Probing heavy dark matter decays with multi-messenger astrophysical data

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Based on 1907.11671

with

S. Ando, M. Arimoto, O. Macias

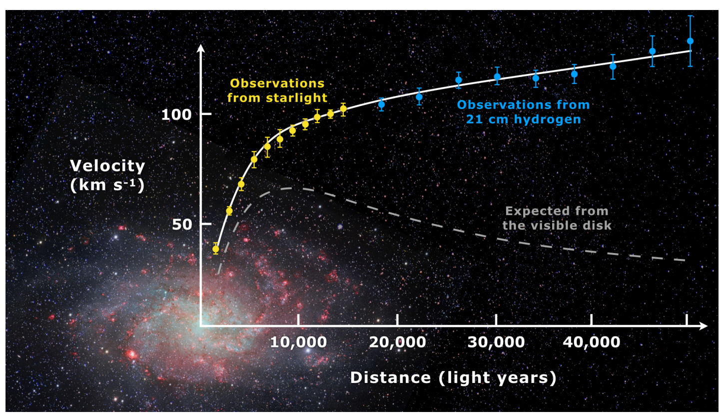
Warsaw, September 14, 2019

Outline

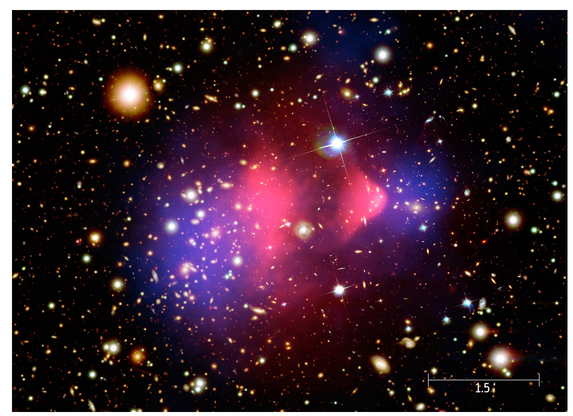
1. Introduction

Evidences for dark matter (DM)

- Rotation curve of galaxies
- Bullet cluster
- Cosmic microwave background (CMB)

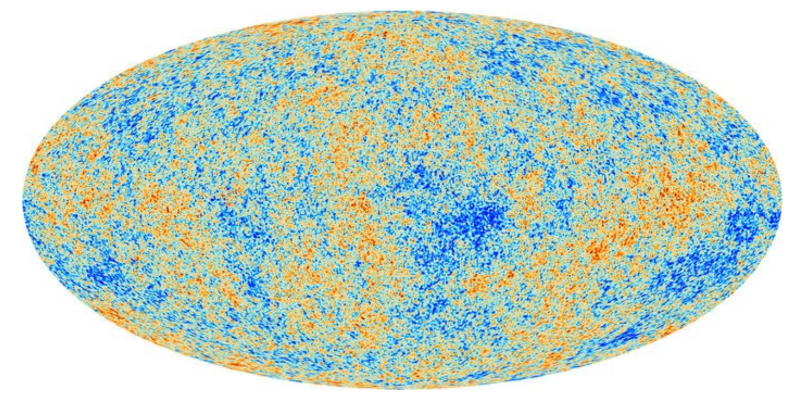


Corbelli, Salucci '00



Markevitch et al. '04

Clowe et al.'04



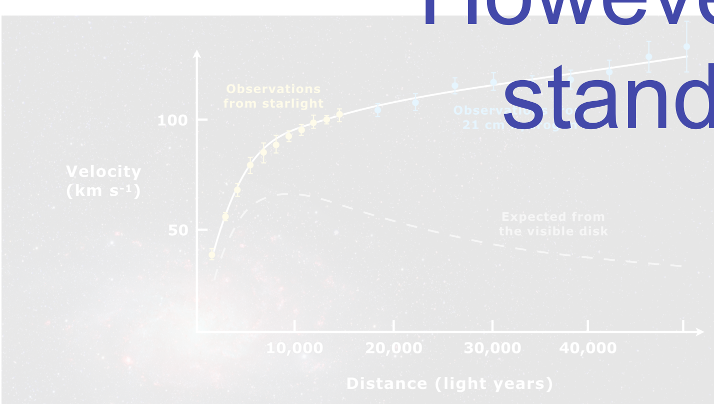
Planck '13

It is confirmed that the DM exists!

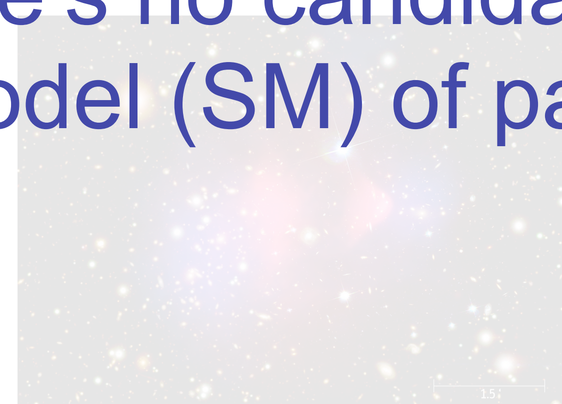
Evidences for dark matter (DM)

- Rotation curve of galaxies
- Bullet cluster
- Cosmic microwave background (CMB)

However, there's no candidate for DM in the standard model (SM) of particle physics

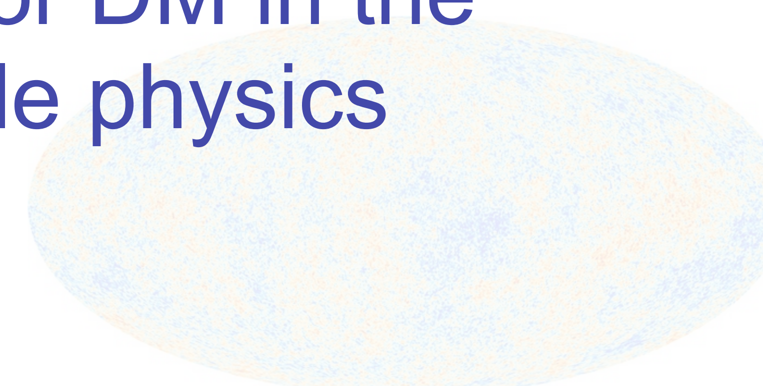


Corbelli, Salucci '00



Markevitch et al. '04

Clowe et al.'04



Planck '13

To be consistent the observations, DM has to be

- Electronically neutral
- Non-baryonic
- Stable or sufficiently long-lived
- Its energy density should agree with the CMB observations
- Non-relativistic

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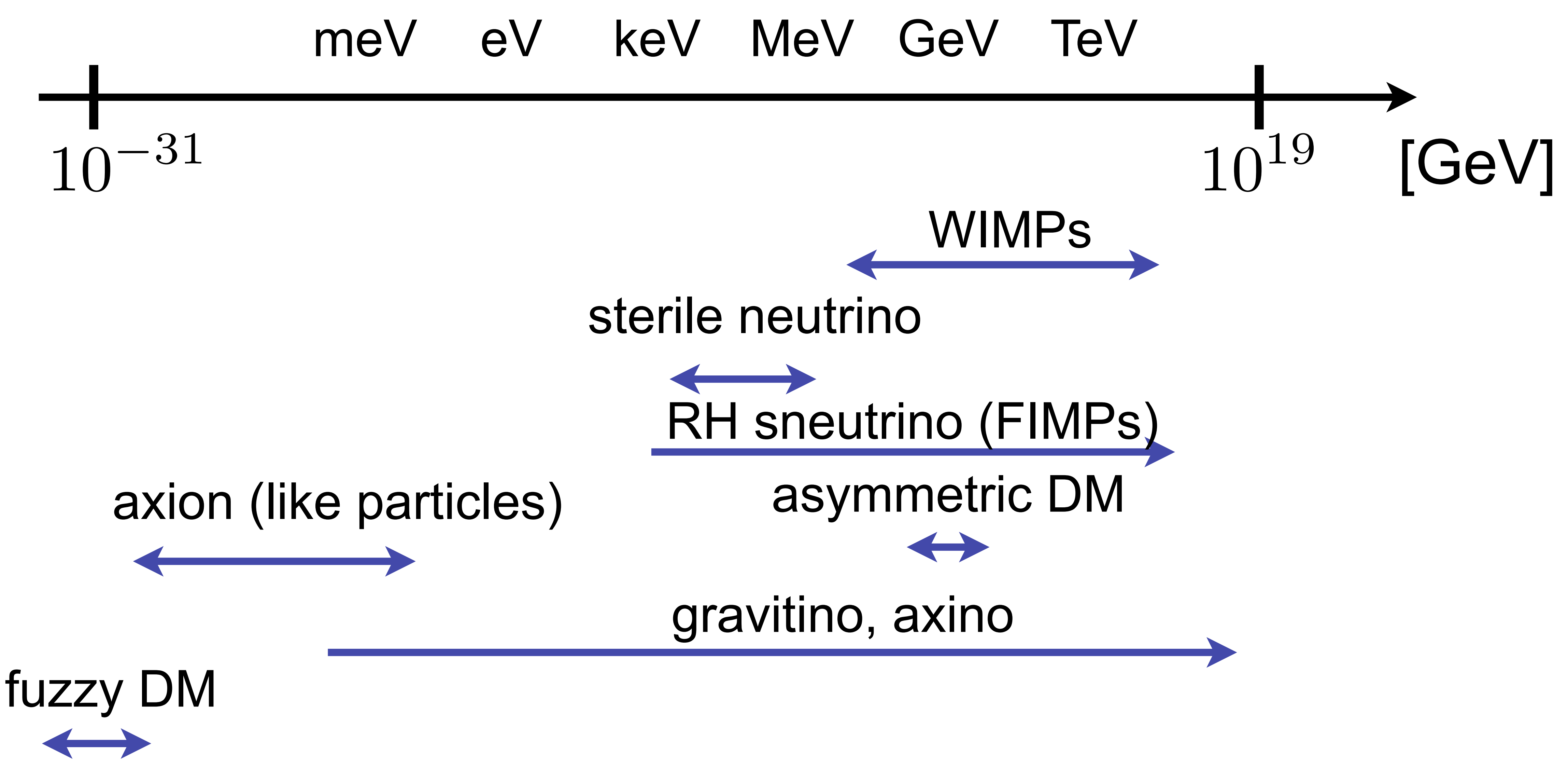
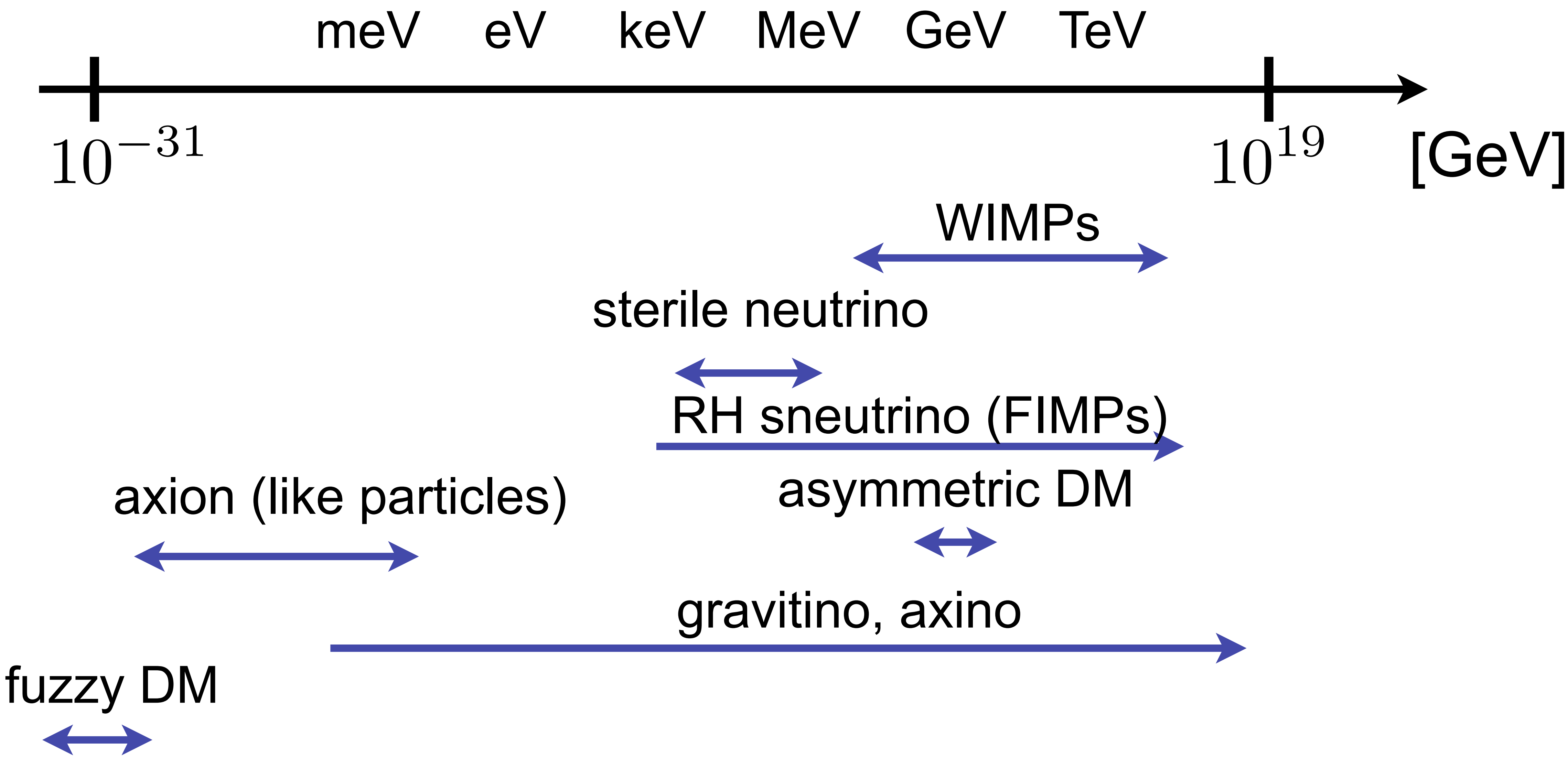
How heavy?

A rough sketch of particle DM candidates



A rough sketch of particle DM candidates



How heavy?

→ Almost unknown

To be consistent the observations, DM has to be

- Electronically neutral
- Non-baryonic
- Stable *or* sufficiently long-lived
- Its energy density should agree with the CMB observation
- Non-relativistic

Stable or unstable?

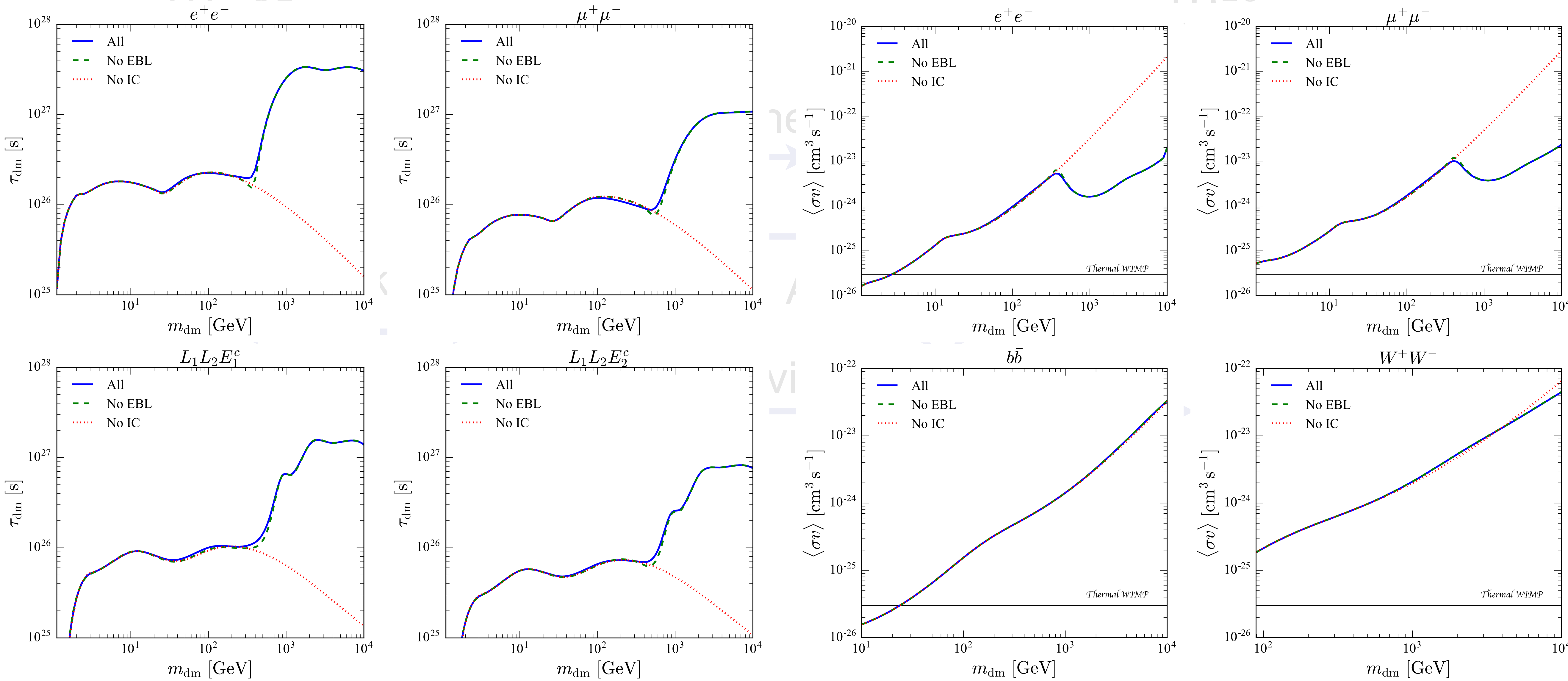
⟶ Unknown

How heavy? → Almost unknown

Stable or unstable? → Unknown

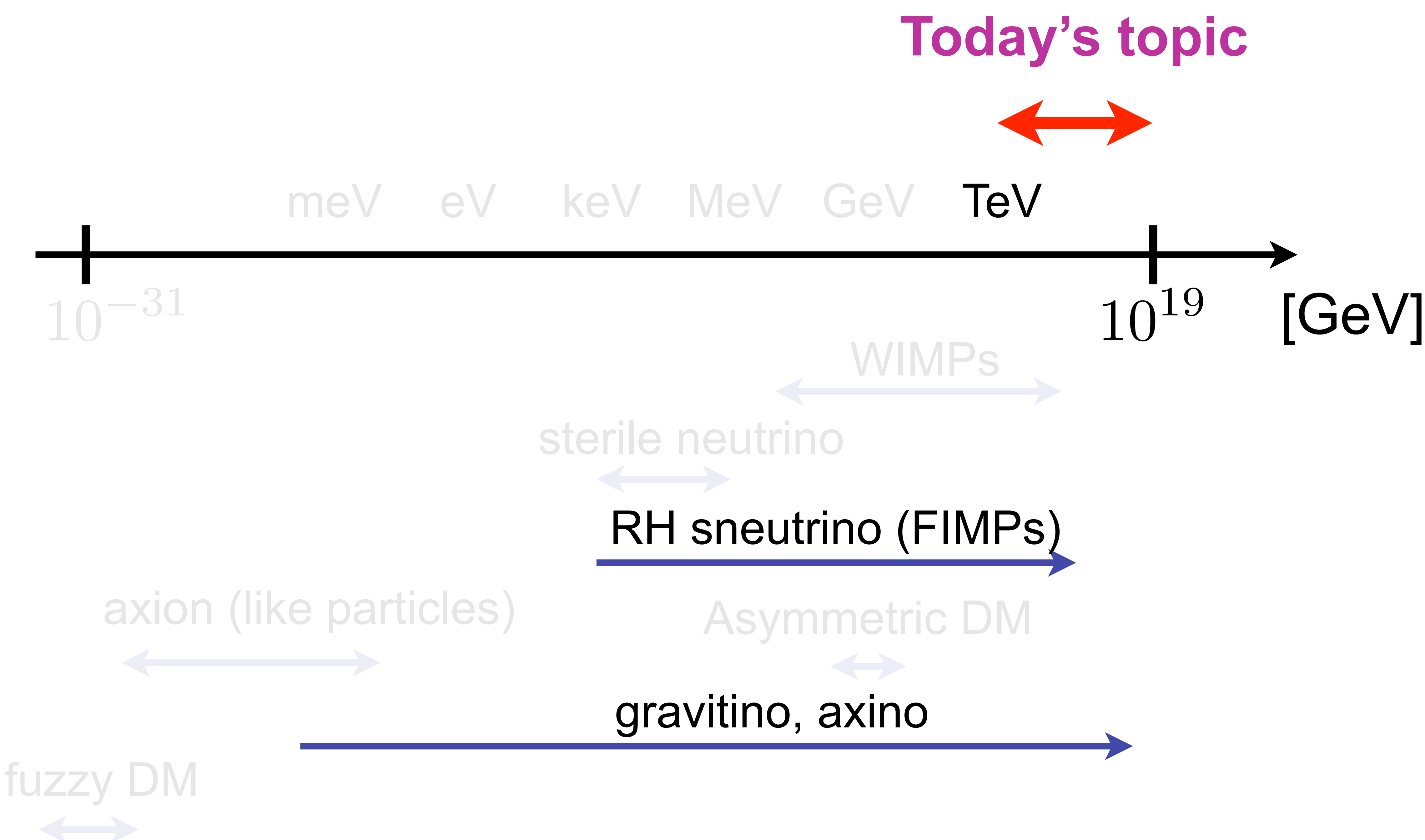
Cosmic rays can be a probe for the questions

Ando, KI '16



Decaying DM

Annihilating DM


Today's topic
meV
eV
keV
MeV
GeV
TeV
10^{-31}
10^{19}
[GeV]
WIMPs
sterile neutrino
RH sneutrino (FIMPs)
axion (like particles)
Asymmetric DM
gravitino, axino
fuzzy DM

Past works on heavy decaying DM:

Esmaili, Ibarra, Peres ’12

Murase, Beacom ’12

Ahlers, Murase ’14

Murase, Laha, Ando, Ahlers ’15

Aloisio, Matarrese, Olinto ’15

Kalashev, Kuznetsov ’16

Cohen, Murase, Rodd, Safdi, Soreq ’17

Kachelriess, Kalashev, Kuznetsov ’18

Sui, Bhupal Dev ’18

But no comprehensive analysis

In our study

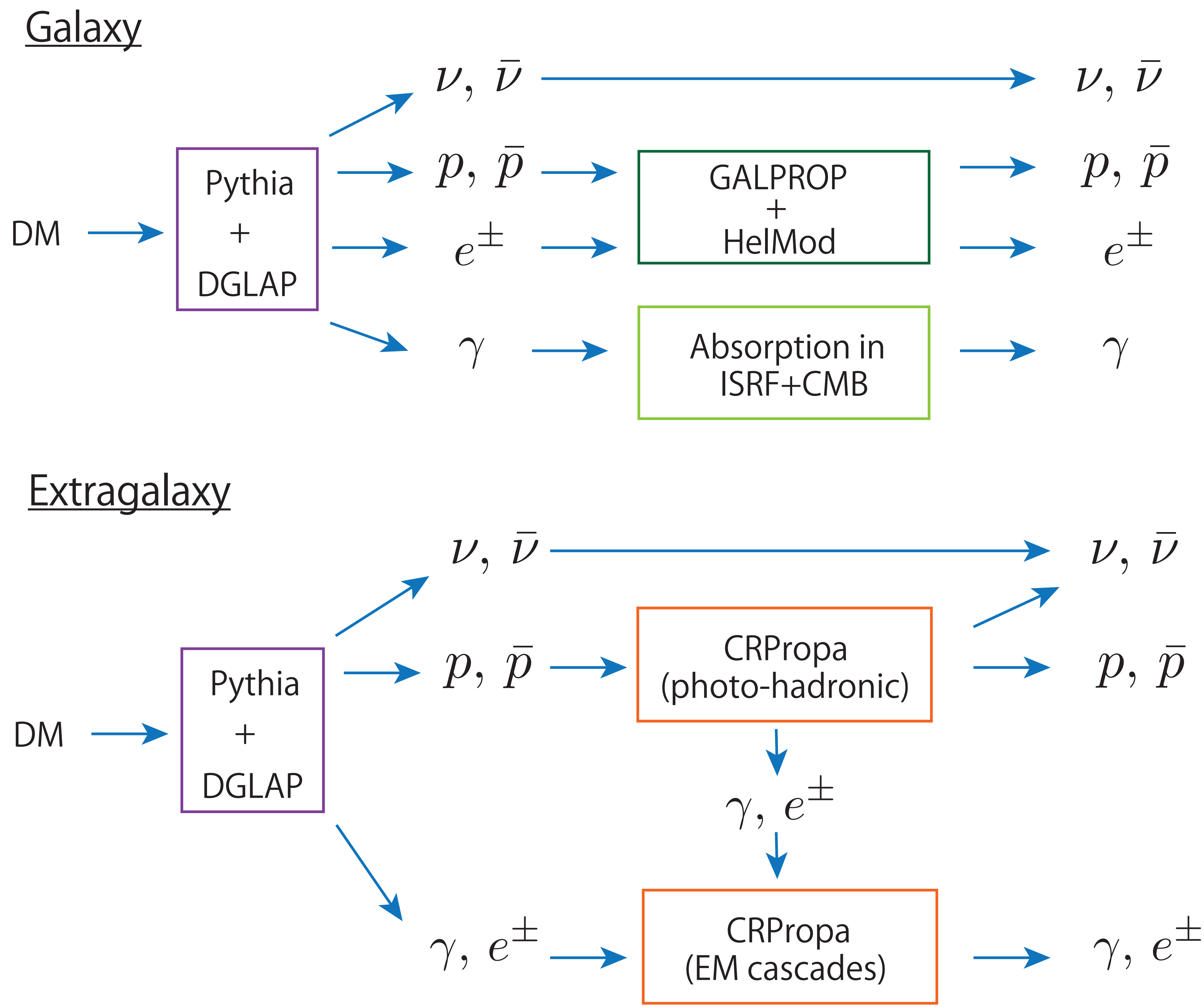
We simulate cosmic-ray (CR) $p, \bar{p}, e^{\pm}, \gamma, \nu\,, \bar{\nu}$ from heavy decaying DM ($10\,\mathrm{TeV} \leq m_{\mathrm{dm}} \leq 10^{16}\,\mathrm{GeV}$) in both

- Galactic
- Extragalactic

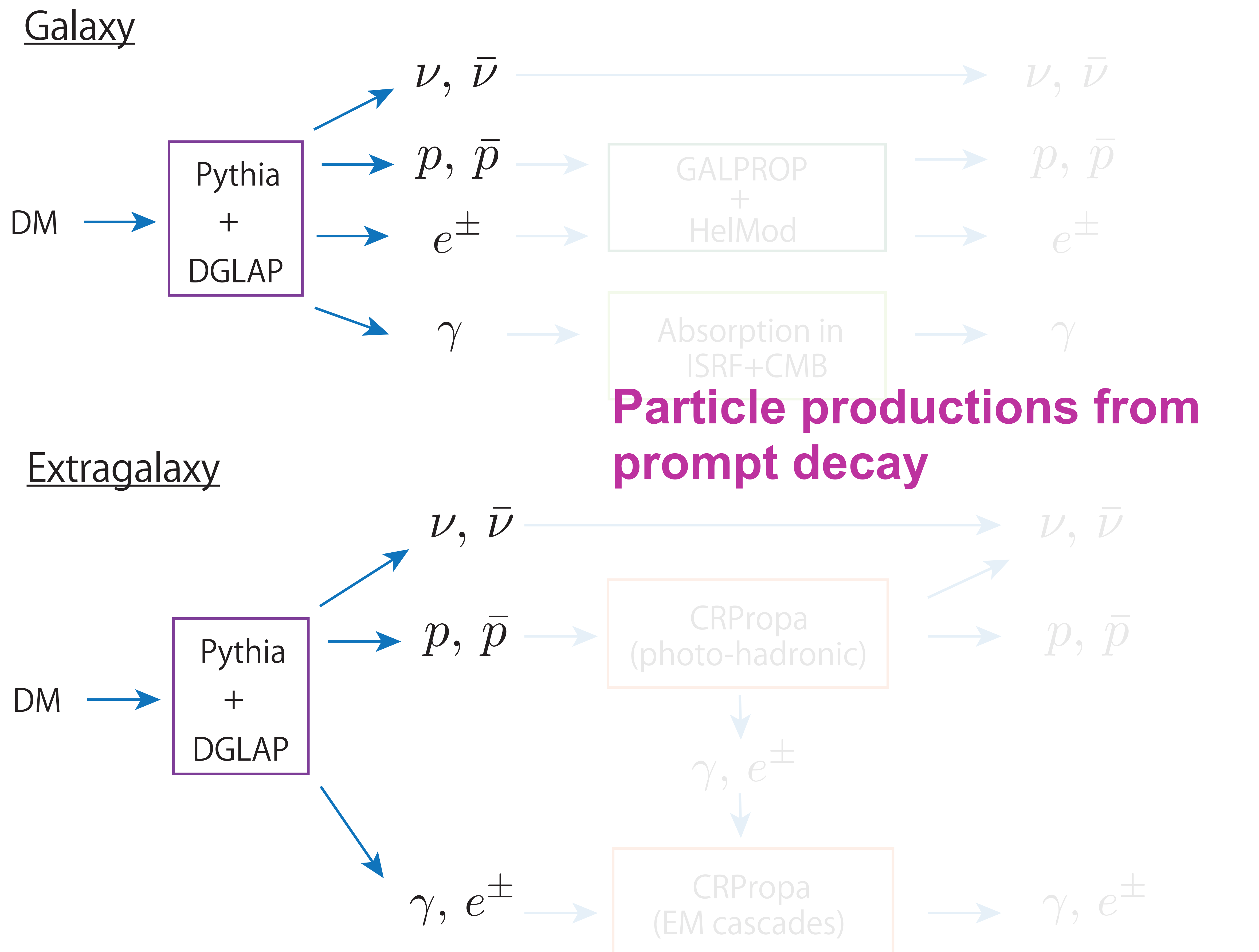
regions and discuss the detectability of the signals with multi-messenger astrophysical data

2. CRs from heavy decaying DM

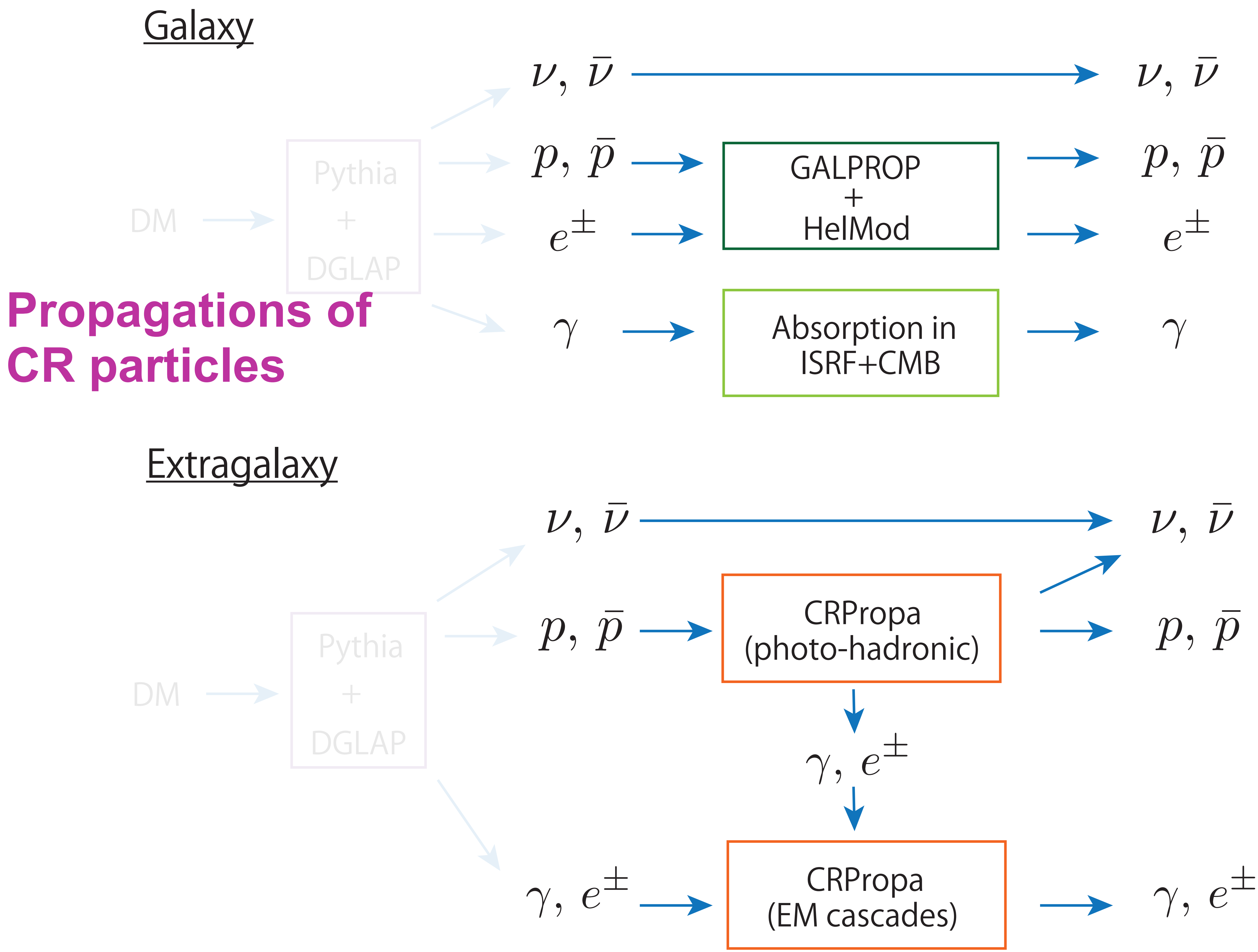
Outline of the simulation



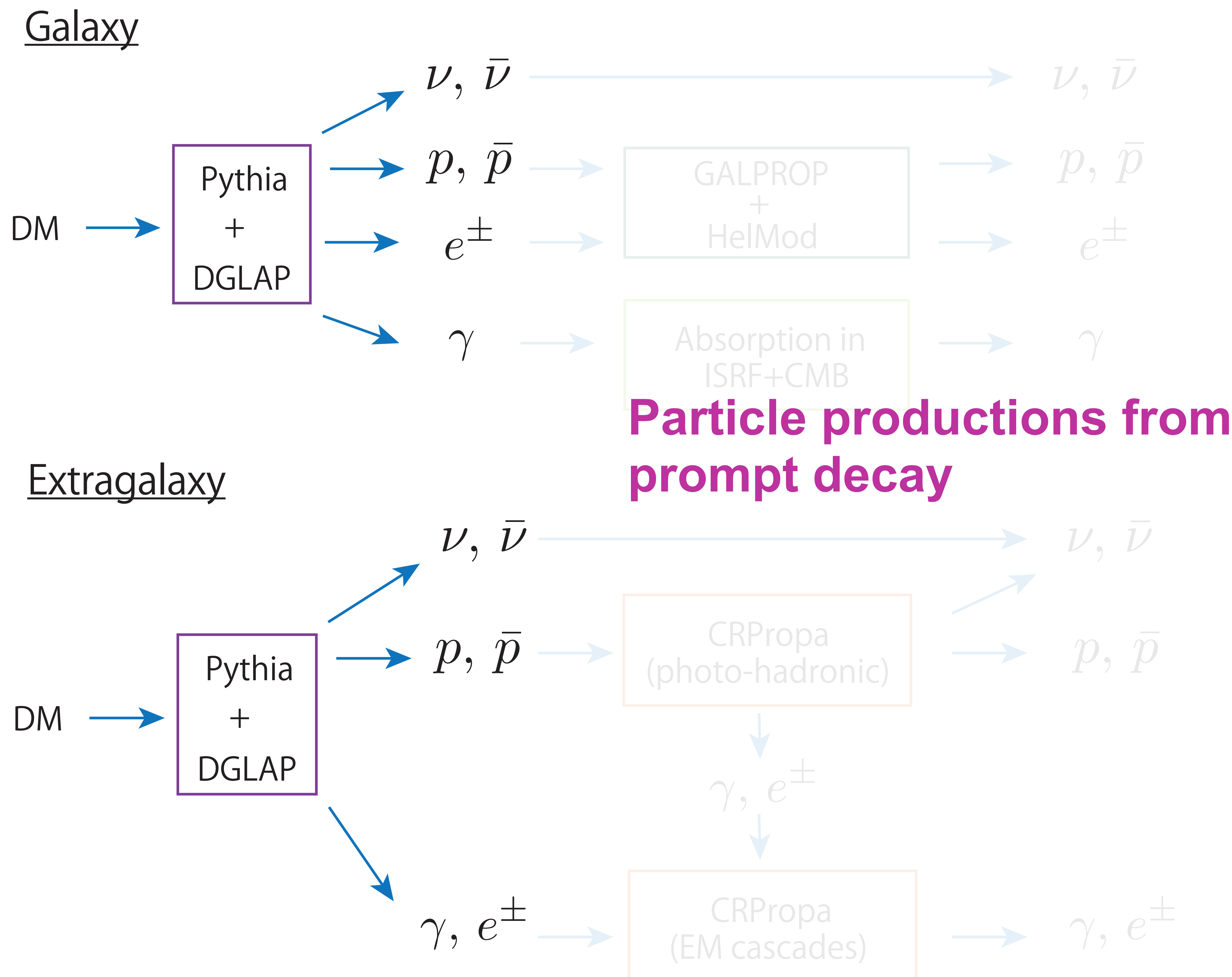
Outline of the simulation



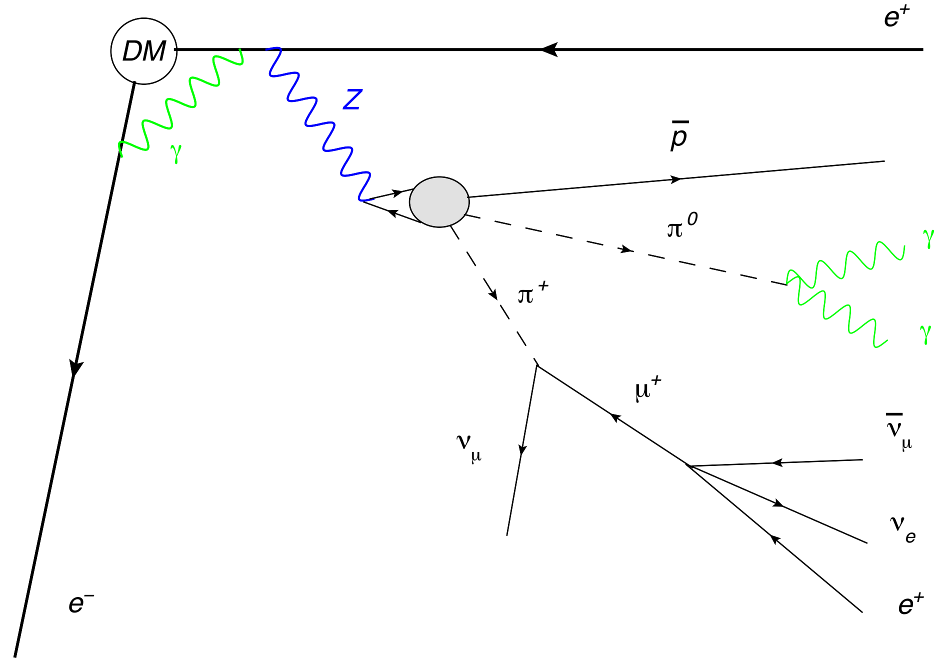
Outline of the simulation



Outline of the simulation



In the decay product of heavy DM ($m_{\rm dm} \gtrsim 10\,{\rm TeV}$), QCD and electroweak (EW) cascades happen



Birkel, Sarkar ’98
Sarkar, Toldra ’02
Berezinsky, Kachelriess ’01
Aloisio, Berezinsky, Kachelriess ’02
Barbot, Drees ’02, ’03
Bahr et al. ’08
Bellm et al. ’15

Fig. from Ciafaloni, Comelli, Riotto, Sala, Strumia, Urbano ’11

You can “find” variety of particles in a single particle, which can be described by Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) Eqs.

In the present work, we focus on $b\bar{b}$ final state

1. Solve DGLAP Eqs. to derive the fragmentation functions of the hadrons h , D_b^h

   $h = \pi^\pm, \pi^0, K^\pm, K^0, \bar{K}^0, n, \bar{n}, p, \bar{p}$

Kniehl, Kramer, Potter '00
Kretzer '00
Albino, Kniehl, Kramer '05
Hirai, Kumano, Nagai, Sudoh '07
Hirai, Kumano '12

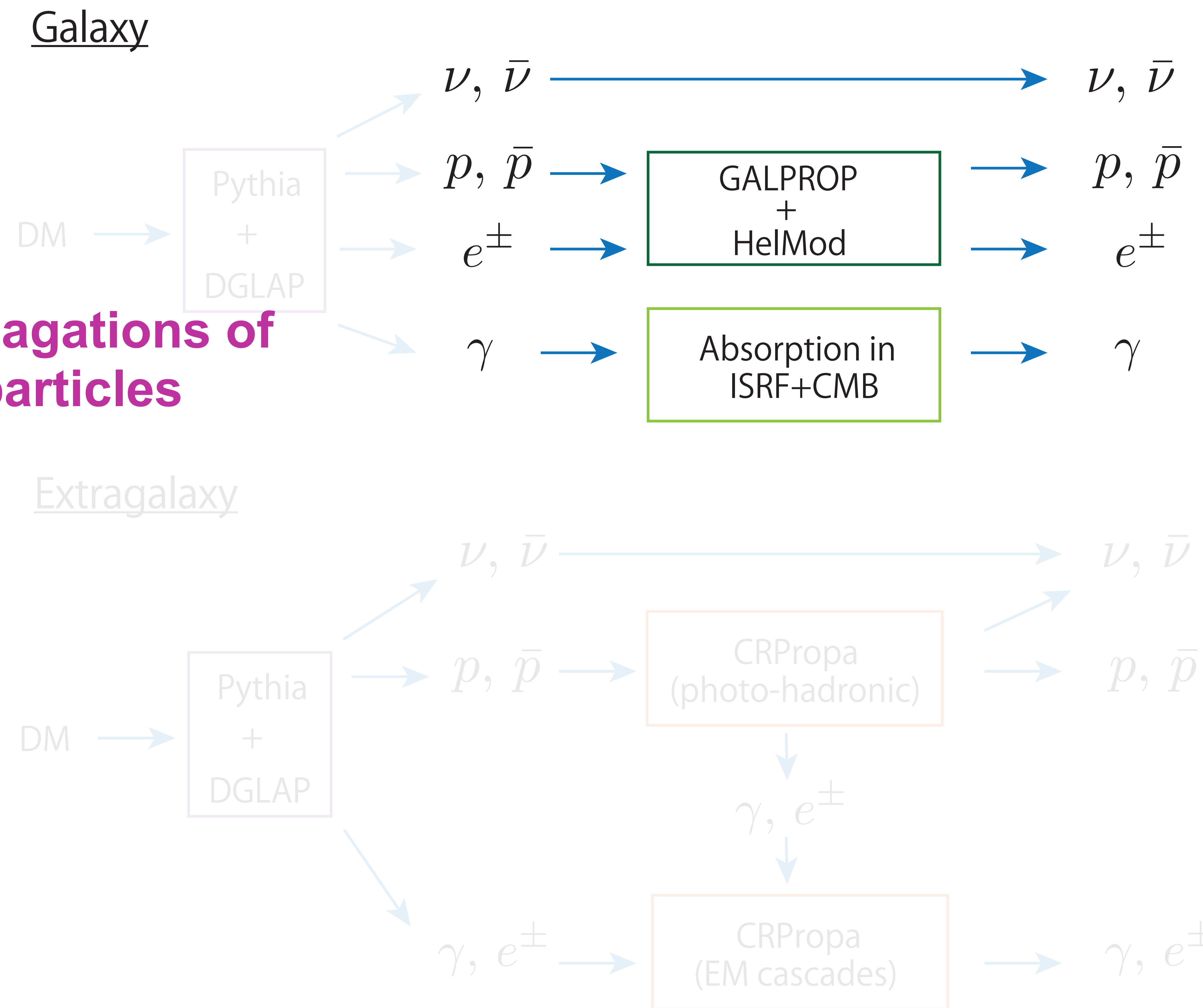
2. Simulate the decays of the hadrons by Pythia to give the distributions of stable particles I, f_h^I

   $I = e^\pm, \gamma, p, \bar{p}, \nu, \bar{\nu}$

$$\frac{dN_I}{dz} = 2 \sum_h \int_z^1 \frac{dy}{y} \underbrace{D_b^h(y, m_{\rm dm}^2)}_{\text{DGLAP}} \underbrace{f_h^I(z/y)}_{\text{Pythia}}$$

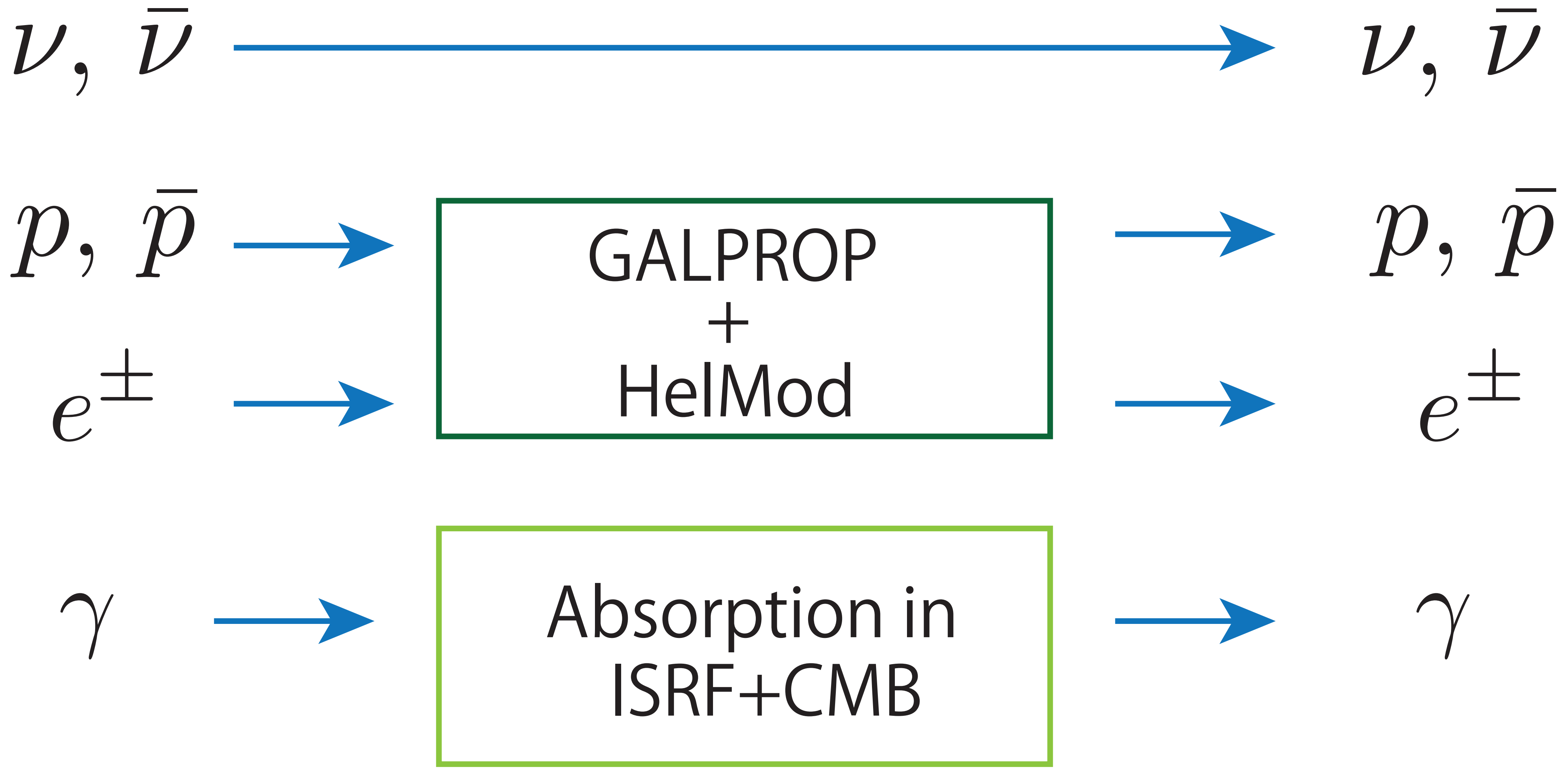
$z = 2E_I/m_{\rm dm}$

Outline of the simulation

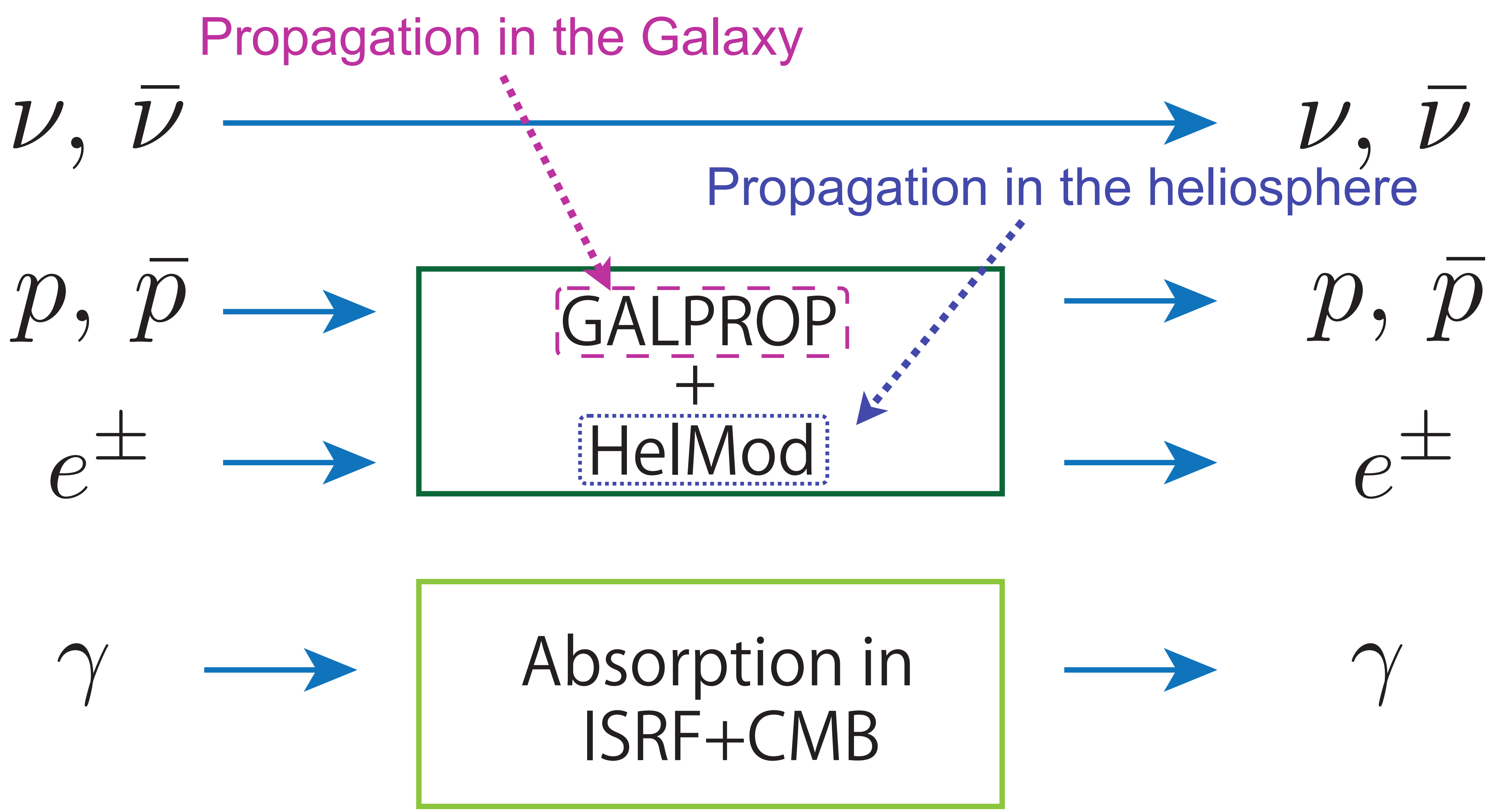


Propagations of CR particles

Propagation of CRs in the Galaxy

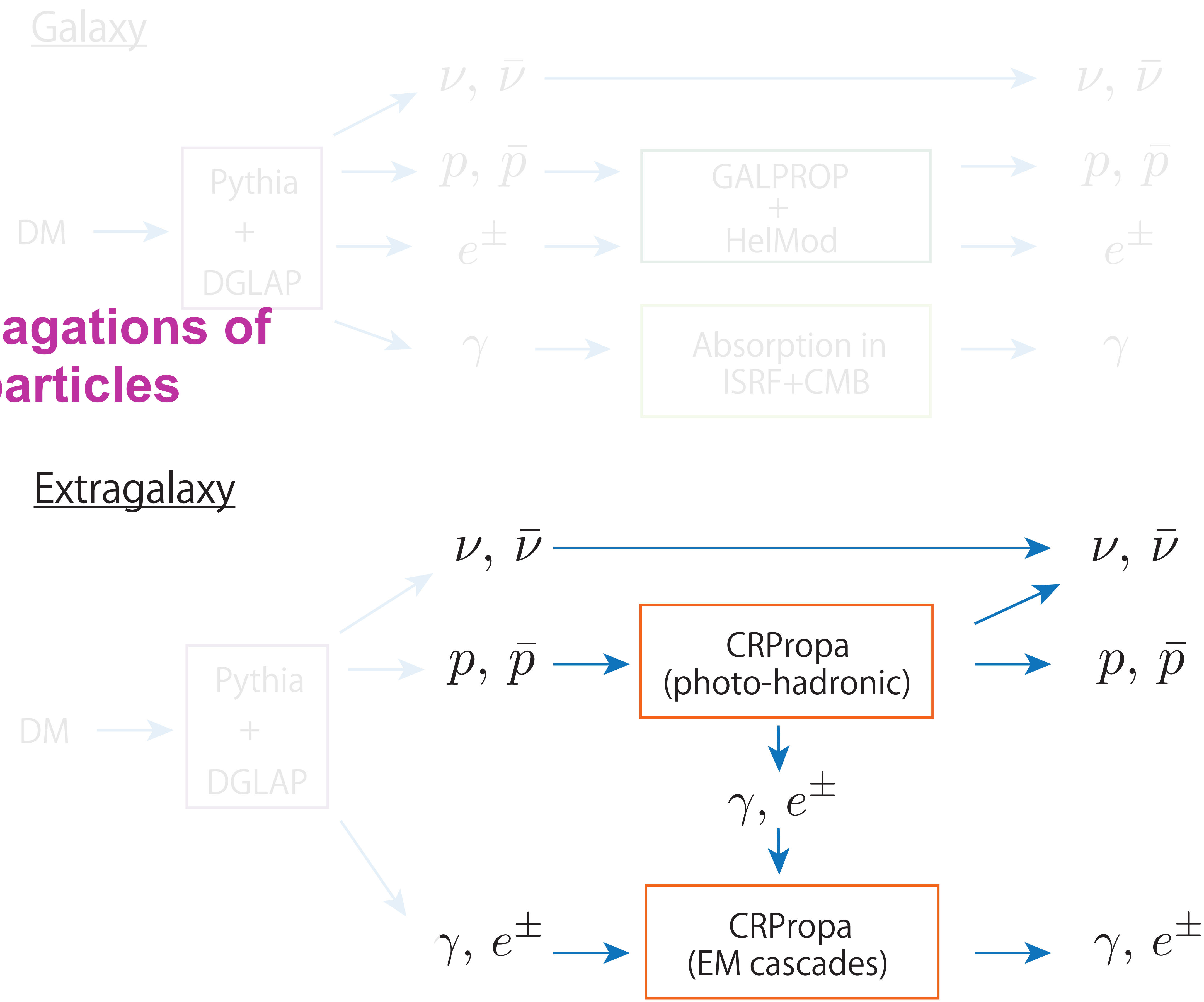


Propagation of CRs in the Galaxy

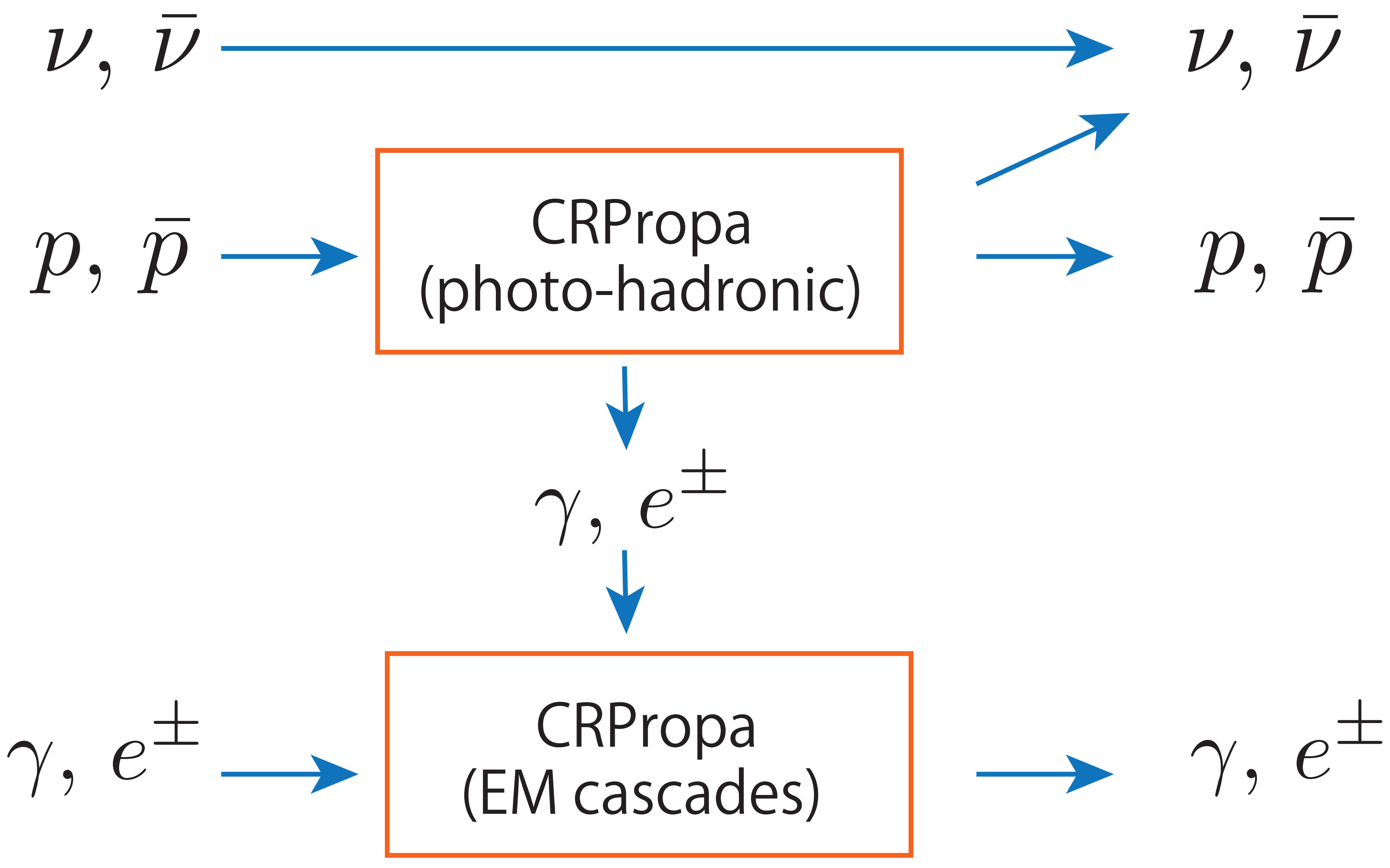


Outline of the simulation

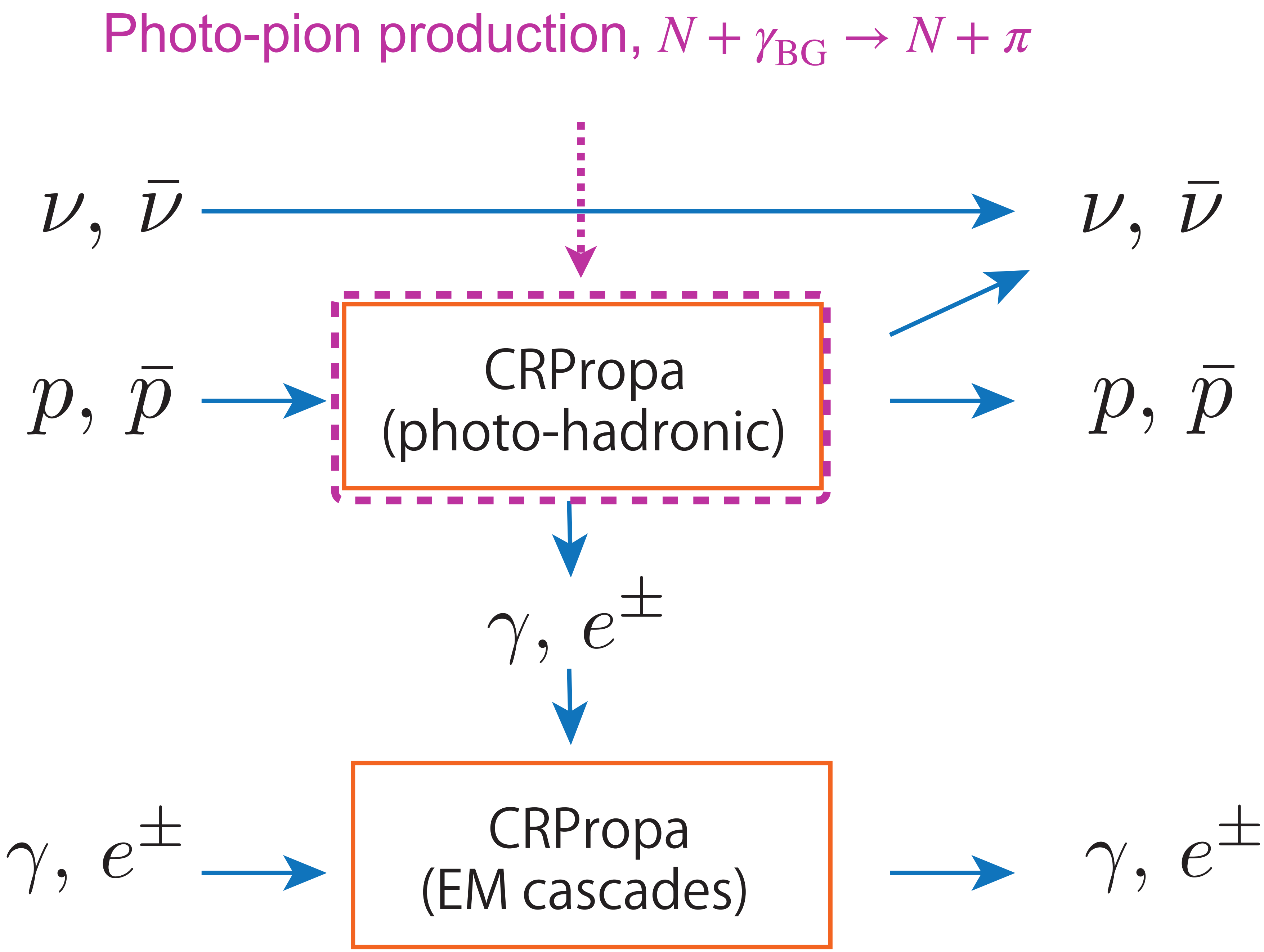
Propagations of CR particles



Propagation of CRs in the extragalactic region



Propagation of CRs in the extragalactic region



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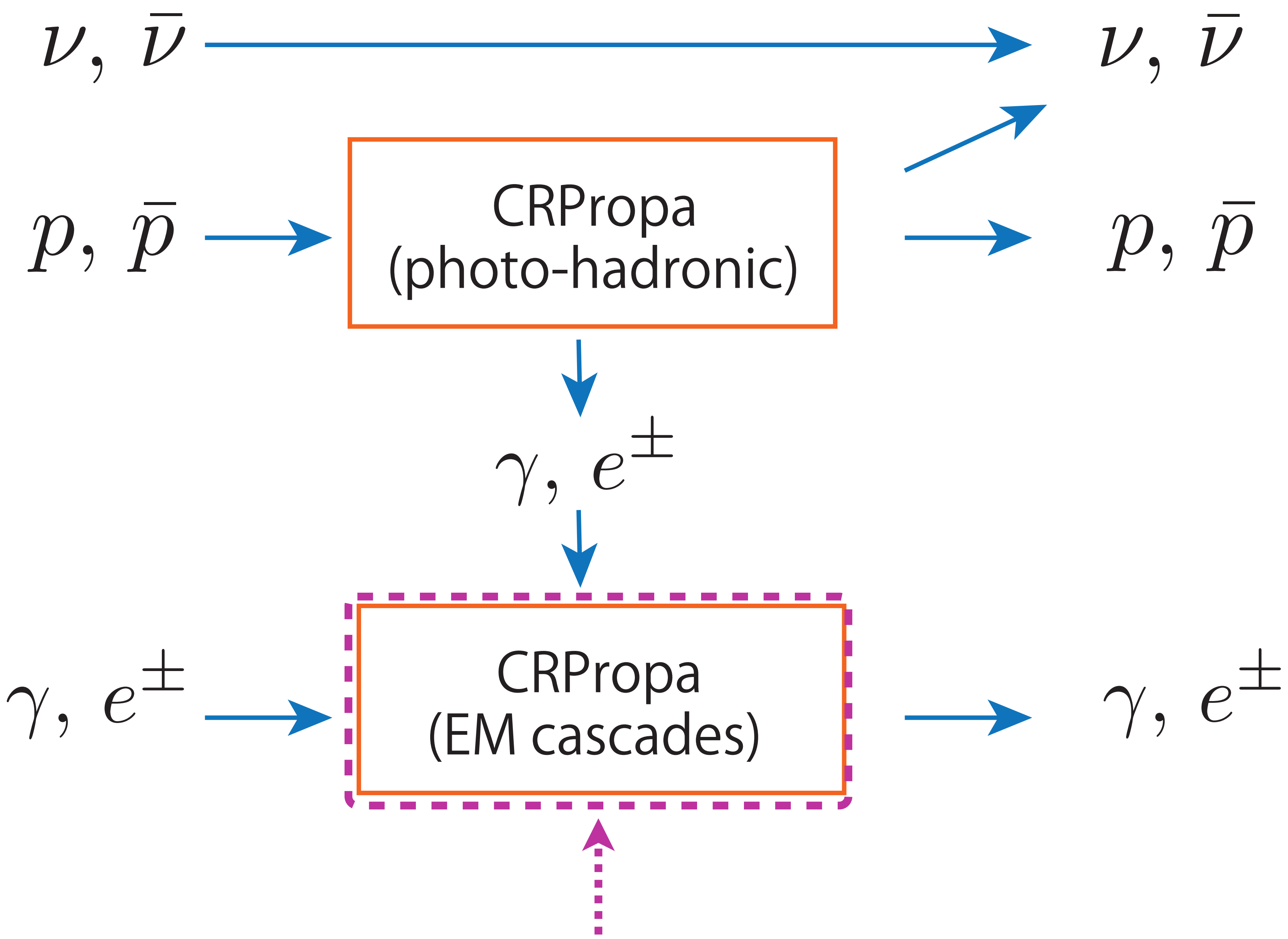
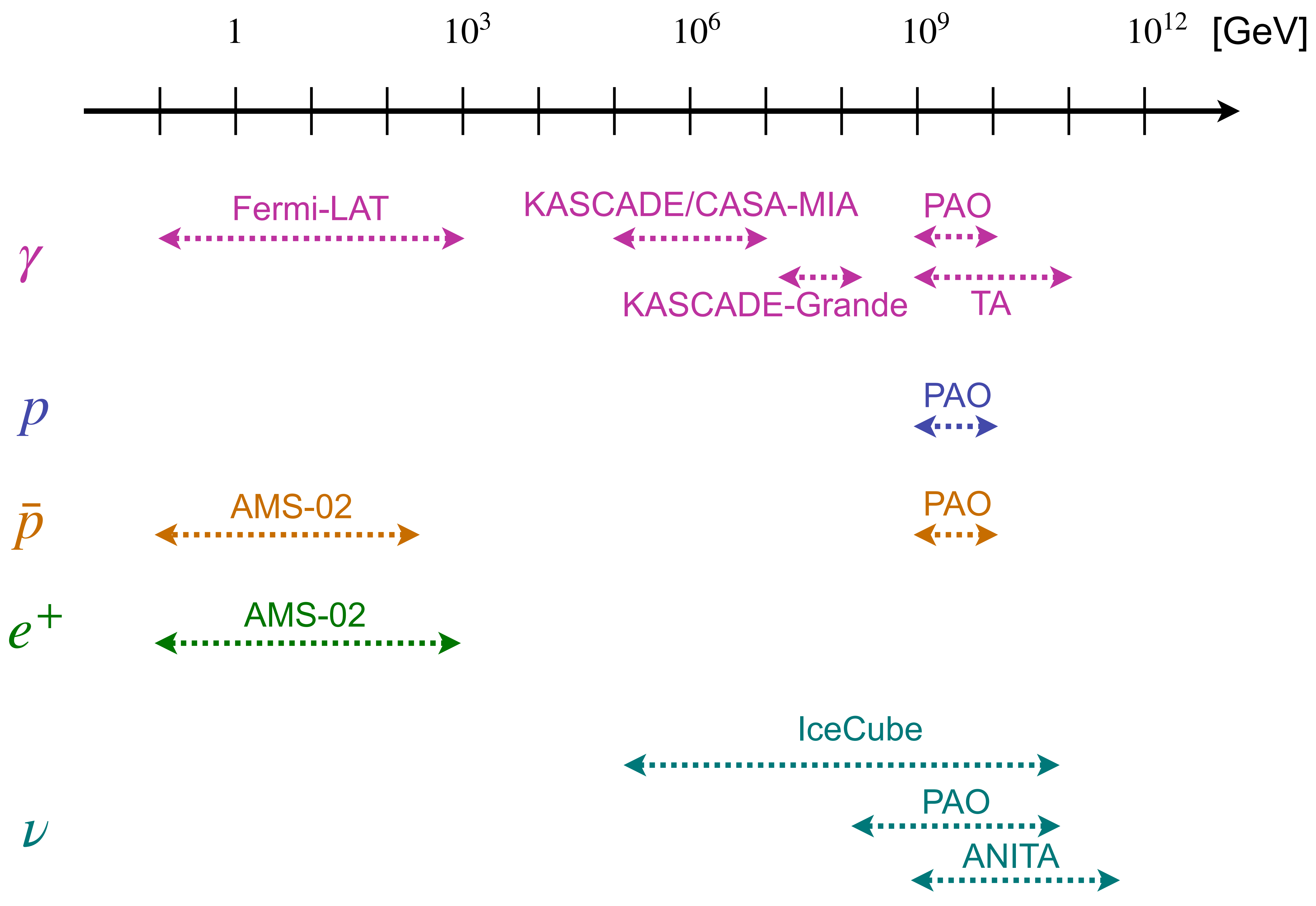


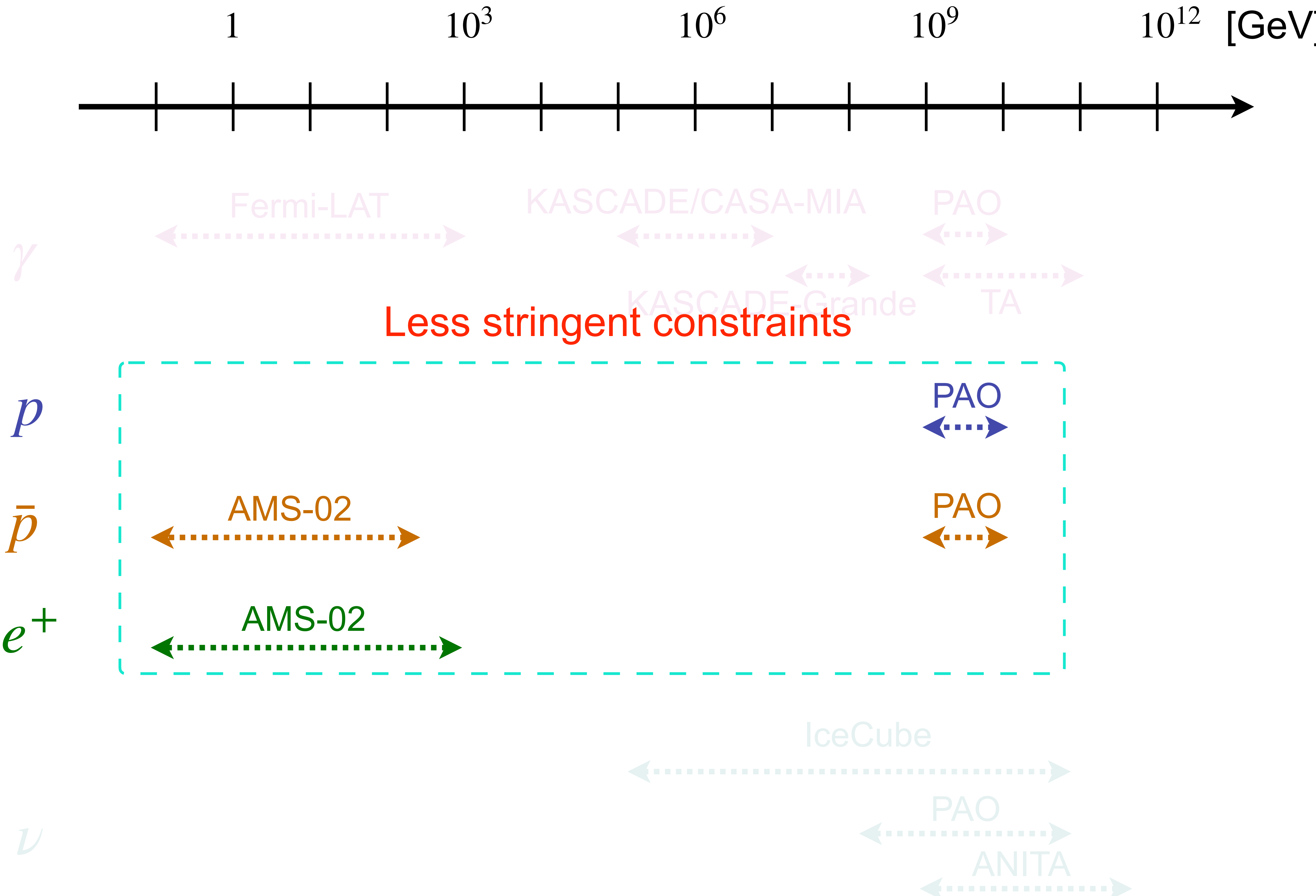
Pair production, $\gamma + \gamma_{\rm BG} \rightarrow e^{+} + e^{-}$

Inverse Compton scattering, $e + \gamma_{\rm BG} \rightarrow e + \gamma$

3. Numerical results



1
10^3
10^6
10^9
10^{12}
[GeV]
γ
Fermi-LAT
KASCADE/CASA-MIA
PAO
KASCADE-Grande
TA
p
PAO
$\bar{p}$
AMS-02
PAO
e^+
AMS-02
IceCube
ν
PAO
ANITA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10^3
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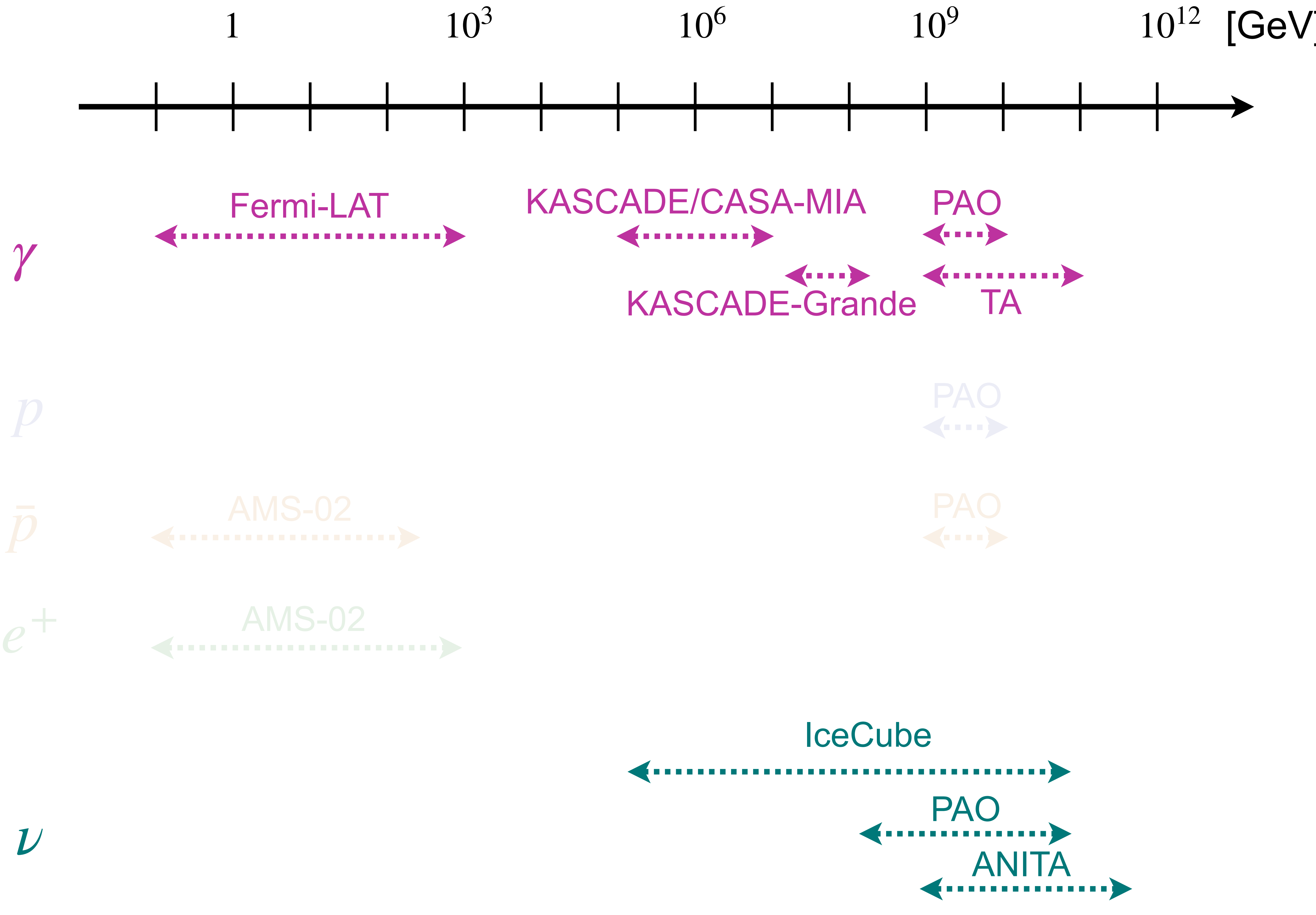
10^{12}
[GeV]
Fermi-LAT
KASCADE/CASA-MIA
PAO
γ
KASCADE-Grande
TA
Less stringent constraints
p
PAO
$\bar{p}$
AMS-02
PAO
e^+
AMS-02
IceCube
PAO
ν
ANITA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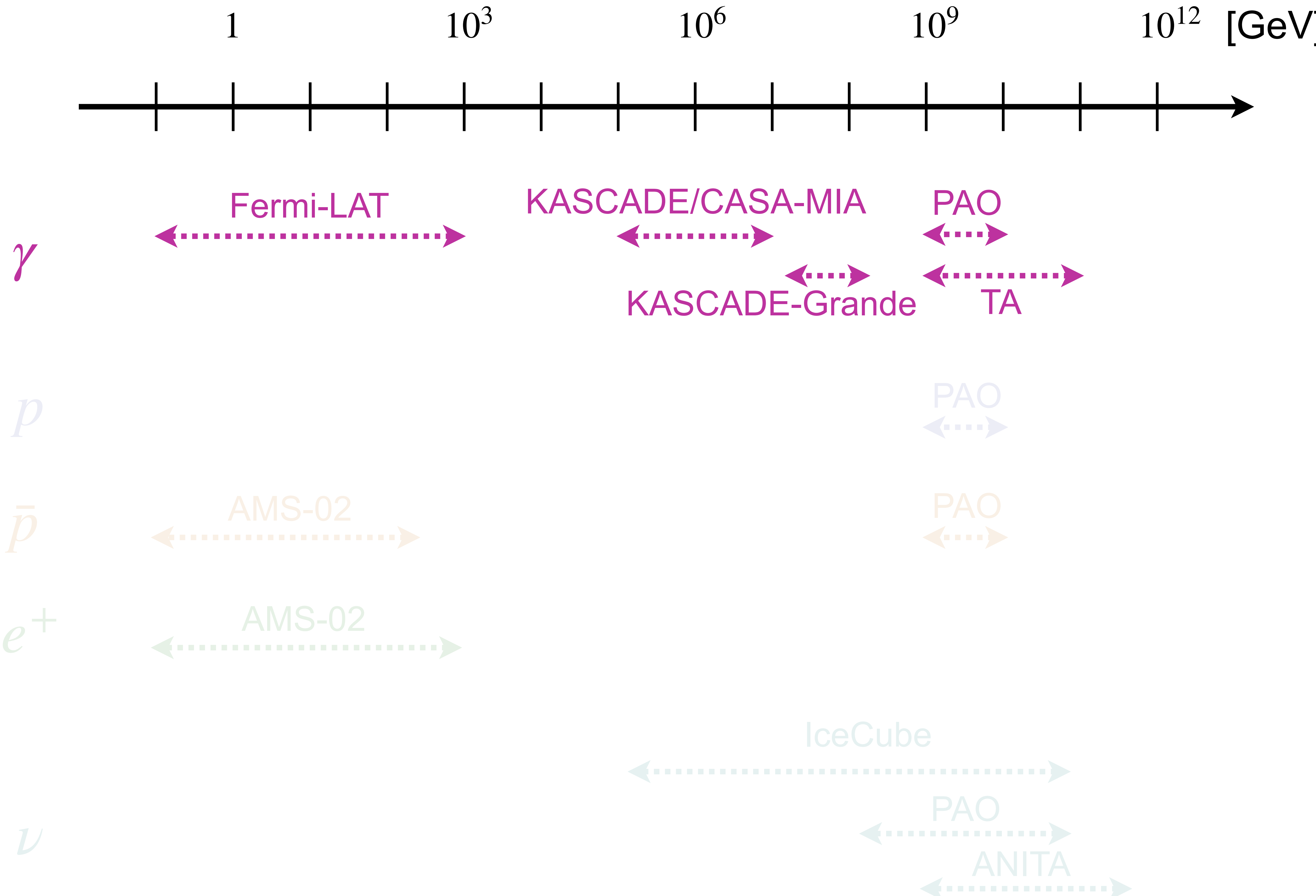
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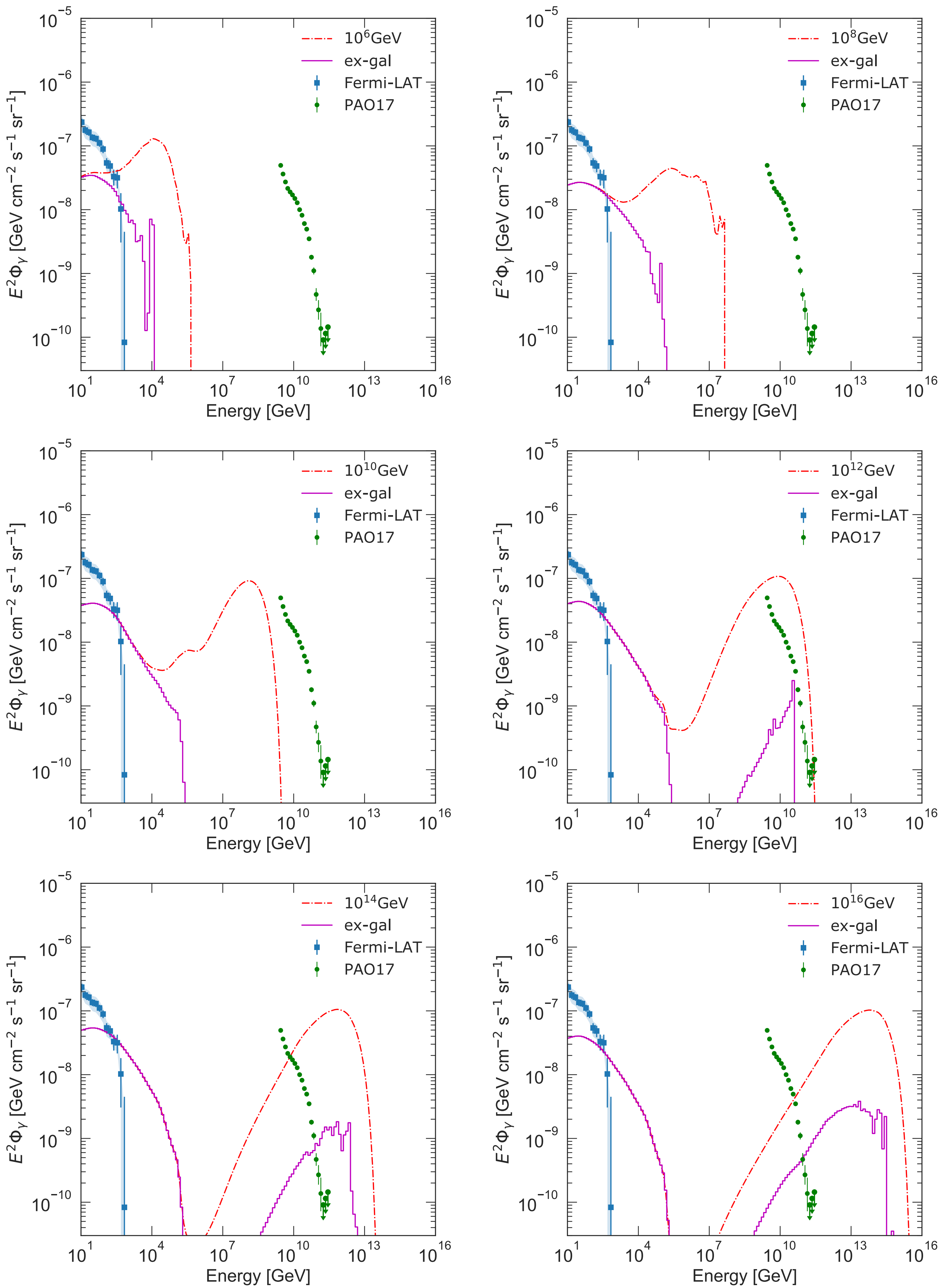
ANITA

γ flux

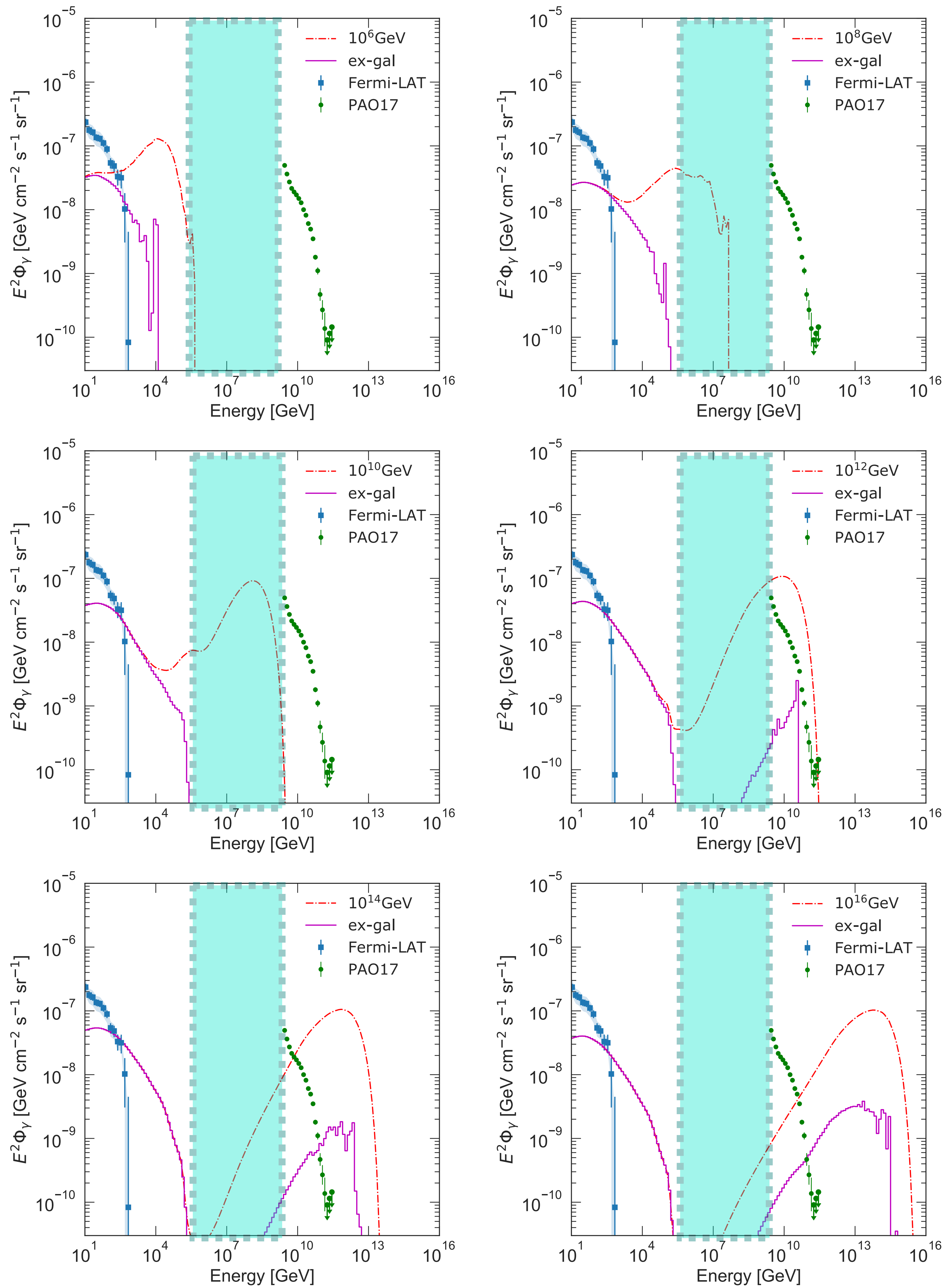
$\tau_{\rm dm} = 10^{27}\,{\rm s}$



γ flux

$\tau_{\rm dm} = 10^{27}\,{\rm s}$

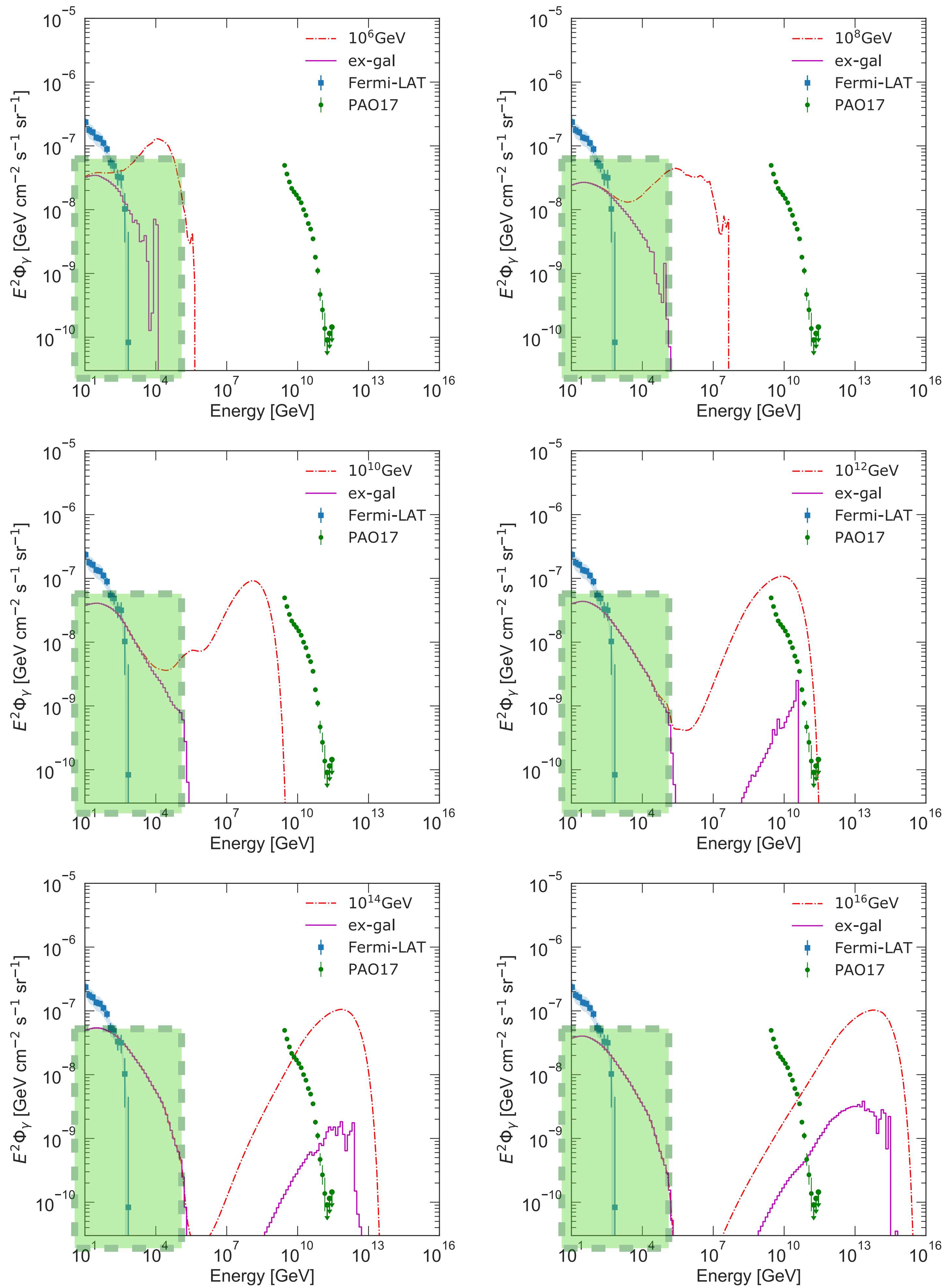
Extragalactic γ in $10^5\,{\rm GeV} \lesssim E_\gamma \lesssim 10^9\,{\rm GeV}$ is suppressed due to the pair production in the CMB



γ flux

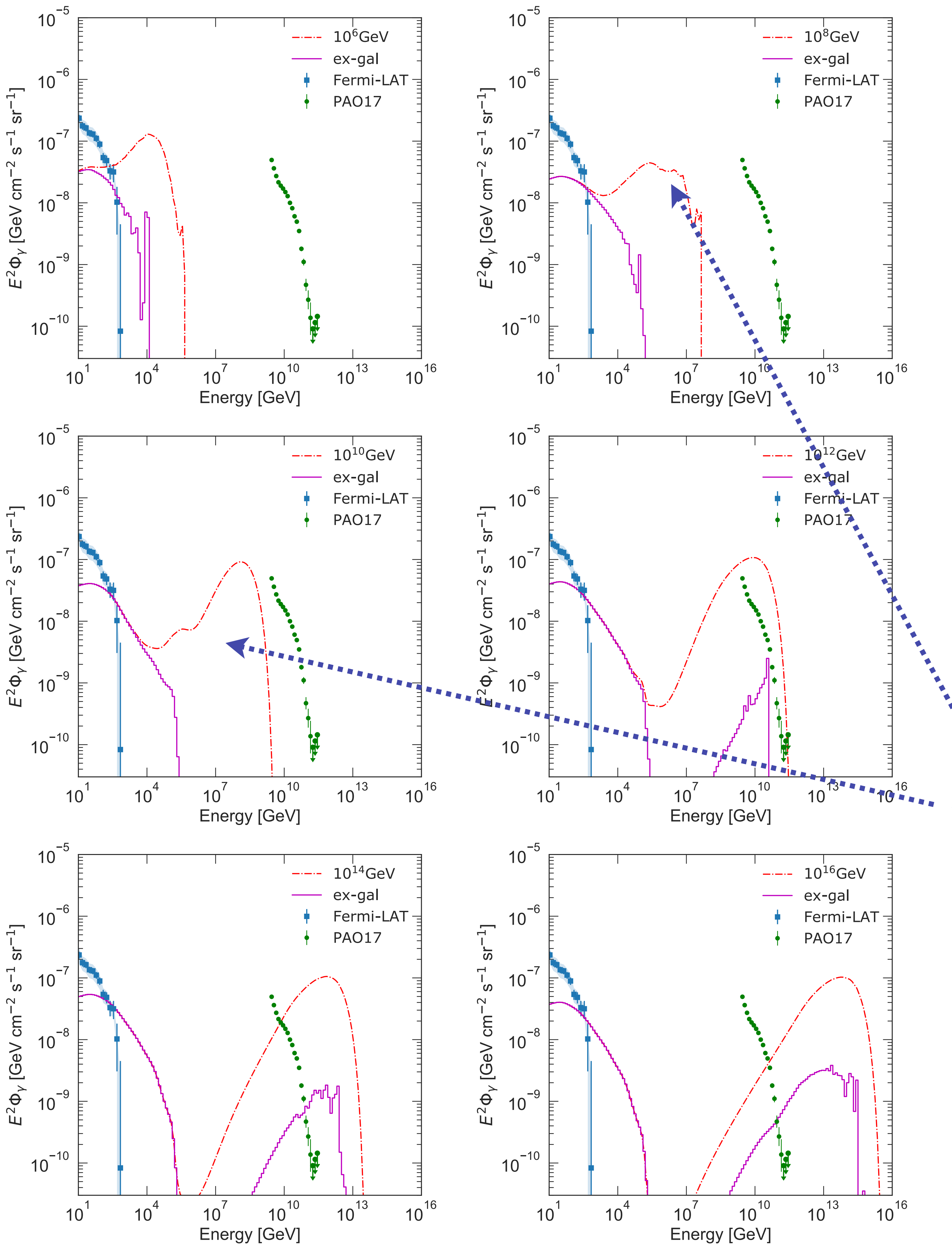
$\tau_{\rm dm} = 10^{27}$ s

Lots of flux in TeV region due to the EM cascades



γ flux

$$\tau_{\rm dm} = 10^{27}\,{\rm s}$$



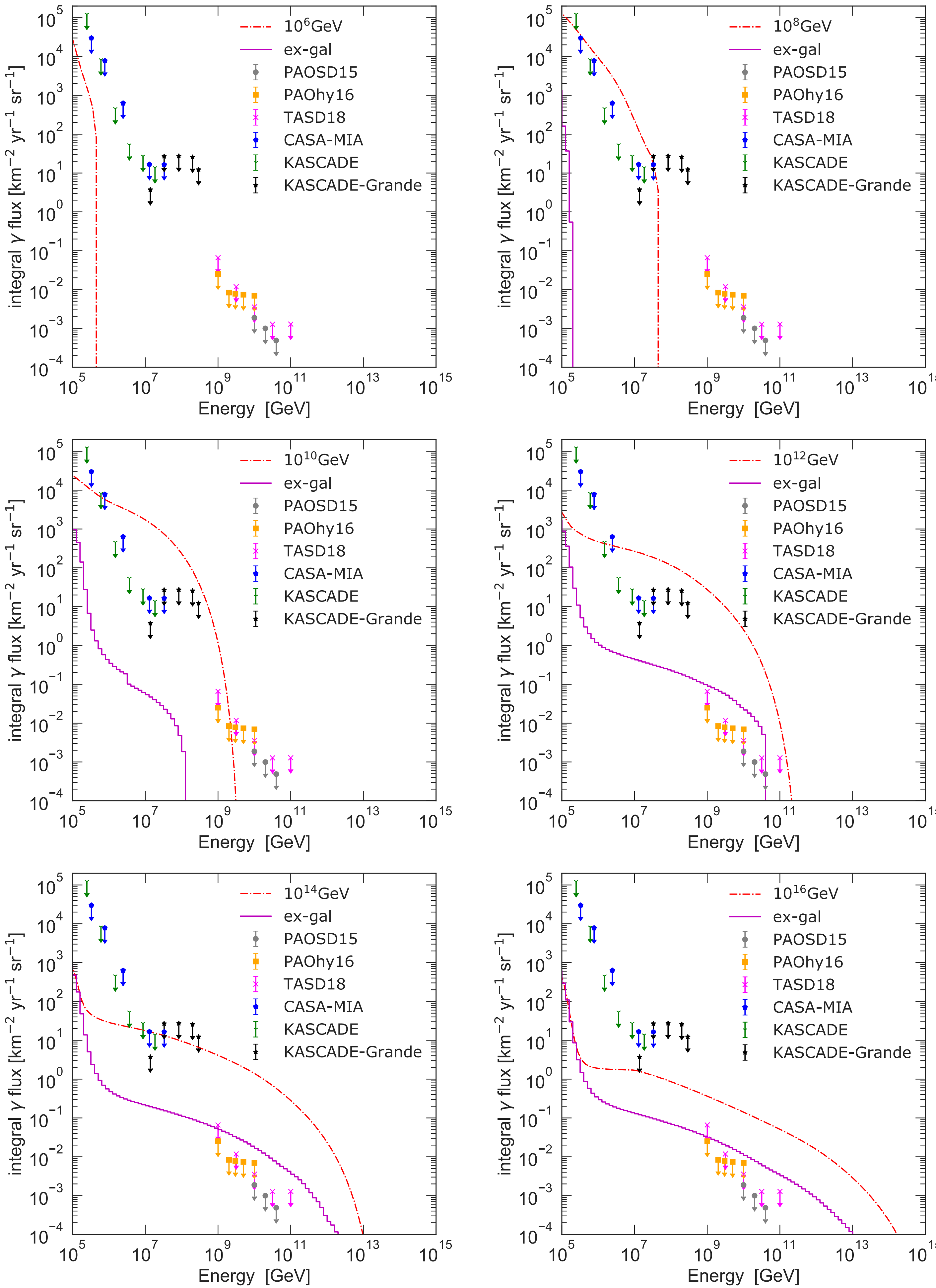
Galactic flux is dominant in high energy region for large $m_{\rm dm}$

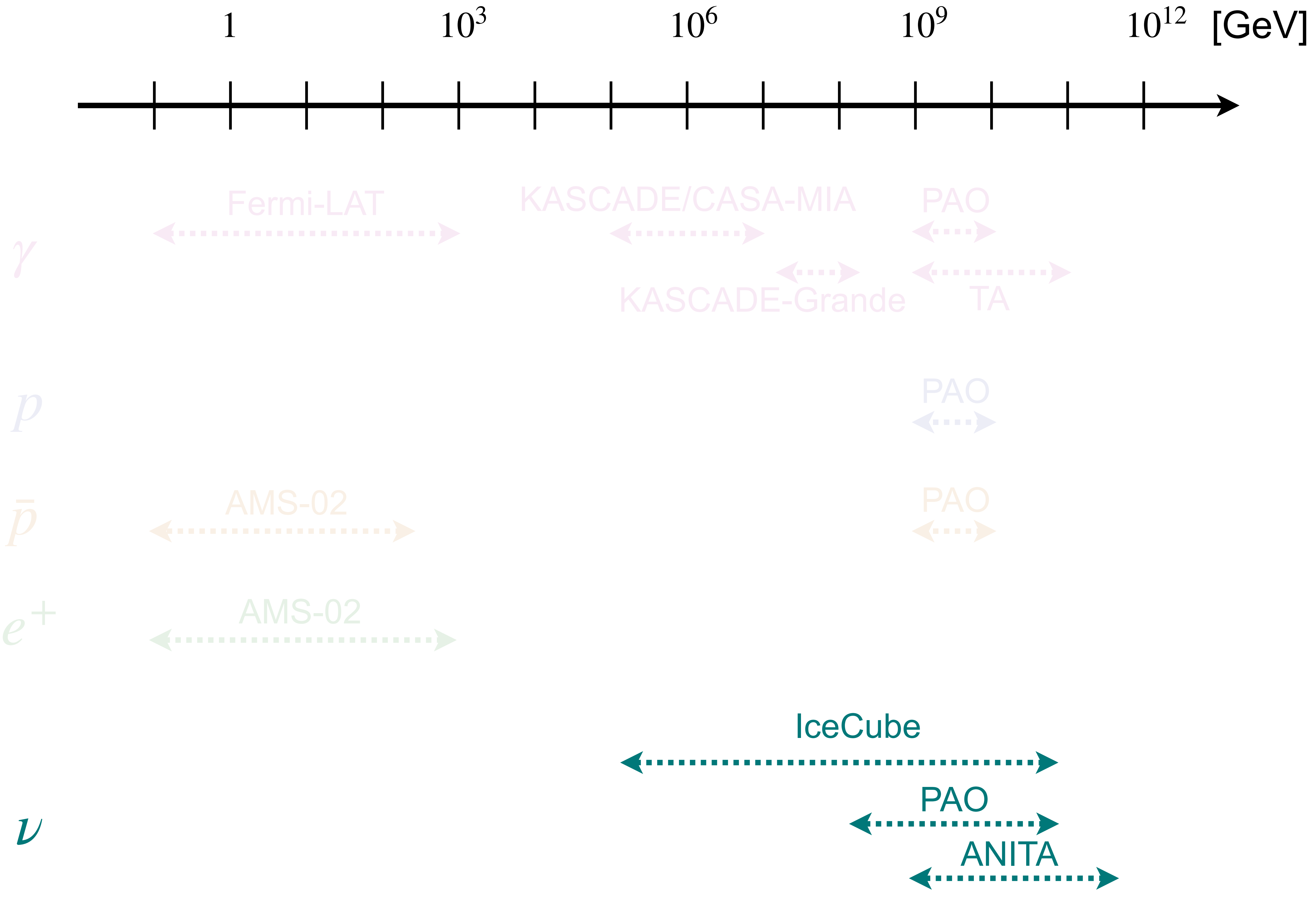
Absorption effect is minor

Integrated γ

$\tau_{\rm dm} = 10^{27}$ s

Galactic flux is dominant in high energy region for large $m_{\rm dm}$





1
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PAO
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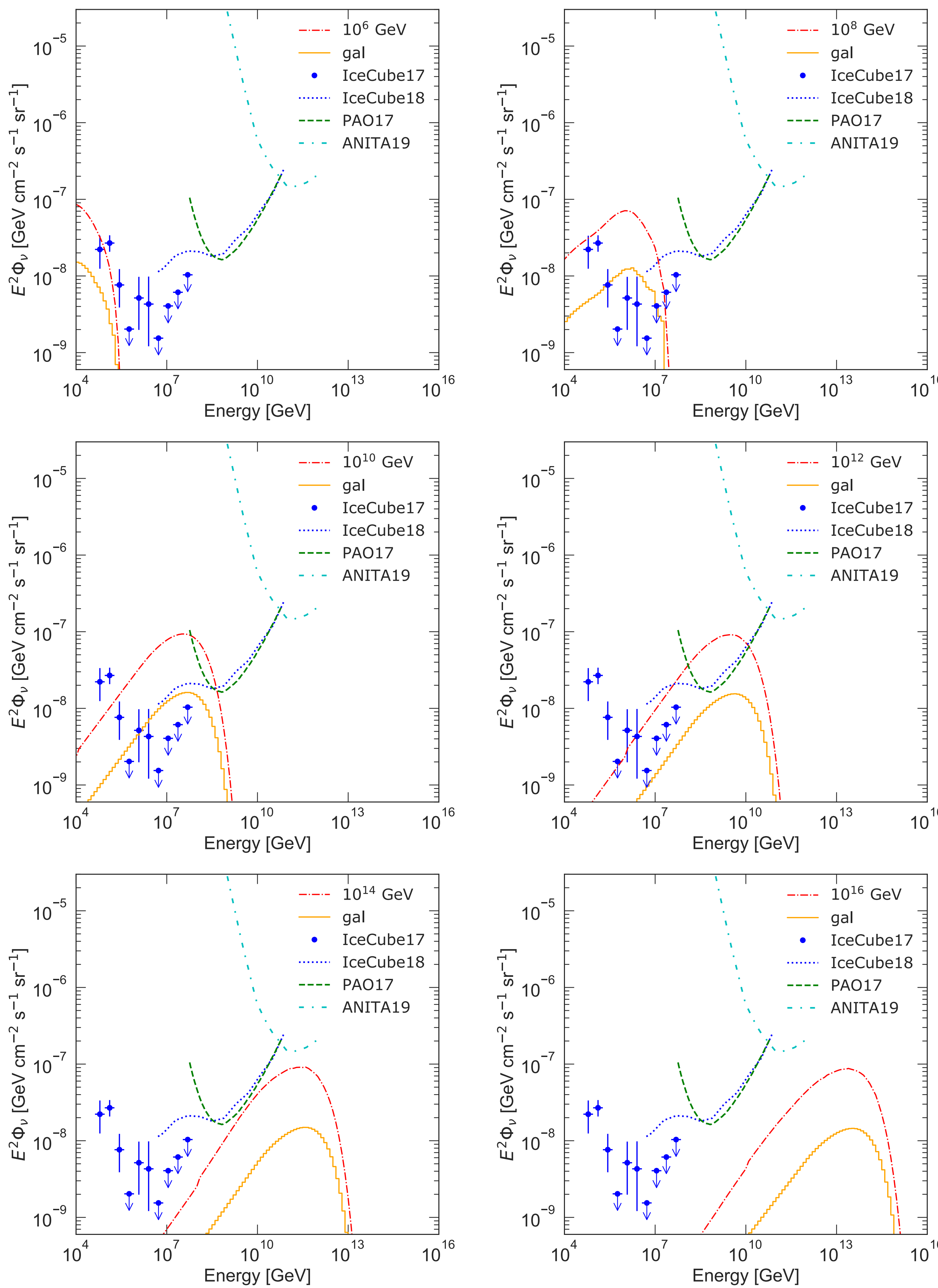
AMS-02
PAO
e+
AMS-02
IceCube
ν
PAO
ANITA

$\nu + \bar{\nu}$ flux

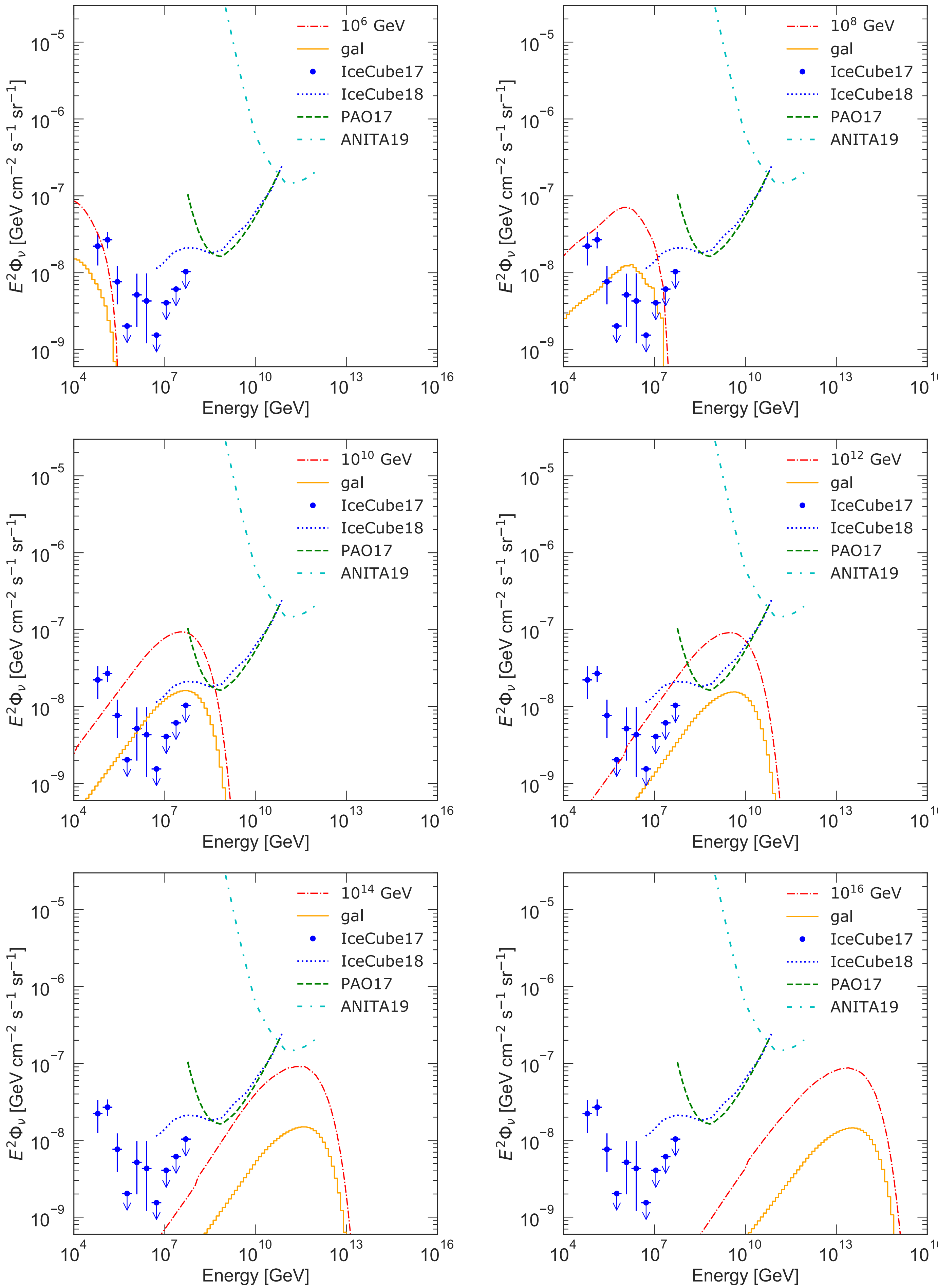
$\tau_{\mathrm{dm}} = 10^{27}\,\mathrm{s}$



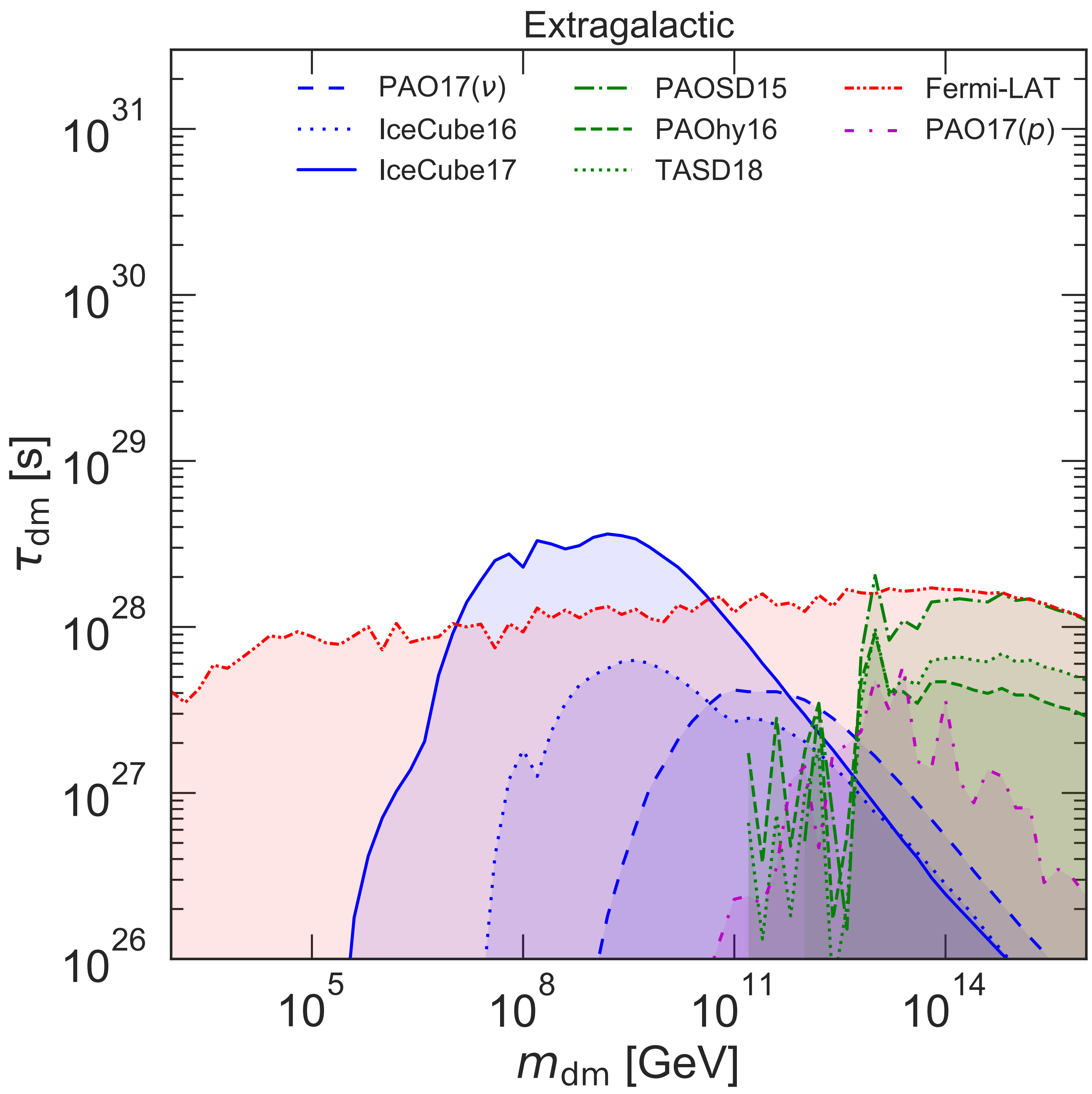
$\nu + \bar{\nu}$ flux

$\tau_{\rm dm} = 10^{27}$ s

Extragalactic flux
is dominant



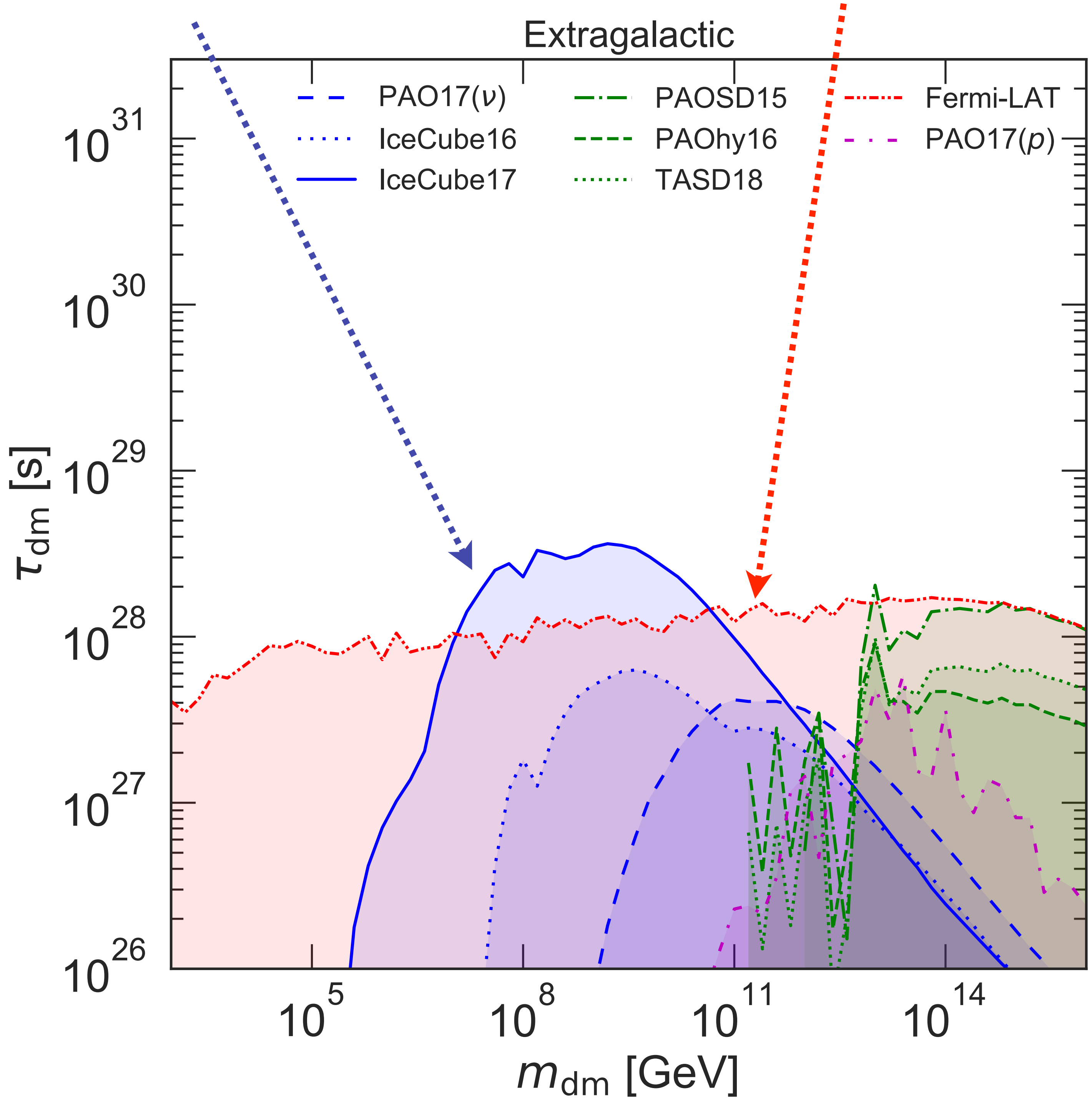
Constraints on DM lifetime (extragalactic)



Constraints on DM lifetime (extragalactic)

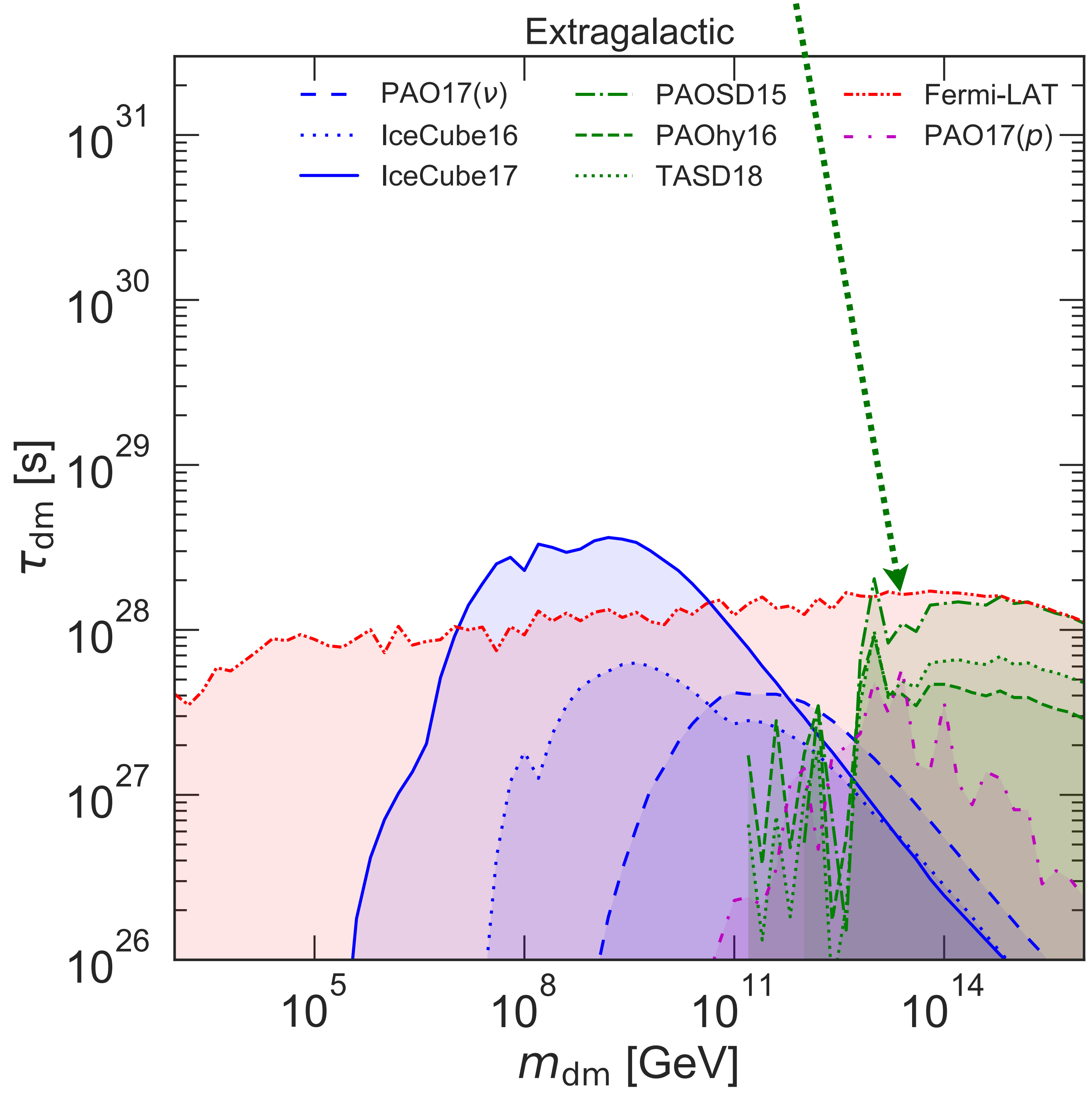
IceCube gives a more stringent bound in $10^{6}\,\mathrm{GeV} \lesssim m_{\mathrm{dm}} \lesssim 10^{11}\,\mathrm{GeV}$

Fermi-LAT gives constrains in wide range of m_{dm}

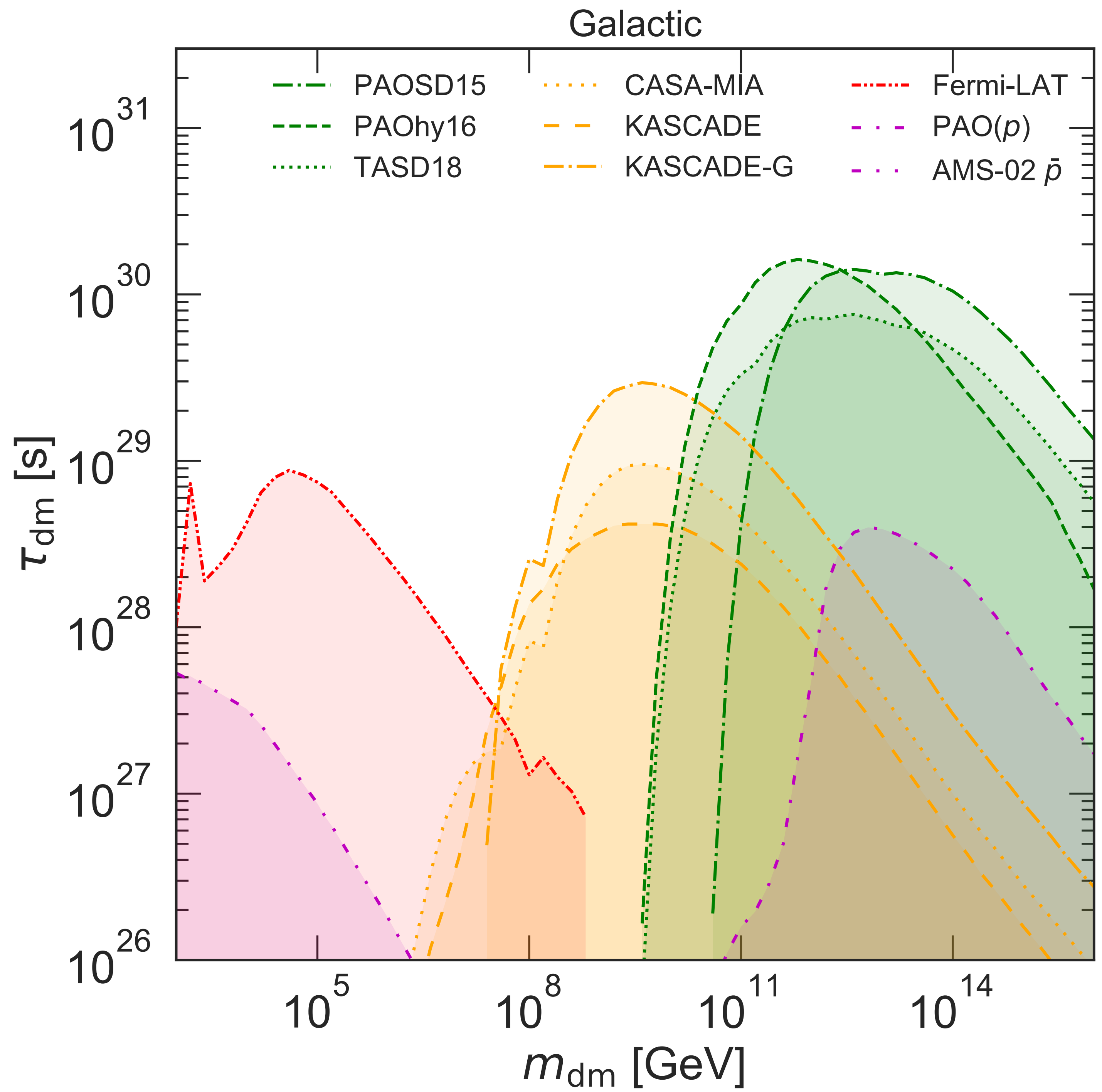


Constraints on DM lifetime (extragalactic)

PAO gives comparable bound in
$m_{\rm dm} \gtrsim 10^{12}\,\mathrm{GeV}$



Constraints on DM lifetime (Galactic)



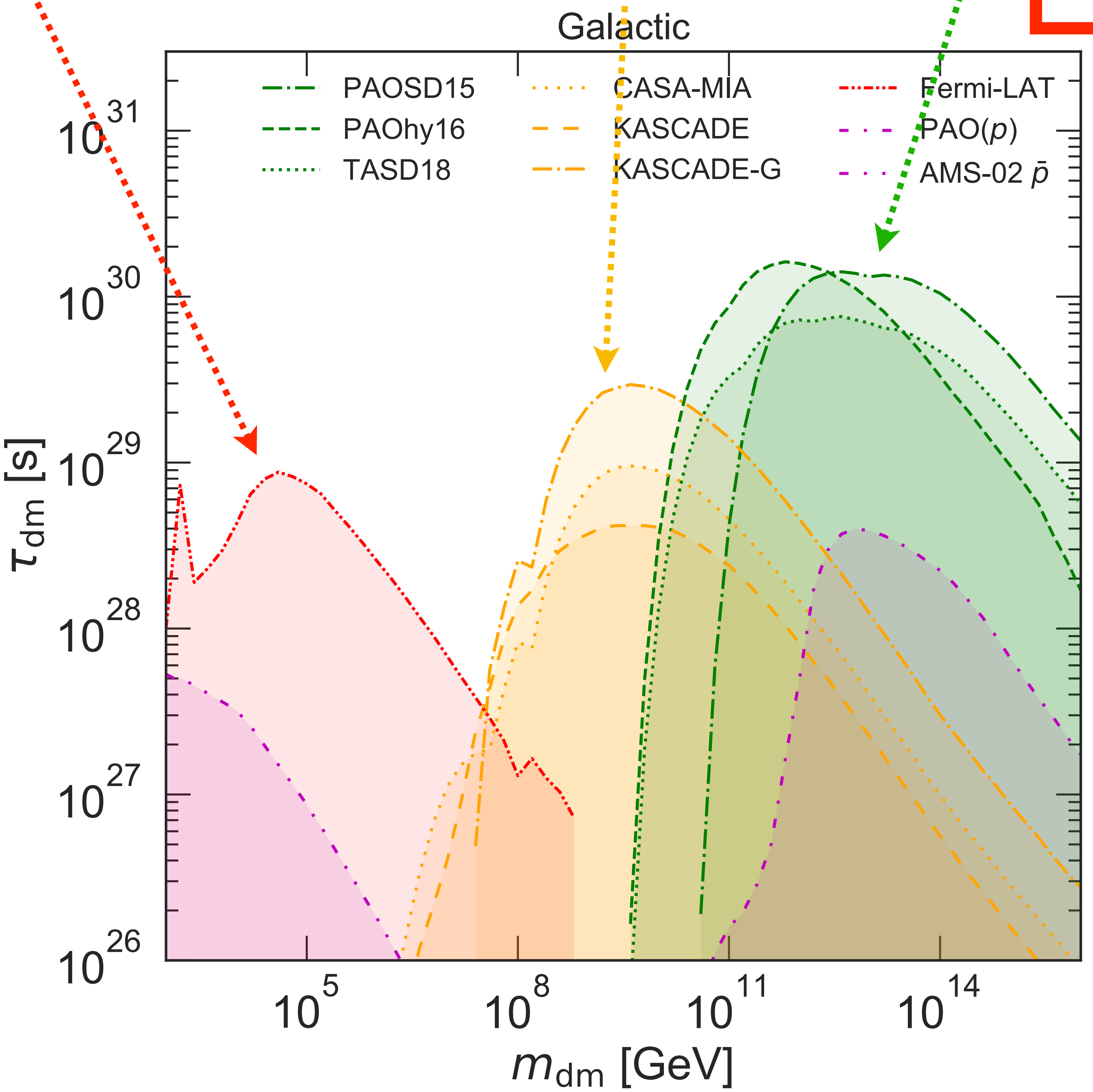
Constraints on DM lifetime (Galactic)

PAO: $10^{10}\,\mathrm{GeV} \lesssim m_{\rm dm}$

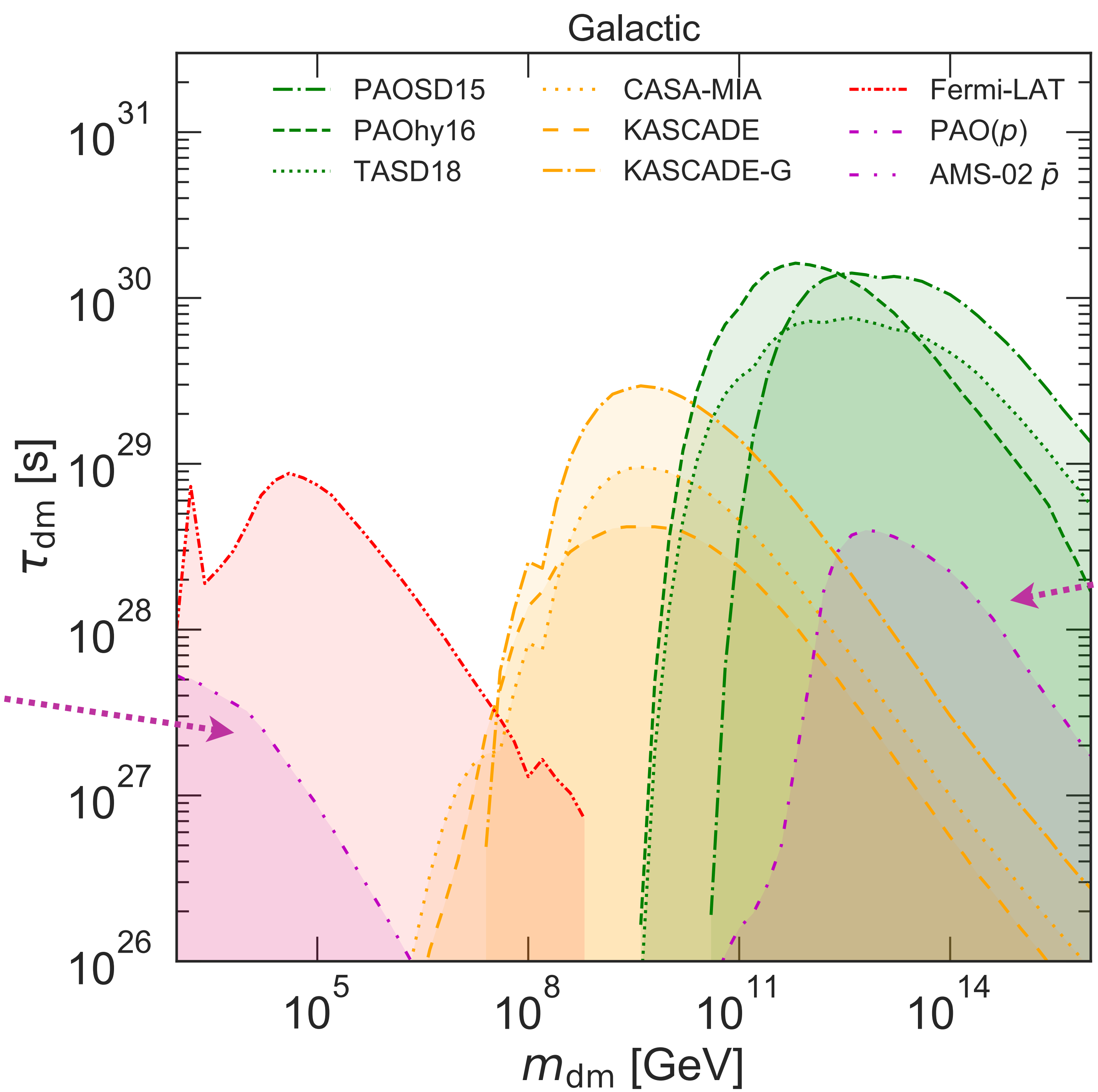
Fermi-LAT: $m_{\rm dm} \lesssim 10^{6}\,\mathrm{GeV}$

KASCADE-Grande:
$10^{8}\,\mathrm{GeV} \lesssim m_{\rm dm} \lesssim 10^{10}\,\mathrm{GeV}$

All γ observations!



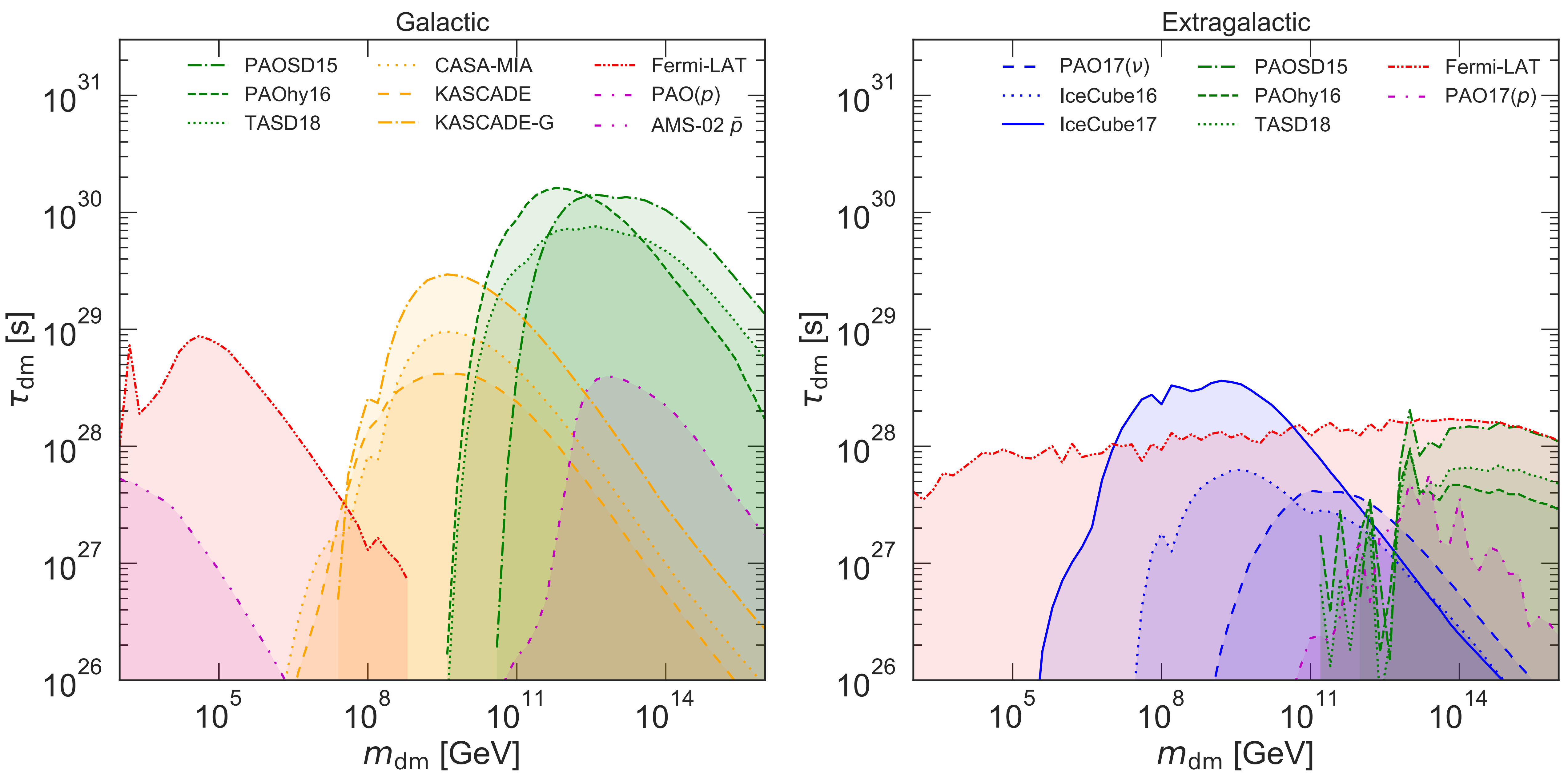
Constraints on DM lifetime (Galactic)



AMS-02 $\bar{p}$ gives much weaker constraints

PAO gives much weaker constraints

Constraints on DM lifetime



Galactic γ & Extragalactic ν give the most stringent constraints

4. Conclusion

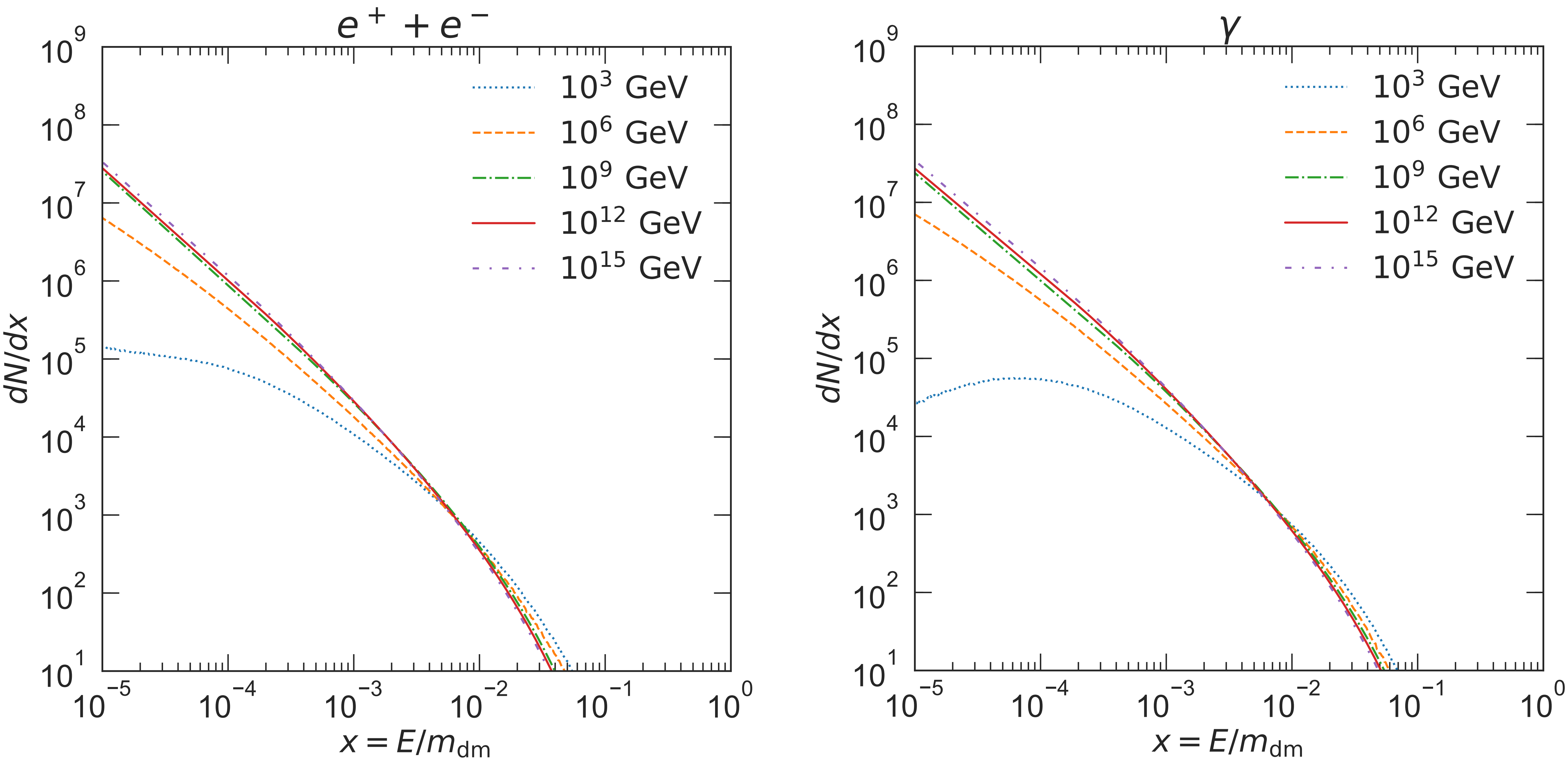
We have done a comprehensive analysis of CRs in heavy decaying DM model with multi-messenger astrophysical data

i.e., DM $\to b\bar{b}$, $10\,\mathrm{TeV} \leq m_{\mathrm{dm}} \leq 10^{16}\,\mathrm{GeV}$

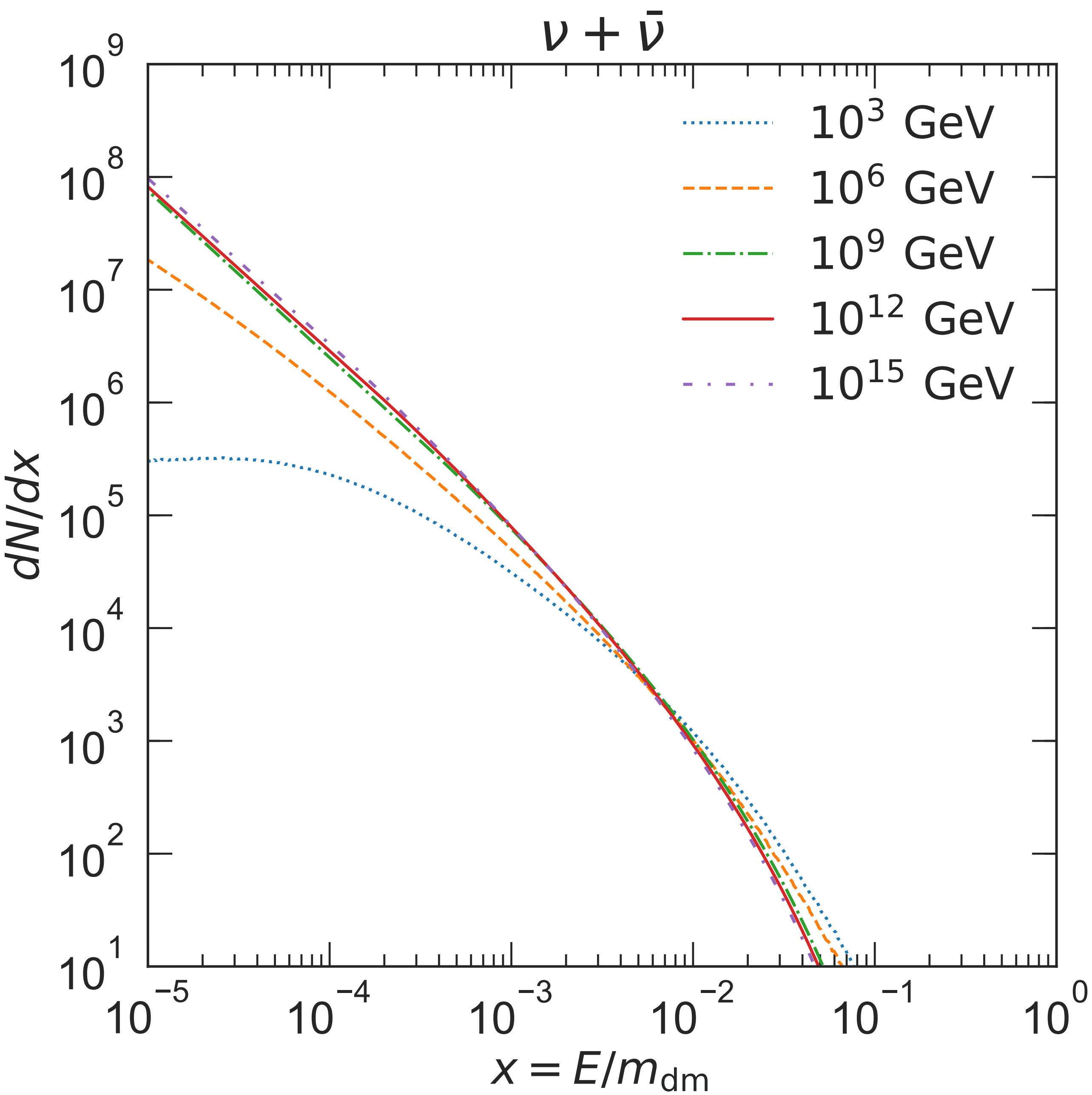
- p, $\bar{p}$, and e^+ give less stringent constraints
- Current γ and ν observations give the most stringent constraints

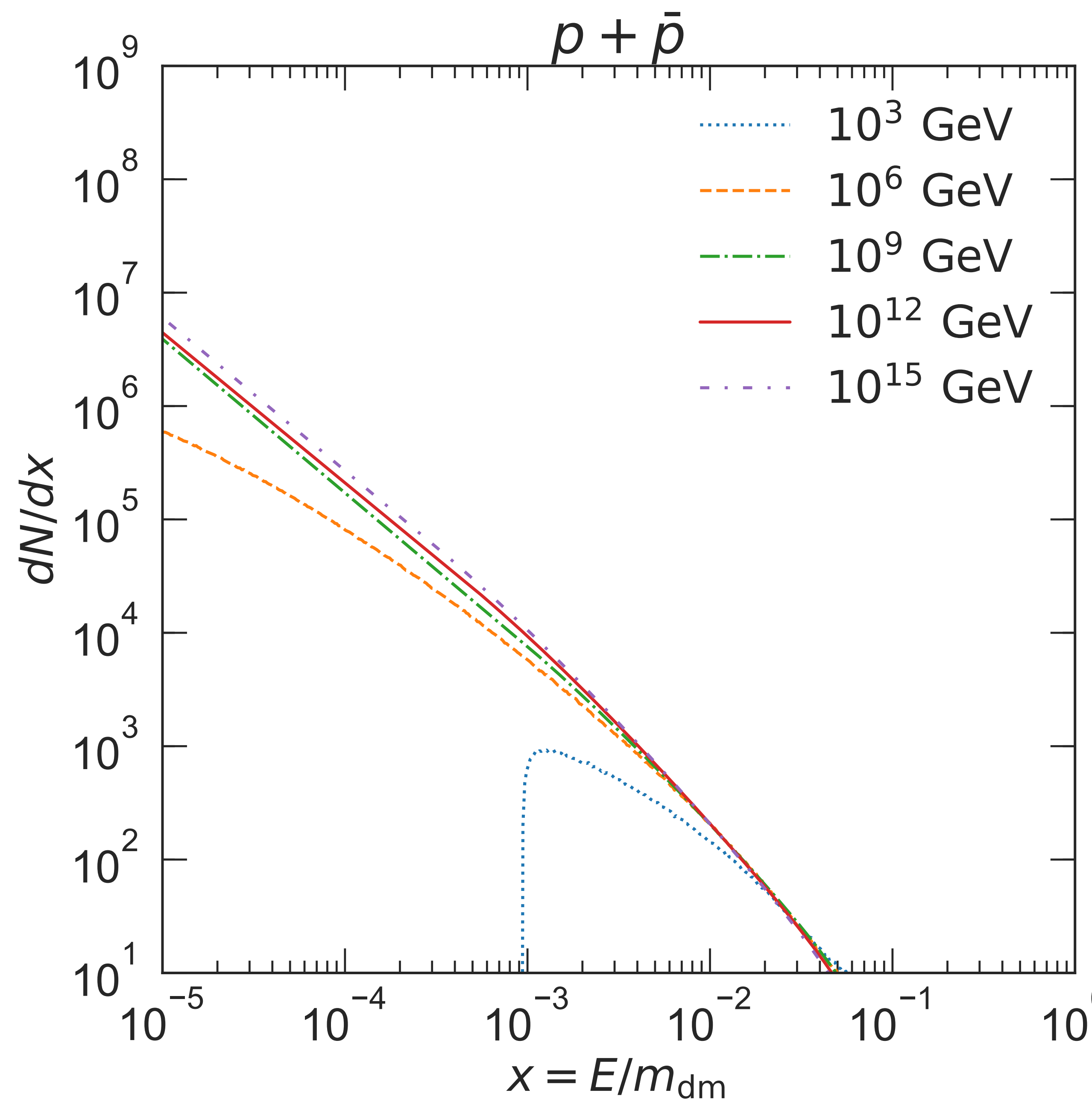
Backups

Energy distributions (results):



Energy distributions (results):





Propagation of CR nuclei

Main process of Greisen-Zatsepin-Kuzmin (GZK) effect

- Photo-pion production

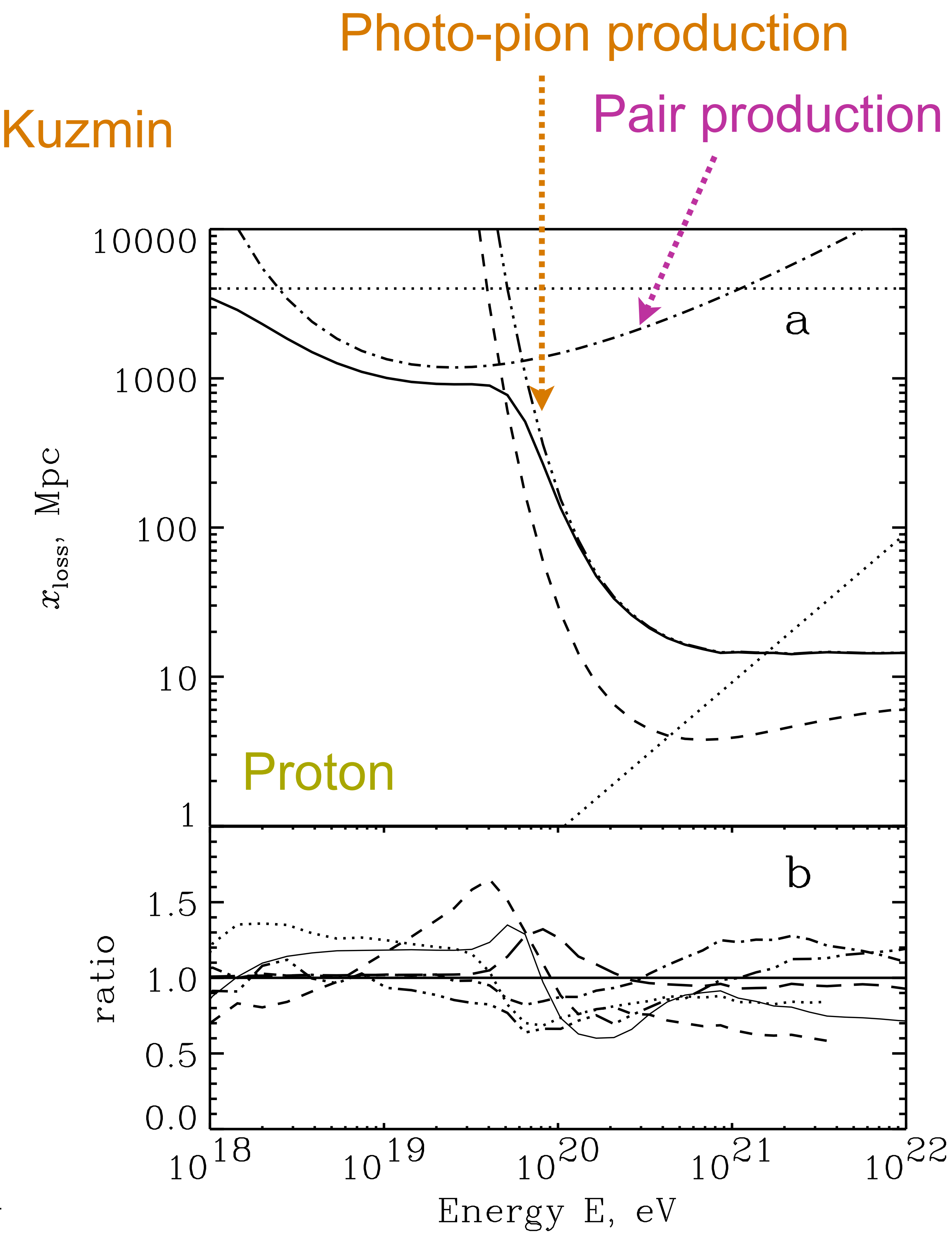
$$N + \gamma_{\rm BG} \rightarrow N + \pi$$

$$E_{\rm th} \sim 6.8 \times 10^{10}\,({\rm meV}/E_{\gamma_{\rm BG}})\,{\rm GeV}$$

- Pair production (Bethe-Heitler)

$${}^{A}_{Z}X + \gamma_{\rm BG} \rightarrow {}^{A}_{Z}X + e^{+} + e^{-}$$

$$E_{\rm th} \sim 4.8 \times 10^{8}\,({\rm meV}/E_{\gamma_{\rm BG}})\,{\rm GeV}$$



$$x_{\rm loss}(E) = \frac{E}{dE/dx}$$

Stanev, Engel, Mücke, Protheroe, Rachen ’00

Propagation of CR EM particles

Heiter, Kuempel, Walz, Erdmann ’17

- Pair production (PP)

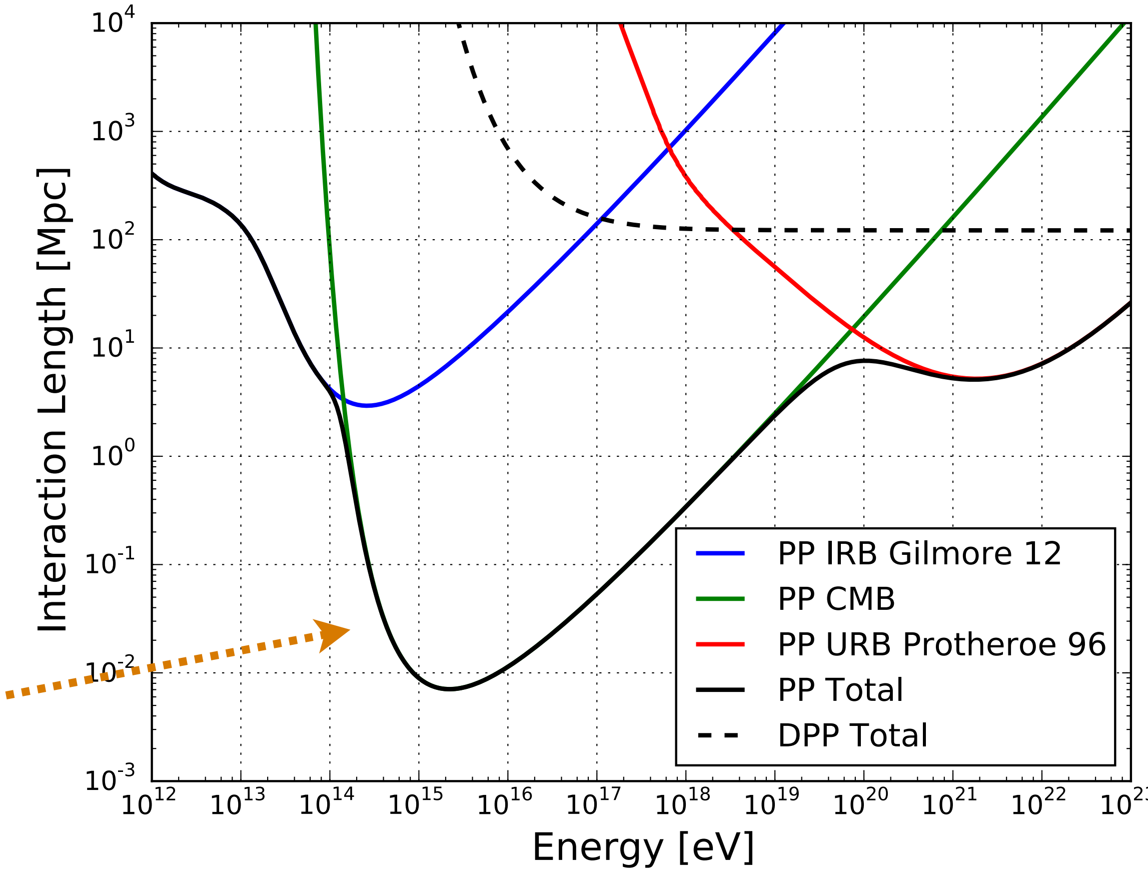
$$\gamma + \gamma_{\mathrm{BG}} \rightarrow e^+ + e^-$$

- Double pair production (DPP)

$$\gamma + \gamma_{\mathrm{BG}} \rightarrow e^+ + e^- + e^+ + e^-$$

PP in the CMB is dominant

$(10^5\,\mathrm{GeV} \lesssim E_\gamma \lesssim 10^{10}\,\mathrm{GeV})$



- Triple pair production (TPP)

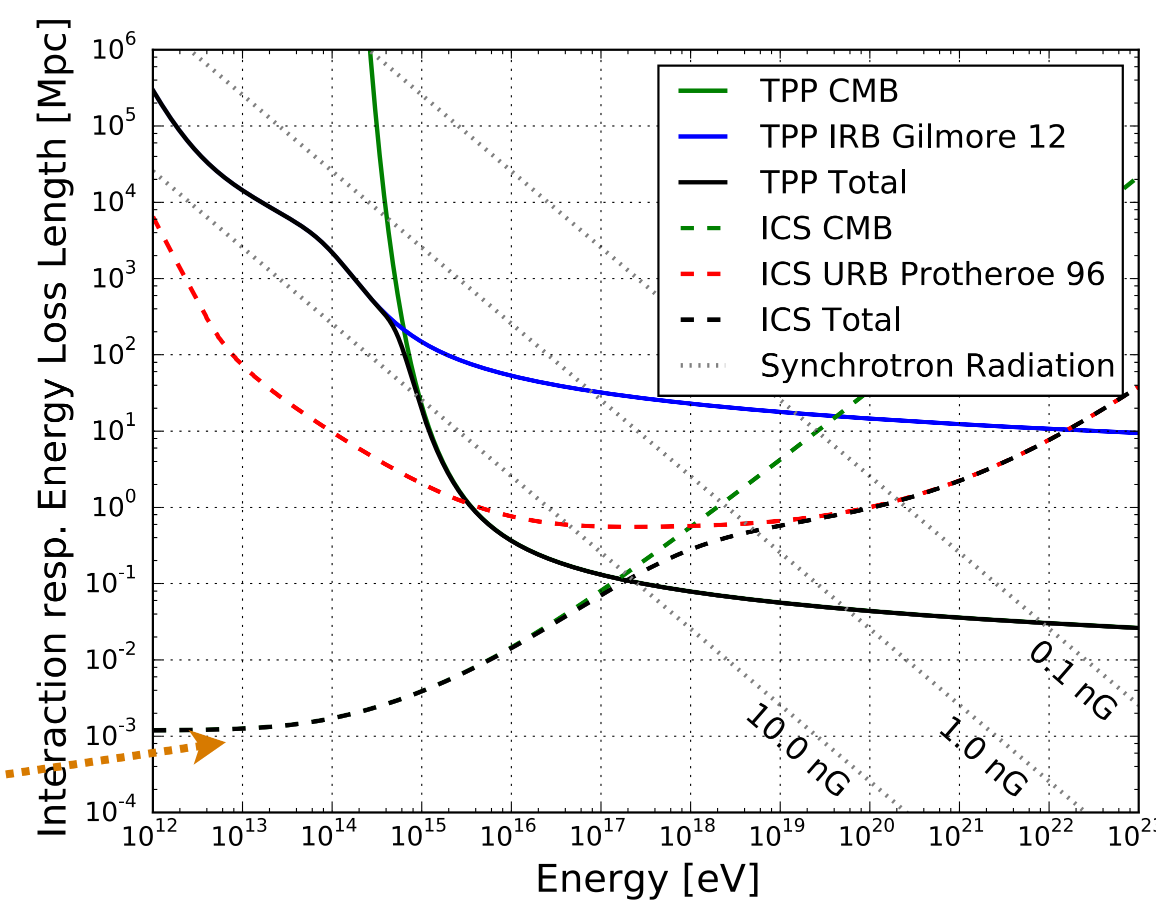
$$e + \gamma_{\mathrm{BG}} \rightarrow e + e^+ + e^-$$

- Inverse Compton scattering (ICS)

$$e + \gamma_{\mathrm{BG}} \rightarrow e + \gamma$$

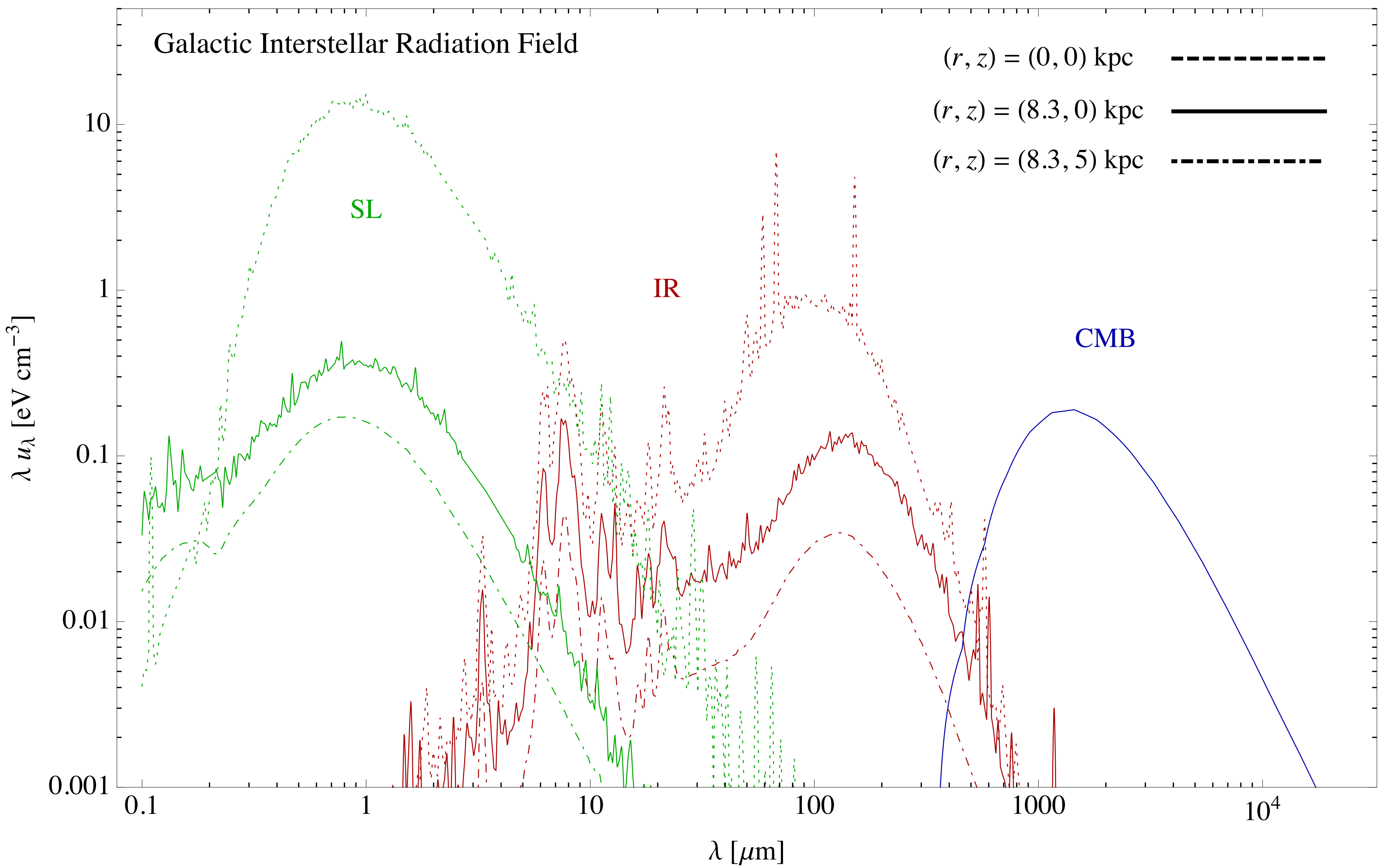
ICS in the CMB is dominant

$(E_e \lesssim 10^8\,\mathrm{GeV})$



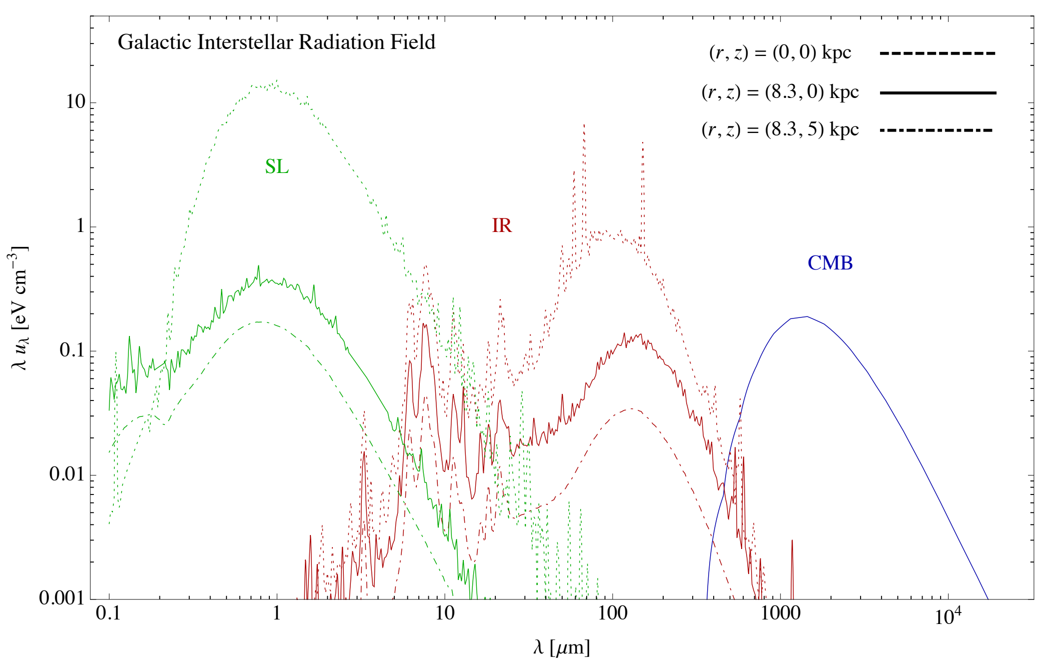
Absorption in ISRF+CMB

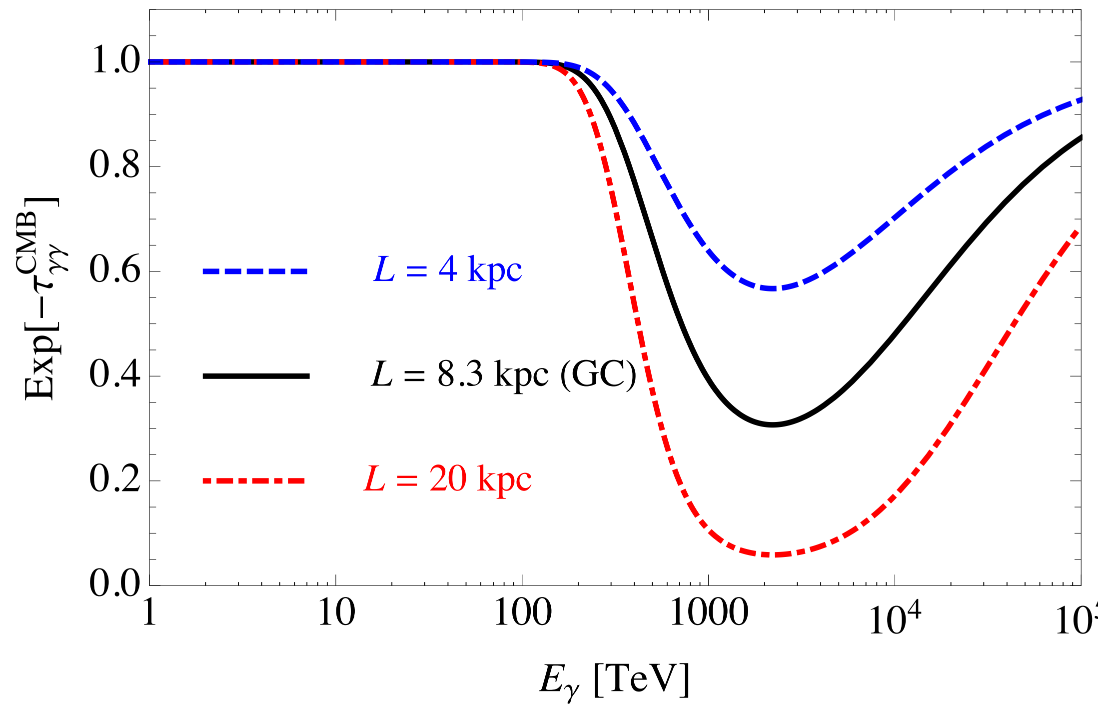
Esmaili, Serpico ’15

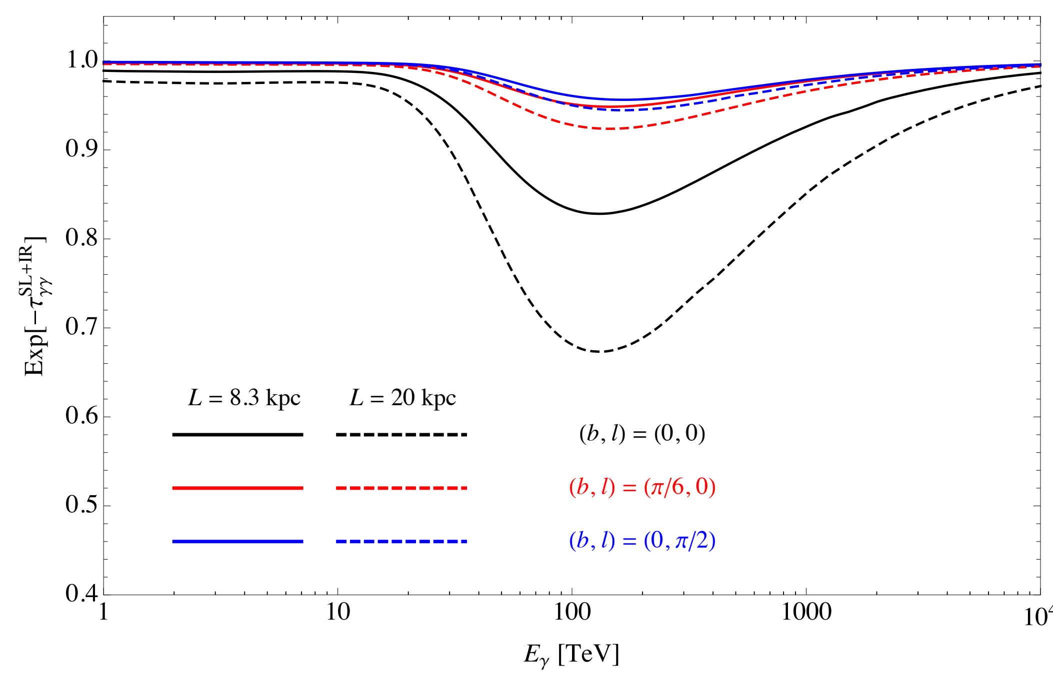


Absorption in ISRF+CMB

Esmaili, Serpico '15

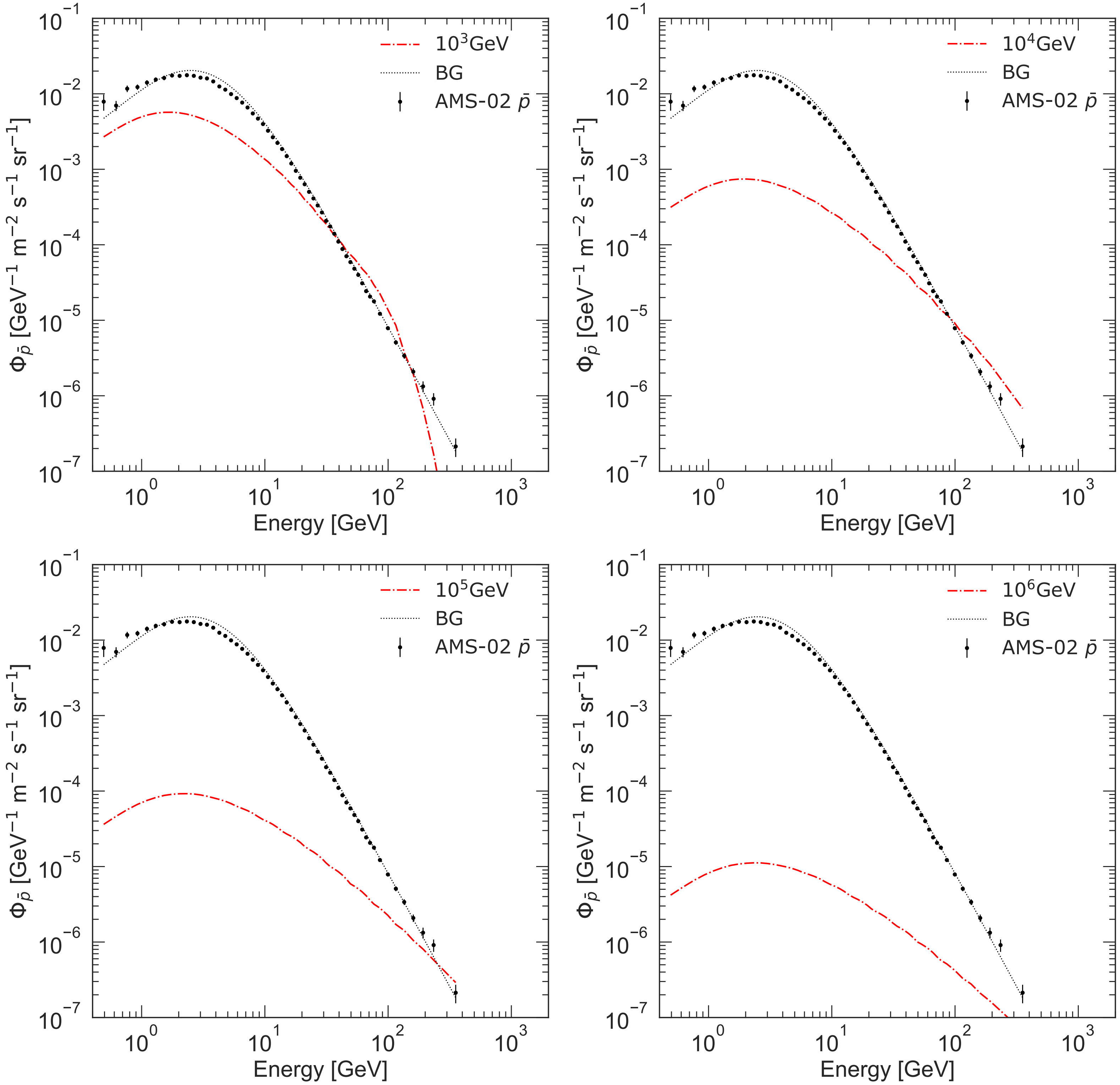






$0.1 - 100$ PeV γ is under the absorption effect

$\bar{p}$ flux in the Galaxy

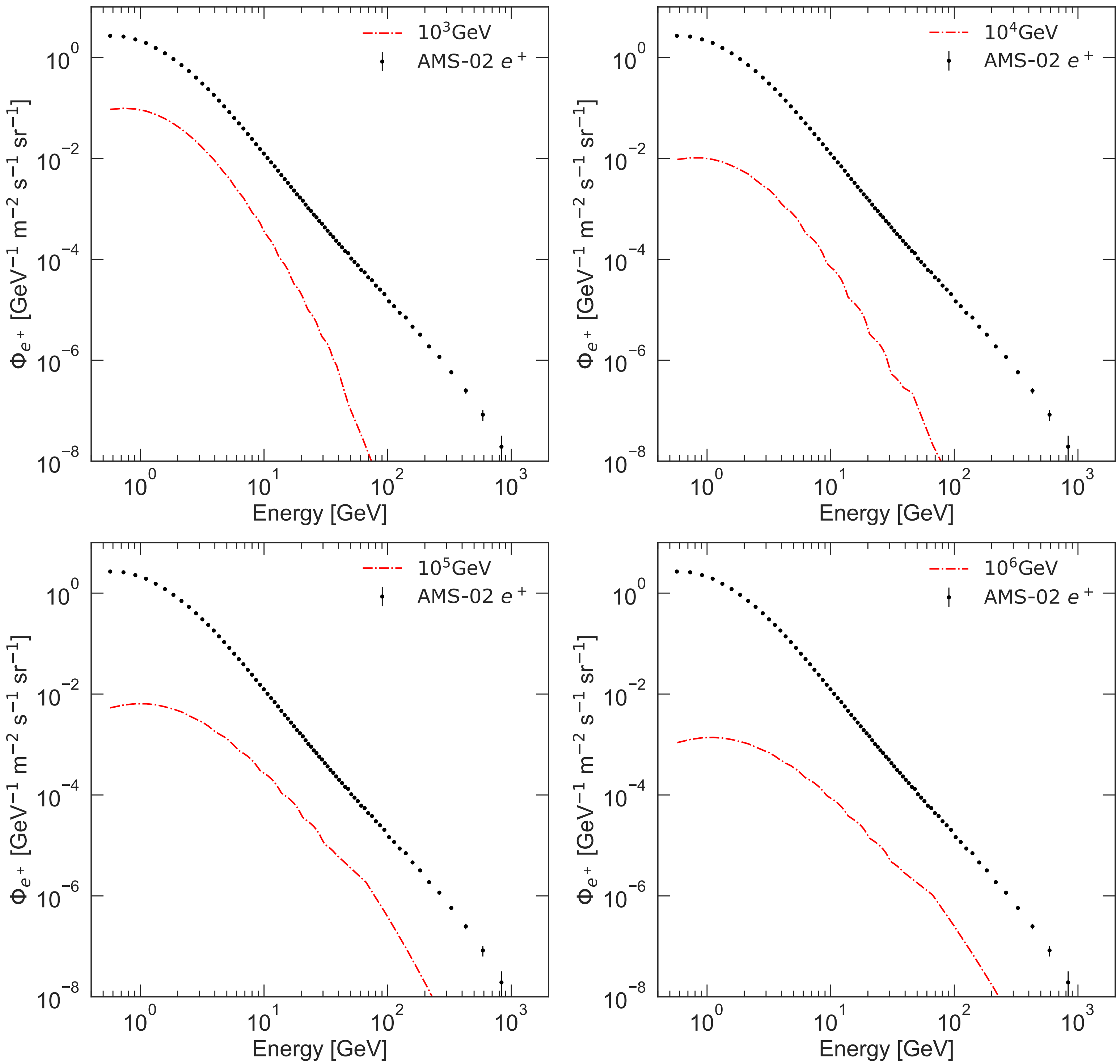


$\tau_{\rm dm} = 10^{27}$ s

Flux gets smaller for larger $m_{\rm dm}$

⟶ Constraints from AMS-02 becomes irrelevant for large $m_{\rm dm}$

e^+ flux in the Galaxy

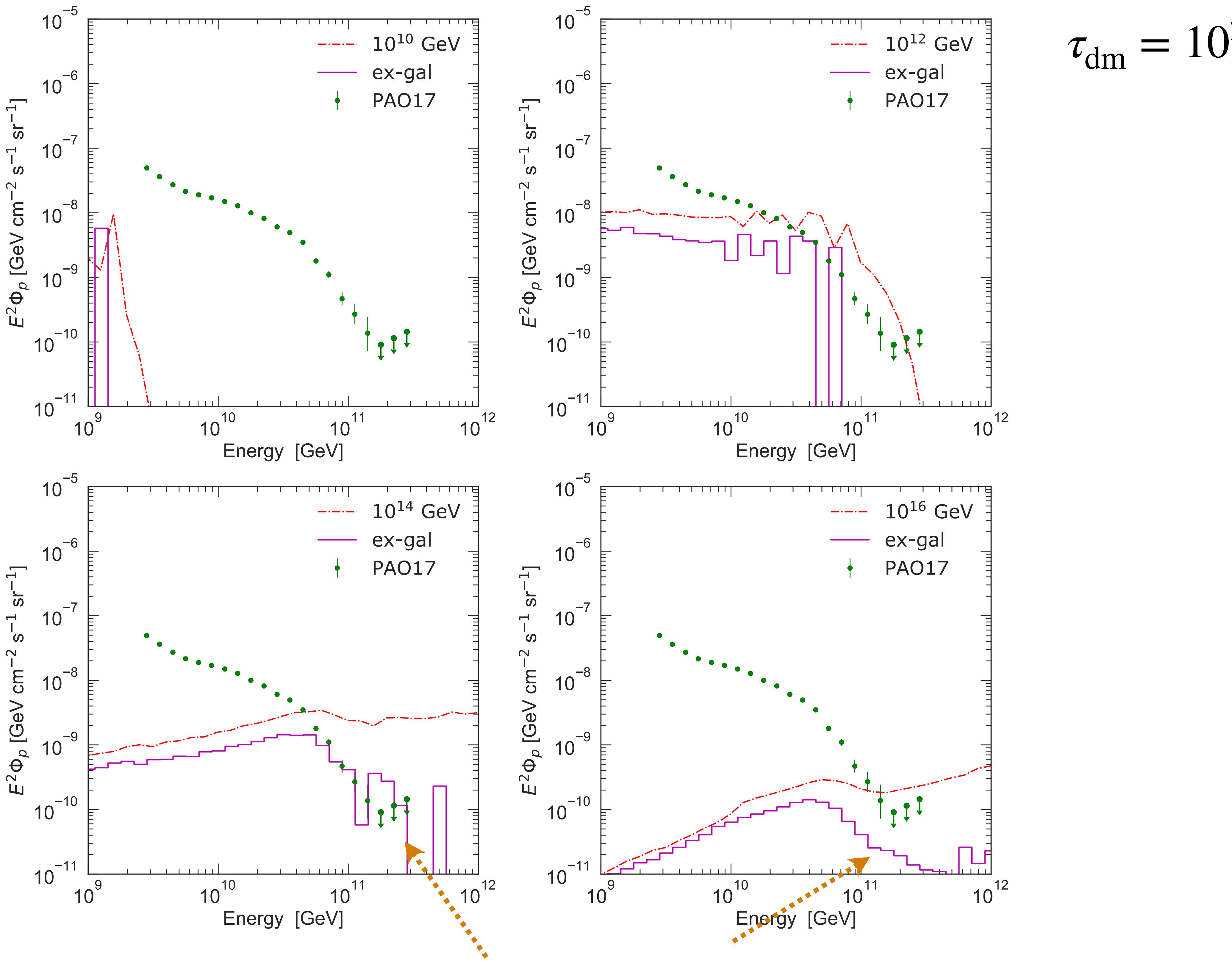


$\tau_{\rm dm} = 10^{27}$ s

Similar behavior to $\bar{p}$ flux

$p + \bar{p}$ flux

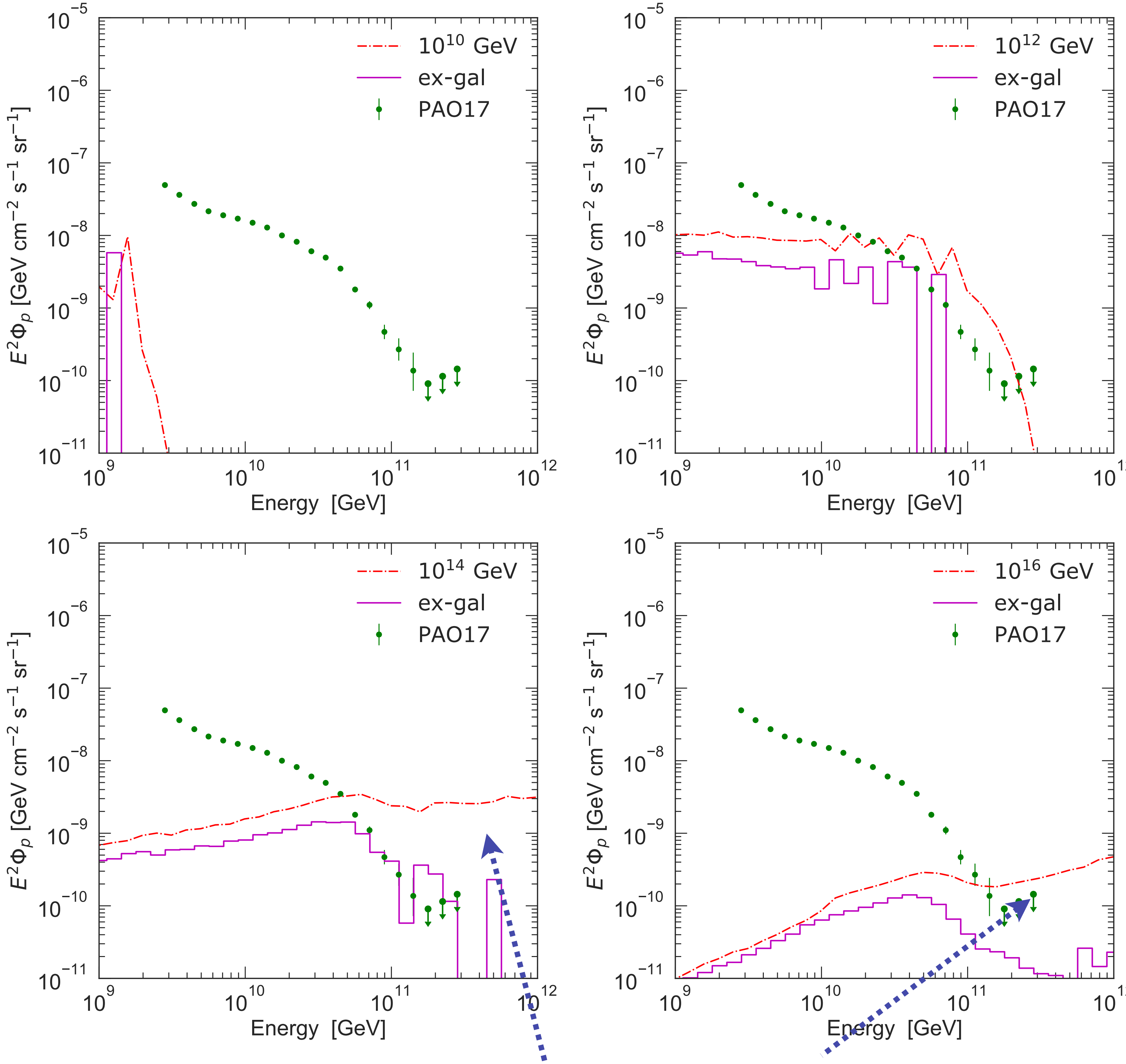
$\tau_{\mathrm{dm}} = 10^{27}\,\mathrm{s}$



GZK effect can be seen in the extragalactic flux

$p + \bar{p}$ flux

$\tau_{\mathrm{dm}} = 10^{27}\,\mathrm{s}$



Galactic flux becomes dominant in the high energy region for large m_{dm}

Combined results