Decaying Dark Matter at IceCube and its Signature in High-Energy Gamma-Ray Experiments

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Motivation

- Neutrinos from IceCube's High-Energy Starting Events (HESE):
  - Dominated by astrophysical neutrinos
  - Astrophysical source — still largely unknown, flux contribution parametrized as an isotropic power-law spectrum $E_{\nu}^{-\gamma}$
- Tensions between HESE and other data samples assuming a single power-law flux
  - 10-year through-going (TG) muon events:
    - Northern hemisphere only, energies larger than 200 TeV
    - best-fit $\gamma = 2.28^{+0.08}_{-0.09}$
  - 7.5 years of HESE events:
    - Covers the entire sky, energies start at 20 TeV
    - best-fit $\gamma = 2.89^{+0.20}_{-0.19}$
- Suggests presence of a two-component flux containing a hard contribution and a softer one, both having an unknown origin

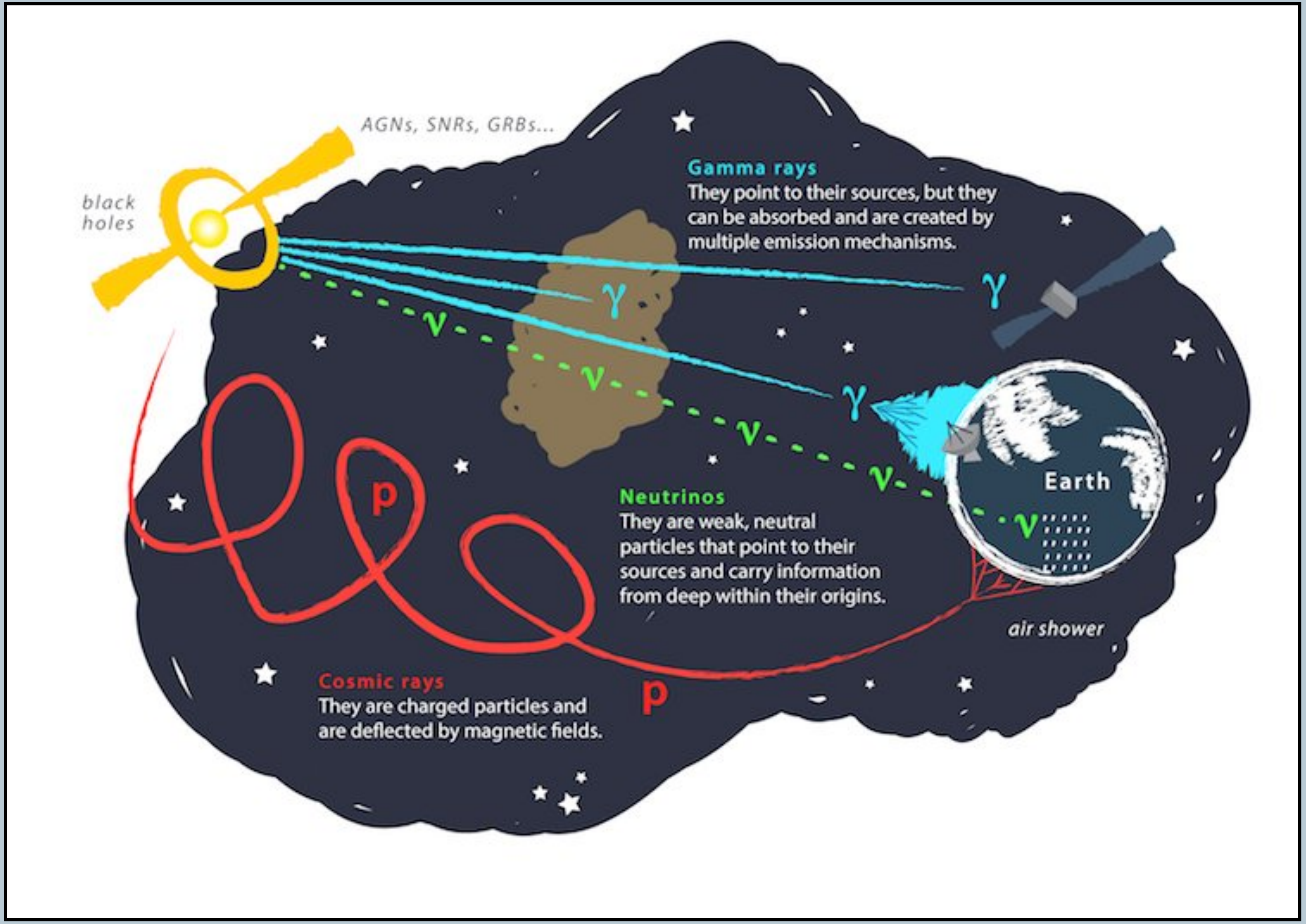

Image: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

Motivation — Tensions in astrophysical neutrino measurements

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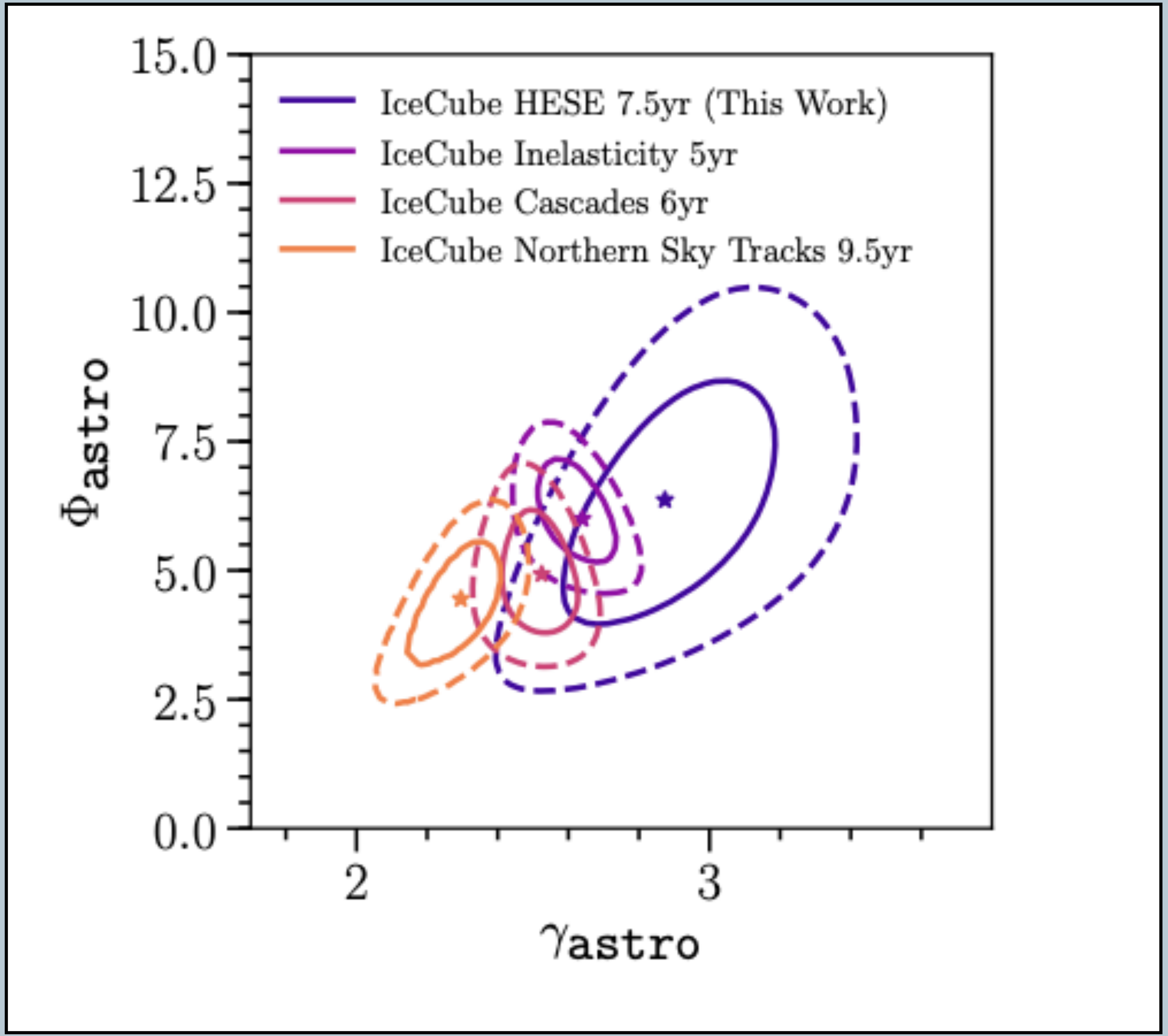
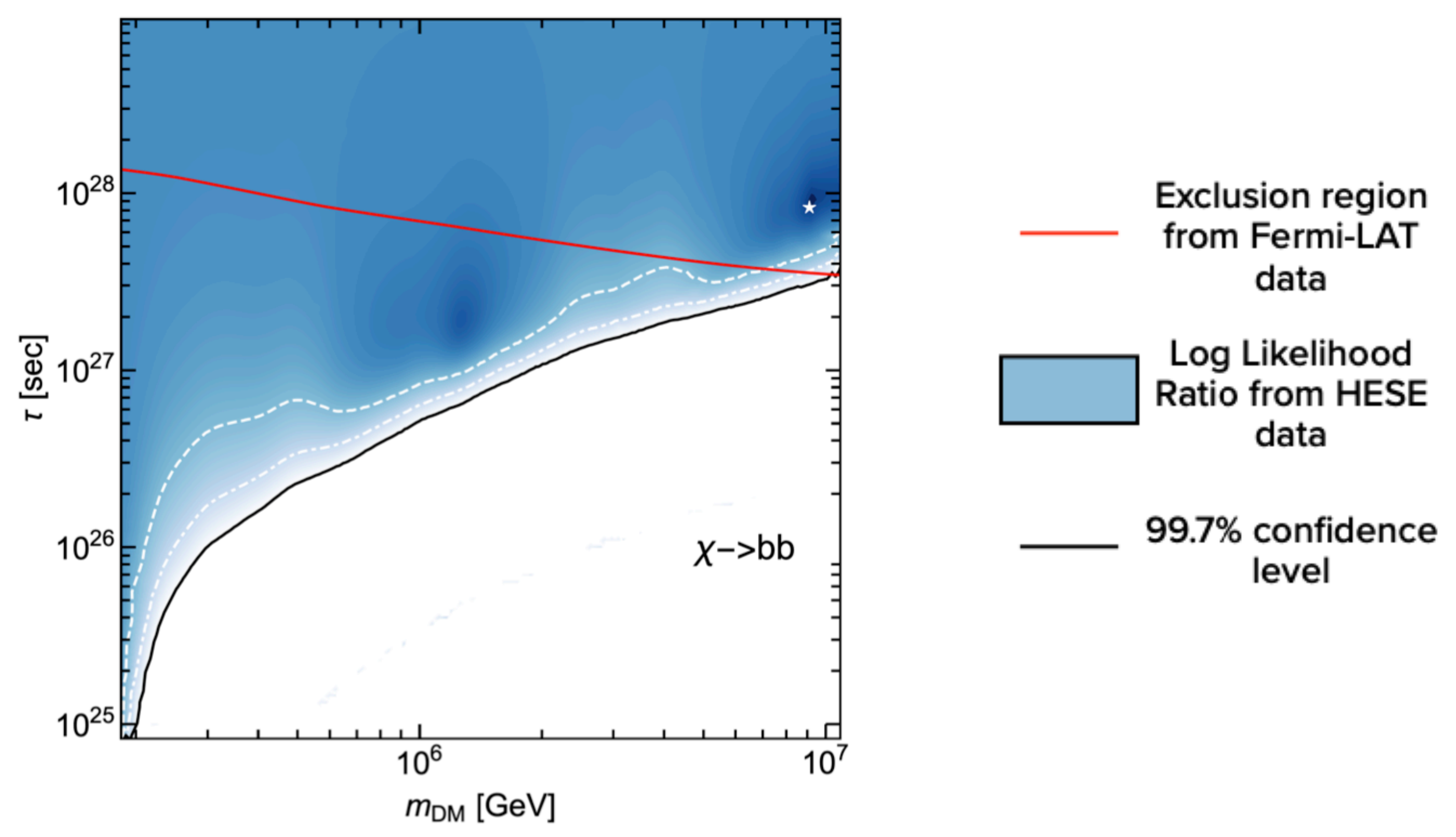


Abbasi et al. arXiv: 2011.03545.

Motivation — previous hints from neutrino telescopes



(a) Channel $b\bar{b}$

Marco Chianese *et al* JCAP11(2019)046

- Constraints from a two-component fit using 7.5 years of HESE and assuming

$$\phi = \phi_{\mathrm{Astro}} + \phi_\chi$$

$$\frac{d^2\phi_{\mathrm{Astro}}}{dEd\Omega} = \phi_0\left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma}$$

- The DM decay flux contribution can potentially resolve tensions in spectral indices (previous slide) and the observed neutrino excess in HESE (plots shown left)
- Excess observed in two places:
  - $m_{\mathrm{DM}} \sim 100\,\mathrm{TeV}, \quad \gamma \sim 2$
  - $m_{\mathrm{DM}} \sim 1\,\mathrm{PeV}, \quad \gamma > 3$
- Our work: attempts to constrain the ϕ_χ contribution further by investigating the uncertainty in the gamma-ray spectrum

Gamma-Rays from Dark-Matter Decay

- Alternative potential source for diffuse ultra-high-energy flux is Dark Matter (DM) decay, where neutrino production accompanies galactic and extragalactic gamma-ray contributions as well

$$\phi_\chi = \phi_{\mathrm{G}} + \phi_{\mathrm{EG}}$$

- Gamma rays arise both directly (photons final states) and indirectly (electron/positron final states) from dark-matter decay

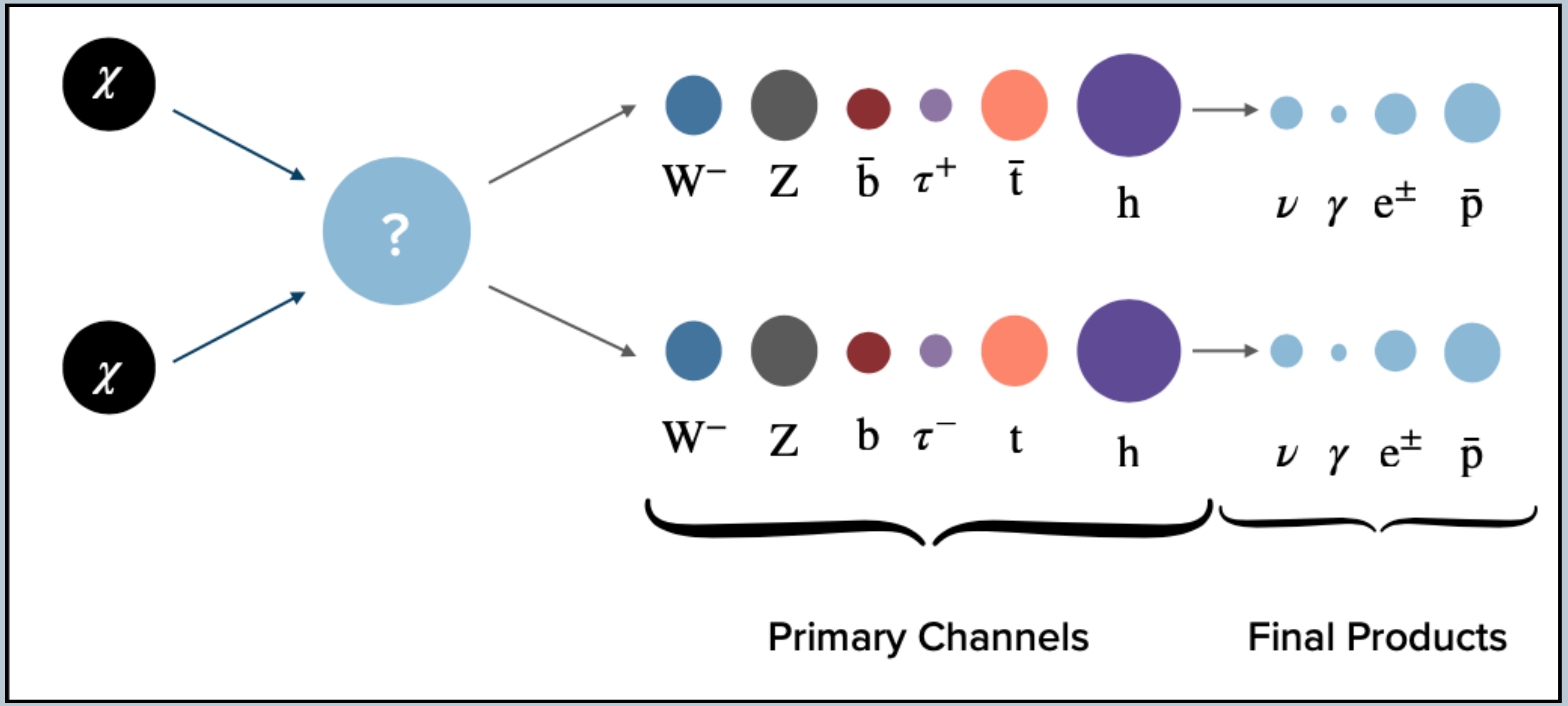
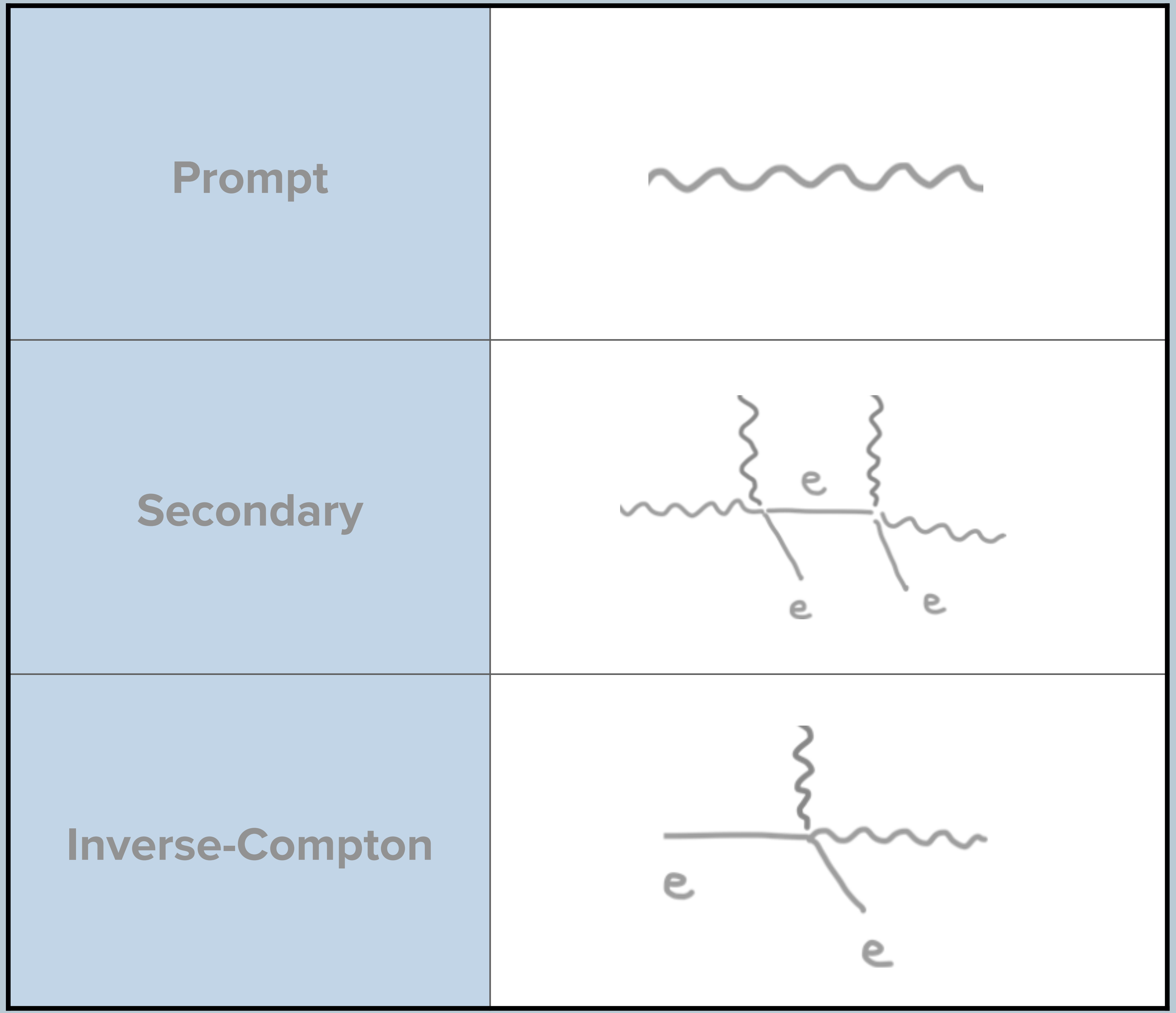


Figure inspired from Juan Aguilar



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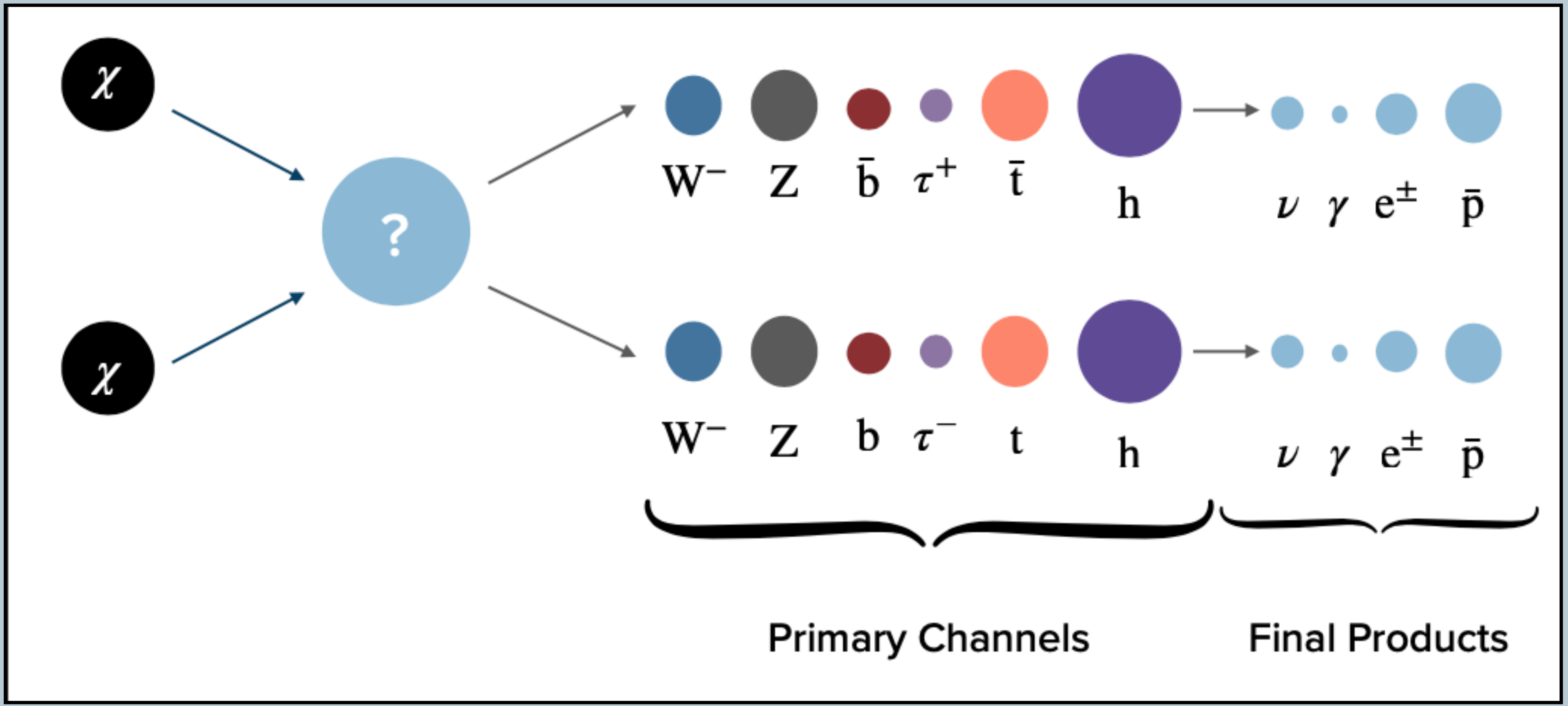

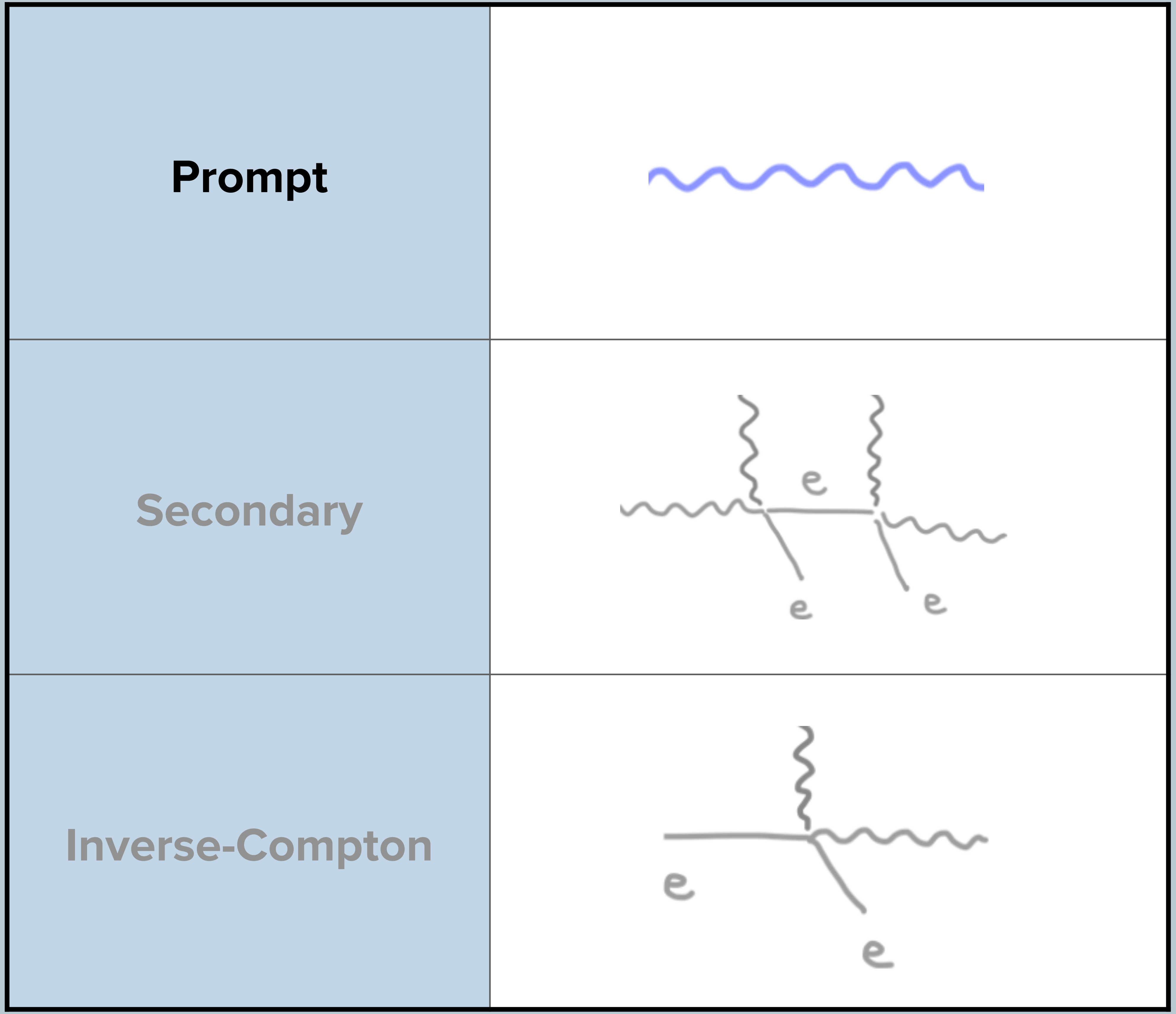

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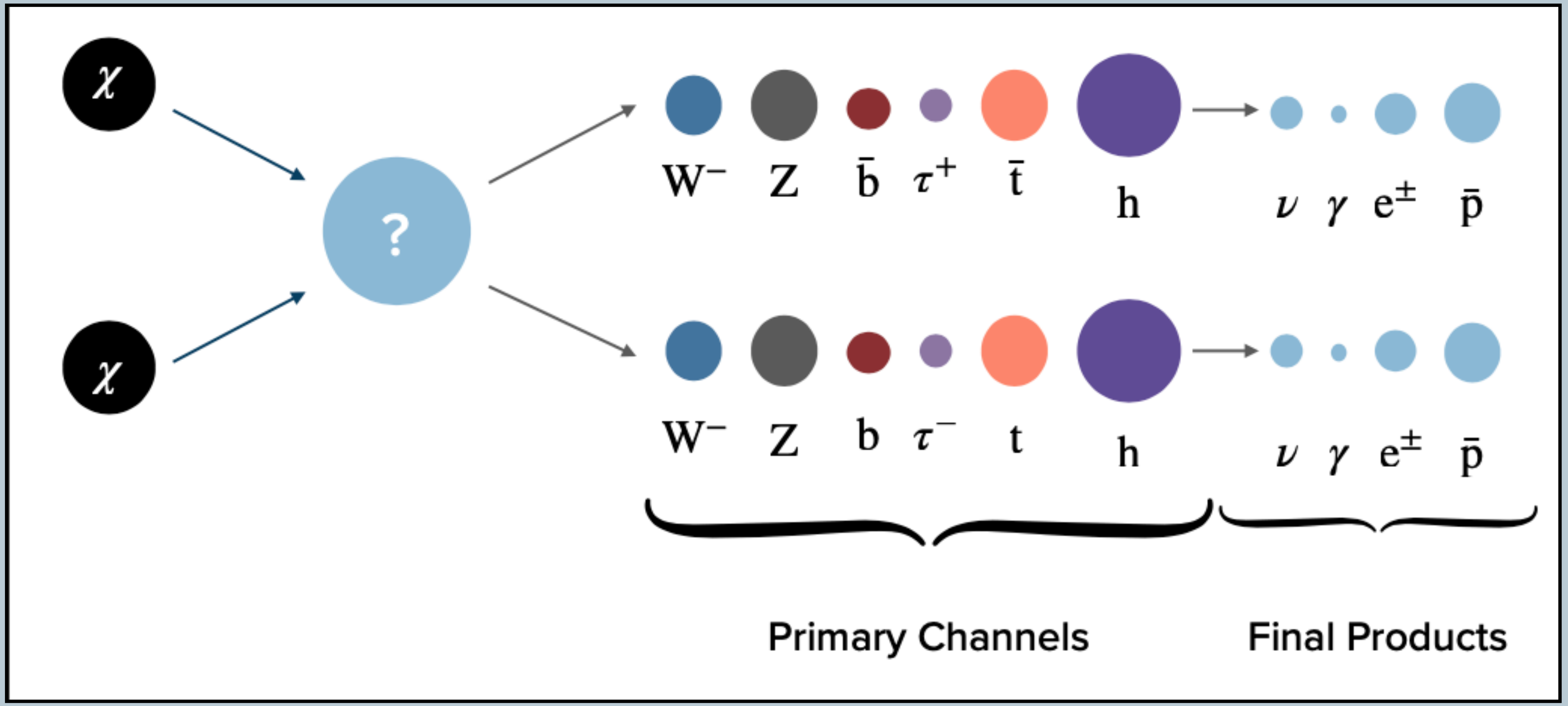

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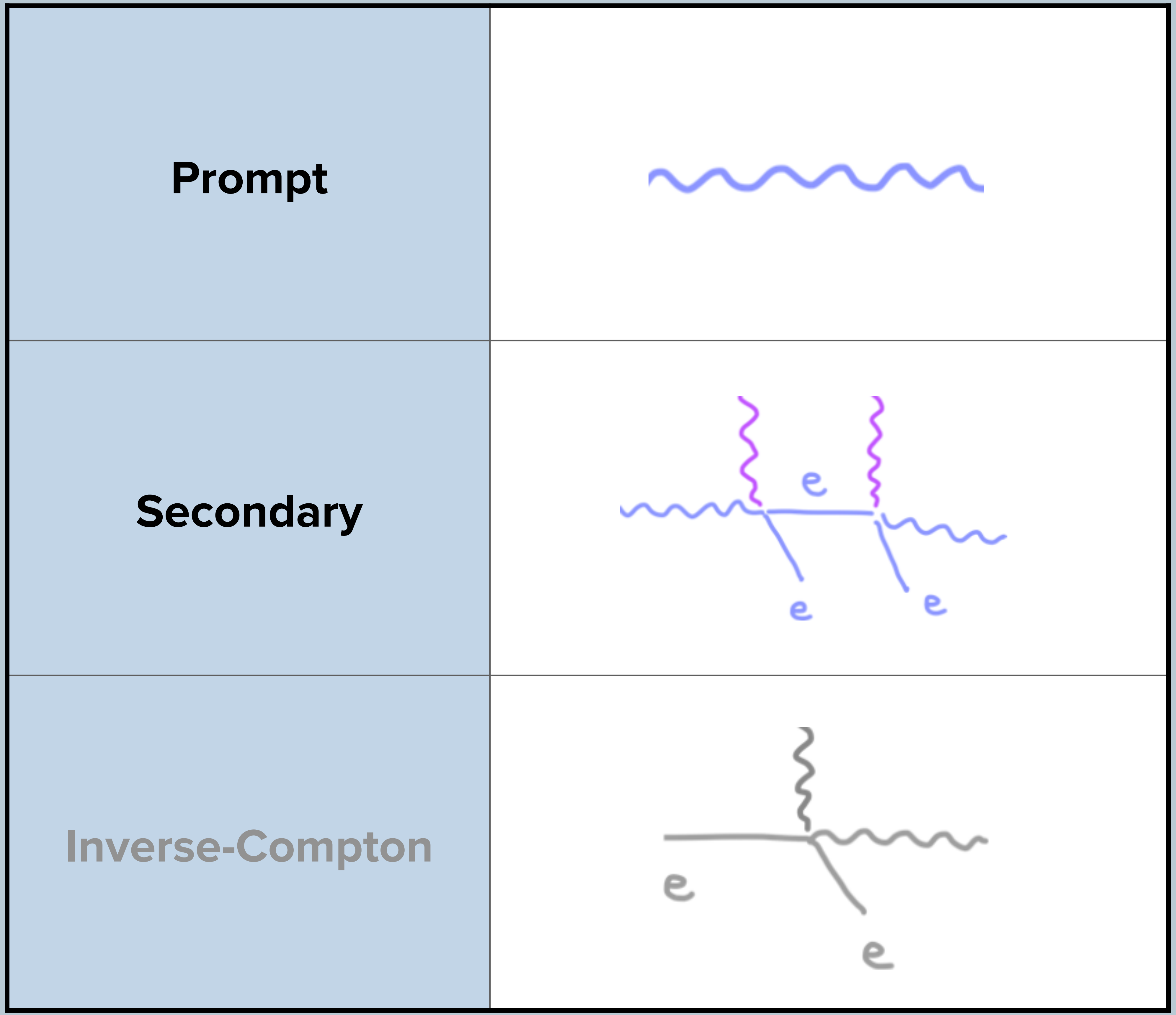

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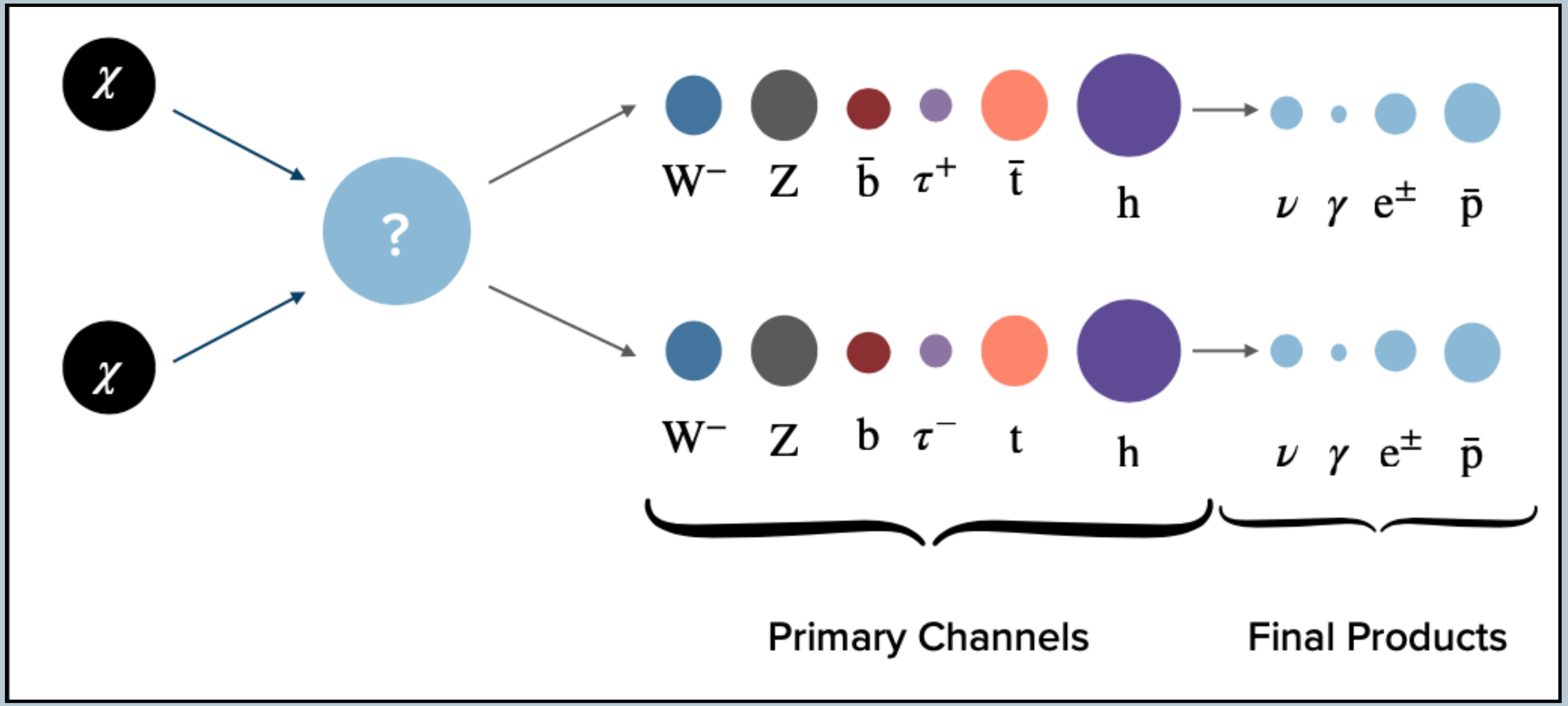


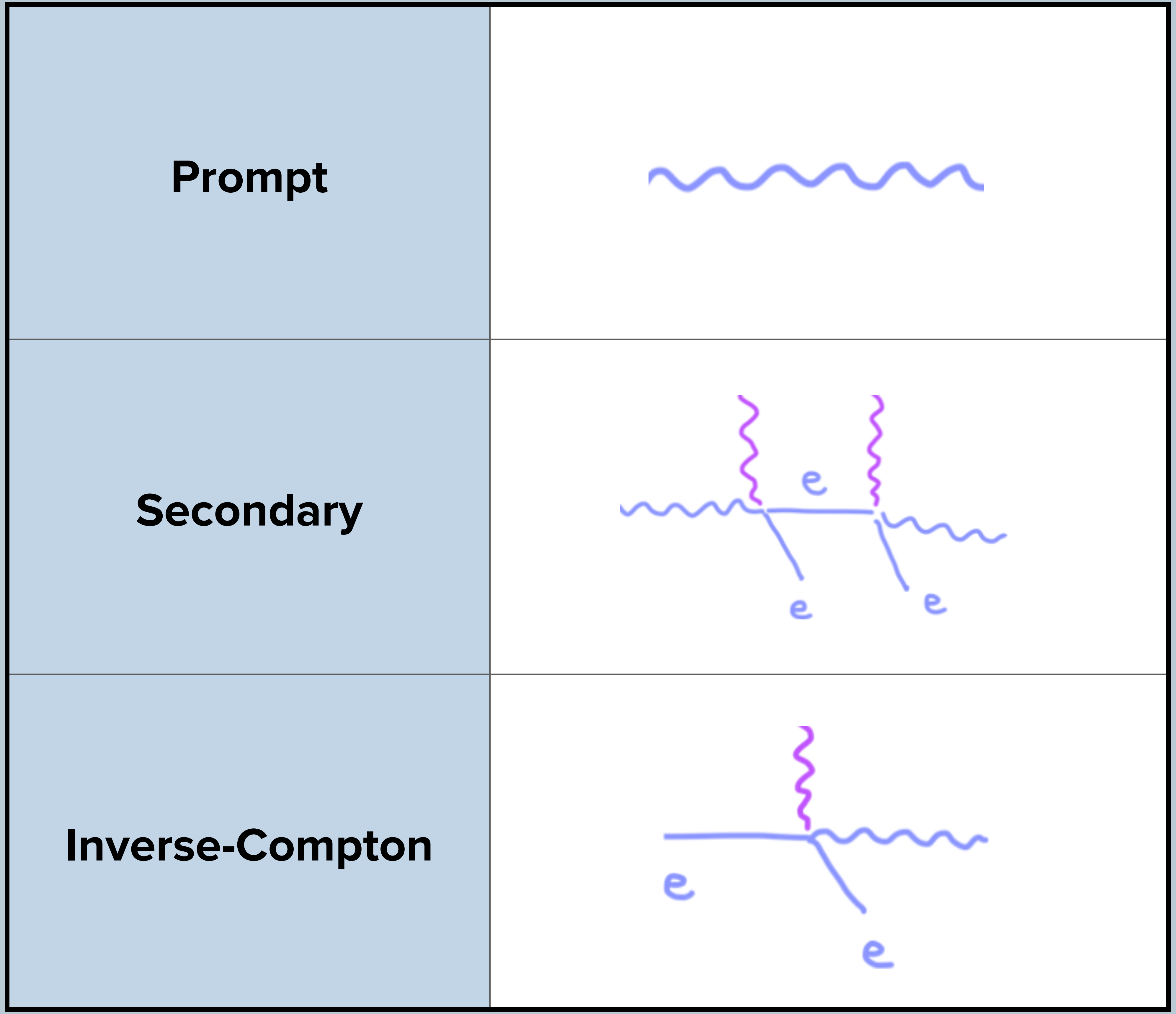
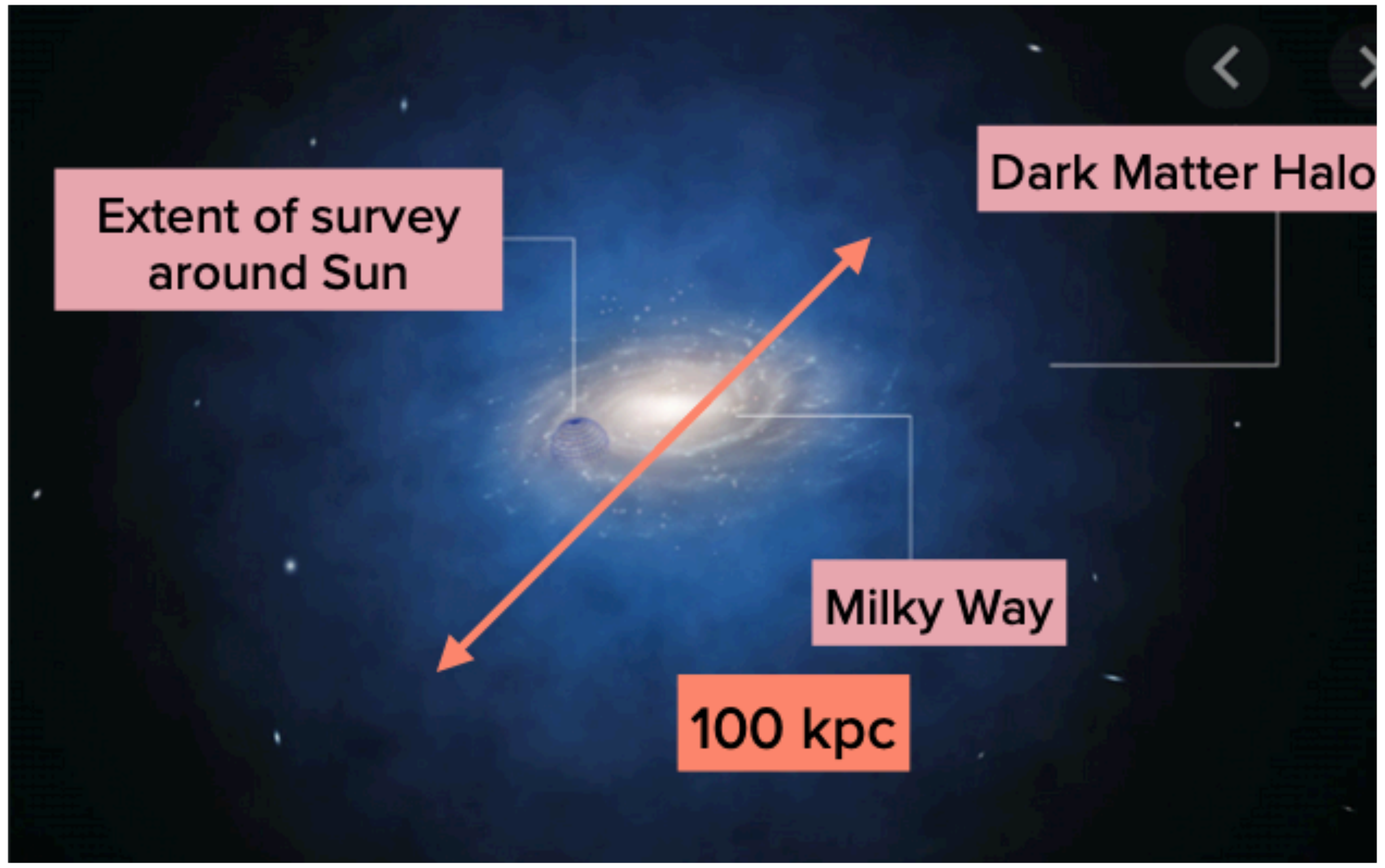
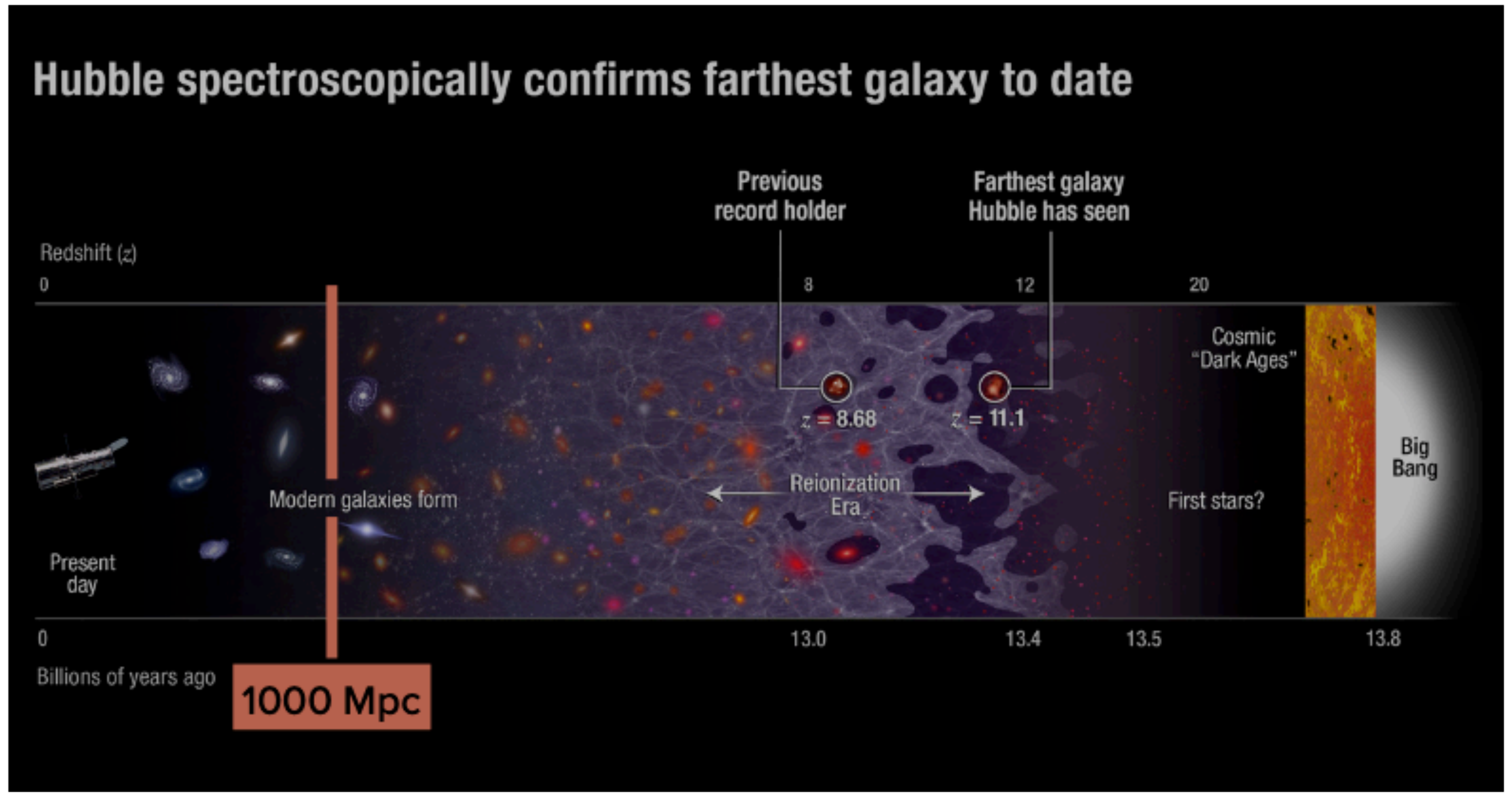


Figure inspired from Juan Aguilar

Gamma-Rays from Dark-Matter Decay

	Primary	Secondary
Galactic (propagation up to 100 kpc)	**Prompt (with attenuation)** $\frac{d^2\phi_G}{dEd\Omega} = \frac{1}{4\pi m_{\mathrm{DM}}\tau}\frac{dN_{\nu+\bar{\nu}}}{dE}\int ds\rho(s,l,b)\mathrm{Att}(E,s)$ $\rho(r) = \rho_s\left(\frac{r}{R_s}\right)^{-\gamma}\left(1+\frac{r}{R_s}\right)^{-3+\gamma}, \quad \rho_0 = 0.4\,\mathrm{GeV/cm^3}, \mathrm{r_c} = 20\,\mathrm{kpc}$ $r(s,l,b) = \sqrt{s^2+R_s^2-2sR_s\cos l\cos b}, \quad R_s = 8.5\,\mathrm{kpc}$	**Bremsstrahlung, Sychrotron, Inverse-Compton by SL+IR and CMB**
Extragalactic (propagation up to 1000 Mpc)	**Prompt (with attenuation)** $\frac{d^2\phi_{\mathrm{EG}}}{dEd\Omega} = \frac{\Omega_\chi\rho_{cr}}{4\pi m_{\mathrm{DM}}\tau}\int\frac{dz}{H(z)}\mathrm{Att}(E,z)\frac{dN_{\nu+\bar{\nu}}(E(1+z))}{dE}$	**Bremsstrahlung, Sychrotron, Inverse-Compton by SL+IR and CMB (with attenuation)**





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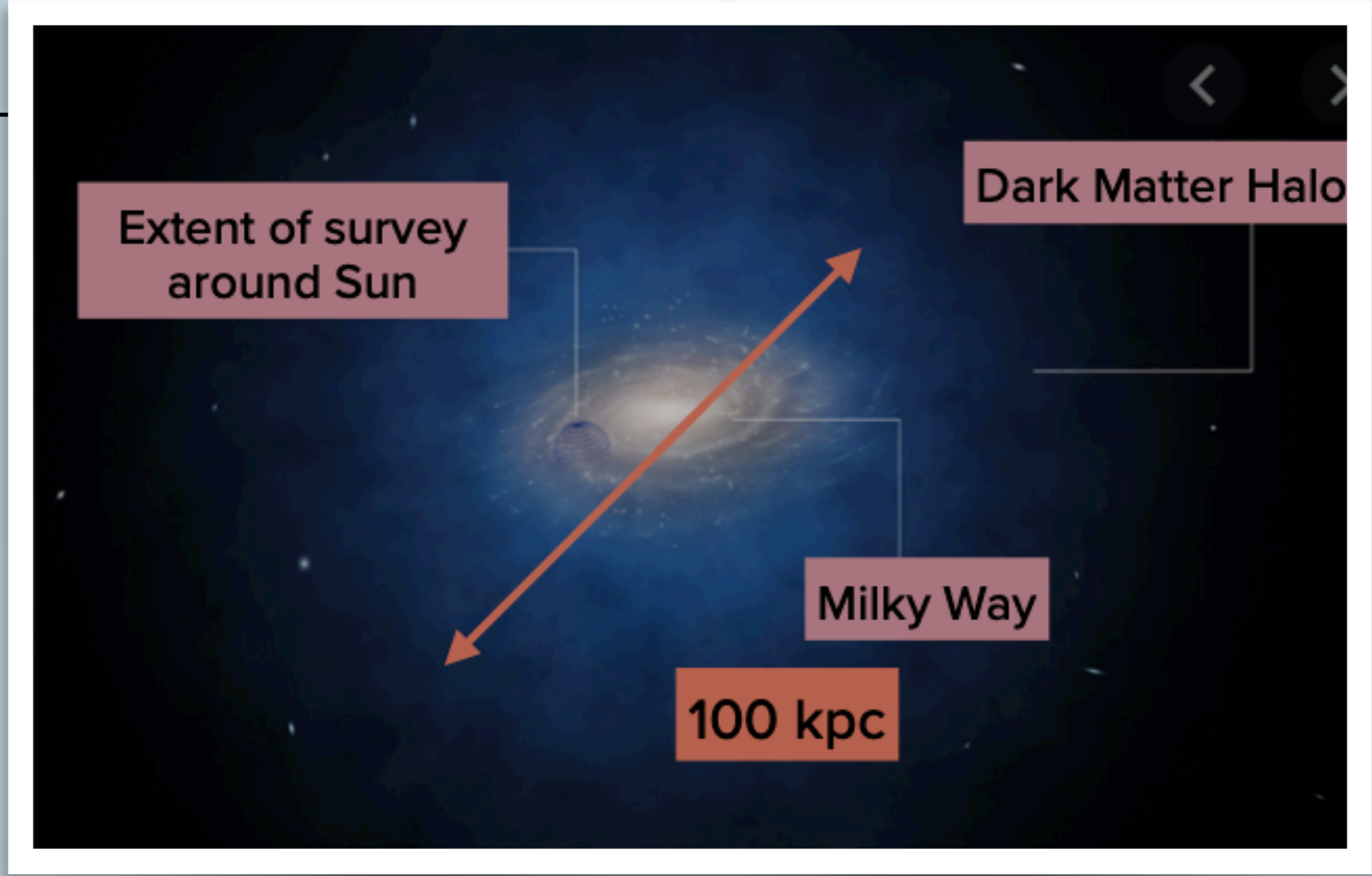
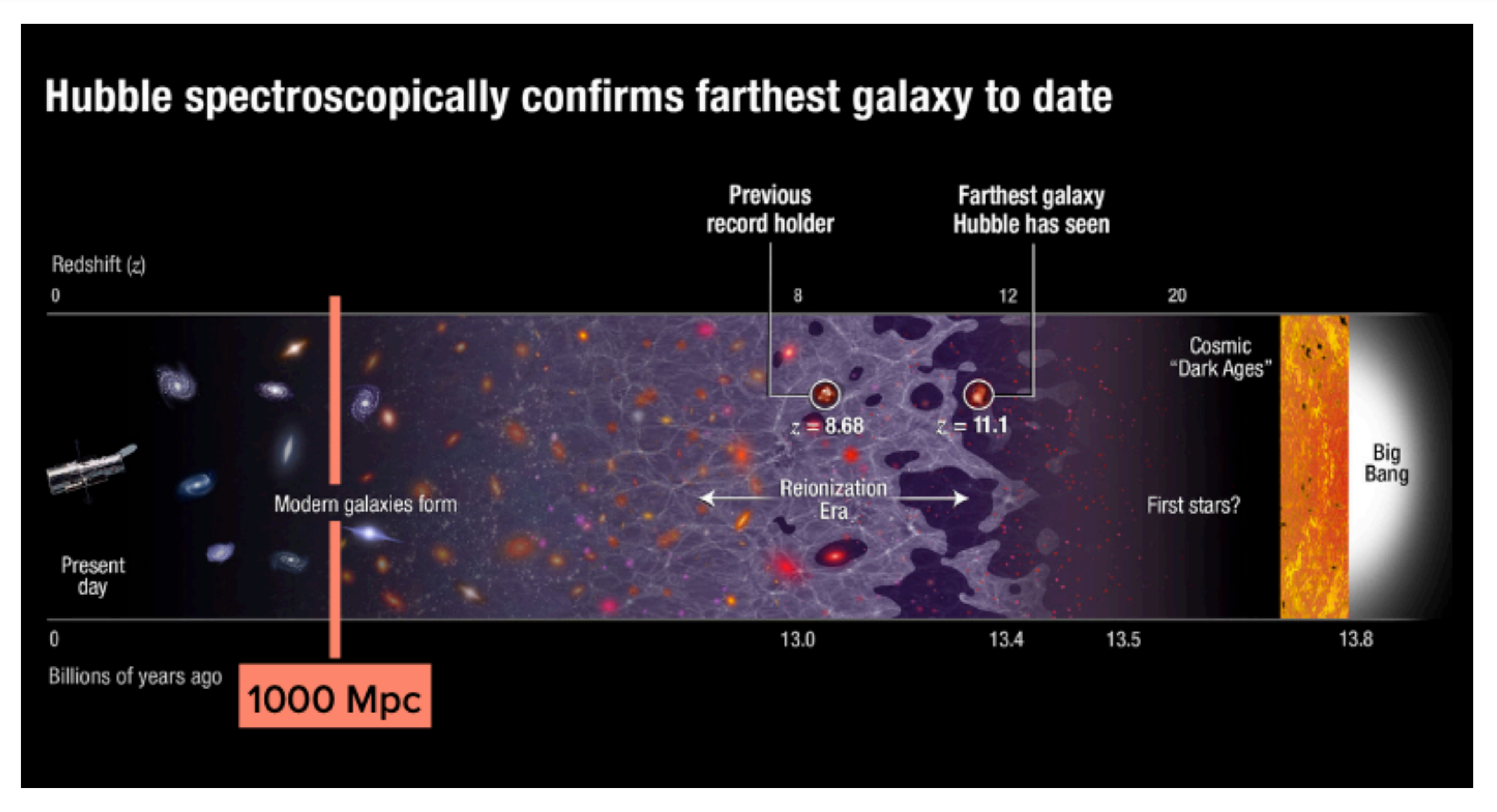
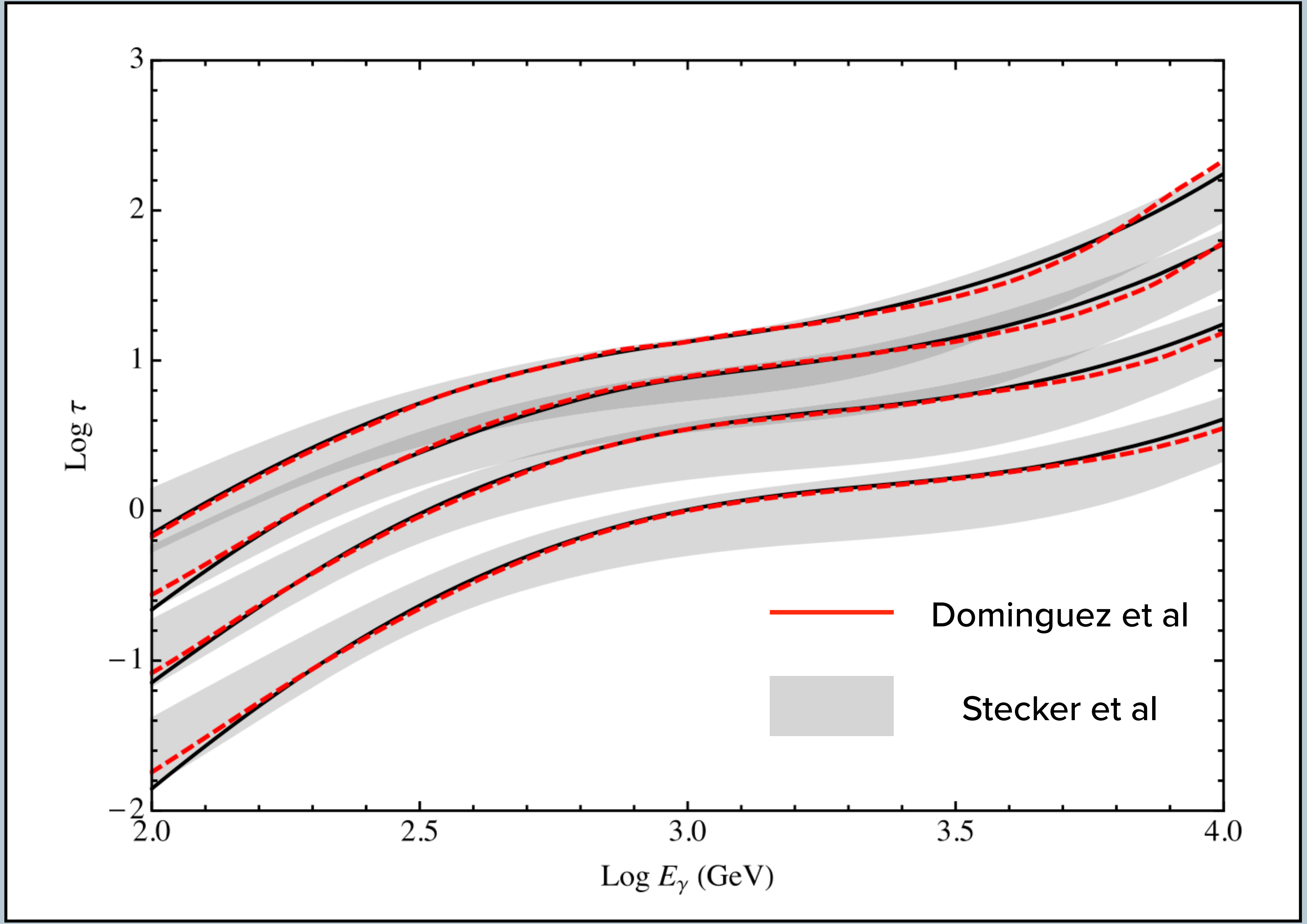




Extragalactic Background Light

Extragalactic Background Light:

- Stellar light emitted throughout the entire history of cosmic evolution
- Two-peak structure in spectral energy distribution (SED) at $\lambda \sim 1\mu m$ and $\lambda \sim 100\mu m$
- Lack of direct knowledge of EBL has led to different models:
  - **Dominguez**: observed evolution model based on rest frame K-band galaxy luminosity function up to $z \sim 4$ along with an estimate of galaxy SED fractions
  - **Stecker (Upper and Lower Bounds)**: backward evolution model that begins with present day galaxy luminosity function and extrapolates this backwards in time

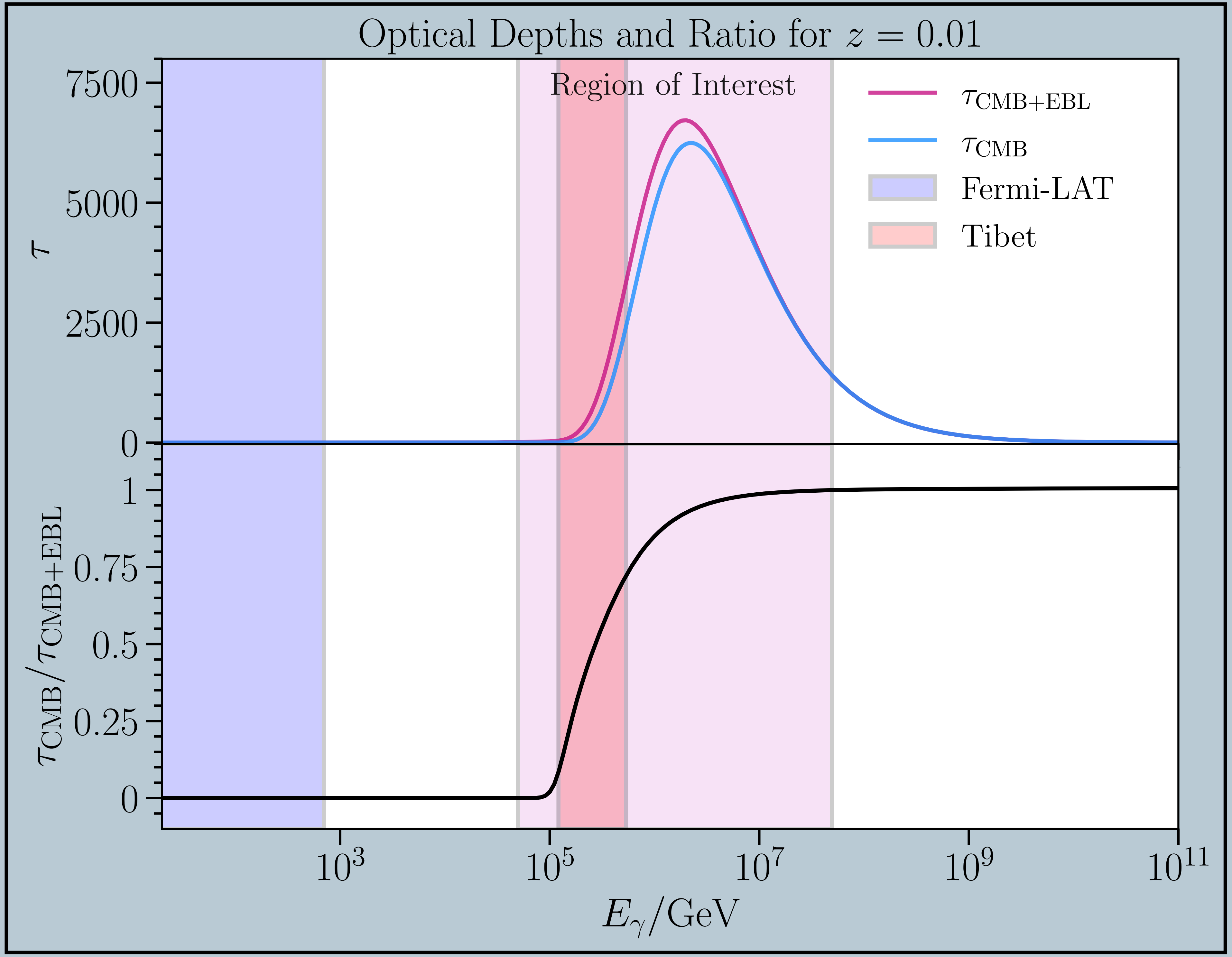


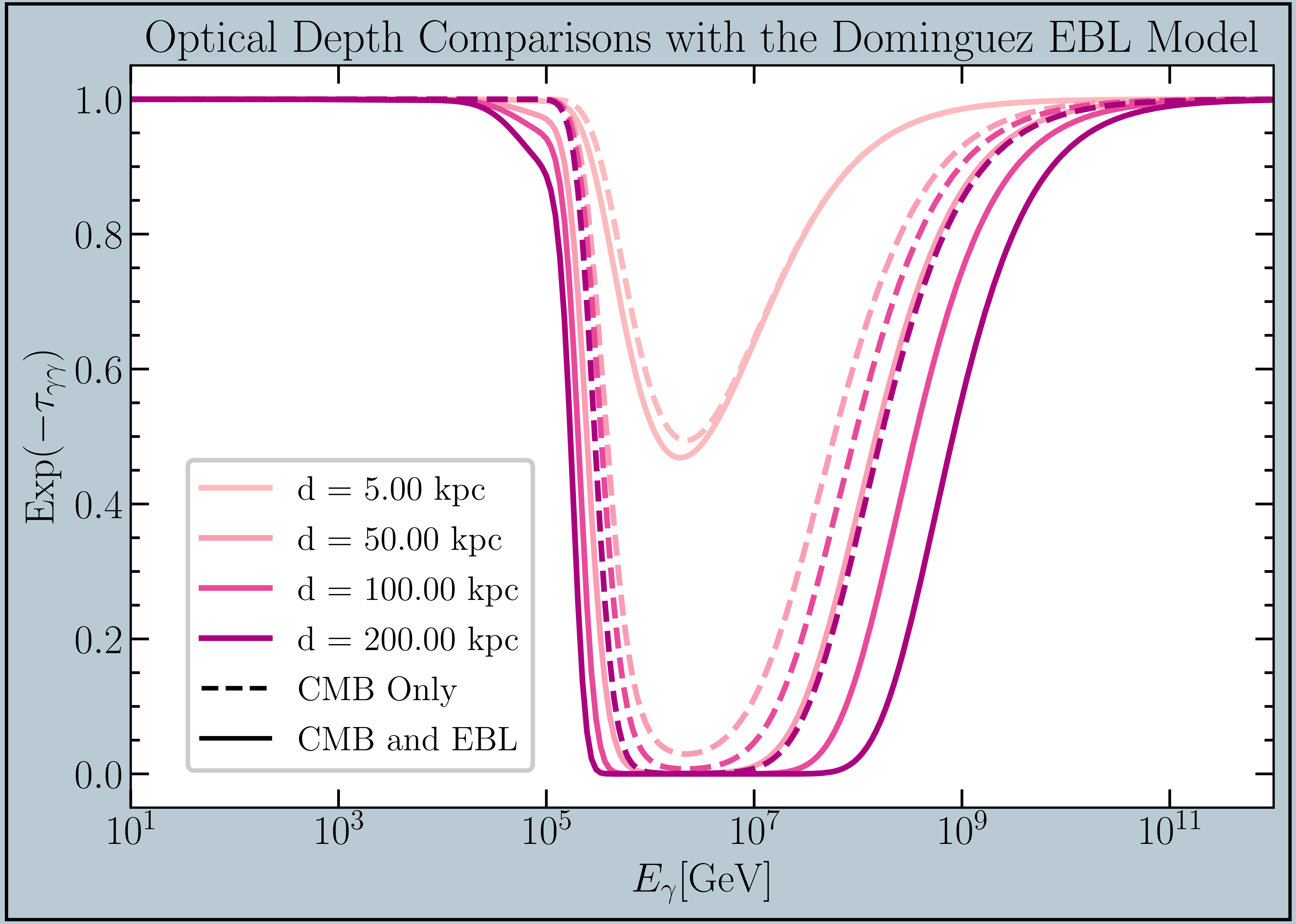
Stecker et al. doi:10.3847/0004-637X/827/1/6

Gamma-Ray Absorption by the CMB and EBL

The amount by which gamma-rays get absorbed through interactions with background radiation can be quantified by the optical depth:

$$\tau_{\gamma\gamma} = L \int\int d\epsilon d\theta \sin\theta \sigma_{\gamma\gamma}(E_\gamma, \epsilon) n(\epsilon) \frac{1-\cos\theta}{2}$$





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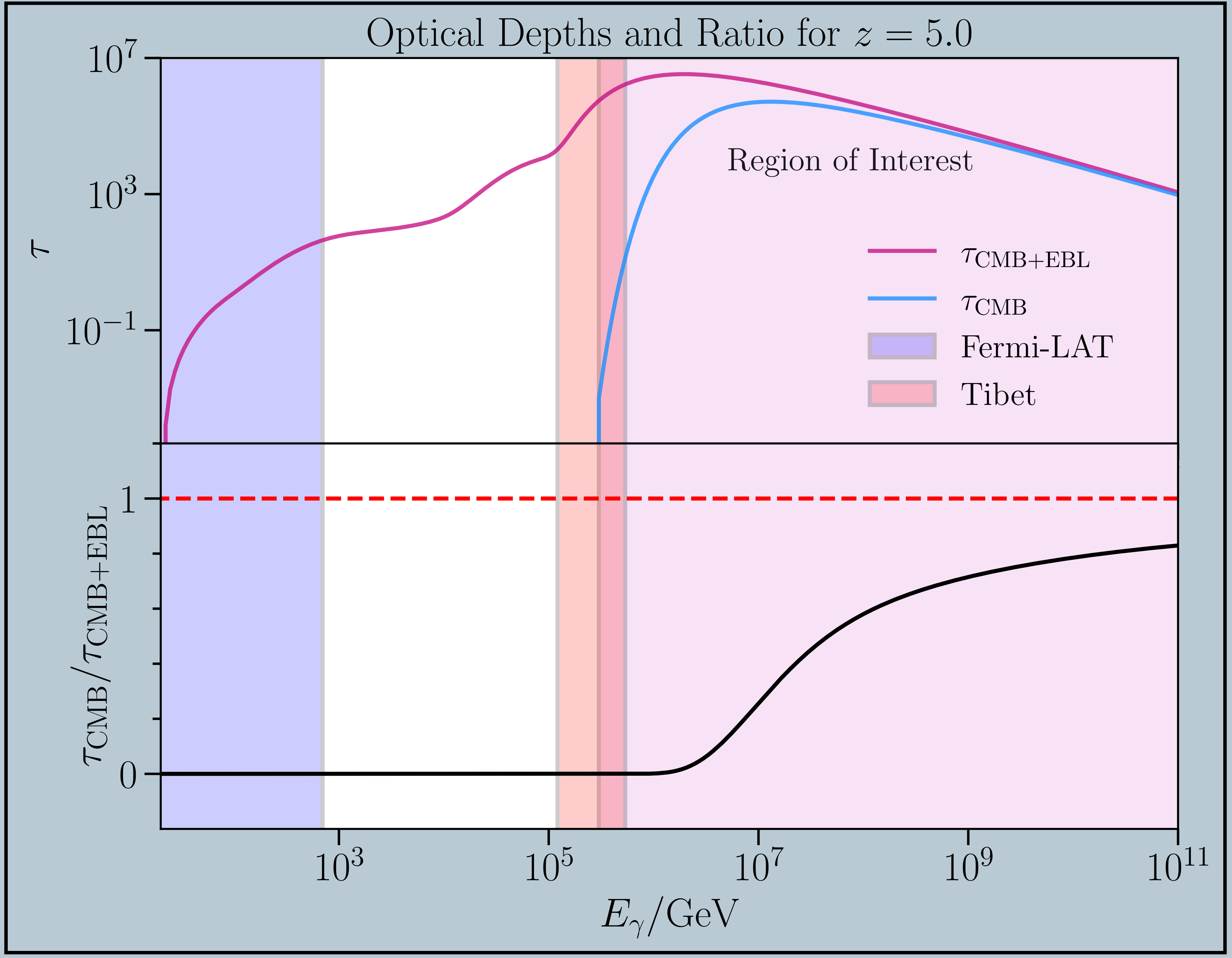
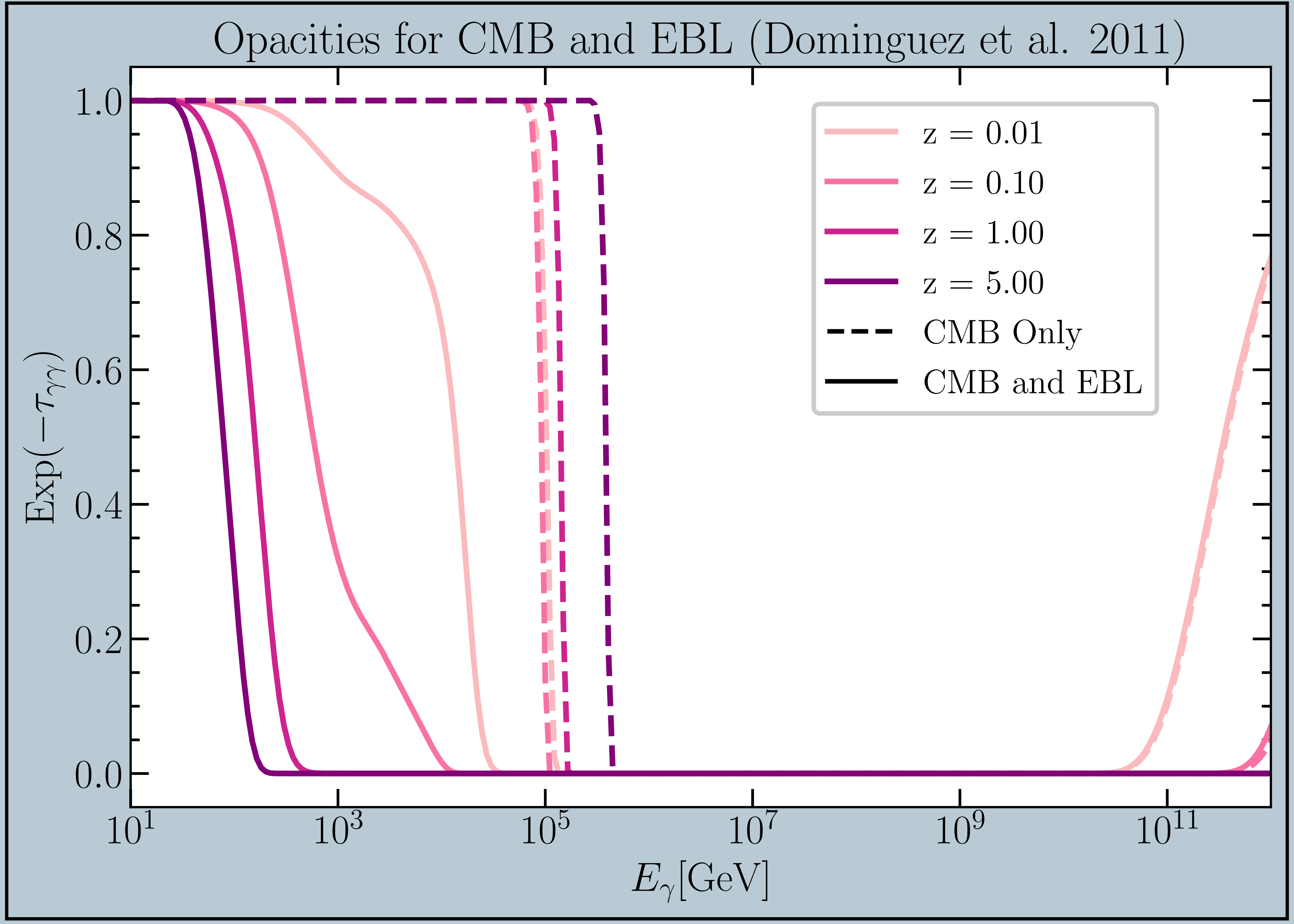




Simulation Details & Monte-Carlo reweighting

This work: Investigates the impact of EBL uncertainty on current limits for dark-matter decay from gamma-ray experiments

Simulation

- Gamma-ray propagation: CRPropa (JCAP 1605 (2016) 038) with an initial spectrum defined uniformly over distance and with a power-law energy dependence: $\phi \sim (E/E_c)^{-1}$
- $E_{\min} = (m_{\rm DM}/2) \times 10^{-6}$ and $E_c = m_{\rm DM}/2$
- Processes considered during propagation:
  - Pair production
  - Double pair production
  - Triplet pair production
  - Inverse-Compton scattering
  - Synchrotron radiation (galactic component with JF12 magnetic field)

Monte-Carlo Reweighting

- To obtain dark-matter spectra, we apply a reweighting scheme that replaces the Monte-Carlo generated weights with weights for dark matter for given dark-matter parameters (HDMSpectra JHEP06(2021)121)
- **Position reweighting:**

$$w = \frac{w_{\rm physical}}{w_{\rm generated}} = \left(\mathrm{DM}(r)\right)\left(\frac{D_{\rm gen}(r)}{\int_{r_{\min}}^{r_{\max}} D_{\rm gen}(r)}\right)^{-1}$$

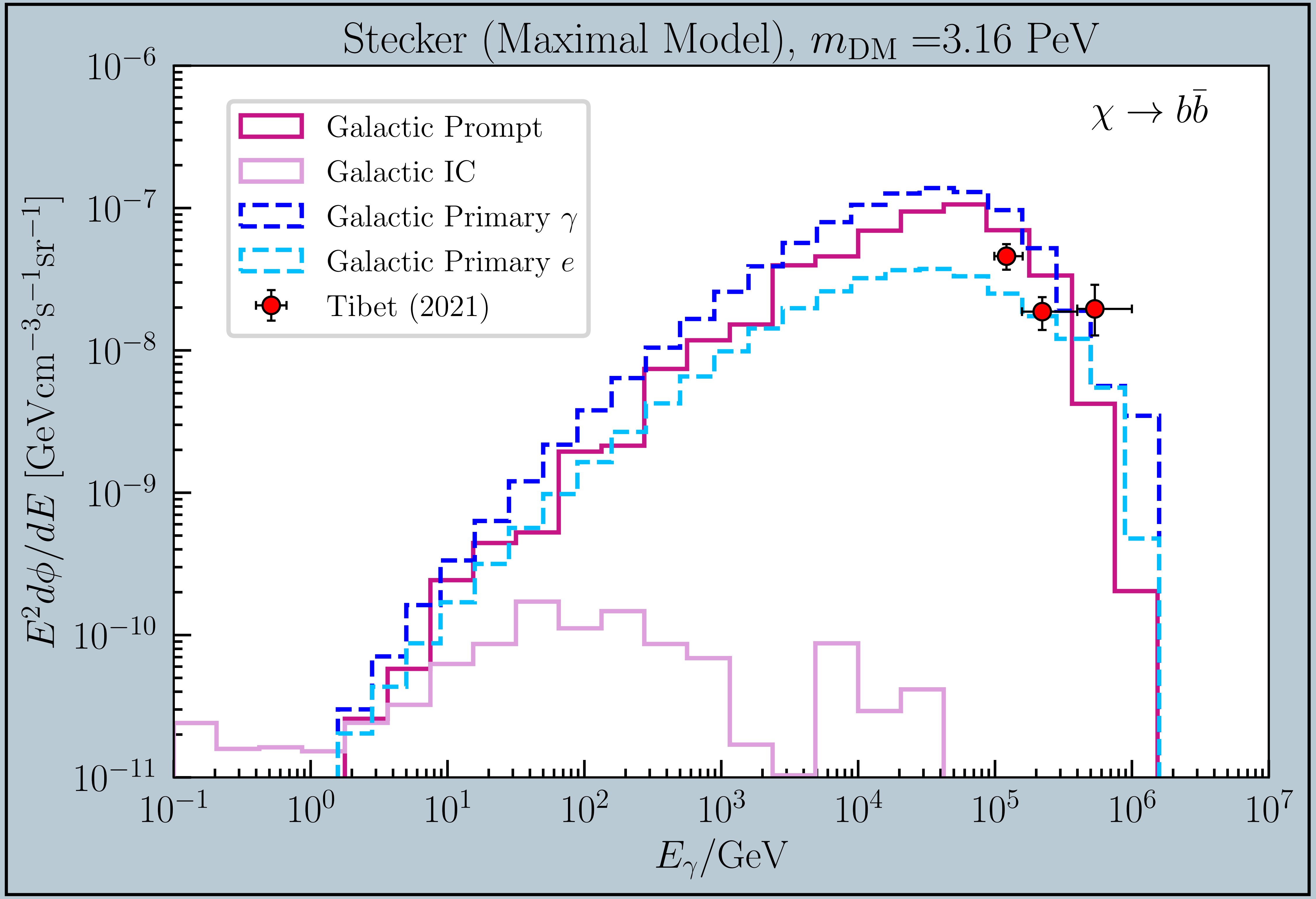
- **Energy reweighting:**

$$w = \frac{w_{\rm physical}}{w_{\rm generated}} = \left(\phi_{\rm DM}(E)\right)\left(\frac{\phi_{\rm gen}(E)}{\int_{E_{\min}}^{E_{\max}} \phi_{\rm gen}(E)}\right)^{-1}$$

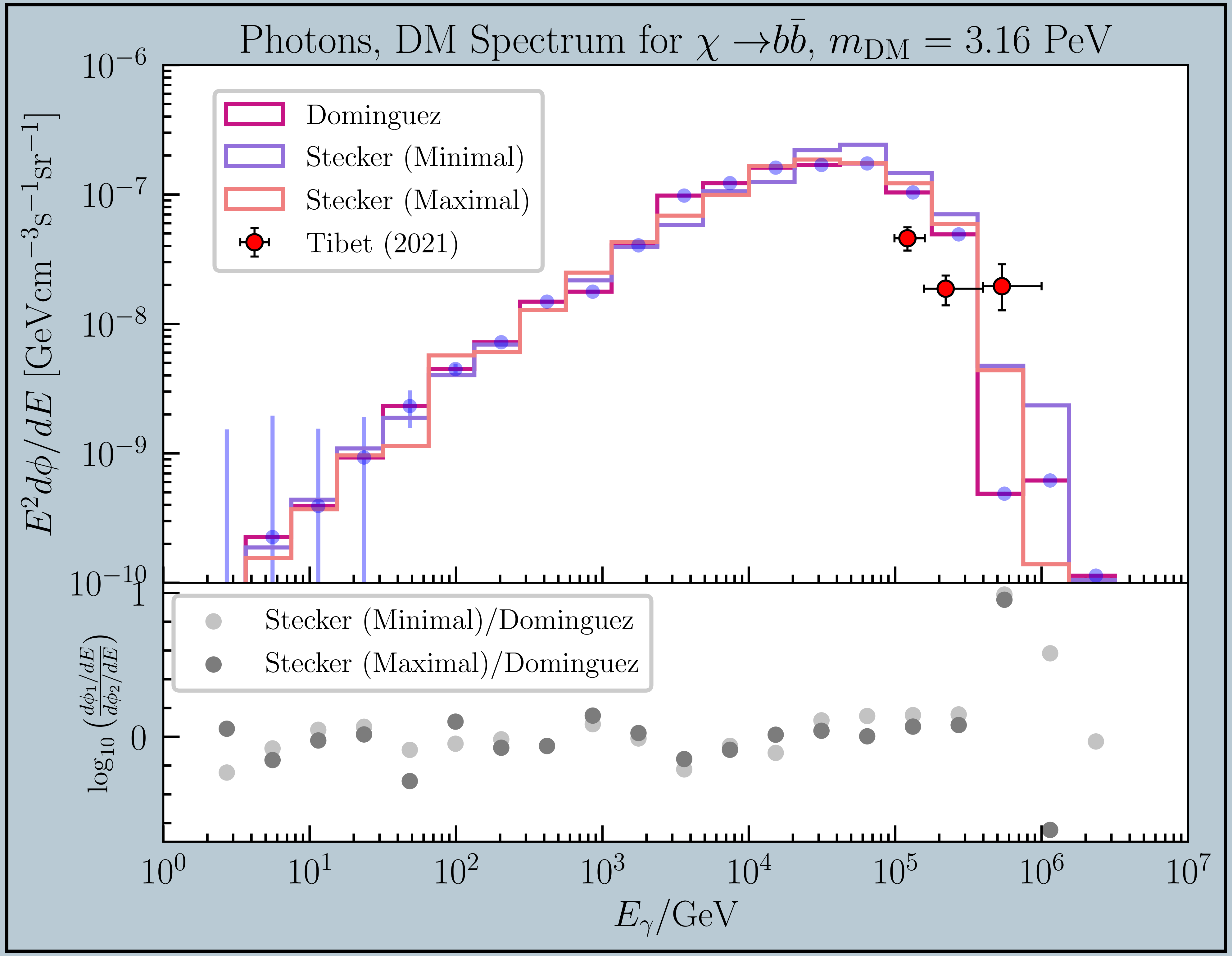
Expected Gamma-Rays from DM Decay at Tibet

Galactic contribution (comparison with Tibet 2021 — Phys. Rev. D **104**, L021301): $-5^\circ < b < 5^\circ, \quad 25^\circ < l < 100^\circ$

Nominal EBL



EBL Model Comparisons for $\tau = 10^{27}$ s



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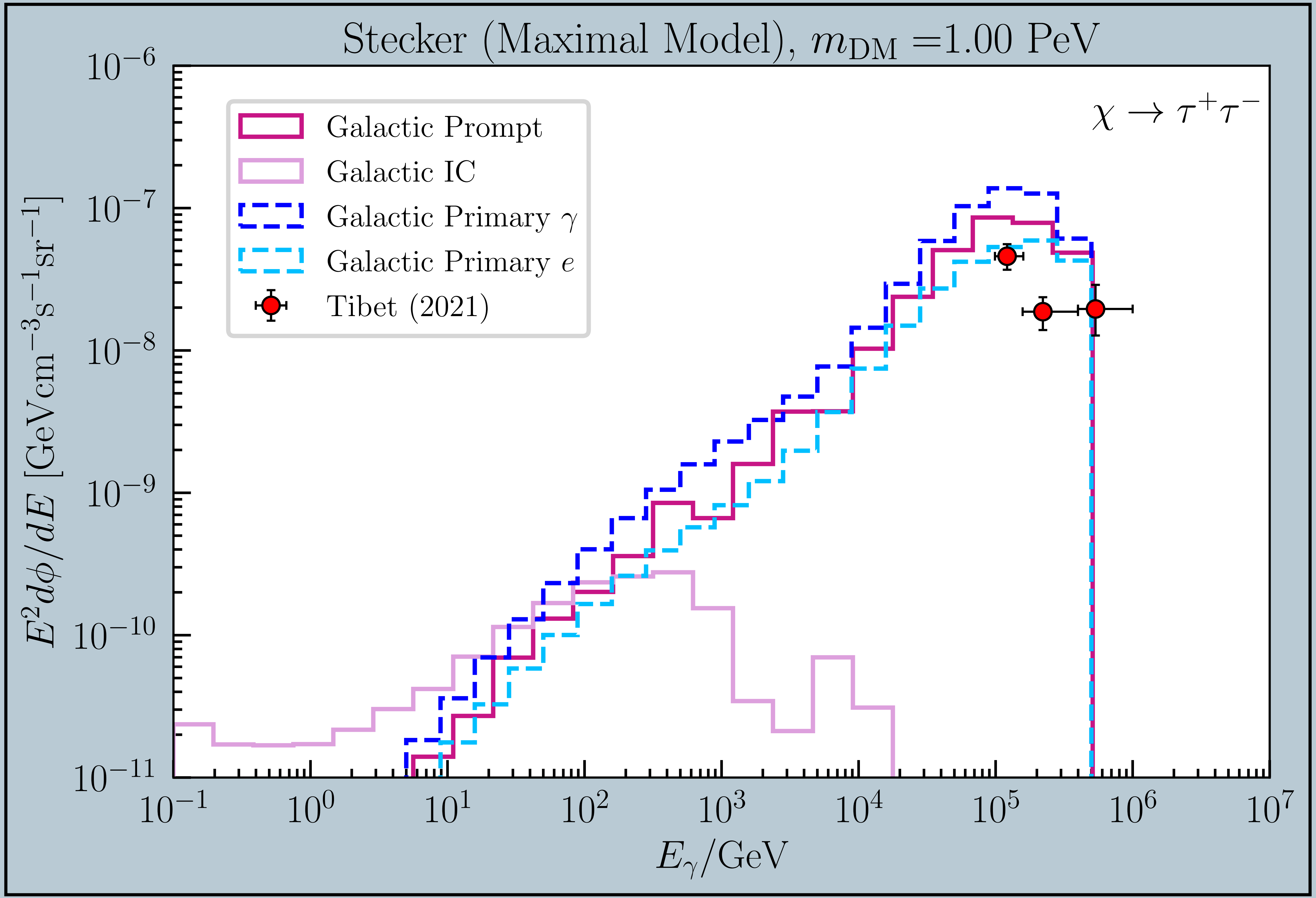

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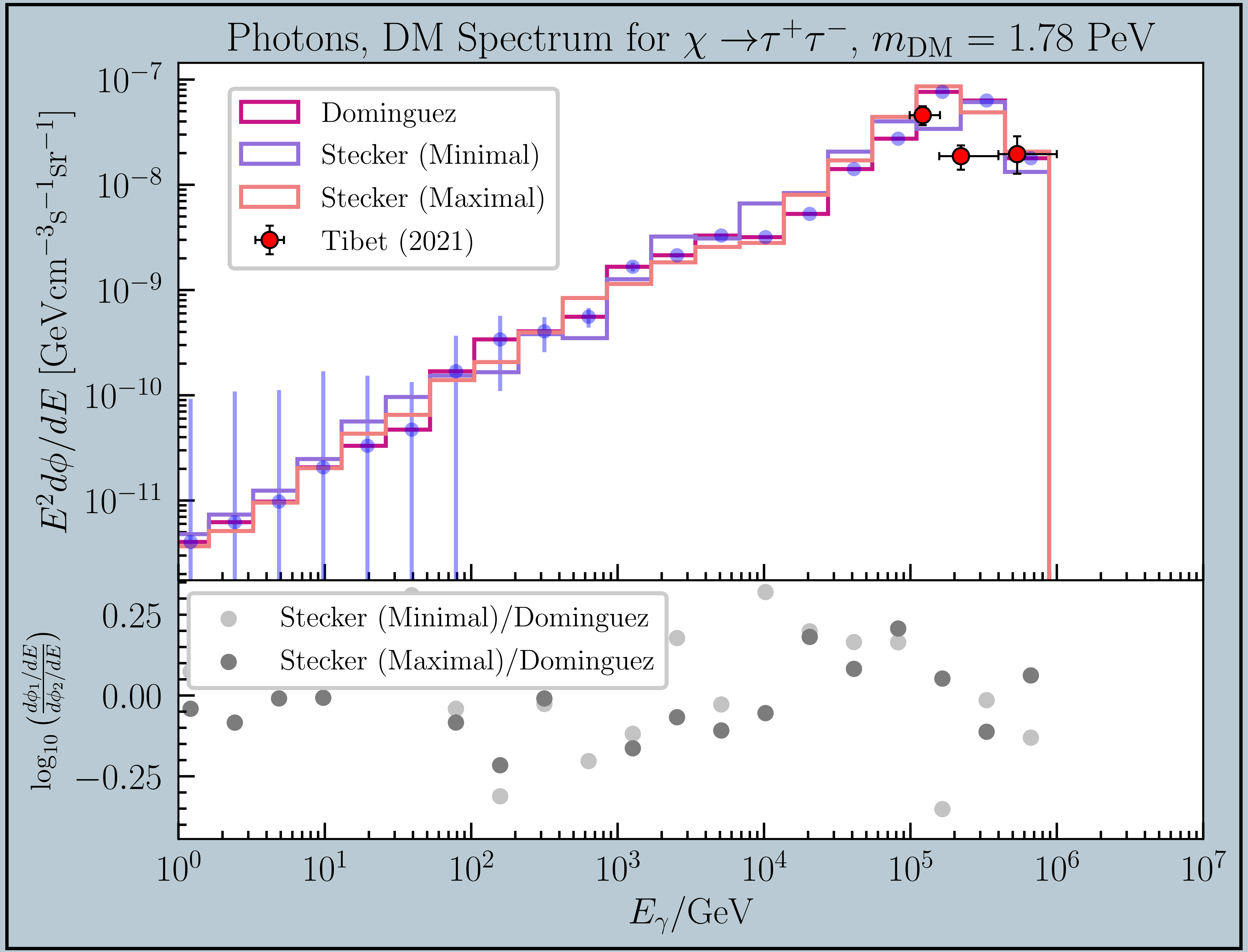
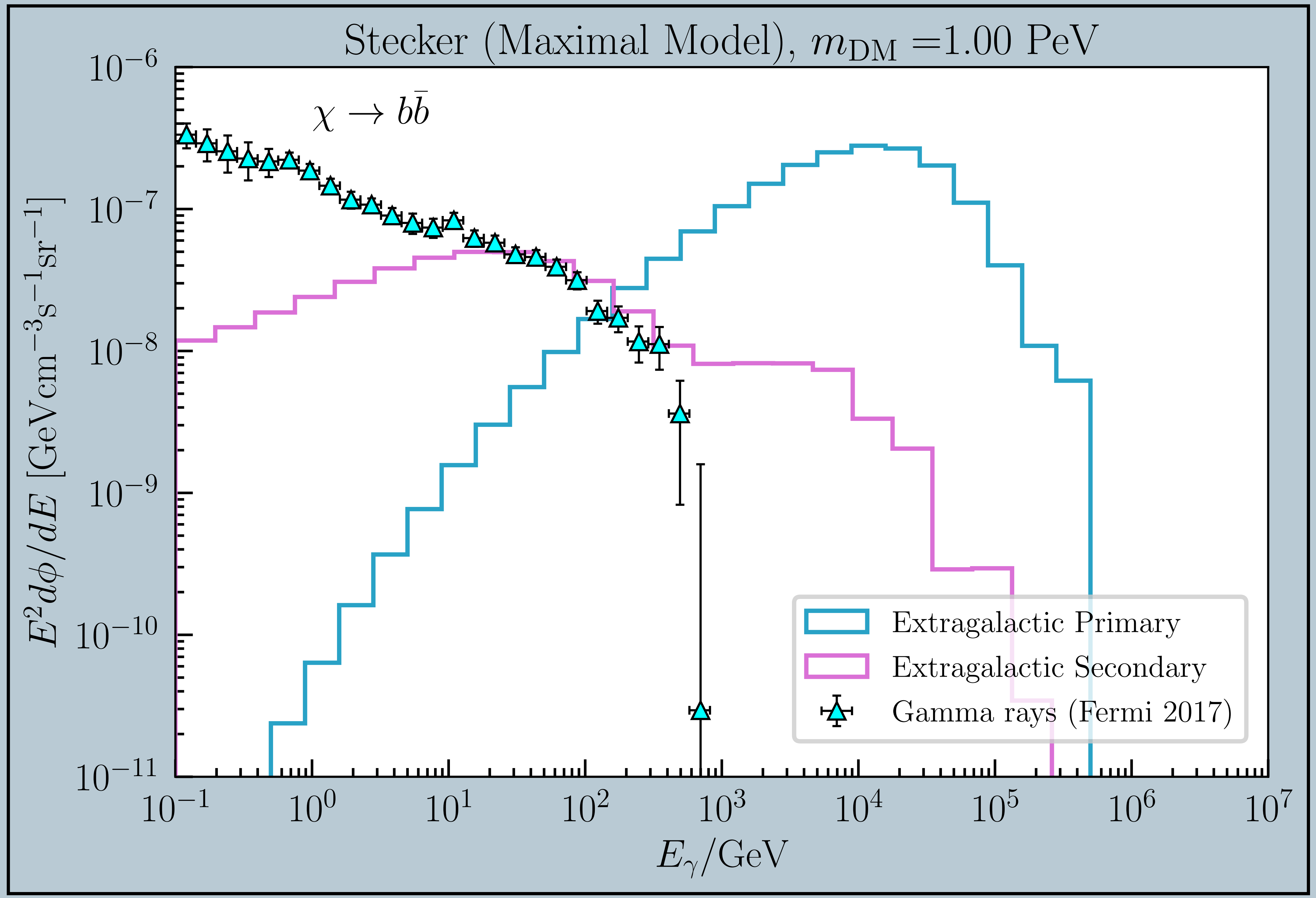


Expected Gamma-Rays from DM Decay at Fermi-LAT

Extragalactic contribution:

Nominal EBL



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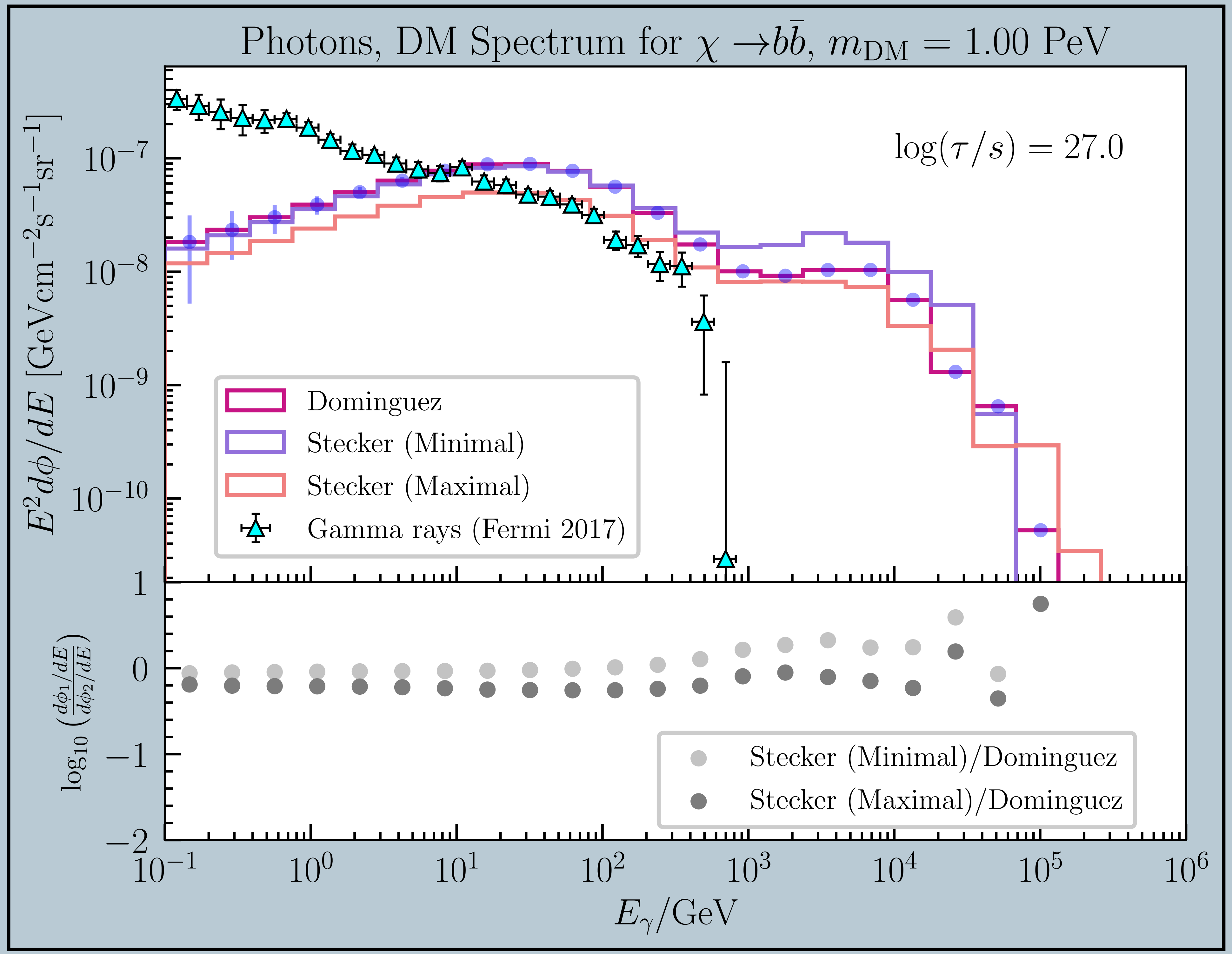
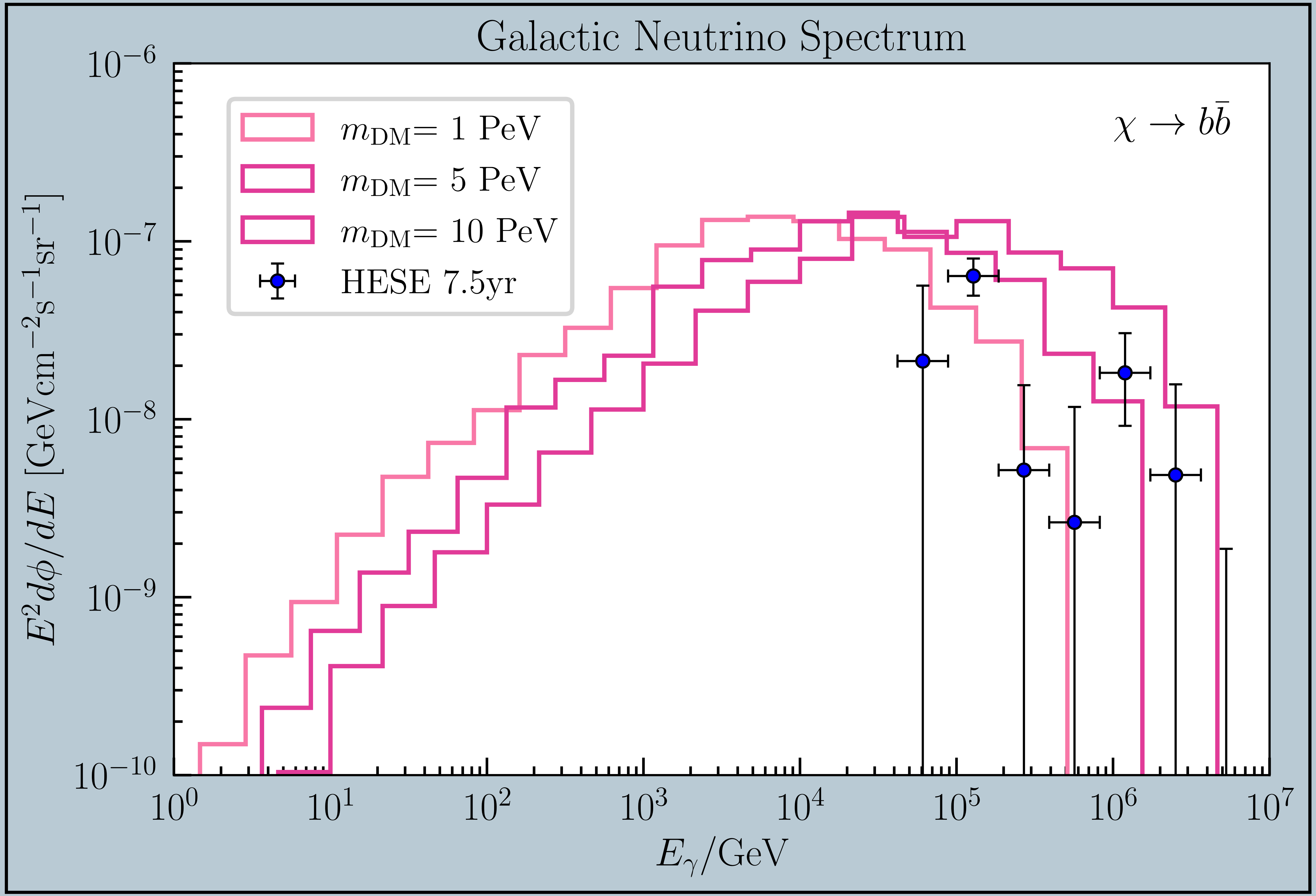


Expected Gamma-Rays from DM Decay at IceCube

Neutrino contribution: data from Abbasi et al. arXiv: 2011.03545.

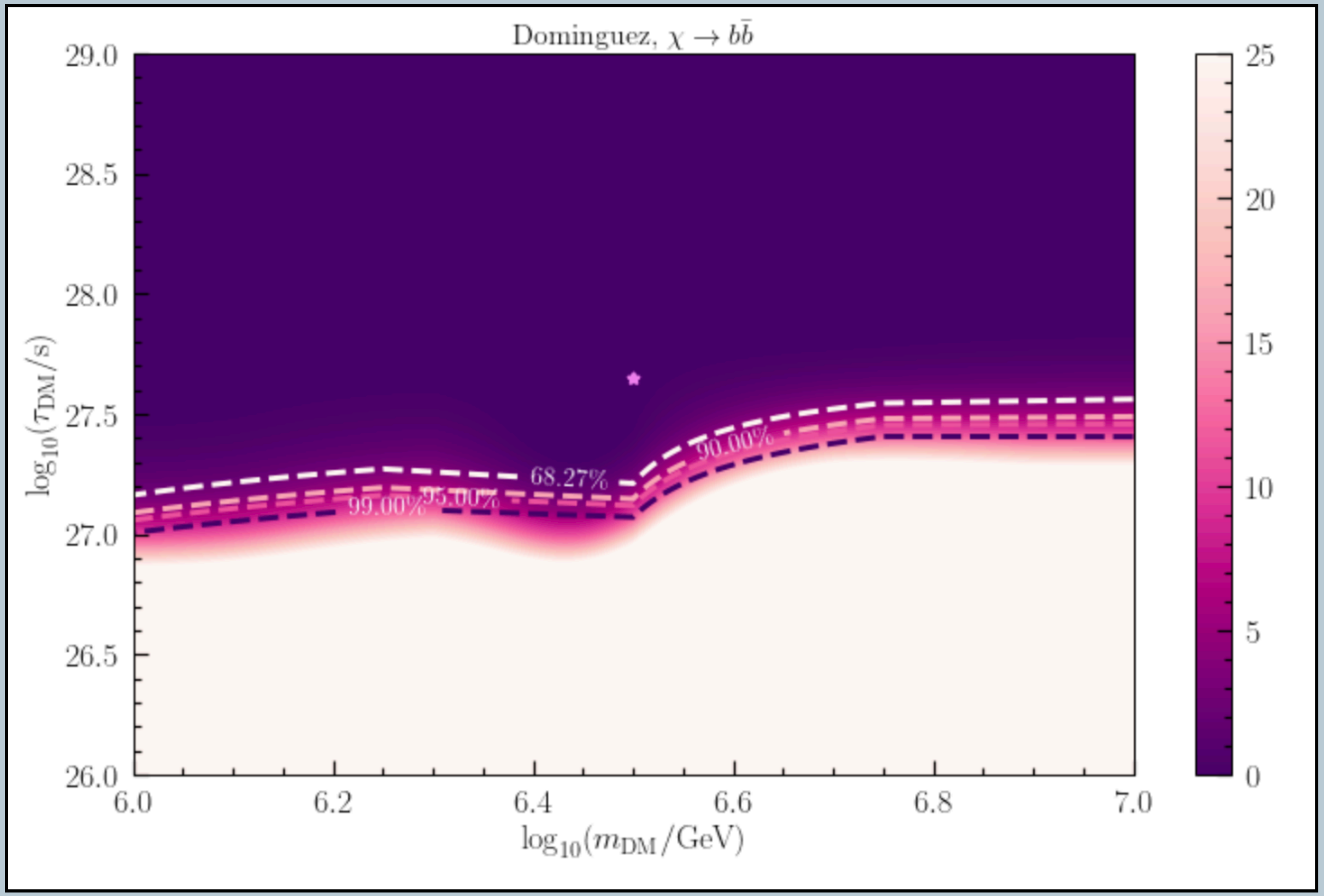
$\tau = 10^{27}$ s



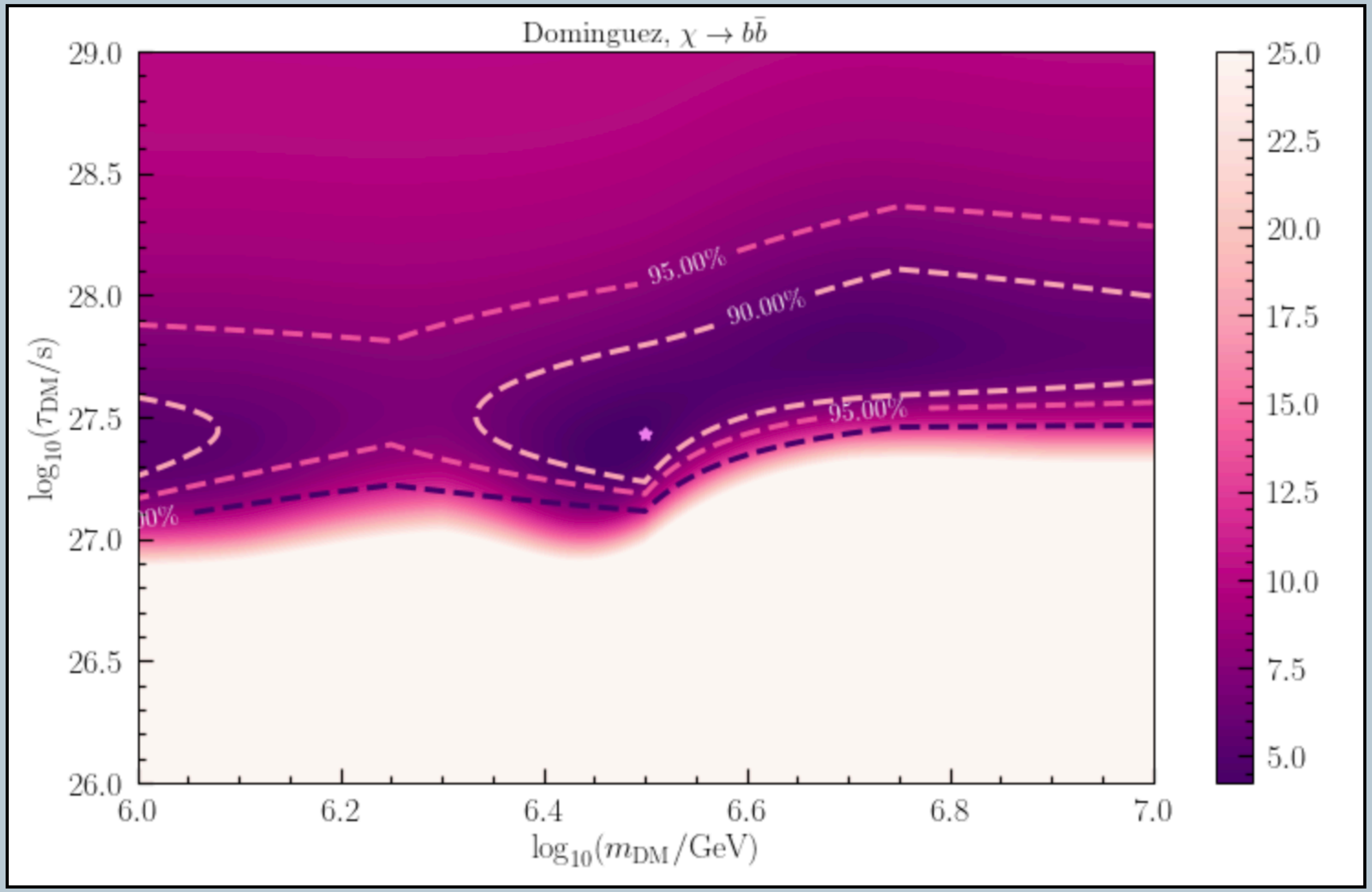
Combined Gamma-Ray Likelihoods for DM Decay

Galactic contribution (comparison with Tibet 2021): $-5^\circ < b < 5^\circ, \quad 25^\circ < l < 100^\circ$

Lower Bounds on Lifetime



Preferred Regions



Likelihoods for DM Decay at Tibet

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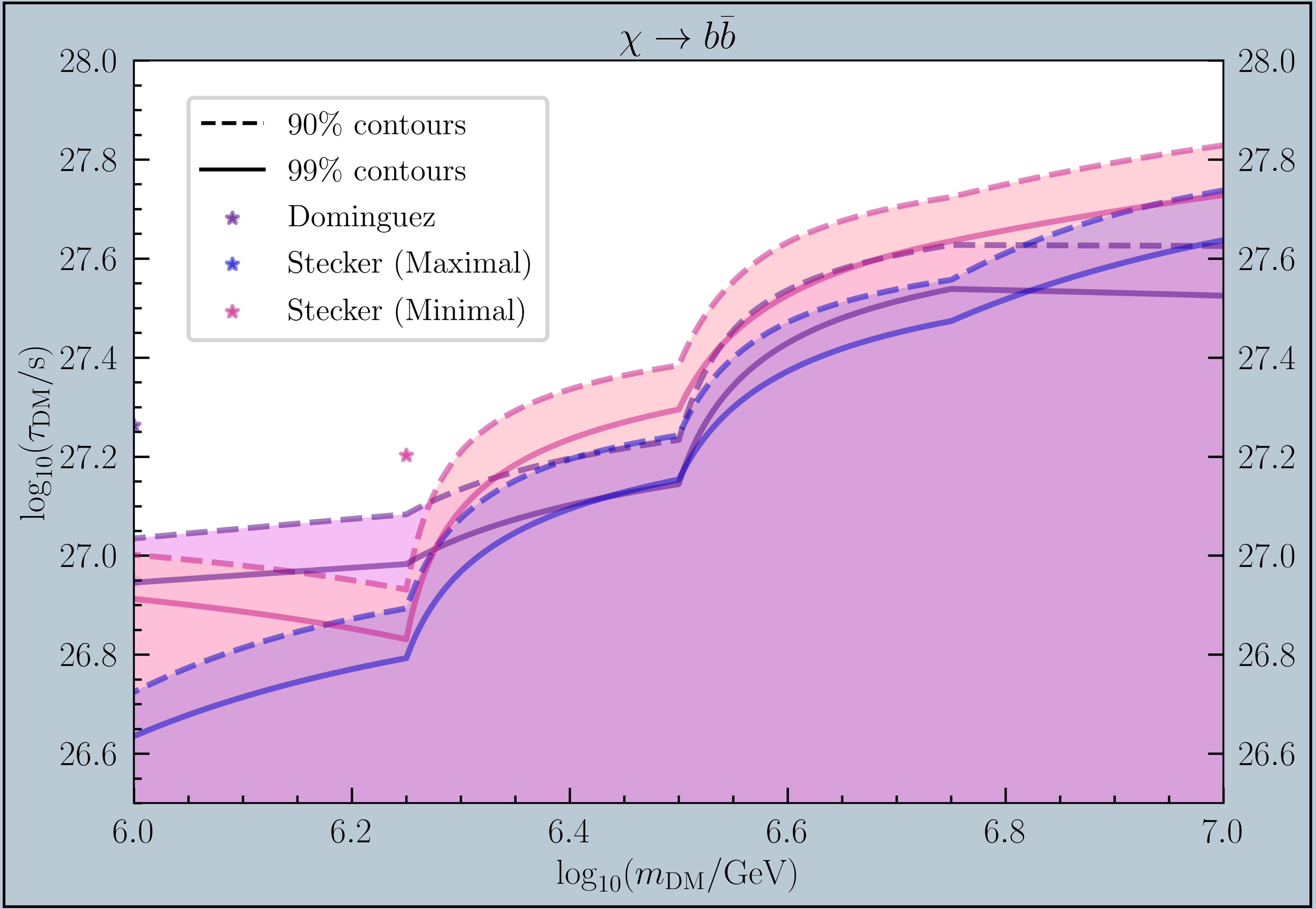

Next Steps/Ongoing Work

Summary

- We propagated photons for three different models of the EBL, obtaining dark-matter gamma-ray spectra that show differences from the nominal model of around 25 percent
- Lower limits on dark-matter lifetime likewise exhibit differences between different EBL models

Ongoing

- Complete this analysis by repeating this for additional dark matter decay channels and by making similar comparisons with Fermi-LAT diffuse data and IceCube data
- We expect that the extragalactic component will see an even larger effect from differences in EBL
- Obtain uncertainties on current dark matter constraints
- Understand interpretation of gamma-ray data and its implications for dark-matter decay
- Upcoming publication on these results