

# New measurement of the anisotropy angular power spectrum in the Fermi-LAT gamma-ray diffuse data [arXiv:1608.07289](https://arxiv.org/abs/1608.07289)

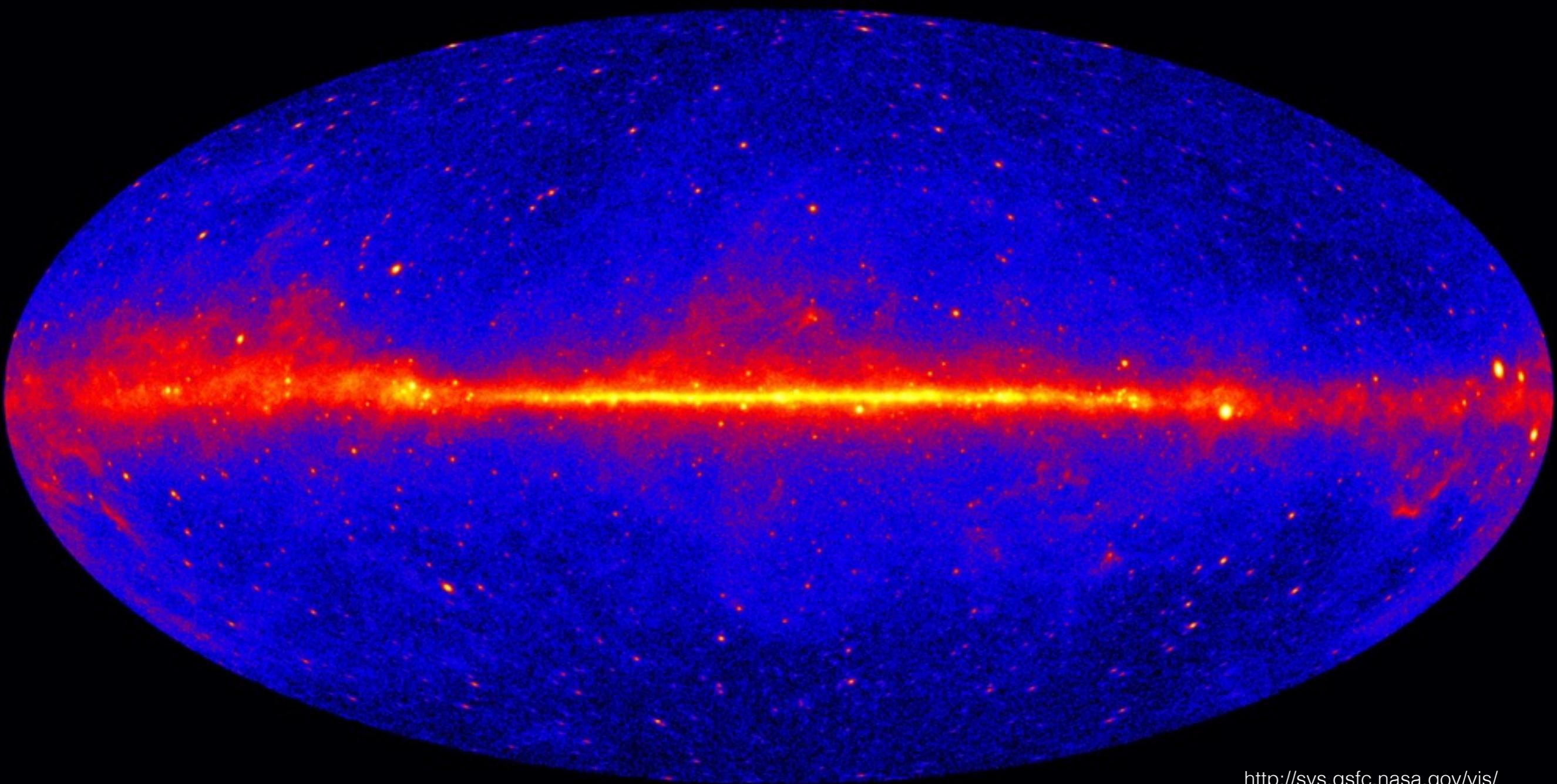
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G. Gomez-Vargas, E. Komatsu, T. Linden, F. Prada, F. Zandanel and A. Morselli

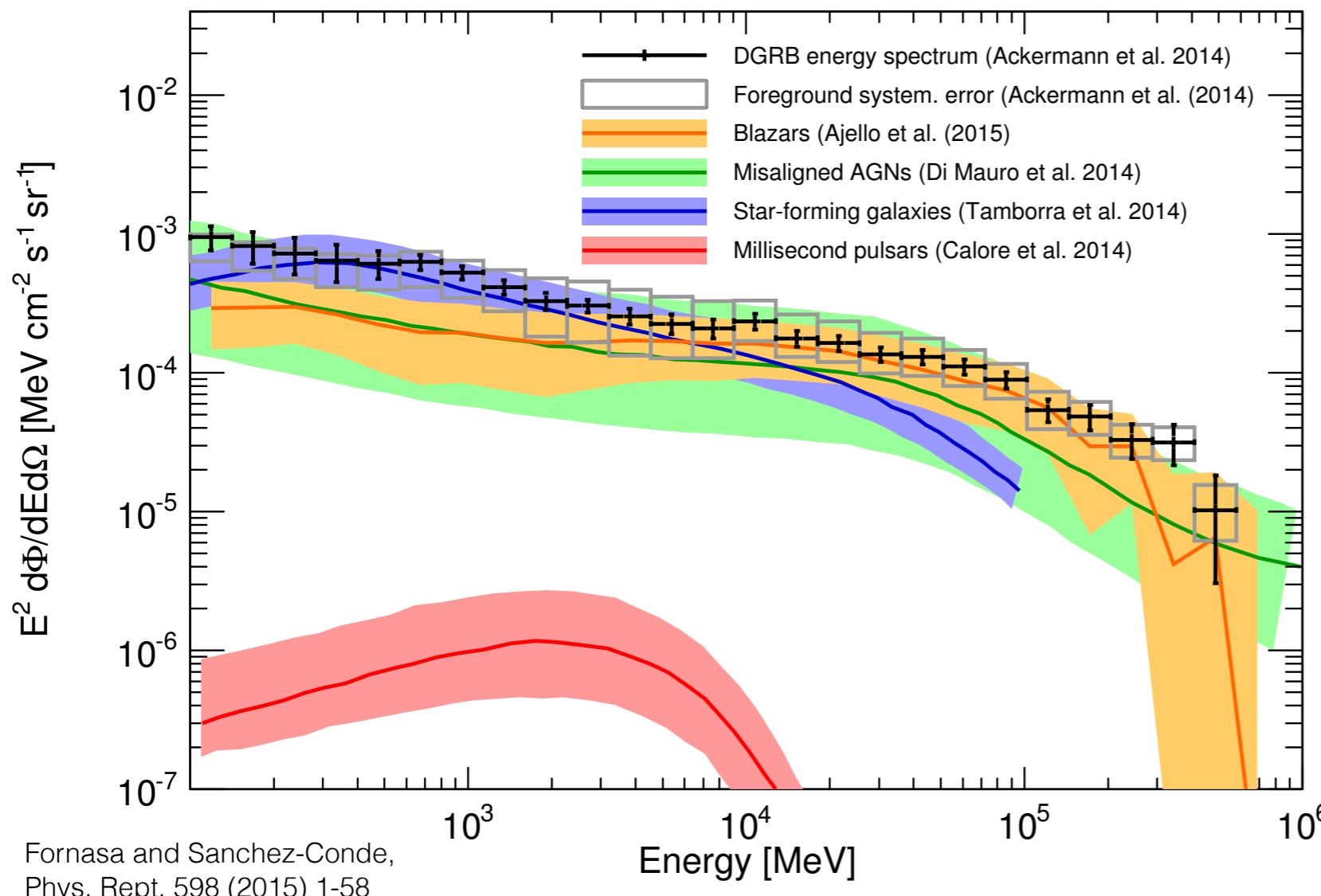


# The Isotropic Gamma-Ray Background (IGRB)



[http://svs.gsfc.nasa.gov/vis/  
a01000/a011300/a011342/](http://svs.gsfc.nasa.gov/vis/a01000/a011300/a011342/)

# Unresolved sources



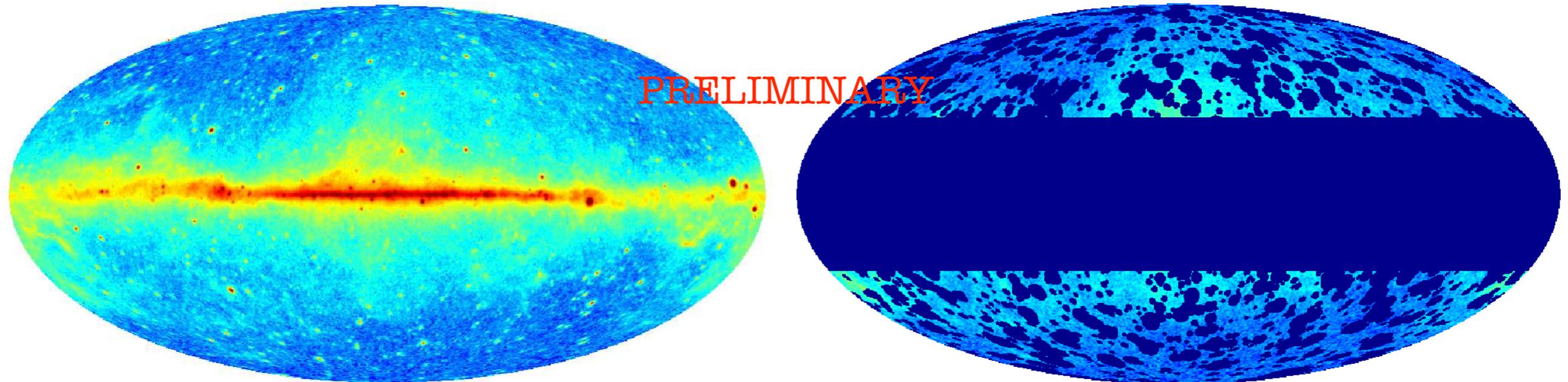
- residual emission after the subtraction of point sources
- cumulative emission of unresolved sources
- guaranteed components from unresolved blazars, star-forming galaxies, misaligned AGNs
- constraints on additional contributors (Dark Matter)

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

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

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

# New APS measurement



Ackermann et al. (2012)

22 months

Pass 6 (DIFFUSE\_v3) front and  
back

4 energy bins  
between 1 and 50 GeV

masking sources in 1FGL

Fornasa et al. (2016)

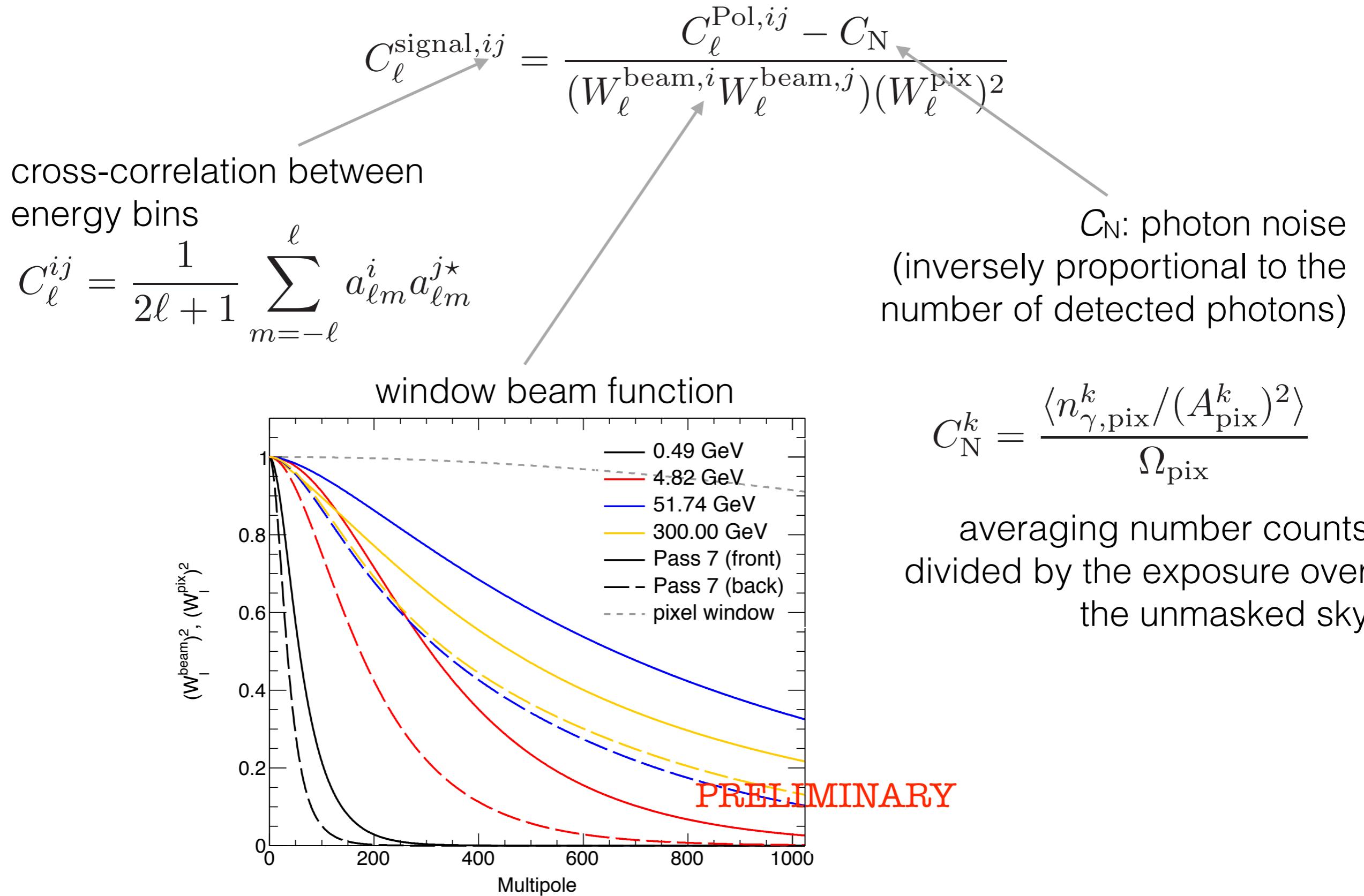
81 months

Pass 7 Reprocessed  
(ULTRACLEAN\_v15) front

13 energy bins  
between 0.5 and 500 GeV

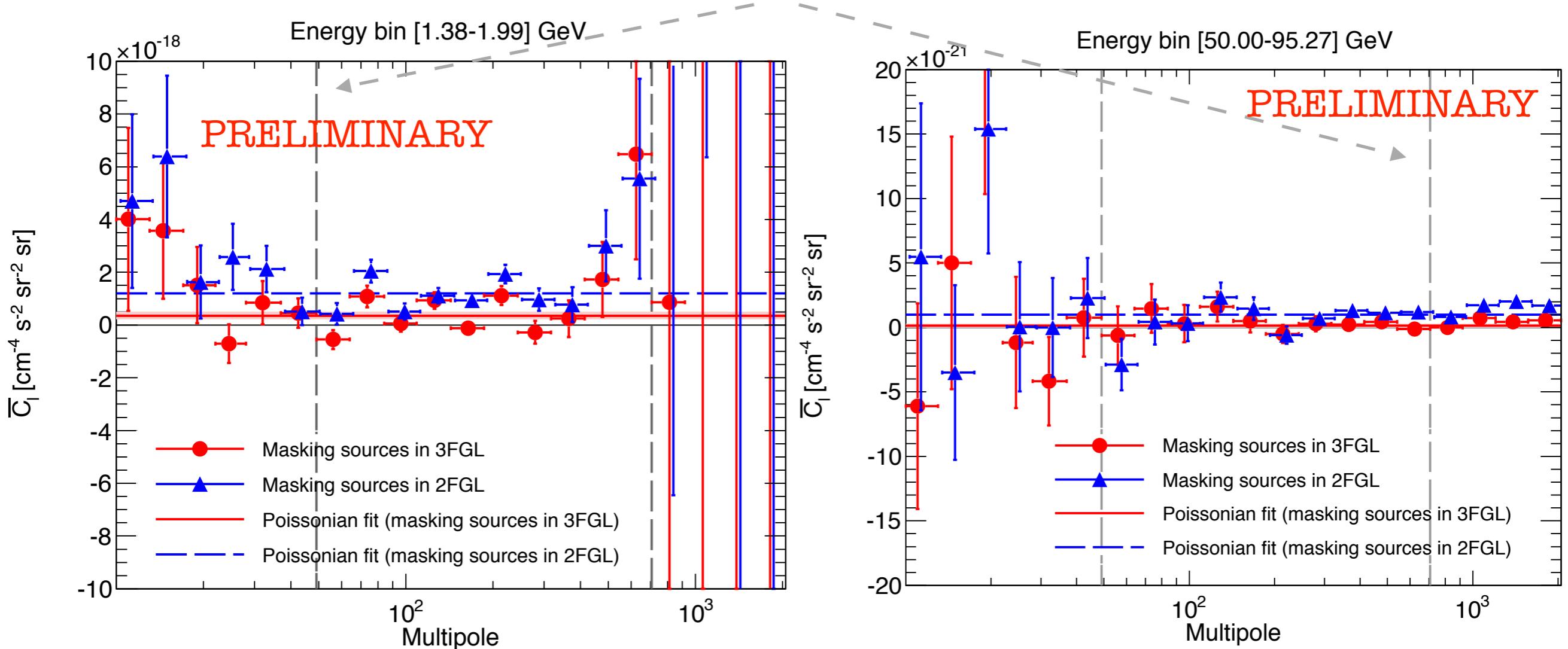
masking sources in 3FGL (separate  
data set masking sources in 2FGL)

# APS estimator



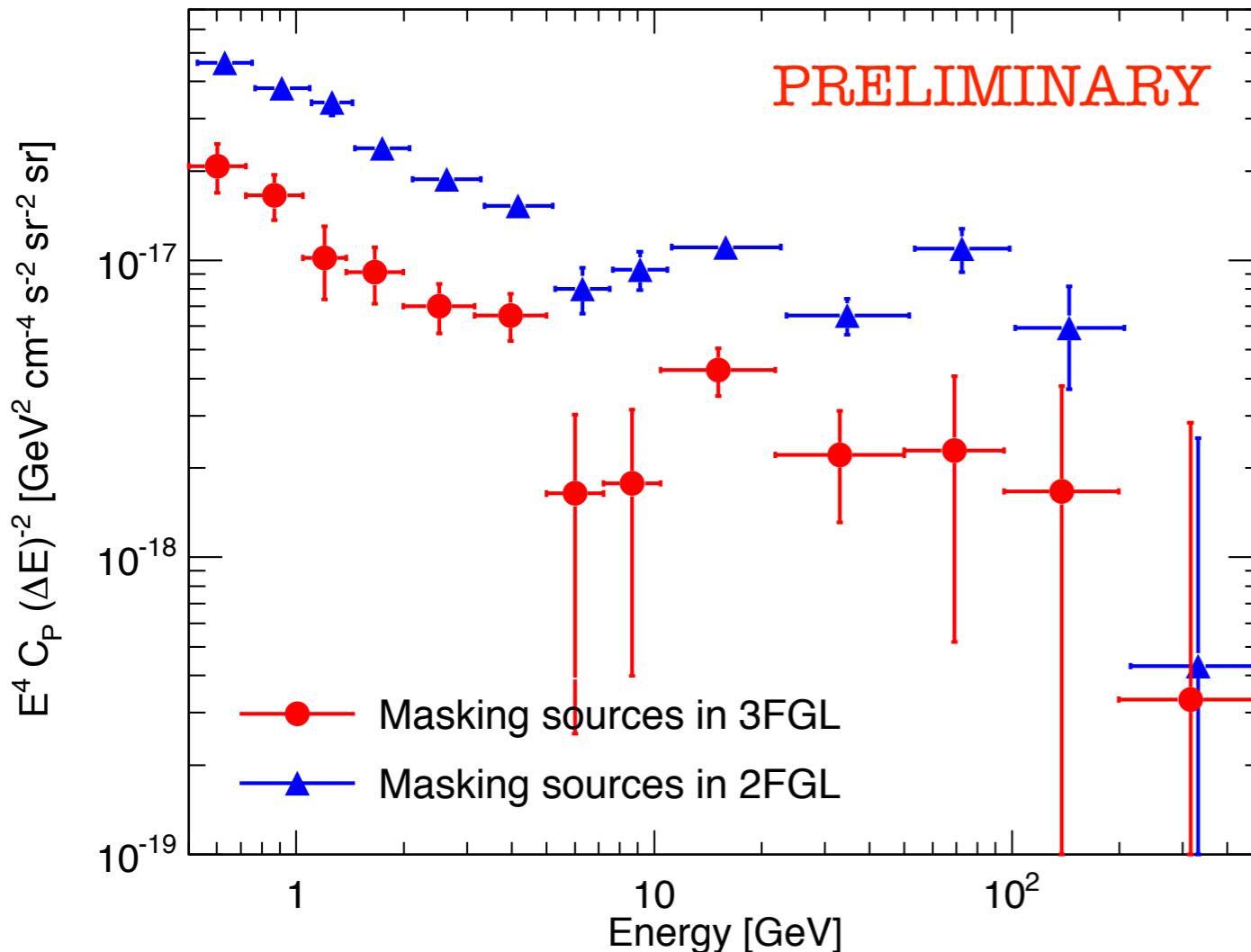
# Binned APS measurement

signal region between  $\ell=49$  and 706



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

$$C_P^{i,j} = I(E_i) I(E_j) \tilde{C}_P$$

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

$$C_P^{i,j} = I_A(E_i) I_A(E_j) \tilde{C}_{P,A} + I_B(E_i) I_B(E_j) \tilde{C}_{P,B}$$

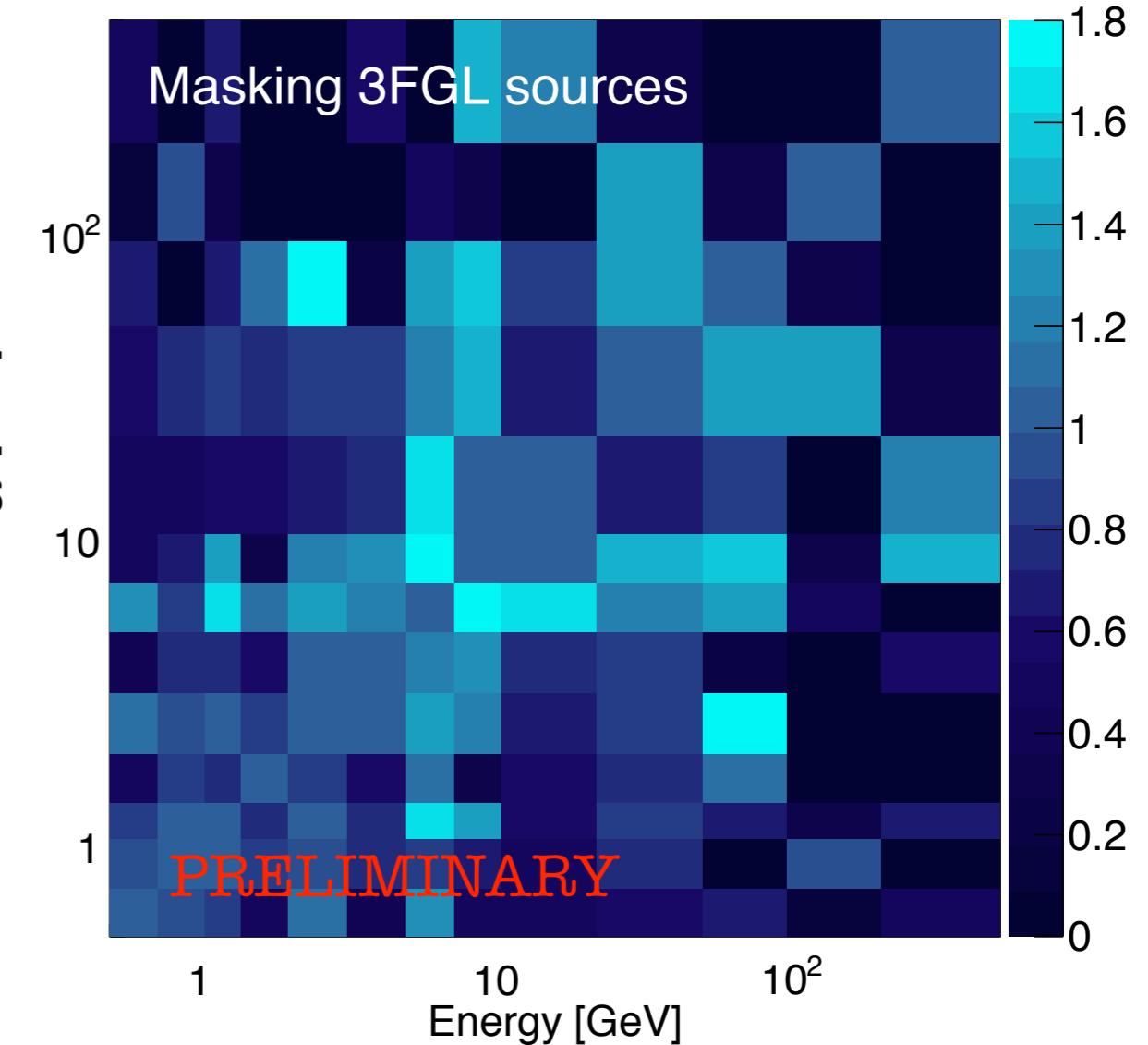
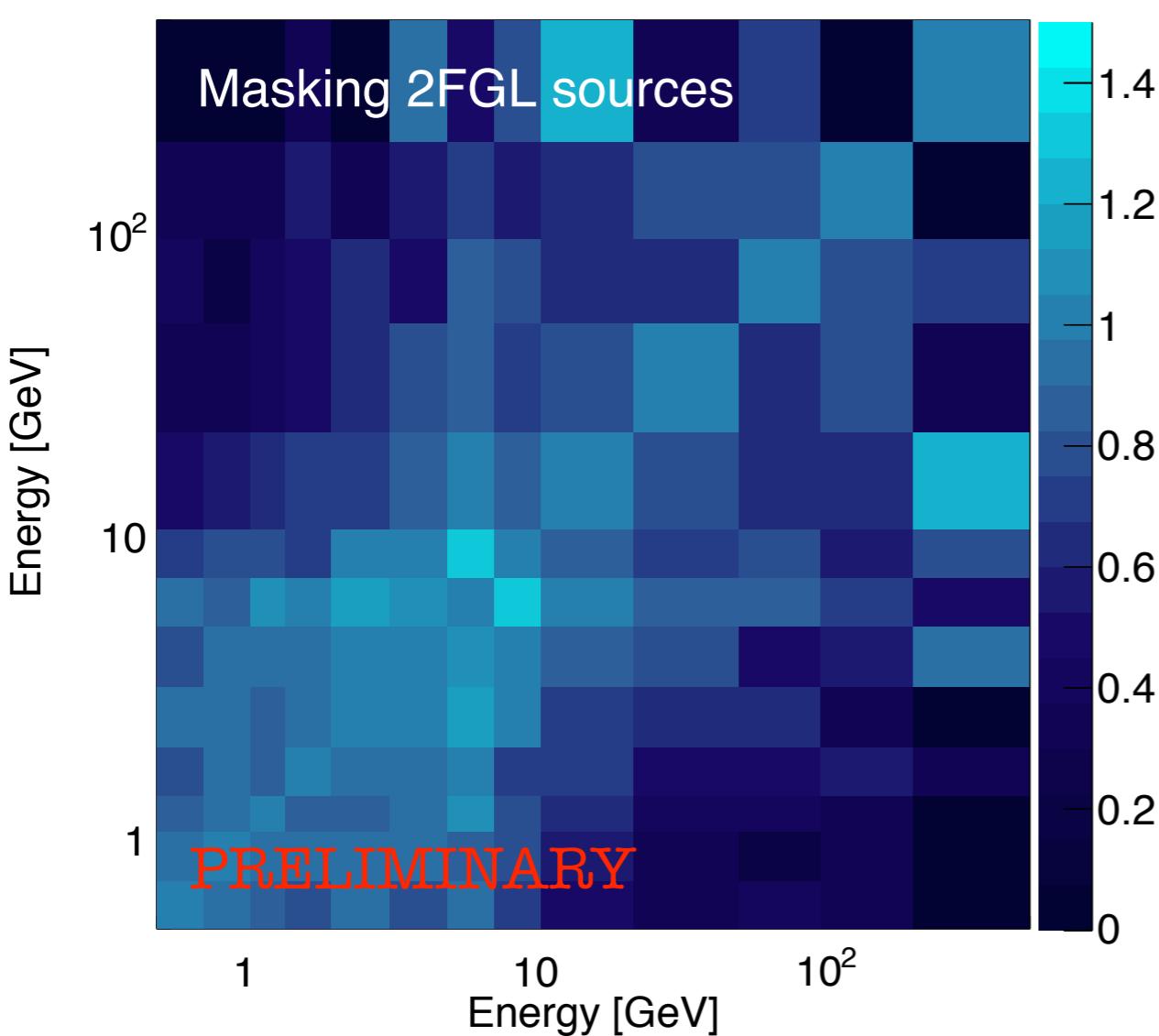
- features in the anisotropy energy spectrum indicates multiple populations of sources

# Cross-correlation APS

$$r_{i,j} = \frac{C_P^{i,j}}{\sqrt{C_P^i C_P^j}}$$

$$C_P^{i,j} = I(E_i) I(E_j) \tilde{C}_P$$

- symmetric along the diagonal (that contains  $r_{i,j}=1$ )
- deviations from 1 indicate multipole populations of sources contributing in different energy ranges



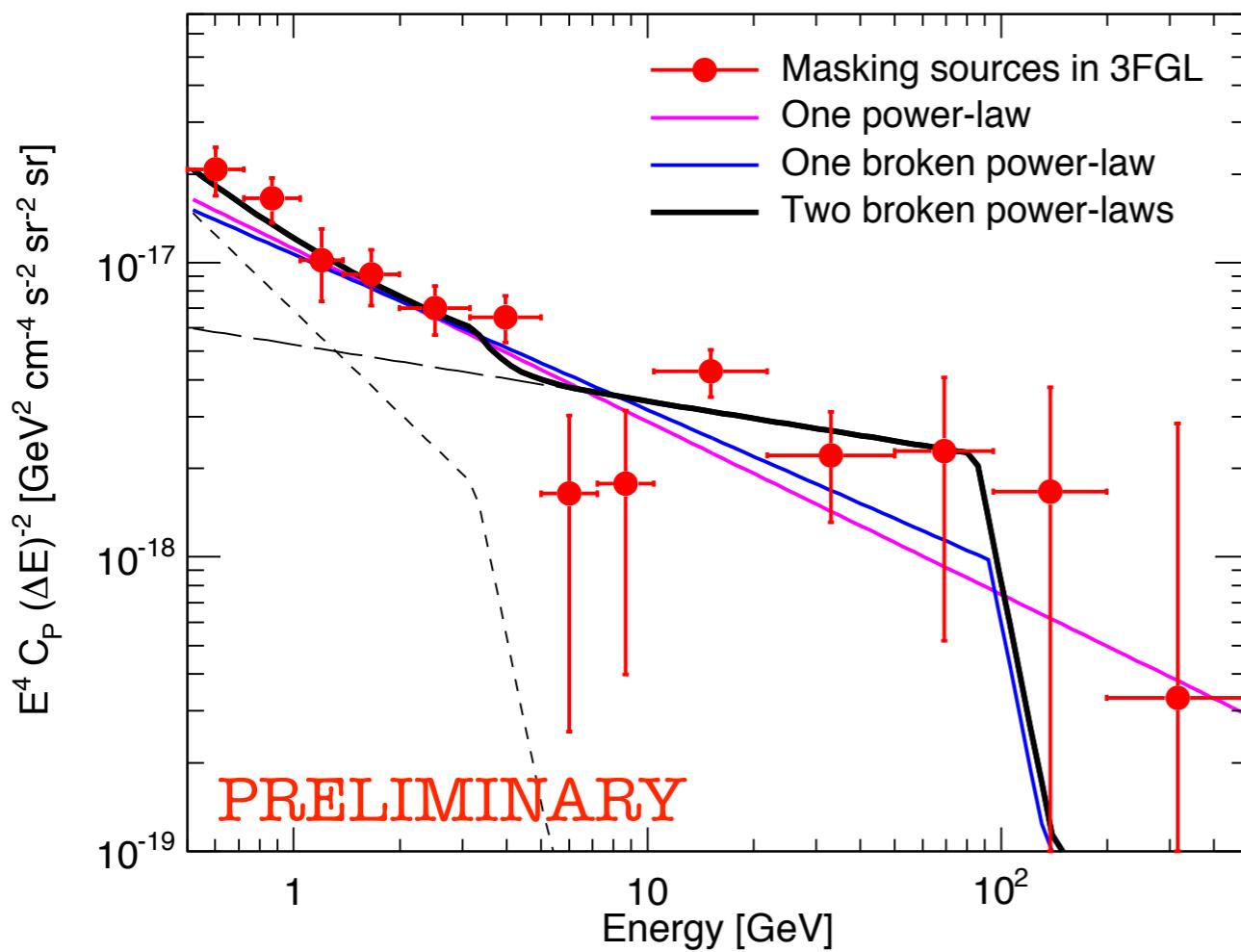
# Interpretation in terms of multiple populations

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

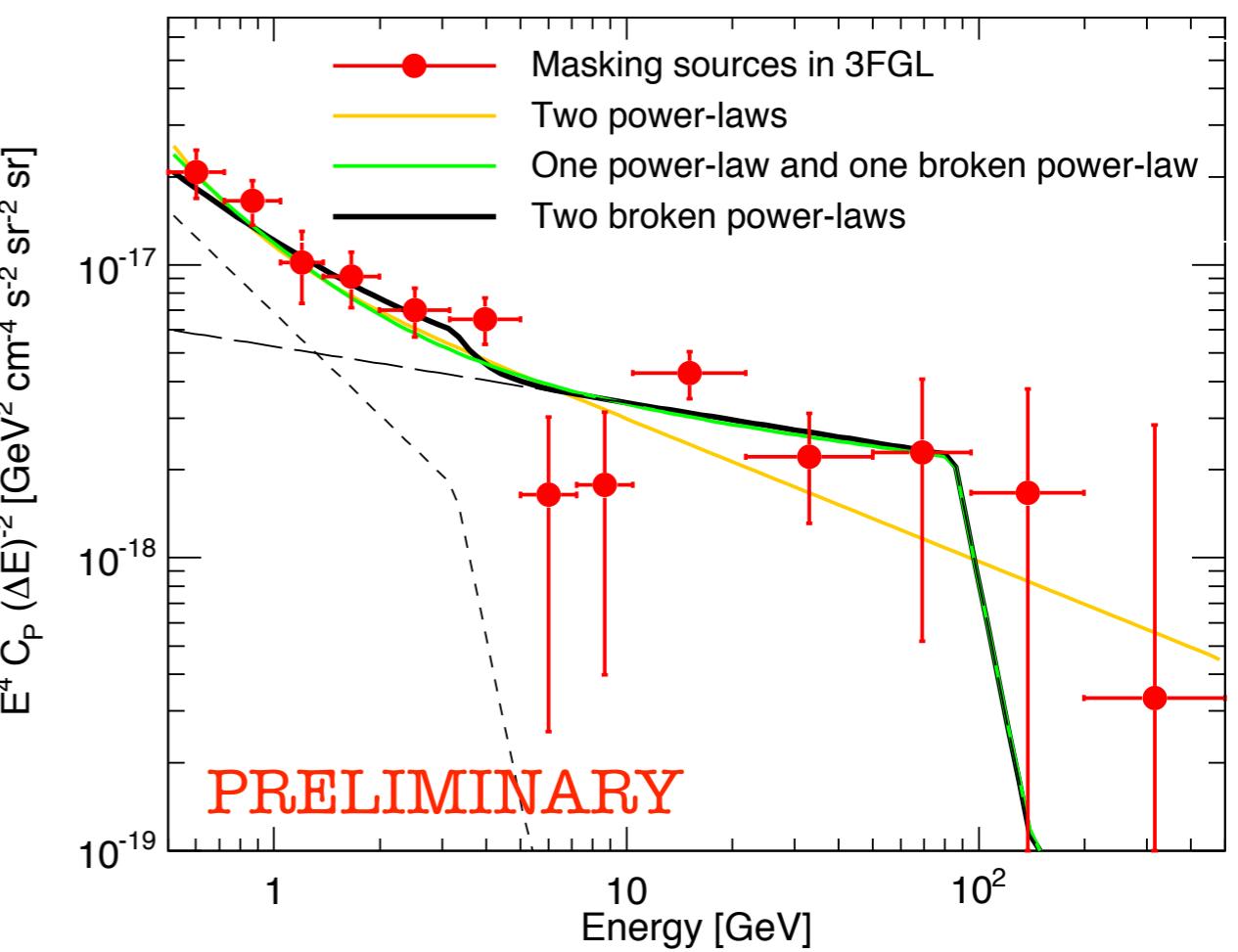
$$I(E) \propto E^{-\alpha}$$

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

1 population



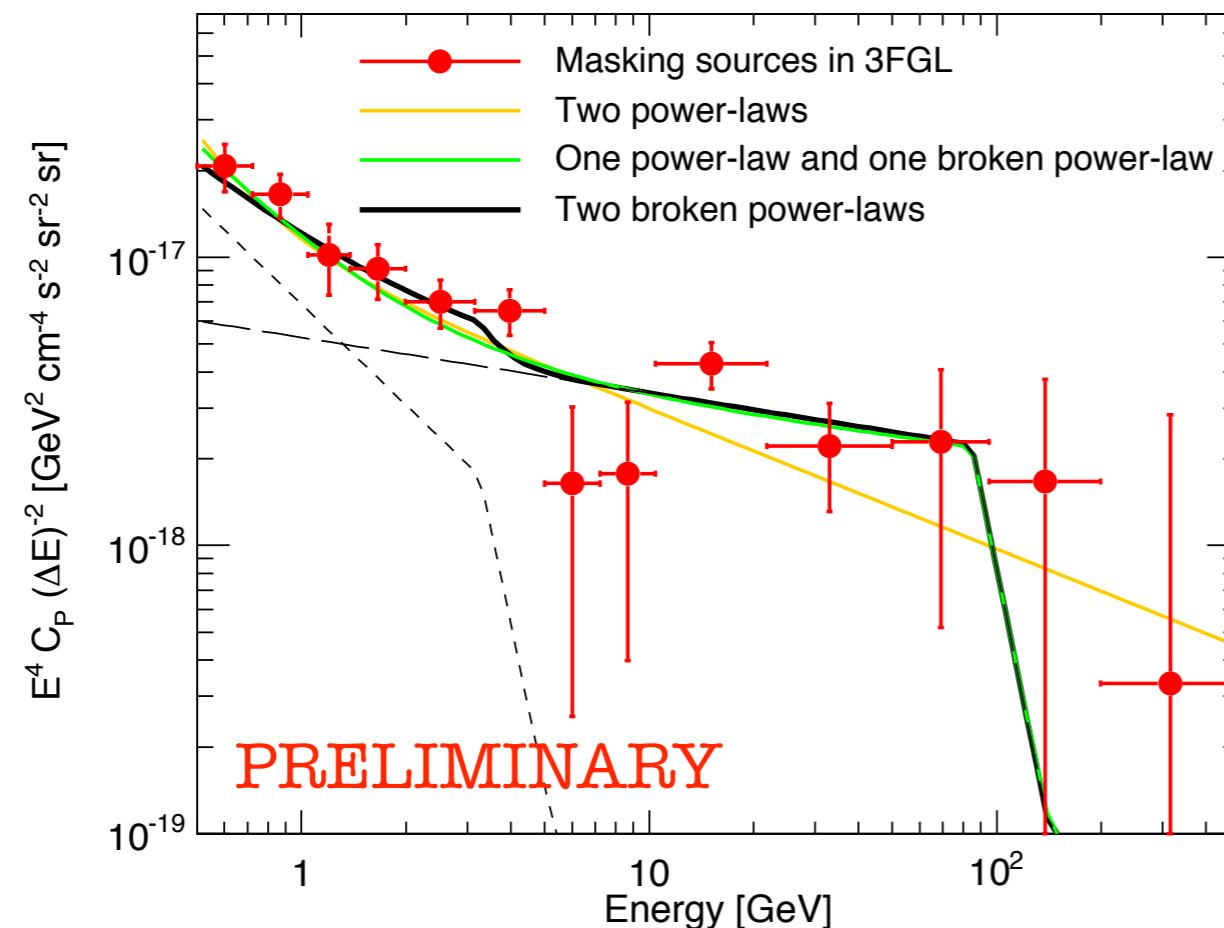
2 populations



# Best-fit interpretation

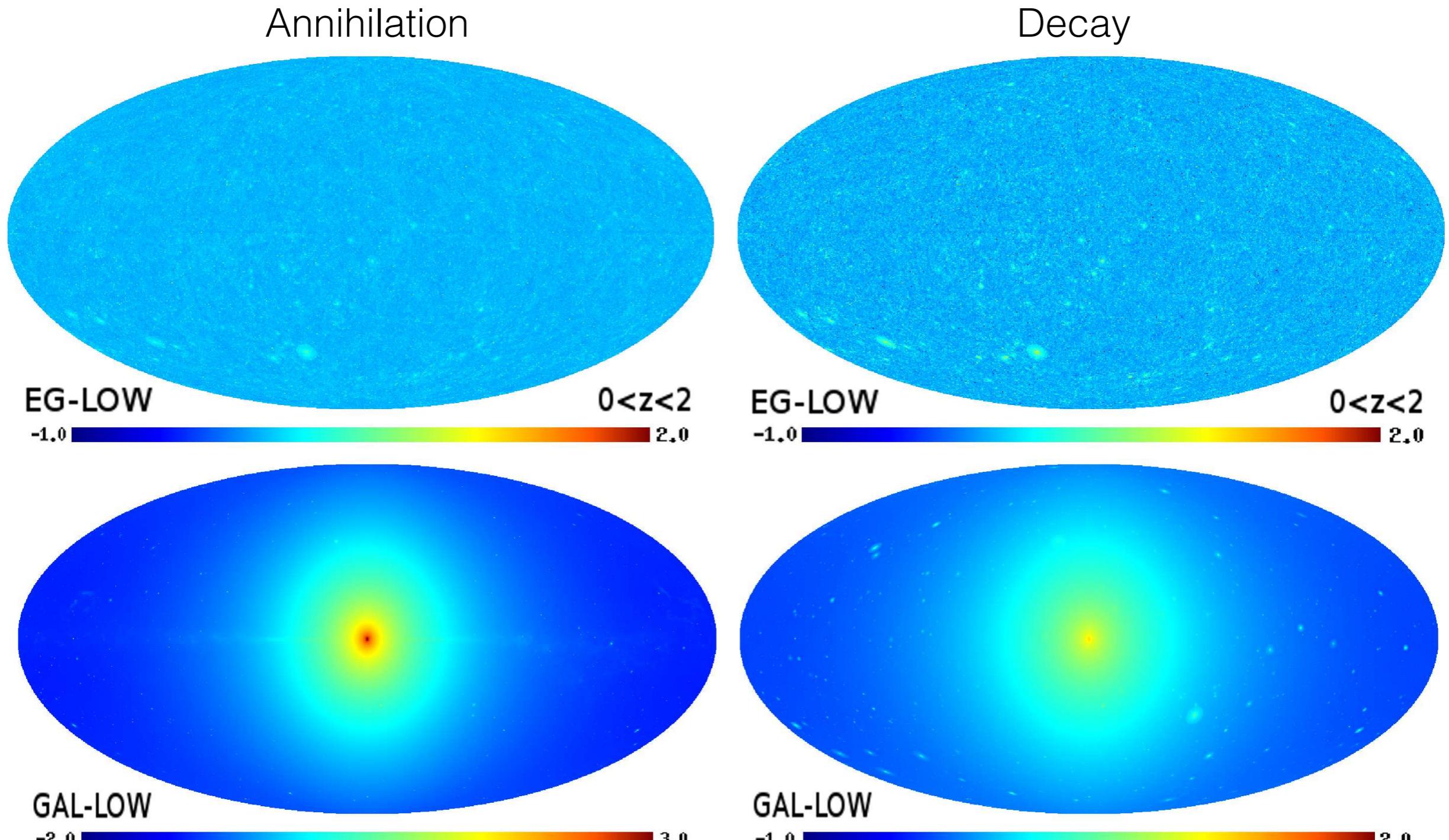
Two populations of sources with broken-power-law spectra has the lowest  $\chi^2$   
( $\chi^2/\text{dof}=1.10$ ,  $p\text{-value}=0.24$ )

1st population	2nd population
$\log_{10}(A / \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}) = -8.58_{-0.05}^{+0.04}$	$\log_{10}(A / \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}) = -8.64_{-0.05}^{+0.04}$
$a = 2.58_{-0.12}^{+0.18}$	$a = 2.10 \pm 0.05$
$\beta > 3.49$ at 68%CL	$\beta > 3.86$ 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

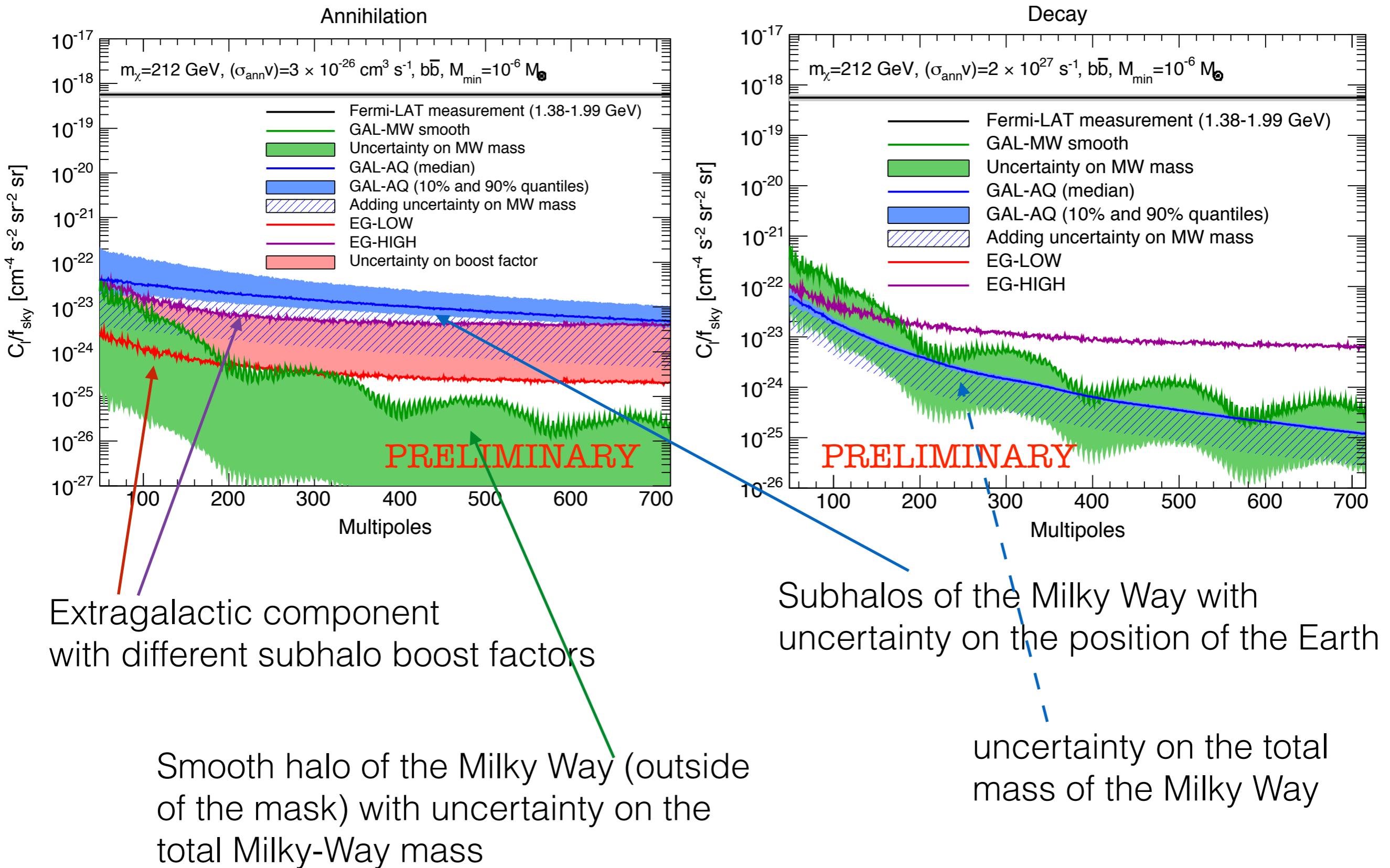
# Gamma-ray anisotropies from Dark Matter



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

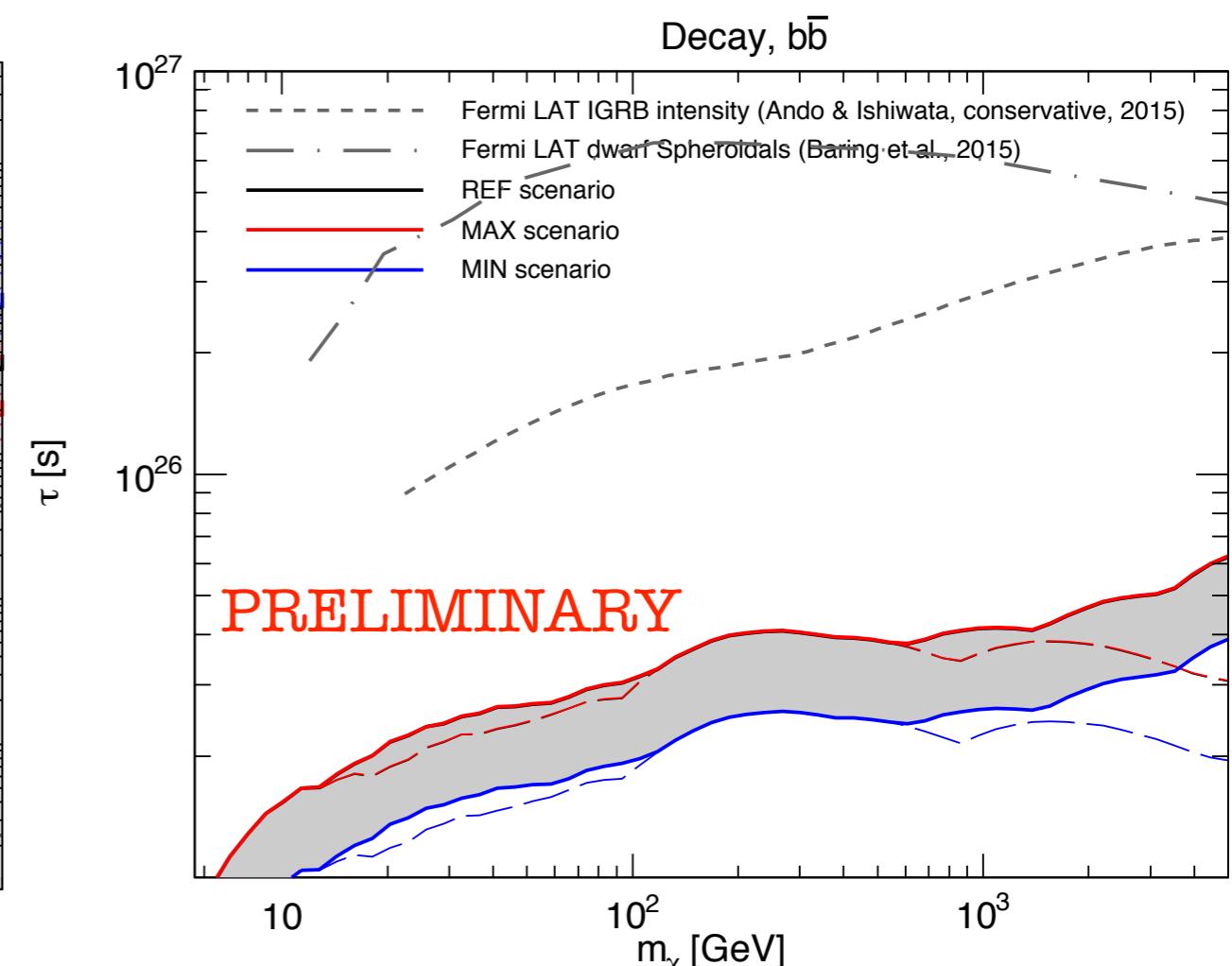
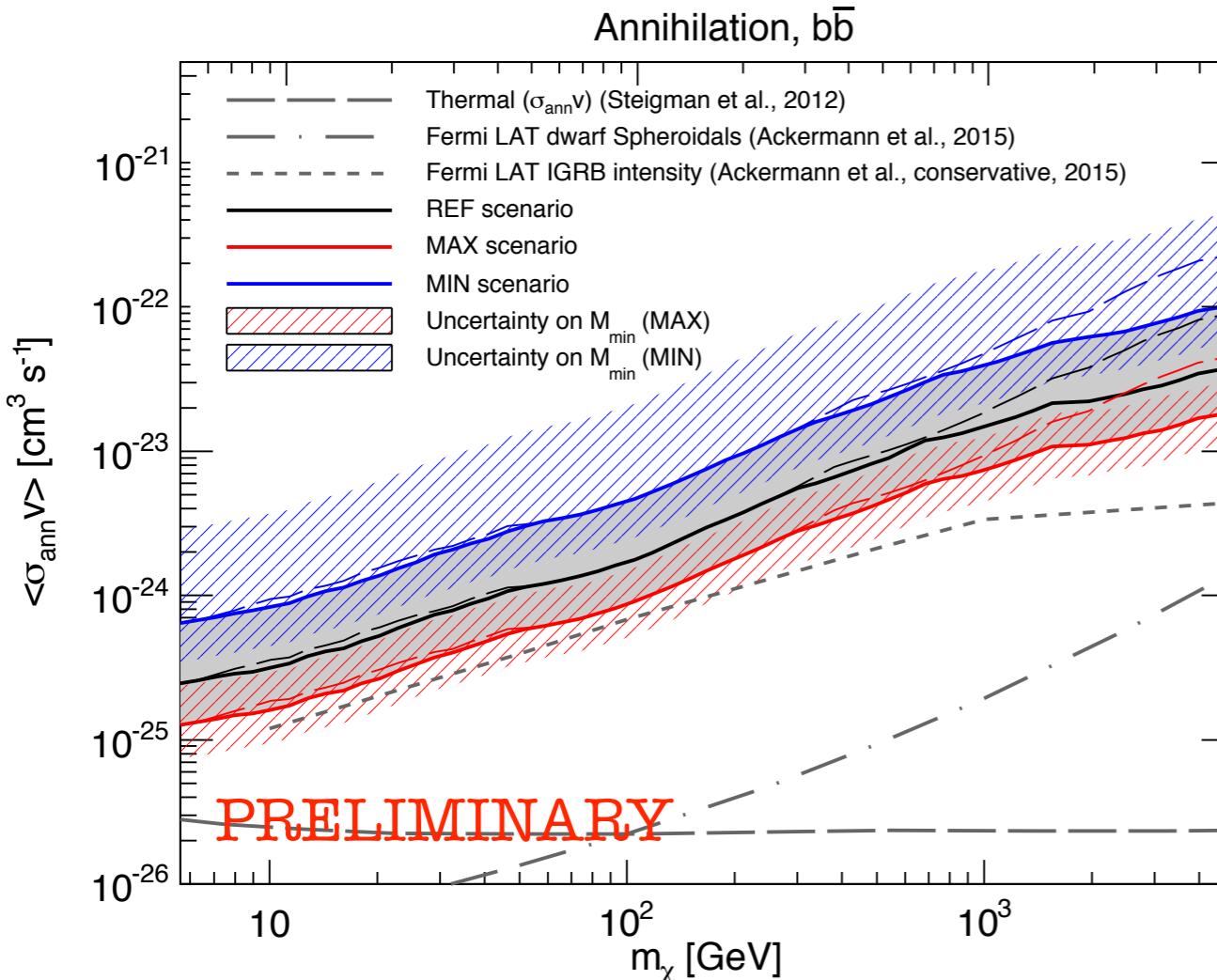
$m_{\chi}=200 \text{ GeV}$ ,  $\sigma v=3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$  (annihilation),  $m_{\chi}=2 \text{ TeV}$ ,  $\tau=2 \times 10^{27} \text{ s}$  (decay)

# DM-induced APS



# Conservative exclusion limits

$$\langle C_{\ell, \text{DM}}^{i,j} \rangle < C_{\text{P}}^{i,j} + 1.64 \sigma_{C_{\text{P}}^{i,j}}$$

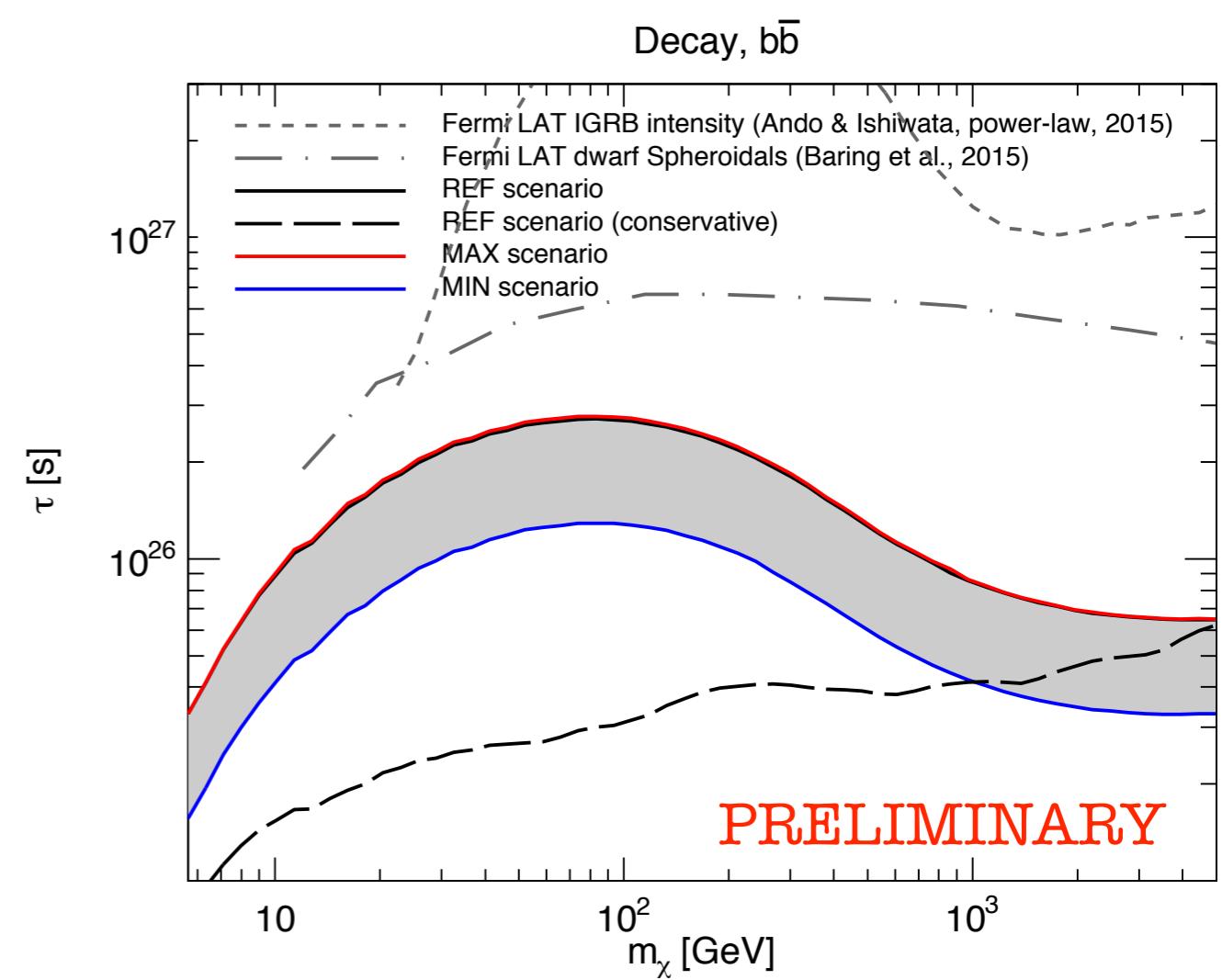
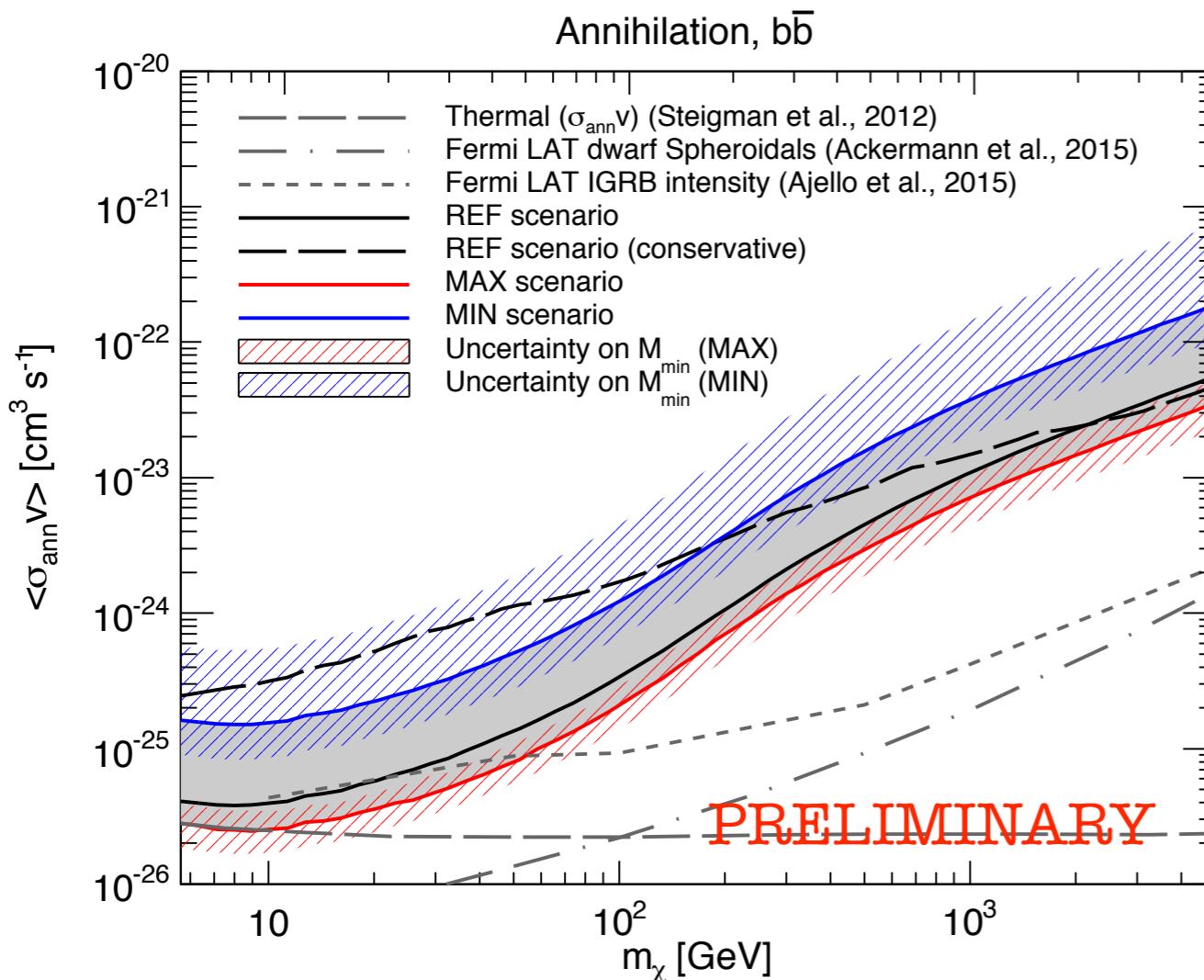


- REF, MIN and MAX encompass the uncertainties considered in the distribution of the DM (for a fixed  $M_{\min}$ )
- shaded bands describe the uncertainty on the value of  $M_{\min}$

# 2-component fit to the binned APS

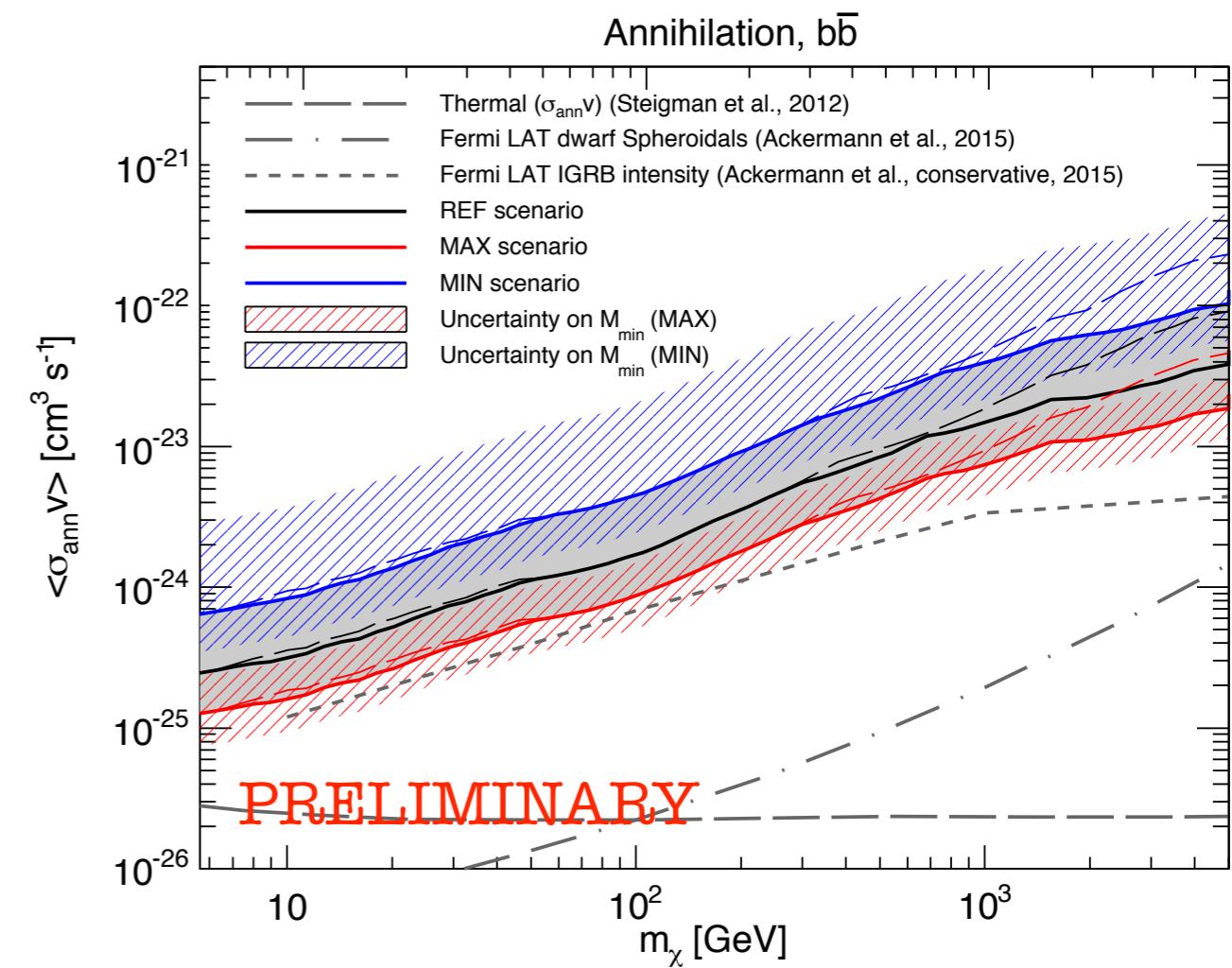
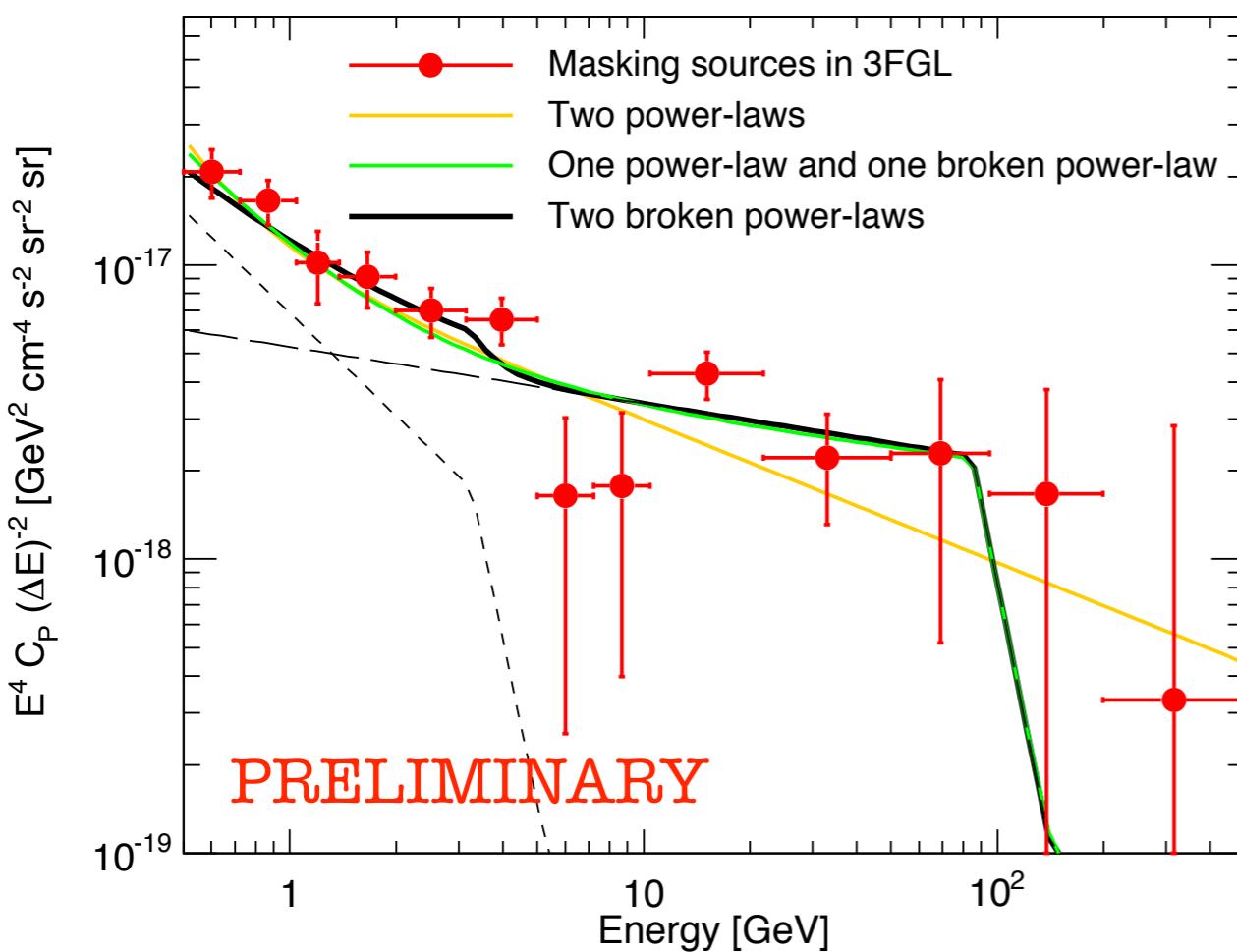
$$\chi^2 = - \sum_{i,j,\ell} \frac{[C_\ell^{i,j} - C_{\ell, \text{DM}}^{i,j} - C_{\text{P}}^{i,j}]^2}{\sigma_{C_\ell^{i,j}}^2}$$

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



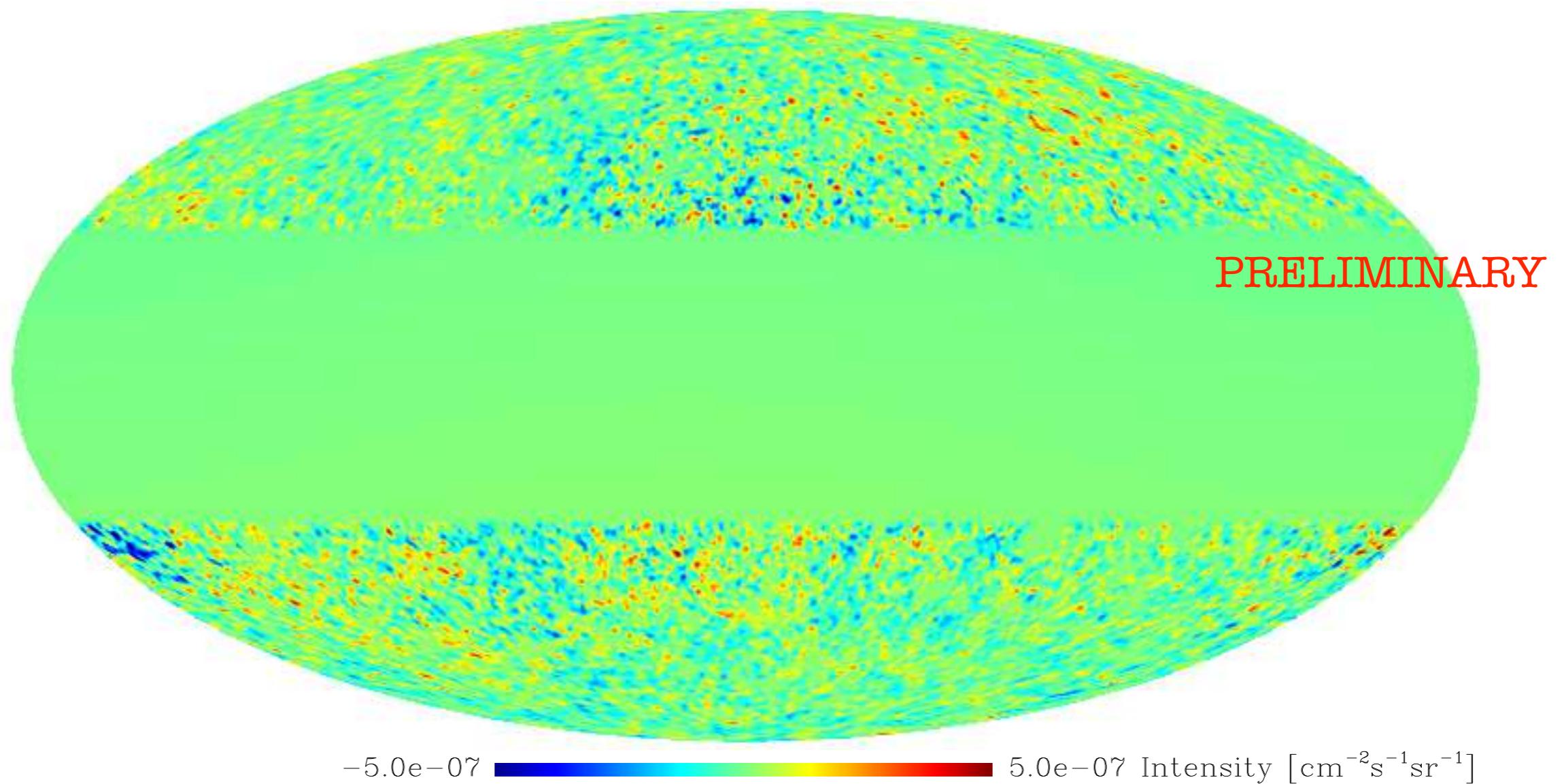
# Conclusions

- updated measurement of anisotropy angular power spectrum
- evidence of multiple components
- insight on unresolved astrophysical sources
- limits on DM competitive with those coming from the overall intensity



# Residual maps

model gll\_iem\_v05\_rev1.fit



# How to bin the APS

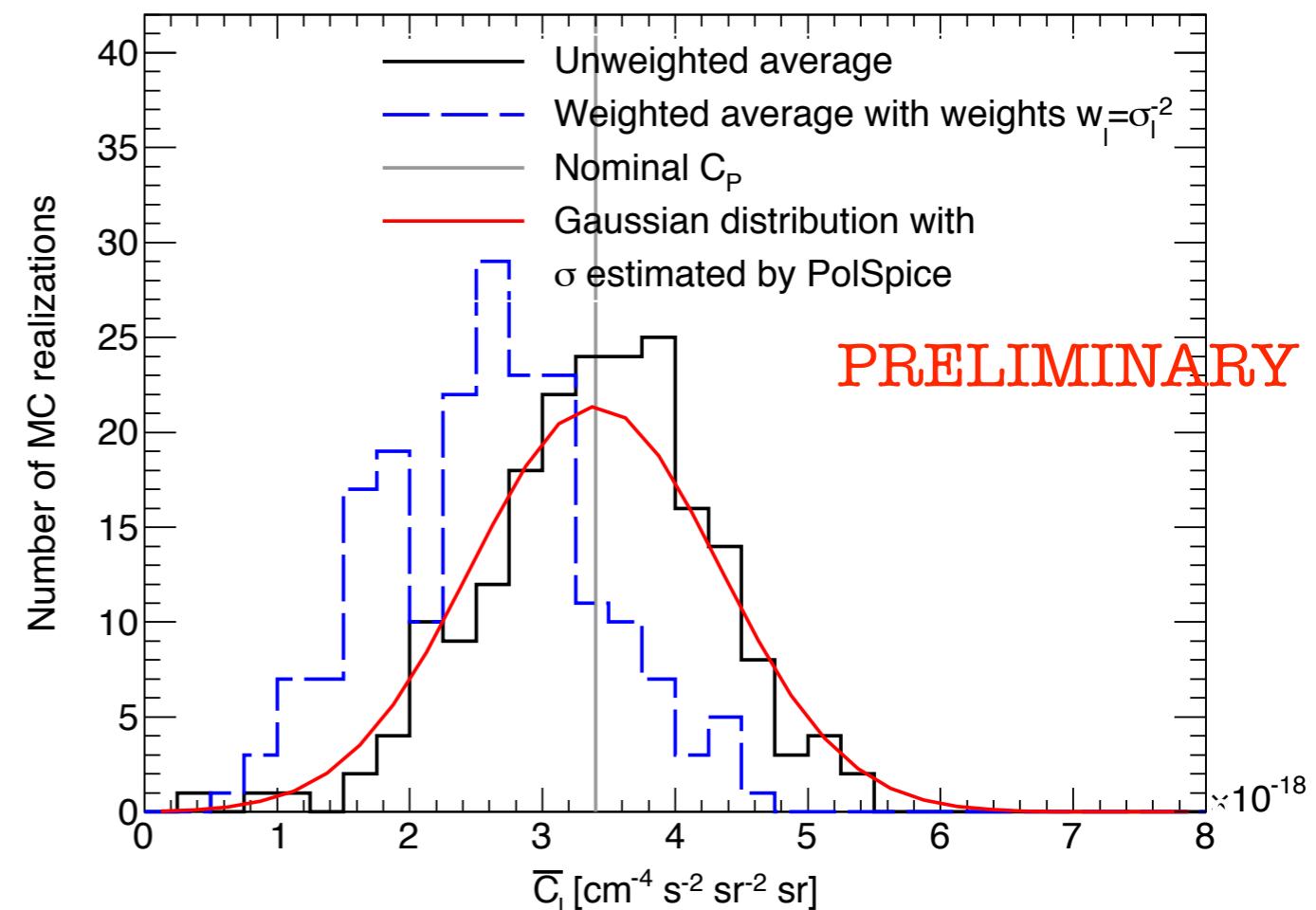
- produce 200 Monte Carlo realisations of the gamma-ray sky with a fixed nominal  $C_P$
- analytical expression for the error is

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

- to bin  $C_\ell$  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 of the binned APS

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

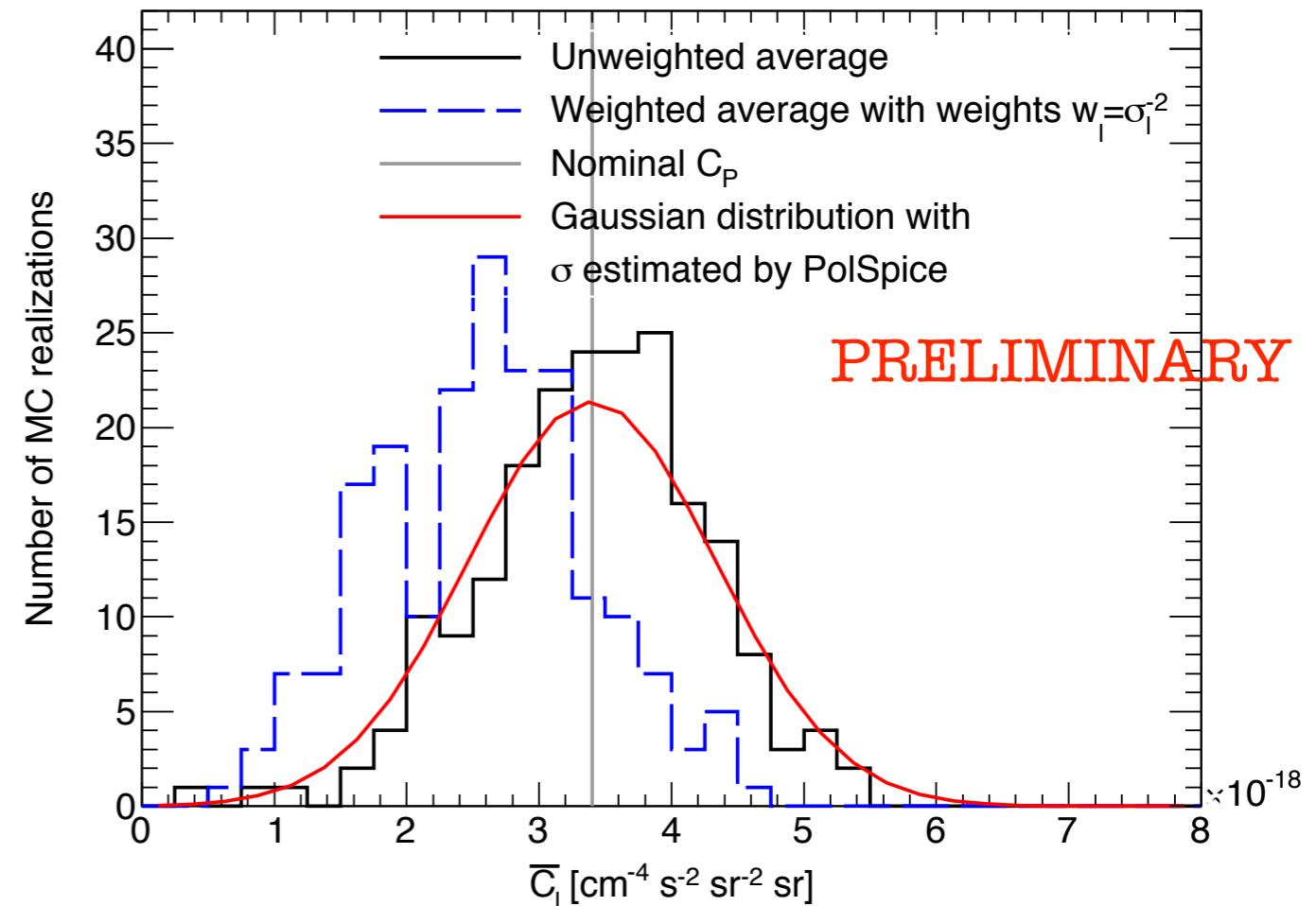
$\sigma_\ell$

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

- method B: weighted average of  $\sigma_\ell$

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

- they agree on the MC data



# How to fit binned APS

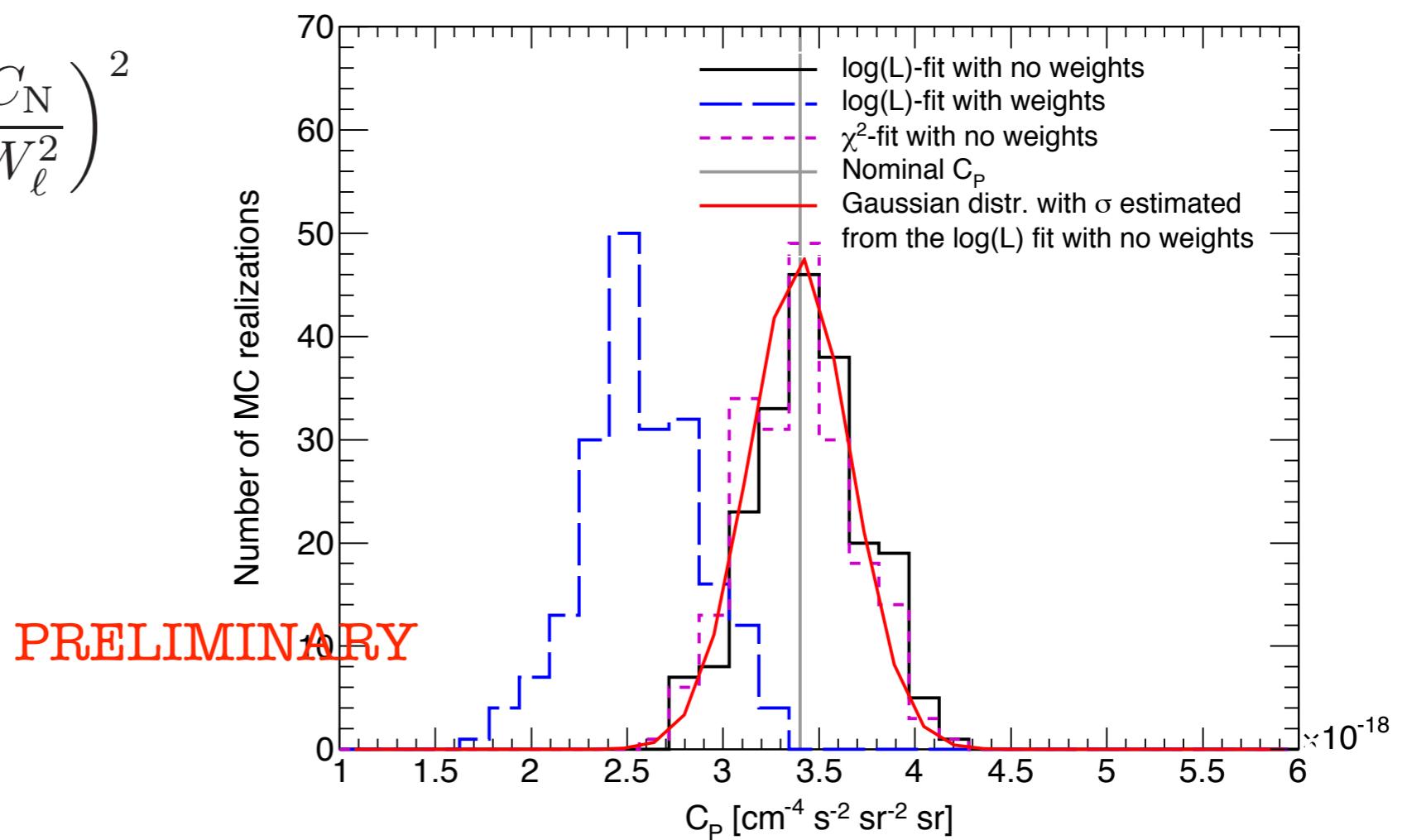
- method A: minimise the  $\chi^2$

$$\chi^2(C_P) = \sum_{\ell} \frac{(\overline{C}_{\ell} - C_P)^2}{\overline{\sigma}_{\ell}^2}$$

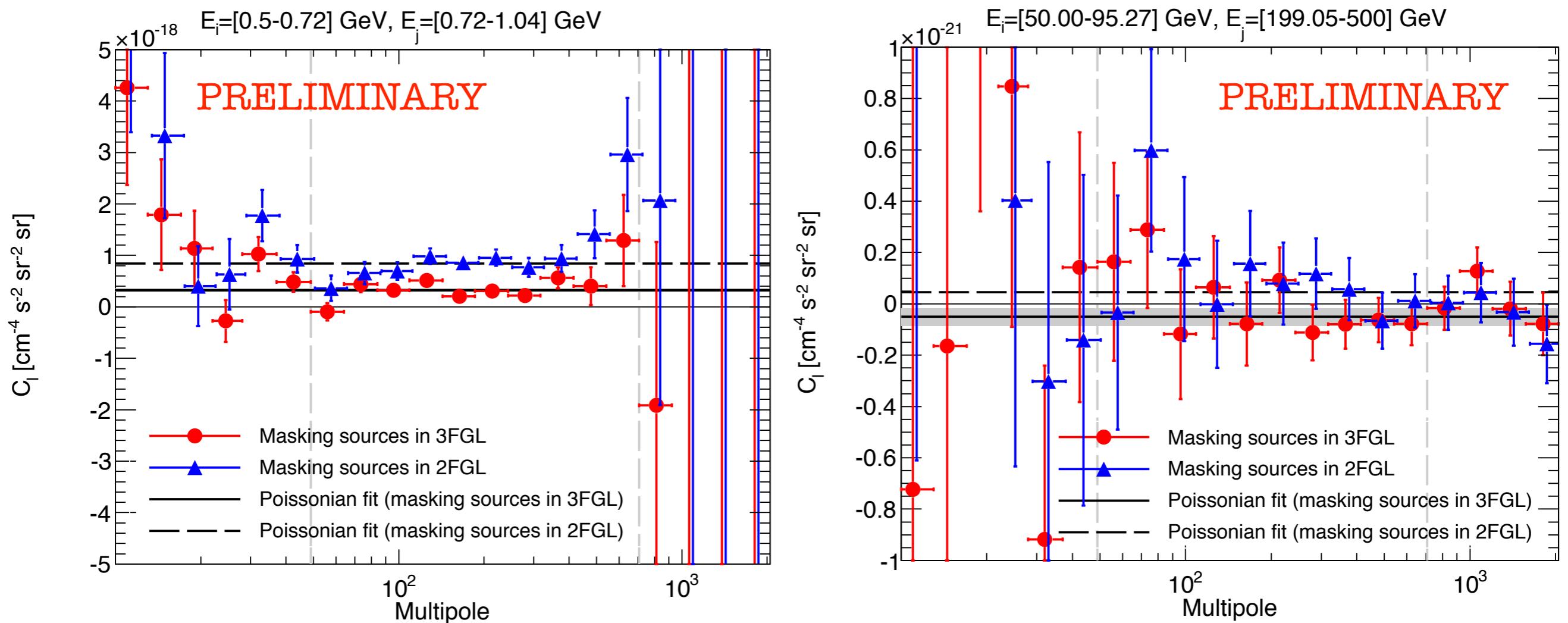
- method B: **maximise the  $\log(\mathcal{L})$**

$$\log \mathcal{L}(C_P) = - \sum_{\ell} \log(\overline{\sigma}_{\ell}) - \frac{1}{2} \sum_{\ell} \frac{(\overline{C}_{\ell} - C_P)^2}{\overline{\sigma}_{\ell}^2}$$

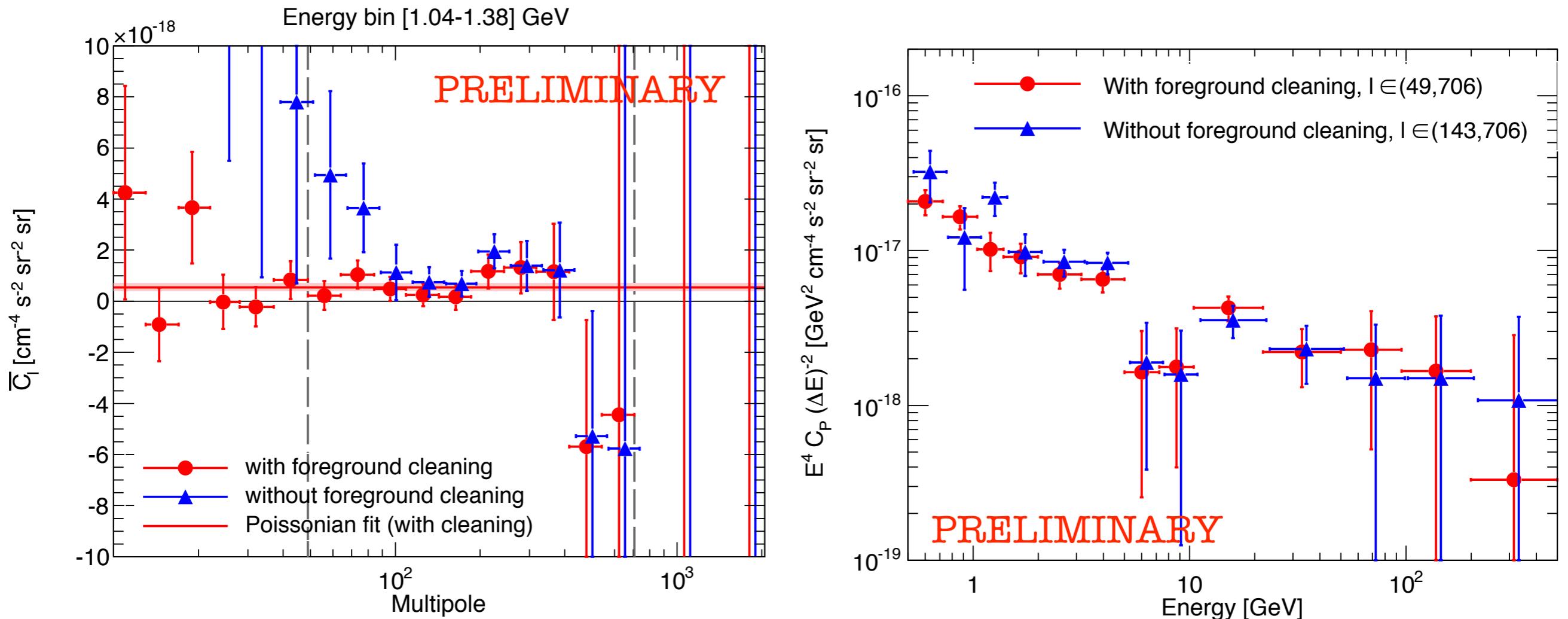
$$\sigma_{\ell}^2 = \frac{2}{(2\ell + 1)f_{\text{sky}}} \left( C_P + \frac{C_N}{W_{\ell}^2} \right)^2$$



# Cross-correlation



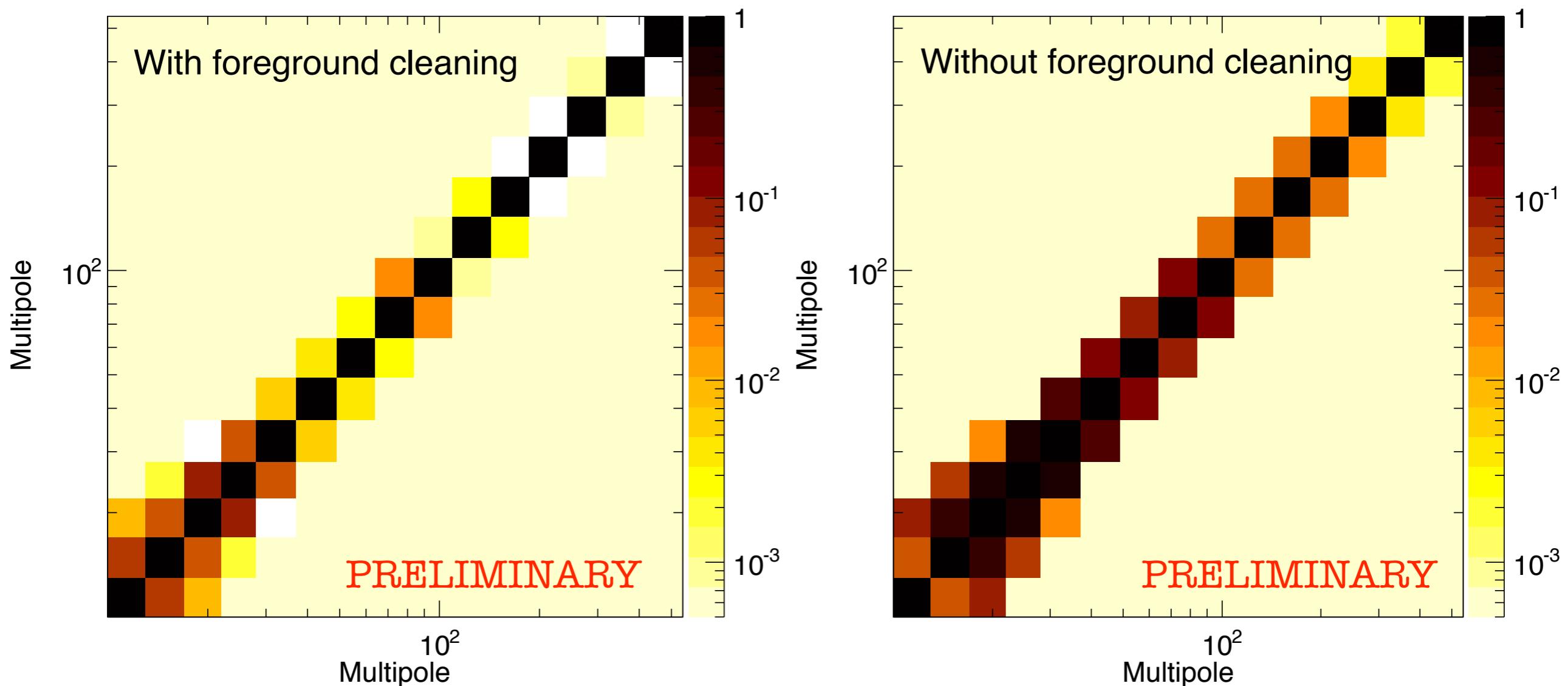
# Validation of foreground cleaning



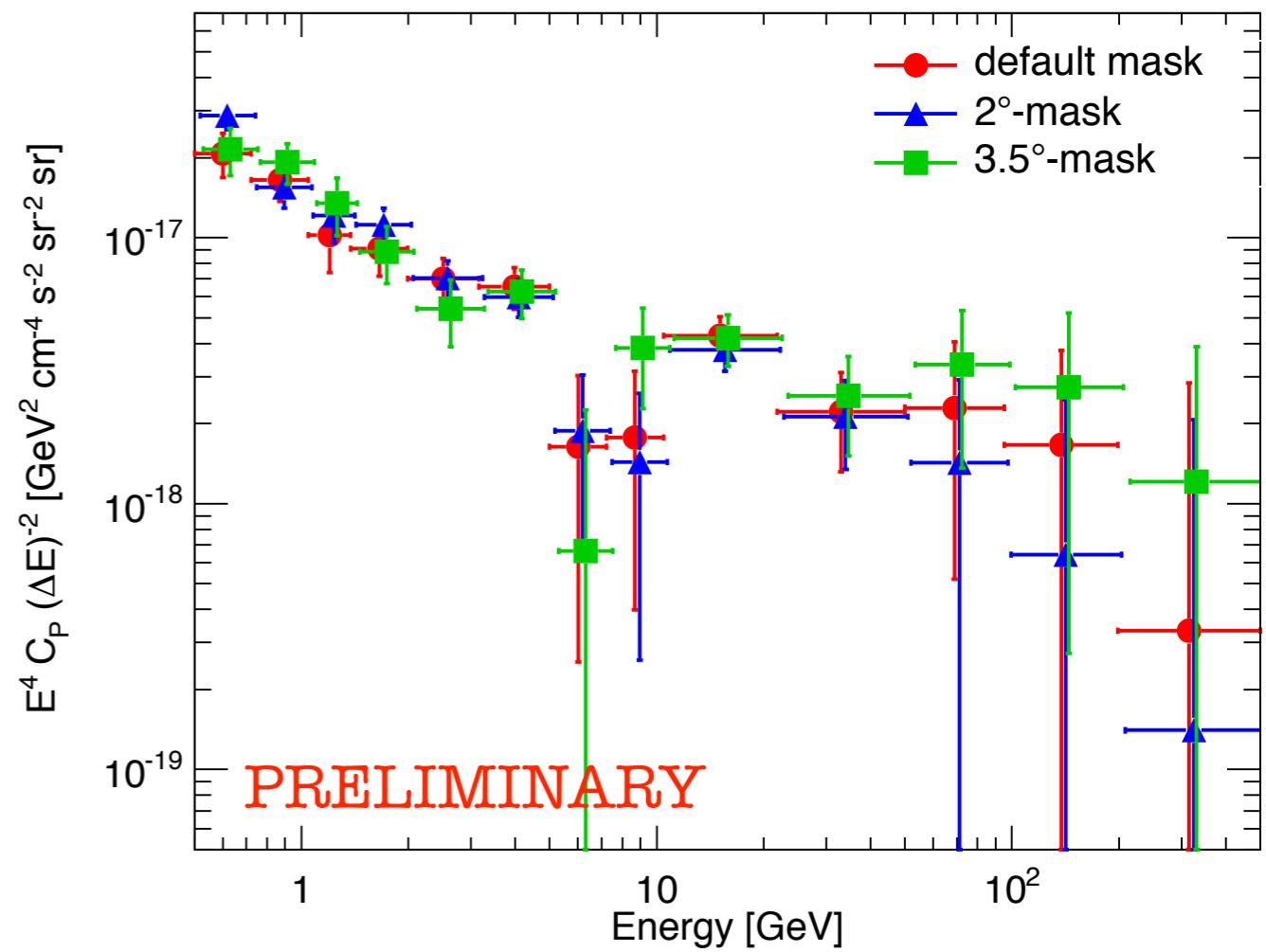
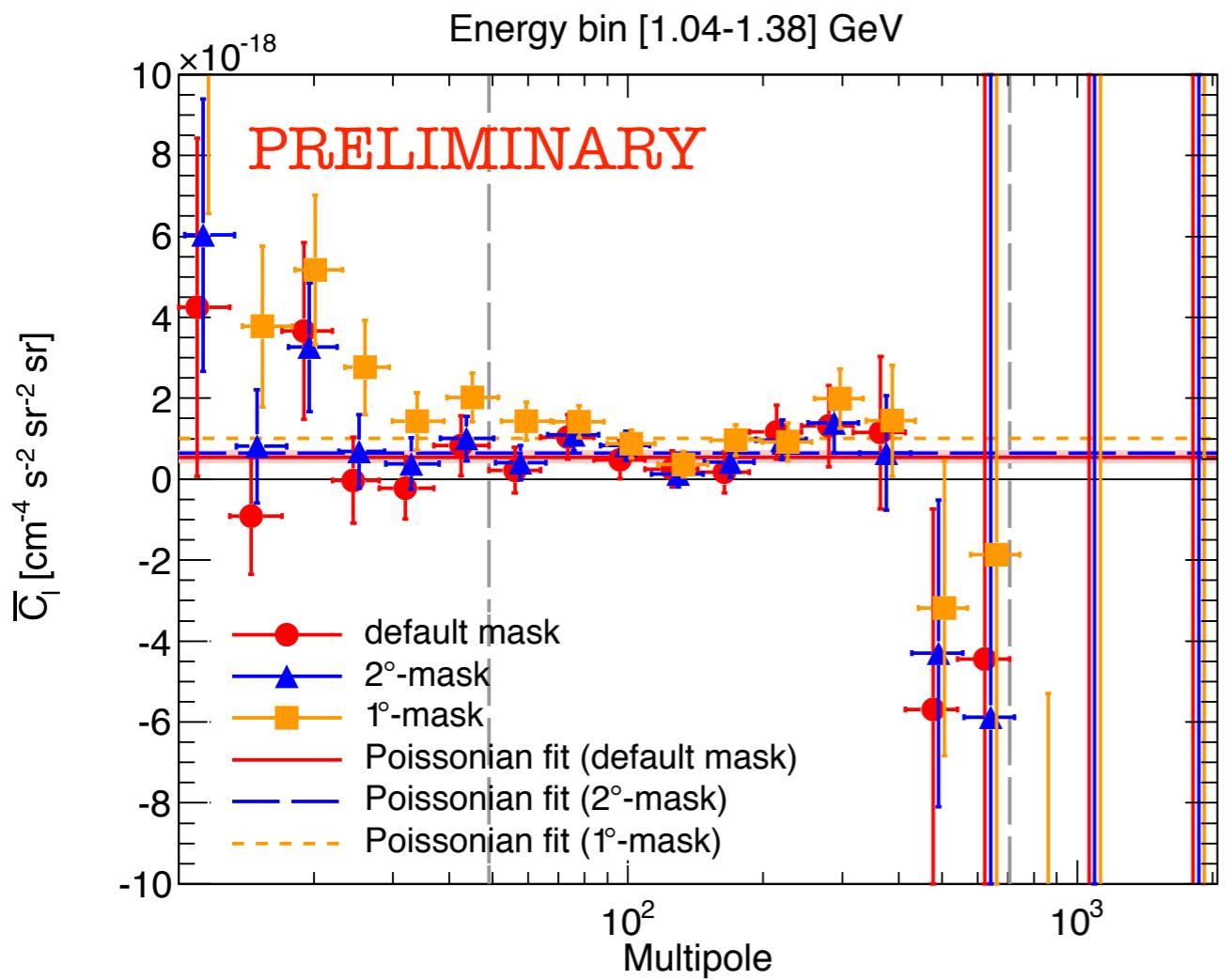
- significant less power at low multipoles (large angular scales)
- region with  $\ell > 143$  (bin #5 in the signal region) is not affected by Galactic foreground, even without cleaning
- foreground cleaning also reduces correlation between multipole bins

# Correlation between multipole bins

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

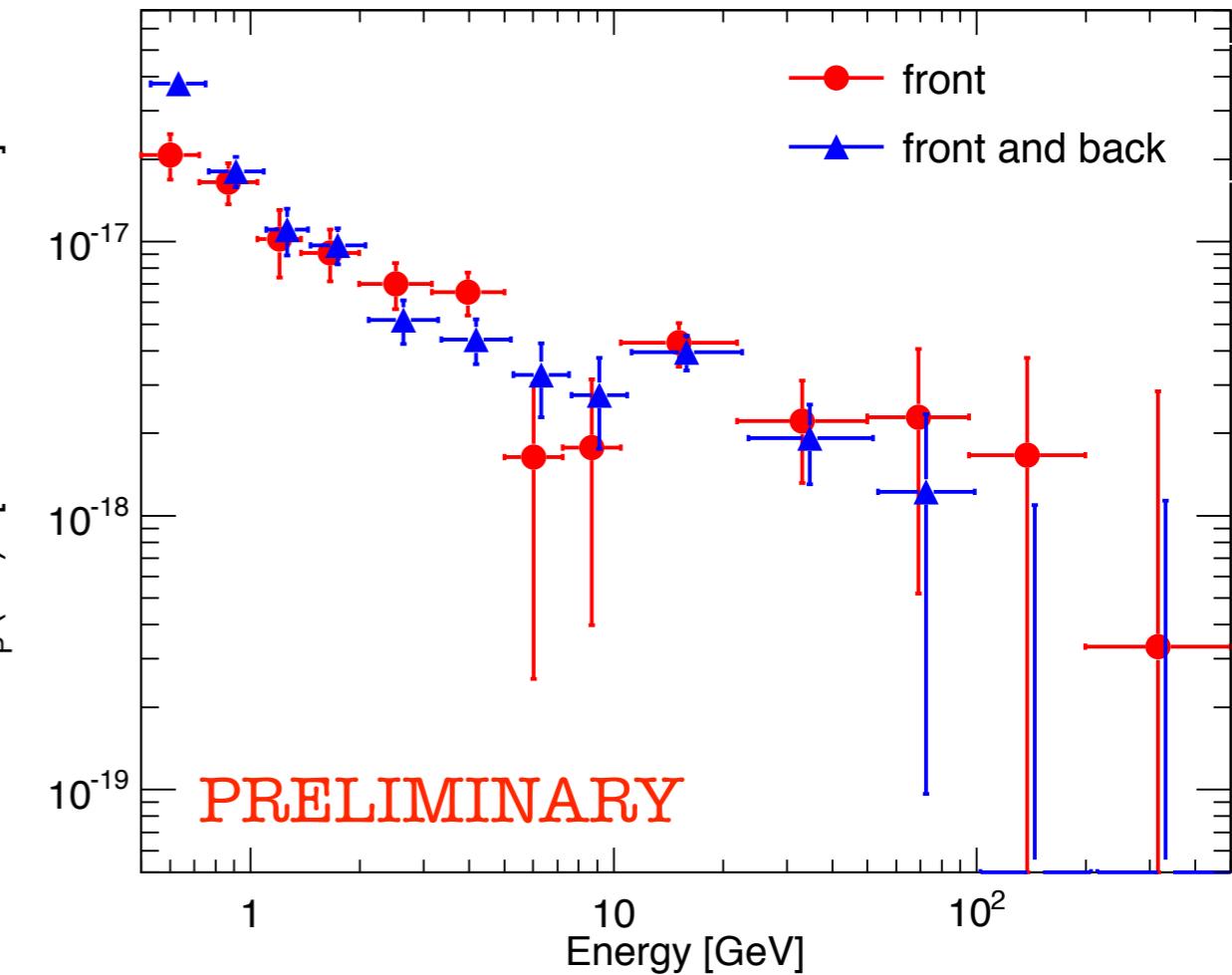
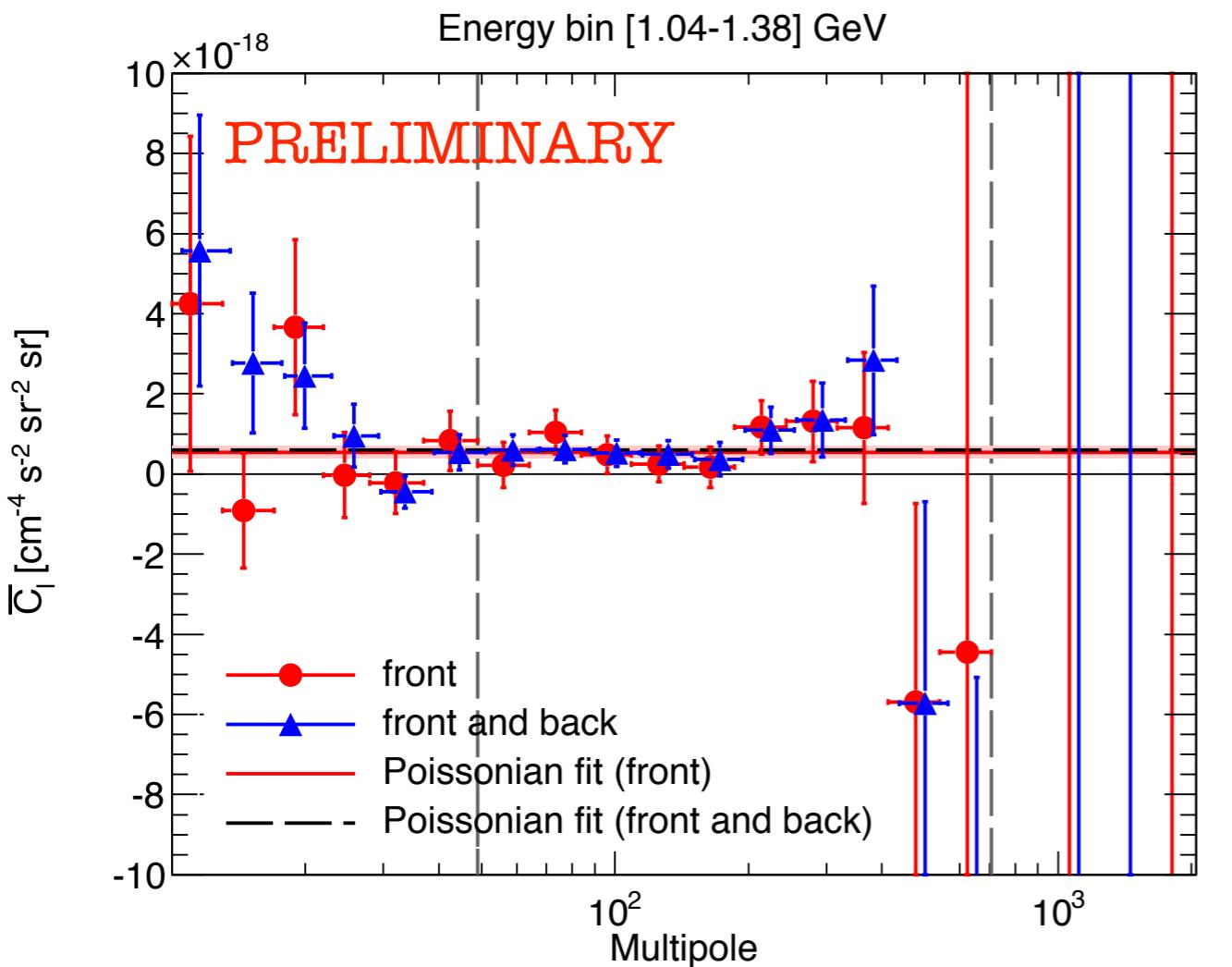


# Validation of the mask around 3FGL point sources



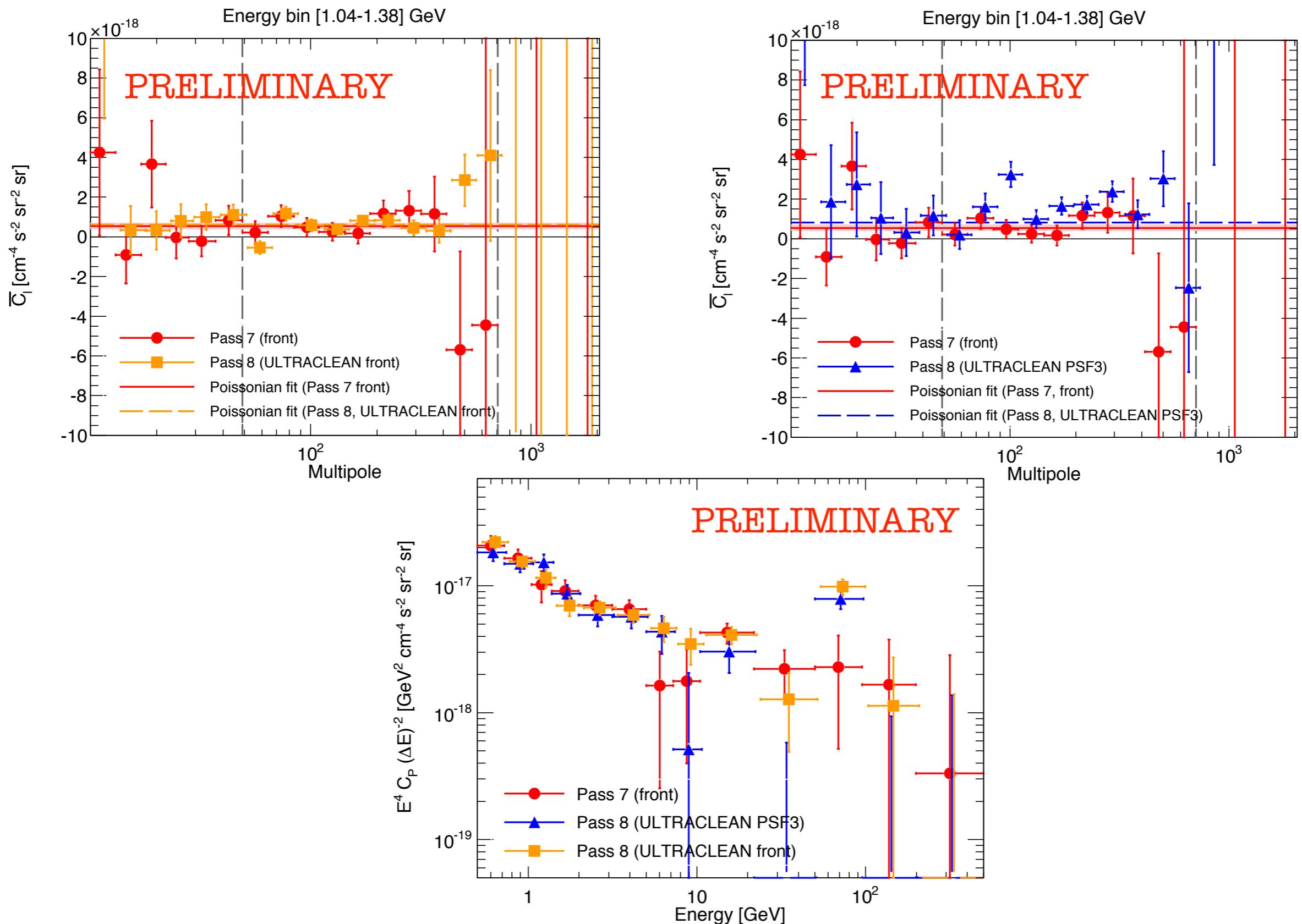
- 1°-mask: disc of 1 deg around all sources
- 2°-mask: disc of 2 deg around 500 brightest sources and disc of 1 deg around all the others
- 3°-mask: disc of 3.5 deg around 500 brightest sources, disc of 2.5 deg around following 500 brightest sources, disc of 2.0 deg around 1000 following brightest sources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

# Front and front+back

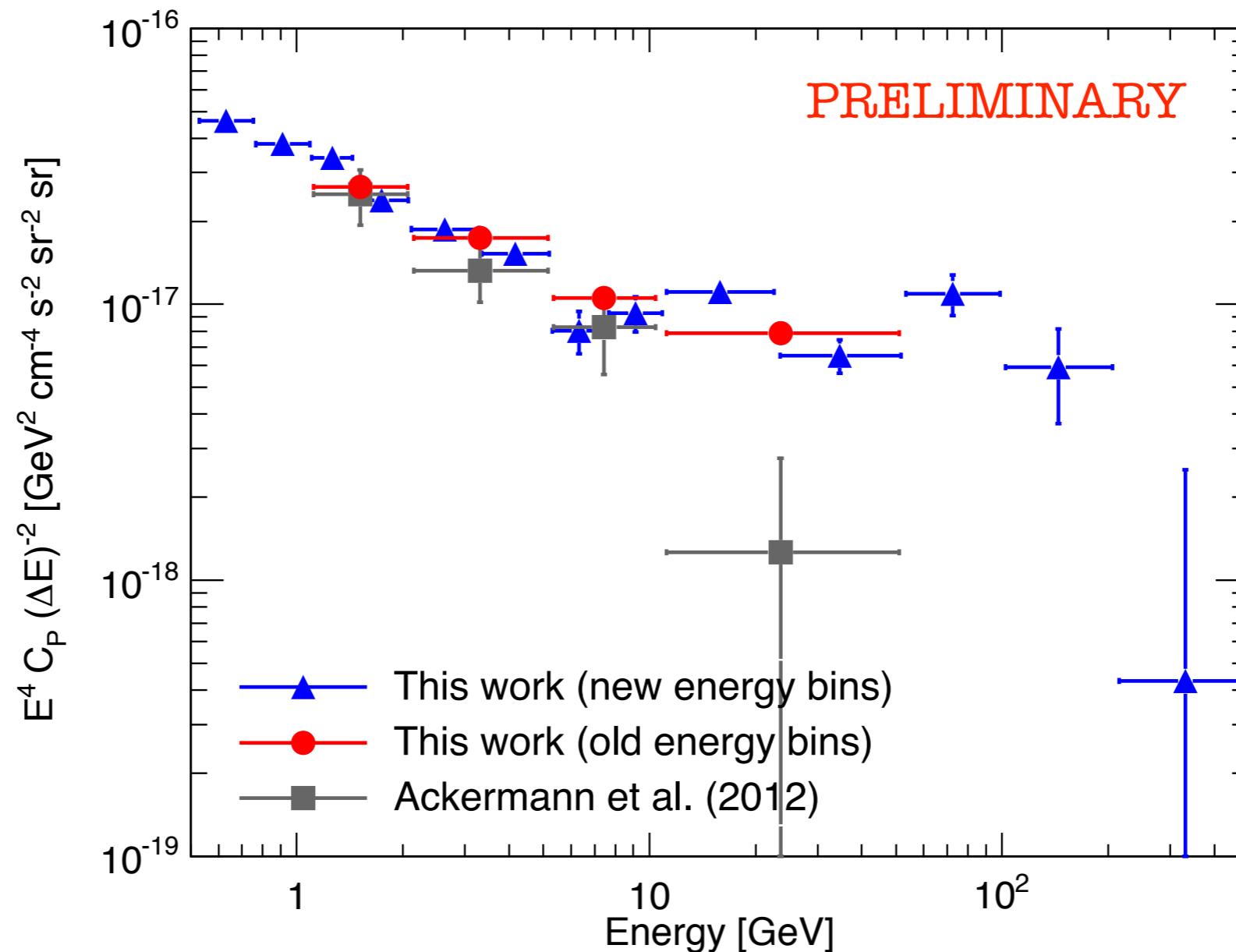


- two data sets are not independent
- possibility of leakage outside of point sources in front+back data set because of the larger PSF

# Pass 7 vs Pass 8

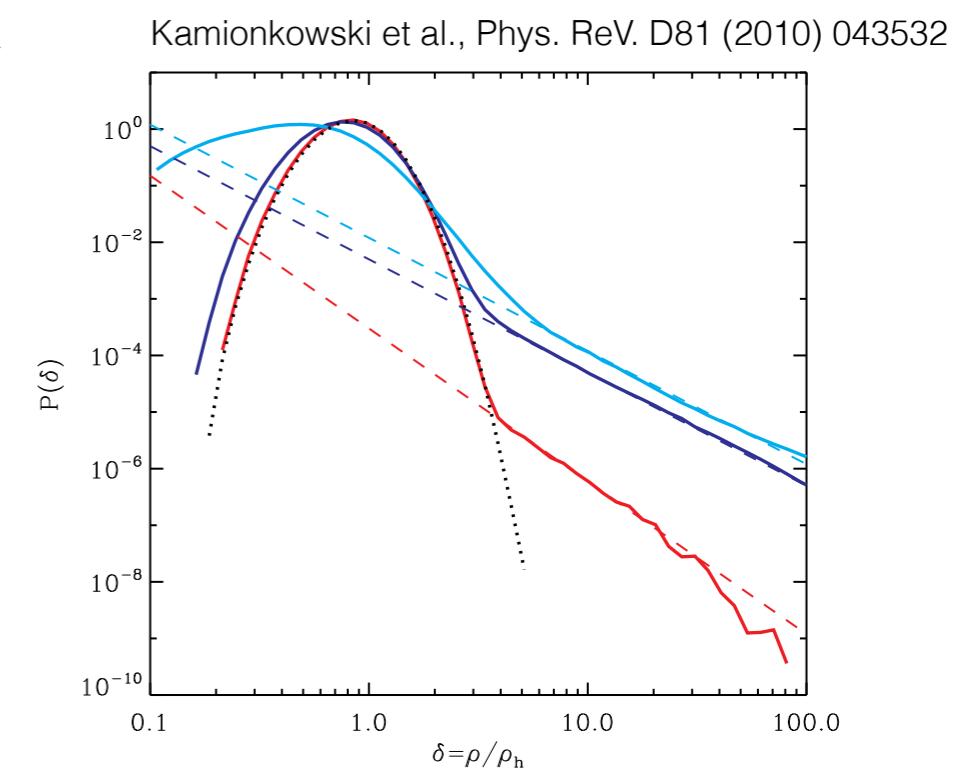
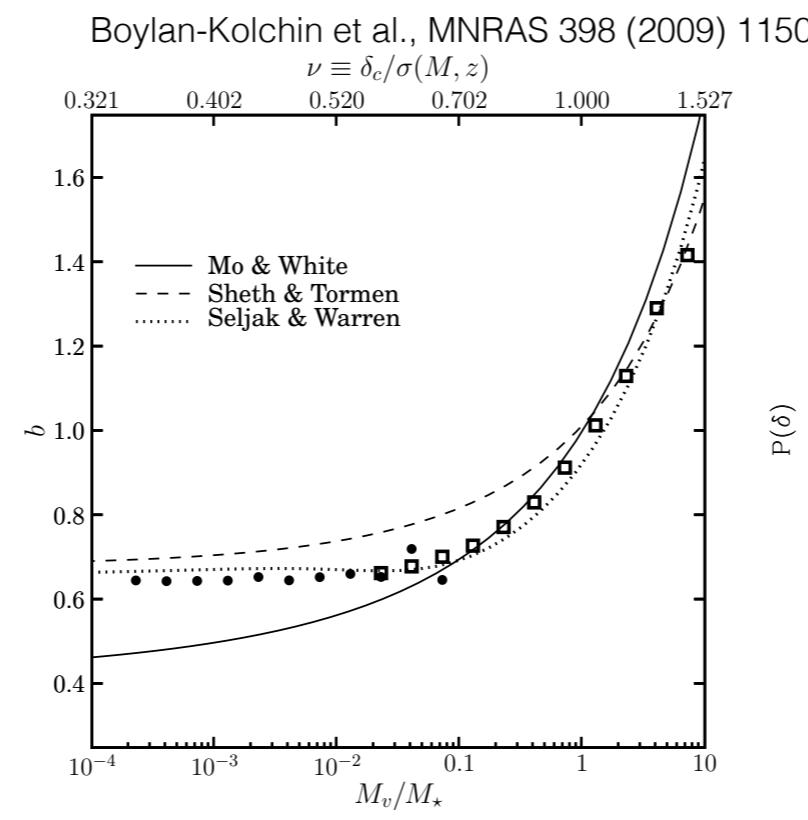
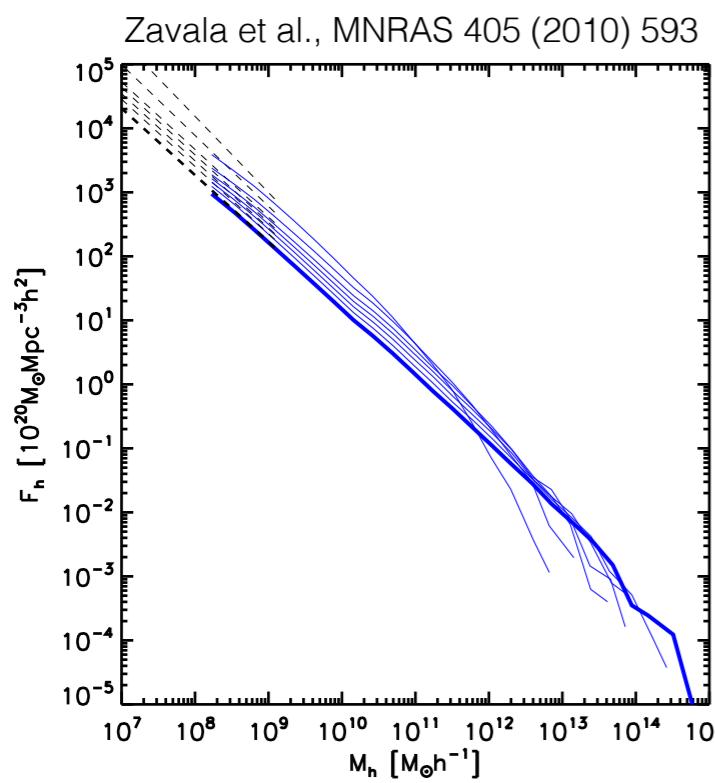


# Comparison with old measurement



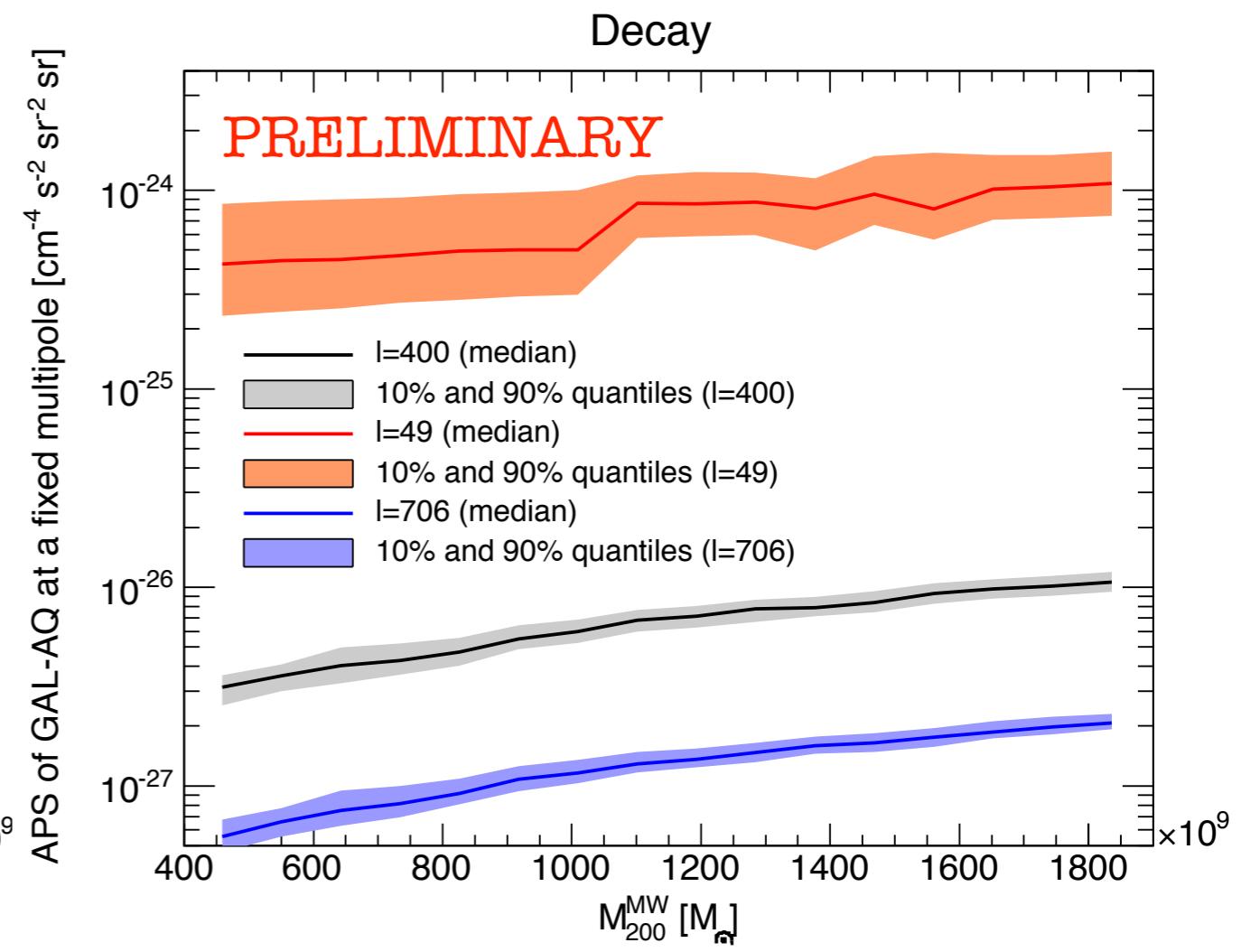
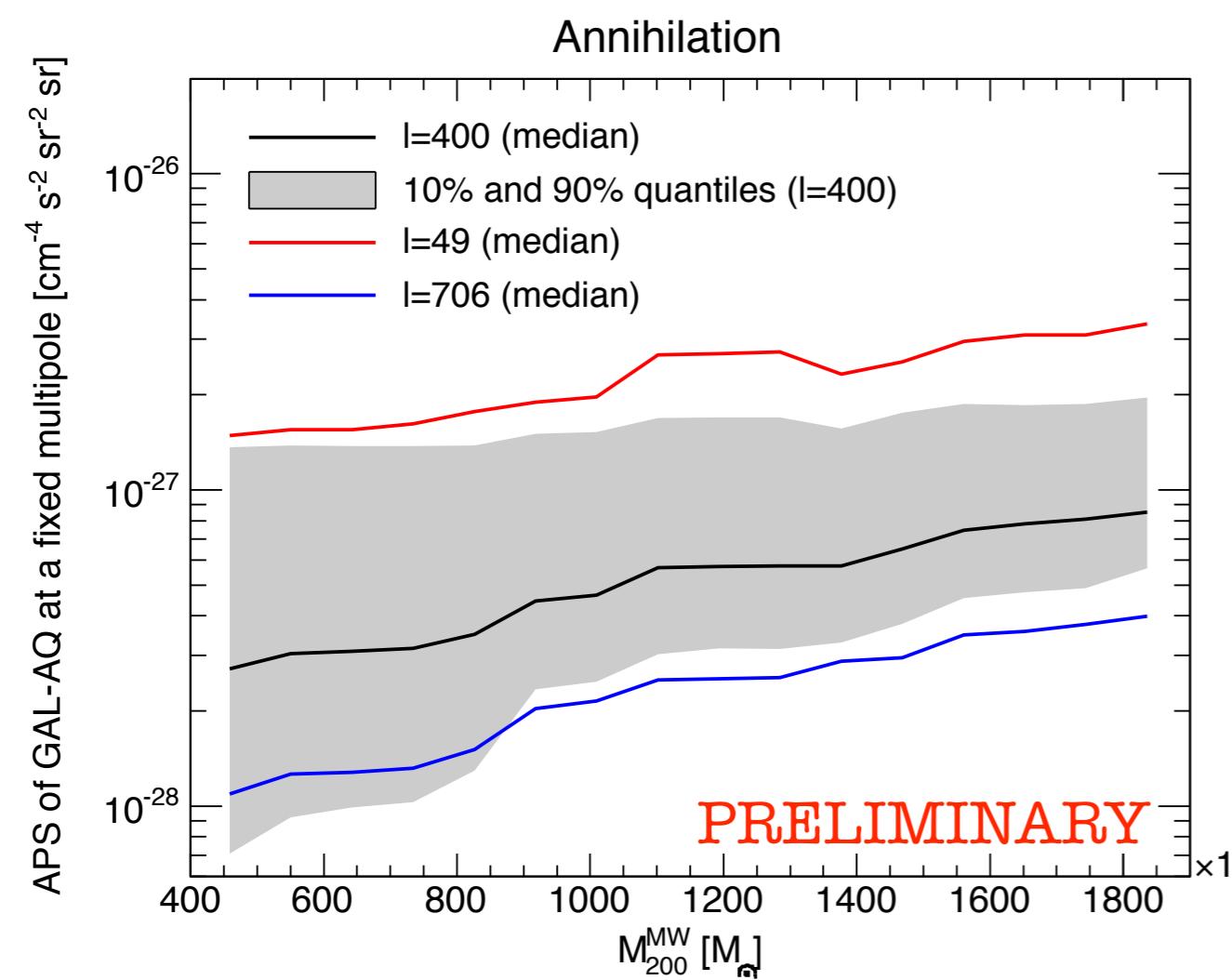
# DM-induced emission

- 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)



# 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  $M_{\text{MW}}$  accounting for a correspondent depletion in the amount of Galactic subhalos
- including uncertainty on the position of the observer

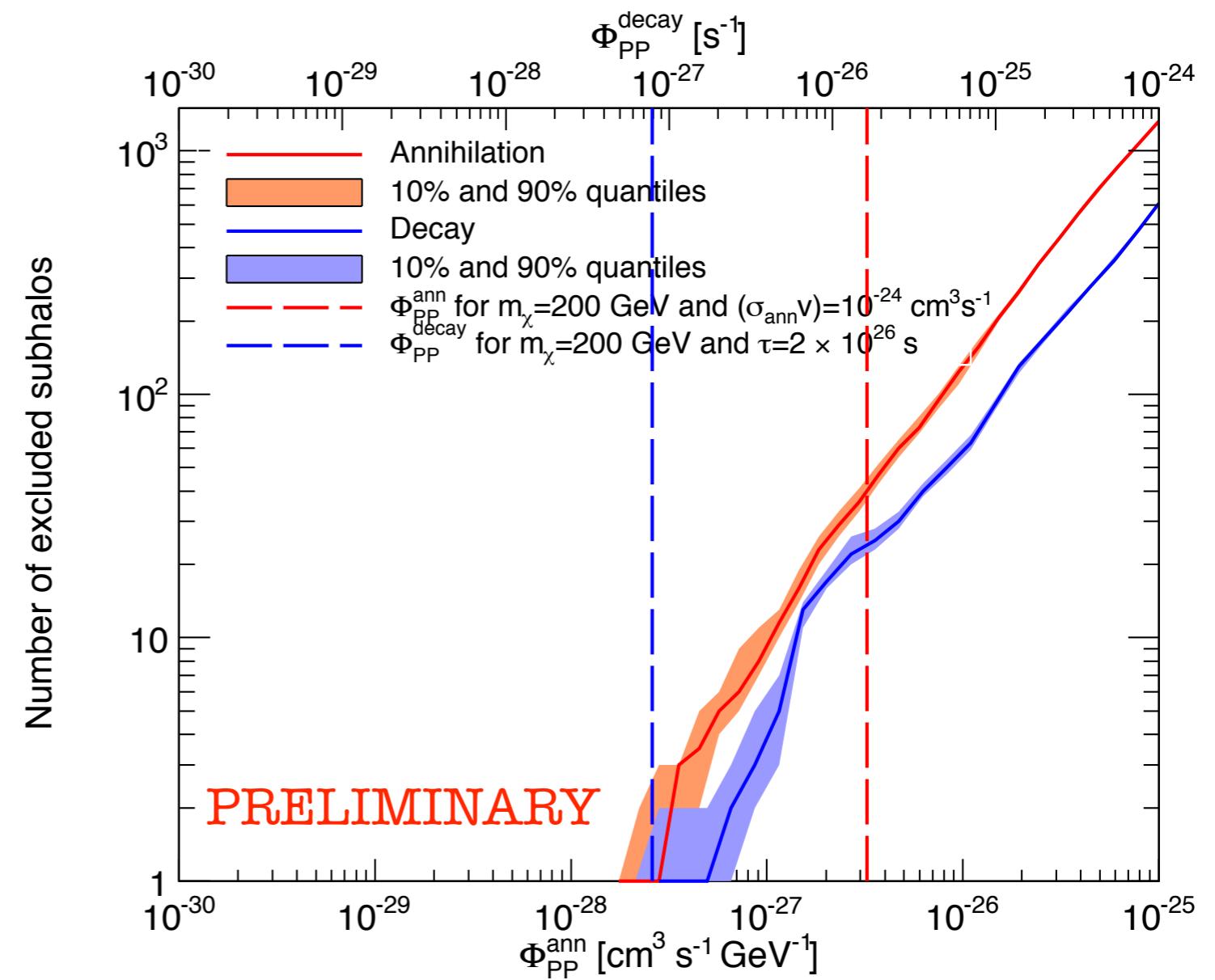


# Effect of an too-bright subhalos on GAL-AQ

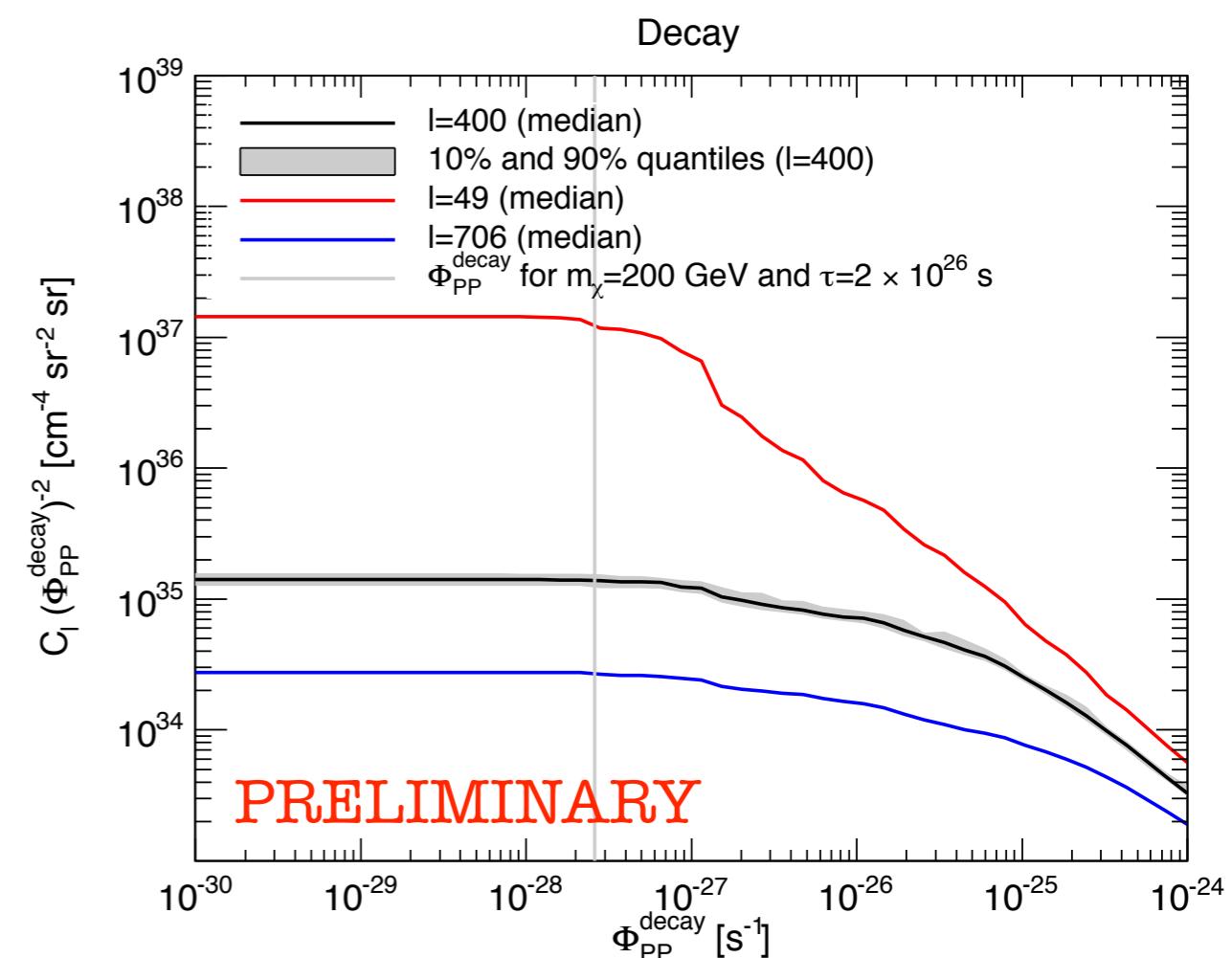
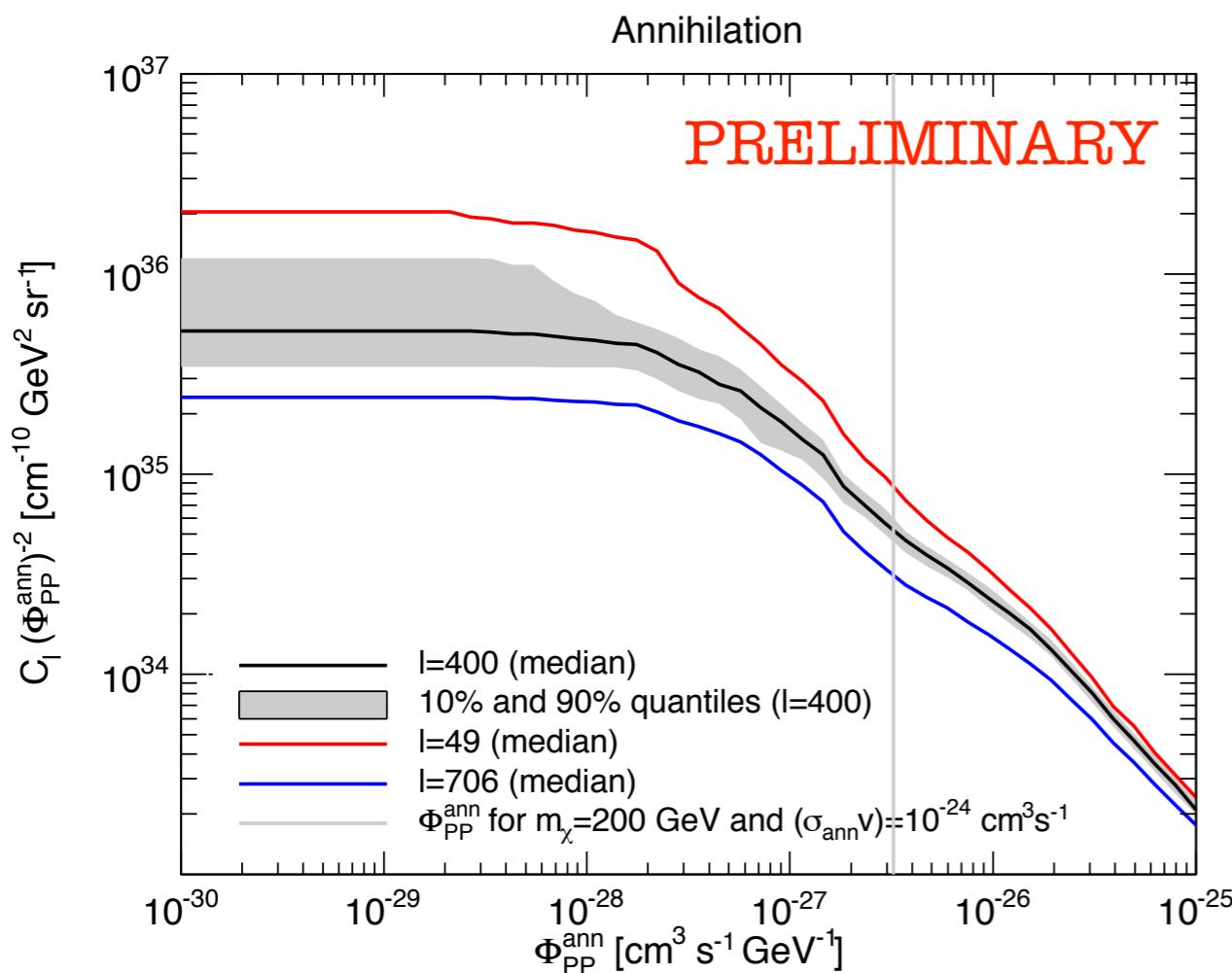
- for certain combination of  $(m_\chi, \sigma_{\text{ann}}v)$  and  $(m_\chi, \tau)$ , some subhalos are brighter than the 3FGL sensitivity
- those structures should be masked

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

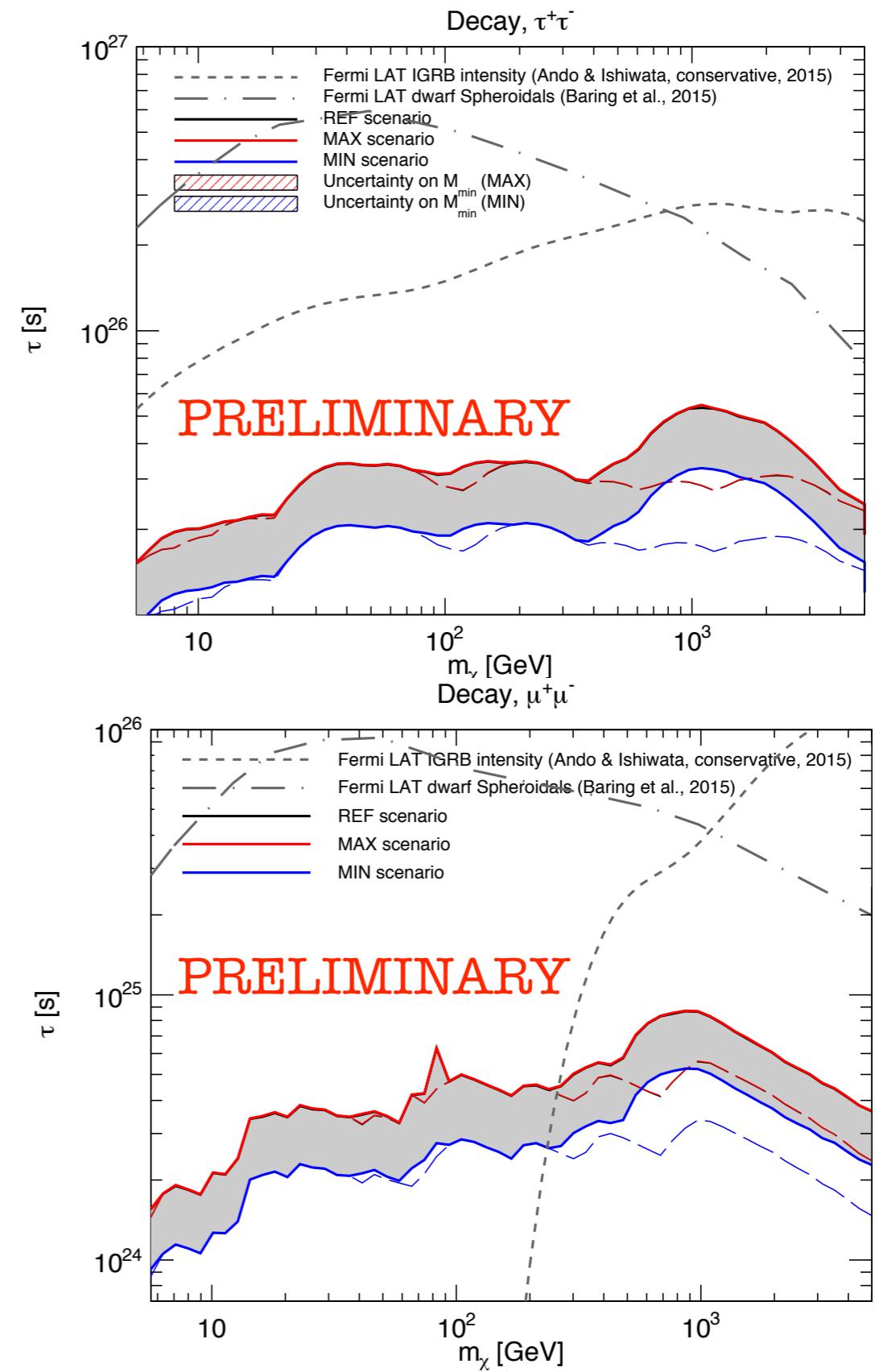
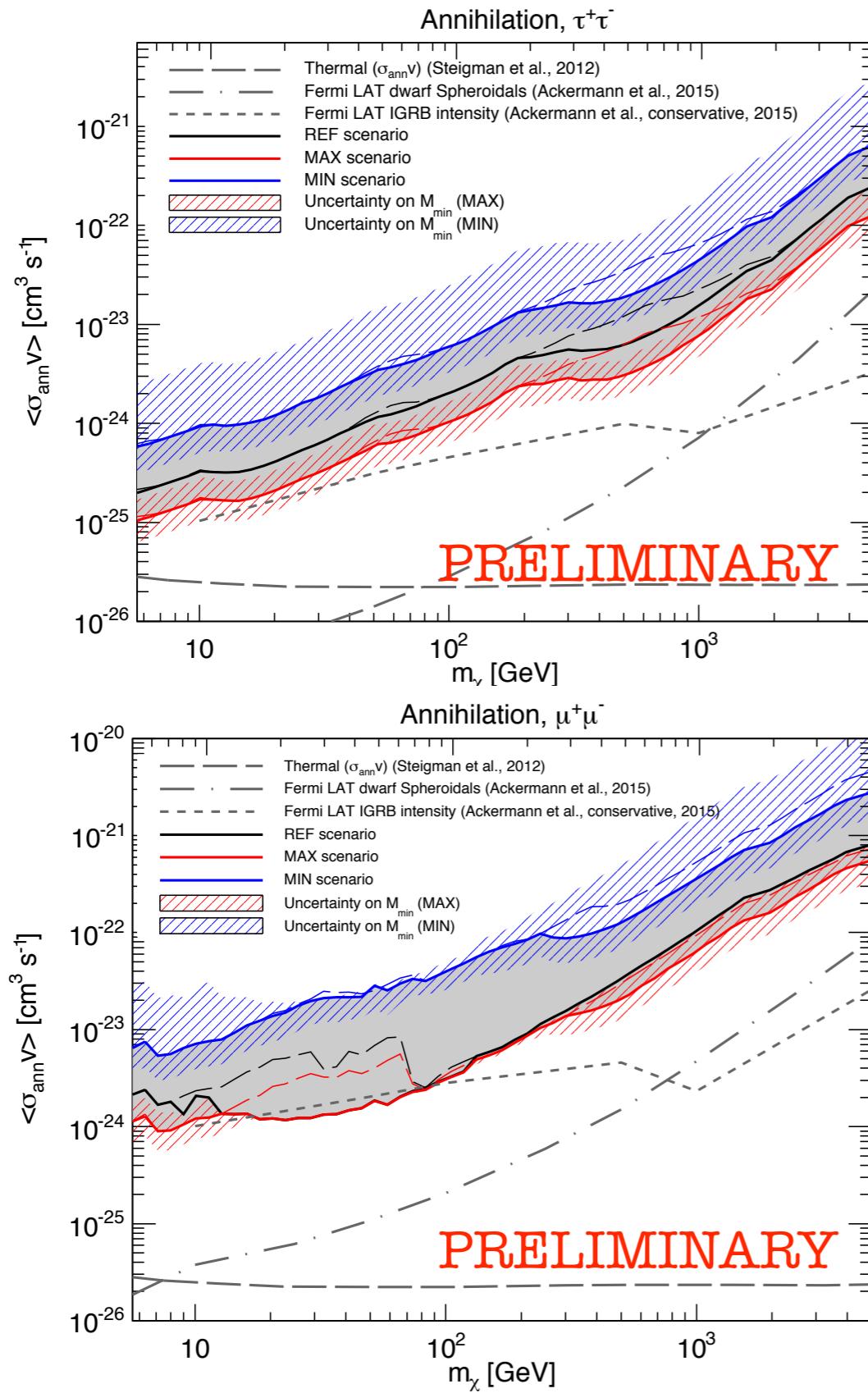
$$\Phi_{\text{PP}}^{\text{decay}} = \frac{1}{m_\chi \tau} \int_{\bar{E}} E \frac{dN_\gamma^{\text{decay}}}{dE} dE$$



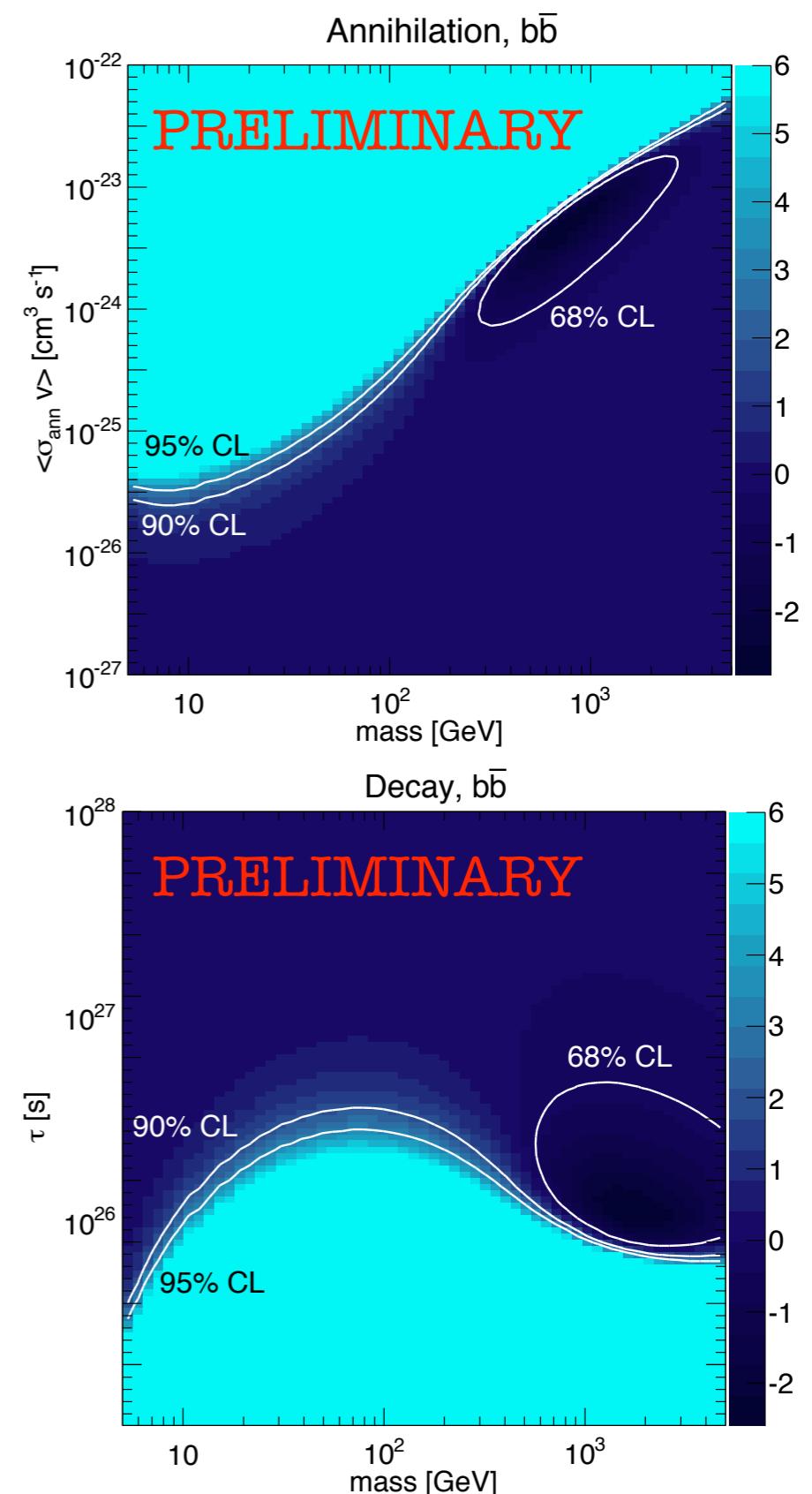
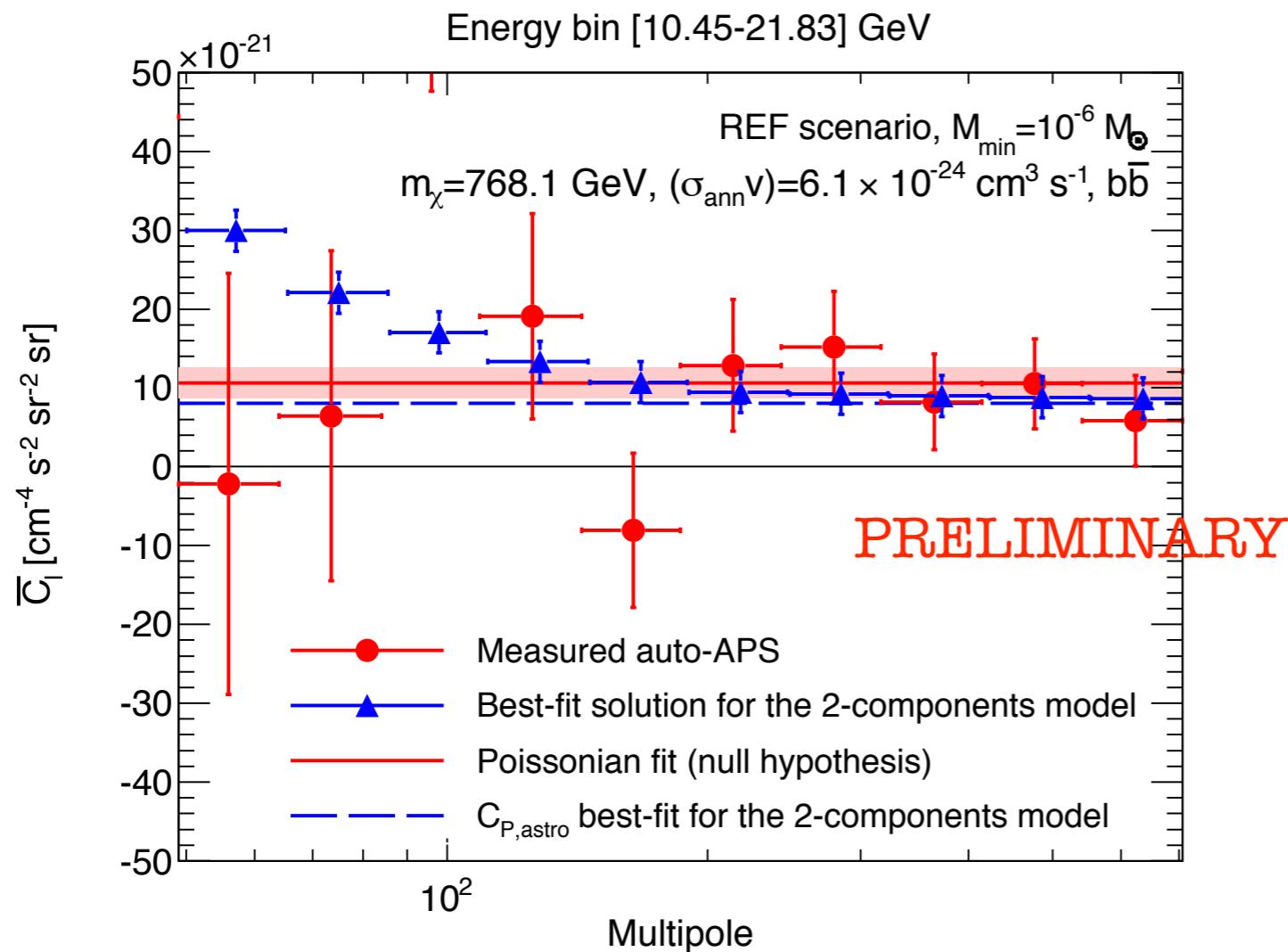
# Effect of an too-bright subhalos on GAL-AQ



# Conservative limits

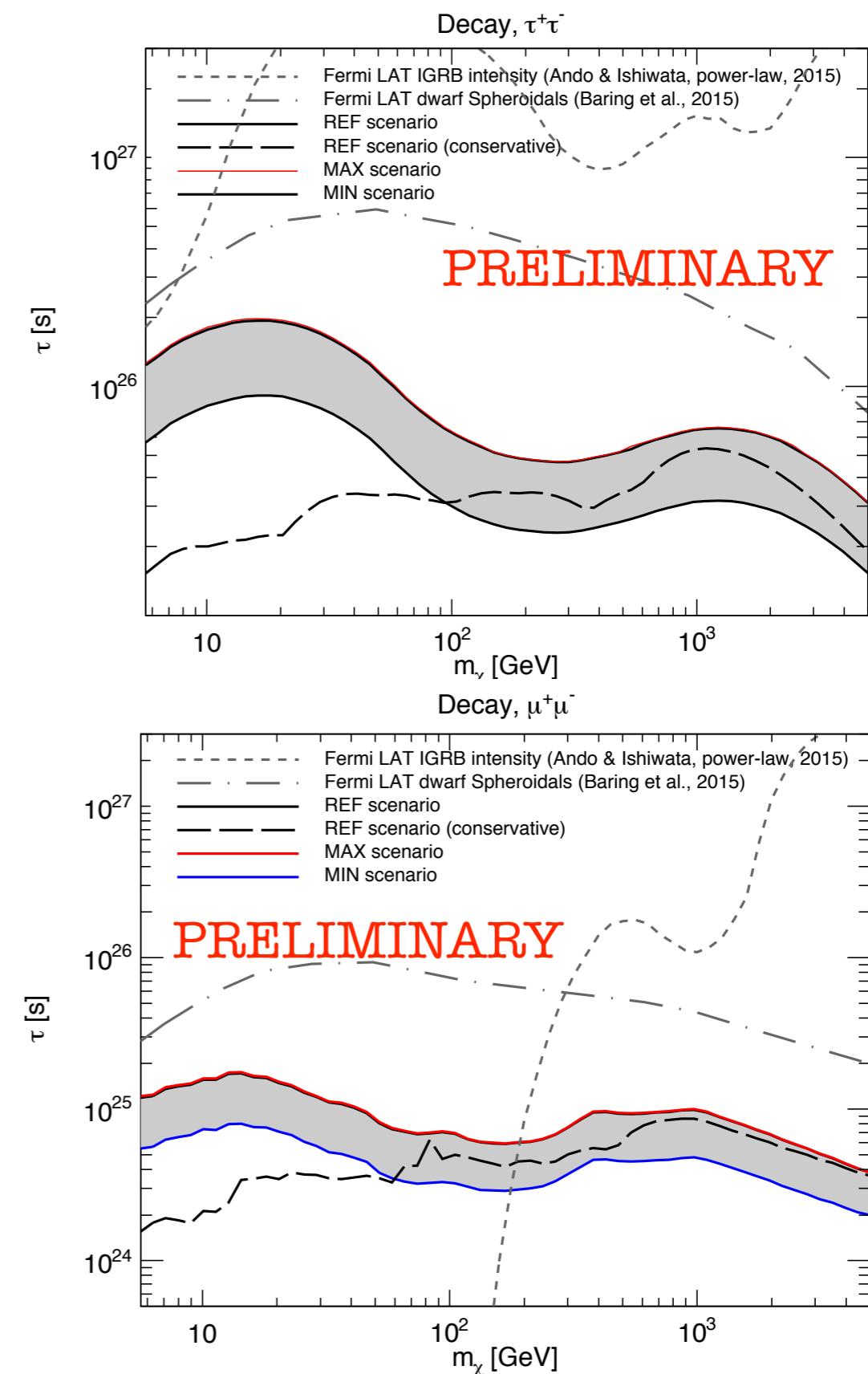
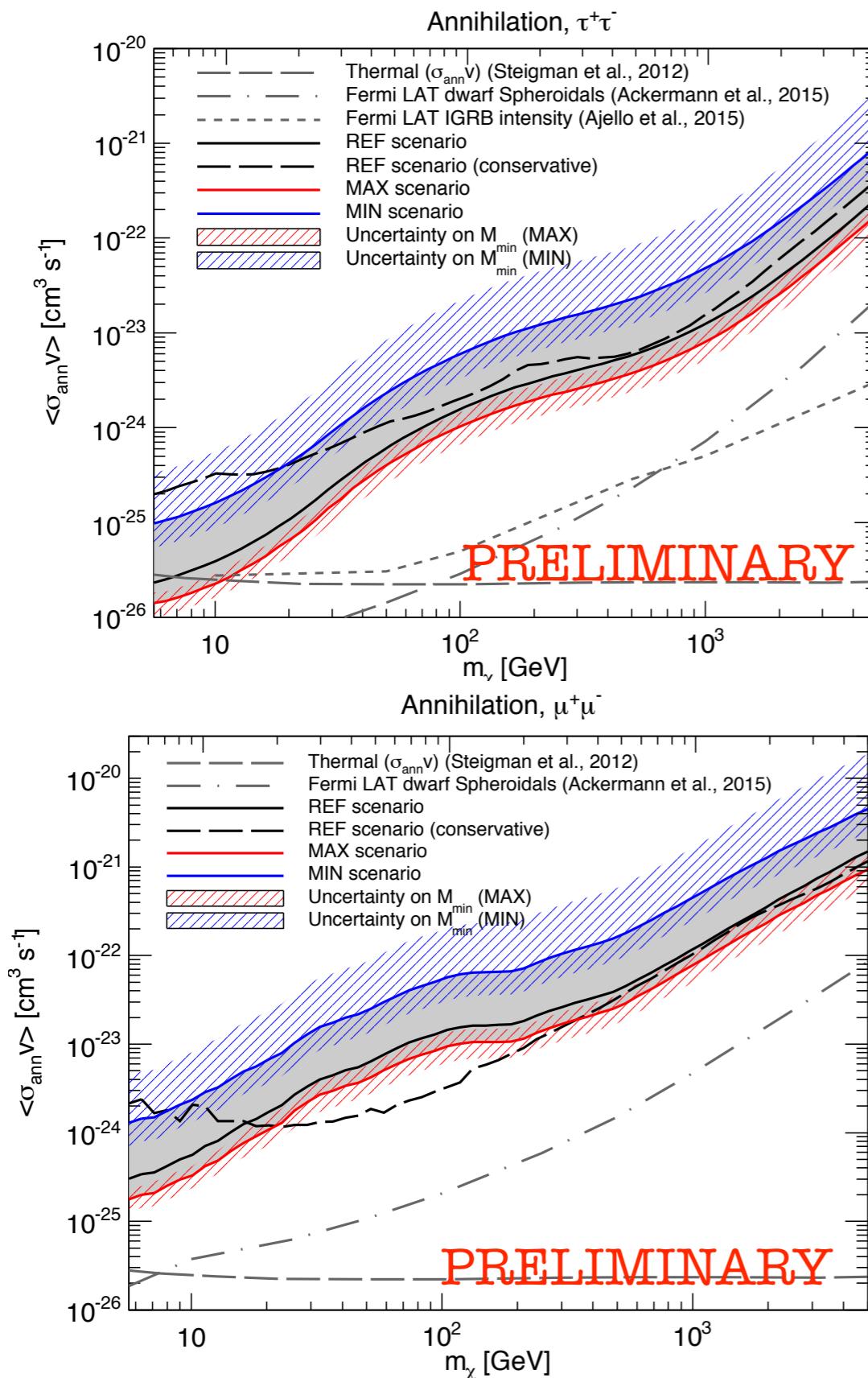


# 2-component fit to the binned APS



- $\text{TS} = -2 \ln[\chi^2(\text{no DM})] + 2 \ln[\chi^2(m_{\chi}, \sigma v)]$
- annihilation best fit:  $\text{TS}=xx$ ,  $m_{\chi}=768.1$  GeV,  $\langle \sigma_{\text{ann}} v \rangle=4.86 \times 10^{-24} \text{ cm}^3 \text{s}^{-1}$
- decay best fit:  $\text{TS}=xx$ ,  $m_{\chi}=1743.2$  GeV,  $\tau=1.15 \times 10^{26} \text{ s}$

# Exclusion limits from 2-component fit



# TS from 2-component fit

