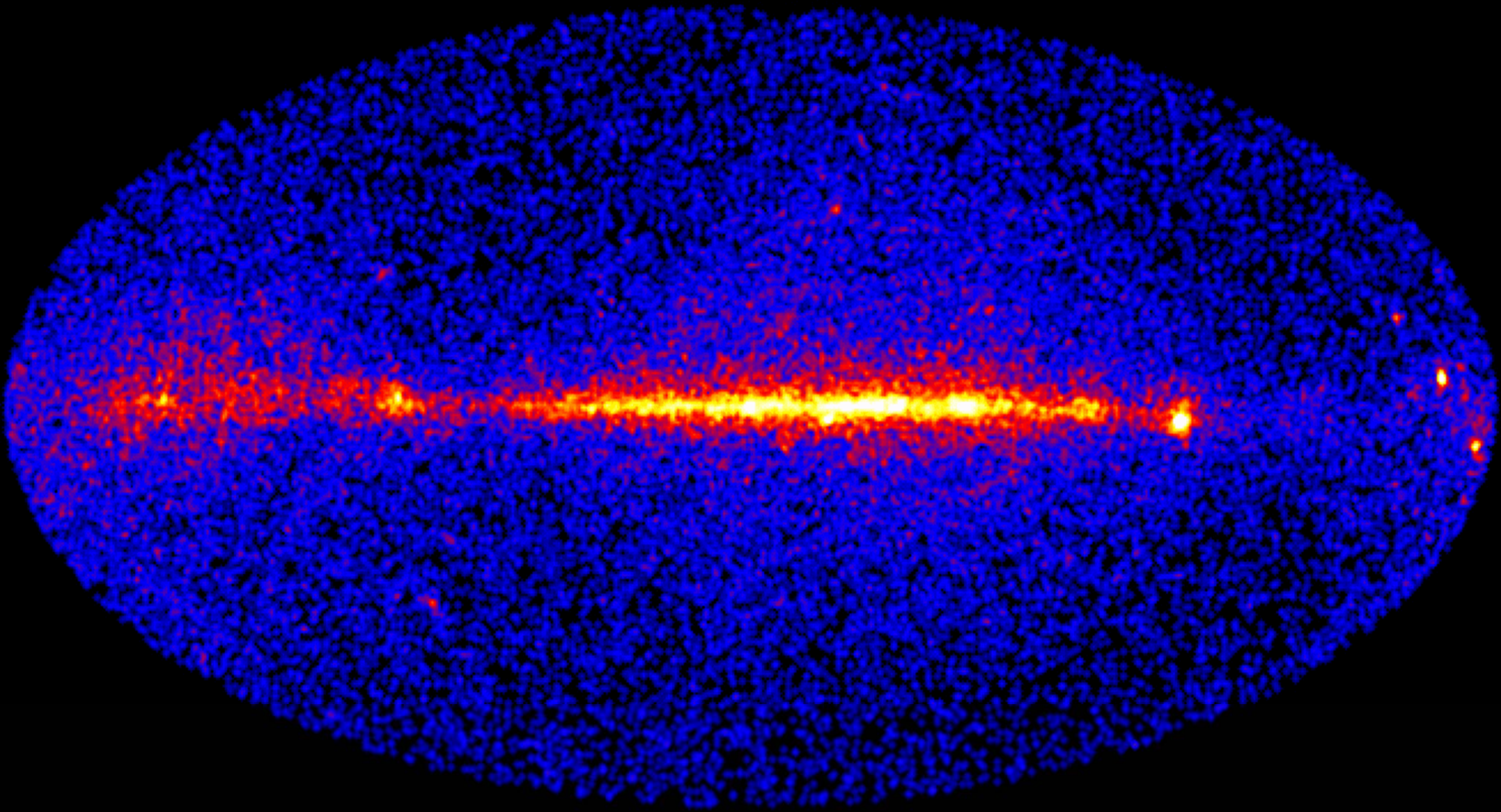
Blazar 3C 454.3's Record Flare



November 3, 2009

Fermi
Gamma-ray
Space Telescope

Fermi Blazar and AGN Science

Fermi Summer Science School

Lewes, Delaware
28 May 2014

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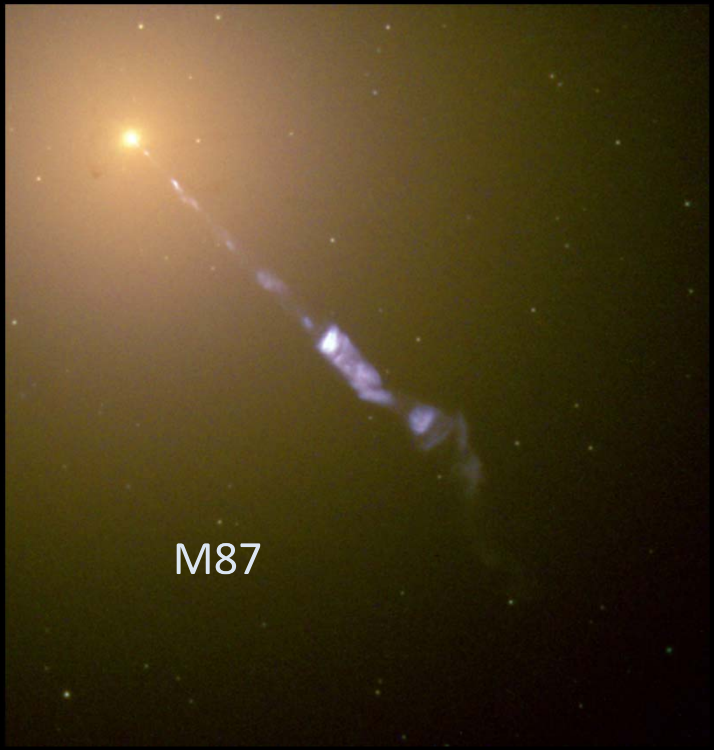
Outline

"…curious straight ray…apparently connected with the nucleus by a thin line of matter." H. E. Curtis, 1918

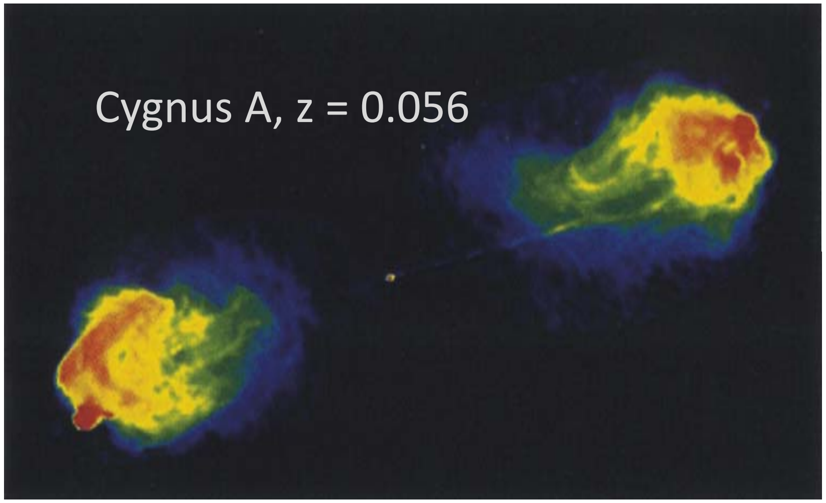
1. The Radio Galaxy/Blazar Paradigm
2. Problems with the Blazar Paradigm
3. Steps forward with Fermi

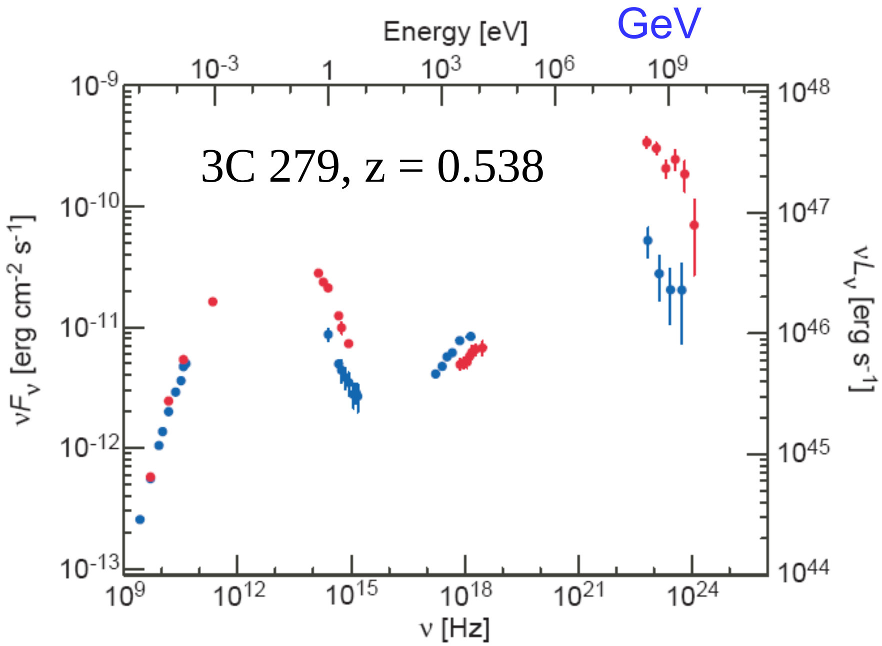
M87 discovered and cataloged by Charles Messier on March 18, 1781 (233 yrs ago)



Distance; 16.4 Mpc
Black hole mass: 6.6(±0.4) x10^9 Solar masses

Blazars: Supermassive Black Holes with Relativistic Jets Pointed at Us





Causality argument for size of emission region

$$R/c \le \Delta t_{\rm var}$$

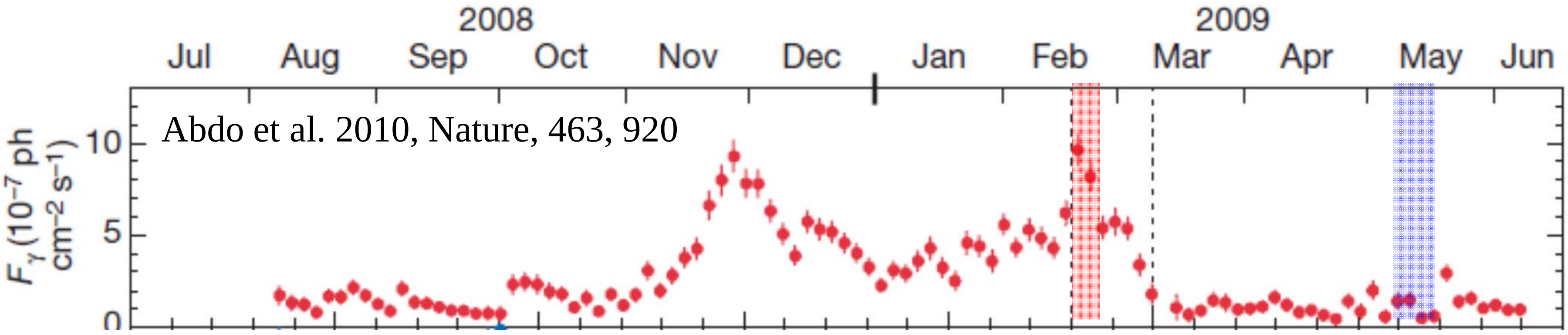
$$\Delta t_{\rm var} \le 1\ day$$

$$R_S = \frac{2GM}{c^2} = 3\times10^{14}(M/M_9)\ cm$$

$$R_S/c \cong 10^{4}(M/M_9)\ s$$

$$L_{Edd} \approx 10^{47}(M/M_9)\ erg/s$$

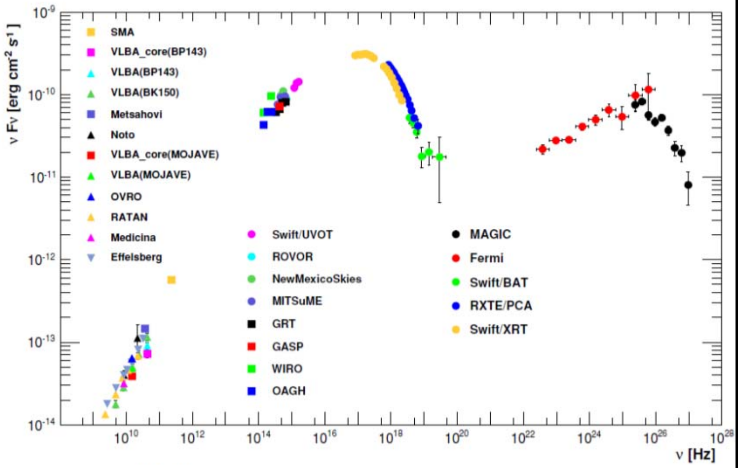
$$L_{iso} \approx 10^{48}(M/M_9)\ erg/s$$



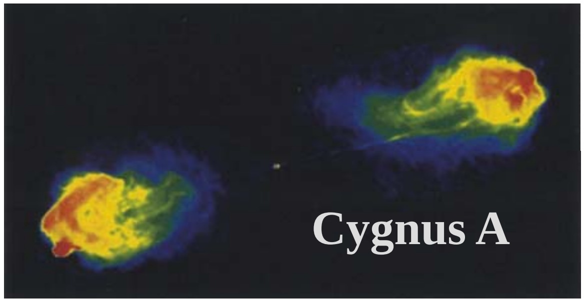
Abdo et al. 2010, Nature, 463, 920

Radio Galaxies, Blazars, and Unification

L ~10^{45} x (f/10^{-10} ergs cm^{-2} s^{-1}) erg s^{-1}

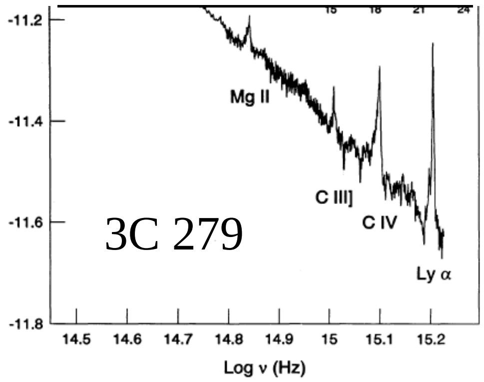


Mrk 421, z = 0.031



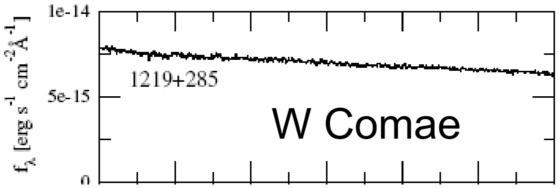
FR1/2: radio power/ morphology correlation; dividing line at ≅ 10^{42} erg s^{-1} (2×10^{25} W/Hz at 178 MHz)

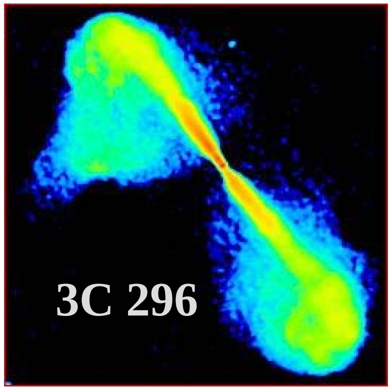
FR2/FSRQ

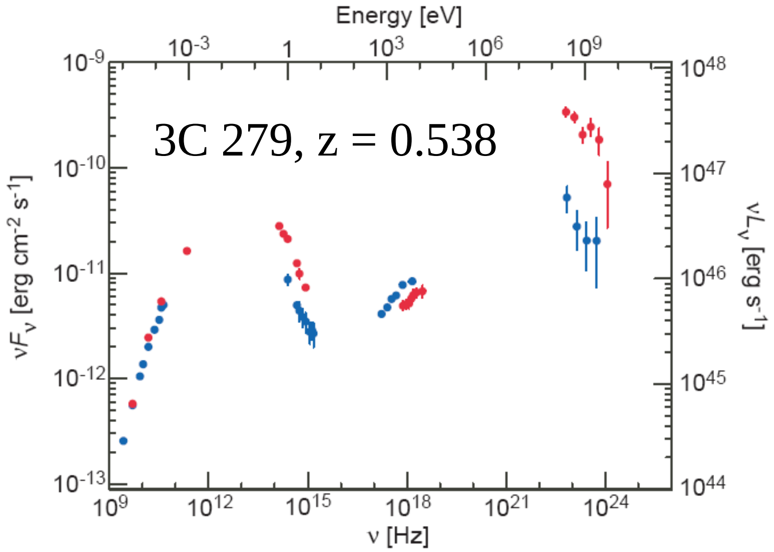


BL Lacs: optical emission line equivalent widths < 5 Å

FR1/BL Lac







Classifying Fermi AGNs

- **Radio:** FR1 vs FR2
- **Optical:** FSRQs vs. BL Lacs
- **SED;** (“synchrotron-peaked”)

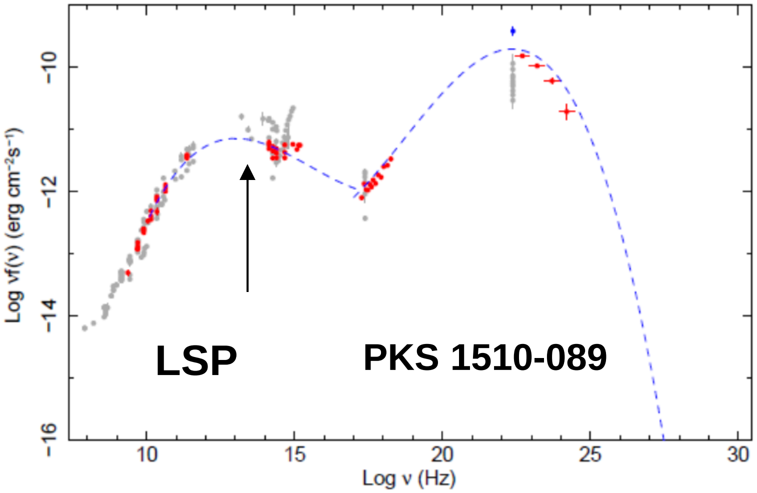
  LSP ($\nu_{pk}^{syn} < 10^{14}$ Hz),

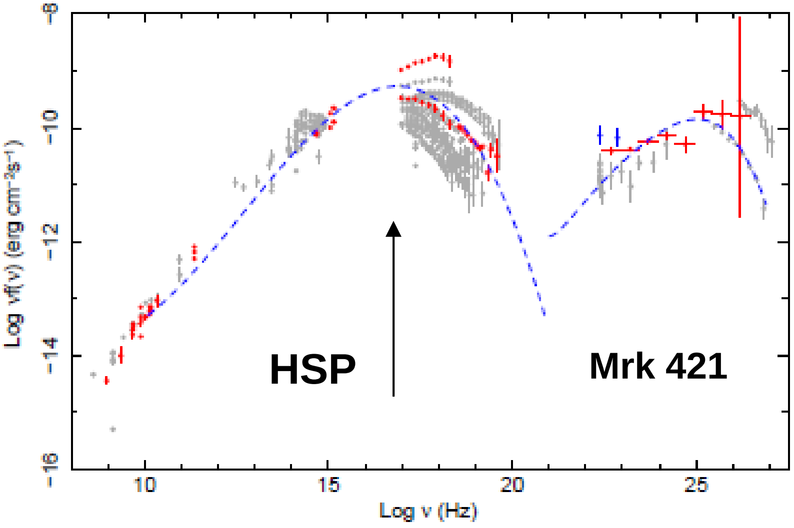
  HSP ($\nu_{pk}^{syn} > 10^{15}$ Hz)

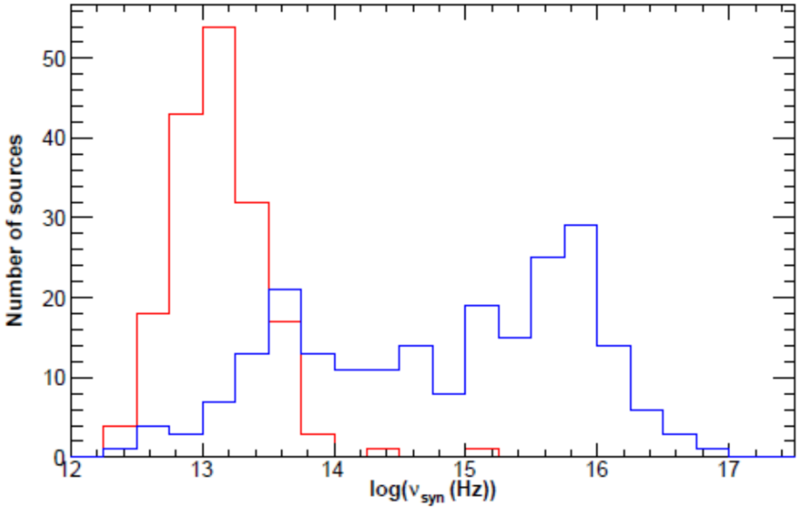
  ISP

Essentially all FSRQs are LSPs

Abdo et al. 2010, ApJ, 710, 1271

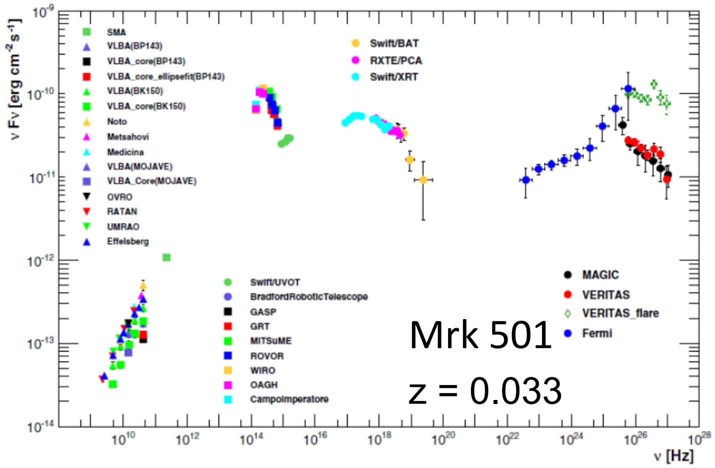






Blazar Spectral Energy Distributions

BL Lacs: emission to VHE/TeV energies

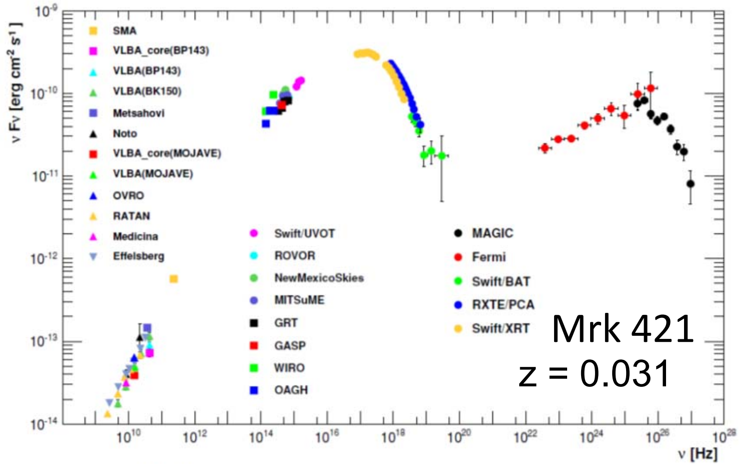


Mrk 501

z = 0.033

Abdo et al. 2011a

Abdo et al. 2011b



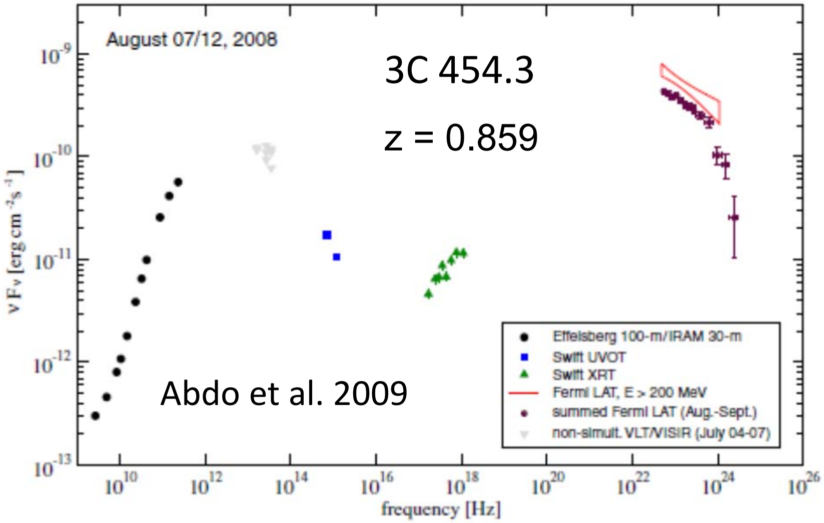
Mrk 421

z = 0.031

VHE (> 100 GeV)

LSP, ISP, HSP

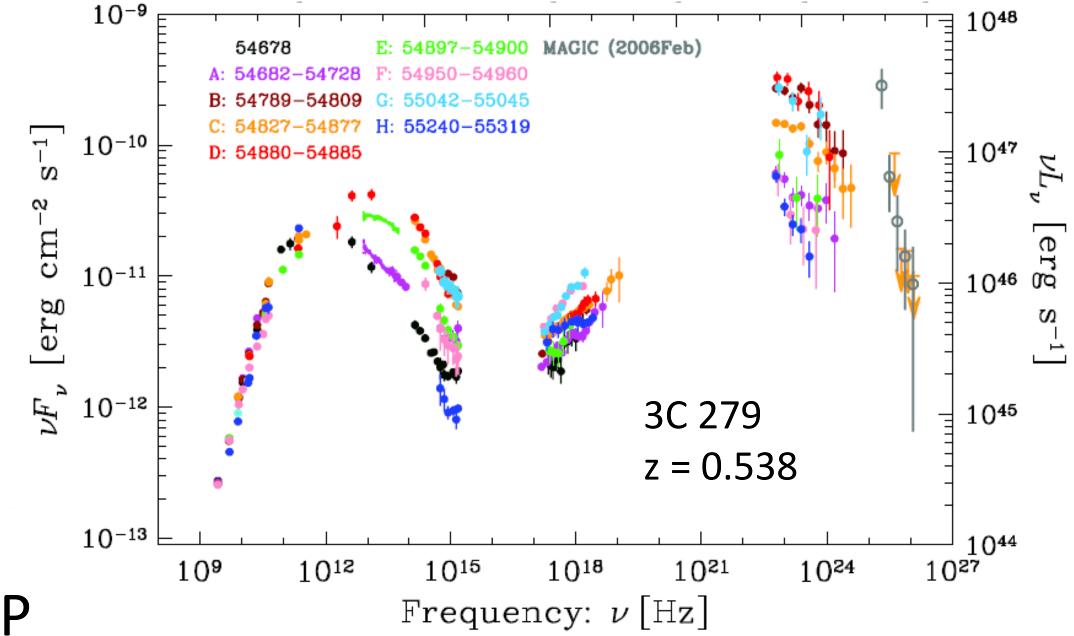
FSRQs: cutoffs at GeV with VHE episodes



3C 454.3

z = 0.859

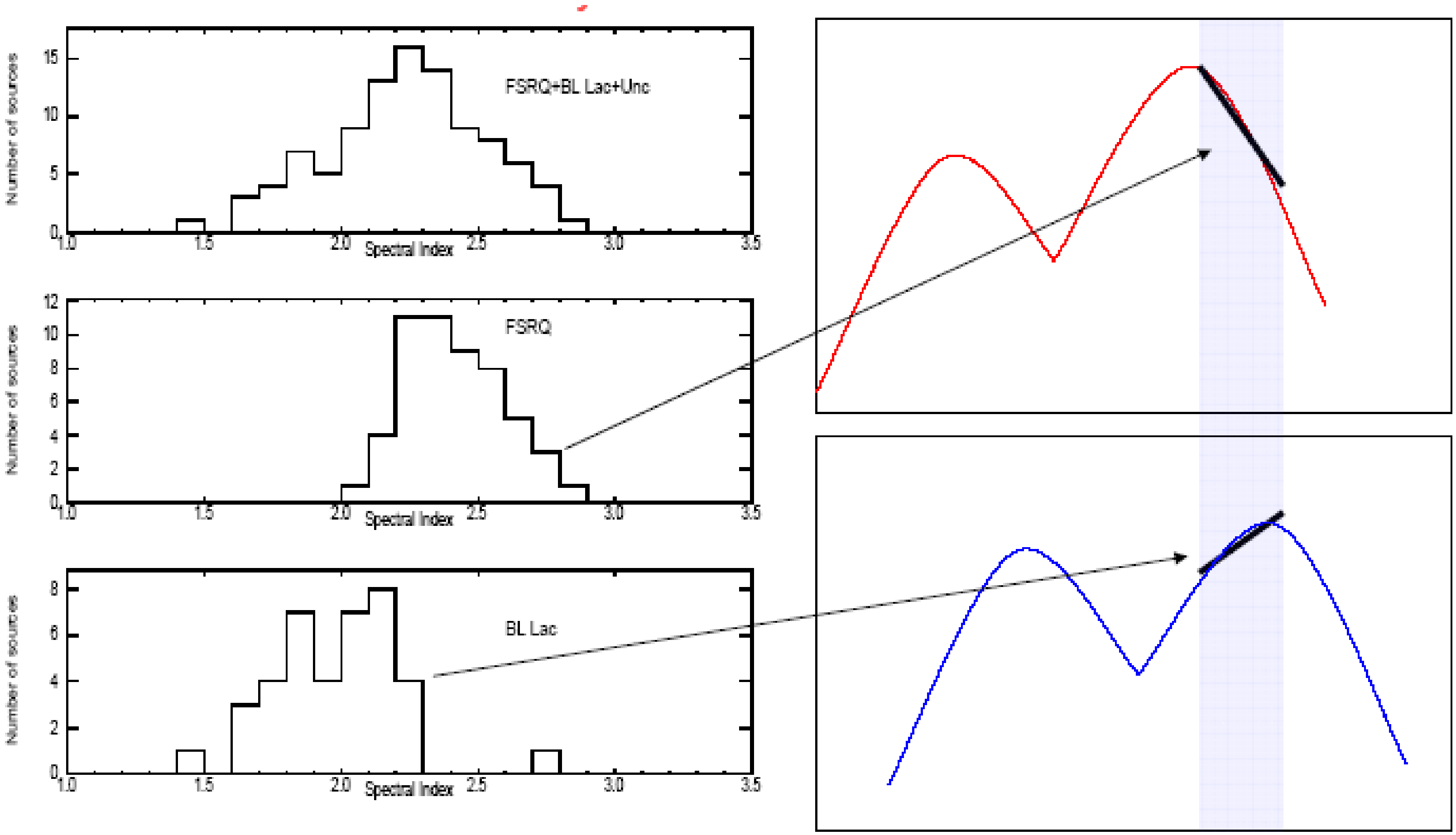
Abdo et al. 2009



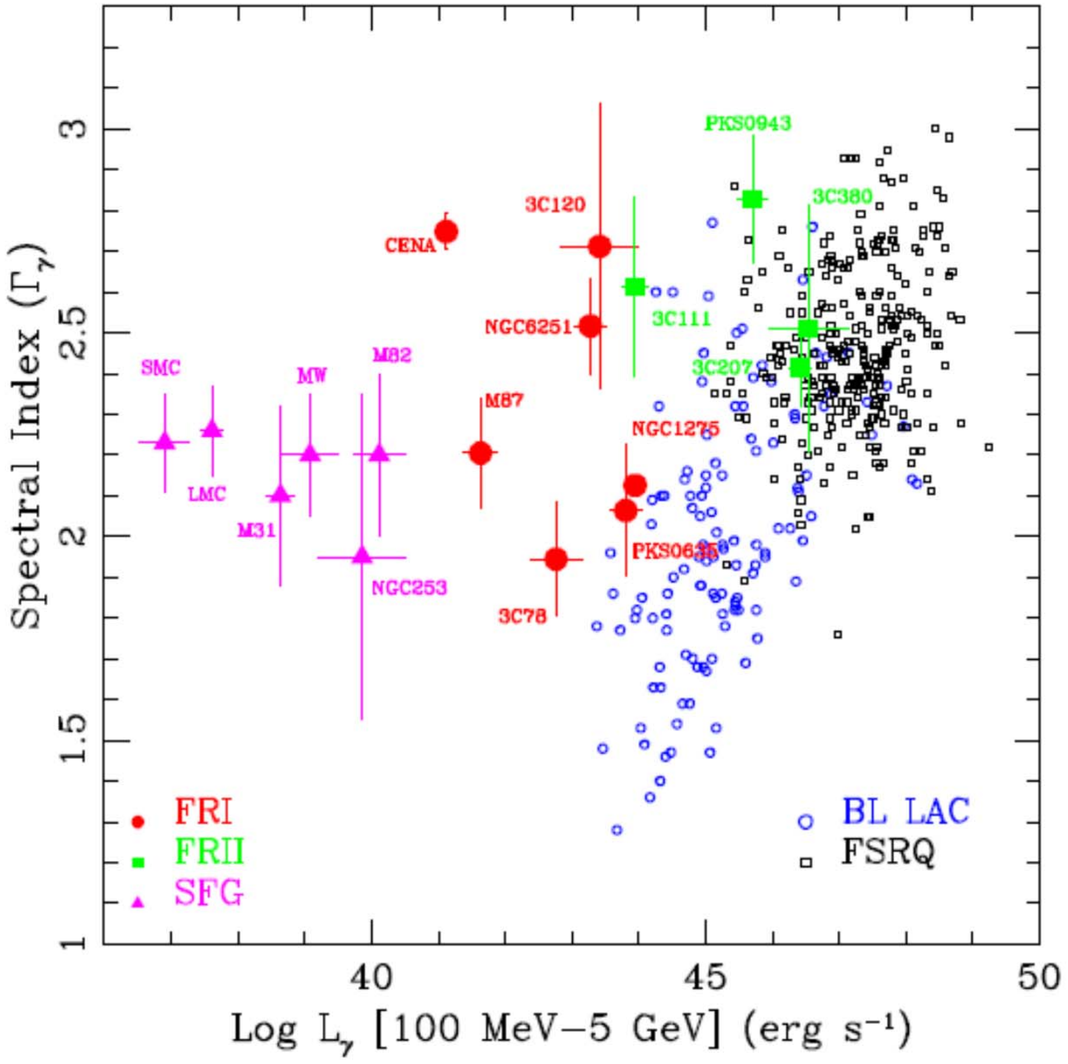
3C 279

z = 0.538

Spectral Energy Distribution and Spectral Index Distribution



γ-Ray Spectral Index vs. γ-Ray Galaxy Luminosity



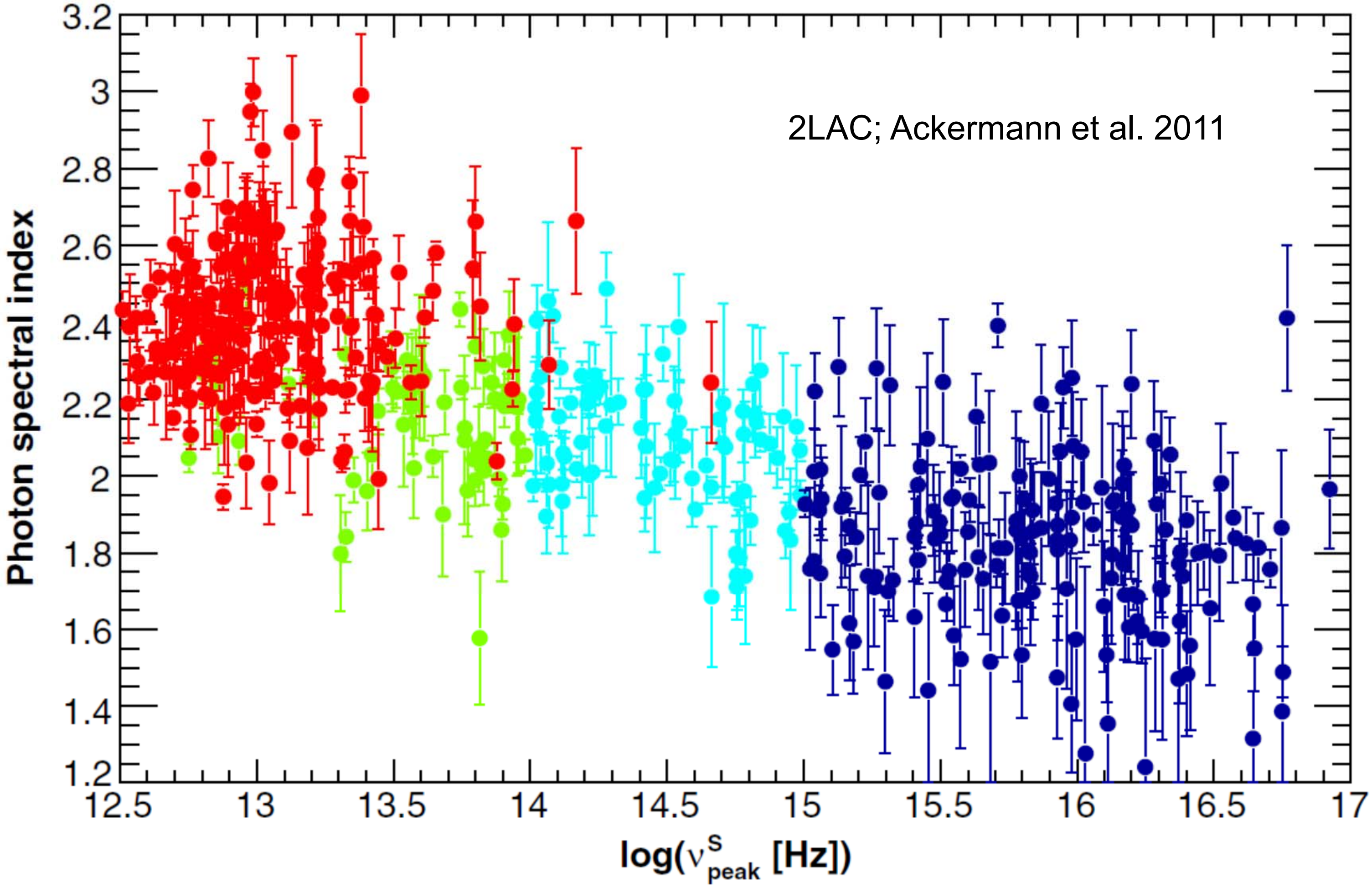
Fermi blazar divide
(Ghisellini et al. 2009)

Misaligned AGNs
(host galaxies of blazars)

Star forming galaxies

Spectral Index vs. Peak Synchrotron Frequency

> 100 MeV γ-ray photon index vs. peak synchrotron frequency



Standard AGN/Blazar Paradigm

AGN: active galactic nucleus

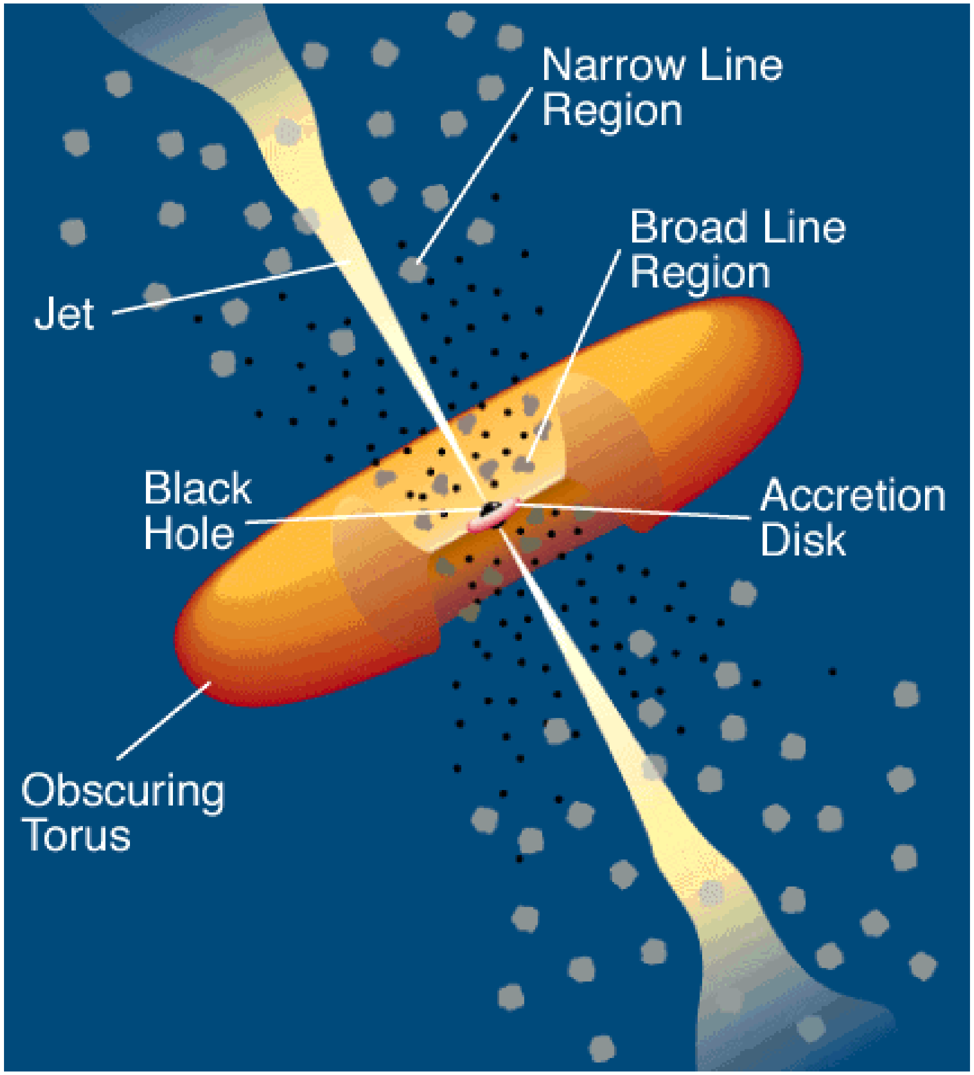
Accretion Disk

- **Molecular Torus**
- **Shakura-Sunyaev Disk**
- **Magneto Rotational Instability**
- **Modified Accretion Disks**
- **Hot Pair Plasma (T<10^9 K)**
- **Fe Lines**
- **Broad Line Region/ Narrow Line Region**

Nonthermal particle acceleration not evident in radio-quiet AGNs

Jets

- **Formation and Collimation**
- **Relativistic Outflows**
  - **Compton catastrophe**
  - **Apparent superluminal motion**
  - **$\gamma\gamma$ opacity arguments**
- **Particle Acceleration Sites**
  - **Within BLR**
  - **Pc scale**
  - **Knots and hot spots**
  - **Lobes**



Urry & Padovani (1995)

Leptonic Blazar Modeling

Leptonic jet model:

Nonthermal synchrotron paradigm

Associated SSC γ-ray component
(**BL Lac objects**)
and SSC/EC components (**FSRQs**)

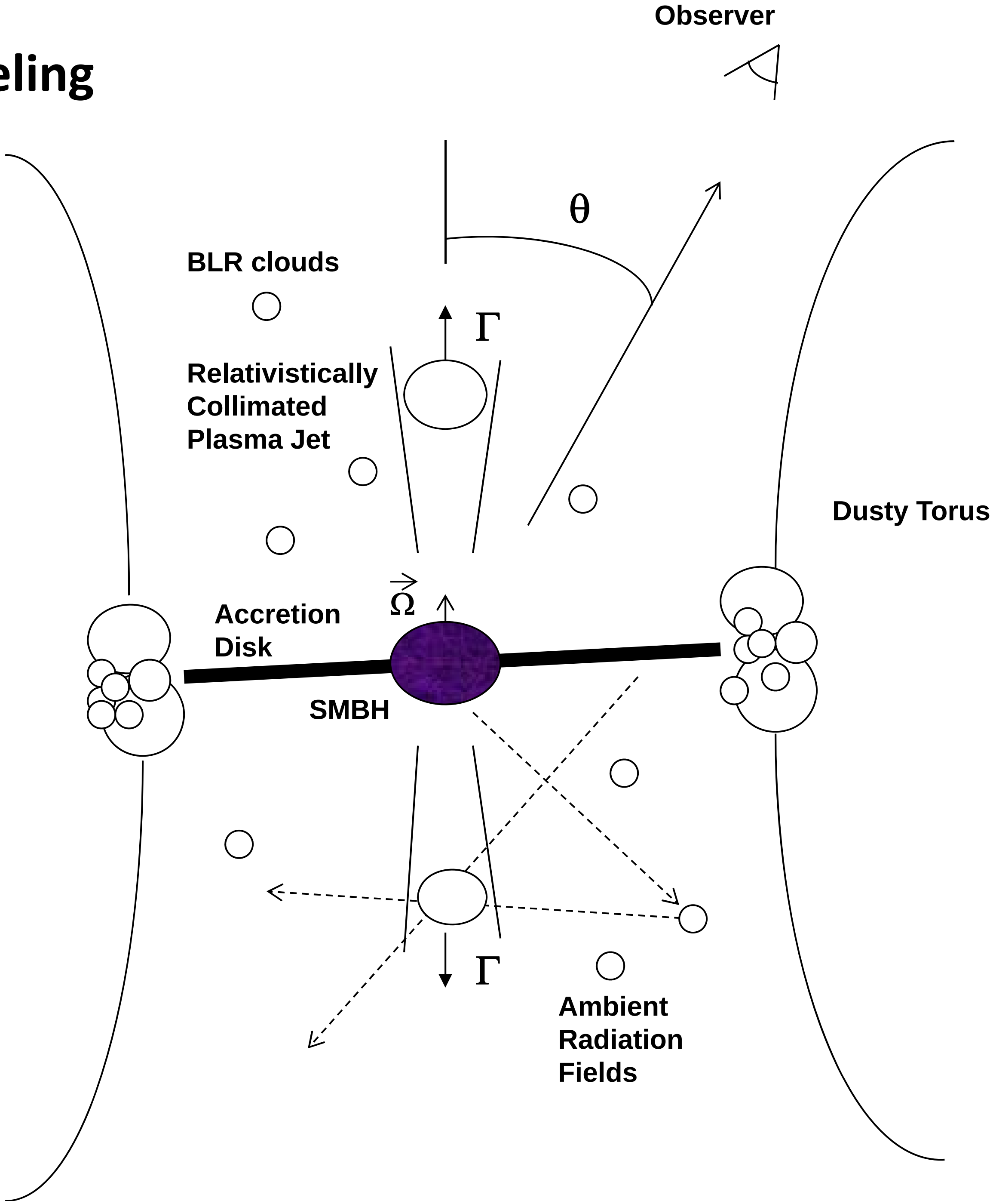
Target photon sources:

Accretion-disk radiation
Broad-line region radiation
IR radiation from molecular torus

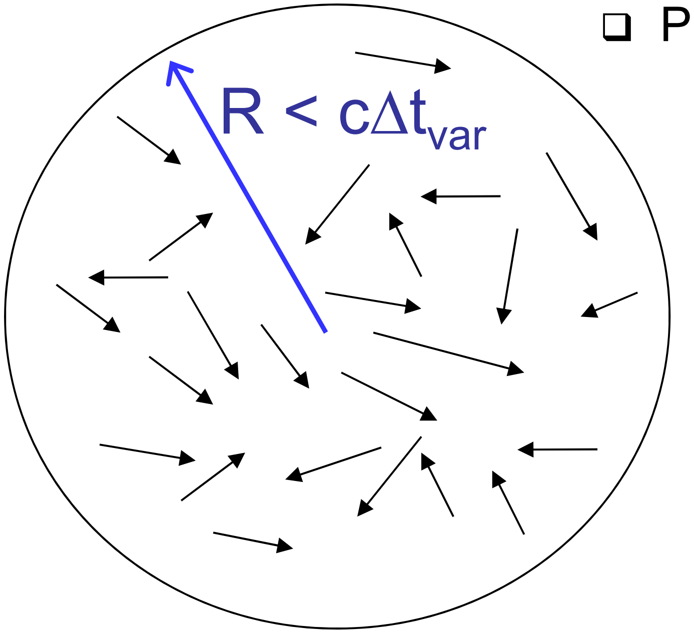
Energy Sources:

1. **Accretion Power**
2. **Rotation Power**

Relativistic plasma outflows: $\Gamma >> 1$



Compactness



- ❑ Puzzle: how to get γ rays out of compact region?

$\gamma\gamma$ opacity $\quad \gamma + \gamma_1 \rightarrow e^+ + e^-$

Threshold: $\varepsilon\varepsilon_1 \equiv \left(\frac{h\nu}{m_e c^2}\right)\left(\frac{h\nu_1}{m_e c^2}\right) > 2$

$$n_\gamma \approx \frac{L_\gamma}{4\pi R^2 c E_\gamma}$$

$$\tau_{\gamma\gamma} \approx \sigma_{\gamma\gamma} n_\gamma R, \ \ \sigma_{\gamma\gamma} \approx \sigma_T$$

Compactness parameter: $\ell \approx \frac{L_\gamma \sigma_T}{4\pi R m_e c^3 \varepsilon}$

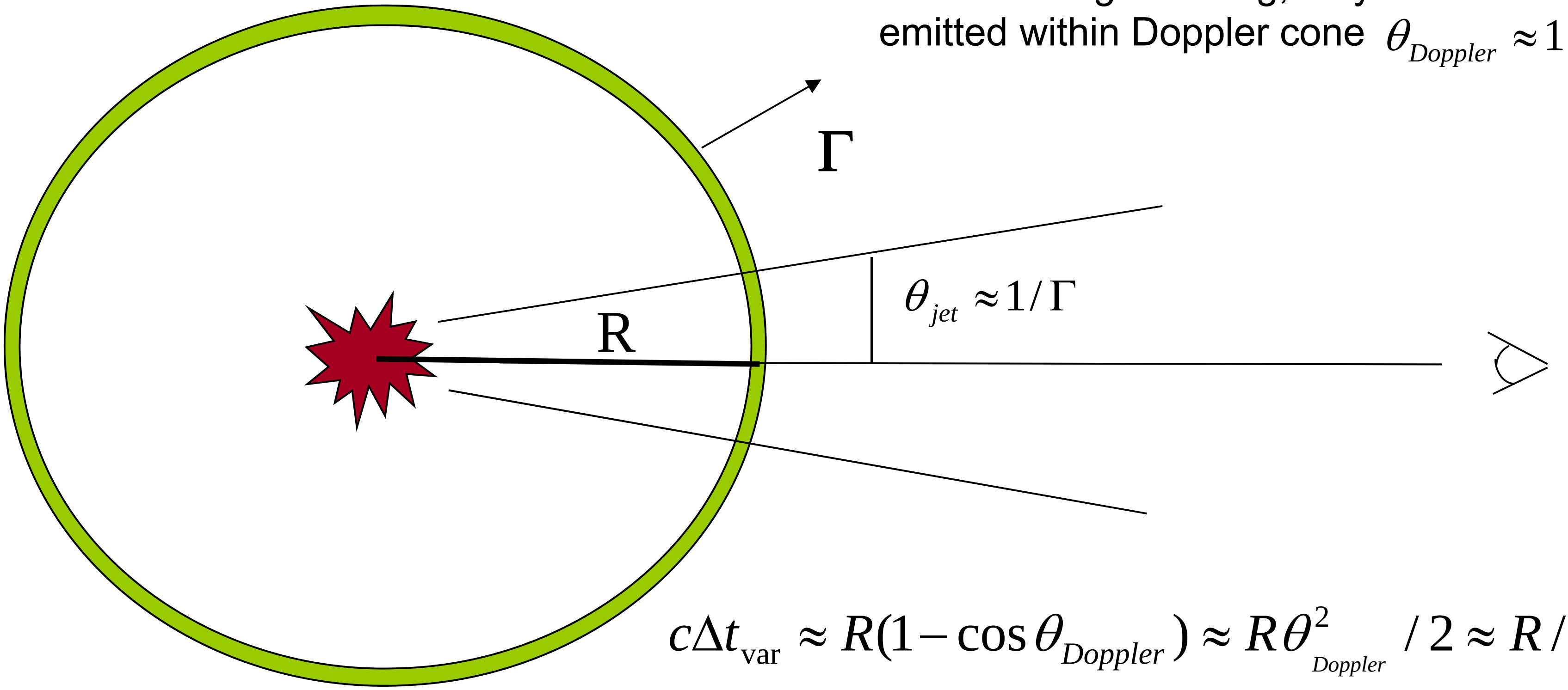
$$\ell \approx \tau_{\gamma\gamma} \approx \frac{\sigma_T L_\gamma}{4\pi m_e c^4 \Delta t_{\rm var}} \approx 10^3 \frac{L_\gamma/(10^{48}\, erg/s)}{\Delta t_{\rm var}(d)}$$

superluminal motion in 3C 120

Solution: Relativistic Bulk Motion

Naively, emission size $R < c\Delta t_{\text{var}}$

- Suppose relativistic spherical shell briefly illuminated, e.g., by shell collisions
- Due to strong beaming, only see emission emitted within Doppler cone $\theta_{Doppler} \approx 1/\Gamma$



$$c\Delta t_{\text{var}} \approx R(1-\cos\theta_{Doppler}) \approx R\theta^2_{Doppler}/2 \approx R/2\Gamma^2$$

$$\Rightarrow R < 2\Gamma^2 c\Delta t_{\text{var}}$$

Emission size ~ Γ^2 larger than values inferred for stationary region

Relativistic Bulk Motion in Blazars

What is Γ, and why is it important?

After redshift z, Γ is the most important property to make the extreme behavior of blazars comprehensible

Doppler factor $\delta_D = [\Gamma(1-\beta\cos\theta)]^{-1}$

$$L \approx \delta_D^4 L' \approx 4\pi c R'^2 \delta_D^4 u'; \, \varepsilon \approx \Gamma\varepsilon'$$

$$R' \approx \delta_D c t_{\text{var}} \Rightarrow L \sim c^3 \delta_D^6 t_{\text{var}}^2 u'$$

$$u'_\gamma \propto \frac{L'_\gamma}{R'^2} \propto \frac{L_\gamma}{\delta_D^6}$$

To be optically thin to $\gamma\gamma$ absorption,
Γ > 10 in Blazars

Particle Acceleration and Radiation in Leptonic Blazar Models

$$\frac{\partial n(\gamma;t)}{\partial t} + \frac{\partial}{\partial \gamma}[\dot{\gamma}\, n(\gamma;t)] + \frac{n(\gamma;t)}{t_{esc}(\gamma,t)} = \dot{n}(\gamma;t)$$

The synchrotron flux is then given by

$$f_{\epsilon}^{\rm syn} = \frac{\delta_{\rm D}^4 \epsilon' J'_{\rm syn}(\epsilon')}{4\pi d_L^2} = \frac{\sqrt{3}\delta_{\rm D}^4 \epsilon' e^3 B}{4\pi h d_L^2} \int_1^{\infty} d\gamma' N'_e(\gamma') R(x).$$

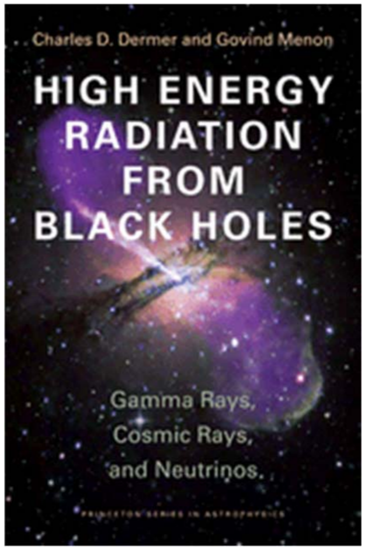
$$f_{\epsilon_s}^{\rm SSC} = \left(\frac{3}{2}\right)^3 \frac{d_L^2 \epsilon_s'^2}{R_b'^2 c \delta_{\rm D}^4 U_B} \int_0^{\infty} d\epsilon' \frac{f_{\tilde{\epsilon}}^{\rm syn}}{\epsilon'^3} \times \int_{\gamma'_{\rm min}}^{\gamma'_{\rm max}} d\gamma' \frac{F_{\rm C}(q,\Gamma_e) f_{\hat{\epsilon}}^{\rm syn}}{\gamma'^5},$$

$$f_{\epsilon}^{EC} = \frac{3}{4} \frac{c\sigma_{\rm T}\epsilon_s^2}{d_L^2} \delta_{\rm D}^3 \int_0^{\infty} d\epsilon_* \frac{u_*(\epsilon_*)}{\epsilon_*^2} \int_{\gamma_{min}}^{\gamma_{max}} d\gamma \frac{N'_e(\gamma',\Omega')}{\gamma^2} F_{\rm C}(q,\Gamma_e)$$

$$f_{\varepsilon} = \nu F_{\nu}$$

1. **Inject power laws and cool**
2. **Separate acceleration and radiation zones**
3. **Single zone; exclude radio**
4. **Power law injection**
5. **Nonlinear losses**
6. **Adiabatic expansion**
7. **Light travel time effects**
8. **Cascading/$\gamma\gamma$ pair production**
9. **Multizone/spine-sheath**
10. **Anisotropic effects**
11. **Reverberation/echo**

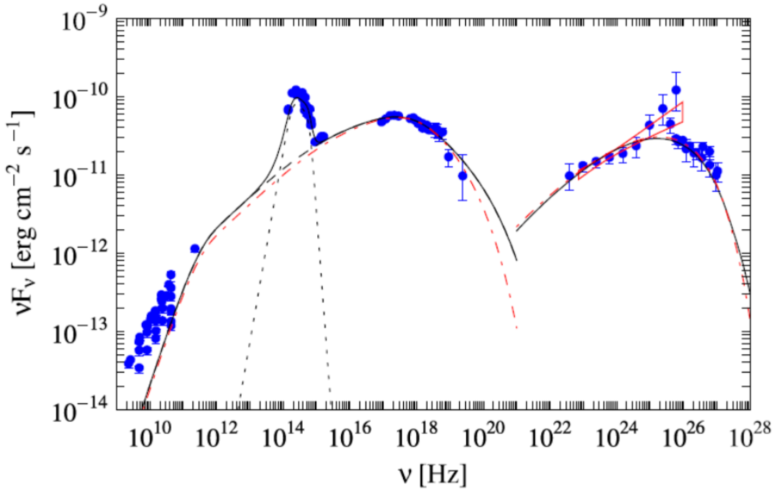
Boettcher & Chiang (2002)
Finke et al. (2008)
Dermer & Menon (2009)



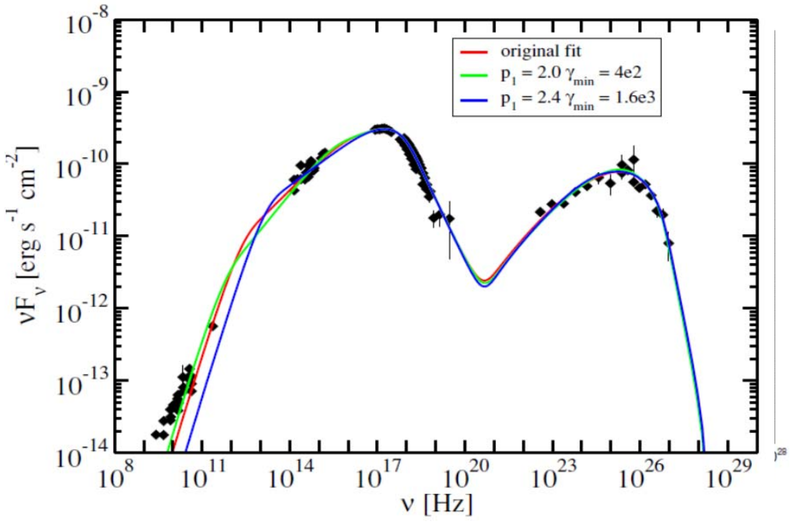
Spectrum and Jet Physics

- **BL Lacs:** synchrotron/SSC model fits

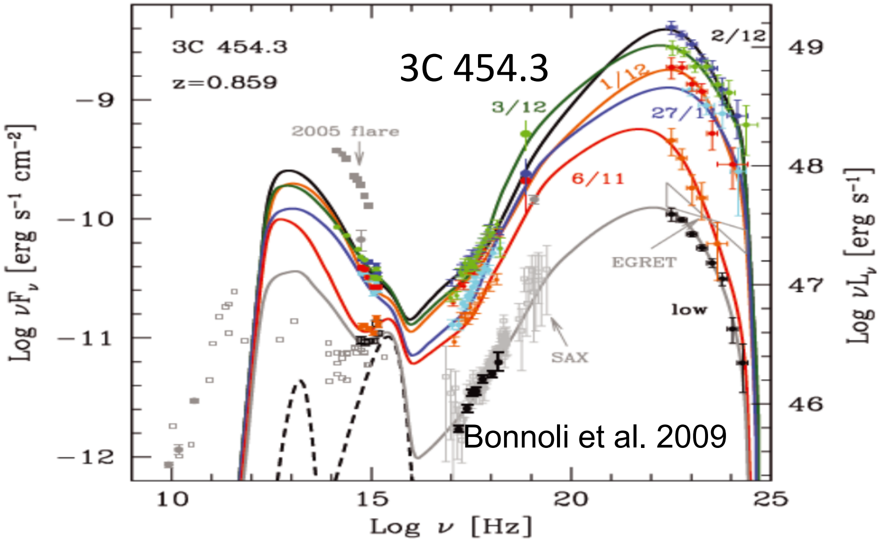
Abdo et al. 2011a



Abdo et al. 2011b

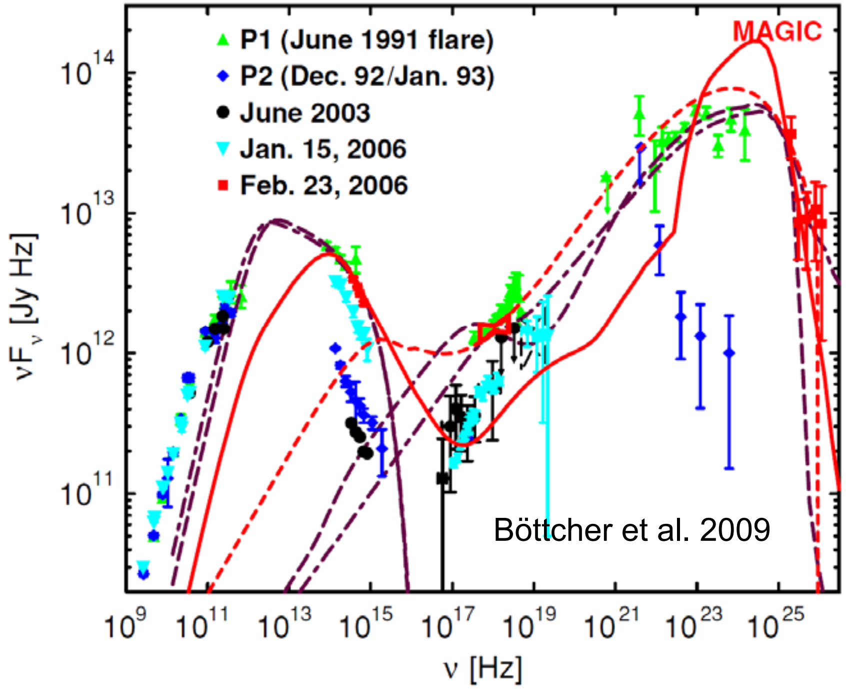


- **FSRQs:** synchrotron/SSC + EC



Bonnoli et al. 2009

3C279

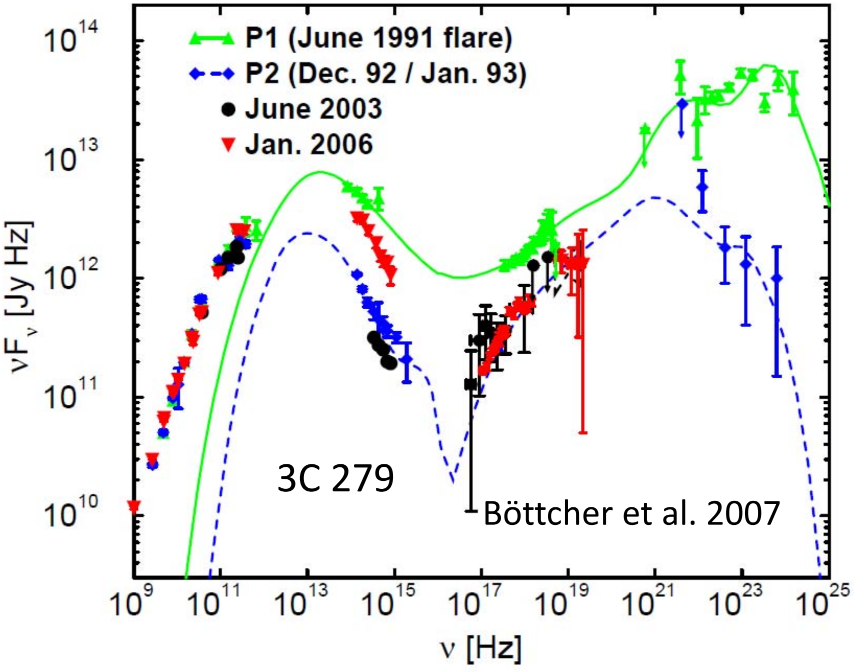


Böttcher et al. 2009

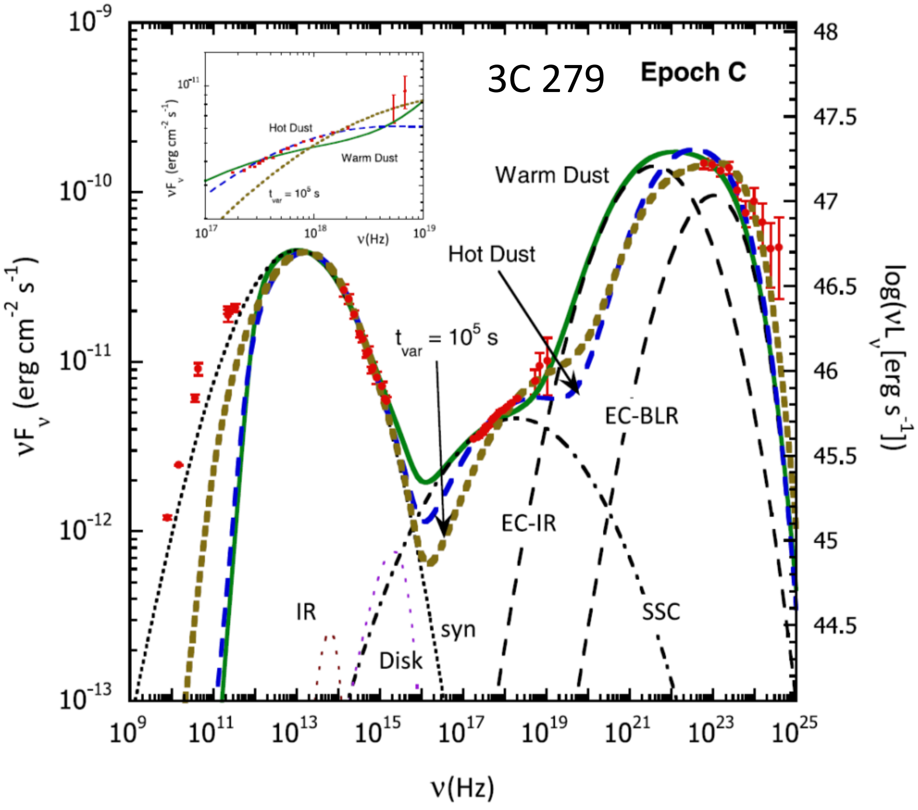
Blazar Spectral Modeling

- Standard Approach
  - synchrotron/SSC + external Compton
  - Inject power laws + cooling

- Equipartition Approach
  - Log-parabola electron distribution
  - Equipartition between magnetic field and nonthermal electrons

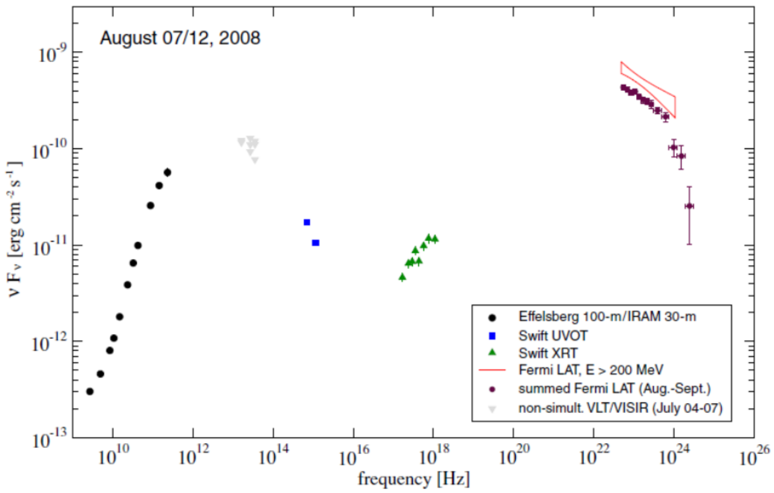


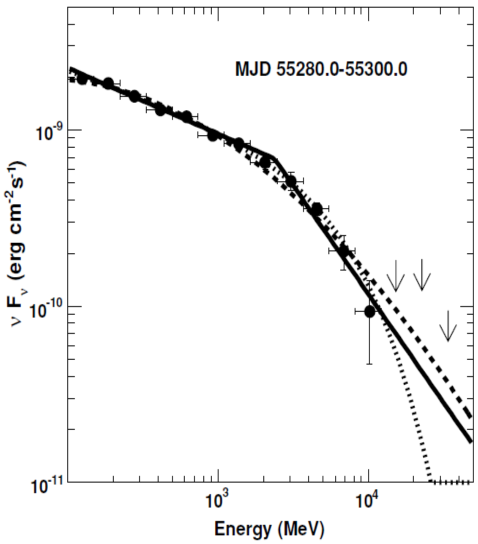
Böttcher et al. 2007

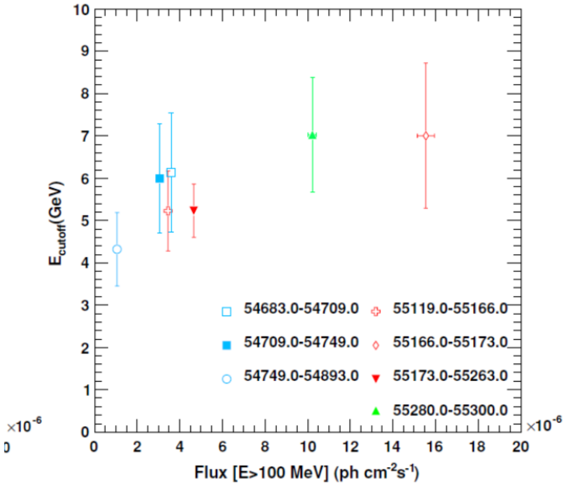


Dermer, Cerruti, Lott, Boisson, Zech 2014

GeV spectral breaks in FSRQs, LSP/ISP blazars







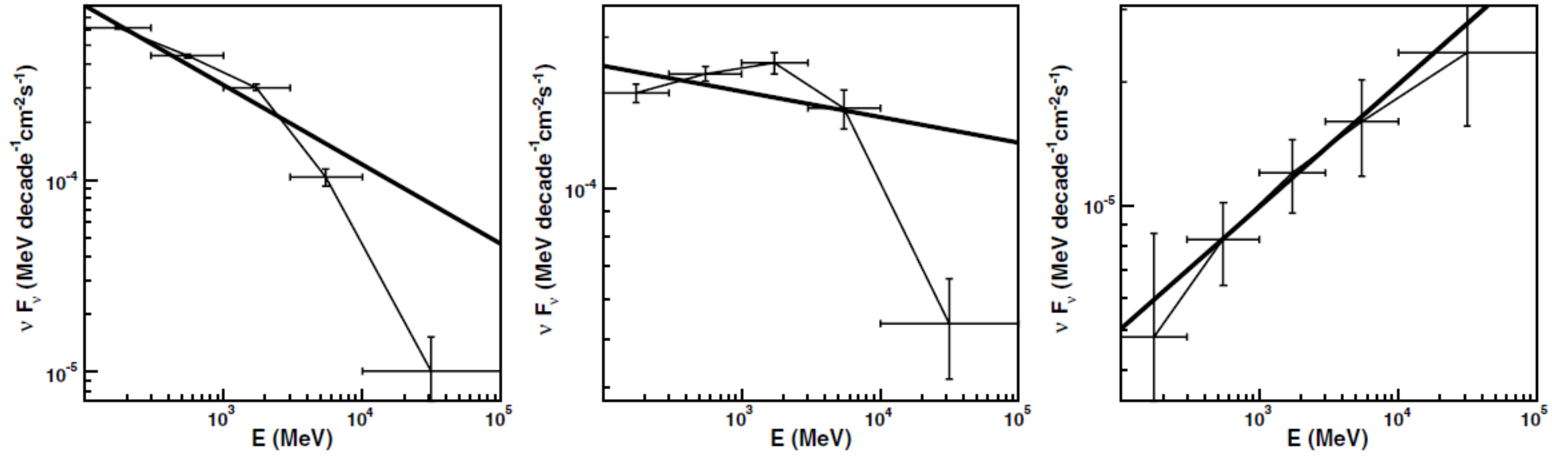
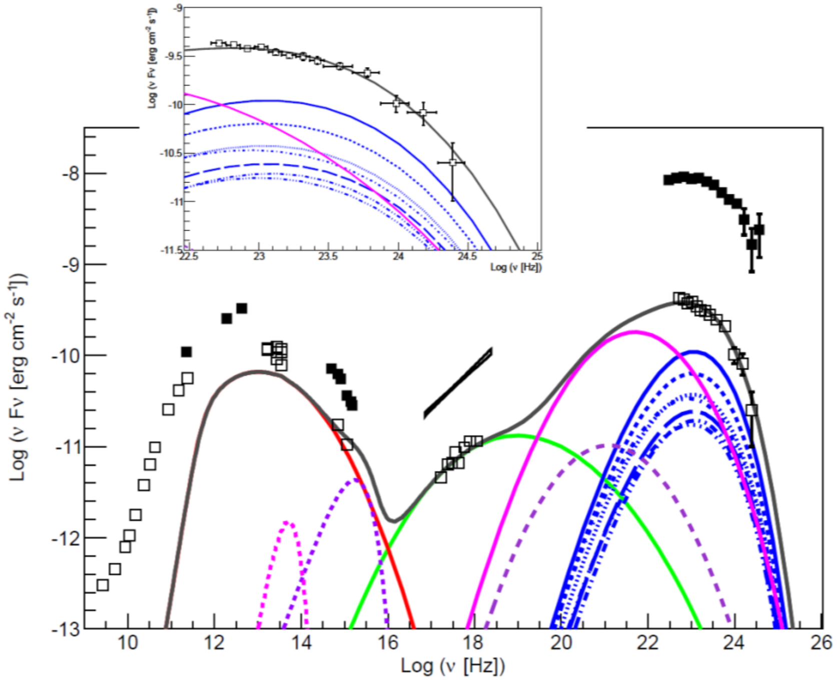
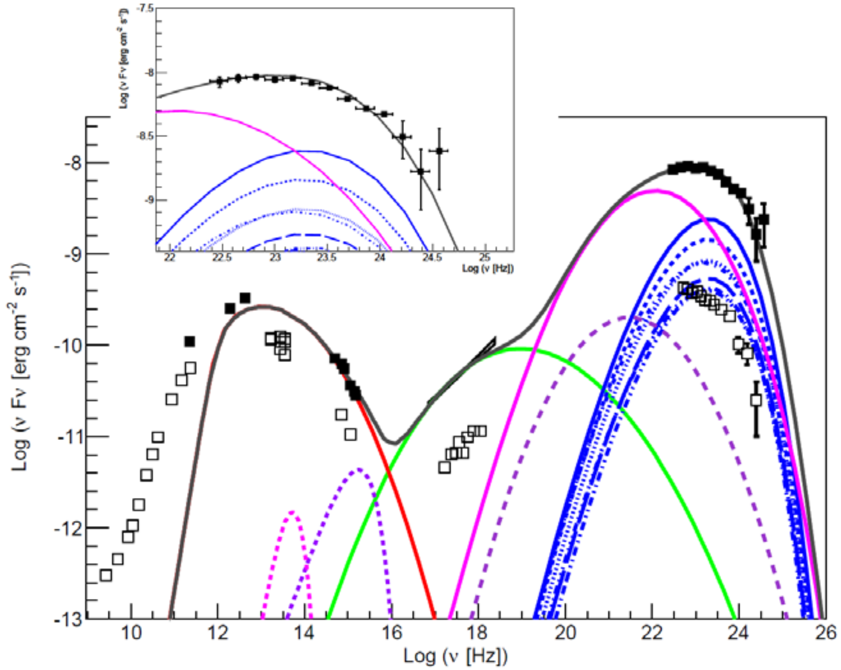


Figure 10. γ-ray SEDs of three bright blazars calculated in five energy bands, compared with the power law fitted over the whole energy range. Left: 3C 454.3 (FSRQ). Middle: AO 0235+164 (IBL). Right: Mkn 501 (HBL).

Spectral Fits to 3C 454.3





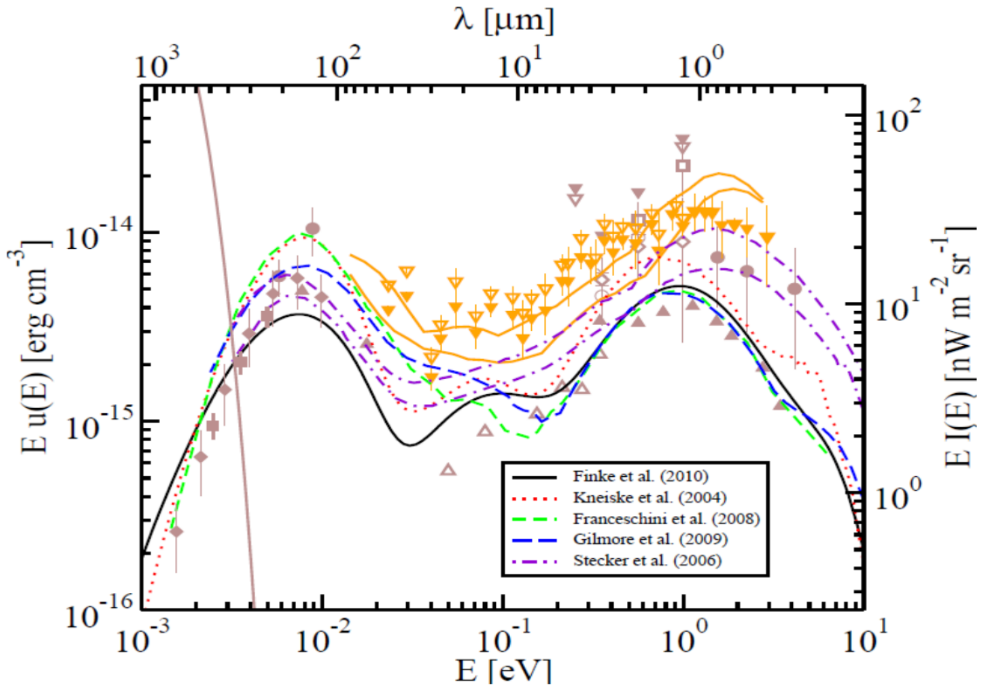
- **Epoch A:** August 2008 low state (Abdo et al. 2009)
- **Epoch B:** November 2010 high state (Abdo et al. 2011; Wehrle et al. 2012)

	Input								Output						
Epoch^a	L_{48}	t_4	ν_{14}	ζ_e	ζ_s	$\zeta_{Ly\alpha}$	ζ_{IR}	b	δ	B	R	γ'_p	$N'_e(\gamma'_p)$	$u_{Ly\alpha}$	L^b_{jet}
										G	10^{16} cm		cm^{-3}	10^{-4} erg cm^{-3}	10^{45} erg s^{-1}
A	0.8	10	0.03	0.6	0.07	1.2	0.96	1.0	22.9	0.76	6.86	204	0.15	1.57	10.1
B	2.4	3.5	0.03	3.5	0.12	10.5	8.4	1.0	39.3	0.56	4.13	180	0.56	2.56	25.1

Cerruti, Dermer, Lott, Boisson, Zech 2012

Predicts no VHE emission: made by separate (hadronic?) process

Extragalactic Background Light (EBL)



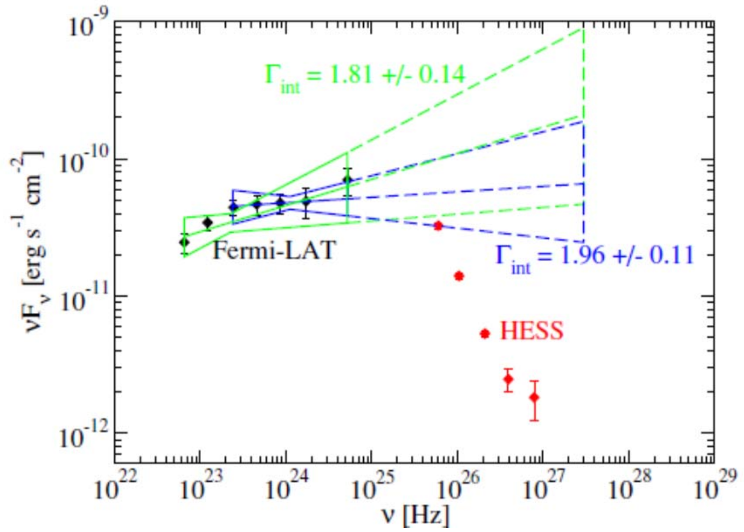
Infrared/optical EBL from past stellar activity and dust absorption and re-radiation
(attenuates TeV radiation)

Difficult to directly measure

Provides a source of γγ opacity in intergalactic space through the process

$$\gamma + \gamma' \rightarrow e^+ + e^-$$

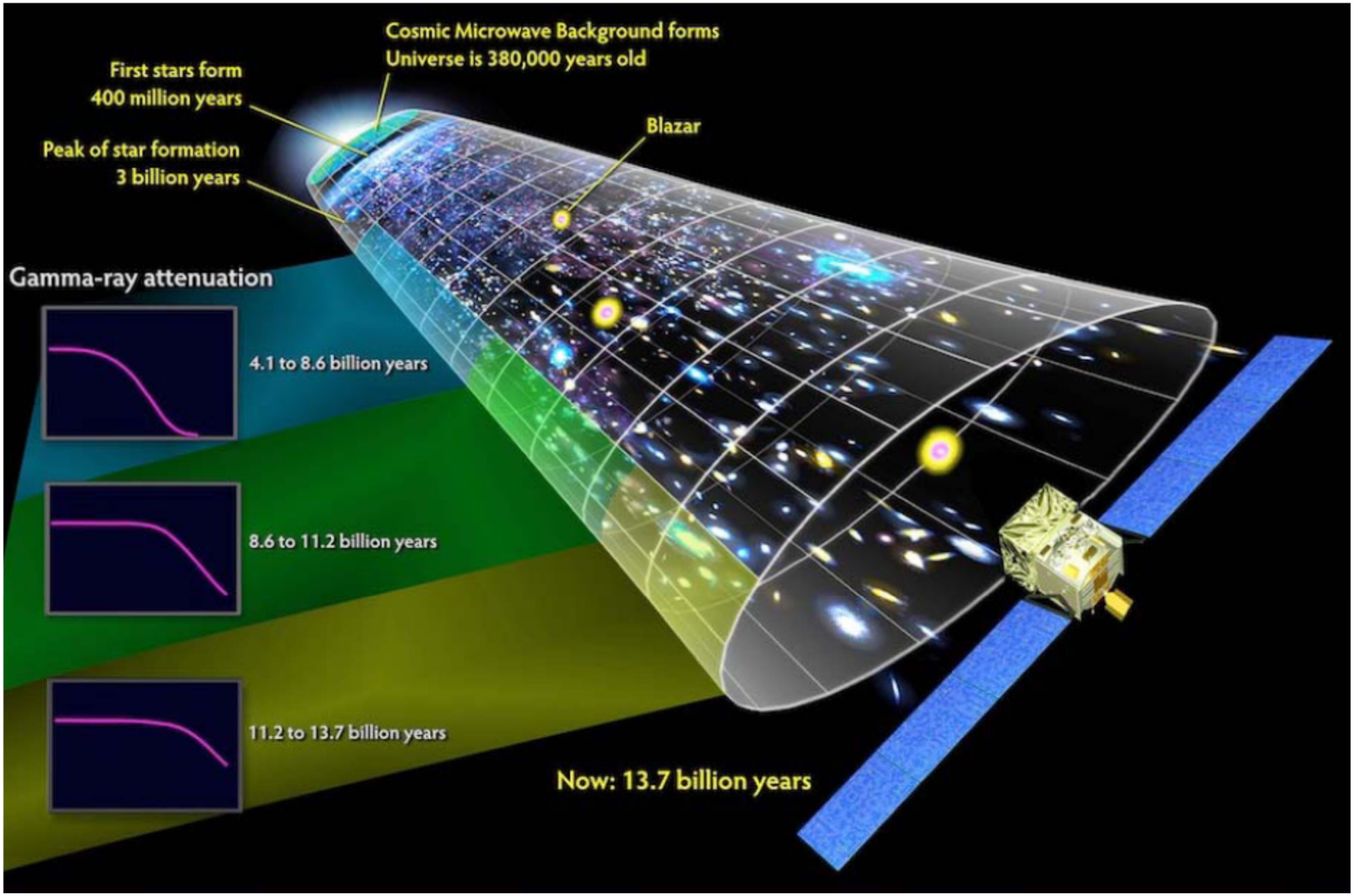
Gould & Schrder 1966
Stecker, de Jager, Salamon 1992



Fermi spectrum extrapolated into TeV range bounded by deabsorbed TeV spectrum– constrains EBL model

Blazars and the Extragalactic Background Light

Ajello/Fermi Collaboration 2012



Problems in Blazar Studies

1) **Short variability times of luminous BL Lac objects**
2) **Unusual weakly variable BL Lac class**
3) **Distinct spectral components revealed by deabsorption of blazar VHE spectra**
4) **Flattening at moderate redshift in the Stecker-Scully relation showing the GeV - TeV spectral index difference versus redshift**
5) **Conflicting results for the location of the γ-ray emission site in blazars**
6) **VHE (> 100 GeV) emission from distant FSRQs γ rays formed by $\gamma\gamma \rightarrow e^+e^-$ with photons of ambient radiation fields**
7) **The Synchrotron Puzzle**

TeV BL Lac Objects

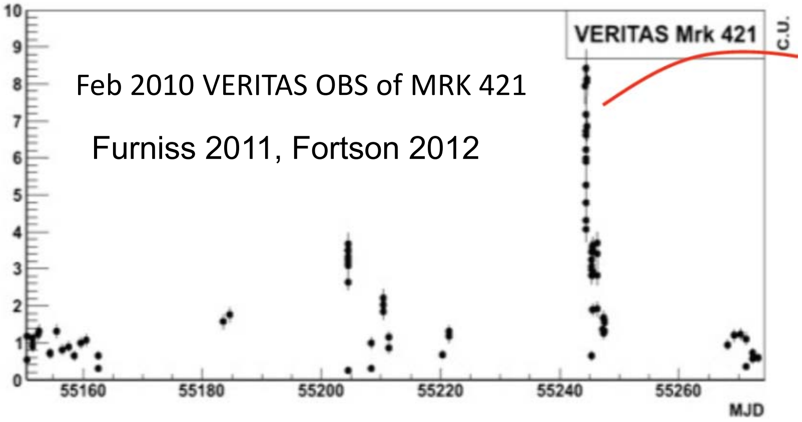
❑ **Strongly variable class**

Mrk 421, z = 0.03

Mrk 501, z= 0.033

PKS 2155-305, z = 0.116

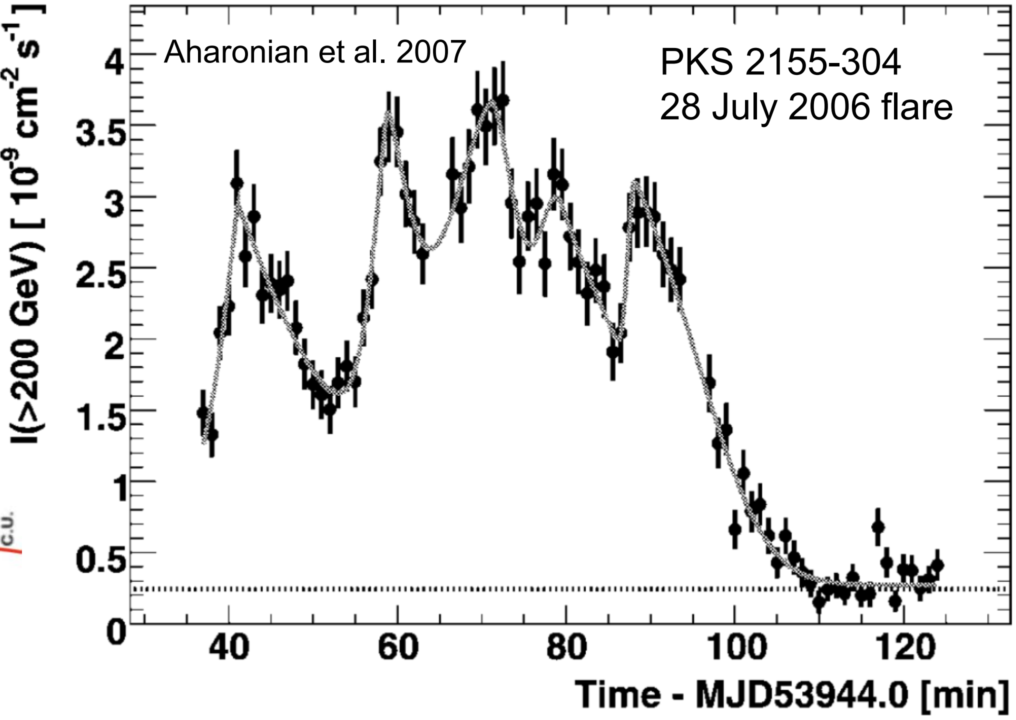
- $t_{var} < R_S/c$, $L > L_{EDD}$
- Extreme sources



Feb 2010 VERITAS OBS of MRK 421

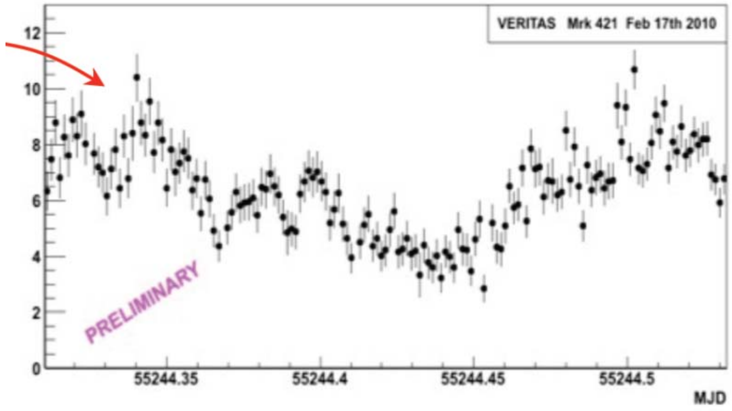
Furniss 2011, Fortson 2012

$$R_S/c = 10^4 M_9 \text{ s}$$
$$t_{var} \sim 5 \text{ min} = 300 \text{ s}$$
$$\Rightarrow (?)\ M << 10^8\ M_0$$



Aharonian et al. 2007

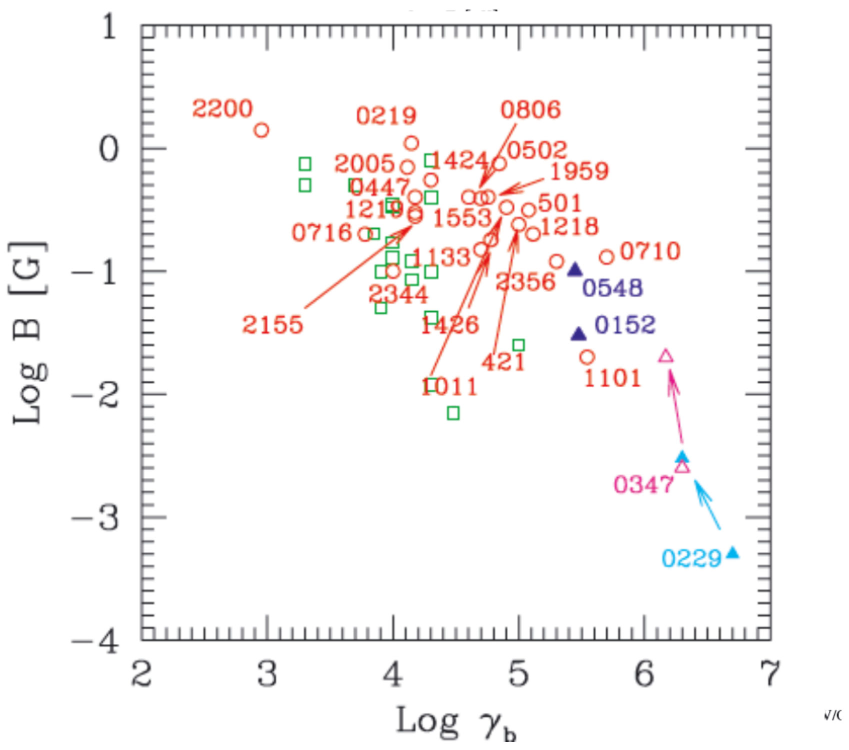
PKS 2155-304
28 July 2006 flare



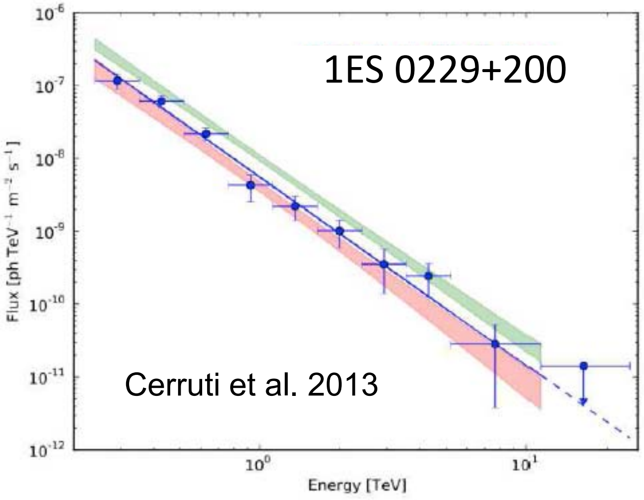
TeV BL Lac Objects

- ❑ **Weakly variable class**
  - – **Weak Fermi LAT fluxes**

1ES 0229+200 z = 0.14
1ES 0347-121 z = 0.186
1ES 1101-232 z = 0.14
1ES 0548-322 z = 0.069
RGB J0152+0.17 z = 0.08



Tavecchio et al. 2011



1ES 0229+200

Cerruti et al. 2013

Compton-scattered CMBR from extended jet/lobe

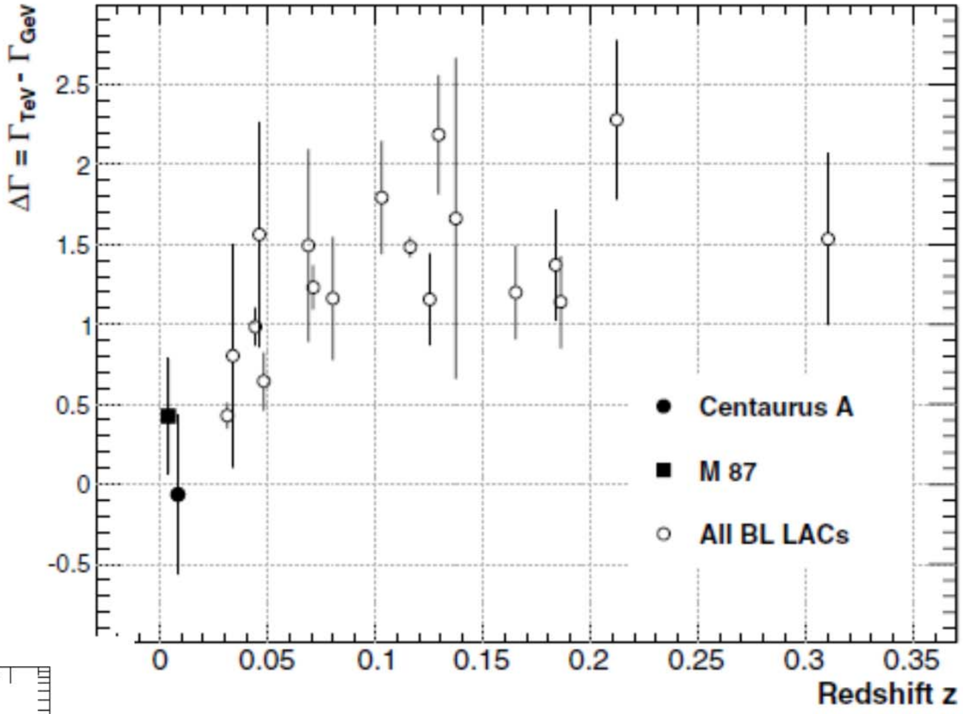
Böttcher et al. 2008

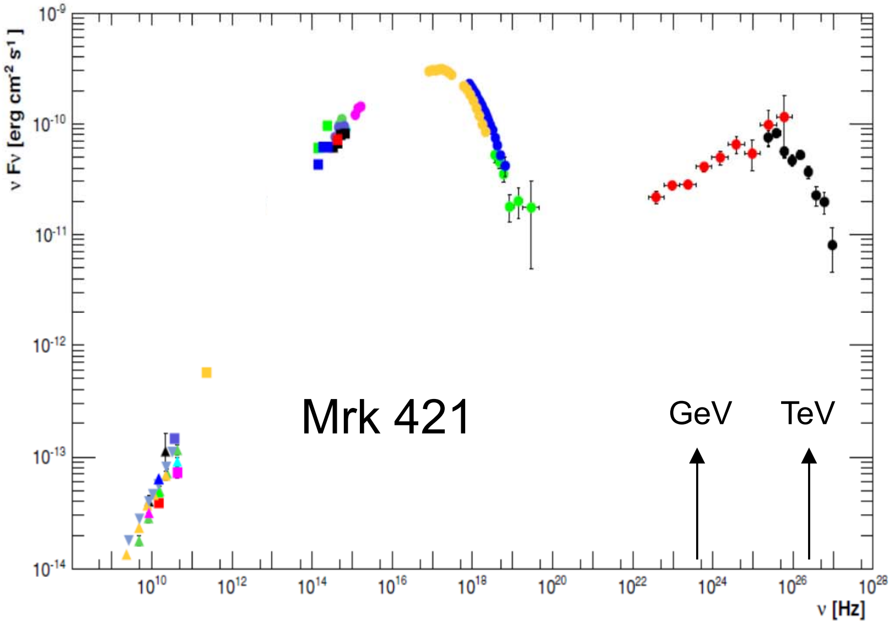
Stecker-Scully Relation
and
High-Redshift VHE Blazars

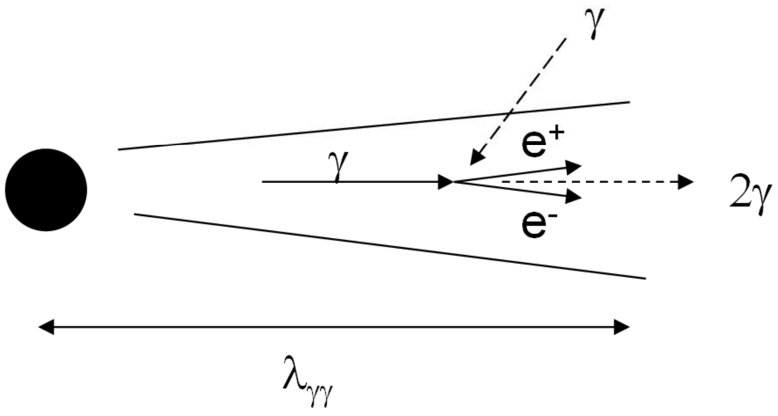
- GeV-TeV Spectral index difference $\Delta\Gamma$

Stecker & Scully (2006, 2010)

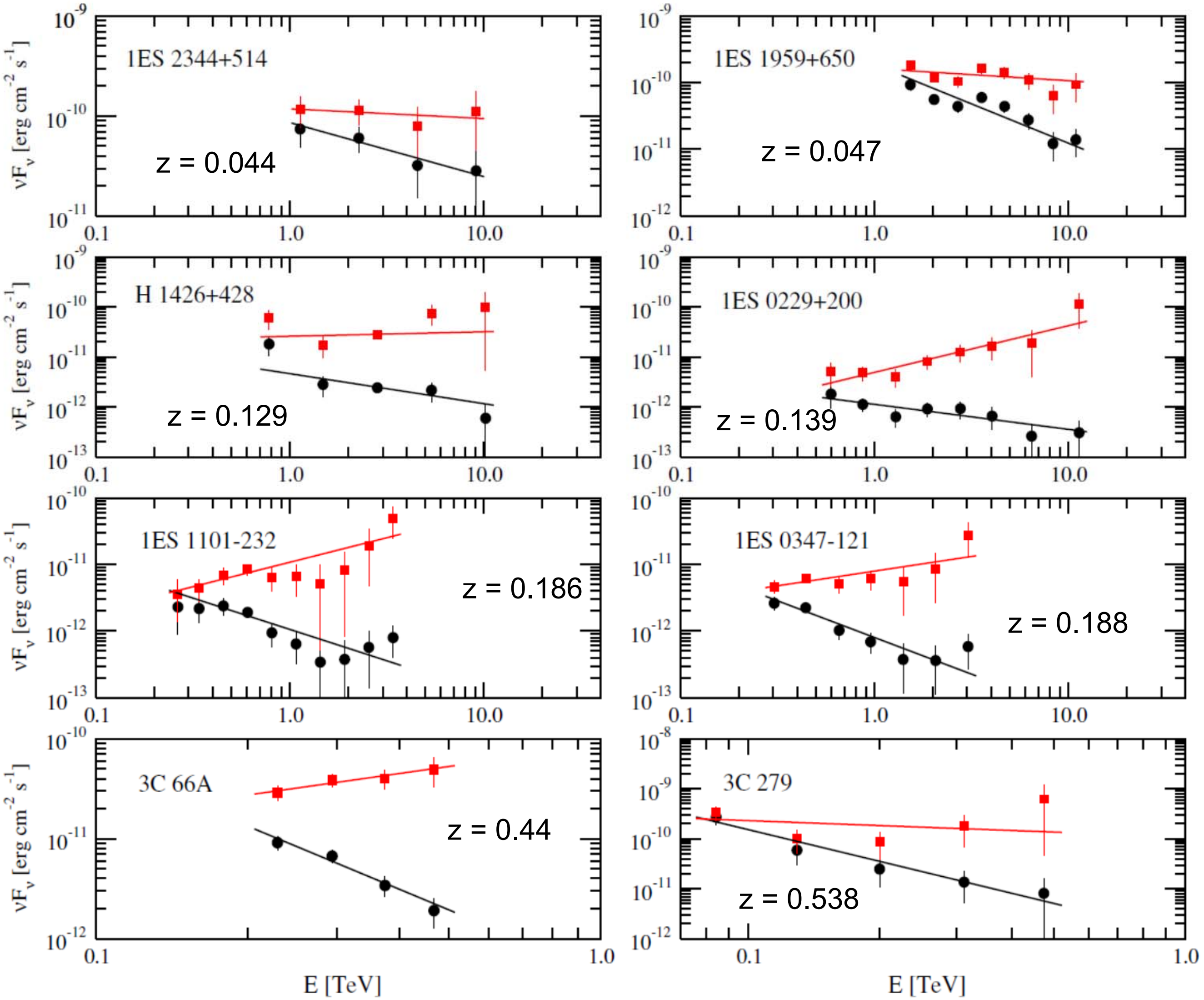
(cf. Sanchez et al. 2013)



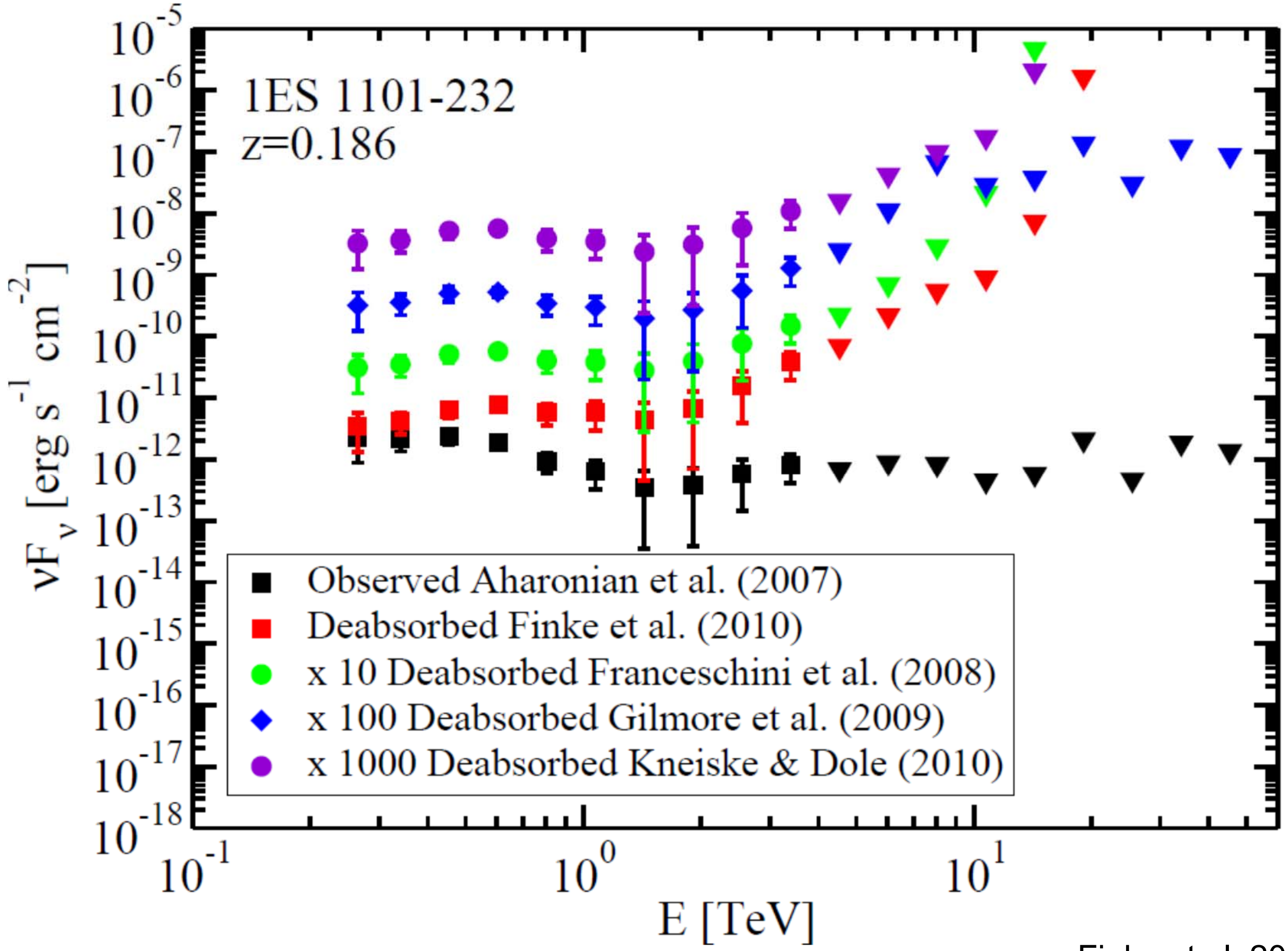




Deabsorbed Blazar Spectra: Evidence for Extra Spectral Component?

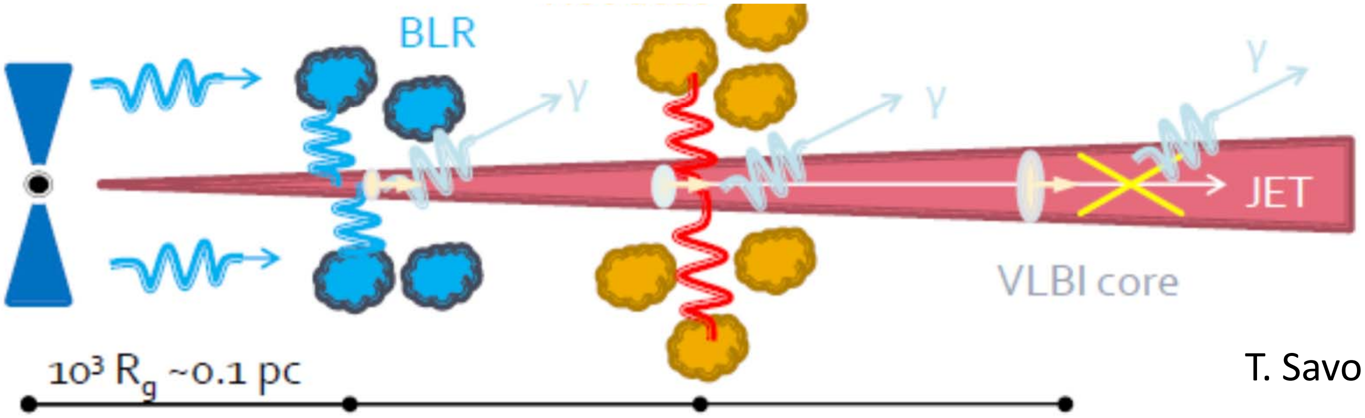


Finke et al. 2010



Finke et al. 2010

Location of γ-Ray Emission Region



T. Savolainen

1. Radio-γ correlations
2. Optical polarization angle swings: 3C 279, PKS 1510-089, OJ 287
3. Rapid variability, large luminosity implies inner jet origin of γ rays

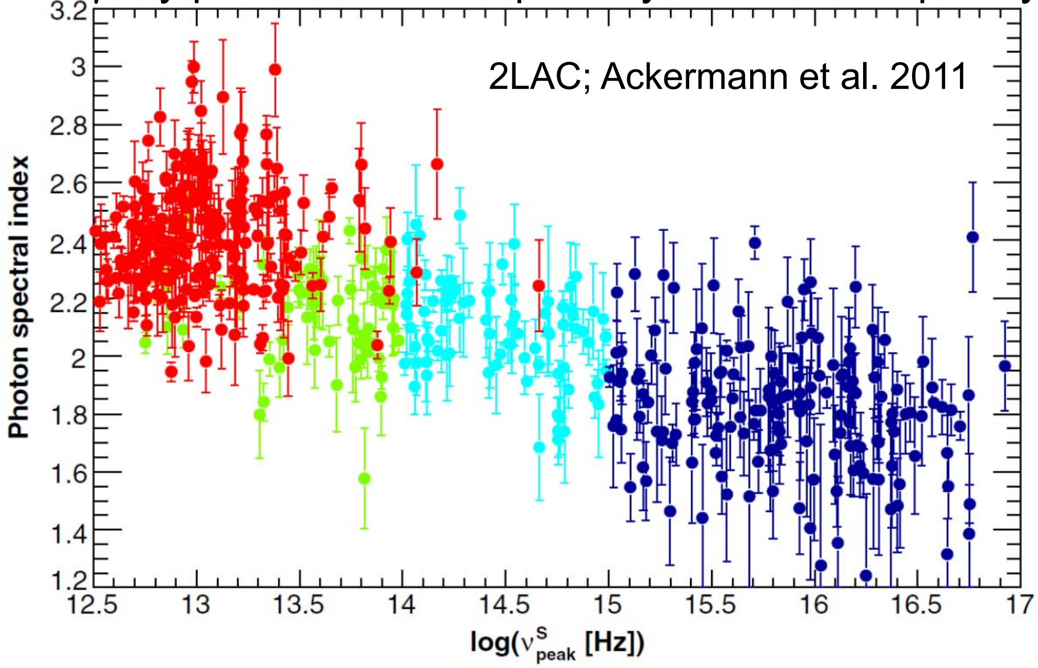
$$R < c\Gamma^2 \Delta t_{\mathrm{var}} \approx 0.05(\Gamma/100)^2(\Delta t_{\mathrm{var}}/10\ \mathrm{min})\ pc$$

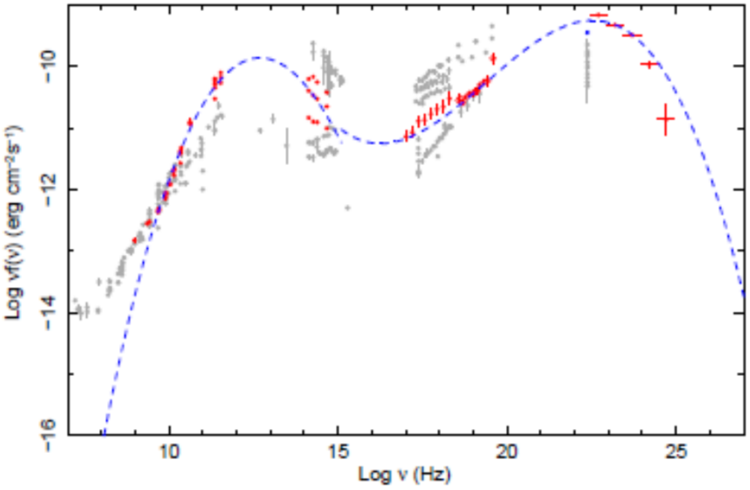
$$R > R_{\gamma\gamma} \Rightarrow R >> R_{BLR} \approx 0.1\, pc$$

4C +21.35

The Synchrotron Puzzle

γ-ray photon index vs. peak synchrotron frequency





In Fermi acceleration scenarios, acceleration timescale > Larmor timescale

Equating synchrotron energy loss time scale with Larmor timescale implies maximum synchrotron energy ~ 100Γ MeV (de Jager & Harding 1992)

Many orders of magnitude greater than peak or maximum synchrotron frequency of blazars!

Steps Forward with Fermi

1) Acceleration Physics
2) Hadronic Component: UHECRs
3) New Physics--Axions

Acceleration Physics

First-Order Fermi Acceleration

$$t_I \approx f t_L \propto f\gamma$$

Second-order Fermi Acceleration

$$t_{II} \propto \varsigma \beta_A^2 \gamma^{2-q}$$

Makes curved particle distribution

$$\gamma'^2 N_e'(\gamma'^2) = K\left(\frac{\gamma'}{\gamma'_{pk}}\right)^{-b\log(\gamma'/\gamma'_{pk})}$$

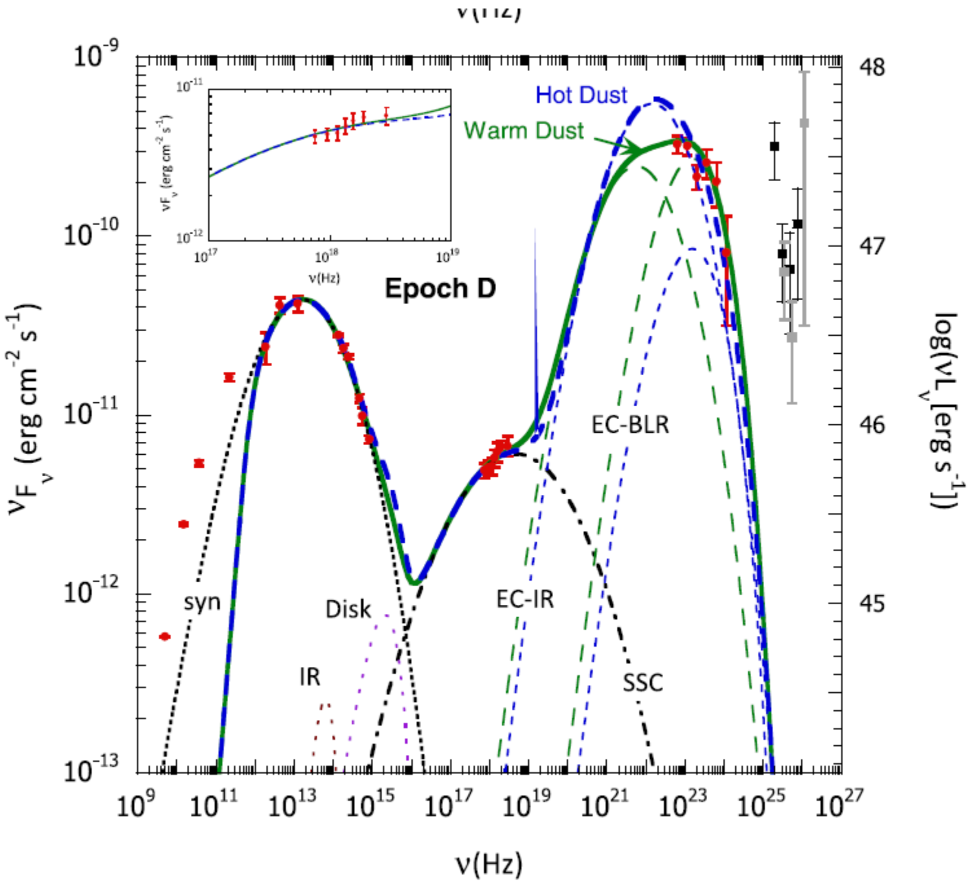
Turbulent particle acceleration scenario
(Lazarian et al.)

Magnetic Reconnection

Giannios, Narayan & Piran 2012

Jets within Jets

Marscher



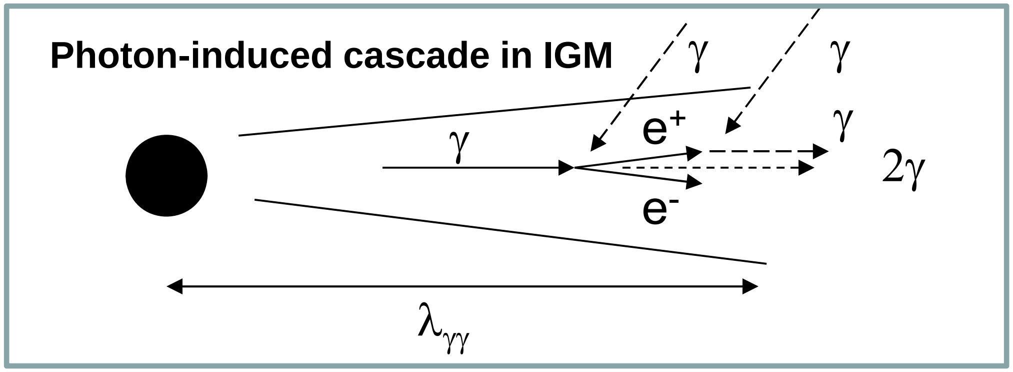
Dermer et al. 2014

Gamma-ray and Cosmic-ray Induced TeV emissions from Jetted Sources

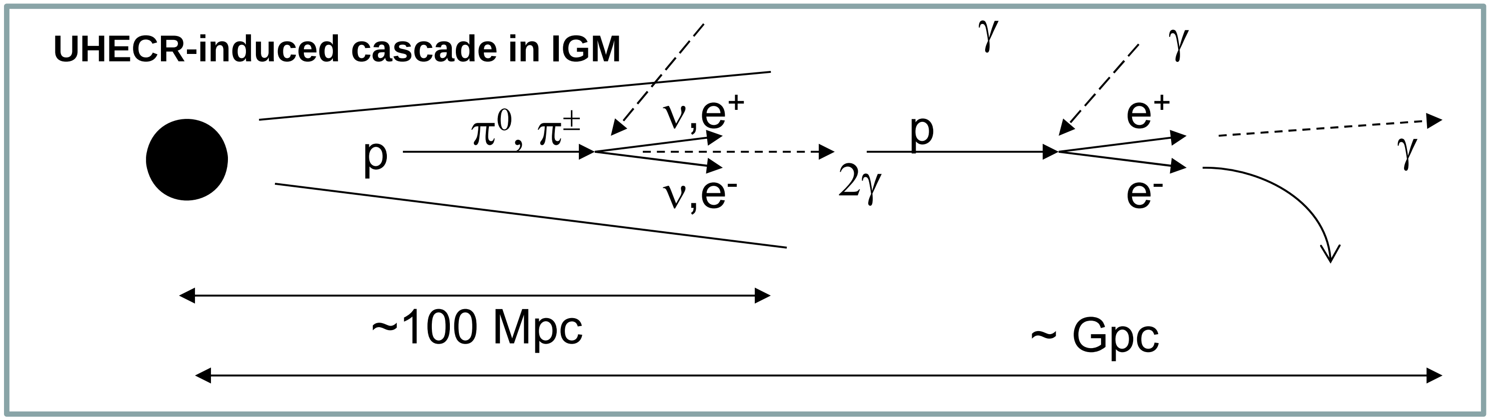
Mechanism for making

Weakly variable cascade radiation

Hard VHE component



Photon-induced cascade in IGM



UHECR-induced cascade in IGM

UHECR protons with energies ~10^{19} eV make ~10^{16} eV $e^{\pm}$ that cascade in transit and Compton-scatter CMBR to TeV energies

Essey, Kalashev, Kusenko, Beacom (2010, 2011)

Limits on IGMF and Correlation Length

Origin of the Intergalactic Magnetic Field (B_{IGMF}):

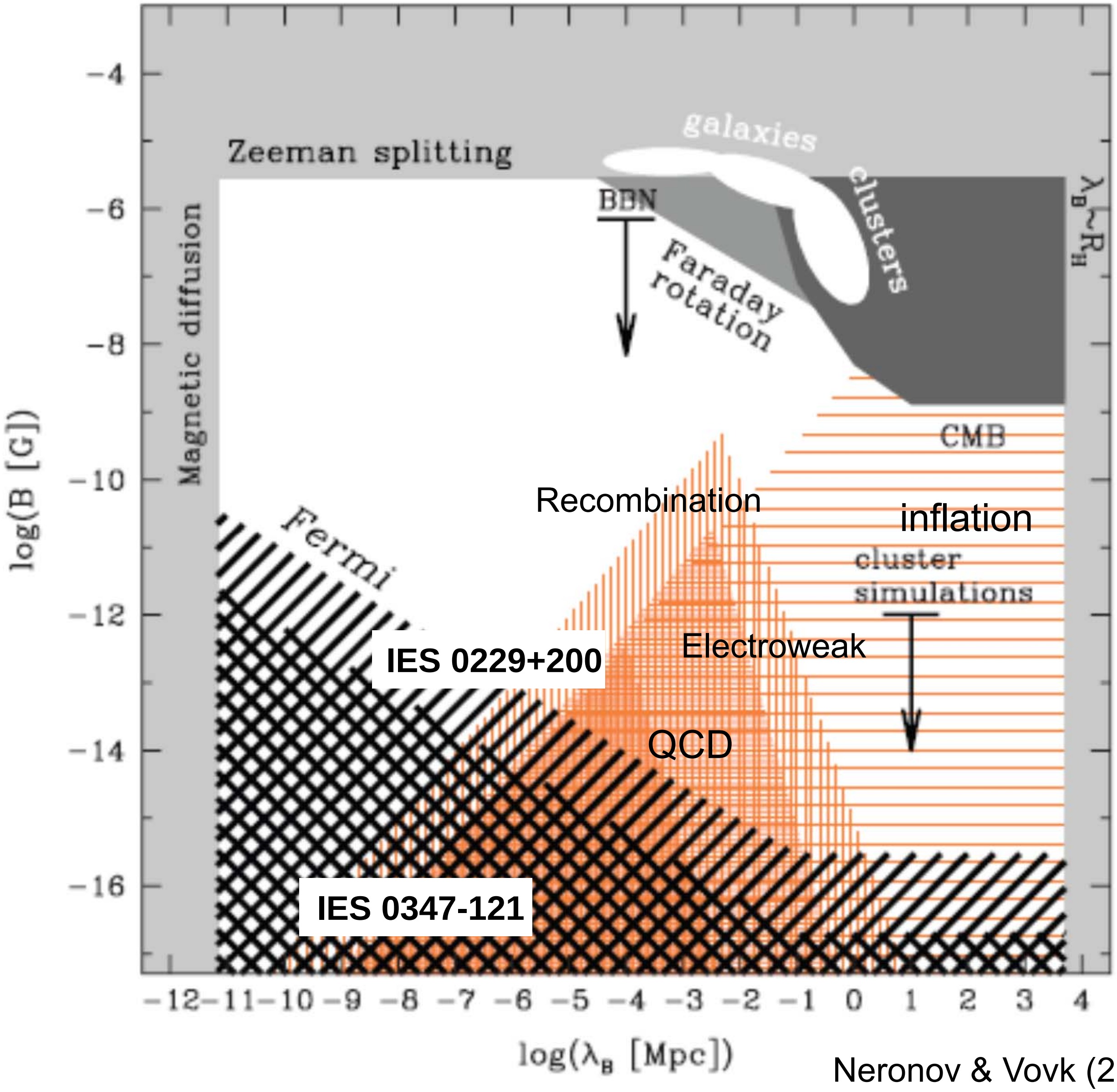
Primordial

Early universe physics

Biermann battery ($\sim 10^{-30}$ G on Mpc scale)

Galaxy dynamo

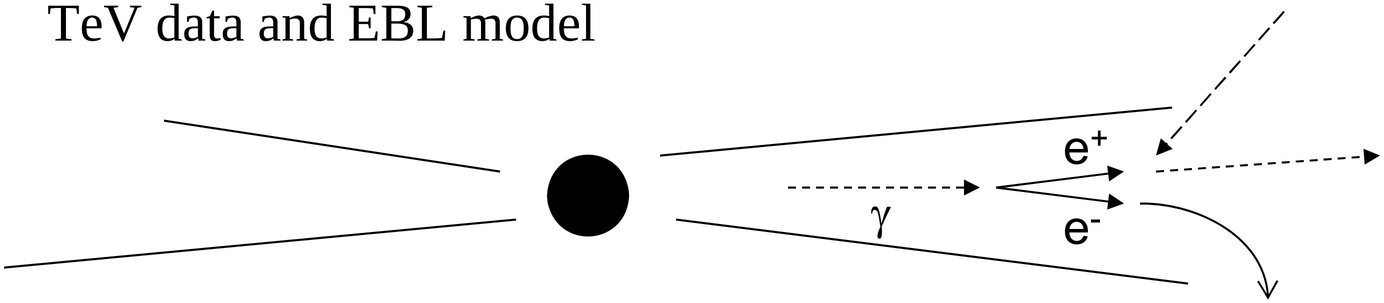
other

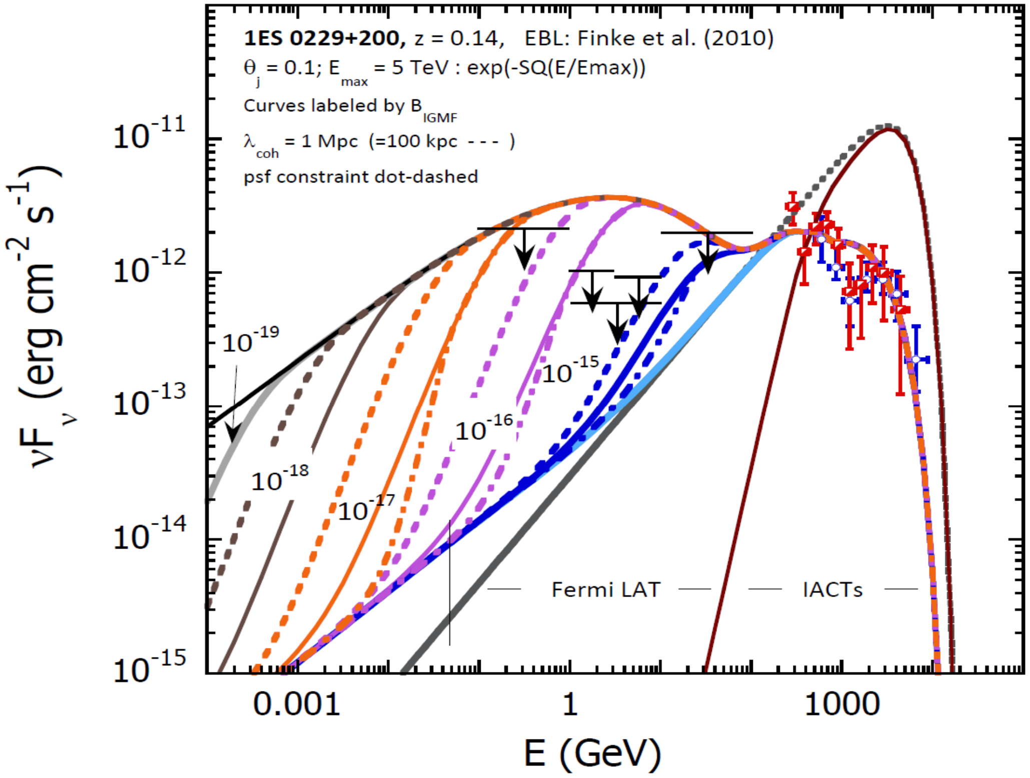


Neronov & Vovk (2010)

Lower Limits on the Intergalactic Magnetic Field

- ❑ Use Fermi upper limits or detections at GeV energies to limit B_{IGMF} given TeV data and EBL model





$\overset{?}{\Rightarrow}$ $B_{IGMF} \gtrsim 10^{-15}$ G

(Neronov & Vovk 2010; Tavecchio et al. 2010)

$\Rightarrow$ $B_{IGMF} \gtrsim 10^{-18}$ G

(relaxing assumption of extended TeV emission)

(CD, Cavadini, Razzaque, Finke, Chiang, Lott, 2011)

Electromagnetic Signatures of UHECRs

Photon-induced cascade in IGM

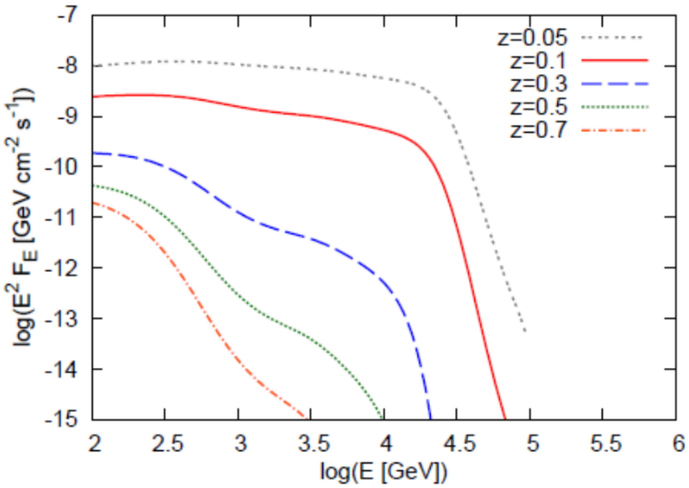
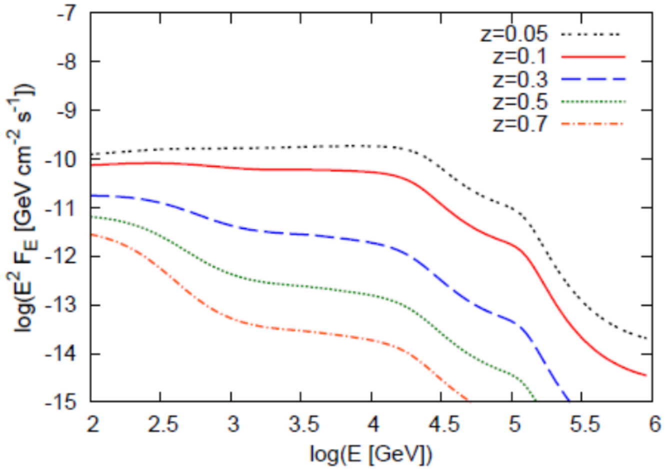
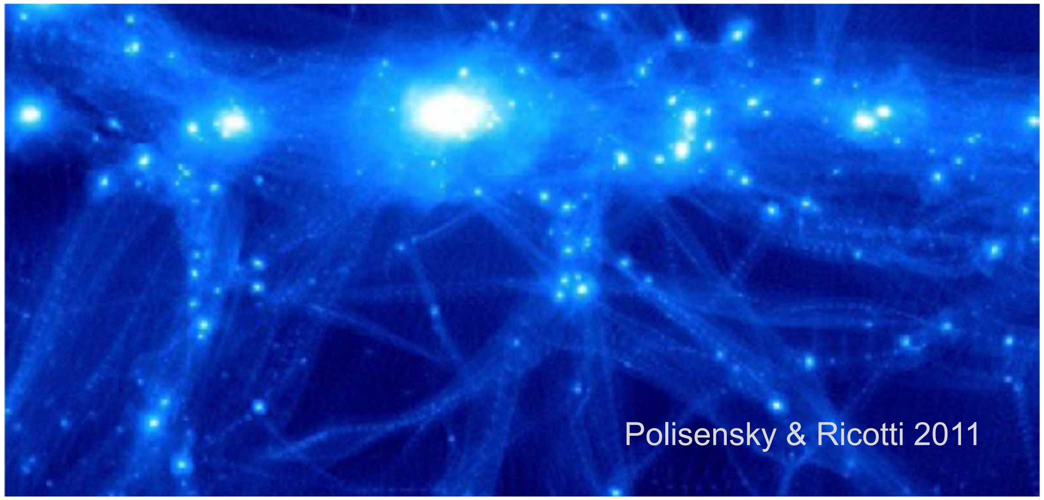


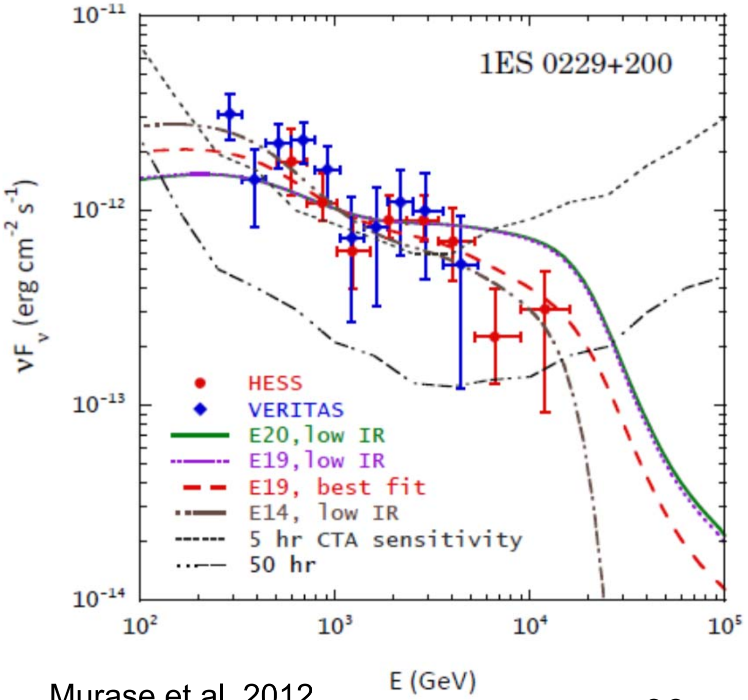
FIG. 1.— Spectra of VHE γ-ray-induced cascade emission for various source redshifts. We assume the total γ-ray luminosity of $L_\gamma = 10^{45}$ erg s^{-1} with $\beta = 2/3$ and $E^{\max} = 100$ TeV. The low-IR EBL model of Kneiske et al. (2004) is used here.

UHECR-induced cascade in IGM





Polisensky & Ricotti 2011



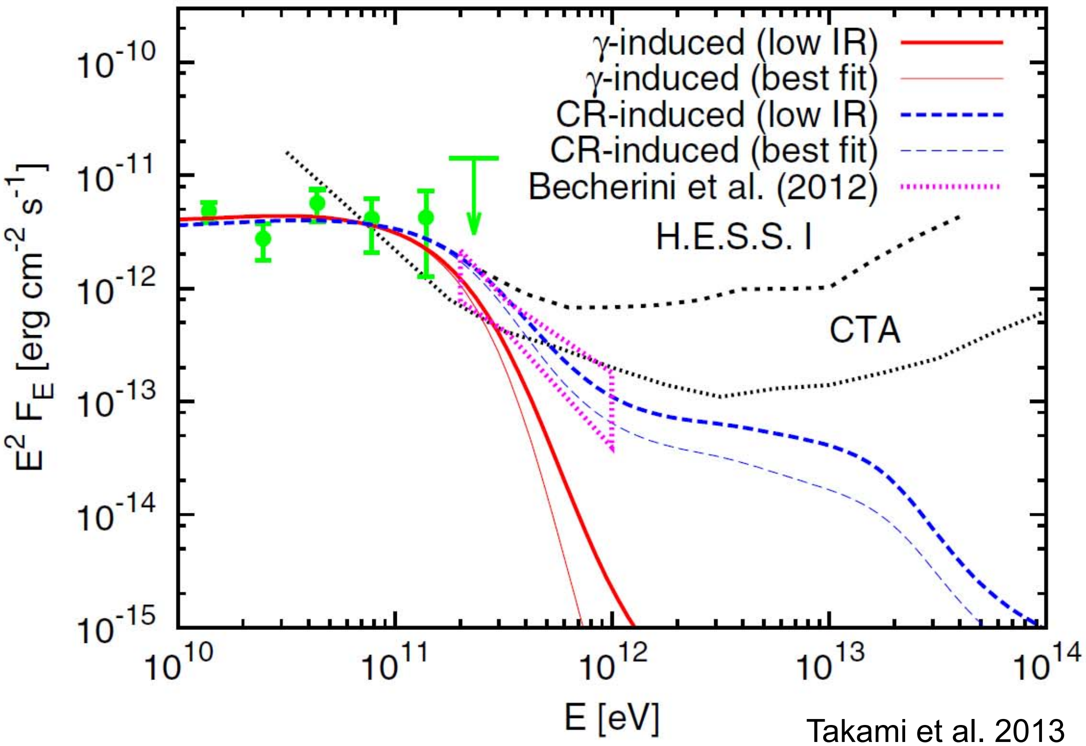
Murase et al. 2012

>10 GeV Sources Explained by Cascade Emission

- **GeV-TeV sources**
  - EBL effects greater on more distant blazars
- **Model >10 GeV Fermi-LAT emission by cascades**

  $\gamma\gamma$/Compton cascade
  - Kneiske et al. (2004) EBL models
  - Assume no suppression from IGMF ($B_{IGMF} < 10^{-15}$ G)
  - Intrinsic spectrum $F(E_\gamma) \propto E_\gamma^{-1.76}$, $5.6\ \mathrm{GeV} < E_\gamma < 100\ \mathrm{TeV}$
- **UHECR-induced cascade**
  - Bethe-Heitler pair production
  - Assume no suppression from IGMF ($B_{IGMF} < 10^{-12}$ G)
  - UHECR proton spectrum:

    $F(E_p) \propto E_p^{-2.6} \exp(-E_p/10^{19}\ \mathrm{eV})$

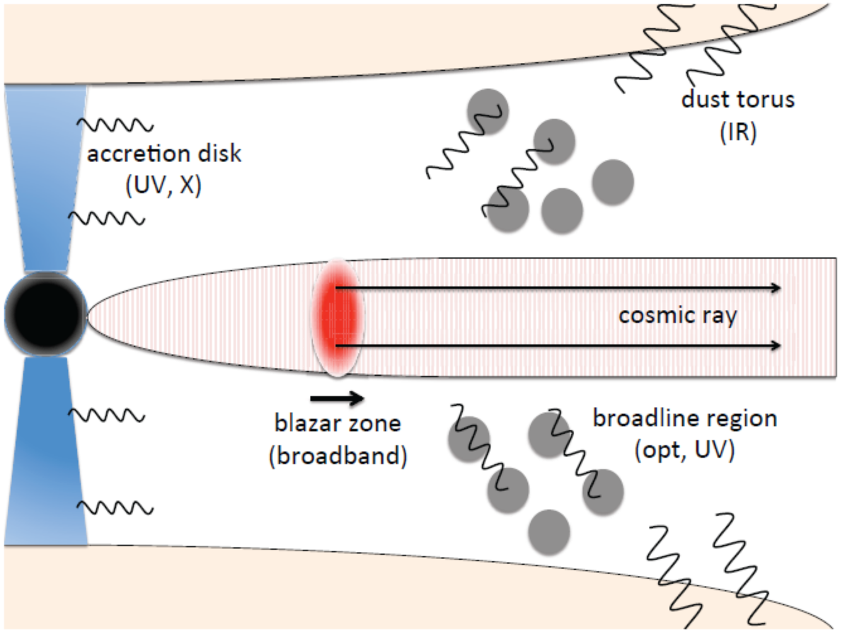


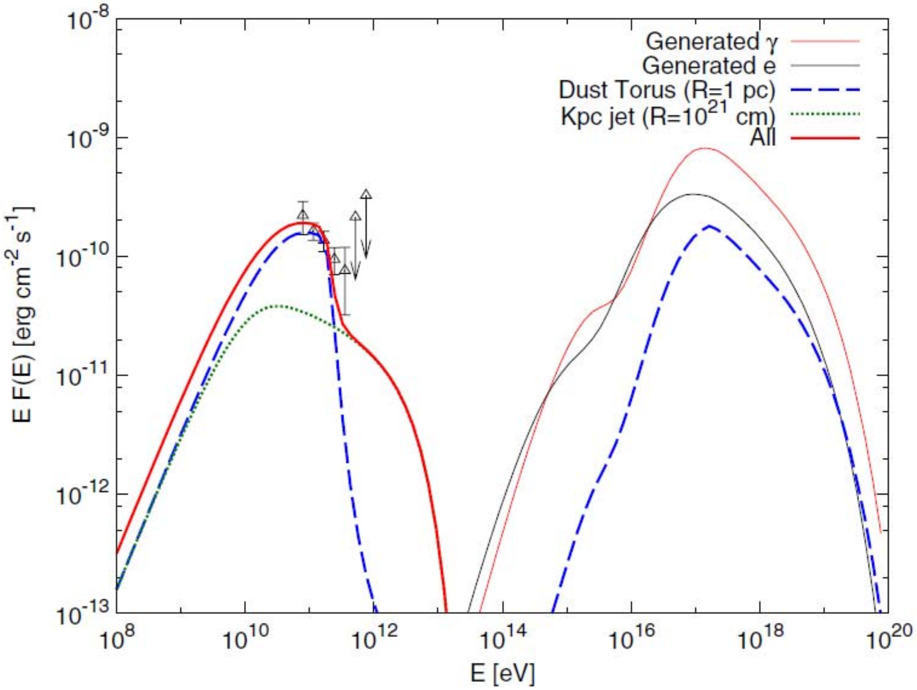
Takami et al. 2013

KUV 00311-1938 (z = 0.61)

- Normalization imposed to fit > 10 GeV Fermi-LAT spectrum from cascade emission
- Definitive test of UHECR Hypothesis with CTA

GeV-TeV Radiation in 4C +21.35 from Hadronic Processes





Ultra-relativistic leptons from UHECRs:

$$n + \gamma \rightarrow \pi^{\pm} \rightarrow e^{\pm} + B \rightarrow \gamma'$$

$$n + \gamma \rightarrow \pi^{0} \rightarrow 2\gamma \rightarrow e^{\pm} + B \rightarrow \gamma'$$

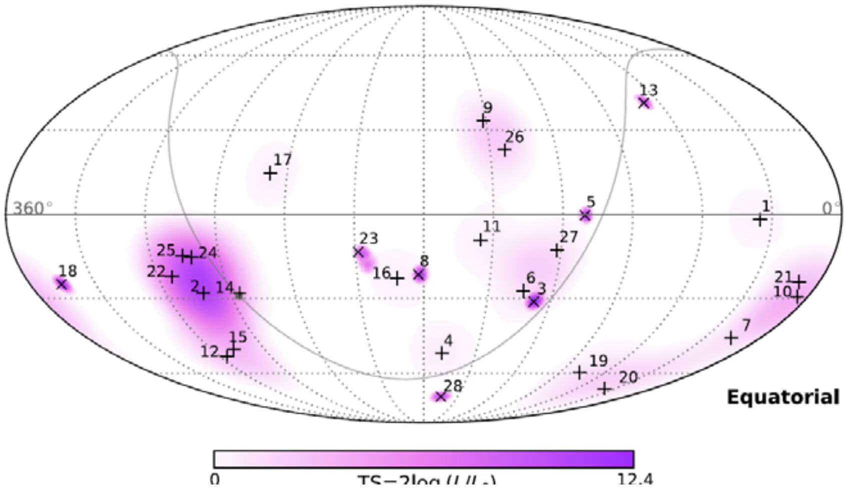
Make synchrotron γ-rays

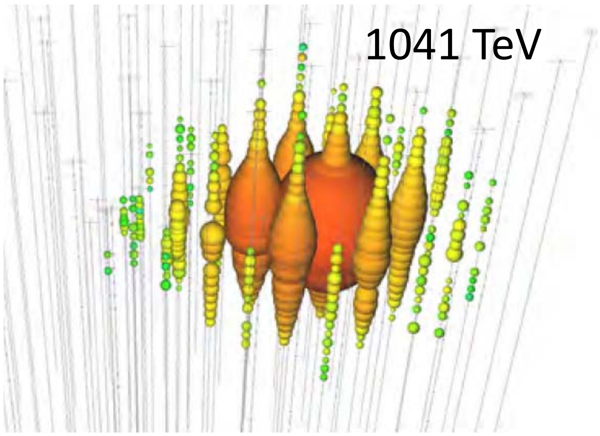
Dermer, Murase, Takami (2012)

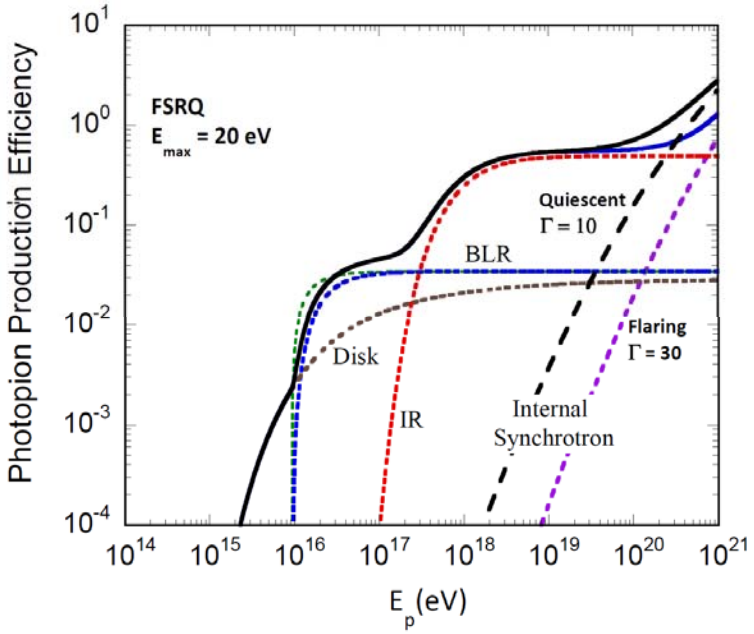
Detailed GeV and VHE studies with Fermi/CTA

Neutrino Production in FSRQs

- **Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector** Science, **342**, Nov. 22, 2013







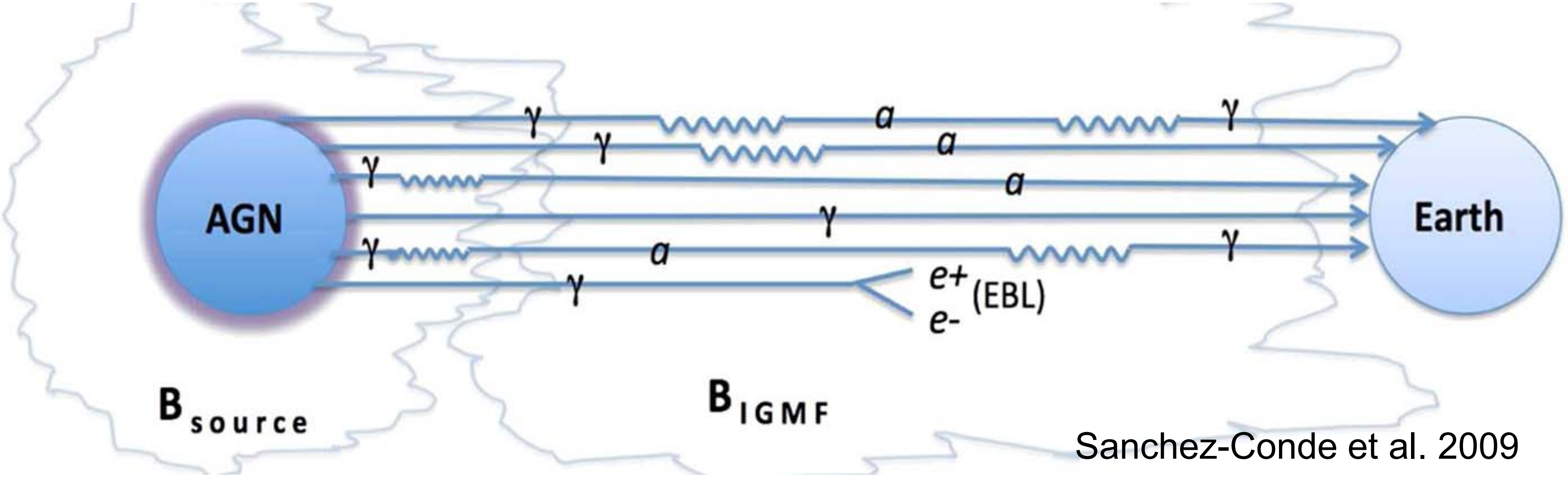
- Broad-line region (Ly α) radiation
- Threshold $\gamma_p\varepsilon_0$ >~ 400, so most neutrinos are made with energy $E_\nu \sim 0.05\, m_pc^2\, \gamma_p$ >~ 0.05 x 10^9 eV $\approx 400/\varepsilon_0 \sim 10^{15}$ eV for $\varepsilon_0 \sim 2 \times 10^{-5}$ (Ly

Murase, Inoue, Dermer 2014

Axions

Axion: light DM particle introduced to solve the strong CP problem in QCD
Photon-axion conversion in presence of a magnetic field

Oscillation of photons to axion-like particles (and vice versa) can lead to an enhancement of the received flux from a distant source. Mixing near source and in intergalactic space



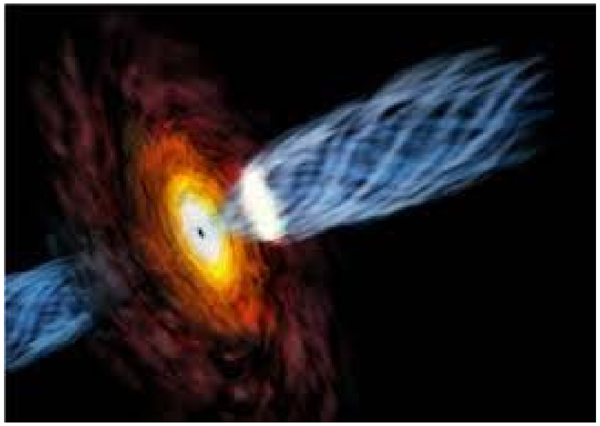
Sanchez-Conde et al. 2009

Spectral features/GeV cutoffs in FSRQs (Mena & Razzaque 2013)

Fermi Blazar and AGN Science: Summary

- ❑ **Standard blazar paradigm: Supermassive black holes with jets explained by leptonic Compton-synchrotron processes in relativistic collimated plasma**

- ❑ **Problems with the blazar paradigm**
  - – **Deabsorbed spectra of distant (z > 0.1) TeV blazars show unexplained hard emission component**
  - – $\Delta\Gamma = \Gamma_{\text{GeV}} - \Gamma_{\text{TeV}}$ **relation violated**
  - – **Location of γ-ray emitting regions in blazars**
  - – **Rapid variability in BL Lac objects**
  - – **Existence of a weakly variable BL Lac class**
  - – **VHE emission from FSRQs**
  - – **Synchrotron puzzle**



- ❑ **Directions forward**
  - – **New thinking about particle acceleration**
  - – **UHECRs in blazar can potentially solve some of these problems**
  - – **New physics**

Fermi AGNs: All Radio-Loud

- LAT Bright AGN Sample (LBAS); First year LAT AGN Catalog (1LAC)

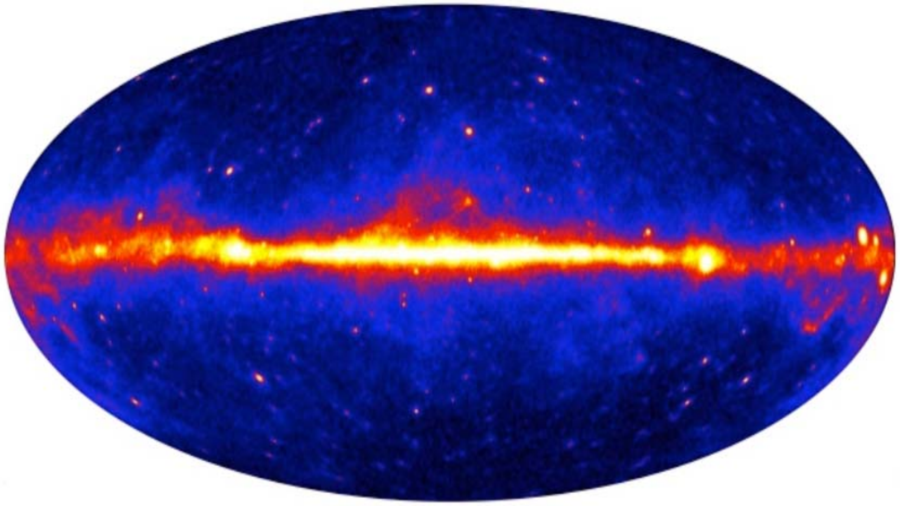
LBAS: 3 month source list: 2008 Aug 4 – Oct 30
1LAC: 1 year catalog: 2008 Aug 4 – 2009 July 4

3EG **(EGRET):**
10 >10σ |b|>10° sources
66 >5σ blazars

LBAS: subset of 0FGL/Bright Source List
w/ 205 sources
TS >100 (>10σ)
106 |b|>10° sources
assc. w/ AGNs

1FGL TS >25
1451 sources
1043 |b|>10° sources

1LAC
TS >25 (> 4.1σ)
671 assc. w/ 709 AGN
(663 hi-conf. associations)
(300 BL Lacs, 296 FSRQ,
41 other AGN, 72 unknown)



2 year Fermi GeV sky

2FGL TS >25
1888 sources **832 AGNs (+268 candidates)**
114 Pulsars **60 SNR/PWNe**
593 unaccounted **7 others**

2LAC 360 FSRQs 420 BL Lacs (~60% with known z)
200 of unknown type ~20 other AGN

Small number of radio galaxies

Coming soon: 3FGL/3LAC

BL Lac and FSRQ: definition

- classify an object as a BL Lac if the equivalent width (EW) of the strongest optical emission line is < 5 Å,

  e.g., [O II] λ3727 and [O III] λ5007

  classification of higher-redshift sources will preferentially use lines at shorter wavelengths (e.g., Lyα λ1216 and C IV λ1549) than for low-redshift sources (e.g., Mg II λ2798 and Hα λ6563).
- a Ca II H/K break ratio C < 0.4,
- Wavelength coverage satisfies $(\lambda_{max} - \lambda_{min})/\lambda_{max} > 1.7$ so that at least one strong emission line would have been detected if present
- Sources for which no optical spectrum or of insufficient quality to determine the optical classification are listed as “unknown type”