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

axions++ 2023

25-28 September

Krzysztof Jodłowski

Institute for Basic Science,
Center for Theoretical Physics
of the Universe, Daejeon

Based on:

KJ, 2305.05710

Intensity frontier BSM searches

Light, weakly interacting particles

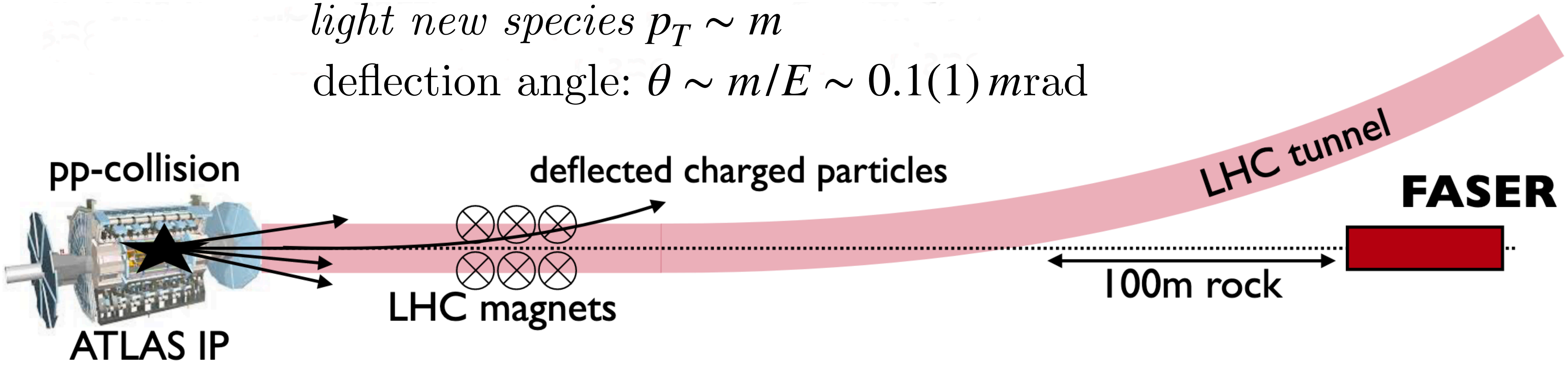
Weak couplings → large luminosities required

$$N_{signal} \sim \text{Lum} \times \sigma_{prod} \times \text{P}_{detection}$$

- Beam dump experiments (proton, electron)
    - ~10-100's GeV energies of beam
    - huge number of collisions on target
    - "zero background"

- FASER(2) at LHC → use "wasted" forward luminosity as a *collimated beam of light new species* $p_T \sim m$
  deflection angle: $\theta \sim m/E \sim 0.1(1)\,m\text{rad}$

ForwArd Search ExpeRiment, 1708.09389



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

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

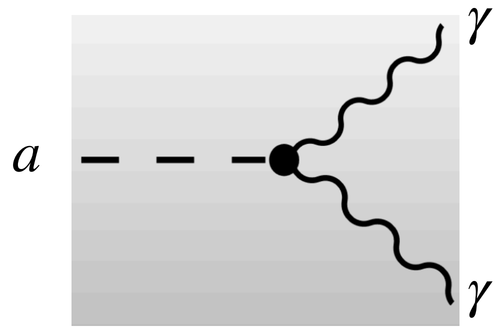
- SUSY - *neutralino* decays into a photon and the LSP:
  - ALPino $\mathscr{L} \supset \frac{\alpha_{\rm em} C_{a\gamma\gamma}}{16\pi f_a} \tilde{a} \gamma_5 \left[\gamma^\mu, \gamma^\nu\right] \tilde{\gamma} F_{\mu\nu}$
  - gravitino $\mathscr{L} \supset -\frac{1}{4 M_{\rm Pl.red.}} \bar{\psi}_\mu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

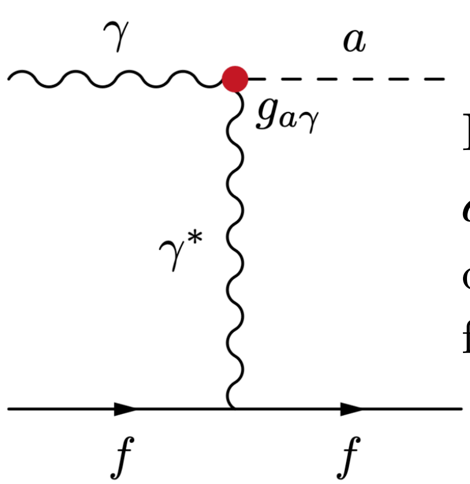
- *Inelastic DM* with EM form factors
  heavier state decays into SM and a stable dark fermion
  - dim 5 - magnetic/electric dipole moment $\mathscr{L} \supset \frac{1}{\Lambda_m} \bar{\chi}_1 \sigma^{\mu\nu} \chi_0 F_{\mu\nu} + \frac{1}{\Lambda_e} \bar{\chi}_1 \sigma^{\mu\nu} \gamma^5 \chi_0 F_{\mu\nu}$
  - dim 6 - anapole moment/charge radius op. $\mathscr{L} \supset -a_\chi \bar{\chi}_1 \gamma^\mu \gamma^5 \chi_0 \, \partial^\nu F_{\mu\nu} + b_\chi \bar{\chi}_1 \gamma^\mu \chi_0 \, \partial^\nu F_{\mu\nu}$

PBC benchmark 9

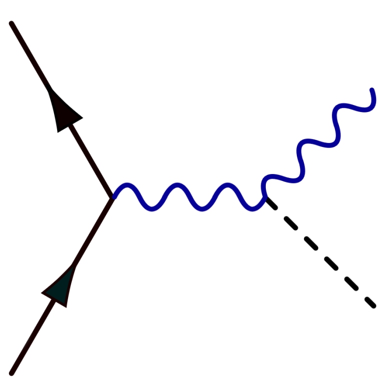
photon-coupled ALP

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

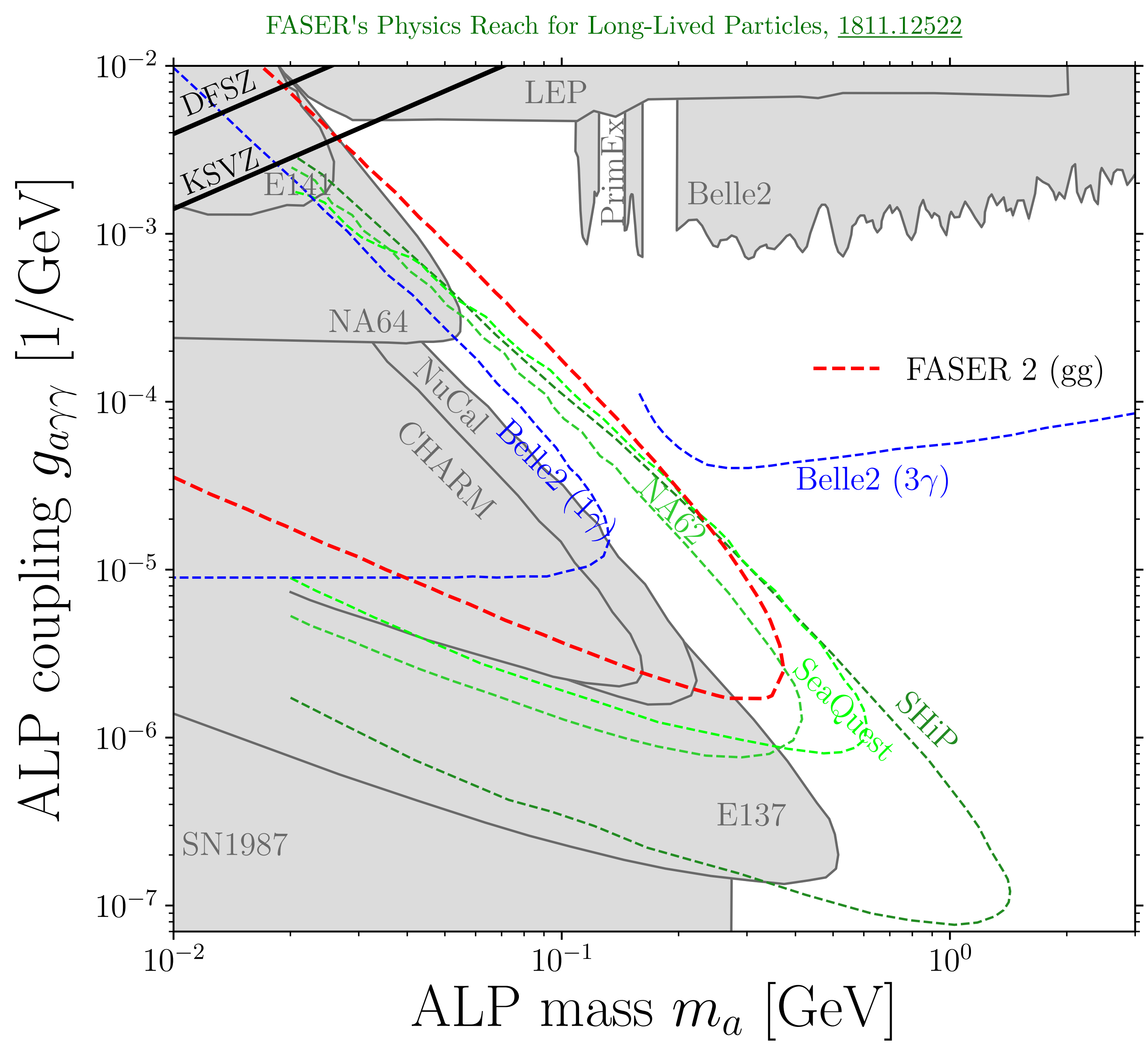




Primakoff scattering
$\sigma_{\gamma N \to aN} \propto \alpha_{em} g_{a\gamma\gamma}^2 Z^2$
dominant production mode
for ALP, spin-2 mediator, ...



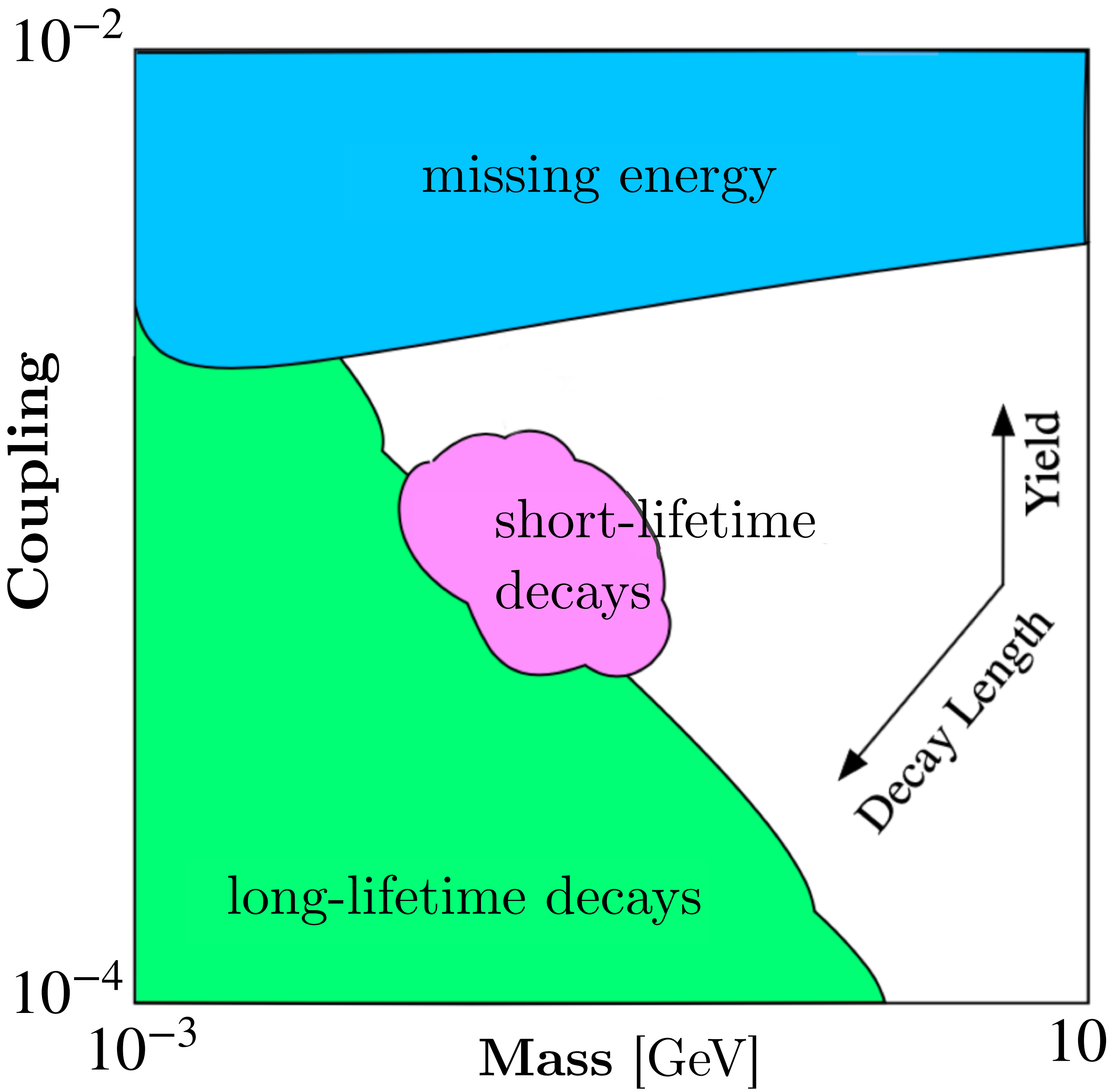
Drell-Yan/vector meson decays
dominant for *single-photon couplings*



$$d_a \sim 100\,m \times \left(\frac{E}{100\,GeV}\right)\left(\frac{0.1\,GeV}{m_a}\right)^4 \left(\frac{1.05\times10^{-5}}{g_{a\gamma\gamma}}\right)^2$$

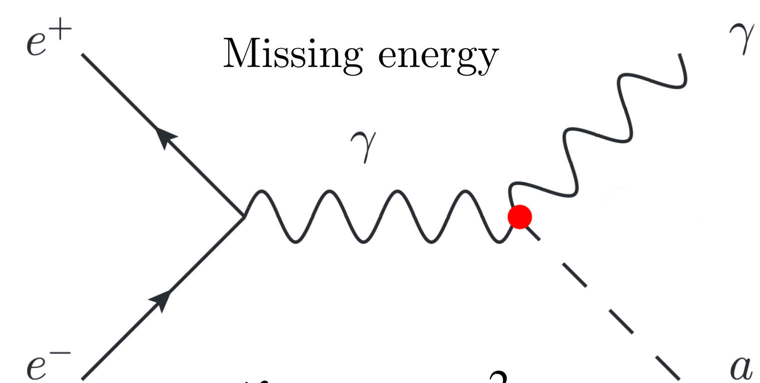
LLP signatures

determined by yield and lifetime



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

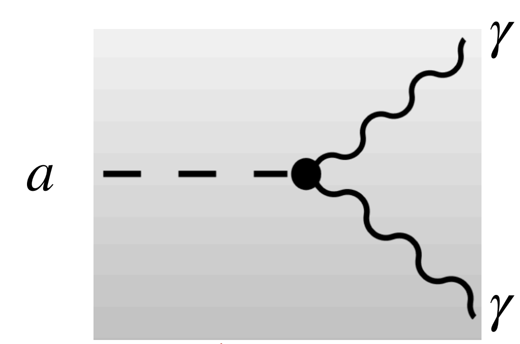
$d \lesssim 10$ m $\rightarrow$ invisible decays/missing energy
10 m $\lesssim d \lesssim 10$ km $\rightarrow$ displaced decays
$d \gtrsim 10$ km $\rightarrow$ astrophysics/cosmology



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

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

Displaced decays



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

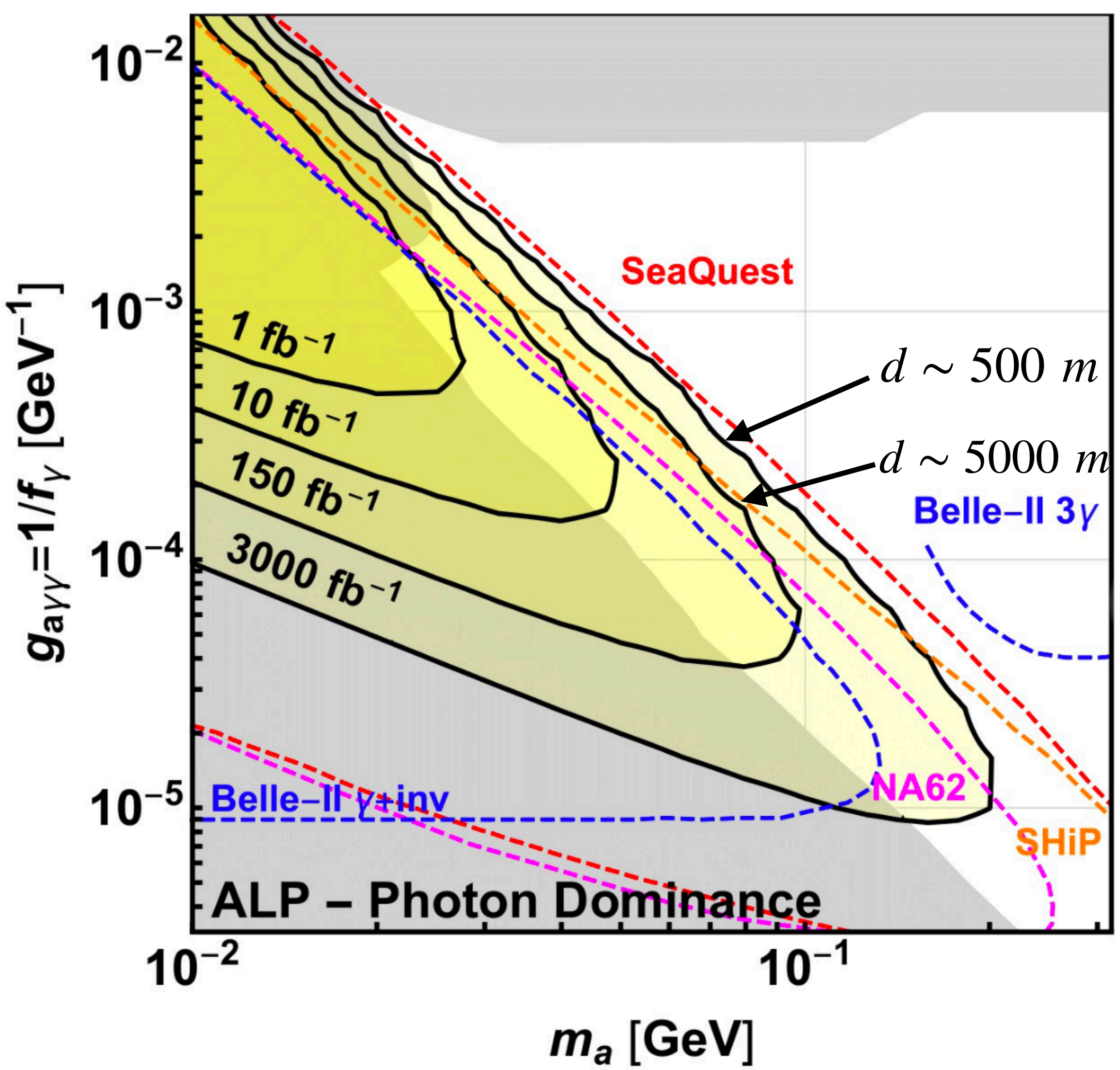
Small $\mathcal{N}_{events}$ with *essentially no background*

ALP decays at beam dumps

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

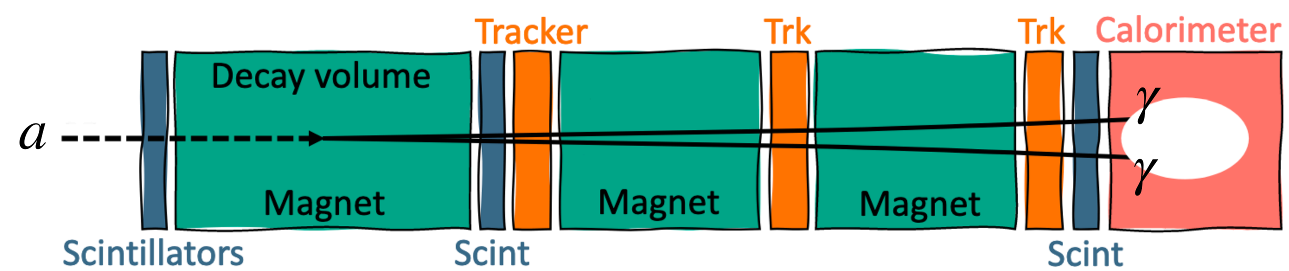
$\rightarrow d$ **is** **exponentially sensitive** **to** L_{min}

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



Displaced vertex $\rightarrow$ 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:

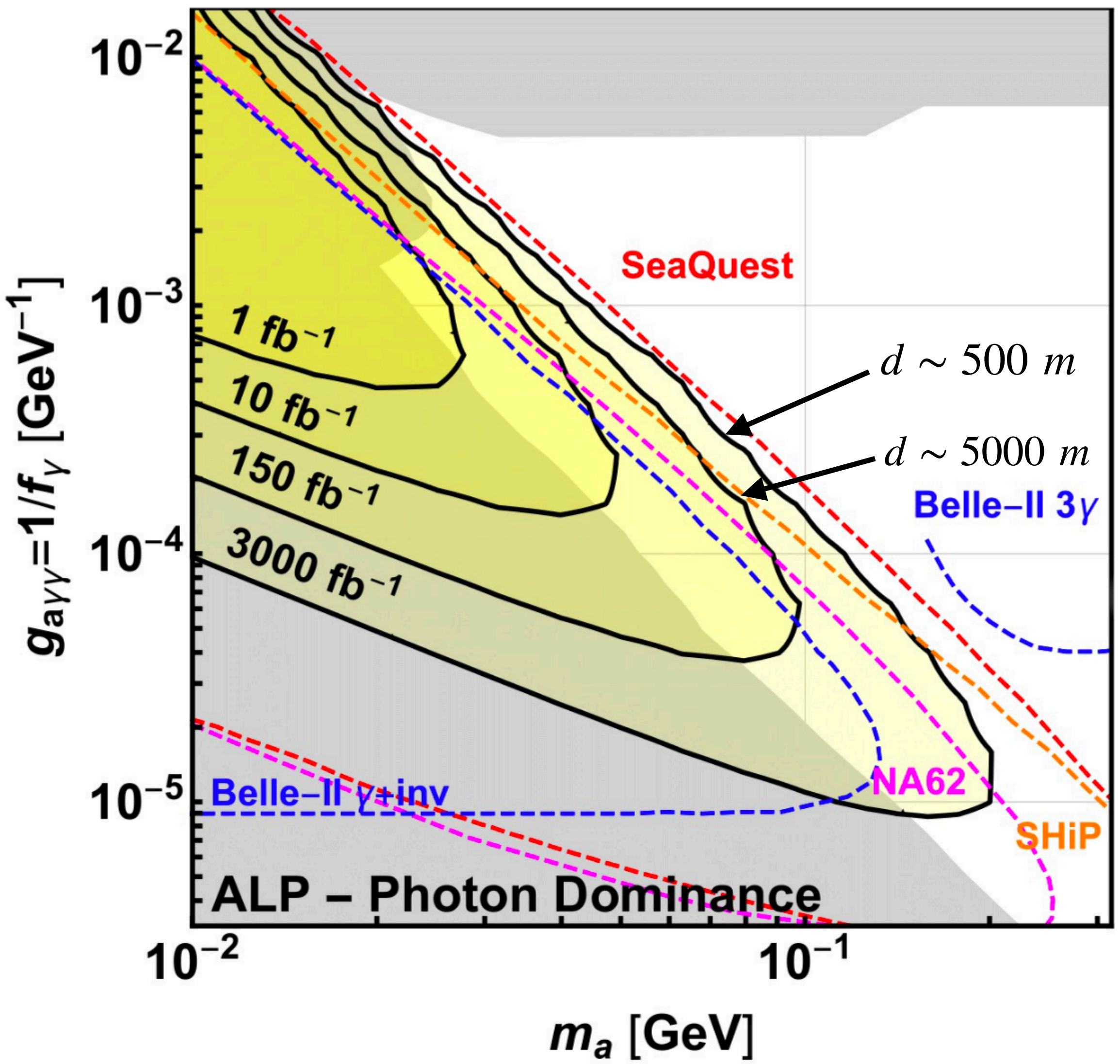
- *big* - large radius r and decay length Δ
- *close* to production point - small L_{min}
- placed in the *forward direction* of the production point

ALP decays at beam dumps

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

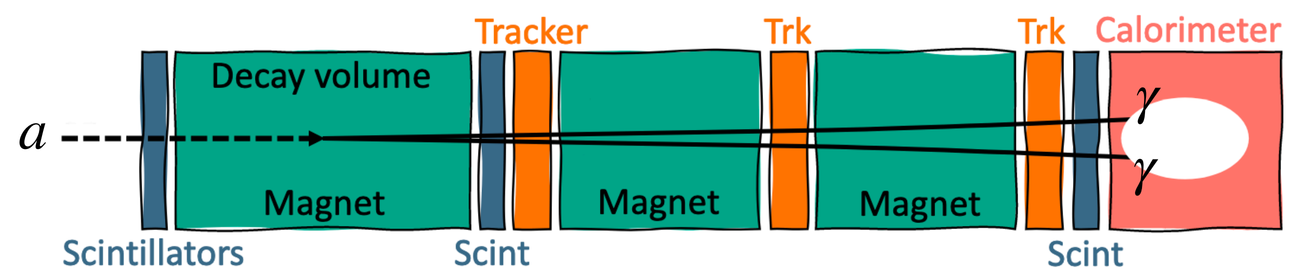
$\rightarrow d$ **is** <u>**exponentially sensitive**</u> **to** L_{min}

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, <u>1811.12522</u>

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



Displaced vertex → essentially *zero background* search

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

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

Good detector is:

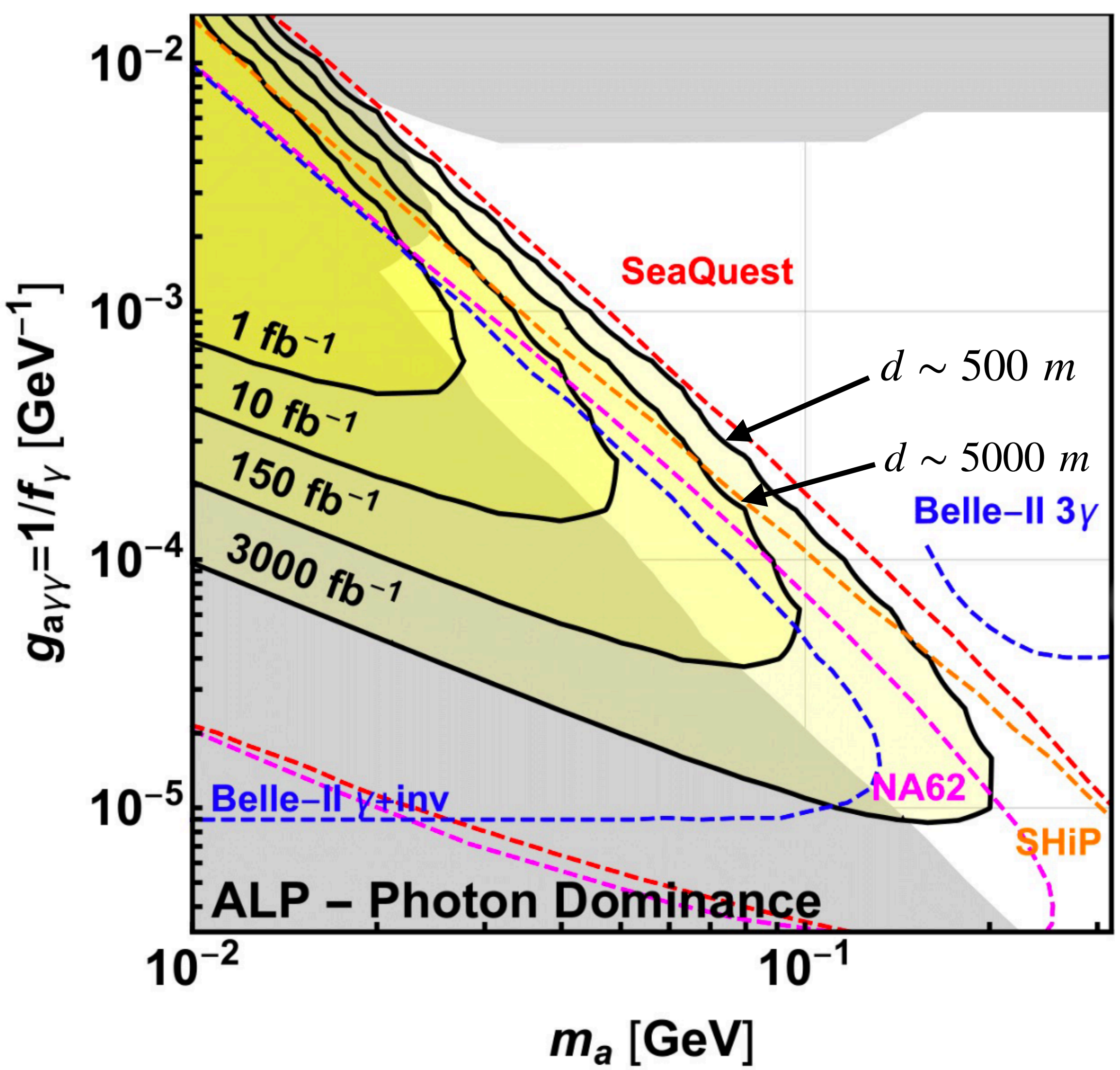
- *big* - large radius r and decay length Δ
- *close* to production point - small L_{min}
- placed in the *forward direction* of the production point

ALP decays at beam dumps

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

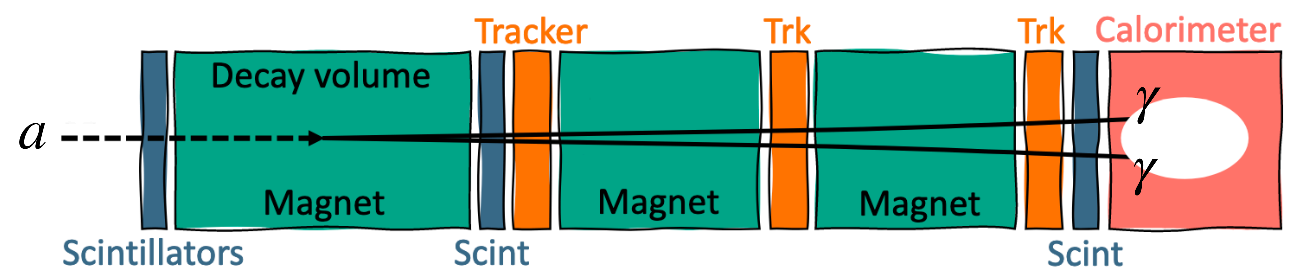
$\rightarrow d$ **is <u>exponentially sensitive</u> to** L_{min}

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, <u>1811.12522</u>

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



Displaced vertex → essentially *zero background* search

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

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

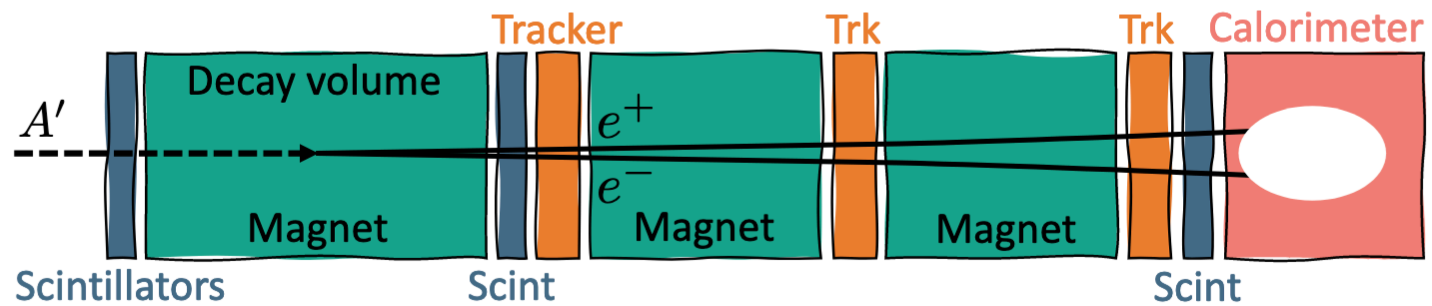
Good detector is:

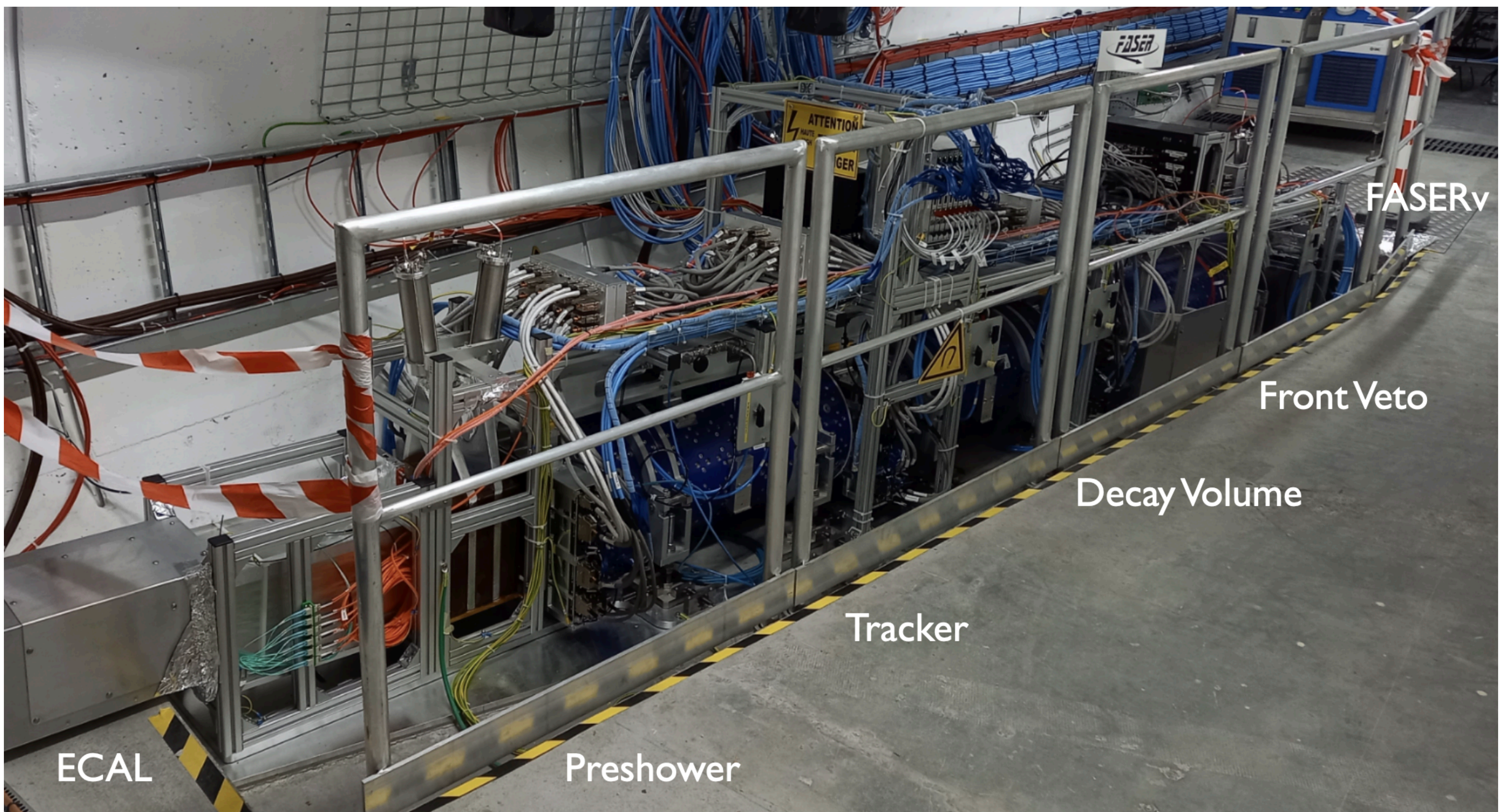
- *big* - large radius r and decay length Δ
- *close* to production point - small L_{min}
- placed in the *forward direction* of the production point

ForwArd Search ExpeRiment

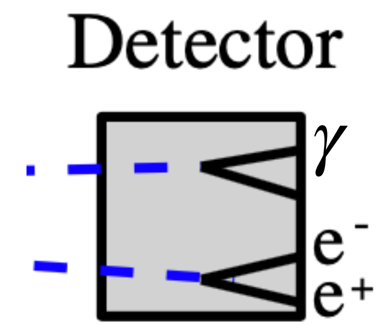
FASER - start with LHC RUN3 (2022-2024), $\mathscr{L} = 150\,\text{fb}^{-1}$
$R = 0.1m$, $L = 1.5m$
FASER2 - start with HL-LHC
$\mathscr{L} = 3000\,\text{fb}^{-1}$; $R = 1m$, $L = 5m$

Feng, Gallon, Kling, Trojanowski, 1708.09389
Letter of Intent for FASER: ForwArd Search ExpeRiment at the LHC, 1811.10243; Technical Proposal for FASER: ForwArd Search ExpeRiment at the LHC, 1812.09139



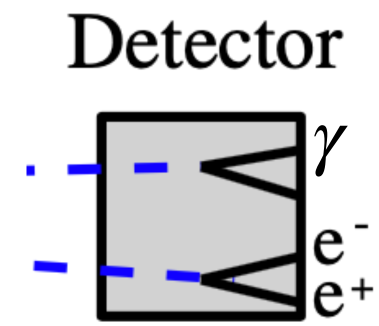


LLP signatures at FASER/FPF



- **LLP signal inside the decay vessel** – e^+e^-, $\gamma\gamma$, **and** $\gamma + X$
  - $E_{vis} > 100$ GeV
  - $\gamma\gamma$, 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*

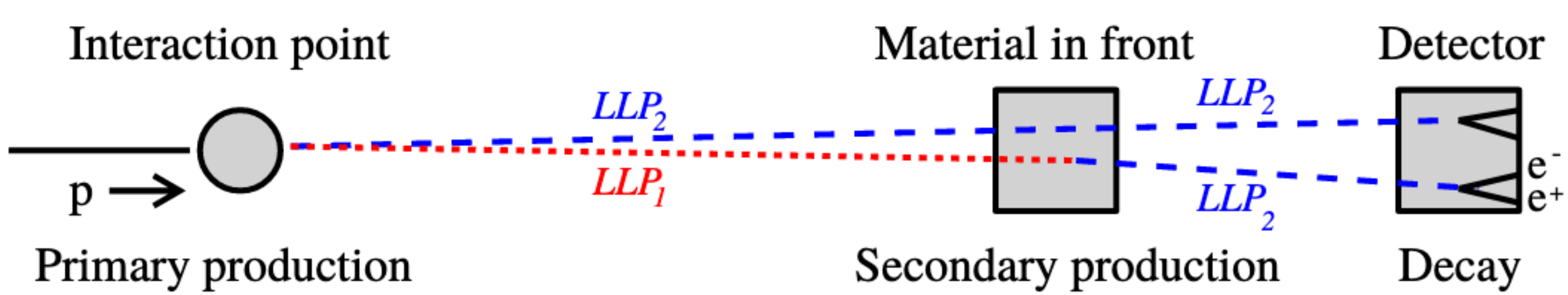
LLP signatures at FASER/FPF



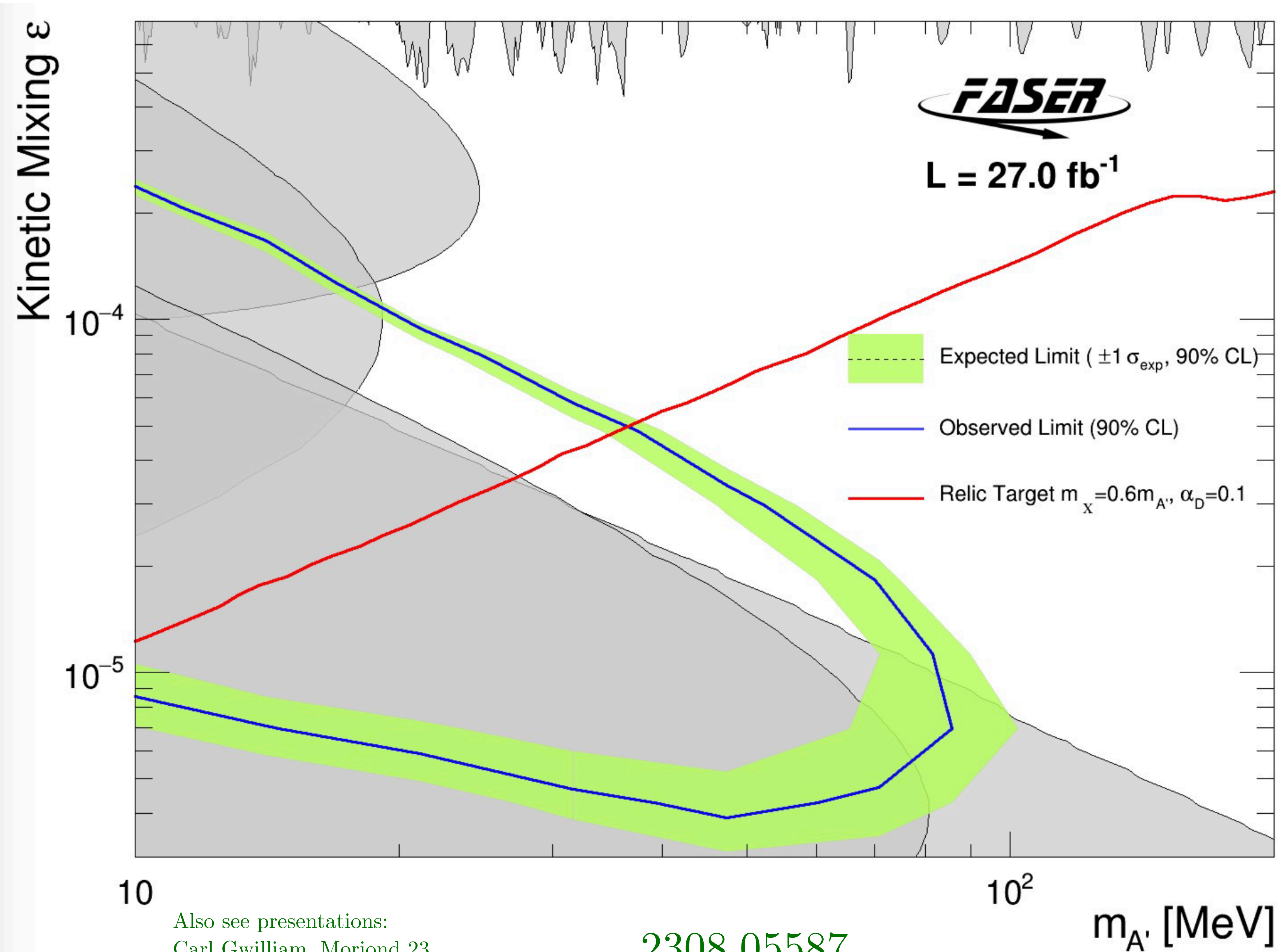
- **LLP signal inside the decay vessel** – e^+e^-, $\gamma\gamma$, **and** $\gamma + X$
  - $E_{vis} > 100$ GeV
  - $\gamma\gamma$, e^+e^- search: negligible background due to high energies of LLP's
  - γ search: KJ, S. Trojanowski, 2011.04751; The FASER W-Si High Precision Preshower Technical Proposal, 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.

- **Secondary LLP production**



First FASER results on LLPs



Also see presentations:
Carl Gwilliam, Moriond 23
Jaime Boyd, Light Dark World 23

2308.05587

Inelastic DM with EM form factors

- Photon as a mediator - heavier state χ_1 decays into SM and the LSP χ_0
  - 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: $\chi_1 \to \chi_0 e^+e^-$

Inelastic DM with EM form factors

- Photon as a mediator - heavier state χ_1 decays into SM and the LSP χ_0
  - dim 5 - magnetic/electric dipole $\mathscr{L} \supset \frac{1}{\Lambda_m}\bar{\chi}_1\sigma^{\mu\nu}\chi_0 F_{\mu\nu} + \frac{1}{\Lambda_e}\bar{\chi}_1\sigma^{\mu\nu}\gamma^5\chi_0 F_{\mu\nu}$ $\rightarrow$ decay: $\chi_1 \rightarrow \chi_0\gamma$
  - dim 6 - anapole/charge radius $\mathscr{L} \supset -a_\chi\bar{\chi}_1\gamma^\mu\gamma^5\chi_0\,\partial^\nu F_{\mu\nu} + b_\chi\bar{\chi}_1\gamma^\mu\chi_0\,\partial^\nu F_{\mu\nu}$ $\rightarrow$ decay: $\chi_1 \rightarrow \chi_0 e^+e^-$

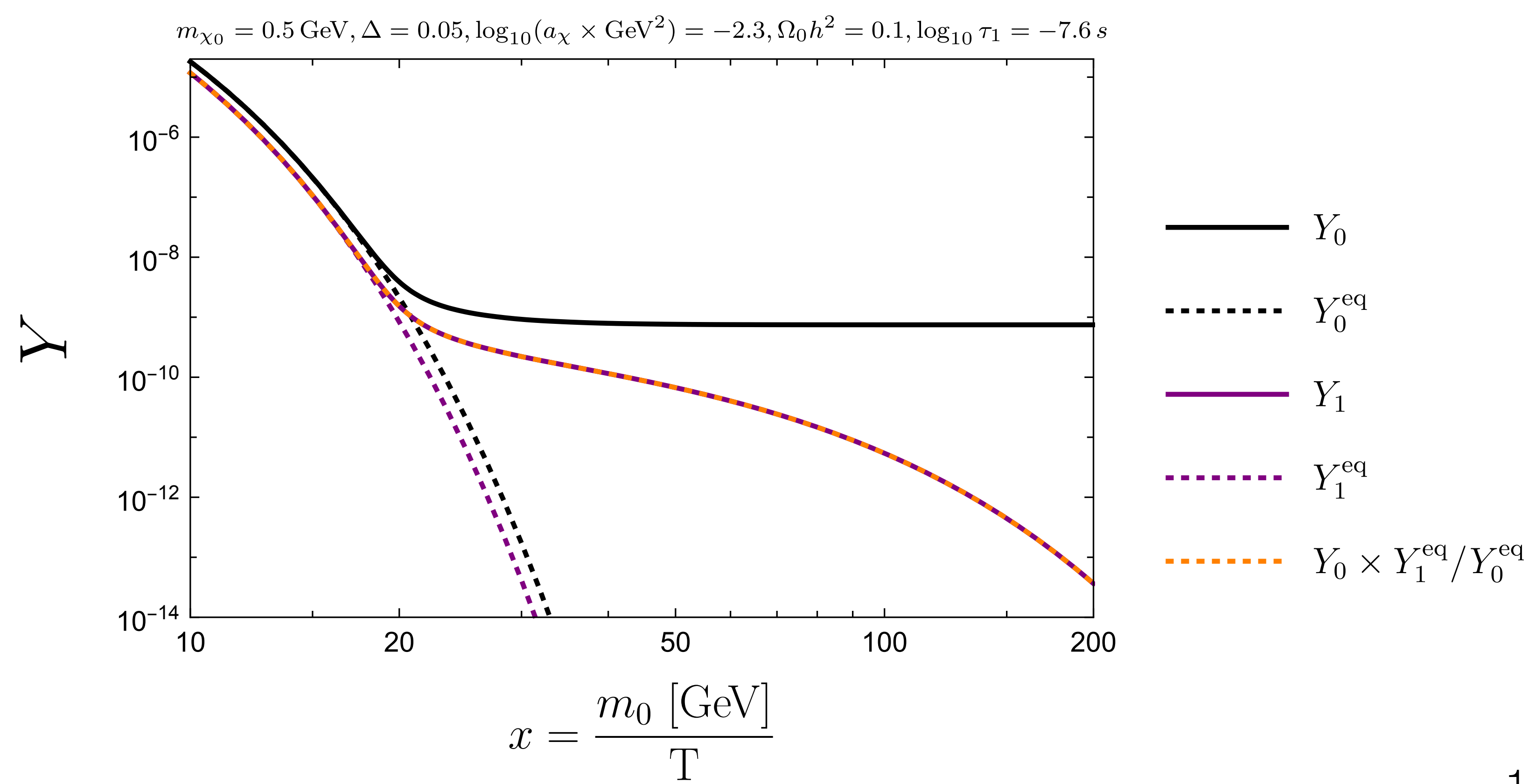
- Relic density set by co-annihilations and decay

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

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

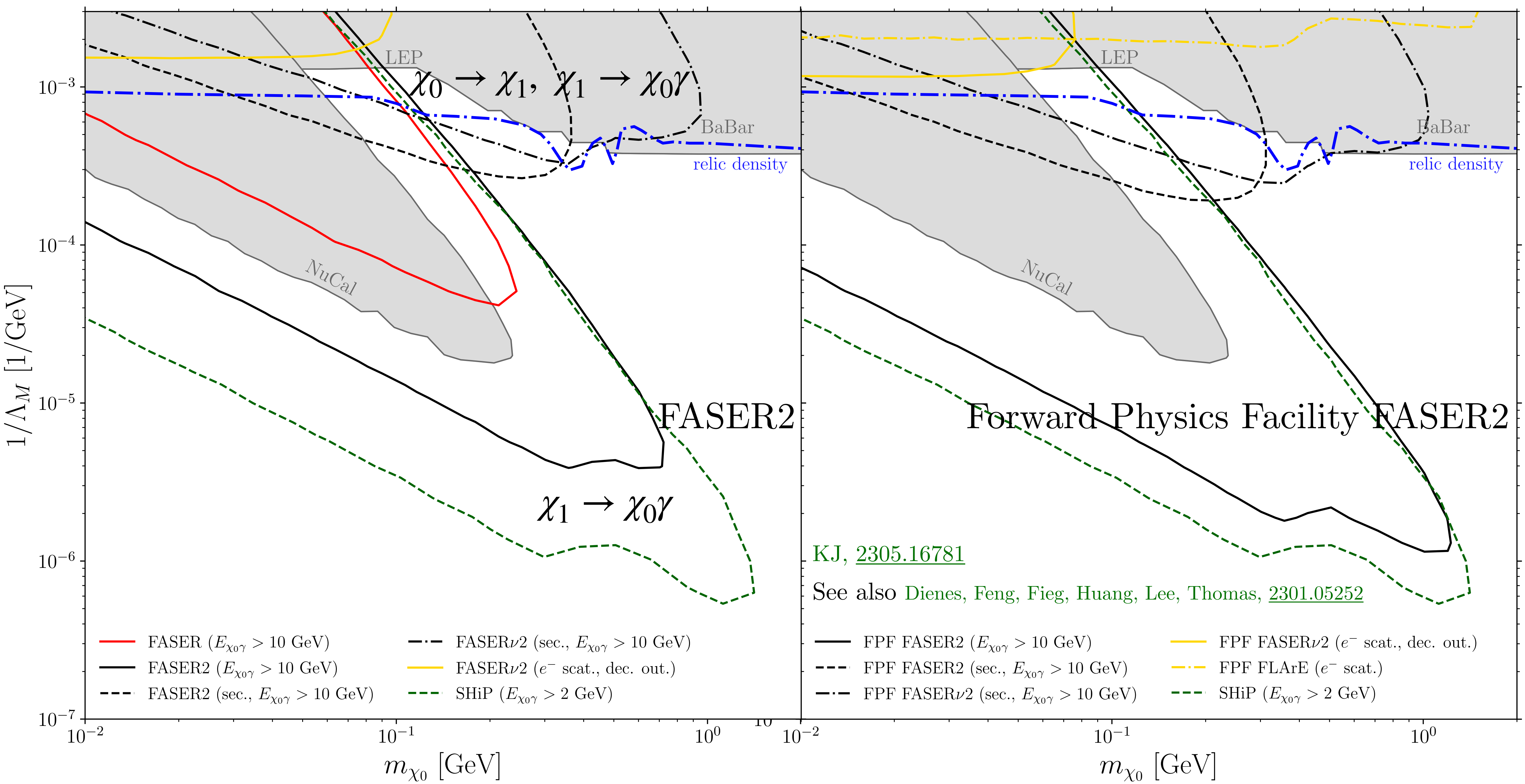
- The mass splitting is bounded, $0 < \Delta \equiv \frac{m_1 - m_0}{m_0} \lesssim O(0.5)$, because $\Gamma_{01\to\rm SM\,SM} \propto \exp(-x\cdot\Delta)$

- $\Omega_0 h^2 \simeq 0.1 \gg \Omega_1 h^2$ 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

Secondary production allows to cover the $d \sim O(1)\, m$ 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.

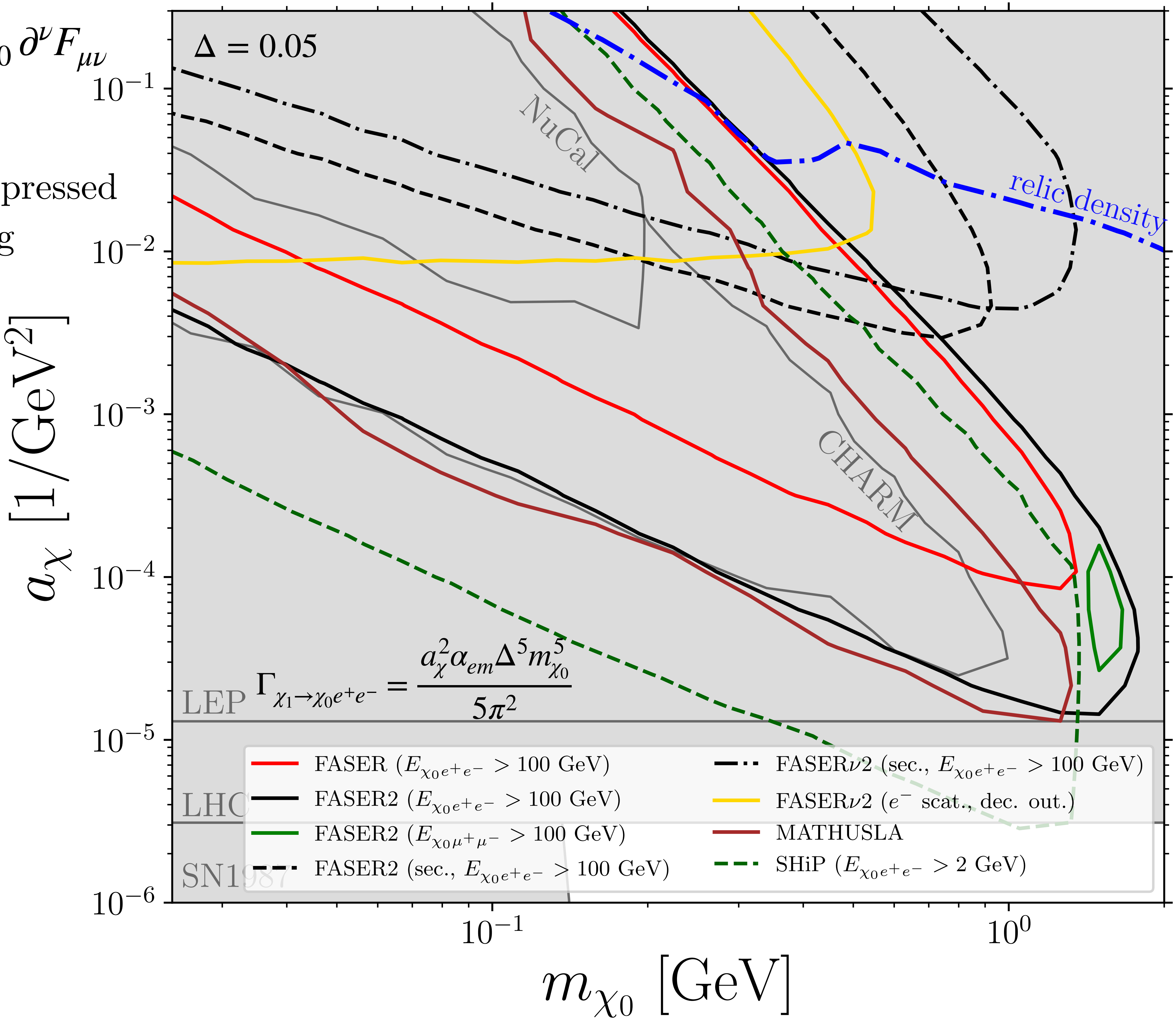


$$\mathscr{L} \supset \frac{1}{\Lambda_m} \bar{\chi}_1 \sigma^{\mu\nu} \chi_0 F_{\mu\nu} \qquad d_{\chi_1} \simeq 100\, m \times \left(\frac{E}{1000\, GeV}\right)\left(\frac{0.1\, GeV}{m_{\chi_0}}\right)^4 \left(\frac{0.05}{\Delta}\right)^3 \left(\frac{\Lambda}{2.55 \times 10^3 GeV}\right)^2$$

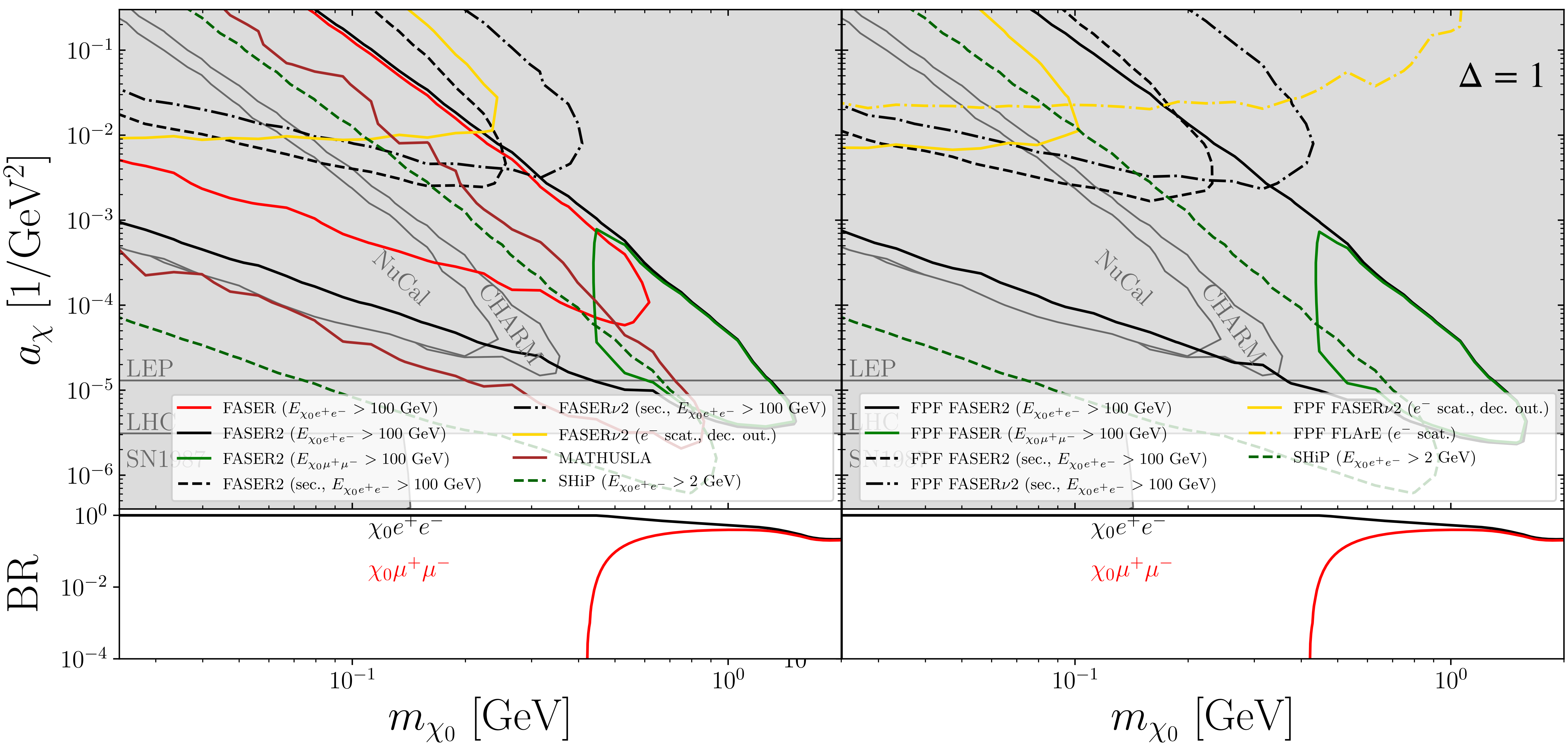
Anapole moment iDM

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

- Vertex $\propto q_\gamma$
  - → scattering suppressed
  - → larger coupling
  - → no $\chi_1 \to \chi_0 \gamma$



Anapole moment iDM



$$\Gamma_{\chi_1\to\chi_0 e^+e^-} = \frac{a_\chi^2 \alpha_{em}\Delta^5 m_{\chi_0}^5}{5\pi^2}$$

$$d_{\chi_1} \simeq 100\,m \times \left(\frac{E}{1000\,\text{GeV}}\right)\left(\frac{0.1\,\text{GeV}}{m_{\chi_0}}\right)^4\left(\frac{0.05}{\Delta}\right)^3\left(\frac{7.65\times10^{-3}\,\text{GeV}^{-2}}{a_\chi}\right)^2$$

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 vet $\langle F_{\mathrm{SUSY}} \rangle$ of aux. field F in the Goldstone supermultiplet $\Phi = \phi + \sqrt{2}\theta\chi + F\theta\theta$. Goldstone fermion χ (goldstino) → gravitino

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

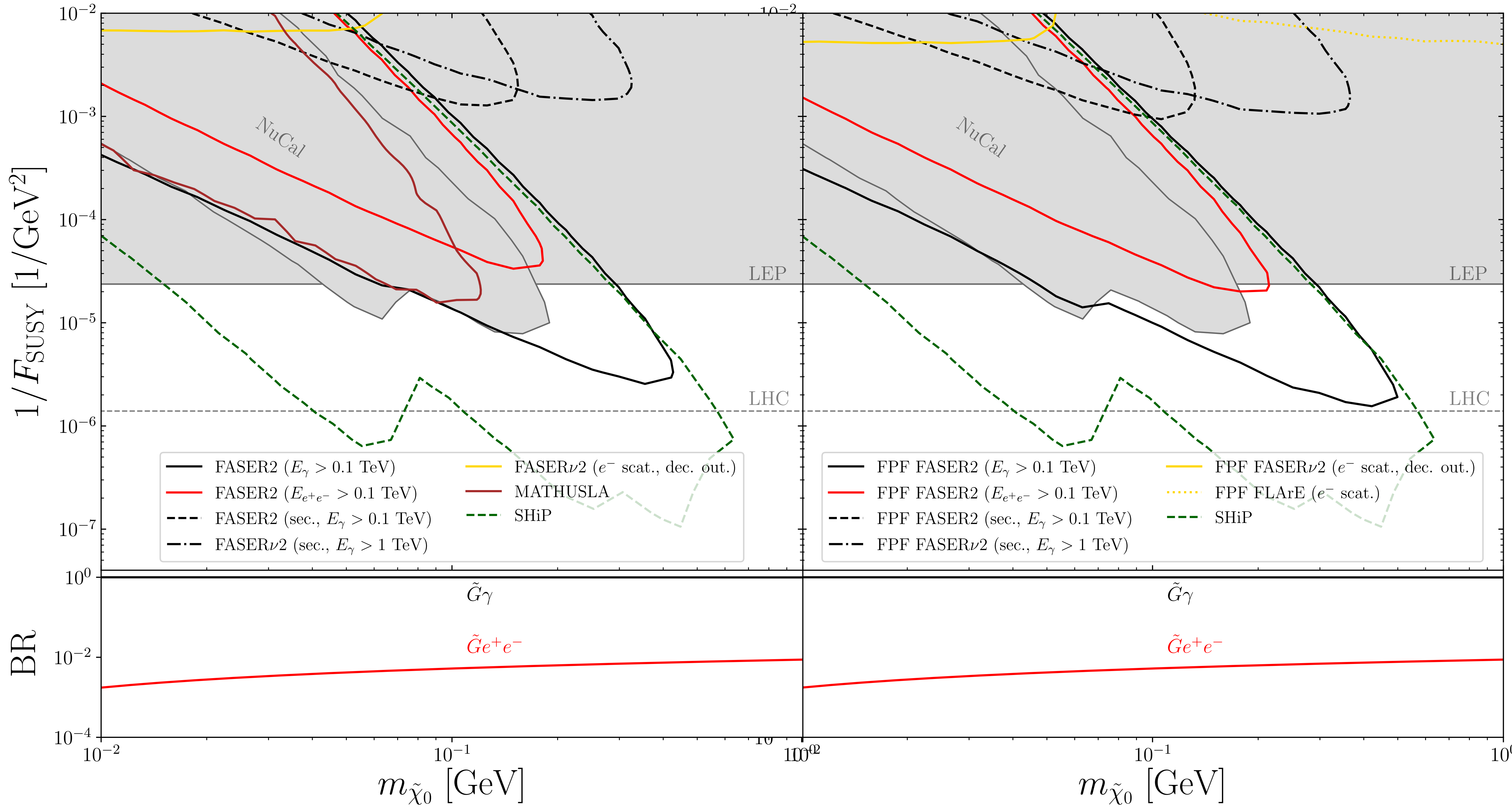
$$\mathcal{L} \supset -\frac{1}{4M_{\mathrm{Pl.red.}}} \bar{\psi}_\mu \sigma^{\rho\sigma} \gamma^\mu \lambda F_{\rho\sigma} \, , \qquad \psi_\mu \sim i\sqrt{\frac{2}{3}} \frac{1}{m_{3/2}} \partial_\mu \chi \, .$$

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

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

Neutralino-gravitino at FASER

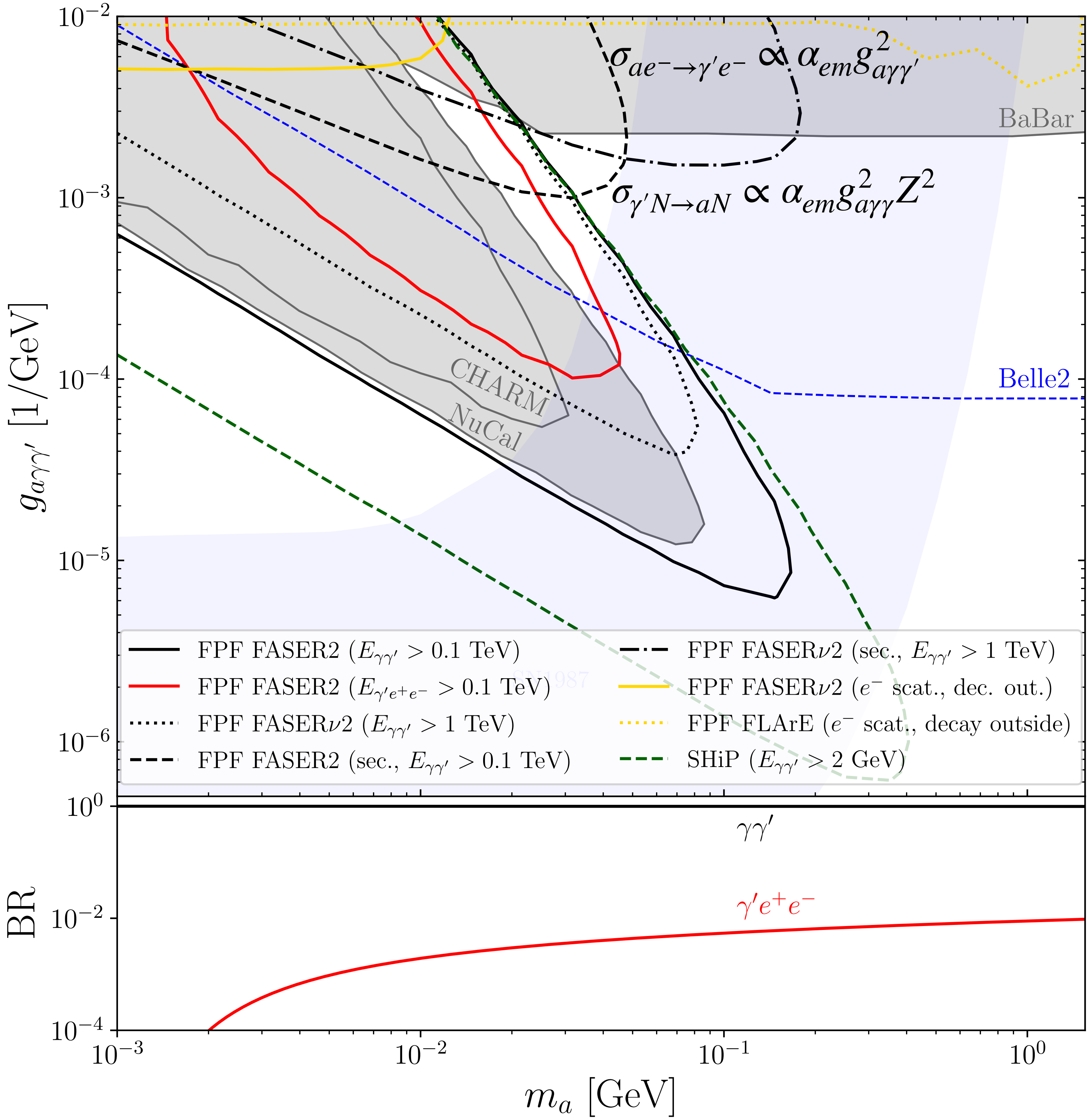
- Neutralino is NLSP, gravitino is LSP $\tilde{\chi}_0 \to \tilde{G}\gamma$



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

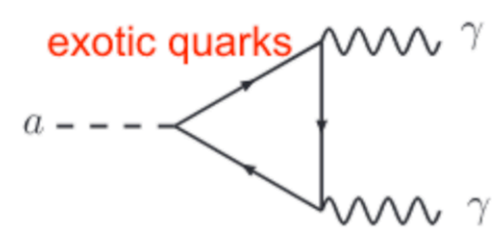
Dark ALP at Forward Physics Facility

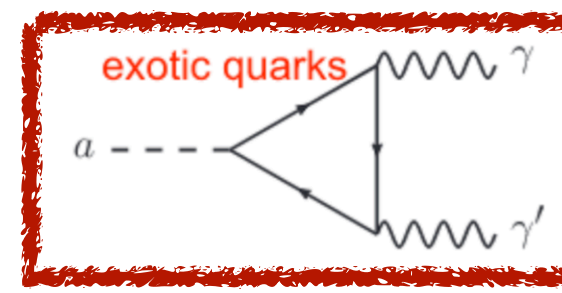
BaBar/Belle: $\gamma + X \to m_{LLP} < 1\,\text{MeV}$ too long-lived → covered by FLArE/FASERν



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

Kunio Kaneta, Hye-Sung Lee, Seokhoon Yun, 1611.01466





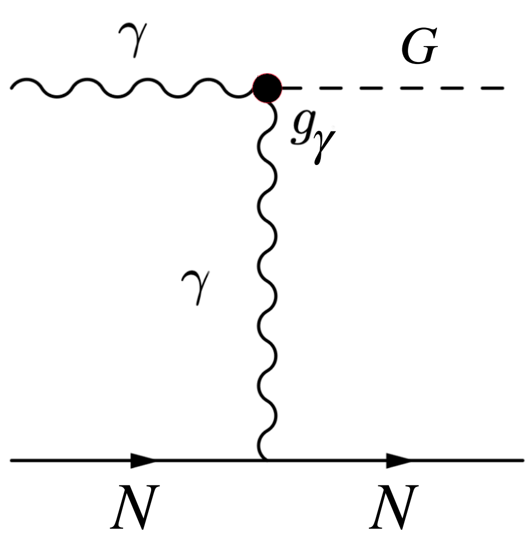
a is the LLP: $m_{\gamma'} \ll m_a$

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

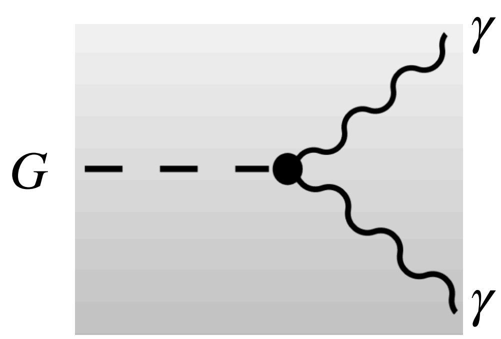
Massive spin-2 mediator at FPF

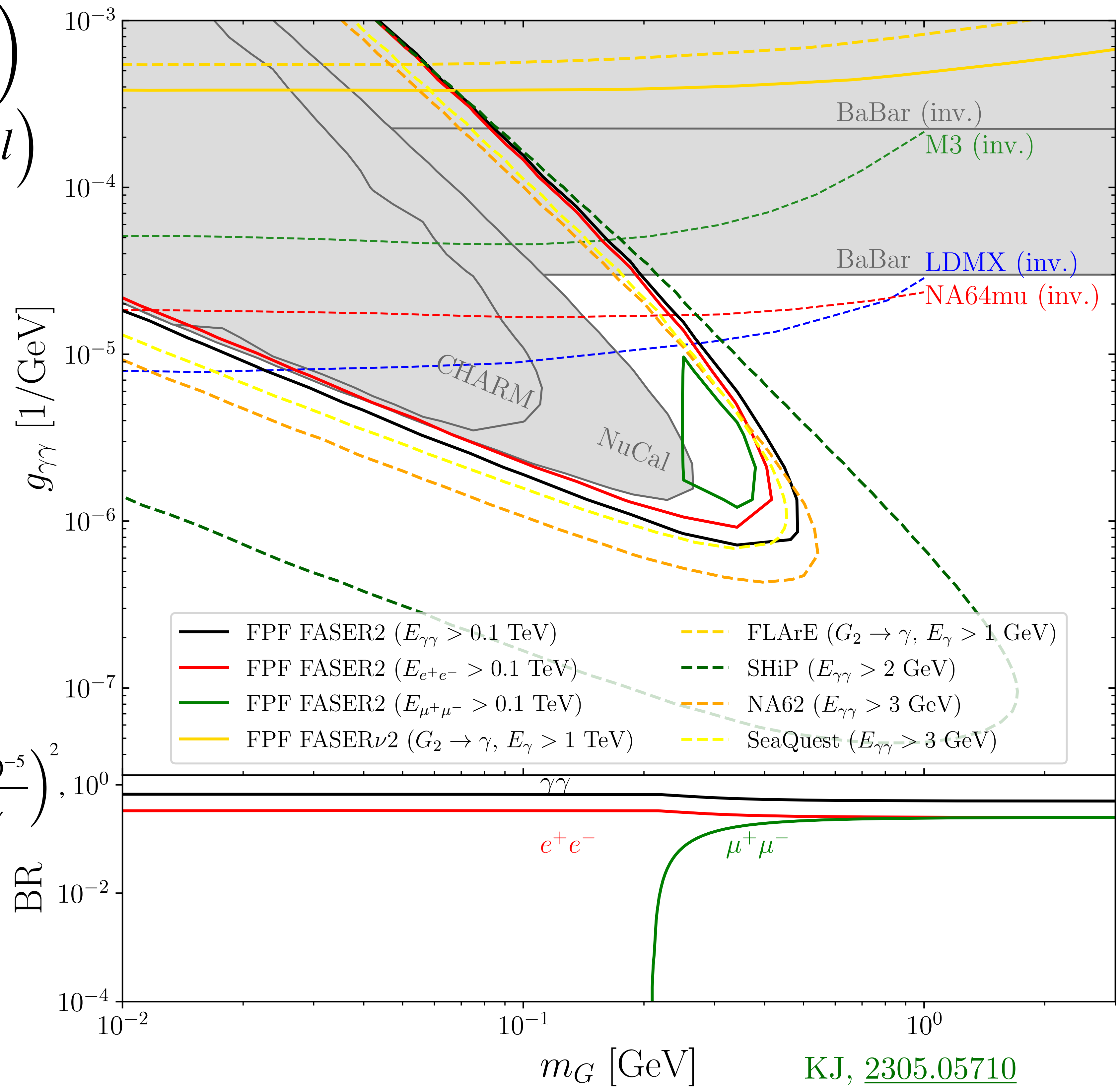
$$\mathscr{L} \supset g_\gamma G^{\mu\nu}\left(\frac{1}{4}\eta_{\mu\nu}F_{\lambda\rho}F^{\lambda\rho} + F_{\mu\lambda}F_{\nu}^{\ \lambda}\right)$$
$$-i\sum_l \frac{g_\ell}{2}G^{\mu\nu}\left(\bar{l}\gamma_\mu D_\nu l - \eta_{\mu\nu}\bar{l}\gamma_\rho D^\rho l\right)$$

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



$$d_G = c\tau\beta\gamma \simeq 100\,m \times \left(\frac{E}{1000\,GeV}\right)\left(\frac{0.1\,GeV}{m_G}\right)^4\left(\frac{5\times10^{-5}}{g_{G\gamma\gamma}}\right)^2,$$





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.