New measurement of the angular power spectrum of anisotropies using the data of the Fermi-LAT

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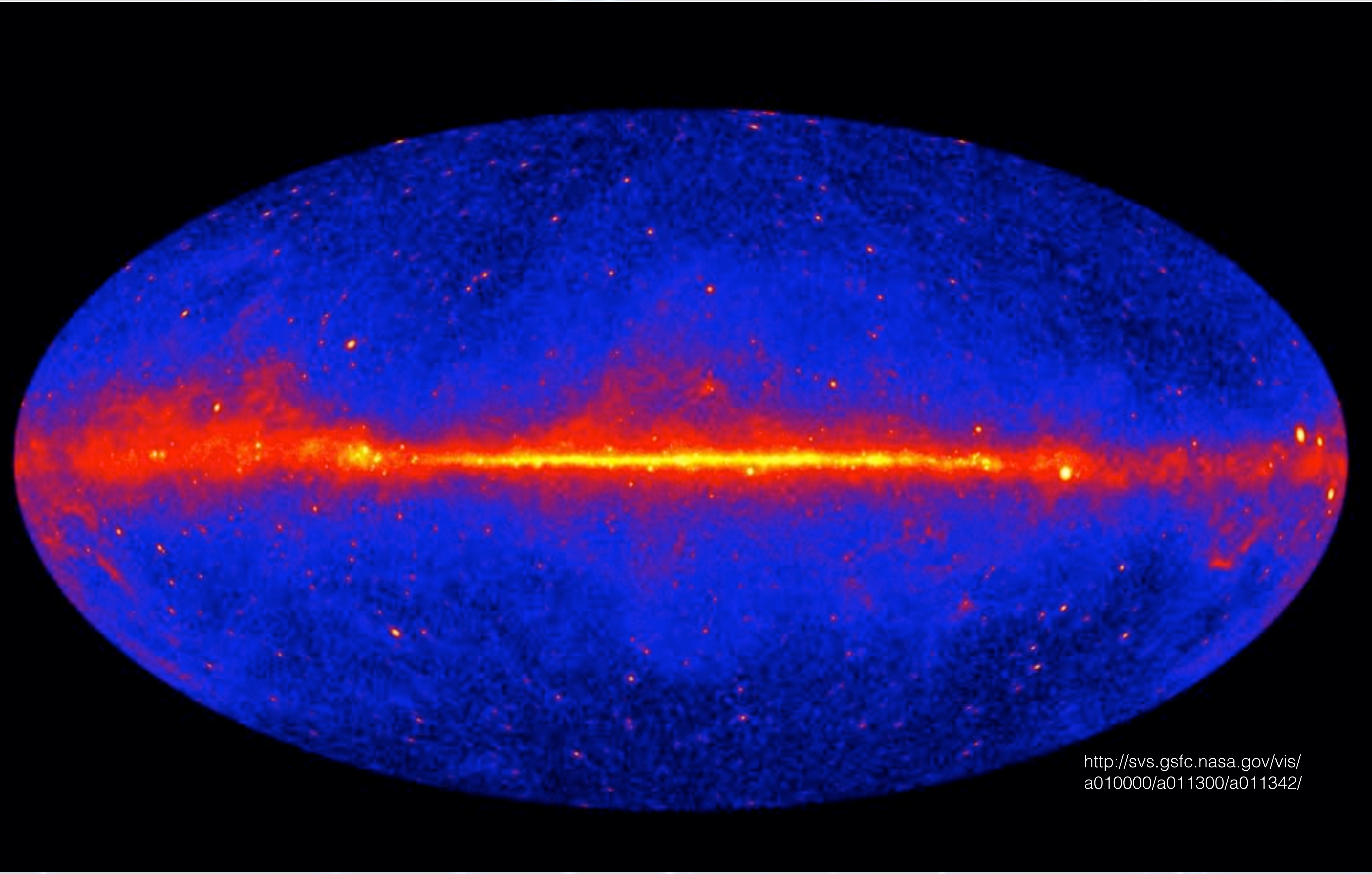
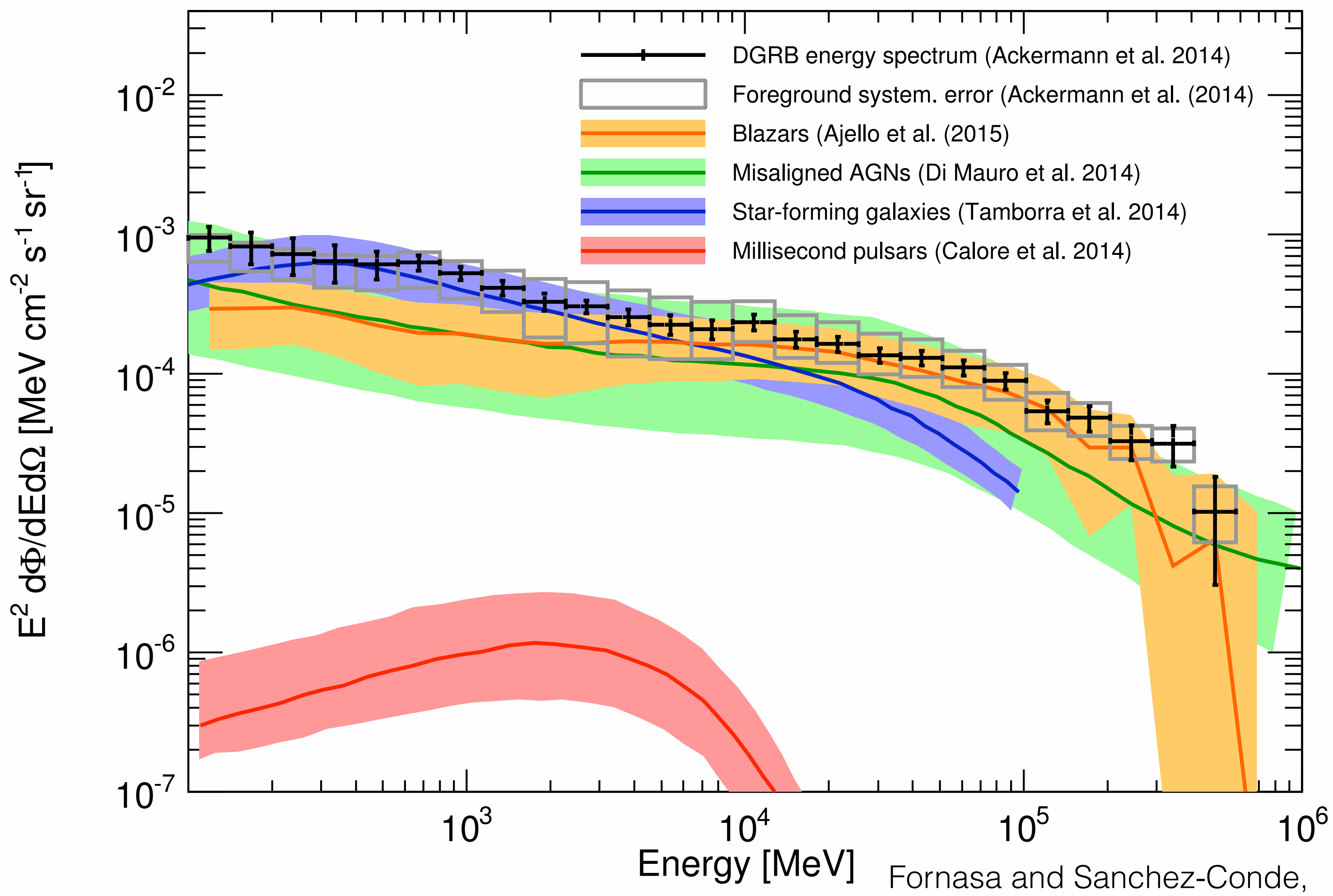
The Diffuse Gamma-Ray Background



Anisotropies in the Diffuse Gamma-Ray Background



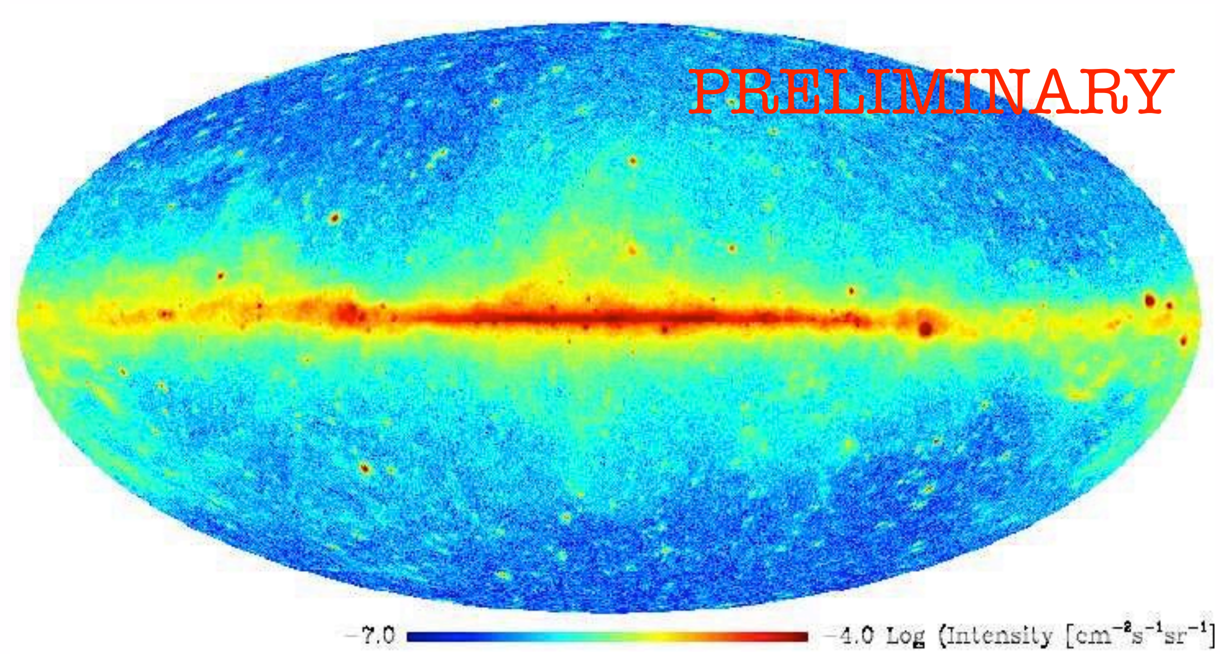
Fornasa and Sanchez-Conde, Phys. Rept. 598 (2015) 1-58

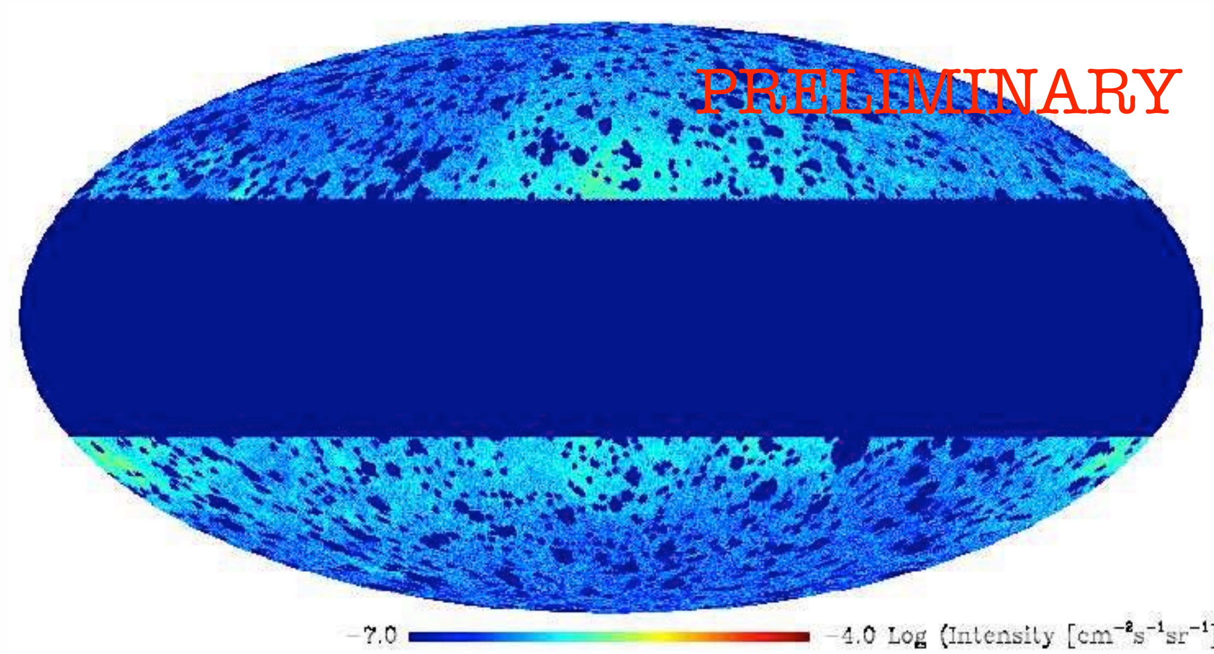
- cumulative emission of unresolved sources
- guaranteed components from unresolved astrophysical sources
- constraints on additional contributors (Dark Matter)

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

- 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





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

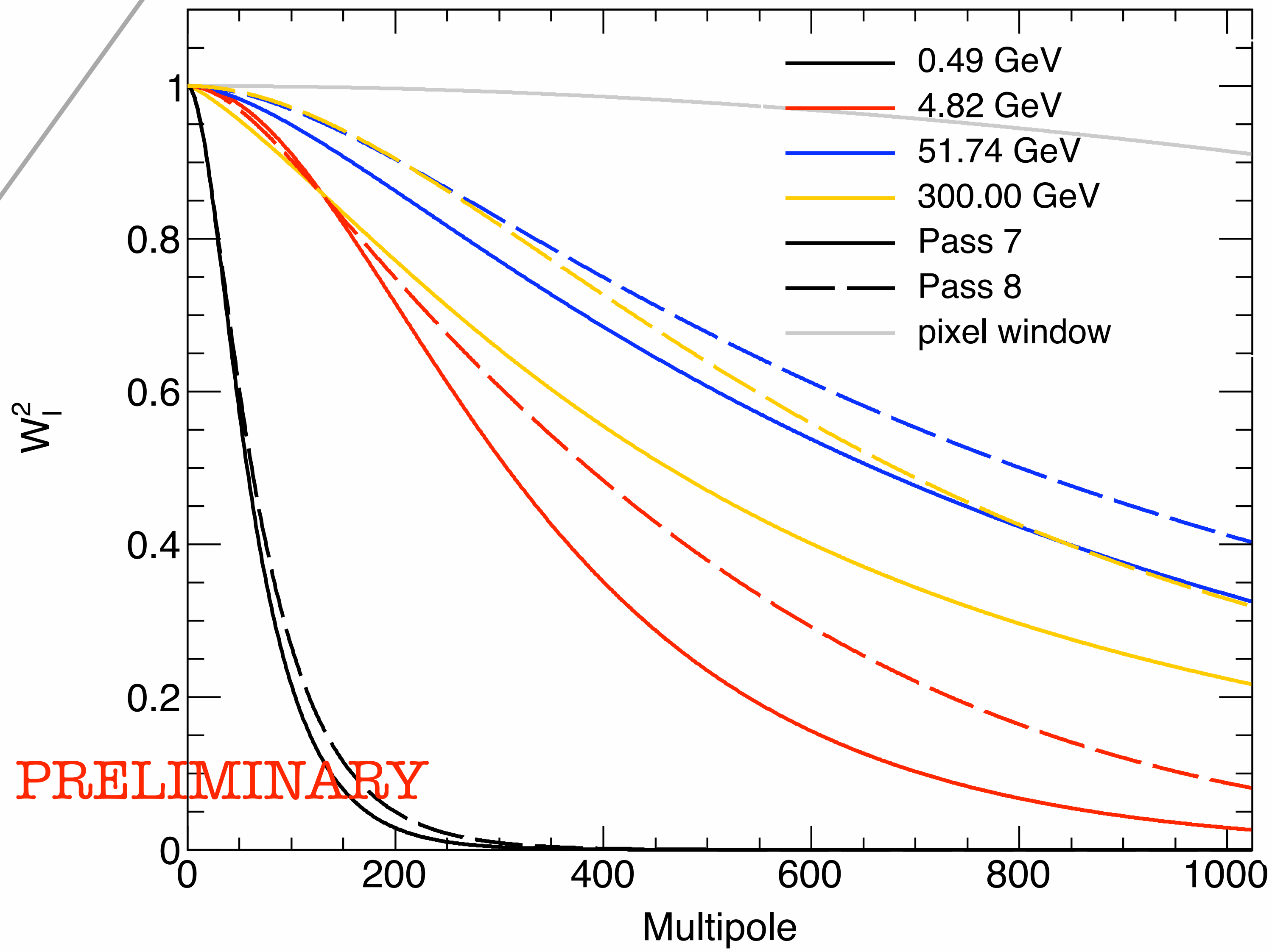
APS estimator

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

output of the decomposition in spherical harmonics

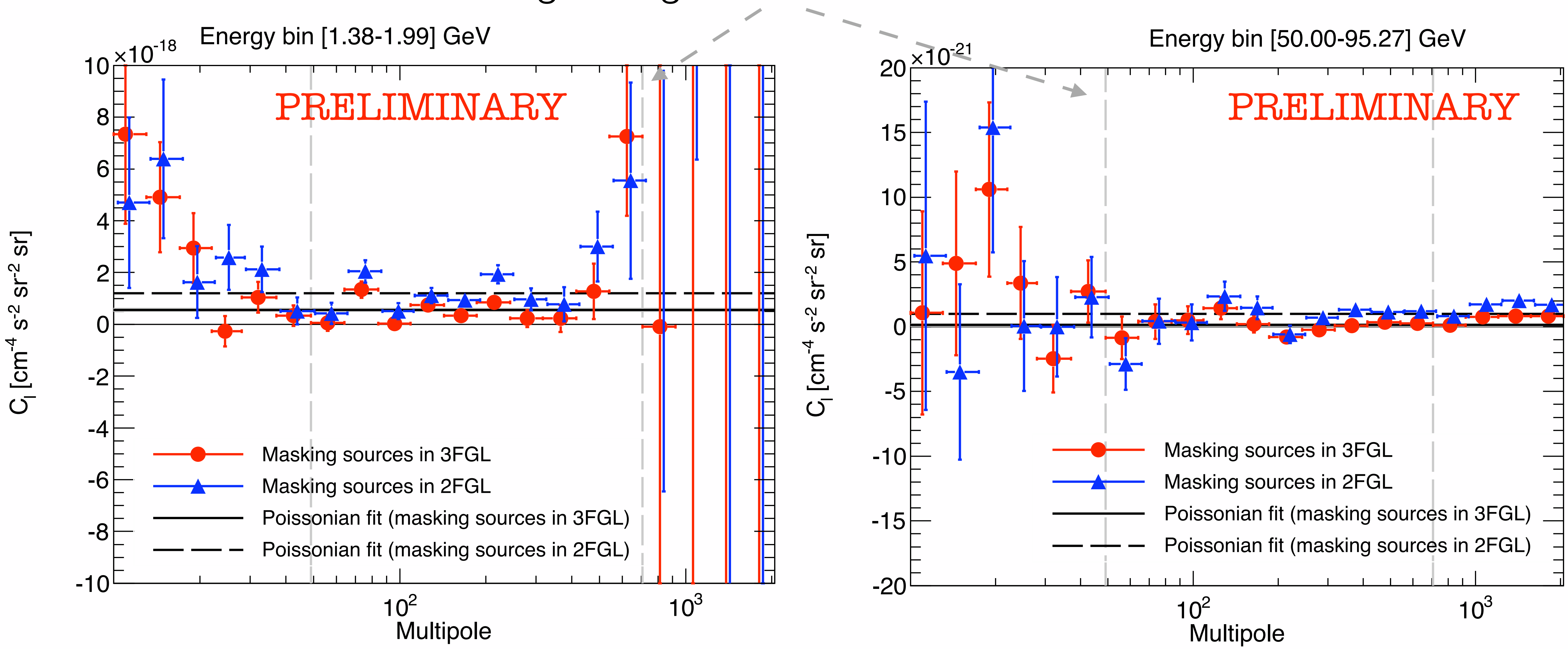
photon noise (inversely proportional to the number of detected photons)

window beam function (it corrects for the experimental PSF)



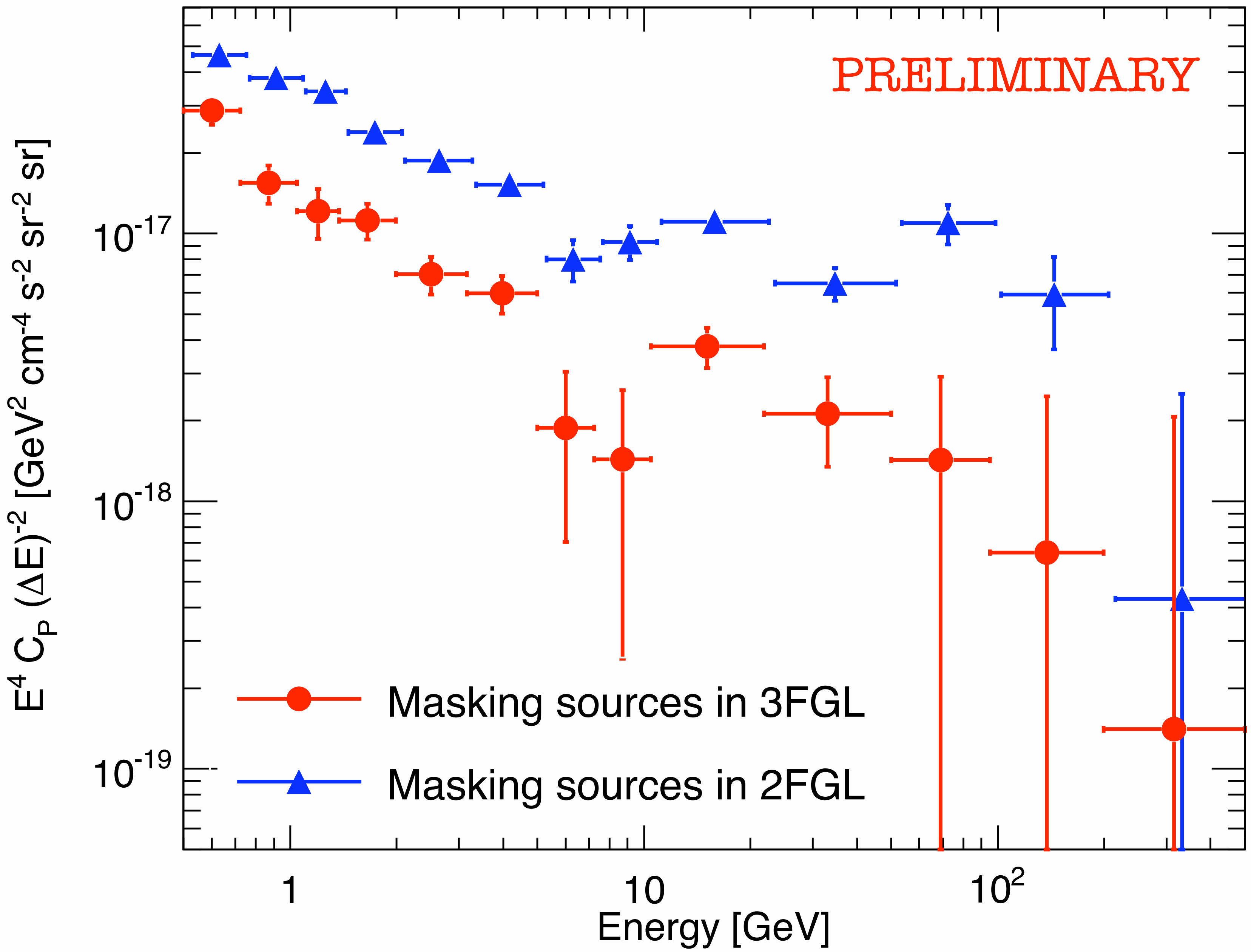
Binned APS measurement

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
- a fit with $A(\ell/\ell 0)^{\alpha}$ has also been considered

Anisotropy energy spectrum



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

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

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

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

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

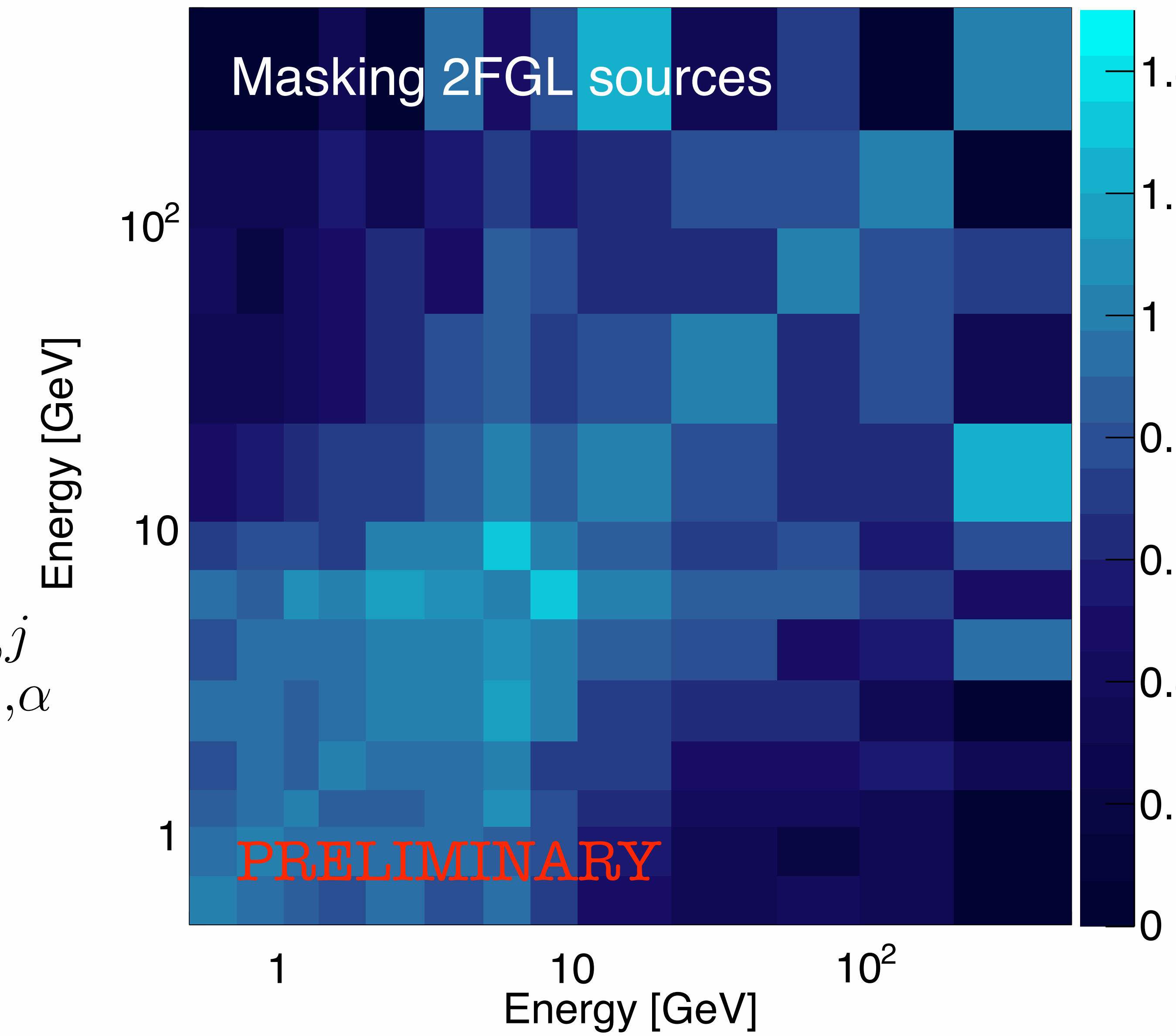
- one source class:

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

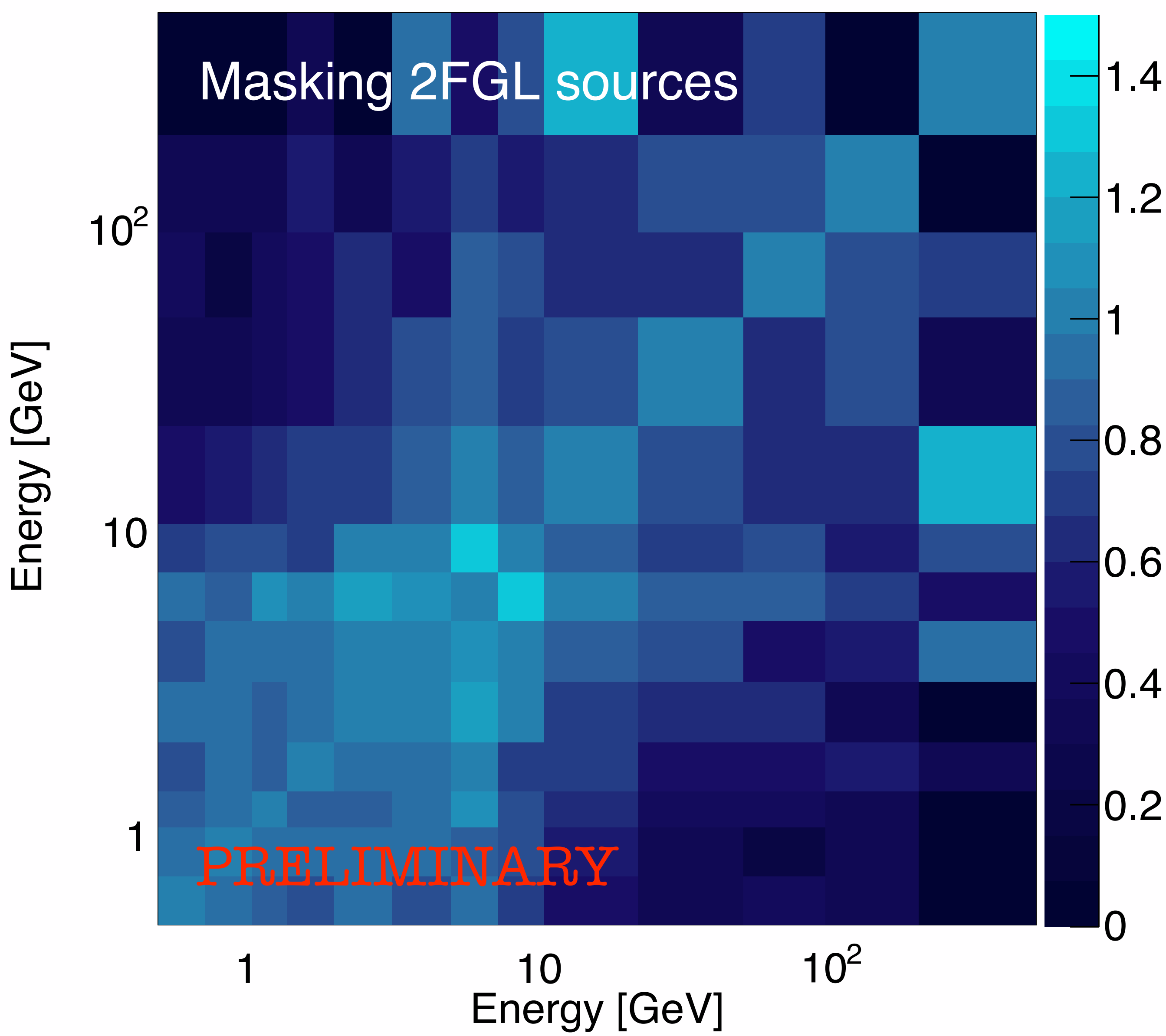
- multiple source classes:

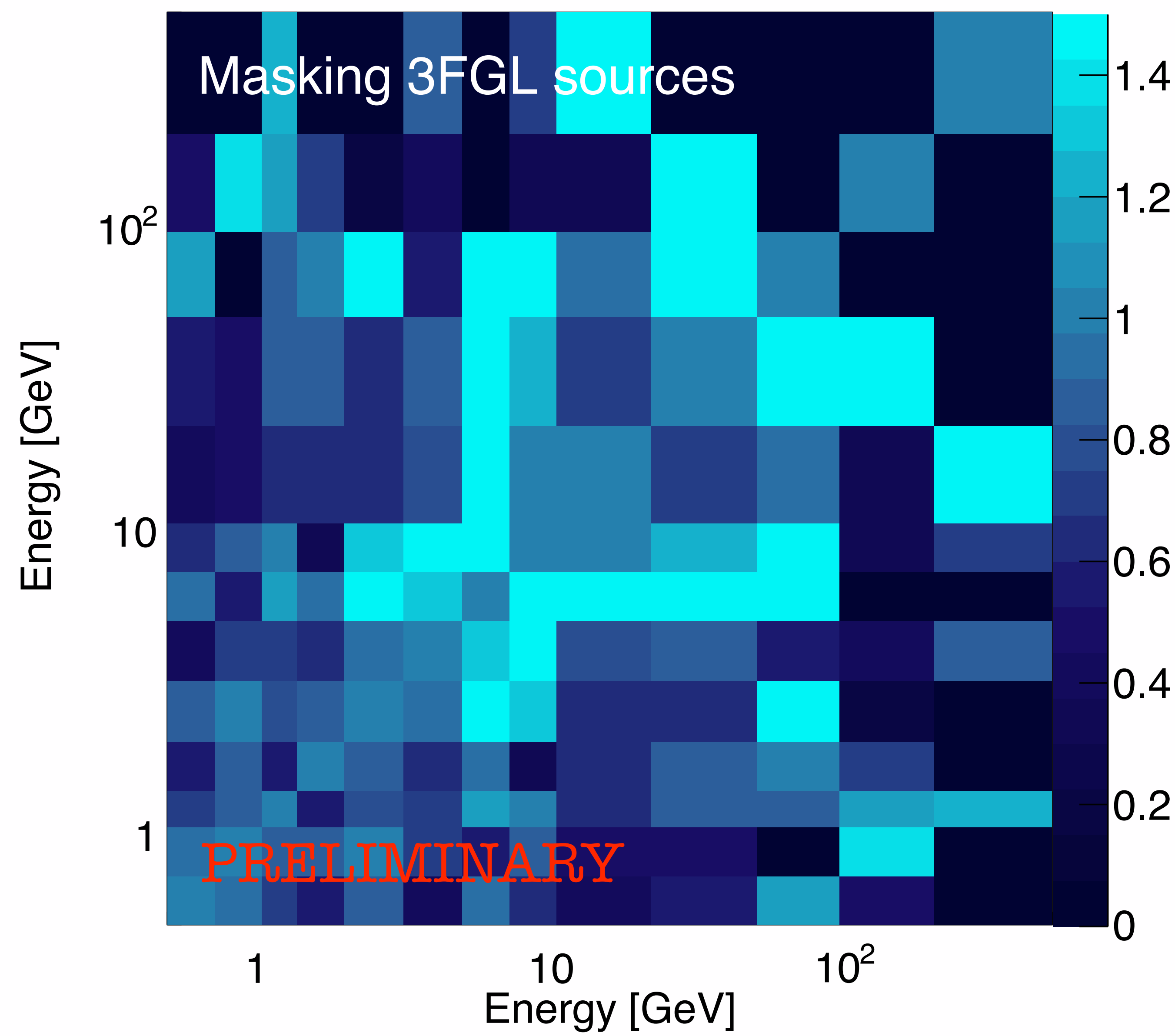
$$C_{\rm P}^{i,j} = \sum_\alpha C_{{\rm P},\alpha}^{i,j} = \sum_\alpha I(E_i) I(E_j) \tilde{C}_{{\rm P},\alpha}^{i,j}$$

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



Cross-correlation APS



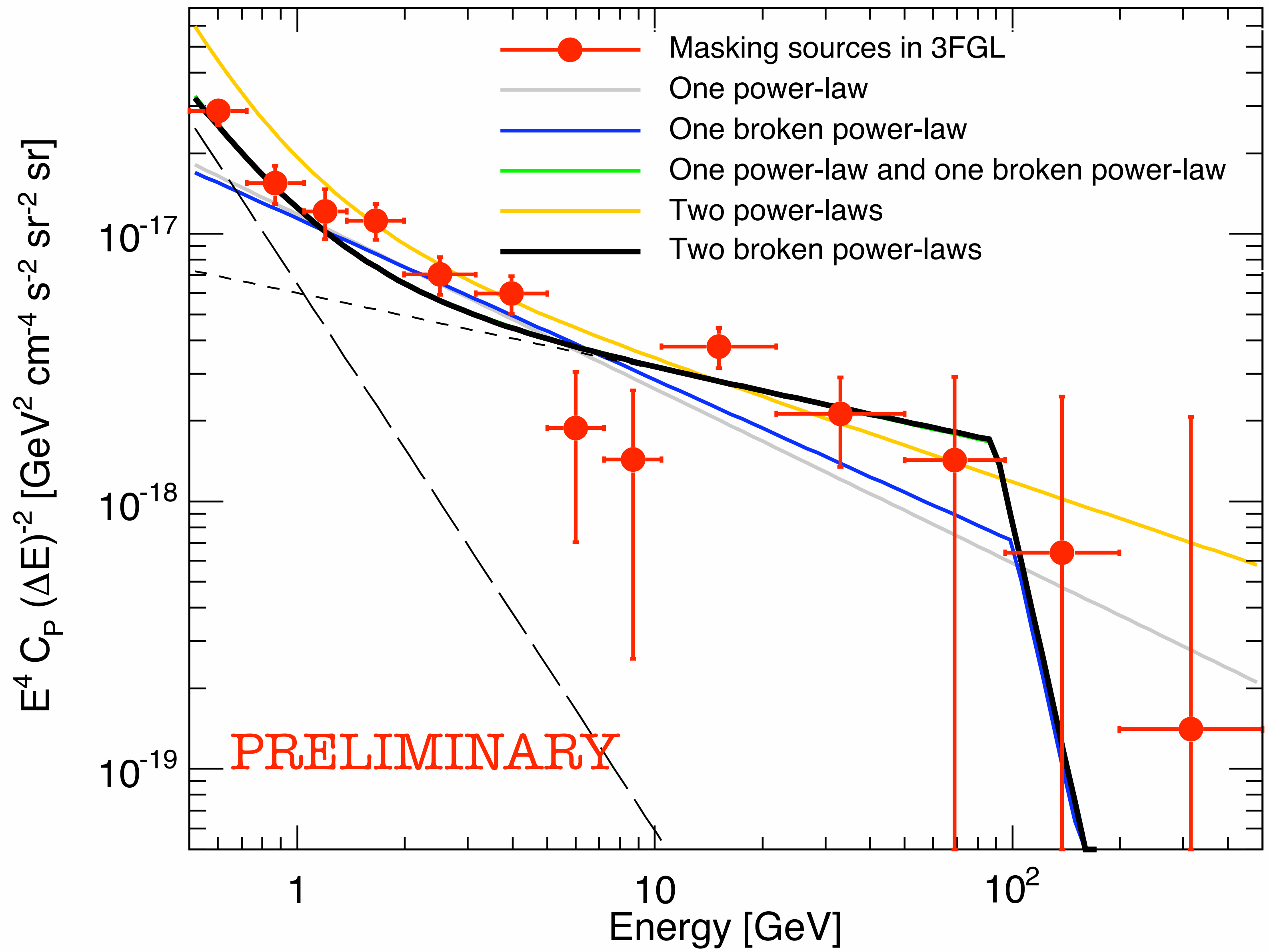


Interpretation in terms of multiple populations

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

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

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

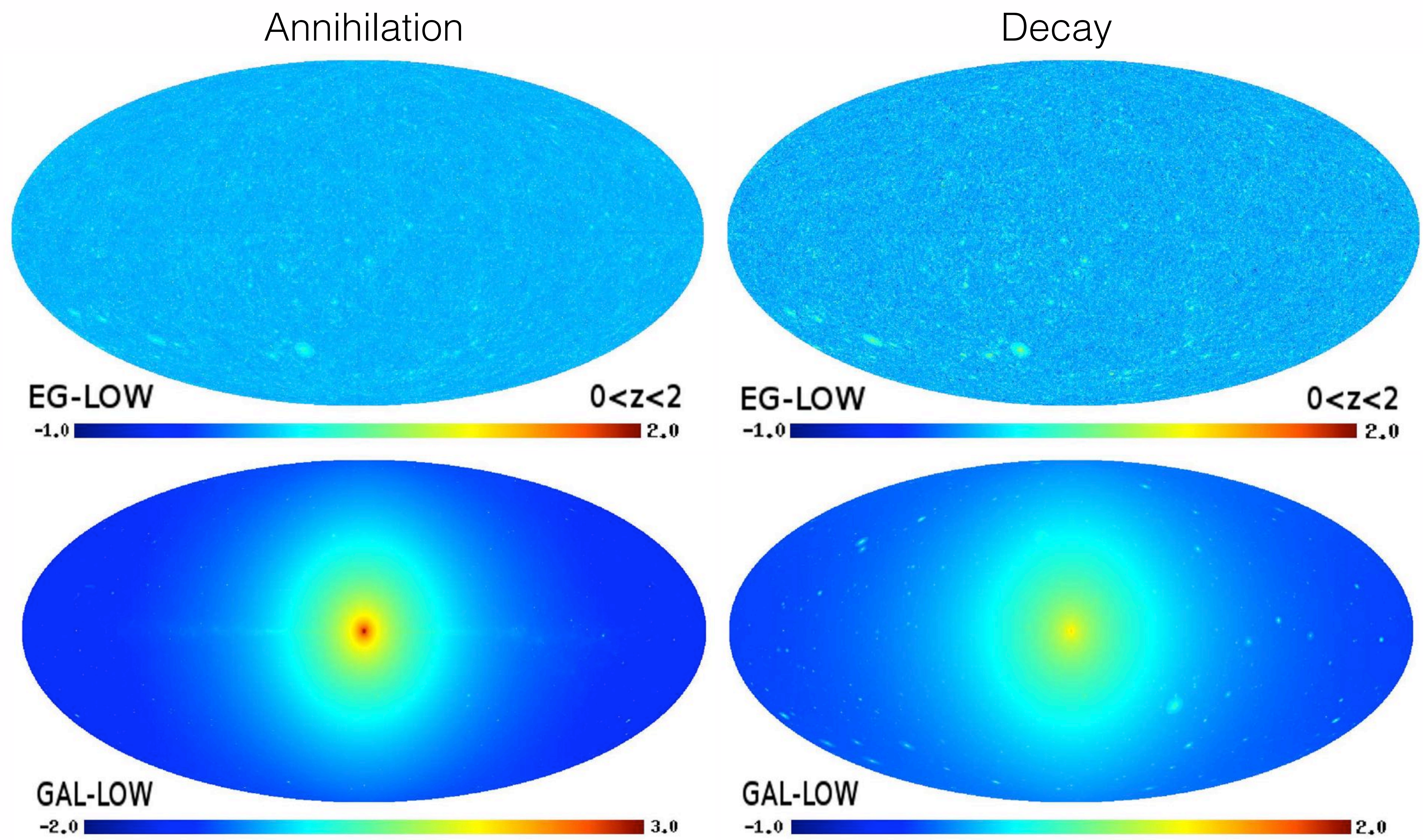


Best-fit model has two contributions both emitting as broken power laws:

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

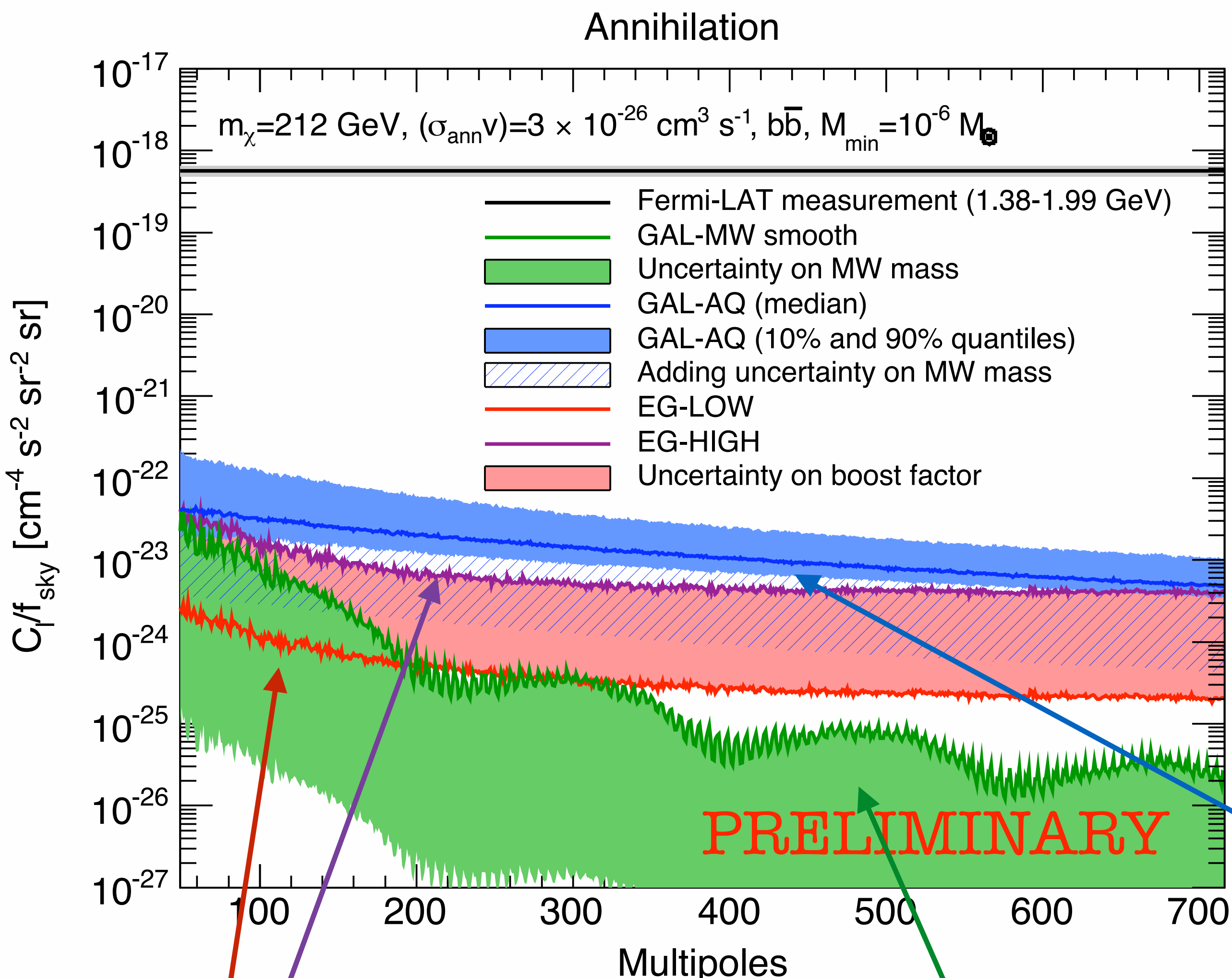
χ^2/dof = 1.21, p-value=0.16

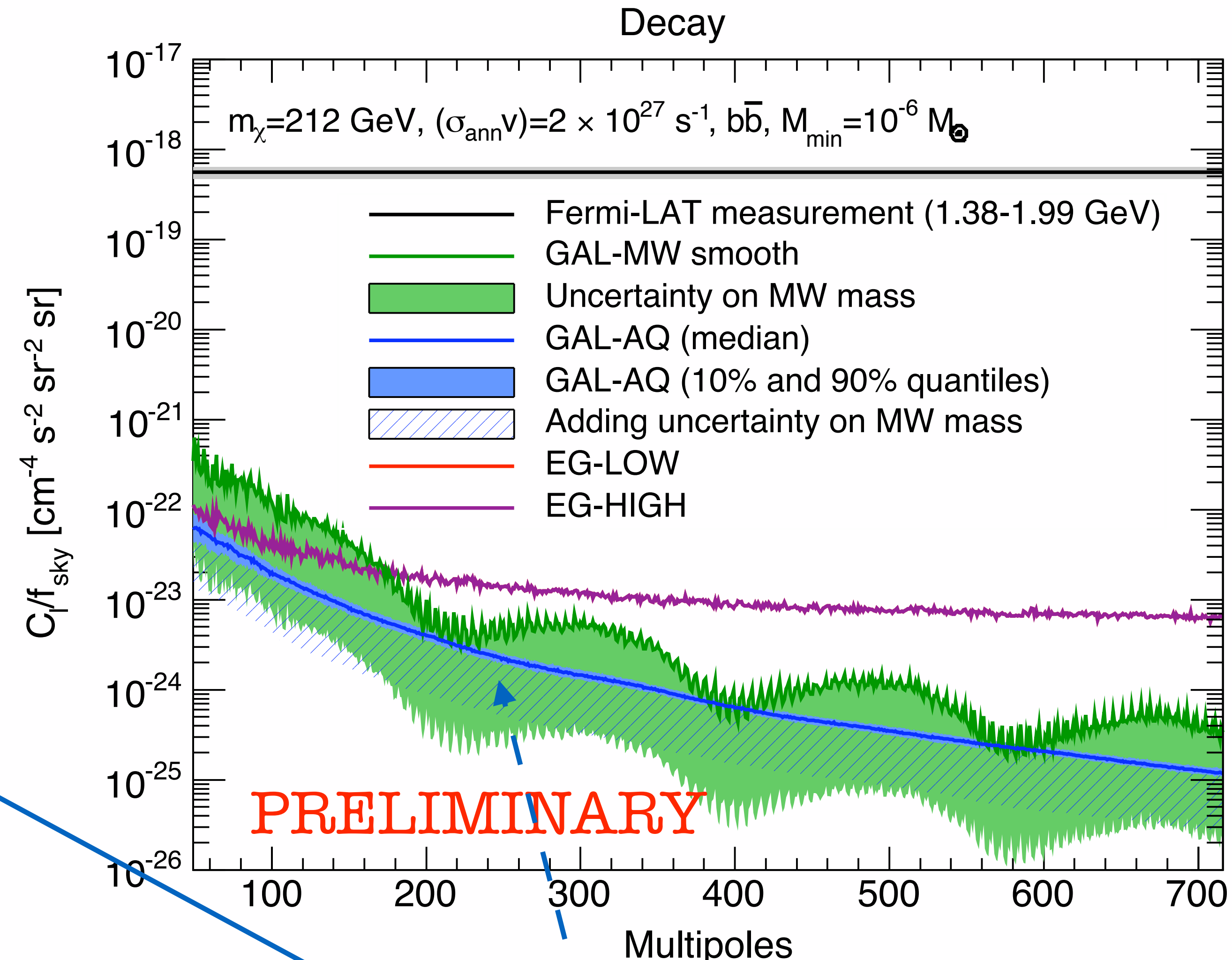
Gamma-ray anisotropies from Dark Matter



E=4 GeV, $M_{min}=10^{-6}$ $M_\odot$, b quarks
m_χ=200 GeV, $\sigma v=3\times10^{-26}\,cm^3s^{-1}$ (annihilation), m_χ=2 TeV, $\tau=2\times10^{27}$ s (decay)

DM-induced APS





Extragalactic component
with different subhalo boost factors

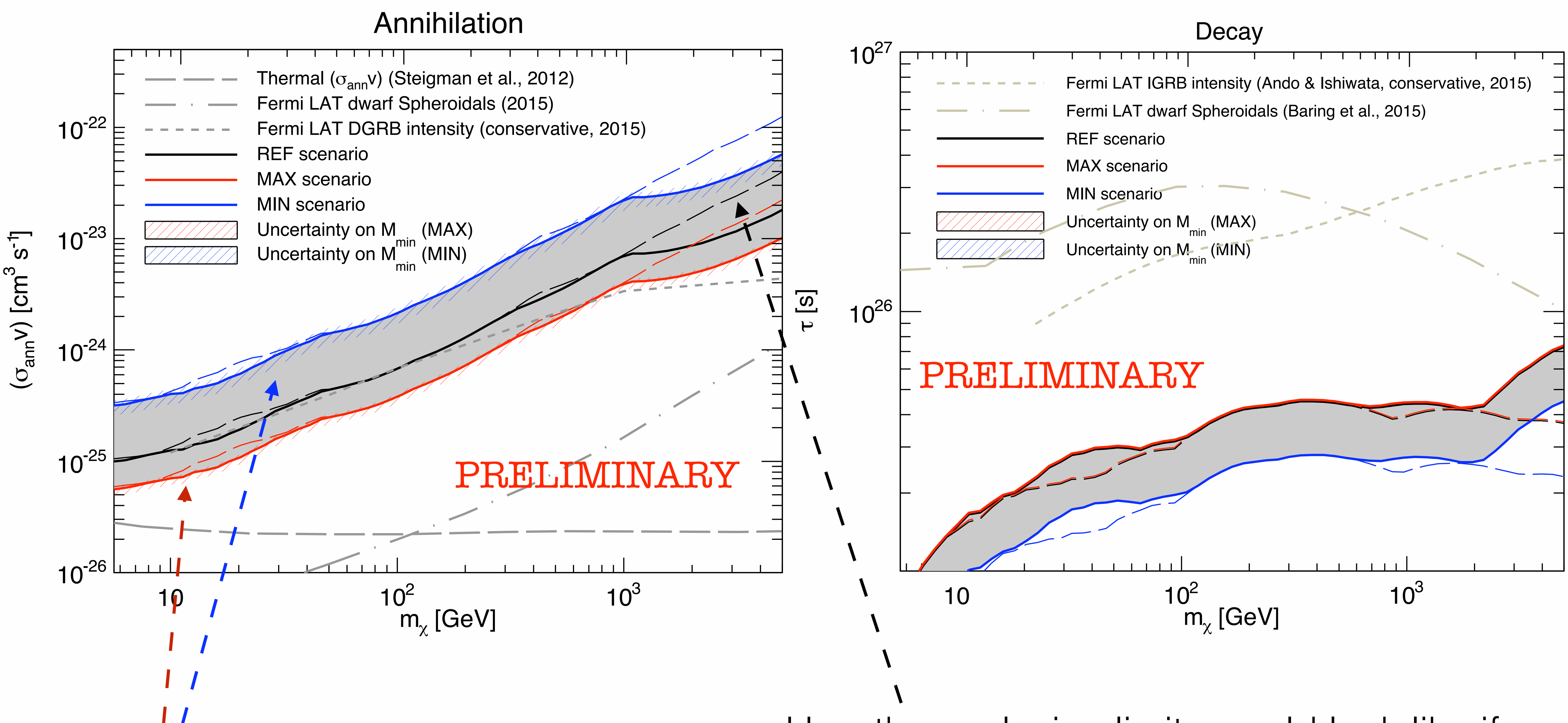
Subhalos of the Milky Way with
uncertainty on the position of the Earth

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

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



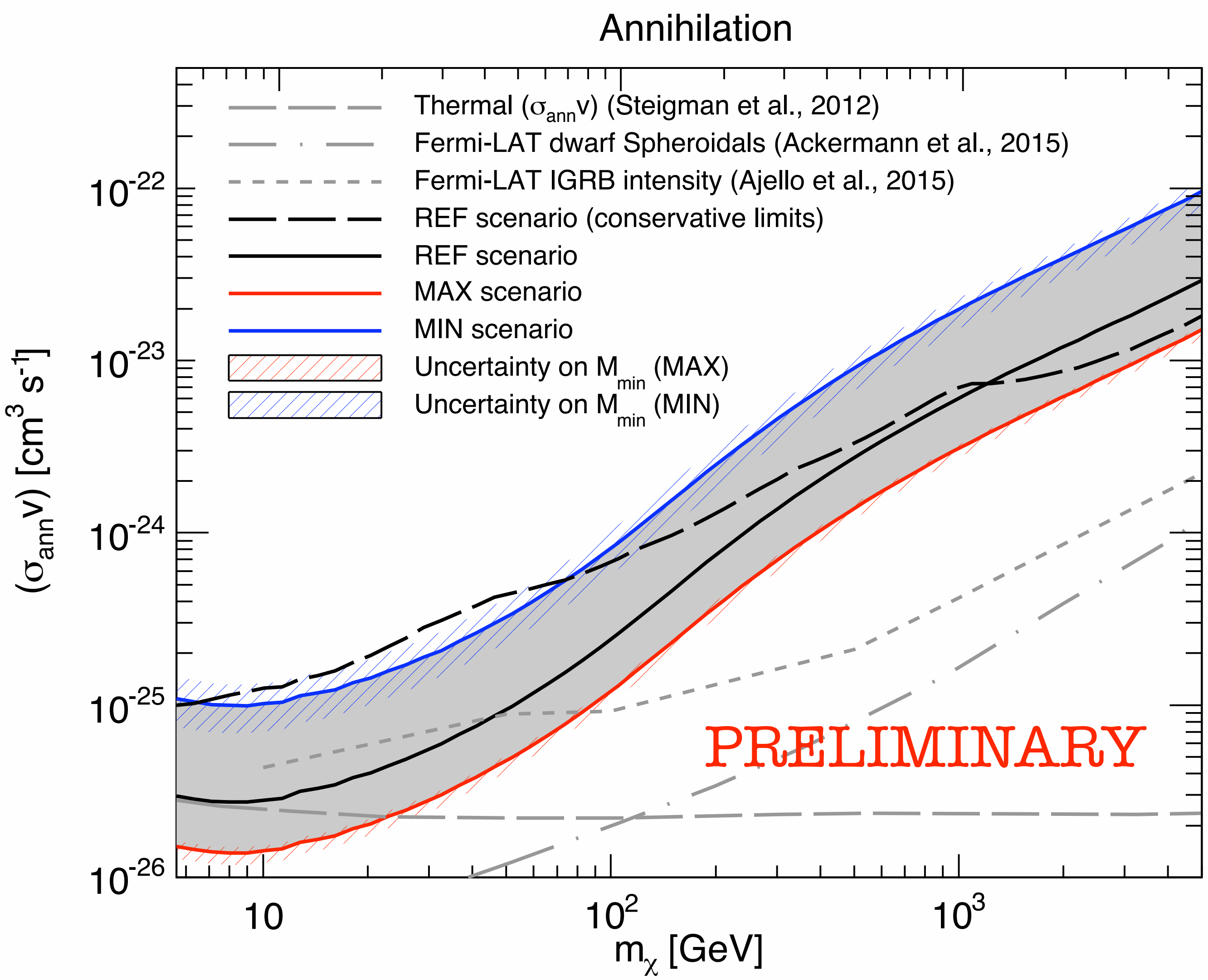
Uncertainty on the value of M_{min}

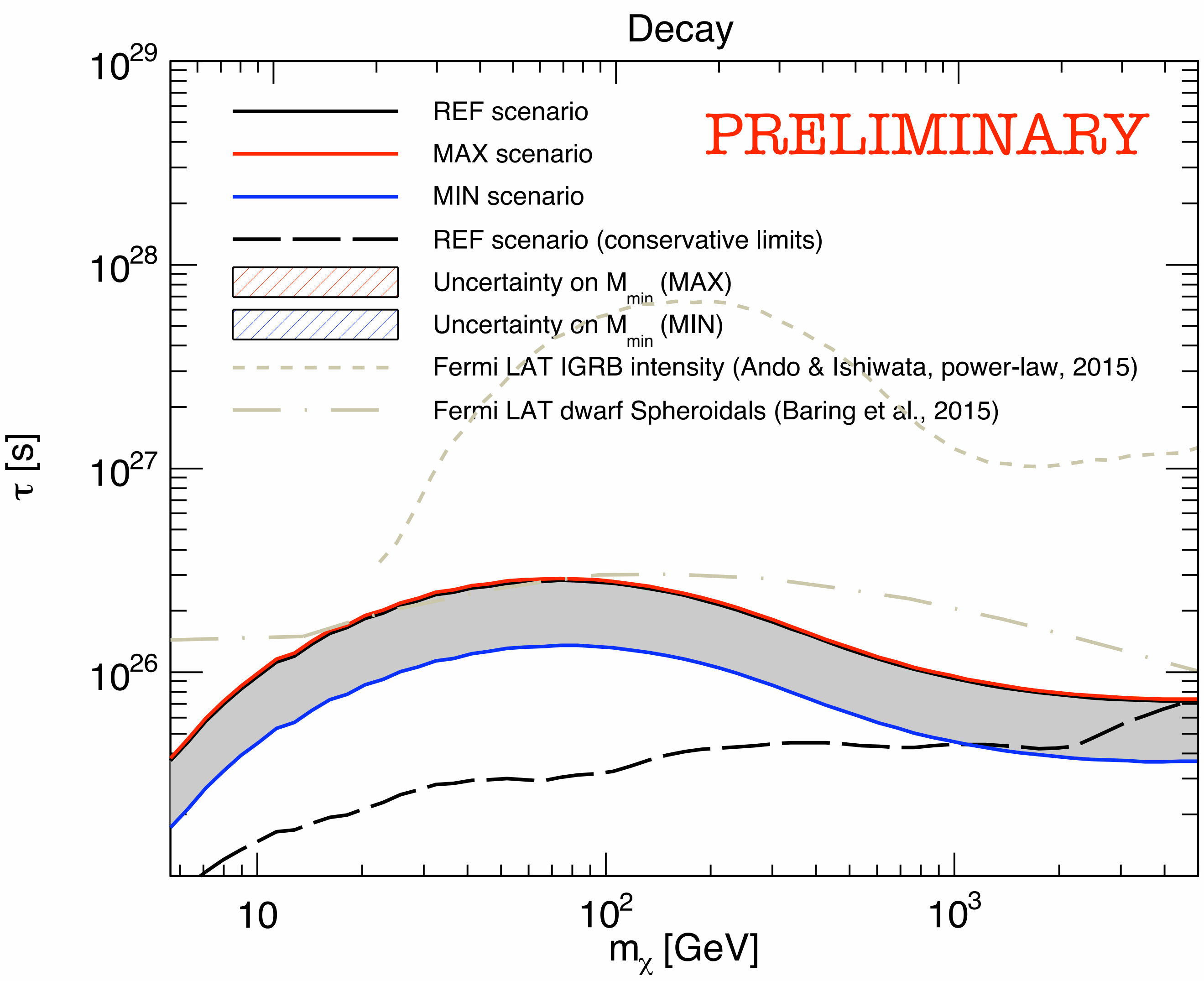
How the exclusion limits would look like if only the auto-correlation APS were used

2-component fit to the binned APS

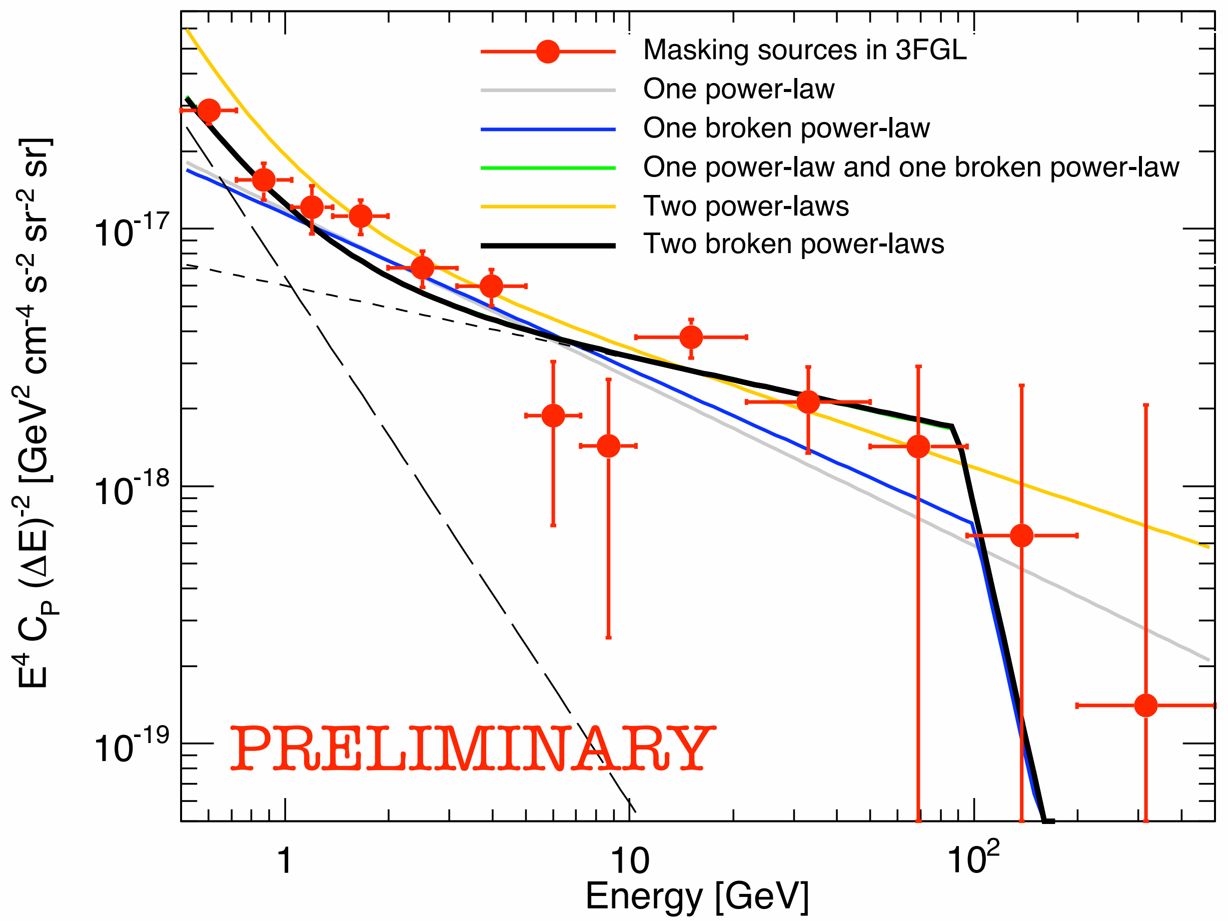
$$\chi^2 = -\sum_{i,j,\ell} \frac{[C_\ell^{i,j} - C_{\ell,\mathrm{DM}}^{i,j} - C_{\mathrm{P}}^{i,j}]^2}{\sigma^2_{C_\ell^{i,j}}}$$

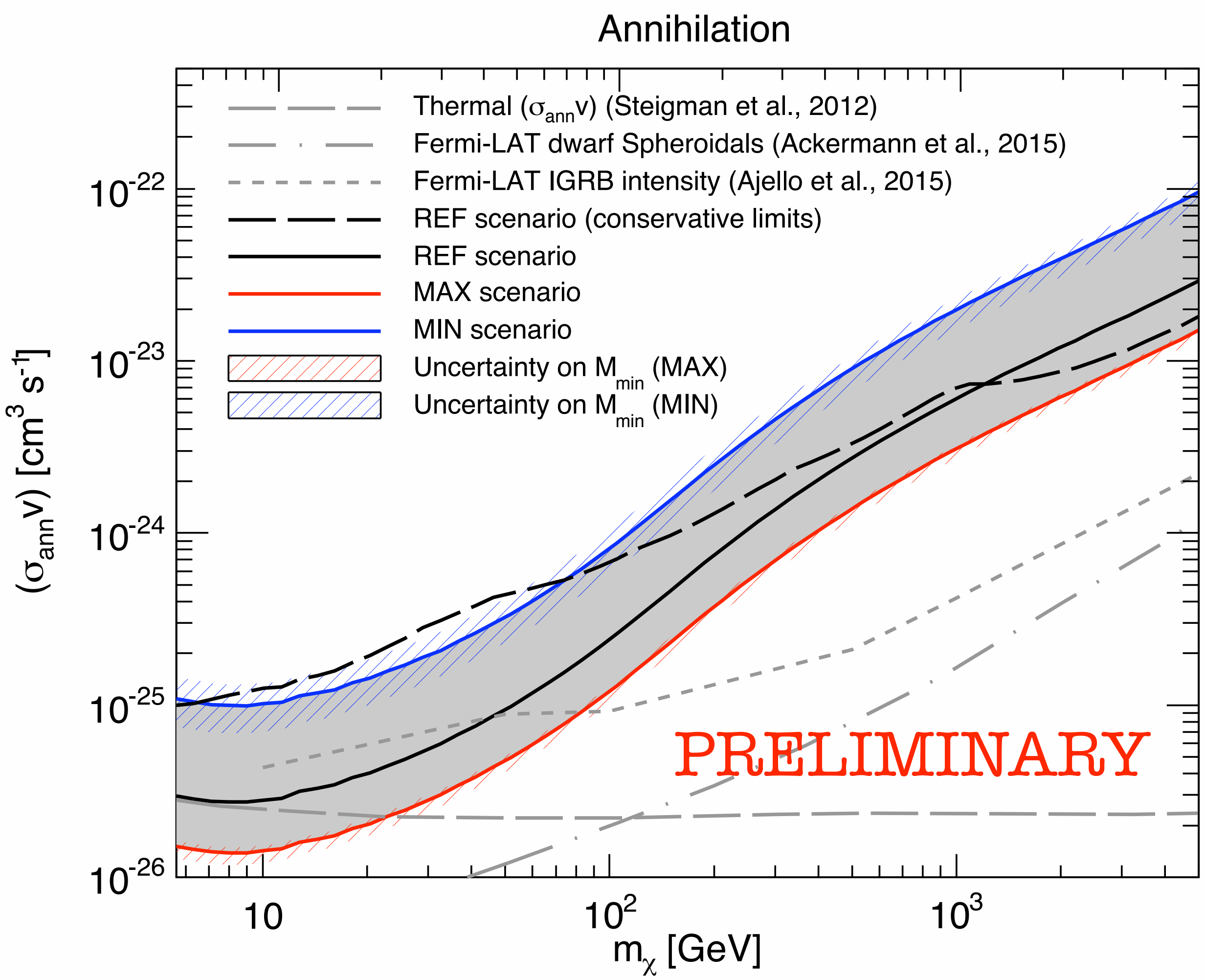
95% CL exclusion limit when Test Statistics $\Delta\chi^2=3.84$





- updated measurement of anisotropy angular power spectrum
- new features, single source population excluded at 95% CL
- impact on understanding of unresolved astrophysical sources
- limits on DM are competitive with those coming from the overall intensity





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

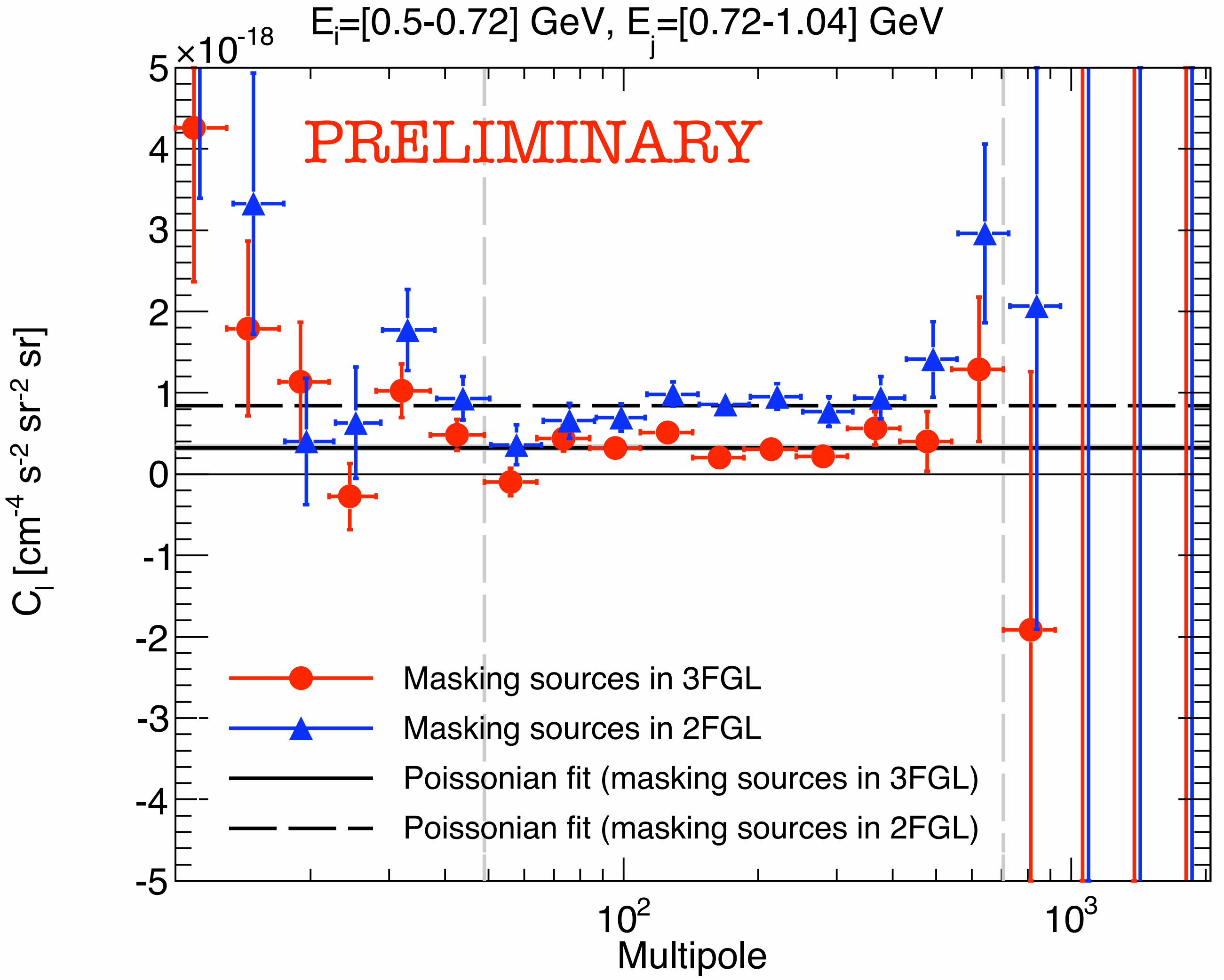
$$\sigma_\ell = \sqrt{2/(2\ell+1)}\left(C_\ell + \frac{C_\mathrm{N}}{W_\ell^2}\right)$$

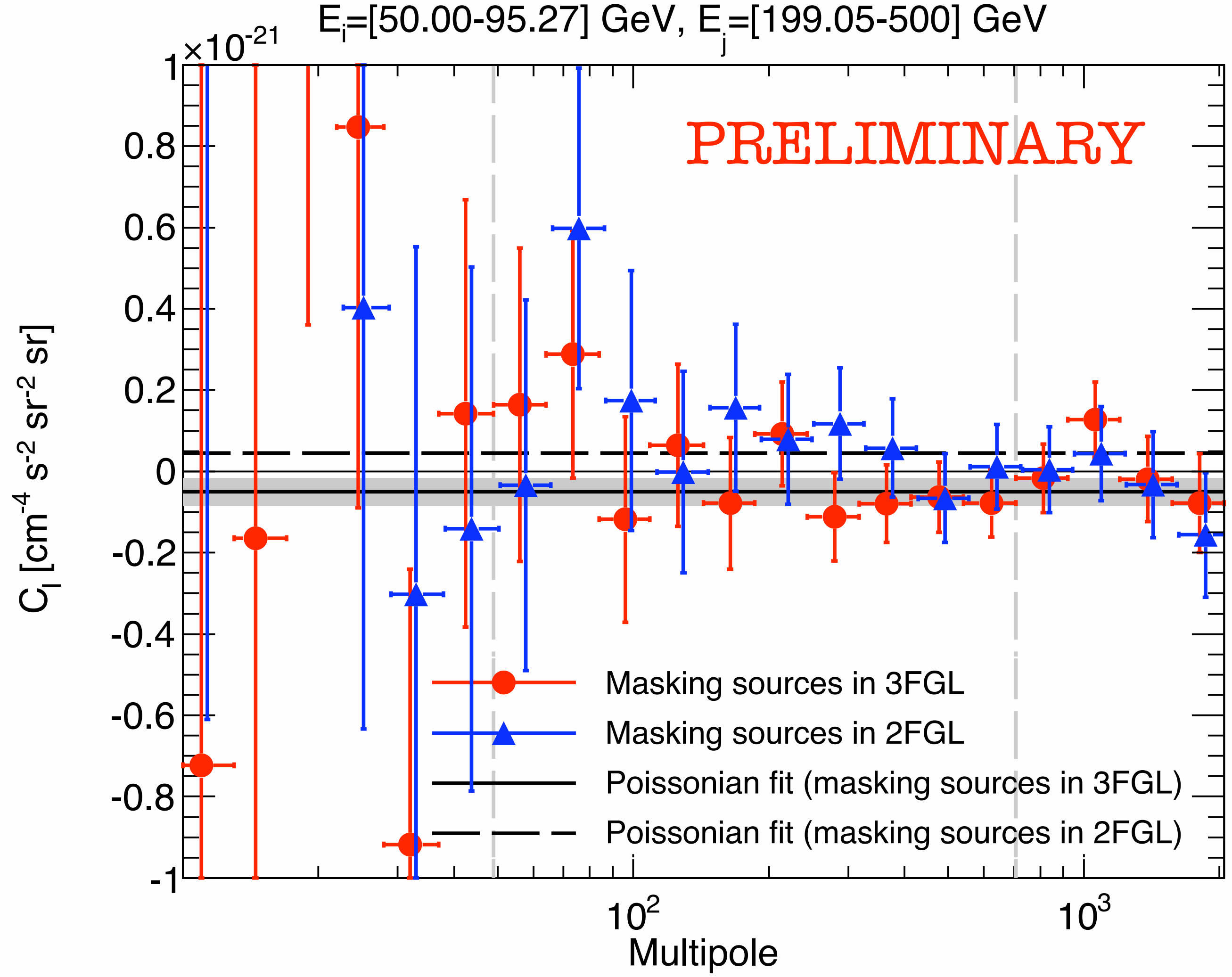
- method B: average of the variances and covariances computed by PolSpice

- the two methods agree

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

Cross-correlation

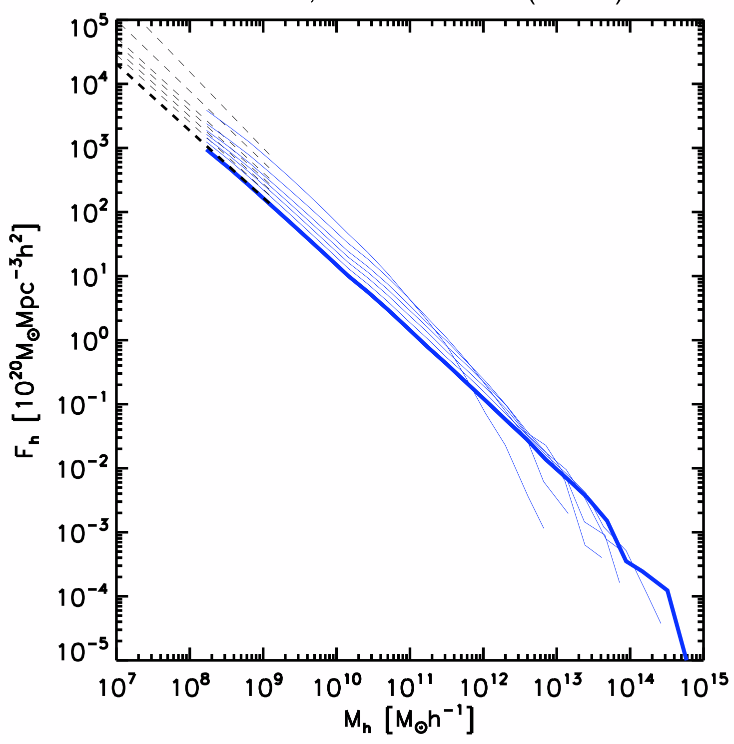




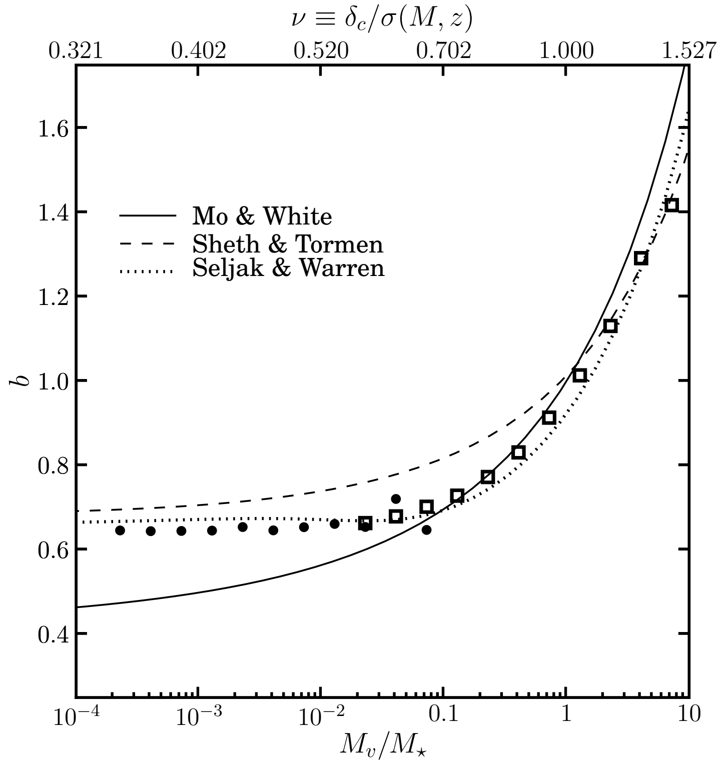
DM-induced emission

- 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)

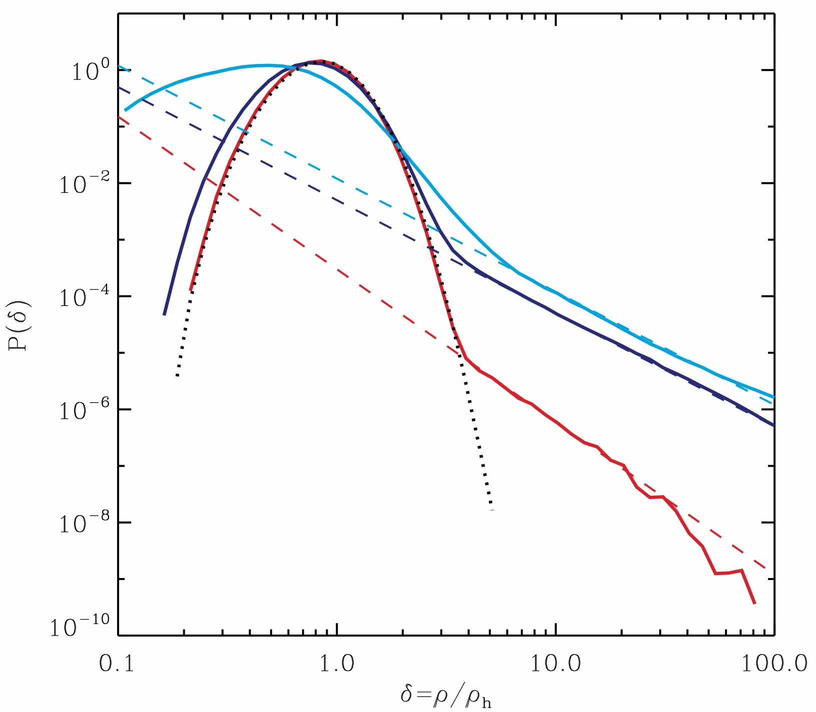
Zavala et al., MNRAS 405 (2010) 593



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

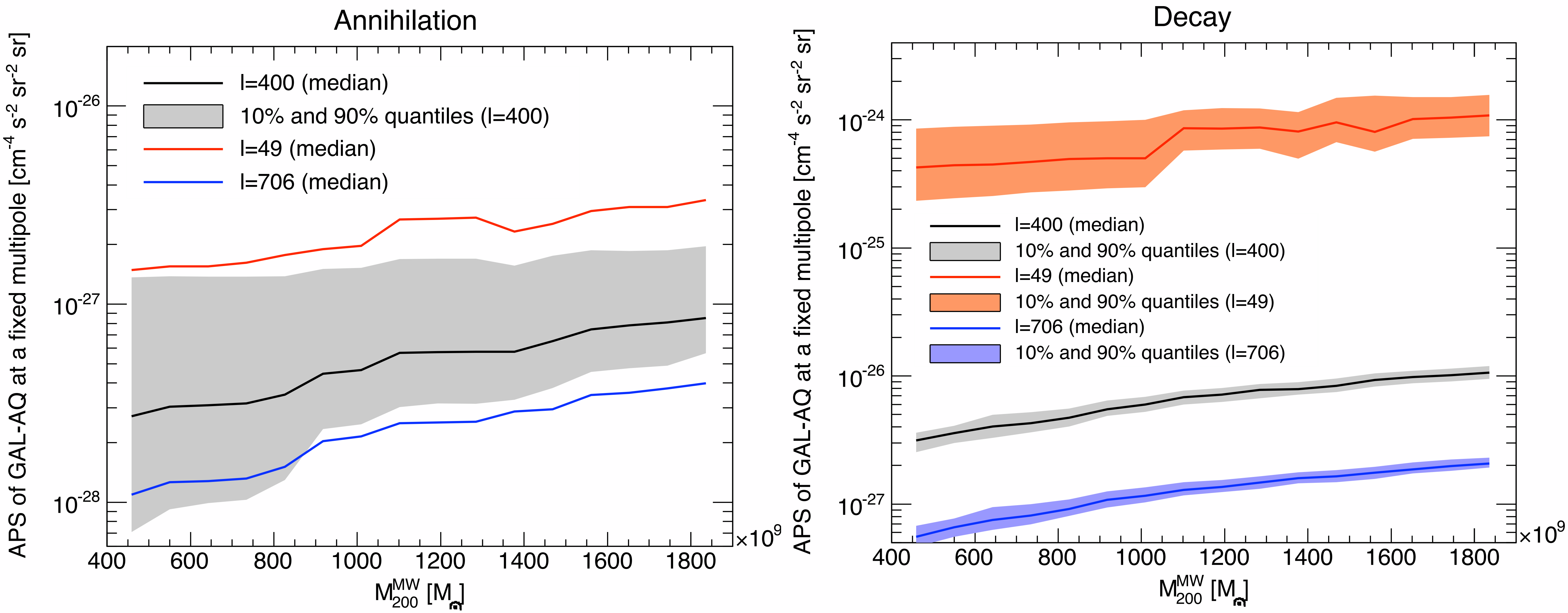


Kamionkowski et al., Phys. ReV. D81 (2010) 043532



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

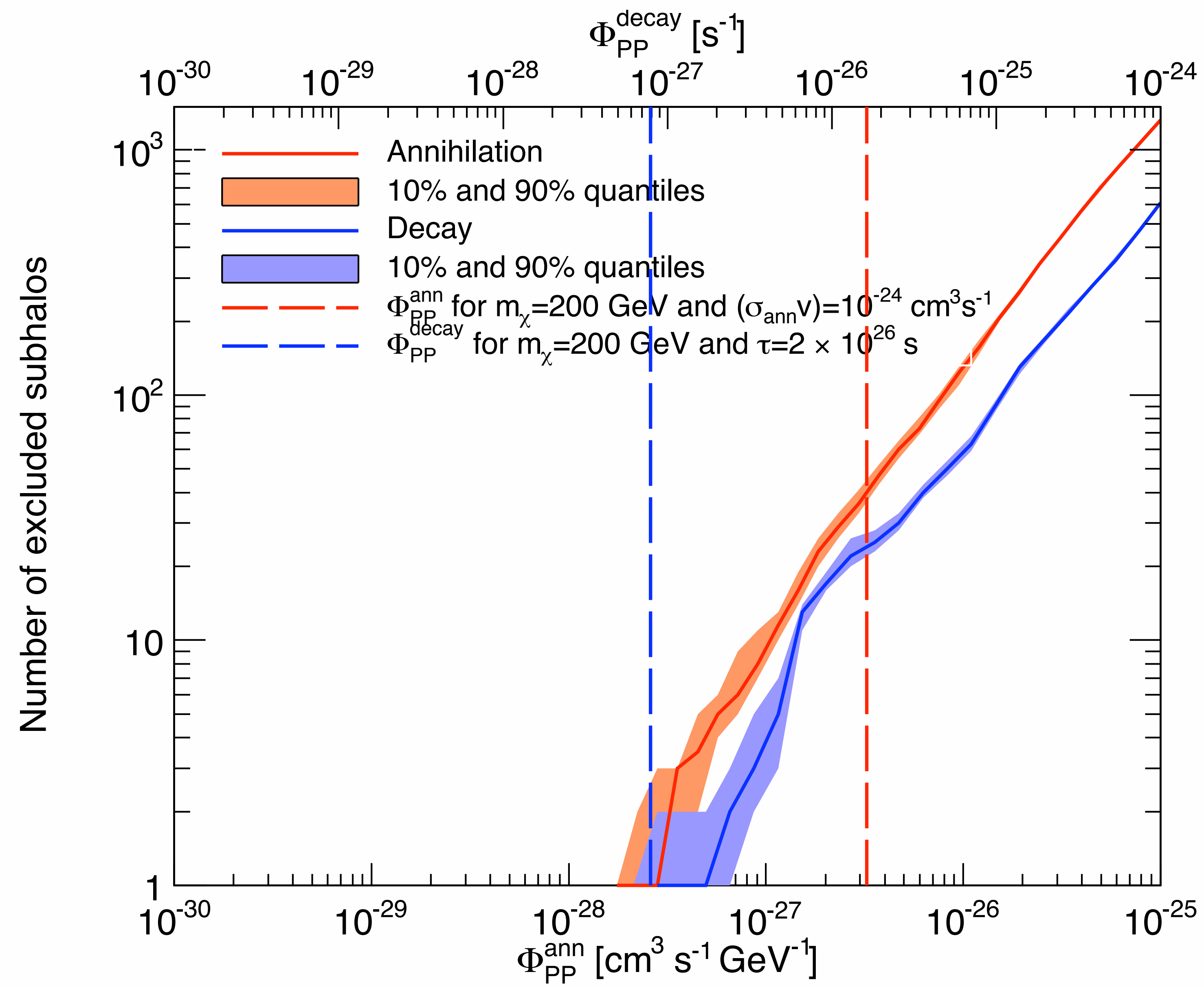


Effect of an too-bright subhalos on GAL-AQ

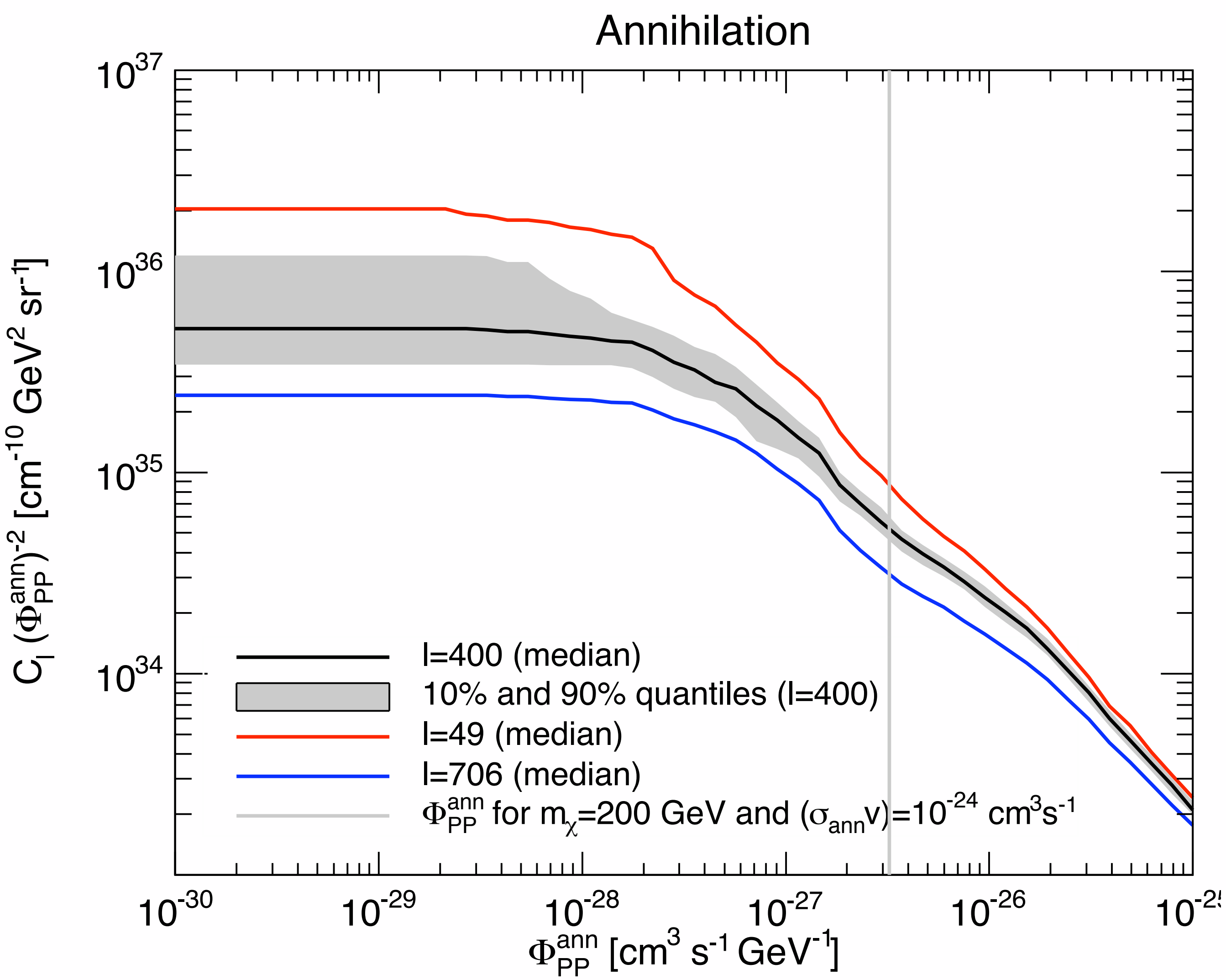
- for certain combination of (m_χ, $\sigma_{ann}v$) and (m_χ, τ), some subhalos are brighter than the 3FGL sensitivity
- those structures should be masked

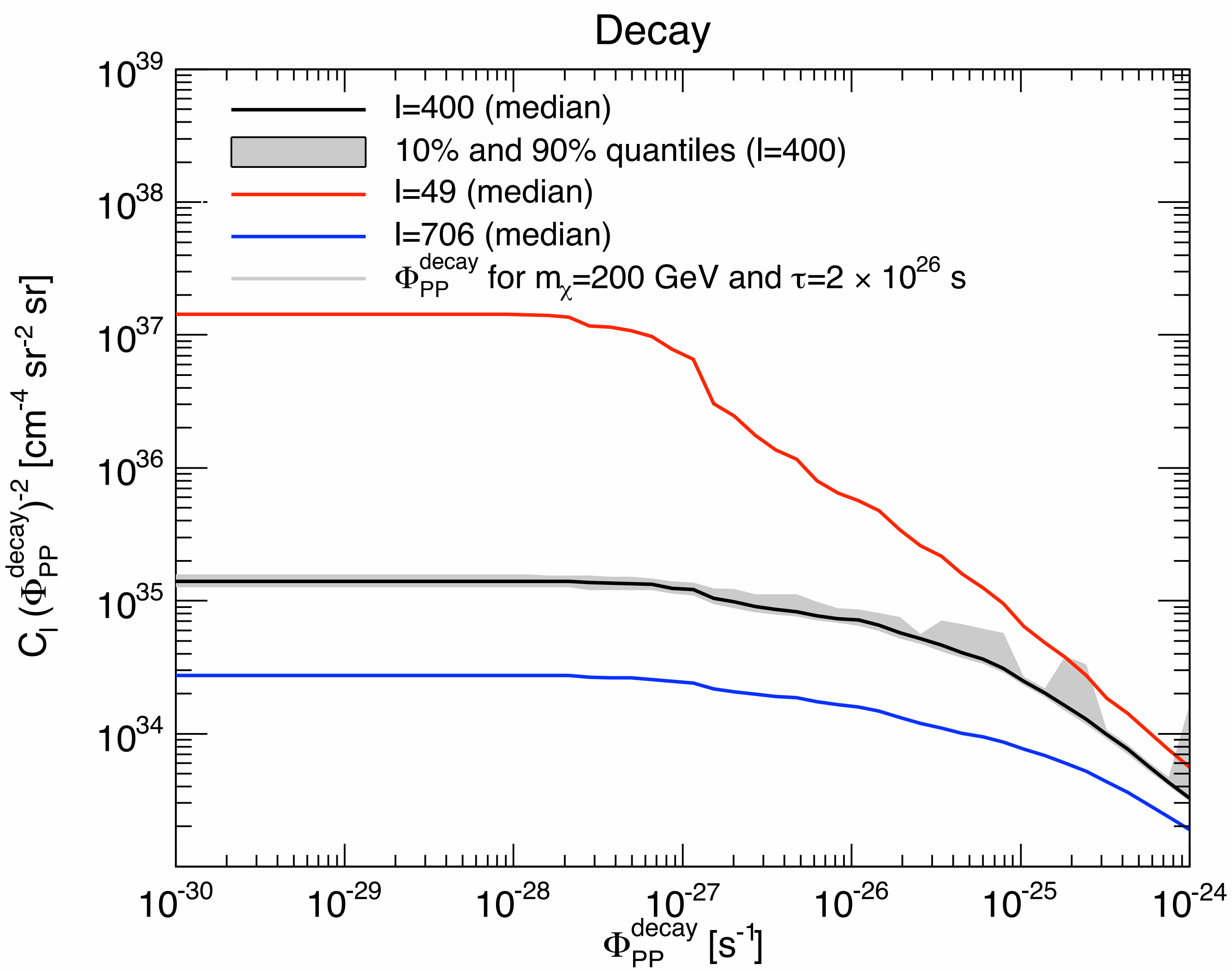
$$\Phi_{\rm PP}^{\rm ann} = \frac{(\sigma_{\rm ann}v)}{2m_\chi^2}\int_{\bar{E}} E\frac{dN_\gamma^{\rm ann}}{dE}dE$$

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

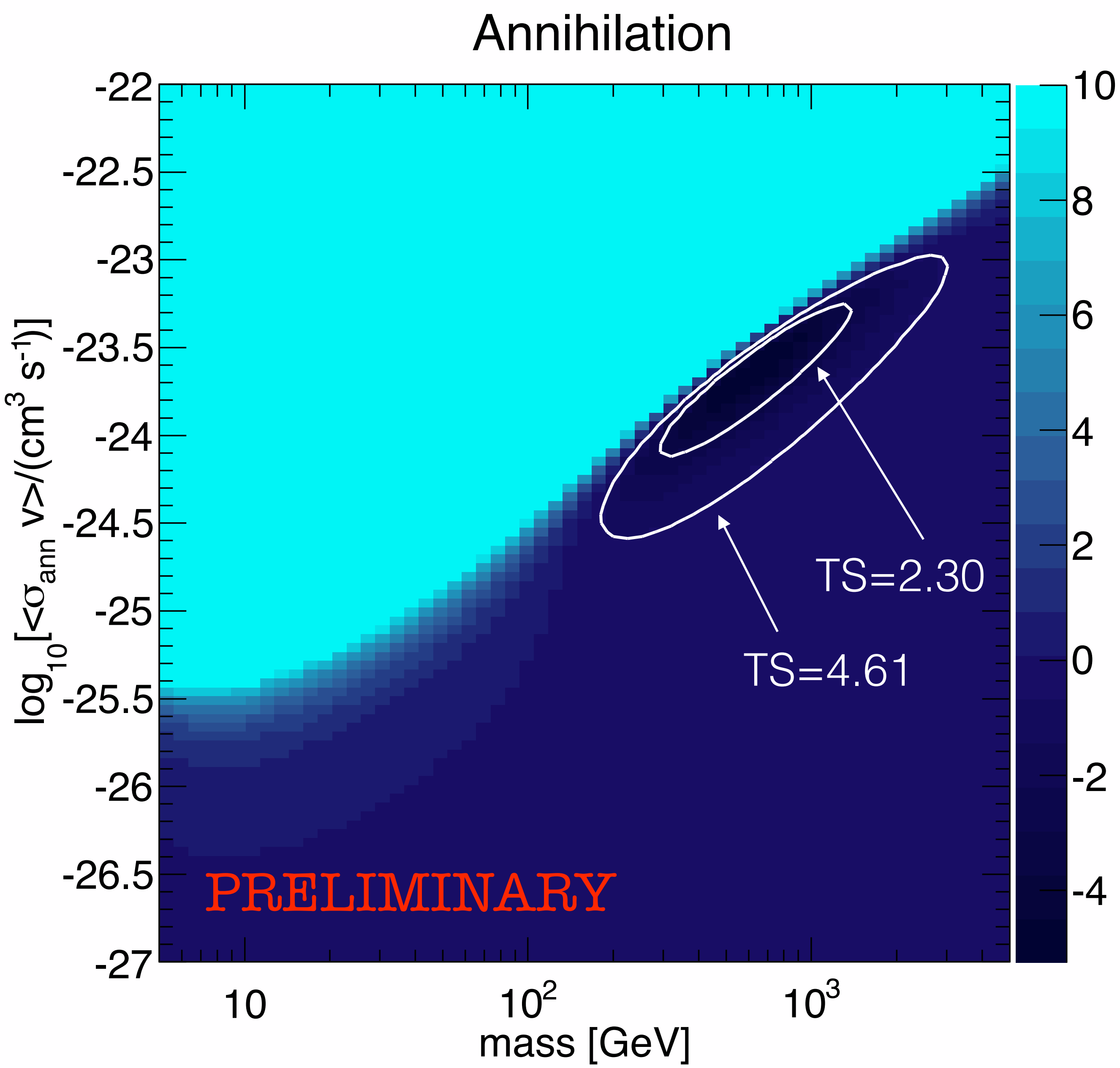


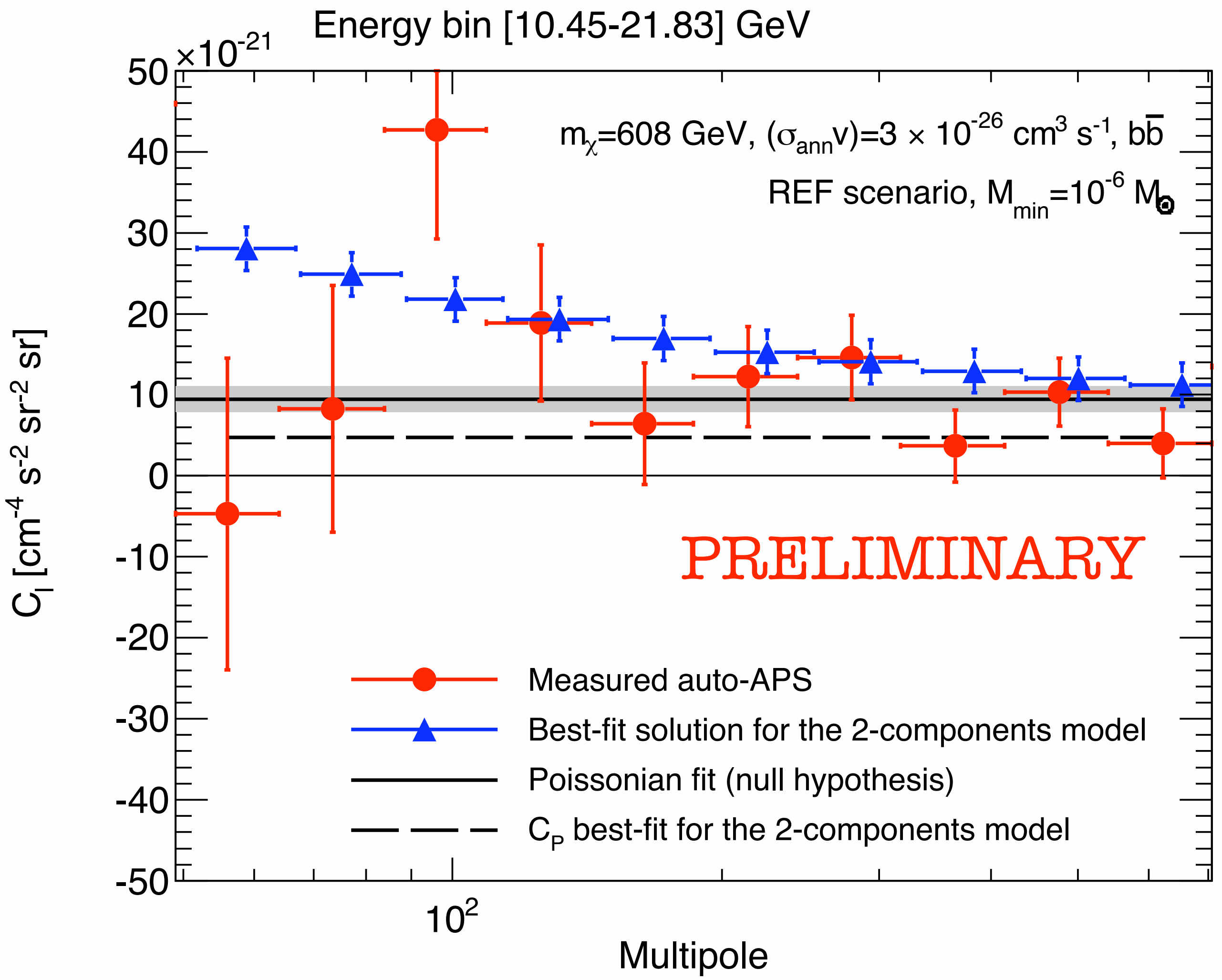
Effect of an too-bright subhalos on GAL-AQ





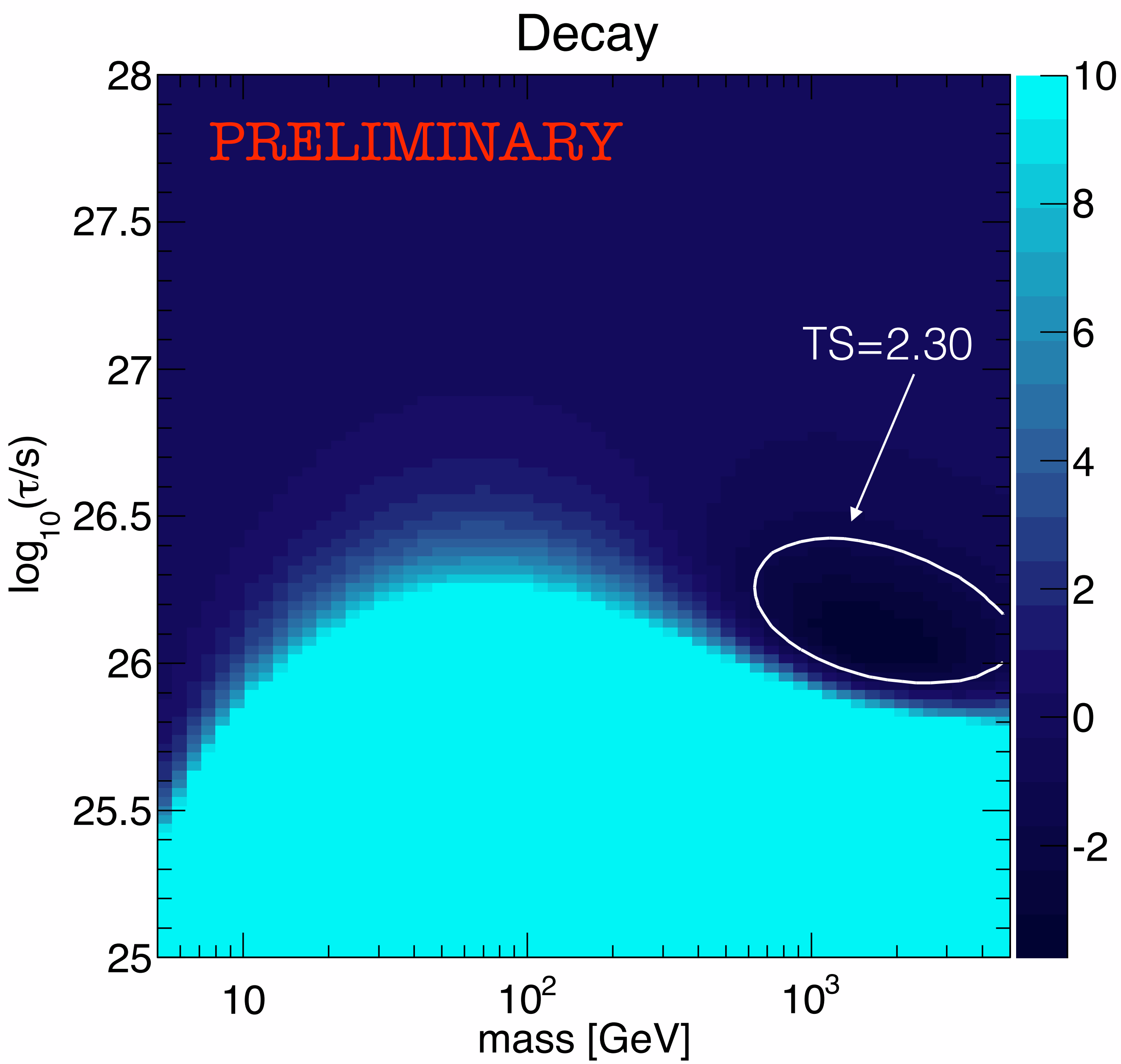
2-component fit to the binned APS





- TS = -2 ln[χ^2(no DM)] + 2 ln[χ^2(m_χ,σv)]
- best-fit solution has TS=-4.5, m_χ=607 GeV, (σ_{ann}v)=2.2×10^{-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