GRAPPA
GRavitation AstroParticle Physics Amsterdam

Measurement and interpretation of the Fermi-LAT angular power spectrum of gamma-ray anisotropies

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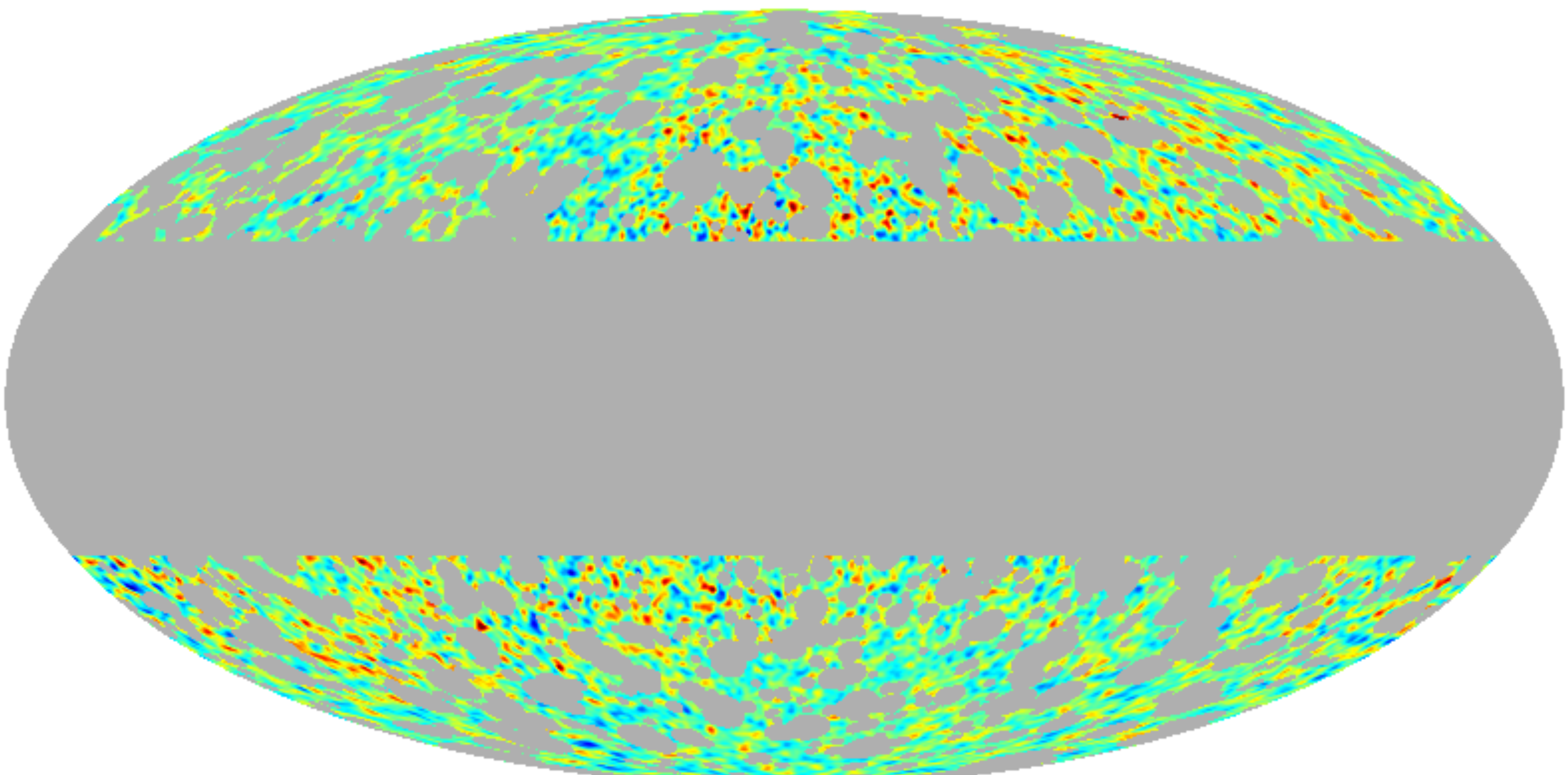
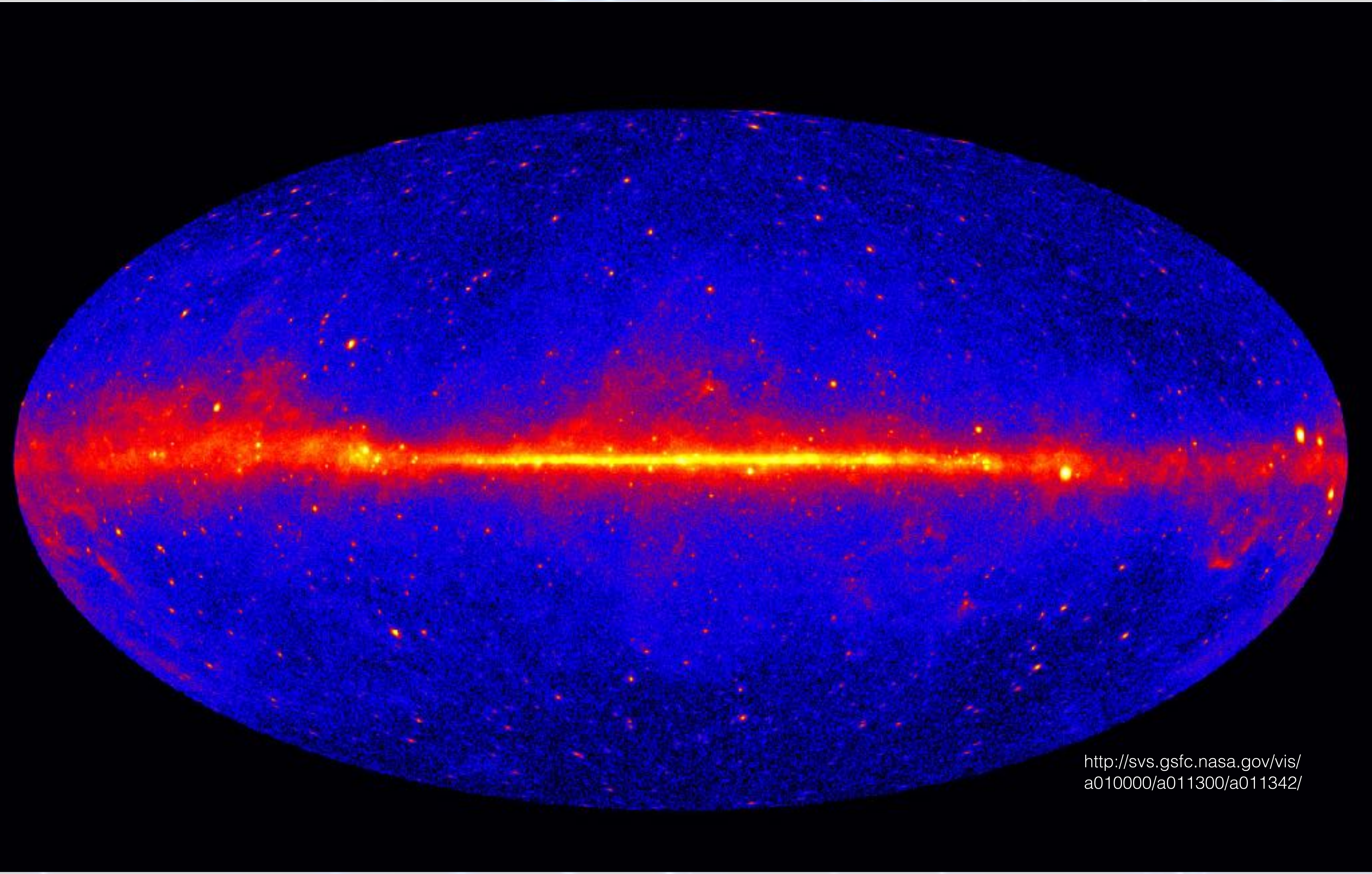
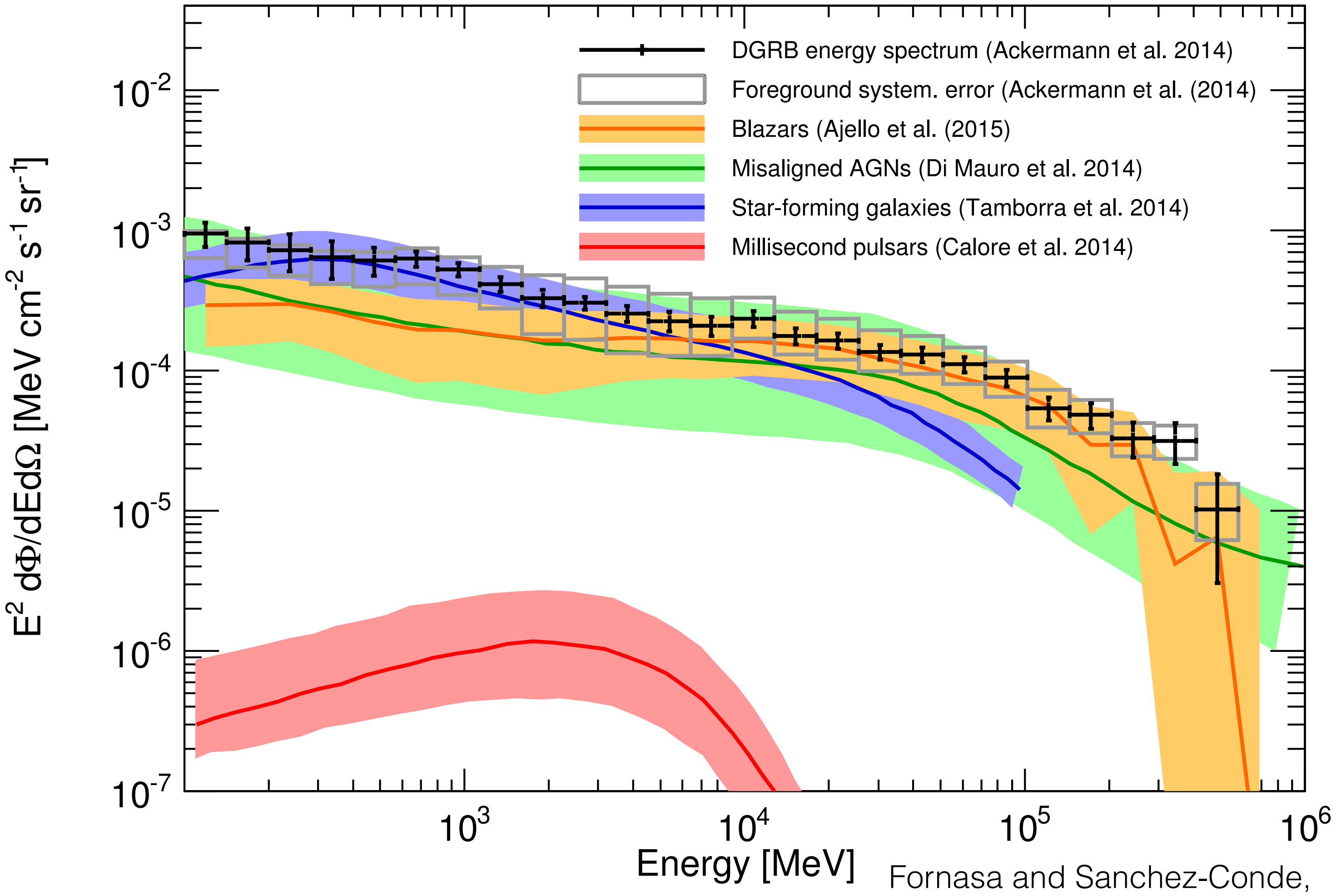
In collaboration with A. Cuoco, J. Zavala, J. Gaskins, M. A. Sanchez-Conde, G. Gomez-Vargas, E. Komatsu, T. Linden, F. Prada, F. Zandanel and A. Morselli



The Diffuse Gamma-Ray Background



Anisotropies in the Diffuse Gamma-Ray Background



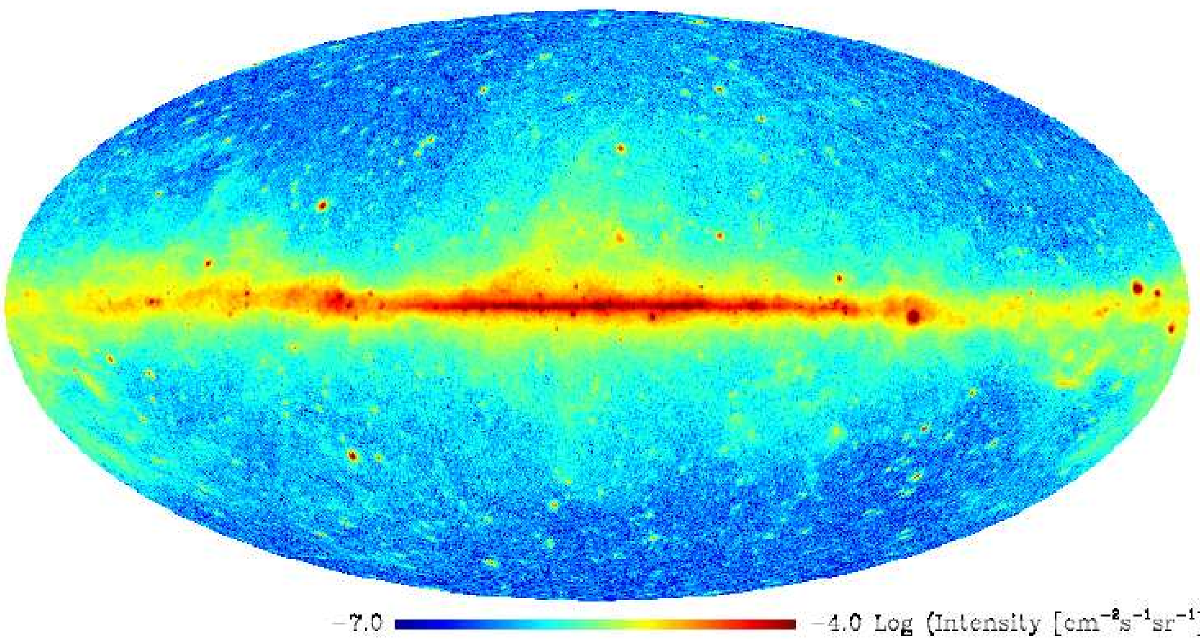
Fornasa and Sanchez-Conde, Phys. Rept. 598 (2015) 1-58

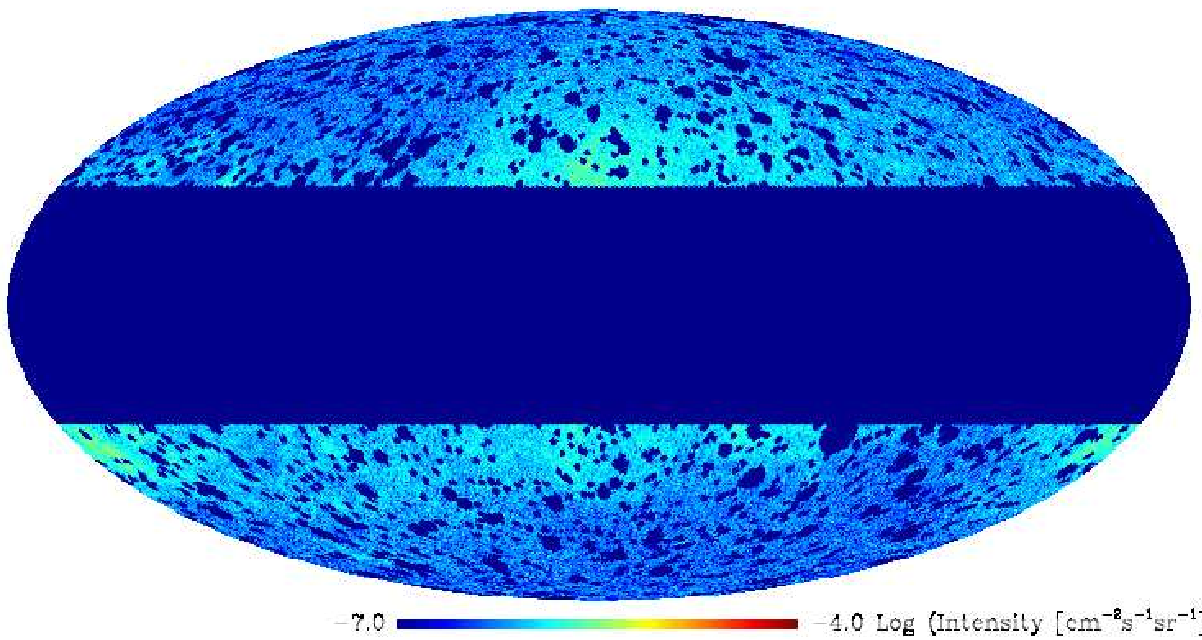
- cumulative emission of unresolved sources
- guaranteed components from unresolved astrophysical sources
- constraints on additional contributors (Dark Matter)

$$I(\psi) = \sum_{\ell m} a_{\ell,m} Y_{\ell,m}(\psi) \qquad C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

- measure C_ℓ (update the 2012 detection by Fermi-LAT)
- develop a model of C_ℓ in terms of astrophysical sources to fit the data

New APS measurement





Fornasa et al. (2016)	Ackermann et al. (2012)
81 months	22 months
Pass 7 reprocessed (ULTRACLEAN_v15) front	Pass 6 (DIFFUSE_v3) front and back
13 energy bins between 0.5-500 GeV	4 energy bins between 1-50 GeV
masking sources in 3FGL	masking sources in 1FGL

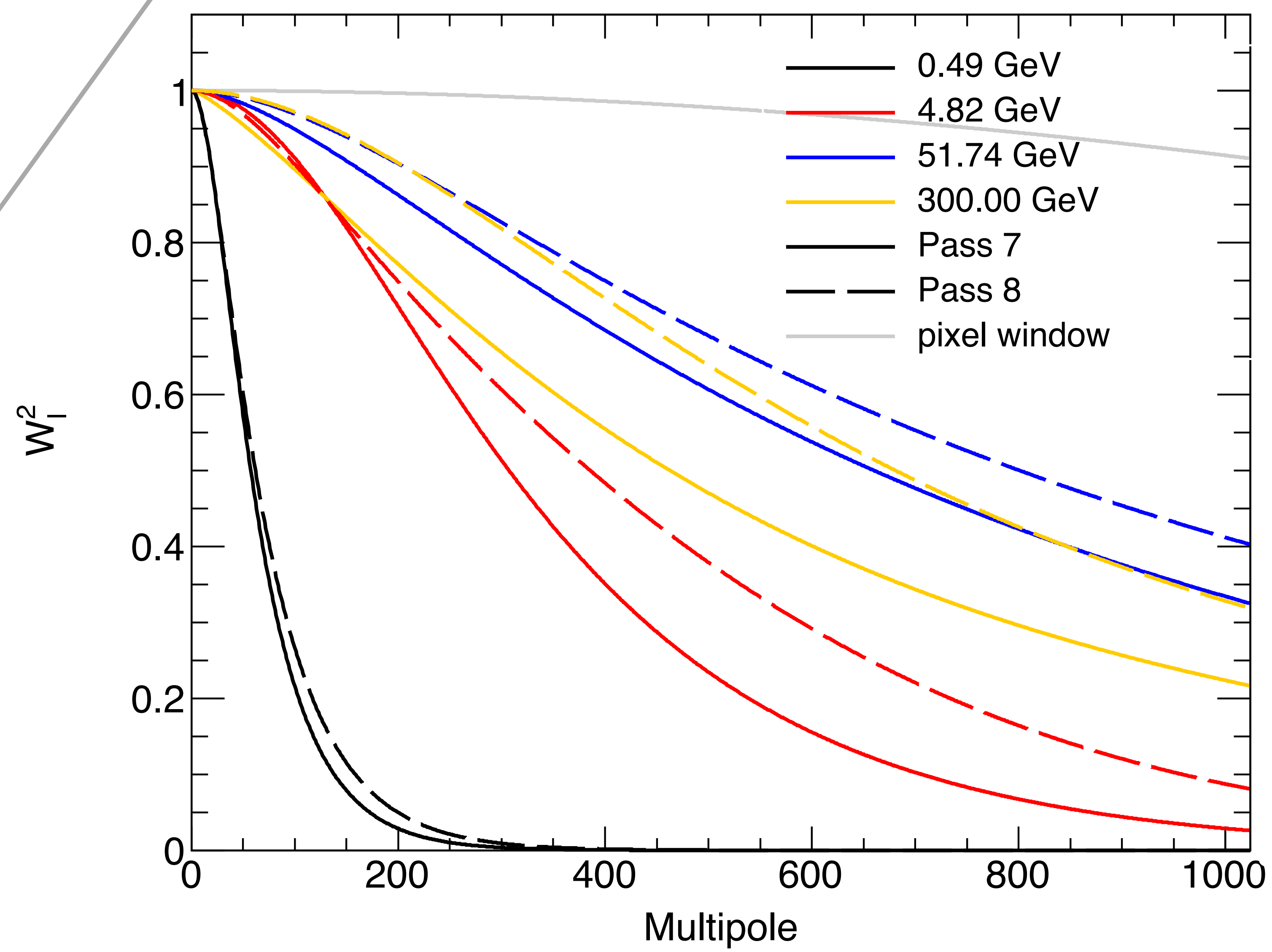
APS estimator

$$C_\ell^{\mathrm{signal},ij} = \frac{C_\ell^{\mathrm{Pol},ij} - C_\mathrm{N}}{(W_\ell^{\mathrm{beam},i} W_\ell^{\mathrm{beam},j})(W_\ell^{\mathrm{pix}})^2}$$

output of the decomposition in spherical harmonics

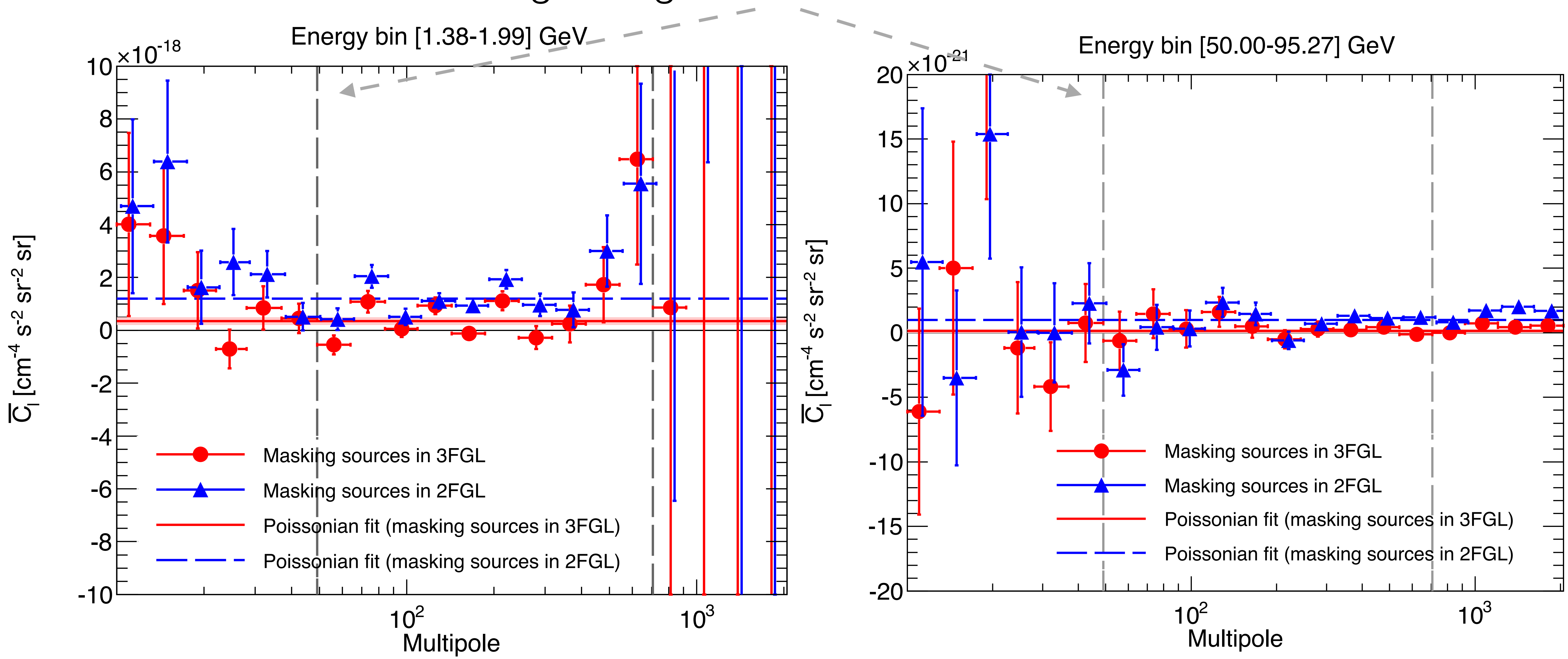
window beam function (it corrects for the experimental PSF)

photon noise (inversely proportional to the number of detected photons)



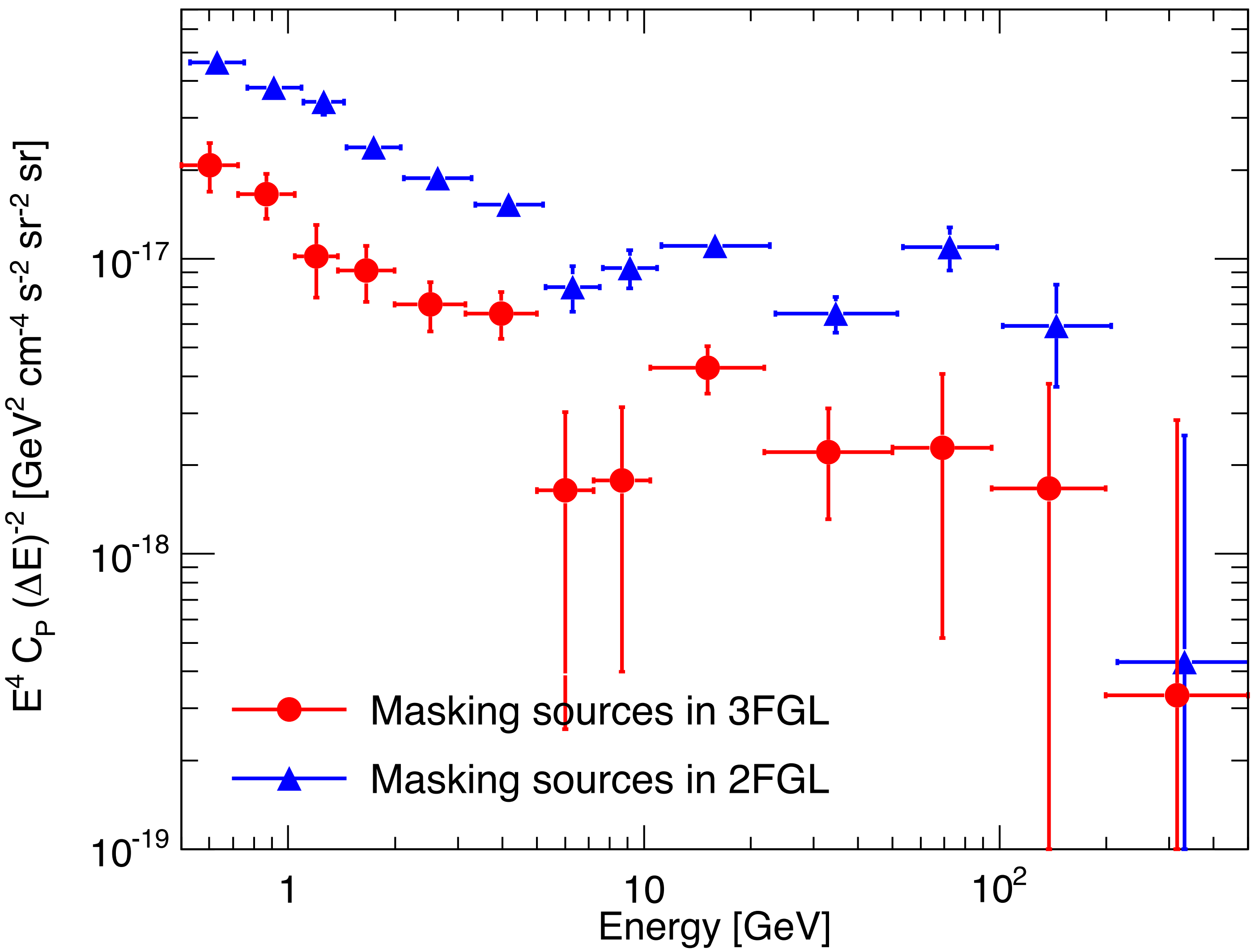
Binned APS measurement

signal region between ℓ=49 and 706



- contamination of Galactic foreground at low ℓ and effect of the beam window function at large ℓ
- fitting the data with a Poissonian APS: χ^2/dof = 0.91, p-value=0.96
- fits with $A(\ell/\ell_0)^\alpha$ leads to a best-fit α of -0.06±0.08, with the same p-value of the Poissonian best fit

Anisotropy energy spectrum



$$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

$$I(\psi) = \sum_{\ell m} a_{\ell,m} Y_{\ell,m}(\psi)$$

- 1 population of source: factor out the energy dependence

$$C_{\mathrm{P}}^{i,j} = I(E_i)\, I(E_j)\, \tilde{C}_{\mathrm{P}}$$

- 2 populations of sources (contributions sum up linearly):

$$C_{\mathrm{P}}^{i,j} = I_{\mathrm{A}}(E_i)\, I_{\mathrm{A}}(E_j)\, \tilde{C}_{\mathrm{P,A}} + I_{\mathrm{B}}(E_i)\, I_{\mathrm{B}}(E_j)\, \tilde{C}_{\mathrm{P,B}}$$

- features in the anisotropy energy spectrum indicates multiple populations of sources

Cross-correlation APS

$$C_\ell^{ij} = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} a_{\ell m}^{i} a_{\ell m}^{j\star}$$

- 91 independent combination of en. bins: 91 Poissonian $C_{\mathrm{P}}^{i,j}$
- cross correction coefficients

$$C_{\mathrm{P}}^{i,j}/\sqrt{C_{\mathrm{P}}^{i,i}C_{\mathrm{P}}^{j,j}}$$

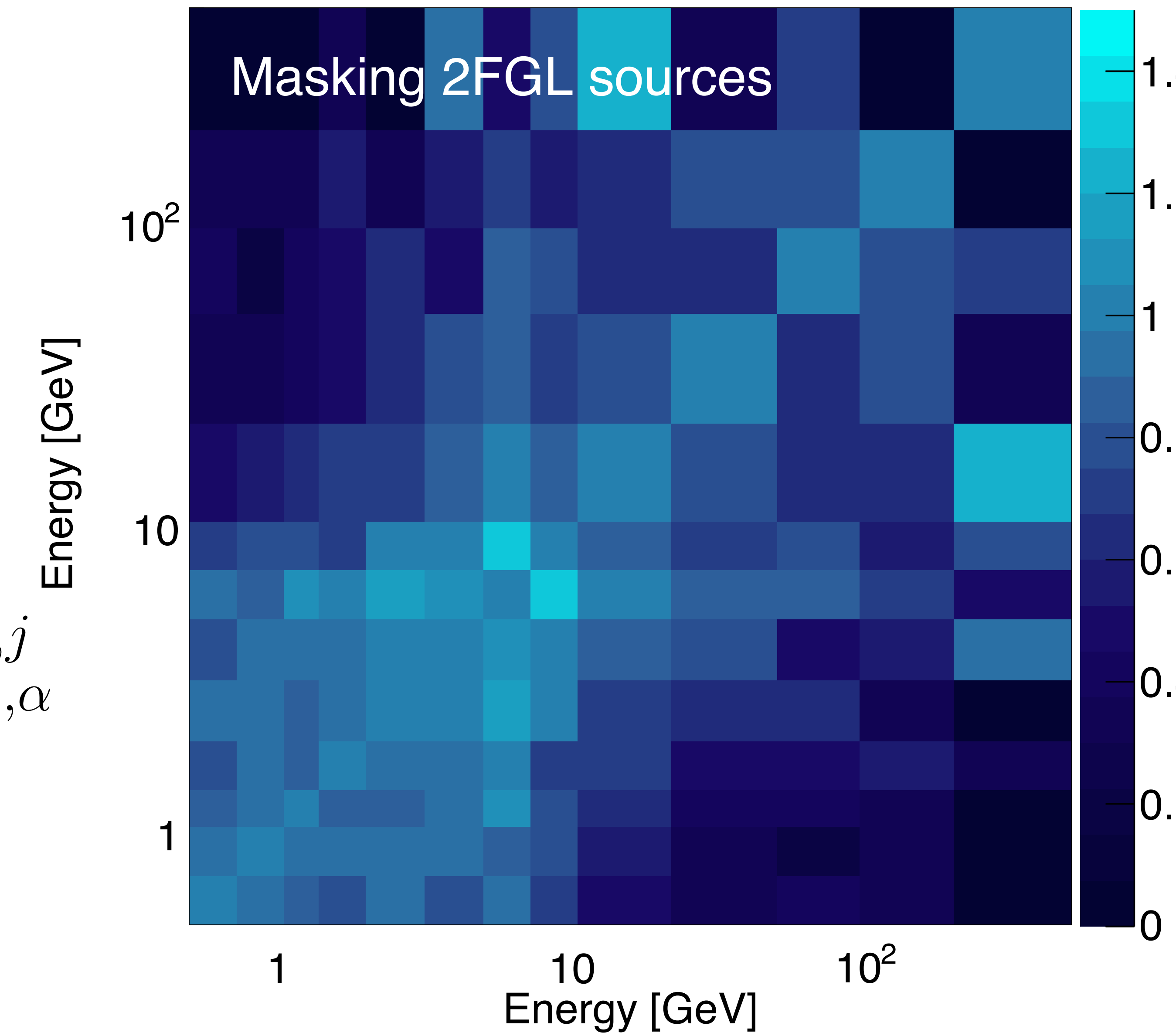
- one source class:

$$C_{\mathrm{P}}^{i,j} = I(E_i)I(E_j)\tilde{C}_{\mathrm{P}}$$

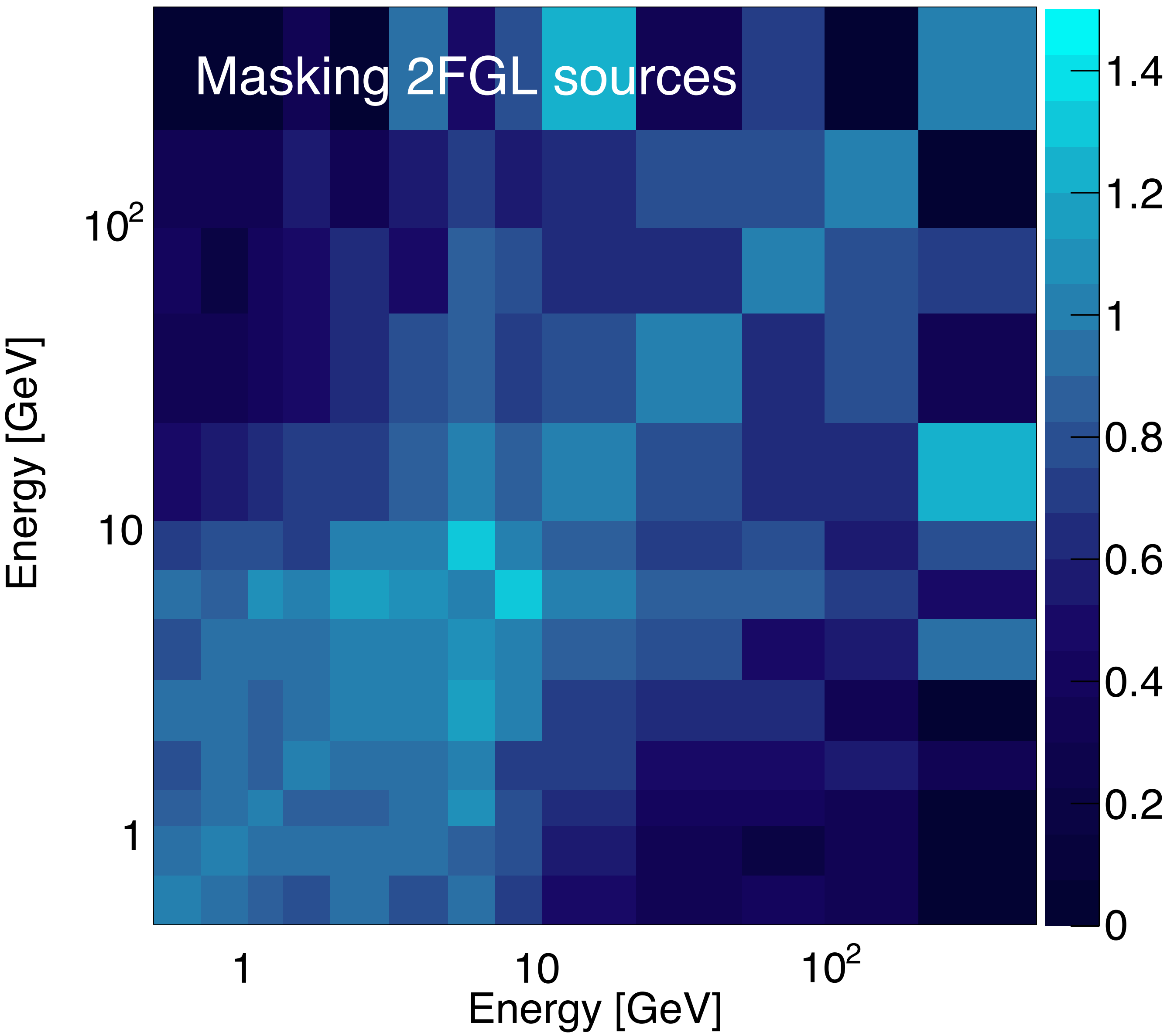
- multiple source classes:

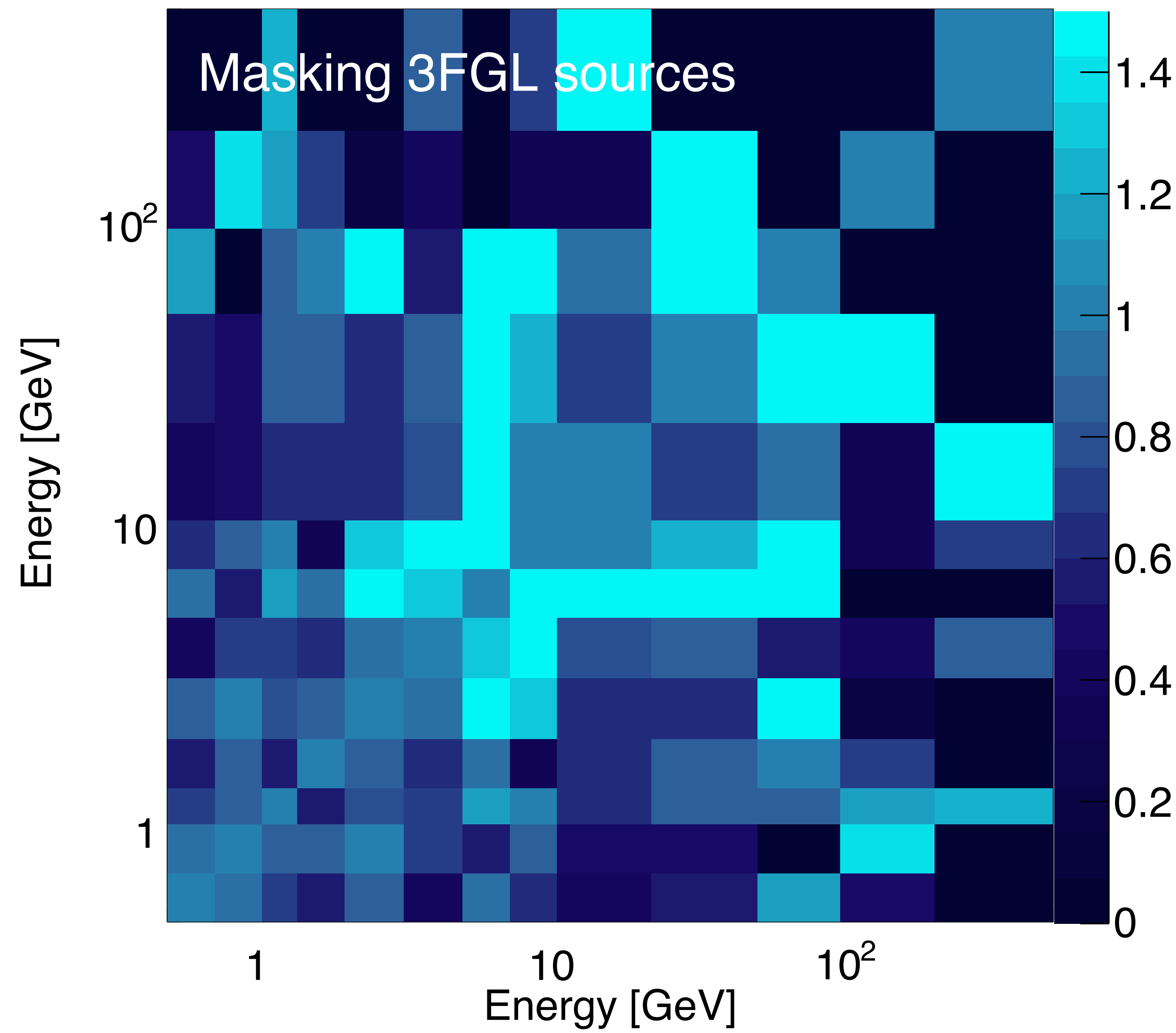
$$C_{\mathrm{P}}^{i,j} = \sum_\alpha C_{\mathrm{P},\alpha}^{i,j} = \sum_\alpha I(E_i)I(E_j)\tilde{C}_{\mathrm{P},\alpha}^{i,j}$$

  - cross-correlation coefficients different than 1.0 hint at multiple components



Cross-correlation APS



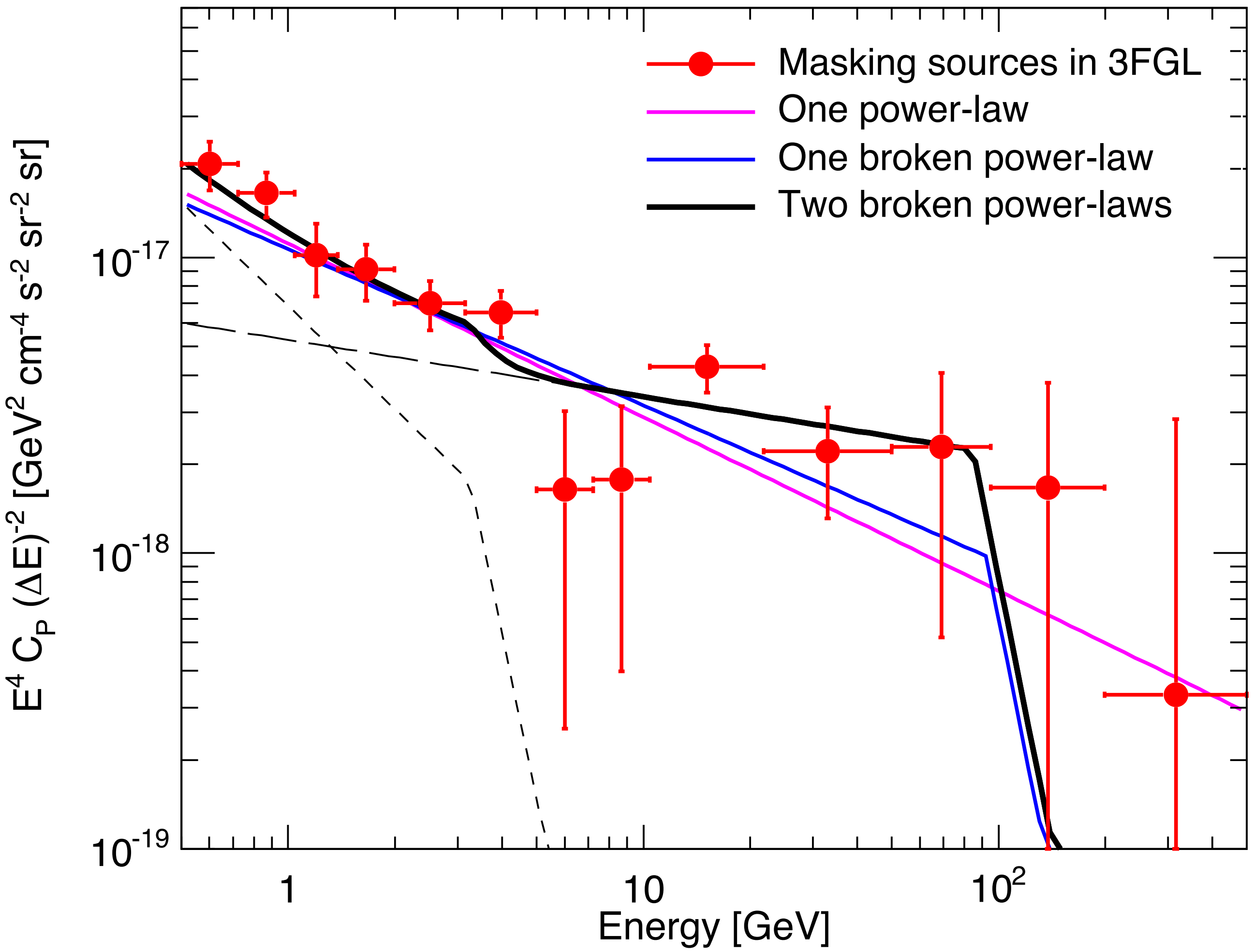


Interpretation in terms of multiple populations

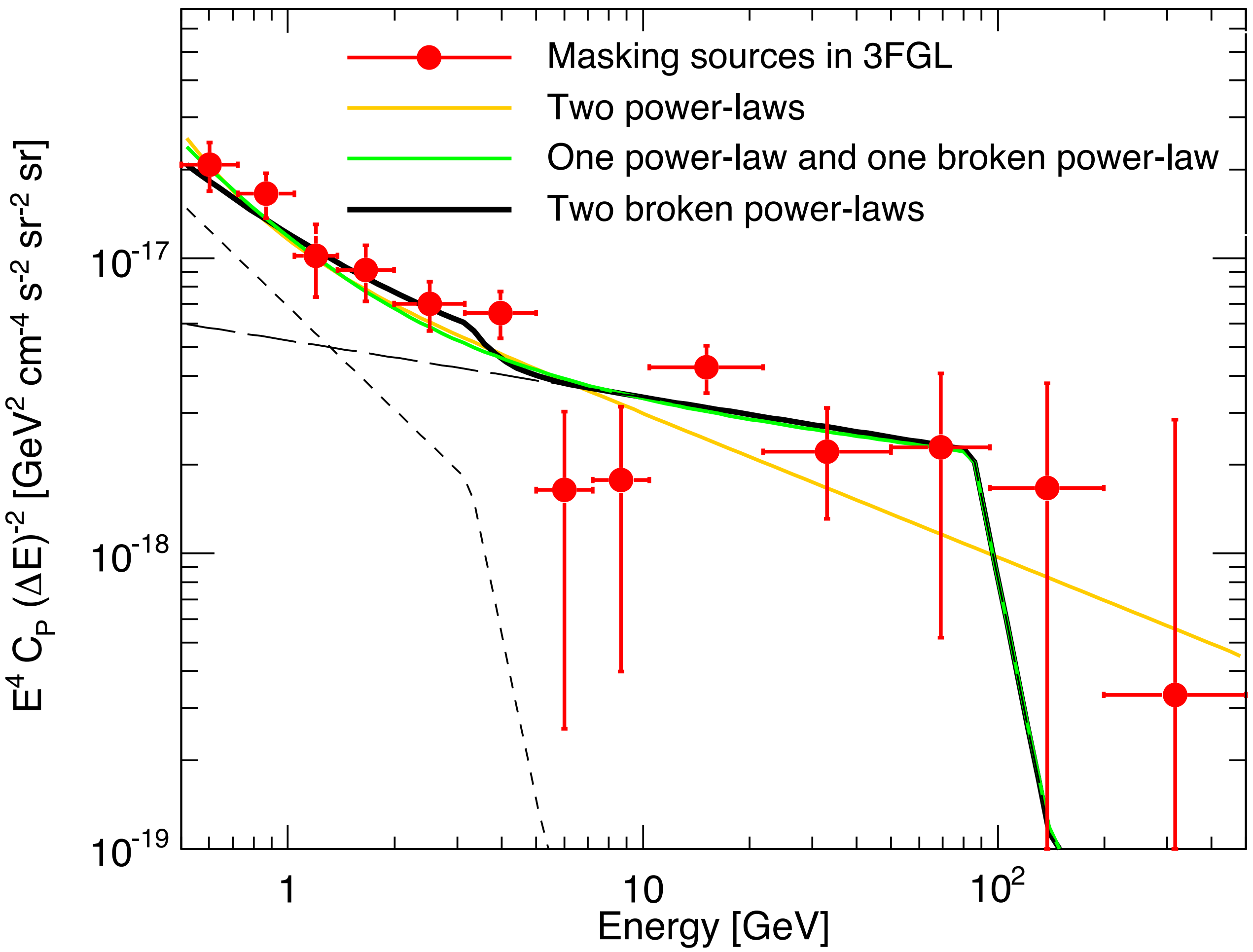
Fitting the data with one or more populations, assuming specific energy spectra:

$$I(E) \propto E^{-\alpha} \qquad I(E) \propto \begin{cases} (E/E_0)^{-\alpha} & \text{if } E \le E_b \\ (E_0/E_b)^{-\alpha+\beta}(E/E_0)^{-\beta} & \text{otherwise} \end{cases}$$

1 population



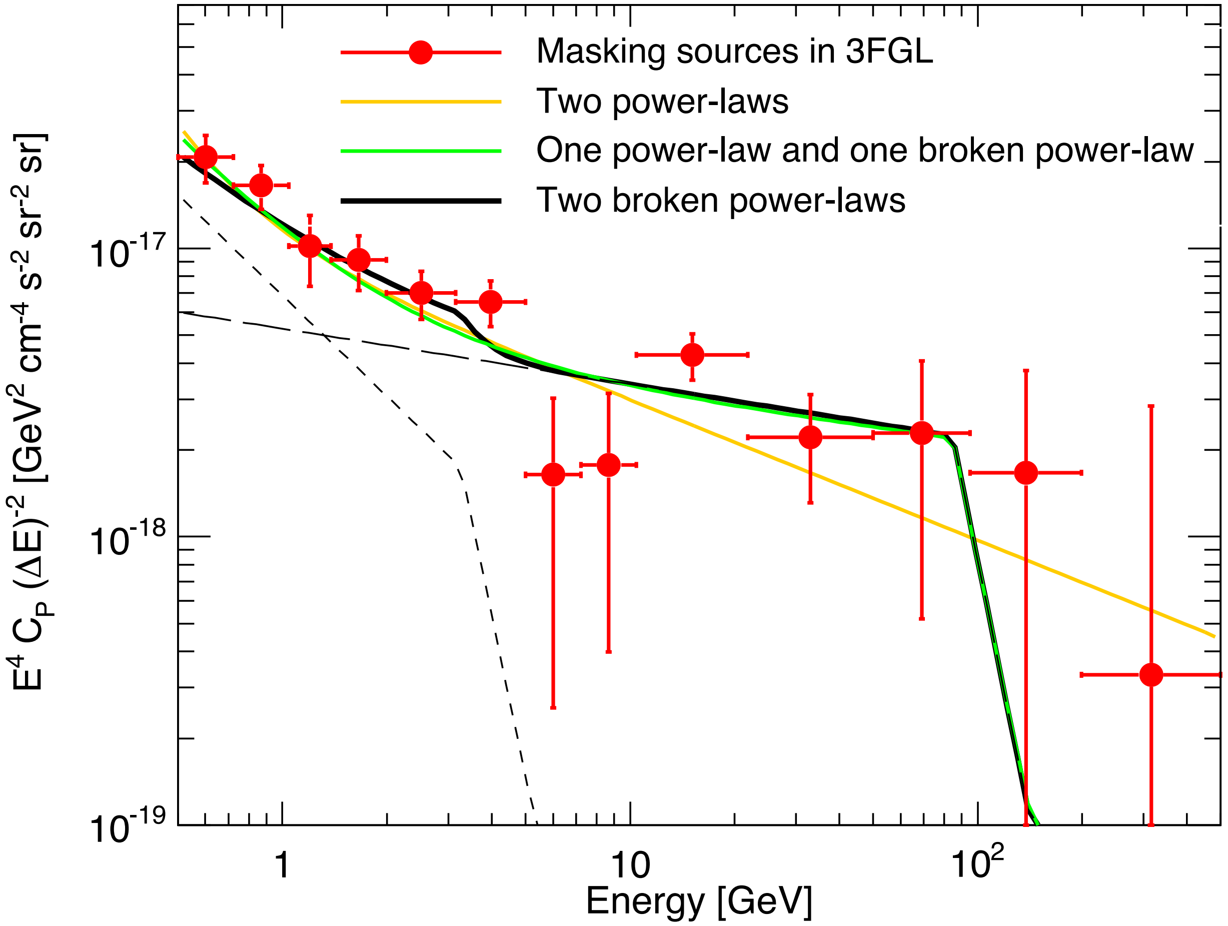
2 populations



Best-fit interpretation

Two populations of sources with broken-power-law spectra has the lowest χ^2 (χ^2/dof=1.10, p-value=0.24)

1st population	2nd population
$\log_{10}(A\ /\ \mathrm{cm^{-2}s^{-1}sr^{-1}}) = -8.58_{-0.05}^{+0.04}$	$\log_{10}(A\ /\ \mathrm{cm^{-2}s^{-1}sr^{-1}}) = -8.64_{-0.05}^{+0.04}$
$\alpha = 2.58_{-0.12}^{+0.18}$	$\alpha = 2.10 \pm 0.05$
β>3.49 at 68%CL	β>3.86 at 68%CL
E_b=$3.26_{-0.64}^{+1.05}$ GeV	E_b=$84.65_{-15.71}^{+10.28}$ GeV



Interpretation with one population of sources is **excluded** at 95% CL

Parametric model for blazars

Luminosity-dependent density evolution:

- double power-law gamma-ray luminosity function

$$\Phi(L_\gamma, z=0, \Gamma) = \frac{dN}{dL_\gamma dV d\Gamma} = \frac{A}{\ln(10)\, L_\gamma}\left[\left(\frac{L_\gamma}{L_0}\right)^{\gamma_1} + \left(\frac{L_\gamma}{L_0}\right)^{\gamma_2}\right]^{-1} \times \exp\left[-\frac{(\Gamma-\mu(L_\gamma))^2}{2\sigma^2}\right]$$

- spectral index Γ depends on luminosity *L*γ (modelling FSRQs and BL Lacs at the same time)

measured in erg s^{-1}

$$\mu(L_\gamma) = \mu^* + \beta\,(\log(L_\gamma) - 46)$$

- evolutionary factor: $\Phi(L_\gamma,z,\Gamma) = \Phi(L_\gamma,0,\Gamma) \times e(z,L_\gamma)$

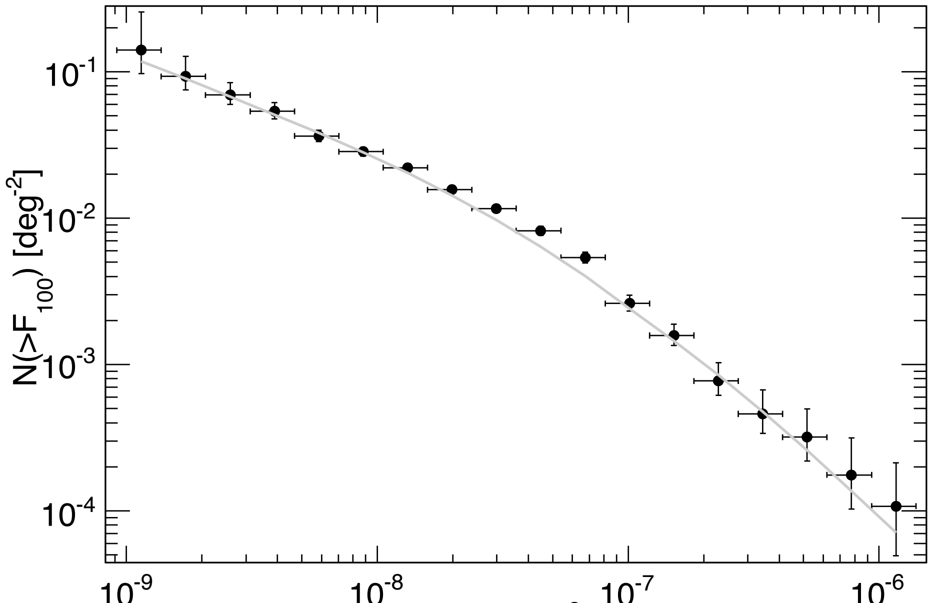
$$e(z, L_\gamma) = \left[\left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{-p_1(L_\gamma)} + \left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{-p_2(L_\gamma)}\right]^{-1}$$

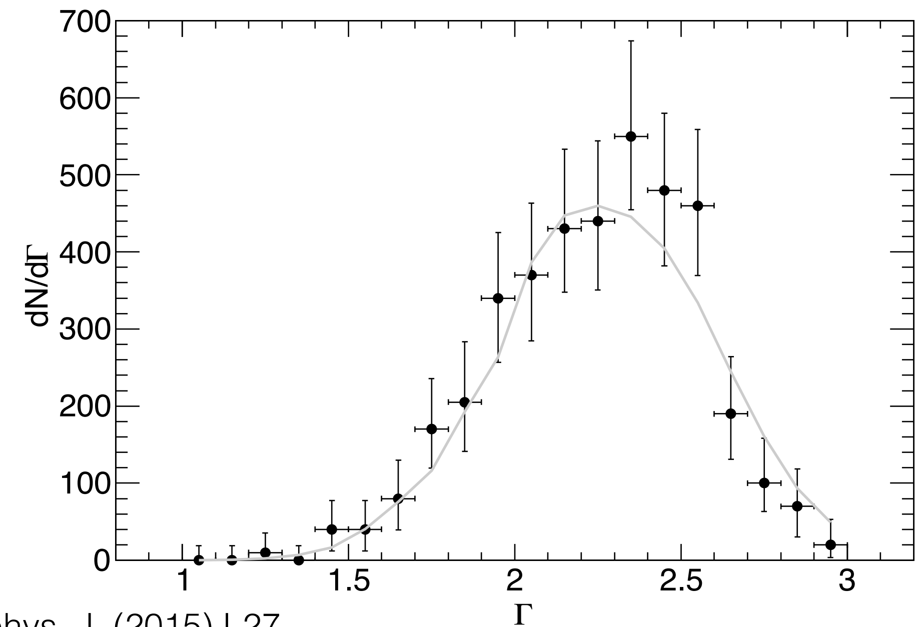
$$z_c(L_\gamma) = z_c^*\left(\frac{L_\gamma}{10^{48}\mathrm{erg\ s}^{-1}}\right)^{\alpha}$$

$$p_1(L_\gamma) = p_1^0 + \tau\,(\log L_\gamma - 44)$$

$$p_2(L_\gamma) = p_2^0 + \delta\,(\log L_\gamma - 44)$$

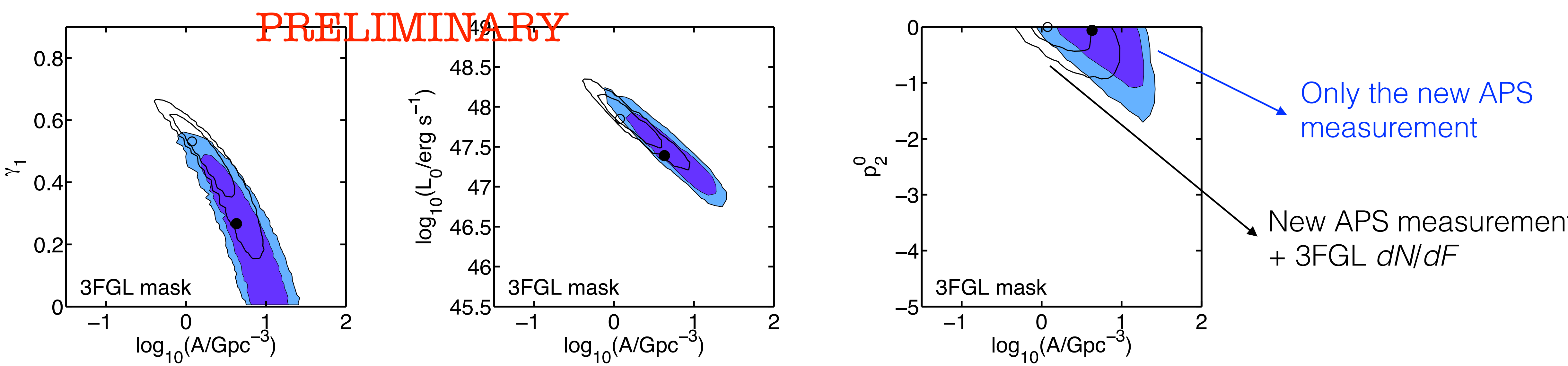
Data (3FGL *dN*/*dF* and APS)



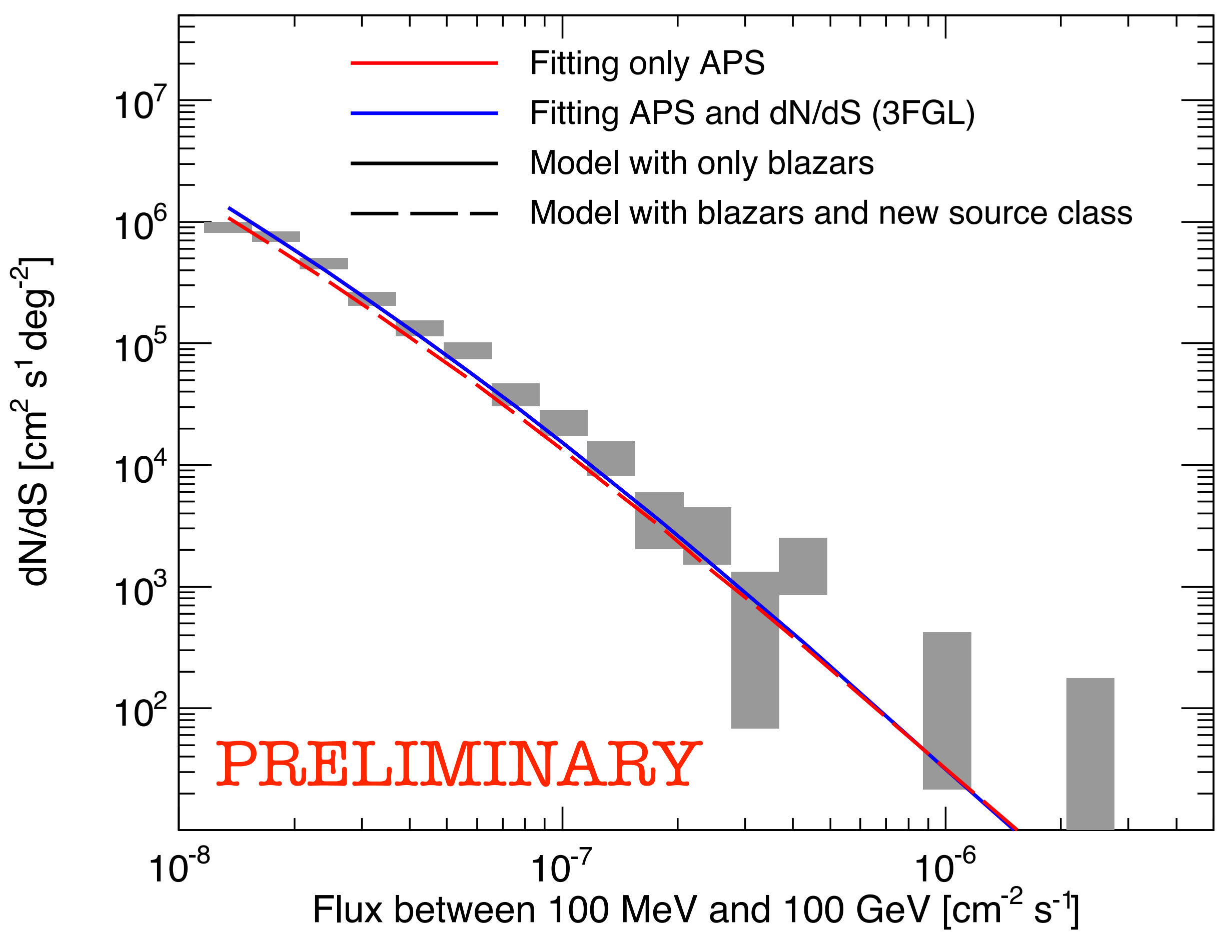


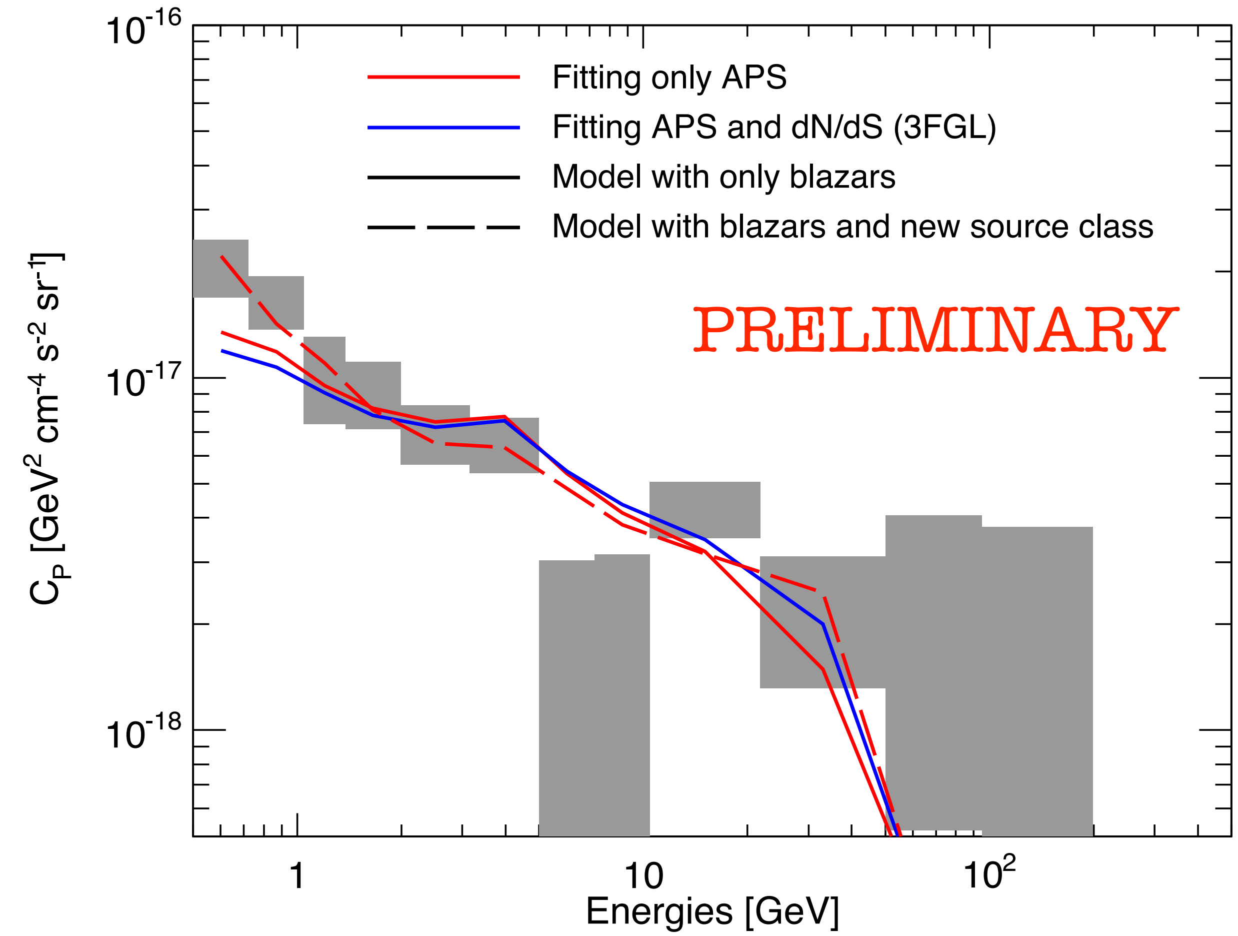
Ajello et al., Astrophys. J. (2015) L27

- best fit from Ajello et al. (2015): γ_2=1.83, μ*=2.22, β=0.1, σ=0.28, z_c*=1.25, α=7.23, p_1^0=3.39
- for unclustered unresolved blazars: $$C_{\rm P} = \int_0^{S_{\rm thr}} S^2 \frac{dN}{dS}$$



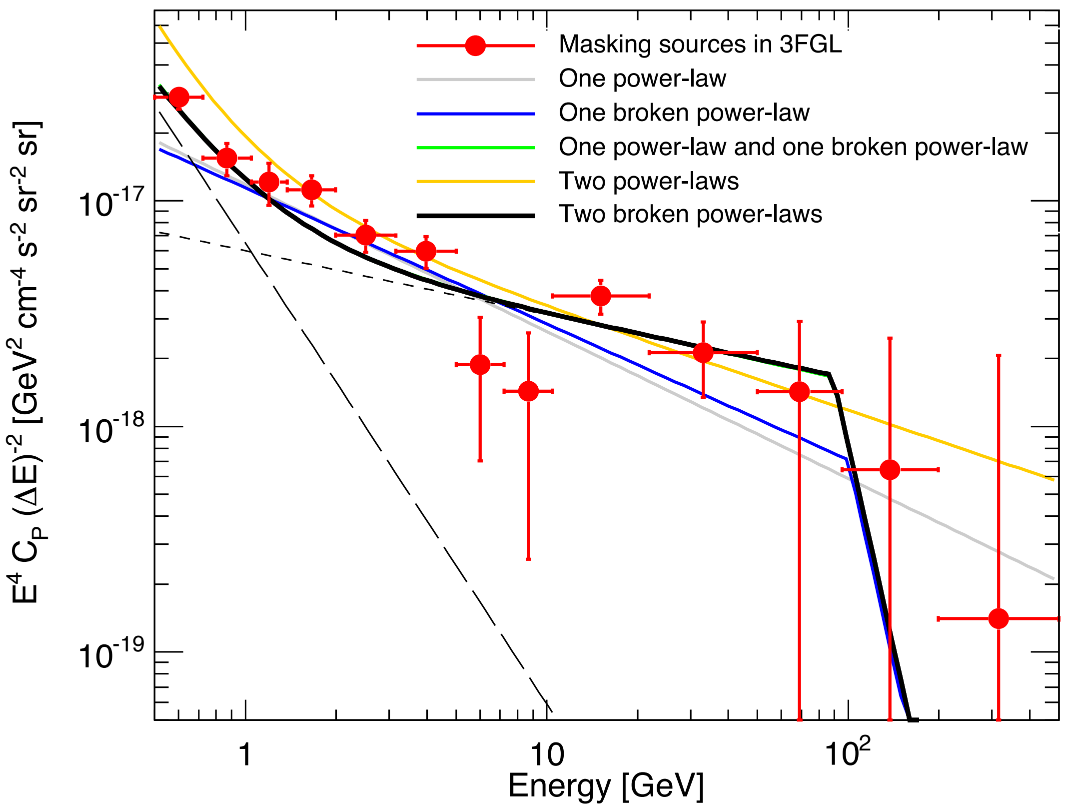
Evidence for new source class

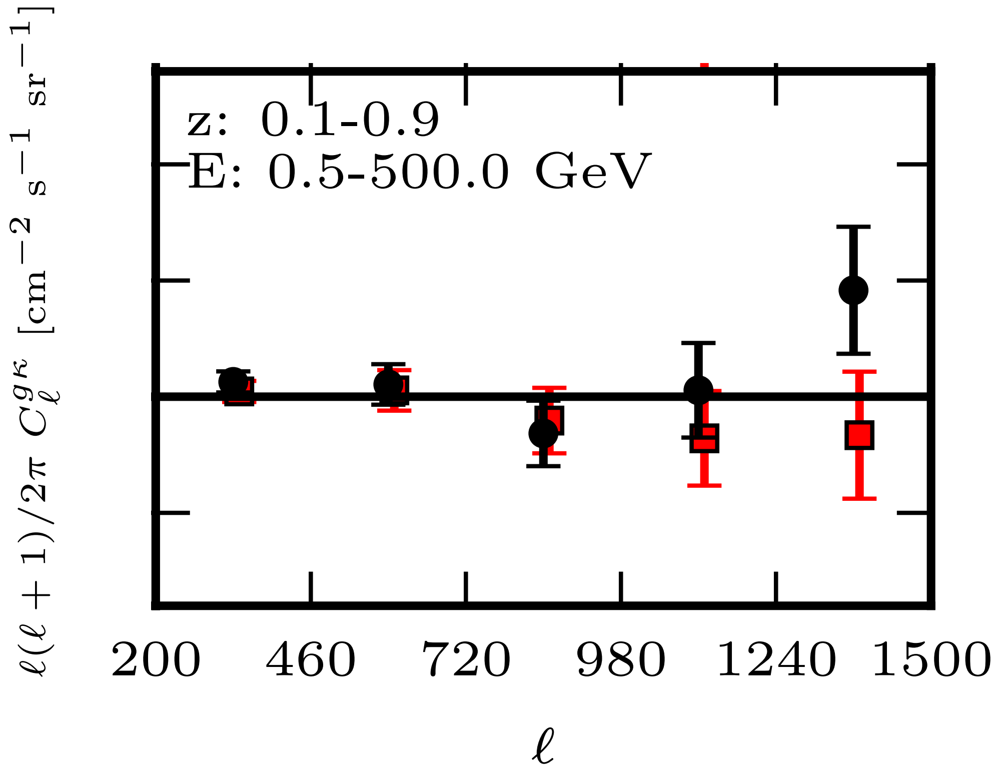


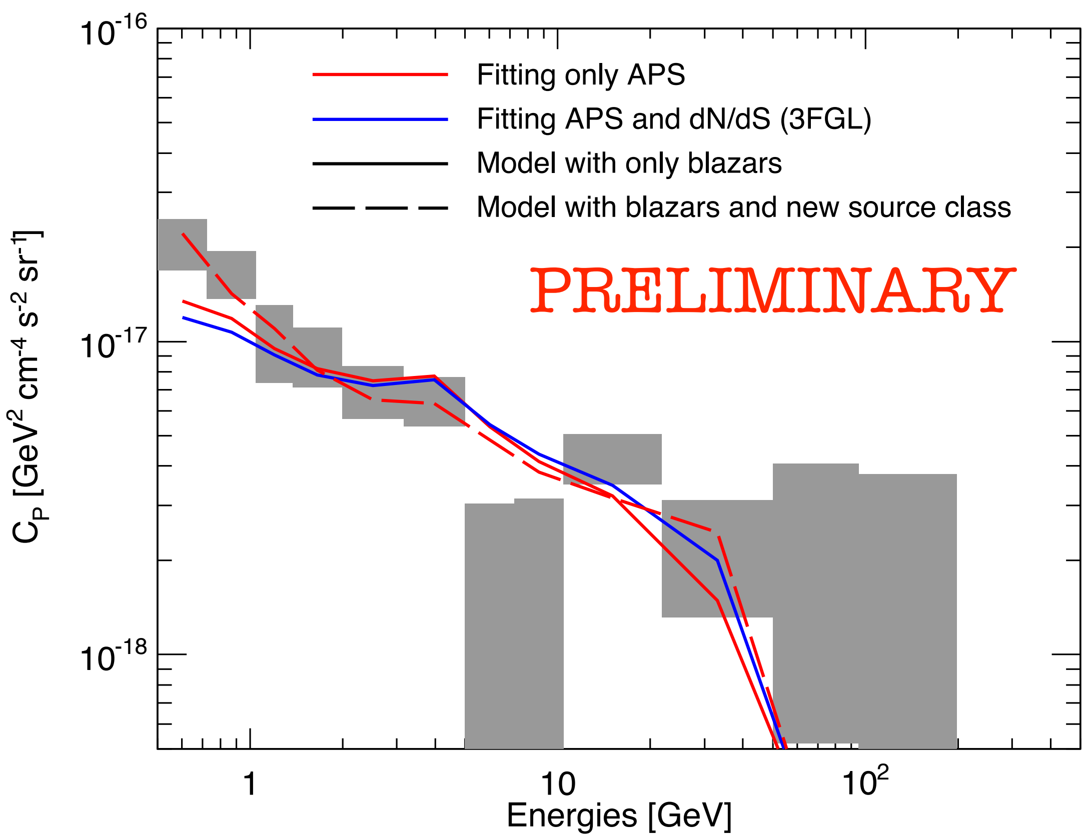


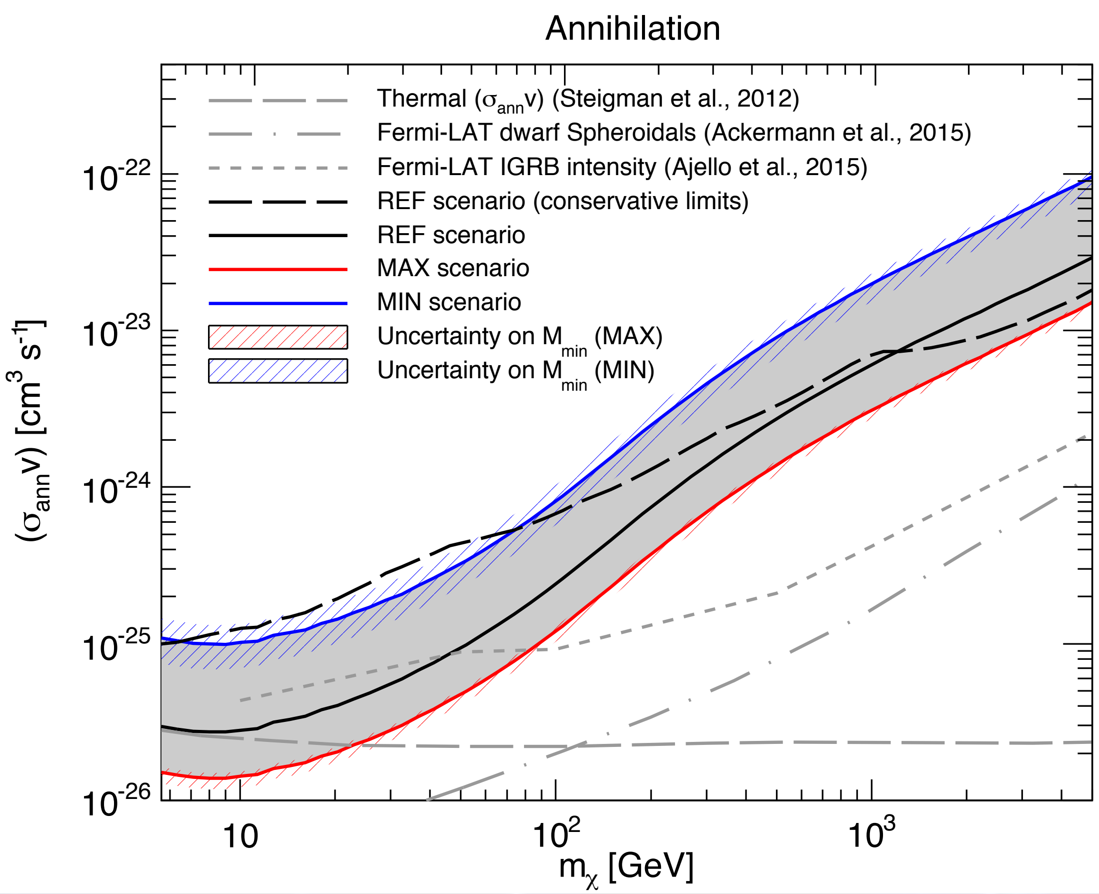
- blazars alone cannot explain the measured APS below 1 GeV: χ^2=1.59 (p-value=0.005) and χ^2=1.70 (p-value=0.0003)
- include an additional class of sources, assuming $C_P(E) \propto E^{-2\Gamma_{new}}$
- new fits including new source class (Γ_{new} and $C_P^{0,0}$): χ^2=1.11 (p-value=0.28) and χ^2= (p-value=). New class is preferred at more than 99%CL.
- best-fit Γ_{new} is $\Gamma_{new}=3.00^{0.27}_{0.22}$ and Γ_{new}=xxxx

Conclusions



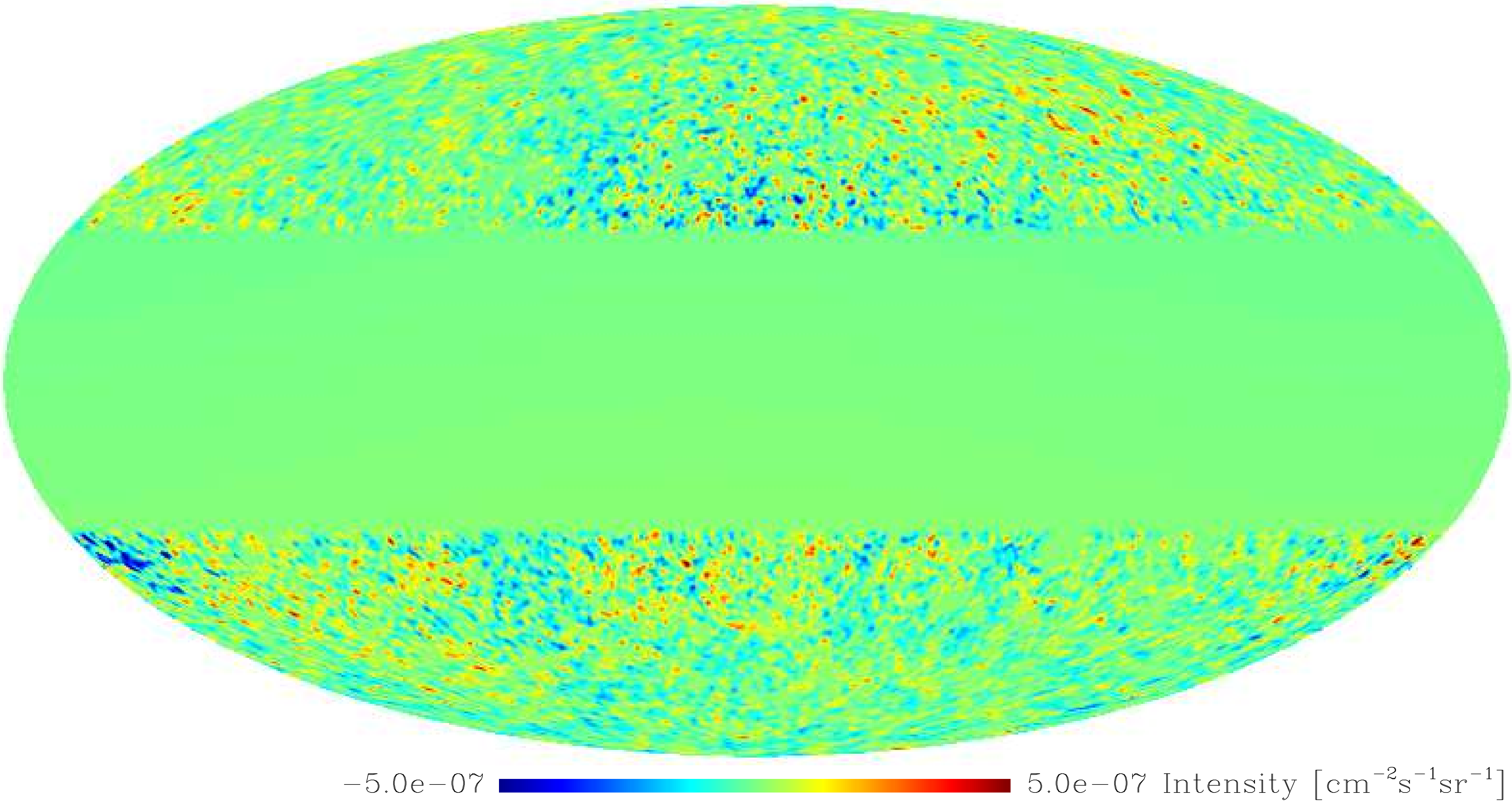




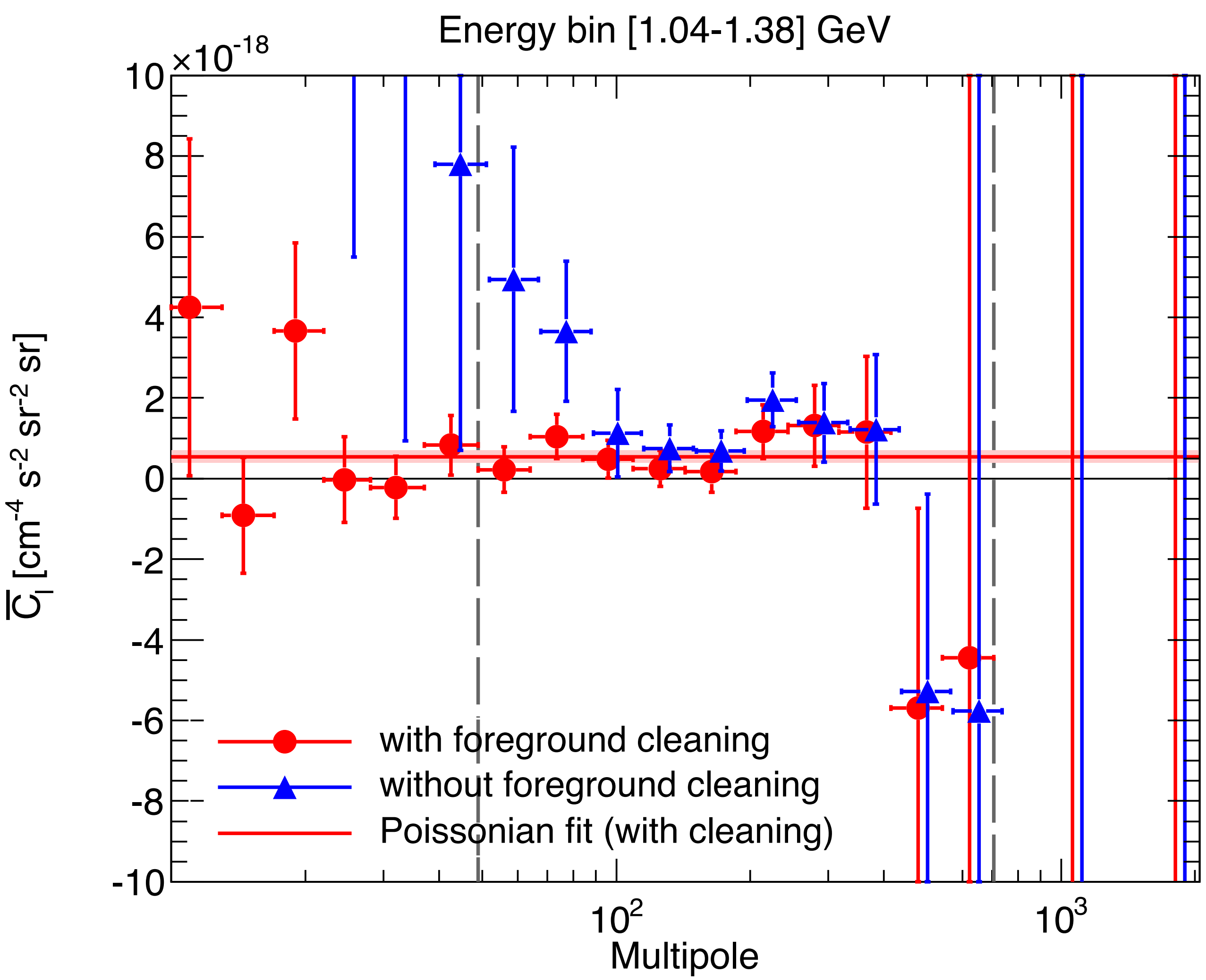


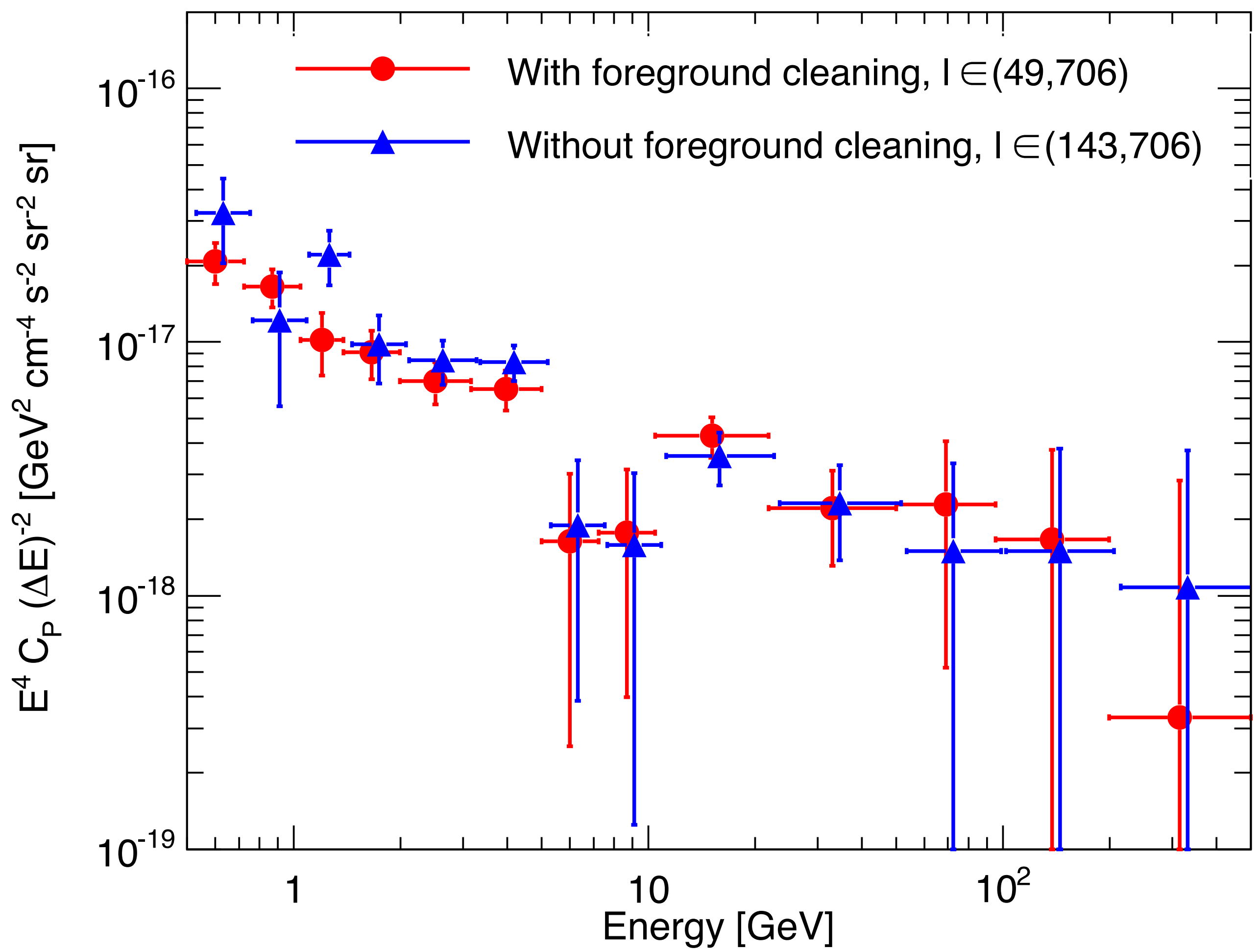
Residuals

model `gll_iem_v05_rev1.fit`



Validation of foreground cleaning

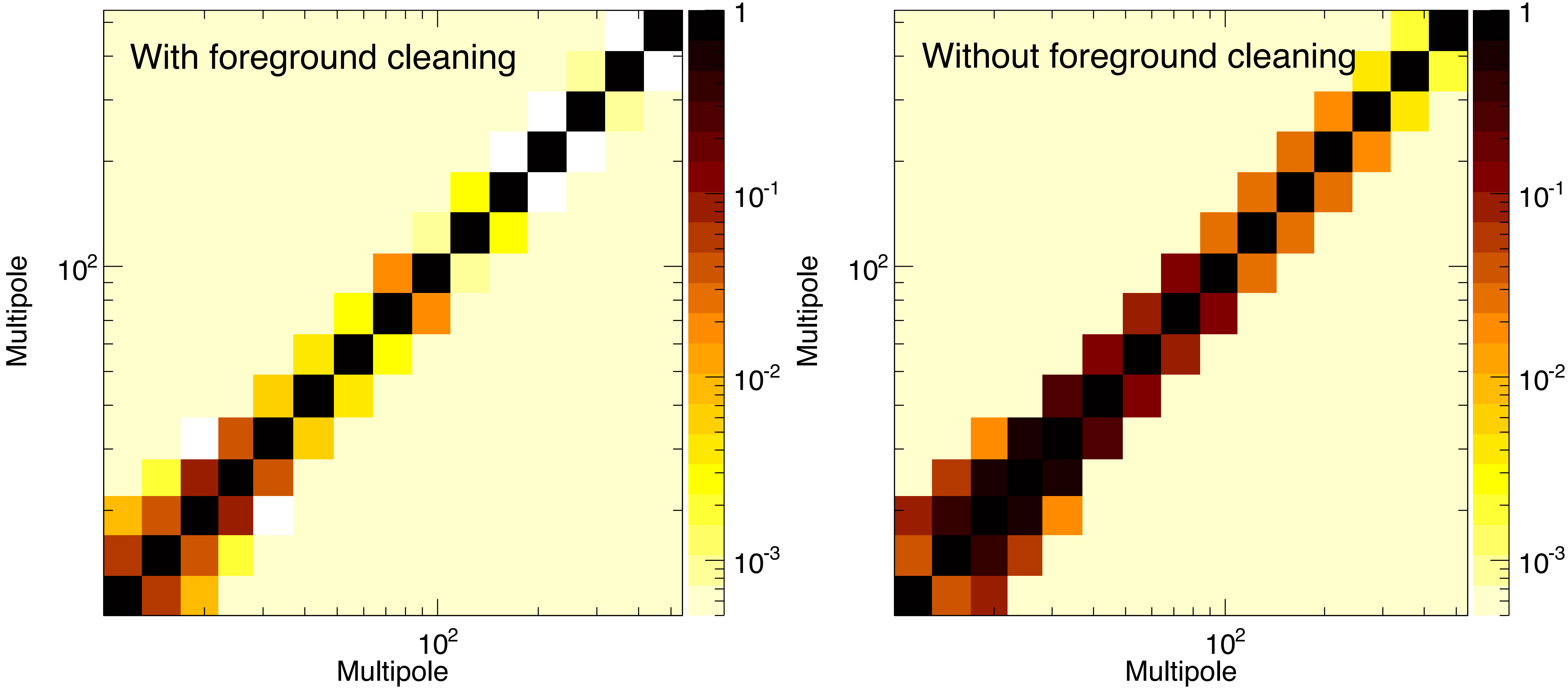




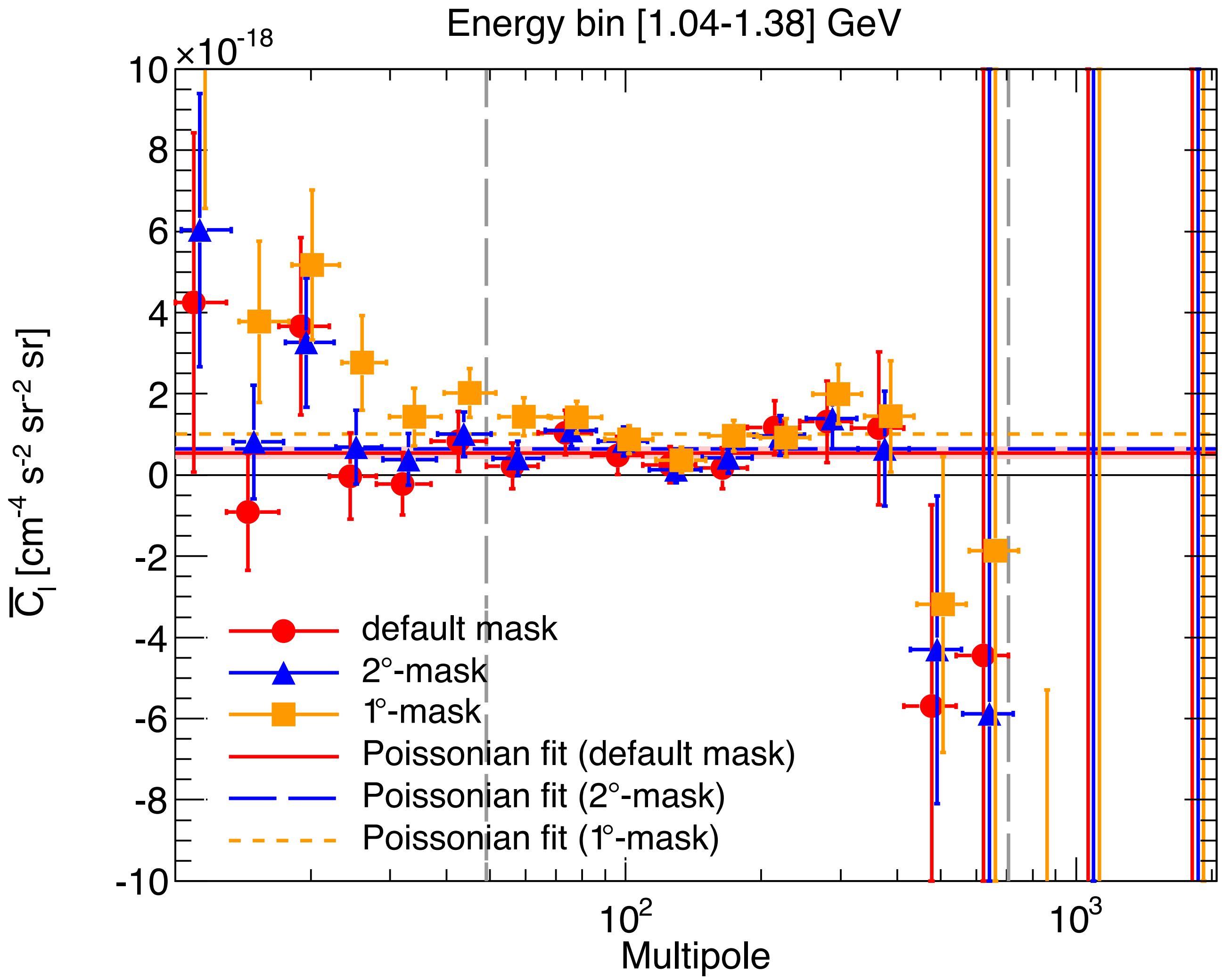
- significant less power at low multipoles (large angular scales)
- region with ℓ>143 (bin #5 in the signal region) is not affected by Galactic foreground, even without cleaning
- foreground cleaning also reduces correlation between multipole bins

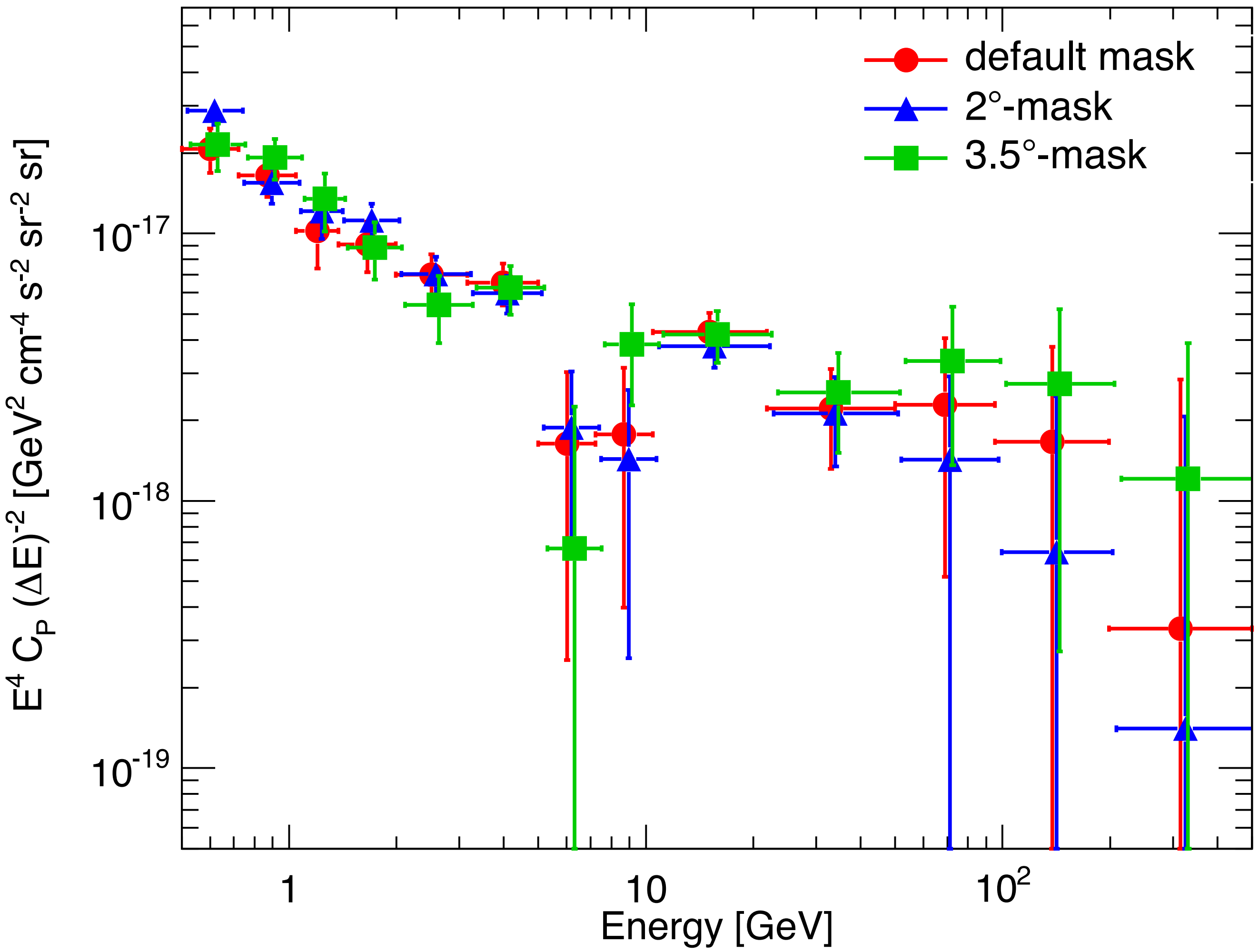
Correlation between multipole bins

$$\frac{\sigma_{i,j}}{\sqrt{\sigma_{i,i}\sigma_{j,j}}}$$



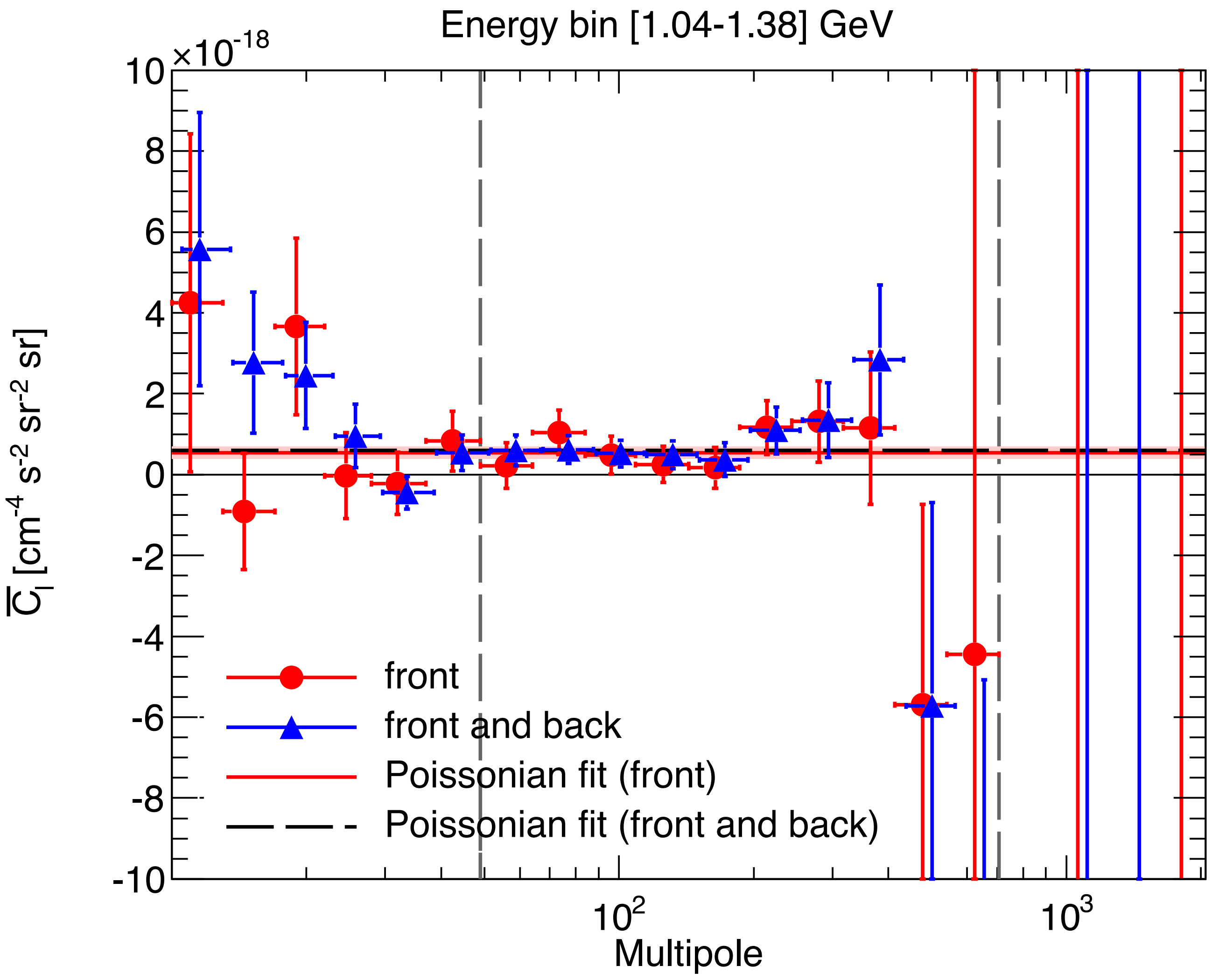
Validation of mask (3FGL)

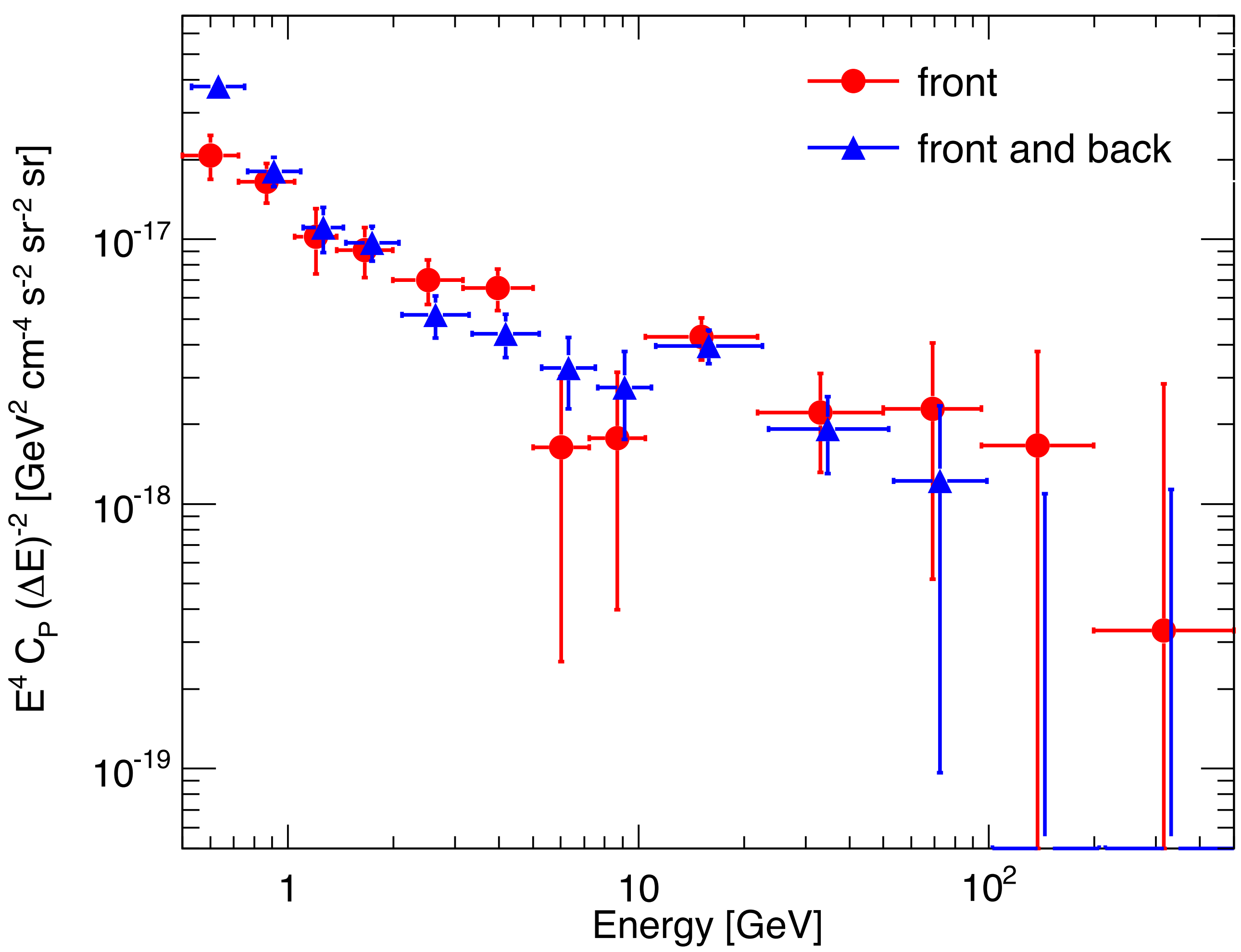




- 1°-mask: disc of 1 deg around all sources
- 2°-mask: disc of 2 deg around 500 brightest sources and disc of 1 deg around all the others
- 3°-mask: disc of 3.5 deg around 500 brightest sources, disc of 2.5 deg around following 500 brightest sources, disc of 2.0 deg around 1000 following brightest sources and disc of 1.5 deg around all the others

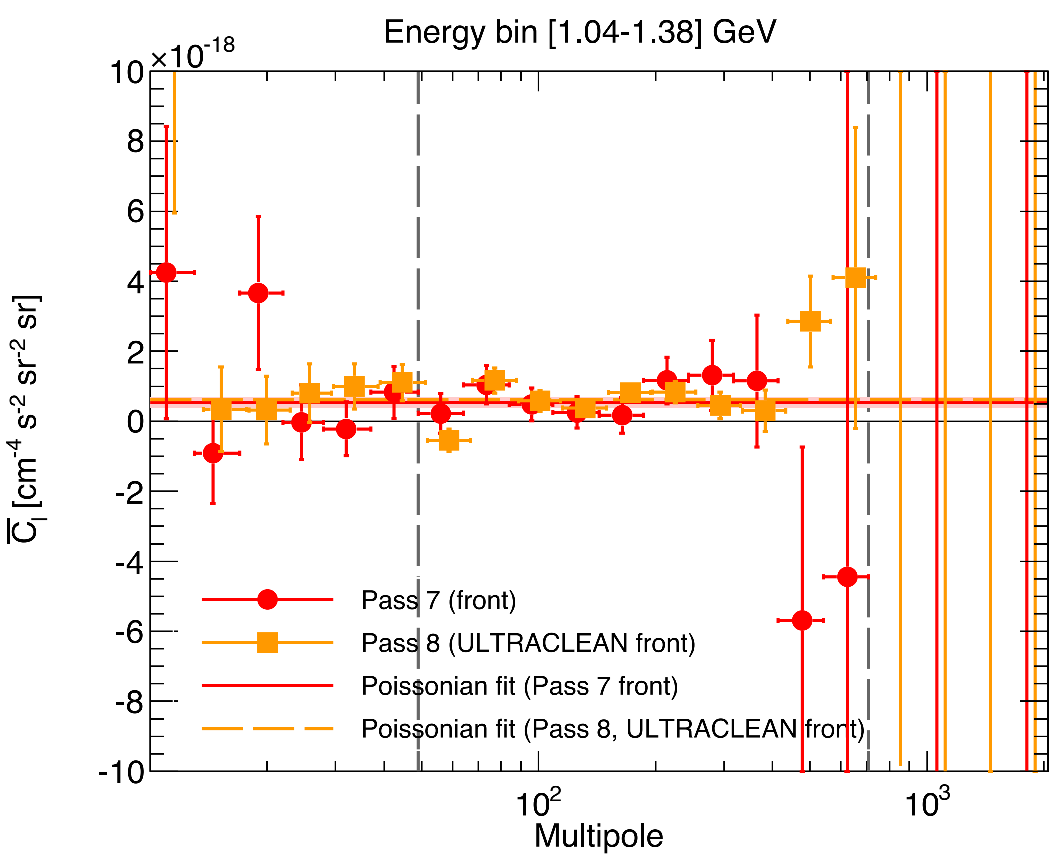
Front only and front+back

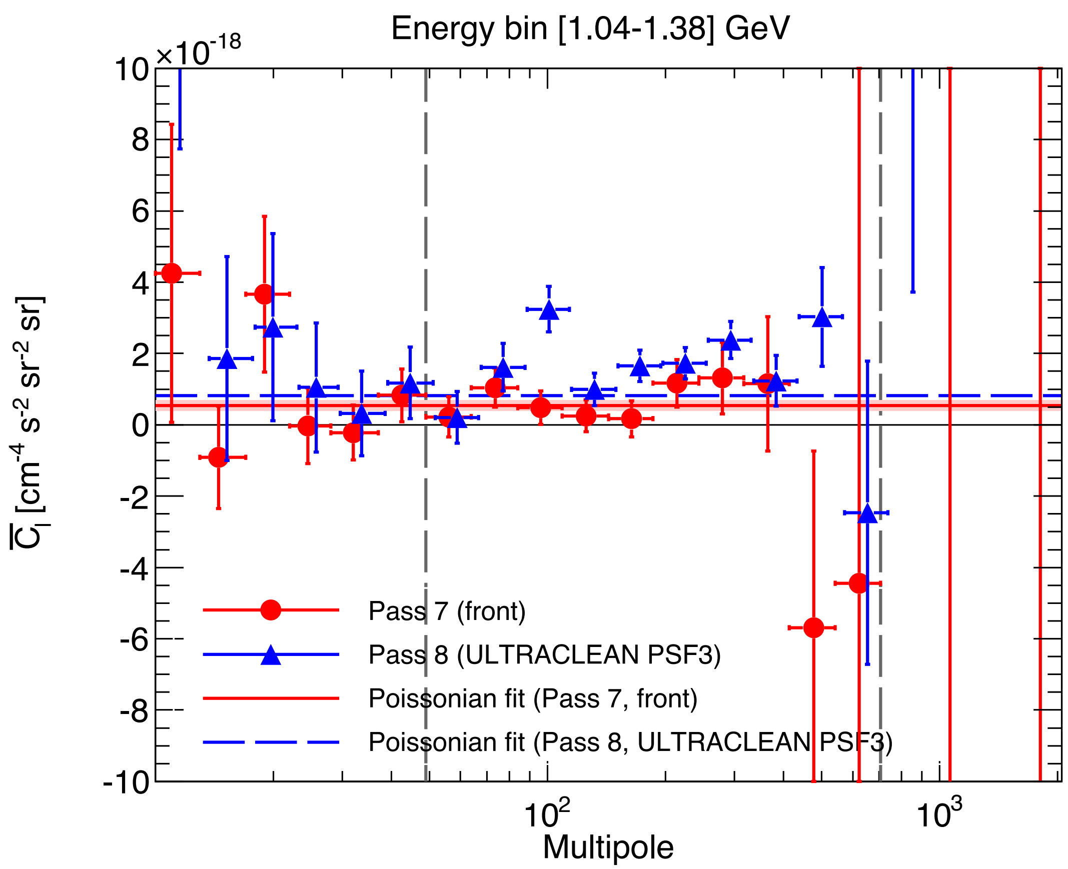


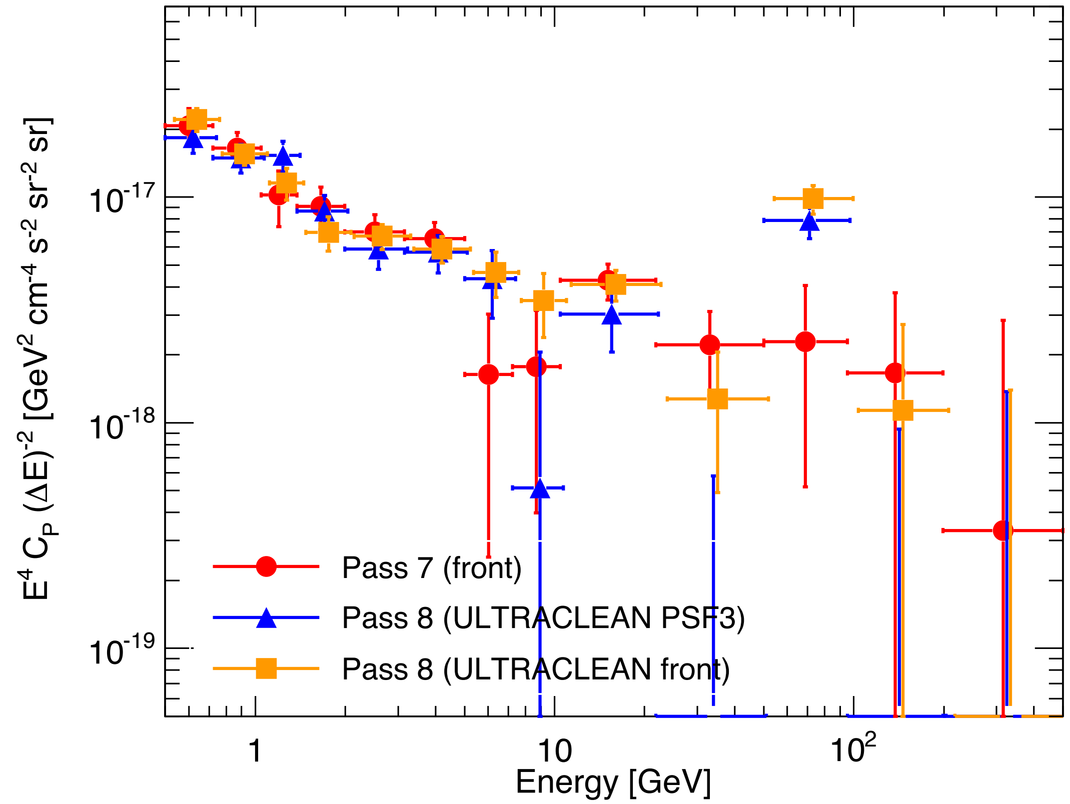


- two data sets are not independent
- possibility of leakage outside of point sources in front+back data set because of the larger PSF

Pass 7 vs. Pass 8







How to bin APS

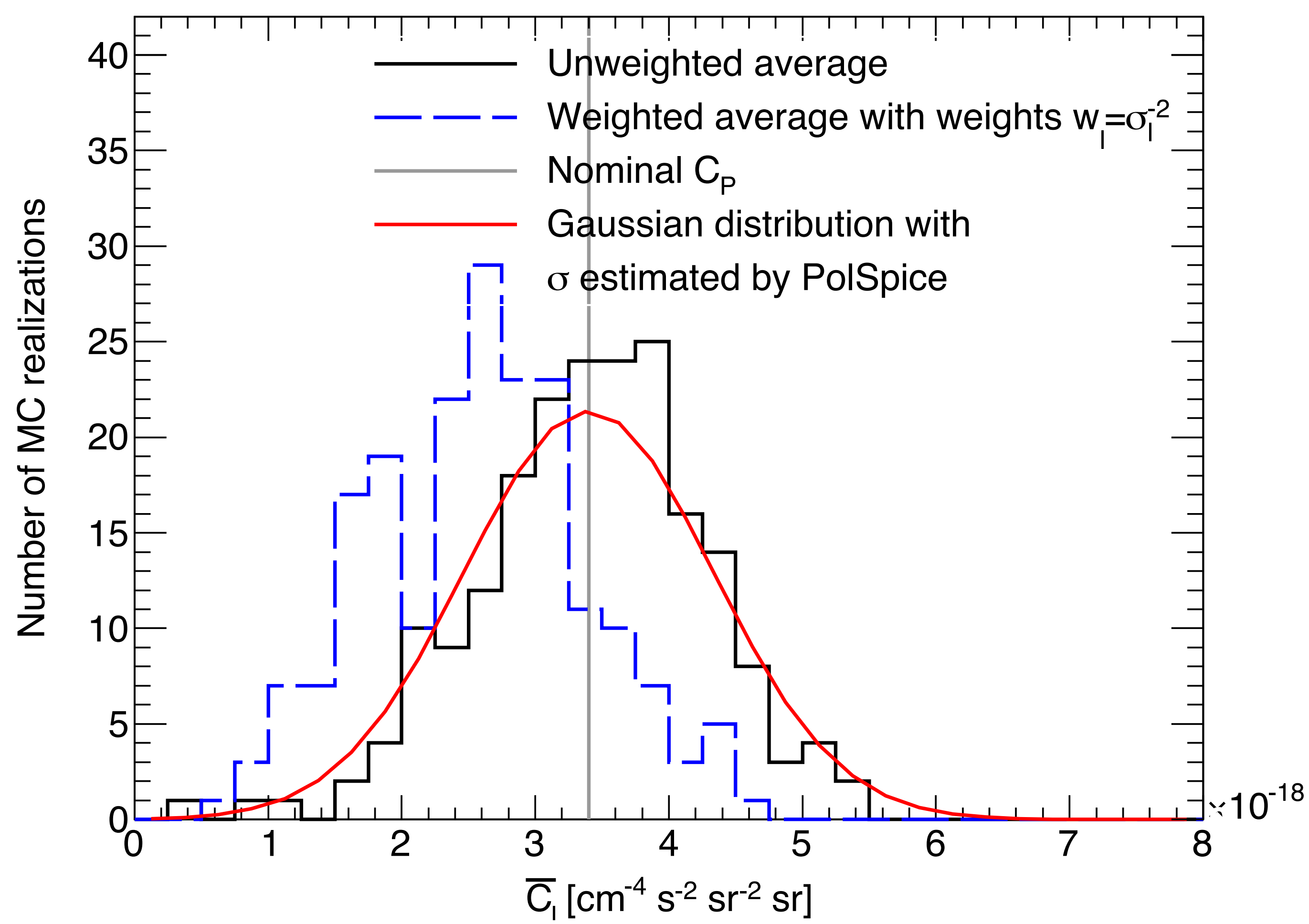
- produce 200 Monte Carlo realisations of the gamma-ray sky with a fixed nominal C_P

- analytical expression for the error is

$$\sigma_\ell = \sqrt{\frac{2}{(2\ell+1)\, f_{\rm sky}}} \left(C_\ell + \frac{C_{\rm N}}{W_\ell^2} \right)$$

- to bin C_ℓ in one multipole bin, you can compute:
    - **A. unweighted average**
    - B. weighted average with weight = $1/\sigma_\ell$
    - C. weighted average with weight = $1/\sigma_\ell$ and only photon noise

- Monte Carlo simulations prove that method B underestimates the APS



How to estimate the error on the binned APS

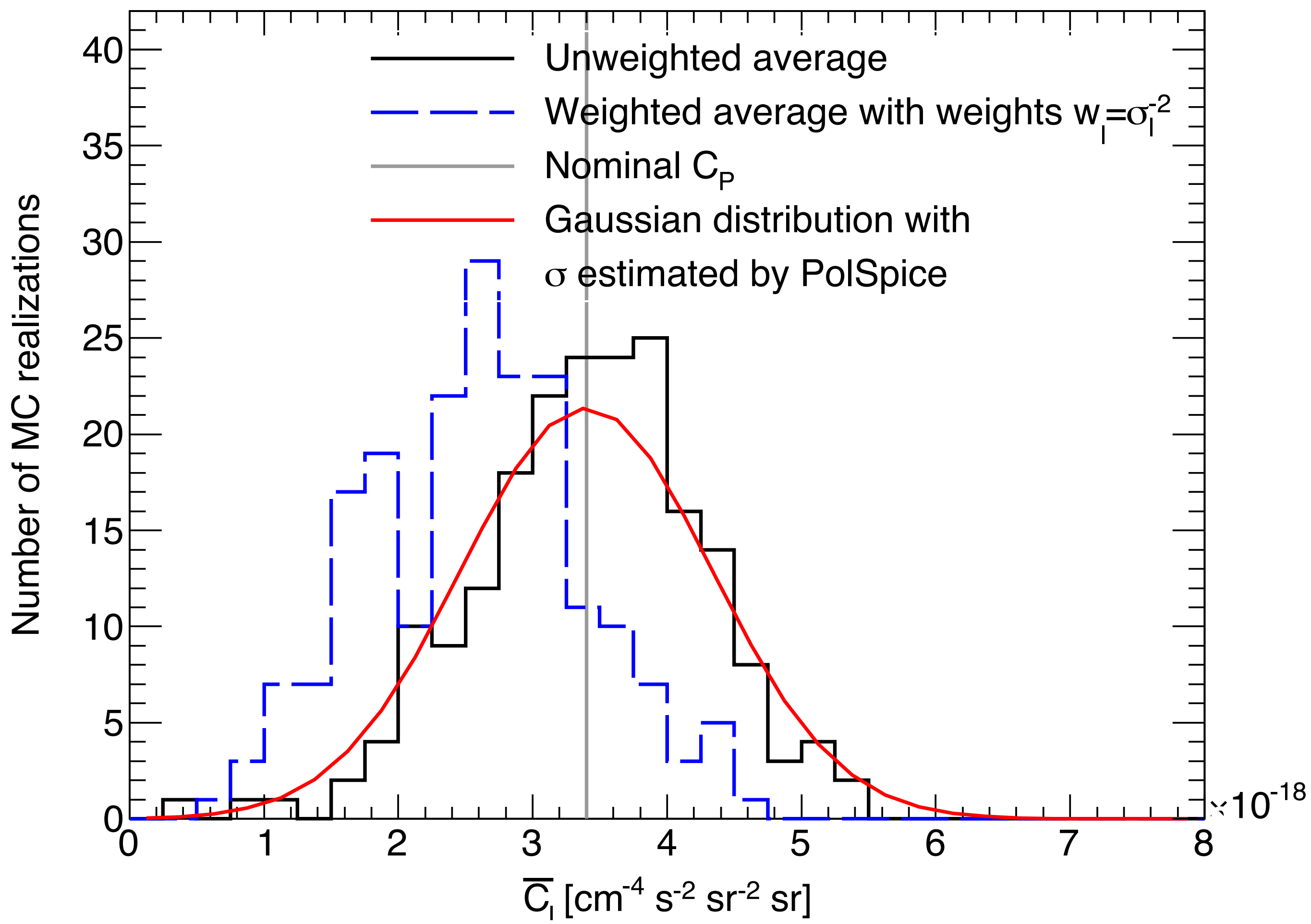
- method A: unweighted average of the analytical expression for the error σ_ℓ

$$\sigma_\ell = \sqrt{\frac{2}{(2\ell+1)\, f_{\rm sky}}}\left(C_\ell + \frac{C_{\rm N}}{W_\ell^2}\right)$$

- method B: weighted average of σ_ℓ

- method C: **average of the variances and covariances computed by PolSpice**

- they agree on the MC data



How to fit the binned APS

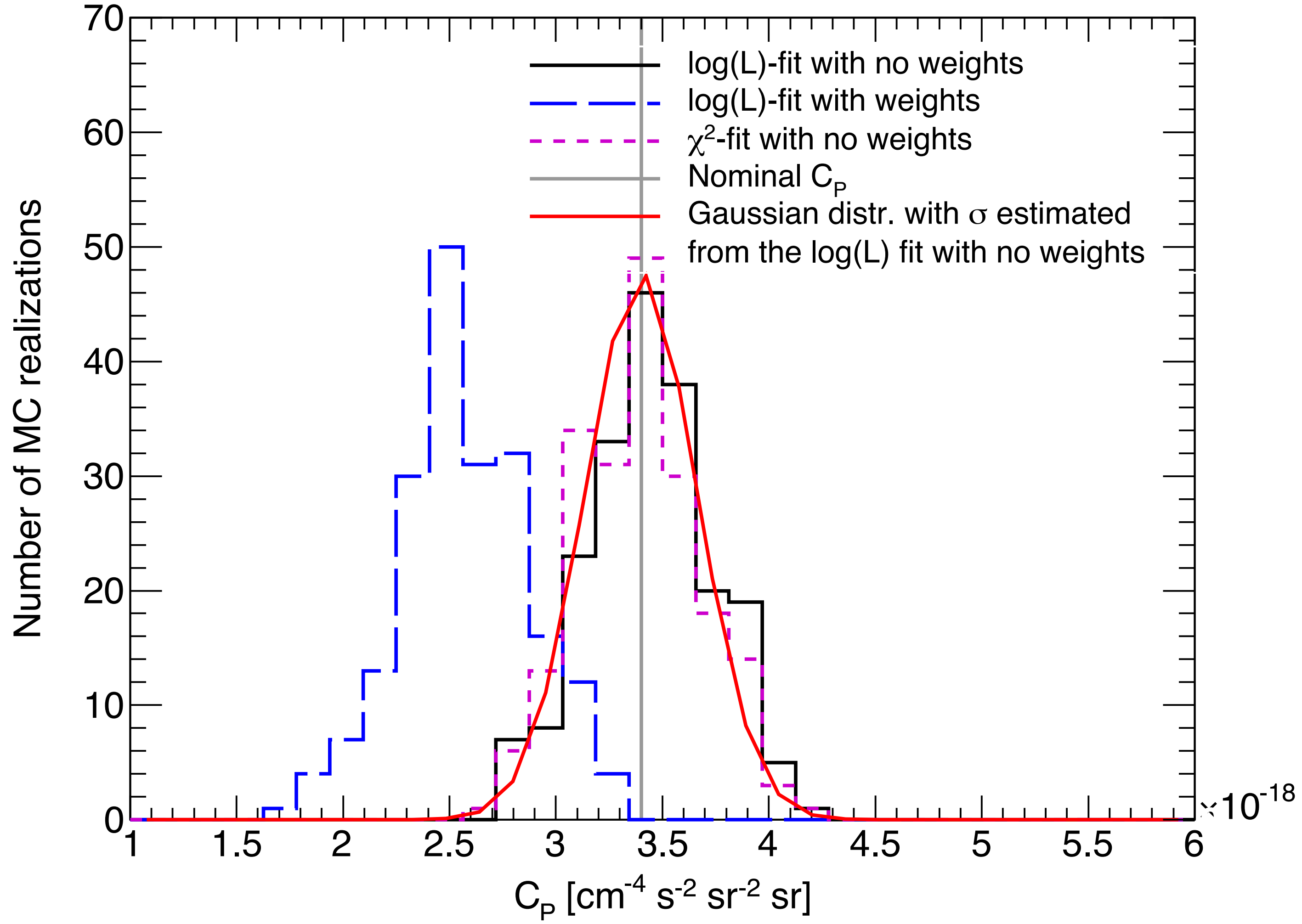
- method A: minimise the χ^2

$$\chi^2(C_\mathrm{P}) = \sum_\ell \frac{(\overline{C_\ell} - C_\mathrm{P})^2}{\overline{\sigma_\ell}^2}$$

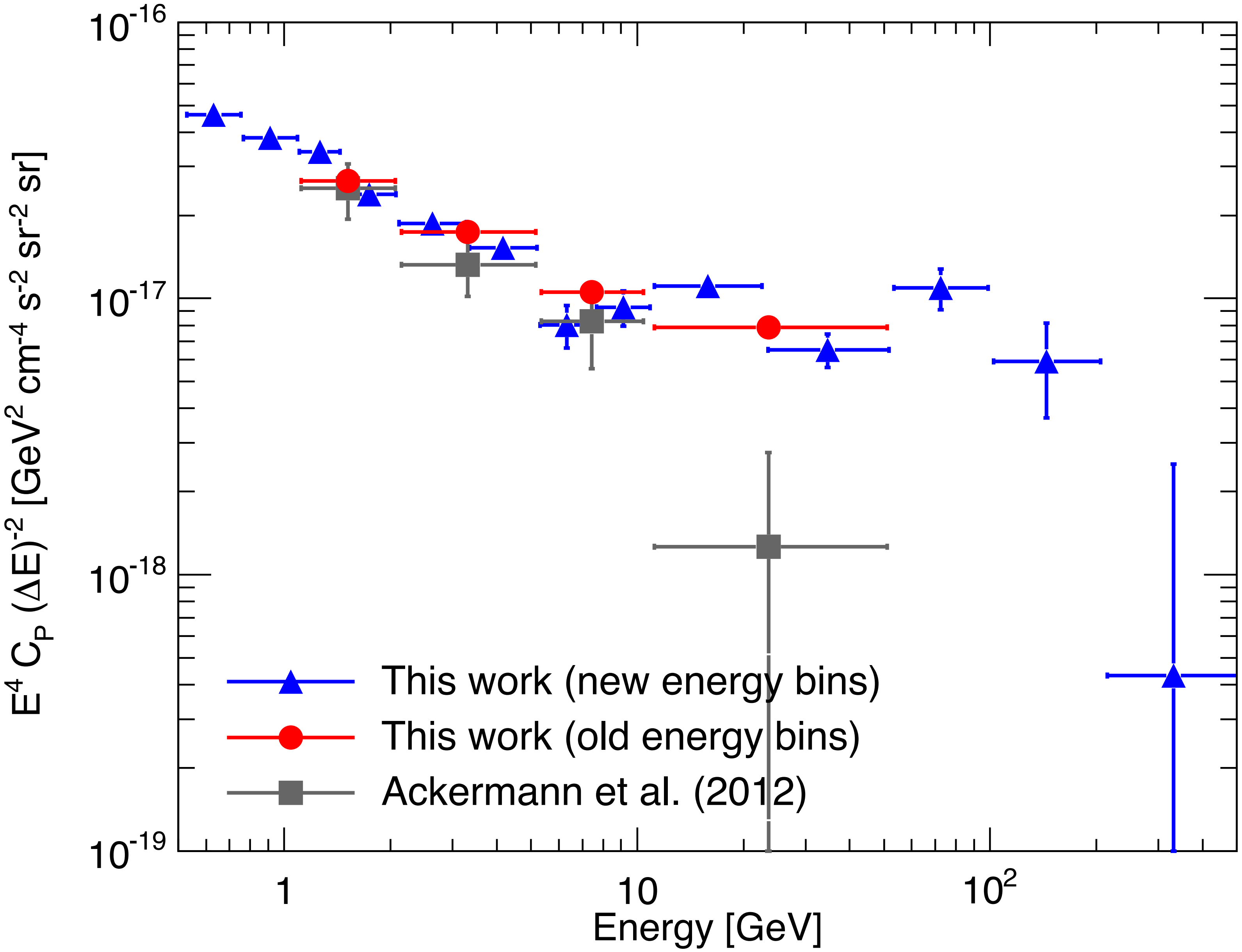
- method B: **maximise the log($\mathcal{L}$)**

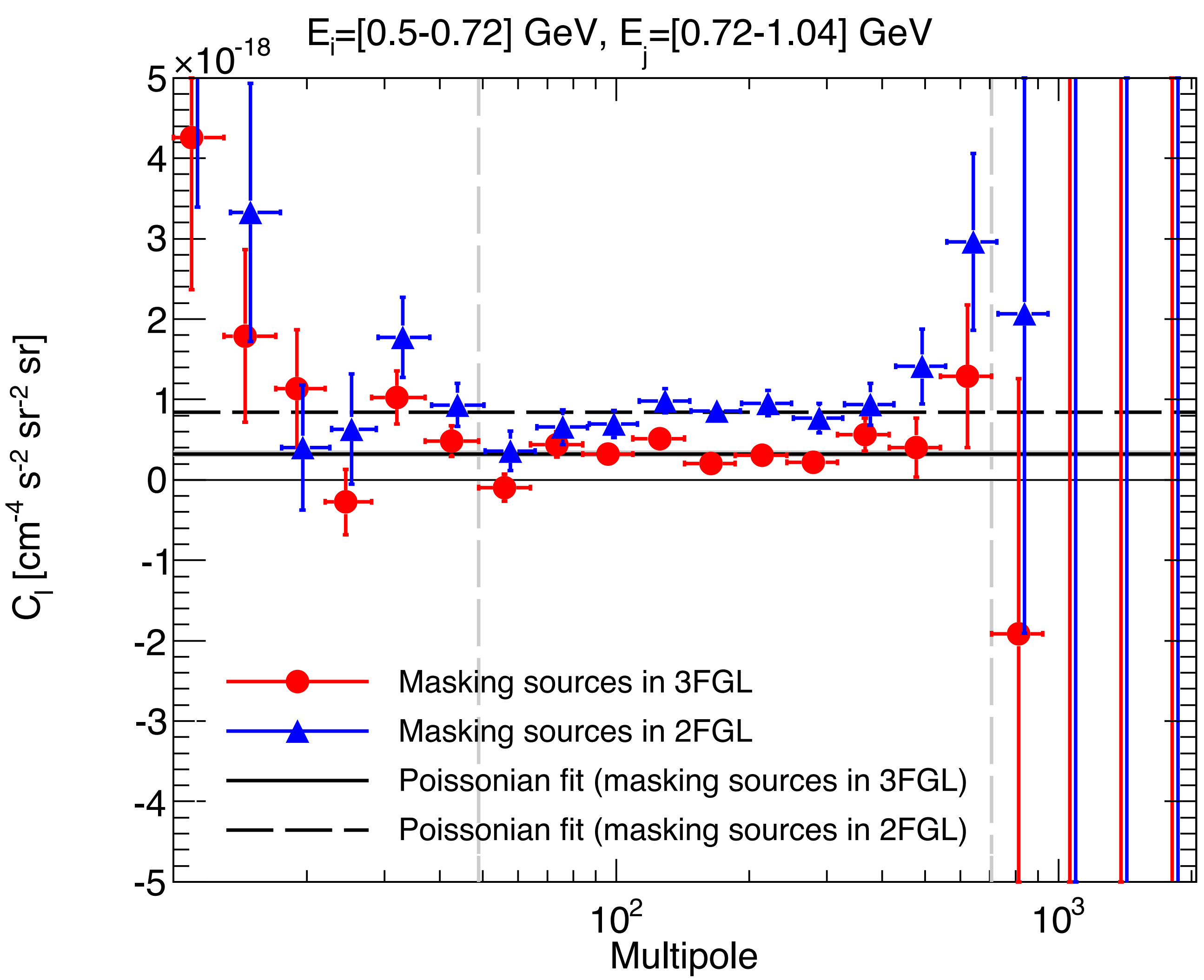
$$\log \mathcal{L}(C_\mathrm{P}) = -\sum_\ell \log(\overline{\sigma_\ell}) - \frac{1}{2}\sum_\ell \frac{(\overline{C_\ell} - C_\mathrm{P})^2}{\overline{\sigma_\ell}^2}$$

$$\sigma_\ell^2 = \frac{2}{(2\ell+1)f_\mathrm{sky}} \left(C_\mathrm{P} + \frac{C_\mathrm{N}}{W_\ell^2}\right)^2$$

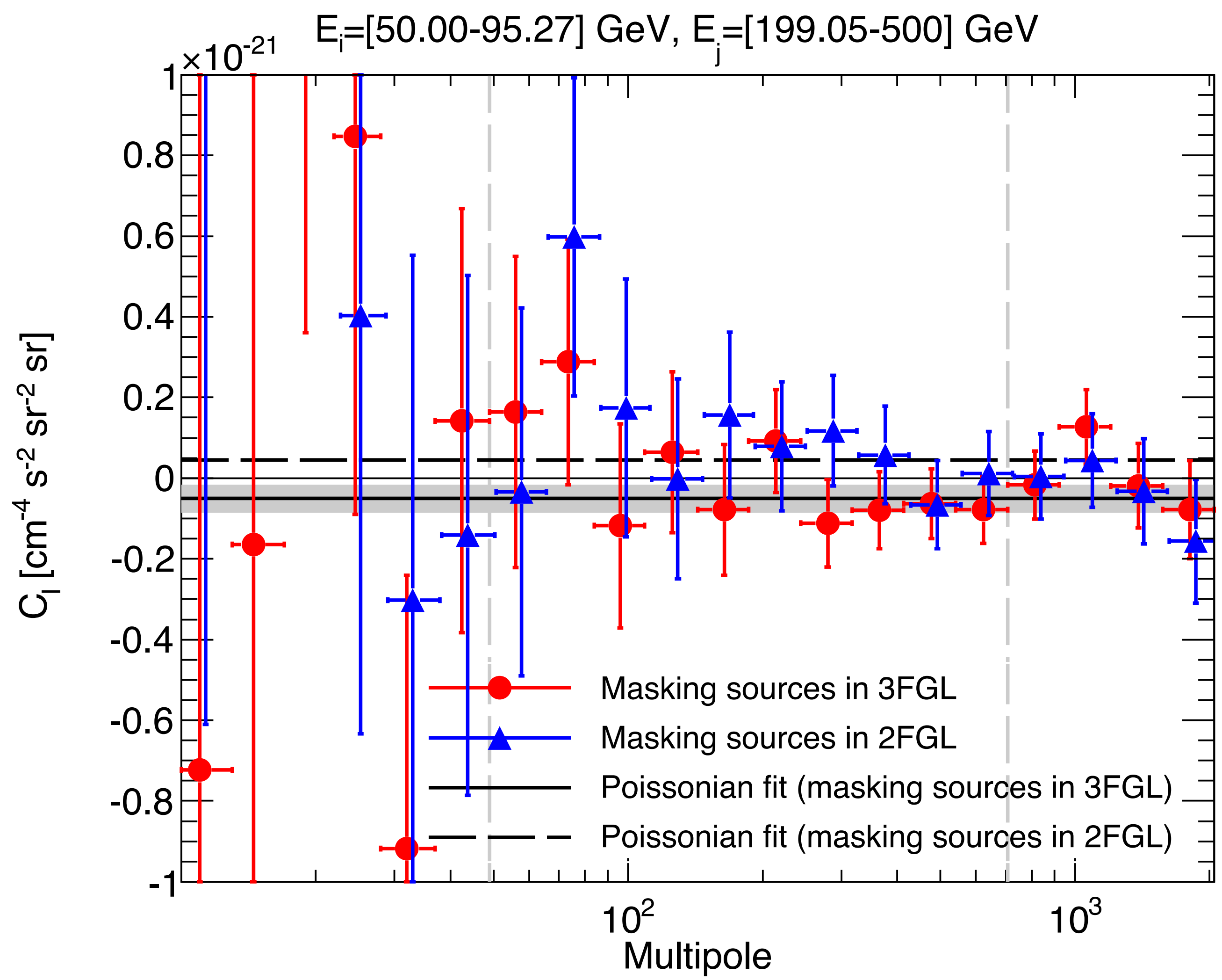


Comparison with old measurement



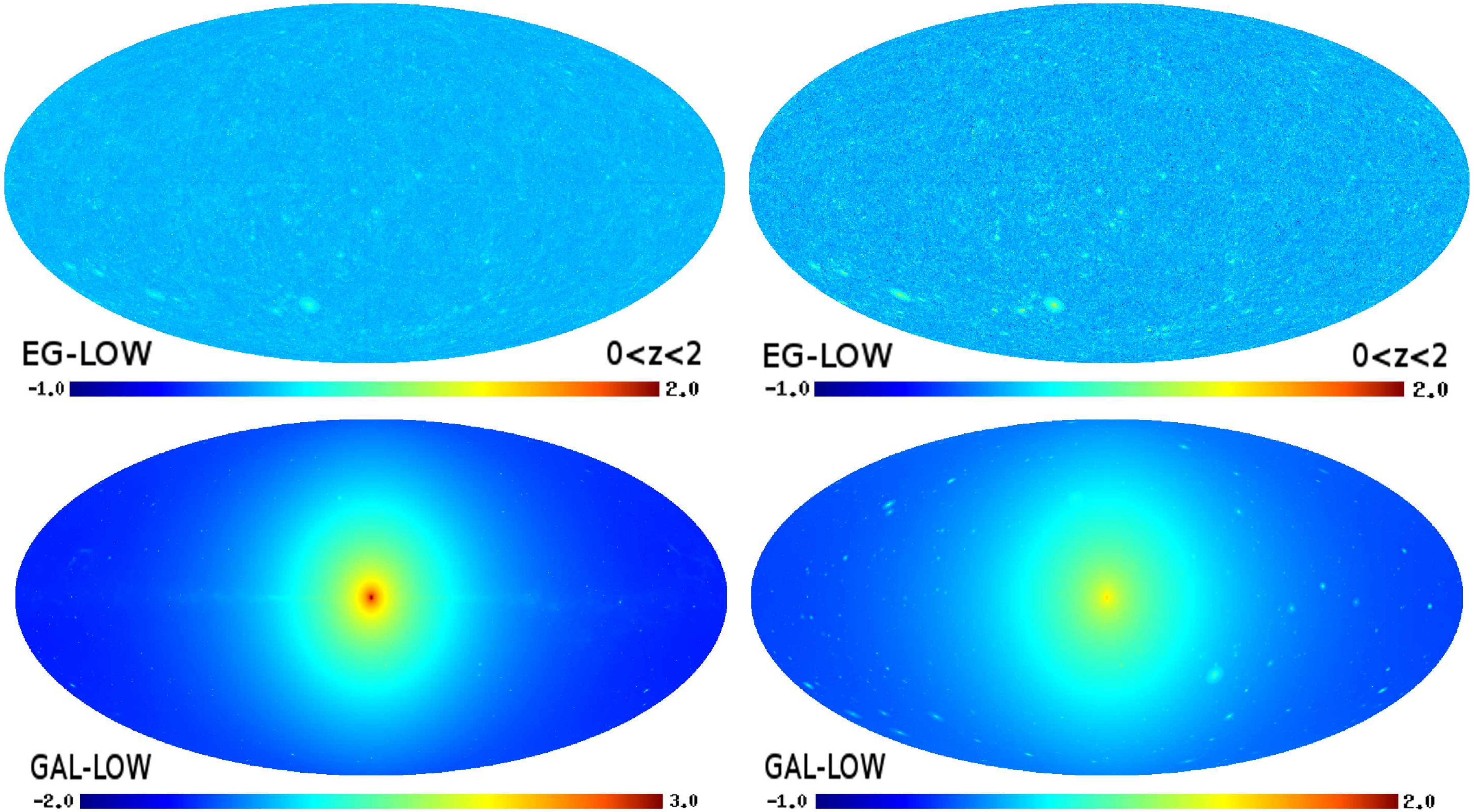


E_i=[0.5-0.72] GeV, E_j=[0.72-1.04] GeV
×10^{-18}
C_l [cm^{-4} s^{-2} sr^{-2} sr]
Multipole
Masking sources in 3FGL
Masking sources in 2FGL
Poissonian fit (masking sources in 3FGL)
Poissonian fit (masking sources in 2FGL)



E_i=[50.00-95.27] GeV, E_j=[199.05-500] GeV
×10^{-21}
C_l [cm^{-4} s^{-2} sr^{-2} sr]
Multipole
Masking sources in 3FGL
Masking sources in 2FGL
Poissonian fit (masking sources in 3FGL)
Poissonian fit (masking sources in 2FGL)

Annihilation | Decay



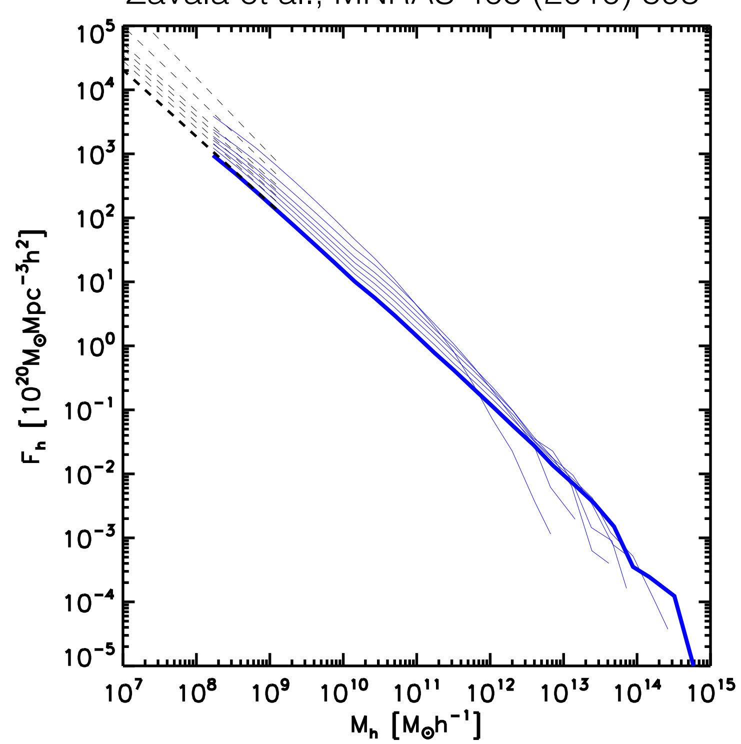
E=4 GeV, $M_{min}=10^{-6}$ $M_{\odot}$, *b* quarks

m_{χ}=200 GeV, $\sigma v=3\times10^{-26}$cm^{3}s^{-1} (annihilation), m_{χ}=2 TeV, $\tau=2\times10^{27}$ s (decay)

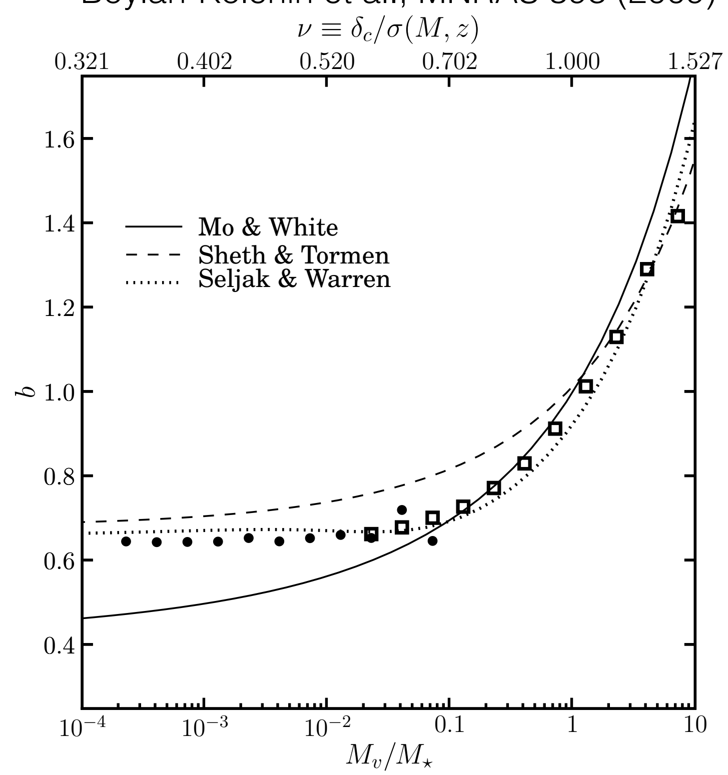
DM-induced emission

- repetition of the Millennium-II simulation box to cover a large portion of the Universe
- extrapolation below the mass resolution of the Millennium-II (assuming low-mass halos trace the smallest halos in Millennium-II)
- unresolved subhalos accounted for through an analytic fit to $P(\rho, r)$
- Milky Way smooth halo and Galactic subhalos from Aquarius (carved in the centre)

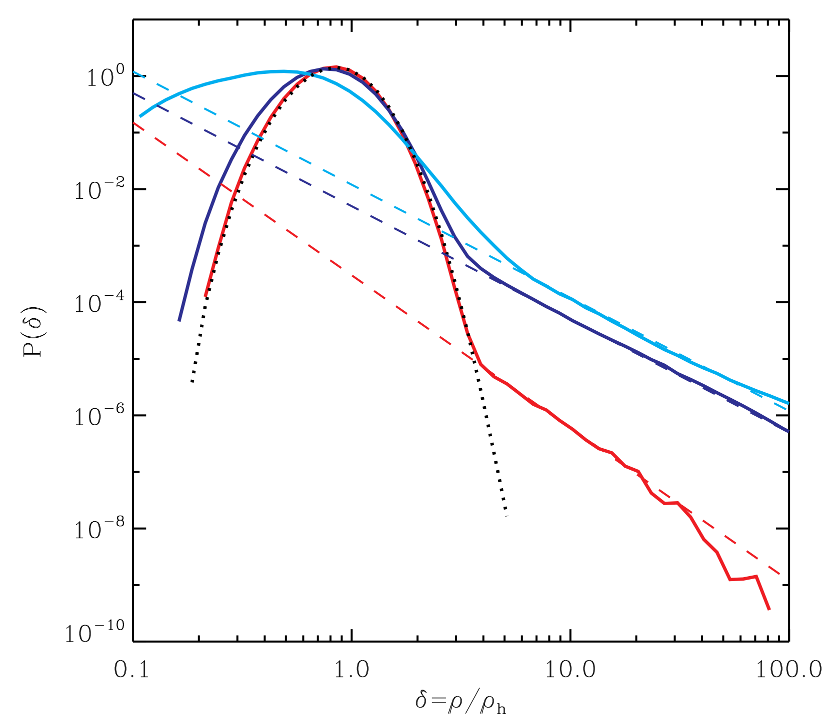
Zavala et al., MNRAS 405 (2010) 593



Boylan-Kolchin et al., MNRAS 398 (2009) 1150

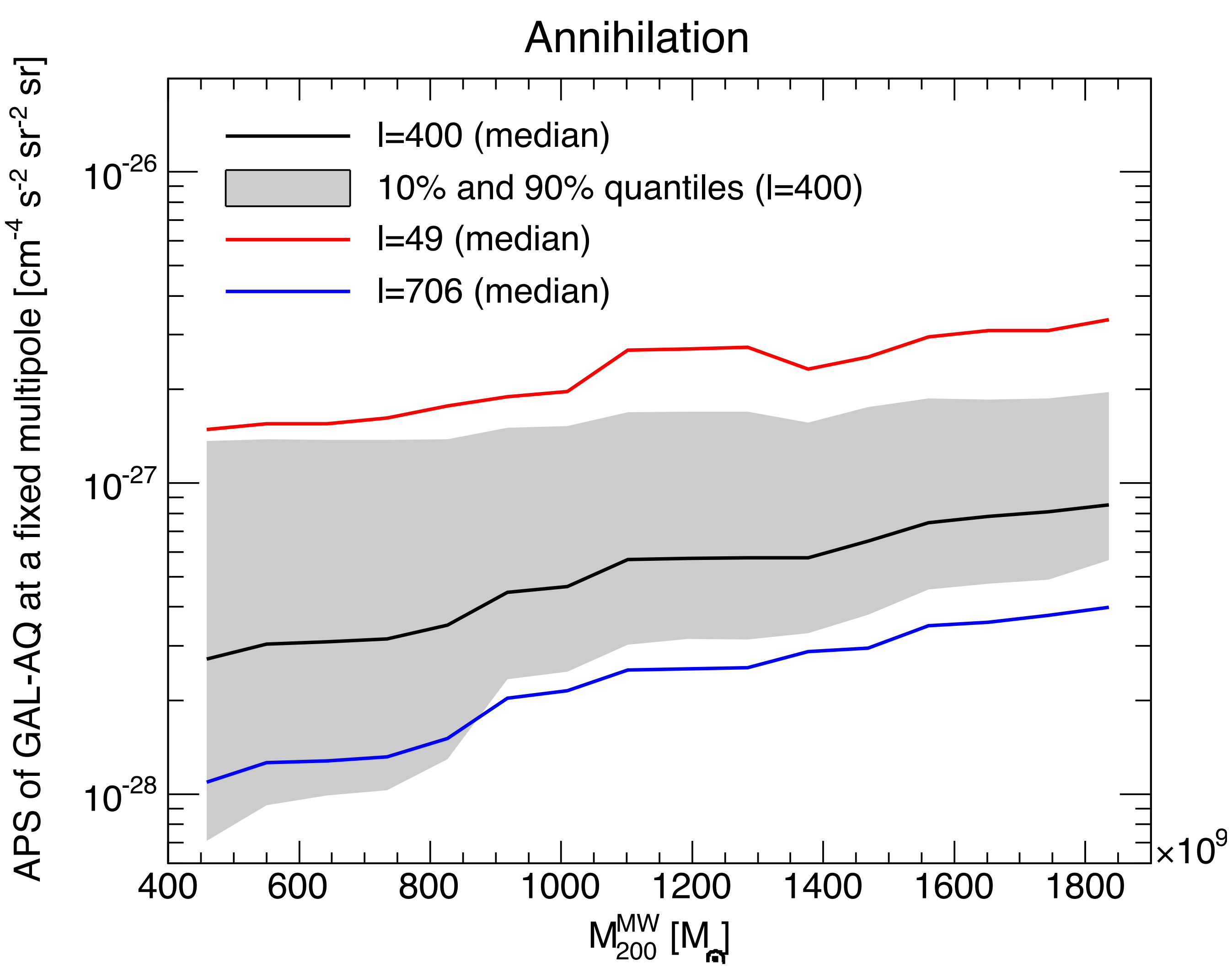


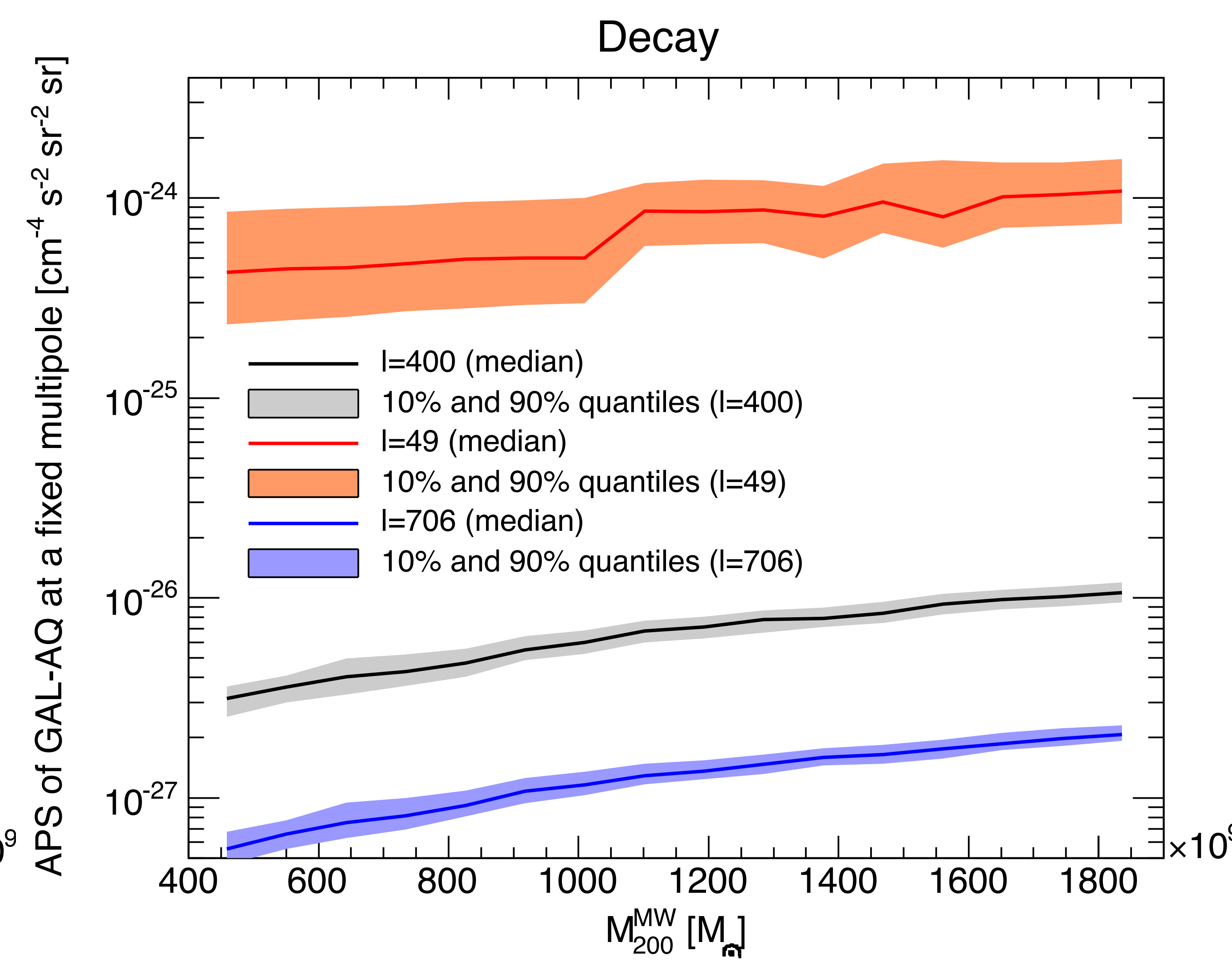
Kamionkowski et al., Phys. ReV. D81 (2010) 043532



Effect of an uncertain MW mass on GAL-AQ

- uncertainty of a factor 4 on the mass of the Milky Way (MW)
- 16 bins in M_{MW} accounting for a correspondent depletion in the amount of Galactic subhalos
- including uncertainty on the position of the observer



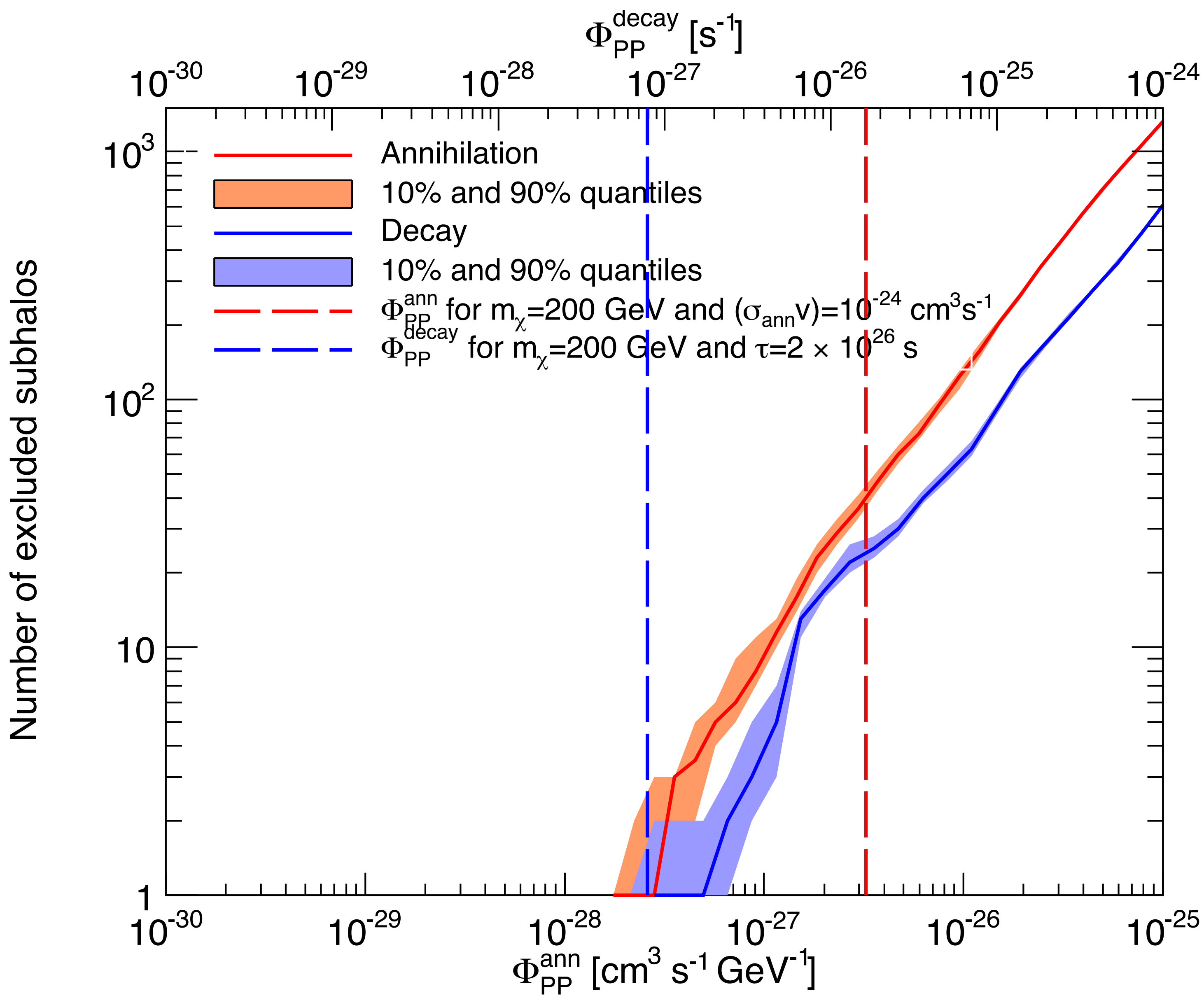


Effect of an too-bright subhalos on GAL-AQ

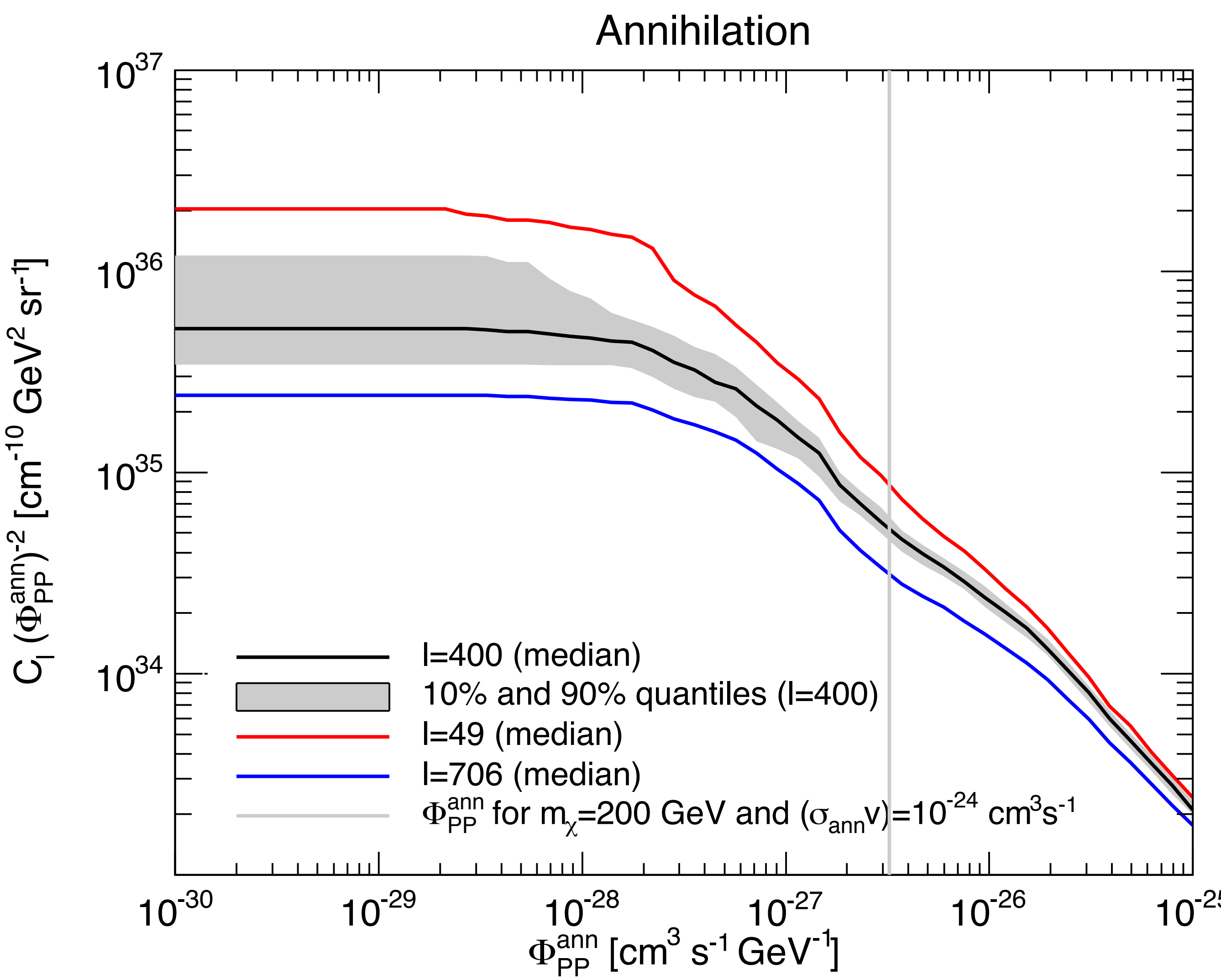
- for certain combination of (m_χ, $\sigma_{ann}v$) and (m_χ, τ), some subhalos are brighter than the 3FGL sensitivity
- those structures should be masked

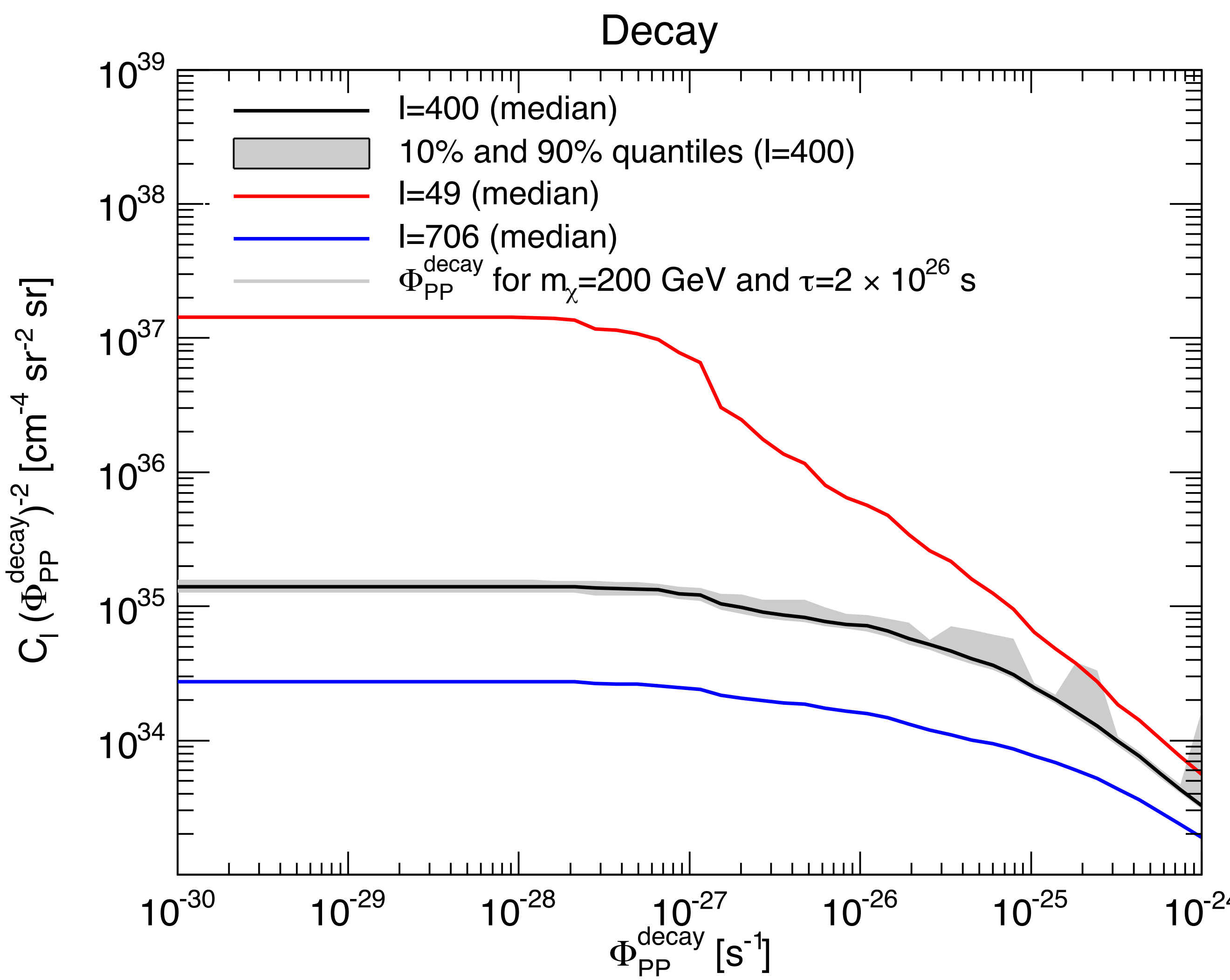
$$\Phi_{\rm PP}^{\rm ann} = \frac{(\sigma_{\rm ann} v)}{2m_\chi^2} \int_{\bar{E}} E \frac{dN_\gamma^{\rm ann}}{dE} dE$$

$$\Phi_{\rm PP}^{\rm decay} = \frac{1}{m_\chi \tau} \int_{\bar{E}} E \frac{dN_\gamma^{\rm decay}}{dE} dE$$

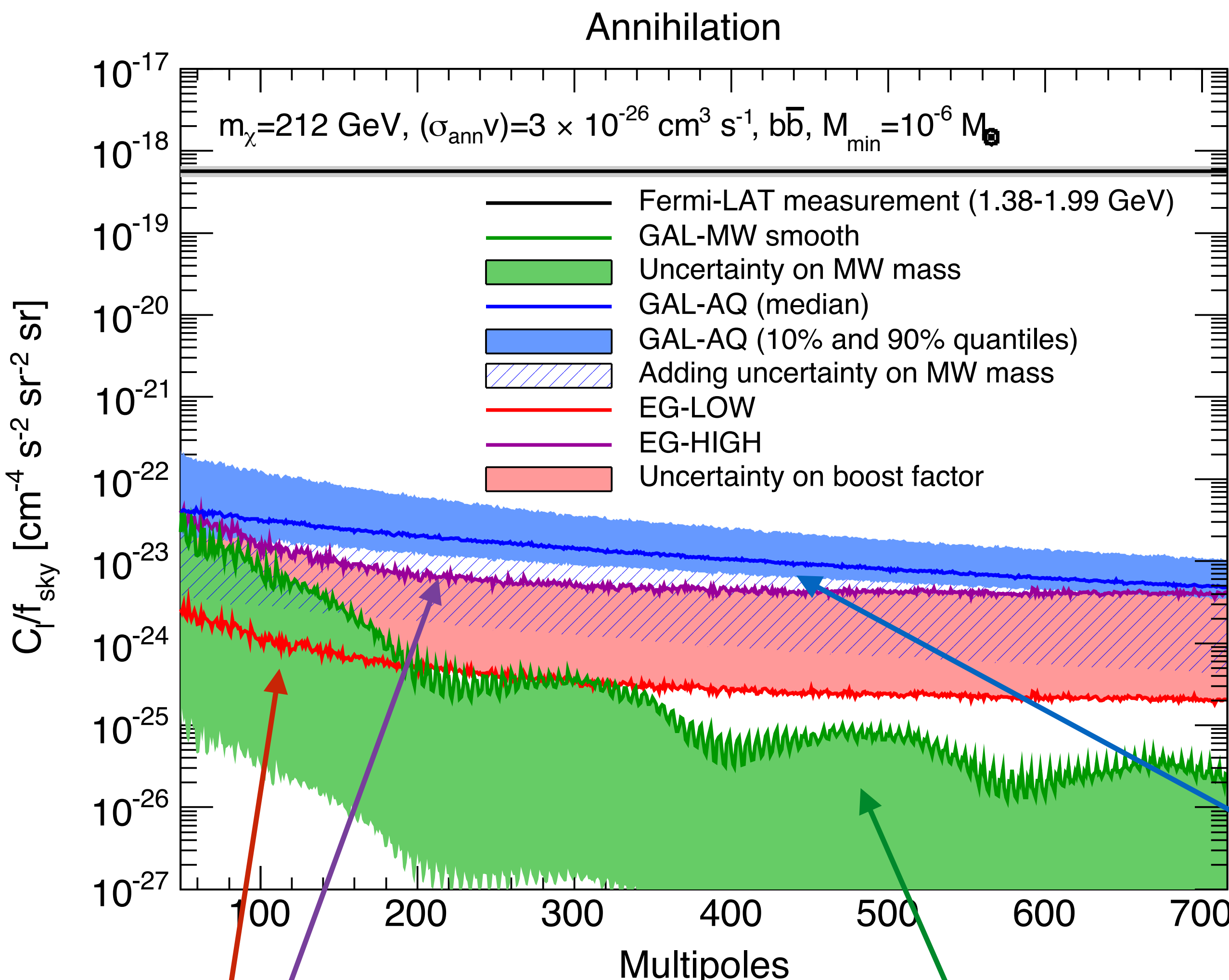


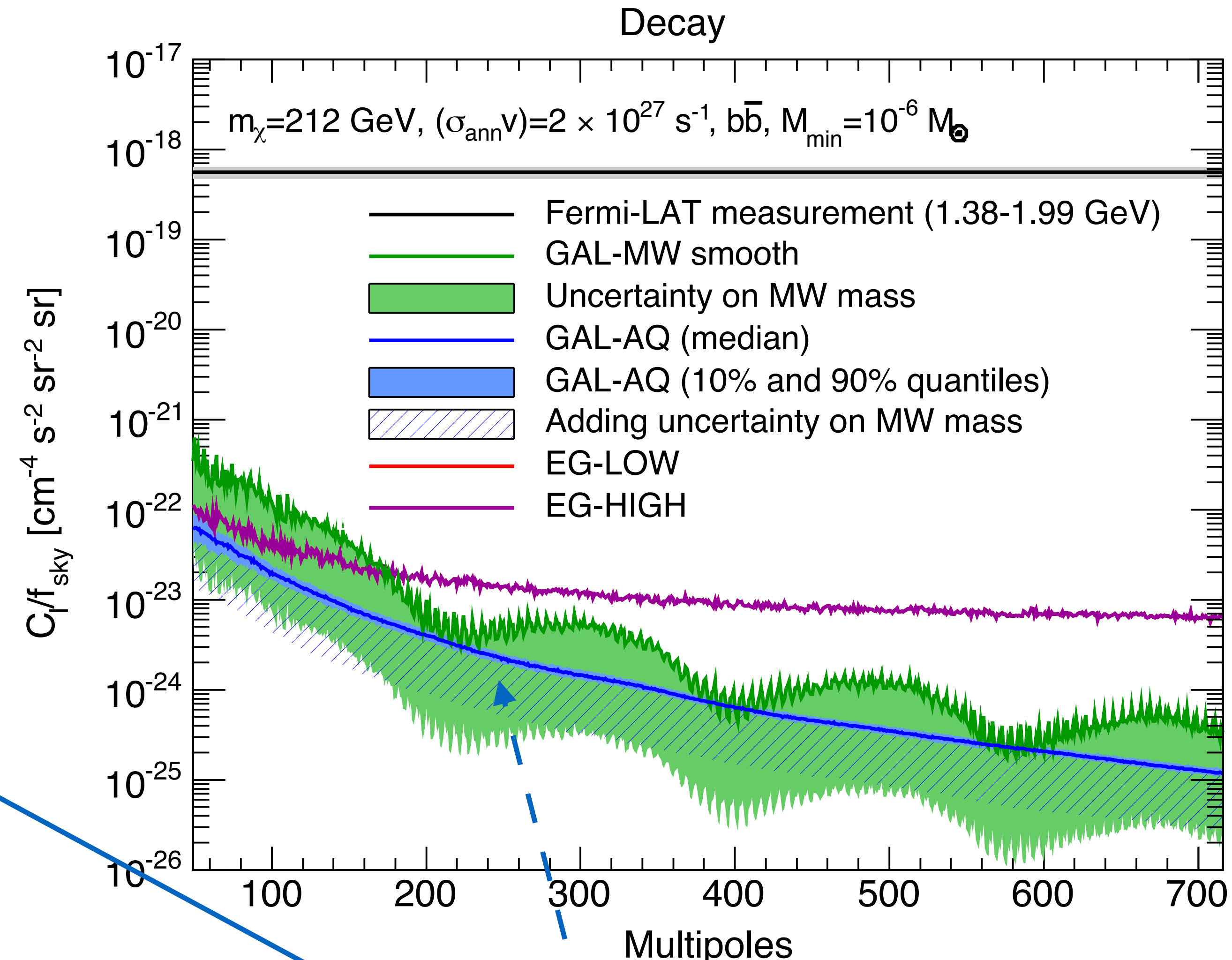
Effect of an too-bright subhalos on GAL-AQ





DM-induced APS





Extragalactic component with different subhalo boost factors

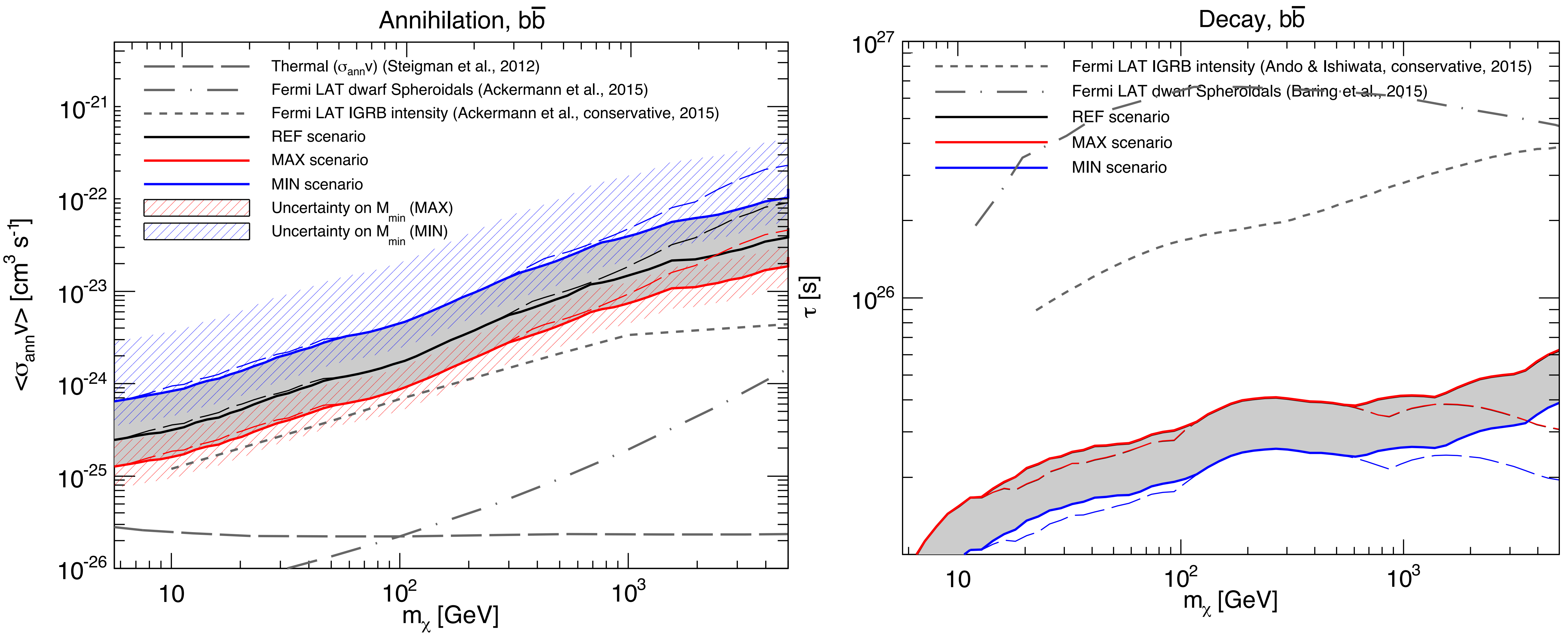
Subhalos of the Milky Way with uncertainty on the position of the Earth

Smooth halo of the Milky Way (outside of the mask) with uncertainty on the total Milky-Way mass

uncertainty on the total mass of the Milky Way

Conservative exclusion limits

$$\langle C^{i,j}_{\ell,\mathrm{DM}} \rangle < C^{i,j}_{\mathrm{P}} + 1.64\,\sigma_{C^{i,j}_{\mathrm{P}}}$$



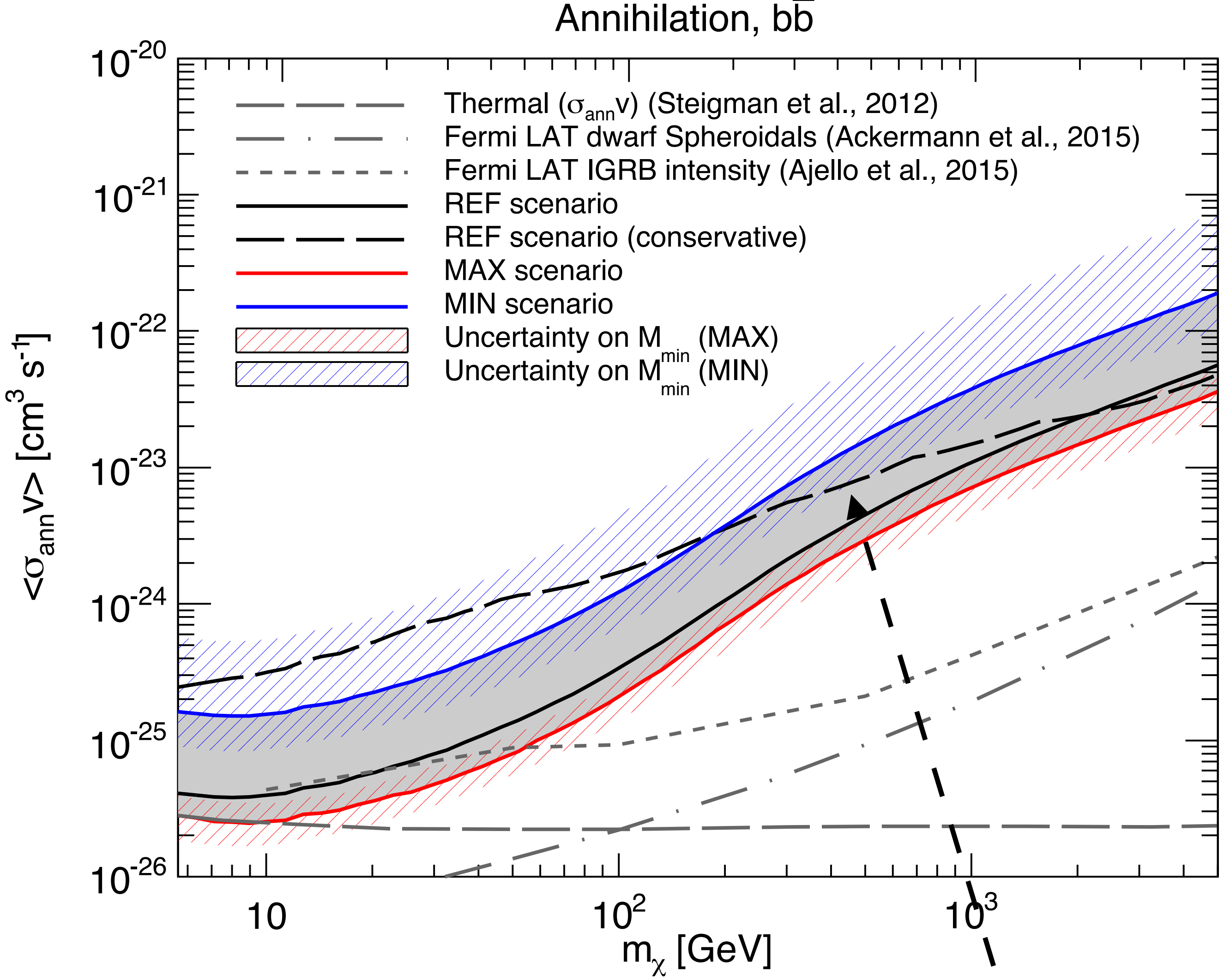
- REF, MIN and MAX encompass the uncertainties considered in the distribution of the DM (for a fixed M_{min})

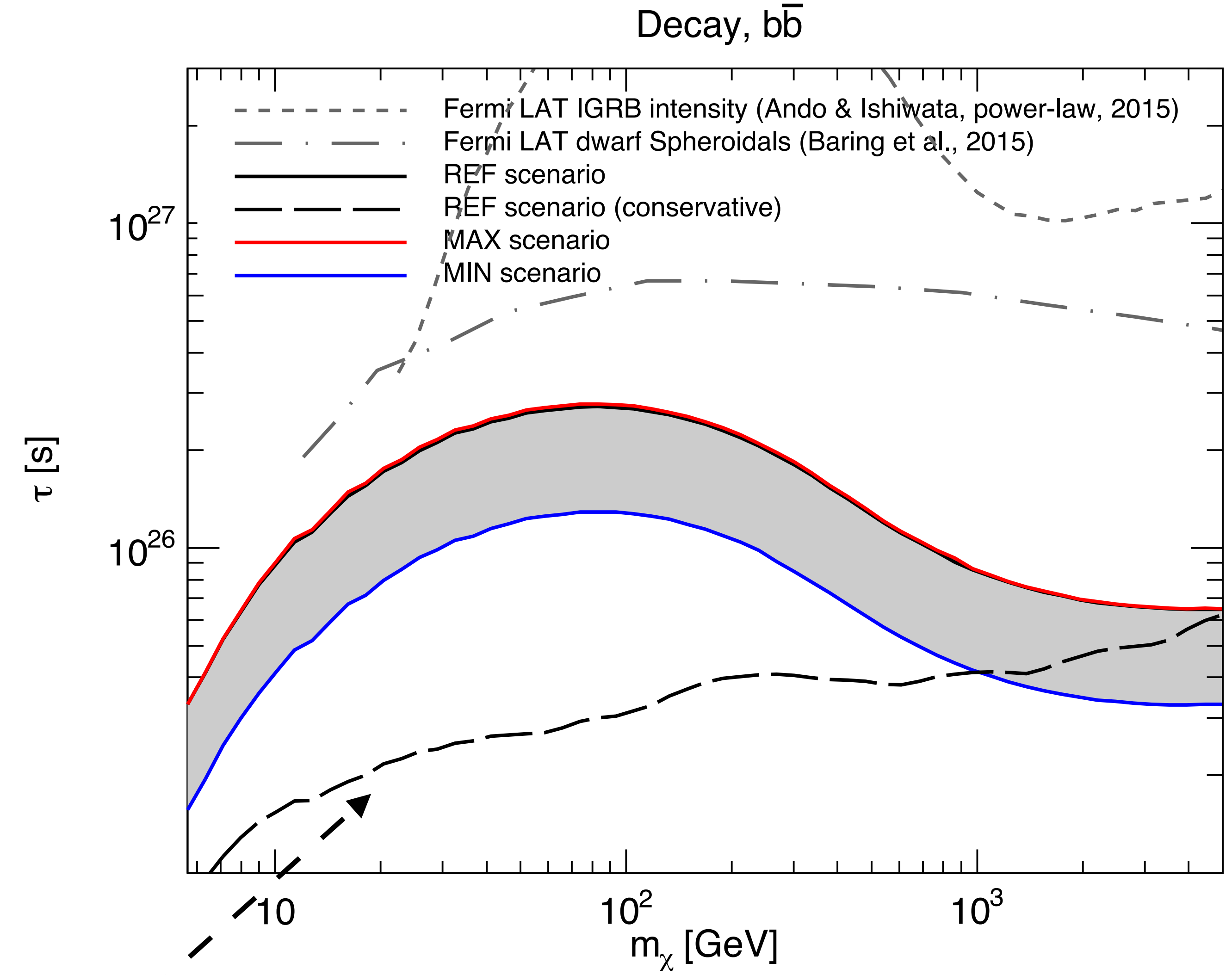
- shaded bands describe the uncertainty on the value of M_{min}

2-component fit to the binned APS

$$\chi^2 = -\sum_{i,j,\ell} \frac{[C_\ell^{i,j} - C_{\ell,\mathrm{DM}}^{i,j} - C_{\mathrm{P}}^{i,j}]^2}{\sigma^2_{C_\ell^{i,j}}}$$

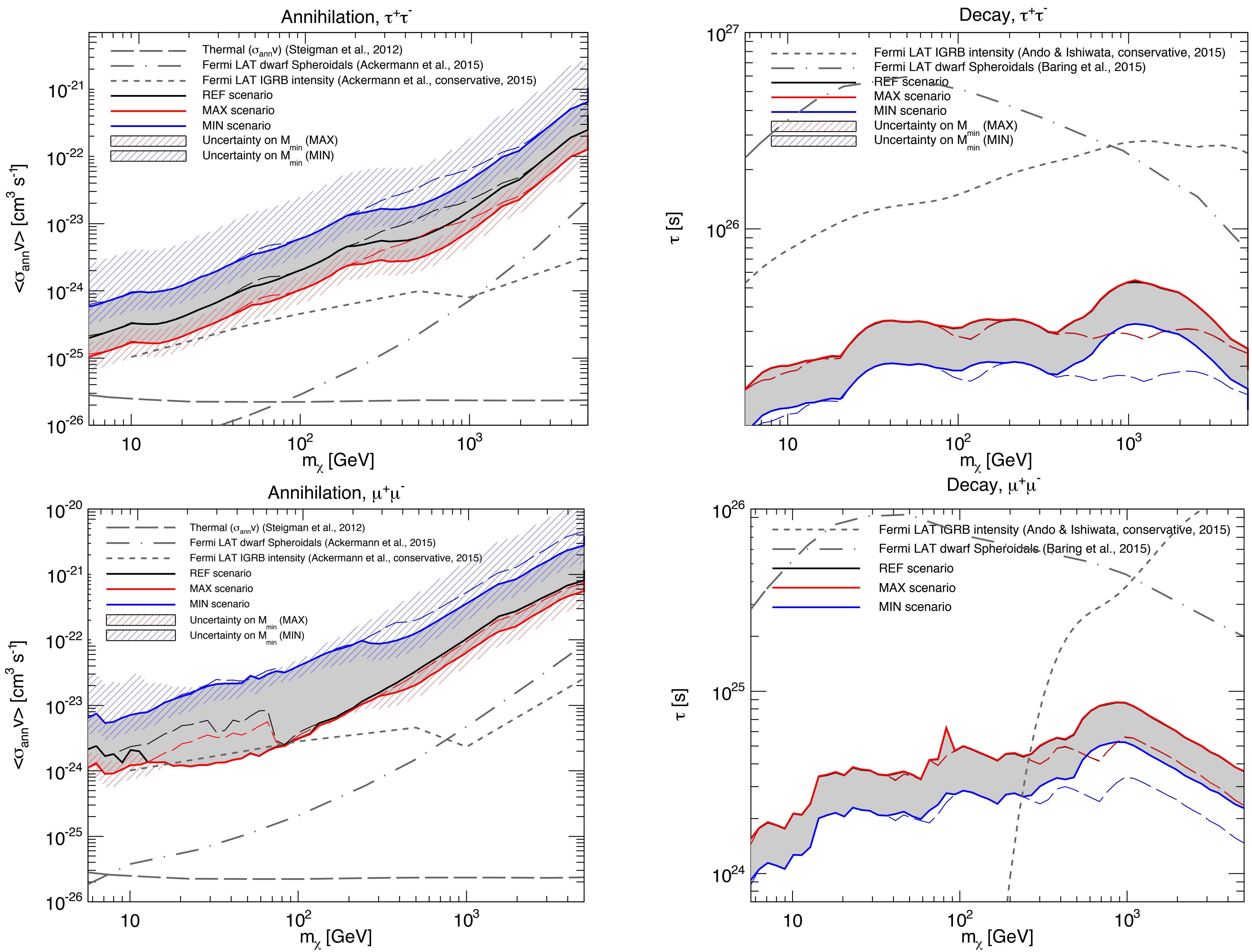
95% CL exclusion limit when Test Statistics $\Delta\chi^2$=3.84



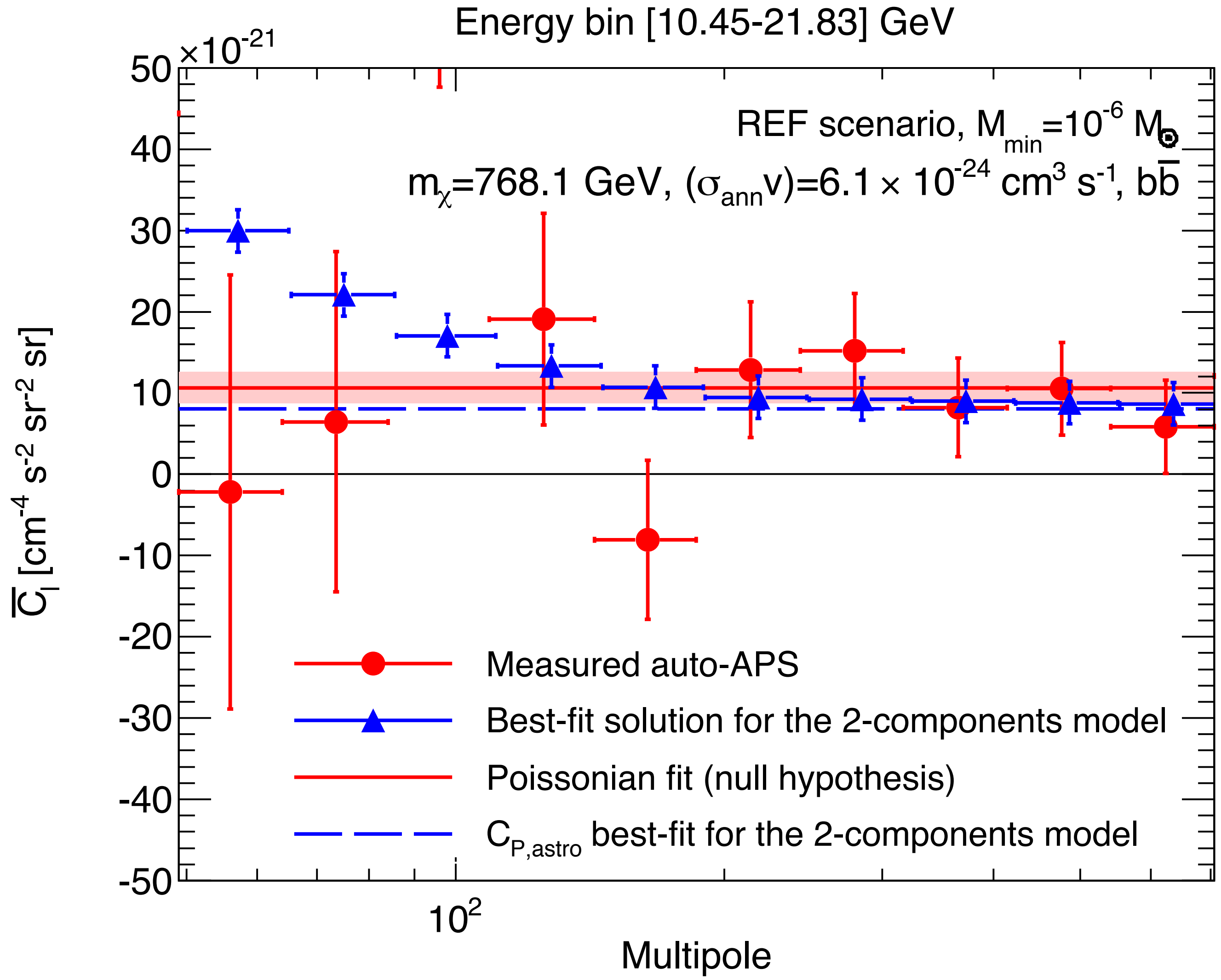


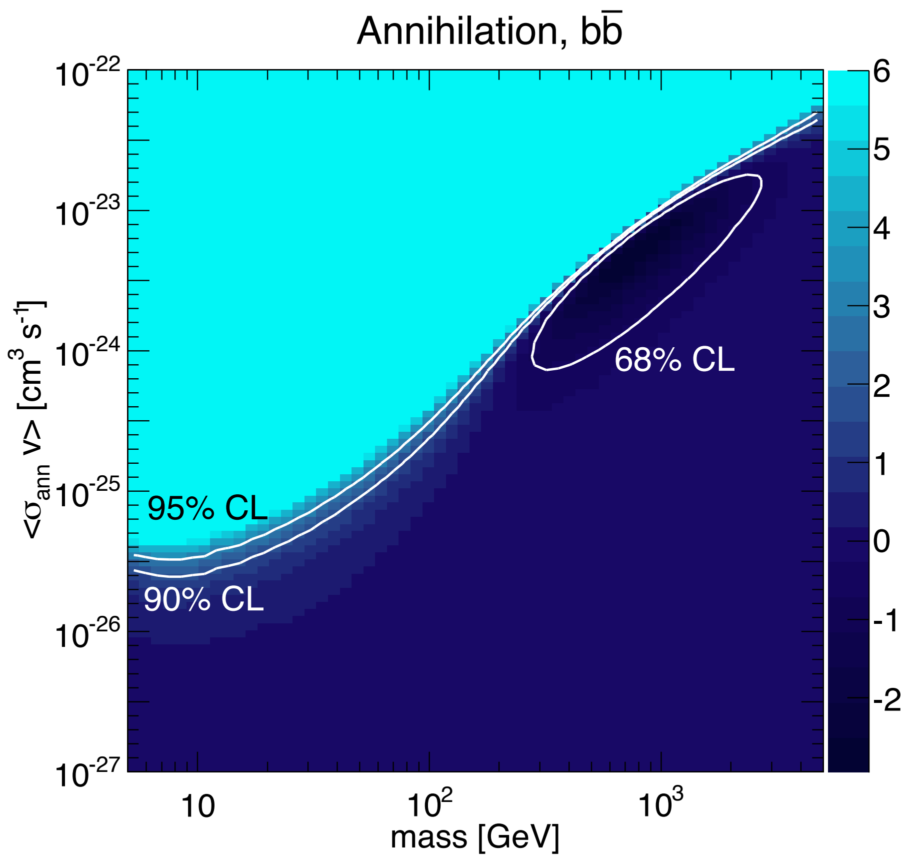
conservative exclusion limits

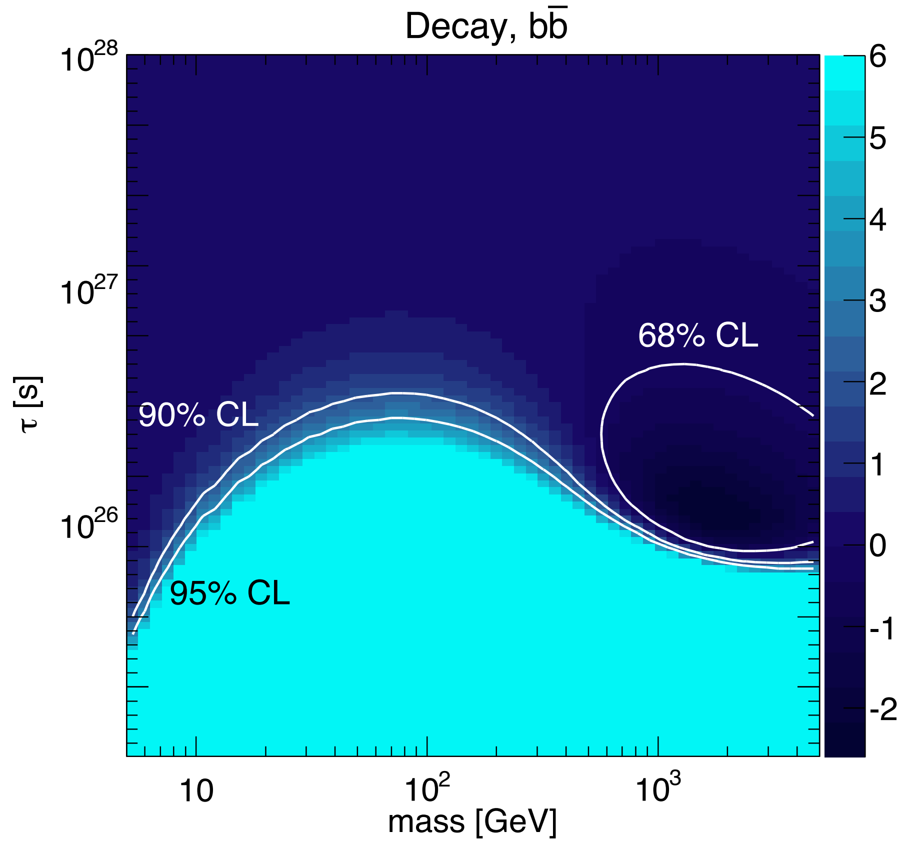
Conservative limits



2-component fit to the binned APS

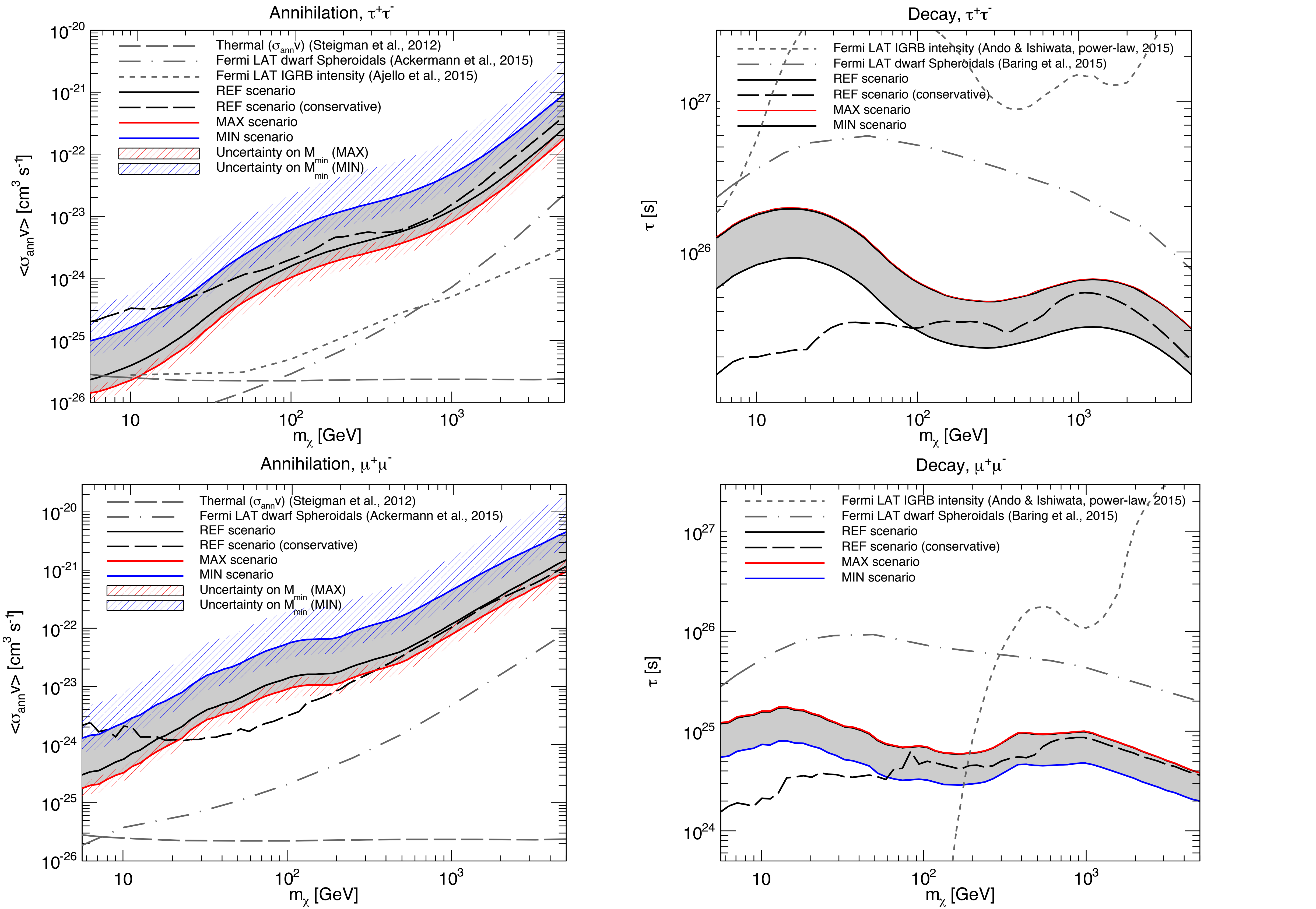






- TS = -2 ln[χ^2(no DM)] + 2 ln[$\chi^2(m_\chi,\sigma v)$]
- annihilation best fit: TS=xx, m_χ=768.1 GeV, $(\sigma_{ann}v)=4.86\times10^{-24}$ cm^{3}s^{-1}
- decay best fit: TS=xx, m_χ=1743.2 GeV, $\tau=1.15\times10^{26}$ s

Exclusion limits for the 2-component fit



TS for 2-component fit