GRAPPA
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Updated measurement of gamma-ray angular power spectrum of anisotropies

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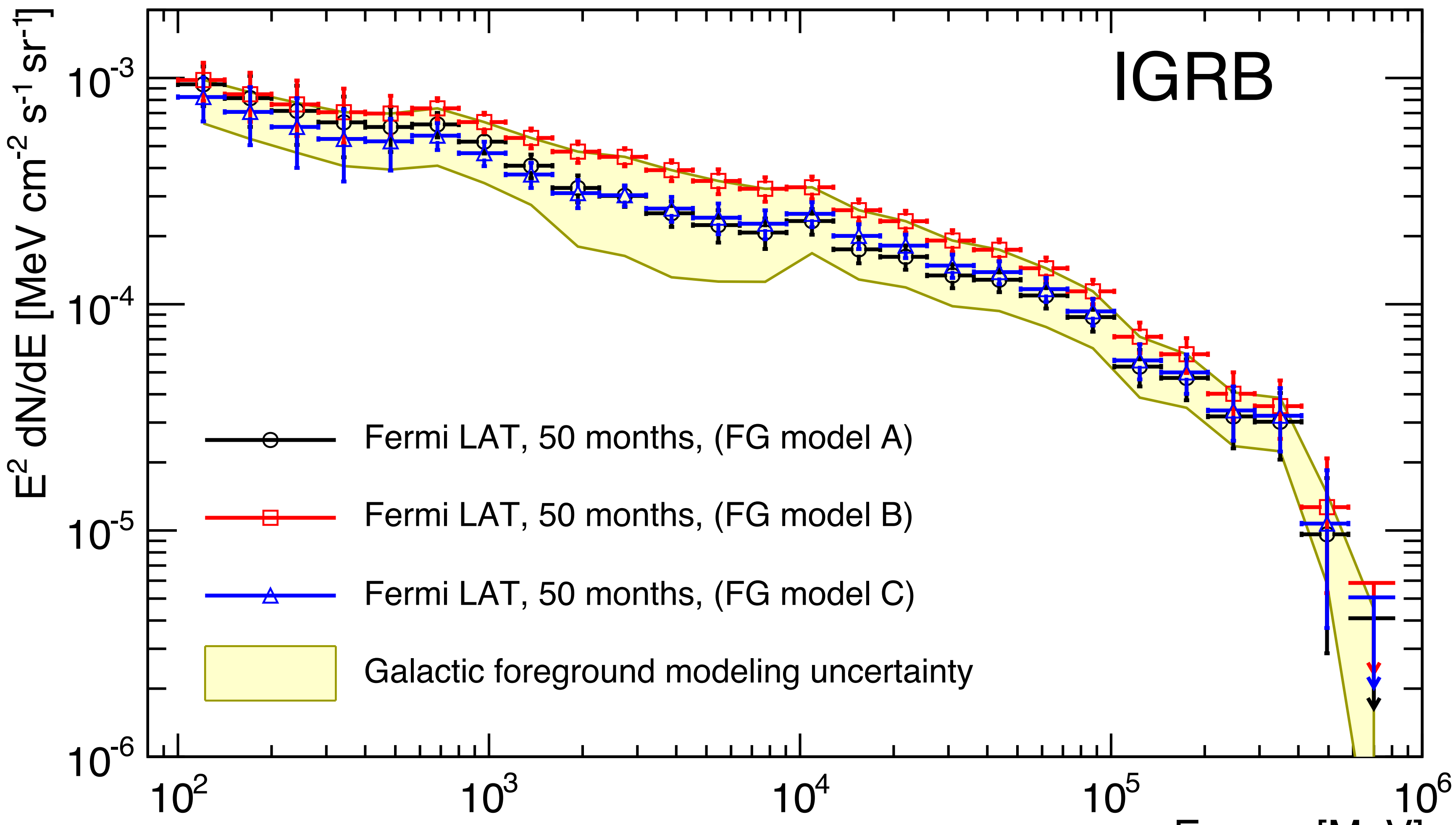
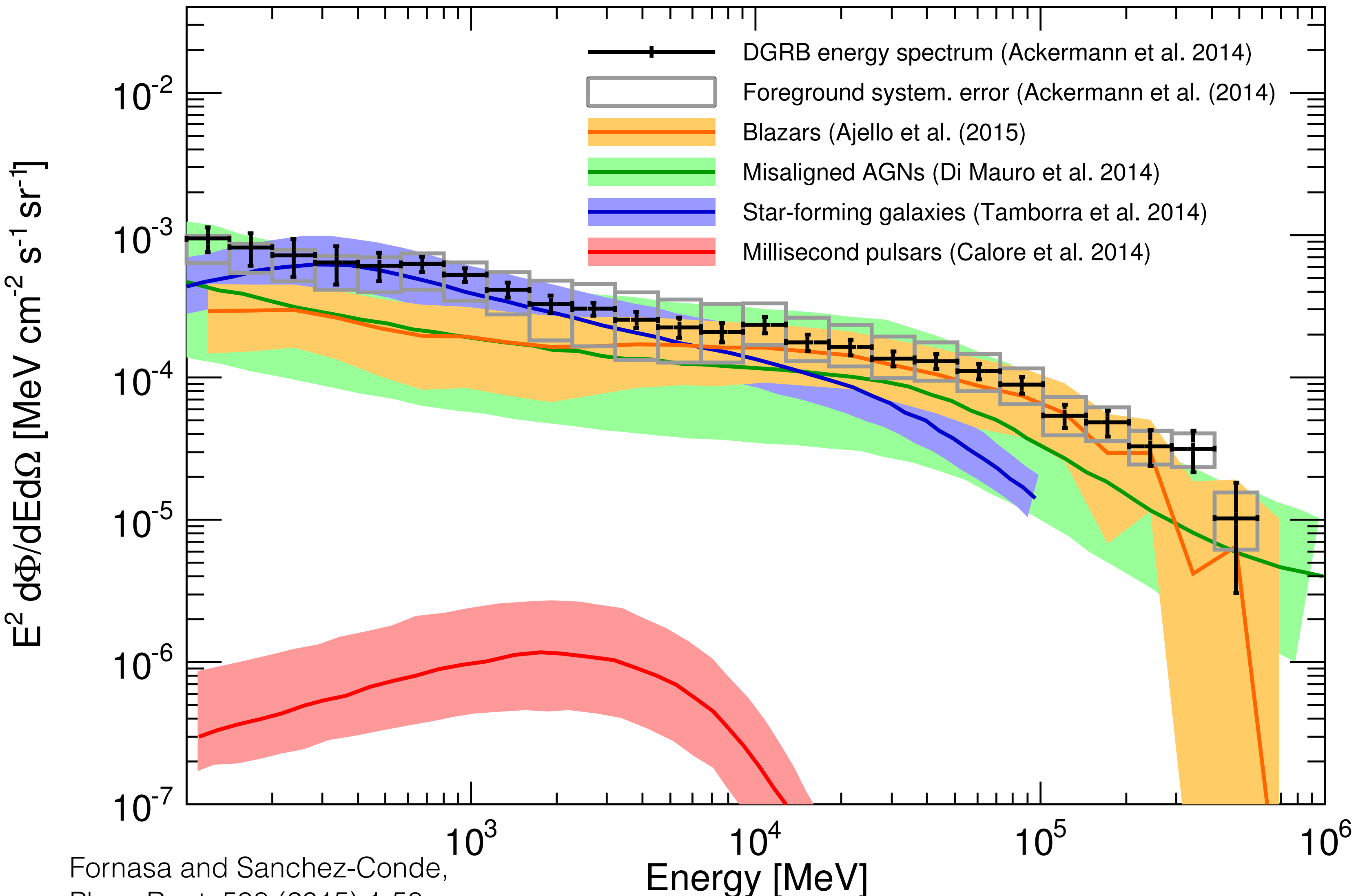
The Diffuse Gamma-Ray Background (DGRB)



Ackermann et al., Astrophys. J. 799 (2015) 1, 86

- multi-component fit to Fermi-LAT data
- power-law energy spectrum with a slope of 2.32±0.02 at lower energies and a cut-off at 279±52 GeV
- systematic uncertainty related to the Galactic foreground (15% to 30%)

Unresolved gamma-ray sources

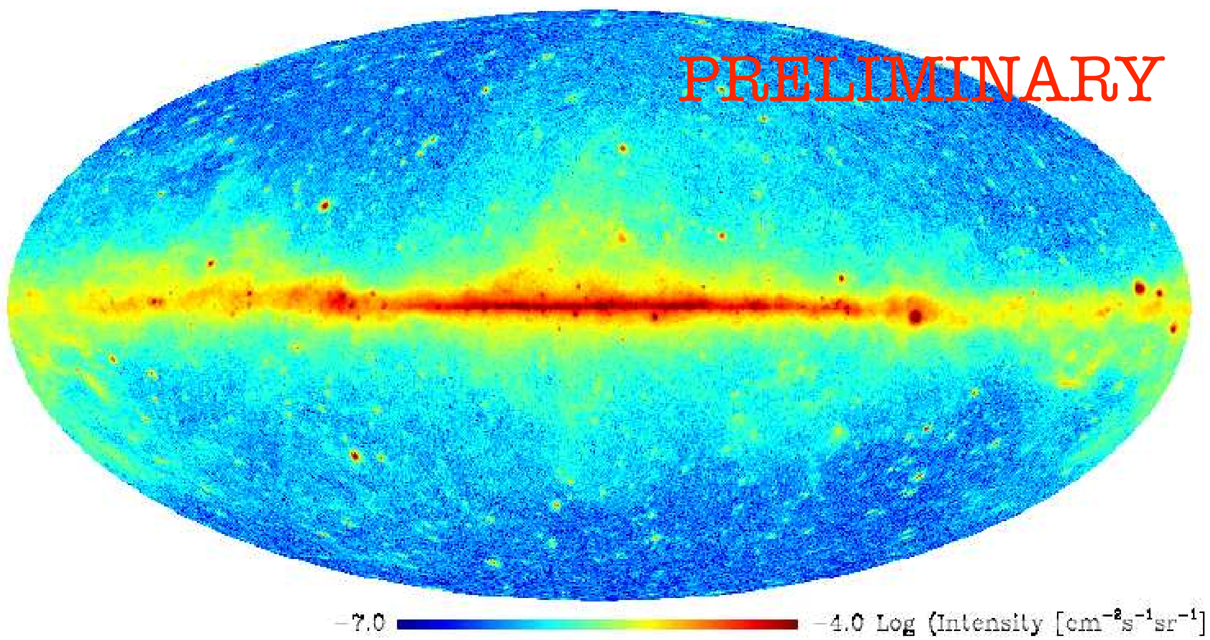


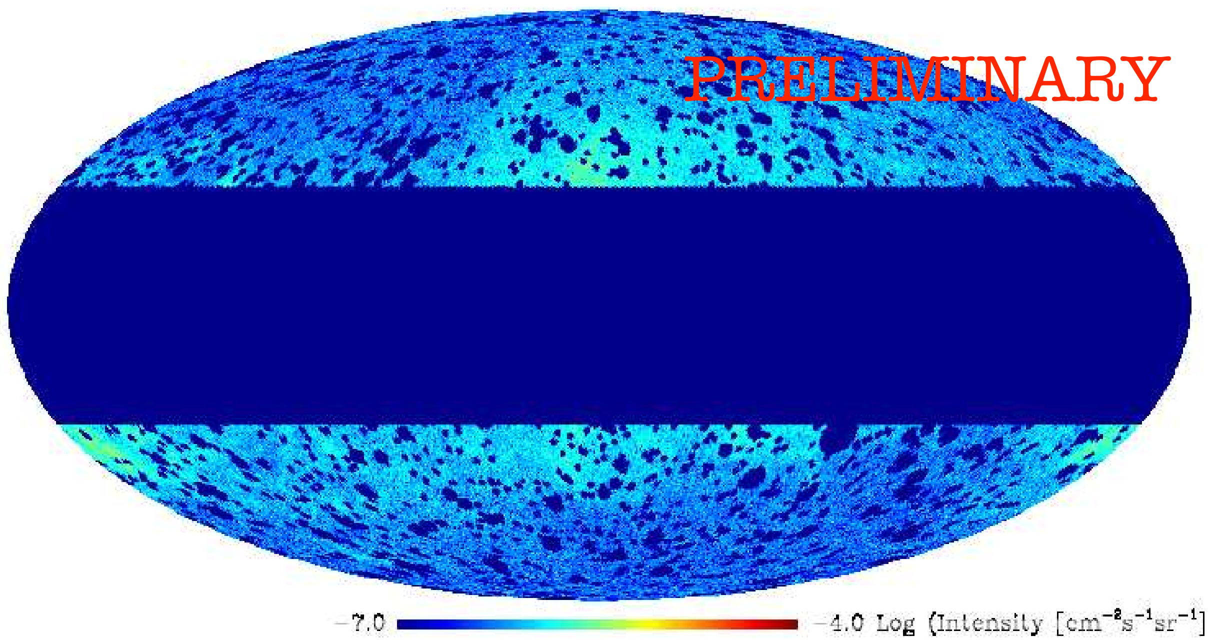
Fornasa and Sanchez-Conde, Phys. Rept. 598 (2015) 1-58

- cumulative emission of unresolved sources
- guaranteed components from unresolved blazars, star-forming galaxies, misaligned AGNs
- build a similar plot for angular power spectrum of anisotropies

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

New APS measurement





New measurement	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

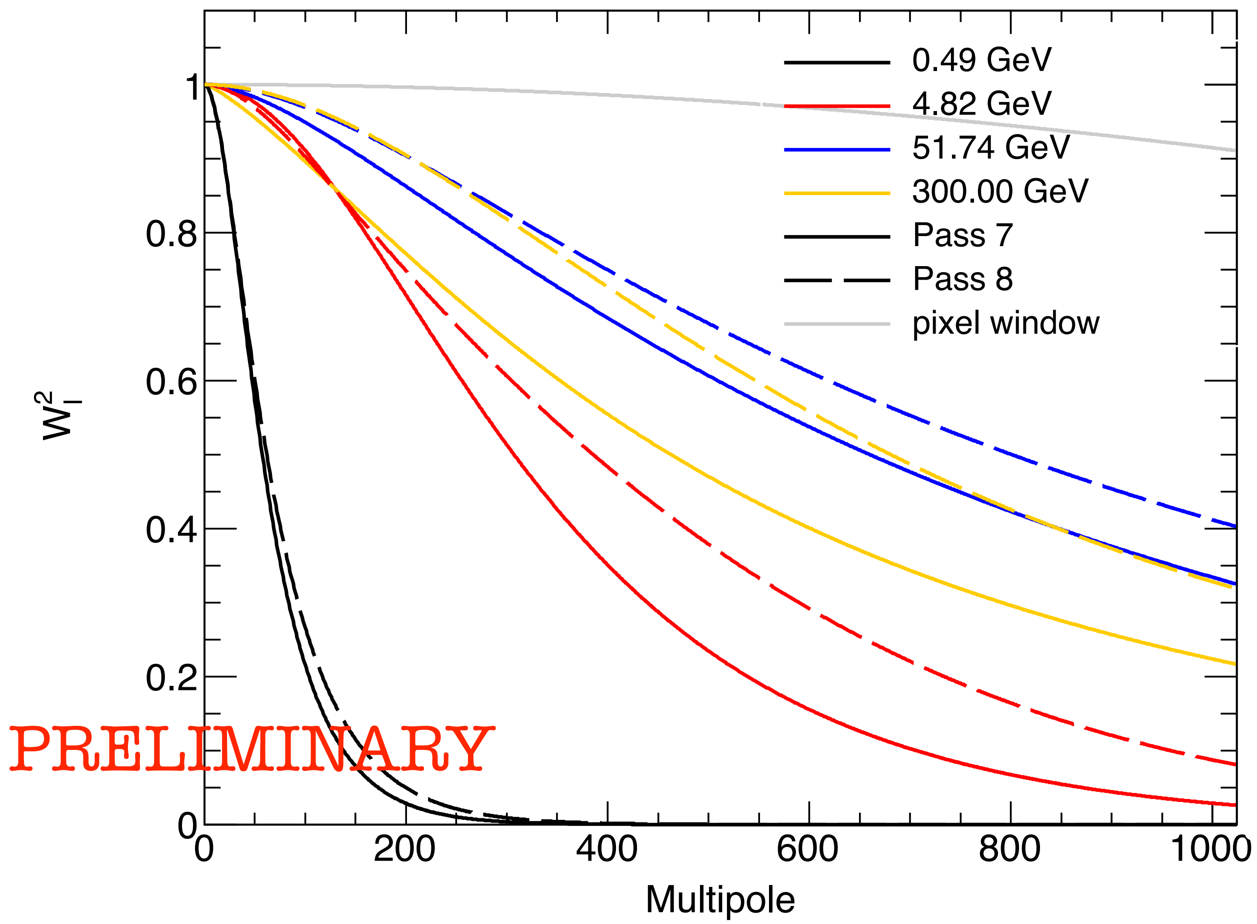
APS estimator

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

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

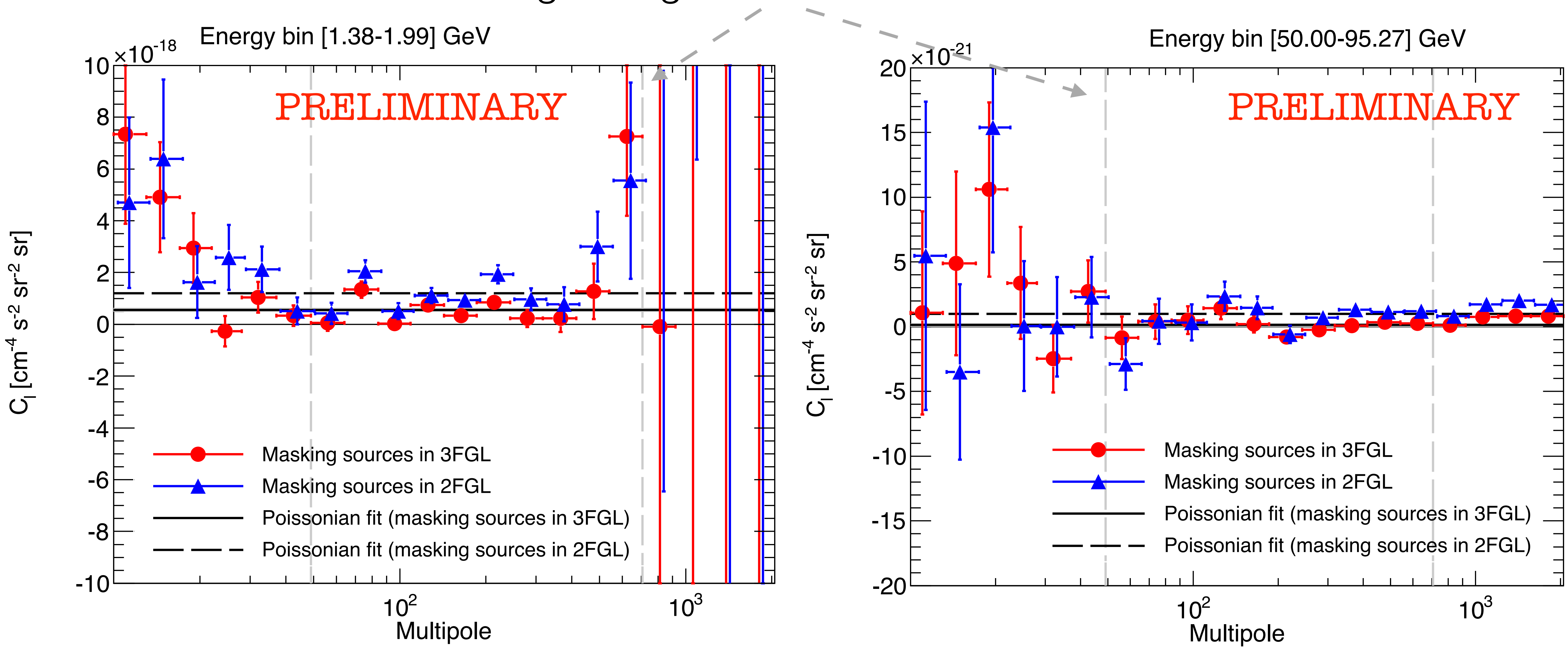
output of the decomposition in spherical harmonics (already corrected for the effect of the mask)

window beam function
(it corrects for the experimental PSF)



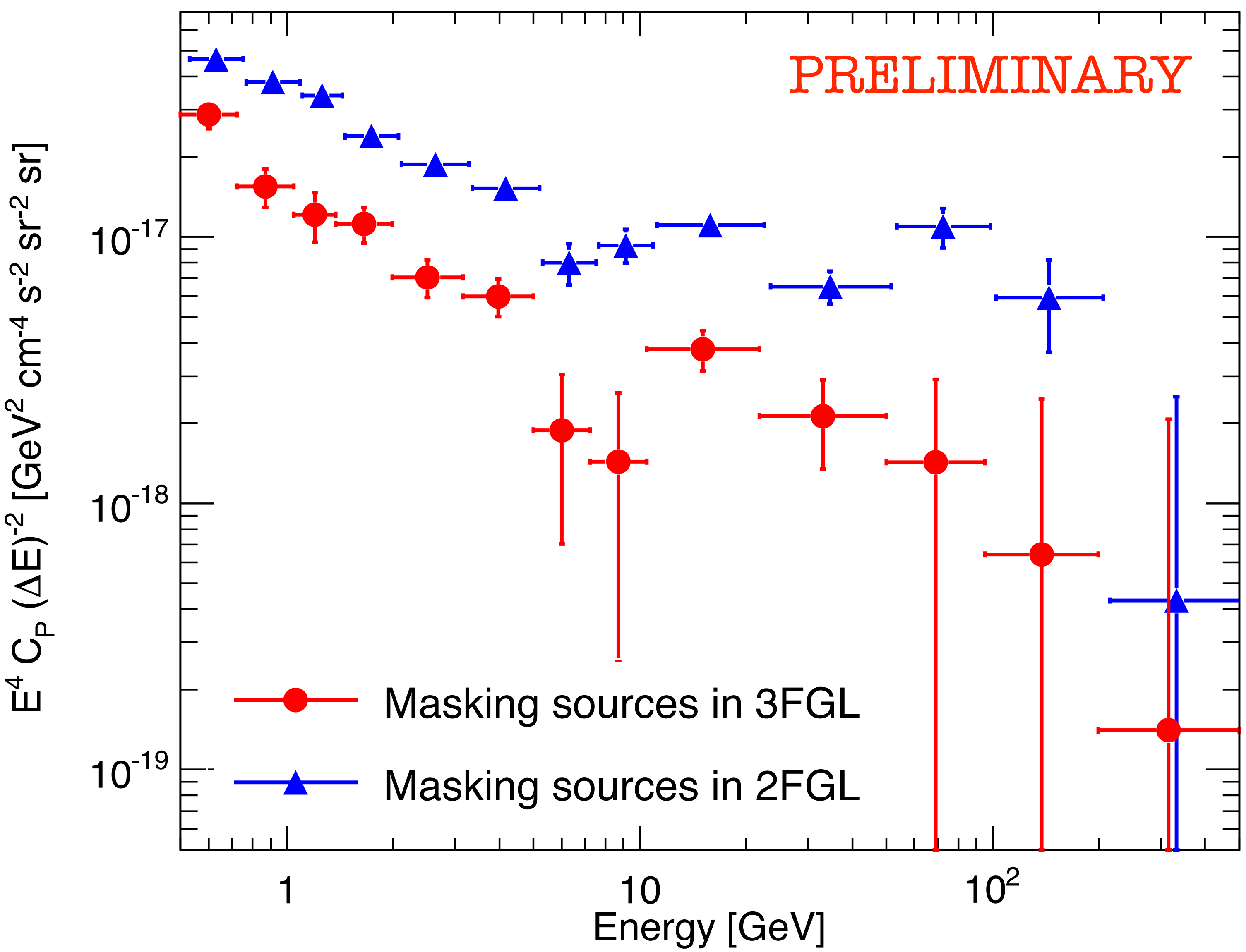
Binned APS measurement

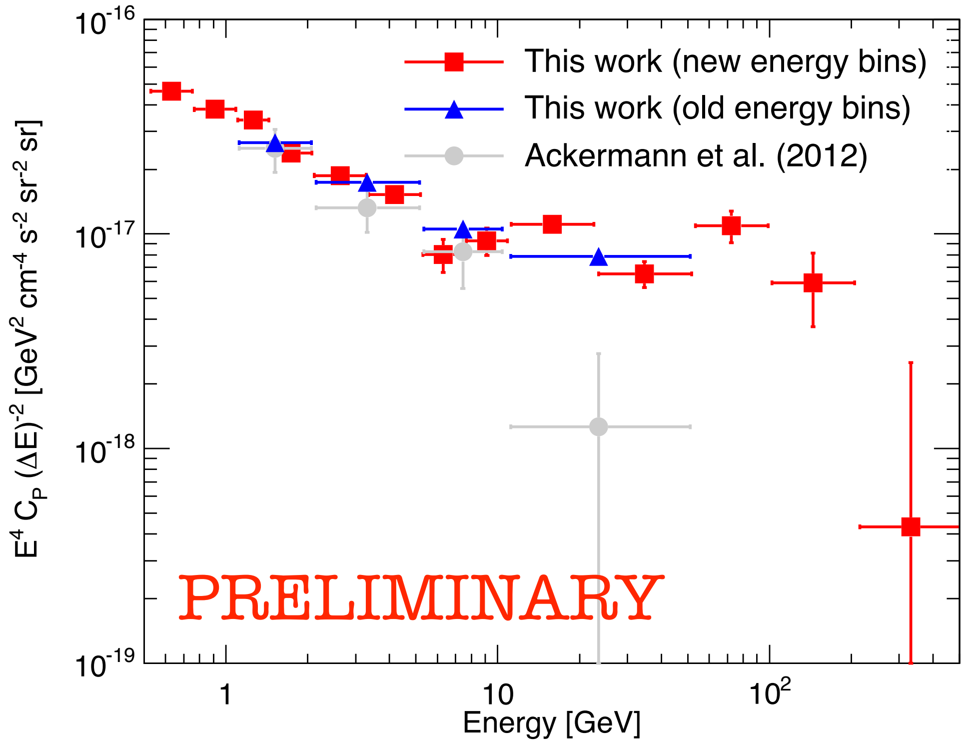
signal region between ℓ=49 and 706



- 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 = 1.01, p-value=0.61
- fits with $A(\ell/\ell0)^\alpha$ and $C_P + A(\ell/\ell0)^\alpha$ have also been considered

Anisotropy energy spectrum





$$I(\psi, E_i) = \sum_{\ell,m} a^i_{\ell,m} Y_{\ell,m}(\psi)$$

$$C^i_{\mathrm{P}} = \sum_{\alpha} C_{i\,\mathrm{P},\alpha} = \sum_{\alpha} I^2_{\alpha}(E_i)\,\tilde{C}_{\mathrm{P},\alpha}$$

- anisotropy energy spectrum traces the intensity energy spectrum of sources
- features in the anisotropy energy spectrum hint at multiple components

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 $C_P^{i,j}$
- cross correction coefficients

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

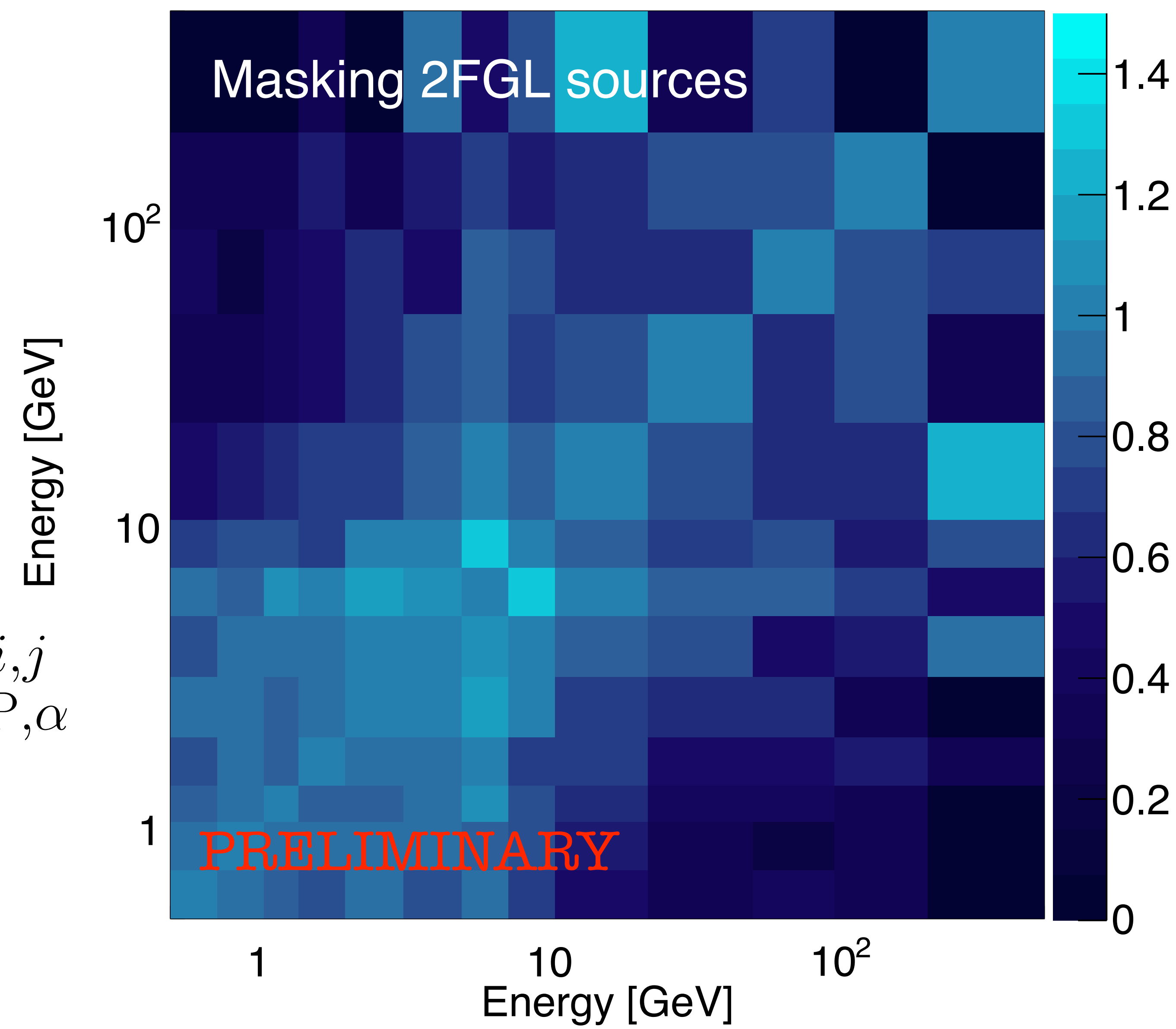
- one source class:

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

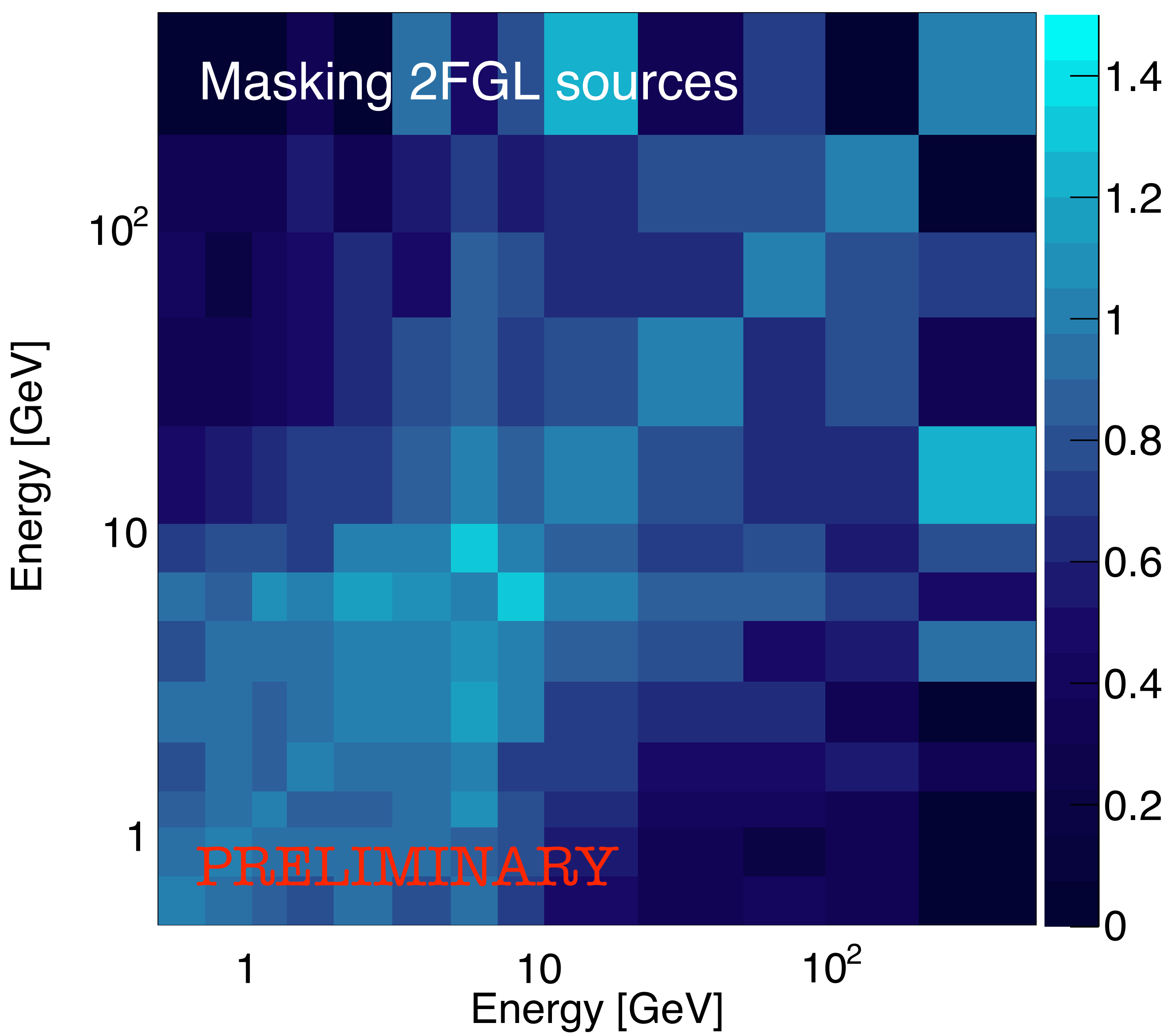
- multiple source classes:

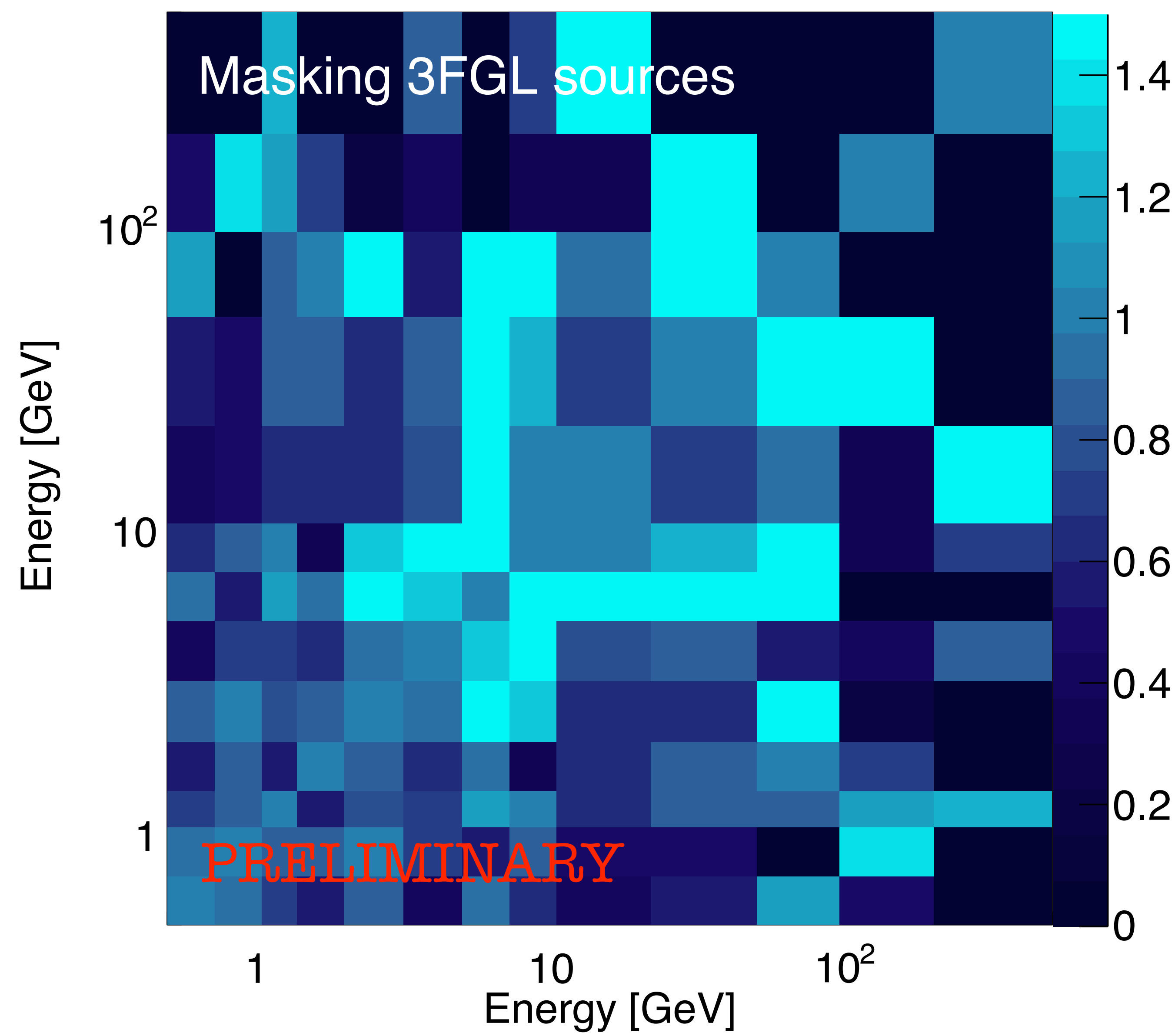
$$C_{\rm P}^{i,j} = \sum_\alpha C_{{\rm P},\alpha}^{i,j} = \sum_\alpha I(E_i)I(E_j)\tilde{C}_{{\rm P},\alpha}^{i,j}$$

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



Cross-correlation APS



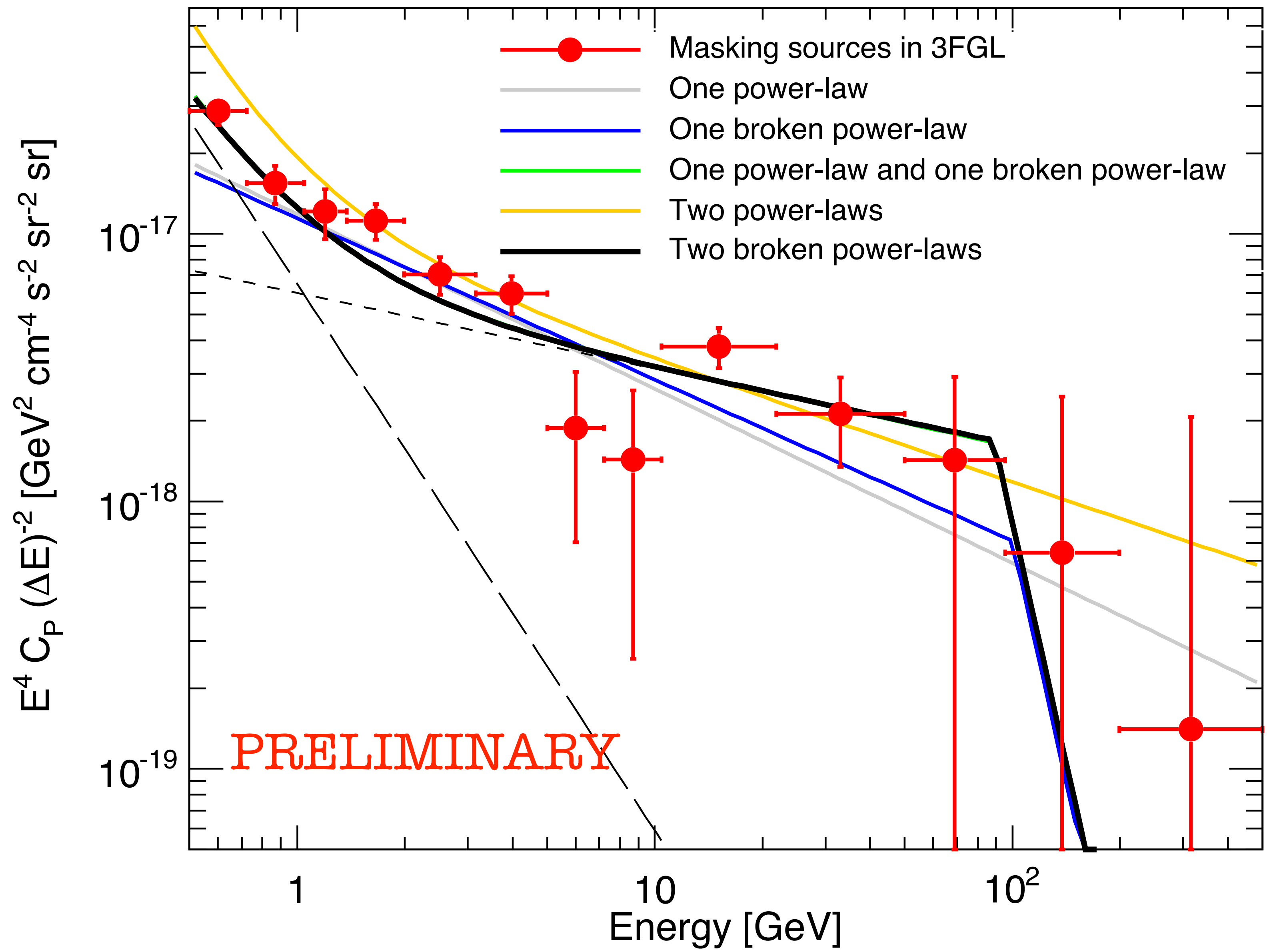


Interpretation in terms of multiple populations

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

$$I(E) \propto E^{-\alpha}$$

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



Best-fit model has two contributions both emitting as broken power laws:

- $E_b=(88.9_{-14.4}^{+9.6})$ GeV, $\alpha=2.15\pm0.05$, $\beta>3.9$
- $E_b>79$ GeV, $\alpha=3.0_{-0.2}^{+0.3}$, $\beta=0.88_{-0.15}^{+0.09}$

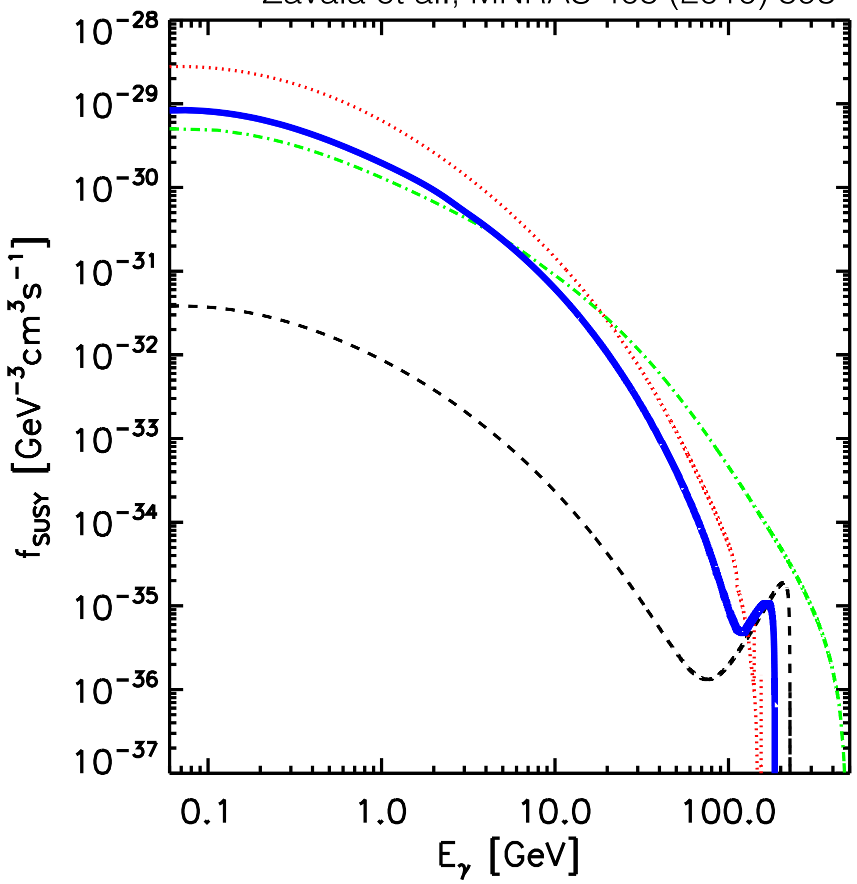
$\chi^2/\text{dof} = 1.21$, p-value=0.16

Gamma-ray emission induced by Dark Matter (DM)

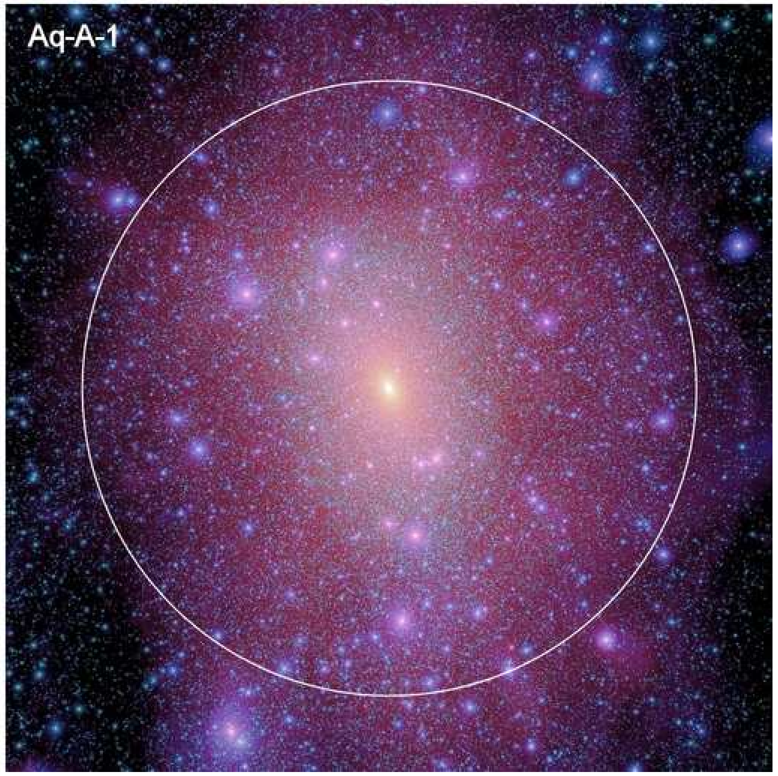
$$\frac{d\Phi}{dE}(E_\gamma,\Psi) = \frac{(\sigma_{ann}v)}{8\pi m_\chi^2}\int_{\mathrm{l.o.s}} d\lambda \sum_i B_i \frac{dN_\gamma^i(E_\gamma(1+z))}{dE}\rho^2(\lambda(z),\Psi)e^{-\tau_{\mathrm{EBL}}(z,E_\gamma)}$$

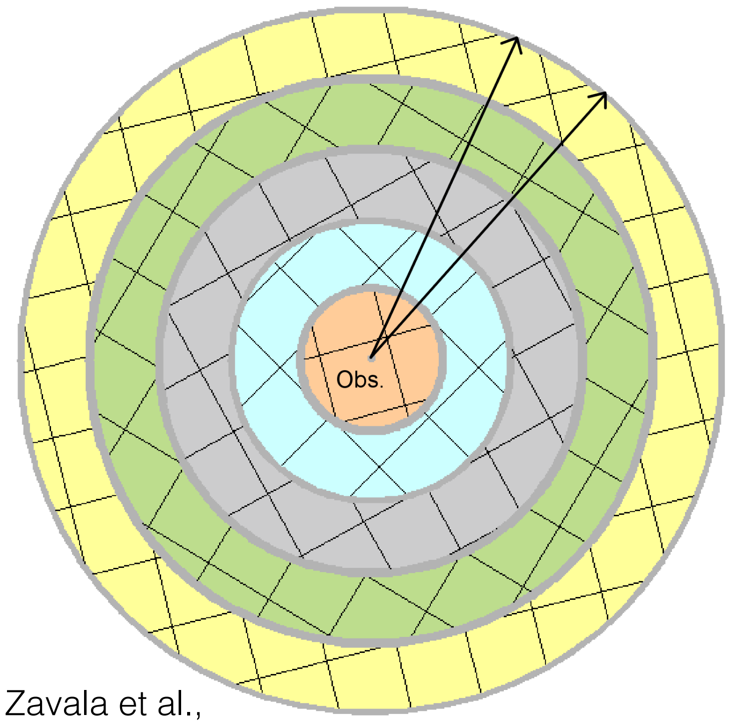
- photon yield: prompt emission, Inverse Compton and hadronic emission
- distribution and shape of DM halos inferred from *N*-body simulations
- couple *N*-body simulations to analytical recipes in order to estimate emission below their mass resolution (hybrid method)

Zavala et al., MNRAS 405 (2010) 593

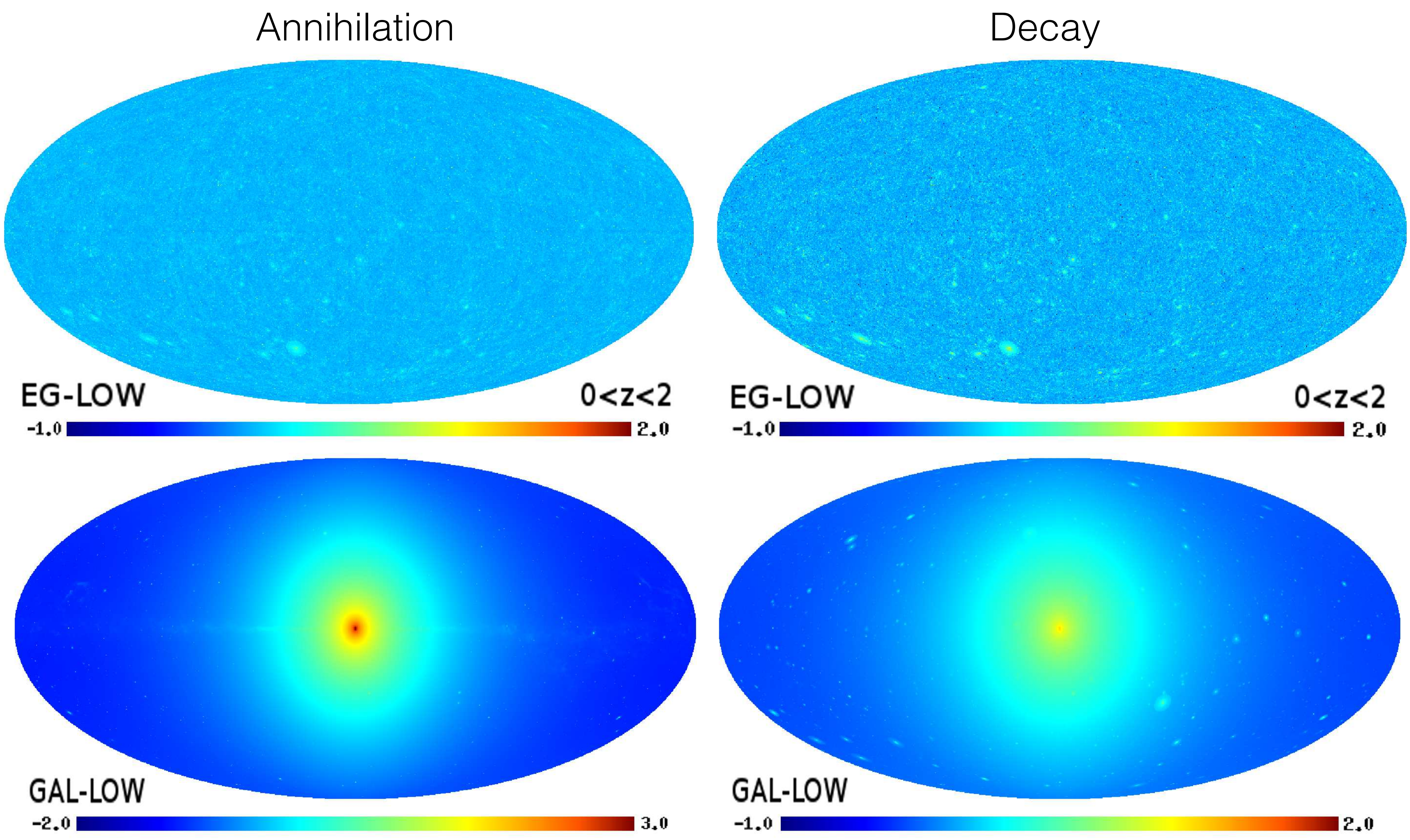


Springel et al., MNRAS 391 (2008) 1685





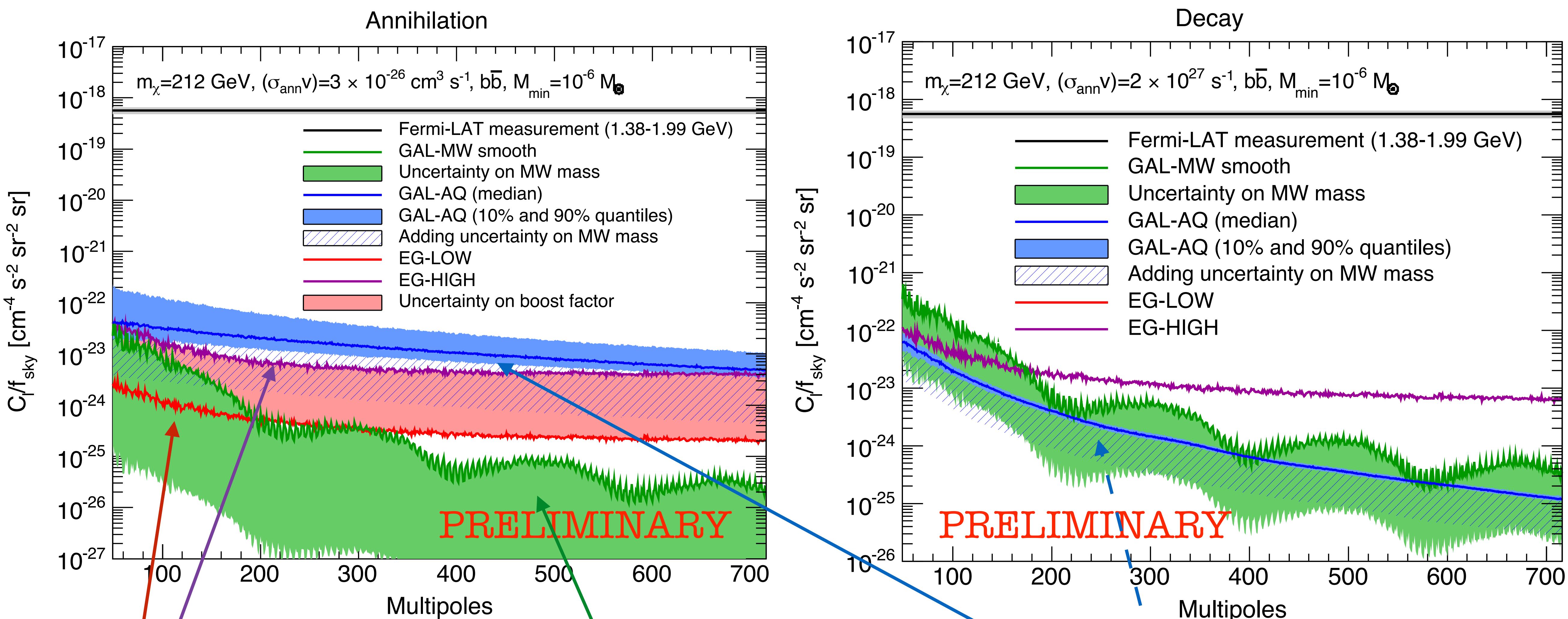
Zavala et al.,
MNRAS 405 (2010) 593



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

m_χ=200 GeV, σv=$3\times10^{-26}cm^3s^{-1}$ (annihilation), m_χ=2 TeV, τ=2×10^{27} s (decay)

DM-induced APS



Extragalactic component with different subhalo boost factors

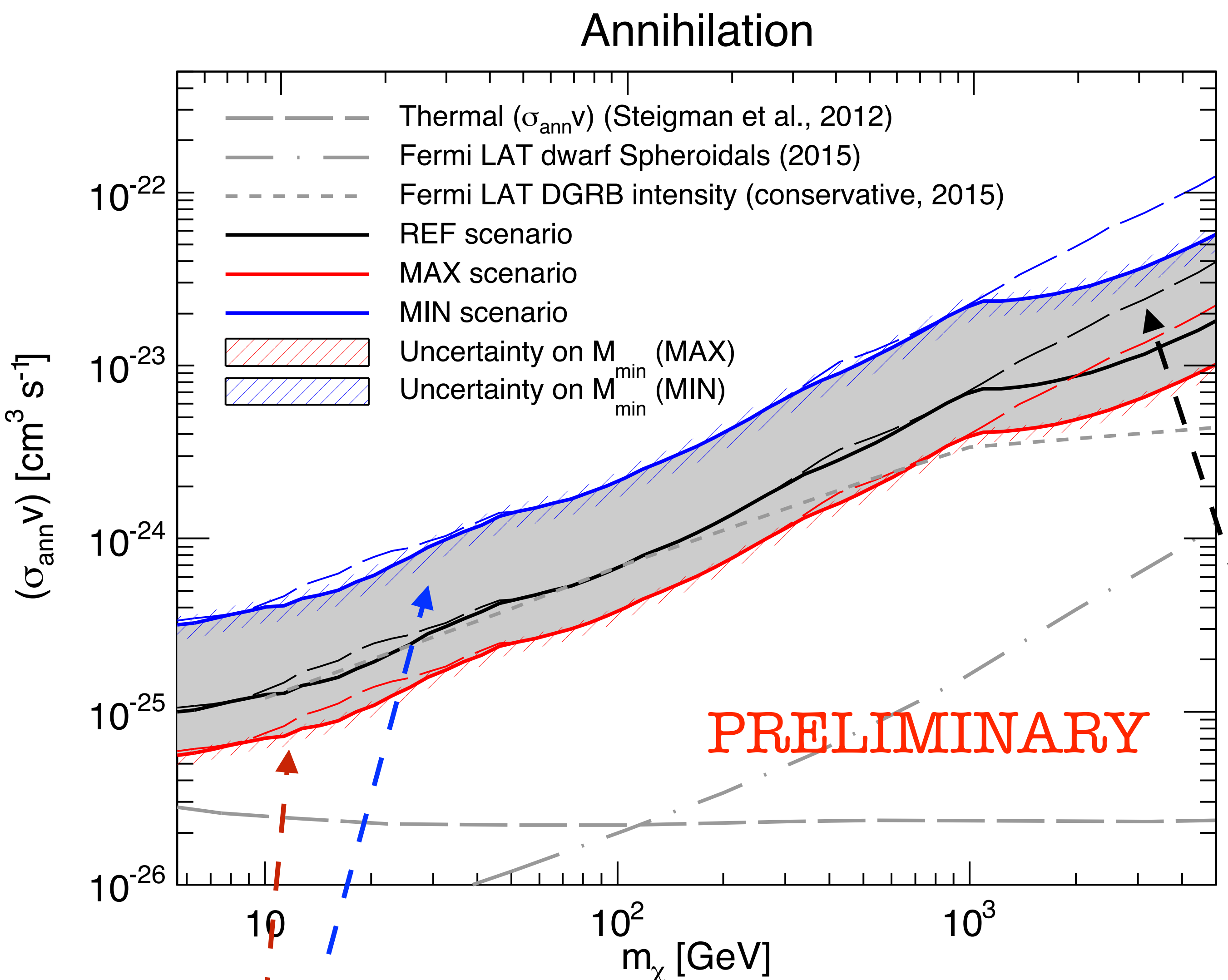
Subhalos of the Milky Way with uncertainty on the position of the Earth

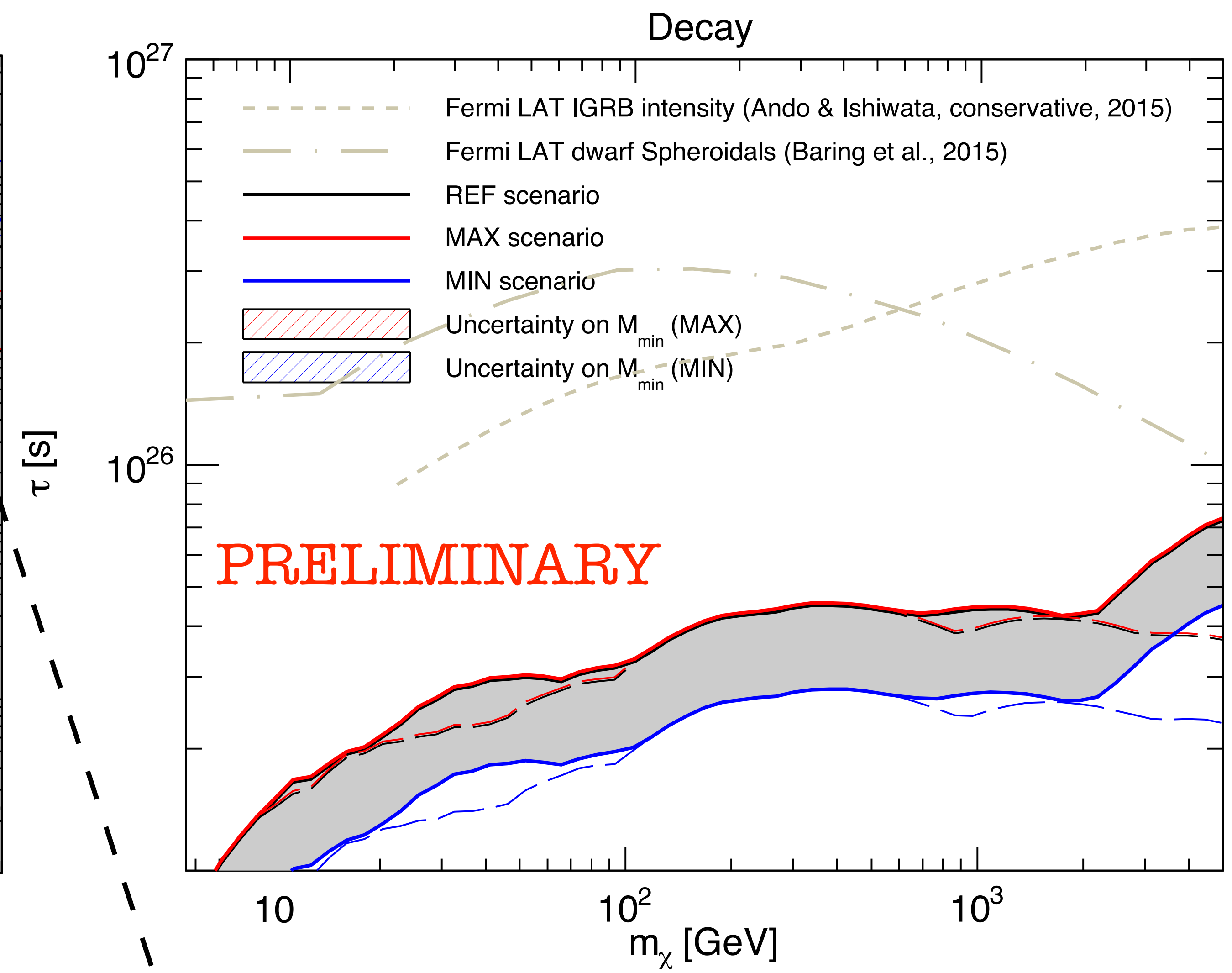
Smooth halo of the Milky Way (outside of the mask) with uncertainty on the total Milky-Way mass

uncertainty on the total mass of the Milky Way

Conservative exclusion limits

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





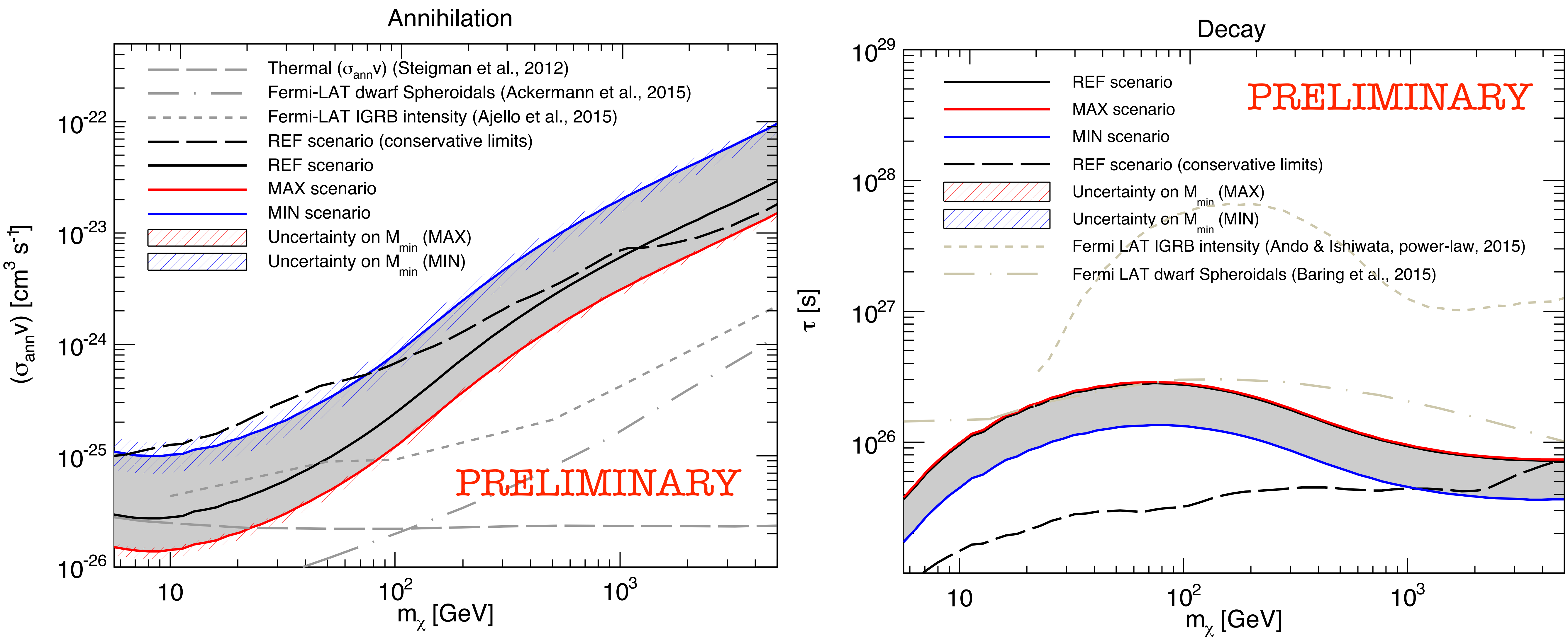
Uncertainty on the value of M_{min}

How the exclusion limits would look like if only the auto-correlation were used

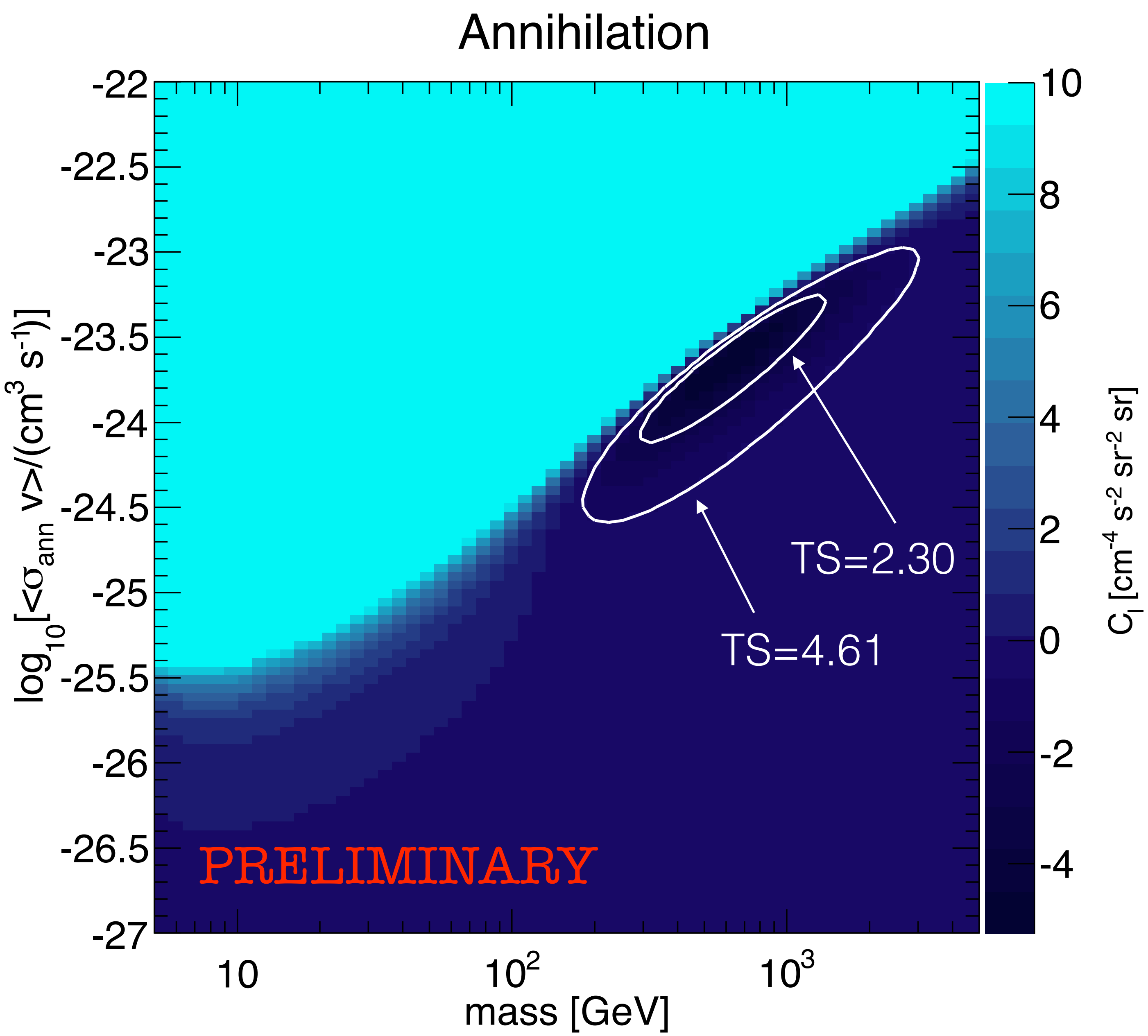
2-component fit to the binned APS

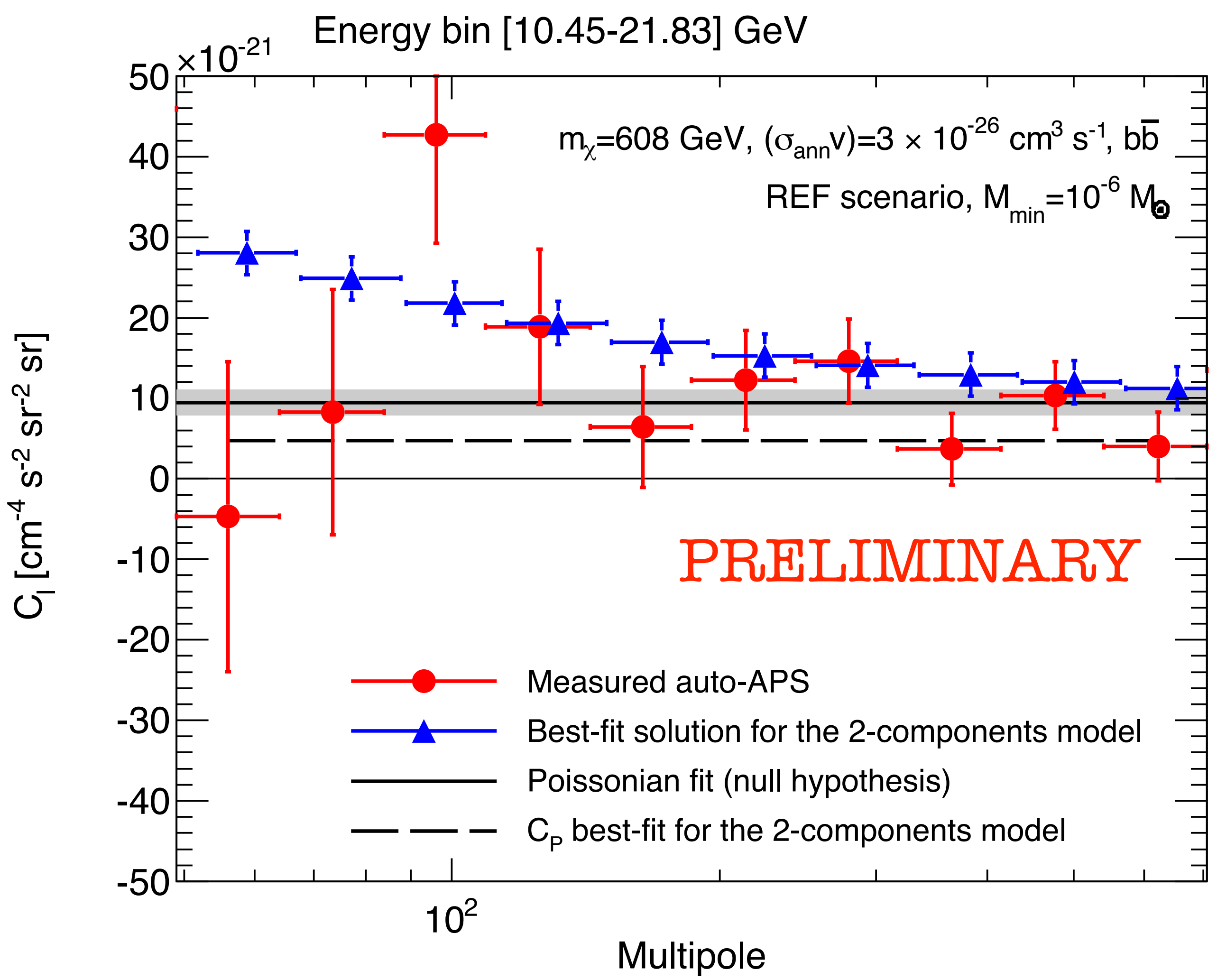
$$\chi^2 = -\sum_{i,j,\ell} \frac{[C_\ell^{i,j} - C_{\ell,\mathrm{DM}}^{i,j} - C_{\mathrm{P}}^{i,j}]^2}{\sigma^2_{C_\ell^{i,j}}}$$

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



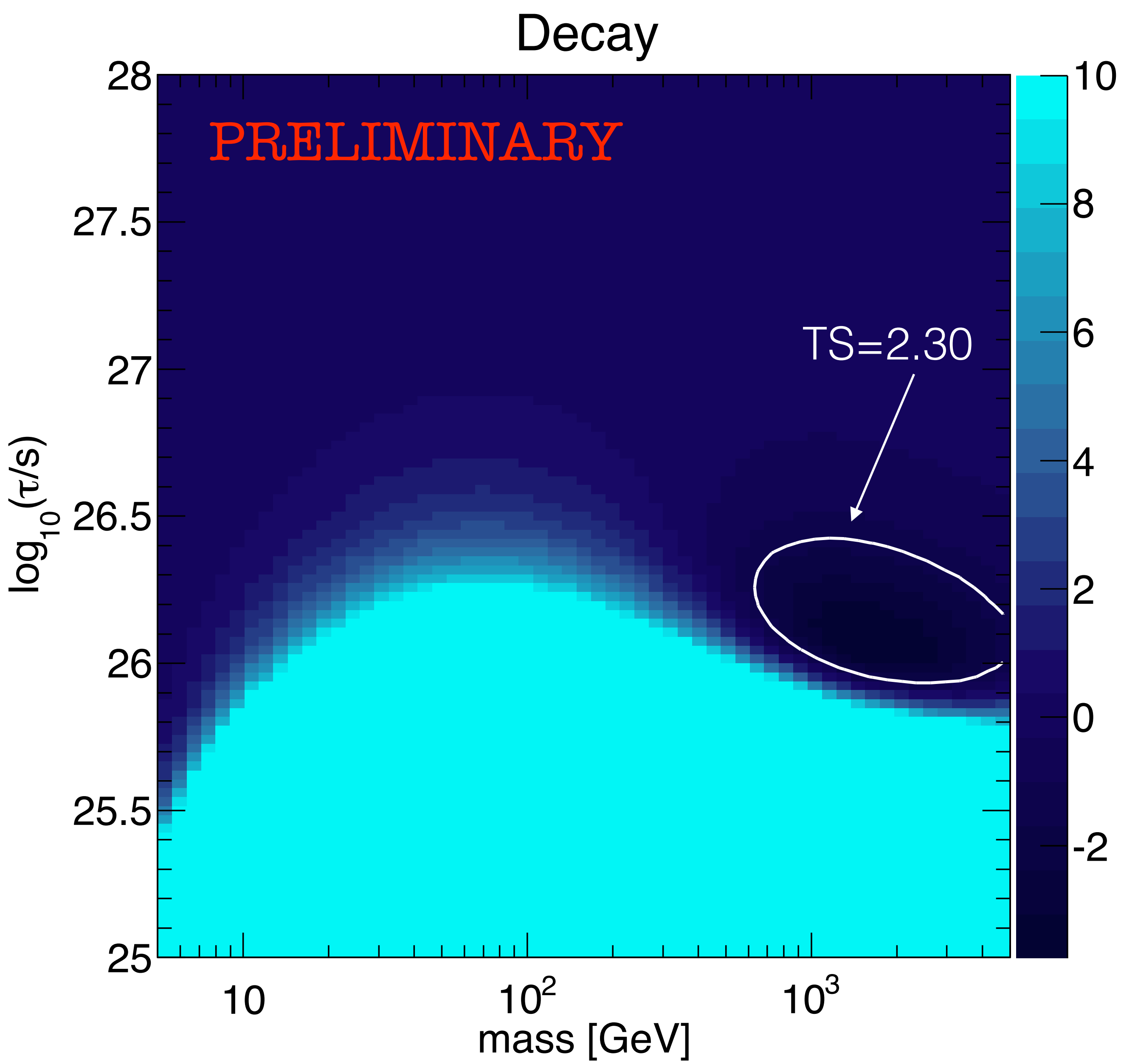
2-component fit to the binned APS





- TS = -2 ln[χ^2(no DM)] + 2 ln[$\chi^2(m_\chi,\sigma v)$]
- best-fit solution has TS=-4.5, m_χ=607 GeV, $(\sigma_{ann} v)=2.2\times10^{-24}$ $cm^3 s^{-1}$

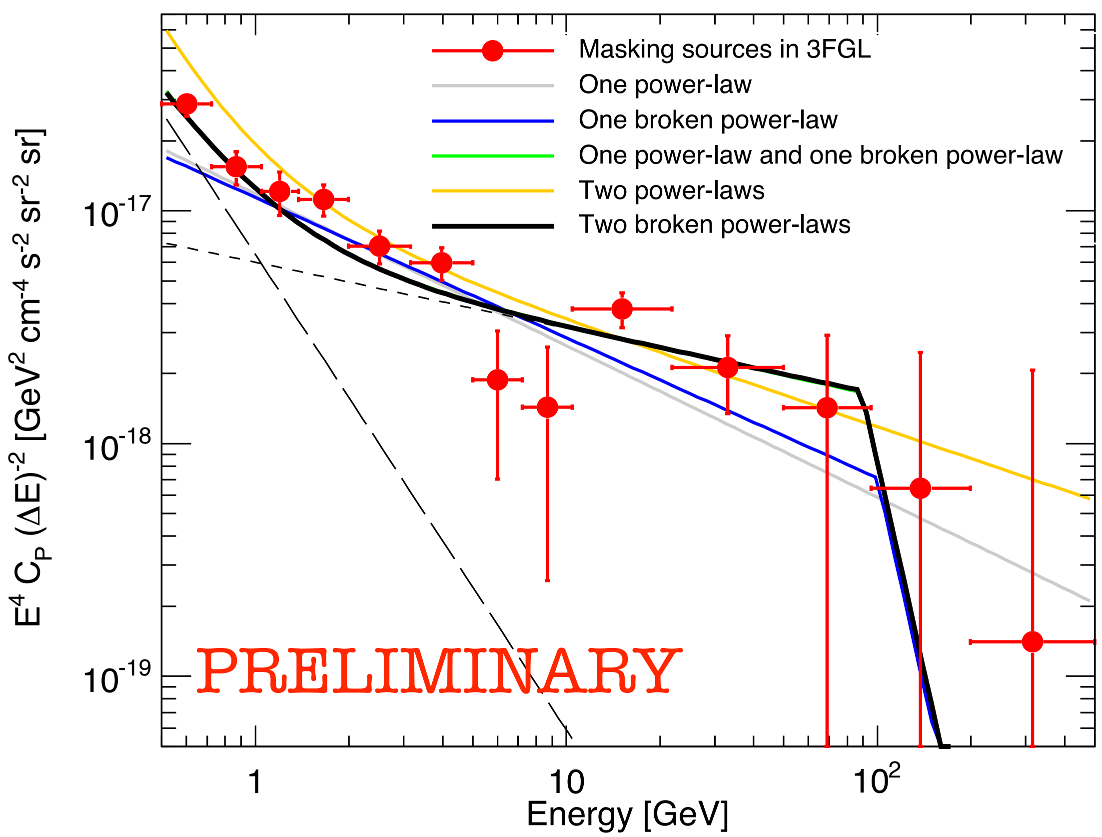
2-component fit to the binned APS

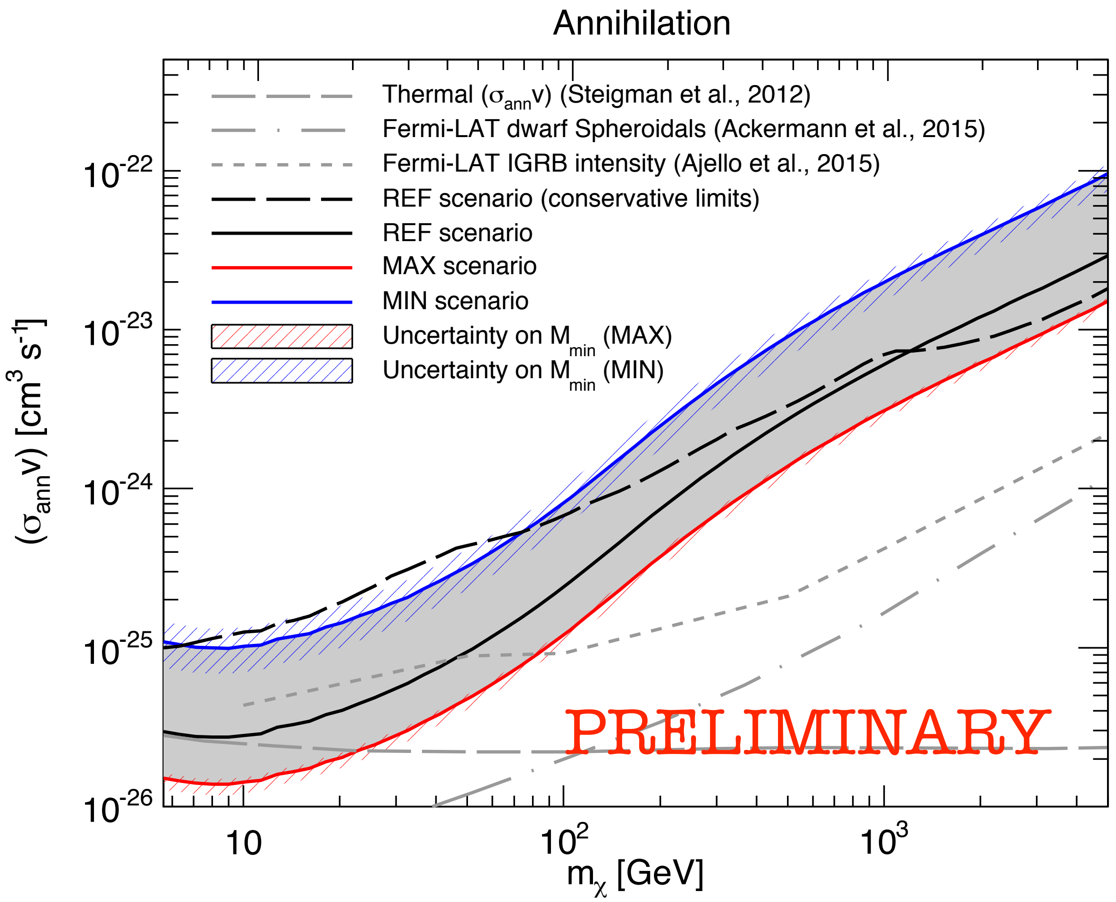


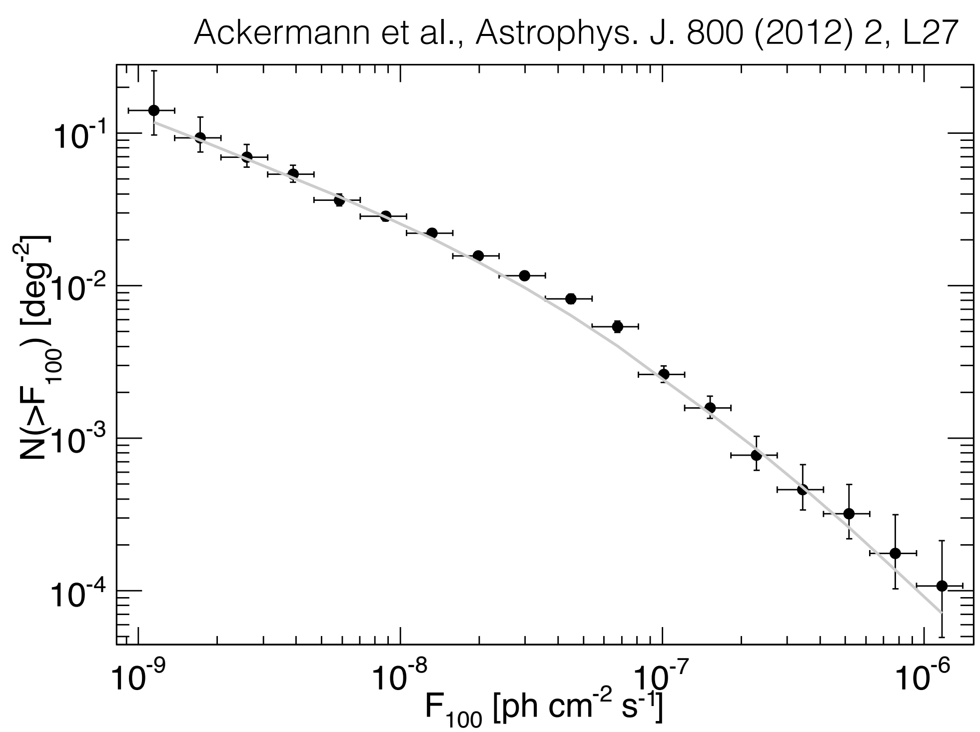
best-fit solution has m_X=1743 GeV, $\tau=1.2\times10^{26}$ s

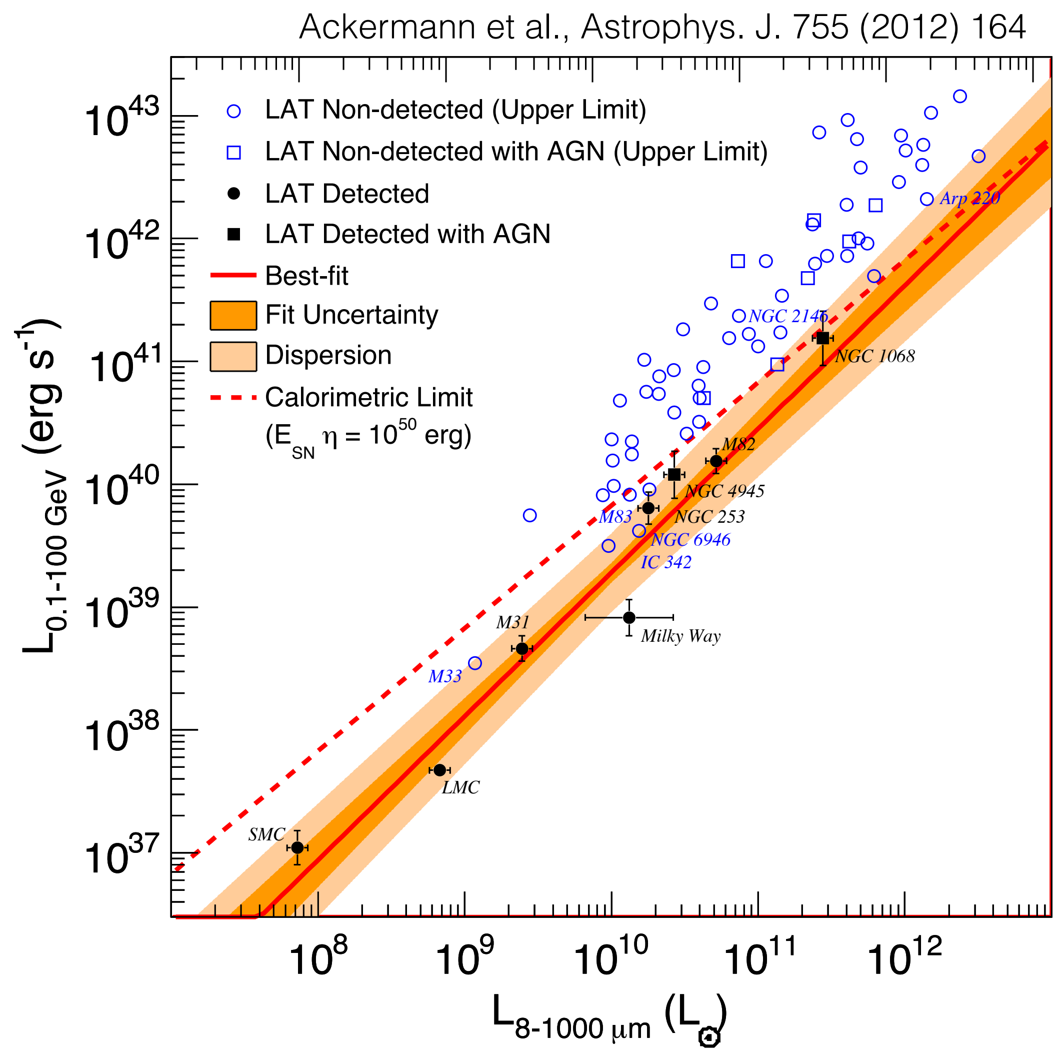
Conclusions

- new measurement of anisotropy angular power spectrum
- possibly two distinct population of sources are responsible for the signal
- constraints on additional components can be derived
- combination with cross-correlation with other tracers of Large Scale Structures and with other messengers (neutrinos)









- abundant sources: number of detected objects as a function of their flux
- rare sources (in gamma rays): measure correlation with other frequencies (IR for star-forming galaxies, radio for misaligned AGNs)

How to bin the APS

- produce 100 Monte Carlo realisations of the gamma-ray sky with a fixed nominal C_P
- PolSpice computes C_ℓ and estimates errors and covariances
- analytical expression for the error is

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

- 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
- method B was used in Ackermann et al. (2012)

How to estimated the error of the binned APS

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

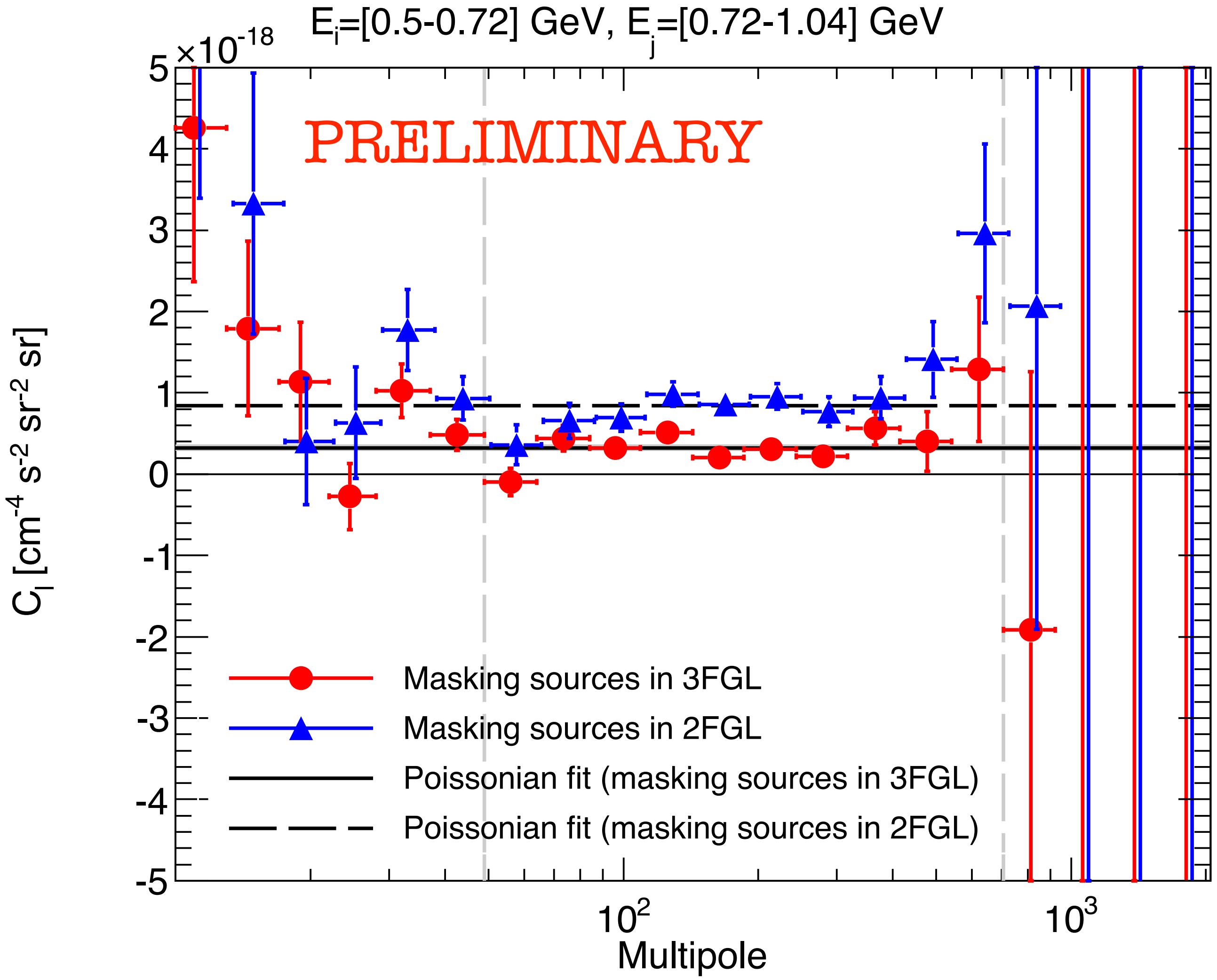
$$\sigma_\ell = \sqrt{2/(2\ell+1)}\left(C_\ell + \frac{C_{\mathrm{N}}}{W_\ell^2}\right)$$

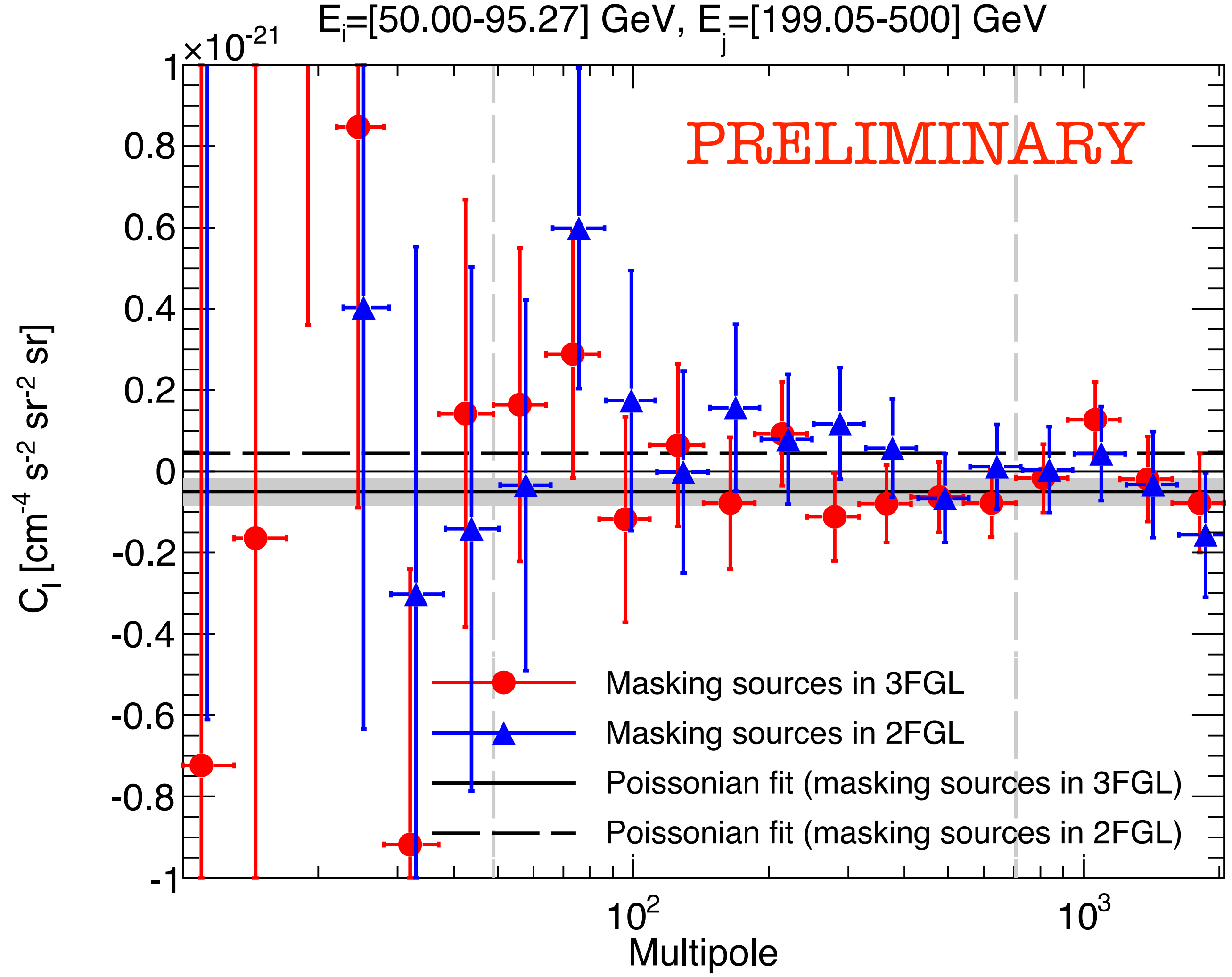
- method B: average of the variances and covariances computed by PolSpice

- the two methods agree

- the estimated error describes well the distribution of the binned C_ℓ from the 100 Monte Carlo realisations

Cross-correlation

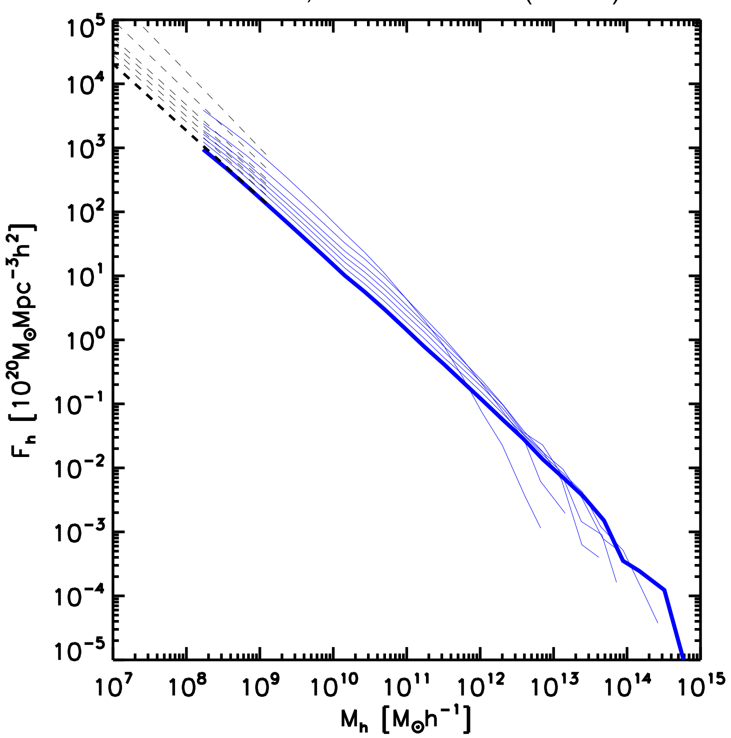




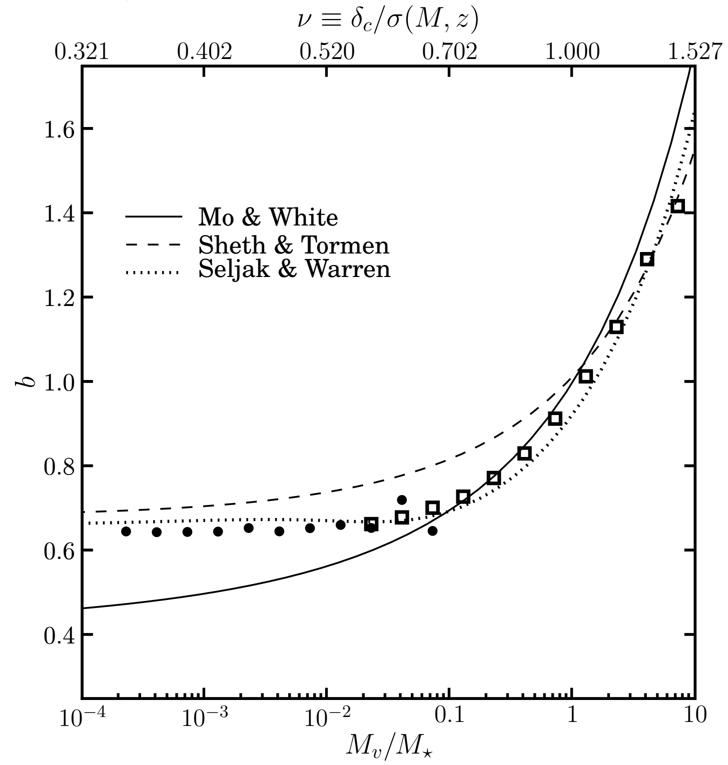
DM-induced emission

- 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)

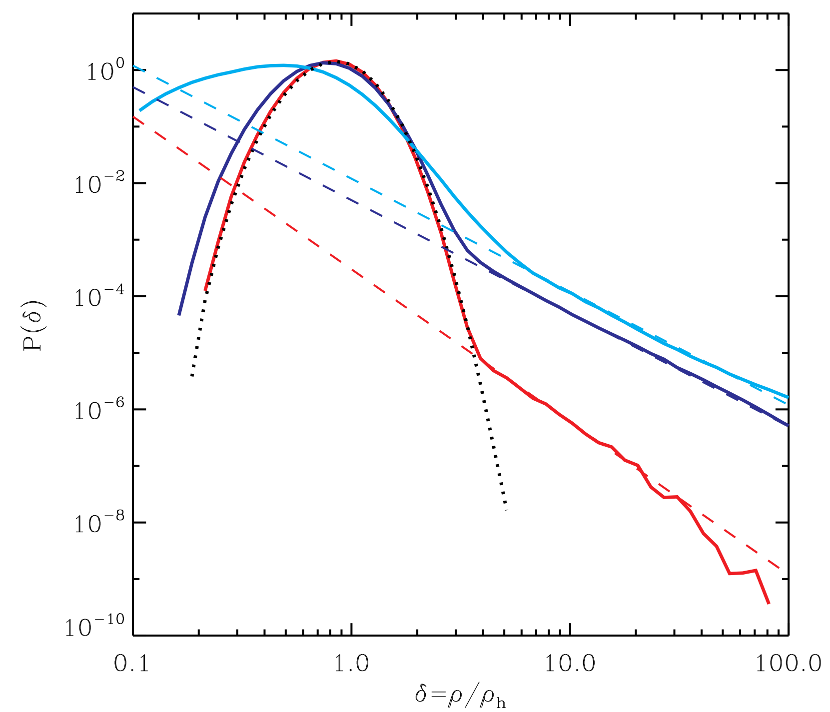
Zavala et al., MNRAS 405 (2010) 593



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

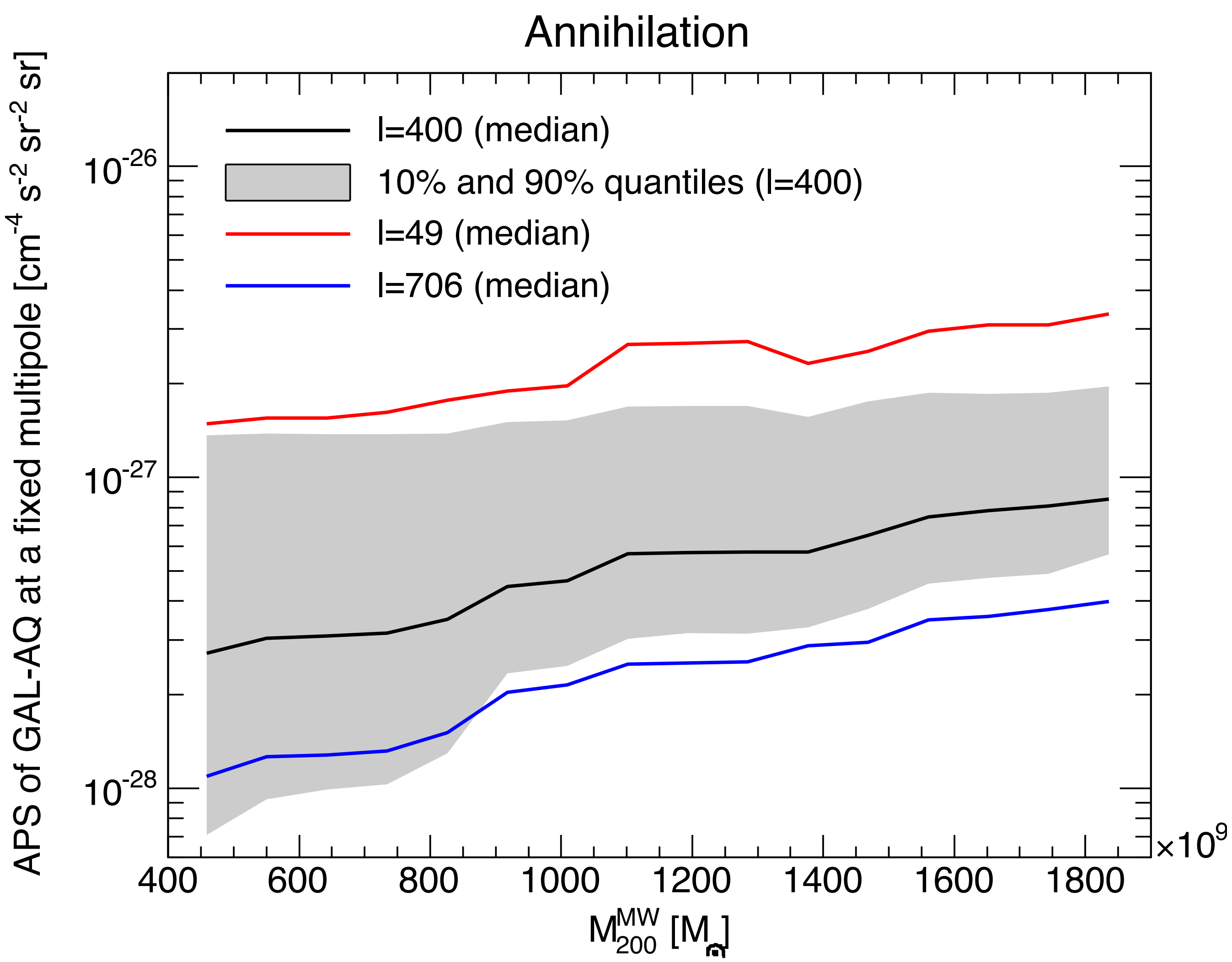


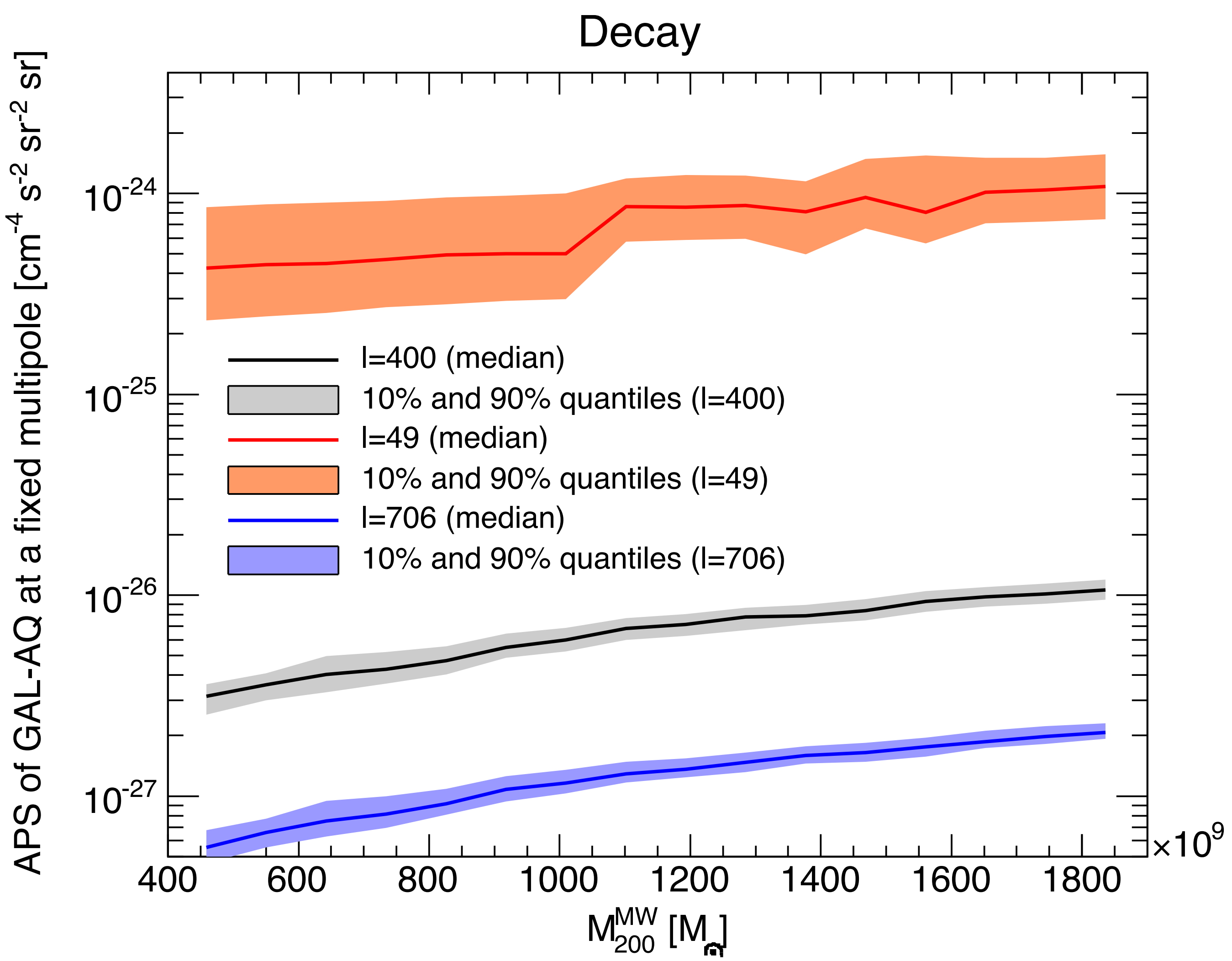
Kamionkowski et al., Phys. ReV. D81 (2010) 043532



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



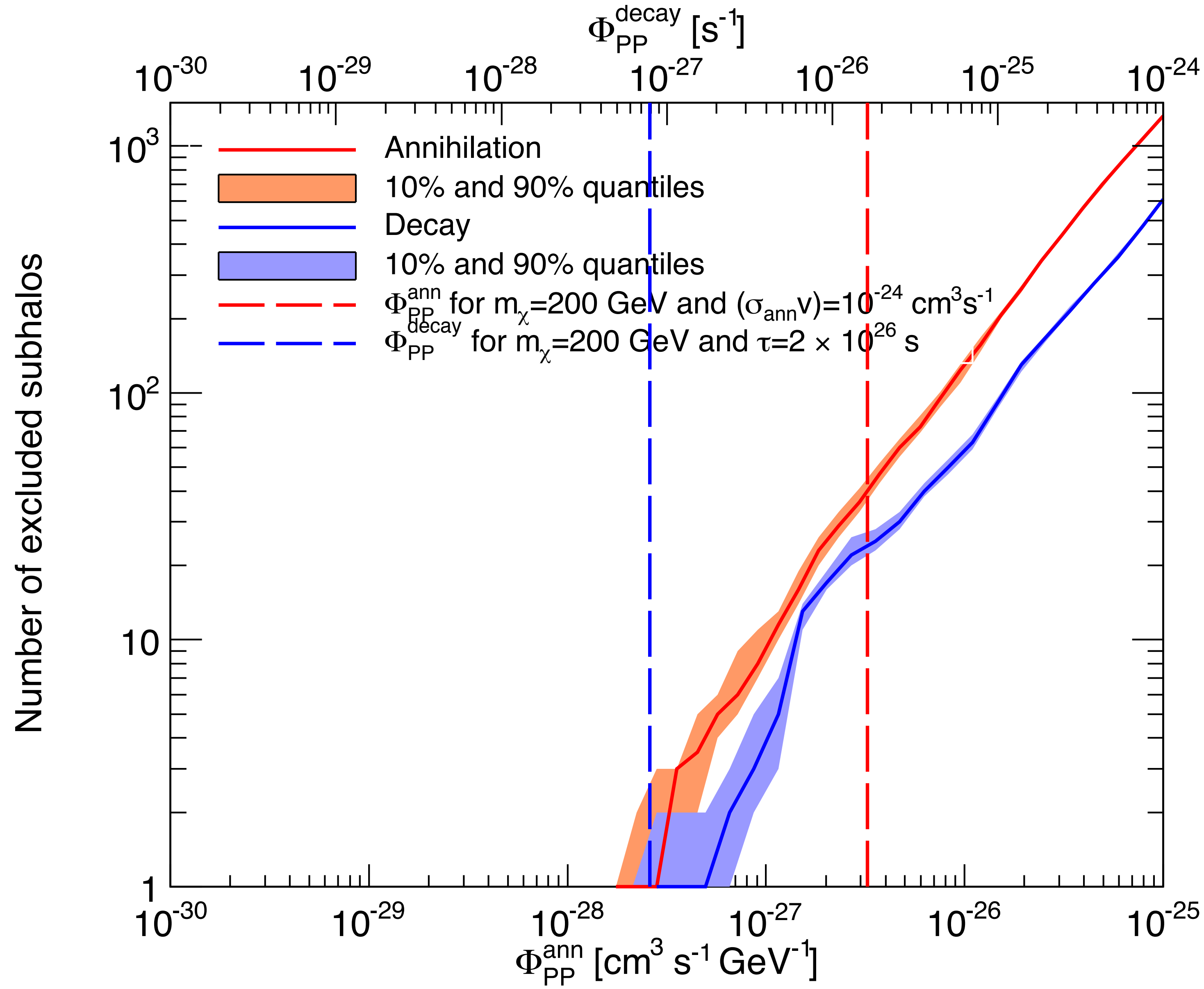


Effect of an too-bright subhalos on GAL-AQ

- 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

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

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



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