Indirect searches on heavy dark matter decays and inflation

Koji Ishiwata

Kanazawa University

Based on

- JCAP 01 (2020) 003 (with O. Macias, S. Ando, M. Arimoto)
- arXiv:2207.05747 (with S. Ando, N. Hiroshima)

The 2nd DMNet International Symposium
“Direct and Indirect Detection of Dark Matter”

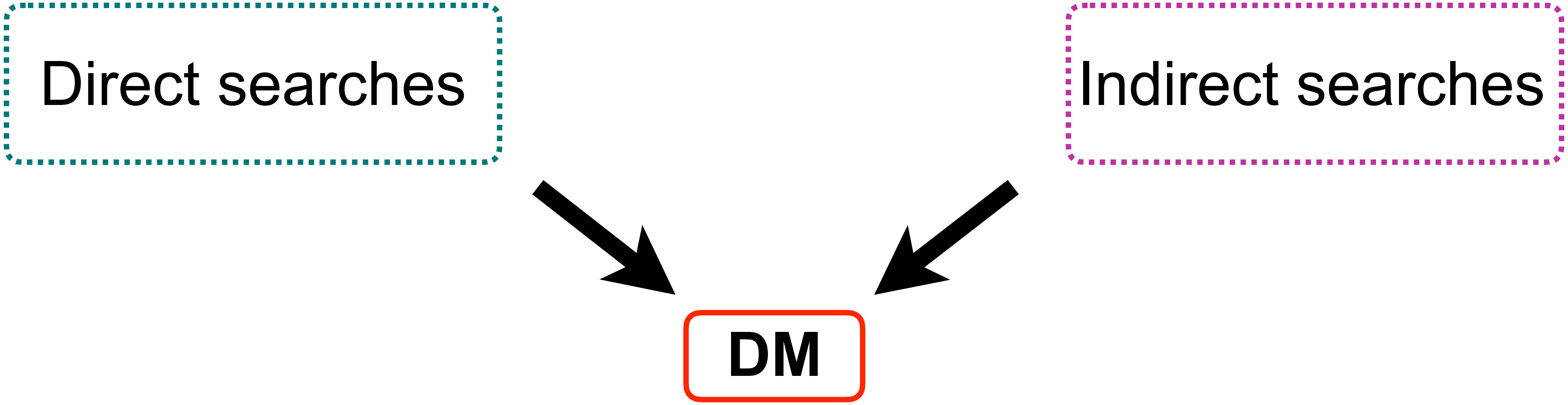
Heidelberg, September 15, 2022

1. Introduction

Dark matter (DM)

- Electrically neutral
- Non-baryonic
- Stable or sufficiently long-lived
- Non-relativistic
- $\Omega_{\rm DM} \simeq 0.26$
- $10^{-31}\ {\rm GeV} < m_{\rm dm} \lesssim M_{\rm Pl}$ or $10^{-14} < m_{\rm dm}/M_\odot \lesssim 10^{-12}$

Approaches from astro-particle physics and cosmology



Direct searches

Indirect searches

DM

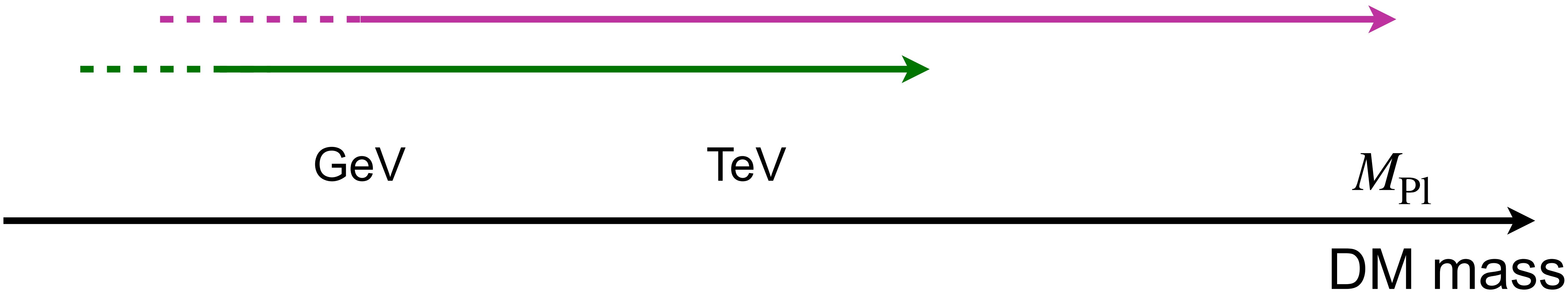
Approaches from astro-particle physics and cosmology

Direct searches

$\mathrm{DM}\ \mathrm{SM} \to \mathrm{DM}^{(\prime)}\ \mathrm{SM}^{(\prime)}$

Indirect searches

$\mathrm{DM}\ (\mathrm{DM}) \to \mathrm{SMs}$



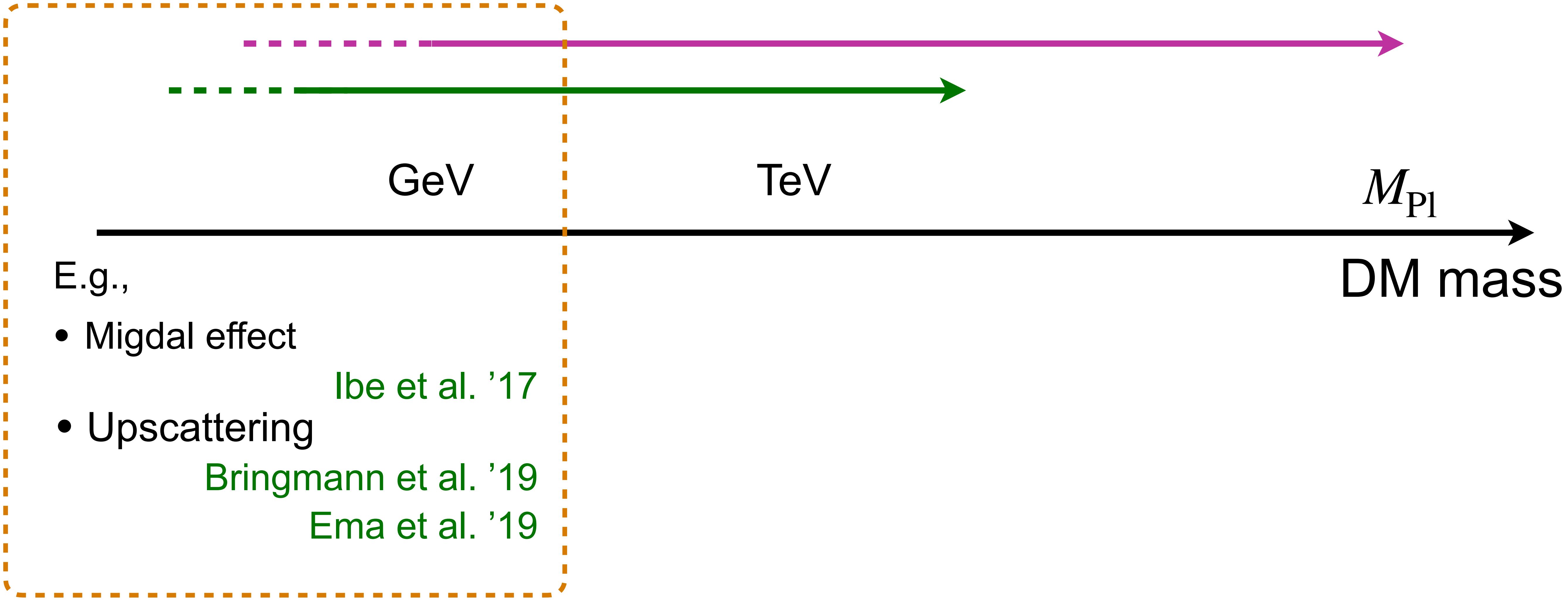
Approaches from astro-particle physics and cosmology

Direct searches

$$\mathrm{DM\ SM} \rightarrow \mathrm{DM}^{(\prime)}\ \mathrm{SM}^{(\prime)}$$

Indirect searches

$$\mathrm{DM\ (DM)} \rightarrow \mathrm{SMs}$$



GeV

TeV

M_{Pl}

DM mass

E.g.,

- Migdal effect

Ibe et al. ’17

- Upscattering

Bringmann et al. ’19

Ema et al. ’19

Approaches from astro-particle physics and cosmology

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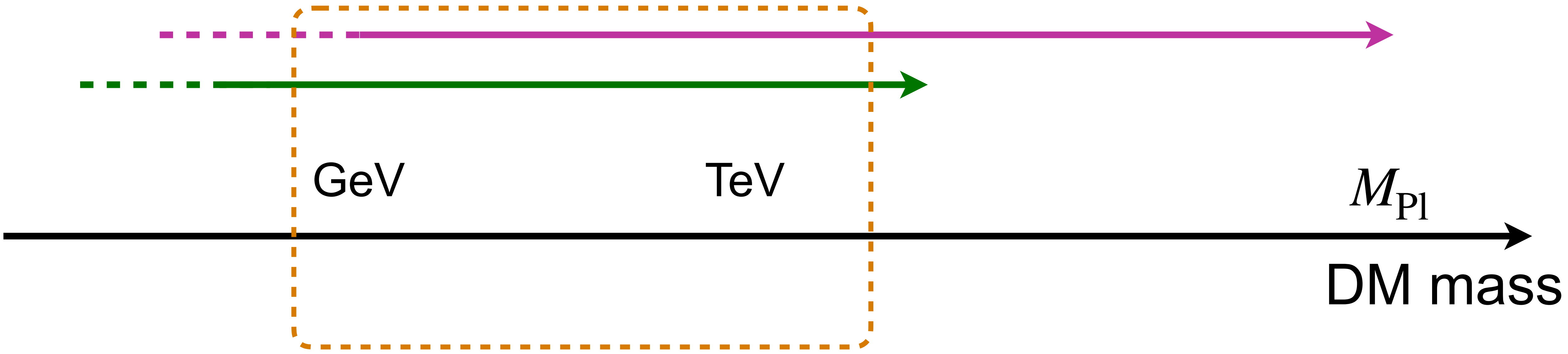
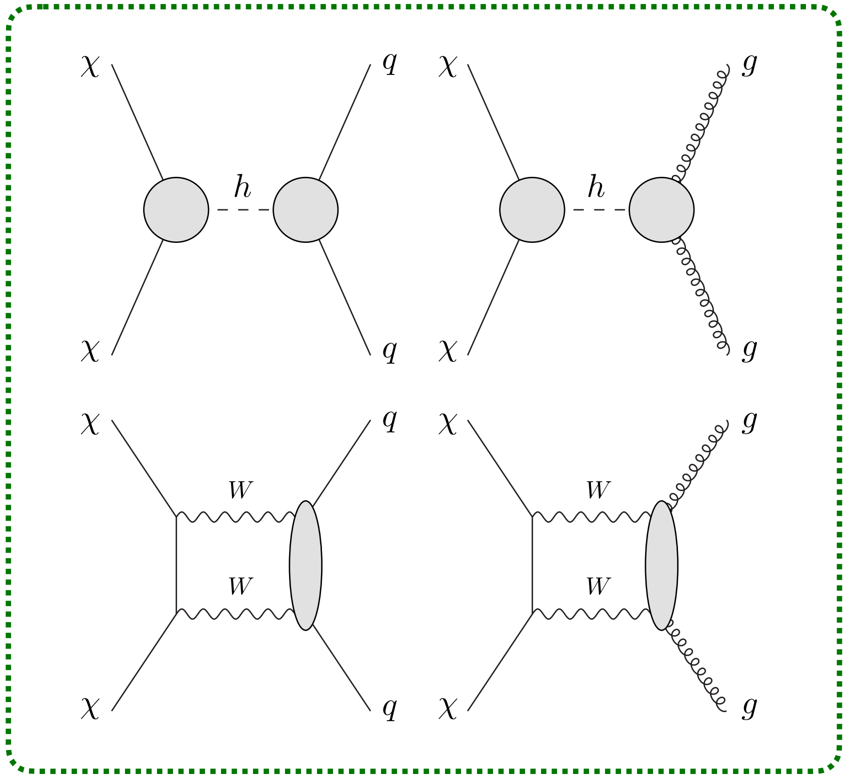
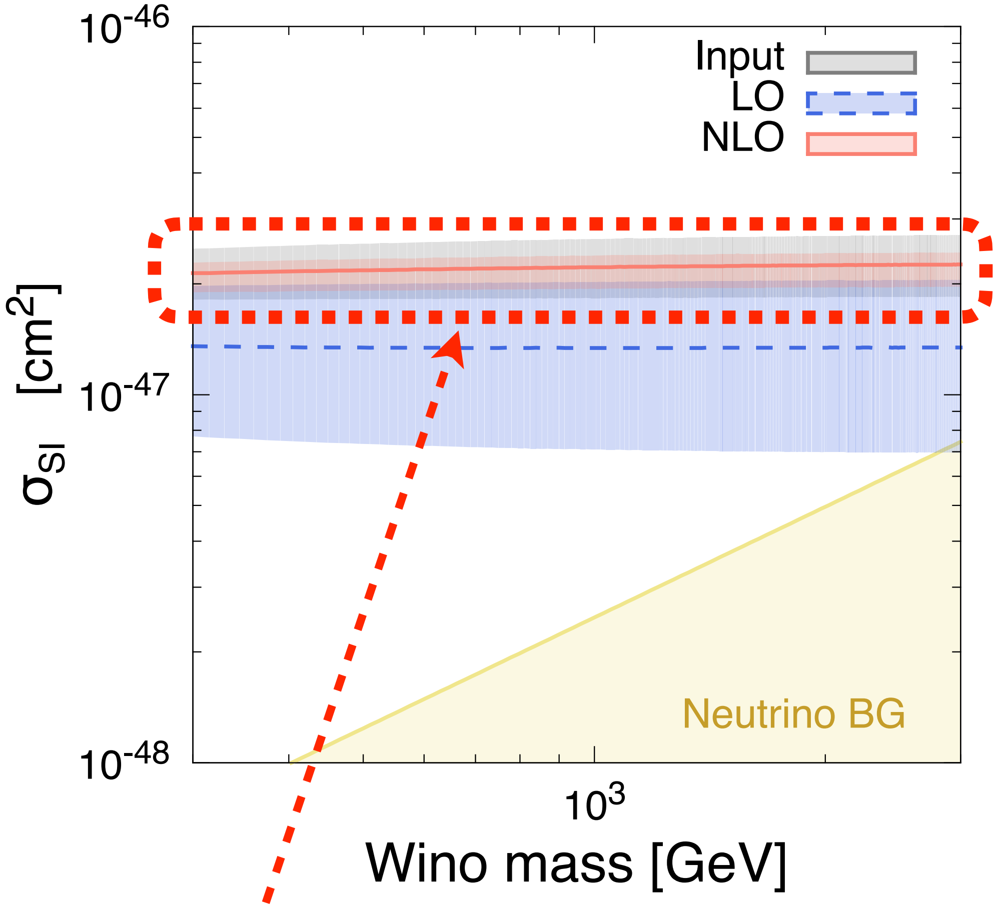


Motivated and
intensively searched

Spin-independent cross section @QCD NLO

Hisano, KI, Nagata '15



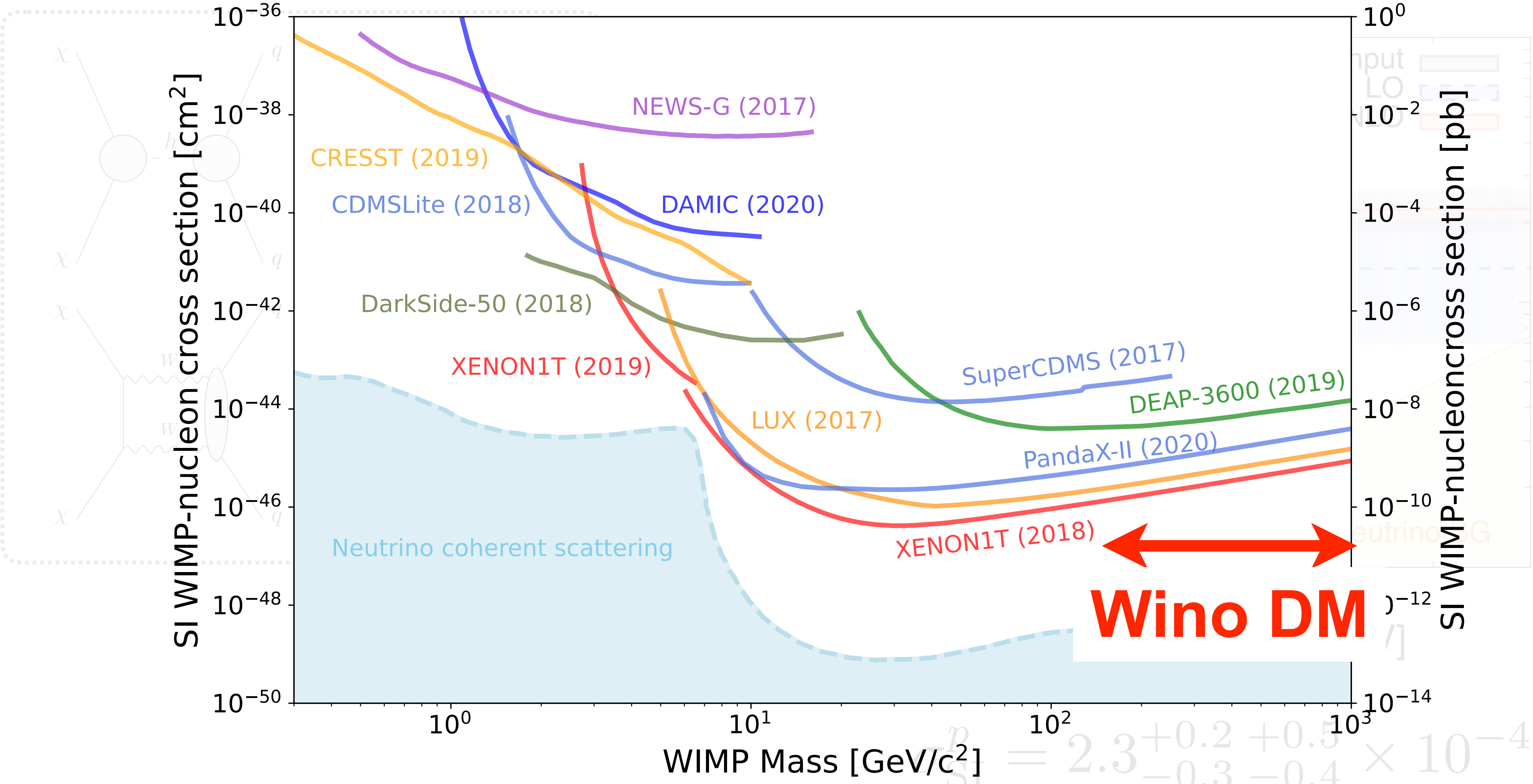


$$\sigma_{\rm SI}^{p} = 2.3^{+0.2}_{-0.3}{}^{+0.5}_{-0.4} \times 10^{-47}\,{\rm cm}$$

Direct searches

Spin-independent cross section @QCD NLO

Hisano, KI, Nagata ’15



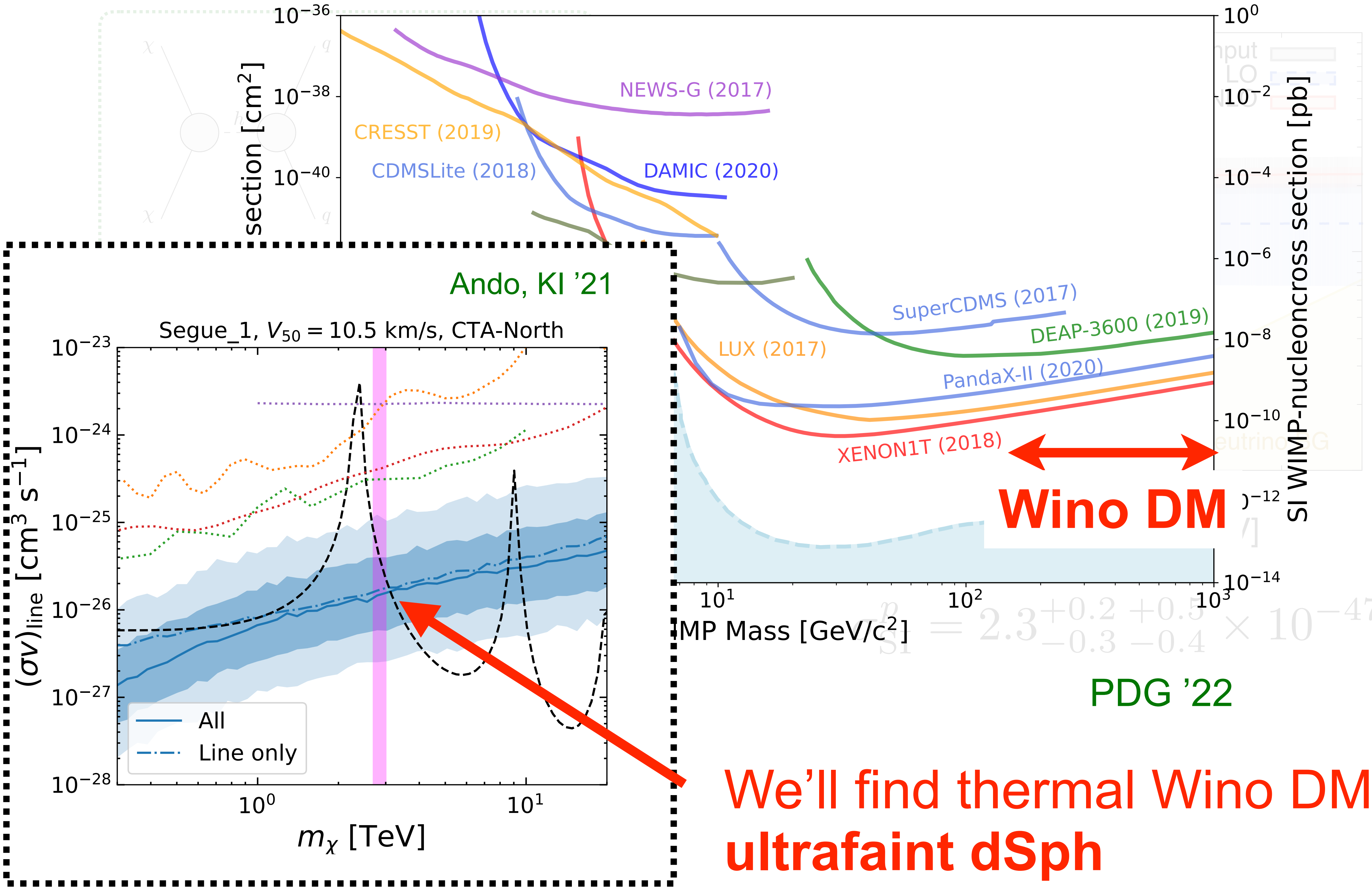
Wino DM

$\sigma_{\rm SI}^{p} = 2.3^{+0.2\,+0.5}_{-0.3\,-0.4} \times 10^{-47}$ cm

PDG ’22

Spin-independent cross section @QCD NLO

Hisano, KI, Nagata ’15



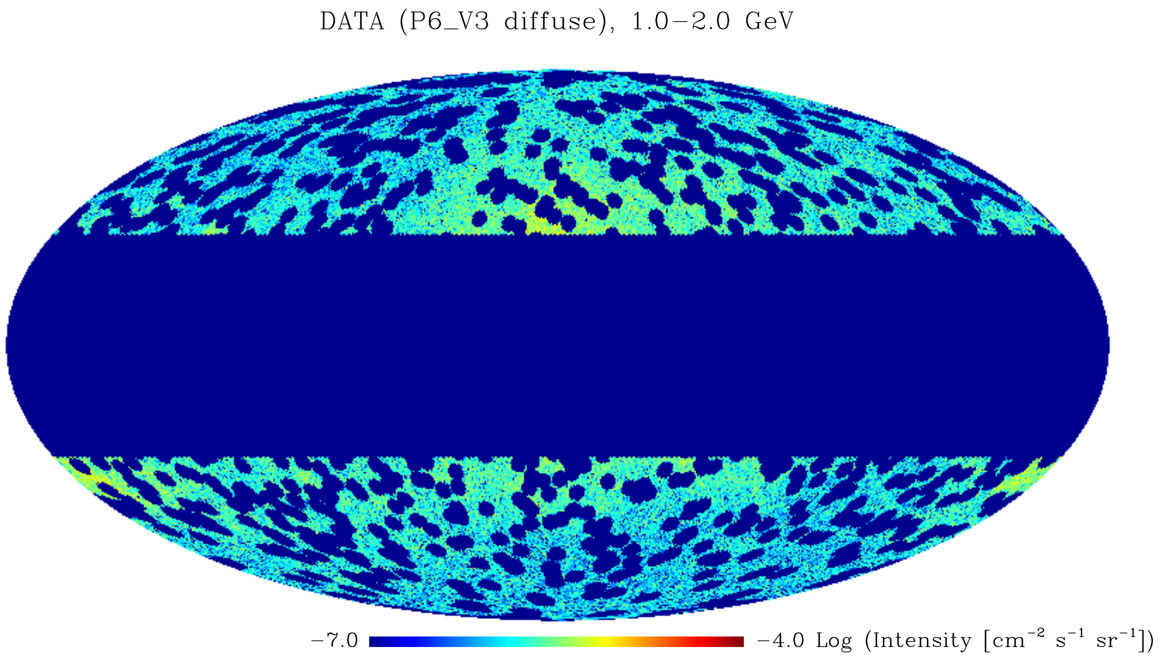
PDG ’22

We’ll find thermal Wino DM from **ultrafaint dSph**

Indirect searches

Ando, Benoit-Lévy, Komatsu '13
Fornengo, Regis '13
Ando '14
Xia, Cuoco, Branchini, Viel '15

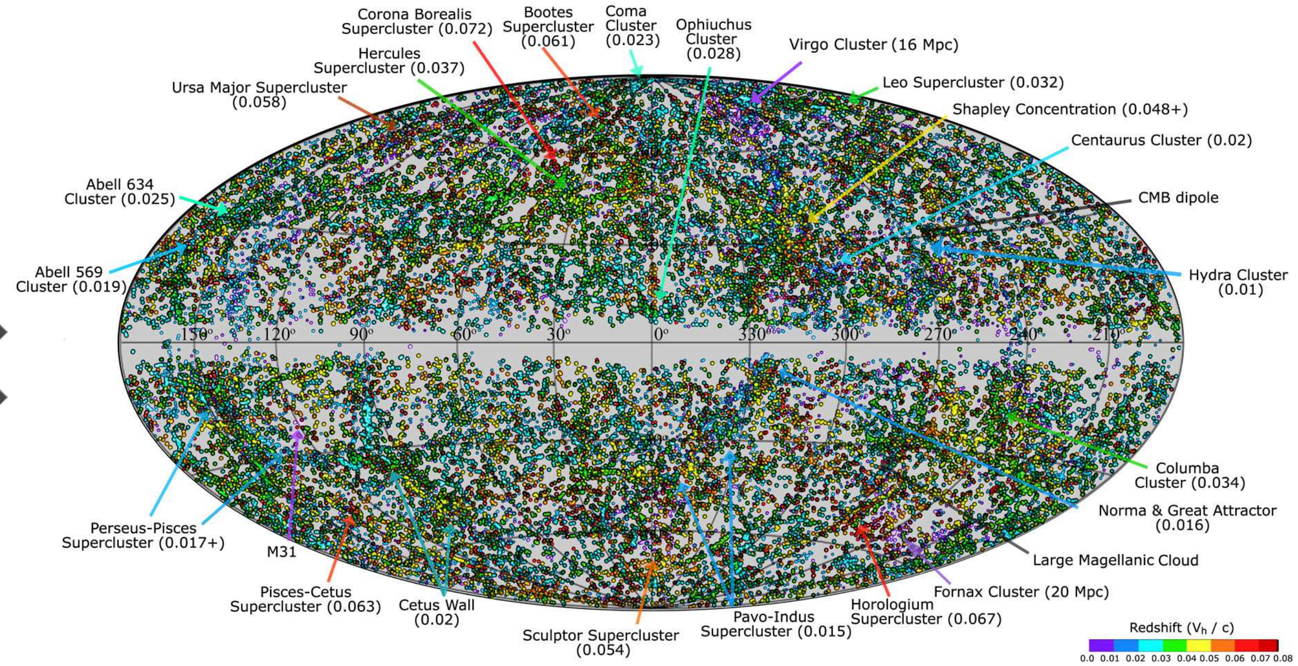
Fermi-LAT '12



Gamma rays

×

2MRS '11



Local galaxy distribution

Tomographic cross-correlation

→ Reducing the astrophysical BG

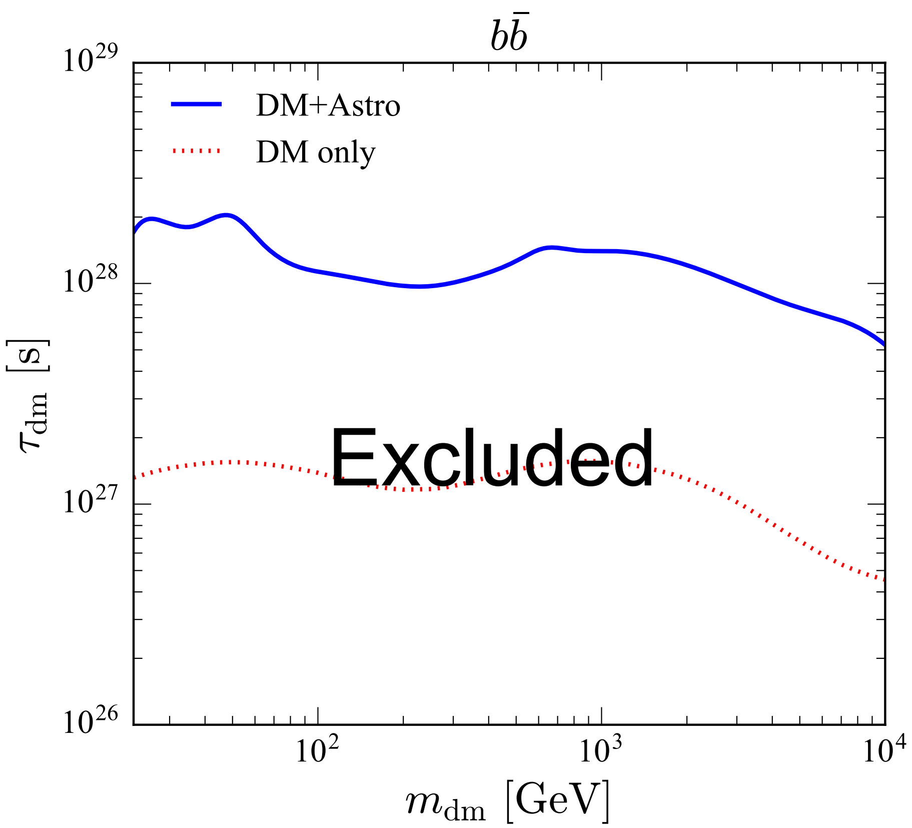
Indirect searches

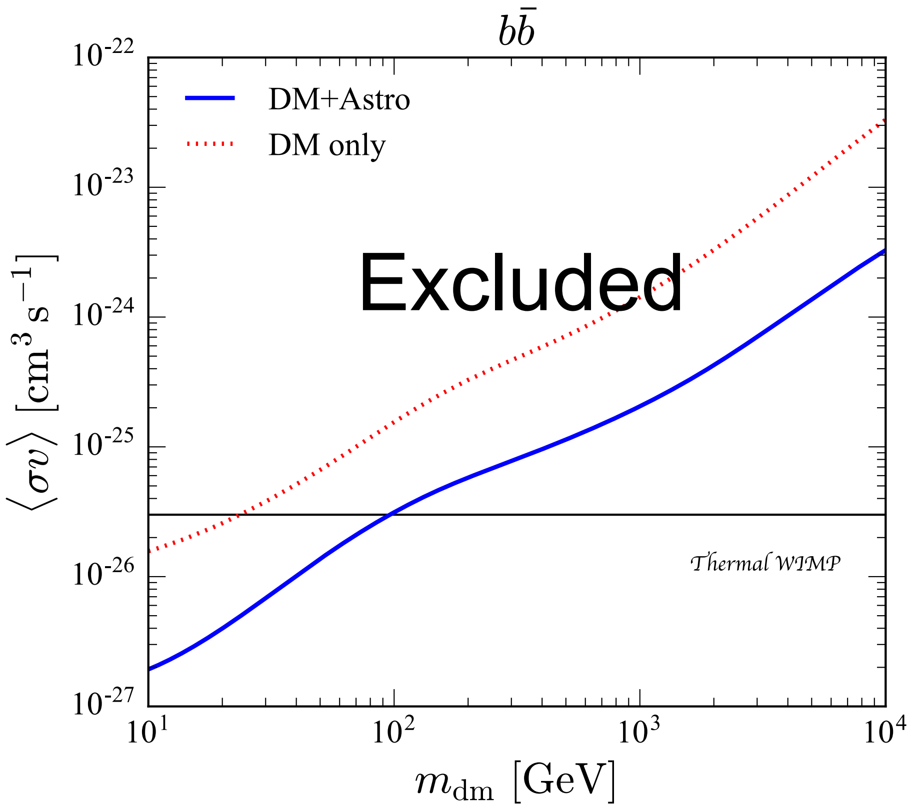
For $b\bar{b}$ channel

Decaying DM

Annihilating DM

Ando, KI '16





For more updates, see
K. Hayashi's talk

Approaches from astro-particle physics and cosmology

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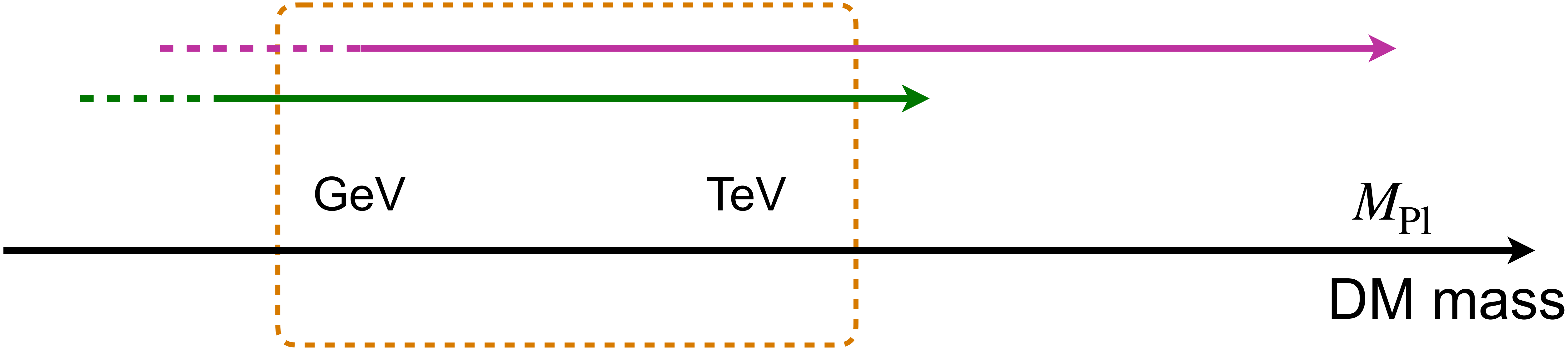

Motivated and
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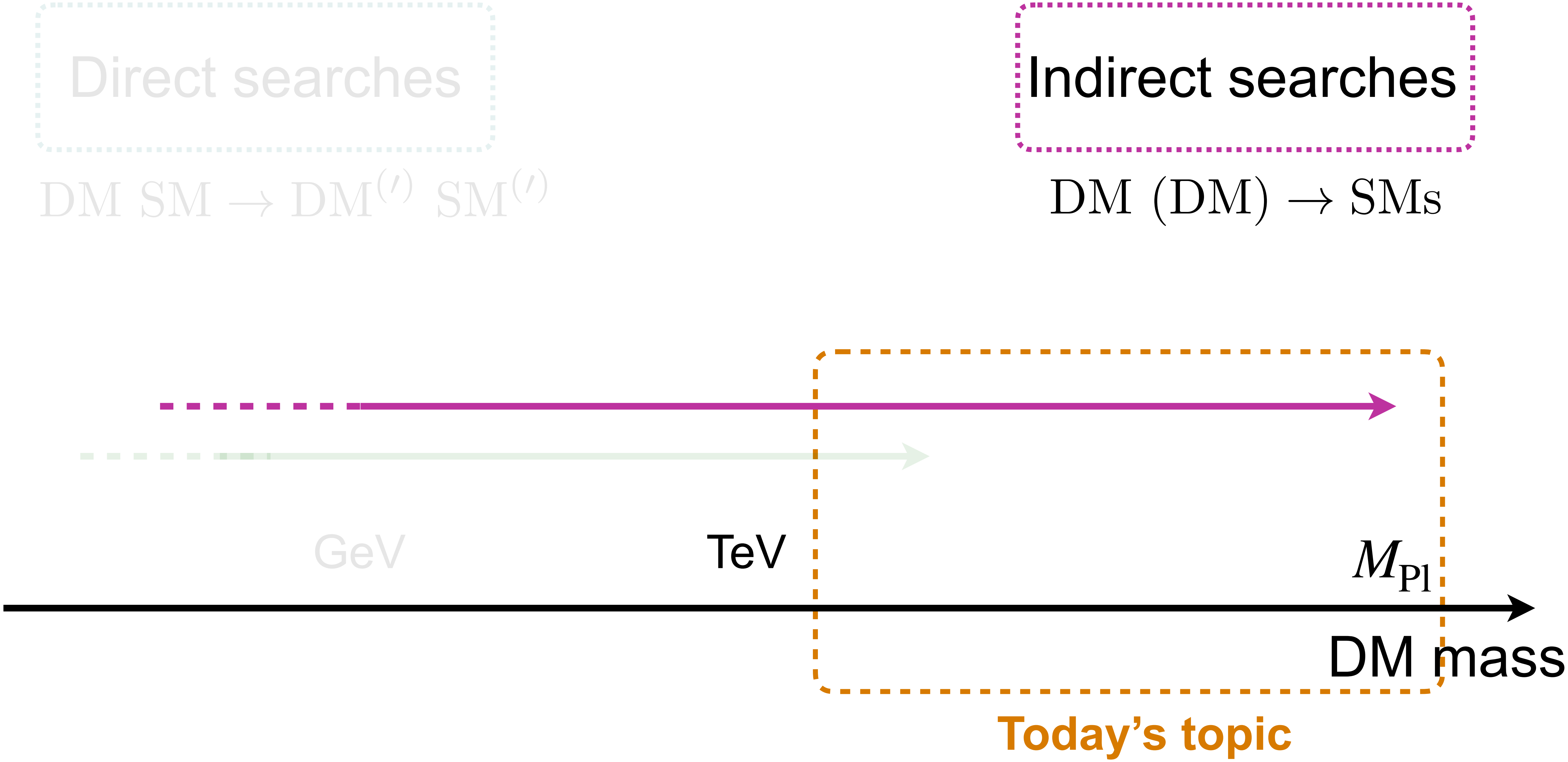


Direct searches

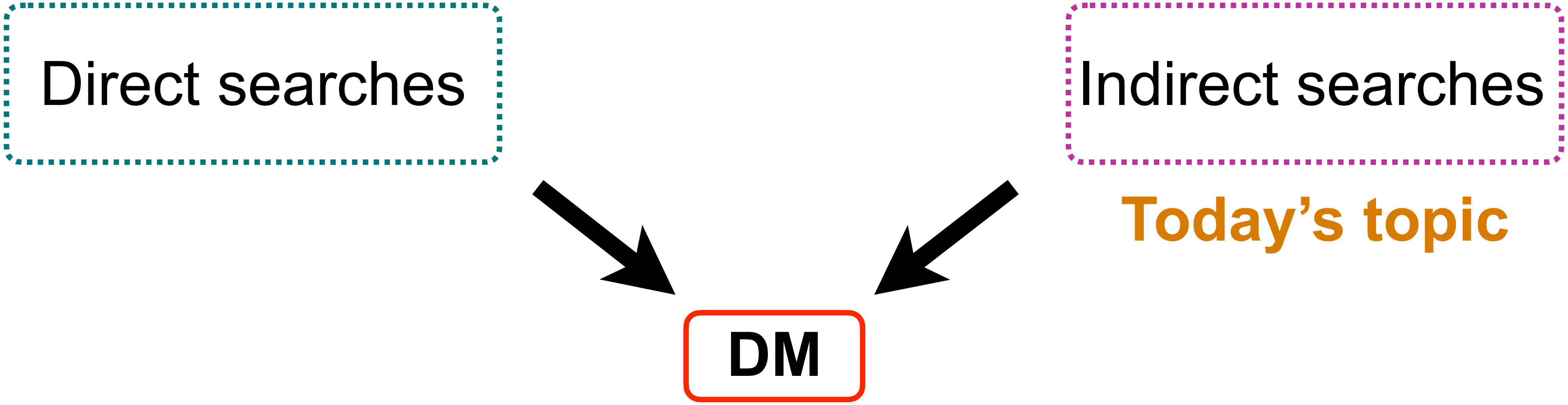
$\mathrm{DM\ SM} \to \mathrm{DM}^{(\prime)}\ \mathrm{SM}^{(\prime)}$

Indirect searches

$\mathrm{DM\ (DM)} \to \mathrm{SMs}$

Today's topic

Approaches from astro-particle physics and cosmology



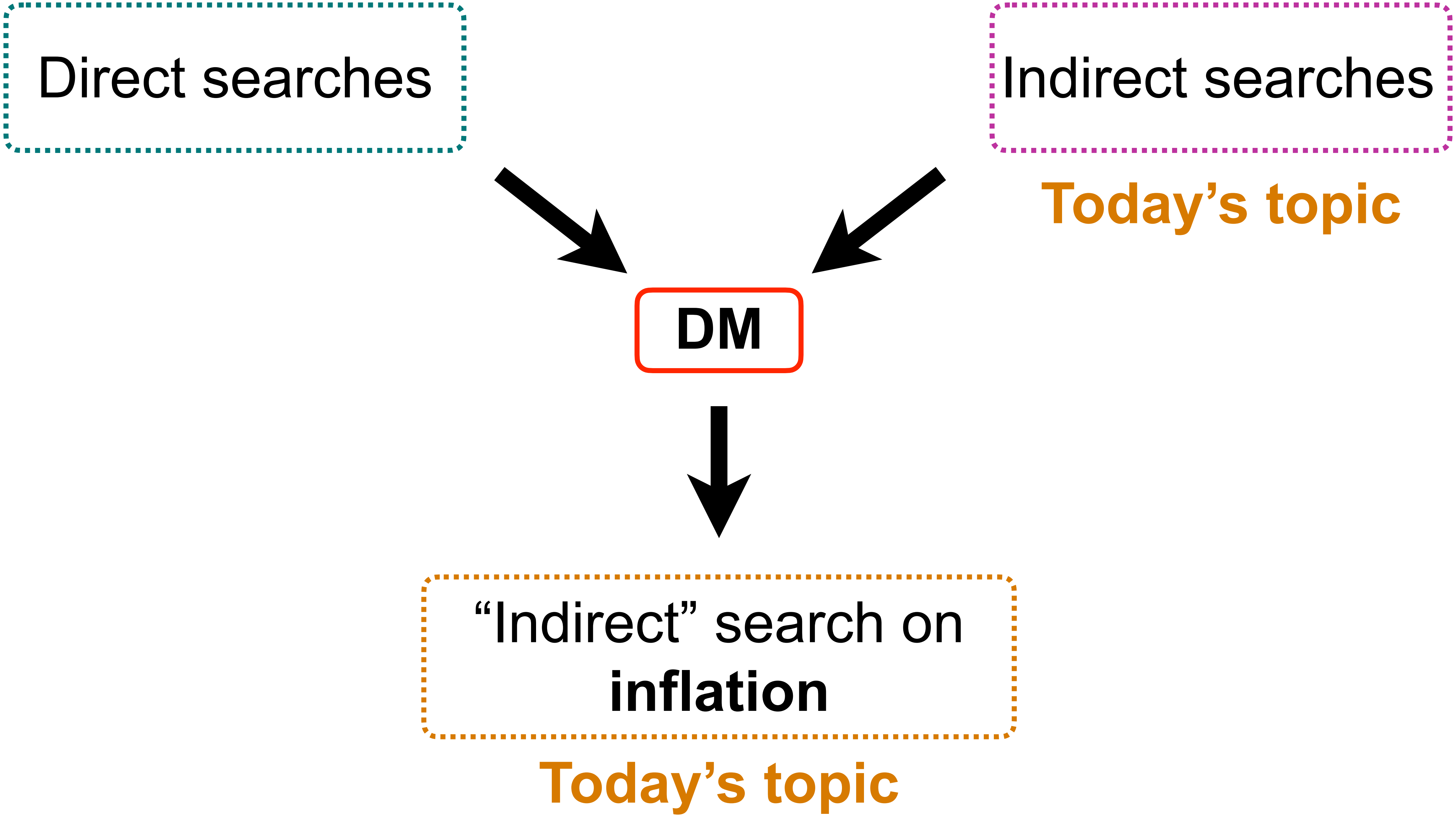
Direct searches

Indirect searches

Today's topic

DM

Approaches from astro-particle physics and cosmology



Direct searches

Indirect searches

Today’s topic

DM

“Indirect” search on **inflation**

Today’s topic

Outline

1. Introduction
2. Cosmic rays (CRs) from decaying heavy DM
3. Primordial curvature perturbations
4. Conclusion

2. CRs from decaying heavy 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

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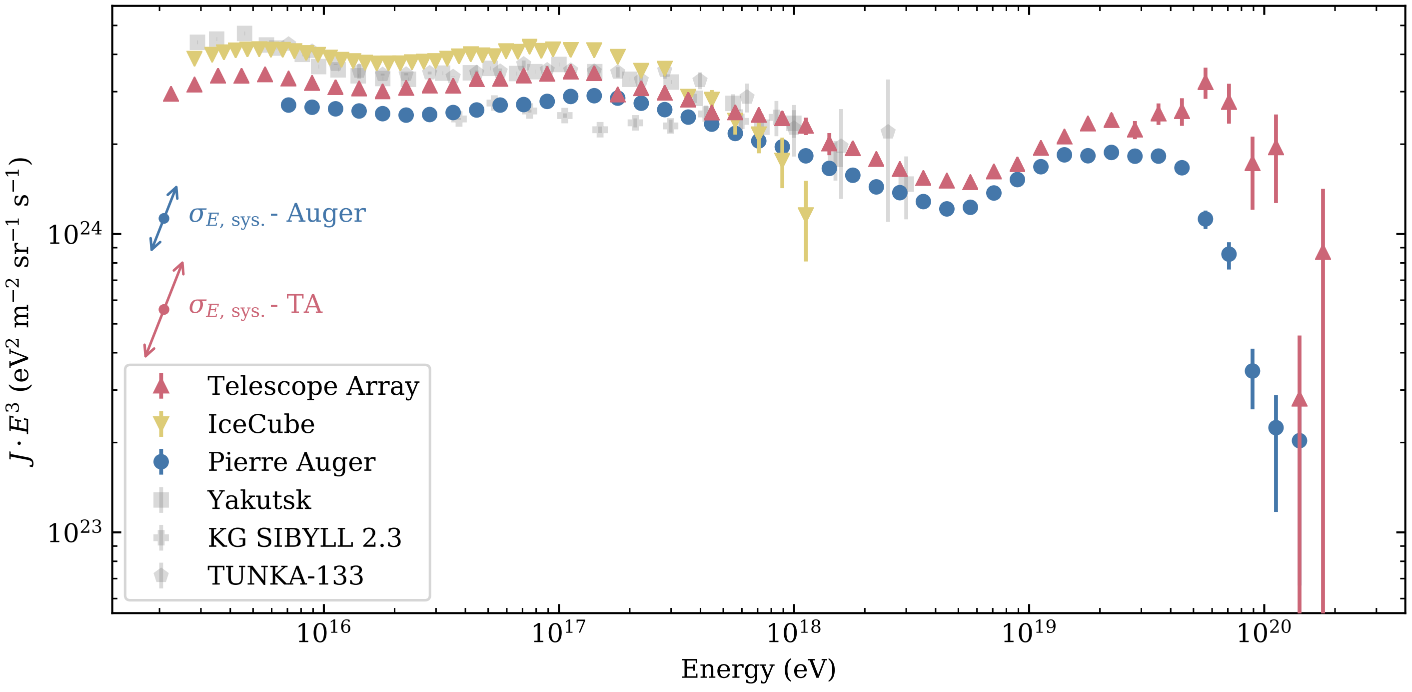
But no comprehensive analysis

Let’s use all data to constrain DM

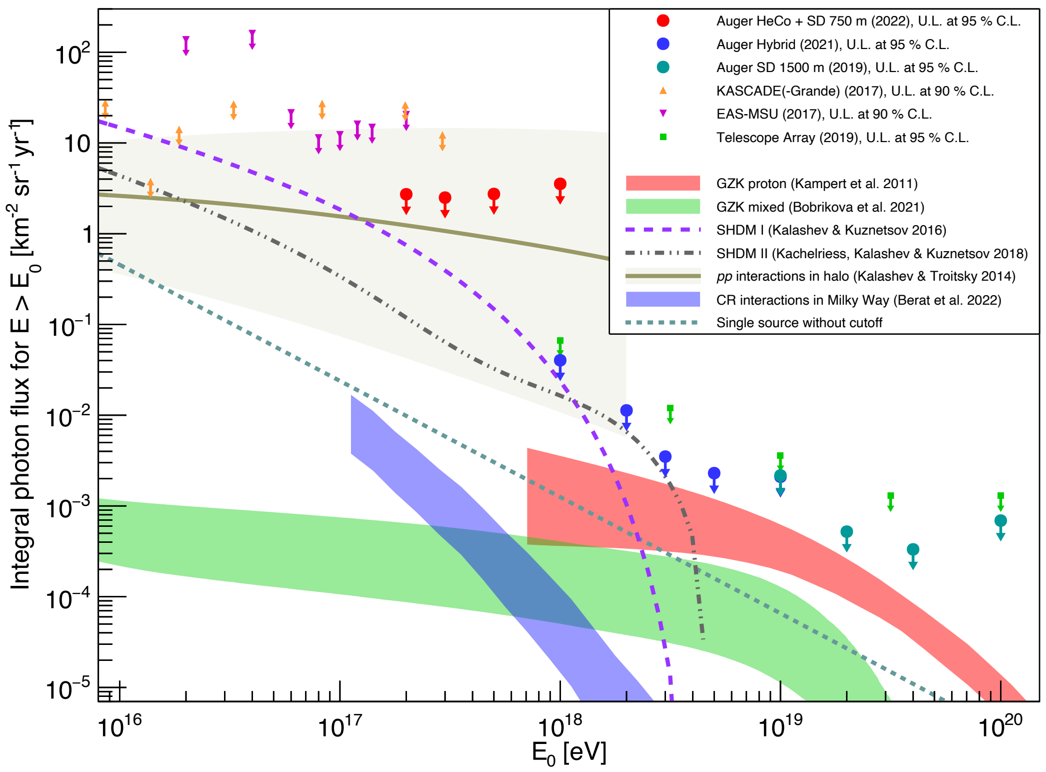
Multimessenger astrophysical data

CRs



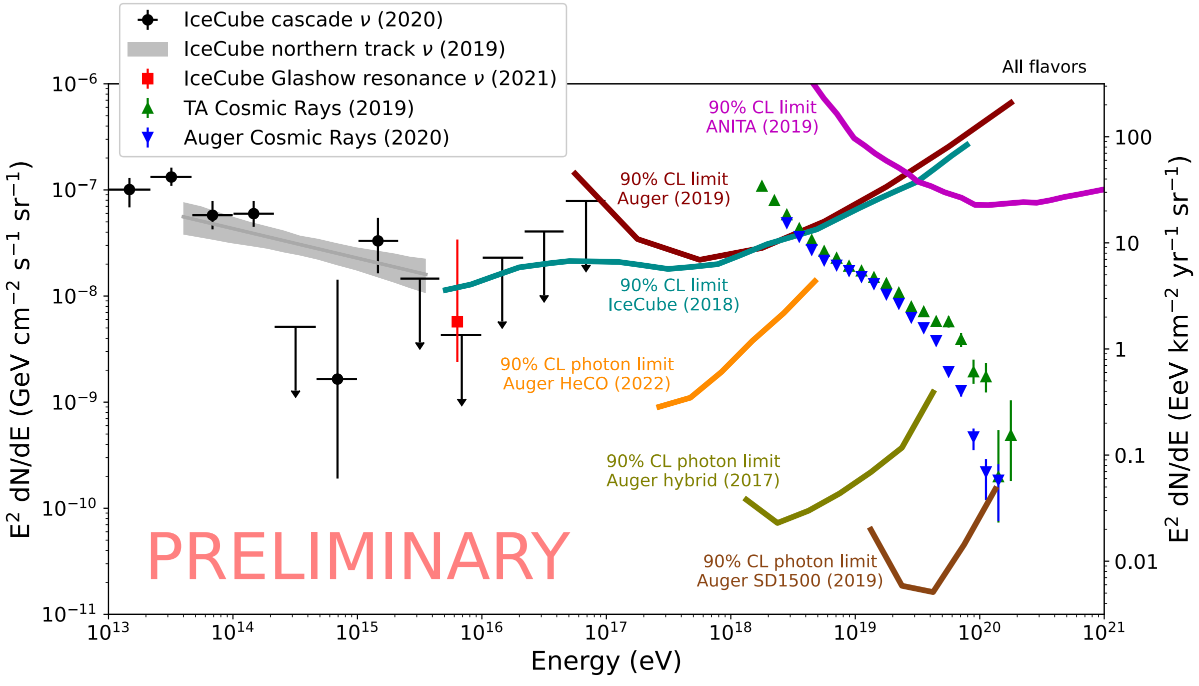
Coleman et al. (Snowmass) ’22

Integrated gamma flux



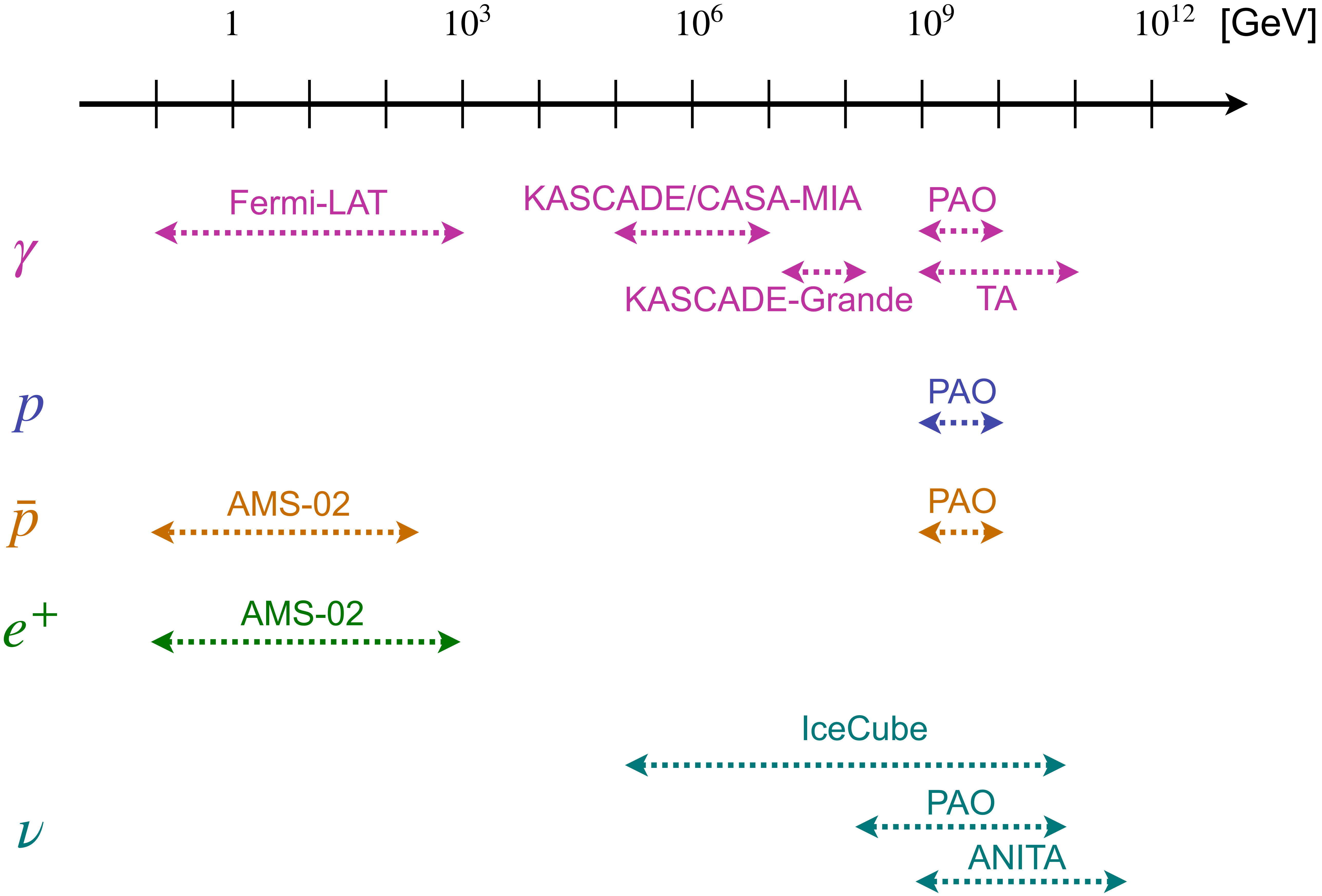
Pierre Auger Observatory (PAO) ’22

Neutrinos

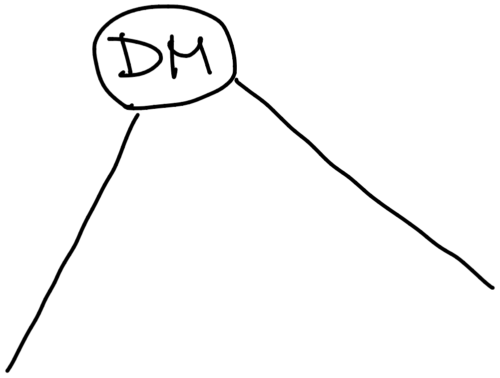


Coleman et al. (Snowmass) ’22

Multimessenger astrophysical data



Heavy DM decay



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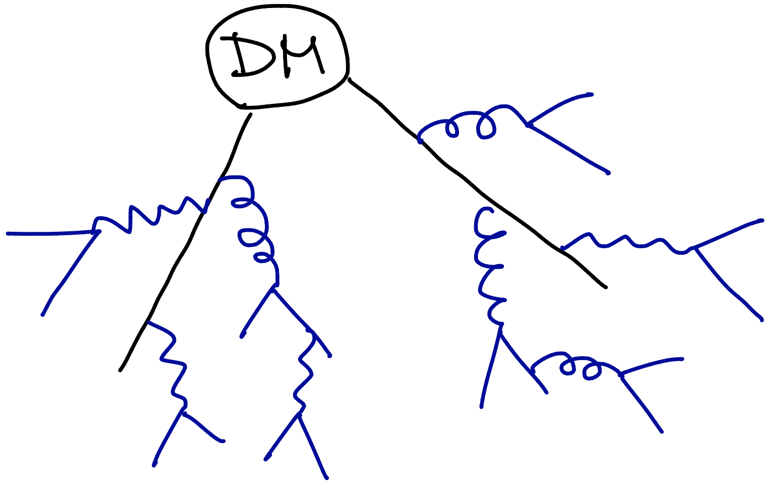
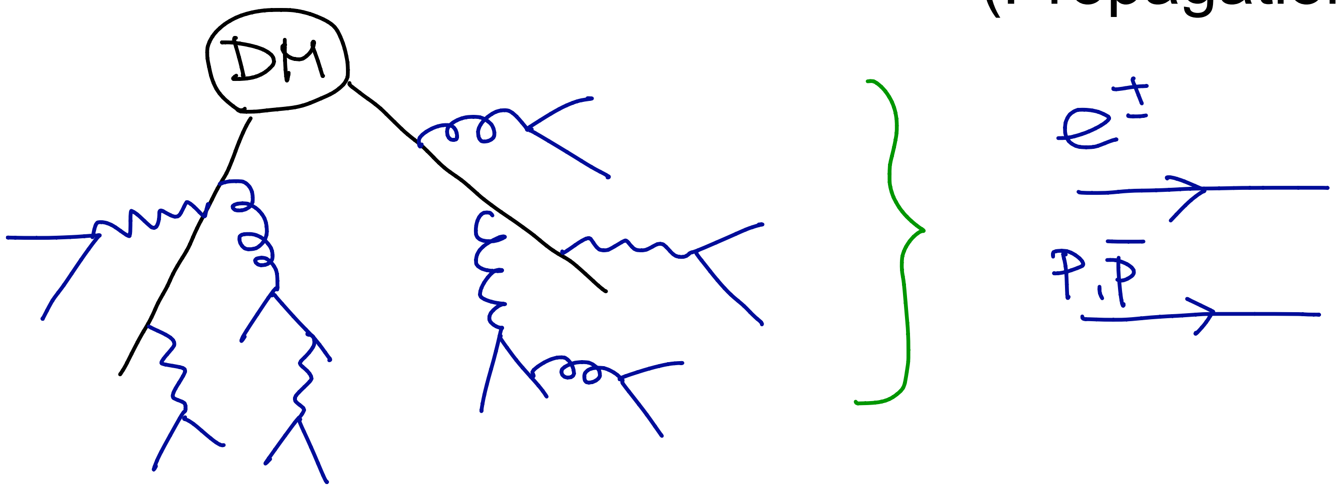


QCD/EW cascades

Heavy DM decay

(Propagation)



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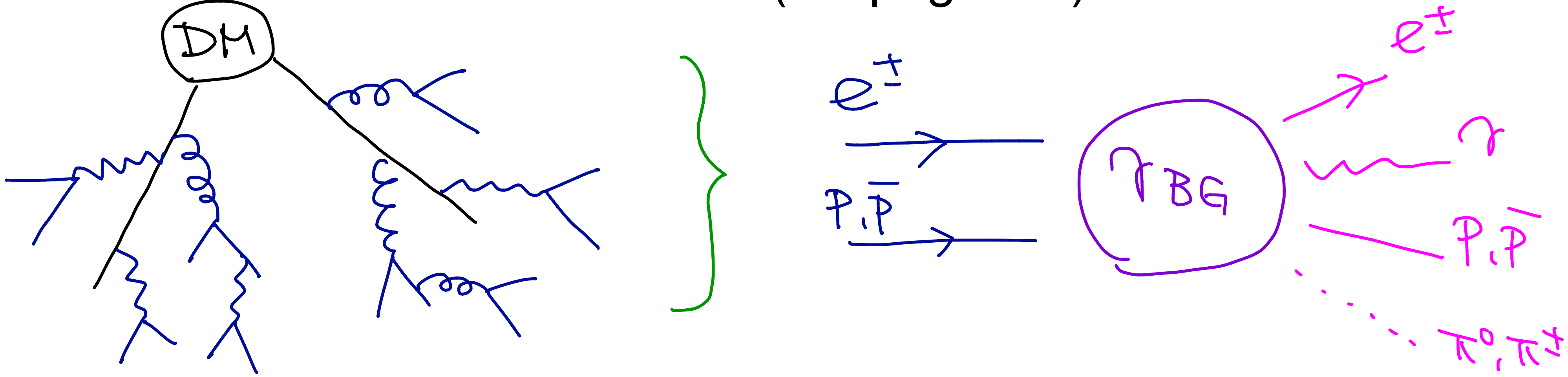
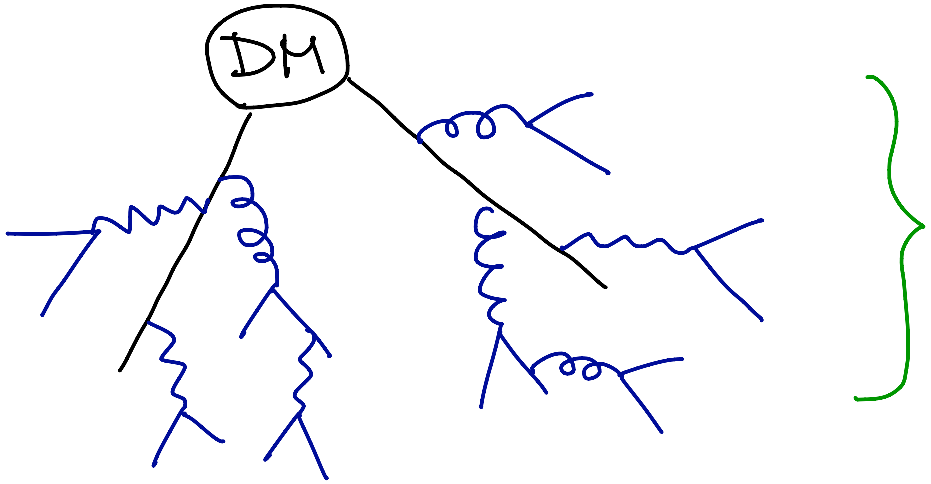


UHECRs

QCD/EW cascades

Hadronic/EM cascades

Heavy DM decay



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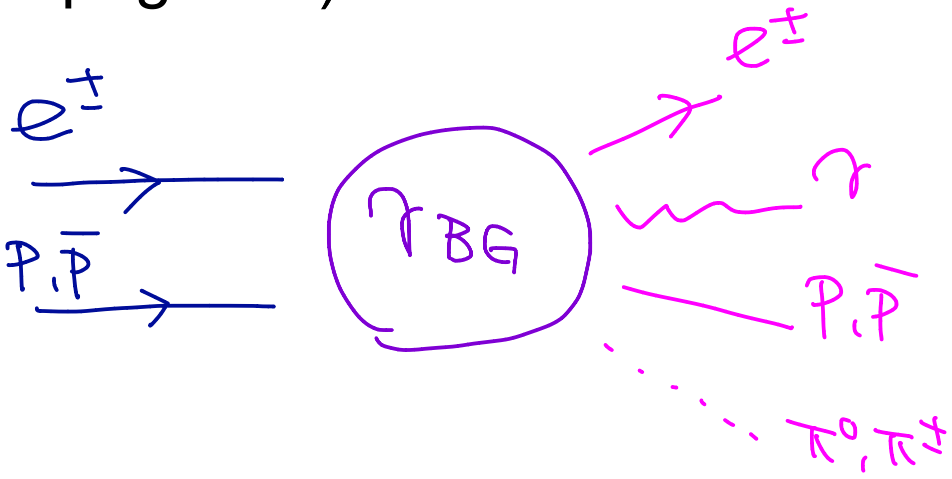

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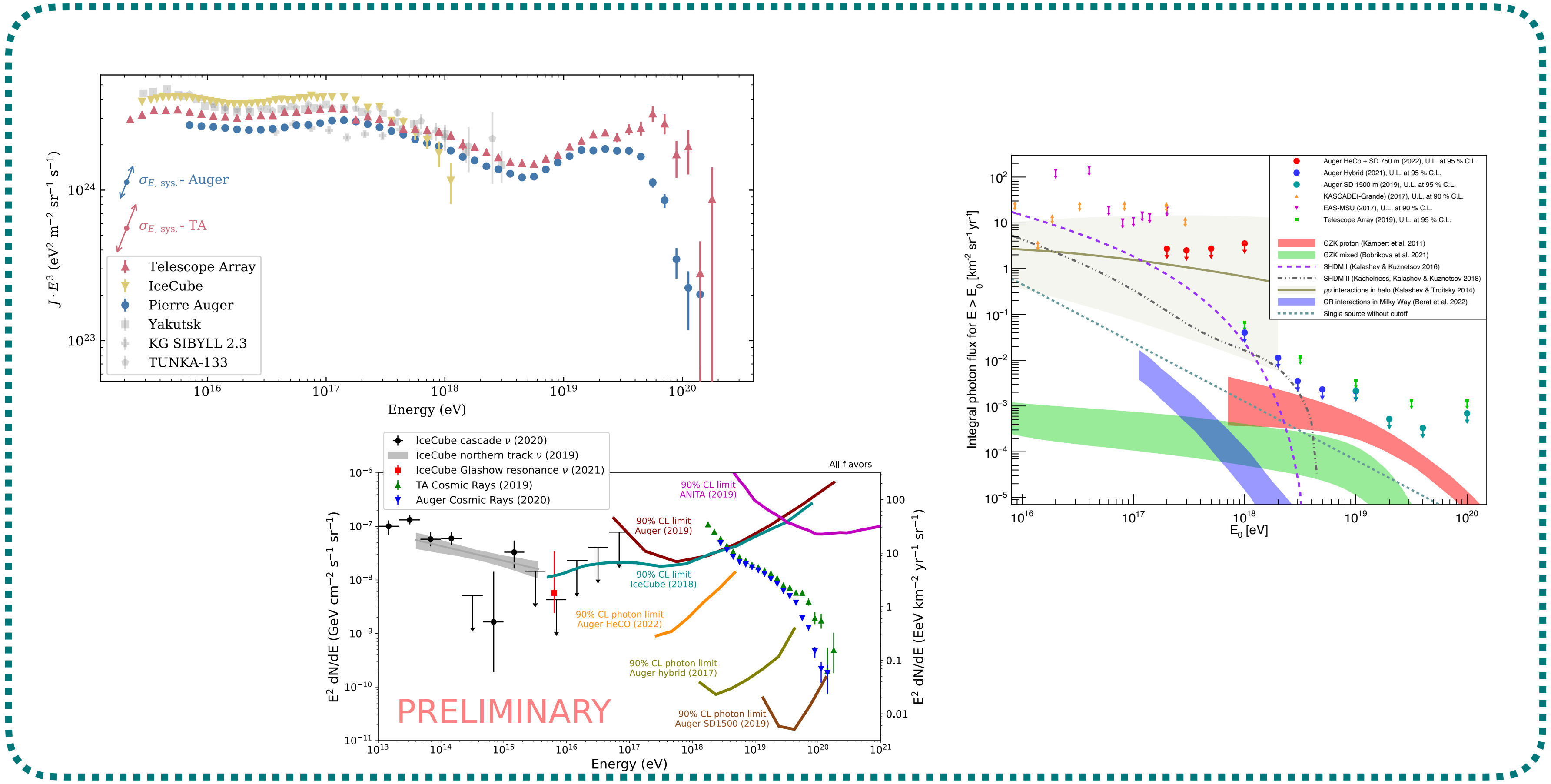
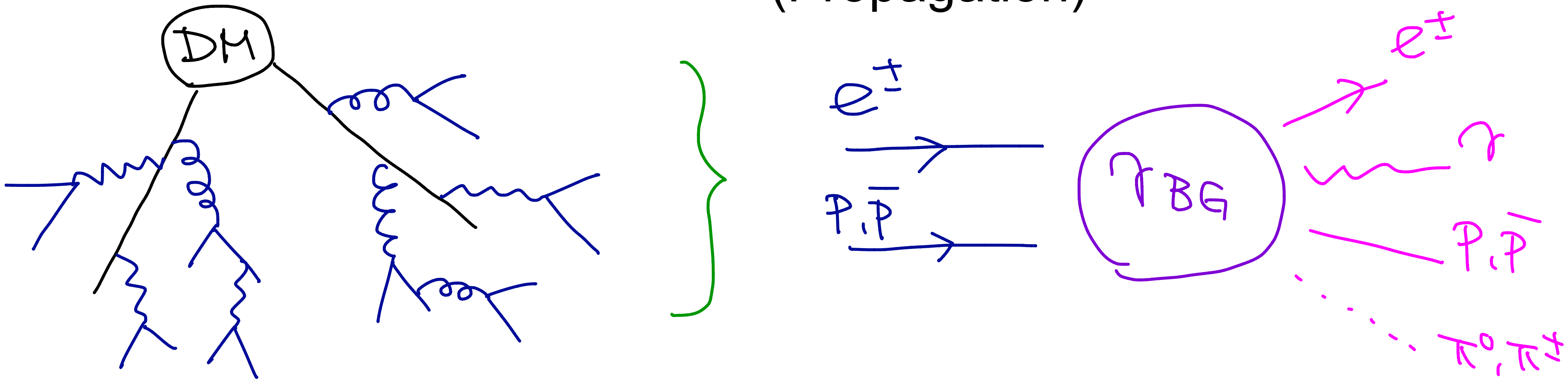


Heavy DM decay

(Propagation)



UHECRs

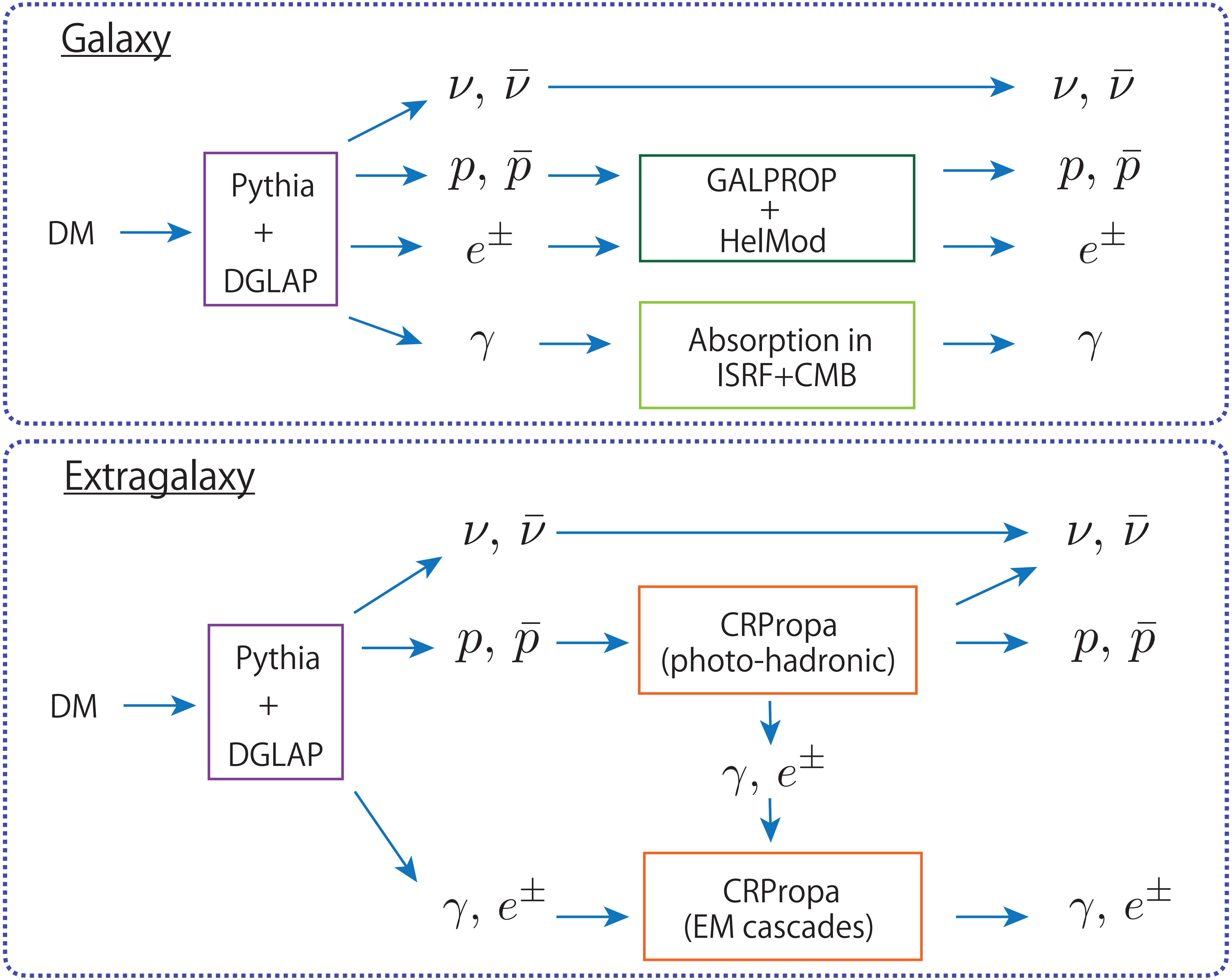
QCD/EW cascades

Hadronic/EM cascades

We need to simulate

- Cascades at the prompt decay
- Cascades during the propagation

Outline of the simulation



Galaxy

DM → Pythia + DGLAP → $\nu,\ \bar{\nu}$ → $\nu,\ \bar{\nu}$

$p,\ \bar{p}$ → GALPROP + HelMod → $p,\ \bar{p}$

$e^{\pm}$ → GALPROP + HelMod → $e^{\pm}$

γ → Absorption in ISRF+CMB → γ

Extragalaxy

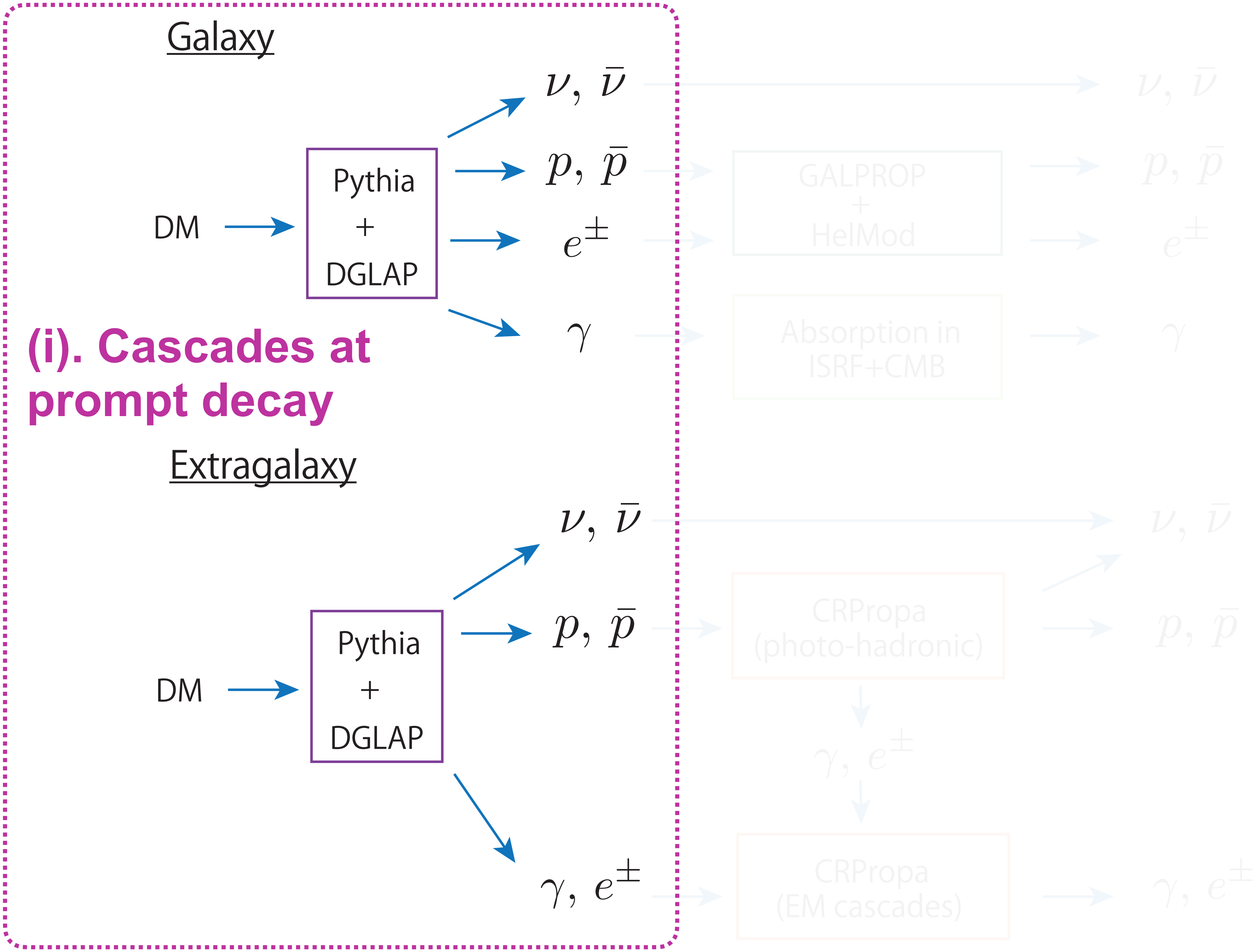
DM → Pythia + DGLAP → $\nu,\ \bar{\nu}$ → $\nu,\ \bar{\nu}$

$p,\ \bar{p}$ → CRPropa (photo-hadronic) → $\nu,\ \bar{\nu}$; $p,\ \bar{p}$

CRPropa (photo-hadronic) → $\gamma,\ e^{\pm}$ → CRPropa (EM cascades)

$\gamma,\ e^{\pm}$ → CRPropa (EM cascades) → $\gamma,\ e^{\pm}$

Outline of the simulation



Galaxy

DM

Pythia
+
DGLAP

$\nu,\ \bar{\nu}$

$p,\ \bar{p}$

$e^{\pm}$

γ

GALPROP
+
HelMod

Absorption in
ISRF+CMB

$\nu,\ \bar{\nu}$

$p,\ \bar{p}$

$e^{\pm}$

γ

(i). Cascades at prompt decay

Extragalaxy

DM

Pythia
+
DGLAP

$\nu,\ \bar{\nu}$

$p,\ \bar{p}$

$\gamma,\ e^{\pm}$

CRPropa
(photo-hadronic)

$\gamma,\ e^{\pm}$

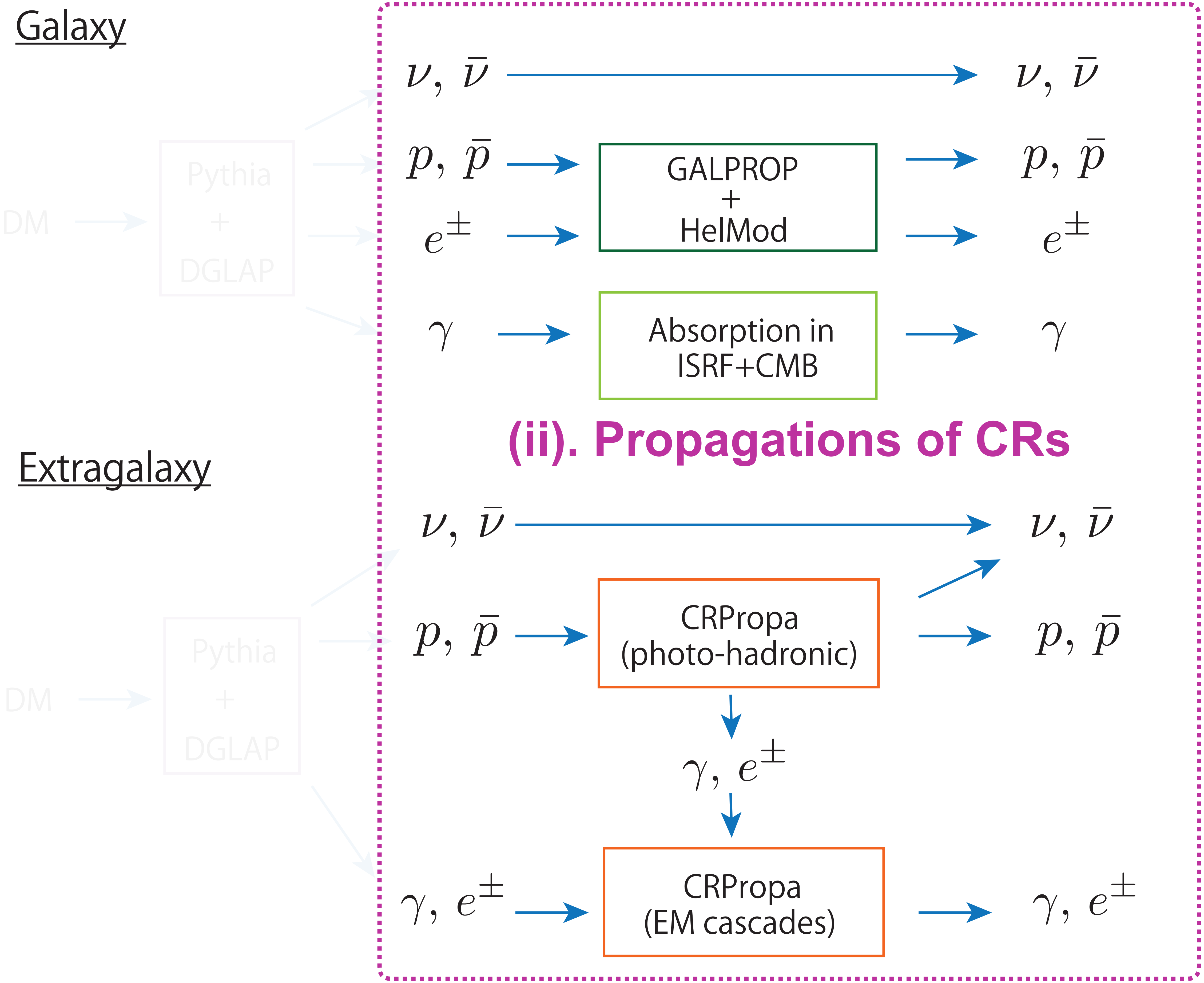
CRPropa
(EM cascades)

$\nu,\ \bar{\nu}$

$p,\ \bar{p}$

$\gamma,\ e^{\pm}$

Outline of the simulation



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$e^{\pm}$ → GALPROP + HelMod → $e^{\pm}$

γ → Absorption in ISRF+CMB → γ

(ii). Propagations of CRs

Extragalaxy

DM → Pythia + DGLAP

$\nu,\ \bar{\nu}$ → $\nu,\ \bar{\nu}$

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CRPropa (photo-hadronic) → $\nu,\ \bar{\nu}$

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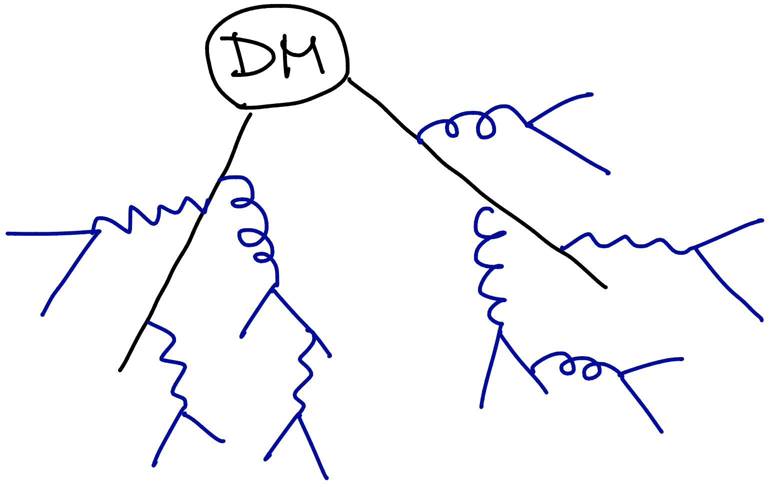
(i). Cascades at prompt decay

Heavy DM decay



QCD/EW cascades

↑

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) Eqs.

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

(i). Cascades at prompt decay

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

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

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

(i). Cascades at prompt decay

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

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

Fragmentation functions of the hadrons h by solving DGLAP Eqs.

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

Kniehl, Kramer, Potter ’00

Kretzer ’00

Albino, Kniehl, Kramer ’05

Hirai, Kumano, Nagai, Sudoh ’07

Hirai, Kumano ’12

(i). Cascades at prompt decay

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

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

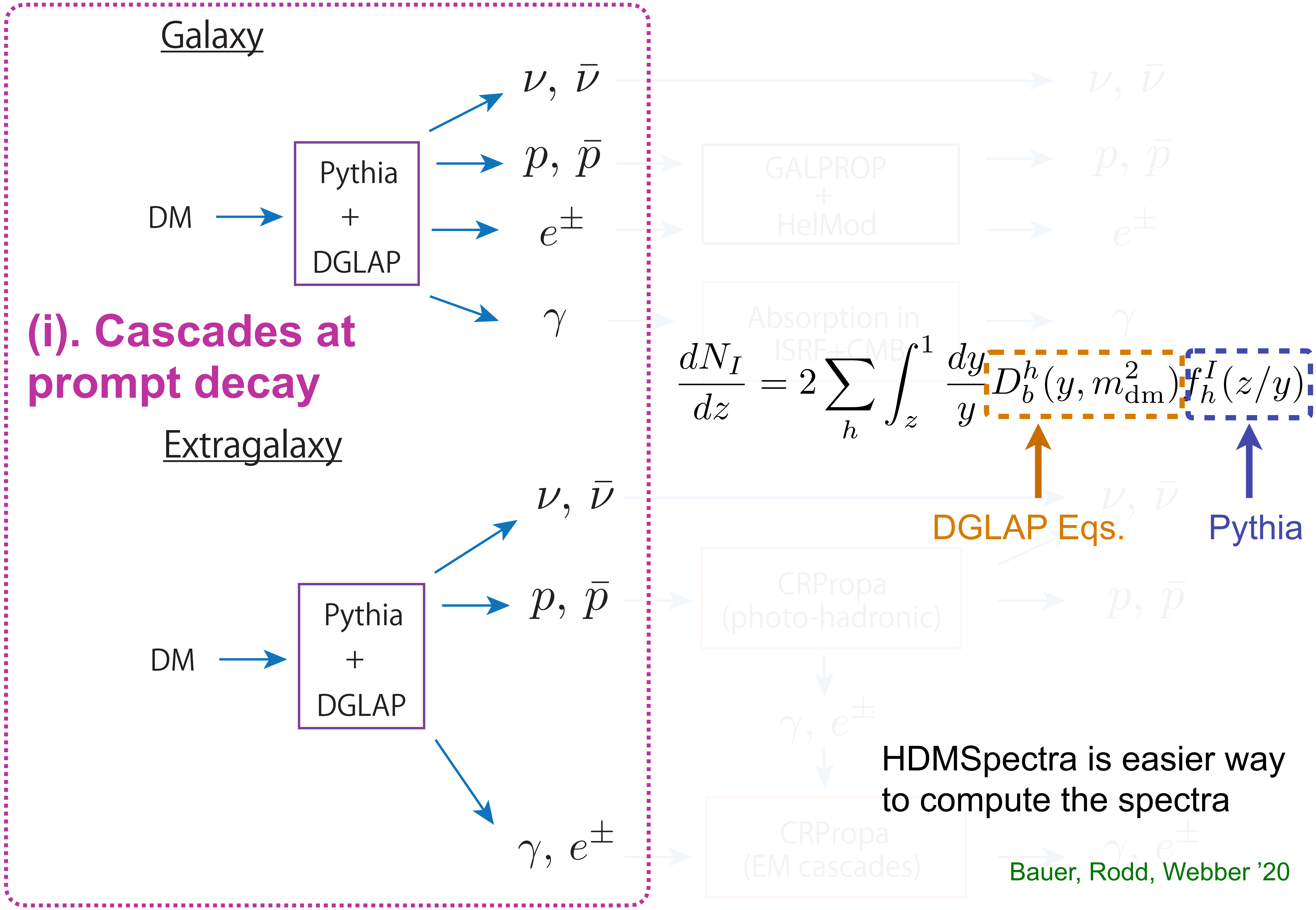
$$z = 2E_I/m_{\rm dm}$$

Distributions function of stable particles I from the hadron decays, given by Pythia

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

Sjstrand et al. ’15

Outline of the simulation



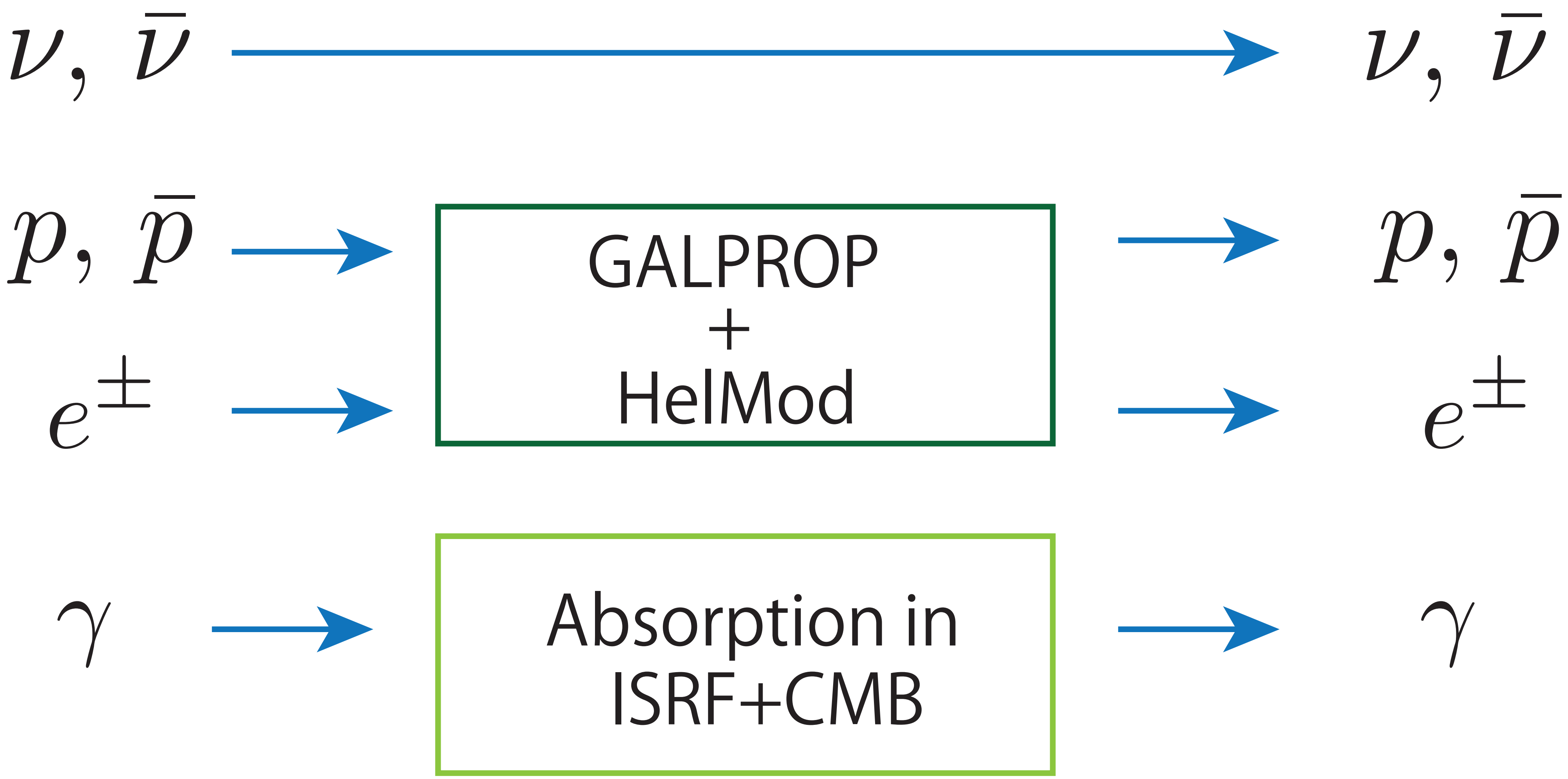
(i). Cascades at prompt decay

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

HDMSpectra is easier way to compute the spectra

Bauer, Rodd, Webber '20

Propagation of CRs in the ***Galaxy***



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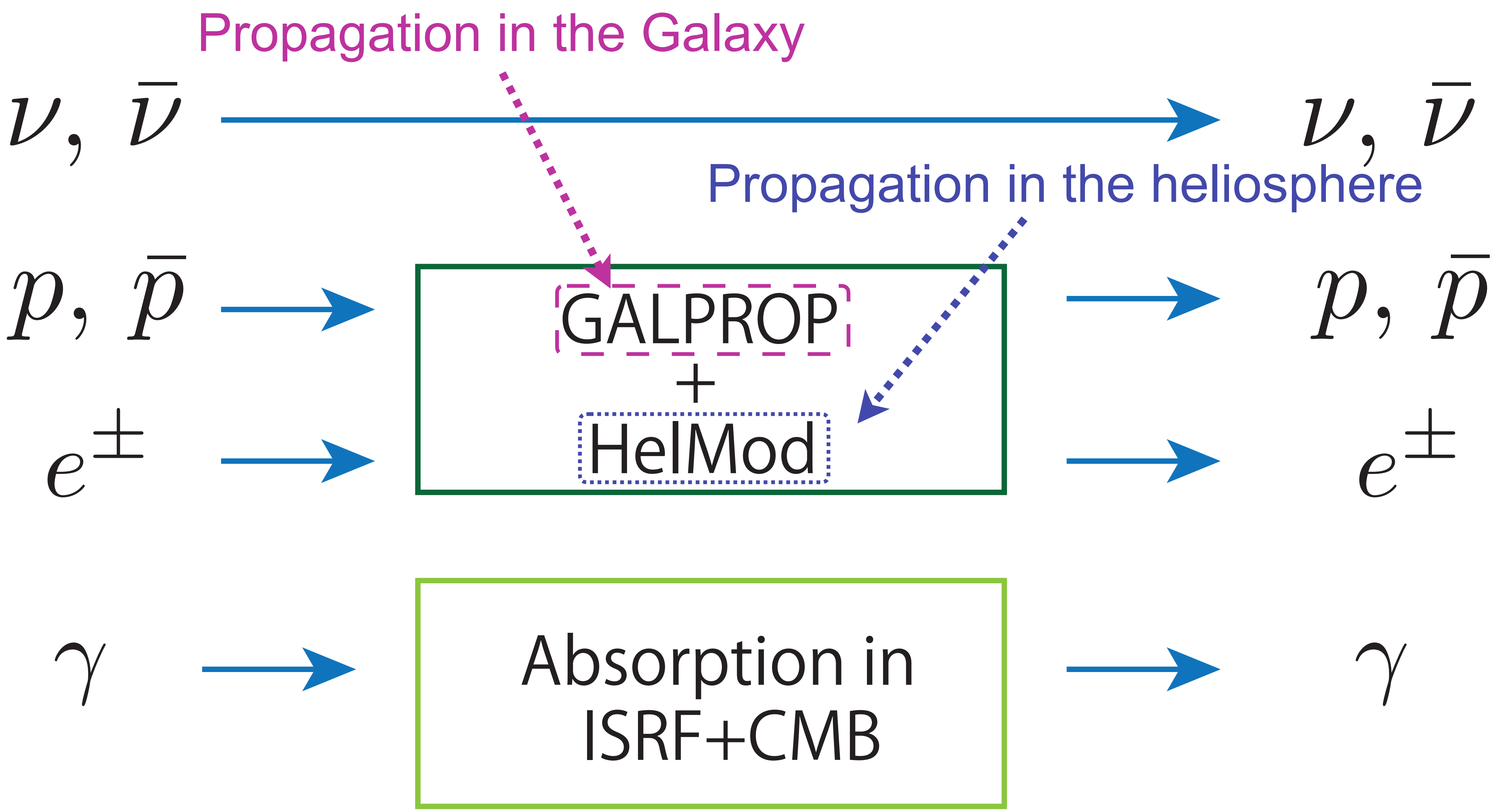
Strong et al. ’00

Boschini et al. ’17

Propagation of CRs in the ***Galaxy***



Strong et al. ’00

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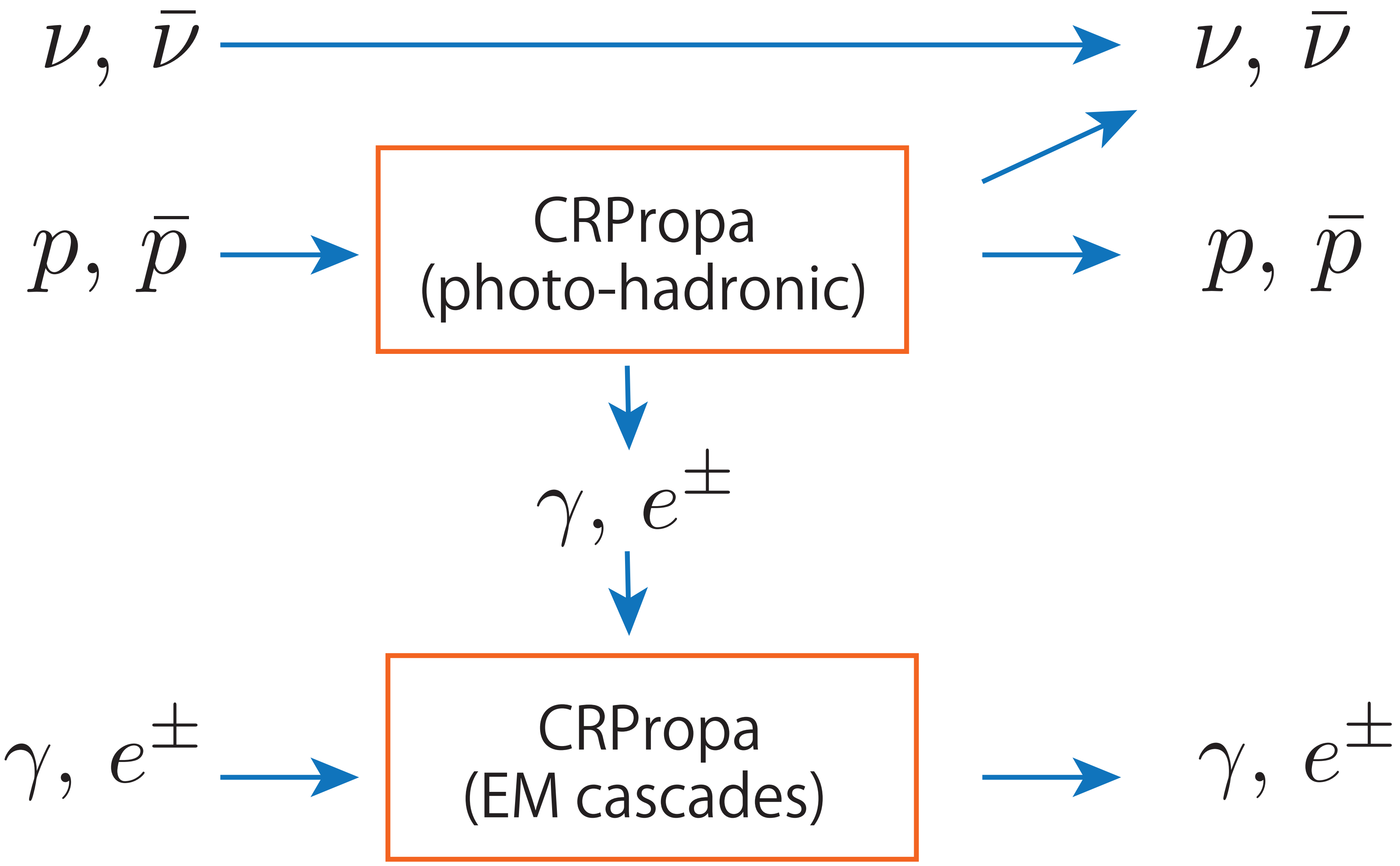
Propagation of CRs in the ***extragalactic*** region



$\nu,\ \bar{\nu}$

$\nu,\ \bar{\nu}$

$p,\ \bar{p}$

CRPropa
(photo-hadronic)

$p,\ \bar{p}$

$\gamma,\ e^{\pm}$

$\gamma,\ e^{\pm}$

CRPropa
(EM cascades)

$\gamma,\ e^{\pm}$

Batista et al. ’16
Heiter et al. ’18
Mucke et al. ’99
Lee ’98

Propagation of CRs in the ***extragalactic*** region

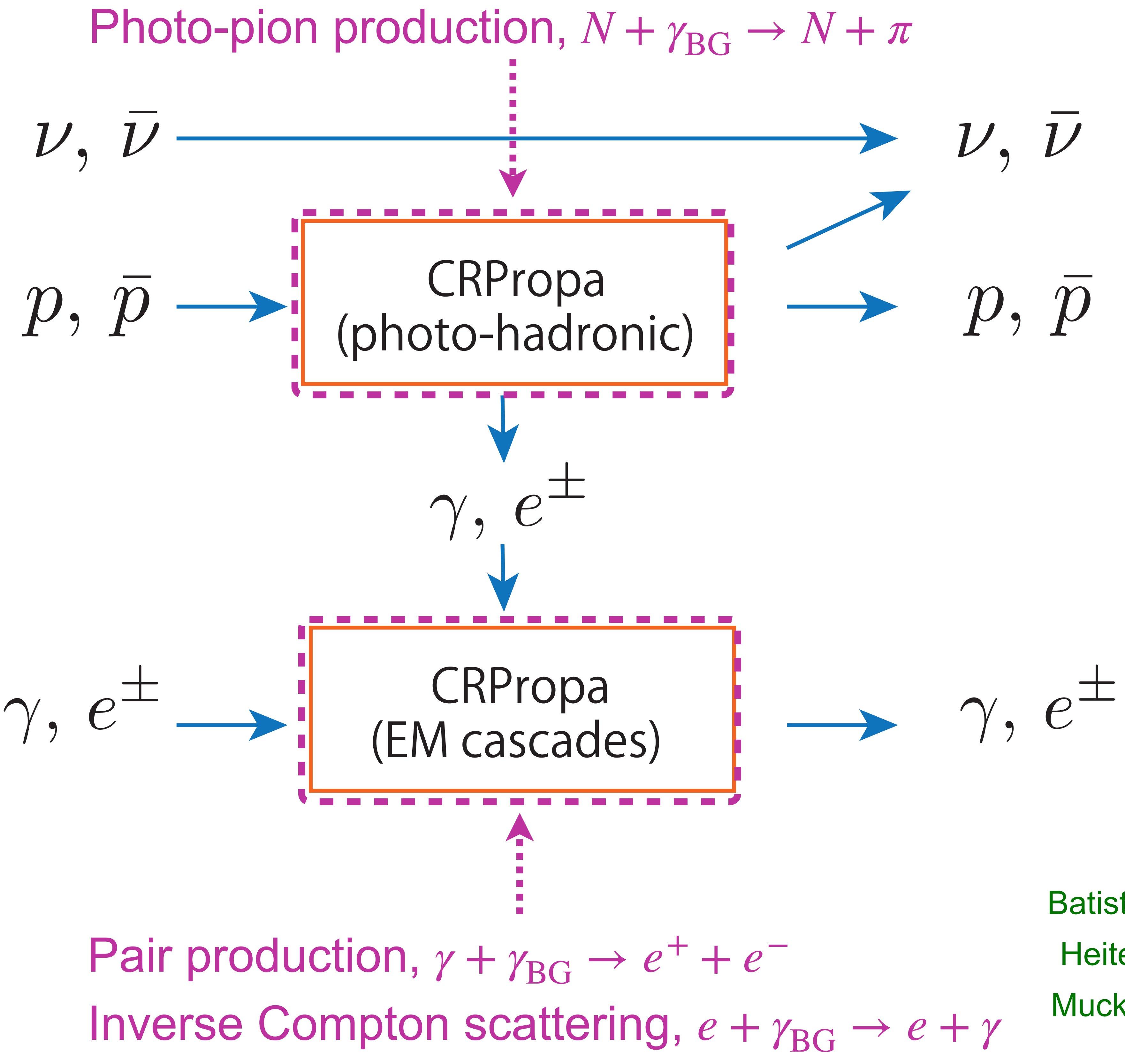


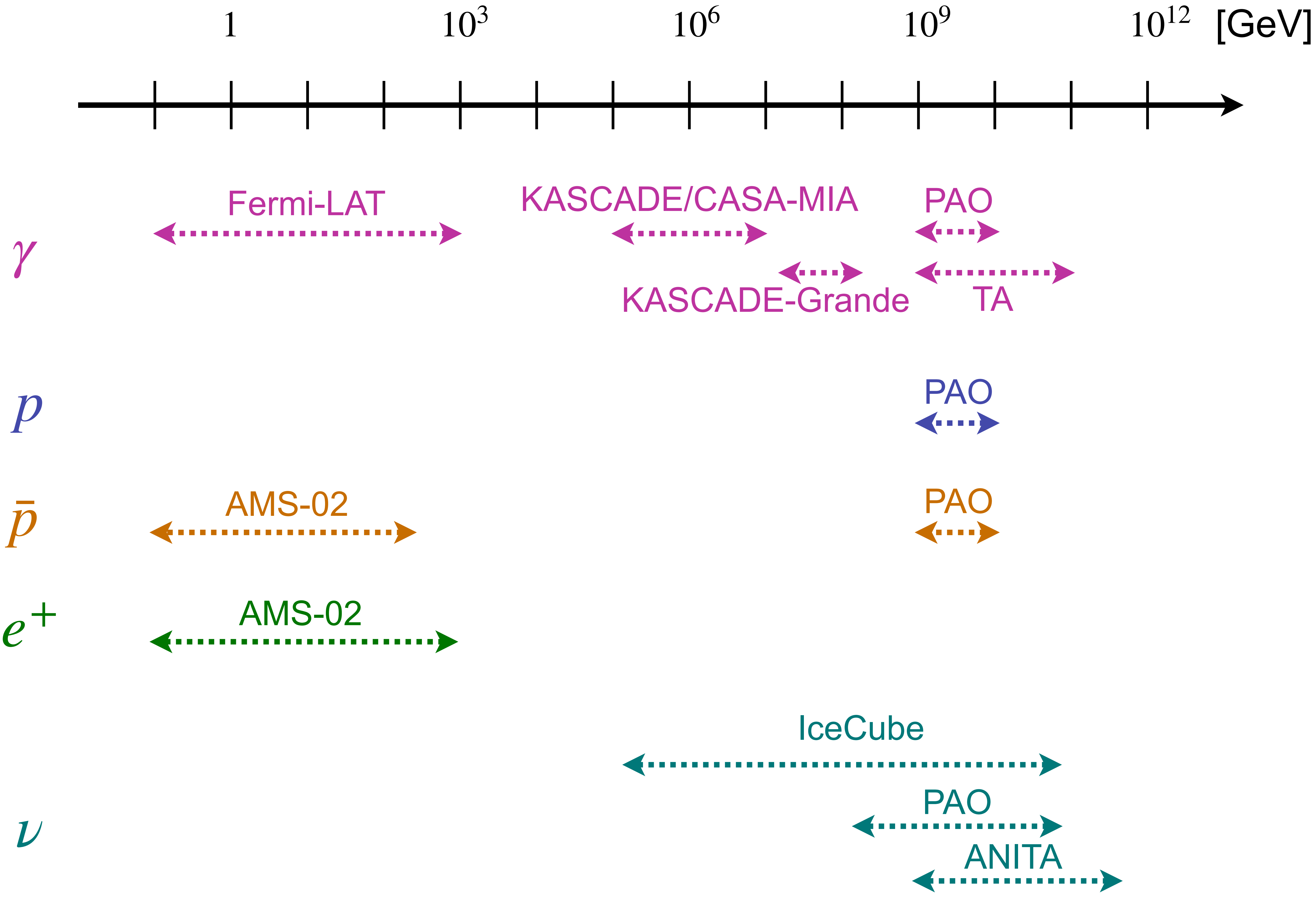
Photo-pion production, $N + \gamma_{\rm BG} \rightarrow N + \pi$

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

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

Batista et al. ’16
Heiter et al. ’18
Mucke et al. ’99
Lee ’98

Multimessenger astrophysical data



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

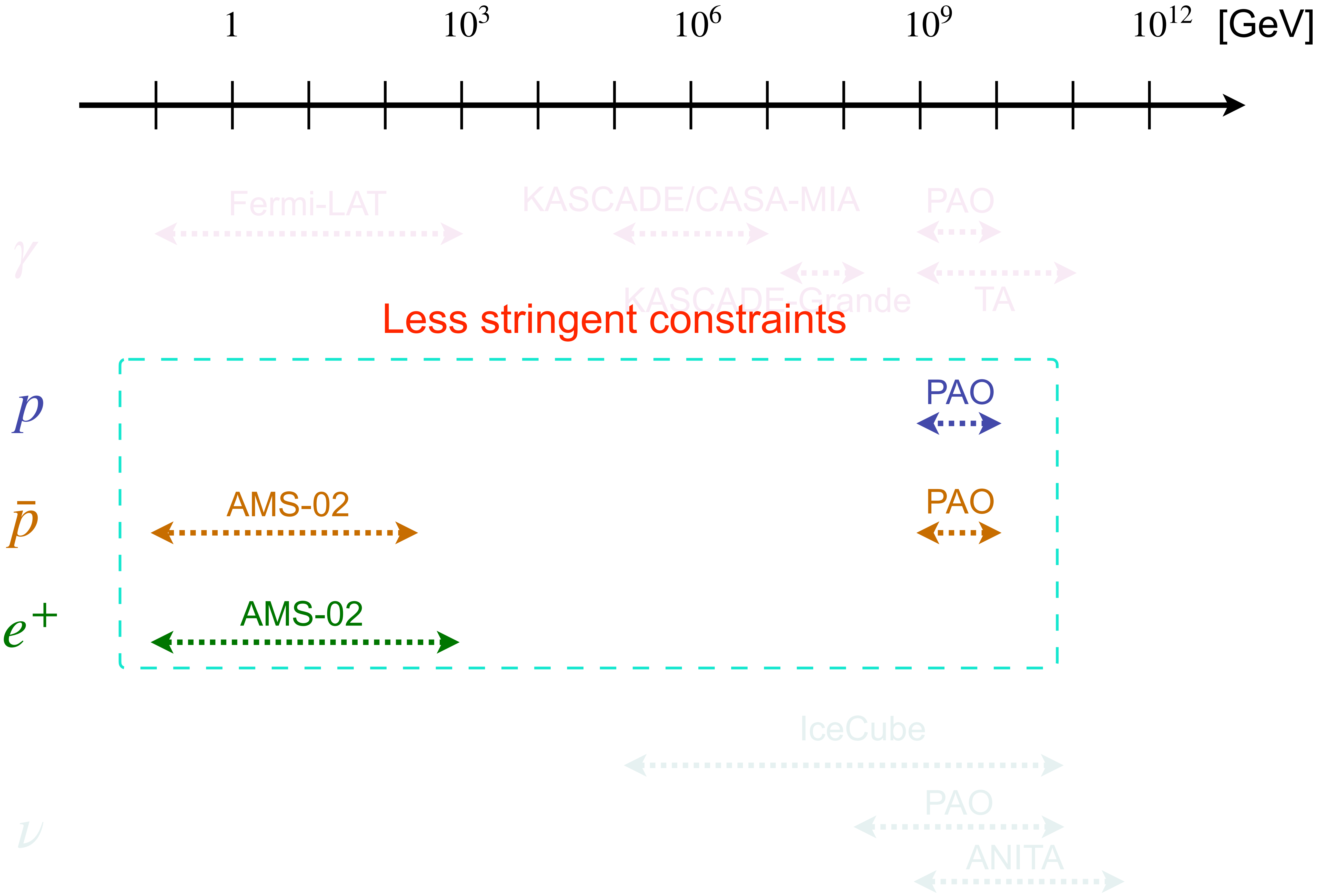
ν

IceCube

PAO

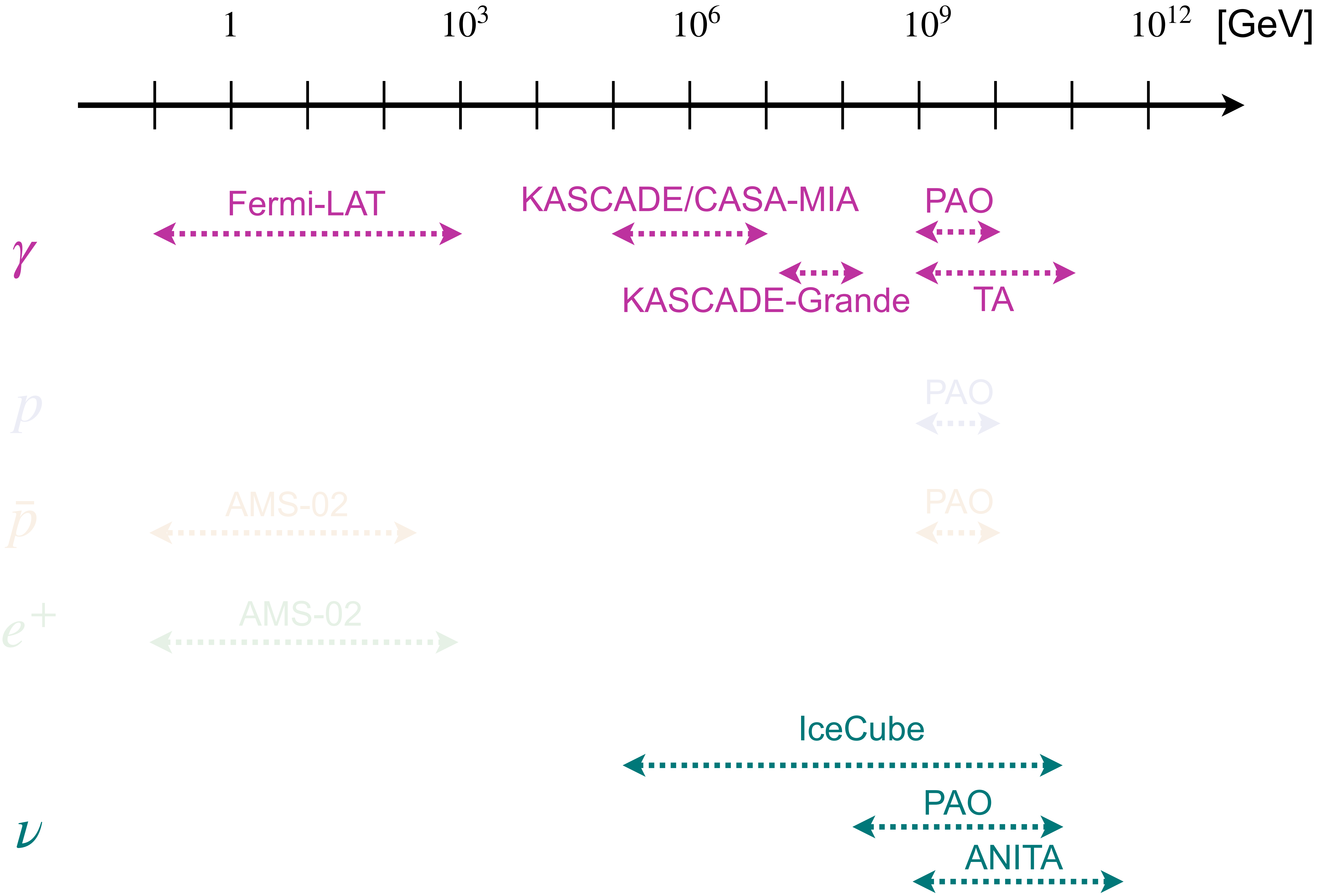
ANITA

Multimessenger astrophysical data



Less stringent constraints

Multimessenger astrophysical data



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

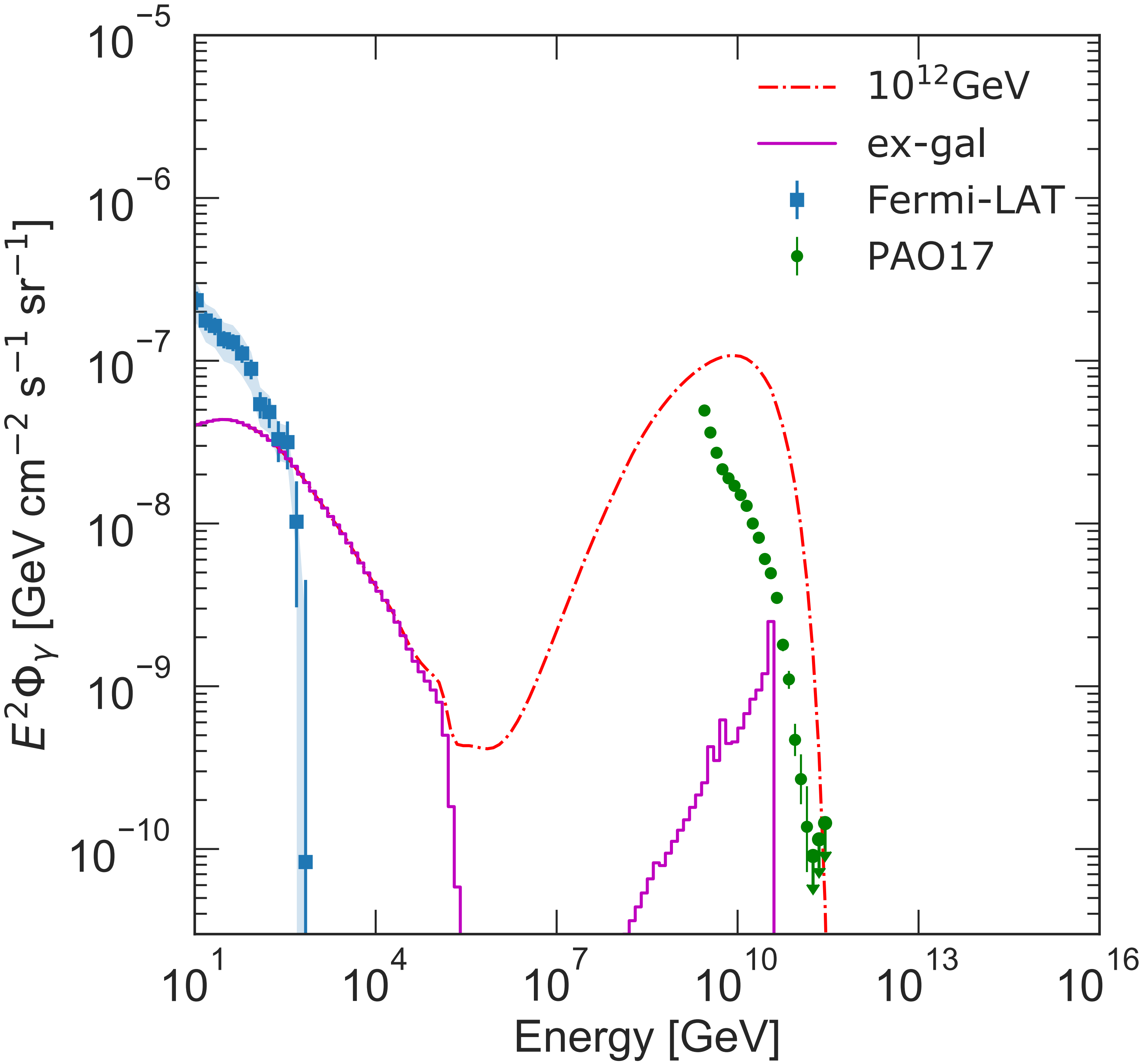
ν

PAO

ANITA

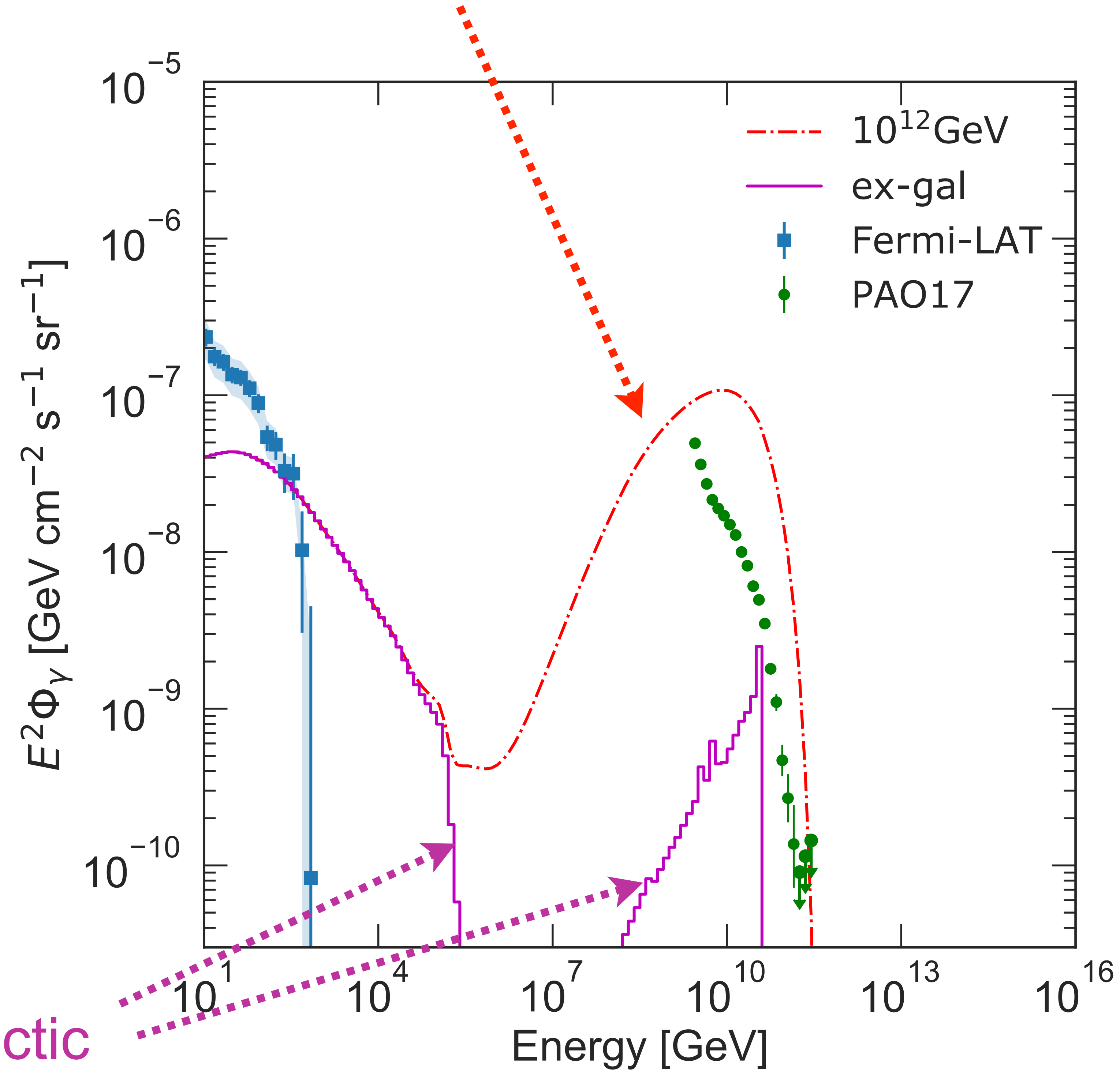
γ flux

$$m_{\rm dm} = 10^{12}\,\mathrm{GeV}$$
$$\tau_{\rm dm} = 10^{27}\,\mathrm{s}$$



γ flux

$$m_{\rm dm} = 10^{12}\,{\rm GeV}$$
$$\tau_{\rm dm} = 10^{27}\,{\rm s}$$

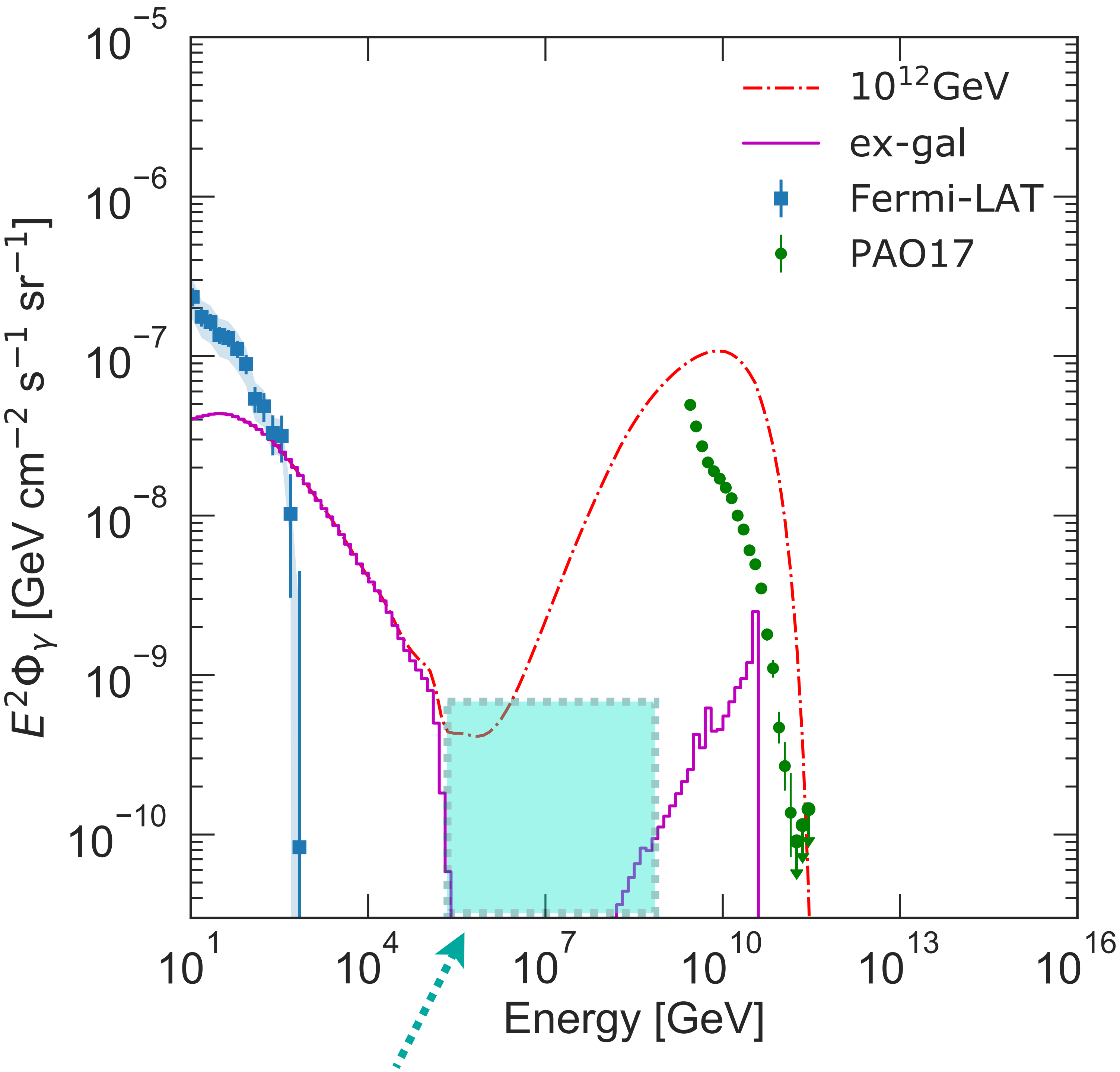


Total

Extragalactic

γ flux

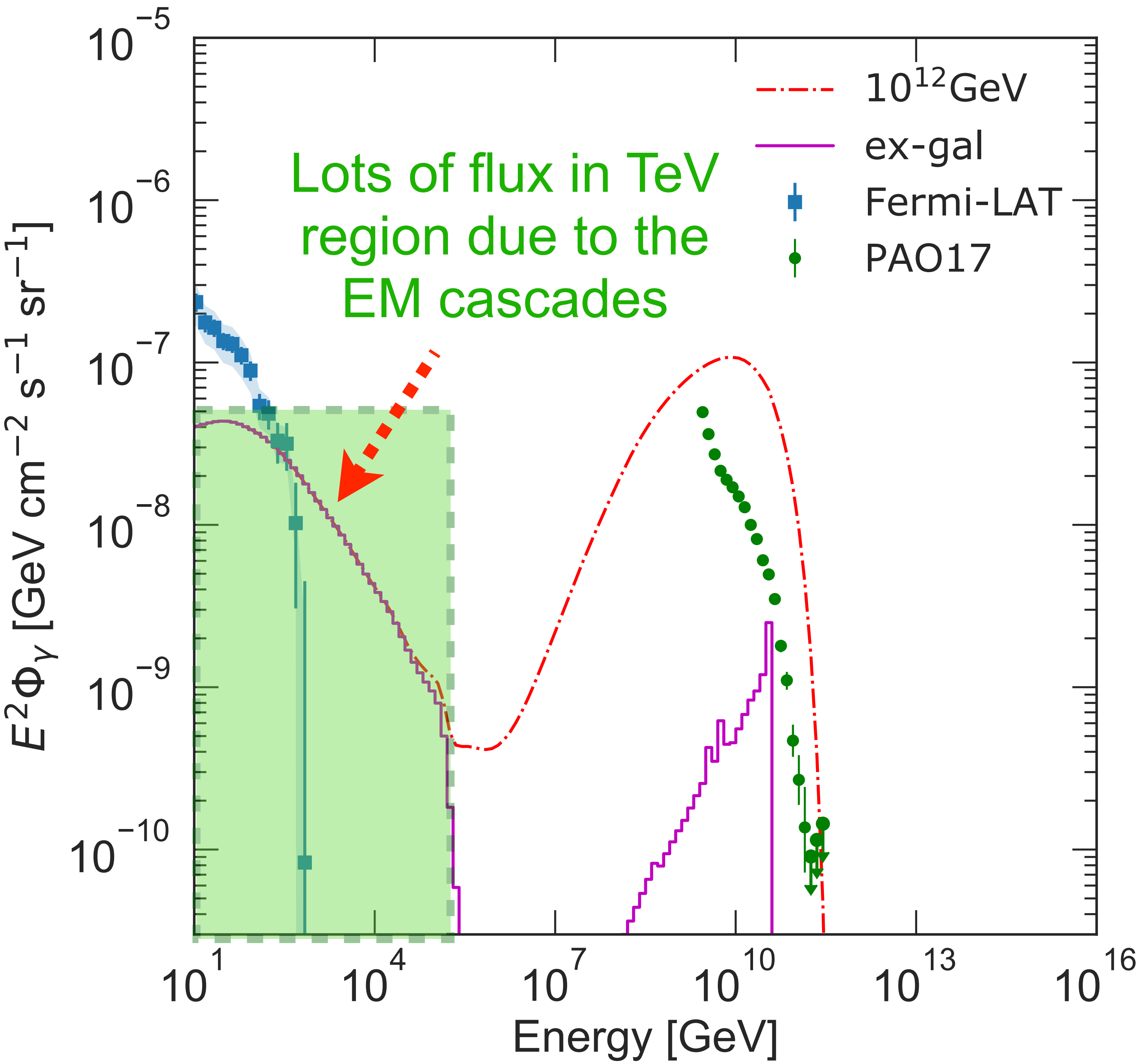
$$m_{\rm dm} = 10^{12}\,{\rm GeV}$$
$$\tau_{\rm dm} = 10^{27}\,{\rm s}$$



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

$$m_{\mathrm{dm}} = 10^{12}\,\mathrm{GeV}$$
$$\tau_{\mathrm{dm}} = 10^{27}\,\mathrm{s}$$

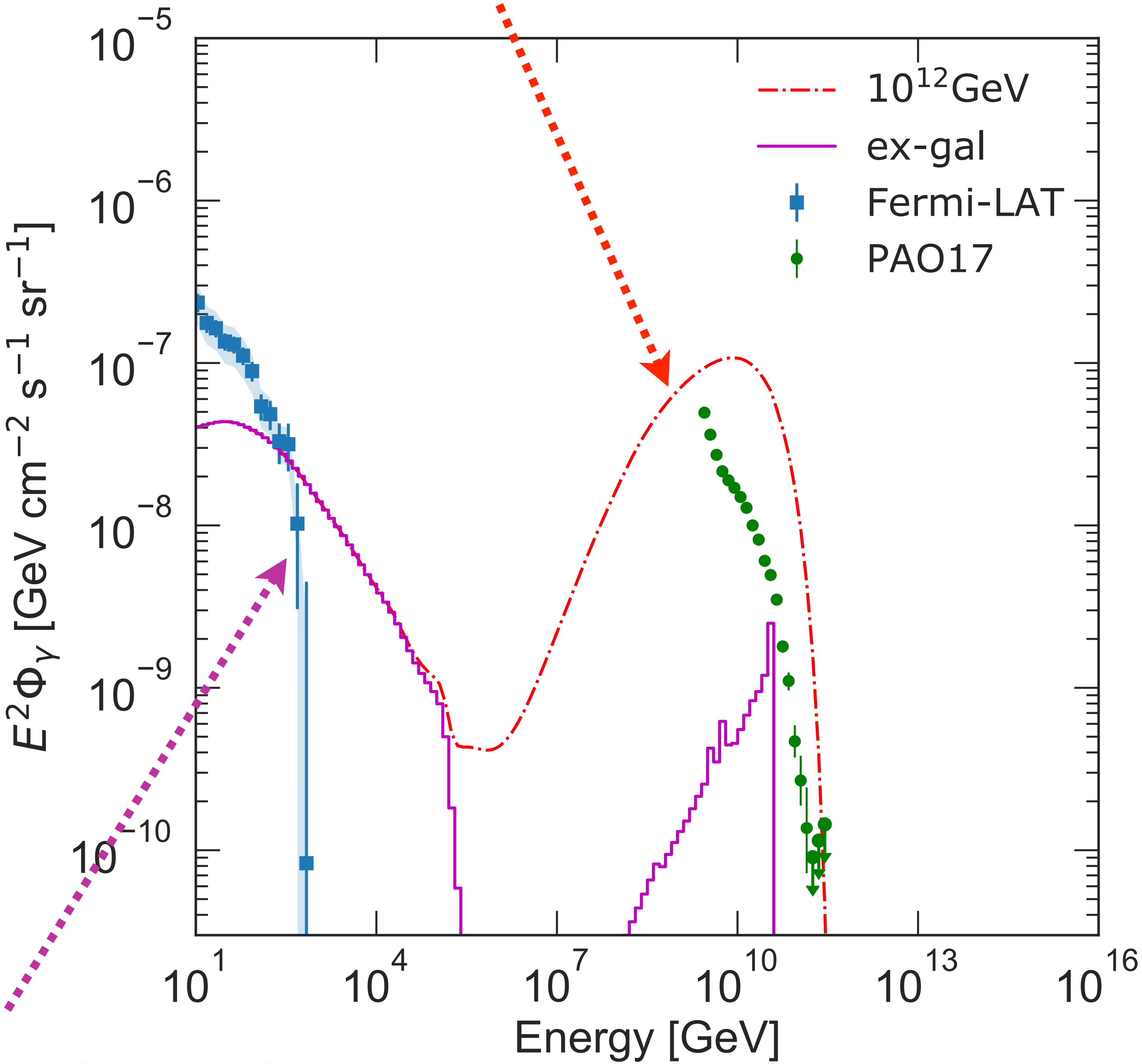


Lots of flux in TeV region due to the EM cascades

γ flux

$$m_{\rm dm} = 10^{12}\,{\rm GeV}$$
$$\tau_{\rm dm} = 10^{27}\,{\rm s}$$

Galactic contribution is constrained by PAO

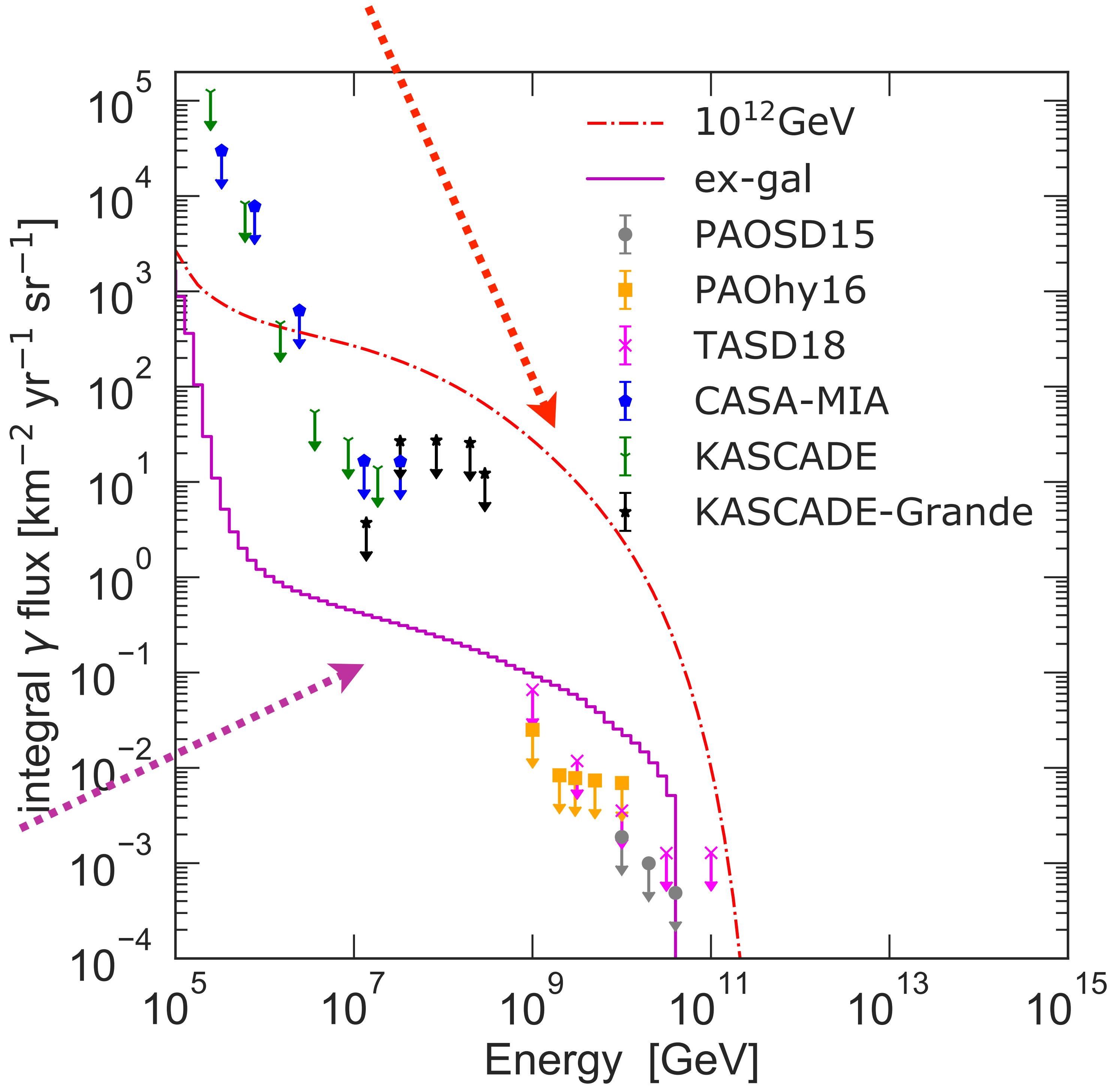


Extragalactic contribution is constrained by Fermi-LAT

Integrated γ

$$m_{\rm dm} = 10^{12}\,{\rm GeV}$$
$$\tau_{\rm dm} = 10^{27}\,{\rm s}$$

Total



Extragalactic

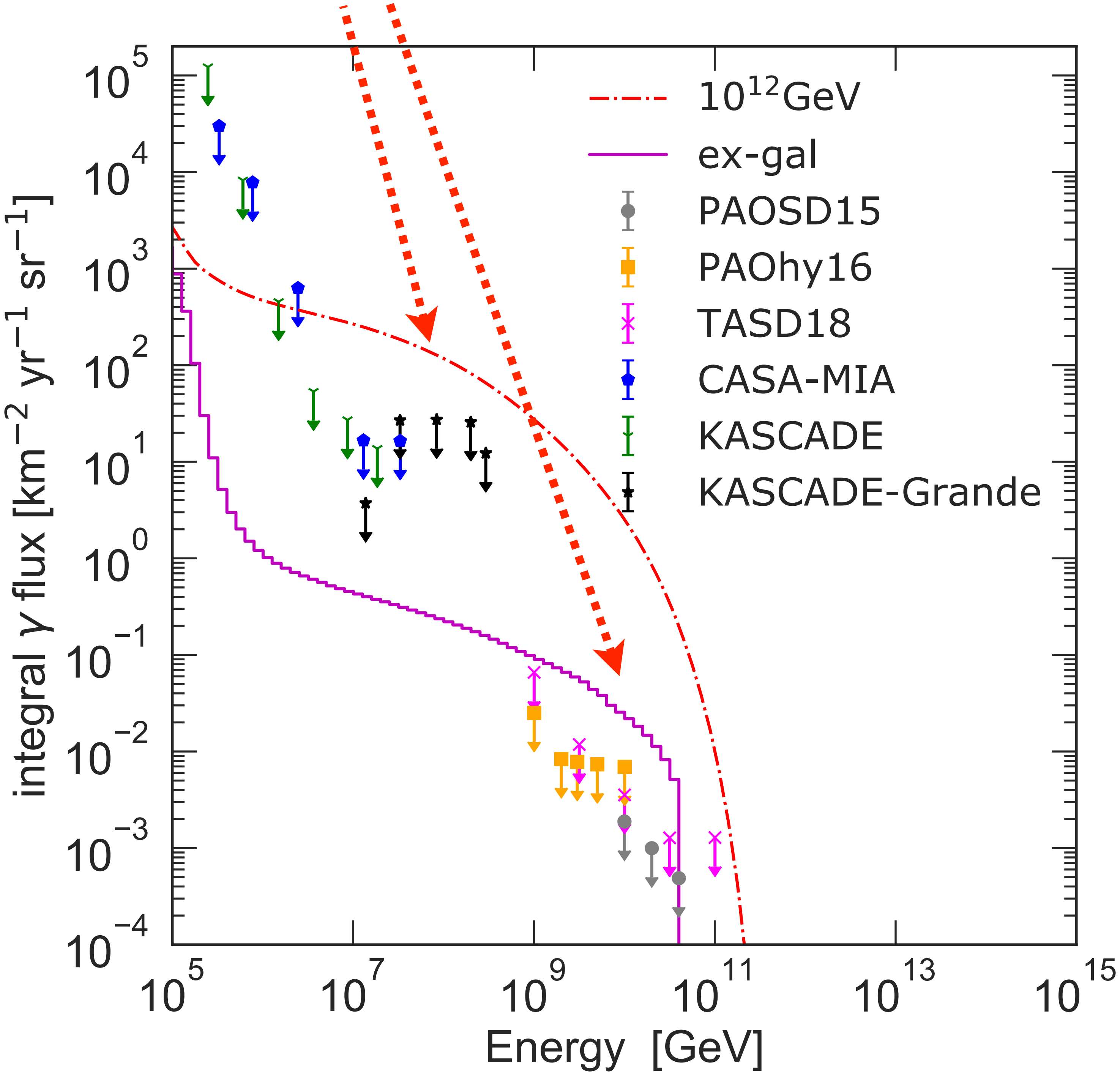
Galactic flux is dominant

Integrated γ

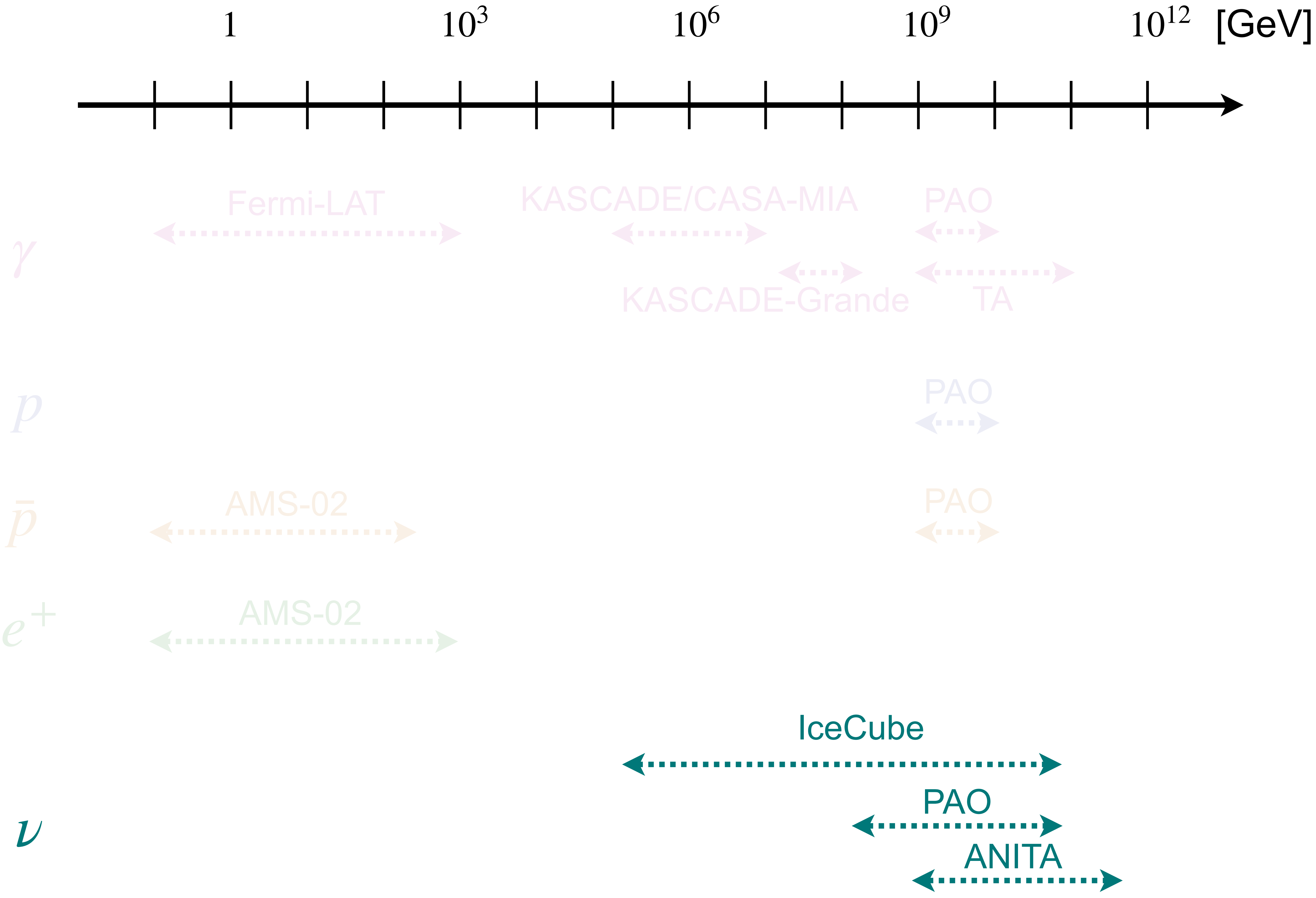
PAO, TA, CASA-MIA, KASCADE, and KASCADE-Grande give constraints

$m_{\rm dm} = 10^{12}\,{\rm GeV}$

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



Multimessenger astrophysical data



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

ν

IceCube

PAO

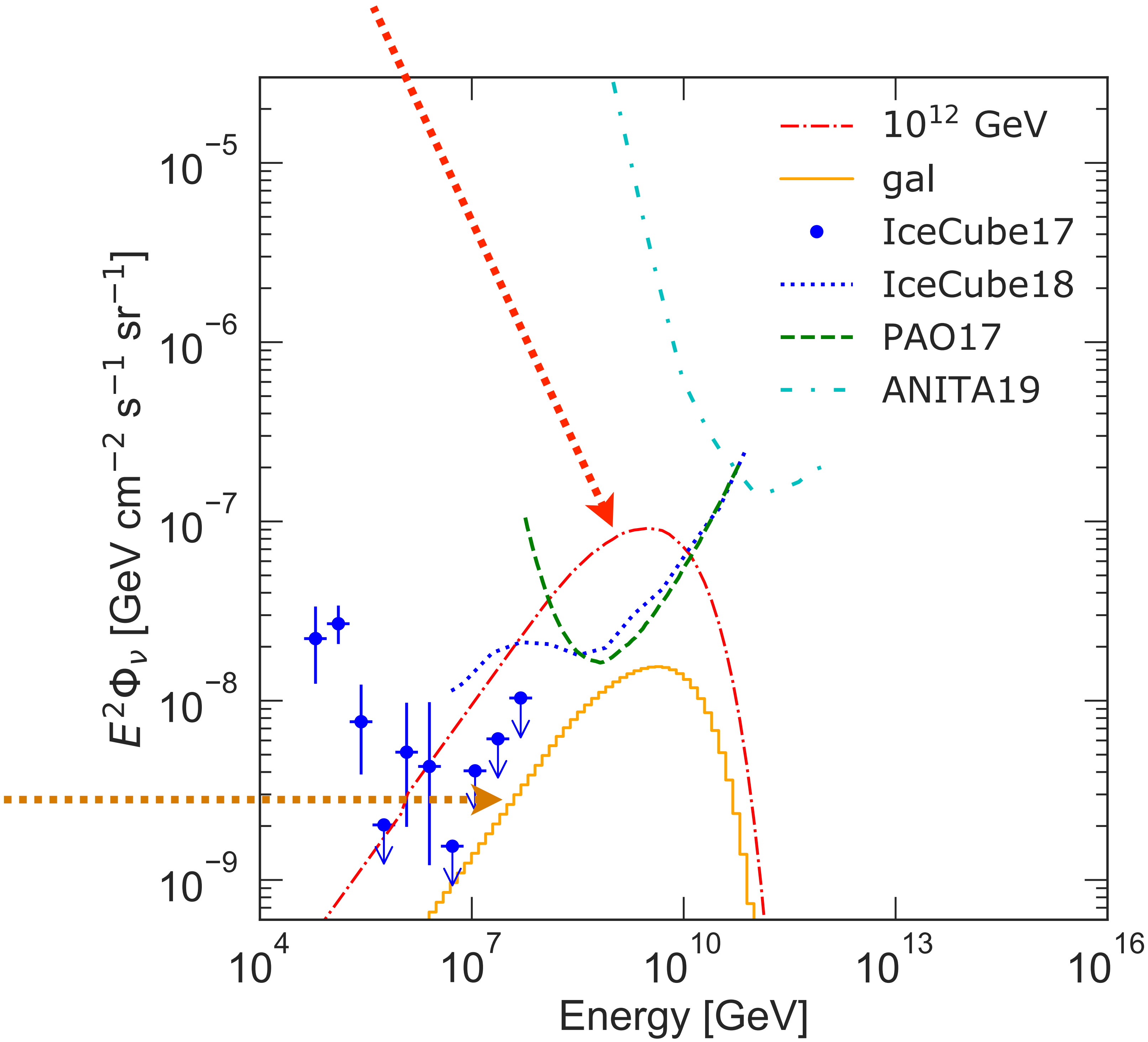
ANITA

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

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

Total

Galactic

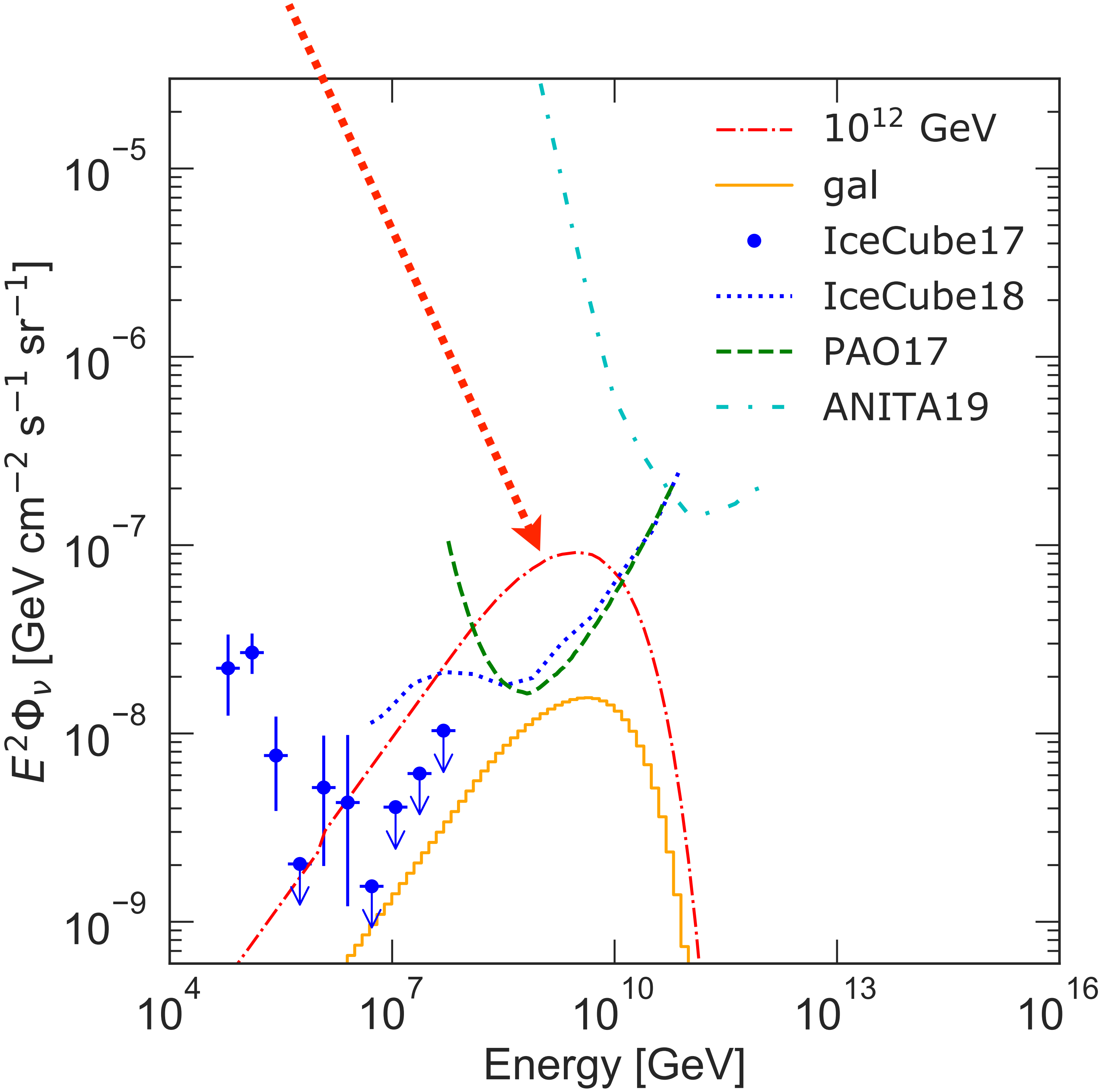


Extragalactic flux is dominant

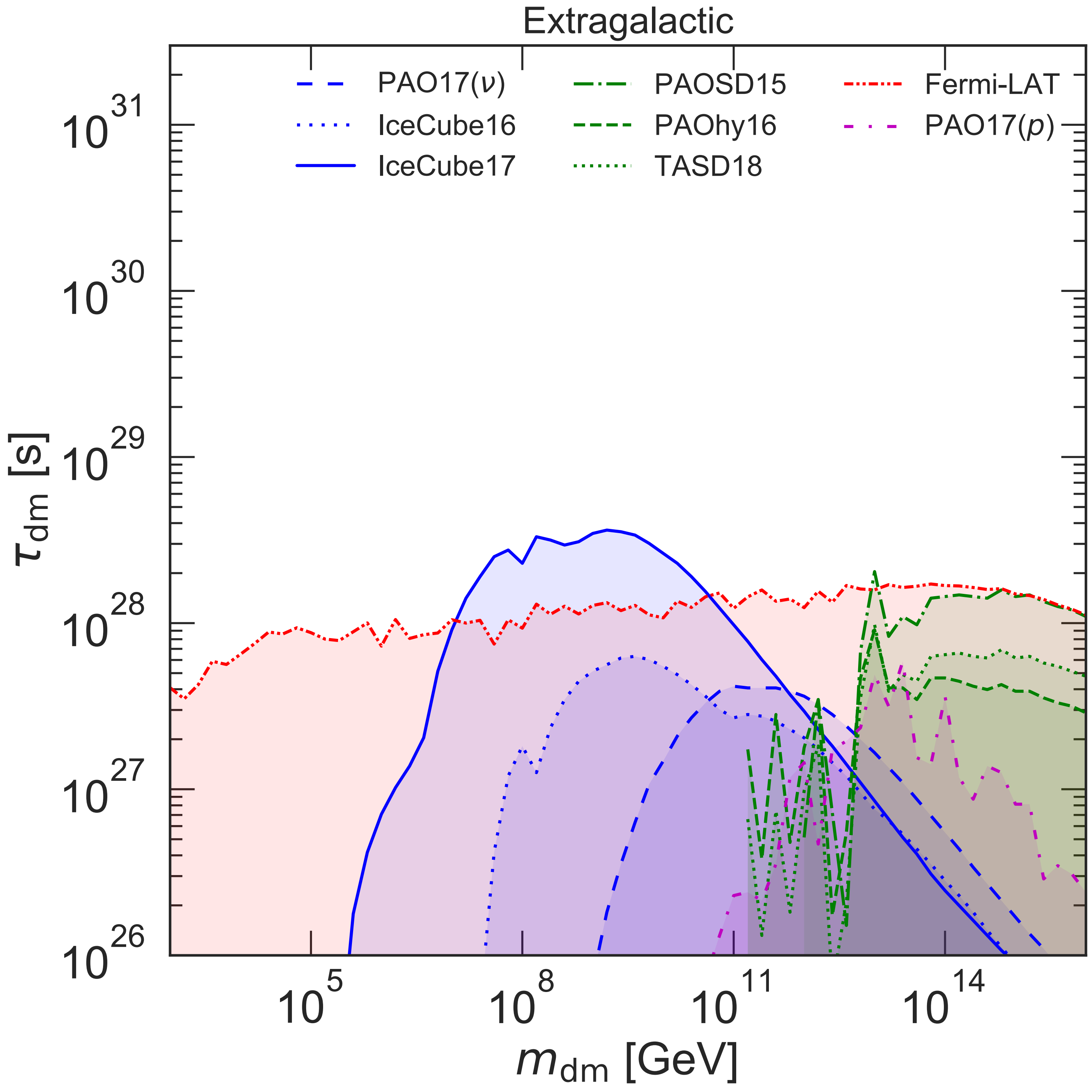
$\nu + \bar{\nu}$ flux

Extragalactic contribution is constrained by IceCube and PAO

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



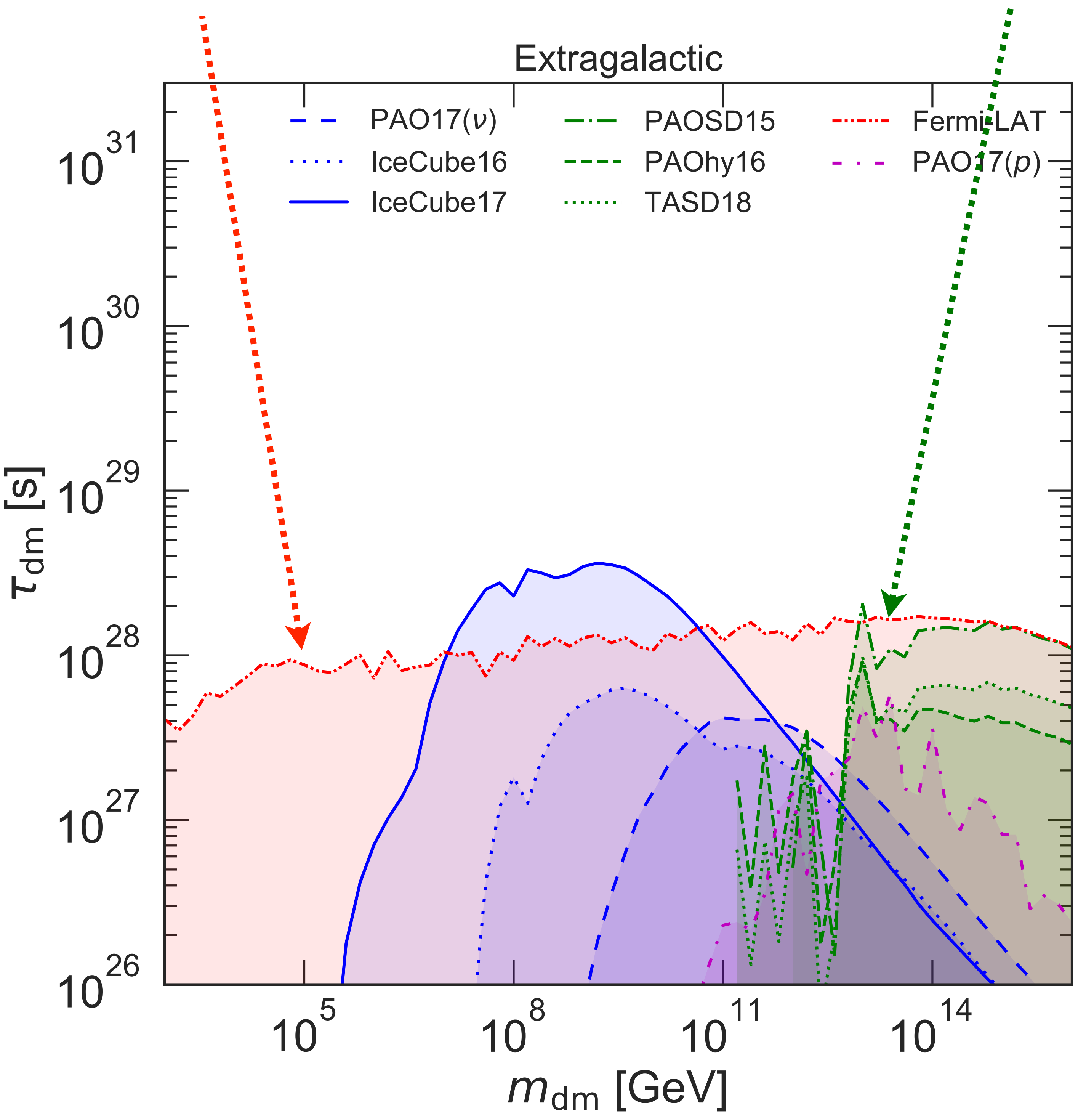
Constraints on DM lifetime (extragalactic)



Constraints on DM lifetime (extragalactic)

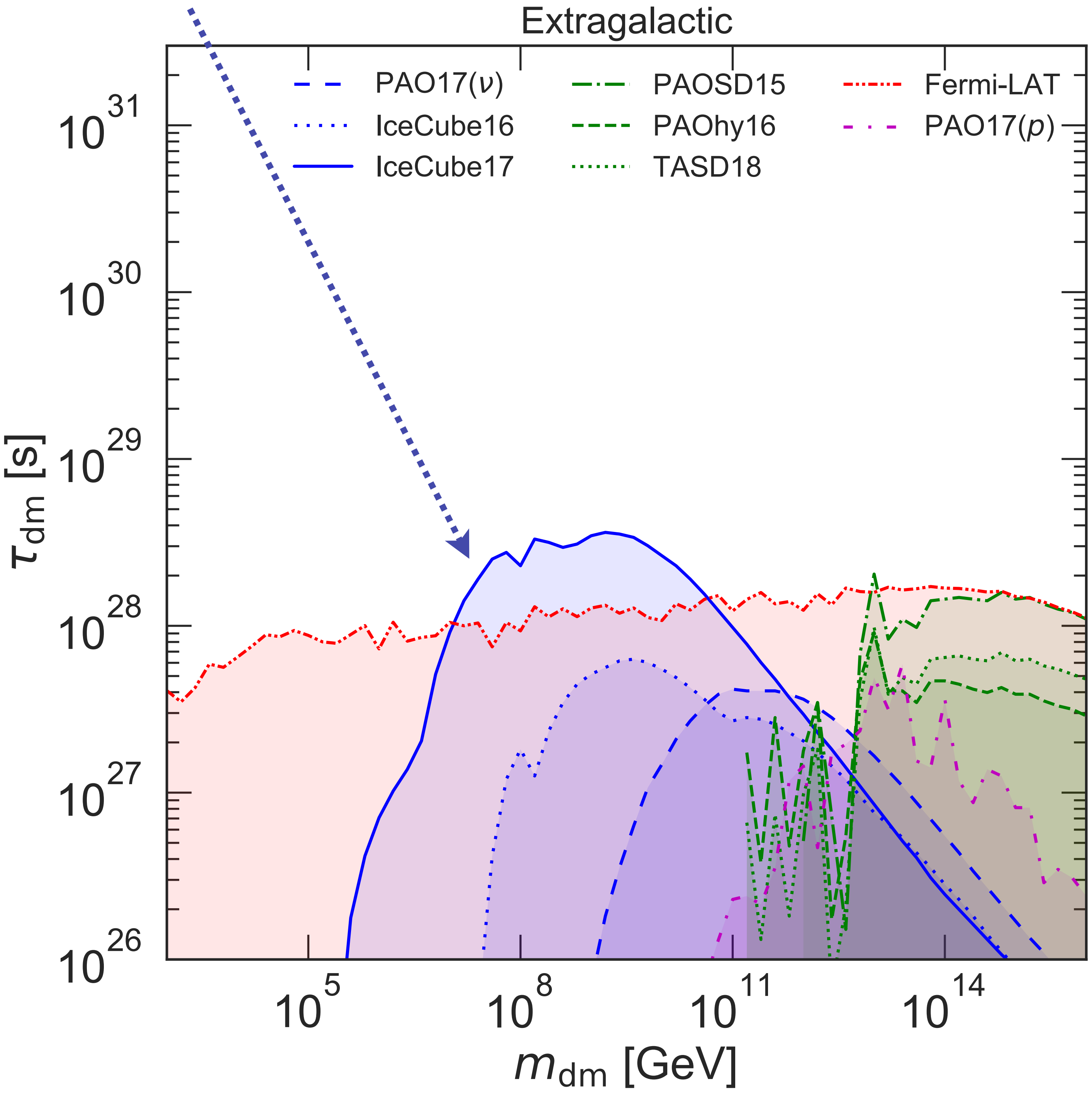
Fermi-LAT gives constrains
in wide range of $m_{\rm dm}$

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

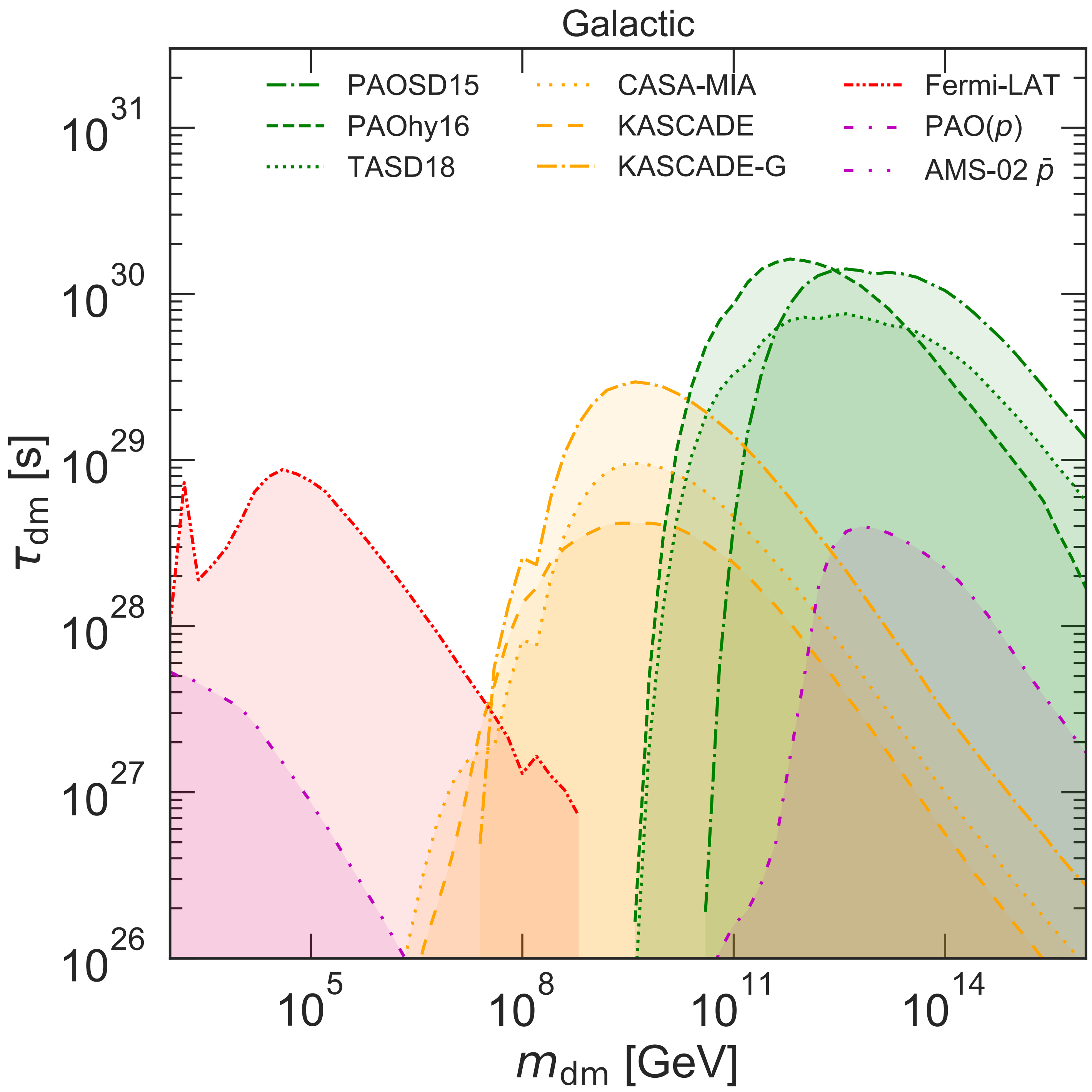


Constraints on DM lifetime (extragalactic)

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



Constraints on DM lifetime (Galactic)



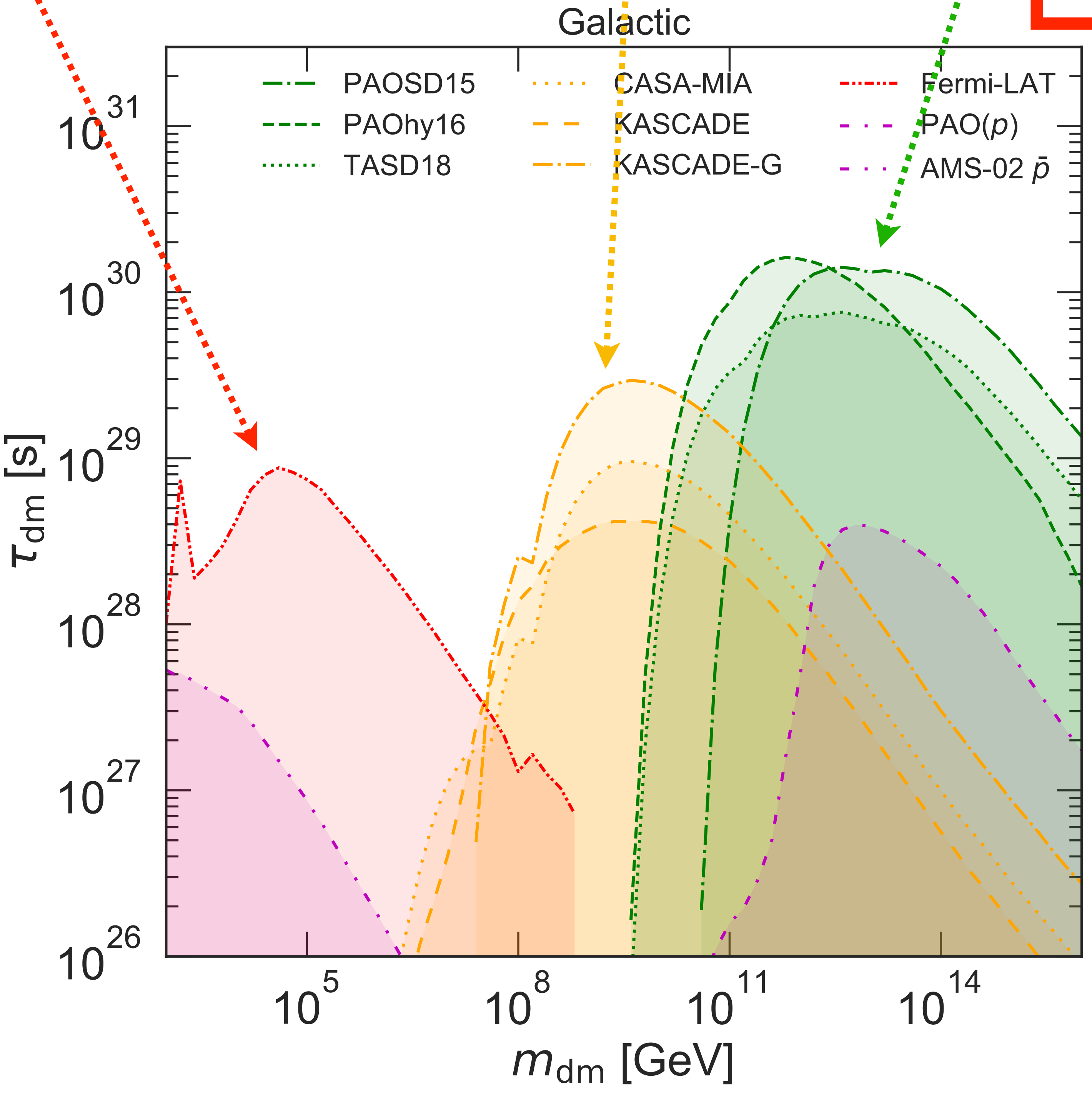
Constraints on DM lifetime (Galactic)

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

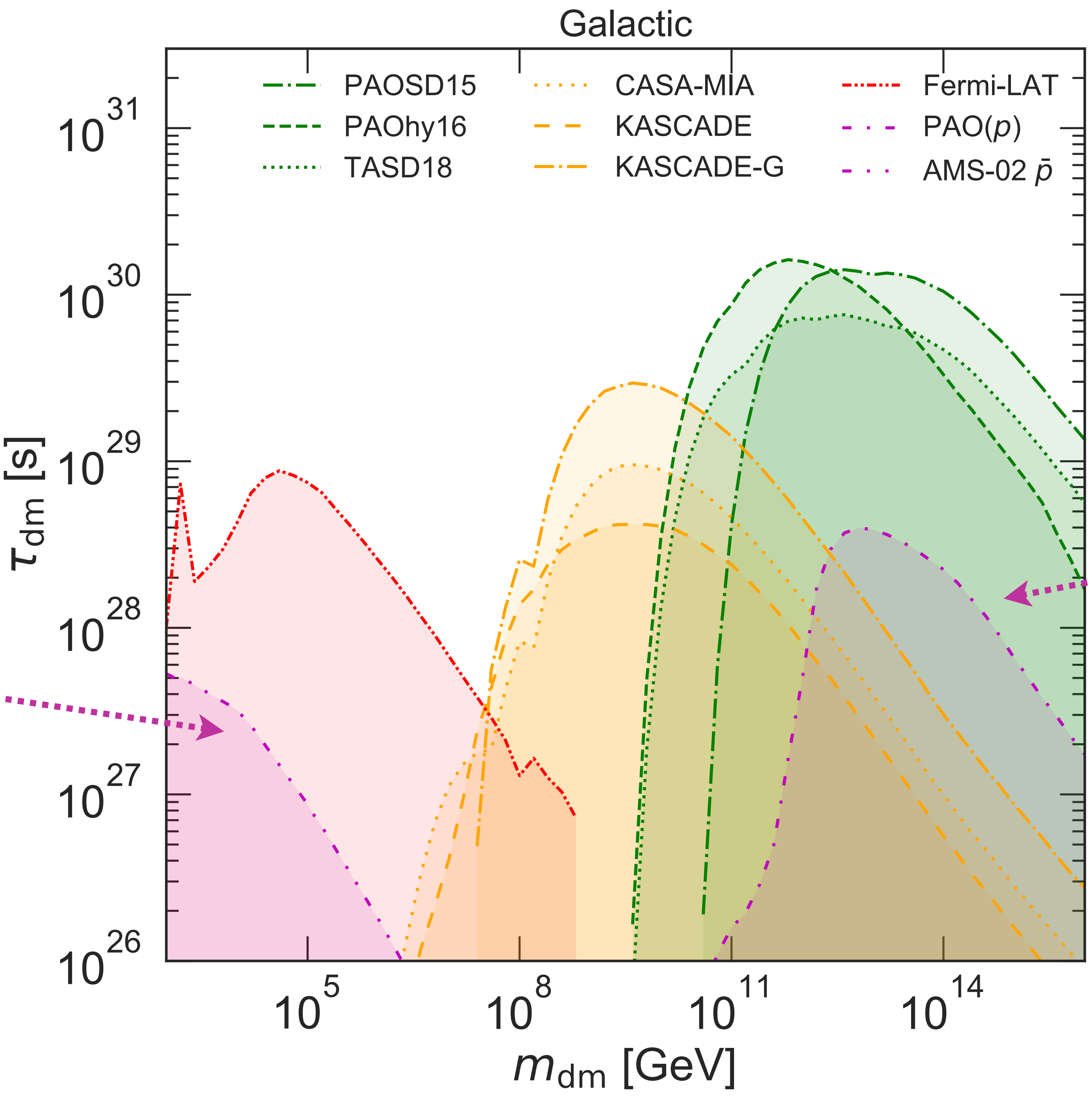
Fermi-LAT: $m_{\mathrm{dm}} \lesssim 10^{6}\,\mathrm{GeV}$

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

All γ observations!



Constraints on DM lifetime (Galactic)

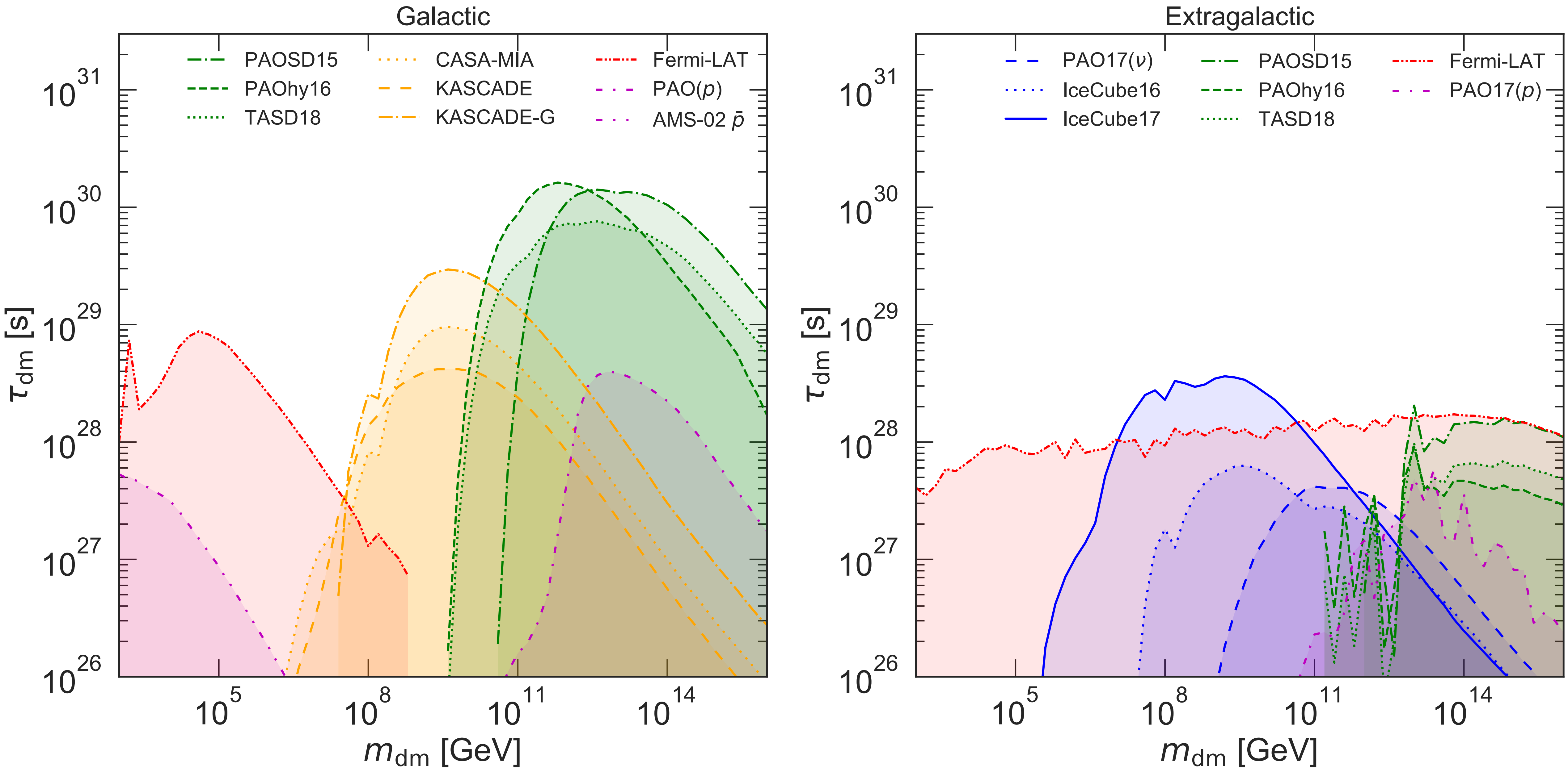


AMS-02 $\bar{p}$ gives much weaker constraints

PAO (p) gives much weaker constraints

Constraints on DM lifetime

Ando, Arimoto, KI, Macias ’02



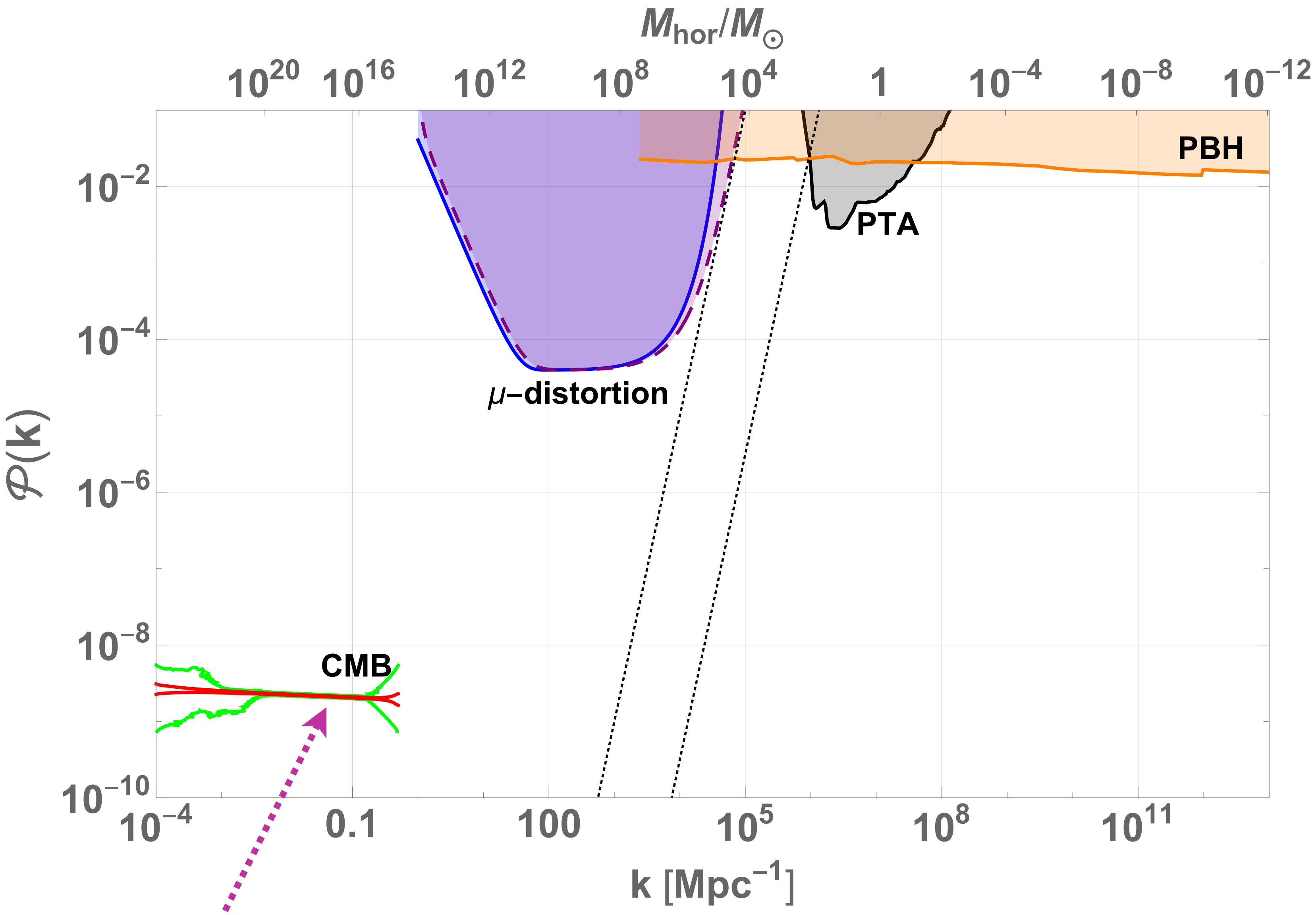
Galactic γ & Extragalactic ν give the most stringent constraints

Outline

1. Introduction
2. CRs from decaying heavy DM
3. Primordial curvature perturbations
4. Conclusion

Constraints on primordial curvature power spectrum

Byrnes, Cole, Patil ’19

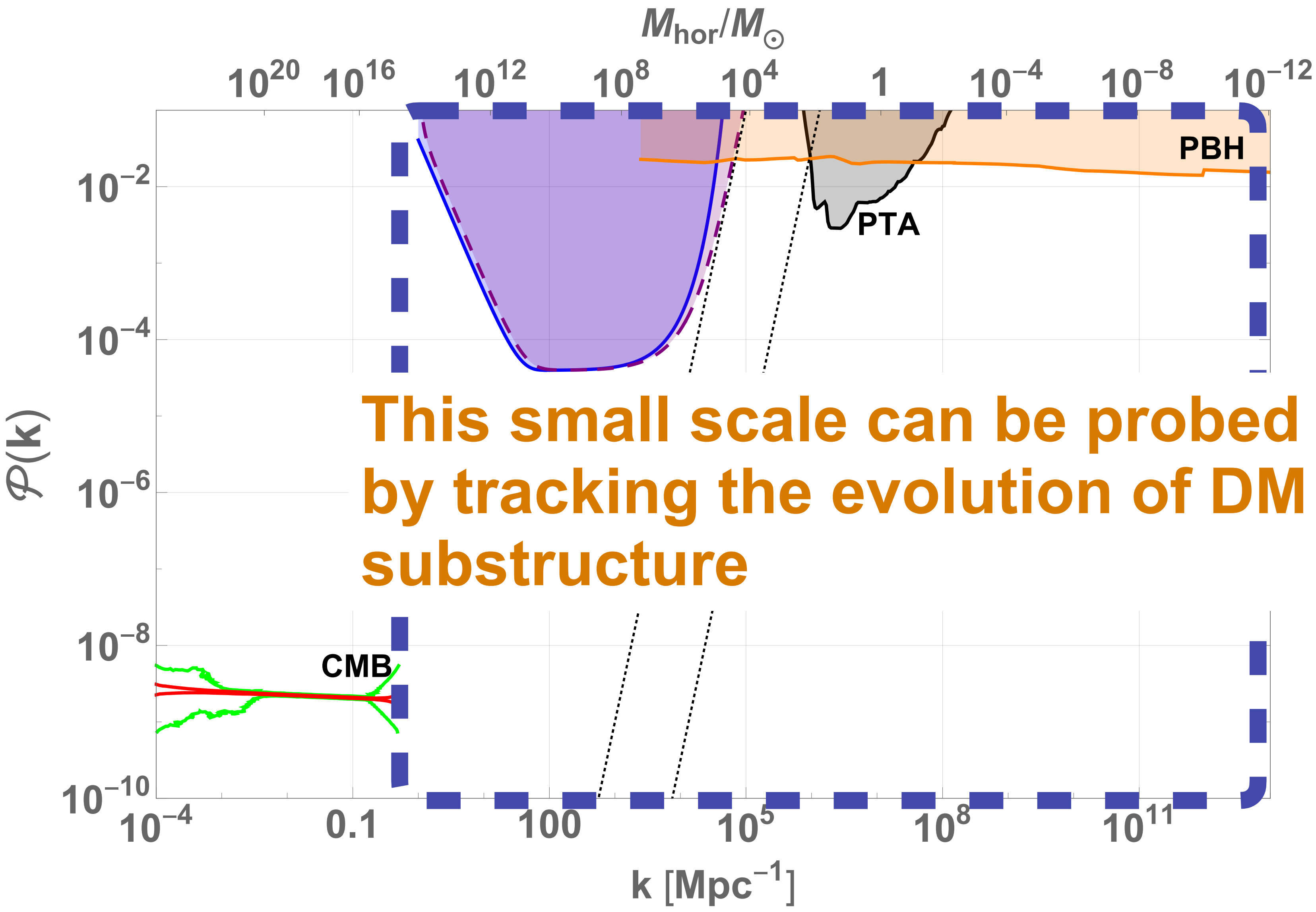


$$\mathcal{P}_R = (2.099 \pm 0.029) \times 10^{-9}$$

Planck ’18

Constraints on primordial curvature power spectrum

Byrnes, Cole, Patil ’19



This small scale can be probed by tracking the evolution of DM substructure

Evolution of halo/subhalos

Curvature perturbation

↓

Host halos and subhalos

↓

Subhalos accrete on a host halo

↓

Subhalos or satellite galaxies

Evolution of halo/subhalos

Curvature perturbation

↓

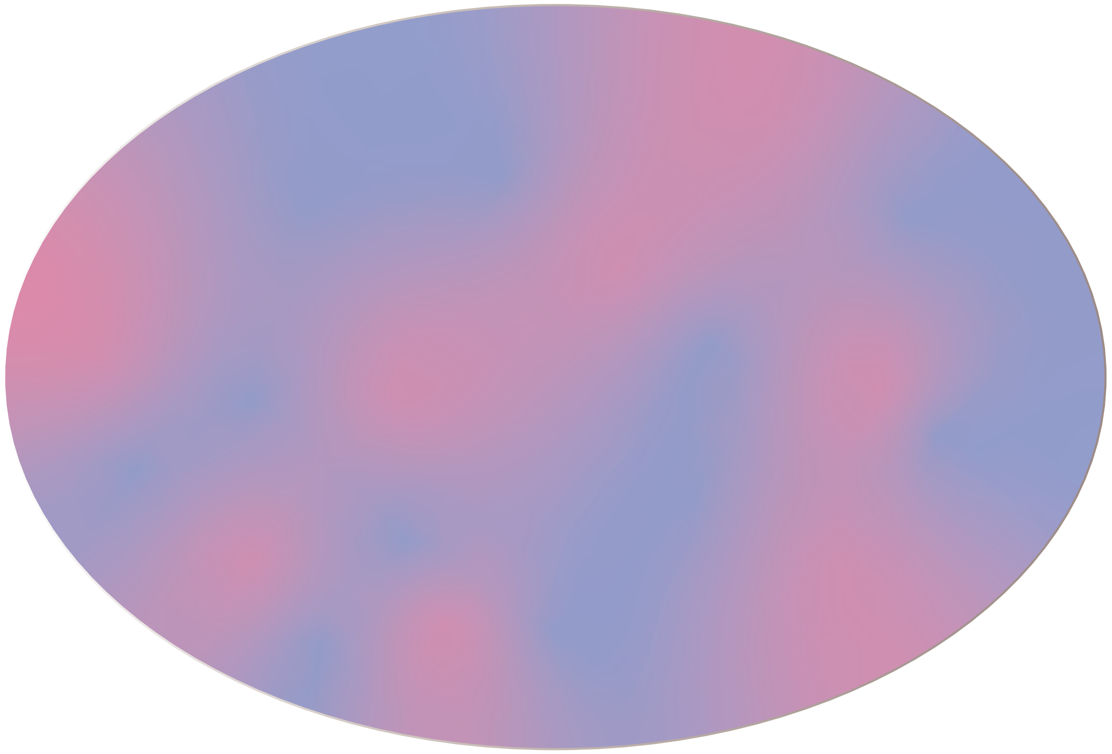
Host halos and subhalos

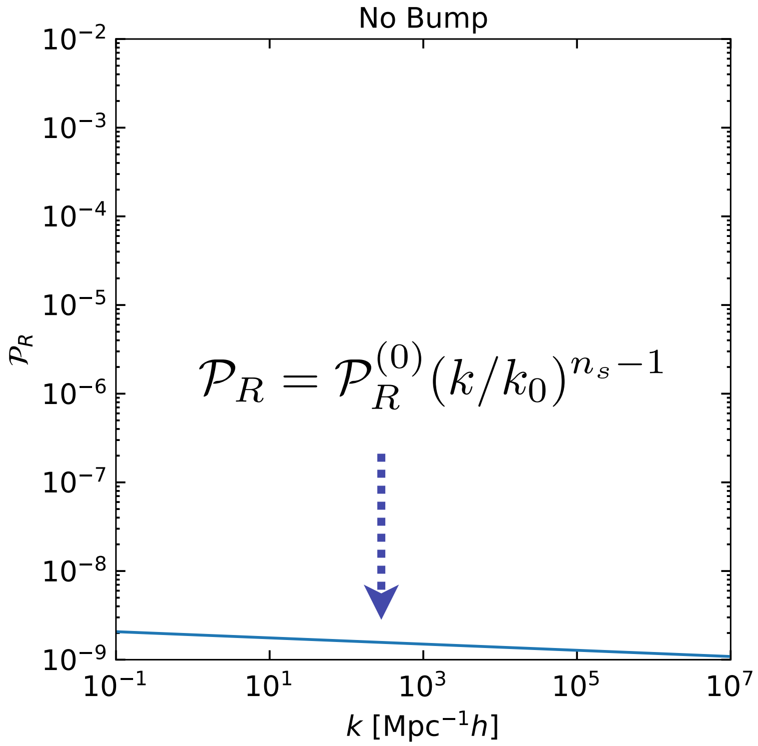
↓

Subhalos accrete on a host halo

↓

Subhalos or satellite galaxies





Evolution of halo/subhalos

Curvature perturbation

↓

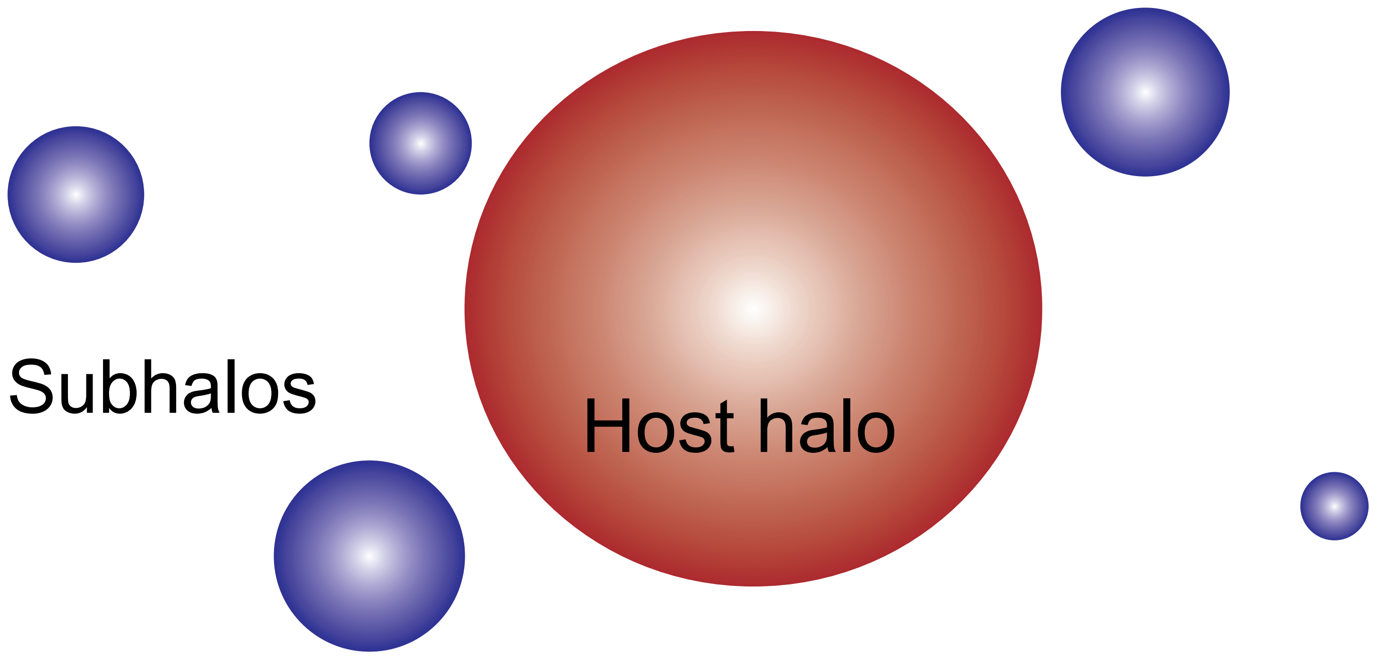
Host halos and subhalos

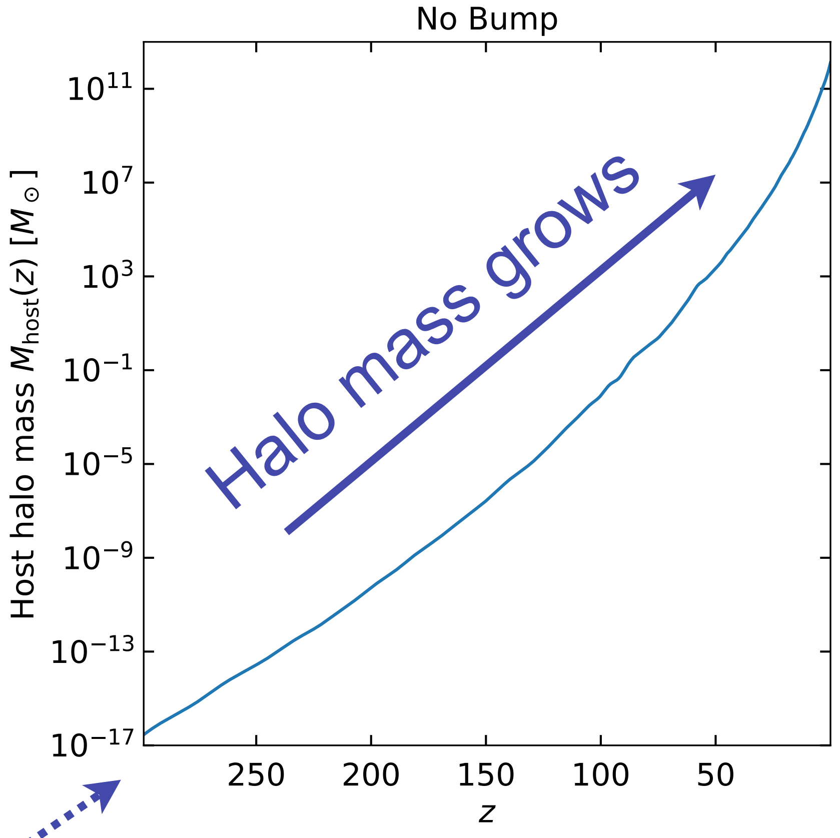
↓

Subhalos accrete on a host halo

↓

Subhalos or satellite galaxies





Halo mass grows gradually based on the extended Press-Schechter formalism

Bond, Cole, Efstathiou, Kaiser ’91

Bower ’91

Lacy, Cole ’93

Yang, Mo, Zhang, van den Bosch ’11

Evolution of halo/subhalos

Curvature perturbation

↓

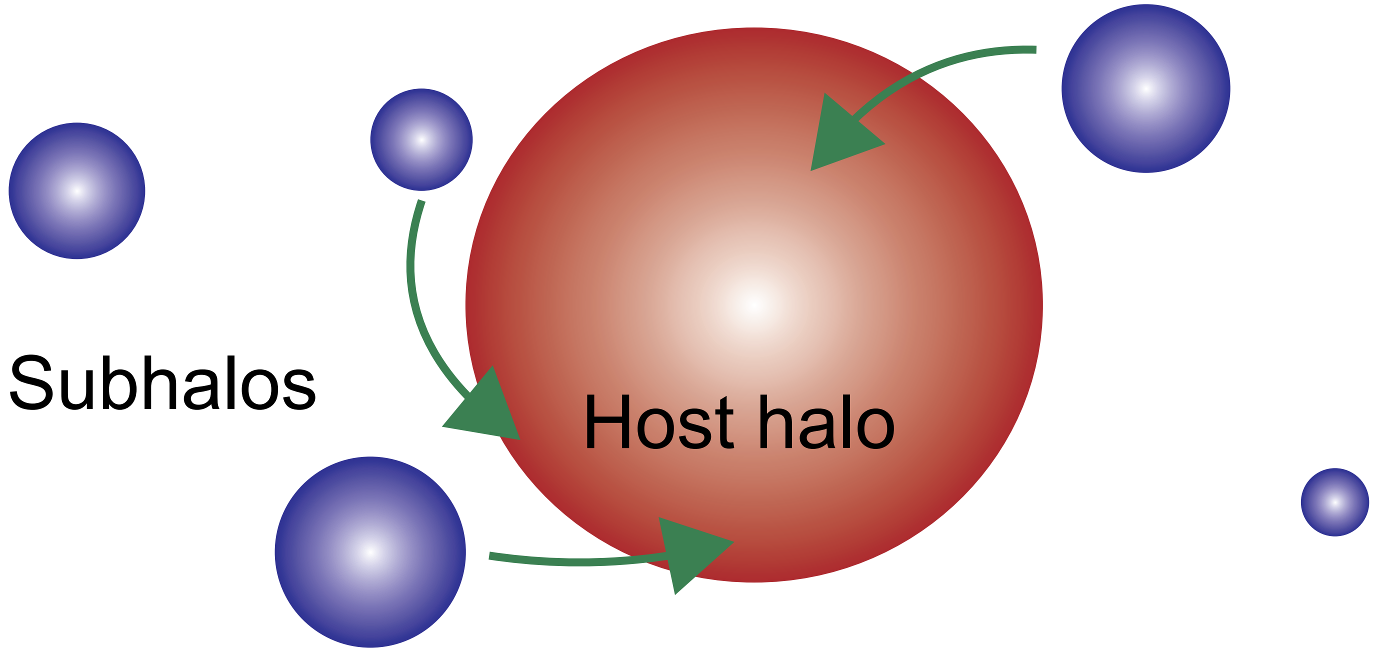
Host halos and subhalos

↓

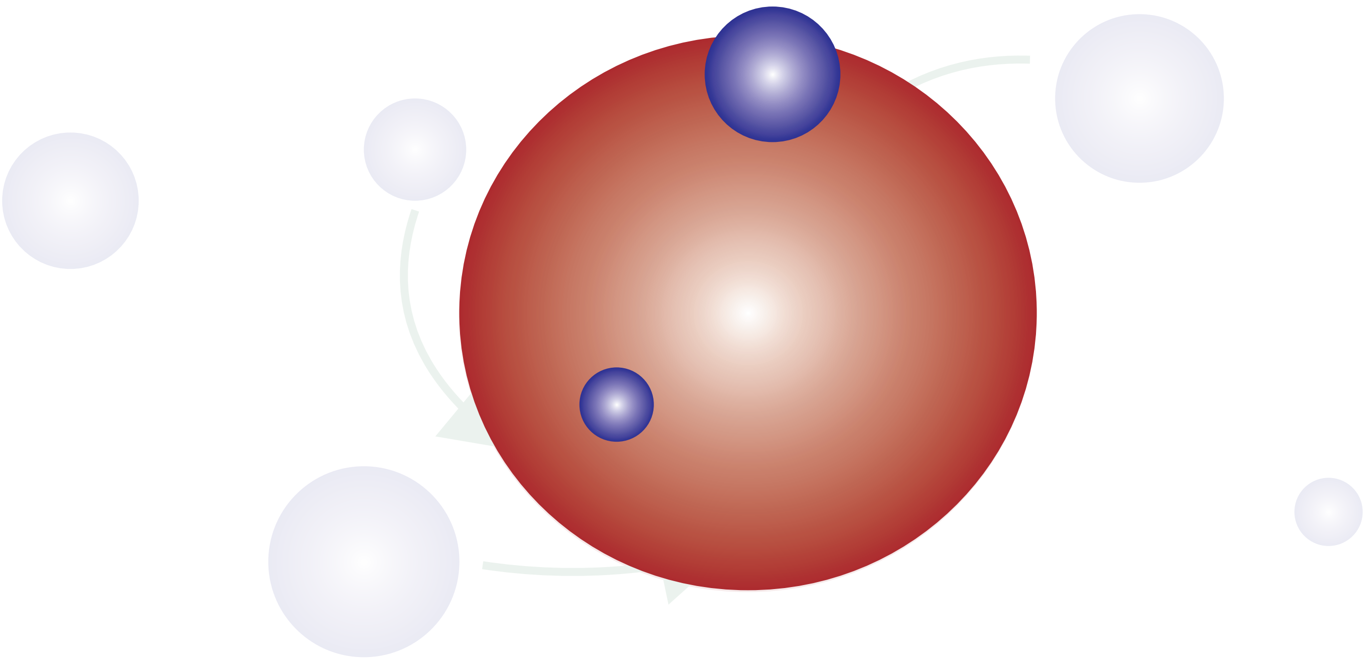
Subhalos accrete on a host halo

↓

Subhalos or satellite galaxies



Evolution of halo/subhalos



Curvature perturbation

↓

Host halos and subhalos

↓

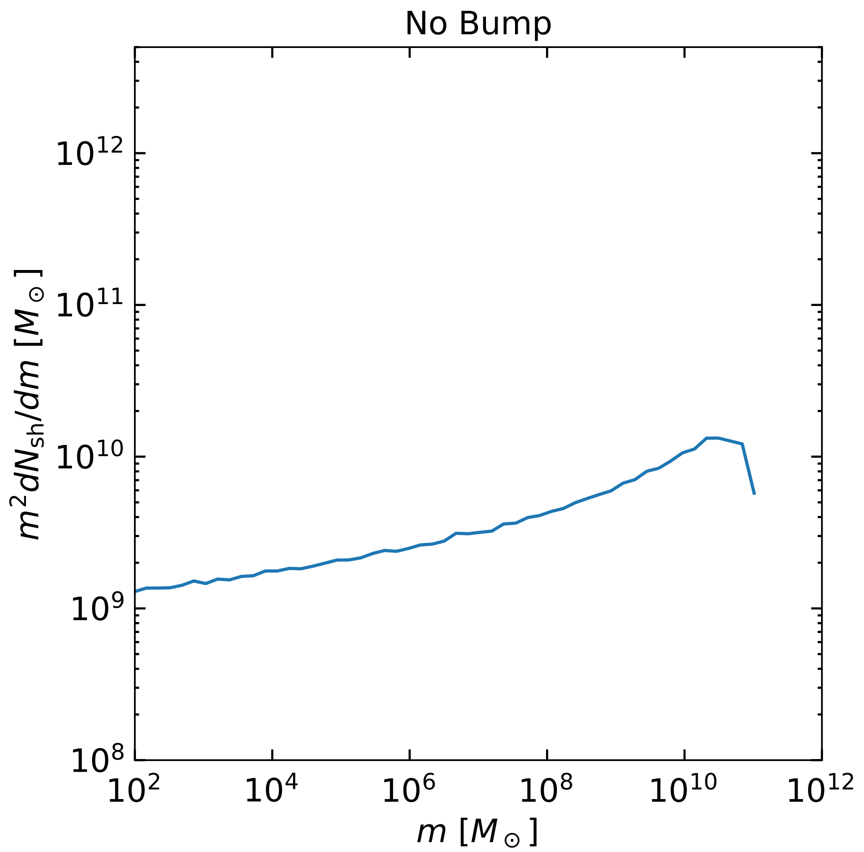
Subhalos accrete on a host halo

↓ Tidal stripping

Subhalos or satellite galaxies

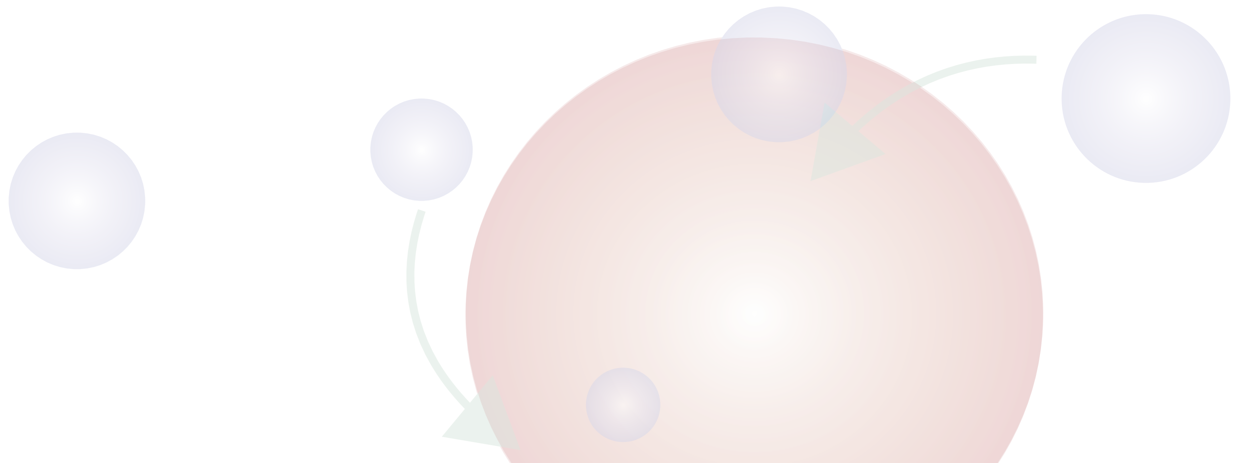
Studied in semi-analytical way
calibrated by N-body simulation

Hiroshima, Ando, Ishiyama ’18

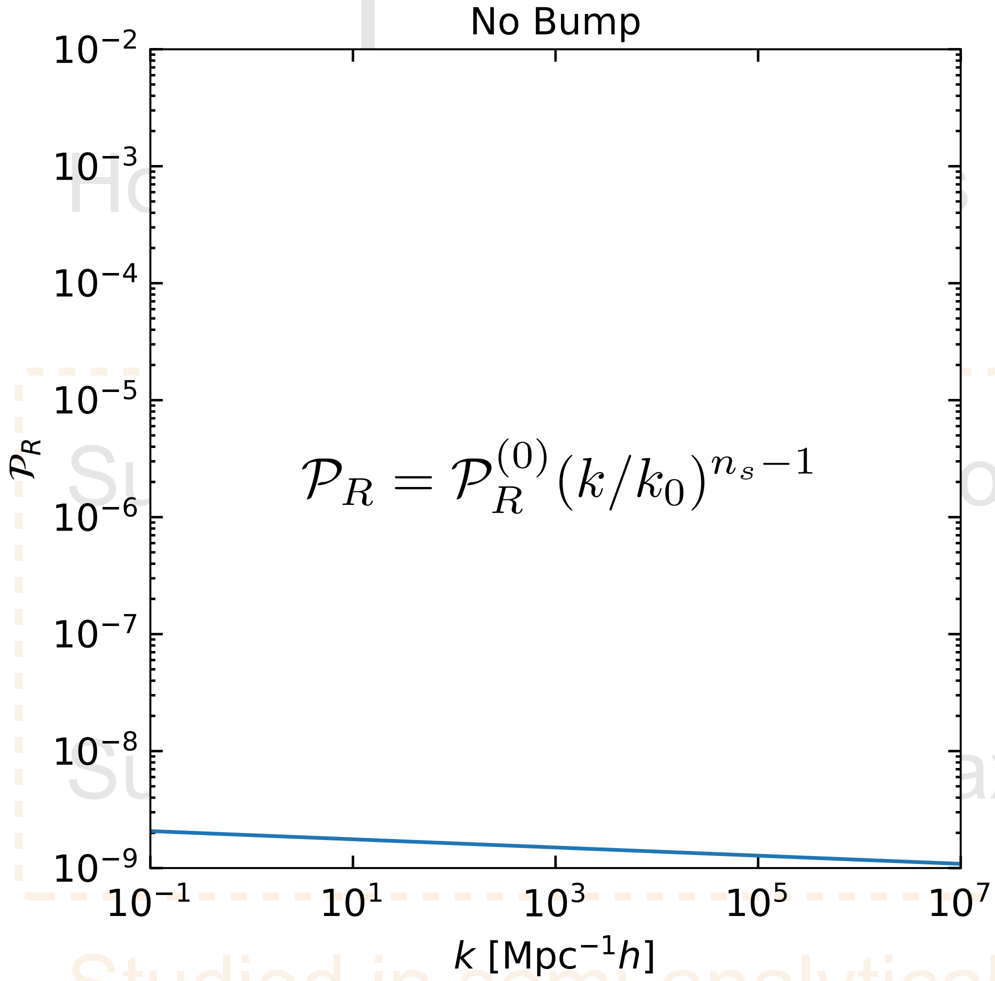


Mass distribution of subhalos

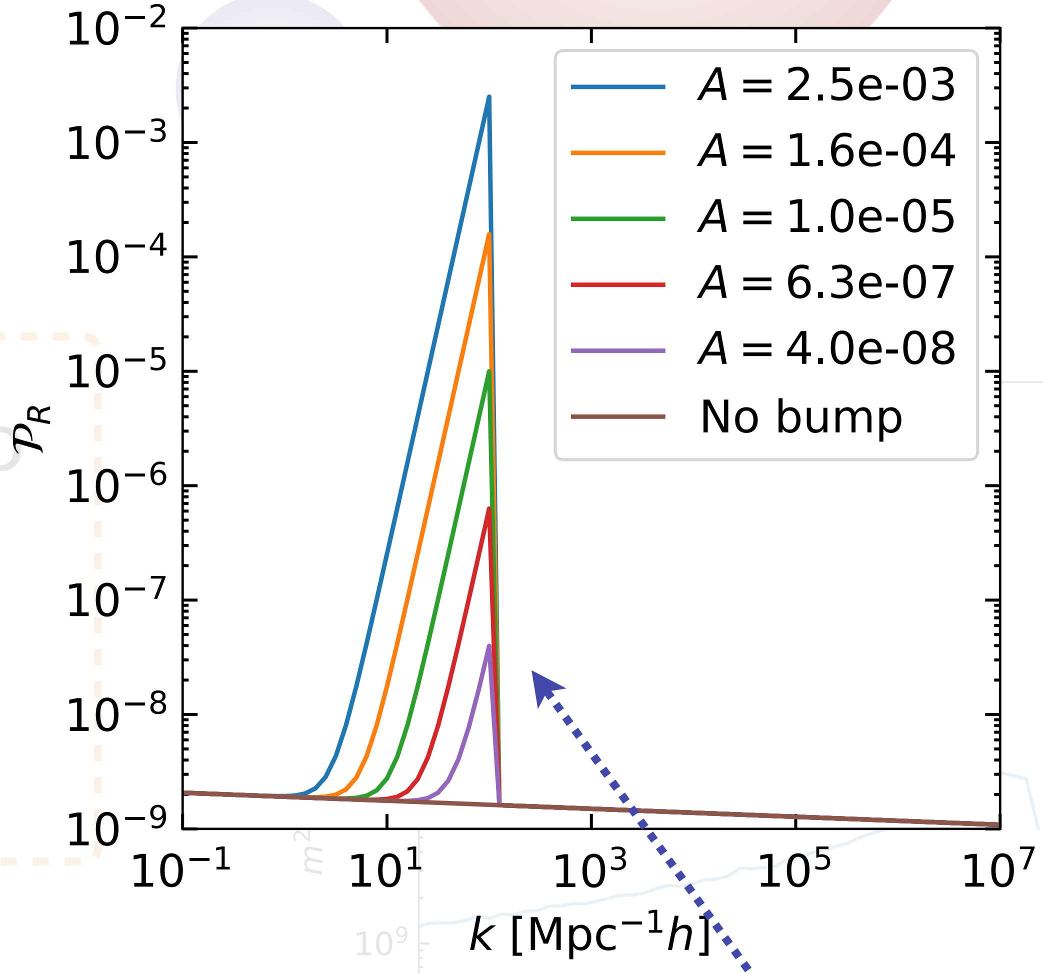
Evolution of halo/subhalos



Curvature perturbation



$$\mathcal{P}_R = \mathcal{P}_R^{(0)}(k/k_0)^{n_s-1}$$



Additional bump

Studied in semi-analytical way
calibrated by N-body simulation

Hiroshima, Ando, Ishiyama '18

What will happen?

Mass distribution of subhalos

Evolution of halo/subhalos

Curvature perturbation

↓

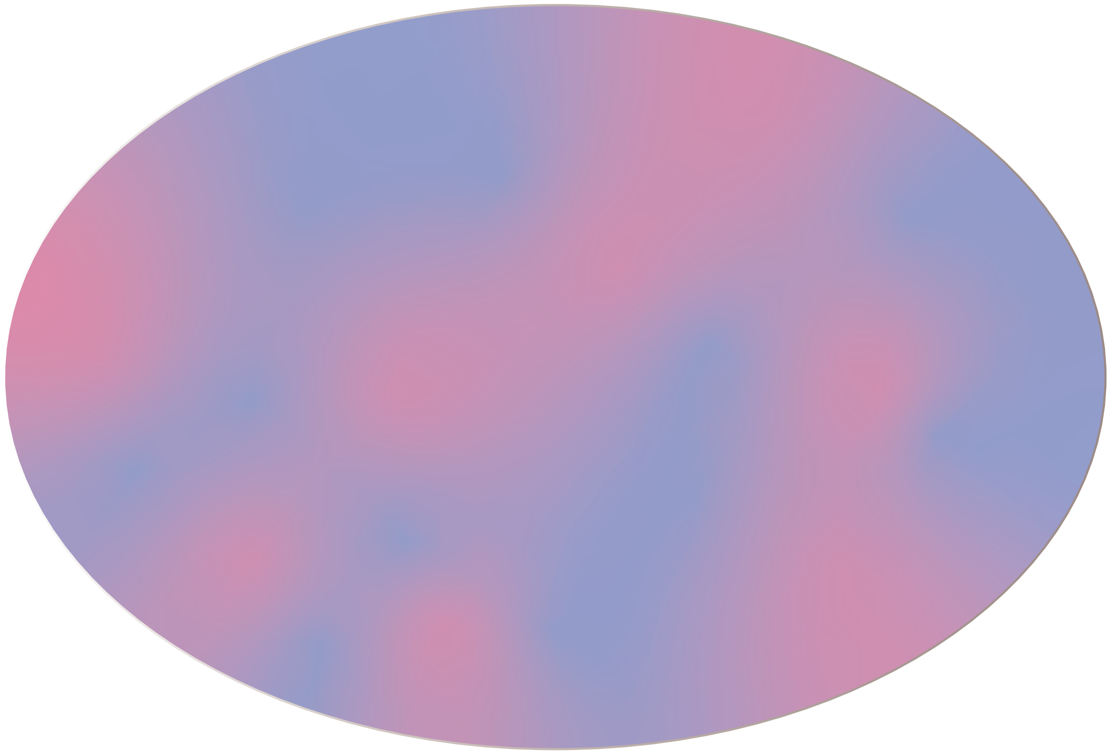
Host halos and subhalos

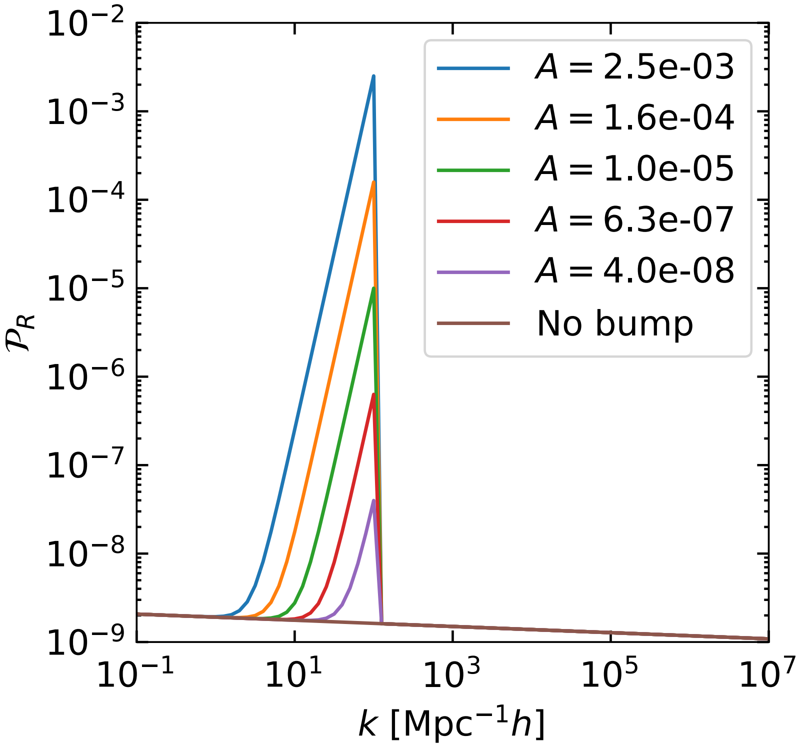
↓

Subhalos accrete on a host halo

↓

Subhalos or satellite galaxies





Evolution of halo/subhalos

Curvature perturbation

↓

Host halos and subhalos

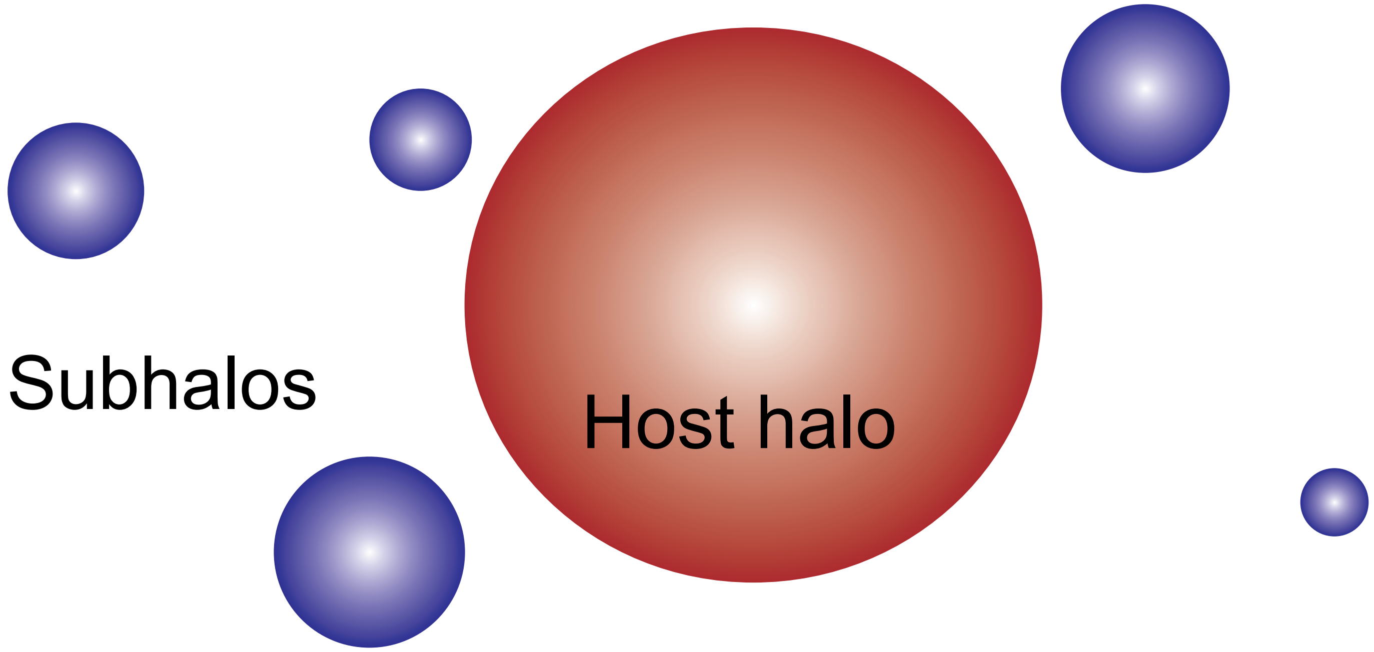
↓

Subhalos accrete on a host halo

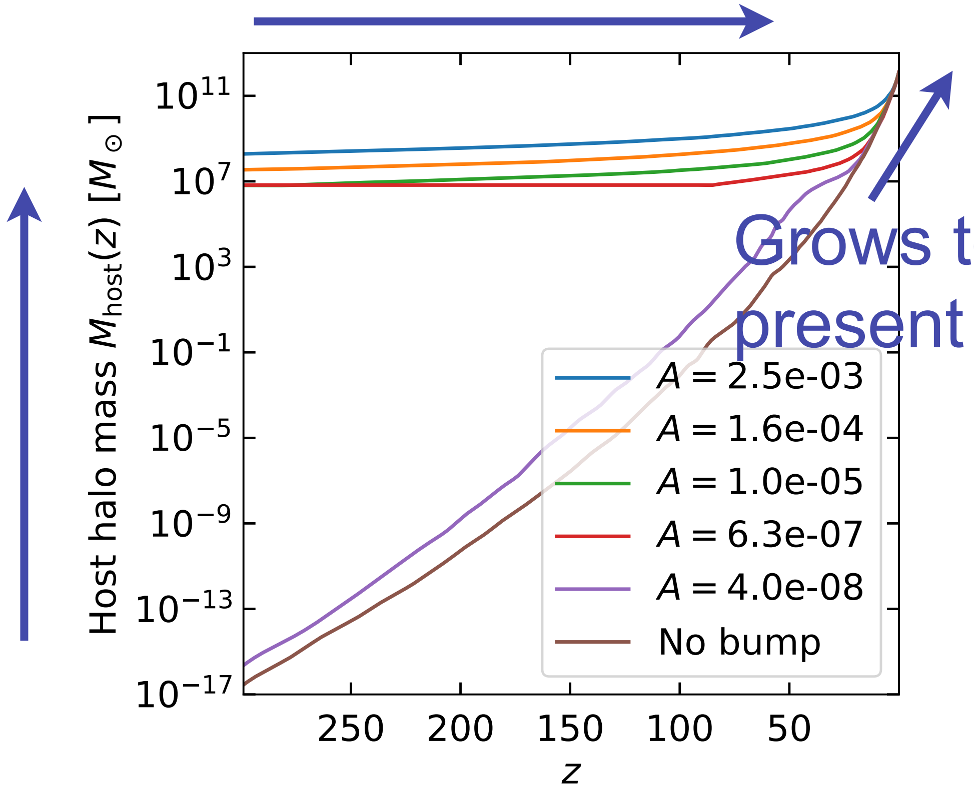
↓

Halo grows to a specific scale *at once*

Subhalos or satellite galaxies



Merely grows for while



Grows to the present mass

Evolution of halo/subhalos

Curvature perturbation

↓

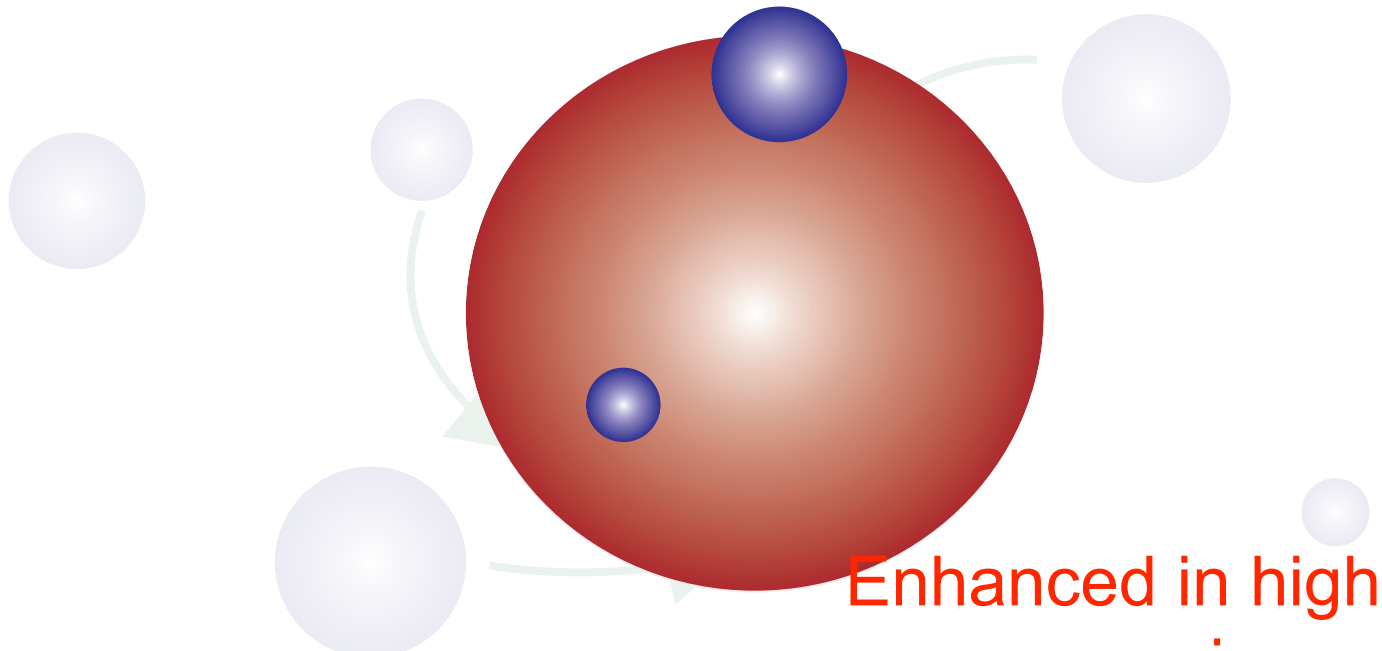
Host halos and subhalos

↓

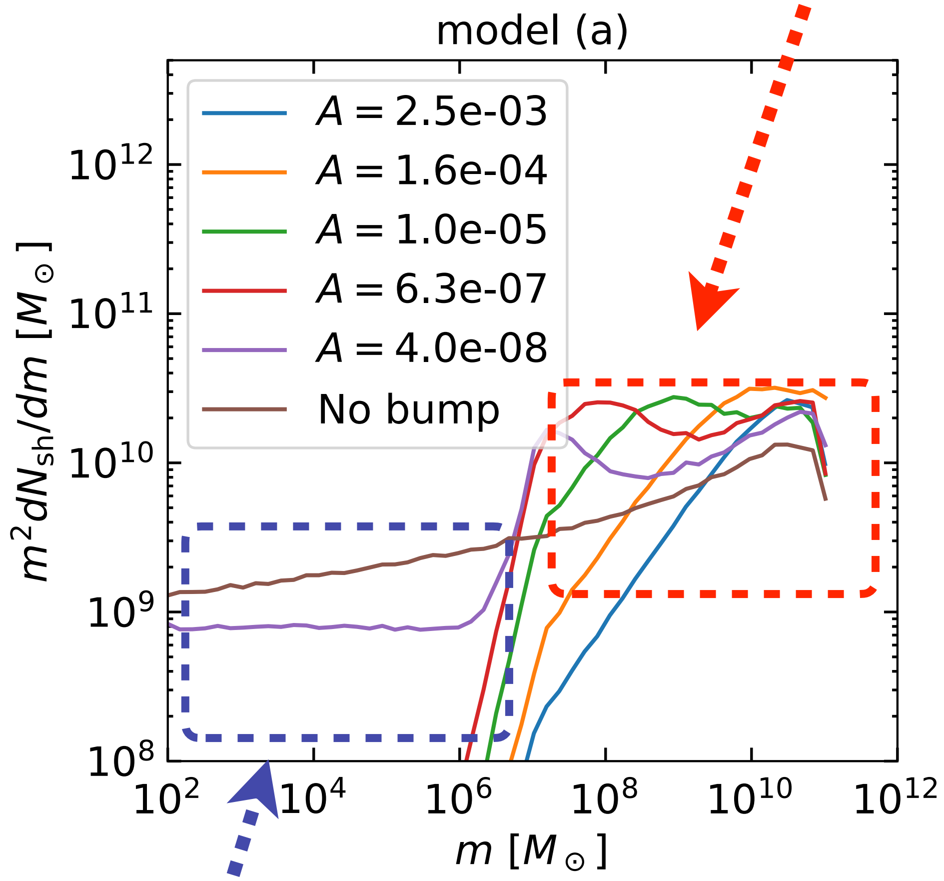
Subhalos accrete on a host halo

↓ Tidal stripping

Subhalos or satellite galaxies



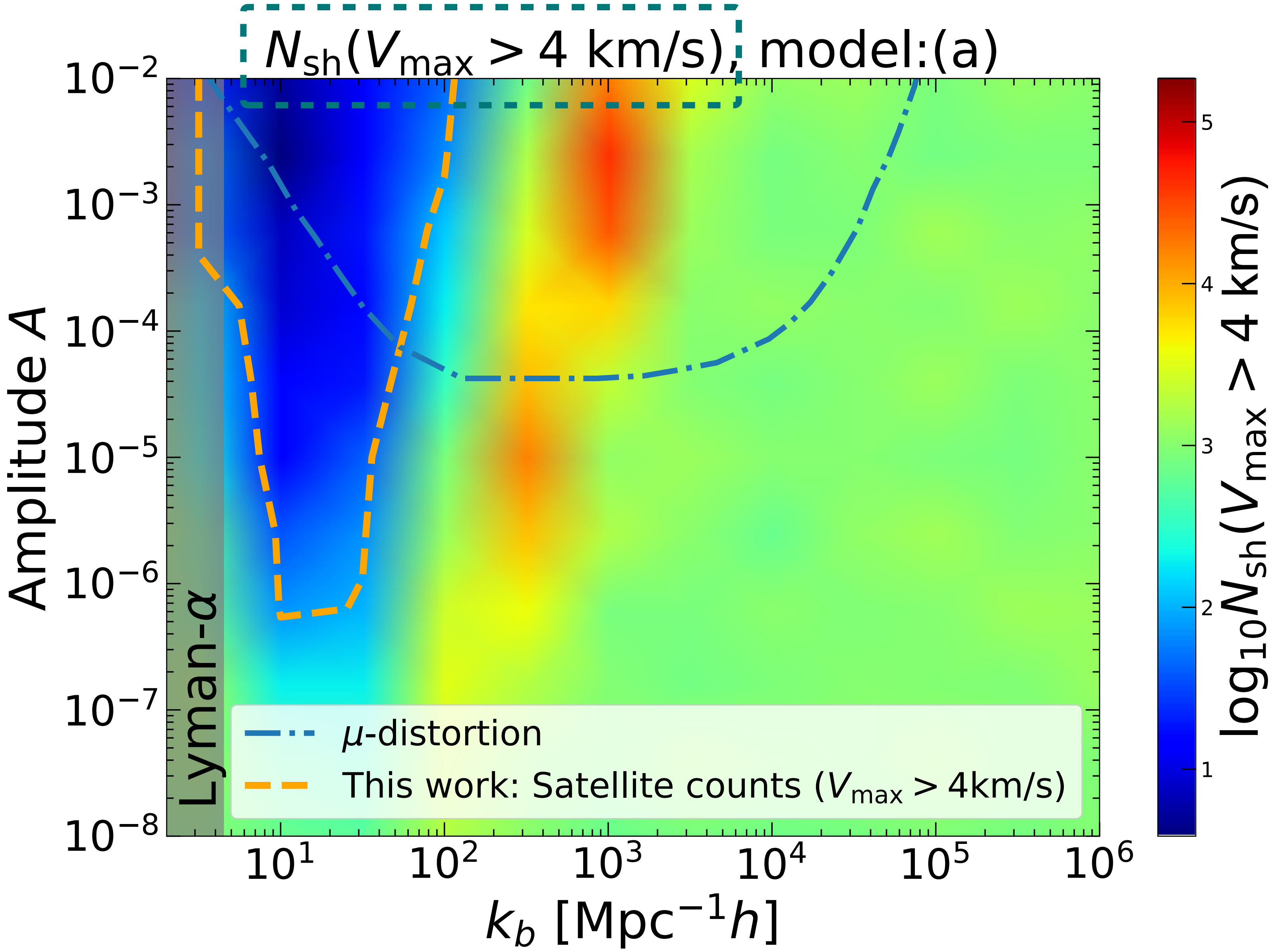
Enhanced in high mass region



Suppressed in low mass region

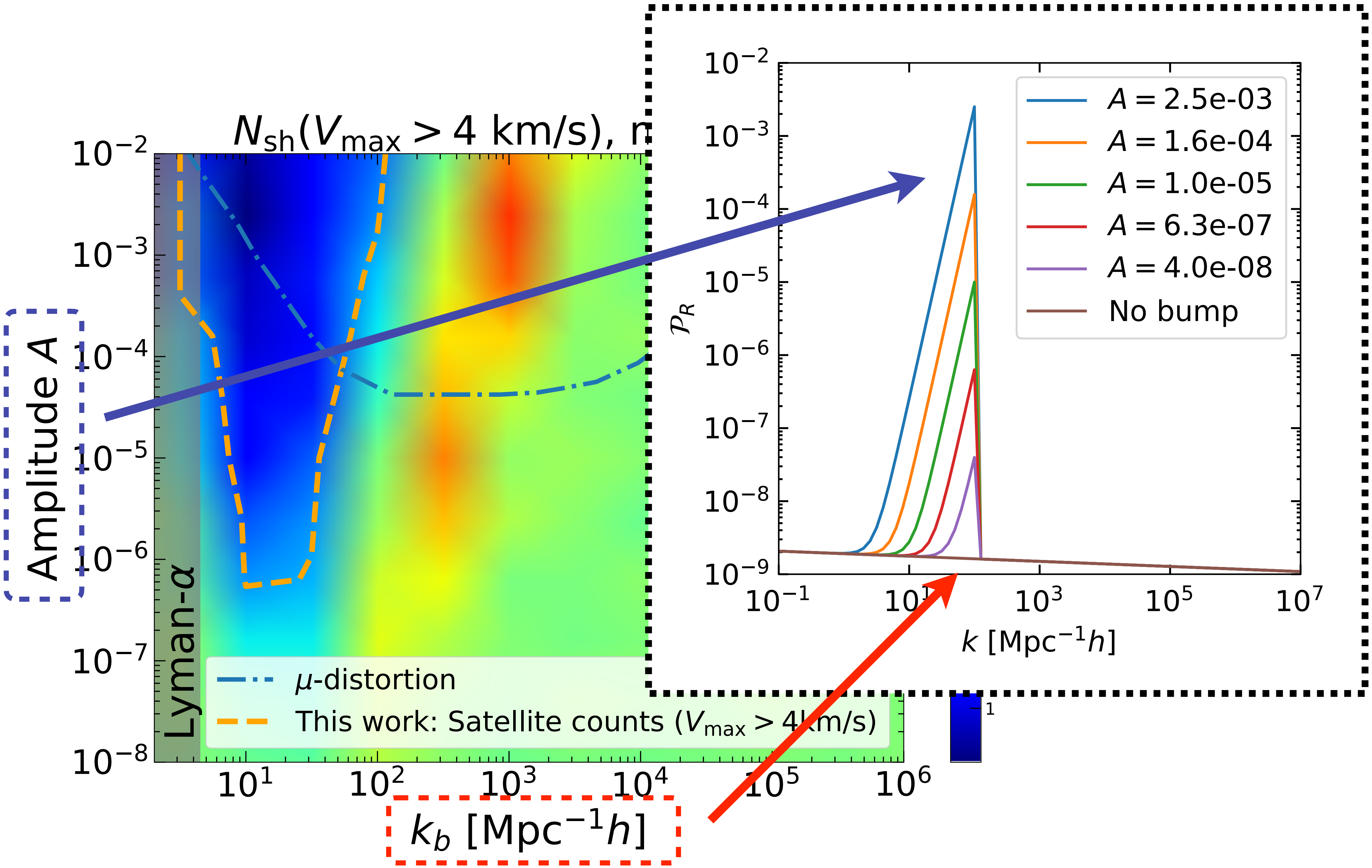
The observable: satellite counts

Number of subhalos whose $V_{\max} > 4\ \mathrm{km/s}$



$V_{\max}$: Maximum circular velocity of subhalos

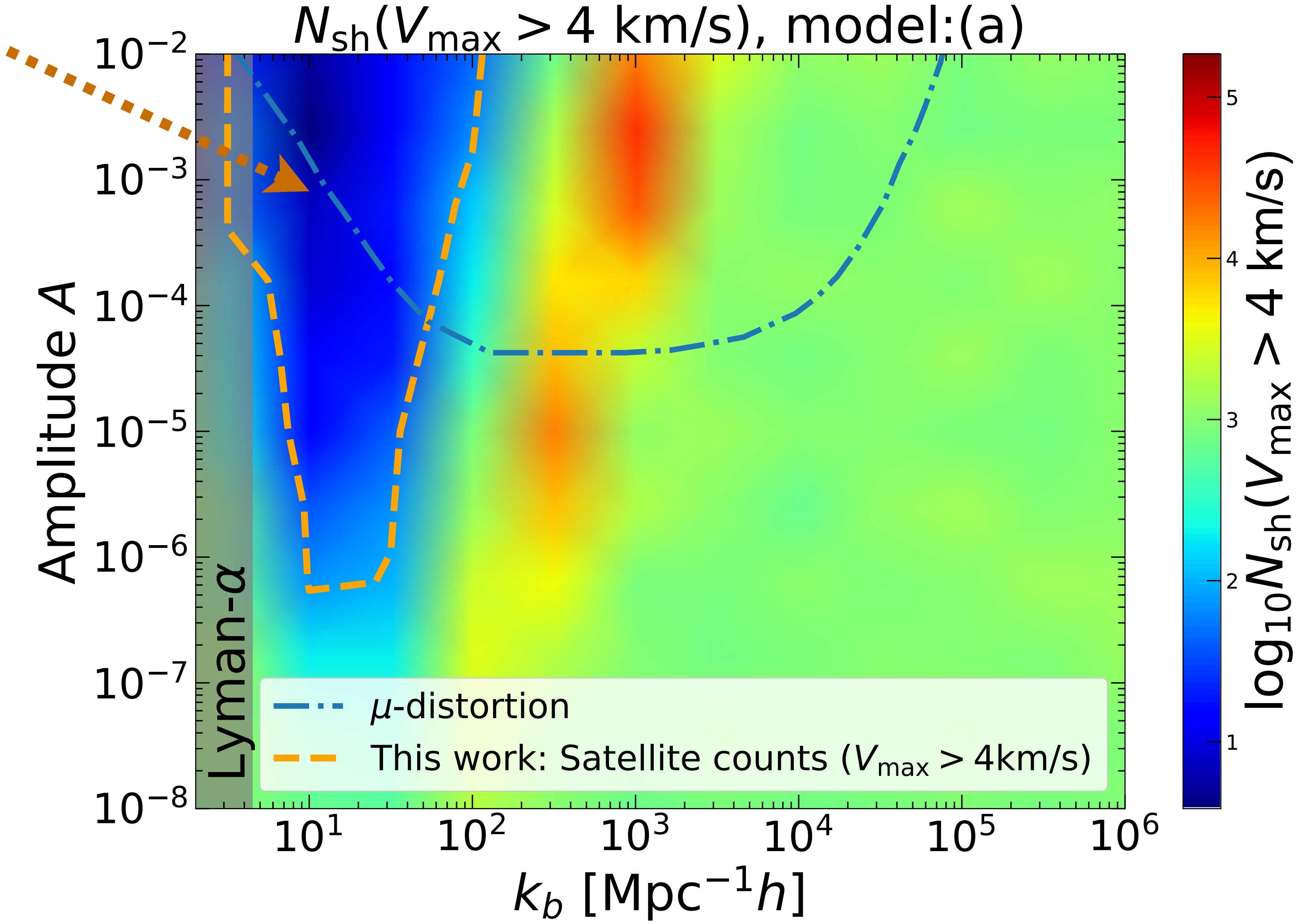
The observable: satellite counts



$V_{\rm max}$: Maximum circular velocity of subhalos

The observable: satellite counts

Excluded



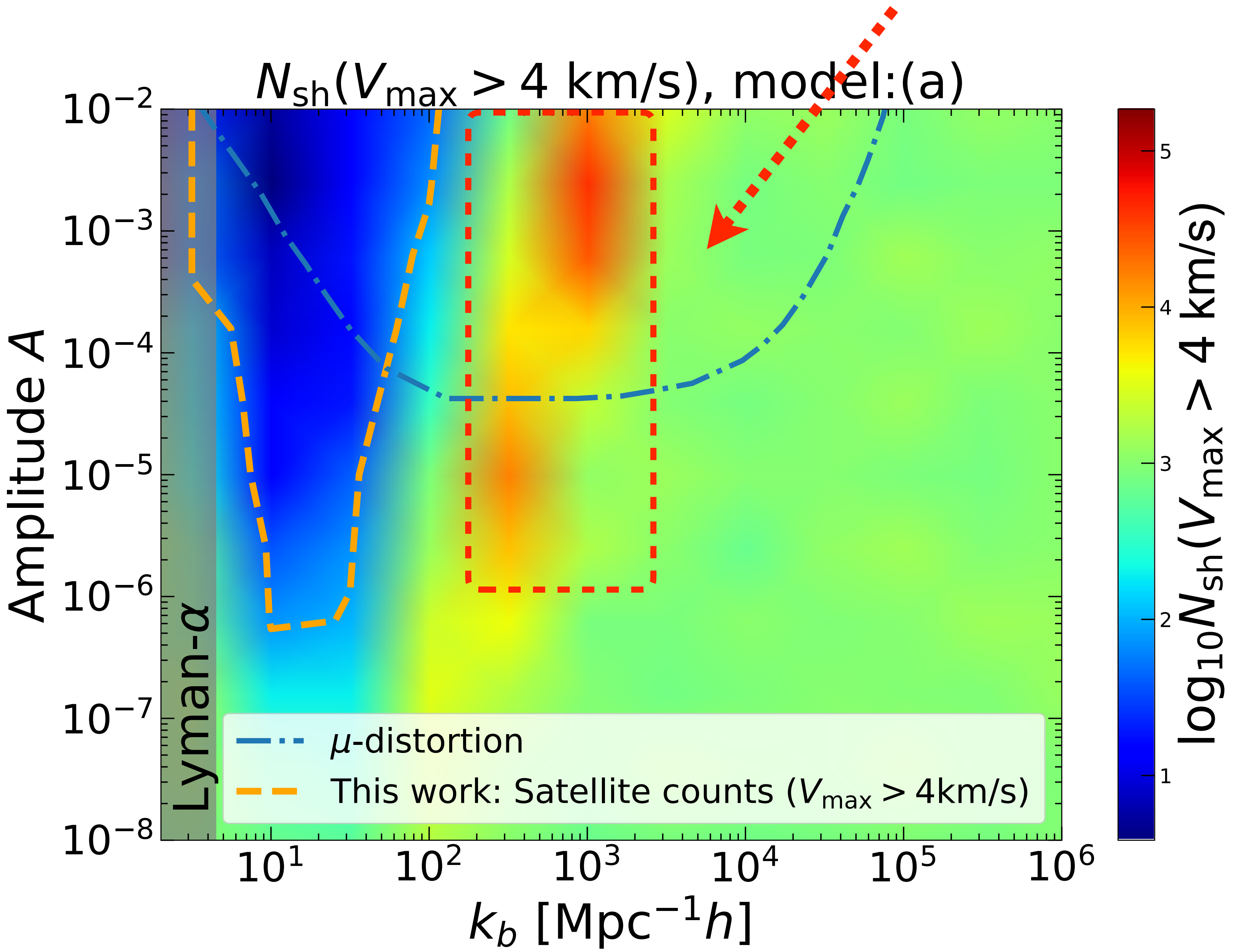
Conservative limit

$$N^{\rm low}_{\rm dSph}(V_{\rm max} > 4~{\rm km/s}) = 94$$

Graus, Bullock, Kelley, Boylan-Kolchin, Garrison-Kimmel, Qi ’19

Dekker, Ando, Correa, Ng ’21

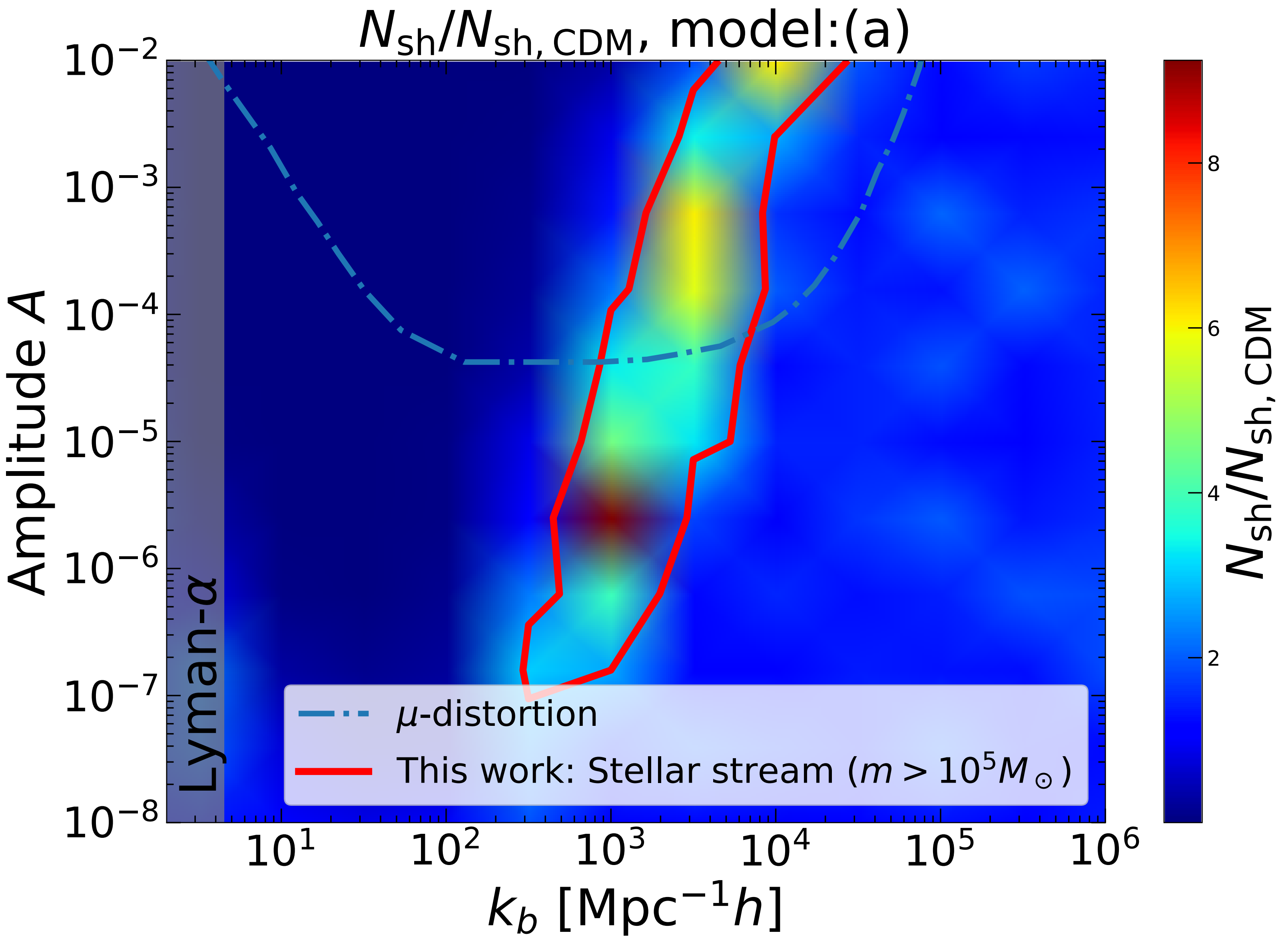
The observable: satellite counts



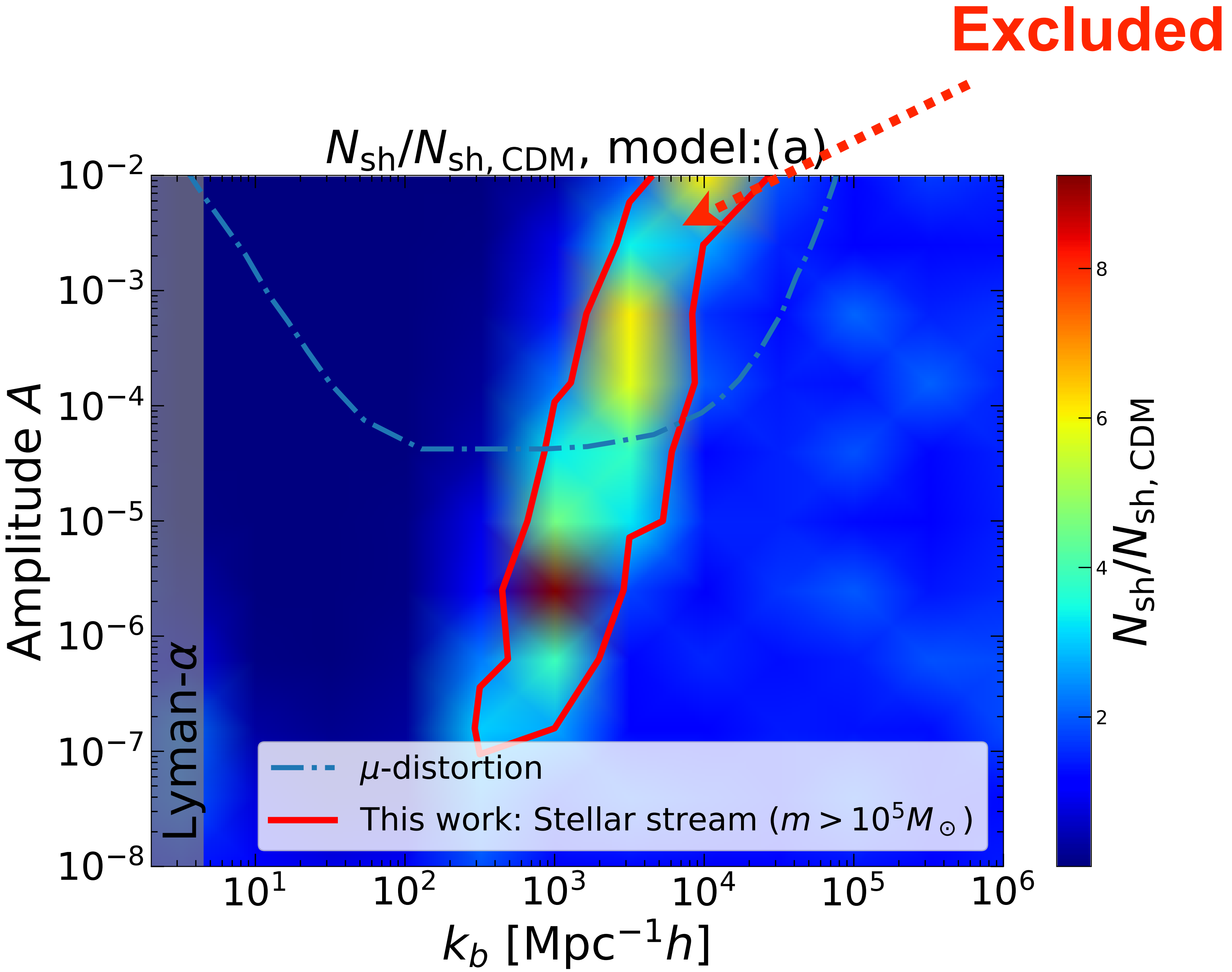
Enhanced

The observable: stellar stream

$N_{\rm sh}$: Number of subhalos whose mass >$10^5 M_\odot$



The observable: stellar stream



Conservative limit

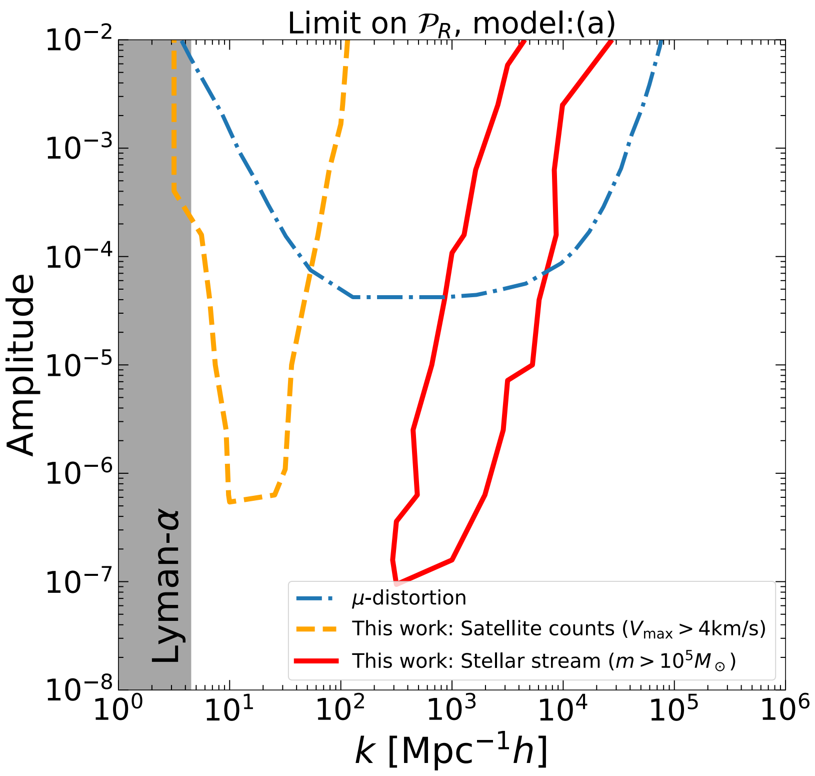
$$N_{\rm sh}/N_{\rm sh,CDM} < 2.7 \ (95\% \ \rm CL)$$

Banik, Bovy, Bertone, Erkal, de Boer ’21

Ando, KI, Hiroshima ’22

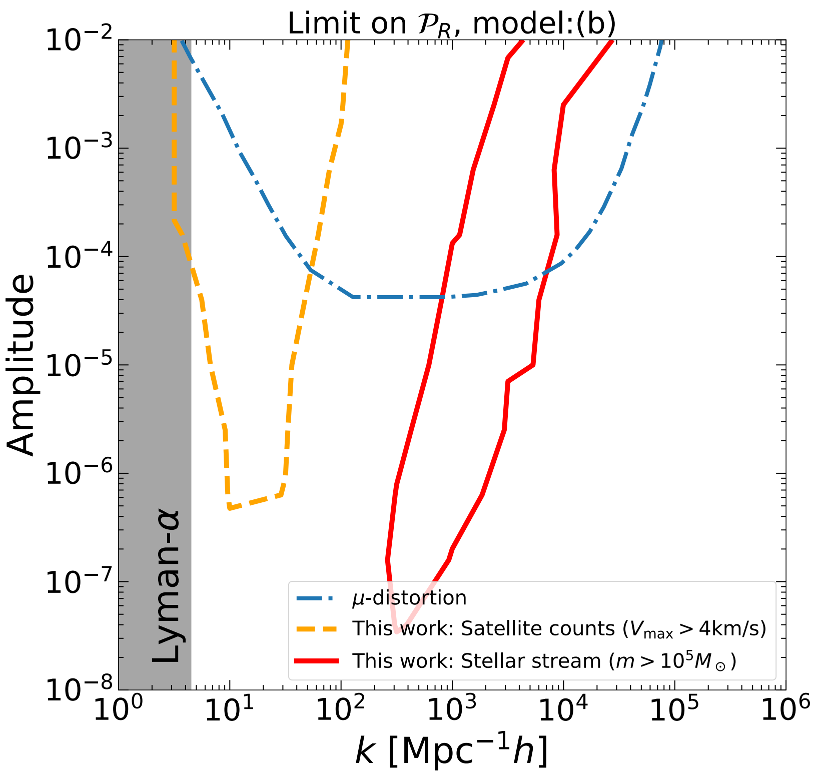
Tidal stripping model

Jiang, van den Bosch ’16

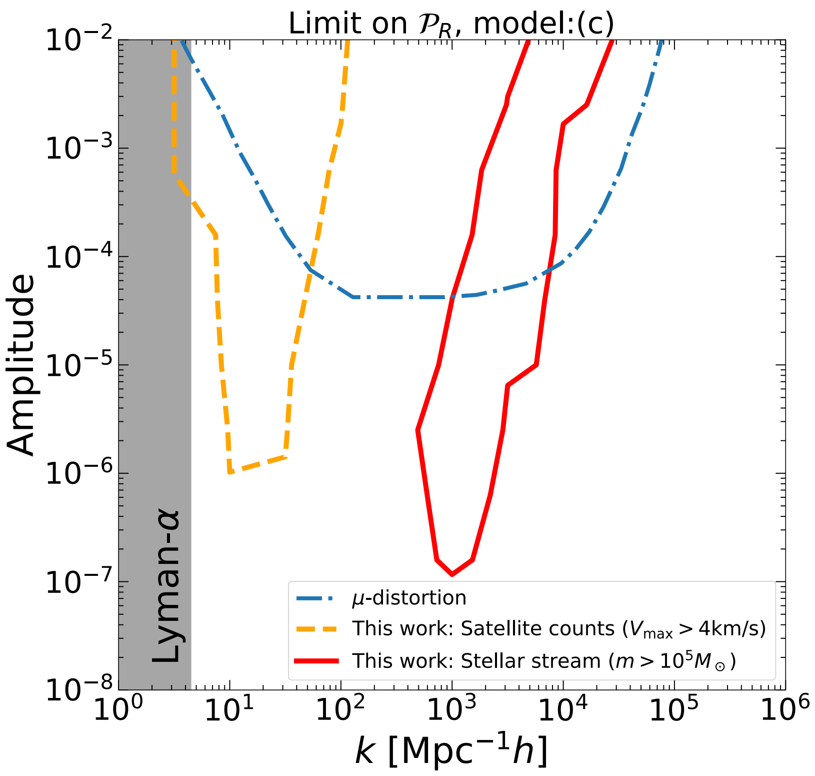


Tidal stripping model

Hiroshima, Ando, Ishiyama ’18



No tidal stripping



No tidal model dependence

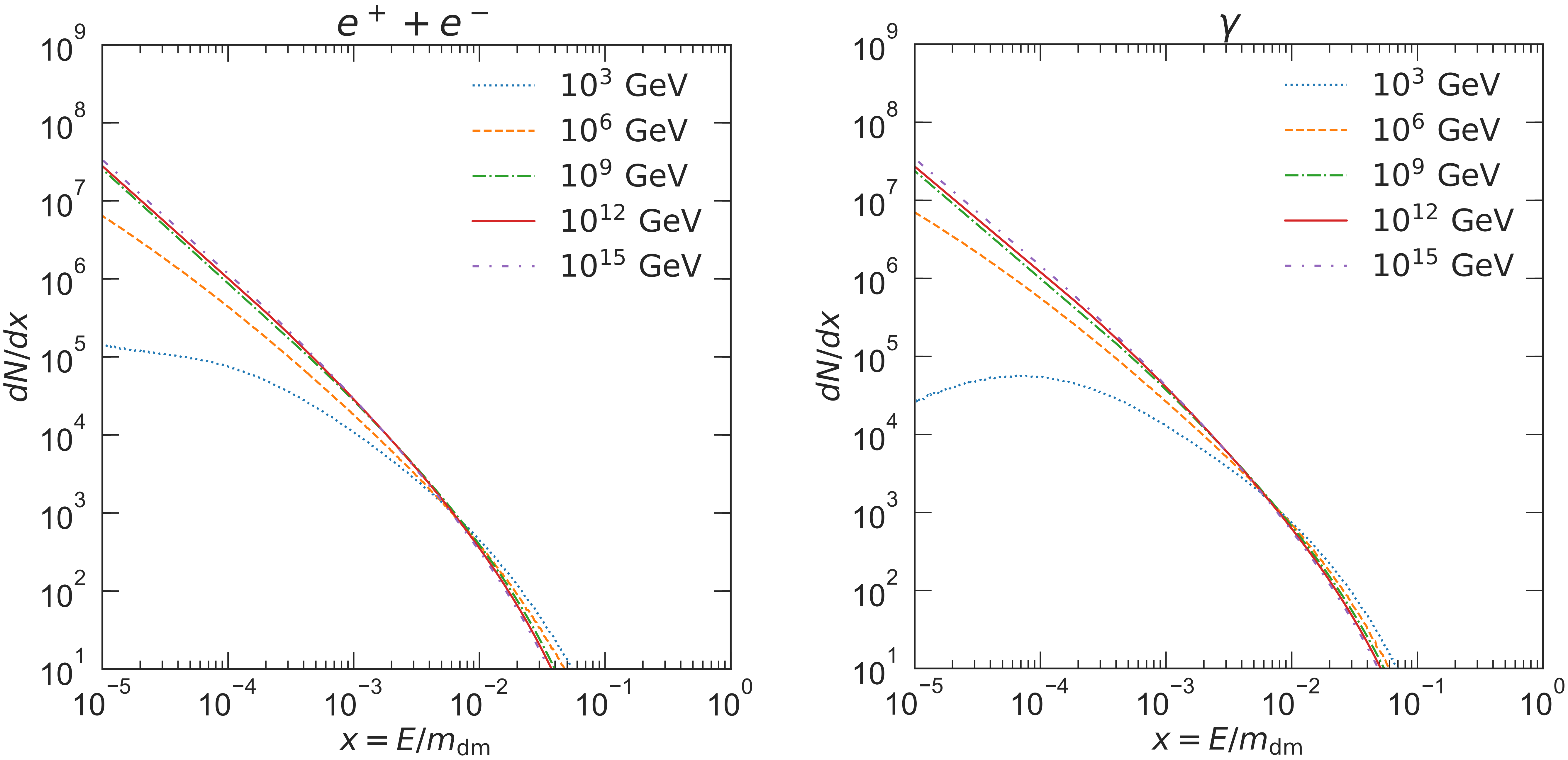
4. Conclusion

We have discussed indirect searches on heavy DM decay and primordial curvature perturbation

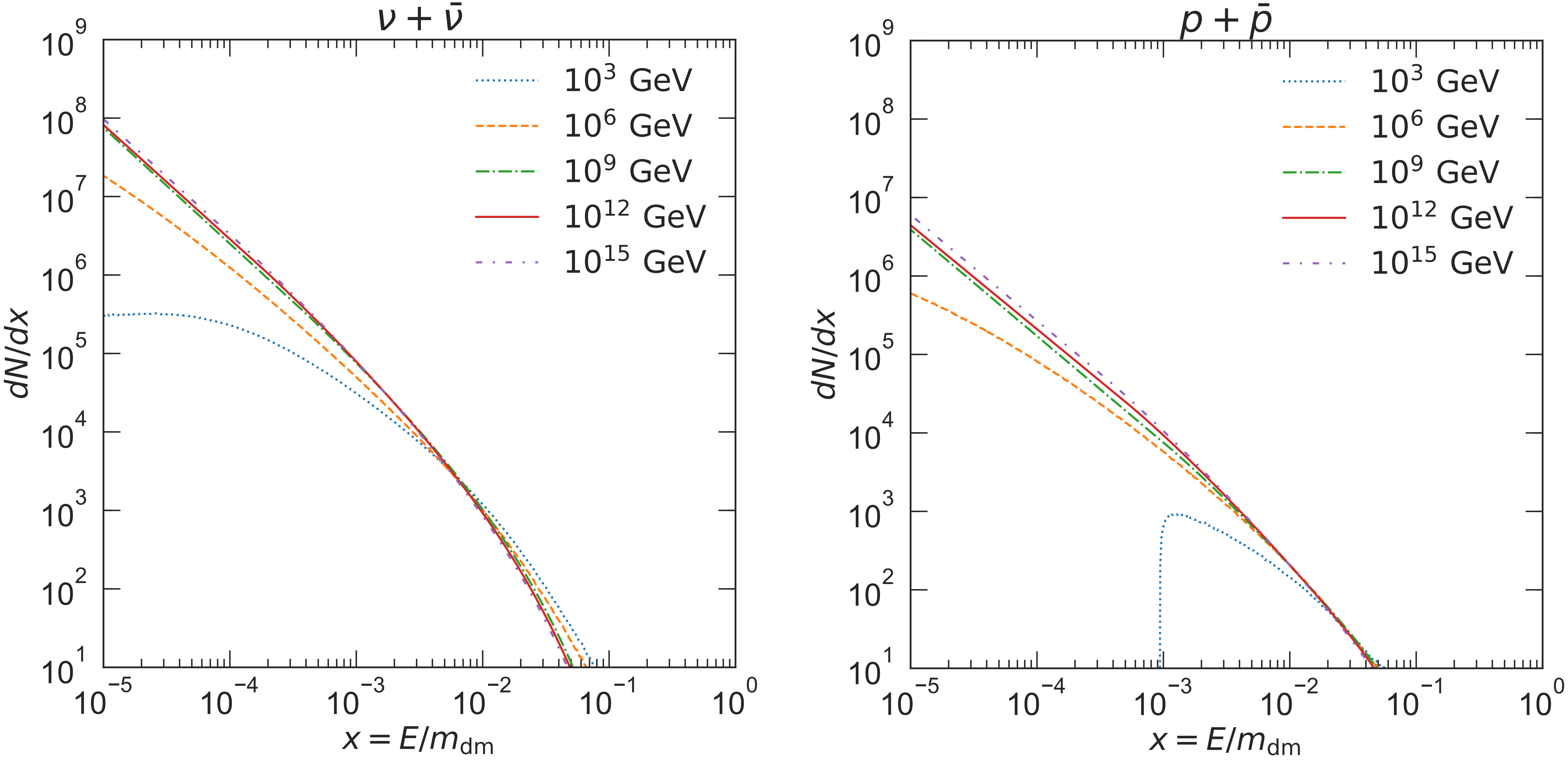
- Multimessenger astrophysical data, especially γ and ν data, is powerful tool to constrain heavy DM decay
- Tracking the evolution of DM substructure is a new technique to probe the primordial curvature perturbation

Backups

Energy distributions:



Energy distributions:



Propagation of CR nuclei

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

- Photo-pion production

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

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

- Pair production (Bethe-Heitler)

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

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

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

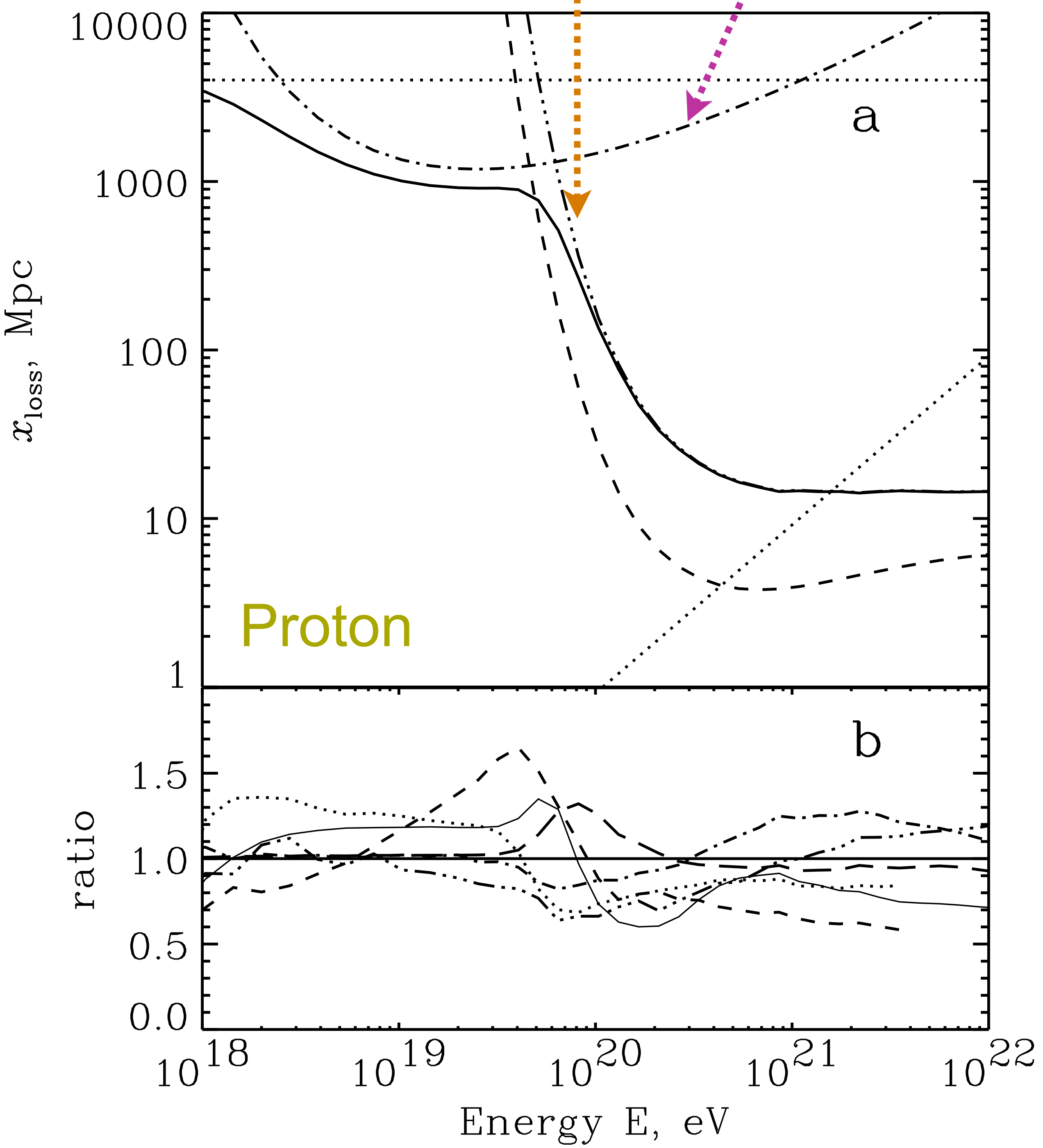


Photo-pion production

Pair production

Stanev, Engel, Mücke, Protheroe, Rachen ’00

Propagation of CR EM particles

Heiter, Kuempel, Walz, Erdmann ’17

- Pair production (PP)

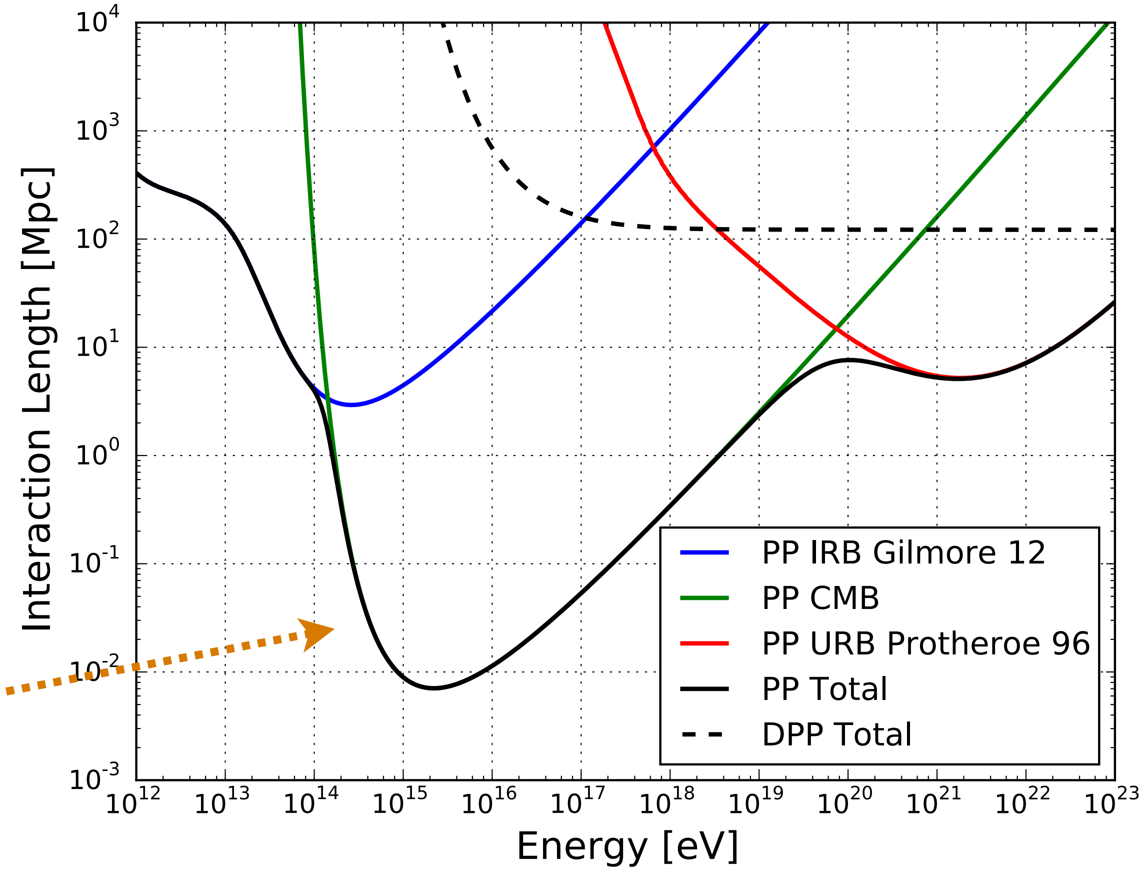
$$\gamma + \gamma_{\rm BG} \rightarrow e^+ + e^-$$

- Double pair production (DPP)

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

PP in the CMB is dominant

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



- Triple pair production (TPP)

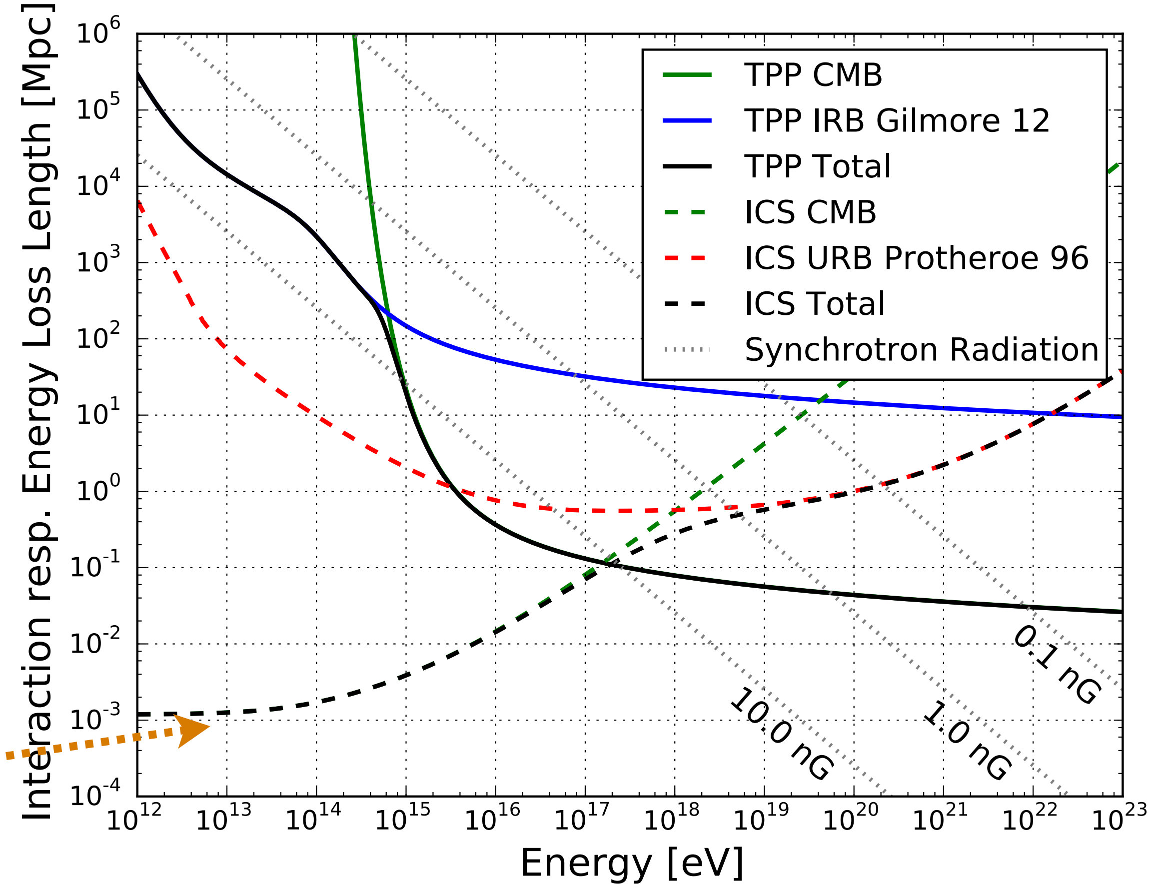
$$e + \gamma_{\rm BG} \rightarrow e + e^+ + e^-$$

- Inverse Compton scattering (ICS)

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

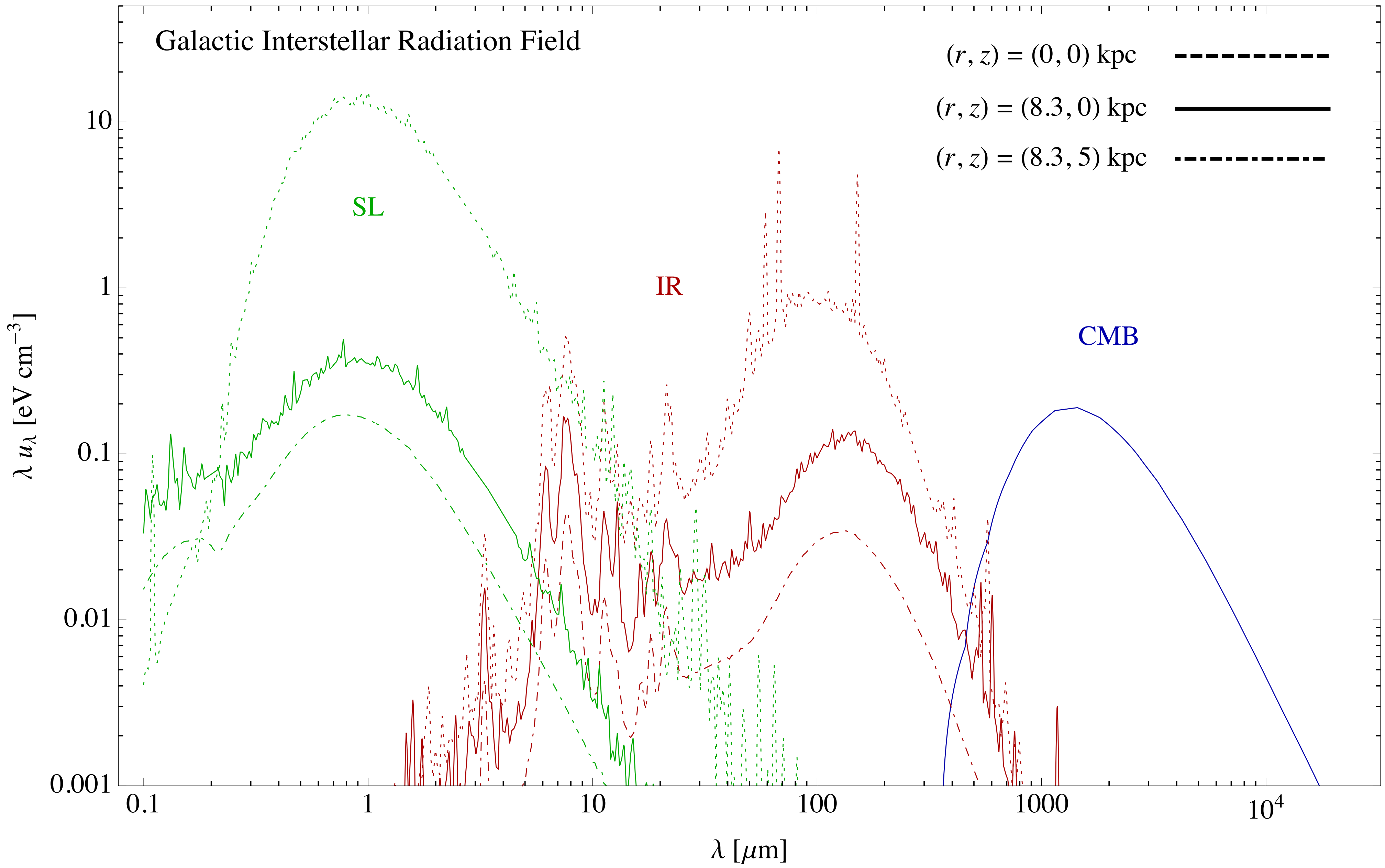
ICS in the CMB is dominant

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



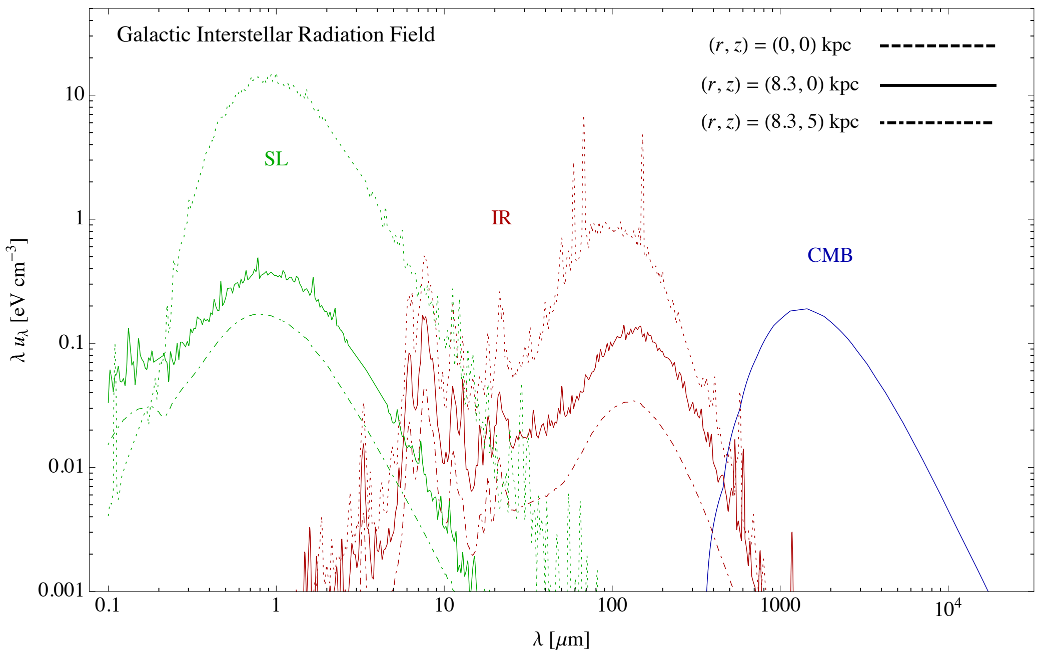
Absorption in ISRF+CMB

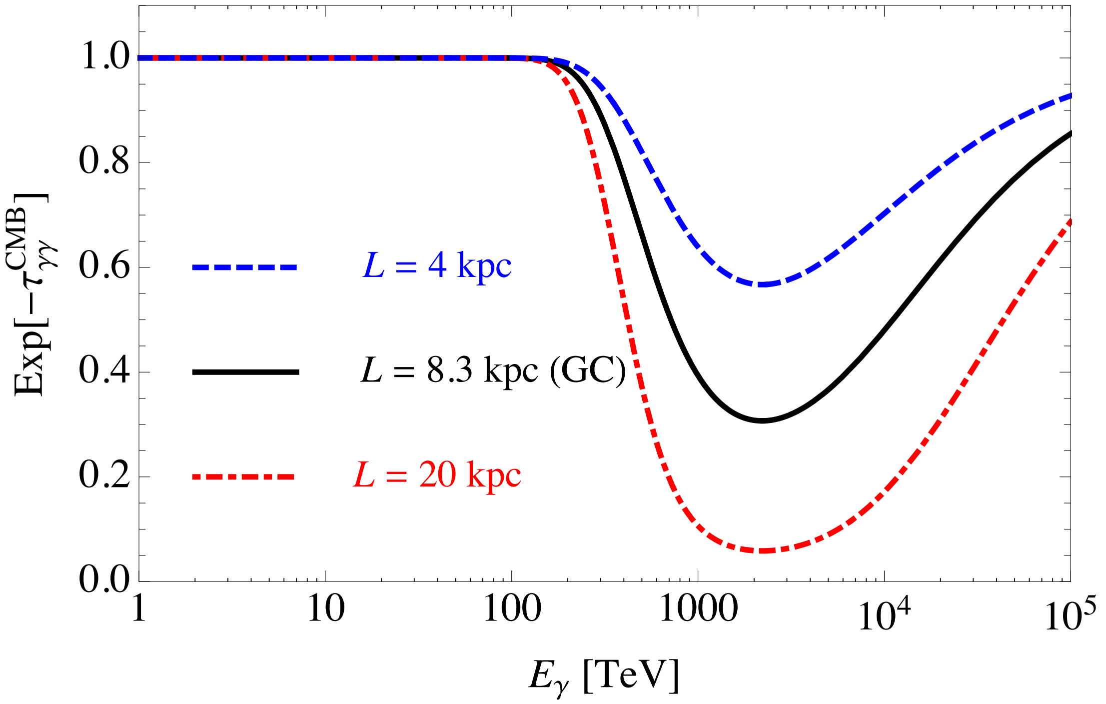
Esmaili, Serpico ’15

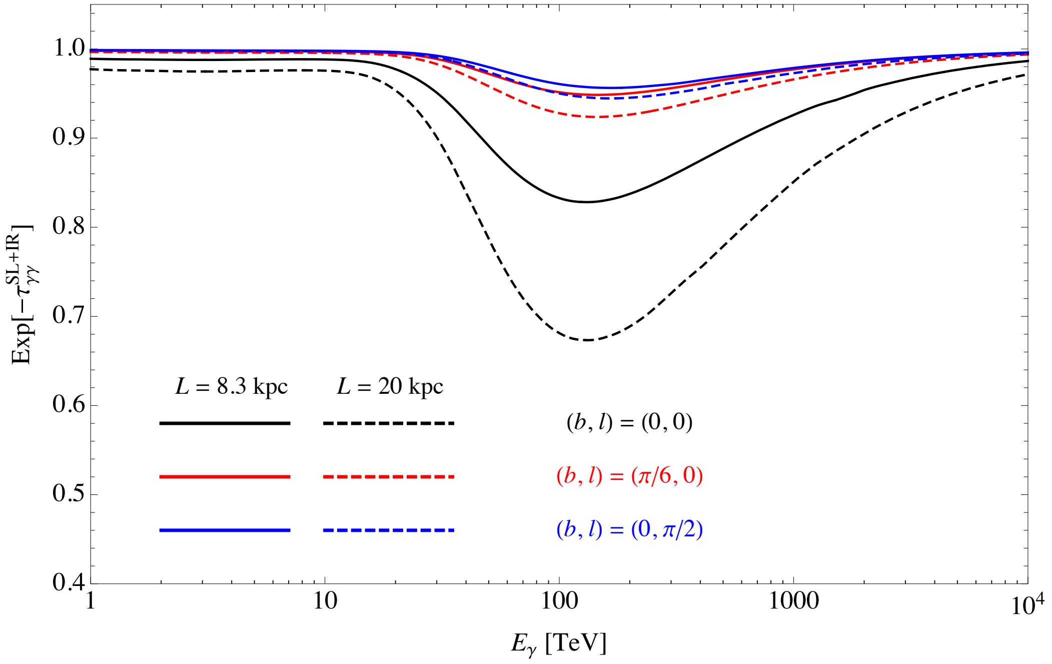


Absorption in ISRF+CMB

Esmaili, Serpico '15

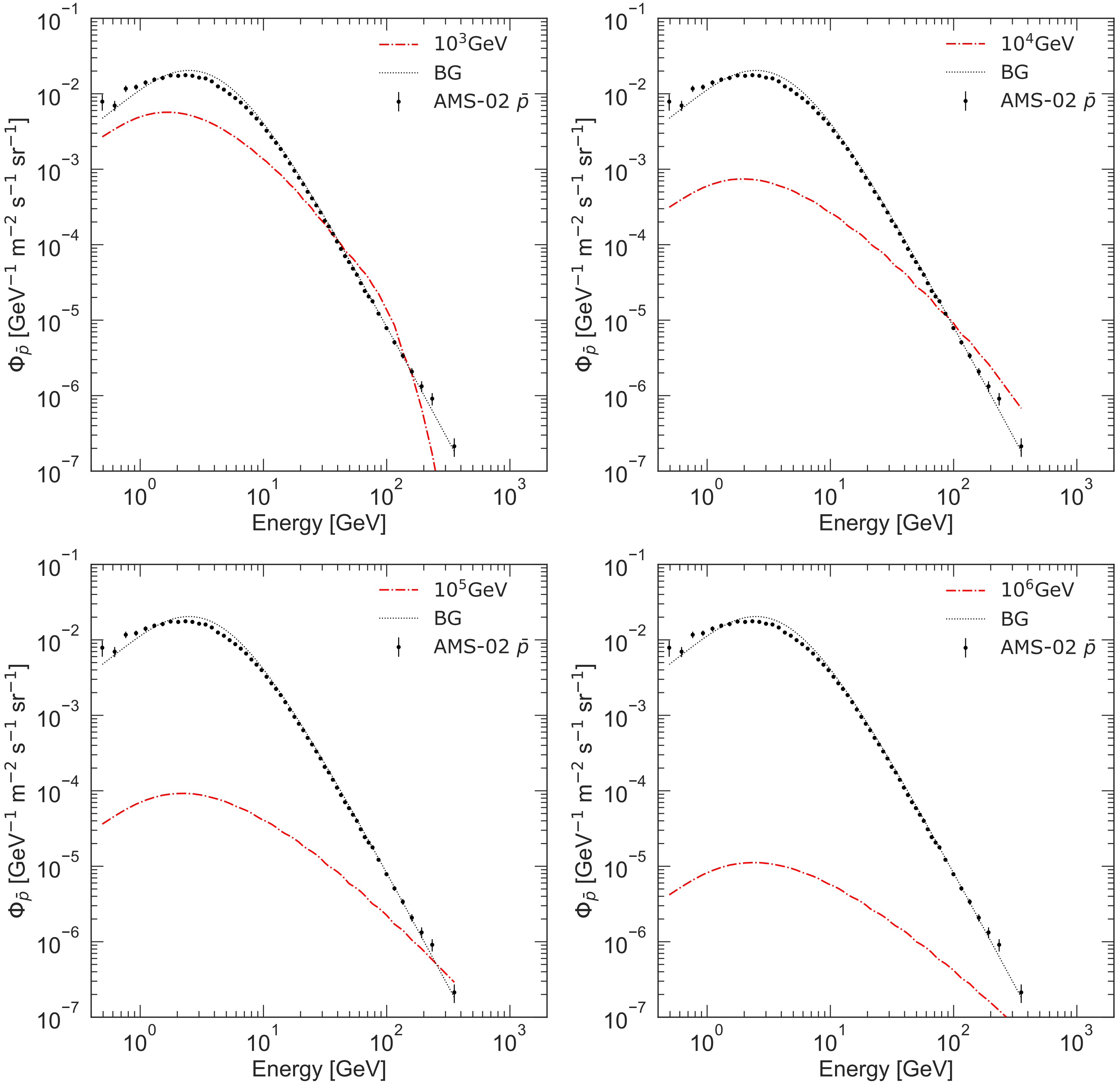






$0.1 - 100$ PeV γ is under the absorption effect

$\bar{p}$ flux in the Galaxy

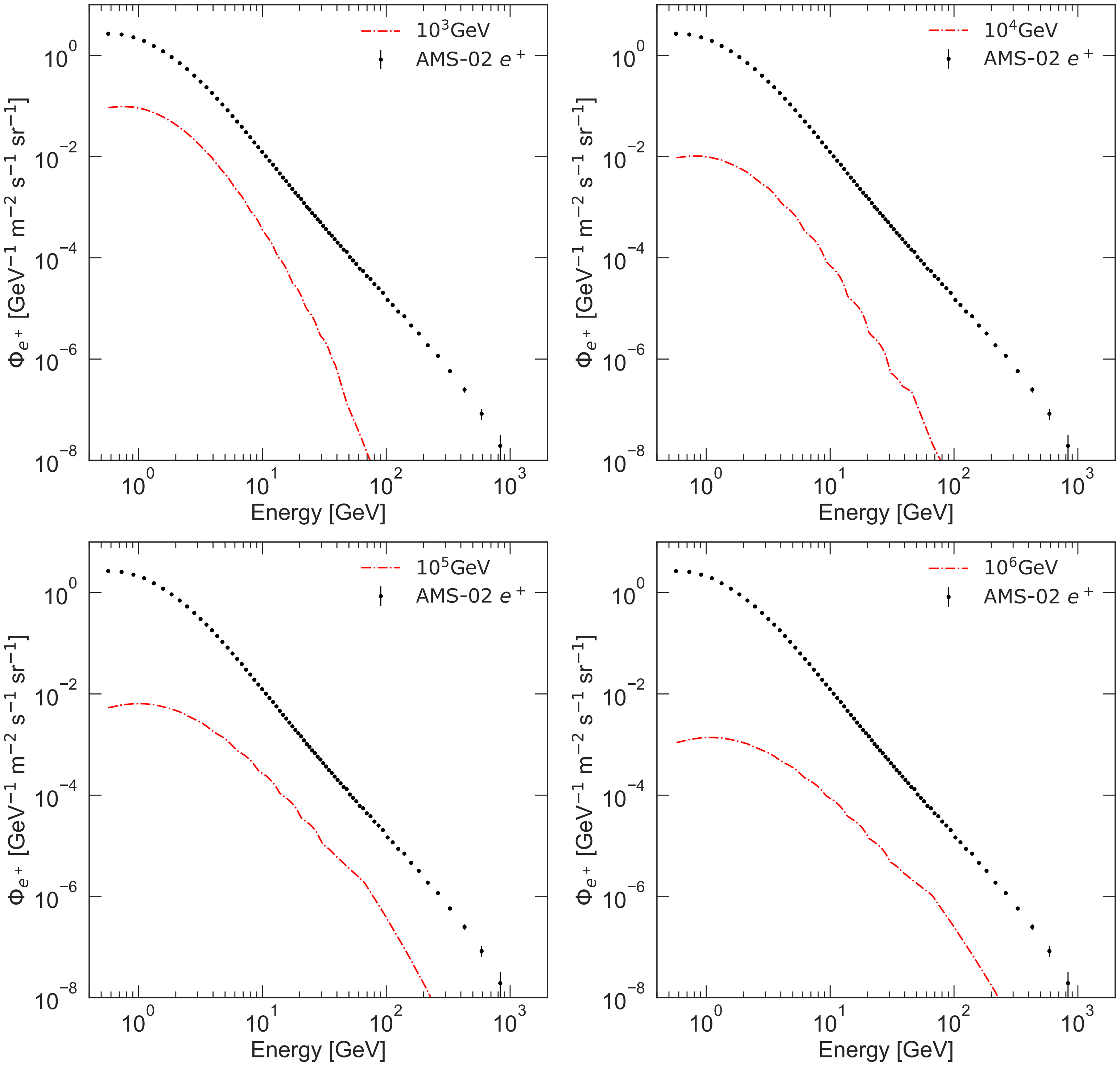


$$\tau_{\rm dm} = 10^{27}\,{\rm s}$$

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

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

e^+ flux in the Galaxy

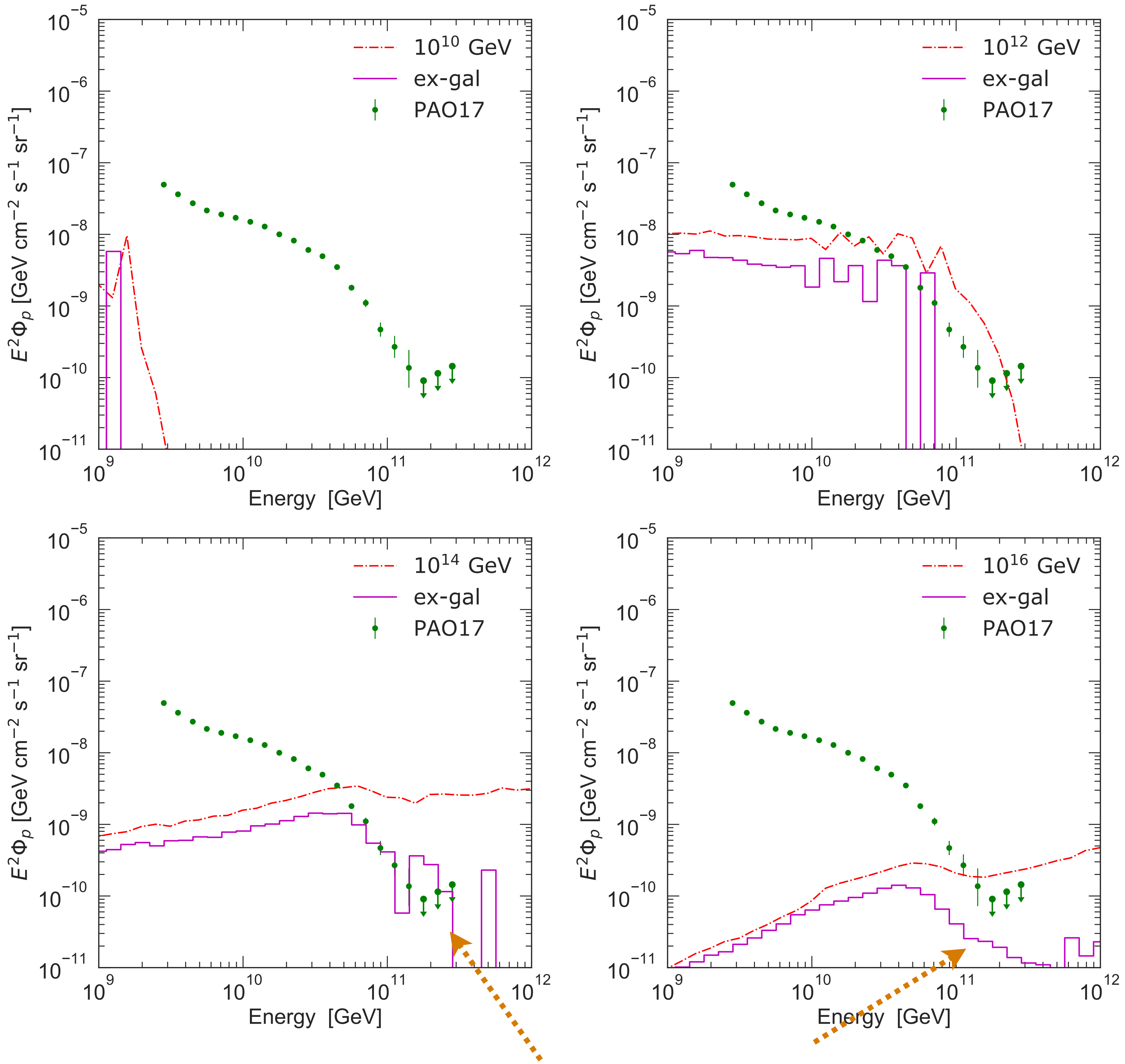


$$\tau_{\rm dm} = 10^{27}\,{\rm s}$$

Similar behavior to $\bar{p}$ flux

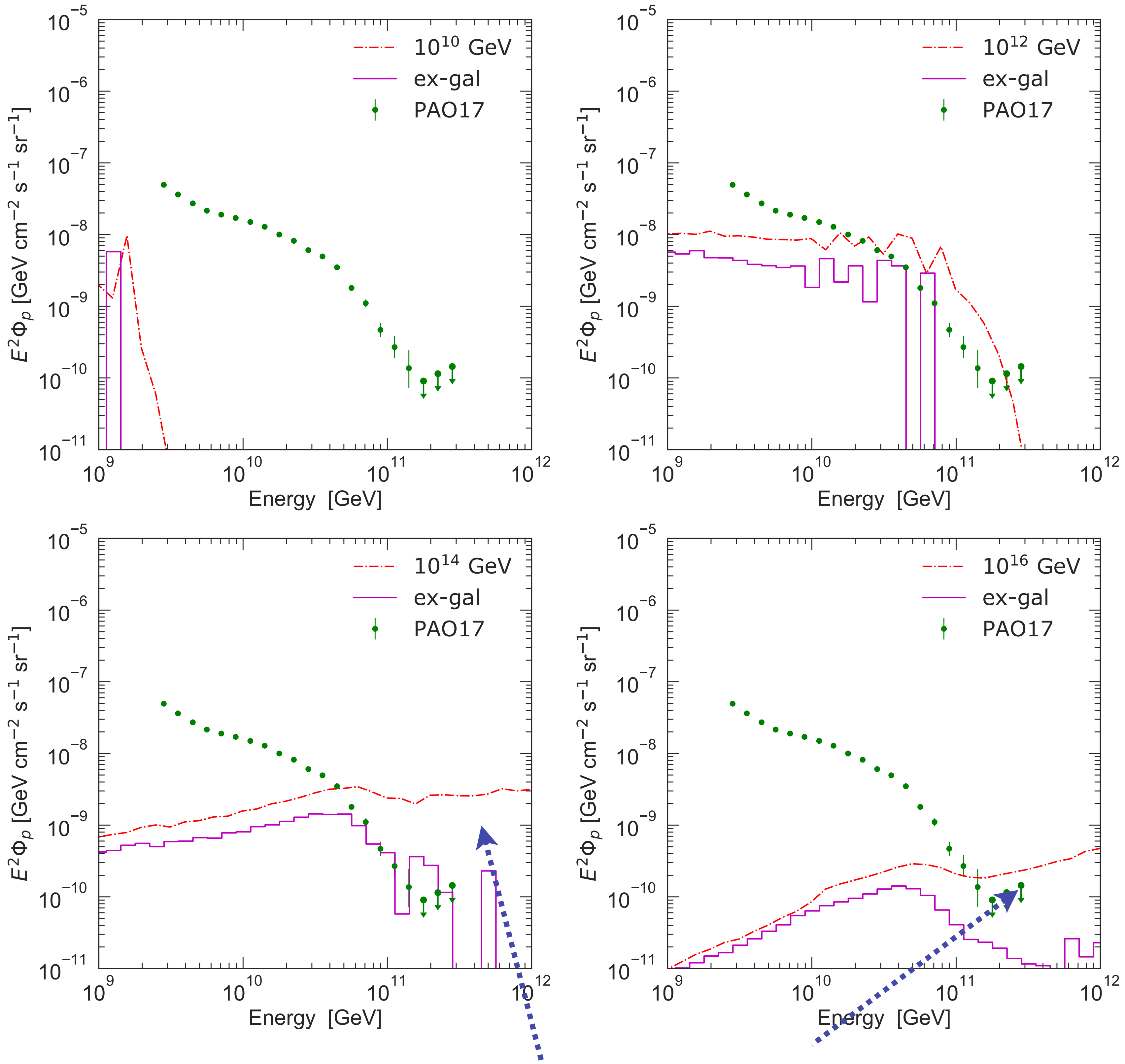
$p + \bar{p}$ flux

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



GZK effect can be seen in the extragalactic flux

$p + \bar{p}$ flux

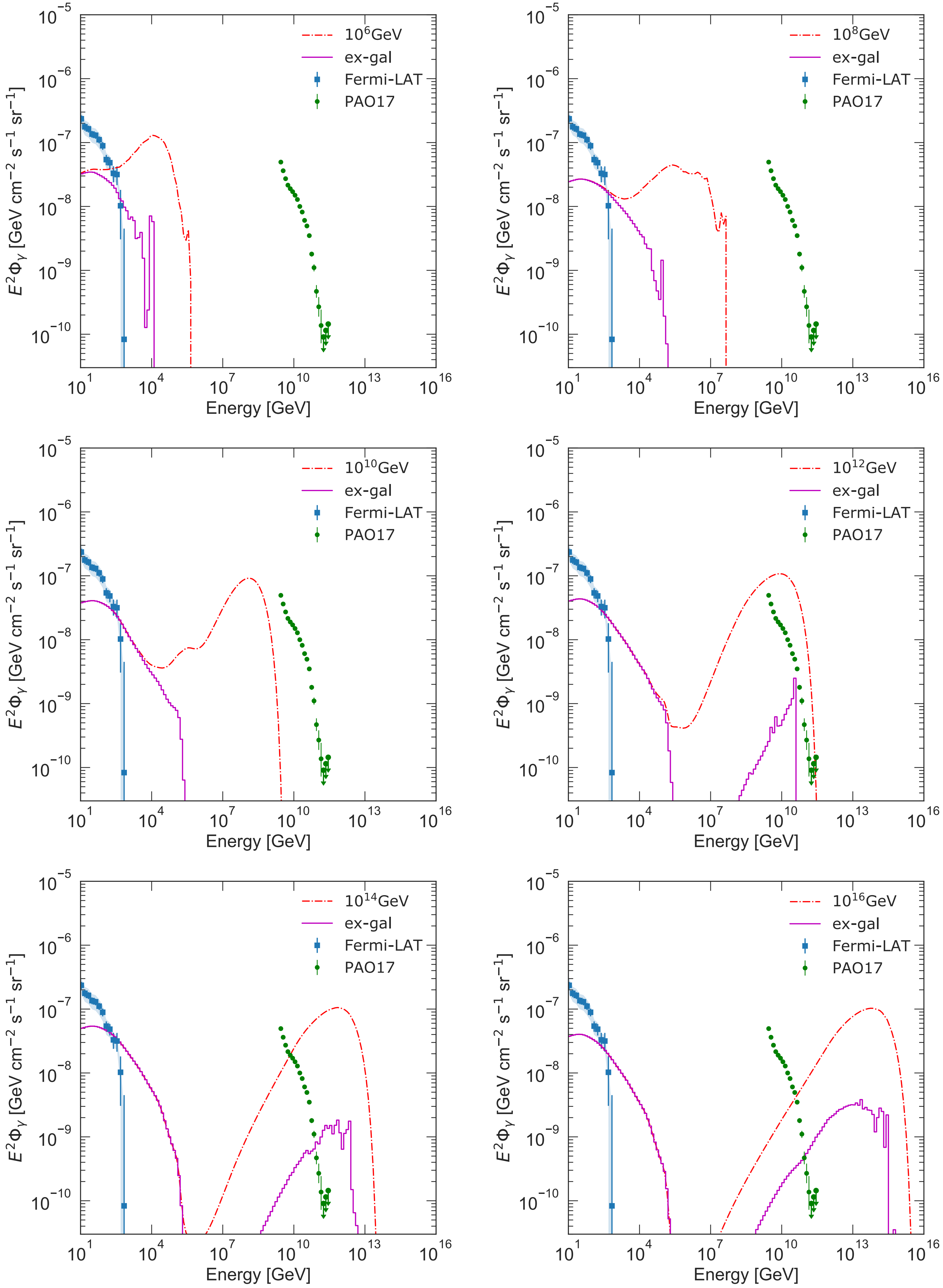


$\tau_{\rm dm} = 10^{27}\,{\rm s}$

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

γ flux

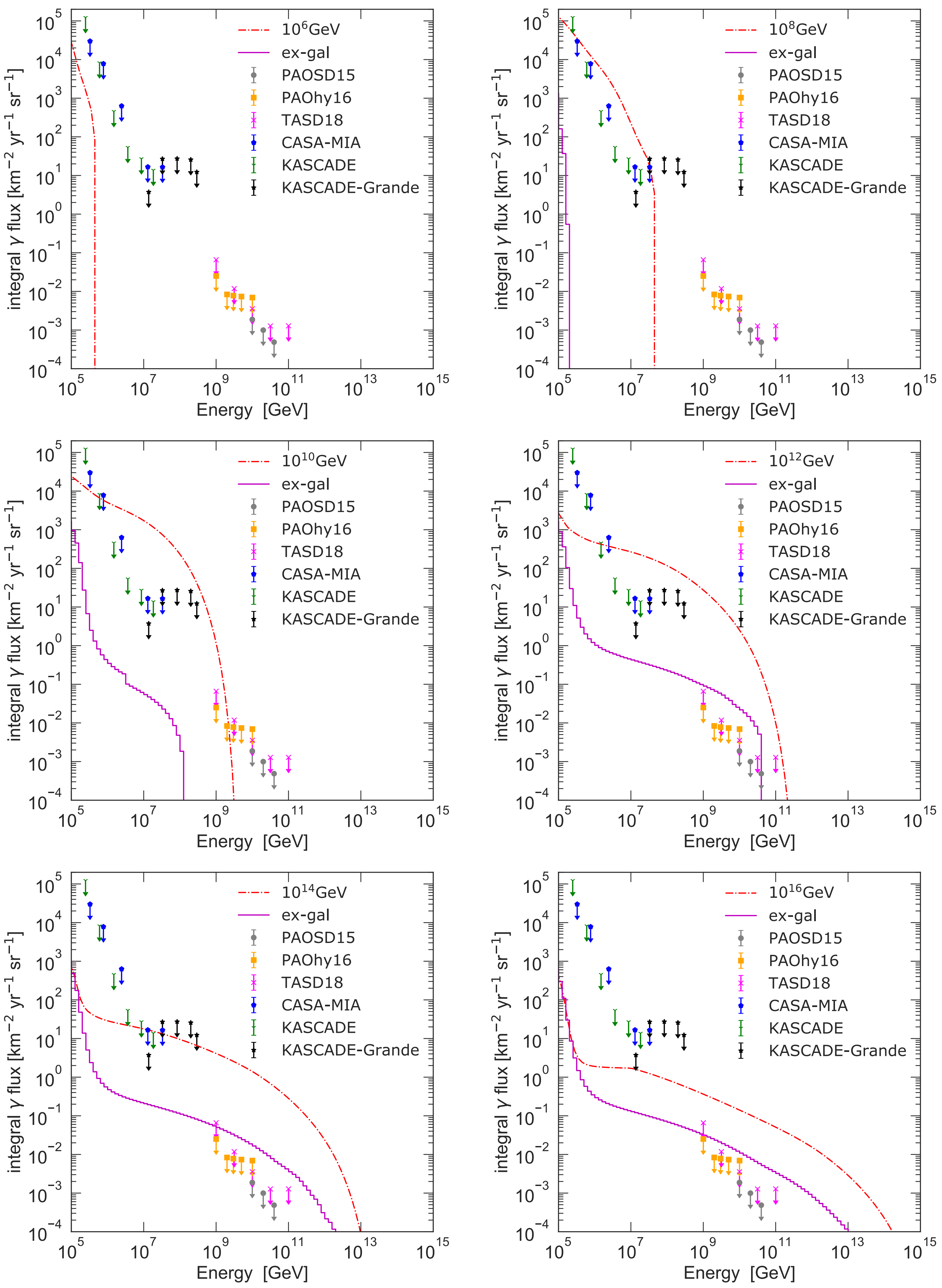
$\tau_{\mathrm{dm}} = 10^{27}$ s



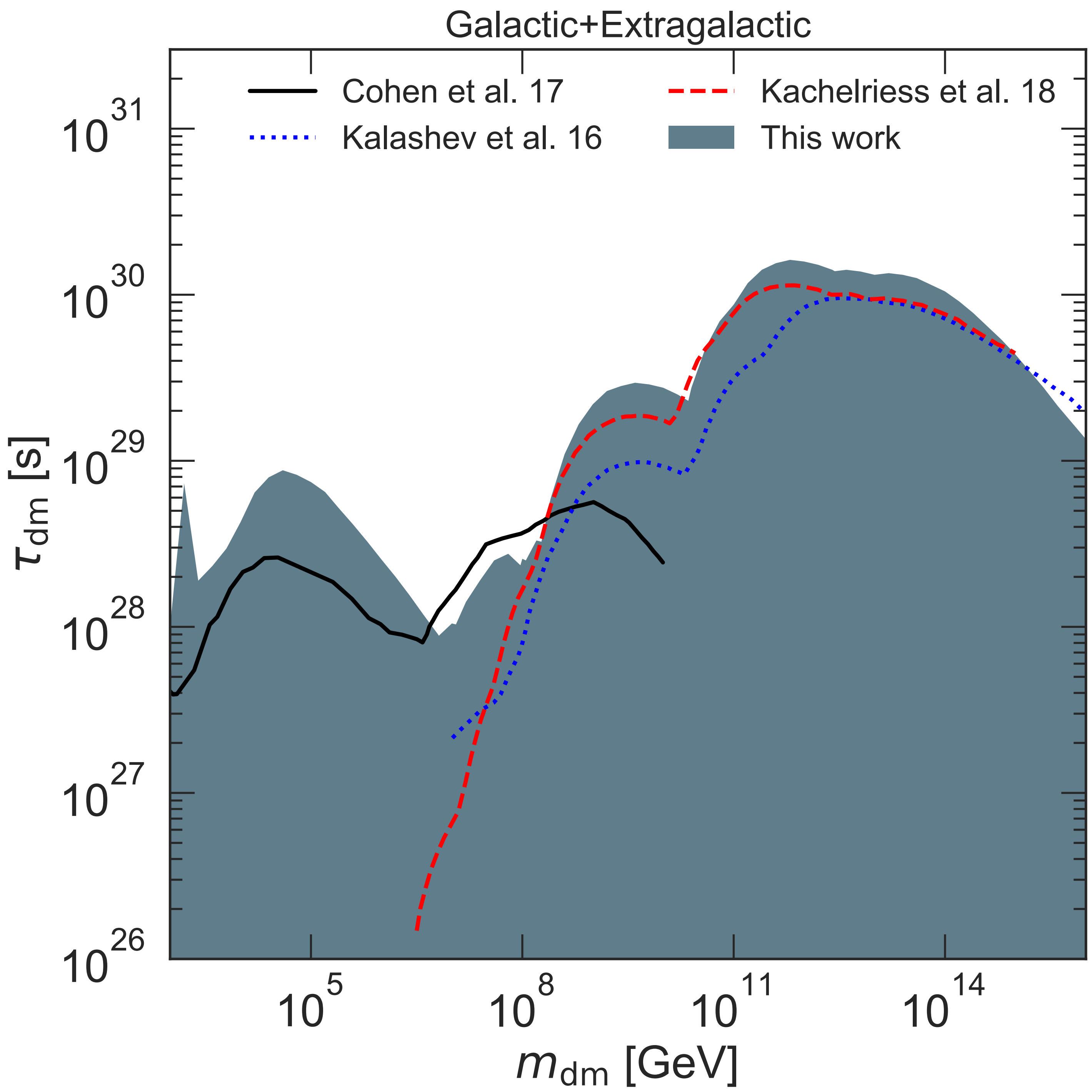
Integrated γ

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

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



Combined results

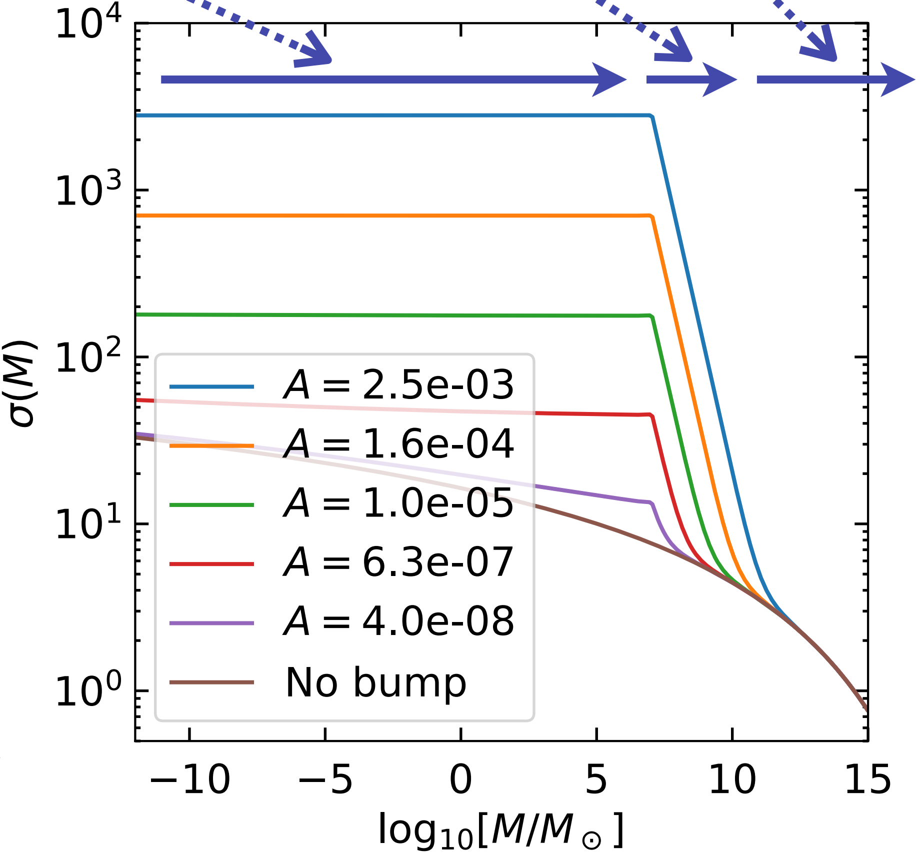


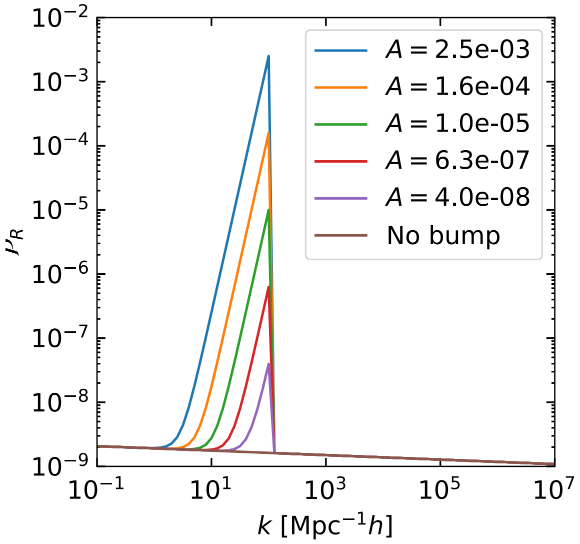
Variance

Halo grows to a specific scale *at once*

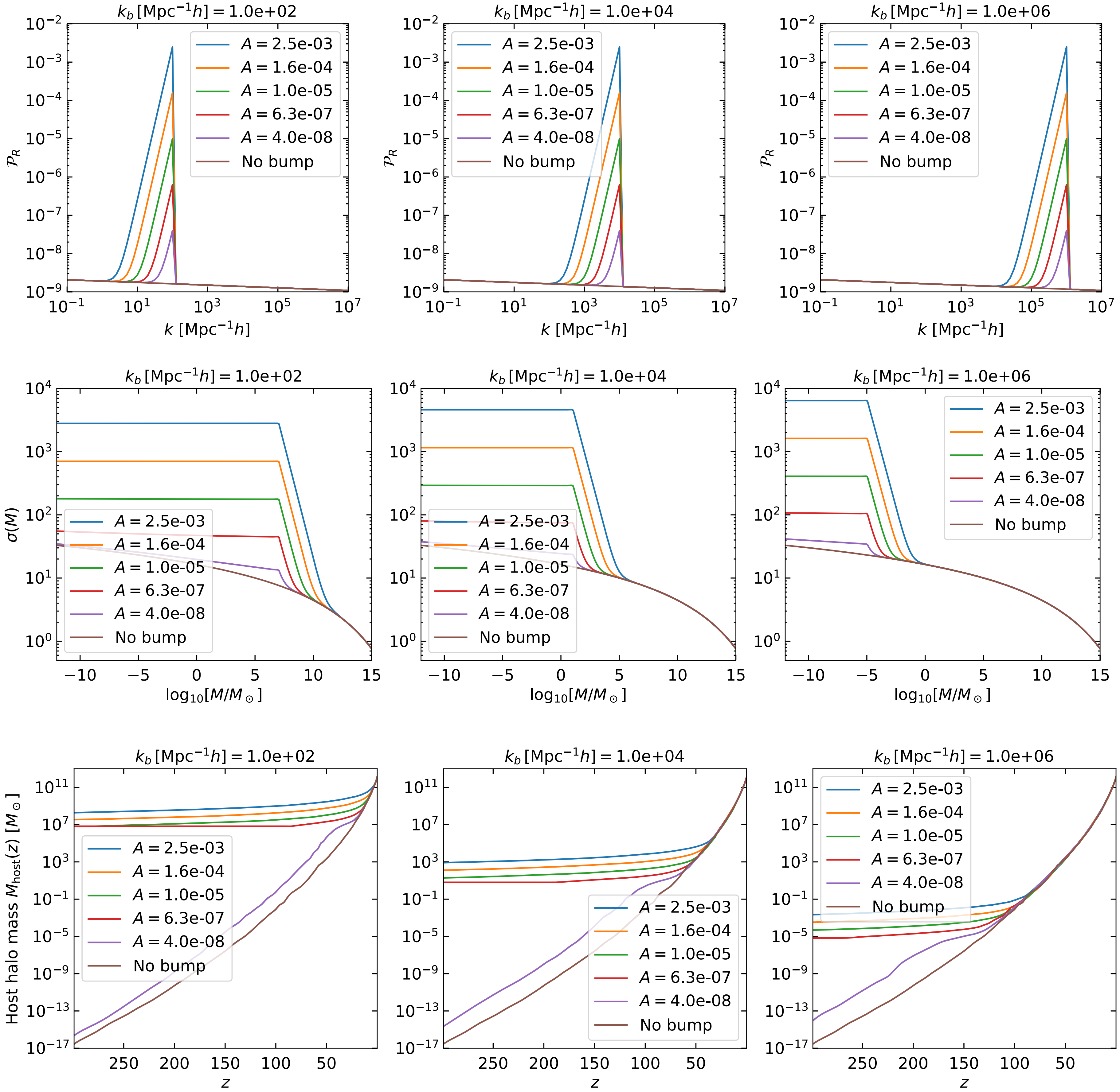
Merely grows for while

Grows to the present mass

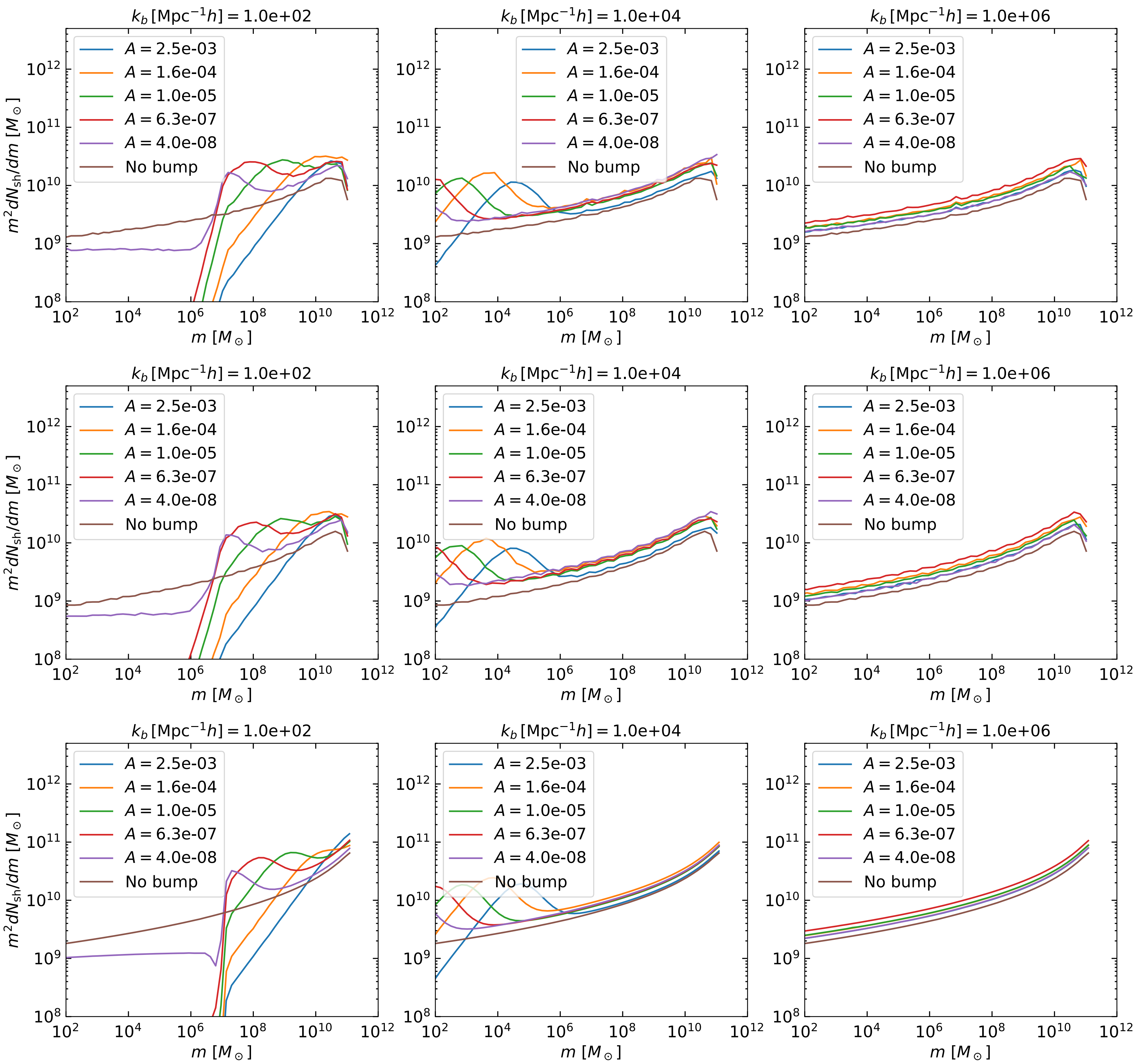




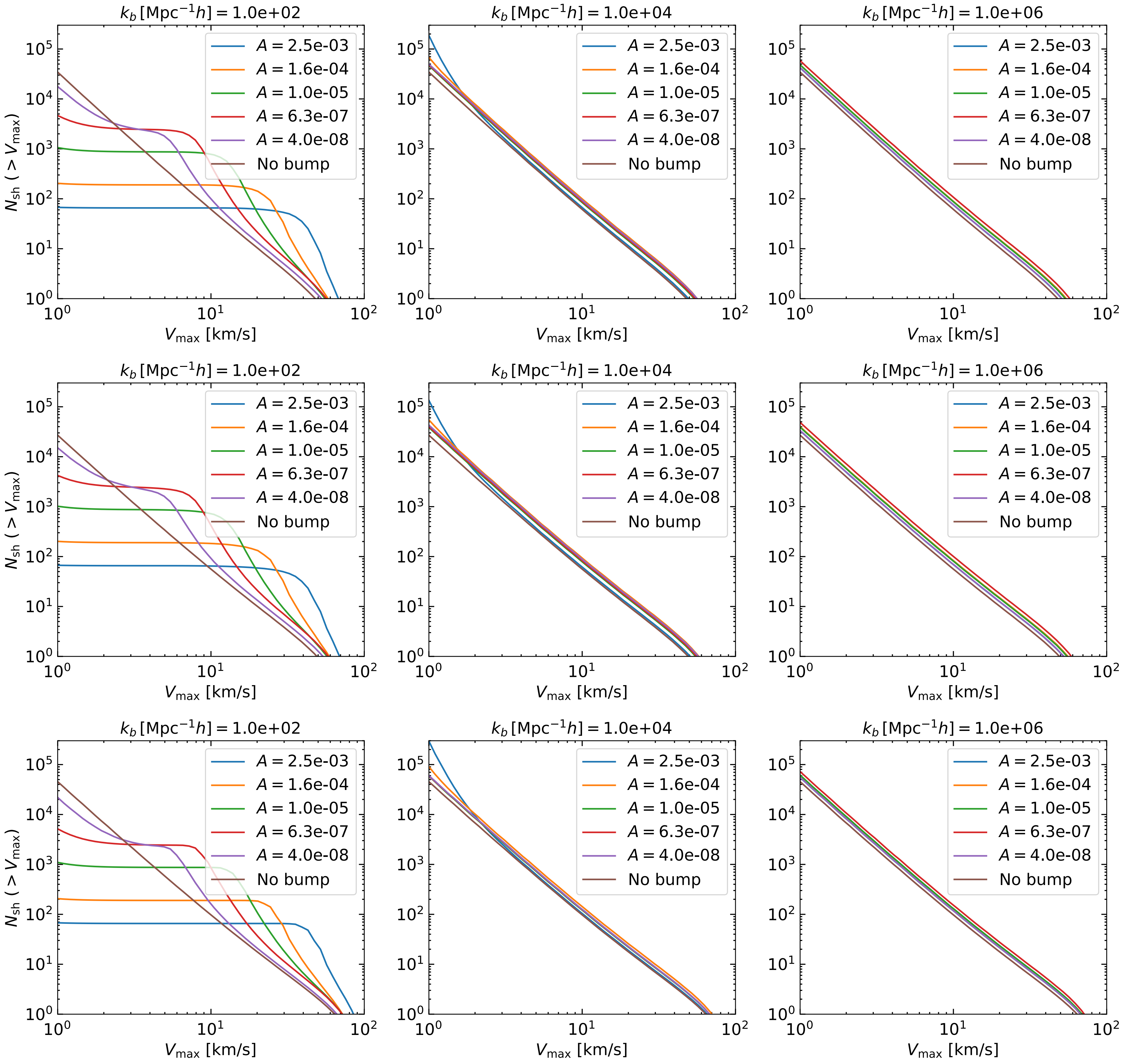
Curvature perturbation, variance, and host halo mass



Subhalo mass function



Cumulative maximum circular velocity function



Cumulative number of subhalos, maximum circular velocity function, and boost factor