On the Cosmic Downsizing of Fermi's FSRQs and on the Isotropic Gamma-ray Background

Marco Ajello

K. Bechtol, M. Ackermann, R. Romani, M. Shaw

on behalf of the Fermi Collaboration

IGRB

RGs

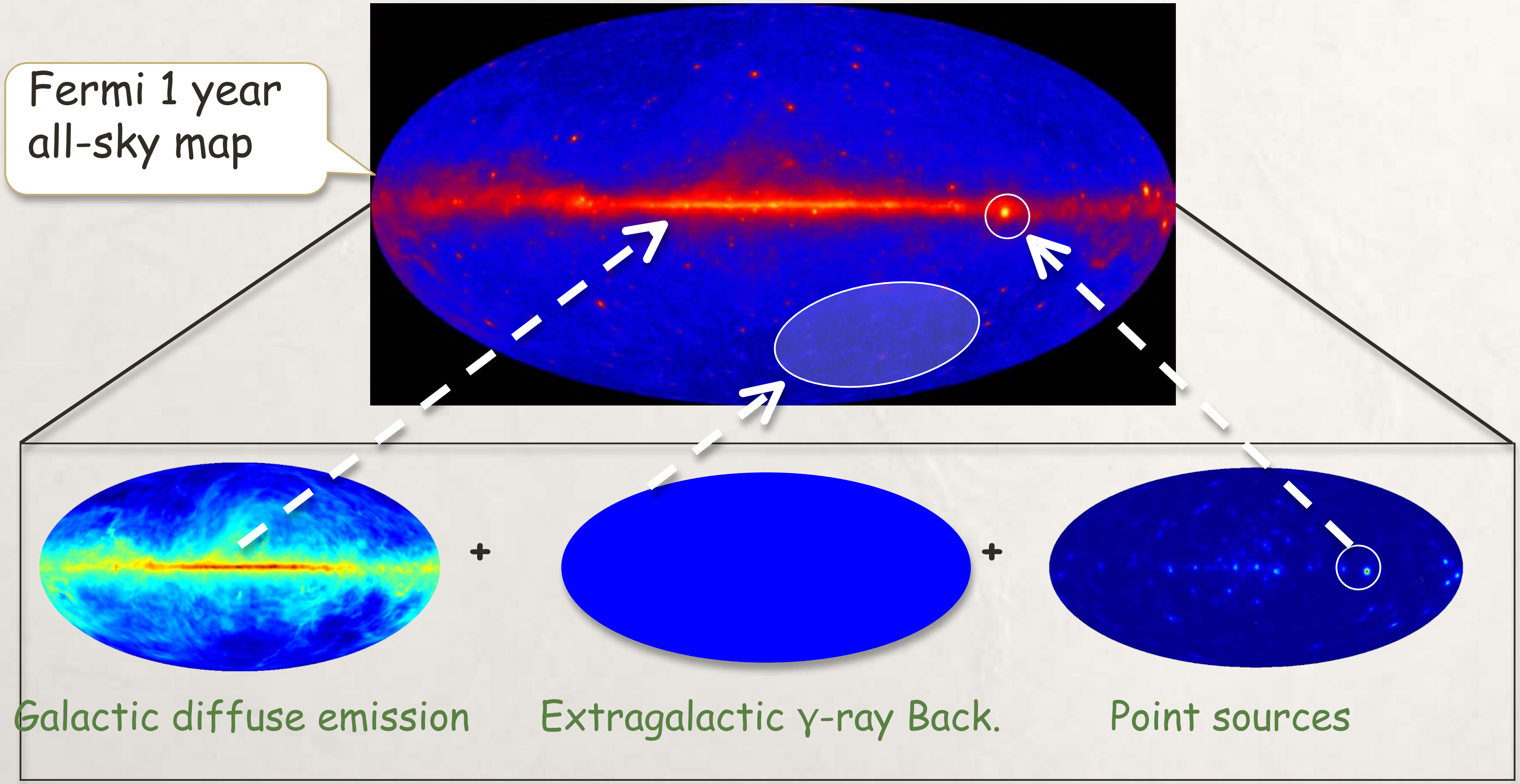
FSRQs

BL Lacs

Galaxies

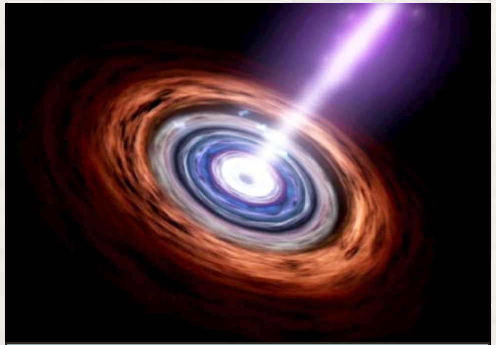
What is the Extragalactic Gamma-ray Background ?

* The gamma-ray sky as observed by Fermi represents the sum of different components: one of them is the Extragalactic Gamma-ray Background



Why is this important ?

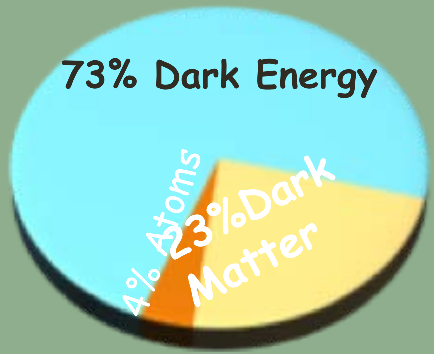
* The Extragalactic Gamma-ray Background may encrypt the signature of the most powerful processes in astrophysics



Blazars contribute 20-100% of the EGB (Stecker&Salomon96, Mücke&Pohl00, Narumoto&Totani04, Dermer07, Inoue&Totani09)

Emission from particle accelerated in Intergalactic shocks (Loeb&Waxmann00)

Emission from star forming galaxies (e.g. Pavlidou&Fields02)

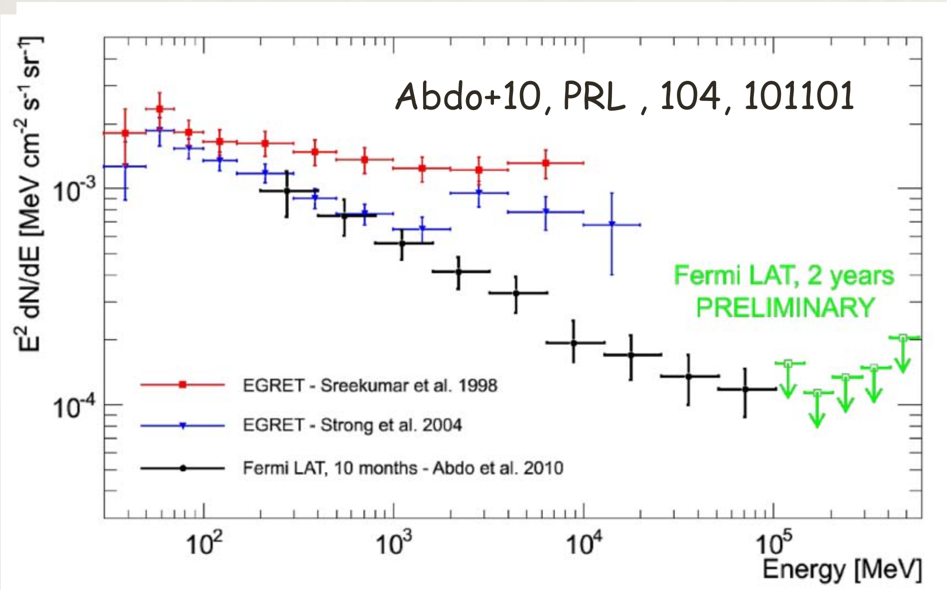


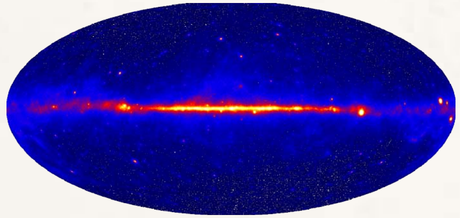
Emission due to the annihilation of Cosmological Dark Matter (eg. Jungman+96)

The Fermi IGRB

Talk to M. Ackermann for details

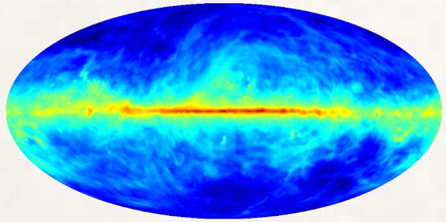
- Simultaneous Maximum Likelihood fit to all |b|>10° sky with:
  - Equal area pixels (0.8 deg^2)
  - Sky models compared to LAT data
  - All sources detected in 9months
  - 9 energy bins, 200 MeV<E< 100 GeV
  - 10 months of LAT data, 19 Ms exposure





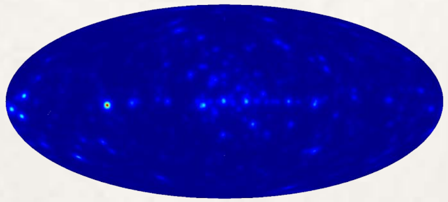
LAT sky

=



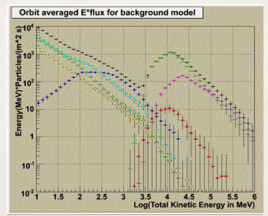
gal. diffuse

+



point sources

+



CRs

The Blazar Population

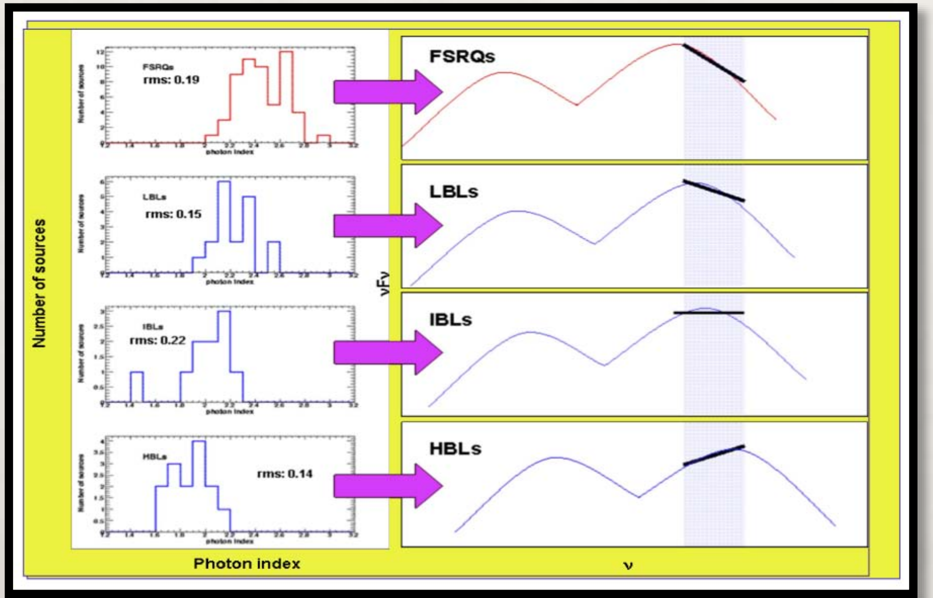
- Blazars potentially represent 85-95% of the high-latitude population
- FSRQs and BL Lac seem to segregate in the luminosity-index plane
- FSRQ and BL Lac have different photon index distributions

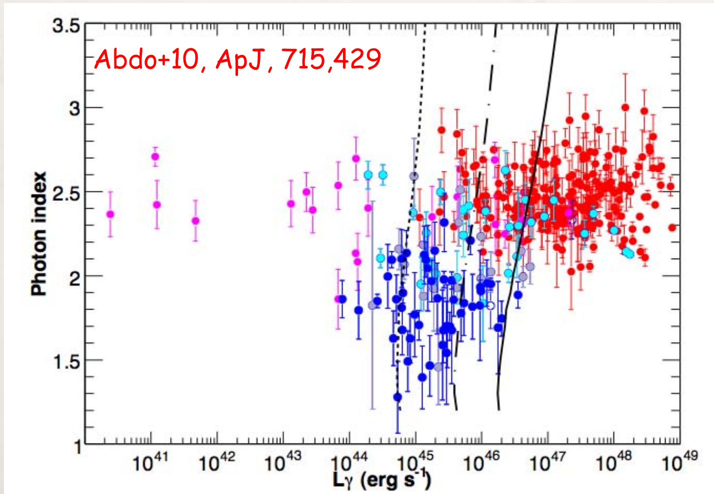
Abdo+10, ApJ 720, 435

CLASS	# objects
Total	425
FSRQs	161
BL Lacs	163
Uncertain[a]	4
Blazar Candidates	24
Radio Galaxies	2
Pulsars	9
Others[b]	6
Unassociated sources	56

[a]Blazars with uncertain classification.

[b]It includes Starburst galaxies, Narrow line Seyfert 1 objects and Seyfert galaxy candidates.

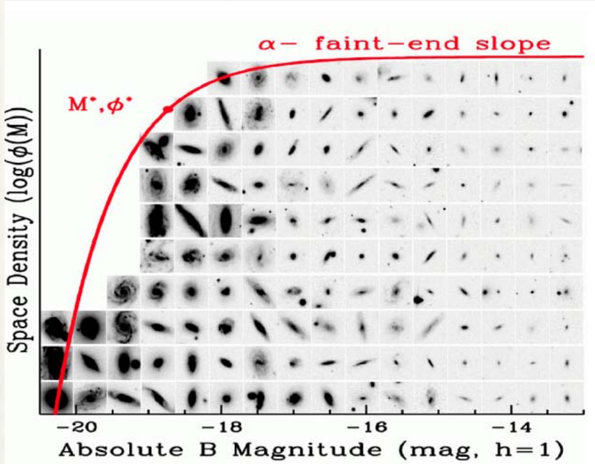




Luminosity function of FSRQs

* Comoving number density of objects with luminosity [L, L+dL]

* $$dN = \varphi(L,z)\, dL\ \ dV$$



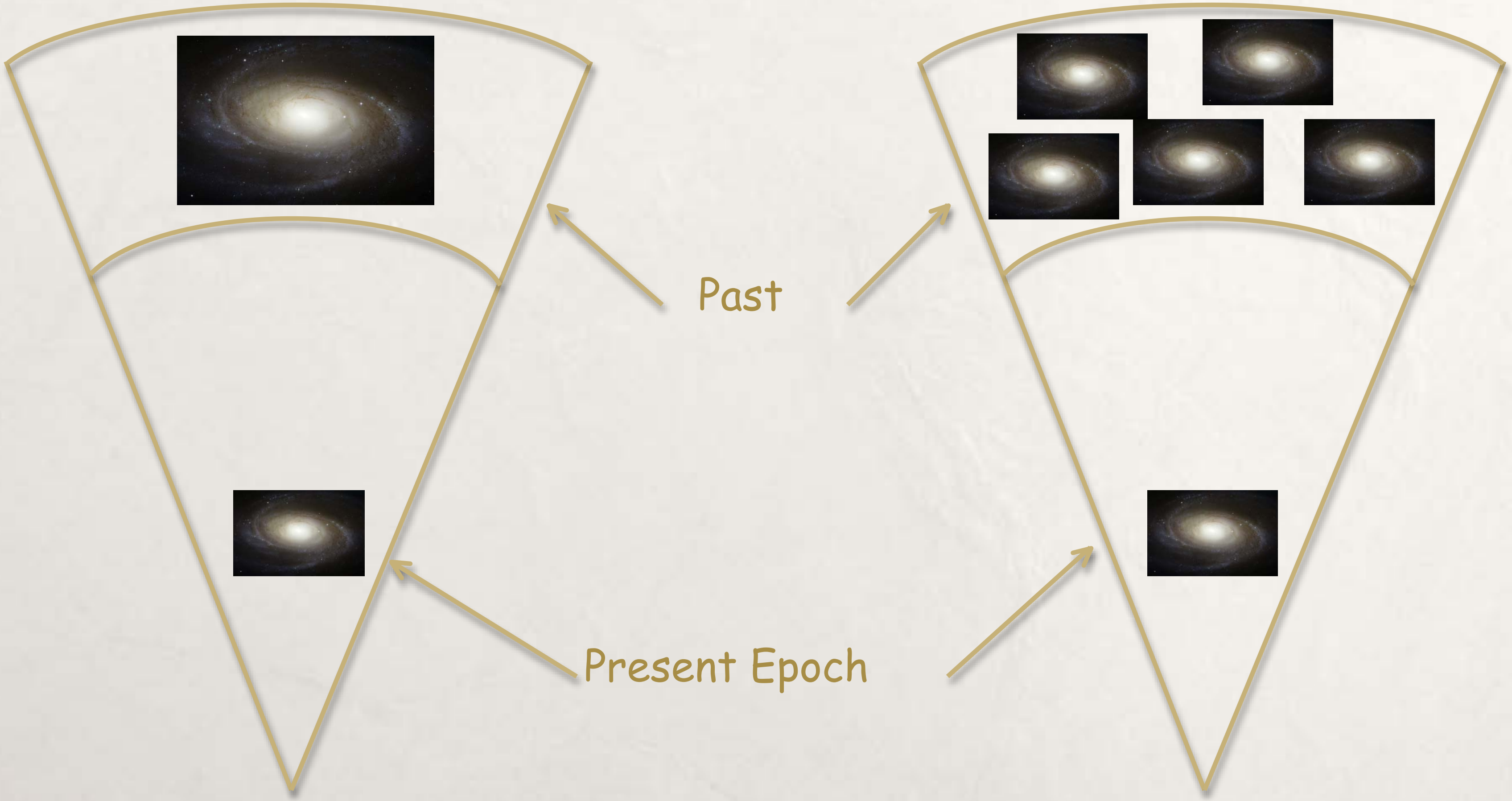
Why is it important ?

- Probe (and constrains models) of the evolution and growth of FSRQs
- Constrain the contribution to the EGB
- Constrain beaming factors and the parent population
- Might be used to constrain the formation of SMBH at high-z (Ghisellini+ Voloneteri+11)

Note: here L is isotropic Luminosity averaged over 11months

The Evolution of the LF

* What you are asking is :
* *Were the objects more luminous or more numerous in the past ?*



The FSRQ sample: properties

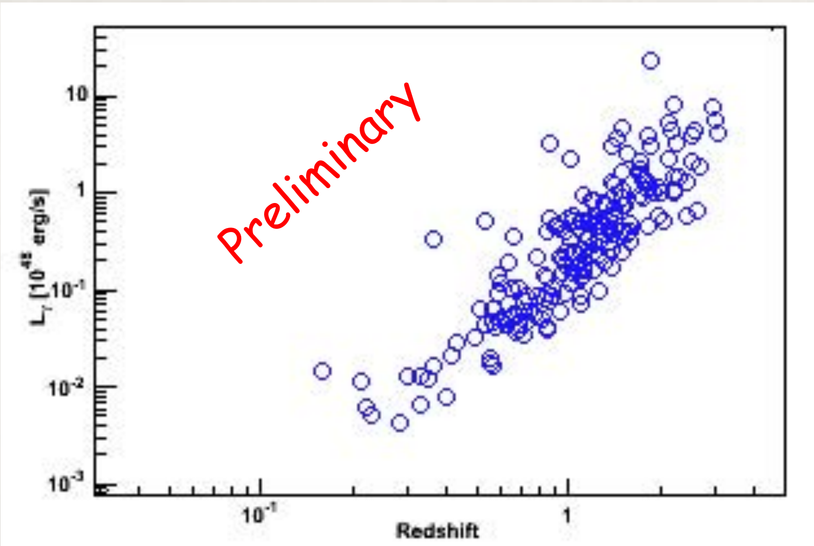
- The sample:
  - Based on the 11month catalog
  - TS >50, |b|>20deg
  - z = [0.1- 3.0]
  - Spans >2dex in flux
  - Spans >4dex in luminosity
- Pretty good dynamical range

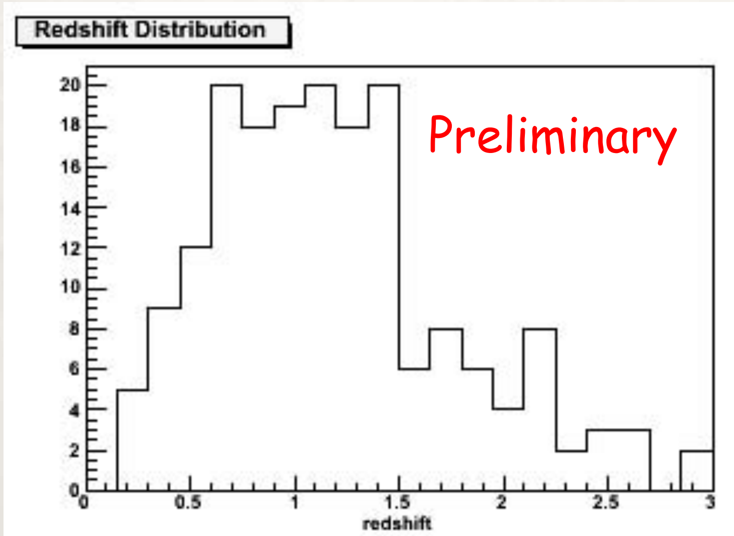
Table 1. Composition of the |b| ≥20, TS≥50, $F_{100} \geq 10^{-8}$ ph cm^{-2} s^{-1} sample used in this analysis.

CLASS	# objects
Total	433
FSRQs	185
BL Lacs	155
Pulsars	8
Others[a]	15
Unassociated sources	70

[a]It includes Starburst galaxies, Narrow line Seyfert 1 objects and Seyfert galaxy candidates.

Preliminary





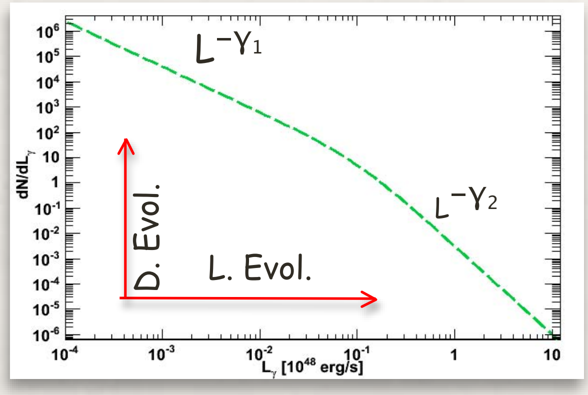
Results: LDDE

* "The best fit is a Luminosity-Dependent Density Evolution"

Luminosity Function

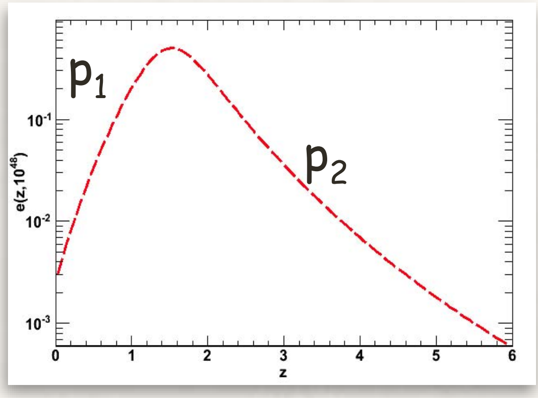
$$\Phi(L_\gamma, z) = \Phi(L_\gamma, 0) \times e(z, L_\gamma) =$$

Local Luminosity Function



×

Density Evolution



$$\Phi(L_\gamma, z=0) \propto \left[\left(\frac{L_\gamma}{L_*}\right)^{\gamma_1} + \left(\frac{L_\gamma}{L_*}\right)^{\gamma_2} \right]^{-1}$$

Typical double power law

$$e(z, L_\gamma) = \frac{1}{\left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{p1} + \left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{-p2}}$$

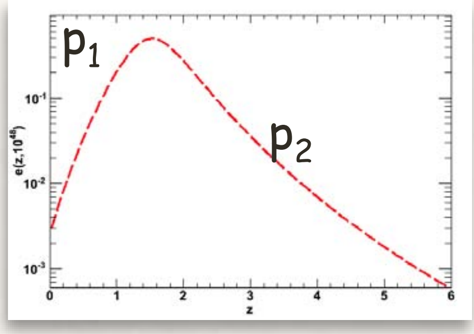
Evolution of the redshift peak with luminosity →

$$z_c(L_\gamma) = z_c \cdot (L_\gamma / 10^{48})^{\alpha}$$

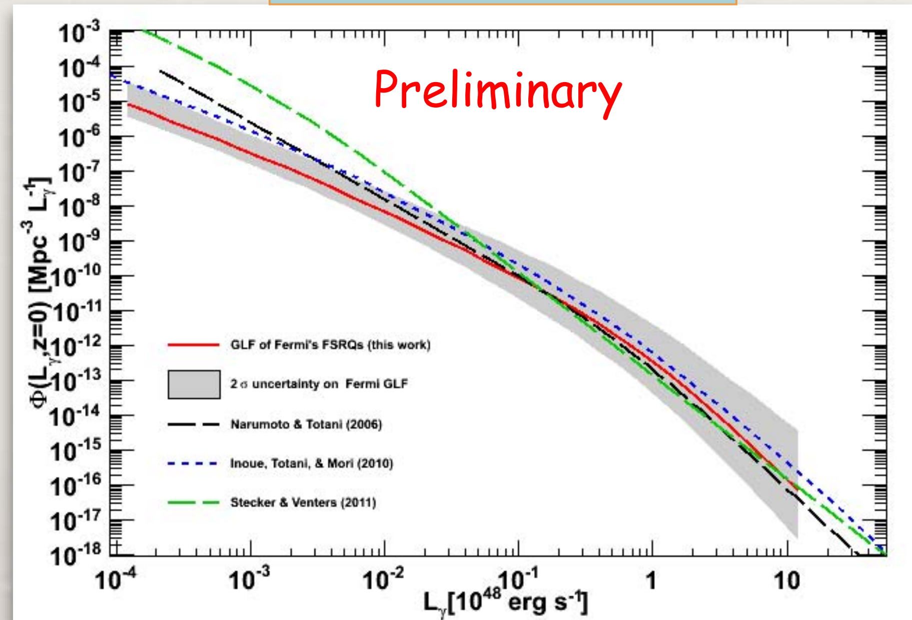
Fermi
Gamma-ray
Space Telescope

FERMI'S GLF

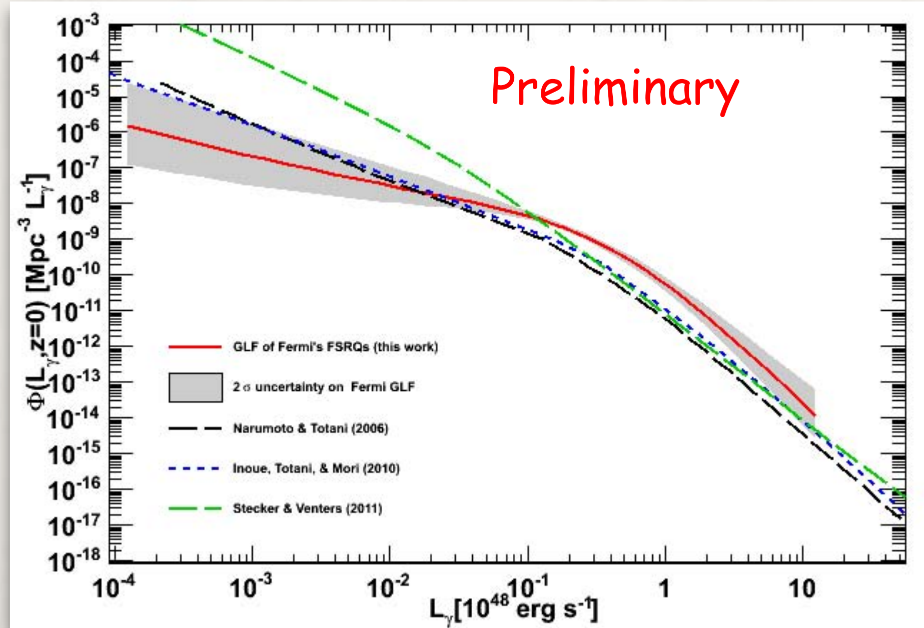
- LDDE represents the data well
- It implies:
  - Strong evolution of FSRQ: factor 100 more FSRQs at z=1.5
  - A cut-off in the evolution that changes with luminosity
- The results are robust against in-completeness (e.g. lack of ID/redshifts) problems



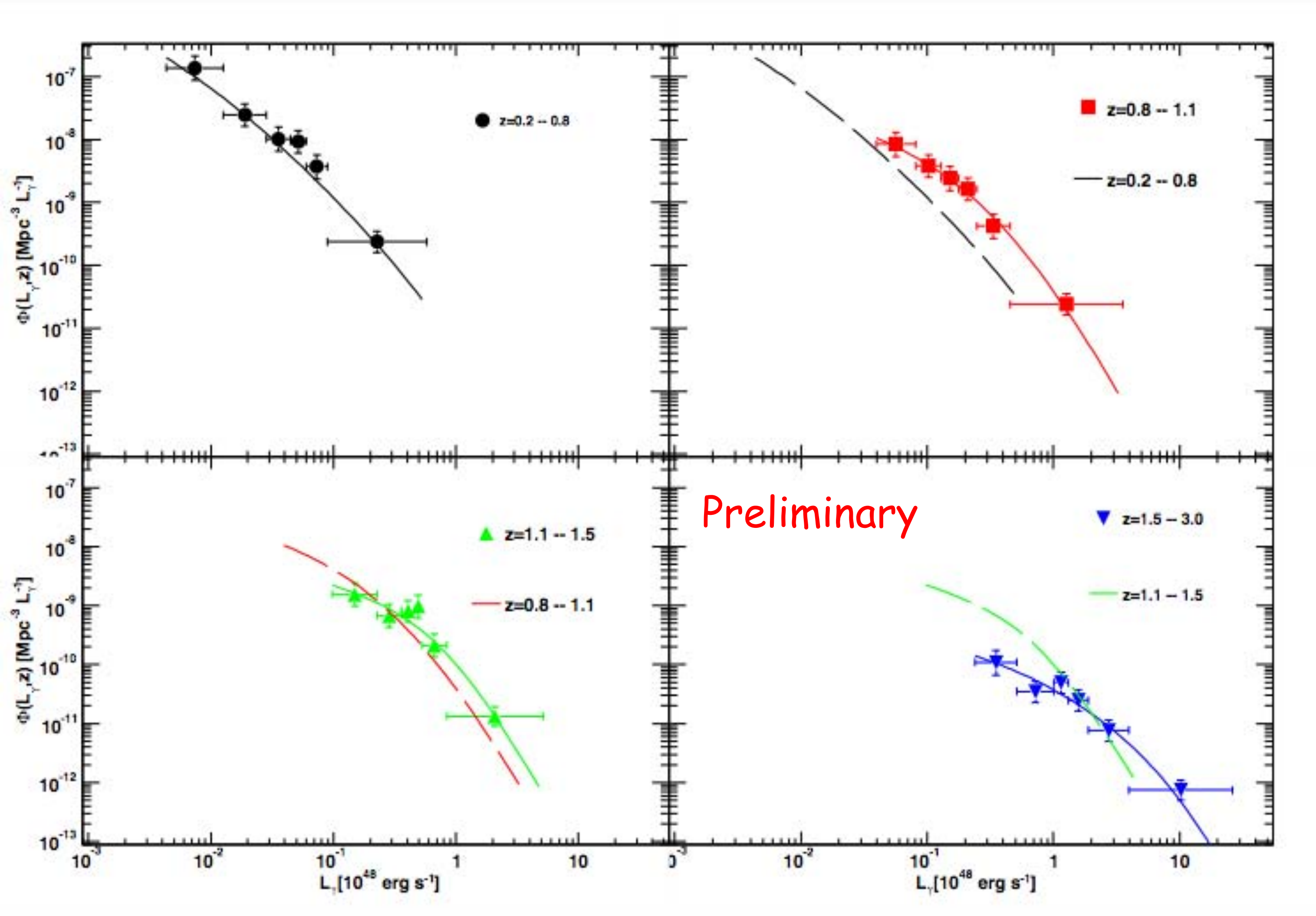
Local GLF (Z=0)



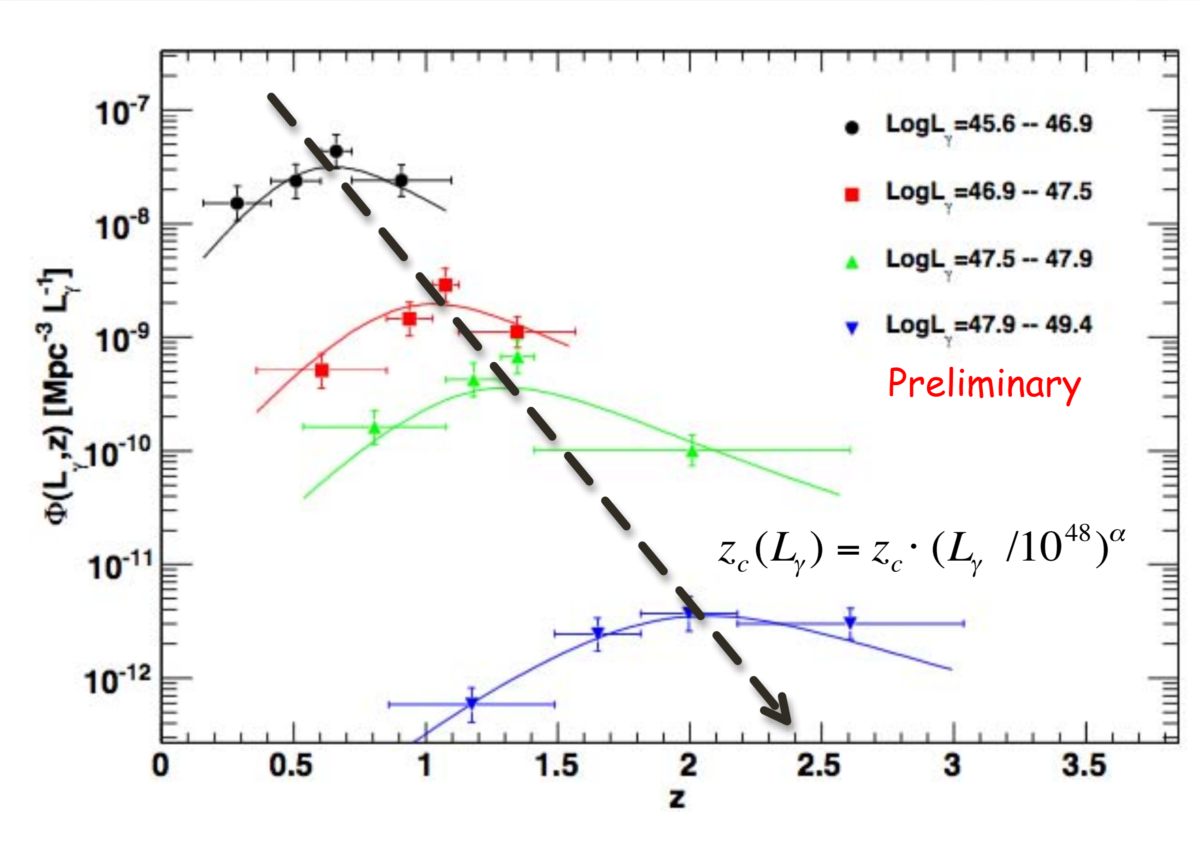
Z=1

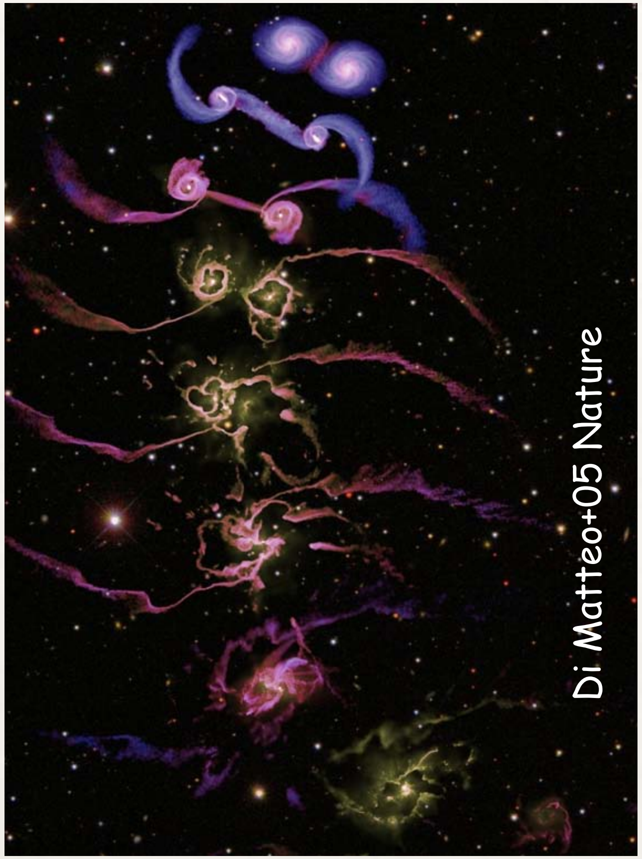


The representation of the GLF



Redshift peak evolution

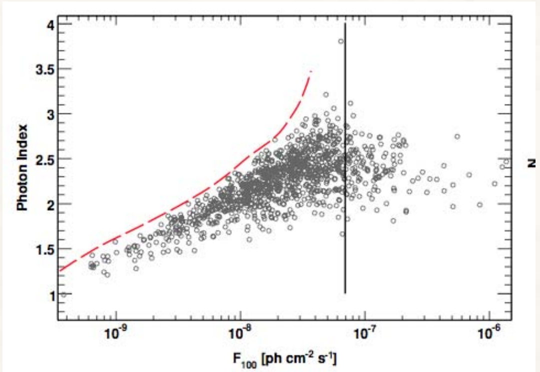




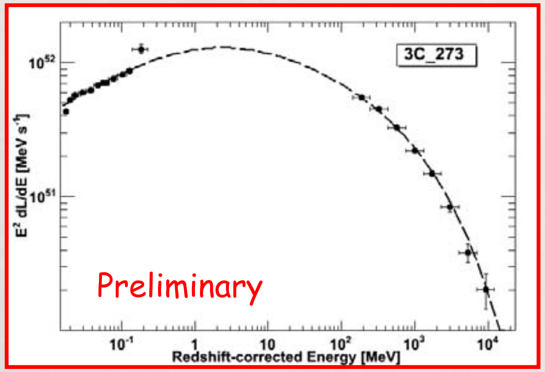
Fermi Gamma-ray Space Telescope

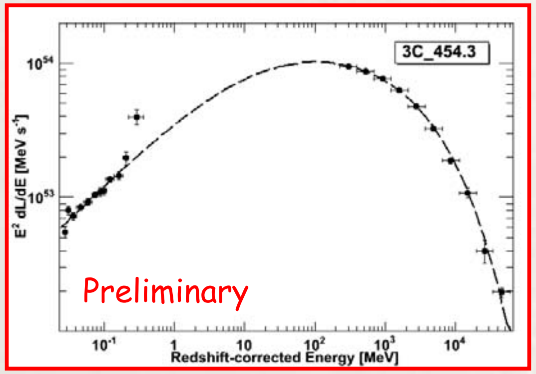
The SEDs of FSRQs

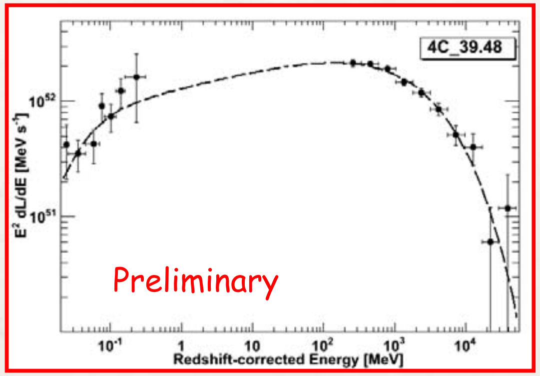
Abdo+10, ApJ 720, 435



- Receipt:
  - Take all the FSRQs in the complete sample
  - Extract *Swift*/BAT and *Fermi-LAT* data
  - Convert to rest-frame
  - Fit them together





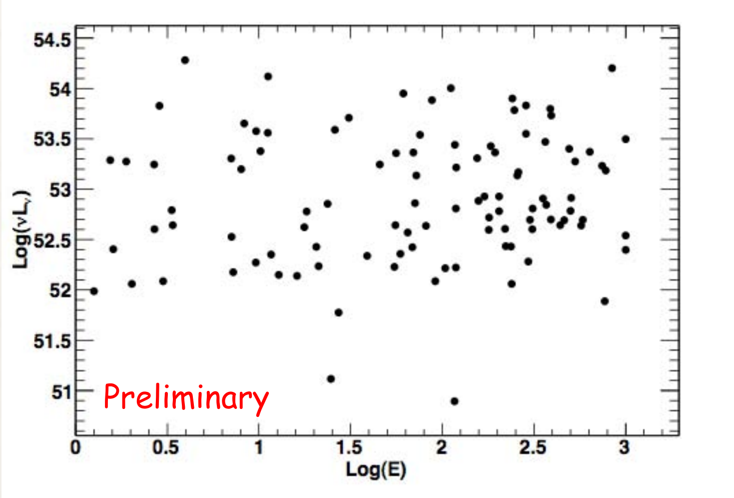


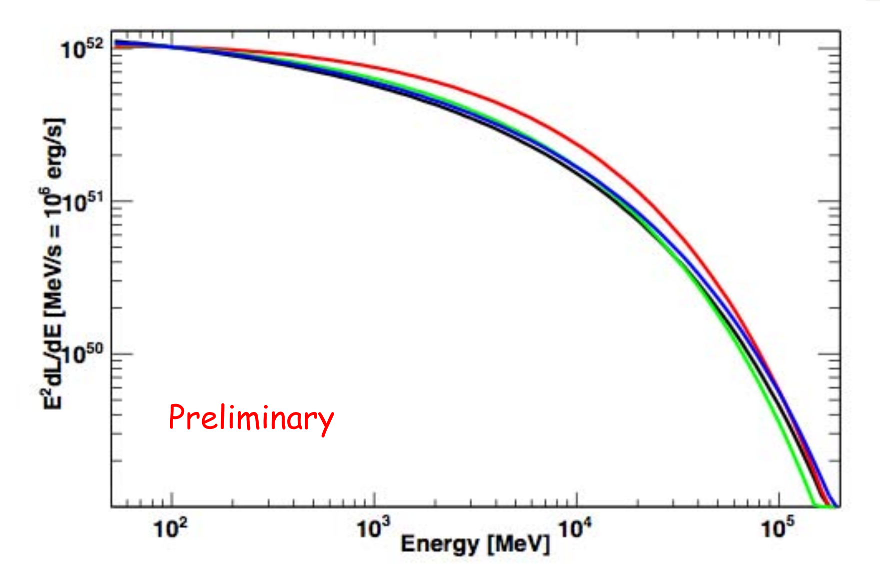
Caveats: Swift data extracted over 2005-2011, Fermi data in 2008-2011
Swift and Fermi might sample two different components (e.g. SSC/EC)

The SED of FSRQs: properties

Bearing in mind the caveats

* No compelling correlation between L_{peak} and E_{peak} independently of fitting function used (e.g. fossati+98,ghisellini+99)

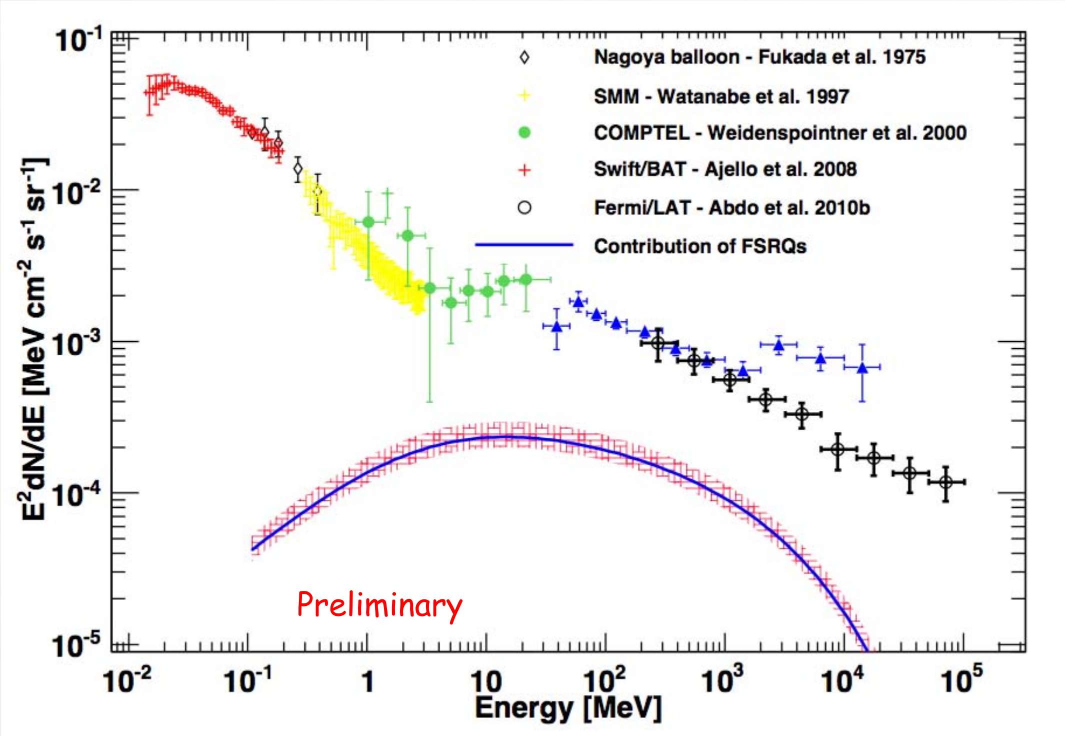




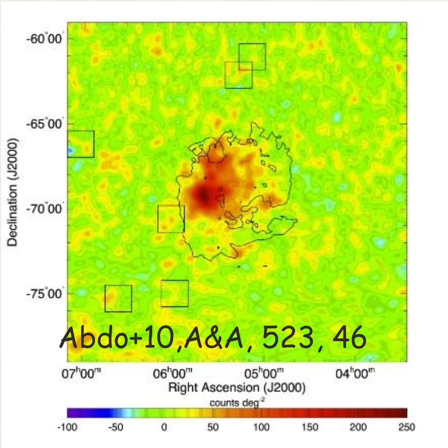
* The 'average' SED does not change with luminosity or redshift

Contribution of FSRQs to EGB

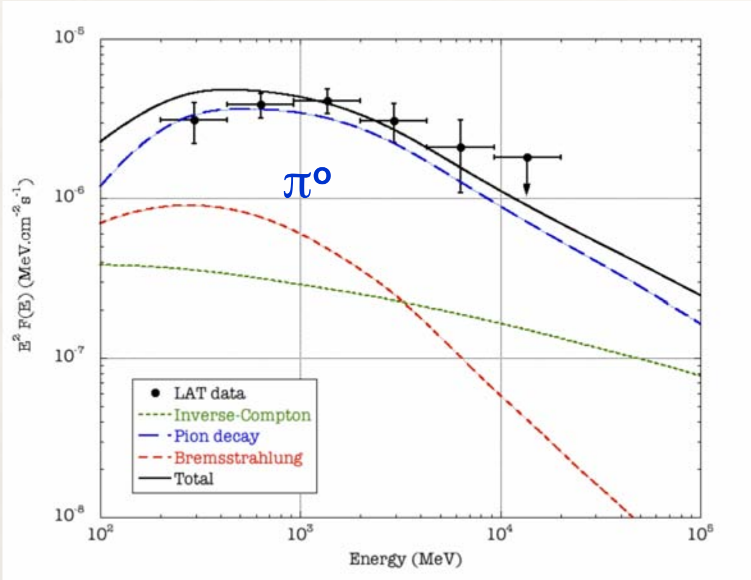
* Total (e.g. resolved + unresolved) emission from FSRQs
* No EBL/cascade considered yet, but unimportant



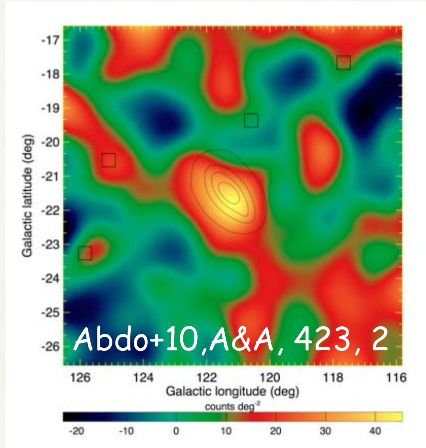
γ-rays from CRs in nearby galaxies



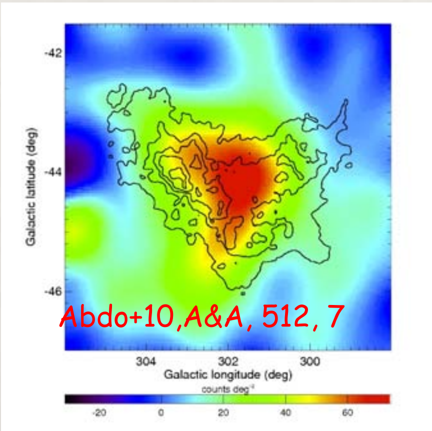
Large Magellanic Cloud



Small Magellanic Cloud Spectrum

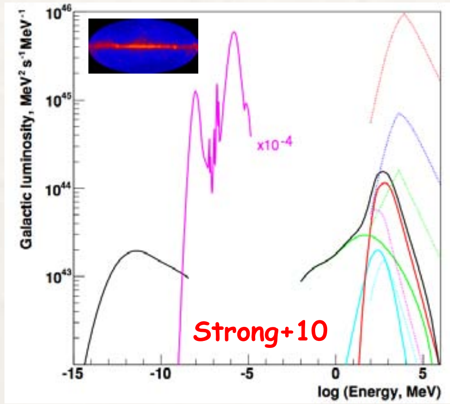


M31



Small Magellanic Cloud

GeV gamma rays in these galaxies come primarily from the interactions of cosmic ray protons and electrons with interstellar matter and photon fields.



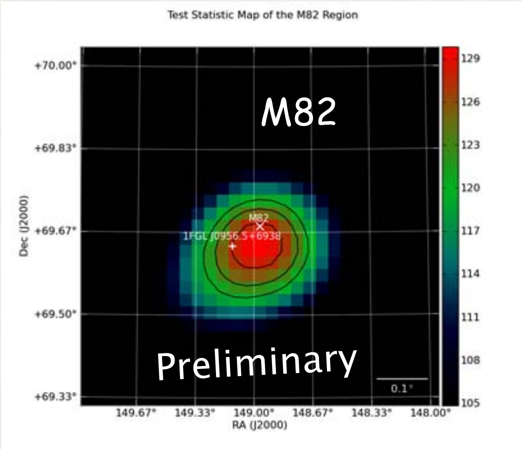
Milky Way

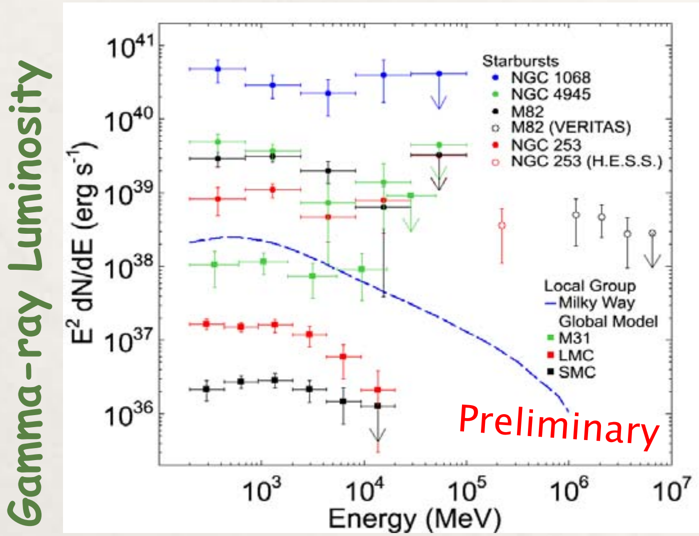
Fermi Gamma-ray Space Telescope

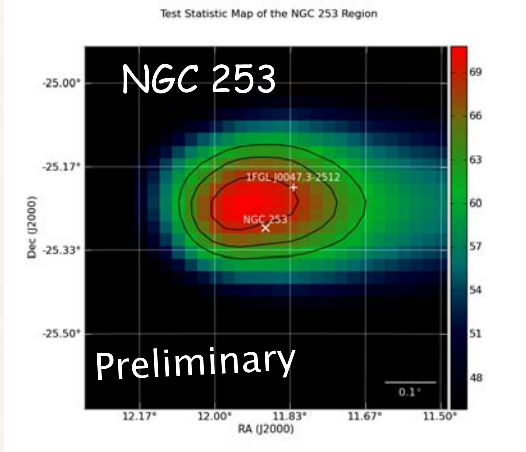
Beyond The Local Group

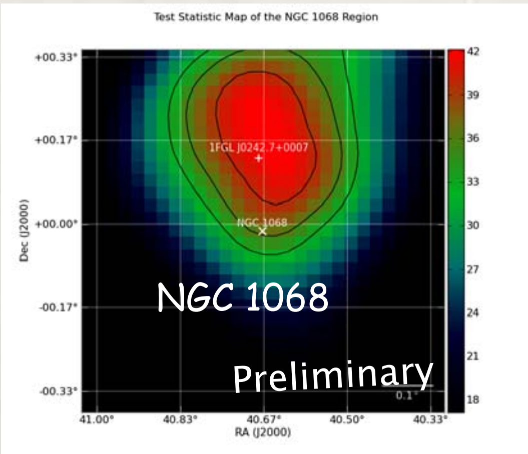
"Courtesy K. Bechtol"

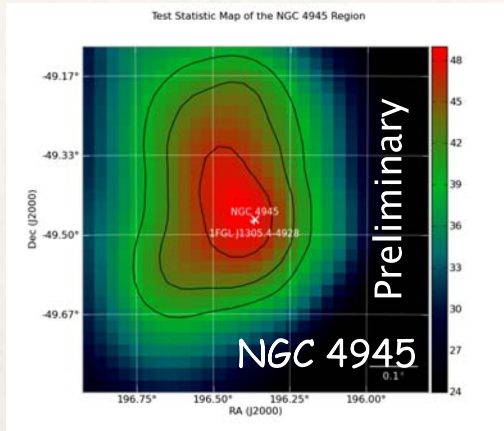
See also Abdo+10, ApJ, 709, 152











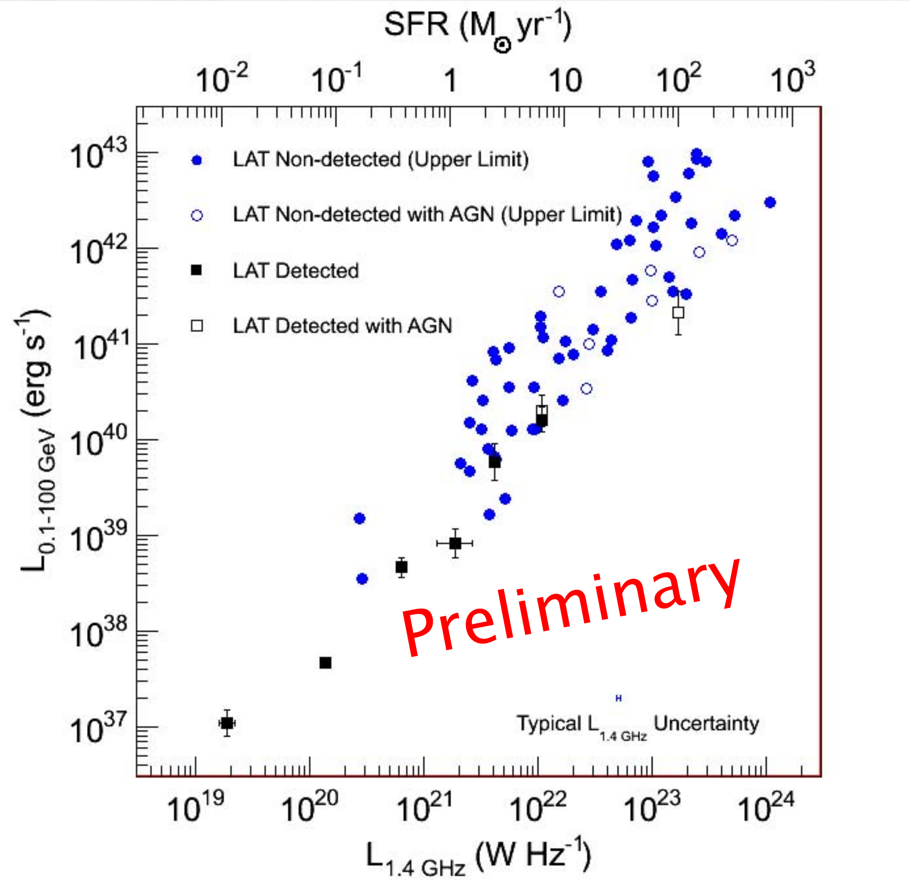
Two prototypical starbursts also detected by IACTs

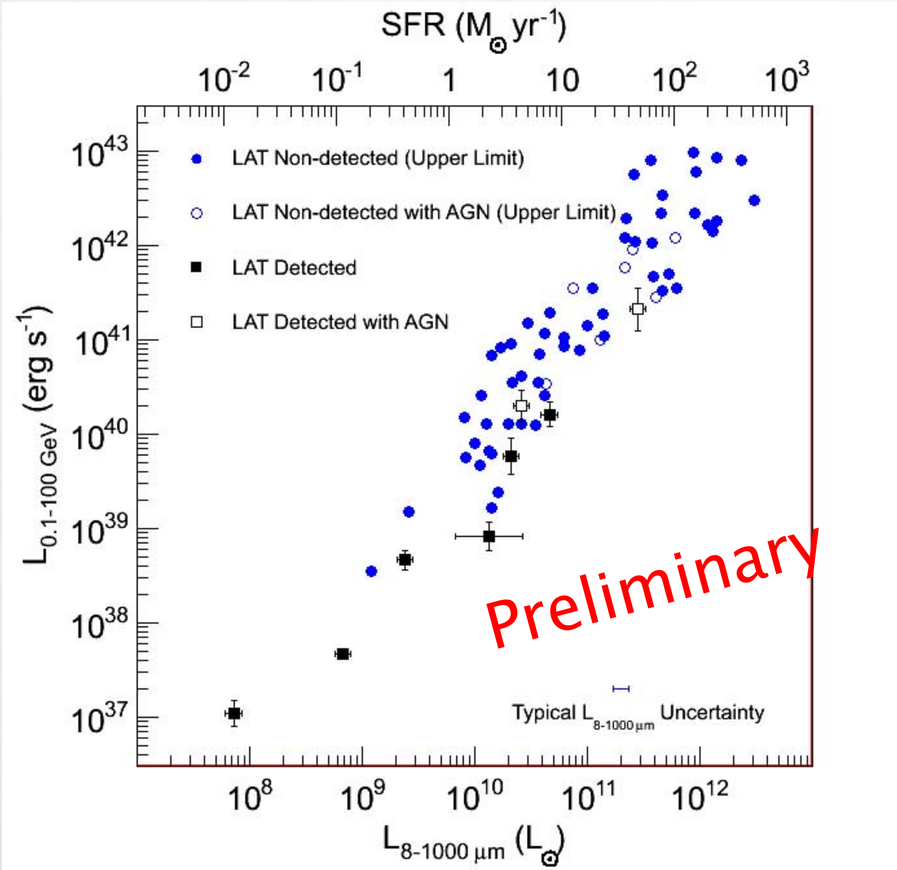
M82 & NGC 253

RC & IR vs Gamma

"Courtesy K. Bechtol"

Sample selection from HCN survey Gao&Solomon04

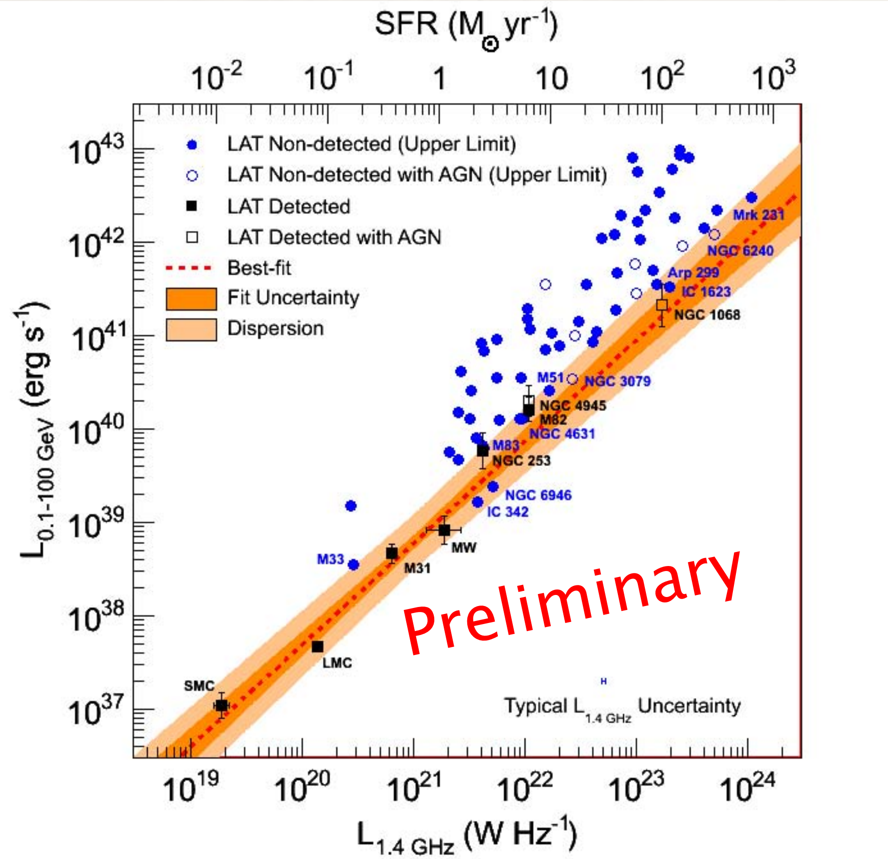


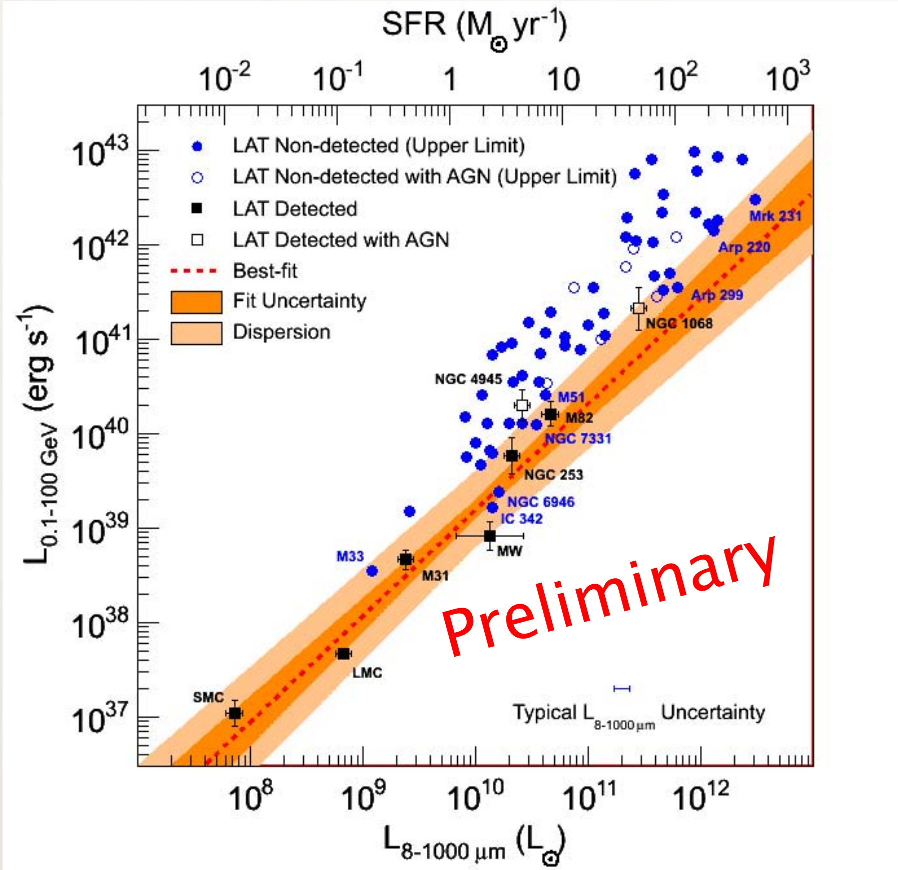


RC & IR vs Gamma

"Courtesy K. Bechtol"

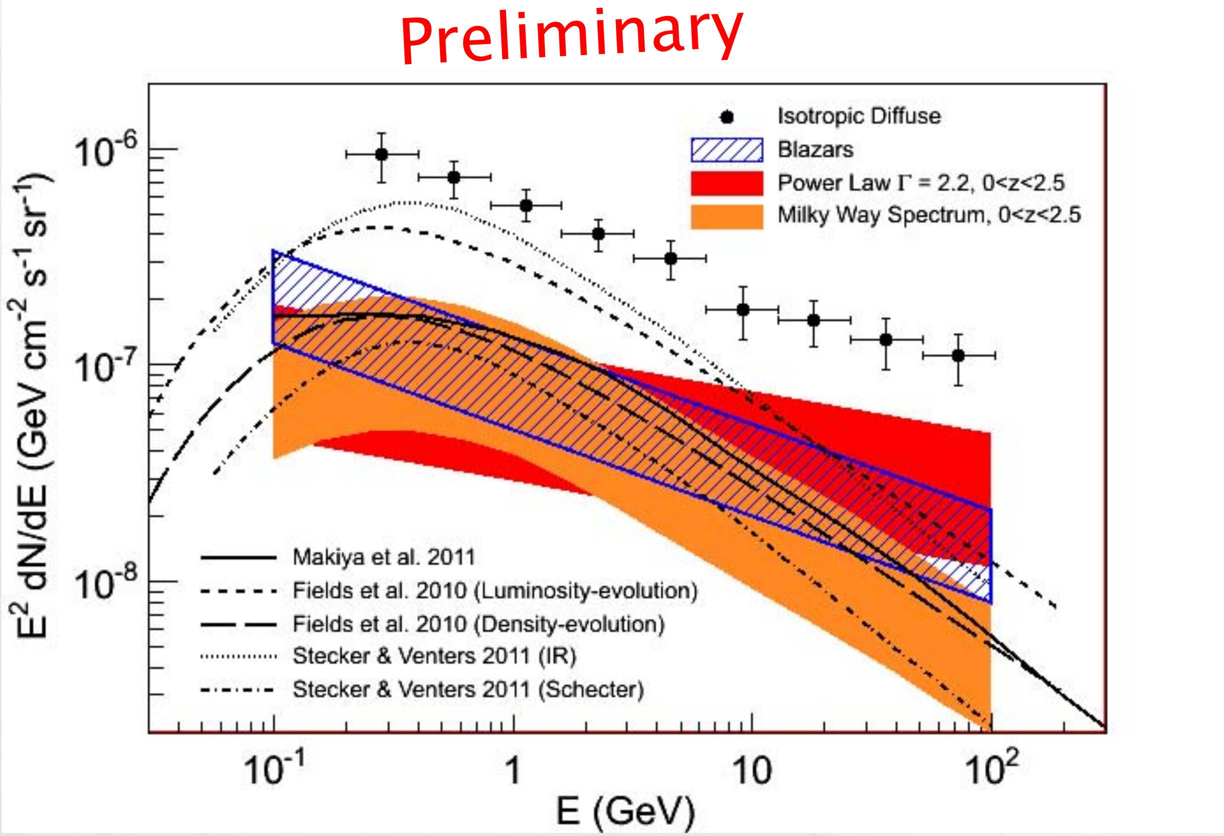
Nearly linear scaling of γ-ray luminosity and tracers of SF





EGB Contribution

"Courtesy K. Bechtol"



Other estimates:
Pavlidou&Fields01
Thompson+07
Fields+10
Makiya+11
Stecker&Venters11

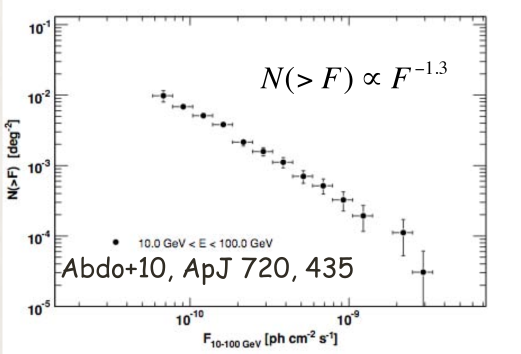
Treating all star-forming galaxies with either **(1) Power Law** or **(2) Re-scaled Milky Way** spectral model (bracket uncertainty)

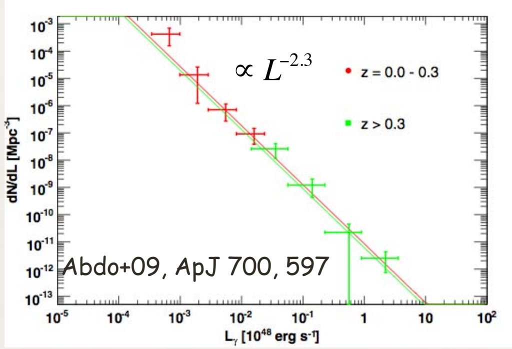
Estimated contribution of star-forming galaxies 0<z<2.5 is 3-25*%

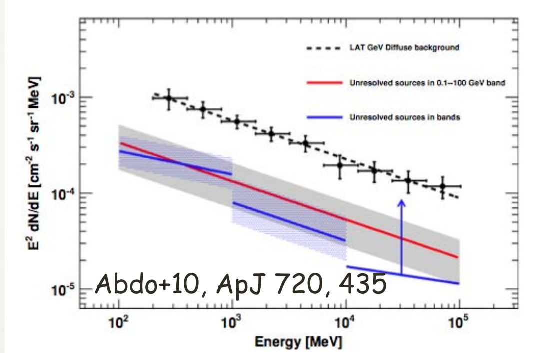
*See Stecker&Venters11 for a discussion about the uncertainty in the estimate of the diffuse emission from SFG

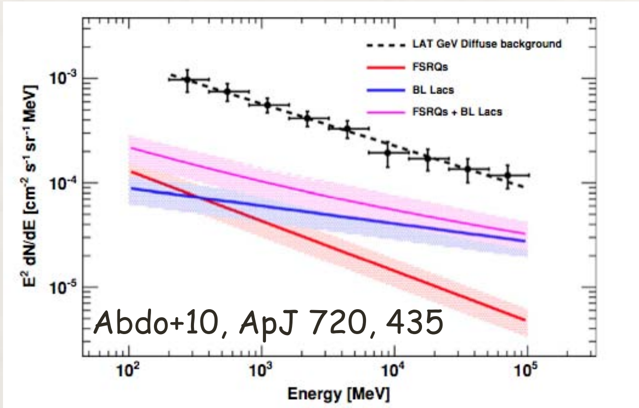
The contribution of BL Lacs

"Waiting for a luminosity function"









1. The 10-100GeV band is an effective way to select BL Lacs (Abdo+10,Neronov+11)

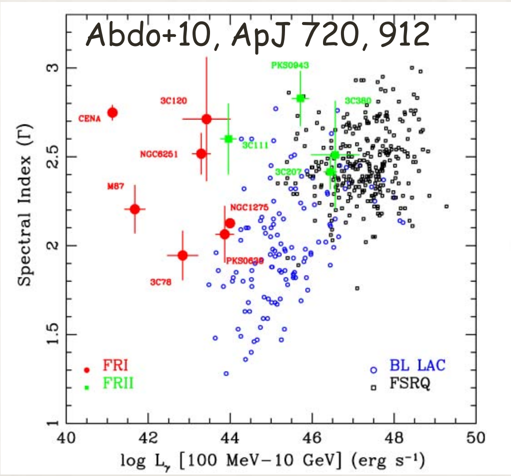
- No Signs of a break in the logN-logS
- Index Compatible with the index of the LF (Abdo+09)
- The contribution of unresolved BL Lac is still a lower limit

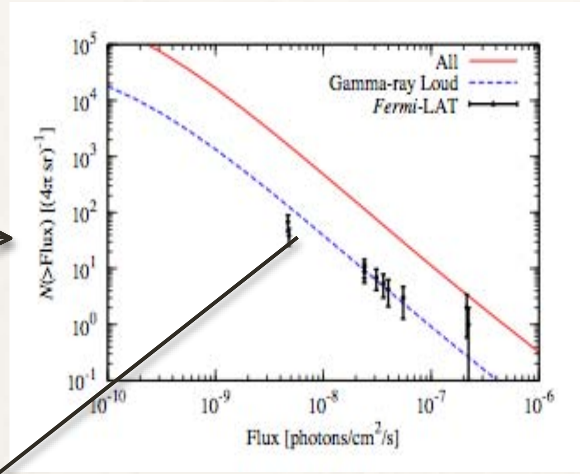
Radio Galaxies

(from Inoue 2011)

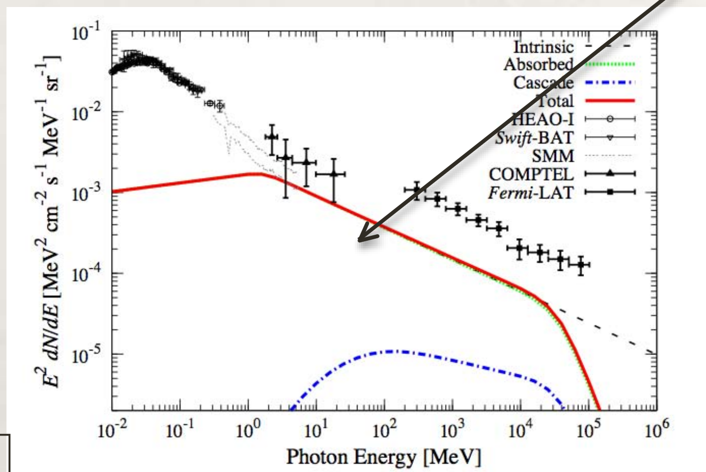
11 RGs reported in 1LAC, possibly 2x more

Contribution evaluated by Inoue+11 by scaling the RLF (Willot+01) and using a γ -ray/Radio correlation



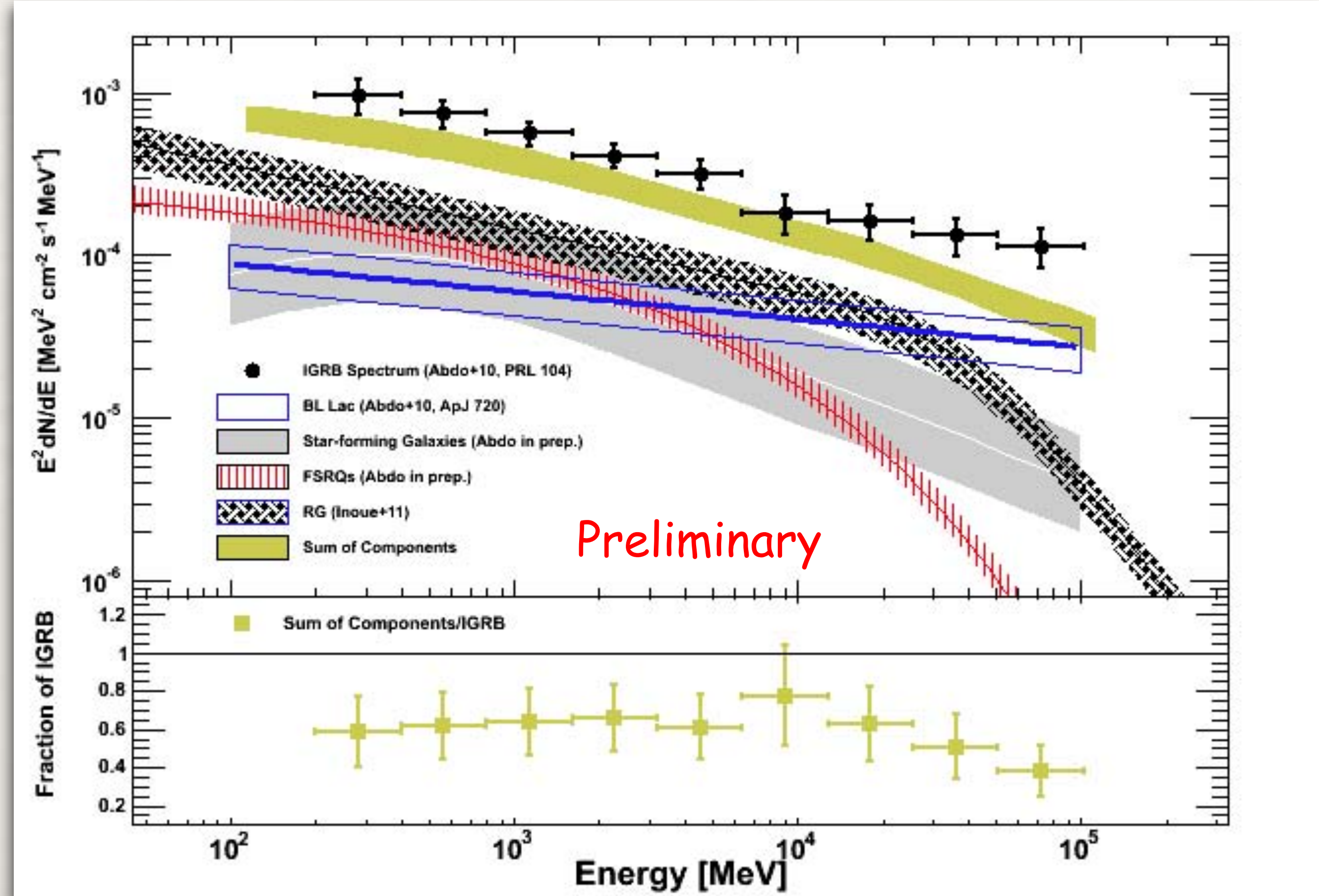


Contribution of RGs might be significant (~24%) but has a ~30% uncertainty



*See also Poster by Bhattacharya

Update on the IGRB



Different contributions reported by: Stecker&Salomon+96, Pavlidou&Fields+02, Narumoto&Totani06,Dermer07, Bhattacharya+09, Inoue&Totani09, Fields+10, Makiya+10, Inoue+11,Abazajian+10, Ghirlanda+11,Stecker&Venters11,Malyshev&Hogg11

Several Other Components

Low Energy (<1GeV): MeV blazars (Ajello+09), RQ AGN (Inoue+08), FR-II lobes (Massaro&Ajello11), Quasar extended components ?

Medium Energy: millisecond pulsars (Faucher-Giguere&Loeb10, Siegal-Gaskins+10)

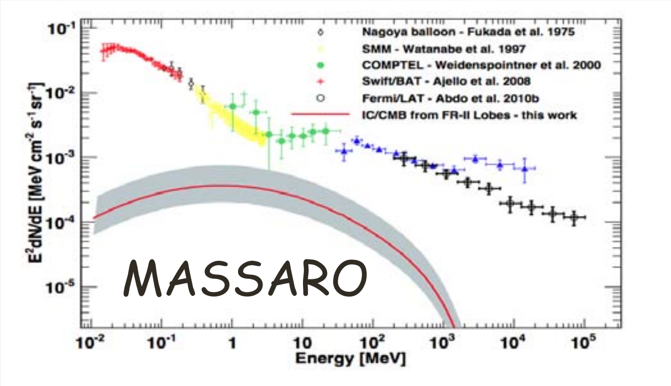
High Energy (>10 GeV): BL Lacs

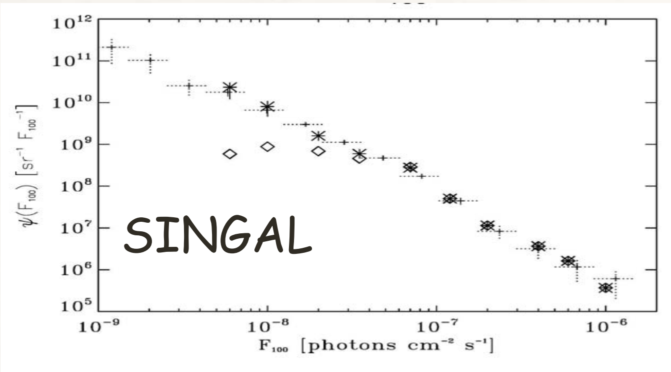
"How often have I said to you that when you have eliminated the impossible, whatever remains, however improbable, must be the truth ?" (Sherlock Holmes)

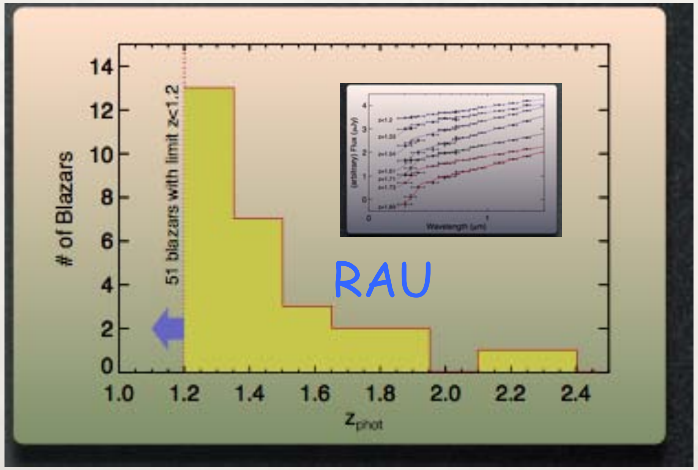
IG shocks (e.g. Keshet03,Miniati02)
Cascades from UHCRs (e.g. Ahlers+10, Venters10)
DM Annihilation (e.g. Ullio+02)

The END

* Amazing wealth of data on the origin of the IGRB
  * Next IGRB measurement will cover both low and high energy using P7 data (talk to M. Ackermann)
  * FSRQs evolution determined from gamma-ray data alone
  * SFG and RG are emerging population (certain contributors)
  * The 1st GLF of BL Lacs coming soon (expect exciting findings)

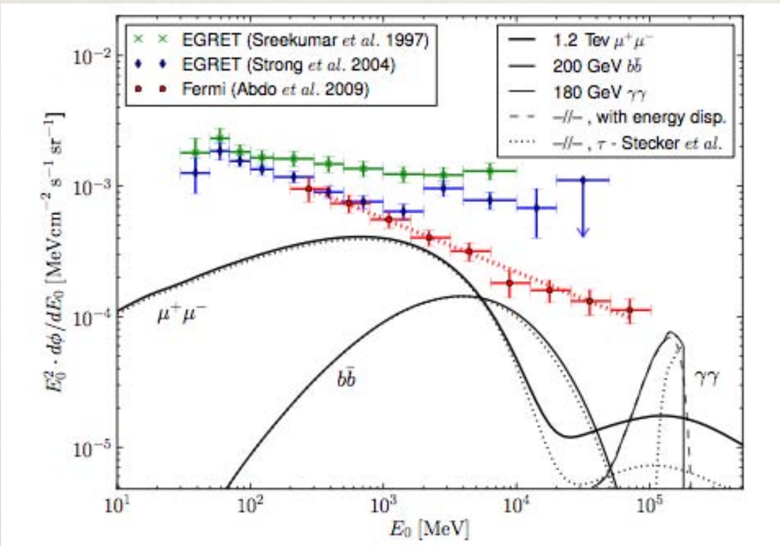


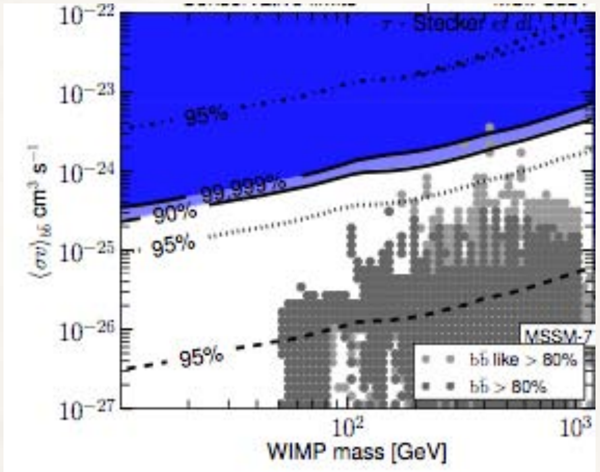


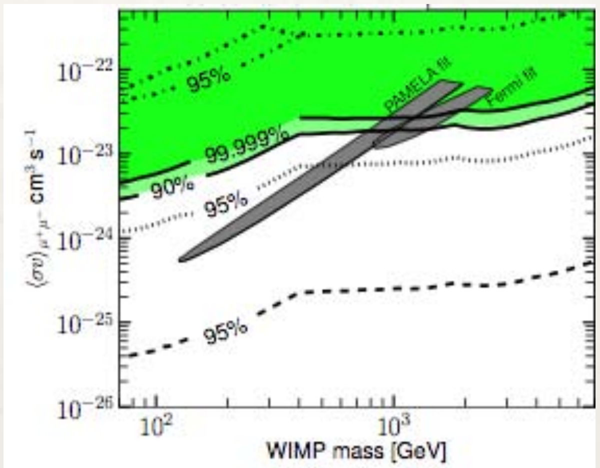


Limits on DM annihilation

- DM annihilation limits can be obtained imposing that the EGB spectrum is not violated
  - Degeneracy between the cross-section and the clustering scenario
  - Limits close to those expected for a thermal relic neutralino

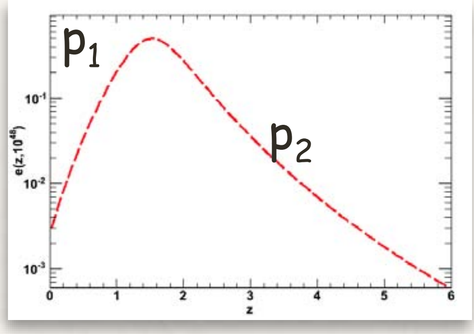






Best Fit results

- LDDE (9 pars) provides a better fit to the data (chance of ~10^{-6})
- It implies:
  - Strong evolution of FSRQ
  - A cut-off in the evolution that changes with
  - luminosity



- The results are robust against in-completeness (e.g. lack of ID/redshifts) problems

Table 3. Best-fit parameters of the Luminosity Dependent Density Evolution GLF

Preliminary

Sample	# Objects	A^a	γ_1	L_*	γ_2	z_c^*	α	p_1^*	p_2	β_1	μ	σ
ALL	185	$3.17(\pm0.23)\times10^4$	0.22 ± 0.12	0.86 ± 0.51	1.58 ± 0.27	1.46 ± 0.16	0.21 ± 0.03	7.38 ± 1.77	-6.41 ± 1.95	···	2.44 ± 0.01	0.18 ± 0.01
ALL	185	$3.16(\pm0.23)\times10^4$	0.22 ± 0.12	0.86 ± 0.51	1.70 ± 0.28	1.55 ± 0.16	0.26 ± 0.03	6.38 ± 1.55	-7.08 ± 2.08	-2.32 ± 1.03	2.44 ± 0.01	0.18 ± 0.01
ALL[b]	220	$3.22(\pm0.21)\times10^4$	0.23 ± 0.12	0.74 ± 0.38	1.67 ± 0.26	1.53 ± 0.18	0.25 ± 0.03	6.42 ± 1.57	-6.03 ± 1.88	-2.19 ± 1.23	2.41 ± 0.01	0.21 ± 0.01

[a] In unit of $10^{-13}\,\mathrm{Mpc}^{-3}\,\mathrm{erg}^{-1}\,\mathrm{s}$.

[b] 35 unassociated sources were included in this sample by drawing random redshifts from the observed redshift distribution of FSRQs.

Systematic Uncertainties

Detection Efficiency

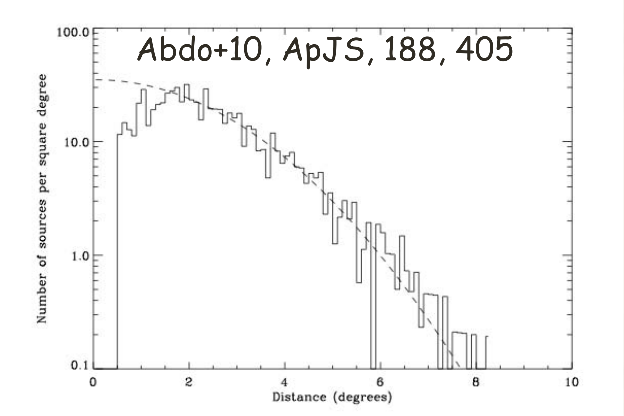
Source Confusion

Curved Spectra

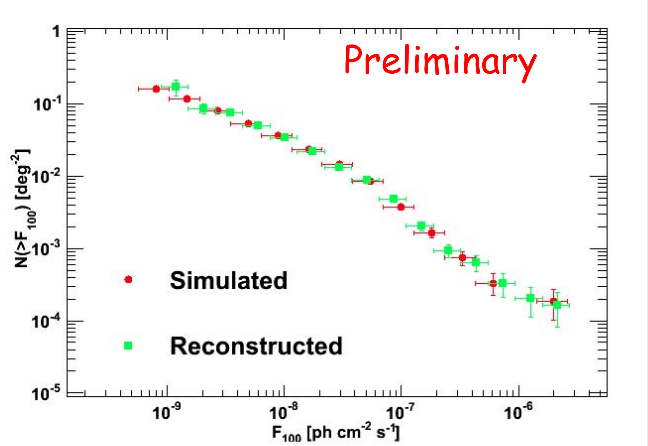
Variability

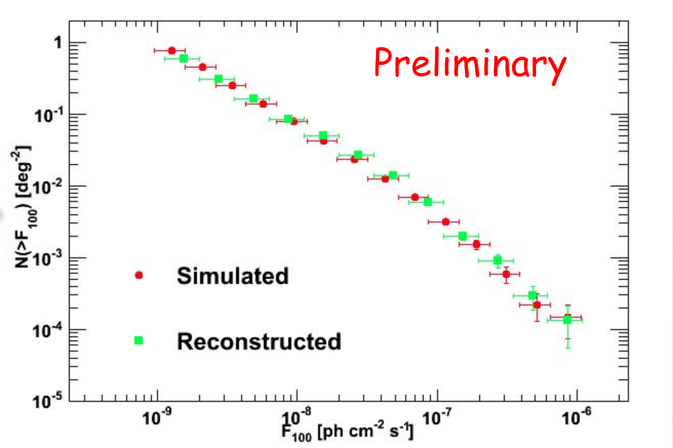
Source Confusion

- Stecker&Venters+11 claim that below $F_{100}<10^{-7}$ ph/cm^2/s sources cannot be resolved anymore (confusion caused by PSF and source density)
  - ->This would make the source counts flatter than reality
  - ->Larger blazars contribution to EGB

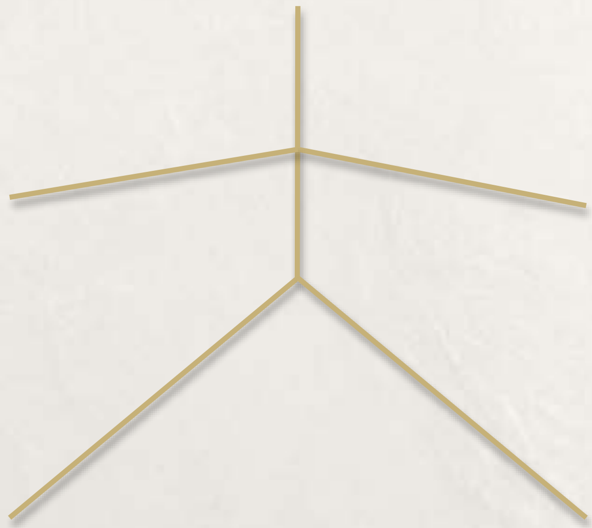


- However:
  - ~8% (80/1043) of the 1LAC sources (TS>25, |b|>10deg) are probably missed because of source confusion
  - No bias in reconstructing source counts even for x10 larger densities

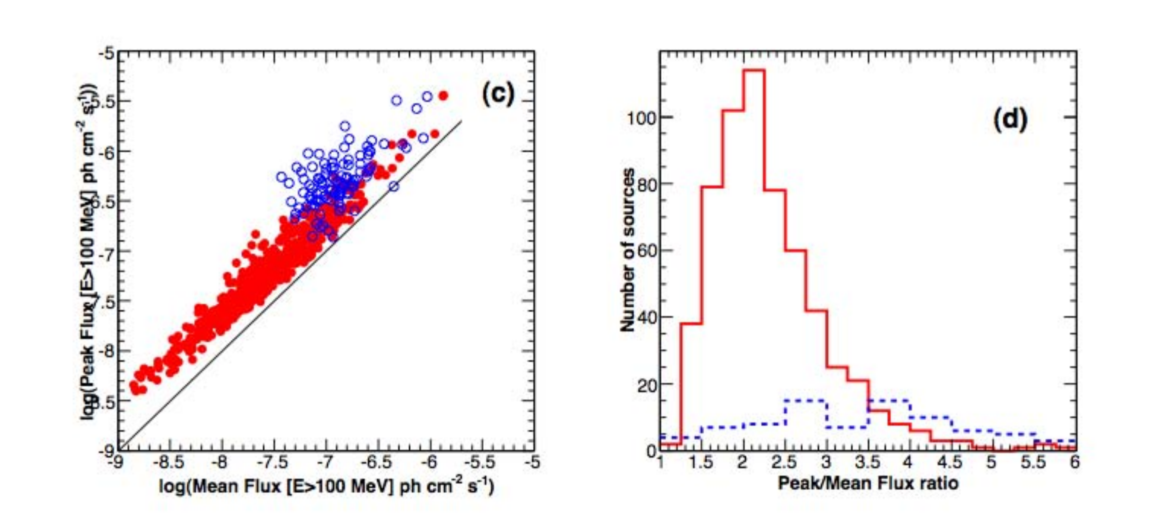




Power Law Sources



Duty Cycle



- Most of the blazars have a variability by a factor ~2
- Detection efficiency is independent of the order of arrival of photons: e.g. 2 sources with same average flux but different duty cycle will still be detected with the same TS (if background is flat)

SWIFT

Best-fit XLF

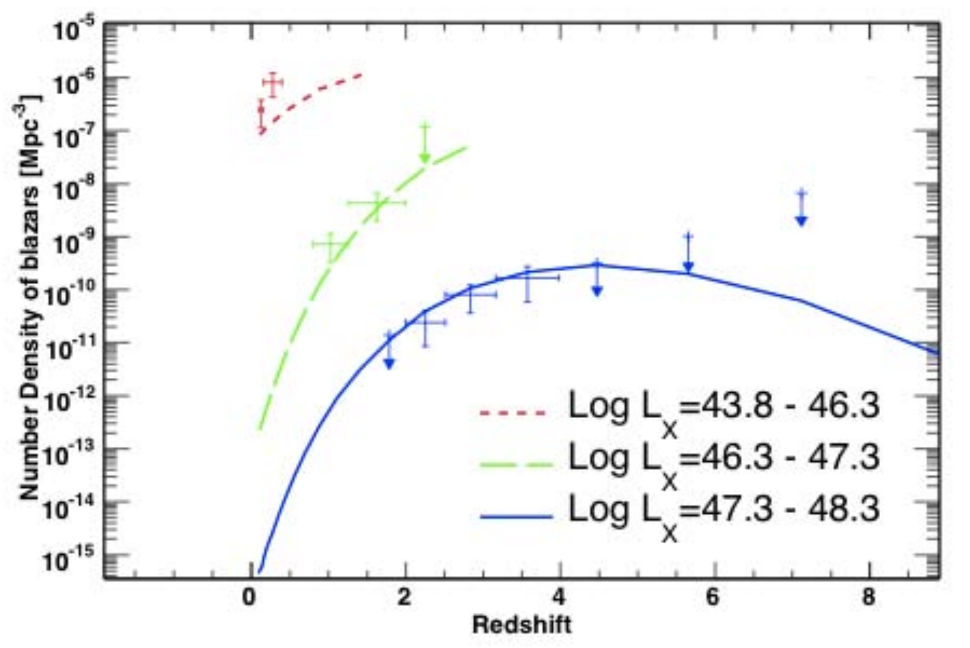
$$\Phi(L_X, z=0) = \frac{dN}{dL_X} = \frac{A}{\ln(10) L_X}\left[\left(\frac{L_X}{L_*}\right)^{\gamma_1} + \left(\frac{L_X}{L_*}\right)^{\gamma_2}\right]^{-1},$$

$$e(z) = (1+z)^{k+\gamma z}.$$

$$\Phi(L_X(z), z) = \Phi(L_X/e(z), z=0),$$

Best Fit Model:

PLE with a redshift cutoff coupled to a local double power law XLF



Parameters:

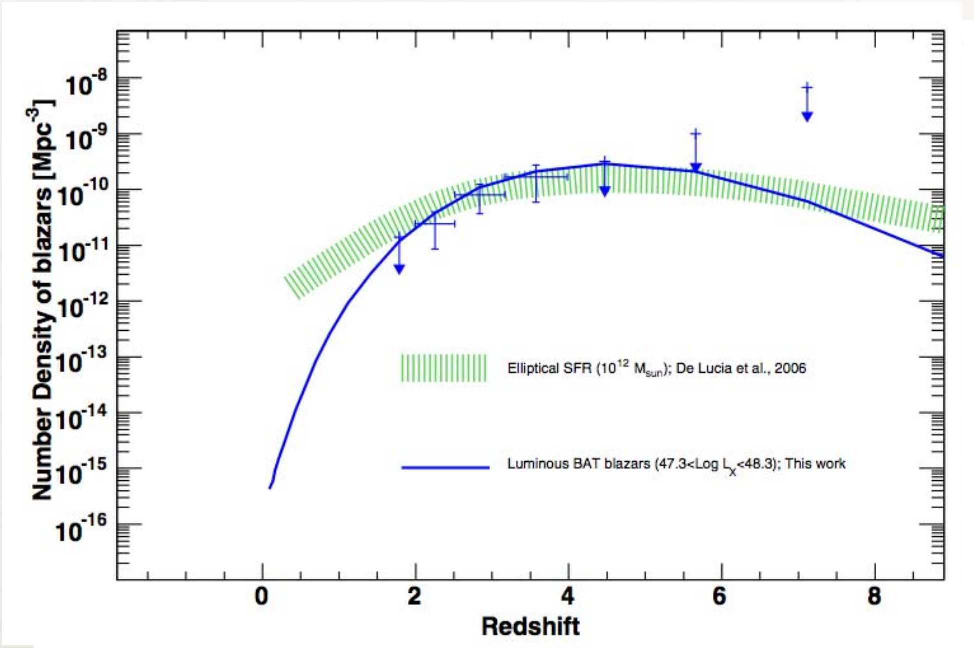
γ_1=-0.87±1.31 <--beaming?

γ_2= 2.73±0.38 (Urry&Schafer84)

k= 3.45 ±0.44

γ=-0.25 ±0.07 <--3σ

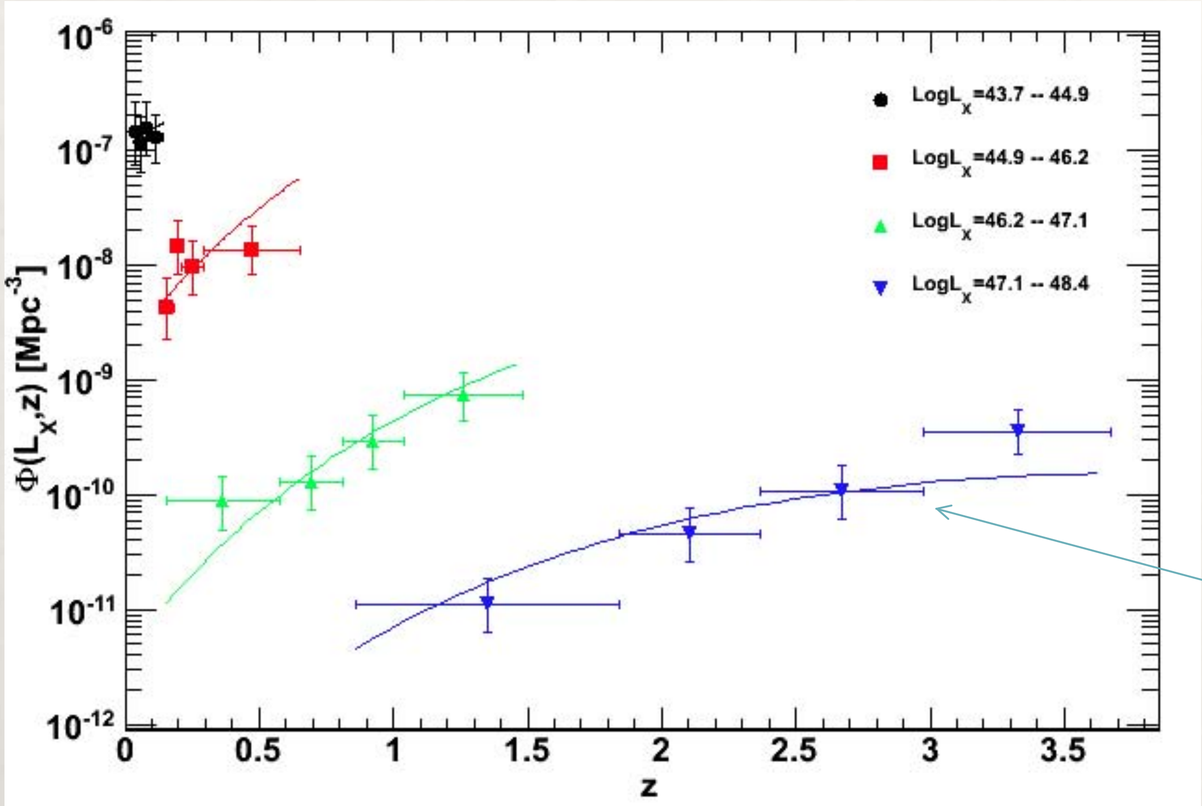
The most luminous FSRQ



- At the moment the most luminous FSRQ, so called MeV blazars, are selected in the hard X-ray band (Ajello+09)
- Their space density peaks at 4.3±0.5… !
- The only similar trend can be found in >$10^{12}M_\odot$ Ellipticals$_\odot$(Ajello+09)
- They are powered by SMBH with M>$10^9M_\odot$(Ghisellini+10)

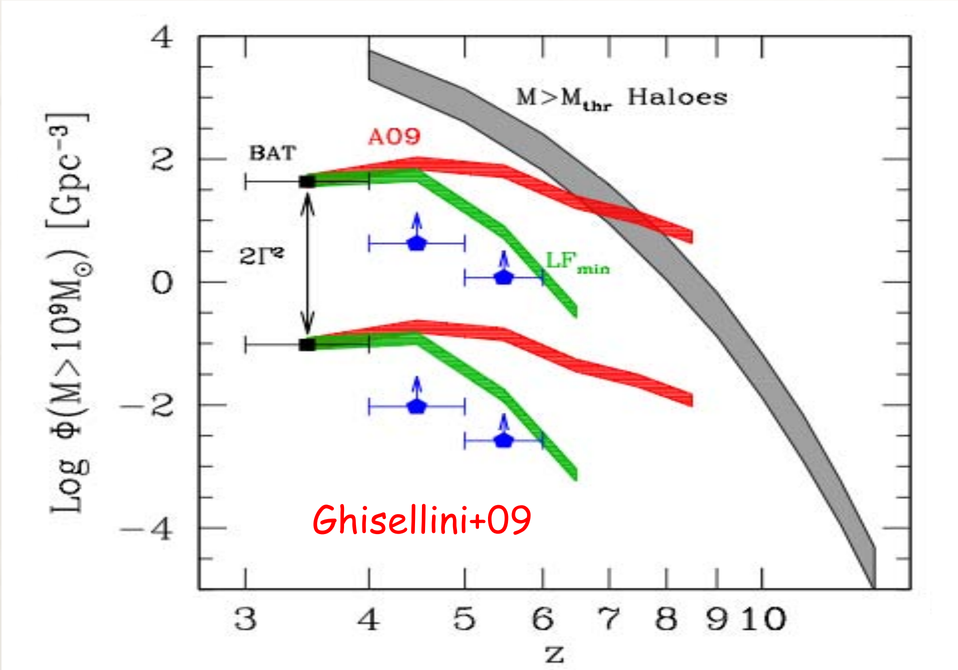
6YR OF DATA CONFIRM RESULTS

* The sample of Cusumano+10 (58months) contains ~85 bona fide blazars (~62 FSRQ)



Redshift peak fully confirmed at z_c=3.5 !

The most luminous FSRQ



* At the moment the most luminous FSRQ, so called MeV blazars, are selected in the hard X-ray band (Ajello+09)

* Their space density peaks at 4.3±0.5… !

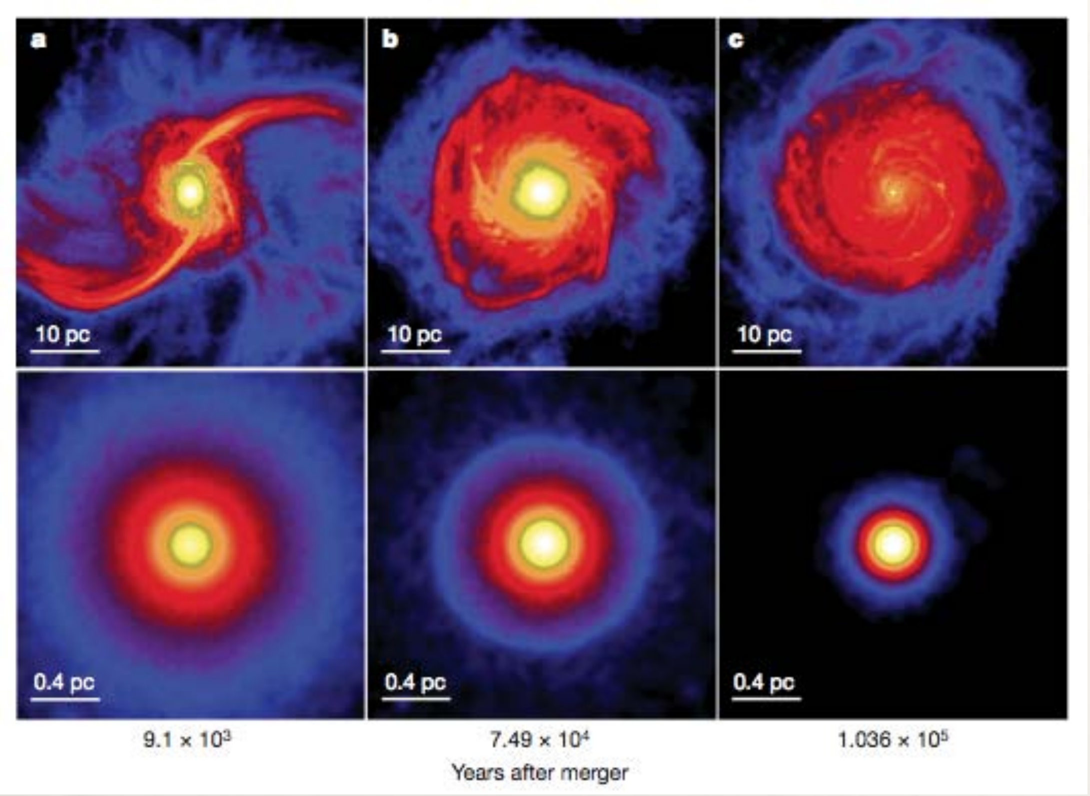
* The only similar trend can be found in $>10^{12}M_\odot$ Ellipticals (Ajello+09)

* They are powered by SMBH with $M>10^9M_\odot$ (Ghisellini+10)

‘Black Hole Arrived Early’

Nature Editor’s summary, Aug. 2010

* Direct formation of 10^5 M_{sun} BH from a massive turbulent disk produced by a merger seems feasible (Mayer+10, Nature)



Volonteri+11

"Blazars in the Early Universe"

BAT high-z FSRQ host a massive black hole accreting at the Eddington limit

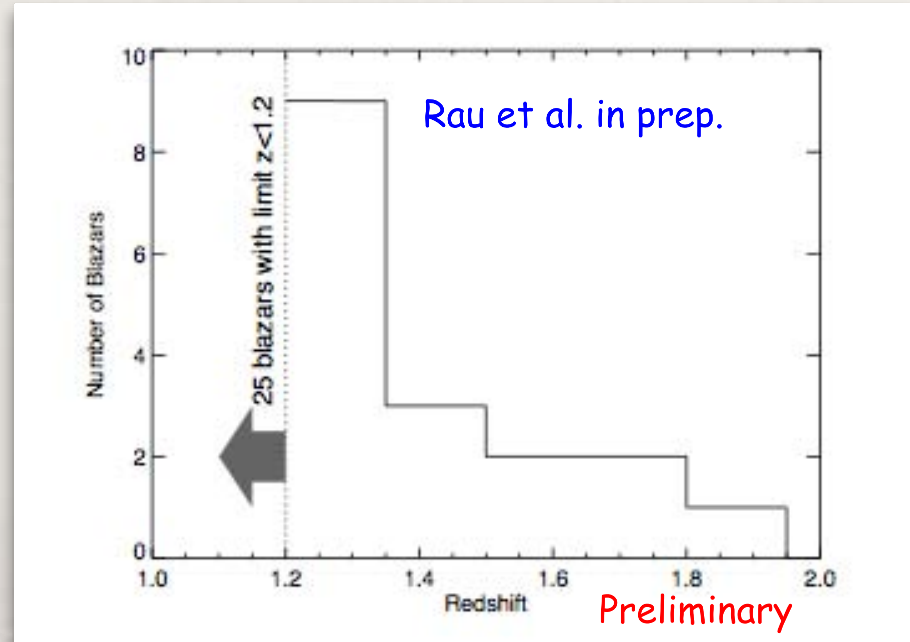
Blazars might be the best way to sample heavy black holes in the early Universe

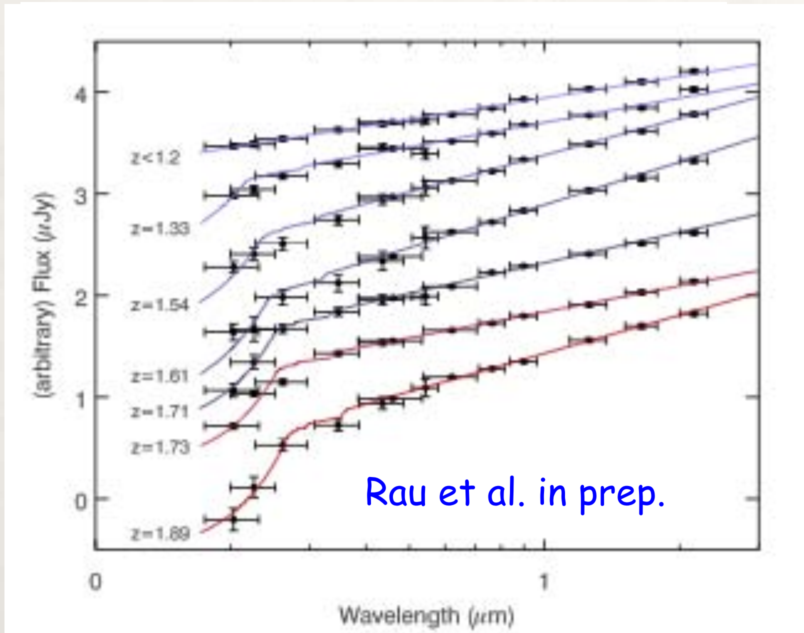
The RL/RQ fraction seem to increase after redshift 3: bias or real-effect ?

Finding more luminous radio-quiet quasars at $z > 5$ is [important but] **finding high redshift blazars might be, in the end, even more important, since each one of those implies the existence of many more misaligned sources. A few blazars detected at $z \sim 6$ would be very challenging for structure formation**, very constraining, and possibly illuminating for the under- standing the early growth of very massive black holes, and its feedback on the host.

(SMBH) Hunting Season: Open

Blazars at high redshift might exist in reasonable numbers



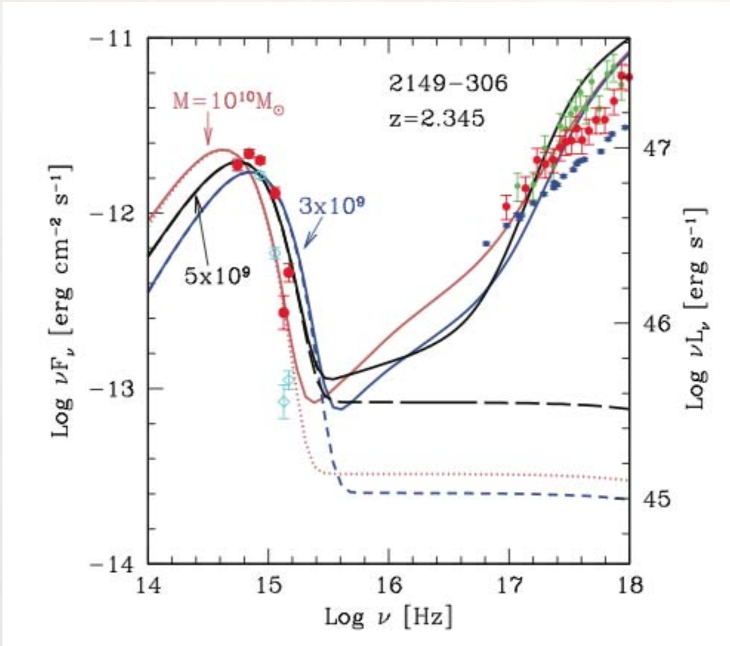


BH Mass Estimate (Ghisellini+10)

- Near-IR, Optical, UV interpreted as signature of the (SS) disk:
  → emits a black body spectrum at each radii

$$T_{\max} \propto \left(\frac{L}{L_{Edd}}\right)^{1/4} M^{-1/4}$$

$$L_{disk} = \eta \dot{M} c^2$$



Halo Mass Estimate (Volonteri+11)

- "Black-hole / dark-halo connection"
  - Stellar vel. Dispersion related to asymptotic circular velocity of galaxies (e.g. Baes+03)

$$\sigma = 200\,\mathrm{km\,s^{-1}} \left(\frac{V_c}{320\,\mathrm{km\,s^{-1}}}\right)^{1.35}$$

  - Haloes collapsing at redshift z have a circular velocity of :

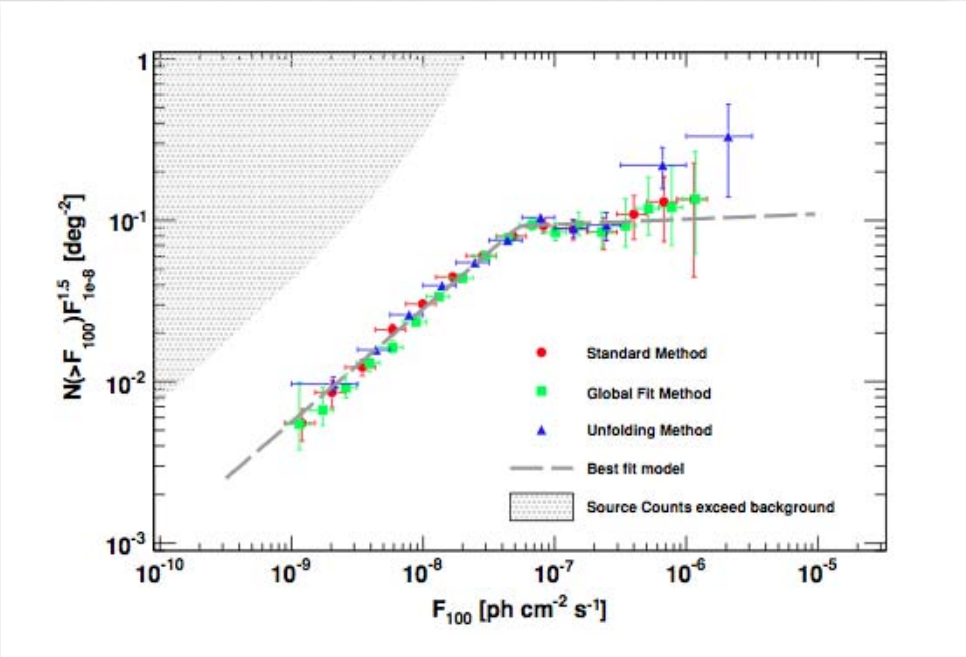
$$V_c = 142\,\mathrm{km\,s^{-1}} \left[\frac{M_h}{10^{12}\,M_\odot}\right]^{1/3} \left[\frac{\Omega_m}{\Omega_m^z}\frac{\Delta_c}{18\pi^2}\right]^{1/6} (1+z)^{1/2},$$

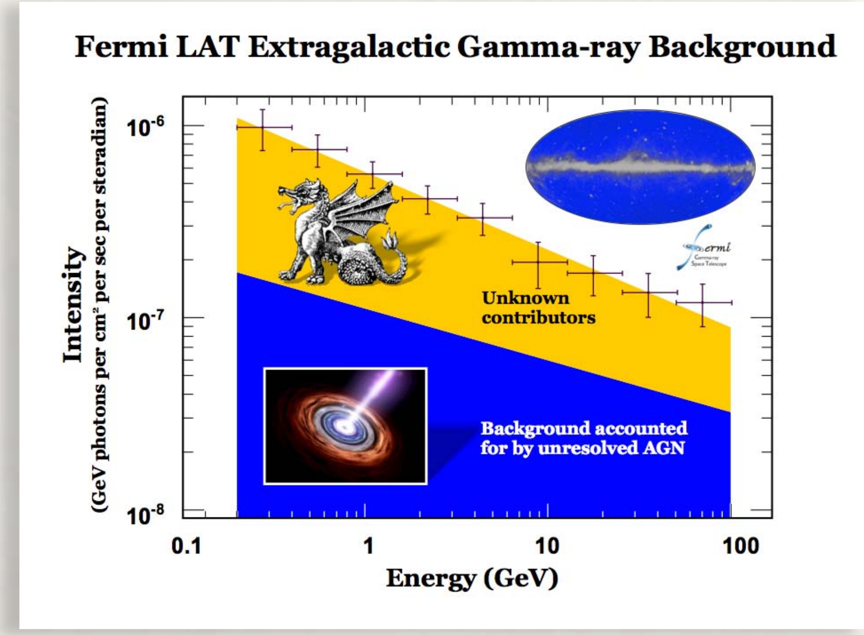
  - Assume M-sigma relation and combining yields:

$$M_{h,13} = 4.1\, M_9^{0.56} \left[\frac{\Omega_m}{\Omega_m^z}\frac{\Delta_c}{18\pi^2}\right]^{-1/2} (1+z)^{-3/2}$$

Contribution of Blazars to EGB

- Blazars represent 85-95 % of the sources detected at high Galactic latitude
- Nevertheless they account for <30-40% of the EGB





Abo+10, ApJ, 720, 435

The Blazars Population

Fermi Gamma-ray Space Telescope

- Blazars potentially represent 85-95% of the high-latitude populations
- How to quantify their diffuse emission ?
  - Derive luminosity function and integrate
  - Derive logN-logS and integrate
- Select a 'clean' sample (TS>50, |b|>20°)
- To quantify selection effects 18 MC simulations were performed:
  - Receipt (e.g. Hasinger+93, Cappelluti+07):
    - Use up to date diffuse models and add a realistic source population

Abdo+10, ApJ 72x0, 435

CLASS	# objects
Total	425
FSRQs	161
BL Lacs	163
Uncertain[a]	4
Blazar Candidates	24
Radio Galaxies	2
Pulsars	9
Others[b]	6
Unassociated sources	56

[a]Blazars with uncertain classification.

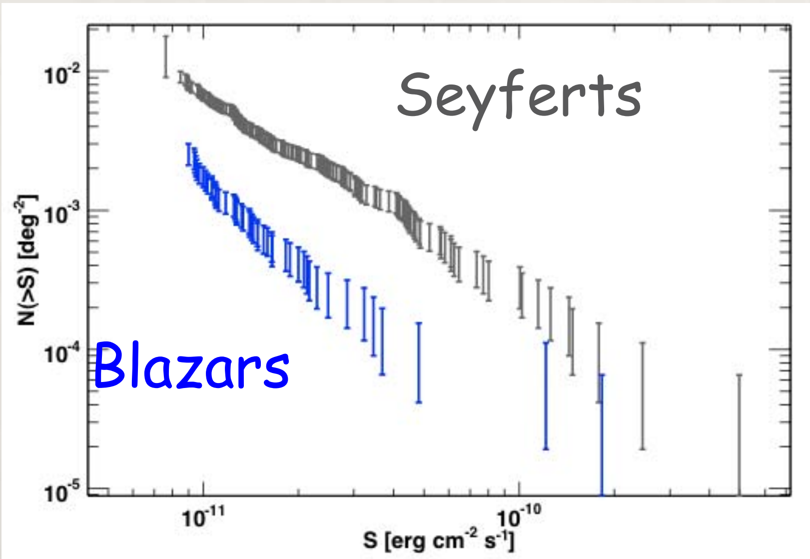
[b]It includes Starburst galaxies, Narrow line Seyfert 1 objects and Seyfert galaxy candidates.

- **Detection:**
  - Perform detection step as close as possible to real data (Abdo+09, ApJS 183, 46)
  - Use Maximum Likelihood to determine spectral parameters and significance

Tests of Evolution

- Evolution already implicit in the density of high-z FSRQs detected by BAT

Sample	$\langle V/V_{MAX} \rangle$	β[a]
Seyferts	0.509 ± 0.021	1.496 ± 0.073
BLAZARs	0.666 ± 0.045	1.932 ± 0.206
FSRQs	0.728 ± 0.056	2.077 ± 0.269
BL Lac objects	0.576 ± 0.083	1.694 ± 0.316

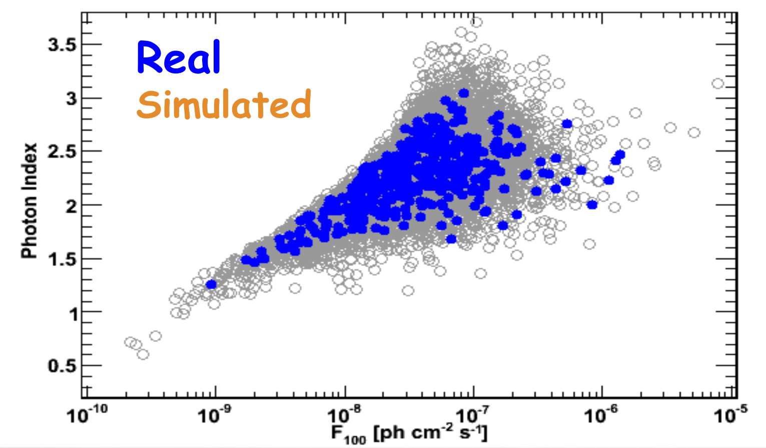


1. Blazars evolve positively at ~3σ

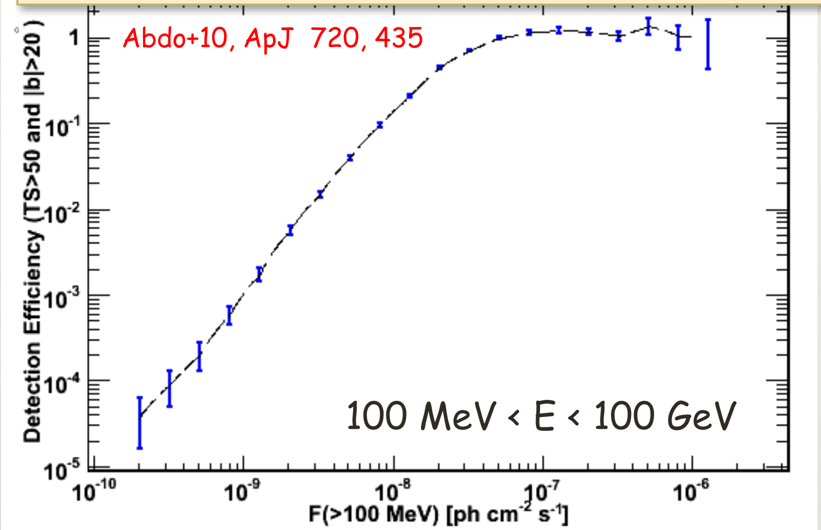
- No significant difference between the 2 sub-classes
- Seyferts 'do not' evolve

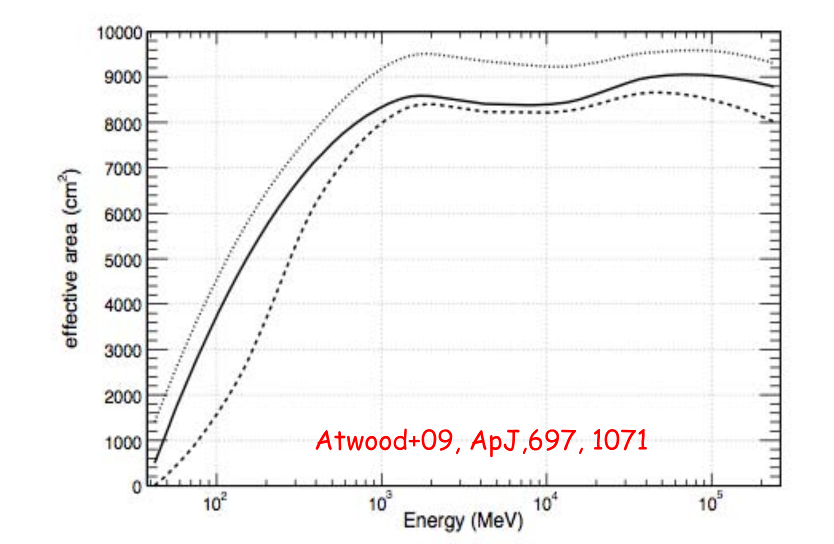
2 words on selection effects

- *Fermi* preferentially selects hard-faint sources
- Selection effects of a survey are *similar* to those of an instrument (e.g. effective area):
  - The survey does not have enough area to detect all the faintest sources
  - The instrument does not have enough area to detect all the low energy photons



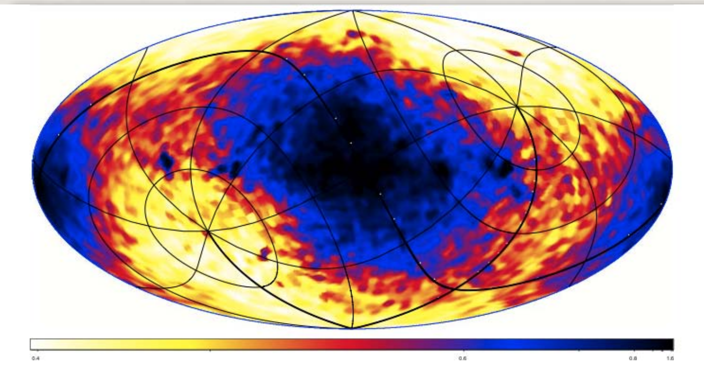
Detection Efficiency

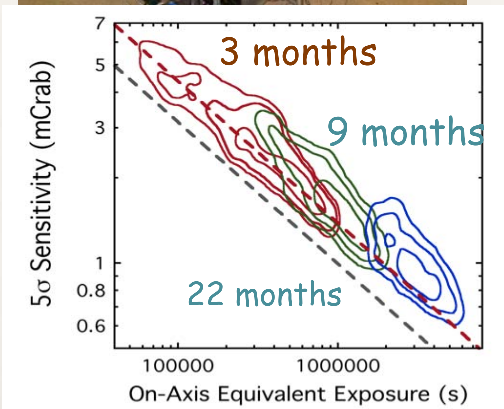




The Swift/BAT all-sky survey

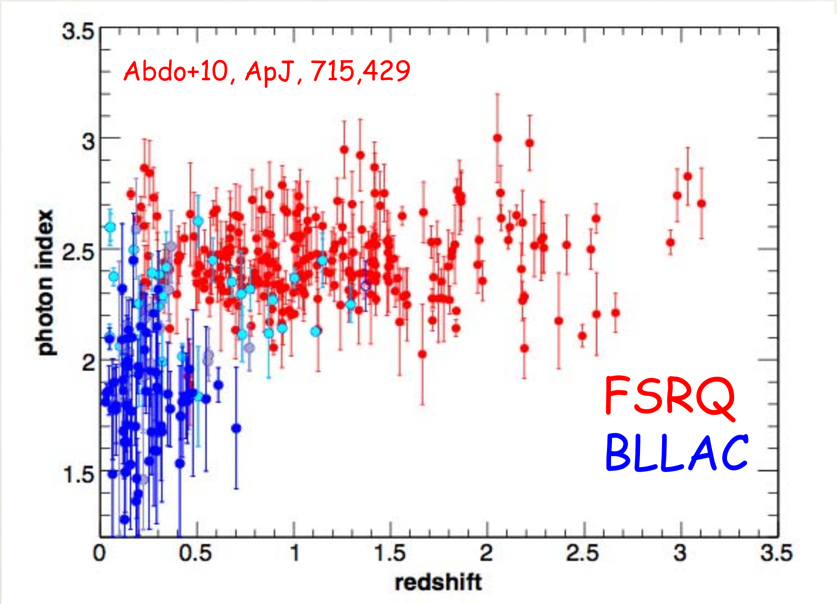
* BAT is a coded-mask wide FoV instrument which surveys 80% of the sky every day
* BAT reaches 1mCrab (e.g. 1e-11 cgs) in 1Ms
* After 6 years:
  * exposure is >10 Ms everywhere
  * ~1000 sources (I think nobody believed it)
  * ~70% are extragalactic
  * ~30% are Galactic
* Results reported in: Ajello+08a,b,c,09a,b Tueller+, Cusumano+09,+10

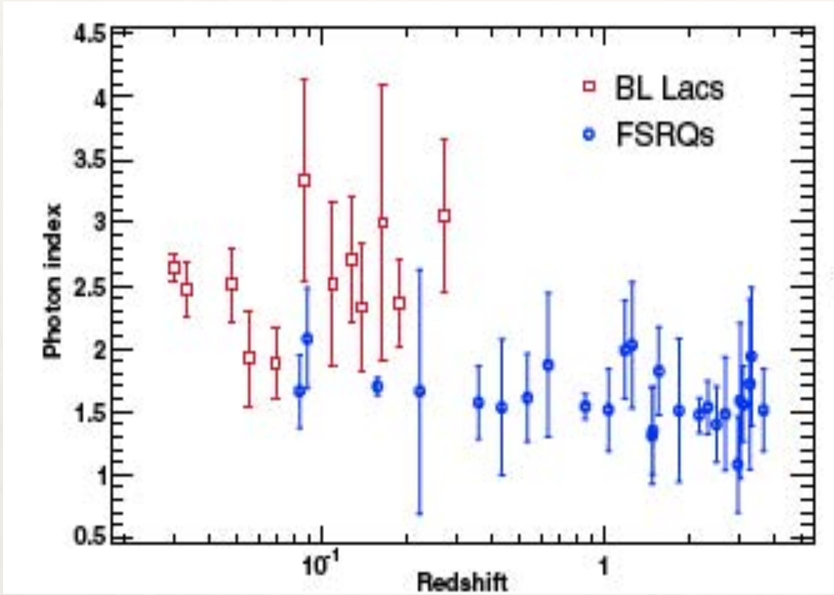




Ajello+09,ApJ 699, 603

The BAT 3yr Sample

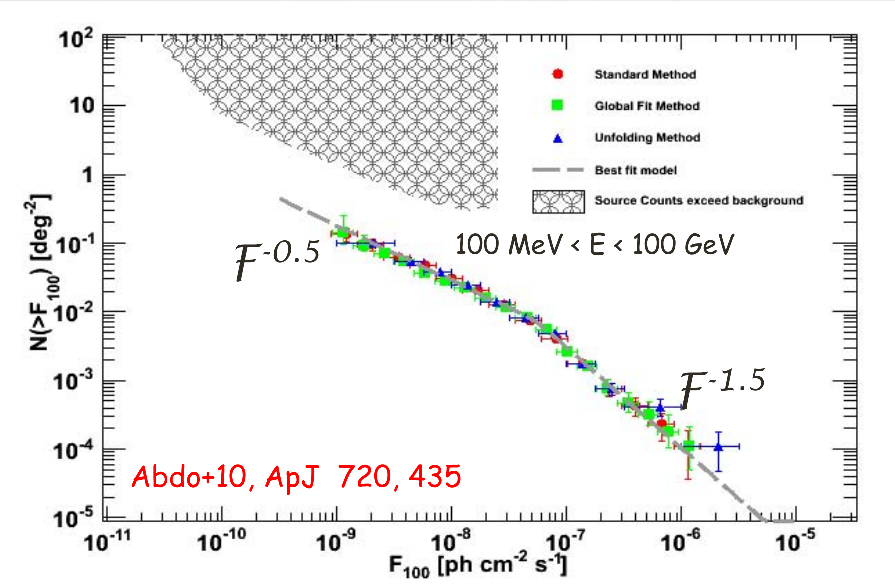


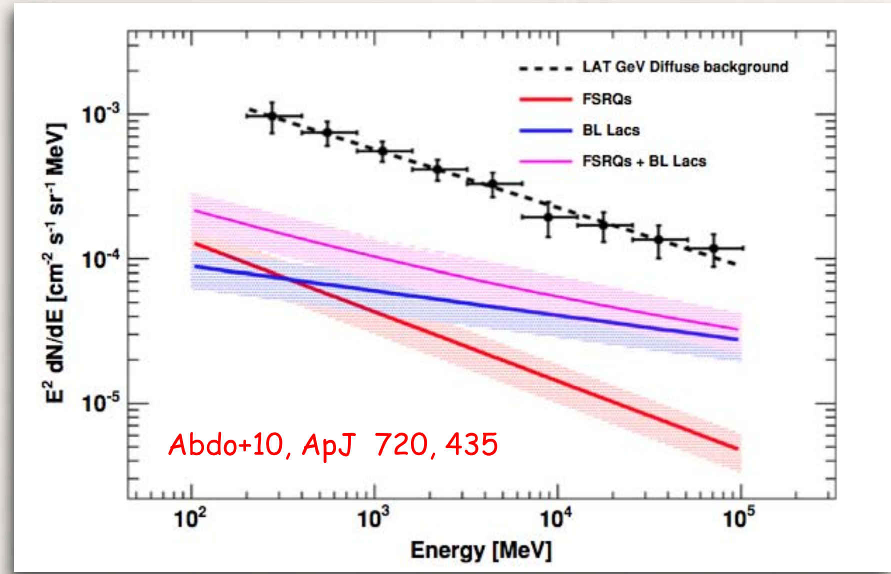


- 38 blazars (26 FSRQs, 12 BL Lacs) detected up to z~4
- Only ~30% are in common with with EGRET/LAT
- No blazars at low L_X and low redshift

The logN-logS of point sources

- Used 3 methods to build source count distribution in the 0.1-100 GeV band
- Compatible with Euclidean at bright fluxes: N(>F) ~ $F^{-3/2}$
- It is flatter below $F_{100} \approx 5\times10^{-8}$ ph cm^{-2} s^{-1}
- Blazars account for <30-40% of the EGB





Pure Luminosity Evolution

* "Best-fit Pure Luminosity Evolution (PLE)"

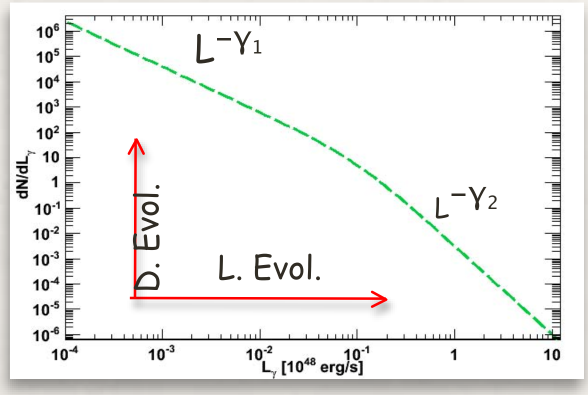
Local Luminosity Function

Evolutionary Factor

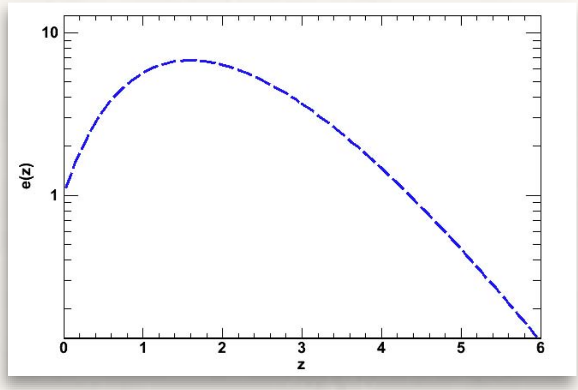
Luminosity Function

$$\Phi(L_\gamma, z) = \Phi(L_\gamma/e(z), z=0)$$

=



+



$$\Phi(L_\gamma, z=0) \propto \left[\left(\frac{L_\gamma}{L_*}\right)^{\gamma_1} + \left(\frac{L_\gamma}{L_*}\right)^{\gamma_2} \right]^{-1}$$

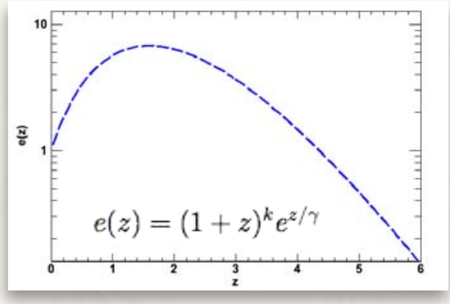
Typical double power law

$$e(z) = (1+z)^k e^{z/\gamma}$$

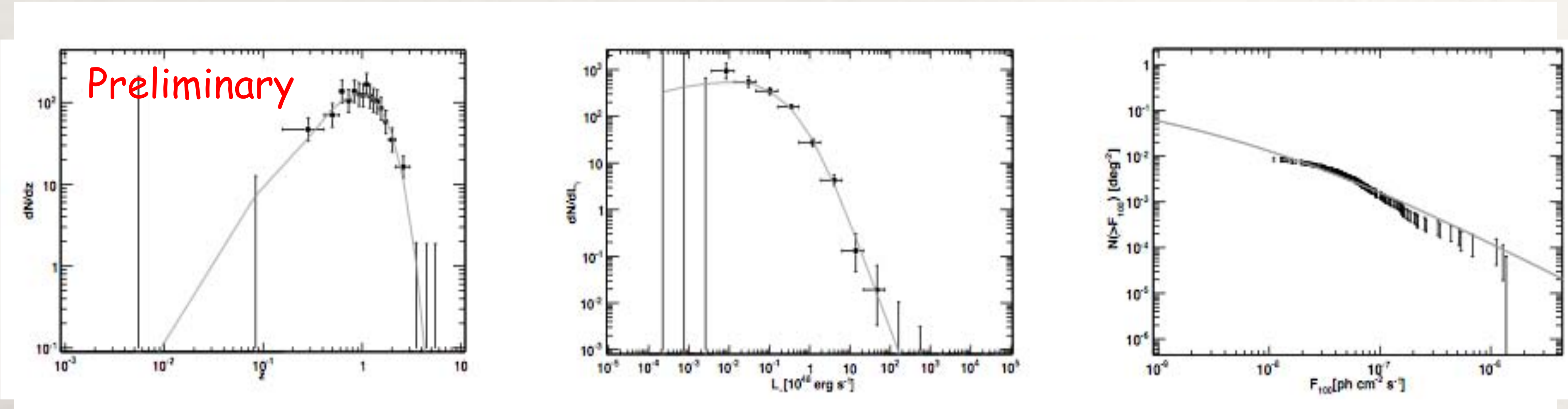
Evolution in luminosity as a power-law with index k and a cut-off after z_{cut}=-1-kγ

Results PLE

- PLE (7 pars) provides a reasonably good fit to the data
- It implies:
  - Strong evolution in luminosity of FSRQ (k=5.6)
  - A cut-off in the evolution after z = ~1.6

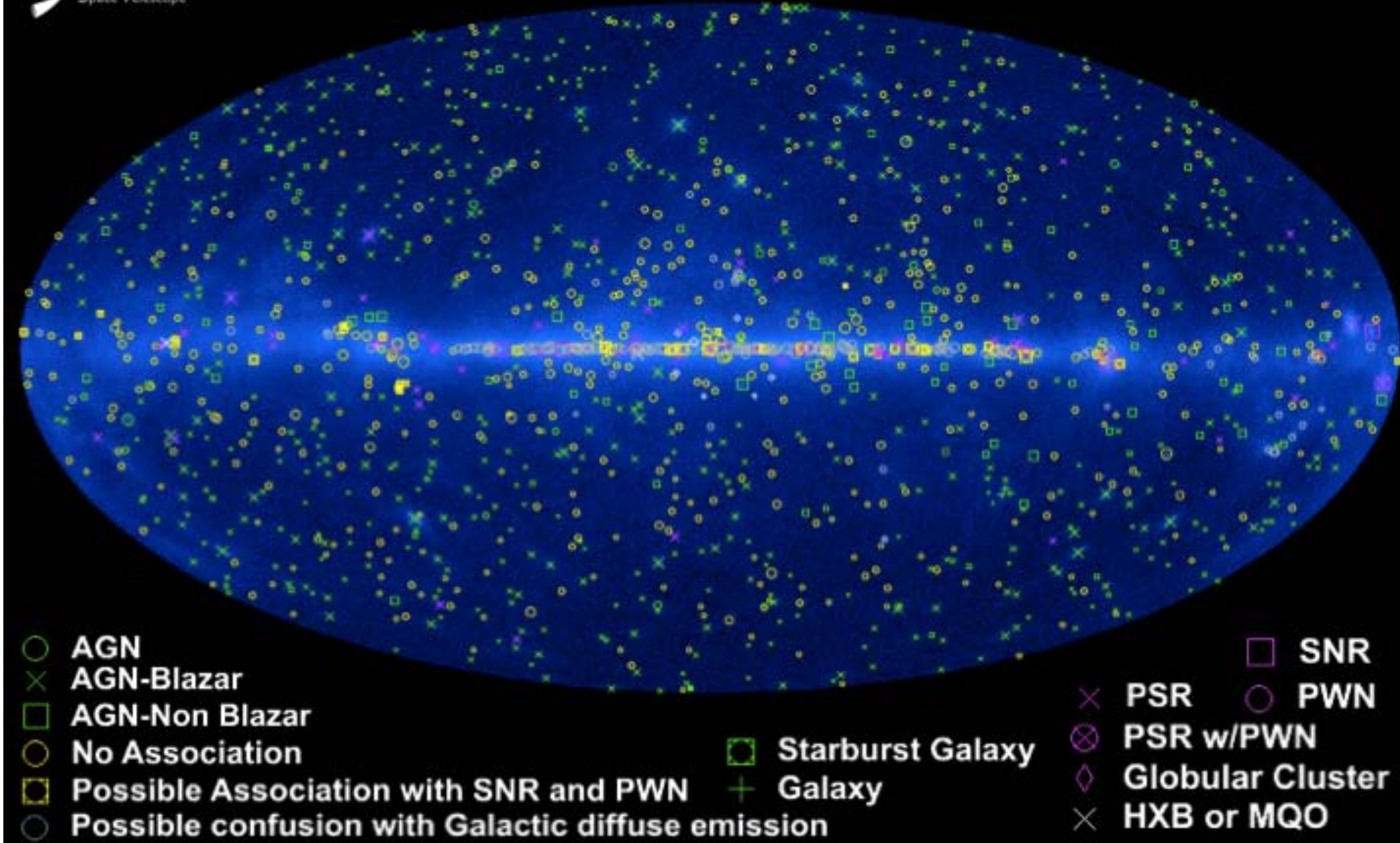


- 2 findings:
  - PLE does not reproduce the source counts very well
  - There are hints that the redshift cut-off changes with luminosity



The Fermi LAT 1FGL Source Catalog

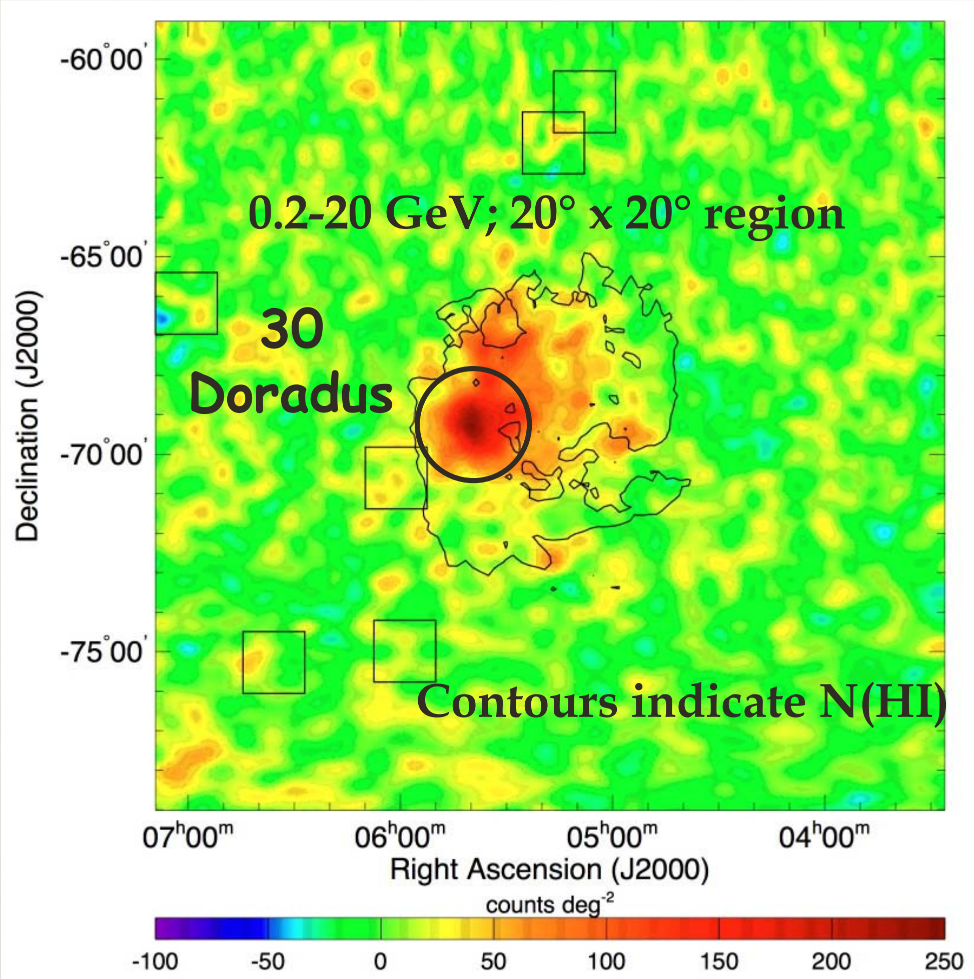
1,451 sources



Credit: *Fermi* Large Area Telescope Collaboration

Abdo, A. A. et al. 2010, A&A, 512, A7

Spatially Resolved LMC



Background-subtracted smoothed residual counts map of the LMC region

* Diffuse emission peaking in massive star-forming region 30 Doradus
* Gamma-ray emission correlates with ***ionized*** gas (1% by mass) rather than with ***total*** gas density
* Cosmic-ray diffusion length small compared to size of LMC