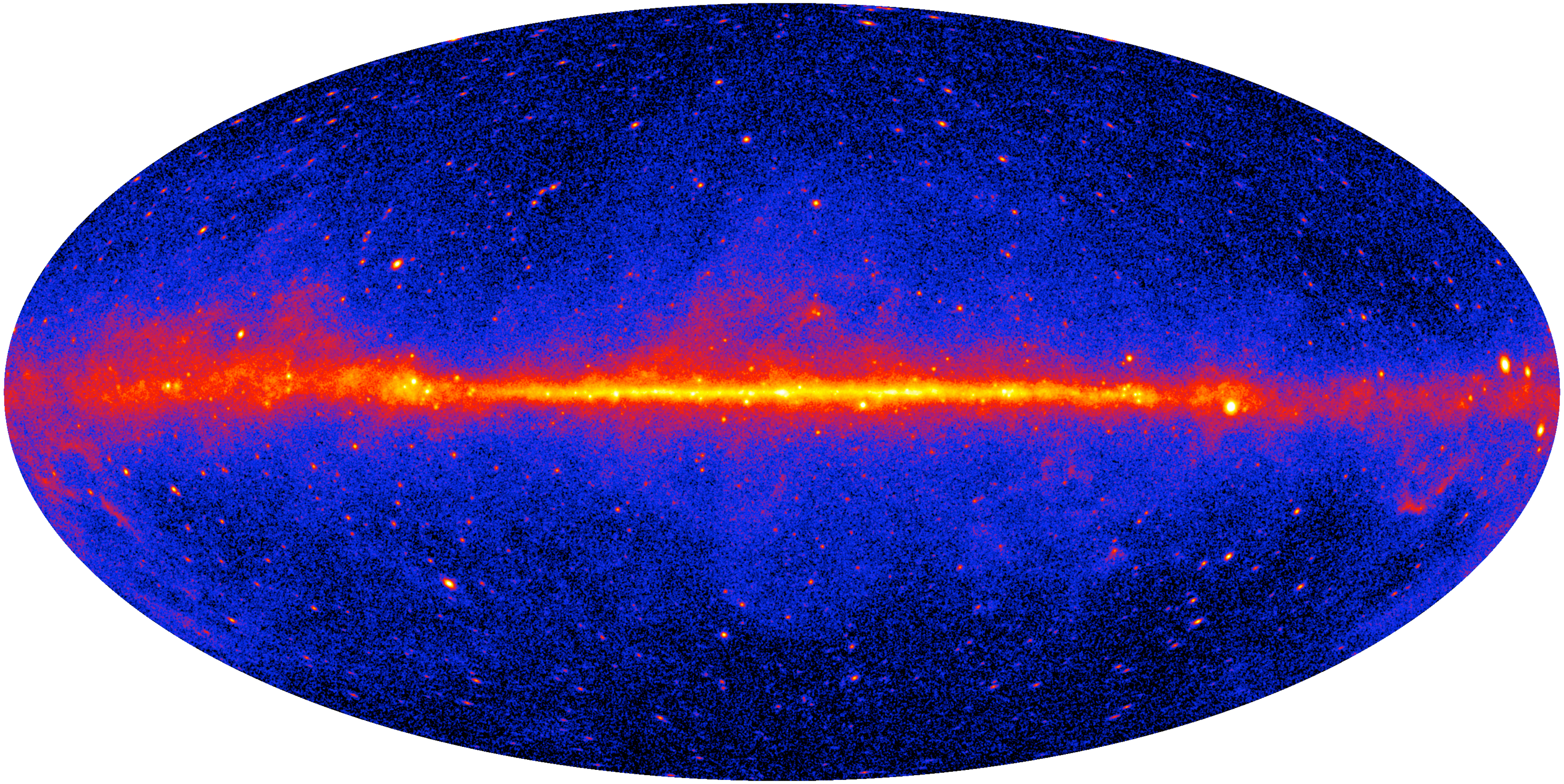
Constraining Dark Matter and Sources in the Diffuse Gamma-ray Background with Anisotropies

Alessandro Cuoco,
Oskar Klein Center,
Stockholm University

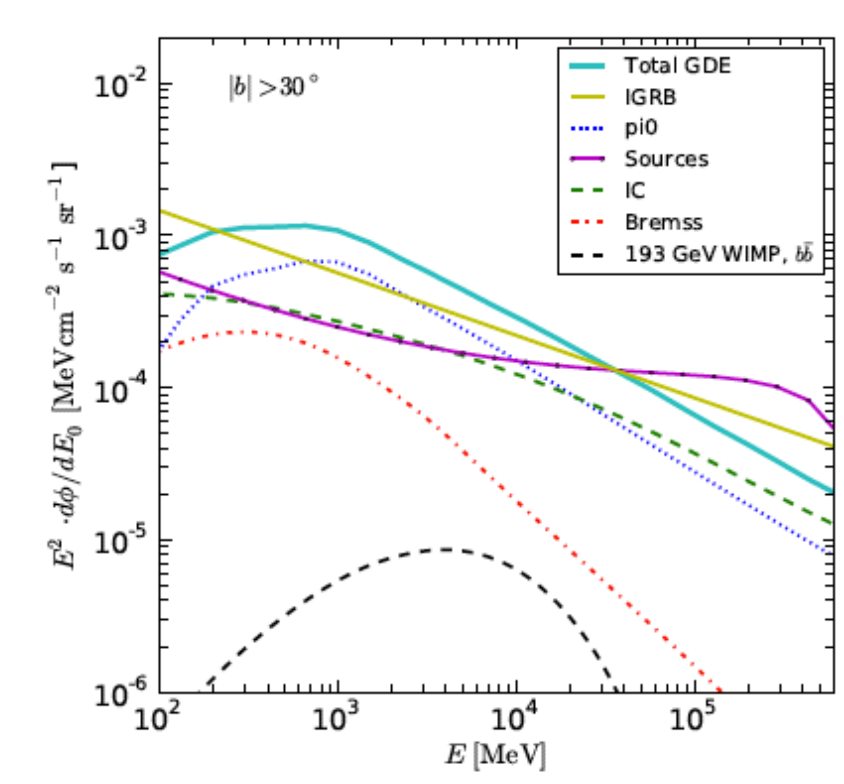
IDM2012, Chicago
July 27th 2012

The Gamma Sky

Fermi Gamma-Sky, Front-only, >1 GeV (36 months, 3.39M events)



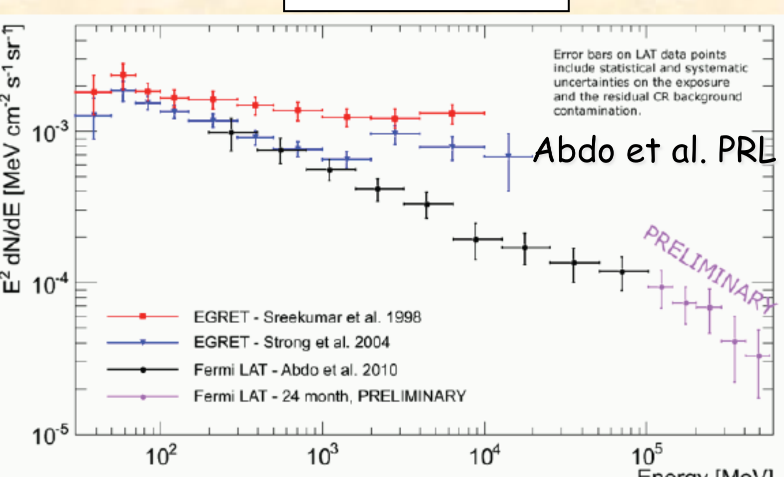
The Gamma Sky



Galactic Contribution from:
1. Pion Decay
2. Inverse Compton
3. Electron Bremsstrahlung

Galprop Foregrounds Model:

4. IGB

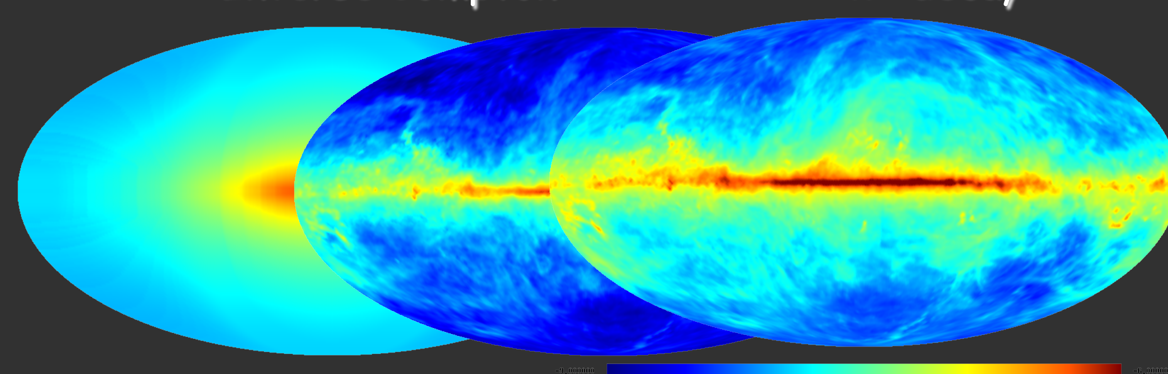


Abdo et al. PRL 2009

Galactic diffuse emission
(CR interactions with the interstellar medium)

Inverse Compton

π^0-decay



Bremsstrahlung

M.Ackermann, TeVPA2011, Stockholm

The origin of the EGB

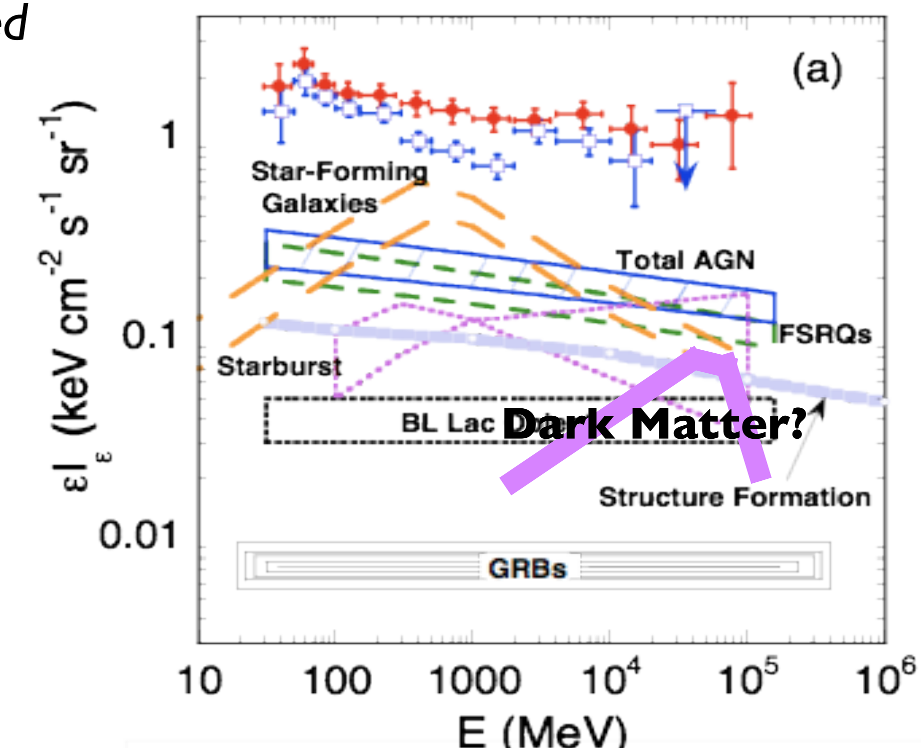
- many astrophysical sources are *guaranteed* to contribute, e.g.:
- blazars
- star-forming galaxies
- millisecond pulsars
- AGNs
- clusters of Galaxies
- clusters Shocks
- cascades from UHECRs

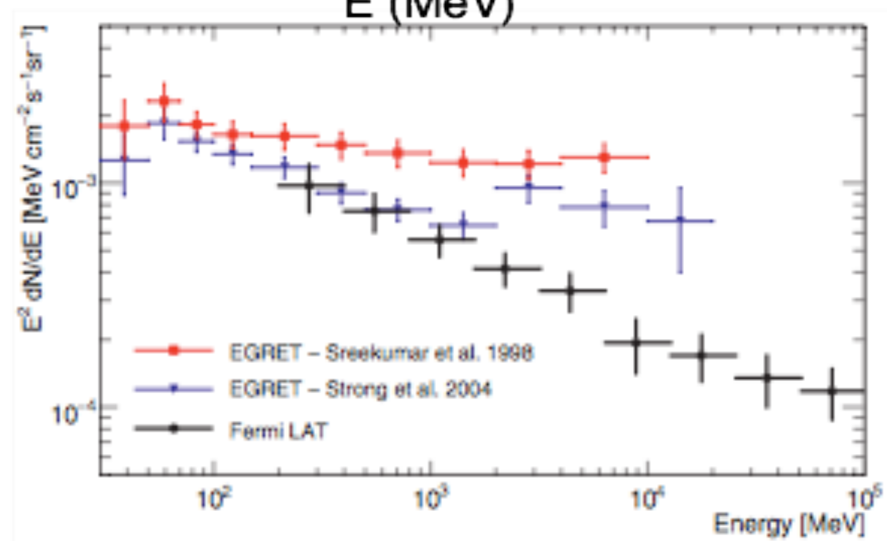
and…

- Dark matter(?)

- relatively featureless total EGB intensity spectrum → lack of spectral handles to ID individual components
- the amplitude and energy dependence of the anisotropy is a complementary tool to disentangle different contributions

Dermer 2007





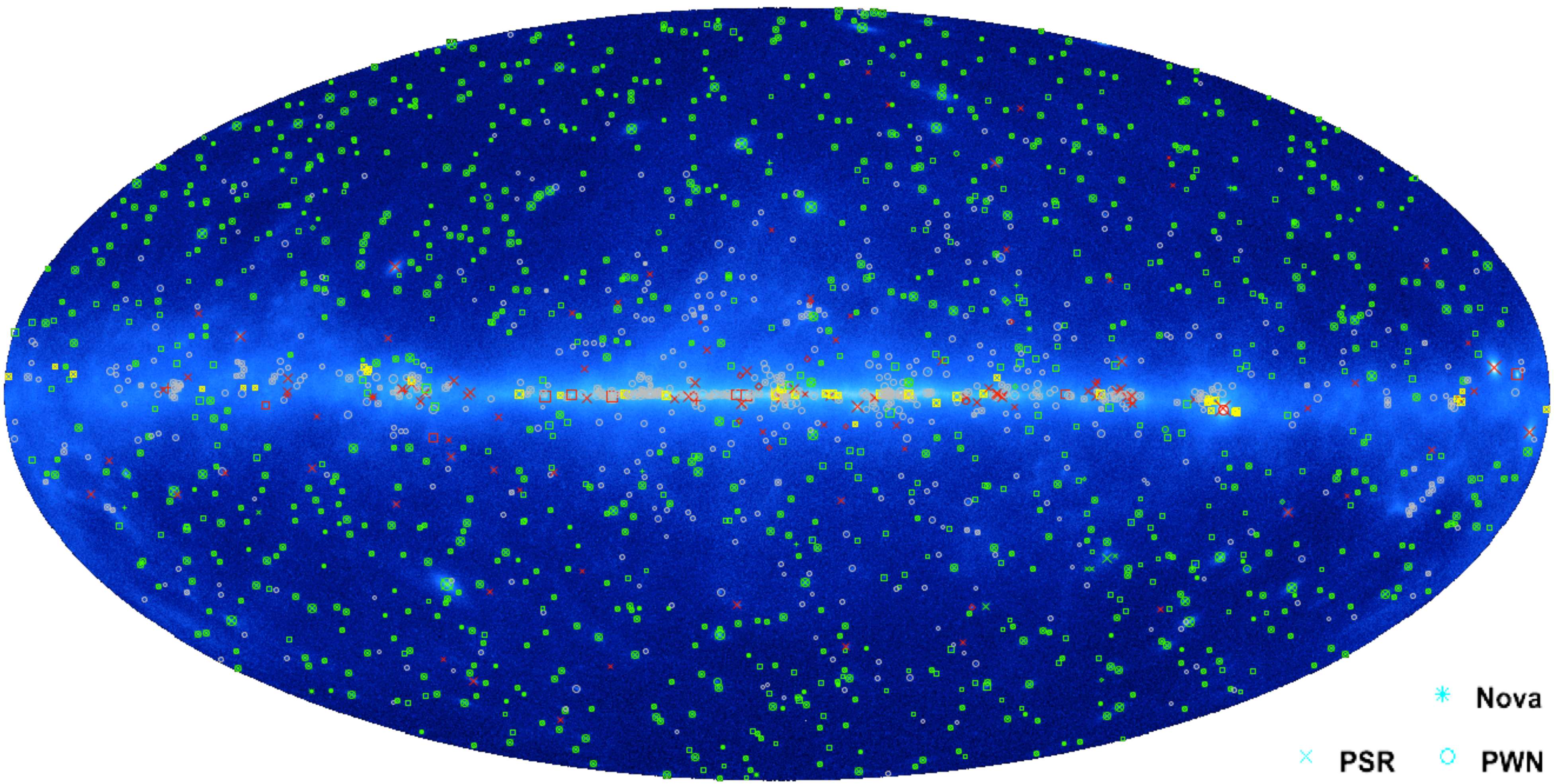
Abdo et al., PRL 104 (2010) 101101

Resolved Sources - 2FGL catalogue

AGN   AGN-Blazar
AGN-Non Blazar

~2000 sources

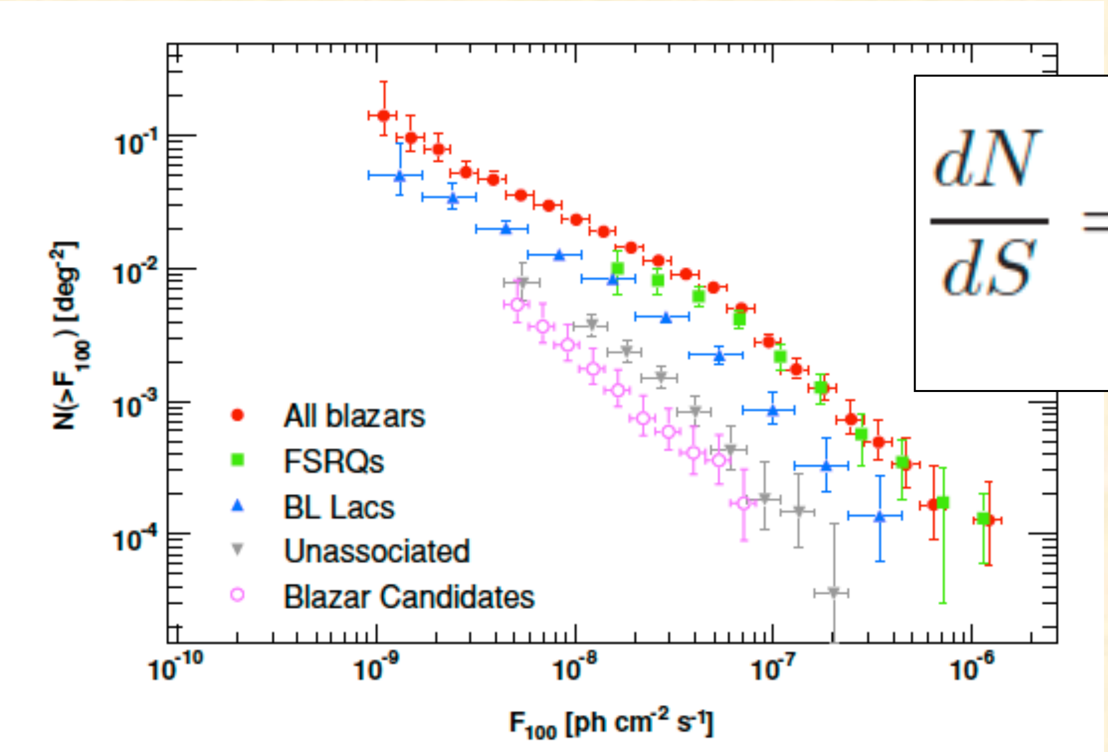
Galaxy   Starburst Galaxy
Radio Galaxy   Seyfert Galaxy



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

Credit: Fermi Large Area Telescope Collaboration

Source Count Statistics (LogN-LogS)



$$\frac{dN}{dS} = \begin{cases} A\, S^{-\beta} & S \geq S_{\rm b} \\ A\, S_{\rm b}{}^{-\beta+\alpha} S^{-\alpha} & S < S_{\rm b} \end{cases}$$

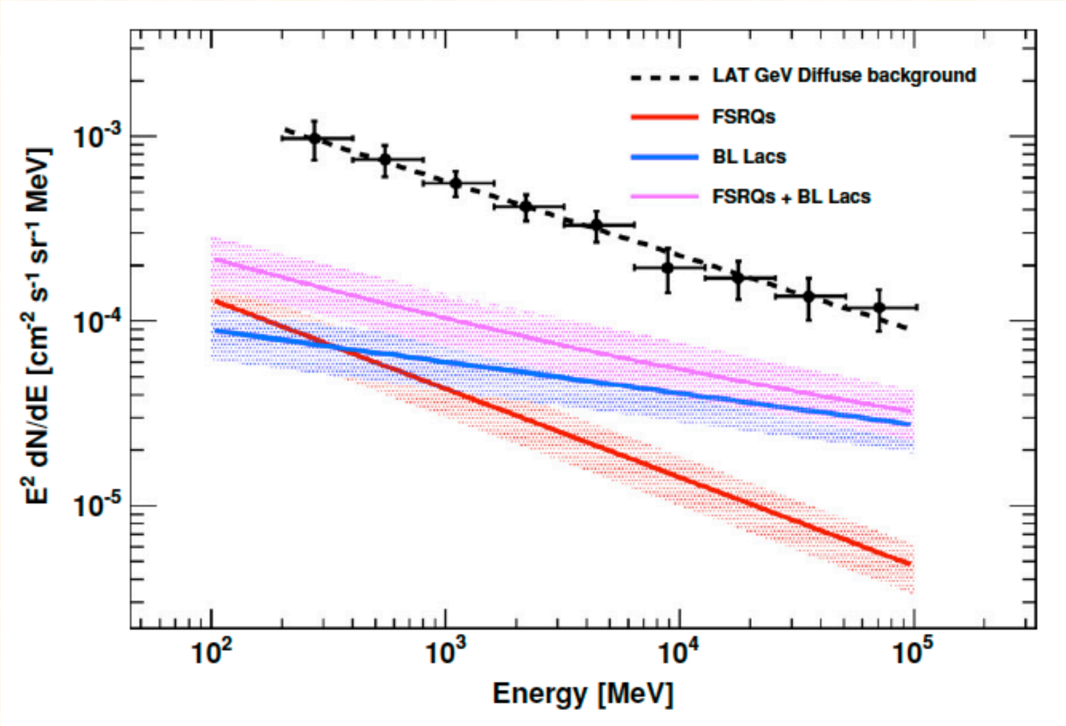
$$I = \int_0^{S_{\rm t}} \frac{dN}{dS} S\, dS$$

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

- Blazars are the dominant extragalactic source population in the LAT energy band
- Extrapolation of source count distribution of resolved LAT blazars allows estimates of their contribution to the EGB, both in intensity and anisotropy

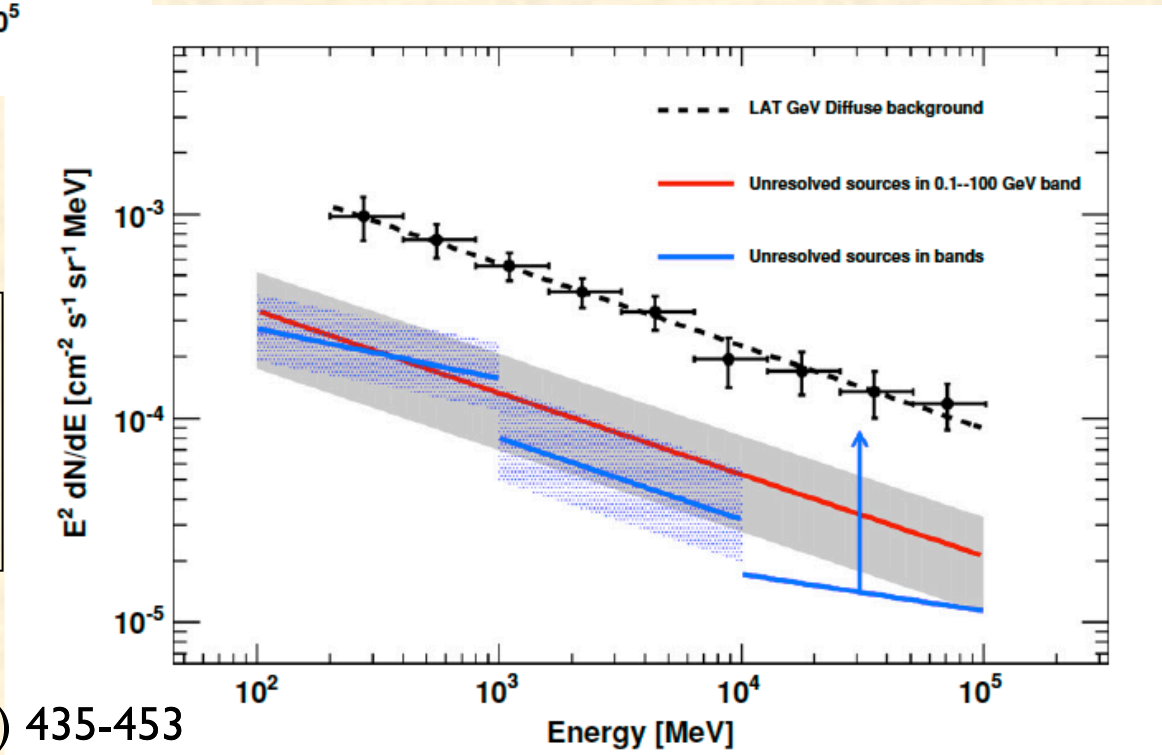
Fermi-LAT collaboration, Astrophys.J. 720 (2010) 435-453

Source Count Statistics (LogN-LogS)



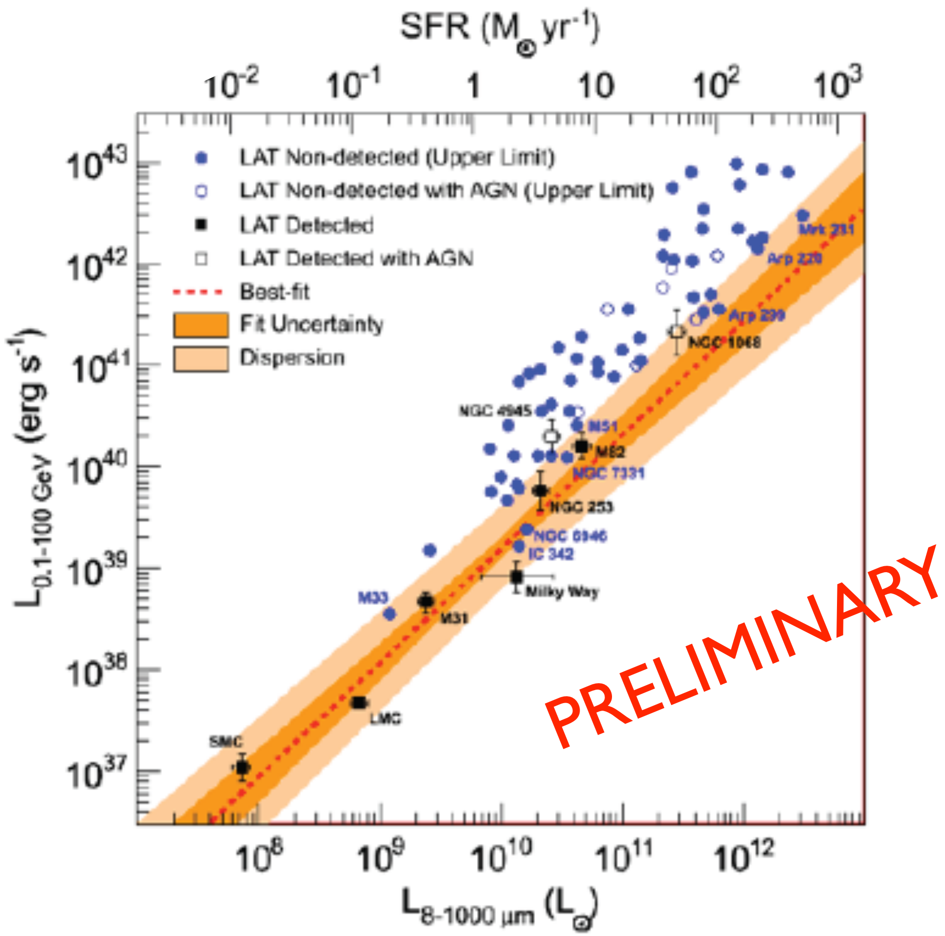
- Total contribution of blazars in 100 MeV - 100 GeV band: 23% +/- 5% stat. +/- 12% sys

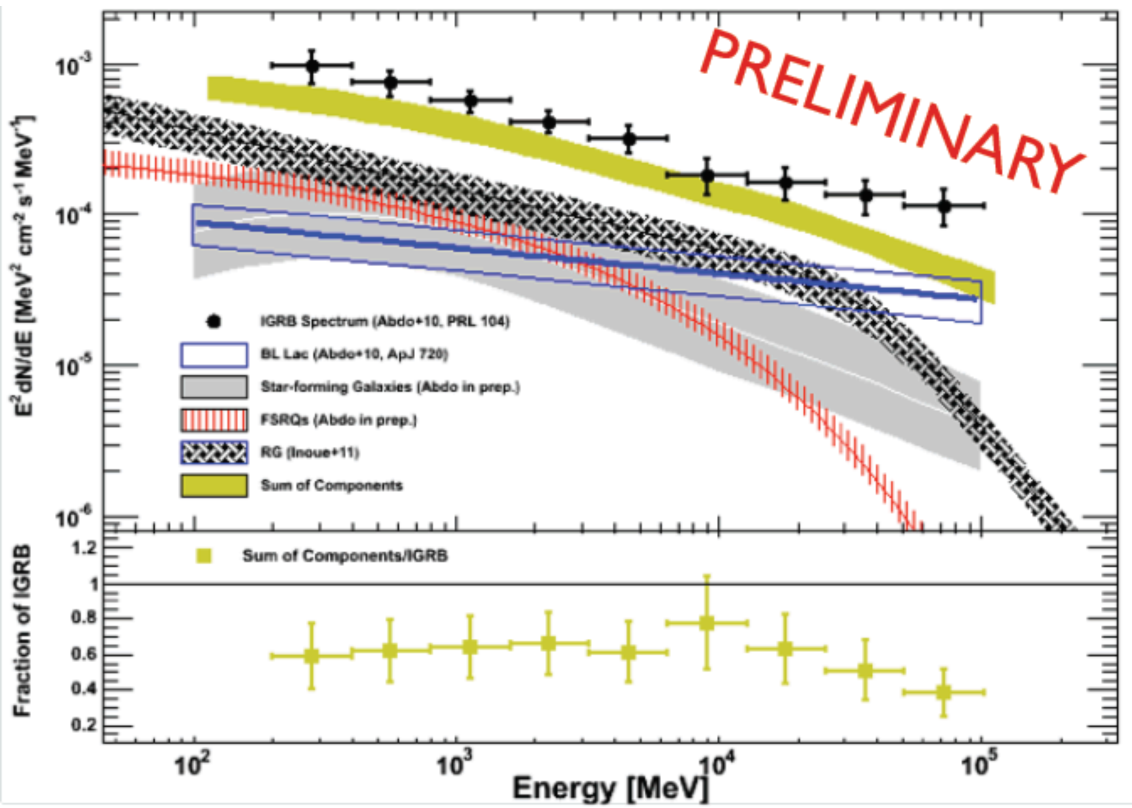
- Analisys can also be done in different energy bands, giving similar percentages



Fermi-LAT collaboration, Astrophys.J. 720 (2010) 435-453

EGB Status





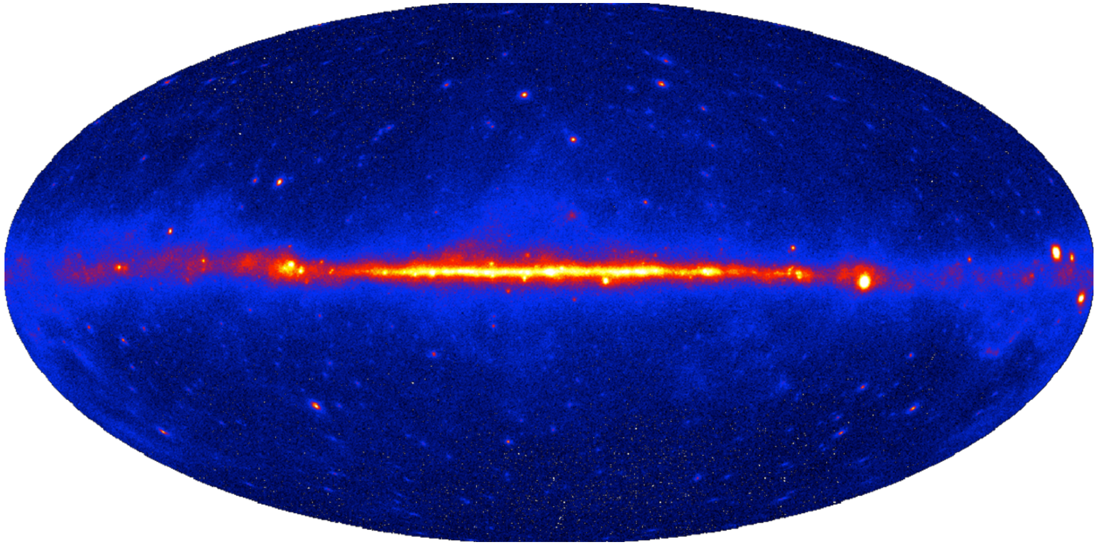
As for the blazars, a luminosity function for normal galaxies can be built, but due to the very few galaxies detected (~10) a calibration on radio observation is required.

AGN contribution more unceratain. Overall the blazar-SFG-AGN model explain almost all the EGB.

Fermi-LAT collaboration, Astrophys.J. (2012)

Sources of Anisotropies in the Gamma-ray Sky

Fermi Gamma-Sky 30 MeV-300 GeV



- Besides the Galactic Component the Gamma-ray sky contains a large-scale isotropic gamma-ray background (IGRB) which can have small scale fluctuations.
- Poisson-like anisotropy from unresolved point sources, for example, is the main sources of such fluctuations on small angular scales
- The correlations term of unresolved point sources is instead typically subdominant.
- Dark Matter, on Galactic or Extra-Galactic scale can be another source of anisotropy.
- the amplitude and energy dependence of the anisotropy can reveal the presence of multiple contributions and constrain their properties

The angular power spectrum

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

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

- Spherical Harmonic transform of the intensity map
- Intensity angular power spectrum: Ensemble average of the harmonic coefficients; indicates *dimensionful* amplitude of anisotropy

$$\frac{C_\ell}{\langle I \rangle^2}$$

- Also widely used is the fluctuation angular power spectrum:
  - *dimensionless*, independent of intensity normalization
  - amplitude for a single source class is the same in all energy bins (if source distribution is independent of energy)

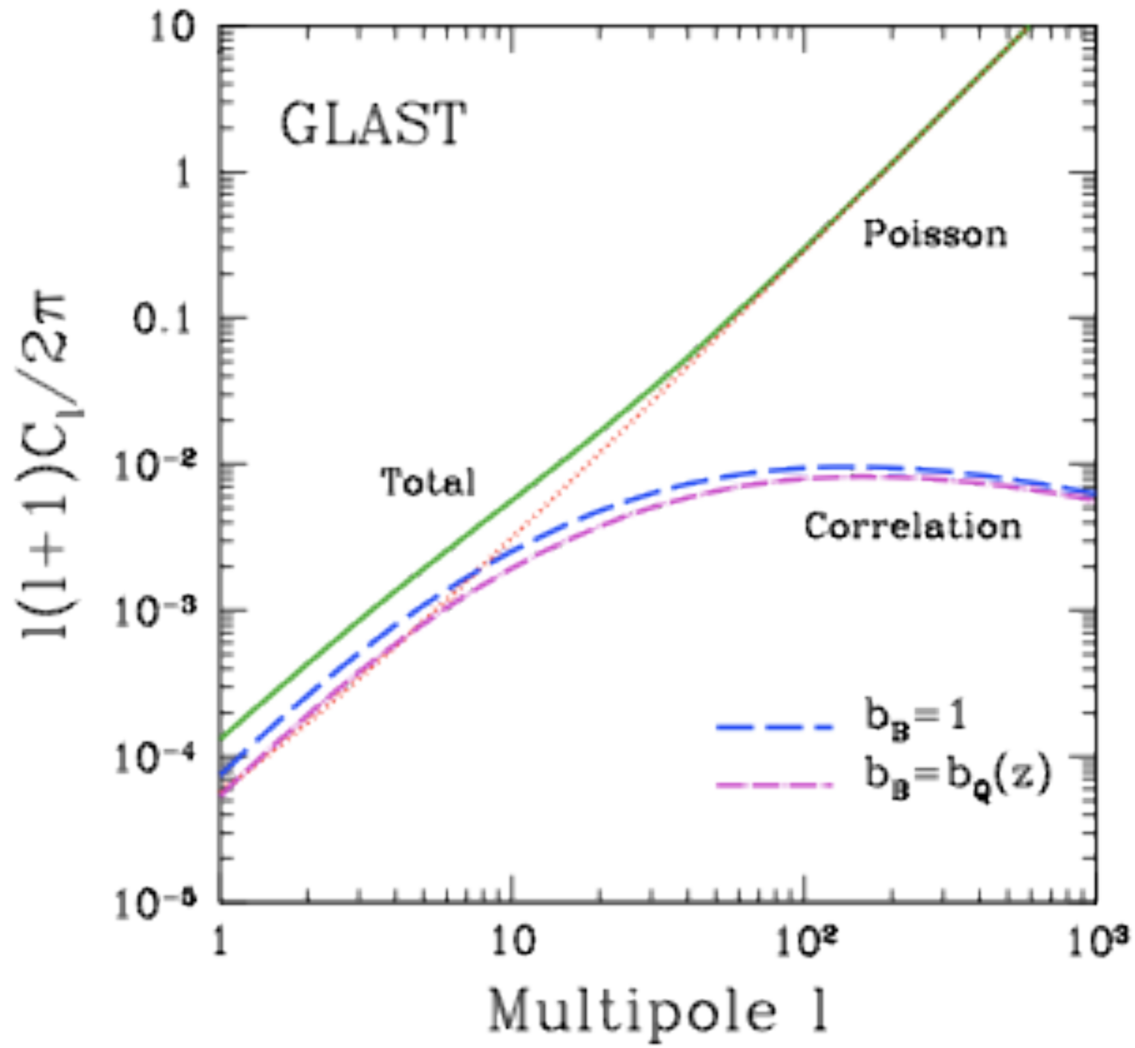
Angular power spectra of unresolved gamma-ray sources

- the angular power spectrum of many gamma-ray source classes is dominated by the Poisson (shot noise) component for multipoles greater than ~ 10

- Poisson angular power arises from unclustered point sources and takes the same value at all multipoles

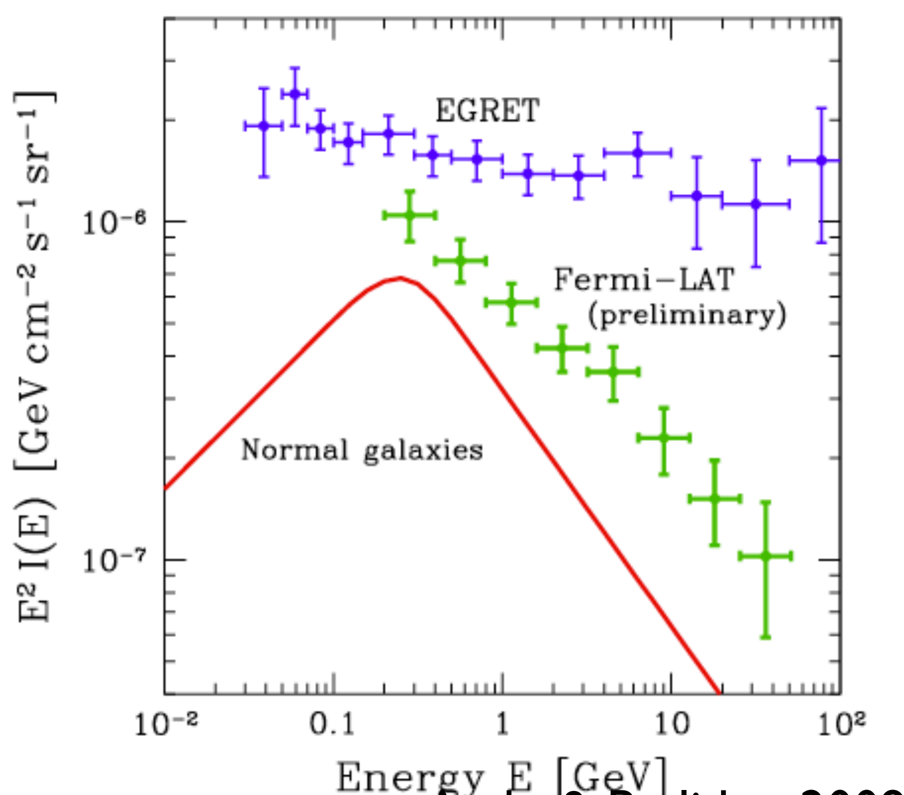
predicted fluctuation angular power $C_\ell/\langle I\rangle^2$ [sr] at l = 100 for a single source class (LARGE UNCERTAINTIES):

- blazars: ~ 1e-4
- starforming galaxies: ~ 1e-7
- dark matter: ~ 1e-4 to ~ 0.1
- MSPs: ~ 1e-2



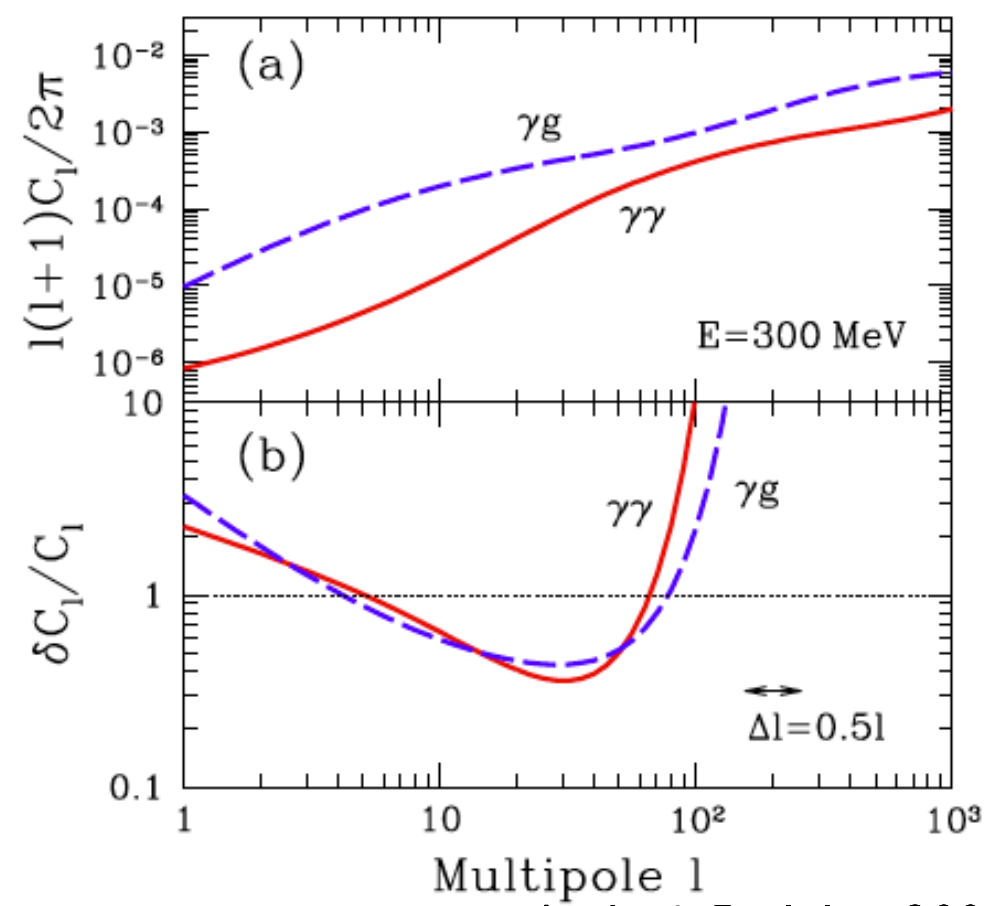
Blazars (Ando, Komatsu, Narumoto & Totani 2007)

Anisotropy from Star Forming Galaxies



Ando & Pavlidou 2009

Auto- and cross-correlation APS

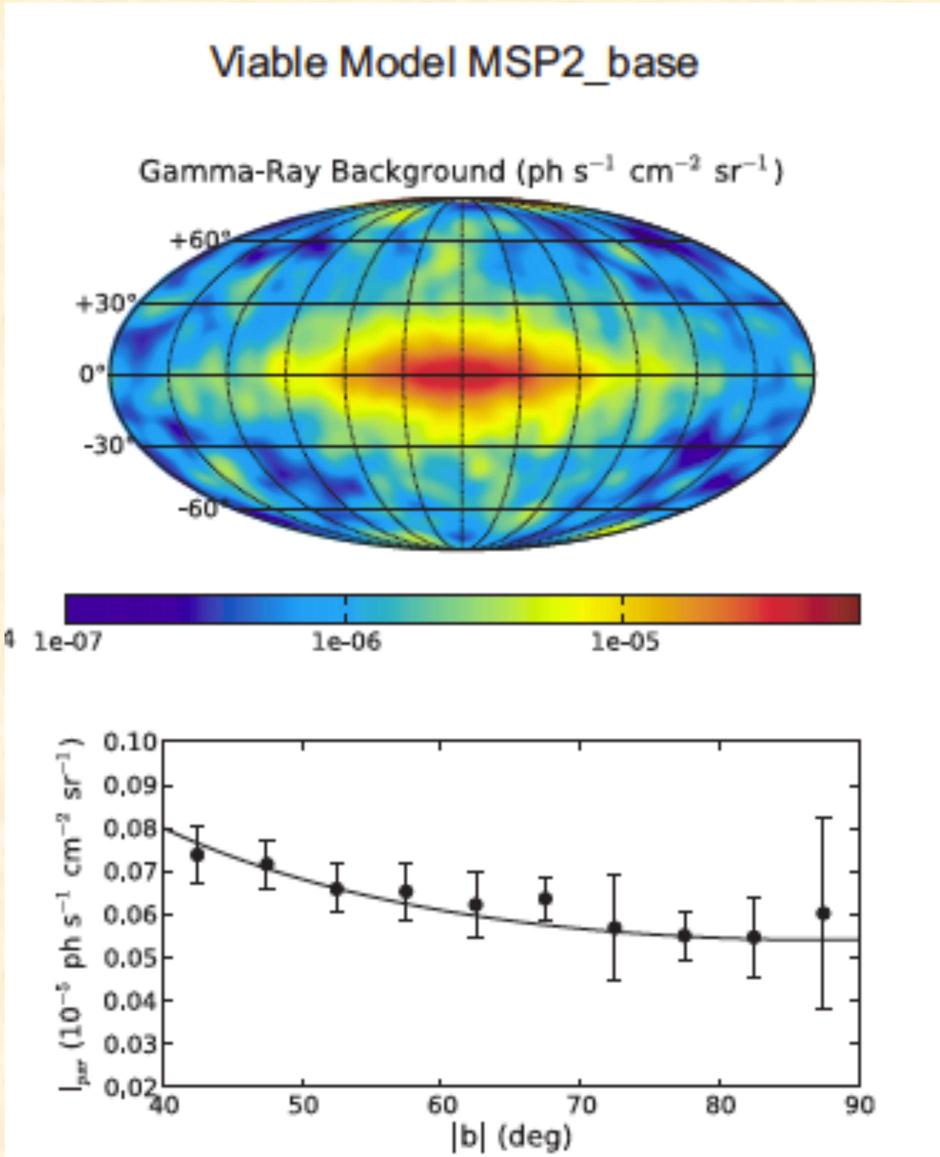


Ando & Pavlidou 2009

Overall, low anisotropy predicted. ~2 orders of magnitude lower than blazars

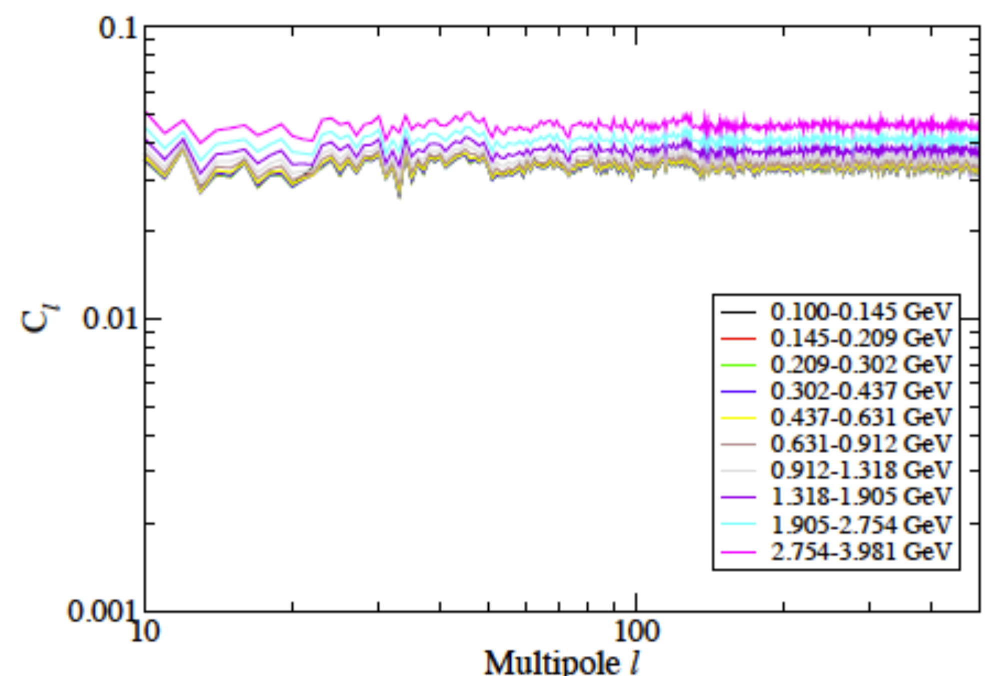
Anisotropy of AGNs is in between, based on their number density

Anisotropy from Millisecond Pulsars



Faucher-Giguere & Loeb 2010

Cl of pulsars

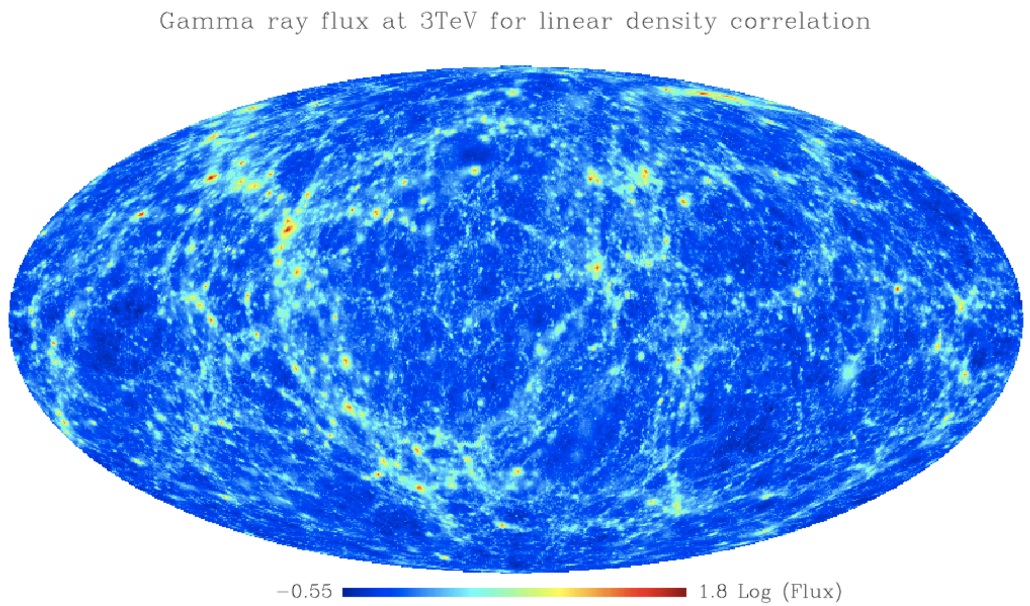


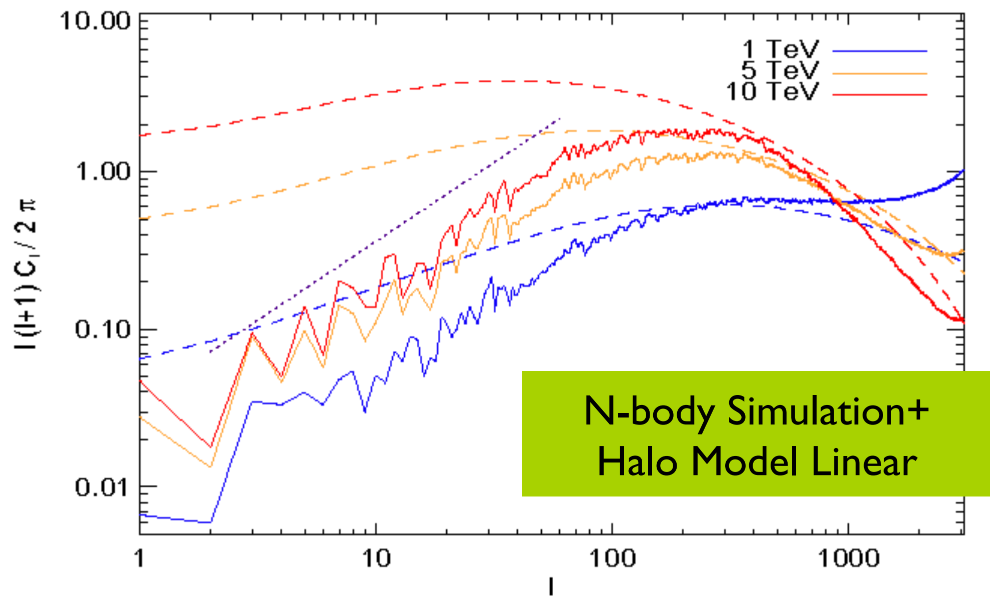
Siegal-Gaskins, Reesman, et al. 2010

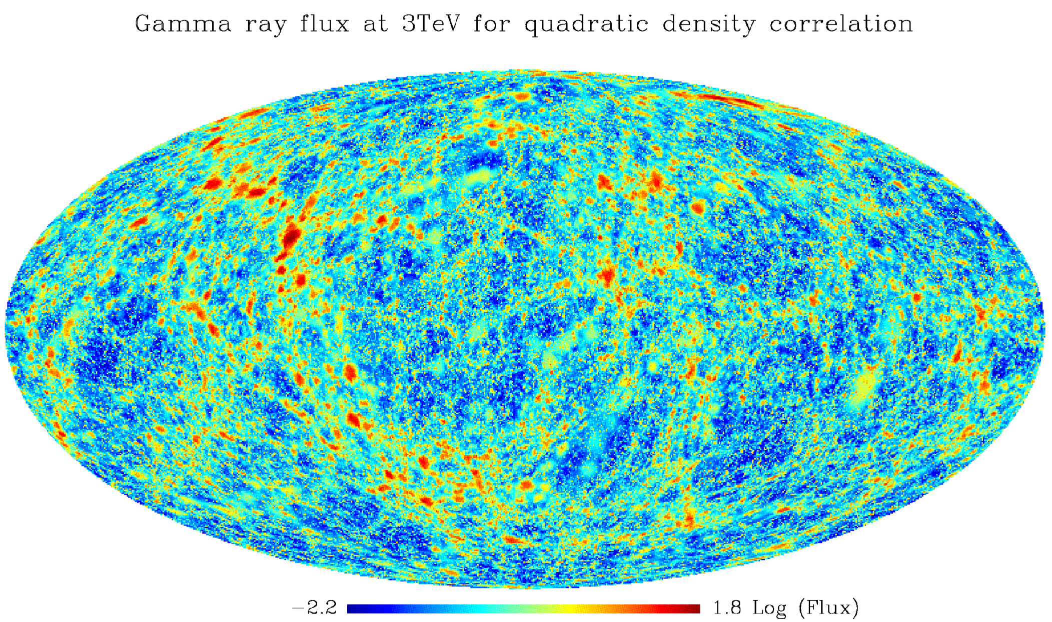
Intrinsic Anisotropy from Millsecond Pulsars is very high (they are powerful and rare). Overall Contribution to EGB is probably low.

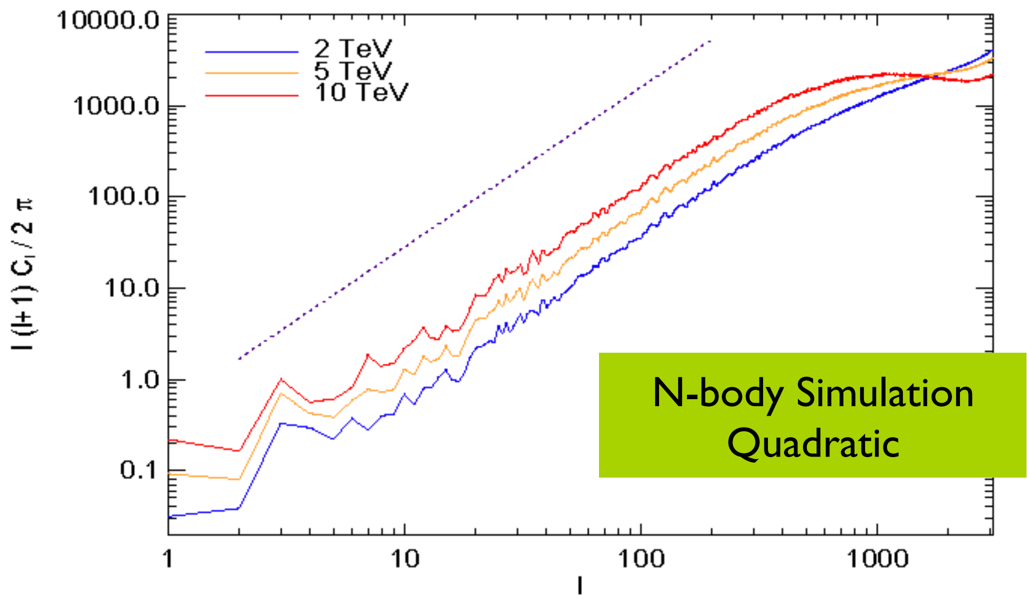
MSPs can migrate to very high b, and contribute to the IGRB.

The IGRB angular power spectrum from N-body Simulations of Large Scale Structures (LSS)



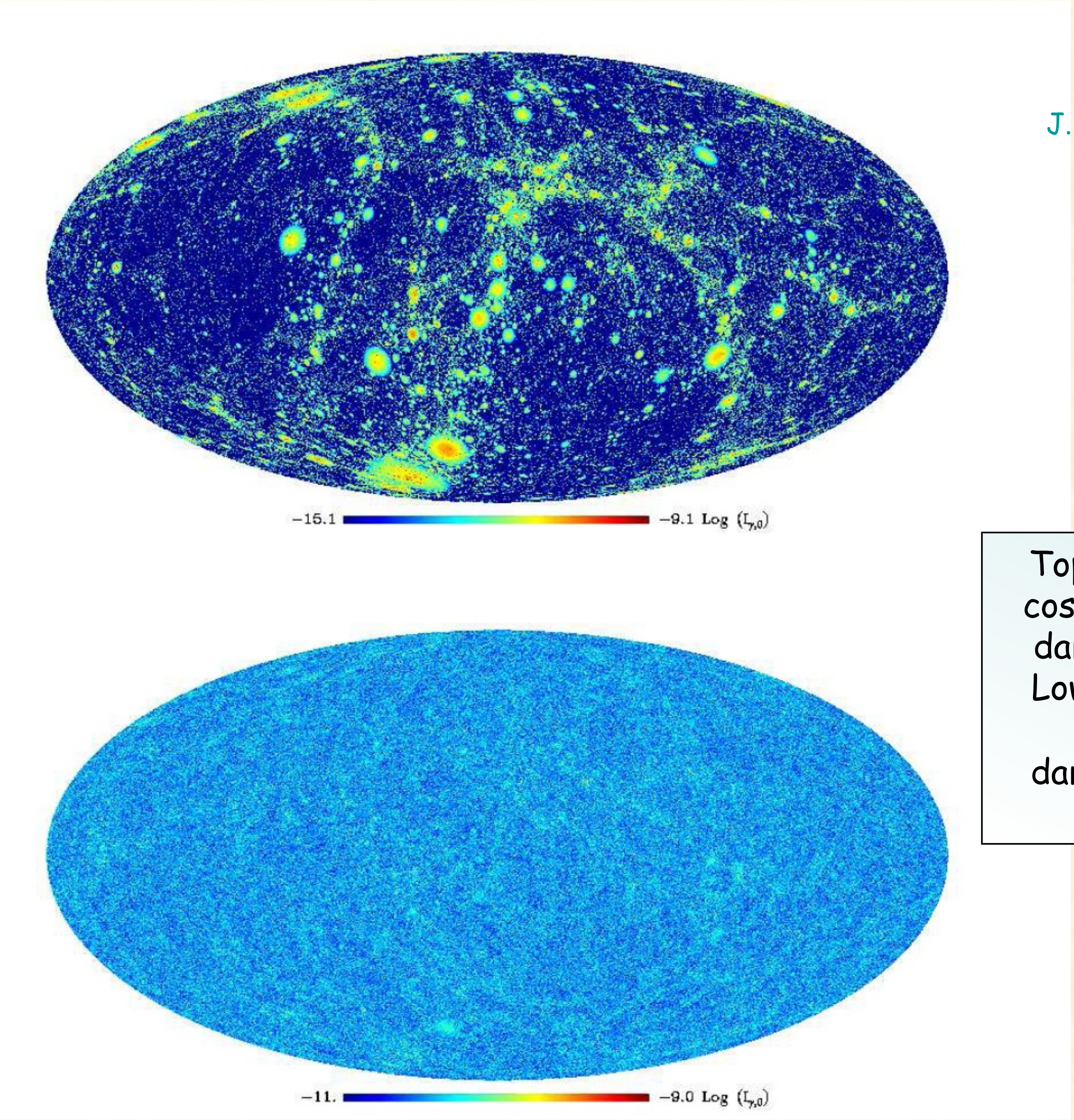






A.Cuoco, S.Hannestad, T.Haugbolle, G.Miele, P.D.Serpico, JCAP 0704:013,2007

MilleniumII simulation

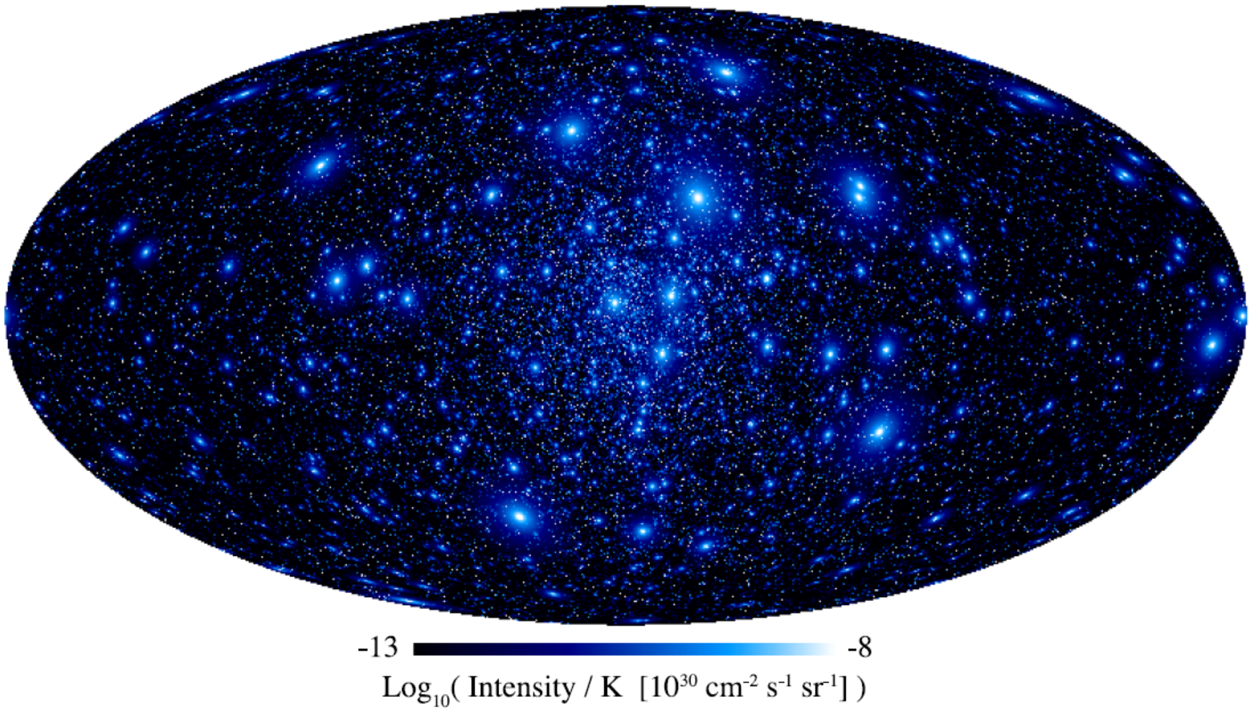


DM Skymaps from the MilleniumII simulation

J. Zavala, V. Springel, M. Boylan-Kolchin, .arXiv: 0908.2428

Top: partial map (z = 0) showing the cosmic -ray background produced by dark matter annihilation at 10 GeV, Lower panel: Co-added map showing the full -ray sky map from dark matter annihilation integrated out to z = 10.

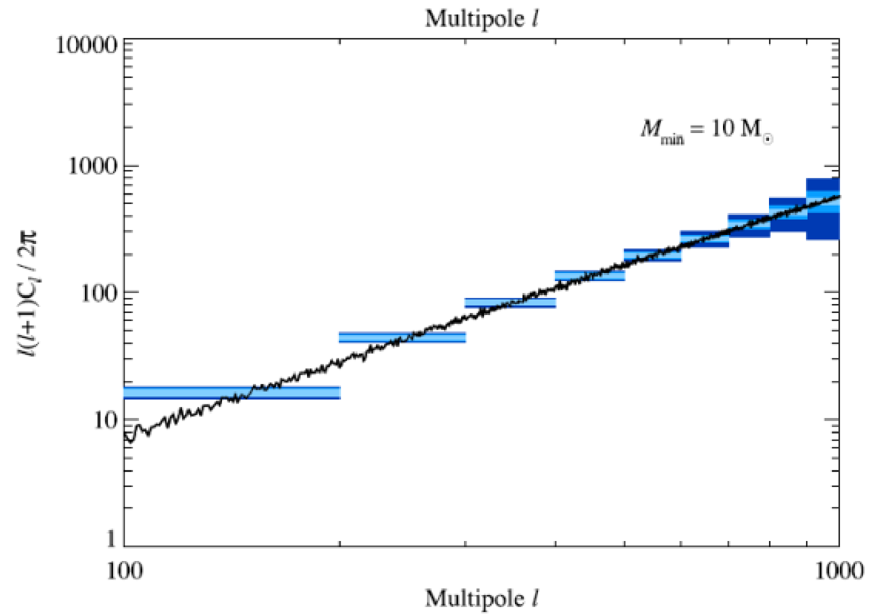
Anisotropies: The Galactic Case

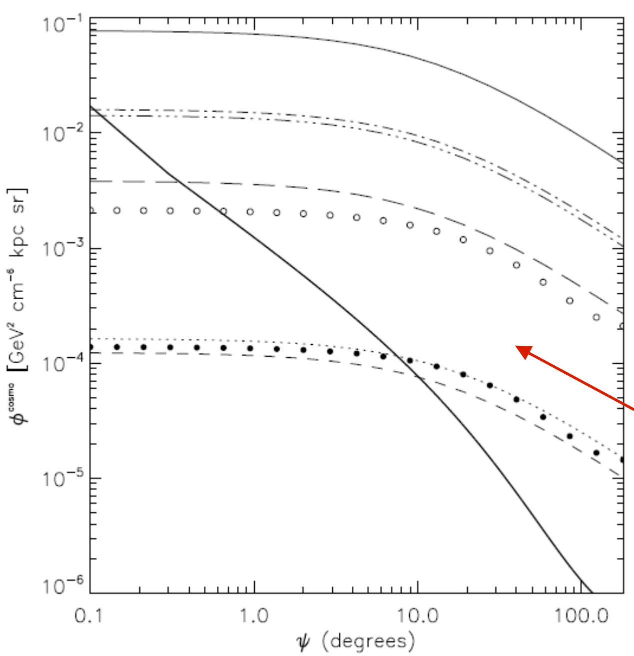


J. Siegal-Gaskins, JCAP 0810:040,2008.

M.Fornasa, L.Pieri, G.Bertone, E.Branchini, Phys.Rev.D80:023518,2009.

L.Pieri, G.Bertone, E.Branchini, Mon.Not.Roy.Astron.Soc.384:1627,2008.





But… huge uncertainties in the normalization of the signal:
sub-halo concentration?
Minimum sub-halo mass?

Angular power spectrum analysis of *Fermi* data

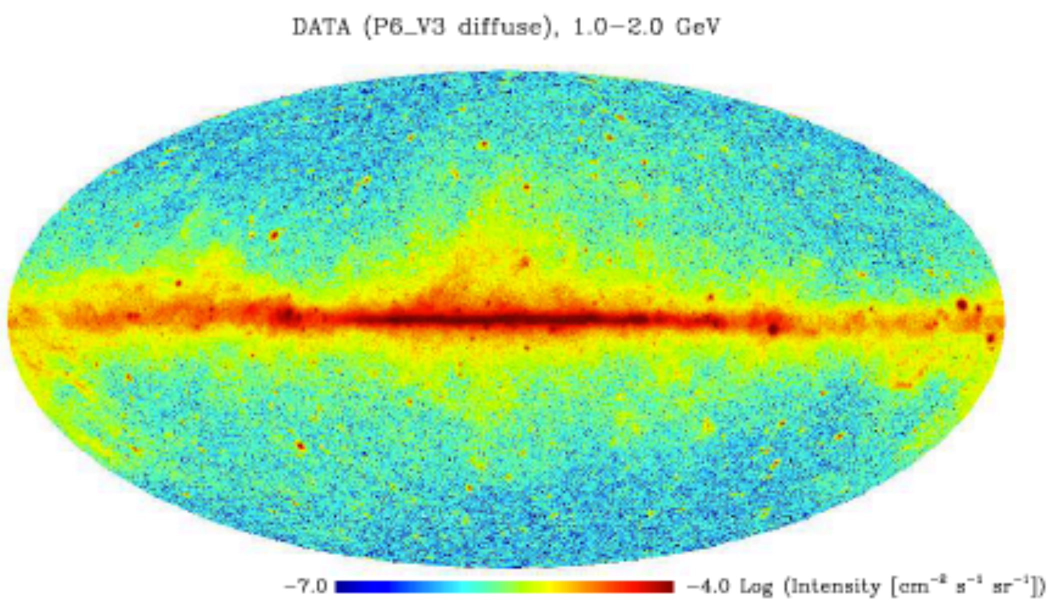
Fermi-LAT collaboration, Phys.Rev. D85 (2012) 083007

- data selection: ~ 22 months of data, diffuse class events
- energy range: 1 GeV - 50 GeV, divided into 4 energy bins for angular power spectrum analysis
- data processing: Fermi Science Tools used to handle instrument response and exposure calculation
- masking: sources in the 11-month catalog are masked within a 2 deg angular radius, and regions heavily contaminated by Galactic diffuse are masked by excluding |b| < 30 deg
- angular power spectrum calculation: performed using HEALPix (Gorski et al. 2005)
- front- and back-converting events: processed separately through angular power spectrum calculation, then results are combined by weighted average
- measurement uncertainties: indicate 1-sigma statistical uncertainty, systematic uncertainty not included

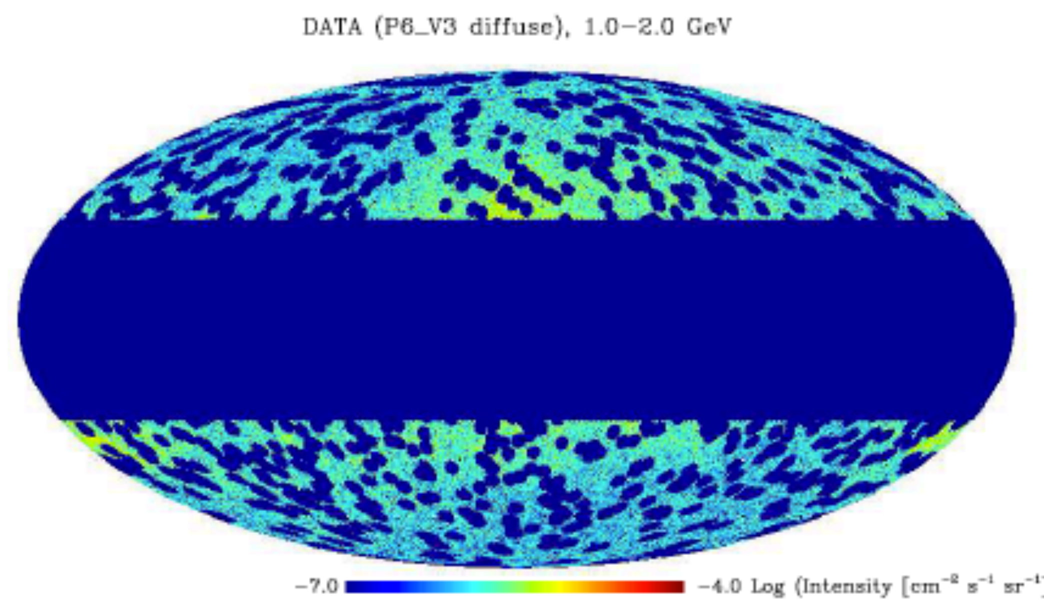
Intensity maps of the data

1-2 GeV

All-sky map



Map with default mask applied



Fermi-LAT collaboration, Phys.Rev. D85 (2012) 083007

Intensity maps of the data

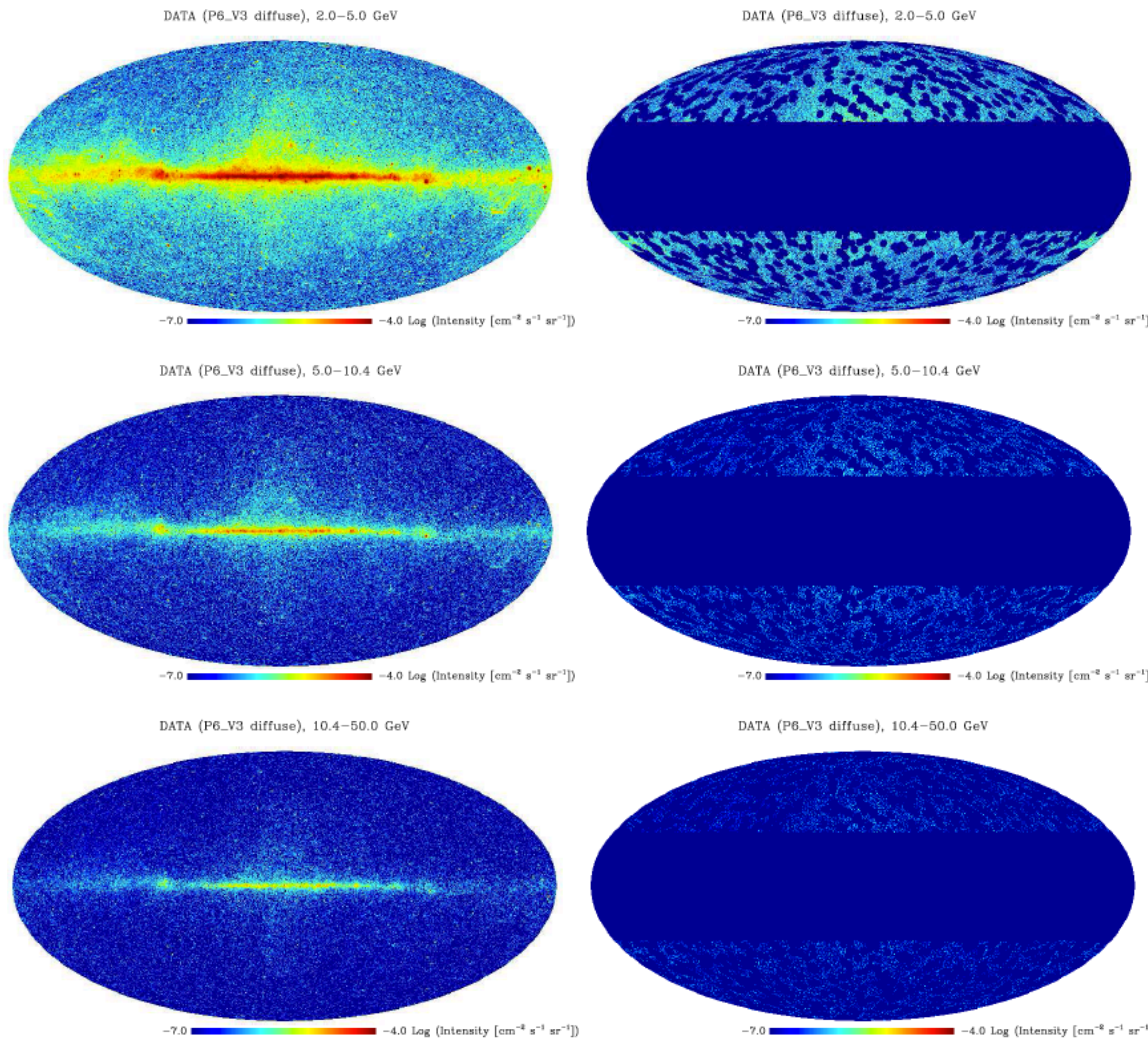
All-sky map

Map with default mask applied

2-5 GeV

5-10 GeV

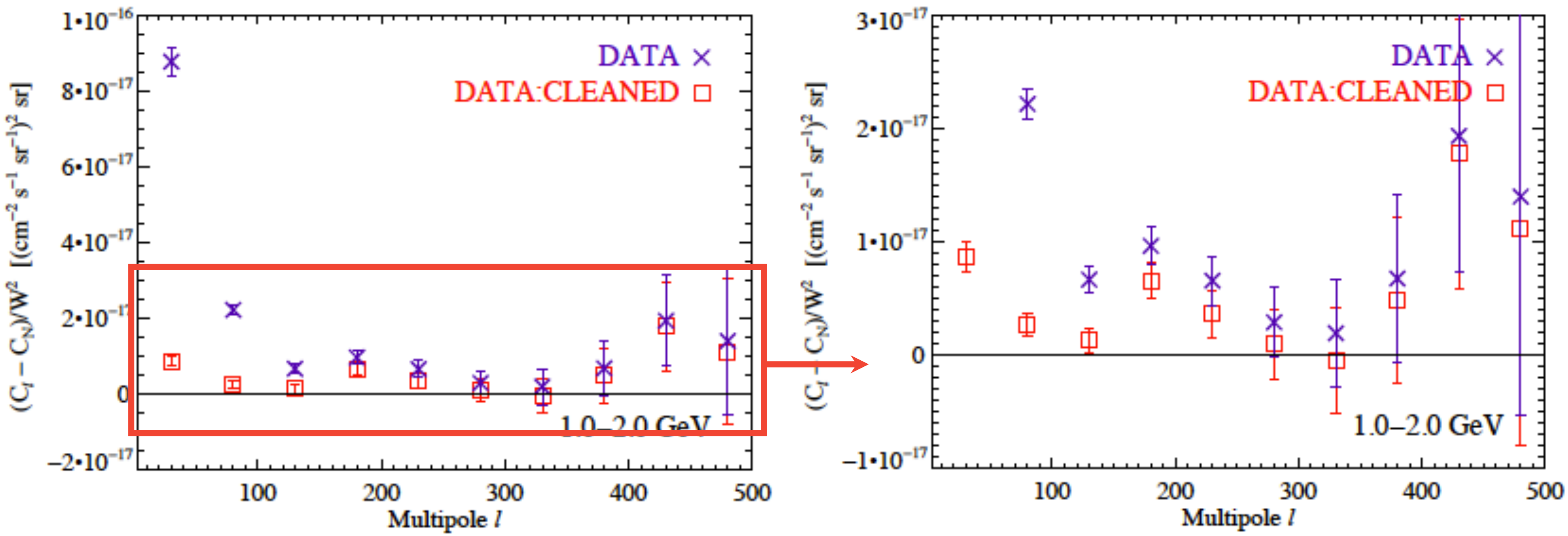
10-50 GeV



Angular power spectra of the data

fluctuation angular power spectra

1 - 2 GeV



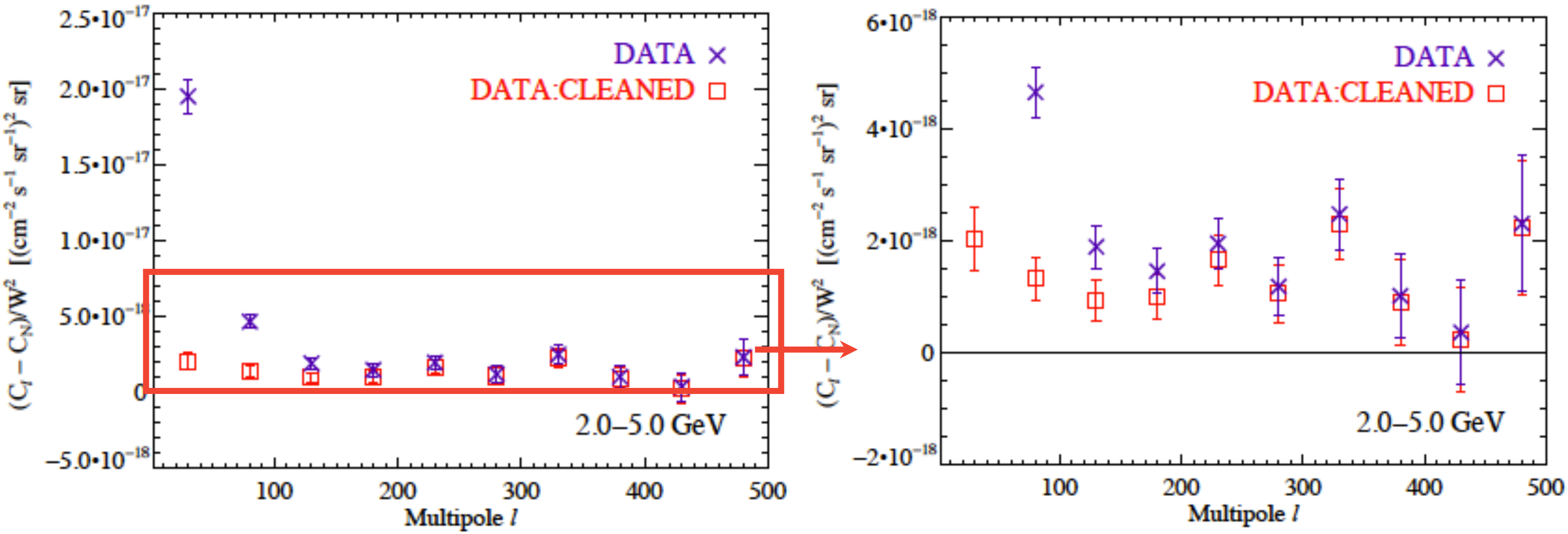
- at low multipoles excess angular power is due to contamination by Galactic diffuse emission; angular power is robustly detected at multipoles above l ~ 150

Fermi-LAT collaboration, Phys.Rev. D85 (2012) 083007

Angular power spectra of the data

fluctuation angular power spectra

2 - 5 GeV



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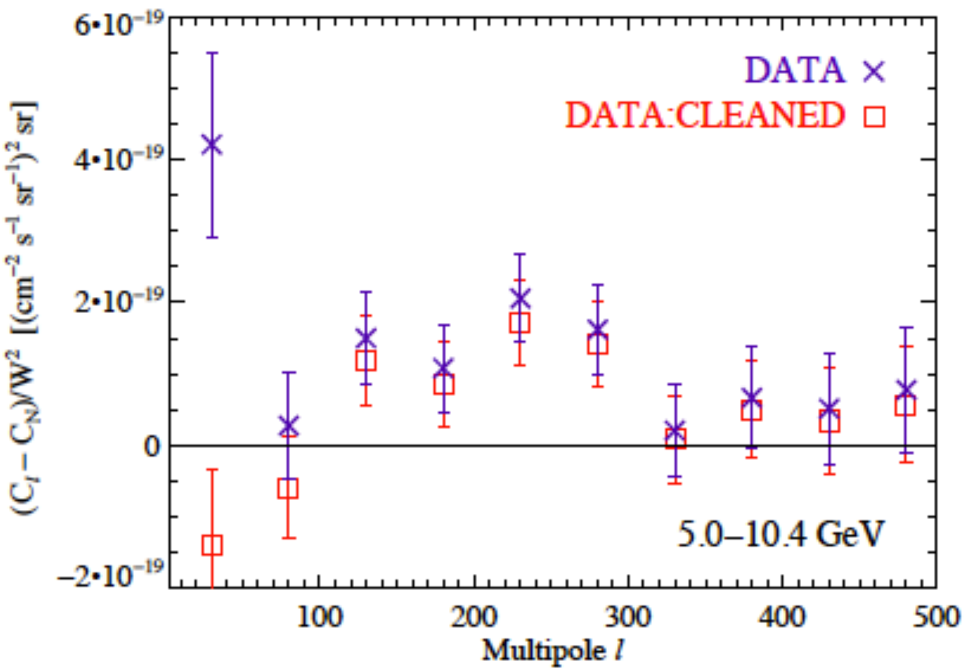
Fermi-LAT collaboration, Phys.Rev. D85 (2012) 083007

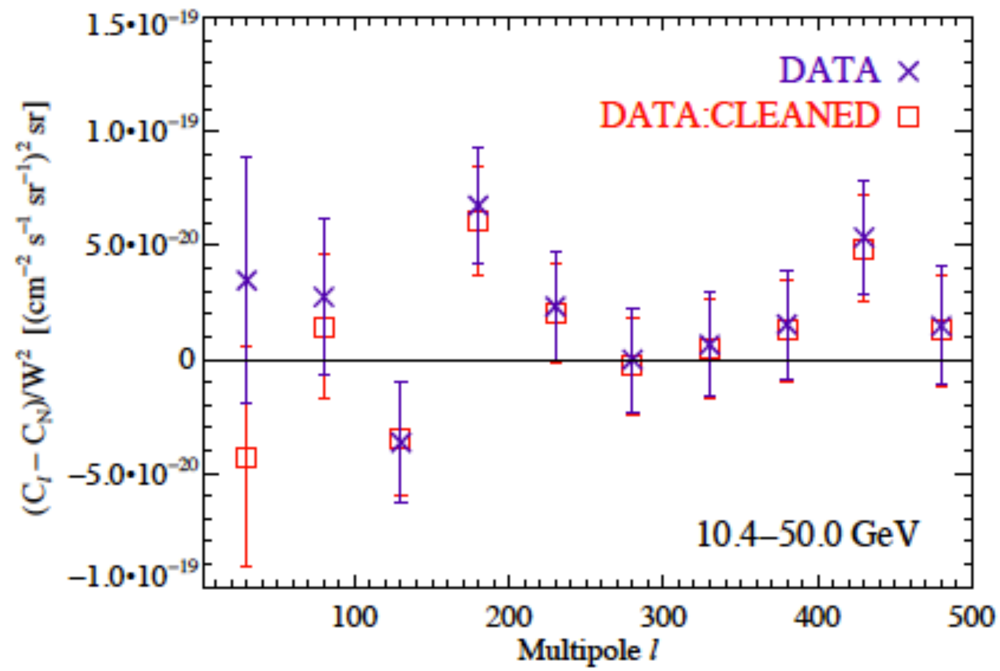
Angular power spectra of the data

fluctuation angular power spectra

5 - 10 GeV

10 - 50 GeV





- at 5-10 GeV angular power is robustly detected at multipoles above l ~ 150
- at 10-50 GeV, angular power is detected at lower significance at multipoles above l ~ 150

Fermi-LAT collaboration, Phys.Rev. D85 (2012) 083007

Angular power in the data

$$C_\ell^{\rm signal} \propto (\ell/\ell_0)^n$$

- in each energy bin, for 155 ≤ l ≤ 504, angular power consistent with constant value (but large uncertainties, some scale dependence not excluded)

$E_{\rm min}$	$E_{\rm max}$	n	χ^2/d.o.f.
1.04	1.99	-1.33 ± 0.78	0.38
1.99	5.00	-0.07 ± 0.45	0.43
5.00	10.4	-0.79 ± 0.76	0.37
10.4	50.0	-1.54 ± 1.15	0.39

- identifying the signal at 155 ≤ l ≤ 504 as Poisson angular power, best-fit value of angular power is determined

- angular power detected at high significance up to 10 GeV, and at lower significance at 10-50 GeV

$E_{\rm min}$ [GeV]	$E_{\rm max}$ [GeV]	$C_{\rm P}$ [(cm^{-2} s^{-1} sr^{-1})^2 sr]	Significance	$C_{\rm P}/\langle I\rangle^2$ [10^{-6} sr]
1.04	1.99	$7.39 \pm 1.14 \times 10^{-18}$	6.5σ	10.2 ± 1.6
1.99	5.00	$1.57 \pm 0.22 \times 10^{-18}$	7.2σ	8.35 ± 1.17
5.00	10.4	$1.06 \pm 0.26 \times 10^{-19}$	4.1σ	9.83 ± 2.42
10.4	50.0	$2.44 \pm 0.92 \times 10^{-20}$	2.7σ	8.00 ± 3.37

Fermi-LAT collaboration, Phys.Rev. D85 (2012) 083007

Comparison with predicted angular power

$C_P/\langle I \rangle^2$ [10^{-6} sr]
10.2 ± 1.6
8.35 ± 1.17
9.83 ± 2.42
8.00 ± 3.37

predicted fluctuation angular power $C_\ell/\langle I \rangle^2$ [sr] at l = 100 for a single source class (LARGE UNCERTAINTIES):

- blazars: ~ 1e-4
- starforming galaxies: ~ 1e-7
- dark matter: ~ 1e-4 to ~ 0.1
- MSPs: ~ 1e-2

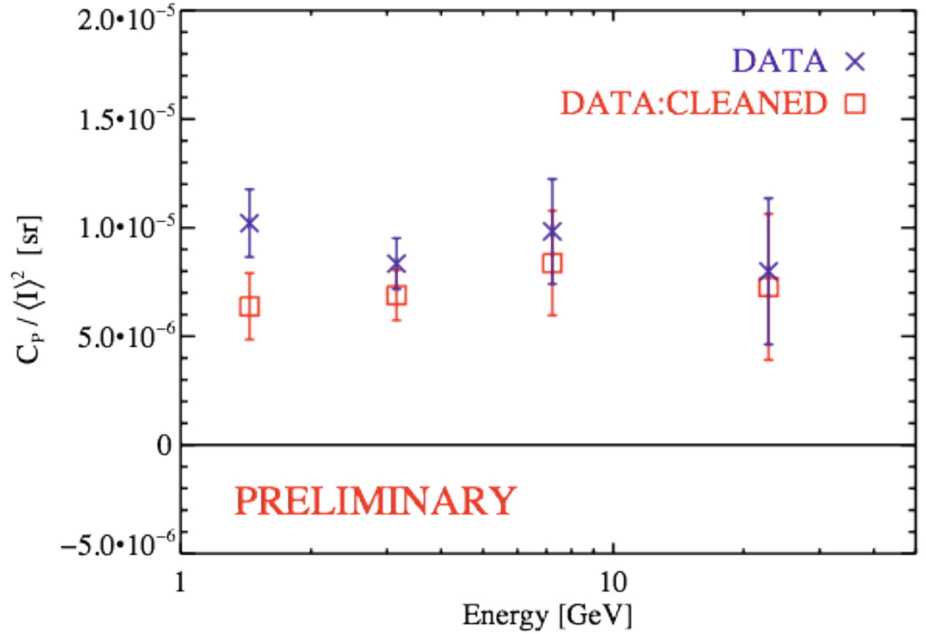
- fluctuation angular power of ~ 1e-5 sr falls in the range predicted for some astrophysical source classes and some dark matter scenarios
- can be used to constrain the IGRB contribution from these populations

Fermi-LAT collaboration, Phys.Rev. D85 (2012) 083007

Energy dependence of anisotropy

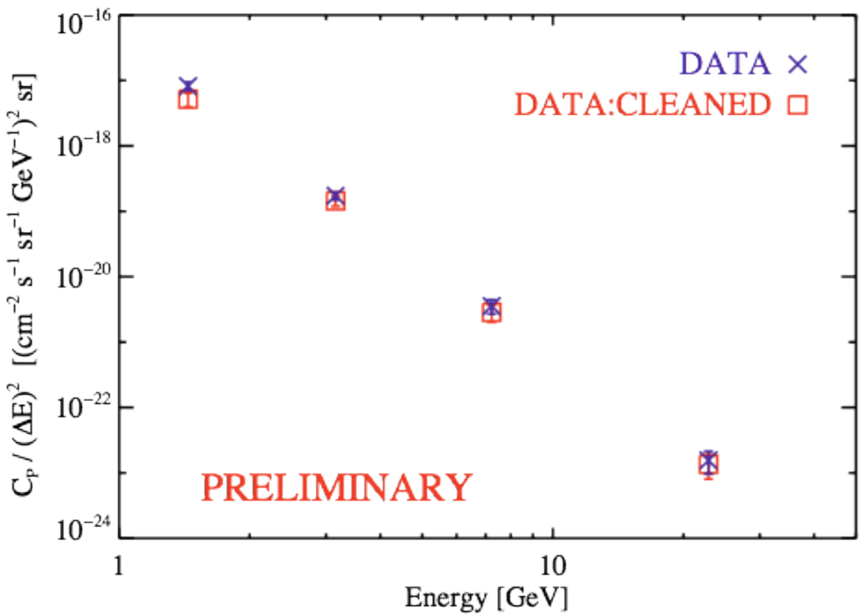
Fluctuation anisotropy energy spectrum

- consistent with no energy dependence, although mild or localized energy dependence not excluded
- consistent with all anisotropy contributed by one or more source classes contributing same fractional intensity at all energies considered



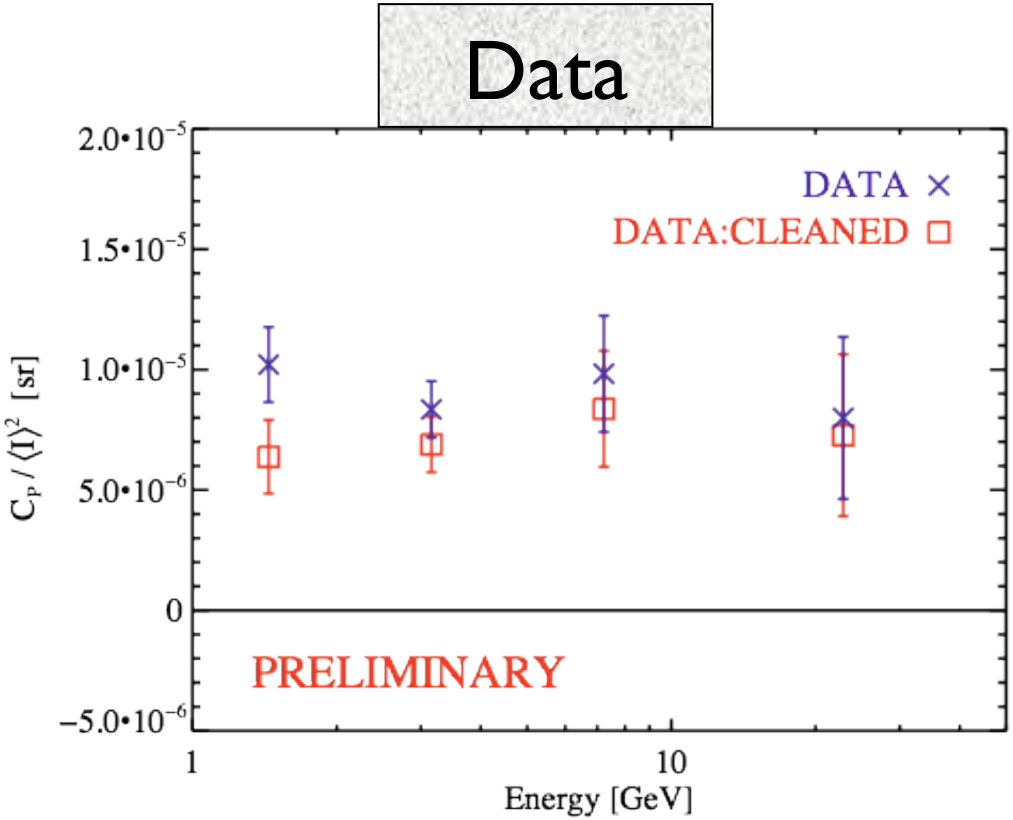
Intensity anisotropy energy spectrum

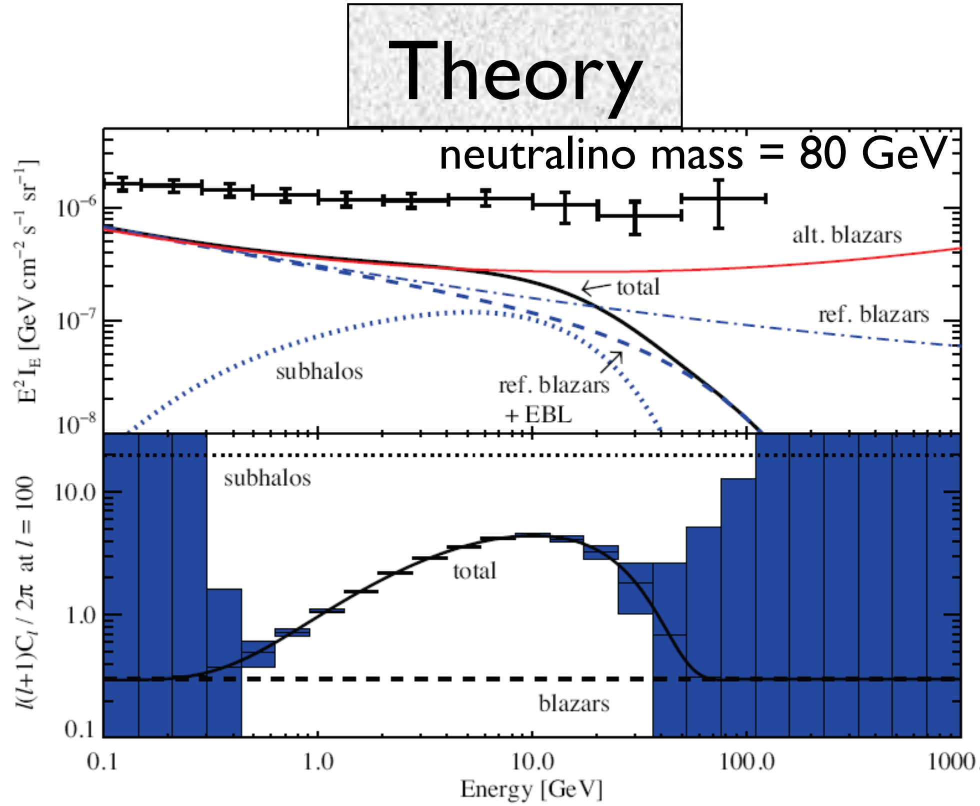
- consistent with that arising from a source class with power-law energy spectrum with $\Gamma = -2.40 \pm 0.07$
- implied source spectral index is good agreement with mean intrinsic spectral index of blazars inferred from detected members



Fermi-LAT collaboration, Phys.Rev. D85 (2012) 083007

Anisotropy Energy Spectrum: Data vs Theory





J. Siegal-Gaskins, V. Pavlidou, Phys.Rev.Lett. 102:241301,2009.

- No bump yet in the data…
- More statistics is needed to improve on the error bars and to increase the number of bins in energy. This will be provided by Fermi in the next few years.

Anisotropy Constraints on the blazars IGRB Contribution (1)

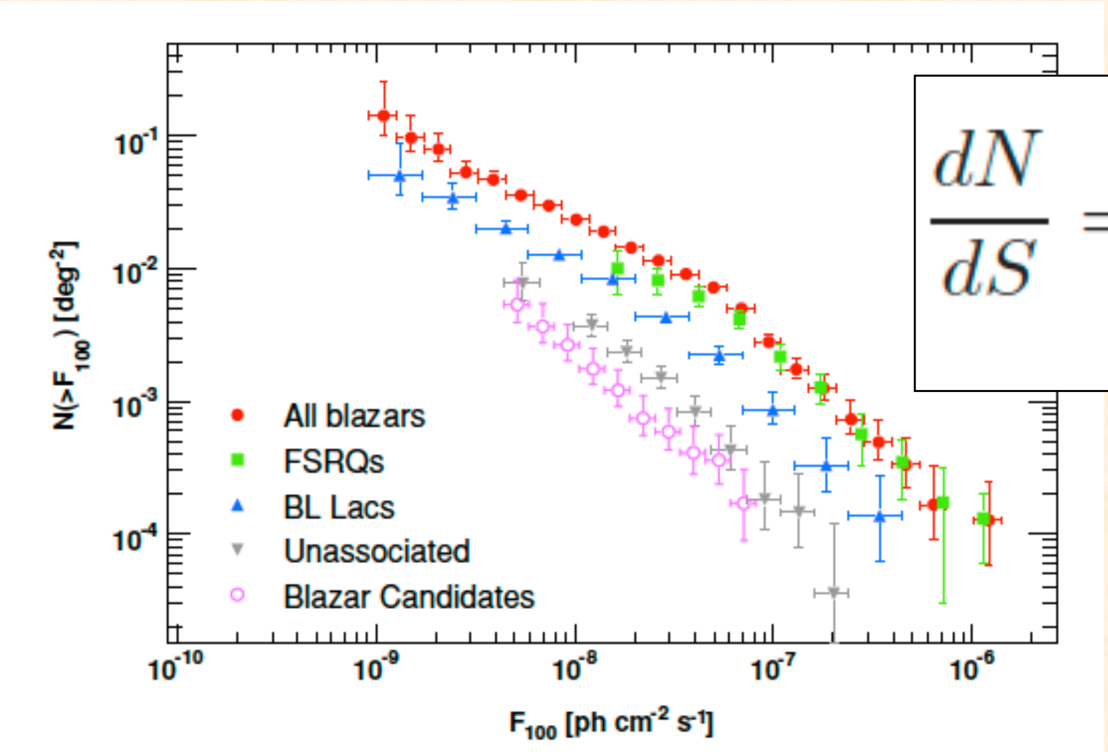
TABLE I. Measured angular power from the foreground-cleaned data in different energy bands, $C_{\mathrm{P,data}}$ [5]; predicted power from unresolved blazars, $C_{\mathrm{P,pred}}$ (this work); and 2σ upper limits on the residual anisotropy, $C^{2\sigma}_{\mathrm{P,U}}$ (this work).

$E_{\min}$ [GeV]	$E_{\max}$ [GeV]	$C_{\mathrm{P,data}}$	$C_{\mathrm{P,pred}}$	$C^{2\sigma}_{\mathrm{P,U}}$
		$[10^{-19}$ $(\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1})^2\ \mathrm{sr}]$		
1.0	10.0	110 ± 12	112 ± 10	< 33
1.04	1.99	46.2 ± 11.1	38.0 ± 3.9	< 32
1.99	5.00	11.30 ± 2.20	9.3 ± 0.9	< 6.7
5.00	10.4	0.845 ± 0.246	0.55 ± 0.05	< 0.80
10.4	50.0	0.211 ± 0.086	0.13 ± 0.01	< 0.254

Perfect Agreement between measured anisotropy and predicted from blazars!!

Cuoco, Komatsu, Siegal-Gaskins, 2012

Source Count Statistics (LogN-LogS)



$$\frac{dN}{dS} = \begin{cases} A\, S^{-\beta} & S \geq S_{\mathrm{b}} \\ A\, S_{\mathrm{b}}{}^{-\beta+\alpha} S^{-\alpha} & S < S_{\mathrm{b}} \end{cases}$$

$$I = \int_0^{S_{\mathrm{t}}} \frac{dN}{dS} S\, dS$$

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

- Blazars are the dominant extragalactic source population in the LAT energy band
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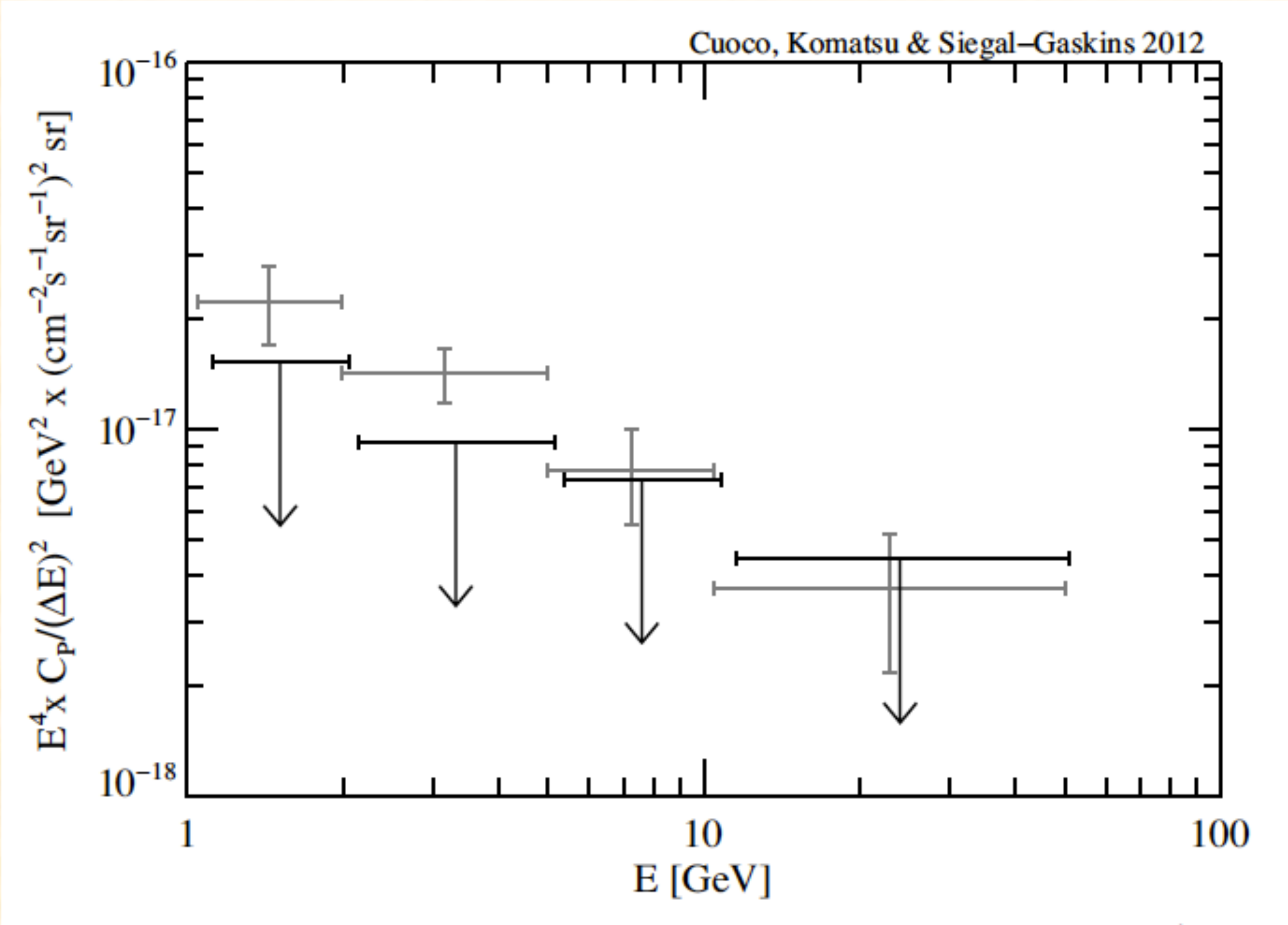
Anisotropy Constraints on the blazars IGRB Contribution (2)



2σ upper limits on the residual anisotropy, after the blazar anisotropy has been subtracted.

Cuoco, Komatsu, Siegal-Gaskins, 2012

Anisotropy Constraints on the blazars IGRB Contribution

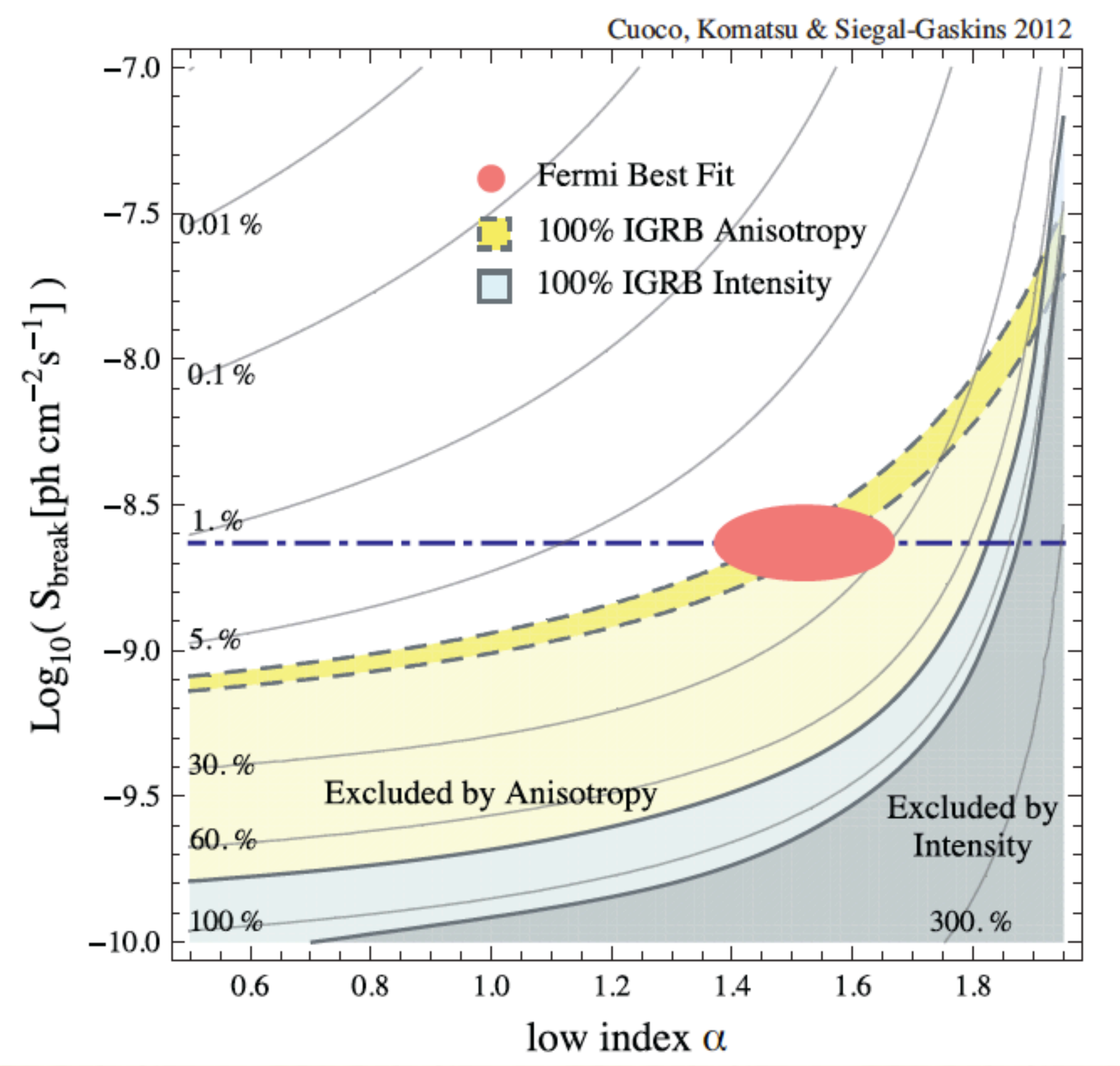
$$\frac{dN}{dS} = \begin{cases} A\ S^{-\beta} & S \geq S_b \\ A\ S_b{}^{-\beta+\alpha} S^{-\alpha} & S < S_b \end{cases}$$

$$I = \int_0^{S_t} \frac{dN}{dS} S dS$$

$$C_P = \int_0^{S_t} \frac{dN}{dS} S^2 dS$$

- Very good agreement between anisotropy measurement and resolved source counts studies!
- New implication: the remaining 70% of the observed EGB must have a very low level of anisotropy! (AGNs, Galaxies…)

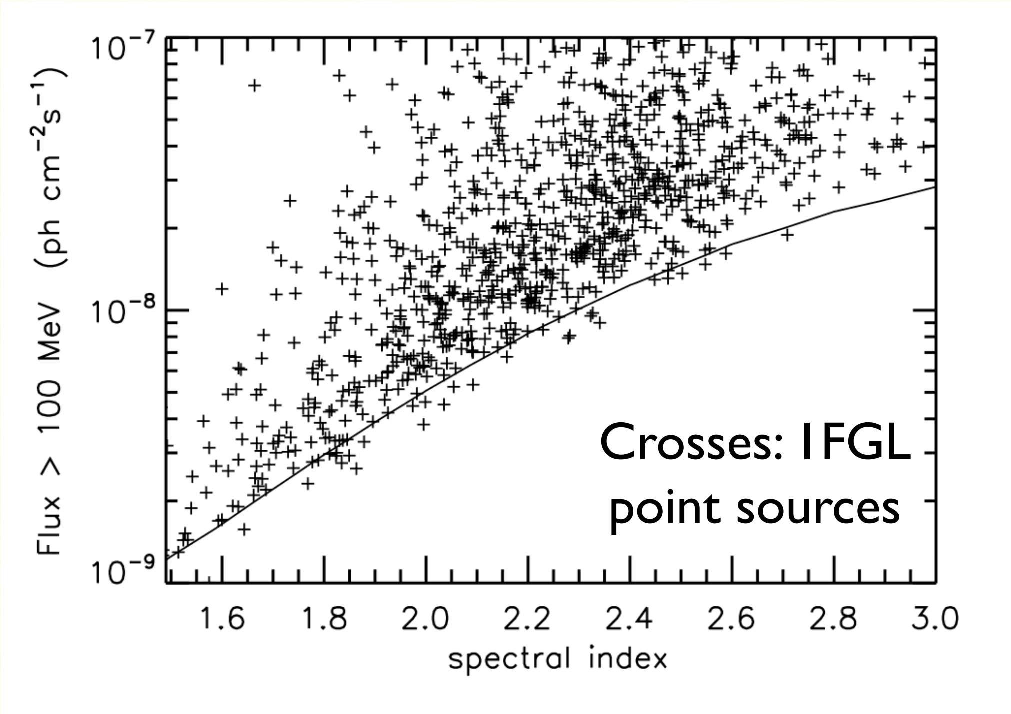
LogN-LogS Parameter Space



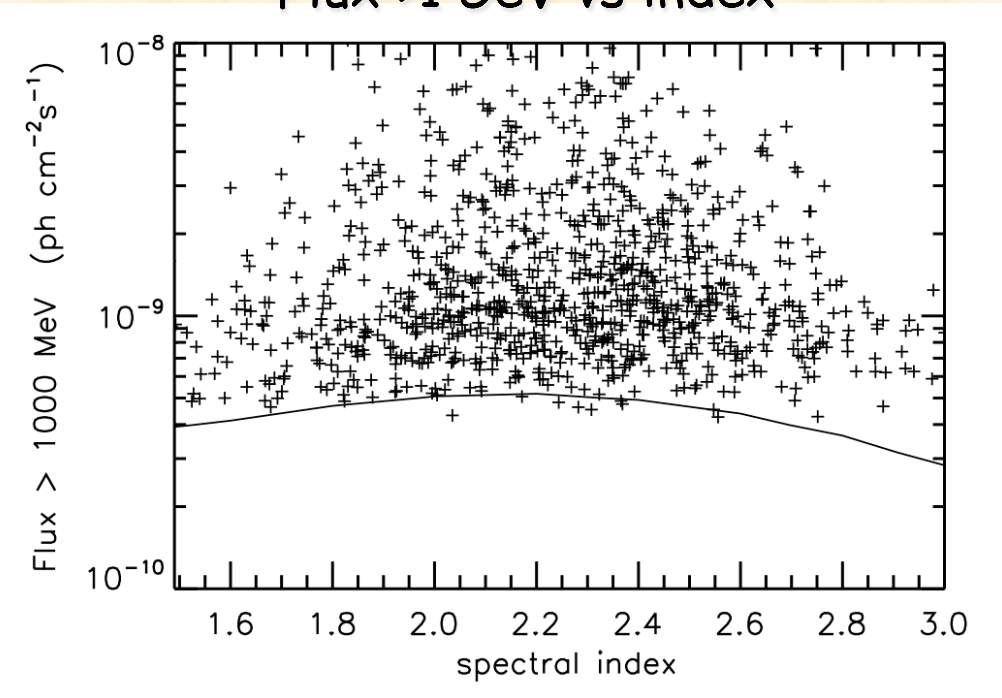
Cuoco, Komatsu, Siegal-Gaskins, 2012

Technical Note

Flux >100 MeV vs index



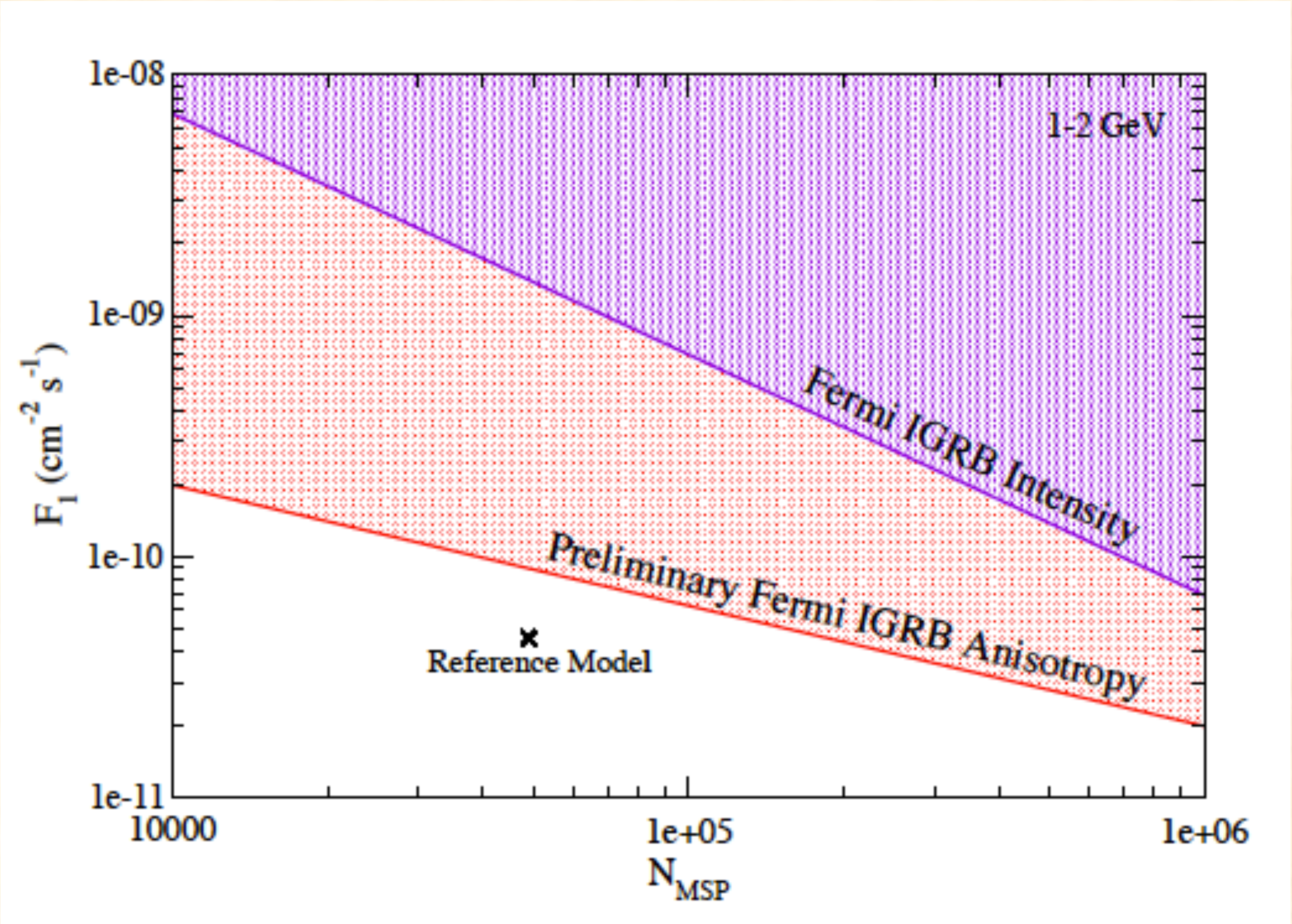
Flux >1 GeV vs index



- A strong spectral index bias is present for the fluxes above 100 MeV
- The bias is almost absent above 1 GeV. For this reason we perform calculations in this energy range

Cuoco, Komatsu, Siegal-Gaskins, 2012

Anisotropy Constraints on the Pulsar Contribution

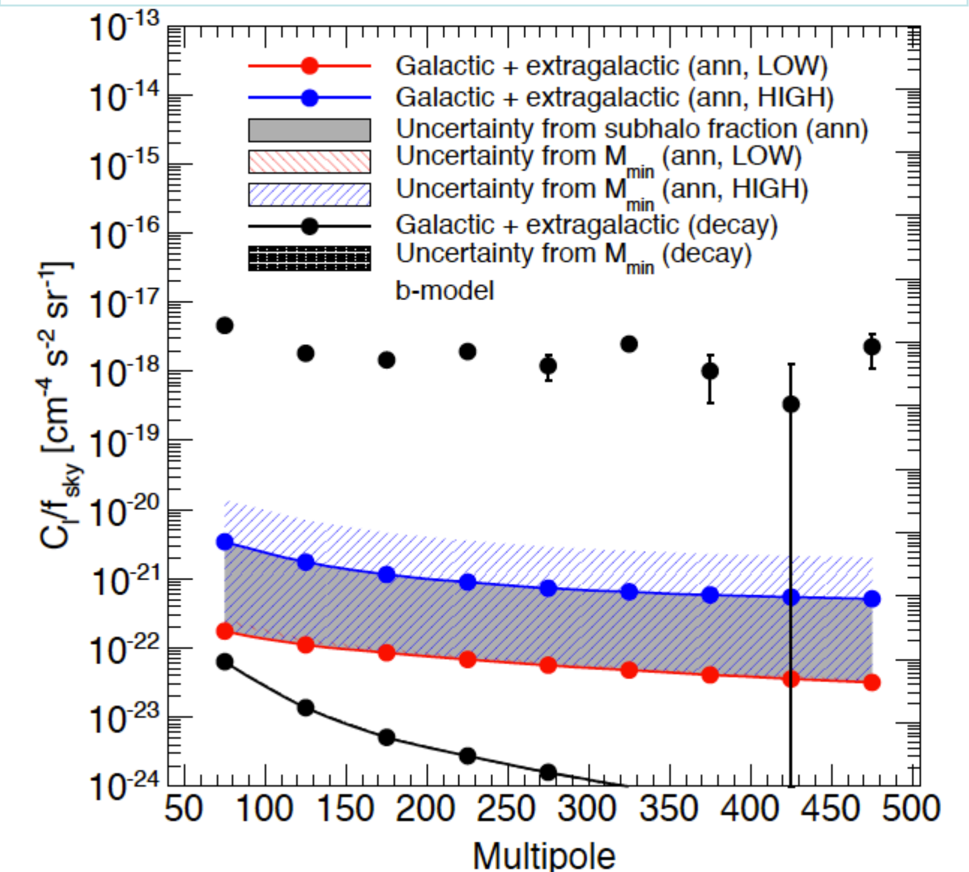


J. M. Siegal-Gaskins, R. Reesman, V. Pavlidou, S. Profumo, T.P. Walker, Mon.Not.Roy.Astron.Soc. 415 (2011) 1074S

- 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

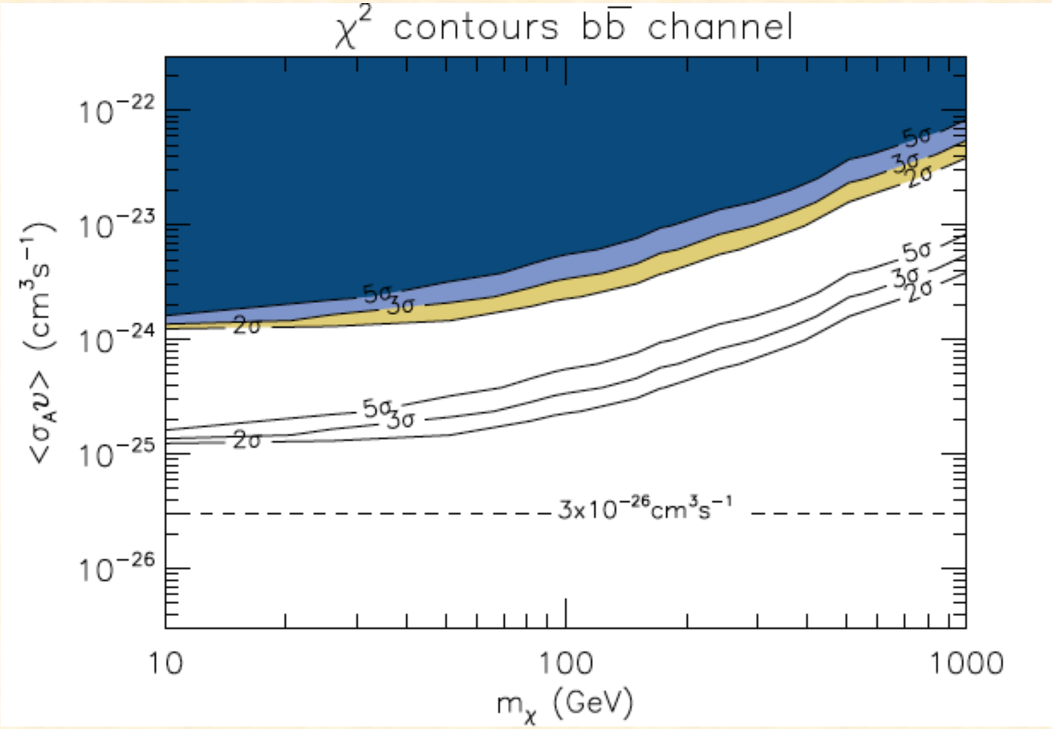
Anisotropy Constraints on the DM Contribution

M_χ=200 GeV, $\sigma v = 3\times10^{-26}$ cm^{3}s^{-1}, E=2-5 GeV



M.Fornasa et al. 2012, Arxiv:1207.0502

- Using theoretical prediction of the galactic and extragalactic DM anisotropy (from numerical simulation like Millennium or Aquarius) constraints on the DM component from anisotropy can be set.
- Joint **Multidark-Fermi** project ongoing.



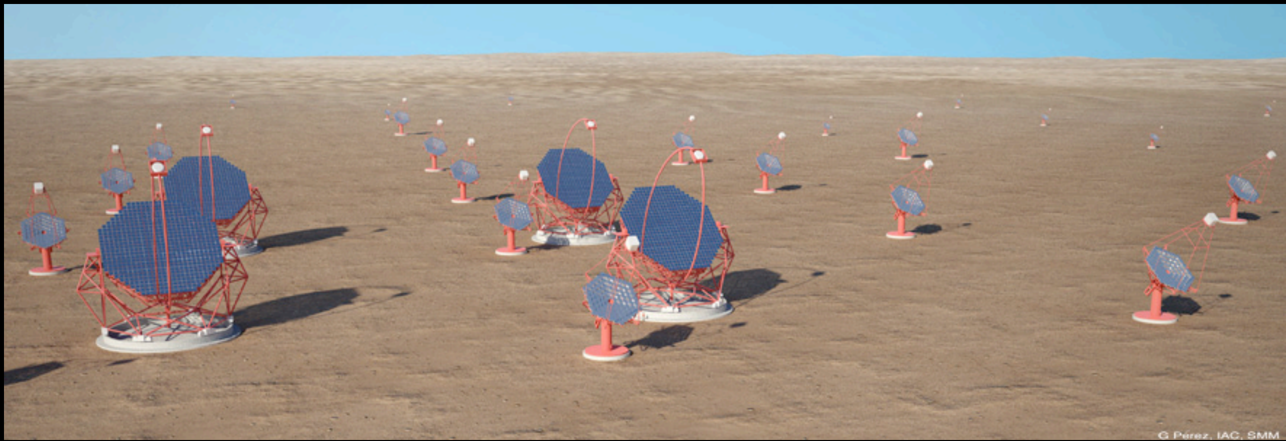
Cuoco, Sellerholm, Conrad, Hannestad, MNRAS 2010

- Interesting values of ‹σv› can be probed depending on the anisotropy properties of DM.

Ground based gamma ray Cerenkov observatories

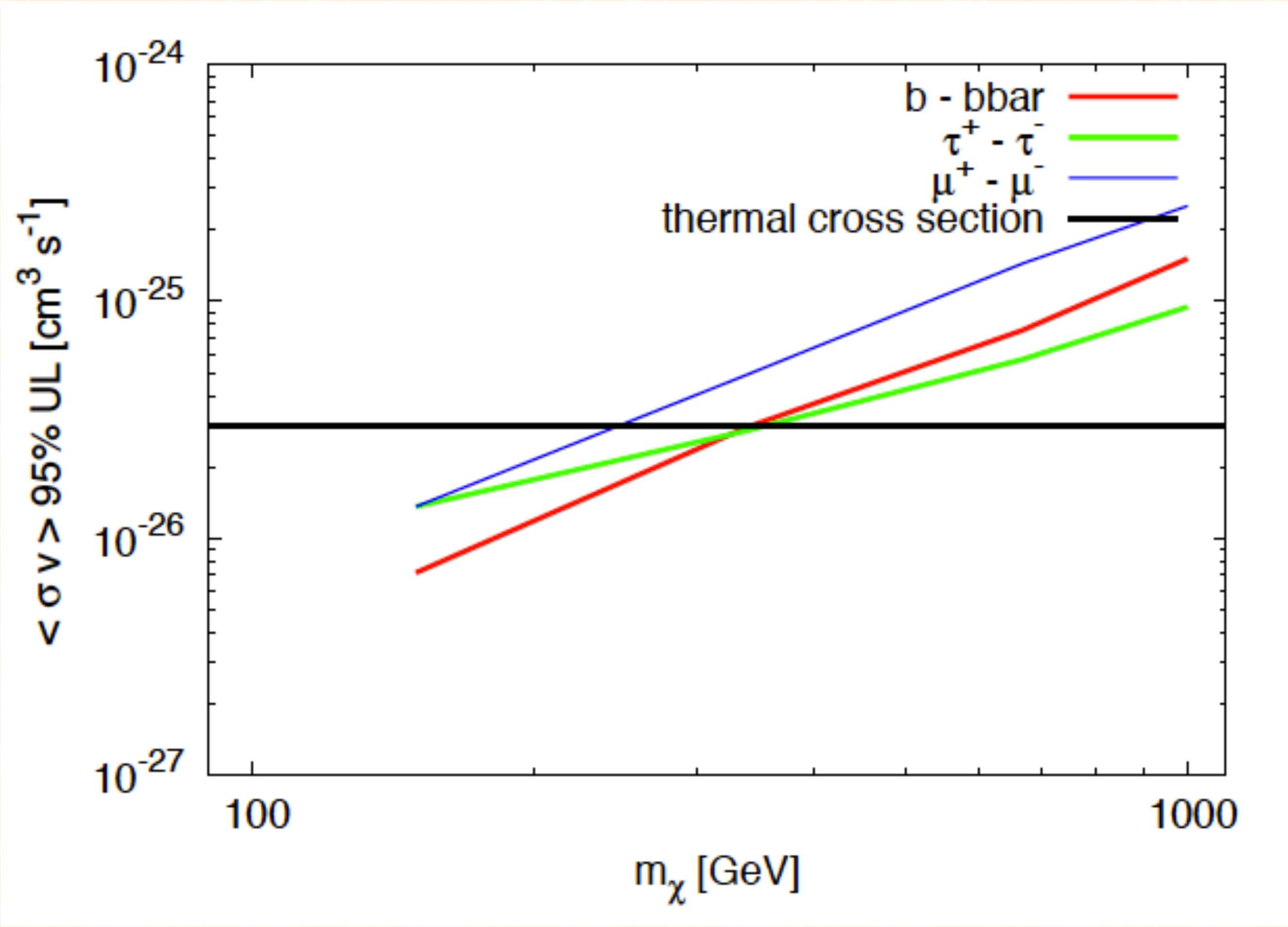
Air Shower Cerenkov telescopes
Energy Range > 50 GeV

CTA: 2018?



DM Anisotropies with Cerenkov telescopes

- Cerenkov telescopes are promising for anisotropy observations at high multipoles (l>100).
- Hadronic background is isotropic at these small scales.
- Important to have good angular resolution

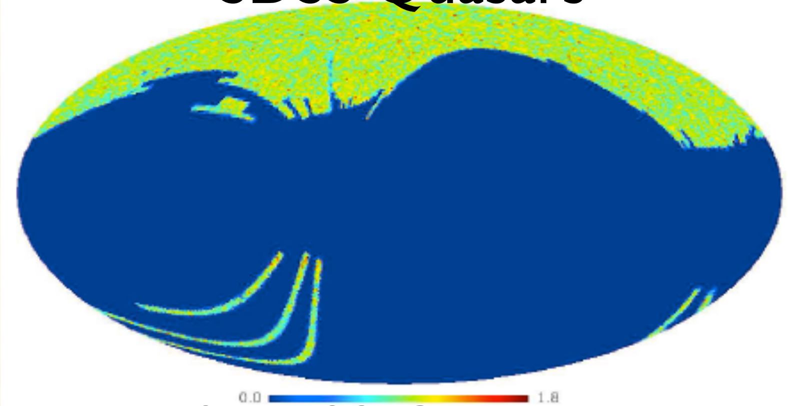


Sensitivity to thermal annihilation cross section seems possible with deep enough exposure and good background rejection.

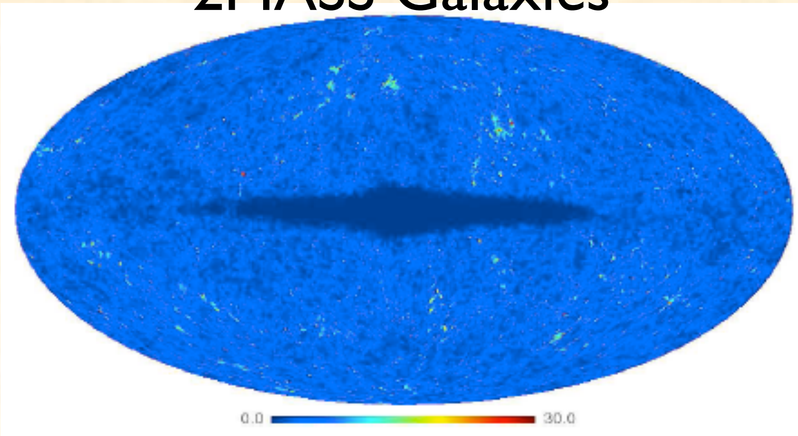
J.Ripken, A.Cuoco, H.Zechlin, D.Horn, J.Conrad, in preparation

Further EGB Probes: X-Correlation

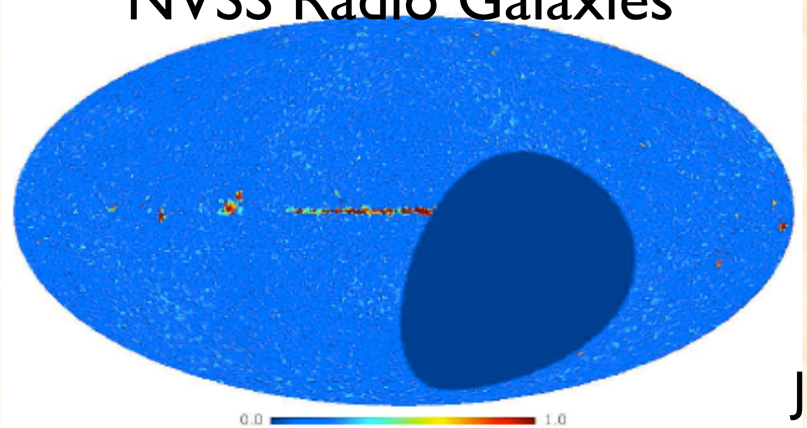
SDSS Quasars



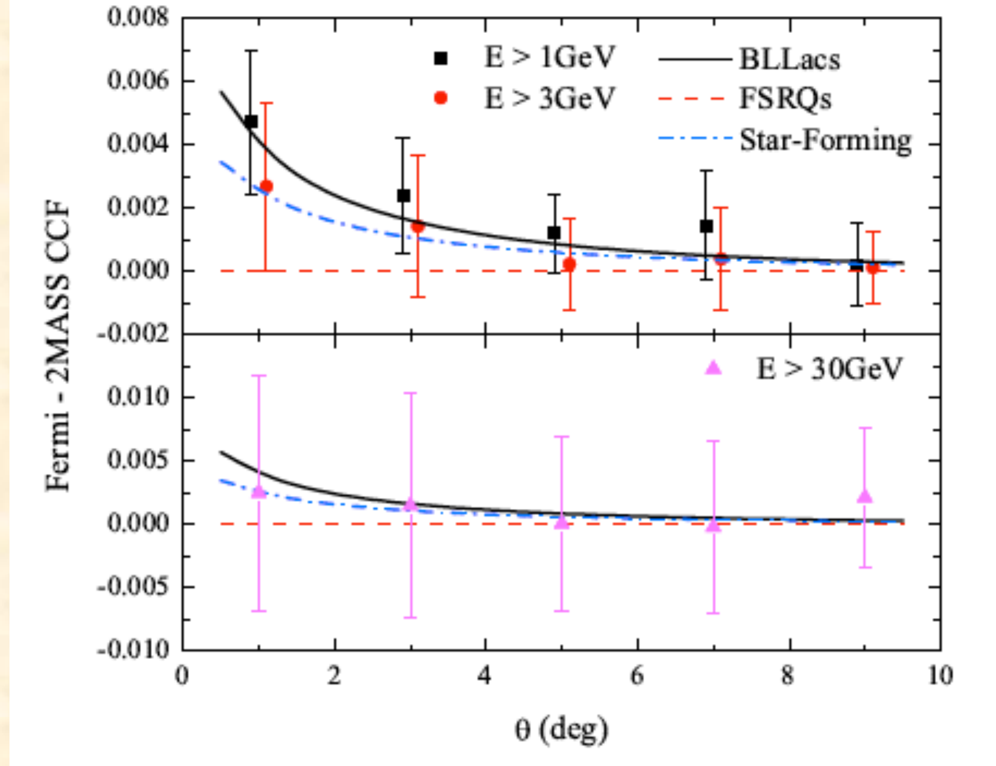
2MASS Galaxies



NVSS Radio Galaxies



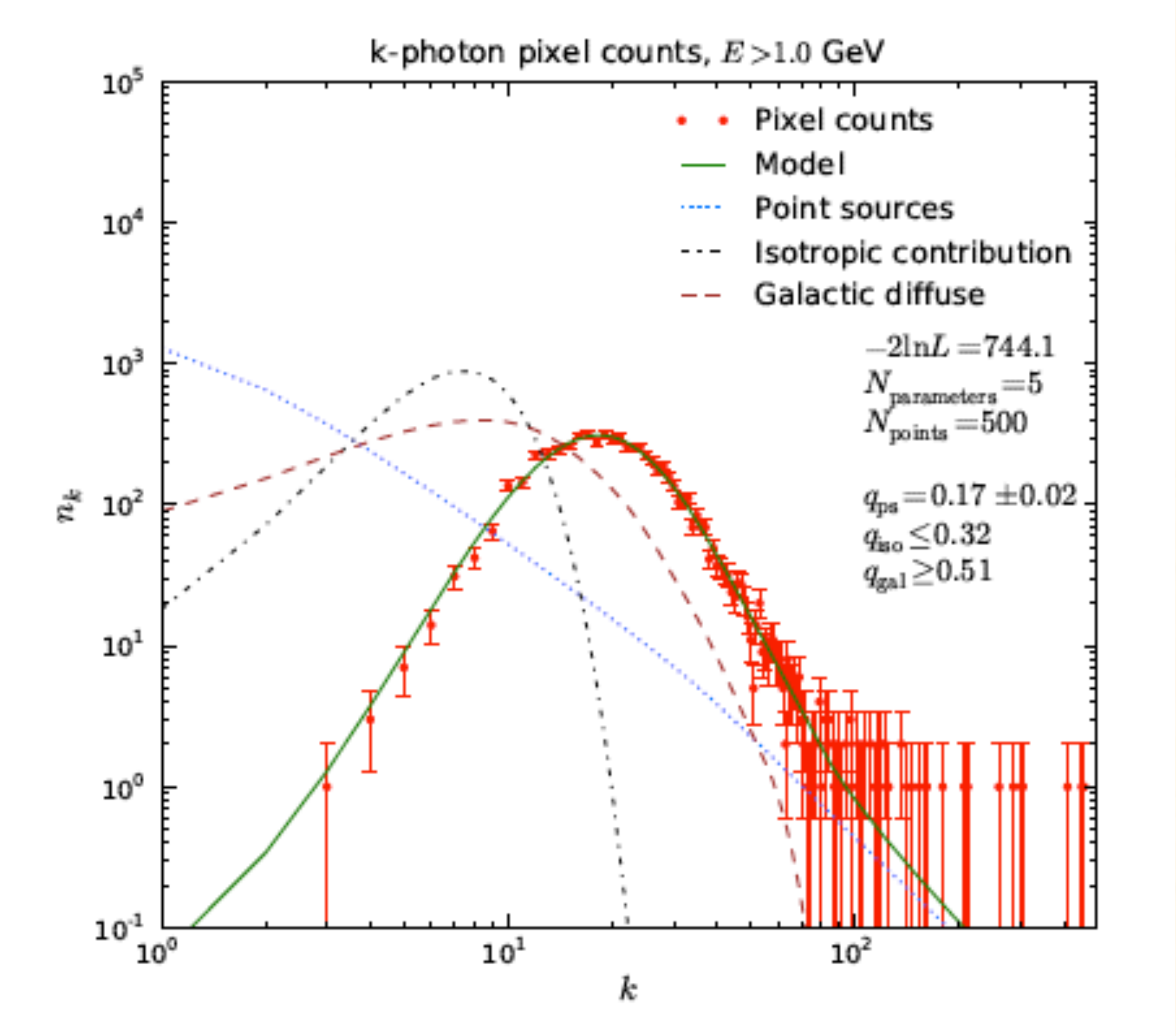
Fermi-2MASS X-Correlation



Some hints of positive cross-correlation between Fermi and 2MASS seems to confirm that normal galaxies give an important contribution to the EGB. Follow up in progress…

J.Xia, A.Cuoco, E.Branchini, M.Fornasa, M.Viel, MNRAS 2011

Further EGB Probes: 1-Point PDF



- It is complementary to the Angular Power Spectrum: 1d statistics vs 2d statistics.
- It is also sensitive to the LogN-LogS of the unresolved sources and indeed gives results consistent with the resolved source counts.

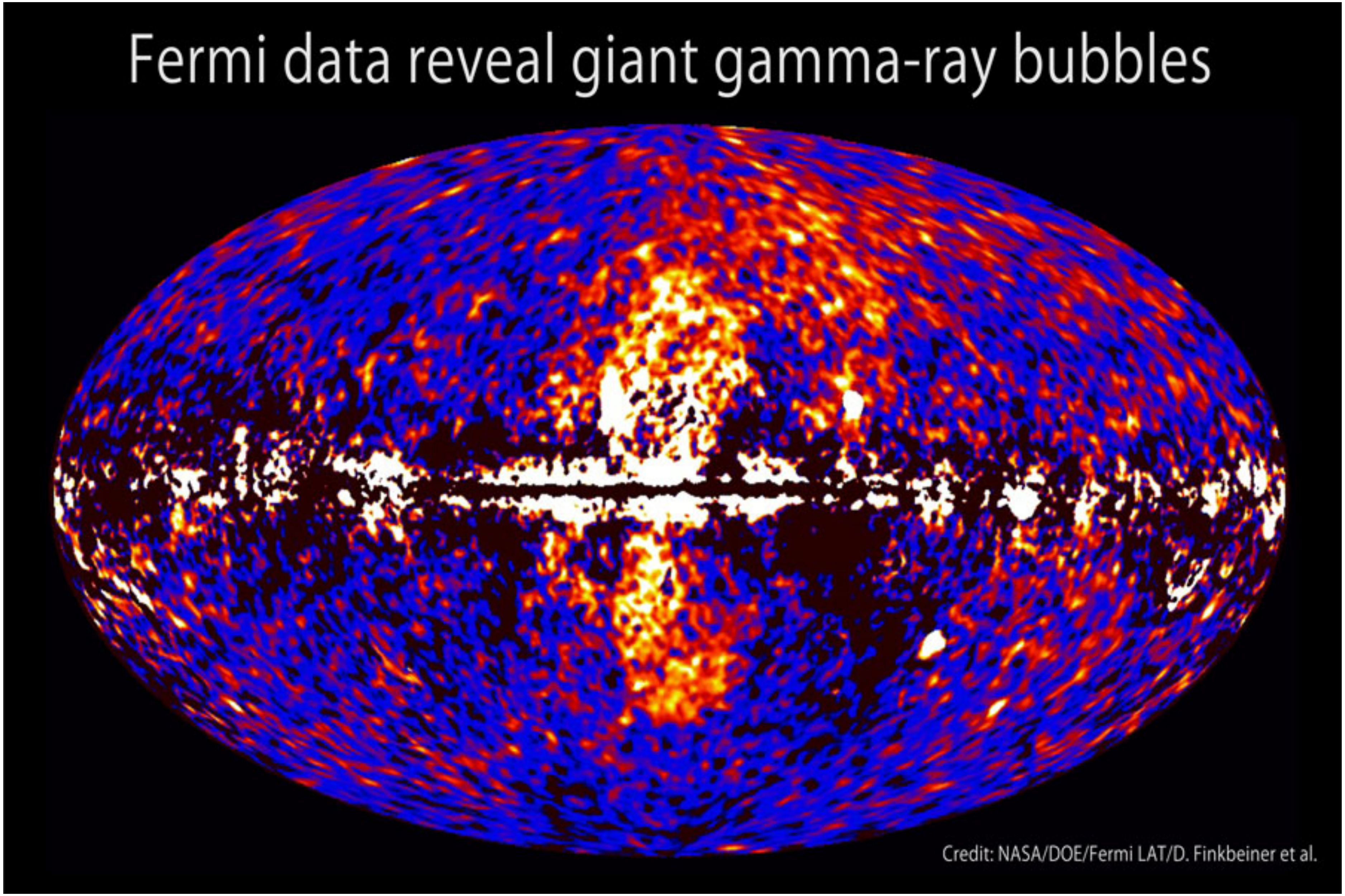
D.Malyshev and D.Hogg, ApJ 2011

Summary

- at multipoles $155 \leq l \leq 504$, angular power is robustly measured in the data at energies from 1 to 10 GeV;
    - scale independence of the power at these multipoles suggests a contribution to the IGRB from one or more unclustered point source populations
- energy dependence in the fluctuation angular power is not evident
    - suggests that the anisotropy is contributed primarily by one source population with constant fractional contributions to the IGRB intensity over this energy range
- the measured energy dependence of the intensity angular power is consistent with the IGRB anisotropy originating from a source population with a power-law energy spectrum with $\Gamma = -2.40 \pm 0.07$
    - this spectral index closely matches the inferred mean intrinsic spectral index of blazars
- A joint analysis of source number counts and anisotropy confirms that blazars are indeed the main source of the measured anisotropy
    - This implies that the remaining ~70% of the EGB must have a low level of anisotropy (AGN? SFG?)
- Other probes like x-correlations and 1-point PDF provide further complementary insights.
- Interesting DM constraints are possible provided uncertainties on theory are pinned down.

Additional slides

Lobes


Fermi data reveal giant gamma-ray bubbles
Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.

Differential blazar anistropy and intensity

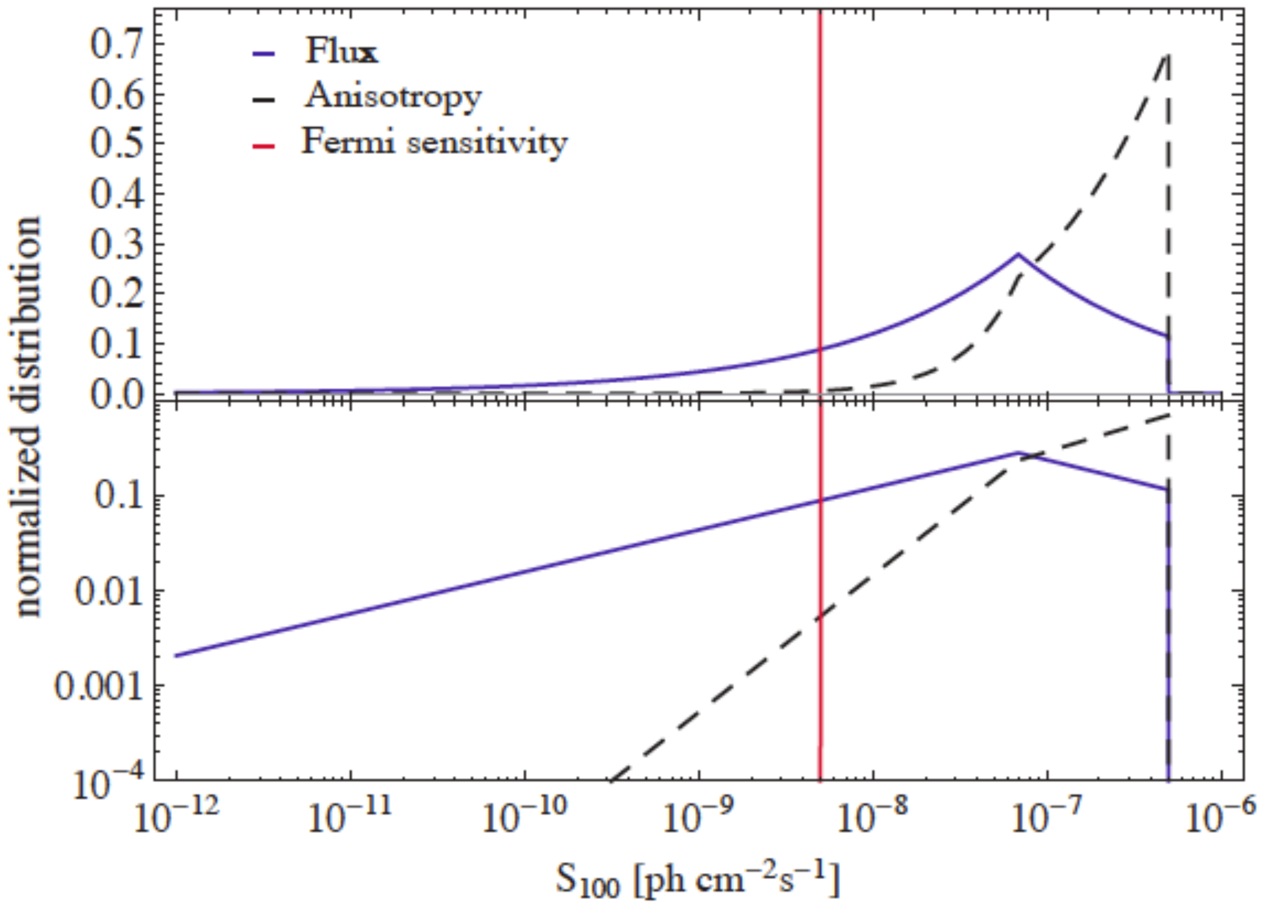


FIG. 3: Differential contribution of blazars in log and linear scale to the IGRB anisotropy and intensity for the *Fermi* best-fit $\log N$-$\log S$ ($E > 100$ MeV) as a function of source flux.