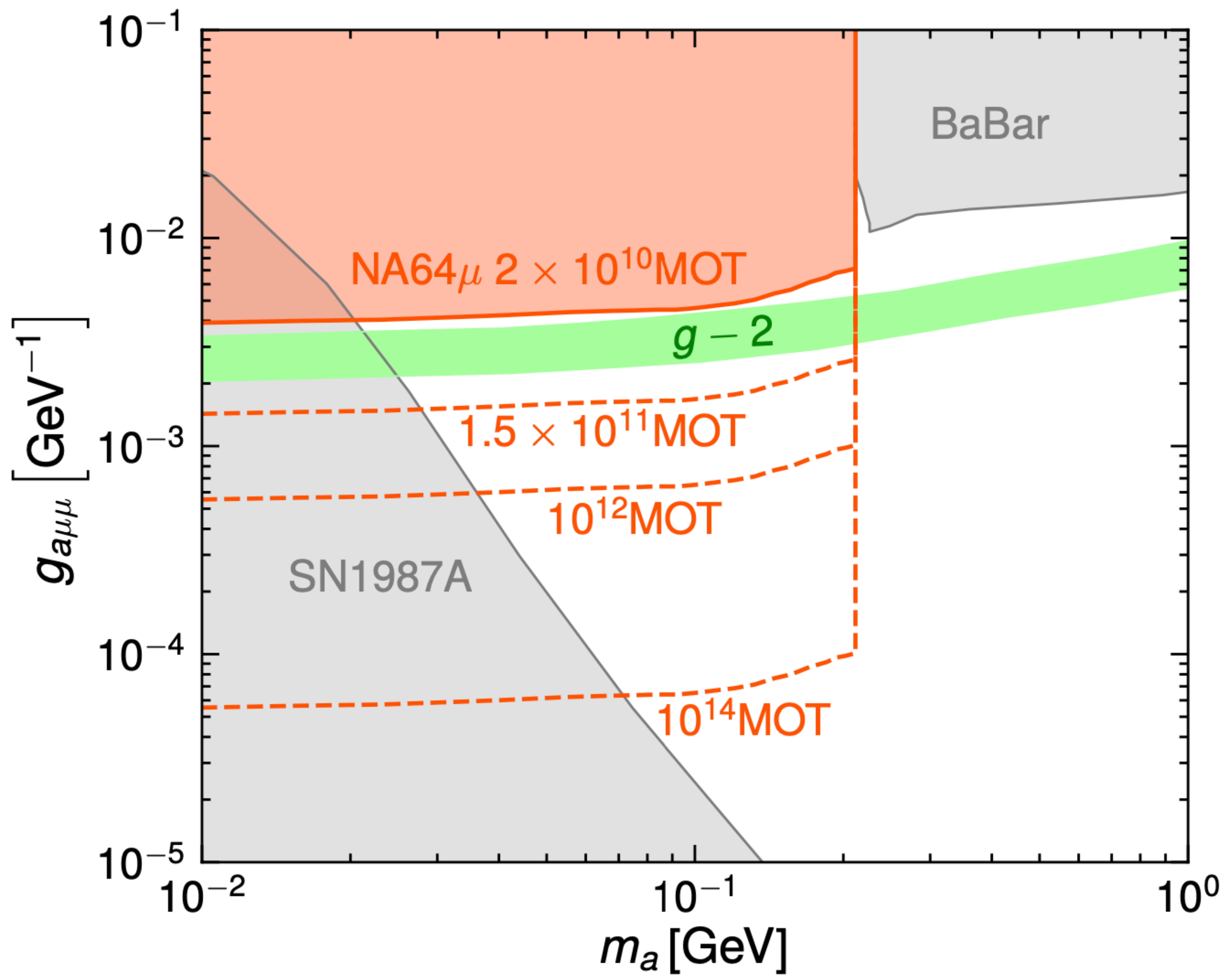
$$\chi = \int_{t_{\min}}^{t_{\max}} \mathrm{d}t \frac{t - t_{\min}}{t^2} F^2(t)$$

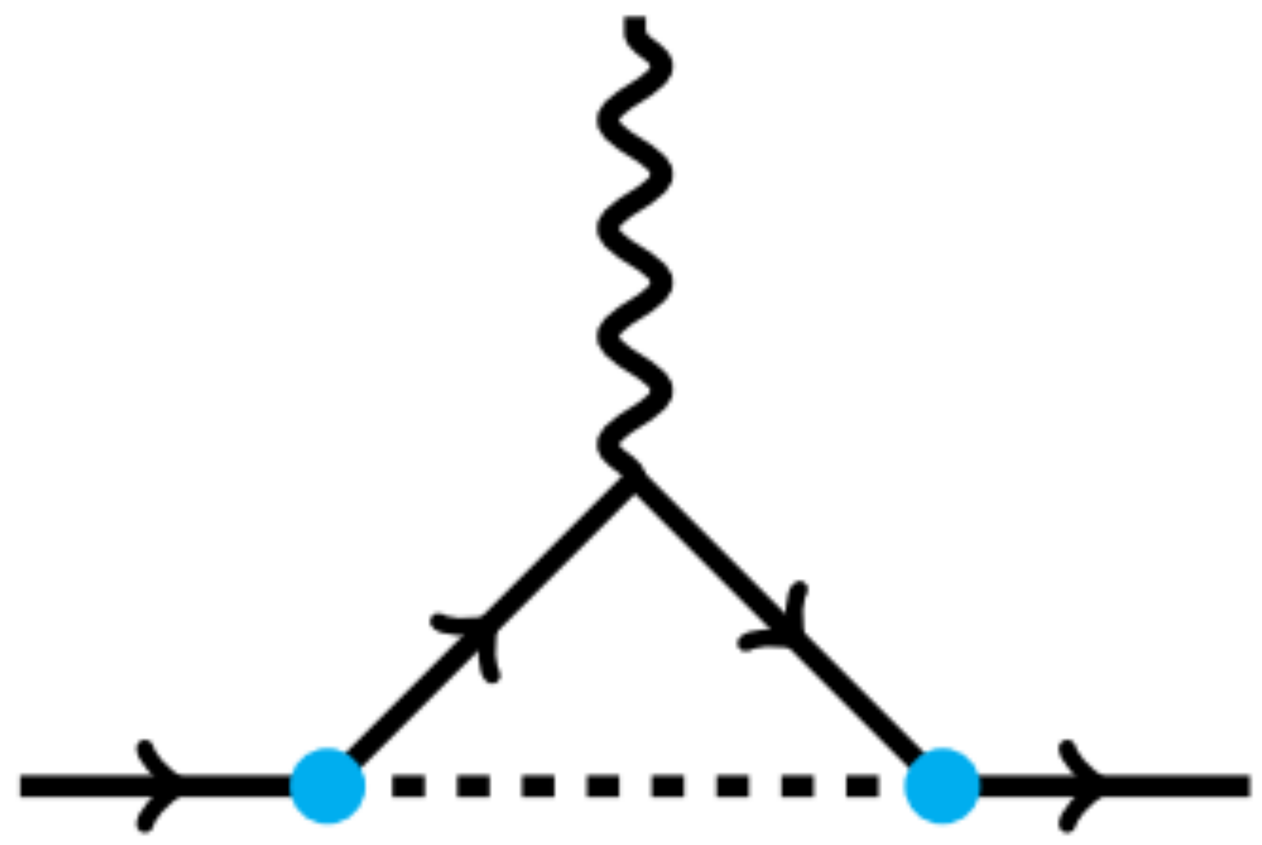
Nucleus elastic form factor

$$F(t) \simeq Z\left(\frac{b^2 t}{1 + b^2 t}\right)\left(\frac{1}{1 + t/d}\right)$$

$$\mathcal{A}_{a-\mu} = e^2 g_{a\mu\mu}^2 4m_\mu^2 \left[\frac{x^2}{1-x} + 2m_a^2 \frac{\tilde{u}x + m_a^2(1-x) + m_\mu^2 x^2}{\tilde{u}^2}\right]$$

Constraints on Axion-Muon Interaction





Buen-Abad et al, JHEP/2104.03267

Li, Liu, **NS**, arXiv: 2501.06294

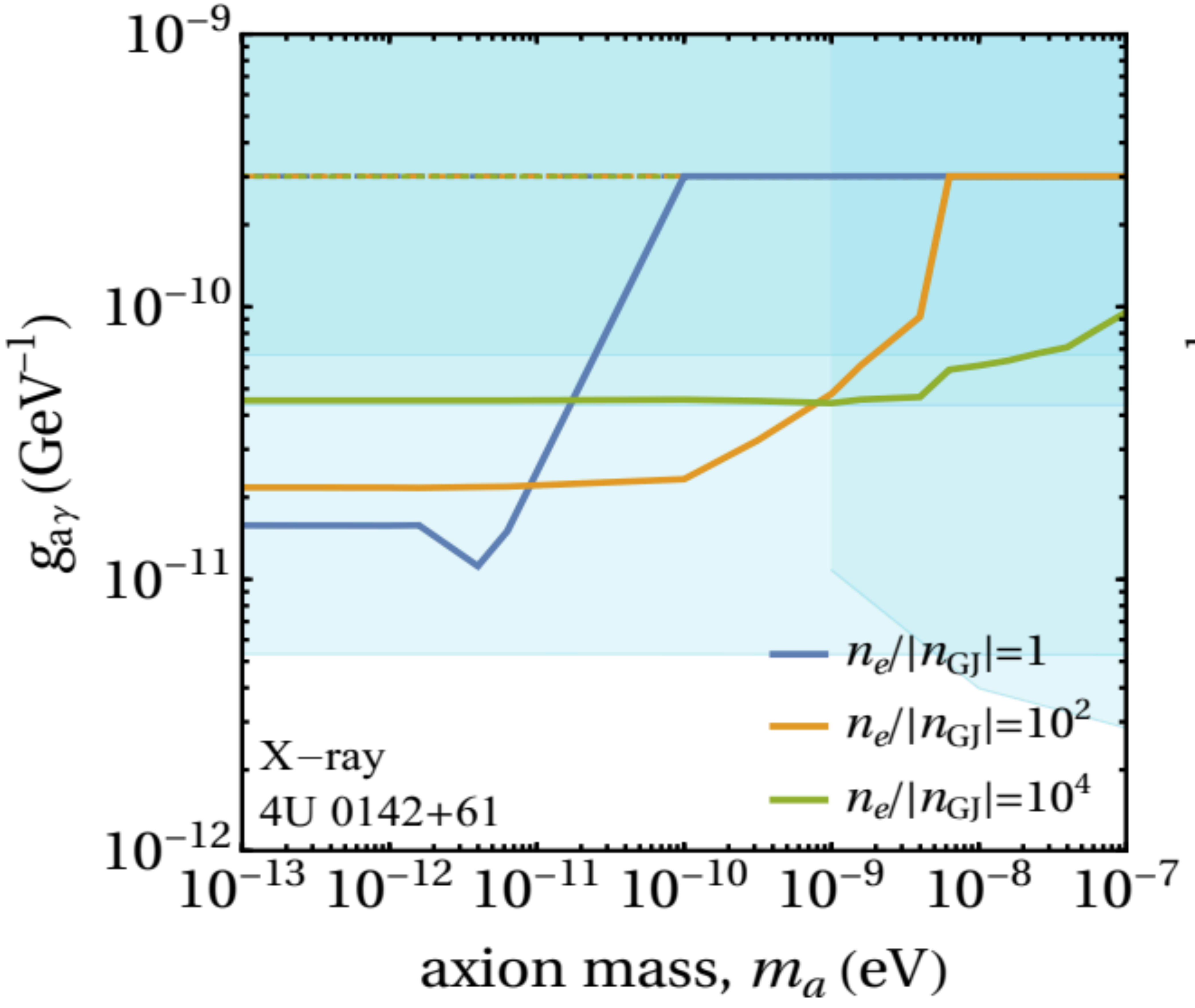
Summary

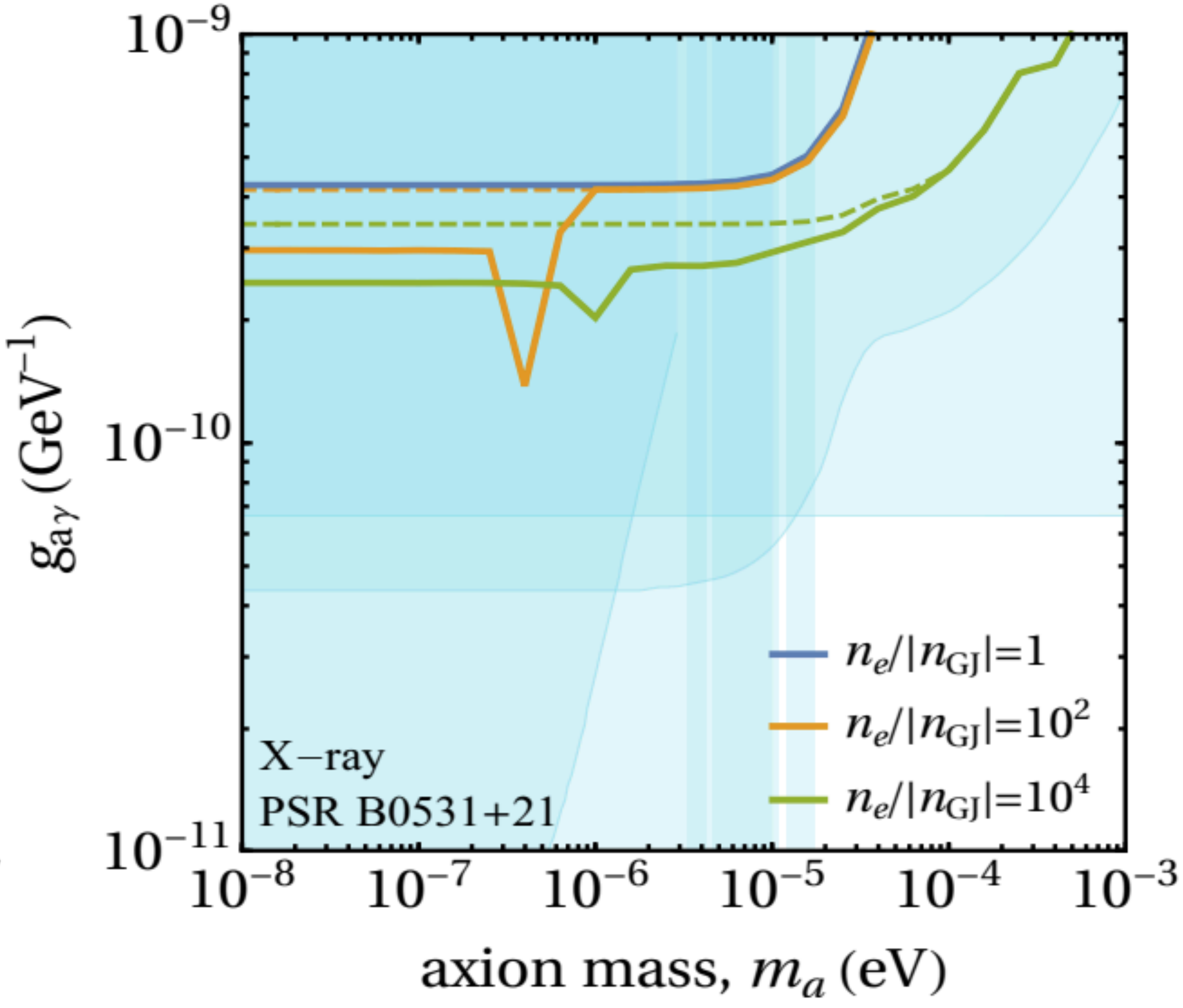
- Polarization measurement from neutron stars could be a powerful tool to search for light axion
- Search for New Physics at NA64μ
  - New gauge boson
  - Axion-photon interaction
  - Axion-muon interaction
  - …

Thanks

Back up

X-ray Polarization Signal

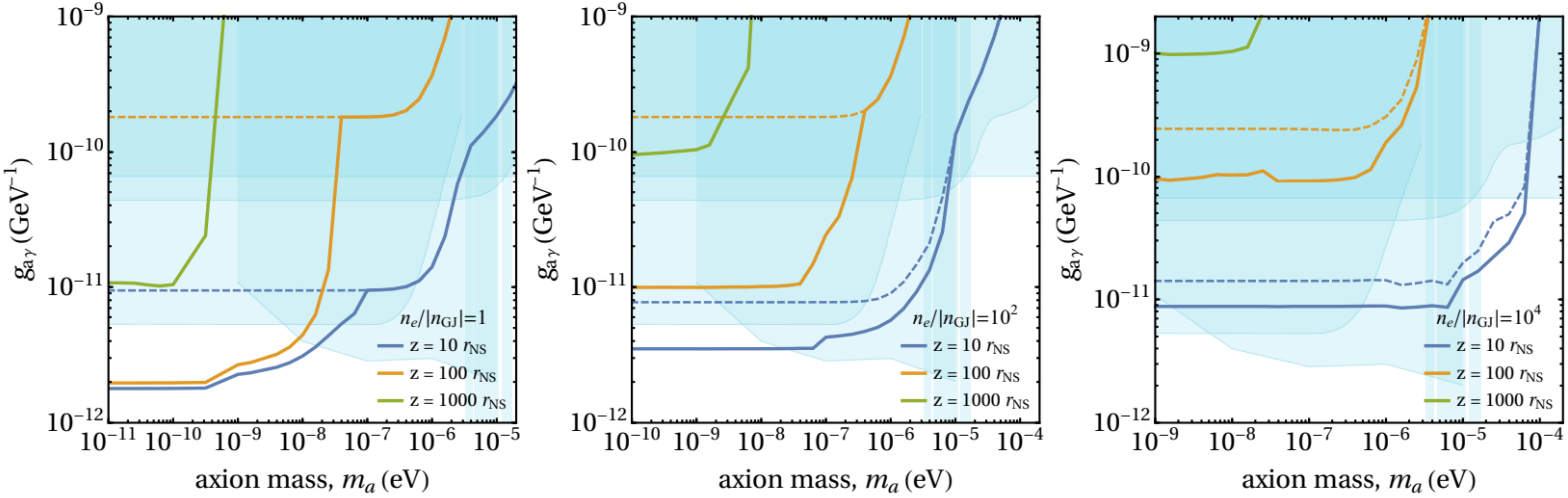




- No resonant conversion is expected in the X-ray energy range as vacuum polarization is too large

NS, Liangliang Su, Lei Wu, PRD/2402.15144

Dependence on Emission Height



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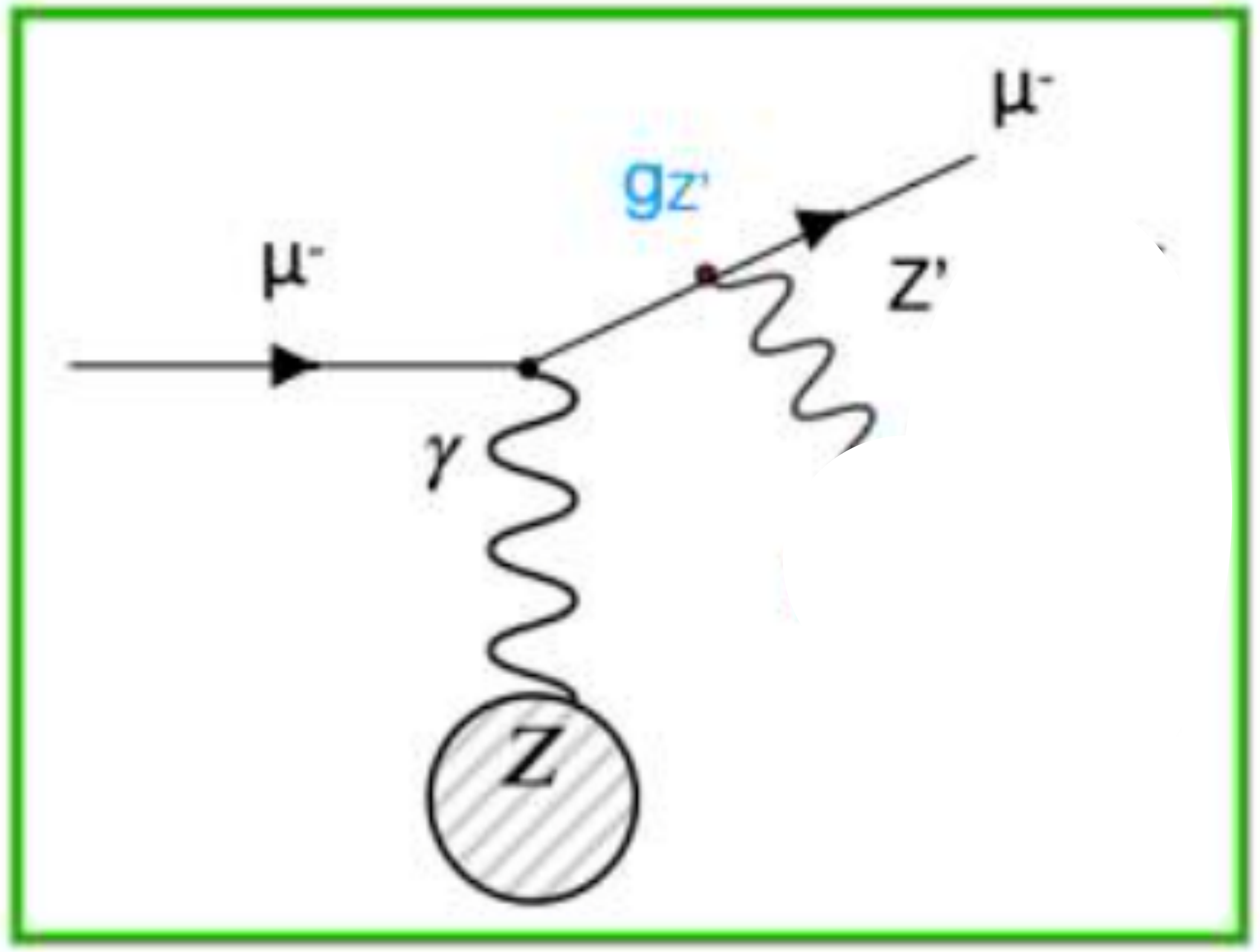
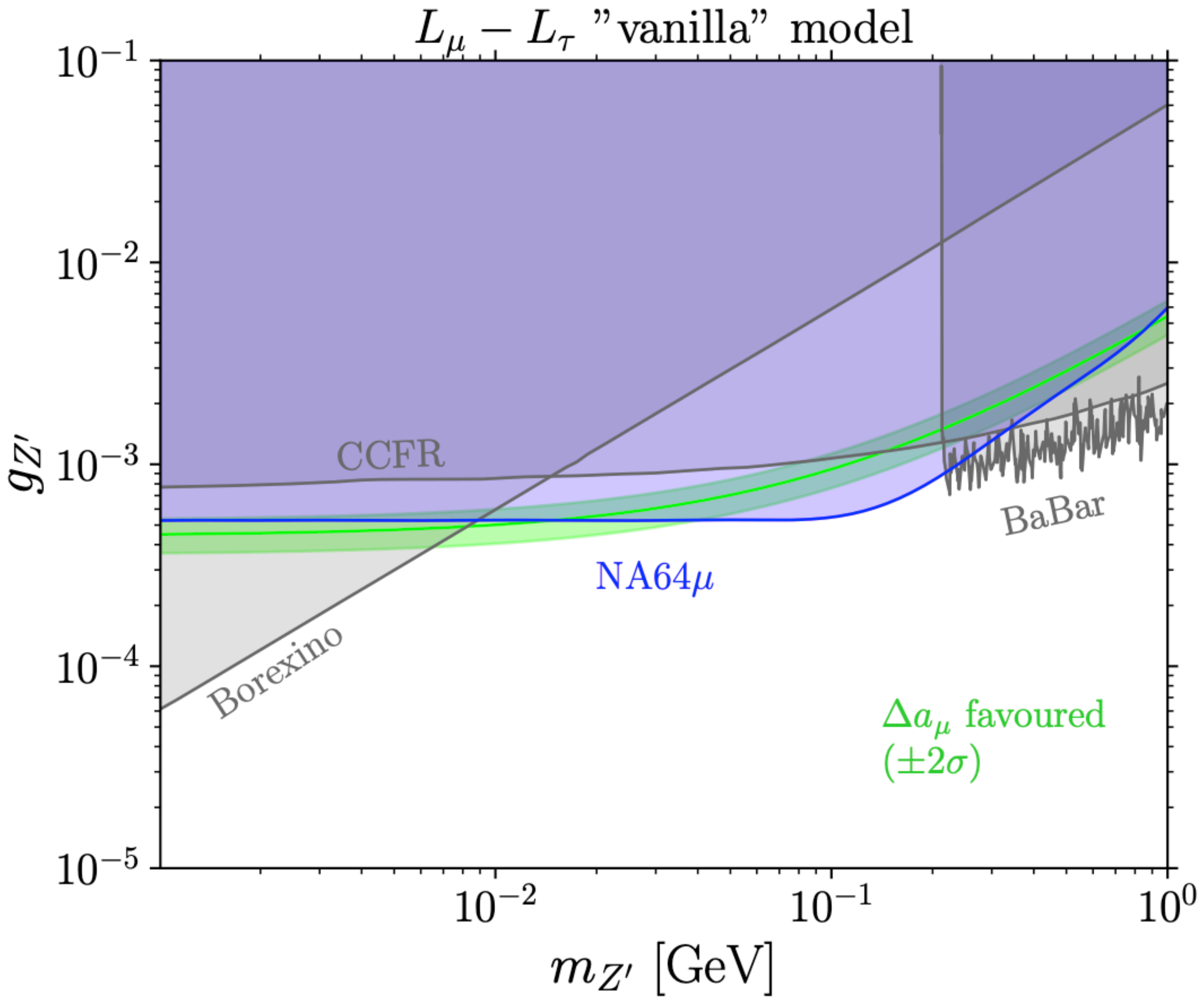
New Physics Search at NA64μ



$Z' \to \nu\bar{\nu}$

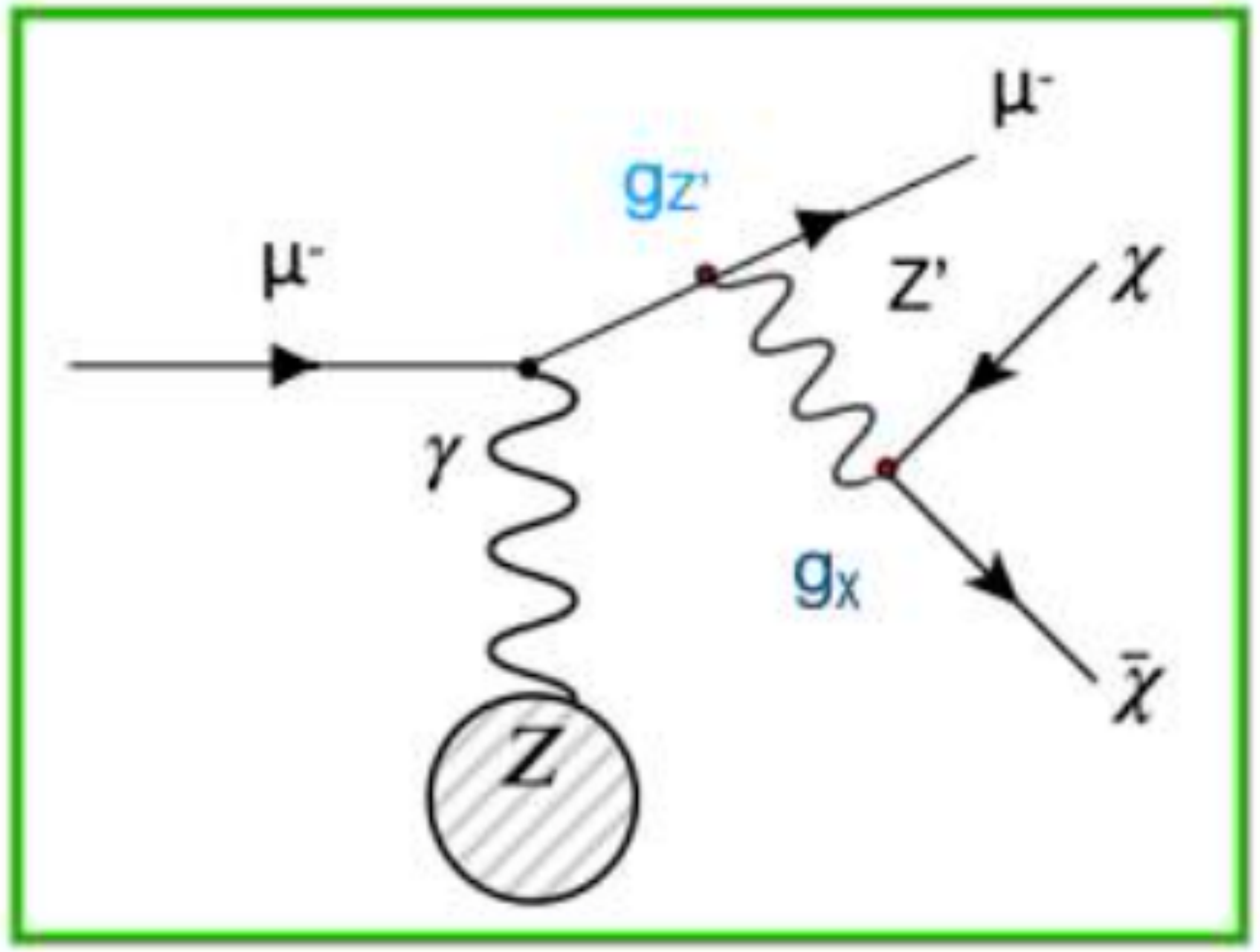
$Z' \to \mu\bar{\mu}$

Search for missing energy



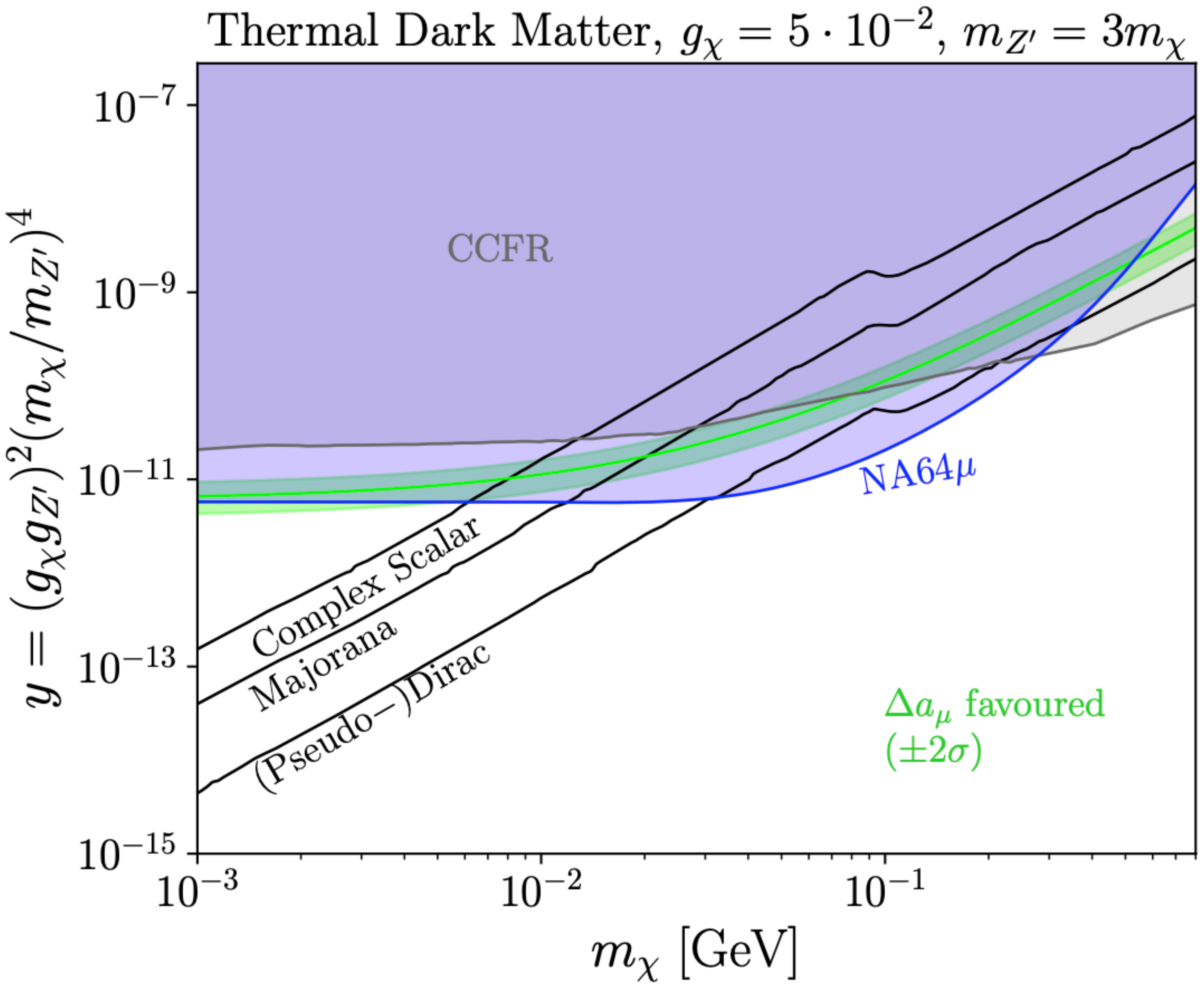
NA64 collaboration, PRL/2401.01708

New Physics Search at NA64μ



$Z' \rightarrow \chi\bar{\chi}$

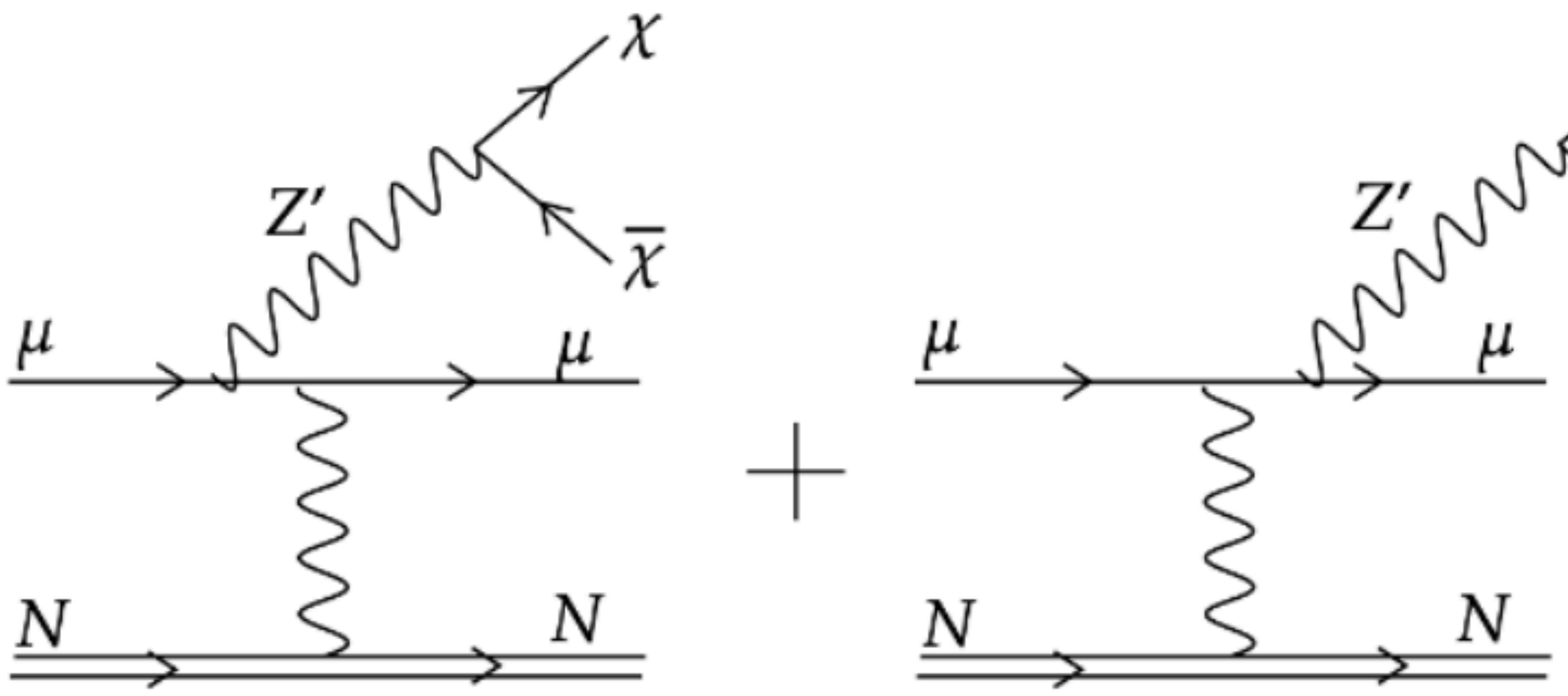
Search for missing energy



NA64 collaboration, PRL/2401.01708

Muonphilic Dark Sector

$$L \supset -\frac{1}{4}Z'_{\alpha\beta}Z'^{\alpha\beta} + g_{Z'}(\bar{\mu}\gamma_\alpha\mu + \bar{\nu}_{\mu L}\gamma_\alpha\nu_{\mu L} - \bar{\tau}\gamma_\alpha\tau - \bar{\nu}_{\tau L}\gamma_\alpha\nu_{\tau L})Z'^{\alpha} + \bar{\chi}(\mathrm{i}\partial\!\!\!/ + g_\chi Z\!\!\!/' - m_\chi)\chi$$



Massless $L_\mu - L_\tau$ mediator with a dark sector

Cross Section

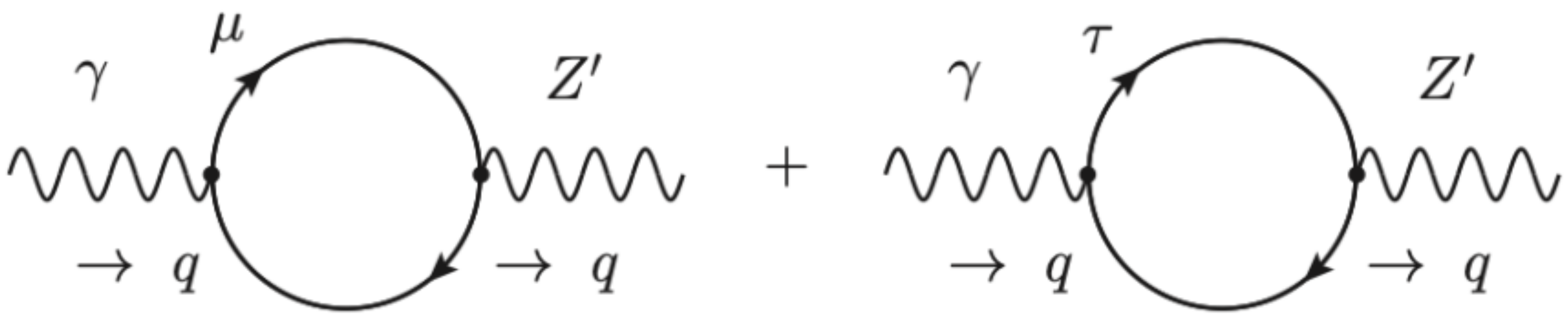
$$N_{\mathrm{signal}} = N_{\mathrm{MOT}} n_{\mathrm{Pb}} L_{\mathrm{tar}} \int d\sigma(\mu N \to \mu N X) \epsilon P_{\mathrm{inv}}$$

$$\begin{aligned} \mathrm{d}\sigma(\mu N \to \mu N \chi\bar{\chi}) =& \mathrm{d}\sigma(\mu N \to \mu N Z') \\ & \times \frac{g_\chi^2}{12\pi^2} \frac{\mathrm{d}Q^2}{Q^2} \sqrt{1 - \frac{4m_\chi^2}{Q^2}} (1 + \frac{2m_\chi^2}{Q^2}) \end{aligned}$$

$$\begin{aligned} \mathcal{A}_{Z'-\chi} =& e^2 g_{Z'}^2 \Big[2\frac{x^2 - 2x + 2}{1 - x} + 4\frac{Q^2 + 2m_\mu^2}{\tilde{u}} \\ & + 4\frac{2m_\mu^4 x^2 + Q^4(1 - x) + m_\mu^2 Q^2(x^2 - 2x + 2)}{\tilde{u}^2} \Big] \end{aligned}$$

Muophilic Millicharge?

$$L \supset -\frac{1}{4} Z'_{\alpha\beta} Z'^{\alpha\beta} + g_{Z'} (\bar{\mu}\gamma_\alpha \mu + \bar{\nu}_{\mu L}\gamma_\alpha \nu_{\mu L} - \bar{\tau}\gamma_\alpha \tau - \bar{\nu}_{\tau L}\gamma_\alpha \nu_{\tau L}) Z'^{\alpha} + \bar{\chi}(i\partial\!\!\!/ + g_\chi Z\!\!\!/' - m_\chi)\chi$$

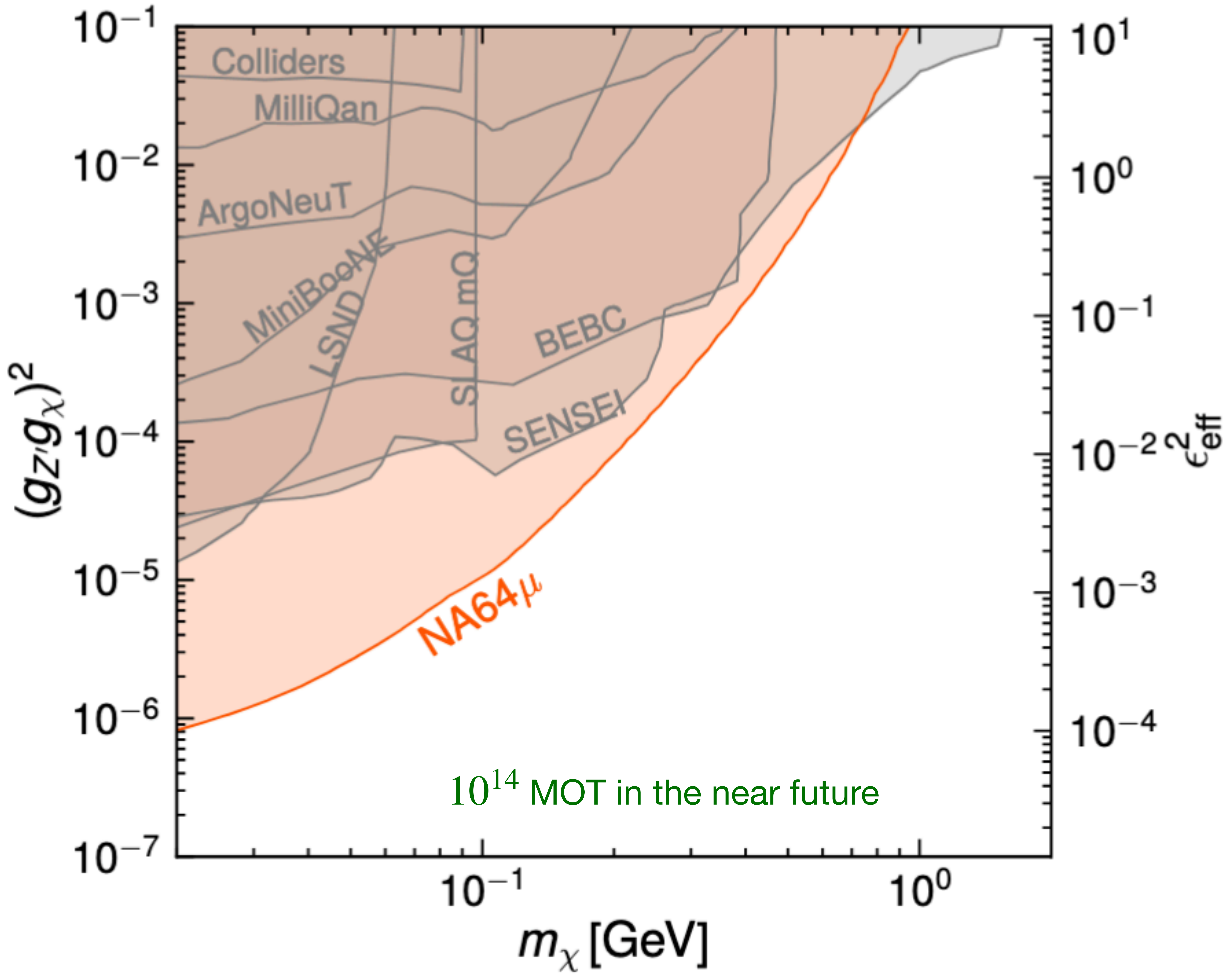


$$\mathcal{L}_{\rm kin} \supset \frac{\Pi(q^2)}{2} Z'_{\mu\nu} F^{\mu\nu}$$

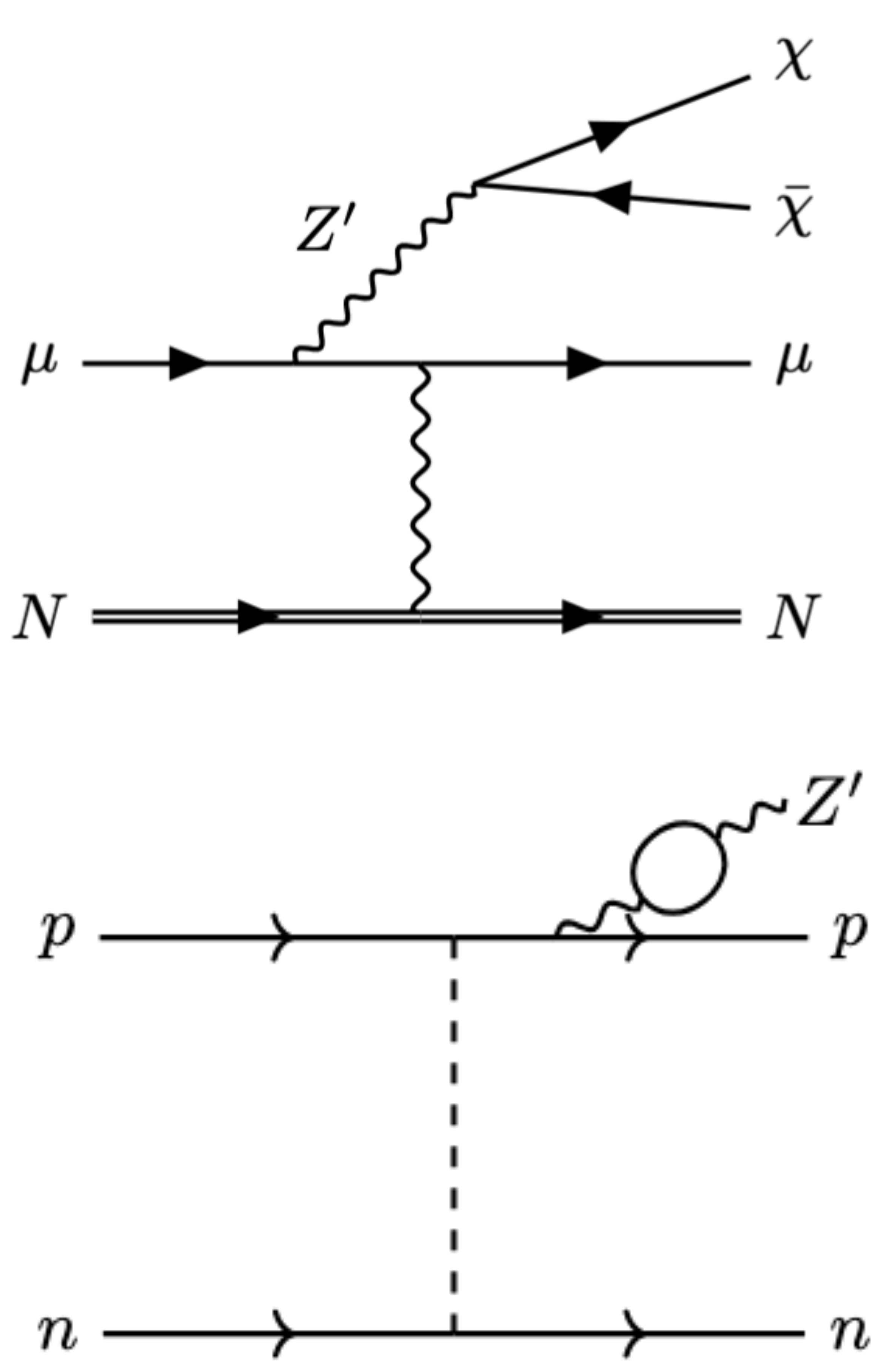
$$\Pi(q^2) = \frac{e g_{Z'}}{2\pi^2} \int_0^1 \mathrm{d}x (1-x) \ln \frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2}$$

$$\epsilon_{\rm eff} = \frac{g_{Z'} g_\chi}{2\pi^2} \int_0^1 \mathrm{d}x (1-x) \ln \frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2}.$$

Constraints on Muonphilic Dark Sector



Croon et al, JHEP/2006.13942



Li, Liu, **NS**, arXiv: 2501.06294