GRAPPA
GRavitation AstroParticle Physics Amsterdam

Model-independent interpretation of the 2016 *Fermi* LAT measurement of gamma-ray anisotropies

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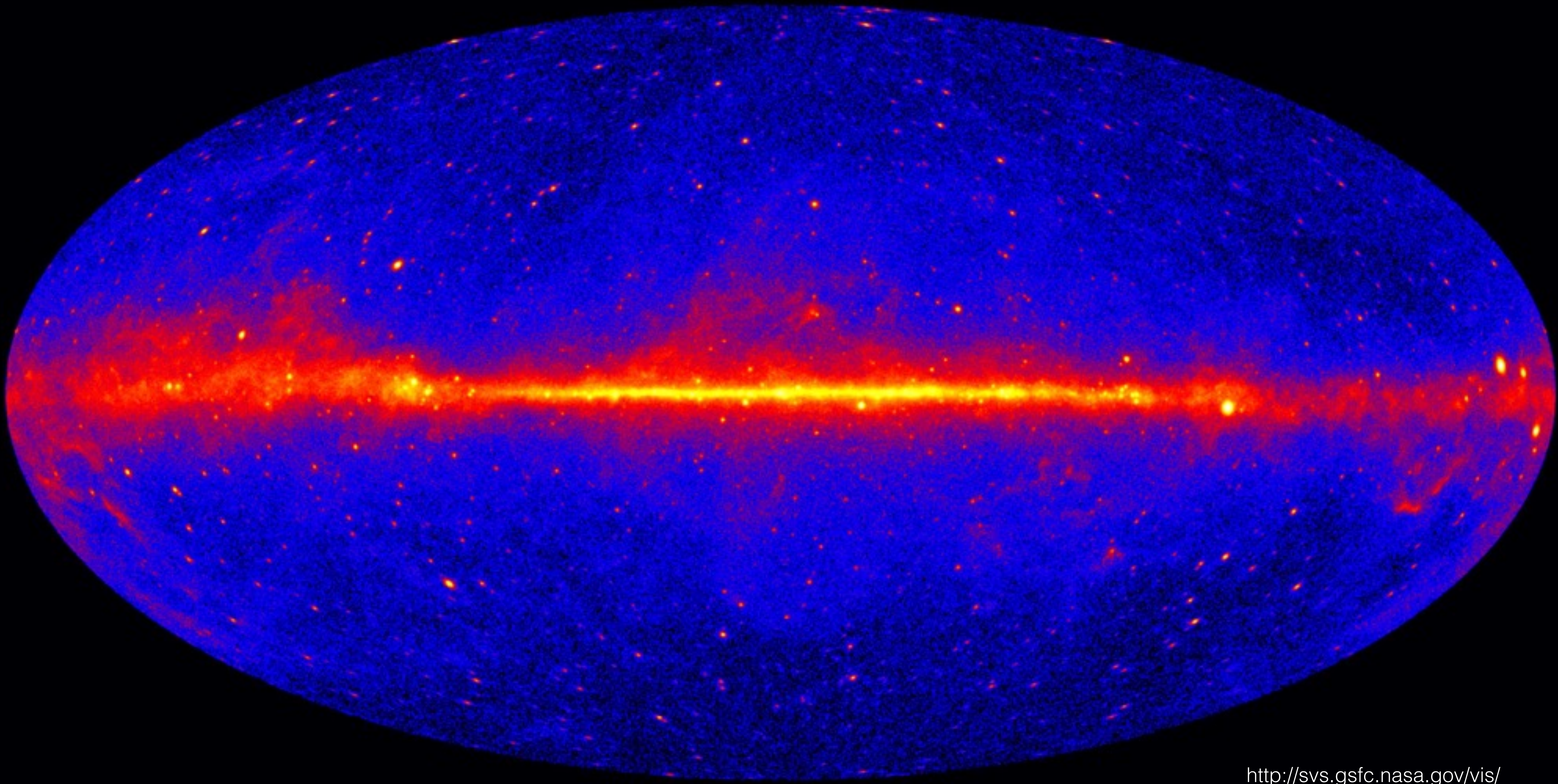
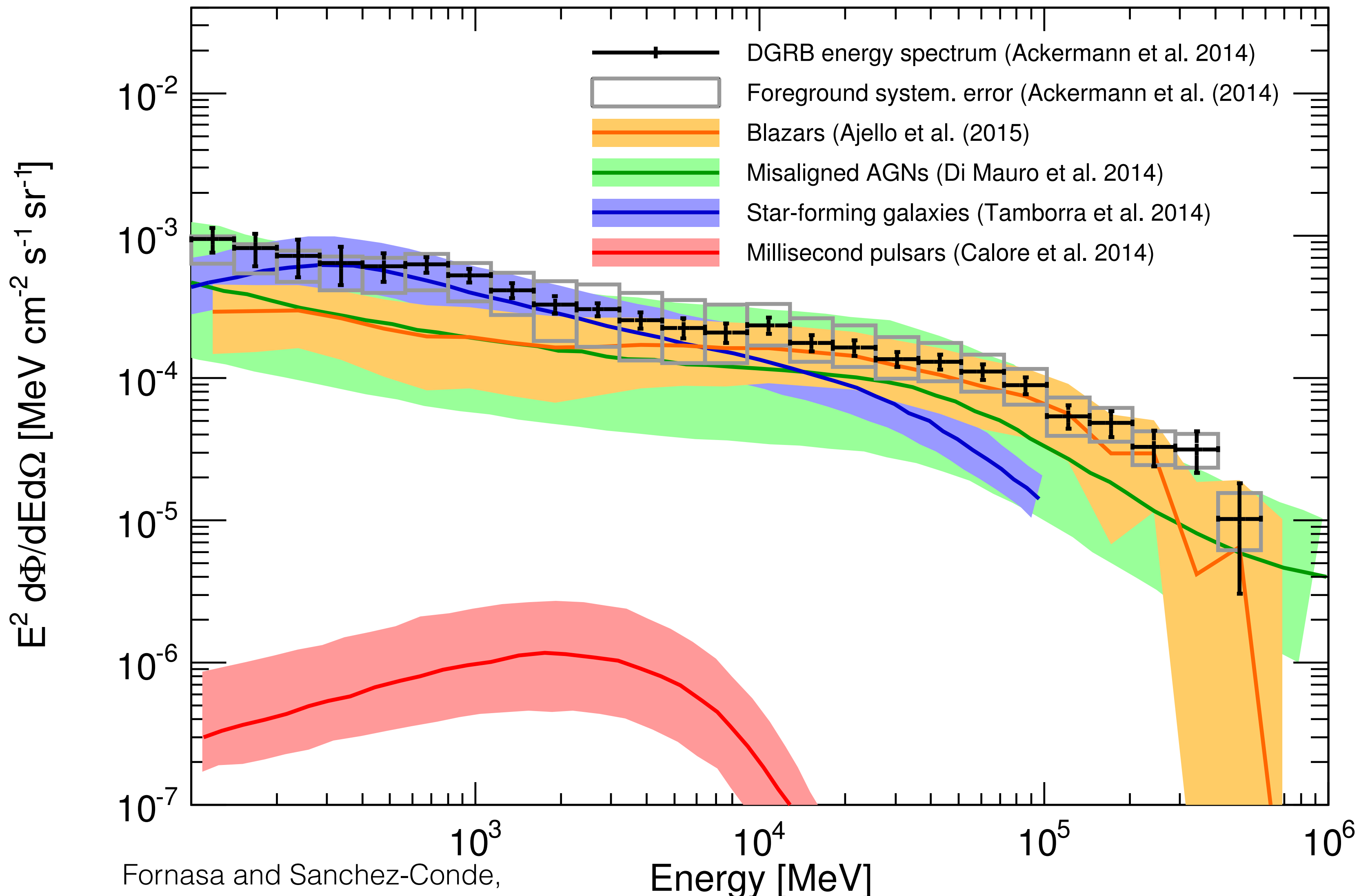
The Diffuse Gamma-Ray Background (DGRB)



http://svs.gsfc.nasa.gov/vis/a010000/a011300/a011342/

The DGRB energy spectrum

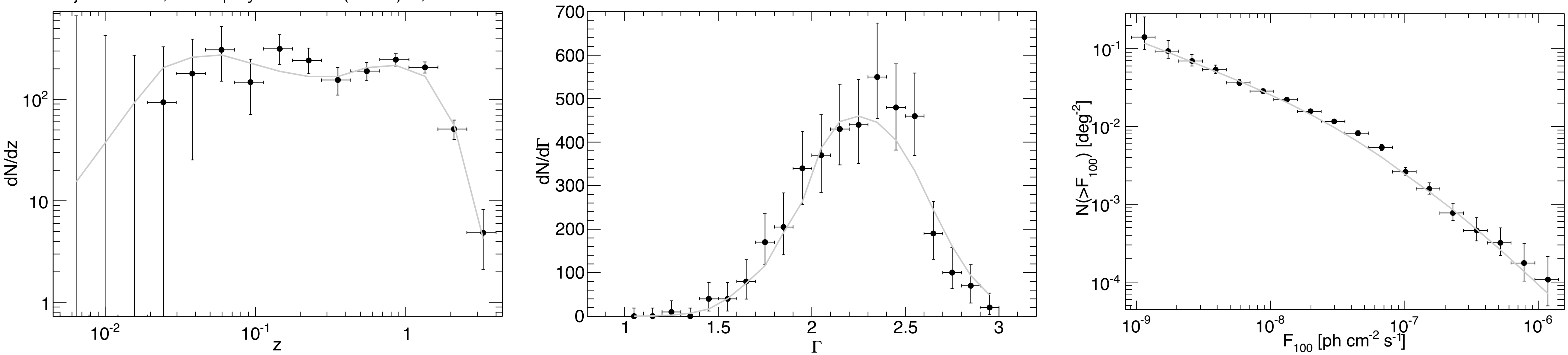


Fornasa and Sanchez-Conde,
Phys. Rept. 598 (2015) 1-58

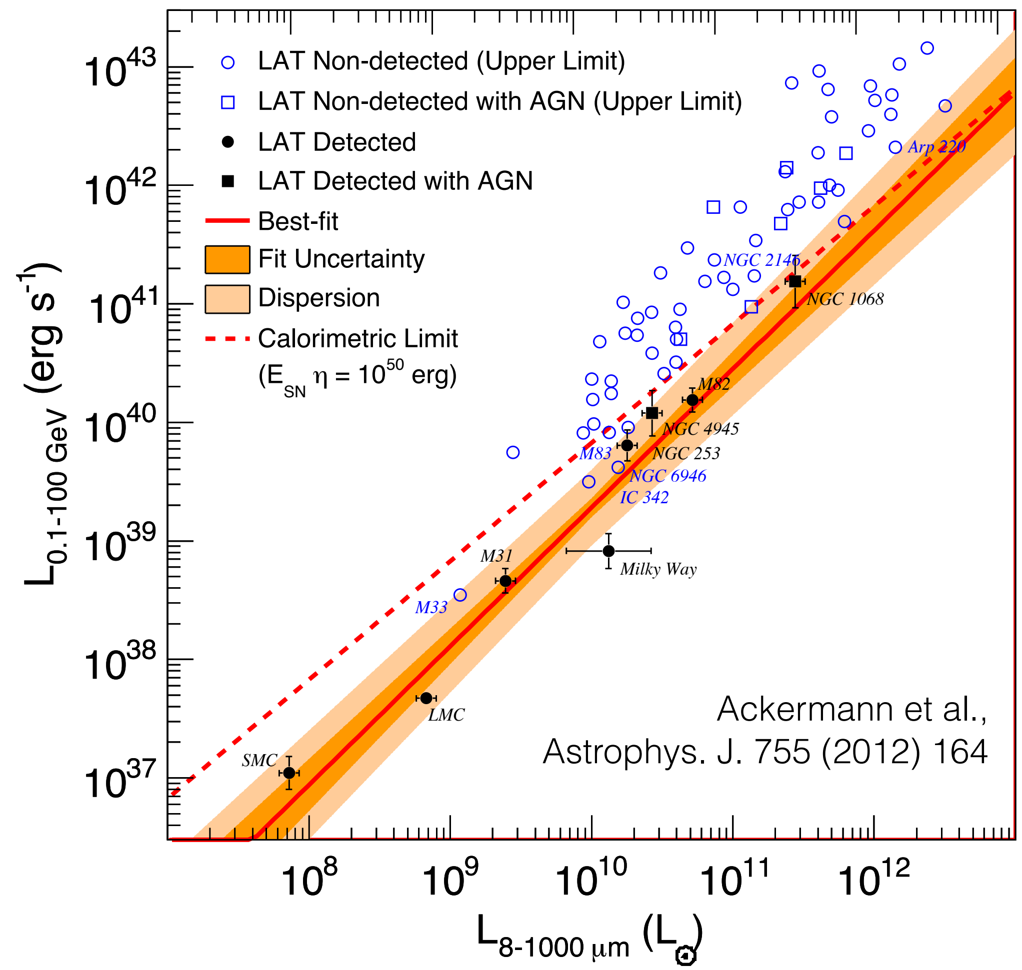
- cumulative emission of unresolved sources (blazars, star-forming galaxies, misaligned AGNs, …)
- model their luminosity functions, distributions and emission mechanisms and constrain them with observations of detected sources

Model-dependent approach

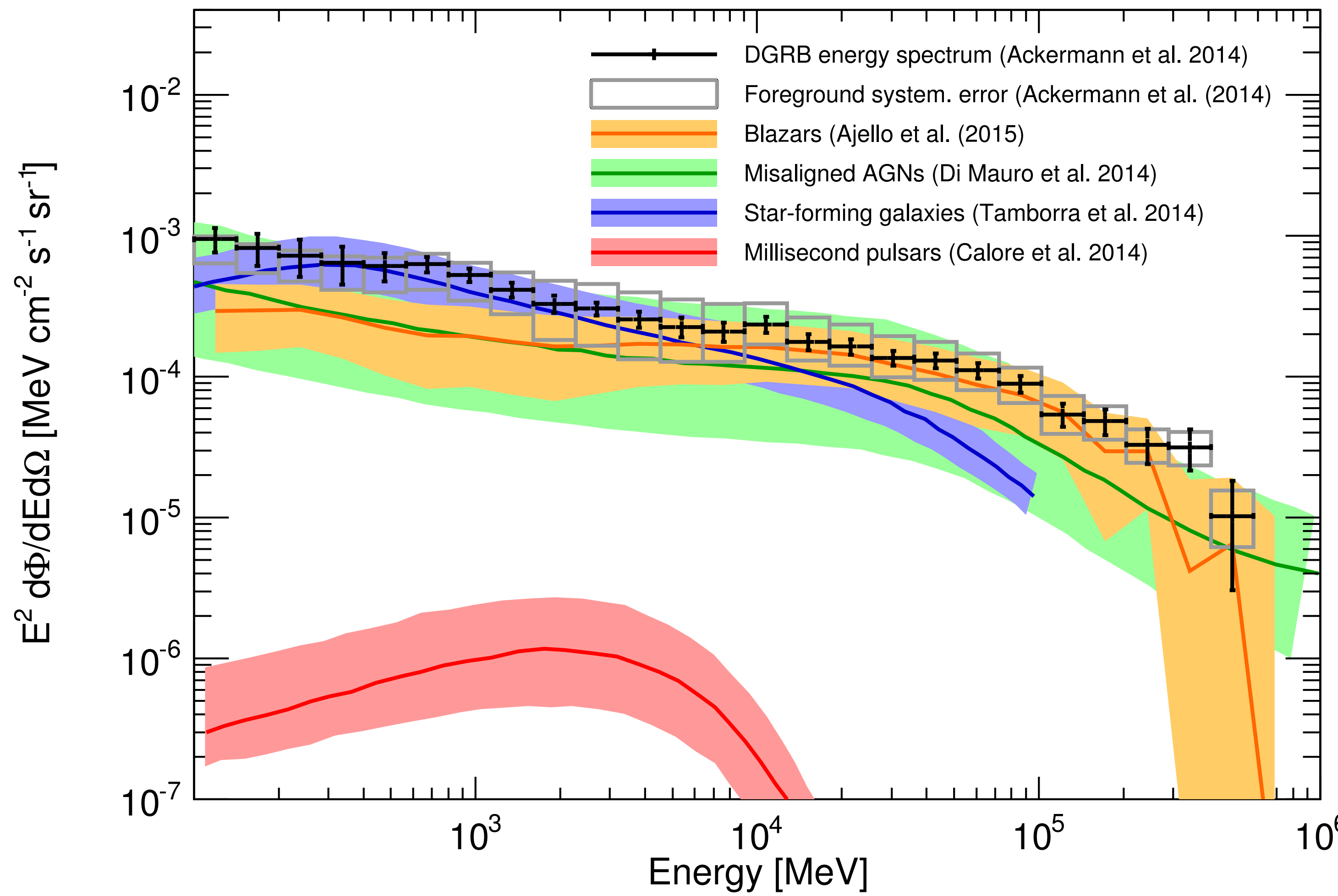
Ajello et al., Astrophys. J. 800 (2015) 2, L27



- abundant sources (blazars): population studies on resolved emitters
- rare sources (star-forming galaxies and misaligned AGNs): assume correlation with other frequencies



Anisotropies and angular power spectrum (APS)

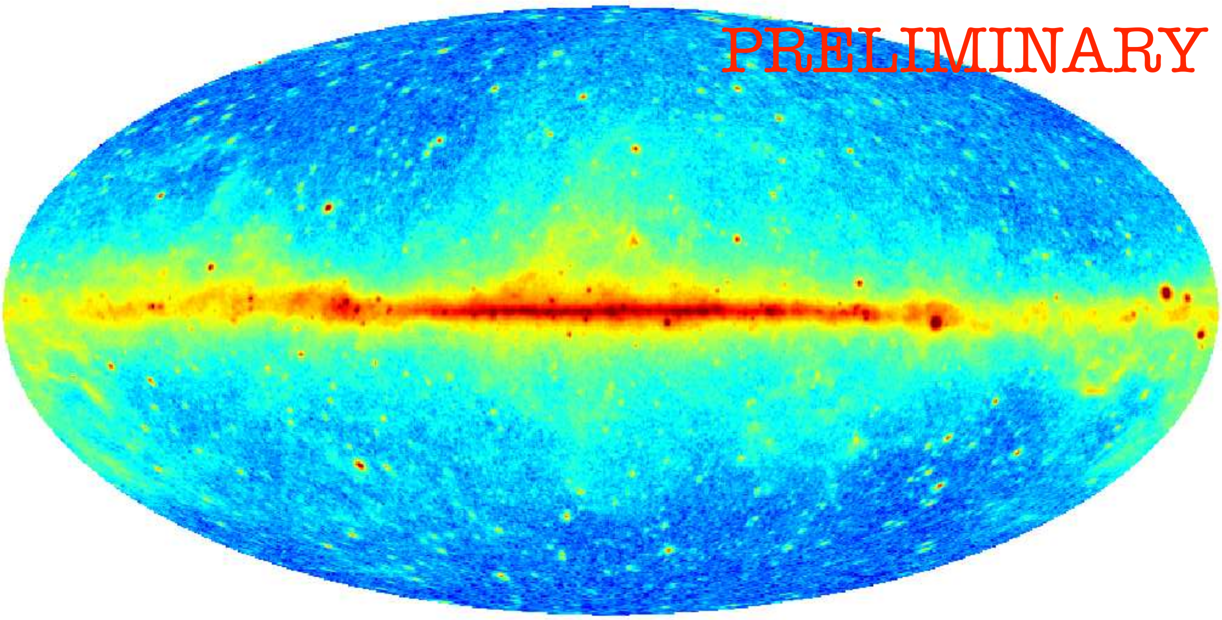


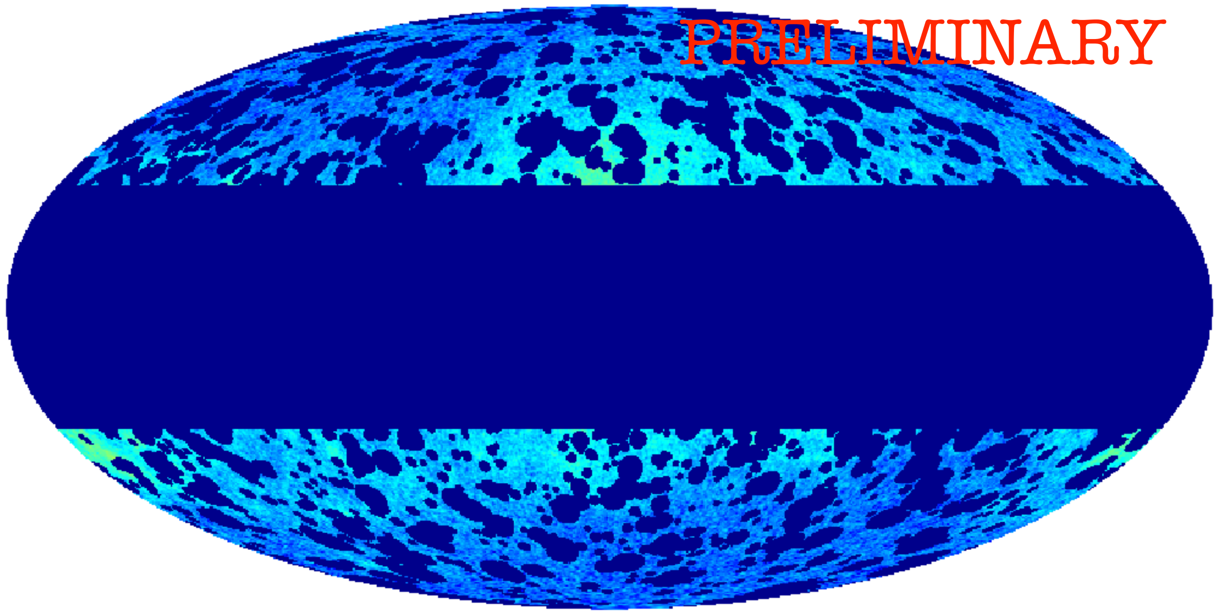
Fornasa and Sanchez-Conde, Phys. Rept. 598 (2015) 1-58

- anisotropies provide a complementary way to reconstruct the composition of the DGRB
- same model can be used to predict the anisotropy APS of unresolved sources

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

New APS measurement





Ackermann et al. (2012)	Fornasa et al. (2016)
22 months	81 months
Pass 6 (DIFFUSE_v3) front and back	Pass 7 reprocessed (ULTRACLEAN_v15) front
4 energy bins between 1-50 GeV	13 energy bins between 0.5-500 GeV
masking sources in 1FGL	masking sources in 3FGL (and 2FGL)

APS estimator

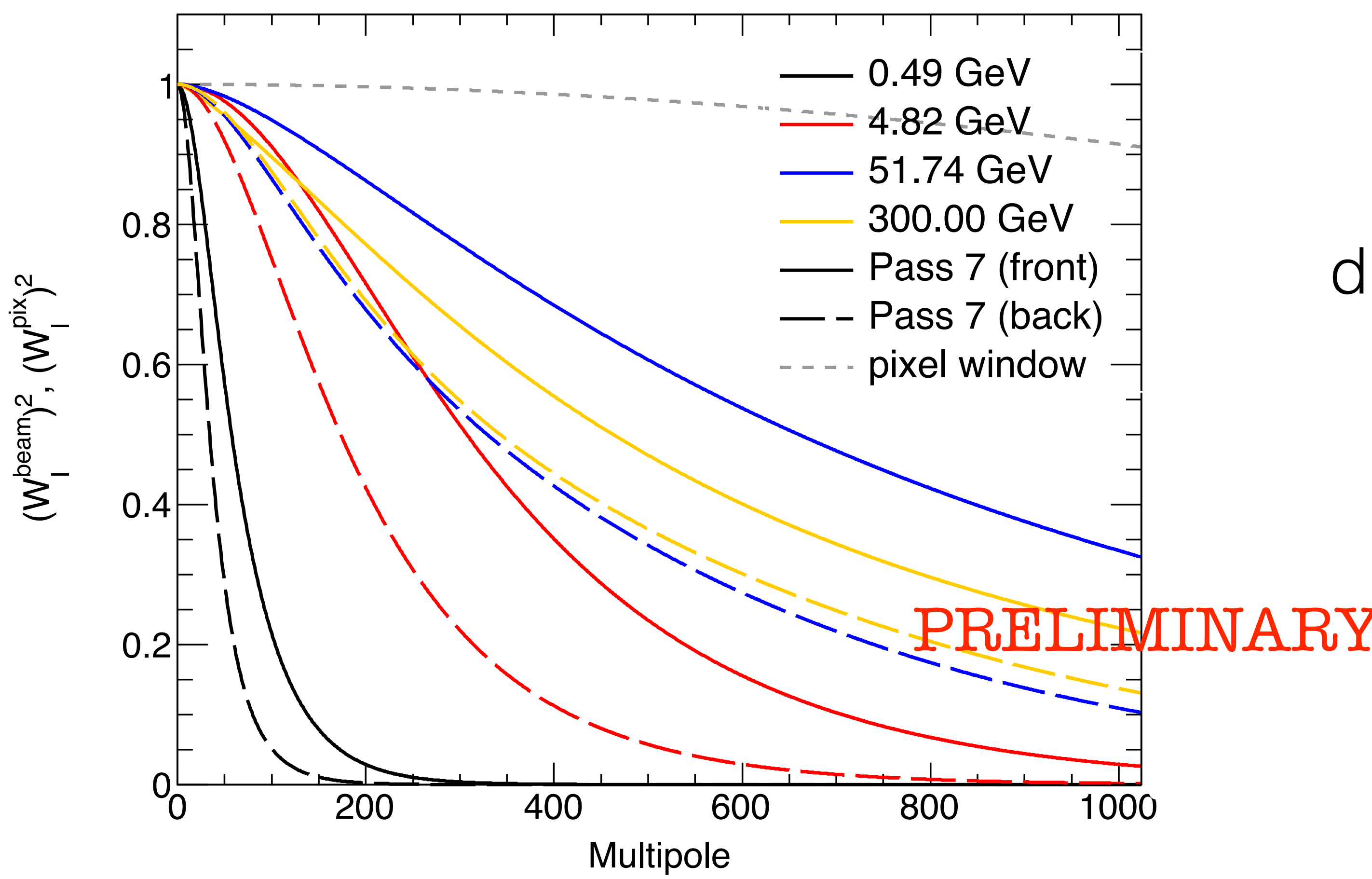
$$C_\ell^{\mathrm{signal},ij} = \frac{C_\ell^{\mathrm{Pol},ij} - C_\mathrm{N}}{(W_\ell^{\mathrm{beam},i} W_\ell^{\mathrm{beam},j})(W_\ell^{\mathrm{pix}})^2}$$

cross-correlation between energy bins

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

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

beam window function

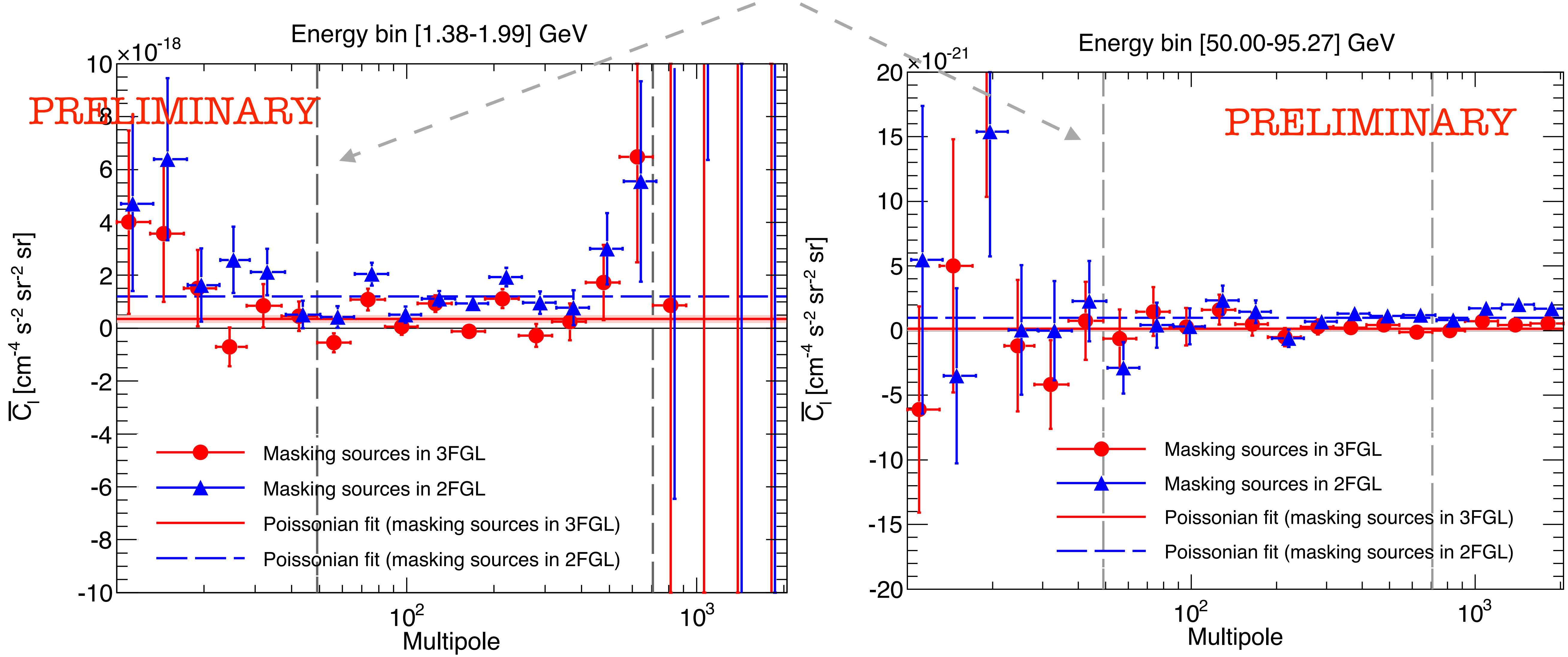


$$C_\mathrm{N}^k = \frac{\langle n_{\gamma,\mathrm{pix}}^k / (A_\mathrm{pix}^k)^2 \rangle}{\Omega_\mathrm{pix}}$$

averaging number counts divided by the exposure over the unmasked sky

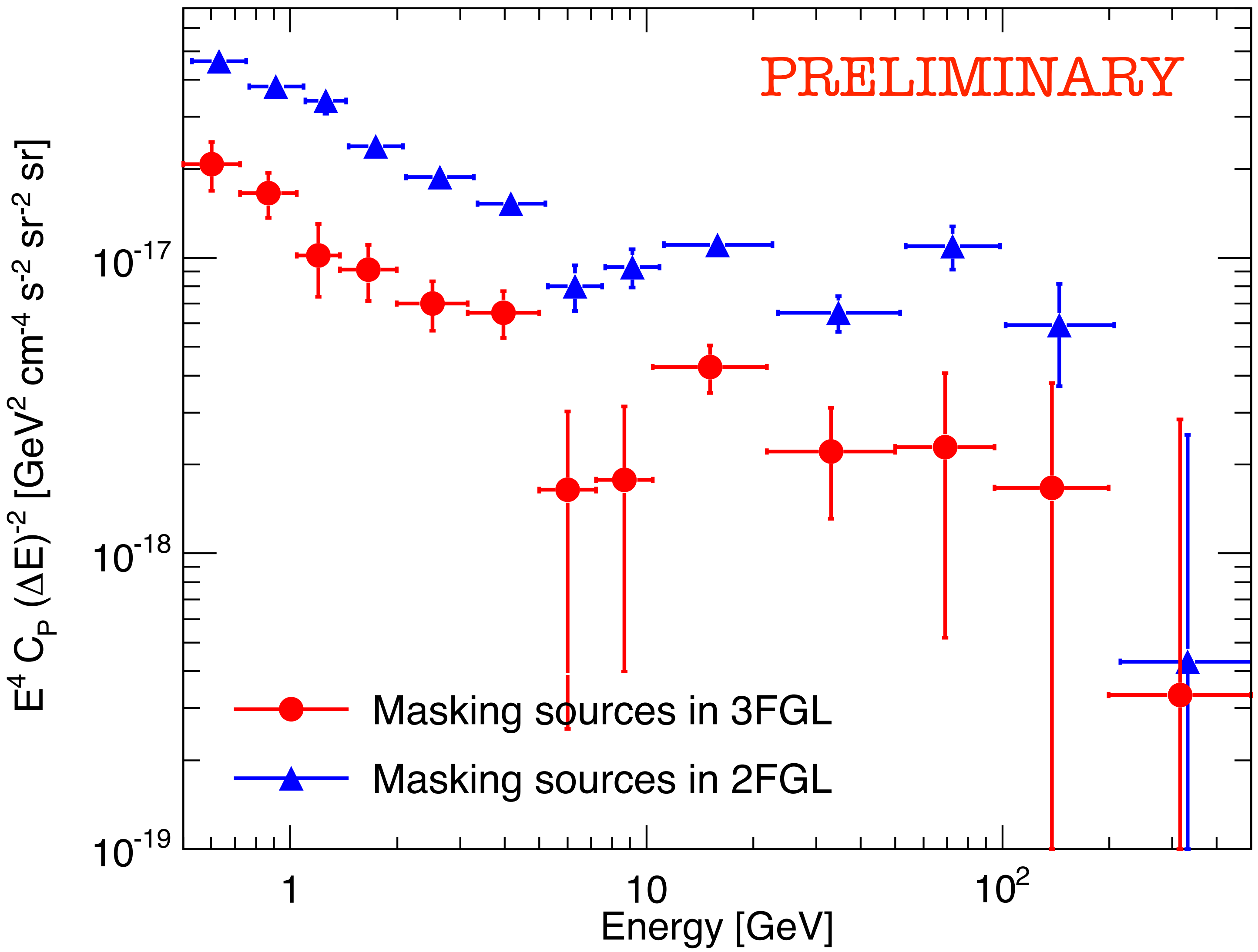
Binned APS measurement

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
- fits with $A(\ell/\ell 0)^\alpha$ and $C_P + A(\ell/\ell_0)^\alpha$ have also been considered

Anisotropy energy spectrum



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

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

- factor out the energy dependence

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

- one population of sources: the energy spectrum can be inferred from the anisotropy energy spectrum

Cross-correlation APS

- 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 indicate multiple populations of sources

- cross-correlation APS:

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

- cross-correlation coefficients:

$$r_{i,j} = \frac{C_{\mathrm{P}}^{i,j}}{\sqrt{C_{\mathrm{P}}^{i}\, C_{\mathrm{P}}^{j}}}$$

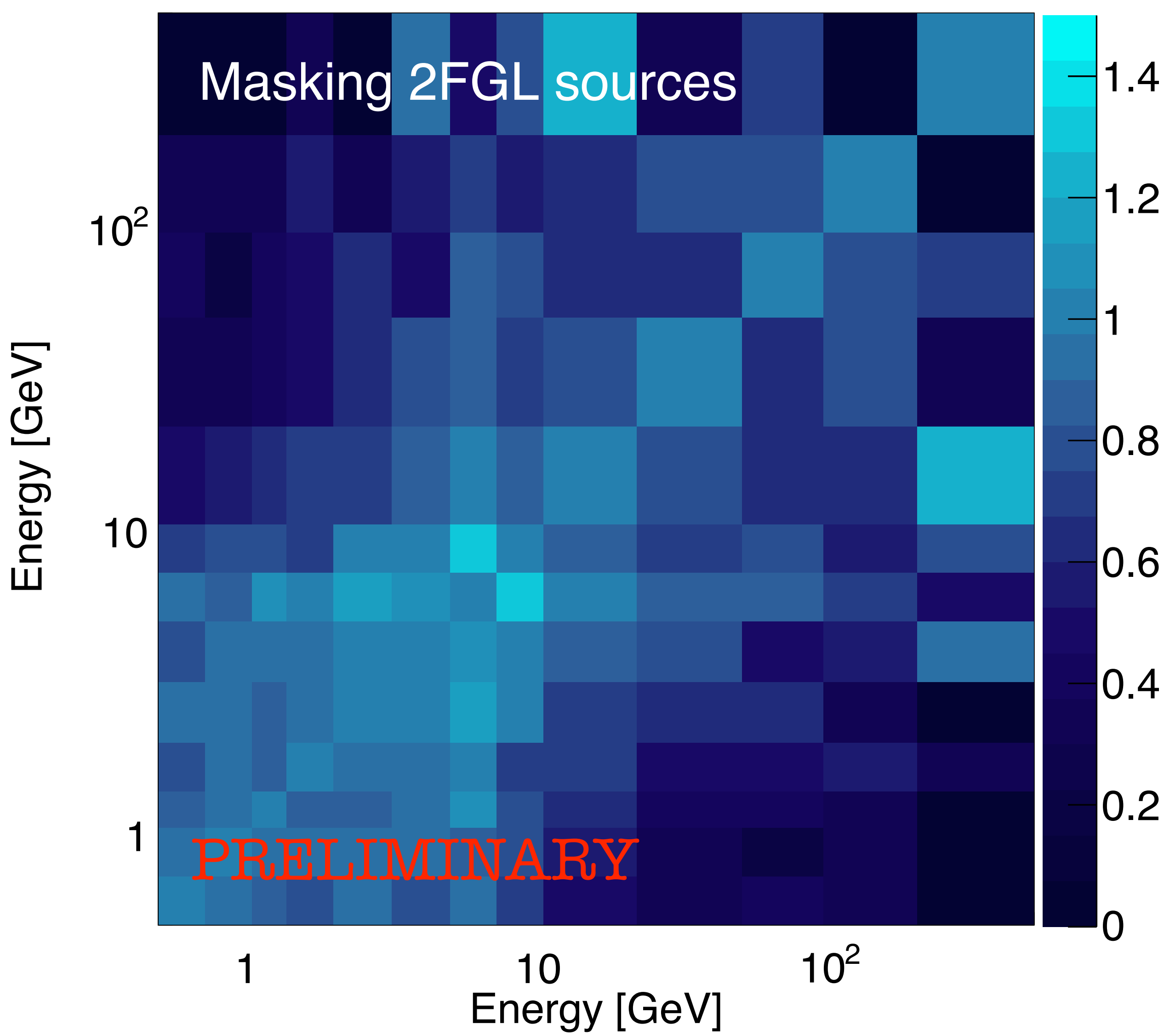
$$C_{\mathrm{P}}^{i,j} = I(E_i)\, I(E_j)\, \tilde{C}_{\mathrm{P}}$$

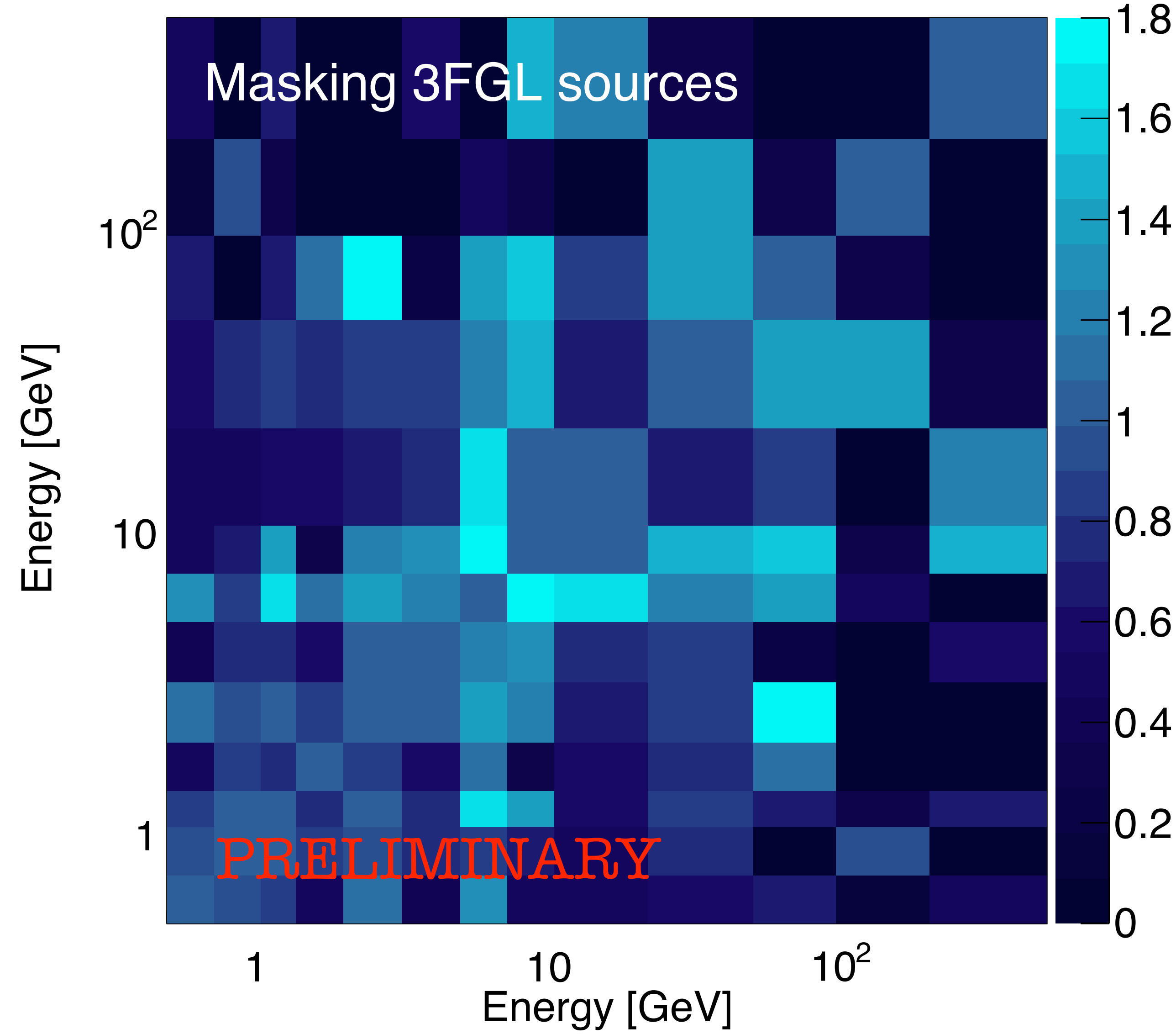
1 population of sources: energy dependence cancels out

2 populations of sources: different energy dependence, no cancellation

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

Cross-correlation coefficients





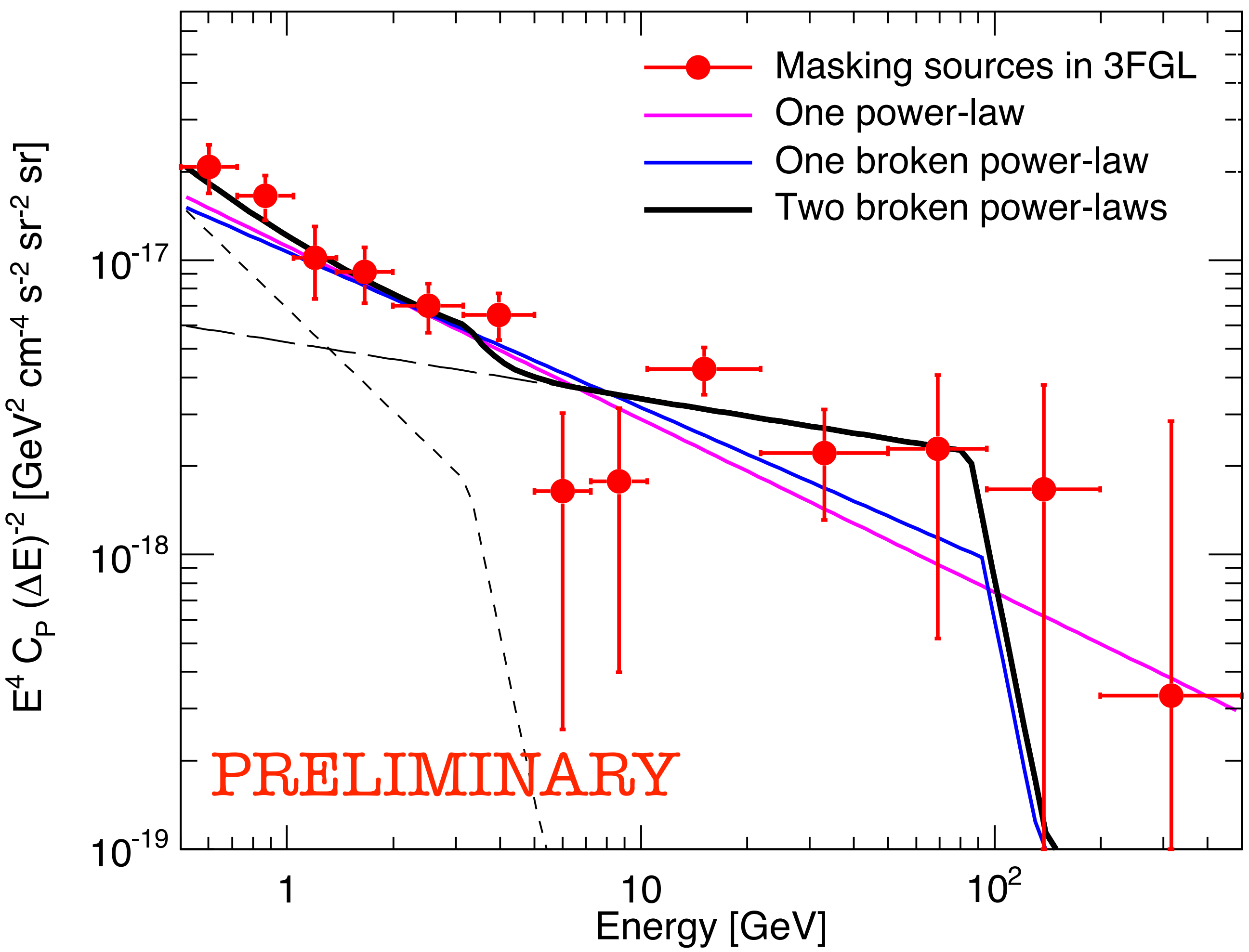
Interpretation in terms of multiple populations

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

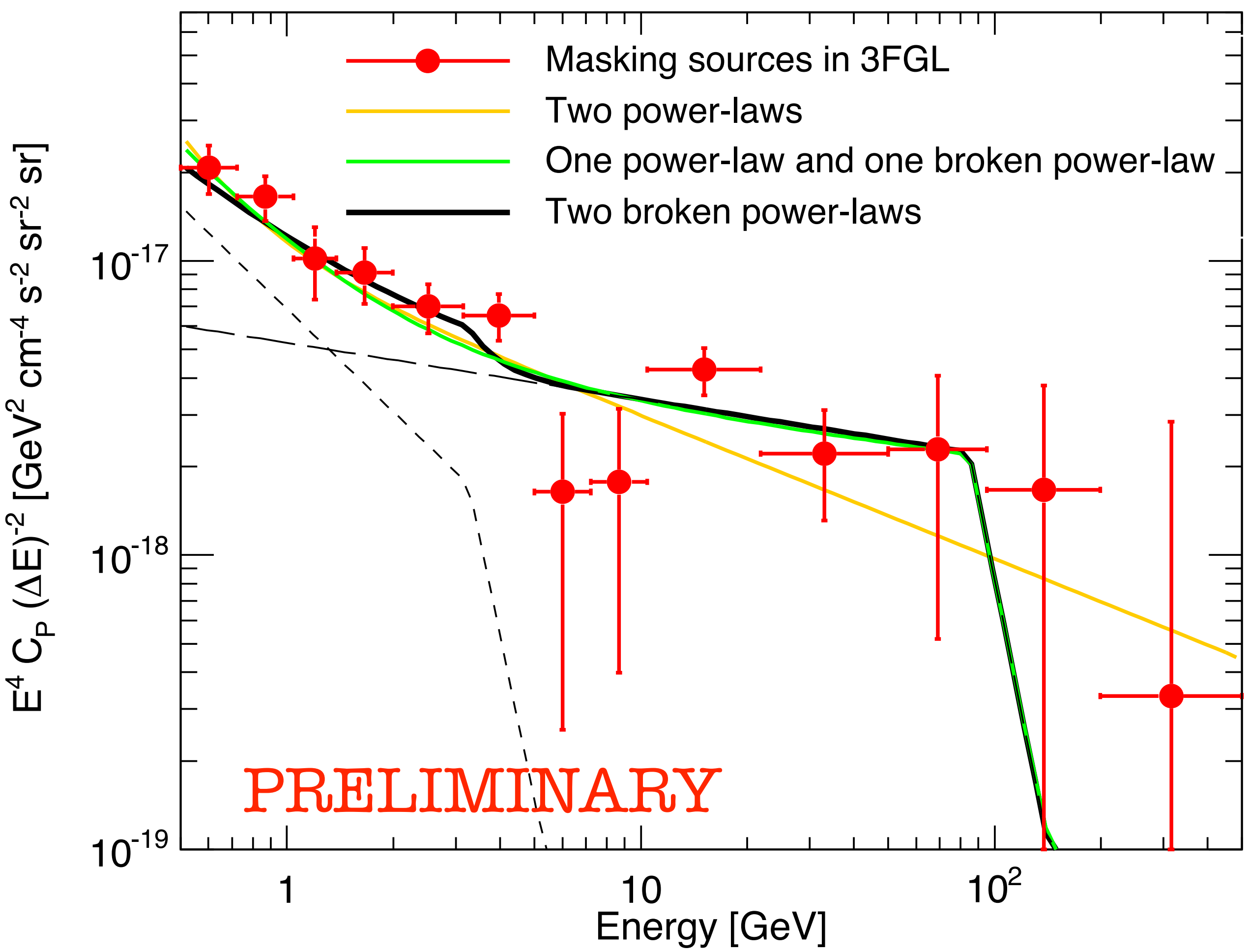
$$I(E) \propto E^{-\alpha}$$

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

1 population



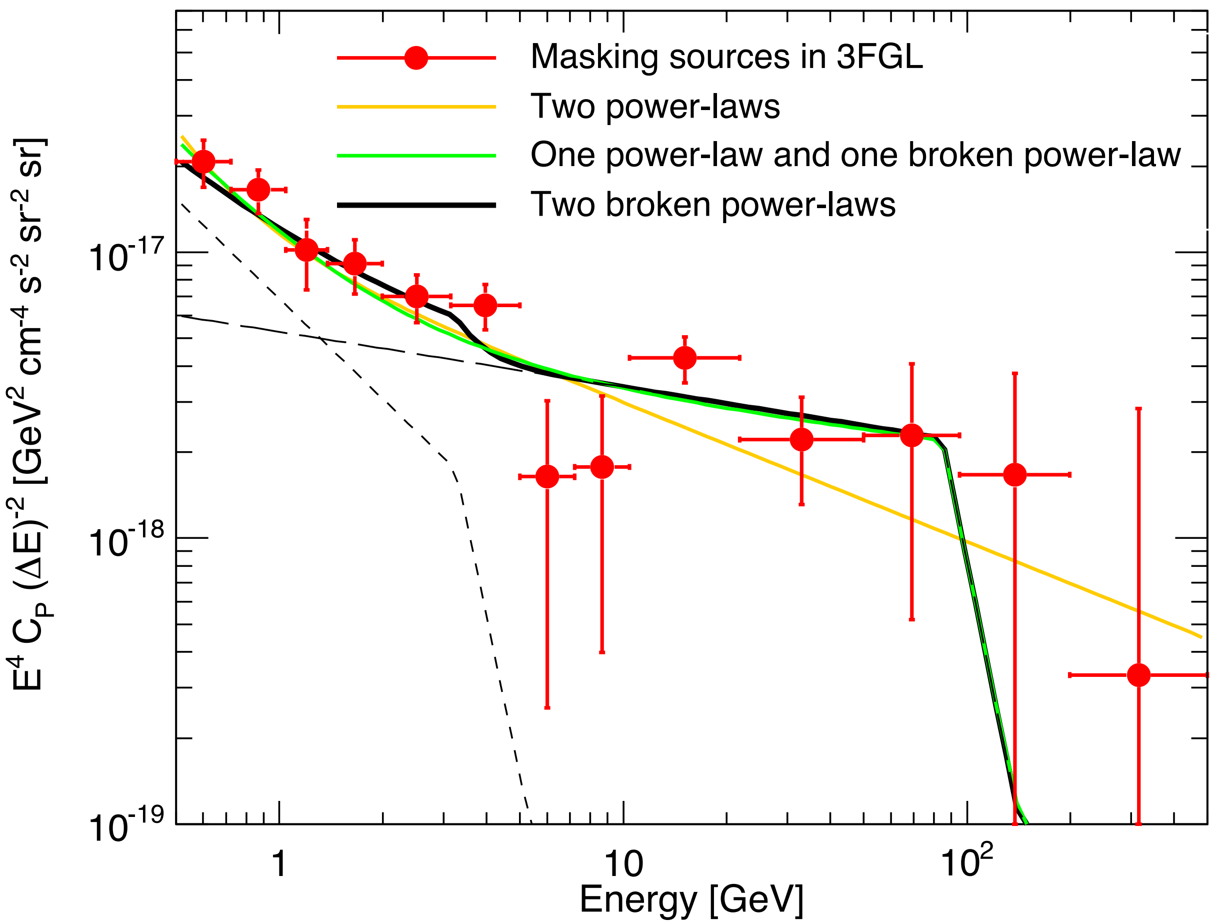
2 populations



Best-fit interpretation

- Two populations of sources emitting 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

Model independent interpretation

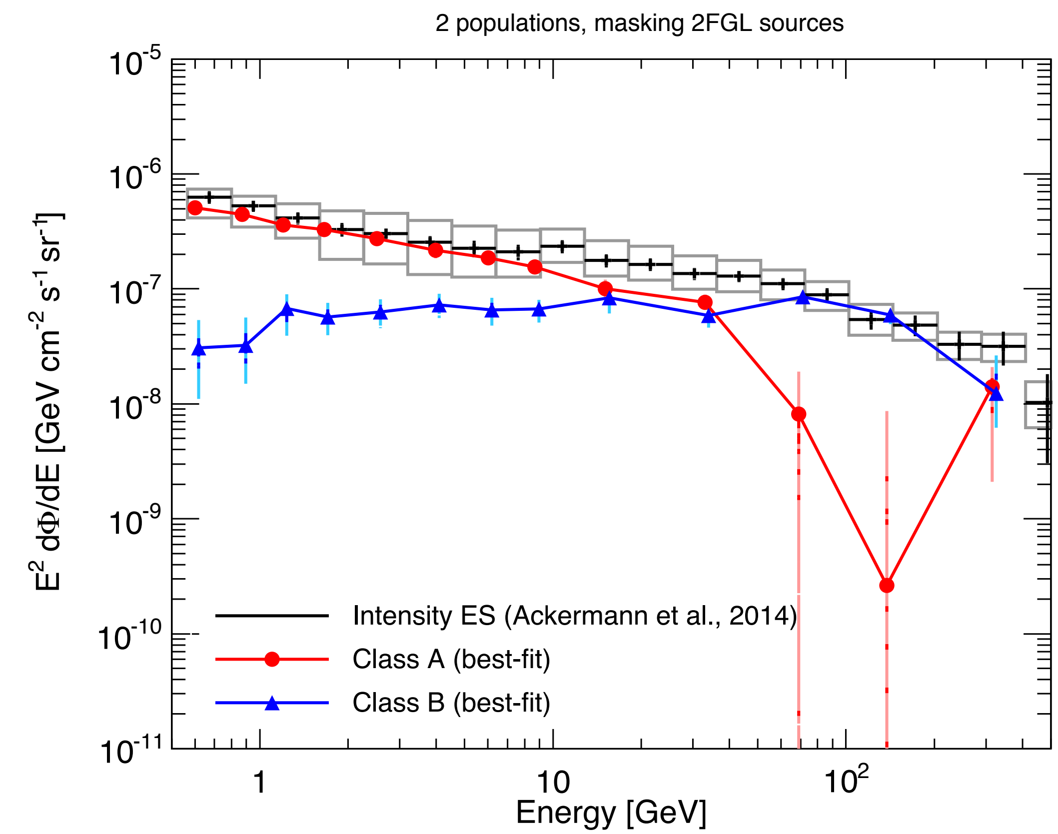
$$C_{\mathrm{P}}^{i,j} = \sum_m I_m(E_i) I_m(E_j)\, \tilde{C}_{\mathrm{P},m}$$

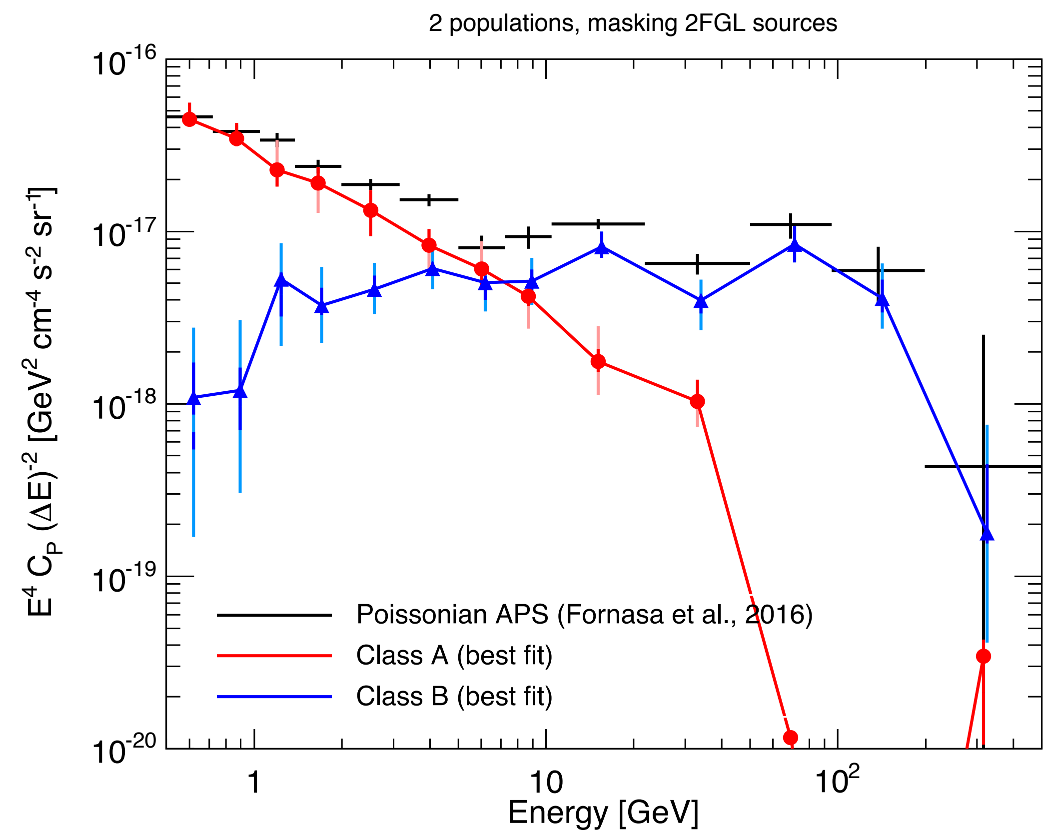
- 91 equations (independent combinations of 13 energy bins)
- *m* source classes
- in each of the 13 energy bins, we have m $I_{\mathrm{m}}(E_{\mathrm{i}})$, summing to the measured intensity
- number of degrees of freedom = 91 - (13-1)*m* - *m* = 91 - 13*m*
- system of equations can be solved up to *m*=7
- for each m, we perform a Bayesian scan over
    1. m $C_{\mathrm{P,m}}$
    2. 13m $I_{\mathrm{m}}(E_{\mathrm{i}})$ with a given sum

  and the following likelihood

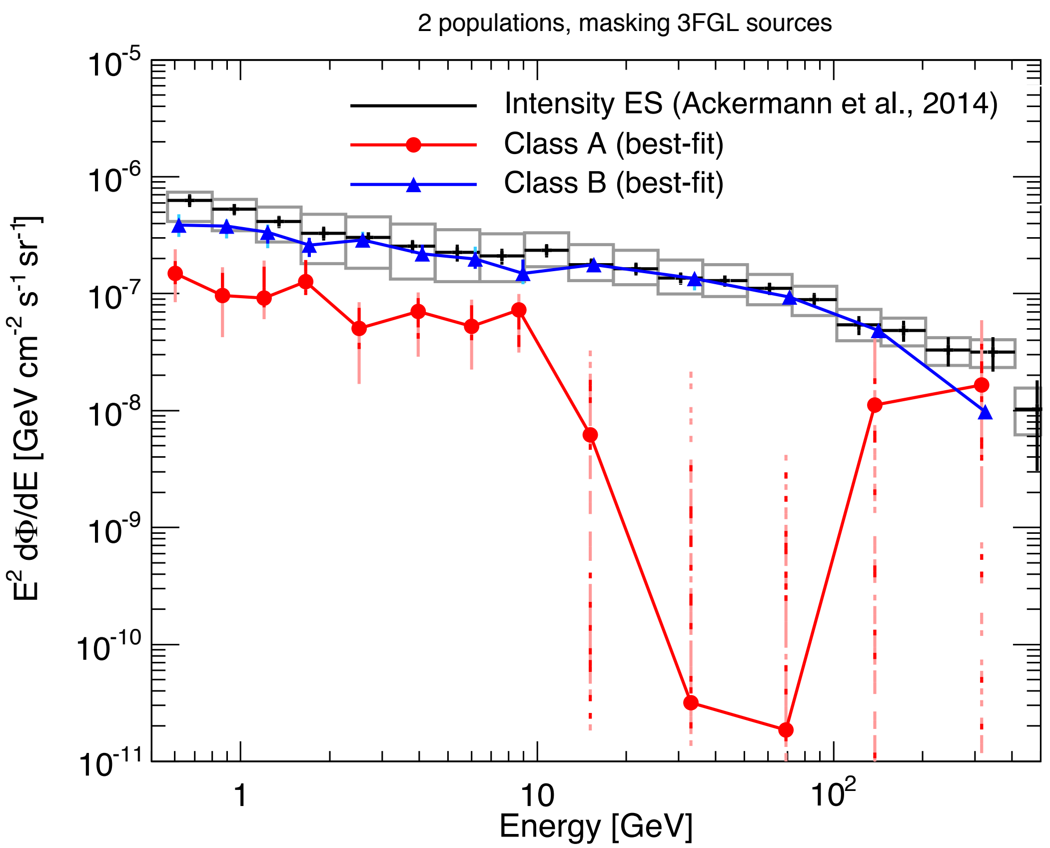
$$\log \mathcal{L}(\mathbf{\Theta}) = -\frac{1}{2} \sum_{i,j} \left(\frac{C_{\mathrm{P}}^{i,j}(\mathbf{\Theta}) - C_{\mathrm{P}}^{i,j}}{\sigma_{\mathrm{P}}^{i,j}} \right)^2$$

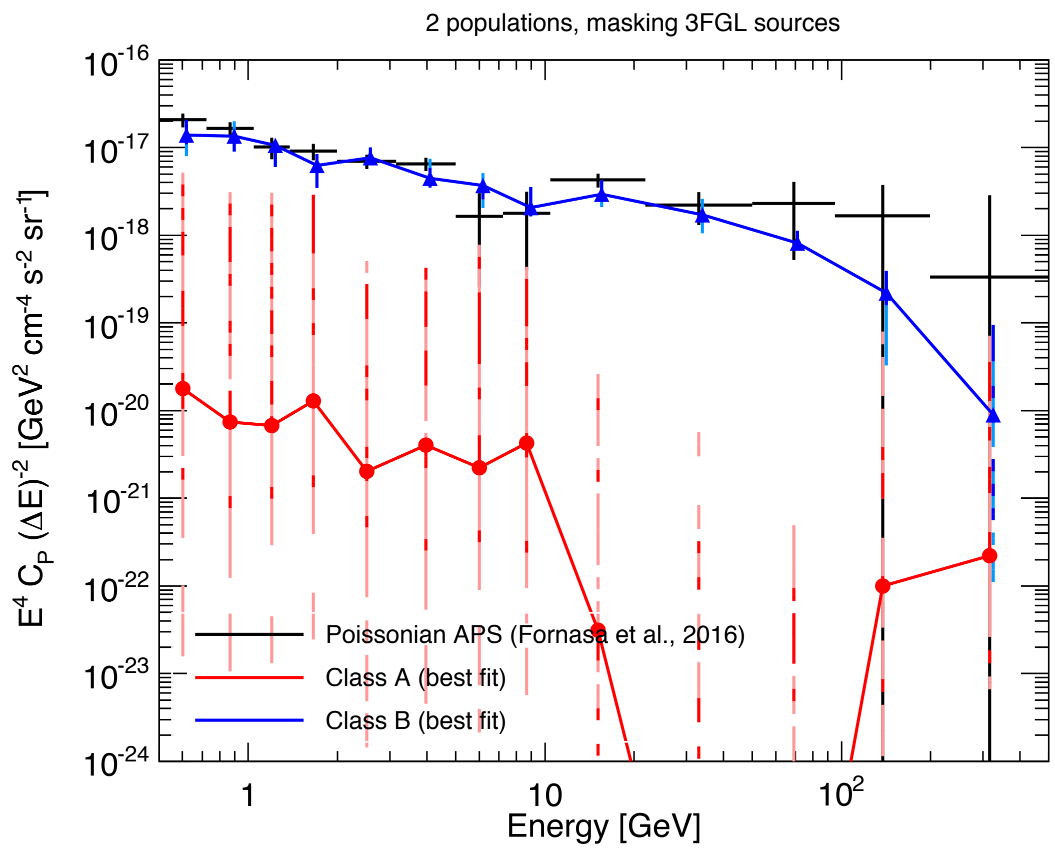
2 populations of sources





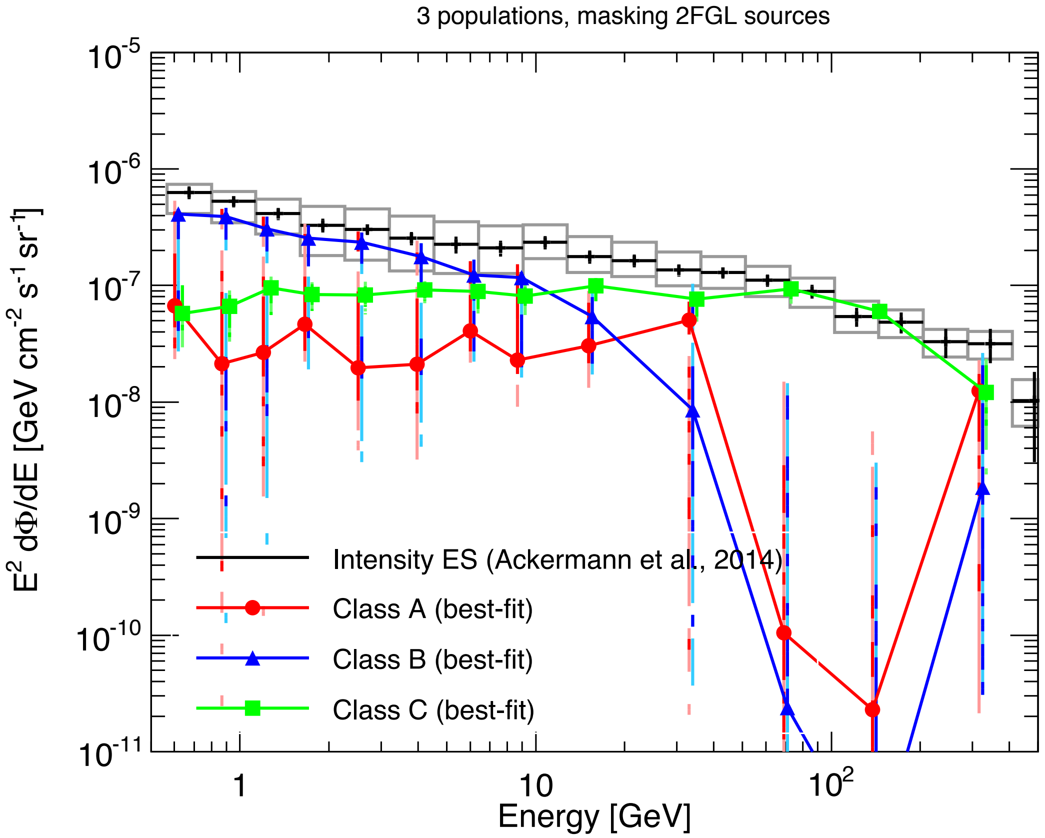
χ^2/dof=1.36
p-value=0.02

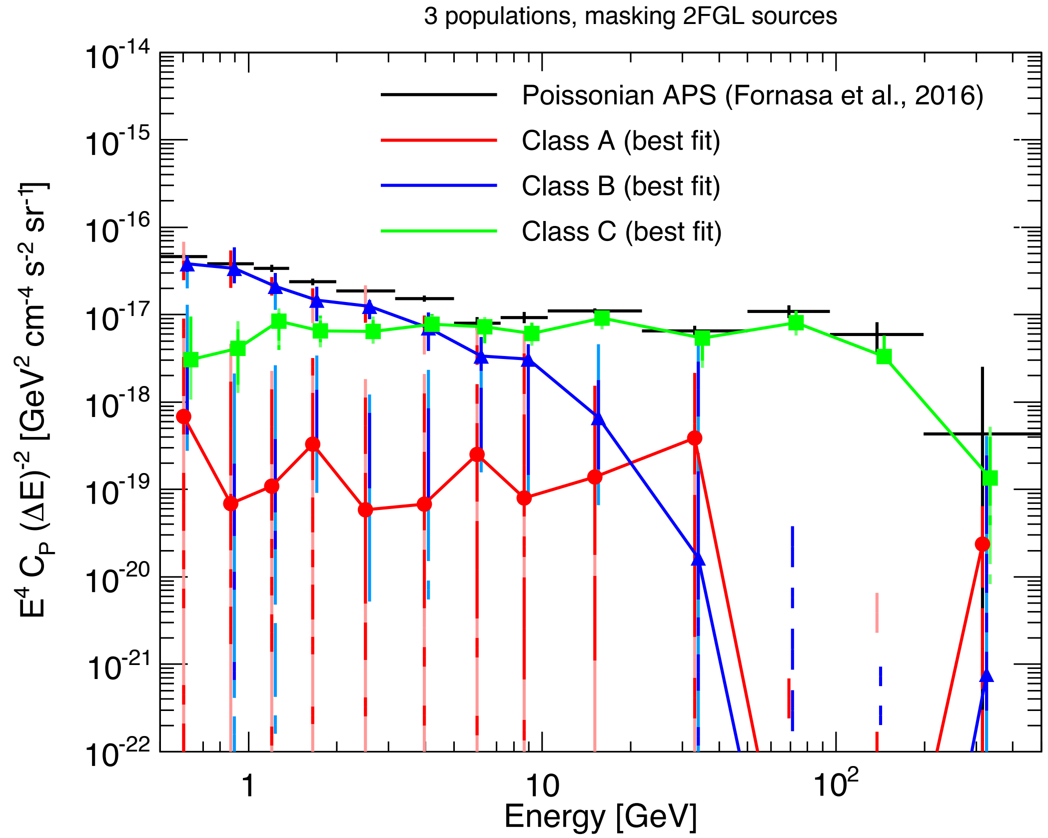




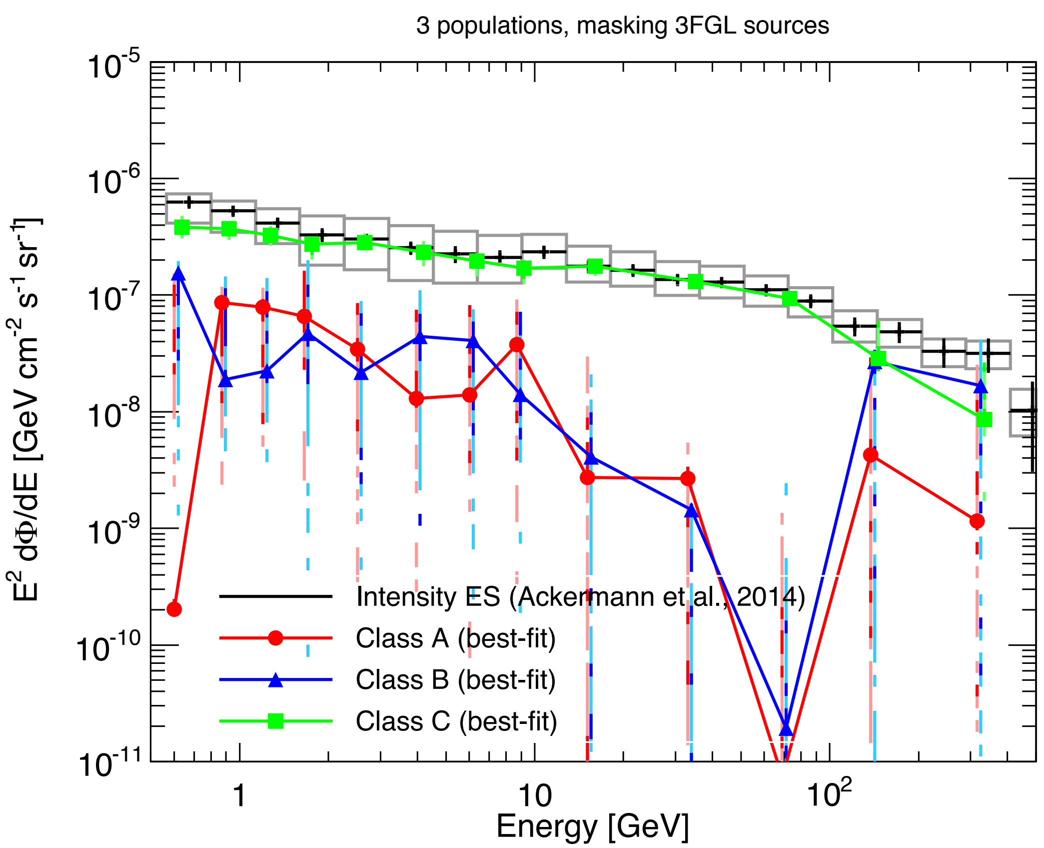
χ^2/dof=1.48
p-value=0.004

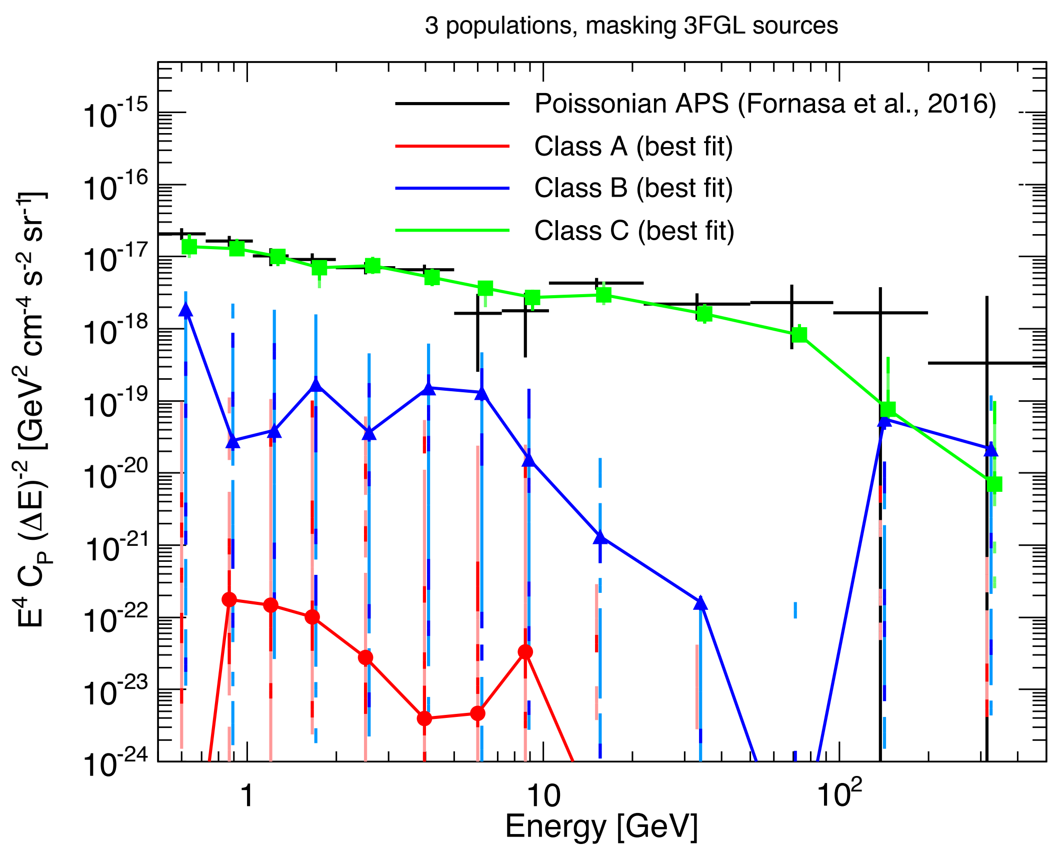
3 populations of sources





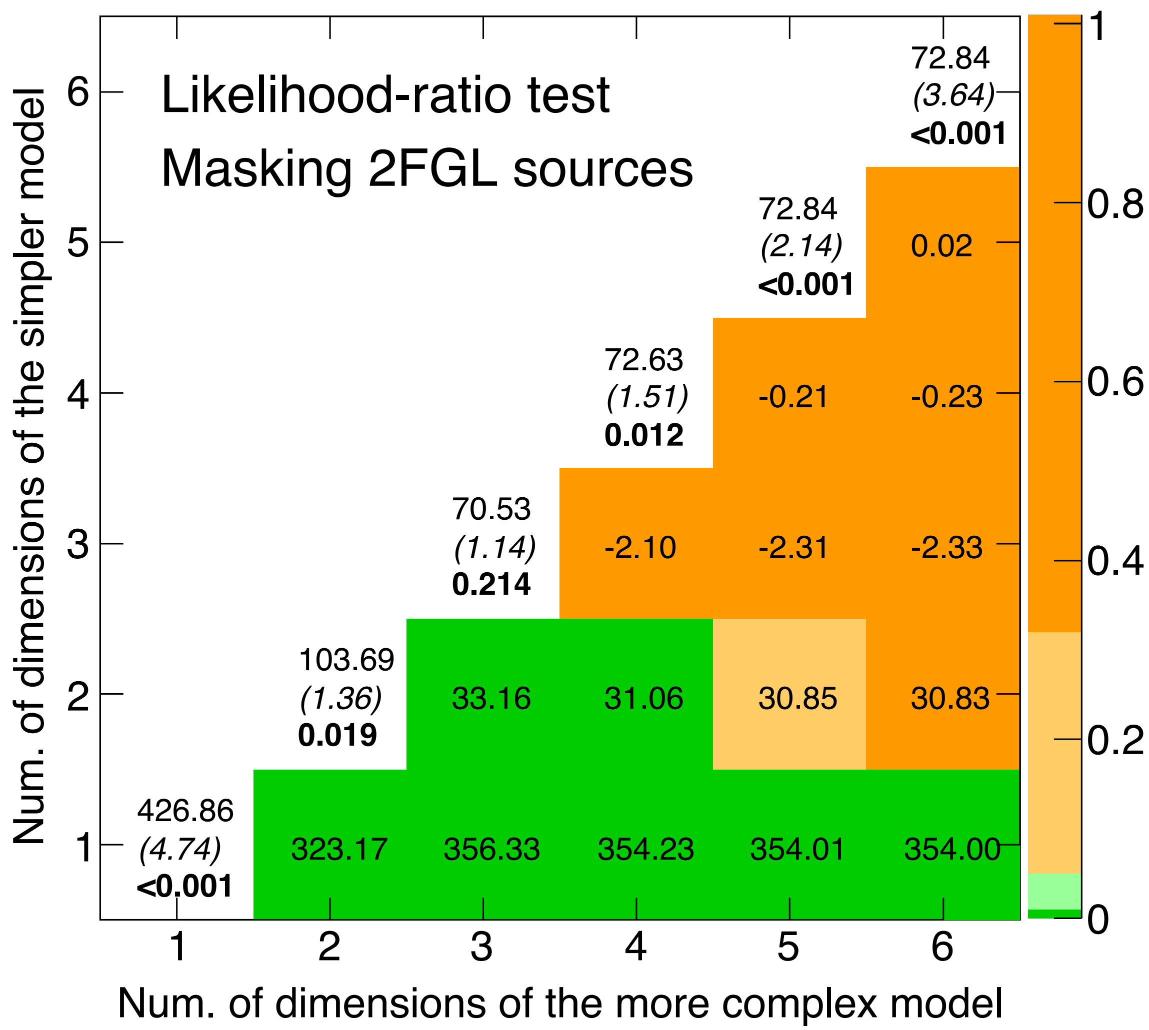
χ^2/dof=1.14
p-value=0.21

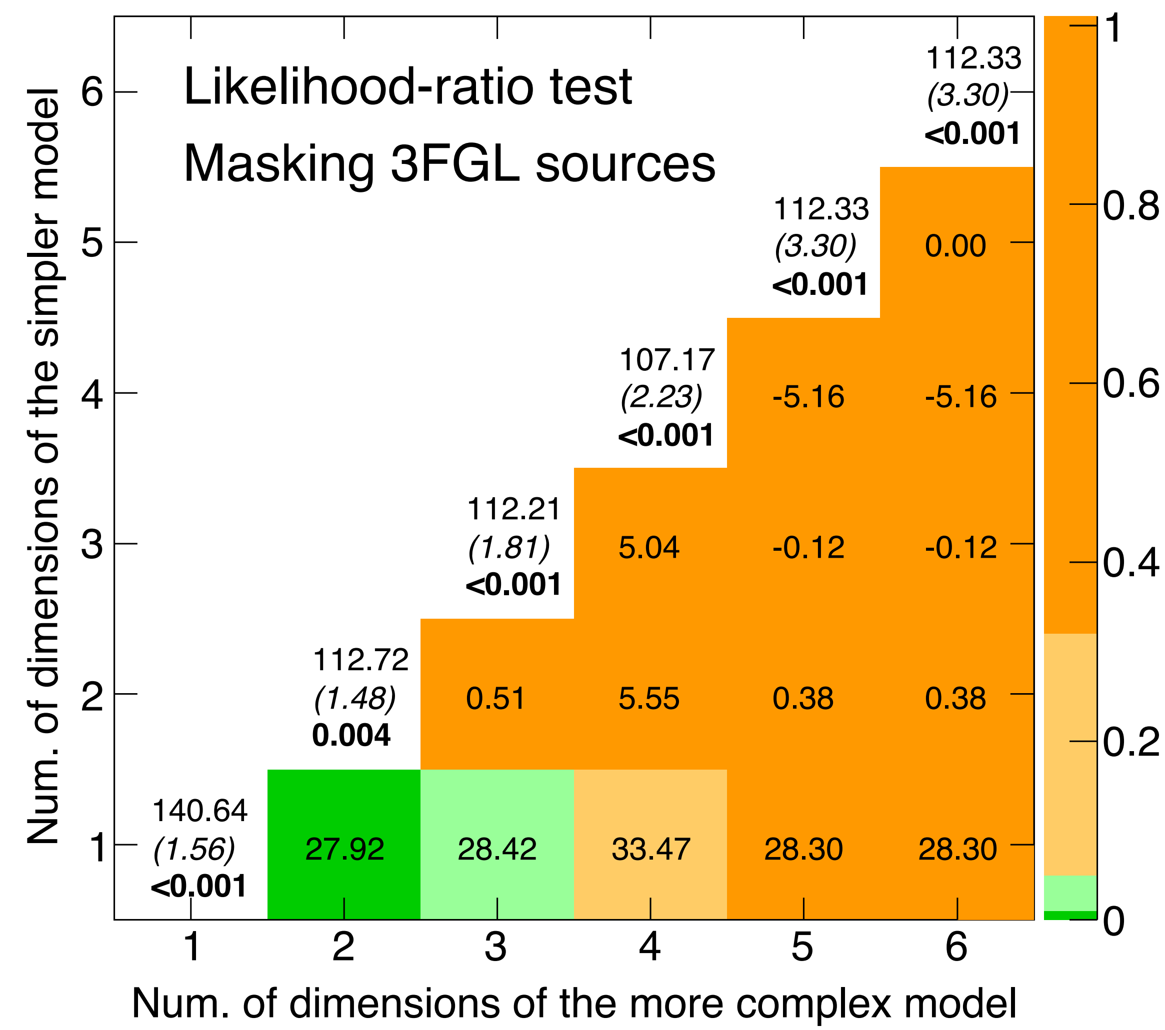




χ^2/dof=1.81
p-value=0.001

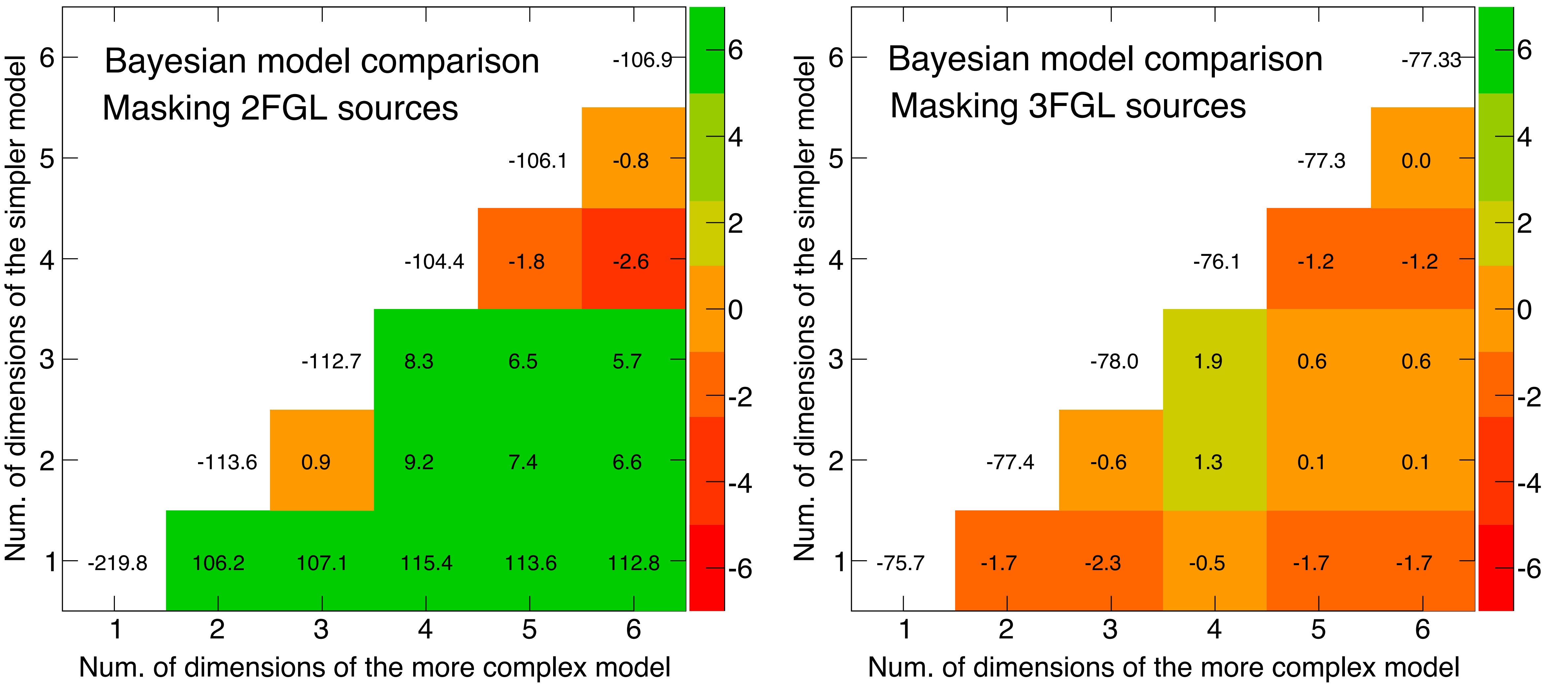
Model comparison (frequentist)





- off-diagonal entries for *m*>*n*: TS = χ^2 of the best fit for the more complex model (*m* sources) - χ^2 of the best fit for the simpler model (*n* sources)
- *p*-values **below 0.01**, **between 0.01 and 0.05**, **between 0.05 and 0.32** and **above 0.32**
- simpler model can be excluded with a significance **larger than 99%**, **between 99% and 95%**, **between 95% and 68%**, **below 68%**

Model comparison (Bayesian)



- diagonal entries: evidence of the scan
- off-diagonal entries for *m*>*n*: Bayes factor
- **strong**, **moderate** and **weak** preference for the simpler model
- **strong**, **moderate** and **weak** preference for the more complex model

Energy dependence of the fluctuation APS

$$I(E,\mathbf{n}) = \int d\chi\, \overline{W}(E,z)\, \rho_f(\mathbf{n},\chi) = \int d\chi\, W(E,z)\, \delta_f(\mathbf{n},\chi)$$

source field
(number of emitters
or squared DM density)

$$\delta(\mathbf{n},z) = \frac{\rho_f(\mathbf{n},\chi)}{\langle \rho_f(z) \rangle}$$

$$C_\ell = \int \frac{d\chi}{\chi^2} W^2(E,z) P_f \left(k = \frac{\ell}{\chi}, z \right)$$

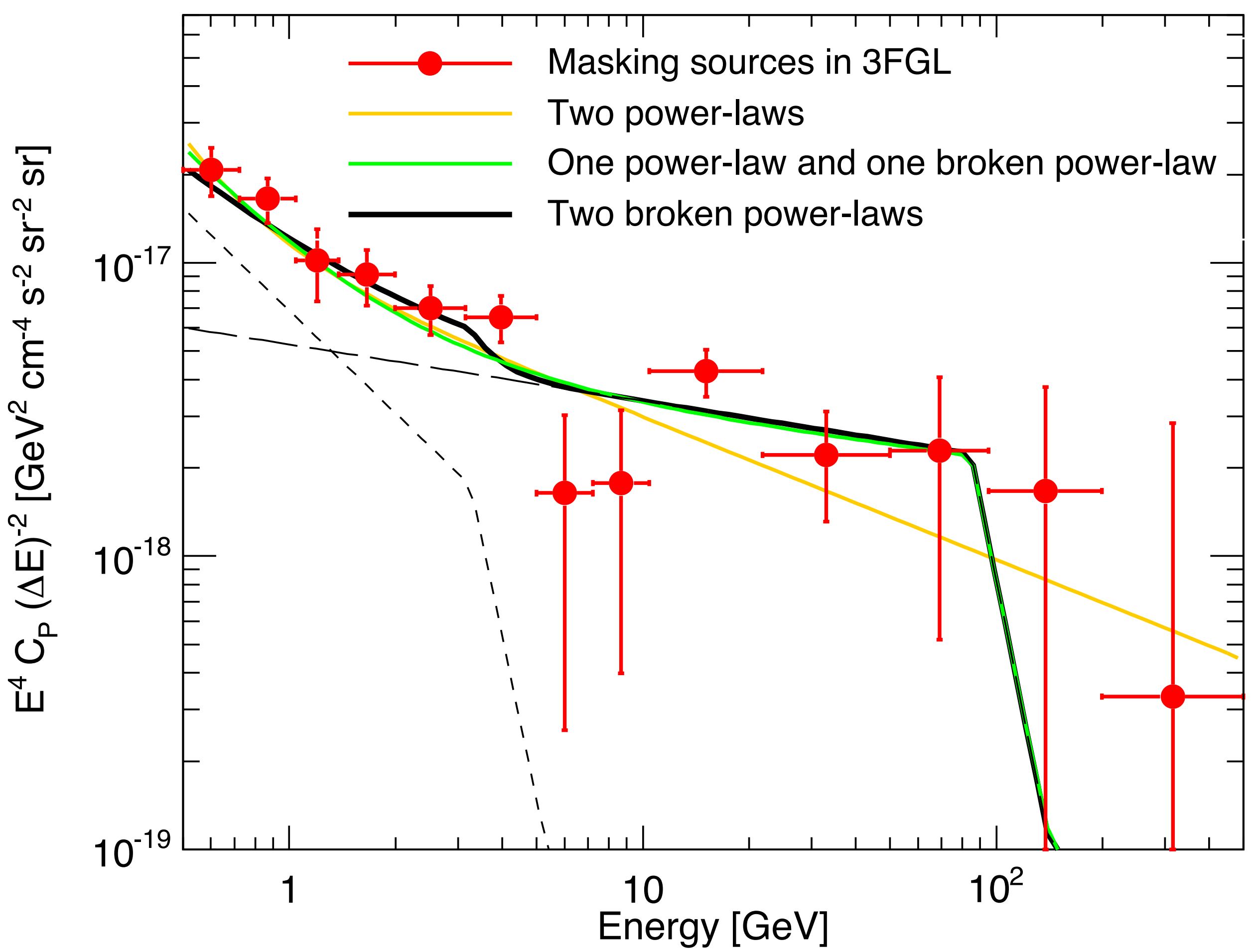
$$\langle \tilde{\delta}_f(\mathbf{k})\, \tilde{\delta}_f(\mathbf{k}') \rangle = (2\pi)^2\, \delta^{(3)}(\mathbf{k}-\mathbf{k}')\, P_f(k)$$

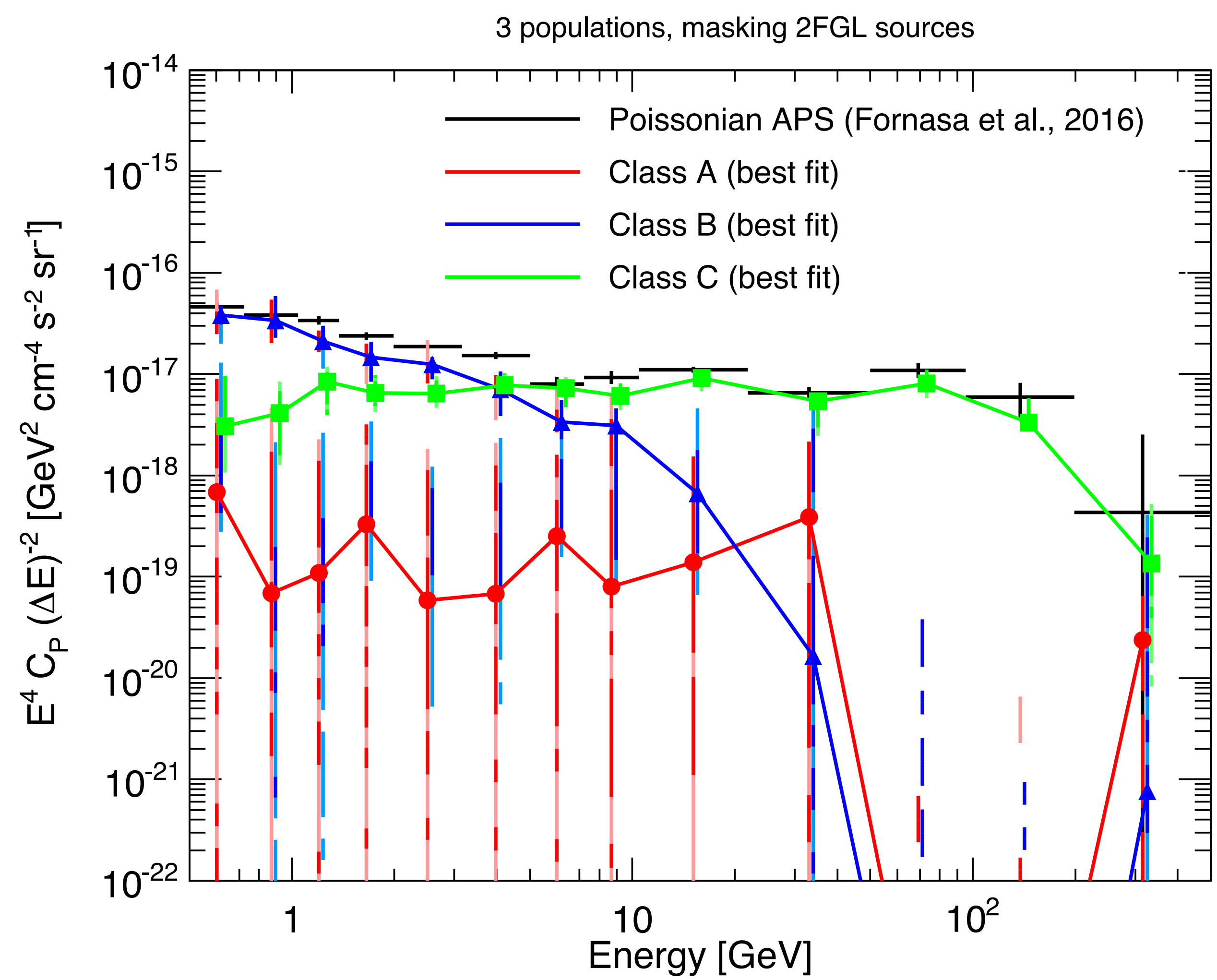
$$\tilde{C}_\ell = \frac{\int d\chi\, \chi^{-2} W^2(E,z)\, P_f\left(k=\ell/\chi, z\right)}{\left[\int d\chi\, W(E,z)\, \langle \rho_f(z) \rangle\right]^2}$$

independent on energy if
***W(E,z)* is separable** in *E* and *z*,
but flux from a source at *z*
normally depends on *E*(1+*z*)

Conclusions

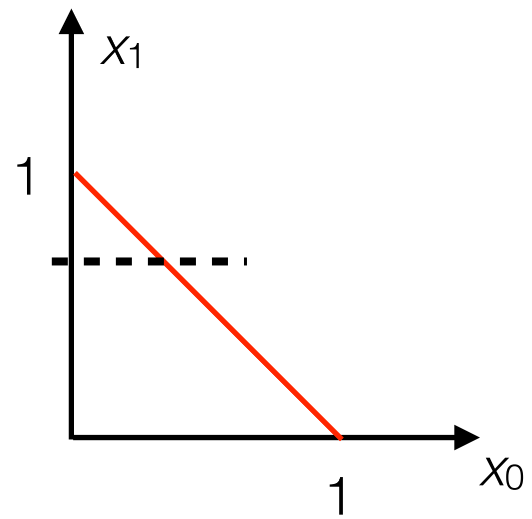
- new measurement of auto- and cross-APS
- multiple contributions of the signal (for 2FGL mask the best χ^2 is reached for 3 populations of sources
- model independent approach tests other interpretations (class C is compatible with blazars and class B with star-forming galaxies but galaxies are not that anisotropic)



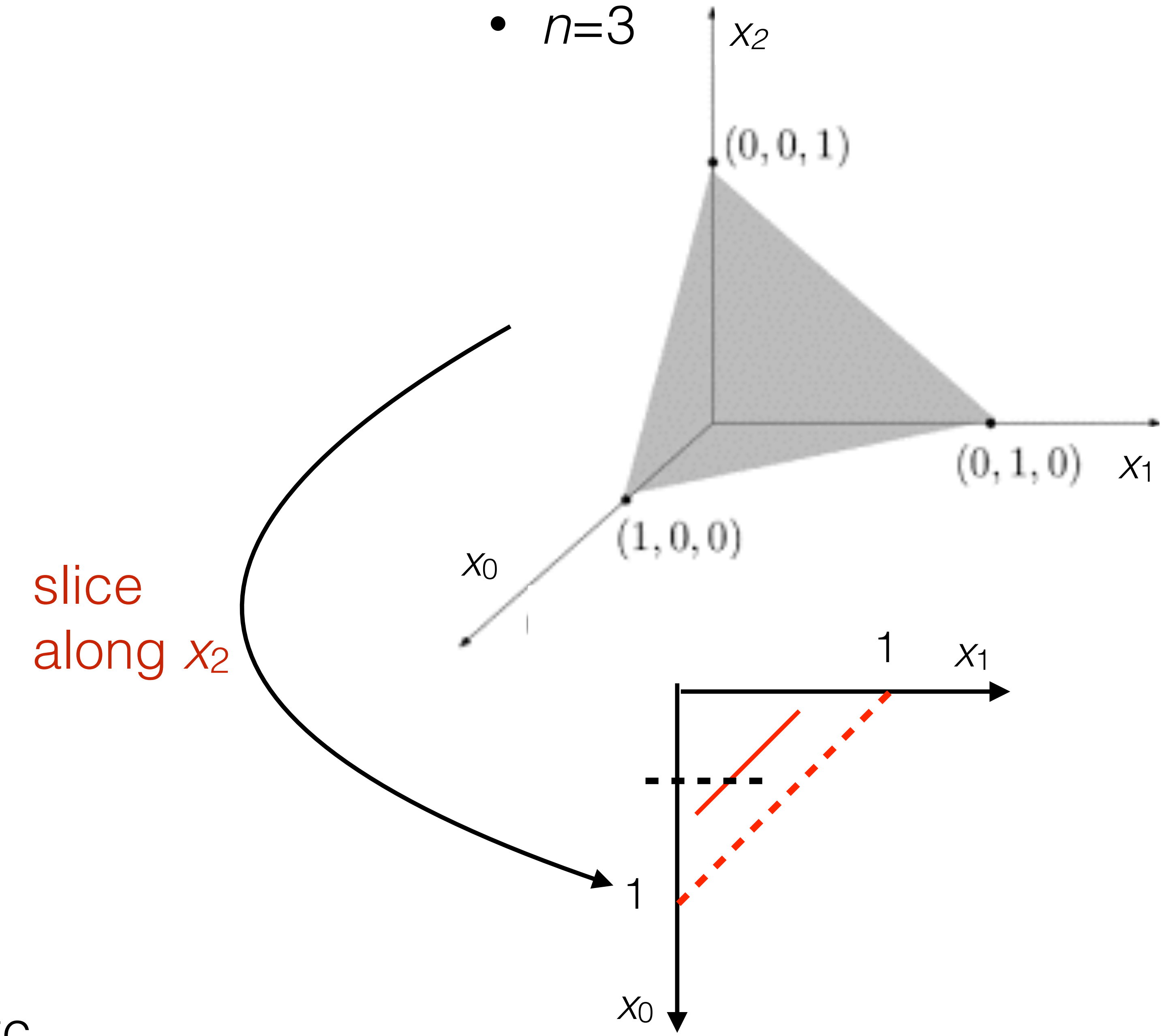


Generating random points on the simplex

- n-dim simplex is the locus of points where $\Sigma_{i=0,n-1}\ x_i=1$
- Dirichlet probability distribution generates random points on the simplex
- n=2



- n=3



- I need m $\{x_i\}$: x_0, …, x_{m-1}, summing to 1
- generate m-1 $\{y_i\}$: y_0, …, y_{m-2}
- y_{m-2} interpreted as $\Sigma_{i=0,n-2}\ x_i$
- y_{m-3} interpreted as $\Sigma_{i=0,n-3}\ x_i$, etc.