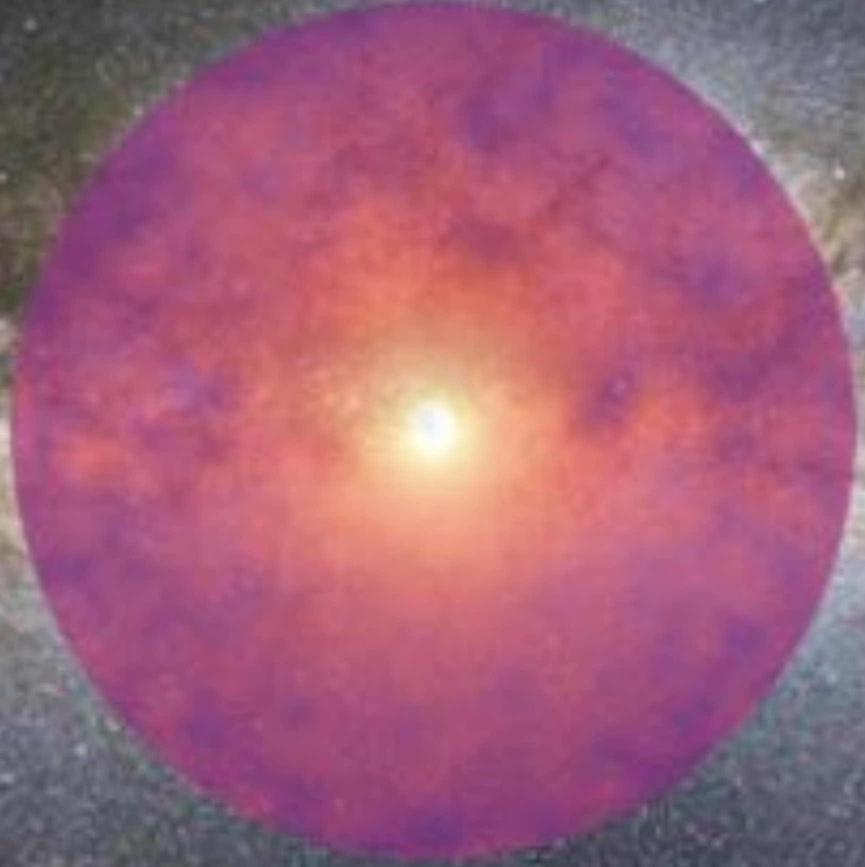
Multimessenger constraints for the dark matter interpretation of the Fermi-LAT Galactic center excess

Mattia Di Mauro



Fellini — Fellowship for Innovation at INFN

INFN — Istituto Nazionale di Fisica Nucleare

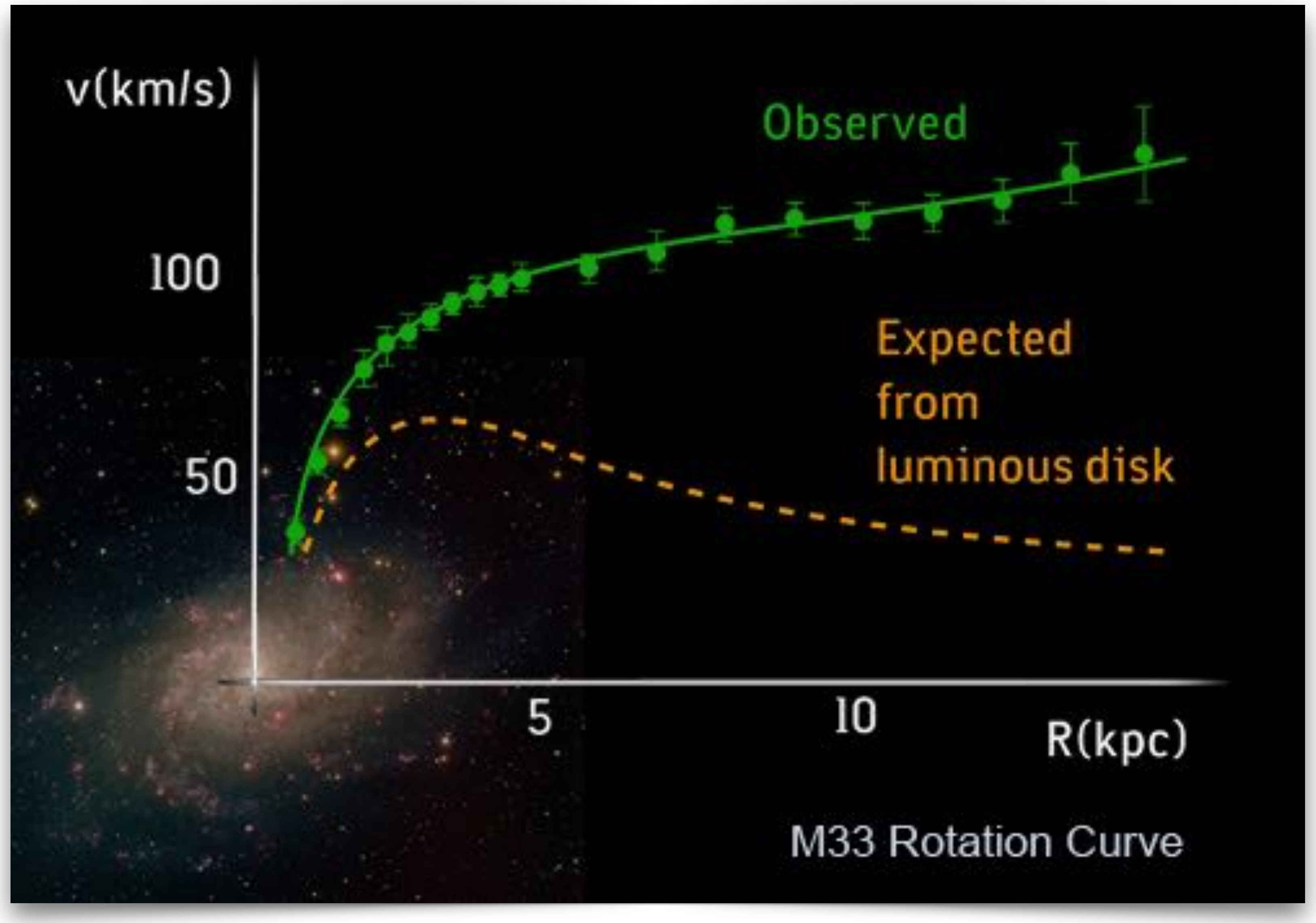
Fellini seminar June 14 2021

Background image: ESO
Central image: Fermi-LAT

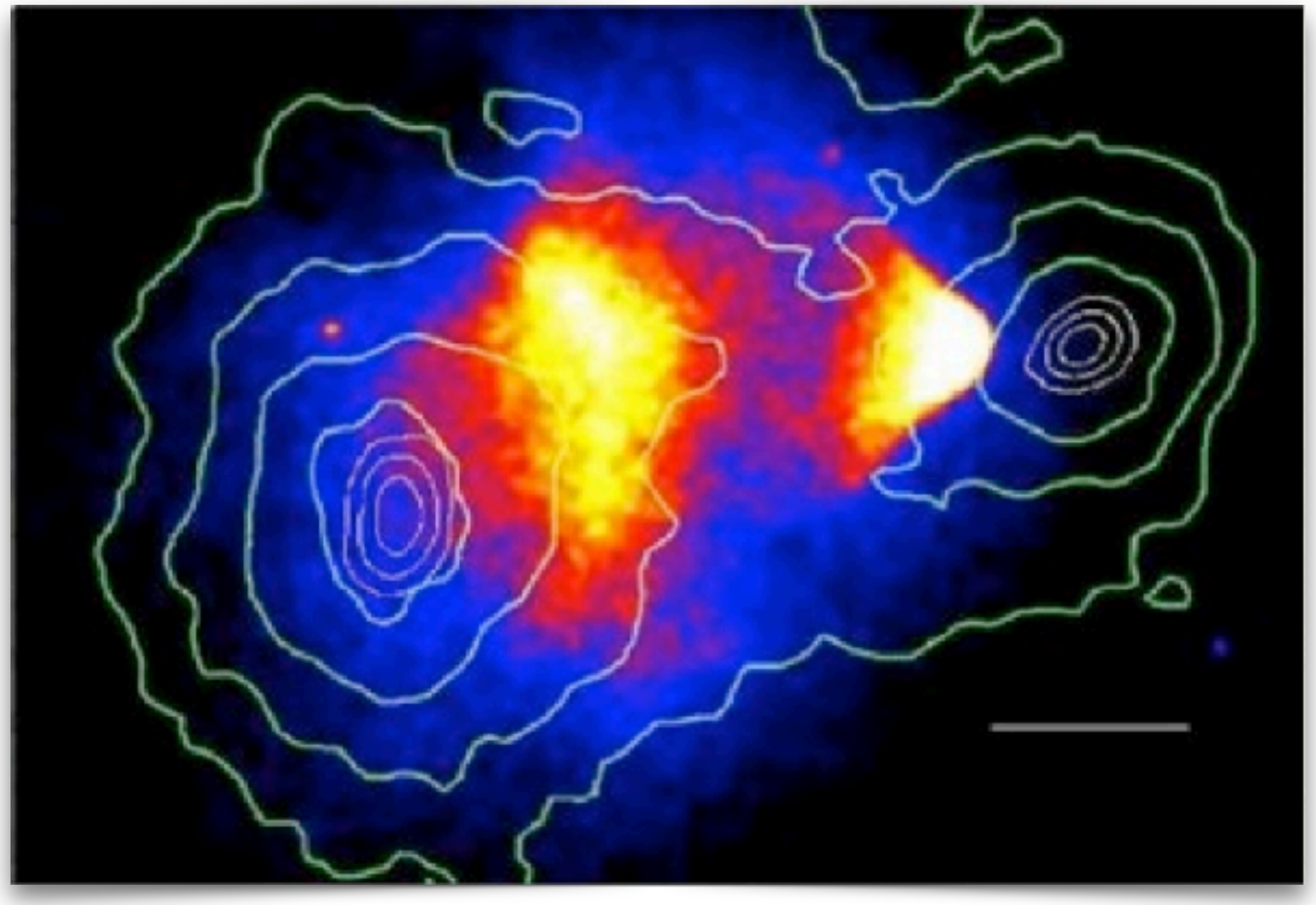
Dark matter: gravitational evidences

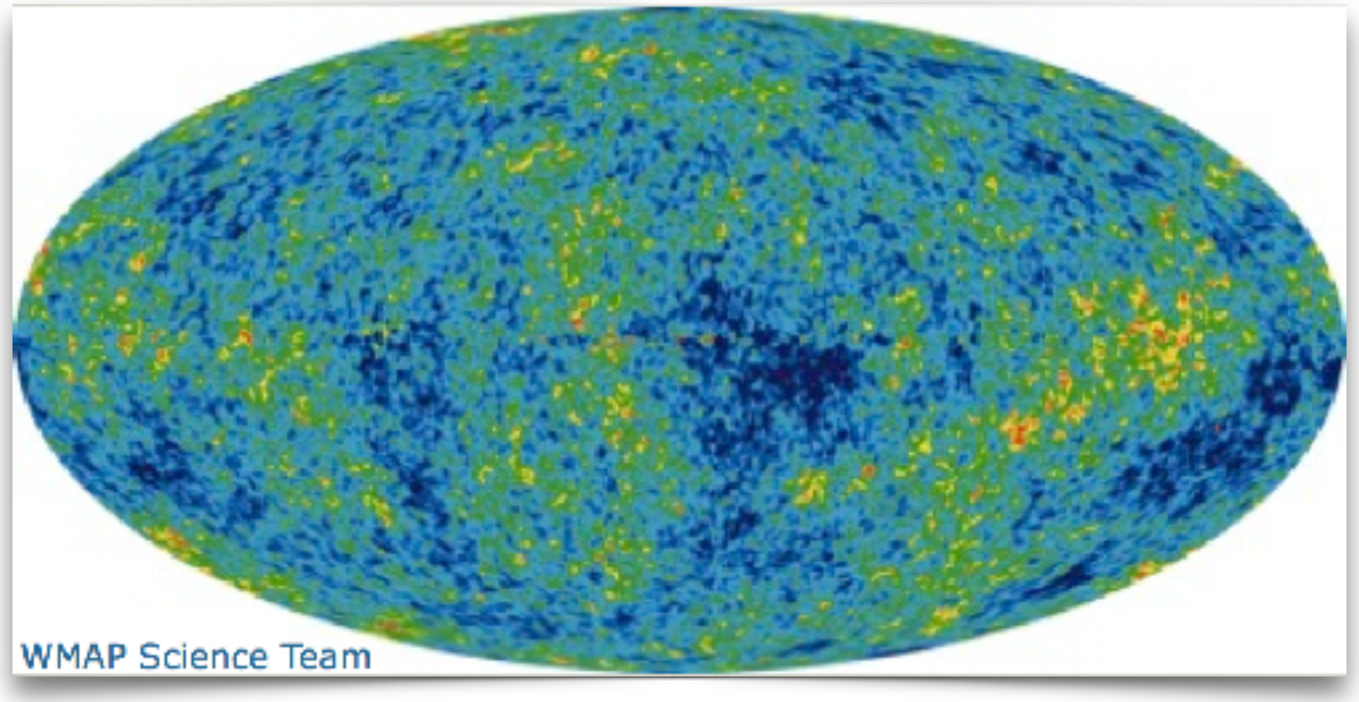
Comprises ***majority*** *of* ***mass*** *in Galaxies*
Missing mass on Galaxy Cluster scale
(Zwicky (1937))

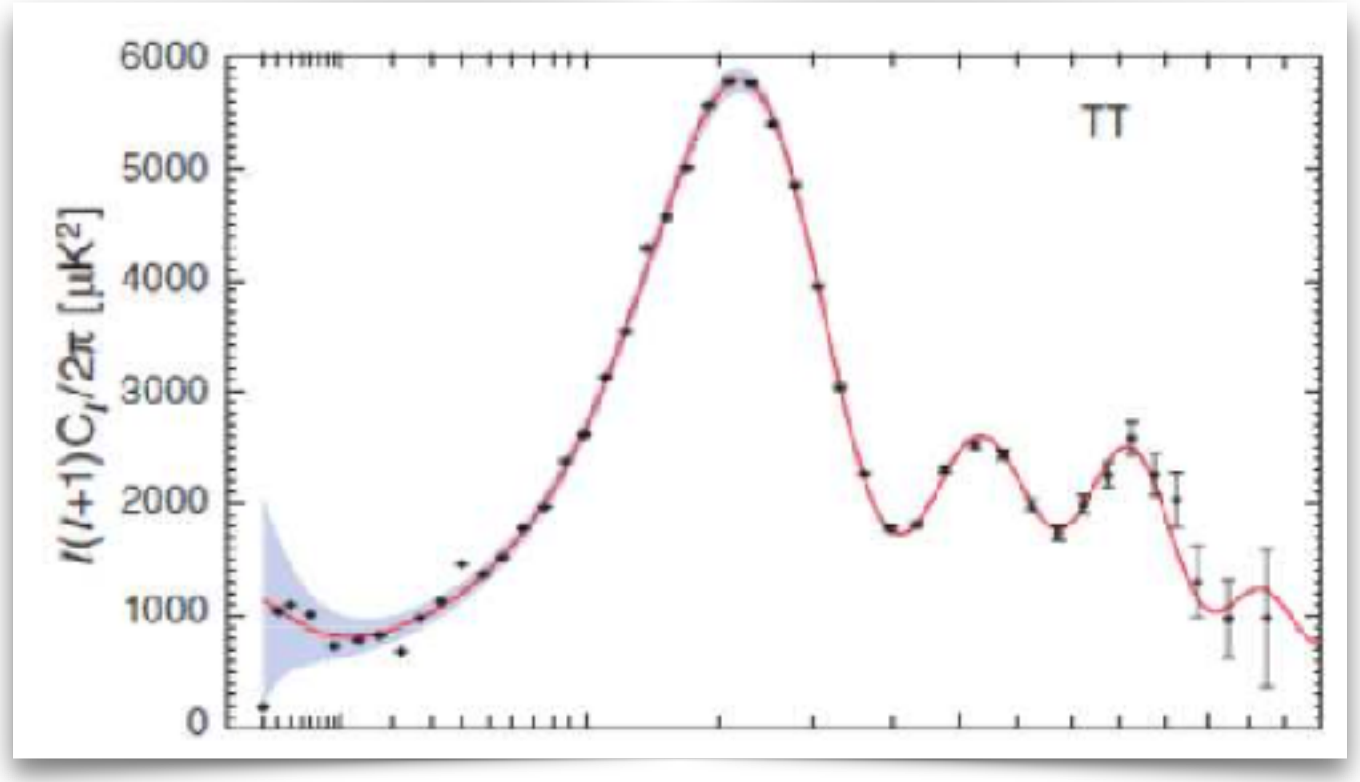
Large ***halos*** *around Galaxies*
Rotation Curves
Rubin+(1980)



Almost ***collisionless***
Bullet Cluster

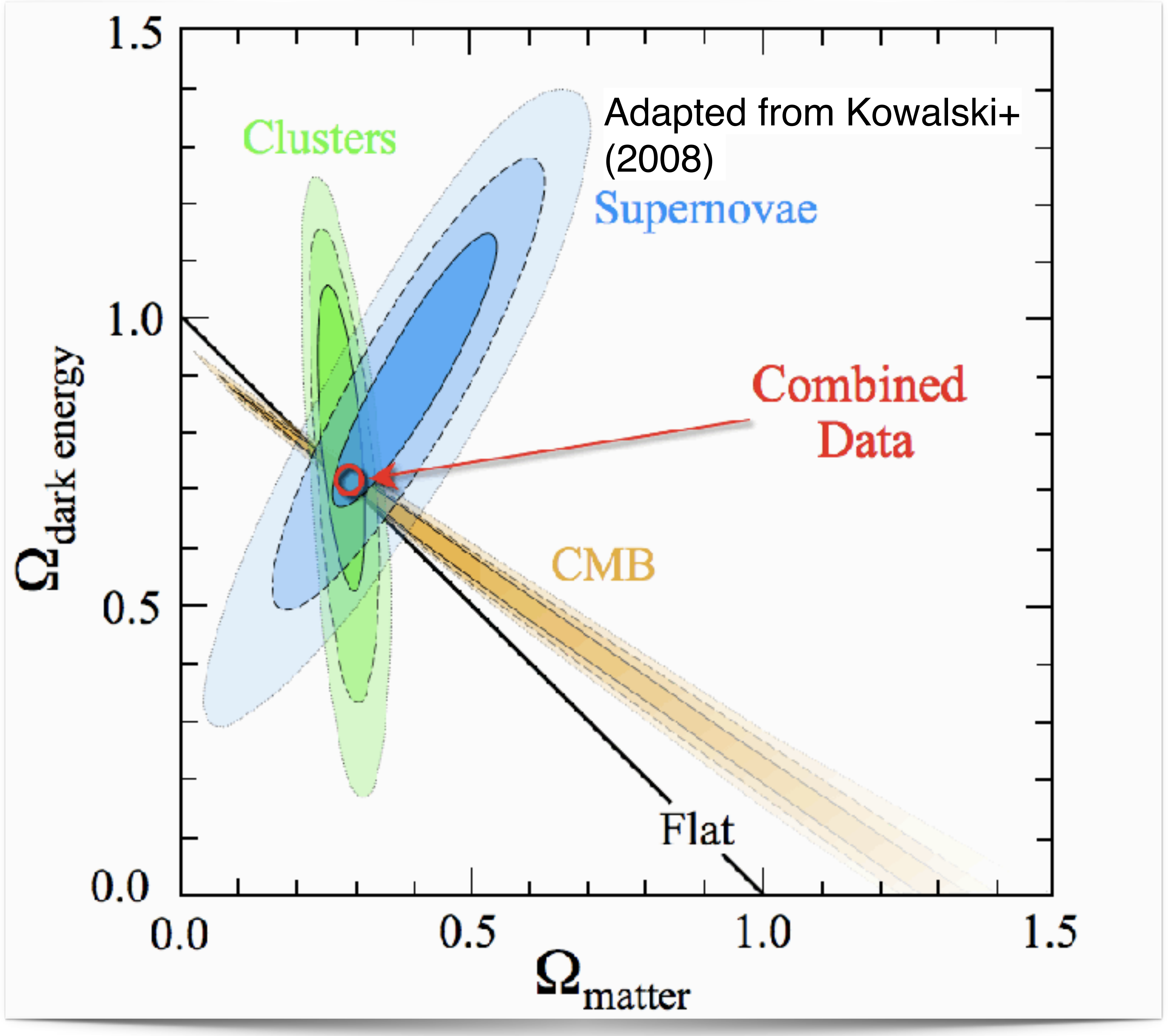


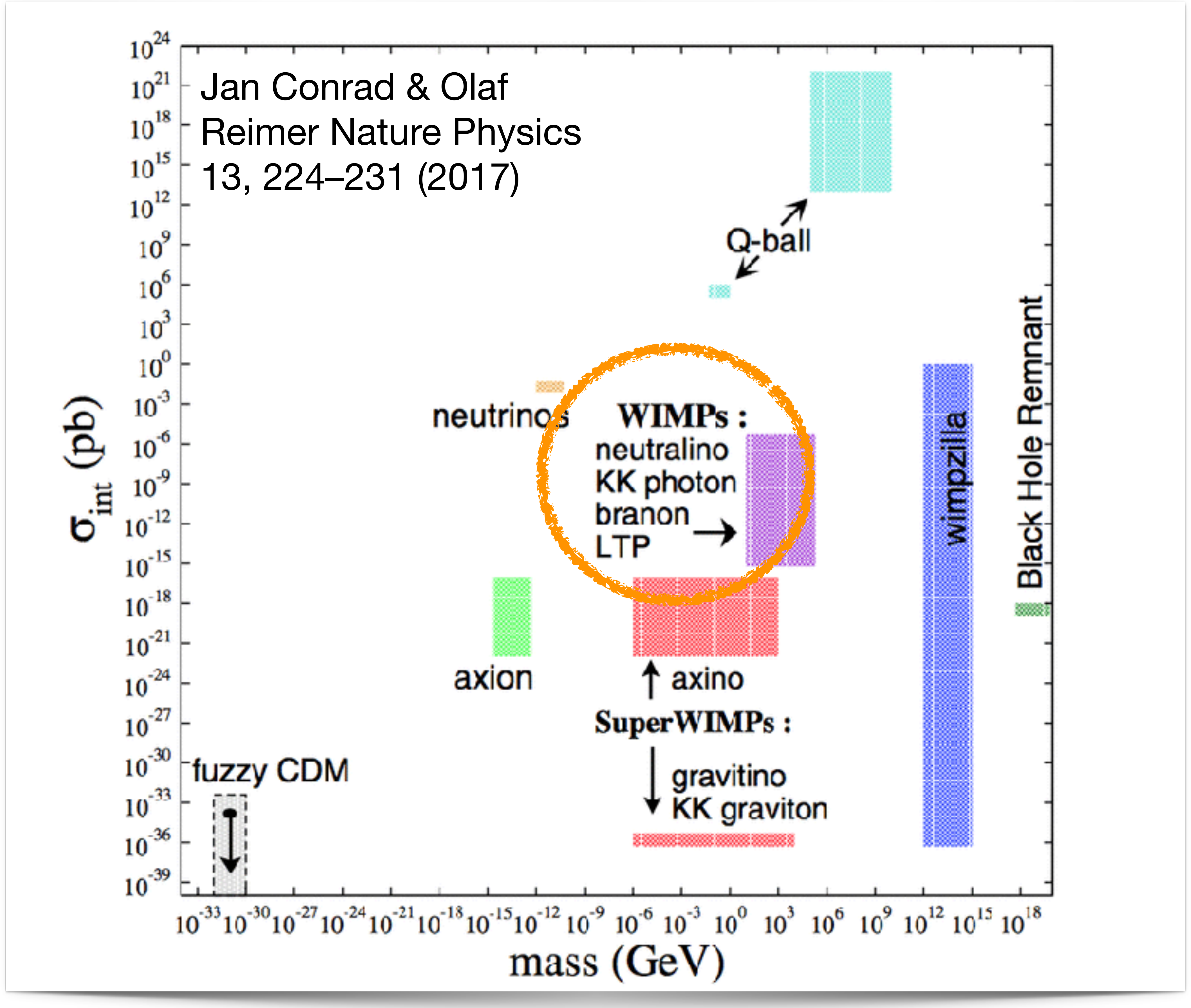




Non-Baryonic
Big-Bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP(2010), Planck(2015)

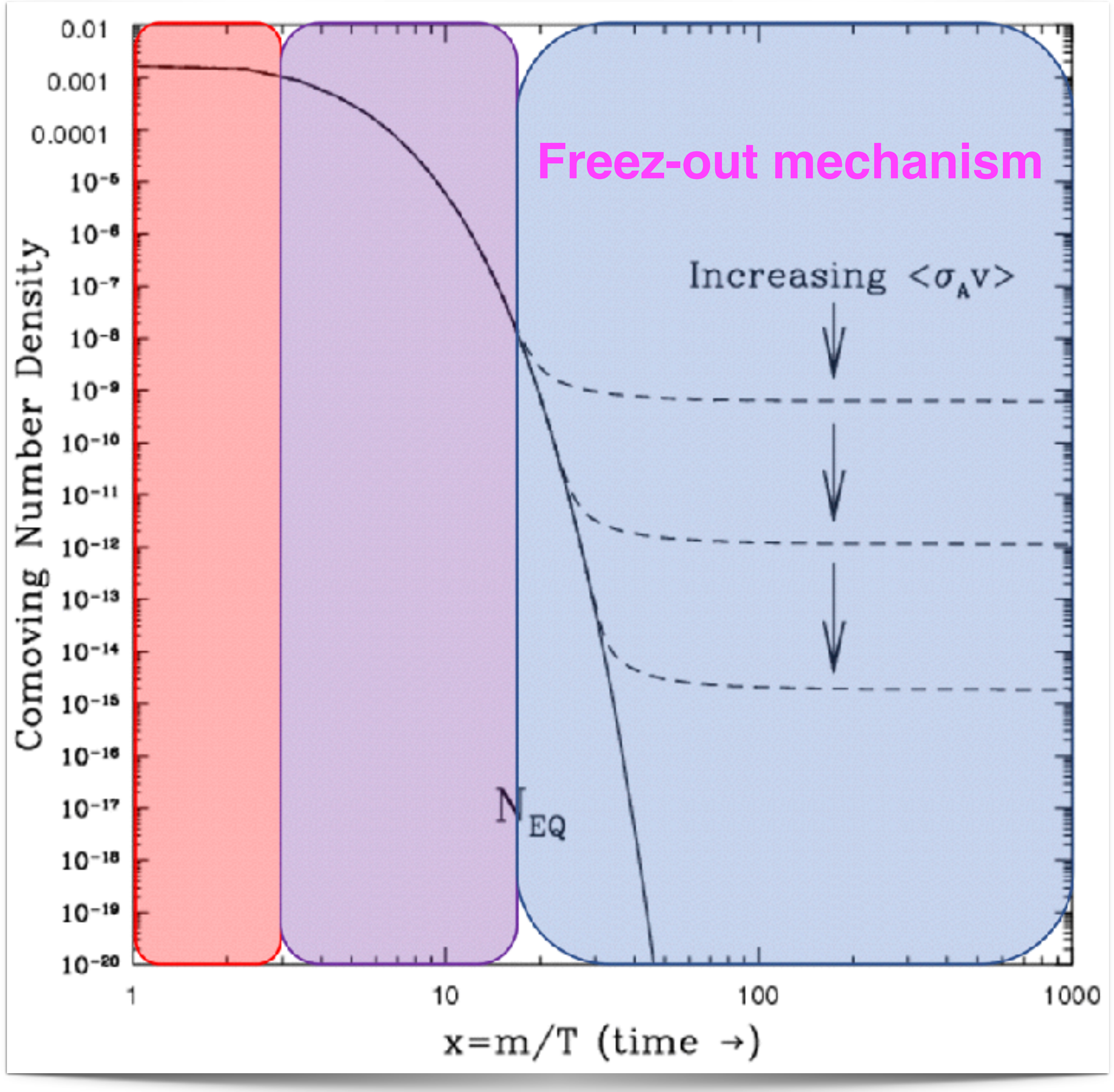
A plethora of dark matter candidates

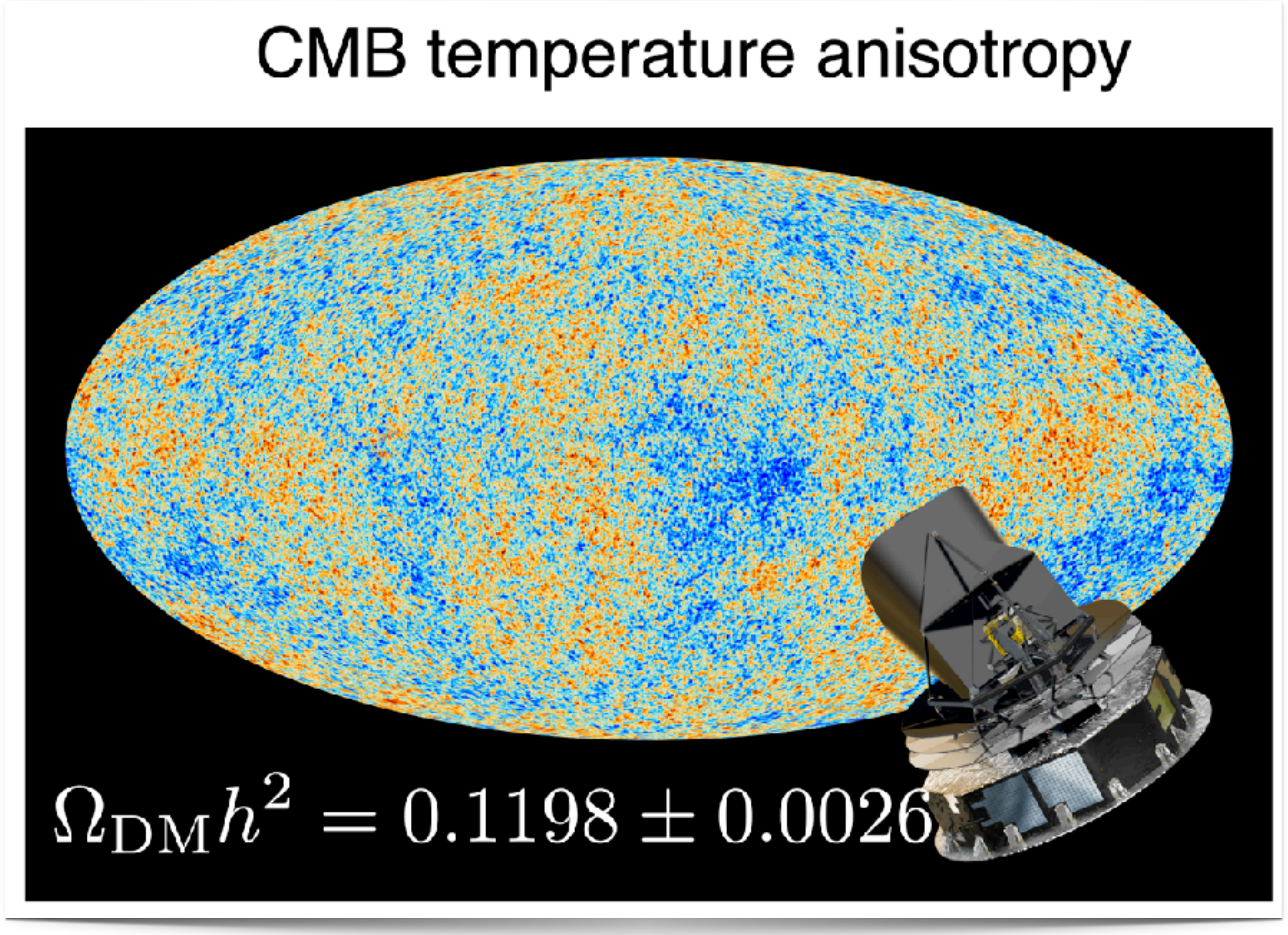




- No Standard Model particle matches the known properties of dark matter
- Many candidate particles have been proposed.
- **The most popular candidate is a particle type that is weakly interacting, but much more massive than a neutrino (weakly interacting massive particle, or WIMP).**

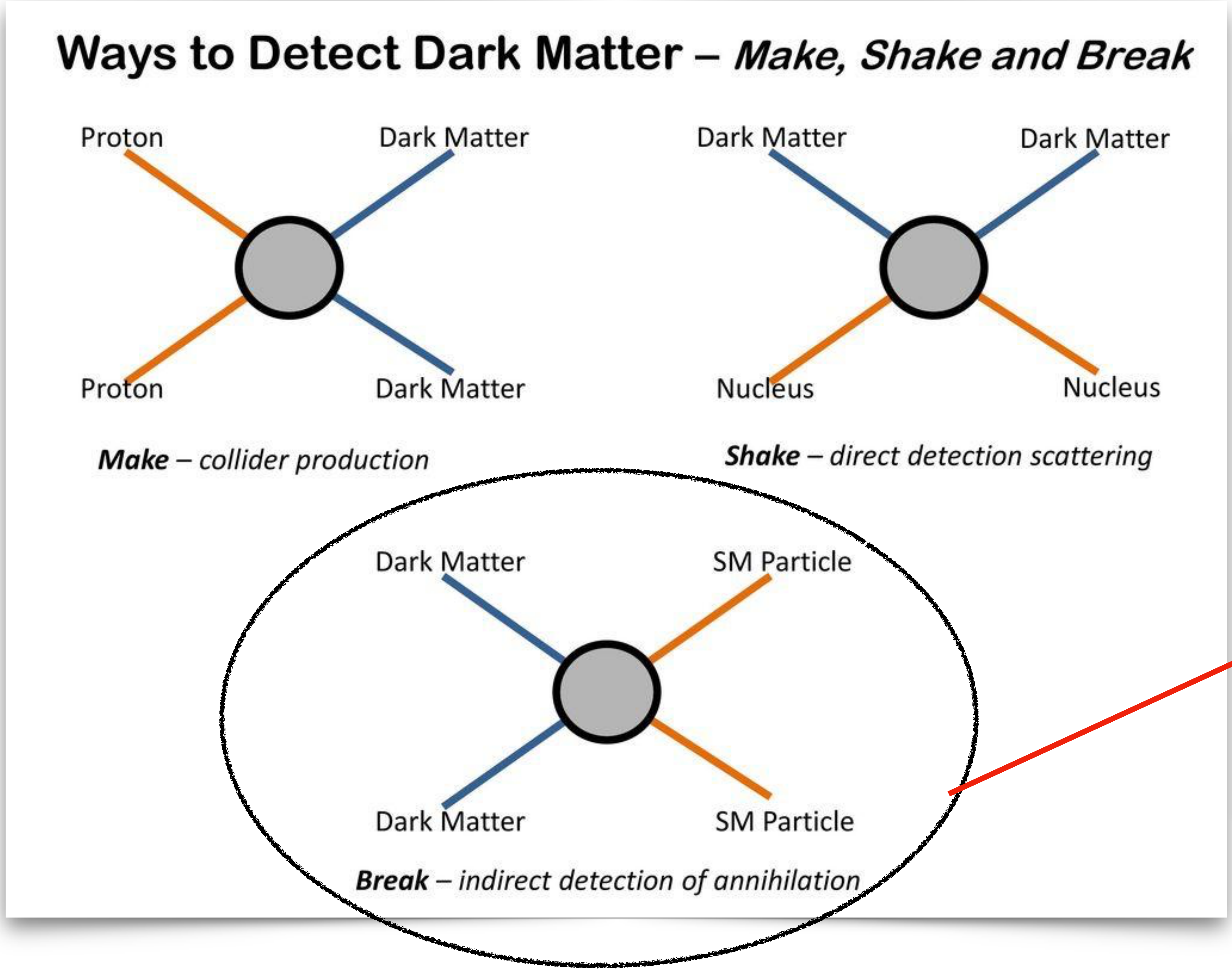
The WIMP 'miracle'

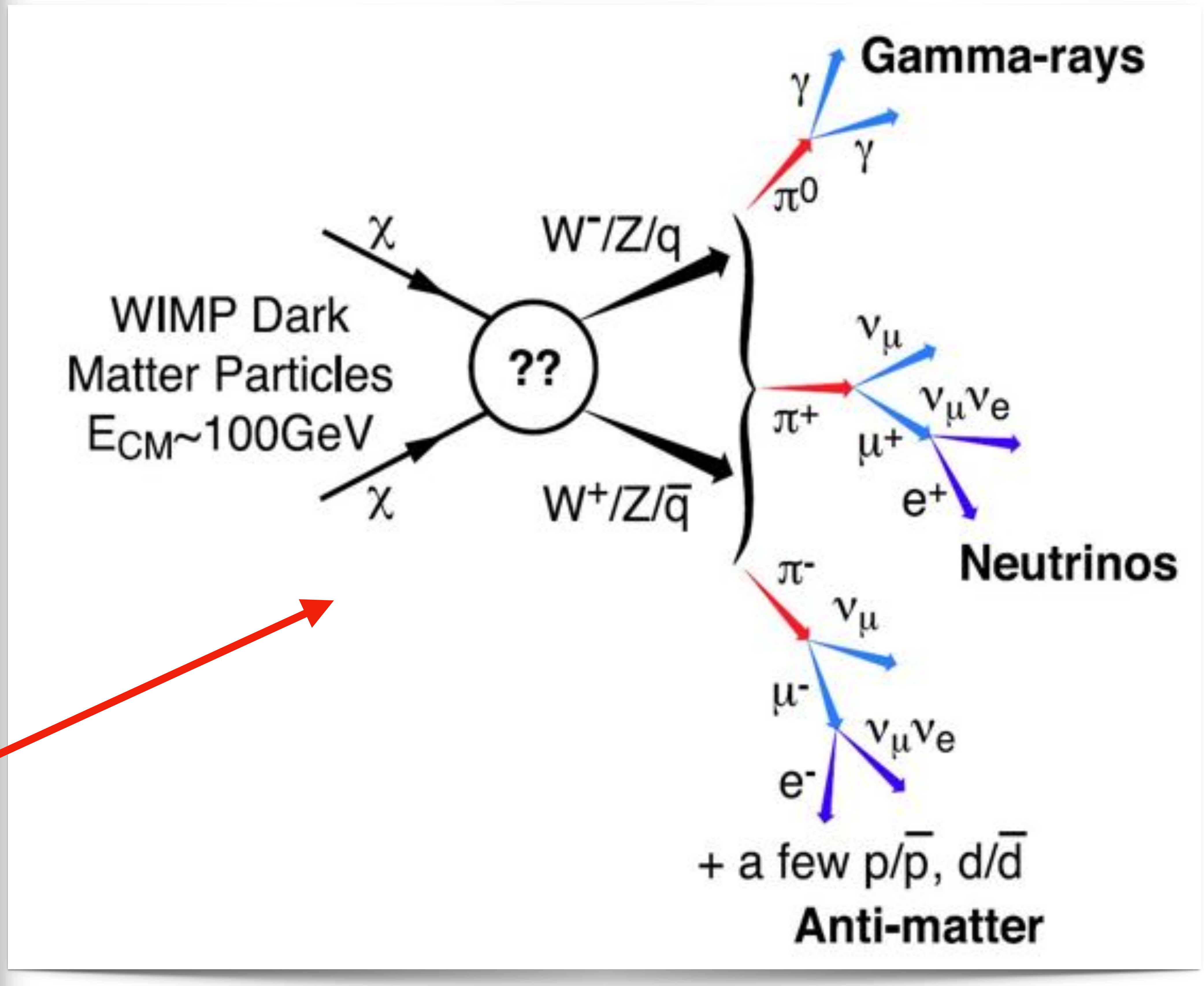




$$\Omega_{\rm DM} h^2 \sim \frac{10^{-27}{\rm cm}^3/{\rm s}}{\langle \sigma({\rm DM\,DM} \to {\rm SM\,SM}) {\rm v}\rangle} \qquad \langle \sigma({\rm DM\,DM} \to {\rm SM\,SM}) {\rm v}\rangle \sim 3 \times 10^{-26}{\rm cm}^3/{\rm s}$$

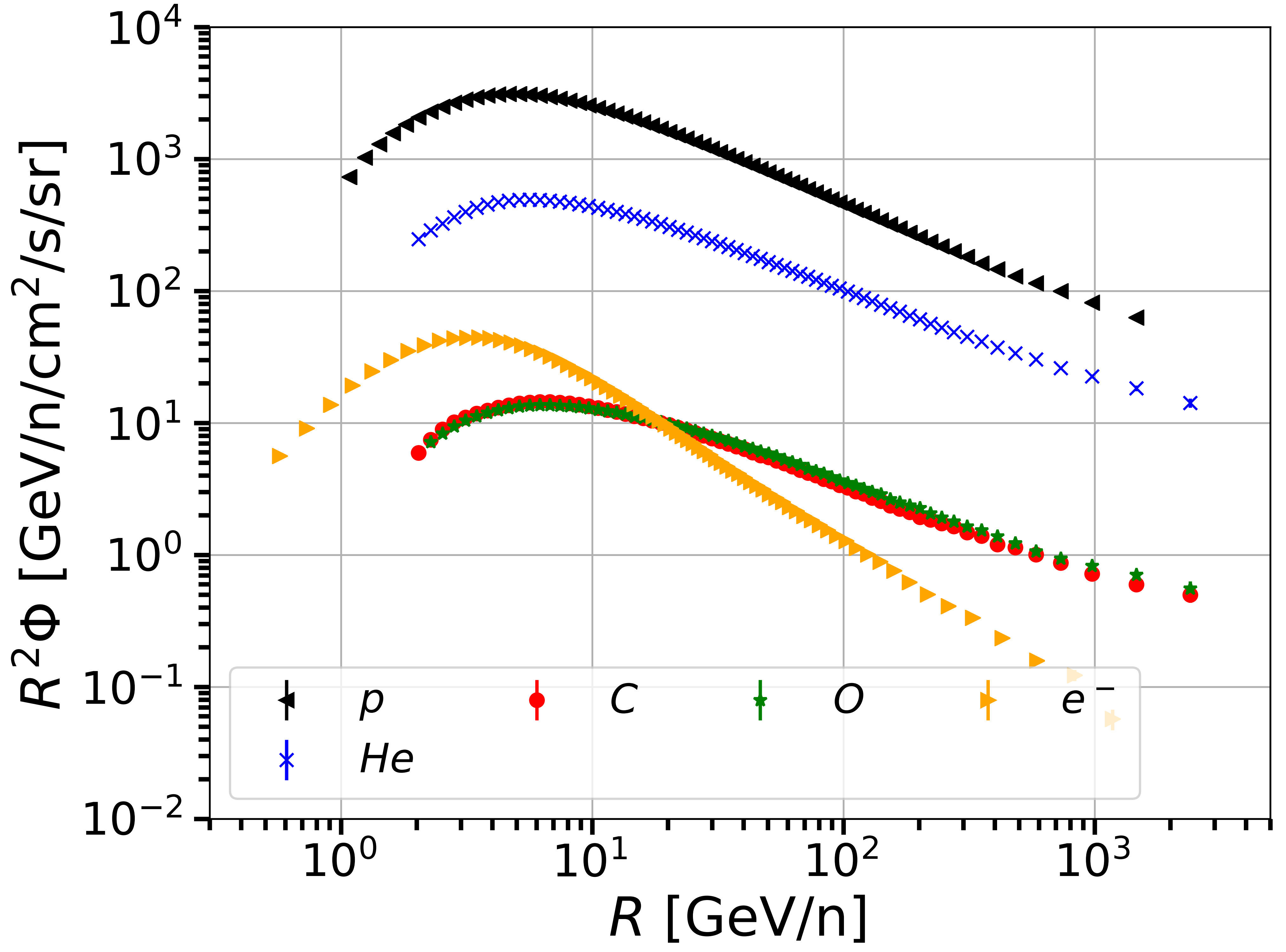
Dark matter searches

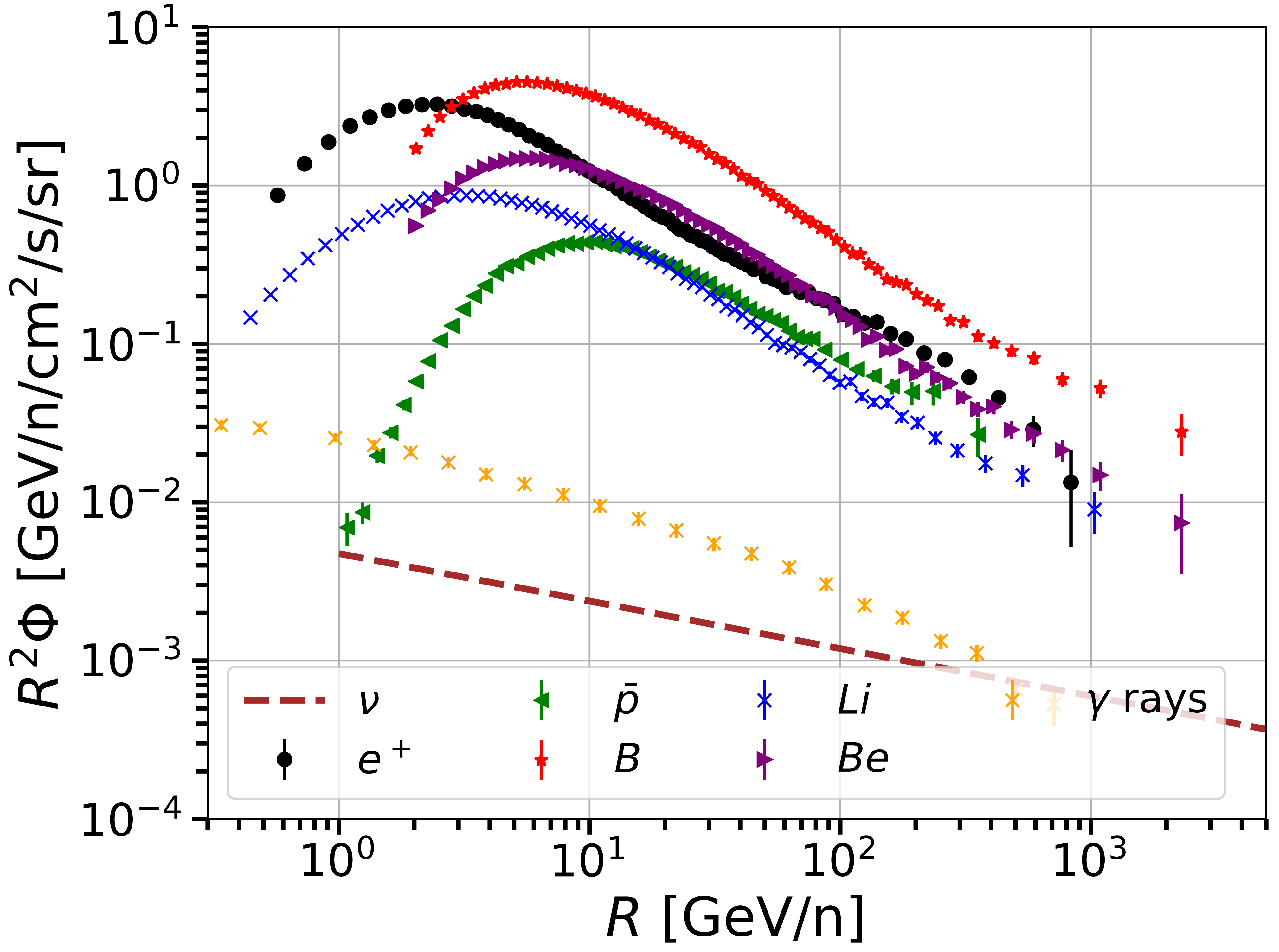




Cosmic particles

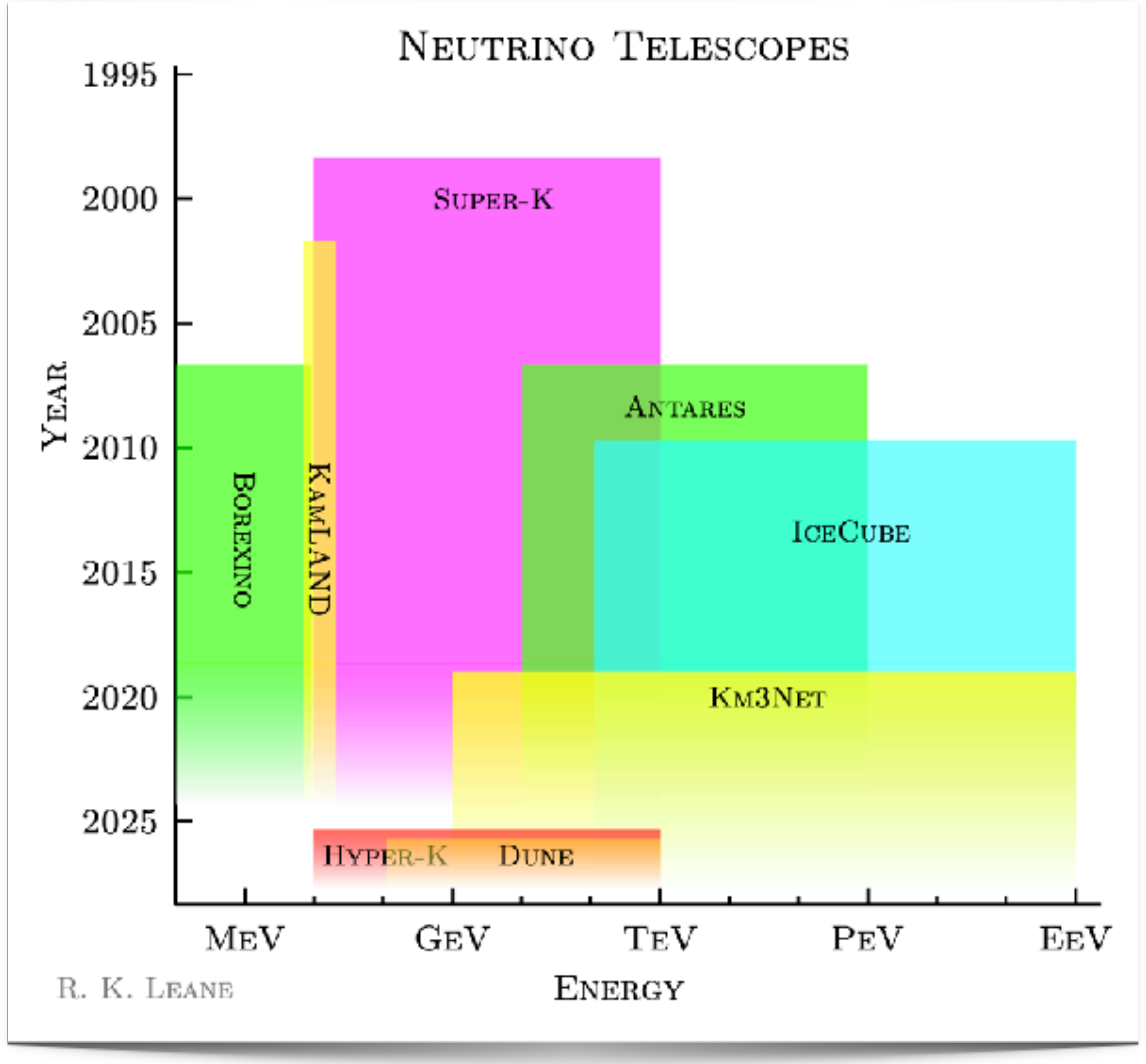
- Among all cosmic rays, secondaries are the most interesting for DM searches.
- In particular antiprotons, positrons, gamma rays and neutrinos are the most studied.
- Antinuclei are also considered because the DM production should exceed the secondary one at low energy.

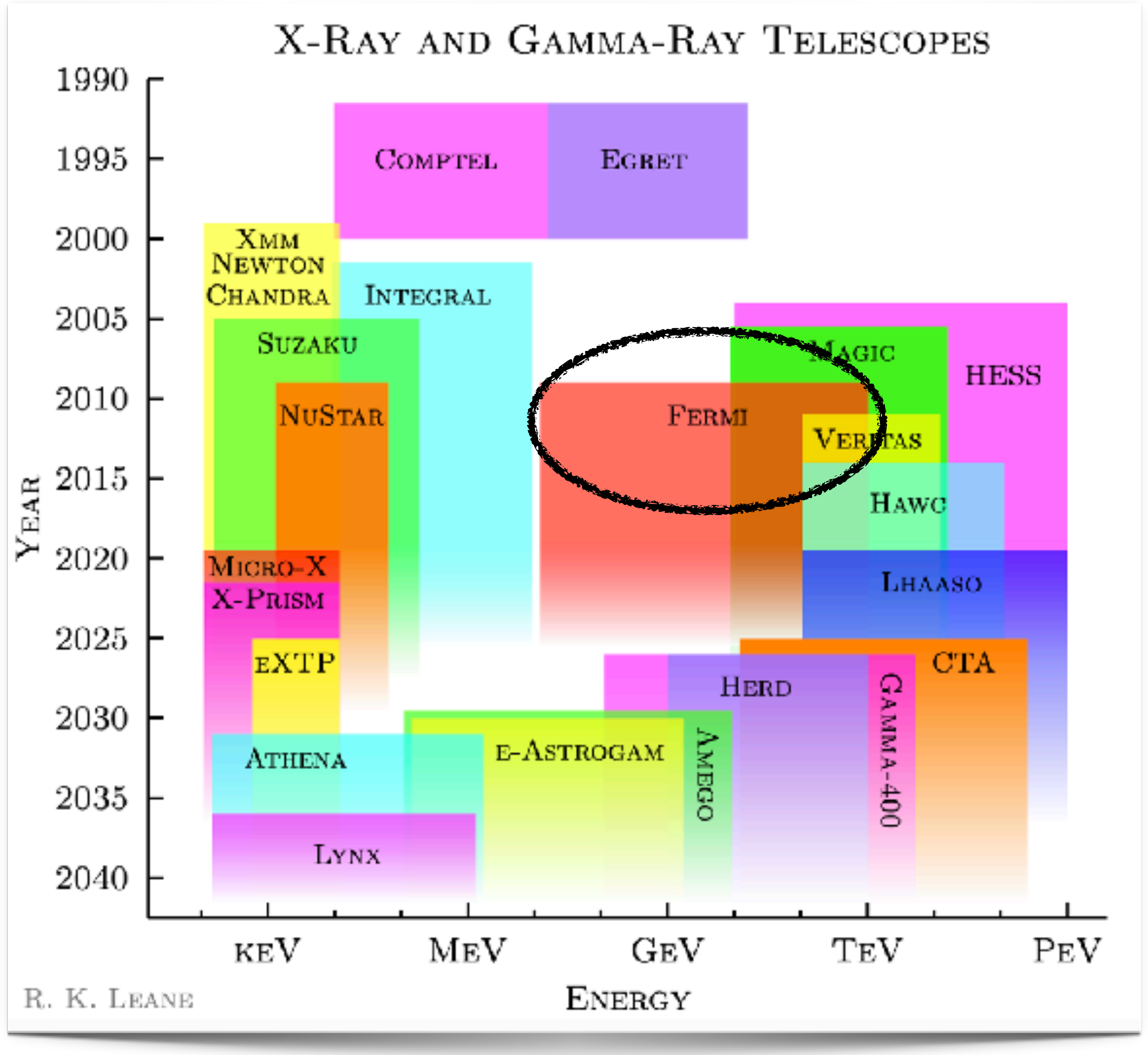


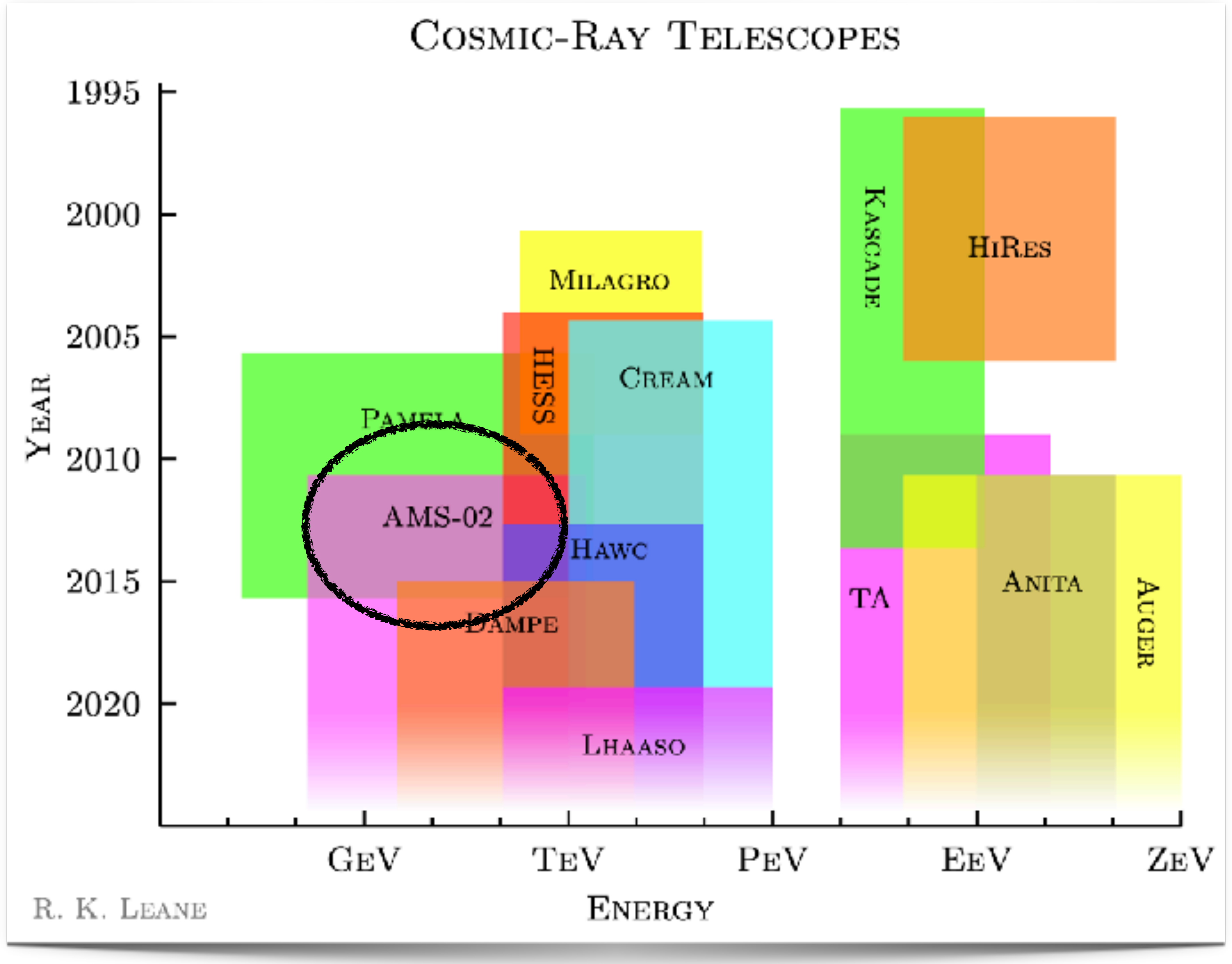


Cosmic-ray and radiation experiments

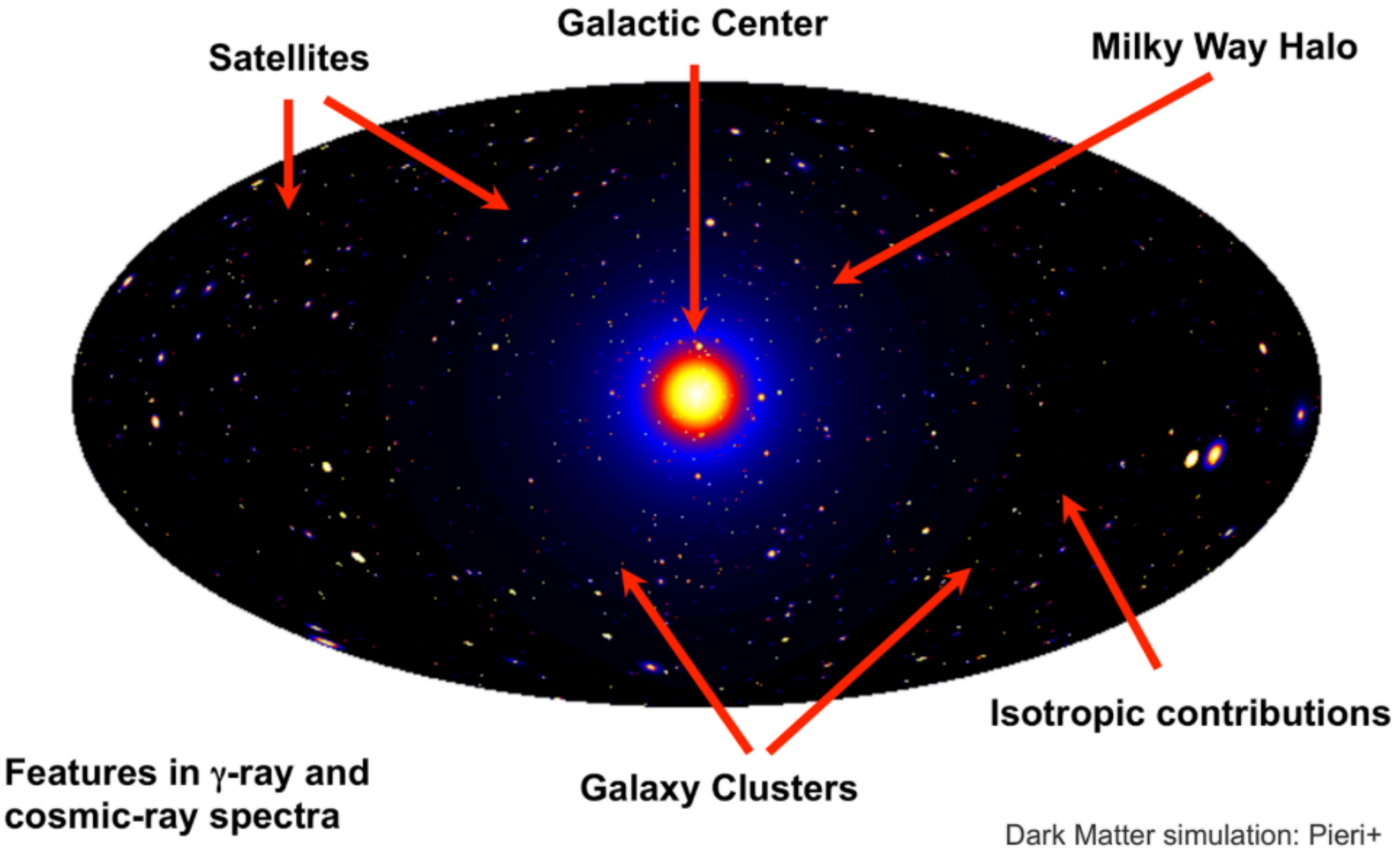
- Currently, there are precise experiments of cosmic ray and radiation.
- The future will be even more interesting!







Gamma-ray map from dark matter annihilation



Dark Matter simulation: Pieri+ 2011PhRvD..83b3518P

Gamma rays from dark matter annihilation

Velocity averaged annihilation cross-section

Signal intensity:
[photon flux per steradian per energy]

Photon energy spectrum per annihilation

$$\frac{d\phi}{d\Omega dE} = \frac{\langle \sigma v_{\rm rel} \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} ds\ \rho(\vec{r}[s,\Omega])^2$$

Dark matter mass density

Dark matter mass

Line-of-sight integral

Particle Physics

Astrophysics

Characteristic **Energy Spectrum**

Characteristic **Morphology**
(point-like, extended or diffuse)

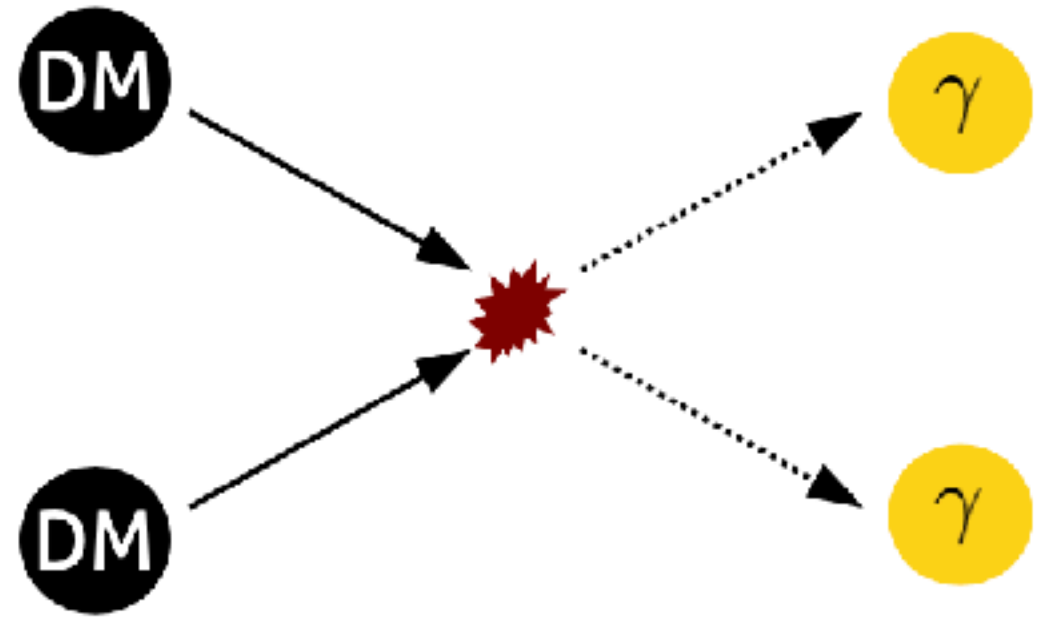
[review DM searches with gamma rays: Bringmann & Weniger (2012)]

It is convenient to define a "J-value":

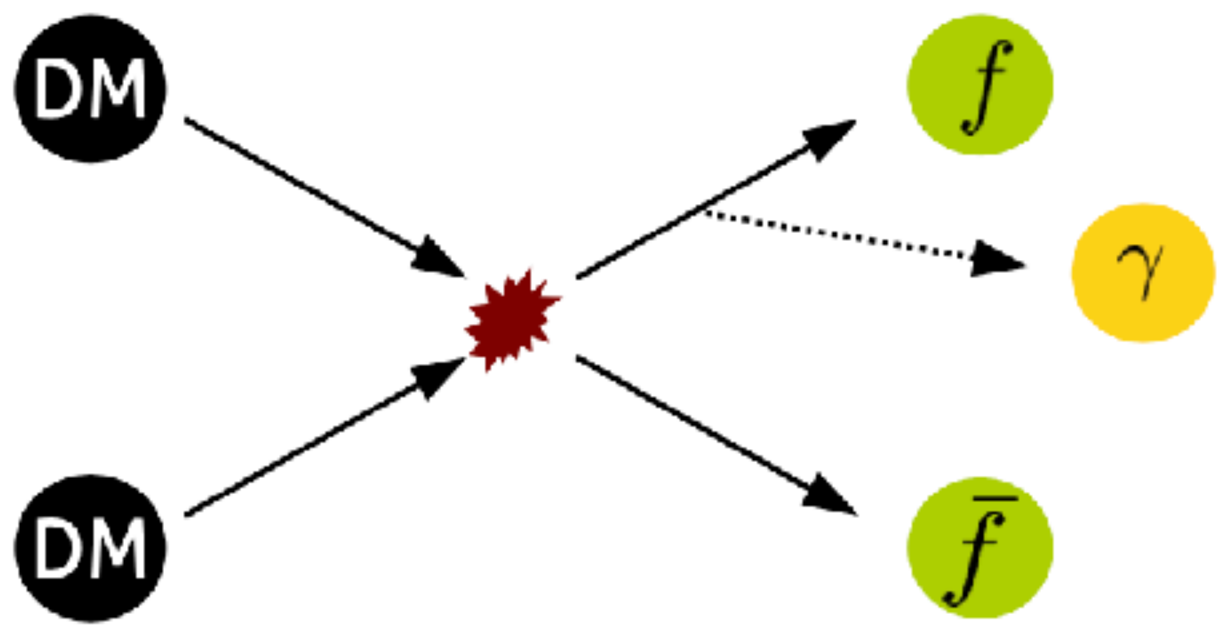
$$J_{\Delta\Omega} \equiv \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} ds \rho(r[\vec{s},\Omega])^2$$

Gamma rays from dark matter annihilation

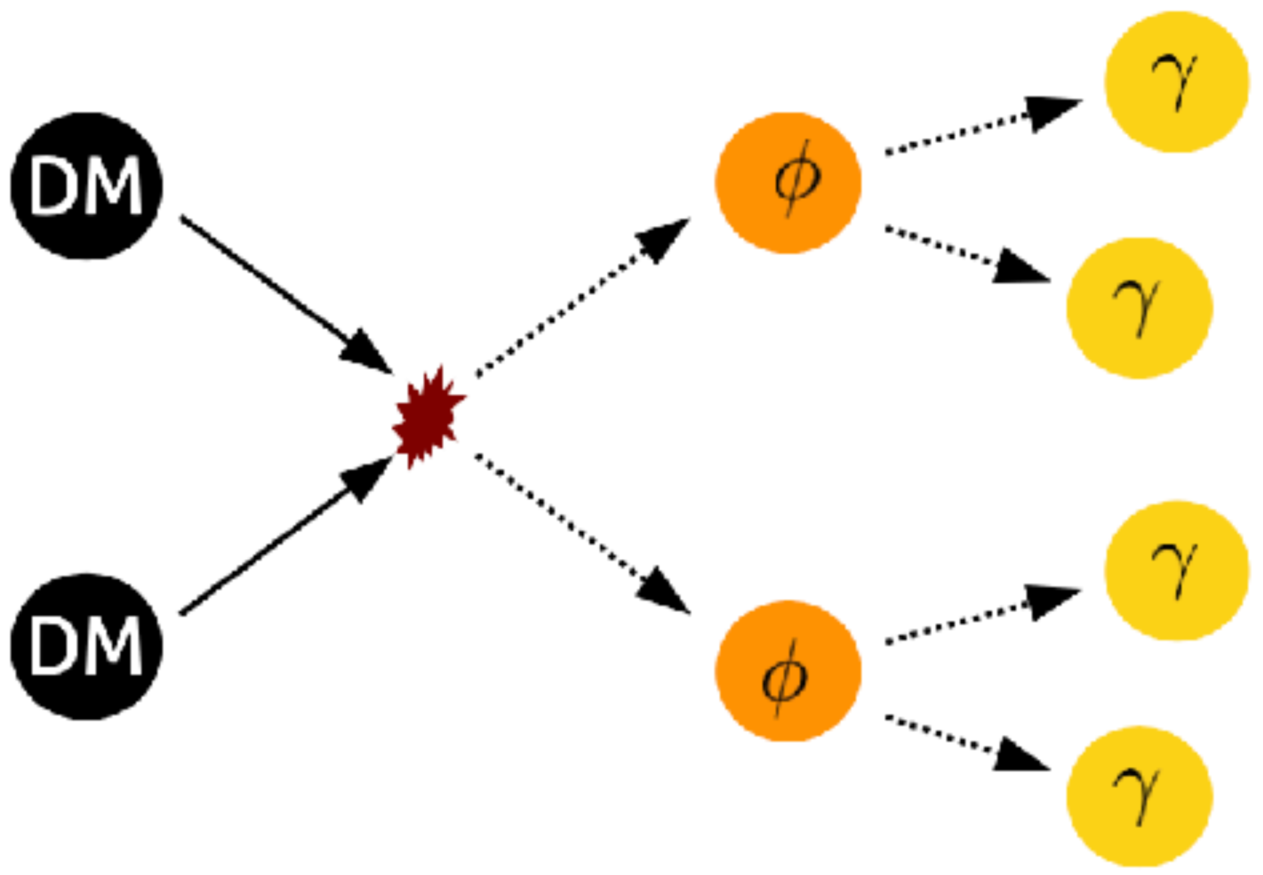
Gamma-ray lines:
Two-body annihilation into photons



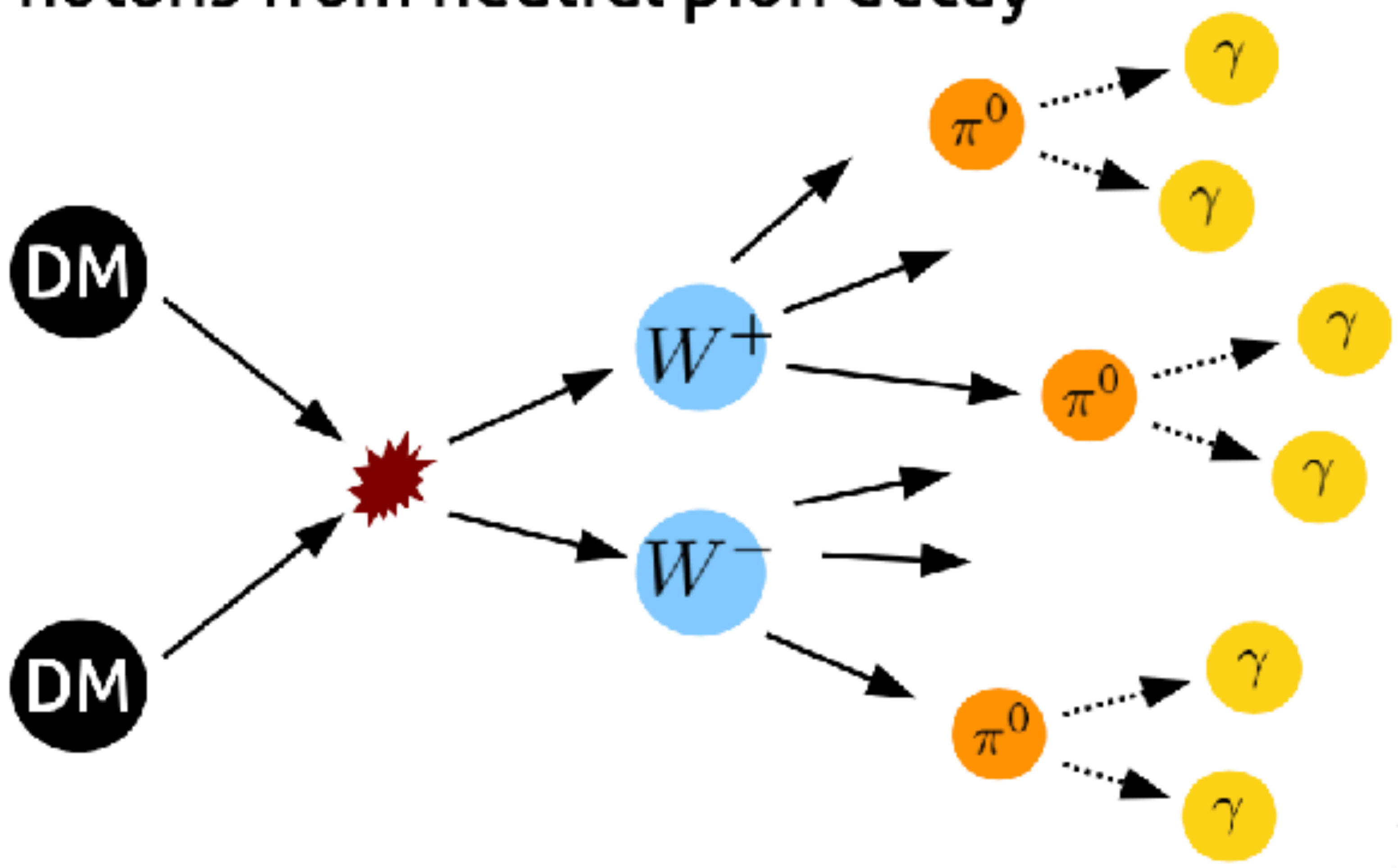
Bremsstrahlung:
Photon production in "hard process"



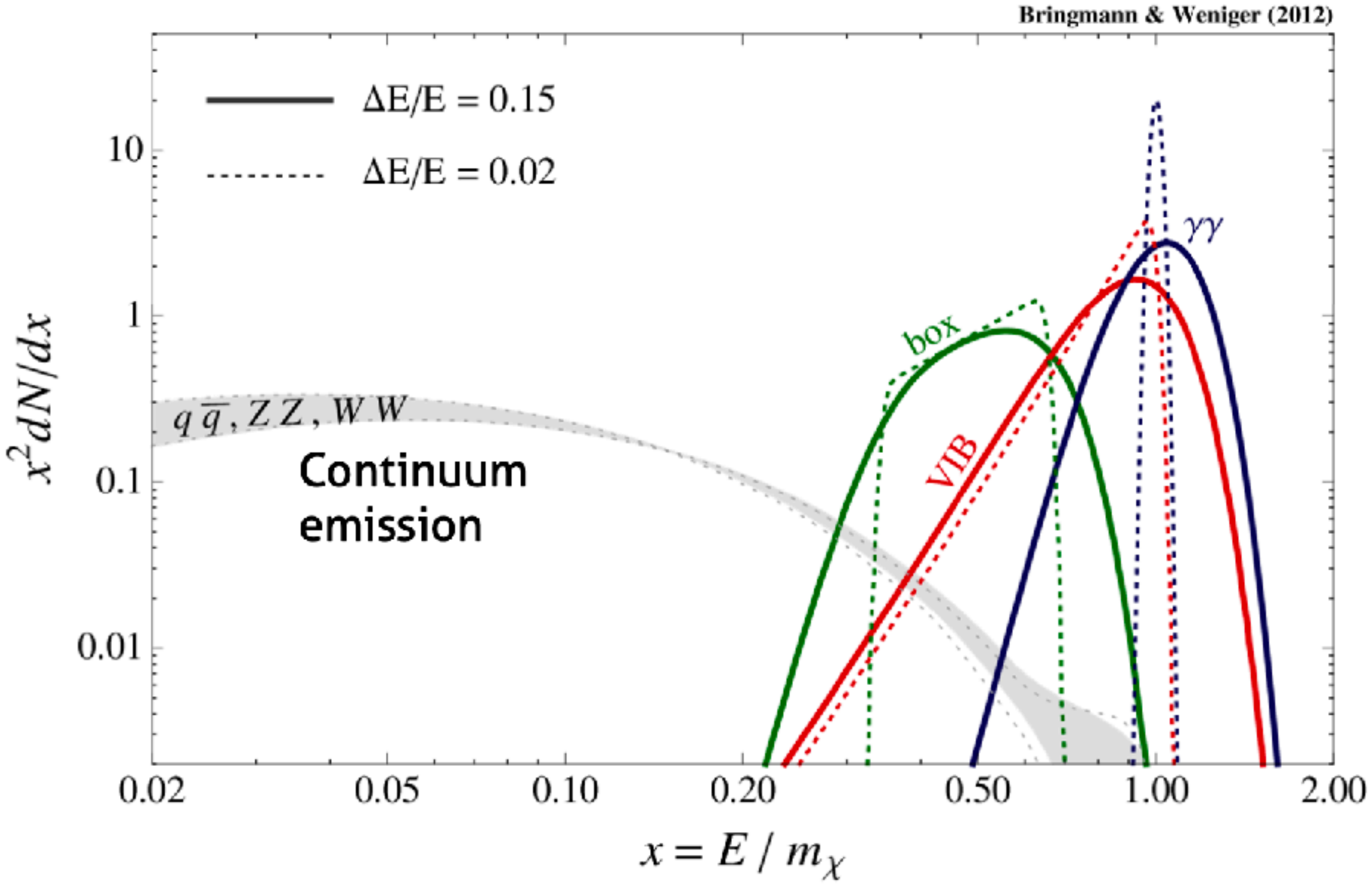
Box-shaped spectra:
Photons from cascade decay



Continuum emission: (Prompt)
Photons from neutral pion decay



Gamma rays from dark matter annihilation



Box-shaped spectra
- Cascade-decay into monochromatic photons
- already at tree level

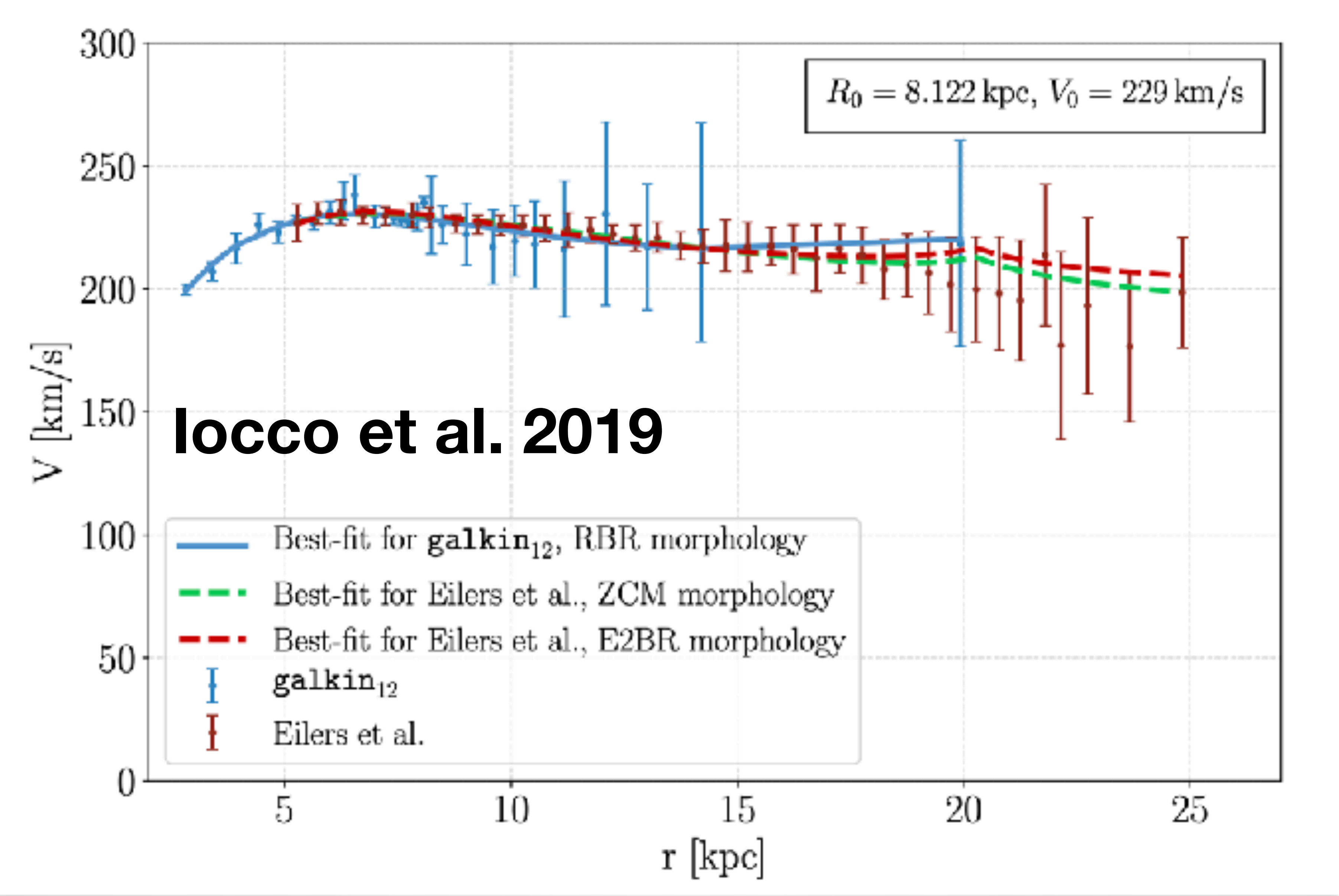
Internal Bremsstrahlung (IB)
- radiative correction to processes with charged final states
- Generically suppressed by O(α)

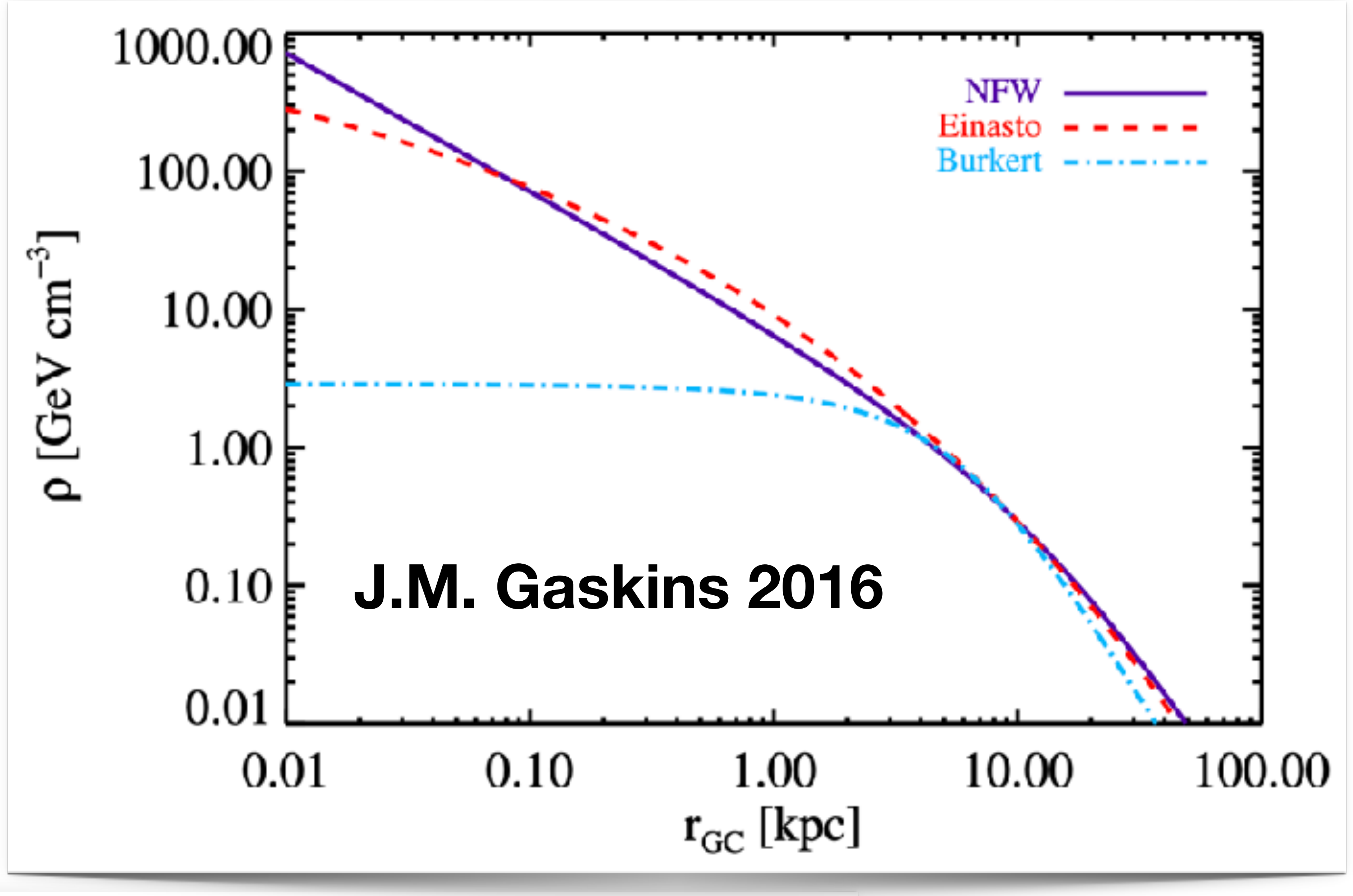
$$\chi\chi \to \bar{f}f\gamma$$

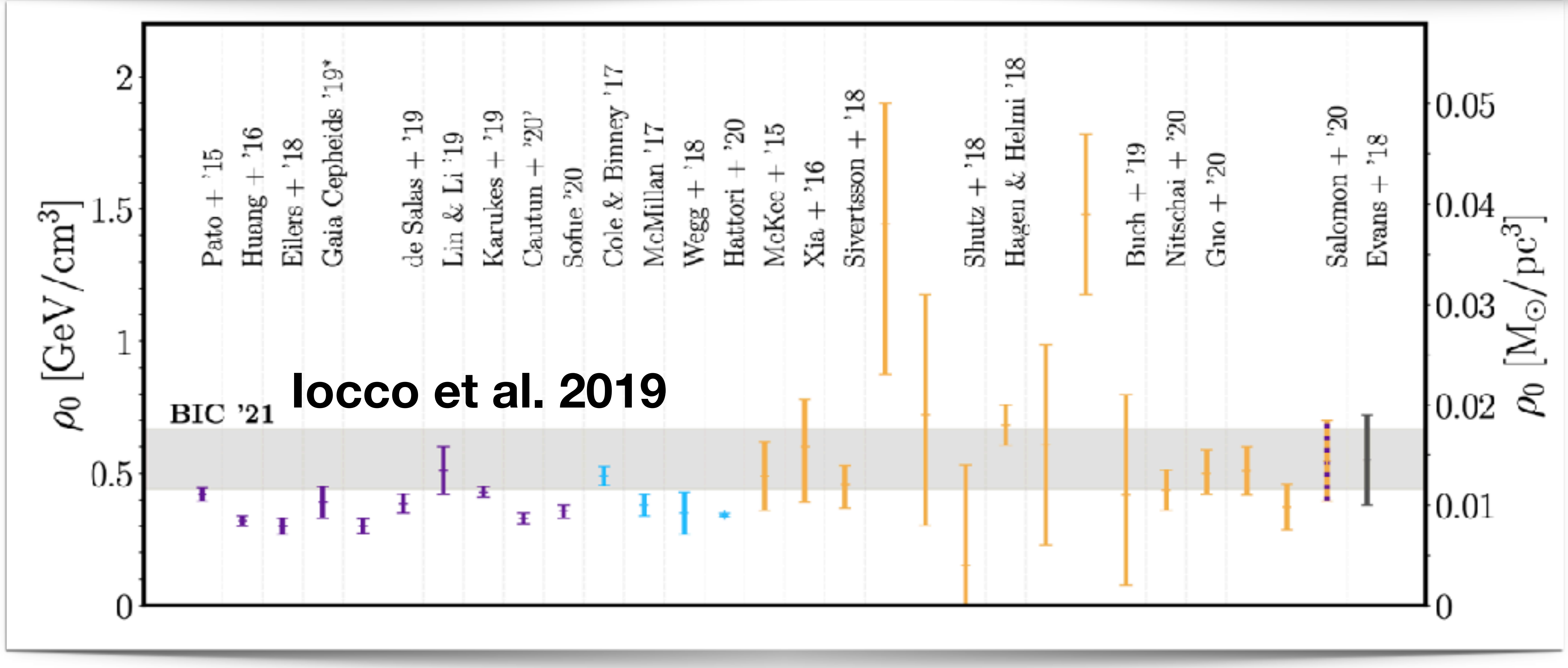
Gamma-ray lines
- from two-body annihilation into photons
- forbidden at tree-leve, generically suppressed by O(α²)

$$\chi\chi \to \gamma\gamma$$

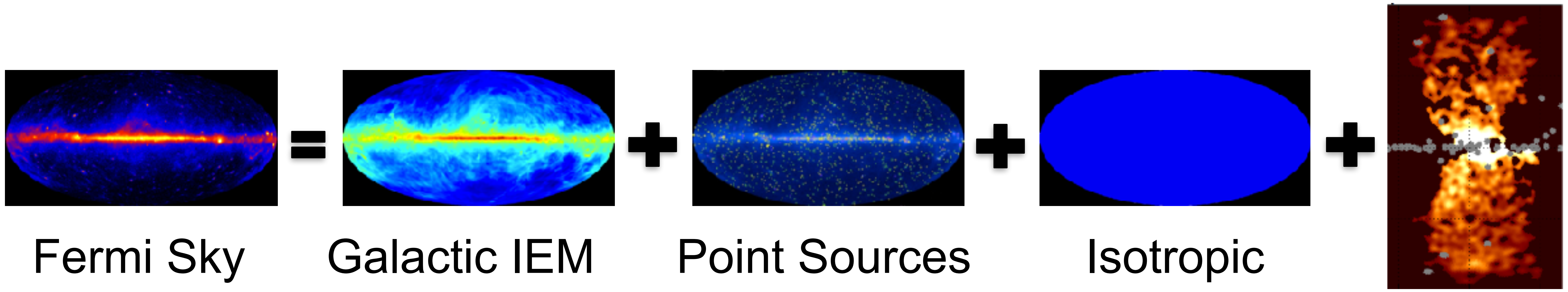
Dark Matter density

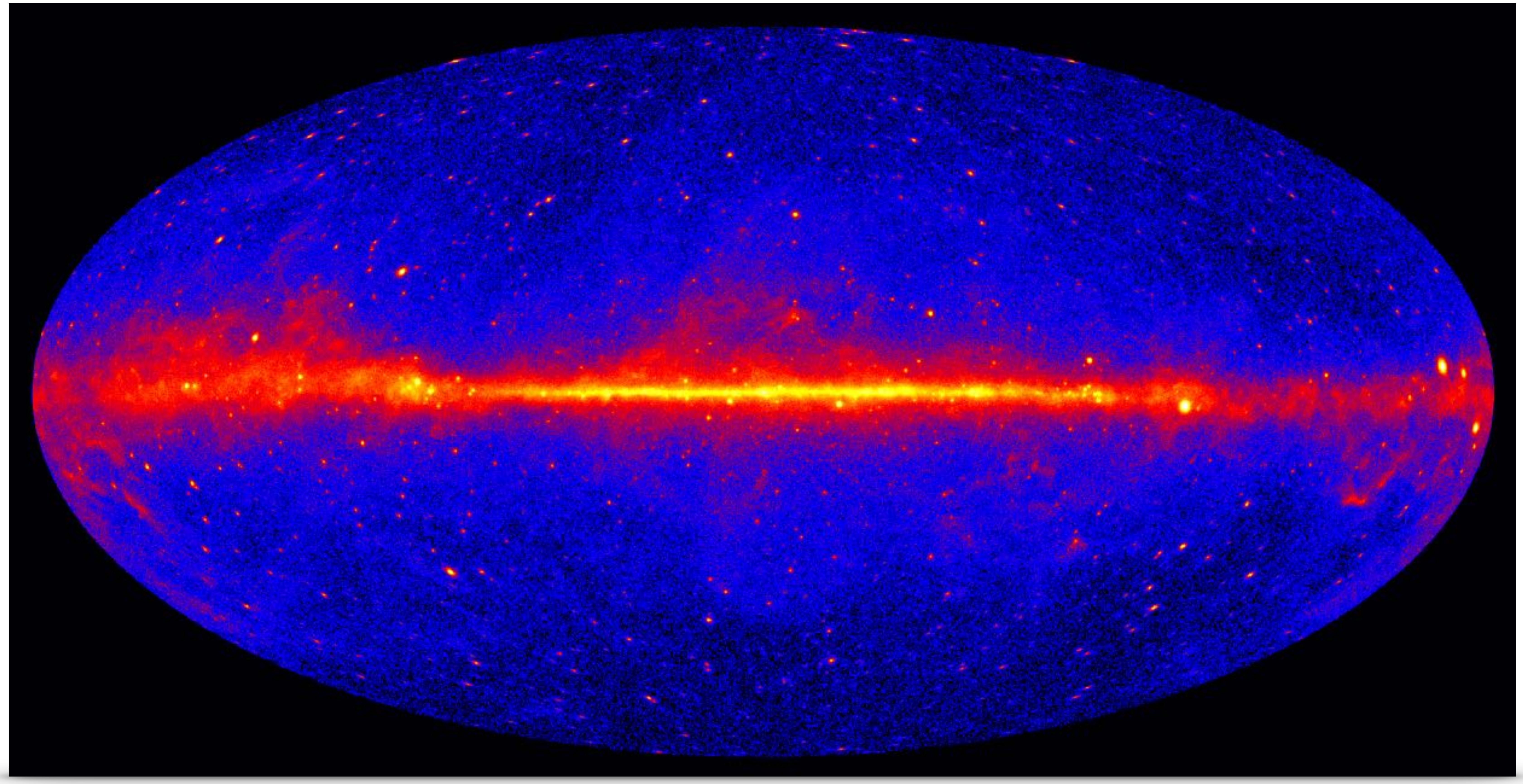




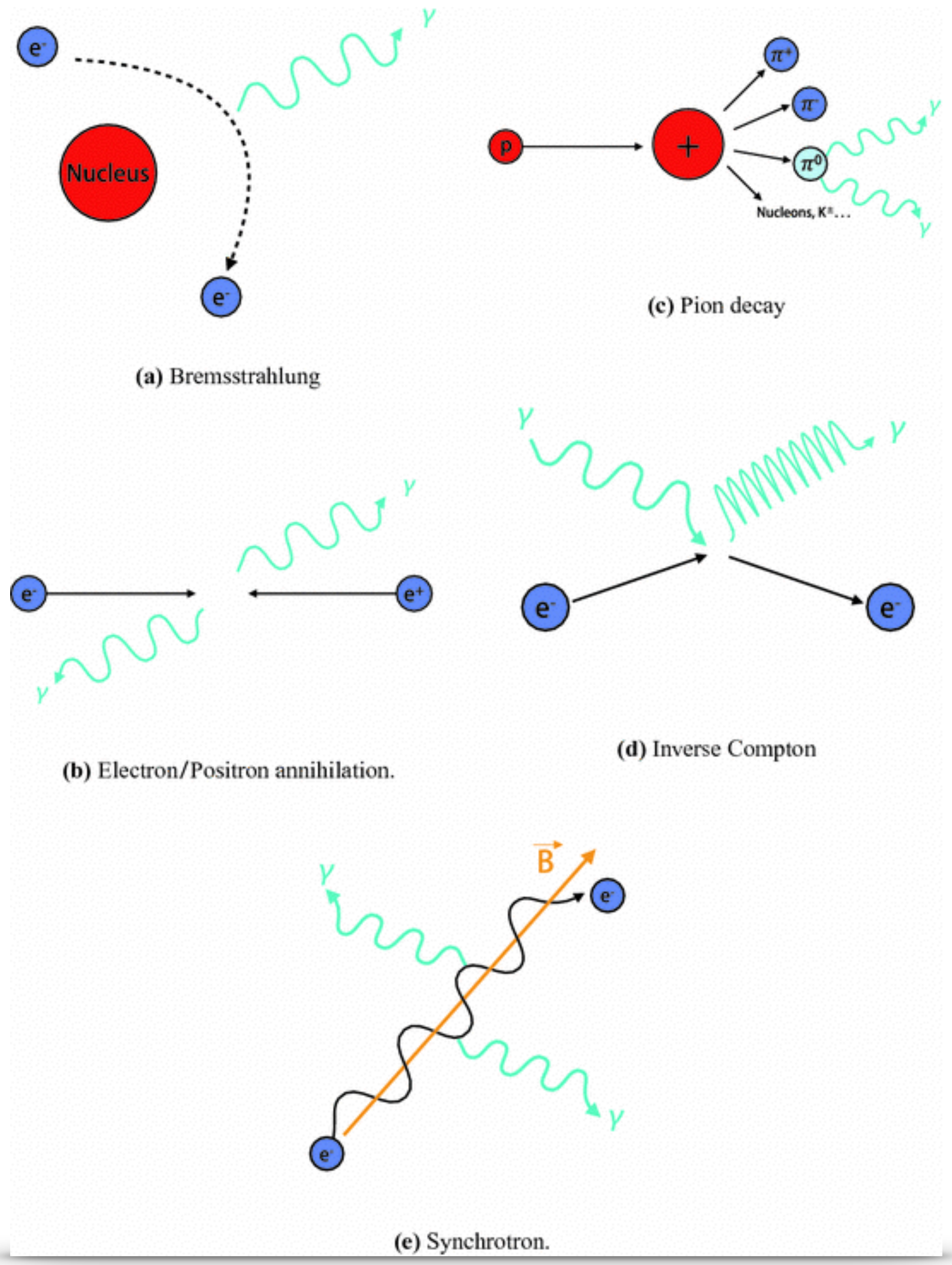


Standard picture for the gamma-ray sky

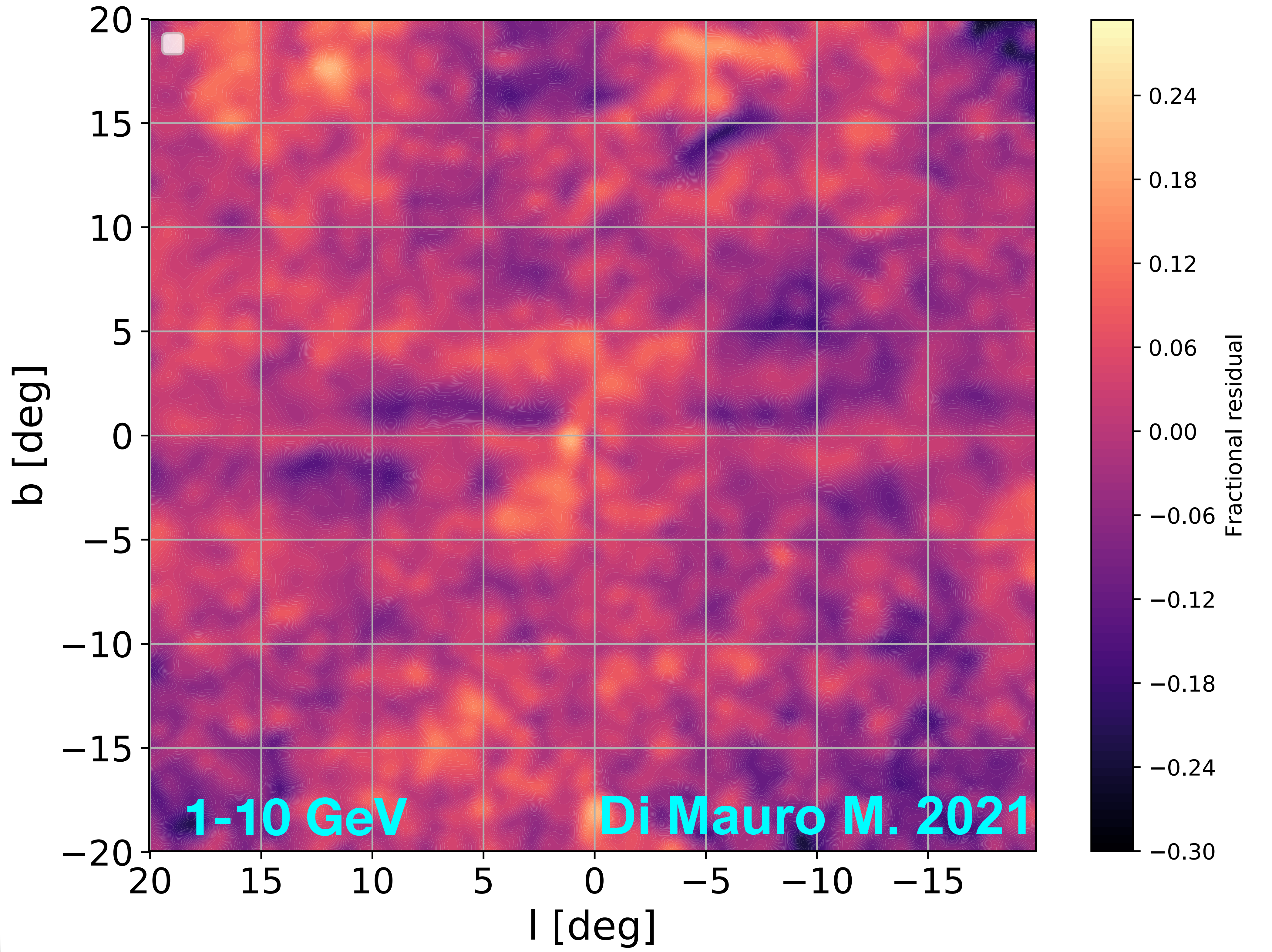




Galactic interstellar emission



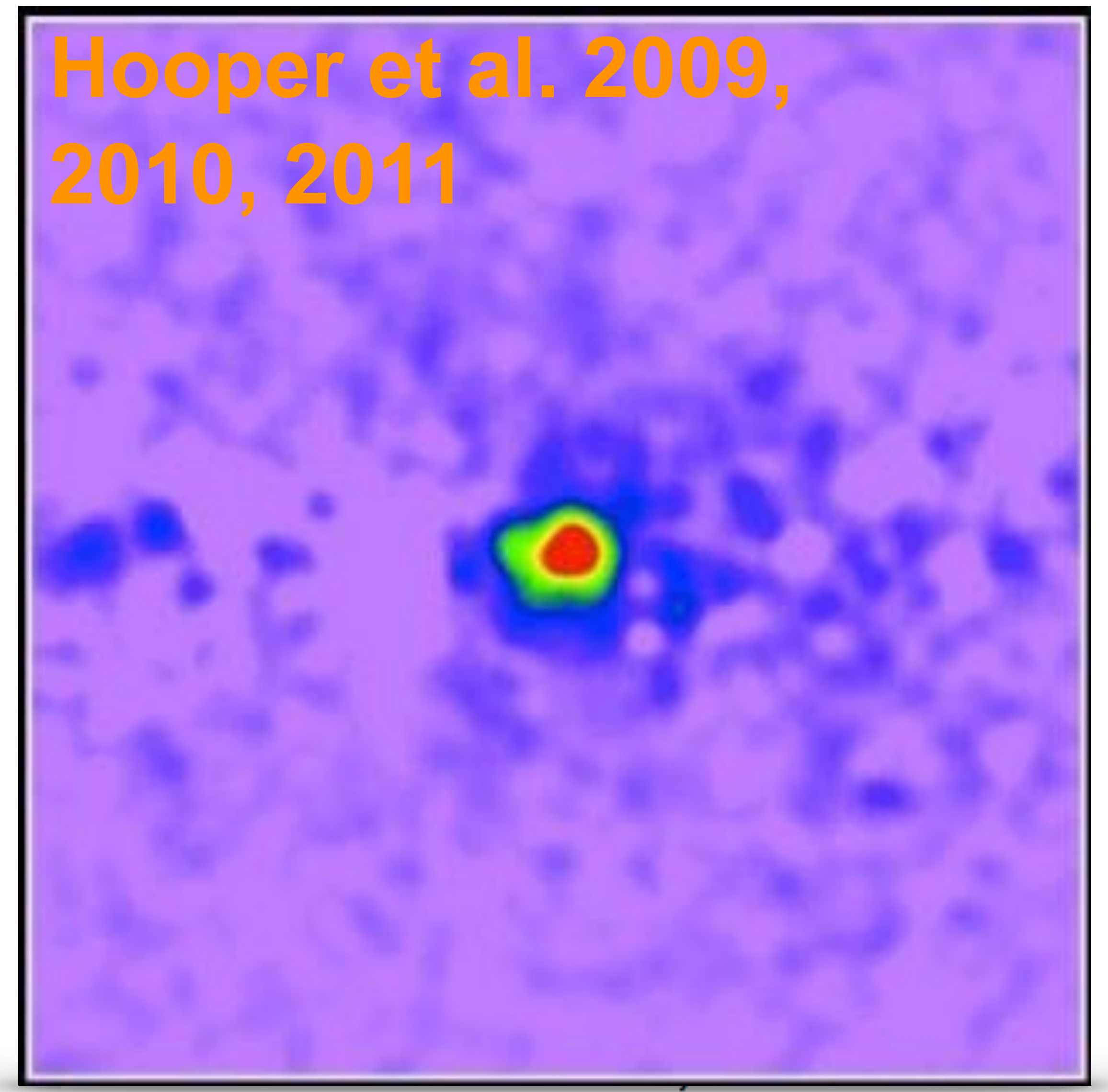
- The models usually used are divided into:
  - Bremsstrahlung, π^0, ICS, isotropic component, Sun/Moon/Loop I and the Fermi bubbles.
- The residuals are roughly at the level of 20-25% of the data.

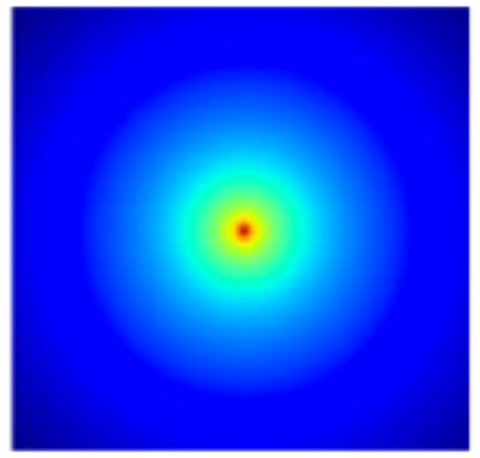


The GeV Excess in the Galactic Center (GCE)

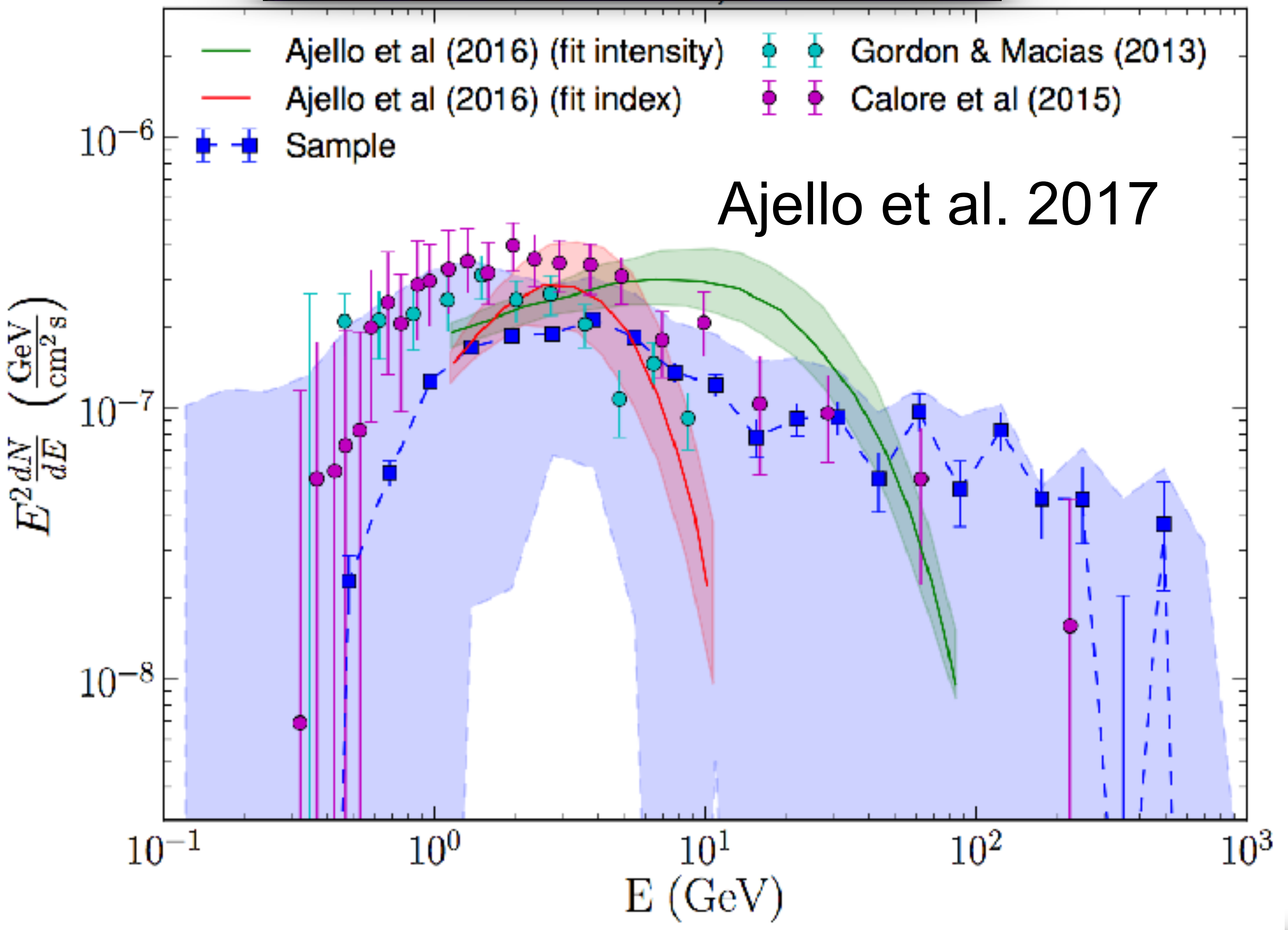
- **Bright** and highly significant.
- **Spatially symmetric** around the Galactic center: dN/dV $\propto r^{-2.5}$ —> compatible with a gNFW profile.
- **Energy spectrum peaked at a few GeV** —> DM annihilating into a bottom-anti-bottom (bb) M_{DM}=40 GeV.
- **Annihilation cross** section roughly equal to the thermal cross section is needed.

The GeV excess is thus perfectly compatible with DM in the halo of our Galaxy

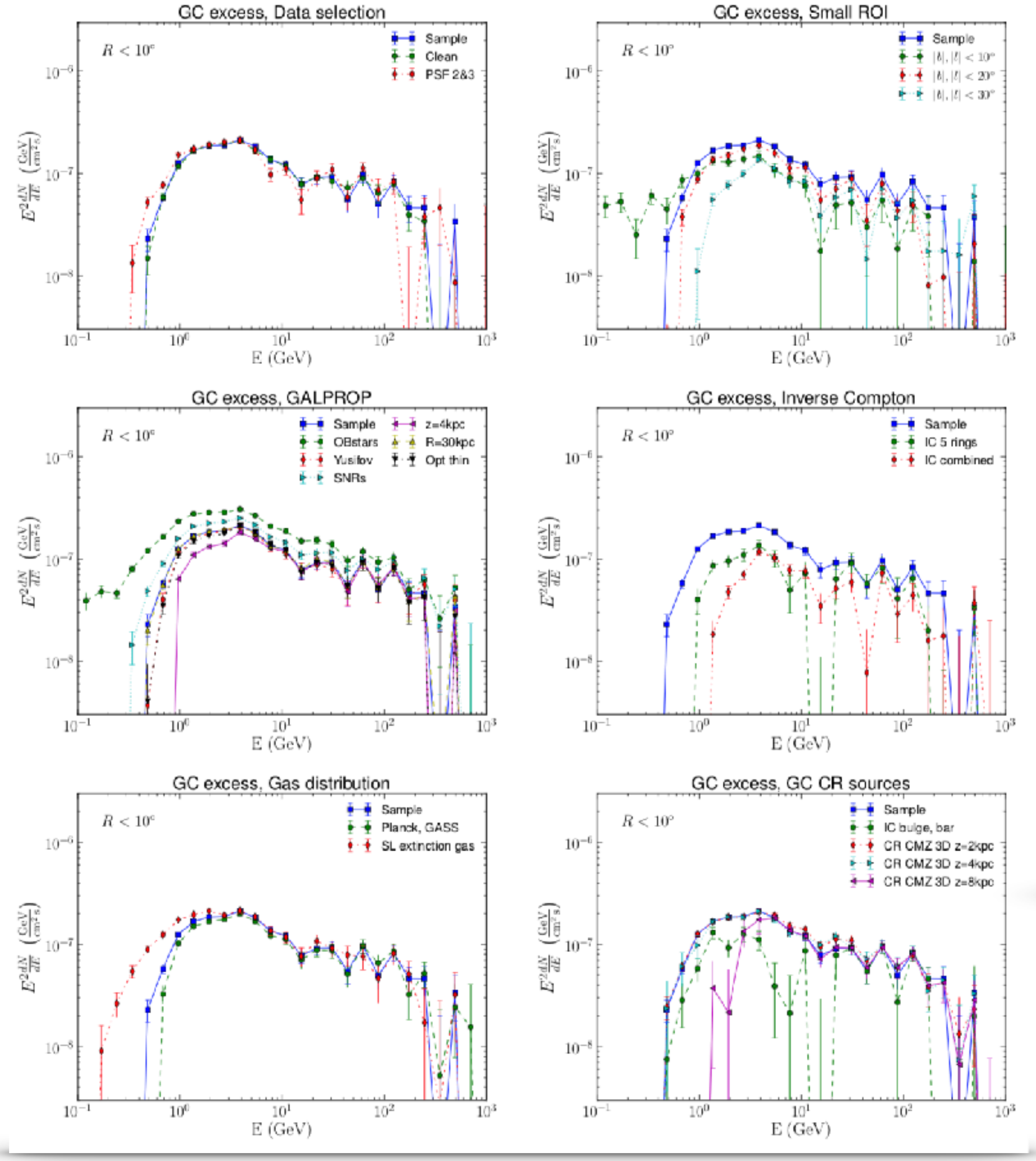


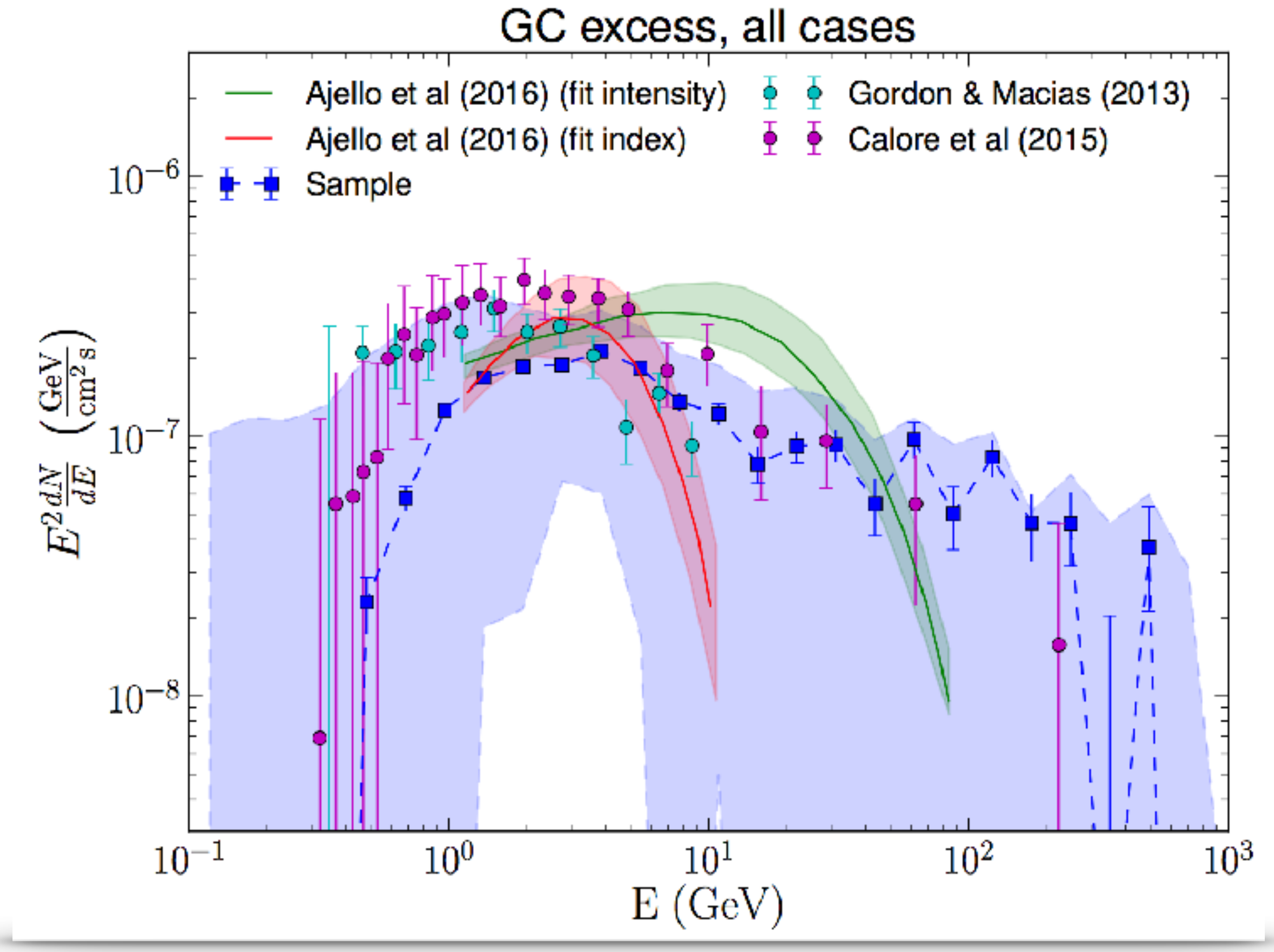


DM



Uncertainties in the GCE flux

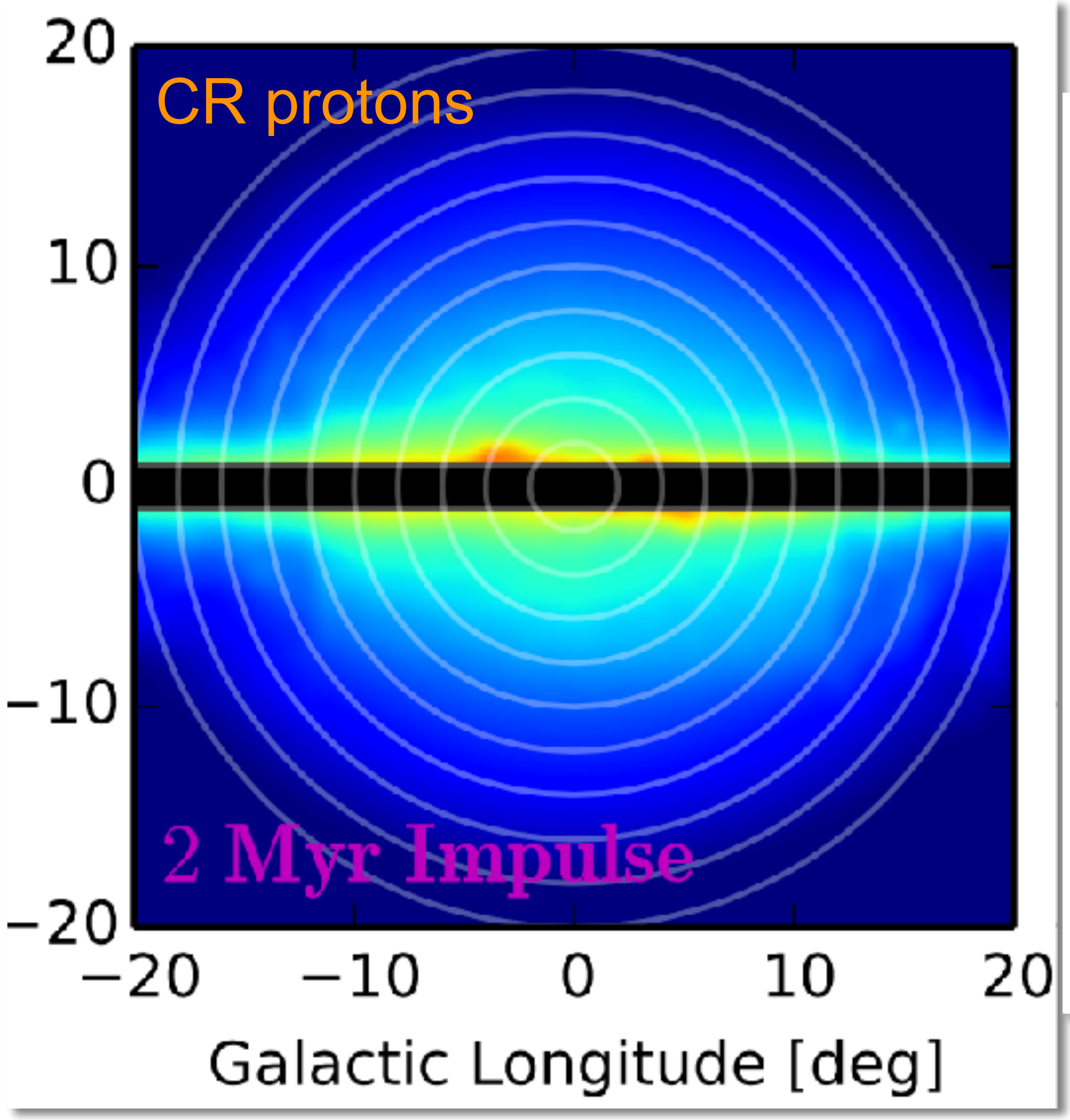




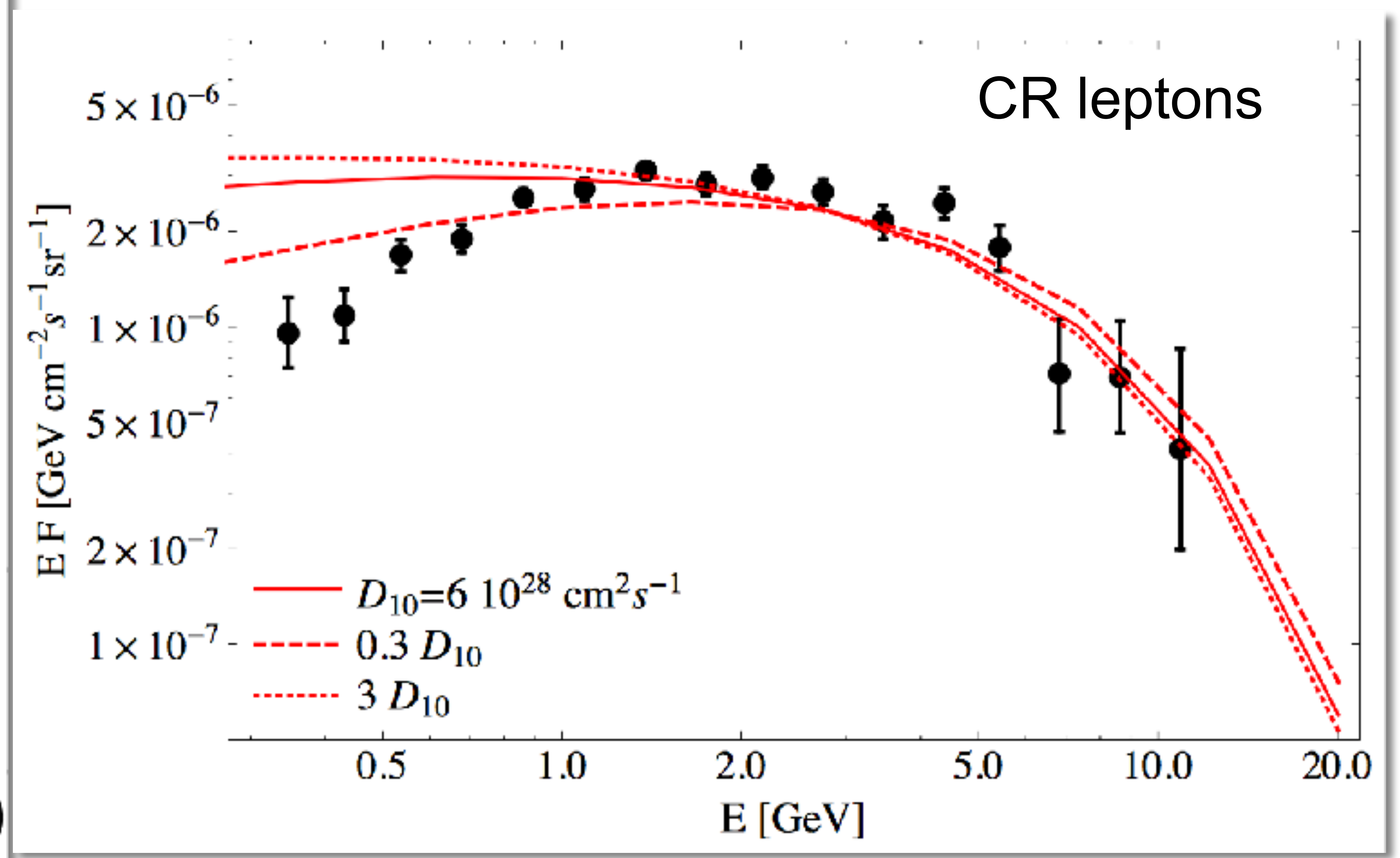
Ajello et al. 2017

Other interpretations for the GeV excess

- Recent outbursts of CR protons or of CR leptons.
- **Hadronic scenario:** γ-ray signal extended along the Galactic plane (Petrovic et al. 2014).
- **Leptonic outburst:** correct spatial distribution but it requires at least two outbursts (Petrovic et al. 2014; Carlson et al. 2014; Cholis et al. 2015a; Gaggero et al. 2015).
- **Additional population of supernova remnants near the GC** (Gaggero et al. 2015; Carlson et al. 2016).



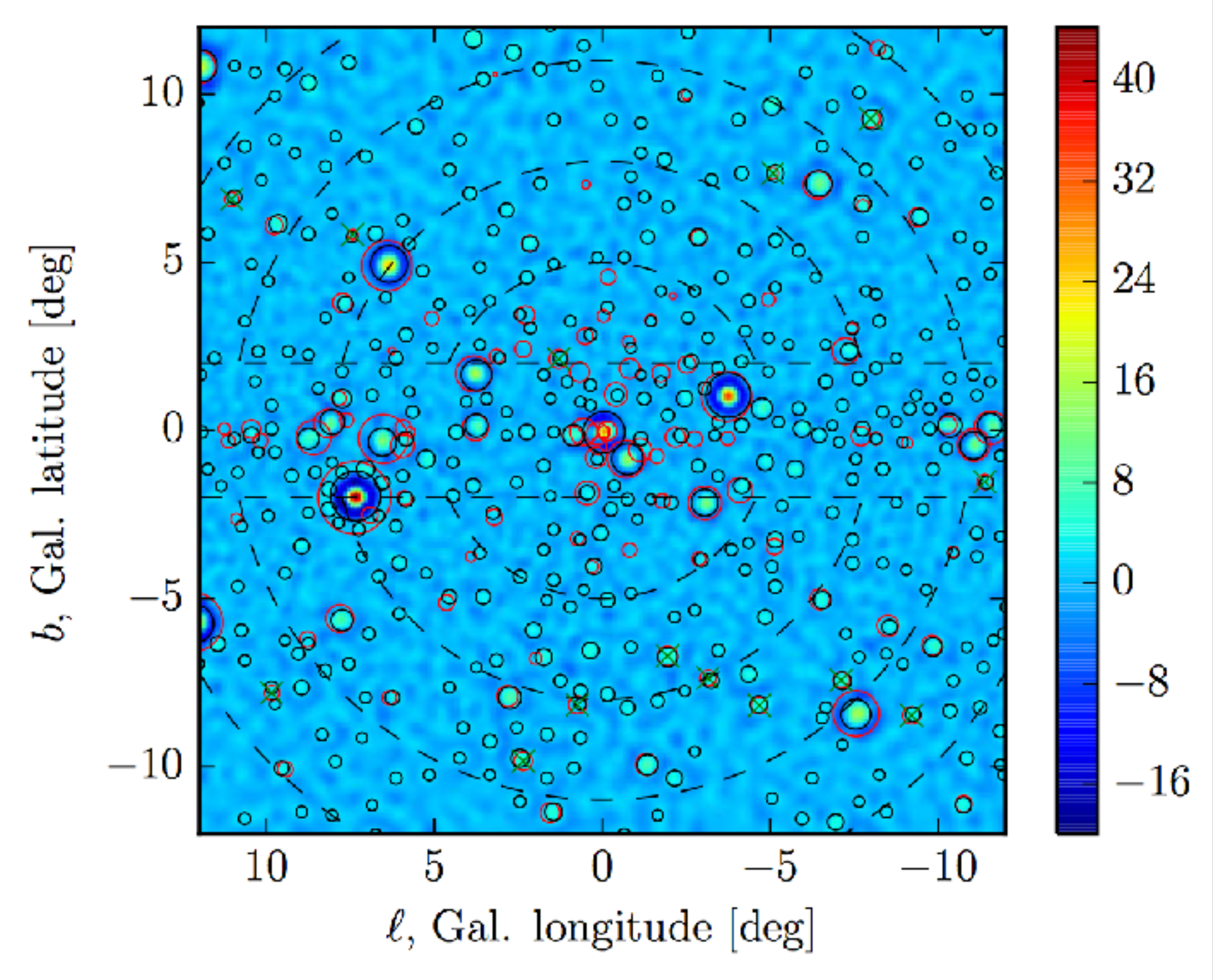
Carlson et al. 2014



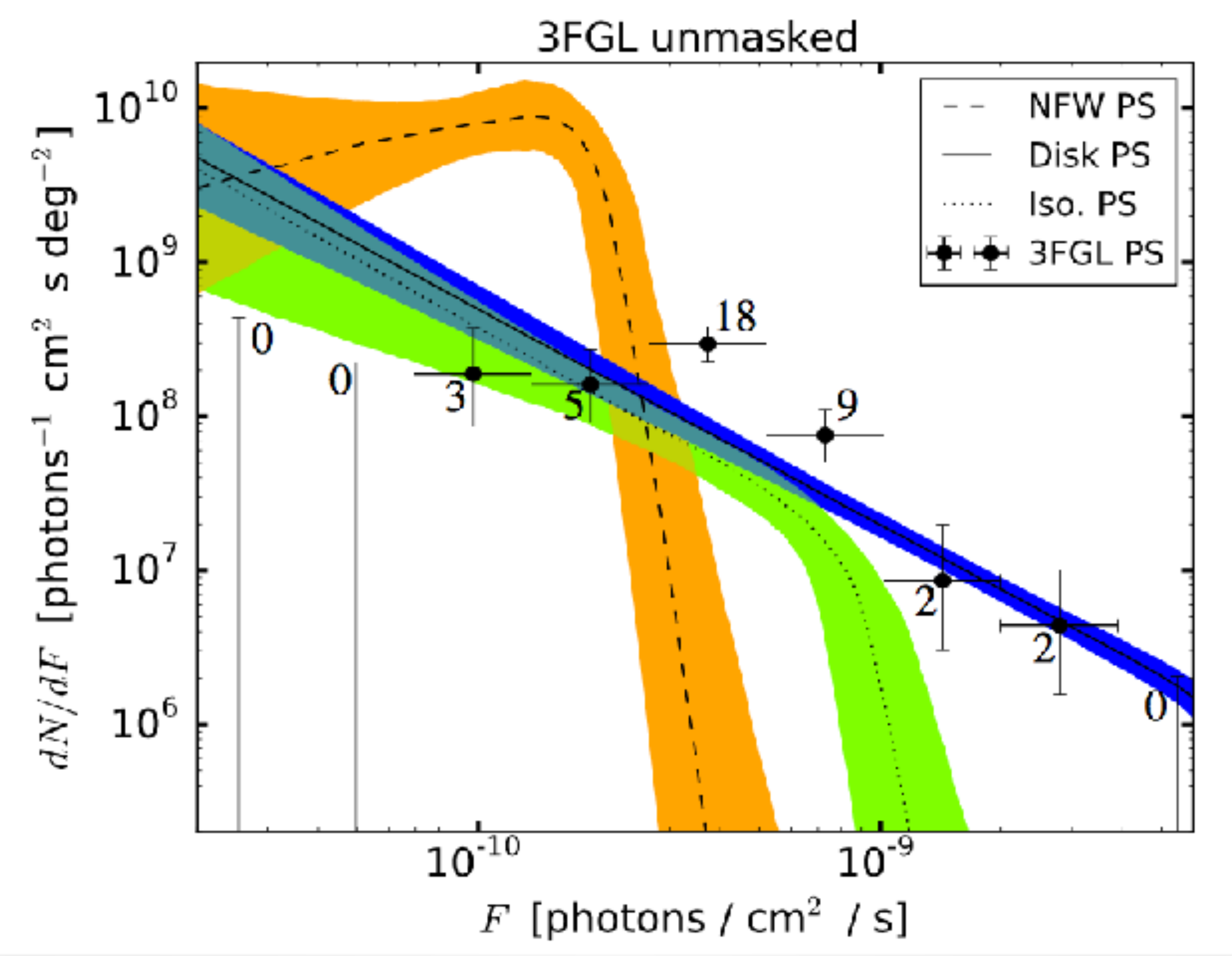
Petrovic et al. 2014

Pulsar interpretation

- **Bartels et al. (2015) and Lee et al. (2015):** population of unresolved sources distributed in the Galactic bulge of our Galaxy → Pulsars in the Galactic bulge (Macias et al).
- The spatial distribution, total γ-ray emission and energy spectrum of this unresolved emission of pulsars is compatible with the GeV excess.
- A fraction of these faint sources should be detected with future Fermi-LAT catalogs (Bartels et al. 2015 and Hooper et al. 2014).



Bartels et al. 2015



Lee et al. 2015

Most recent papers

- *Leane et al. 2019 and Chang et al. 2019:* the NPTF can misattribute to point sources or DM un-modeled point sources imperfection in the modeling of data.
- *Zhong et al. 2019* applied a wavelet method with 4FGL, and **do not find any evidence** of a faint population of un-modeled sources.
- *Buschmann et al. 2020:* They use a state-of-the-art model IEM find that the NPTF results continue to favor the interpretation that **the GCE excess is due, in part, to unresolved astrophysical point sources**.
- *List et al. 2019:* we find that the NN estimates for the flux fractions from the background templates are consistent with the NPTF; however, **the GCE is almost entirely attributed to smooth emission**.

The situation is thus rather confusing and dark matter has recently gained interest.

Papers related to this talk

Investigating the *Fermi* Large Area Telescope sensitivity of detecting the characteristics of the Galactic center excess

Paper I — *PRD 102, 103013 2020*

Mattia Di Mauro,*
NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA and
Catholic University of America, Department of Physics, Washington DC 20064, USA

The characteristics of the Galactic center excess measured with 11 years of *Fermi*-LAT data

Paper II — *PRD 103, 063029 (2021)*

Mattia Di Mauro,*
NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA and
Catholic University of America, Department of Physics, Washington DC 20064, USA

Multimessenger constraints on the dark matter interpretation of the *Fermi*-LAT Galactic center excess

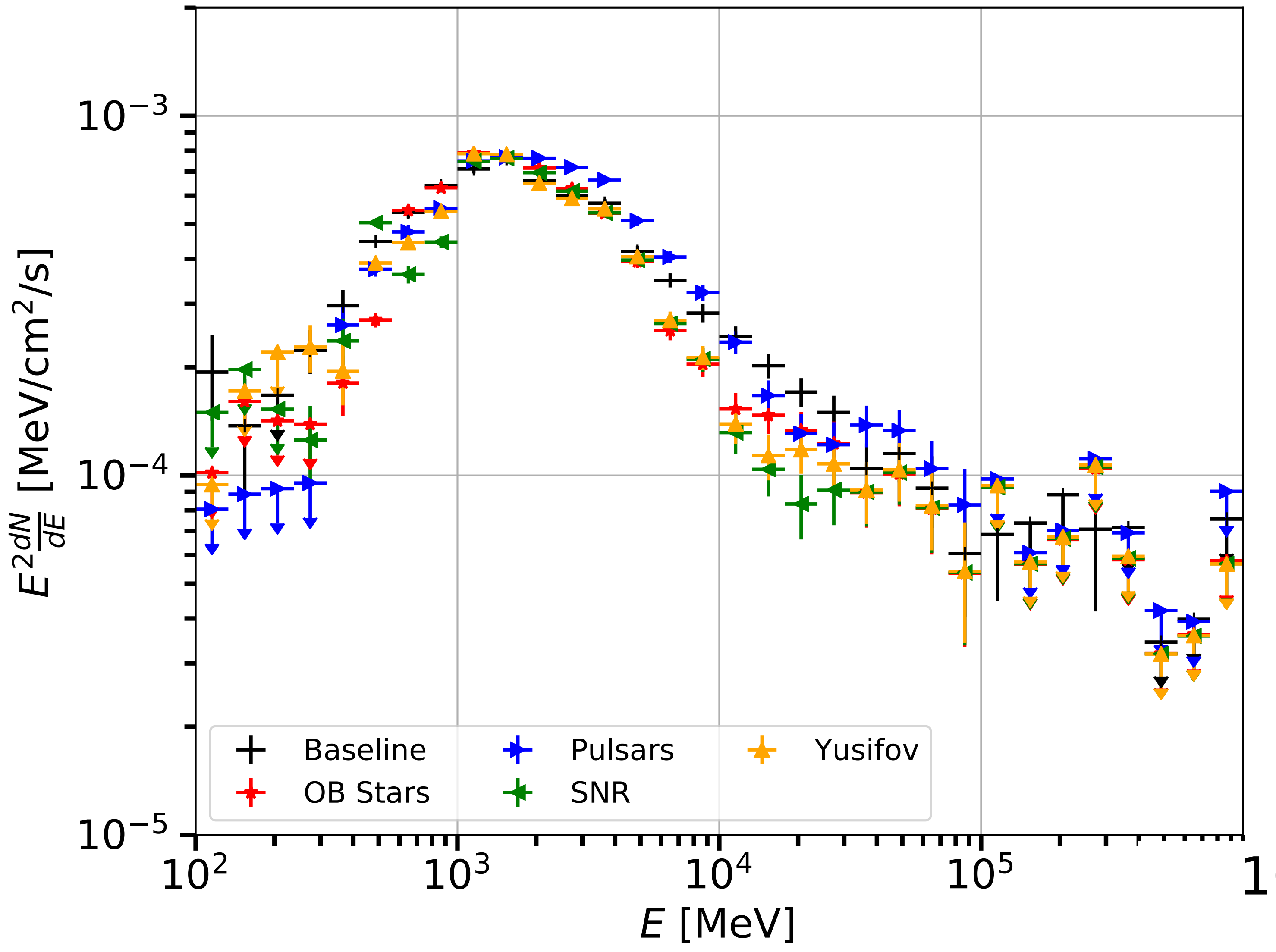
Paper III — *PRD 103, 123005 (2021)*

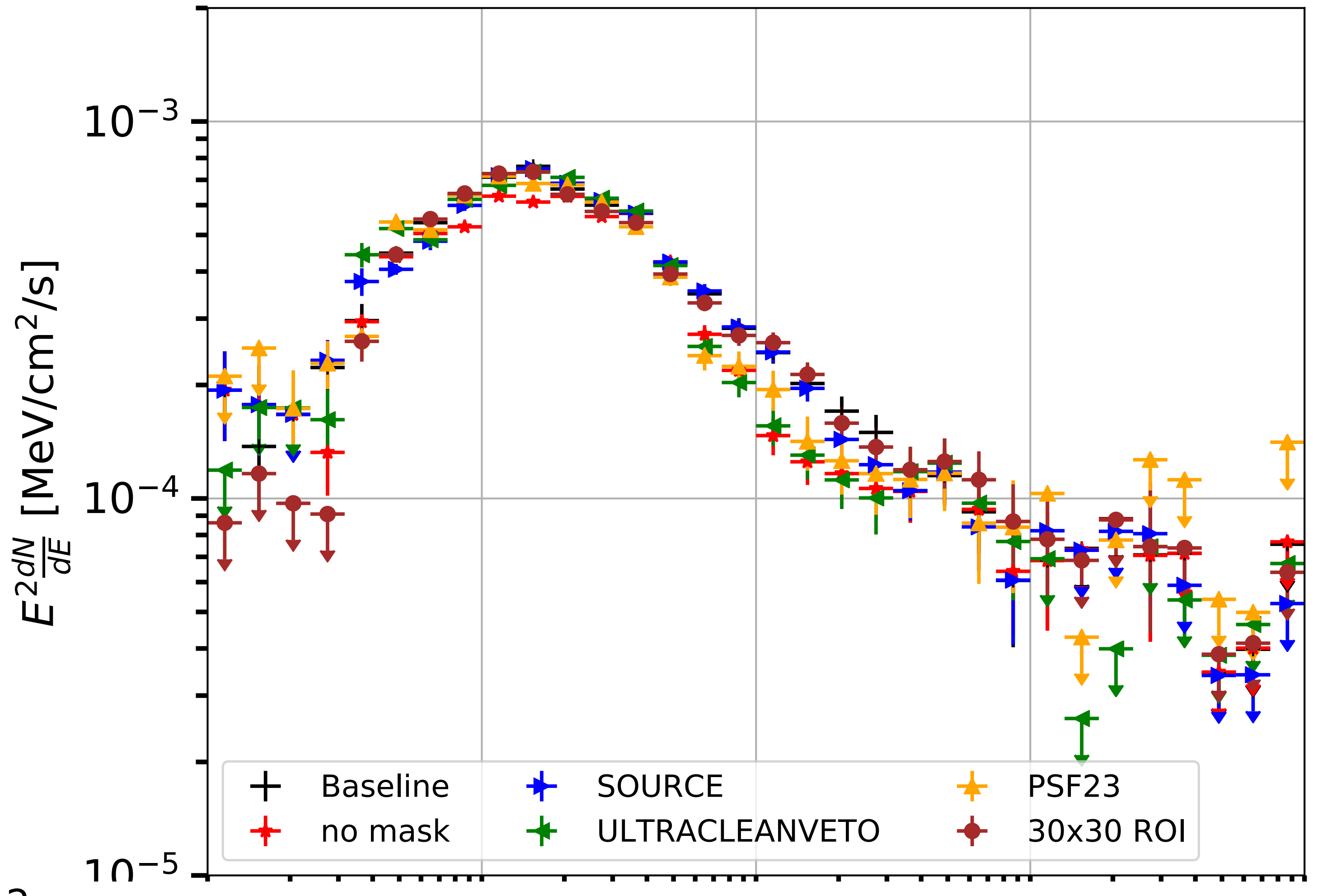
Mattia Di Mauro
Istituto Nazionale di Fisica Nucleare, via P. Giuria, 1, 10125 Torino, Italy

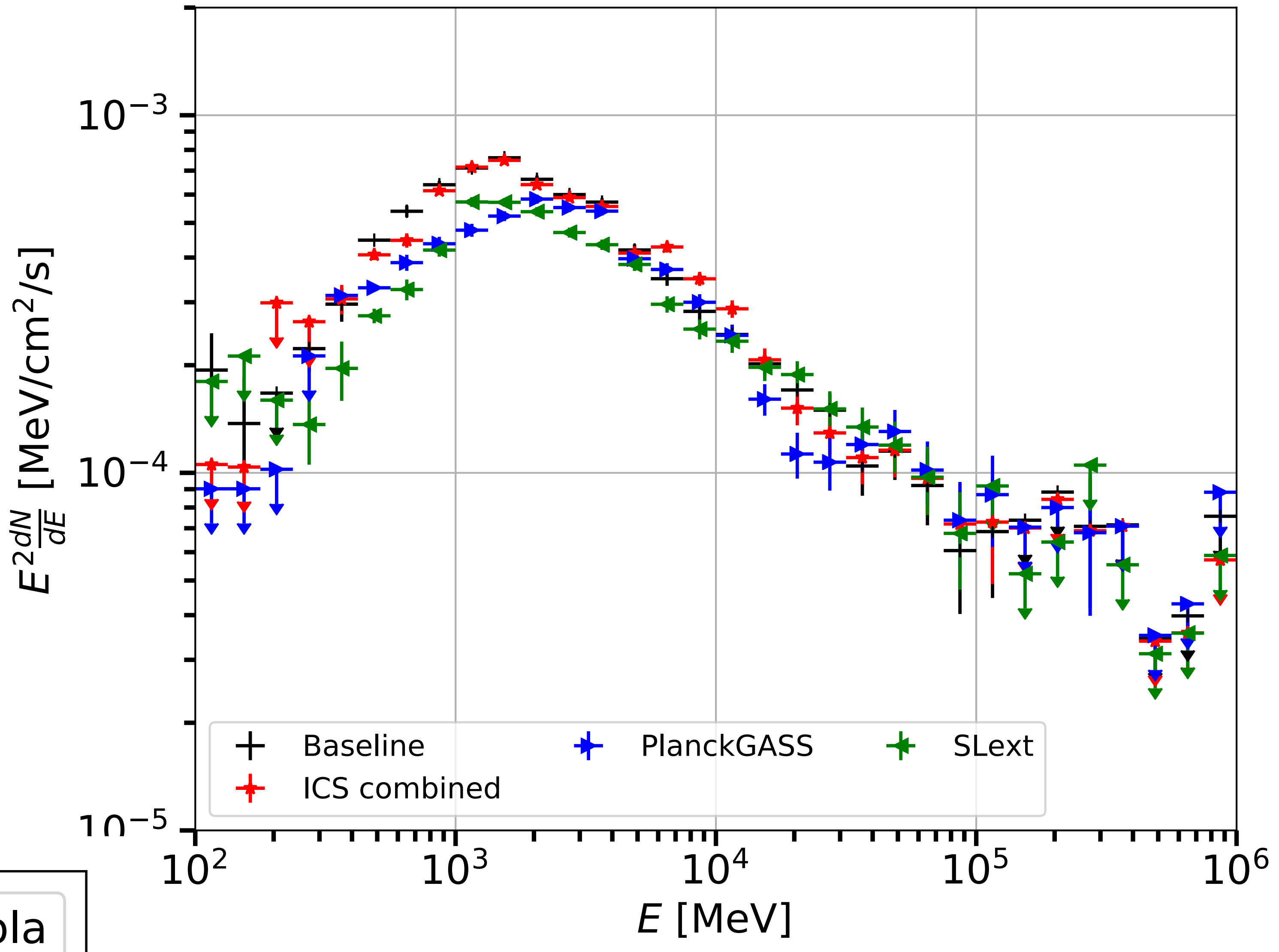
Martin Wolfgang Winkler
Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden

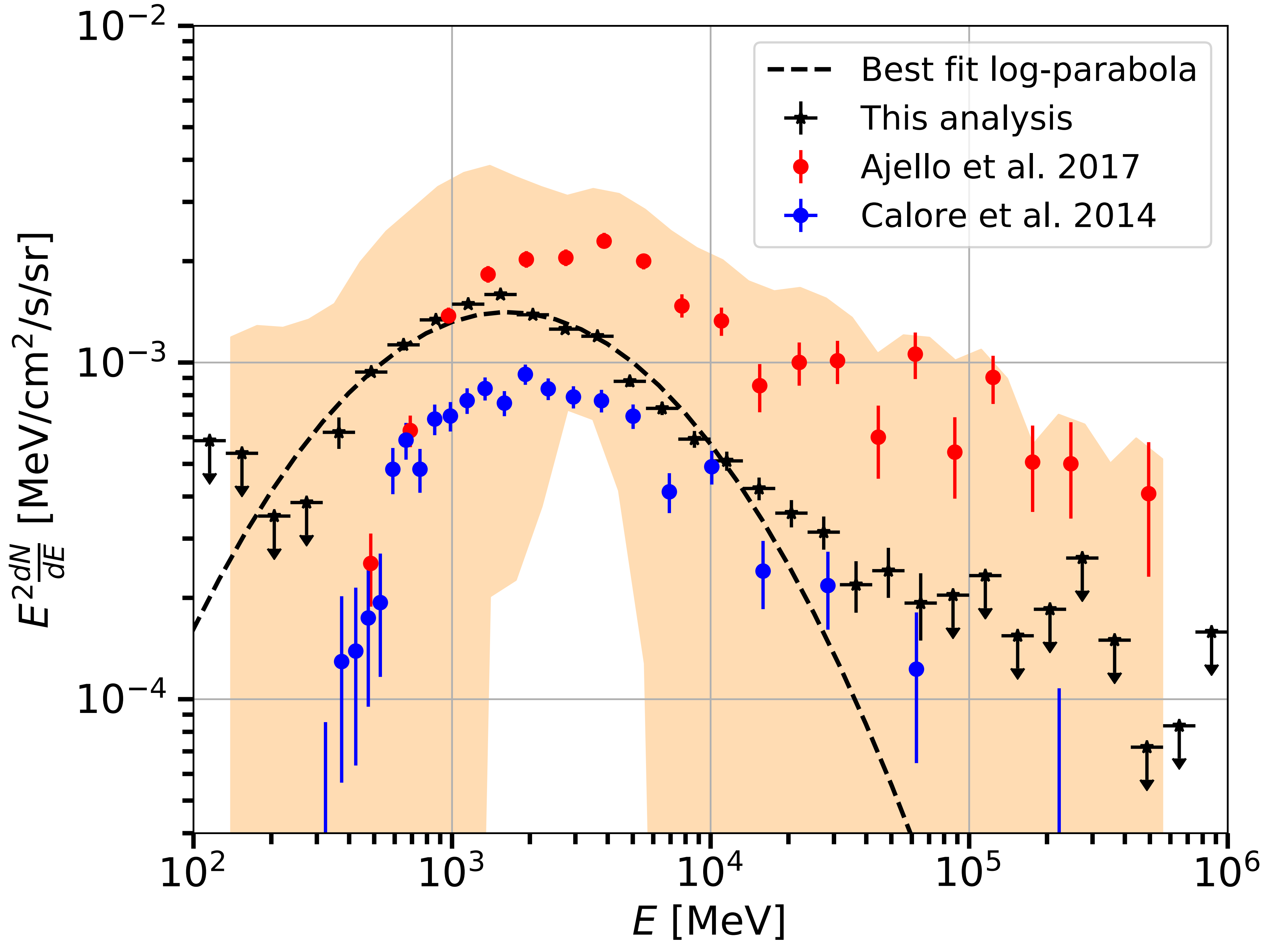
Paper II

GCE Energy spectrum



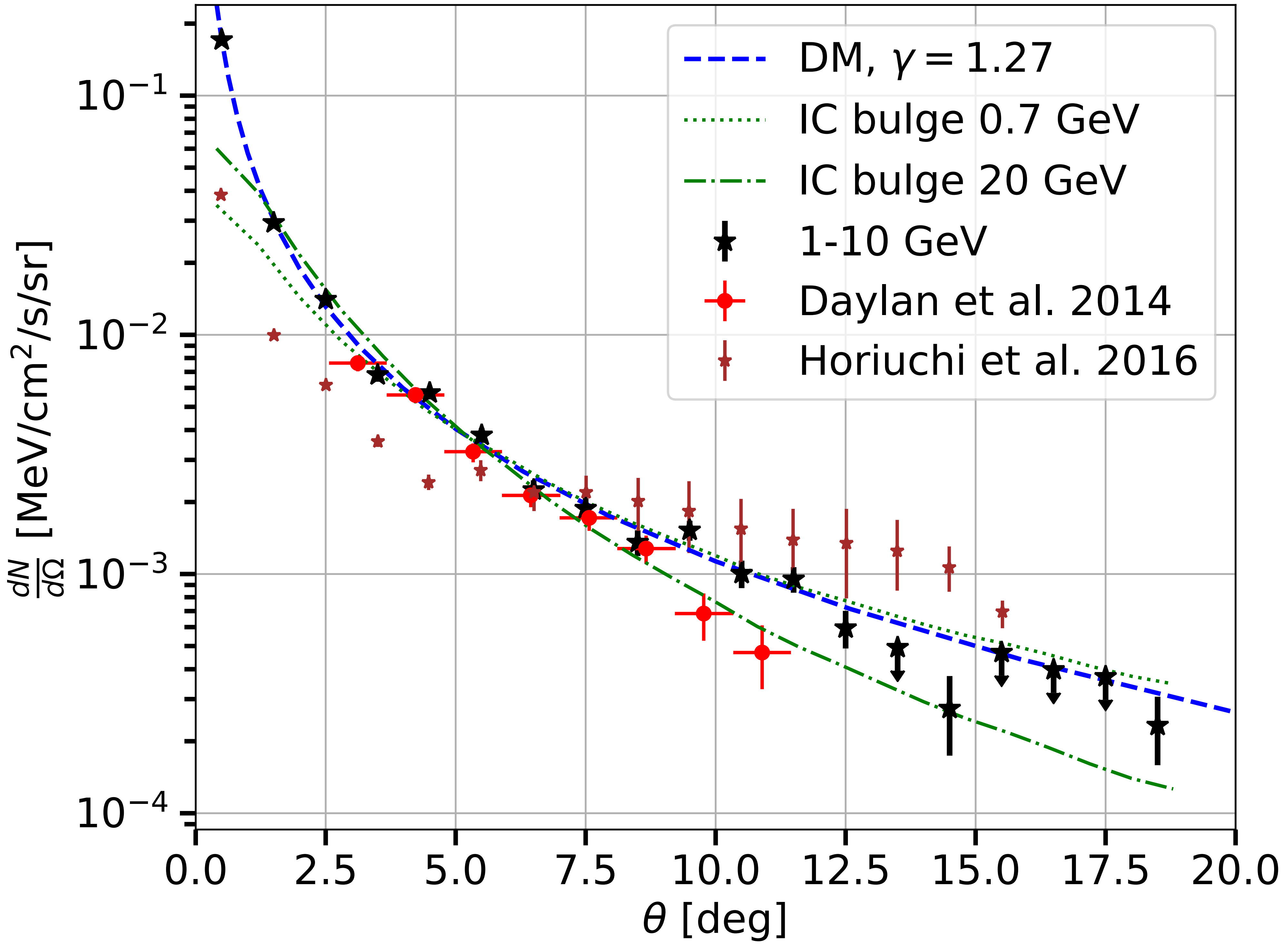


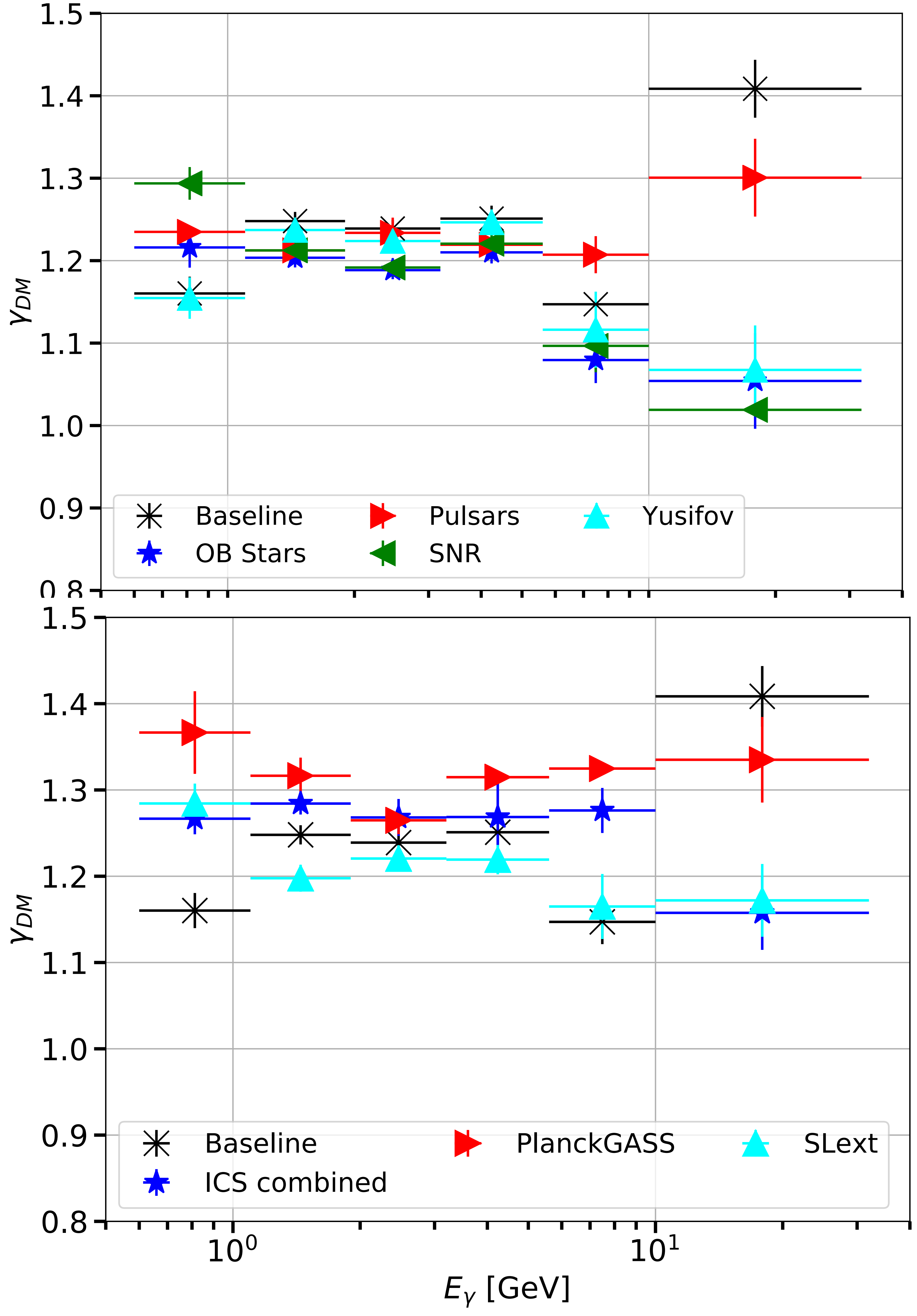




GCE spatial distribution

- There is no clear evidence of an energy variation of the spatial morphology.
- **The value of gamma is roughly 1.2-1.3.**





Paper II

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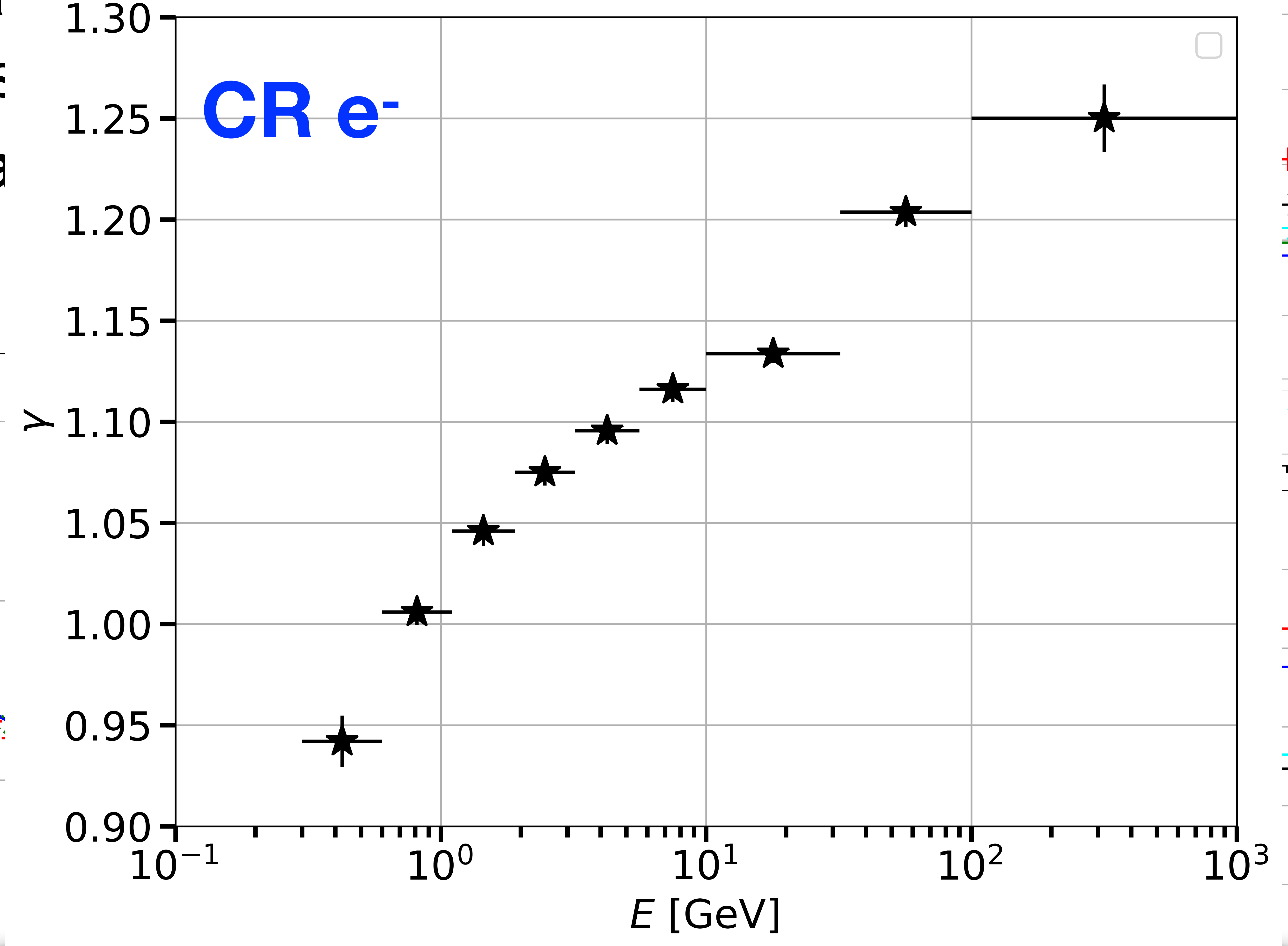
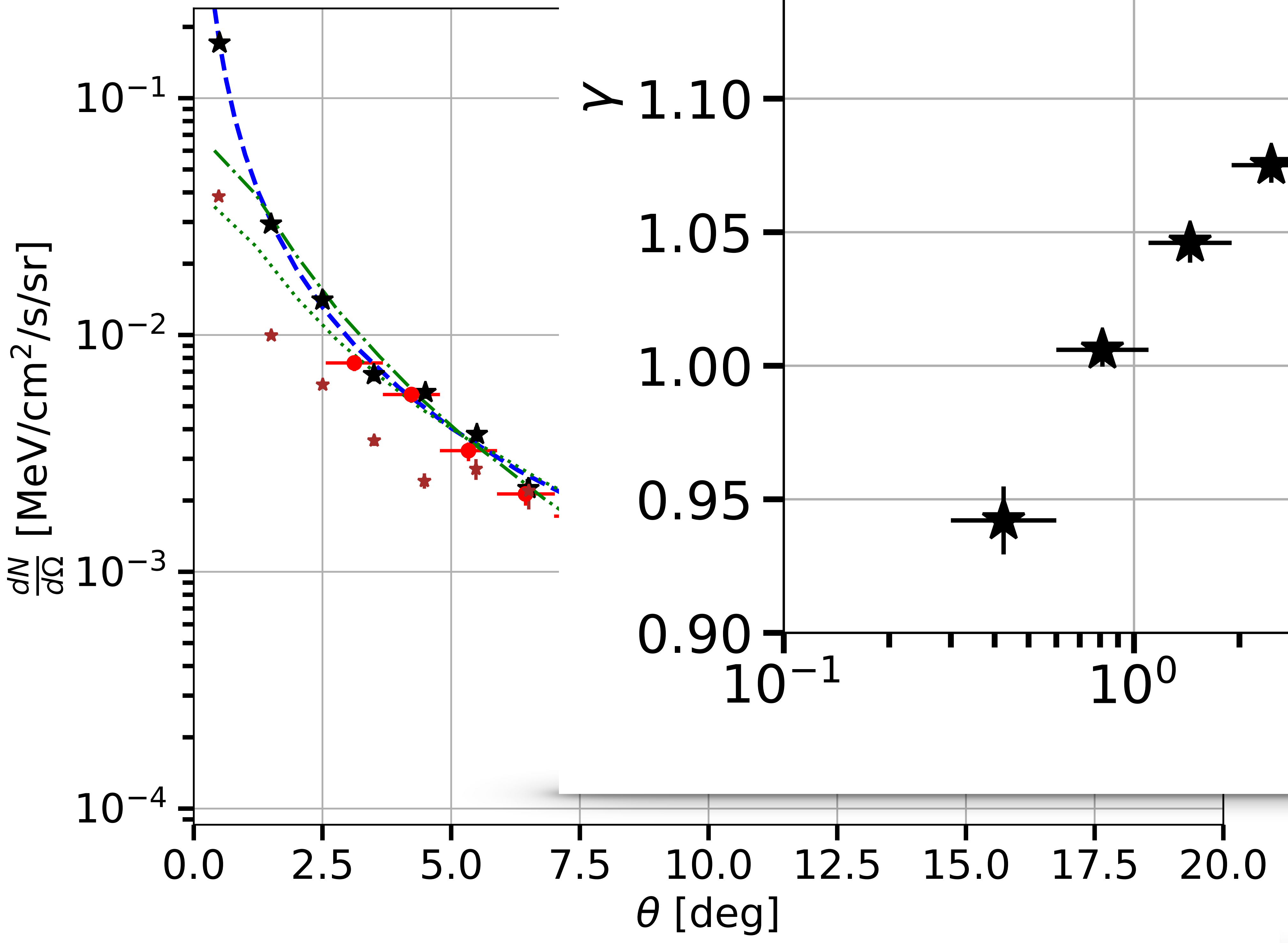
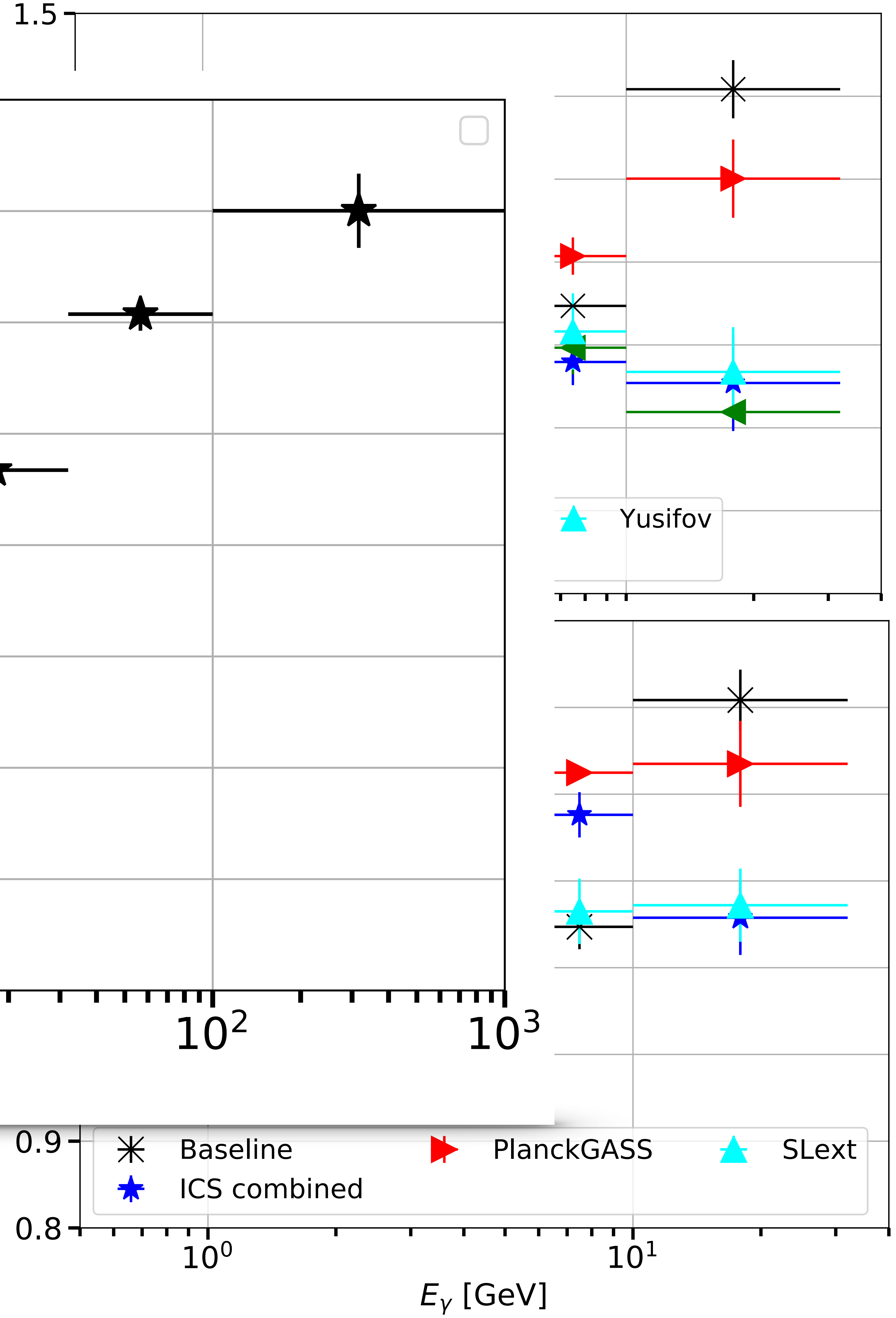
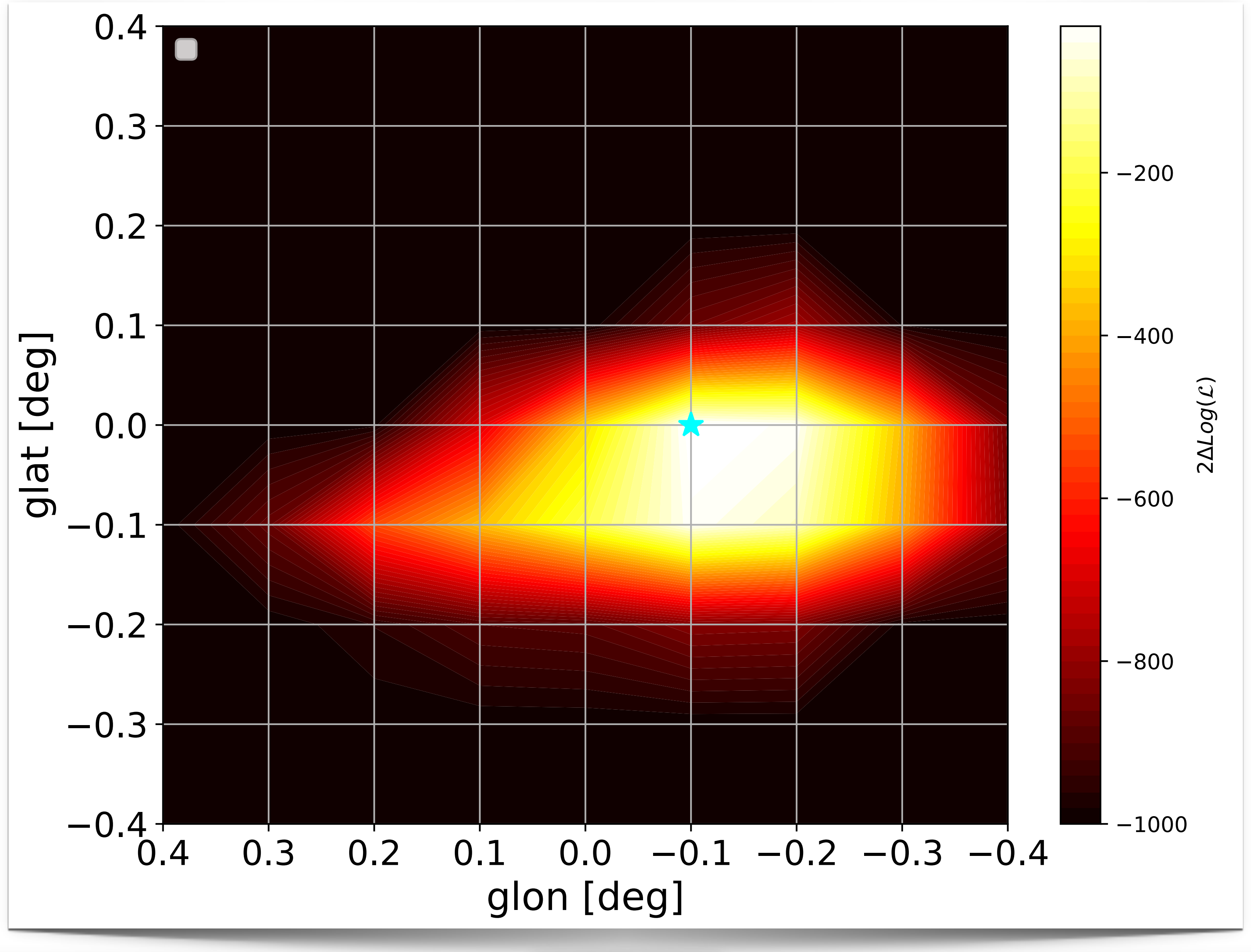


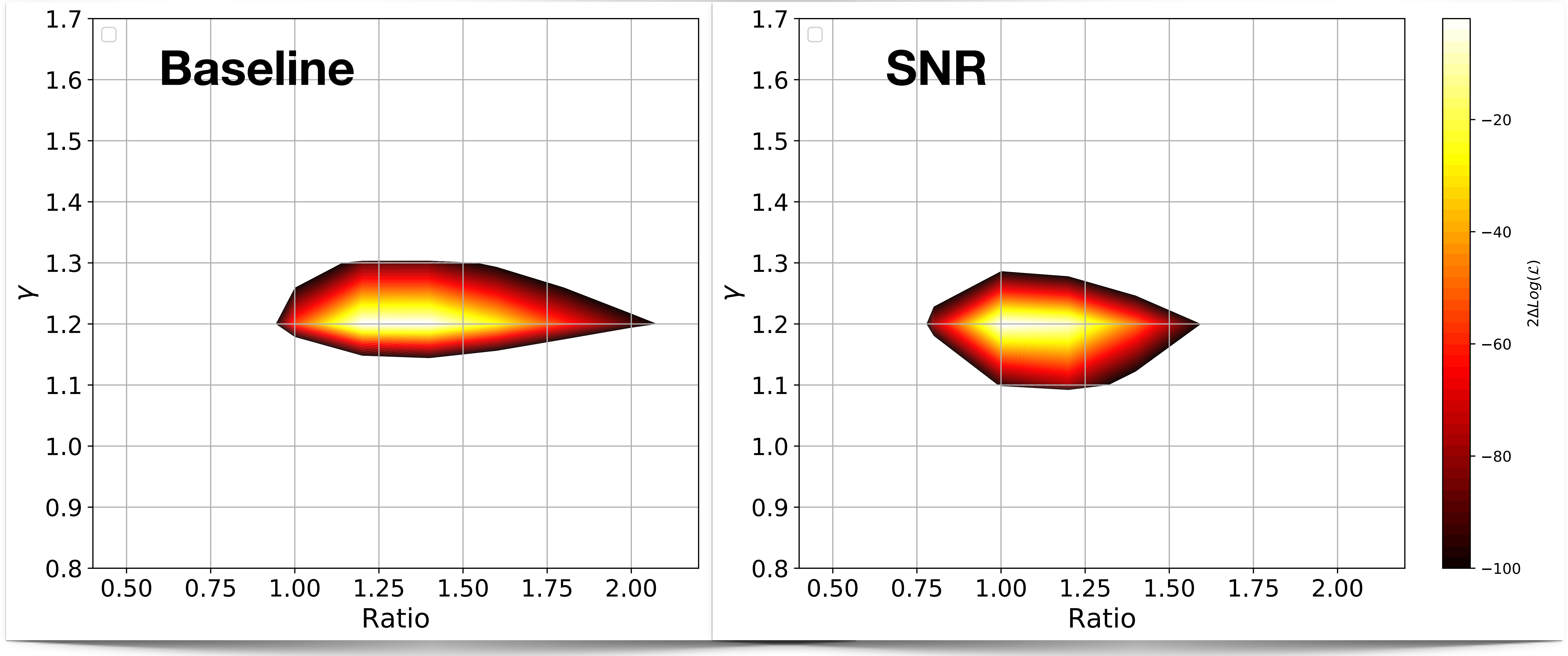




Position and sphericity of the GCE

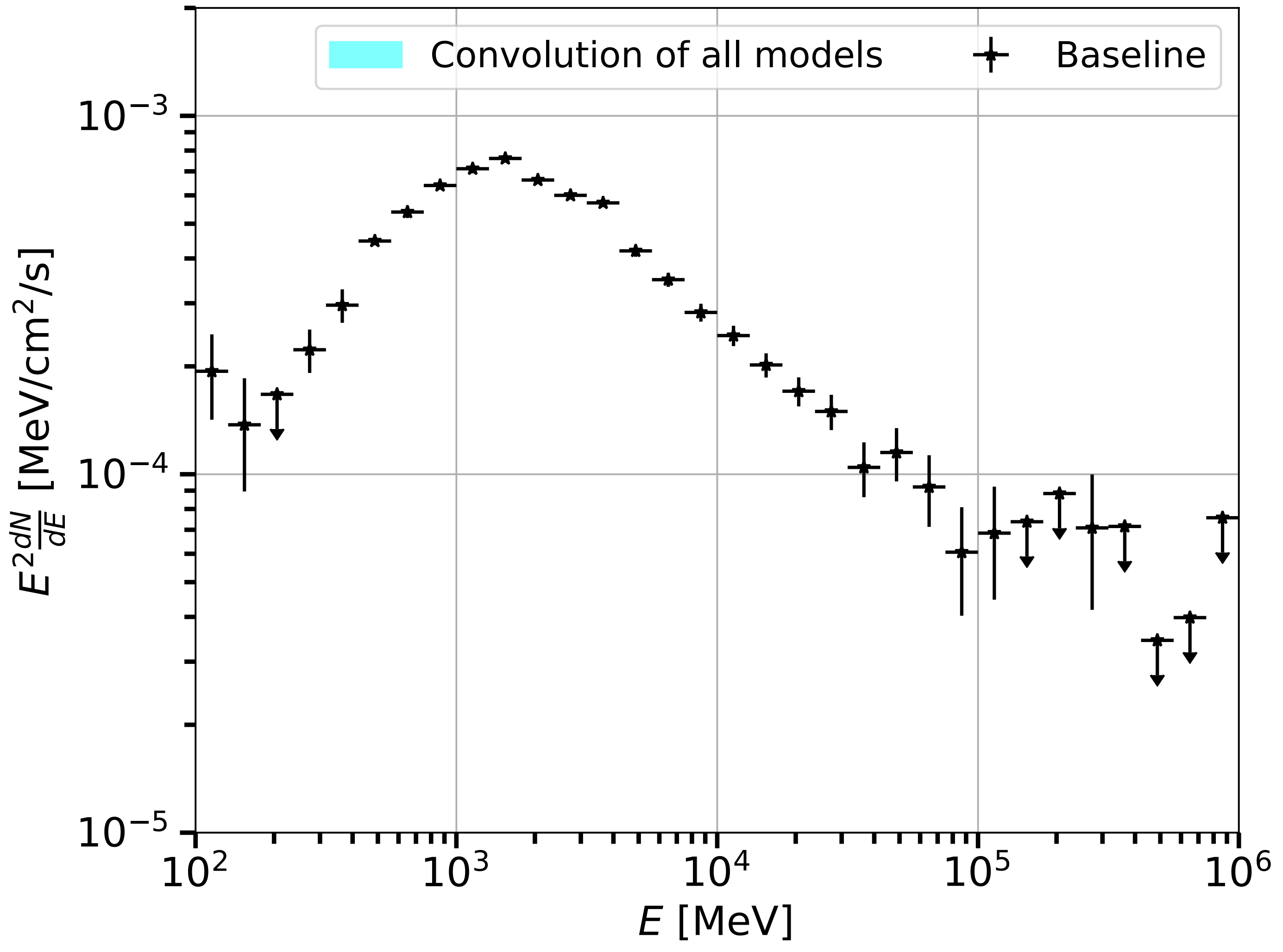
- ***POSITION***
  - The position is peaked at around l=(-0.05,-0.15).
  - **Very close to the dynamical position of the Galaxy (SagA).**
- ***SPHERICITY***
  - I run the analysis with an elliptical morphology where I vary the ratio between the two axis (ratio) and the value of gamma.
  - **I find that ratio = [0.8-1.20] and gamma=[1.1,1.2].**



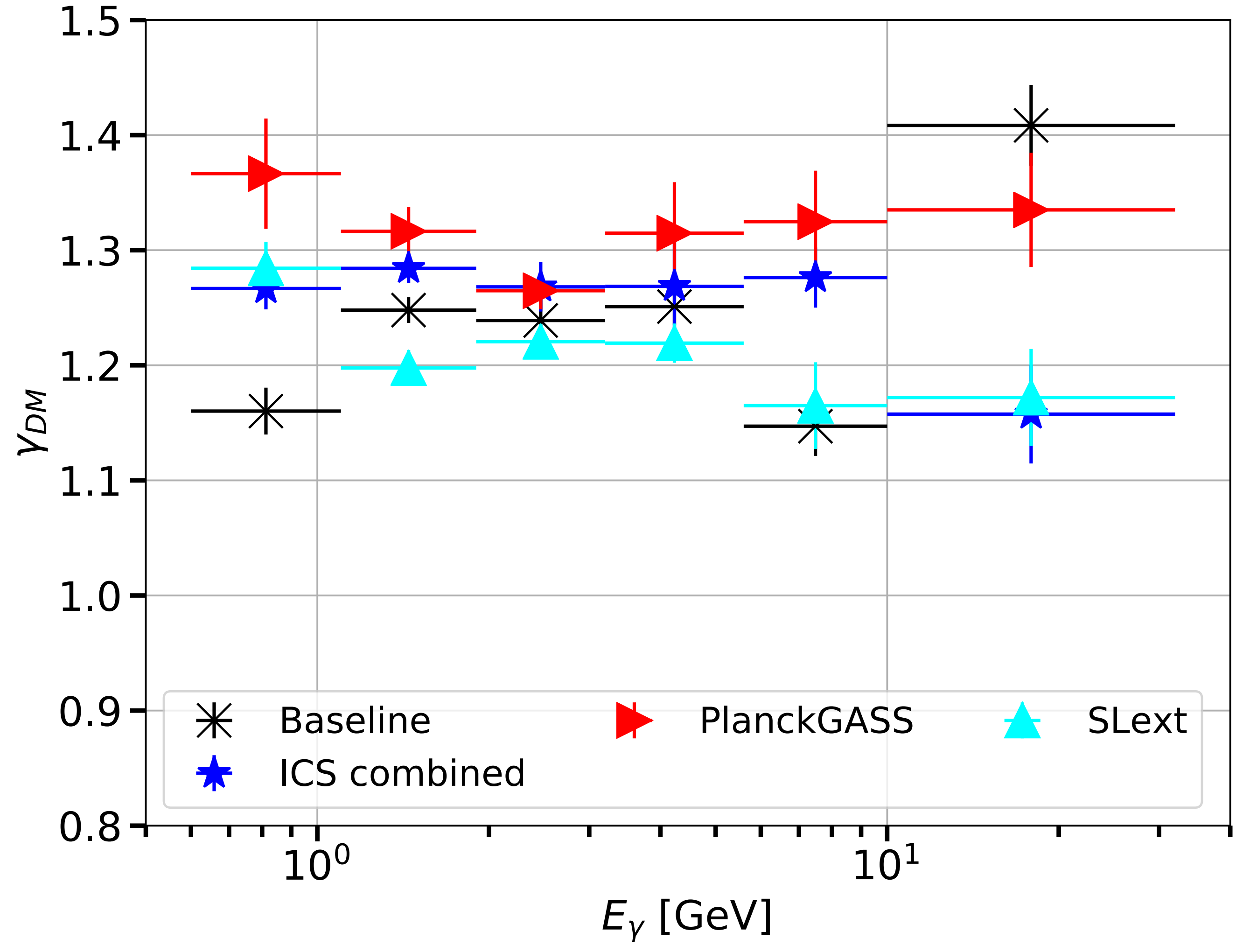


Characteristics of the GCE: Summary

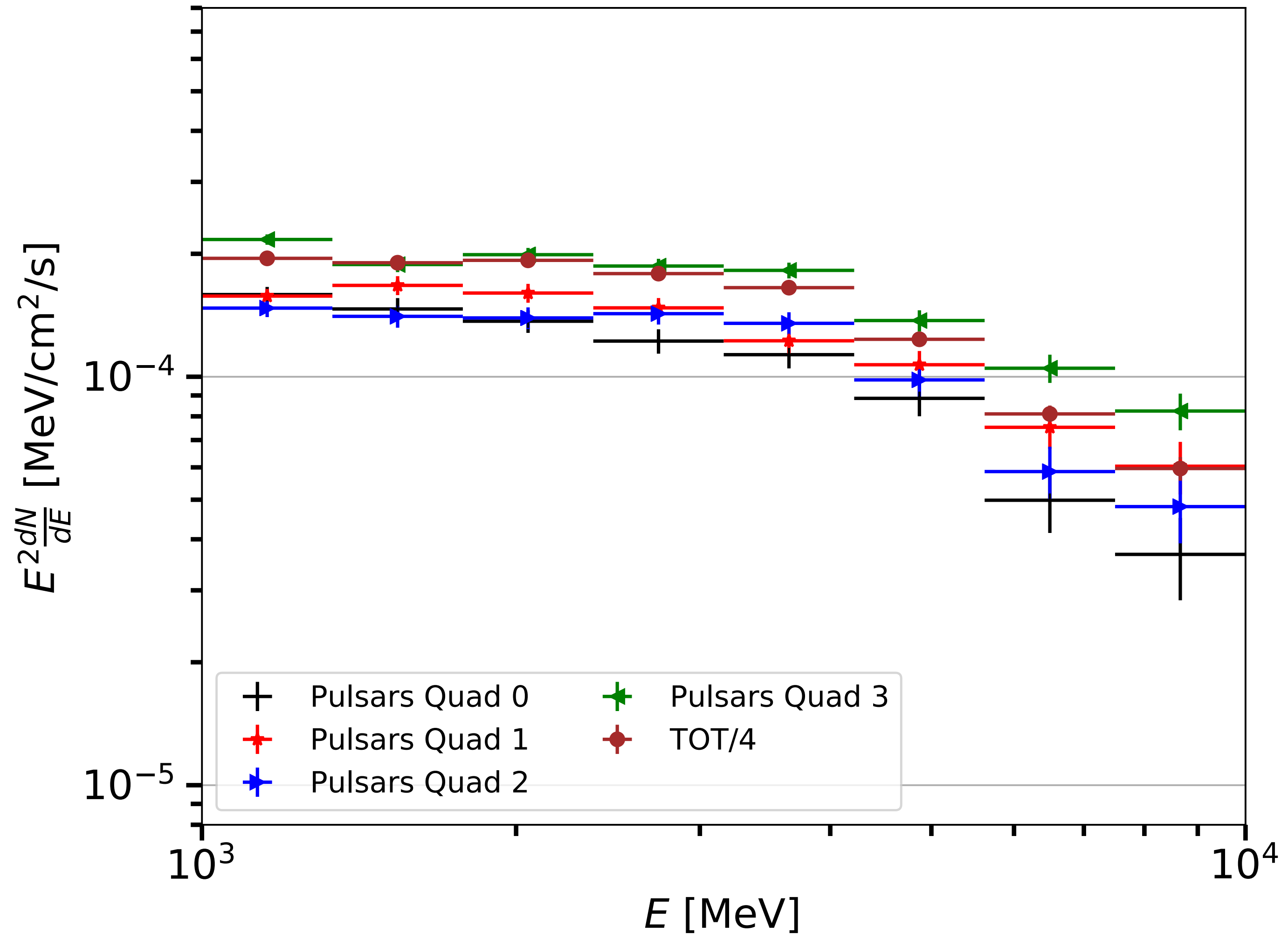
Spectrum peaked at a few GeV



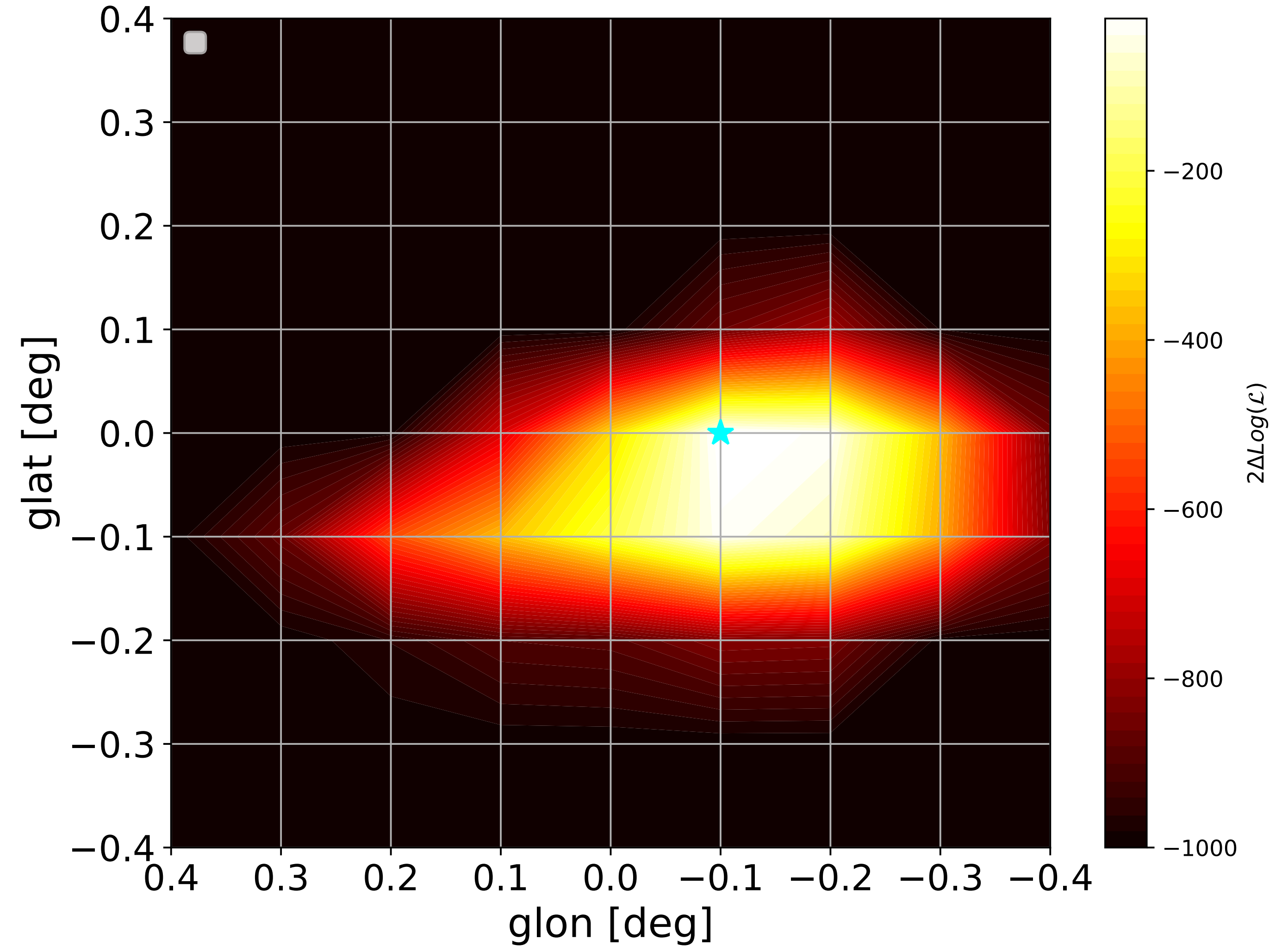
No energy dependence of spatial morphology.



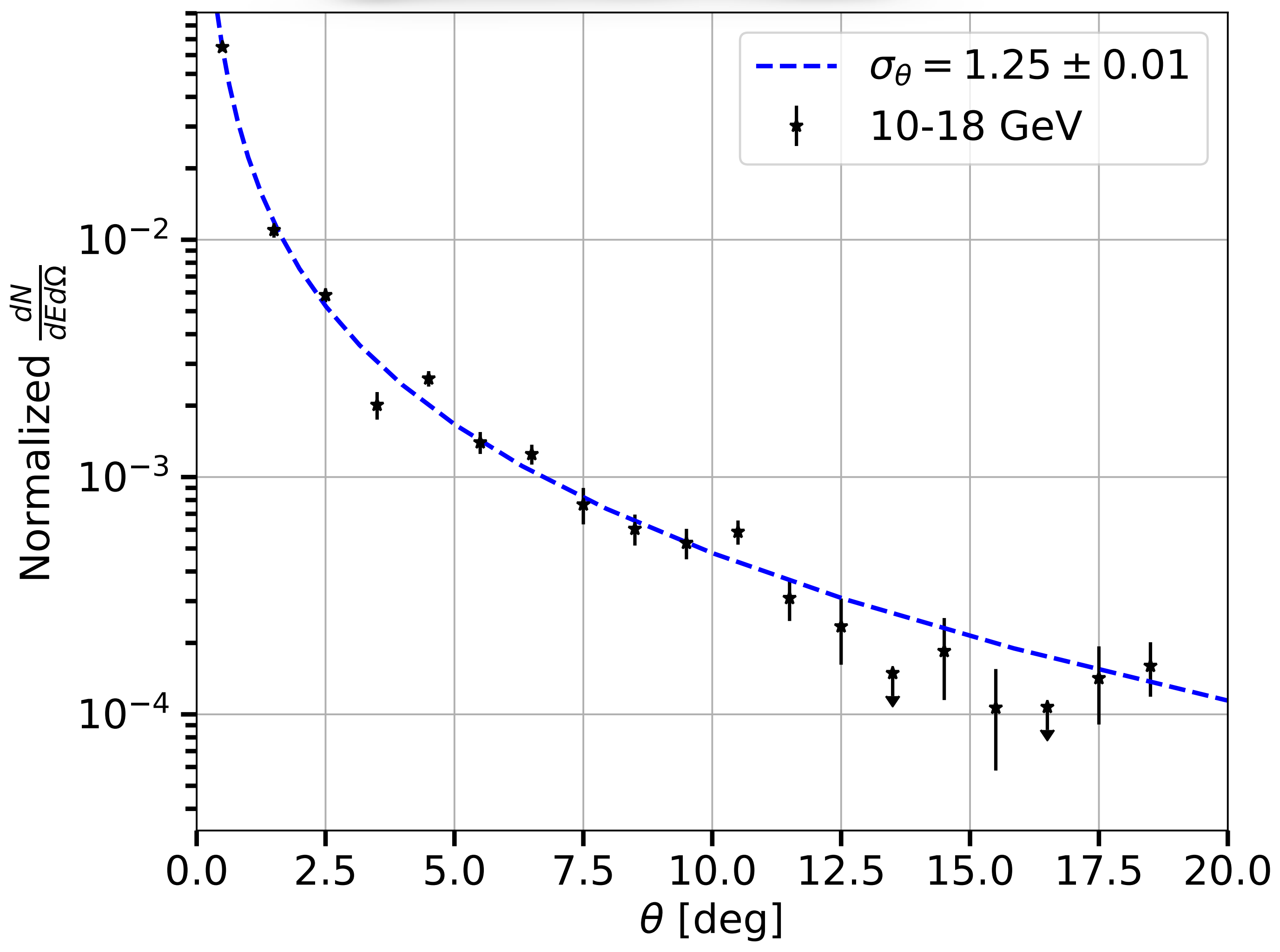
The GCE is approximatively spherically symmetric.

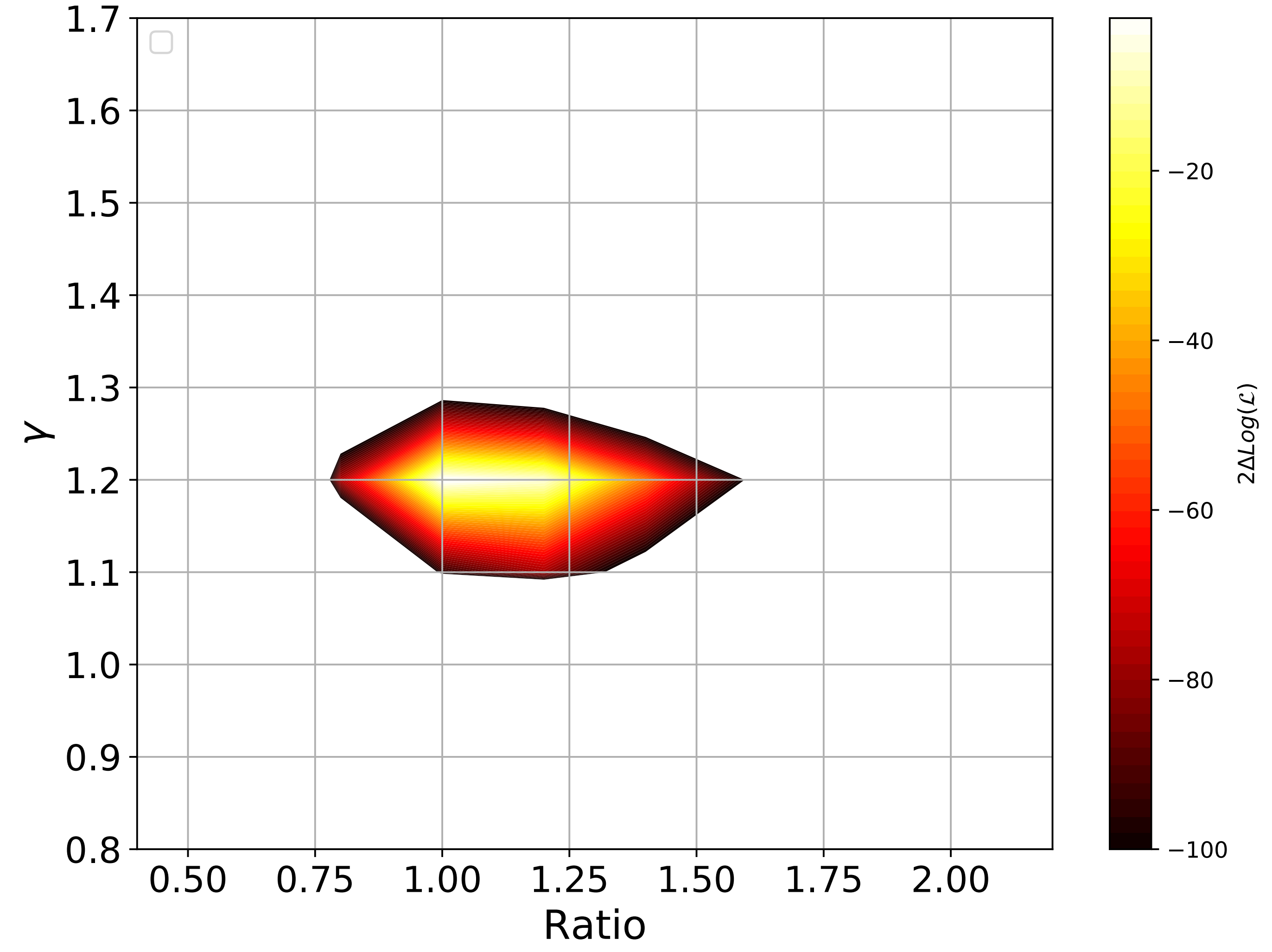


Centered in the GC



gamma=1.25





Paper III

Dark matter density distribution

Salas et al. 2019 Rotation curve galaxy data

DM density	slope	ρ_s [GeV/cm^3]	r_s [kpc]	$\mathcal{J}$
$\rho_\odot = 0.30$ GeV/cm^3 $M_{200} = 5.5 \cdot 10^{11}$ $M_\odot$				
gNFW	1.20	0.416	12.87	111.5
gNFW	1.30	0.314	14.18	155.3
Einasto	0.13	0.376	7.25	288.9
$\rho_\odot = 0.34$ GeV/cm^3 $M_{200} = 6.2 \cdot 10^{11}$ $M_\odot$				
gNFW	1.20	0.587	11.57	166.1
gNFW	1.30	0.449	12.67	231.0
Einasto	0.13	0.569	6.35	449.3
$\rho_\odot = 0.38$ GeV/cm^3 $M_{200} = 7.0 \cdot 10^{11}$ $M_\odot$				
gNFW	1.20	0.851	10.20	246.8
gNFW	1.30	0.649	11.20	339.1
Einasto	0.13	0.864	5.51	686.7

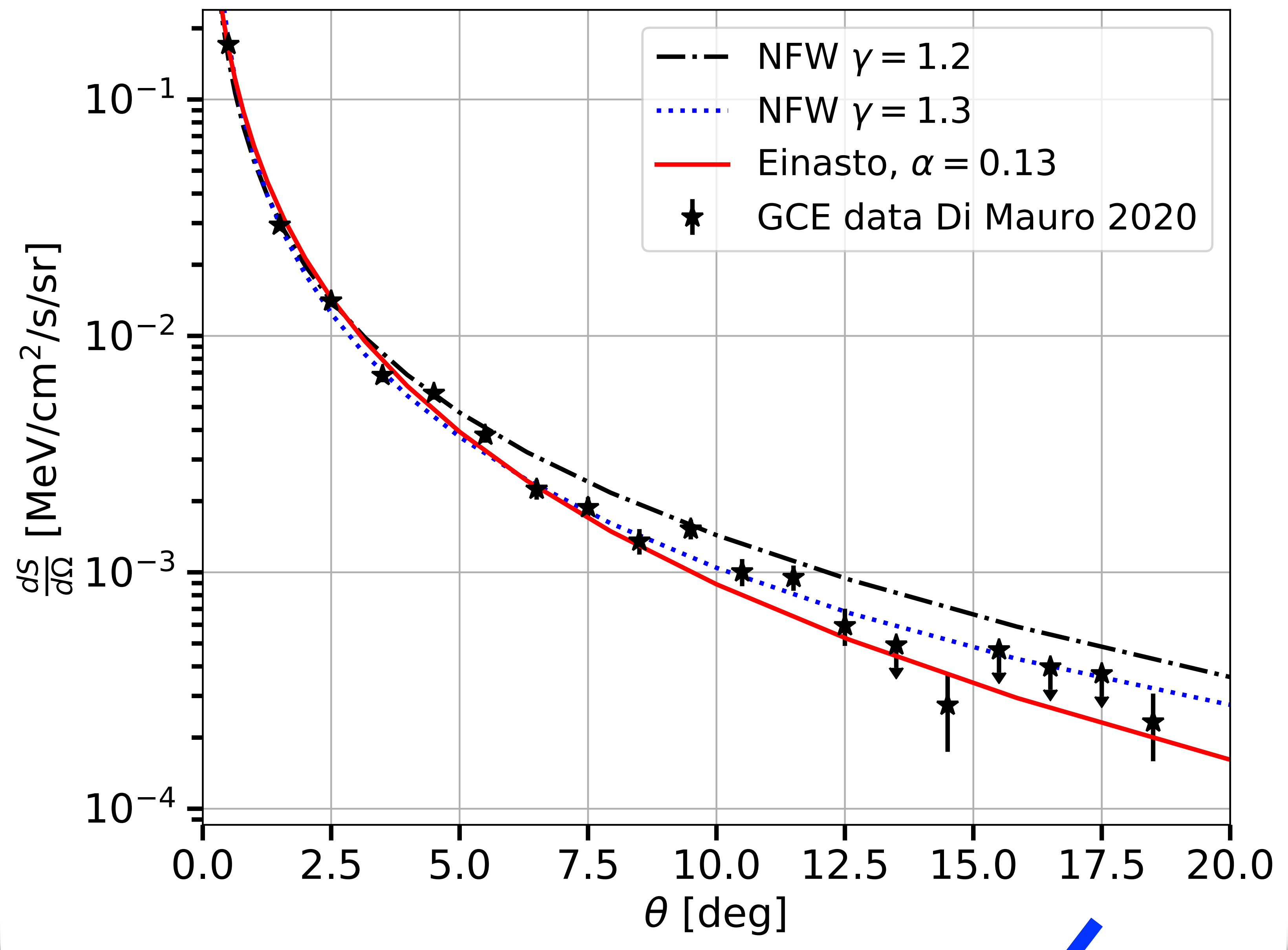
MIN

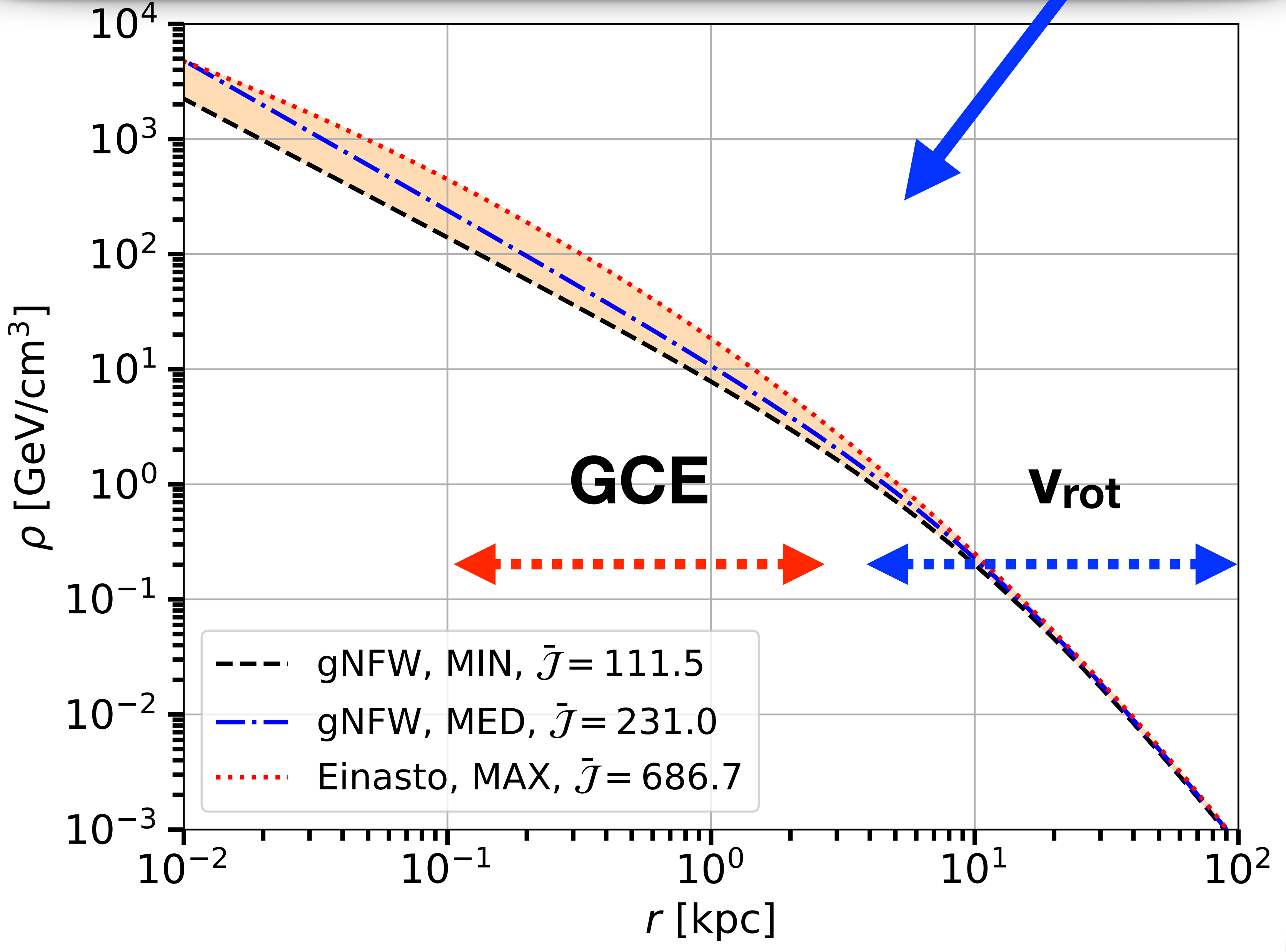
MED

MAX

$$\bar{\mathcal{J}} = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{l.o.s.} \frac{ds}{r_\odot}\left(\frac{\rho(r(s,\Omega))}{\rho_\odot}\right)^2$$

Geometrical factor integrate in our ROI

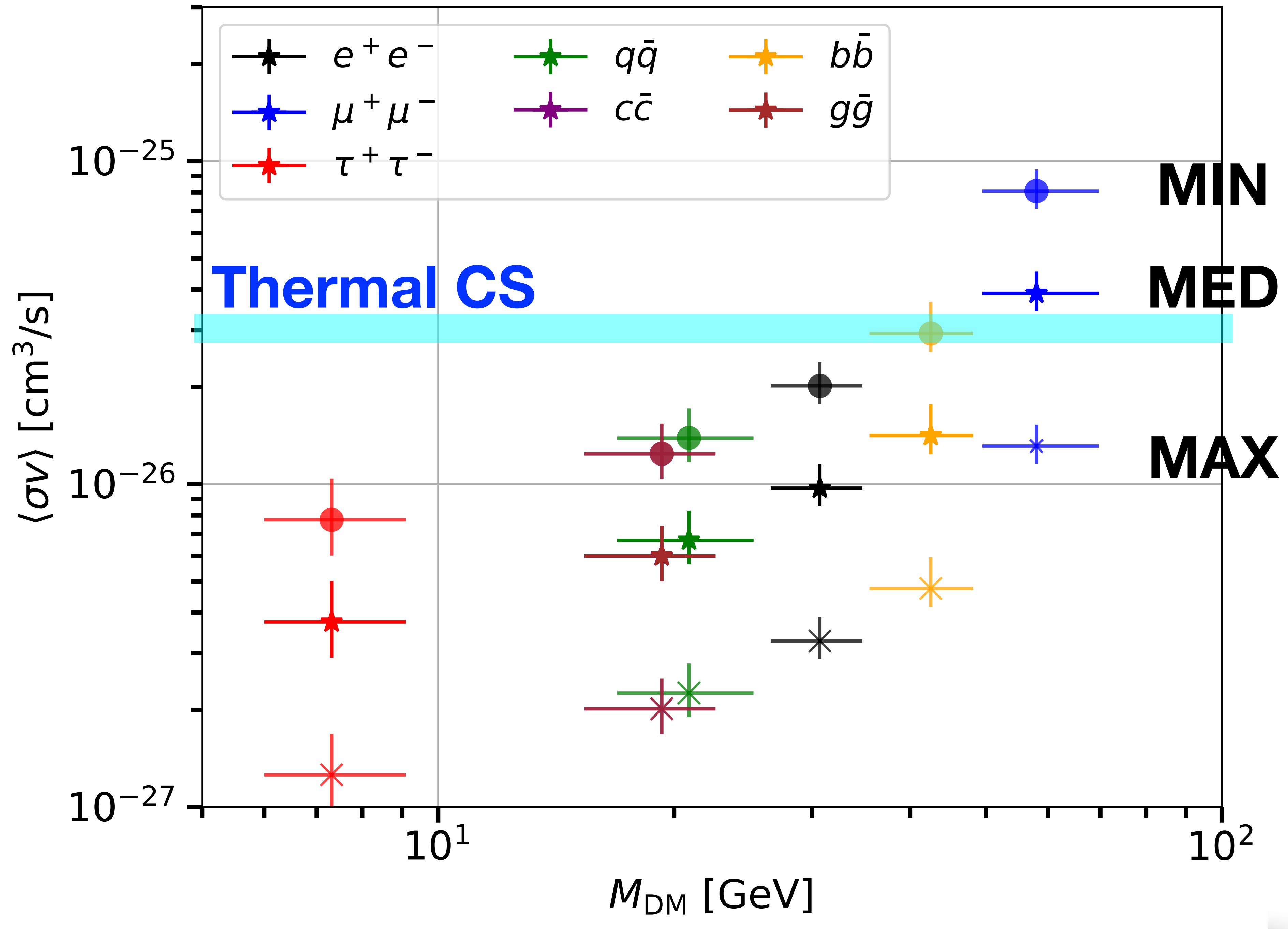


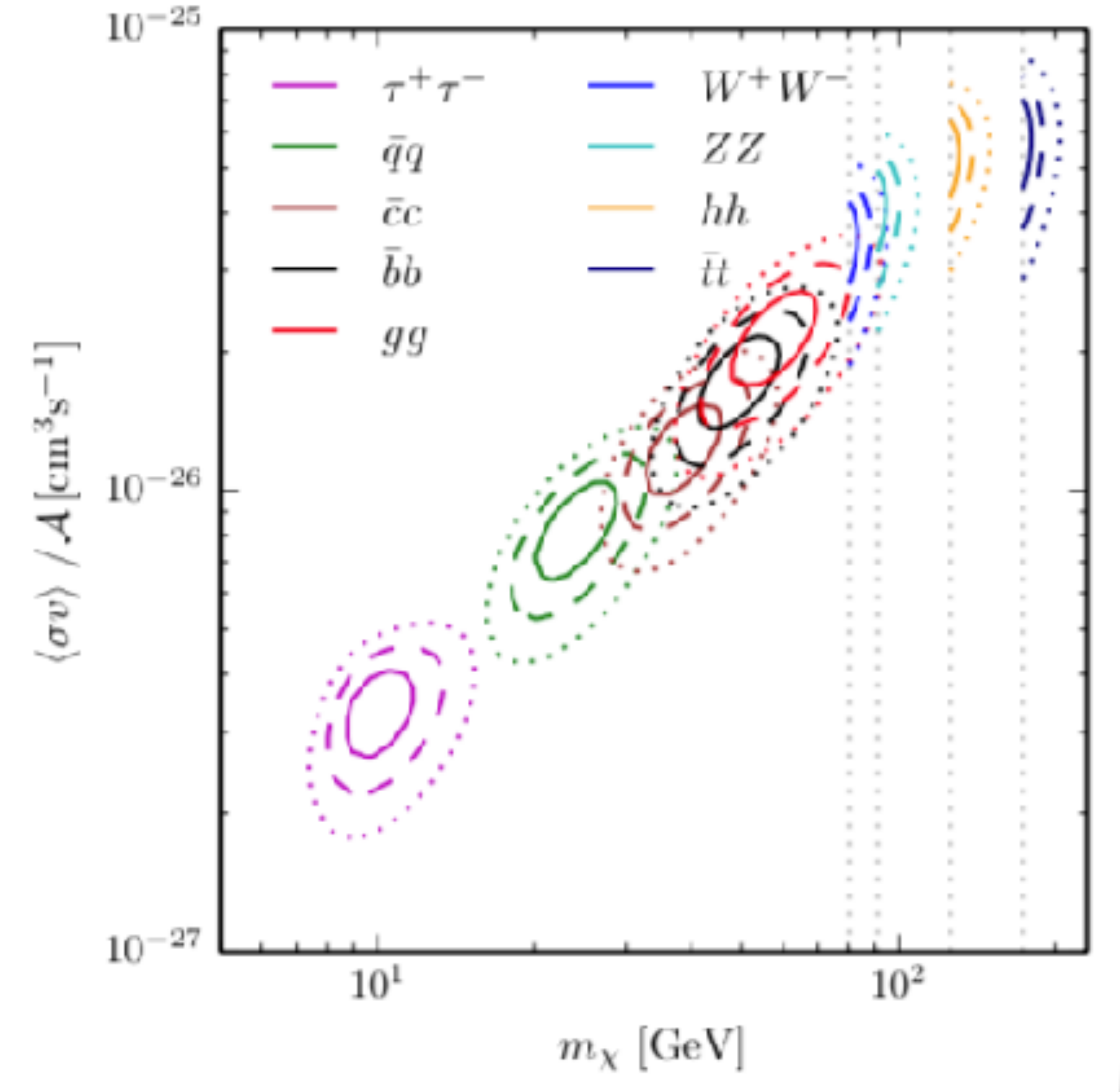


Theory for the gamma-ray flux from Dark matter

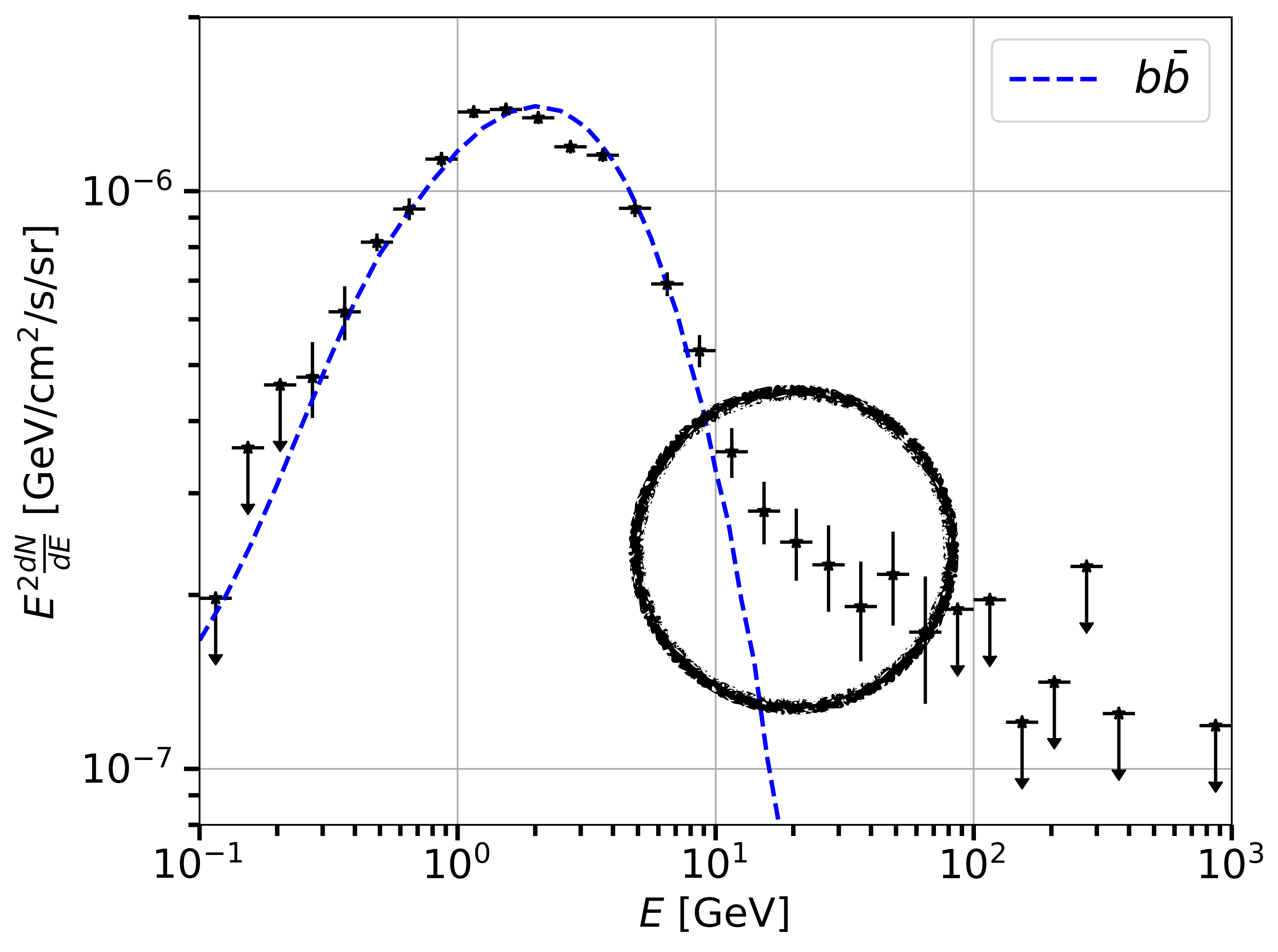
- We use a model that accounts for prompt and ICS emission from DM.
- The diffusion process has a much smaller effect that energy losses in the GC.
- The bremsstrahlung component is also negligible.

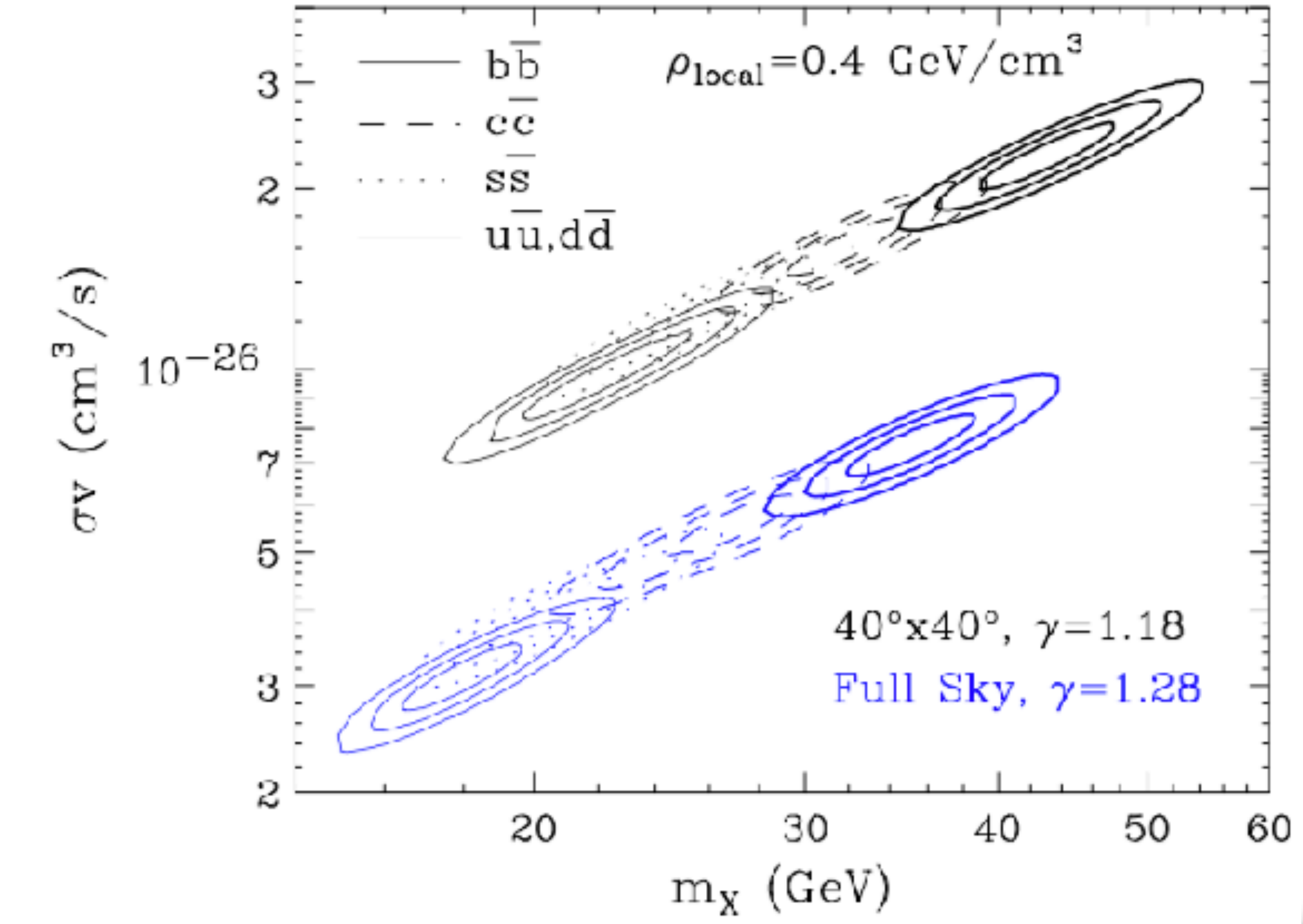
Fitting the GCE data with one channel (BR=1)





Calore et al. 2015





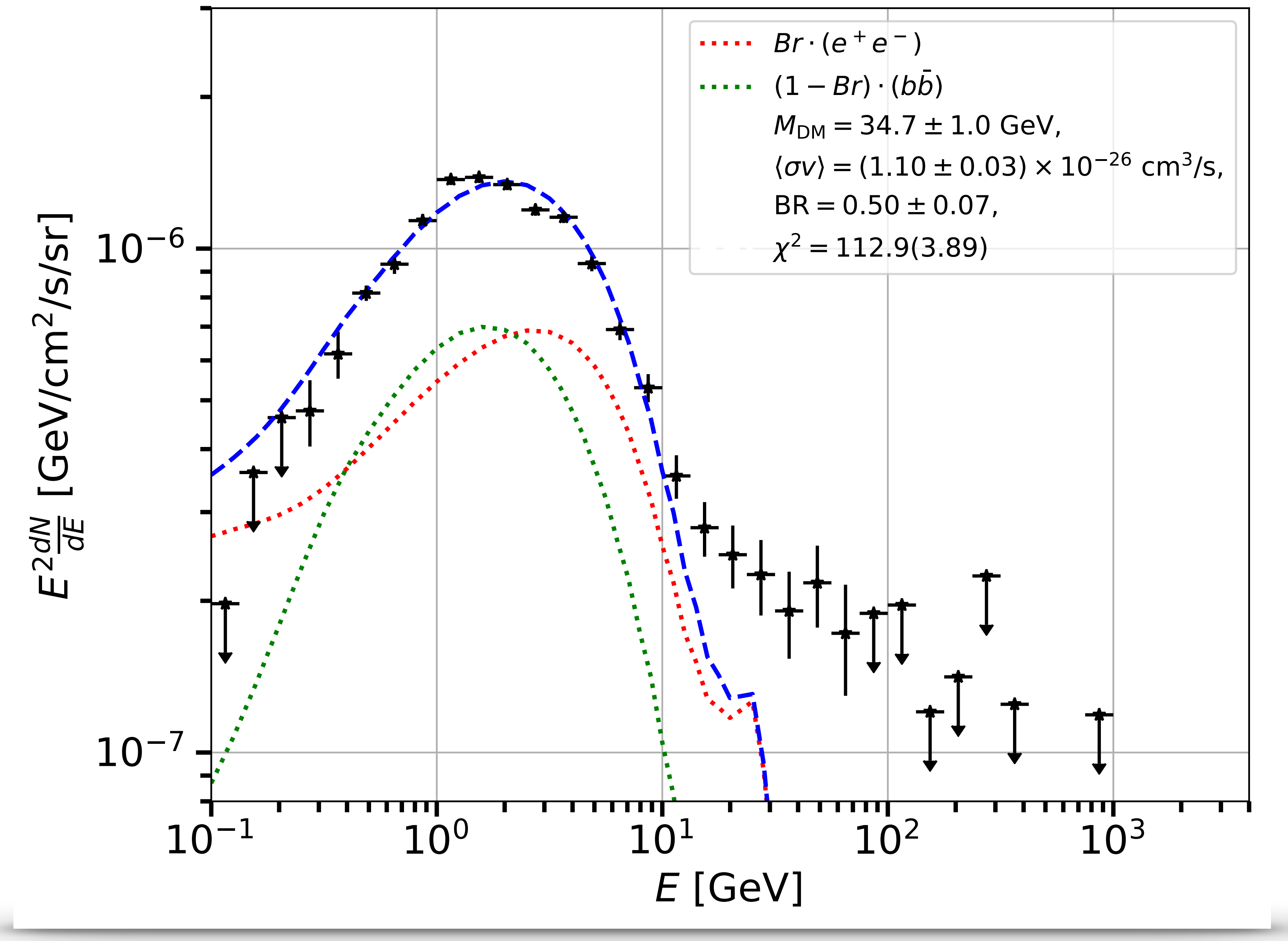
Linden et al. 2014

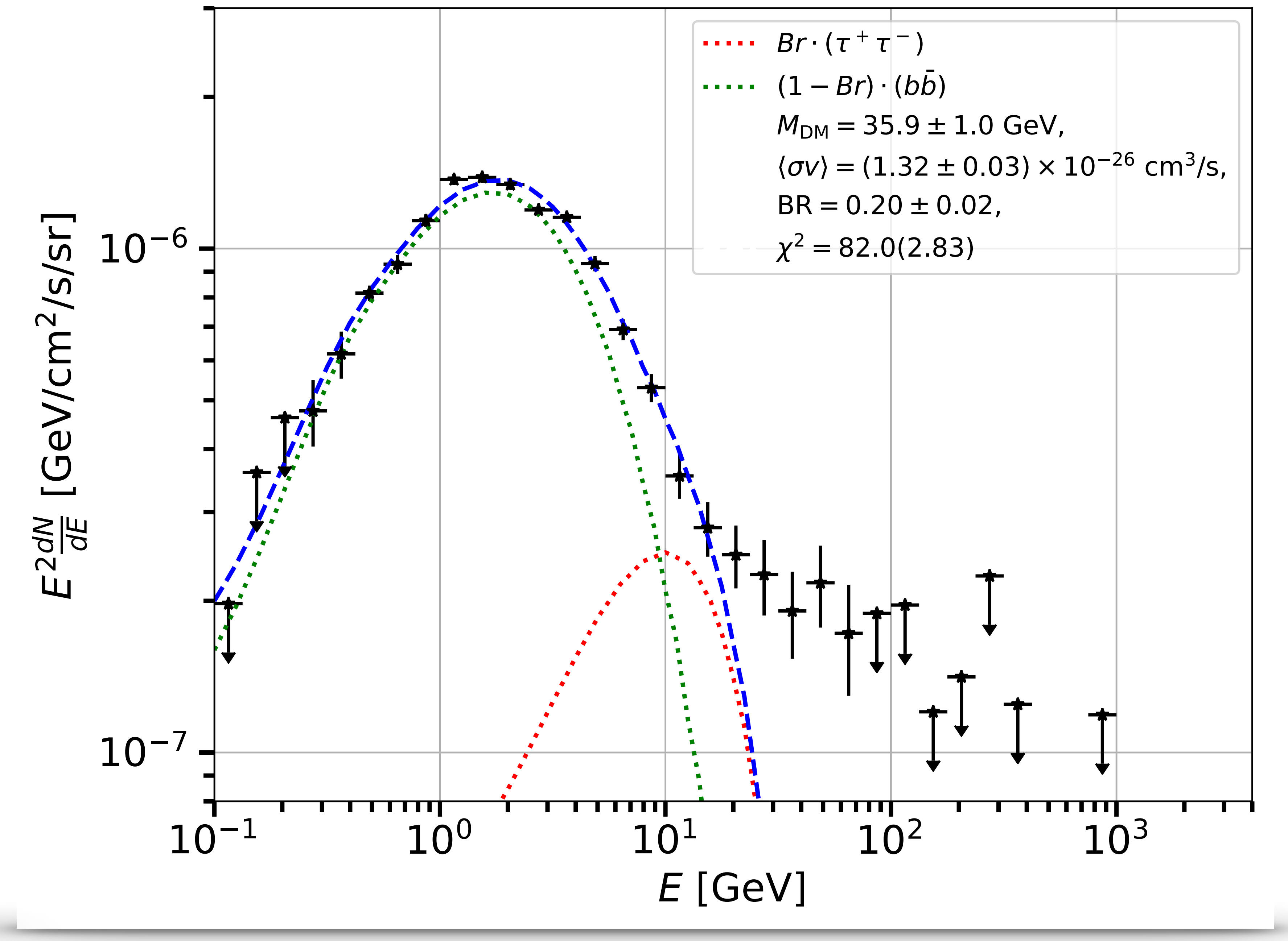
Paper III

Fitting the GCE data with two channels

Channel 1	Channel 2	$M_{\rm DM}$ [GeV]	$\langle\sigma v\rangle$ [10^{-26} cm^3/s]	Br	$\chi^2(\tilde{\chi}^2)$	$\Delta\chi^2$(sign.)
$\tau^+\tau^-$	$b\bar{b}$	35.9	1.32	0.20	82.0(2.83)	82(9.0σ)
$\mu^+\mu^-$	$b\bar{b}$	47.8	2.42	0.65	90.5(3.12)	74(8.4σ)
e^+e^-	$\tau^+\tau^-$	27.1	0.95	0.84	113.7(3.92)	31(5.4σ)
e^+e^-	$c\bar{c}$	24.3	0.79	0.50	112.3(3.87)	32(5.5σ)
e^+e^-	$b\bar{b}$	34.7	1.10	0.50	112.9(3.89)	32(5.5σ)
$c\bar{c}$	$b\bar{b}$	33.8	1.11	0.32	115.1(3.97)	61(7.7σ)

$$\frac{dN_\gamma}{dE} = Br\frac{dN_{\tau^+\tau^-}}{dE} + (1-Br)\frac{dN_{b\bar{b}}}{dE}$$

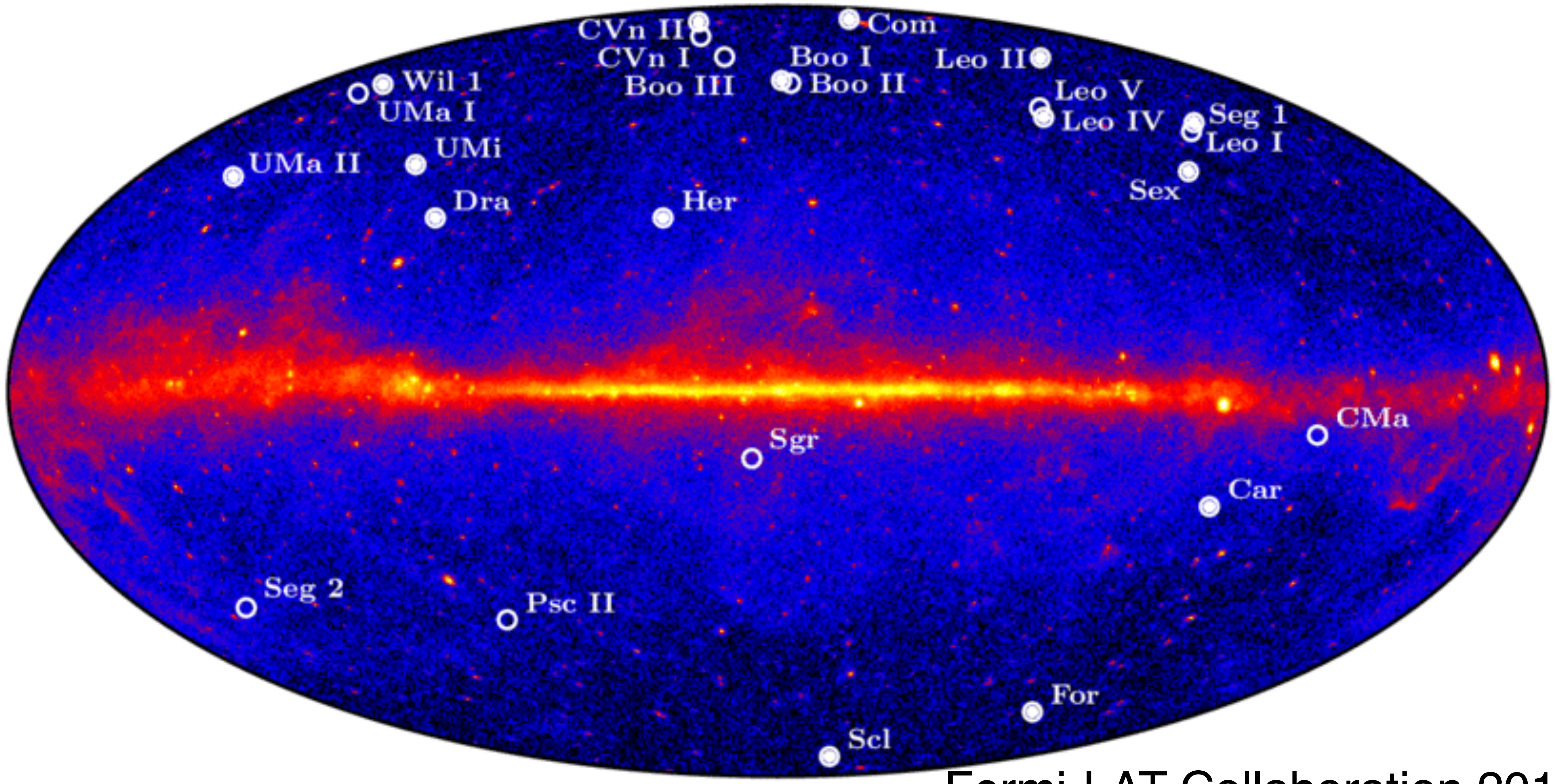




Paper III

Milky Way dwarf spheroidal satellite galaxies

- dSphs are among the most promising targets for the indirect search of DM with γ-rays.
- Mass-to- luminosity ratio of the order of 100 – 1000.
- They have an environment with predicted low astrophysical background

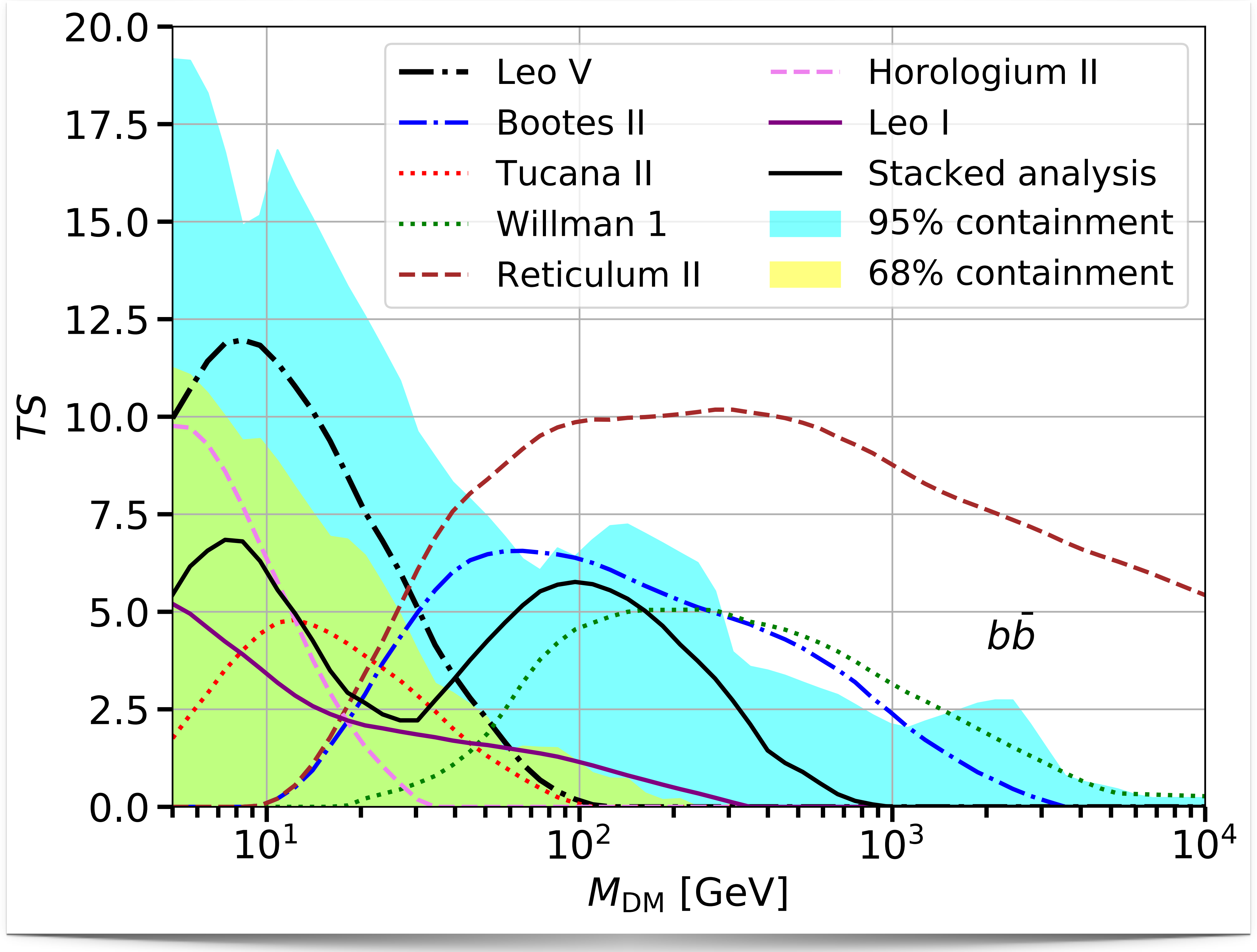


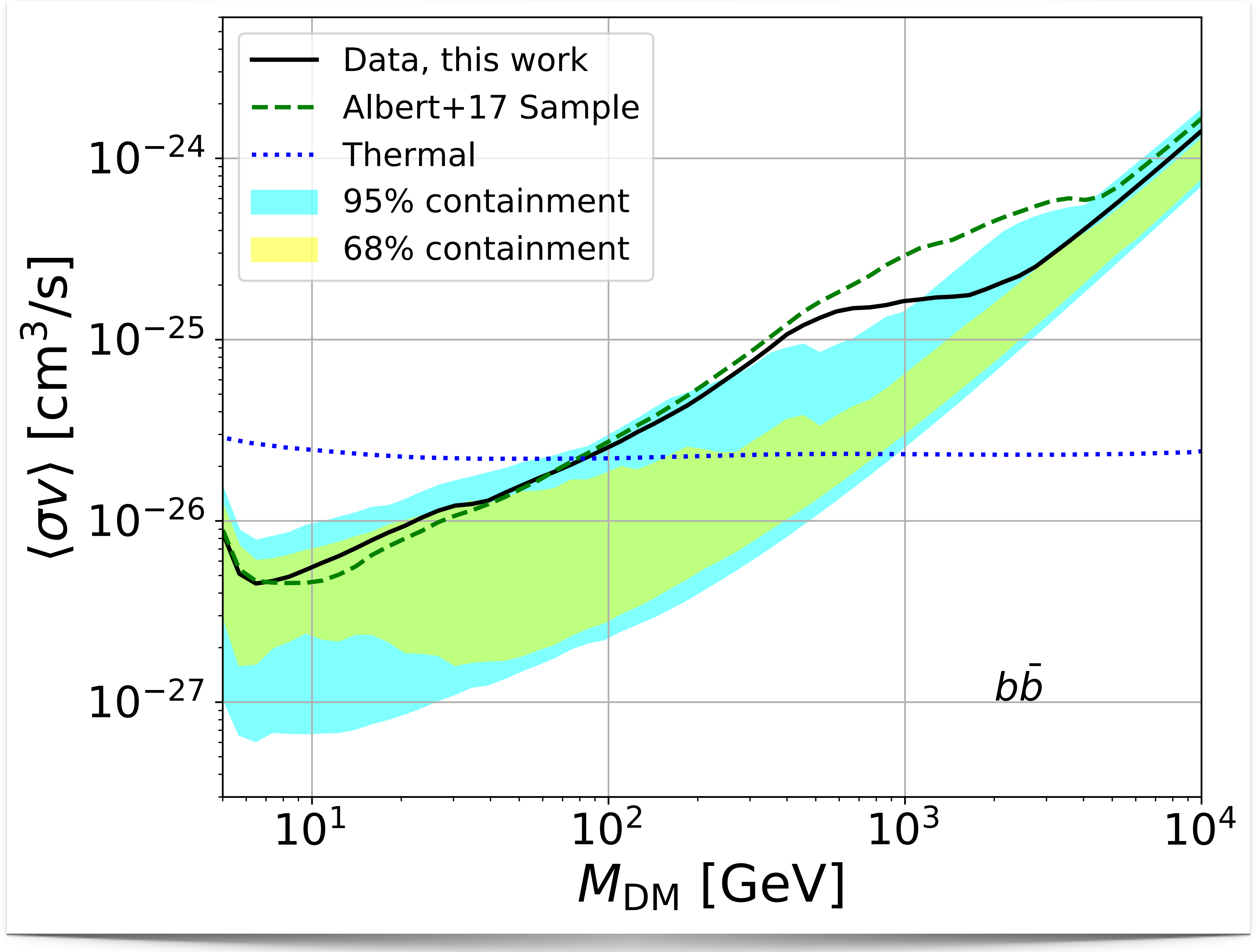
Fermi-LAT Collaboration 2013

Paper III

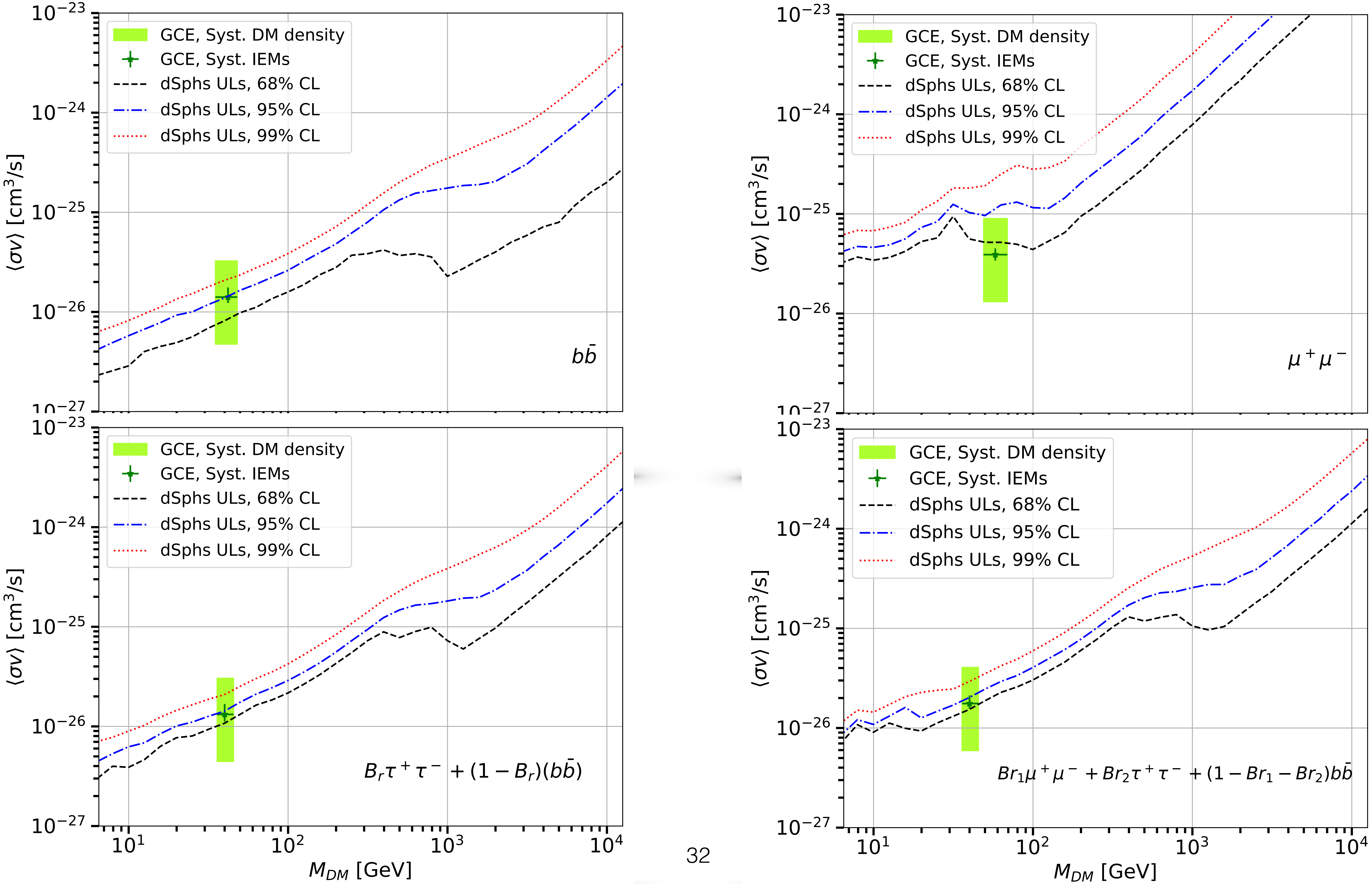
Combined analysis for dSphs

- We perform a combined analysis of 48 dSphs (Pace and Strigari 2018).
    - We also test the sample from Albert et al. 2017.
- The pipeline we use is the one employed in previous *Fermi*-LAT papers.
- There is no significant emission in the stacked sample.





dSphs vs GCE



GCE, Syst. DM density
GCE, Syst. IEMs
dSphs ULs, 68% CL
dSphs ULs, 95% CL
dSphs ULs, 99% CL
$\langle\sigma v\rangle$ [cm^3/s]
M_{DM} [GeV]
$b\bar{b}$
$\mu^+\mu^-$
$B_r\tau^+\tau^- + (1-B_r)(b\bar{b})$
$Br_1\mu^+\mu^- + Br_2\tau^+\tau^- + (1-Br_1-Br_2)b\bar{b}$

Cosmic-ray antiprotons

Diffusion

$$K = K_0 \beta^{\eta} \left(\frac{\mathcal{R}}{\mathrm{GV}}\right)^{\delta} \left(1 + \left(\frac{\mathcal{R}}{\mathcal{R}_b}\right)^{\Delta\delta/s}\right)^{-s}$$

Energy losses

$$b_{\mathrm{disc}} = b_{\mathrm{coul}} + b_{\mathrm{ion}} + b_{\mathrm{brems}} + b_{\mathrm{reac}}$$

Reacceleration

$$K_{EE} = \frac{4}{3}\frac{V_a^2}{K}\frac{p^2}{\delta(4-\delta)(4-\delta^2)}$$

Annihilation rate

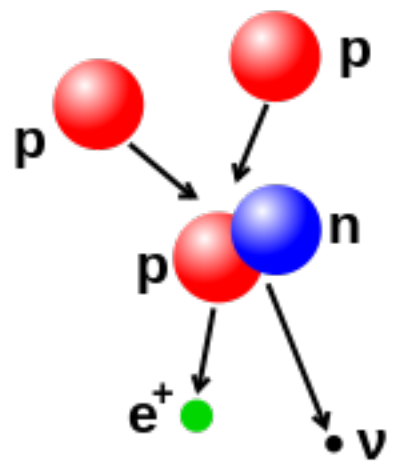
$$-K\Delta\mathcal{N}_i + 2h\delta(z)\left[\partial_E\left(b_{\mathrm{disc}}\mathcal{N}_i - K_{EE}\,\partial_E\mathcal{N}_i\right) + \Gamma_{\mathrm{ann}}\,\mathcal{N}_i\right] + \partial_E\left(b_{\mathrm{halo}}\mathcal{N}_i\right) = 2h\delta(z)\mathcal{Q}_i^{\mathrm{sec}} + \mathcal{Q}_i^{\mathrm{prim}}\,.$$

$$b_{\mathrm{halo}} = b_{\mathrm{ic}} + b_{\mathrm{synch}}$$

Energy losses

$$\mathcal{Q}_i^{\mathrm{sec}} = \sum_{j,k} 4\pi \int dE' \left(\frac{d\sigma_{jk\to i}}{dE}\right) n_k\,\Phi_j(E')$$

Secondary



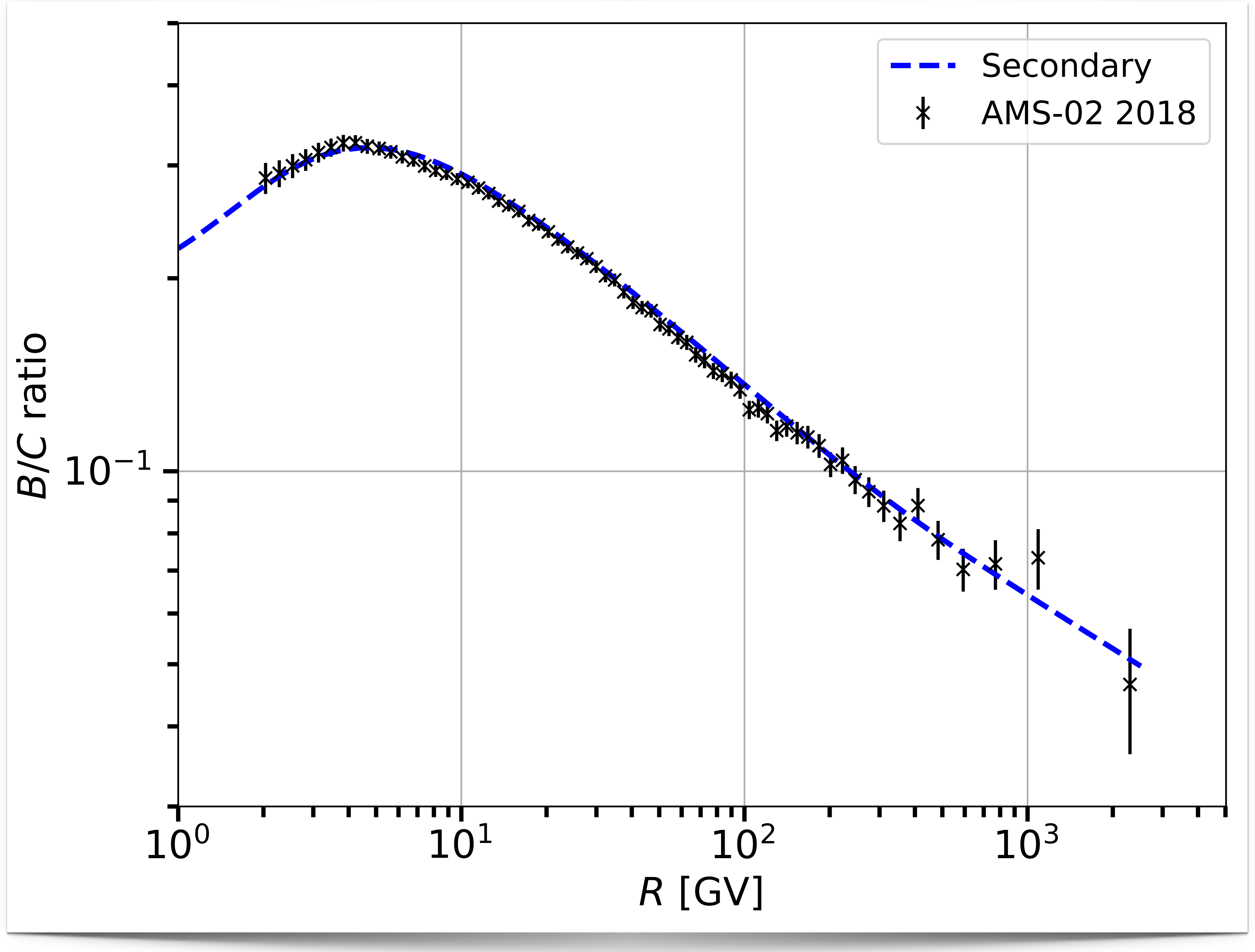
Primary

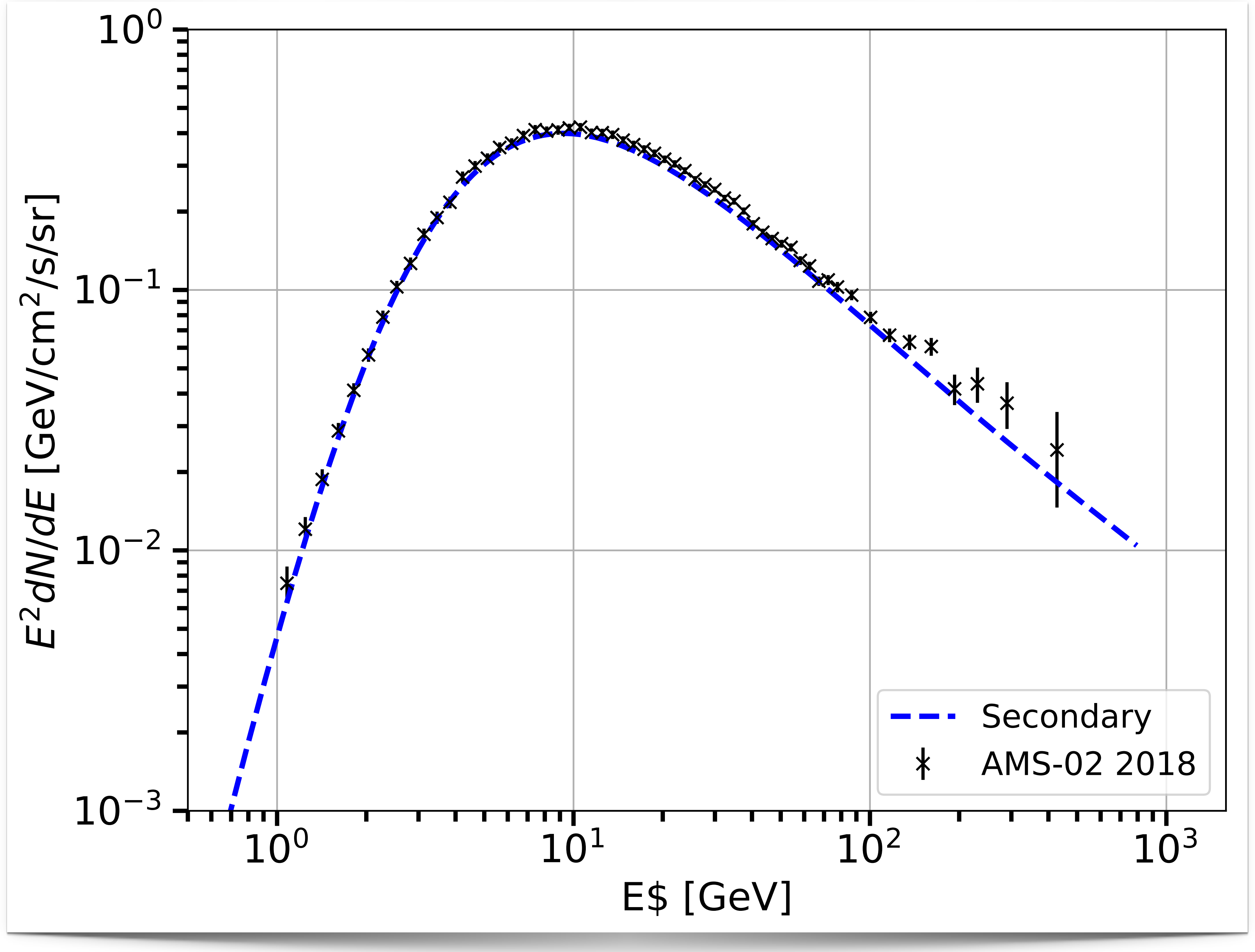
L vertical size of the diffusive halo

Antiprotons vs GCE

- We use the same analysis as in **Reinert and Winkler 2018**.
  - A combined fit to AMS-02 and Voyager p, AMS-02 and Pamela anti-p, AMS-02 B/C is performed.

- **δ = 0.459**
- **L = 4 kpc (fixed)**
- **K_0 = 0.042 kpc²/Myr**
  - **K_0/L should stay fixed**
- **Fisk potential I use phi = 0.72 GV**

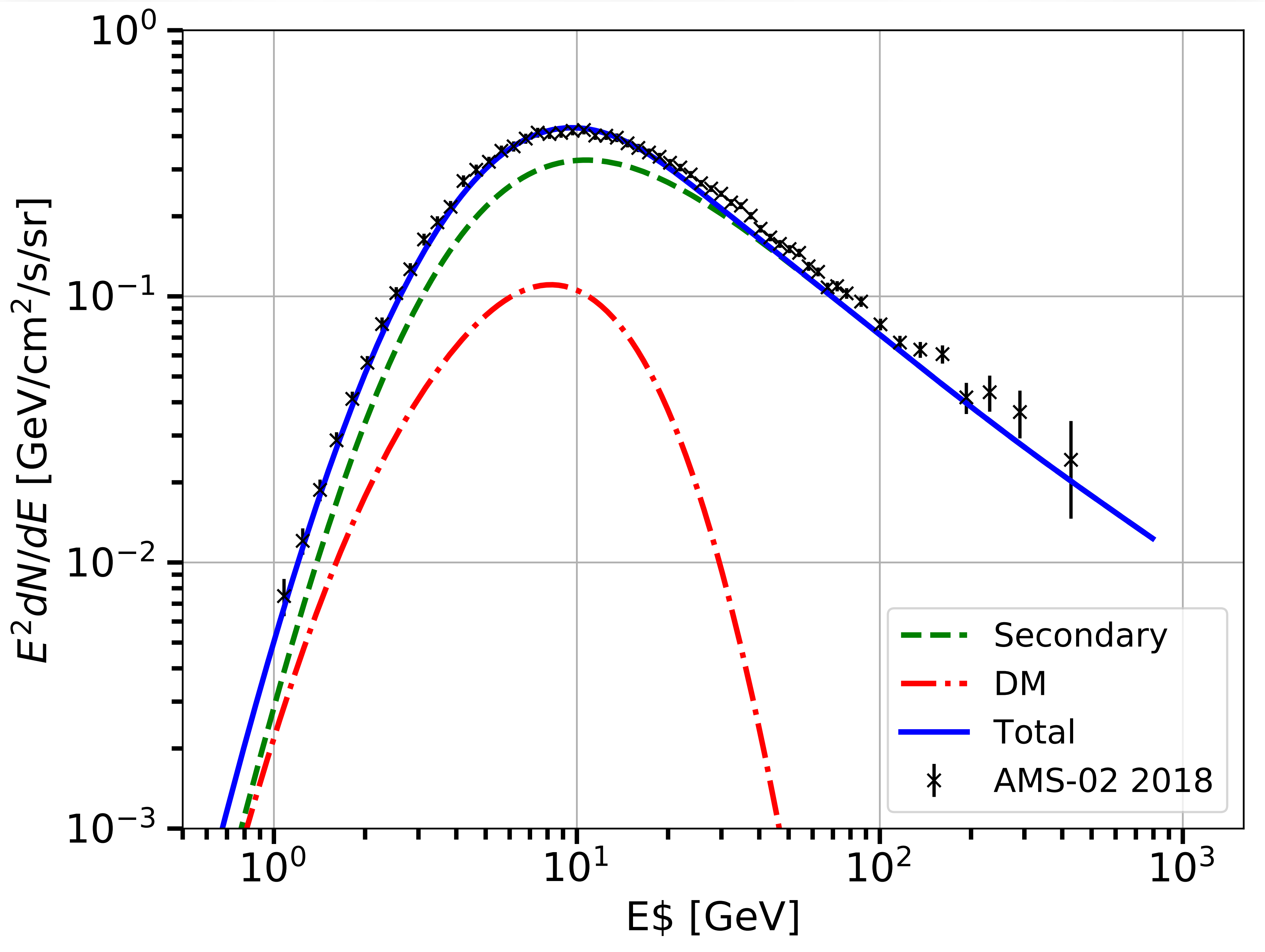


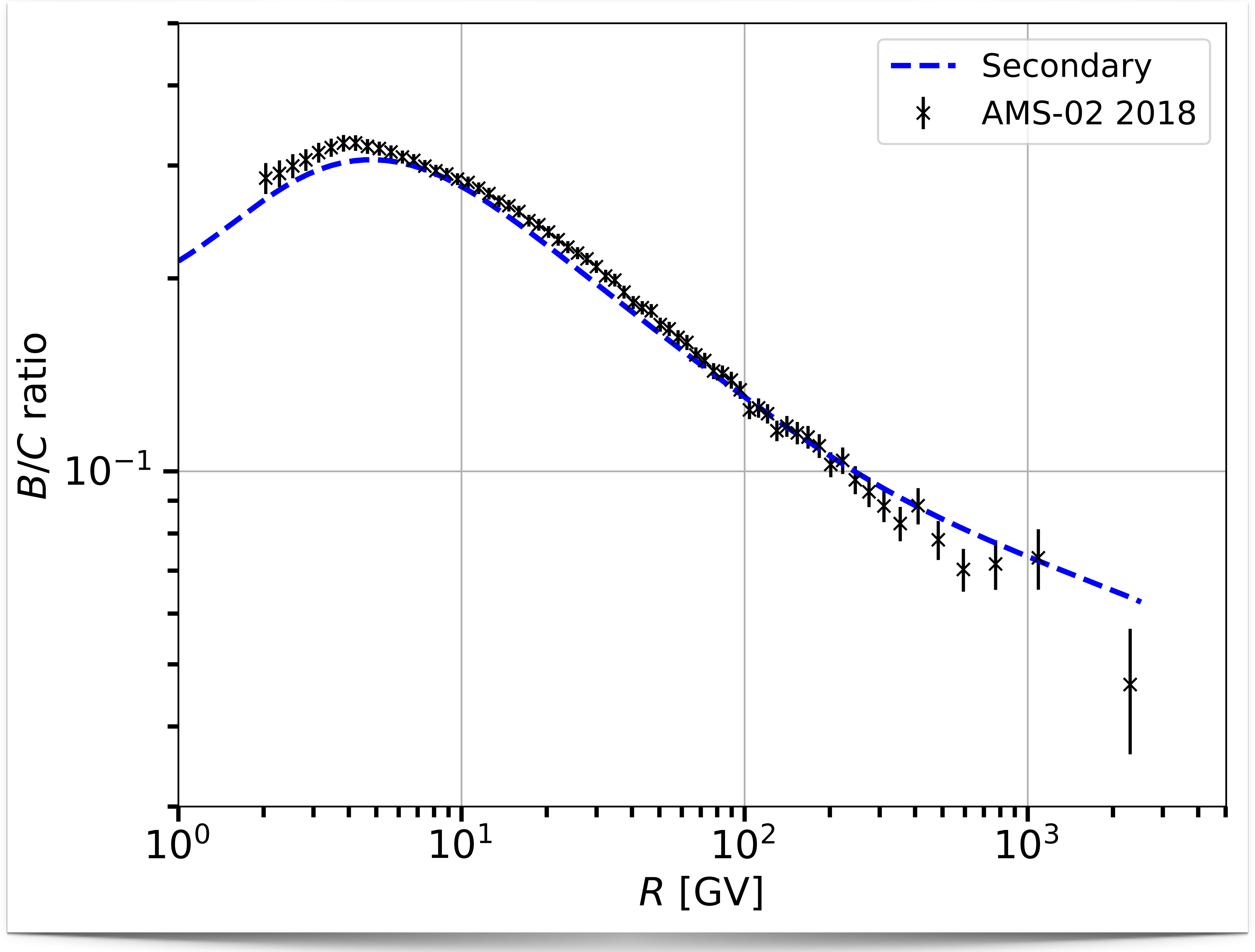


Antiprotons vs GCE

- We use the same analysis as in **Reinert and Winkler 2018**.
  - A combined fit to AMS-02 and Voyager p, AMS-02 and Pamela anti-p, AMS-02 B/C is performed.

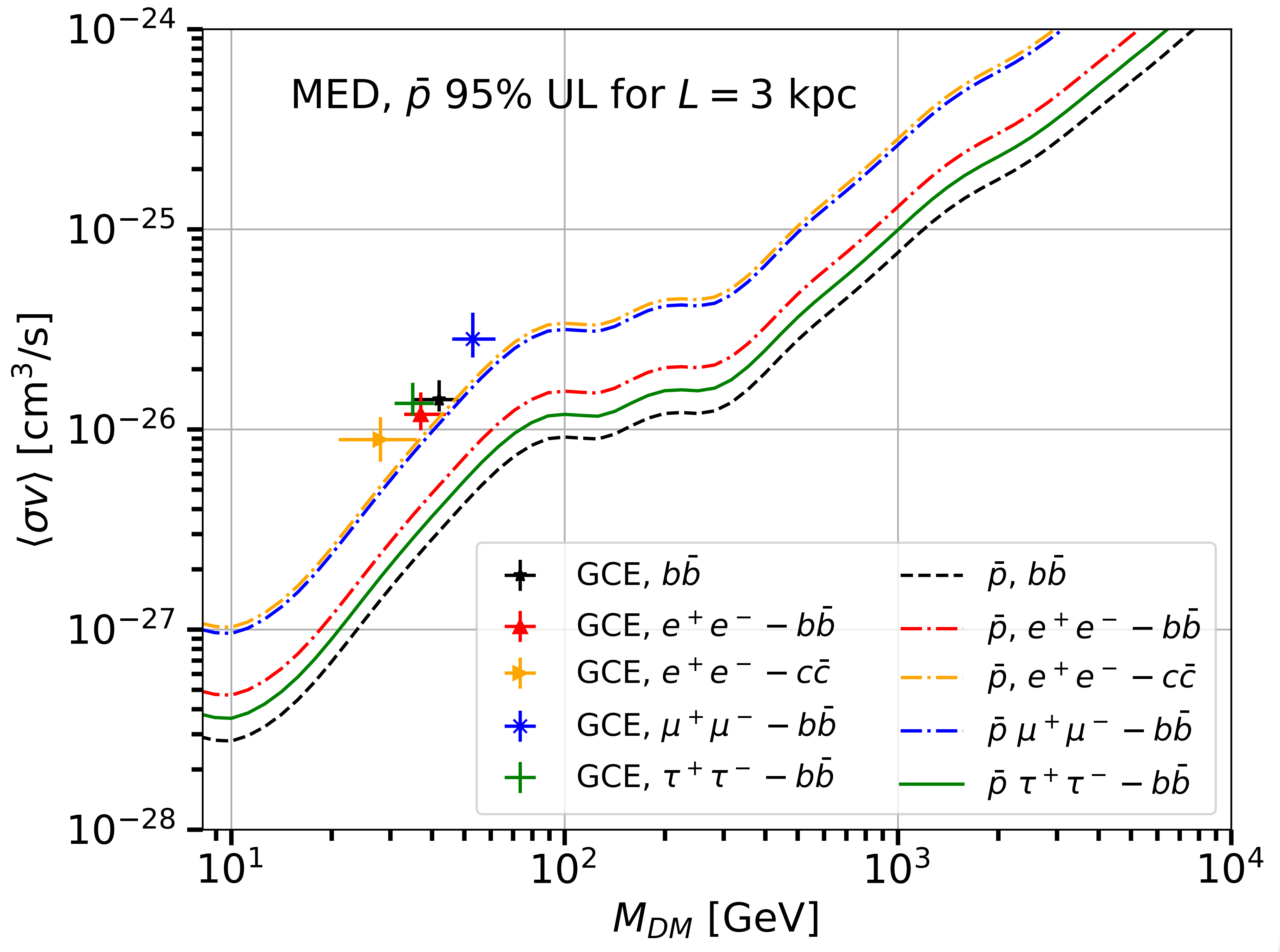
- **The addition of best-fit DM for the GCE with bottom channel worsens the fit with a delta chi-square of 44 (6σ worsening).**
- **We have used L=3kpc.**

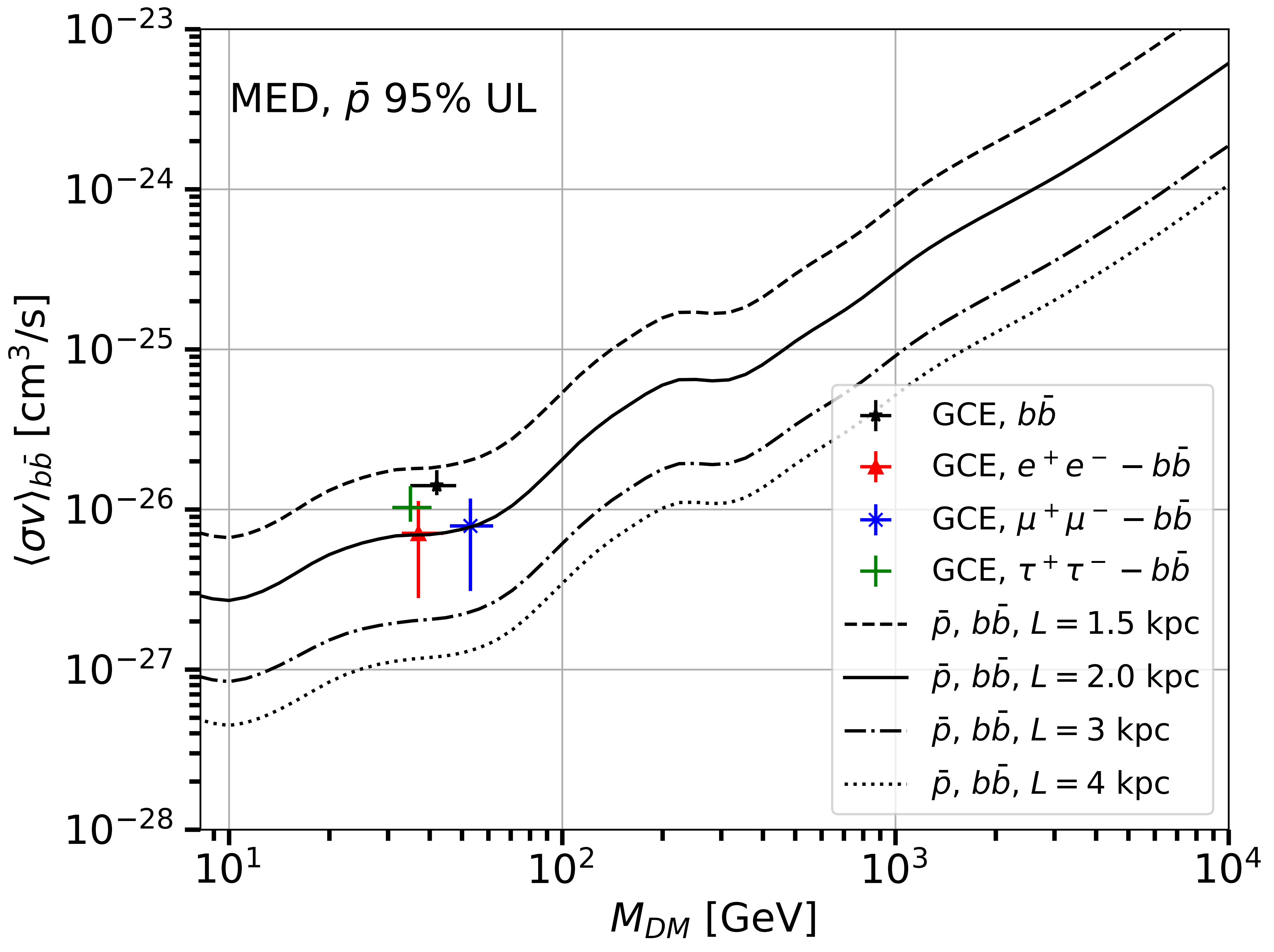




Antiprotons vs GCE

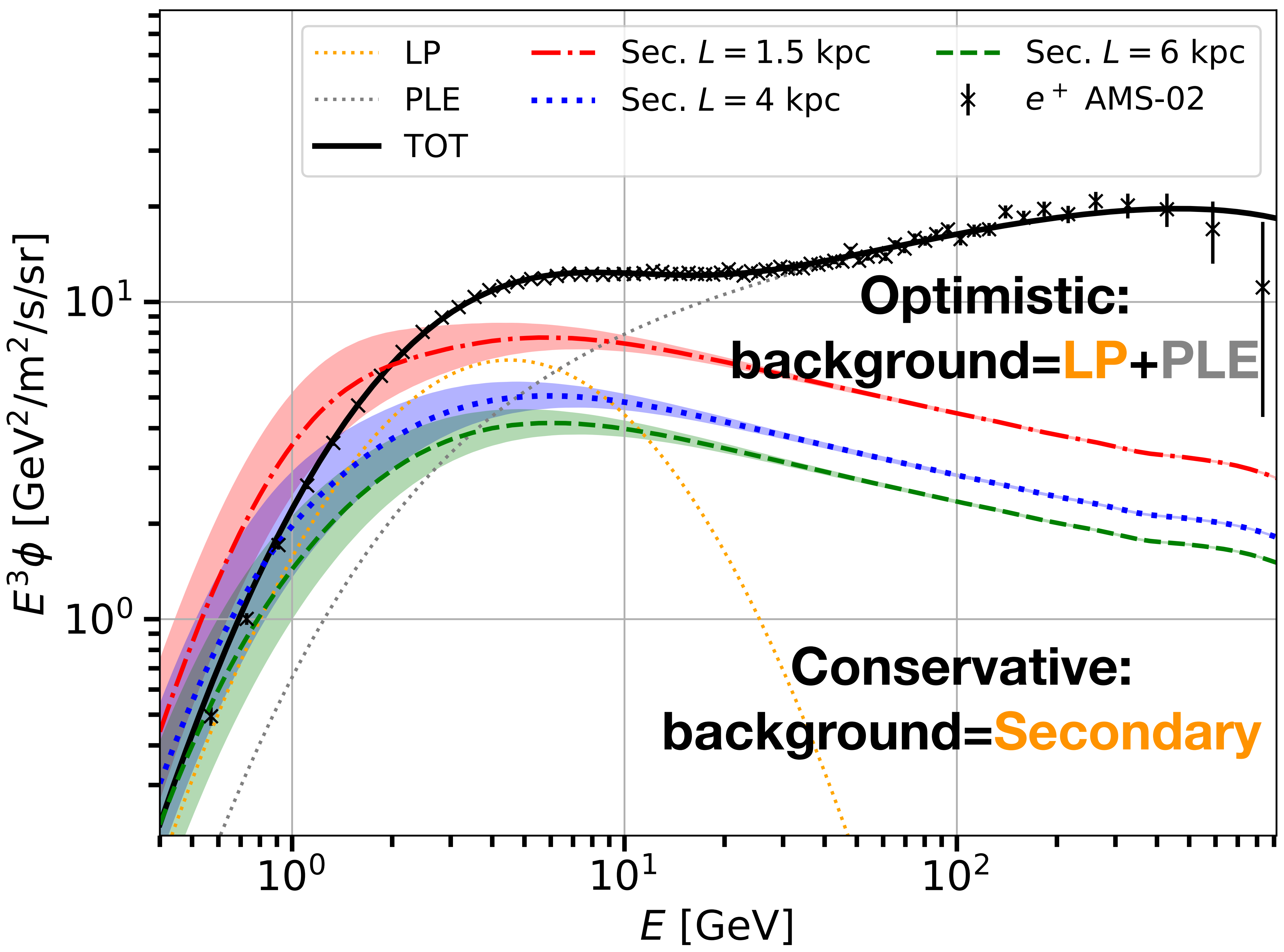
- GCE DM candidates with purely hadronic final states compatible with ULs only for L < 1.8 kpc.
- This constraints on L are relaxed for semi-hadronic final states with L ≤ 2.6 kpc, respectively.
- ULs on L are 2-3σ below results obtained with latest radioactive CR data.

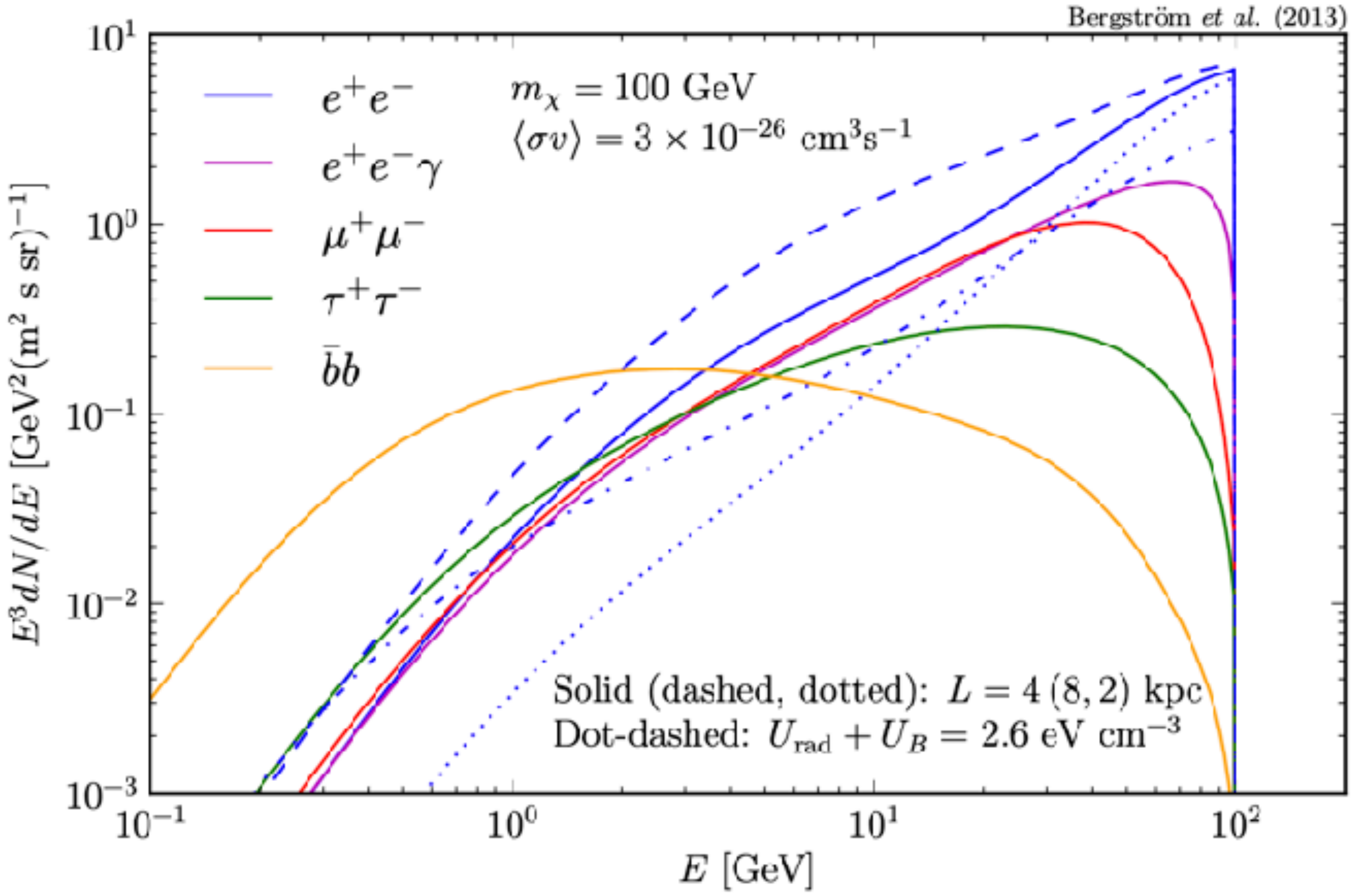




Cosmic-ray Positrons

- Low-energy positrons are primarily of secondary origin.
- Positrons above 10 GeV probably come from pulsar wind nebulae.
- We assumed a conservative and an optimist approach.

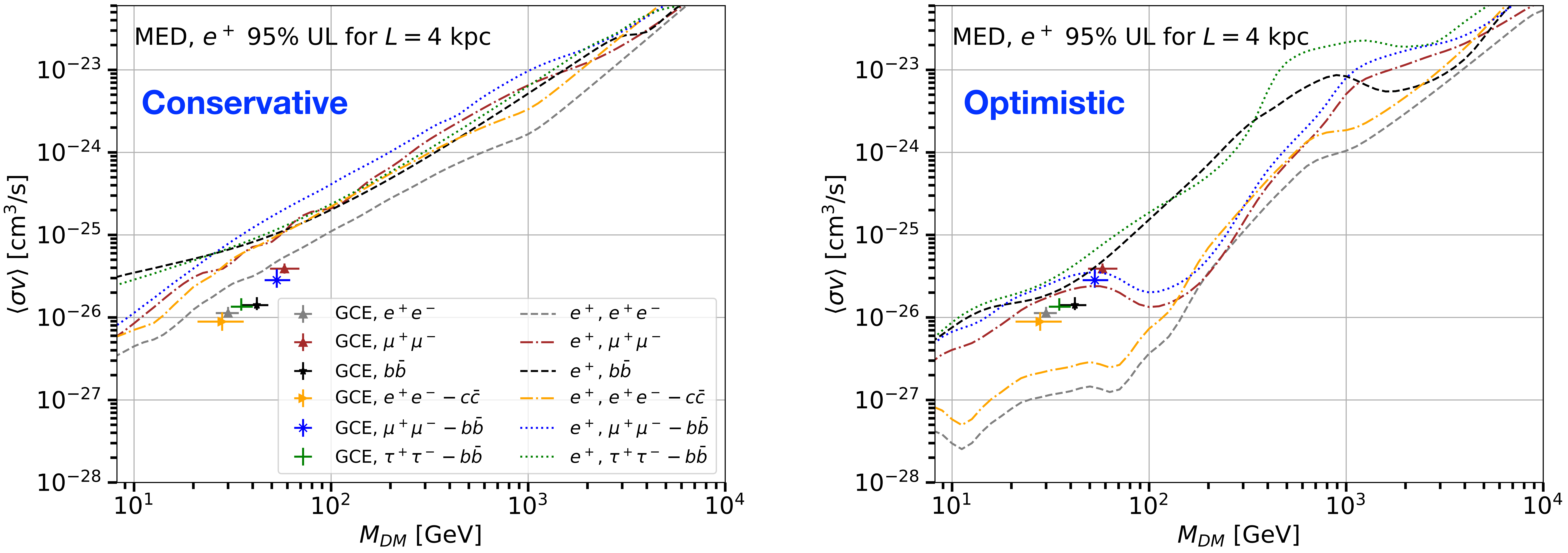




Paper III

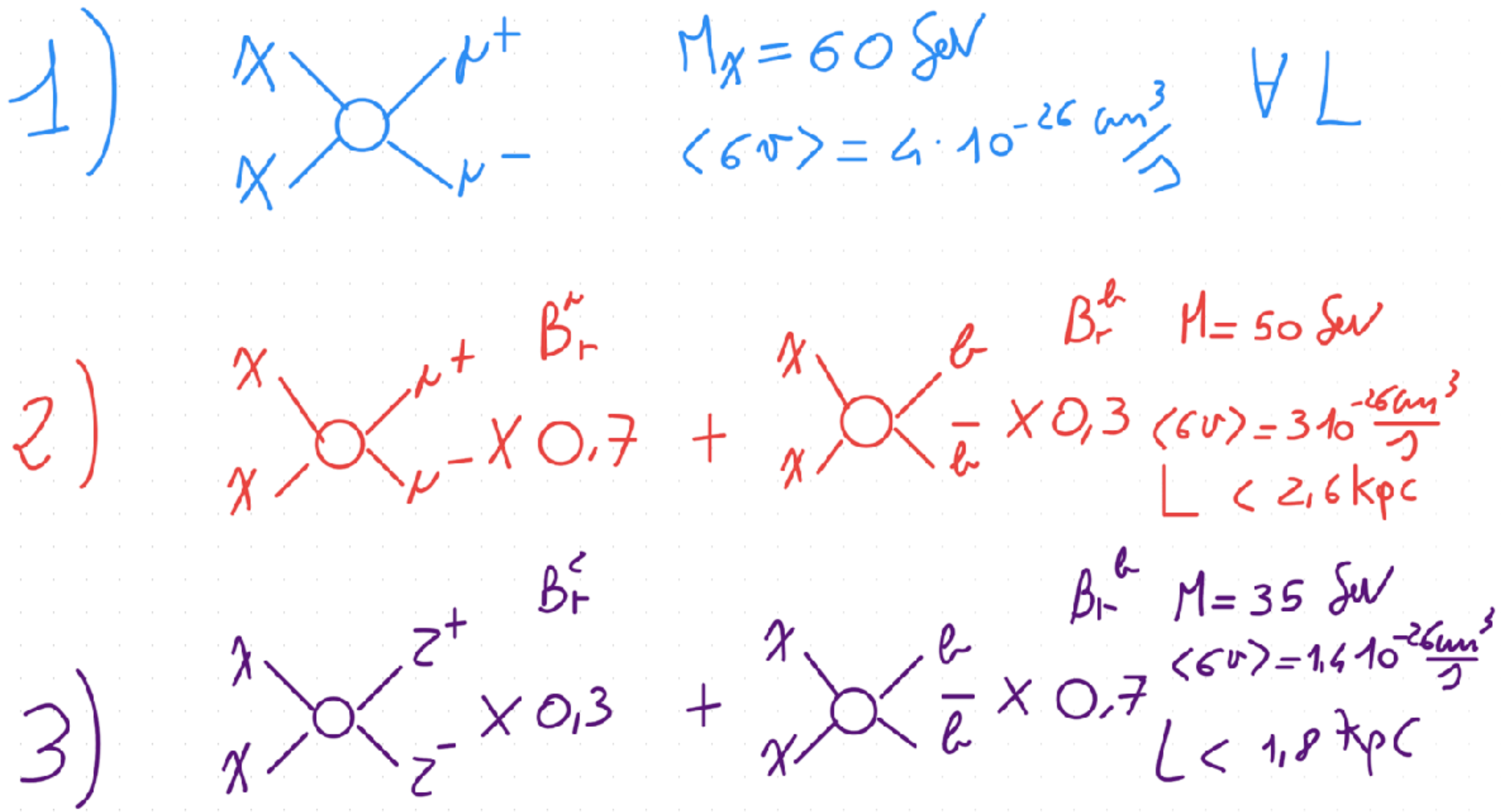
Positrons vs GCE

- The conservative upper limits are all compatible with the GCE.
- Instead, the optimistic ones are compatible for the bb, and mixed channels with muons and tau leptons.
- The channels with electrons are below the GCE DM candidates cross sections.



Conclusions

- **The GCE has all the right characteristics to be due to annihilating DM particles.**
- ULs from dSphs are compatible with the GCE candidates.
- ULs from antiprotons put tight constraints on purely hadronic final state DM.
- ULs from positrons put severe constraints on DM annihilating, even partially, into electrons.



Future works

- Further study about the pulsar contribution.
  - Several of these pulsars in the Galactic bulge should be probably already detected by Fermi-LAT.
  - The Galactic bulge population does not have a perfect spherical symmetry.
- Study the GCE and CRs upper limits in the contest of Beyond Standard Model theories.
- Improve the Galactic interstellar emission model and use latest Fermi-LAT catalogs to improve even more the measurements for the GCE.

STAY TUNED….

Backup slides