Exploring the full information of the Extragalactic gamma-ray sky maps

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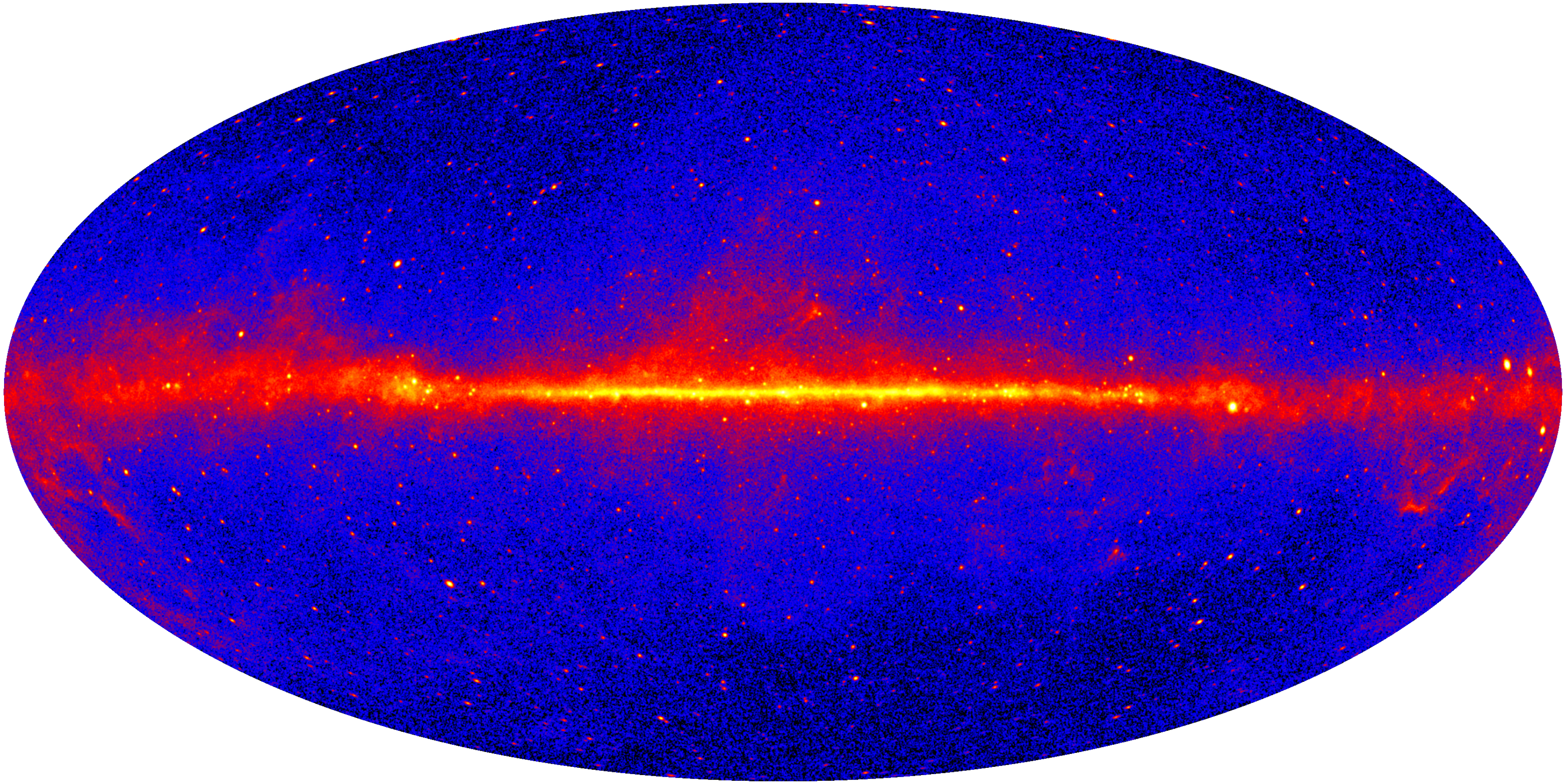
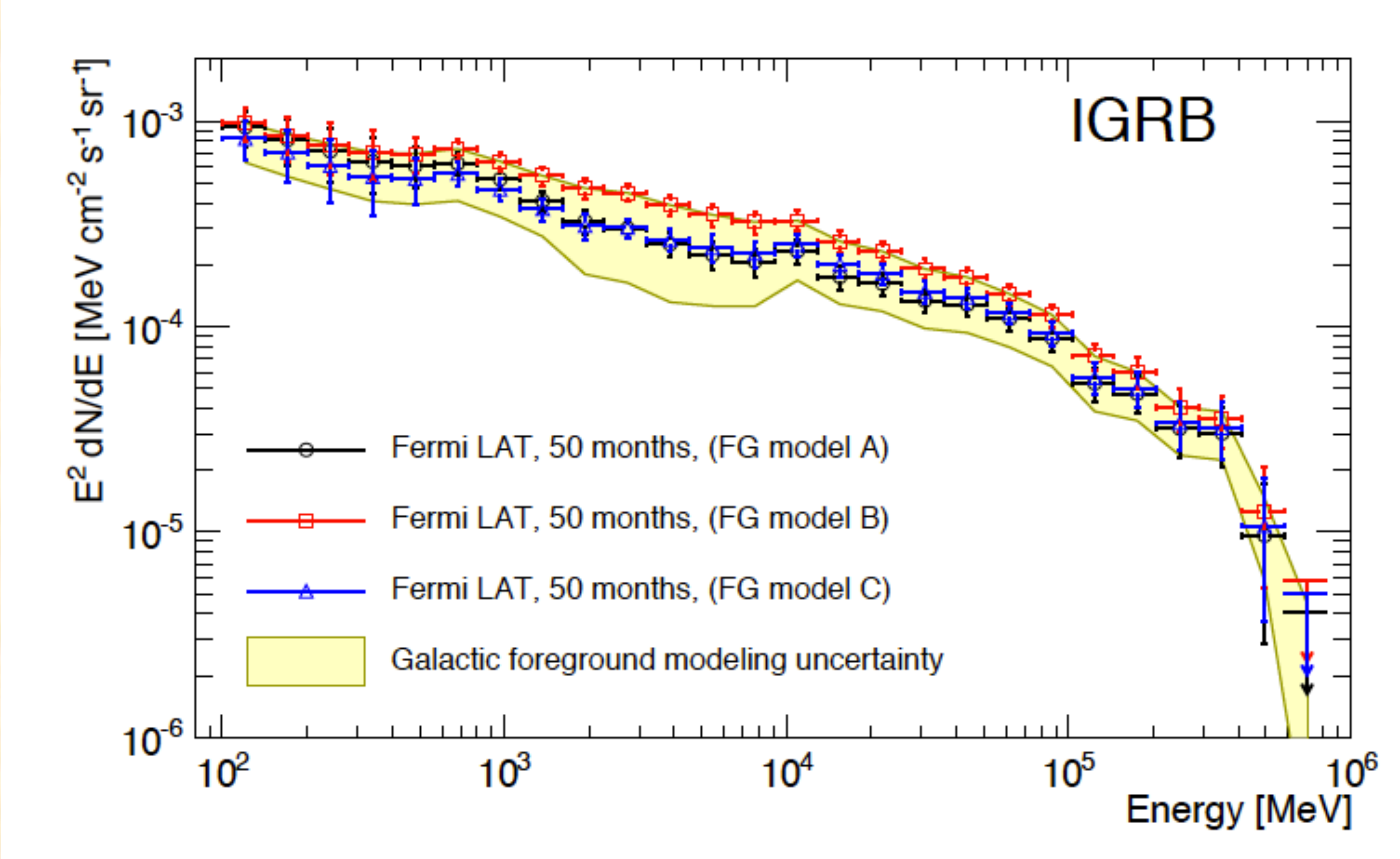
The Gamma Sky

Fermi Gamma-Sky, P8, PSF3-only, >1 GeV
(72 months(6 yrs), ~3.4M events)



The Extra-Galactic Gamma-ray Background (EGB)



Fermi LAT collaboration, Astrophys.J. 799 (2015) 1, 86

- Power Law for E < 100 GeV
- Spectral softening at high energies

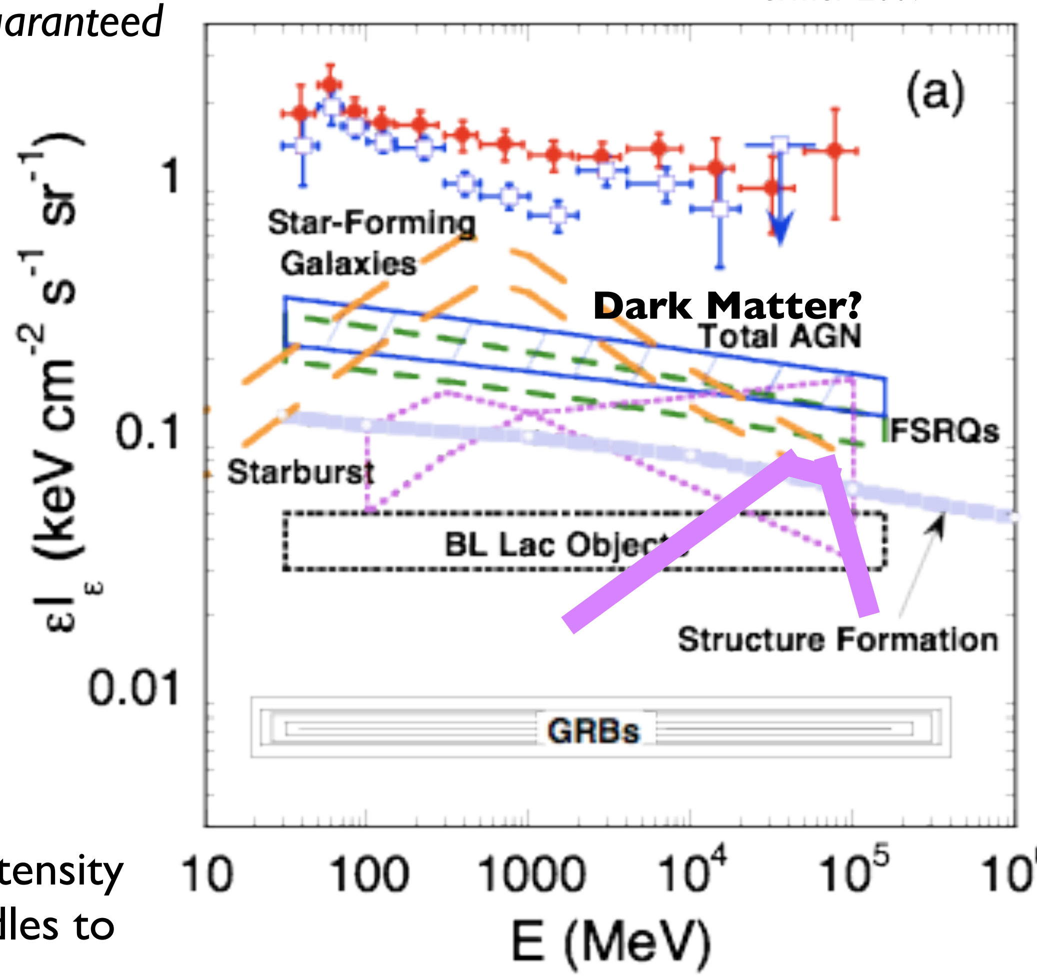
The origin of the EGB

- many astrophysical sources are *guaranteed* to contribute, e.g.:
- blazars
- star-forming galaxies
- millisecond pulsars
- AGNs
- clusters of Galaxies
- clusters Shocks
- cascades from UHECRs

and…

- Dark matter(?)

Dermer 2007

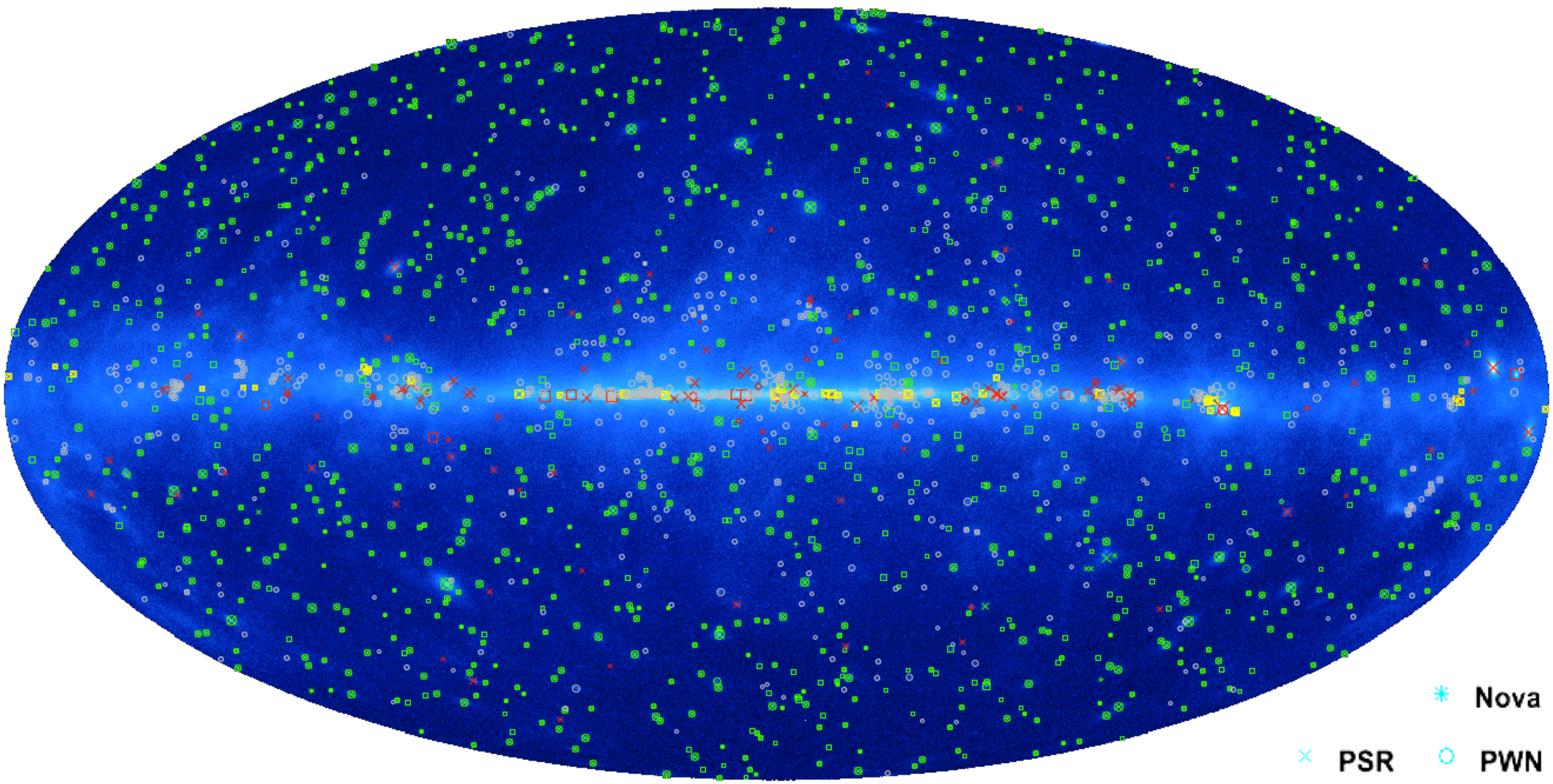


- relatively featureless total EGB intensity spectrum → lack of spectral handles to ID individual components

Resolved Sources - 3FGL catalogue

~3000 sources

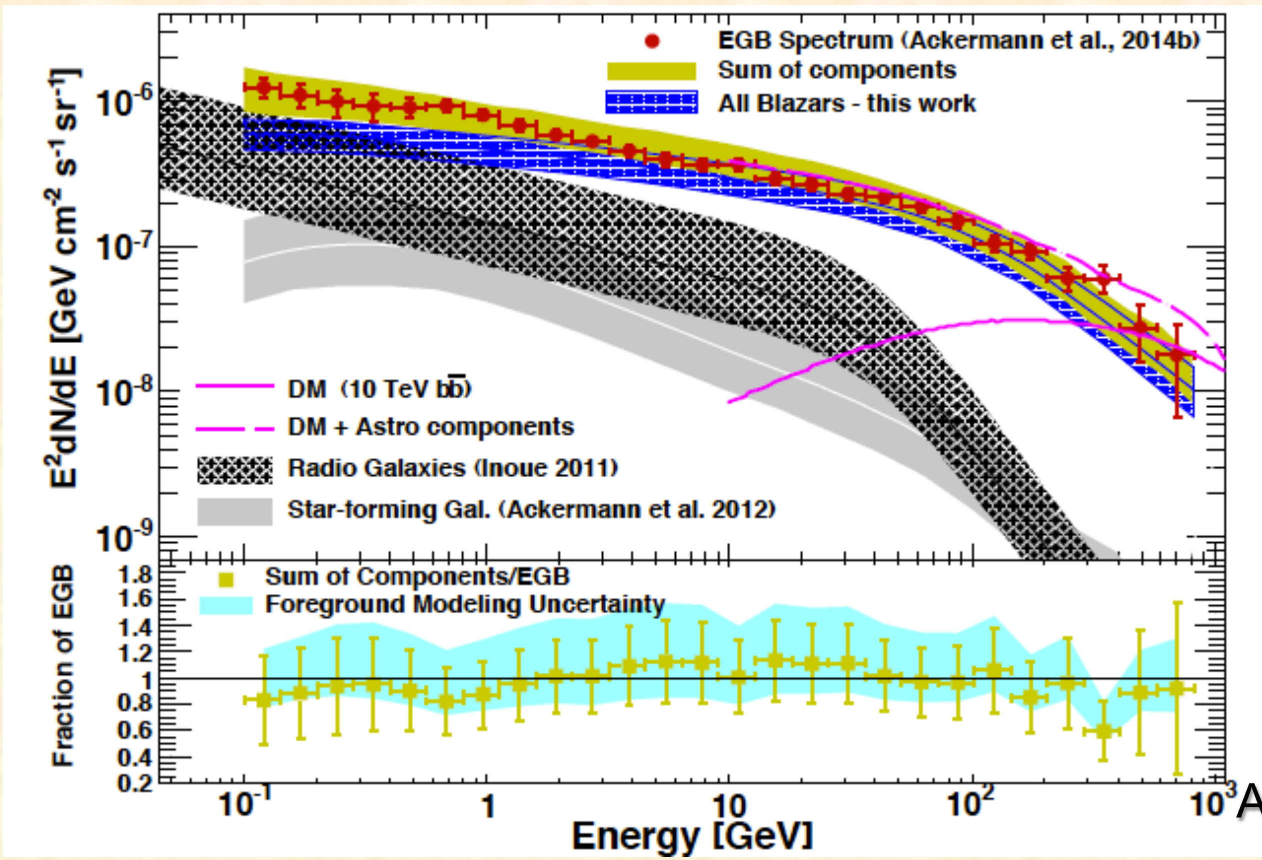
AGN
AGN-Blazar
AGN-Non Blazar
Galaxy
Starburst Galaxy
Radio Galaxy
Seyfert Galaxy



Nova
PSR
PWN
Unassociated
PSR w/PWN
SNR
Possible Association with SNR and PWN
Globular Cluster
HMB

Credit: Fermi Large Area Telescope Collaboration

IGRB Energy Sprectrum



Ajello et al. ApjL 2015

- The IGRB energy spectrum can be well fitted by a sum of different astro-physical components.
  - No obvious need of Dark Matter
- However, an unsatisfactory point is that this result is based on extrapolations

The Gamma Sky

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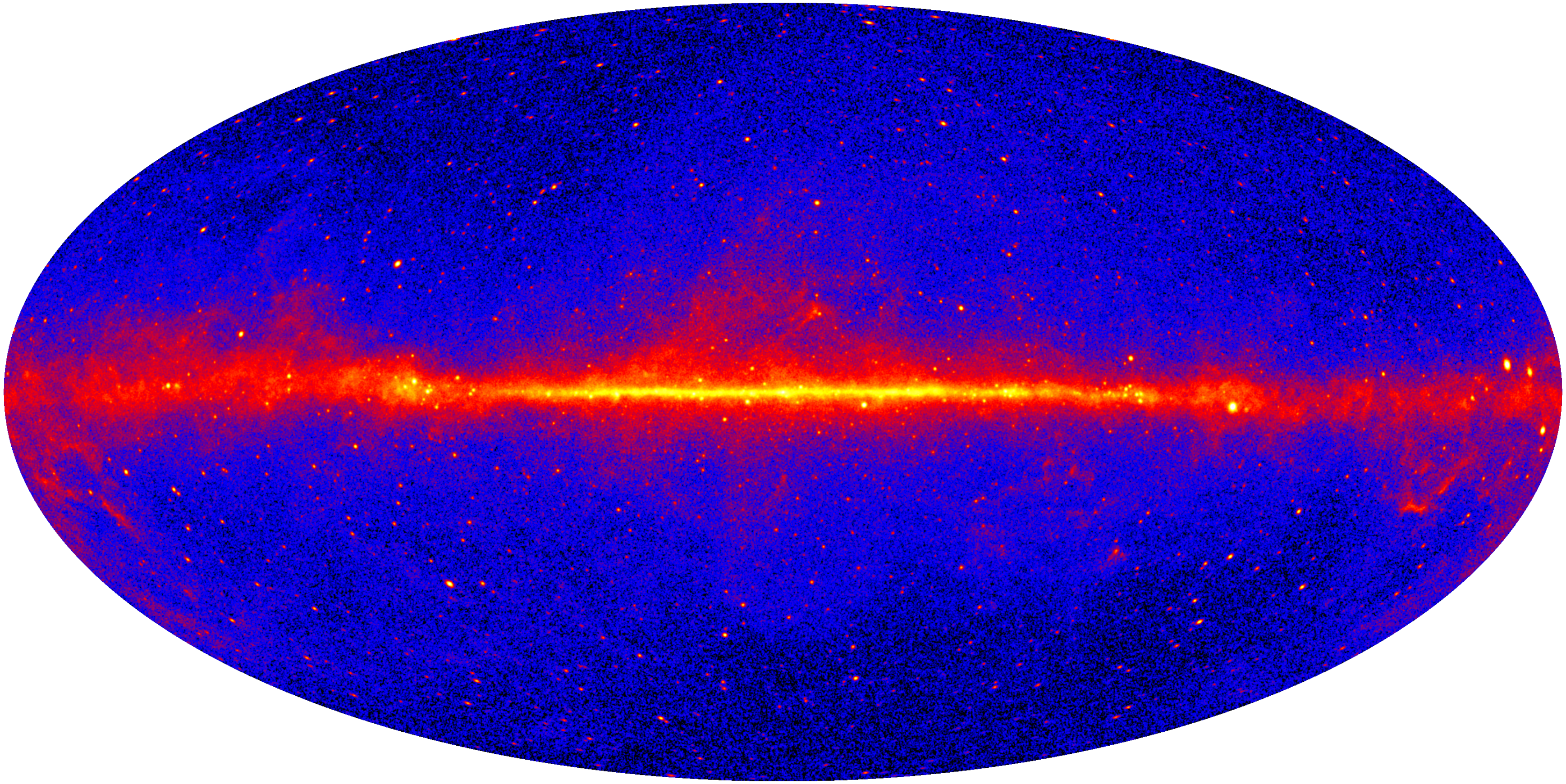
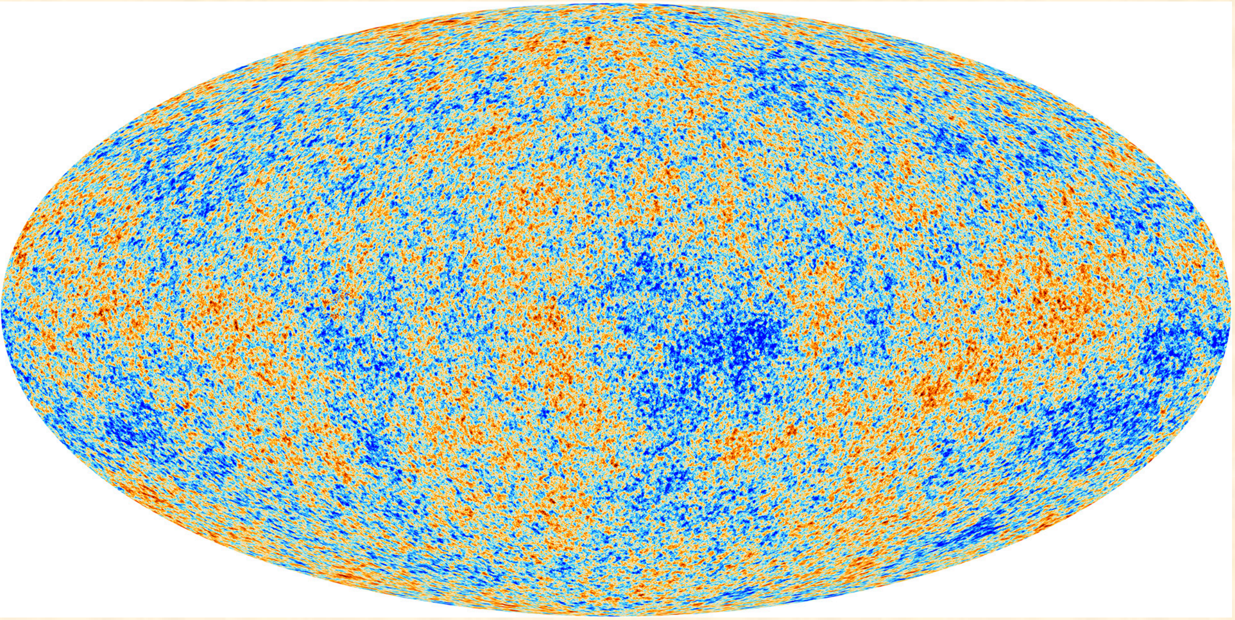


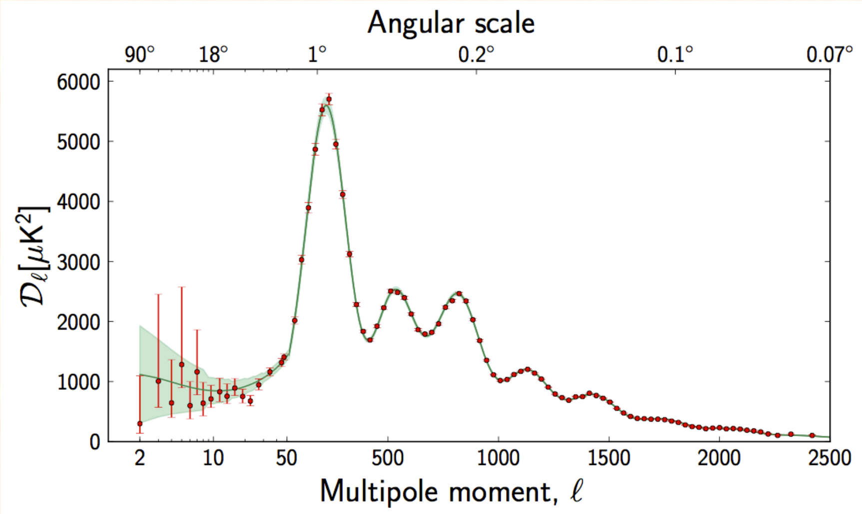
Beside the energy spectrum, much more information is contained in the whole map.
Various techniques can be used to extract it.

Auto-Correlation of the CMB

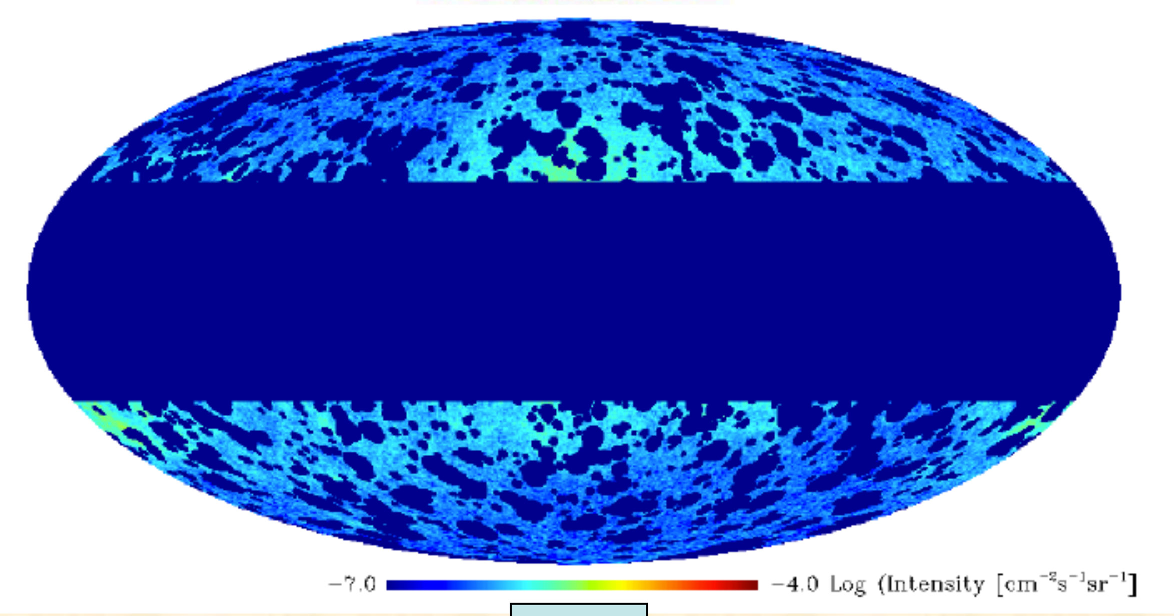


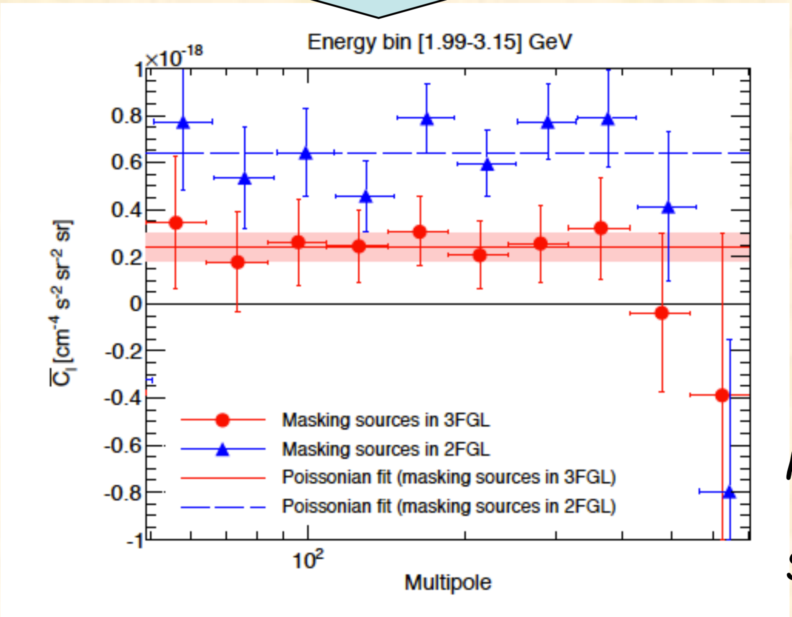
$$I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi)$$

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$



Auto-Correlation of the Gamma-ray sky





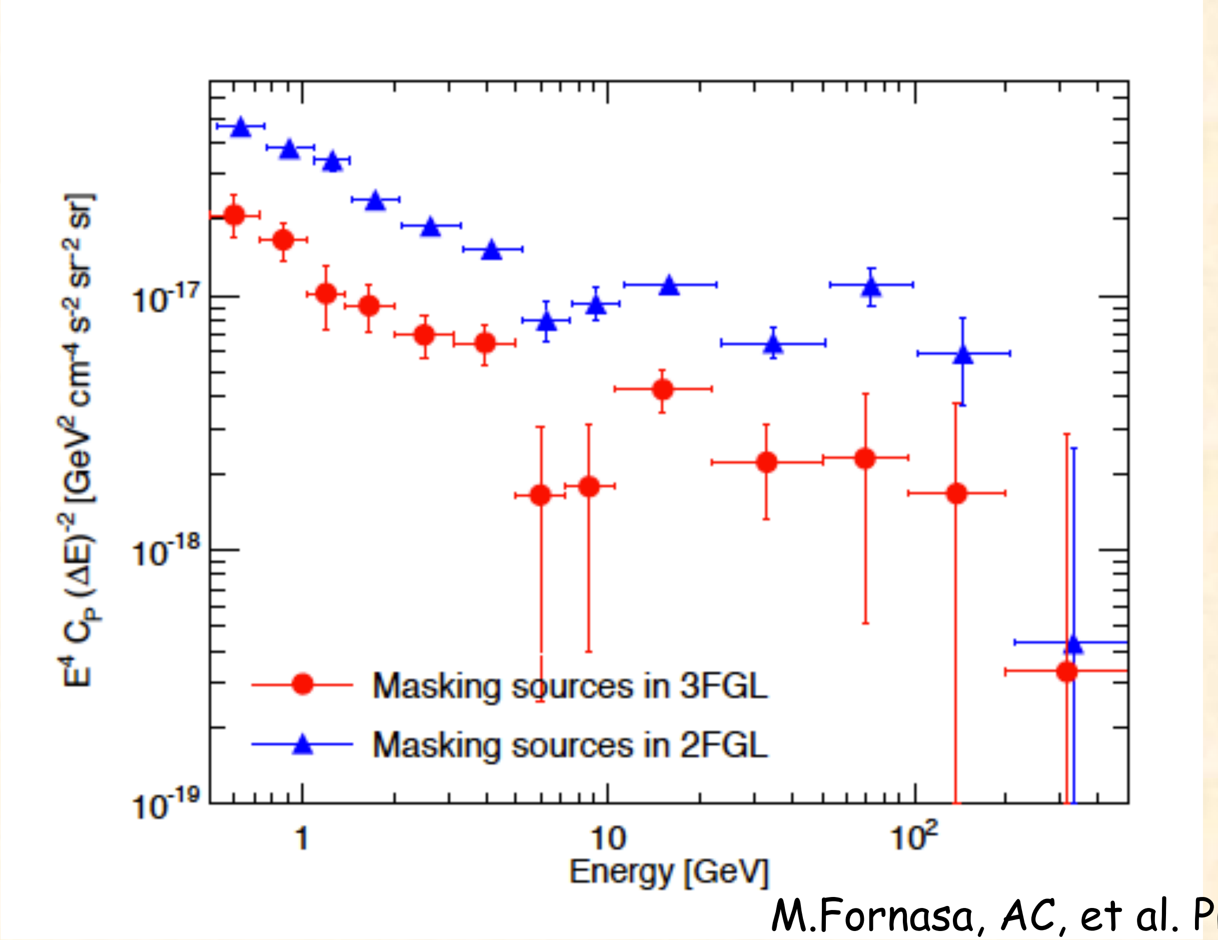
$$I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi)$$

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$

M.Fornasa, AC, et al. PRD 2016

See also talk of Michela Negro

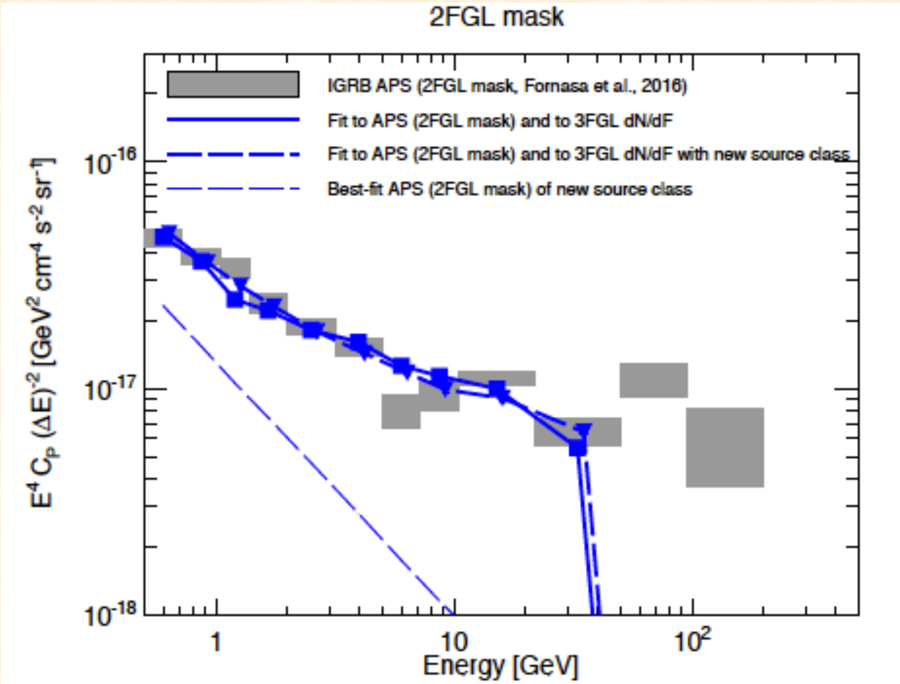
Auto-Correlation of the Gamma-ray sky

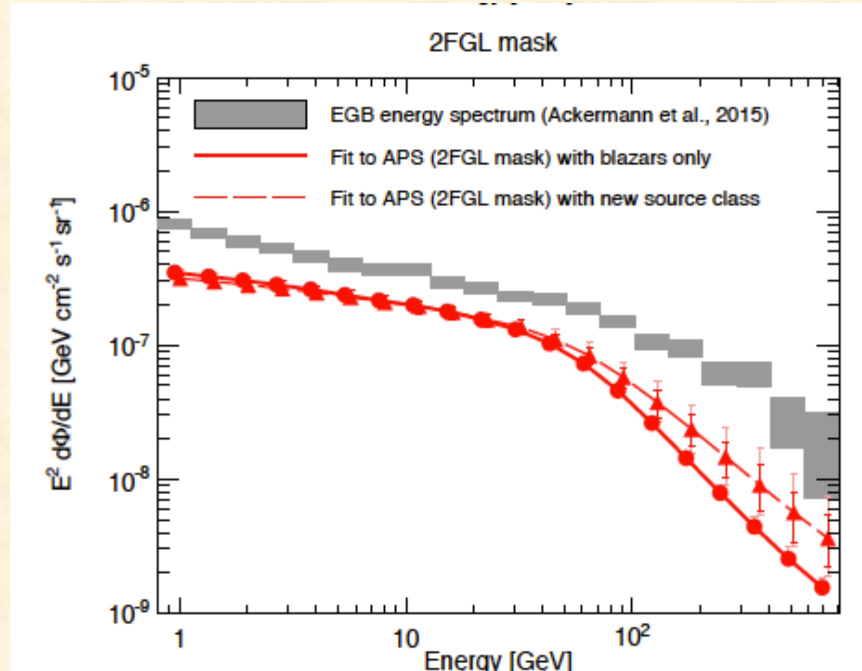


M.Fornasa, AC, et al. PRD 2016

- An energy spectrum of the anisotropy can be build, which provides a new observable (beside the intensity energy spectrum) to be checked against models

Auto-Correlation of the Gamma-ray sky

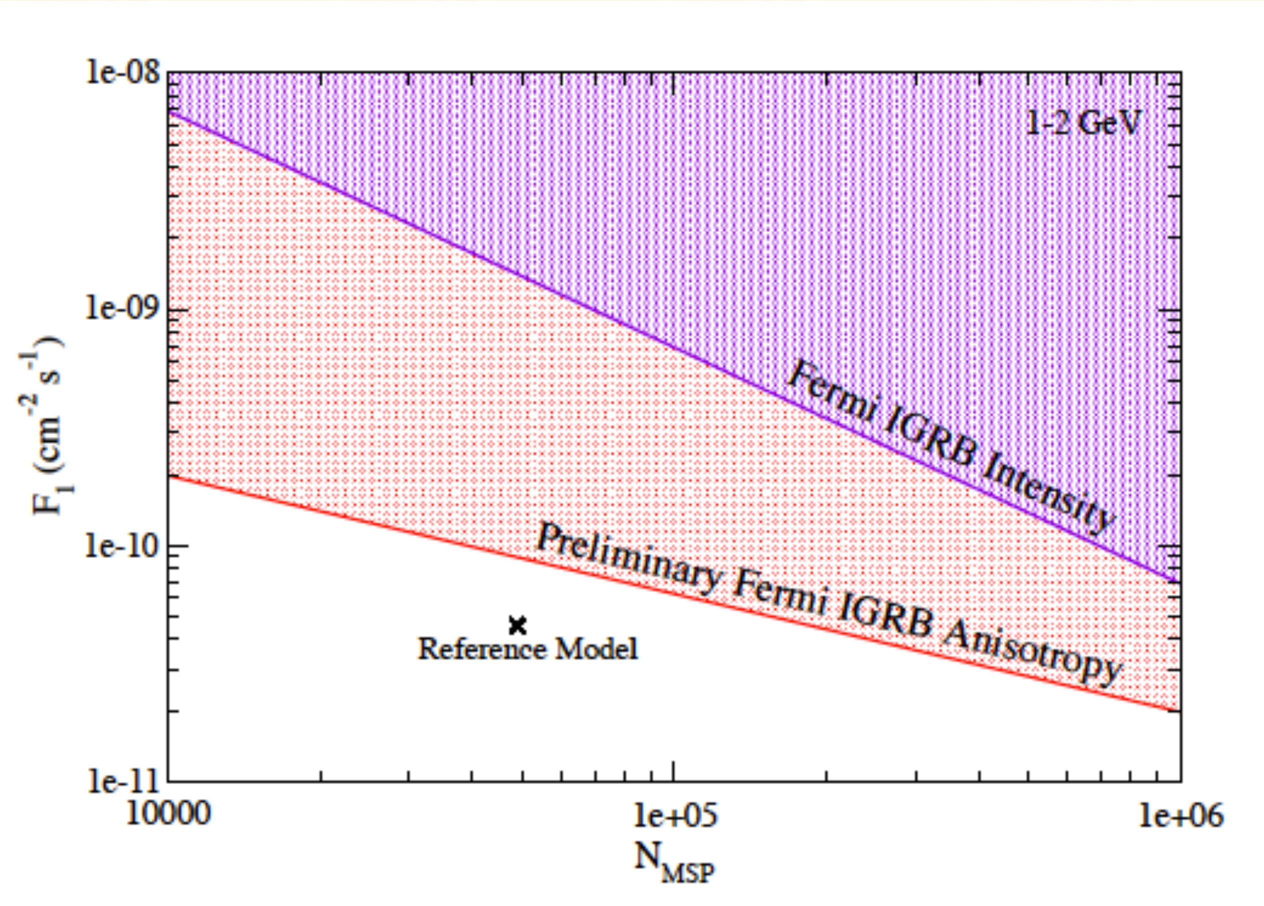




Ando et al. PRD 2017

- Using the anisotropy the result that blazars makes ~30% of the emission is confirmed, without the use of extrapolations
- Remaining ~70% must be produced by objects with a high number density (SFGs, MAGNs…)

Anisotropy Constraints on the Pulsar Contribution



J. M. Siegal-Gaskins, R. Reesman, V. Pavlidou, S. Profumo, T.P. Walker, Mon.Not.Roy.Astron.Soc. 415 (2011) 1074S

- Constraints on the parameter space of Pulsars are ~1 order of magnitude stronger using anisotropy
- Reference models should be detectable/testable with a slight improvement in the anisotropy measurement

Auto-Correlation of the Gamma-ray sky

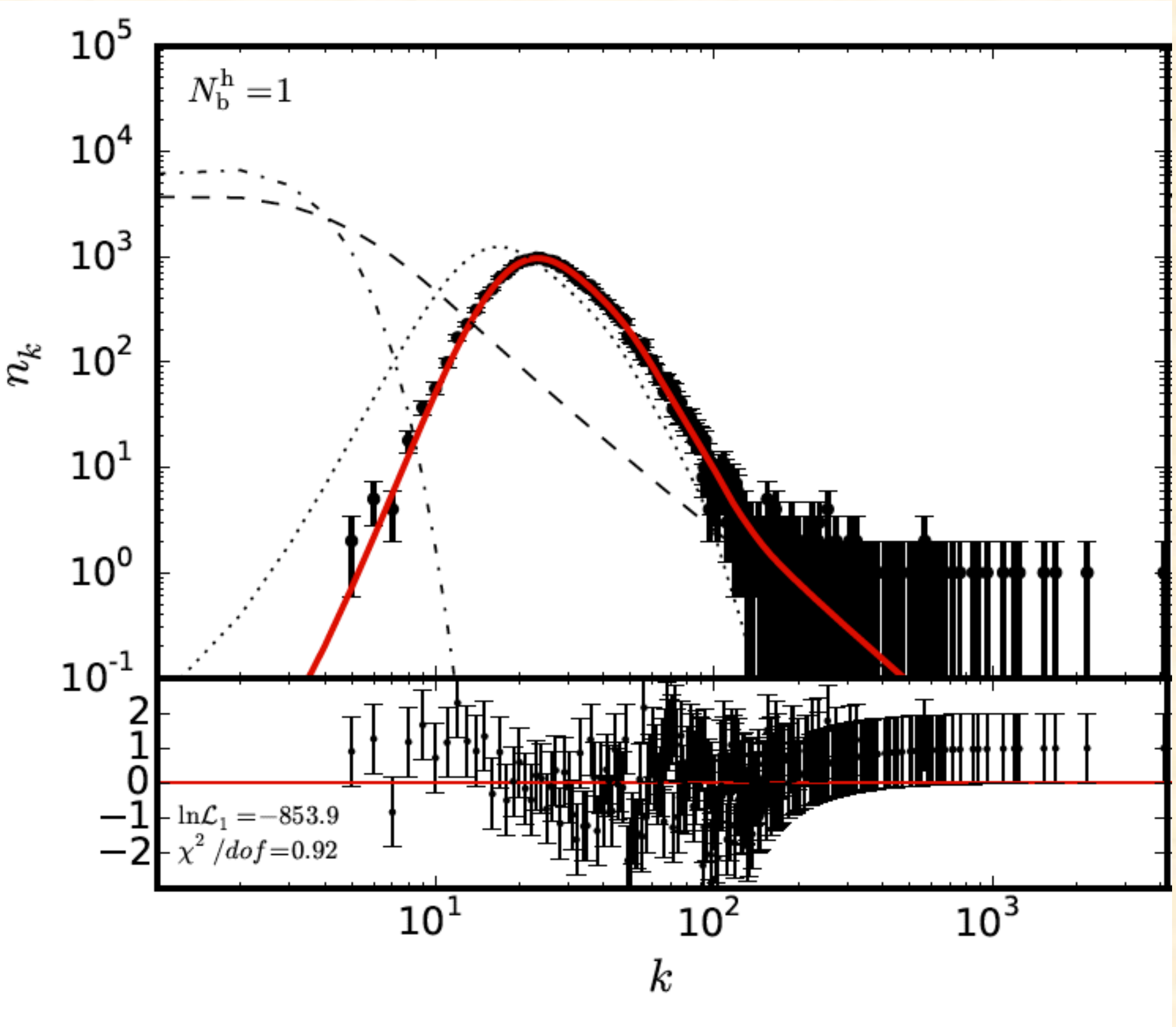
- Cross-check your EGB model against anisotropy data !

$$C_{\mathrm{P}} = \int_0^{S_{\mathrm{t}}} \frac{dN}{dS} S^2 dS.$$

- Anisotropy poses strong constraints, especially on models involving blazars

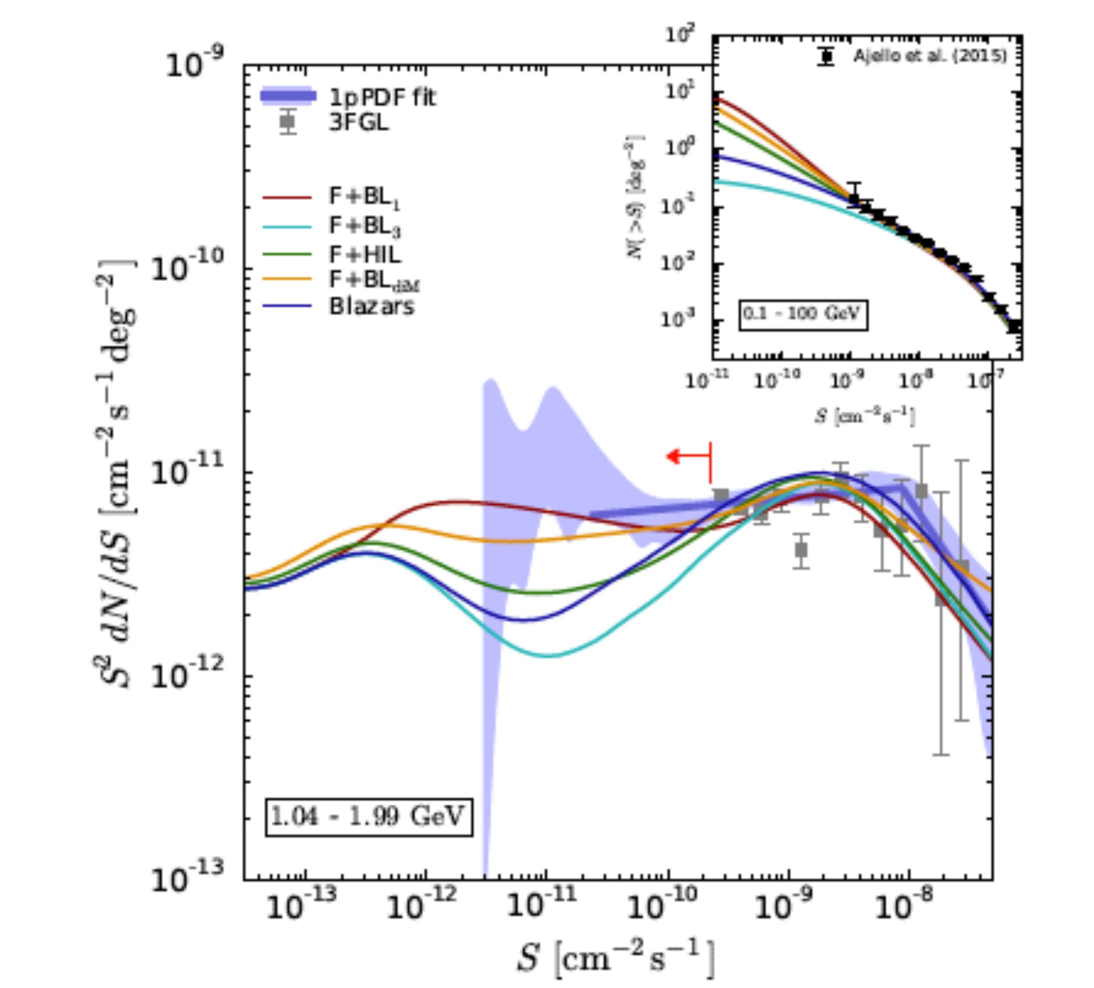
- Constraints on objects with large number density (e.g., galaxies) might be weaker

Pixel Counts statistics or 1pPDF



Malyshev & Hogg ApJ 2011, Lisanti+ ApJ 2016, Zechlin+ ApJS 2015, ApjL 2016, Feyereisen+ JCAP 2015

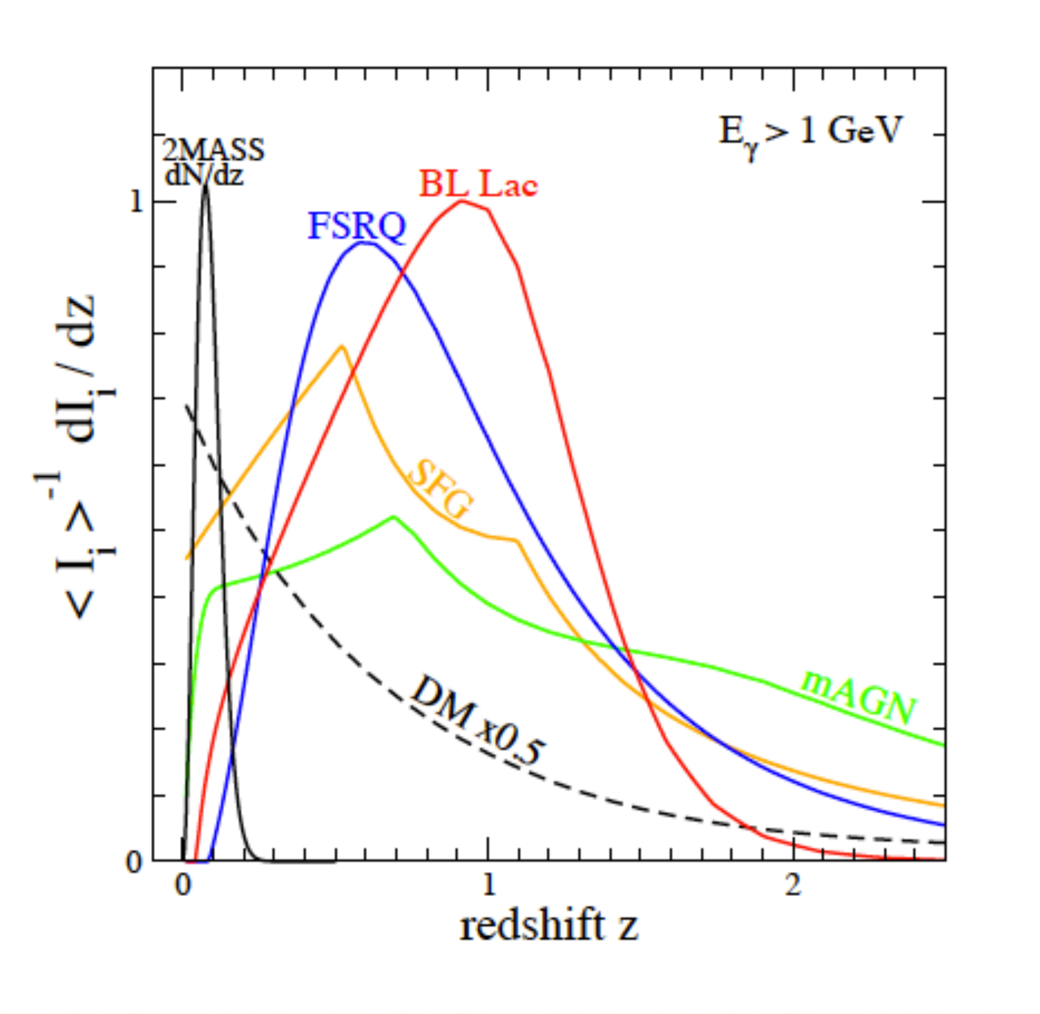
Pixel Counts statistics or 1pPDF



Zechlin, AC, Donato, Fornengo, Regis ApJL 2016

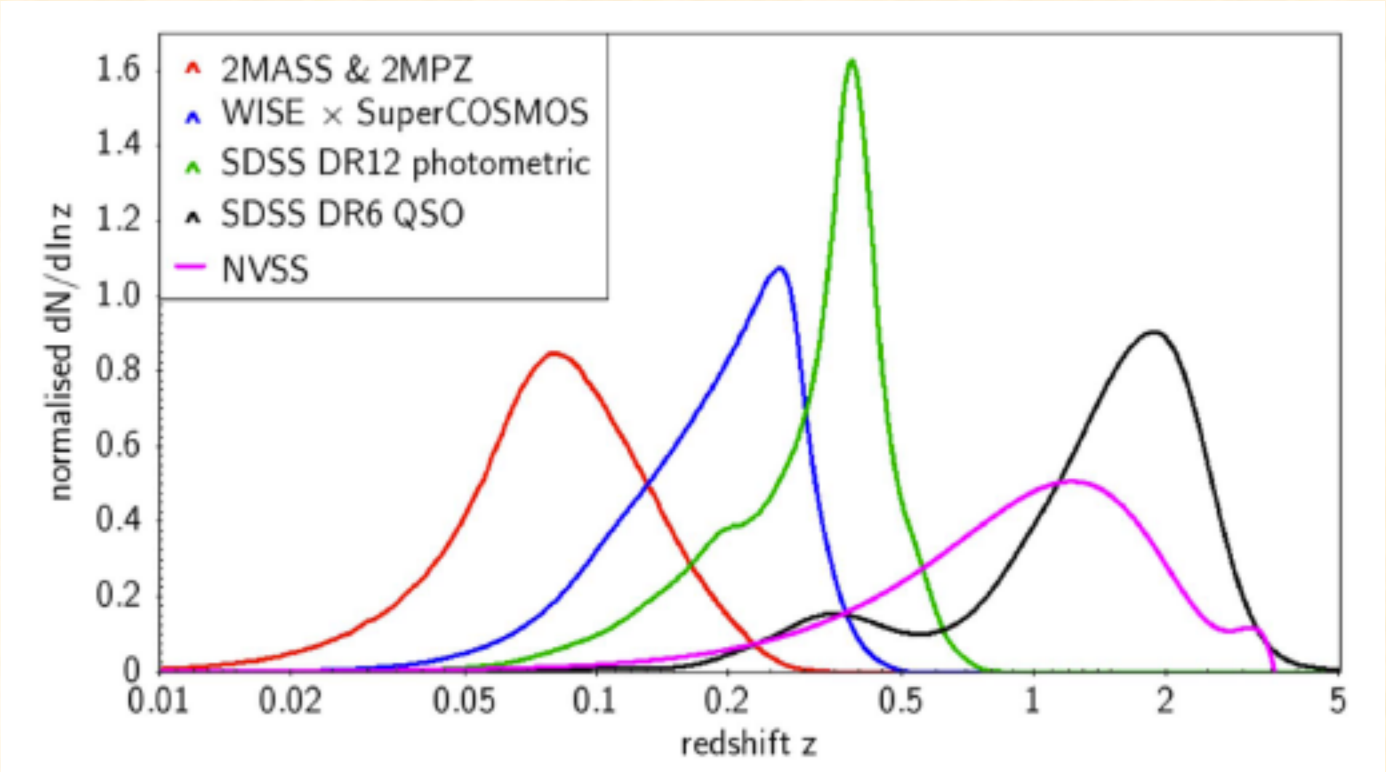
This technique also explores the unresolved regime, and gives constraints which are not possible using only resolved sources

IGRB redshift distribution



- Besides the energy spectrum, the various components differ also by their distribution in z. In particular DM is expected to peak at low redshift.
- Need to isolate the IGRB emission coming from different redshifts!

Tomography of the IGRB via x-correlation with LSS



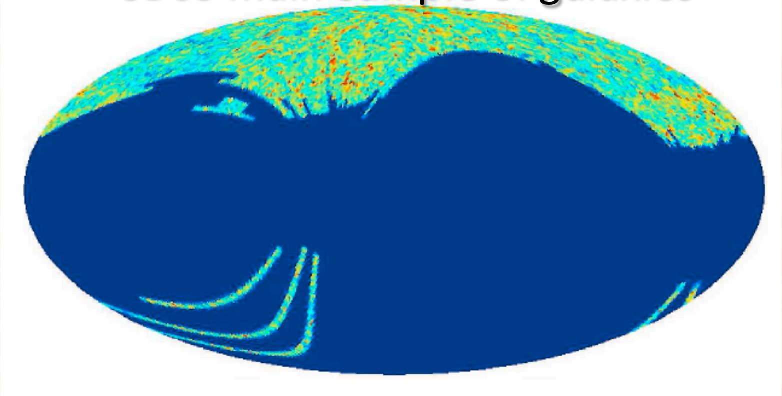
See also:
Xia et al. MNRAS 2011,
Ando, JCAP 2014,
Ando, Benoit-Levy,
Komatsu PRD 2014

Xia et al. ApJS, 2015
Cuoco et al. ApJS, 2017

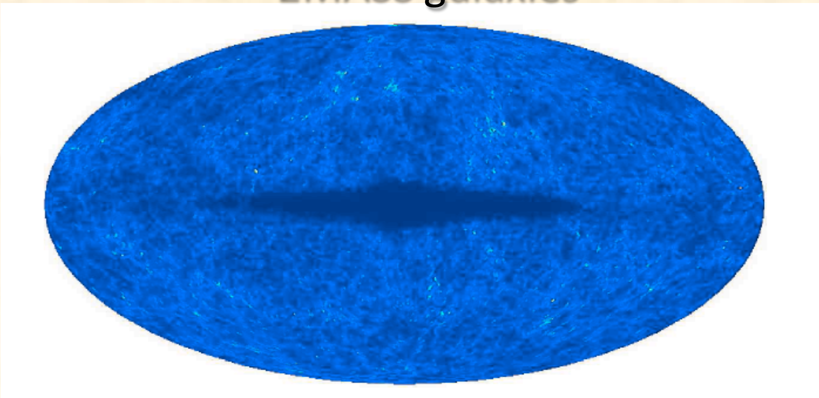
- The different z-coverage of each catalogue allows to isolate the IGRB at different z effectively performing a Tomography of the IGRB
- This provides a strong handle to better separate components and eventually DM

cross-correlation with LSS: catalogues

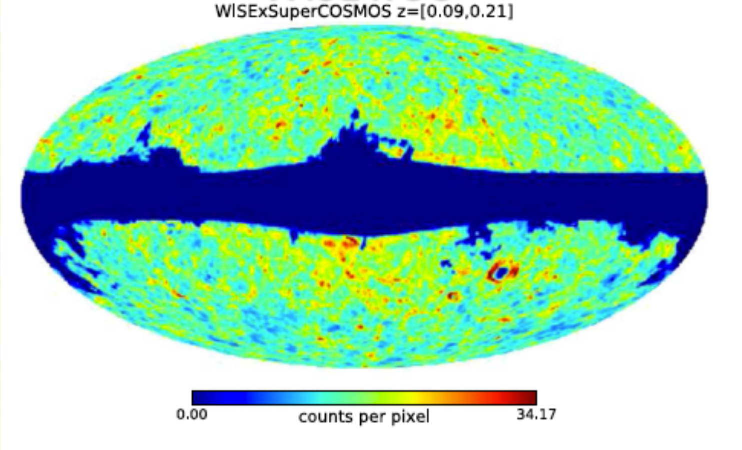
SDSS main Sample of galaxies



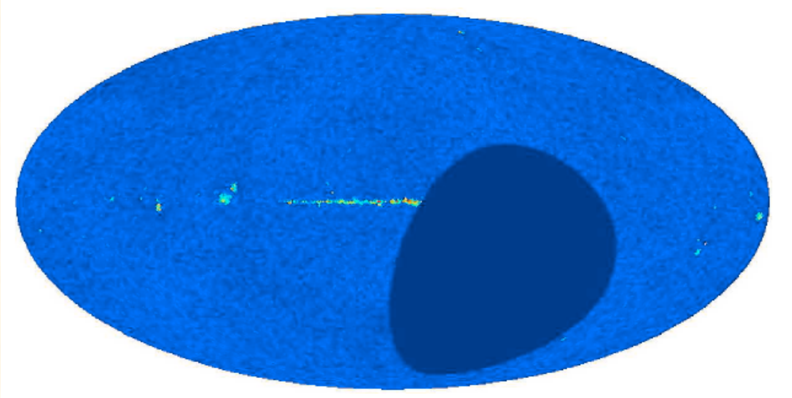
2MASS galaxies



WISE x SC



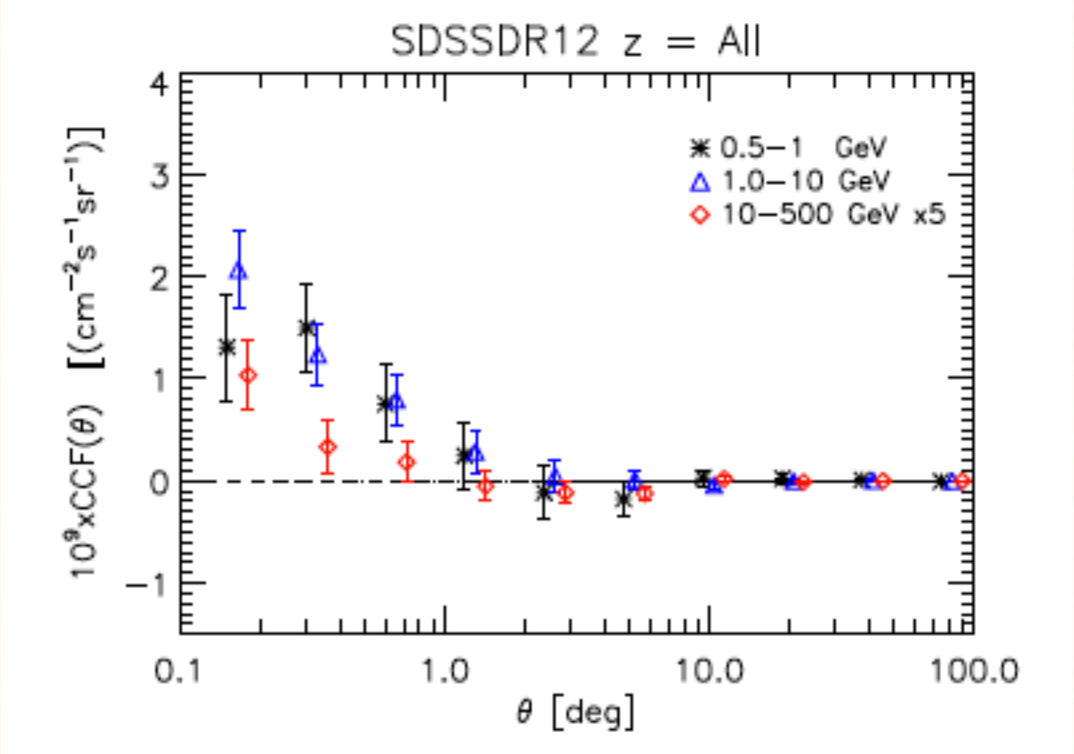
NVSS radio sources



- DM emission in the IGRB should trace the Large Scale Structures of the Universe.
- Galaxy Catalogues can be used as LSS template to cross-correlate with

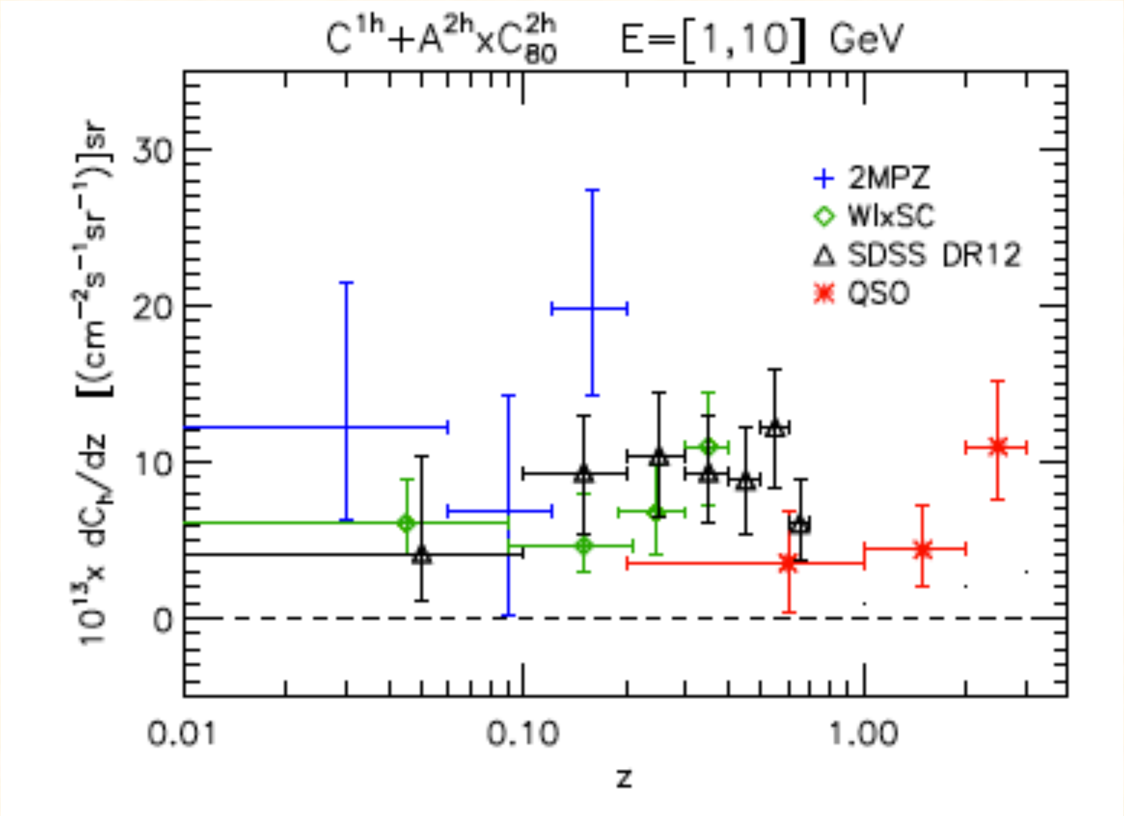
Xia, Cuoco, Branchini, Viel, ApJS, 2015
Regis, Xia, Cuoco+ PRL 2015
Cuoco, Xia, Regis,+ ApJS, 2015
Cuoco, Bilicki, Xia, Branchini, ApJS, 2017

Fermi- SDSS X-Correlation



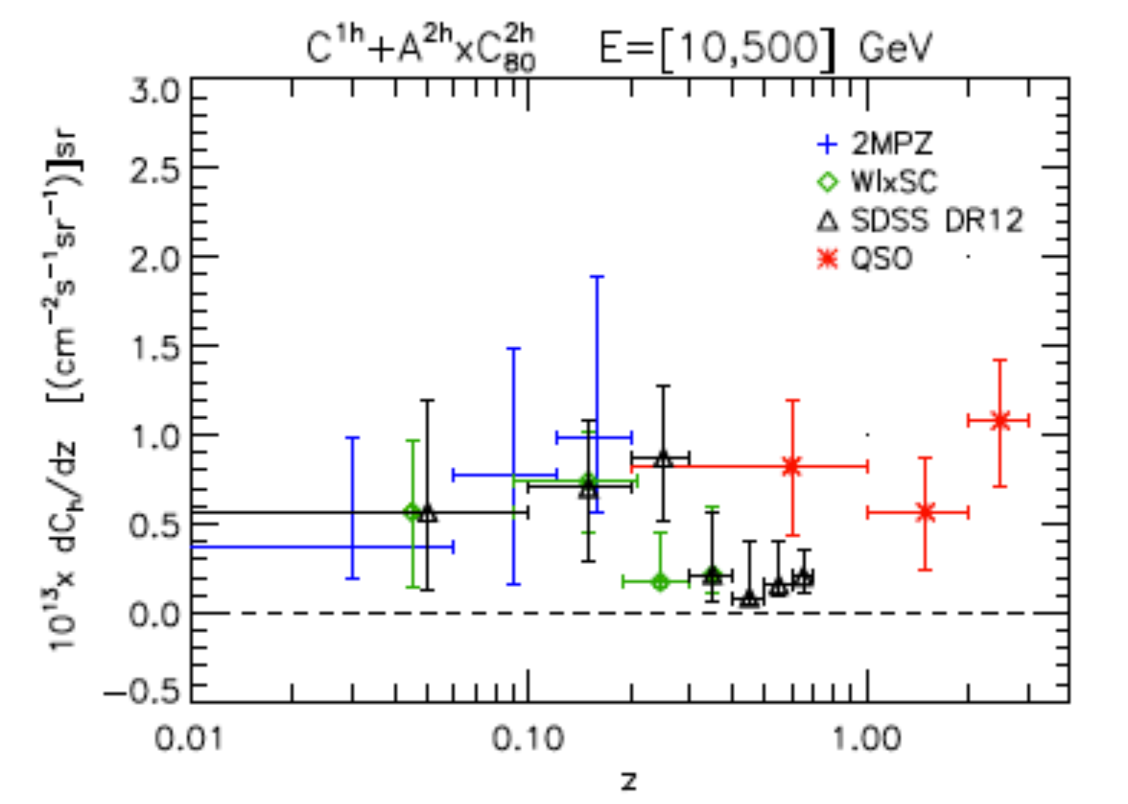
- Cross-correlation detected with a high significance (> 5 sigma)

Measured IGRB redshift distribution



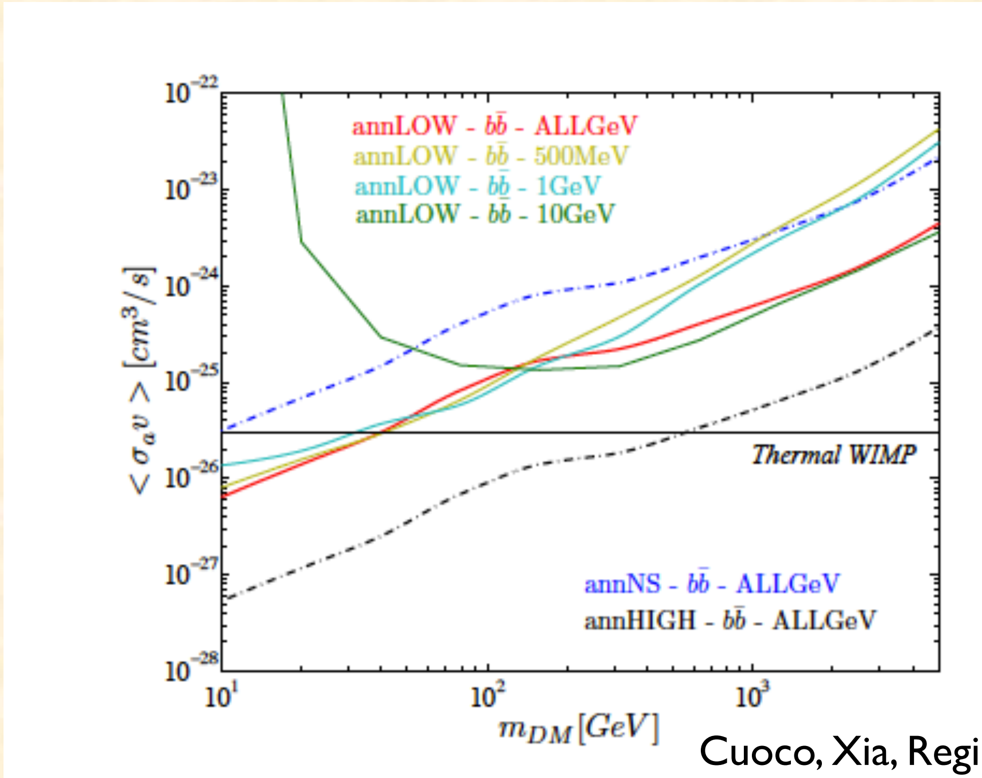
- Exploiting the redshift information of the catalogs, a fine-binning tomography of the IGRB can be performed and the redshift distribution can be reconstructed

Measured IGRB redshift distribution



- The IGRB redshift distribution can be studied in energy bins.
- Indications that above 10 GeV the IGRB emission is much closer (z<0.3)

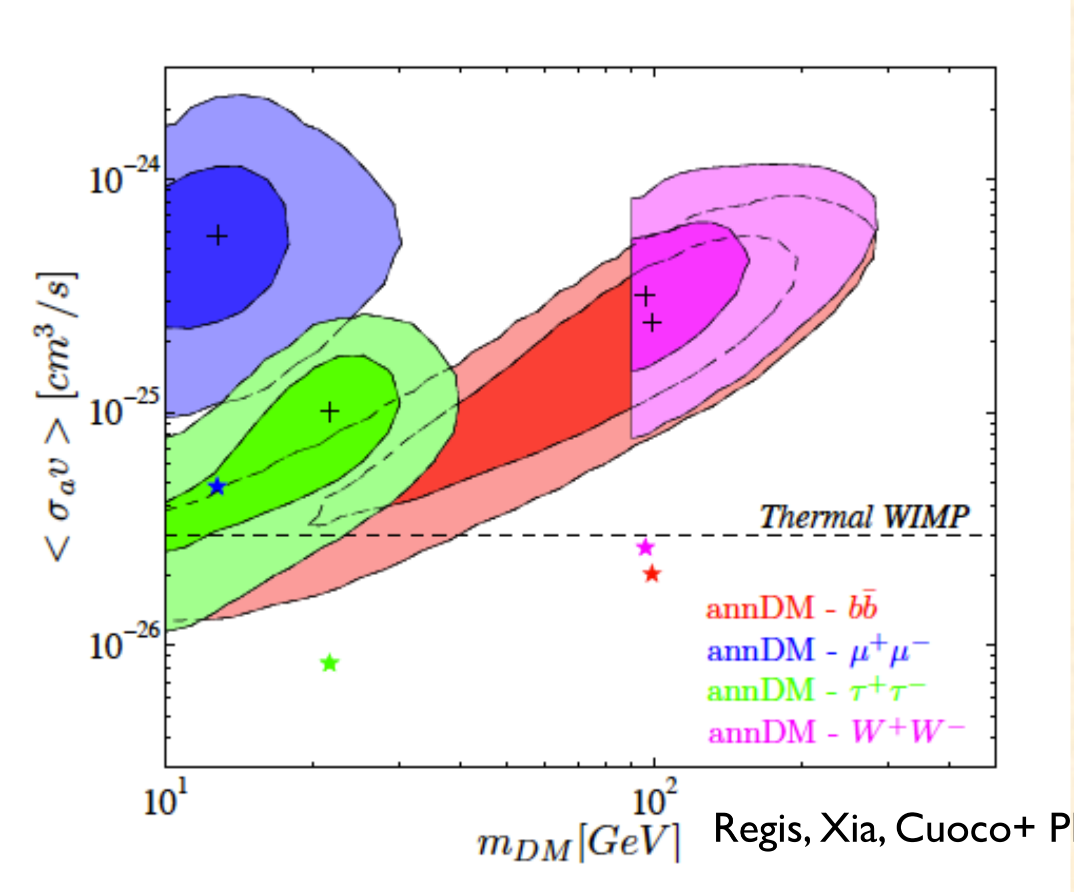
Dark Matter Constraints



Cuoco, Xia, Regis,+ ApJS, 2015

- Limits on the DM contribution can be placed, although they depend on the DM Halo substructure modeling.
- They are, however, competitive even in the most conservative substructure boost scenario (i.e. no boost)

Dark Matter Interpretation



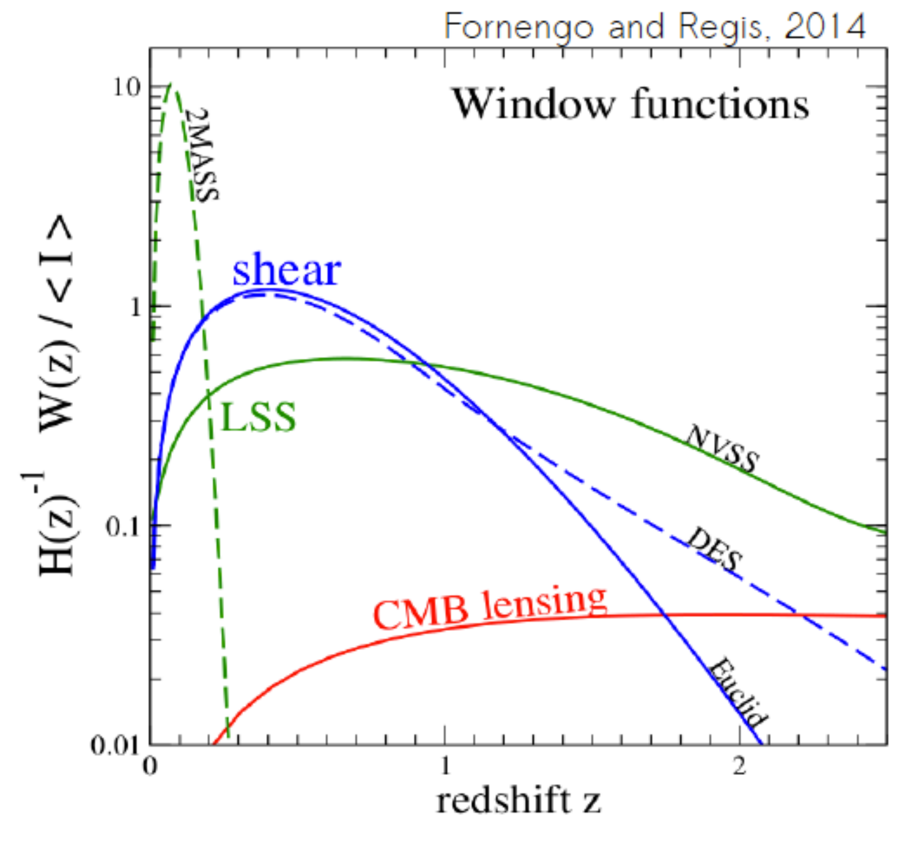
Regis, Xia, Cuoco+ PRL 2015

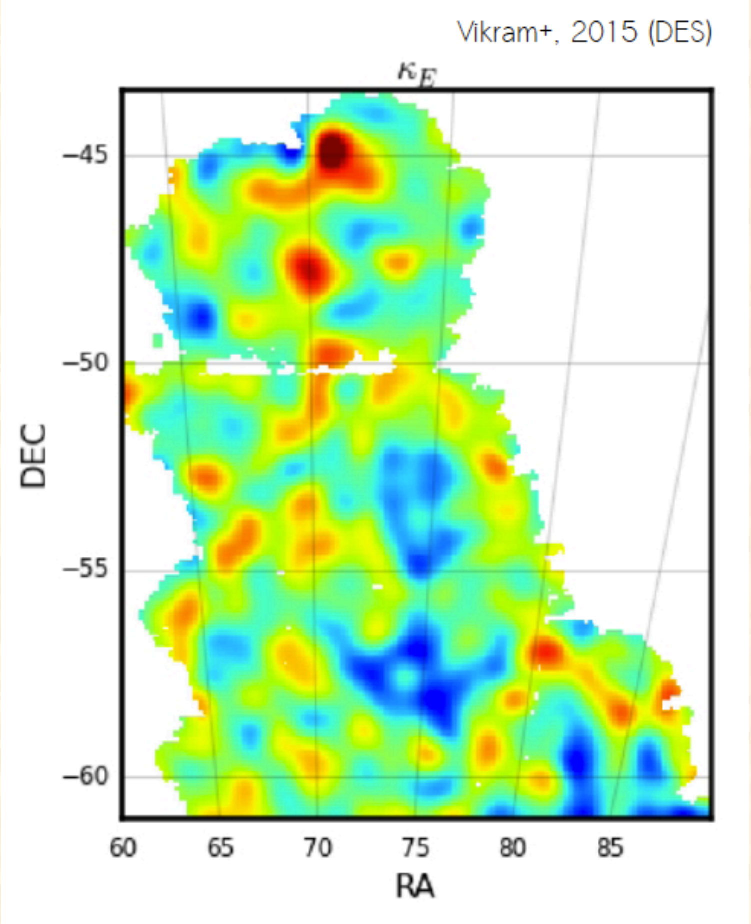
- A large DM contribution to the 2MASS correlation cannot be excluded, since, due to the peaking at low z, an high 2MASS correlation does not affect the correlations at higher z.
- Further analyses with more statistics will help to clarify this picture

Summary and Conclusions

- There is much more information in the maps of the gamma-ray sky besides the intensity energy spectrum!
- Auto-correlation and pixel count statistics provide strong constraints on blazars models
- Anisotropy predictions are easy to derive and compare with data
- Cross correlation of the IGRB with LSSs provides a way to isolate the IGRB contribution in different redshift, i.e. to perform **Tomography**
- The methods provides strong constraints on the DM contribution to the IGRB
- The picture is evolving rapidly and soon more gamma-ray data, and more LSS catalogues and precise lensing shear maps will provide further insights and stronger sensitivities

x-correlation with Lensing Shear



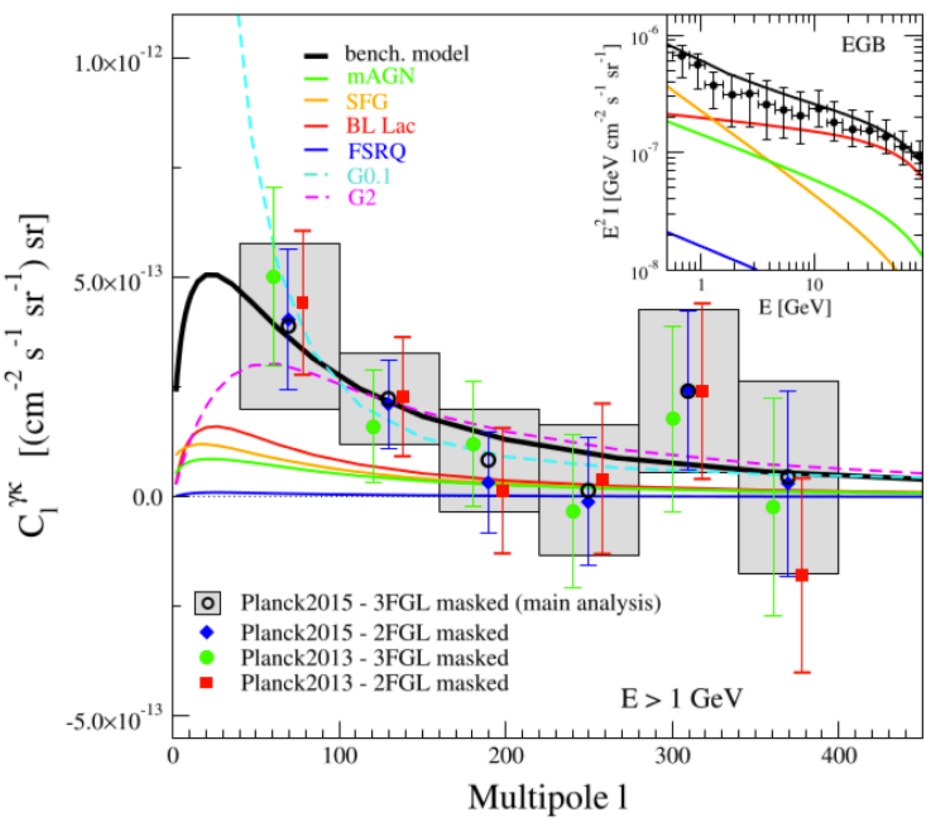


- Advantage: traces directly the total matter. No bias modeling required.
- Disadvantage: not ready yet. Best result at the moment a small patch of the sky from DES. But interesting results to come with full DES maps and in the future Euclid.

x-correlation with CMB Lensing

Fornengo, Perotto, Regis, Camera, ApJ 2015

Planck Collaboration 2015, arXiv:1502.01591



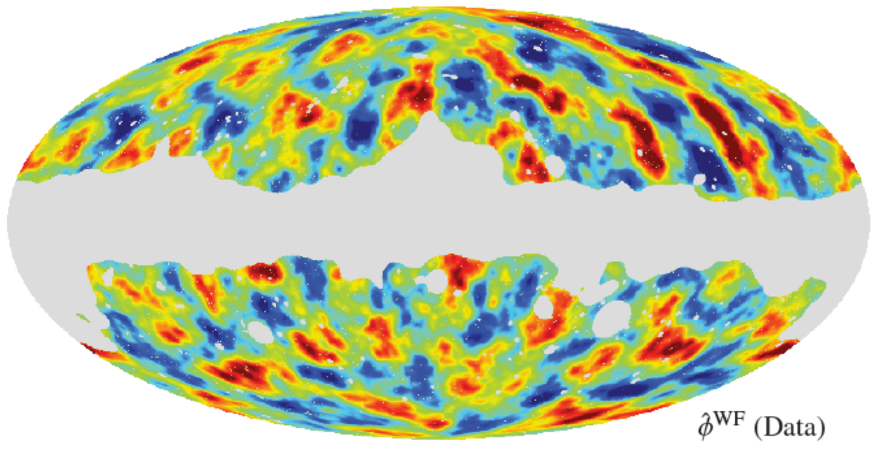


Fig. 2 Lensing potential estimated from the SMICA full-mission CMB maps using the MV estimator. The power spectrum of this map forms the basis of our lensing likelihood. The estimate has been Wiener filtered following Eq. (5), and band-limited to $8 \leq L \leq 2048$.

- A further possibility is to cross-correlate with the LSS gravitational potential estimated through its lensing effect on the CMB.
- Indeed, a ~3 sigma correlation is present (Fornengo+ ApJ, 2015). Interesting for the future if lensing maps will improve.