銀河外ガンマ線による宇宙暗黒物質探索

Koji Ishiwata

Kanazawa University

Based on

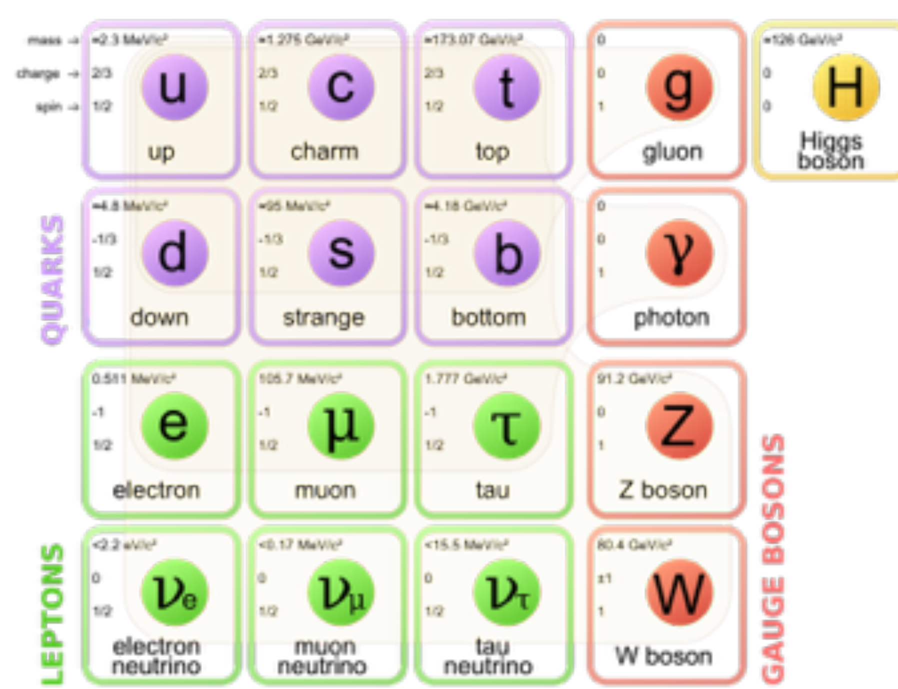
- JCAP 1505 (2015) 05, 024 (with S. Ando)
- JCAP 1606 (2016) 06, 045 (with S. Ando)

Kyoto, August 6, 2018

1. Introduction

After the Higgs discovery in 2012,

- The Standard model (SM) has been found to be a very good theory below a TeV scale
- But there're some inconsistencies, especially *cosmological* side



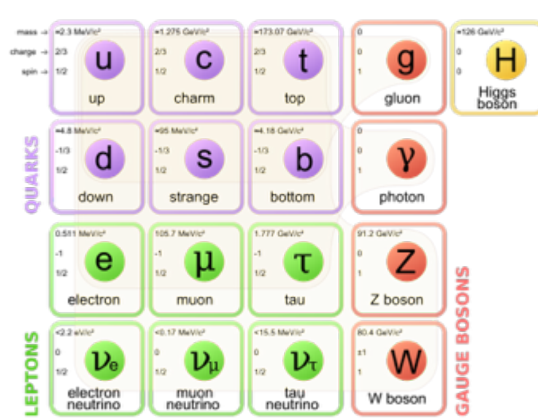
+ something

Cosmological issues:

- Isotropic, homogenous, flat universe
- Baryon asymmetry
- Dark matter
- Dark energy

Cosmological issues:

- Isotropic, homogenous, flat universe
- Baryon asymmetry
- ★ Dark matter
    - Dark matter (DM) is beyond the SM physics
    - Many DM searches are ongoing
- Dark energy



+ something

(DM, …)

DM searches

- Direct detection
- Indirect detection (via cosmic rays)
- Collider
- Axion like particle searches

Fermi-LAT

LHC

XENON1T

CAST

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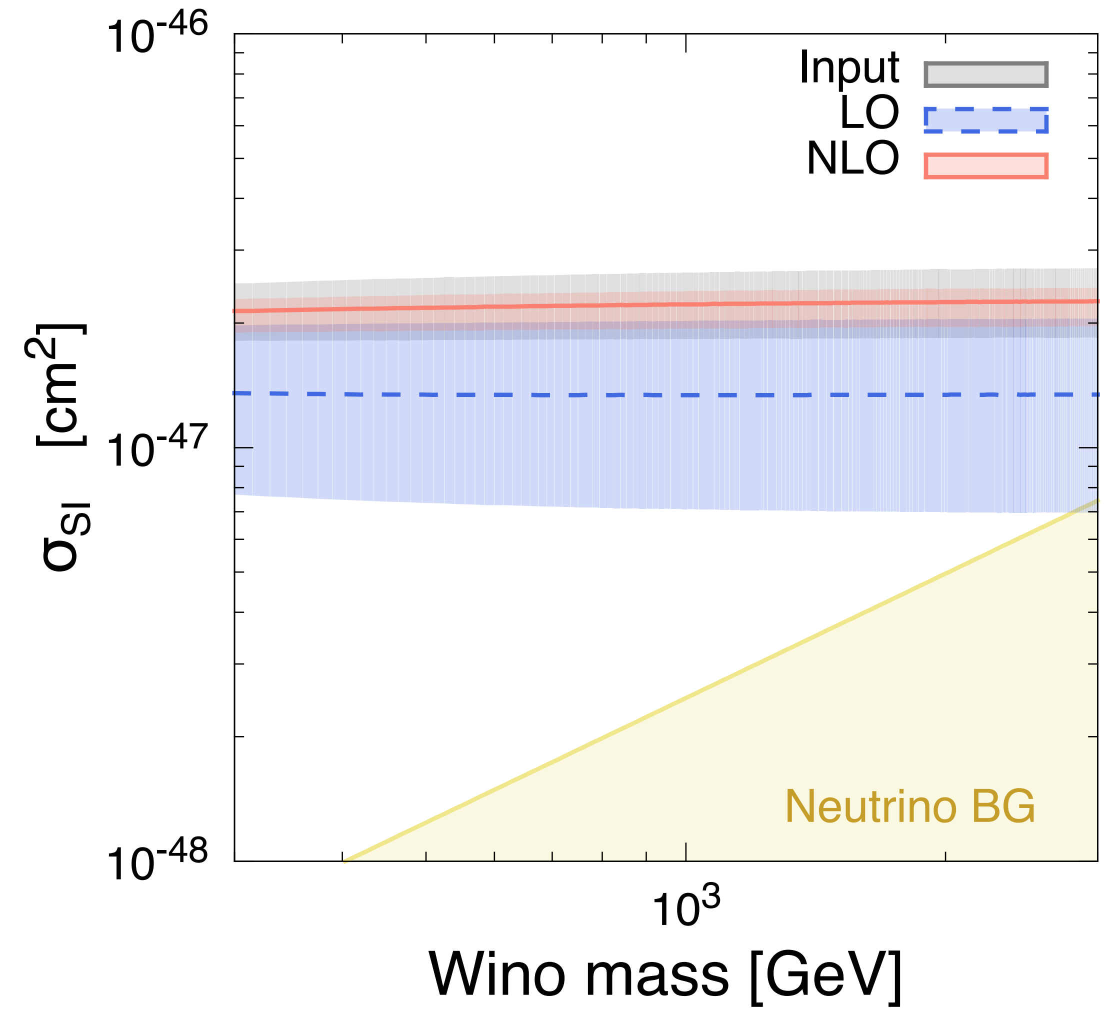
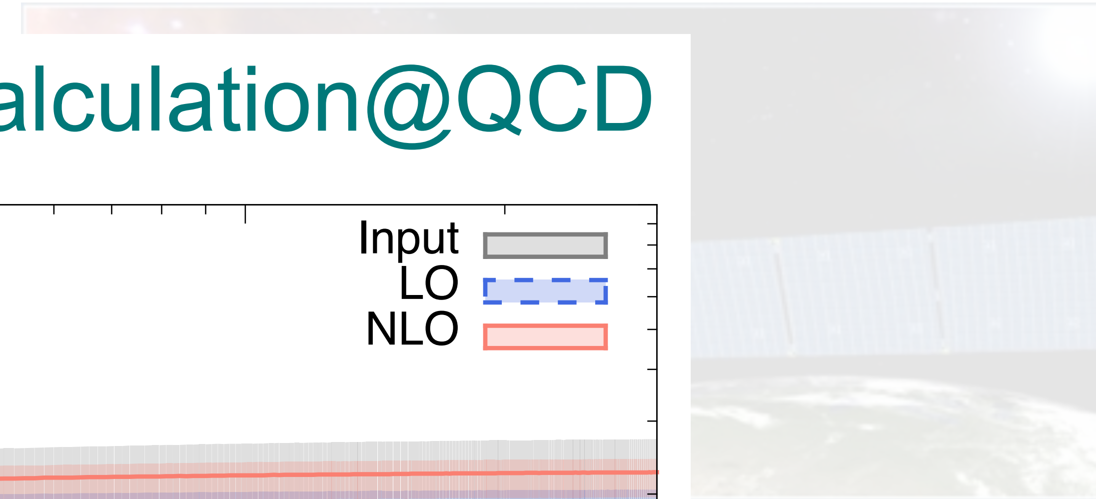
NLO calculation@QCD



Hisano, KI, Nagata ’15

XENON1T



Fermi-LAT

LHC

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Fermi-LAT

LHC

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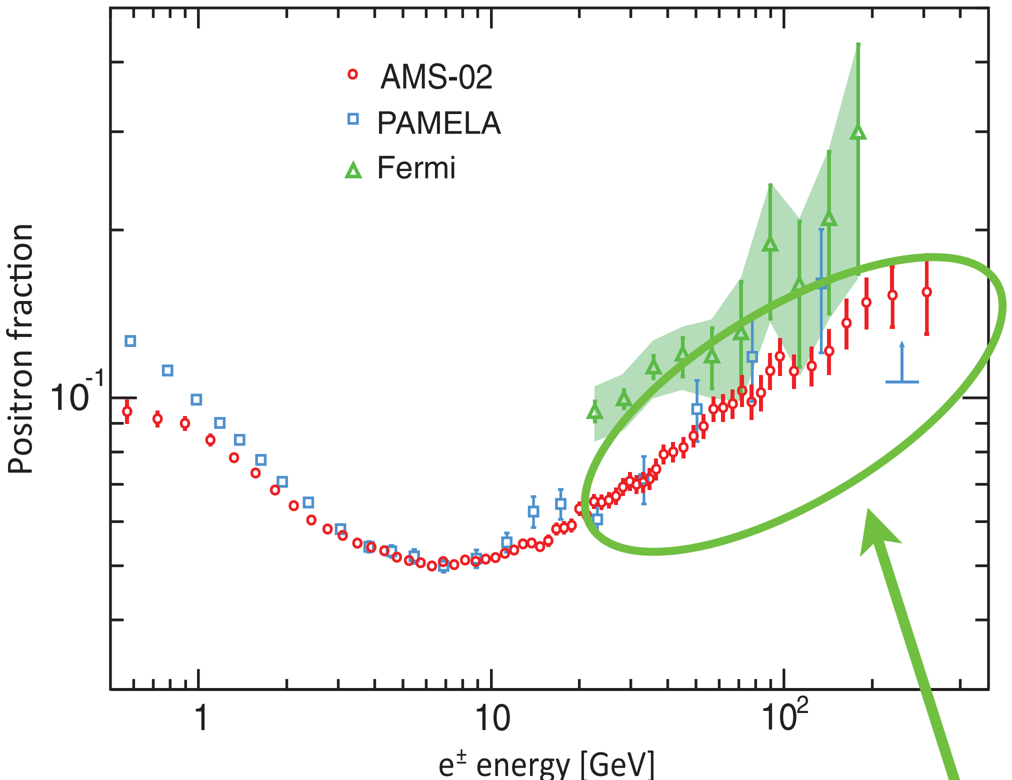
Motivations for indirect DM search (*theoretical side*)

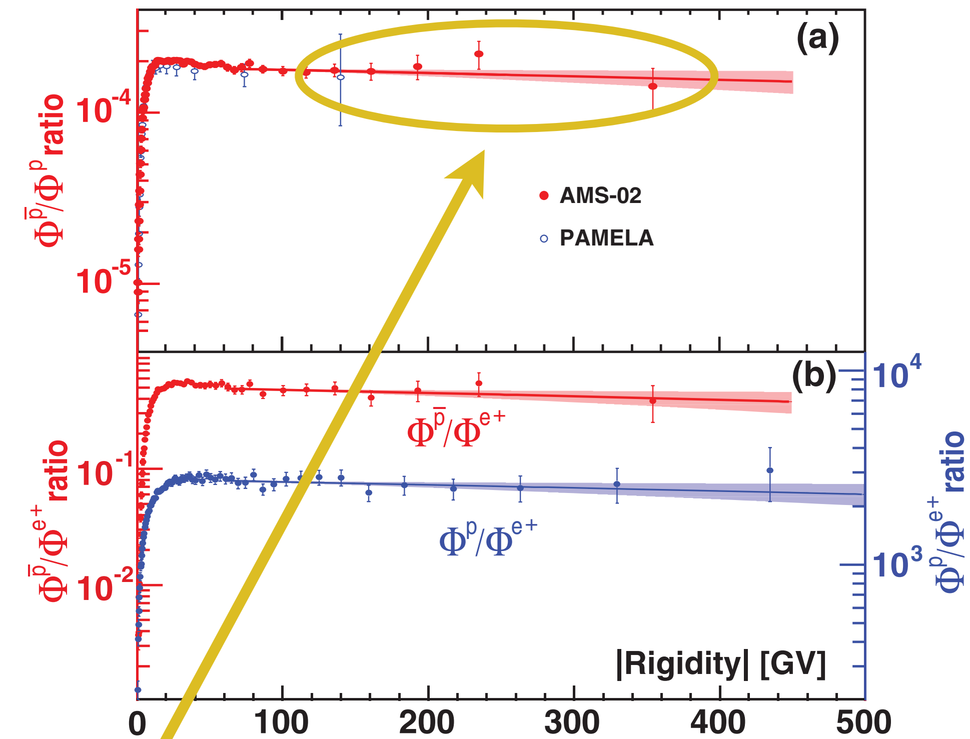
- It consists of about 27% of the total energy of the universe
- There’s a possibility to detect DM that interact with SM particles very weakly, i.e., to open the discussion of its stability

Motivations for indirect DM search (*experimental side*)

- Positron AMS-02 '13



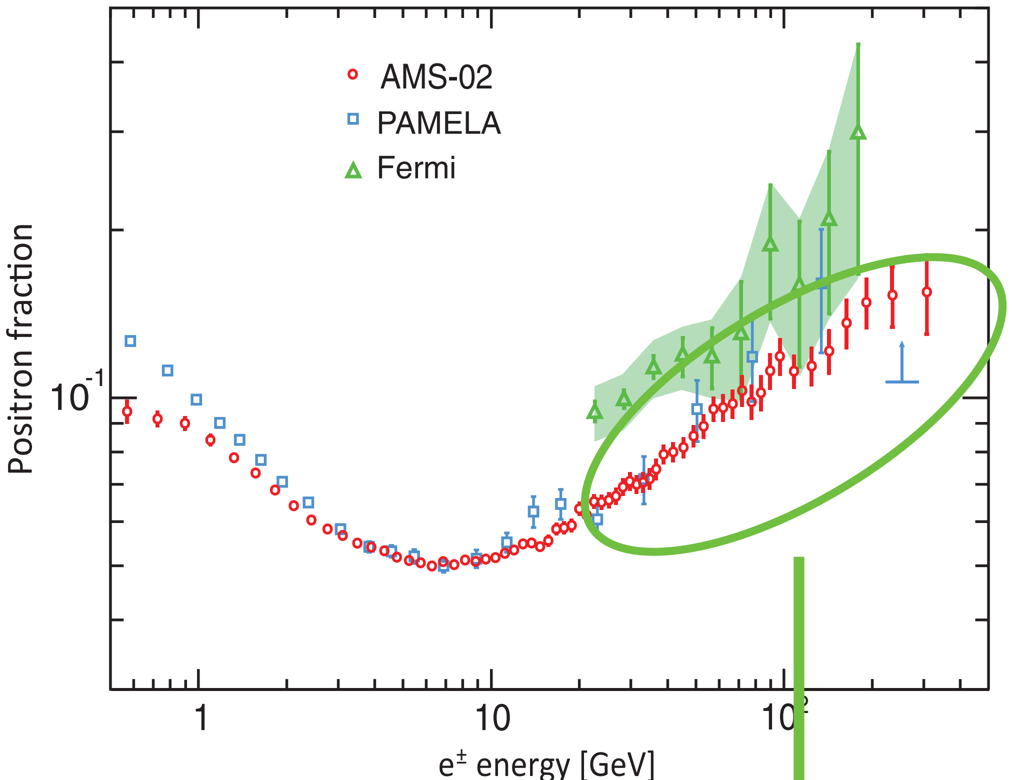
- Antiproton AMS-02 '16



Excesses over 100 GeV

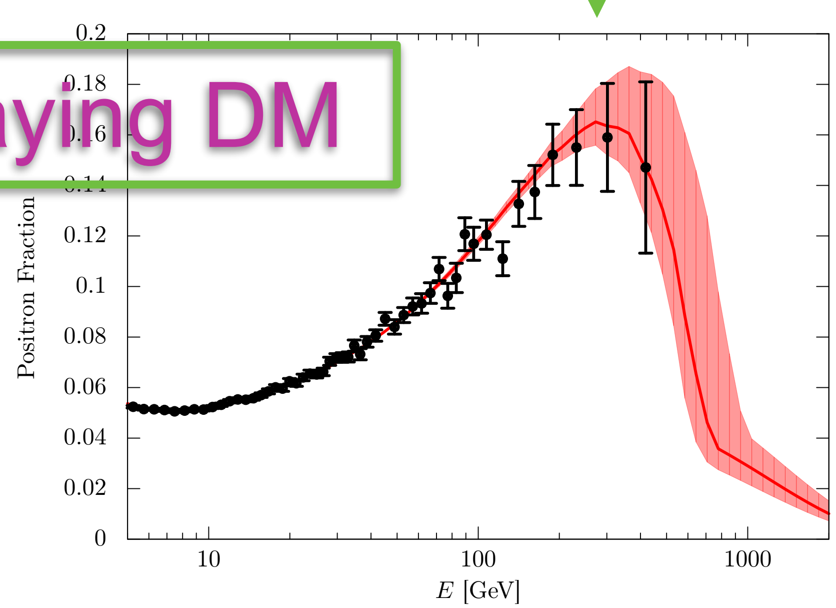
Motivations for indirect DM search (*experimental side*)

- Positron AMS-02 '13



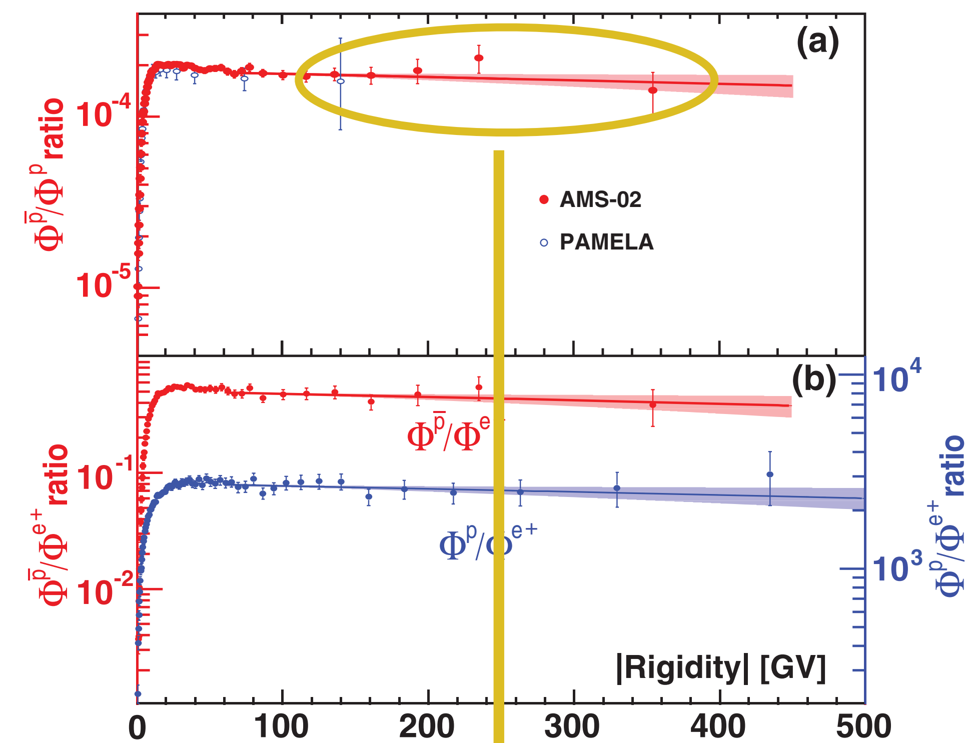
e.g.,

Decaying DM

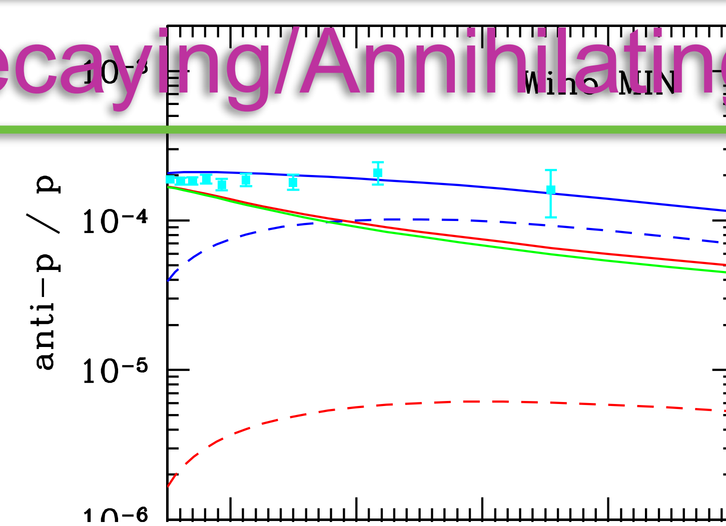


Ibe, Matsumoto, Shirai, Yagagida '14

- Antiproton AMS-02 '16

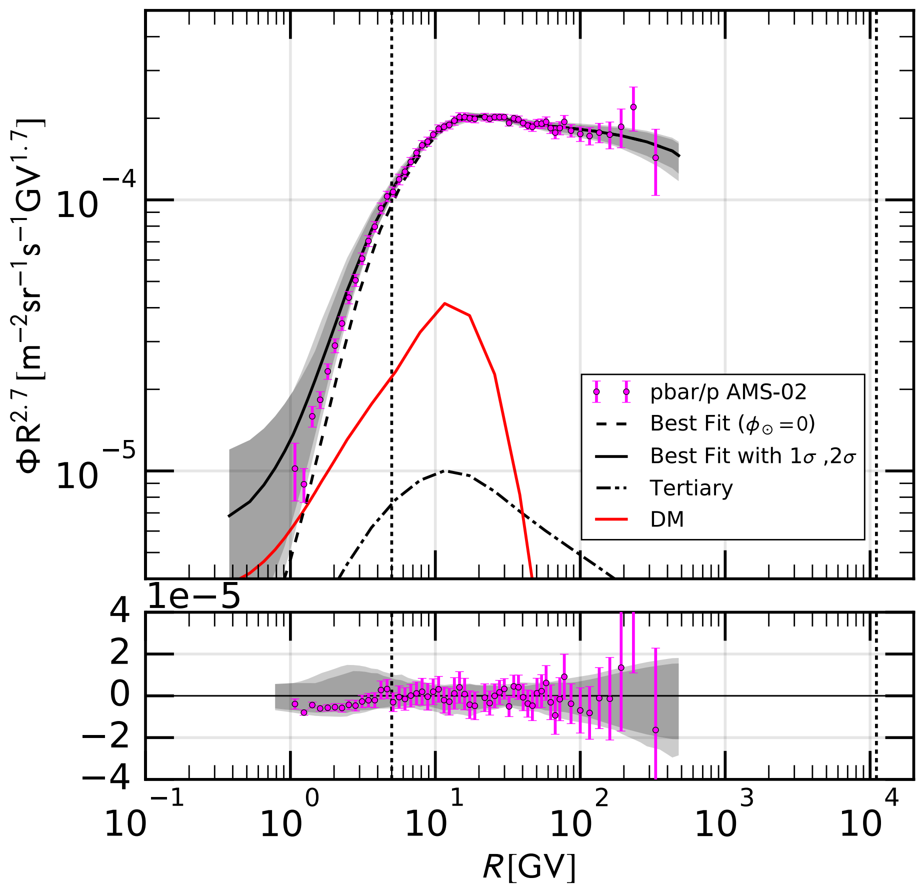


Decaying/Annihilating DM



Hamaguchi, Moroi, Nakayama '15

Motivations for indirect DM search (*experimental side*)



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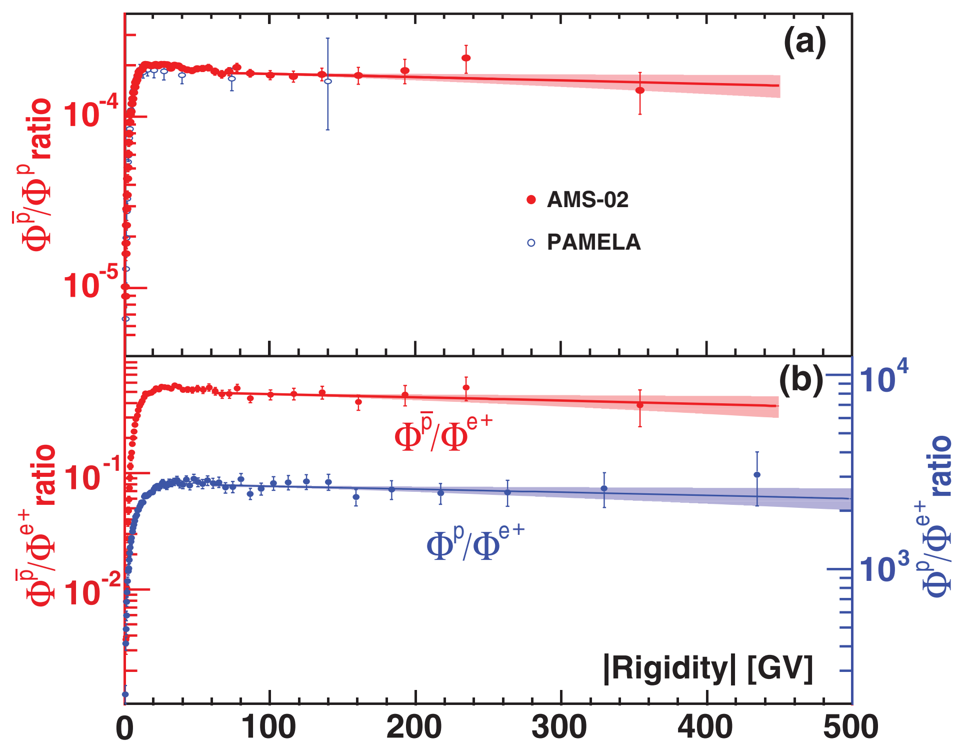

4.5σ indication of a DM signal for DM masses near 80 GeV

Cuoco, Krämer, Korsmeier '17

Cui, Yuan, Tsai, Fan '17

Are those really DM signals?

Are those really DM signals?

→ We may check with other observables

<u>Today's topic</u>

DM search using extragalactic gamma rays

(including local galaxy distributions)

Important ingredients for our study:

a). Inverse-Compton (IC) γ-rays in the *extragalactic* region

b). Astrophysical sources in the *extragalactic* region

c). Tomographic cross-correlation using local galaxy distribution

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a). Inverse-Compton (IC) γ-rays in the *extragalactic* region

KI, Matsumoto, Moroi '09

Profumo, Jeltema '09

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Ando, KI '15

Part I

c). Tomographic cross-correlation using local galaxy distribution

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Cuoco, Xia, Regis, Branchini, Fornengo, Viel ’15

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$\boxed{\textbf{Part II}}$

Ando, KI '16

Outline

1. Introduction
2. Part I: DM and the extragalactic gamma rays
3. Part II: DM and local galaxy distributions
4. Ultra high energy cosmic rays and DM
5. Conclusion

2. Part I:
DM and the extragalactic gamma rays

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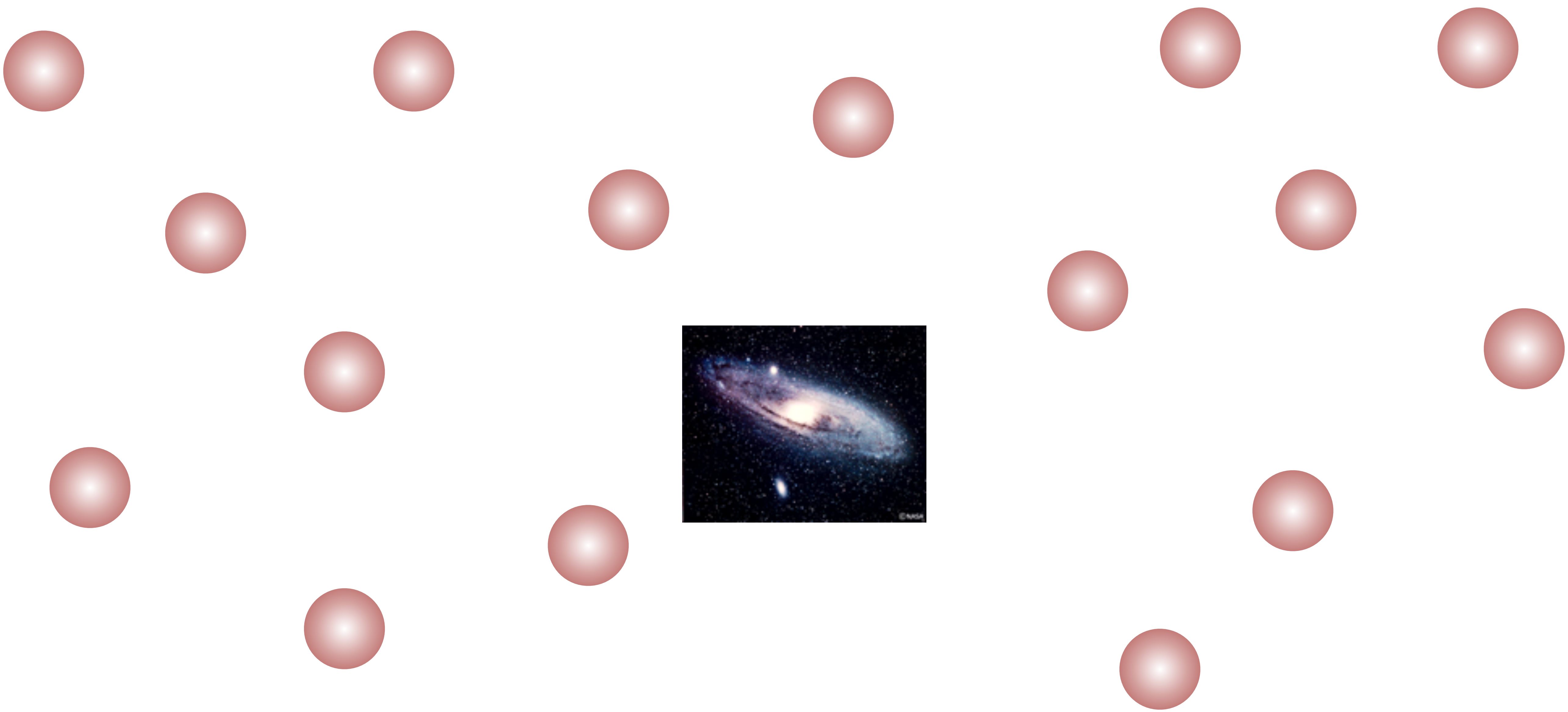
a). Inverse-Compton (IC) γ-rays in the extragalactic region

1. About 27% of the total energy of the universe is DM
2. Assume that high energy $e^{\pm}$ are produced by decay or annihilation of DM
3. They hit the CMB photons and produce high energy γ-rays



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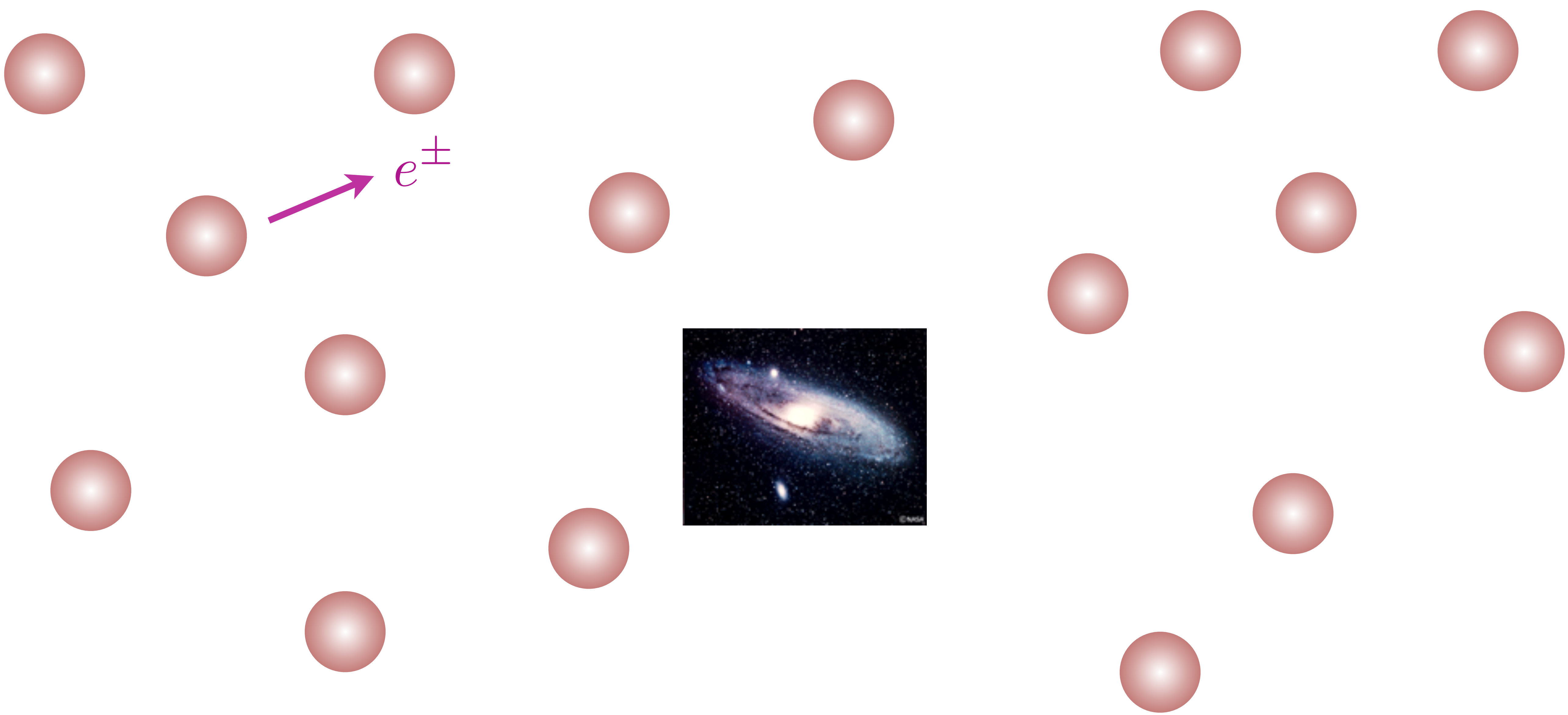

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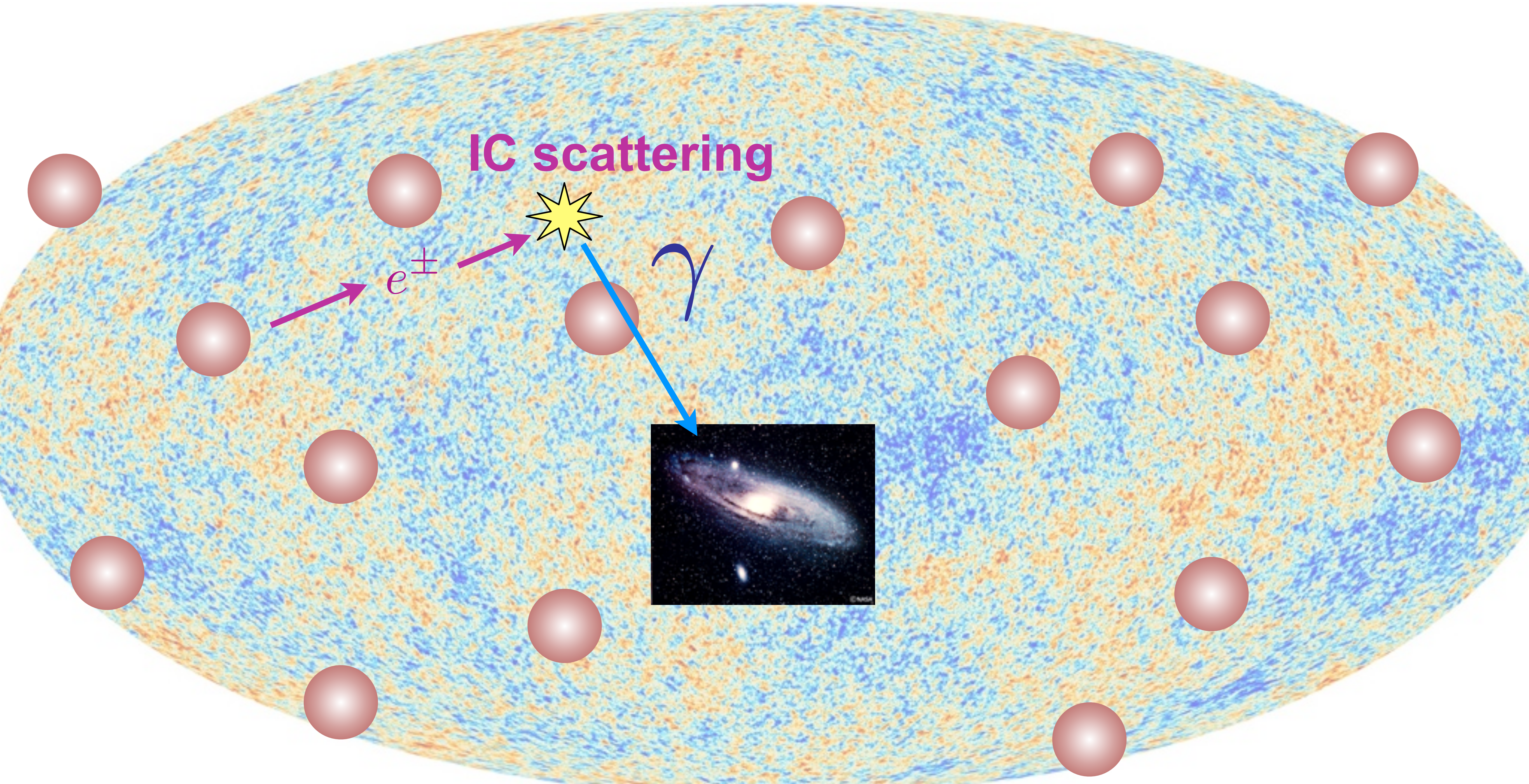
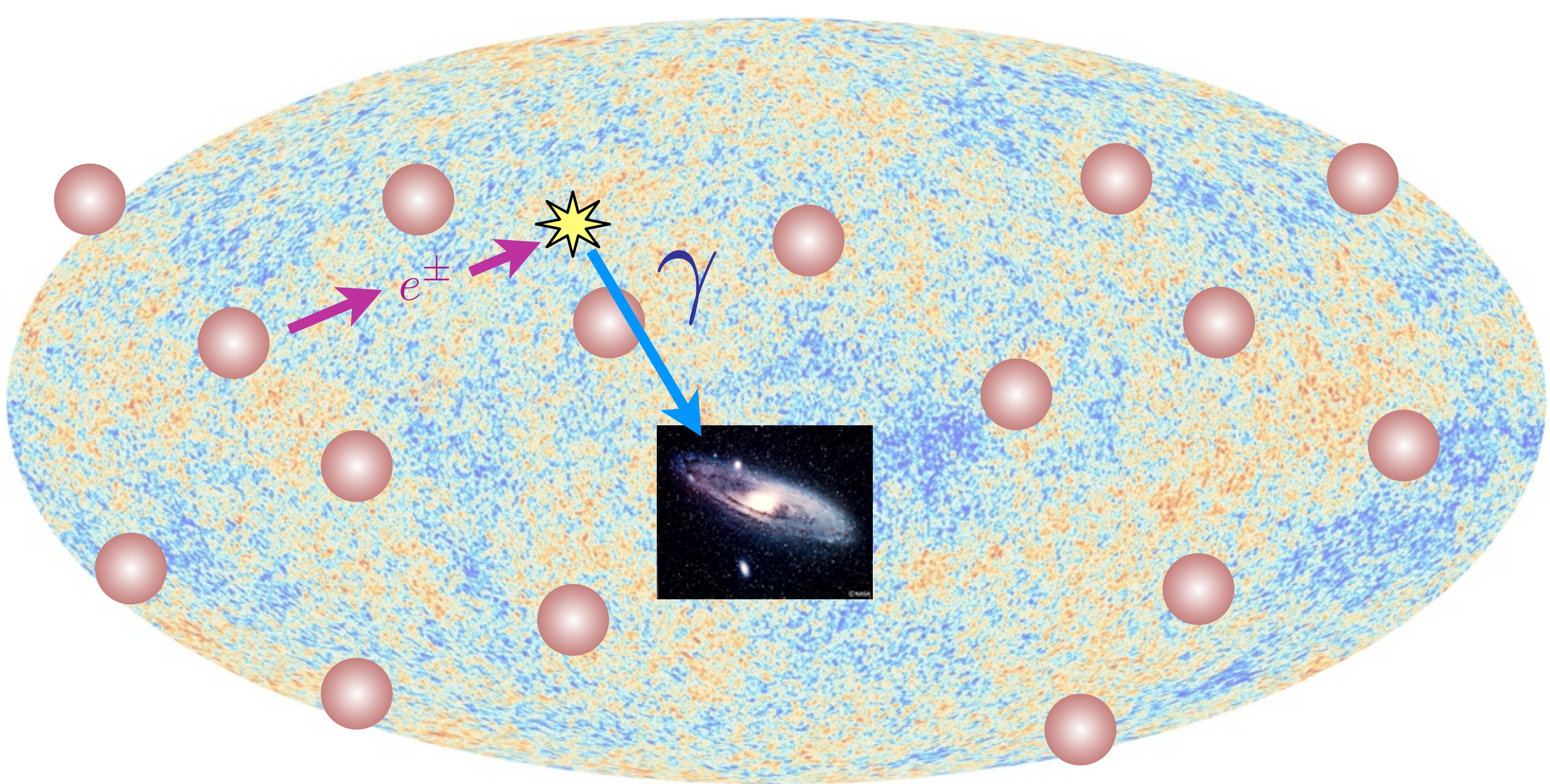


a). Inverse-Compton (IC) γ-rays in the extragalactic region

KI, Matsumoto, Moroi '09

Profumo, Jeltema '09

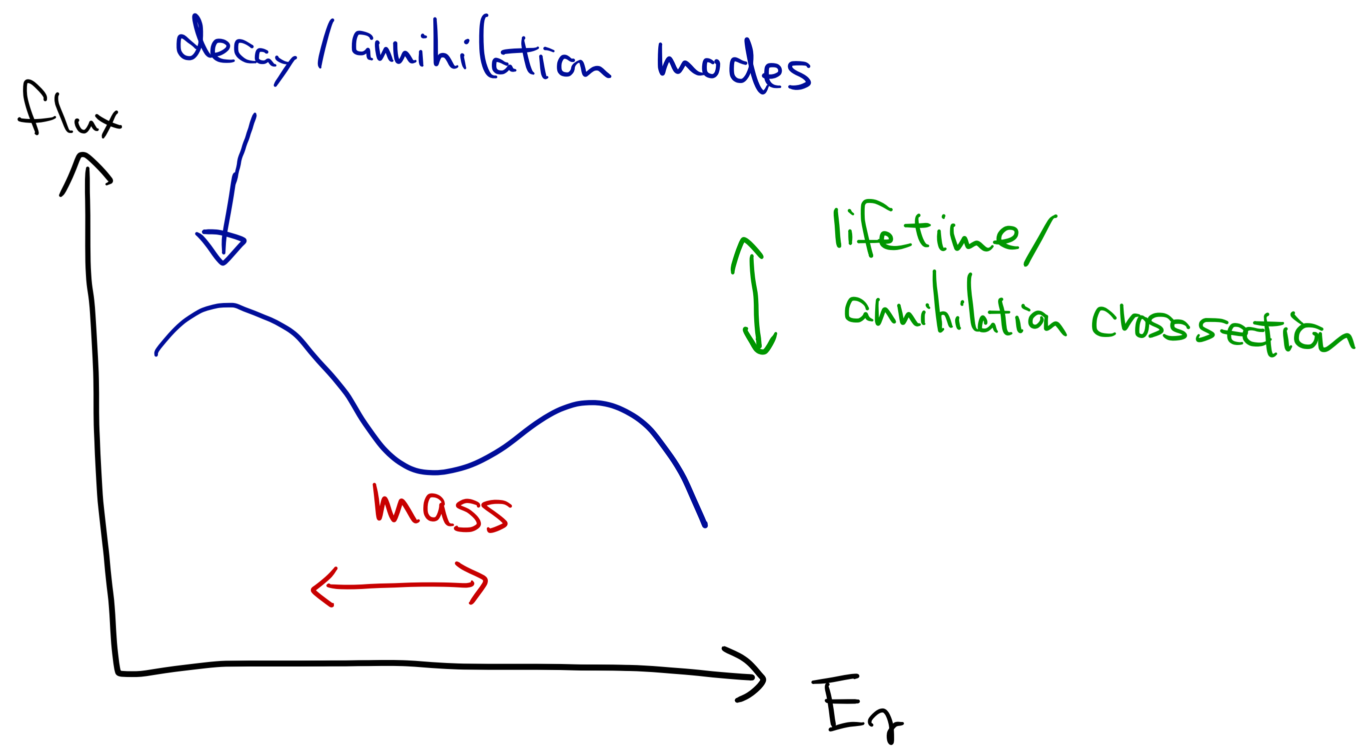
- The story is very simple
- If we specify DM model, the QED tells us the IC spectrum exactly especially for decaying DM
- A good tool to test DM scenarios which accommodate the anomalous positron or antiproton excess

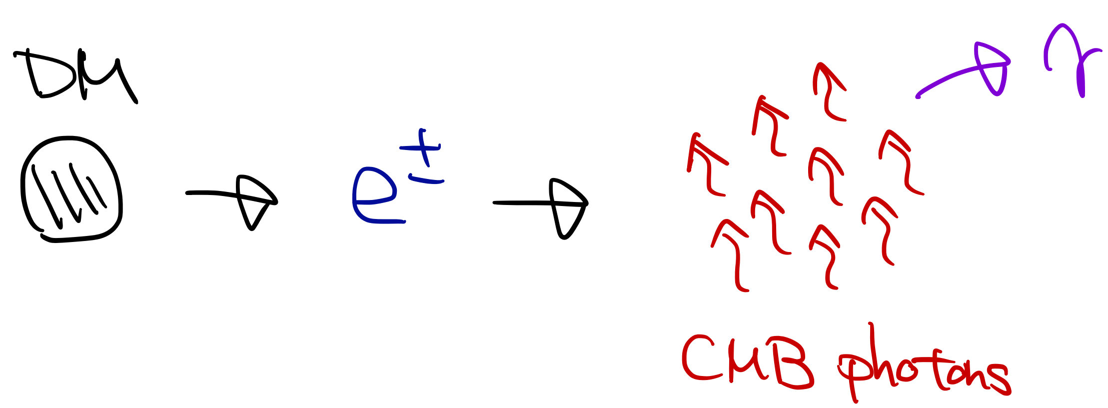


a). Inverse-Compton (IC) γ-rays in the extragalactic region

DM model

- Mass
- Lifetime/annihilation cross section
- Decay modes



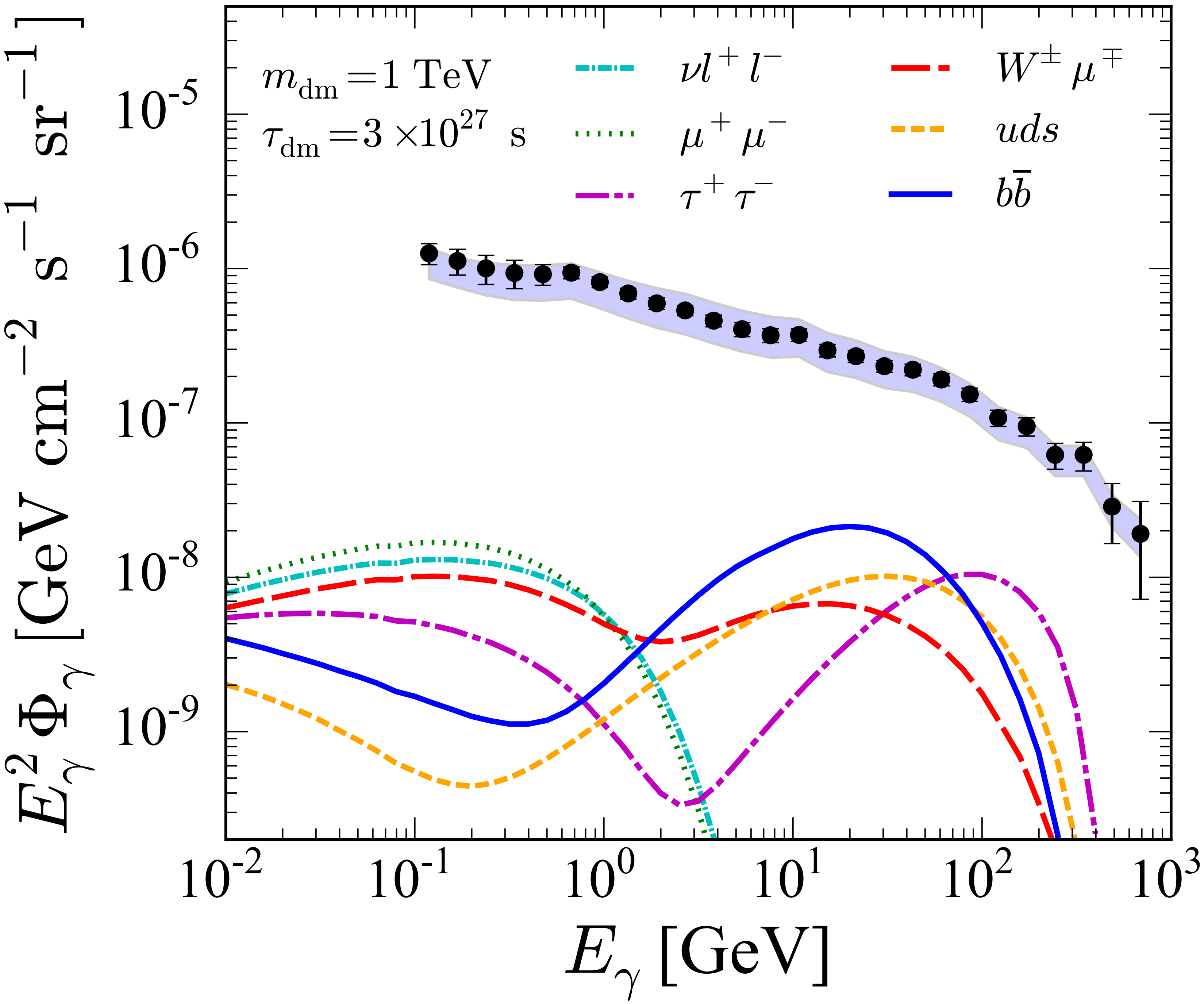


IC scattering

a). Inverse-Compton (IC) γ-rays in the extragalactic region

Gamma-ray spectrum in various DM models

Ando, KI ’15



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a). Inverse-Compton (IC) γ-rays in the

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b). Astrophysical sources in the extragalactic region

- Blazars

M. Ajello et al. ’12, ’13 & ’15

- Star-forming galaxies (SFG)

Fermi-LAT ’12

C. Gruppioni et al. ’13

Tomborra, Ando, Murase ’14

- Misaligned active galactic nuclei (mAGN)

Inoue ’11

Mauro, Calore, Donato, Ajello, Latronico ’14

They are determined due to recent updates in multi-frequency measurements of gamma rays

b). Astrophysical sources in the extragalactic region

Blazars

M. Ajello et al. ’12, ’13 & ’15

- active galaxies whose jets are directed toward us
- correlation between gamma and X ray
- ~ 50% of the total EGBR
- uncertainty: ~ 30%

SFG

Fermi-LAT ’12
C. Gruppioni et al. ’13
Tomborra, Ando, Murase ’14

- e.g., Milky Way galaxy
- correlation between gamma and infrared
- ~ 10-30% of the total EGBR
- uncertainty: ~ 60%

b). Astrophysical sources in the extragalactic region

Inoue '11

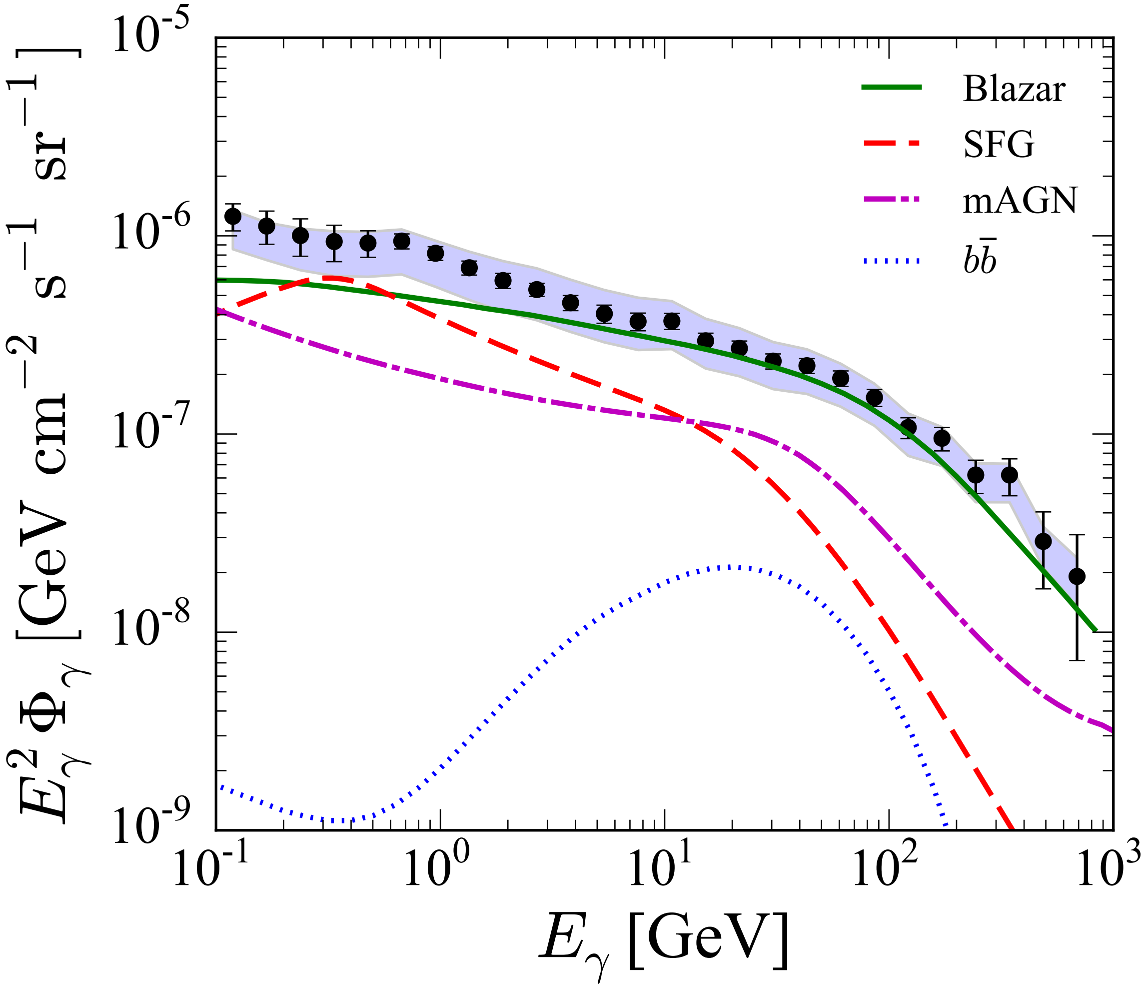
Mauro, Calore, Donato, Ajello, Latronico '14

mAGN

- active galaxies whose jets are NOT directed toward us
- correlation between gamma and radio
- uncertainty: ~ 200%

b). Astrophysical sources in the extragalactic region

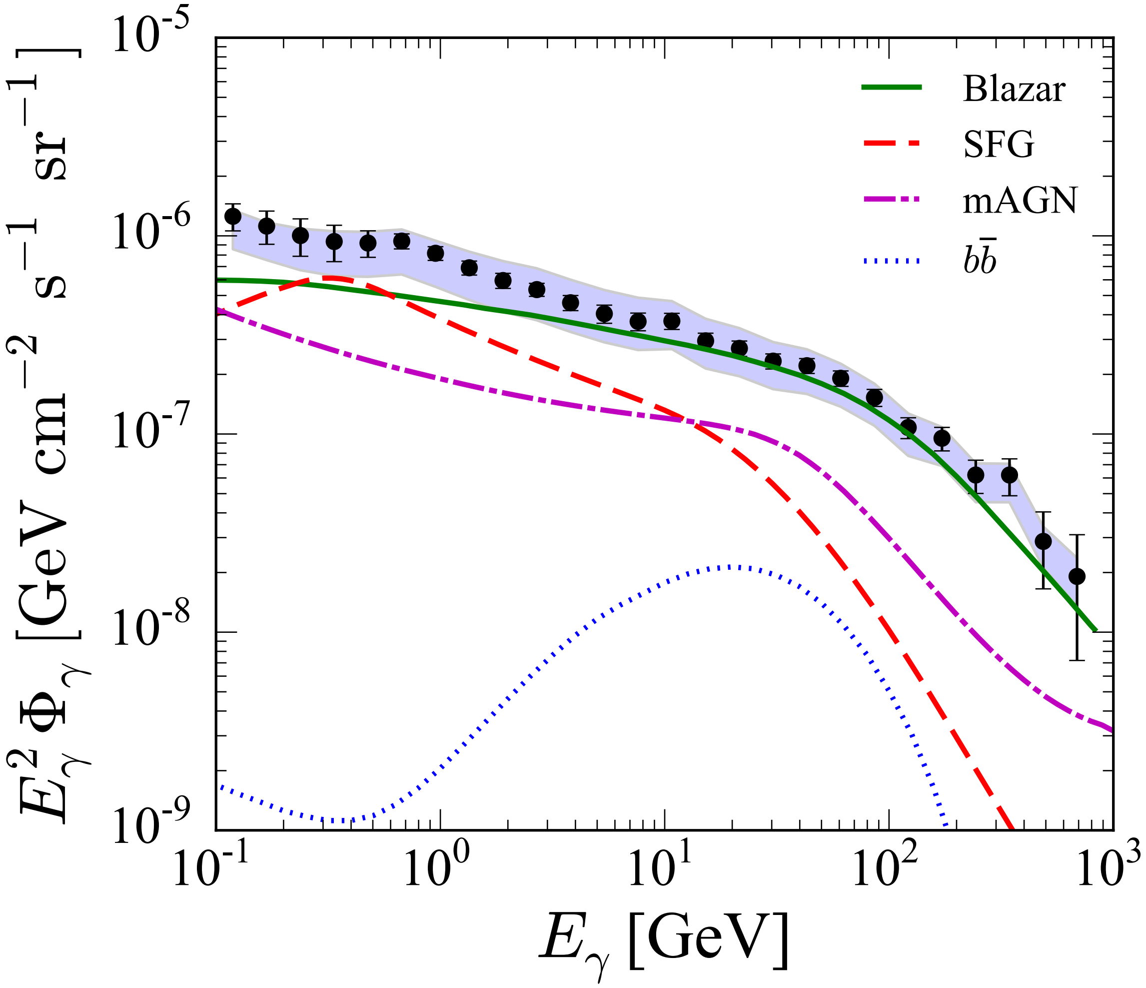
Ando, KI '15



Blazars and SFGs well explain the observed gamma rays

b). Astrophysical sources in the extragalactic region

Ando, KI '15



Blazars and SFGs well explain the observed gamma rays

→ Constraints on DM scenarios

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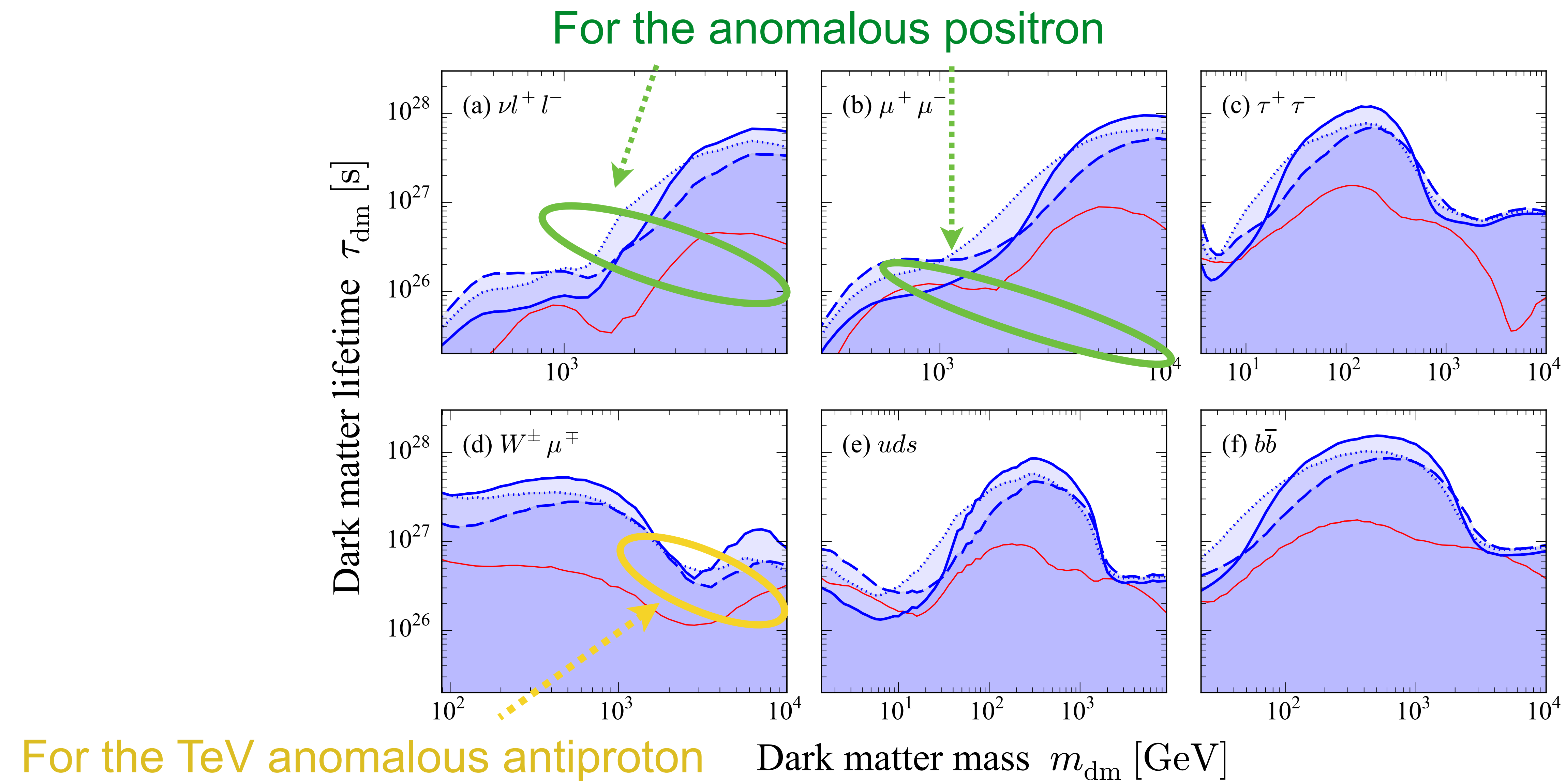
Ando, KI '15

c). Tomographic cross-correlation using local galaxy distribution

Decaying DM

Ando, KI '15

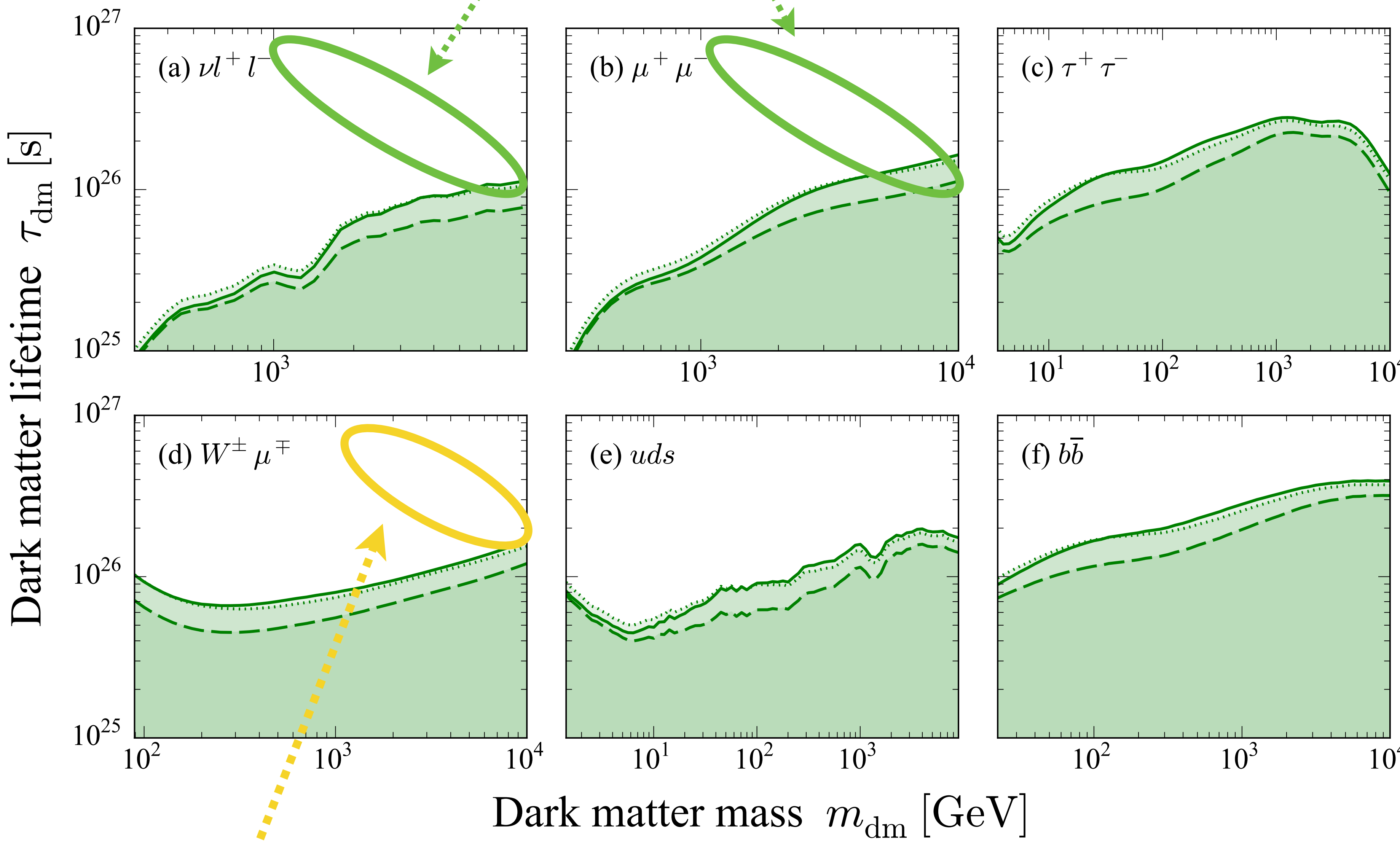


Decaying DM scenarios to explain the anomalous positron or antiproton are partly excluded

Without astrophysical components

Ando, KI '15

For the anomalous positron



For the TeV anomalous antiproton

In the study, we considered that the gamma rays from the extragalactic region is

- Statistically isotropic
- Integrated over the cosmological distances

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- Statistically isotropic
- Integrated over the cosmological distances

But due to the recent observational developments,

- Anisotropies
- Cosmological distances

of the gamma rays can be used for the study

Important ingredients for our study:

a). Inverse-Compton (IC) γ-rays in the

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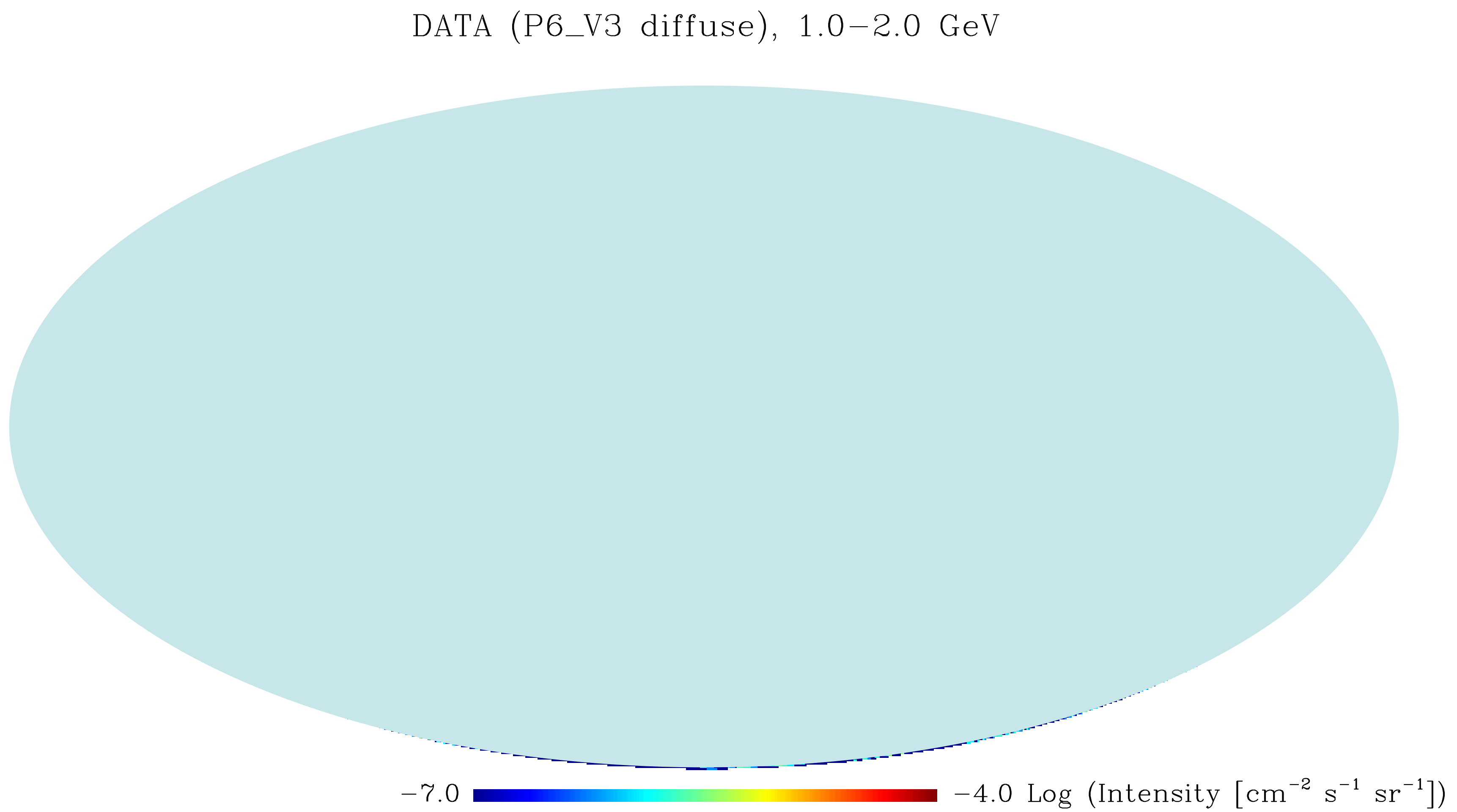
3. Part II:
DM and local galaxy distributions

Ingredients for further analysis:

- Anisotropies
- Cosmological distances

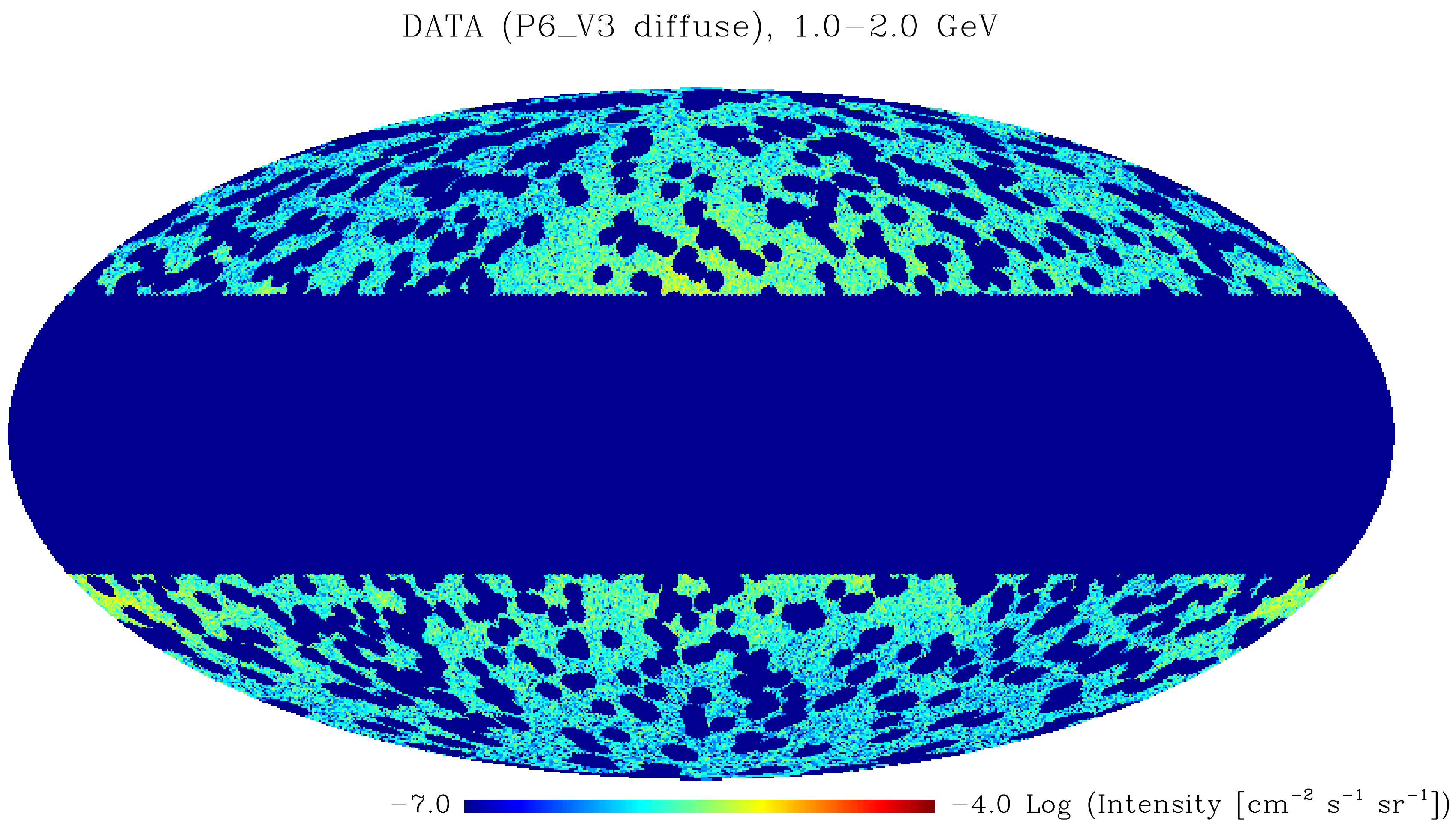
c). Tomographic cross-correlation using local galaxy distribution

Gamma rays are almost isotropic, but ..



c). Tomographic cross-correlation using local galaxy distribution

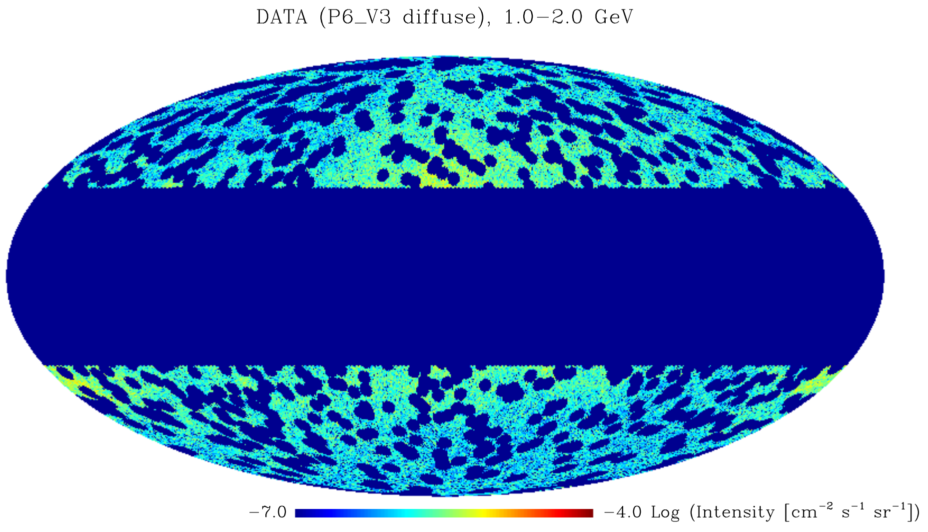
There're **anisotropies**



Fermi-LAT '12

Ingredients for further analysis:

- Anisotropies
- Cosmological distances



Fermi-LAT ’12

Ingredients for further analysis:

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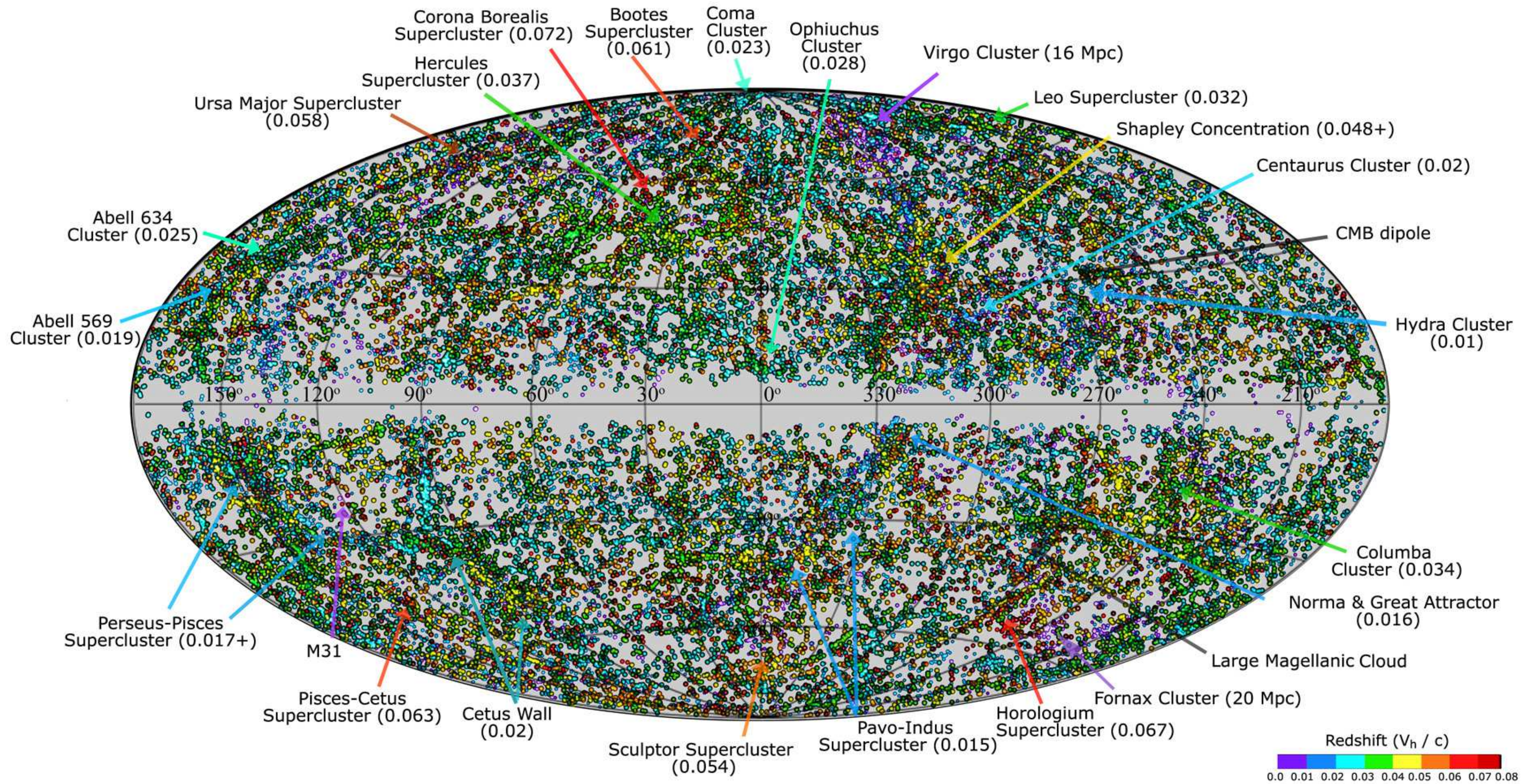
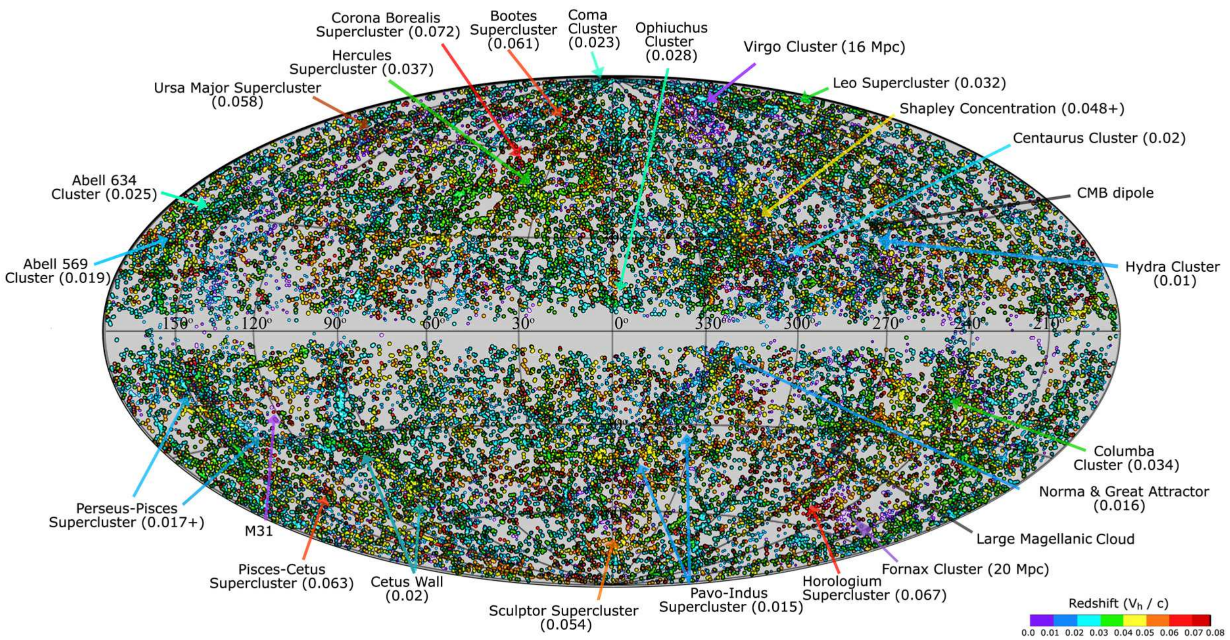
c). Tomographic cross-correlation using local galaxy distribution

Galaxy distribution



2MRS '11

c). Tomographic cross-correlation using local galaxy distribution



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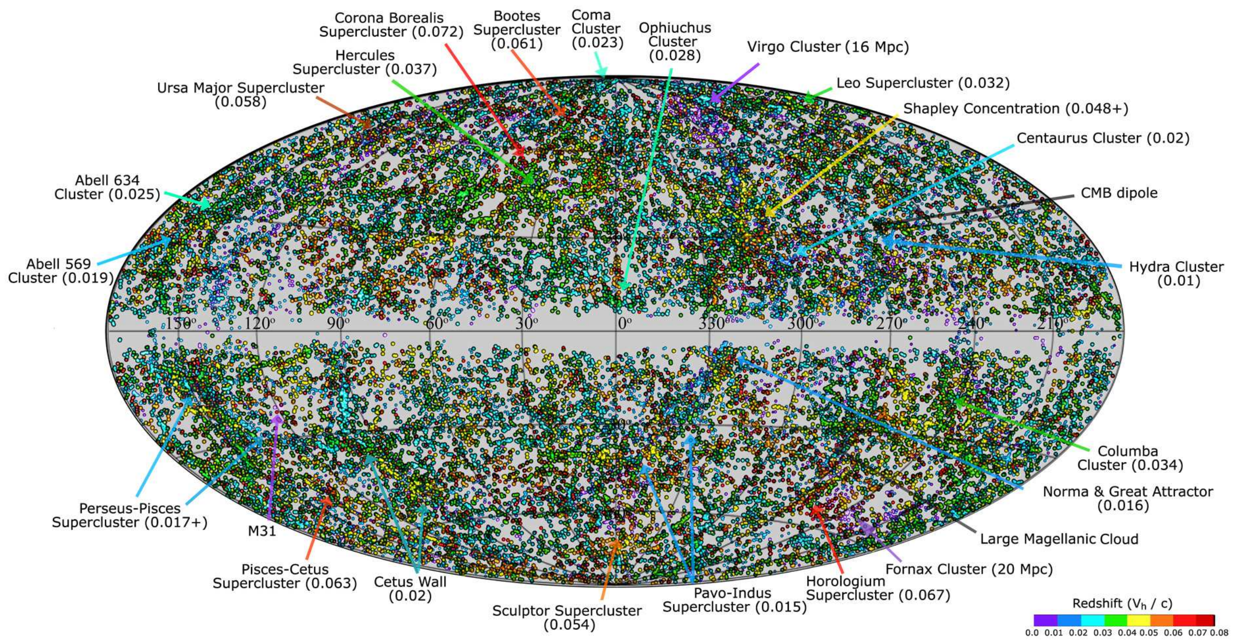
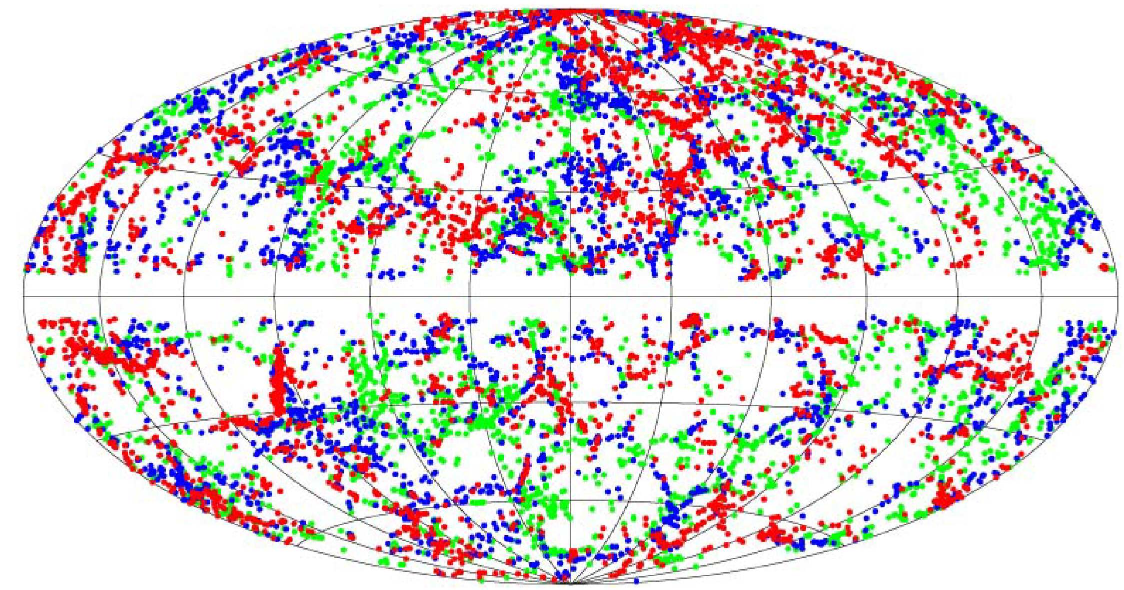




6000<v<7000km/s

7000<v<8000km/s

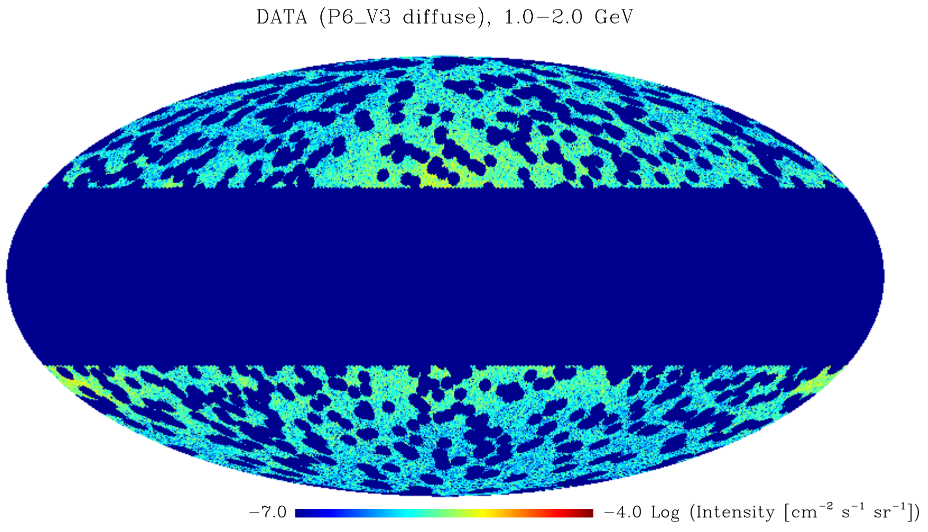
8000<v<9000km/s

We know the distance from each galaxy by its redshift

c). Tomographic cross-correlation using local galaxy distribution

Ingredients for further analysis:

- Anisotropies
- Cosmological distances



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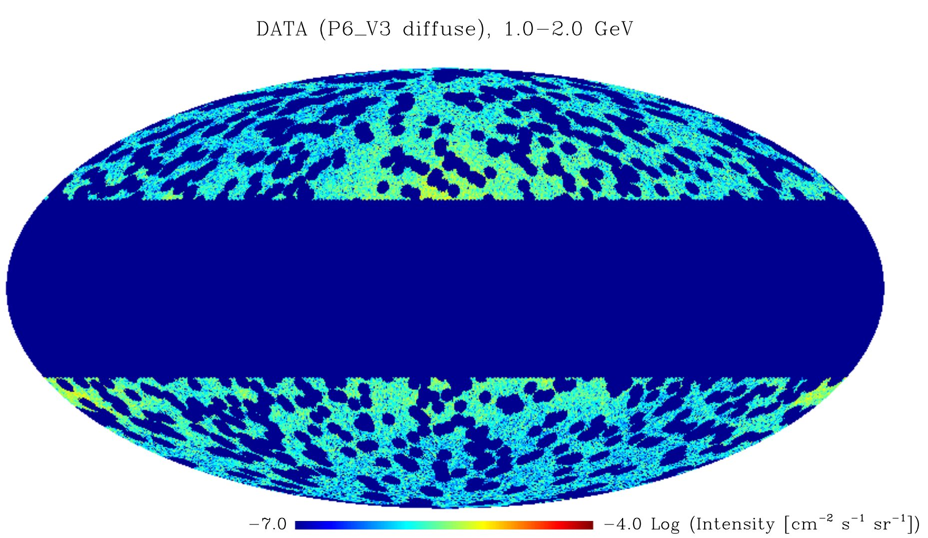
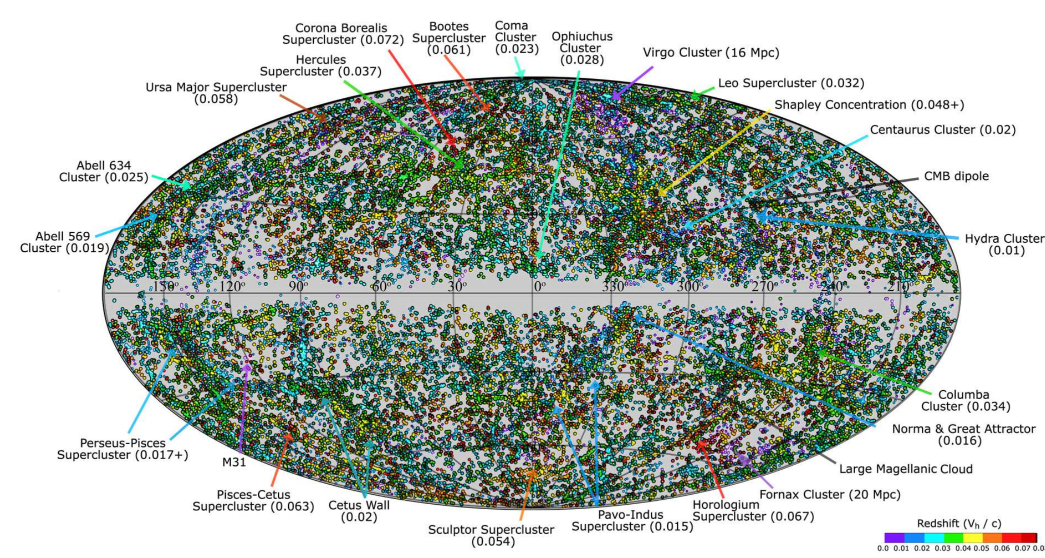
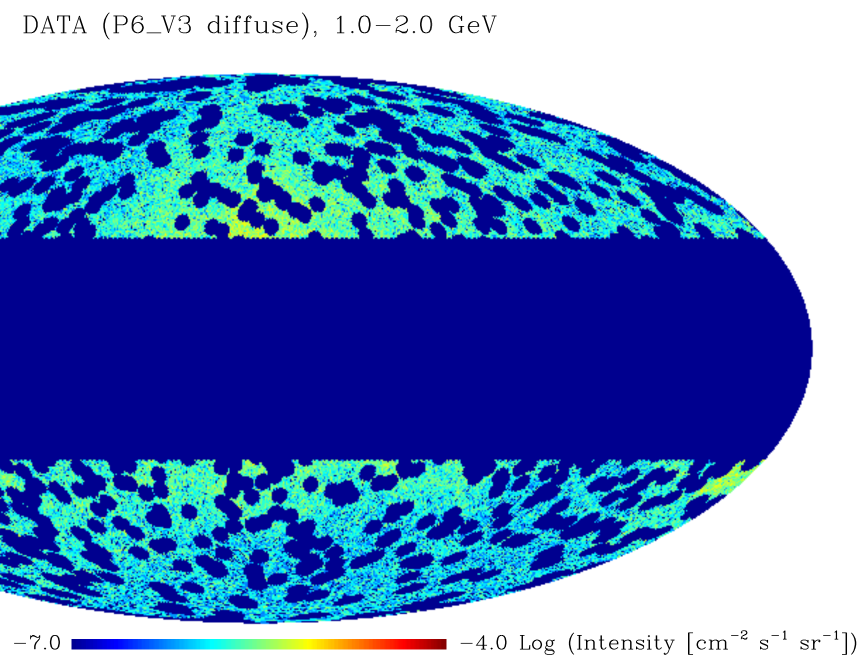
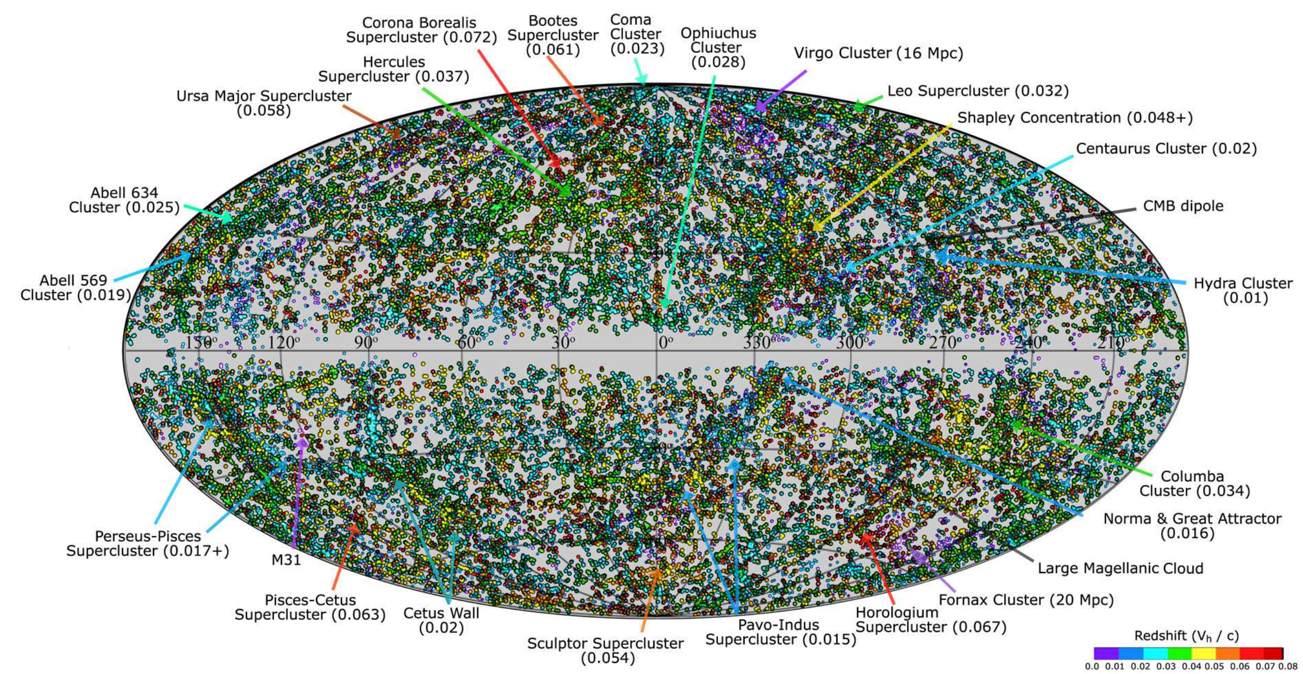


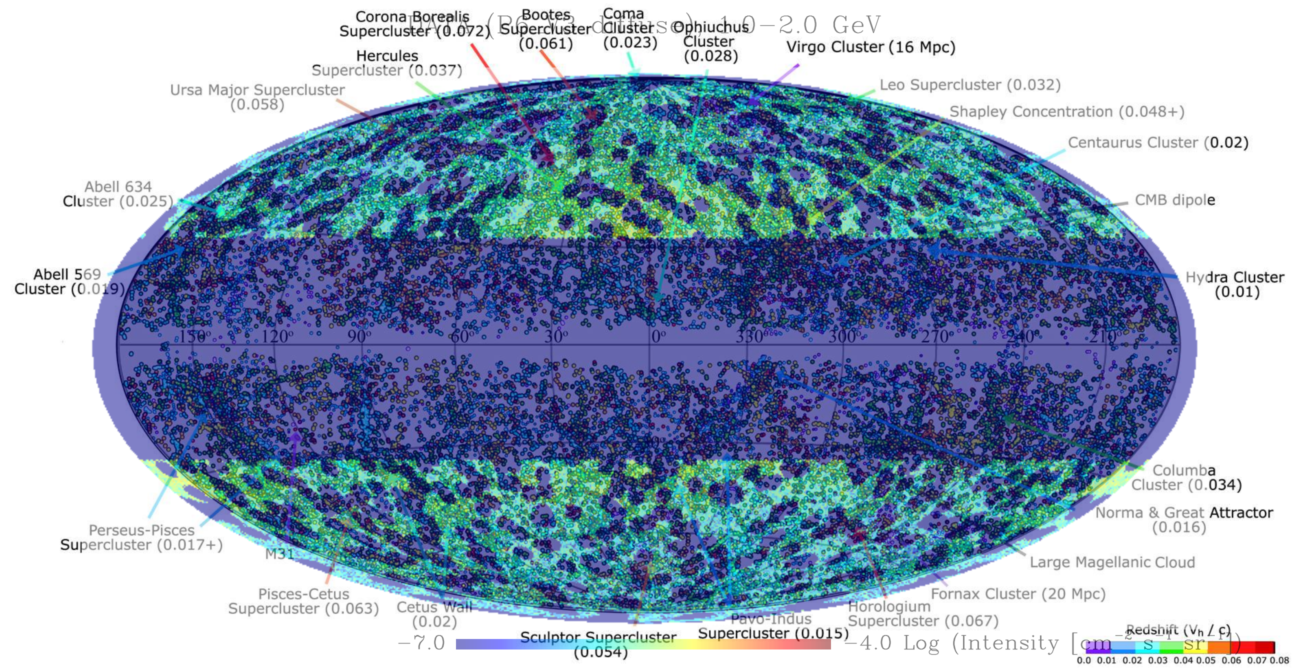


c). Tomographic cross-correlation using local galaxy distribution





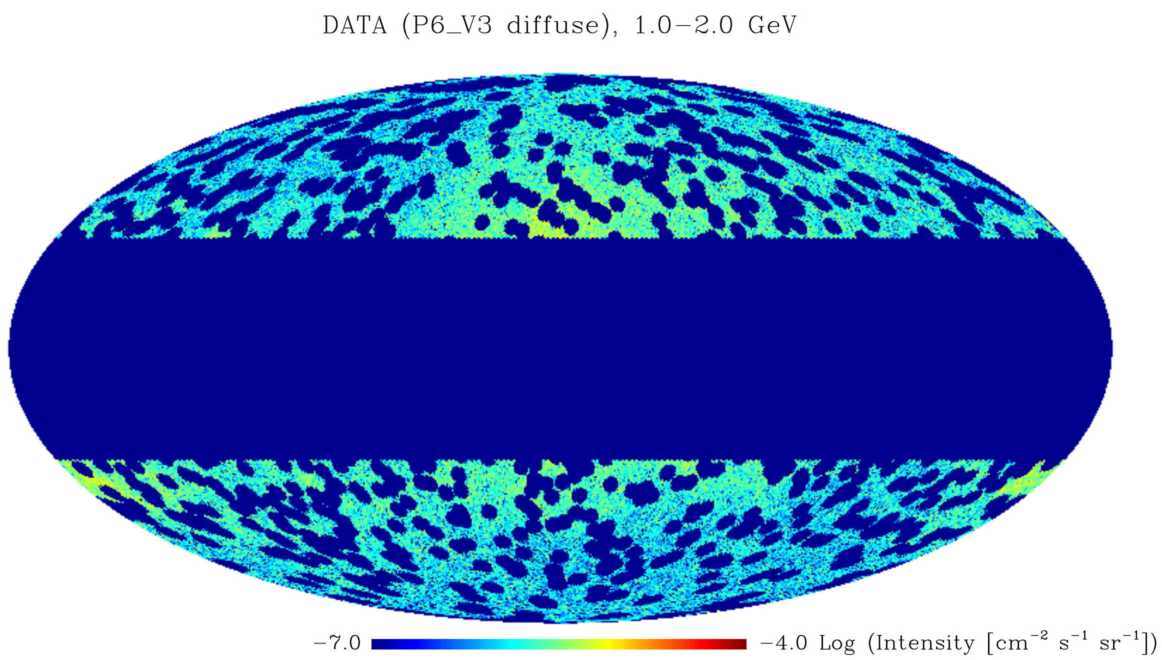
c). Tomographic cross-correlation using local galaxy distribution



Gamma rays are expected to trace galaxy distribution

→ Cross correlation

c). Tomographic cross-correlation using local galaxy distribution



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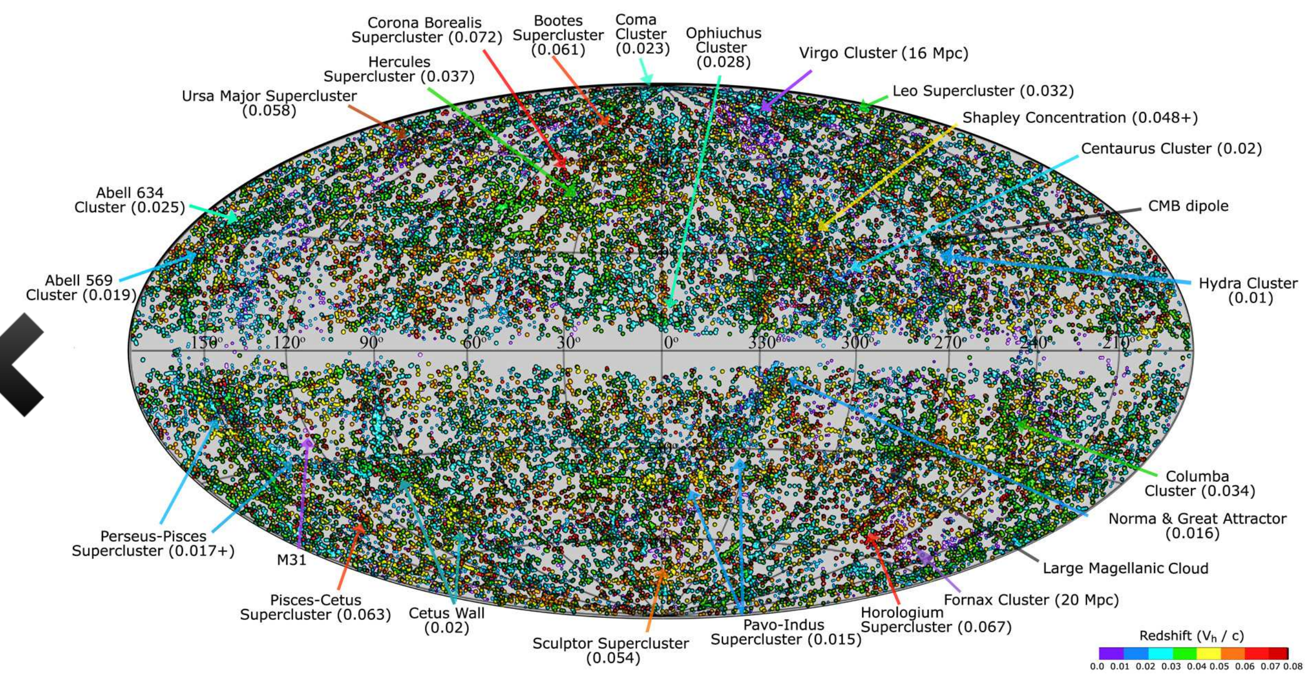
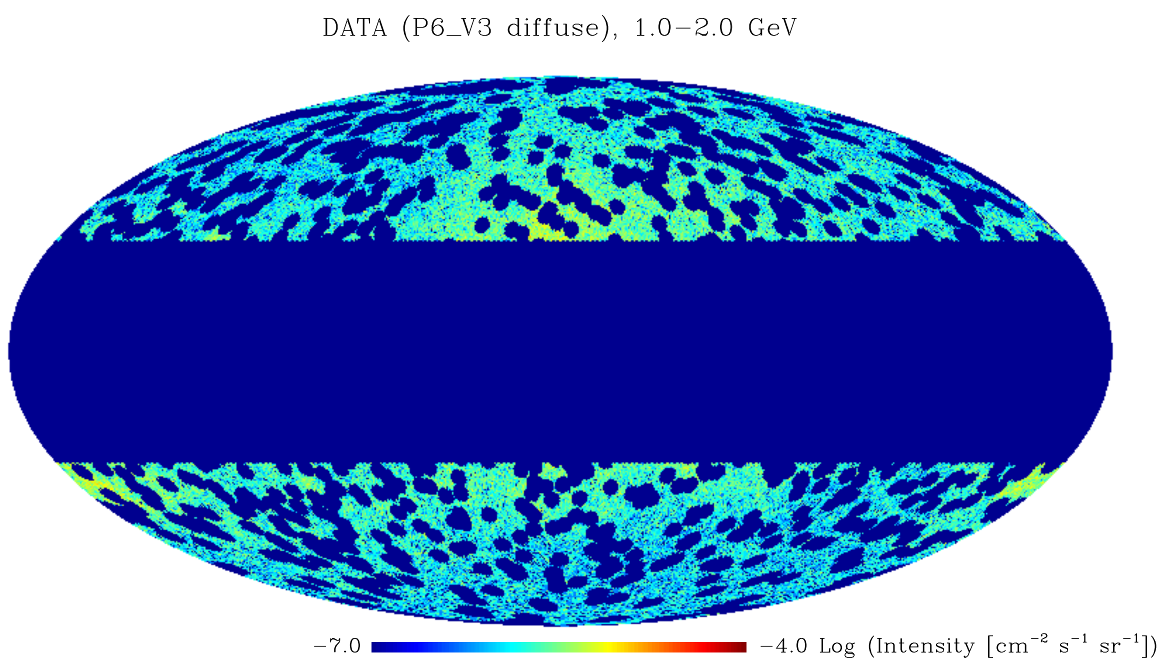
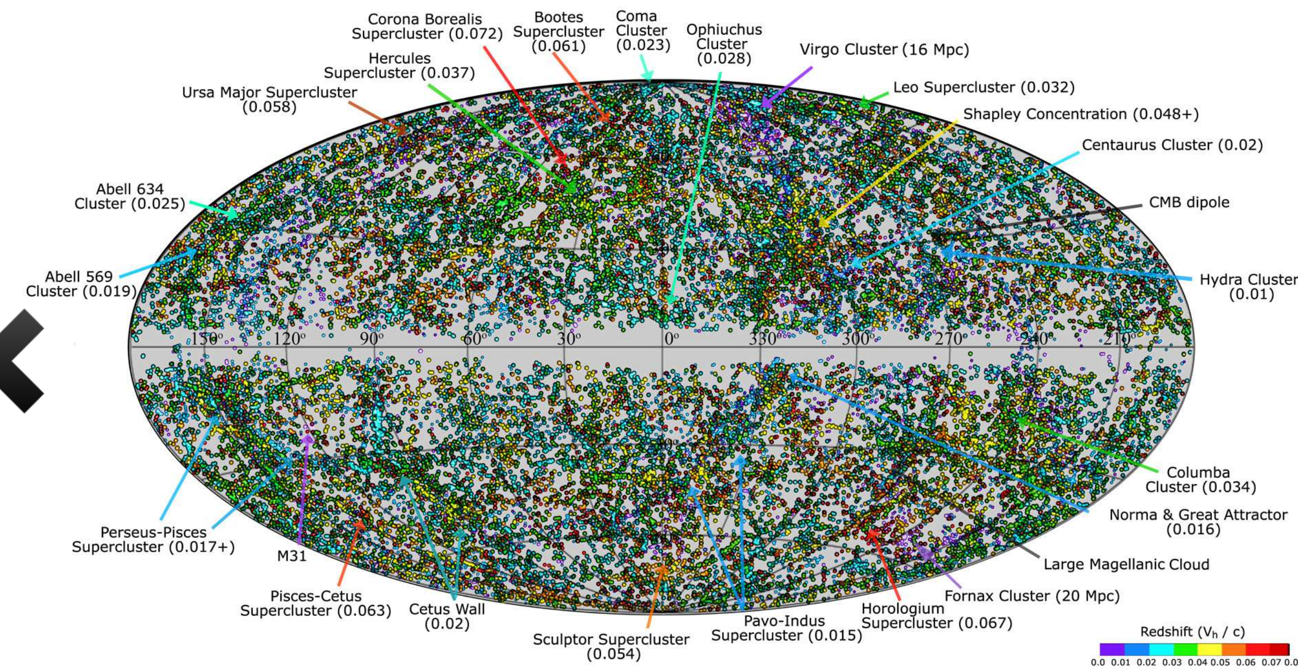


c). Tomographic cross-correlation using local galaxy distribution

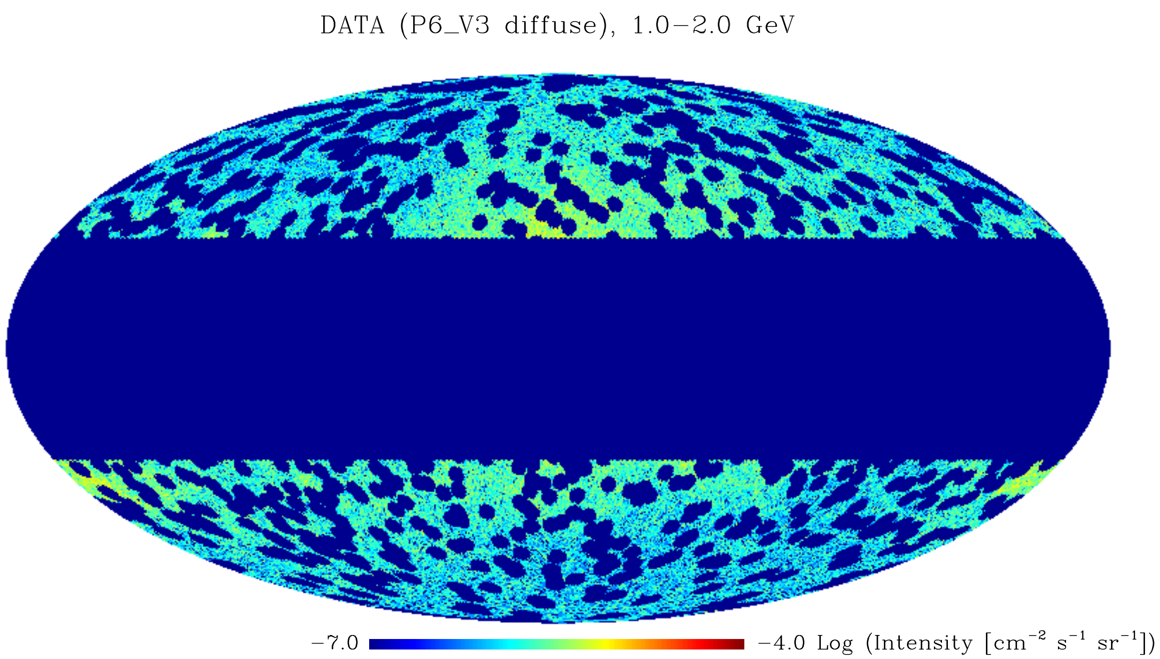


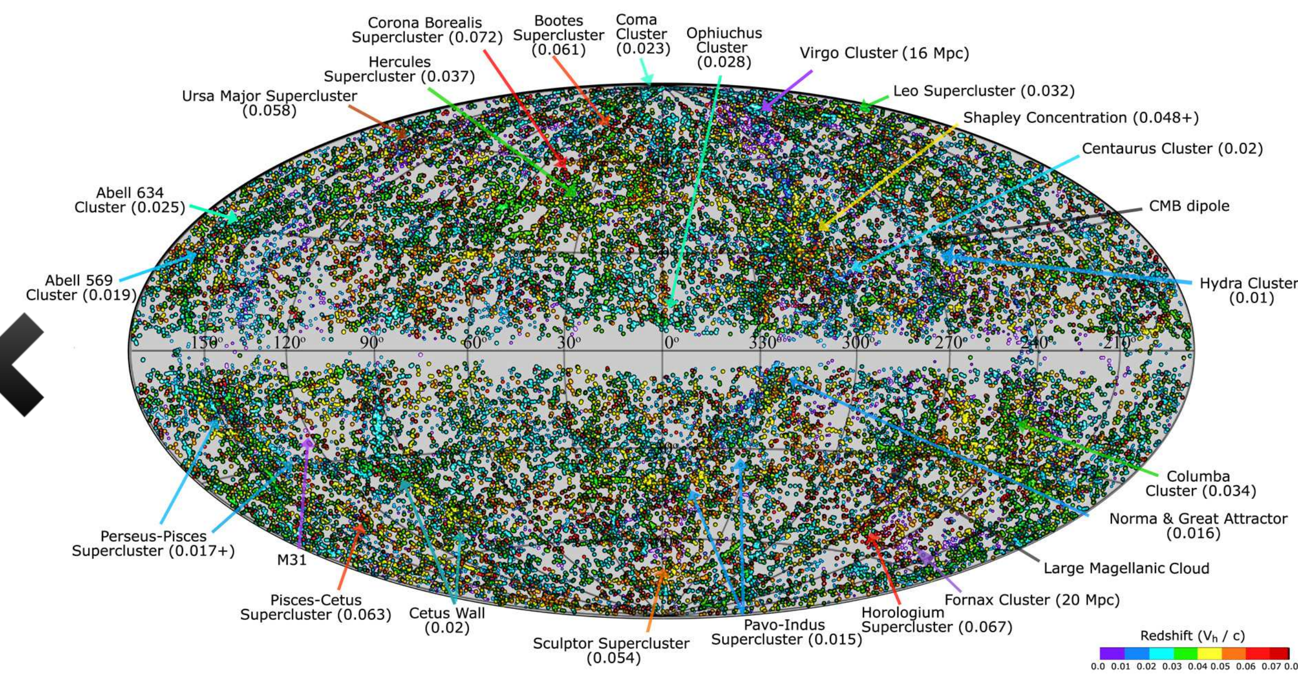


galaxy catalog:

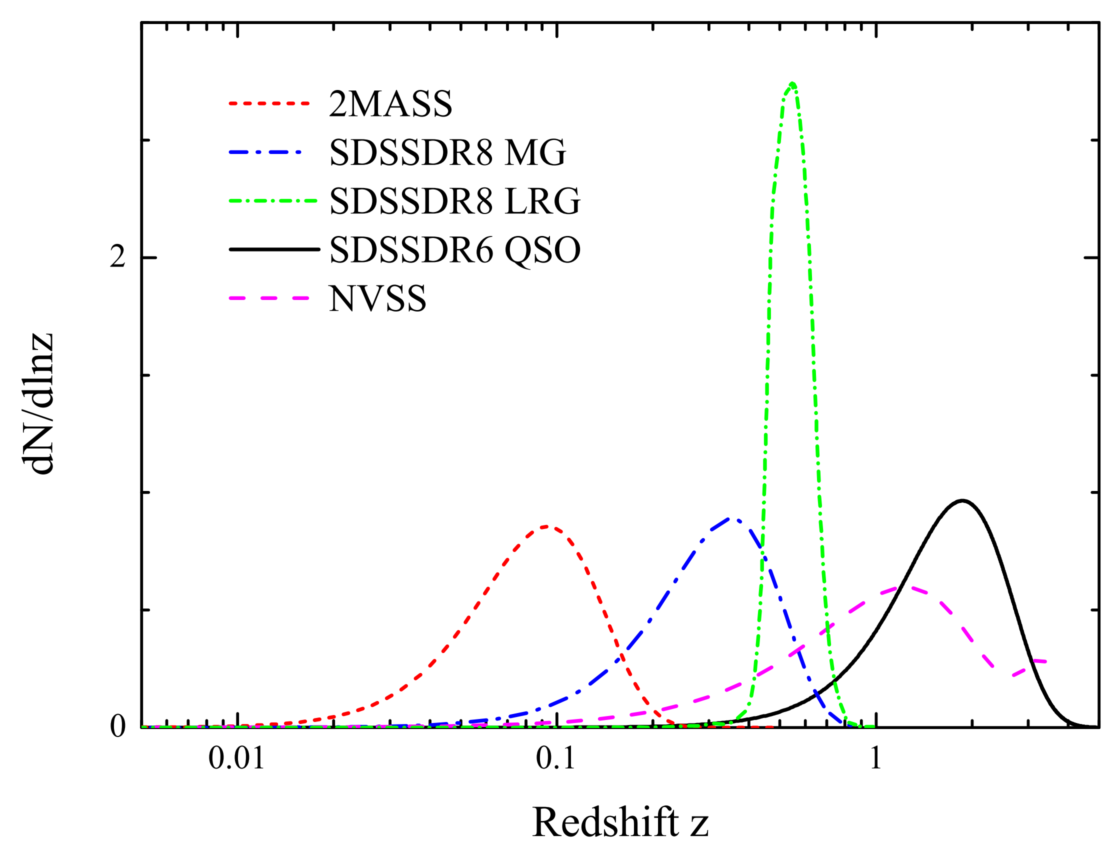
2MRS,QSO,
2MASS,NVSS,MG,LRG

c). Tomographic cross-correlation using local galaxy distribution

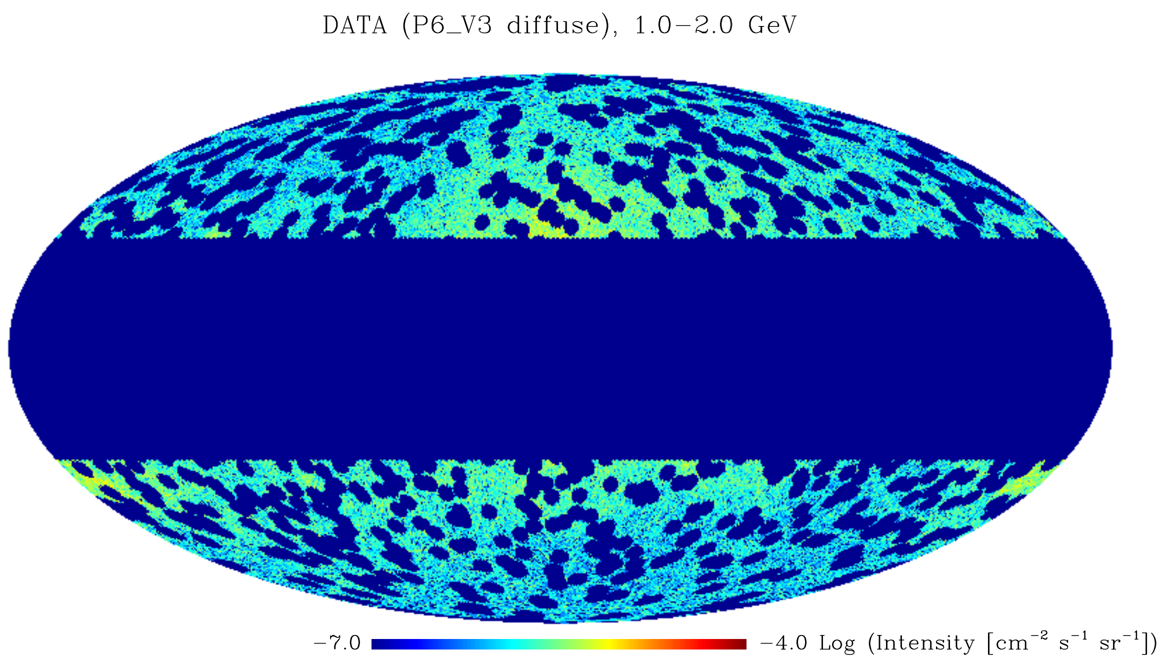




Redshift distribution



c). Tomographic cross-correlation using local galaxy distribution



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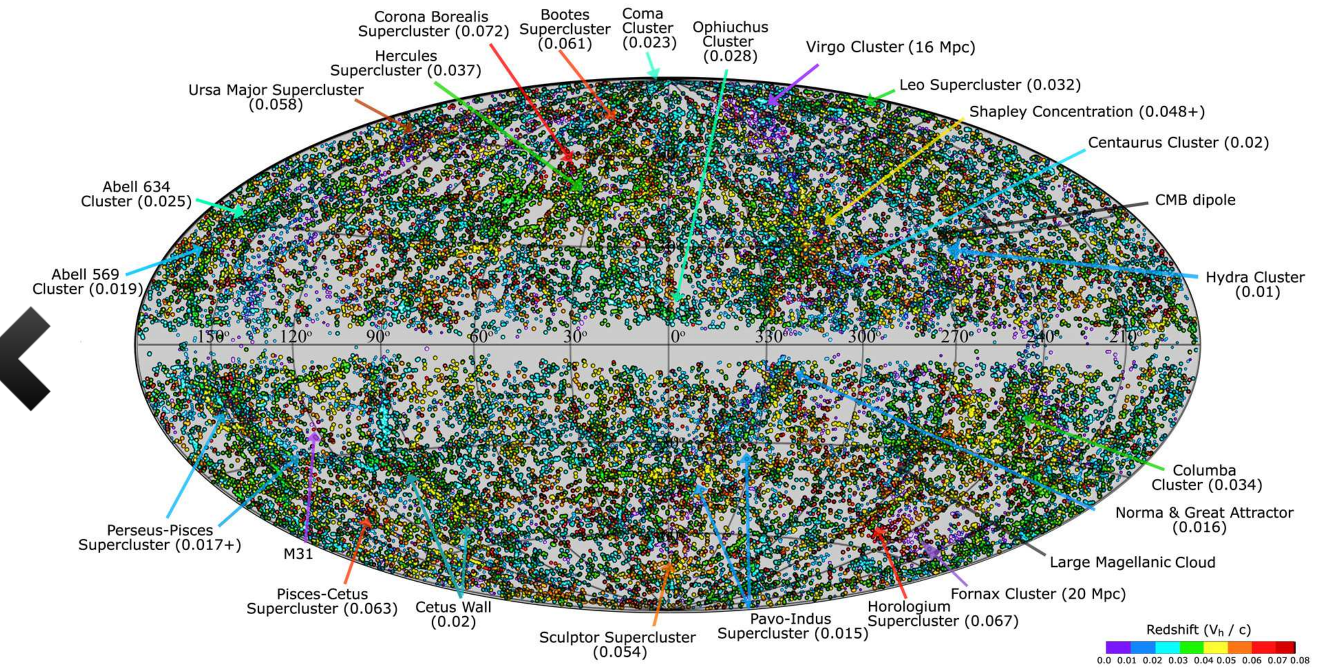
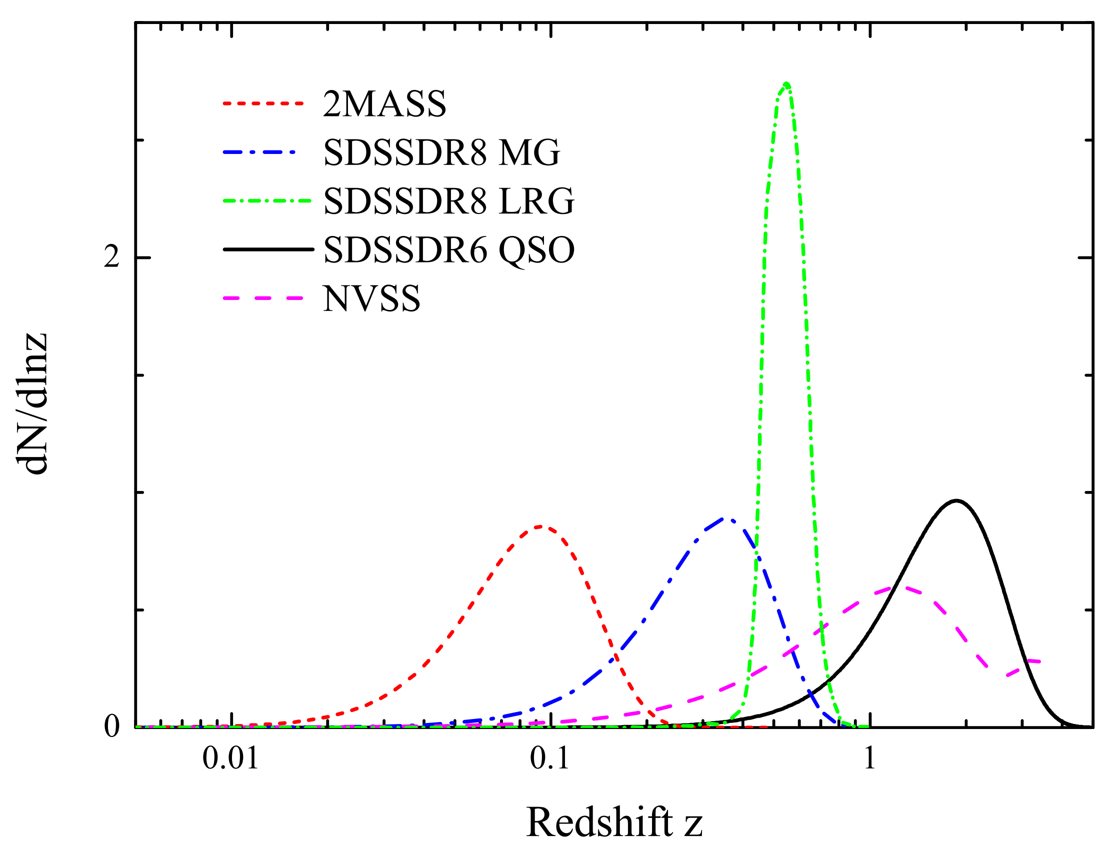


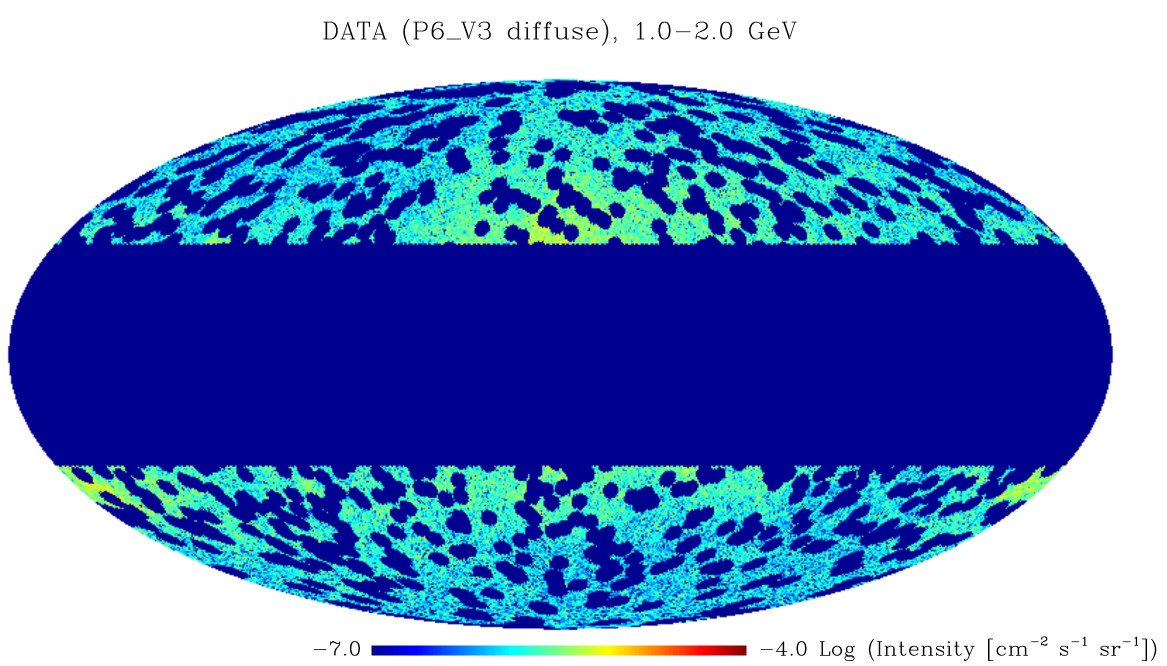
Selecting a galaxy catalog

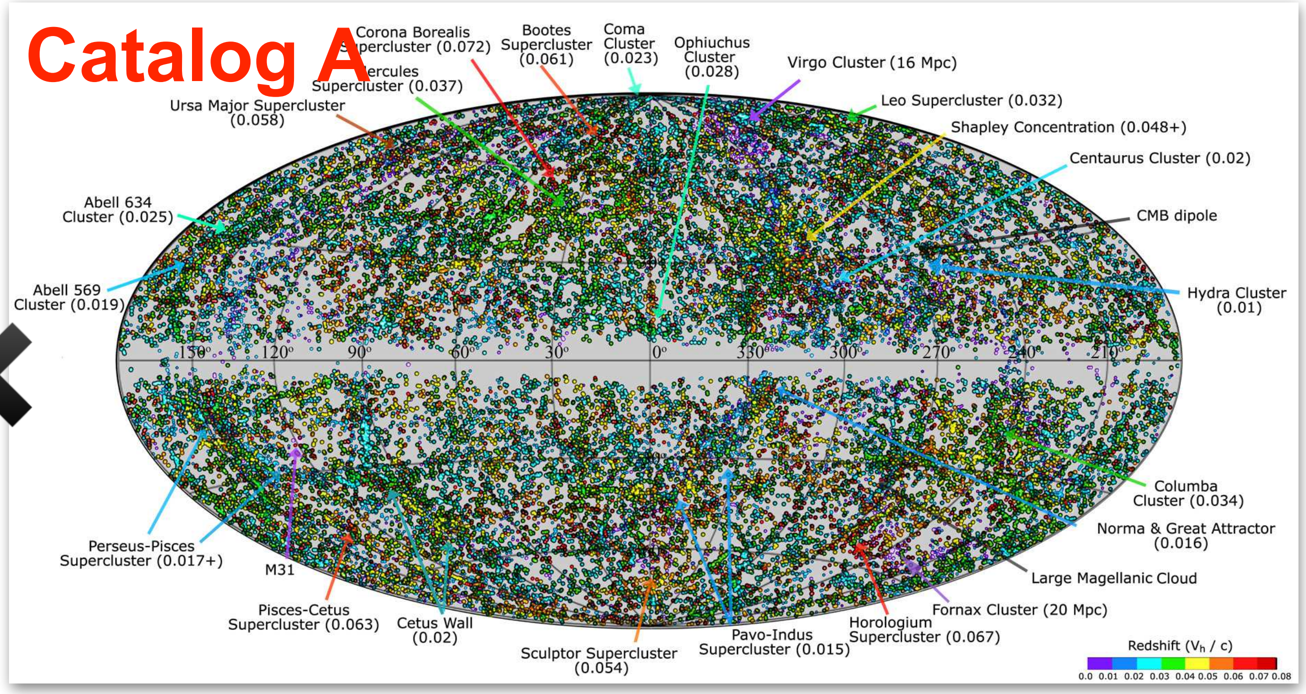
→ You can get cross-correlation for corresponding redshift region

Redshift distribution

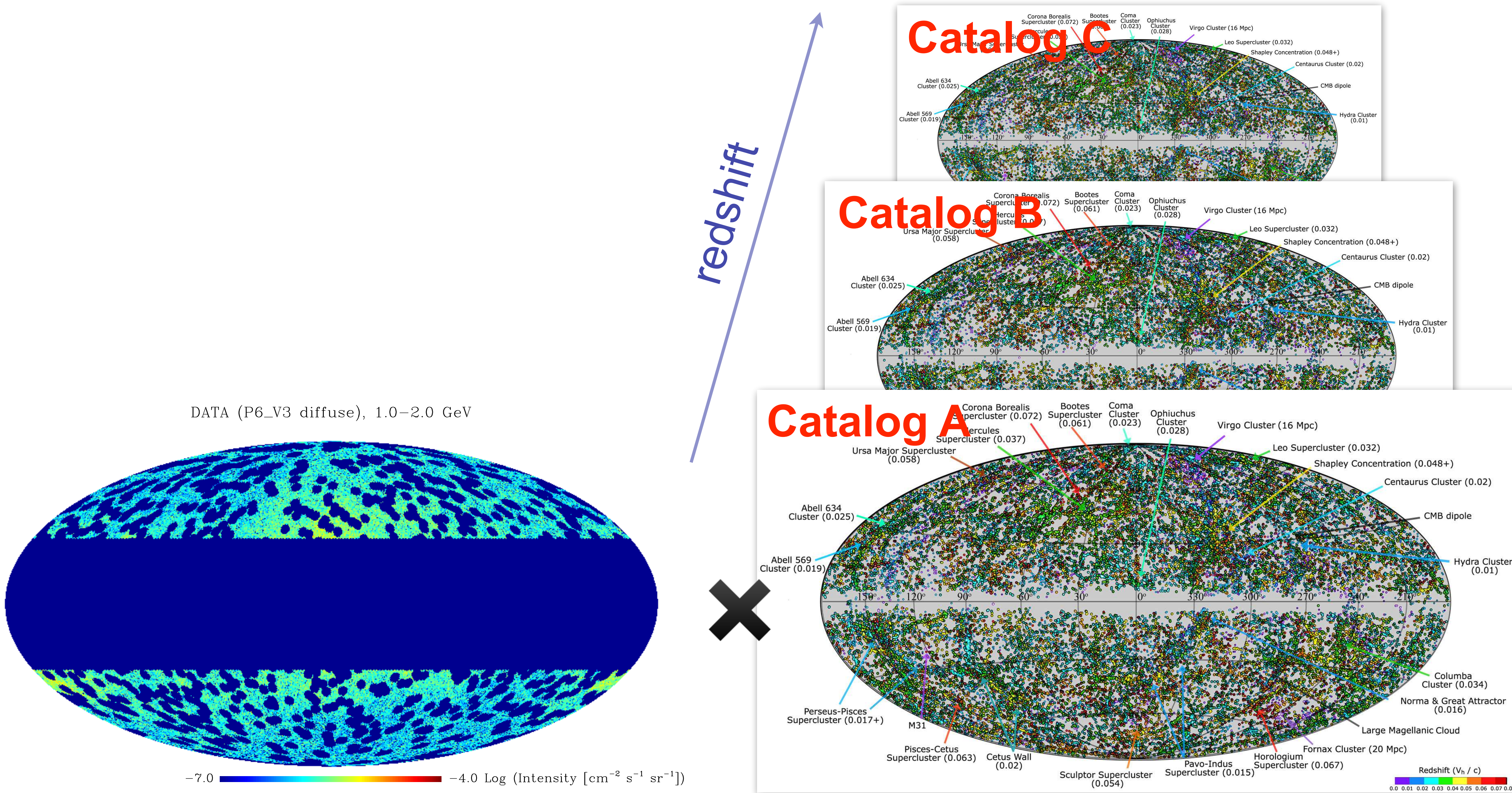


c). Tomographic cross-correlation using local galaxy distribution





c). Tomographic cross-correlation using local galaxy distribution



Tomographic cross-correlation

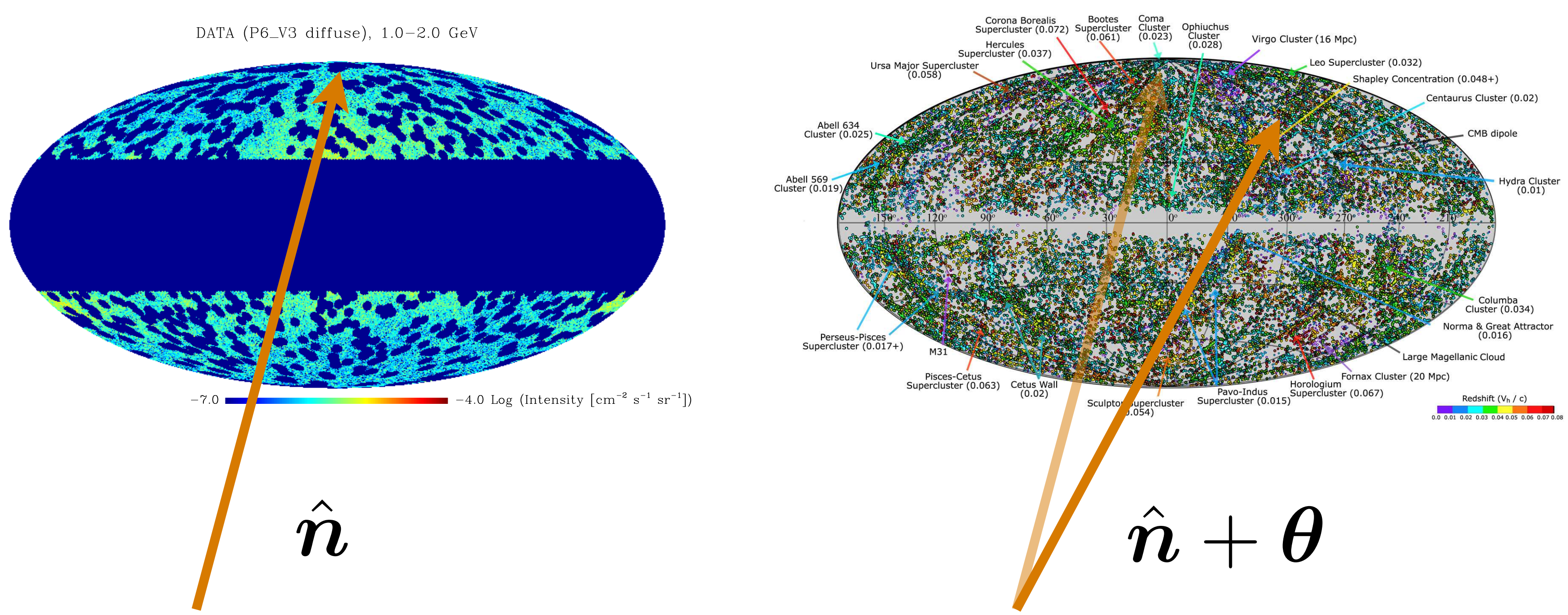
c). Tomographic cross-correlation using local galaxy distribution

$$\delta I_\gamma = I_\gamma - \langle I_\gamma \rangle$$
$$\delta \Sigma_g = \Sigma_g - \langle \Sigma_g \rangle$$

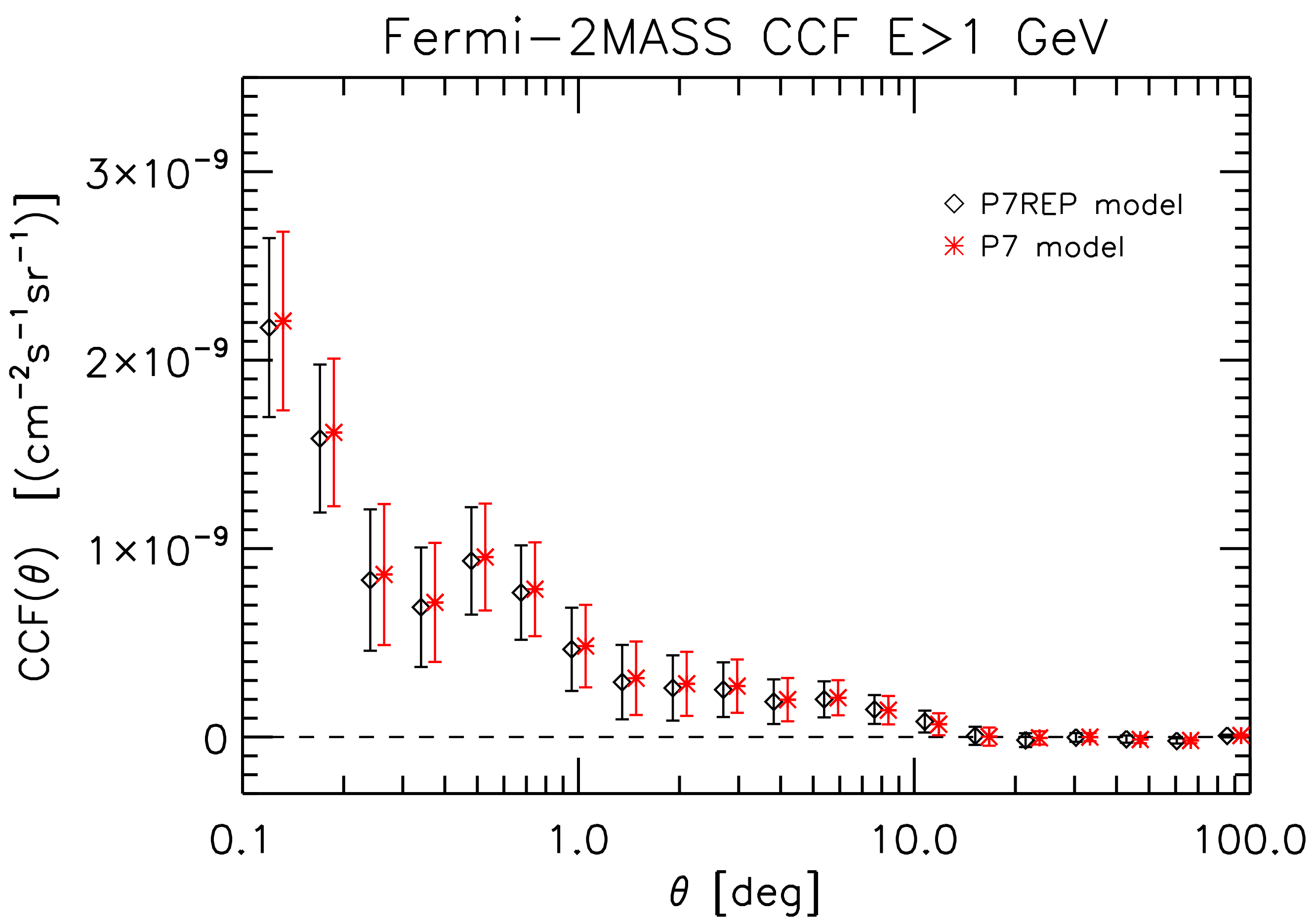
$$C^{\gamma g}(\theta) = \langle \underbrace{\delta I_\gamma(\hat{\boldsymbol{n}})}_{\gamma\text{-ray flux}} \, \underbrace{\delta \Sigma_g(\hat{\boldsymbol{n}} + \boldsymbol{\theta})}_{\text{galaxy distribution}} \rangle$$

γ-ray flux

galaxy distribution



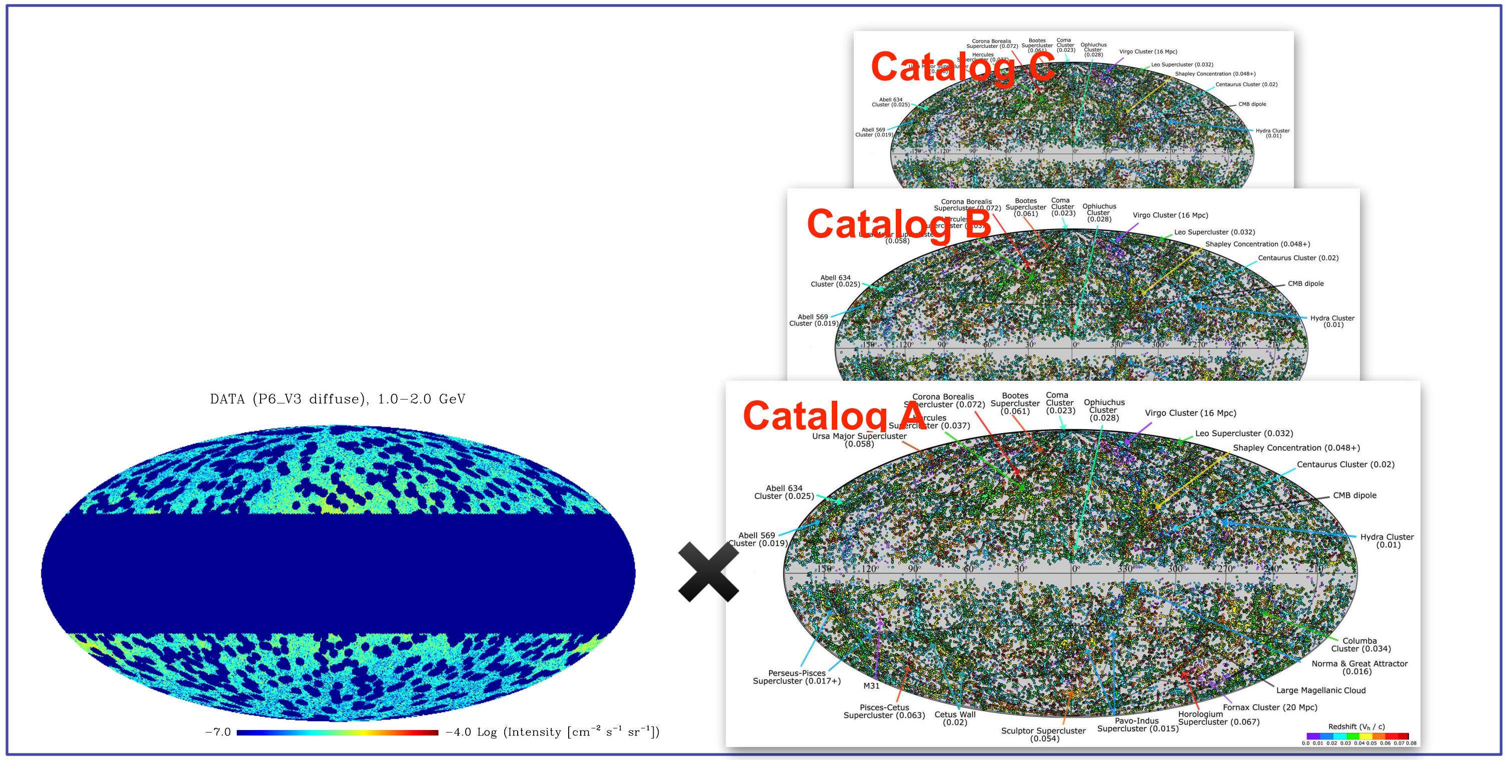
c). Tomographic cross-correlation using local galaxy distribution



Xia, Cuoco, Branchini, Viel ’15

Cross-correlation signal for $< 1^\circ$

c). Tomographic cross-correlation using local galaxy distribution



obs. ✖ obs.

Xia, Cuoco, Branchini, Viel ’15

th. ✖ obs.

Compare both, then exclude the theory which deviates from obs. ✖ obs.

c). Tomographic cross-correlation using local galaxy distribution

Theoretical calculation

$$\delta I_\gamma = I_\gamma - \langle I_\gamma \rangle$$
$$\delta \Sigma_g = \Sigma_g - \langle \Sigma_g \rangle$$

$$C^{\gamma g}(\theta) = \langle \underbrace{\delta I_\gamma(\hat{\boldsymbol{n}})}_{\gamma\text{-ray flux}} \, \underbrace{\delta \Sigma_g(\hat{\boldsymbol{n}} + \boldsymbol{\theta})}_{\text{galaxy distribution}} \rangle$$

c). Tomographic cross-correlation using local galaxy distribution

Theoretical calculation

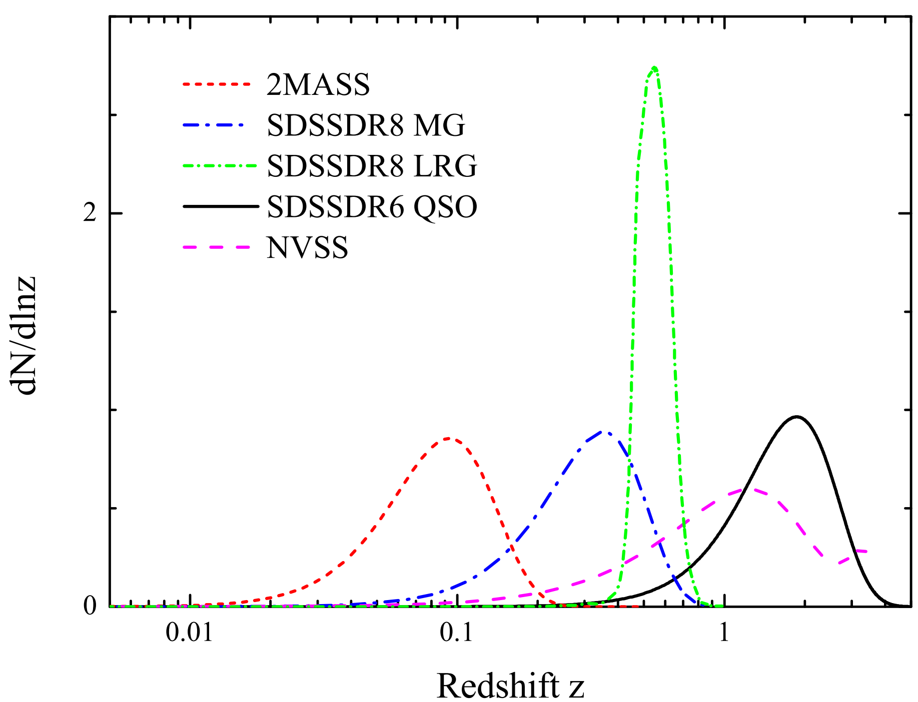
$$\delta I_\gamma = I_\gamma - \langle I_\gamma \rangle$$

$$\delta \Sigma_g = \Sigma_g - \langle \Sigma_g \rangle$$

$$C^{\gamma g}(\theta) = \langle \underbrace{\delta I_\gamma(\hat{\boldsymbol{n}})}_{\gamma\text{-ray flux}} \, \underbrace{\delta \Sigma_g(\hat{\boldsymbol{n}} + \boldsymbol{\theta})}_{\text{galaxy distribution [dimensionless]}} \rangle$$

$$\Sigma_g = \int d\chi \underbrace{W_g(z)}_{\text{window function}} \frac{n_g(\chi \hat{\boldsymbol{n}}, z)}{\langle n_g \rangle}$$

$$W_g(z) = \frac{d \log N_g}{dz} \frac{dz}{d\chi}$$



$$\langle \Sigma_g \rangle = 1$$

c). Tomographic cross-correlation using local galaxy distribution

Theoretical calculation

$$\delta I_\gamma = I_\gamma - \langle I_\gamma \rangle$$

$$\delta \Sigma_g = \Sigma_g - \langle \Sigma_g \rangle$$

$$C^{\gamma g}(\theta) = \langle \underbrace{\delta I_\gamma(\hat{\boldsymbol{n}})}_{\gamma\text{-ray flux}} \, \underbrace{\delta \Sigma_g(\hat{\boldsymbol{n}} + \boldsymbol{\theta})}_{\text{galaxy distribution}} \rangle$$

γ-ray flux

= DM + astro. sources

$[\mathrm{cm}^{-2} s^{-1} \mathrm{str}^{-1}]$

galaxy distribution

Decaying DM

$$I_\gamma^{\mathrm{dm}} = \int d\chi W_\gamma^{\mathrm{dm}}(z) \left[\frac{\rho_{\mathrm{dm}}(\chi \hat{\boldsymbol{n}}, z)}{\langle \rho_{\mathrm{dm}} \rangle} \right]$$

$$W_\gamma^{\mathrm{dm}}(z) = \int dE_\gamma \, \frac{d\Phi_\gamma^{\mathrm{dm}}}{d\chi}(E_\gamma, z) \qquad [\mathrm{cm}^{-3} s^{-1} \mathrm{str}^{-1}]$$

$$\frac{d\Phi_\gamma^{\mathrm{dm}}}{d\chi}(E_\gamma, z) = \frac{1}{4\pi} \frac{\Omega_{\mathrm{dm}} \rho_c}{m_{\mathrm{dm}} \tau_{\mathrm{dm}}} \frac{1}{1+z} Q_\gamma^{\mathrm{dm}}(E'_\gamma, z) \, e^{-\tau(E'_\gamma, z)} \qquad [\mathrm{GeV}^{-1} \mathrm{cm}^{-3} s^{-1} \mathrm{str}^{-1}]$$

c). Tomographic cross-correlation using local galaxy distribution

Theoretical calculation

$$\delta I_\gamma = I_\gamma - \langle I_\gamma \rangle$$

$$\delta \Sigma_g = \Sigma_g - \langle \Sigma_g \rangle$$

$$C^{\gamma g}(\theta) = \langle \underbrace{\delta I_\gamma(\hat{\boldsymbol{n}})}_{\gamma\text{-ray flux}} \, \underbrace{\delta \Sigma_g(\hat{\boldsymbol{n}} + \boldsymbol{\theta})}_{\text{galaxy distribution}} \rangle$$

γ-ray flux

= DM + astro. sources

$\left[\mathrm{cm}^{-2} s^{-1} \mathrm{str}^{-1}\right]$

galaxy distribution

Annihilating DM

$$I_\gamma^{\mathrm{dm}} = \int d\chi W_\gamma^{\mathrm{dm}}(z) \left[\frac{\rho_{\mathrm{dm}}(\chi \hat{\boldsymbol{n}}, z)}{\langle \rho_{\mathrm{dm}} \rangle} \right]^2$$

$$W_\gamma^{\mathrm{dm}}(z) = \int dE_\gamma \, \frac{d\Phi_\gamma^{\mathrm{dm}}}{d\chi}(E_\gamma, z) \qquad \left[\mathrm{cm}^{-3} s^{-1} \mathrm{str}^{-1}\right]$$

$$\frac{d\Phi_\gamma^{\mathrm{dm}}}{d\chi}(E_\gamma, z) = \frac{\langle \sigma v \rangle}{8\pi} \left(\frac{\Omega_{\mathrm{dm}} \rho_c}{m_{\mathrm{dm}}} \right)^2 (1+z)^3 Q_\gamma^{\mathrm{dm}}(E'_\gamma, z) \, e^{-\tau(E'_\gamma, z)} \qquad \left[\mathrm{GeV}^{-1} \mathrm{cm}^{-3} s^{-1} \mathrm{str}^{-1}\right]$$

c). Tomographic cross-correlation using local galaxy distribution

Theoretical calculation

$$\delta I_\gamma = I_\gamma - \langle I_\gamma \rangle$$
$$\delta \Sigma_g = \Sigma_g - \langle \Sigma_g \rangle$$

$$C^{\gamma g}(\theta) = \langle \underbrace{\delta I_\gamma(\hat{\boldsymbol{n}})}_{\uparrow} \, \underbrace{\delta \Sigma_g(\hat{\boldsymbol{n}} + \boldsymbol{\theta})}_{\uparrow} \rangle$$

γ-ray flux

galaxy distribution

= DM + astro. sources

Decaying/Annihilating DM (source term)

$$Q_\gamma^{\rm dm}(E'_\gamma, z) = Q_{\gamma_{\rm pr}}^{\rm dm}(E'_\gamma, z) + Q_{\gamma_{\rm fsr}}^{\rm dm}(E'_\gamma, z) + Q_{\gamma_{\rm ic}}^{\rm dm}(E'_\gamma, z) \qquad [{\rm GeV}^{-1}]$$

$$Q_{\gamma_{\rm pr}}^{\rm dm}(E'_\gamma, z) + Q_{\gamma_{\rm fsr}}^{\rm dm}(E'_\gamma, z) = (1+z)\frac{dN_\gamma}{dE}(E'_\gamma)$$

$$Q_{\gamma \rm ic}^{\rm dm}(E'_\gamma, z) = c \int dE_e \, dE_{\gamma_{\rm BG}} (1+z) \frac{d\sigma_{\rm IC}}{dE'_\gamma}(E'_\gamma, E_e, E_{\gamma_{\rm BG}}) f_\gamma^{\rm BG}(E_{\gamma_{\rm BG}}, z) \frac{Y_e(E_e)}{b_{\rm IC}(E_e, z)}$$

$$f_\gamma^{\rm BG}(E_{\gamma_{\rm BG}}, z) = f_\gamma^{\rm CMB}(E_{\gamma_{\rm BG}}, z) + f_\gamma^{\rm EBL}(E_{\gamma_{\rm BG}}, z) \qquad [{\rm GeV}^{-1}{\rm cm}^{-3}]$$

$$Y_e(E_e) = \sum_{I=e^\pm} \int_{E_e}^{\infty} dE \frac{dN_I}{dE}(E)$$

$$b_{\rm IC}(E_e, z) = \int dE'_\gamma dE_{\gamma_{\rm BG}} (E'_\gamma - E_{\gamma_{\rm BG}}) \frac{d\sigma_{\rm IC}}{dE'_\gamma}(E'_\gamma, E_e, E_{\gamma_{\rm BG}}) f_\gamma^{\rm BG}(E_{\gamma_{\rm BG}}, z) \; [{\rm GeV\, s}^{-1}]$$

c). Tomographic cross-correlation using local galaxy distribution

Theoretical calculation

$$\delta I_\gamma = I_\gamma - \langle I_\gamma \rangle$$
$$\delta \Sigma_g = \Sigma_g - \langle \Sigma_g \rangle$$

$$C^{\gamma g}(\theta) = \langle \underbrace{\delta I_\gamma(\hat{\boldsymbol{n}})}_{\gamma\text{-ray flux}} \, \underbrace{\delta \Sigma_g(\hat{\boldsymbol{n}} + \boldsymbol{\theta})}_{\text{galaxy distribution}} \rangle$$

γ-ray flux

= DM + astro. sources

galaxy distribution

Astro. sources

$$I_\gamma^X = \int d\chi W_\gamma^X(z) \left[\frac{n_X(\chi \hat{\boldsymbol{n}}, z)}{\langle n_X \rangle} \right]$$

$X =$ blazar, SFG

$$W_\gamma^X(z) = \chi^2 \int dL_\gamma \frac{dn_\gamma^X(L_\gamma, z)}{dL_\gamma} F_\gamma(L_\gamma, z) \quad [\mathrm{cm}^{-3} s^{-1} \mathrm{str}^{-1}]$$

Acero *et al.* '15
Ajello *et al.* '15

Ackermann *et al.* '12
Gruppioni *et al.* '13
Tamborra, Ando, Murase '14

c). Tomographic cross-correlation using local galaxy distribution

Theoretical calculation

$$\delta I_\gamma = I_\gamma - \langle I_\gamma \rangle$$
$$\delta \Sigma_g = \Sigma_g - \langle \Sigma_g \rangle$$

$$C^{\gamma g}(\theta) = \langle \underbrace{\delta I_\gamma(\hat{\boldsymbol{n}})}_{\gamma\text{-ray flux}} \, \underbrace{\delta \Sigma_g(\hat{\boldsymbol{n}} + \boldsymbol{\theta})}_{\text{galaxy distribution}} \rangle$$

γ-ray flux

= DM + astro. sources

galaxy distribution

Astro. sources (window function)

$$W_\gamma^X(z) = \chi^2 \int dL_\gamma \frac{dn_\gamma^X(L_\gamma, z)}{dL_\gamma} F_\gamma(L_\gamma, z) \quad [\mathrm{cm}^{-3} s^{-1} \mathrm{str}^{-1}]$$

$\frac{dn_\gamma^X(L_\gamma, z)}{dL_\gamma}$: luminosity function $[\mathrm{erg}^{-1} \mathrm{s\,cm}^{-3}]$

$F_\gamma(L_\gamma, z)$: number flux of photons from a source with luminosity L_γ and redshift z $[\mathrm{cm}^{-2} \mathrm{s}^{-1} \mathrm{str}^{-1}]$

L_γ : luminosity $[\mathrm{erg\,s}^{-1}]$

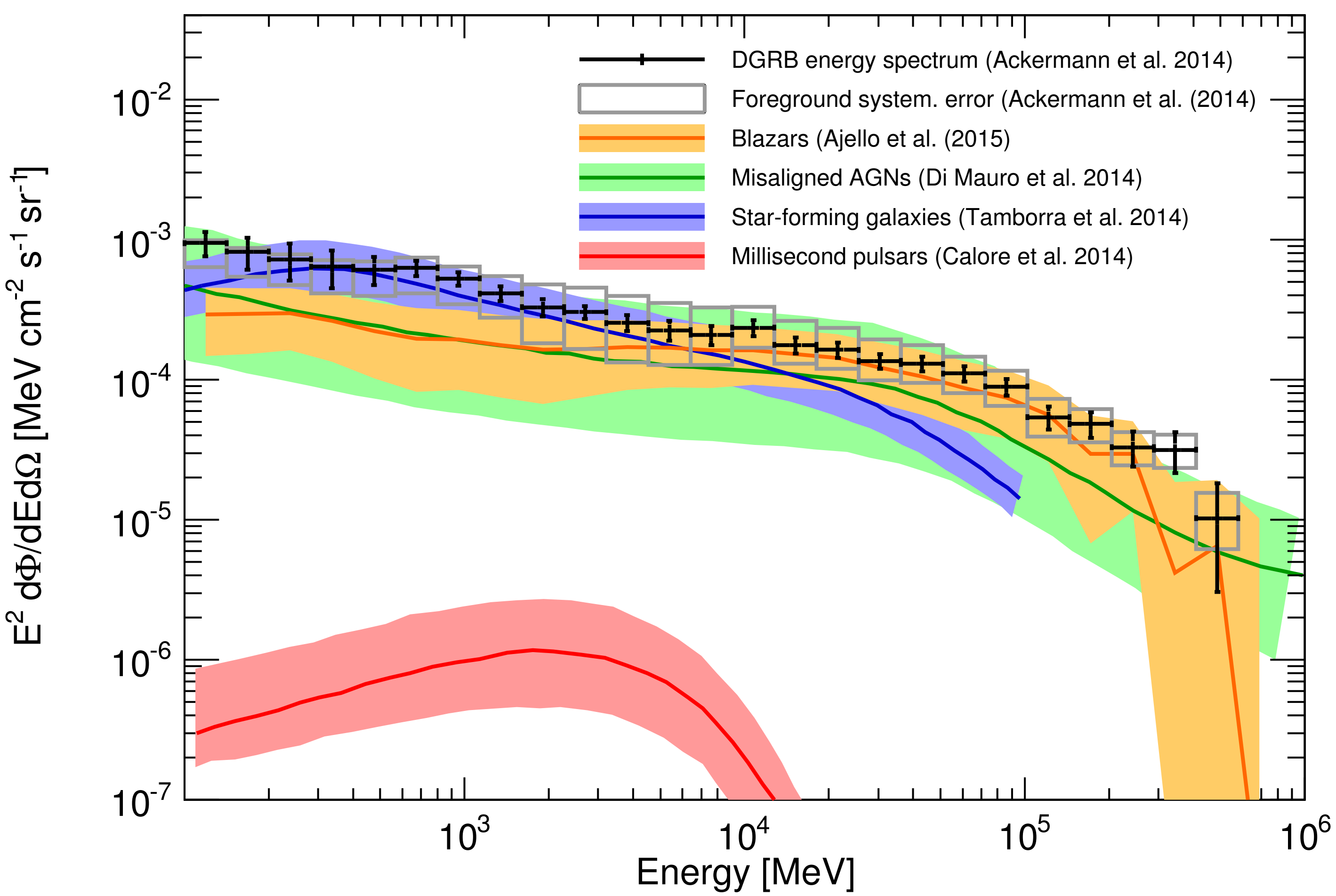
c). Tomographic cross-correlation using local galaxy distribution

Theoretical calculation

$$\delta I_\gamma = I_\gamma - \langle I_\gamma \rangle$$
$$\delta \Sigma_g = \Sigma_g - \langle \Sigma_g \rangle$$

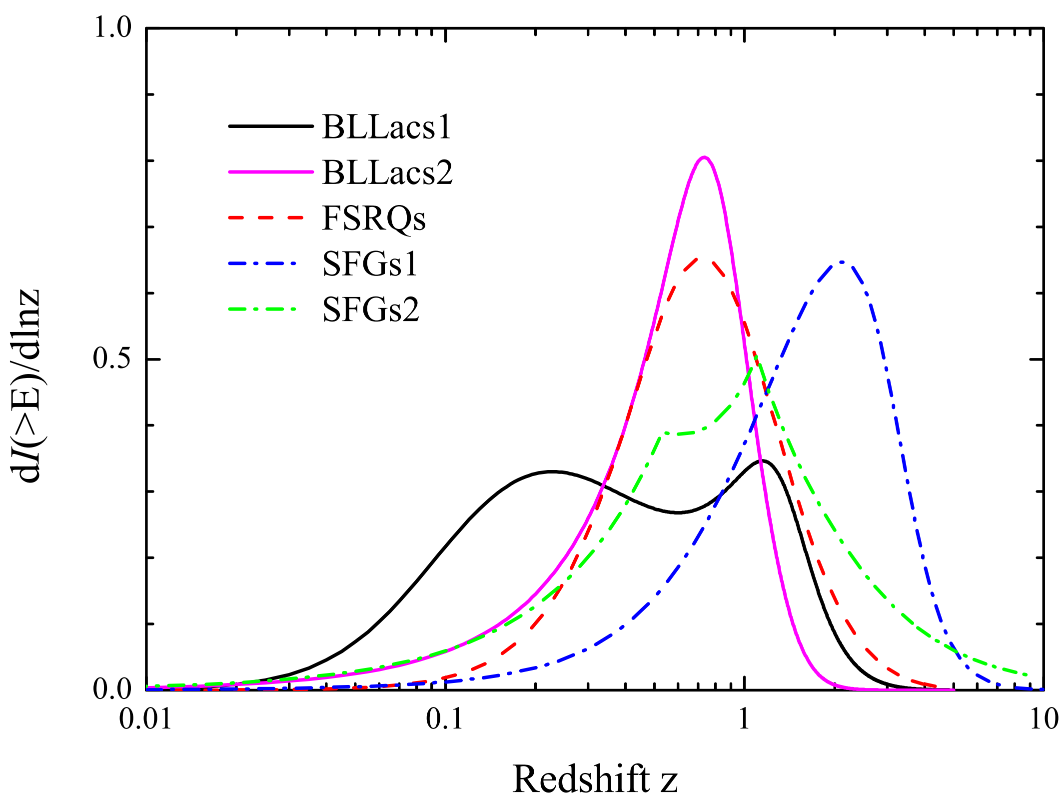
$$C^{\gamma g}(\theta) = \langle \underbrace{\delta I_\gamma(\hat{\boldsymbol{n}})}_{\gamma\text{-ray flux}} \underbrace{\delta \Sigma_g(\hat{\boldsymbol{n}} + \boldsymbol{\theta})}_{\text{galaxy distribution}} \rangle$$

Fornasa, Sánchez-Conde ’15

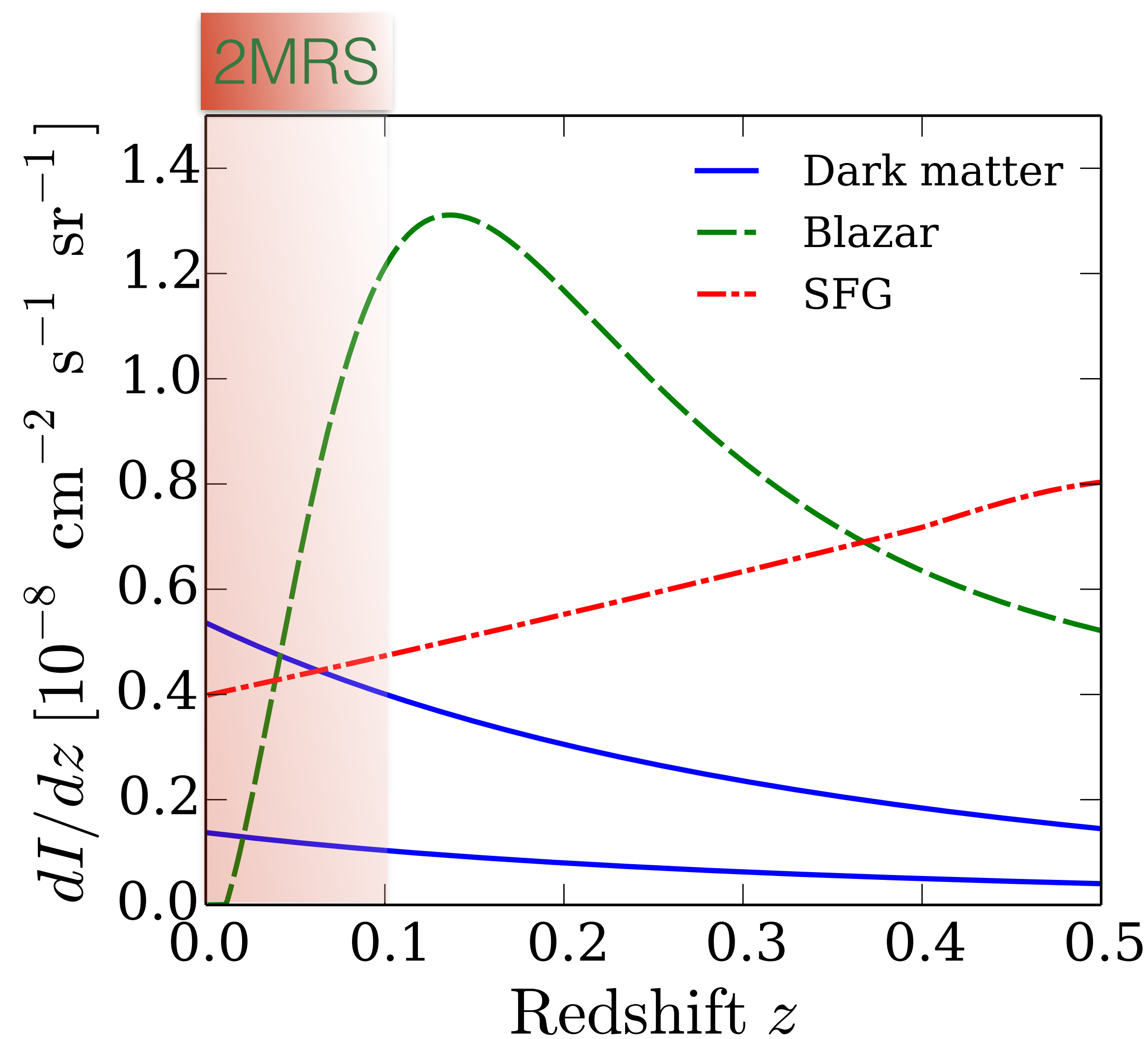


c). Tomographic cross-correlation using local galaxy distribution

Advantages of tomography



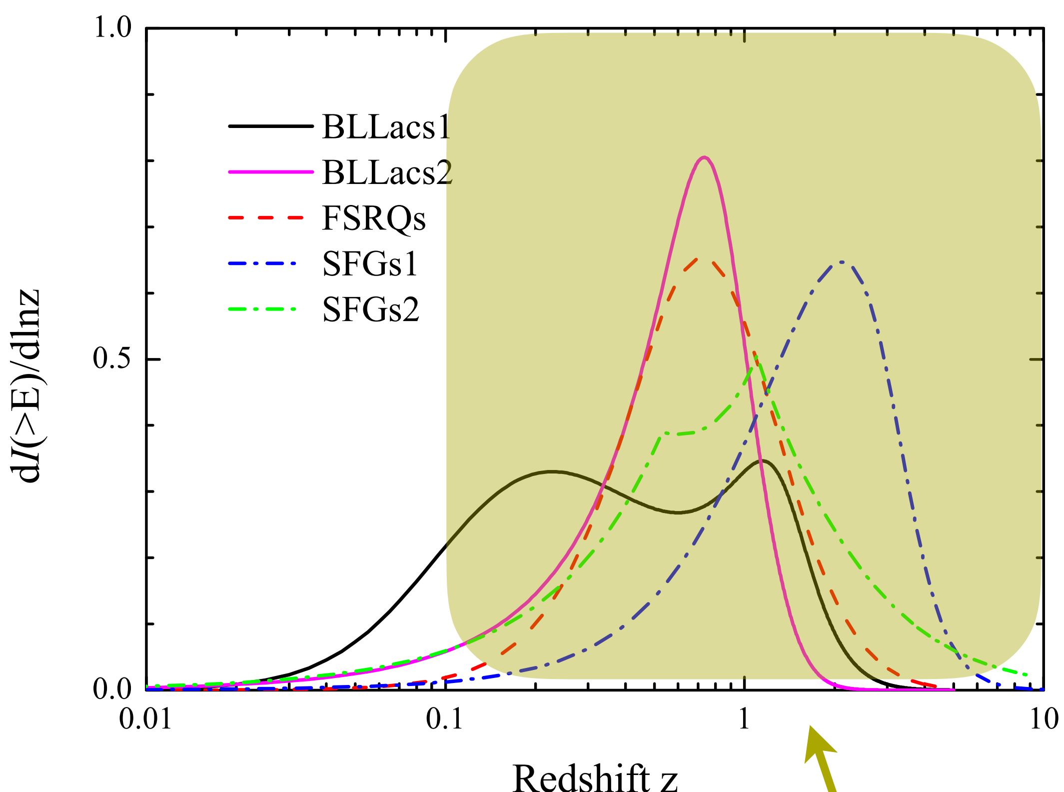
Xia, Cuoco, Branchini, Viel '15

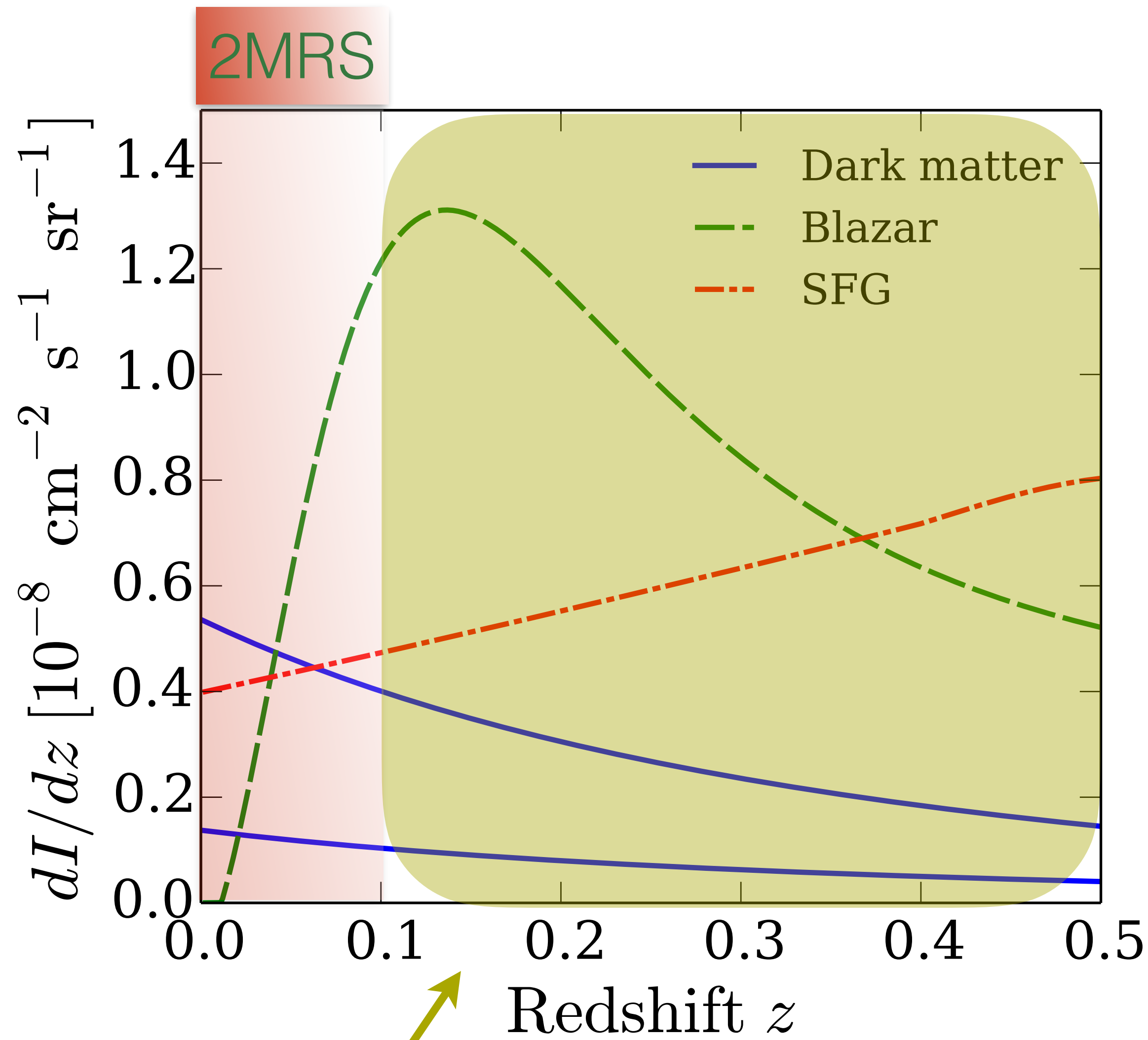


Ando '14

c). Tomographic cross-correlation using local galaxy distribution

Advantages of tomography





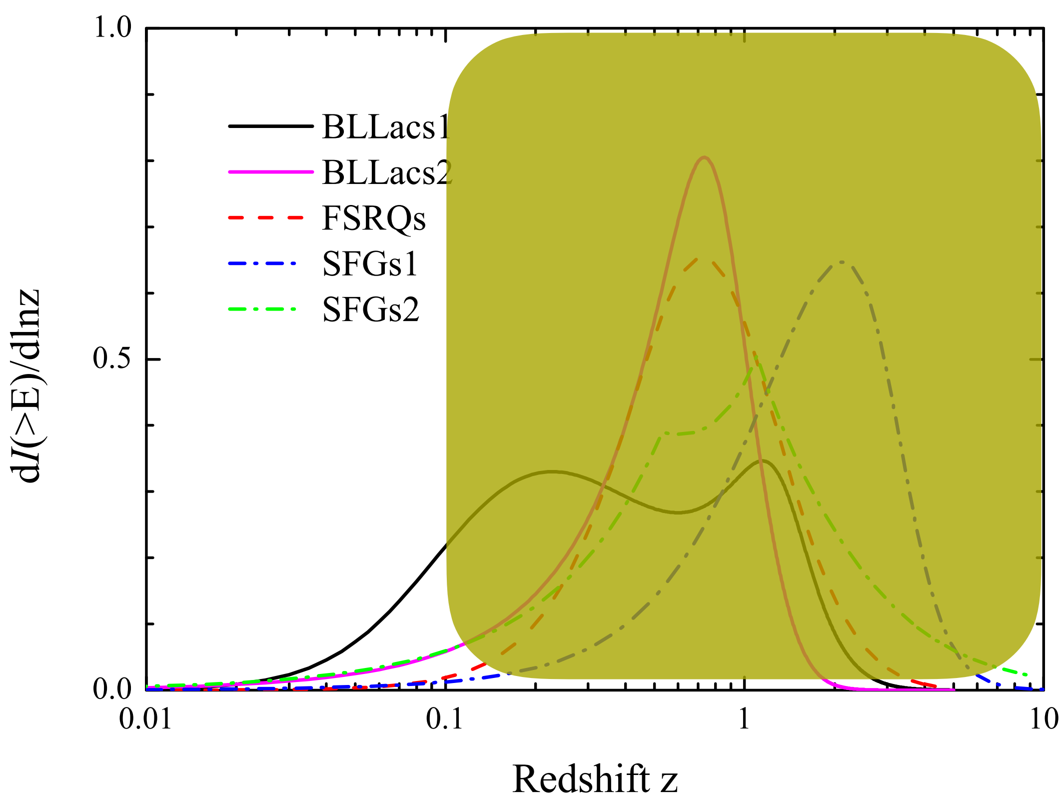
Xia, Cuoco, Branchini, Viel '15

Ando '14

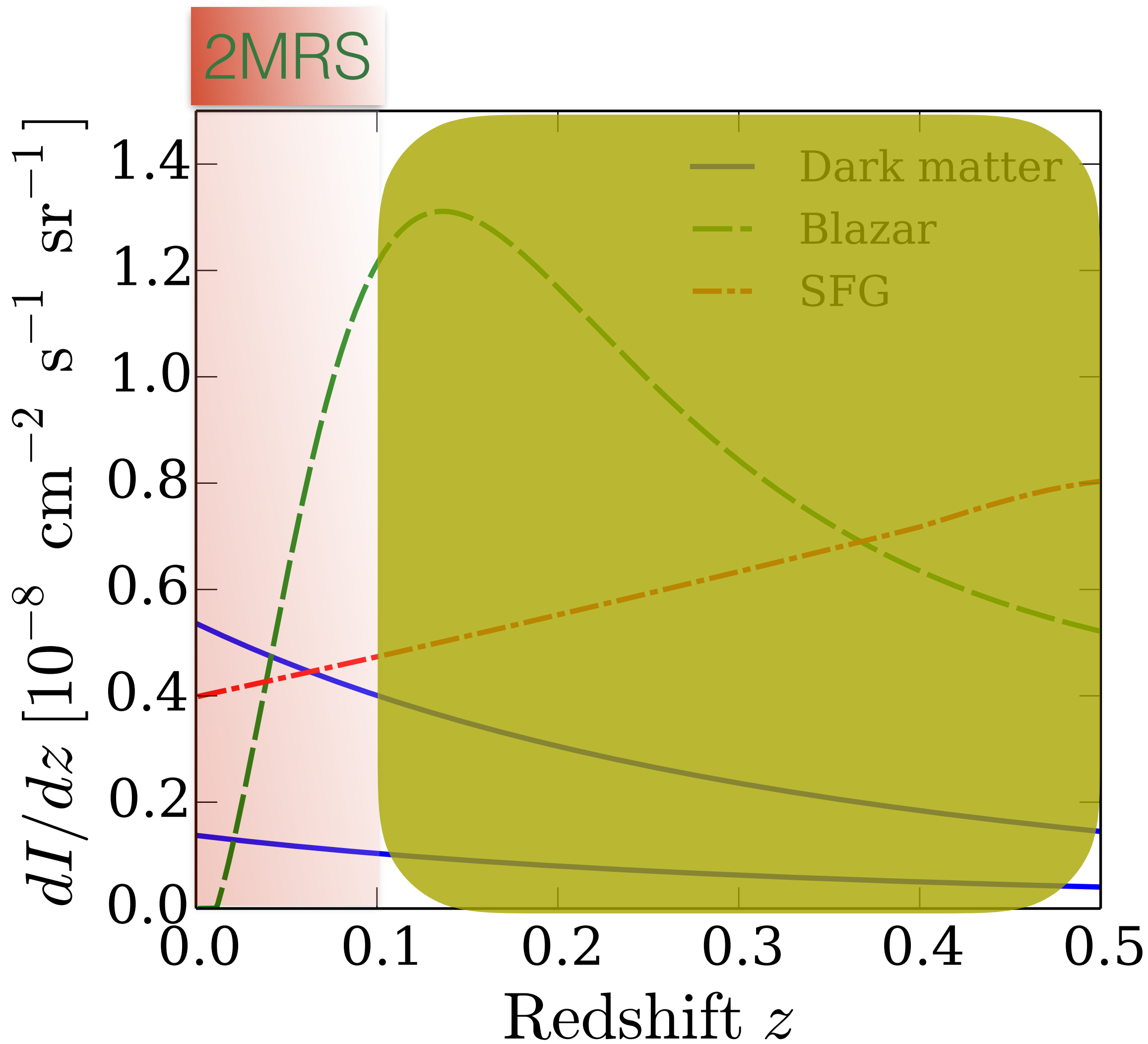
Blazars and SFGs are dominant in $z > 0.1$

c). Tomographic cross-correlation using local galaxy distribution

Advantages of tomography



Xia, Cuoco, Branchini, Viel '15



Ando '14

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

c). Tomographic cross-correlation using local galaxy distribution

Theoretical calculation

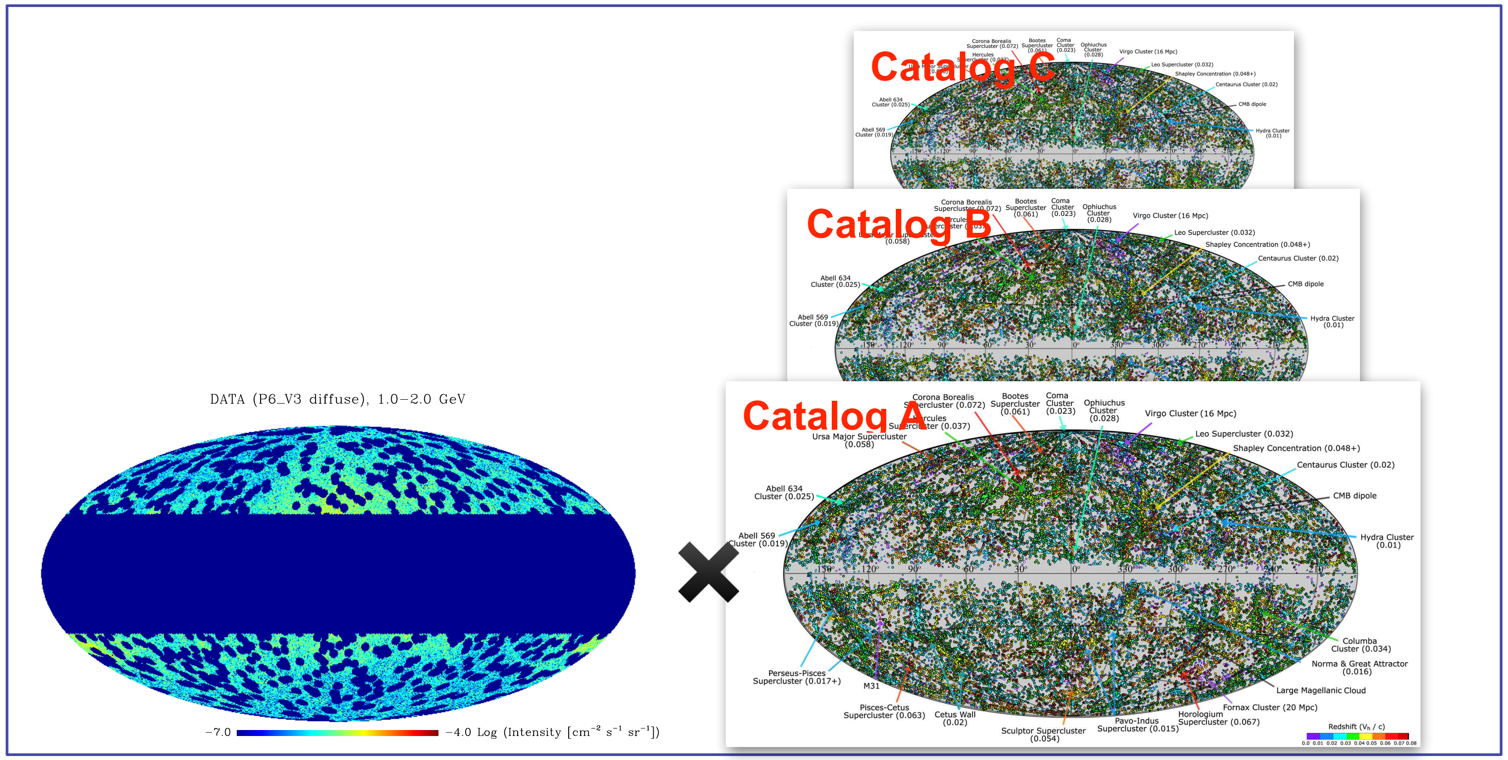
$$\delta I_\gamma = I_\gamma - \langle I_\gamma \rangle$$
$$\delta \Sigma_g = \Sigma_g - \langle \Sigma_g \rangle$$

$$C^{\gamma g}(\theta) = \langle \underbrace{\delta I_\gamma(\hat{\boldsymbol{n}})}_{\gamma\text{-ray flux}} \, \underbrace{\delta \Sigma_g(\hat{\boldsymbol{n}} + \boldsymbol{\theta})}_{\text{galaxy distribution}} \rangle$$

$$= \sum_\ell \frac{2\ell + 1}{4\pi} C_\ell^{\gamma g} P_\ell(\cos\theta)$$

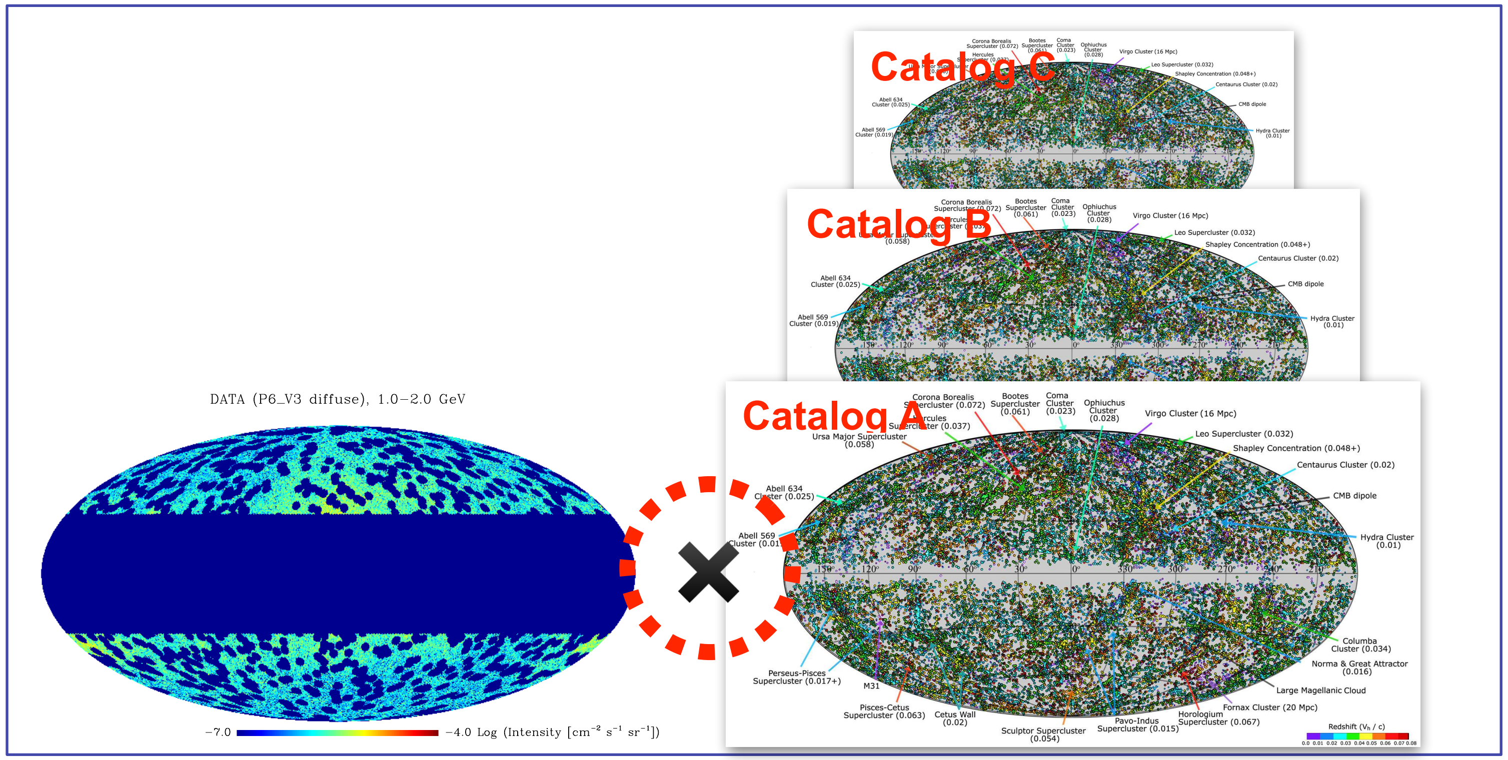
$$\longrightarrow \quad C_\ell^{\gamma g} = \int \frac{d\chi}{\chi^2} W_\gamma(z) W_g(z) \underbrace{P_{\gamma g}\left(k = \frac{\ell}{\chi}, z\right)}_{\text{cross-power spectrum between } \gamma\text{-ray sources and galaxies}}$$

c). Tomographic cross-correlation using local galaxy distribution



$$C_\ell^{\gamma g} = \int \frac{d\chi}{\chi^2} W_\gamma(z) W_g(z) P_{\gamma g}\left(k = \frac{\ell}{\chi}, z\right)$$

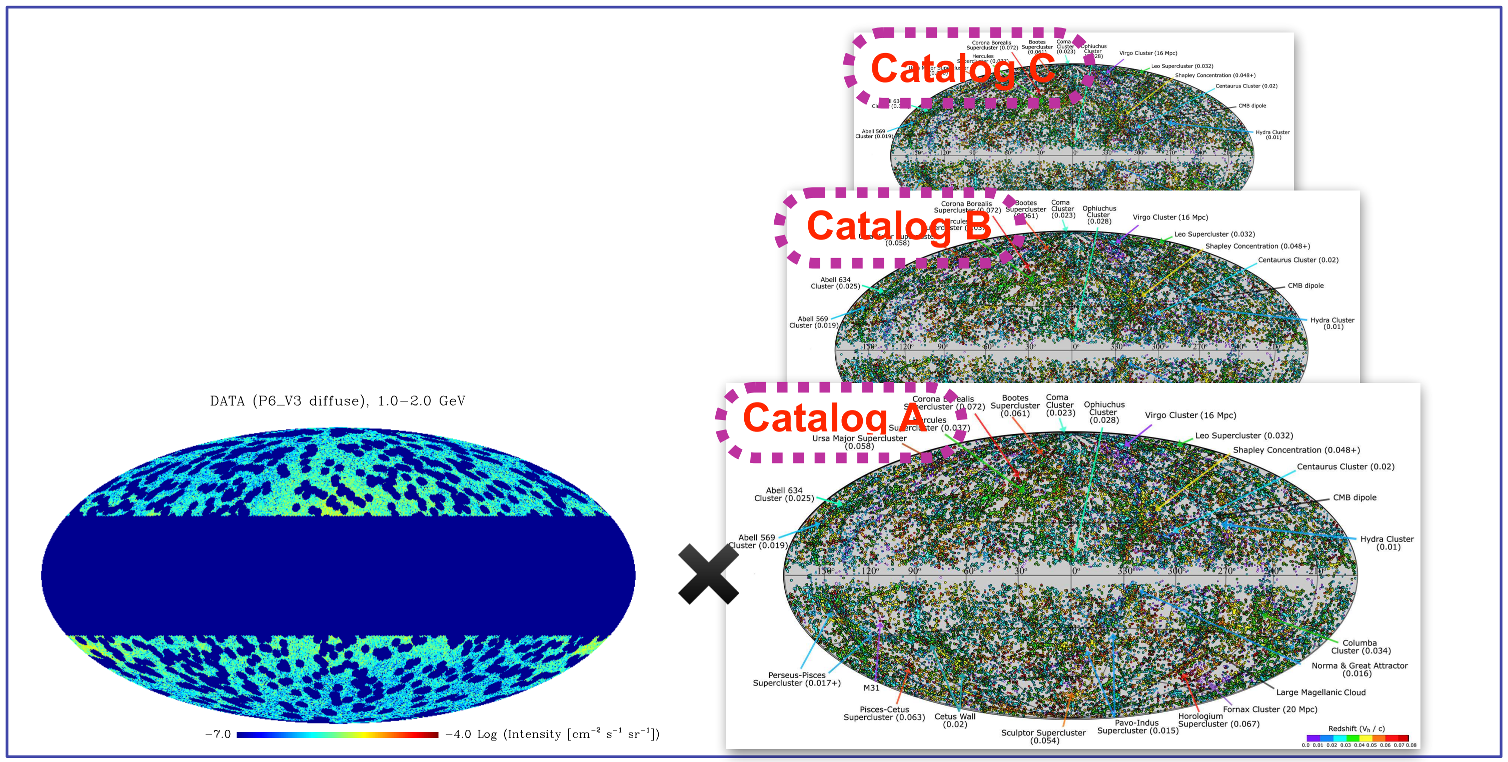
c). Tomographic cross-correlation using local galaxy distribution



cross-correlation

$$C_\ell^{\gamma g} = \int \frac{d\chi}{\chi^2} W_\gamma(z) W_g(z) P_{\gamma g}\left(k = \frac{\ell}{\chi}, z\right)$$

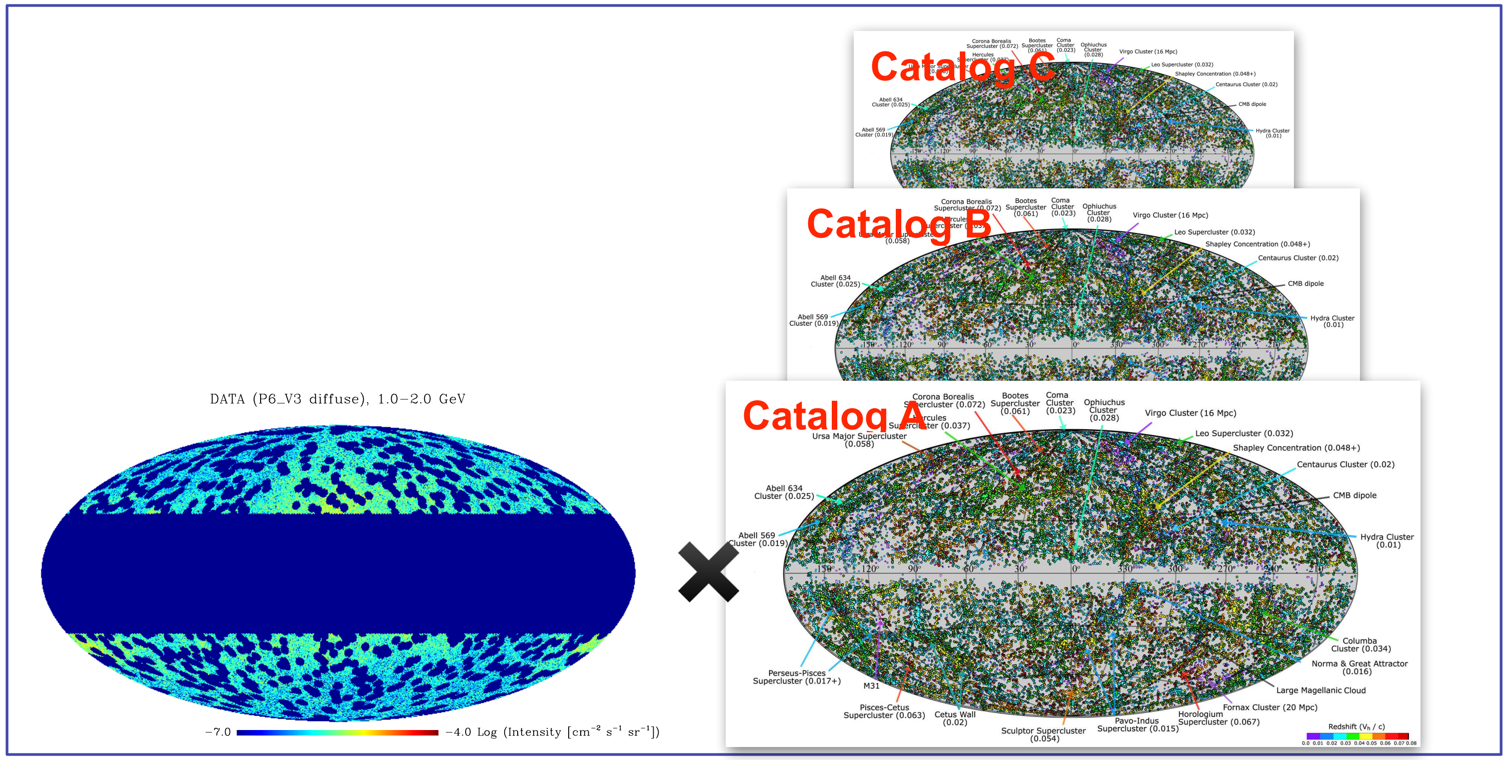
c). Tomographic cross-correlation using local galaxy distribution



tomography

$$C_\ell^{\gamma g} = \int \frac{d\chi}{\chi^2} W_\gamma(z) W_g(z) P_{\gamma g}\left(k = \frac{\ell}{\chi}, z\right)$$

c). Tomographic cross-correlation using local galaxy distribution



obs. ✖ obs.

Xia, Cuoco, Branchini, Viel ’15

th. ✖ obs.

Compare both, then exclude the theory which deviates from obs. ✖ obs.

c). Tomographic cross-correlation using local galaxy distribution

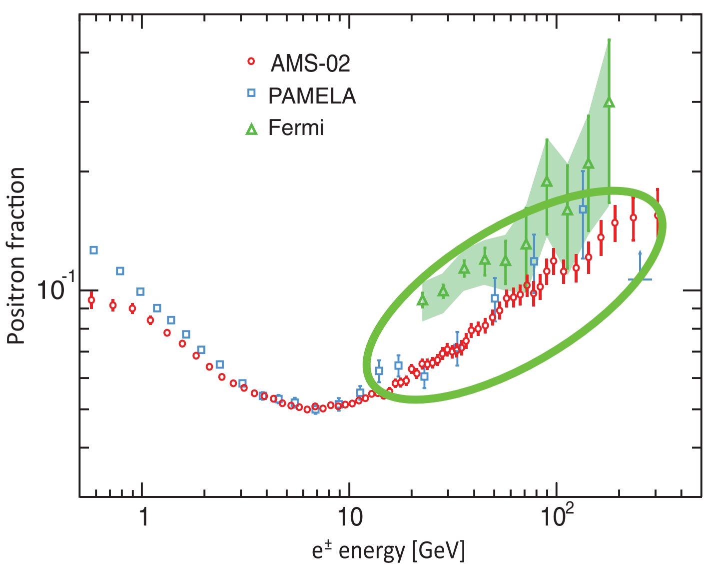
Galaxy catalogs

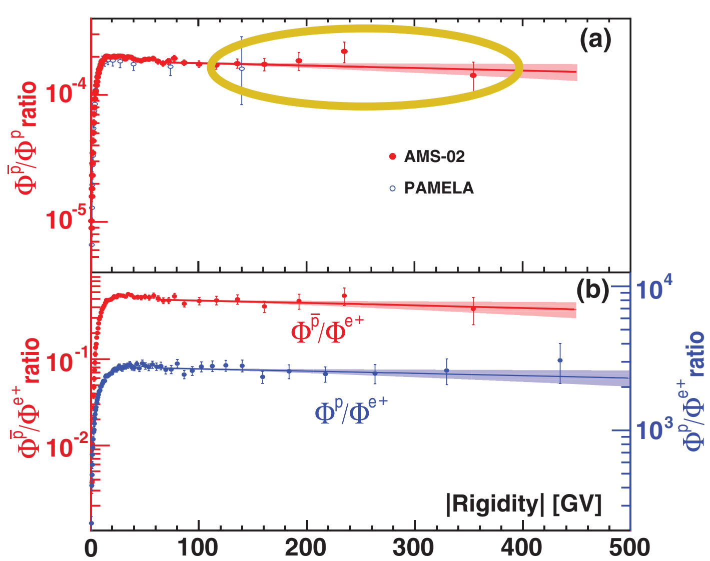
Ando '14

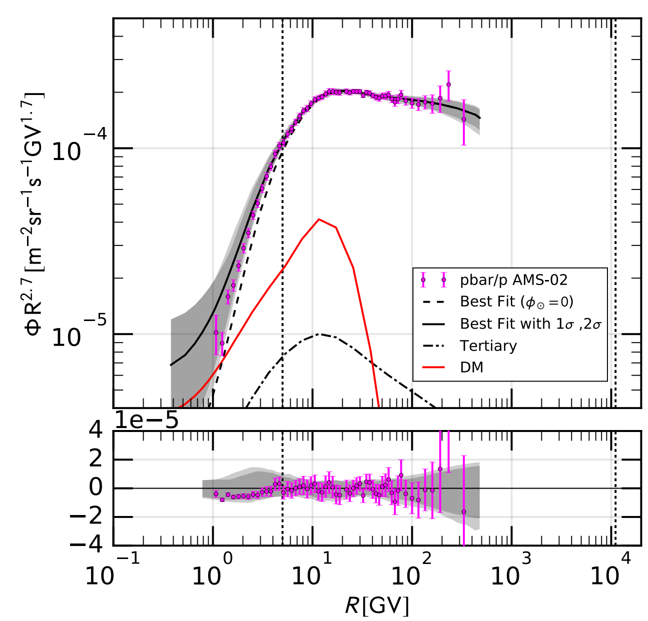
Catalog	Redshift boundaries	$N_{\rm g}$ per bin
2MRS	(0.003, 0.1)	43500
2MRS-N2	(0.003, 0.027, 0.1)	21750
2MRS-N3	(0.003, 0.021, 0.035, 0.1)	14500
2MXSC	(0.003, 0.3)	770000
2MXSC-N2	(0.003, 0.083, 0.3)	385000
2MXSC-N3	(0.003, 0.066, 0.10, 0.3)	257000
2MXSC-N4	(0.003, 0.058, 0.083, 0.11, 0.3)	193000
2MXSC-N5	(0.003, 0.052, 0.073, 0.093, 0.12, 0.3)	154000
2MXSC-N10	(0.003, 0.039, 0.052, 0.063, 0.073, 0.083, 0.093, 0.10, 0.12, 0.14, 0.3)	77000

The reported anomalous cosmic rays:

- Positron
- Antiproton (over 100 GeV)
- Antiproton (~ 80 GeV DM mass)







The reported anomalous cosmic rays:

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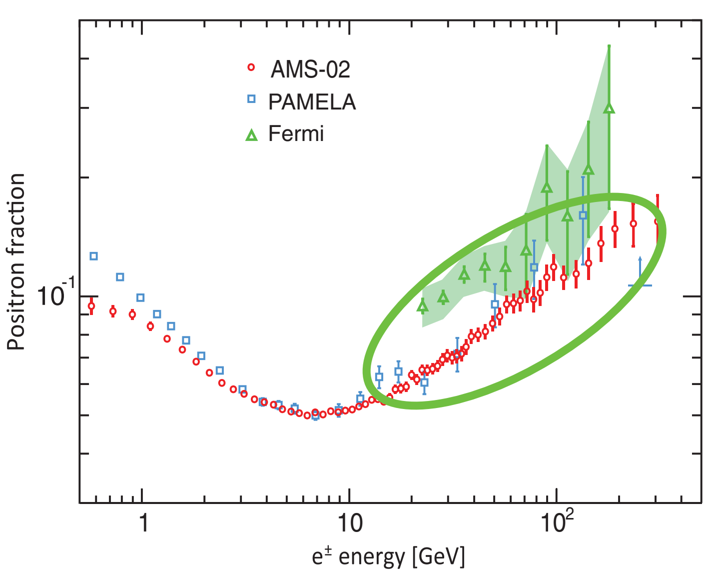
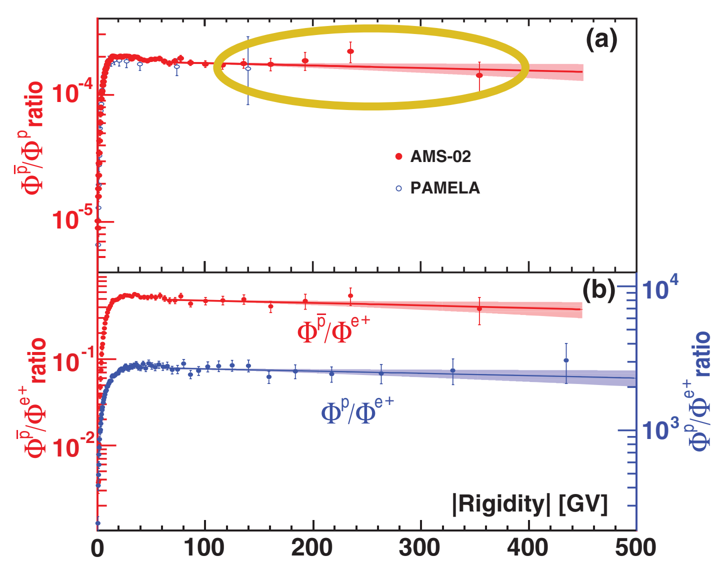
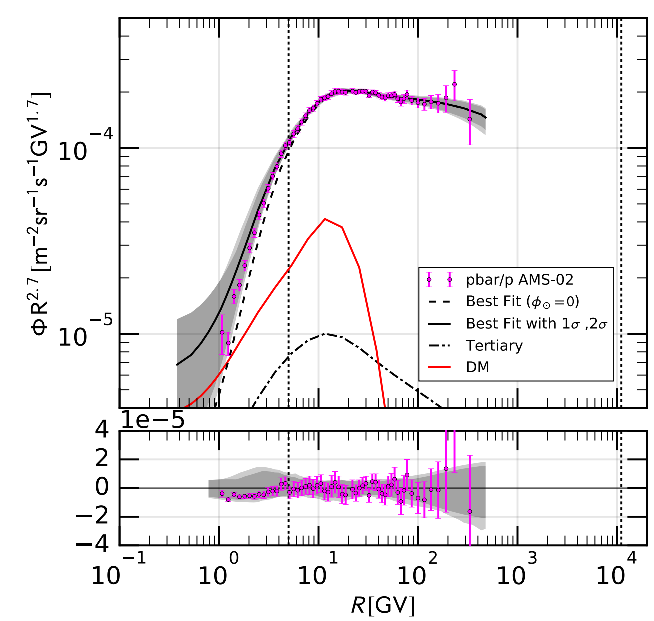


Decaying DM



Decaying DM

Annihilating DM



Annihilating DM

Decaying DM (for the anomalous e^{+})

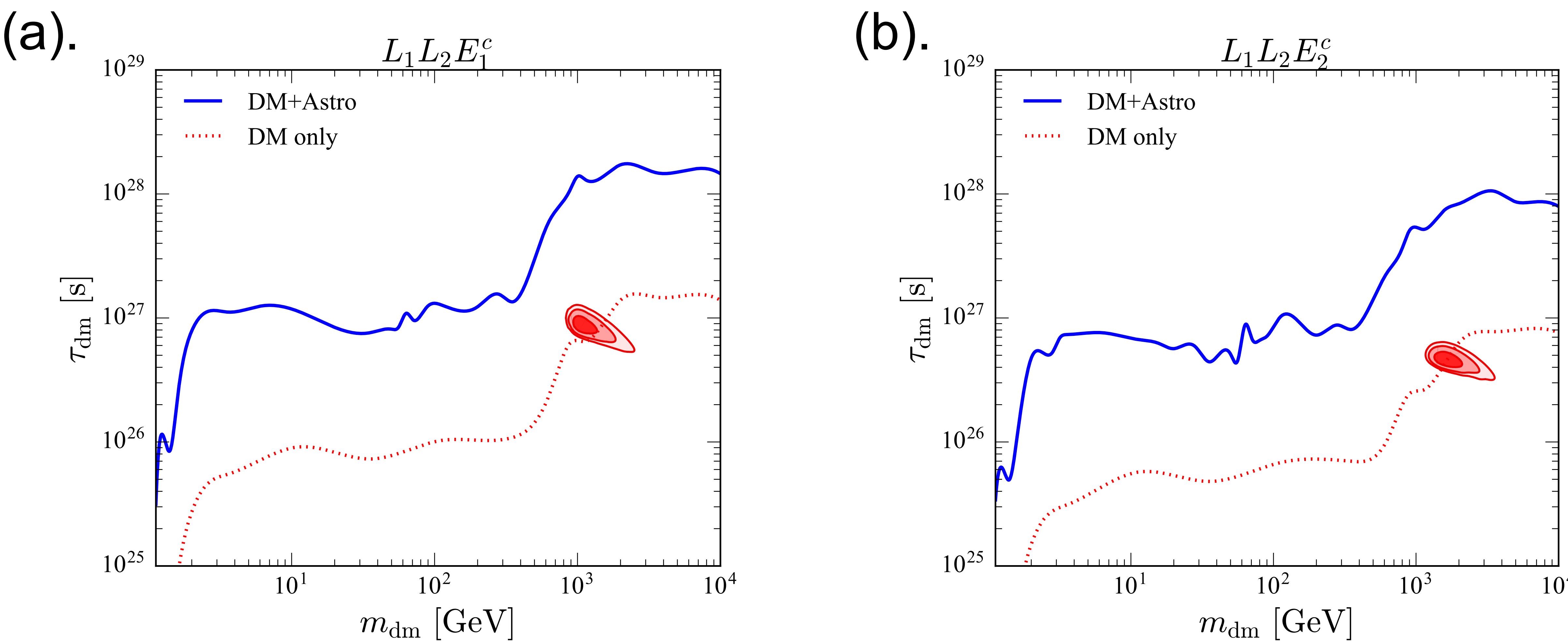
Here we focus on three-body leptonic decay: $\mathrm{DM} \to \nu l^{\pm} l^{\mp}$

(a). $\nu\mu^{\pm}e^{\mp} \& \nu e^{\pm}e^{\mp}$ (mainly $e^{\pm}$)

(b). $\nu\mu^{\pm}\mu^{\mp} \& \nu e^{\pm}\mu^{\mp}$ (mainly $\mu^{\pm}$)

Decaying DM (for the anomalous e^+)

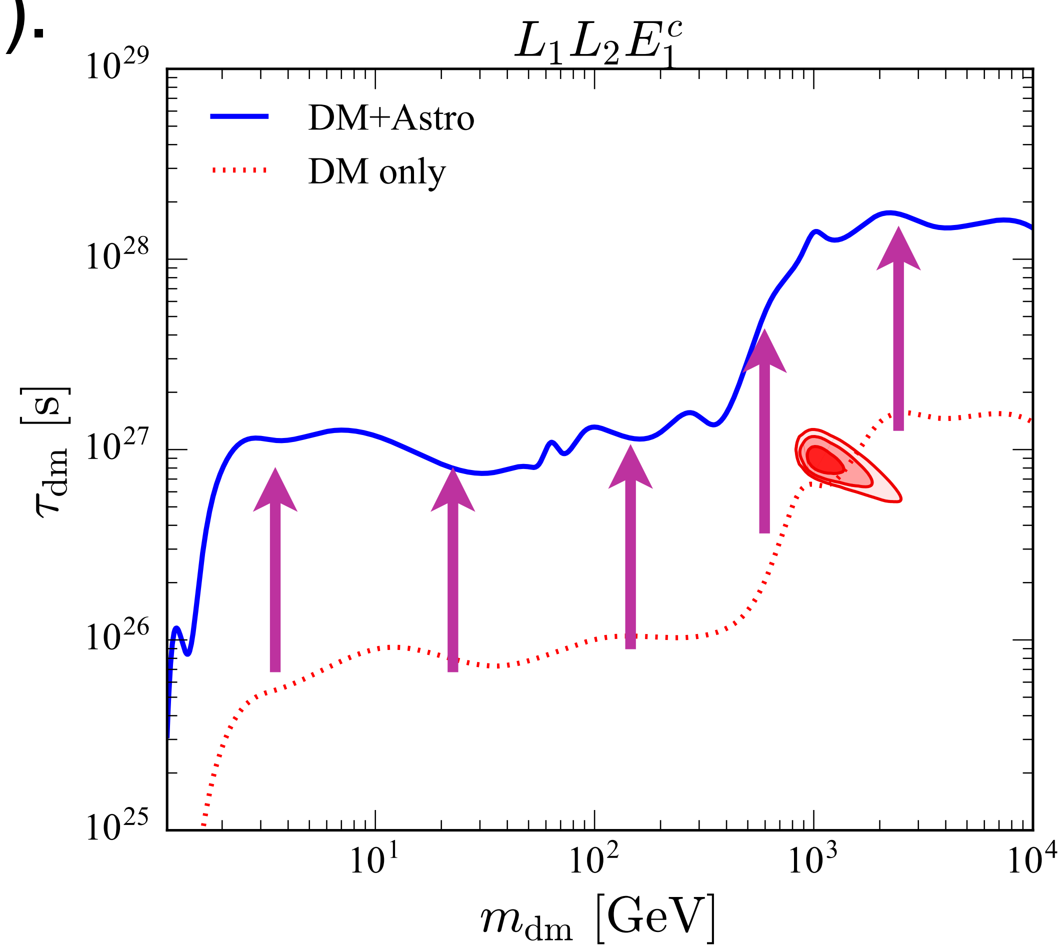
Ando, KI '16



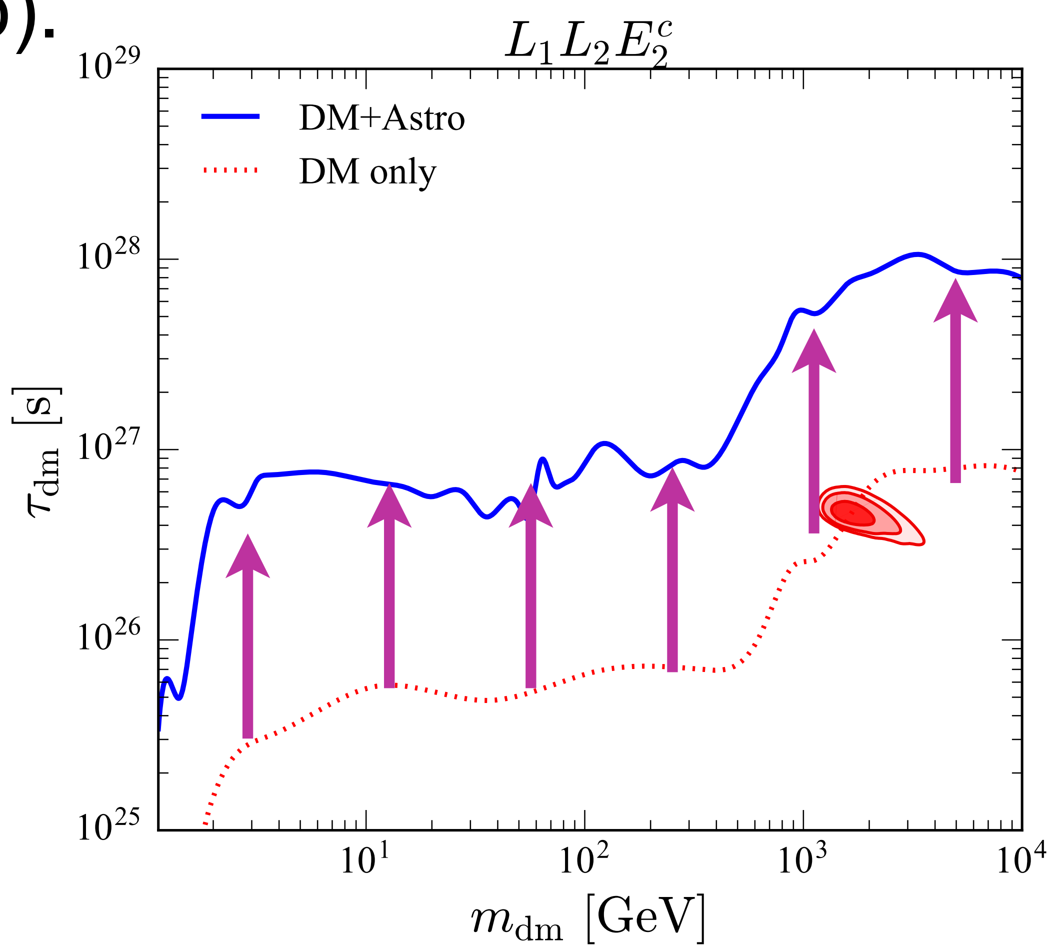
Decaying DM (for the anomalous e^+)

Ando, KI '16

(a).



(b).

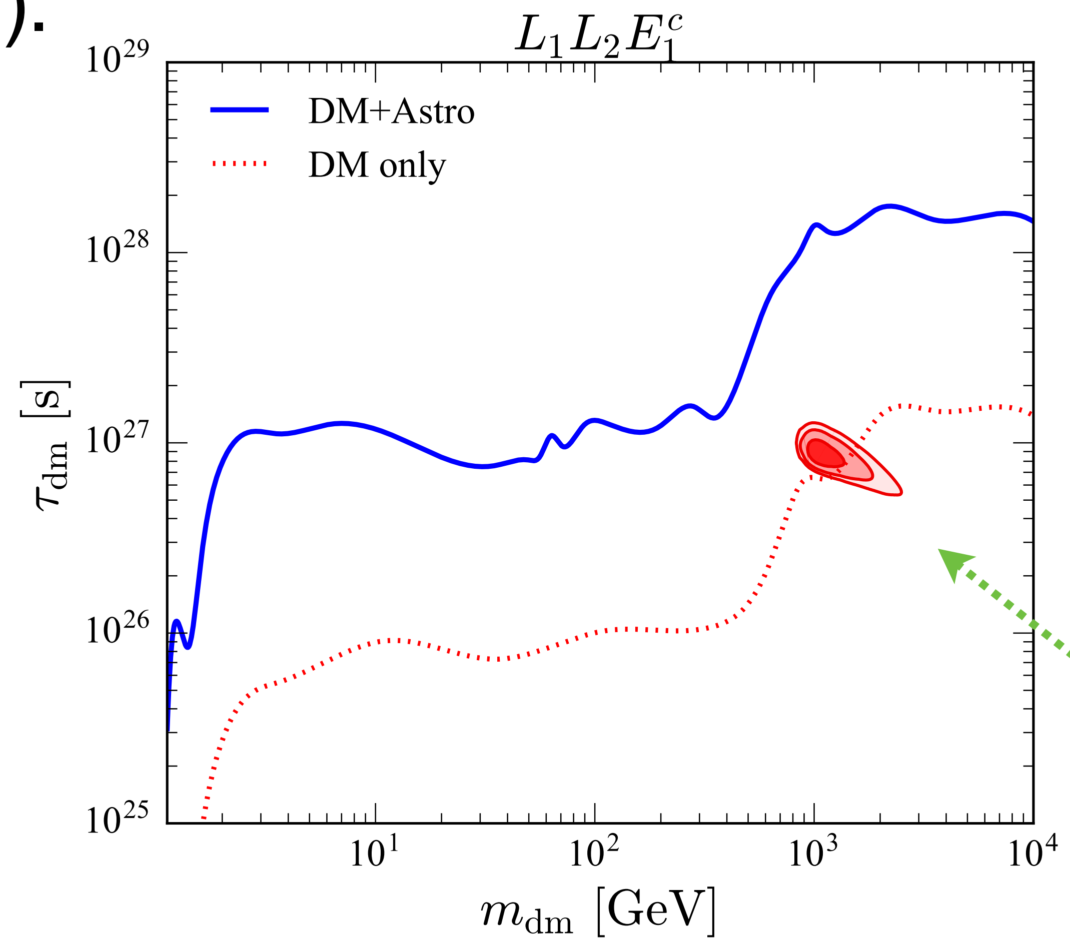


Including astrophysical sources give ~10 times stronger constraints

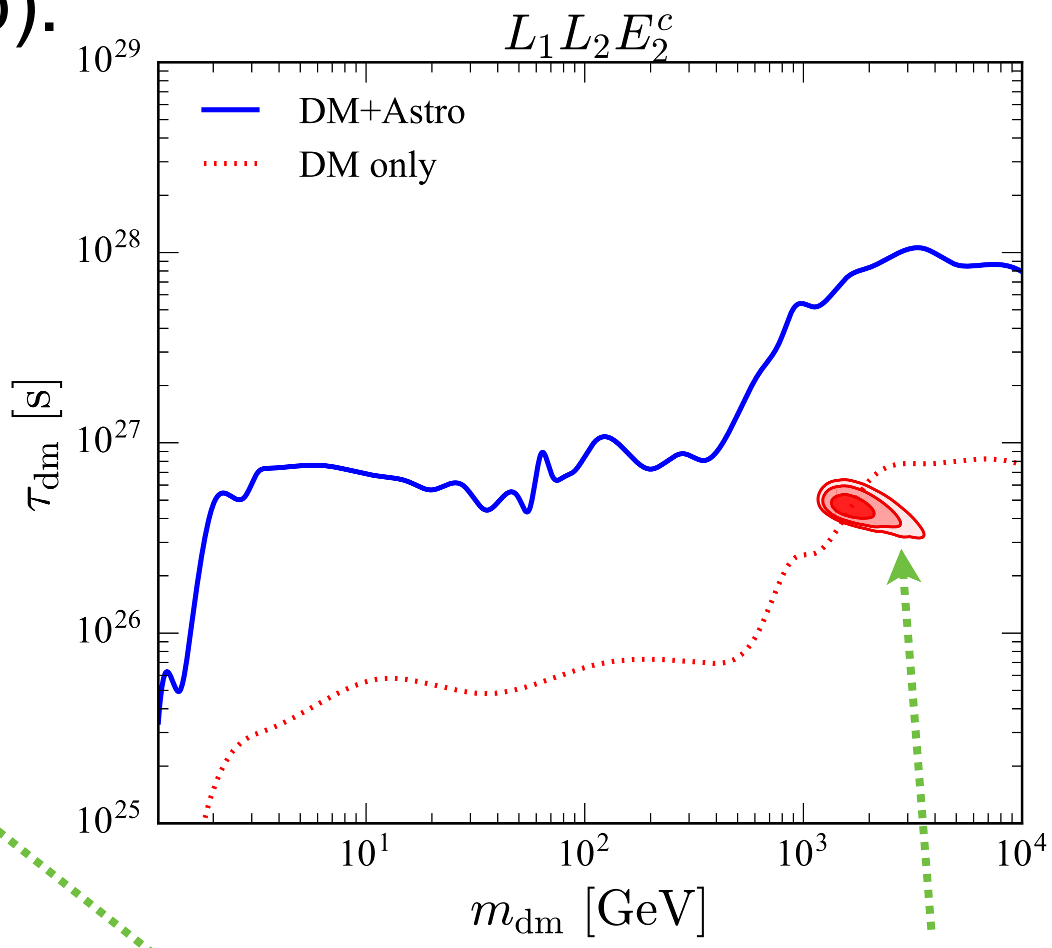
Decaying DM (for the anomalous e^+)

Ando, KI '16

(a).



(b).



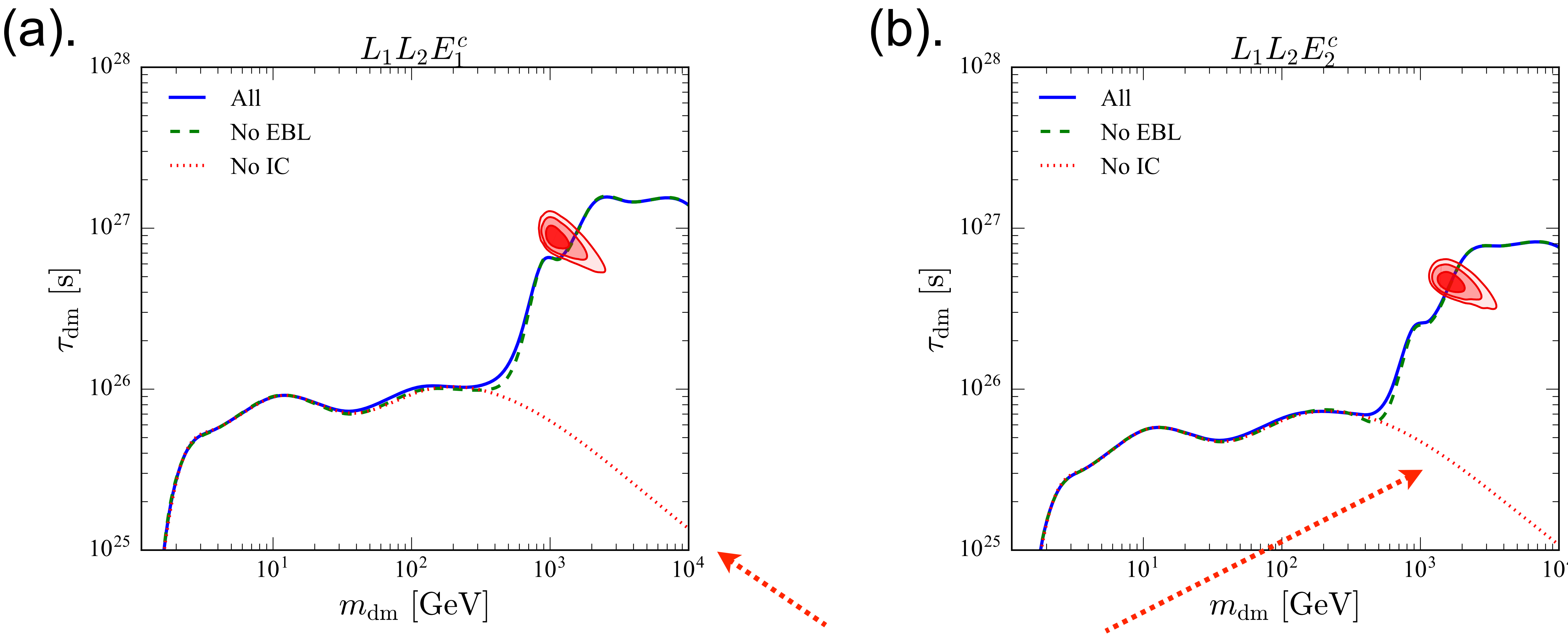
Best fit regions taken from
Ibe et al.'14

The preferred regions are excluded

Ando, KI '16

Impacts of IC gamma rays

(Results without astro. comp.)



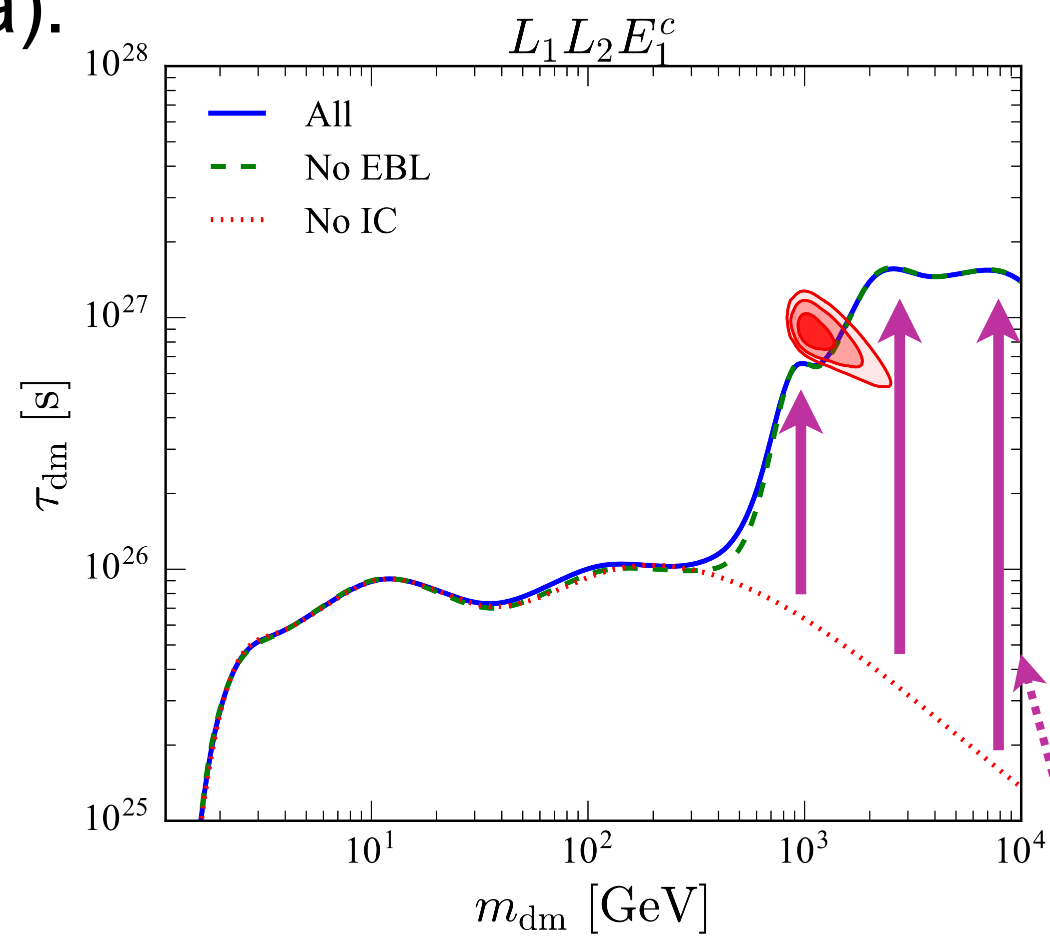
Results without IC
(consistent with Regis et al. '15)

Ando, KI '16

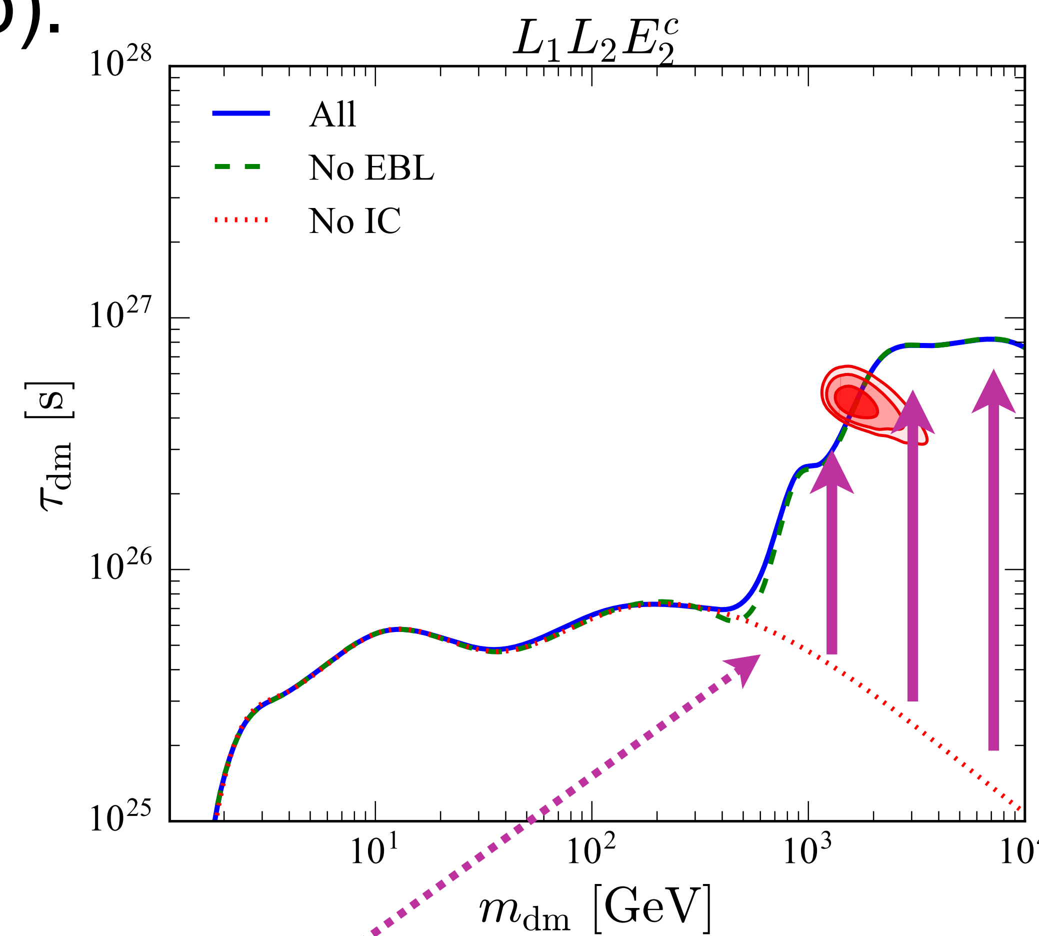
Impacts of IC gamma rays

(Results without astro. comp.)

(a).



(b).



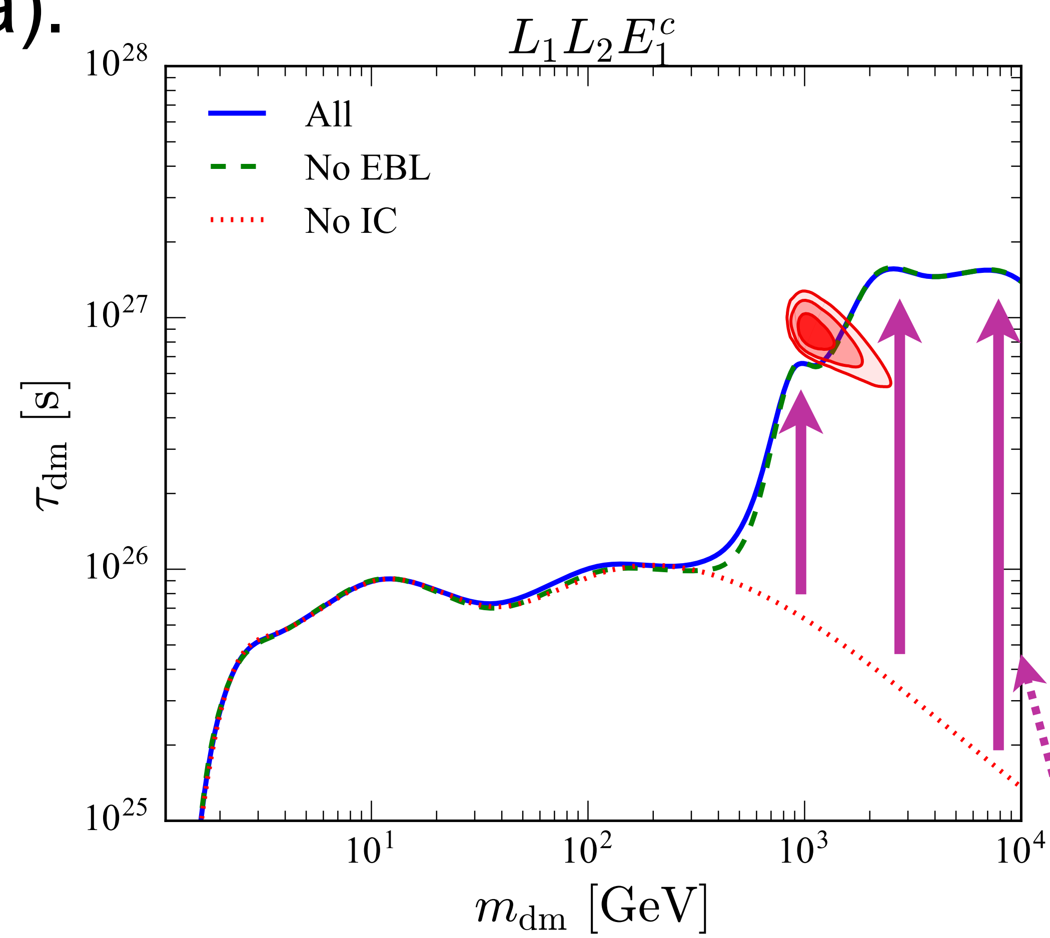
IC gamma gives 1-2 orders of magnitude stronger constraints over TeV region

Impacts of IC gamma rays

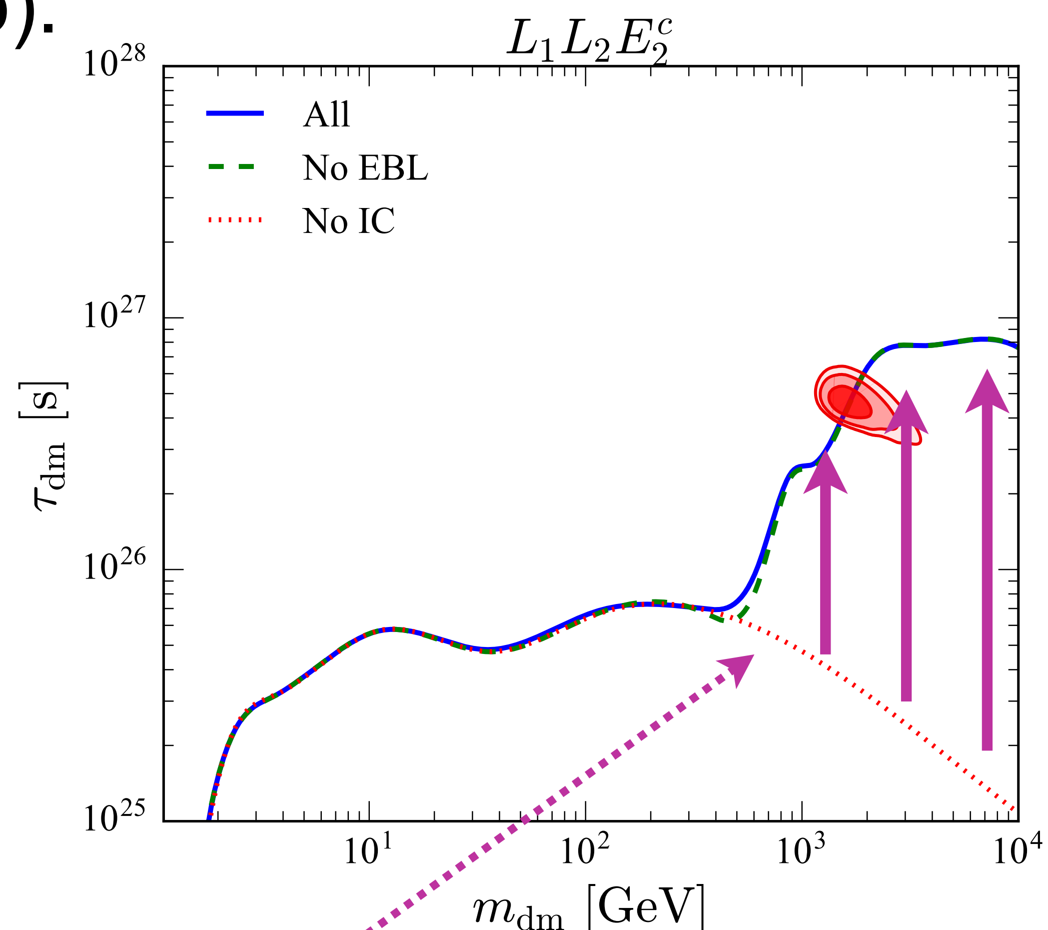
Ando, KI '16

(Results without astro. comp.)

(a).



(b).

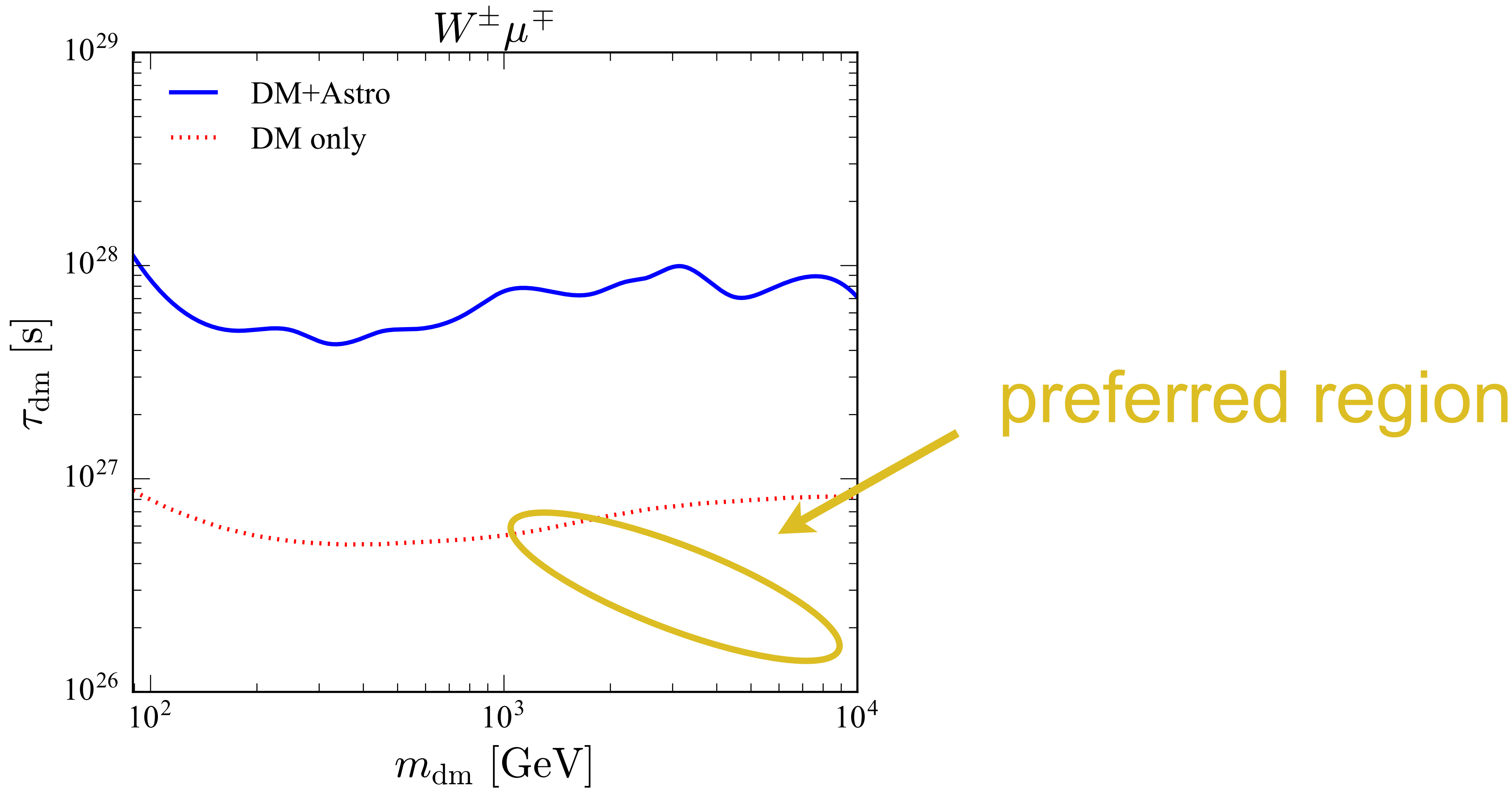


IC gamma gives 1-2 orders of magnitude stronger constraints over TeV region

→ IC gamma rays are crucial to constrain over TeV DM

Decaying DM (for the anomalous $\mathcal{O}(100)$ GeV $\bar{p}$) Ando, KI '16

$$\mathrm{DM} \to W^{\pm}\mu^{\mp}$$

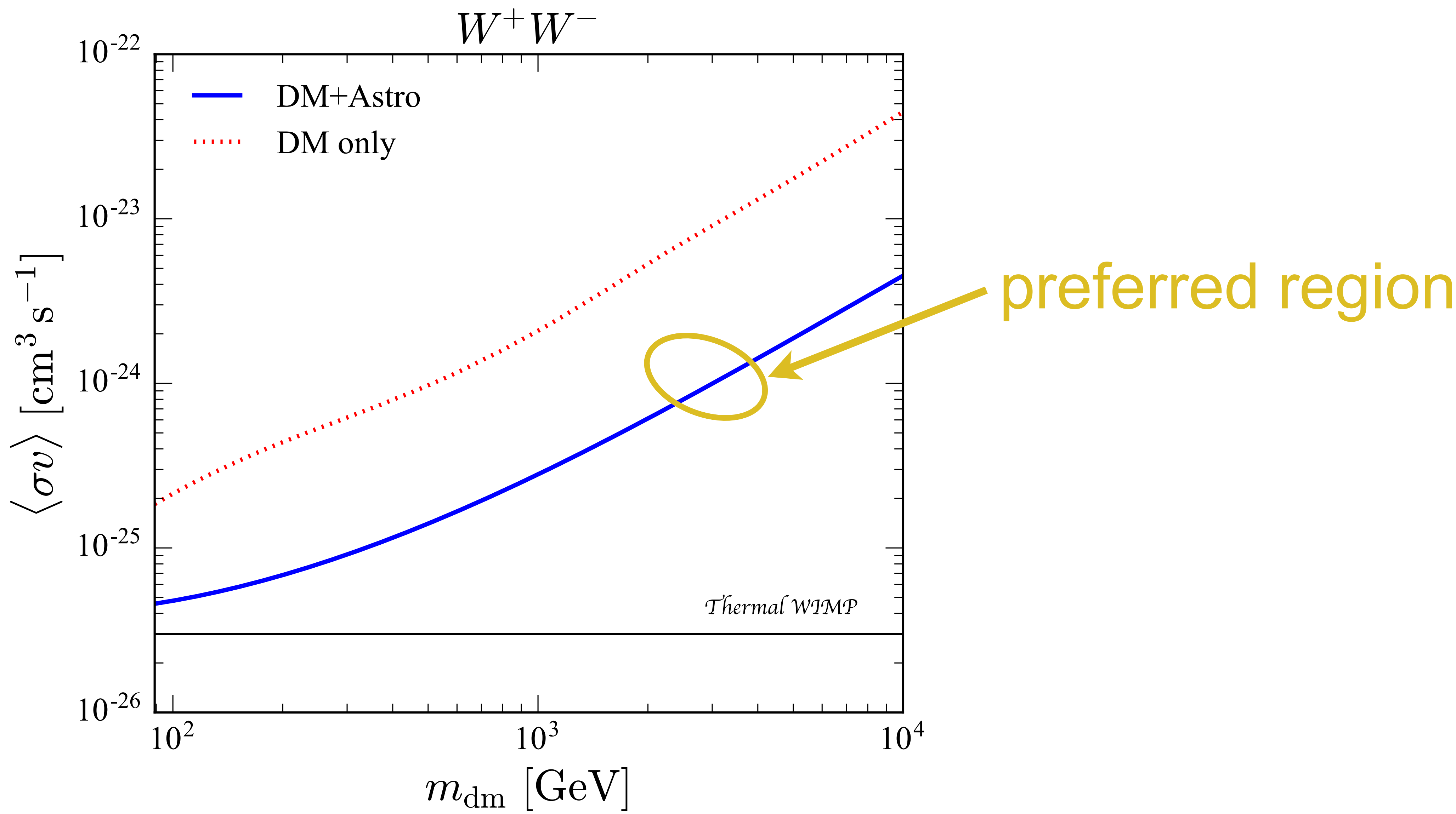


The preferred regions are excluded
(only by DM component)

Annihilating DM (for the anomalous $\mathcal{O}(100)$ GeV $\bar{p}$)

Ando, KI '16

$$\mathrm{DM\ DM} \to W^+W^-$$



The preferred regions are excluded
(by including astro components)

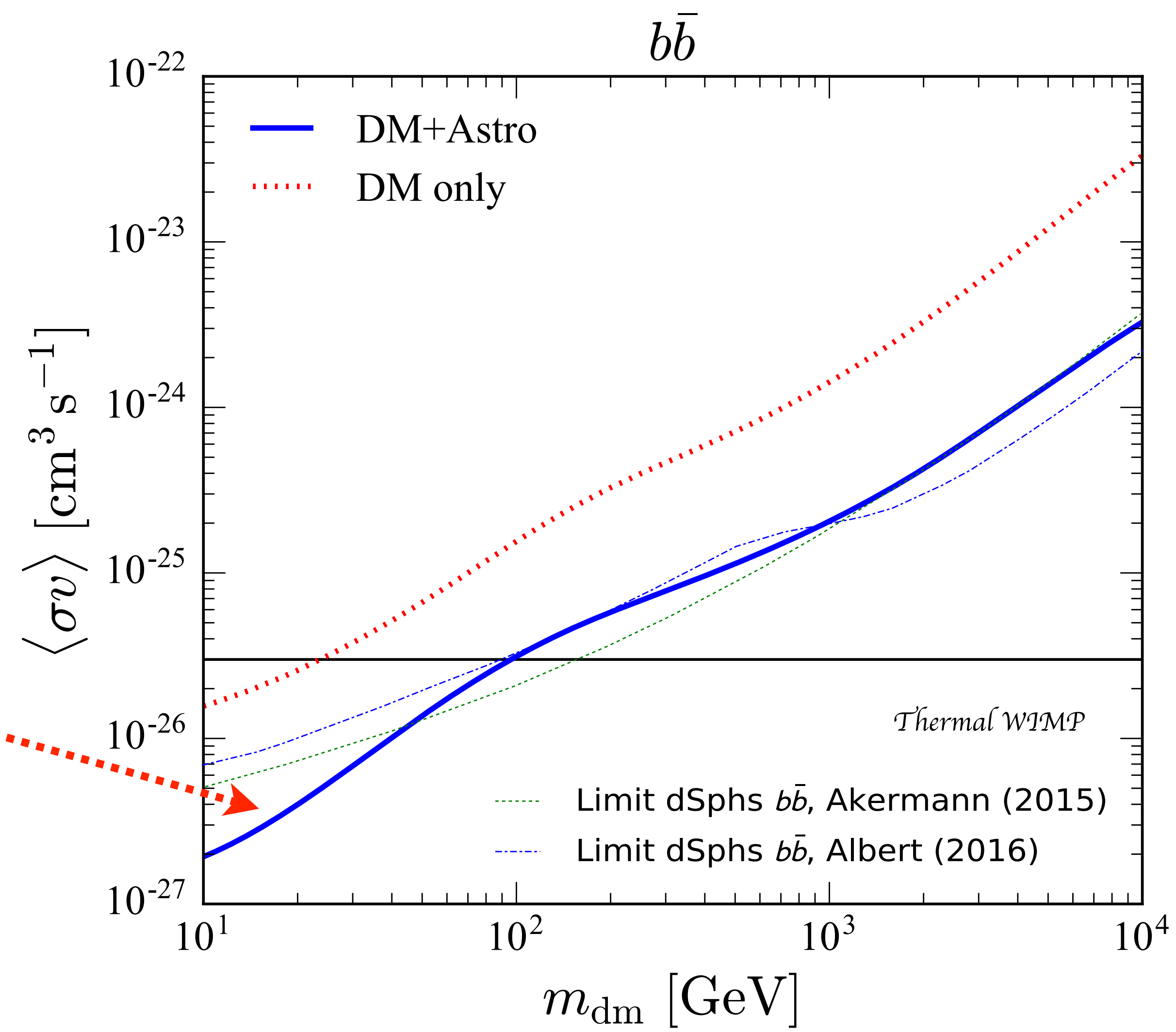
Annihilating DM (for the anomalous $\mathcal{O}(1)$ GeV $\bar{p}$)

$$\mathrm{DM}\ \mathrm{DM} \to b\bar{b}$$

Ando, KI ’16

Obtained constraints are similar to those given by dwarf galaxy

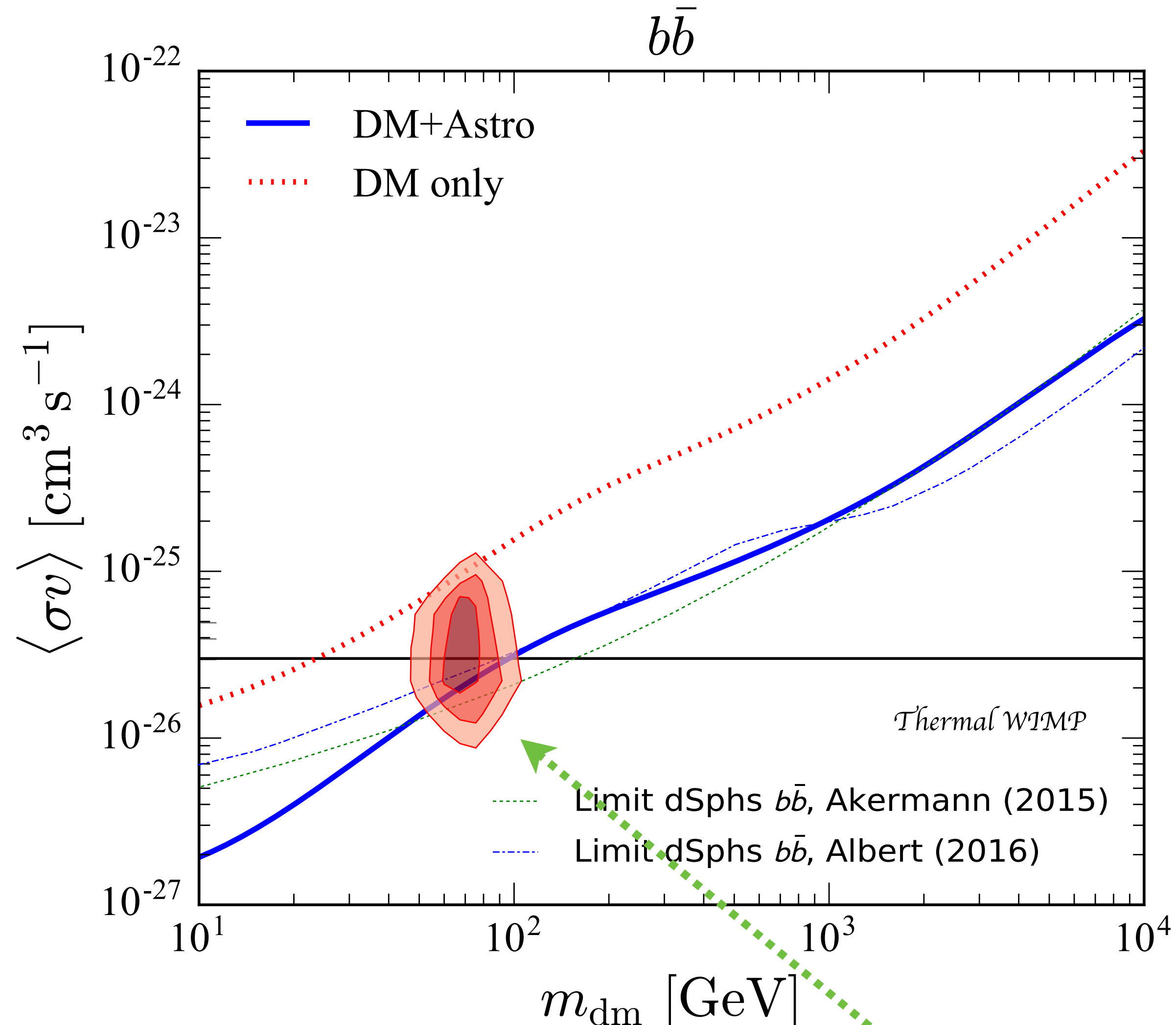
(consistent with Cuoco et al. ’15)



Annihilating DM (for the anomalous $\mathcal{O}(1)$ GeV $\bar{p}$)

$\mathrm{DM\ DM} \to b\bar{b}$

Ando, KI '16



Best fit regions given by Cuoco et al. '17

The motivated region is partly excluded

4. Ultra high energy cosmic rays and DM

Although we've shown the constraints on DM models,

Our goal is to find the DM!

For the goal, a naive step to take next would be to consider

- Lower DM mass
- Higher DM mass

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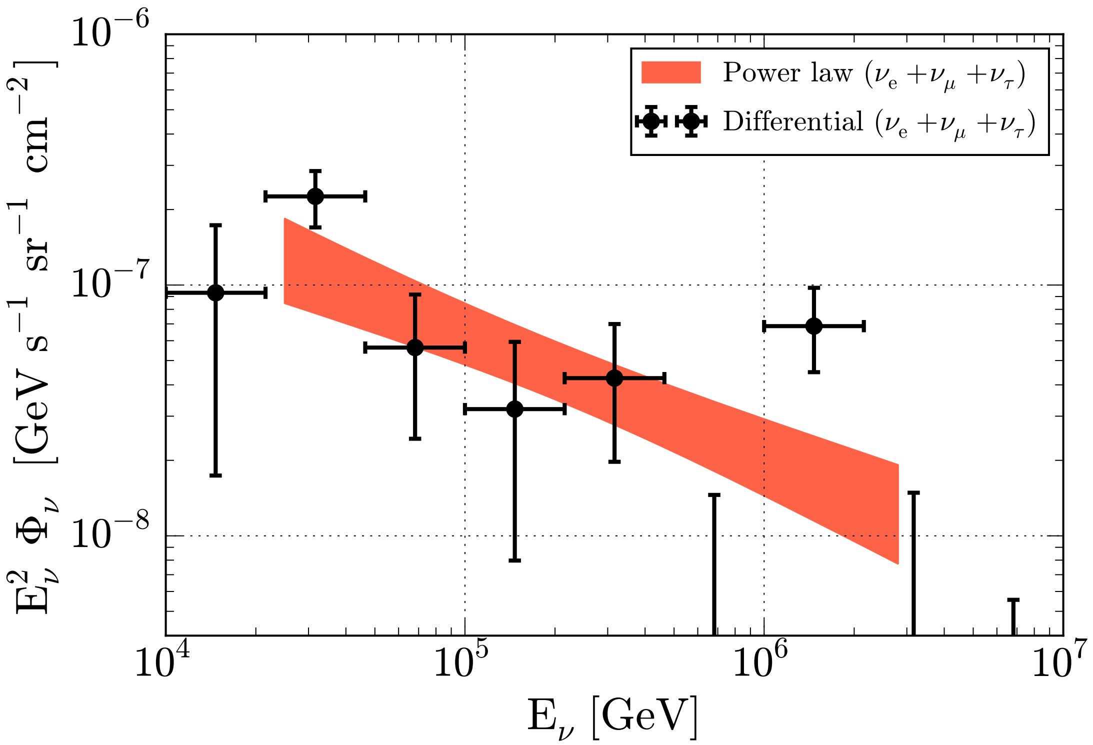
DM signal might be in PeV neutrino data



IceCube '15

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Our goal is to find the DM!

For the goal, a naive step to take next would be to consider

- Lower DM mass
- Higher DM mass

People are getting interested in heavier DM

Cohen, Murase, Rodd, Safdi, Soreq '17

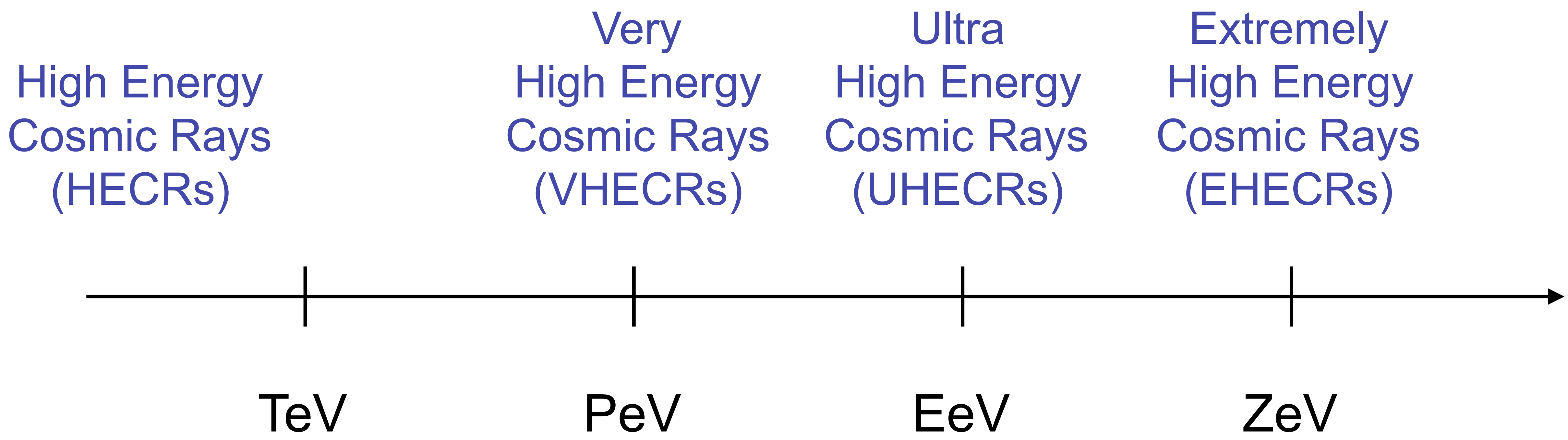
Kalashev, Kuznetsov '16

Kachelriess, Kalashev, Kuznetsov '18

Dudas, Gherghetta, Kaneta, Mambrini, Olive '18

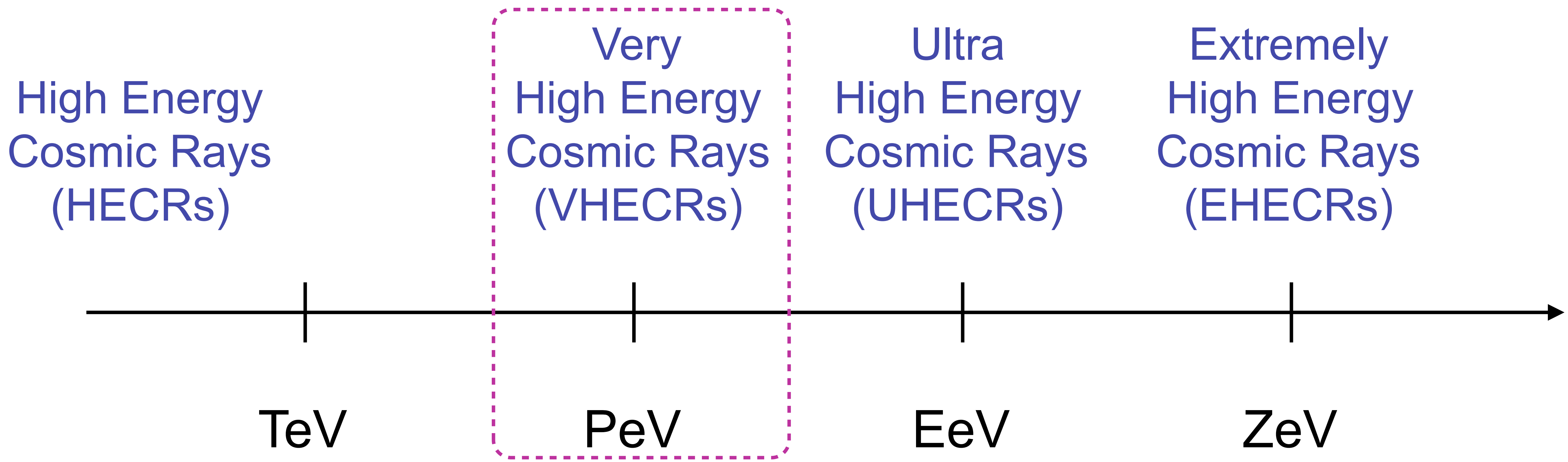
Beyond High Energy Cosmic Rays

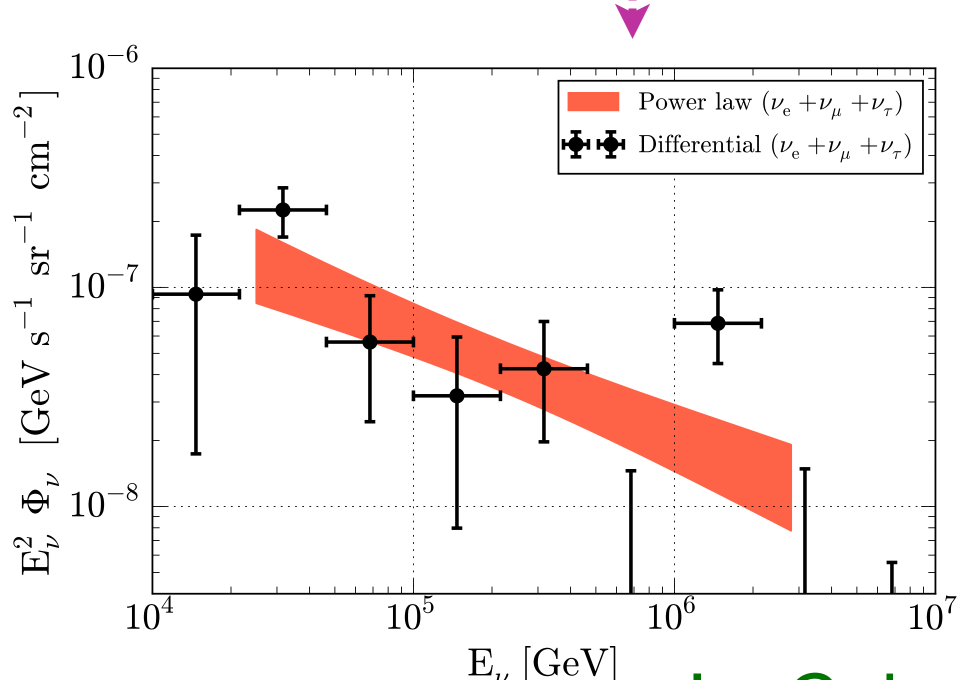
Fonseca ’03



Beyond High Energy Cosmic Rays

Fonseca ’03





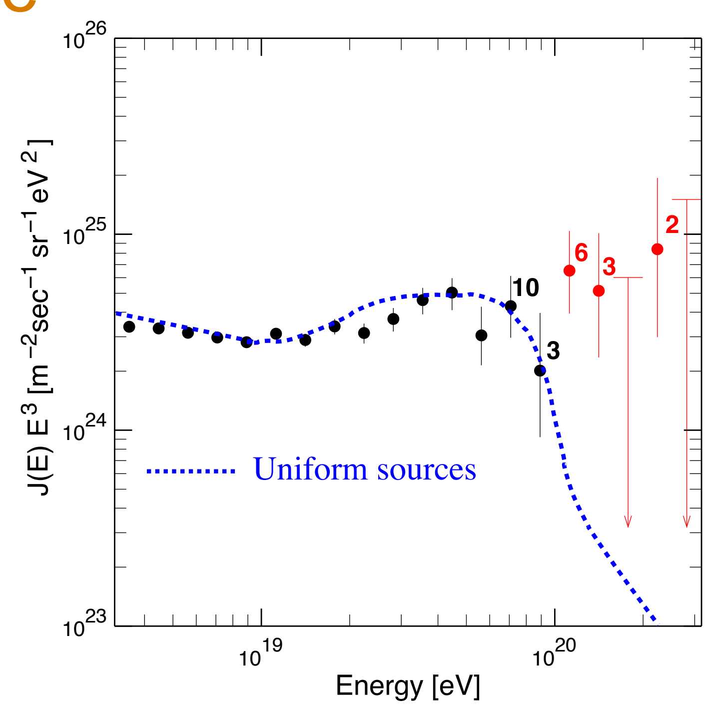
IceCube ’15

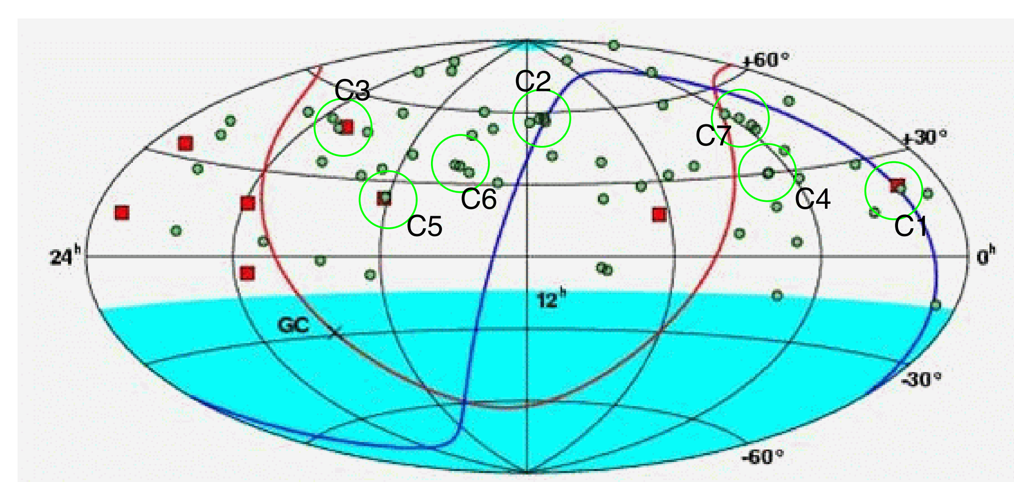
Beyond High Energy Cosmic Rays

Fonseca '03

High Energy Cosmic Rays (HECRs)	Very High Energy Cosmic Rays (VHECRs)	Ultra High Energy Cosmic Rays (UHECRs)	Extremely High Energy Cosmic Rays (EHECRs)
TeV	PeV	EeV	ZeV

More will be by Pierre Auger Observatory





AGASA '03

Propagation of UHECR

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

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Electrons	CBR	Inverse Compton scattering*	γ
Electrons	B-field	Synchrotron radiation*	γ

Propagation of UHECR nuclei

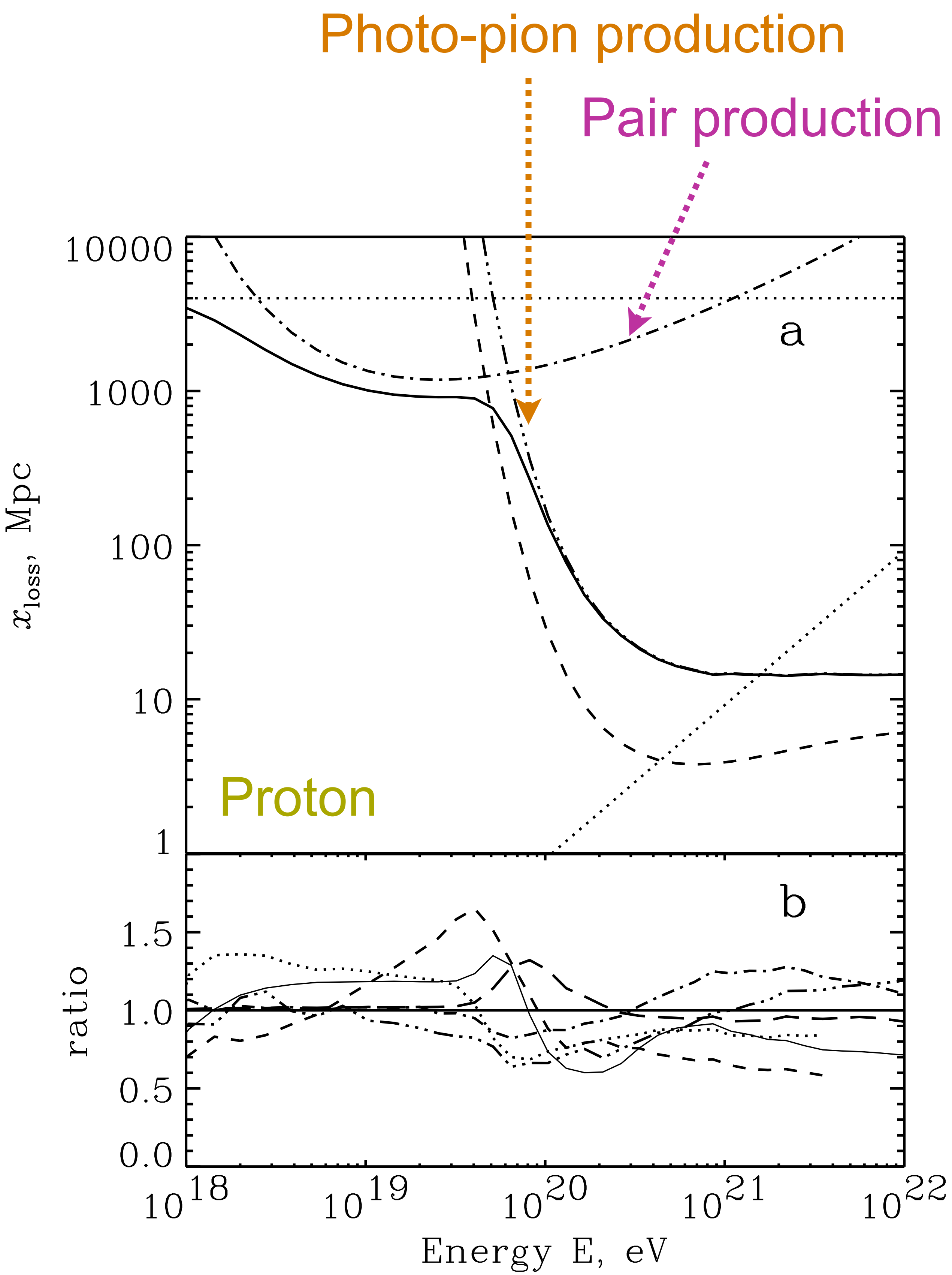
- Photo-pion production

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

- Pair production (Bethe-Heitler)

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

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



Stanev, Engel, Mücke, Protheroe, Rachen ’00

Propagation of UHECR

Heiter, Kuempel, Walz, Erdmann '17

Initial state	Target field	Process	Secondaries
Nuclei	CBR	Pair production (Bethe-Heitler)	$e^{\pm}$
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Electrons	CBR	Inverse Compton scattering*	γ
Electrons	B-field	Synchrotron radiation*	γ

EW cascade

Propagation of UHECR EM particles

Heiter, Kuempel, Walz, Erdmann ’17

- Pair production (PP)

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

- Double pair production (DPP)

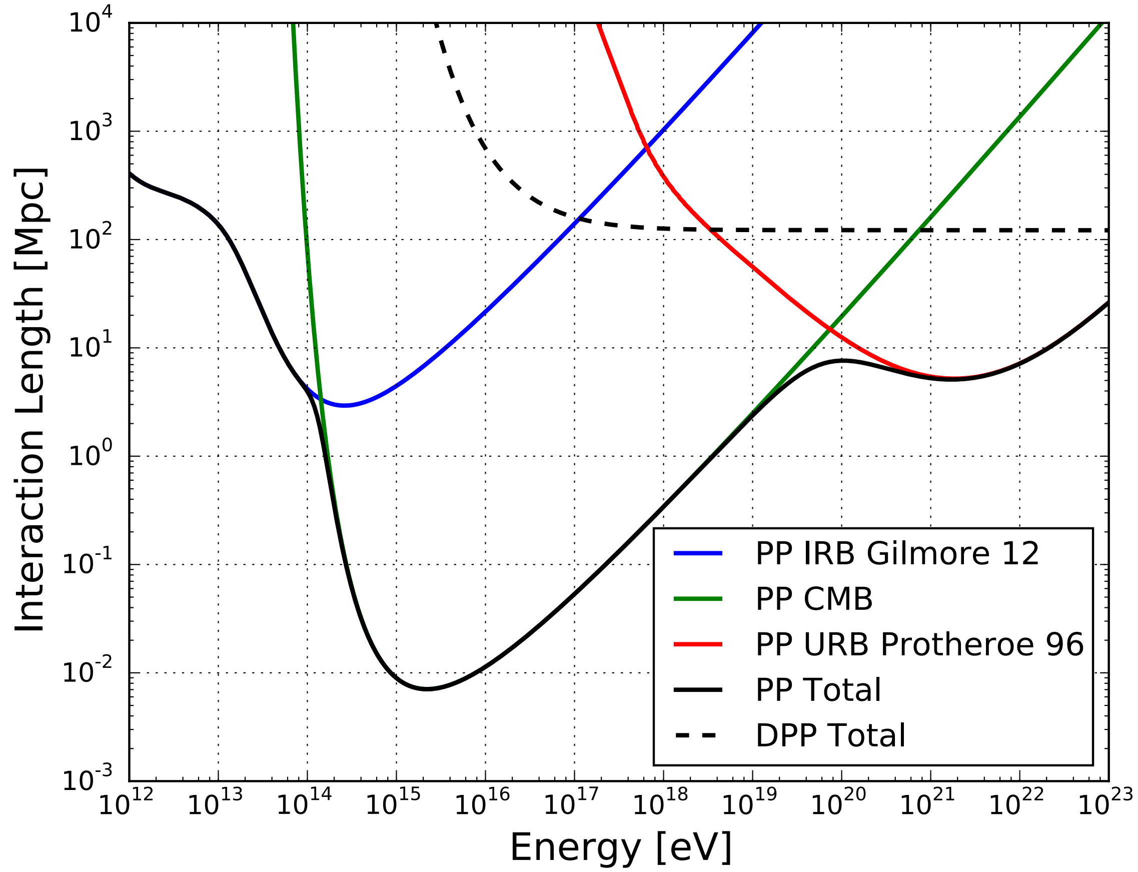
$$\gamma + \gamma_{\mathrm{BG}} \rightarrow e^{+} + e^{-} + e^{+} + e^{-}$$

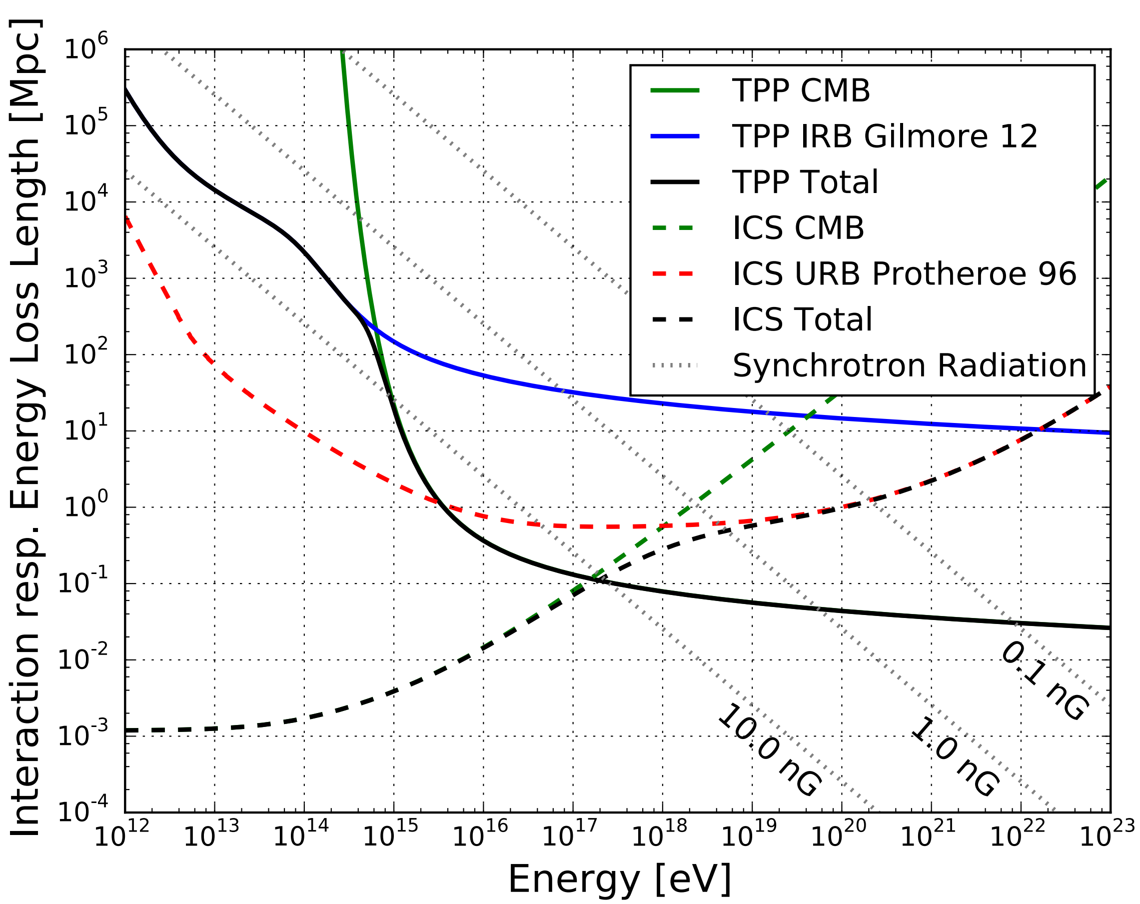
- Triple pair production (TPP)

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

- Inverse Compton scattering (ICS)

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

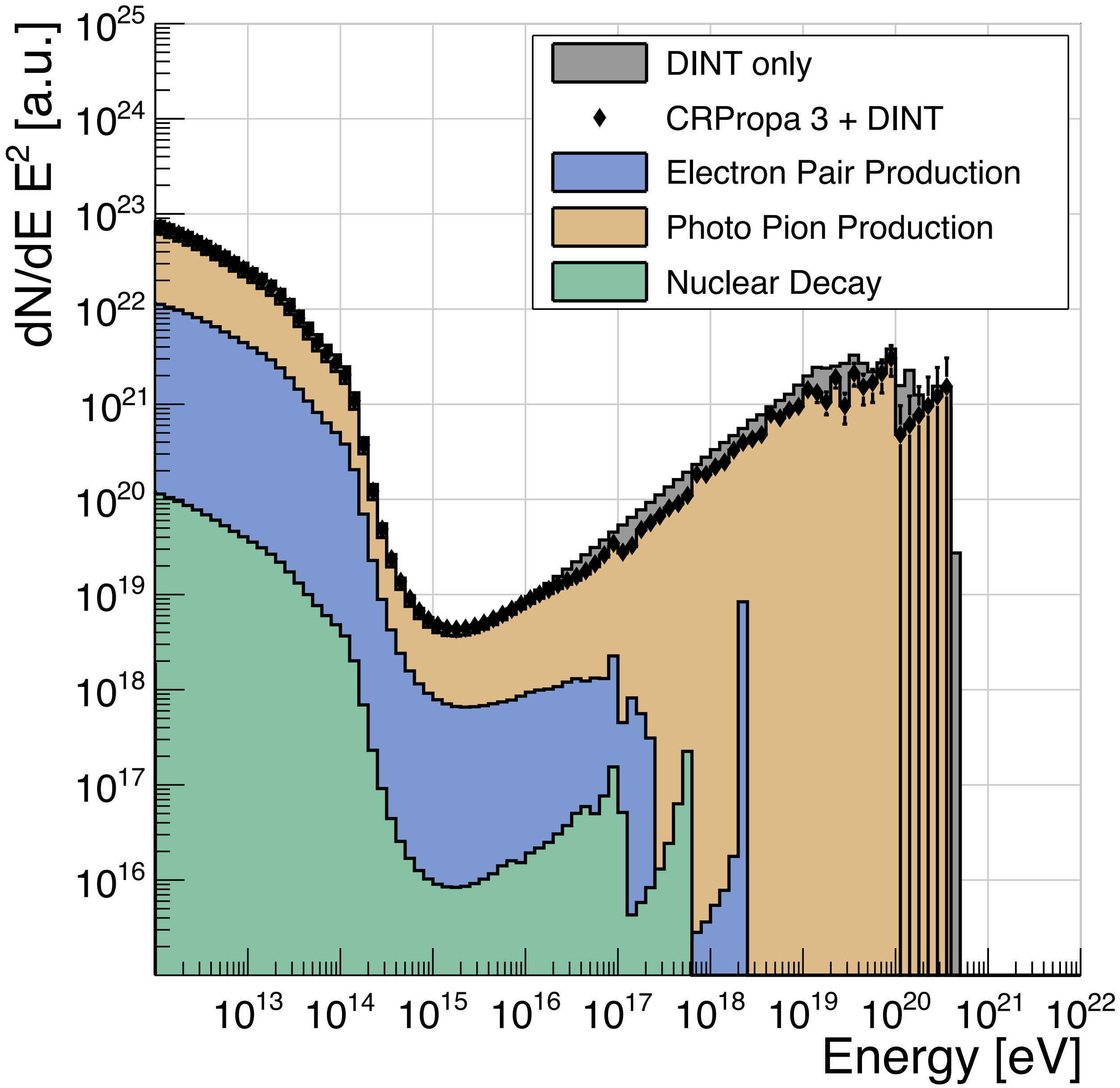




CRpropa 3

Batista, Dundovic, Erdmann, Kampert, Kuempel,
Müller, Sigl, Vliet, Walz, Winchen ’16

A public astrophysical simulation framework for propagating extraterrestrial ultra-high energy particles



Proton injection

- 1-1000 EeV with $dN/dE \propto E^{-1}$
- uniformly distributed at 3-1000 Mpc

CRpropa 3

Batista, Dundovic, Erdmann, Kampert, Kuempel,
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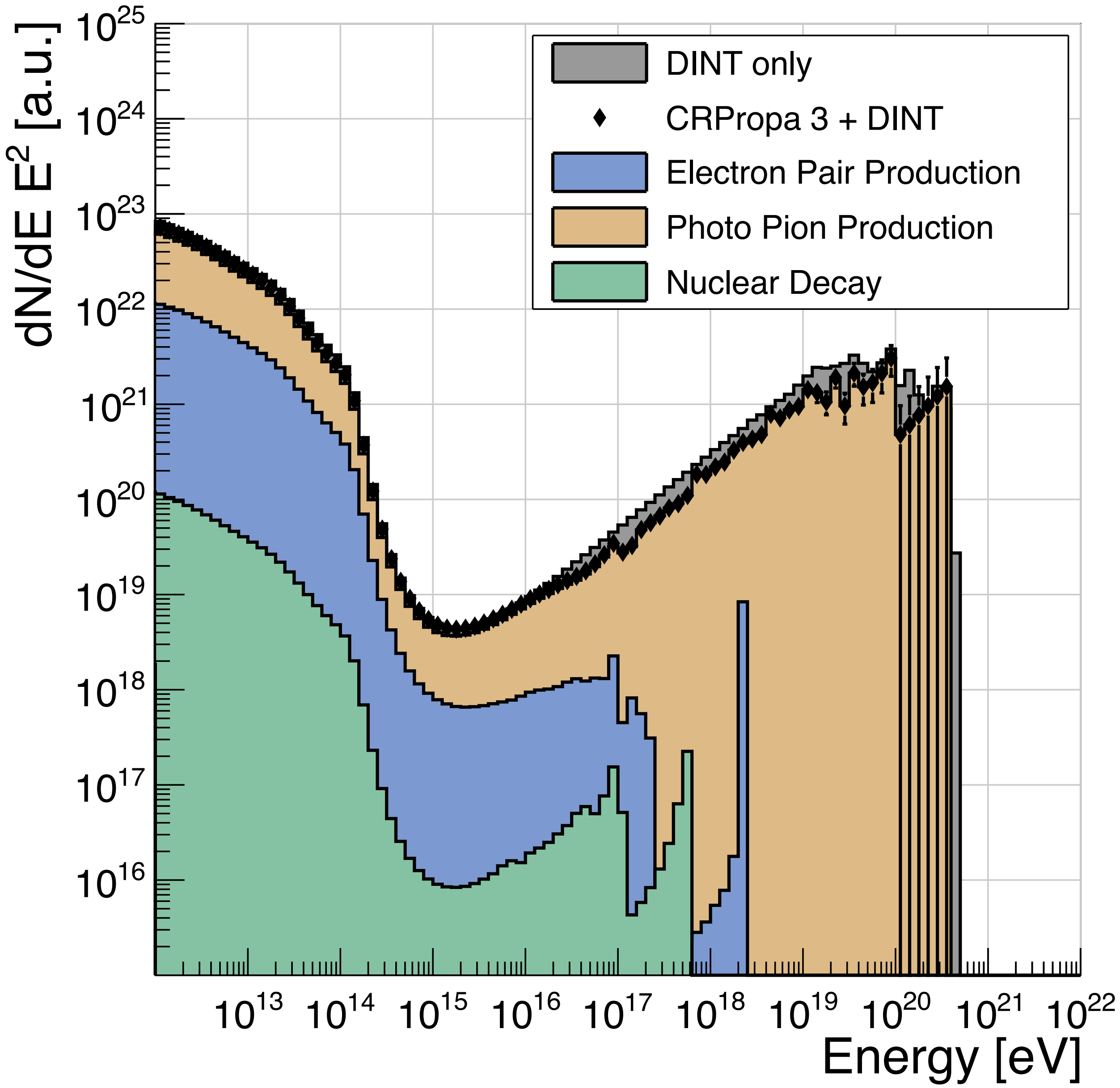

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in preparation with
S. Ando and M. Arimoto

→ CRs from DM can be simulated similarly

CRpropa 3

Batista, Dundovic, Erdmann, Kampert, Kuempel, Müller, Sigl, Vliet, Walz, Winchen '16

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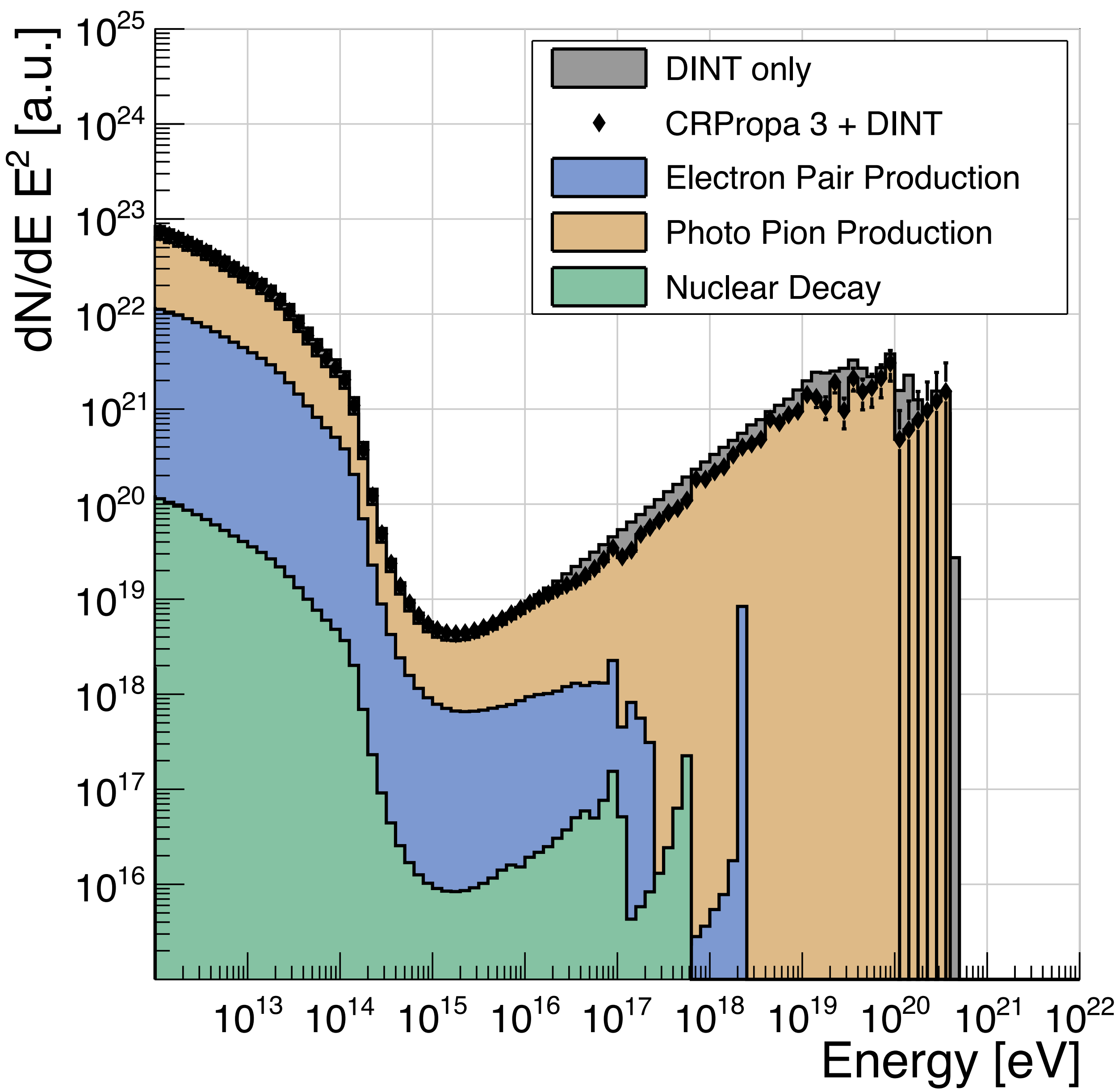

Proton injection

- 1-1000 EeV with $dN/dE \propto E^{-1}$
- uniformly distributed at 3-1000 Mpc

→ CRs from DM can be simulated similarly

5. Conclusions

We have studied DM using extragalactic gamma rays and local galaxy distribution

- The preferred regions for the anomalous e^+ flux are excluded
- IC-induced gamma rays are crucial for the exclusion
- The preferred regions for the anomalous $\mathcal{O}(100\,\mathrm{GeV})$ $\bar{p}$ are excluded
- The 80 GeV annihilating DM motivated by the anomalous $\mathcal{O}(1\,\mathrm{GeV})$ $\bar{p}$ is partly excluded
- More to work on