Signatures of light dark matter and long-lived particles at FASER

Krzysztof Jodłowski

CTPU Welcome Workshop on Particle Physics and Cosmology
2 November 2022

Based on:

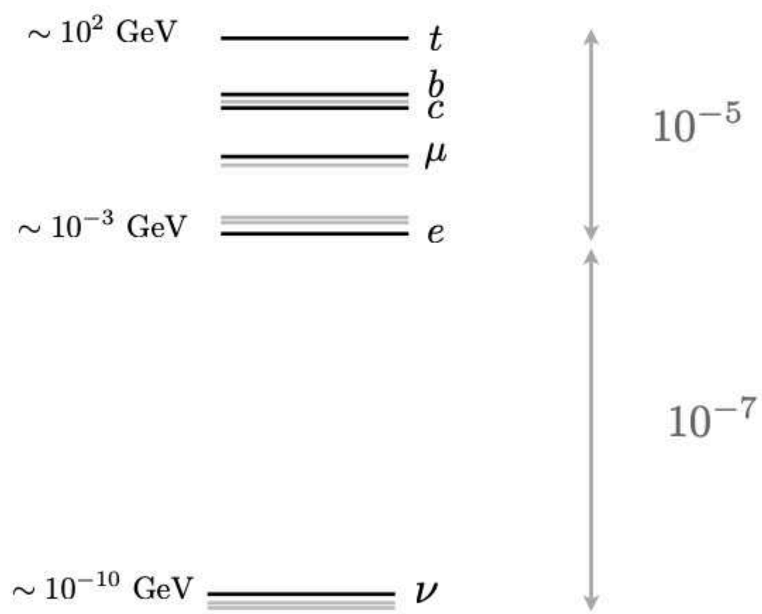
KJ, F. Kling, L. Roszkowski, S. Trojanowski, 1911.11346; KJ, S. Trojanowski, 2011.04751; KJ Ongoing work

Physics Beyond the Standard Model

*SM is **not** a complete description of Nature:*

$$\mathcal{L}_{SM} = \mathcal{L}_{kin} + gA_\mu \bar{F}\gamma_\mu F + Y_{ij}\bar{F}_i H F_j + \lambda(H^\dagger H)^2 + \ldots$$ **d=4**

- cosmological constant — $+c_0\,\Lambda_{UV}^4\sqrt{g}$ — $c_0 \sim -10^{-60}\left(\frac{\mathrm{TeV}}{\Lambda_{UV}}\right)^4$ — **d=0**
- hierarchy problem — $+c_2\,\Lambda_{UV}^2\,H^\dagger H$ — $c_2 \simeq 0.008\left(\frac{\mathrm{TeV}}{\Lambda_{UV}}\right)^2$ — **d=2**
- strong CP problem — $+\theta\,\tilde{G}_{\mu\nu}\tilde{G}^{\mu\nu}$ — $\theta \lesssim 10^{-10}$ — **d=4**
- neutrino masses



fine tuning?

- GUT, SUSY, XD
- string theory (QG)
- EFT, portals,...

The Dark Universe

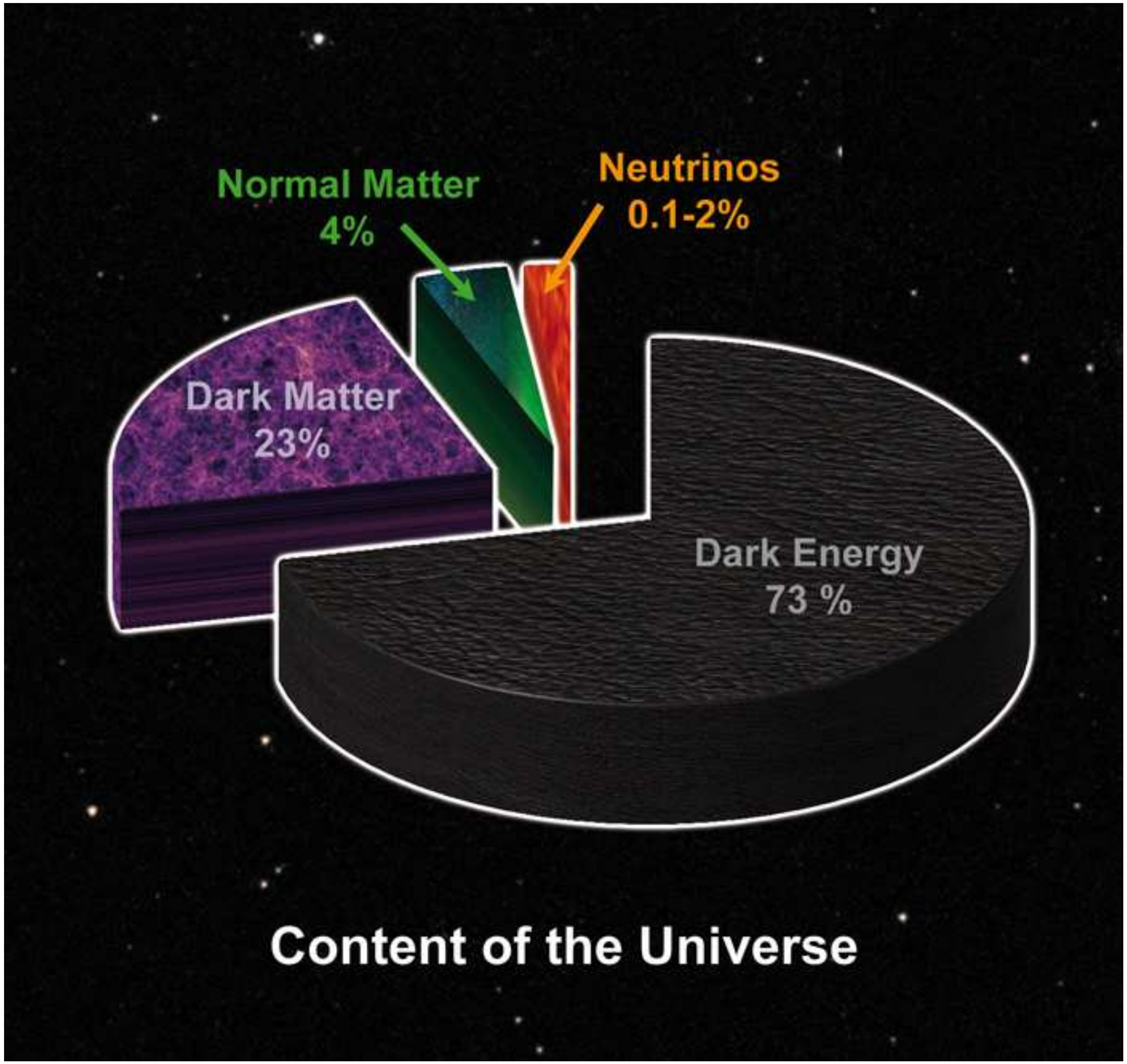
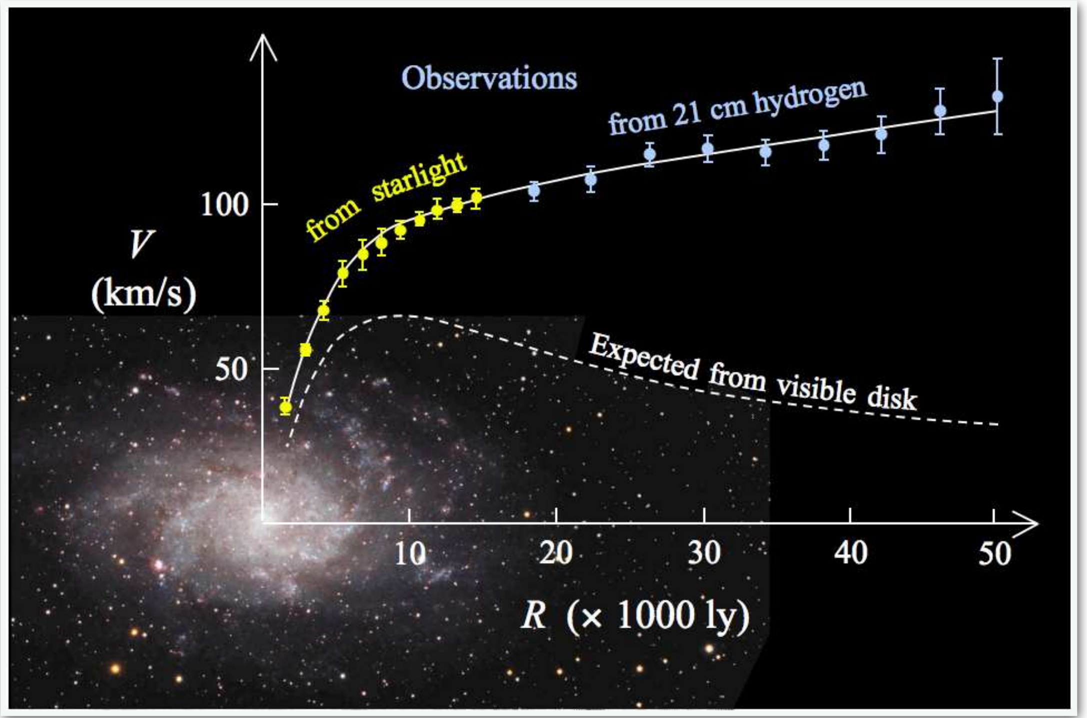
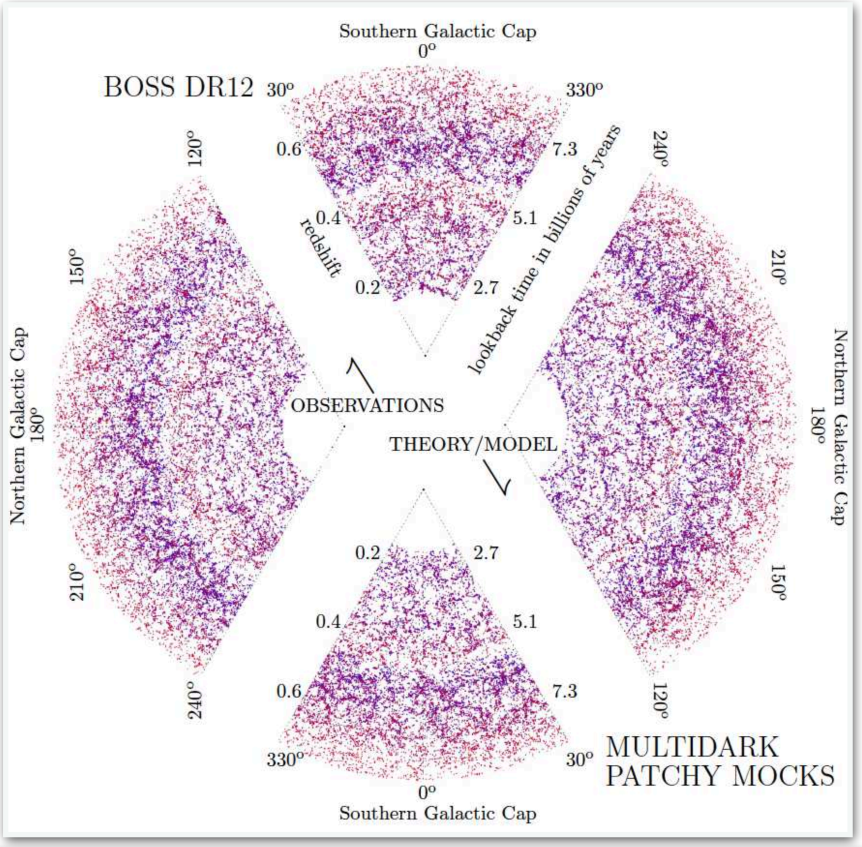


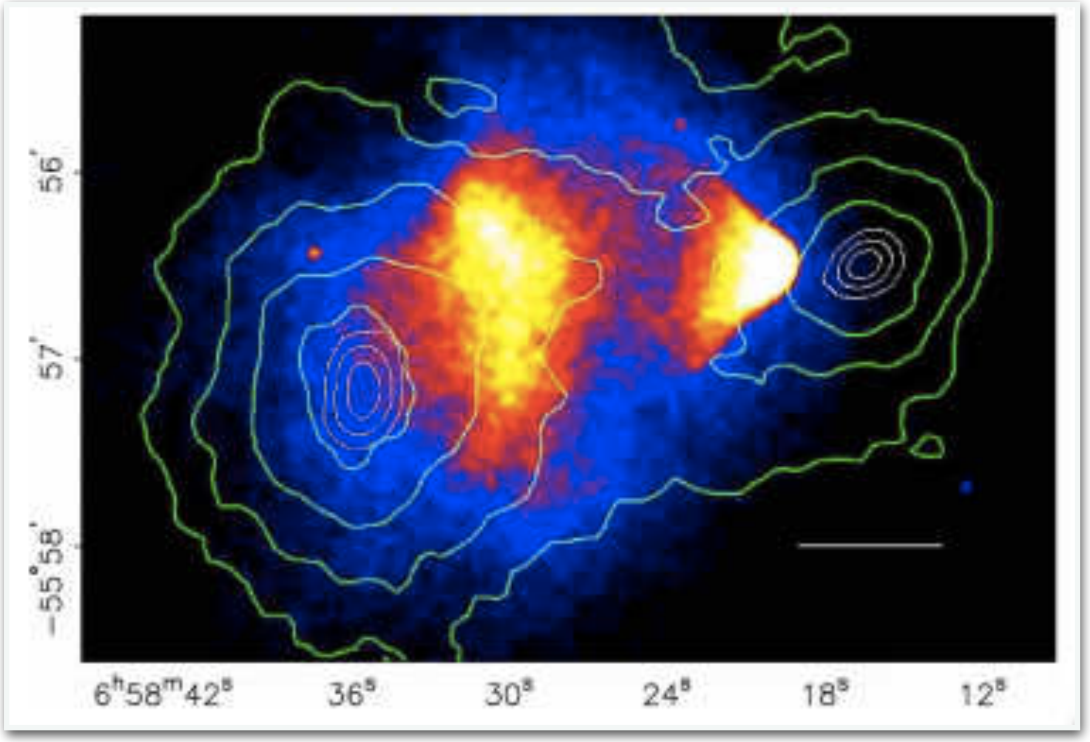
Fig. HAP / A. Chantelauze

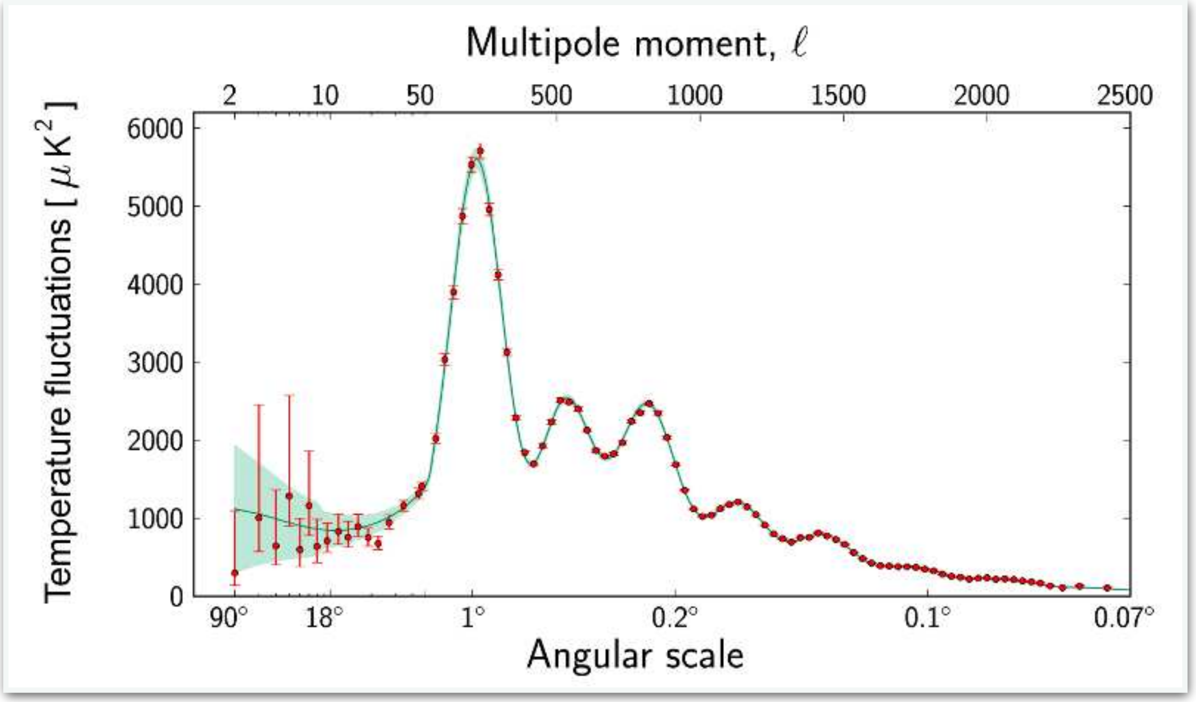
Dark Matter in the Universe

Evidence on multiple scales due to gravitational interactions:



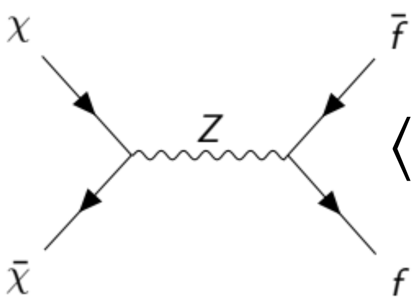




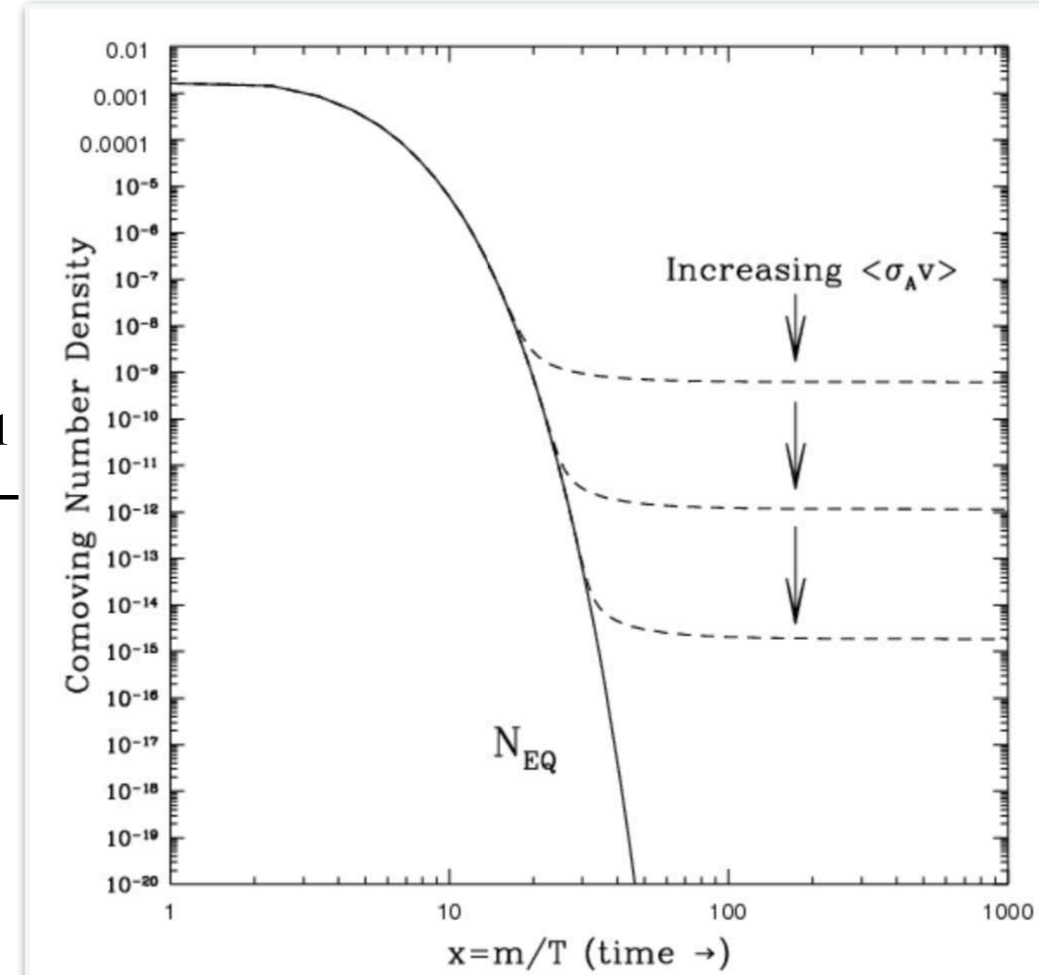


Canonical particle DM - WIMP

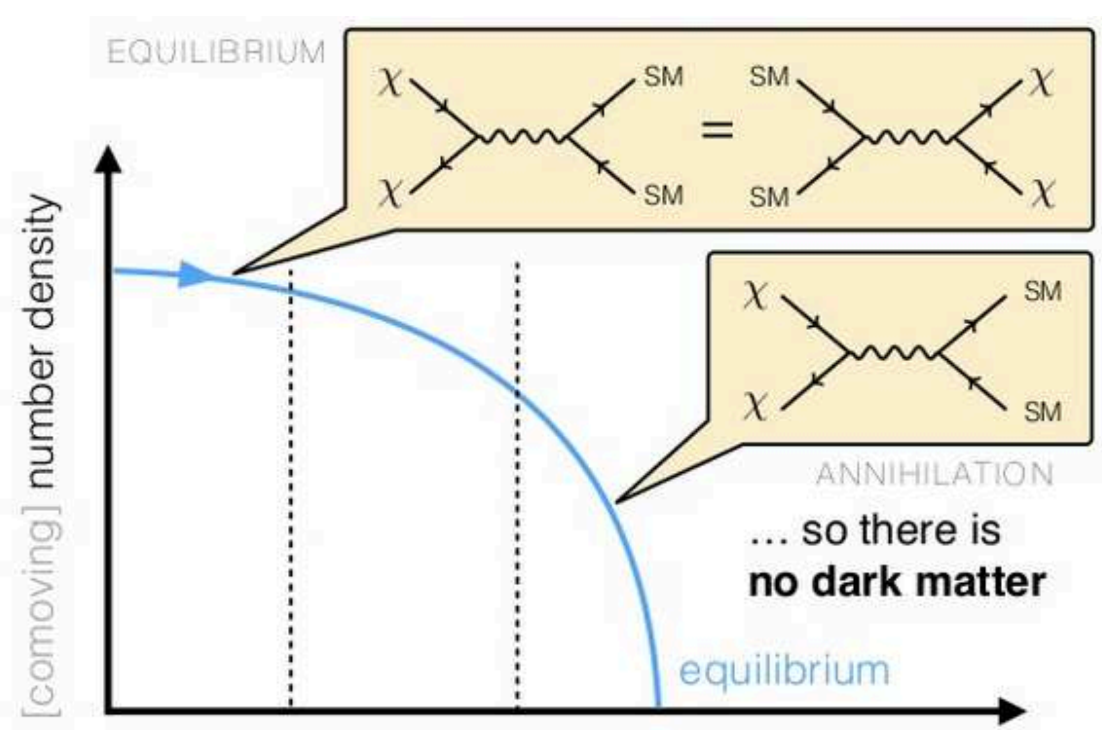
Since late 70's, its well known that new particle with electroweak-scale mass and weak interaction with SM naturally provides the observed relic density $\Omega h^2 \approx 0.1$.



$$\langle \sigma v \rangle \propto \frac{g^4}{m_\chi^2} v \longrightarrow \Omega_\chi h^2 \approx 0.1 \frac{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma v \rangle}$$



Lee, Weinberg '77,
Dolgov, Zeldovich '70s



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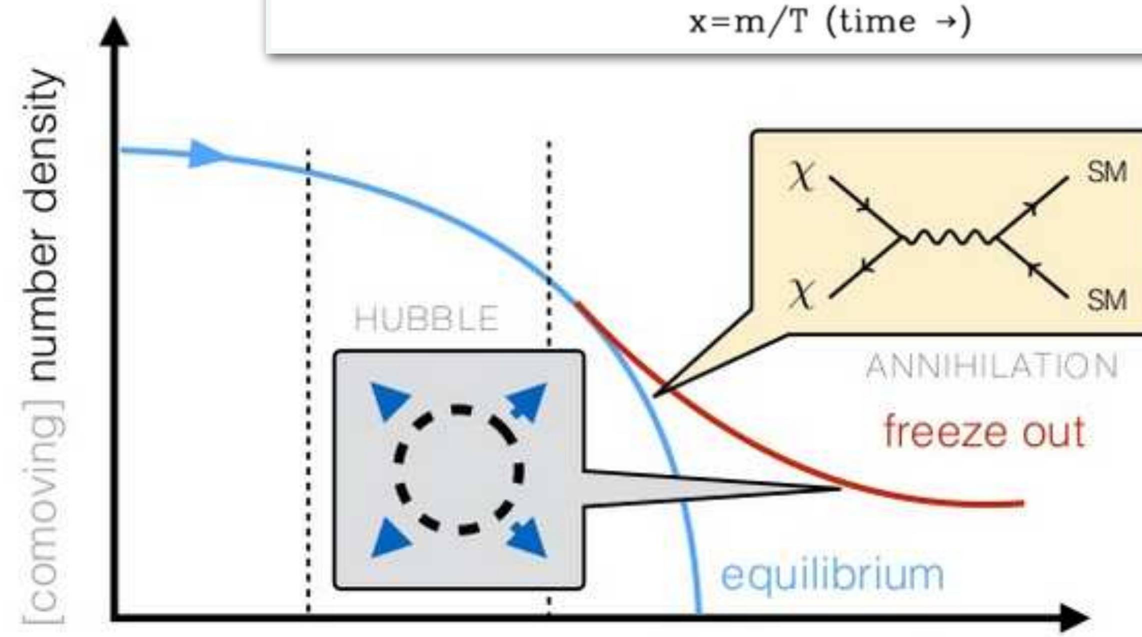
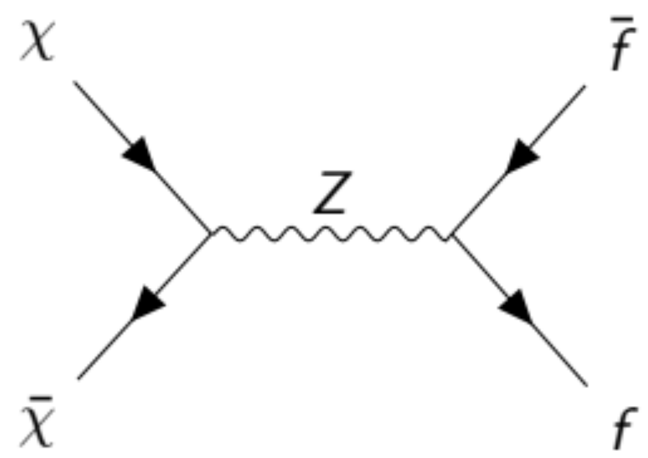


Figures by F. Tanedo

Looking for WIMPs



$$\langle \sigma v \rangle \propto \frac{g^4}{m_\chi^2} v$$

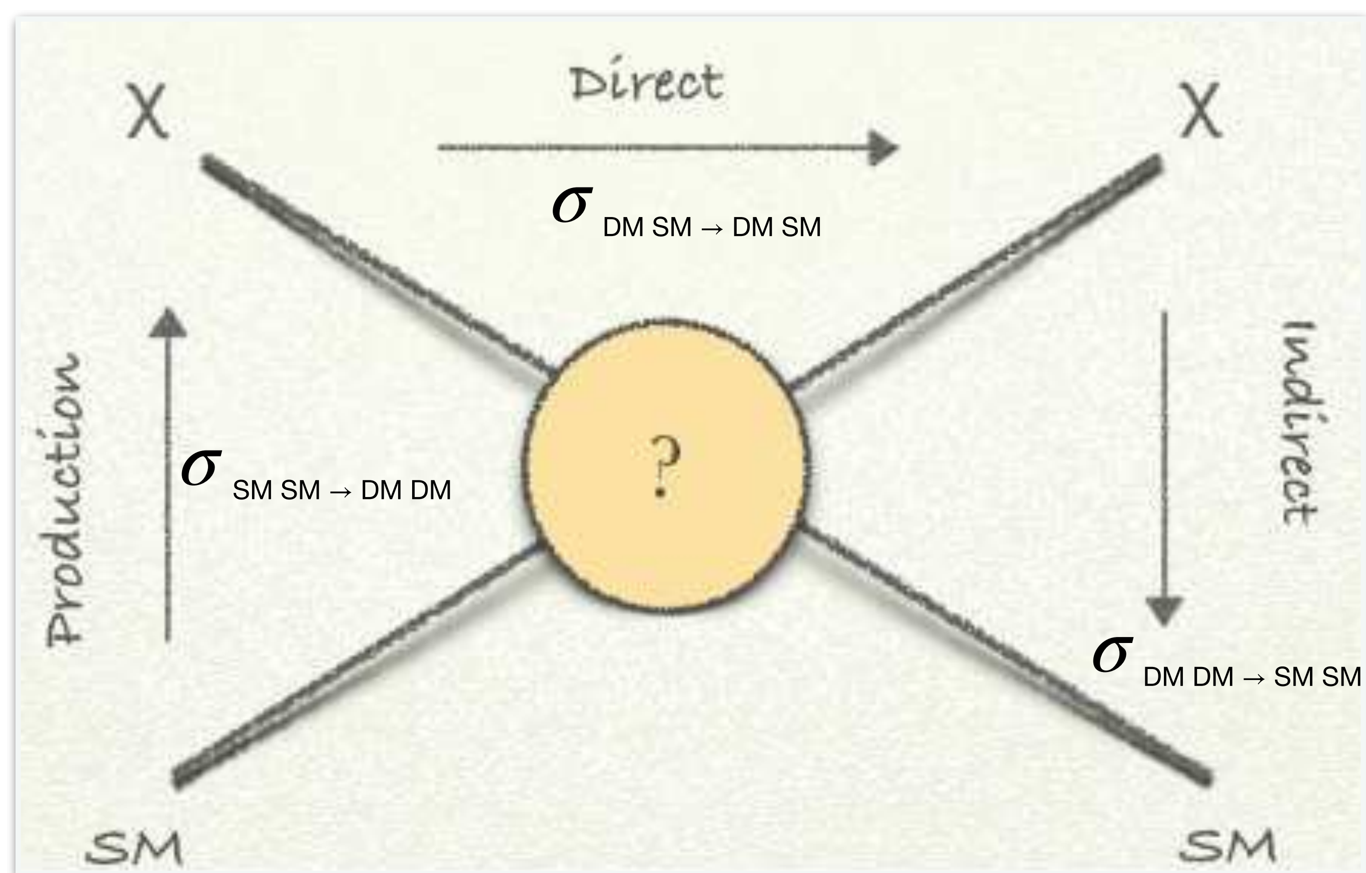
$$\Omega_\chi h^2 \approx 0.1 \frac{3 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}}{\langle \sigma v \rangle}$$

Crossing symmetry

$\sigma_{\mathrm{DM\,DM} \to \mathrm{SM\,SM}}$ related to $\sigma_{\mathrm{SM\,SM} \to \mathrm{DM\,DM}}$

$\sigma_{\mathrm{DM\,SM} \to \mathrm{DM\,SM}}$

multiple detection possibilities



Status of WIMP DM

Null signal of WIMP DM so far → stringent constraints obtained,
but the benchmark $\langle \sigma v \rangle \approx 2.2 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}$ has not yet been fully tested.

Well motivated extensions of the WIMP paradigm:

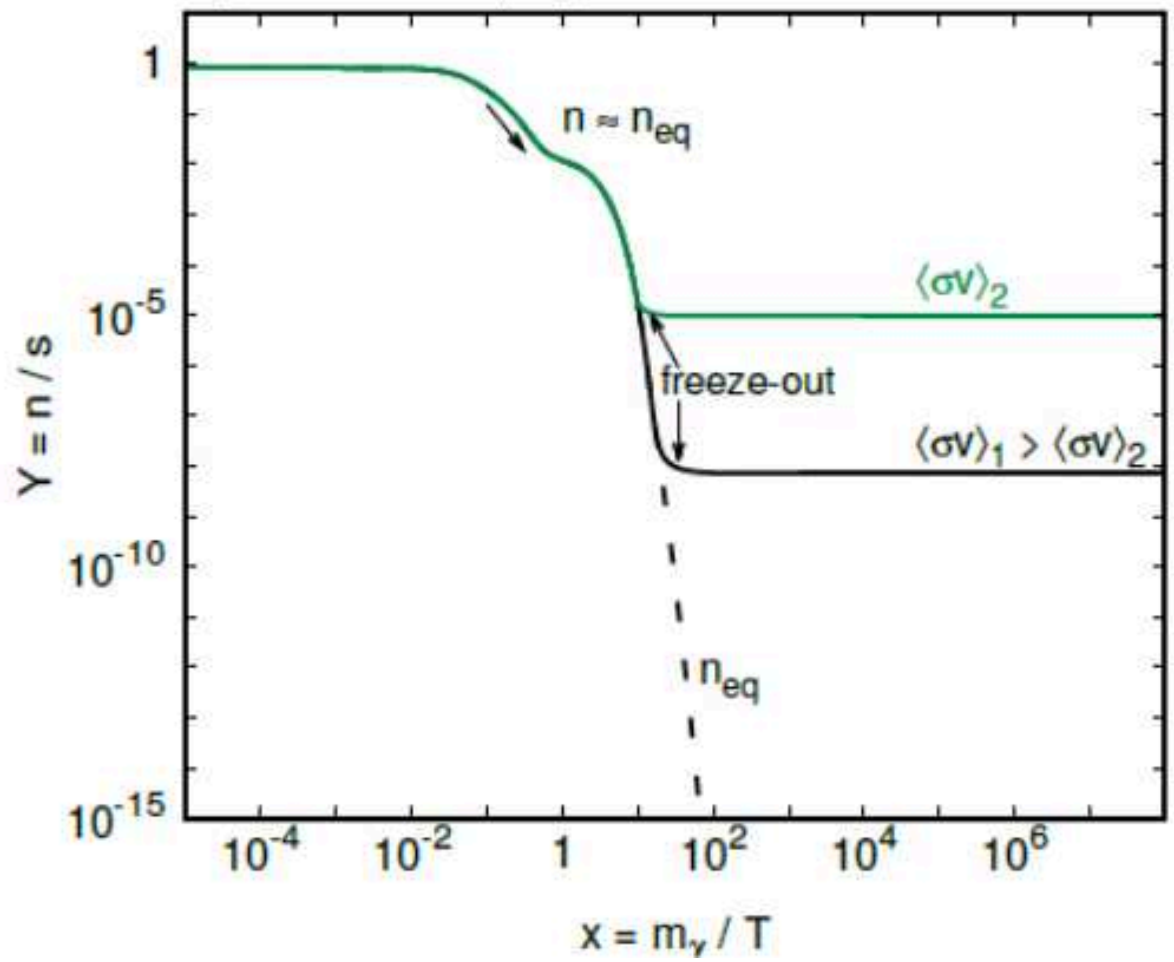
- WIMP annihilating into gauge bosons (1-loop coupling to quarks)
- Light sub-GeV WIMP
- Co-annihilations within the DS
- Secluded WIMP
- Multi-component DM - *e.g.*, axions+WIMP
- Modified cosmology - *e.g.*, early matter domination, late-time reheating
- ...

→ DD signal suppressed

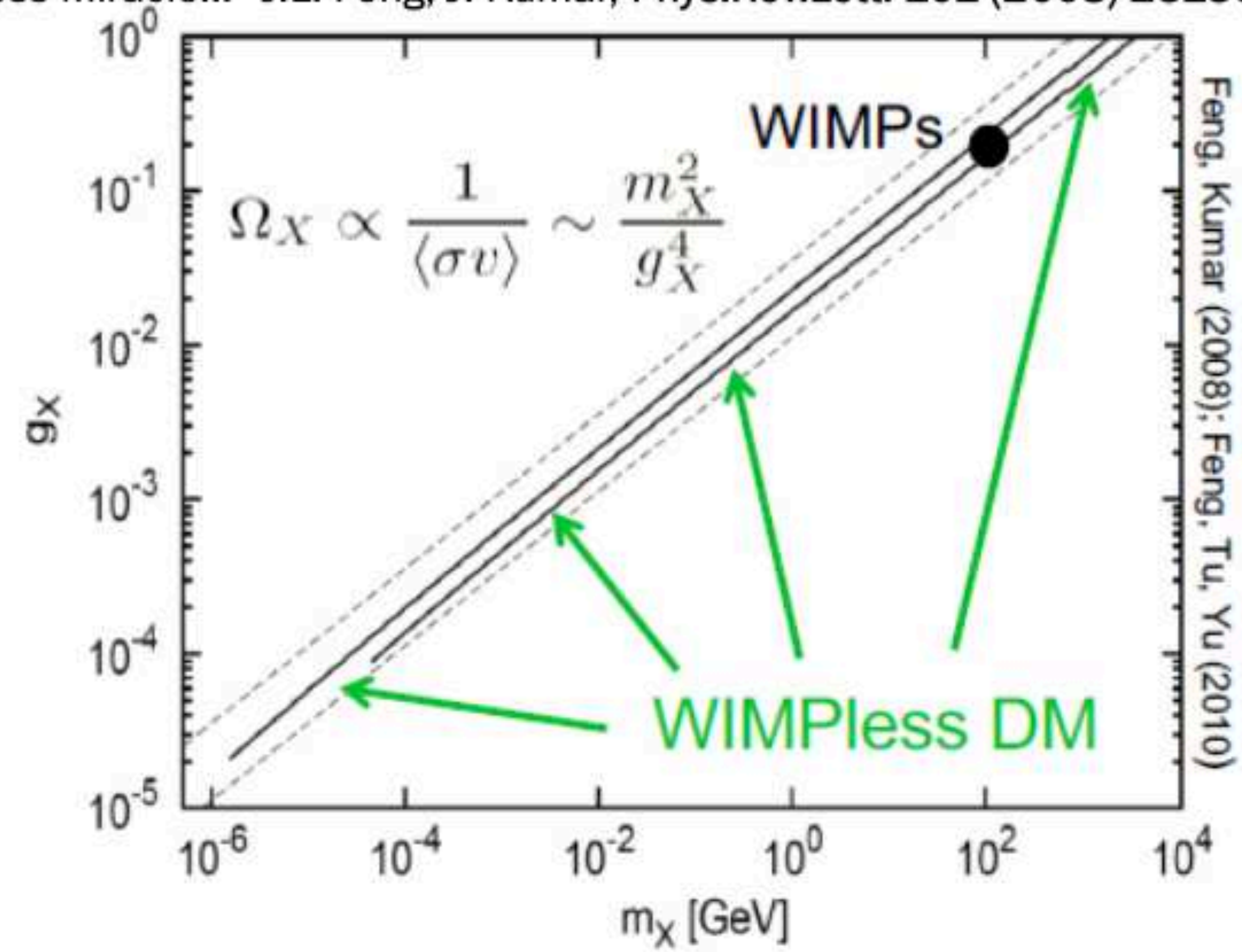
→ ID signal suppressed

WIMPless Dark Matter

L. Roszkowski, E.M. Sessolo, ST, 1707.06277



„The WIMPless Miracle..." J.L. Feng, J. Kumar, Phys.Rev.Lett. 101 (2008) 231301

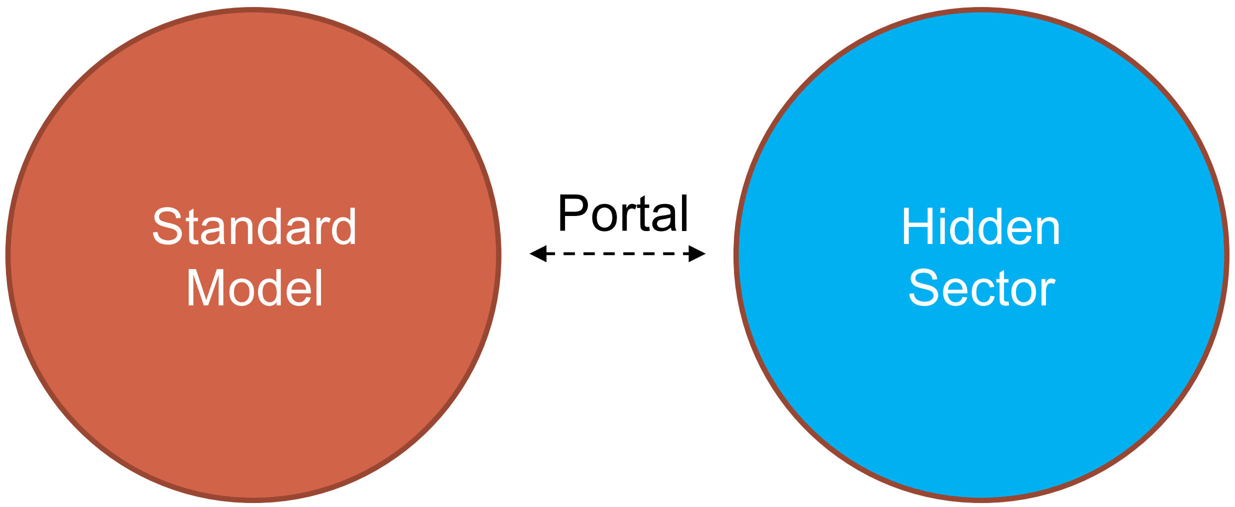


Forget about hierarchy problem but preserve WIMP mechanism by keeping $\langle\sigma v\rangle \propto \dfrac{g^4}{m_\chi^2} \equiv 2.2 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}$ $\longrightarrow$ WIMPless DM

- $m \sim 0.1$ GeV
- $g \sim 0.001$

Sub-GeV New Physics

- Typical scenario: extend SM by Dark Sector + Mediator
- DM freezes out while the mediator decays into SM particles



- Restricting to dim-4 operators, there are only 3 possibilities:
  - $\mathscr{L}_{\text{vector portal}} = -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$
  - $\mathscr{L}_{\text{scalar portal}} = \alpha_1 S H^\dagger H + \alpha S^2 H^\dagger H$
  - $\mathscr{L}_{\text{neutrino portal}} = F_\ell \left(\epsilon_{ab} \overline{L}_{\ell,a} H_b \right) N$
- At dim-5: fermion portal, *axion portal*, Higgs-dark fermion portal, ...

Intensity frontier

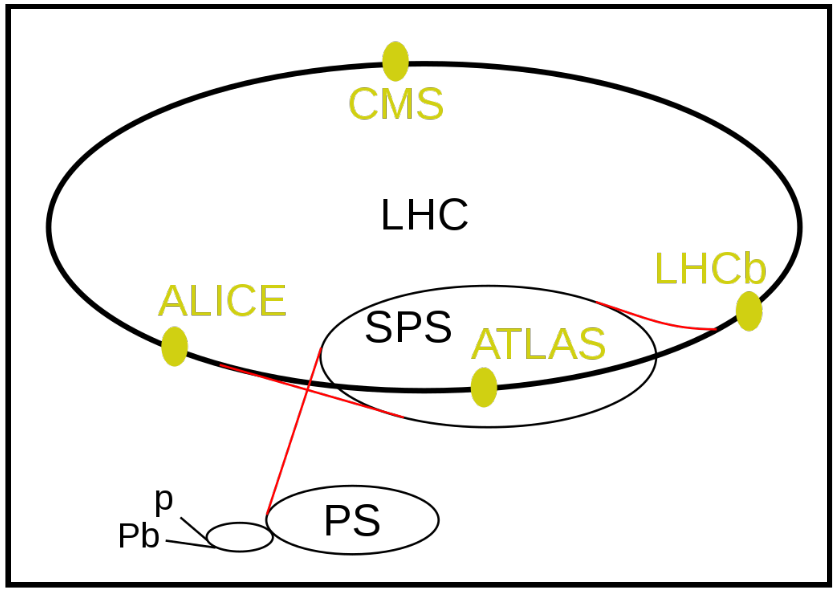
Light, weakly interacting particles

Weak couplings → large luminosities required

- Cosmology
  - Light relics:
    freeze out/freeze in DM,
    gravitational waves, ΔN_{eff}, …
  - …
- Beyond SM physics
  - Neutrino masses, leptogenesis
  - $(g-2)_\mu$, beryllium anomalies
  - …

$$N_{signal} \simeq \mathrm{Lum} \times \sigma_{prod} \times \mathrm{P}_{det} \times \mathcal{G}$$

- Beam dump experiments (proton, electron)
  - Small energies of beam
  - Huge number of collisions on target
- LHC → use "wasted" luminosity as a *collimated beam of light new species* $p_T \sim m$



$\theta \sim m/E \sim 100\mu\mathrm{rad}$

ForwArd Search
ExpeRiment
Feng, Galon, Kling,
Trojanowski 1708.09389

Intensity frontier and long-lived particles

Some experimental signatures

Look for:

- highly-displaced visible decay signatures of light long-lived particles (LLPs) in a distant detector, which is *well-shielded from SM background*
- missing energy in invisible decays
- scatterings with electrons/nucleus, ...

Realistic BSM models typically predict multiple LLPs which can provide additional detection modes

- SUSY

  Arkani-Hamed, Delgado, Giudice, 0601041
- renormalizable portals

  Physics Beyond Colliders, 1901.09966
- axion-like particles

  Bauer et al, 1808.10323
- heavy neutral leptons

  Cottin, Helo, Hirsch, 1806.05191
- Twin Higgs, NNaturalness, ...

ForwArd Search ExpeRiment

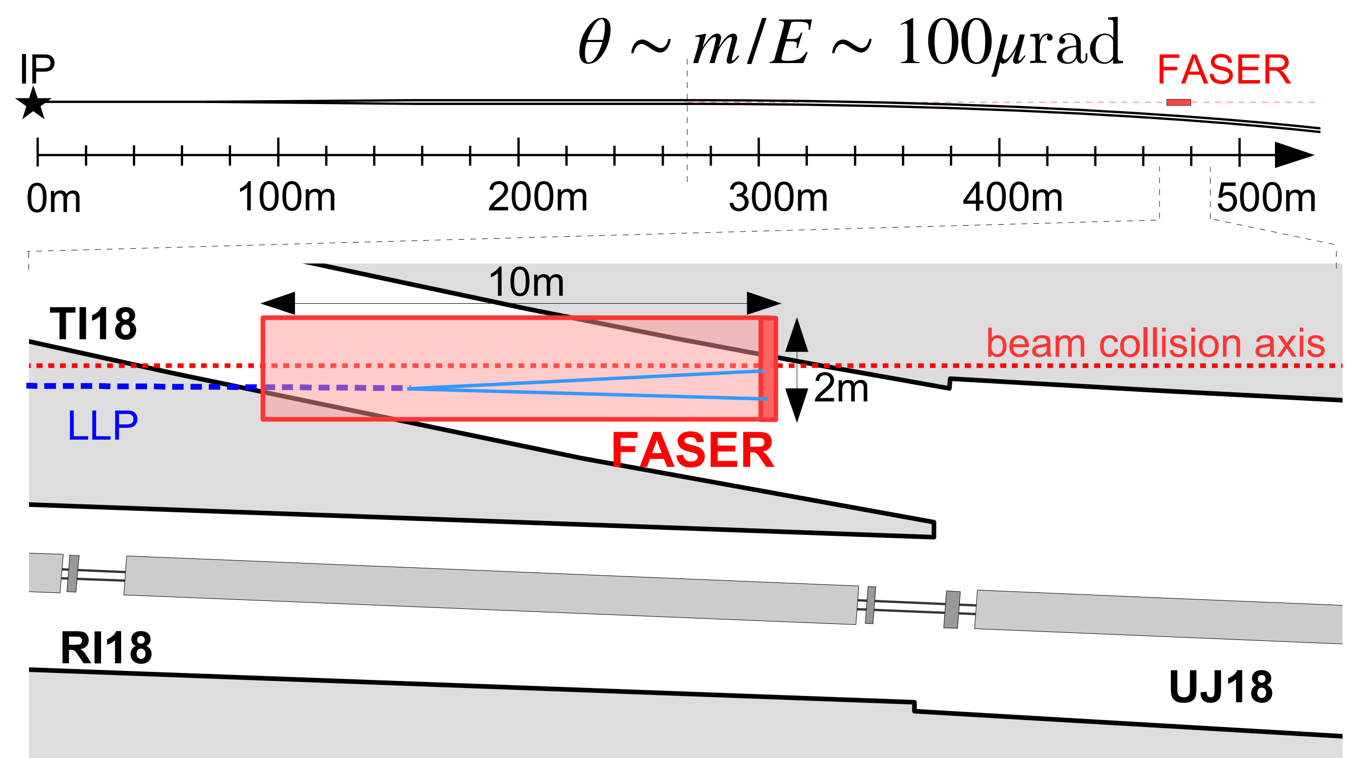
FASER - start with LHC RUN3 (2022-2024), $\mathscr{L} = 150\mathrm{fb}^{-1}$

$R = 1m$, $L = 1.5m$

FASER2 - start with HL-LHC

$\mathscr{L} = 3000\mathrm{fb}^{-1}$; $R = 1m$, $L = 5m$

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



$$N_{\pi^0} \sim 1/2 N_\gamma \approx 2.3 \times 10^{17}, \quad N_\eta \approx 2.5 \times 10^{16}, \quad N_D \approx 1.1 \times 10^{15}, \quad N_B \approx 7.1 \times 10^{13}$$

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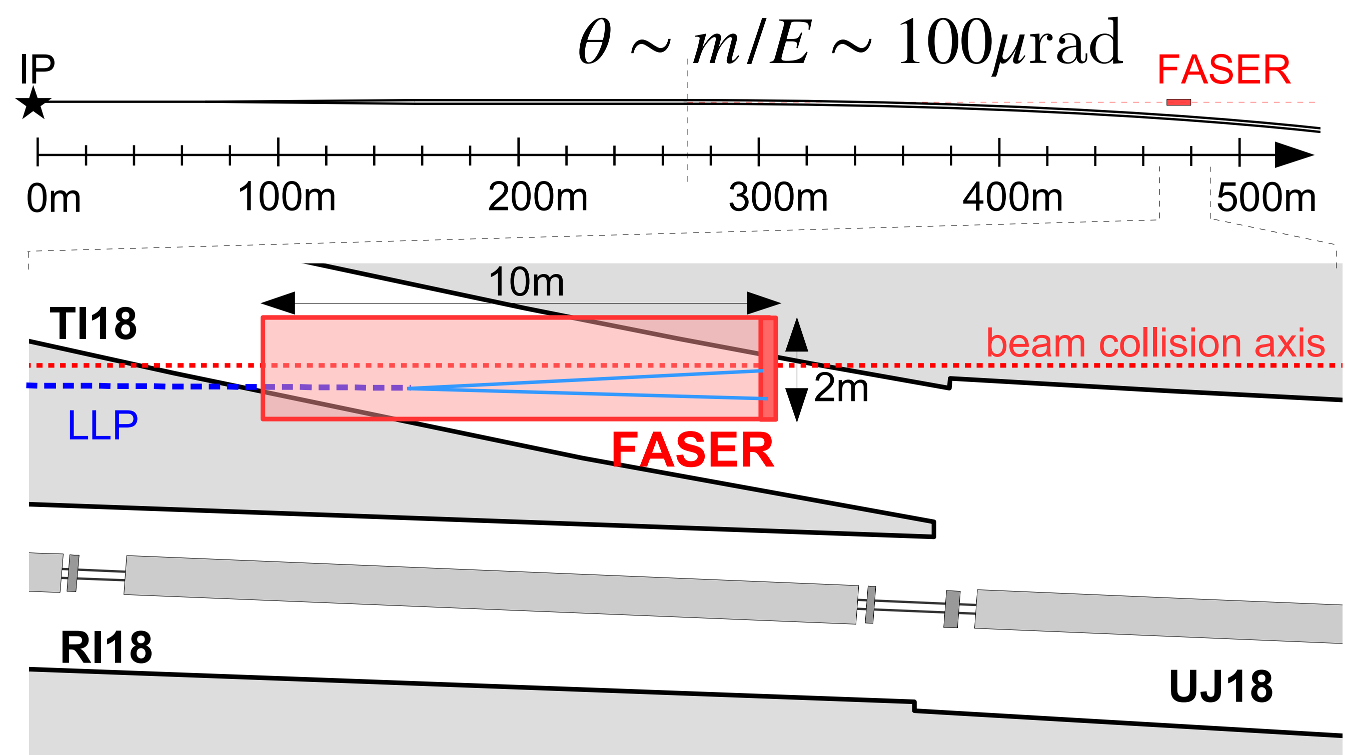

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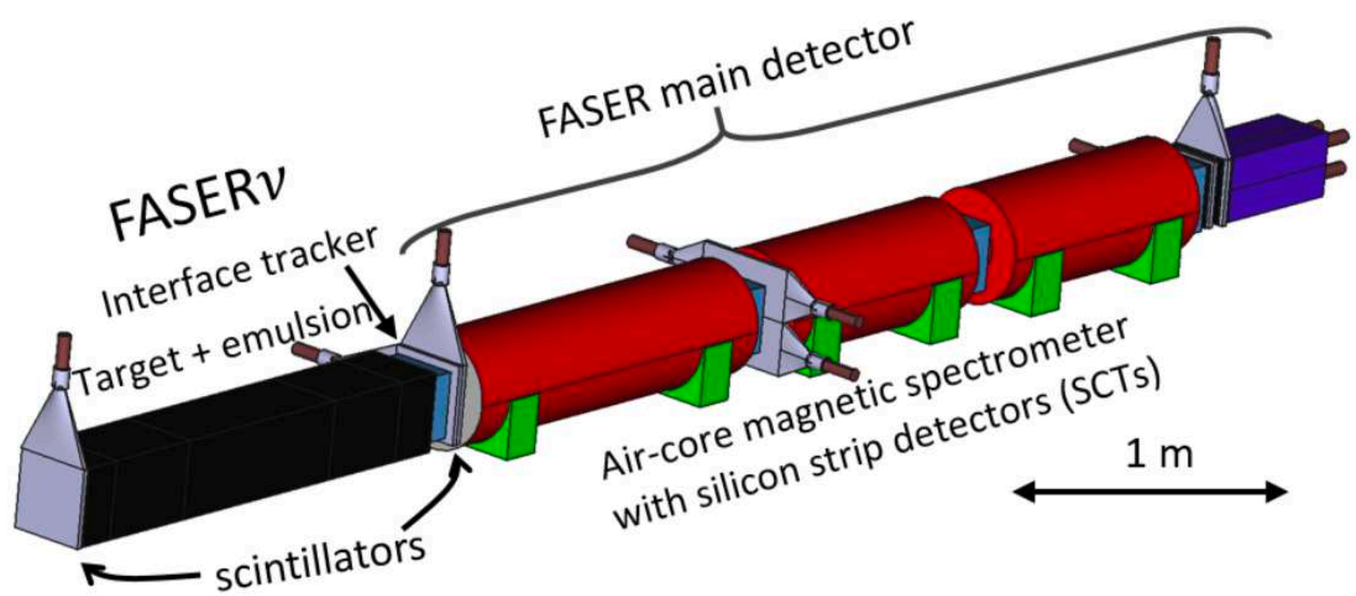
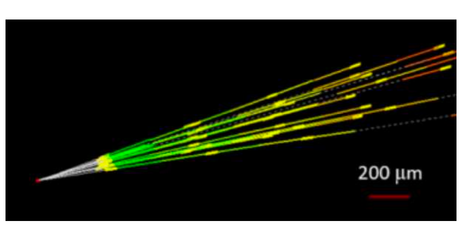
FASERν/FASER2ν

$0.25 \times 0.25 \times 1m$ / $0.5 \times 0.5 \times 2m$ detector ($^{184}_{74}W$) put in front of the decay vessel

$\rightarrow$ *probing high energy neutrinos;*





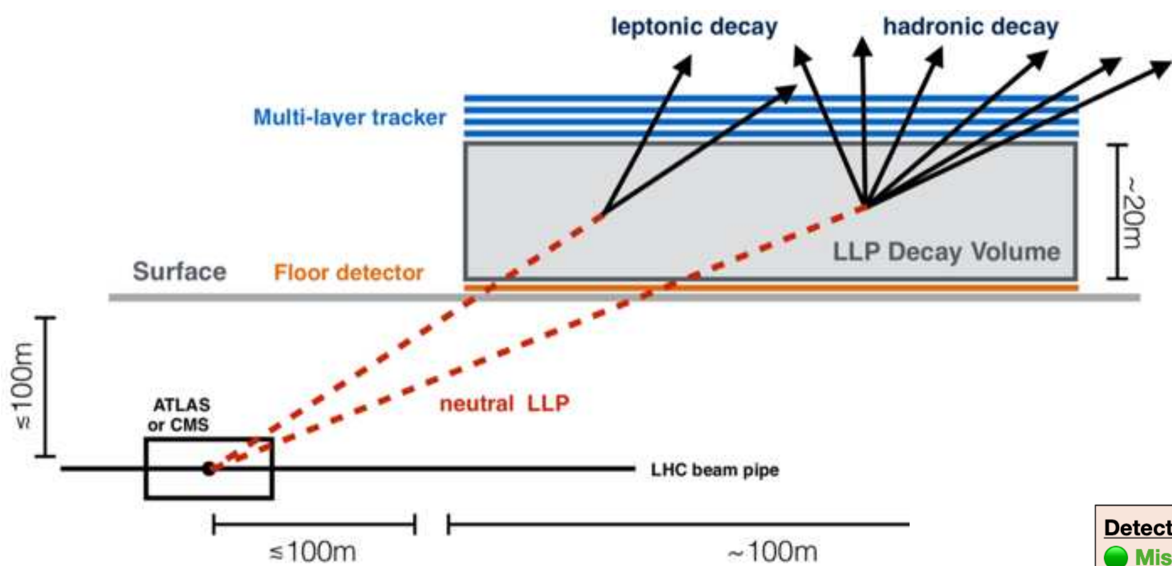
$N_{\nu_e} \sim 1300,\ N_{\nu_\mu} \sim 10000,\ N_{\nu_\tau} \sim 20$

First neutrino interaction candidates at the LHC 2105.06197

Technical Proposal: FASERnu 2001.03073
Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC 1908.02310

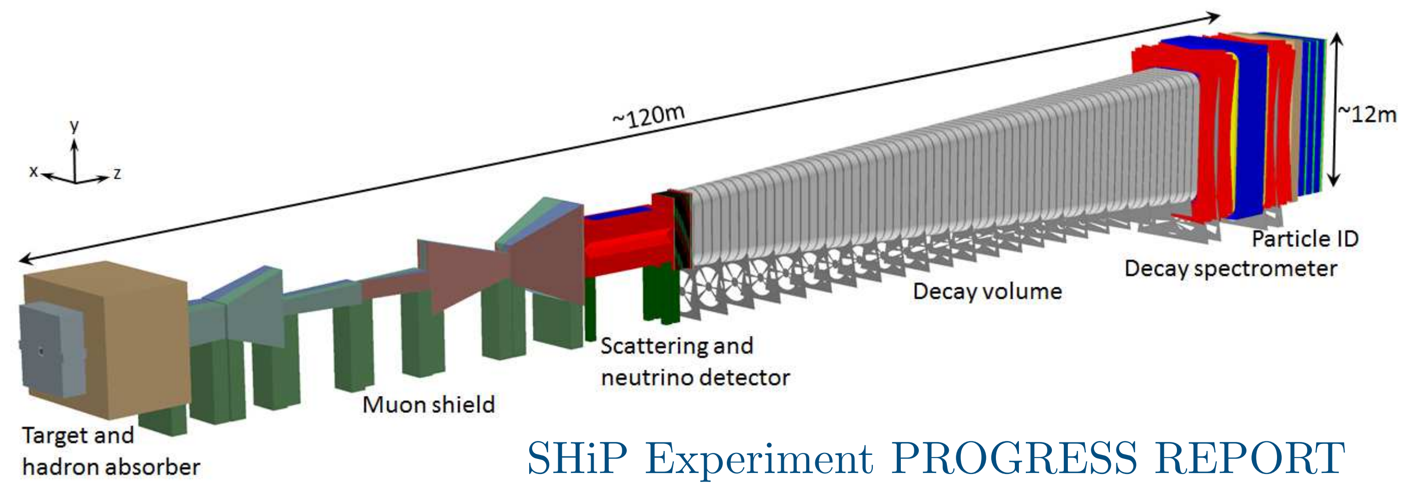
Other CERN based intensity frontier experiments

MATHUSLA - start with HL LHC (proposed)



E. Torró for the MATHUSLA Collaboration

SHiP - start about HL LHC (proposed)



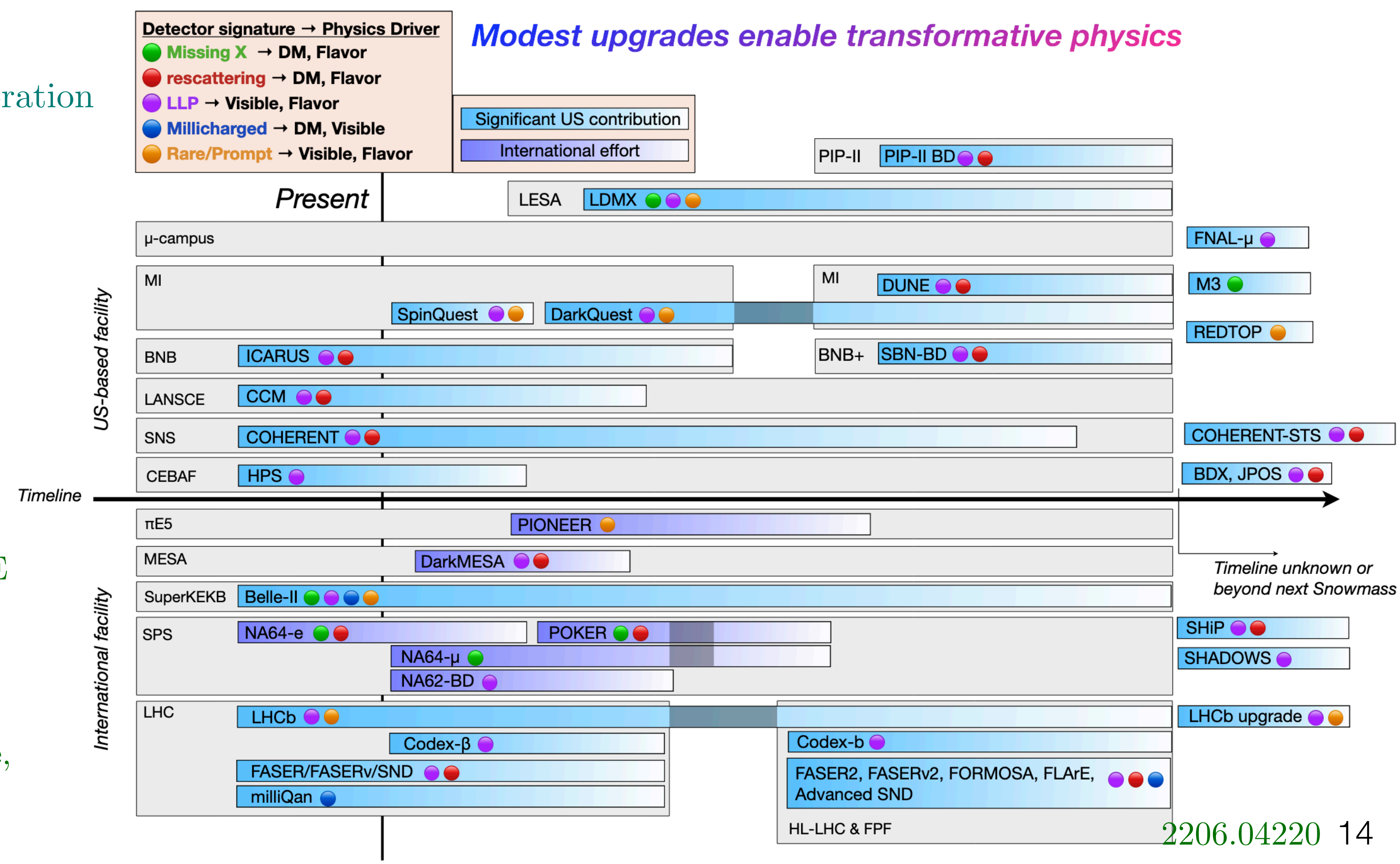
SHiP Experiment PROGRESS REPORT

Many more proposals and ideas related to lab-based Dark Sector searches were discussed at Snowmass

e.g., 2206.04220, 2207.00597, 2207.06898 *Forward Physics Facility*, 2109.10905, FLArE 2101.10338, ...

Some previous studies:

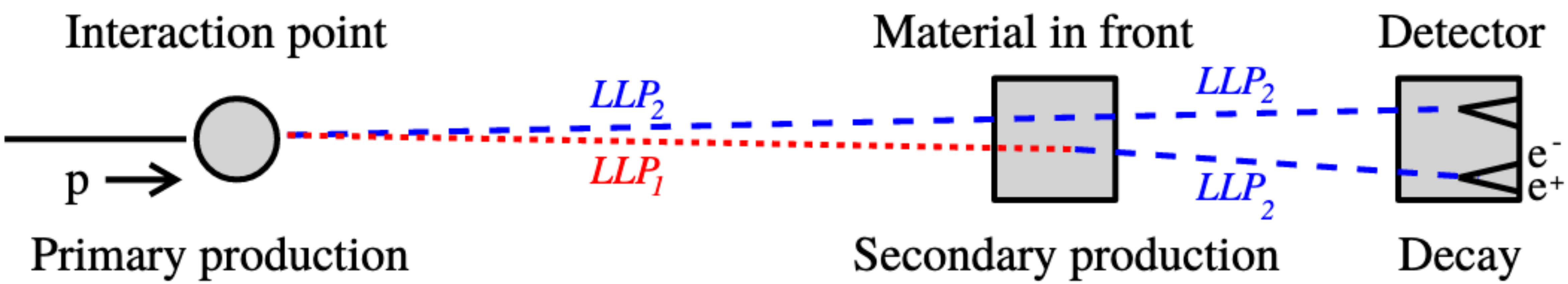
Batell, Pospelov, Ritz, 0906.5614, deNiverville, Pospelov, Ritz, 1107.4580,



2206.04220

Secondary production of LLPs - going beyond the long lifetime regime

Assume nonminimal BSM particle content featuring LLP's with $m_{\mathrm{LLP}_2} > m_{\mathrm{LLP}_1}$



- *Primary production* limited to a certain lifetime regime of new particles that must reach the detector before decaying

$$\mathscr{P}_{decay} = \exp\left(-\frac{L_{min}}{\bar{d}}\right)\left[1-\exp\left(-\frac{L_{max}-L_{min}}{\bar{d}}\right)\right], \qquad N_{\mathrm{sig}} \propto \begin{cases} \mathcal{L}^{\mathrm{int}}\,\epsilon^2\, e^{-L_{\mathrm{min}}/\bar{d}} & \text{for } \bar{d} \ll L_{\mathrm{min}} \\ \mathcal{L}^{\mathrm{int}}\,\epsilon^2\, \frac{L_{\mathrm{max}}-L_{\mathrm{min}}}{\bar{d}} & \text{for } \bar{d} \gg L_{\mathrm{min}} \end{cases}$$

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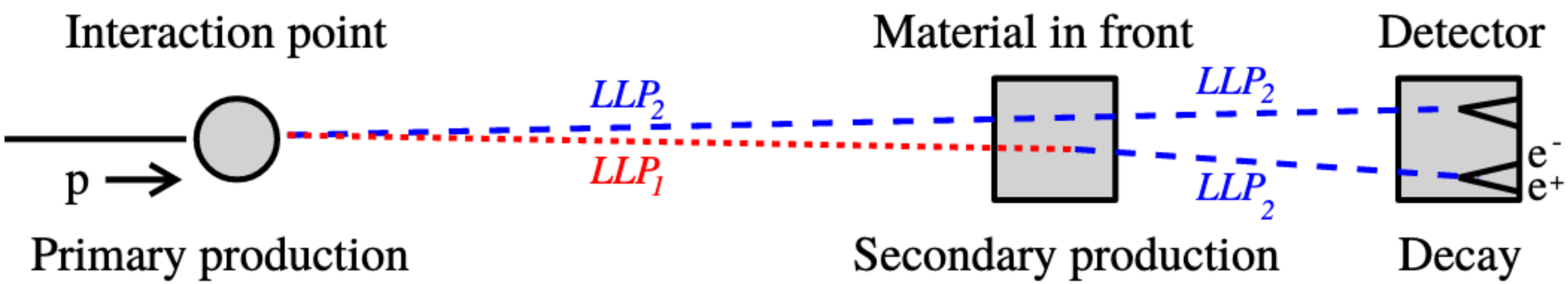

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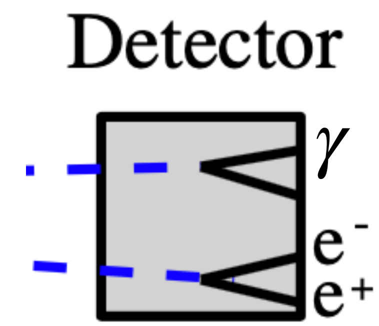
- **Secondary production:** $\mathrm{LLP}_1 + \mathrm{SM} \rightarrow \mathrm{LLP}_2 + \mathrm{SM}$
  - Signal due to $\mathrm{LLP}_2 \rightarrow \mathrm{LLP}_1 +$ visible or $\mathrm{LLP}_{1,2} + e^- \rightarrow \mathrm{LLP}_2 + e^-$

Experimental signatures of new physics at FASER

- **LLP signal inside the decay vessel – e^+e^- and γ**
  - $E_{vis} > 100$ GeV
  - e^+e^- search: negligible background due to high energies of LLP's
  - γ search:
    - 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*



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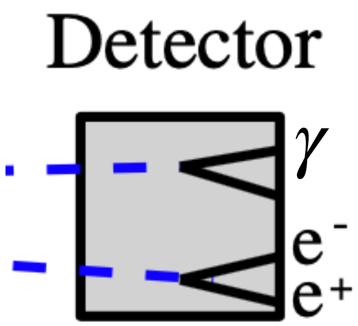

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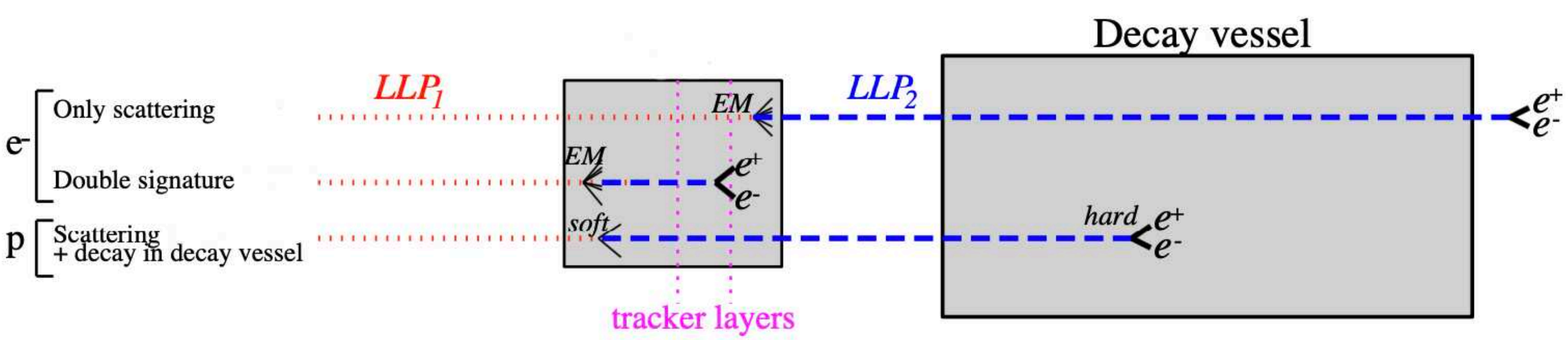
- **Prompt decays of high-energy LLPs inside the emulsion detector**
  - looking for very high-energy photons $E_\gamma > 1$ TeV or 3 TeV unaccompanied by any time-coincident muon (timing layers placed between the emulsion plates to gain temporal resolution needed to veto muon induced γ)
- **Scattering off electrons**
  - new-physics-induced neutrino scatterings off electrons producing detectable electron recoils inside the neutrino detector.
  - **Energy and angular cuts**:
    - Electron energy and angular cuts following the DM scattering signature

Batell, Feng, Trojanowski, 2101.10338

  - The cuts have been designed to minimize the neutrino-induced BG to the level of $O(10)$ such expected events in FASERν2.

- **Collinear double-bang signature**



Vector Portal - Dark Photon

- Extend SM by "dark" $U(1)_D$ gauge group:

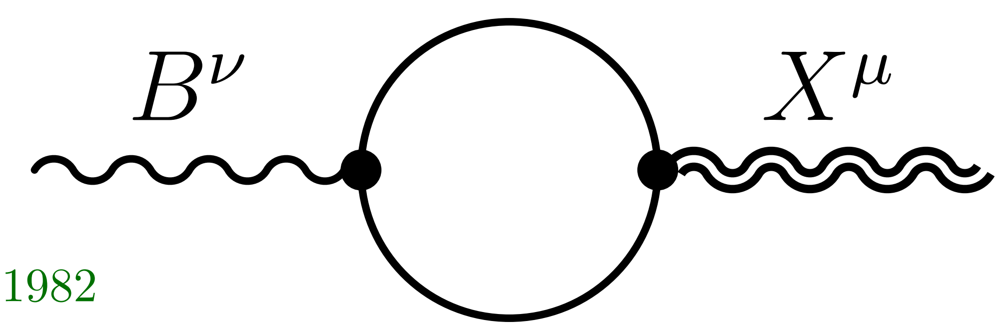
$$\mathscr{L} \supset -\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{4}F^{\mu\nu'}F'_{\mu\nu} - \frac{\epsilon}{2}B^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_A^2 A'^{\mu}A'_{\mu}$$

- QED + Dark $U(1)_D$ + Kinetic mixing + Mass term

$$-\frac{\epsilon}{2}B^{\mu\nu}F'_{\mu\nu}$$

- Even if $\epsilon = 0$ at tree level, non-zero value induced by loops

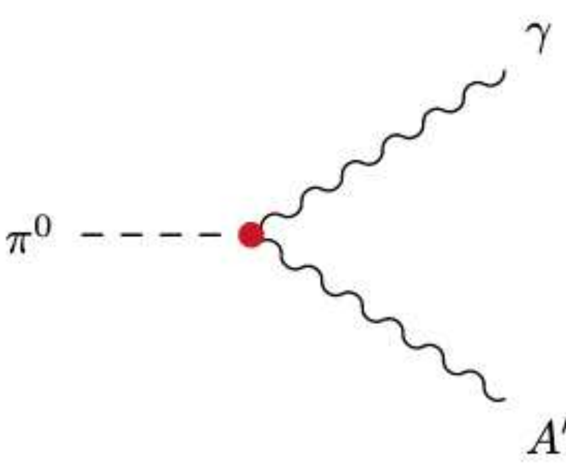
$$\epsilon \sim \frac{g_{DS}g_{SM}}{16\pi^2} \sim 10^{-4}$$

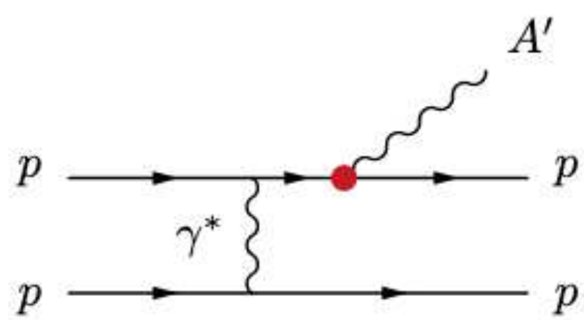


Okun, 1982
Holdom, 1985

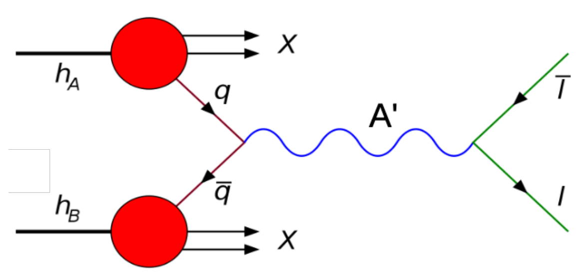
Dark Photon - production, detection

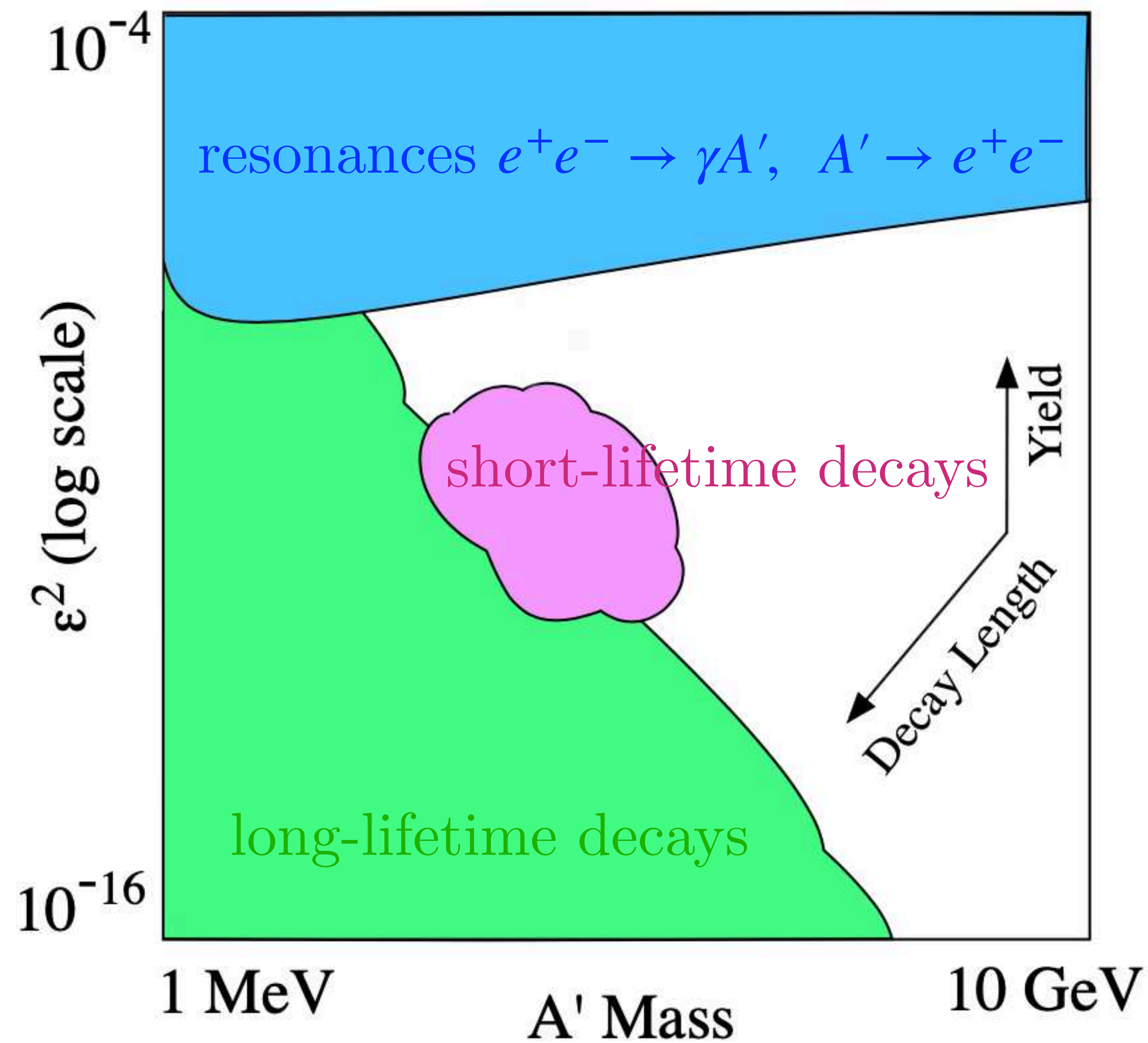
- Mesons decay
- Bremsstrahlung





- Drell-Yan





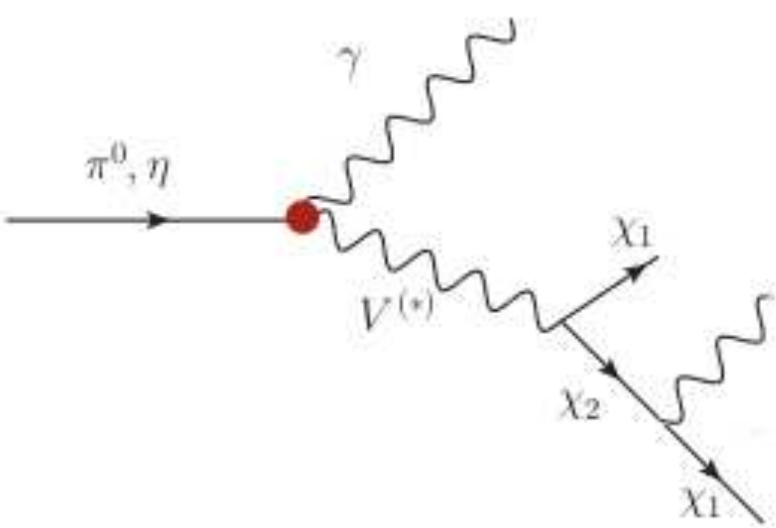
Production contributions for masses of interest only weakly dependent on the Dark Sector matter specification

Inelastic DM

$$\mathscr{L}_{int} \supset g_{12}\bar{\chi}_2\gamma^\mu\chi_1 X_\mu + h.c.$$

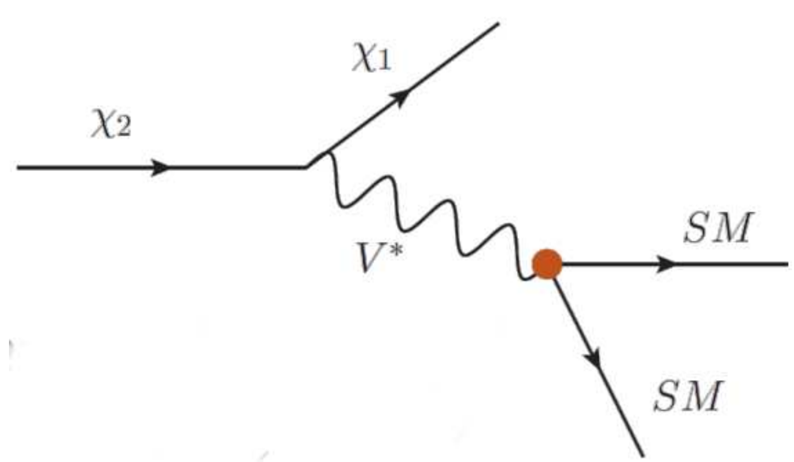
Smith, Weiner, 0101138

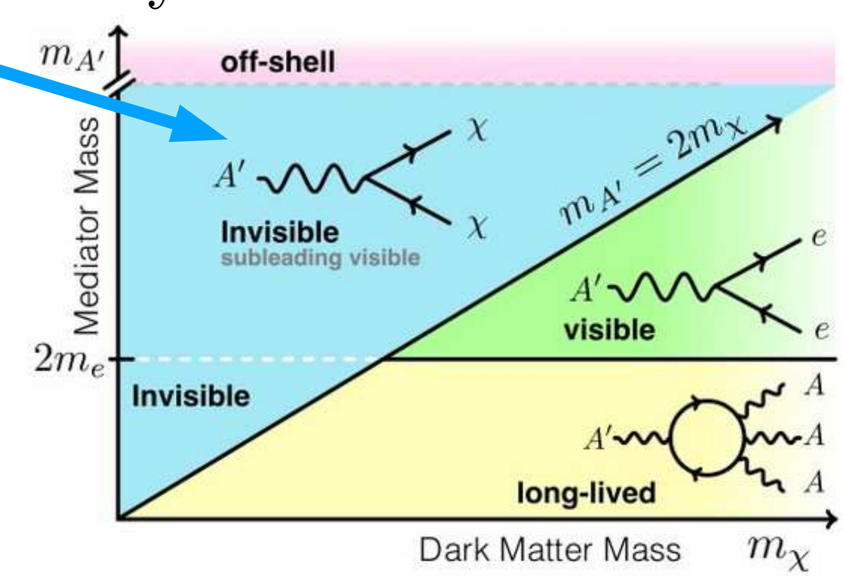
- Two fermions with *dominant non-diagonal* couplings to dark photon
- χ_1 is stable; relic density obtained thanks to $\chi_1\chi_2$ *(co-)annihilations*
- Masses in regime where dark photon predominantly decays into χ_1 and χ_2 while dark photon is produced mainly in mesons decays



Masses leading to invisible decays

$$m_{\chi_1} : m_{\chi_2} : m_{A'} \sim 1:3:4$$

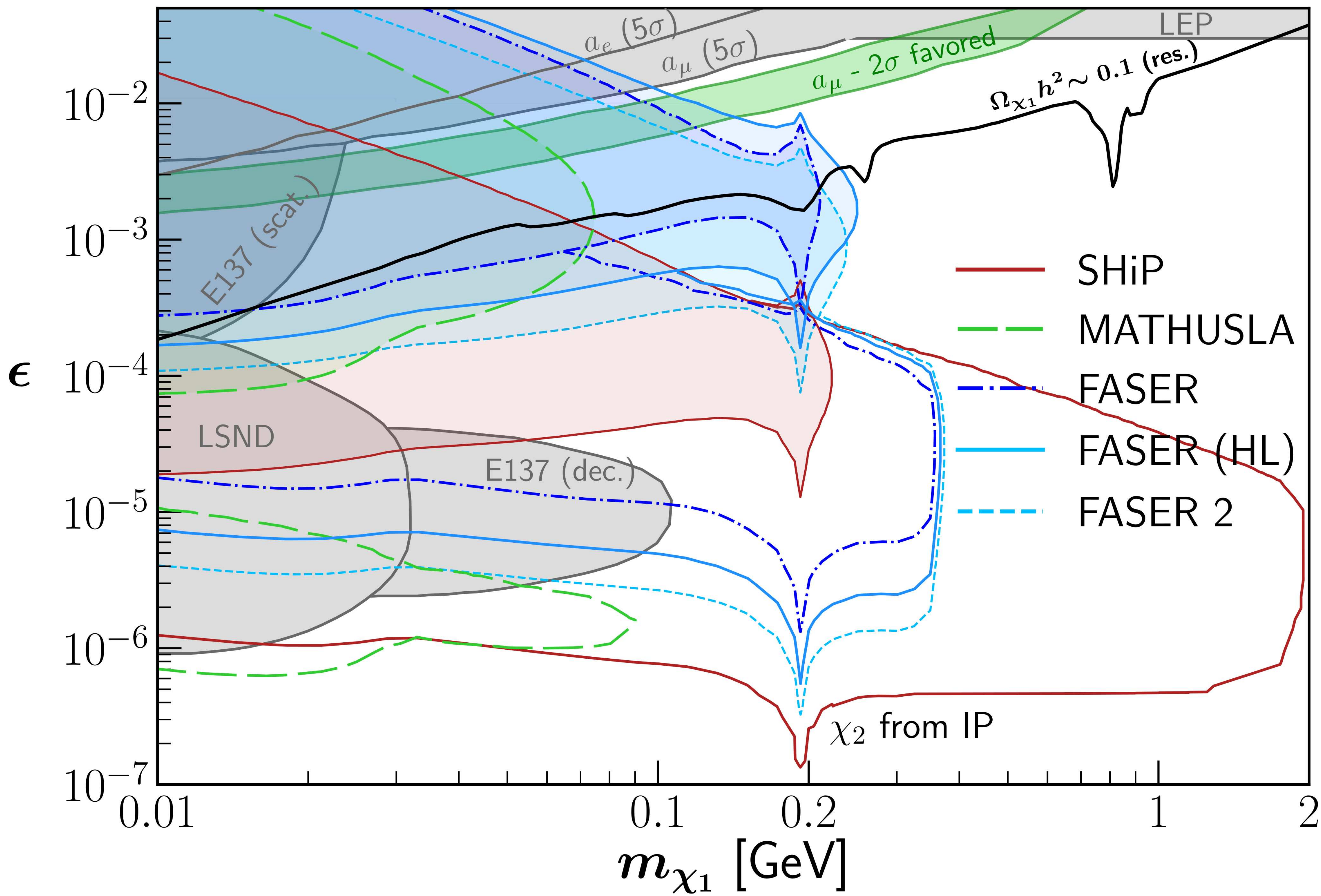




- Typical lifetime

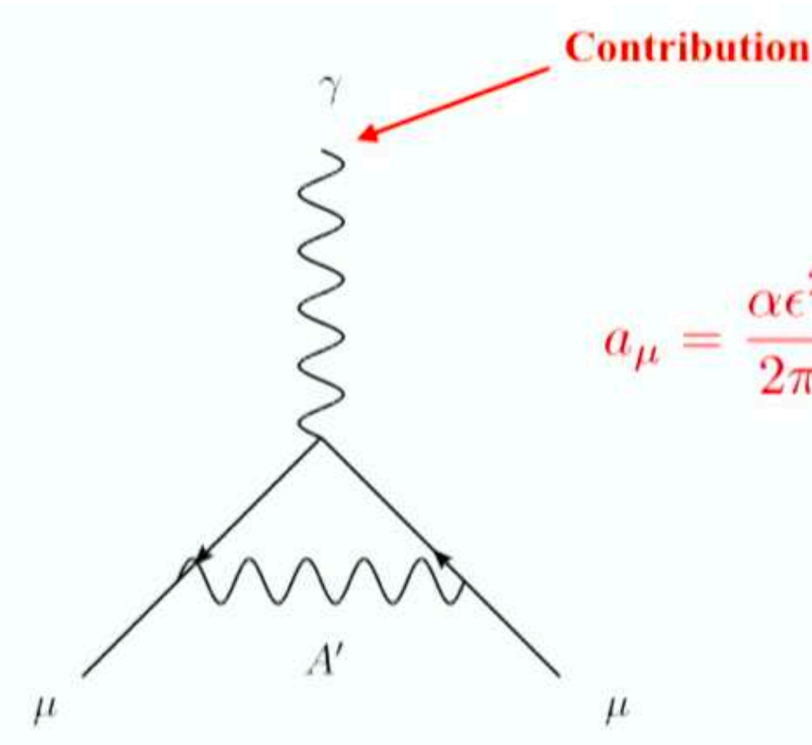
$$c\tau_{\chi_2}\gamma\beta \propto 1\mathrm{m} \times \left(\frac{0.1}{\alpha_D}\right)\left(\frac{5\cdot 10^{-4}}{\varepsilon}\right)^2\left(\frac{2}{\Delta_\chi}\right)^5\left(\frac{100\mathrm{MeV}}{M_{\chi_1}}\right)^5\left(\frac{M_V}{400\mathrm{MeV}}\right)^4\frac{E_{\chi_2}}{100GeV}$$

Results: iDM



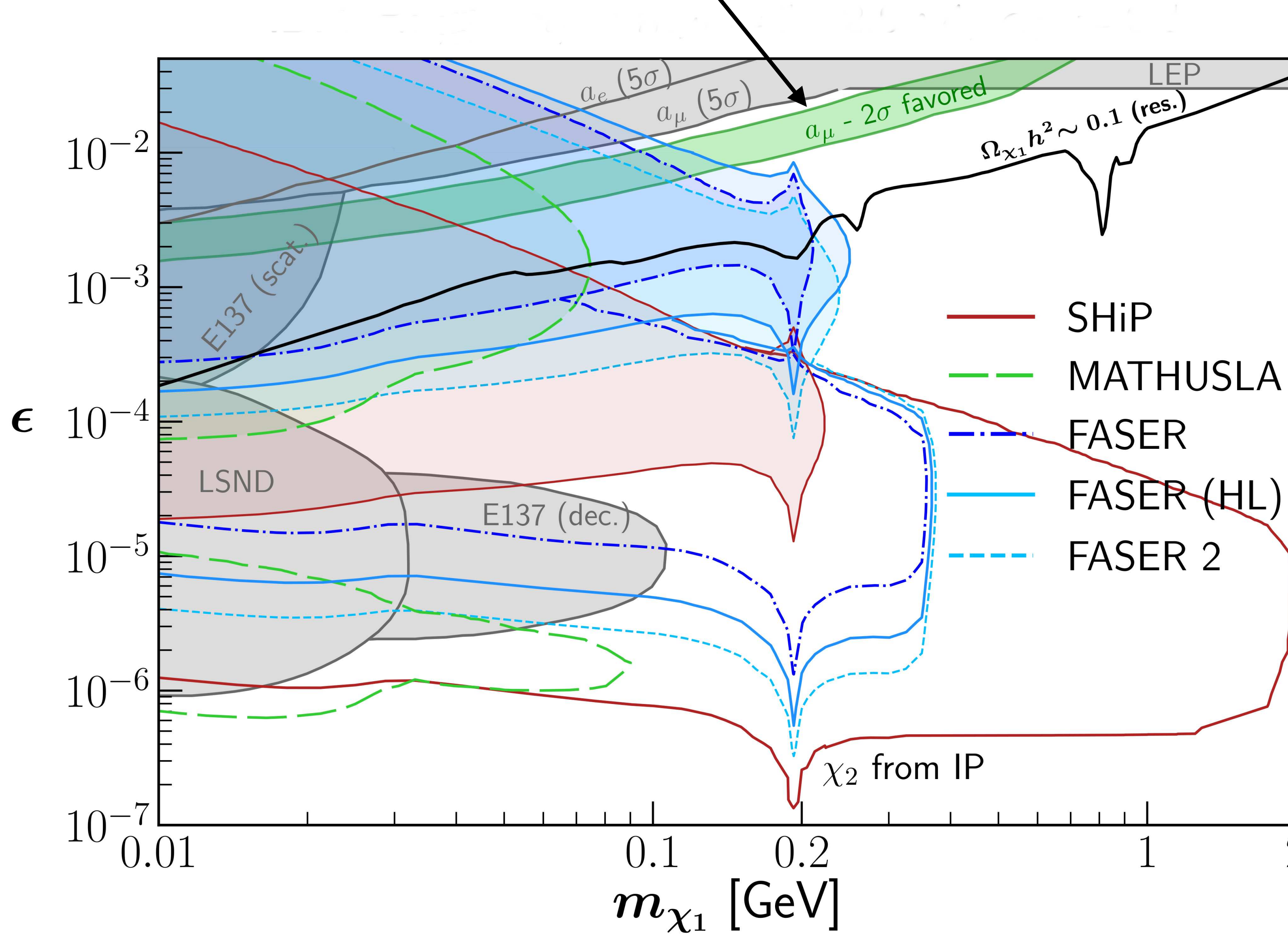
LEP
a_e (5σ)
a_μ (5σ)
a_μ - 2σ favored
$\Omega_{\chi_1} h^2 \sim 0.1$ (res.)
E137 (scat.)
LSND
E137 (dec.)
χ_2 from IP
SHiP
MATHUSLA
FASER
FASER (HL)
FASER 2
ϵ
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.01
0.1
0.2
1
2
m_{χ_1} [GeV]

Secondary production - covering $\Omega h^2 \sim 0.1$, $(g-2)_\mu$

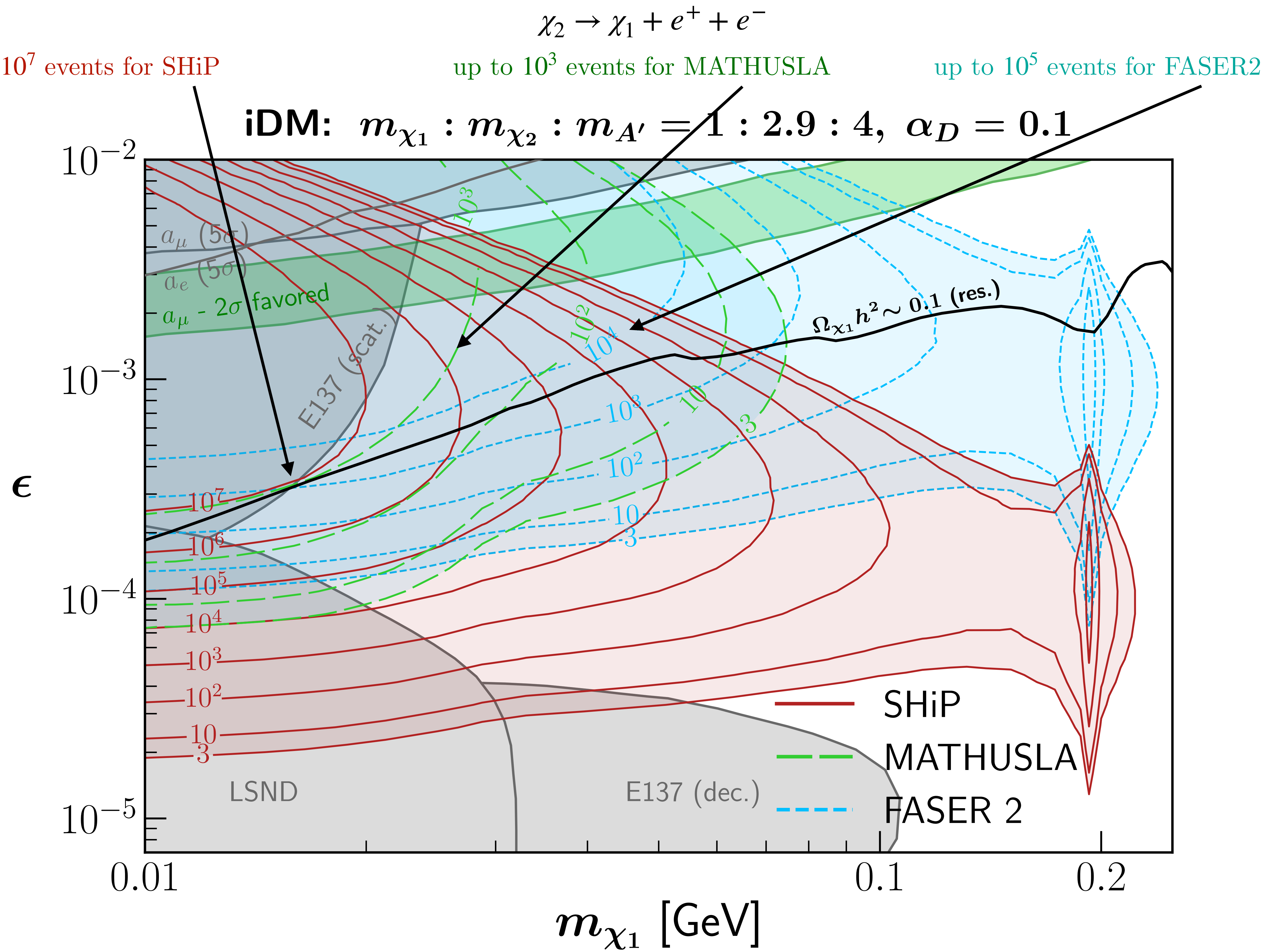


$$a_\mu = \frac{\alpha \epsilon^2}{2\pi} \int_0^1 dz \frac{2m_\mu^2 z(1-z)^2}{m_\mu^2 (1-z)^2 + m_{A'}^2 z}$$

April 2021 @ Fermilab - confirmation of $\sim 4.2\sigma$ discrepancy!

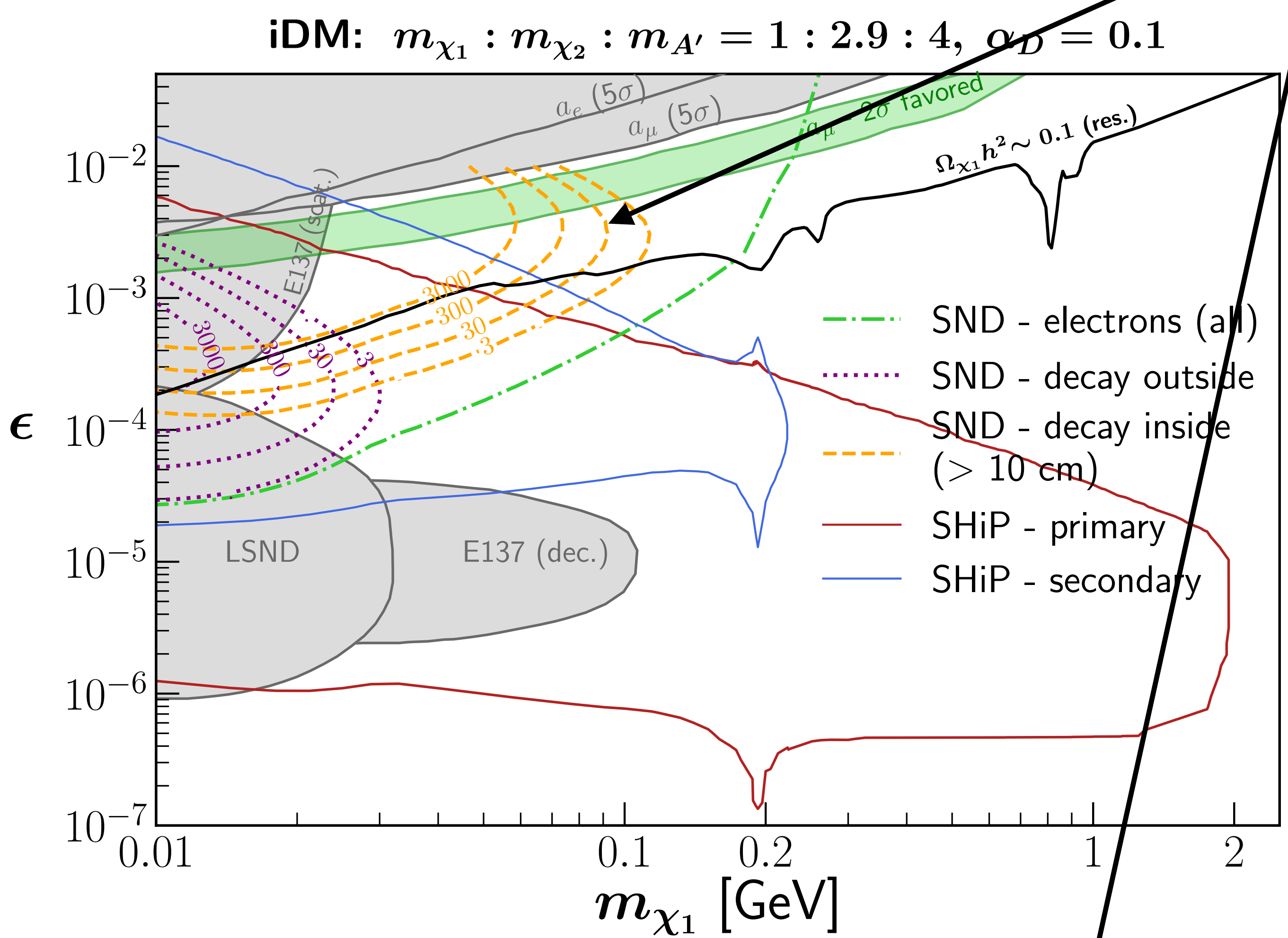


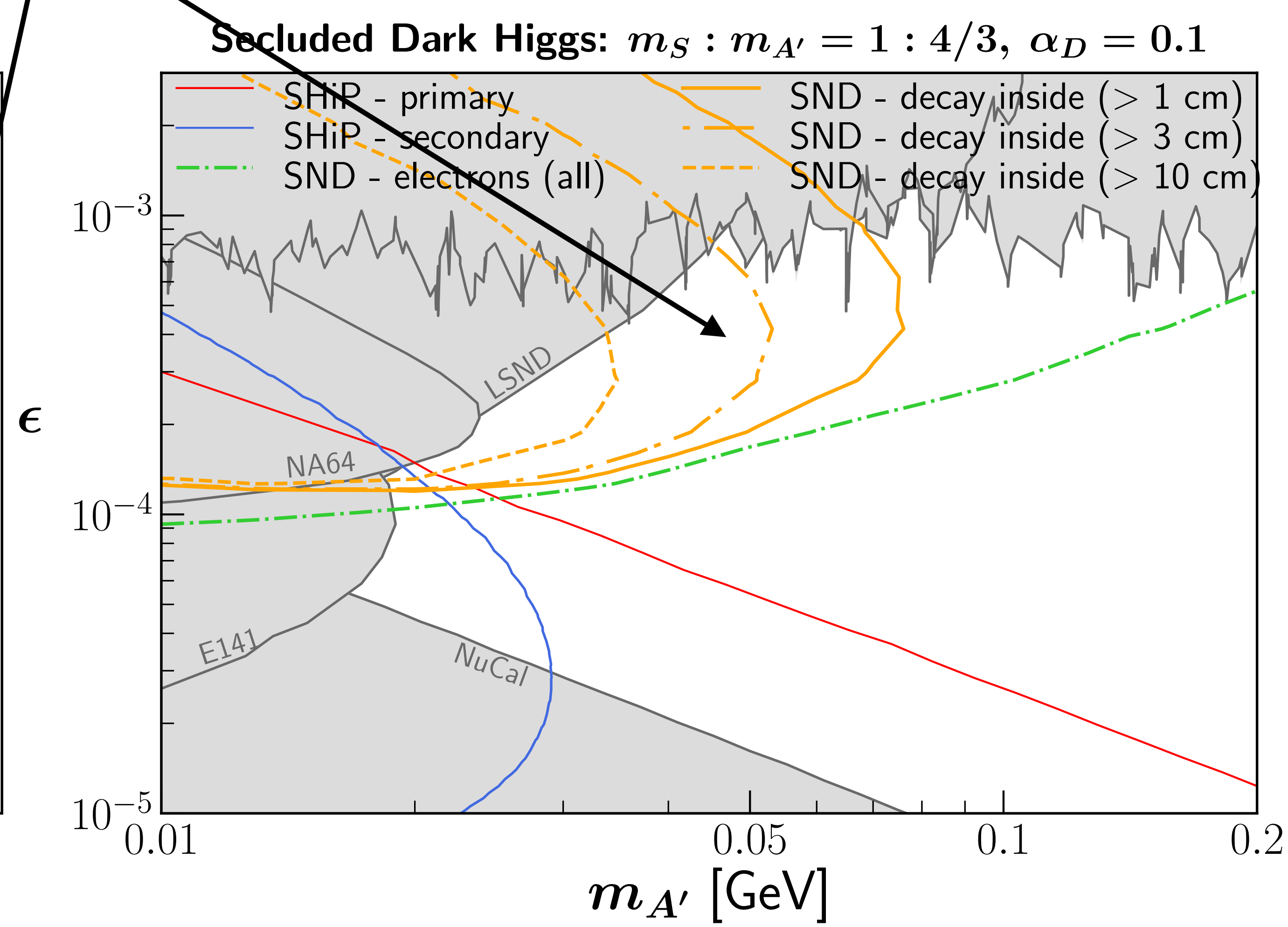
Secondary production contribution

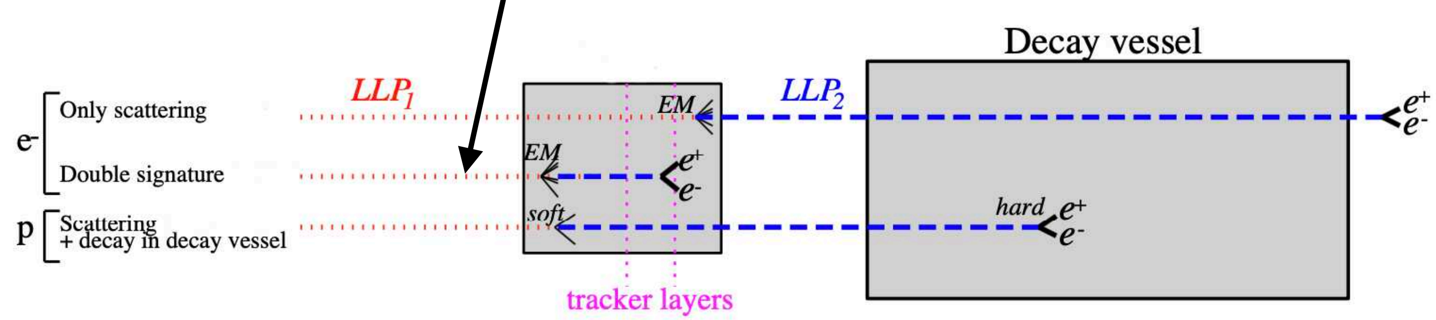


Electron scattering events - SND@SHiP

up to 3000 events with two collinear, time-coincident
and spatially separated EM showers satisfying cuts







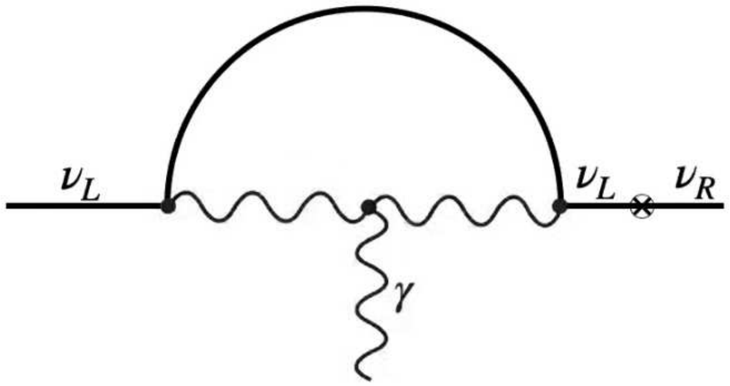
Neutrino non-standard interactions

- Neutrino magnetic moment

$$\mathscr{L} \supset \mu_N \bar{\nu}_L \sigma_{\mu\nu} N_R F^{\mu\nu} + \text{h.c.},$$

In SM $\mu_\nu < 10^{-19}\mu_B$, where $\mu_B \equiv \frac{\sqrt{4\pi\alpha}}{2m_e} \simeq 300\ \text{GeV}^{-1}$

Petcov, Fujikawa, Shrock 1979



DM DD experiments (Xenon anomaly), neutrino experiments, cosmology/astrophysics

- Gninenko (MiniBooNE), 0902.3802, 1009.5536, 1201.5194
- Coloma, Machado, Martinez-Soler, Shoemaker (IceCube), 1707.08573
- Magill, Plestid, Pospelov, Tsai (SHiP), 1803.03262
- Shoemaker, Wyenberg (Xenon), 1811.12435
- Brdar, Greljo, Kopp, Opferkuch, 2007.15563 ⟵ UV complete model based on TeV-scale leptoquarks

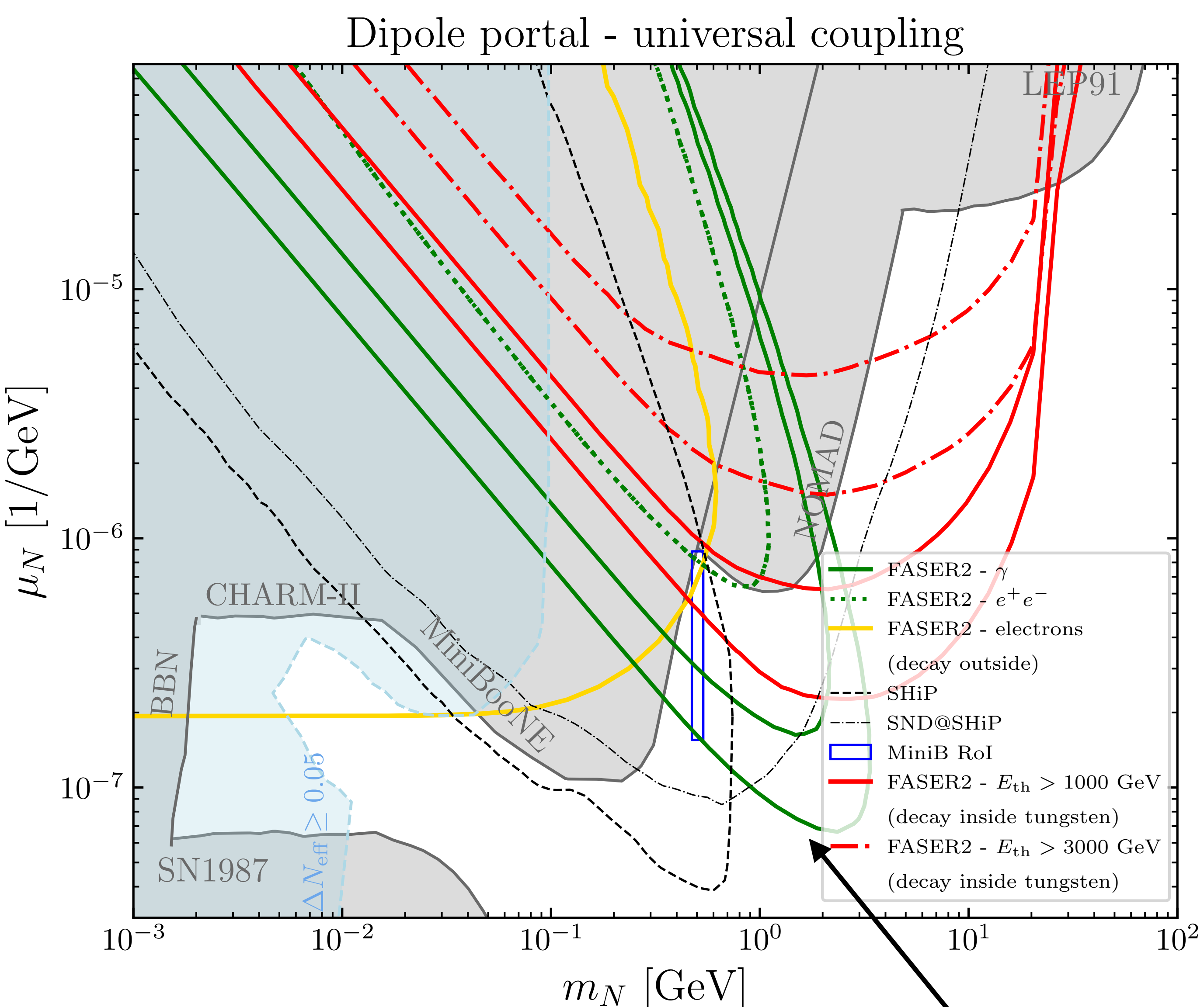
- Light Z_D mediator from dark gauge group $U(1)_D$ - dark neutrino model

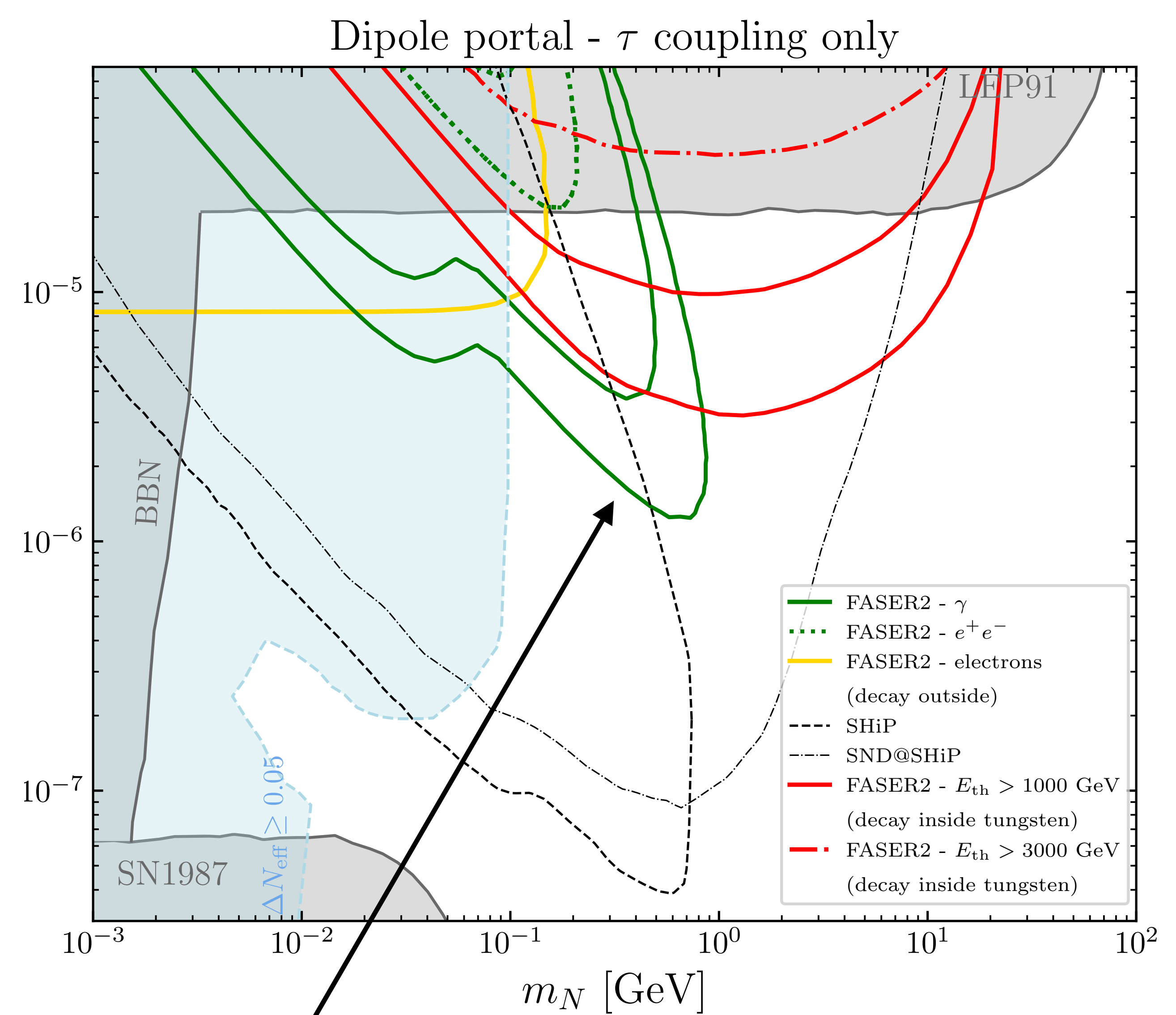
$$\mathscr{L}_D \supset \frac{m_{Z_D}^2}{2} Z_{D\mu} Z_D^\mu + g_D Z_D^\mu \bar{N}\gamma_\mu N + e\epsilon Z_D^\mu J_\mu^{\text{em}},$$

MiniBooNE Anomaly, natural light m_ν generation

- Bertuzzo, Jana, Machado, Zukanovich Funchal 1807.09877, 1808.02500
- Argüelles, Hostert, Tsai, 1812.08768
- Ballett, Pascoli, Ross-Lonergan, 1808.02915
- Ballett, Hostert, Pascoli, 1903.07589

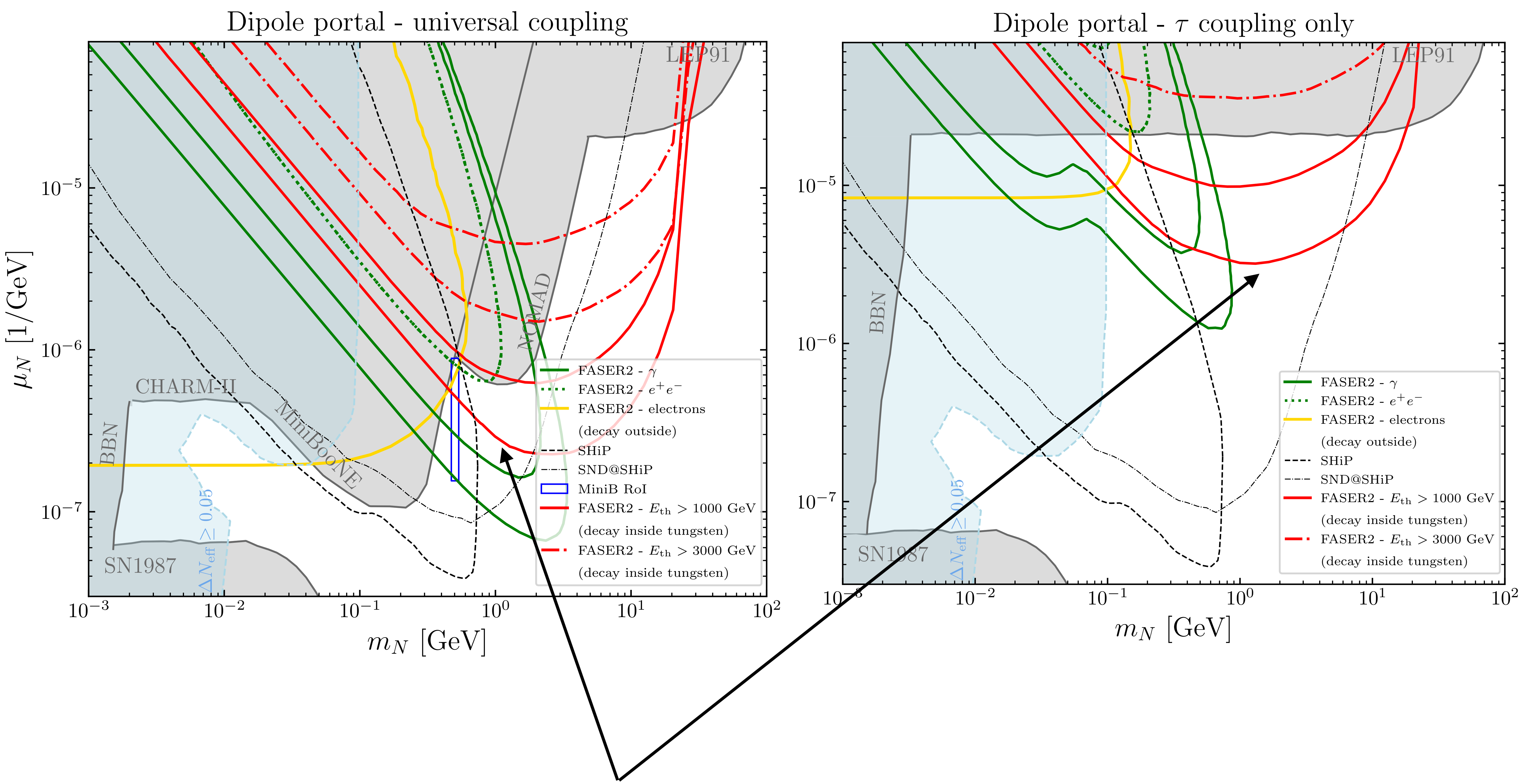
Neutrino magnetic moment





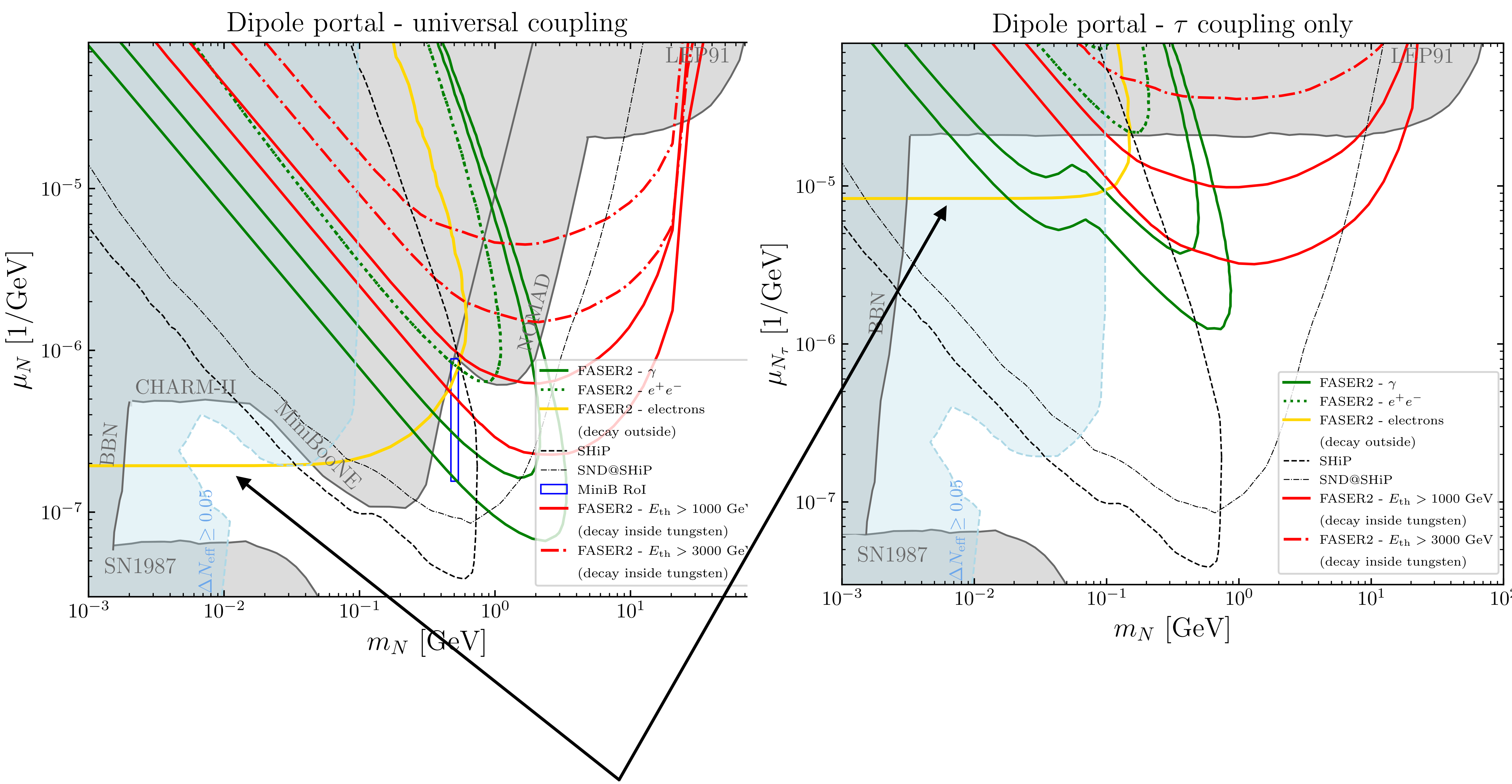
Upscattering $\nu X \to NX$ followed by LLP decay $N \to \nu\gamma$ inside main detector

Neutrino magnetic moment



decays of high-energy LLPs inside ECC detector (E_γ > 1TeV)

Neutrino magnetic moment

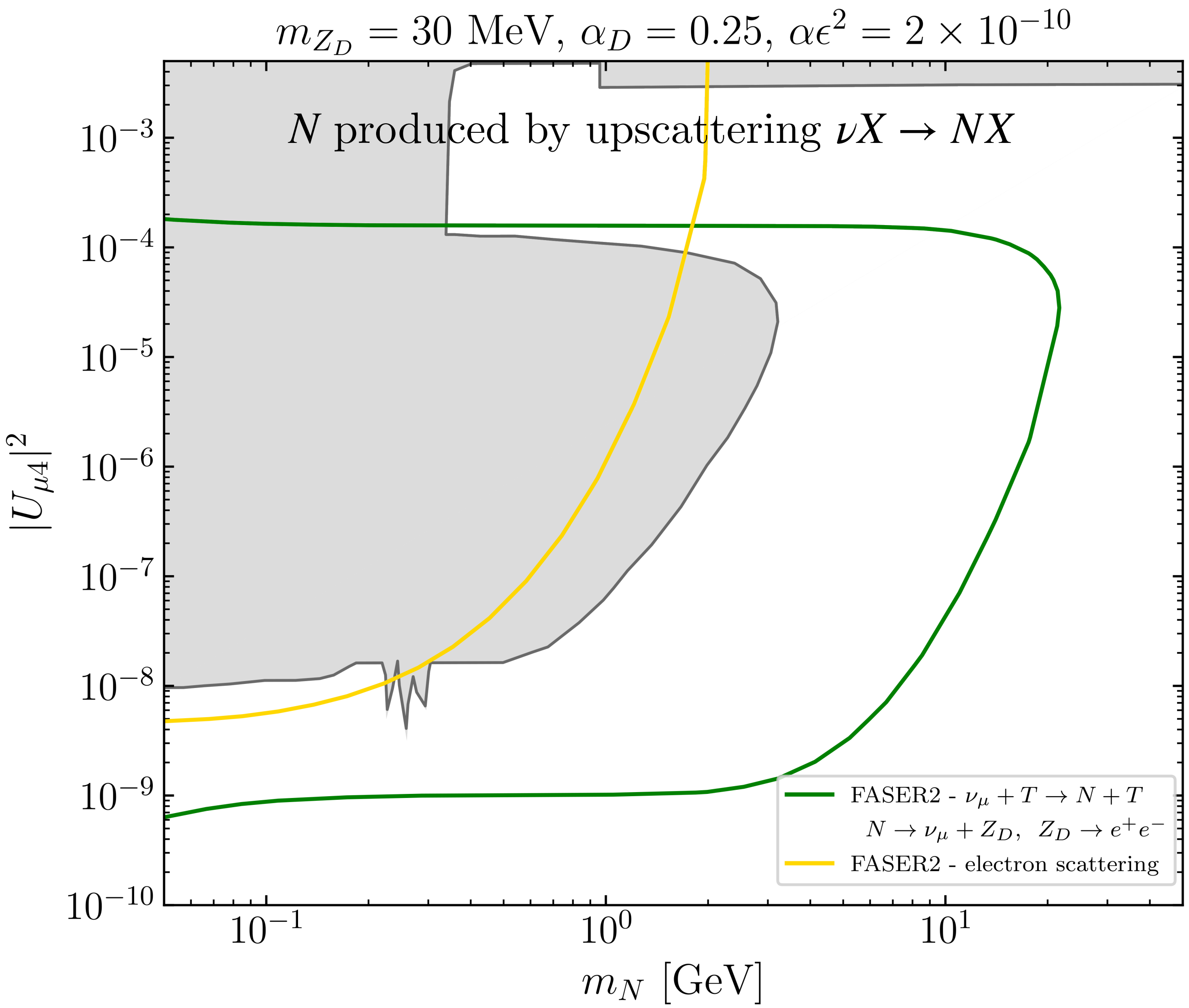


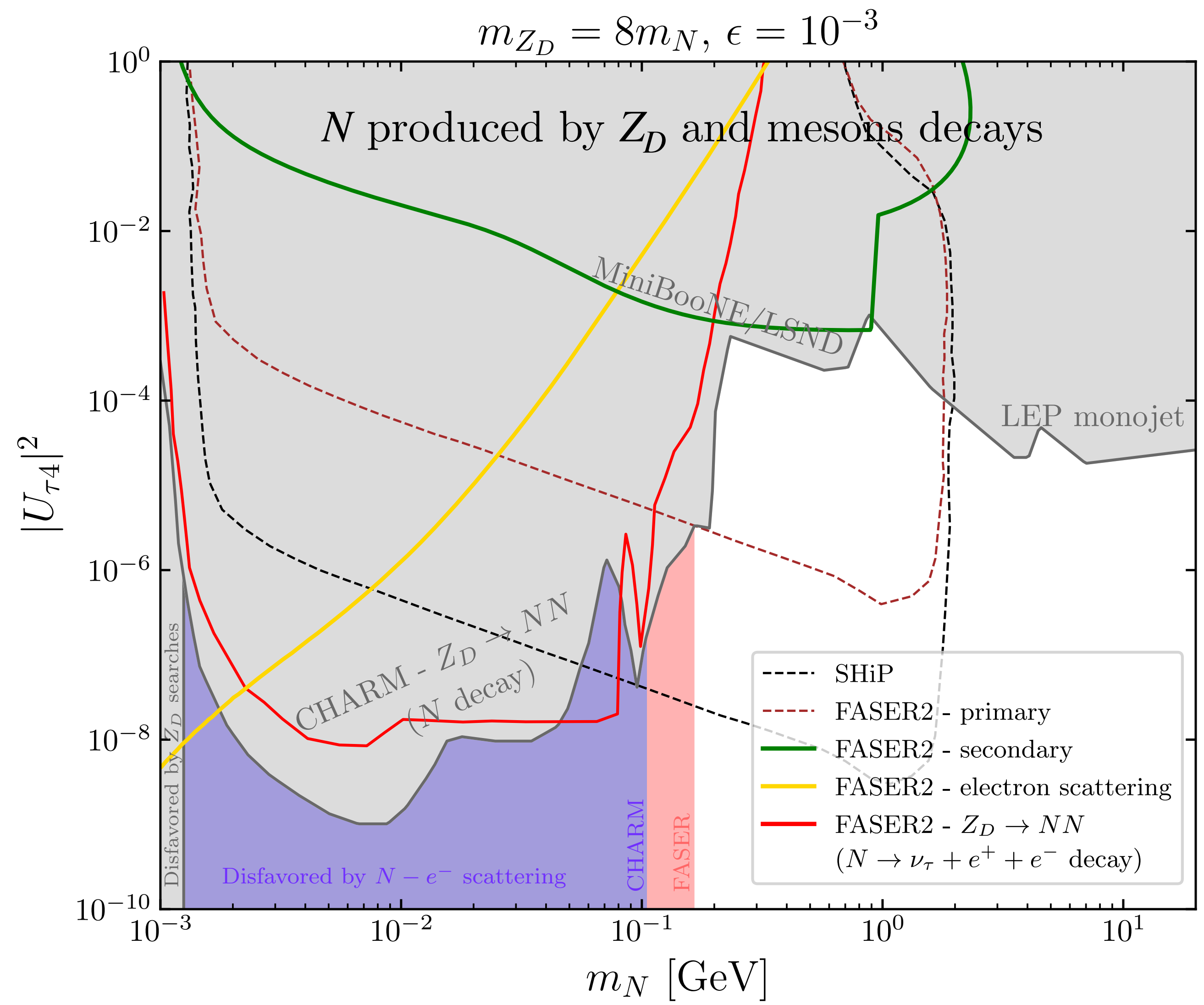
scattering off electrons

$$\nu e^- \to N e^-$$

Light Z_D mediator

$m_{Z_D} < m_N$ $\quad$ $m_{Z_D} > m_N$





electron scattering: $Ne^- \to Ne^-$ and $\nu e^- \to Ne^-$

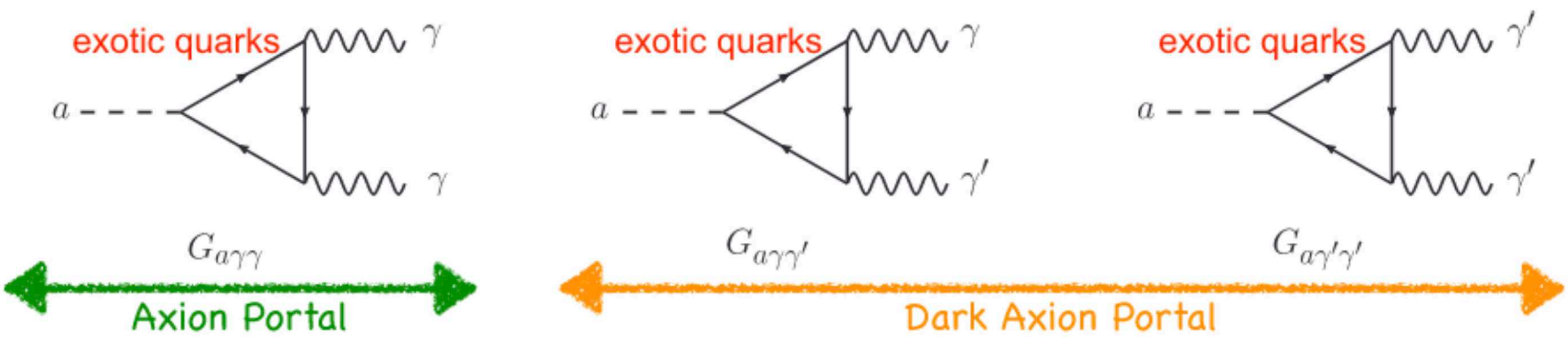
Dark KSVZ ALP at FASERν2

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

$$\mathscr{L}_{\text{dark axion portal}} = \frac{G_{a\gamma'\gamma'}}{4} a Z'_{\mu\nu}\tilde{Z}'^{\mu\nu} + \frac{G_{a\gamma\gamma'}}{2} a F_{\mu\nu}\tilde{Z}'^{\mu\nu}$$

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 $U(1)_Y$.

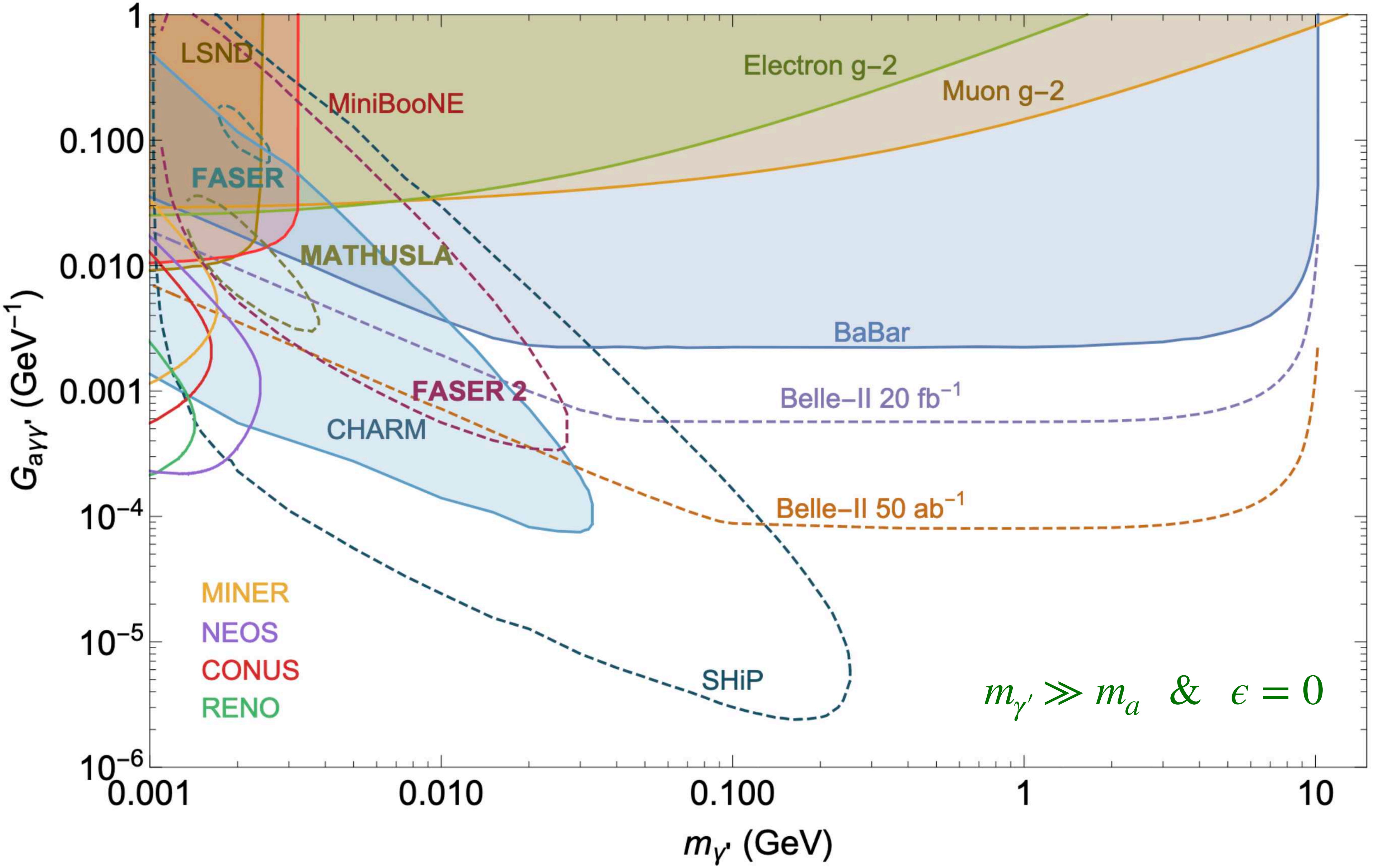


Kaneta, Lee, Yun, 1611.01466

Motivation

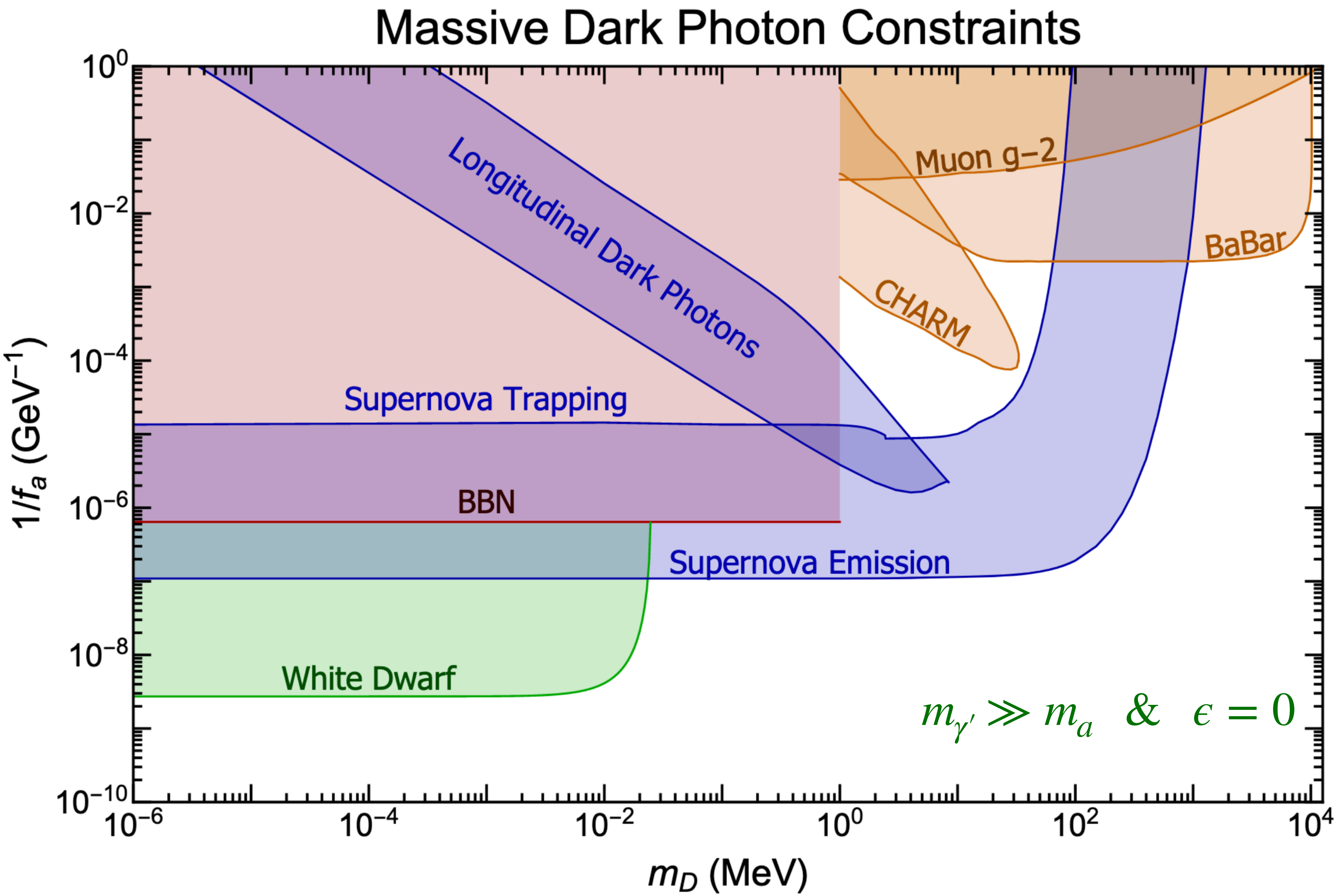
- Dark photon DM
  Kaneta, Lee, Yun 1704.07542, Gutiérrez et al. 2112.11387
- Cosmological relaxation
  Choi, Kim, Sekiguchi 1611.08569; Domcke, Schmitz, You 2108.11295
- $(g-2)_\mu$
  deNiverville, Hye-Lee, Seo, 1806.00757; Ge, Ma, Pasquini 2104.03276
- Axion-photon-dark photon oscillation
  Choi, Kim, Sekiguchi 1802.07269; Choi, Lee, Seong, Yun 1806.09508, 1911.00532;
- Lab searches - displaced vertices, missing energy,...
  deNiverville, Hye-Lee, Seo 1806.00757, 1904.13061, 2011.03276
- Astrophysical searches - supernovae, white dwarves...
  Arias et al. 2007.12585; Hook, Marques-Tavares, Ristow 2105.06476
- Laser/LSW searches
  Hye-Lee, Lee, Yi 2201.11906
- ....

Beam dump and collider limits



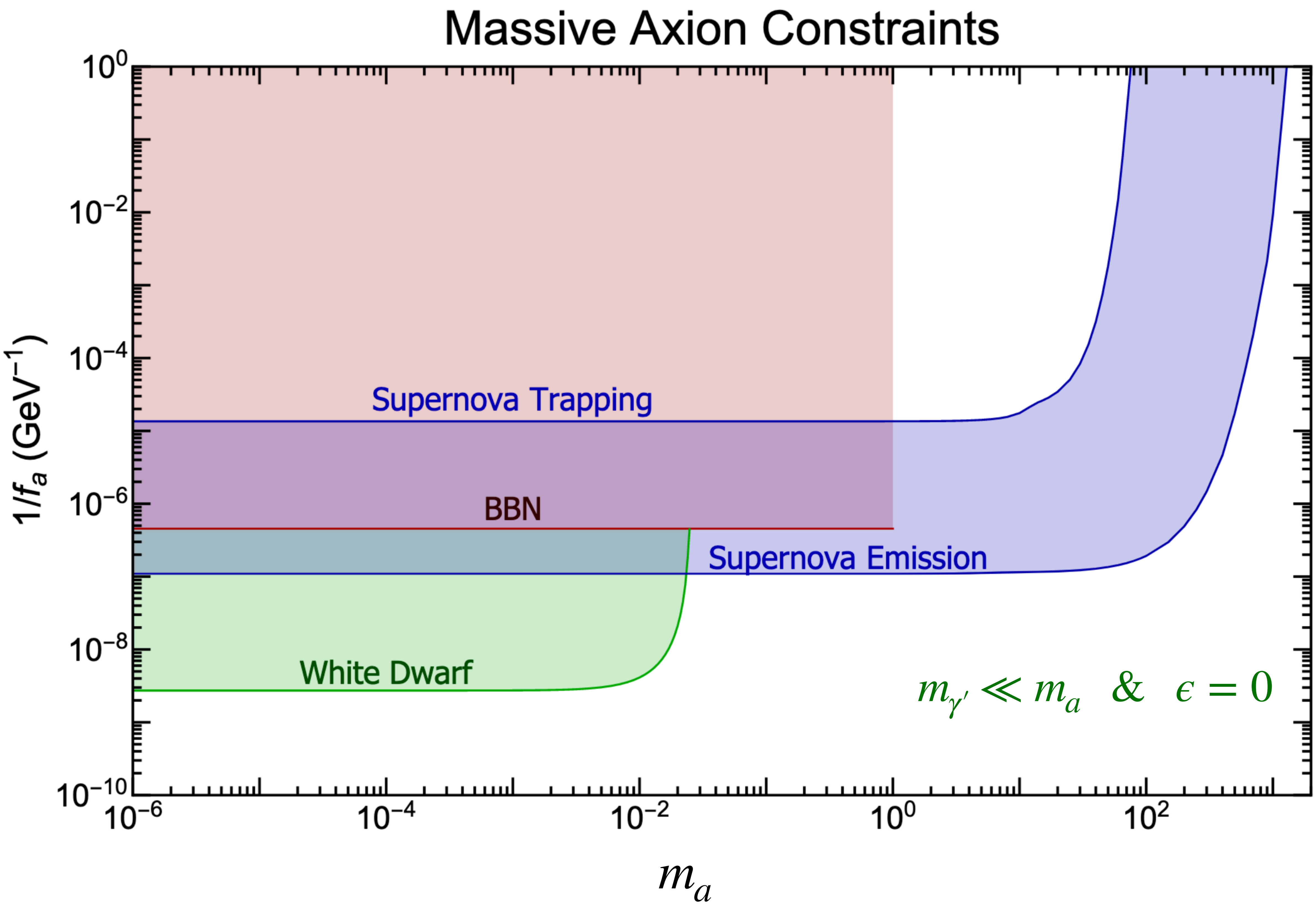
deNiverville, Hye-Lee, Min-Seok Seo, 1806.00757, 1904.13061, 2011.03276

Adding astrophysical limits



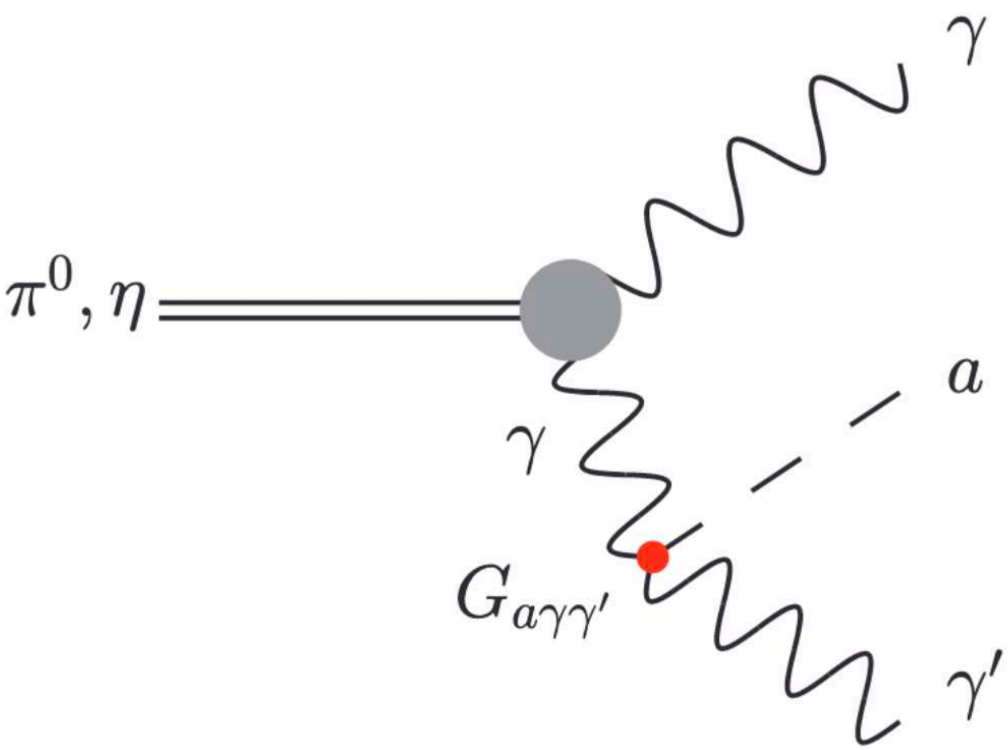
Hook, Marques-Tavares, Ristow, 2105.06476

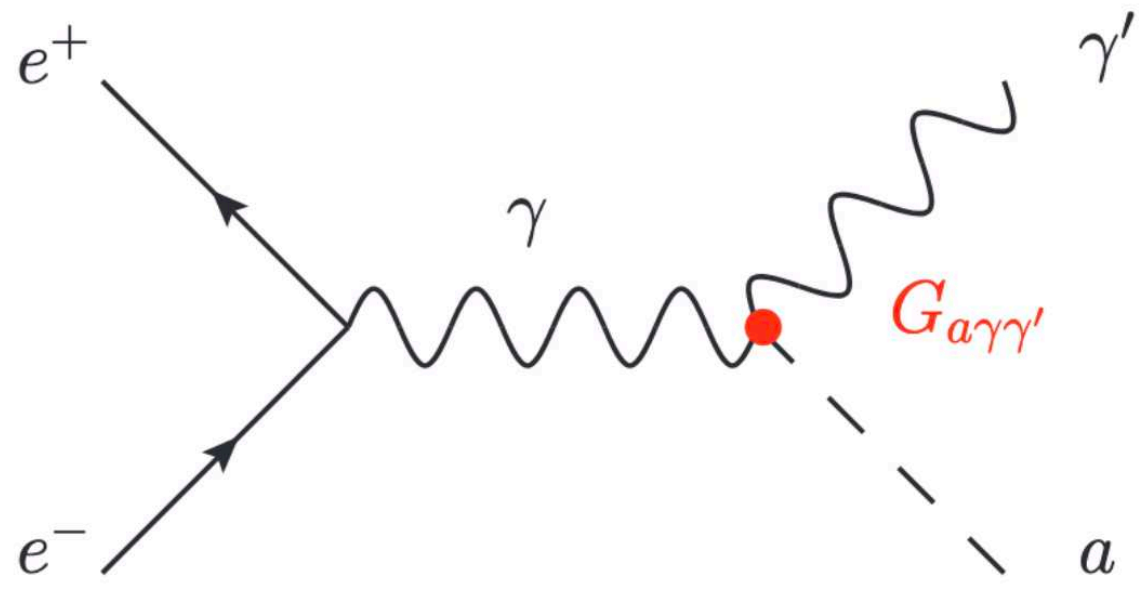
Inverted mass hierarchy

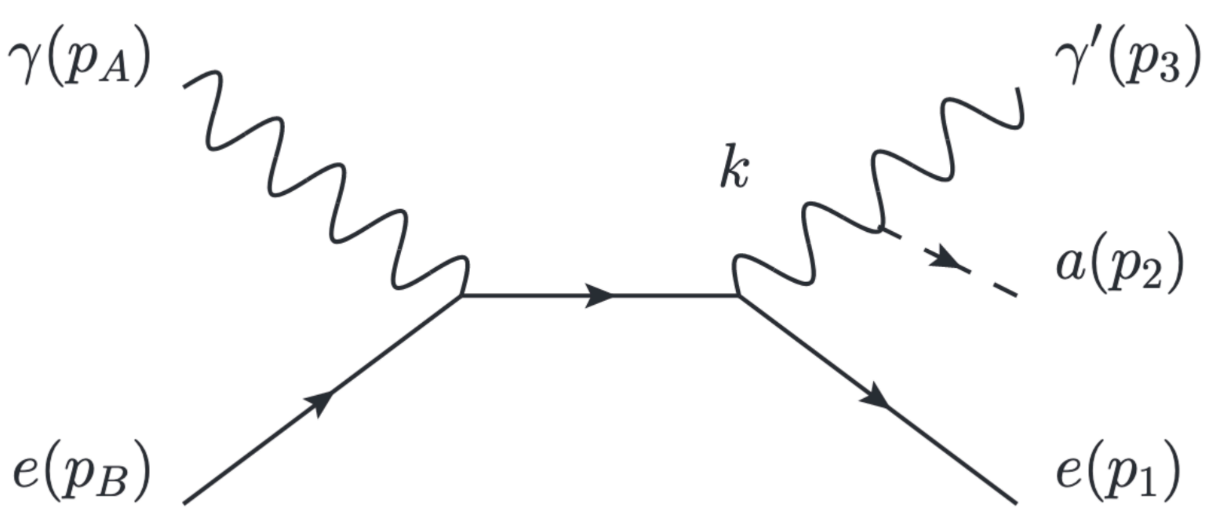


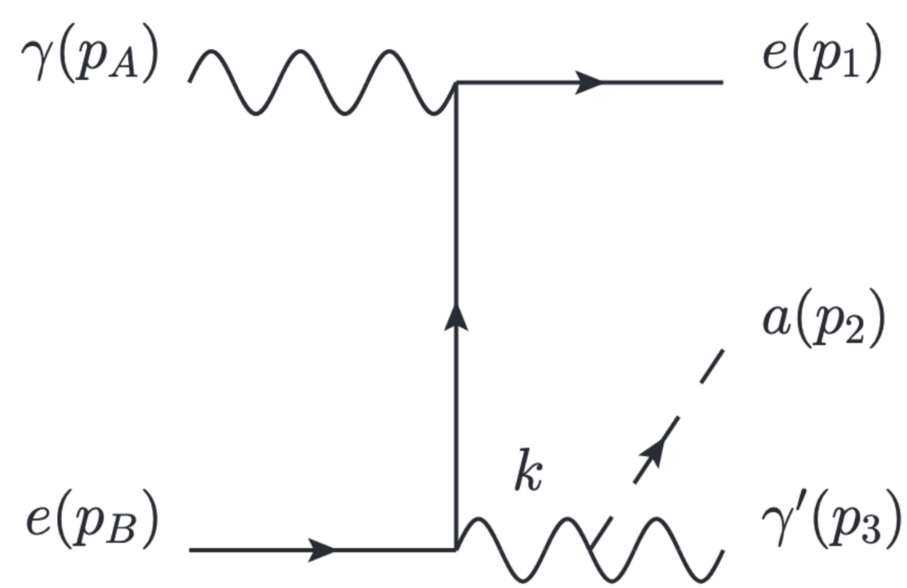
Hook, Marques-Tavares, Ristow, 2105.06476

Production



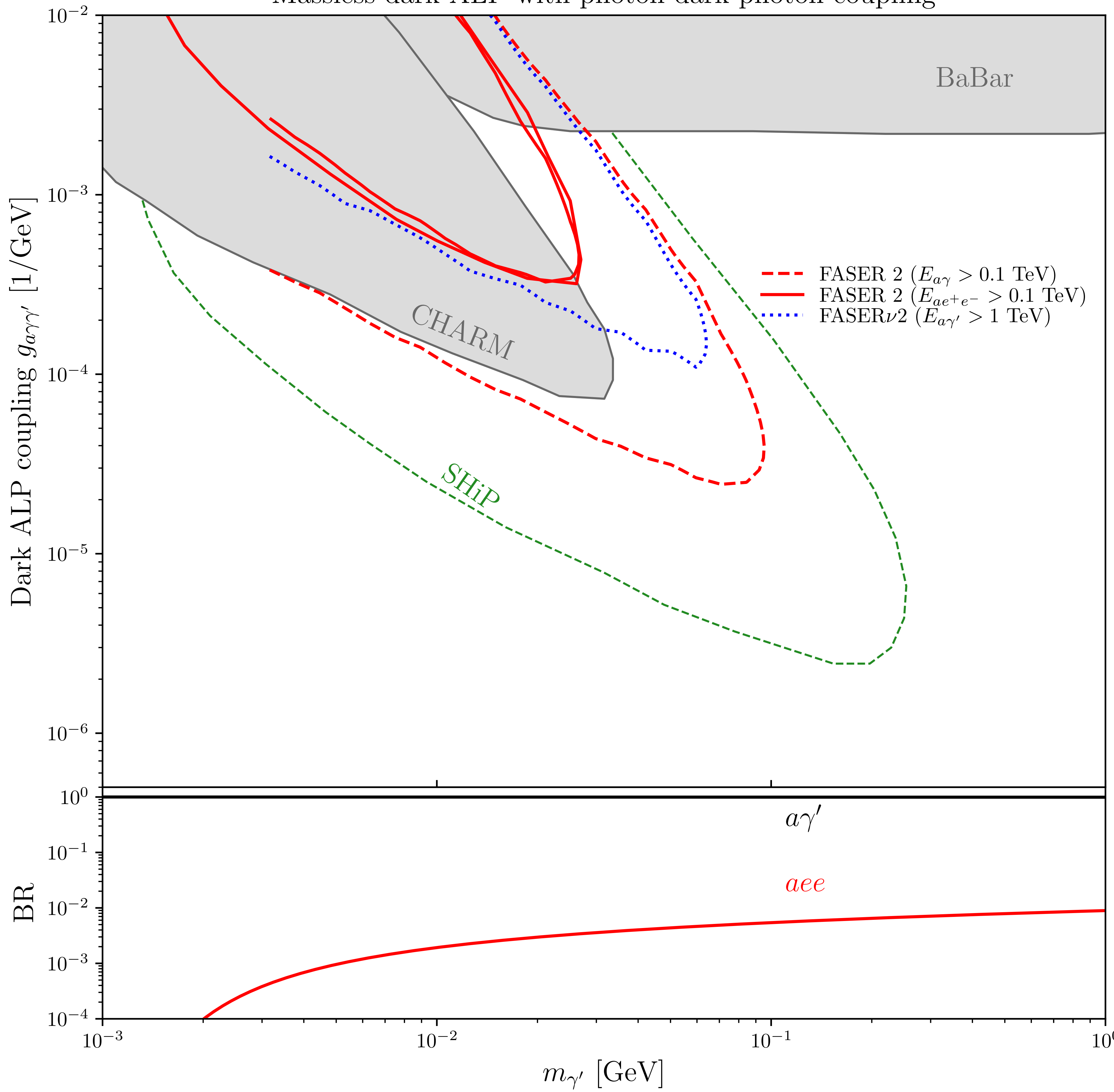






deNiverville, Hye-Lee, Min-Seok Seo, 1806.00757, 1904.13061, 2011.03276

Massless dark ALP with photon-dark photon coupling



Work in progress

Conclusions

- Realistic BSM scenarios often predict more than a single sub-GeV new particle
- If weakly coupled and unstable, such particle will be long-lived and pertinent to the displaced vertex searches $\rightarrow$ low SM background but searches restricted by fixed decay length

- Realistic BSM scenarios often predict more than one LLP, *so that secondary LLP production can take place right in front of the detector*, extending the sensitivity to shorter lifetimes. One can employ several complementary signatures for such LLPs:
    - two high-energy oppositely-charged tracks
    - high-energy photons appearing in the detector
    - the single-electron scattering signature without further EM/hadronic activity