Cosmological Evolution of Blazars

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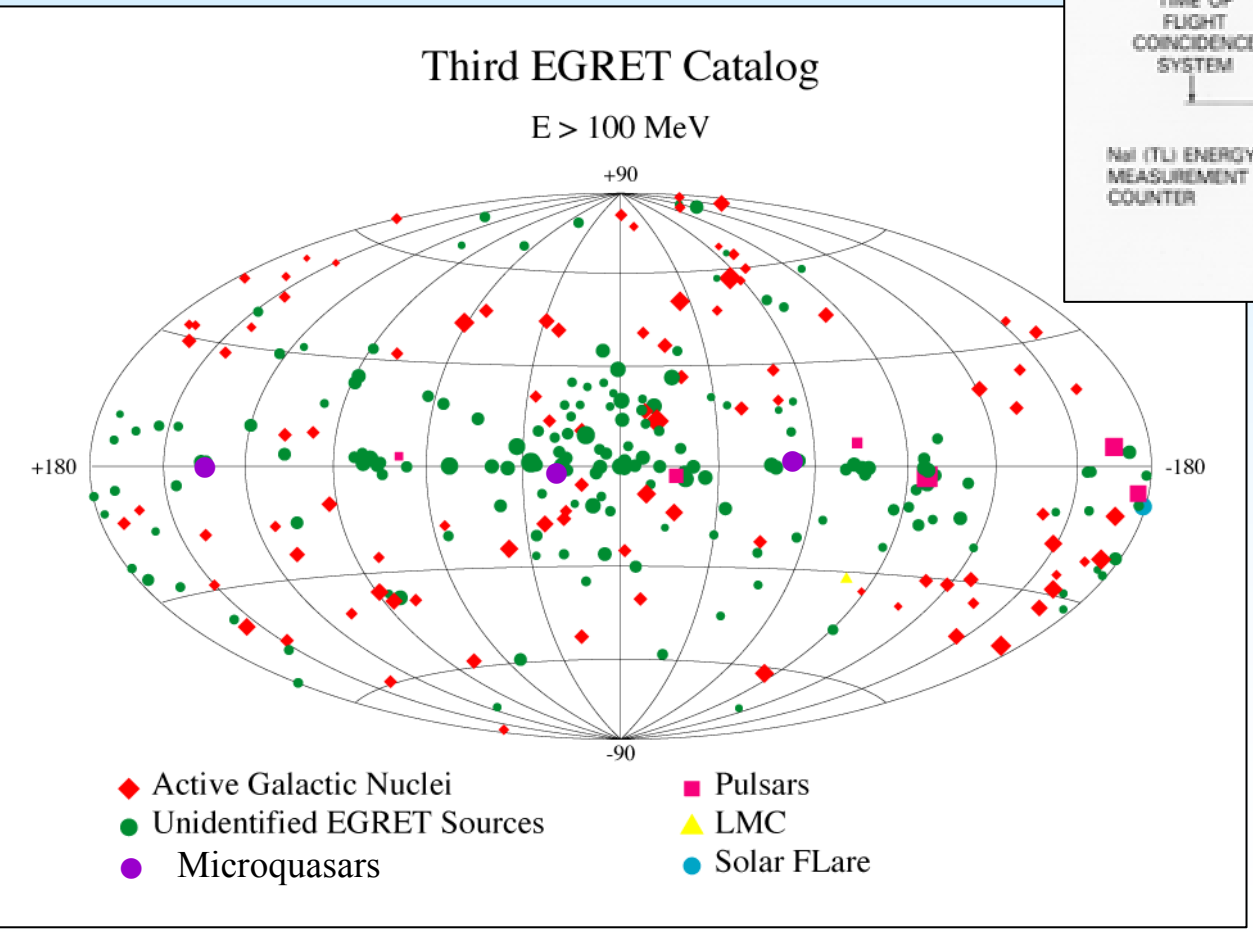
"The impact of high energy astrophysics experiments on cosmological physics"
Kavli Institute for Cosmological Physics
University of Chicago
October 28, 2008

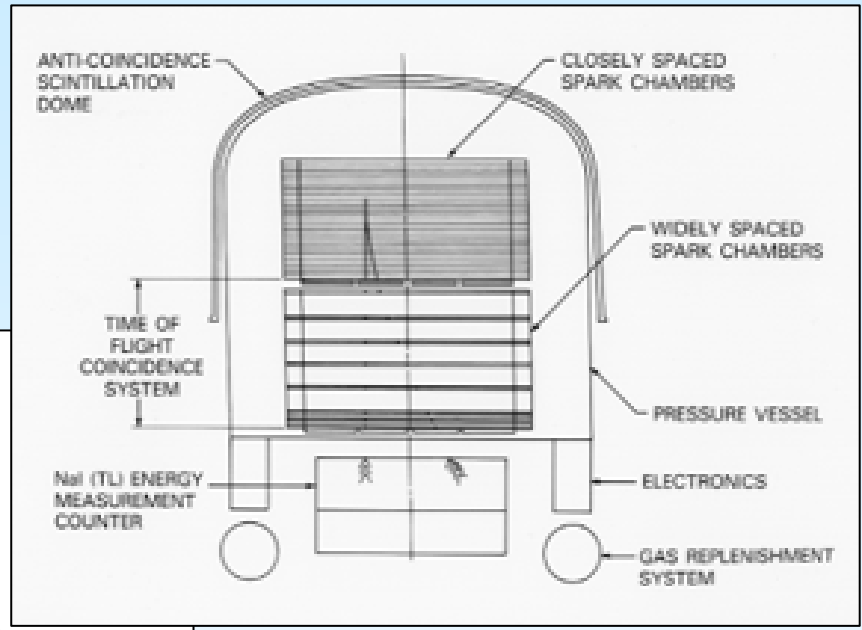
1. EGRET blazar model statistics $\Rightarrow$ predictions for Fermi
2. Unresolved/diffuse extragalactic γ-ray background
3. UHECRs from radio galaxies and blazars

EGRET Legacy

3EG catalog: 270 sources, 66 high confidence blazars Hartman et al. (1999)
(Cen A)



EGRET



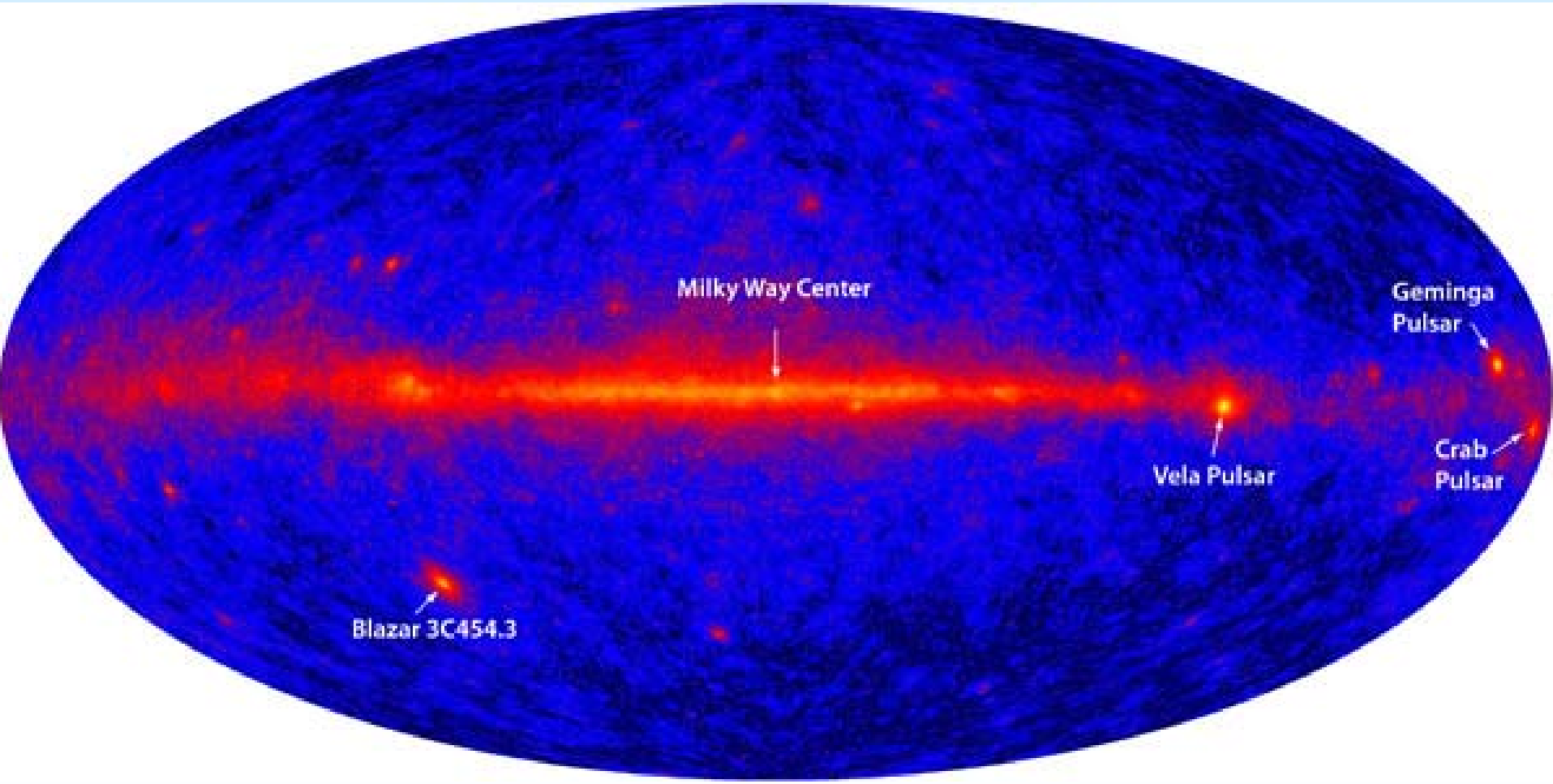
Ground γ Telescopes

> 25 TeV/XBL blazars

1 radio galaxy: M87

Fermi First Light Image

3.1 days/74 hours

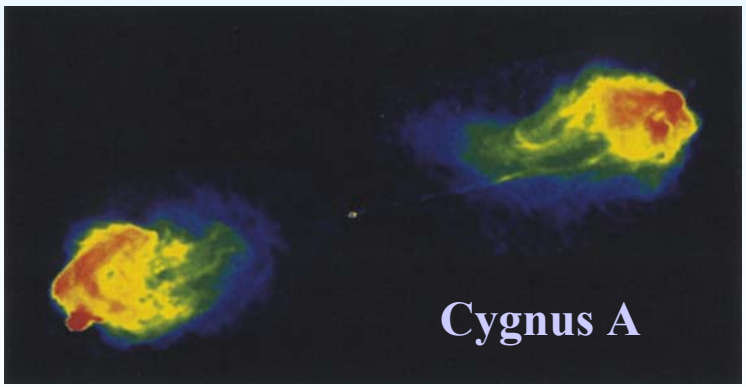


Unification of Radio Galaxies and Blazars

Urry and Padovani (1995)

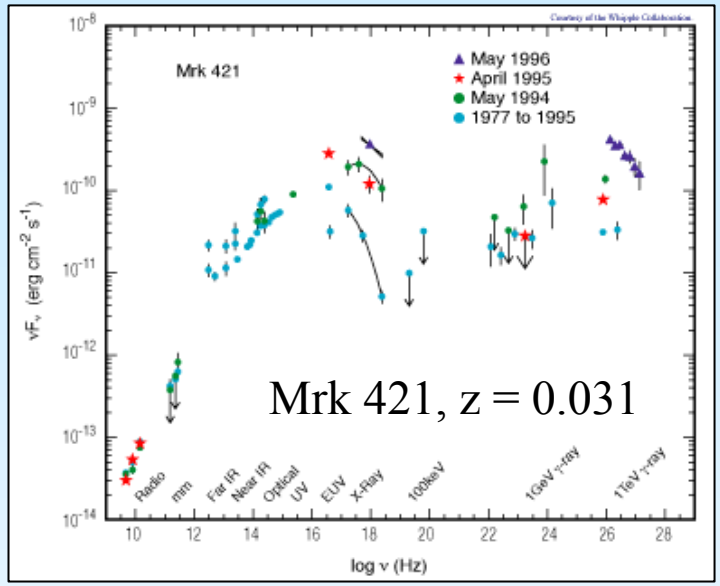
Fanaroff-Riley Classification:
Morphology correlates with radio power at 2×10^{25} W/Hz at 178 MHz ($\cong 4 \times 10^{40}$ ergs s^{-1}), or total radio power of $\cong 10^{42}$ ergs s^{-1}

Optical emission lines in FR IIs brighter by an order of magnitude than in FR Is for same galaxy host brightness

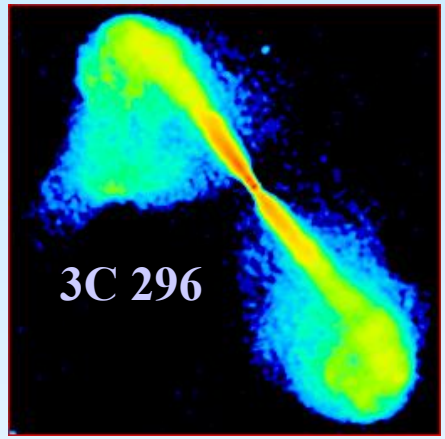


FR II: high luminosity, lobe dominated

$L \sim 5 \times 10^{48} \times (f/10^{-9}$ ergs cm^{-2} $s^{-1}) ergs\ s^{-1}$



FR I: low luminosity, twin jet sources



$L \sim 10^{45} \times (f/10^{-10}$ ergs cm^{-2} $s^{-1}) ergs\ s^{-1}$

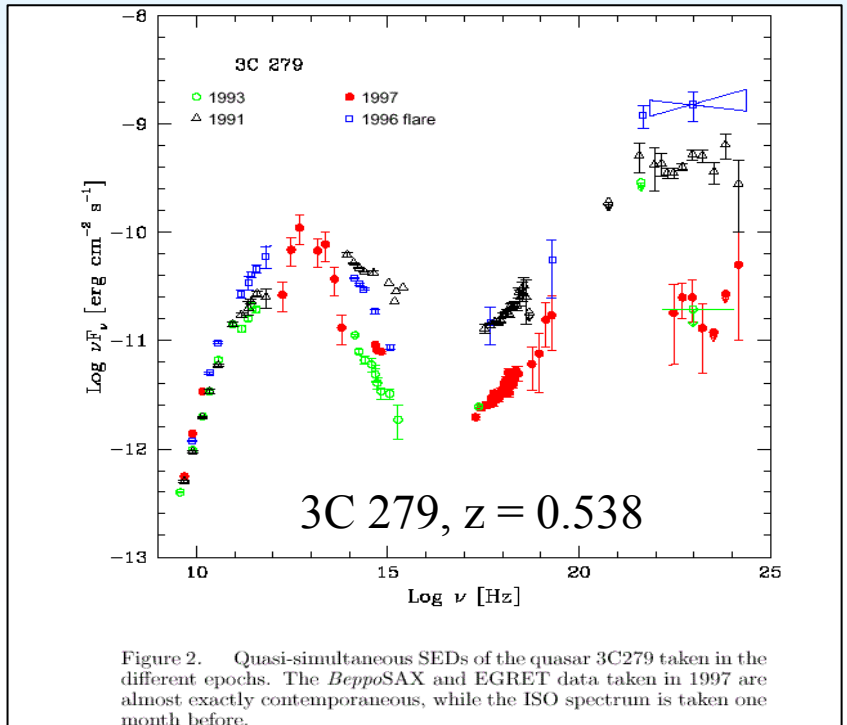


Figure 2. Quasi-simultaneous SEDs of the quasar 3C279 taken in the different epochs. The *Beppo*SAX and EGRET data taken in 1997 are almost exactly contemporaneous, while the ISO spectrum is taken one month before.

Blazar Population Studies

1. (Parent) Population Studies of Beamed Sources
2. Density and Luminosity Evolution
3. V/Vmax test (Chiang et al. 1995; Chiang & Mukherjee 1998)
   requires luminosity evolution
4. Radio/γ-ray Correlation (Stecker & Salamon 1996; 2001)
   ~100% of DEGRB; 10000 blazars after 5 years with Fermi
5. Radio/γ-ray correlation questioned (Mücke et al. 1997)
6. γ-ray-only treatment of statistics (Mücke & Pohl 2000)
   Density evolution given only by z_{max}
7. Treatment employing density and luminosity evolution
   (Dermer 2007)
8. Treatment based on blazar main sequence
   (Inoue & Totani 2008)

γ-Rays, EGRET and Fermi/GLAST

γ Ray flux measured in units of ϕ_{-8} [10^{-8} ph(>100 MeV) cm^{-2} s^{-1}]

($\phi_{-8} = 1 \leftrightarrow \approx 7 \times 10^{-12}$ ergs cm^{-2} s^{-1} for a flat νF_ν spectrum)

EGRET: $\phi_{-8} = 15$; on-axis 2-week pointing, 1/24th full sky (background limited)

($\approx 10^{-10}$ ergs cm^{-2} s^{-1})

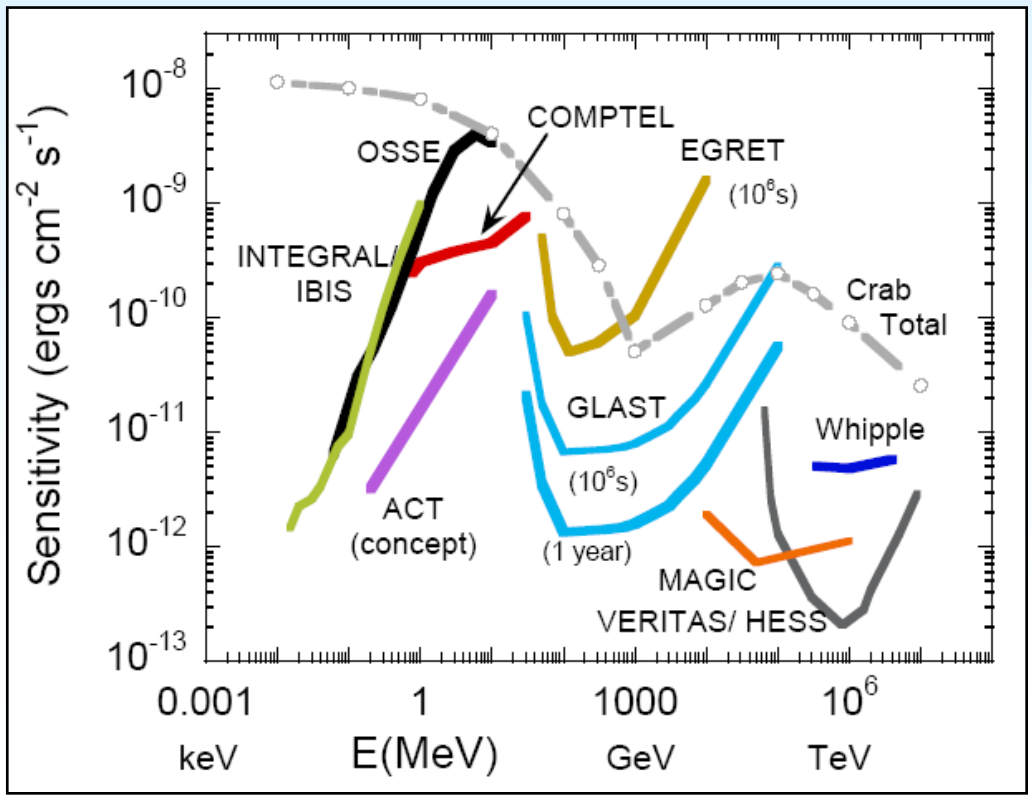
Fermi/GLAST: $\phi_{-8} = 15$ in 1 – 2 days, full sky (signal limited)

$\phi_{-8} = 0.4$ in 1 year, full sky (background limited)

($\approx 10^{-12}$ ergs cm^{-2} s^{-1})

More sensitive to weak hard-spectrum than soft-spectrum sources

Sub-hour scale variability when $\phi_{-8} > 200$ (>10^{-9} ergs cm^{-2} s^{-1})

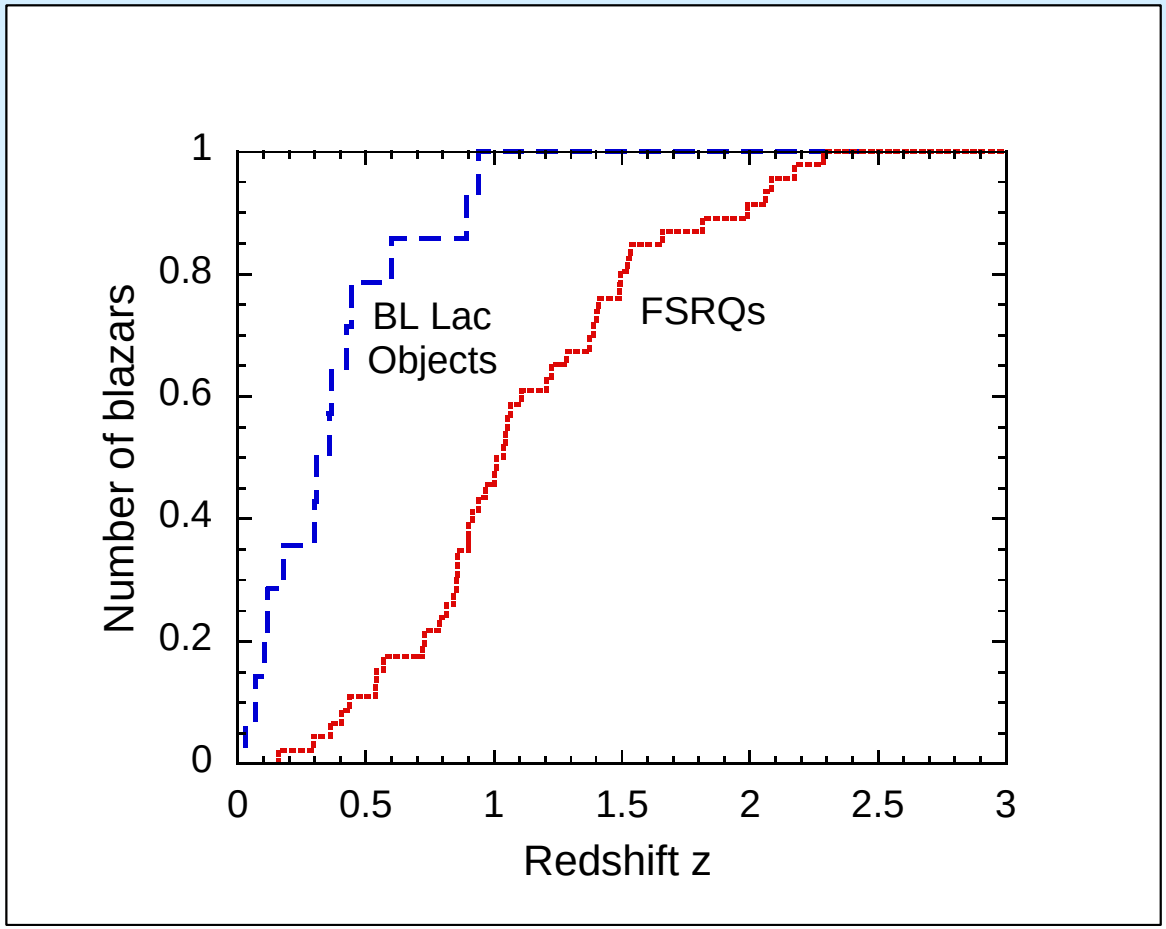


Blazar Statistics

Redshift Distribution of EGRET γ-Ray Blazars

Uniform exposure:
EGRET all-sky survey
Fichtel et al. (1994):
1EG catalog

EGRET blazar sample:
46 FSRQs
14 BL Lac Objects

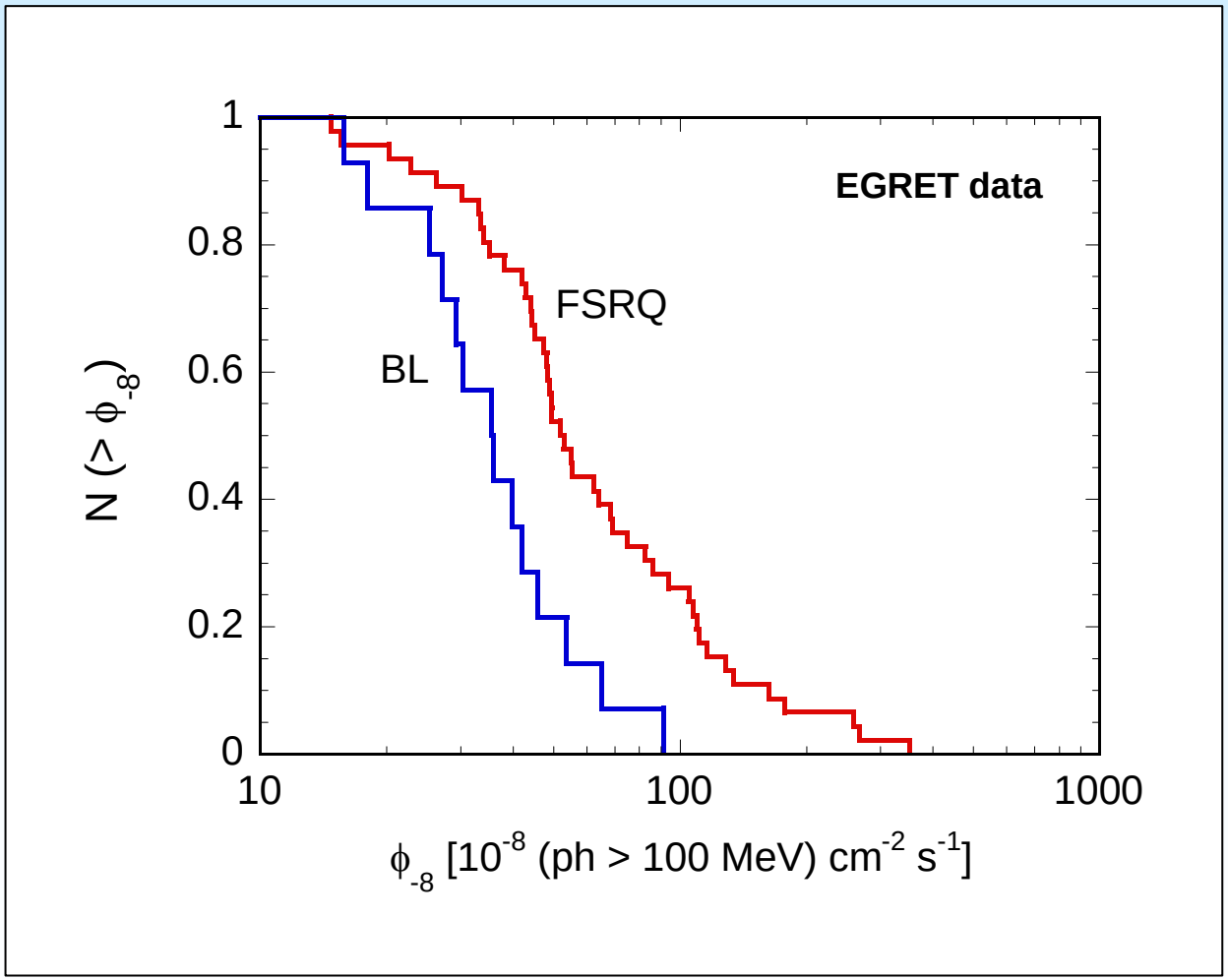


Size Distribution of EGRET γ-Ray Blazars

Two-week on-axis sensitivity of EGRET:

≈ 15x10^{-8} ph(>100 MeV) cm^{-2} s^{-1}

≈ 10^{-10} erg cm^{-2} s^{-1} (100 MeV – 5 GeV)



Blazars: the Platonic Ideal

Basic Radiation Physics:

$$\nu F_\nu = f_\varepsilon \; (ergs\ cm^{-2}\ s^{-1})$$

Threshold condition:

$$f_\epsilon^{proc} = \frac{\ell'_e \delta_D^q \epsilon_z^{\alpha_\nu}}{d_L^2(z)} \geq f_\epsilon$$

Telescope sensitivity

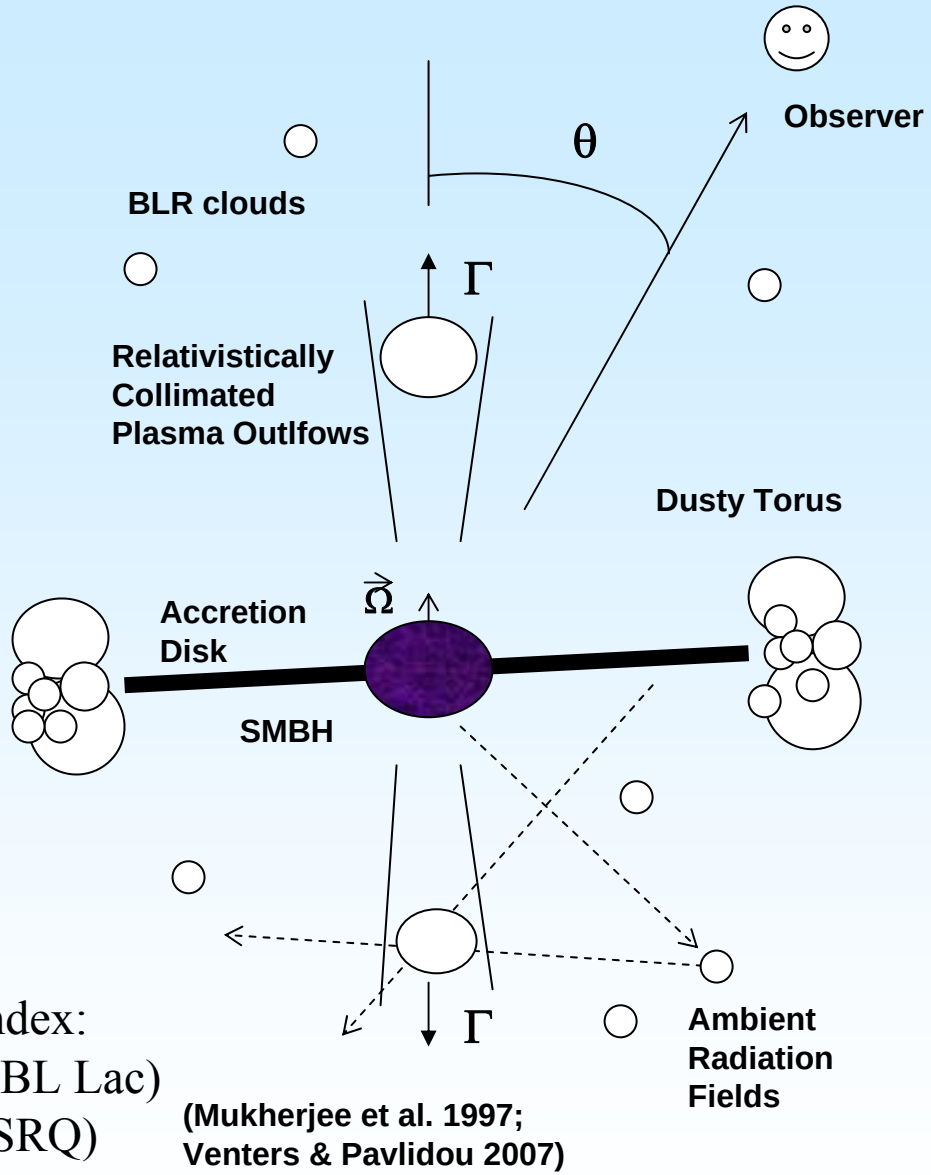
$$\varepsilon_z = (h\nu / m_e c^2)(1+z)$$

$$\delta_D = [\Gamma(1-\beta\mu)]^{-1}, \alpha_\nu = (3-p)/2$$

comoving directional luminosity

$$\ell'_e \; (ergs\ s^{-1}\ sr^{-1})$$

Spectral index:
α_ν = -0.2 (BL Lac)
= 0 (FSRQ)



(Mukherjee et al. 1997; Venters & Pavlidou 2007)

1. synchrotron/SSC
2. external Compton

$$q = \begin{cases} (p+5)/2, & \text{synchrotron/SSC} \quad \text{(BL Lac)} \\ p+3 & \text{EC} \quad \text{(FSRQ)} \end{cases}$$

(Dermer 1995)

Statistics of Blazars: Redshift and Size Distribution

Model redshift and size distributions of EGRET blazars

local rate density

BFR
Blazar Formation Rate

$$\frac{d\dot{N}_{bl}}{d\Omega}(>f_\epsilon) = 2c\dot{n}_{bl}\int_0^\infty dz\,|\frac{dt_*}{dz}|\,\frac{d_L^2(z)\Sigma_{bl}(z)}{(1+z)^2}$$

$$\times\int_1^\infty d\Gamma\; N(\Gamma;z)\int_0^\infty d\ell'_e\; N(\ell'_e;z)\;[1-\max(-1,\hat{\mu})]$$

Γ-factor evolution

luminosity evolution

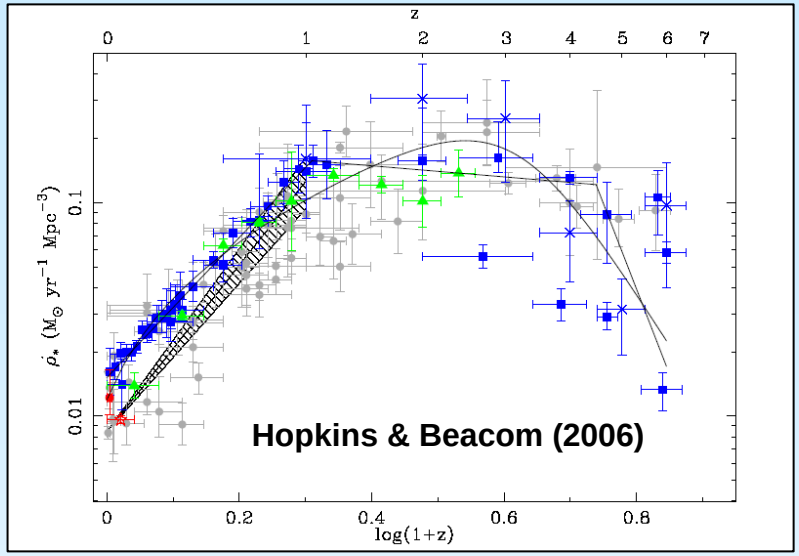
threshold term

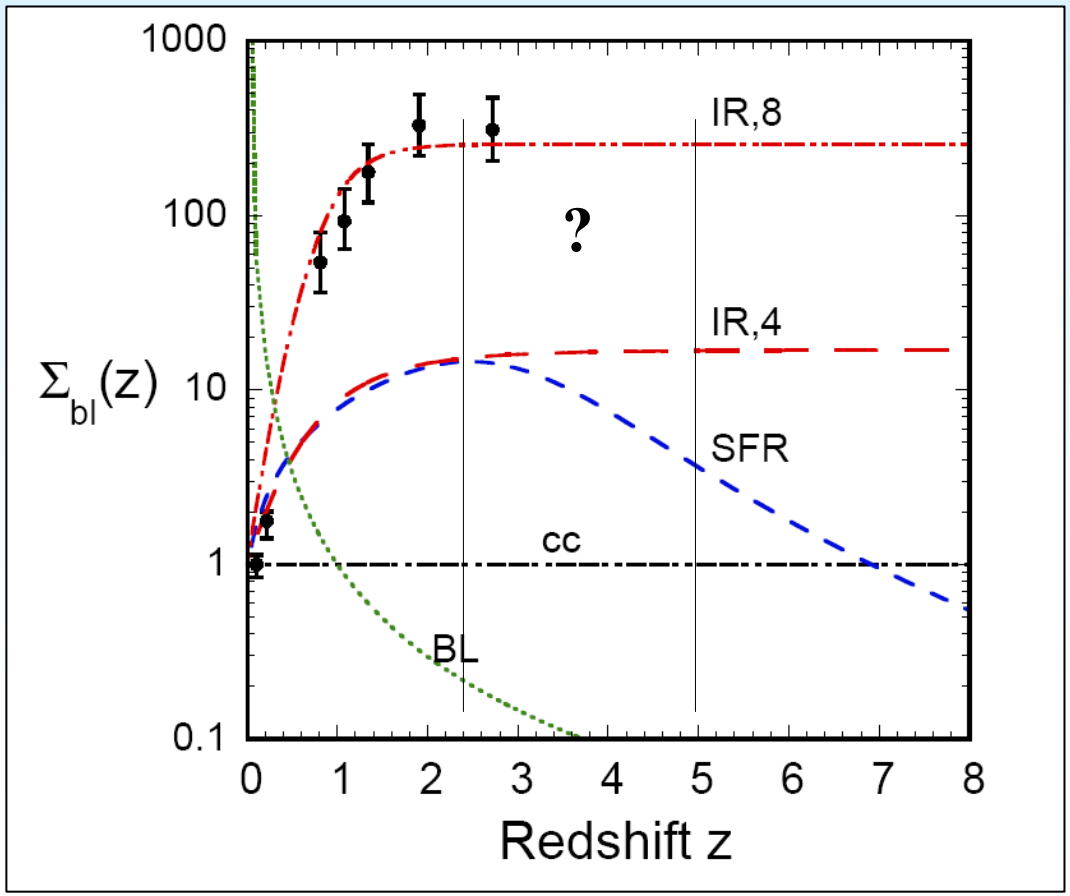
Simplest model: fixed Γ, fixed ℓ'_e (no luminosity evolution; luminosity function due to kinematic effects only)

Use analystic Blazar Formation Rate

Blazar Cosmology

1. Comoving Density (or Rate Density) Evolution
2. Luminosity Evolution





Blazar Formation History (BFH)

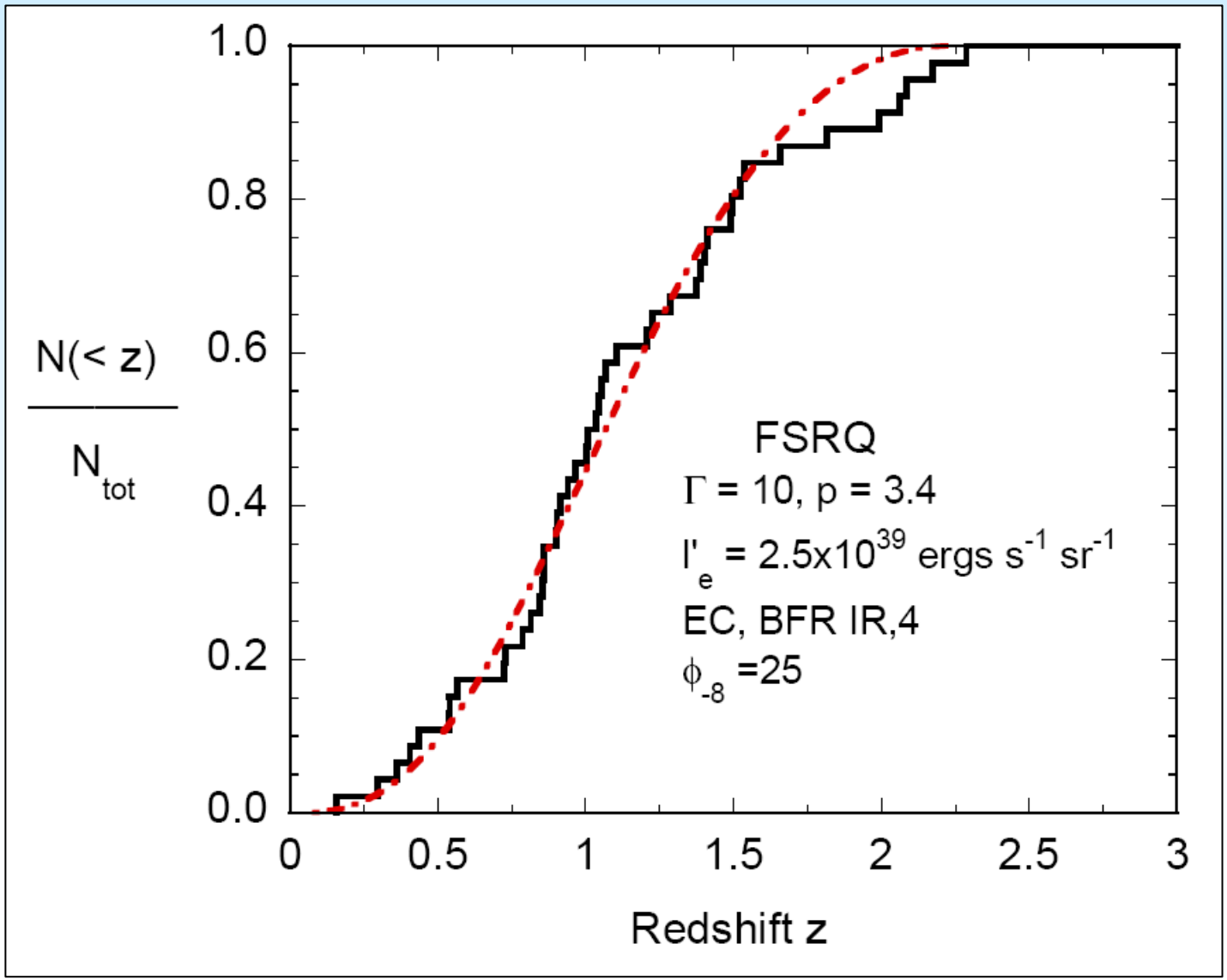
Constant Comoving Rate

Star Formation Rate (SFR)

IR,8 (Sanders 2004)

SFH BL

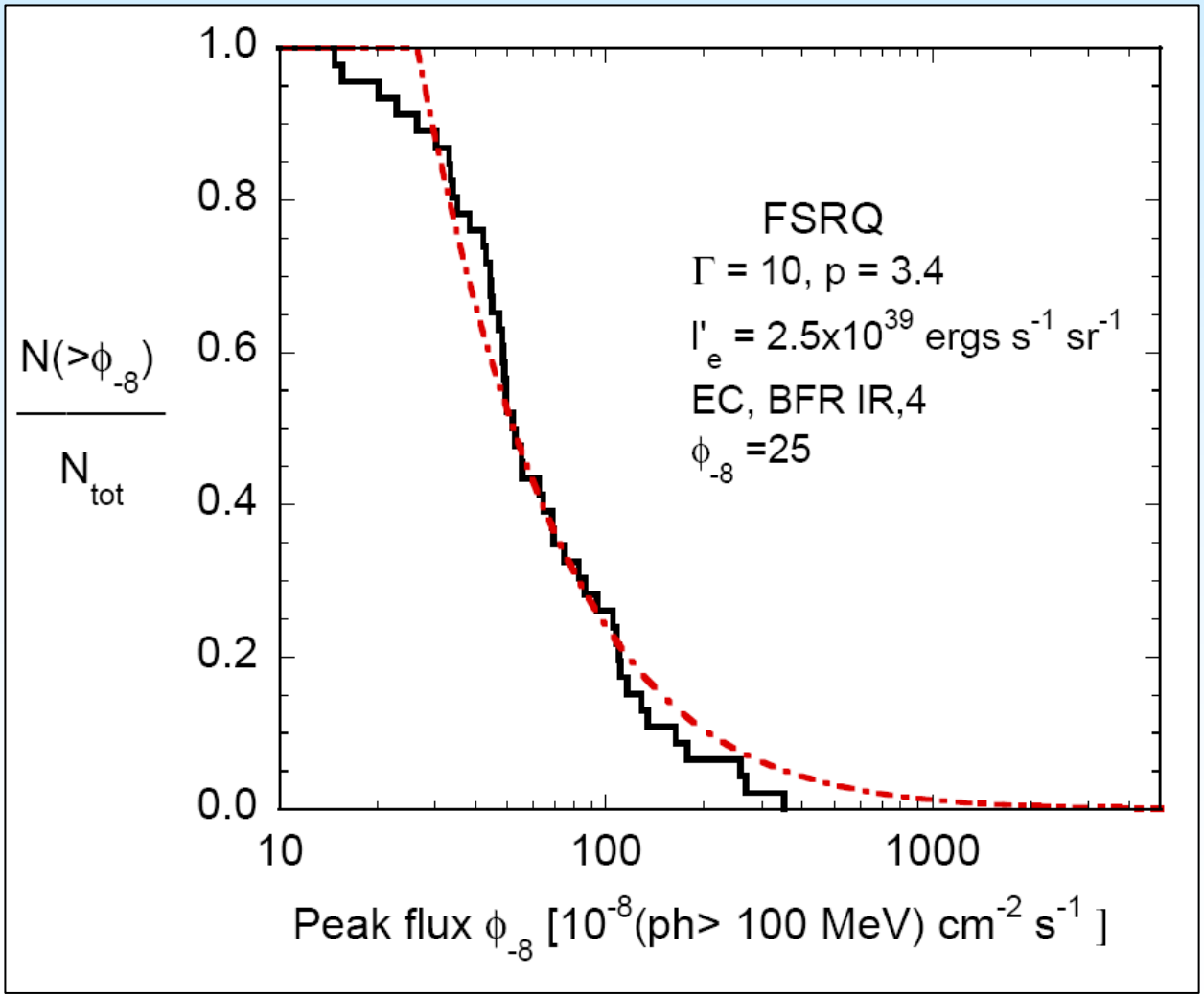
Fit of FSRQ Model to Redshift Distribution



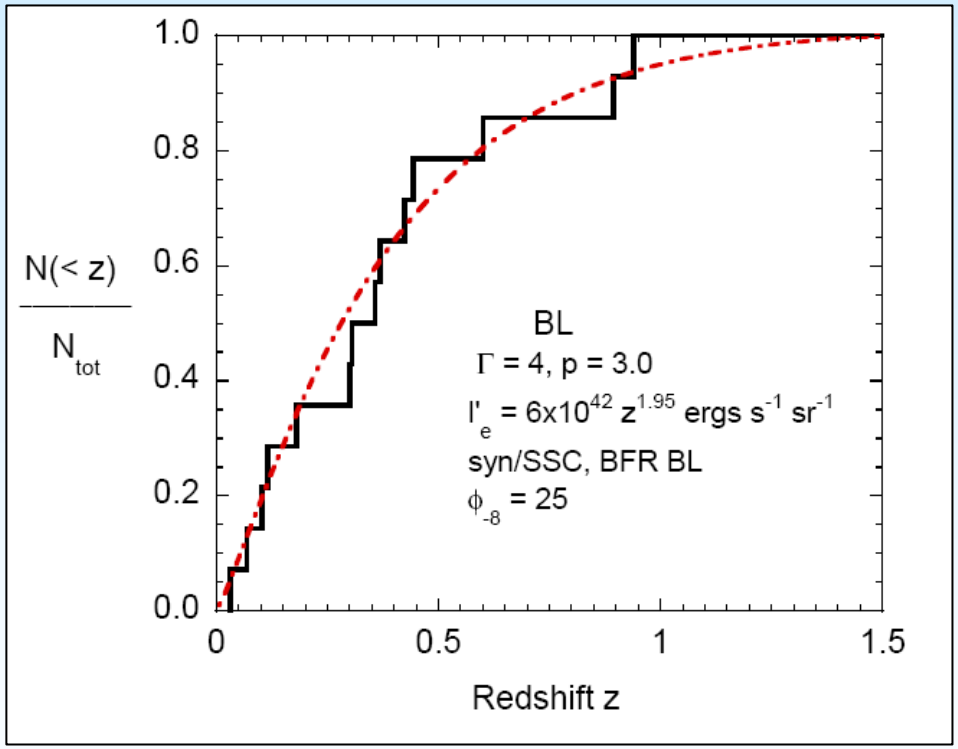
Mono-parameter L_* Blazar

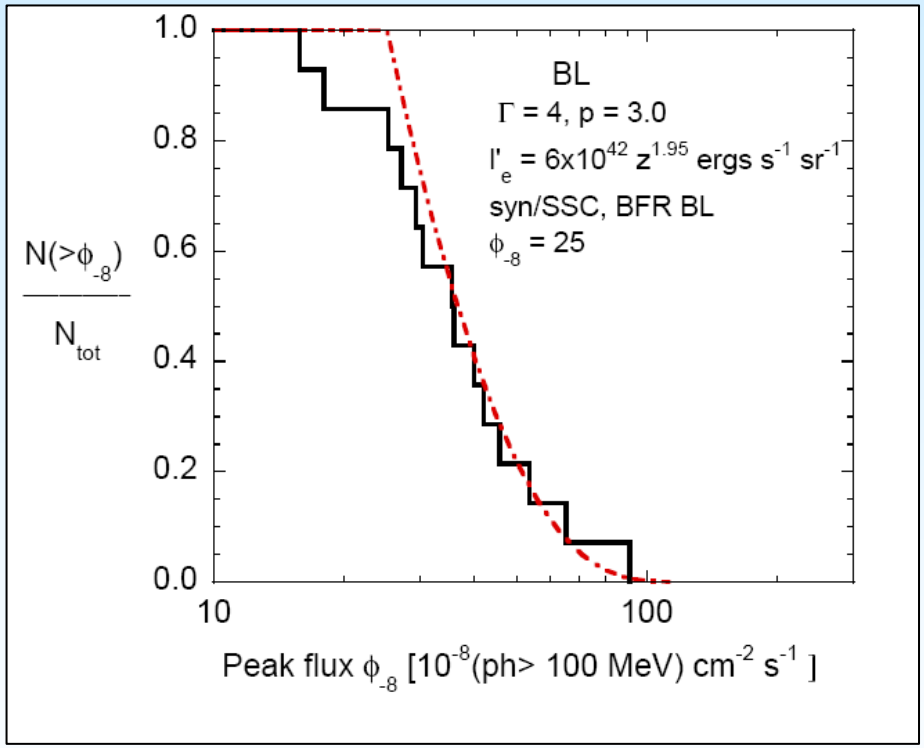
SFR IR,4

Size Distribution of Model FSRQ



Redshift and Size Distributions of BL Lac Objects

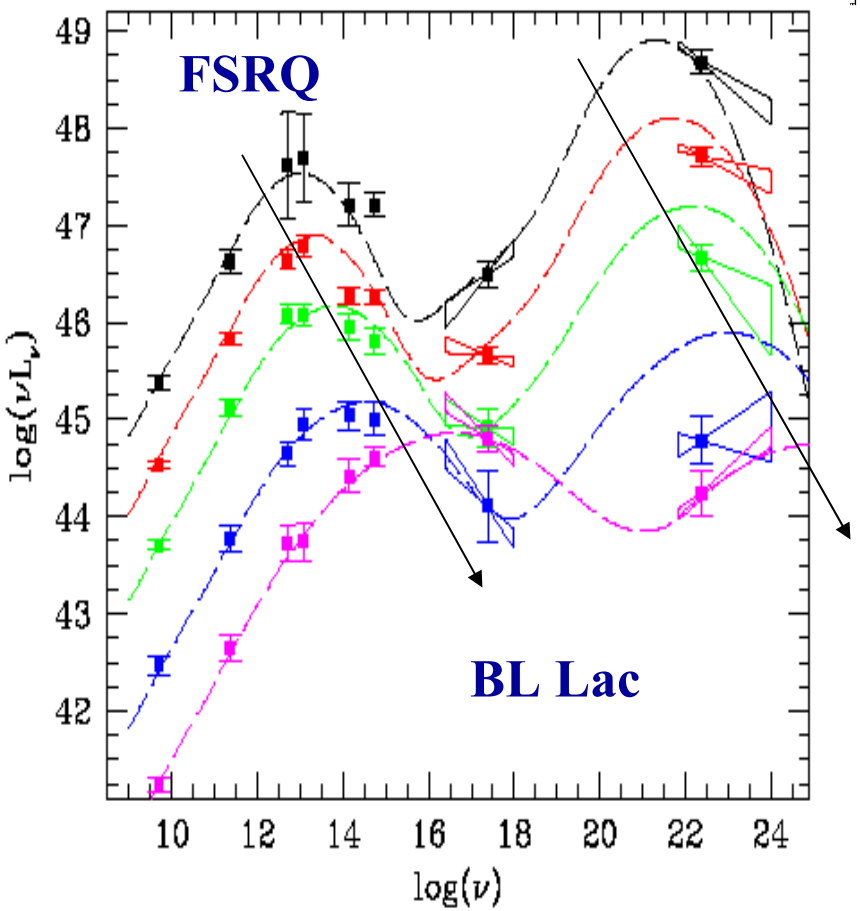




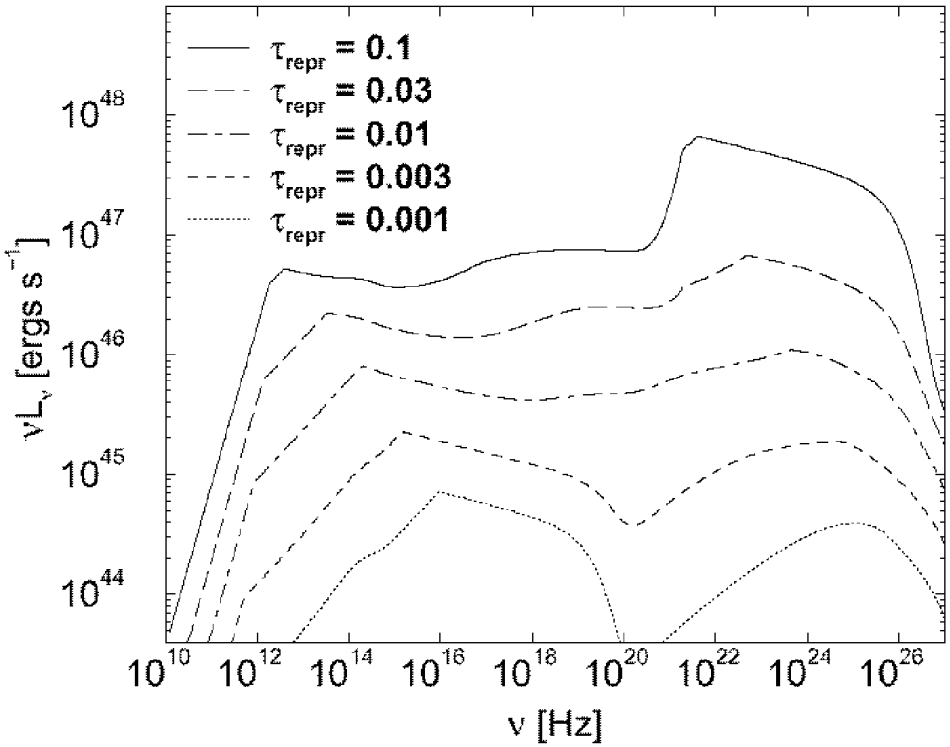
Require negative density evolution (fewer BL Lacs at early times)

Positive luminosity evolution (brighter at early time)

Blazar Main Sequence



Sambruna et al. (1996); Fossati et al. (1998)
Ghisellini et al. (1998)

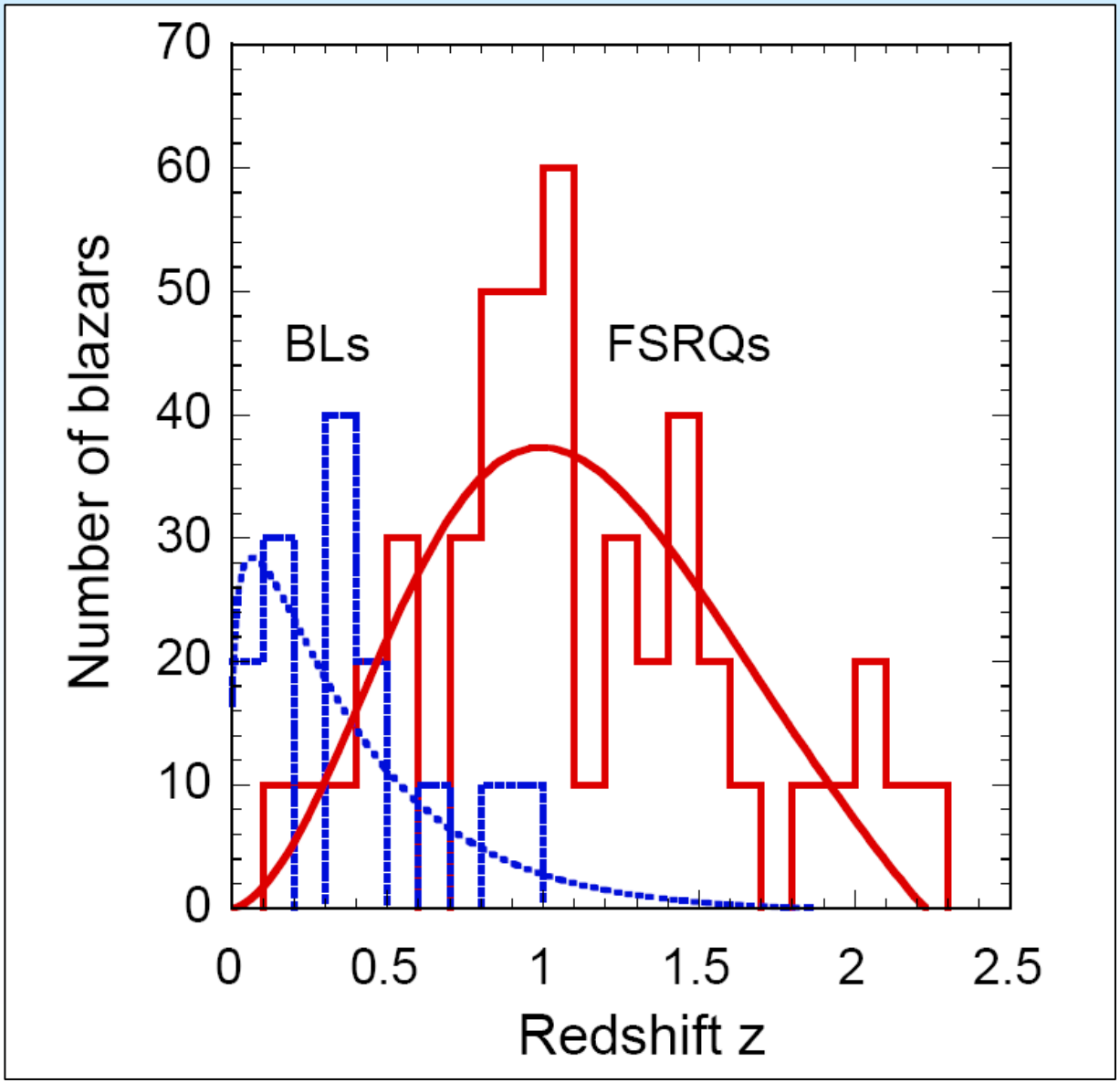


Evolution from FSRQ to BL Lac Objects in terms of a reduction of fuel from surrounding gas and dust

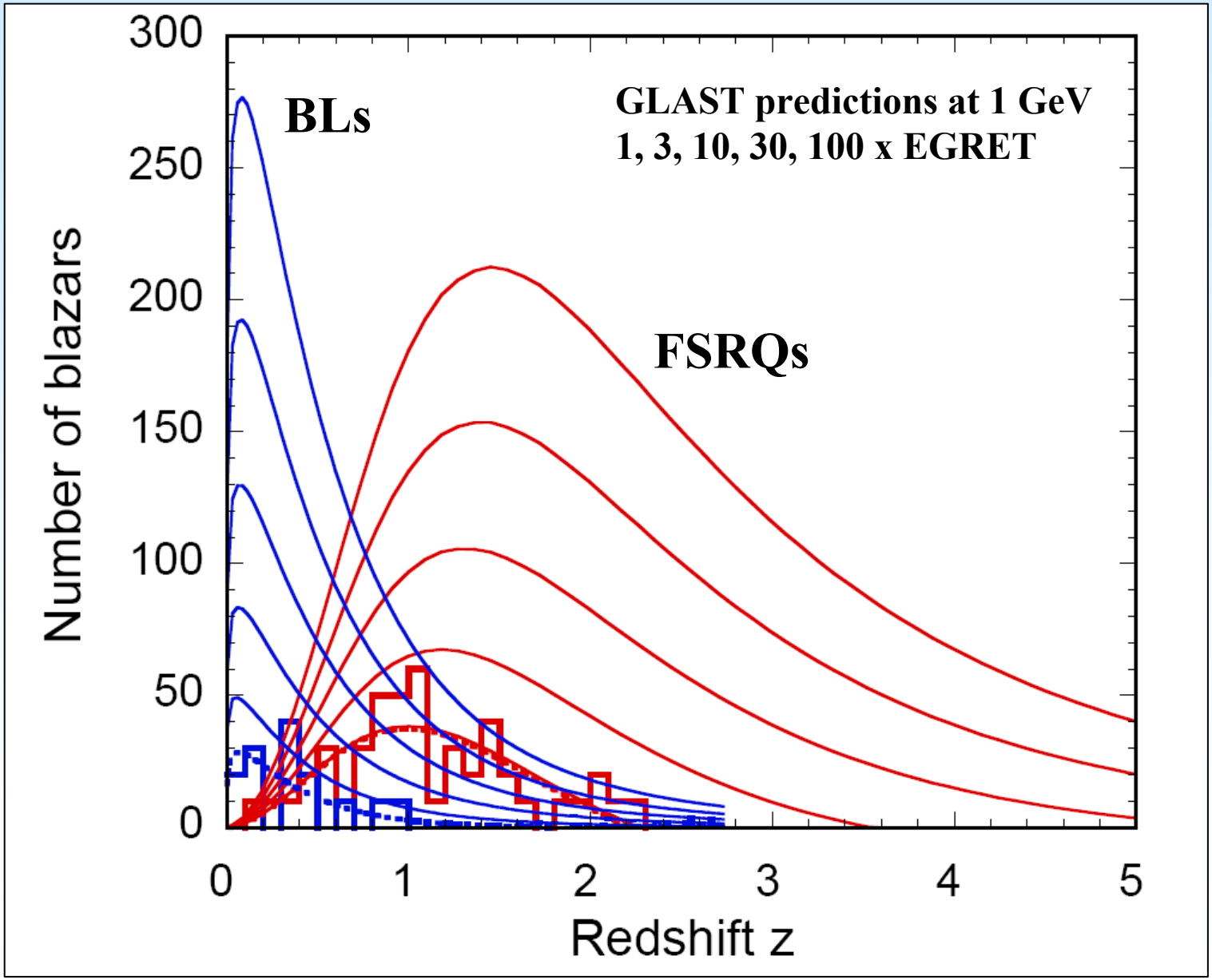
Böttcher and Dermer (2000)
Cavaliere and d'Elia (2000)

BL Lac objects are late stages of FSRQs: in accord with analysis of EGRET data
(1) Blazar main sequence valid? (2) BL Lac BH Masses > FSRQ BH masses?

Model Redshift Distribution of EGRET γ-Ray Blazars



Redshift Predictions for Fermi γ-Ray Blazars

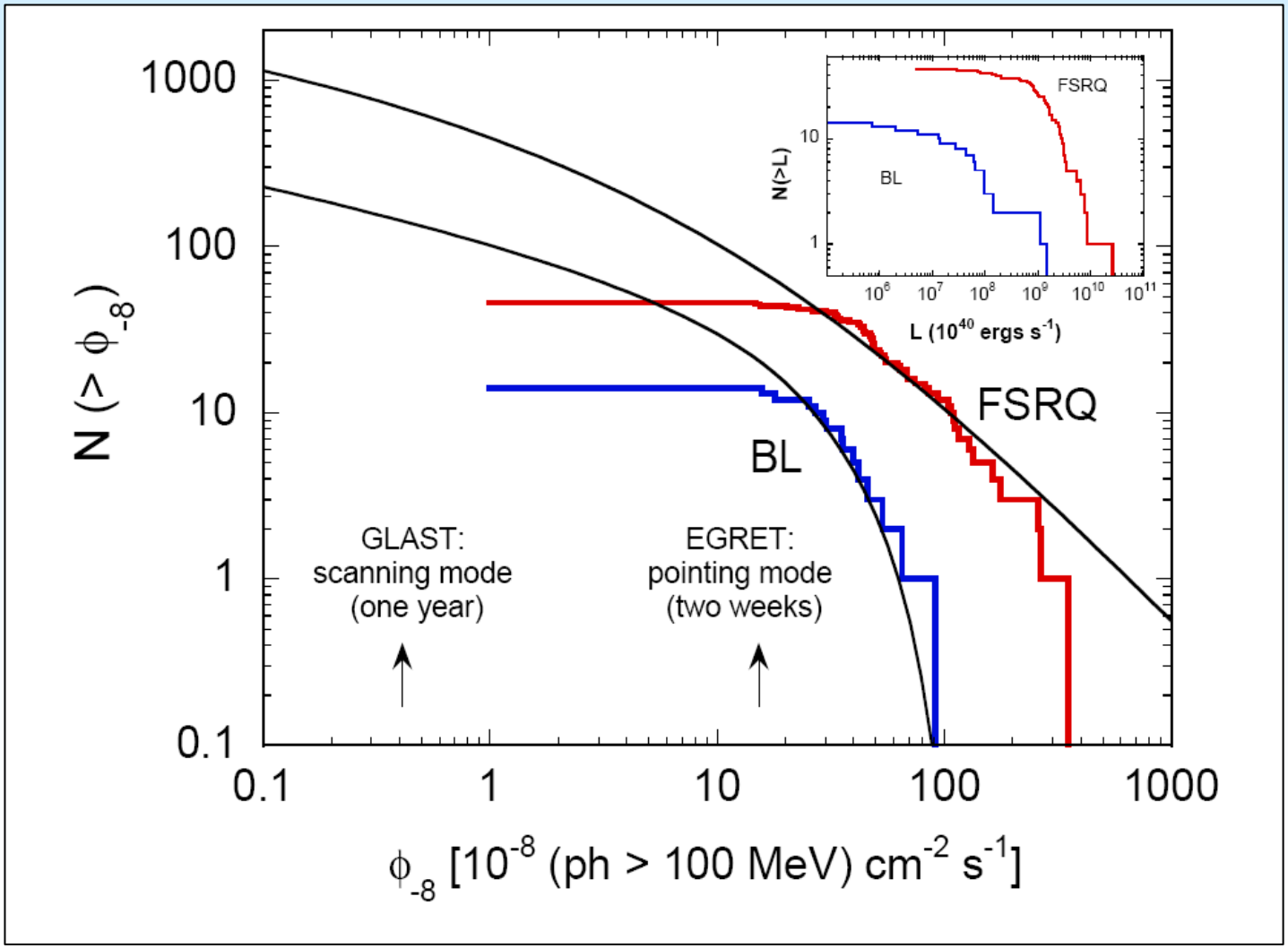


Predicted Number of Blazars with GLAST

GLAST reaches sensitivity of 0.4×10^{-8} ph(>100 MeV)/cm^2 s in one year

~700 FSRQ/FR2s and ~150 BL/FR1s by end of first year of operation

Dermer (2007)

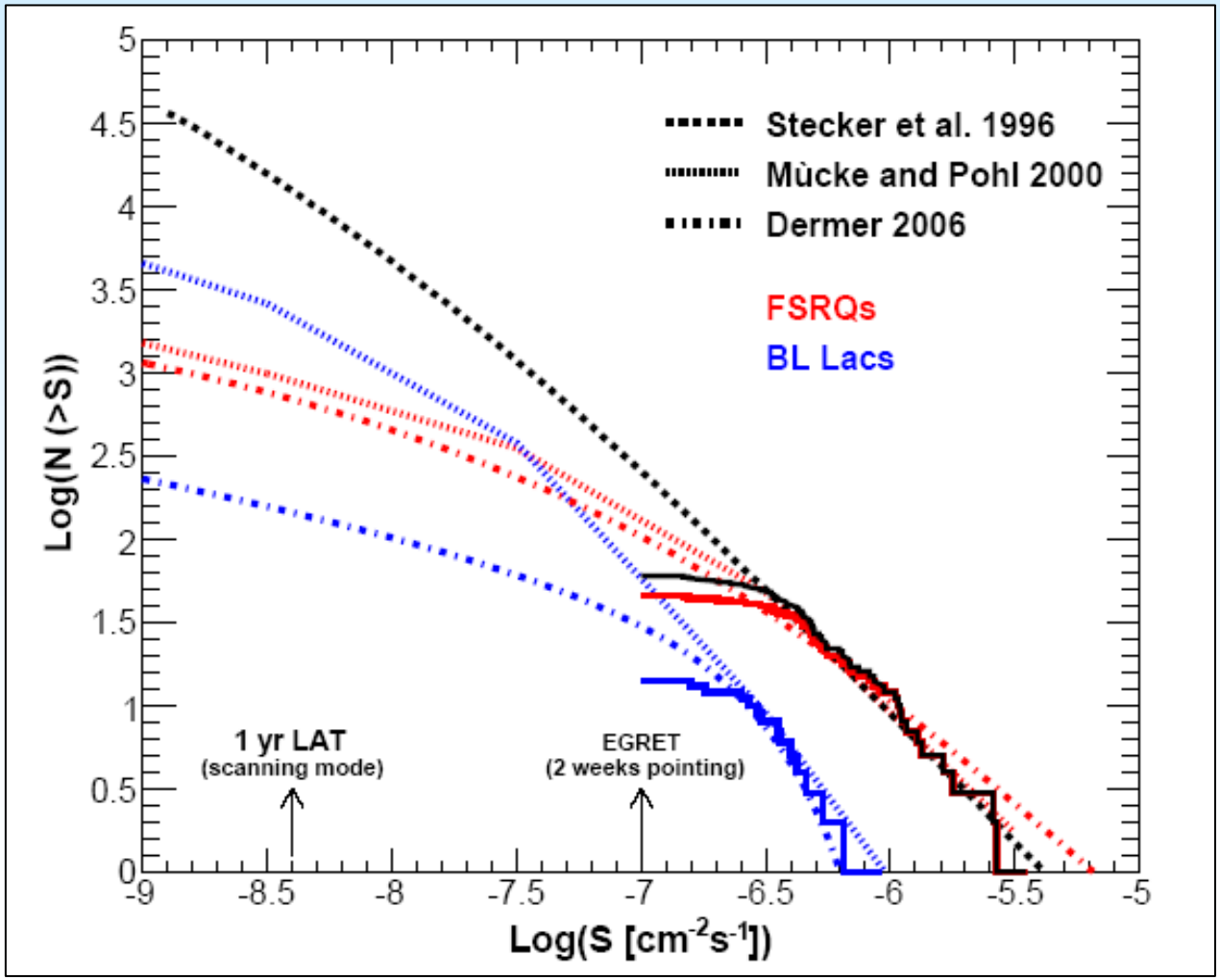


Predicted Number of Blazars with GLAST

Peak flux size distribution of EGRET blazars for two-week pointings during the all-sky survey

Dotted curves: Mücke and Pohl (2000)

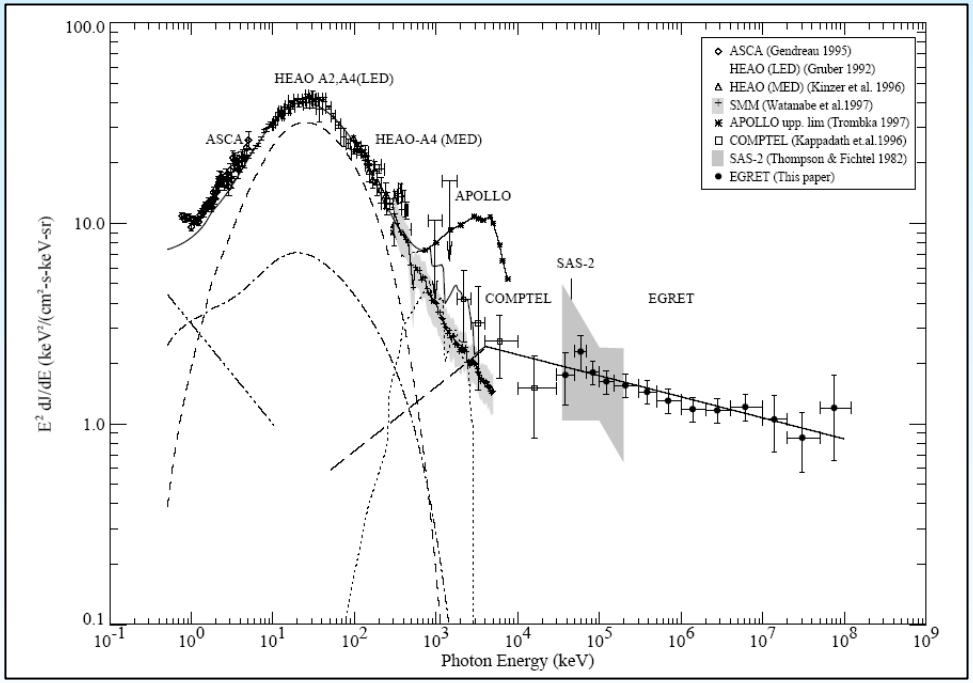
Stecker predicts 8000-10000 GLAST blazars based on Stecker & Salamon (1996) treatment

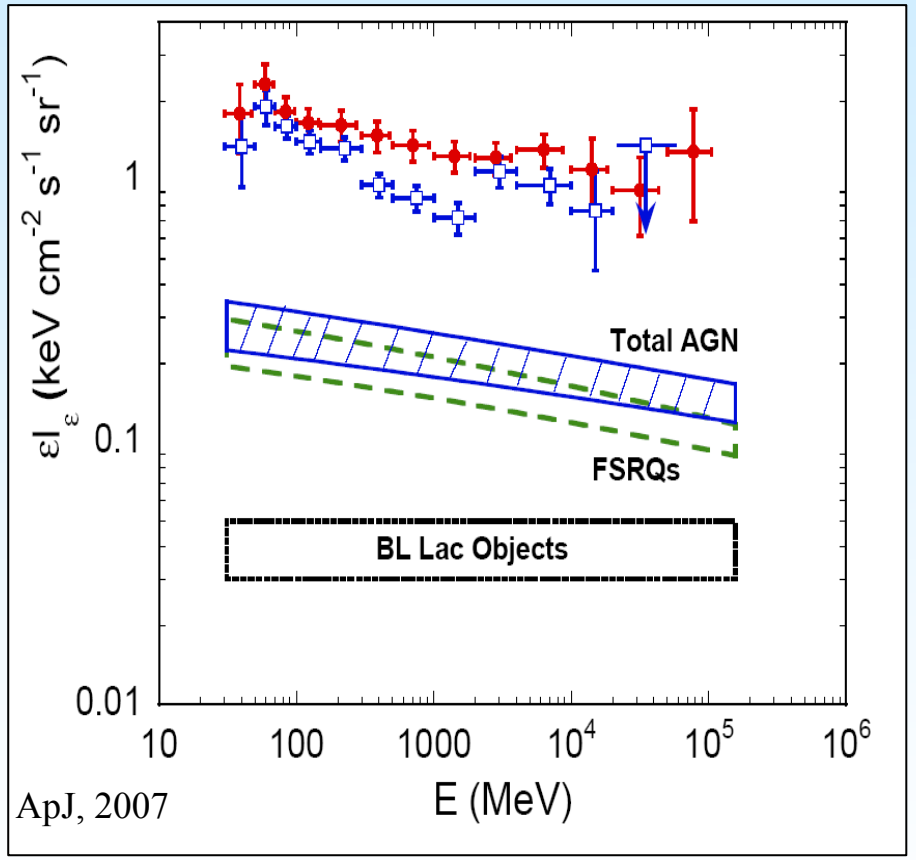


Blazar Contribution to Unresolved/Diffuse γ-Ray Background

Data: Sreekumar et al. (1998)

Strong, Moskalenko, & Reimer (2000)





- **EGRET Analysis** (Sreekumar et al. 1998)

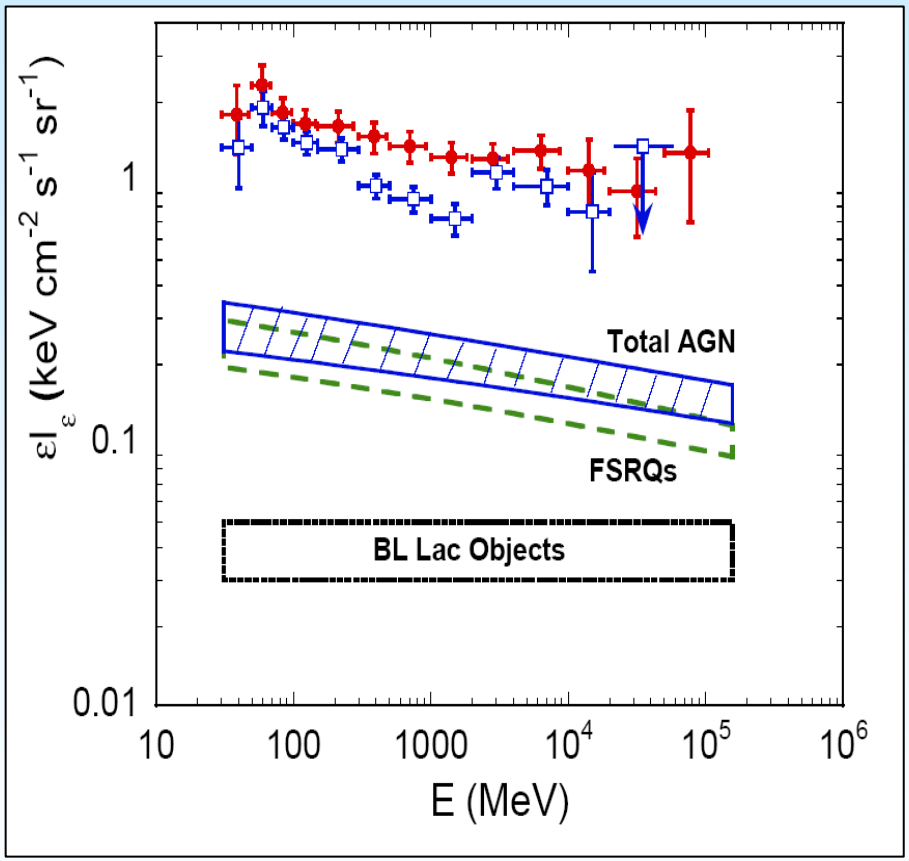
- **GALPROP Model** (Strong, Moskalenko, & Reimer 2000)

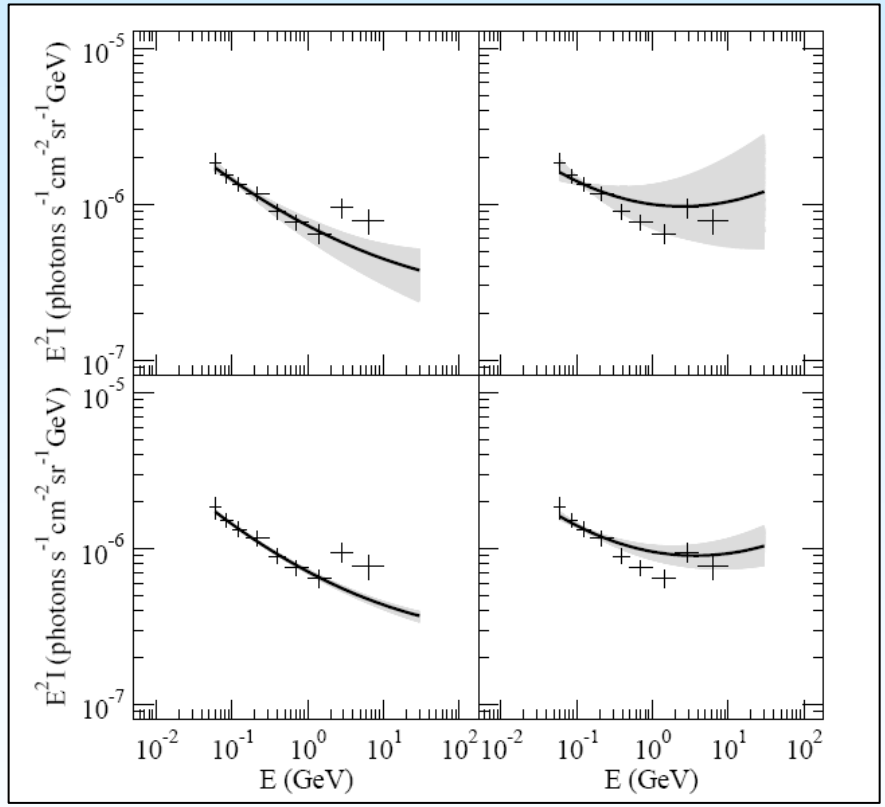
Analysis:

BL Lacs: ~2 - 4% (at 1 GeV)

FSRQs: ~ 10 - 15%

Realistic Spectral Index Distribution



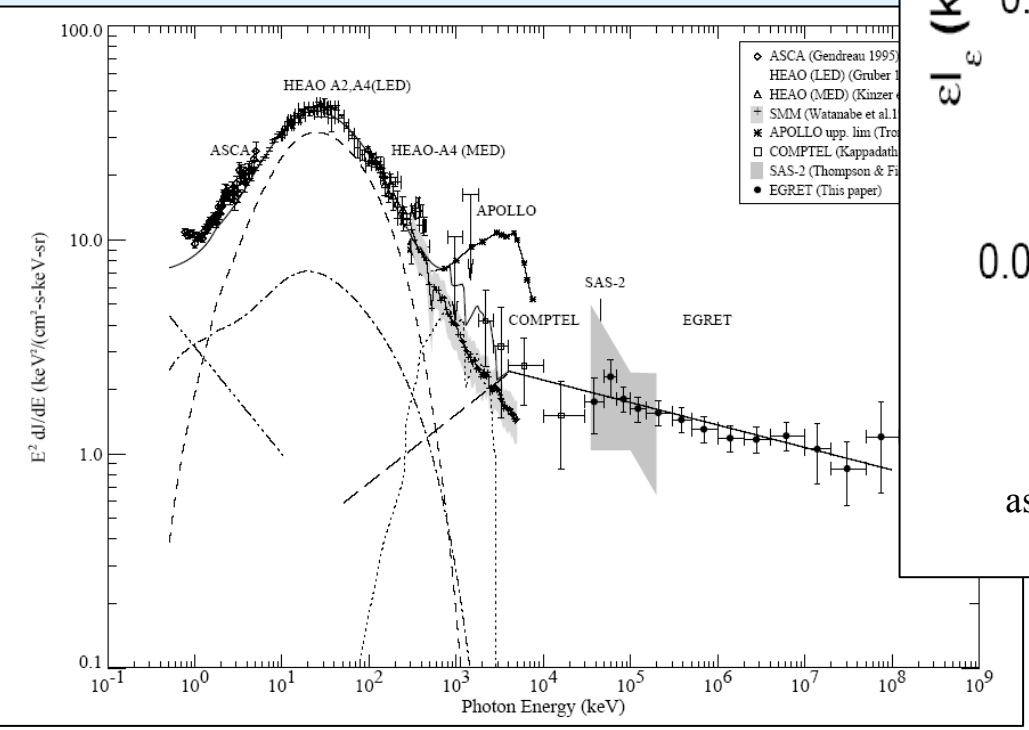


Pavlidou & Venters (2008)

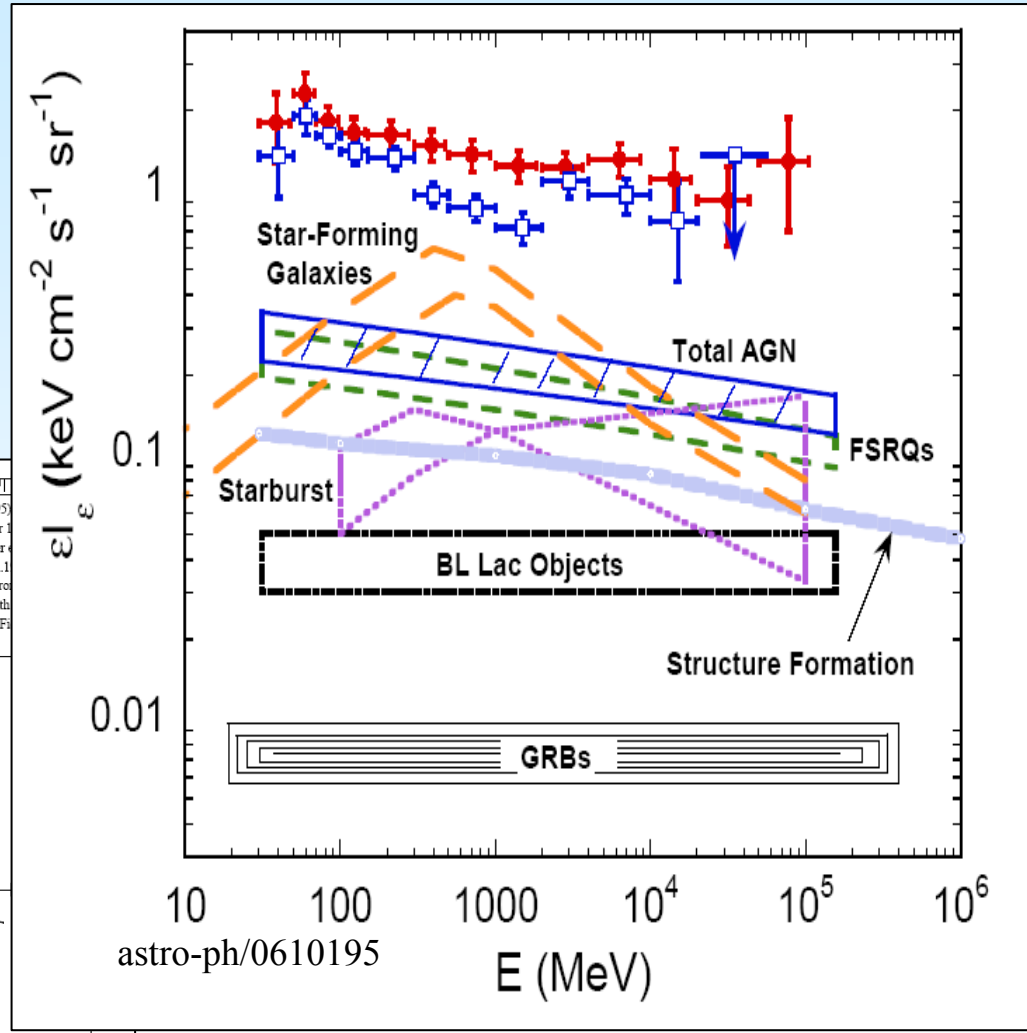
Unresolved γ-Ray Background

BL Lacs: ~2 - 4% (at 1 GeV)
FSRQs: ~ 10 - 15%

Star-forming galaxies (Pavlidou & Fields 2002)
Starburst galaxies (Thompson et al. 2006)
Pulsar contribution near 1 GeV
Galaxy cluster shocks (Keshet et al. 2003, Blasi Gabici & Brunetti 2007)



Two puzzles: deficit << 1 GeV
deficit >> 1 GeV



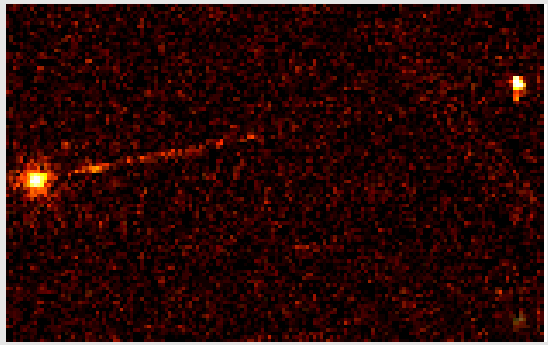
Data: Sreekumar et al. (1998)
Strong, Moskalenko, & Reimer (2000)

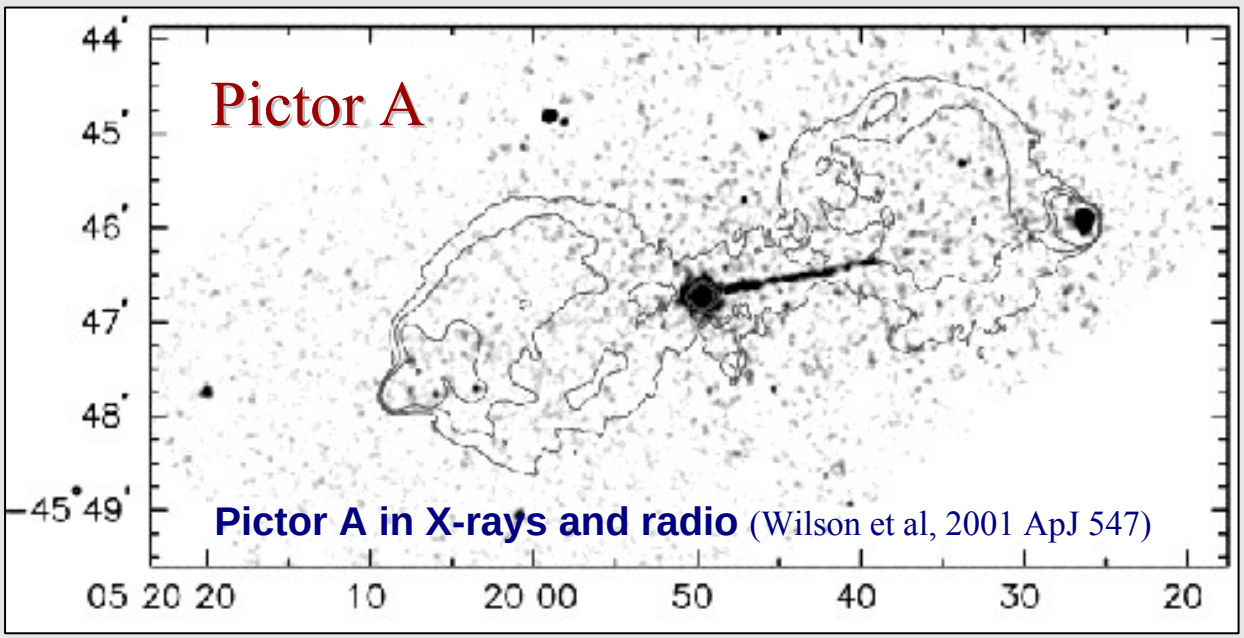
UHECRs from Radio Galaxies and Blazars

d ~ 200 Mpc

l_{jet} ~ 1 Mpc (l_{proj} = 240 kpc)

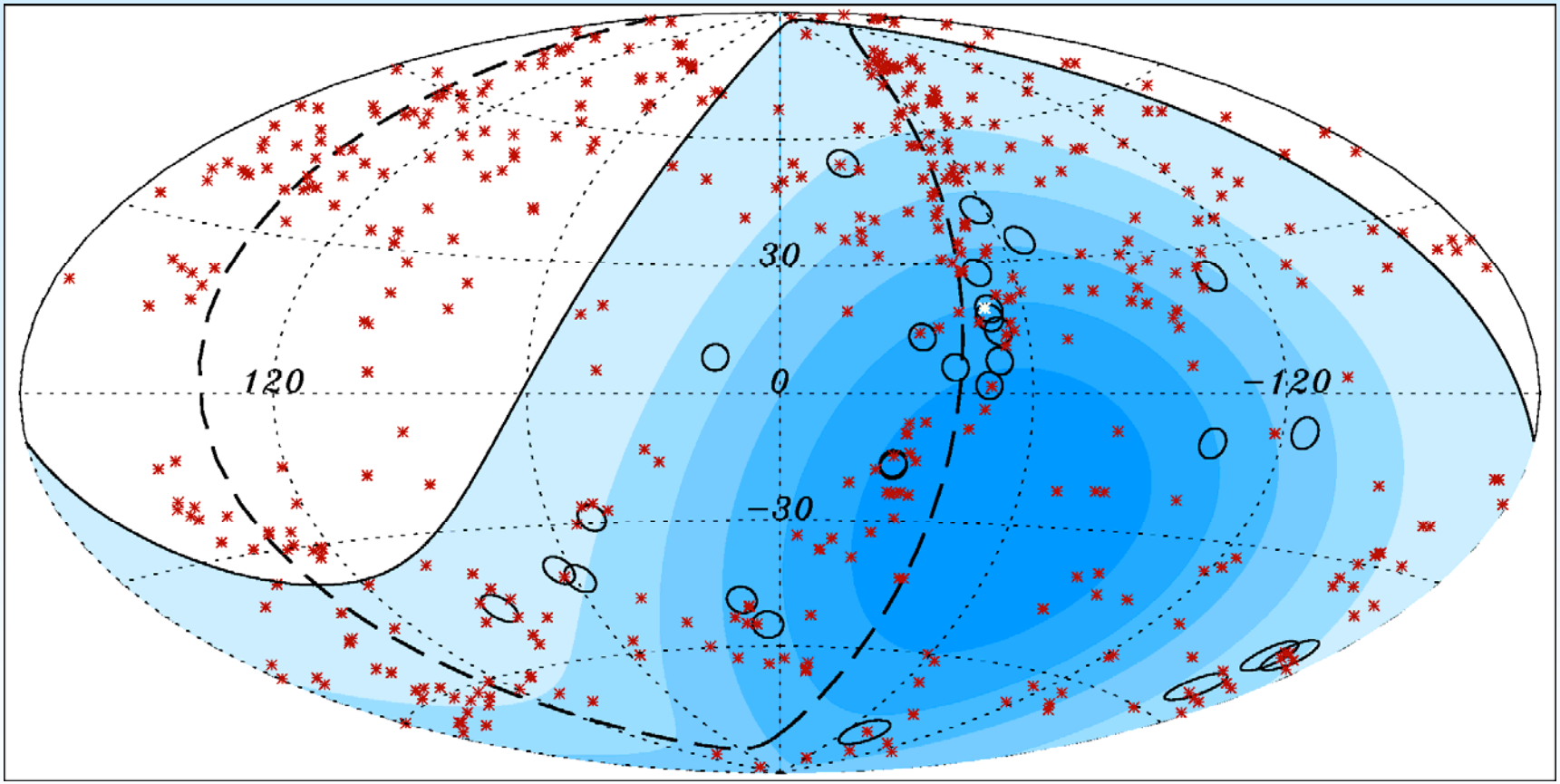
Deposition of energy through ultra-high energy neutral beams (Atoyan and Dermer 2003)





Pictor A in X-rays and radio (Wilson et al, 2001 ApJ 547)

UHECR Charged Particle Astronomy

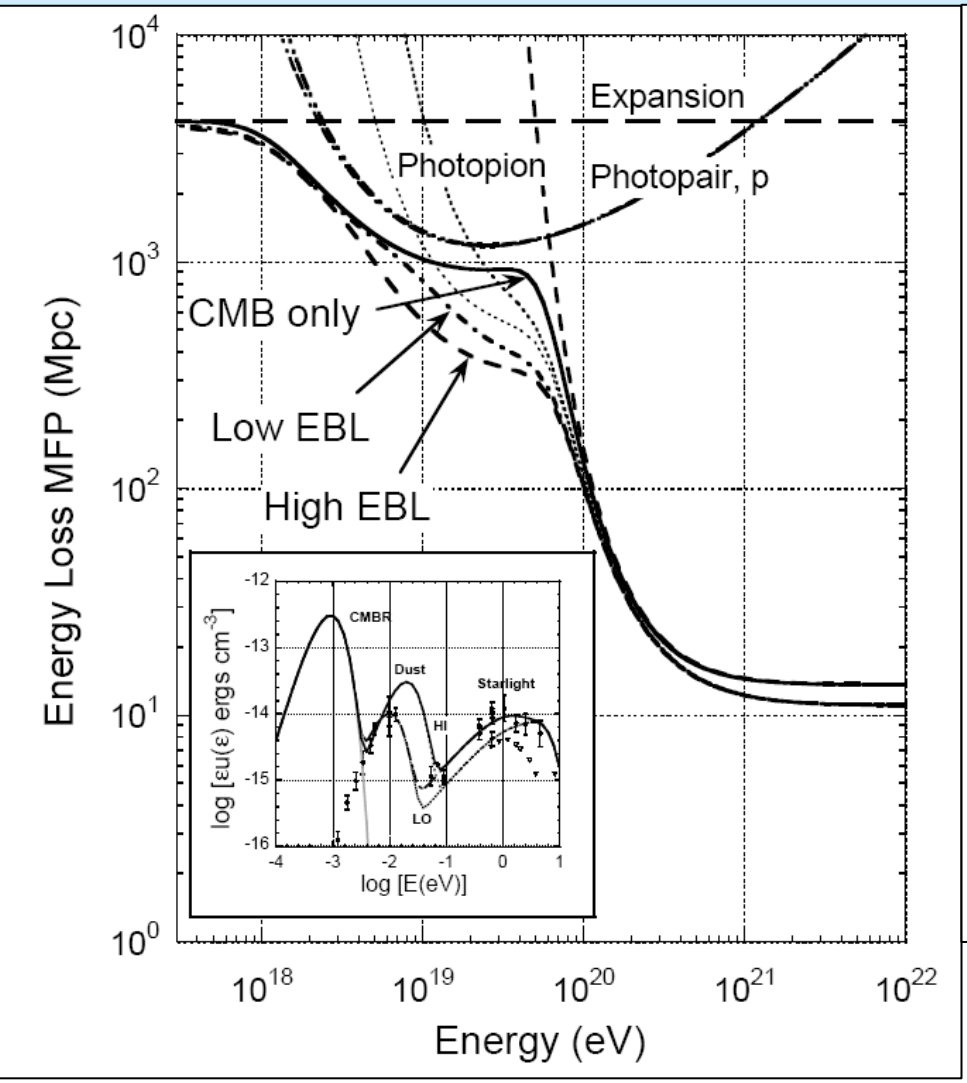


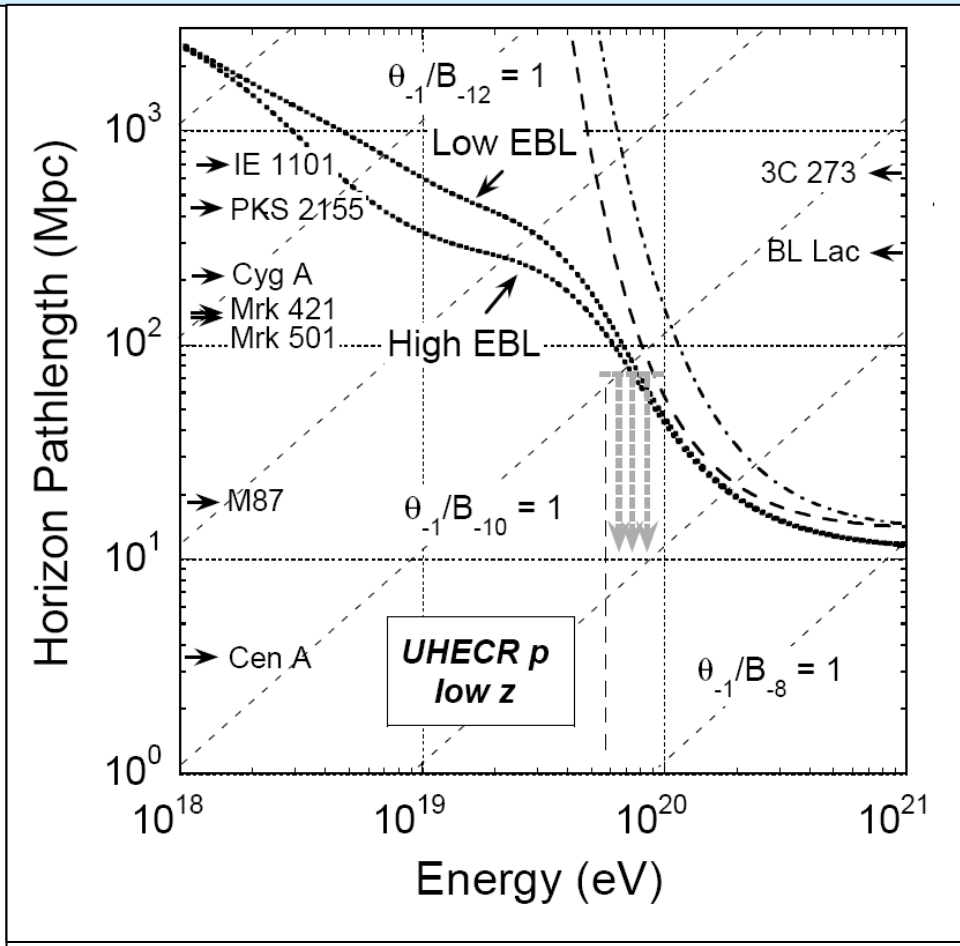
AGN Catalog of Veron and Veron Cetty

Auger Collaboration, Science, Nov. 2007

>56 EeV (27 events) 694 AGNs z < 0.024 (< 75 Mpc)

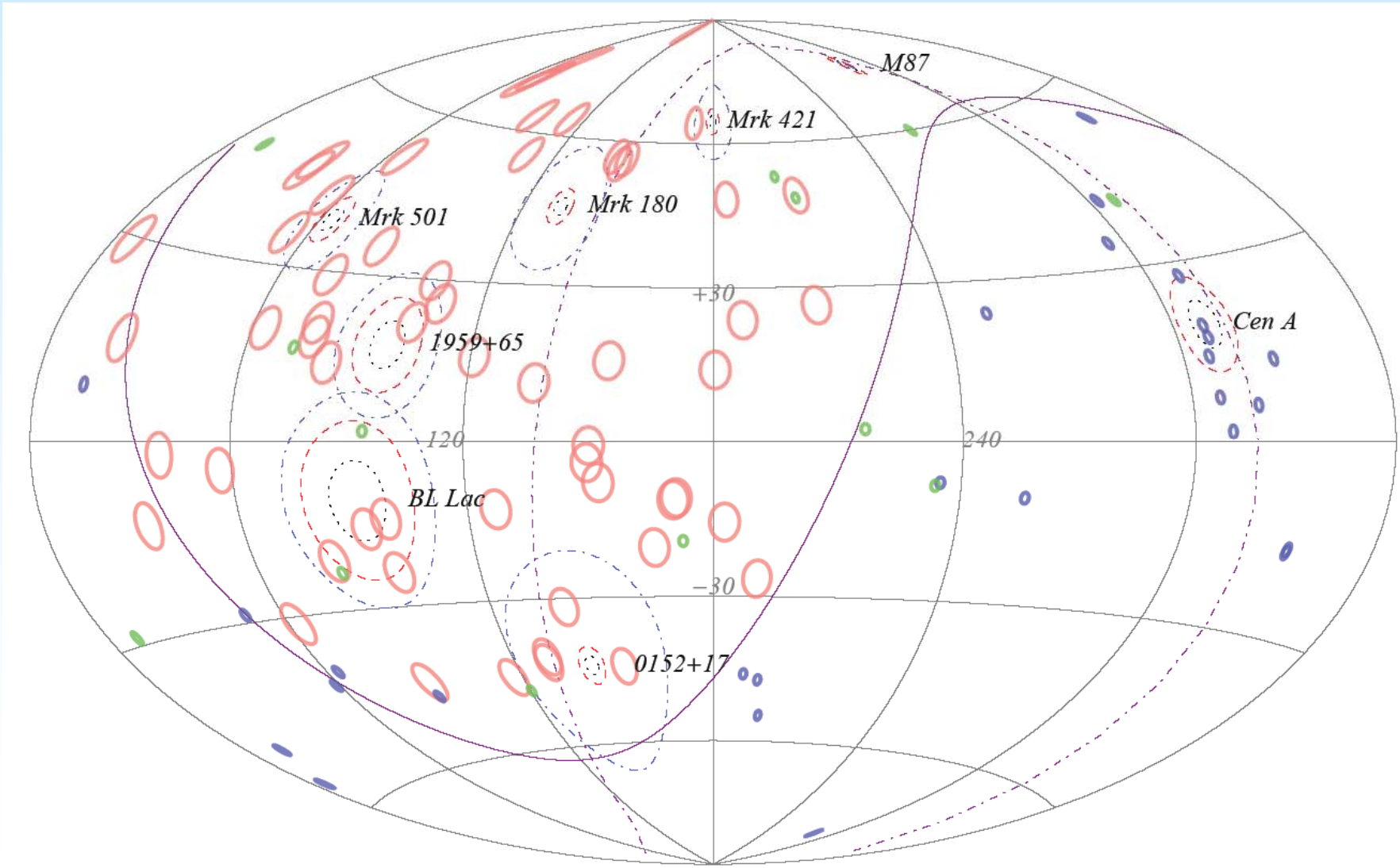
MFP and Horizon Distance





Dermer, Razzaque, Finke, Atoyan, (2008)

UHECR Arrival Directions for Radio Galaxies



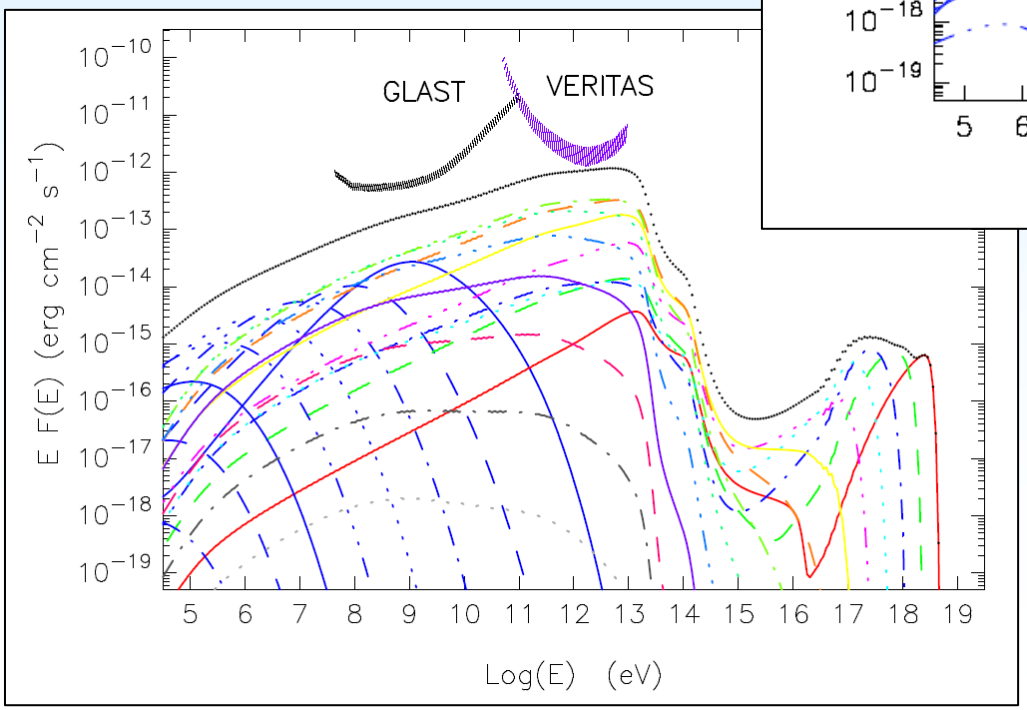
Cascade radiation from UHECRs in Radio Galaxies

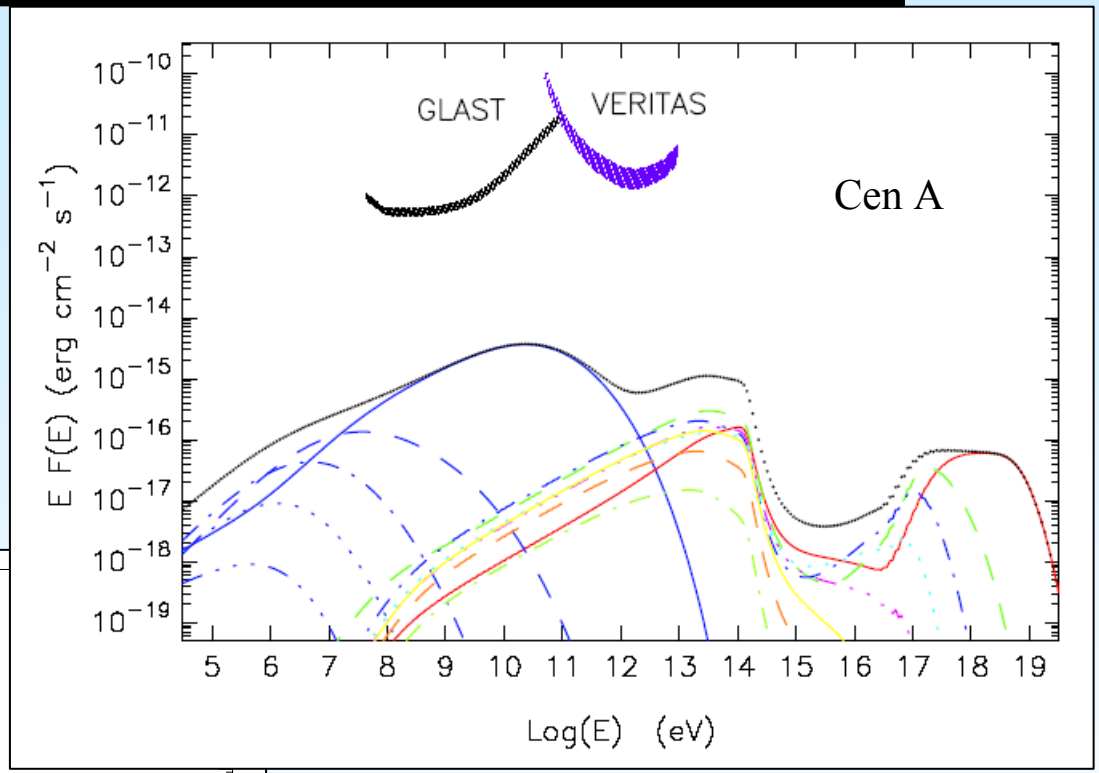
Rectilinear cascade from UHECRs accelerated by radio galaxies

$B_{IGM} = 10^{-8}$ G

Pair halos from misaligned blazar

(Stawarz et al. 2006 for Cen A)





Calculations: Armen Atoyan; to be published

(see also Gabici & Aharonian 2005)

source at 100 Mpc

Summary

- **Fermi prediction of number and evolution of blazars:**
  Test picture that FSRQs evolve into BL Lacs

- **Residual diffuse isotropic γ-ray background:**
  hard blazar emission components?
  new populations of γ-ray sources?
  other?

- **Are radio galaxies the sources of UHECRs?**

- **Fermi can detect anomalous γ-ray emission signatures, e.g., cascade radiation, associated with hadronic acceleration in blazar jets**