Indirect detection of long-lived particles
via a less-simplified dark Higgs portal

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Searching for long-lived particles at the LHC and beyond: Tenth workshop of the LLP Community
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Based on:

KJ, L. Roszkowski and S. Trojanowski, 2111.xxxxx

Physics Beyond the Standard Model

SM is not a complete description of Nature:

- Dark matter candidate is missing:

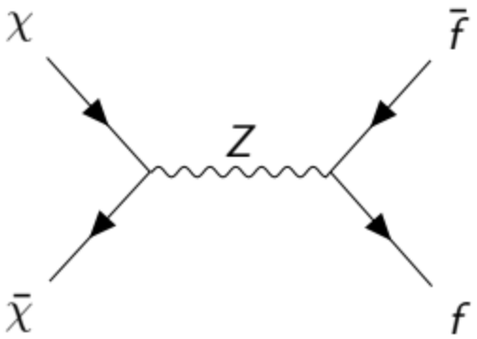
Neutrinos are massive, weakly interacting, however $1.6\,\% > \dfrac{\Omega_\nu}{\Omega_{\rm DM}} > 0.5\,\%$ (CMB & LSS)

- Neutrino masses
- Hierarchy problem
- Baryogenesis
- Quantum gravity
- ...

Physics BSM can take many forms
from minimal extensions to many hidden (dark) sectors.

Looking for WIMPs

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



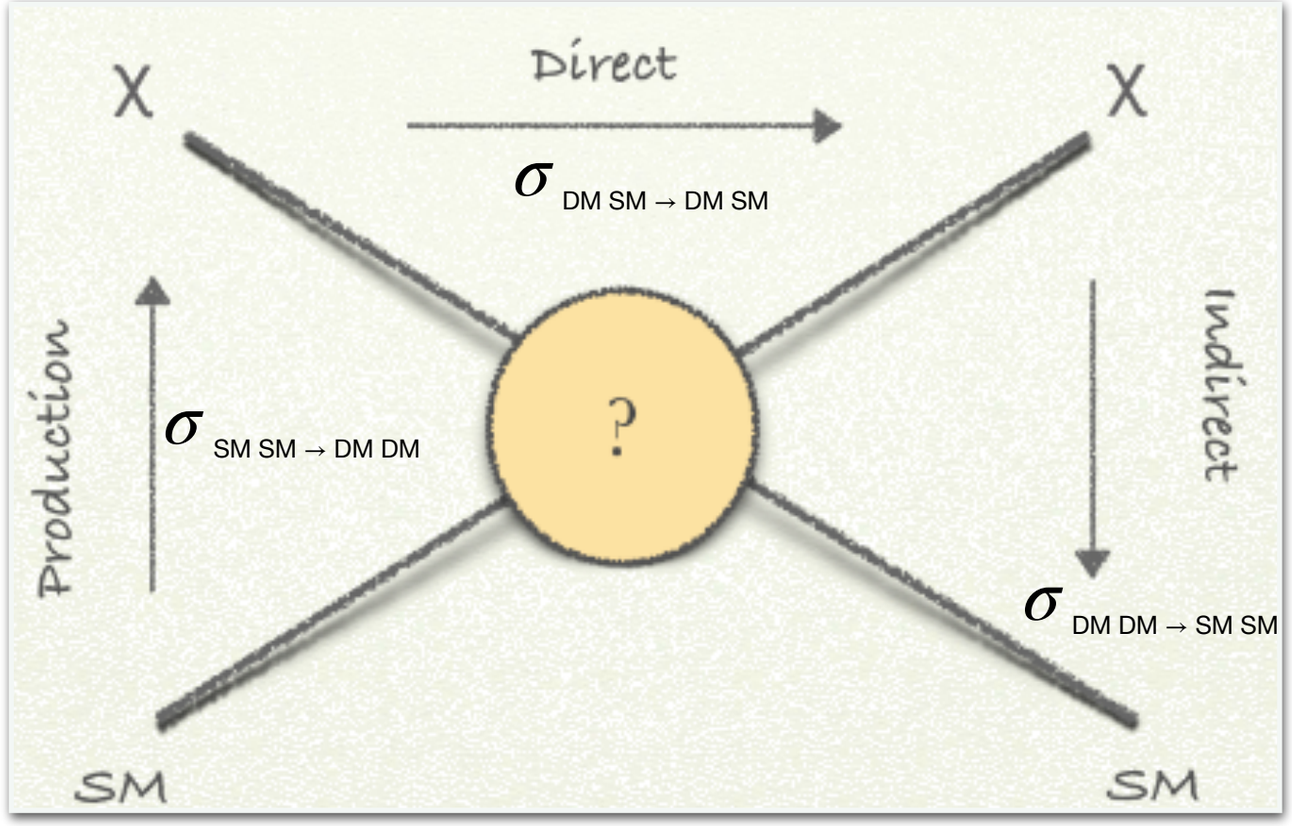
$$\sigma \propto \frac{g^4}{m_\chi^2}$$

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

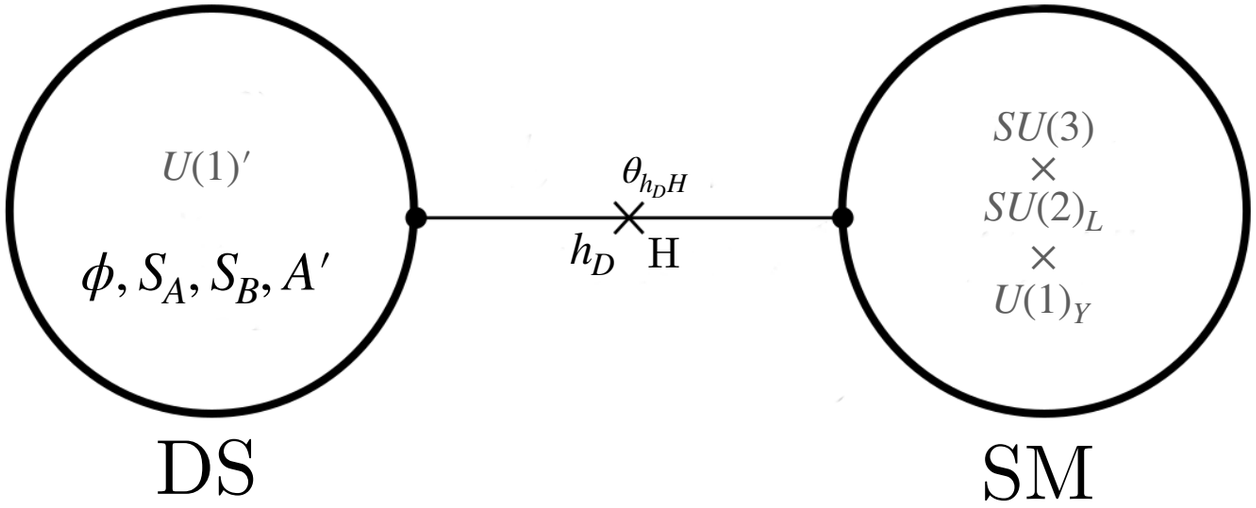
Crossing symmetry

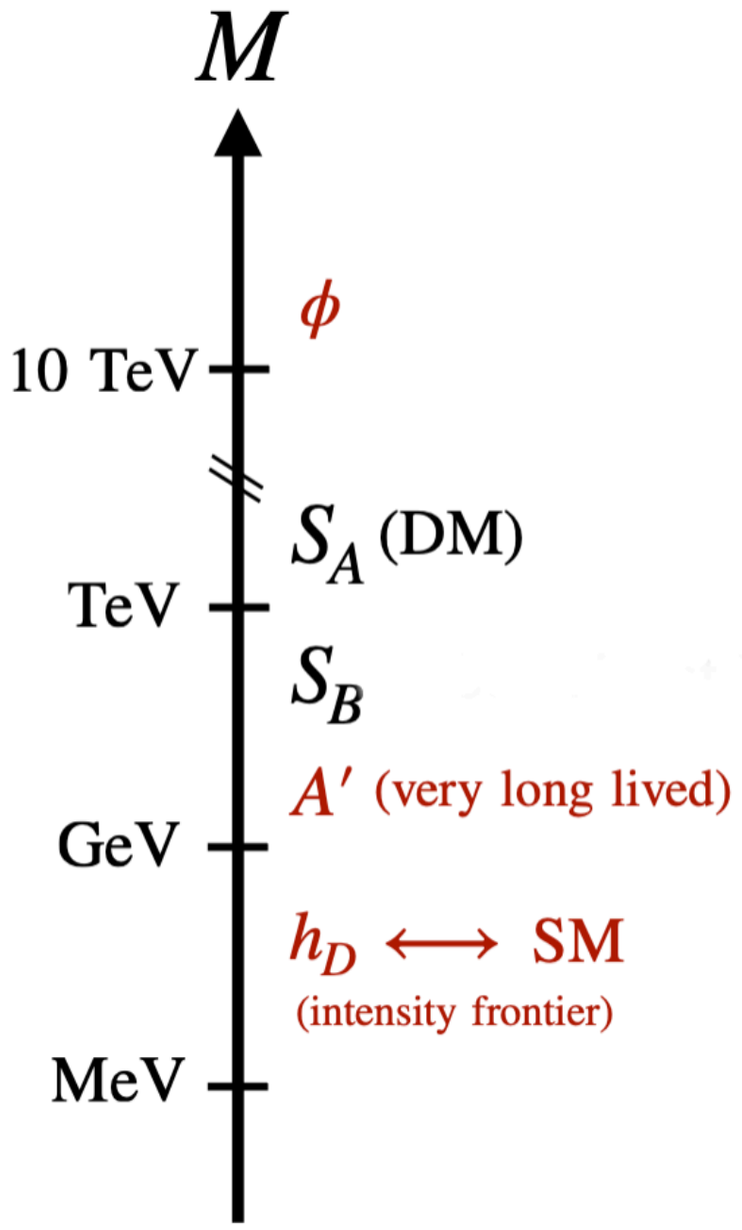
→ $\sigma_{\text{DM DM} \to \text{SM SM}}$ related to $\sigma_{\text{SM SM} \to \text{DM DM}}$ $\sigma_{\text{DM SM} \to \text{DM SM}}$

multiple detection possibilities



Heavy WIMP & LLP





DM is comprised of complex scalars S_A, S_B
which are connected by heavy auxiliary field ϕ.

S_A *annihilates within the dark sector* in such way that $\Omega_{S_A} h^2 \sim 0.1 \gg \Omega_{S_B} h^2$.

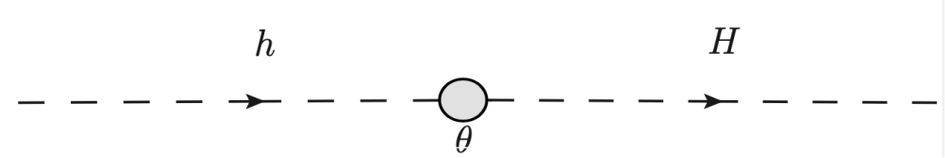
↓

CMB bounds evaded

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.

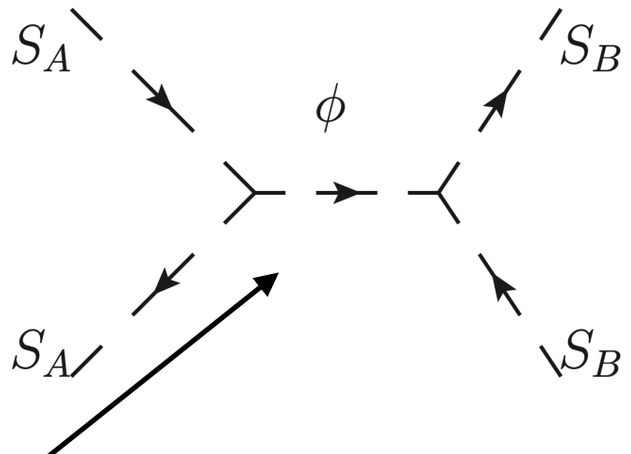
$$\Phi = \left(0, (v_h + H)/\sqrt{2}\right)^T, \quad \sigma = (v_{\text{D}} + H_{\text{D}})/\sqrt{2}$$

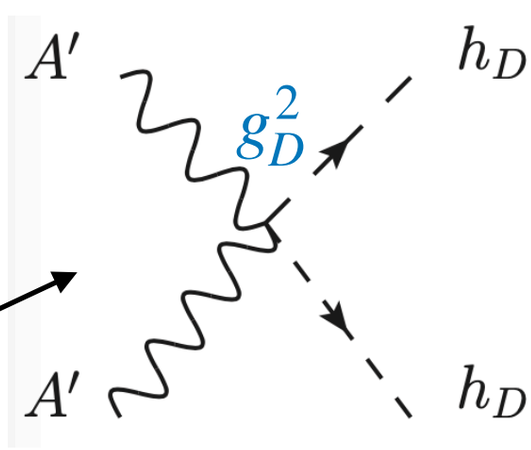
Moreover, *dark photon obtains mass* $m_{A'} = g_D v_D$, $m_{h_D} = \sqrt{\lambda_D} v_D$

Matter fields - two component DM

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

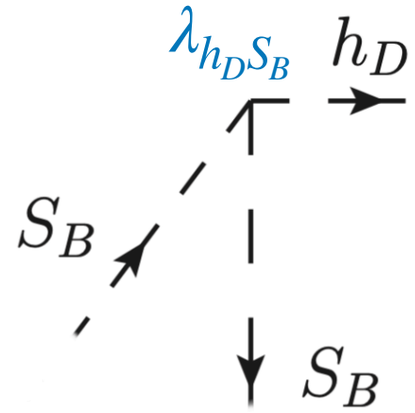
Interactions within the DS

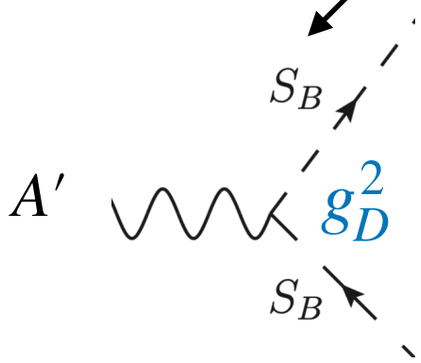




$$\mathscr{L}_{\text{DS}} \supset \mu_{S_A} \left|S_A\right|^2 \phi + \mu_{S_B} \left|S_B\right|^2 \phi + \left(q_H g_D\right)^2 A'^{\mu} A'_{\mu} \left|H\right|^2$$

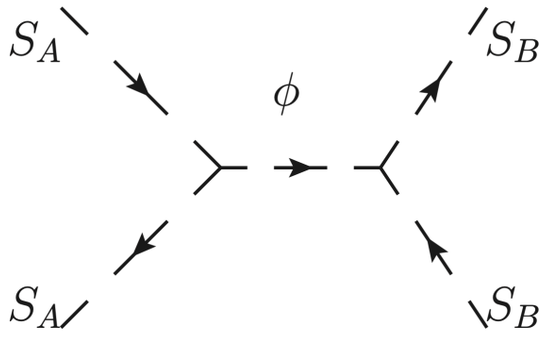
$$+ i q_{S_B} g_D A'_{\mu} \left[S_B^* \left(\partial^{\mu} S_B\right) - \left(\partial^{\mu} S_B^*\right) S_B\right] - \lambda_{h_D S_B} h_D^2 \left|S_B\right|^2 \longrightarrow$$





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

Thermal history

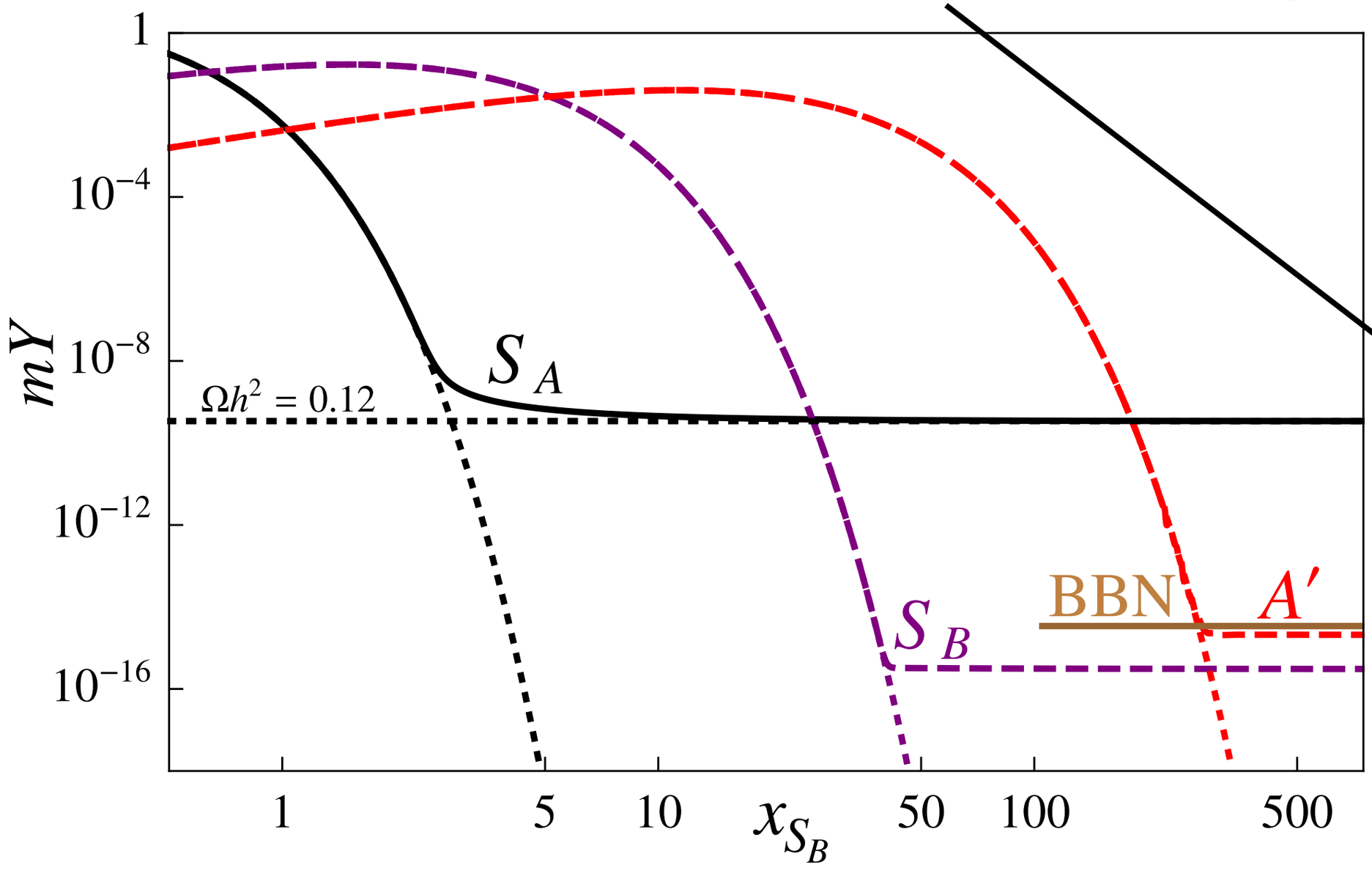


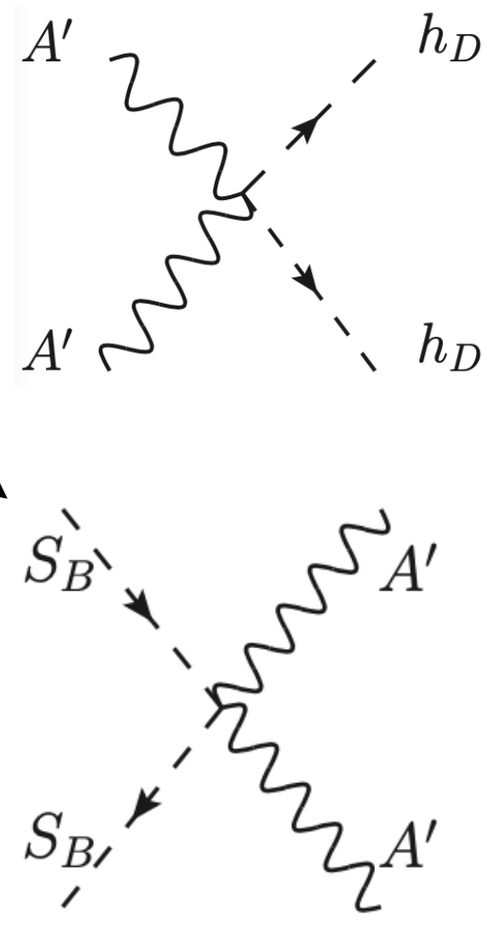
$$\frac{dY_{S_A}}{dx} = -\frac{\lambda_{S_A}}{x^2}\left(Y_{S_A}^2 - \frac{Y_{S_B}^2}{\left(Y_{S_B}^{\rm eq}\right)^2}\left(Y_{S_A}^{\rm eq}\right)^2\right)$$

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

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

Assisted freeze-out



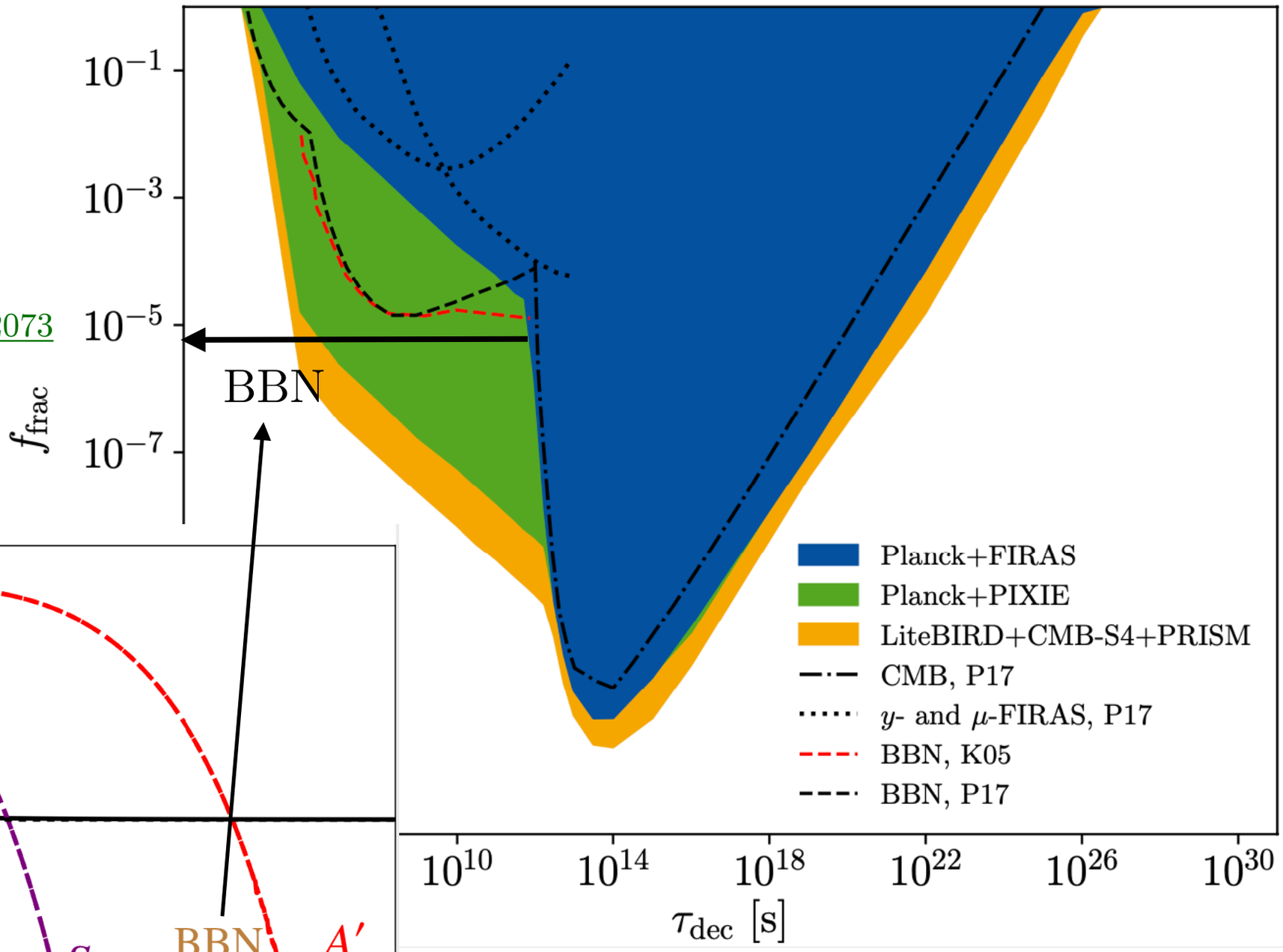


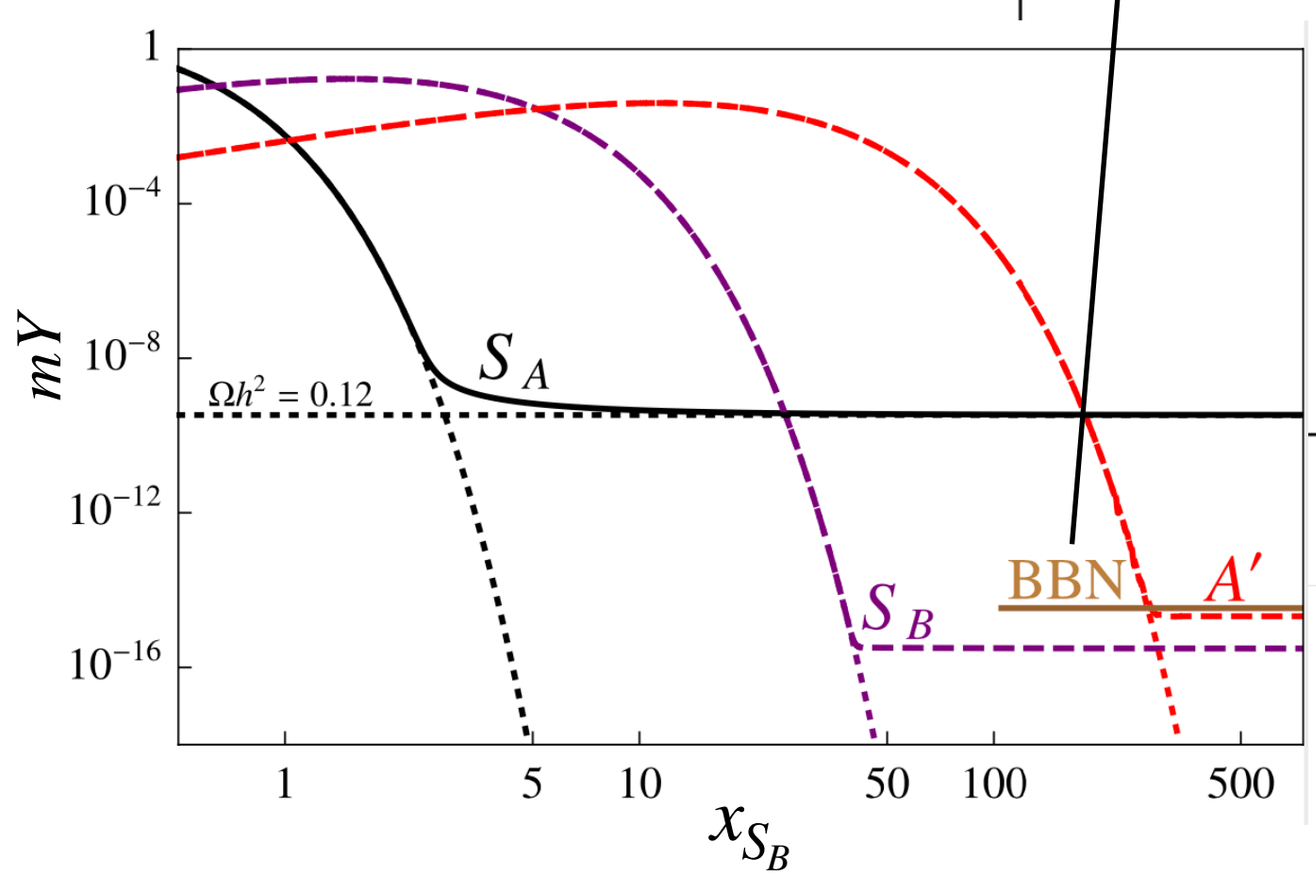
Limits on decaying DM - late energy injections

Late energy injections
can *destroy light elements*

Dashed lines - BBN
Poulin, Serpico, Lesgourgues, 1606.02073

Lucca, Schoneberg, Hooper, Lesgourgues, Chluba, 1910.04619



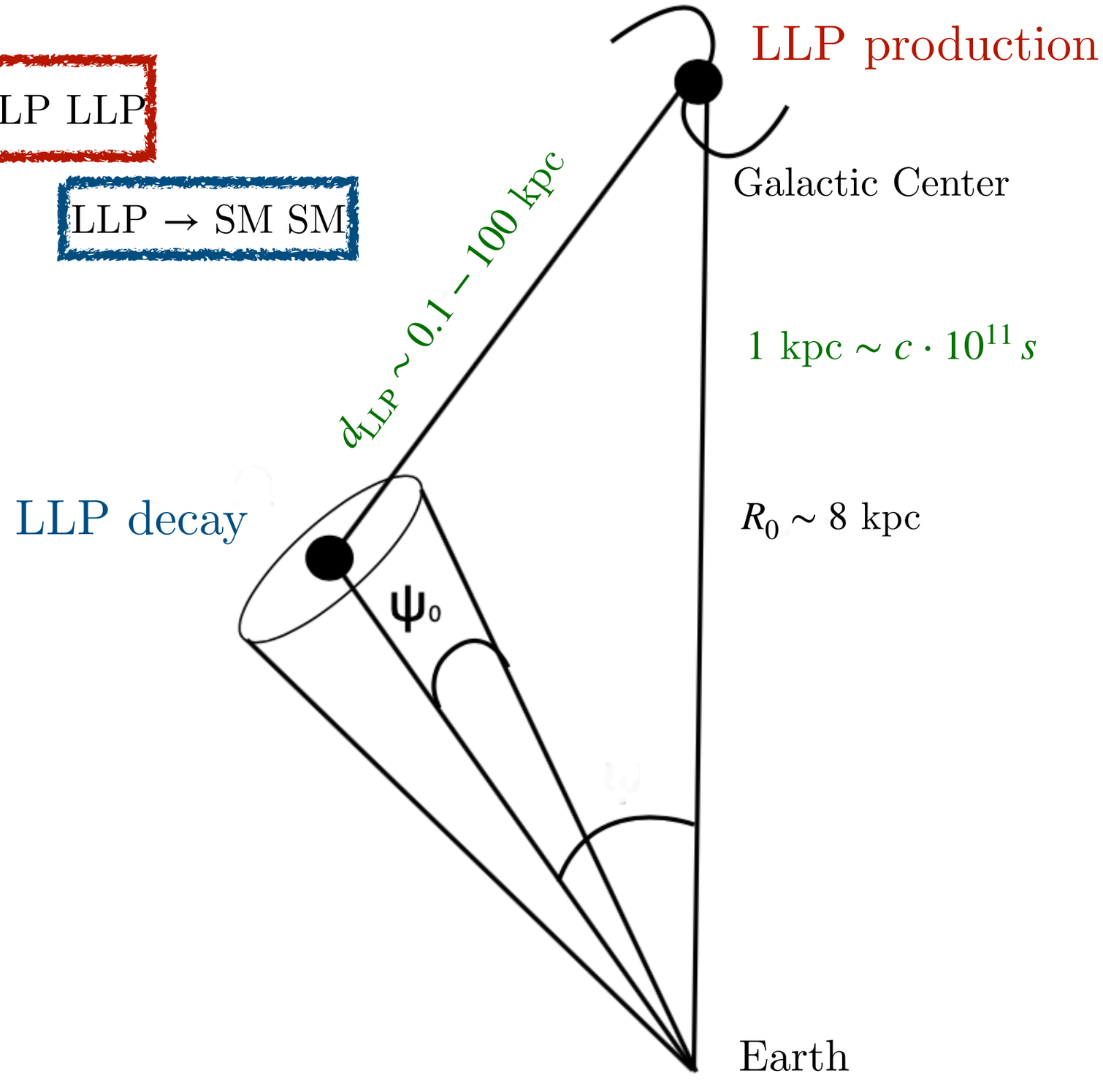


$$c\tau_{A'} \simeq 1\,\mathrm{kpc}\left(\frac{g_D}{1}\right)^4\left(\frac{4\times10^{-6}}{\lambda_{h_D S_B}}\right)^4\left(\frac{m_{S_B}}{150\mathrm{GeV}}\right)^4\left(\frac{3\mathrm{GeV}}{m_{A'}}\right)^5$$

ID of LLPs

DM DM → LLP LLP

LLP → SM SM



Long lifetime regime

DM DM → LLP LLP

LLP $\left(d_{\rm LLP} \sim 0.1 - 100\ {\rm kpc}\right)$ → 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:

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

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Compare to formula for WIMP ID → *non-local J-factor*

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

→ *no longer direct relationship between* $\Phi_{\rm LLP}(\vec{r}_0)$ *and* $\rho_{\rm DM}^2(\vec{r}_0)$.

Non-relativistic mediators
Rothstein, Schwetz, Zupan, 0903.3116

ID anomalies
Chu, Kulkarni, Salati, 1706.08543

Long lifetime regime

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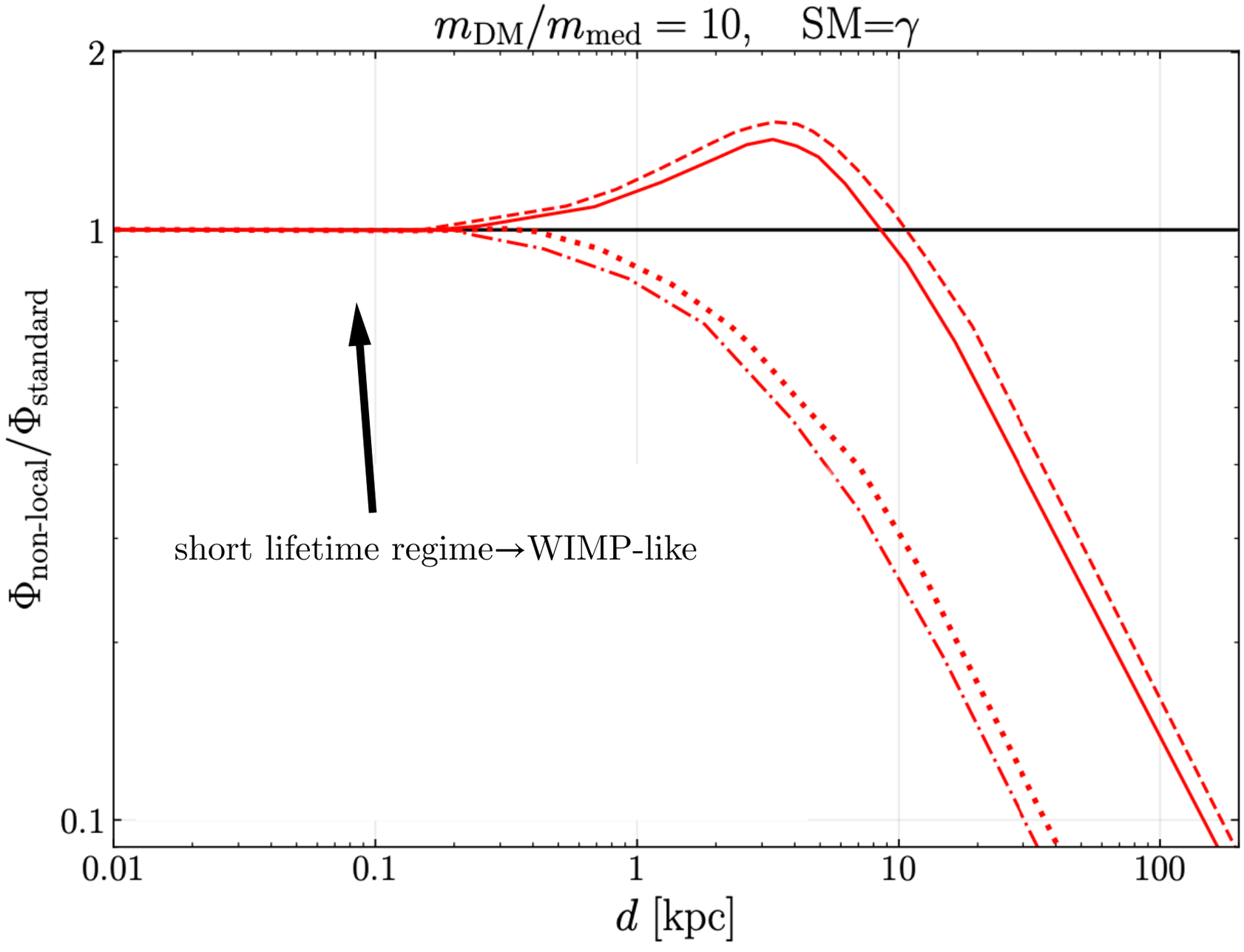

Long lifetime regime

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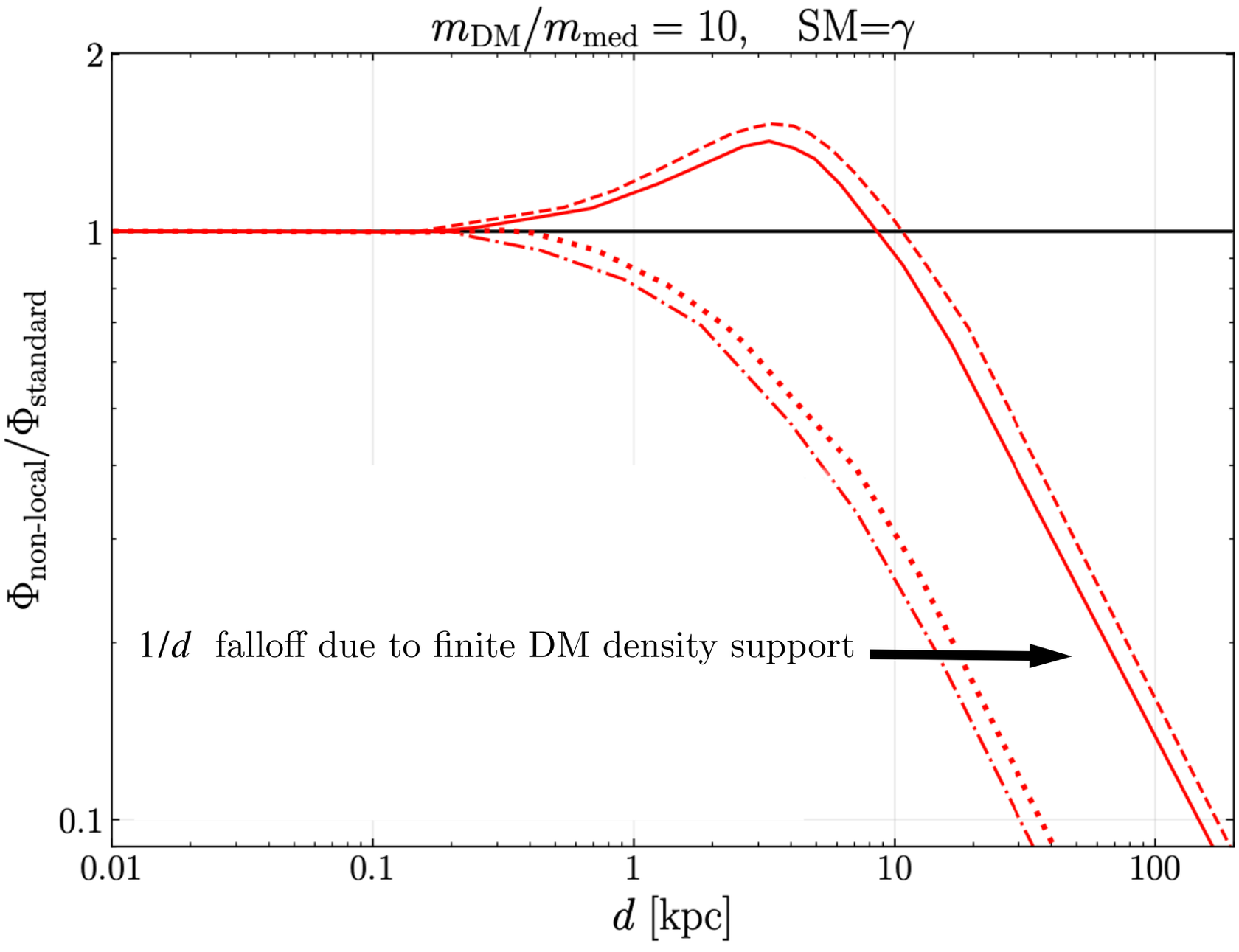

Long lifetime regime

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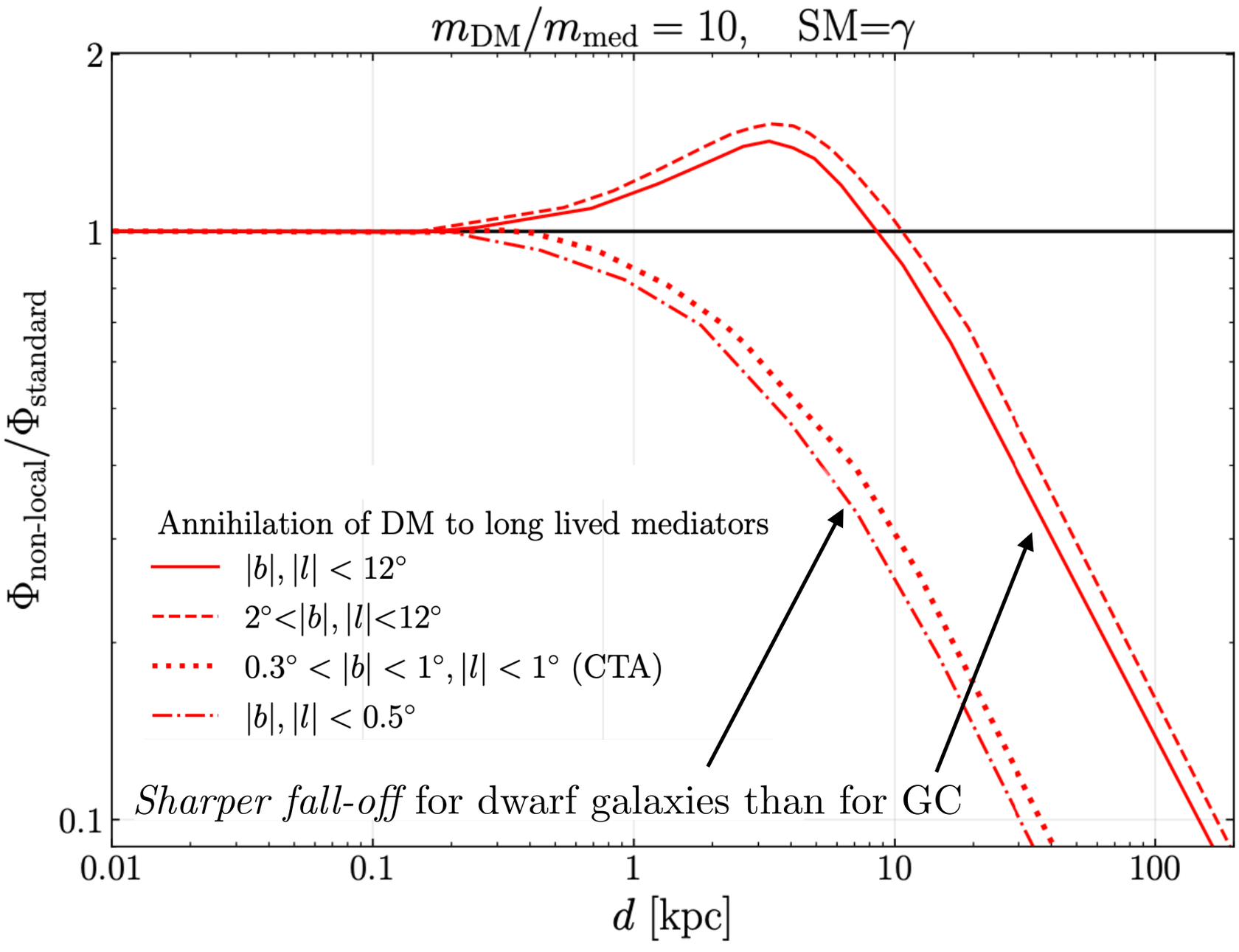

Long lifetime regime

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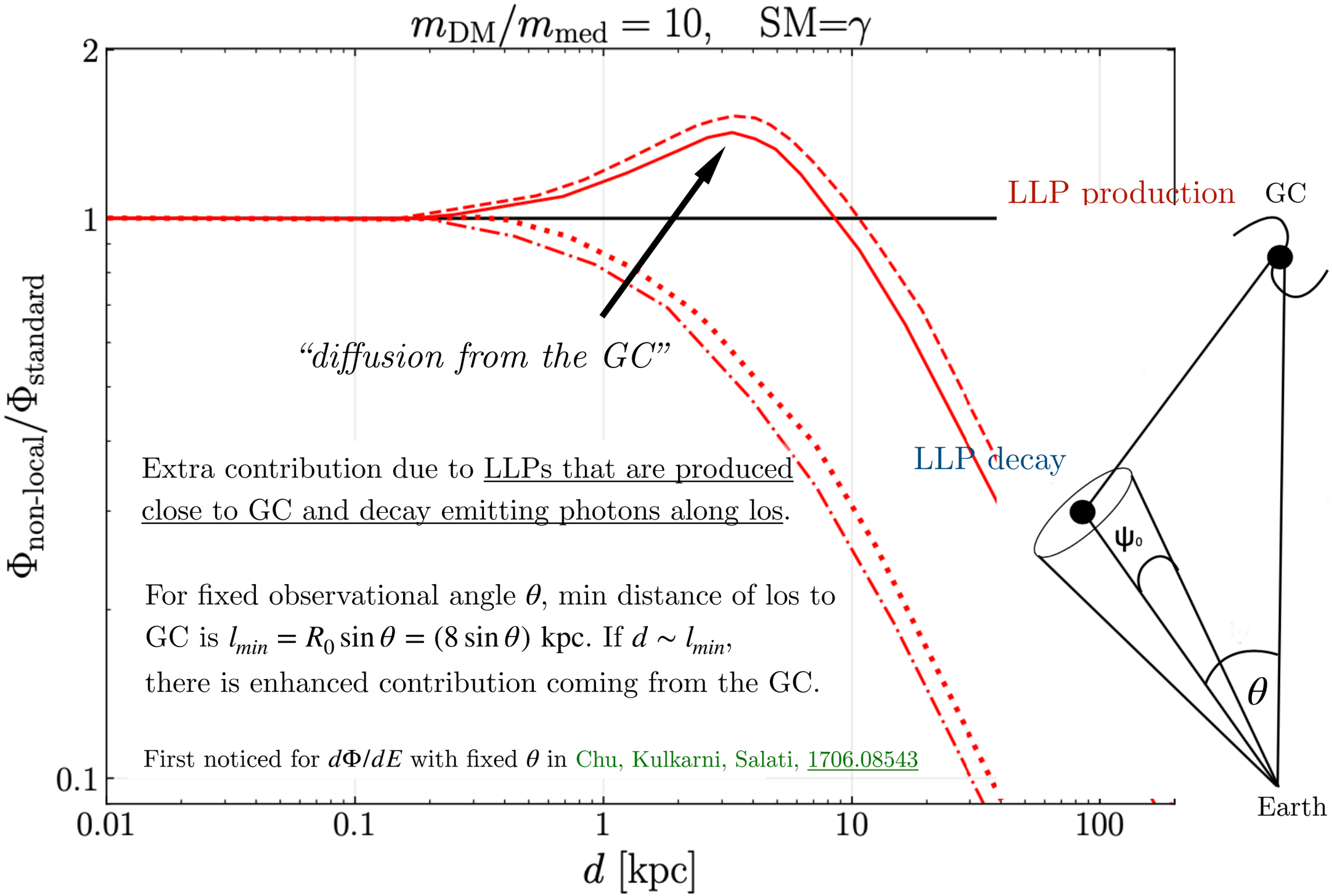


Extra contribution due to LLPs that are produced close to GC and decay emitting photons along los.

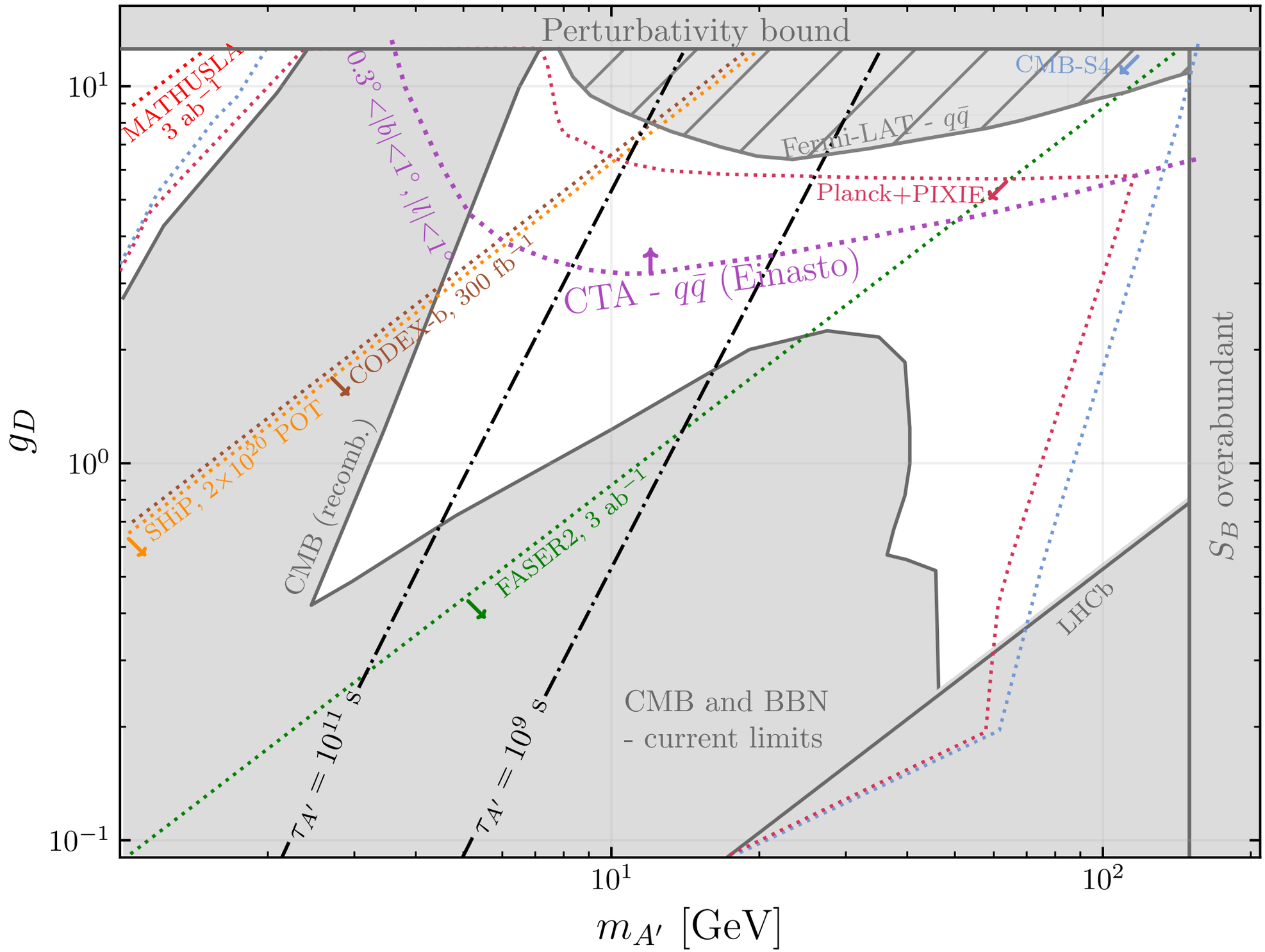
For fixed observational angle θ, min distance of los to GC is $l_{min} = R_0 \sin\theta = (8 \sin\theta)$ kpc. If $d \sim l_{min}$, there is enhanced contribution coming from the GC.

First noticed for $d\Phi/dE$ with fixed θ in Chu, Kulkarni, Salati, 1706.08543

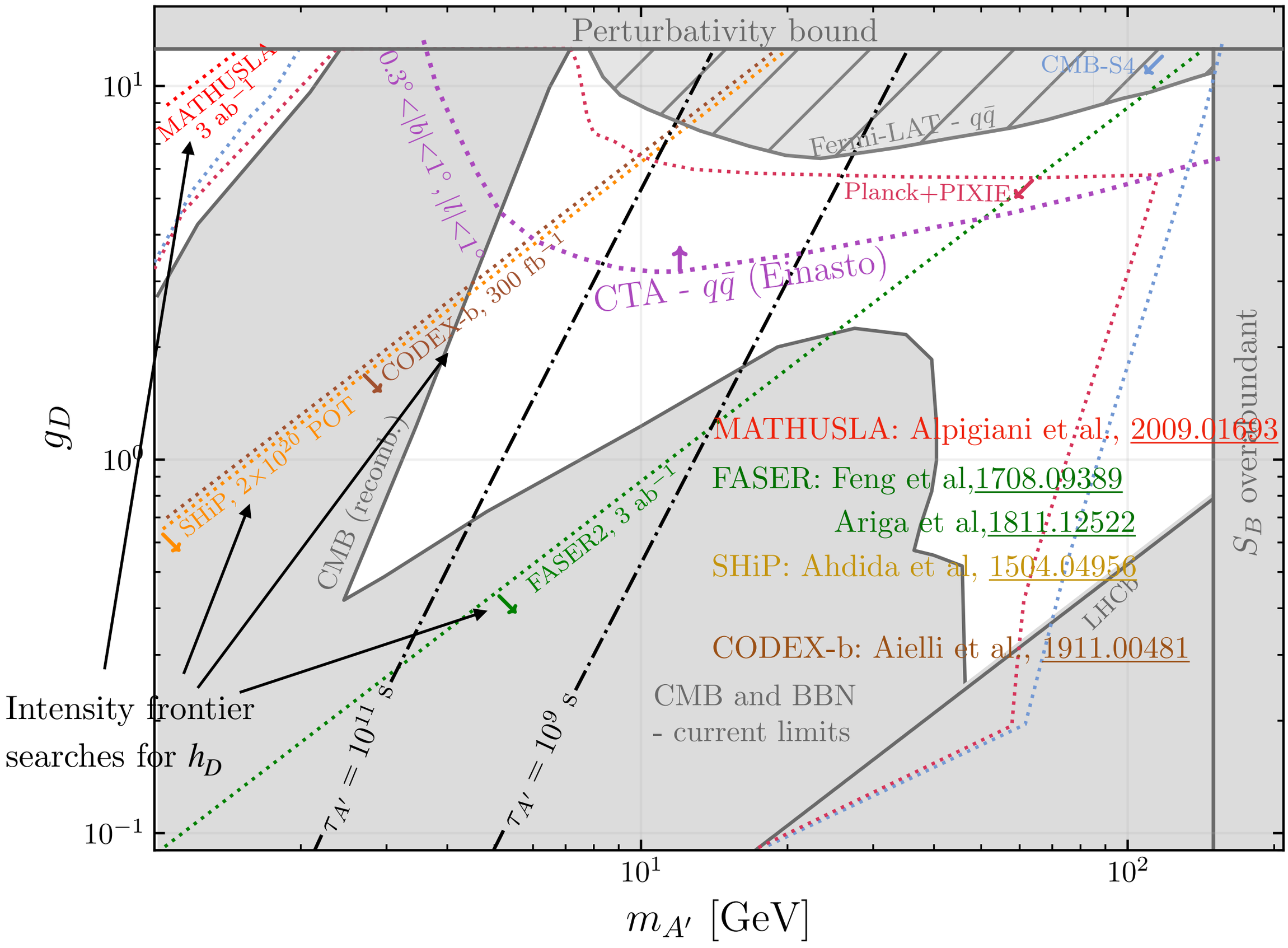
Indirect Detection & Intensity Frontier

searches for LLPs - complementarity

$$m_{h_D} = 500 \text{ MeV}, \lambda_{h_D S_B} = 4 \times 10^{-6}$$



$m_{h_D} = 500$ MeV, $\lambda_{h_D S_B} = 4 \times 10^{-6}$



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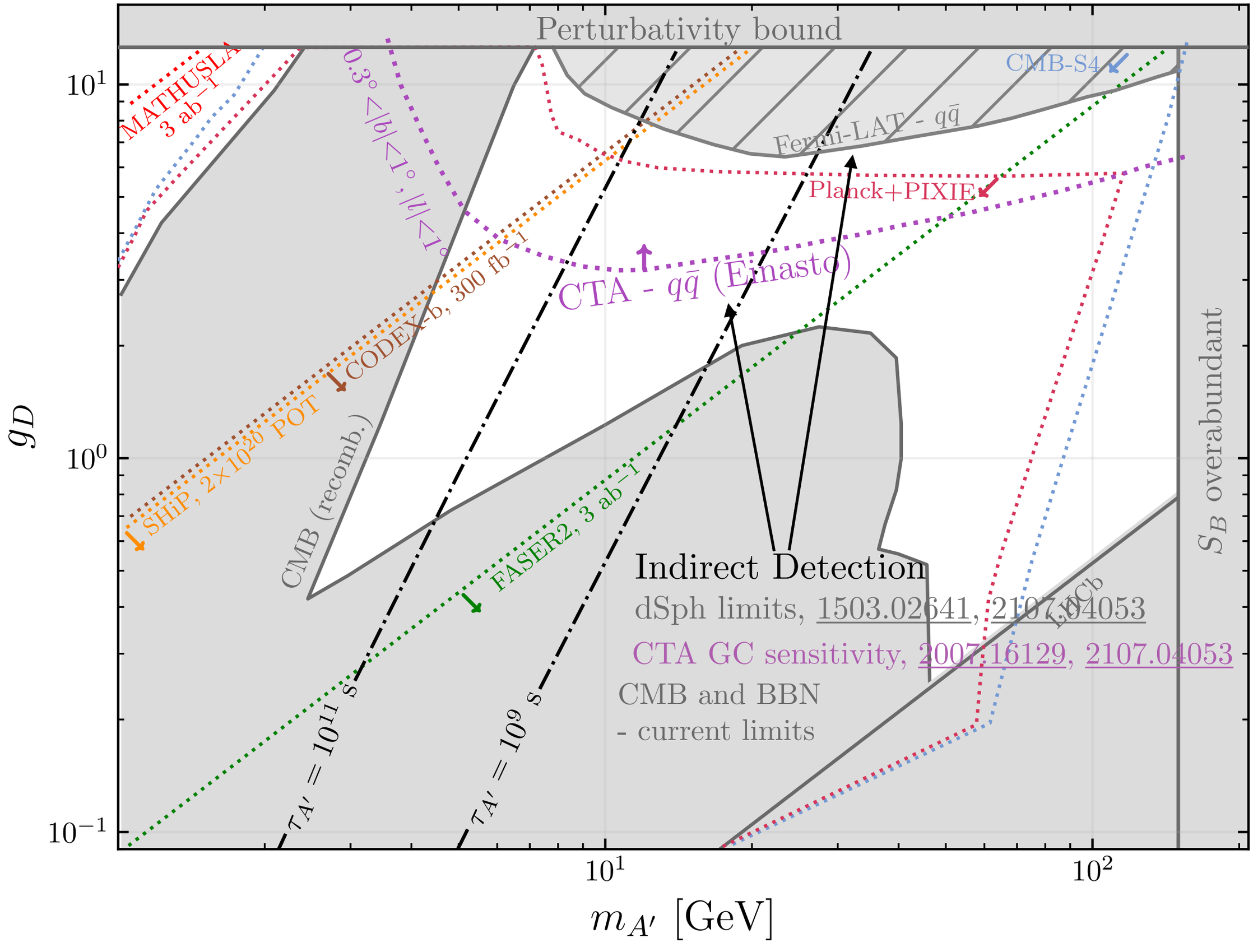

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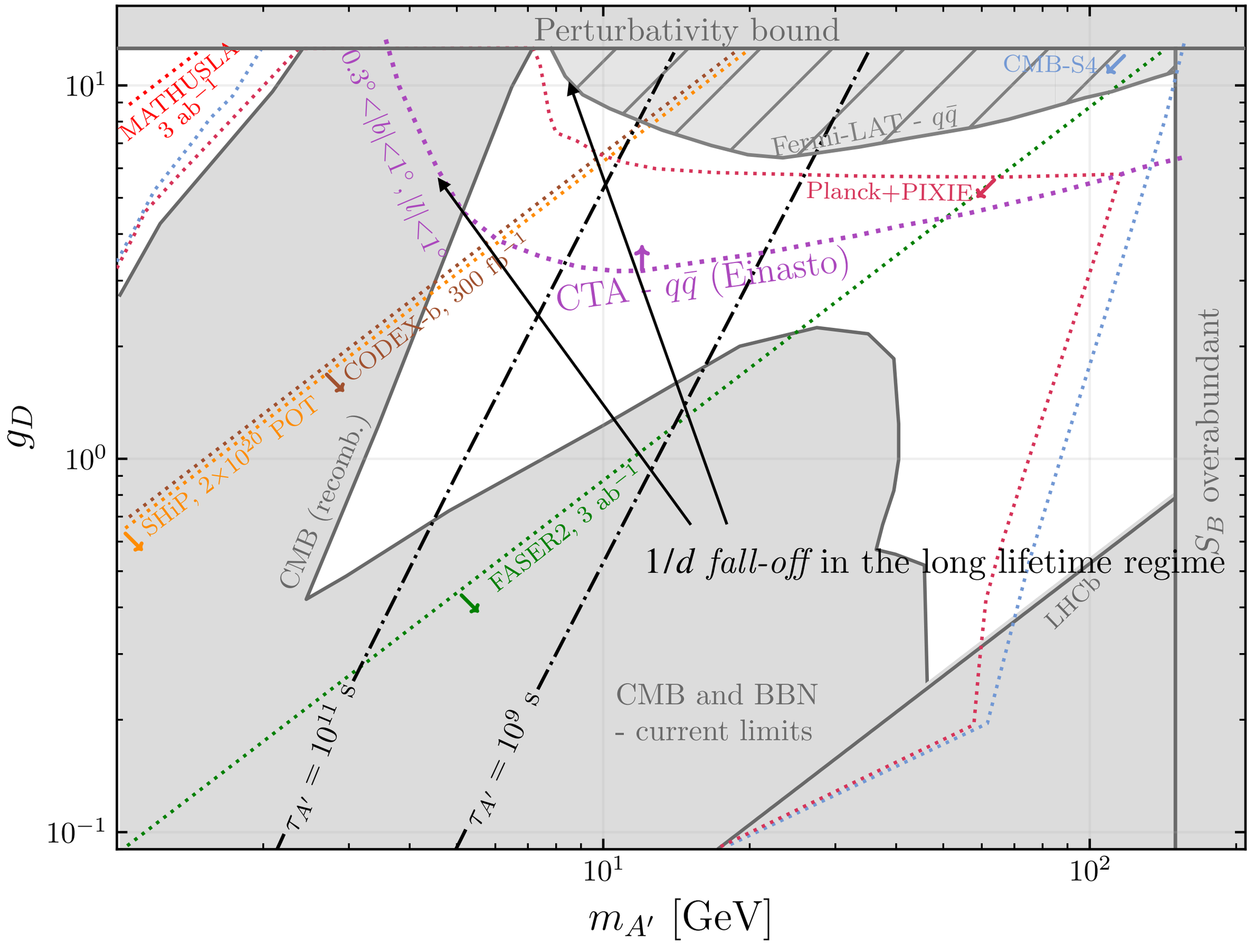
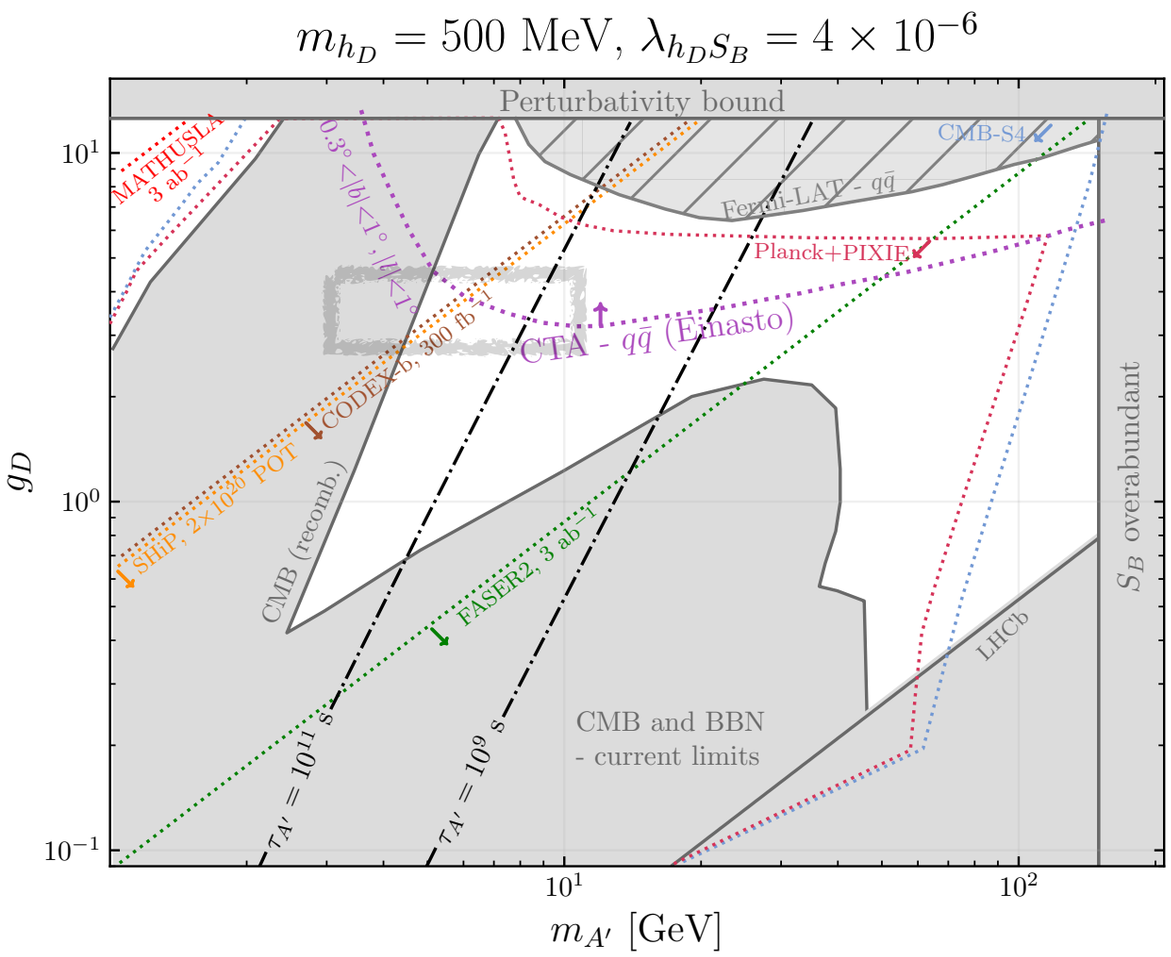
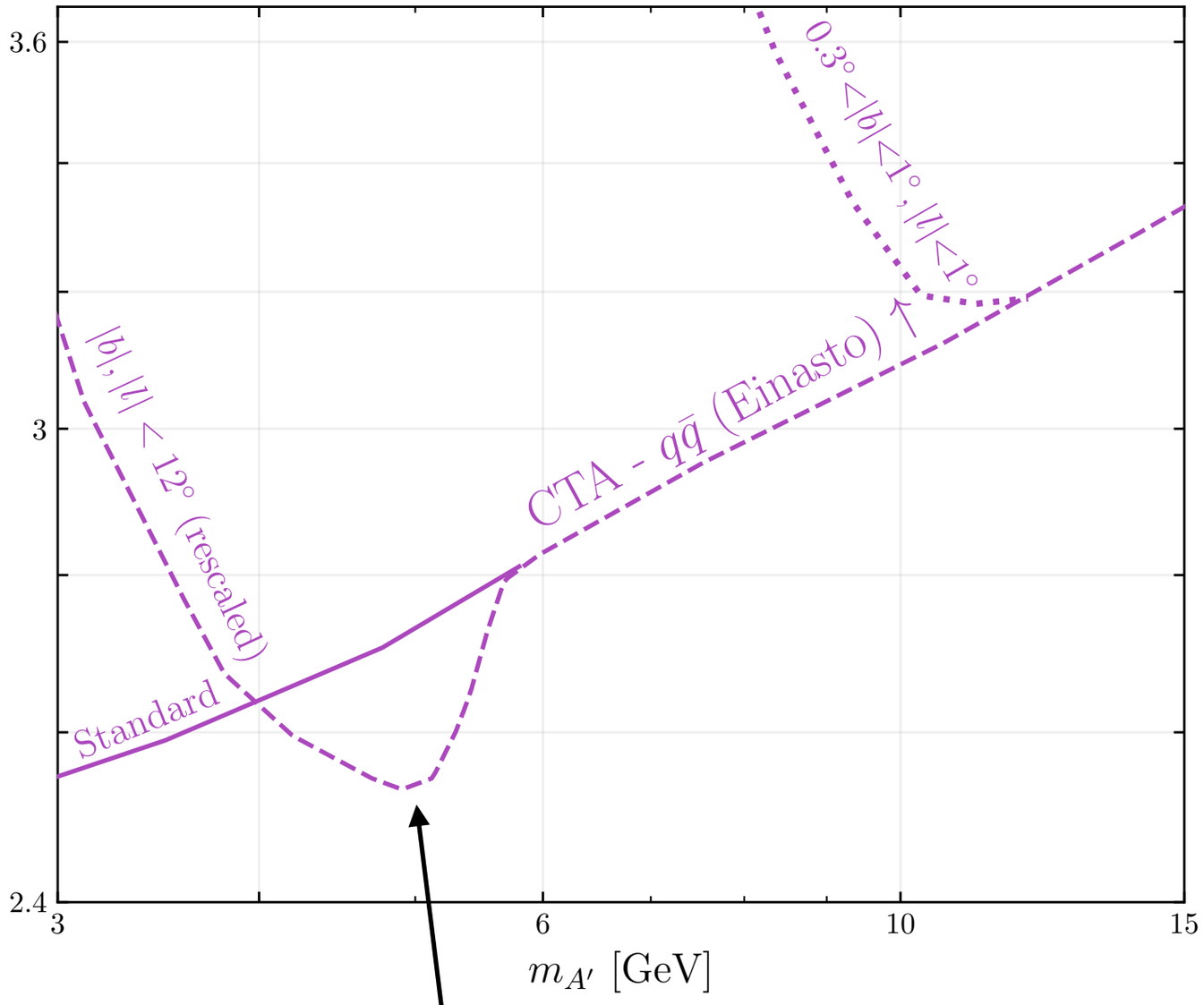
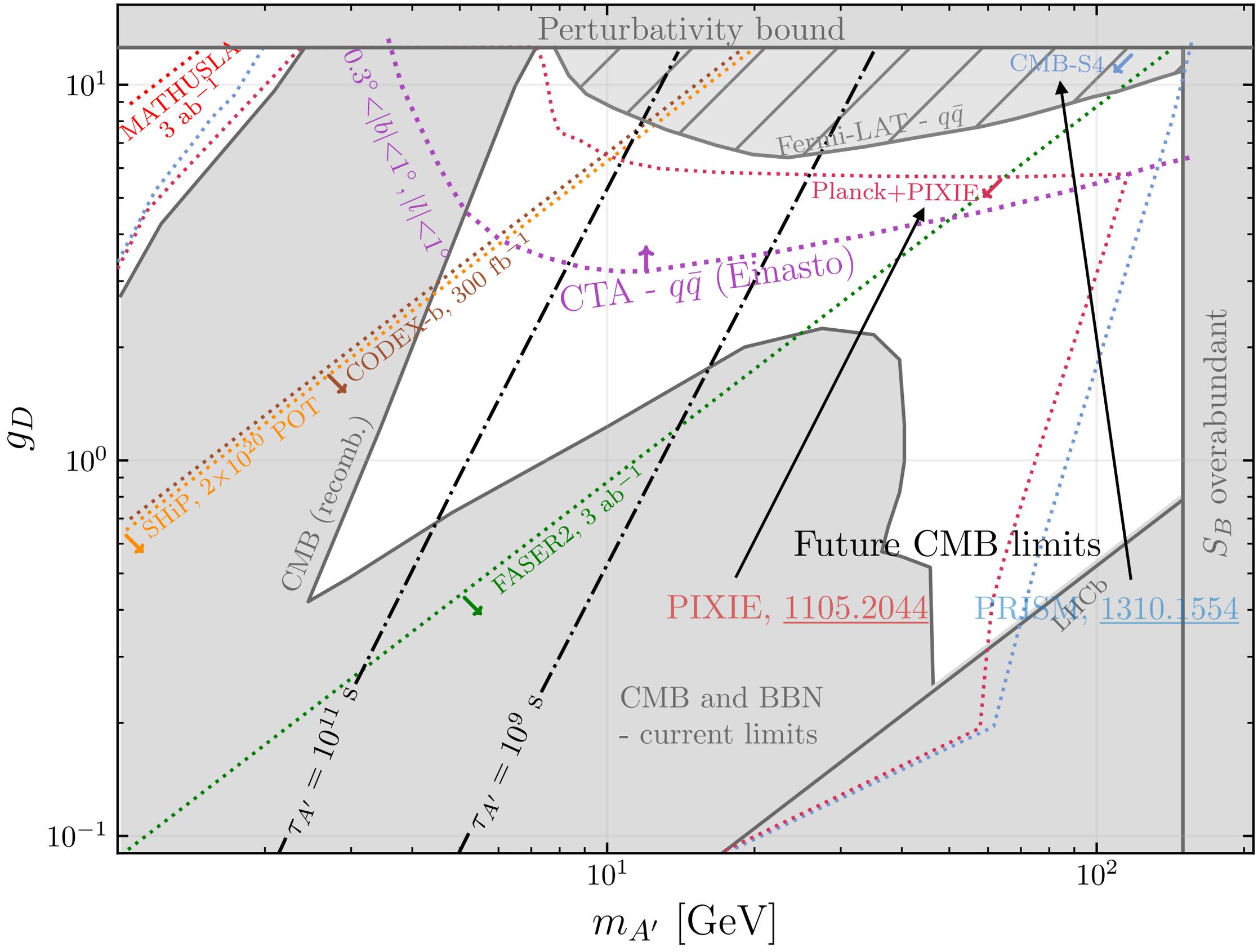






peak due to "*diffusion from the GC*"

$m_{h_D} = 500$ MeV, $\lambda_{h_D S_B} = 4 \times 10^{-6}$



Conclusions

- Combination of WIMP-like DM and light new physics is an interesting theoretical framework and a promising experimental target.

- We explored the possibility of indirect detection (ID) of long-lived particles in non-minimal dark Higgs-dark photon portal with heavy scalar DM.

- We found that ID provides important coverage of the long-lived regime, complementary to the *intensity frontier searches.*

- We observed several *non-local effects in ID* arising from the galactic spatial separation of LLP production and decay:

  ✤ an additional contribution to the flux coming from the "*diffusion from the GC*"

  ✤ the photon flux as a function of LLP decay length d

  - decreases linearly in the long lifetime regime due to the finite support of the dark matter density → evading constraints
  - decreases faster for dSph than for GC