Probing heavy dark matter decays with multi-messenger astrophysical data

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Kanazawa University

Based on JCAP 01 (2020) 003

with

S. Ando, M. Arimoto, O. Macias

Osaka, November 26, 2020

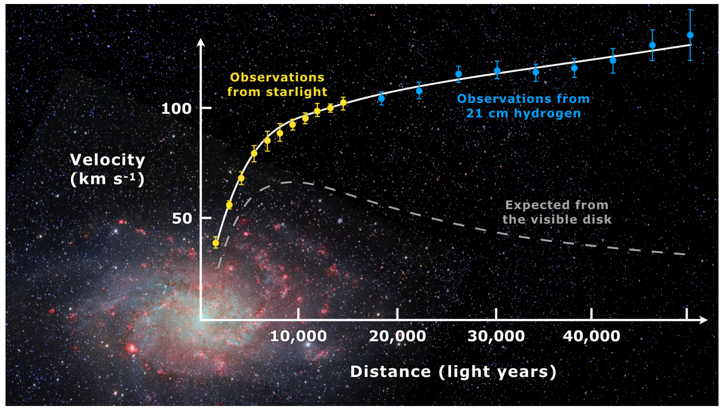
Outline

1. Introduction
2. CRs from decaying heavy DM
3. Numerical results
4. Conclusion

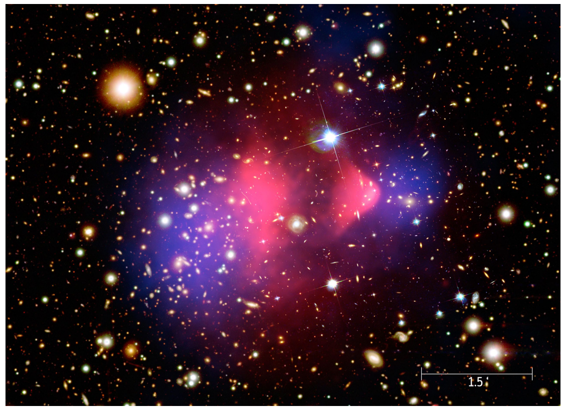
1. Introduction

Evidences for dark matter (DM)

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

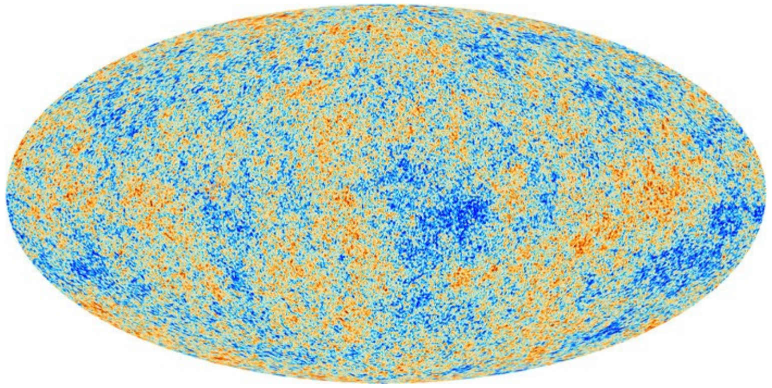


Corbelli, Salucci '00



Markevitch et al. '04

Clowe et al.'04



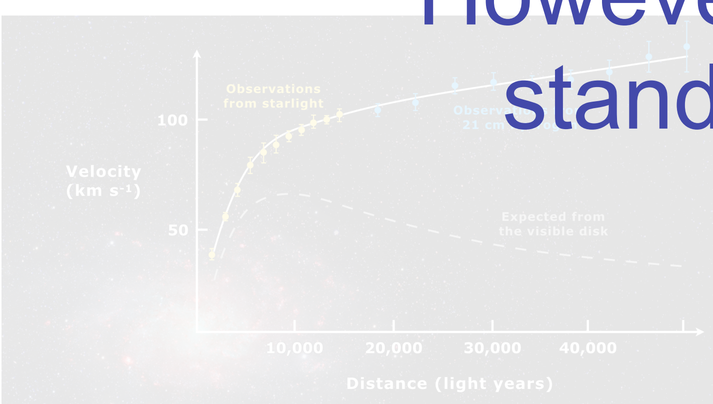
Planck '13

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



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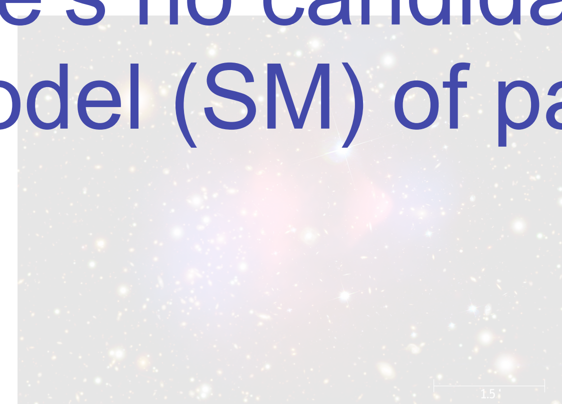

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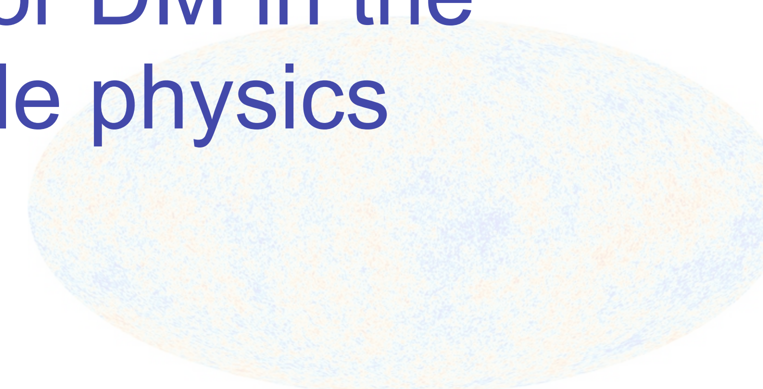

Planck '13

To be consistent the observations, DM has to be

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

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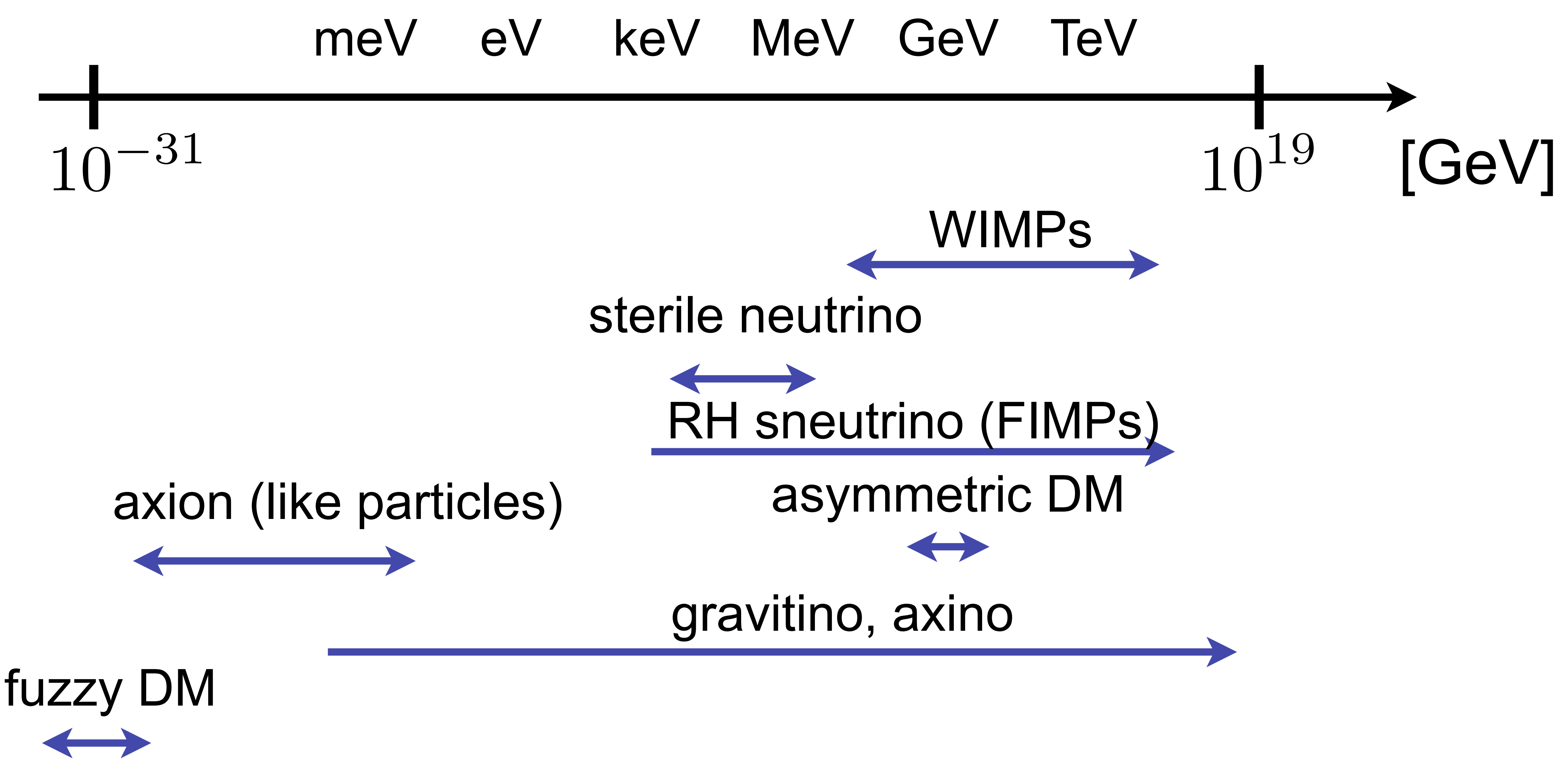
How heavy?

A rough sketch of particle DM candidates



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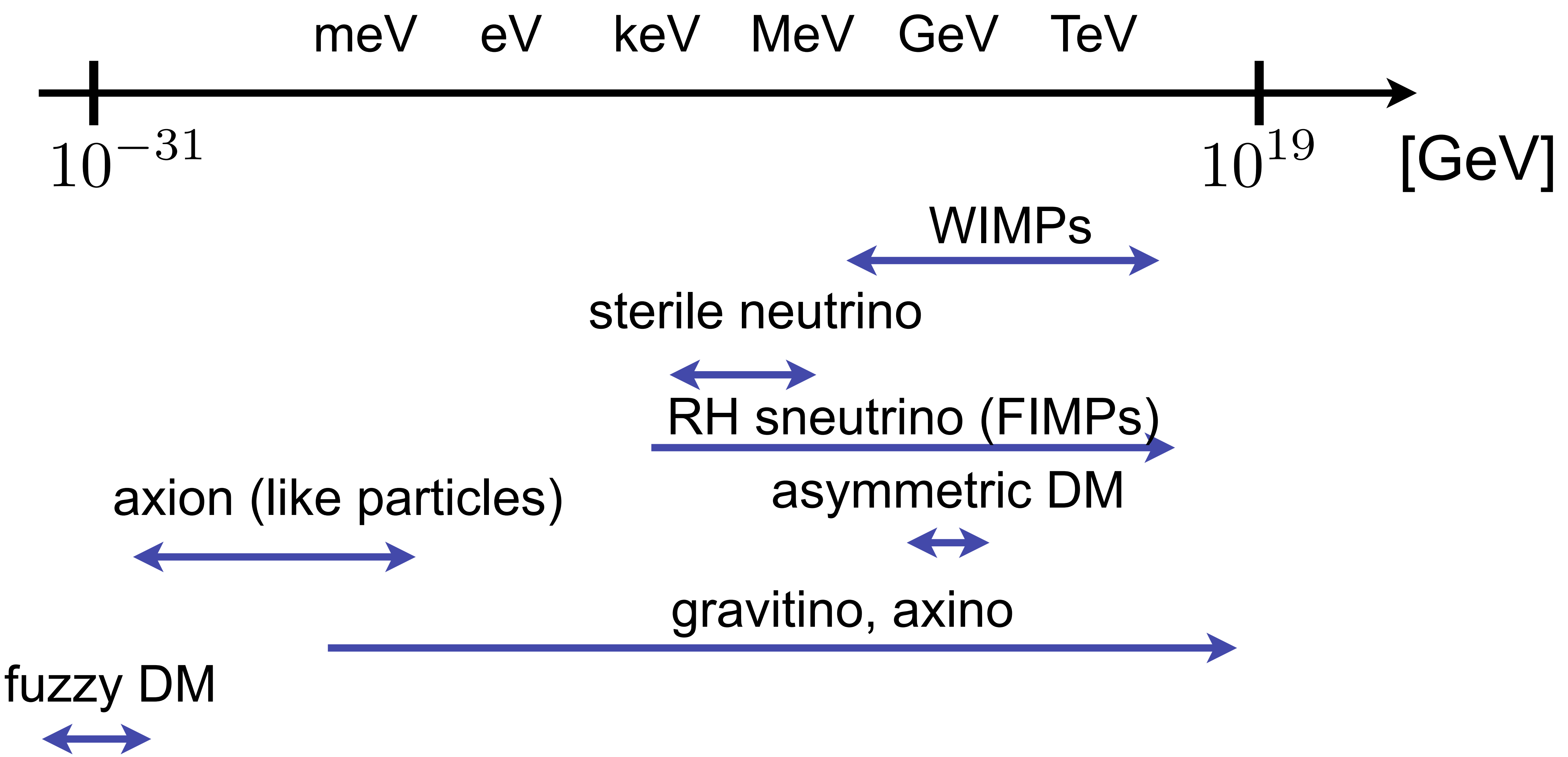

How heavy?

→ Almost unknown

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Stable or unstable?

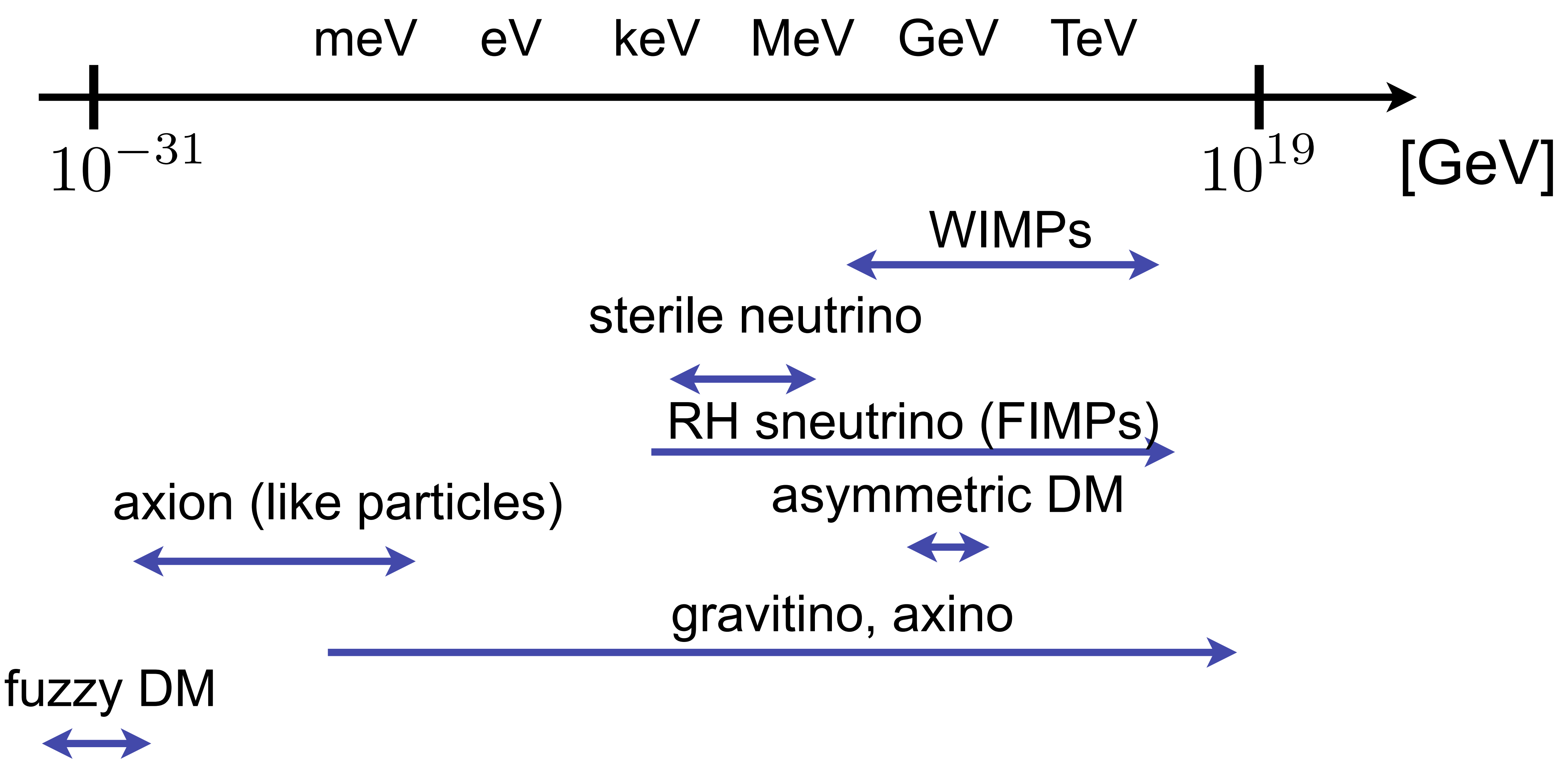
→ Unknown

How heavy? → Almost unknown

Stable or unstable? → Unknown

Cosmic rays can be a probe for the questions

A rough sketch of particle DM candidates



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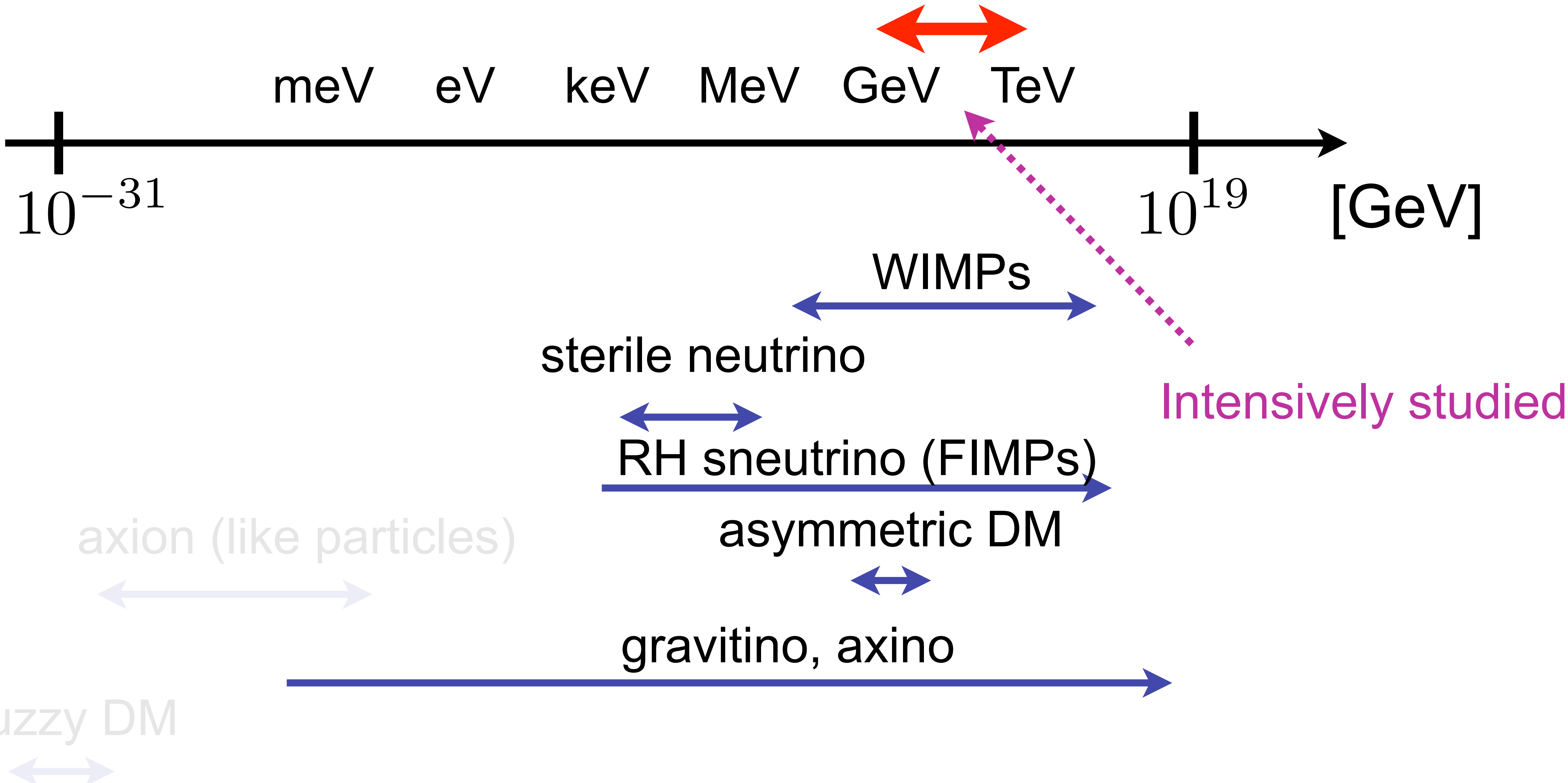
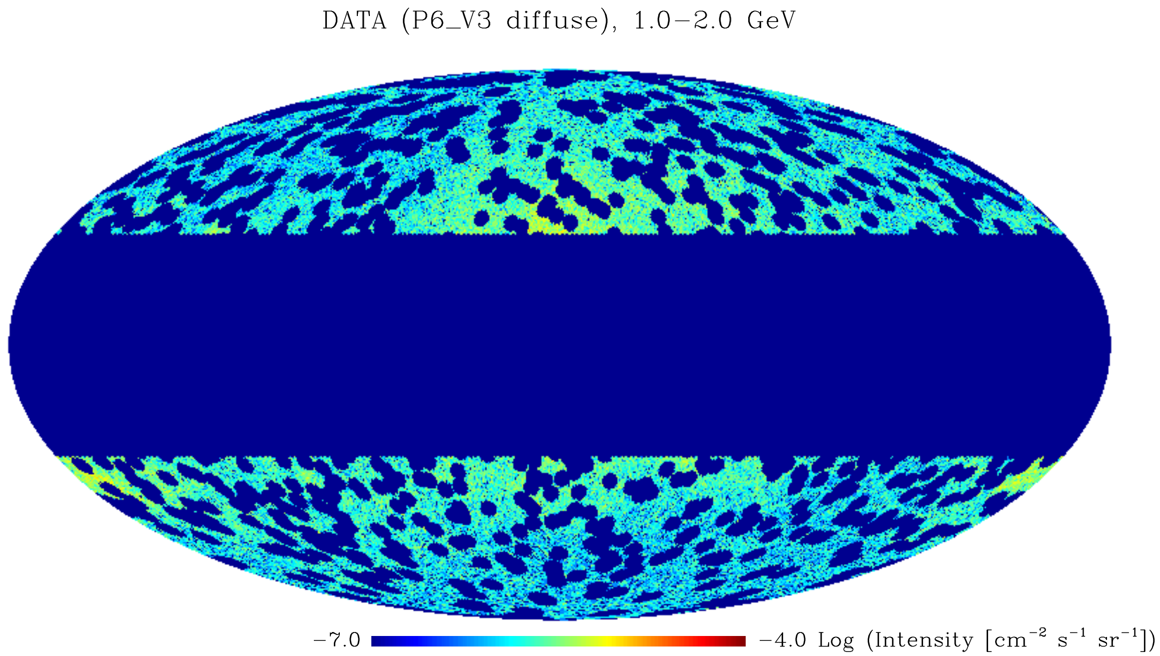
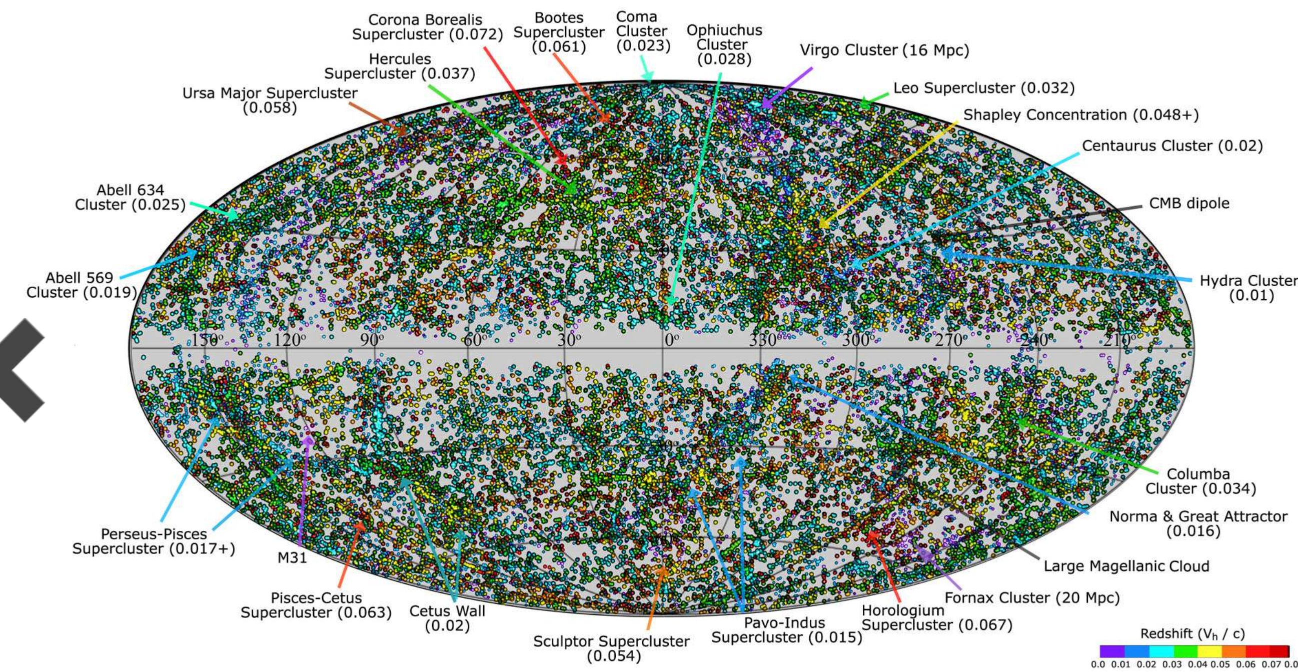


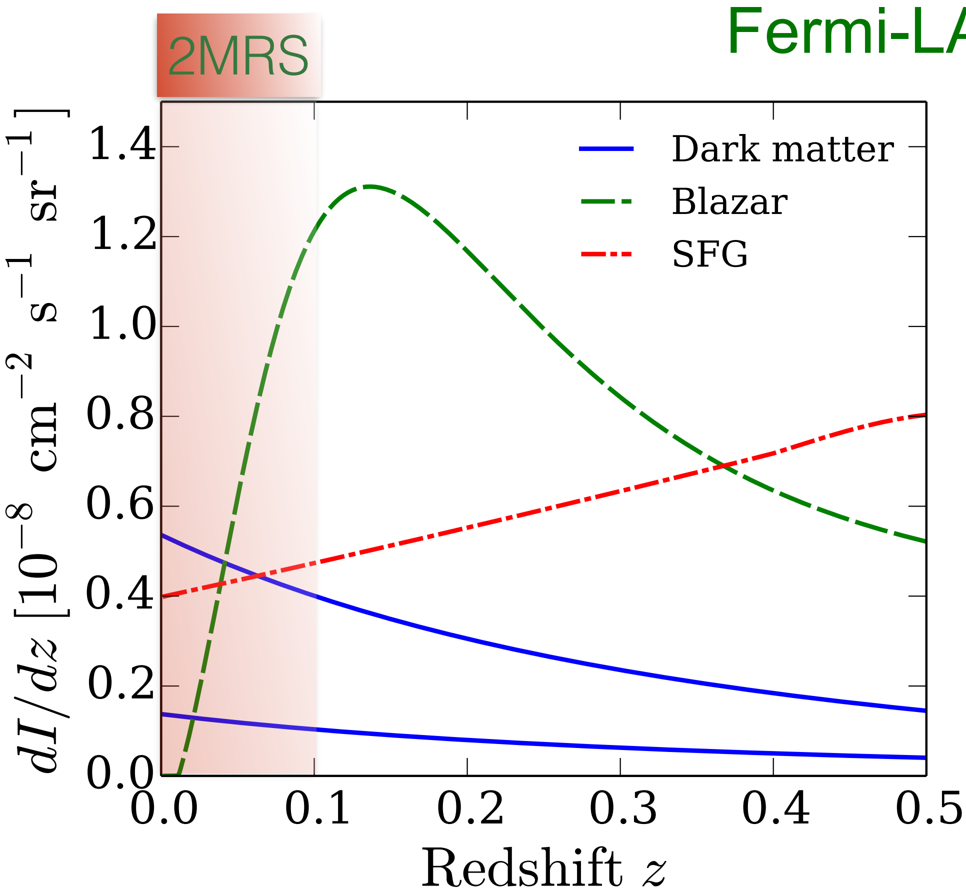
e.g., tomographic cross-correlation using local galaxy distribution

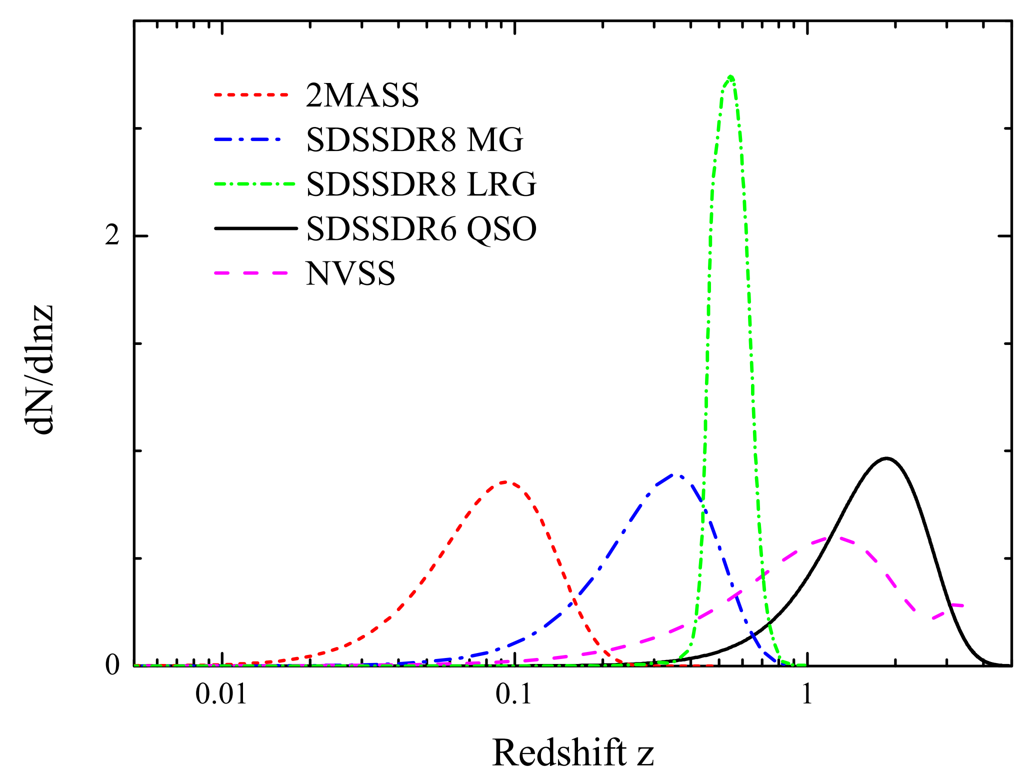




Fermi-LAT '12

2MRS '11



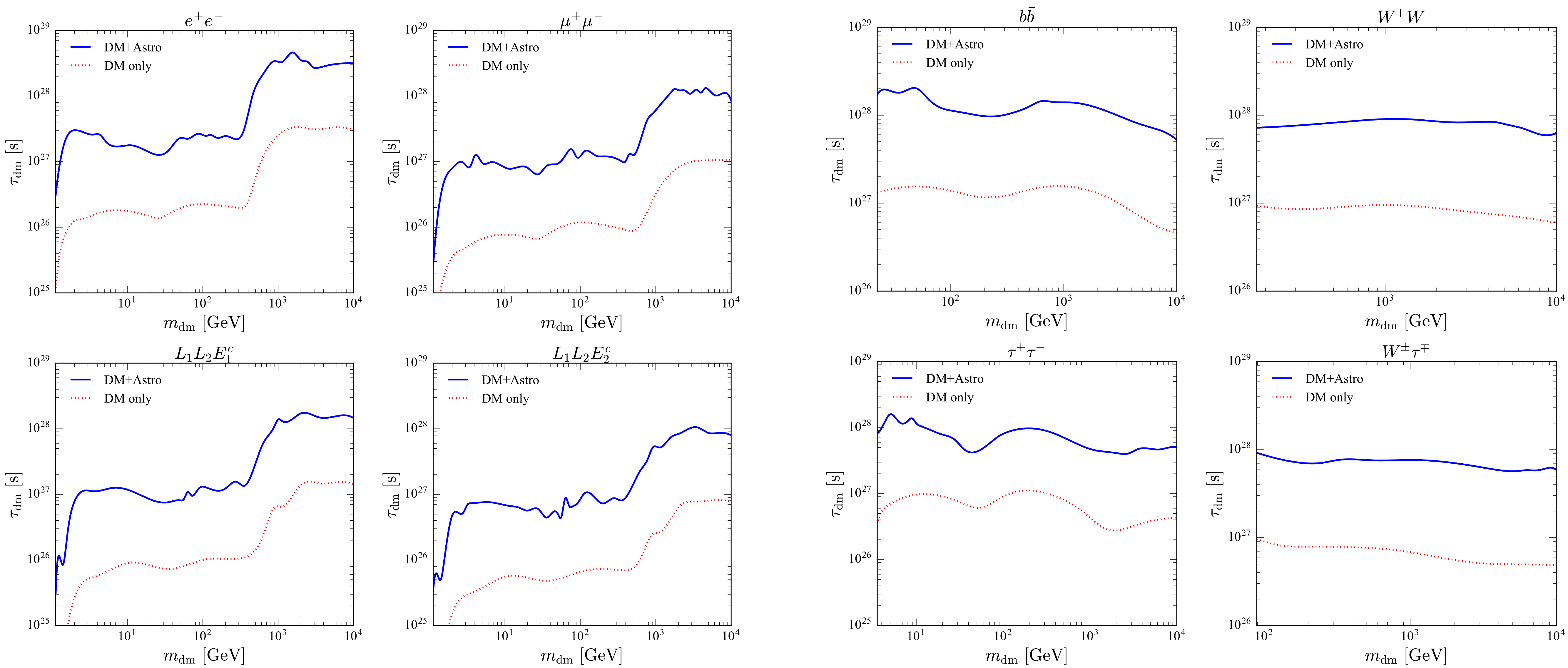


Astro. BG can be reduced in $z < 0.1$

e.g., tomographic cross-correlation using local galaxy distribution

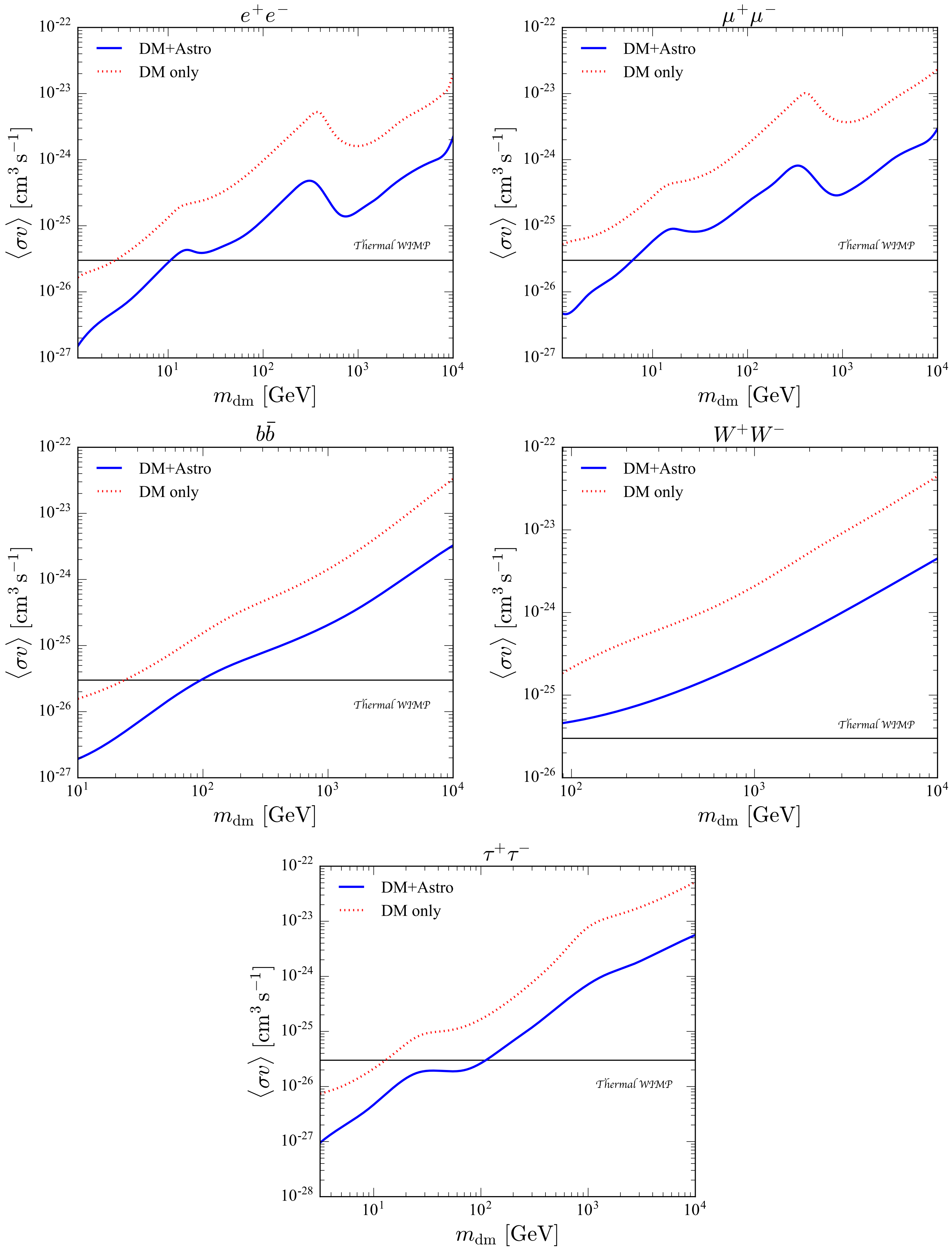
Decaying DM

Ando, KI '16



DM models to explain the anomalous positron flux are excluded

e.g., tomographic cross-correlation using local galaxy distribution



Ando, KI '16

Annihilating DM

As stringent bound as dSph galaxies

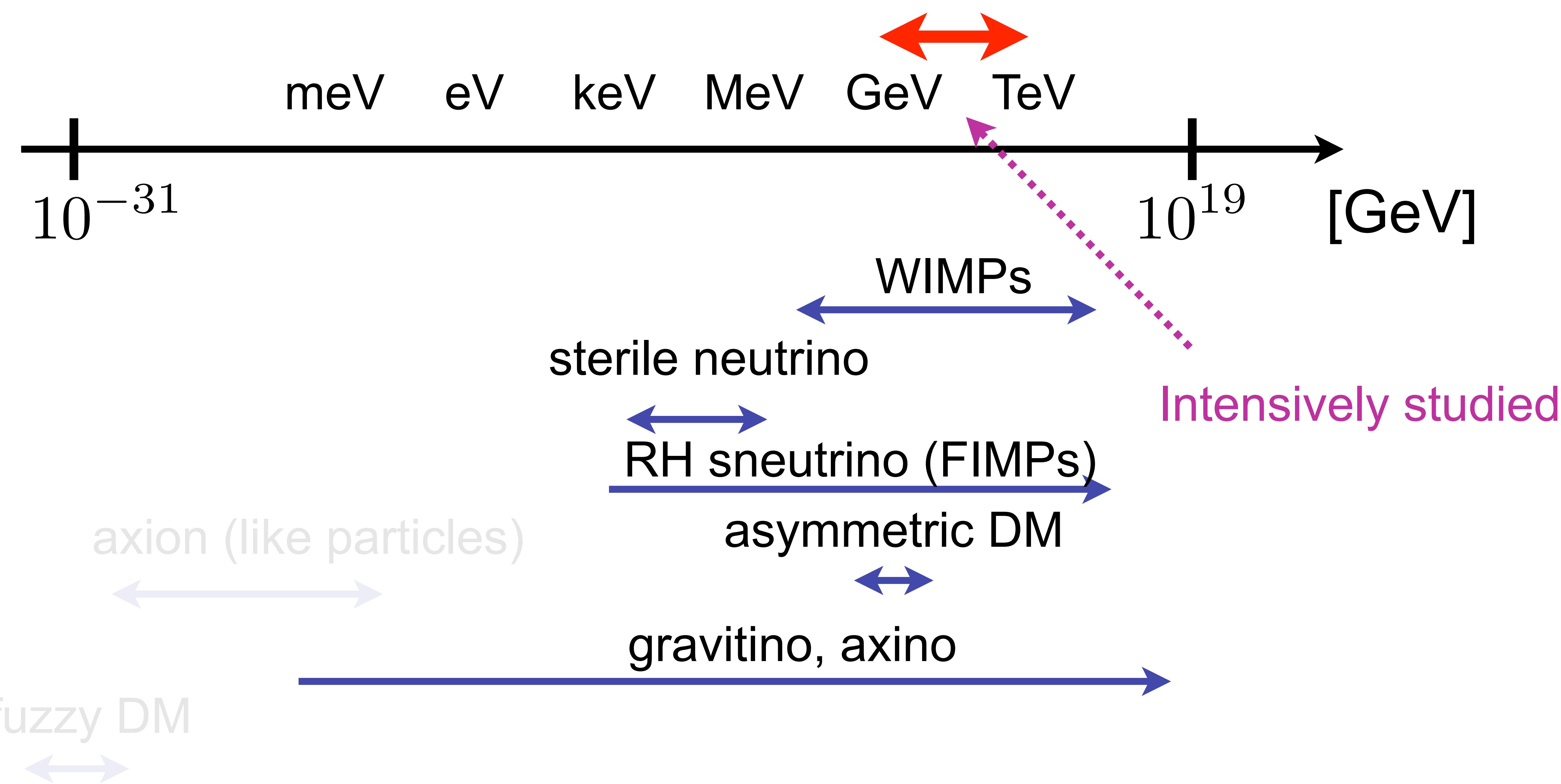
Ando, Geringer-Sameth, Hiroshima, Hoof, Trotta, Walker '20

Alvarez, Calore, Genina, Read, Serpico, Zaldivar '20

for recent progress

Hiroshima-san's talk

A rough sketch of particle DM candidates



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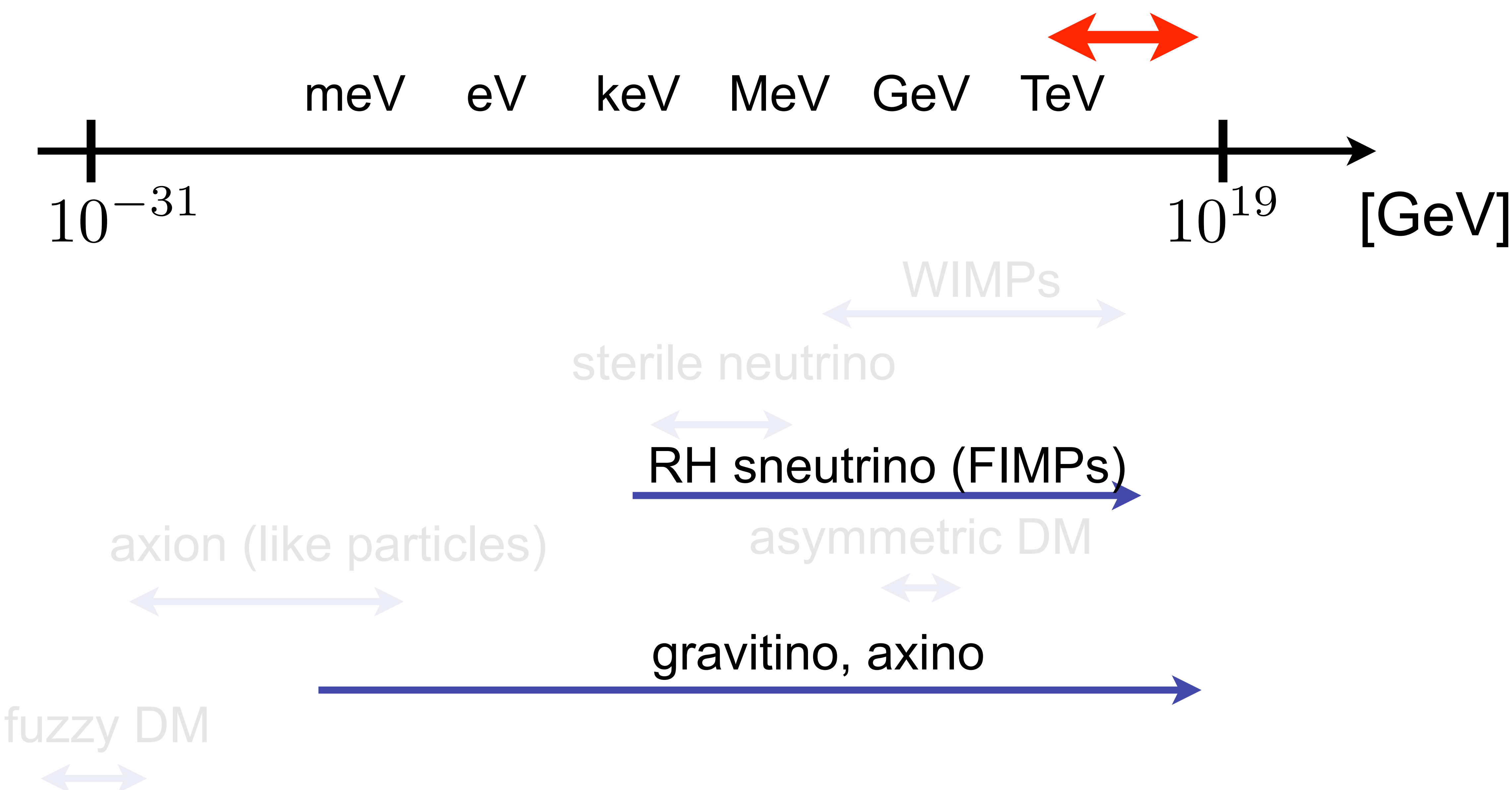


Past works on heavy decaying DM:

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

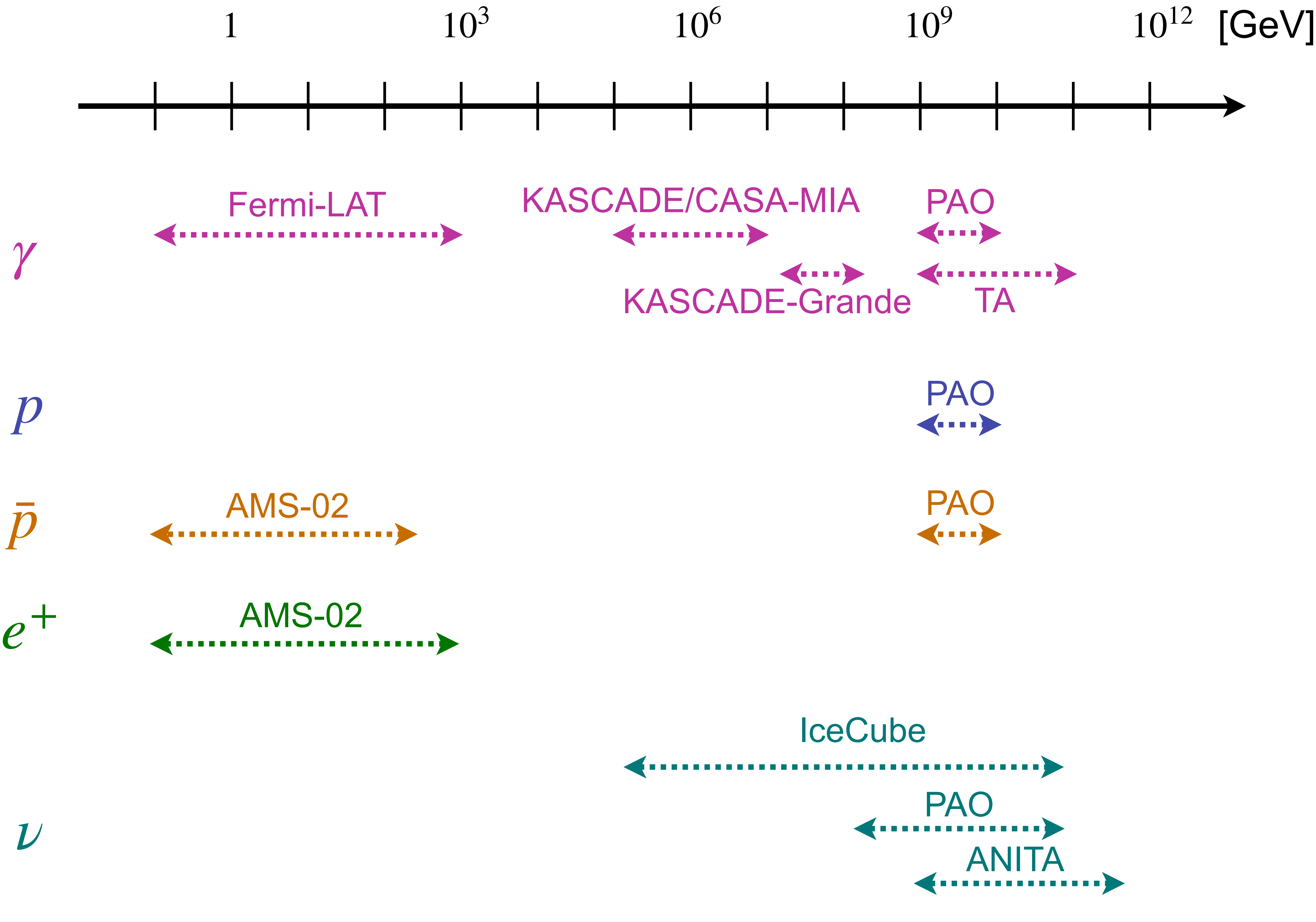
We simulate cosmic-ray (CR) $p, \bar{p}, e^{\pm}, \gamma, \nu , \bar{\nu}$ from heavy decaying DM $(10\,\mathrm{TeV} \leq m_{\mathrm{dm}} \leq 10^{16}\,\mathrm{GeV})$ in both

- Galactic
- Extragalactic

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

List of the observations

CRs	Observations	Energy [GeV]	Detected	CL upper limits
Gamma (γ)	Fermi-LAT [30]	$10^{-1} - 10^{3}$	✓	
	CASA-MIA [36]	$10^{5} - 10^{7}$		90%
	KASCADE [35]	$10^{5} - 10^{7}$		90%
	KASCADE-Grande [35]	$10^{7} - 10^{8}$		90%
	PAO [40, 41]	$10^{9} - 10^{10}$		95%
	TA [44]	$10^{9} - 10^{11}$		95%
Proton (p)	PAO [47]	$10^{9} - 10^{11}$	✓	84%
Anti-proton ($\bar{p}$)	PAO [47]	$10^{9} - 10^{11}$	✓	84%
	AMS-02 [31]	$10^{-1} - 10^{2}$	✓	
Positron (e^{+})	AMS-02 [32]	$10^{-1} - 10^{3}$	✓	
Neutrino (ν)	IceCube [45]	$10^{5} - 10^{8}$	✓	90%
	IceCube [46]	$10^{6} - 10^{11}$		90%
	PAO [47]	$10^{8} - 10^{11}$		90%
	ANITA [48]	$10^{9} - 10^{12}$		90%



1
10^3
10^6
10^9
10^12
[GeV]
γ
Fermi-LAT
KASCADE/CASA-MIA
PAO
KASCADE-Grande
TA
p
PAO
p̄
AMS-02
PAO
e+
AMS-02
IceCube
ν
PAO
ANITA

Plan to talk

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2. CRs from heavy decaying DM
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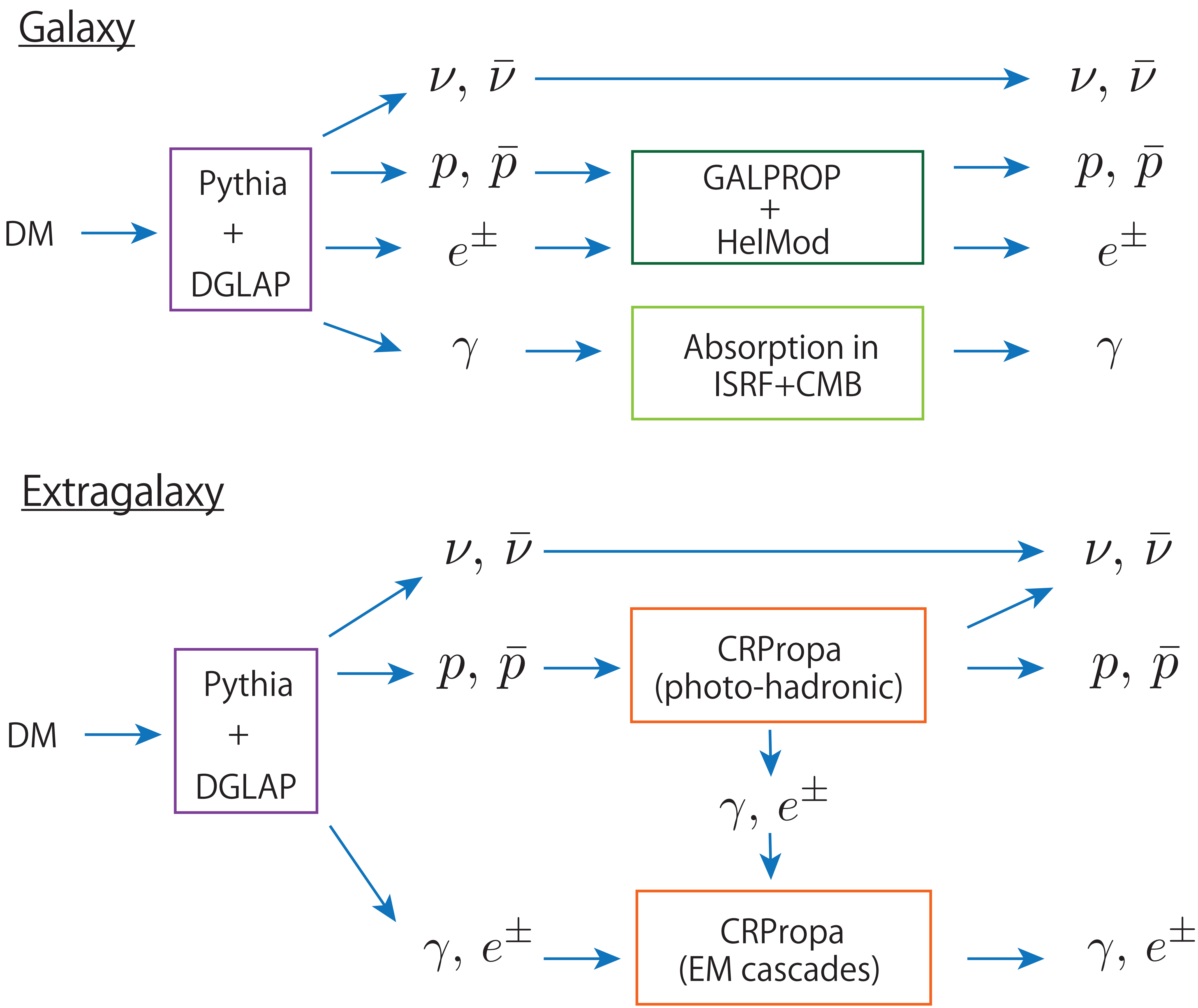
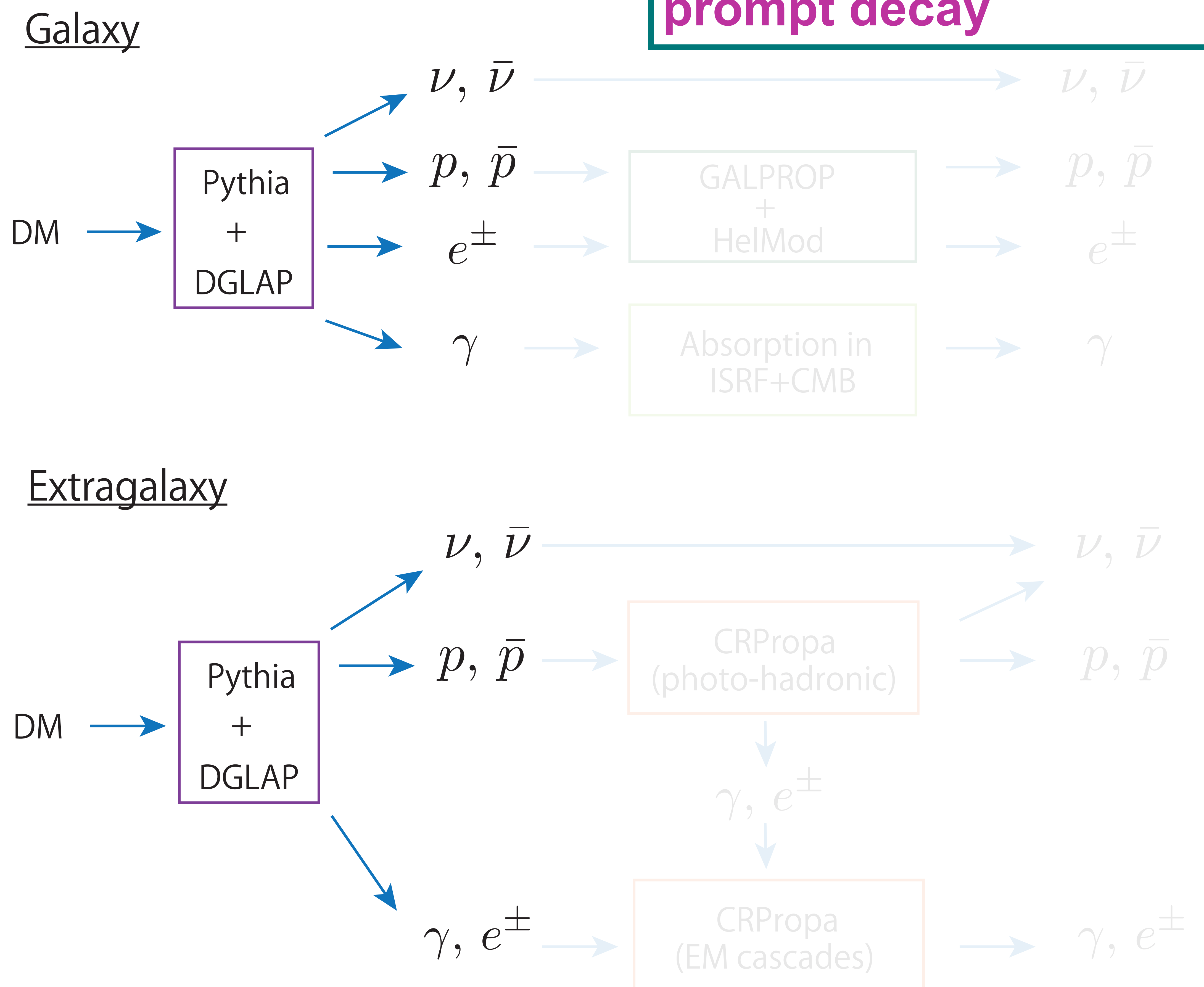
2. CRs from heavy decaying DM

Outline of the simulation



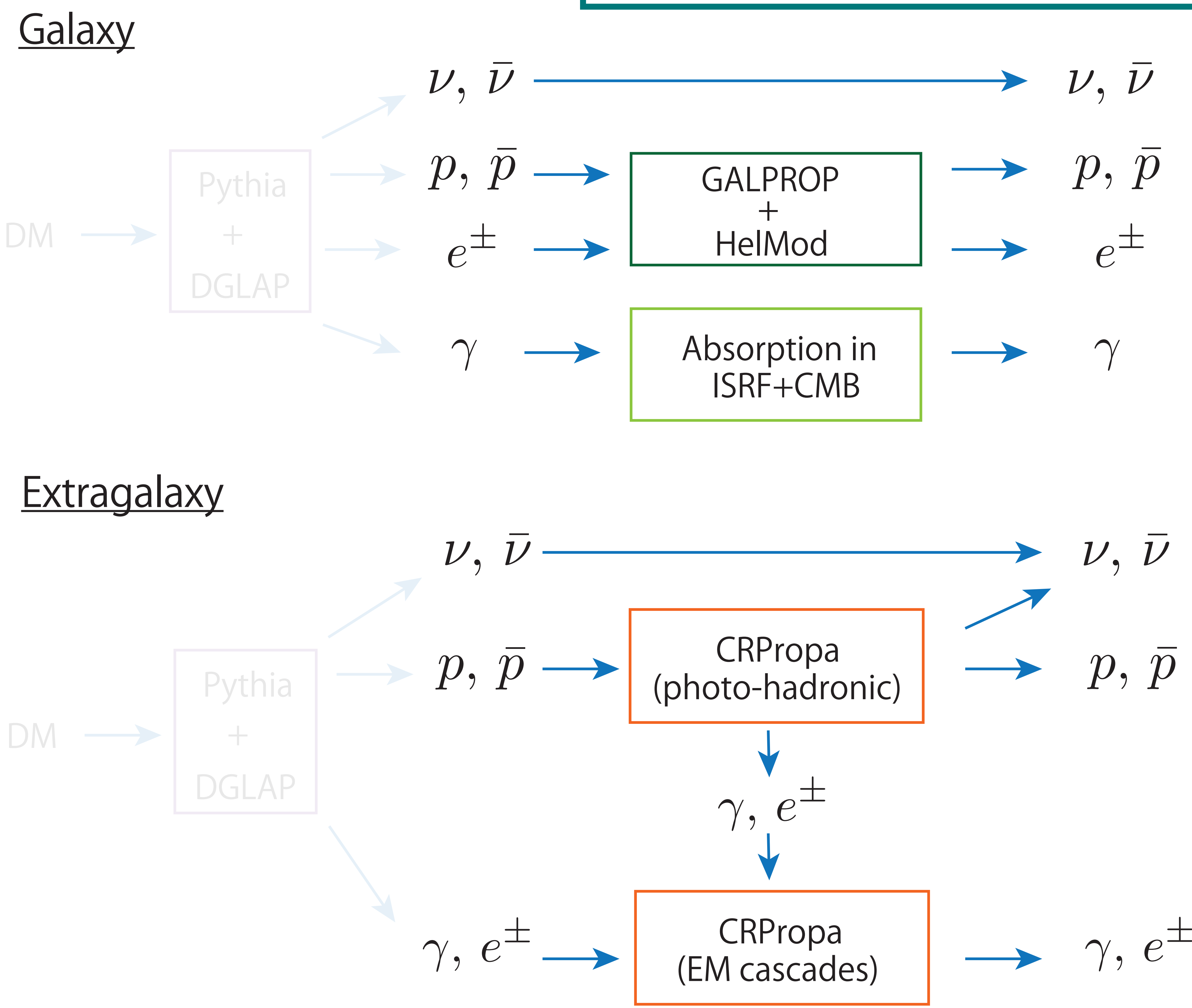
Outline of the simulation

Particle productions from prompt decay

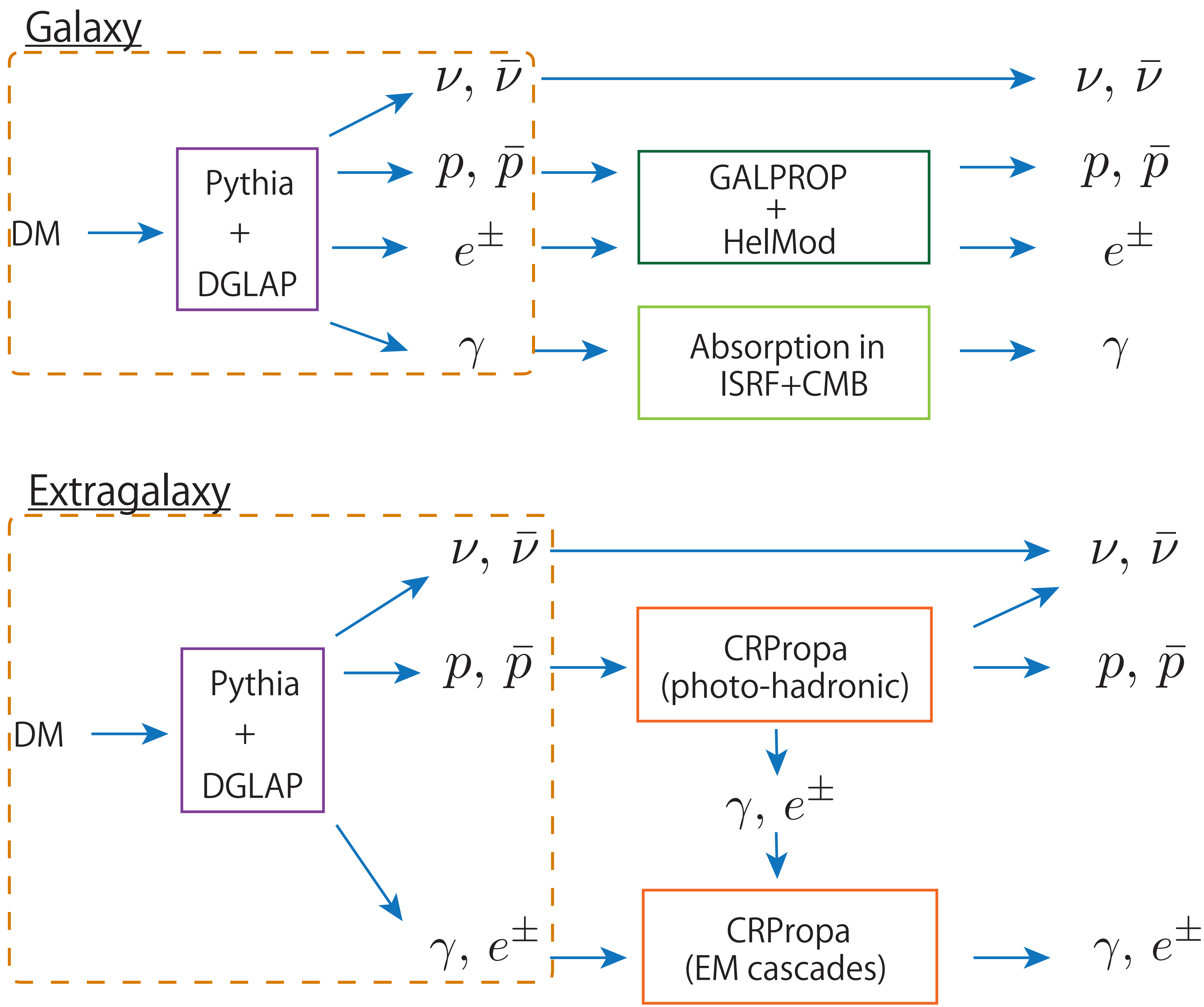


Outline of the simulation

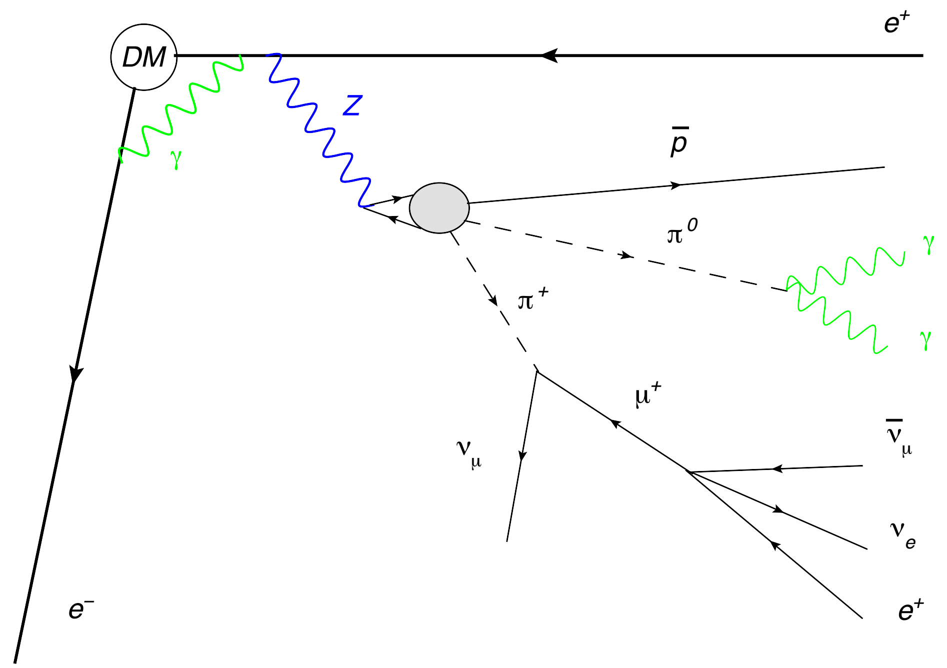
Propagations of CR particles



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

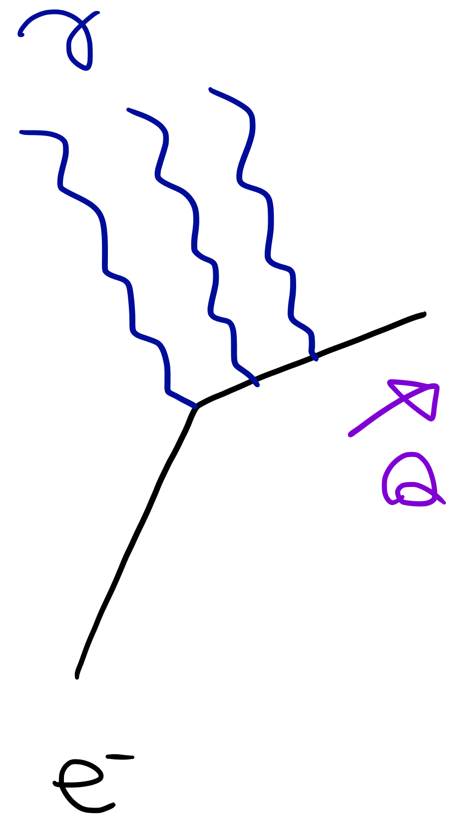
You can “find” variety of particles in a single particle, which can be described by Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) Eqs.

If we consider multiple γ emission

Number of γ ↑

~ Virtuality of e^- ↑

~ $\sum p_\perp^2$ ~ Q^2 ↑



Q evolution described by DGLAP Eqs.:

$$\frac{d}{d\log Q}\begin{pmatrix} D_e(x,Q) \\ D_\gamma(x,Q) \end{pmatrix} = \frac{\alpha(Q)}{\pi}\begin{pmatrix} P_{ee}(x) & 2P_{e\gamma}(x) \\ P_{\gamma e}(x) & P_{\gamma\gamma}(x) \end{pmatrix} \otimes \begin{pmatrix} D_e(x,Q) \\ D_\gamma(x,Q) \end{pmatrix}$$

$D_i(x,Q)$: fragmentation function (FF)

$P_{ij}(x)$: splitting function

$$i,j = e,\gamma$$

$$f(x)\otimes g(x) \equiv \int_x^1 \frac{dy}{y} f(y) g(z/y)$$

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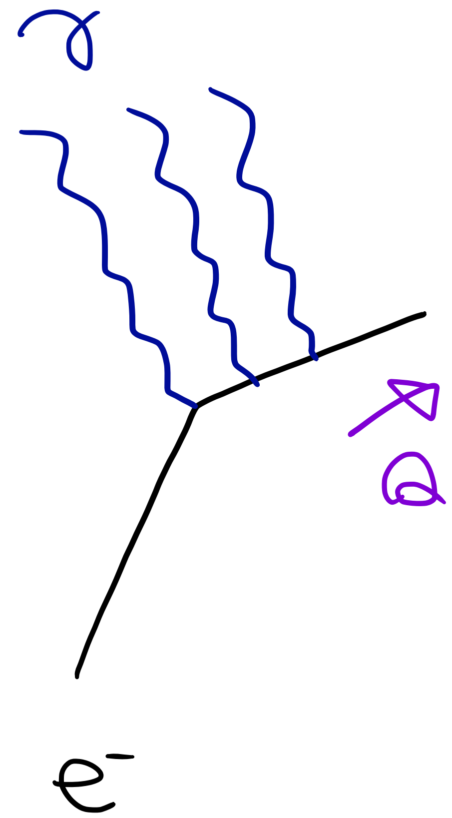

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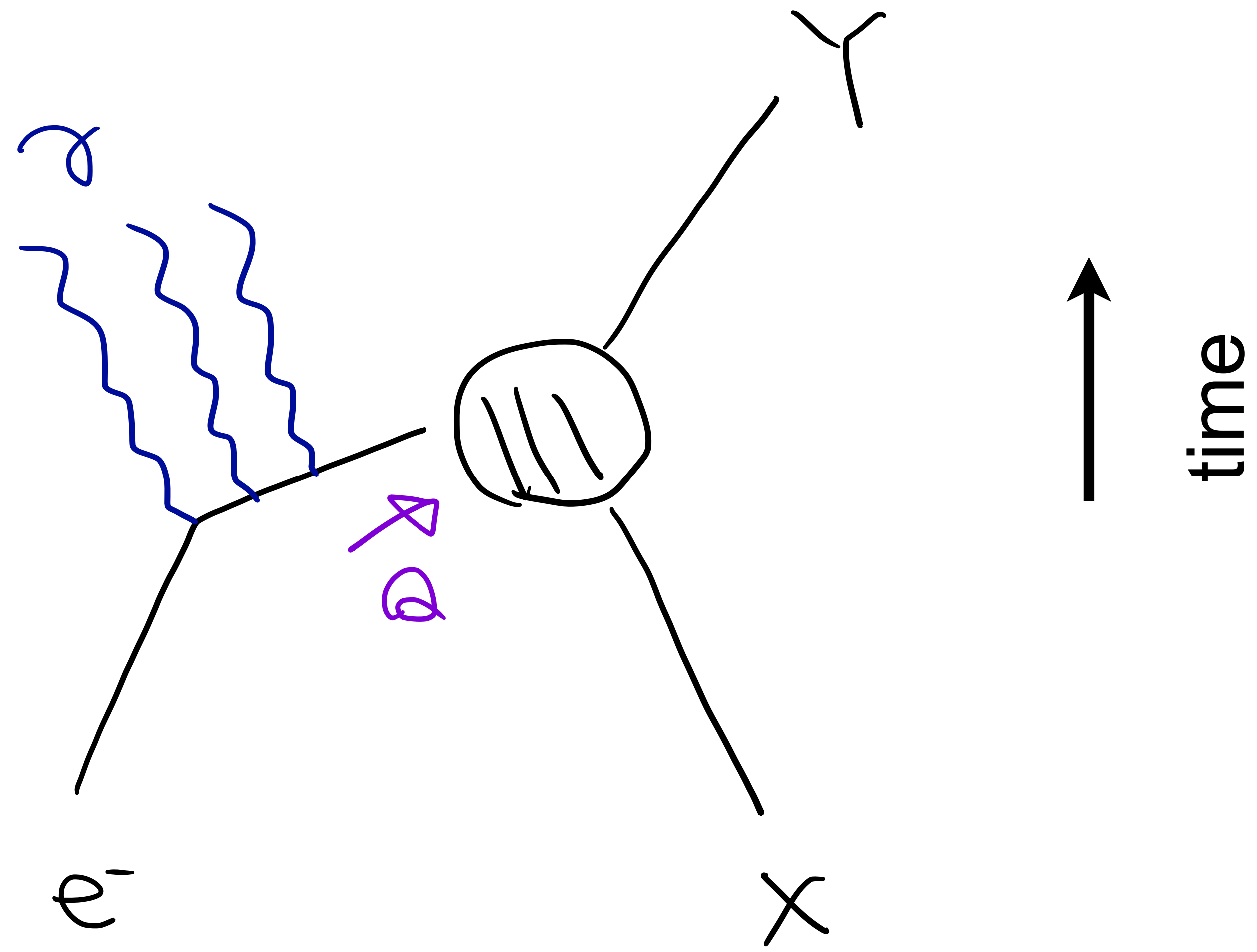
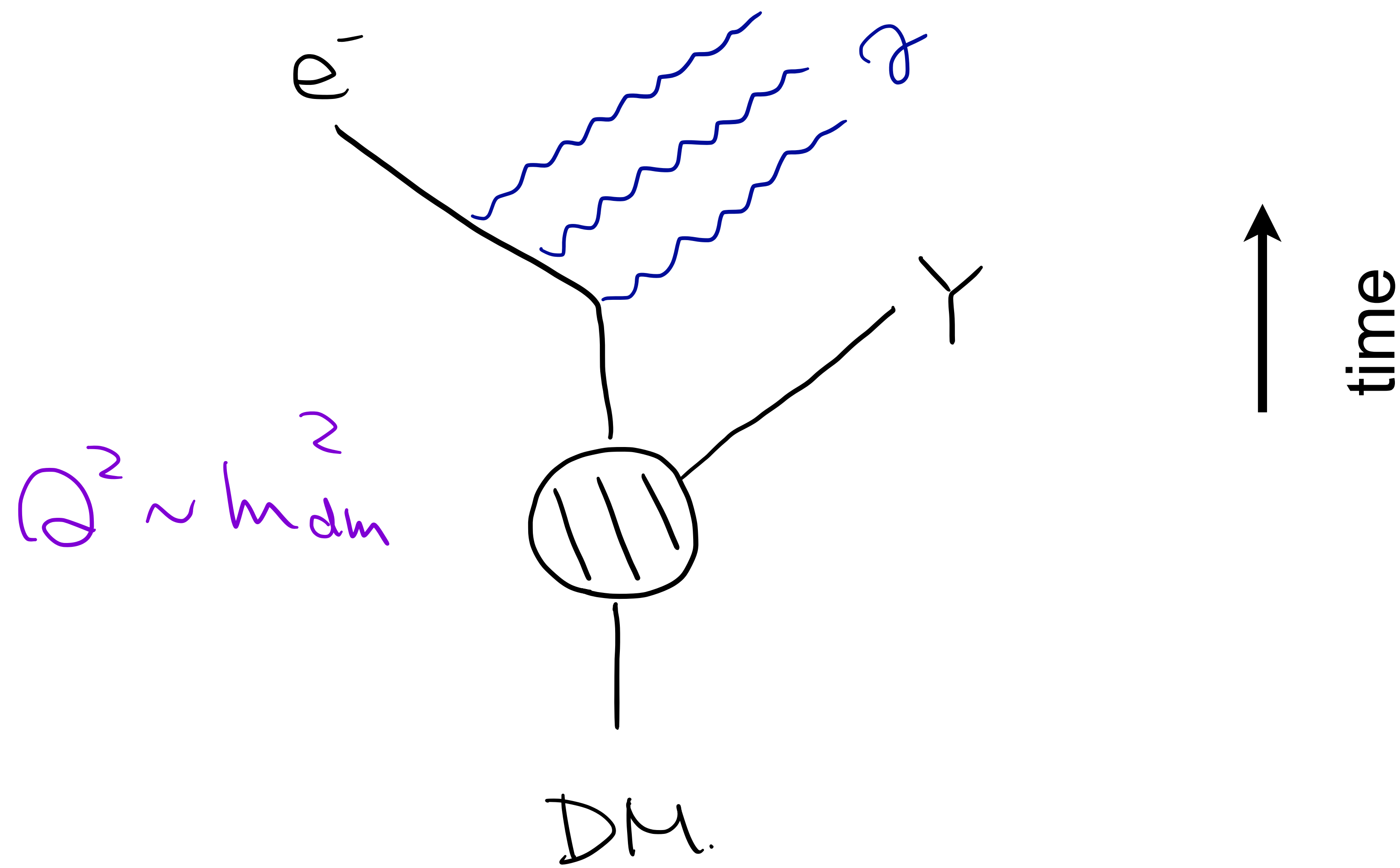
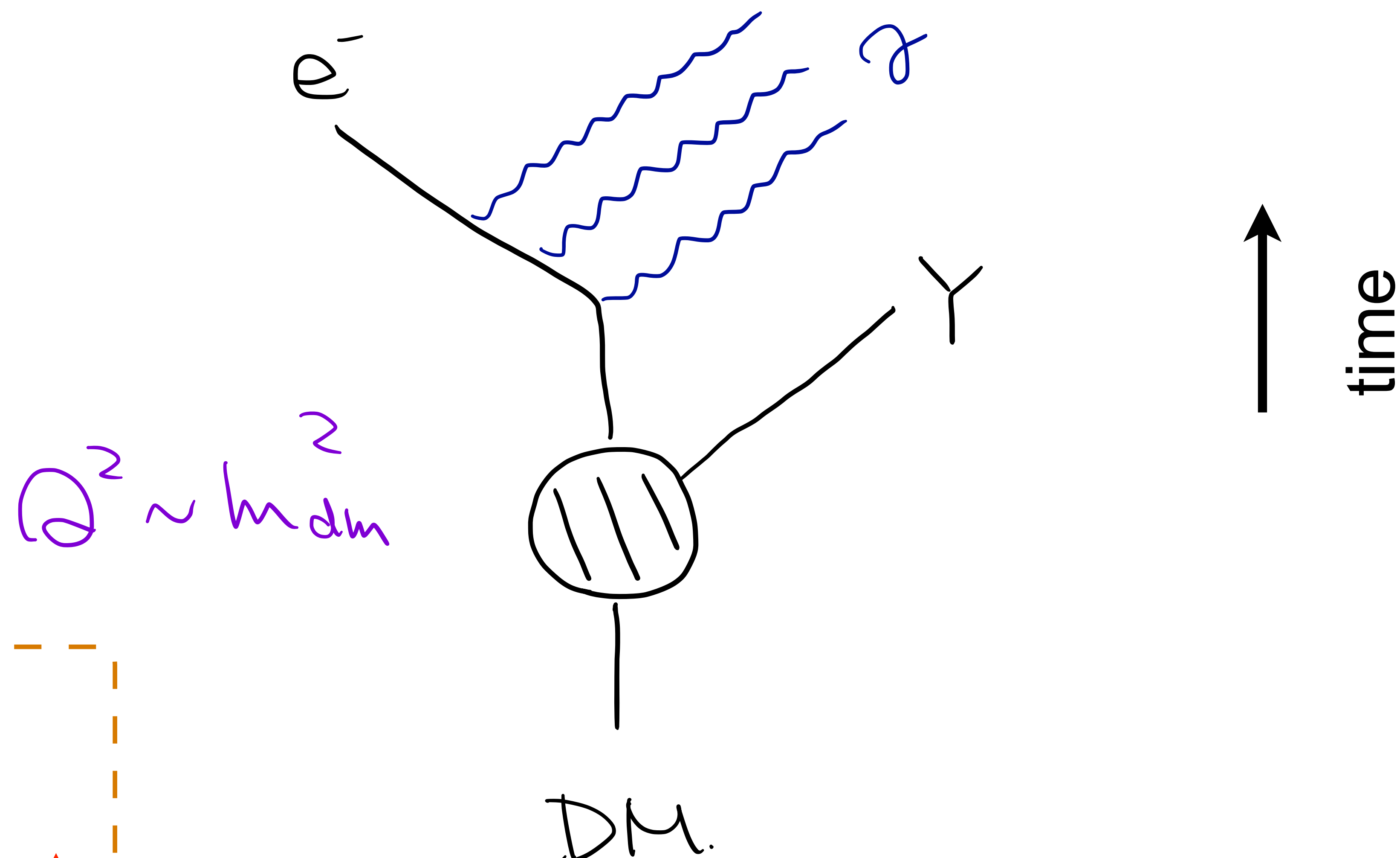


Q^2 is, for example, momentum transfer in the scattering process



You can apply the DGLAP evolution to calculate DM decay

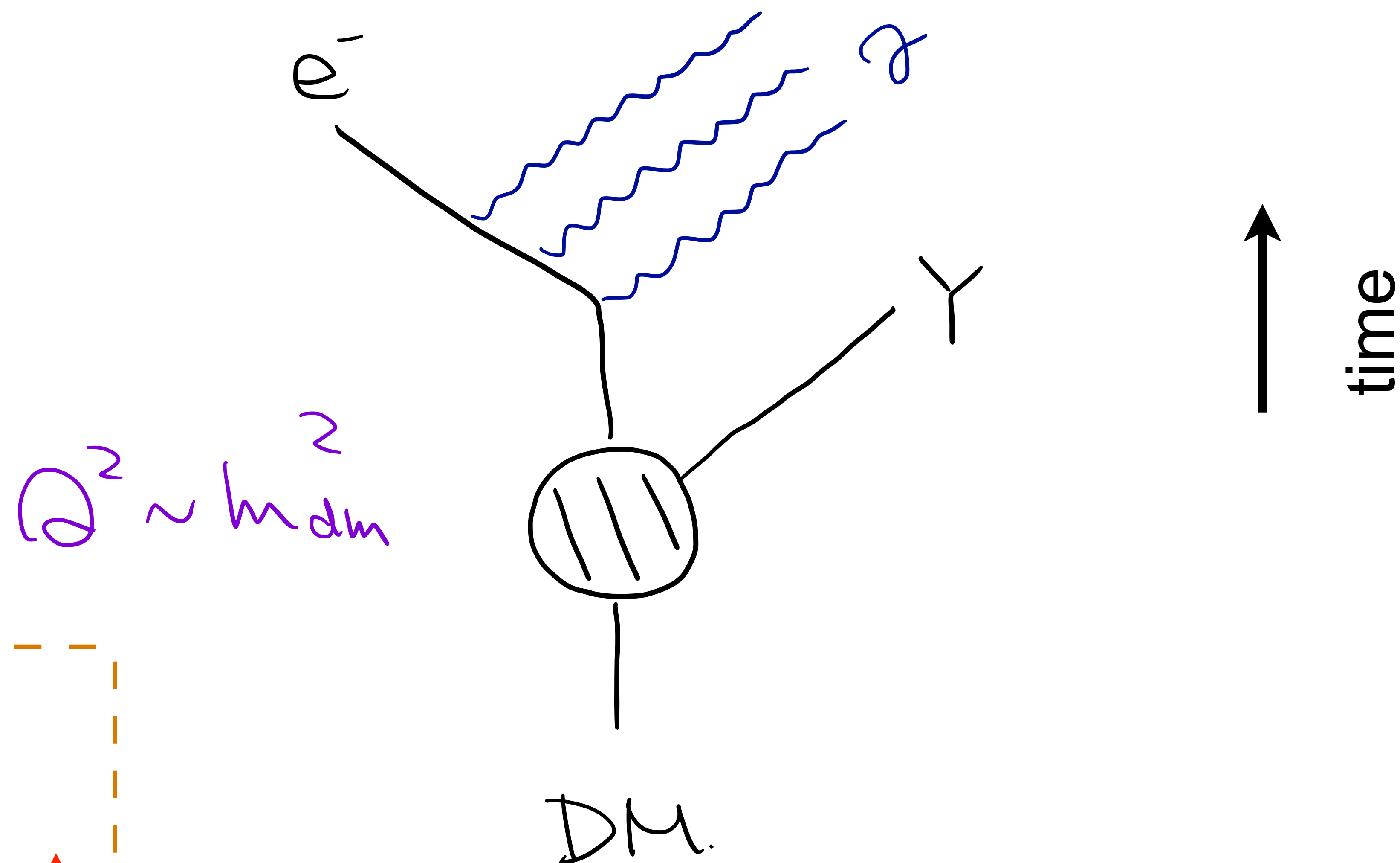


Number of γ ↑

~ Virtuality of e^- ↑

~ $\sum p_\perp^2$ ~ Q^2 ↑

→ Large DM mass gives lots of γ



Number of γ ↑

~ Virtuality of e^- ↑

~ $\sum p_\perp^2$ $\sim Q^2$ ↑

DGLAP eqs. should be extended to QCD and EW theory

→ Large DM mass gives lots of γ

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

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

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

DGLAP Pythia

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

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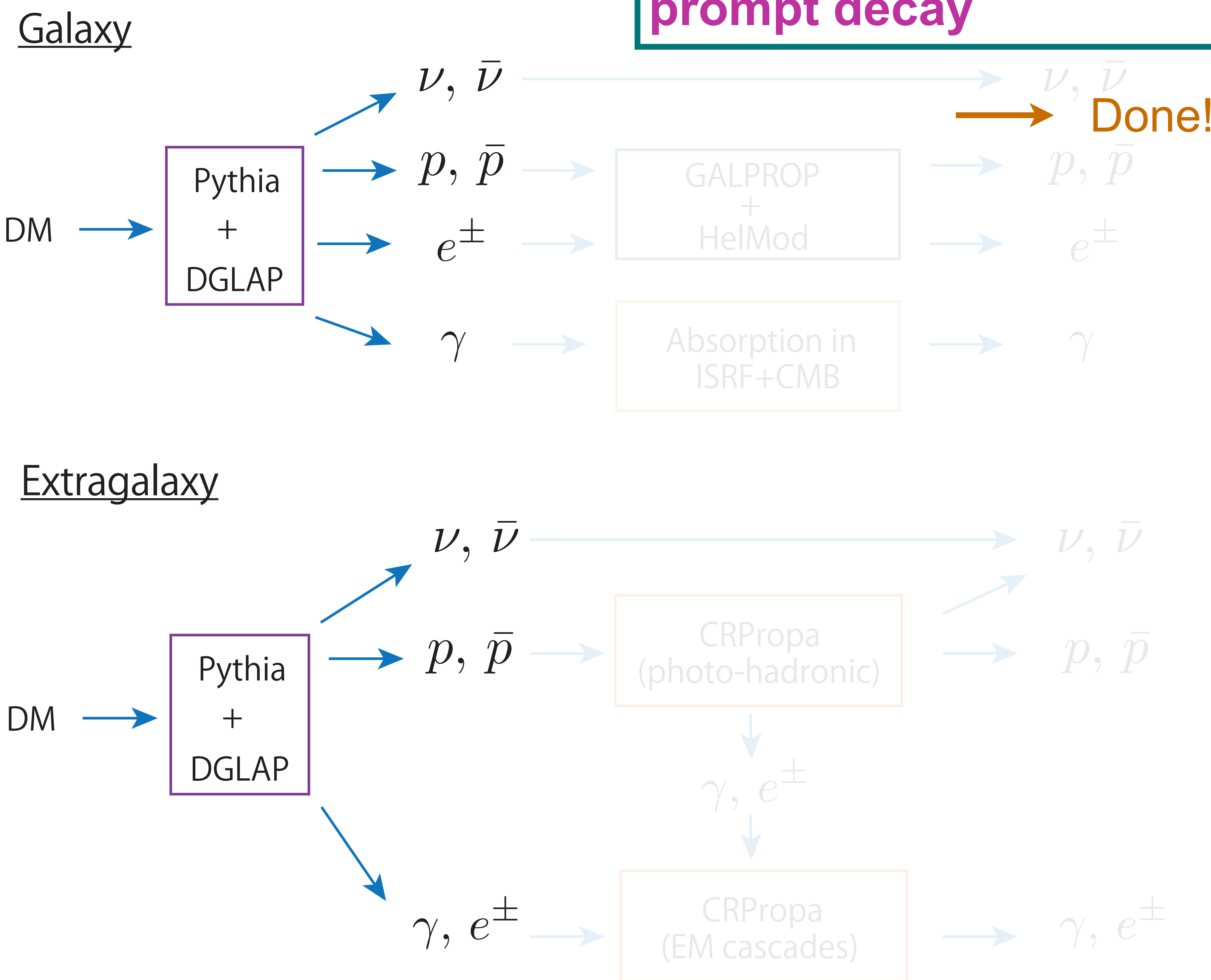

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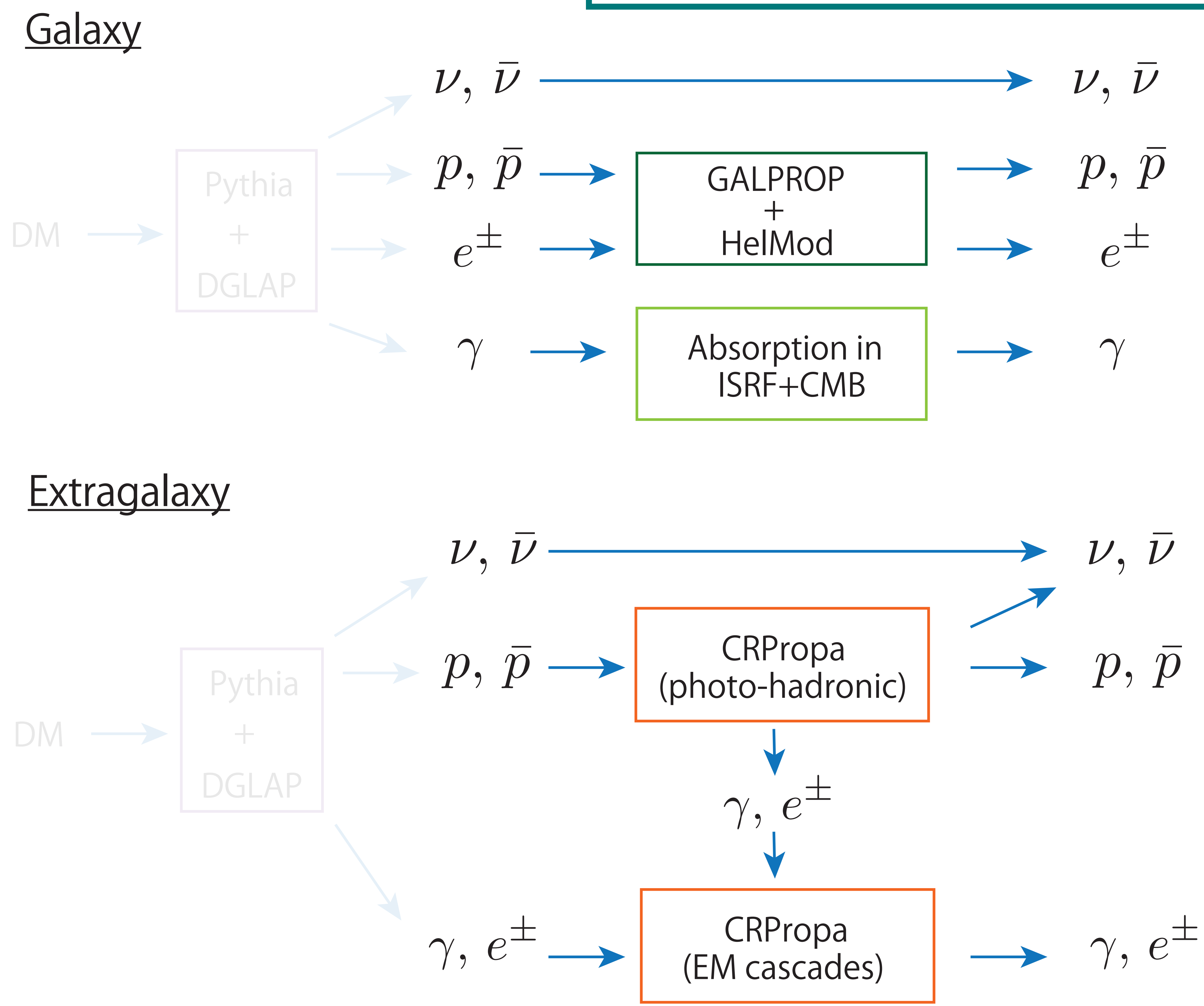

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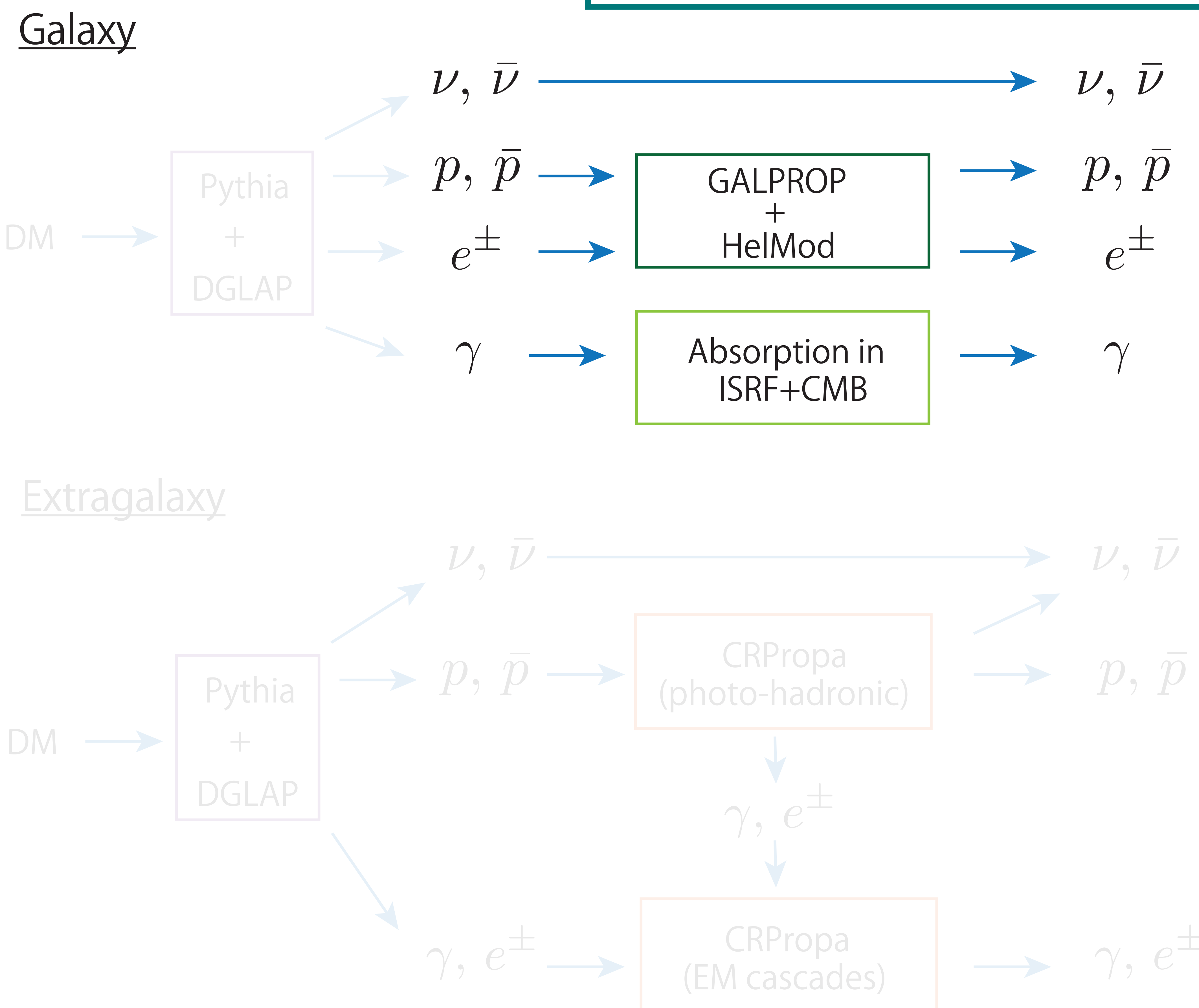
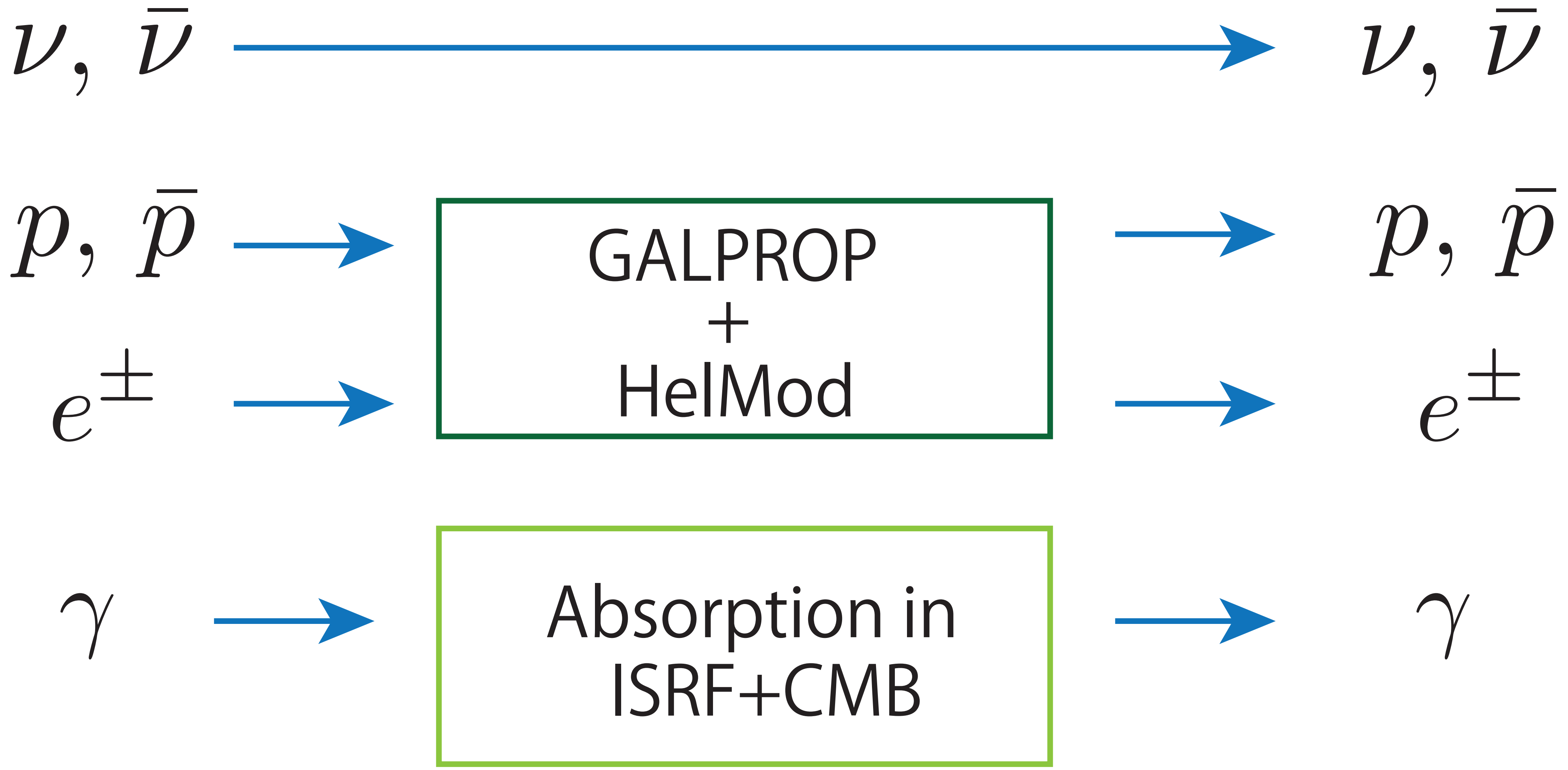


Propagation of CRs in the Galaxy



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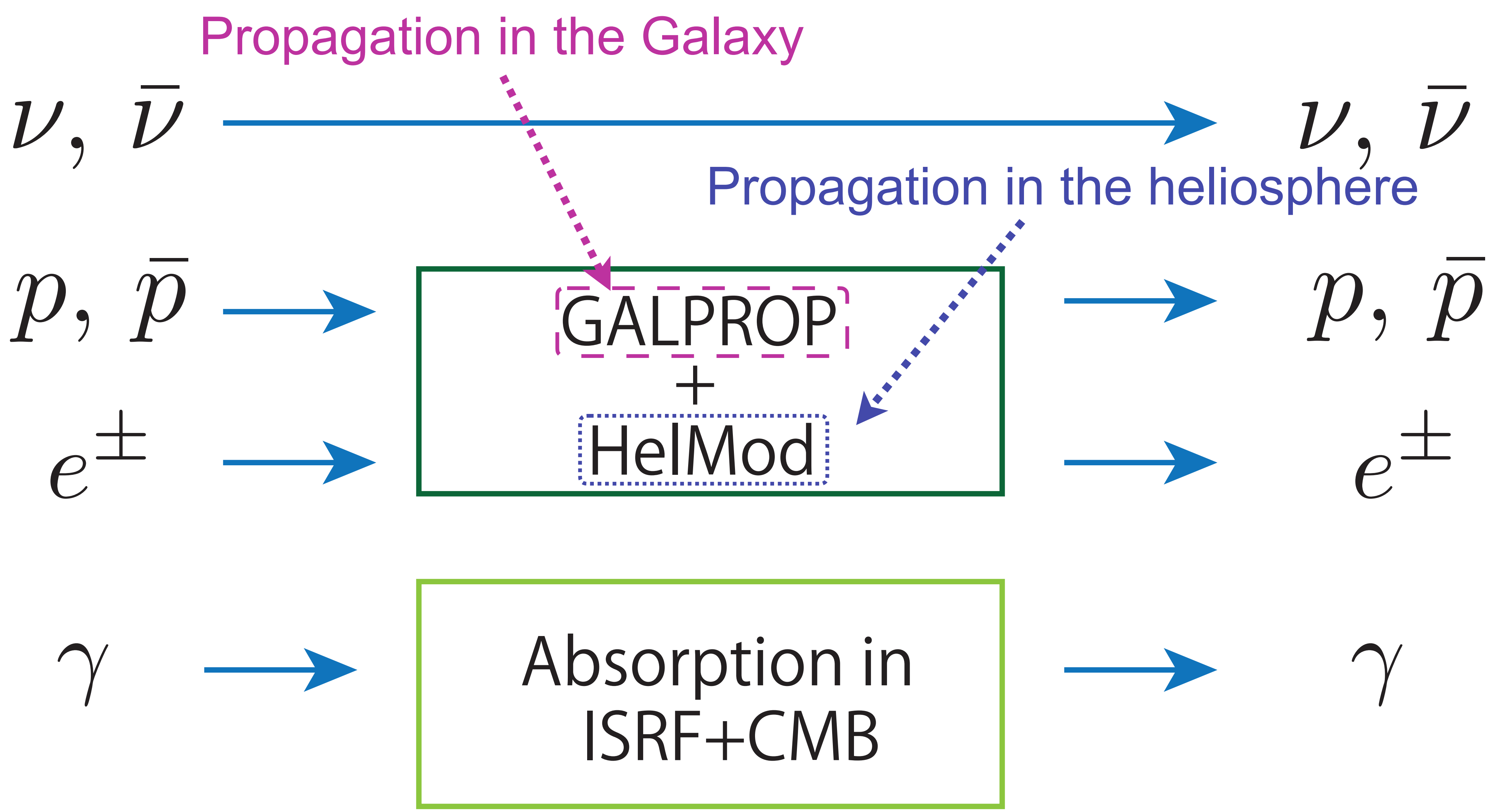

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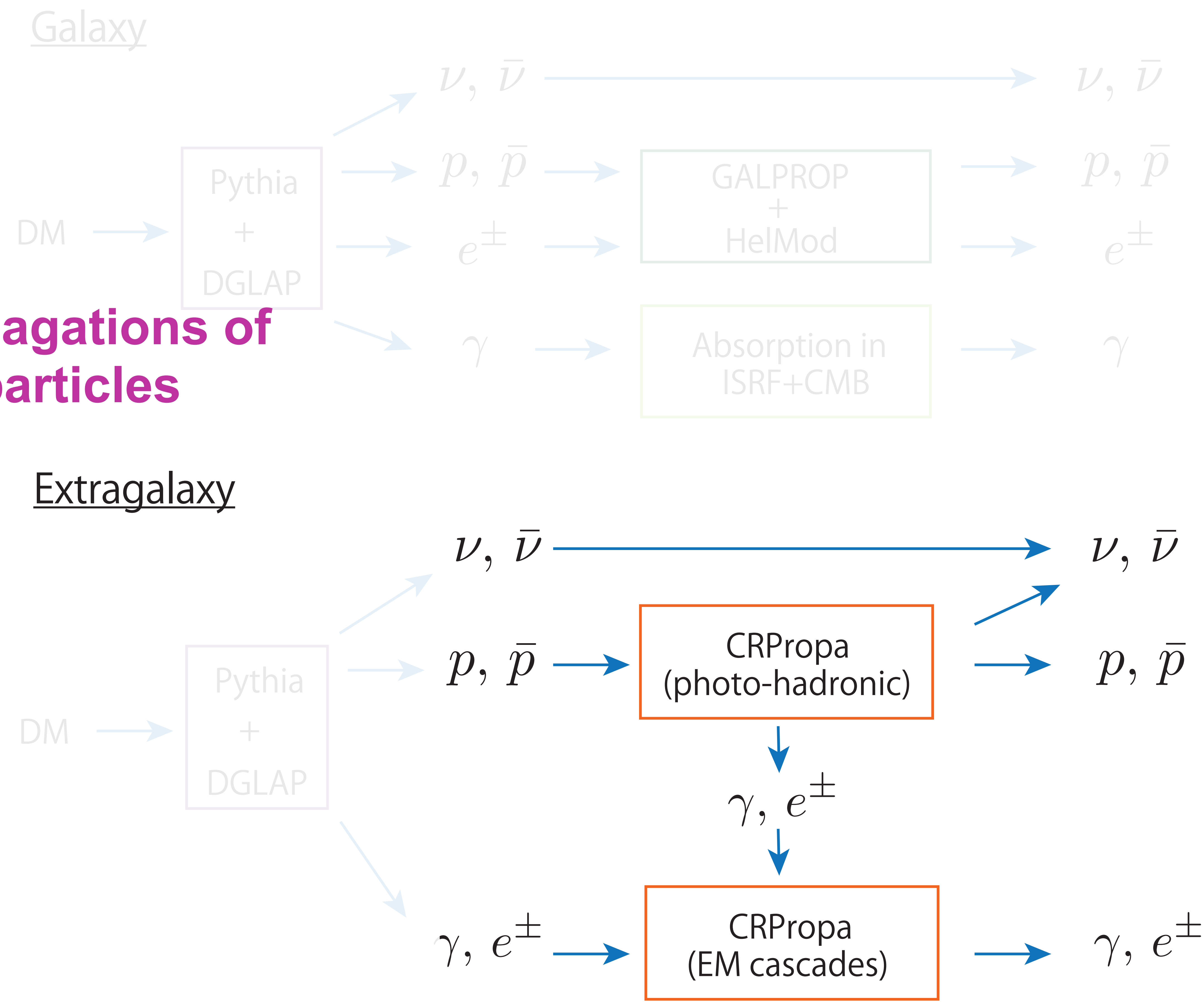

The interactions of CRs in the extragalactic region

Heiter, Kuempel, Walz, Erdmann '17

Initial state	Target field	Process	Secondaries
Nuclei	CBR	Pair production (Bethe-Heitler)	$e^{\pm}$
Nuclei	CBR	Photo-pion production	$p, n, \nu, e^{\pm}, \gamma$
Nuclei	CBR	Photodisintegration	$p, n, d, t, {}^{3}\mathrm{He}, \alpha, \gamma^{*}$
Nuclei	CBR	Elastic scattering*	γ
Nuclei	–	Nuclear decay	$p, n, \nu, e^{\pm}, \gamma^{*}$
Photons	CBR	Pair production* (Breit-Wheeler)	$e^{\pm}$
Photons	CBR	Double pair production*	$e^{\pm}$
Electrons	CBR	Triplet pair production*	$e^{\pm}$
Electrons	CBR	Inverse Compton scattering*	γ
Electrons	B-field	Synchrotron radiation*	γ

The interactions of CRs in the extragalactic region

Photo-hadronic

Heiter, Kuempel, Walz, Erdmann '17

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EM cascades

Photo-hadronic processes

- Photo-pion production

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

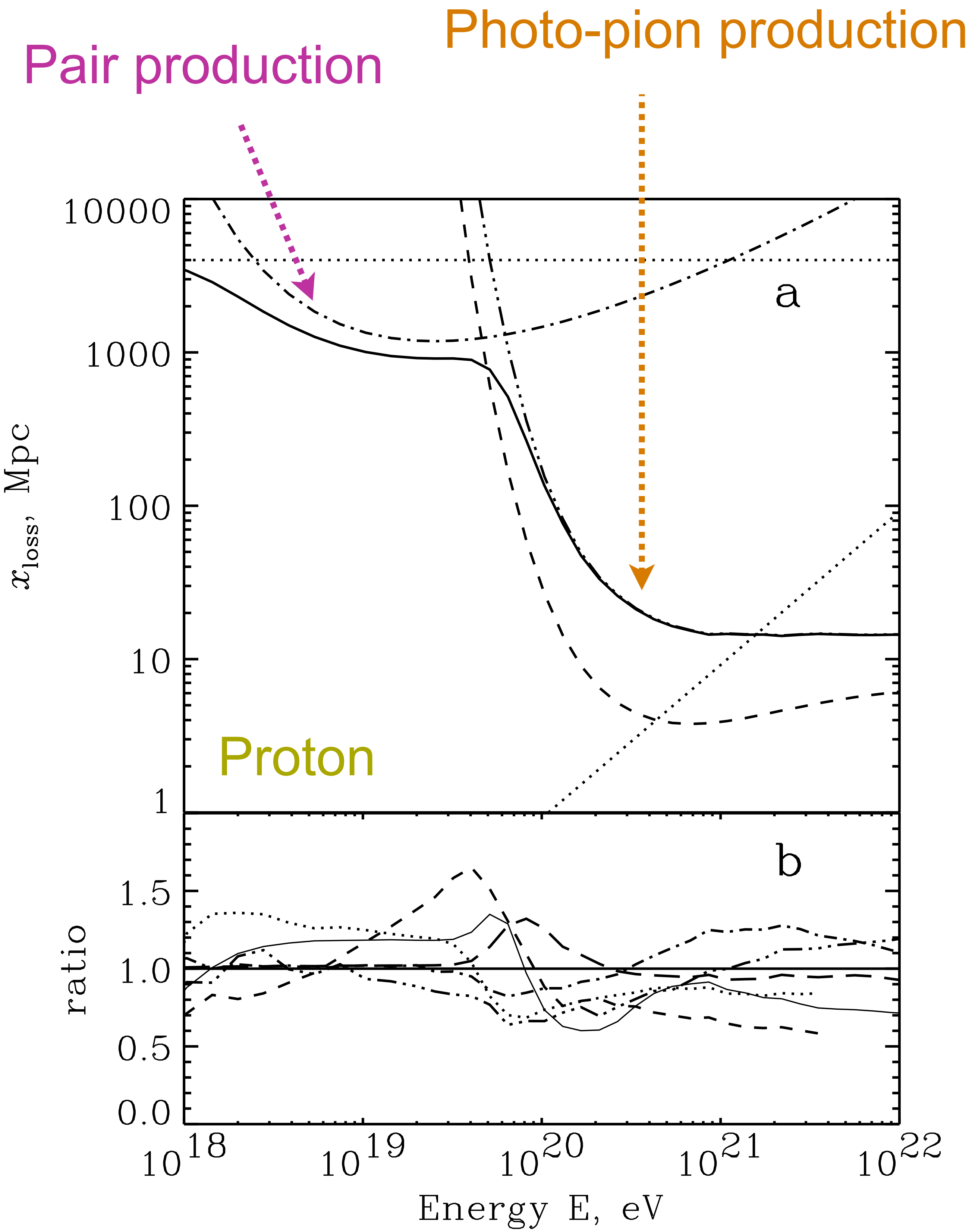
$$E_{\rm th} \sim 6.8 \times 10^{10}\,({\rm meV}/E_{\gamma_{\rm BG}})\,{\rm GeV}$$

- Pair production

$${}^A_Z X + \gamma_{\rm BG} \to {}^A_Z X + e^+ + e^-$$

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

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



Stanev, Engel, Mücke, Protheroe, Rachen '00

Photo-hadronic processes

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

- Photo-pion production

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

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

$\lambda \sim 1$ Mpc

- Pair production

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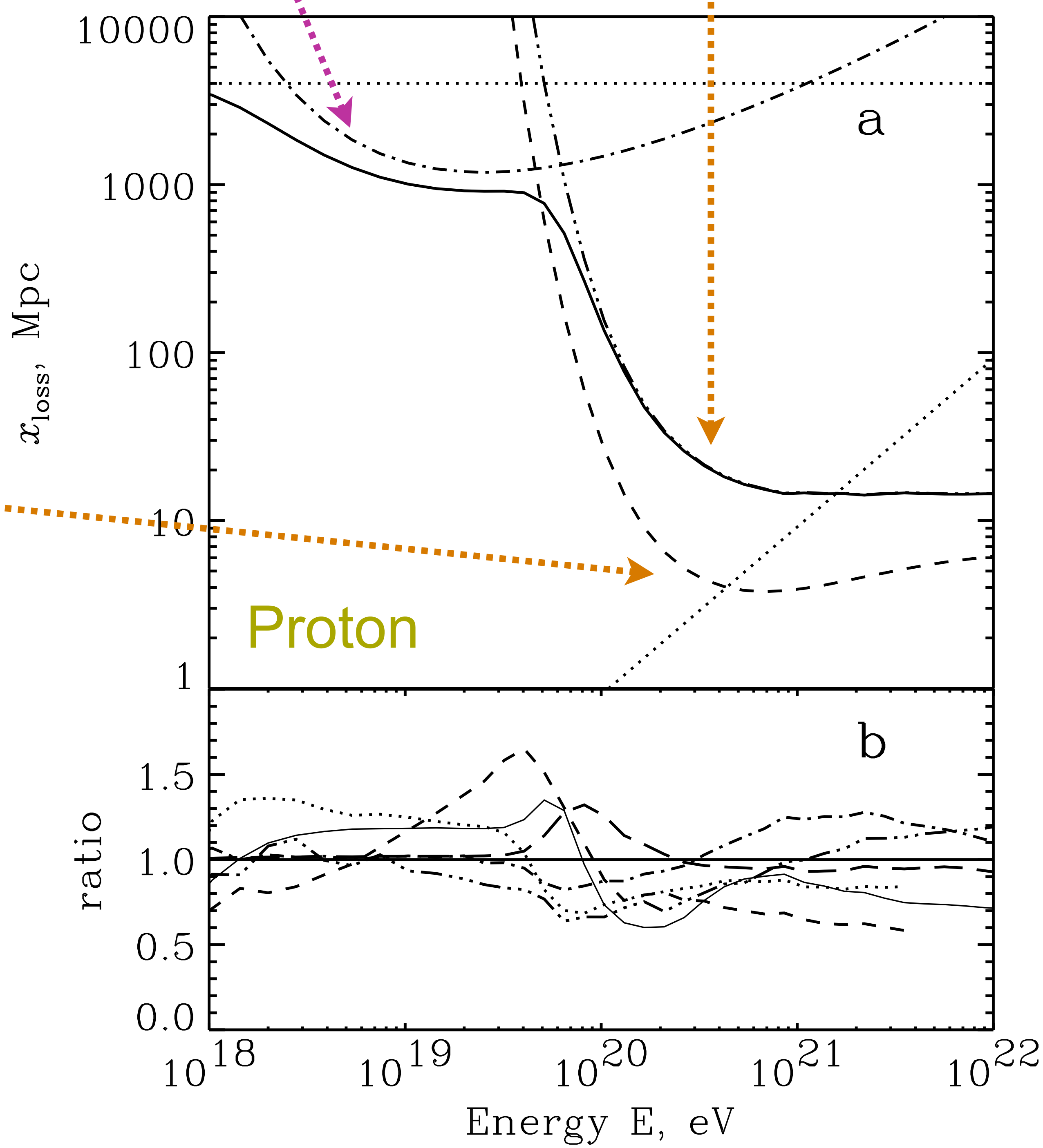
Pair production

Photo-pion production



Stanev, Engel, Mücke, Protheroe, Rachen '00

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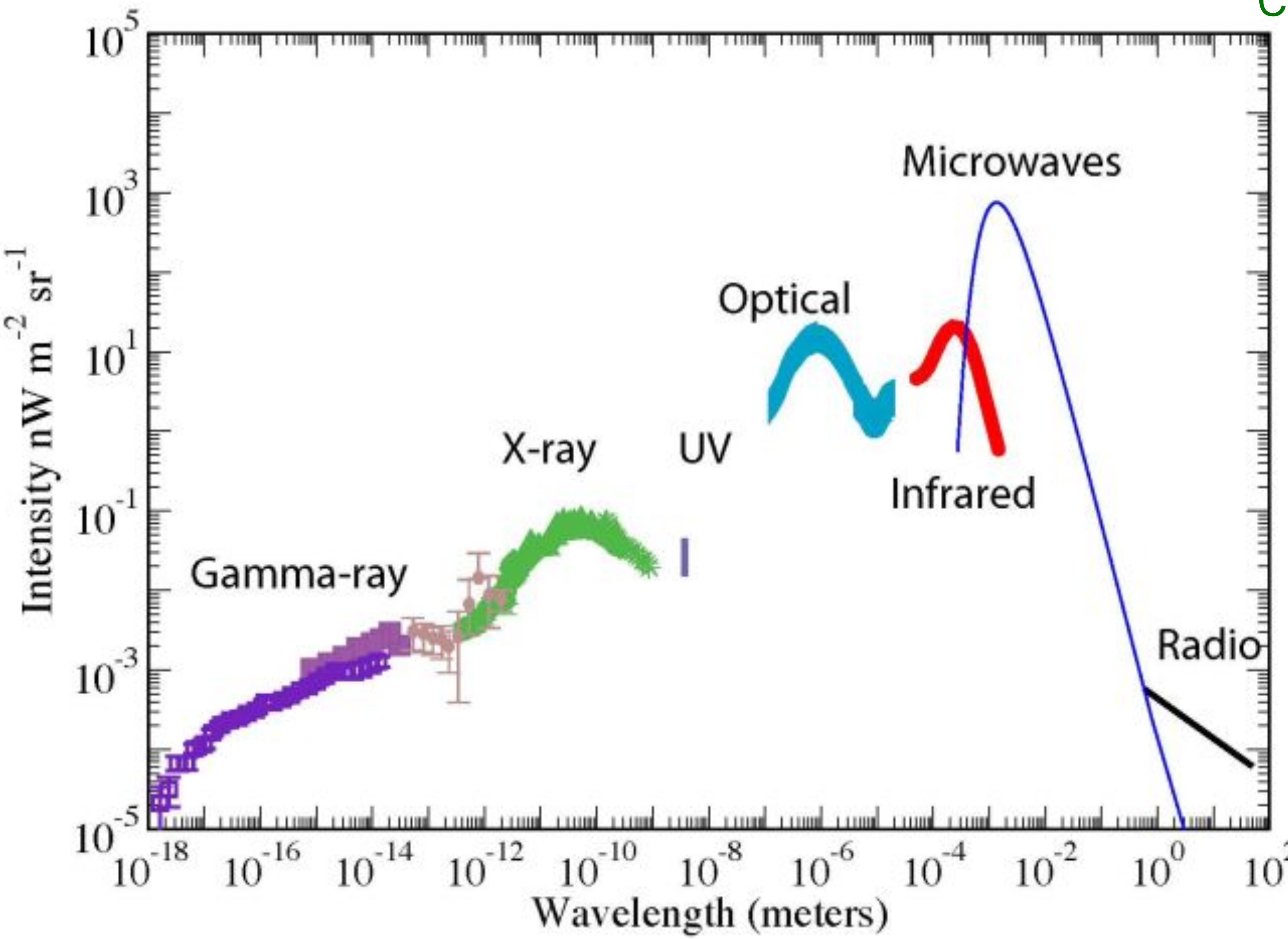
Electrons	CBR	Triplet pair production*	$e^{\pm}$
Electrons	CBR	Inverse Compton scattering*	γ
Electrons	B-field	Synchrotron radiation*	γ

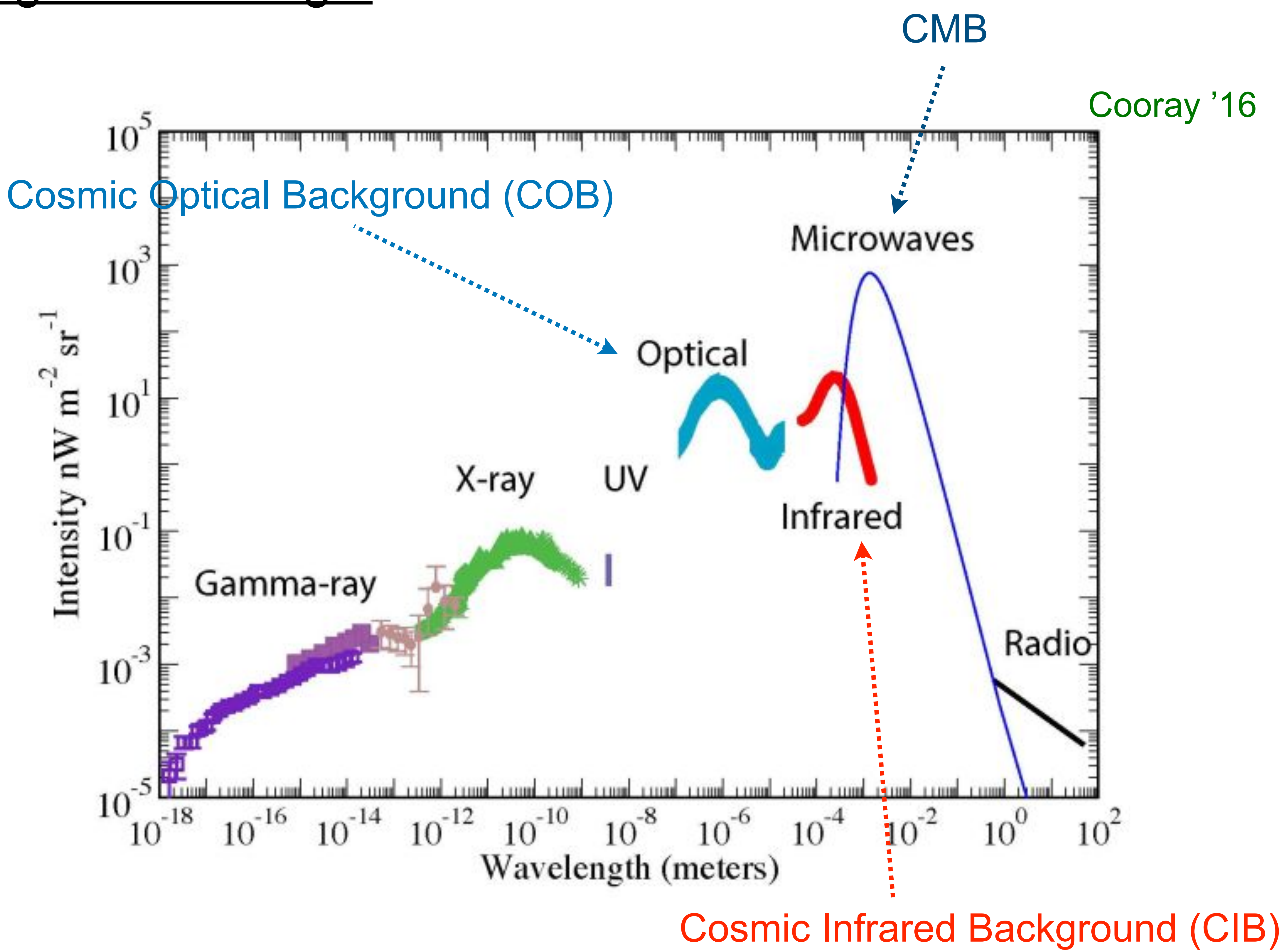
EM cascades

Extragalactic BG light

Cooray '16



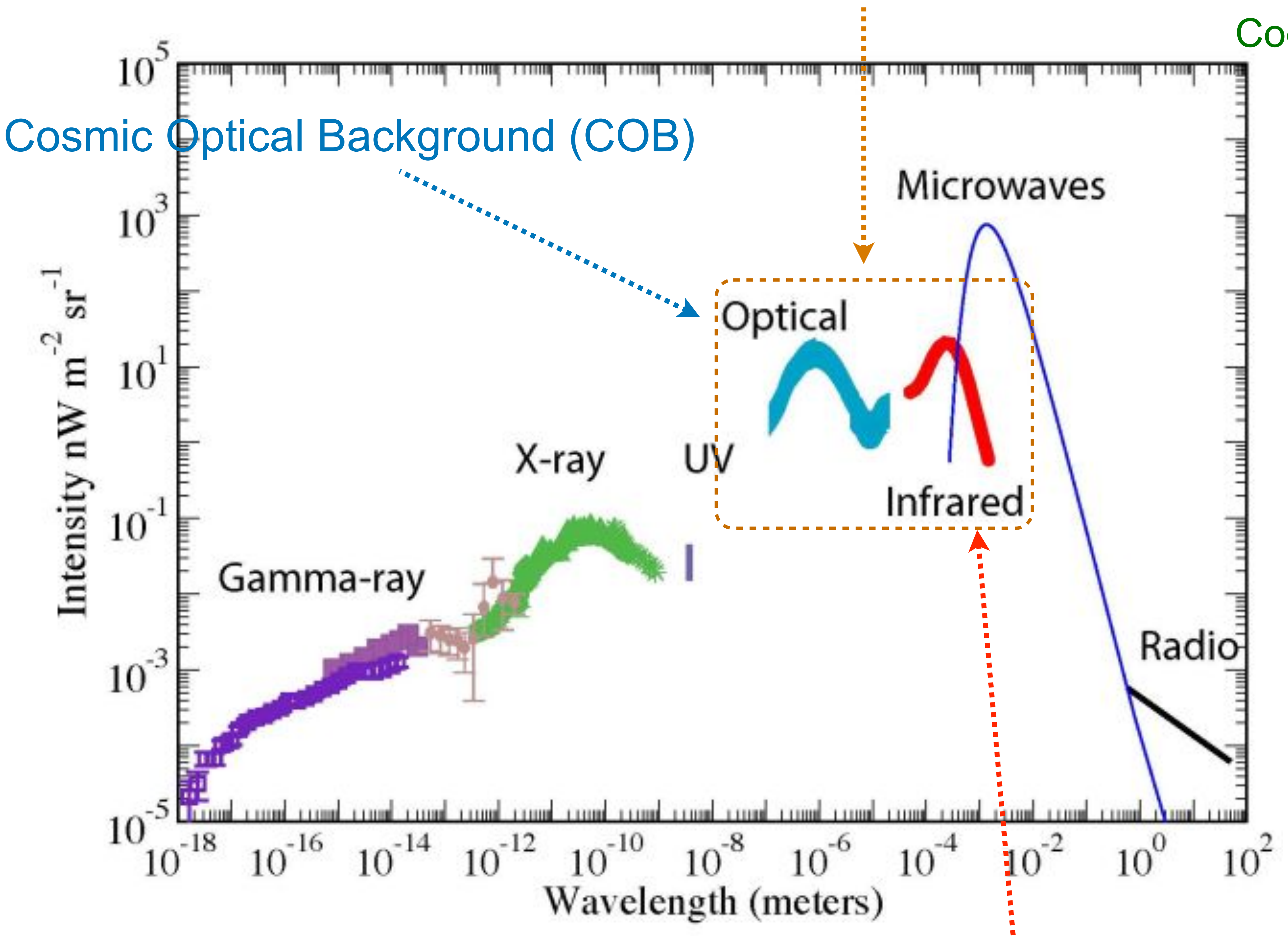
Extragalactic BG light



Extragalactic BG light

Extragalactic Background Light (EBL)
or
Infrared and optical background (IRB)

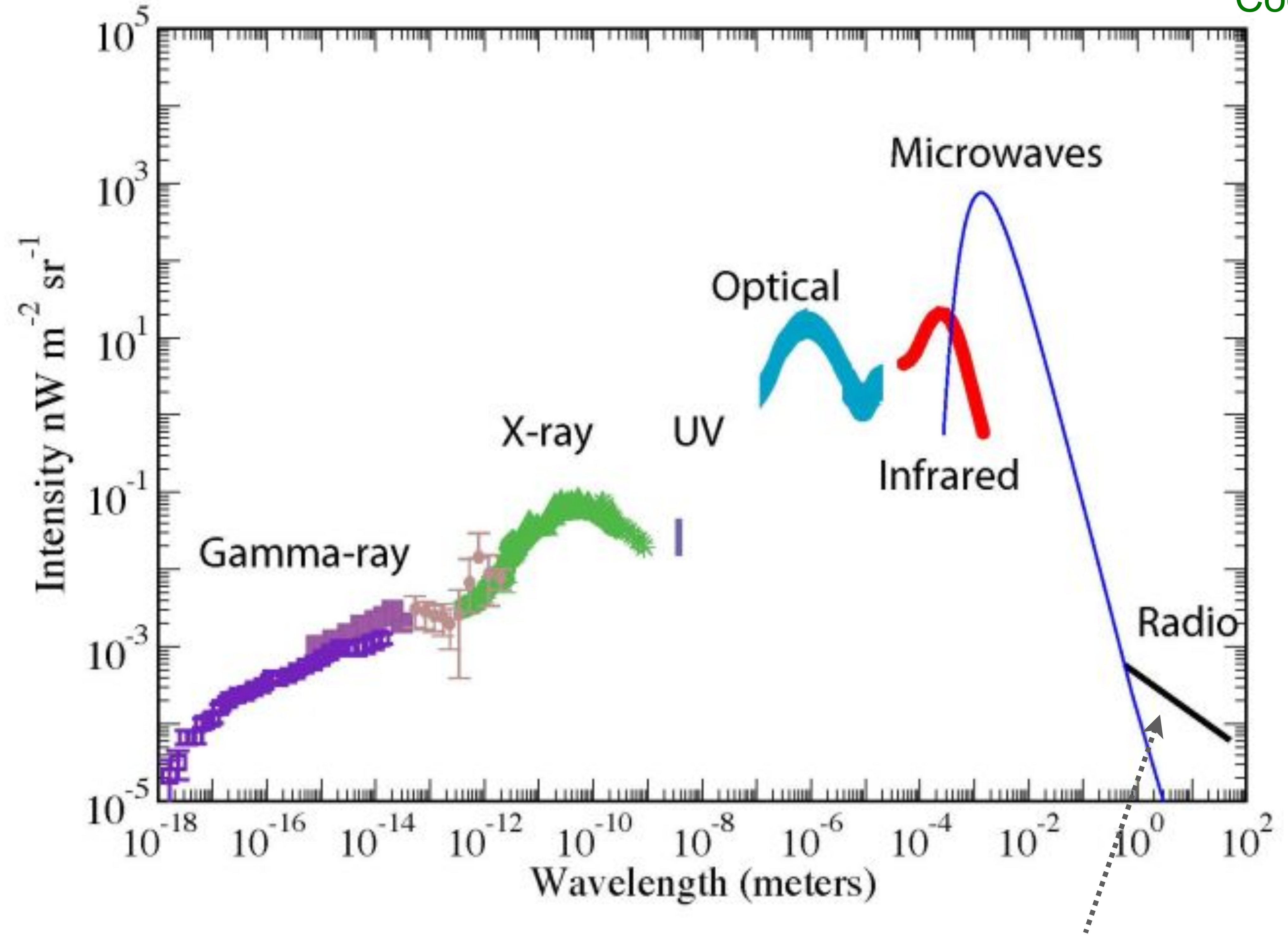
Cooray '16



Cosmic Infrared Background (CIB)

Extragalactic BG light

Cooray '16



(Universal) Radio Background (URB)

EM cascades

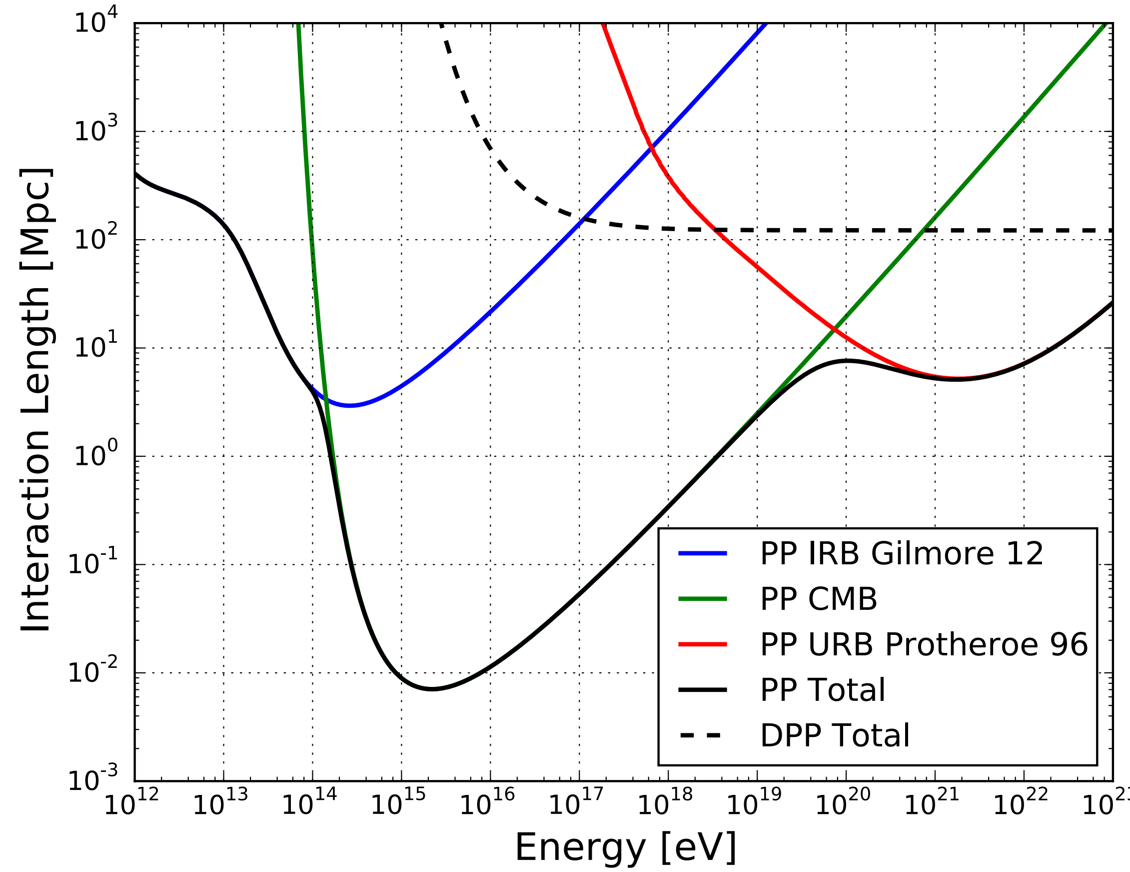
Heiter, Kuempel, Walz, Erdmann '17

- Pair production (PP)

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

- Double pair production (DPP)

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

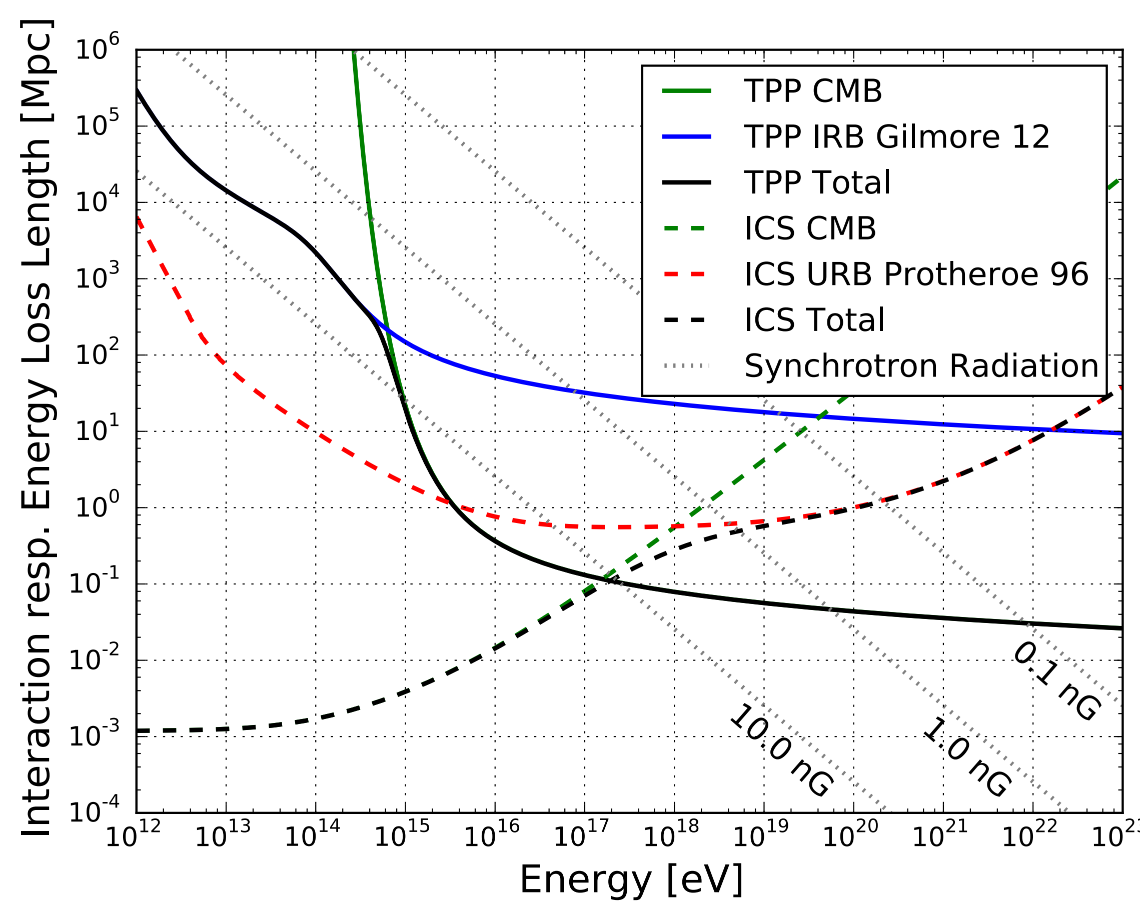


- Triple pair production (TPP)

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

- Inverse Compton scattering (ICS)

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



EM cascades

Heiter, Kuempel, Walz, Erdmann '17

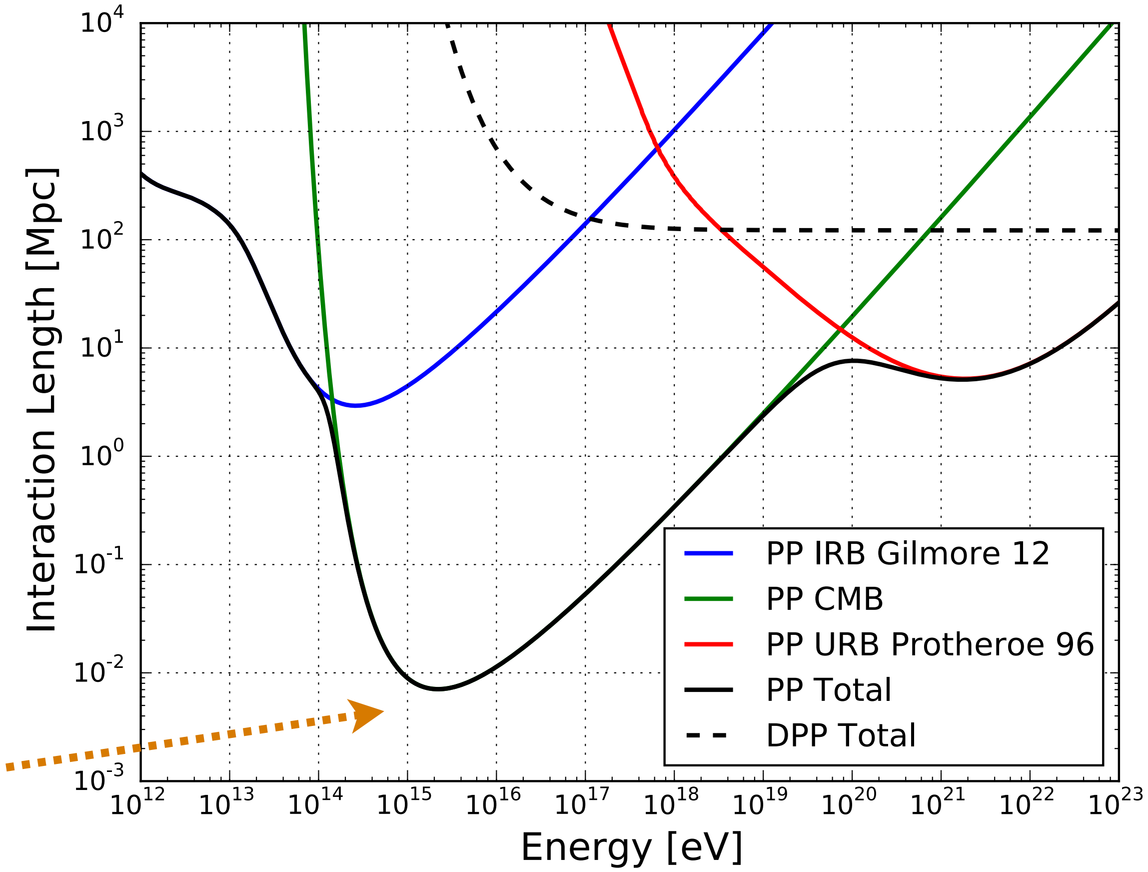
- Pair production (PP)

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

- Double pair production (DPP)

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

$\lambda \sim 1$ kpc

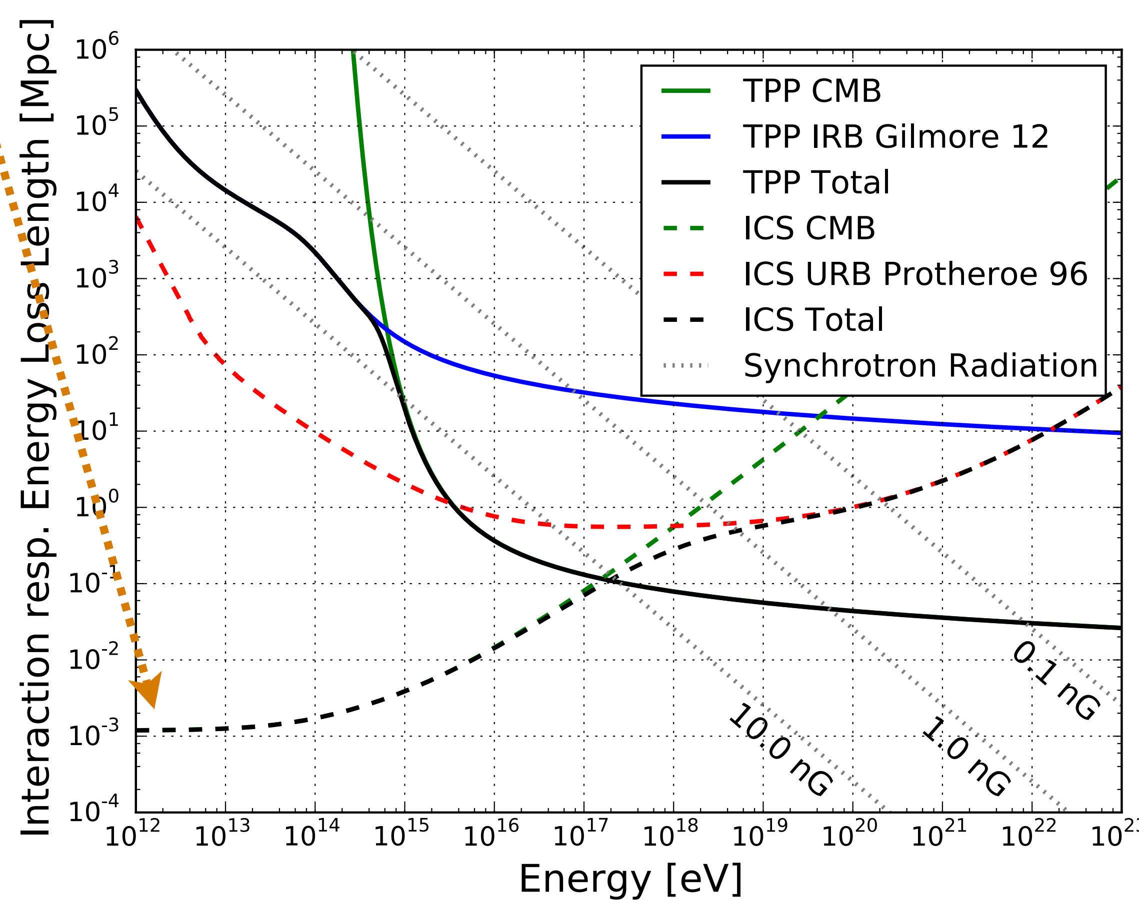


- Triple pair production (TPP)

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

- Inverse Compton scattering (ICS)

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



EM cascades

Heiter, Kuempel, Walz, Erdmann ’17

- Pair production (PP)

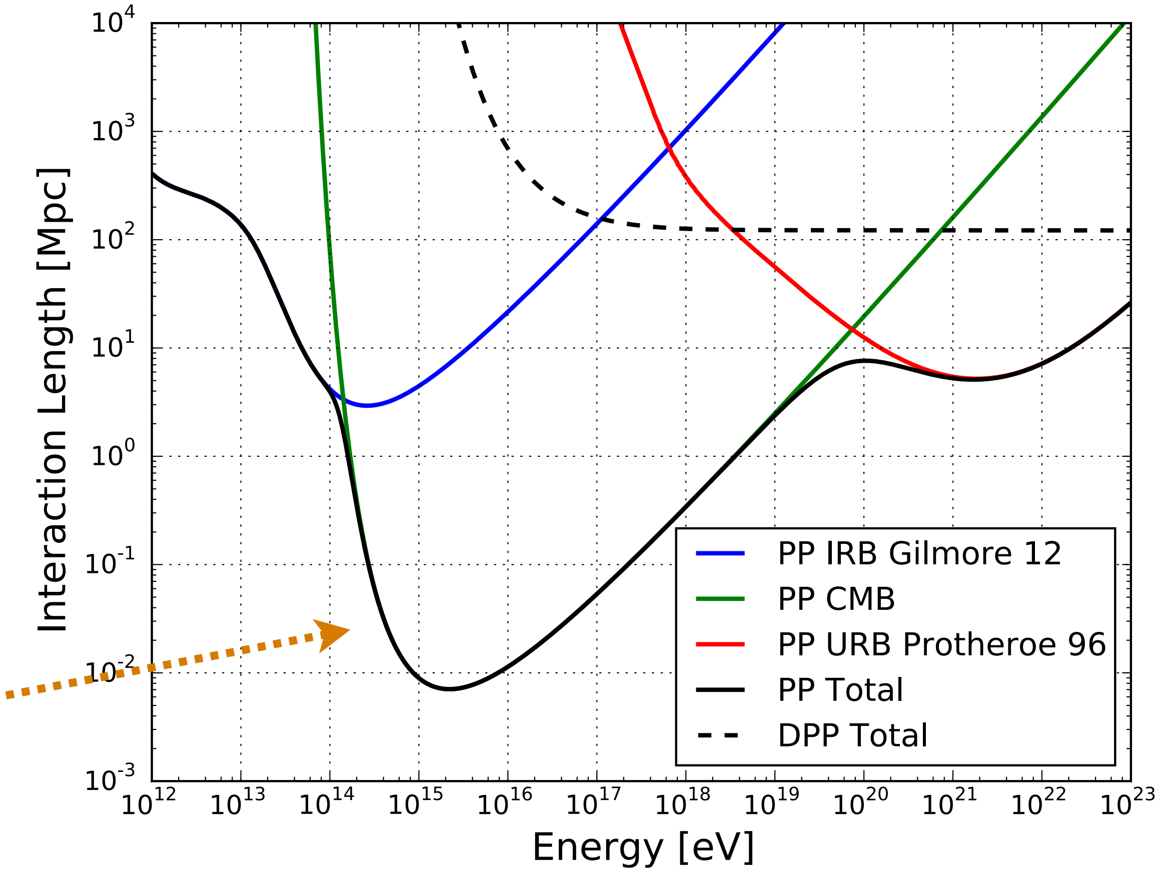
$$\gamma + \gamma_{\mathrm{BG}} \rightarrow e^+ + e^-$$

- 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)

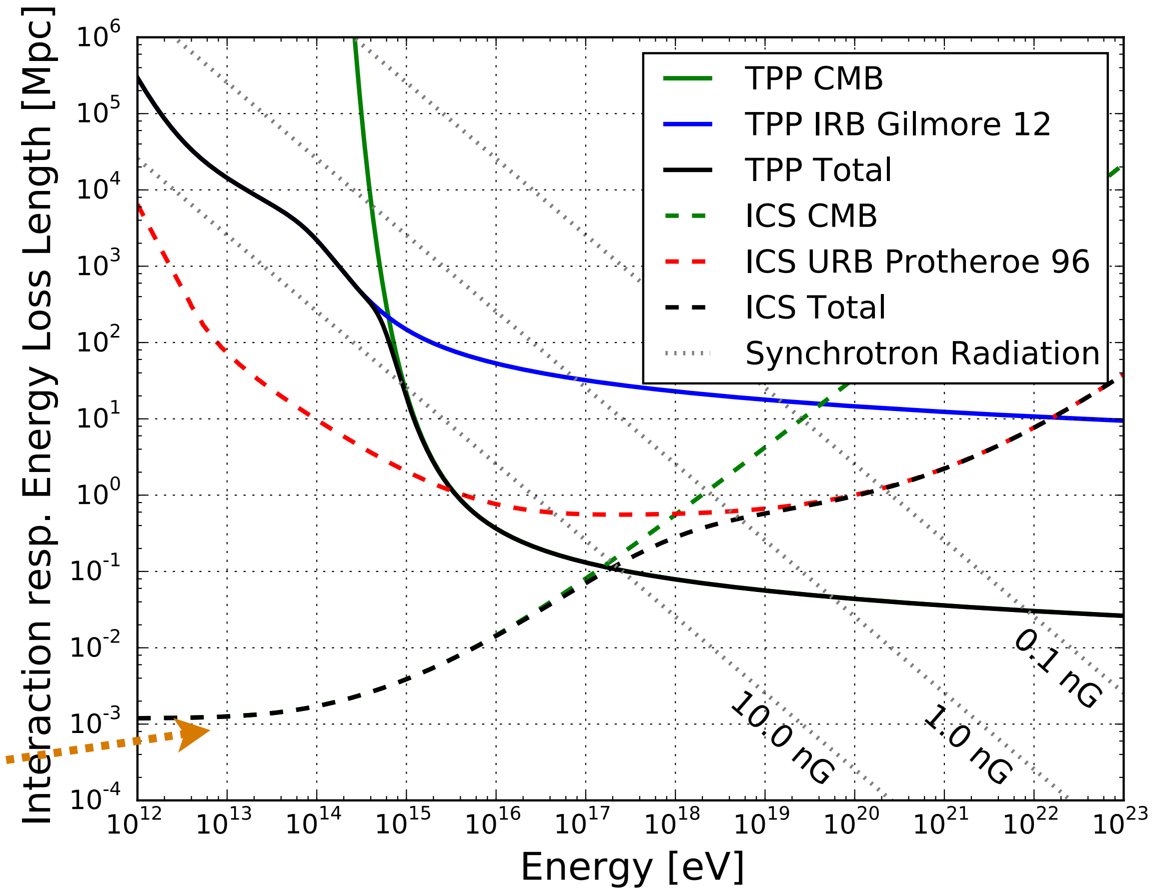
$$e + \gamma_{\mathrm{BG}} \rightarrow e + e^+ + e^-$$

- Inverse Compton scattering (ICS)

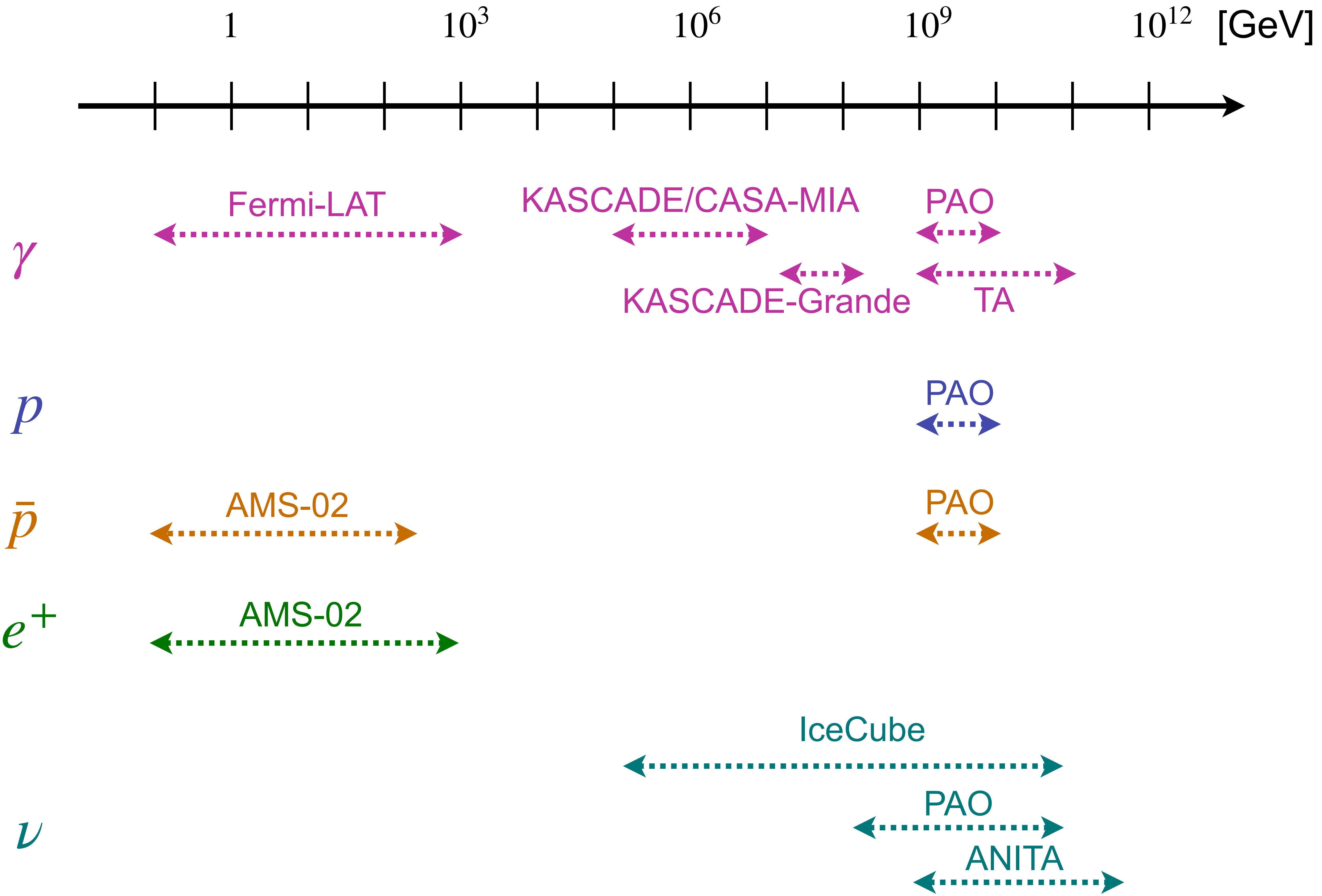
$$e + \gamma_{\mathrm{BG}} \rightarrow e + \gamma$$

ICS in the CMB is dominant

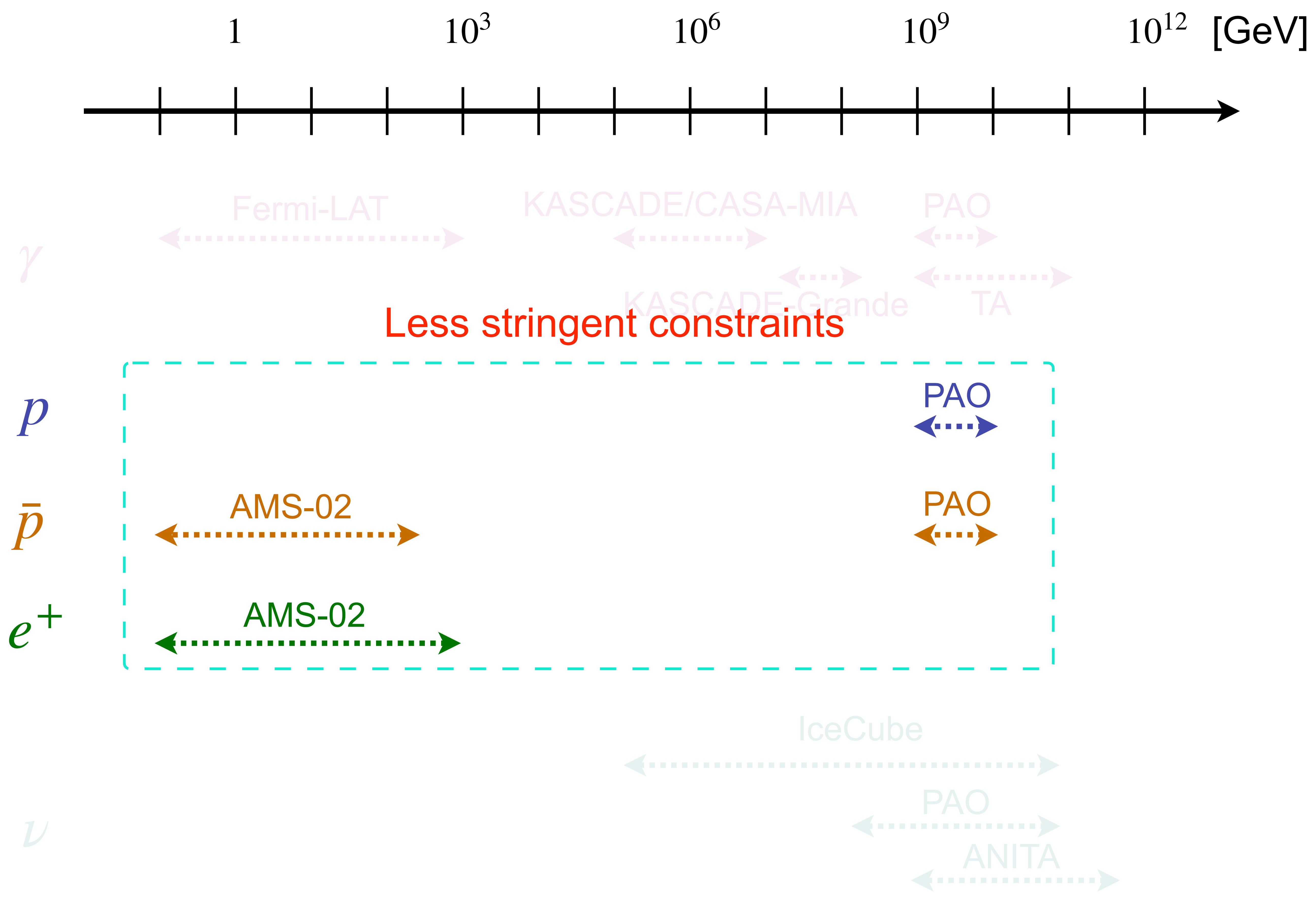
$(E_e \lesssim 10^8\,\mathrm{GeV})$

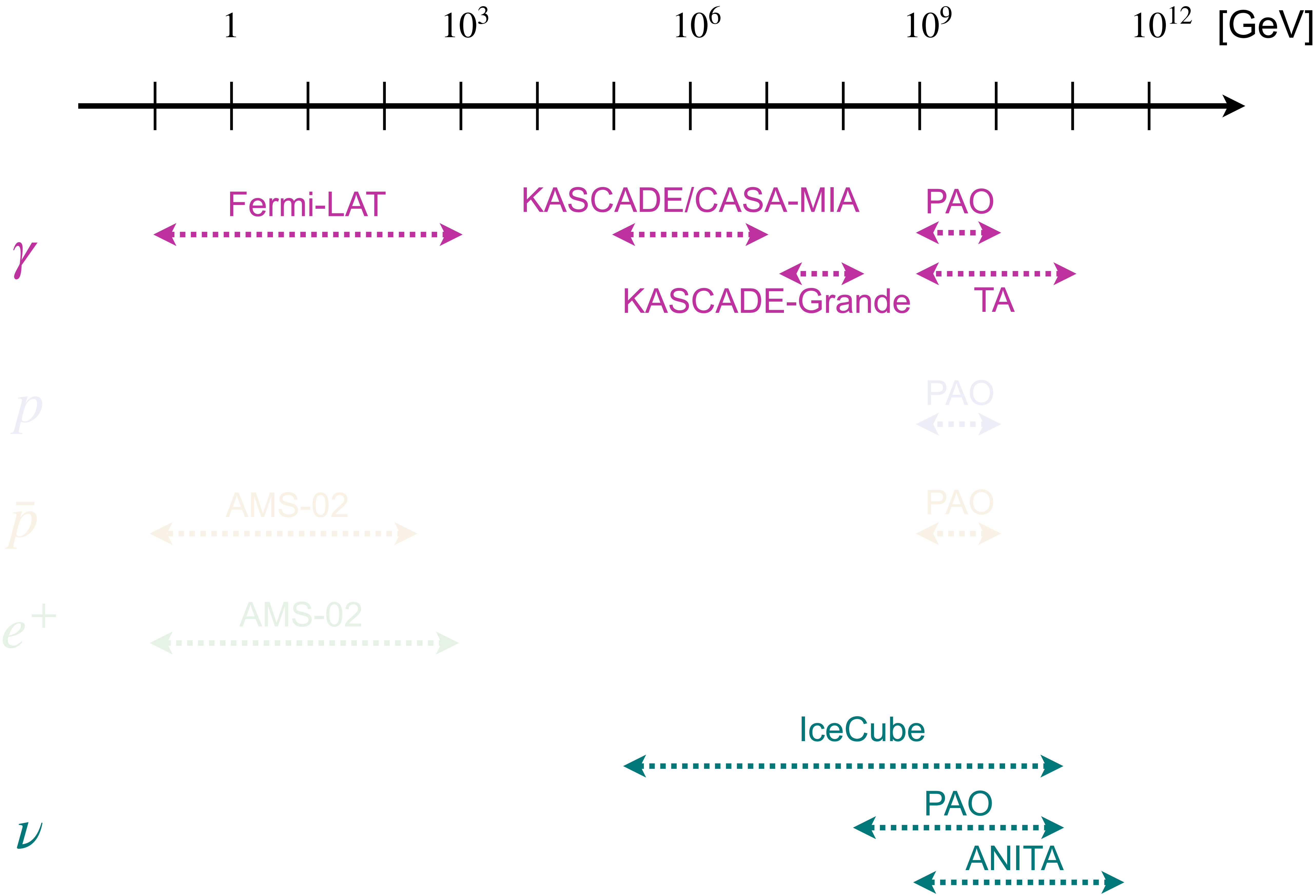


3. Numerical results



1
10^3
10^6
10^9
10^12
[GeV]
γ
Fermi-LAT
KASCADE/CASA-MIA
PAO
KASCADE-Grande
TA
p
PAO
p̄
AMS-02
PAO
e+
AMS-02
IceCube
ν
PAO
ANITA


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



1
10^3
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Fermi-LAT
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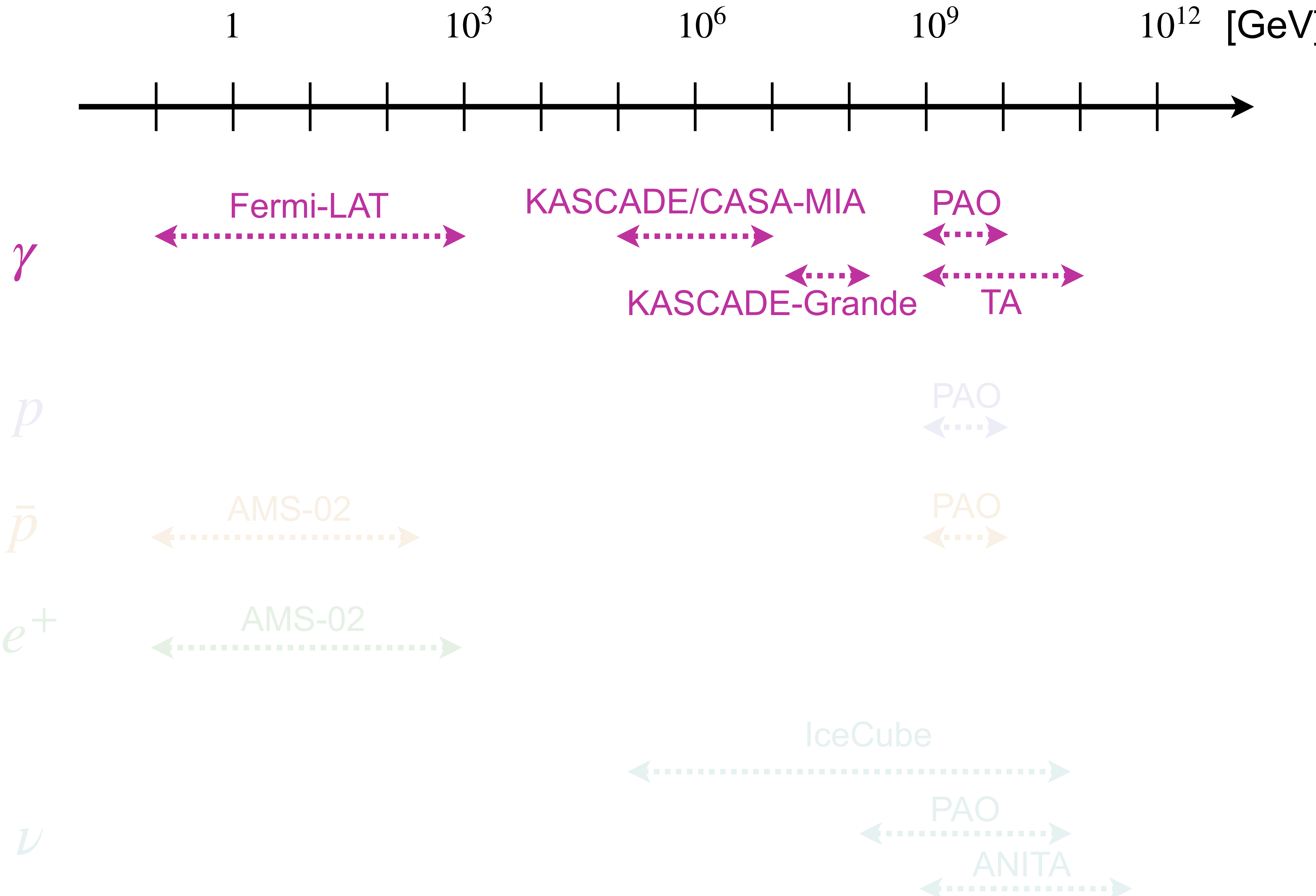
1
10^3
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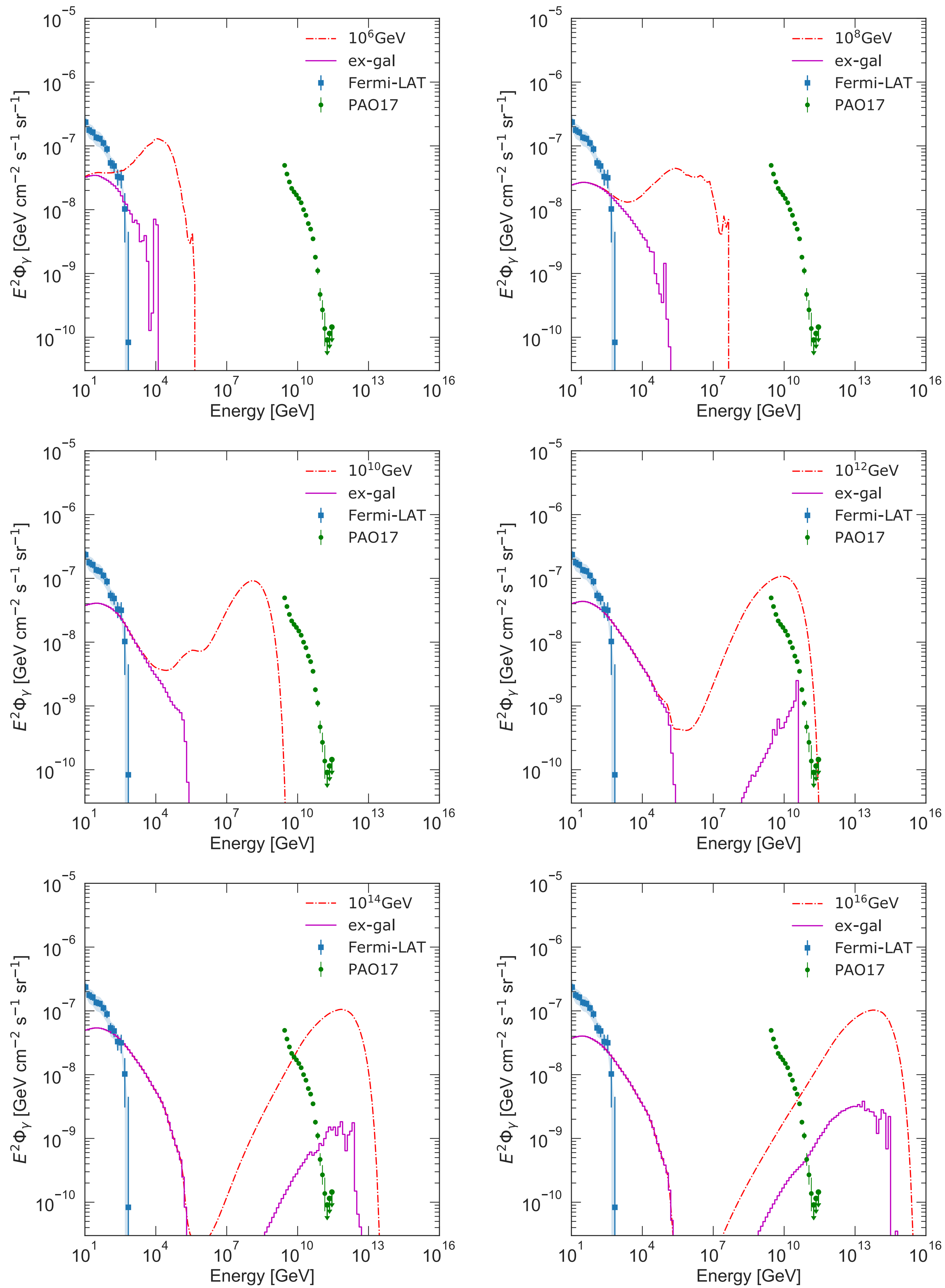
ν

γ flux

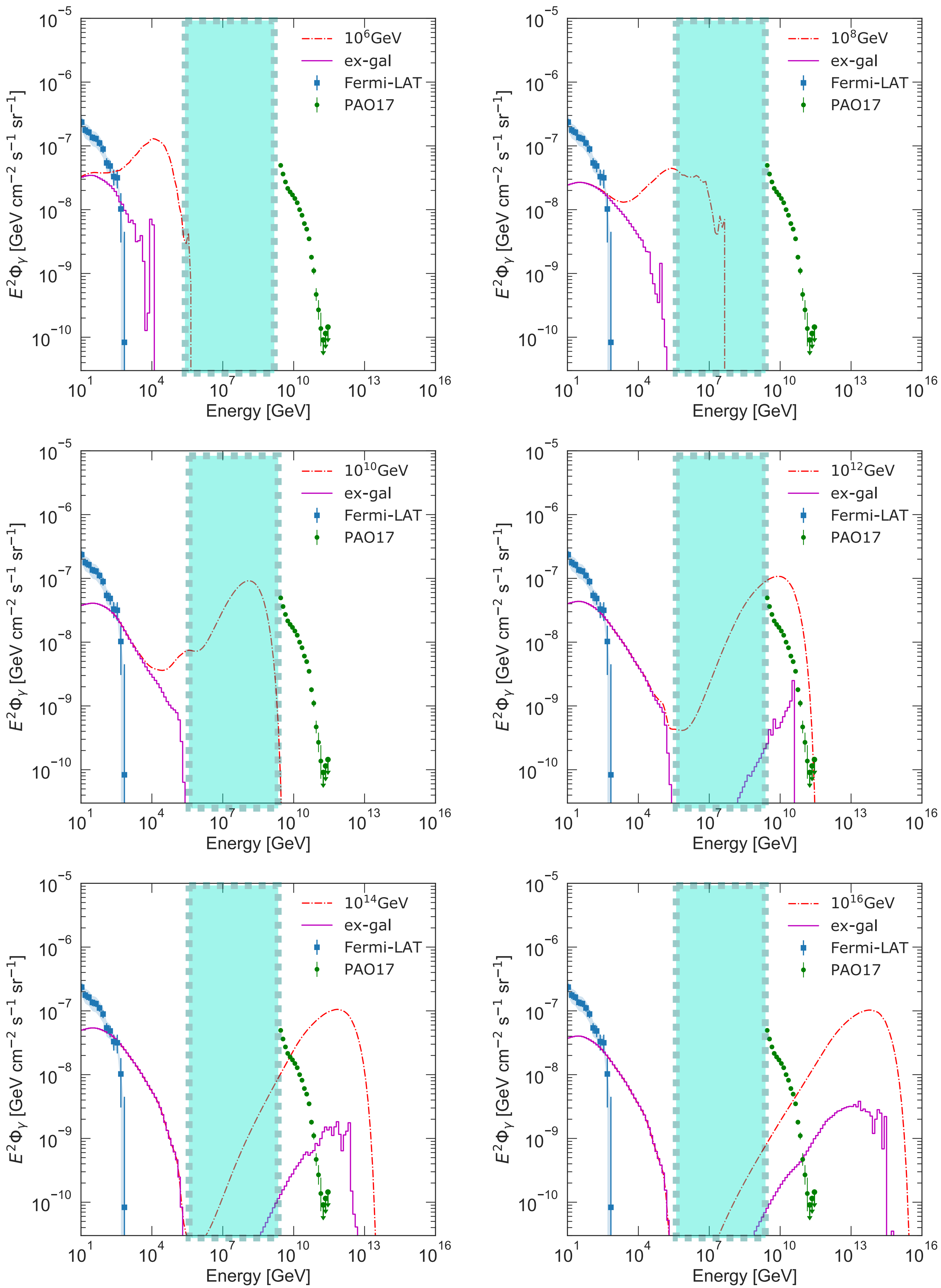
$\tau_{\rm dm} = 10^{27}\,{\rm s}$



γ flux

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

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

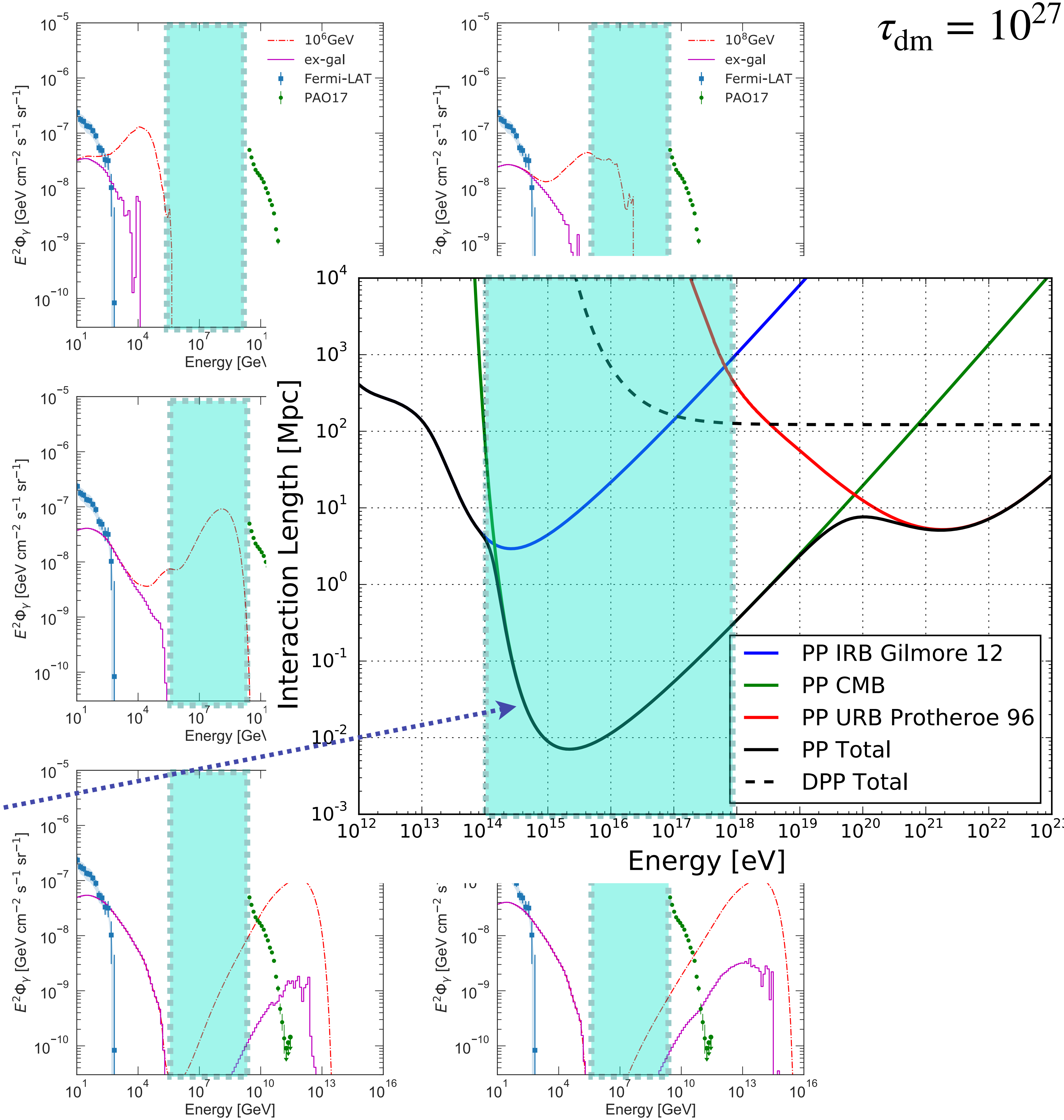


γ flux

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

Extragalactic γ in $10^5\,\mathrm{GeV} \lesssim E_\gamma \lesssim 10^9\,\mathrm{GeV}$ is suppressed

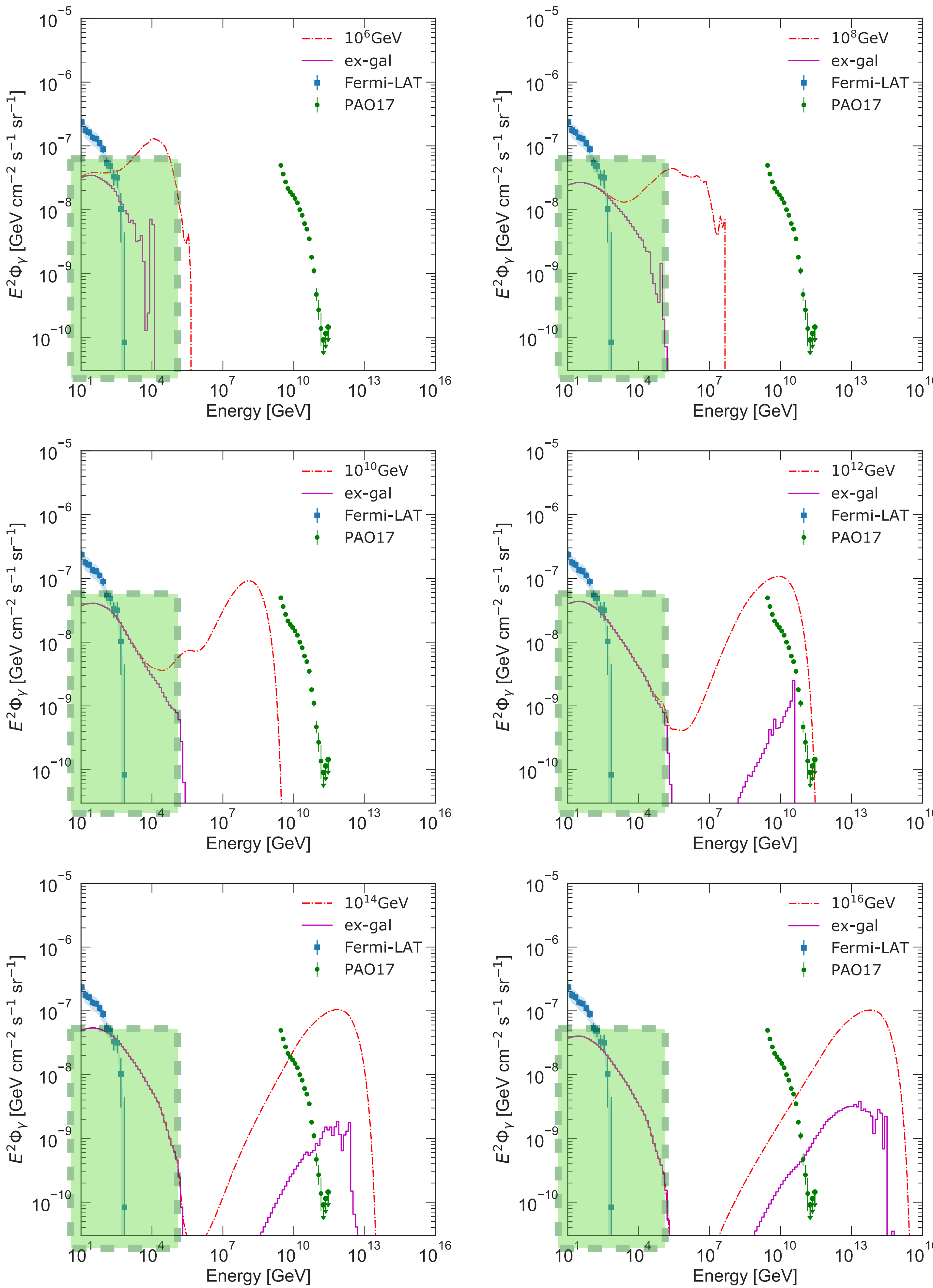
Due to the PP in the CMB



γ flux

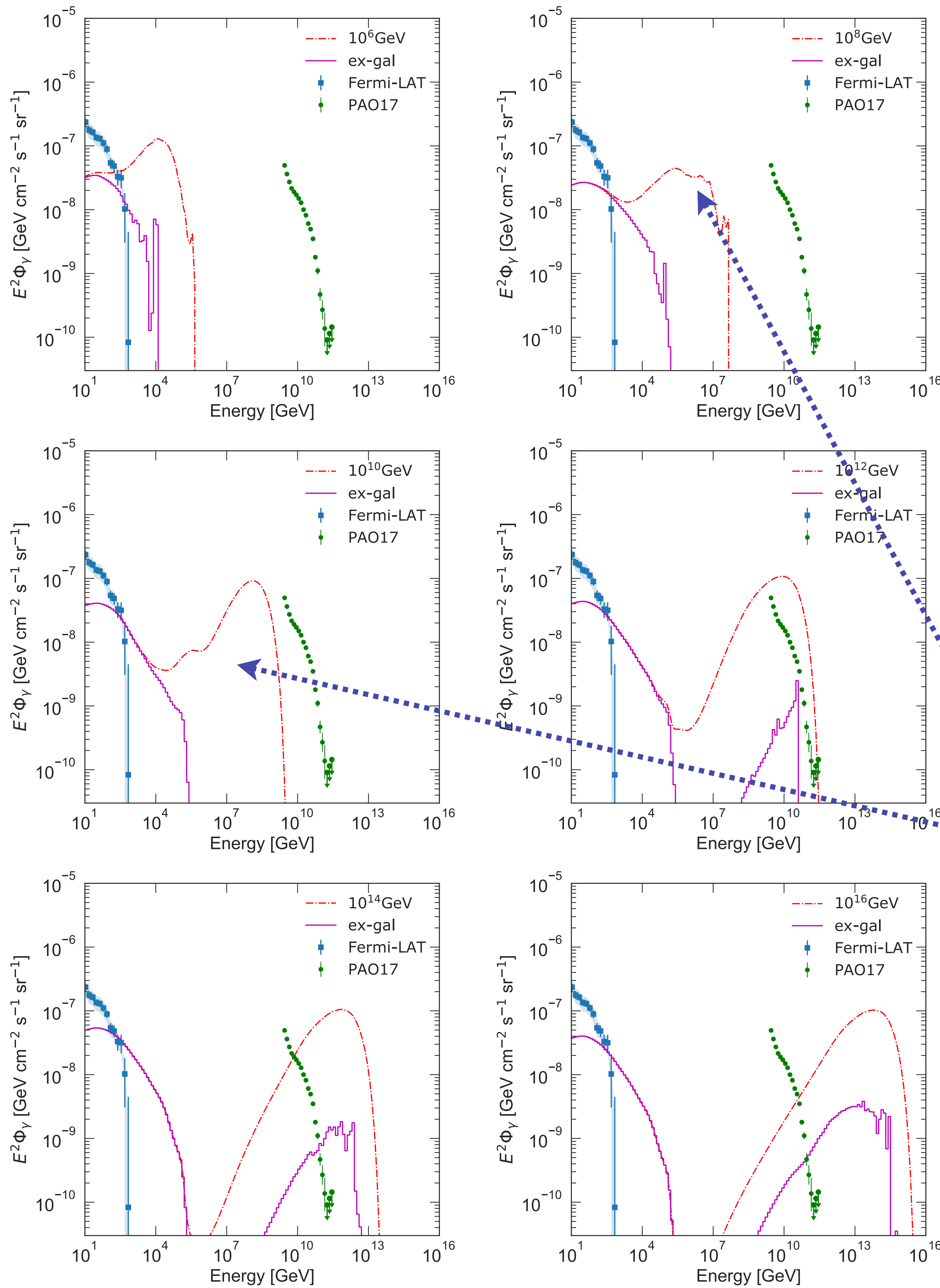
$\tau_{\mathrm{dm}} = 10^{27}\,\mathrm{s}$

Lots of flux in TeV region due to the EM cascades



γ flux

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

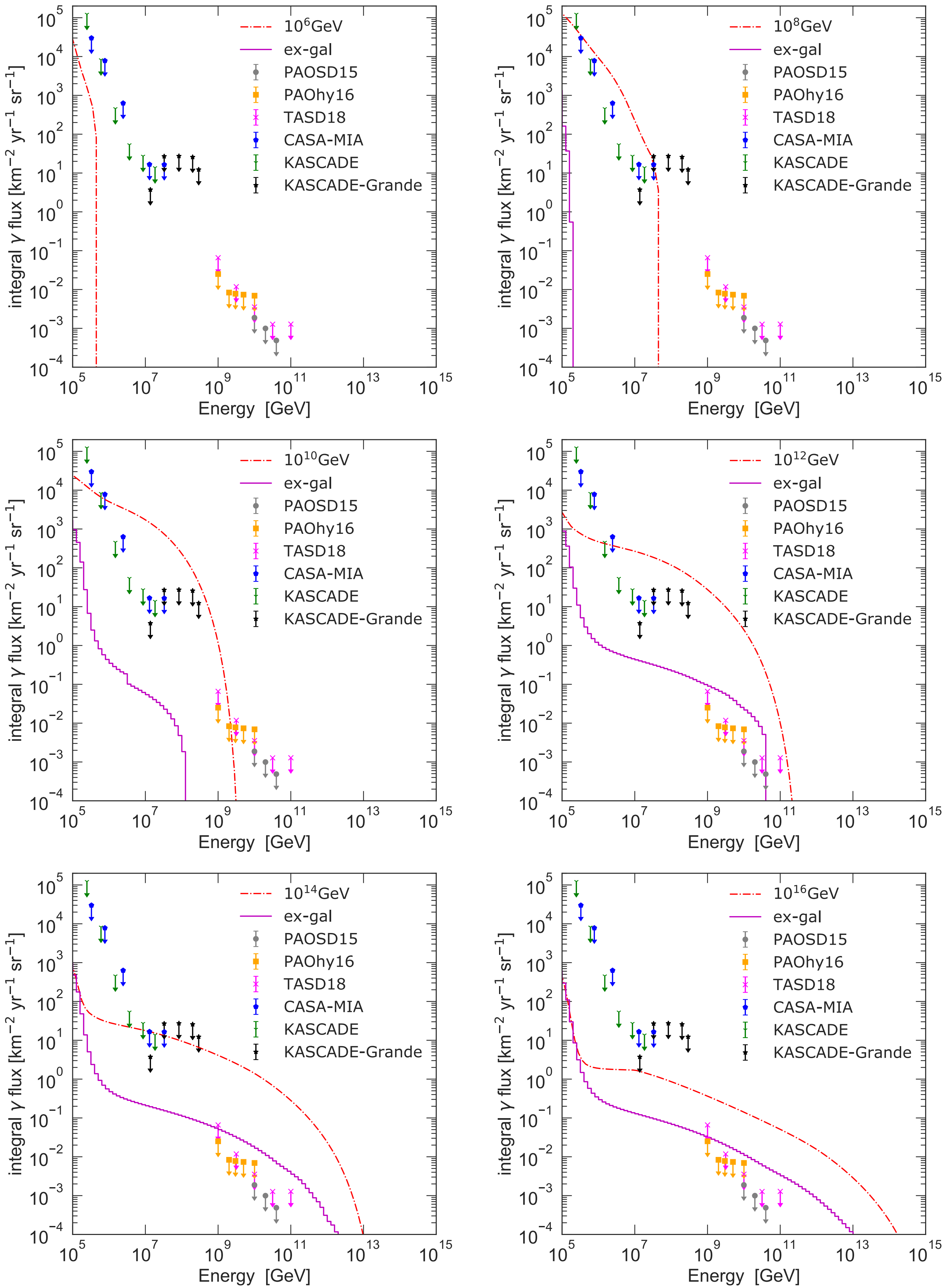


Galactic flux is dominant in high energy region for large m_{dm}

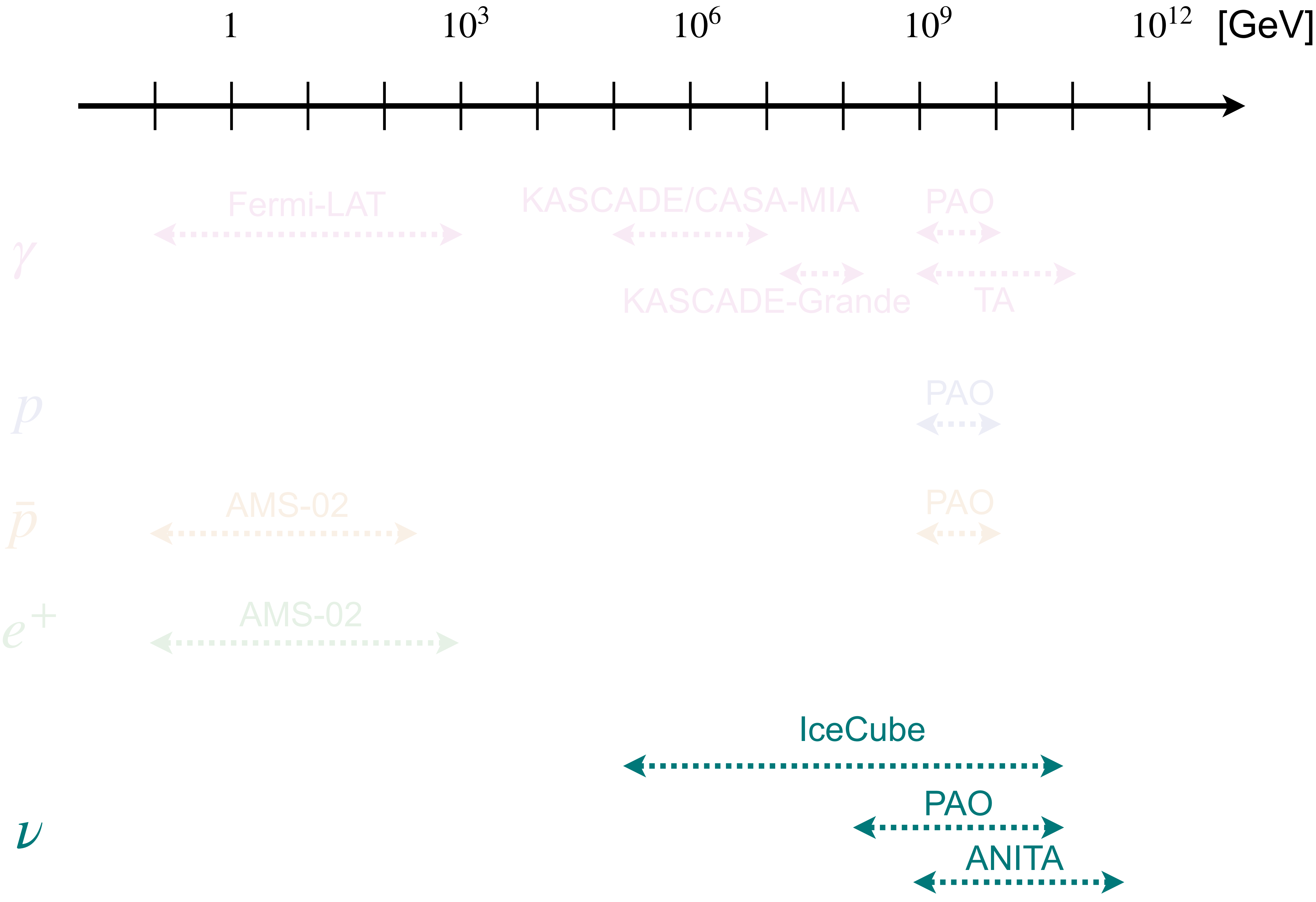
Absorption effect is minor

Integrated γ

τdm = 10^27 s

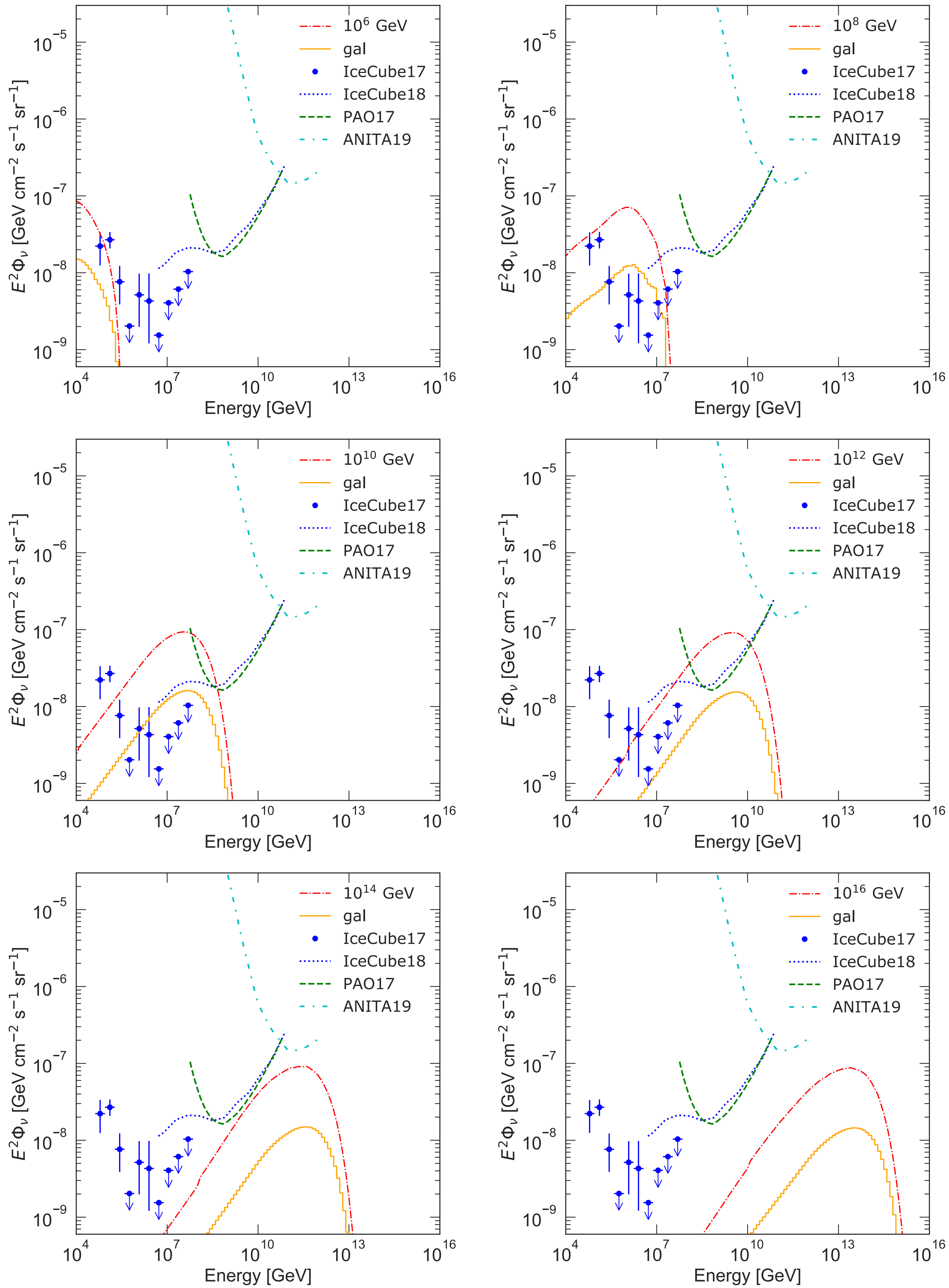


Galactic flux is dominant in high energy region for large $m_{\rm dm}$


1
10^3
10^6
10^9
10^12
[GeV]
Fermi-LAT
KASCADE/CASA-MIA
PAO
KASCADE-Grande
TA
PAO
AMS-02
PAO
AMS-02
IceCube
PAO
ANITA

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

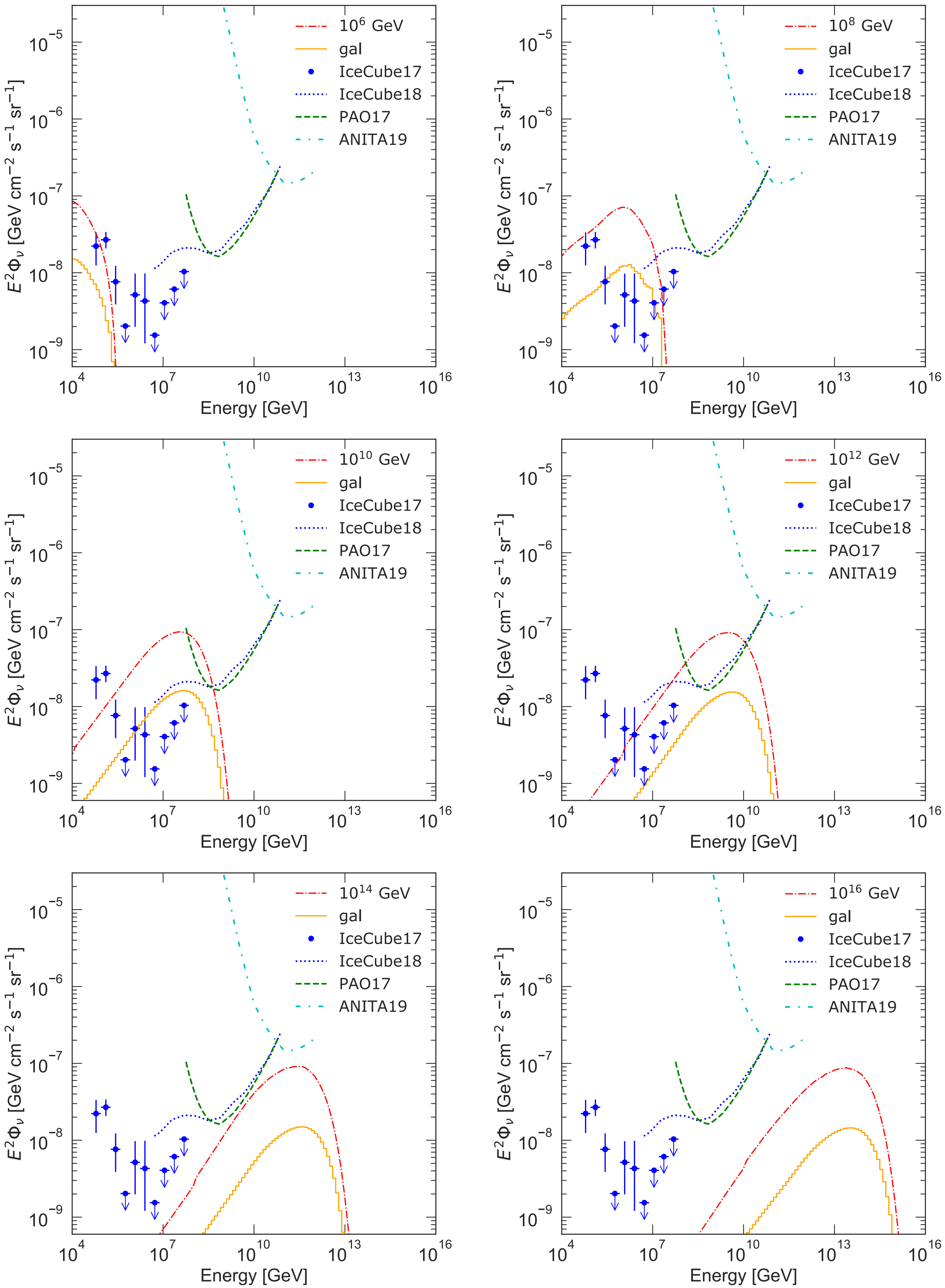
$\tau_{\rm dm} = 10^{27}$ s



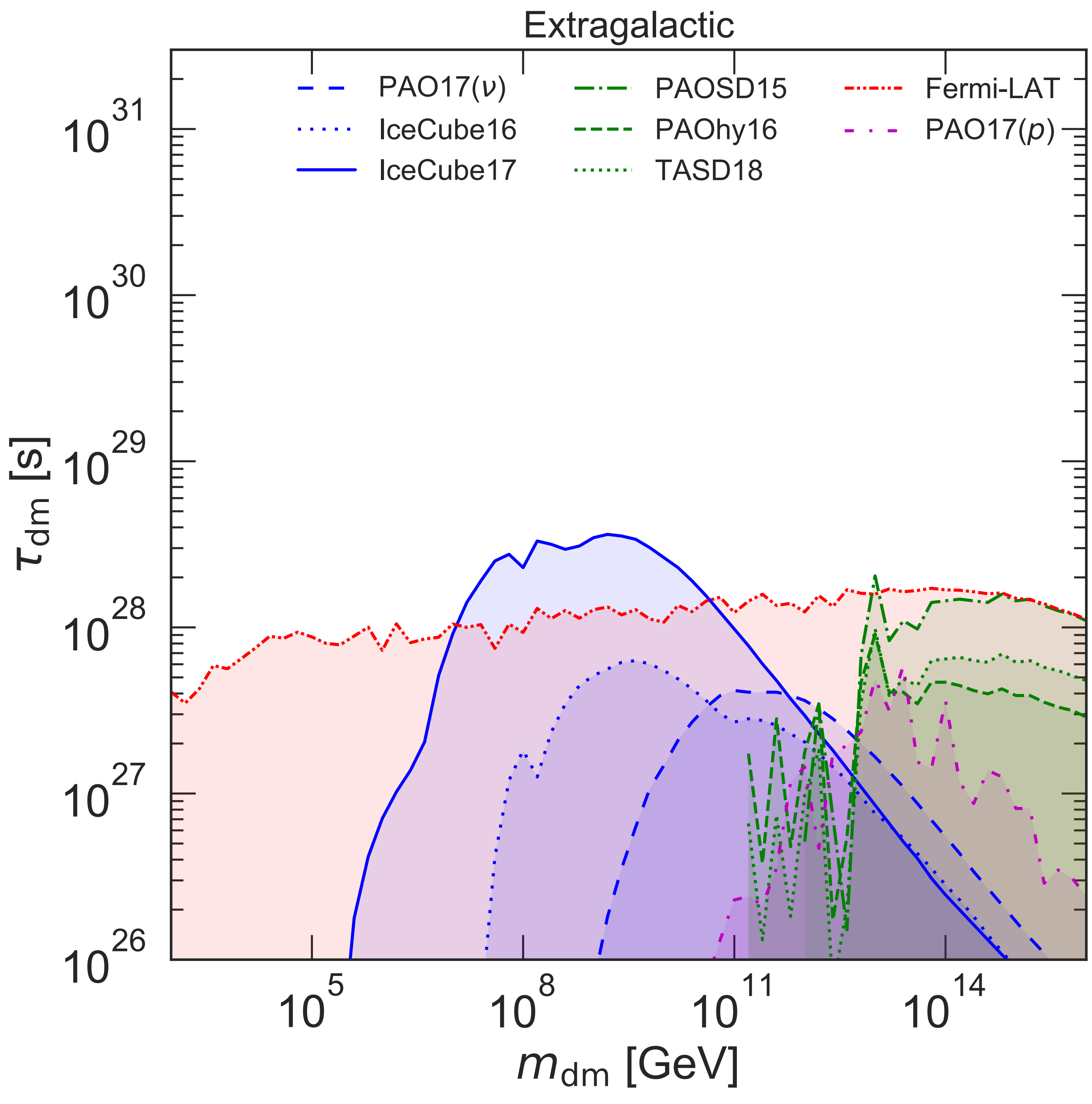
$\nu + \bar{\nu}$ flux

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

Extragalactic flux is dominant



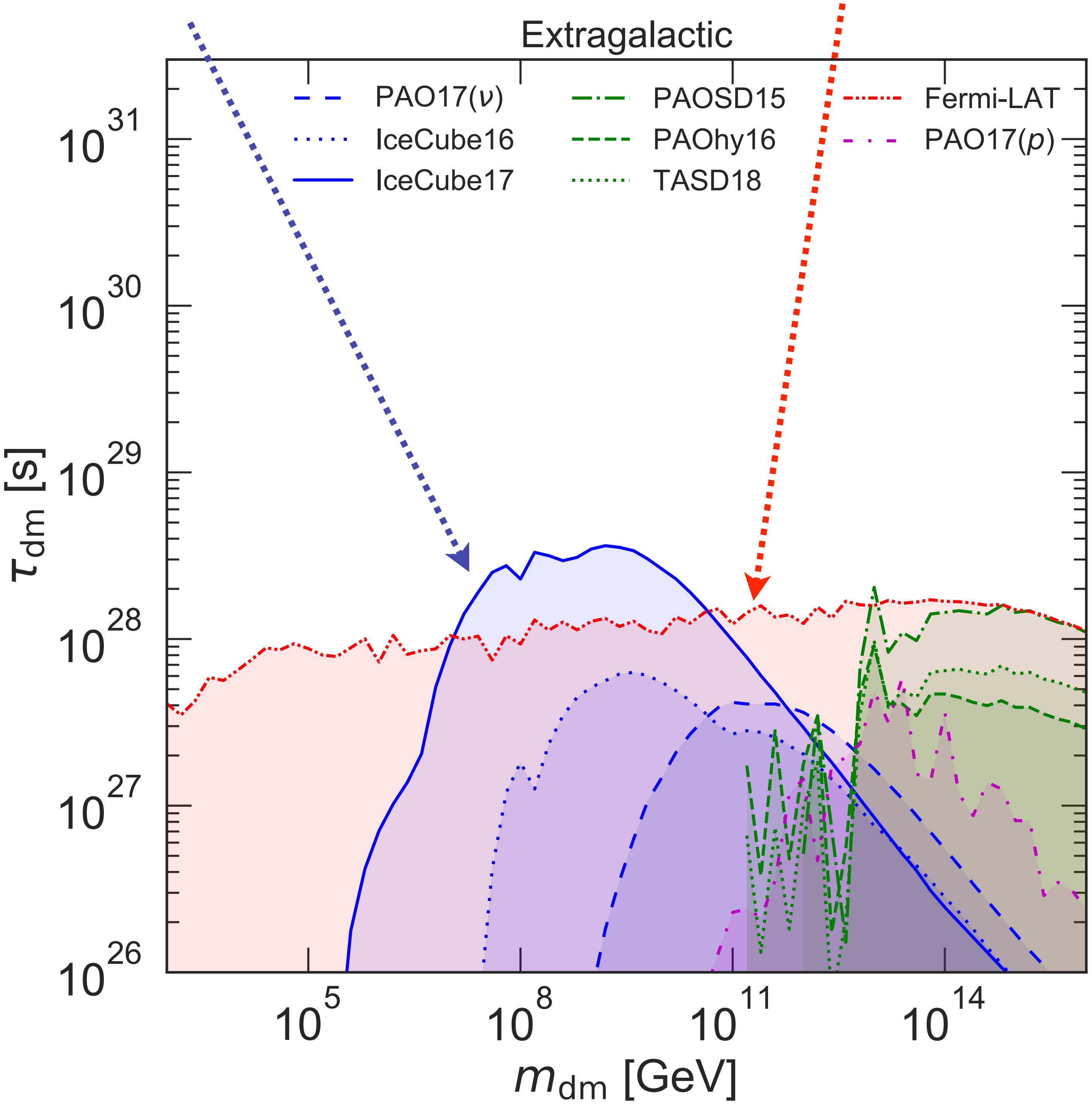
Constraints on DM lifetime (extragalactic)



Constraints on DM lifetime (extragalactic)

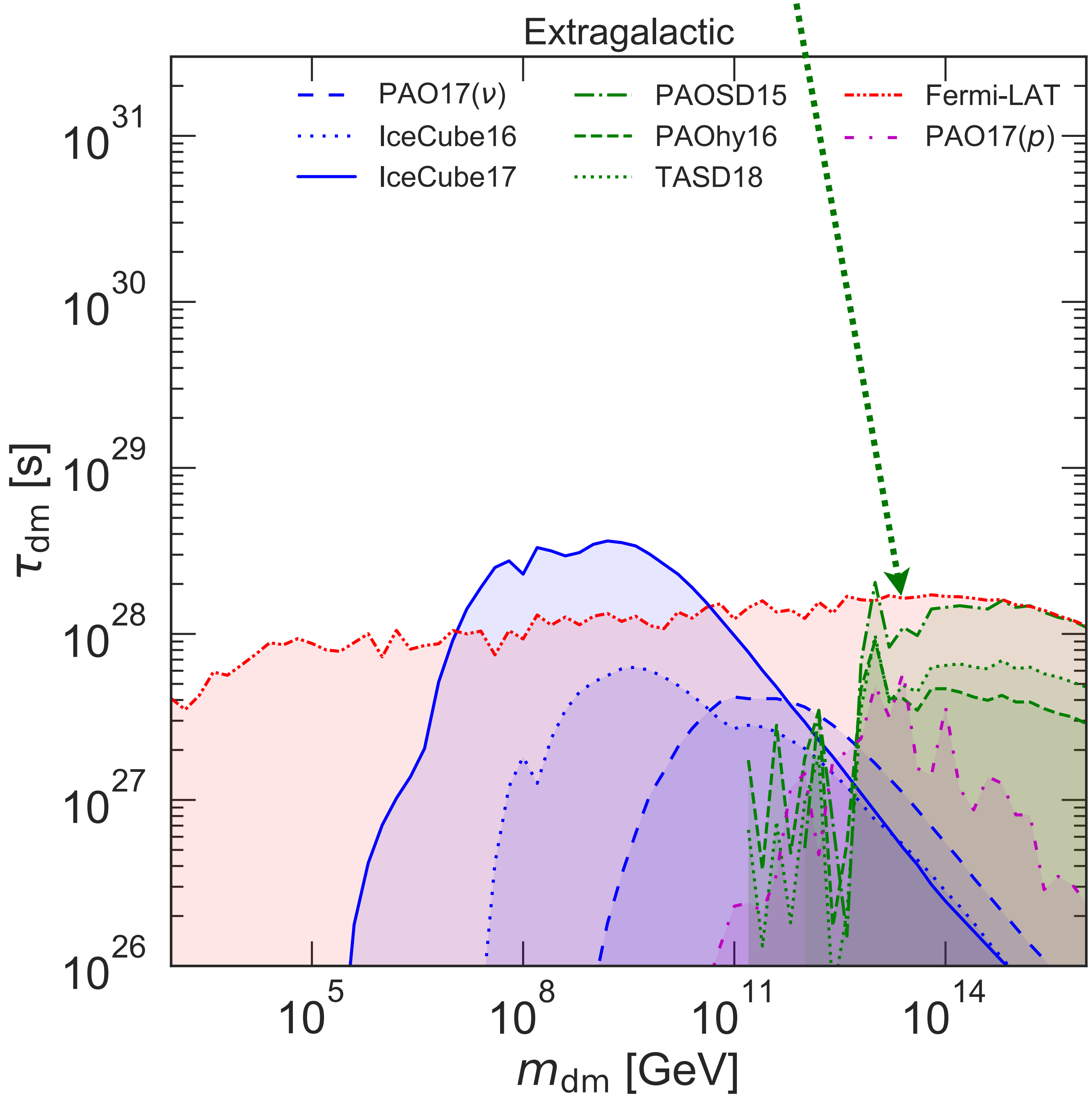
IceCube gives a more stringent bound in $10^6\,\mathrm{GeV} \lesssim m_{\rm dm} \lesssim 10^{11}\,\mathrm{GeV}$

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

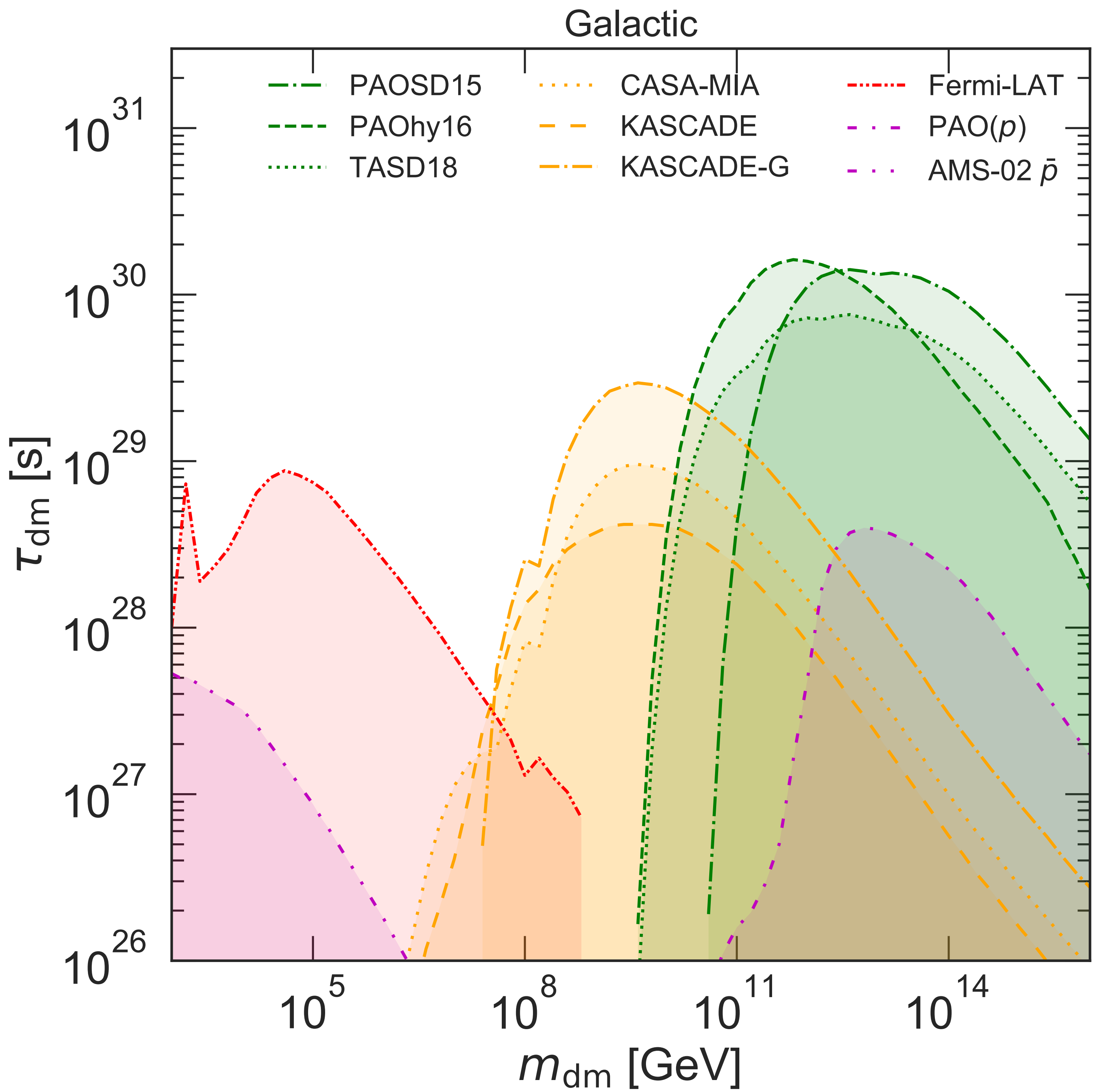


Constraints on DM lifetime (extragalactic)

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



Constraints on DM lifetime (Galactic)



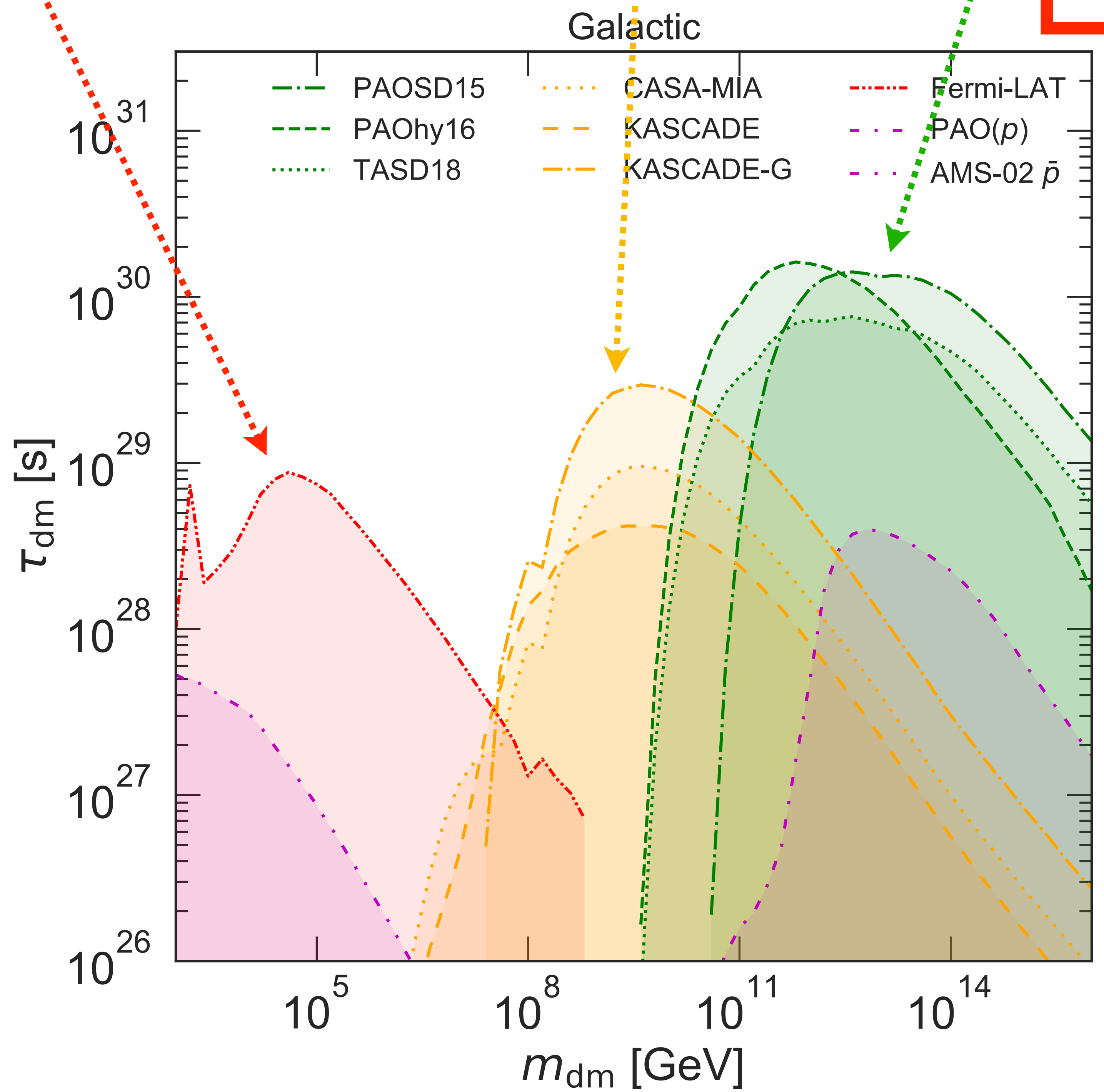
Constraints on DM lifetime (Galactic)

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

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

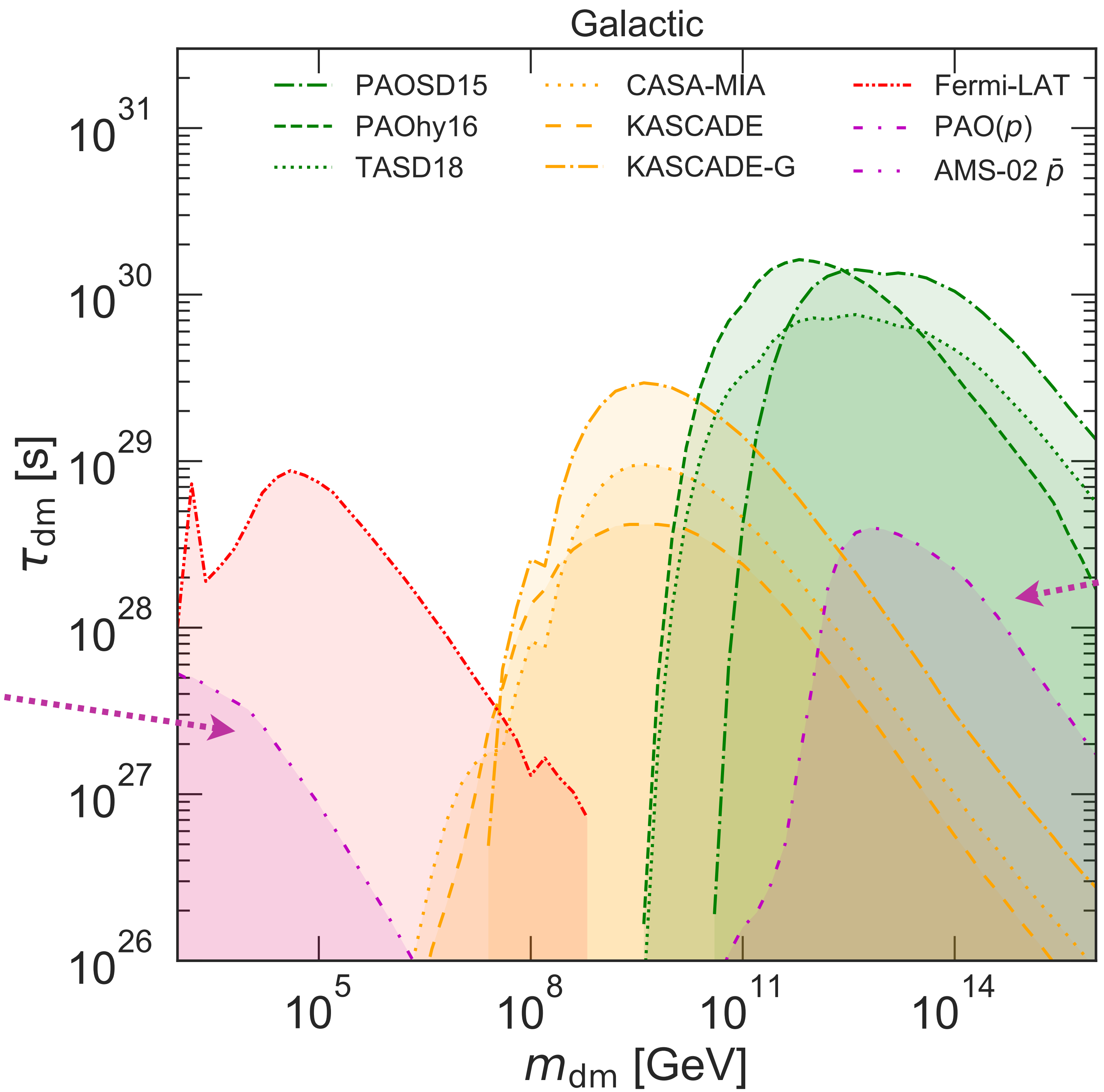
KASCADE-Grande:
$10^8\,\mathrm{GeV} \lesssim m_{\rm dm} \lesssim 10^{10}\,\mathrm{GeV}$

All γ observations!



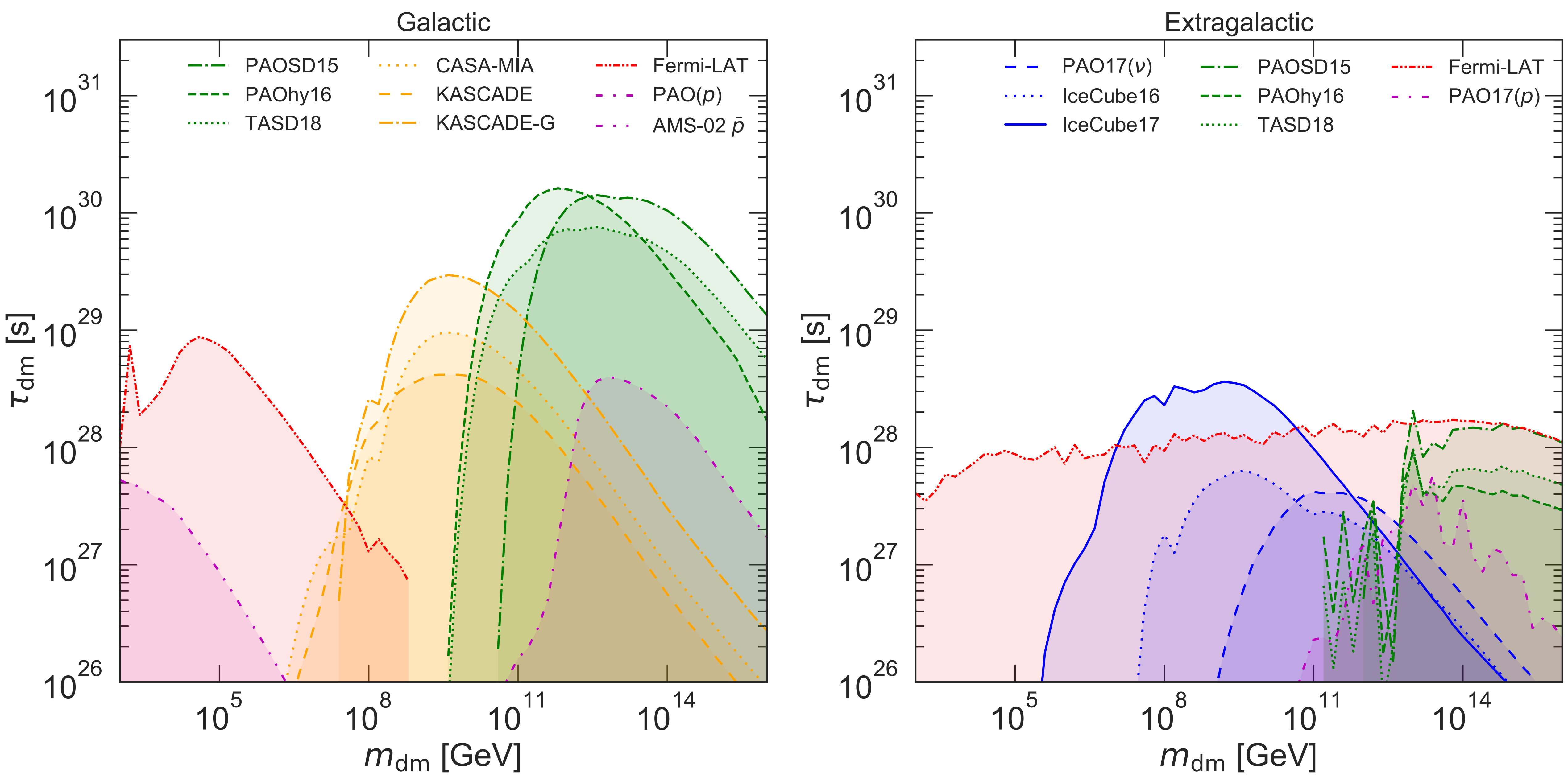
Constraints on DM lifetime (Galactic)

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

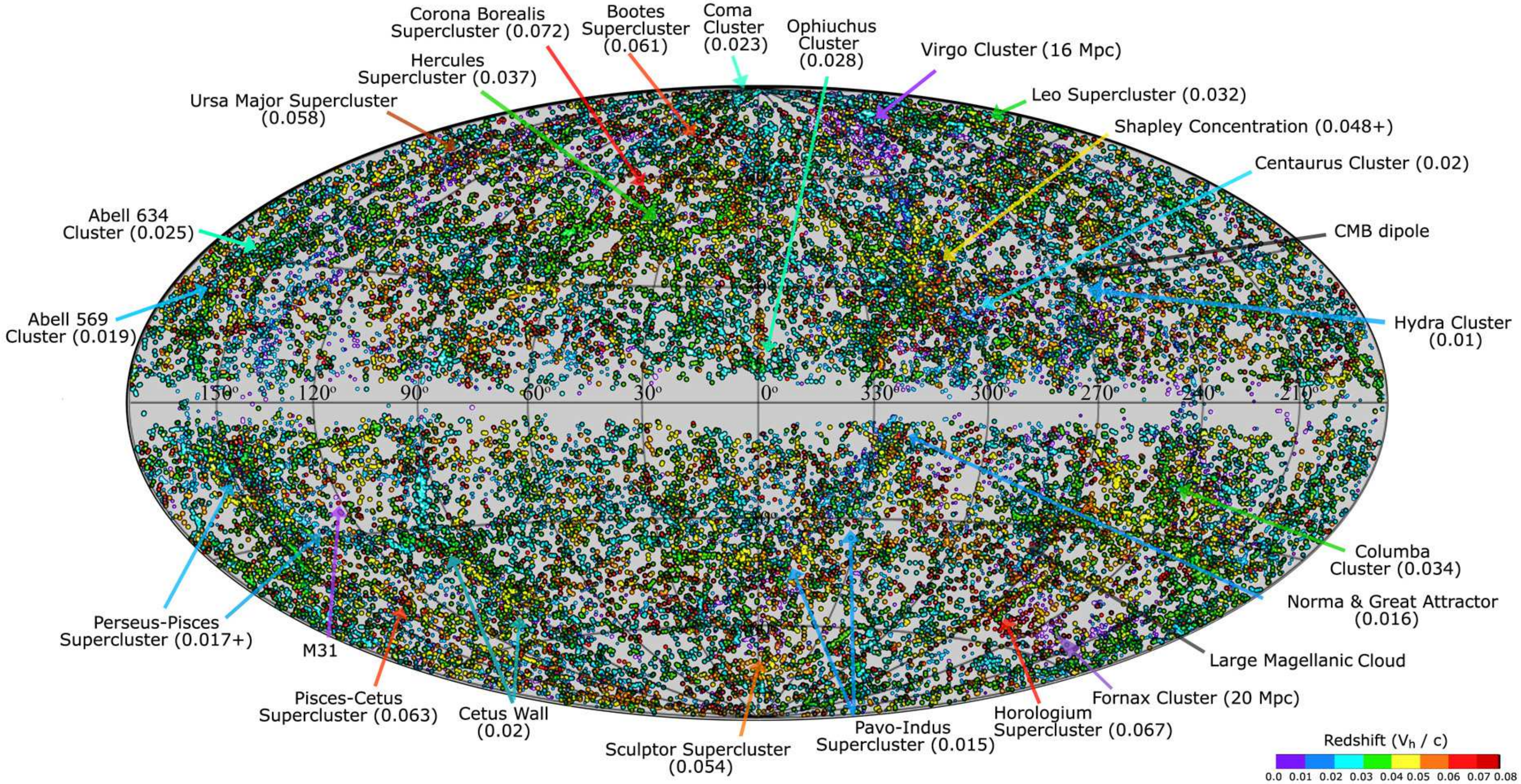
i.e., DM $\to b\bar{b}$, $10\,\mathrm{TeV} \leq m_{\mathrm{dm}} \leq 10^{16}\,\mathrm{GeV}$

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

Backups

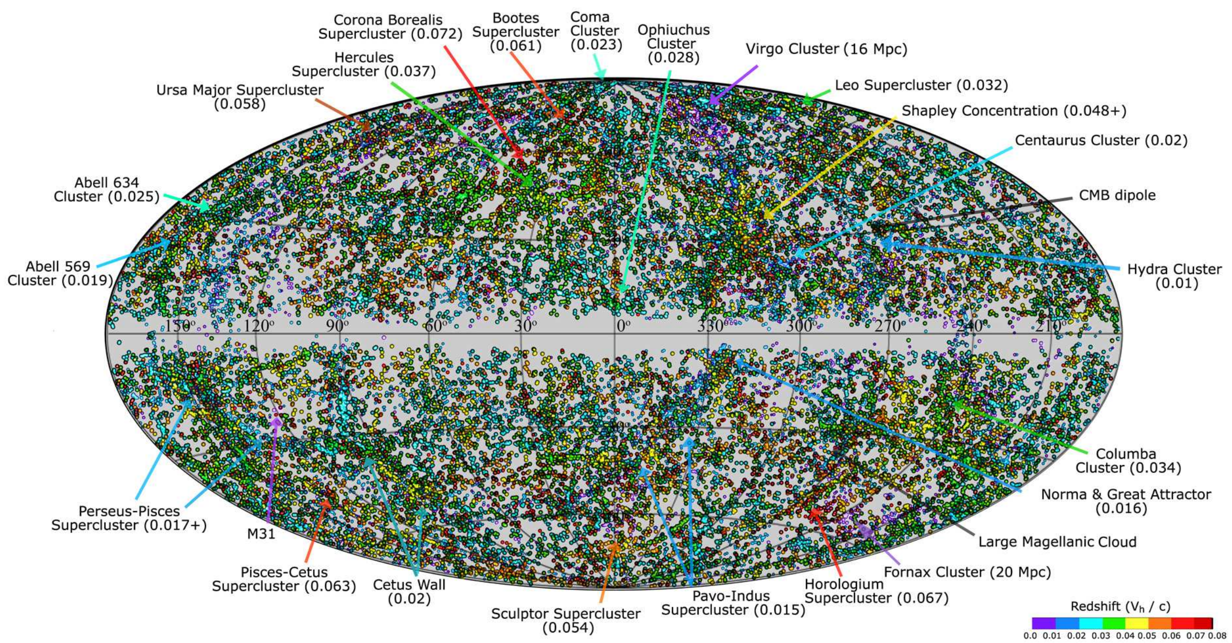
e.g., tomographic cross-correlation using local galaxy distribution

Galaxy distribution



2MRS '11

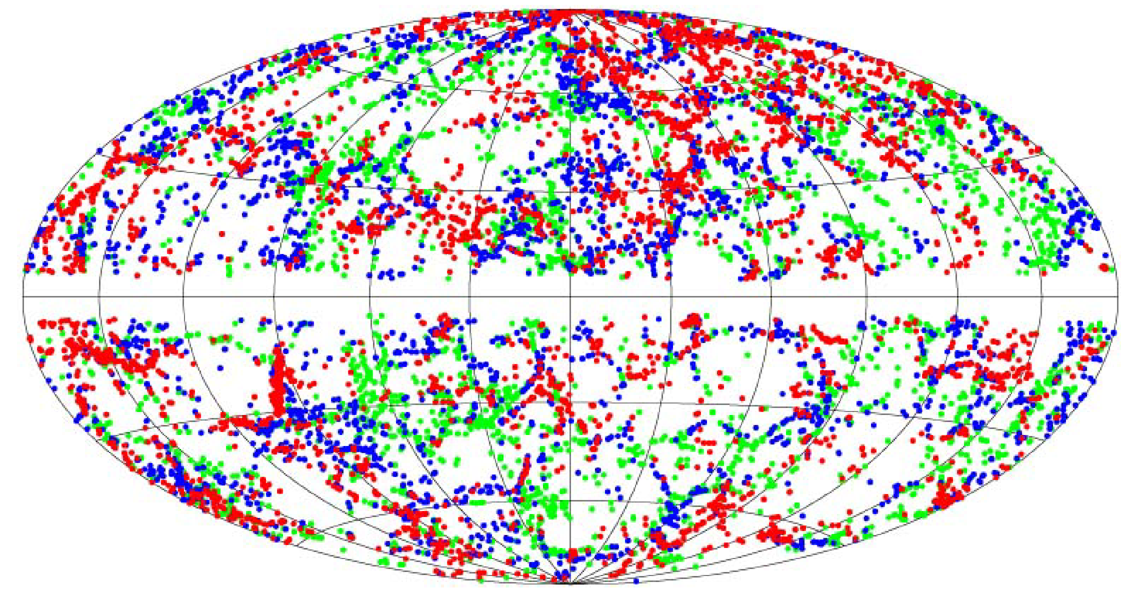
e.g., tomographic cross-correlation using local galaxy distribution



6000<v<7000km/s

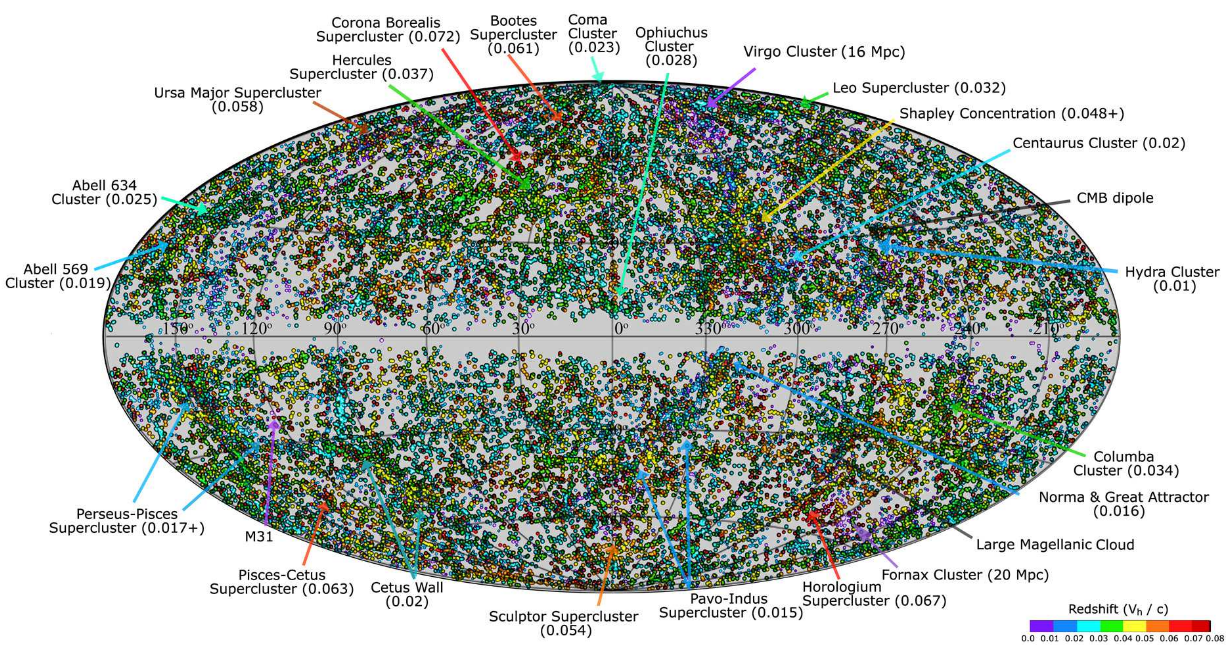
7000<v<8000km/s

8000<v<9000km/s



2MRS ’11

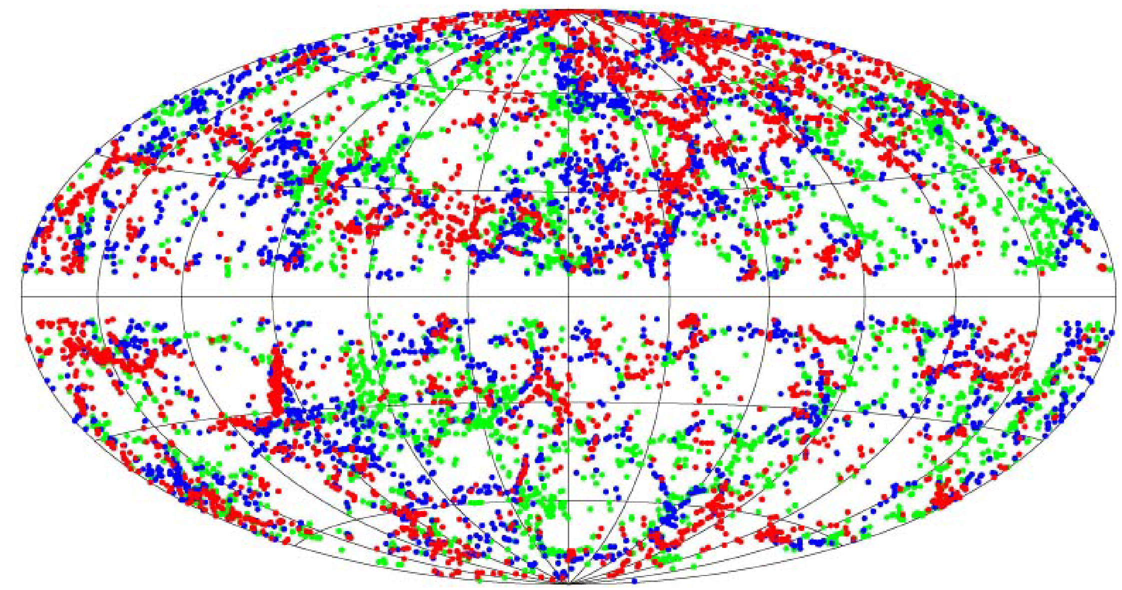
e.g., tomographic cross-correlation using local galaxy distribution



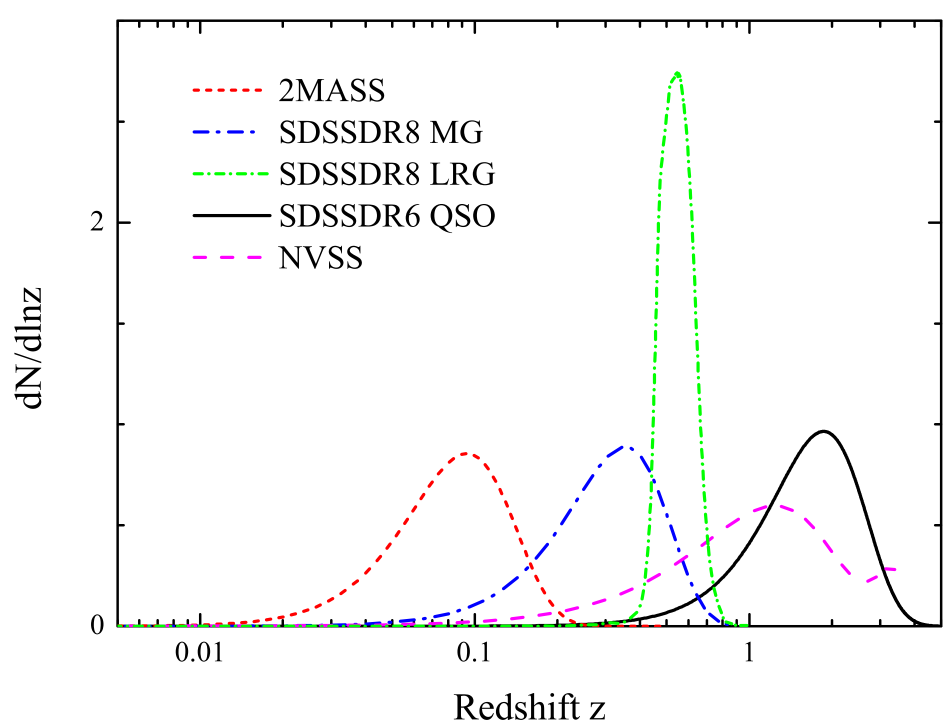
6000<v<7000km/s

7000<v<8000km/s

8000<v<9000km/s



We know the distance (or redshift) from each galaxy by its velocity

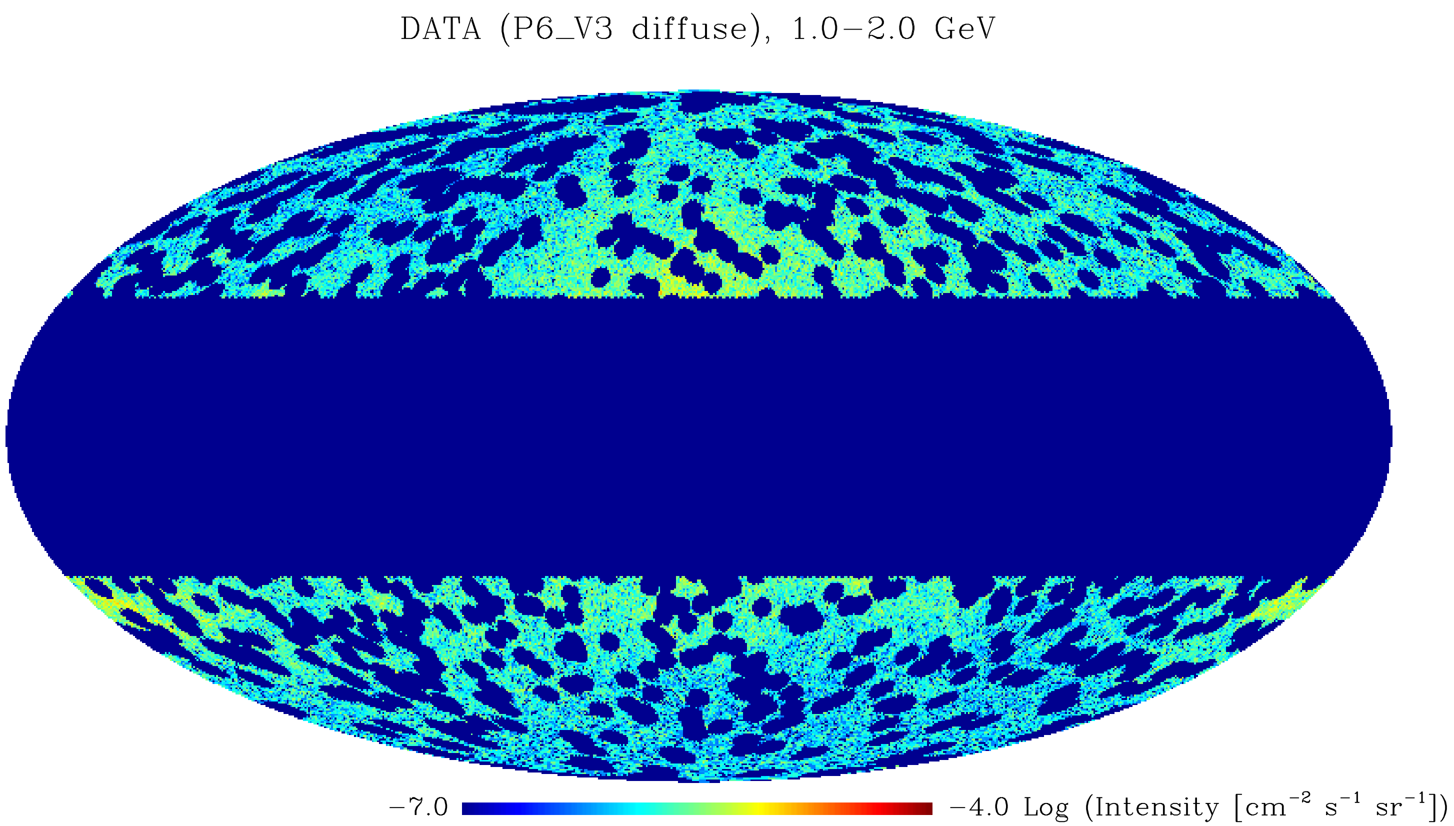


Redshift distribution

e.g., tomographic cross-correlation using local galaxy distribution

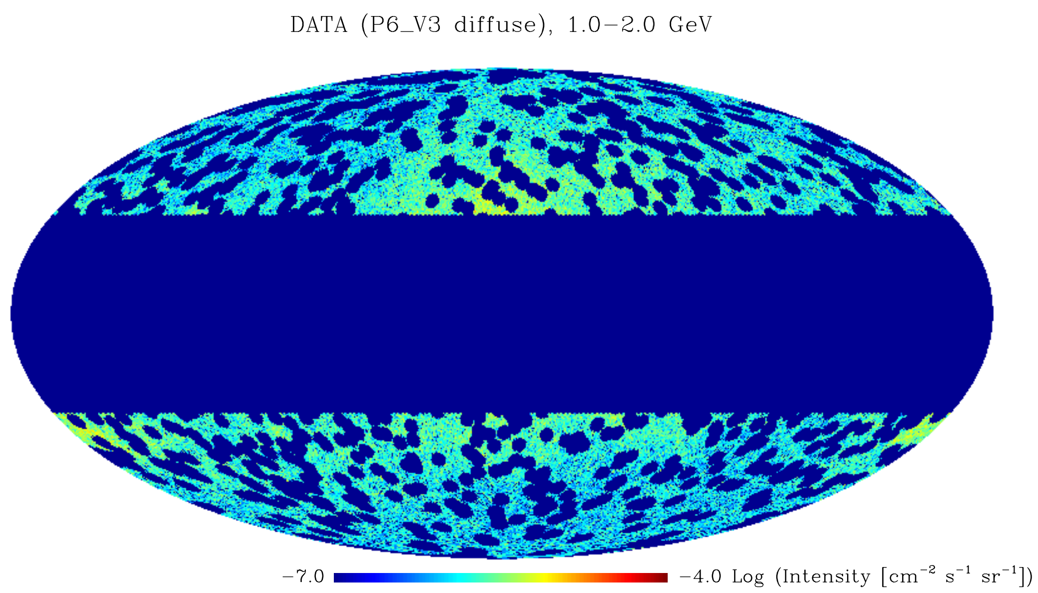
Anisotropy of gamma ray

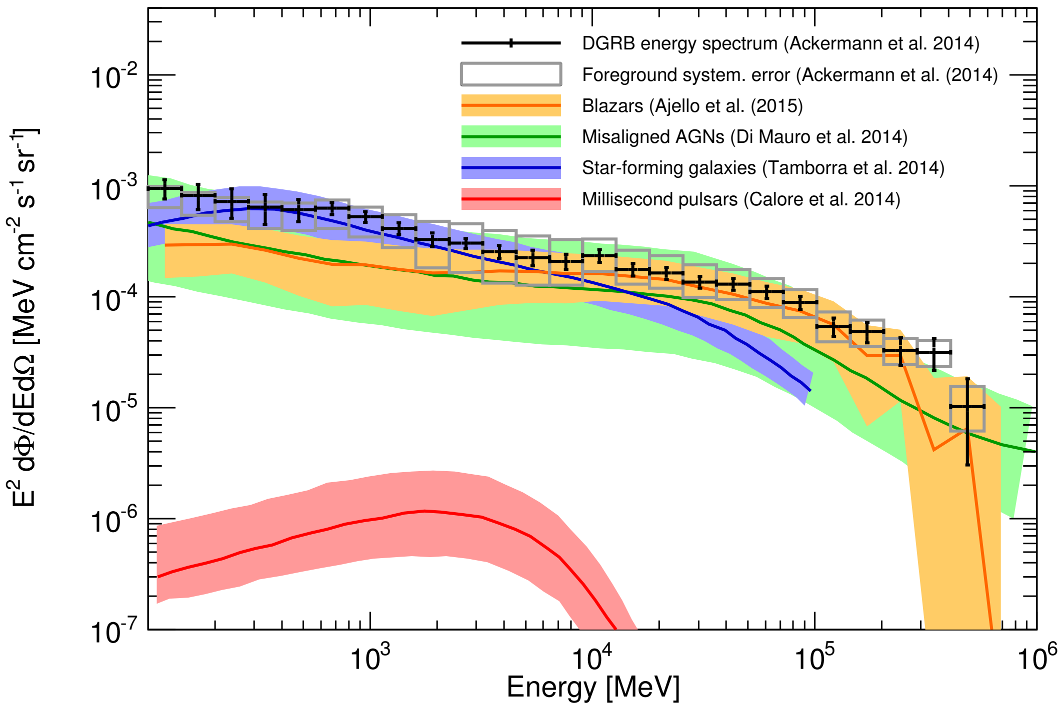
Fermi-LAT ’12



e.g., tomographic cross-correlation using local galaxy distribution

Fornasa, Sánchez-Conde ’15

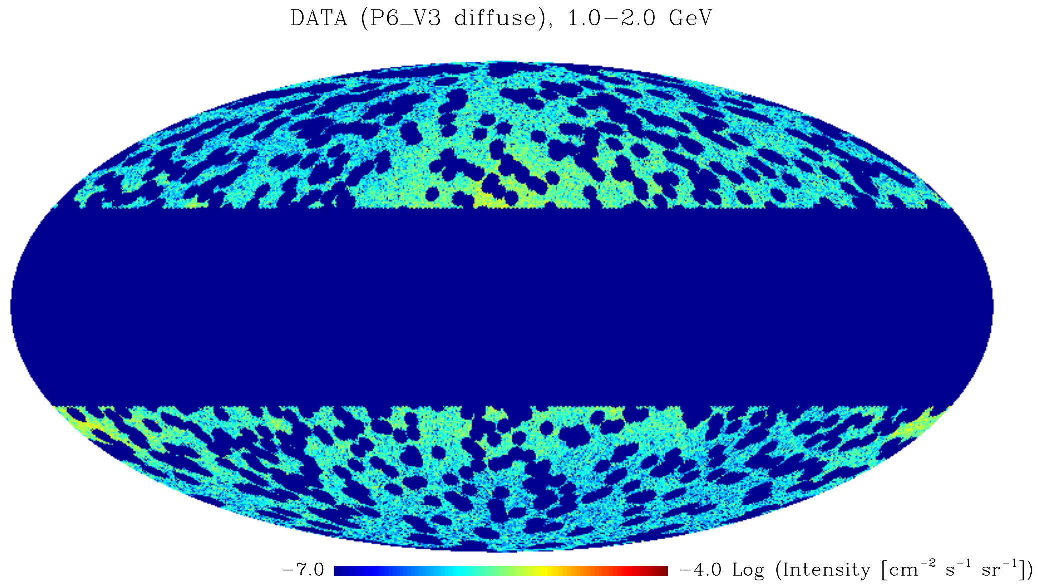




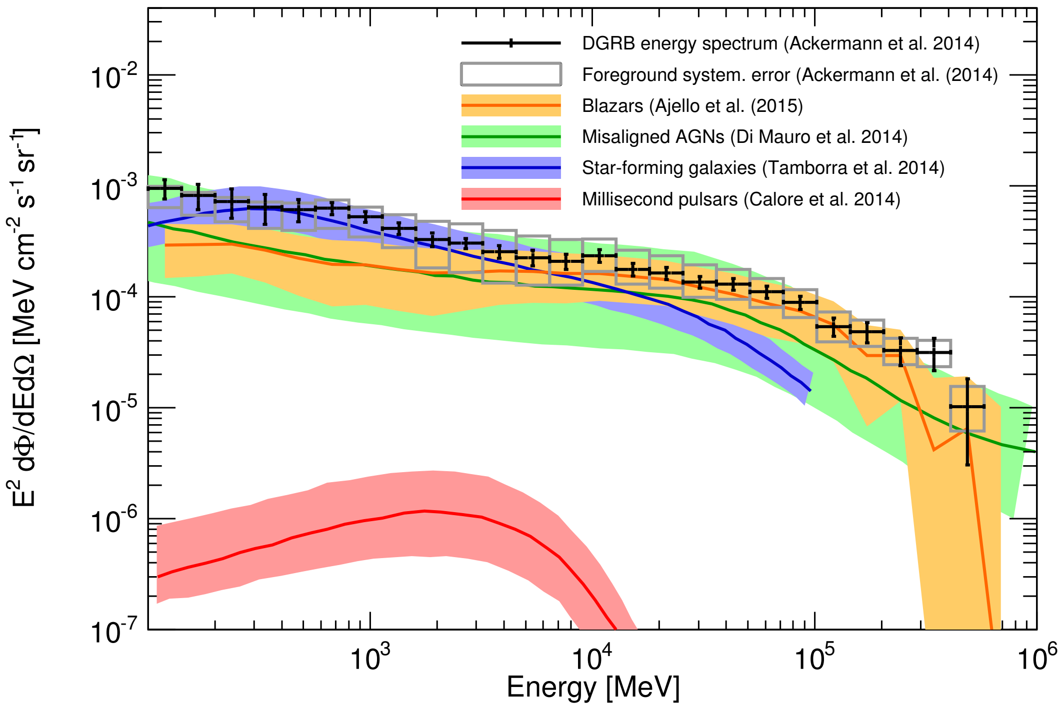
This should be explained by

Blazers + SFGs + AGNs (+DM)

e.g., tomographic cross-correlation using local galaxy distribution

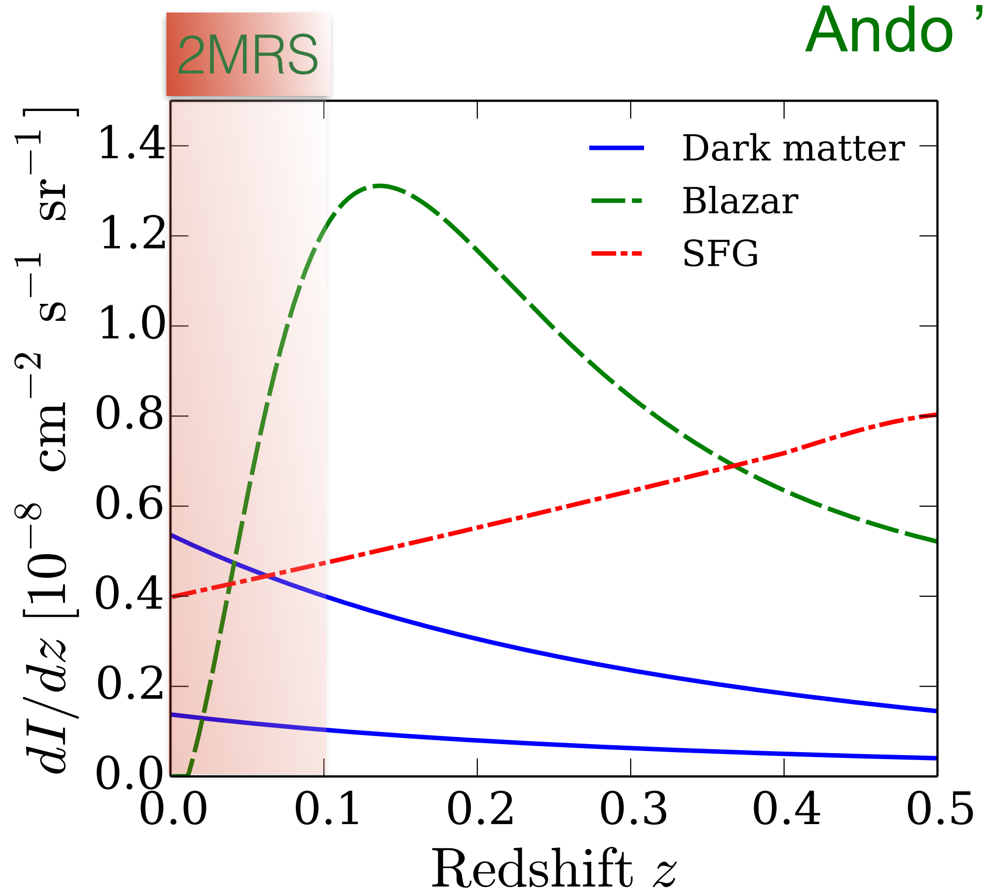


Fornasa, Sánchez-Conde '15

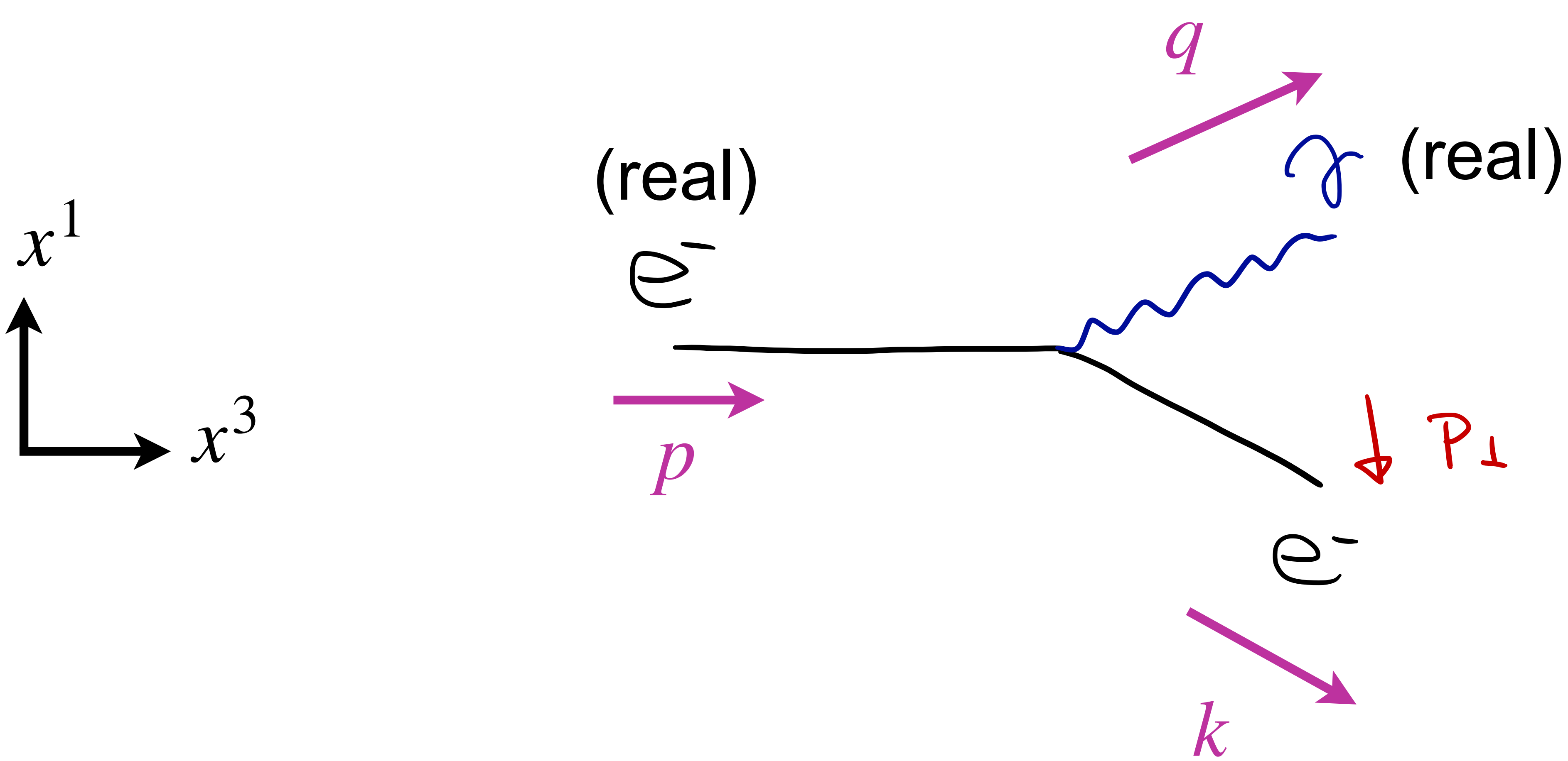


Ando '14

Each component has a typical redshift distribution



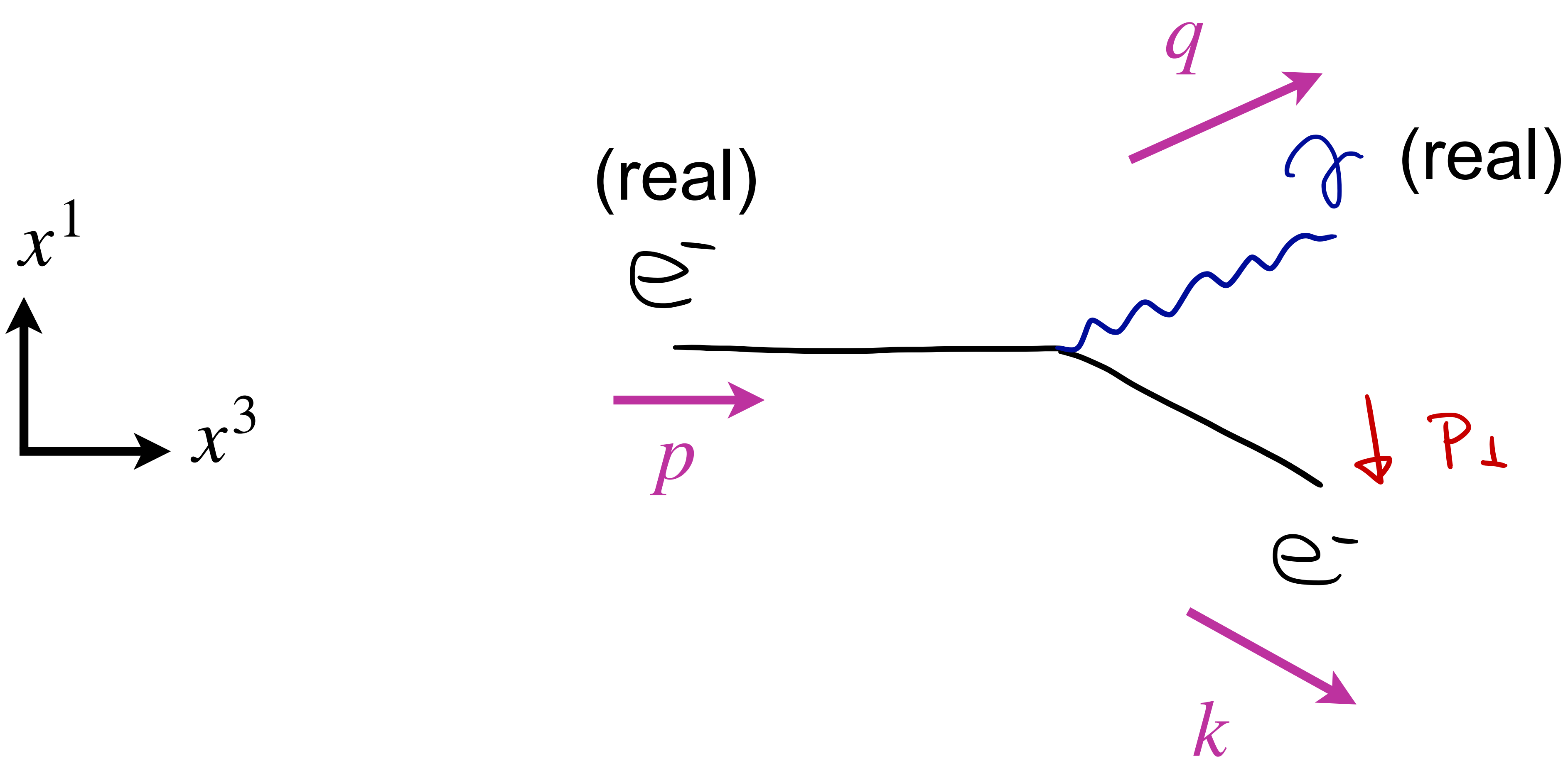
e.g., QED case



$$q = (xp, \; -p_\perp, 0, xp - \frac{p_\perp^2}{2xp})$$

$$k = ((1-x)p, p_\perp, 0, (1-x)p + \frac{p_\perp^2}{2xp})$$

x : momentum fraction of γ in x^3 direction e.g., QED case



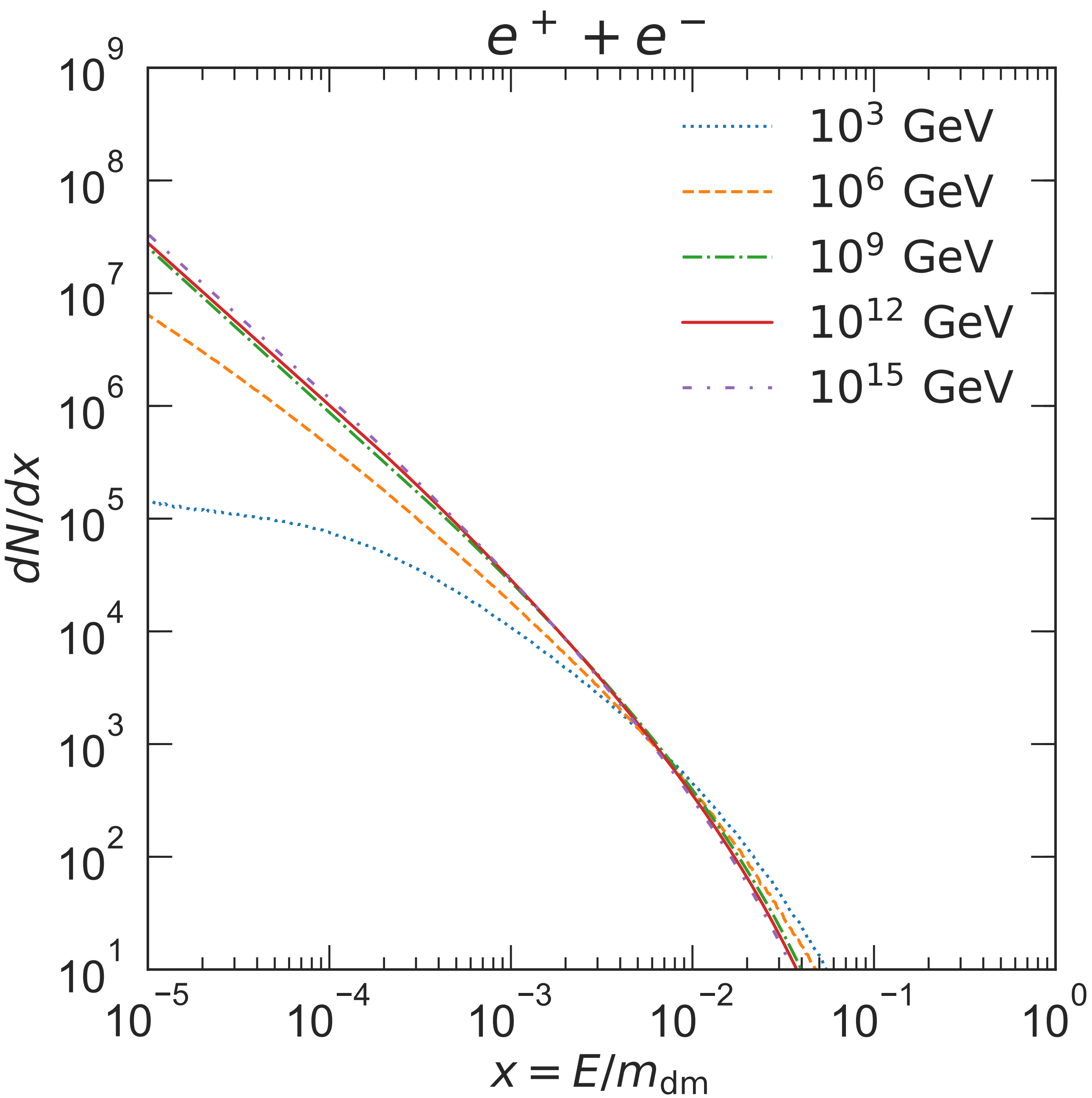
$$q^2 = \mathcal{O}(p_\perp^4)$$

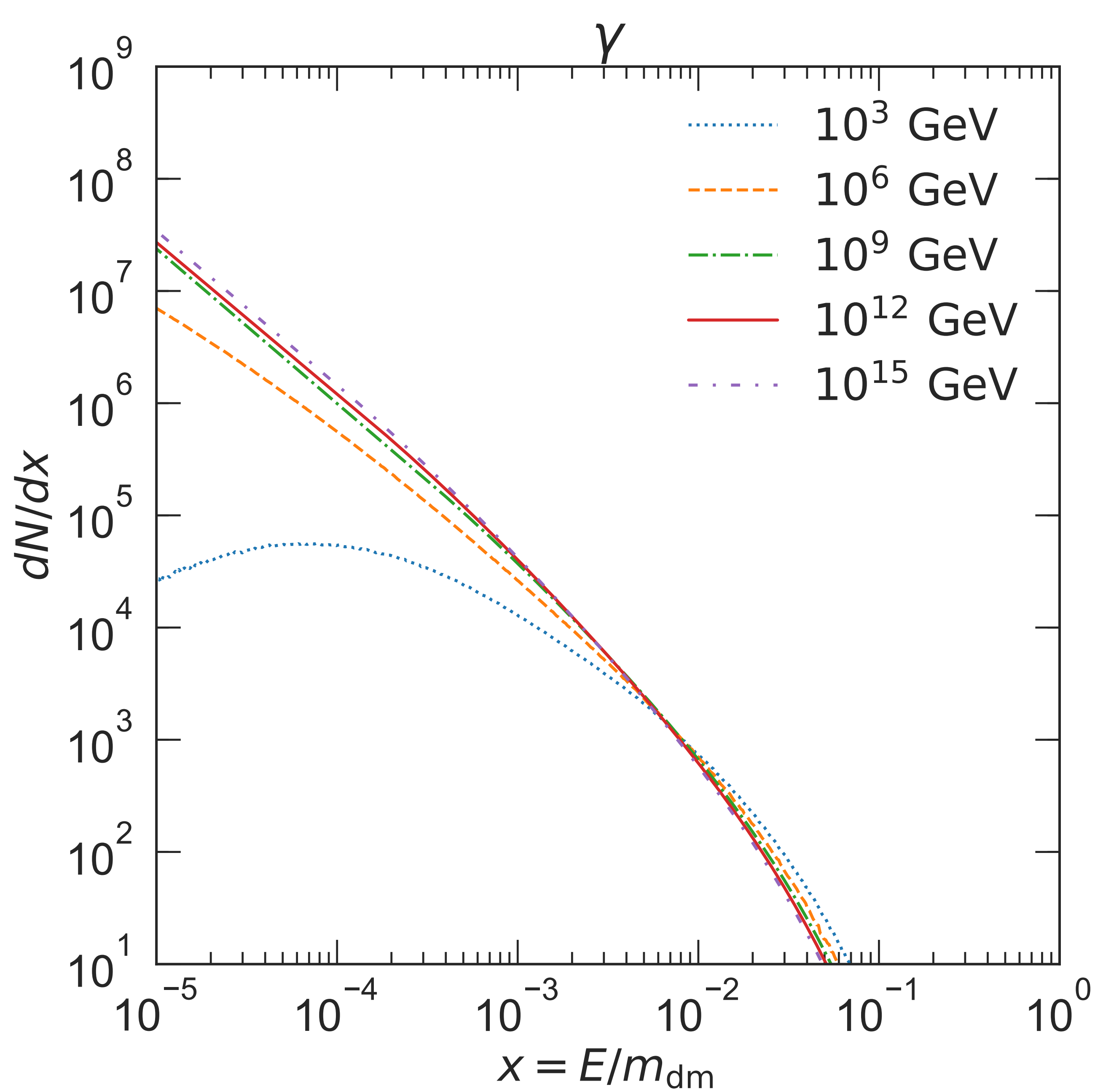
$$\longrightarrow \quad k^2 = -\frac{p_\perp^2}{x} + \mathcal{O}(p_\perp^4)$$

(k^2 plays the role of momentum transfer)

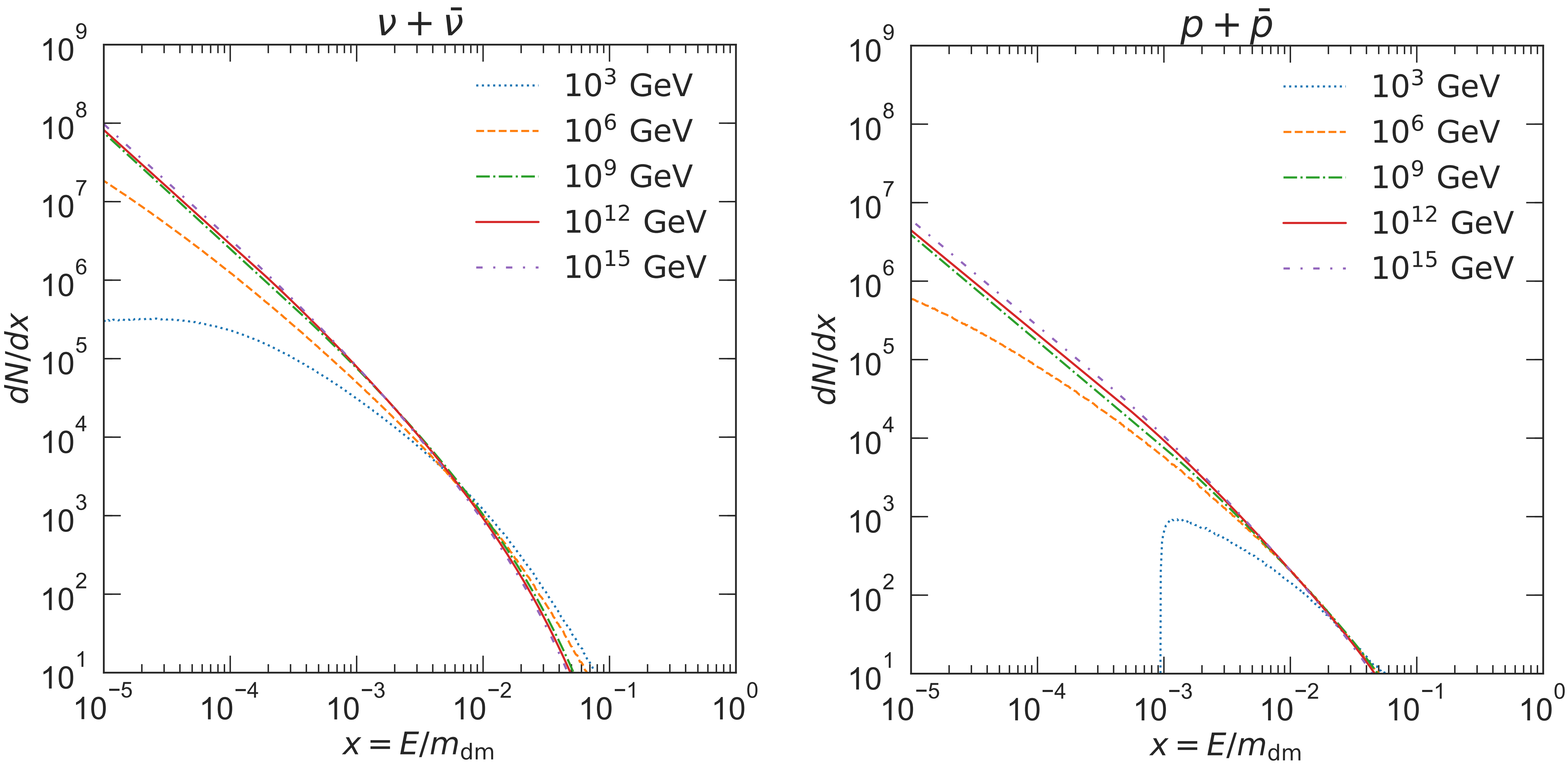
x : momentum fraction of γ in x^3 direction

Energy distributions (results):





Energy distributions (results):



The interactions are characterized by the mean interaction length:

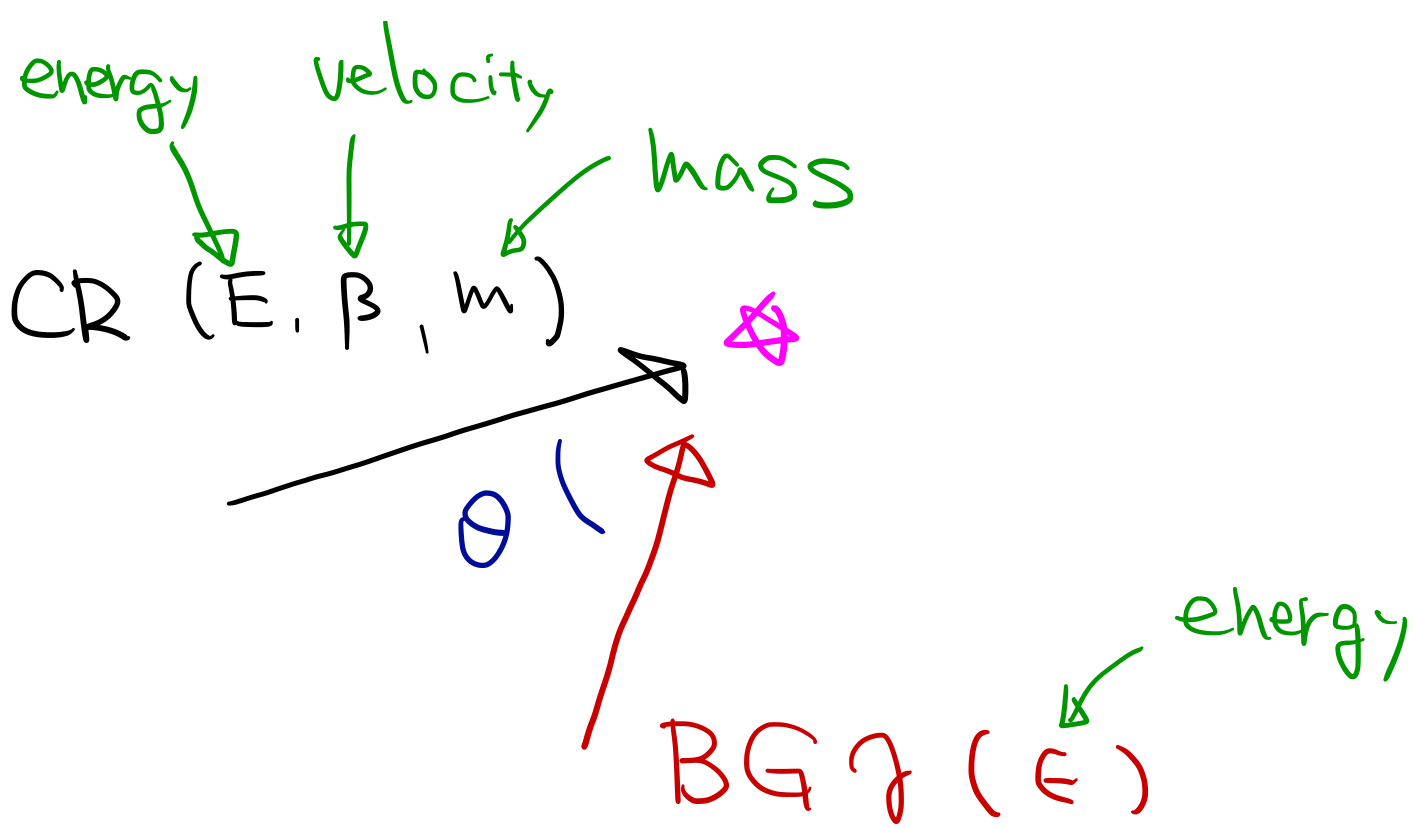
Szabo, Protheroe '94

$$\lambda^{-1}(E) = \frac{1}{8\beta E^2}\int_0^\infty \frac{d\epsilon}{\epsilon^2}\frac{dn(\epsilon)}{d\epsilon}\int_{s_{\rm th}}^{s_{\rm max}} ds(s-m^2)\sigma(s)$$

$$s = m^2 + 2E\epsilon(1-\beta\cos\theta)$$

$$= \int_0^\infty d\epsilon \frac{dn(\epsilon)}{d\epsilon}\frac{1}{2}\int_{-1}^{1} d\cos\theta(1-\beta\cos\theta)\sigma(s)$$

cross section averaged over θ



Examples:

- Proton - CMB photon

$$\lambda^{-1} \sim \frac{T_0^3}{\pi^2} \times \mathrm{mb} \longrightarrow \lambda \sim 1\,\mathrm{Mpc}$$

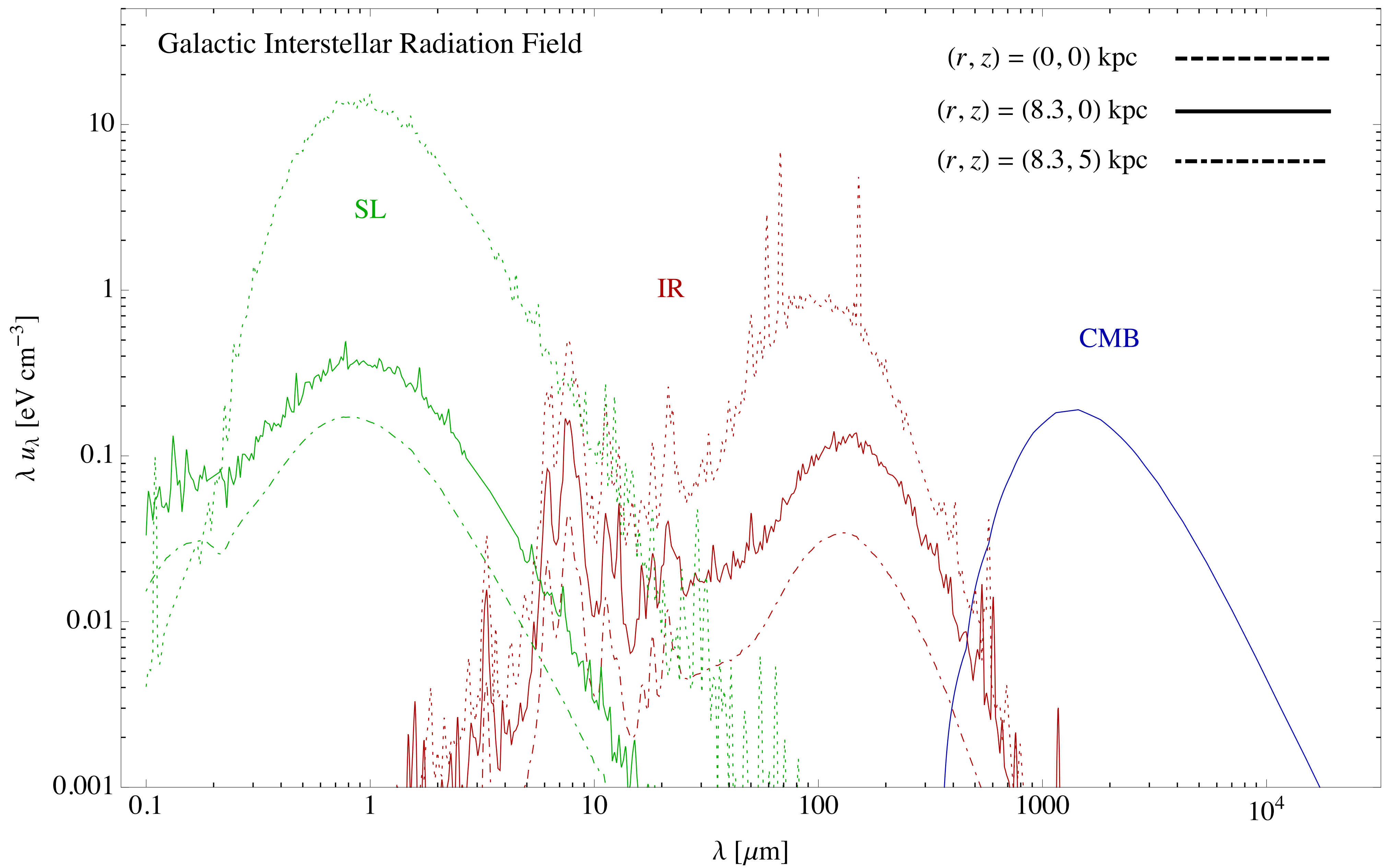
- Electron - CMB photon

$$\lambda^{-1} \sim \frac{T_0^3}{\pi^2} \times \mathrm{b} \longrightarrow \lambda \sim 1\,\mathrm{kpc}$$

$$T_0 \simeq 2.7\,\mathrm{K}$$

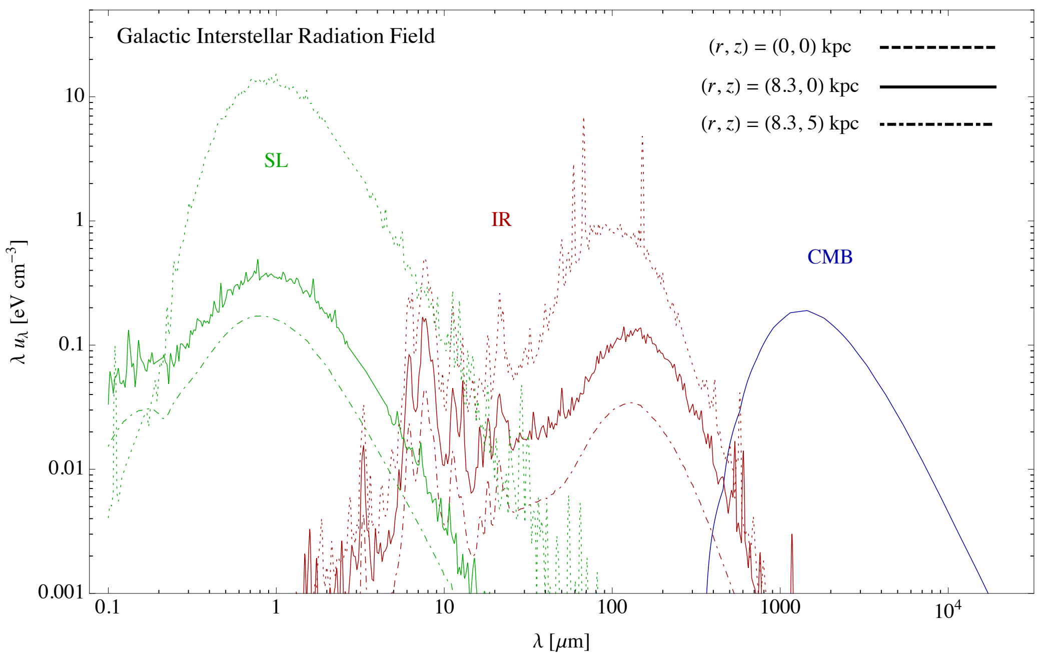
Absorption in ISRF+CMB

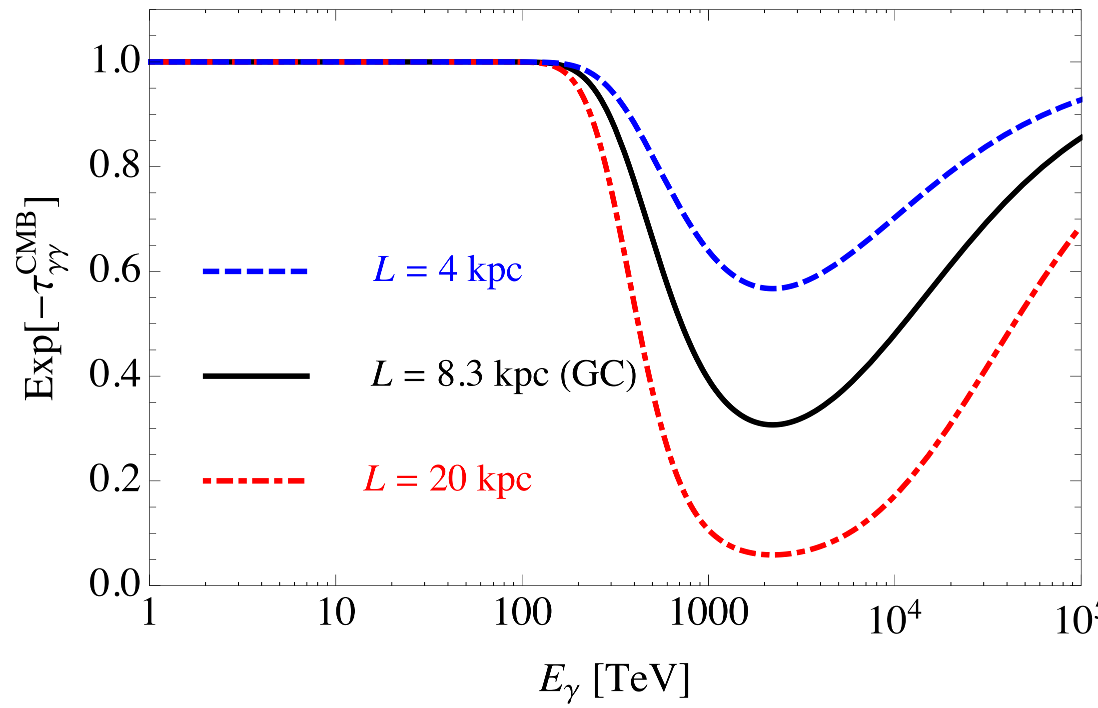
Esmaili, Serpico '15

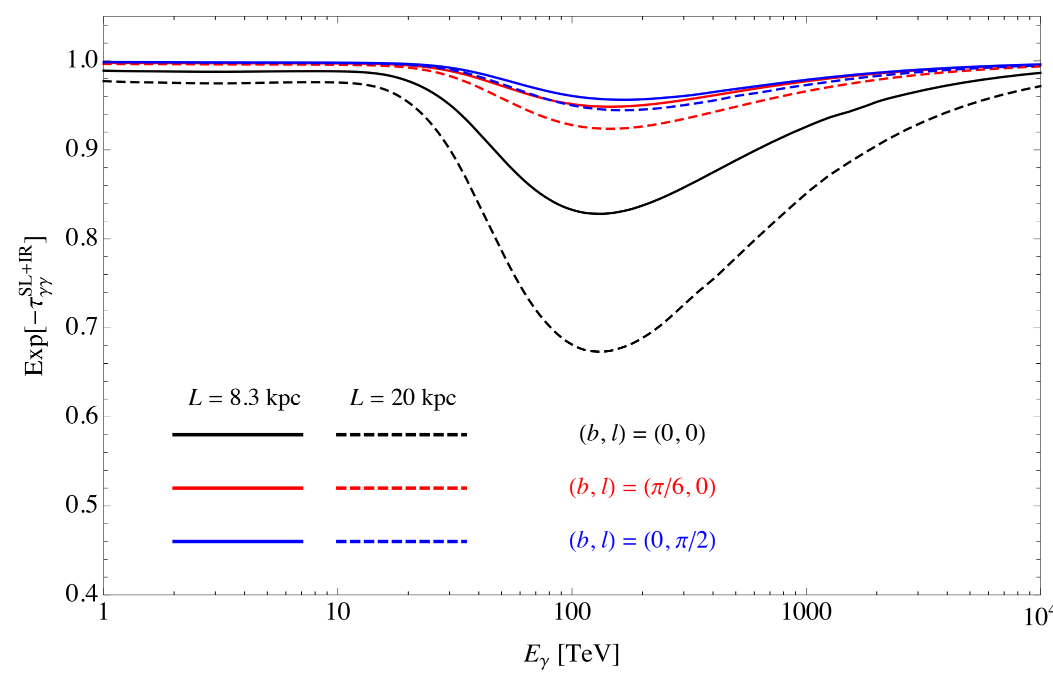


Absorption in ISRF+CMB

Esmaili, Serpico '15

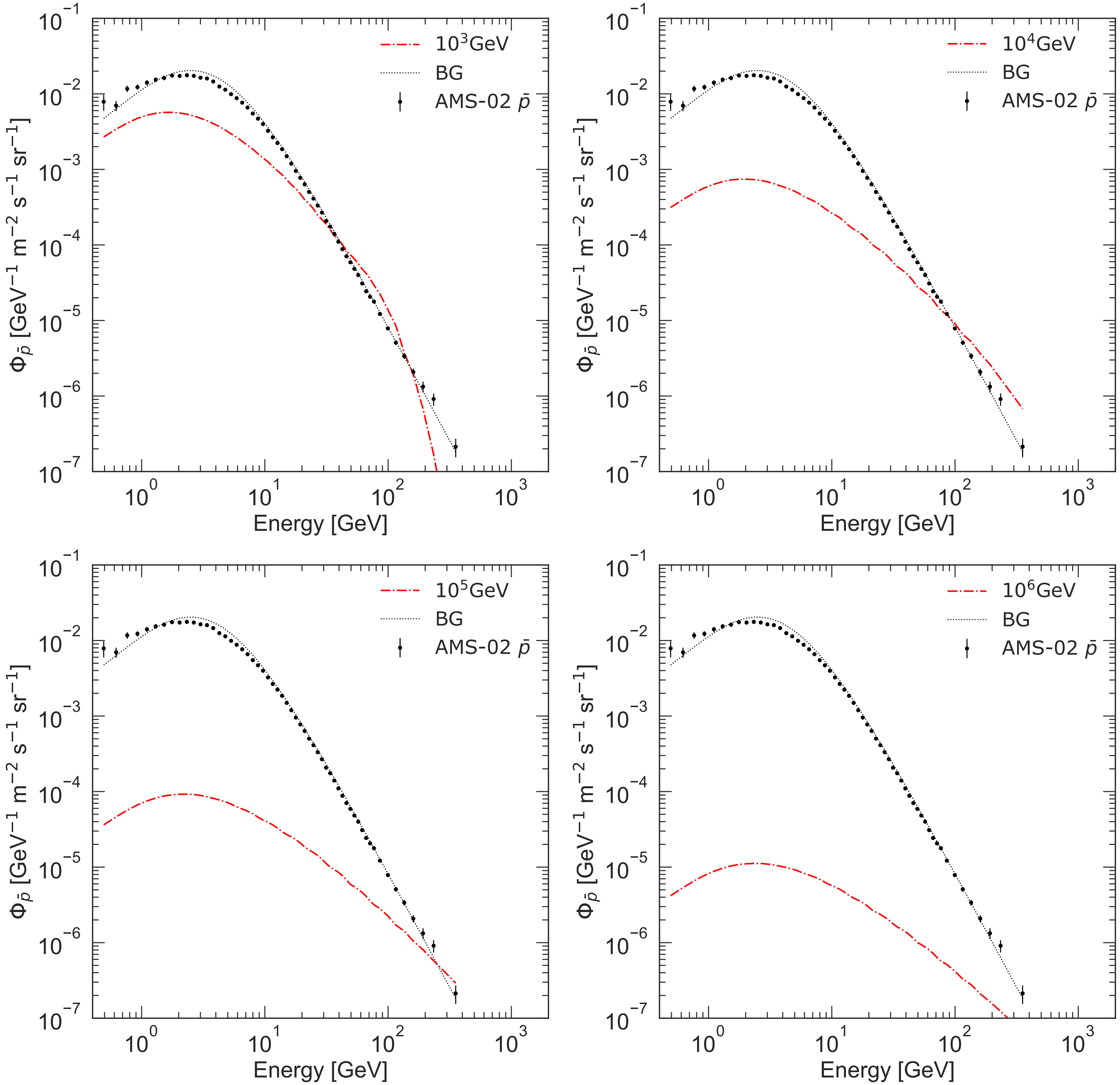






$0.1 - 100$ PeV γ is under the absorption effect

$\bar{p}$ flux in the Galaxy

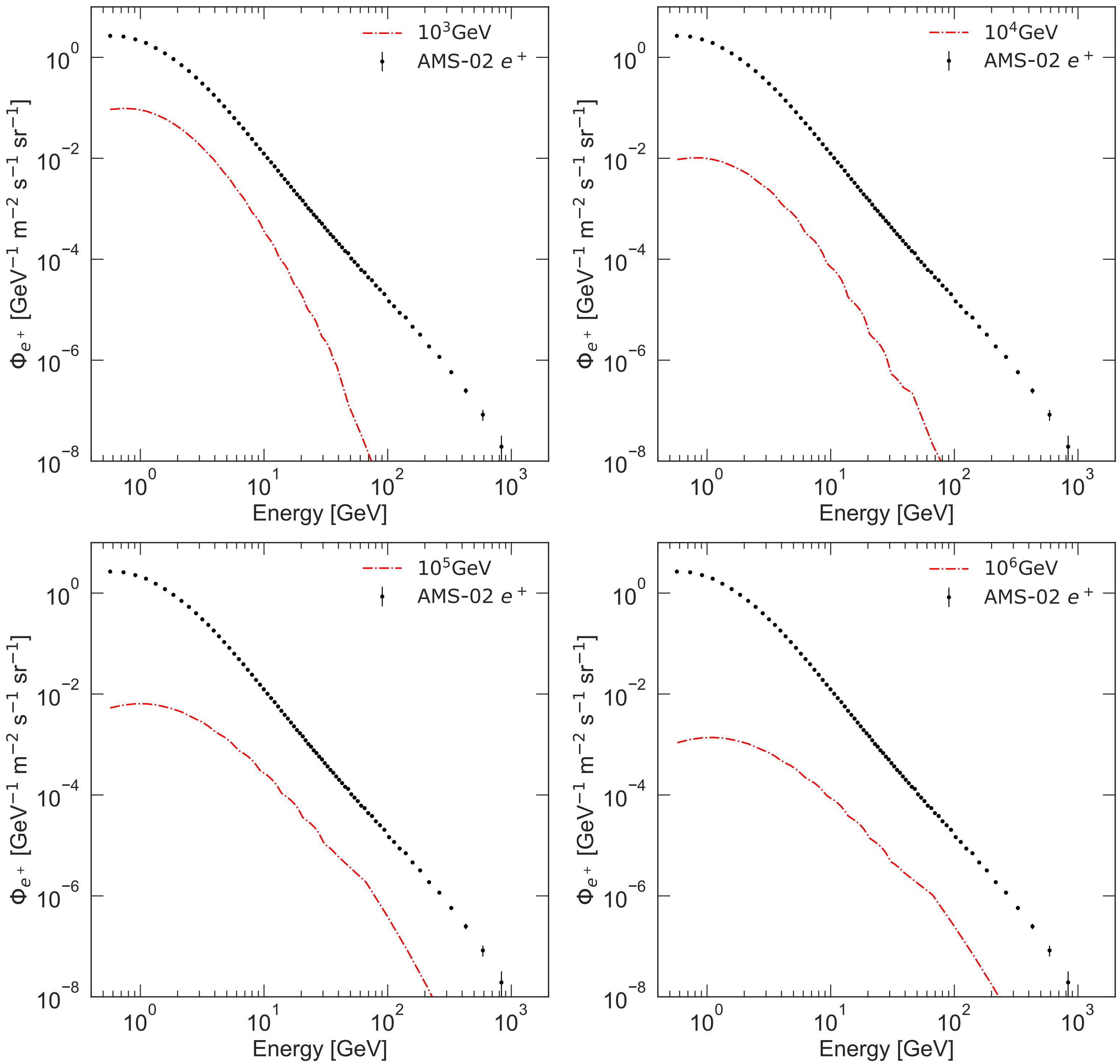


$\tau_{\rm dm} = 10^{27}\,{\rm s}$

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

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

e^+ flux in the Galaxy

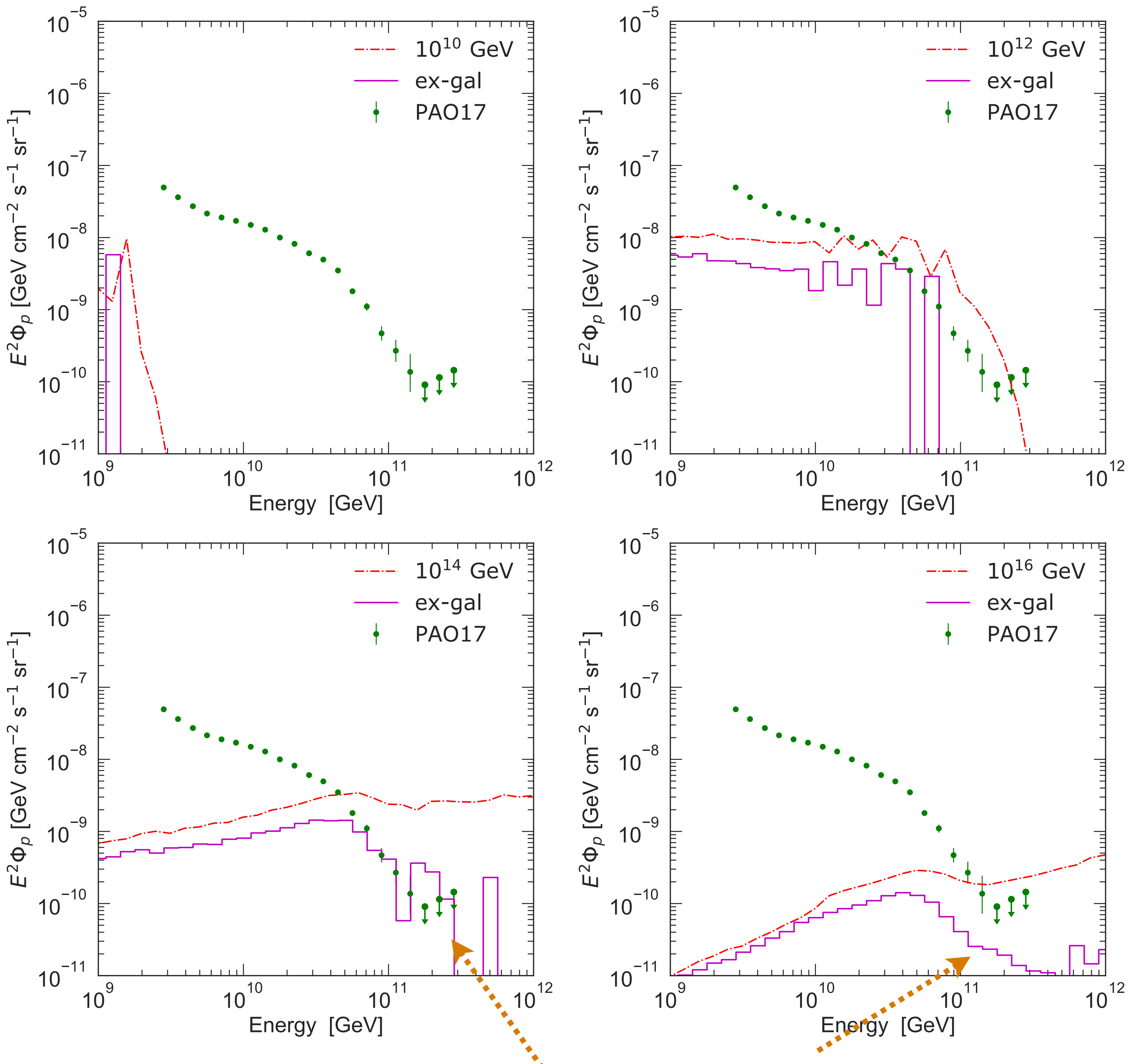


$$\tau_{\mathrm{dm}} = 10^{27}\ \mathrm{s}$$

Similar behavior to $\bar{p}$ flux

$p + \bar{p}$ flux

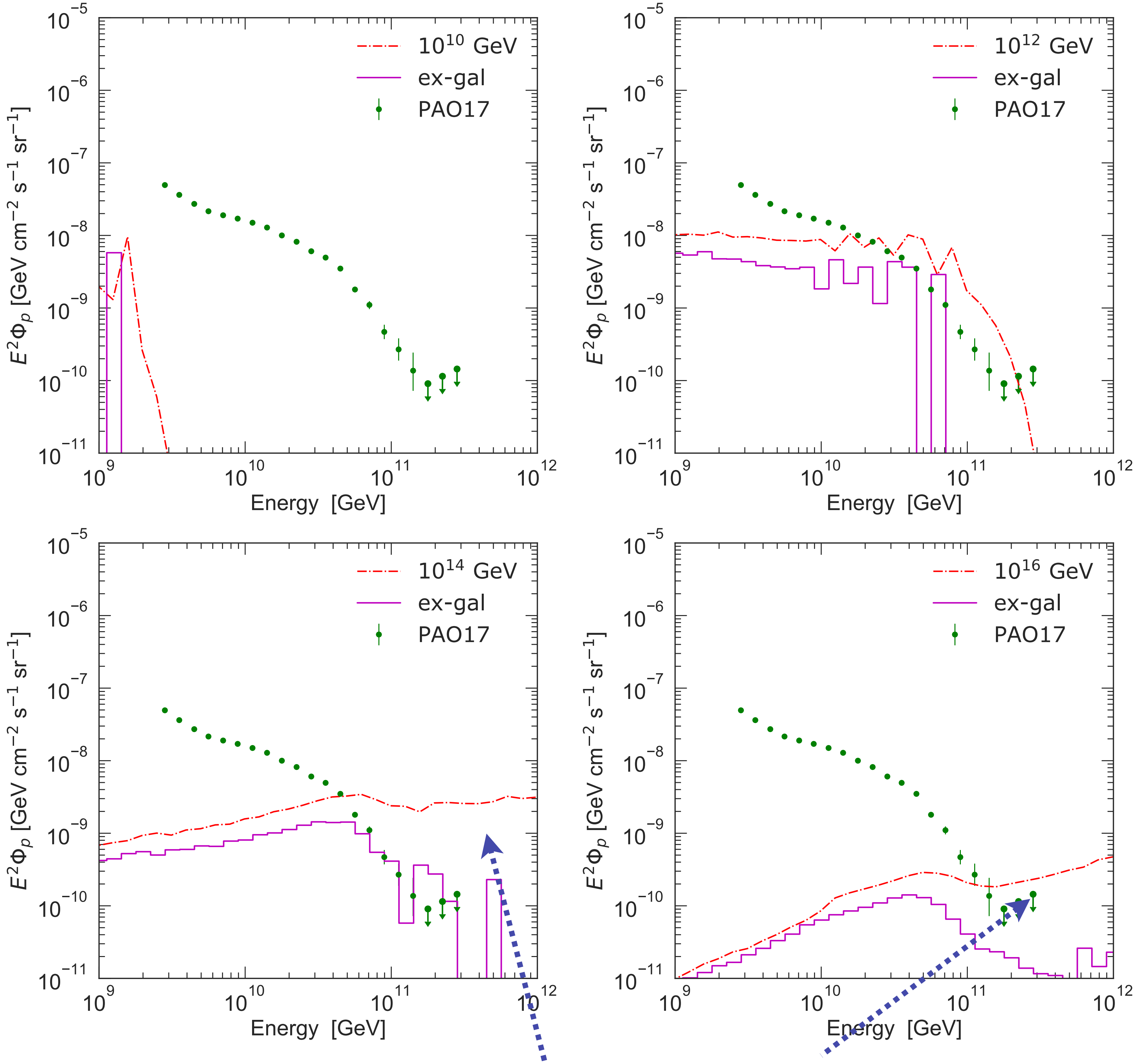
$\tau_{\rm dm} = 10^{27}$ s



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