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

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Opening New Windows to the Universe
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Based on:

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

Outline

1. Motivation

    - WIMPs and complementary searches for them
    - Intensity frontier - searches for long lived particles (LLPs)

2. ***ID of LLPs* within non-minimal dark Higgs-dark photon portal**

    - phenomenology of the model
    - ID of LLPs formalism and main effects
    - complementarity of searches

3. Conclusions

Motivation

Physics Beyond the Standard Model

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

- **Dark matter** candidate is missing:

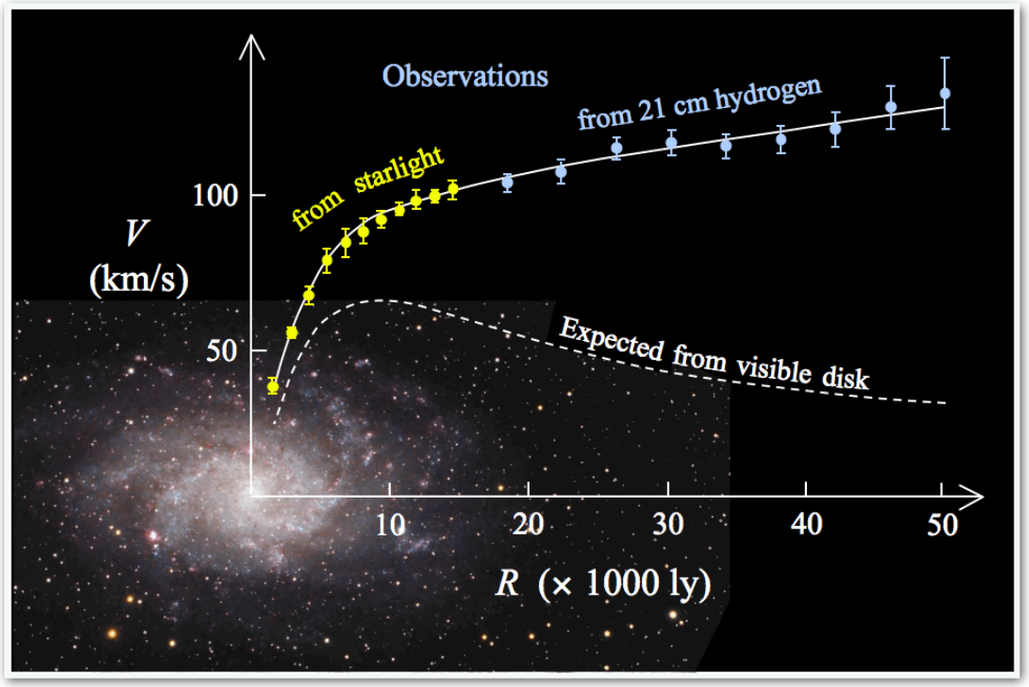
Neutrinos are massive, weakly interacting, however $1.6\,\% > \frac{\Omega_\nu}{\Omega_{\mathrm{DM}}} > 0.5\,\%$ (CMB & LSS)

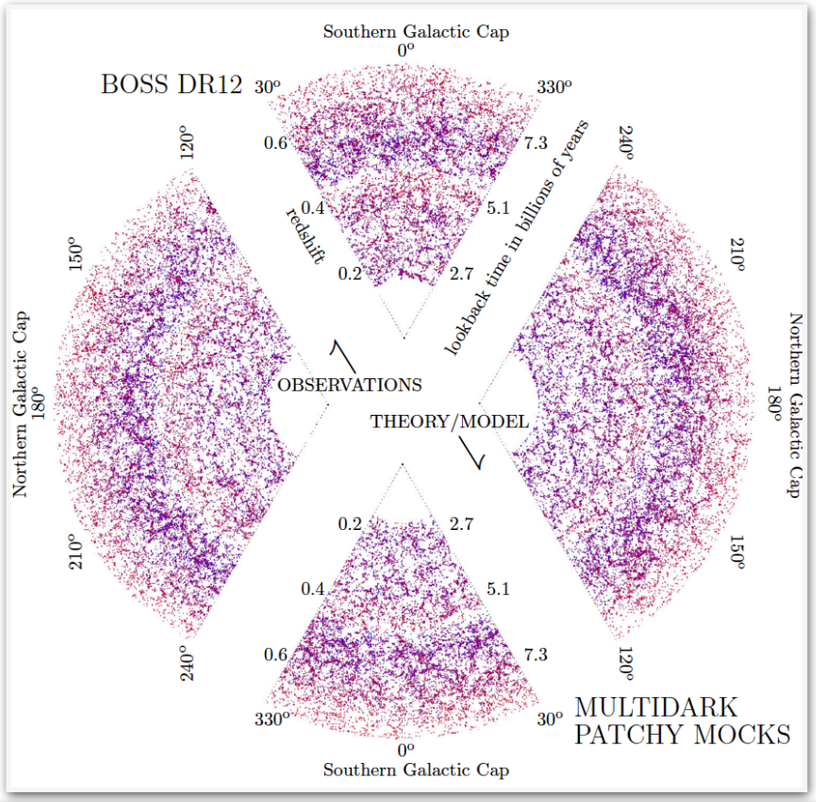
- Neutrino masses
- Hierarchy problem
- Baryogenesis
- Quantum gravity
- …

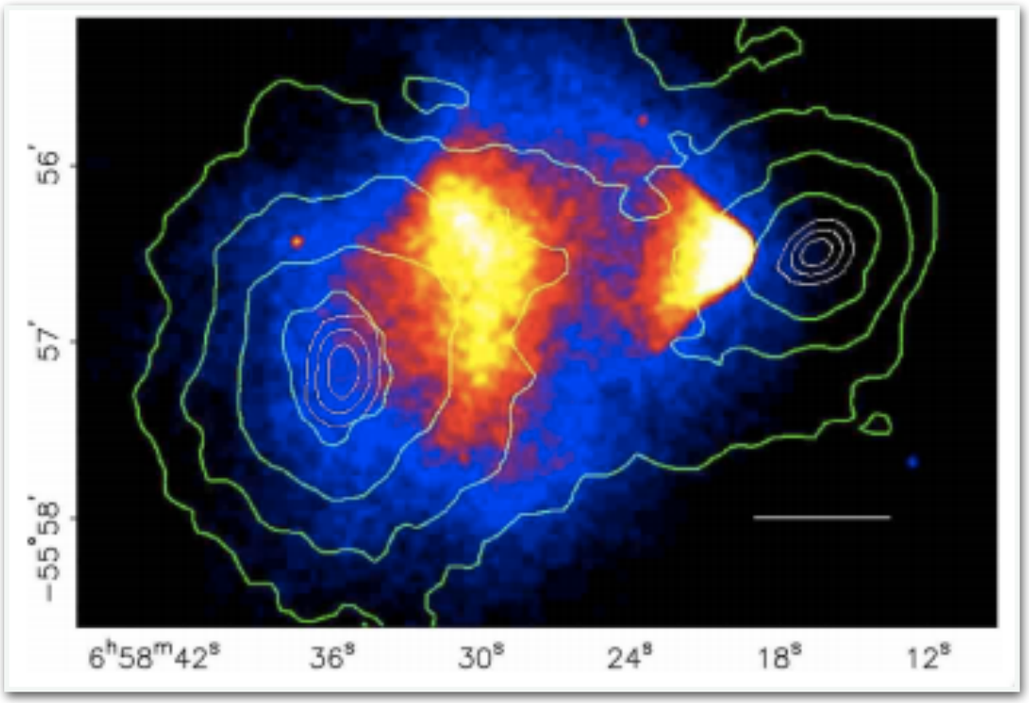
Physics BSM can take many forms - from minimal extensions to many hidden (dark) sectors.

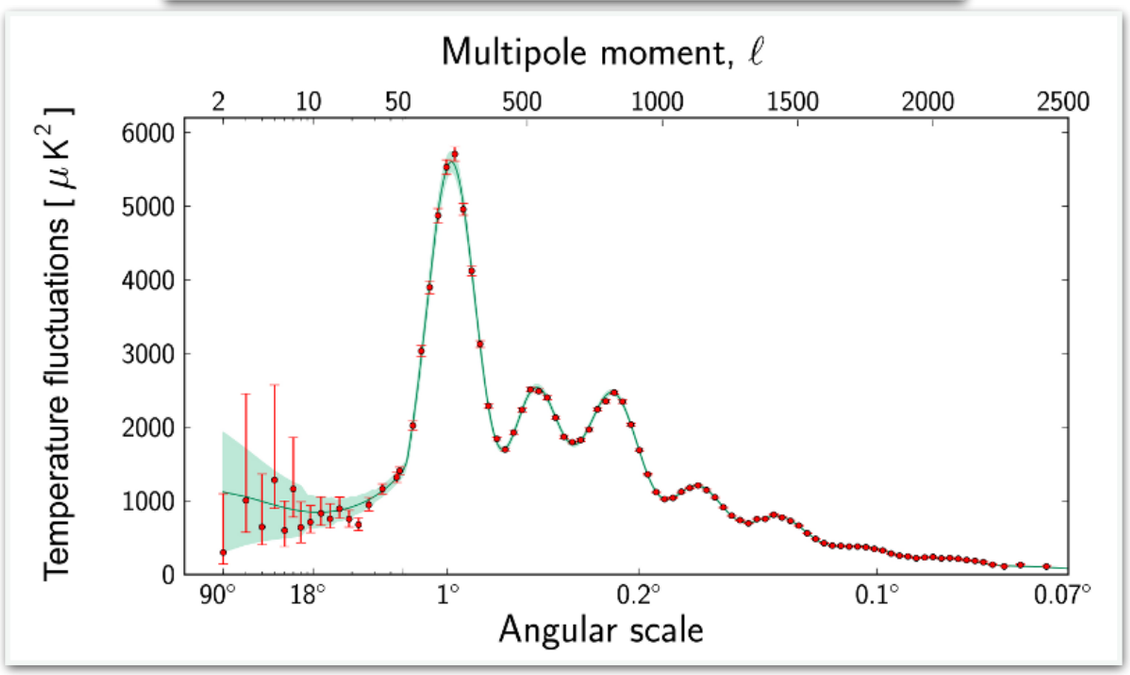
Dark Matter in the Universe

Evidence on *multiple scales* due to gravitational interactions:



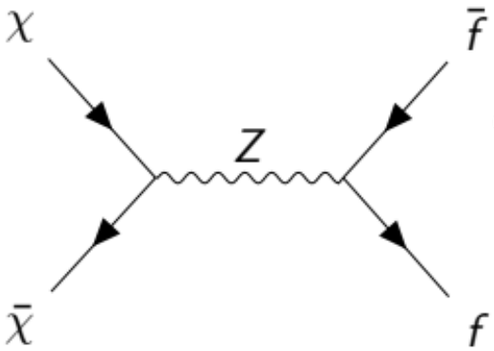






Thermal DM benchmark - WIMP

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 $\Omega h^2 \approx 0.1$.



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

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

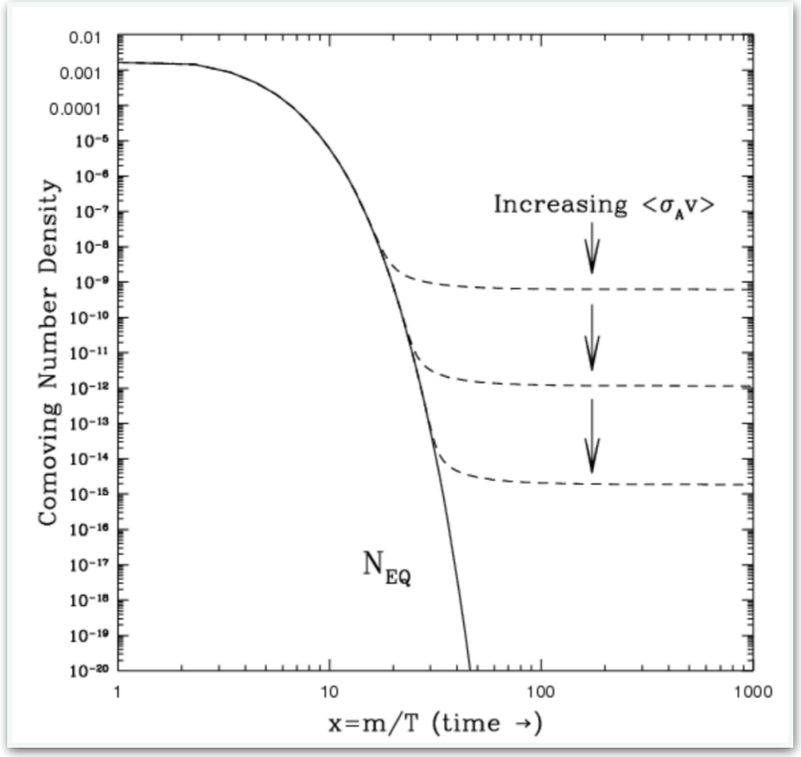
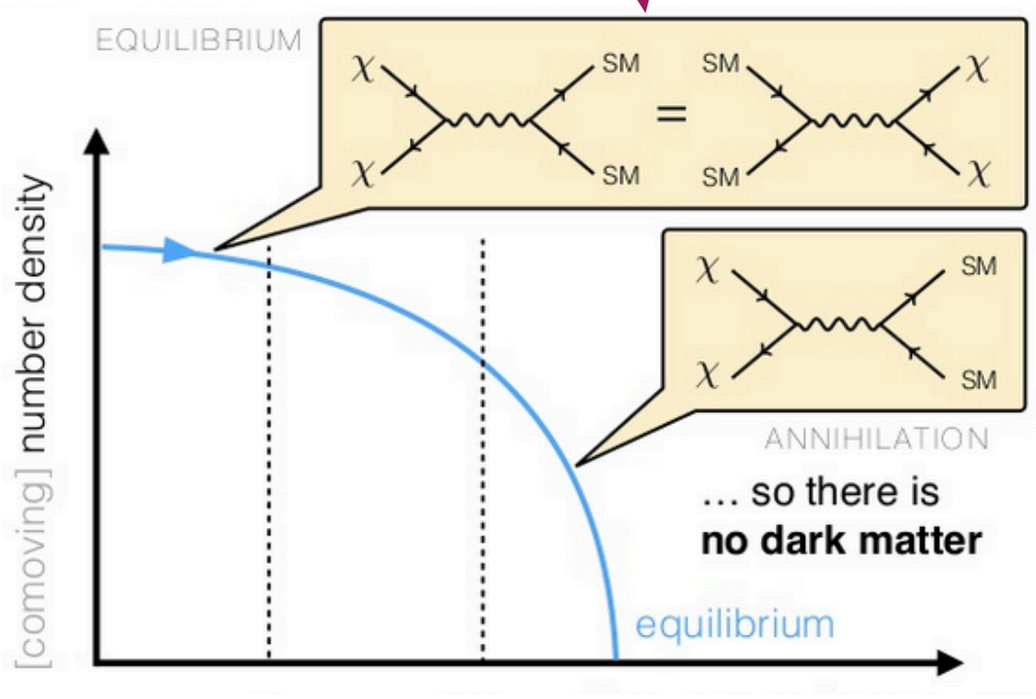
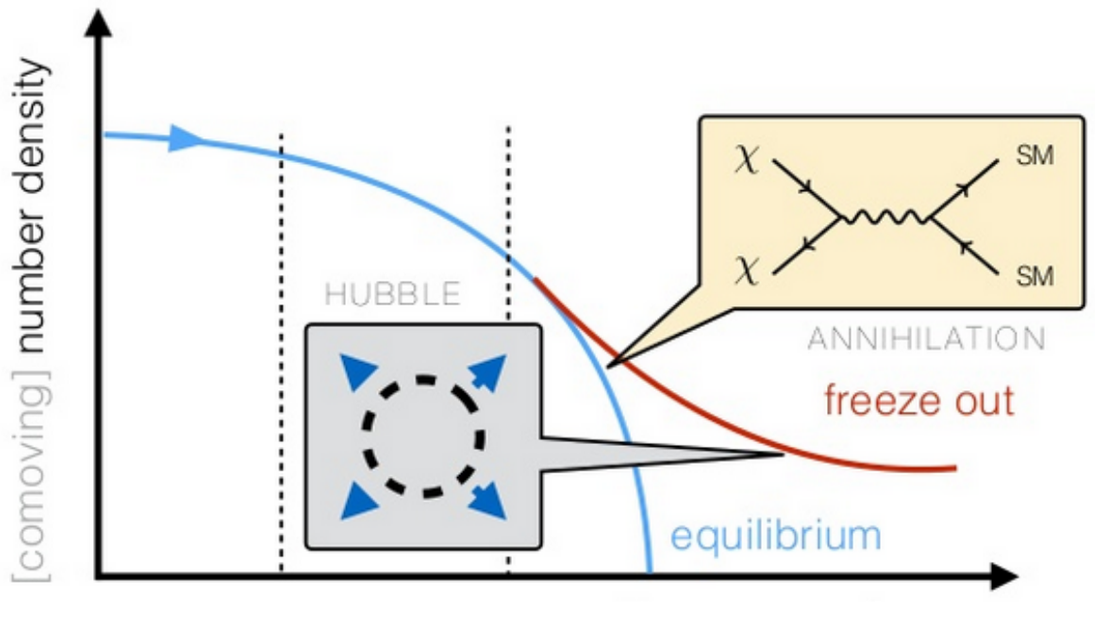


Figure by E. Kolb and M. Turner





Figures by F. Tanedo

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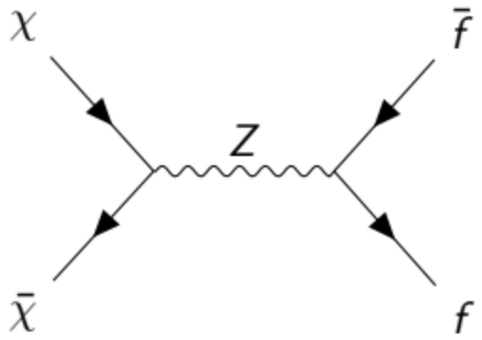
Looking for WIMPs

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 $\Omega h^2 \approx 0.1$.



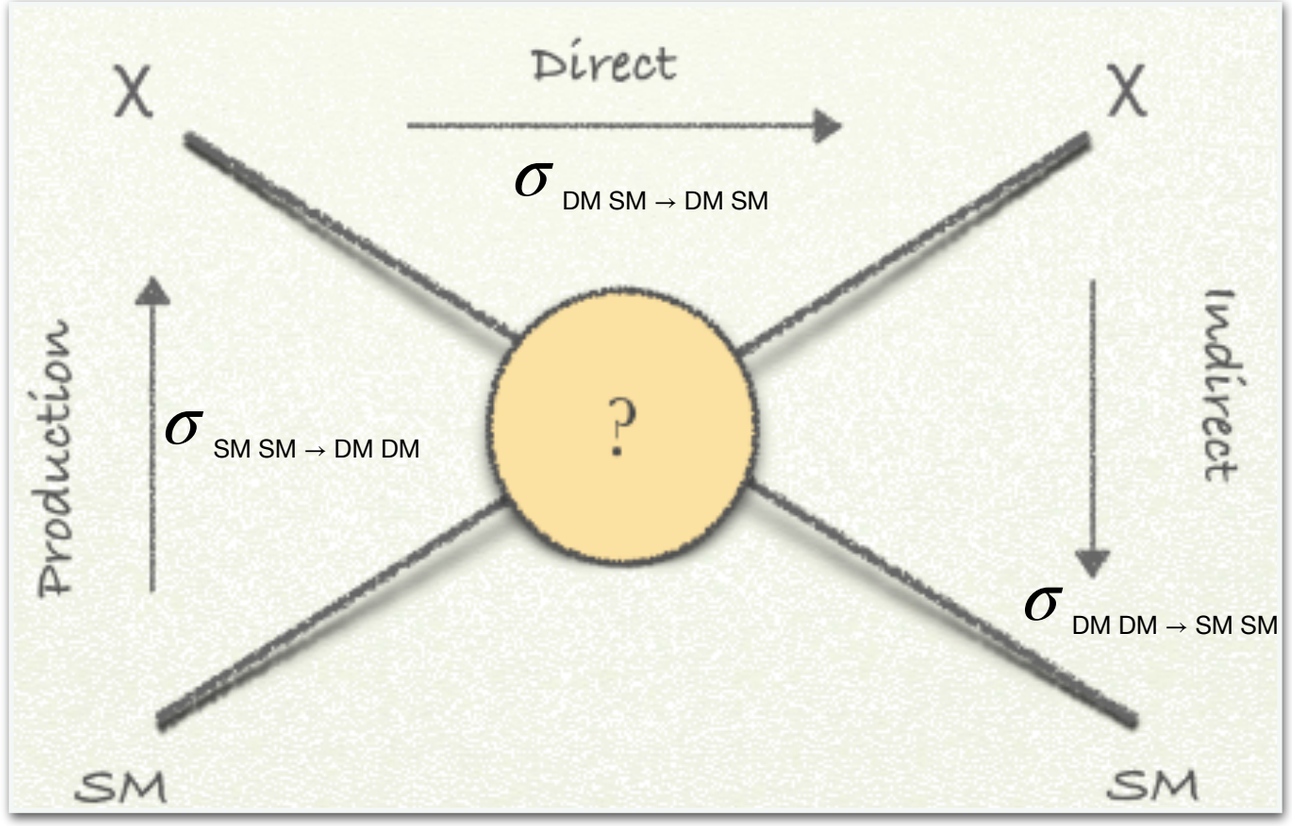
$$\sigma \propto \frac{g^4}{m_\chi^2}$$

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

Crossing symmetry

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

multiple detection possibilities



Indirect Detection of WIMPs

DM+DM→SM+SM

$$\left[\frac{1}{\mathrm{cm^2\ s\ GeV}}\right] \quad \frac{\mathrm{d}\Phi_\gamma^{\mathrm{DM}}}{\mathrm{d}E}(\Delta\Omega, E) = \frac{\sigma v_0}{8\pi m_{\mathrm{DM}}^2}\frac{\mathrm{d}N_\gamma(E)}{\mathrm{d}E} \times J(\Delta\Omega)$$

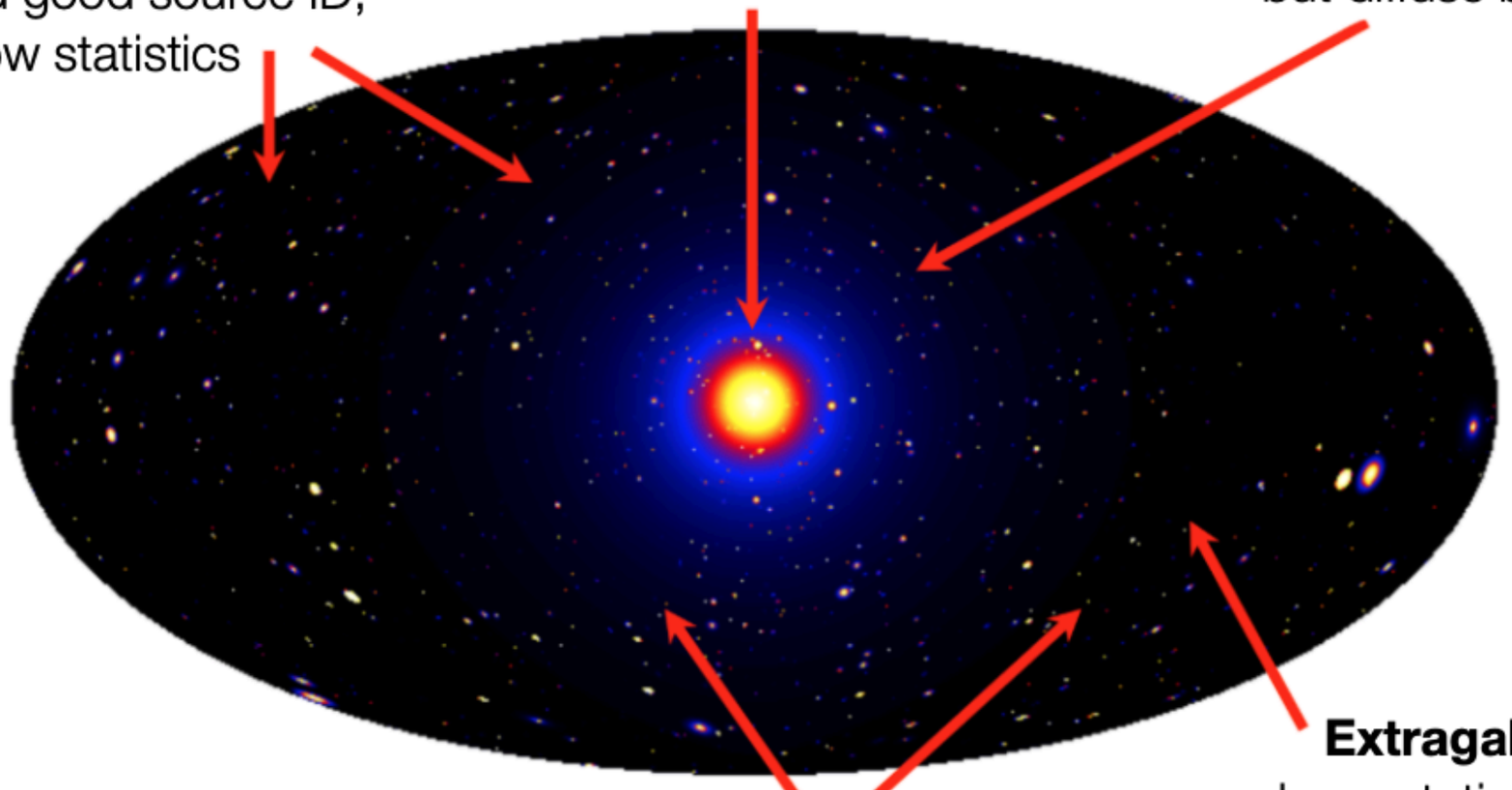
Flux ⟶ counting the photons

$$J(\Delta\Omega) \equiv \int_{\Delta\Omega} \mathrm{d}\Omega \int_0^\infty \mathrm{d}s\ \rho_{\mathrm{DM}}^2(r(s,\theta))$$

Dwarf Satellite Galaxies
low BG and good source ID,
but low statistics

Galactic Center
good statistics, but source confusion
and diffuse background

Milky Way Halo
good statistics,
but diffuse background



Galaxy Clusters
low background,
but low statistics

Extragalactic
large statistics, but
astrophysical foregrounds and
Galactic diffuse background

Fig. J. Kopp

arXiv:0908.0195,
Fermi-LAT,
KIPAC/Stanford

Long Lived Particles

Intensity Frontier

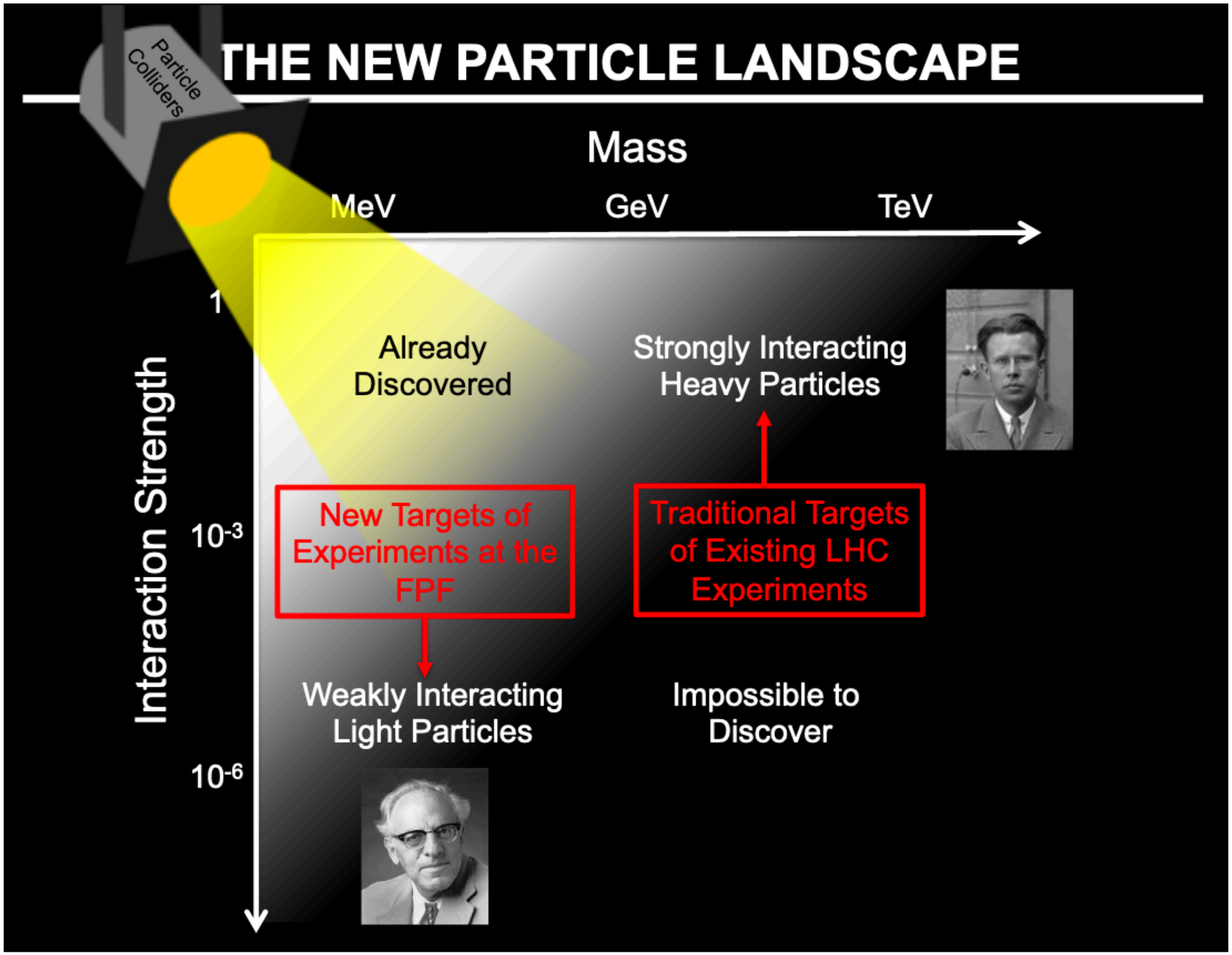


Figure by J. Feng

Intensity Frontier

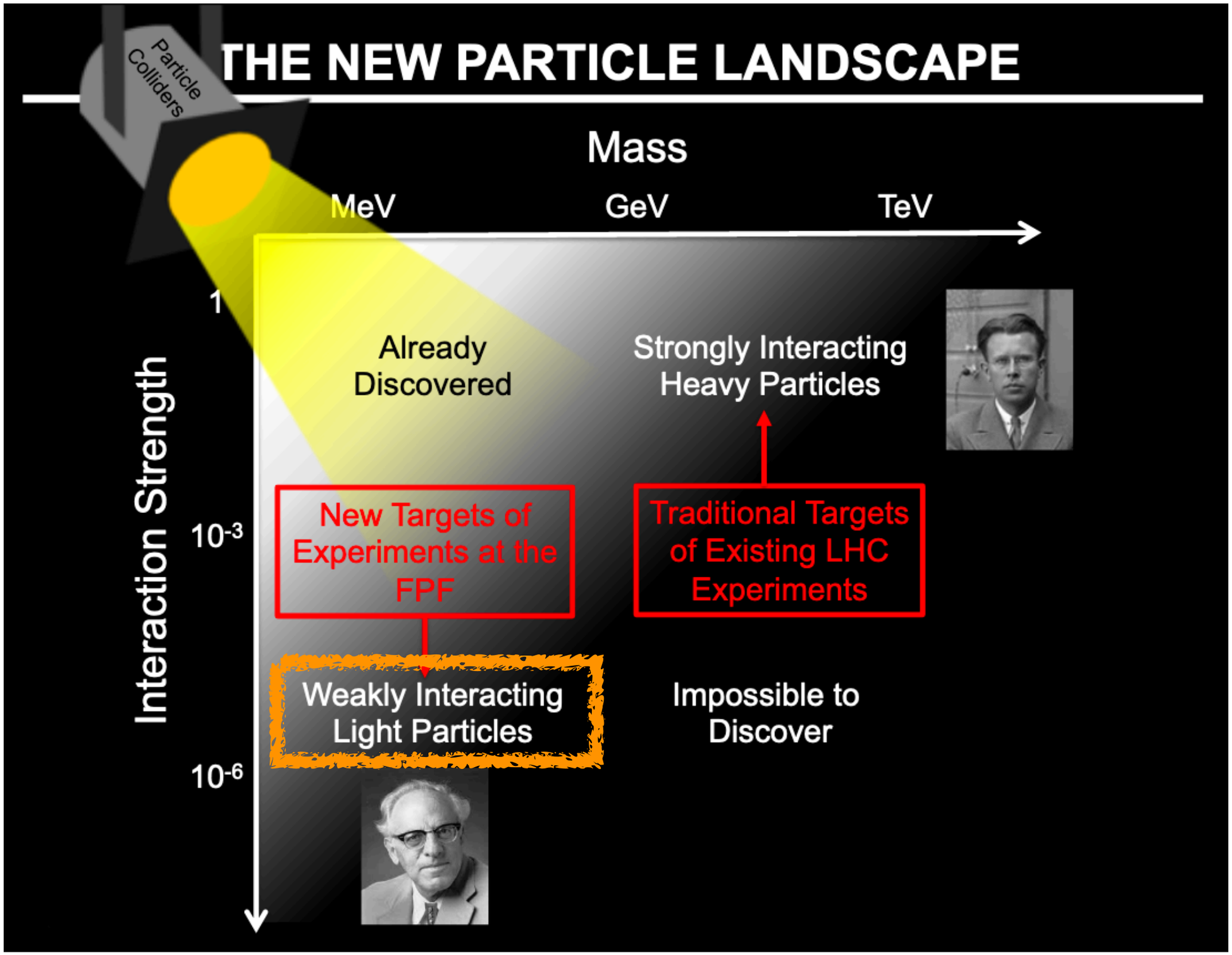


Figure by J. Feng

Intensity frontier searches

Light, weakly interacting particles

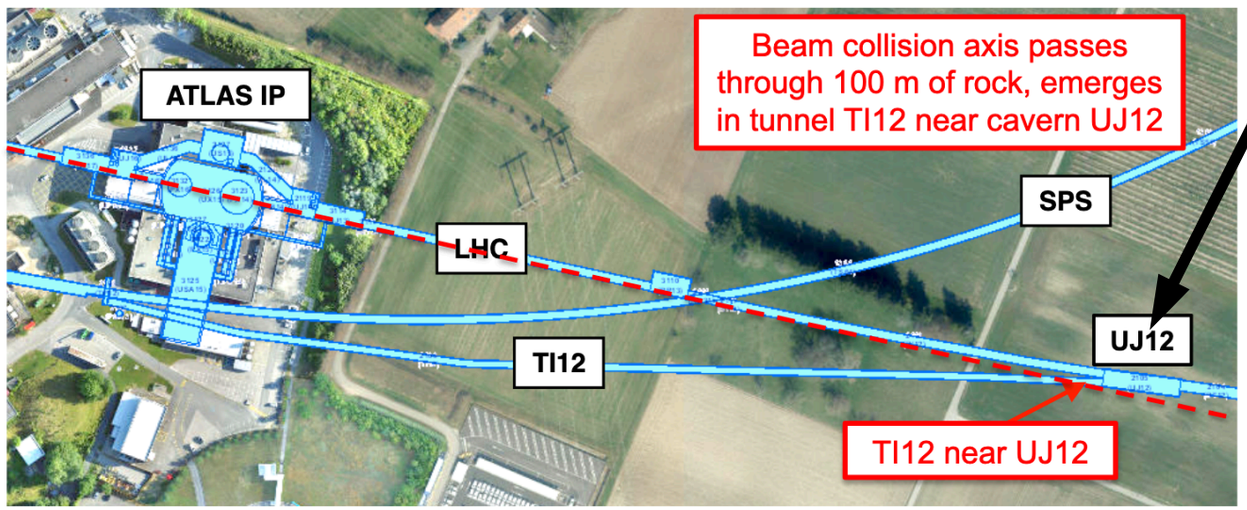
Weak couplings ⟶ large luminosities required

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

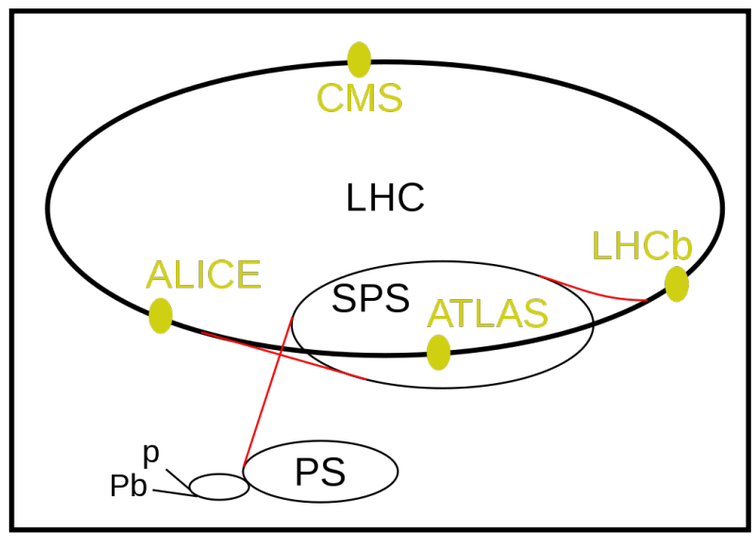
- WIMPless-DM
- $(g-2)_\mu$
- neutrino masses, HNL
- …

- Beam dump experiments (proton, electron)
- Use LHC wasted luminosity as “beam”

→ *Forward Physics Facility*



The Forward Physics Facility, 2109.10905



LLPs are ubiquitous

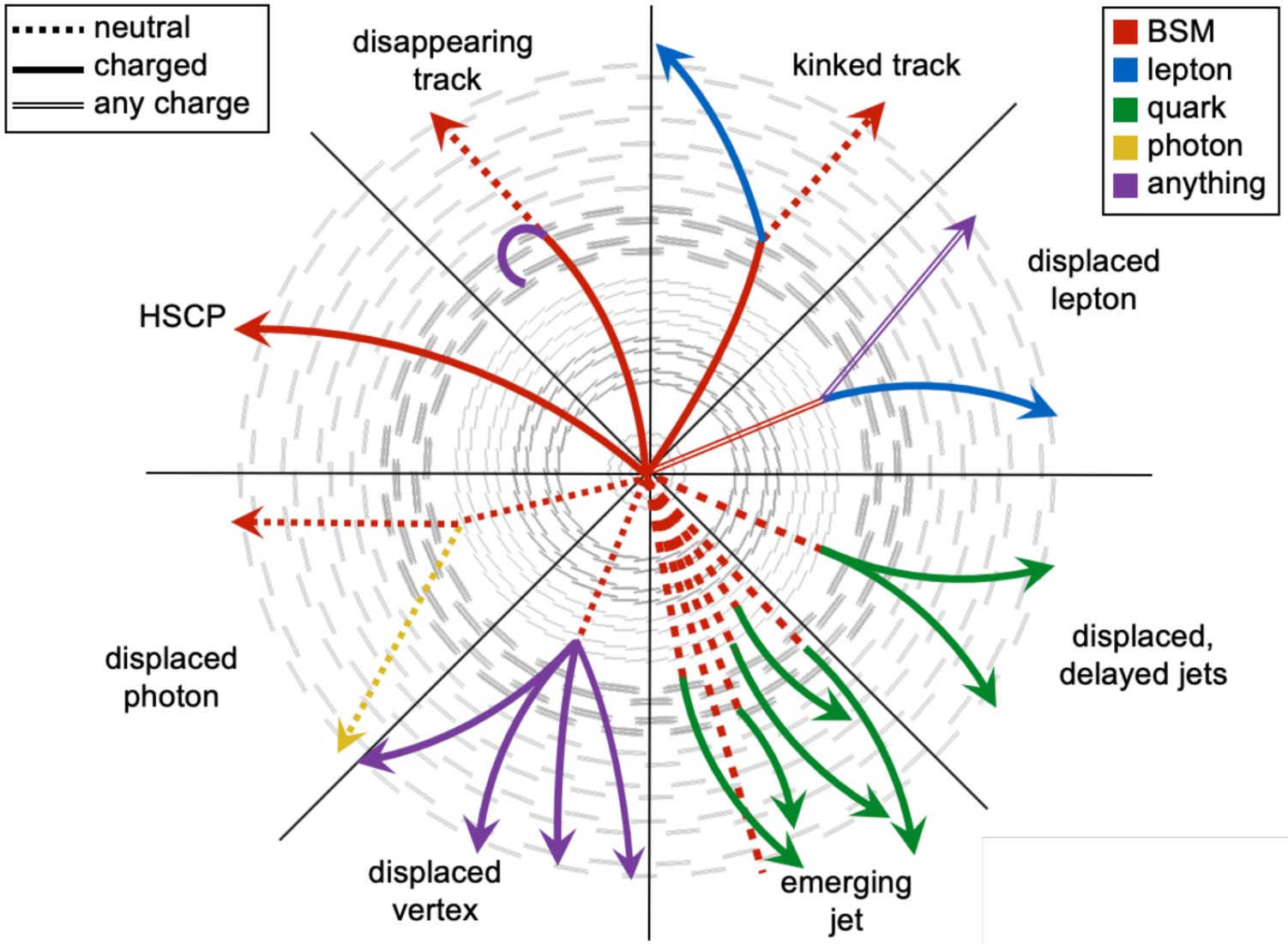


Fig. from S. Westhoff

- 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
- …

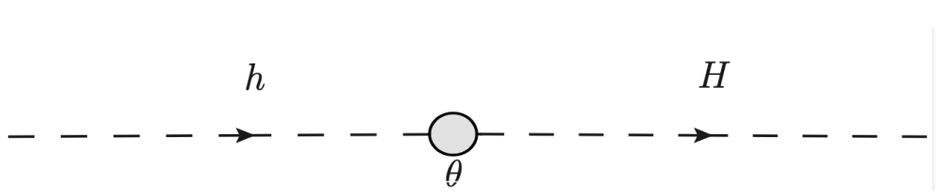
often invoked in context of baryogenesis, neutrino masses, hierarchy problem, …

dark Higgs-dark photon portal to heavy DM

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 $h_D \to \text{SM SM}$.

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

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

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

Further, we set $\epsilon = 0$, so A' has no direct coupling to SM. General case - future work.

No interactions breaking C-symmetry
$\rightarrow \epsilon = 0$ preserved at the loop level.

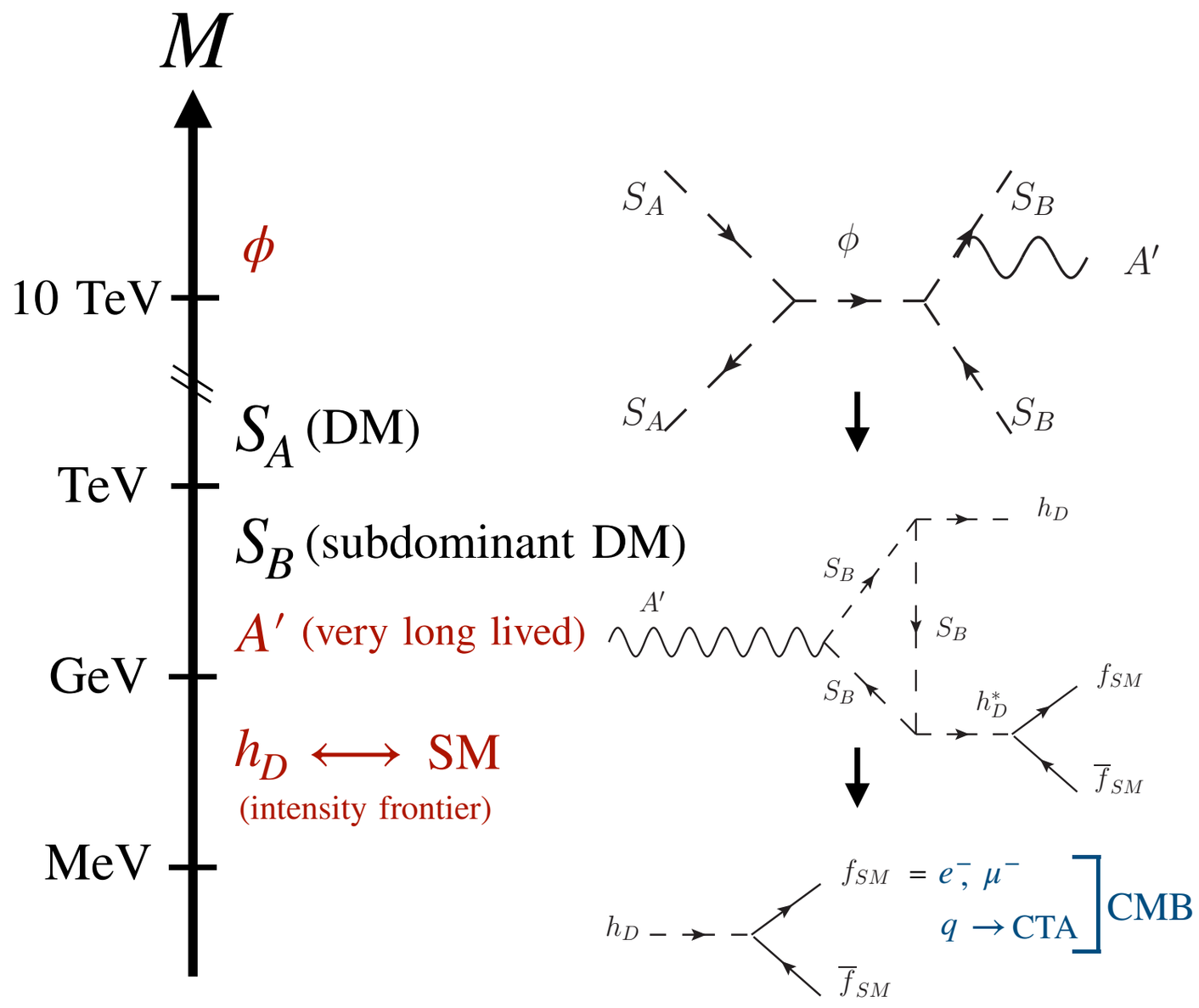
Matter fields - two component DM

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

DM is comprised of complex scalars S_A, S_B which we connect by heavy connector 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



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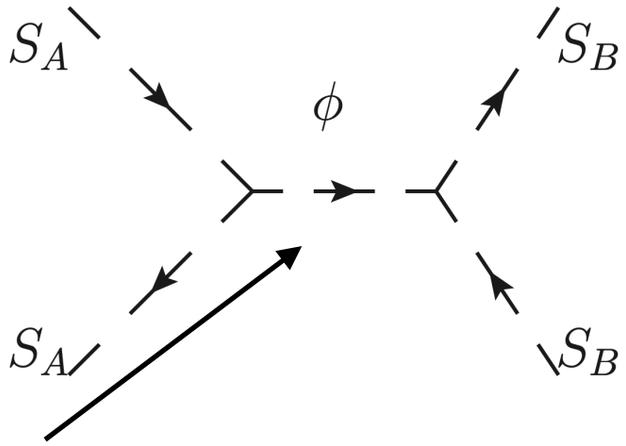
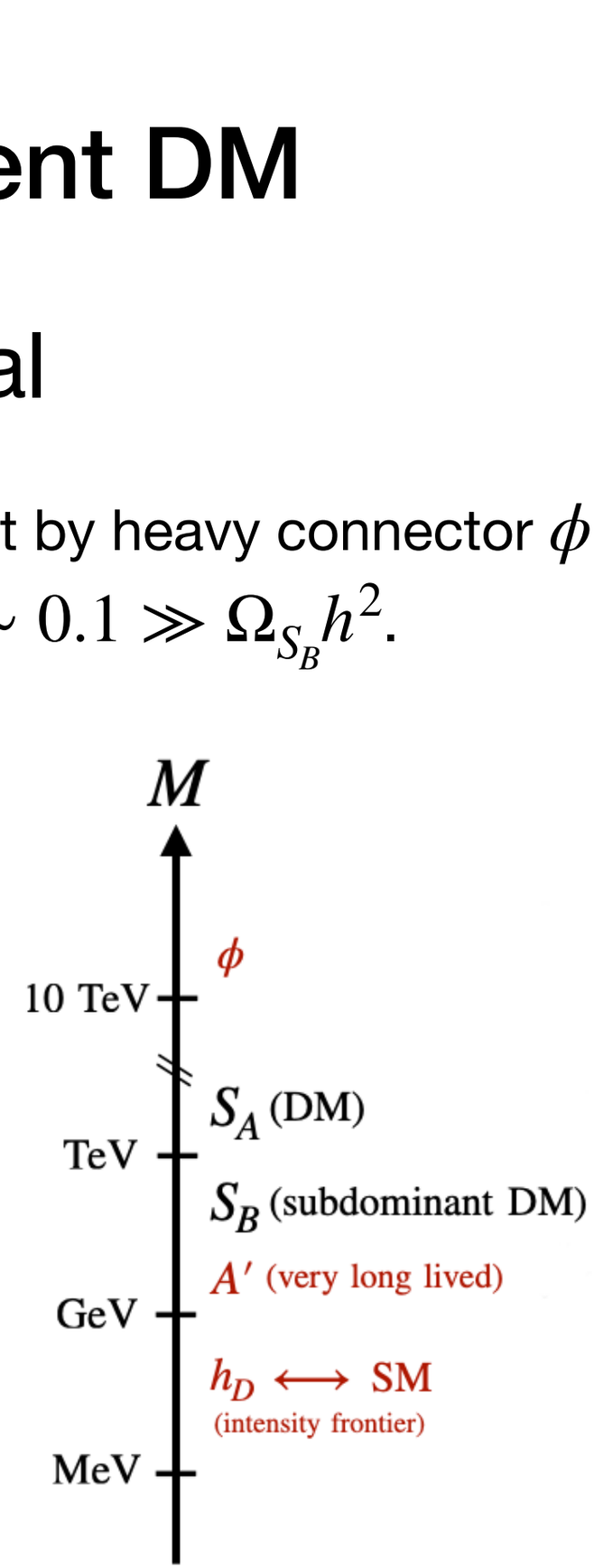


Interactions within the DS

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



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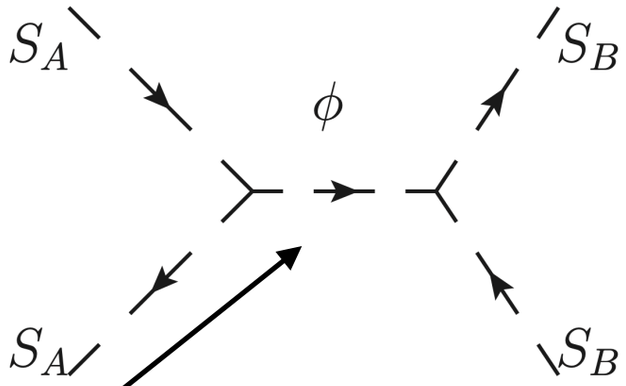

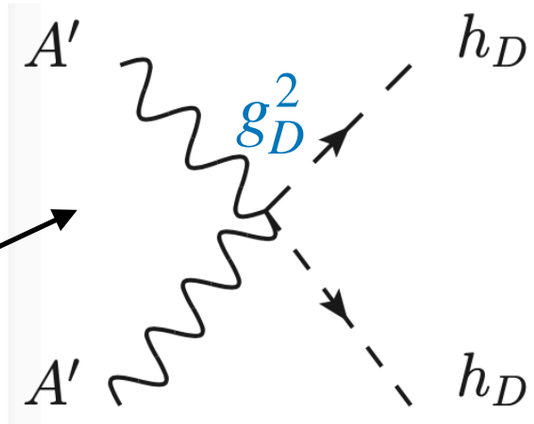

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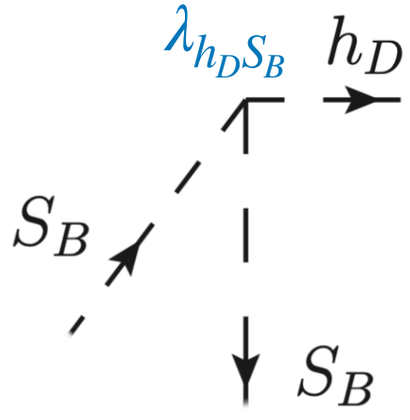
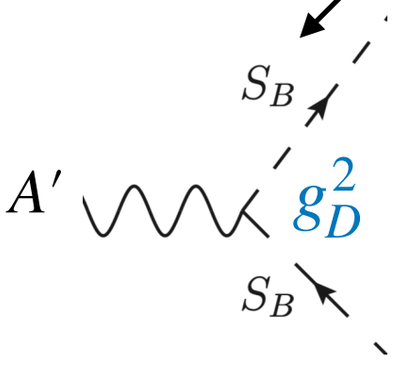
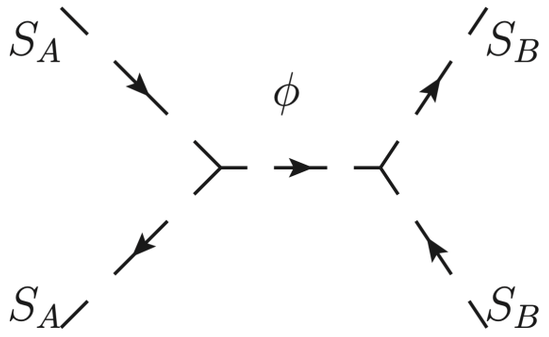
$$+ i q_{S_B} g_D A'_{\mu} \left[S_B^* \left(\partial^{\mu} S_B\right) - \left(\partial^{\mu} S_B^*\right) S_B\right] - \lambda_{h_D S_B} h_D^2 \left|S_B\right|^2 \longrightarrow$$





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

Thermal history

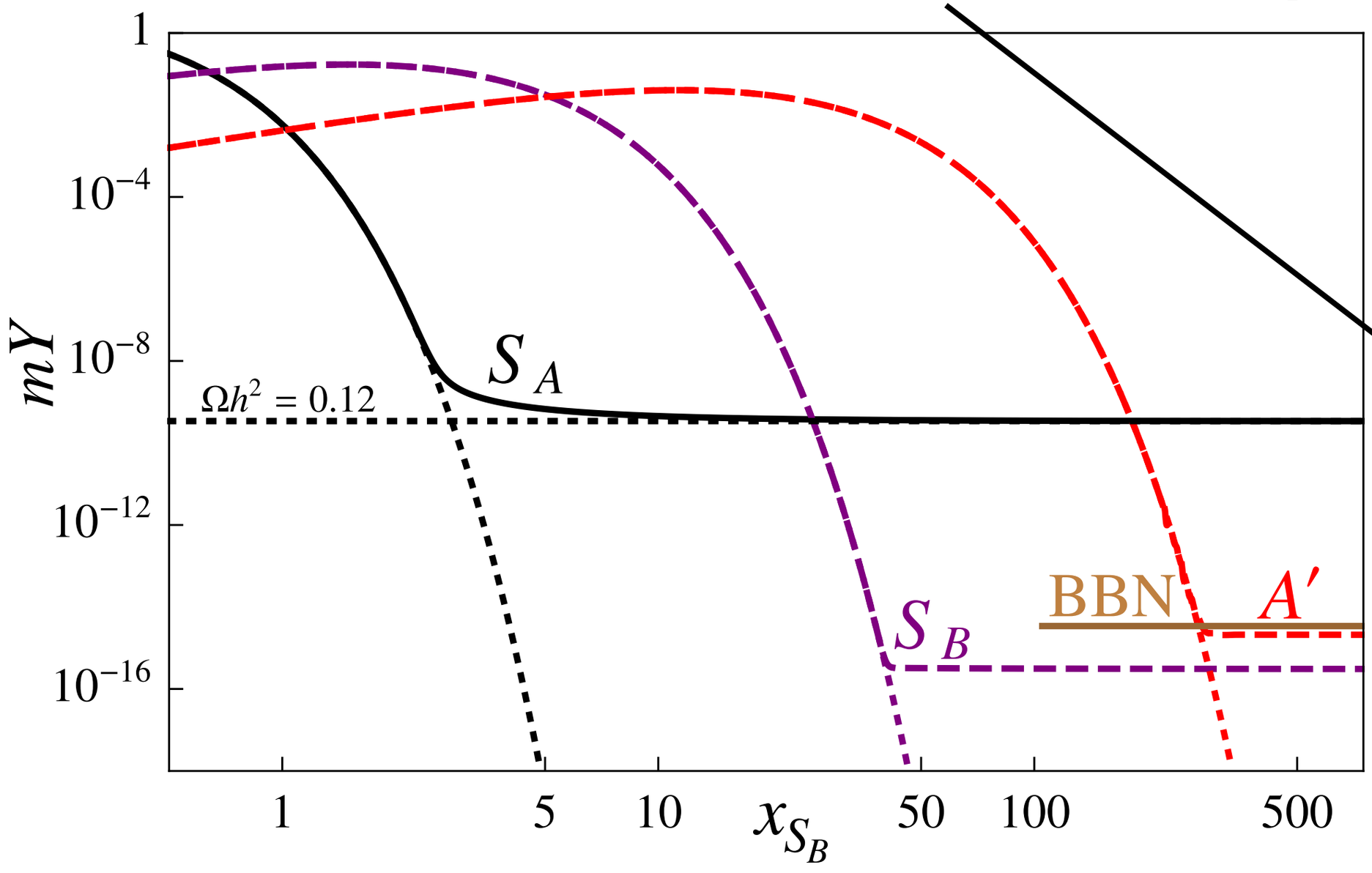


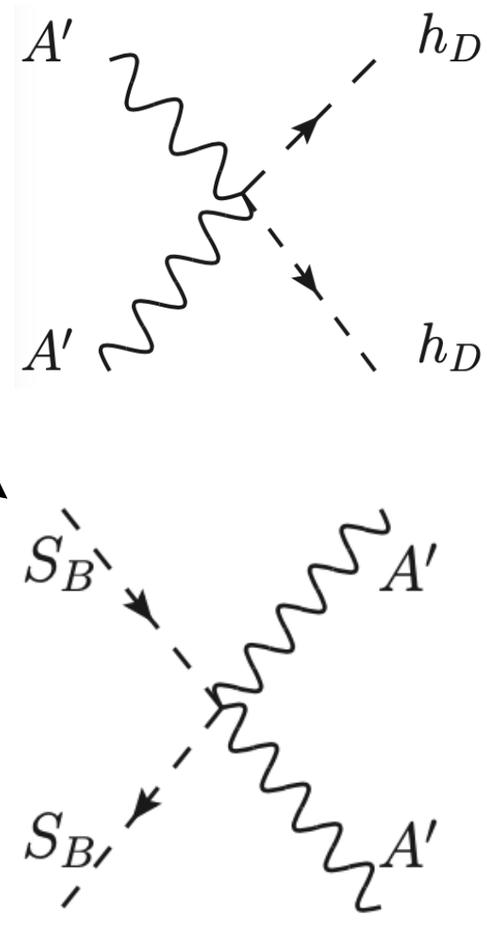
$$\frac{dY_{S_A}}{dx} = -\frac{\lambda_{S_A}}{x^2}\left(Y_{S_A}^2 - \frac{Y_{S_B}^2}{\left(Y_{S_B}^{\rm eq}\right)^2}\left(Y_{S_A}^{\rm eq}\right)^2\right)$$

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

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

Assisted freeze-out



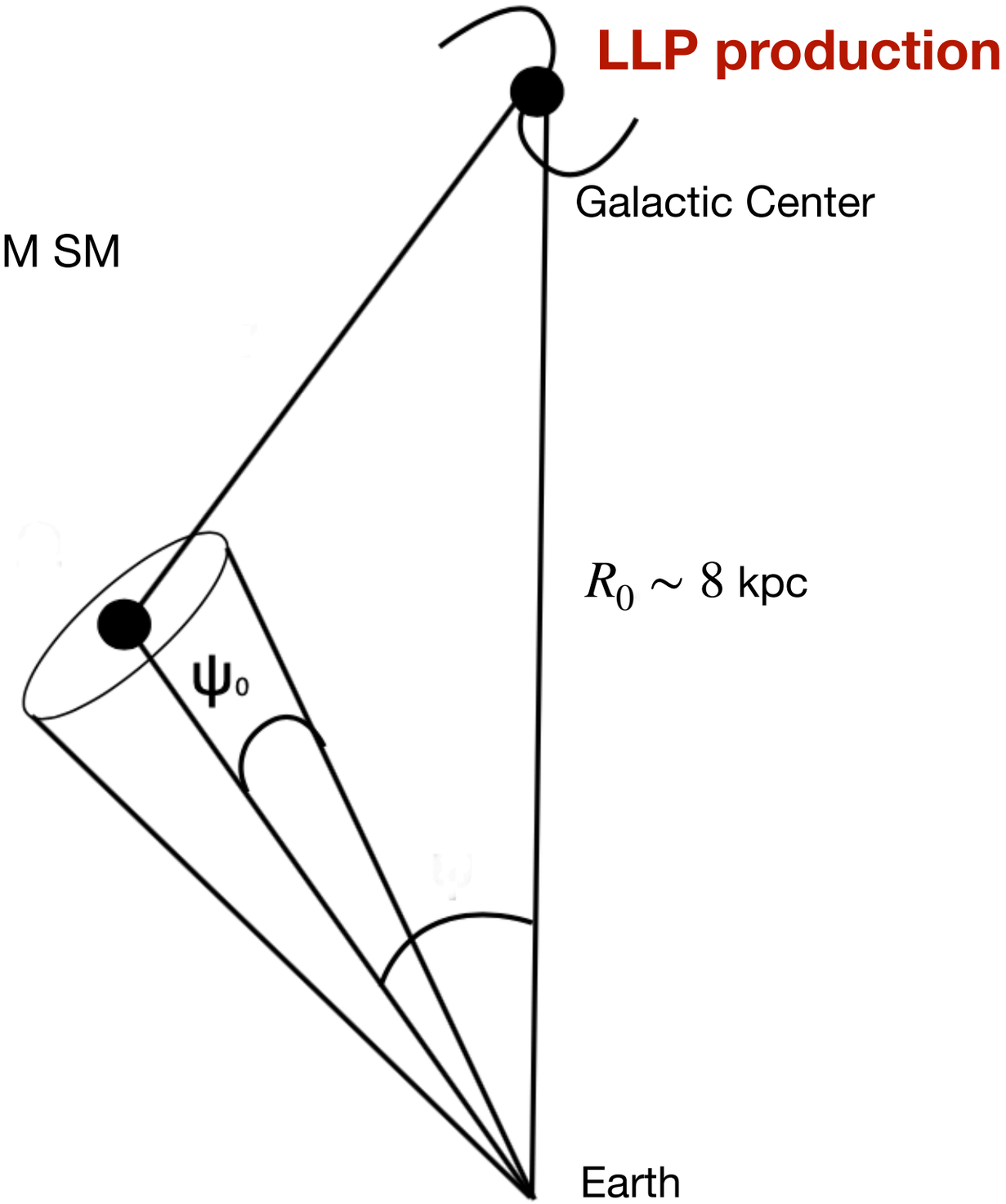


Indirect Detection of Long Lived Particles

ID of LLPs

DM DM → LLP LLP

LLP → SM SM



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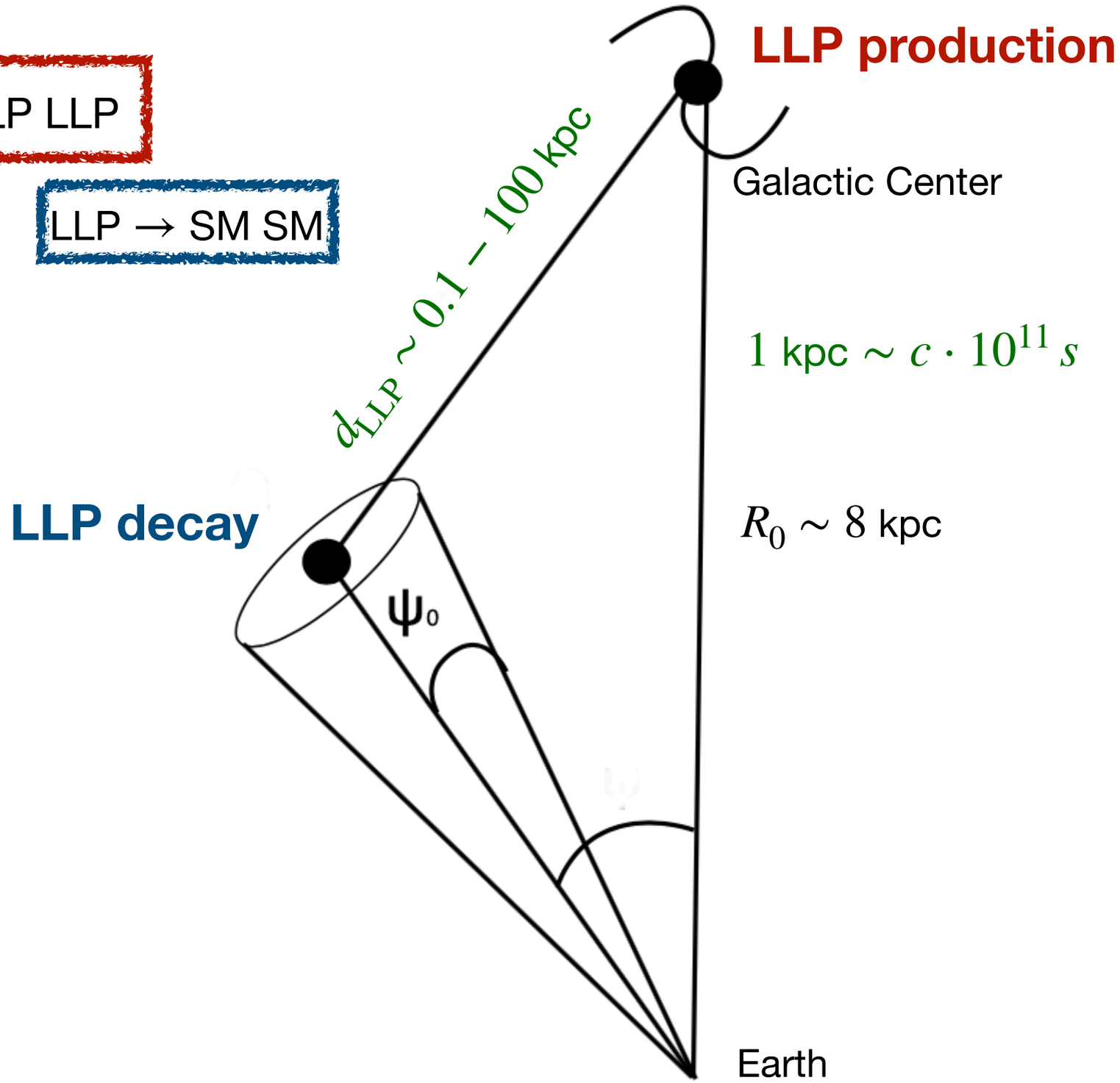
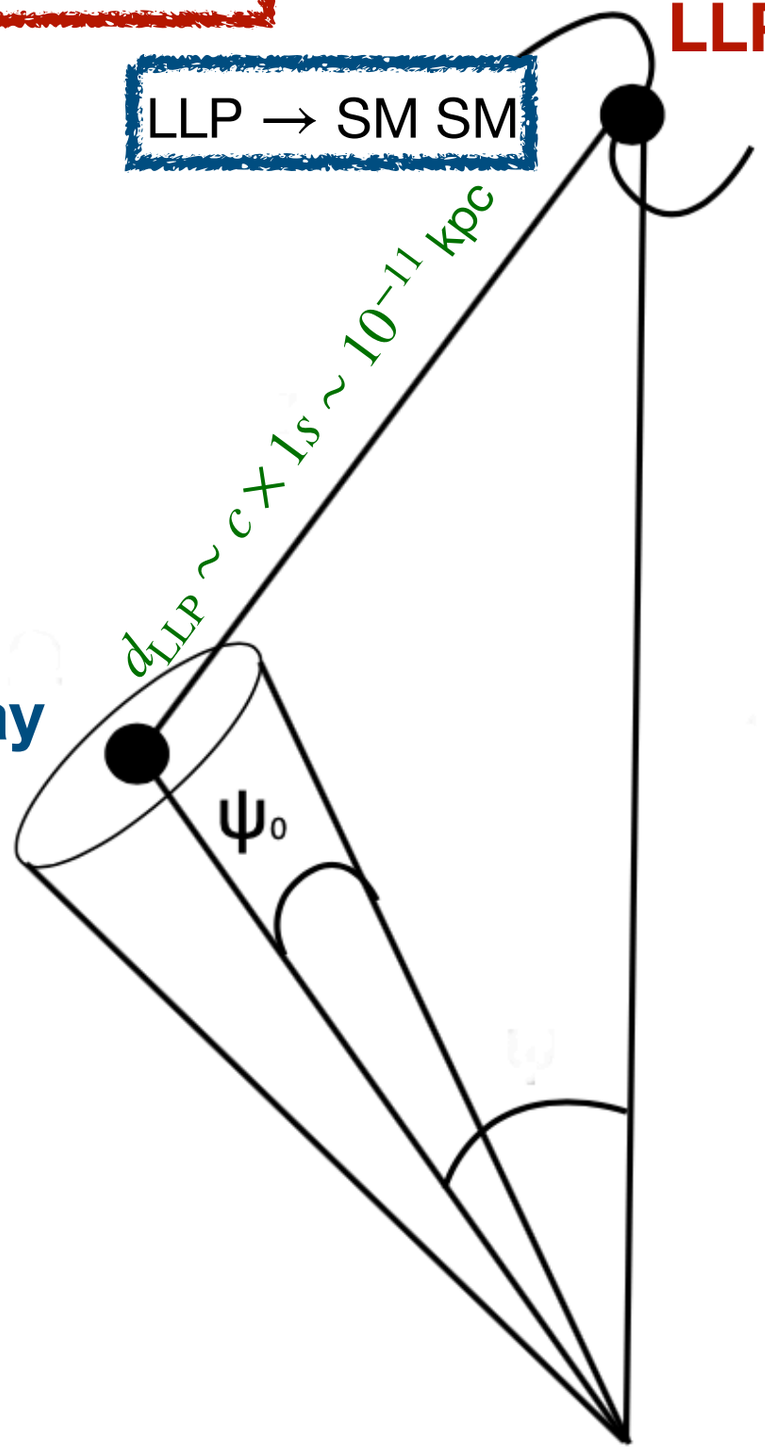


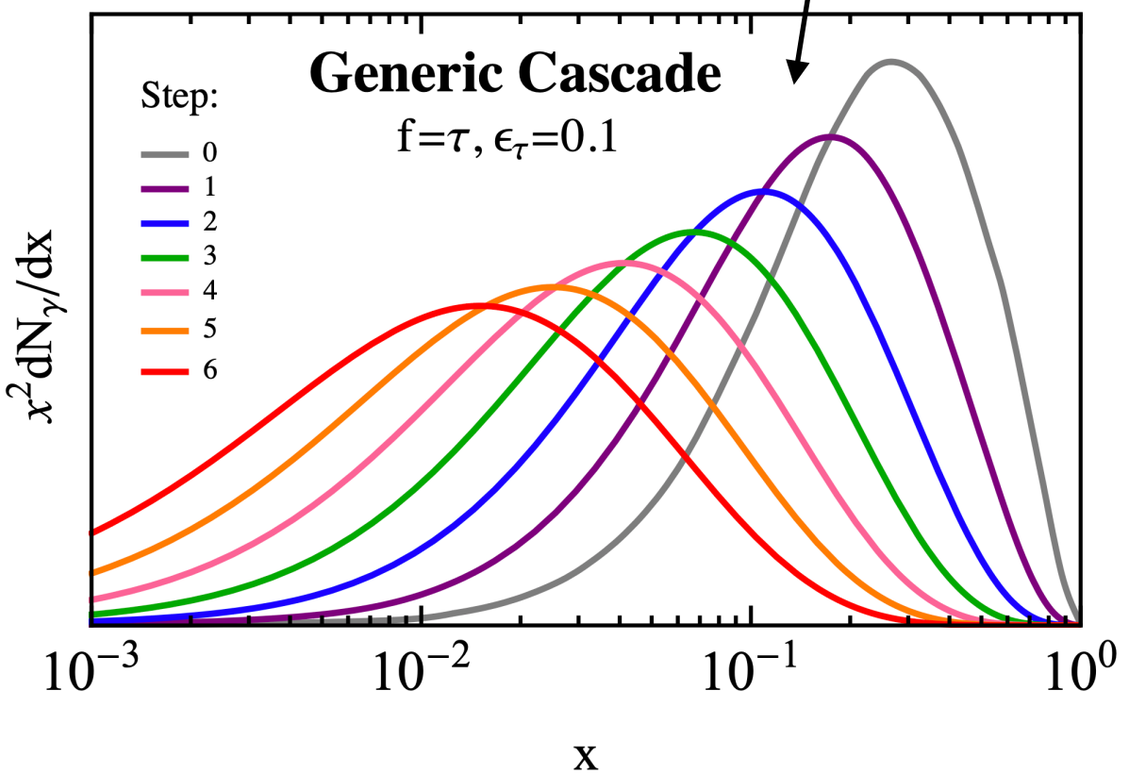
Short lifetime regime - secluded WIMP

DM DM → LLP LLP

LLP → SM SM



Bringmann, Weniger, 1208.5481
Elor, Rodd, Slatyer, 1503.01773
…



Cascades lead to softer spectrum

Master formula unchanged, only spectrum changes

$$\frac{dN_\gamma}{dx_1} = 2\int_{t_{1,\min}}^{t_{1,\max}} \frac{dx_0}{x_0\sqrt{1-\epsilon_1^2}} \frac{dN_\gamma}{dx_0}$$

Boost from LLP RF to LAB

$x_i = 2E_\gamma/m_i \qquad \epsilon_1 = m_{LLP}/m_{DM}$

Long lifetime regime

DM DM → LLP LLP

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

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

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

DM DM → LLP LLP

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

Survival probability of LLP

spectrum

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

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.

Compare to formula for WIMP ID

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

Short lifetime regime → WIMP ID

DM DM → LLP LLP

LLP → SM SM

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

For short lifetime, the only contribution comes from $\vec{r}_{DM} \to \vec{r}_{LLP}$, therefore $\rho = const$ and there is no anisotropy → *we regain the standard result.*

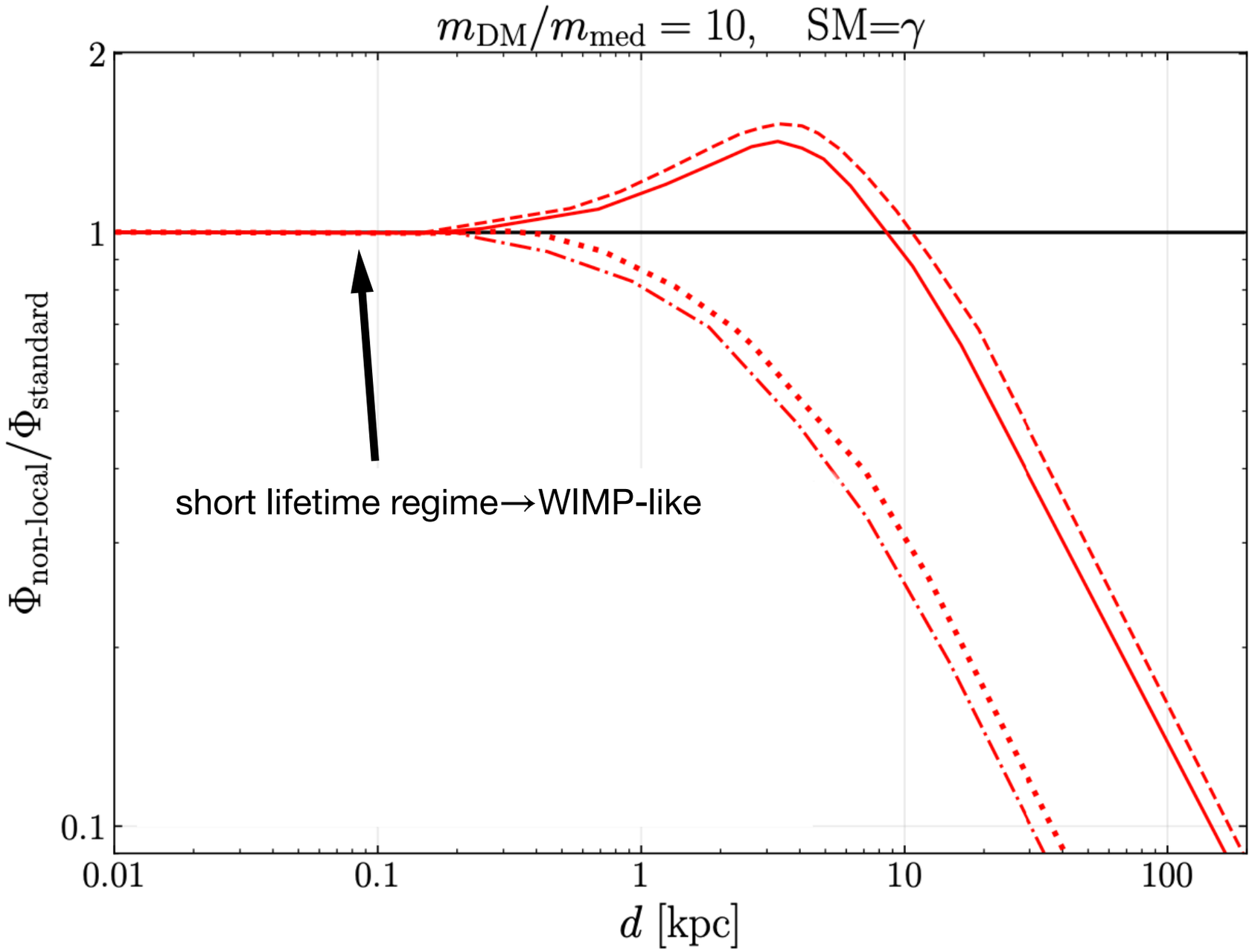
$$\Phi_{d_{\rm LLP}\to 0} = \frac{\langle \sigma v \rangle_0}{8\pi m_{\rm DM}^2} \int_{\Delta\Omega} d\Omega \int_{\rm los} \rho_{\rm DM}^2 ds \int_{\Delta E_\gamma} dE_\gamma \frac{dN_\gamma^X}{dE_\gamma}$$

Long lifetime regime

DM DM → LLP LLP

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

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



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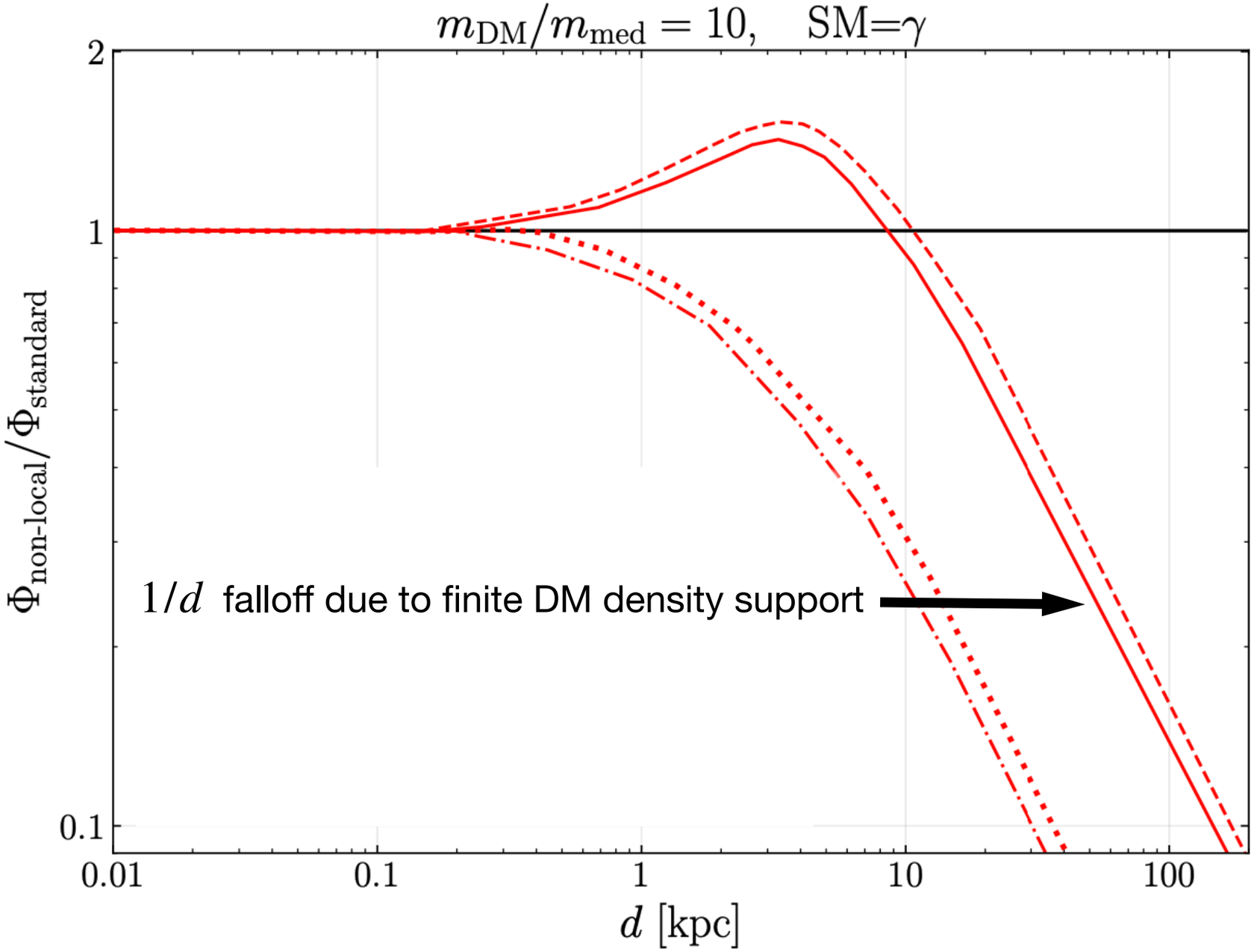

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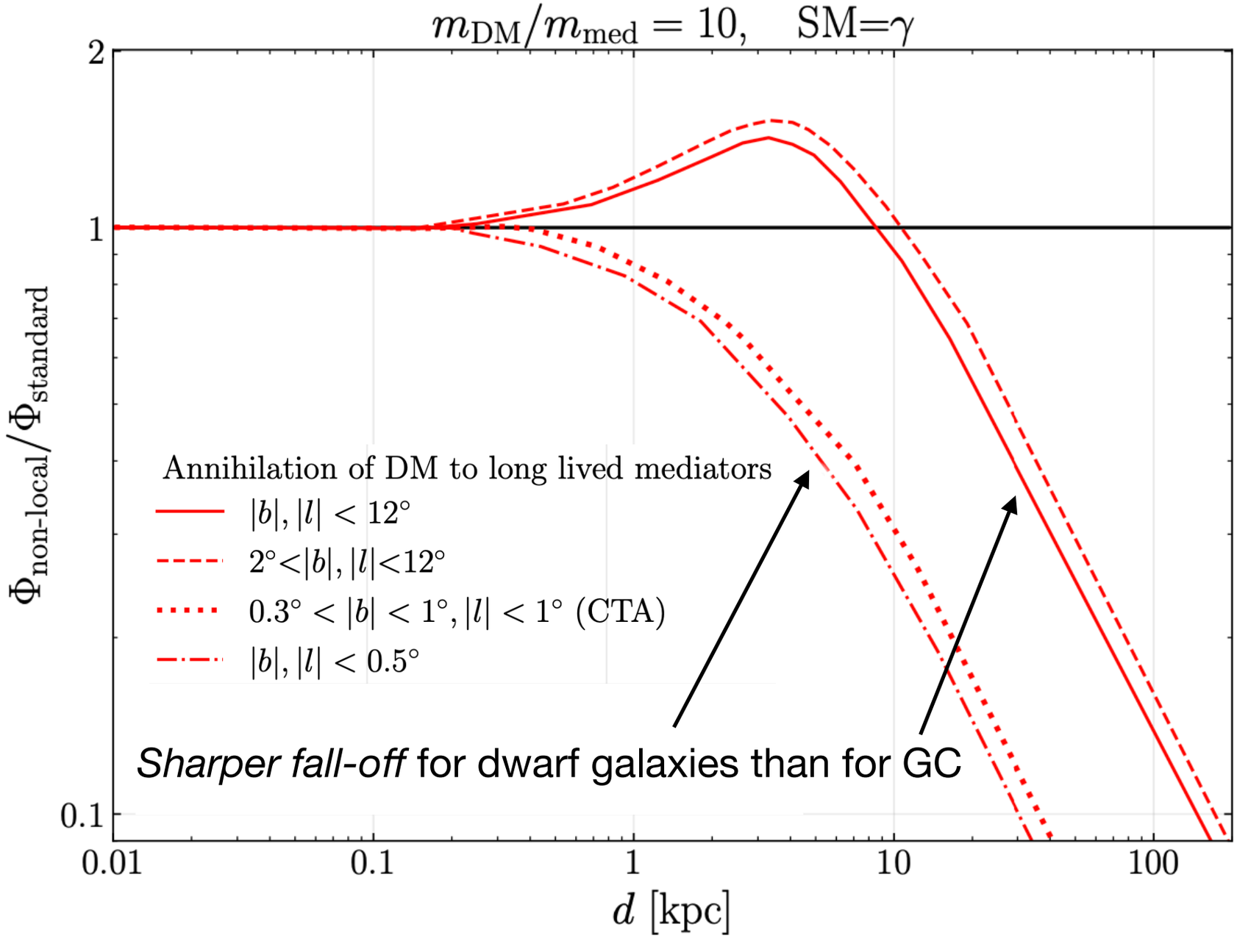

Long lifetime regime

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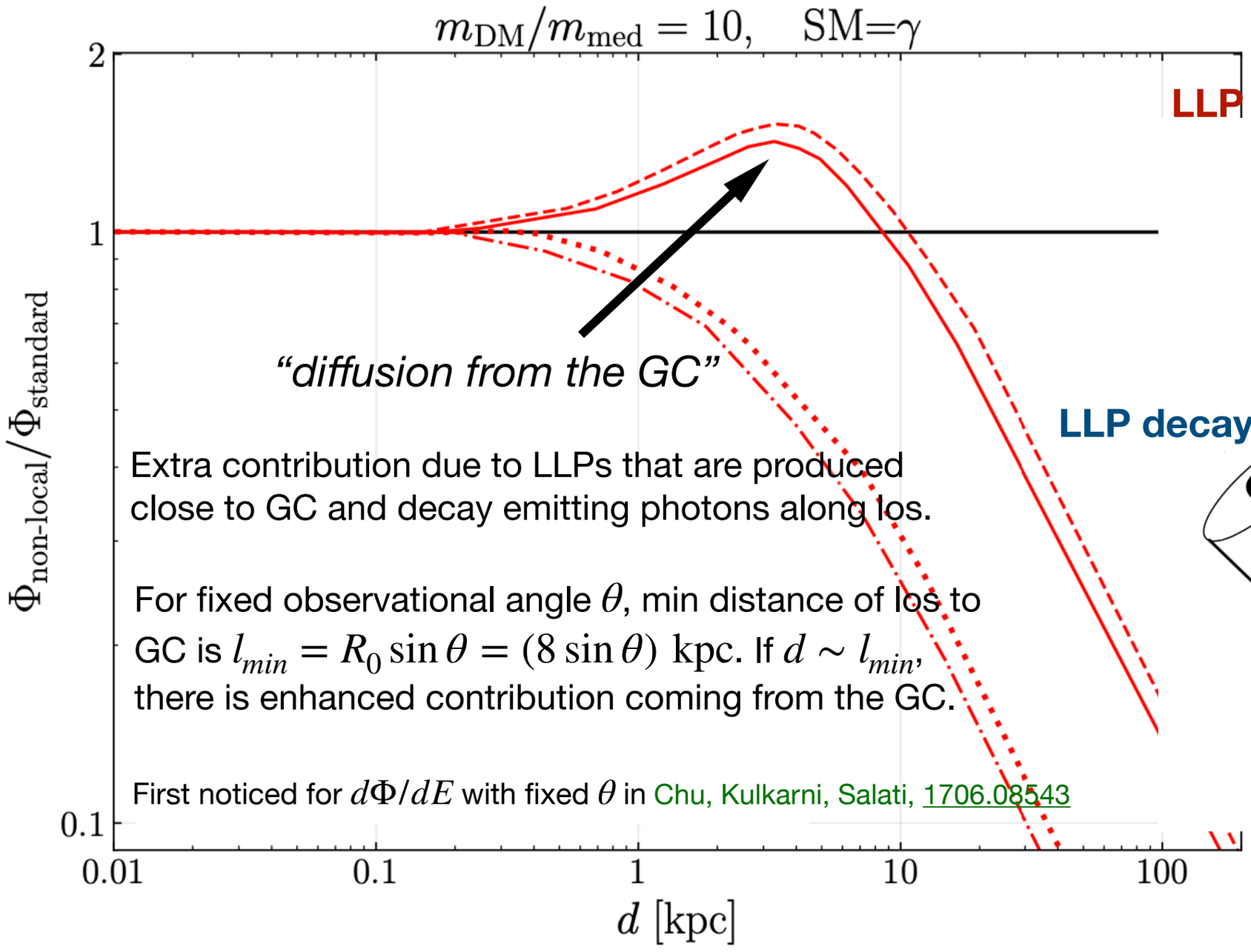
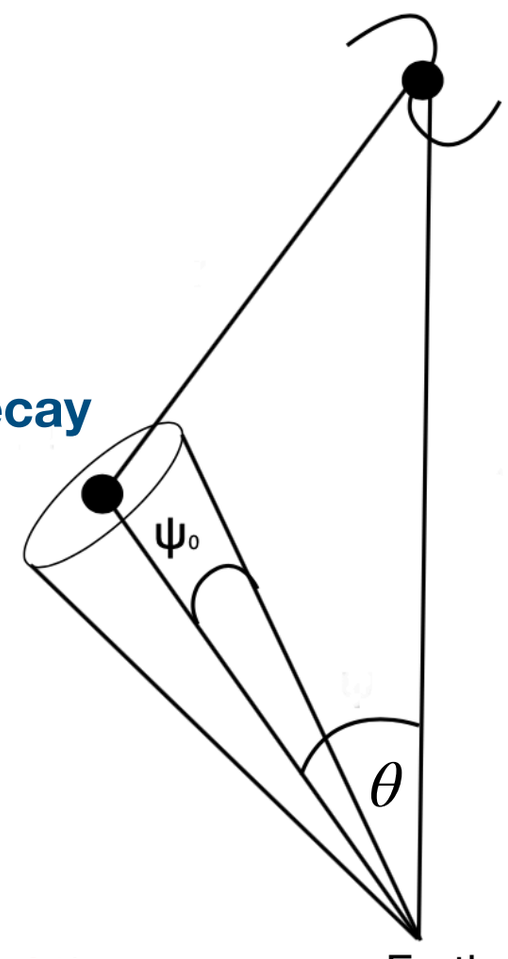


Extra contribution due to LLPs that are produced close to GC and decay emitting photons along los.

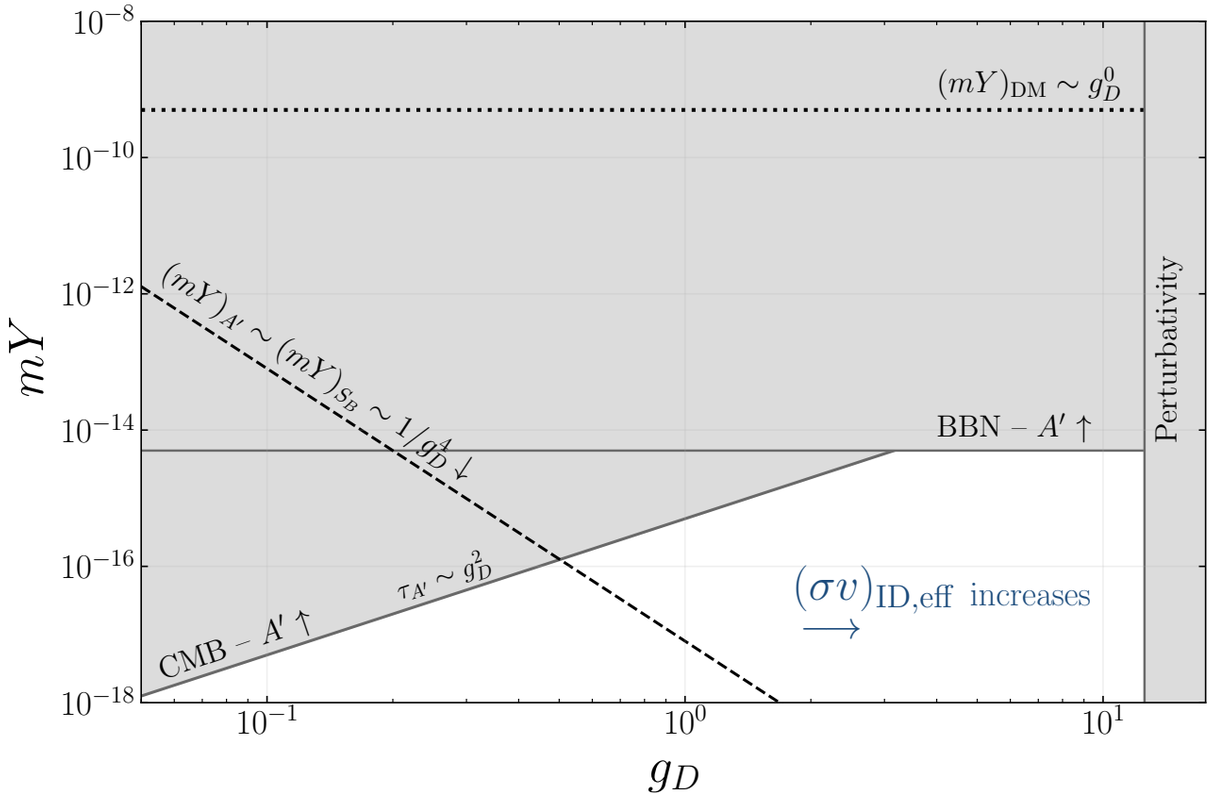
For fixed observational angle θ, min distance of los to GC is $l_{min} = R_0 \sin\theta = (8\sin\theta)$ kpc. If $d \sim l_{min}$, there is enhanced contribution coming from the GC.

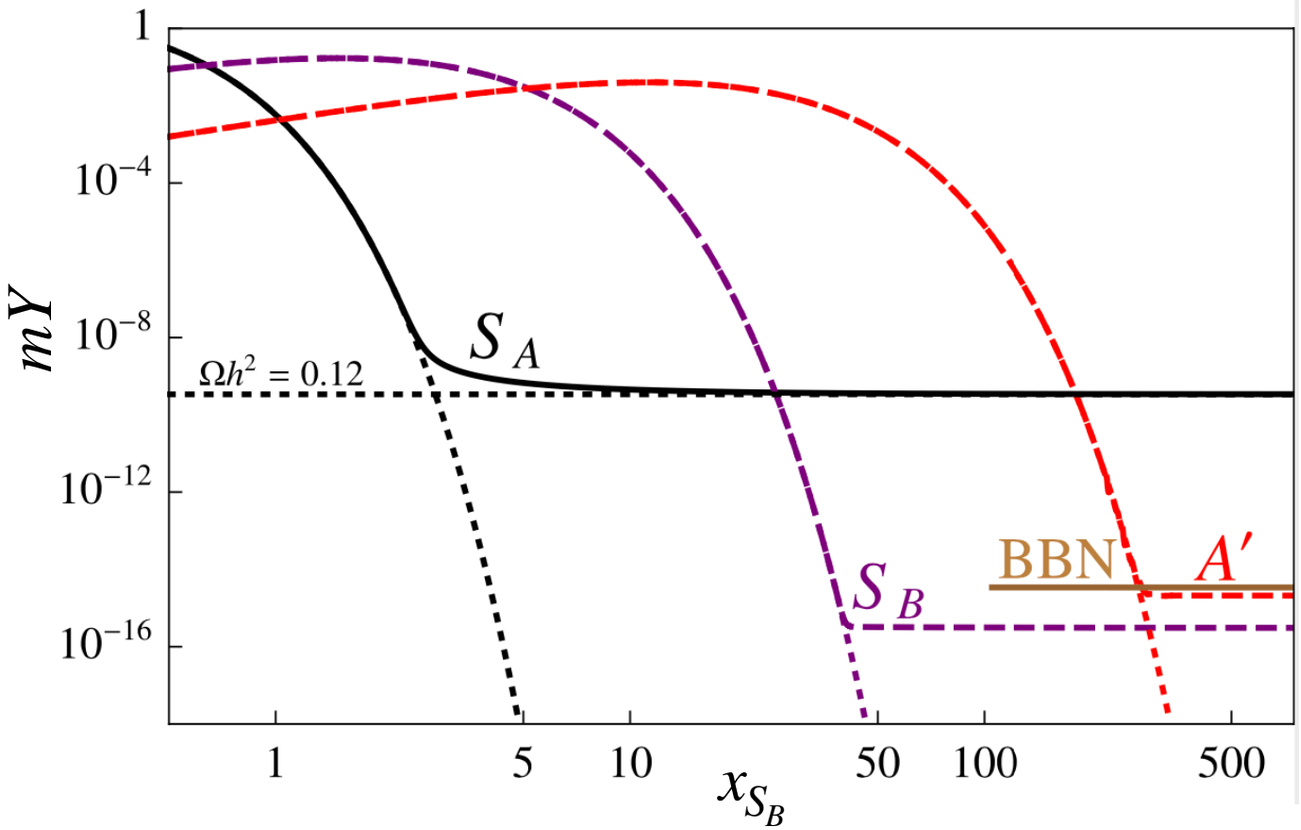
First noticed for $d\Phi/dE$ with fixed θ in Chu, Kulkarni, Salati, 1706.08543

LLP production

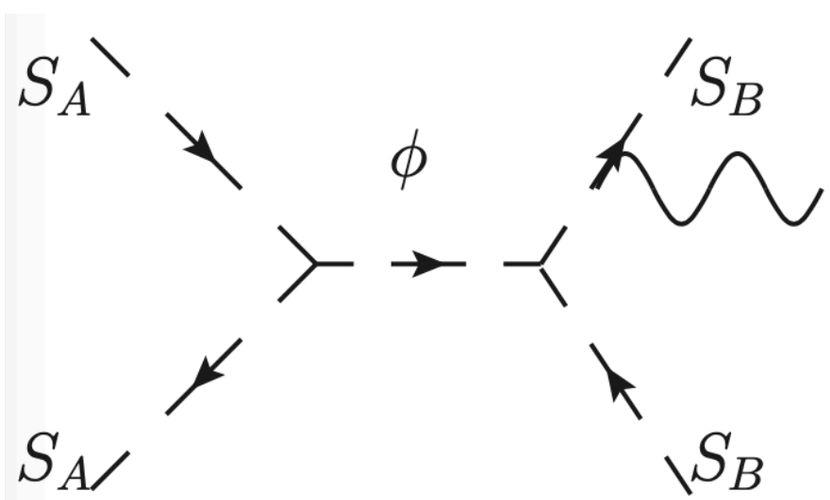


Thermal history impact on ID

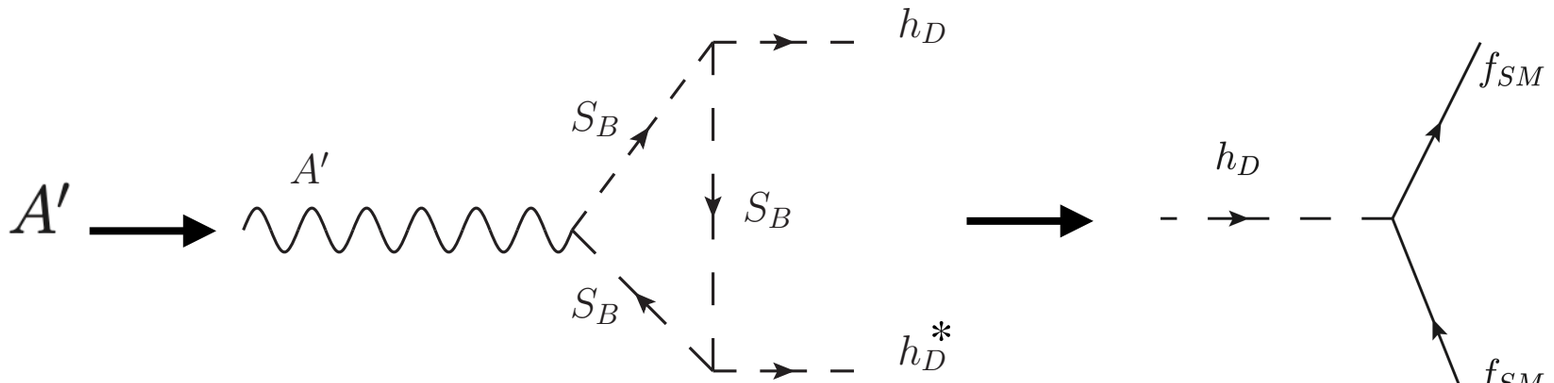




Indirect Detection



$S_A\, S_A \rightarrow\ S_B\, S_B\, A'$



*A' **is LLP naturally** due to loop-suppressed decay*

h_D is short lived

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

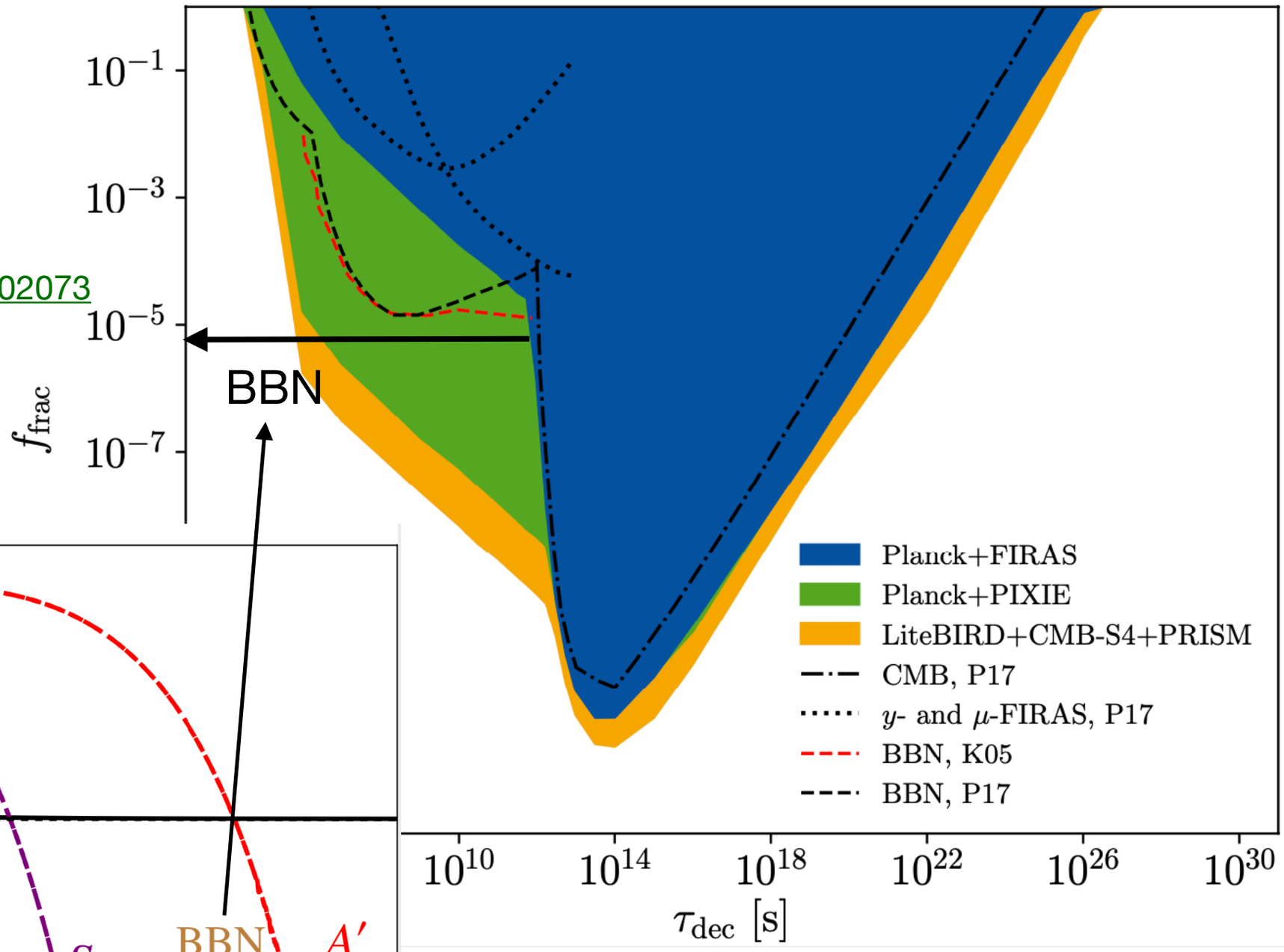
$A' \rightarrow h_D\, h_D \qquad h_D \rightarrow$ SM SM

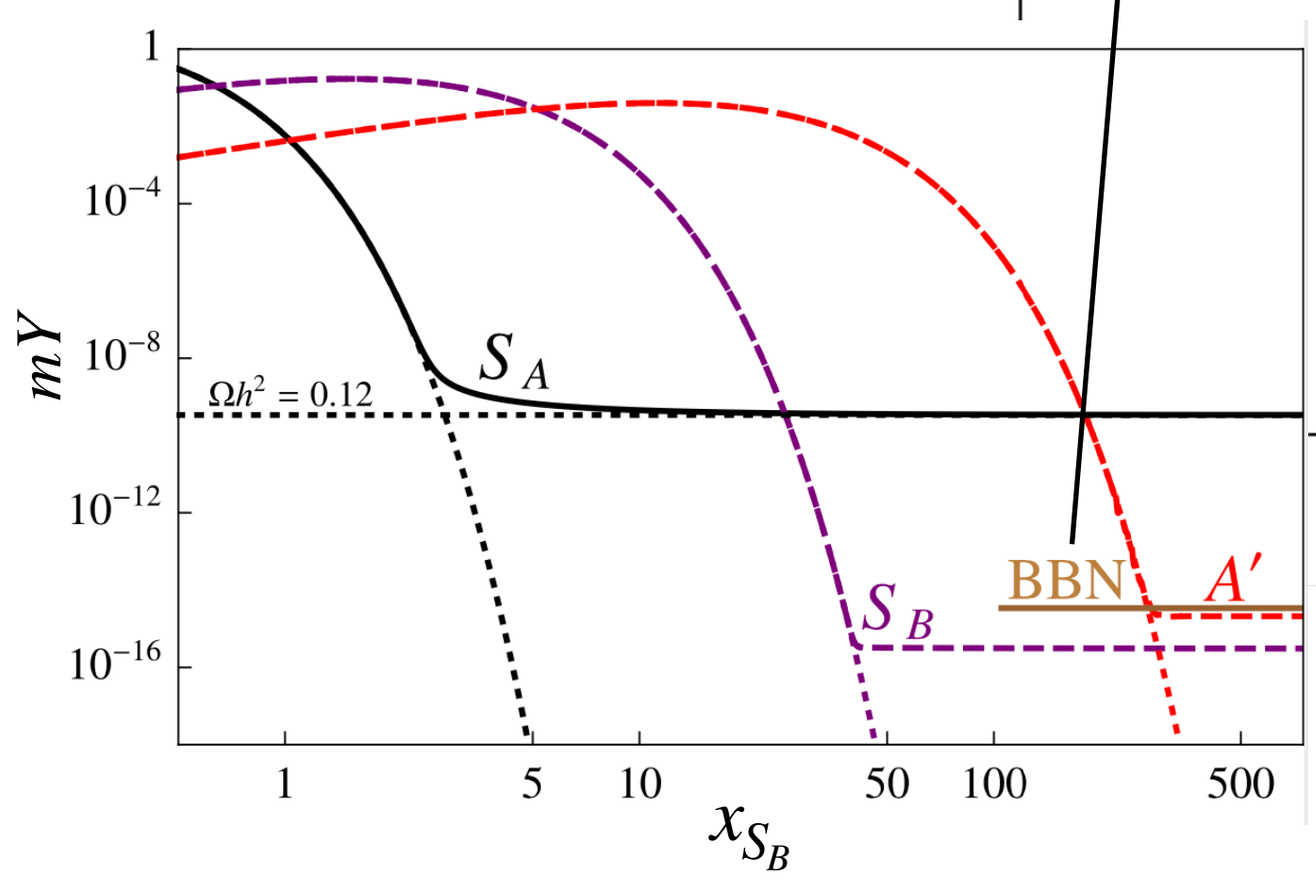
Limits on decaying DM - late energy injections

Late energy injections
can *destroy light elements*

Dashed lines - BBN
Poulin, Serpico, Lesgourgues, 1606.02073

Lucca, Schoneberg, Hooper, Lesgourgues, Chluba, 1910.04619





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

Limits on decaying DM - late energy injections

Late energy injections can *distort black body CMB* spectrum.

Dashed-dotted, dotted lines - existing CMB limits.

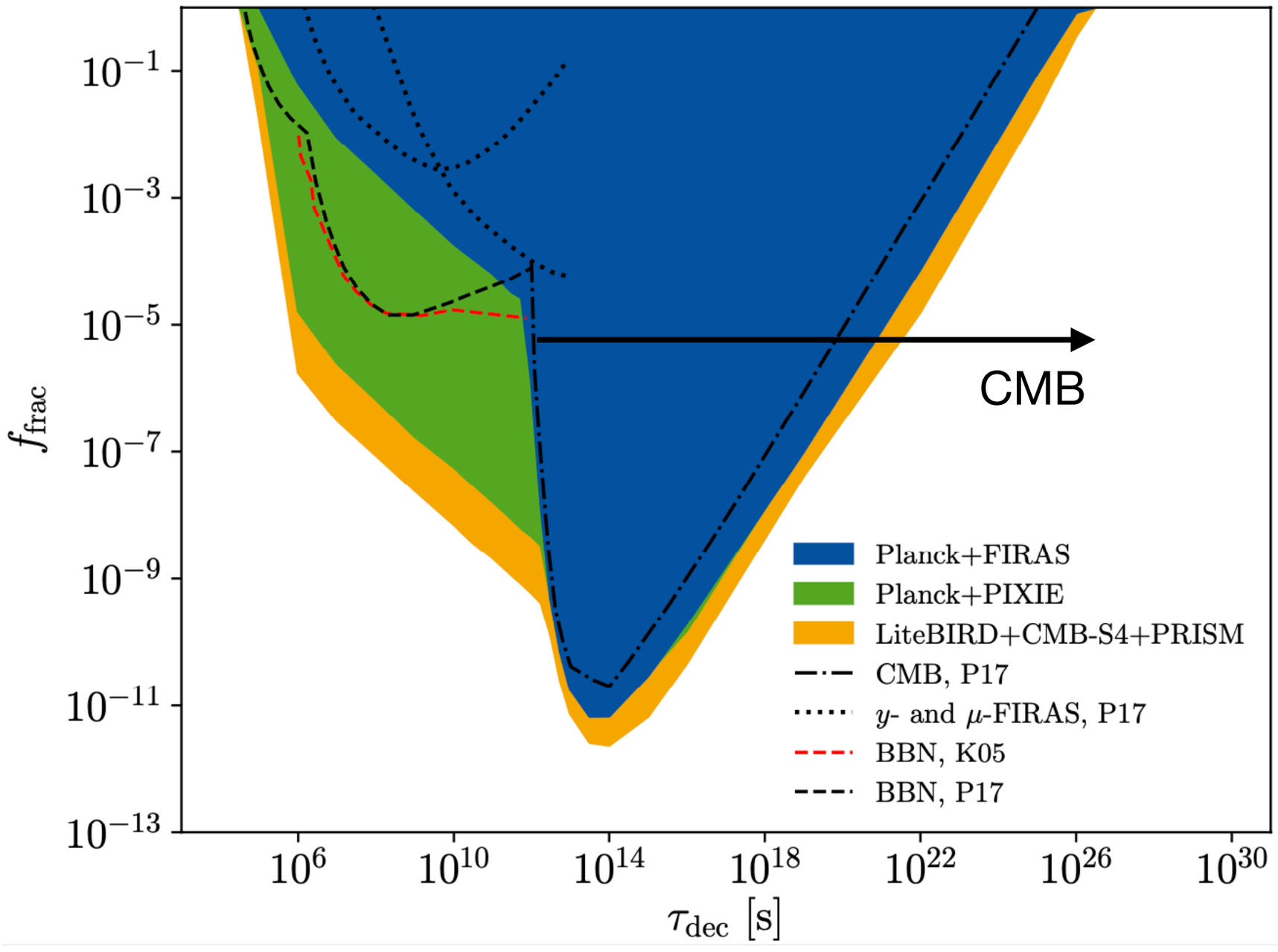
FIRAS, 9810373

Projections

PIXIE, 1105.2044

PRISM, 1310.1554

Lucca, Schoneberg, Hooper, Lesgourgues, Chluba, 1910.04619



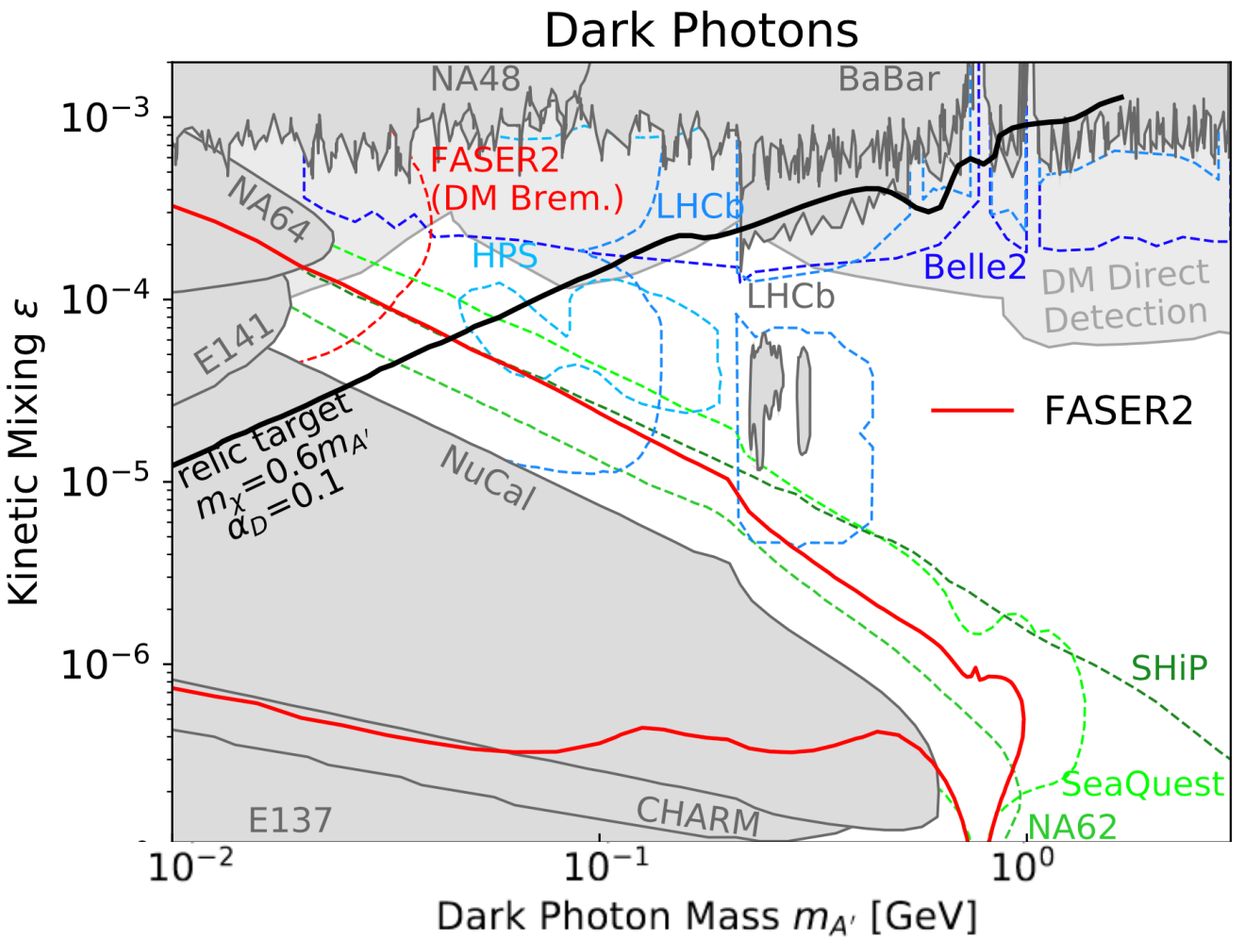
* $$c\tau_{A'} \simeq 1\,\mathrm{kpc}\left(\frac{g_D}{1}\right)^4\left(\frac{4\times10^{-6}}{\lambda_{h_D S_B}}\right)^4\left(\frac{m_{S_B}}{150\mathrm{GeV}}\right)^4\left(\frac{3\mathrm{GeV}}{m_{A'}}\right)^5$$

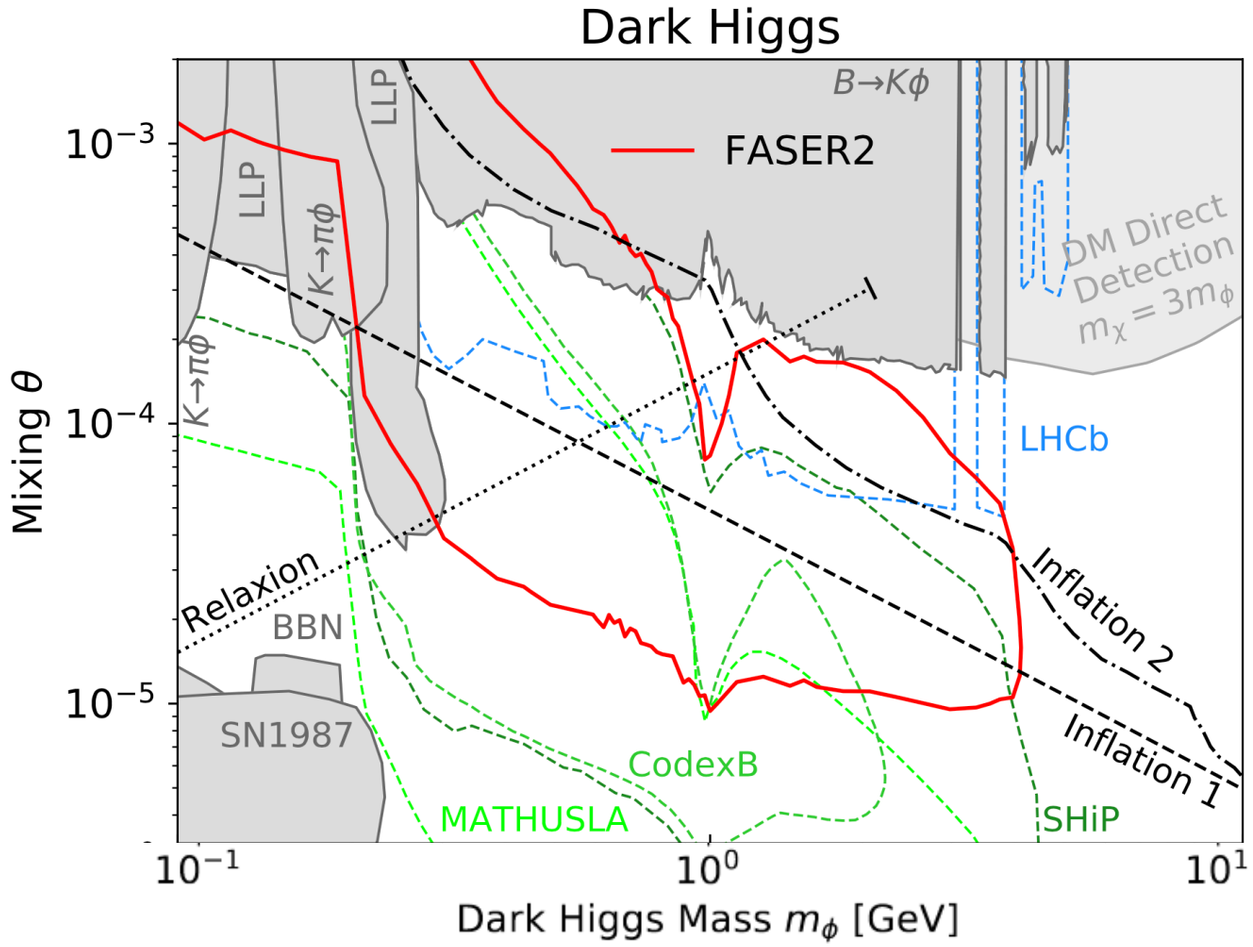
Complementarity in searches for Long Lived Particles

Intensity frontier searches

$$\mathscr{L}_{\text{vector portal}} = -\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

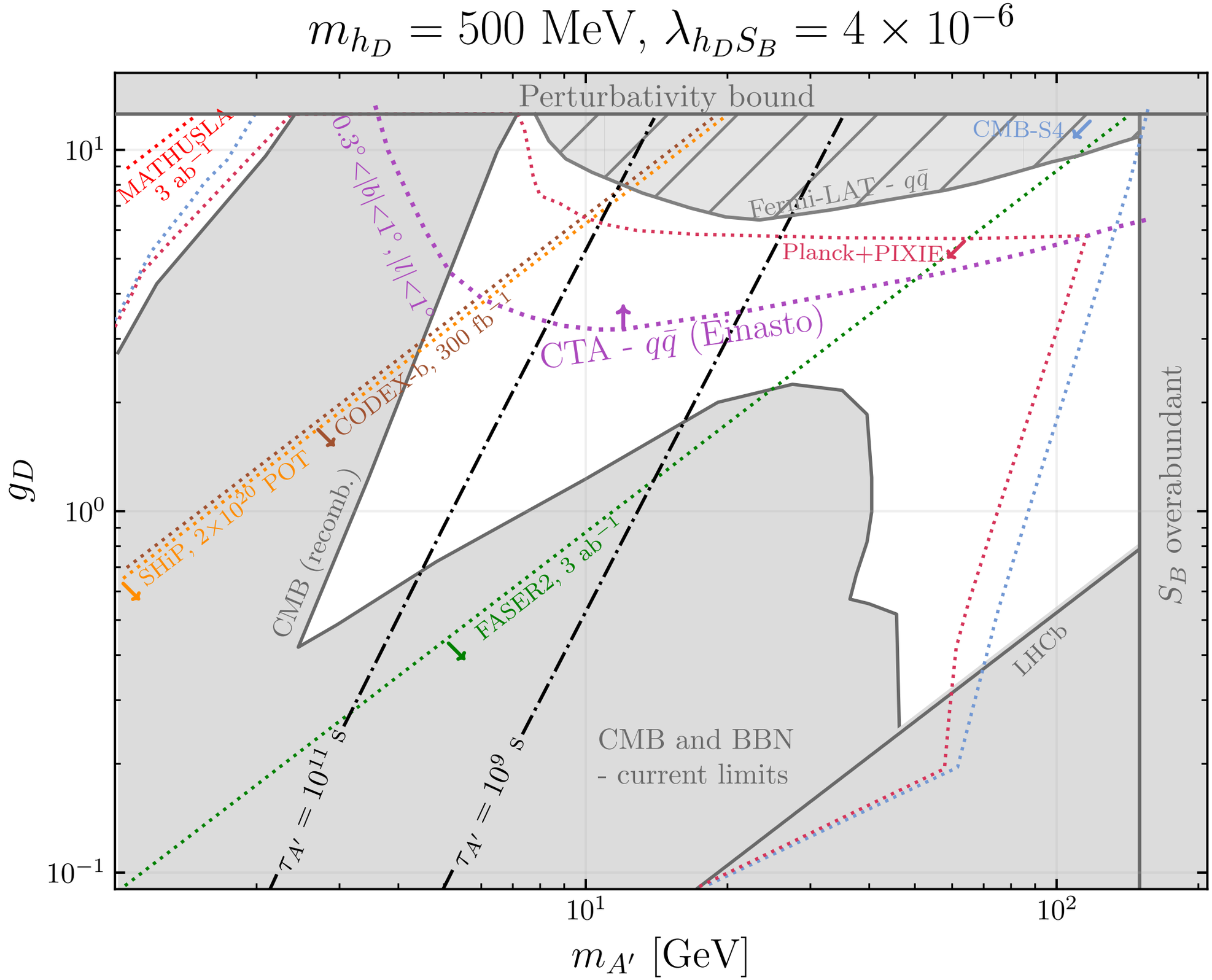
$$\mathscr{L}_{\text{scalar portal}} = \alpha_1 S H^\dagger H + \alpha S^2 H^\dagger H$$



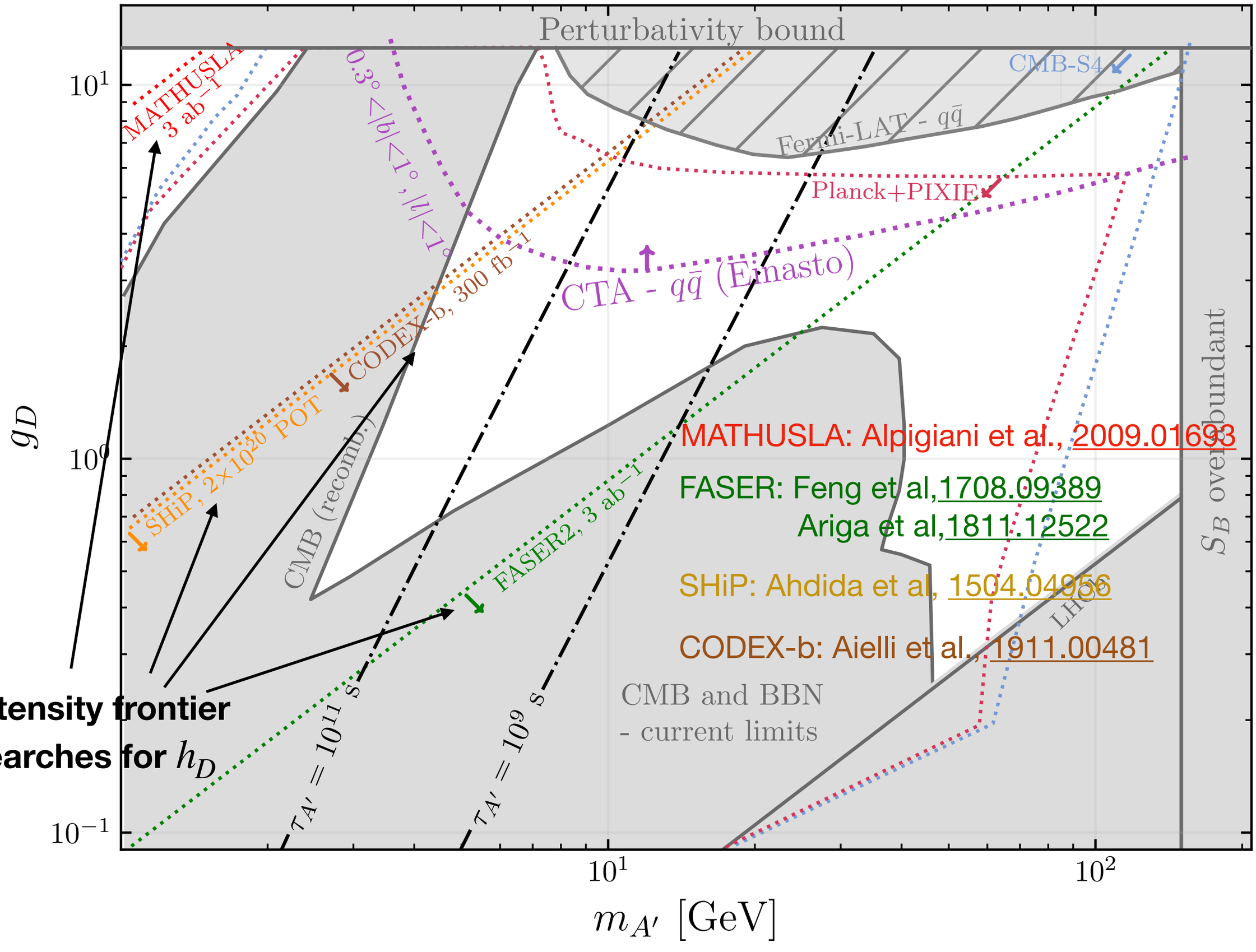


The Forward Physics Facility, 2109.10905

Indirect Detection & Intensity Frontier searches for LLPs - complementarity



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



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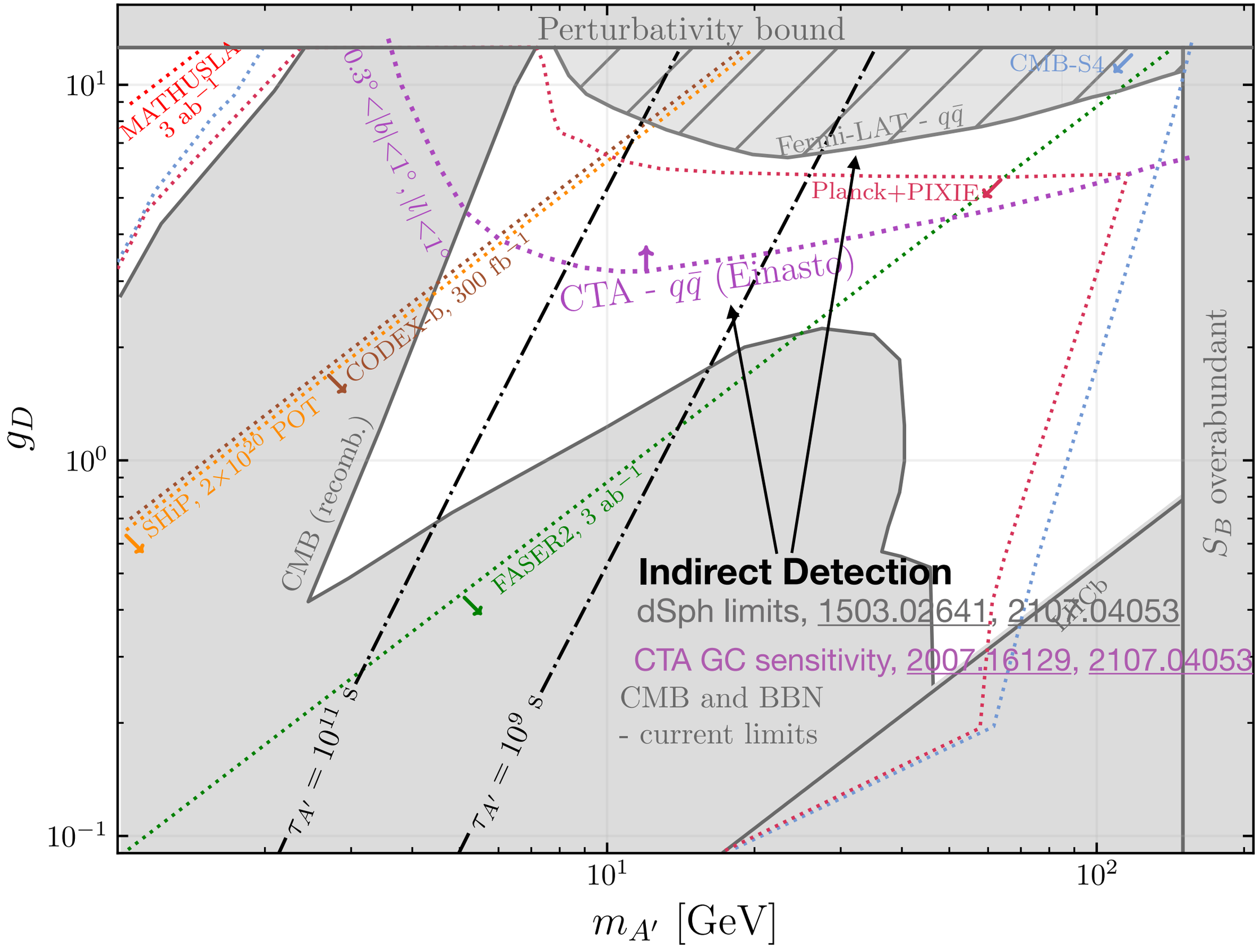
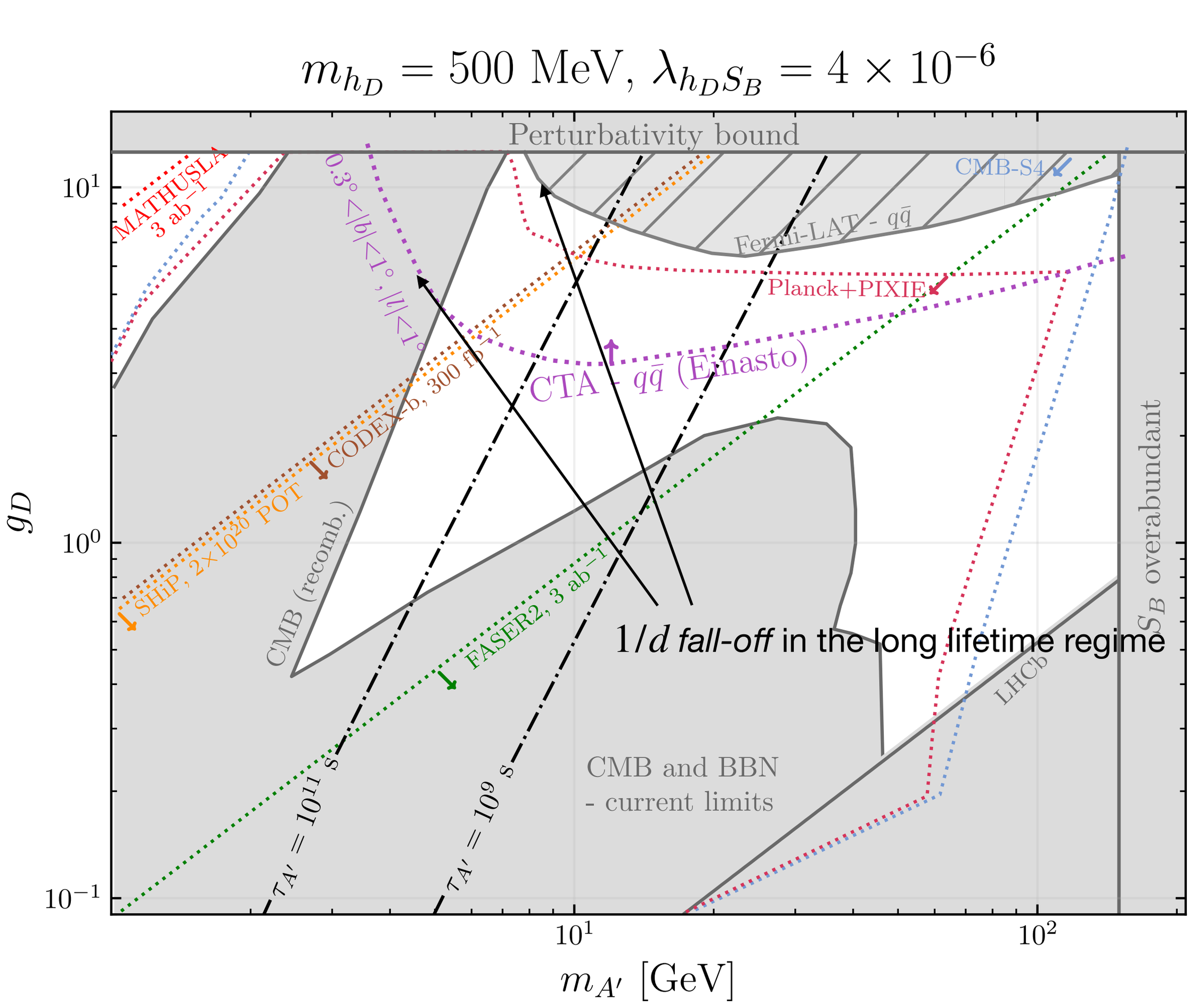
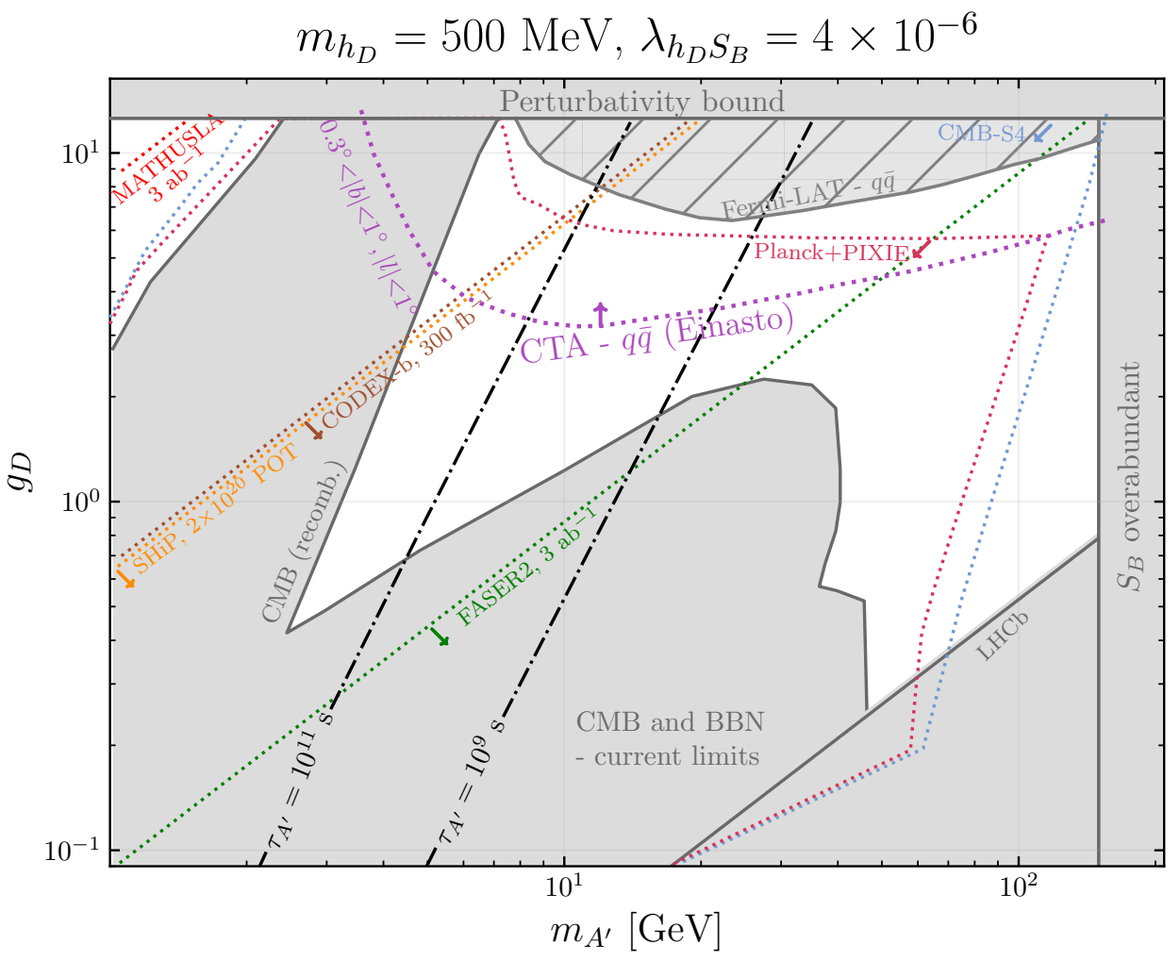
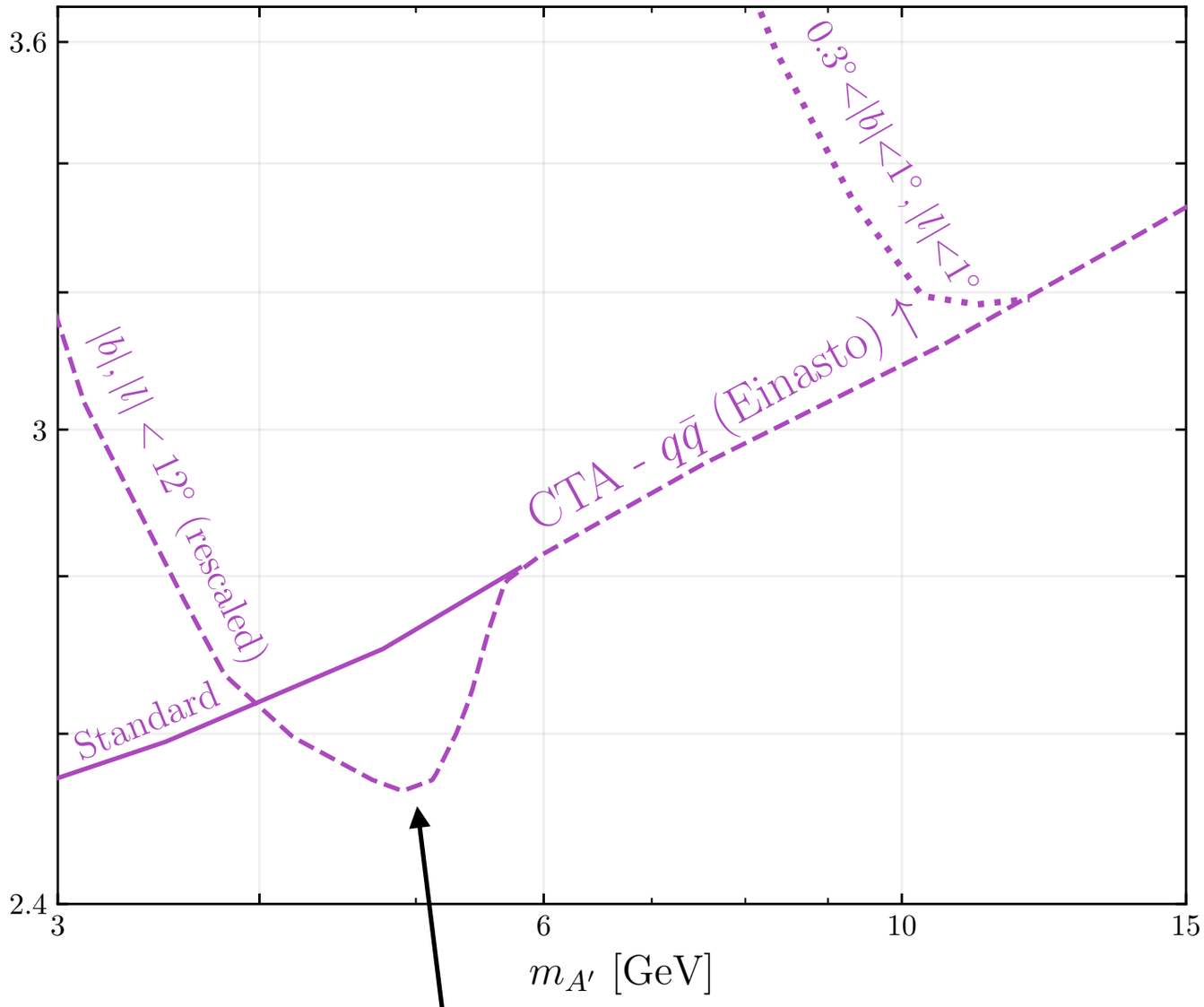


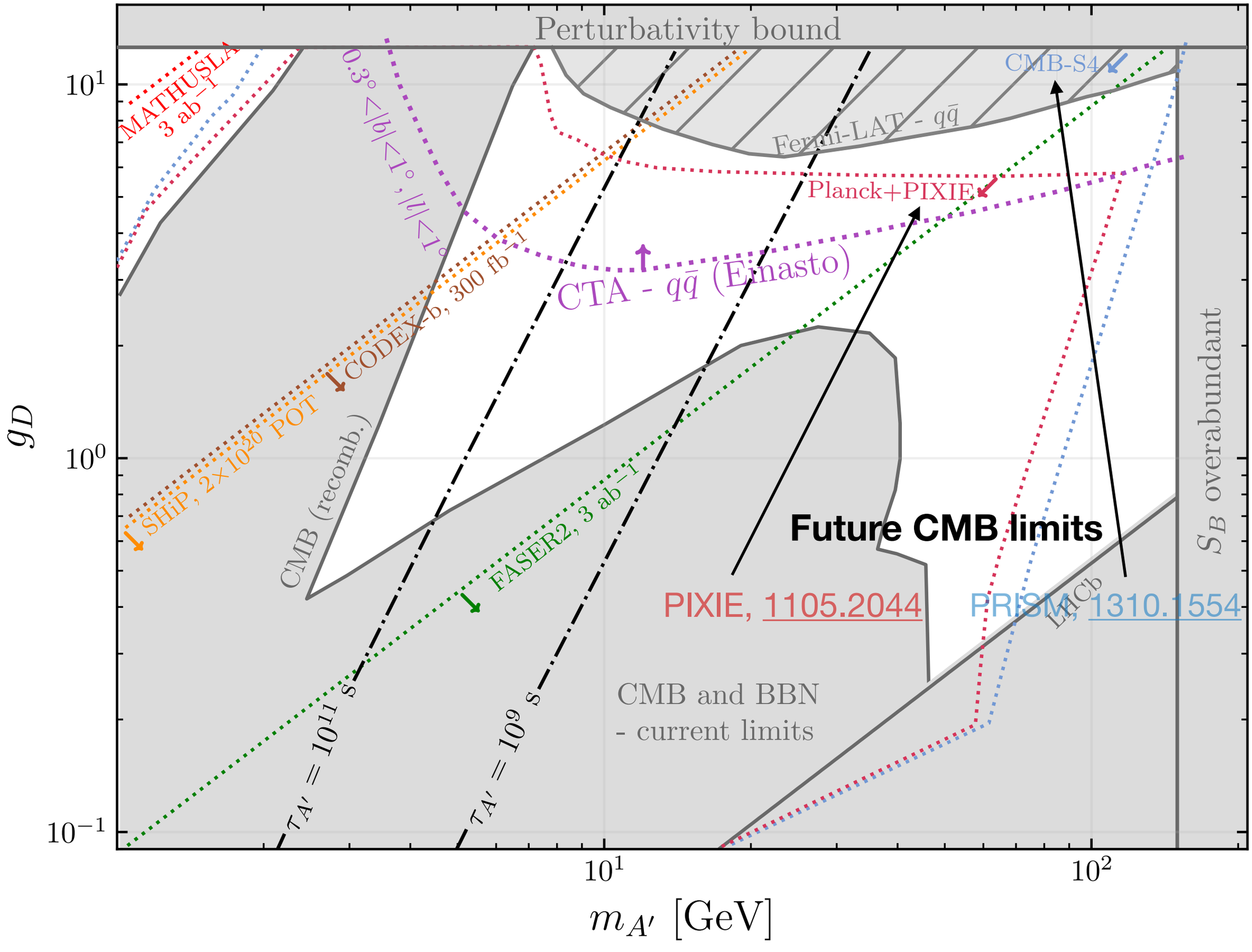

$m_{h_D} = 500$ MeV, $\lambda_{h_D S_B} = 4 \times 10^{-6}$
Perturbativity bound
MATHUSLA, 3 ab^{-1}
$0.3° < |b| < 1°$, $|l| < 1°$
CMB-S4
Fermi-LAT - $q\bar{q}$
Planck+PIXIE
CODEX-b, 300 fb^{-1}
CTA - $q\bar{q}$ (Einasto)
SHiP, 2×10^{20} POT
CMB (recomb.)
FASER2, 3 ab^{-1}
$1/d$ *fall-off* in the long lifetime regime
$\tau_{A'} = 10^{11}$ s
$\tau_{A'} = 10^{9}$ s
CMB and BBN
- current limits
LHCb
S_B overabundant
g_D
$m_{A'}$ [GeV]
10^1
10^0
10^{-1}
10^1
10^2





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 <u>additional contribution to the flux</u> 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