Searching for rich dark sectors in the FPF through secondary production and in indirect dark matter searches

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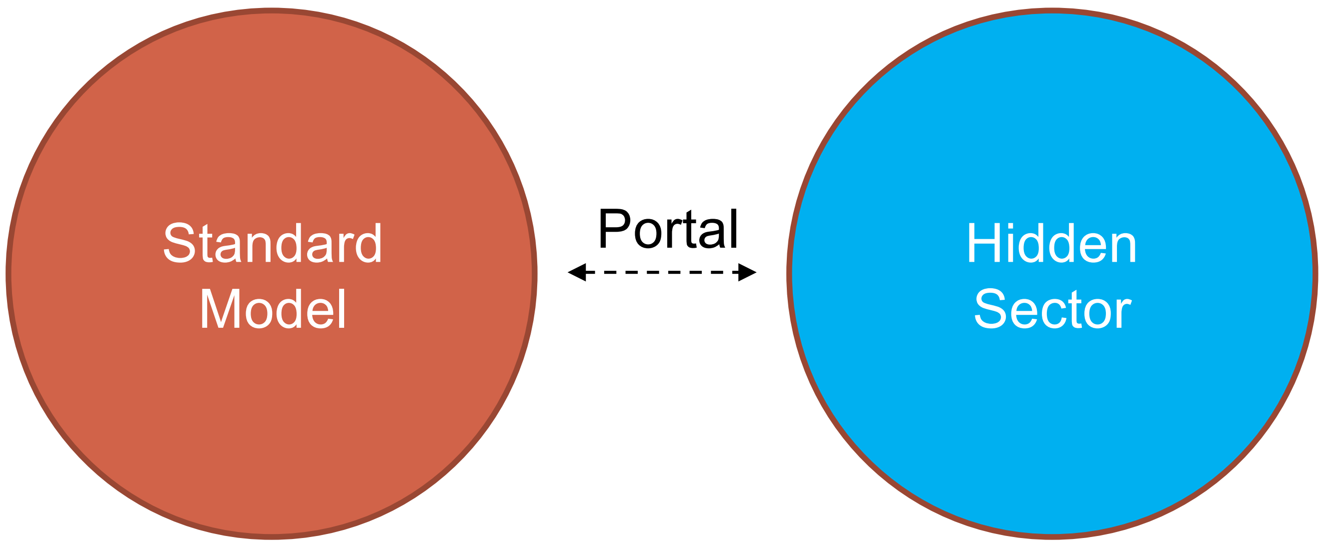
Based on:
KJ, F. Kling, L. Roszkowski, S. Trojanowski, 1911.11346; KJ, S. Trojanowski, 2011.04751; KJ, L. Roszkowski, S. Trojanowski, 2112.11993

Sub-GeV New Physics

- Exploring lower mass ranges while preserving basic mechanism of freeze-out
- DM freezes out while the mediator decays into SM particles

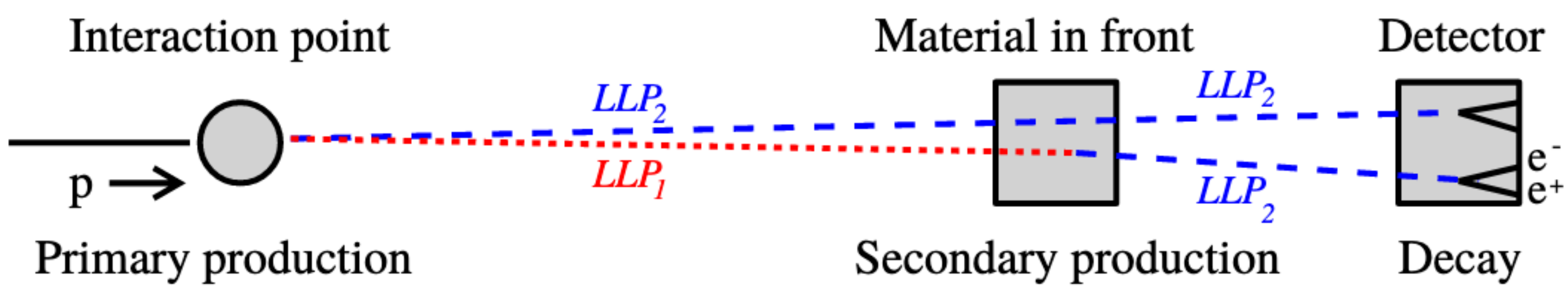


- Restricting to dimension 4 operators, there are only 3 possibilities:
  - $\mathscr{L}_{\text{vector portal}} = -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$
  - $\mathscr{L}_{\text{scalar portal}} = \alpha_1 S H^\dagger H + \alpha S^2 H^\dagger H$
  - $\mathscr{L}_{\text{neutrino portal}} = F_\ell \left(\epsilon_{ab}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

Secondary production of long-lived particles

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

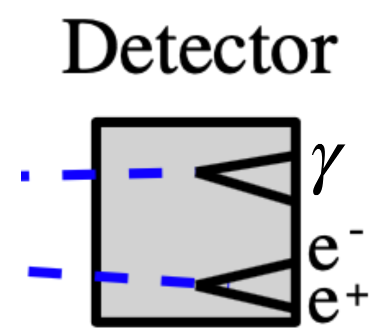
$$\mathscr{P}_{decay} = \exp\left(-\frac{L_{min}}{\bar{d}}\right)\left[1 - \exp\left(-\frac{L_{max} - L_{min}}{\bar{d}}\right)\right],$$

$$N_{\mathrm{sig}} \propto \begin{cases} \mathcal{L}^{\mathrm{int}}\, \epsilon^2\, e^{-L_{\mathrm{min}}/\bar{d}} & \text{for} \quad \bar{d} \ll L_{\mathrm{min}} \\ \mathcal{L}^{\mathrm{int}}\, \epsilon^2\, \frac{L_{\mathrm{max}} - L_{\mathrm{min}}}{\bar{d}} & \text{for} \quad \bar{d} \gg L_{\mathrm{min}} \end{cases}$$

- ***Secondary production***:
  - Signal due to $\mathrm{LLP}_2 \to (\mathrm{LLP}_1 +)$ visible or $\mathrm{LLP}_2 + e^- \to \mathrm{LLP}_2 + e^-$

Experimental signatures of new physics

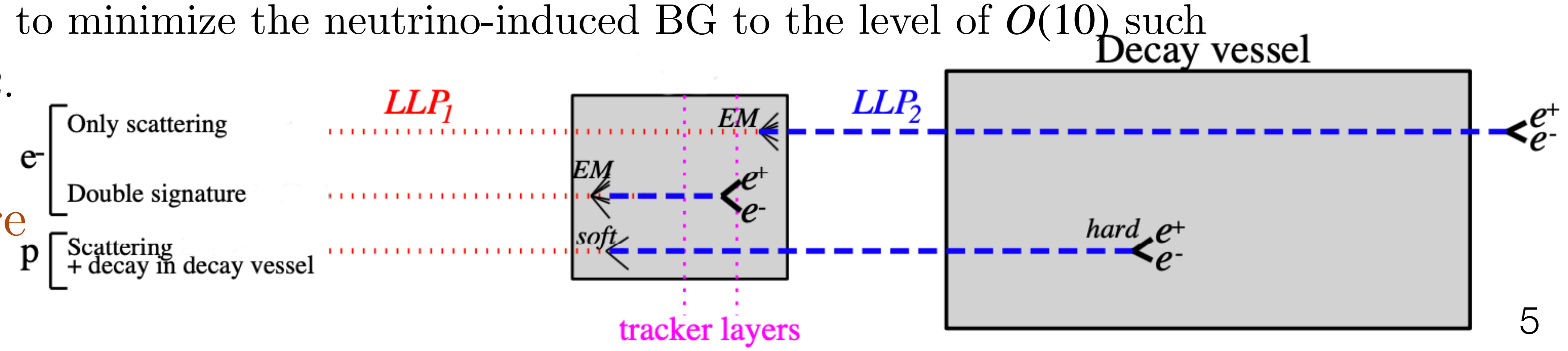
- LLP signal inside the FASER decay vessel – e^+e^- and γ
  - $E_{vis} > 100$ GeV
  - e^+e^- search: negligible background due to high energies of LLP's
  - γ search:
    - neutrino-induced BG minimized by dedicated preshower detector
    - BG from muon-induced photons expected to be vetoed by detecting a time-coincident muon going through the detector → excess of single-photon events unaccompanied by any muon indicative of new physics



- Prompt decays of high-energy LLPs inside the ECC detector
  - looking for very high-energy photons $E_\gamma > 1$ TeV or 3 TeV unaccompanied by any time-coincident muon
- 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

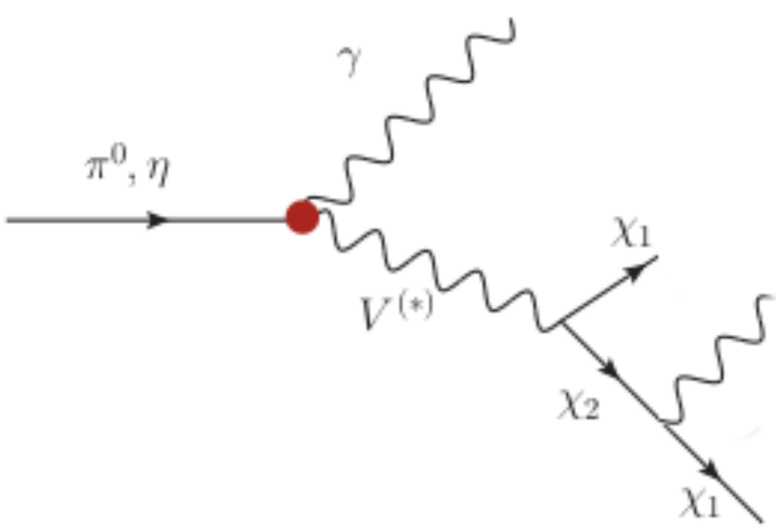


Inelastic DM

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

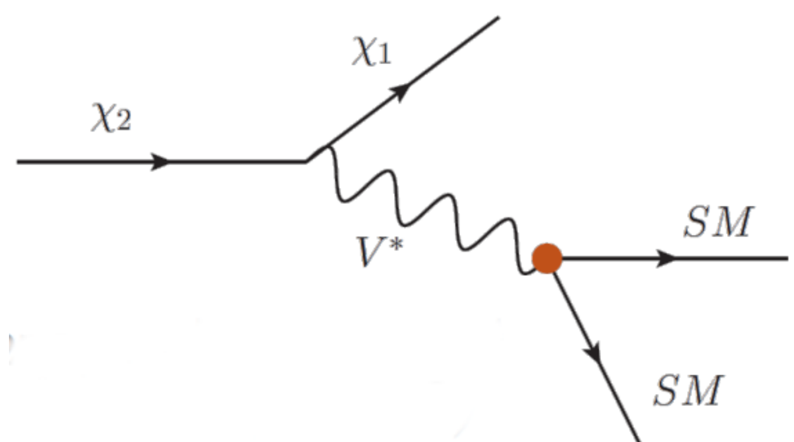
Smith, Weiner, 0101138

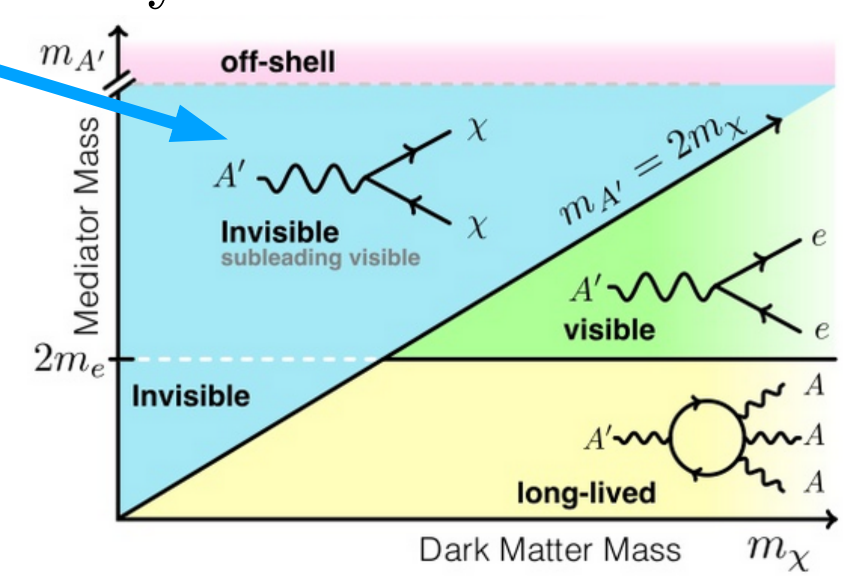
- Two fermions with *dominant non-diagonal* couplings to dark photon
- χ_1 is stable; relic density obtained thanks to $\chi_1\chi_2$ (co-)annihilations
- Masses in regime where dark photon predominantly decays into χ_1 and χ_2 while dark photon is produced mainly in mesons decays



Masses leading to invisible decays

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

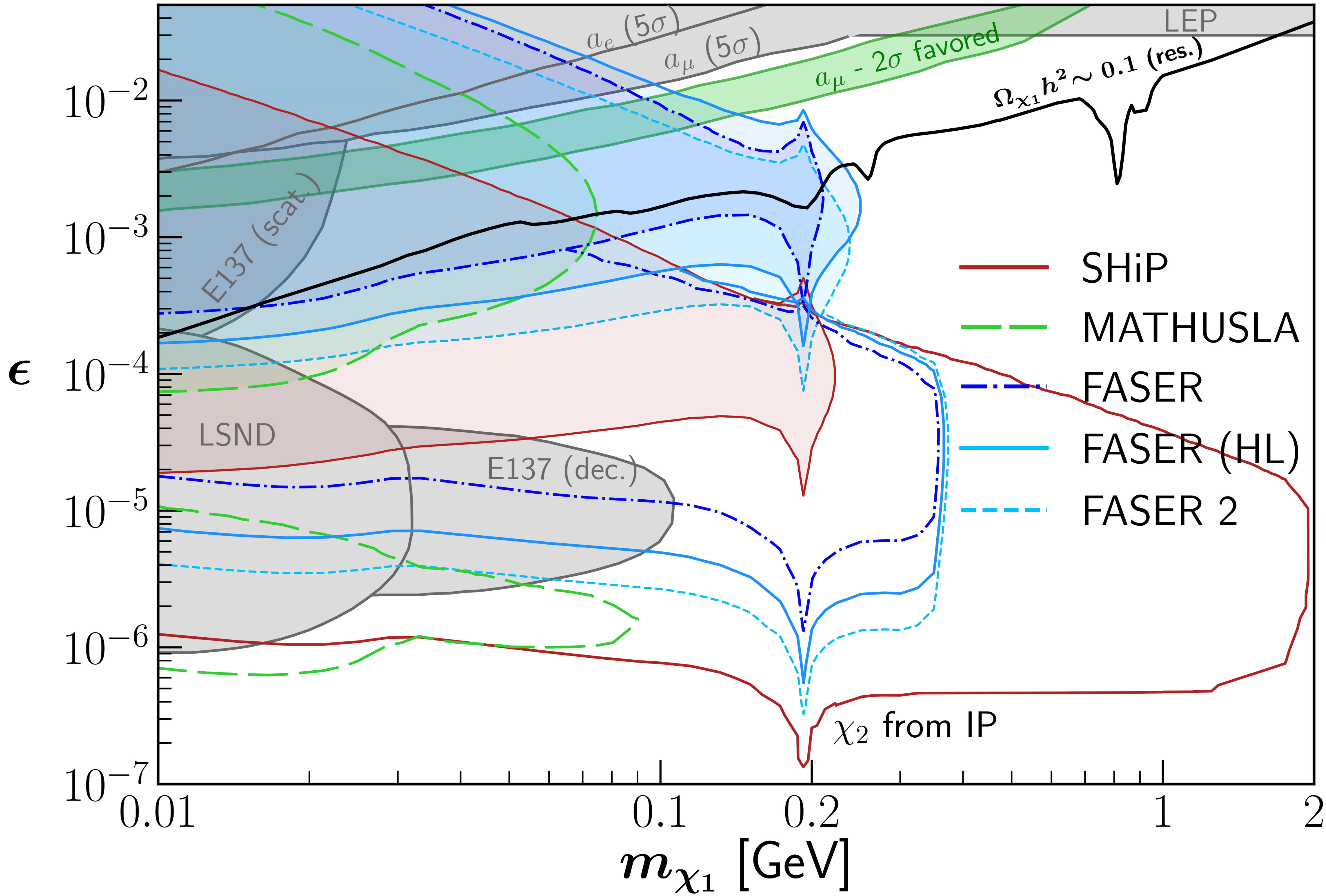




- Typical lifetime

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

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]

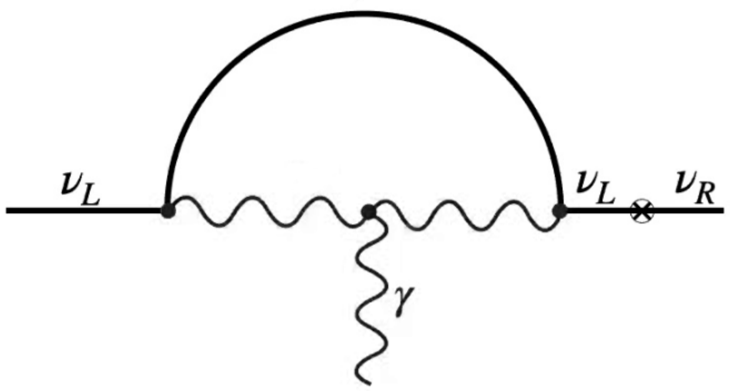
Neutrino non-standard interactions

- 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 ← Example of UV complete model based on TeV-scale leptoquarks

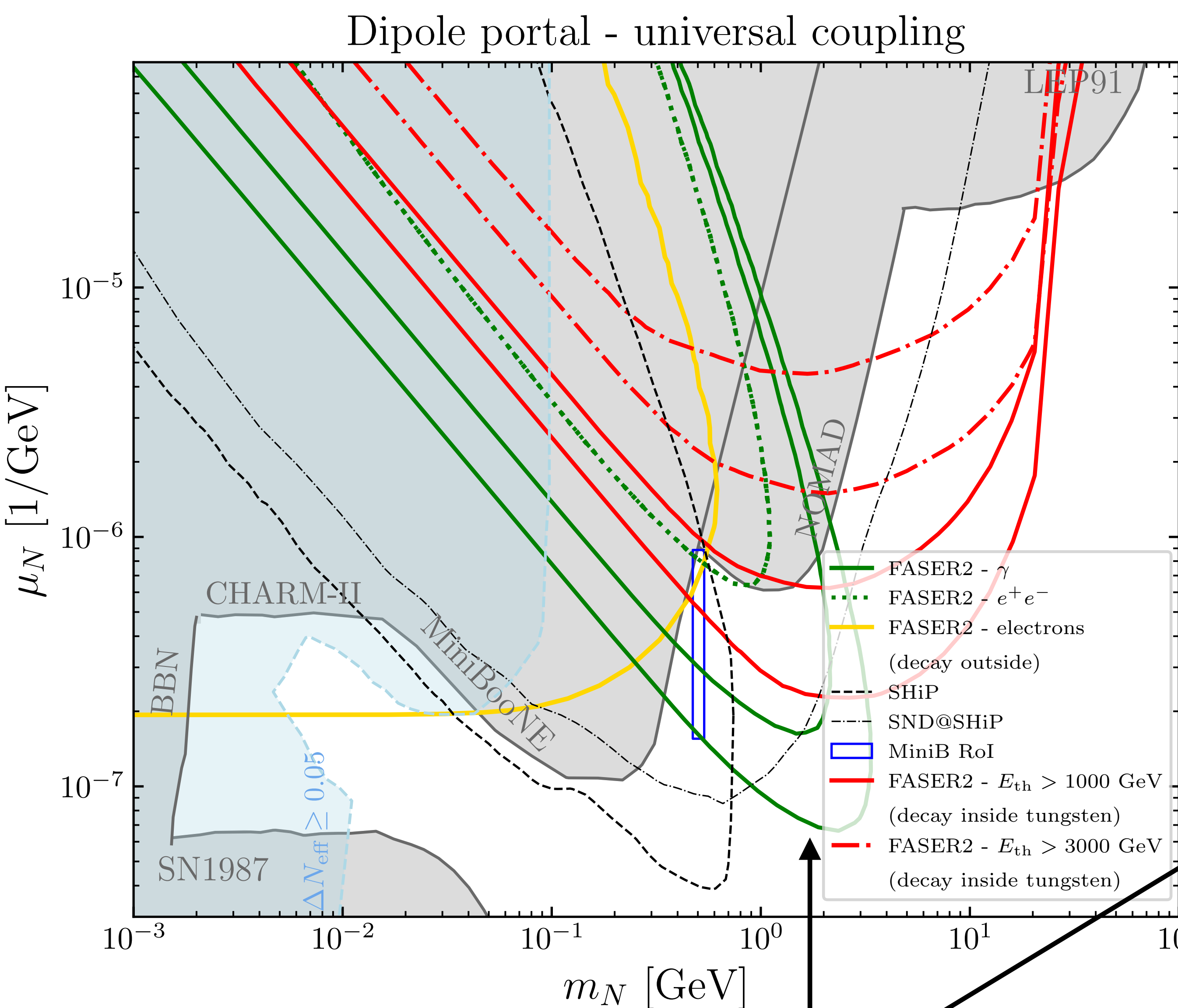
- Light Z_D mediator from dark gauge group $U(1)_D$ - dark neutrino model

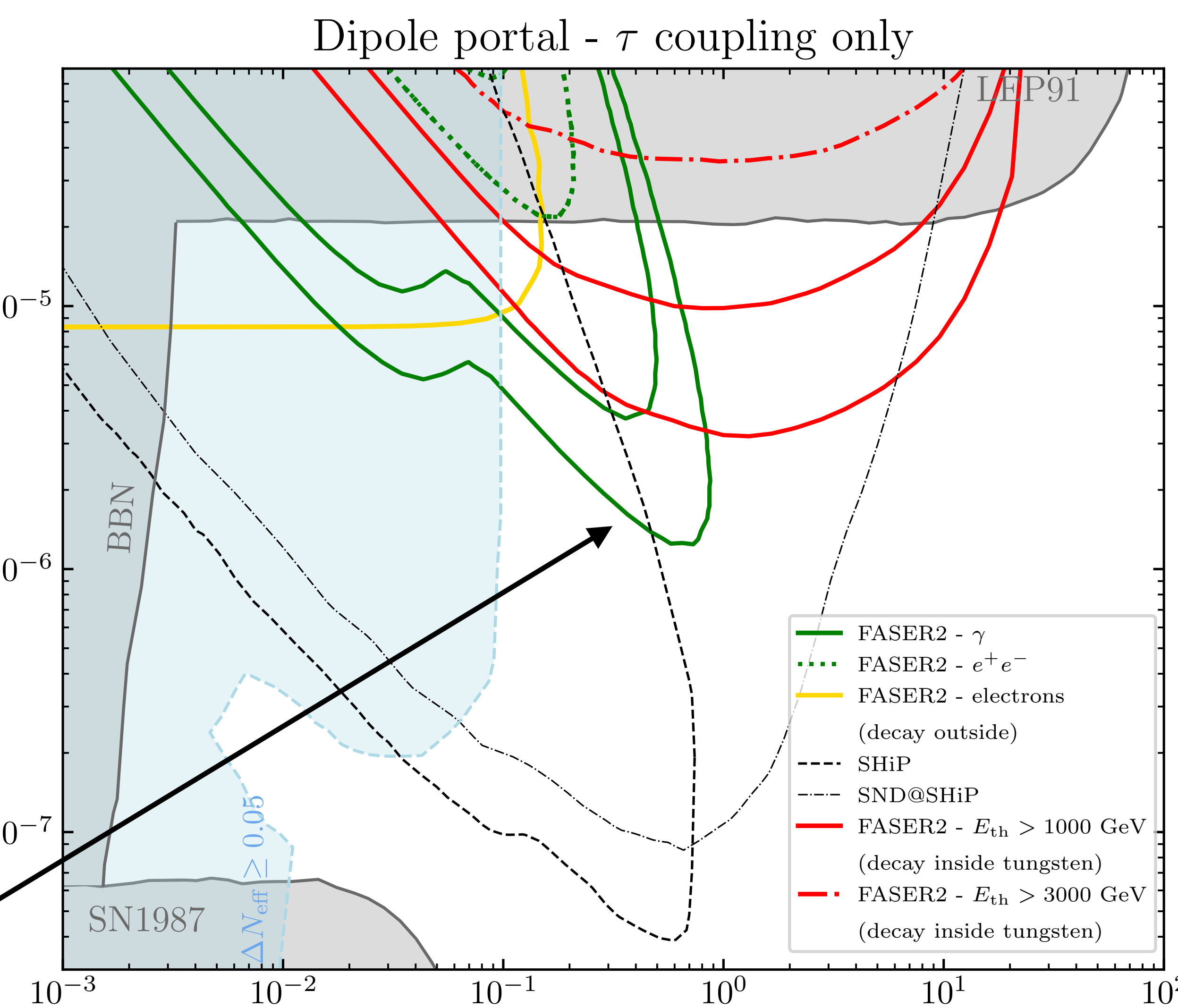
$$\mathscr{L}_D \supset \frac{m^2_{Z_D}}{2} Z_{D\mu} Z^\mu_D + g_D Z^\mu_D \bar{N}\gamma_\mu N + e\epsilon Z^\mu_D J^{\text{em}}_\mu,$$

MiniBooNE Anomaly, natural light m_ν generation

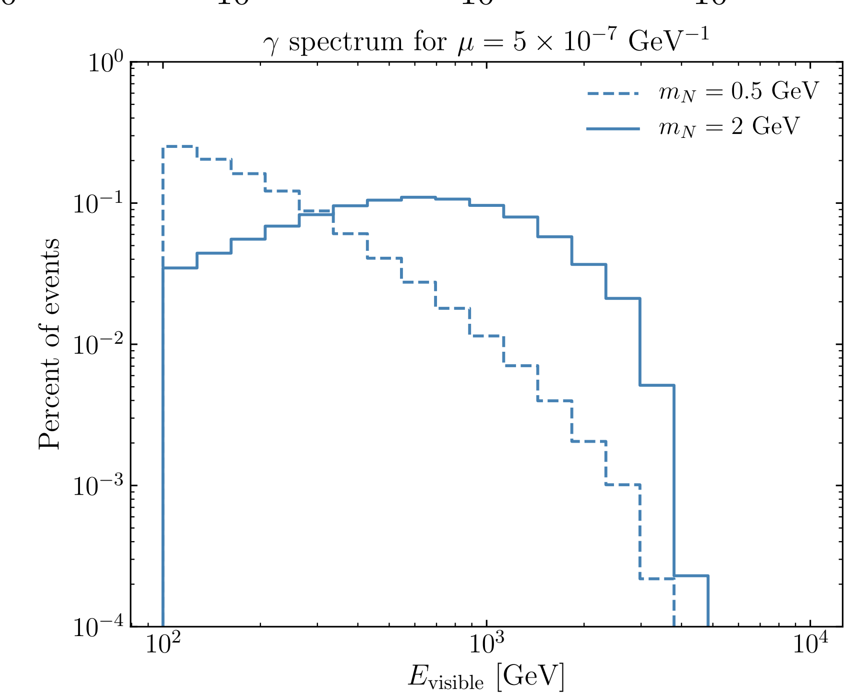
- Bertuzzo, Jana, Machado, Zukanovich Funchal 1807.09877, 1808.02500
- Argüelles, Hostert, Tsai, 1812.08768
- Ballett, Pascoli, Ross-Lonergan, 1808.02915
- Ballett, Hostert, Pascoli, 1903.07589

Neutrino magnetic moment



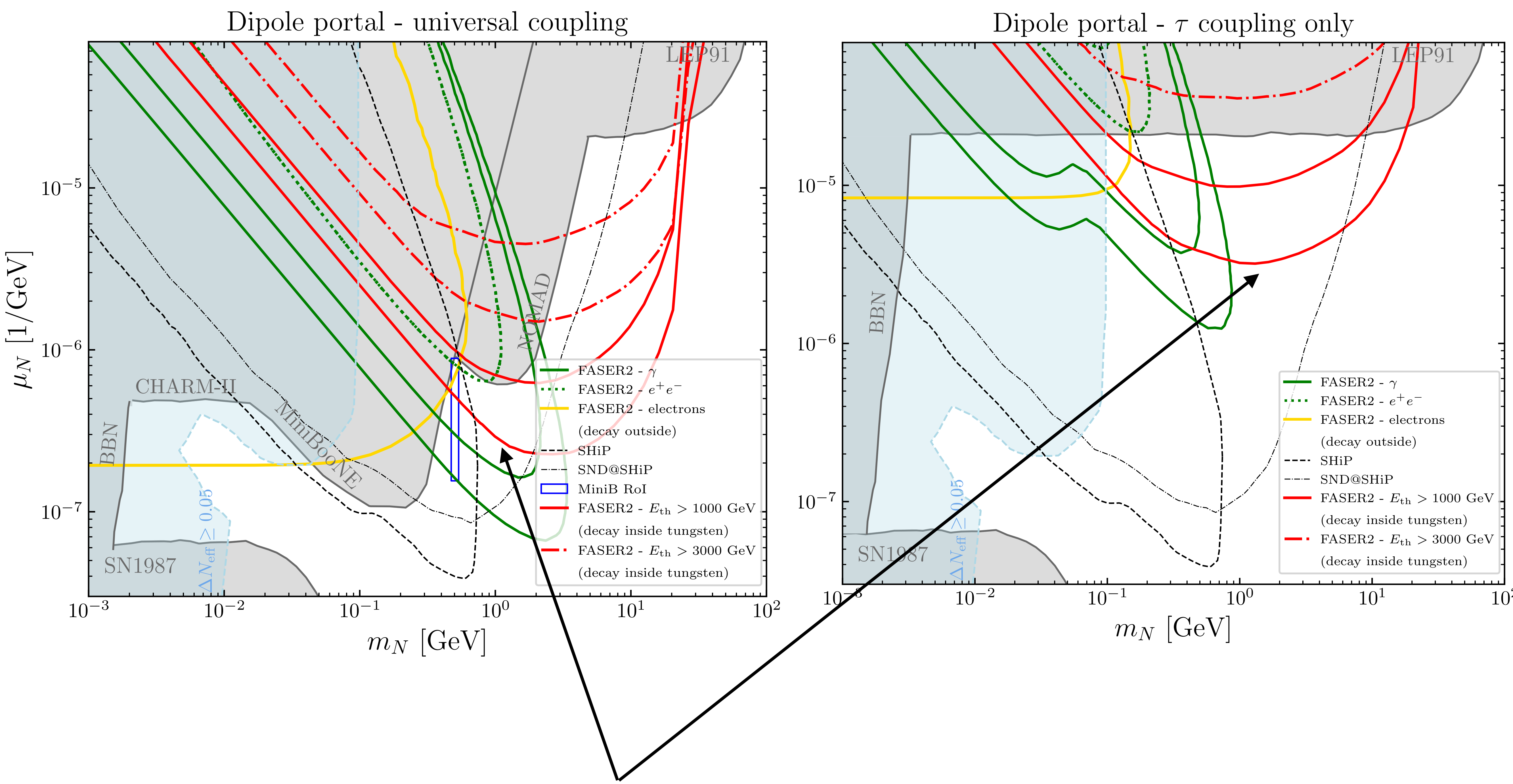


Upscattering $\nu X \to N X$ followed by LLP decay $N \to \nu\gamma$



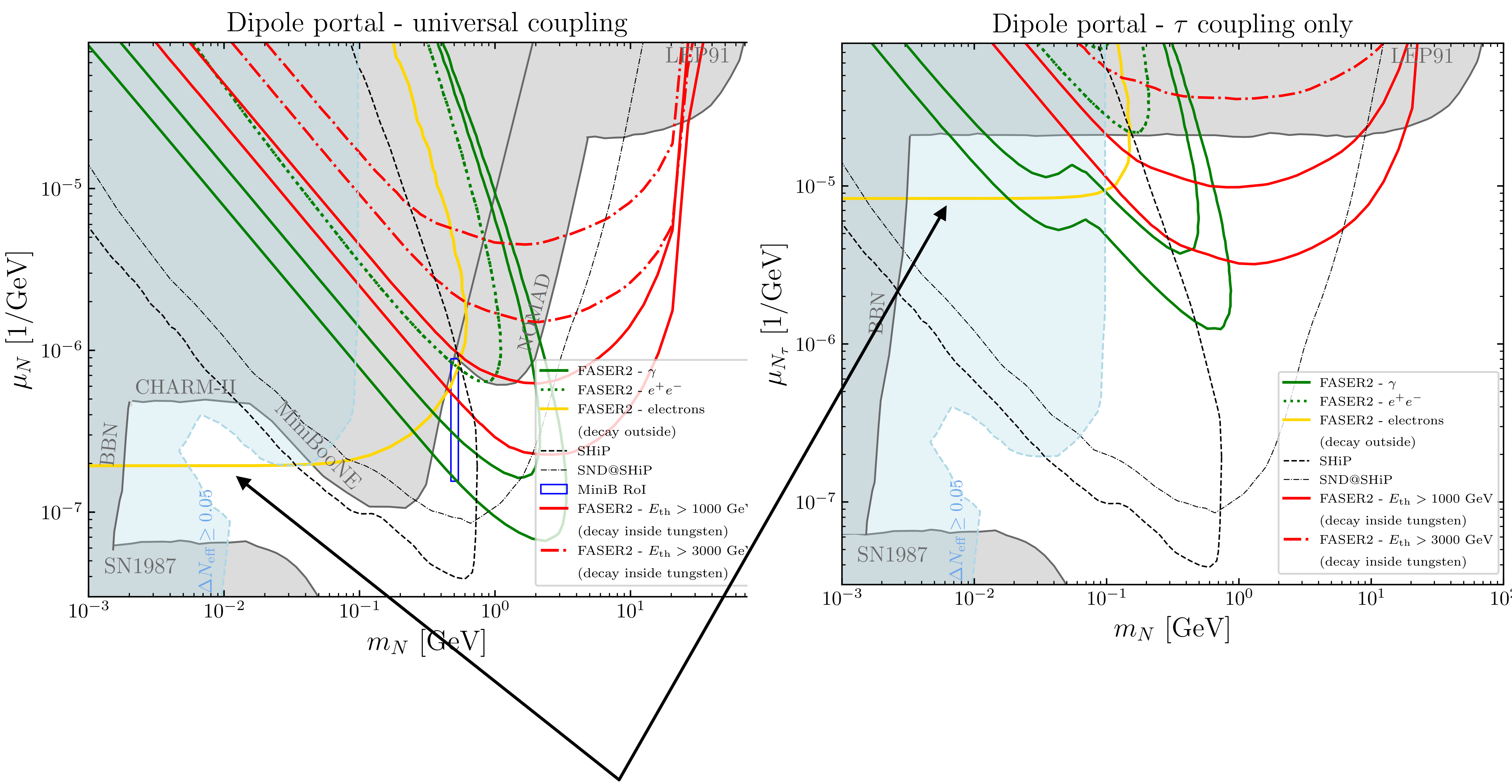
Spectrum of high-energy photons in the decay vessel

Neutrino magnetic moment



decays of high-energy LLPs inside ECC detector

Neutrino magnetic moment



scattering off electrons

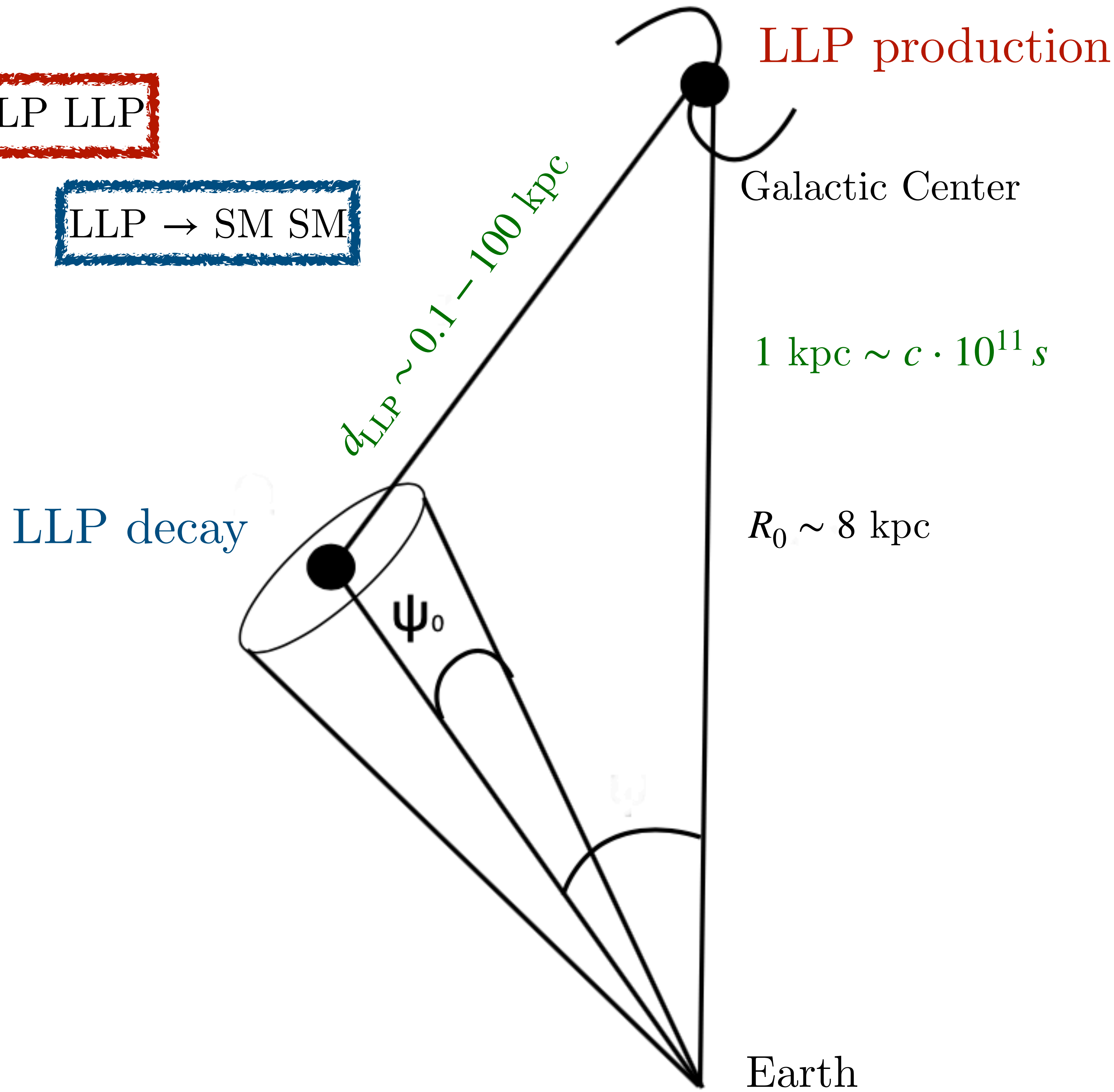
$$\nu e^- \rightarrow N e^-$$

Complementarity between FPF and ID of LLPs

ID of LLPs

DM DM → LLP LLP

LLP → SM SM



DM annihilating into LLP

Non-relativistic mediators
Rothstein, Schwetz, Zupan, 0903.3116

ID anomalies
Chu, Kulkarni, Salati, 1706.08543

DM DM → LLP LLP

LLP ($d_{\rm LLP} \sim 0.1 - 100$ kpc) → SM SM

$$\Phi_{\rm LLP} = \frac{\langle \sigma v \rangle_0}{8\pi m_{\rm DM}^2} \int_{\Delta\underline{\Omega}} d\underline{\Omega} \int_{\rm los} ds \int_{V_{\rm DM}} d^3\vec{r}_{\rm DM} \frac{\rho_{\rm DM}^2\left(|\vec{r}_{\rm DM} - \vec{d}\,|\right)}{\left|\vec{r}_{\rm LLP} - \vec{r}_{\rm DM}\right|^2} \frac{1}{d_{\rm LLP}} \exp\left(-\frac{\left|\vec{r}_{\rm LLP} - \vec{r}_{\rm DM}\right|}{d_{\rm LLP}}\right) \gamma(1-\beta\cos\theta) \frac{f(\theta)}{4\pi} \int_{\Delta E_\gamma} dE_\gamma \frac{dN}{dE_\gamma}$$

Survival probability of LLP

spectrum

DM density profile

Boost factor

Anisotropy function

Integral over all positions of DM that result in LLP decaying at $(s, \underline{\Omega})$.

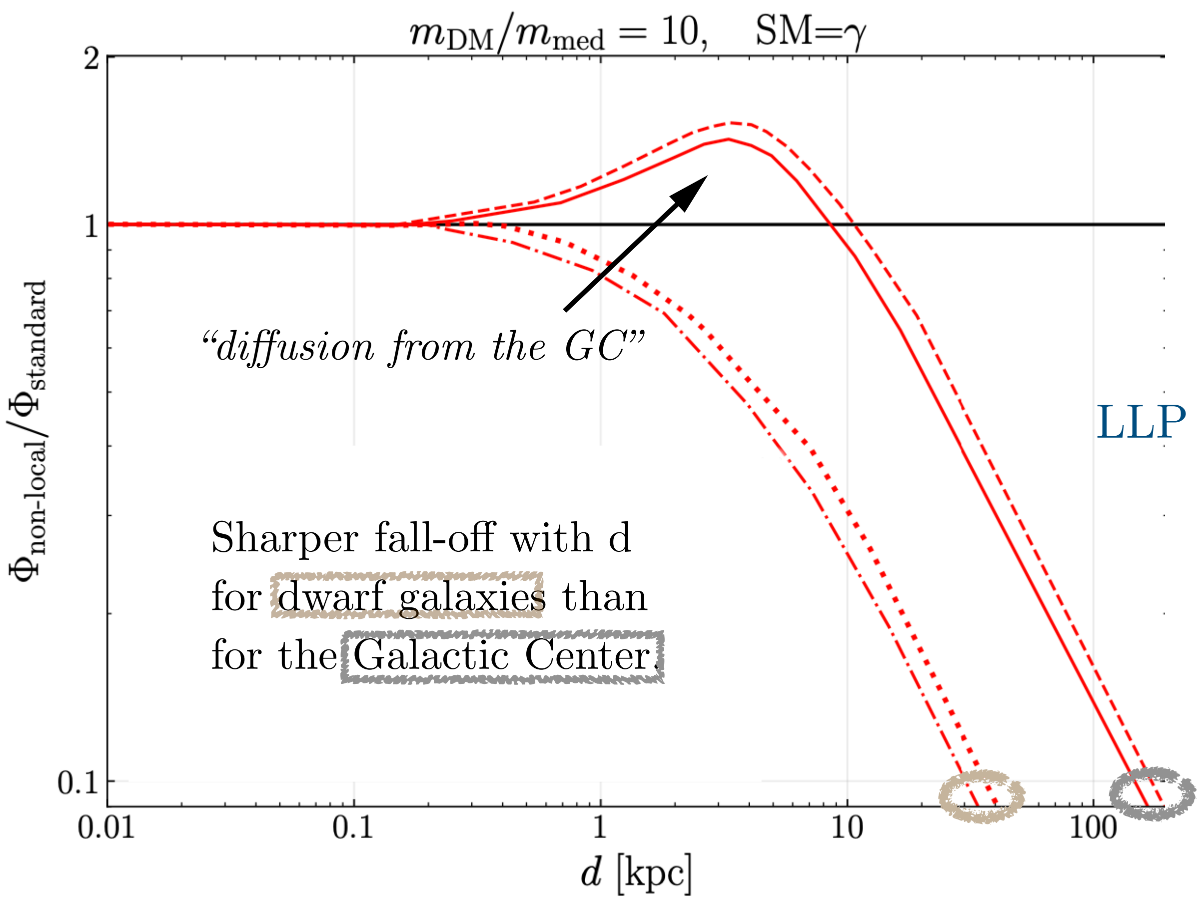
Integral over line of sight - position of LLP→ SM.

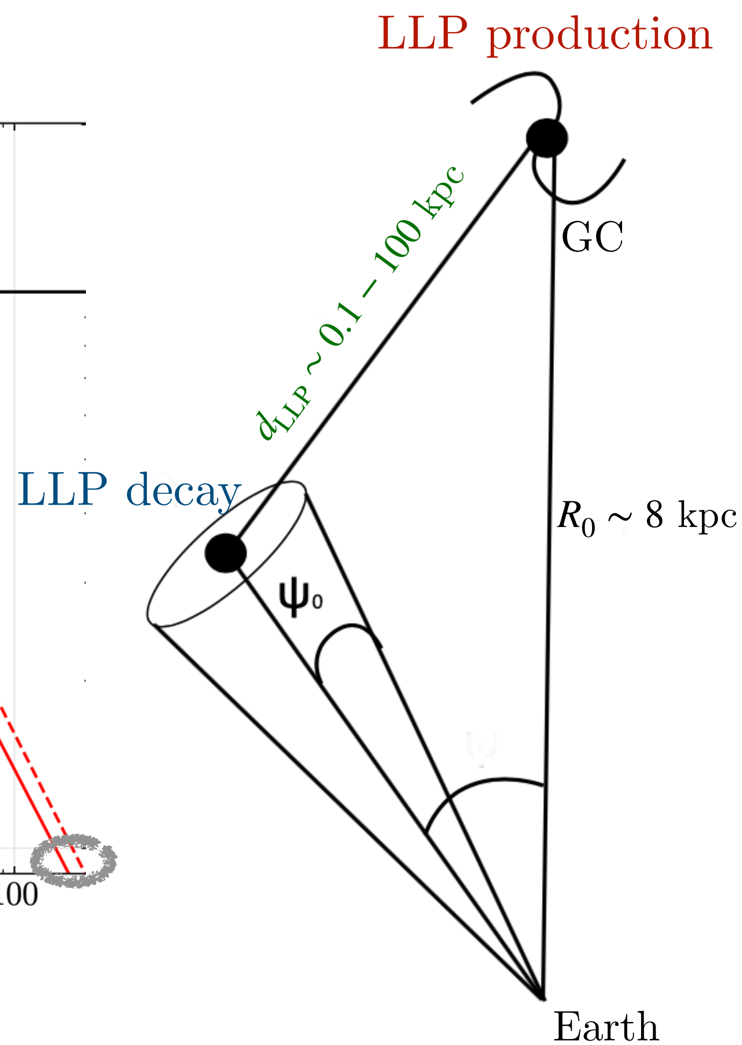
Formula for WIMP ID:

$$\Phi_{WIMP} = \frac{\langle \sigma v \rangle_0}{8\pi m_{\rm DM}^2} \left(\int_{\Delta\Omega} d\Omega \int_{\rm los} \rho_{\rm DM}^2 ds\right) \times \left(\int_{\Delta E_\gamma} dE_\gamma \frac{dN_\gamma^X}{dE_\gamma}\right)$$

For LLPs there is no direct relationship between $\Phi_{\rm LLP}(\vec{r}_0)$ and $\rho_{\rm DM}^2(\vec{r}_0)$.

Non-local ID effects



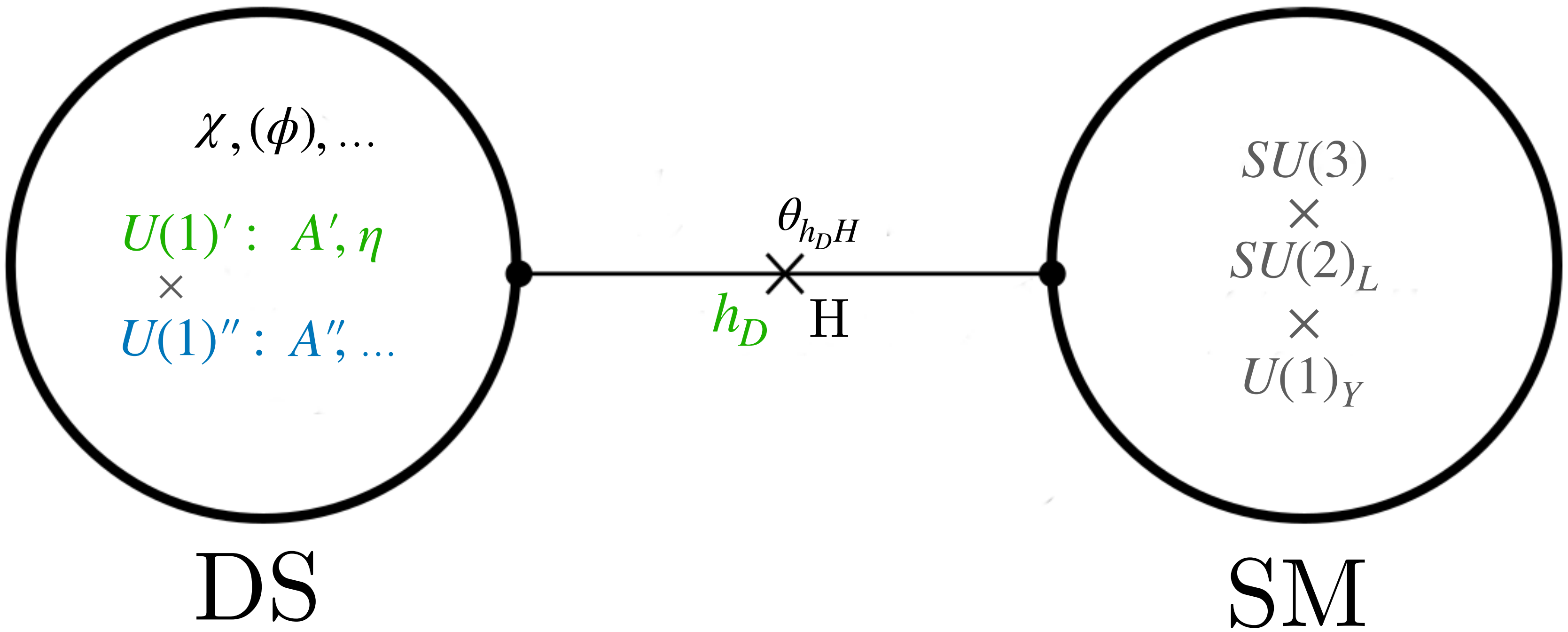


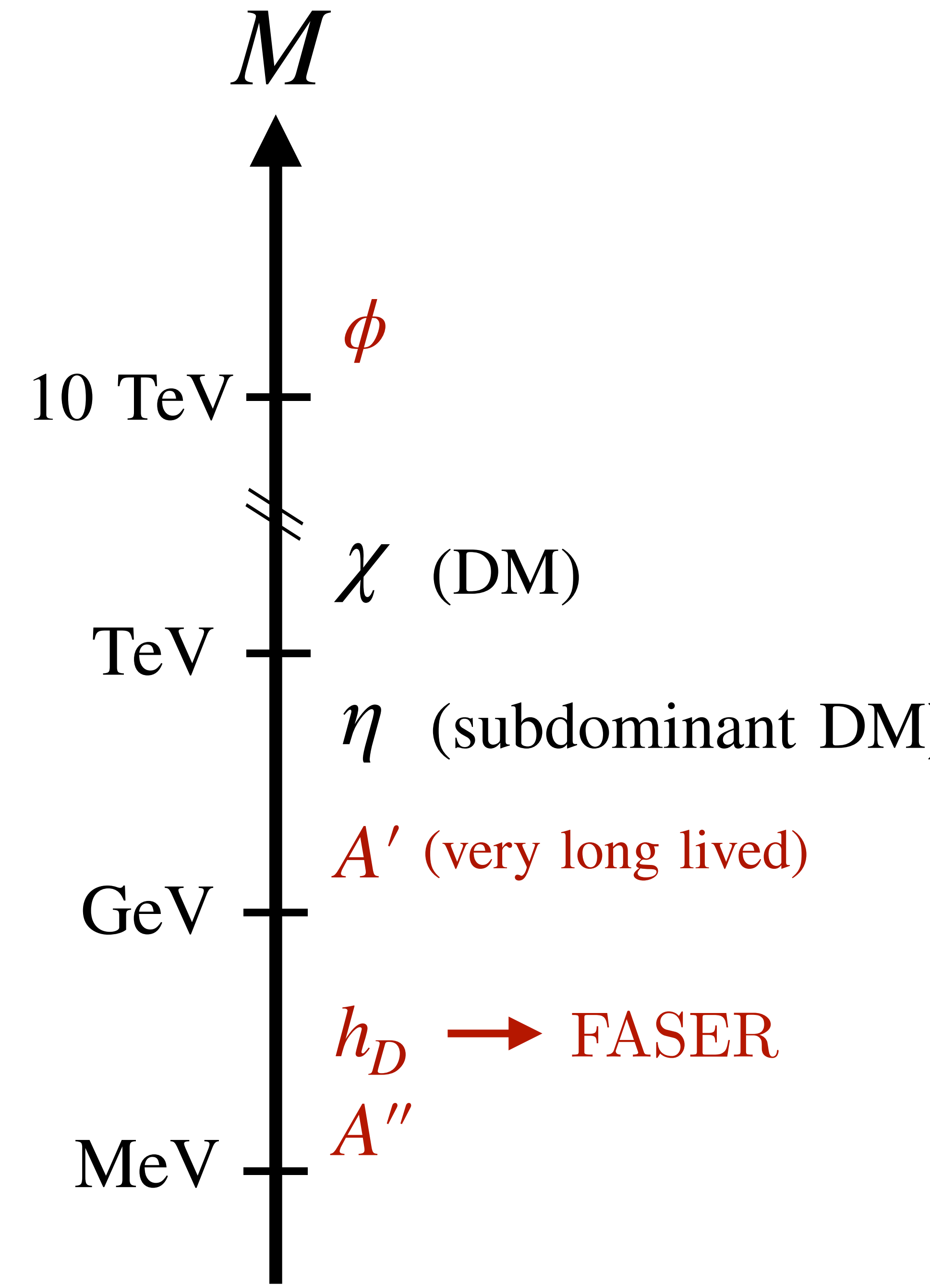
"diffusion from the GC"

Additional contribution due to LLPs that are produced near the GC and decay by emitting photons along los.

For a fixed observational angle θ, min distance from the los to GC is $l_{min} = R_0 \sin\theta = (8 \sin\theta)$ kpc. If $d \sim l_{min}$, there is enhanced contribution coming from the GC.

Heavy DM & LLP





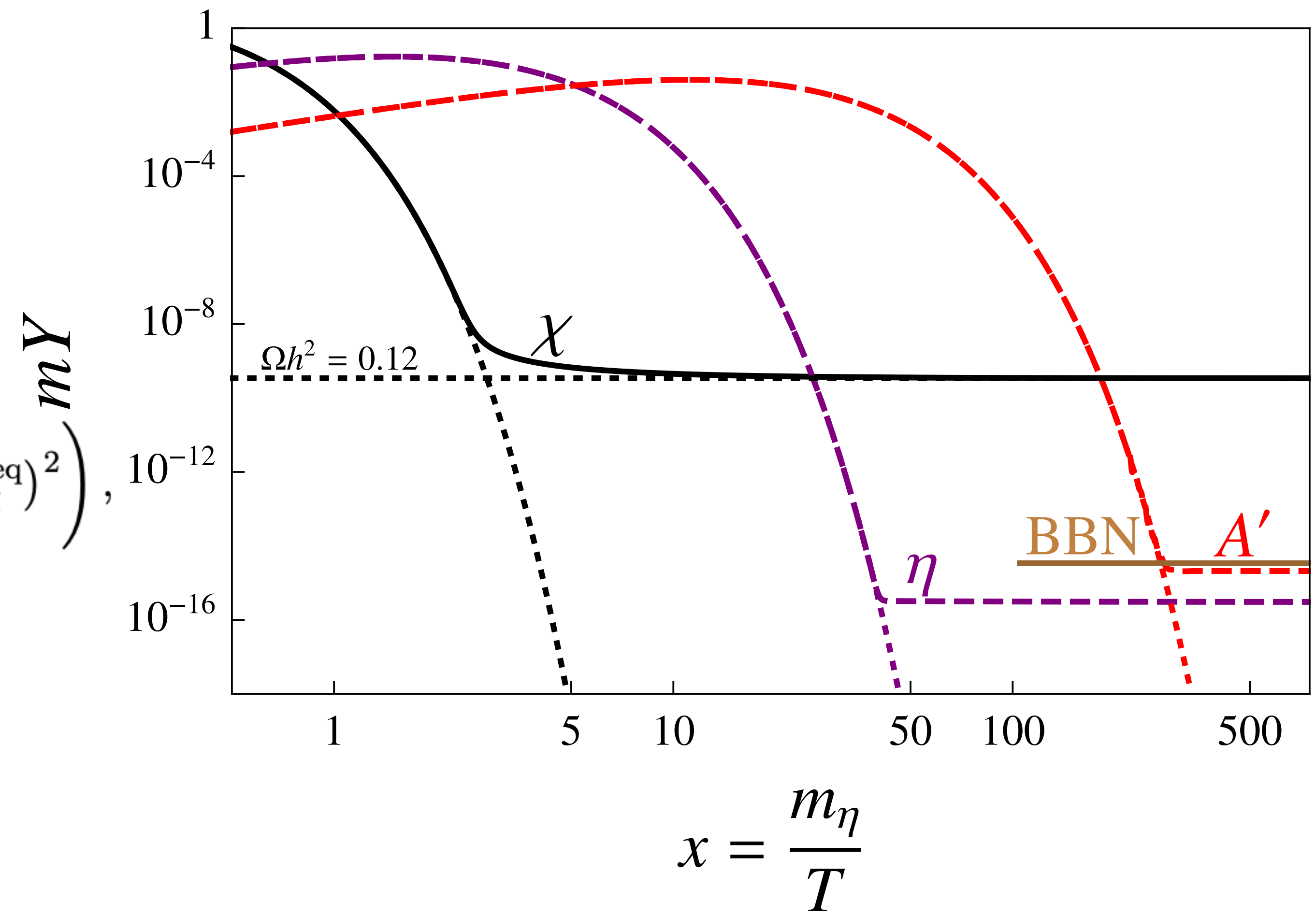
The DM consists of complex scalars χ, η which are connected by a heavy auxiliary field ϕ.

χ *annihilates within the dark sector* in such way that $\Omega_\chi h^2 \sim 0.1 \gg \Omega_\eta h^2$.

↓

CMB bounds evaded

Thermal history impact on ID



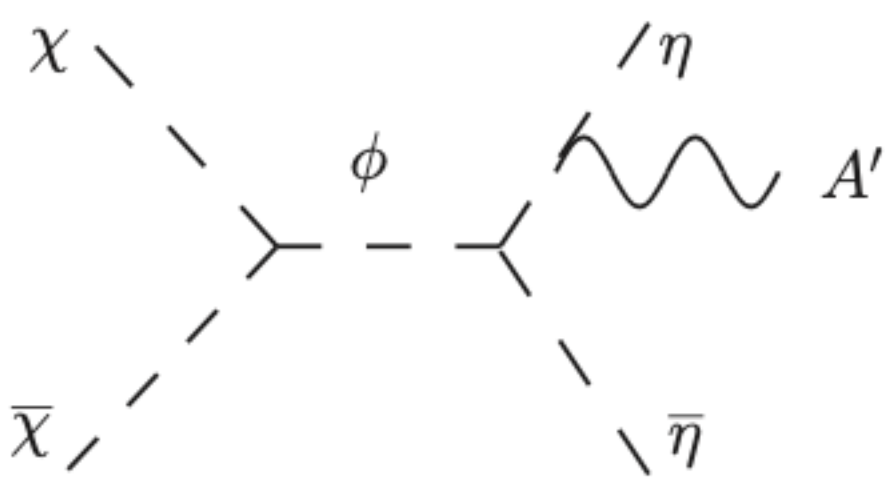
Relic density

$$\frac{dY_\chi}{dx} = -\frac{\lambda_\chi}{x^2}\left(Y_\chi^2 - \frac{Y_\eta^2}{(Y_\eta^{\rm eq})^2}(Y_\chi^{\rm eq})^2\right),$$

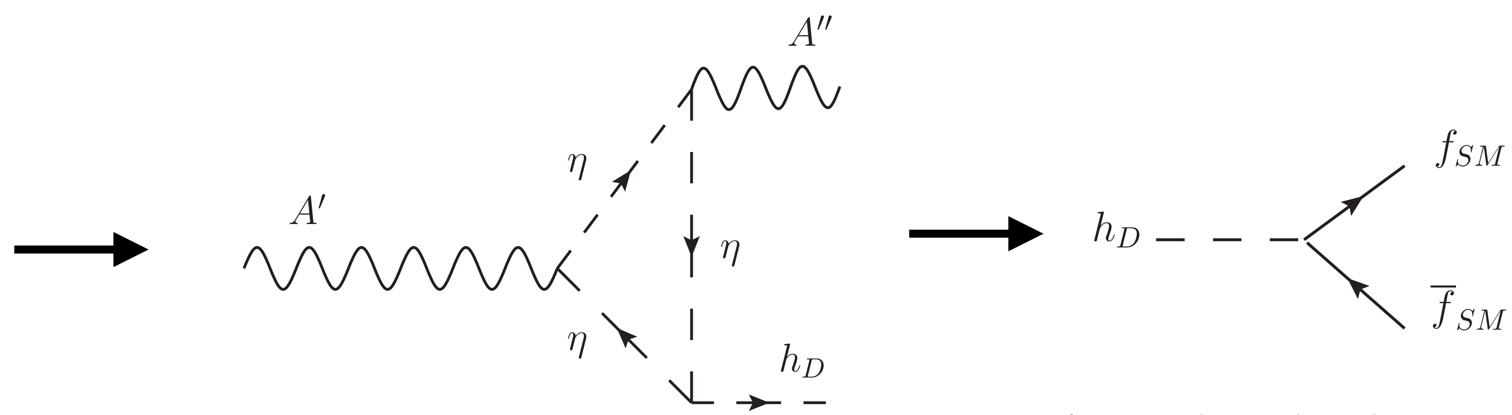
$$\frac{dY_\eta}{dx} = -\frac{\lambda_\eta}{x^2}\left(Y_\eta^2 - (Y_\eta^{\rm eq})^2\frac{Y_{A'}^2}{(Y_{A'}^{\rm eq})^2}\right) + \frac{\lambda_\chi}{x^2}\left(Y_\chi^2 - \frac{Y_\eta^2}{(Y_\eta^{\rm eq})^2}(Y_\chi^{\rm eq})^2\right),$$

$$\frac{dY_{A'}}{dx} = \frac{\lambda_\eta}{x^2}\left(Y_\eta^2 - (Y_\eta^{\rm eq})^2\frac{Y_{A'}^2}{(Y_{A'}^{\rm eq})^2}\right) - \frac{\lambda_{A'}}{x^2}\left(Y_{A'}^2 - (Y_{A'}^{\rm eq})^2\right),$$

Indirect Detection



$\chi\chi \to \eta\eta A'$



A' is LLP naturally due to loop-suppressed decay

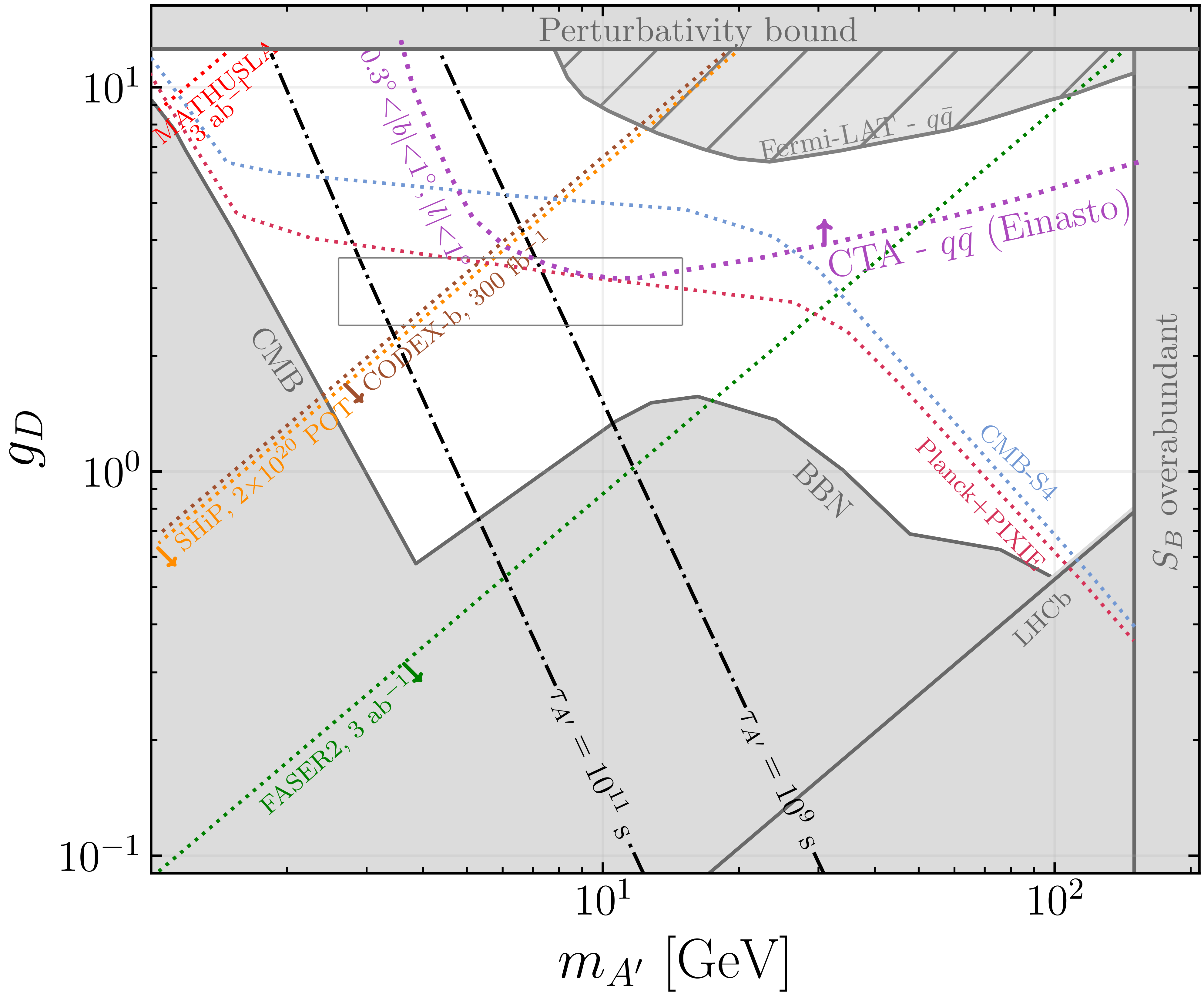
h_D is short lived

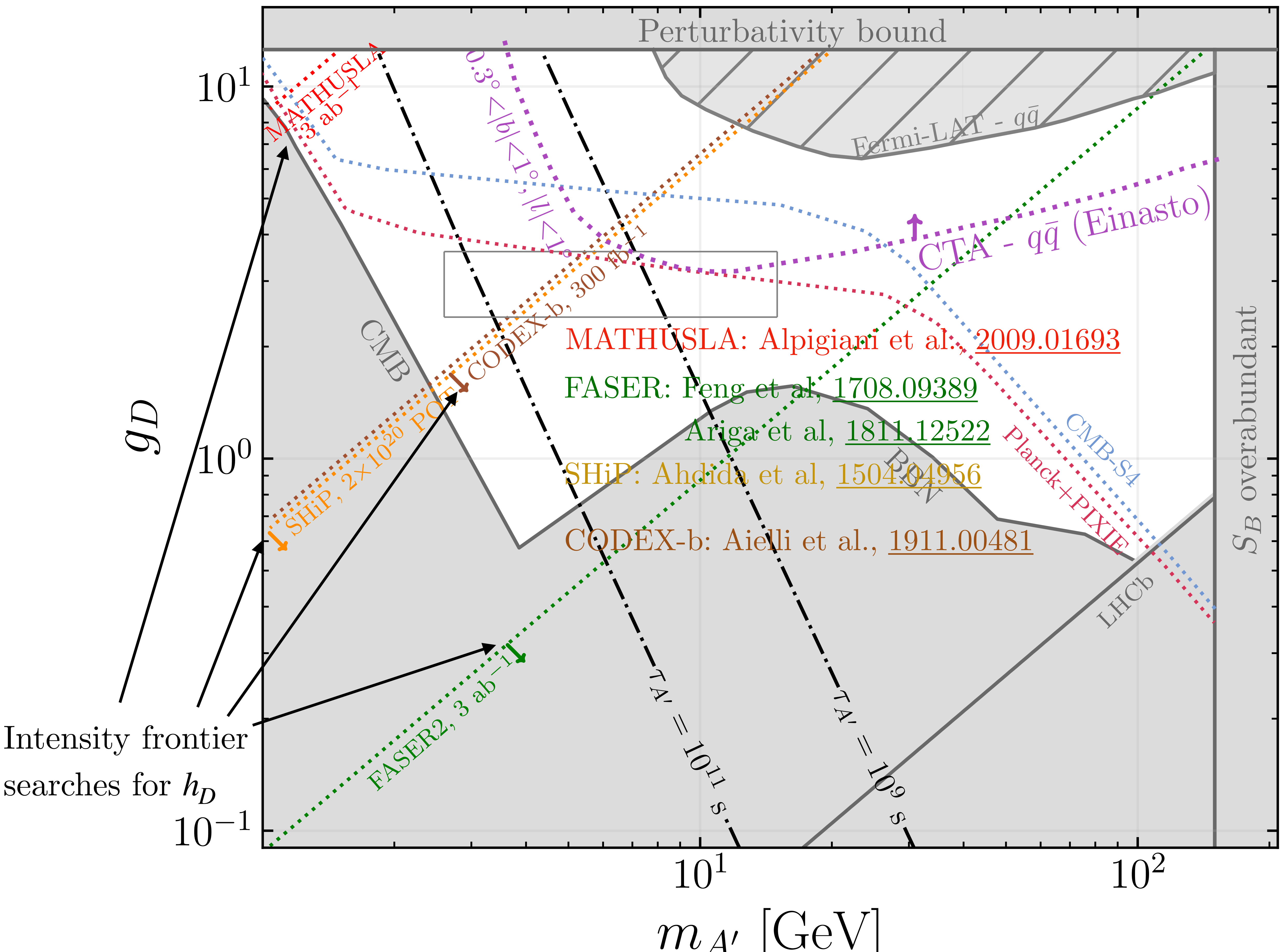
m_{h_D} determines $\frac{dN}{dE_\gamma}$

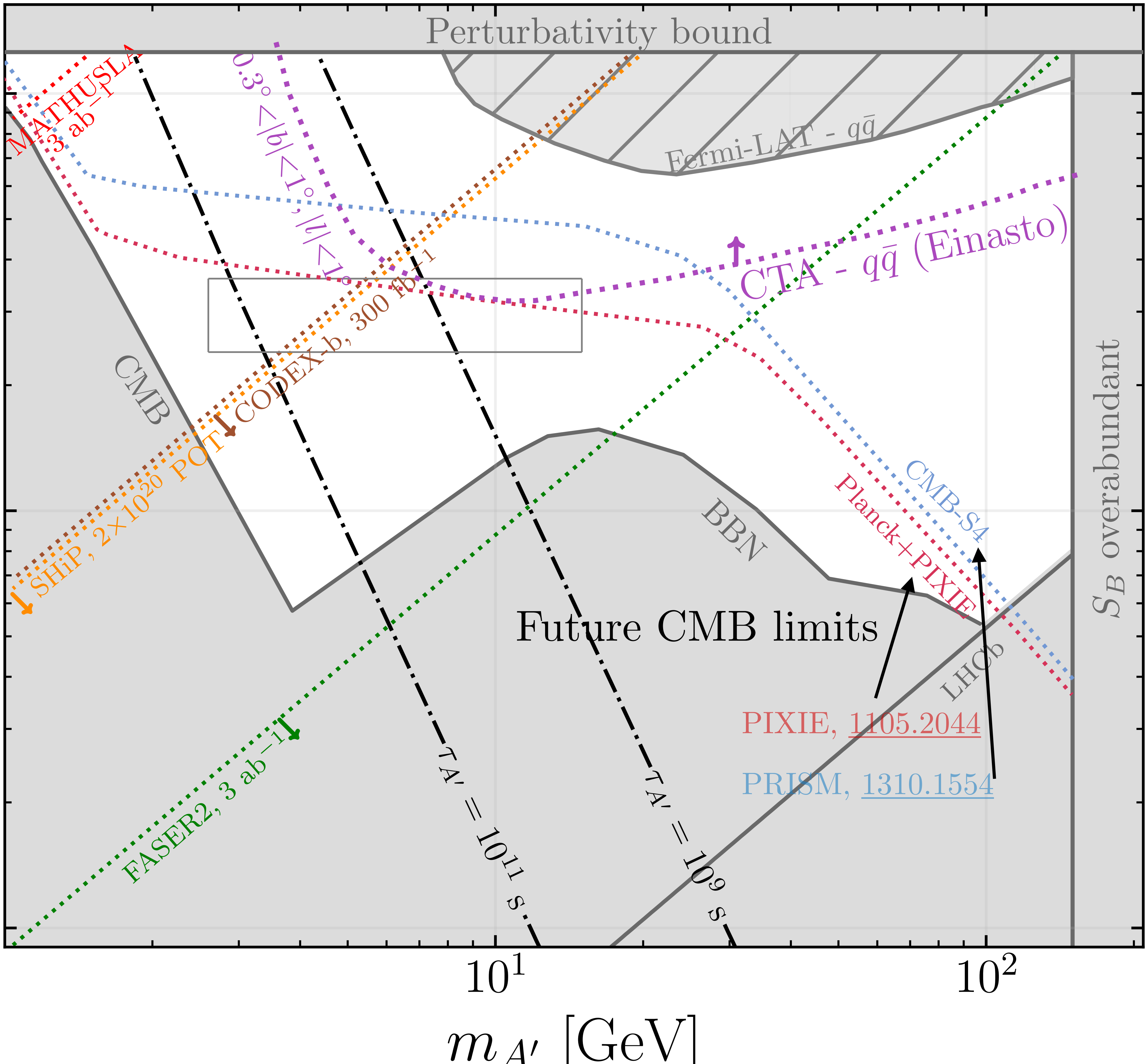
$A' \to A''\, h_D$ $\quad$ $h_D \to$ SM SM

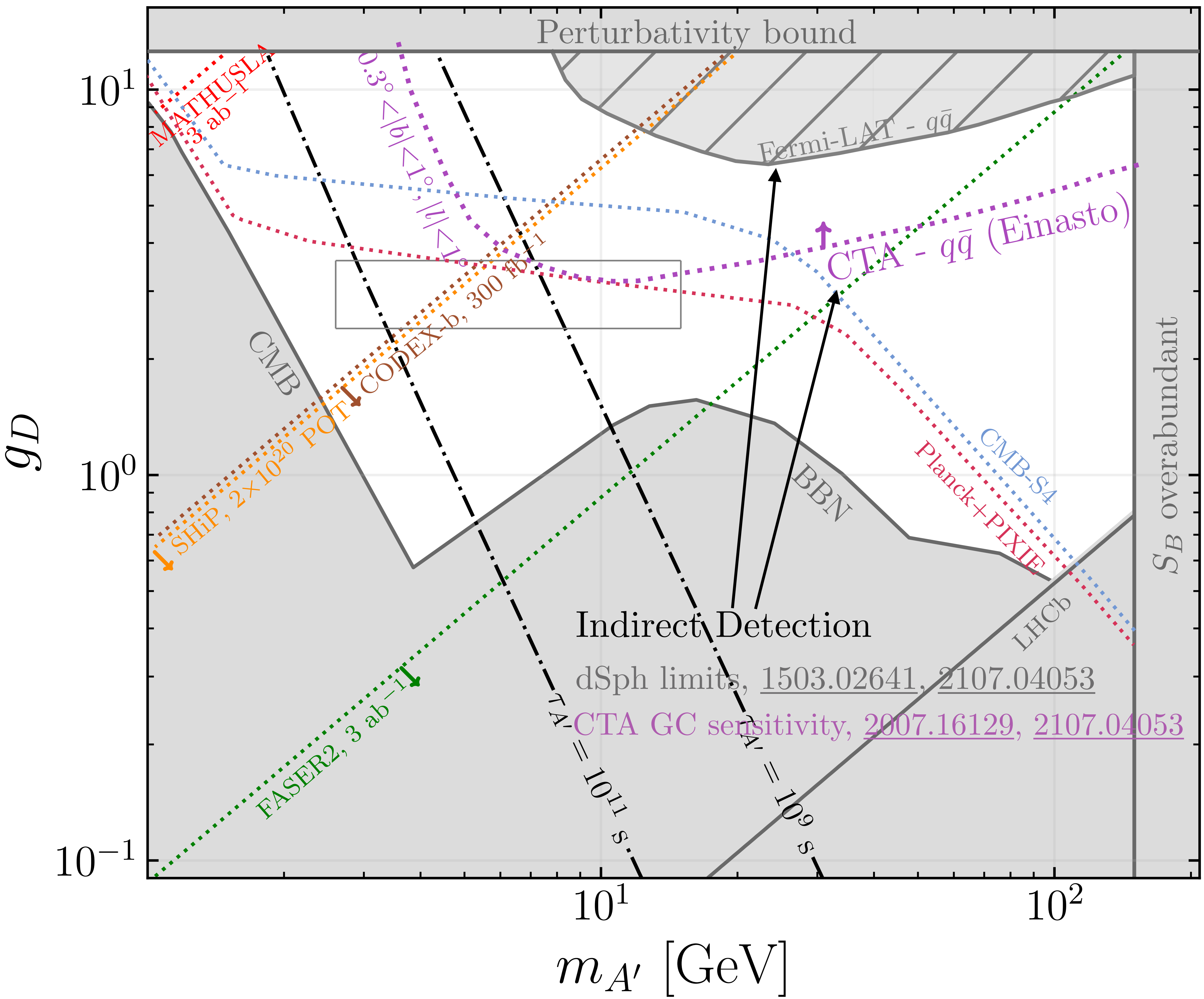
Indirect Detection & Intensity Frontier

searches for LLPs - complementarity

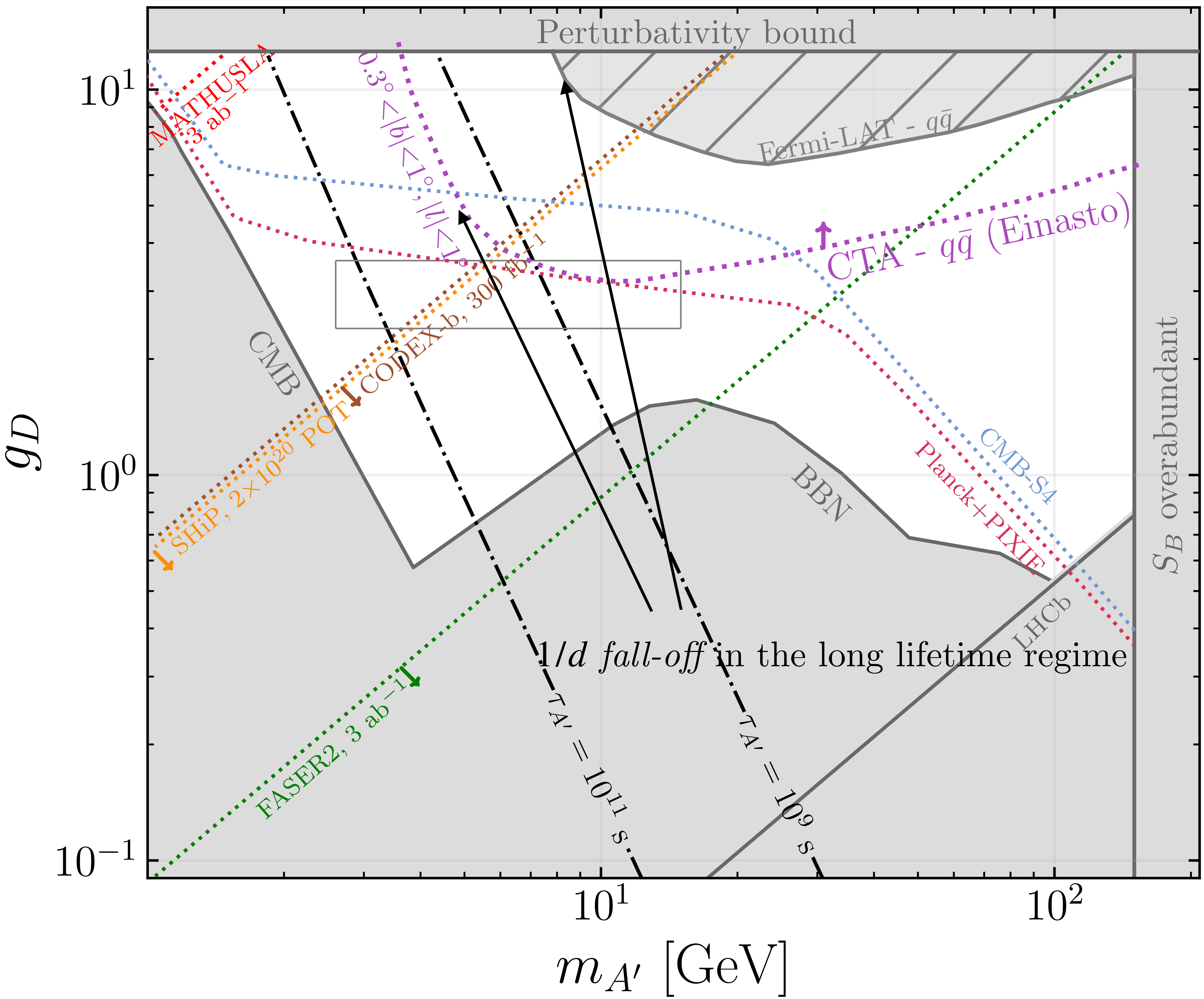



Perturbativity bound
Fermi-LAT - $q\bar{q}$
CTA - $q\bar{q}$ (Einasto)
$0.3° < |b| < 1°, |l| < 1°$
MATHUSLA 3 ab^{-1}
CODEX-b, 300 fb^{-1}
SHiP, 2×10^{20} POT
FASER2, 3 ab^{-1}
CMB
BBN
LHCb
CMB-S4
Planck+PIXIE
S_B overabundant
$\tau_{A'} = 10^{11}$ s
$\tau_{A'} = 10^{9}$ s
MATHUSLA: Alpigiani et al., 2009.01693
FASER: Feng et al, 1708.09389
Ariga et al, 1811.12522
SHiP: Ahdida et al, 1504.04956
CODEX-b: Aielli et al., 1911.00481
Intensity frontier searches for h_D
g_D
$m_{A'}$ [GeV]

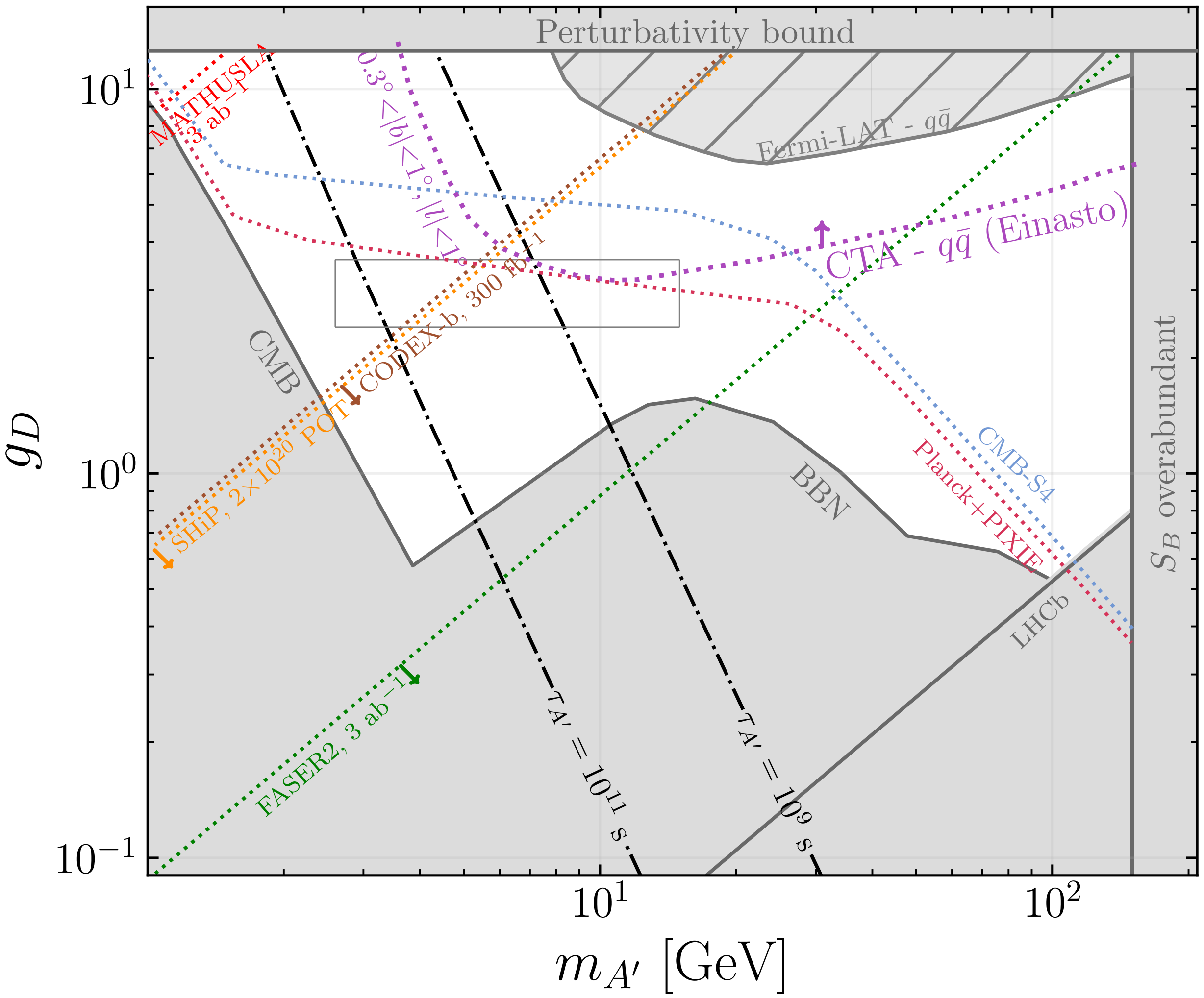

Perturbativity bound
MATHUSLA 3 ab−1
$0.3° < |b| < 1°, |l| < 1°$
Fermi-LAT - $q\bar{q}$
CTA - $q\bar{q}$ (Einasto)
CODEX-b, 300 fb−1
SHiP, 2×10^20 POT
CMB
BBN
CMB-S4
Planck+PIXIE
Future CMB limits
LHCb
S_B overabundant
$\tau_{A'} = 10^{11}$ s
$\tau_{A'} = 10^{9}$ s
FASER2, 3 ab−1
PIXIE, 1105.2044
PRISM, 1310.1554
g_D
$m_{A'}$ [GeV]

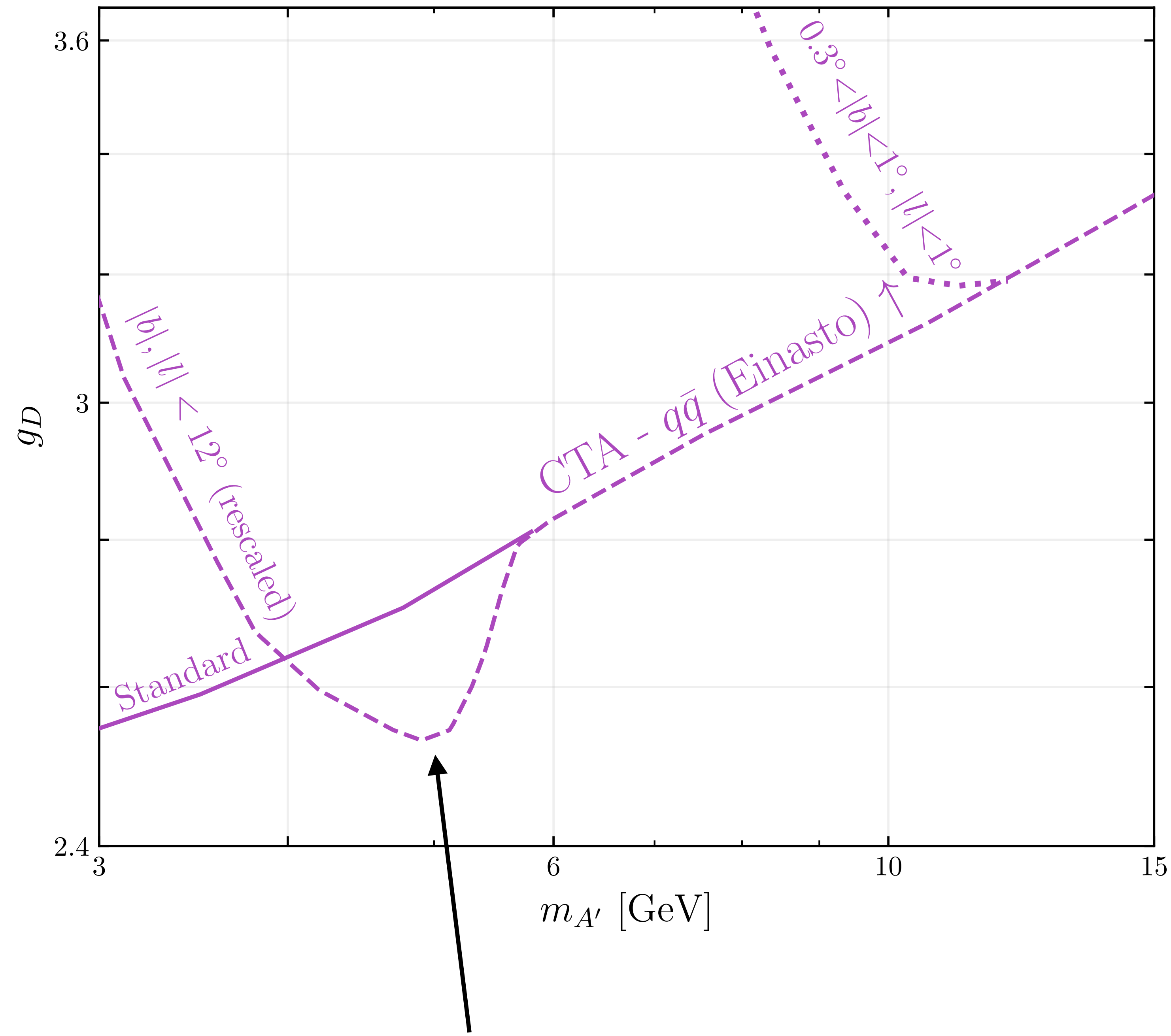


Perturbativity bound
Fermi-LAT - $q\bar{q}$
MATHUSLA, 3 ab^{-1}
$0.3° < |b| < 1°, |l| < 1°$
CTA - $q\bar{q}$ (Einasto)
CODEX-b, 300 fb^{-1}
SHiP, 2×10^{20} POT
CMB
BBN
CMB-S4
Planck+PIXIE
S_B overabundant
LHCb
FASER2, 3 ab^{-1}
$\tau_{A'} = 10^{11}$ s
$\tau_{A'} = 10^{9}$ s
Indirect Detection
dSph limits, 1503.02641, 2107.04053
CTA GC sensitivity, 2007.16129, 2107.04053
g_D
$m_{A'}$ [GeV]



Perturbativity bound
Fermi-LAT - $q\bar{q}$
CTA - $q\bar{q}$ (Einasto)
$0.3° < |b| < 1°, |l| < 1°$
MATHUSLA
3 ab^{-1}
CODEX-b, 300 fb^{-1}
SHiP, 2×10^{20} POT
CMB
BBN
CMB-S4
Planck+PIXIE
LHCb
S_B overabundant
FASER2, 3 ab^{-1}
$1/d$ *fall-off* in the long lifetime regime
$\tau_{A'} = 10^{11}$ s
$\tau_{A'} = 10^{9}$ s
g_D
$m_{A'}$ [GeV]





peak due to *"diffusion from the GC"*

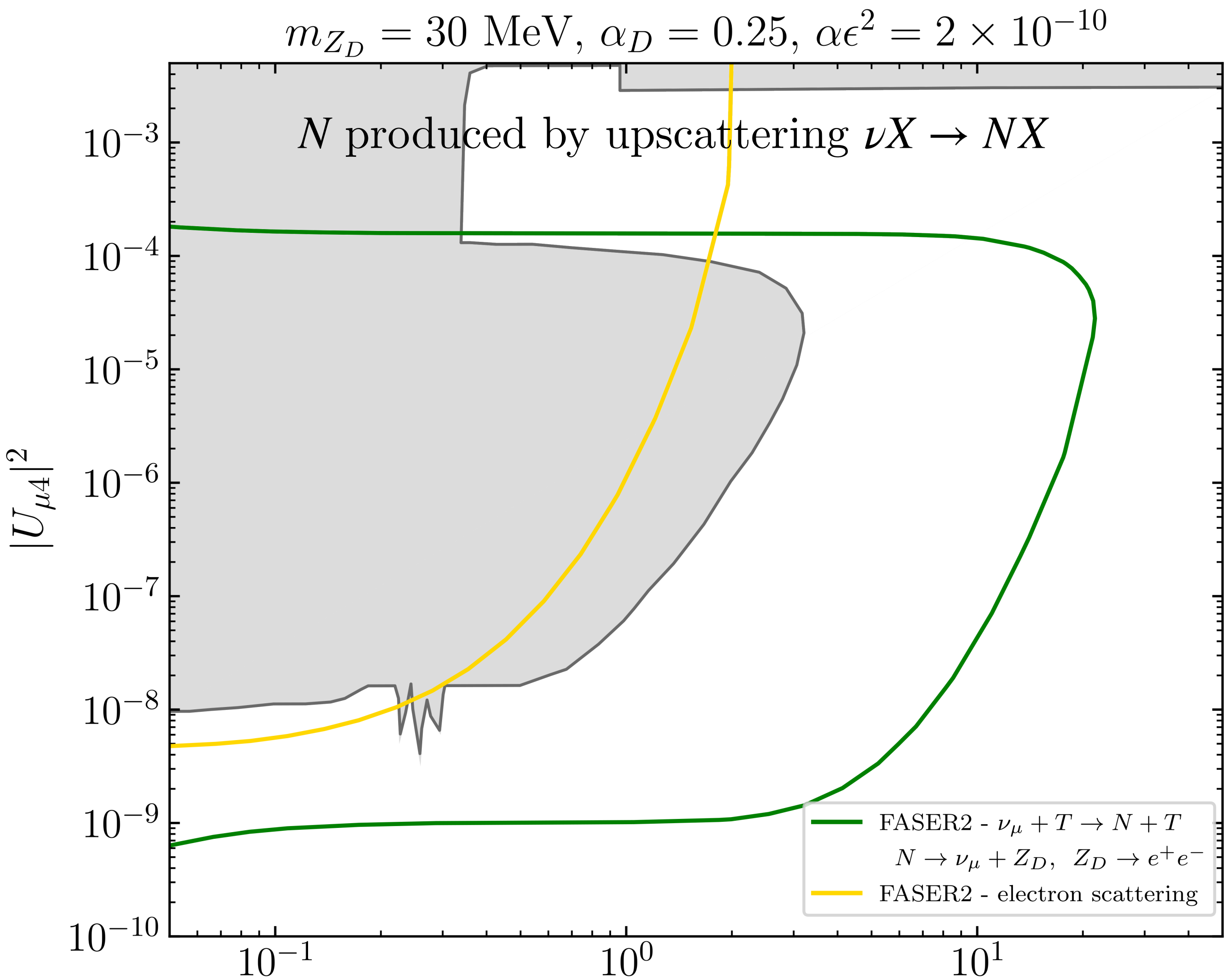
Conclusions

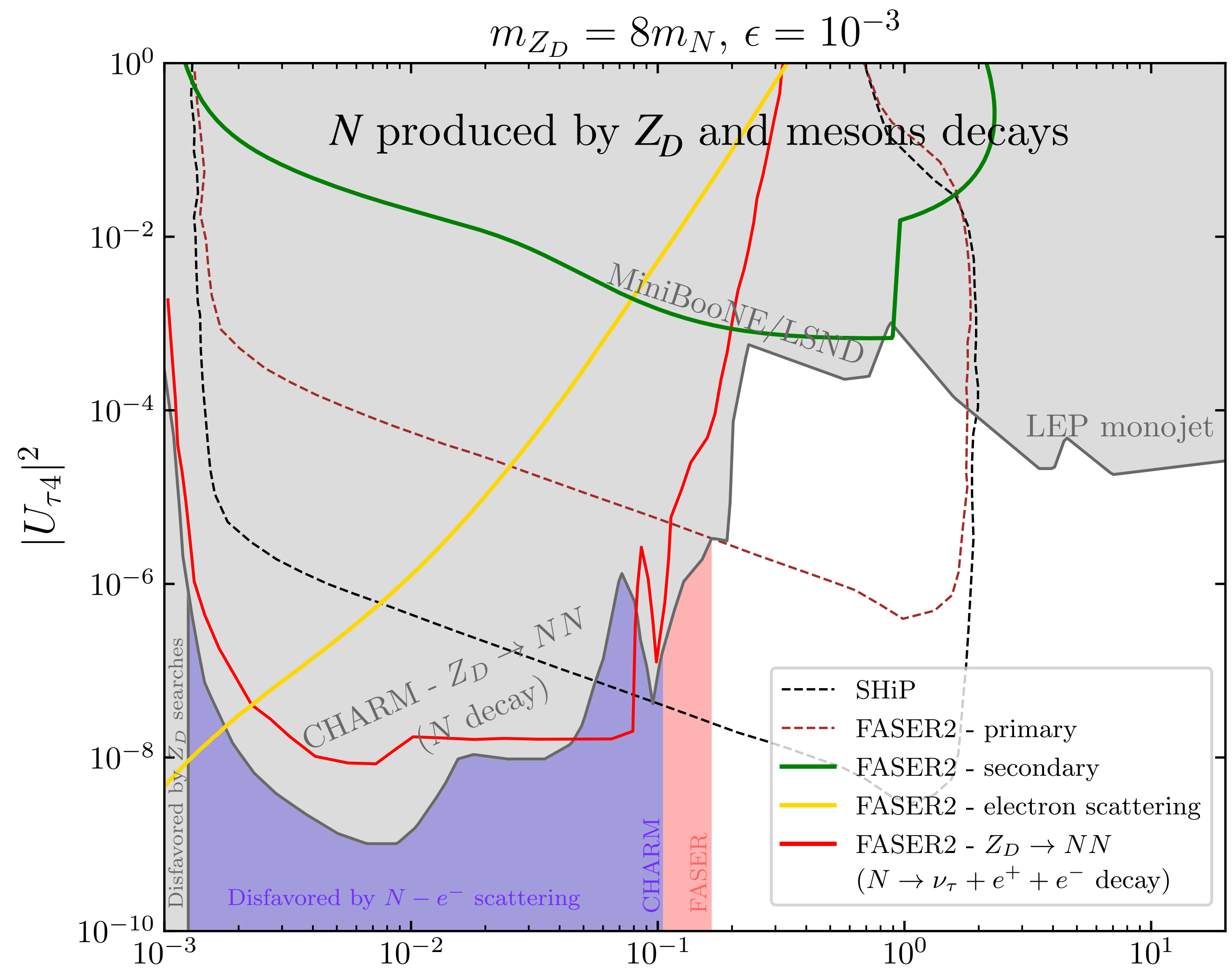
- Realistic BSM scenarios often predict more than one LLP, so that secondary LLP production can take place right in front of the detector, extending the sensitivity to shorter lifetimes, employing several experimental signatures:
    - standard search for two high-energy oppositely-charged tracks
    - the single-electron scattering signature
    - the search for high-energy photons appearing in the detector.

- We also studied
    - indirect detection of LLPs, which introduce distinct non-local effects
    - intensity frontier searches for a light mediator
- The complementarity between them will allow to probe even more extended scenario invoking heavy DM, LLPs and a light mediator.

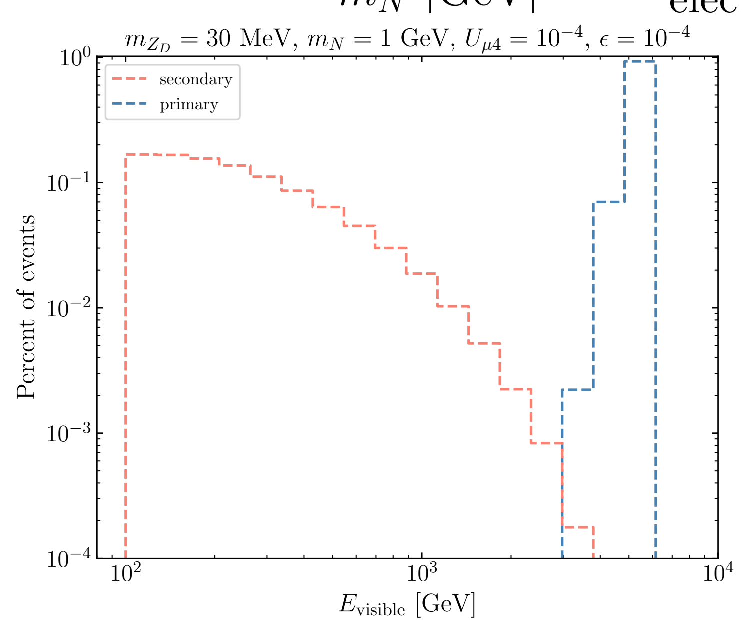
Light Z_D mediator

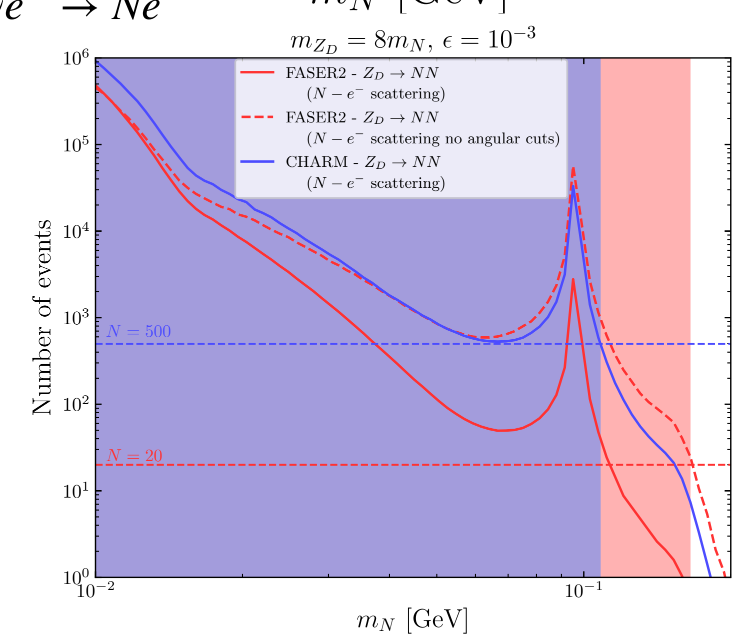
$m_{Z_D} < m_N$ $\quad$ $m_{Z_D} > m_N$





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

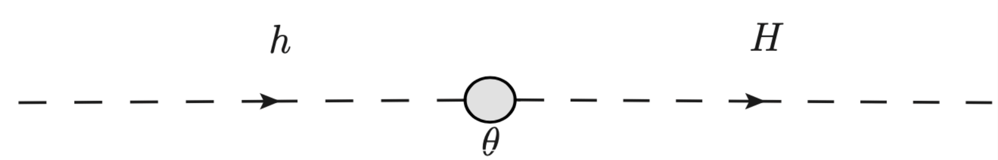




Mediators - dark Higgs h_D & dark photon A'

$$\mathcal{L}_{\text{portal}} = -\lambda_{hh_D}|\Phi|^2|\sigma|^2 - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$

After spontaneous symmetry breaking, h and h_D mix



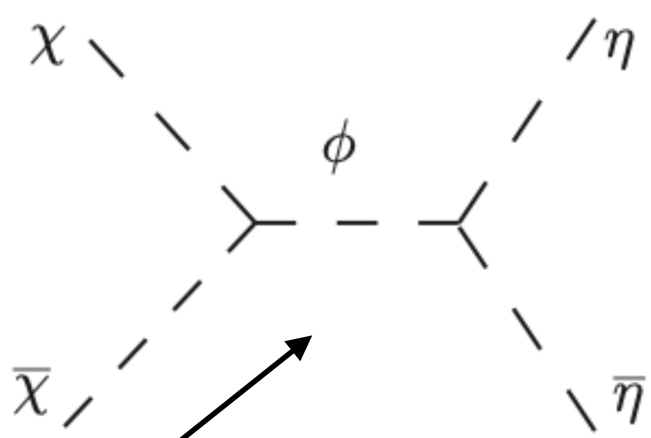
which connects DS to SM. Indirect detection signature due to $h_D \to$ SM SM.

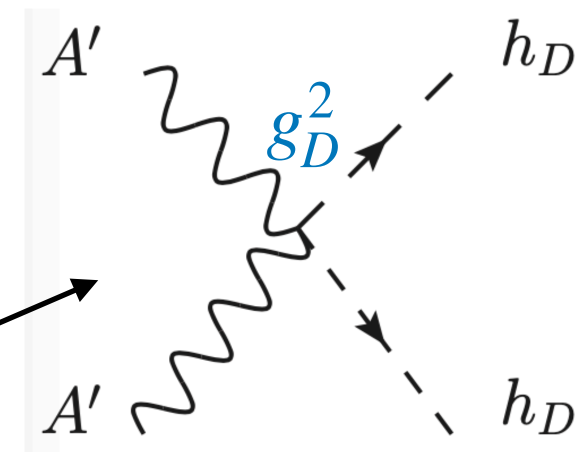
$$\Phi = \left(0, (v_h + H)/\sqrt{2}\right)^T, \quad \sigma = (v_\text{D} + H_\text{D})/\sqrt{2}$$

Moreover, *dark photon obtains mass* $m_{A'} = g_D v_D$, $m_{h_D} = \sqrt{\lambda_D} v_D$

Matter fields - two component DM

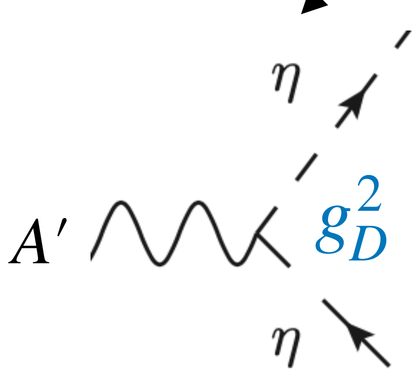
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{\rm DS} + \mathscr{L}_{\rm portal}$$



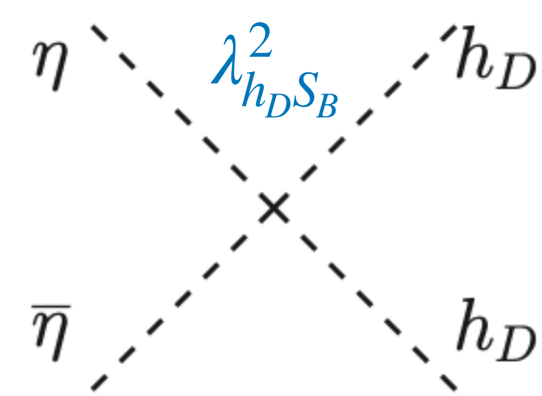


Interactions within the DS

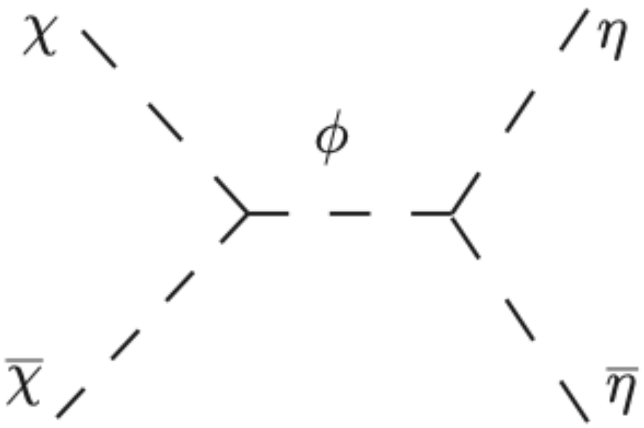
$$\mathscr{L}_{\rm DS} \supset \mu_\chi \left|\chi\right|^2 \phi + \mu_\eta \left|\eta\right|^2 \phi + \left(q_H g_D\right)^2 A'^{\mu} A'_\mu \left|H\right|^2$$
$$+ i q_\eta g_D A'_\mu \left[\eta^* \left(\partial^\mu \eta\right) - \left(\partial^\mu \eta^*\right) \eta\right] - \lambda_{h_D \eta} h_D^2 \left|\eta\right|^2$$



We connect η to both mediators: h_D and A' which moreover are connected to each other.



Thermal history

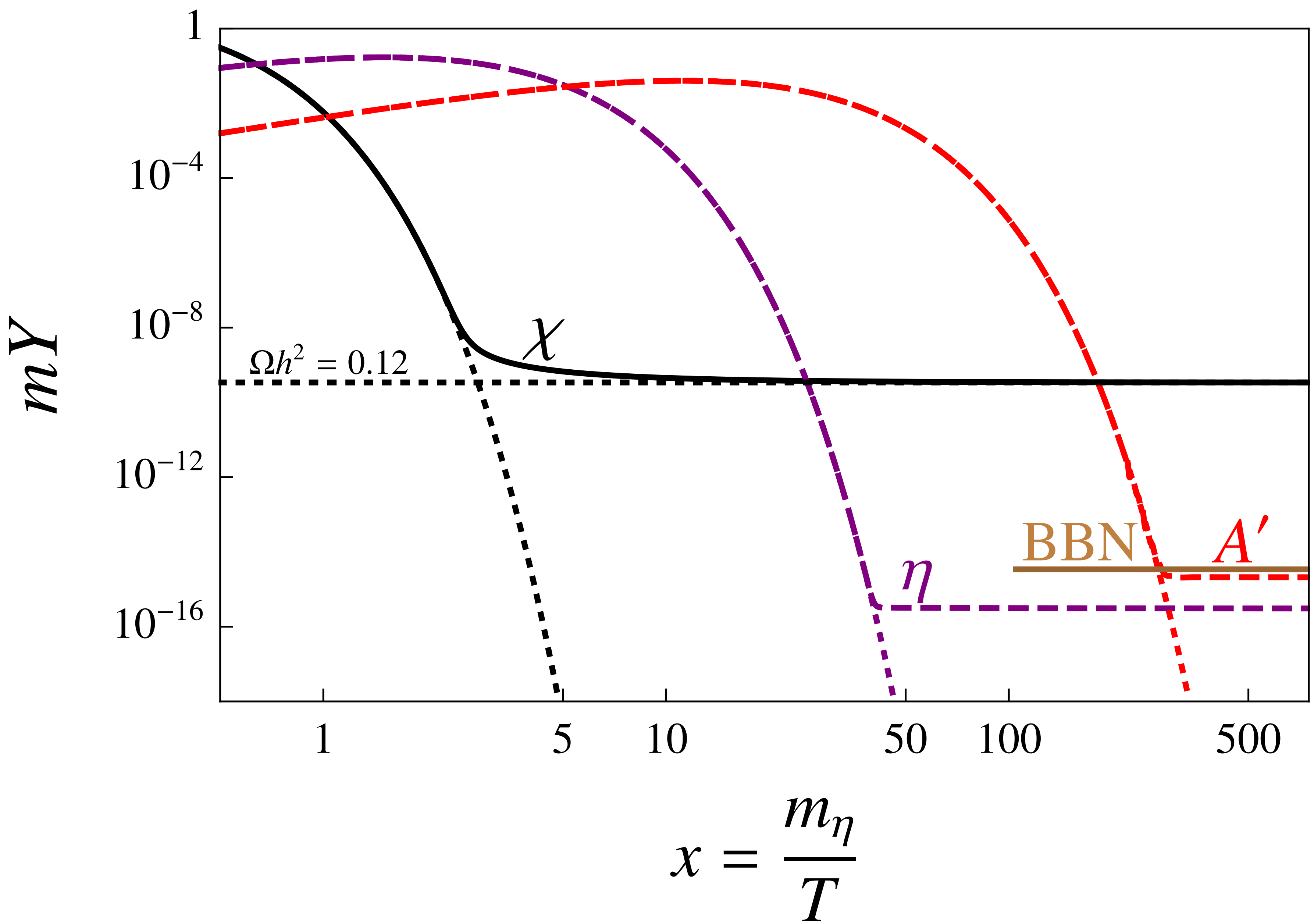


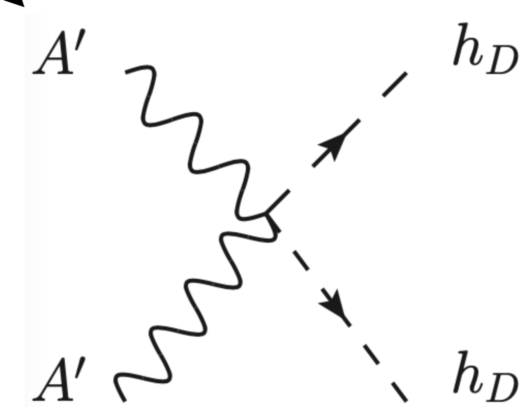
$$\frac{dY_\chi}{dx} = -\frac{\lambda_\chi}{x^2}\left(Y_\chi^2 - \frac{Y_\eta^2}{(Y_\eta^{\rm eq})^2}\,(Y_\chi^{\rm eq})^2\right),$$

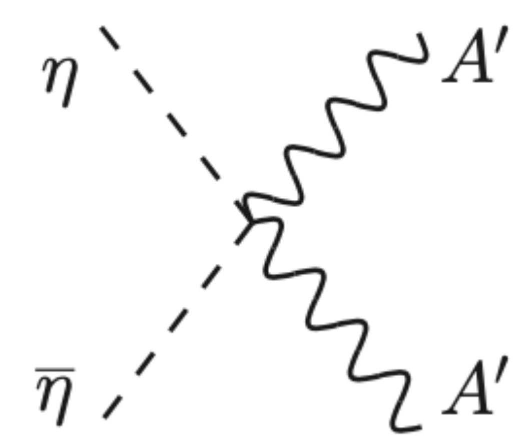
$$\frac{dY_\eta}{dx} = -\frac{\lambda_\eta}{x^2}\left(Y_\eta^2 - (Y_\eta^{\rm eq})^2\,\frac{Y_{A'}^2}{(Y_{A'}^{\rm eq})^2}\right) + \frac{\lambda_\chi}{x^2}\left(Y_\chi^2 - \frac{Y_\eta^2}{(Y_\eta^{\rm eq})^2}\,(Y_\chi^{\rm eq})^2\right),$$

$$\frac{dY_{A'}}{dx} = \frac{\lambda_\eta}{x^2}\left(Y_\eta^2 - (Y_\eta^{\rm eq})^2\,\frac{Y_{A'}^2}{(Y_{A'}^{\rm eq})^2}\right) - \frac{\lambda_{A'}}{x^2}\left(Y_{A'}^2 - (Y_{A'}^{\rm eq})^2\right),$$

Assisted freeze-out







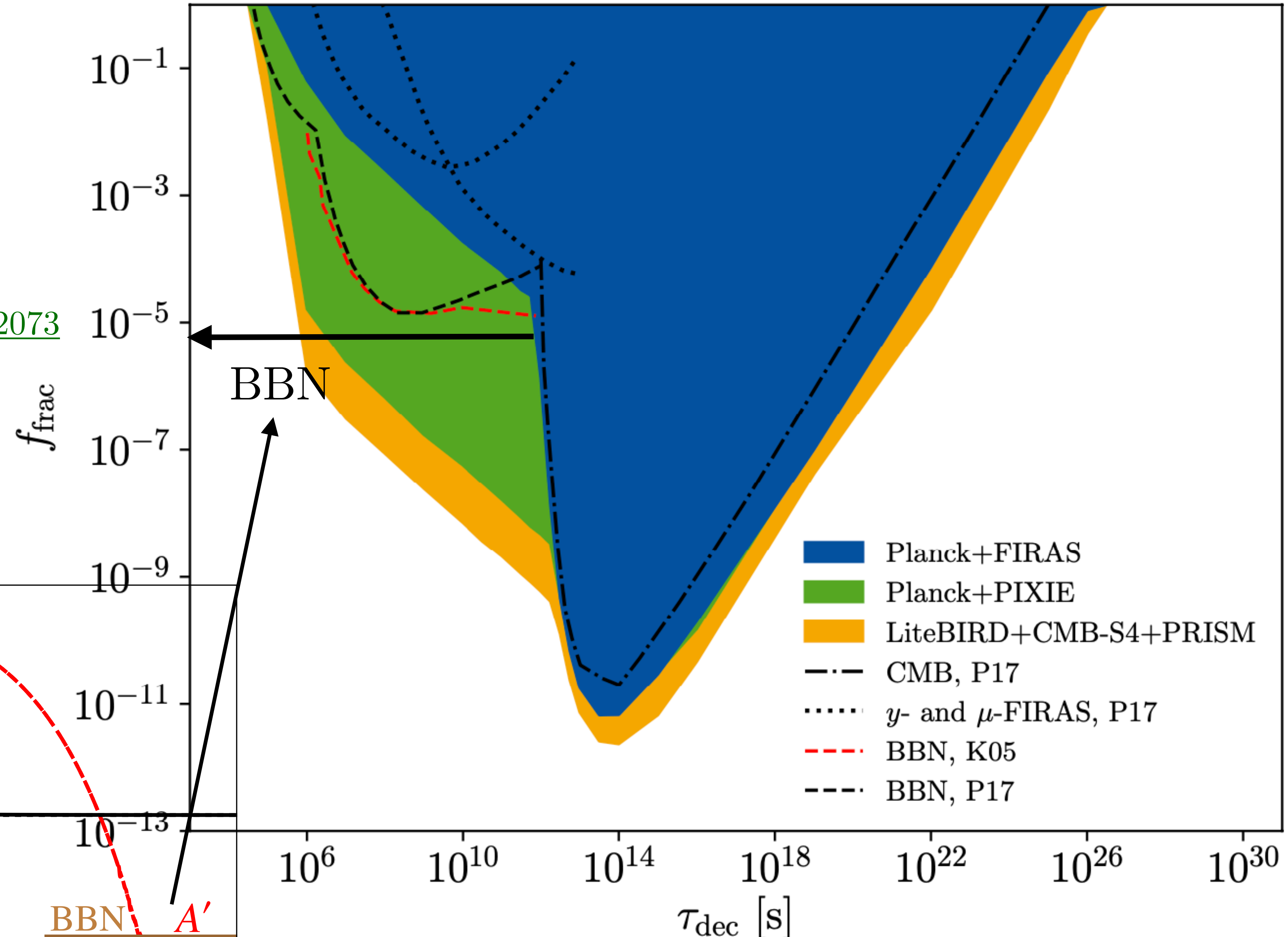
Limits on decaying DM - late energy injections

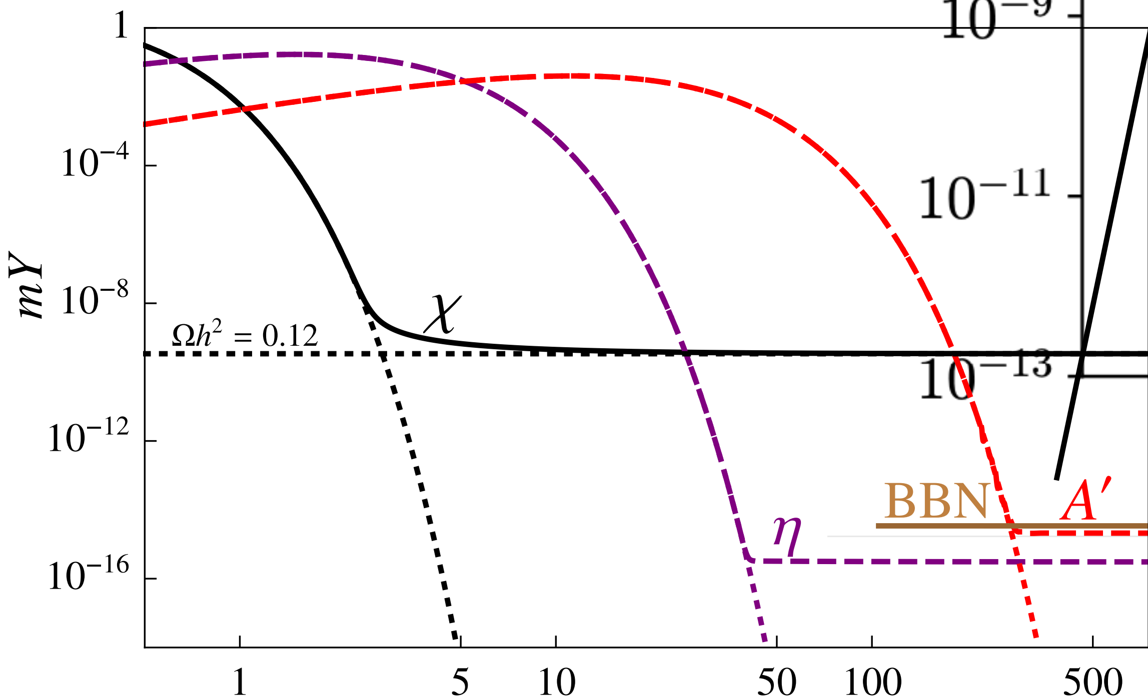
Lucca, Schoneberg, Hooper, Lesgourgues, Chluba, 1910.04619

Late energy injections can *destroy light elements*

Dashed lines - BBN

Poulin, Serpico, Lesgourgues, 1606.02073





$$c\tau_{A'} \simeq 1\ \mathrm{kpc} \left(\frac{1}{g_D}\right)^2 \left(\frac{10^{-6}}{\tilde{\epsilon}}\right)^2 \left(\frac{4\times 10^{-6}}{\lambda_{h_D\eta}}\right)^2 \left(\frac{m_\eta}{150\,\mathrm{GeV}}\right)^4 \left(\frac{10\,\mathrm{GeV}}{m_{A'}}\right)^5$$