Looking forward to photon-coupled sub-GeV long-lived particles

Forward Physics Facility Theory Workshop

18-19 September

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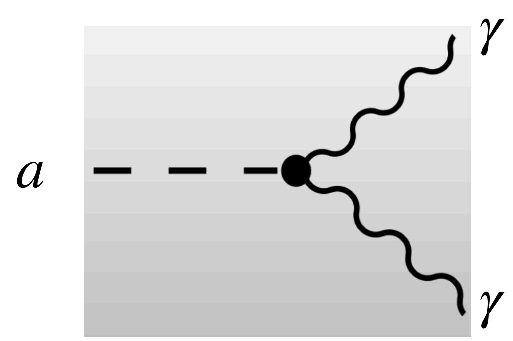
Center for Theoretical Physics
of the Universe, Daejeon

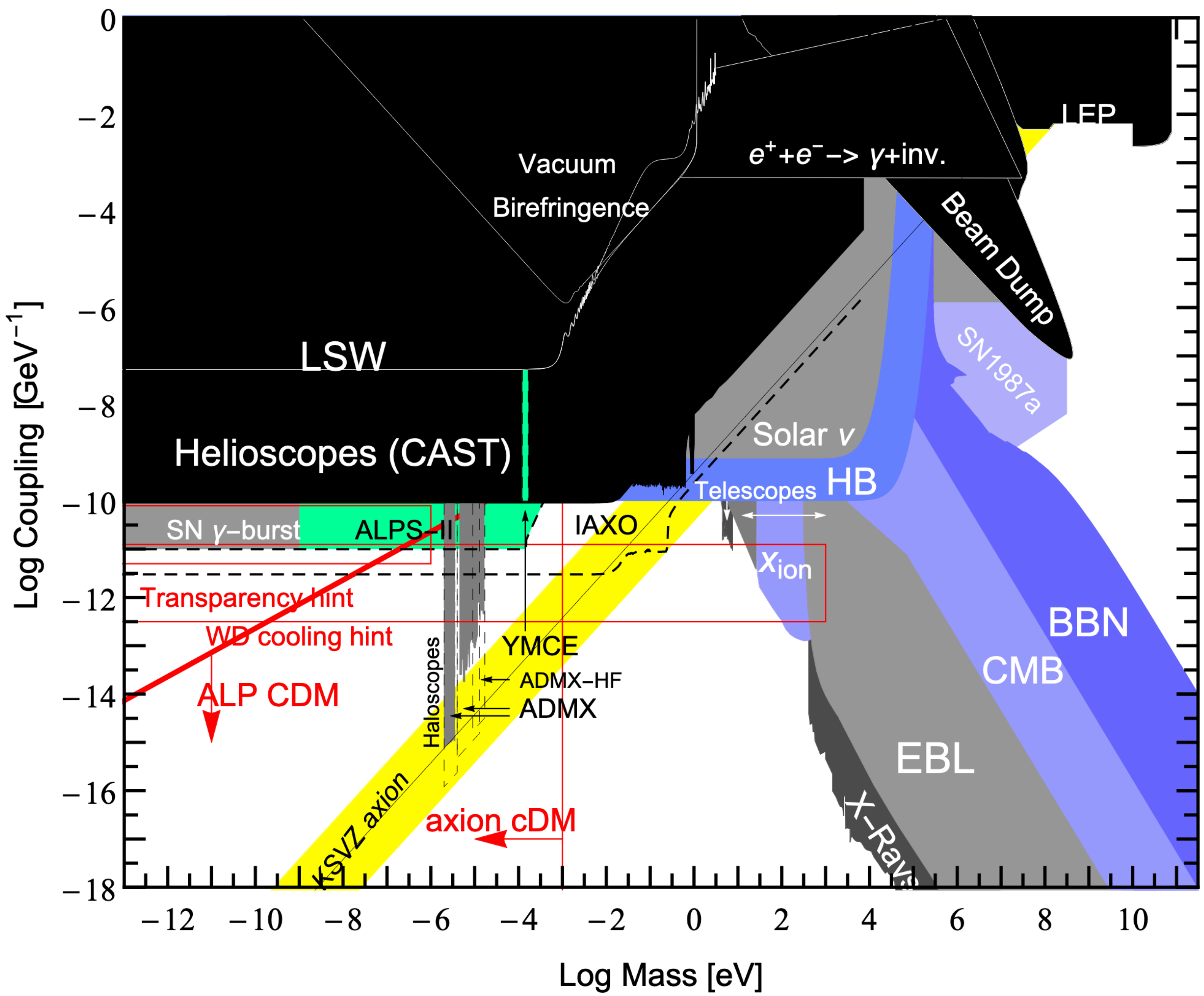
Based on:

KJ, 2305.10409; related works: 2305.05710, 2305.16781, 2306.00982

PBC benchmark 9
photon-coupled ALP

$$\mathscr{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

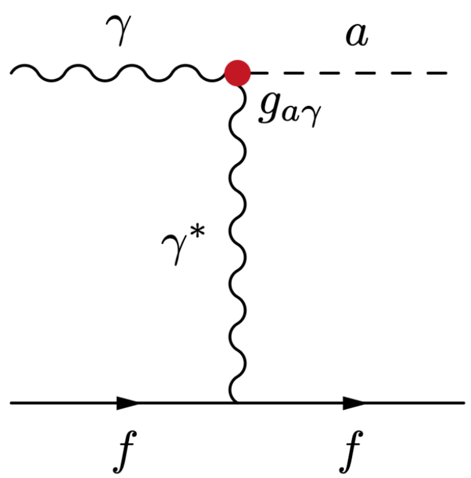




Consider sub-GeV
weakly coupled ALP

- unrelated to strong CP problem
- wide experimental program: astronomy, cosmology, and lab
- ...

ALP at beam dumps and the LHC

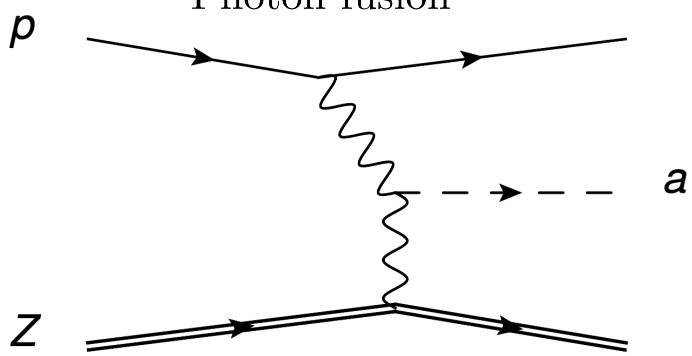


Primakoff scattering

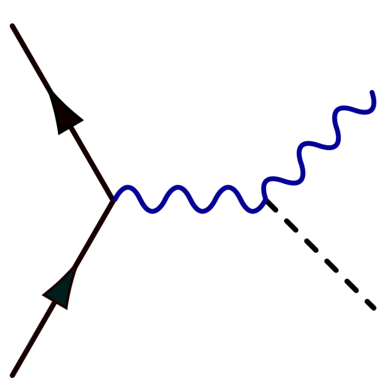
$\sigma_{\gamma N \to aN} \propto \alpha_{em} g_{a\gamma\gamma}^2 Z^2$

dominant production mode

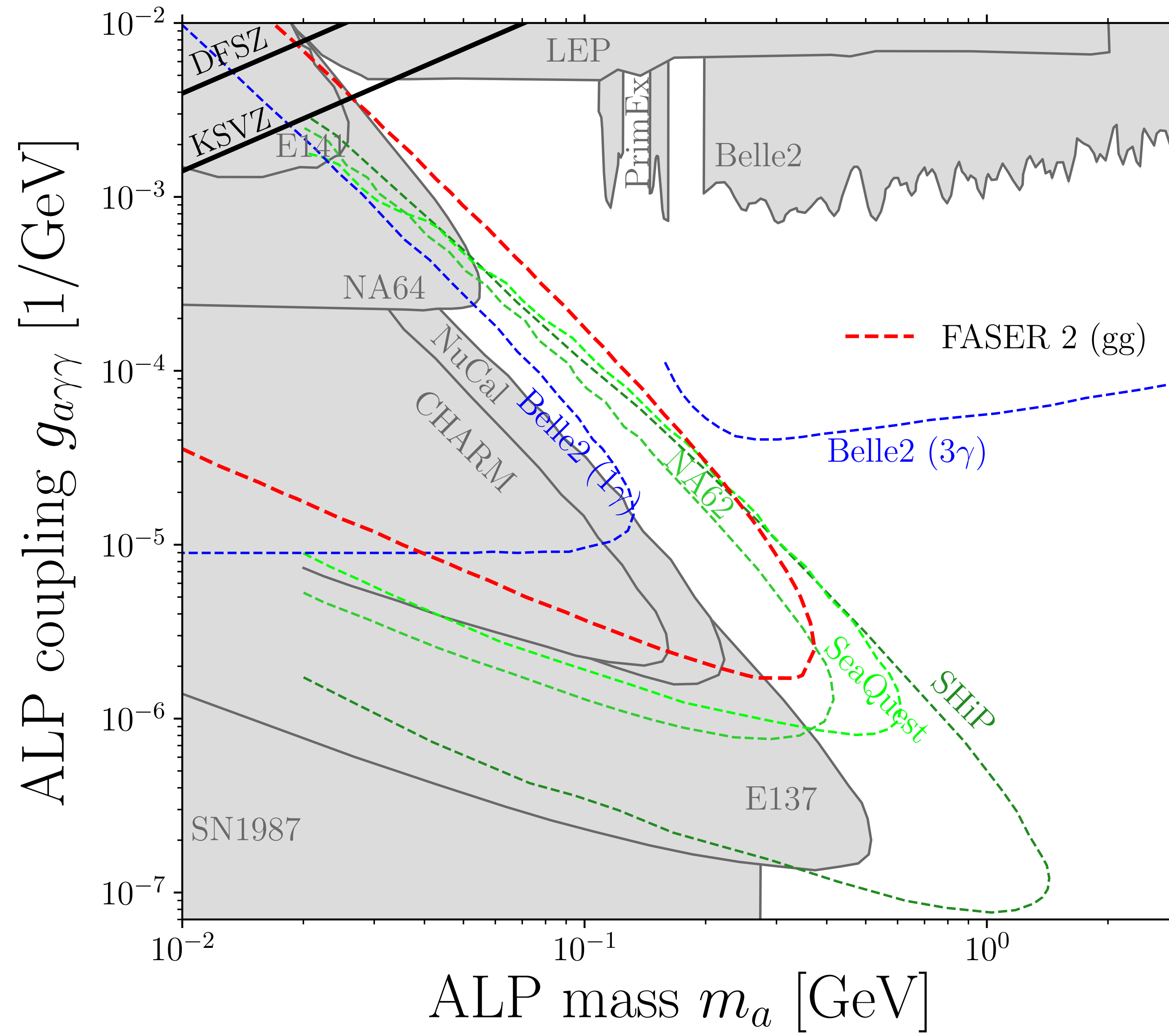
Photon fusion



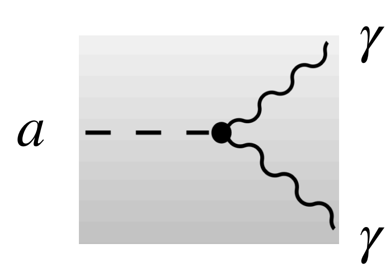
Drell-Yan/vector meson decays



FASER's Physics Reach for Long-Lived Particles, 1811.12522



Typical lifetime



$$\mathscr{P}_{decay} = \exp\left(-\frac{L_{min}}{\bar{d}}\right) - \exp\left(-\frac{L_{max}}{\bar{d}}\right) \sim \frac{L_{max} - L_{min}}{d}$$

$$d_a \sim 100\,m \times \left(\frac{E}{100\,GeV}\right)\left(\frac{0.1\,GeV}{m_a}\right)^4\left(\frac{1.05\times 10^{-5}}{g_{a\gamma\gamma}}\right)^2$$

Sub-GeV LLPs coupled to a photon

- *Massive spin-2 mediator* decays into two photons

$$\mathscr{L} \supset g_\gamma G^{\mu\nu}\left(\frac{1}{4}\eta_{\mu\nu}F_{\lambda\rho}F^{\lambda\rho} + F_{\mu\lambda}F_{\nu}^{\ \lambda}\right) - i\sum_l \frac{g_\ell}{2}G^{\mu\nu}\left(\bar{l}\gamma_\mu D_\nu l - \eta_{\mu\nu}\bar{l}\gamma_\rho D^\rho l\right)$$

- *Dark ALP* decays into to a photon and a dark photon

$$\mathscr{L} \supset \frac{g_{a\gamma\gamma'}}{4} a F^{\mu\nu}\tilde{F}'_{\mu\nu}$$

- SUSY - *neutralino* decays into a photon and the LSP:
  - ALPino $\mathscr{L} \supset \frac{\alpha_{\text{em}} C_{a\gamma\gamma}}{16\pi f_a}\tilde{a}\gamma_5\left[\gamma^\mu, \gamma^\nu\right]\tilde{\gamma}F_{\mu\nu}$
  - gravitino $\mathscr{L} \supset -\frac{1}{4M_{\text{Pl.red.}}}\bar{\psi}_\mu\sigma^{\rho\sigma}\gamma^\mu\lambda F_{\rho\sigma}$

- *Inelastic DM* with EM form factors - heavier state decays into SM and a stable dark fermion

  Dienes, Feng, Fieg, Huang, Lee, Thomas, 2301.05252

  - dim 5 - magnetic/electric dipole moment $\mathscr{L} \supset \frac{1}{\Lambda_m}\bar{\chi}_1\sigma^{\mu\nu}\chi_0 F_{\mu\nu} + \frac{1}{\Lambda_e}\bar{\chi}_1\sigma^{\mu\nu}\gamma^5\chi_0 F_{\mu\nu}$
  - dim 6 - anapole moment/charge radius op. $\mathscr{L} \supset -a_\chi\bar{\chi}_1\gamma^\mu\gamma^5\chi_0\,\partial^\nu F_{\mu\nu} + b_\chi\bar{\chi}_1\gamma^\mu\chi_0\,\partial^\nu F_{\mu\nu}$

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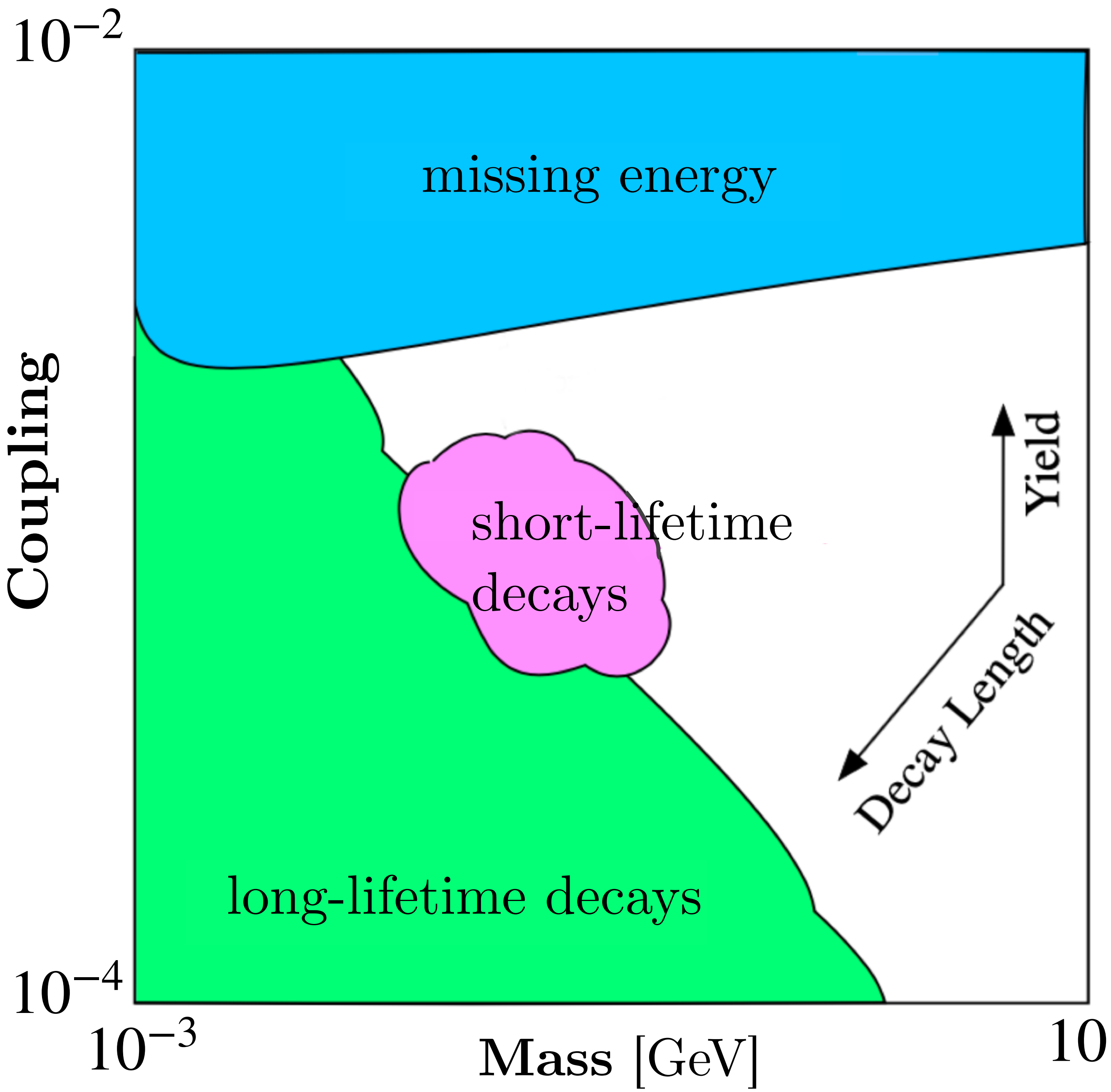
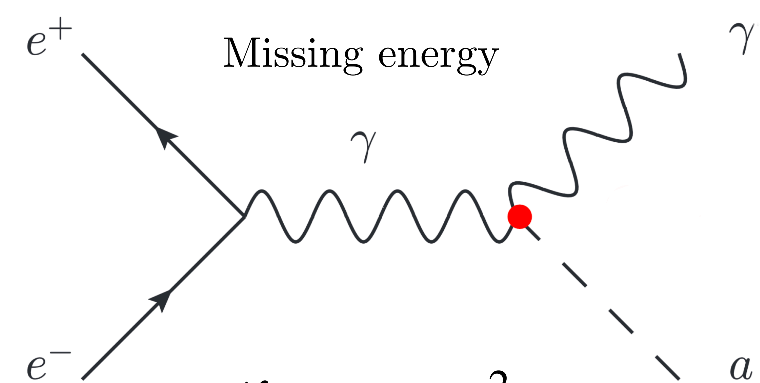
LLP signatures

determined by yield and lifetime



Similar dependence for many models:
i) dark photon, ii) dark Higgs, iii) ALP, ...

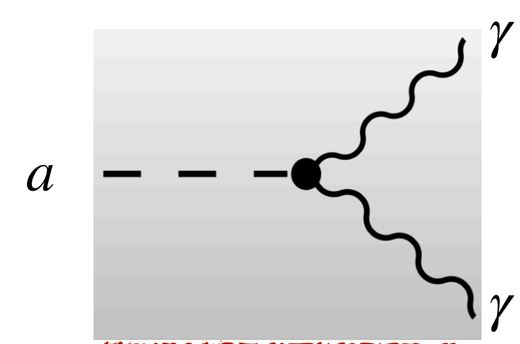
$d \lesssim 10$ m $\rightarrow$ invisible decays/missing energy
10 m $\lesssim d \lesssim$ 10 km $\rightarrow$ displaced decays
$d \gtrsim 10$ km $\rightarrow$ astrophysics/cosmology



$\mathcal{N}_{events} \propto g^2$

Large $\mathcal{N}_{events}$ with large backgrounds

Displaced decays



$\mathcal{N}_{events} \propto g^4$

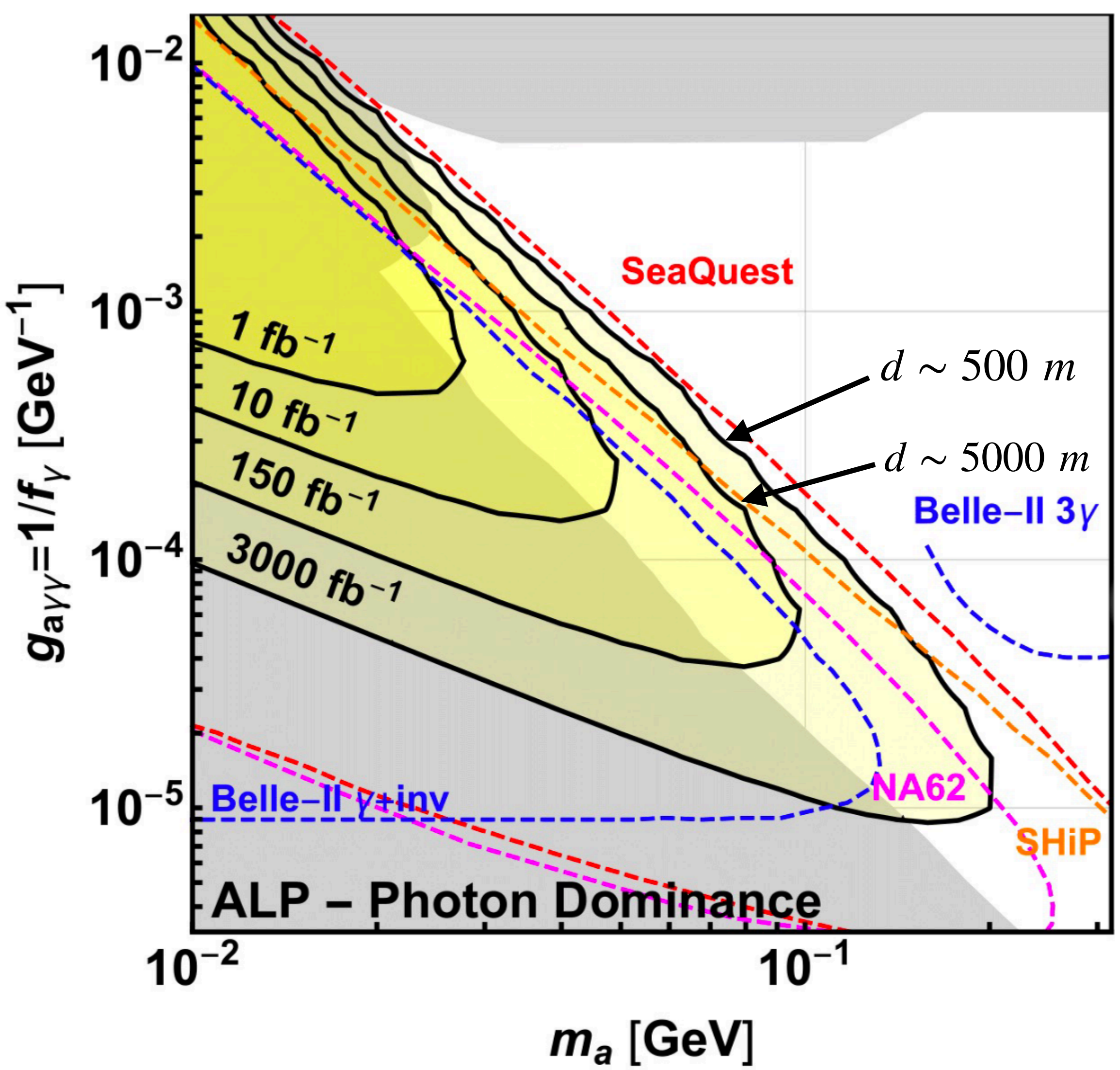
Small $\mathcal{N}_{events}$ with essentially no background

ALP decays at beam dumps

$$\mathscr{P}_{decay} = \exp\left(-\frac{L_{min}}{d}\right) - \exp\left(-\frac{L_{max}}{d}\right) = \begin{cases} \frac{L_{max} - L_{min}}{d} \equiv \frac{\Delta}{d} & : \text{ for } d \gg L_{min} \\ \exp(-L_{\min}/d) & : \text{ for } d \ll L_{min} \end{cases}$$

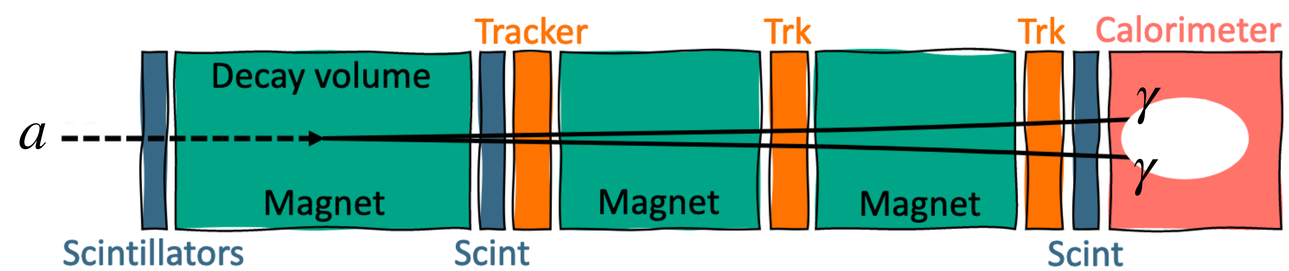
$\rightarrow$ d **is <u>exponentially sensitive</u> to** L_{min}

Distance to the decay vessel L_{min} *determines the scale of LLP decay length* d*, which can be probed.*



FASER's Physics Reach for Long-Lived Particles, 1811.12522

ALP: $d = c\tau\gamma \sim 100\ \mathrm{m} \times (100\ \mathrm{MeV}/m_a)^2 \times (10^{-5}/g)^2$



Displaced vertex → essentially *zero background* search

$$\mathscr{N}_{events} = \text{production} \times \text{solid angle} \times \text{decay inside detector}$$

$$= \mathscr{L}_{lumi} \cdot g^2 \times \left(\frac{r}{L_{\max}}\right)^2 \times \mathscr{P}_{decay} \propto g^2/d \propto g^4$$

Good detector is:

- *big* - large radius r and decay length Δ
- *close* to production point - small L_{min}
- placed in the *forward direction* of the production point

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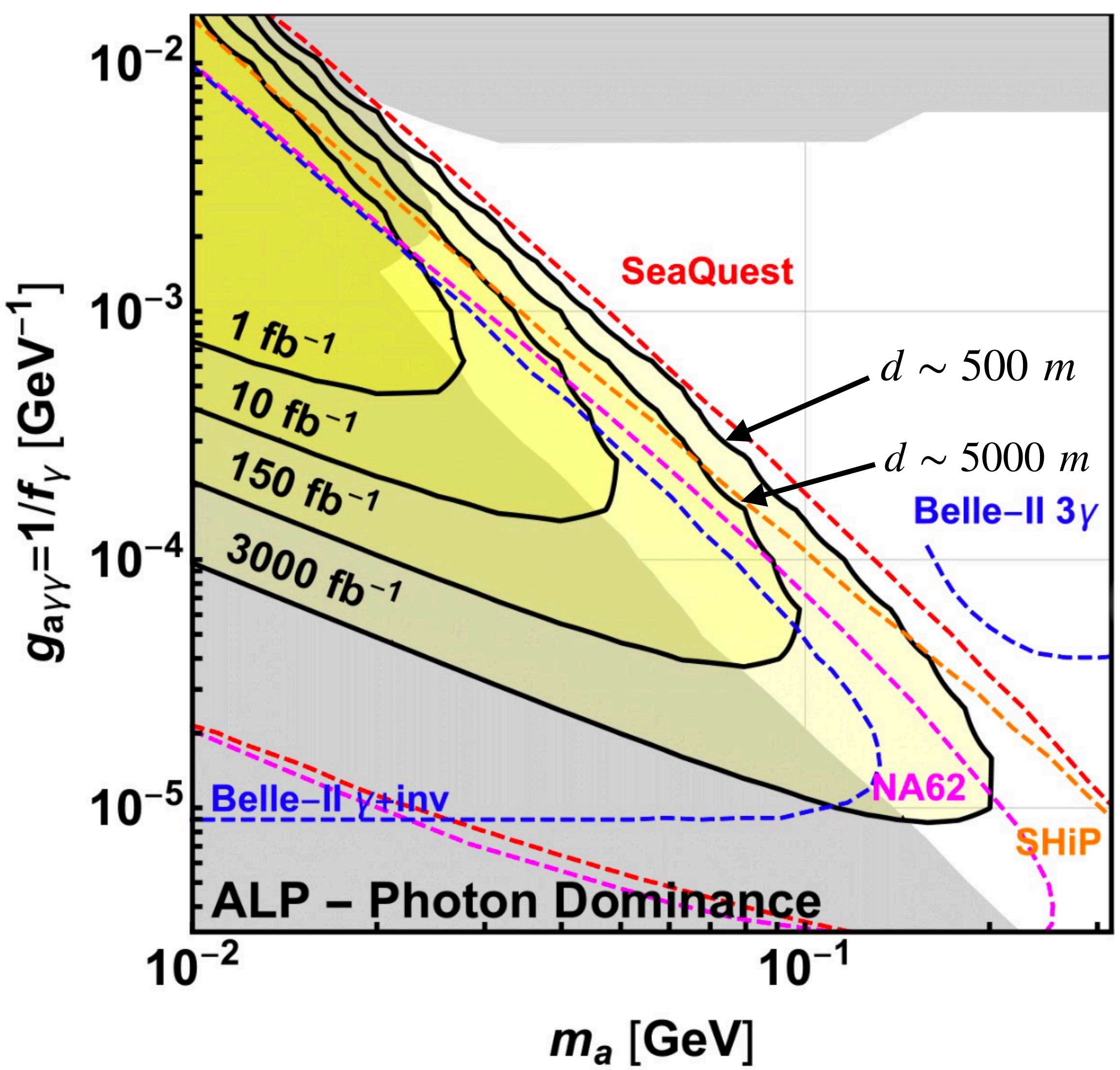

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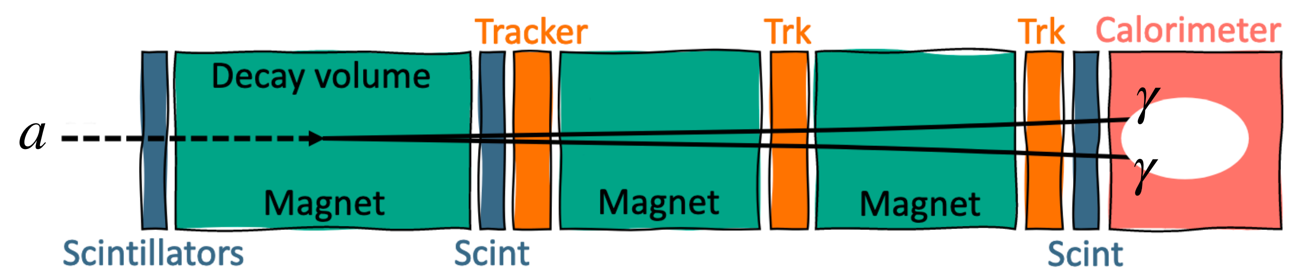

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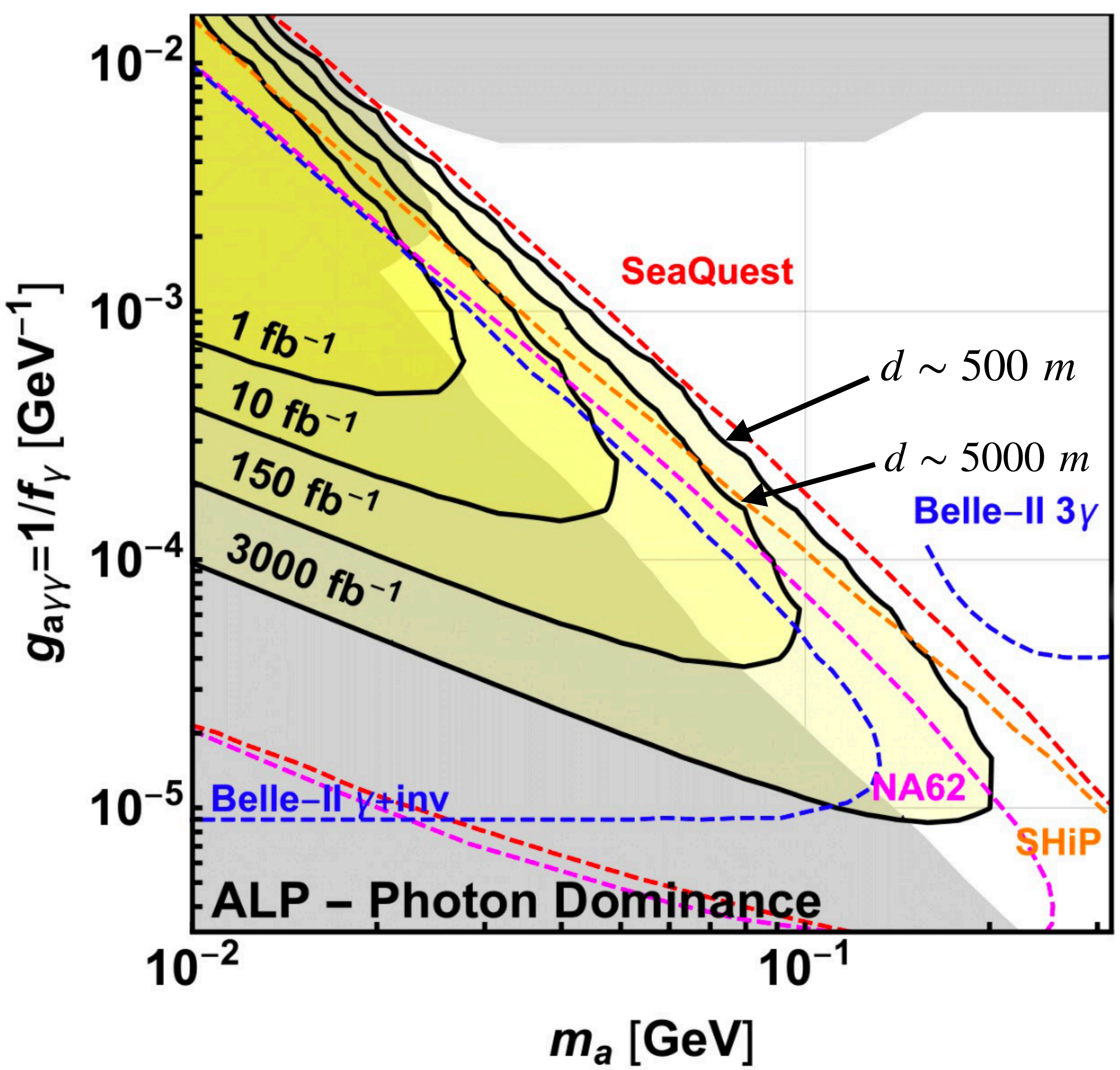

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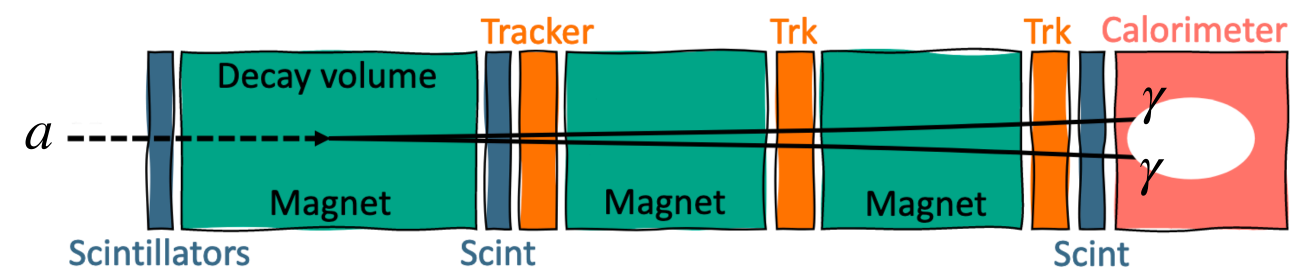

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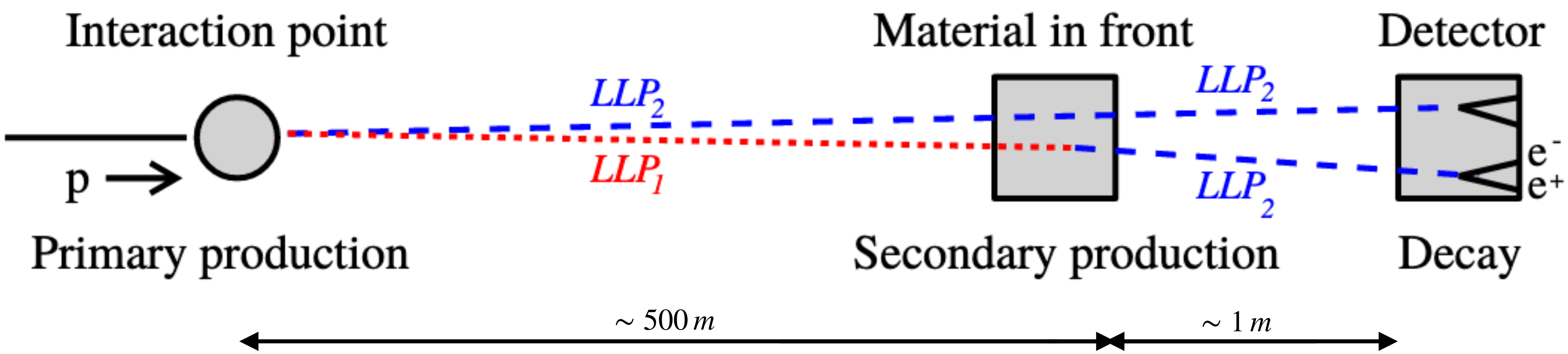
Primakoff-like upscattering

Secondary production on tungsten layers of FASERν2 - upscattering of LSP into LLP by coherent nucleus scattering

KJ, F. Kling, L. Roszkowski, S. Trojanowski, 1911.11346



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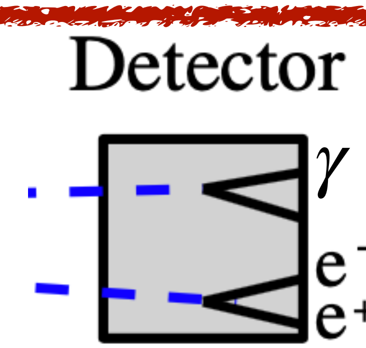
Primary production is limited to the LLP lifetime regime of $d \sim L_{min}$.

Secondary production opens up $d \sim 1\,m$: $\mathrm{LLP_1 + SM \rightarrow LLP_2 + SM}$ followed by $\mathrm{LLP_2 \rightarrow LLP_1 +}$ visible

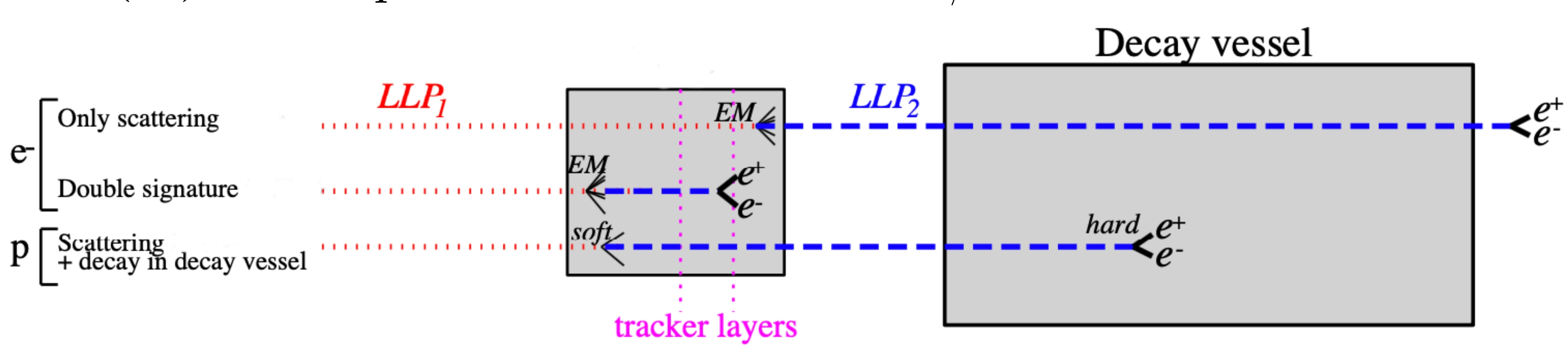
Coherent upscattering on nucleus ($\propto Z^2$) mediated by photon exchange is enhanced by the photon propagator $\sim 1/t$ → Primakoff-like process for photon-coupled LLPs can be particularly effective.

LLP signatures at FASER/FPF

- **LLP signal inside the decay vessel – $\gamma\gamma$ or $\gamma + X$**
  - $E_{vis} > 100$ GeV
  - e^+e^- search: negligible background due to high energies of LLP's
  - γ search: KJ, S. Trojanowski, 2011.04751; The FASER W-Si High Precision Preshower Technical Proposal, CERN-LHCC-2022-006
    - neutrino-induced BG minimized by preshower put in front of the calorimeter
    - BG from muon-induced photons vetoed by scintillators detecting a time-coincident muon going through the detector → *excess of single-photon events unaccompanied by any muon indicative of new physics*



- **Scattering off electrons**
  - new-physics-induced neutrino scatterings off electrons producing electron recoils inside the neutrino detector.
  - *Energy and angular cuts:* Batell, Feng, Trojanowski, 2101.10338 (FLArE)
    - Electron energy and angular cuts following the DM scattering signature
    - The cuts have been designed to minimize the neutrino-induced BG to the level of $O(10)$ such expected events in FASERν2/FPF.



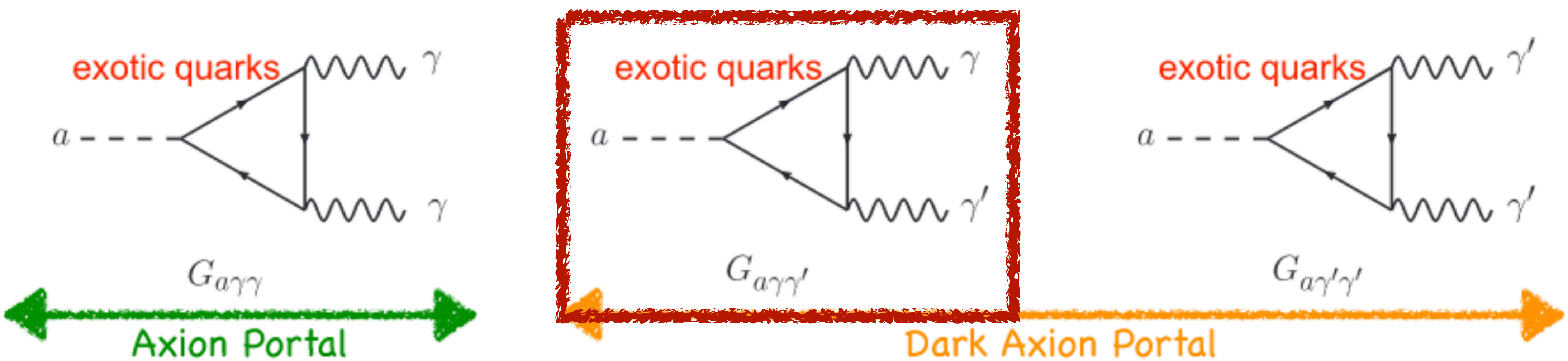
Dark ALP via dim-5 portal

- Connection between a dark photon and ALP *independent of kinetic mixing*

$$\mathscr{L}_{\text{dark axion portal}} = \frac{g_{a\gamma\gamma'}}{2} a F_{\mu\nu} \tilde{F}'^{\mu\nu}$$

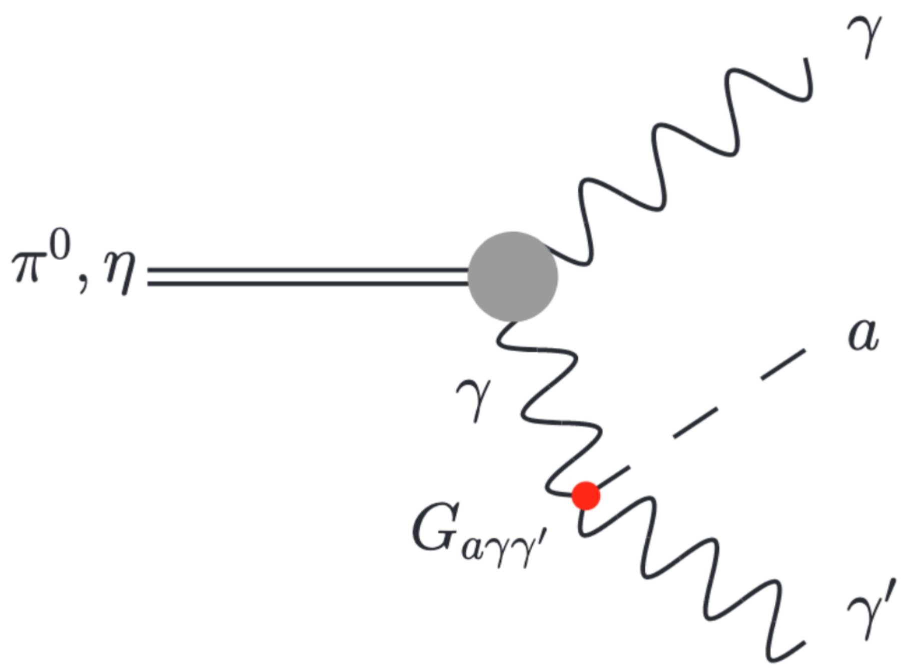
Ejlli, 1609.06623
Kaneta, Lee, Yun, 1611.01466

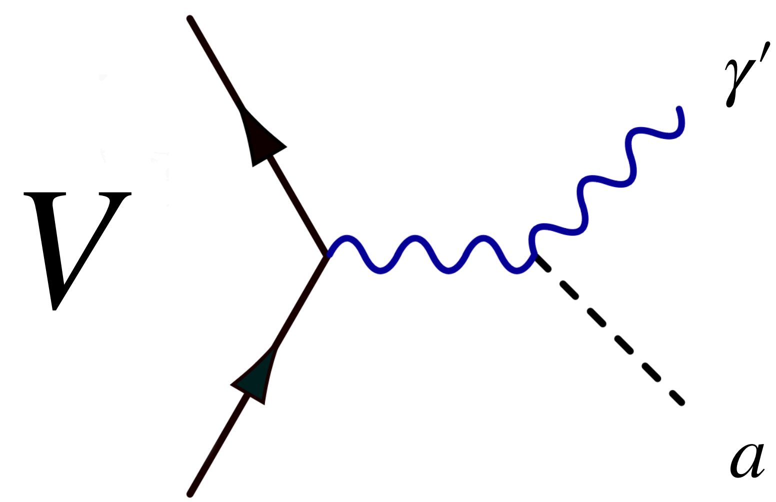
  - Example model: dark KSVZ axion - loops with heavy quarks induce $g_{a\gamma\gamma}$, $g_{a\gamma\gamma'}$, $g_{a\gamma'\gamma'}$ if they are charged under $U(1)_D$ and $U(1)_Y$.



Kaneta, Lee, Yun, 1611.01466

LLP production modes

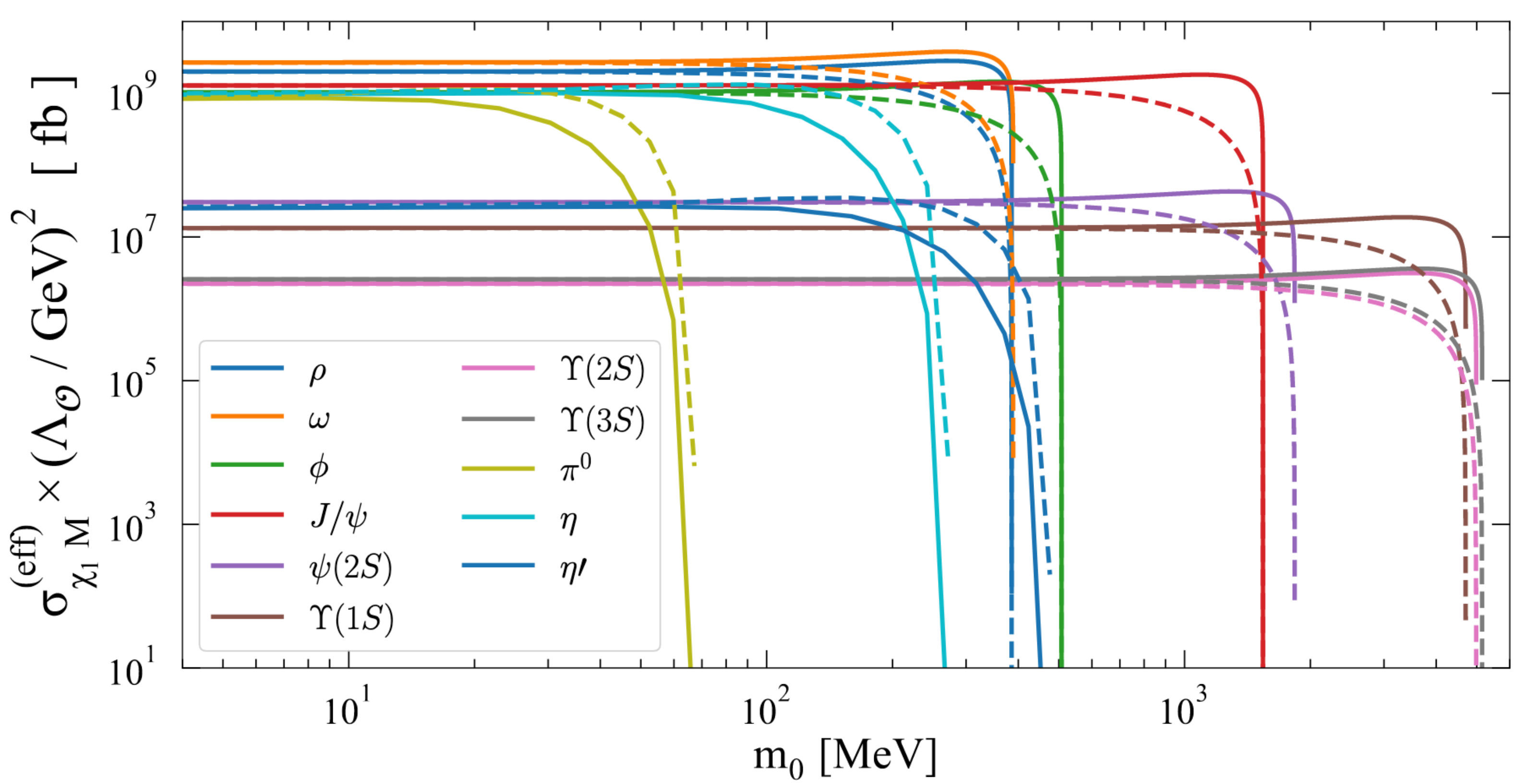




vector meson decays
are more efficient than pseudoscalar meson decays
missing in previous works!

BR of pseudoscalar/vector meson M decays into DS states are **approximately proportional to** m_M^2 → heavy vector meson decays dominate pseudoscalar decays

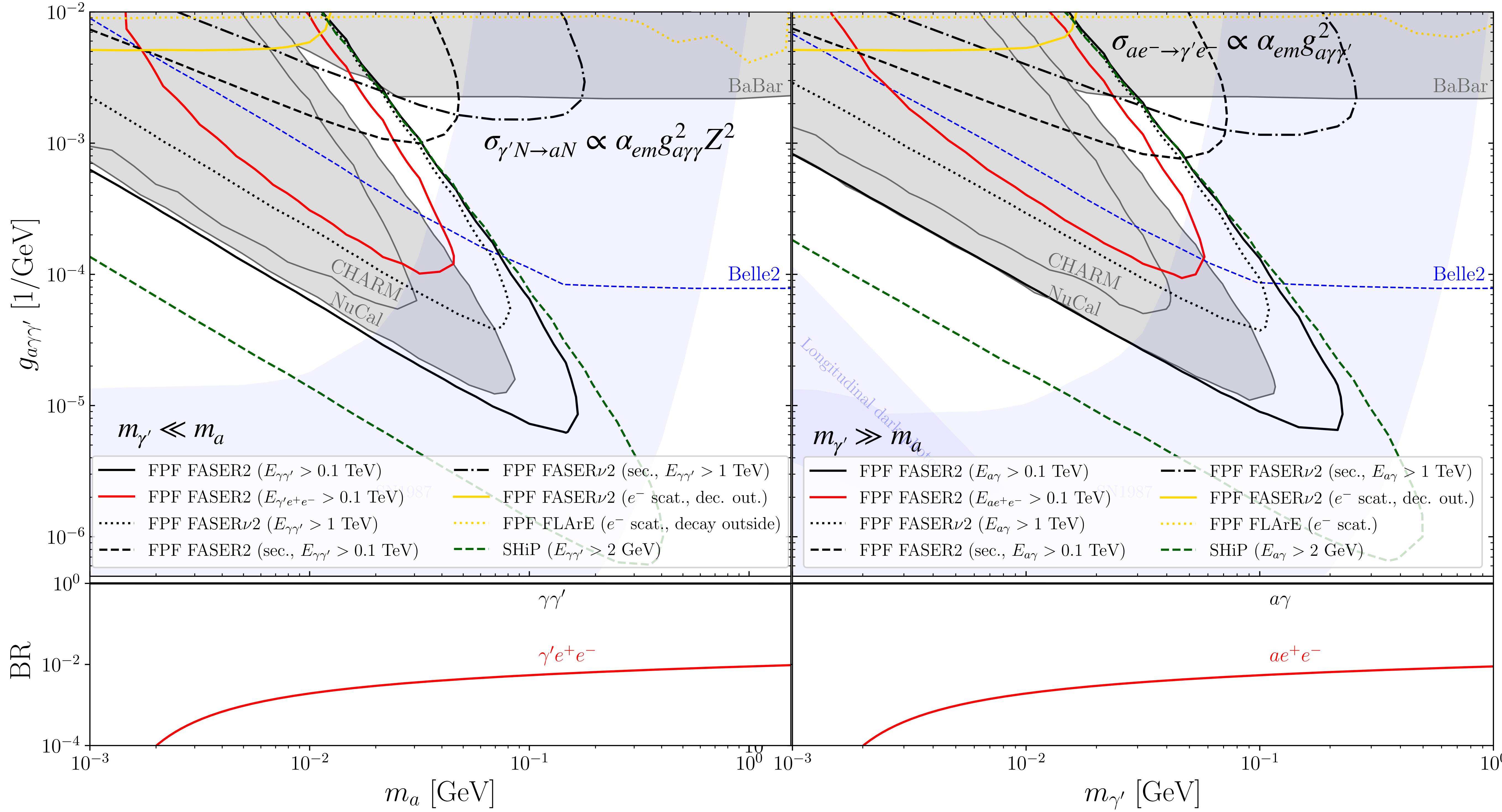
Chu, Kuo, Pradler, 2001.06042
Dienes, Feng, Fieg, Huang, Lee, Thomas, 2301.05252



Same behavior as in magnetic dipole iDM Dienes, Feng, Fieg, Huang, Lee, Thomas, 2301.05252

Dark ALP at FASER/FPF

KJ, 2305.10409

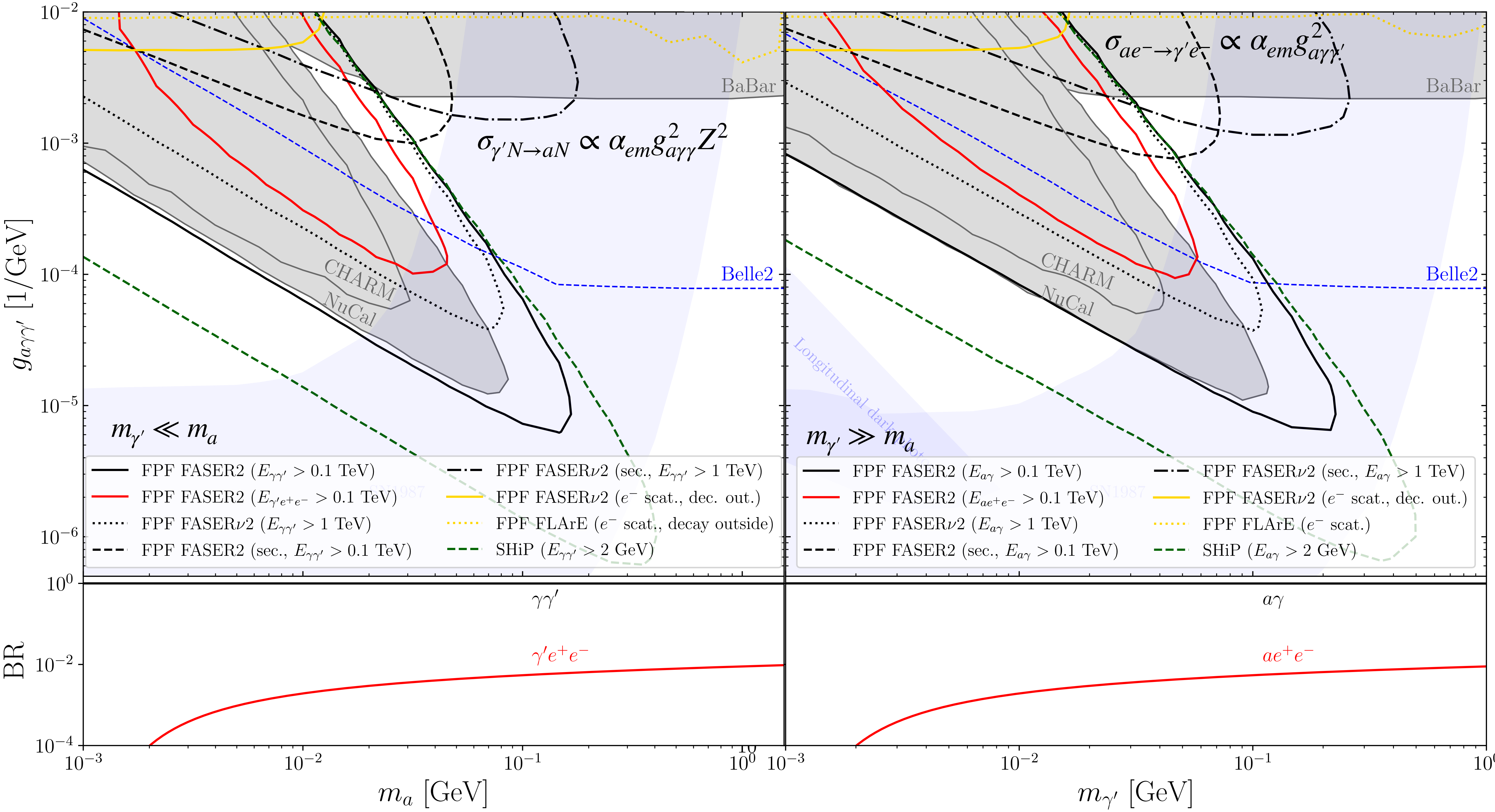


$$d_a \simeq 100\, m \times \left(\frac{E}{1000\,\text{GeV}}\right)\left(\frac{0.1\,\text{GeV}}{m_a}\right)^4\left(\frac{4\times 10^{-5}}{g_{a\gamma\gamma'}}\right)^2,$$

$$d_{\gamma'} \simeq 100\, m \times \left(\frac{E}{1000\,\text{GeV}}\right)\left(\frac{0.1\,\text{GeV}}{m_{\gamma'}}\right)^4\left(\frac{7\times 10^{-5}}{g_{a\gamma\gamma'}}\right)^2,$$

Dark ALP at FASER/FPF

mono-γ from LLP decay inside detector → no BaBar/Belle sens. for $m < 1$ MeV → FLArE/FASERν



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Neutralino-gravitino

- Promote global SUSY to local symmetry → spin 3/2 partner of massless graviton (called gravitino)

$$S = \int \mathrm{d}^4 x e \left[-\frac{1}{2\kappa^2} R - \frac{1}{2} \epsilon^{\kappa\lambda\mu\nu} \overline{\psi}_\kappa \gamma^5 \gamma_\lambda \partial_\mu \psi_\nu \right]$$

- SUSY breaking by VEV $\langle F_{\rm SUSY} \rangle$ → Goldstone fermion (goldstino)

- Gravitino is the LSP, neutralino (bino) is NLSP and acts as a LLP,

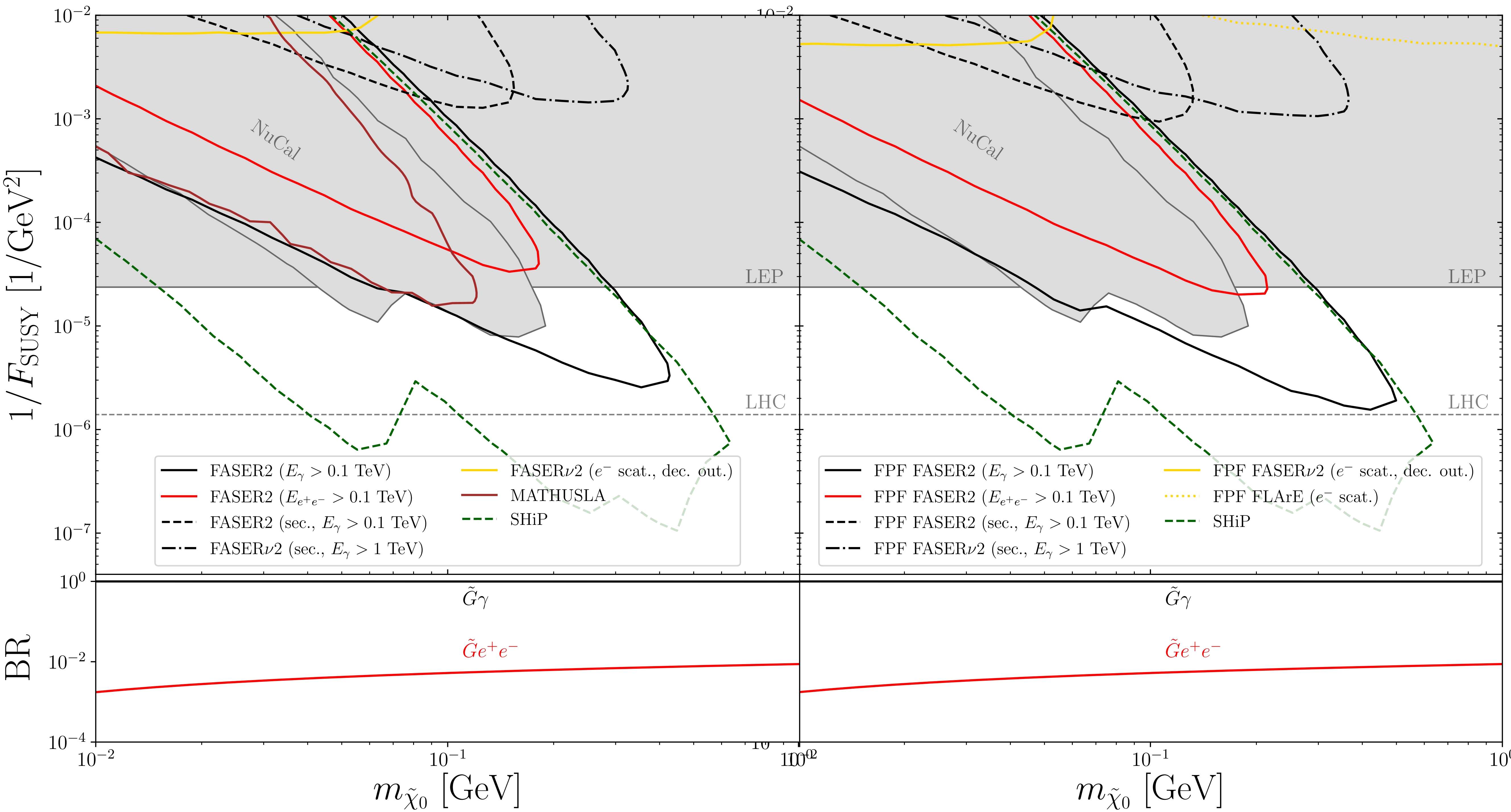
$$\mathcal{L} \supset -\frac{1}{4M_{\rm Pl.red.}} \bar{\psi}_\mu \sigma^{\rho\sigma} \gamma^\mu \lambda F_{\rho\sigma}, \quad \psi_\mu \sim i \sqrt{\frac{2}{3}} \frac{1}{m_{3/2}} \partial_\mu \chi \, .$$

- After SUSY breaking $m_{3/2} \sim F^2_{SUSY}/m_{Pl.}$ the goldstino becomes the $\pm 1/2$ helicity of the gravitino (super-Higgs mechanism) and the couplings becomes enhanced by $1/m_{3/2}$. Result: γ-$\tilde{G}$-$\tilde{\chi}_0$ coupling is $\propto 1/\sqrt{F_{\rm SUSY}}$.

- Light gravitino - there is still allowed space within $\begin{array}{ccc} 10^{-5}\ \mathrm{eV} < & m_{\tilde{G}} & < 10\ \mathrm{eV} \\ 200\ \mathrm{GeV} < & \sqrt{F} & < 200\ \mathrm{TeV} \end{array}$ range

Neutralino-gravitino at FASER

- Neutralino is NLSP, gravitino is LSP $\tilde{\chi}_0 \to \tilde{G}\gamma$



$$d_{\tilde{\chi}} \simeq 100m \times \left(\frac{E}{1000\,\mathrm{GeV}}\right)\left(\frac{0.1\,\mathrm{GeV}}{m_{\tilde{\chi}}}\right)^5\left(\frac{F_{\mathrm{SUSY}}}{(60\,\mathrm{GeV})^2}\right)^2$$

Conclusions

- FASER2/FPF will explore a range of models predicting sub-GeV long-lived particles coupled to a photon by dim-5 or -6 operators.

- FASER is a particularly suitable to cover a large part of available parameter space for i) *dark ALP portal, ii) neutralino coupled to axino or gravitino, iii) iDM with EM form factors, and iv) massive spin-2 mediator*.

- Secondary LLP production via Primakoff-like upscattering of the LSP on tungsten FASERν2, will allow to *cover the* $d_{LLP} \sim 1\,m$ *region of parameter space*.

- Monte Carlo simulation is implemented in an extended version of FORESEE.

Massive spin-2 portal

A portal with massive spin-2 field coupled *universally* to SM gauge bosons and matter fields

$$\mathscr{L} \supset g_\gamma G^{\mu\nu}\left(\frac{1}{4}\eta_{\mu\nu}F_{\lambda\rho}F^{\lambda\rho} + F_{\mu\lambda}F_\nu{}^\lambda\right) - i\sum_l \frac{g_\ell}{2}G^{\mu\nu}\left(\bar{l}\gamma_\mu D_\nu l - \eta_{\mu\nu}\bar{l}\gamma_\rho D^\rho l\right), \quad g_\ell = g_\gamma$$

Non-universal couplings lead to (perturbative) unitarity violation in, e.g., $q\bar{q} \to \gamma G$ process: $|\text{amplitude}|^2 \propto 1/m_G^4$ (helicity-0 modes do not decouple; helicity-1 modes give $\propto 1/m_G^2$, while helicity-2 $\propto 1/m_G^0$) Artoisenet et al. 1306.6464 - also see recent Gill, Sengupta, Williams, 2303.04329.

Motivation

- Quantum gravity and extra dimensions

  Kaluza-Klein States from Large Extra Dimensions, Han, Lykken, Zhang, 9811350

  Quantum gravity and extra dimensions at high-energy colliders, Giudice, Rattazzi, Wells, 9811291

- Missing energy searches

  Probing hidden spin-2 mediator of dark matter with NA64e, LDMX, NA64μ and M3, Voronchikhin, Kirpichnikov, 2210.00751

- Dark Matter

  Planckian Interacting Massive Particles as Dark Matter: Garny, Sandora, Sloth, 1511.03278

  Massive Gravitons as Feebly Interacting Dark Matter Candidates: Cai, Cacciapaglia, Lee, 2107.14548

- Gravity-mediation

  Gravity-mediated Scalar Dark Matter in Warped Extra-Dimensions: Folgado, Donini, Rius, 1907.04340

  Lightening gravity-mediated dark matter: Kang, Lee, 2001.04868

- Fixed target experiments (lab long-lived particles searches)

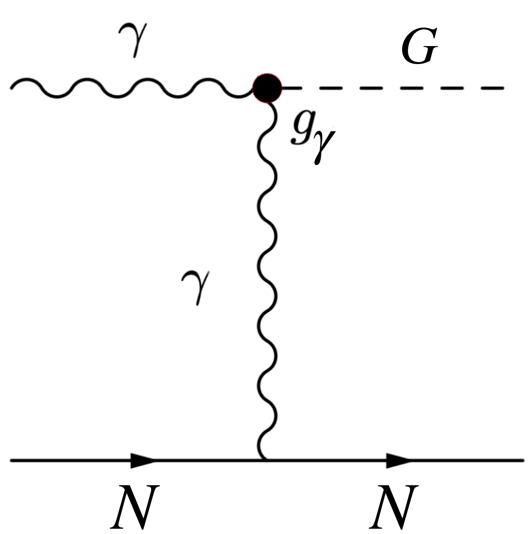
  Probing hidden spin-2 mediator of dark matter with NA64e, LDMX, NA64μ and M3, Voronchikhin, Kirpichnikov, 2210.00751

  The resonant probing spin-0 and spin-2 dark matter mediators with fixed target experiments, Voronchikhin, Kirpichnikov, 2304.14052

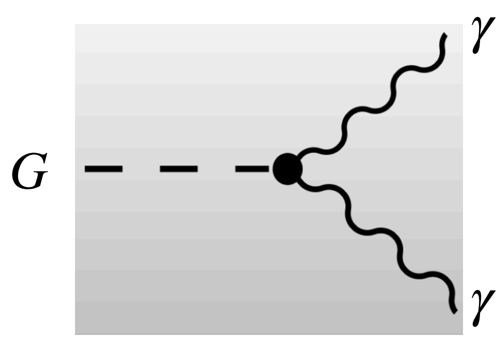
Massive spin-2 mediator at FPF

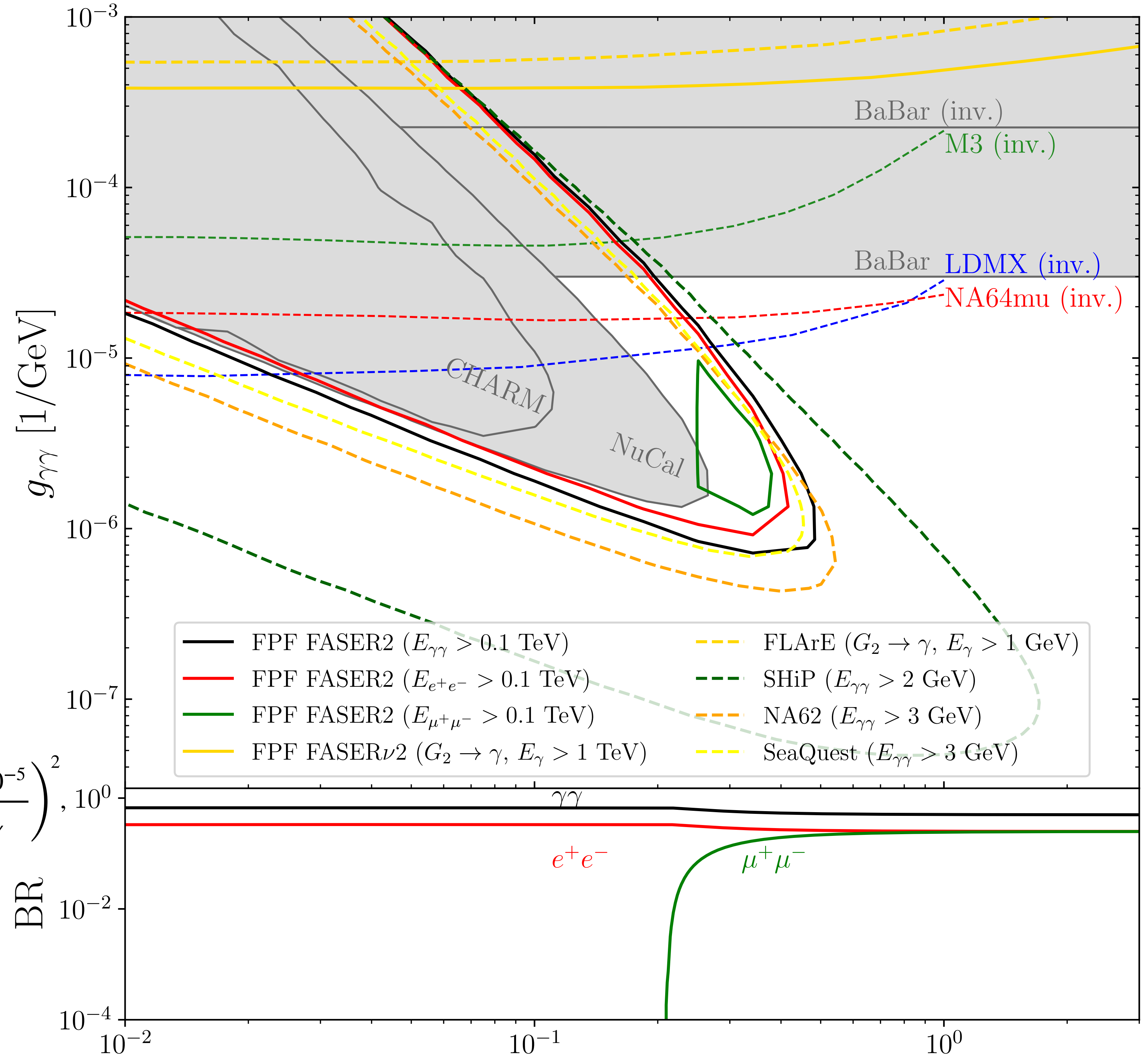
$$\mathscr{L} \supset g_\gamma G^{\mu\nu}\left(\frac{1}{4}\eta_{\mu\nu}F_{\lambda\rho}F^{\lambda\rho} + F_{\mu\lambda}F_{\nu}^{\ \lambda}\right)$$
$$-i\sum_{l}\frac{g_\ell}{2}G^{\mu\nu}\left(\bar{l}\gamma_\mu D_\nu l - \eta_{\mu\nu}\bar{l}\gamma_\rho D^\rho l\right)$$

$$\sigma_{\gamma N\to GN} \simeq \frac{\alpha_{em} g_{G\gamma\gamma}^2 Z^2}{2}\left[\log\left(\frac{d}{1/a^2 + t_{max}}\right) - 2\right]$$



$$d_G = c\tau\beta\gamma \simeq 100\,m \times \left(\frac{E}{1000\,GeV}\right)\left(\frac{0.1\,GeV}{m_G}\right)^4\left(\frac{5\times 10^{-5}}{g_{G\gamma\gamma}}\right)^2,$$





KJ, 2305.05710

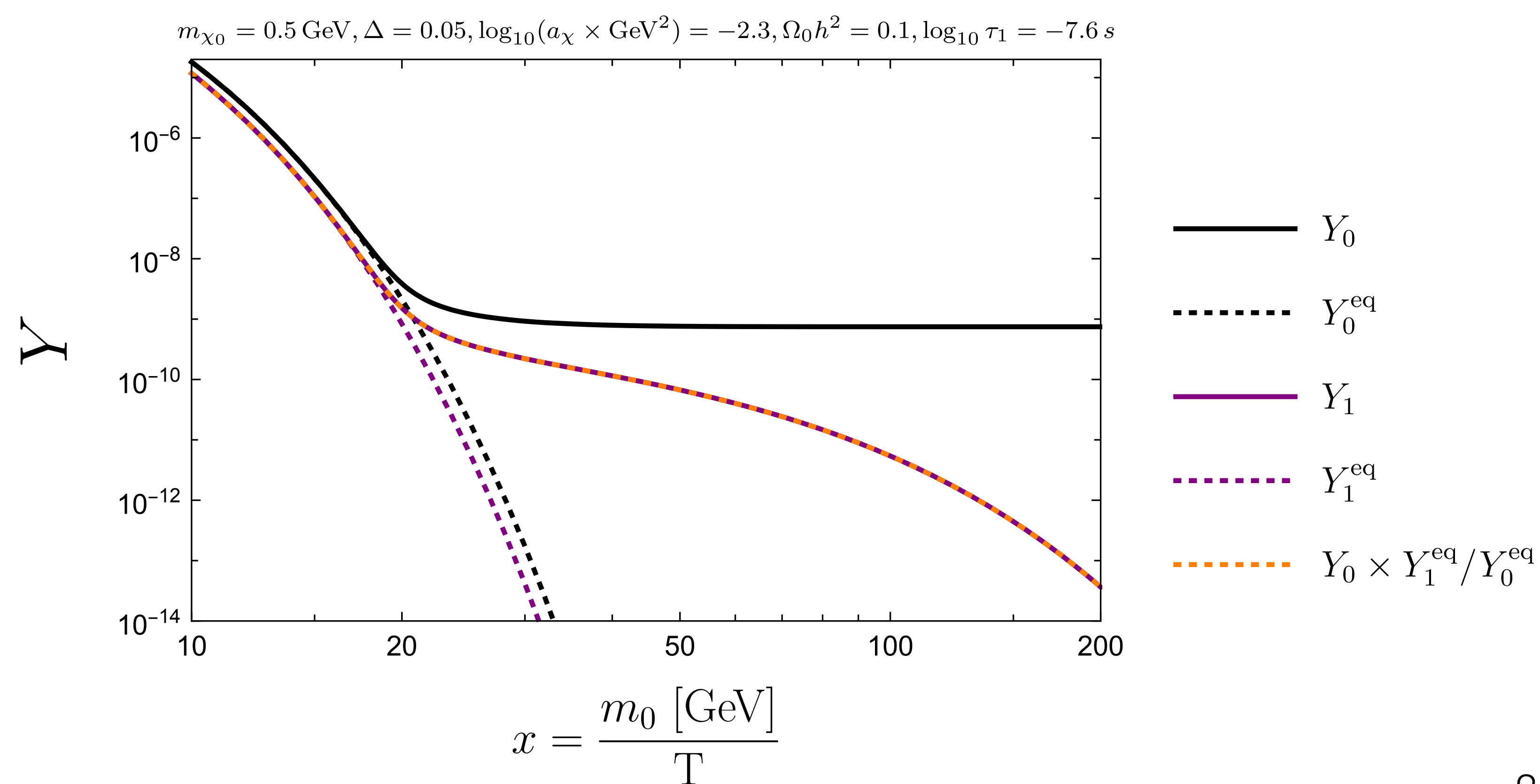
Inelastic DM with EM form factors

- Inelastic DM with EM form factors - heavier state decays into SM and the LSP
  - dim 5 - magnetic/electric dipole $\mathscr{L} \supset \frac{1}{\Lambda_m}\bar{\chi}_1\sigma^{\mu\nu}\chi_0 F_{\mu\nu} + \frac{1}{\Lambda_e}\bar{\chi}_1\sigma^{\mu\nu}\gamma^5\chi_0 F_{\mu\nu}$ → decay: $\chi_1 \to \chi_0\gamma$
  - dim 6 - anapole/charge radius $\mathscr{L} \supset -a_\chi\bar{\chi}_1\gamma^\mu\gamma^5\chi_0\,\partial^\nu F_{\mu\nu} + b_\chi\bar{\chi}_1\gamma^\mu\chi_0\,\partial^\nu F_{\mu\nu}$ → decay: $\chi_1 \to \chi_0 e^+e^-$
- Relic density set by co-annihilations and decay (dim-5 iDM was discussed in Dienes et al, 2301.05252)

$$\frac{dY_0}{dx} = -\lambda\left(Y_0Y_1 - Y_0^{\rm eq}Y_1^{\rm eq}\right)\left\langle\sigma_{01\to {\rm SMSM}}v\right\rangle - \lambda\left(Y_0 - Y_1\frac{Y_0^{\rm eq}}{Y_1^{\rm eq}}\right)\left\langle\sigma_{0e^-\to 1e^-}v\right\rangle + \tilde{\lambda}\left(Y_1 - Y_0\frac{Y_1^{\rm eq}}{Y_0^{\rm eq}}\right)\left\langle\Gamma_{1\to 0e^+e^-}\right\rangle$$

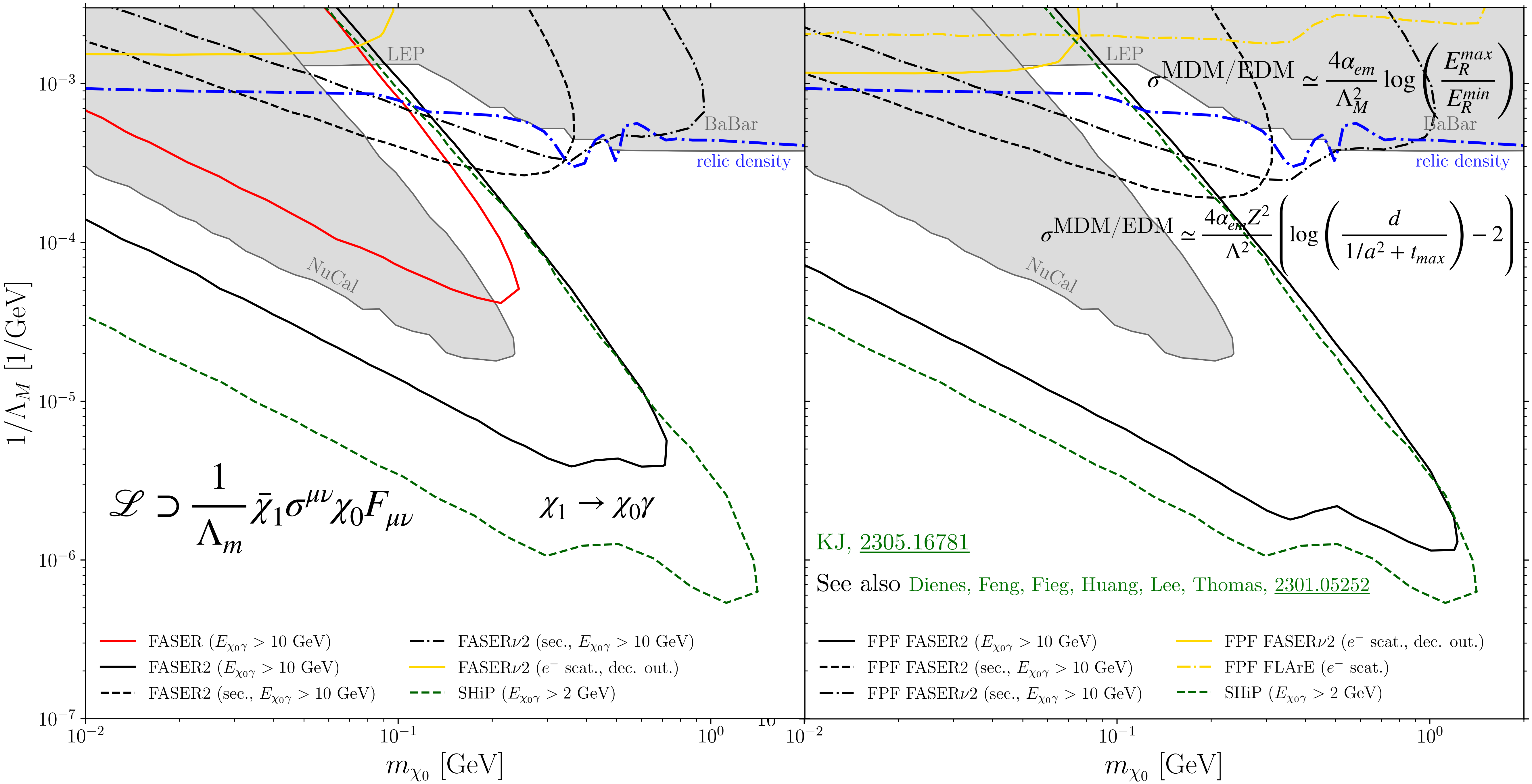
$$\frac{dY_1}{dx} = -\lambda\left(Y_0Y_1 - Y_0^{\rm eq}Y_1^{\rm eq}\right)\left\langle\sigma_{01\to {\rm SMSM}}v\right\rangle + \lambda\left(Y_0 - Y_1\frac{Y_0^{\rm eq}}{Y_1^{\rm eq}}\right)\left\langle\sigma_{0e^-\to 1e^-}v\right\rangle - \tilde{\lambda}\left(Y_1 - Y_0\frac{Y_1^{\rm eq}}{Y_0^{\rm eq}}\right)\left\langle\Gamma_{1\to 0e^+e^-}\right\rangle$$

- The mass splitting is bounded, $0 < \Delta \equiv \frac{m_1 - m_0}{m_0} \lesssim O(0.5)$, because $\left\langle\sigma_{01\to {\rm SMSM}}v\right\rangle \propto \exp(-x\cdot\Delta)$
- $\Omega_0 h^2 \simeq 0.1$, $\Omega_1 h^2 \simeq 0$ due to decays and down-scatterings, which guarantee $Y_1(x) \simeq Y_0(x)\frac{Y_1^{\rm eq}(x)}{Y_0^{\rm eq}(x)}$.



Magnetic dipole iDM at FASER

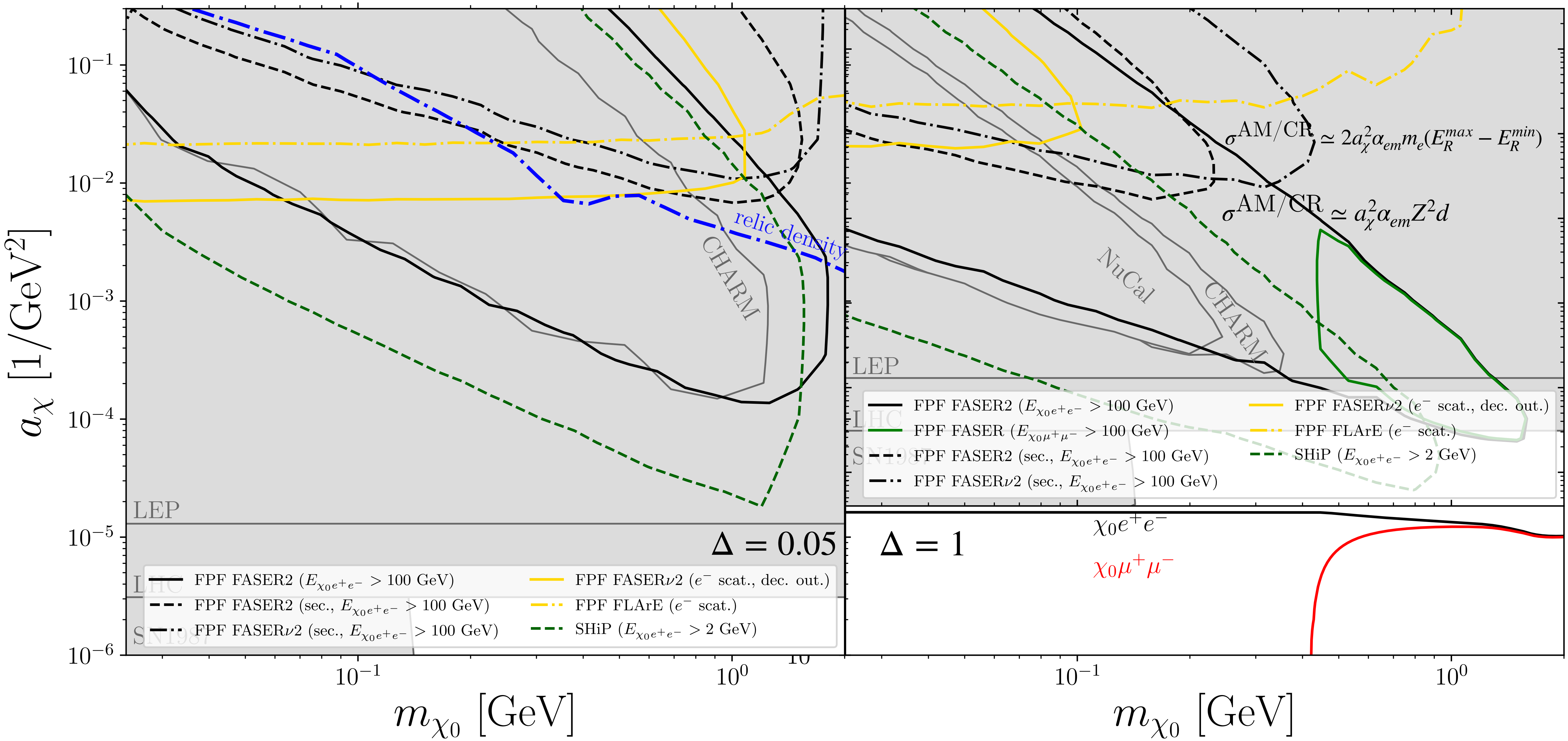
Secondary production allows to cover the $\sim O(1)\,m$ regime. The low mass regime is also covered by electron scatterings - sec. prod. is more efficient than e^- scattering thanks to the Z^2 enhancement.



$$d_{\chi_1} \simeq 100\,m \times \left(\frac{E}{1000\,GeV}\right)\left(\frac{0.1\,GeV}{m_{\chi_0}}\right)^4\left(\frac{0.05}{\Delta}\right)^3\left(\frac{\Lambda}{2.55\times 10^3 GeV}\right)^2$$

Anapole moment iDM at FASER

$\mathscr{L} \supset -a_\chi \bar{\chi}_1 \gamma^\mu \gamma^5 \chi_0 \partial^\nu F_{\mu\nu}$



$\chi_1 \to \chi_0 e^+ e^-$ $\quad$ $\Gamma_{\chi_1 \to \chi_0 e^+e^-} = \dfrac{a_\chi^2 \alpha_{em} \Delta^5 m_{\chi_0}^5}{5\pi^2}$ $\quad$ $d_{\chi_1} \simeq 100\, m \times \left(\dfrac{E}{1000\,\text{GeV}}\right)\left(\dfrac{0.1\,\text{GeV}}{m_{\chi_0}}\right)^4 \left(\dfrac{0.05}{\Delta}\right)^3 \left(\dfrac{7.65\times 10^{-3}\text{GeV}^{-2}}{a_\chi}\right)^2$