Black-Hole Jets of Ultra-High Energy Cosmic Rays: Clues from Auger and Fermi

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Outline

- Ultra-High Energy Cosmic Rays (UHECRs; $\gtrsim 10^{18}$ eV)
- Pierre Auger Observatory: Results and Implications
- Requirements for UHECR sources:
  - Extragalactic (but within the GZK radius)
  - Emissivity ($>10^{44}$ ergs Mpc^{-3} yr^{-1})
  - Power ($> 10^{46}$ ergs s^{-1})
- Extragalactic Gamma Ray Sources
- Fermi Gamma Ray Space Telescope
- Radio Galaxies and Blazars as Sources of the UHECRs
- Gamma-Ray Bursts as Sources of the UHECRs

See Razzaque, Dermer, Finke (Nature Physics, submitted, 2009)
Dermer, Razzaque, Finke, Atoyan (New Journal of Physics, 2009)
Dermer and Menon, "High Energy Radiation from Black Holes"
(Princeton University Press, 2009)

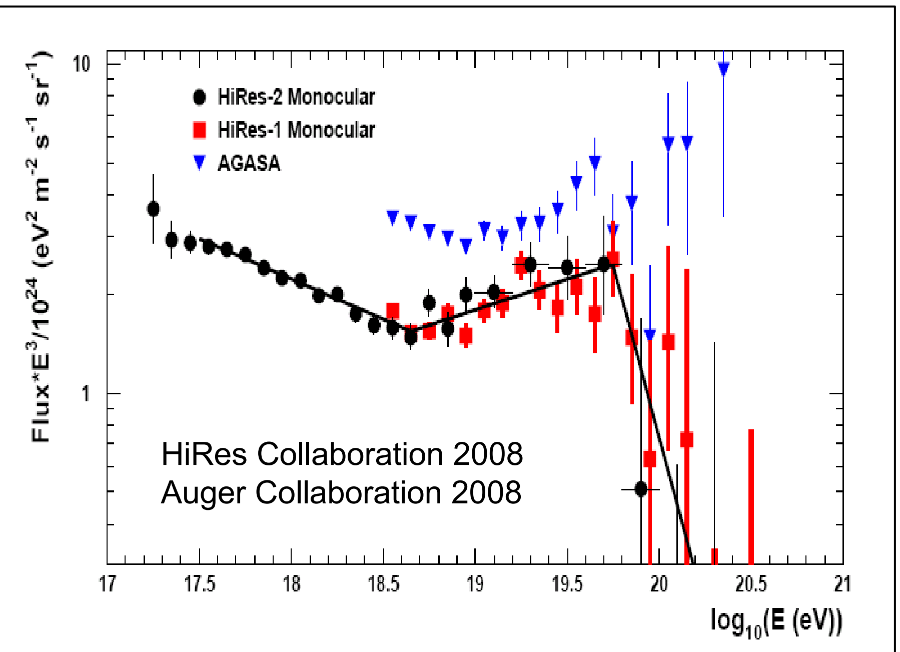
Ultra-High Energy Cosmic Rays

Knee Feature at 3×10^{15} eV

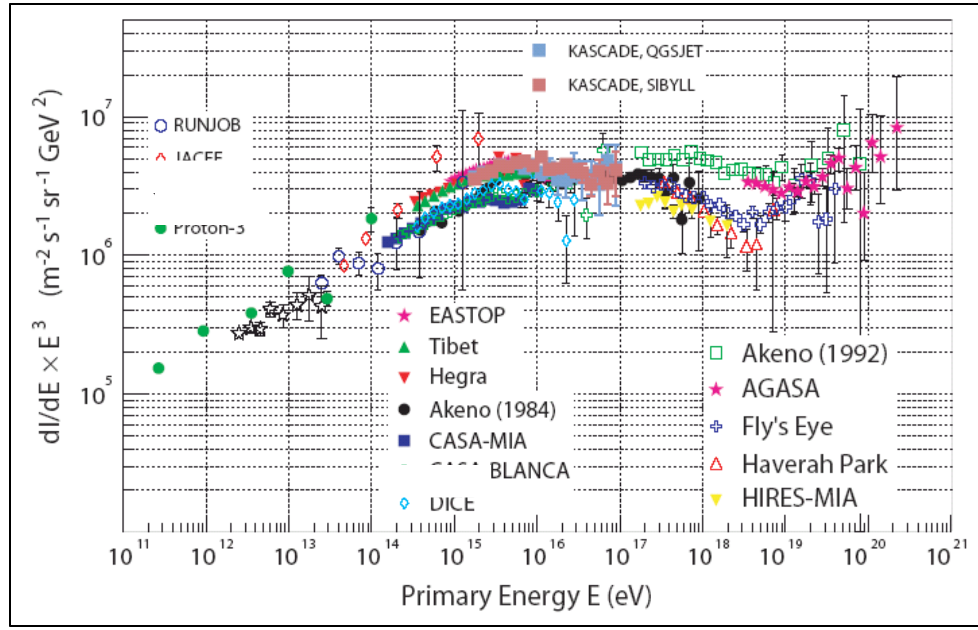
Second Knee at 4×10^{17} eV

Ankle Feature at 5×10^{18} eV

GZK Cutoff at 6×10^{19} eV (predicted by Greisen, Zatsepin, and Kuzmin in 1966)



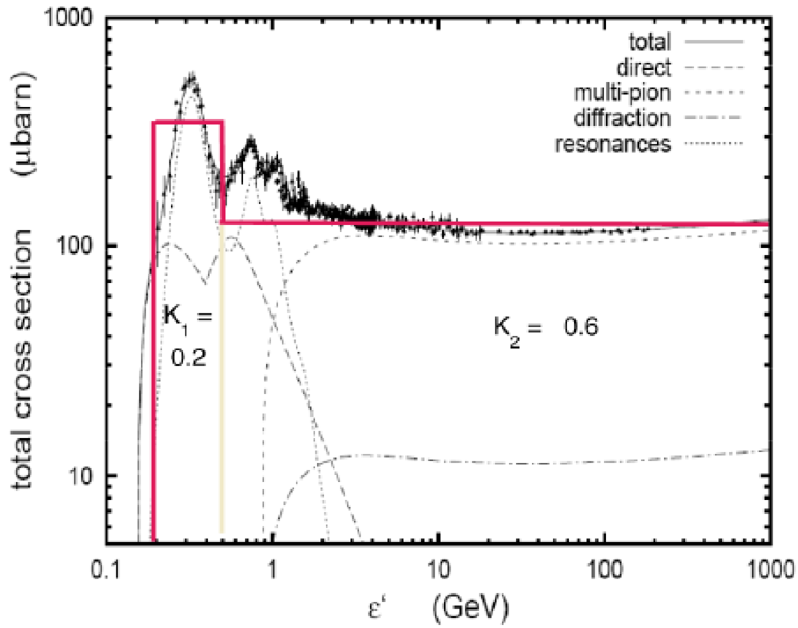
(Differential number flux multiplied by E^3)

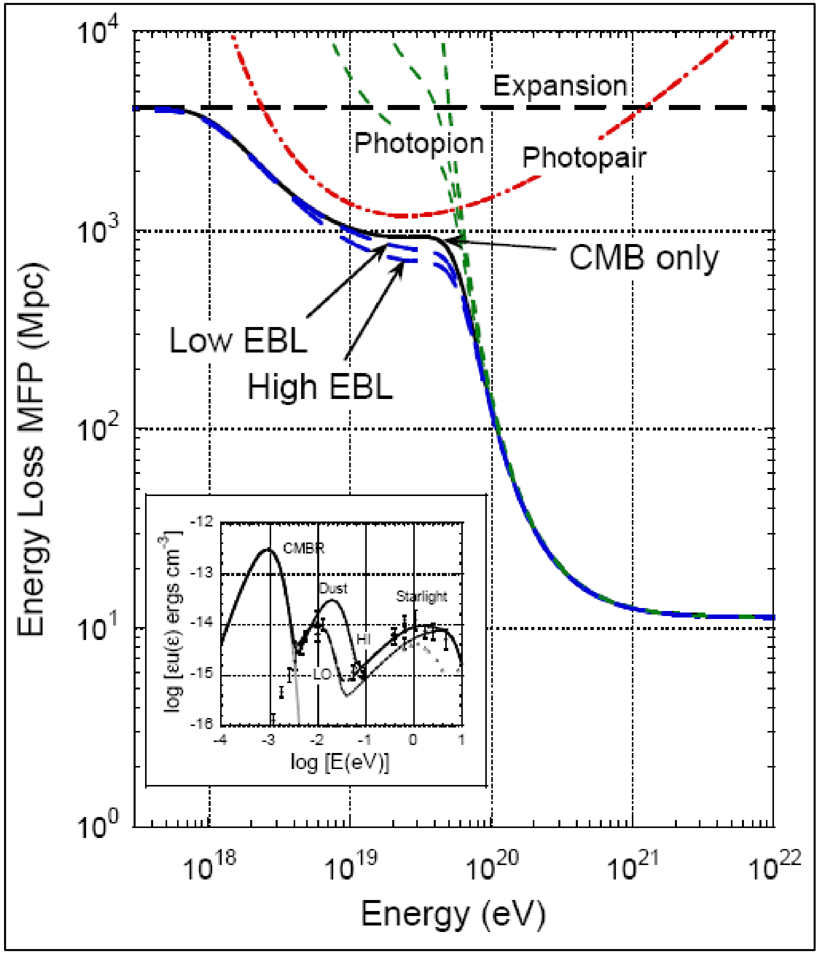


- Origin: sources of cosmic rays
- Acceleration: how accelerated to high energies
- Propagation: transport of cosmic rays
- Reception: detection at Earth and in space

Greisen-Zatsepin-Kuzmin (GZK) Cutoff

- Photopion production cross section
  $p + \gamma \rightarrow p + \pi^o$, $n + \pi^o$





- Photo-ion disintegration cross sections (giant dipole resonance) $N + \gamma \rightarrow N' + p, n, \alpha$

CMB photons reach threshold for π production for $E \sim 10^{20}$ eV protons

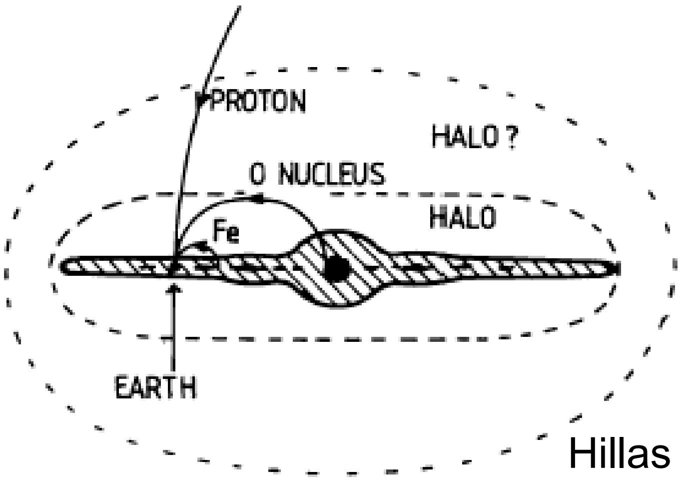
Extragalactic Origin of UHECRs

Galactic Disk Magnetic Field: 2 – 5 μG

Thickness ~ 200 pc

Galactic Halo Magnetic Field: 0.1 μG

Thickness ~ 1 – 5 kpc



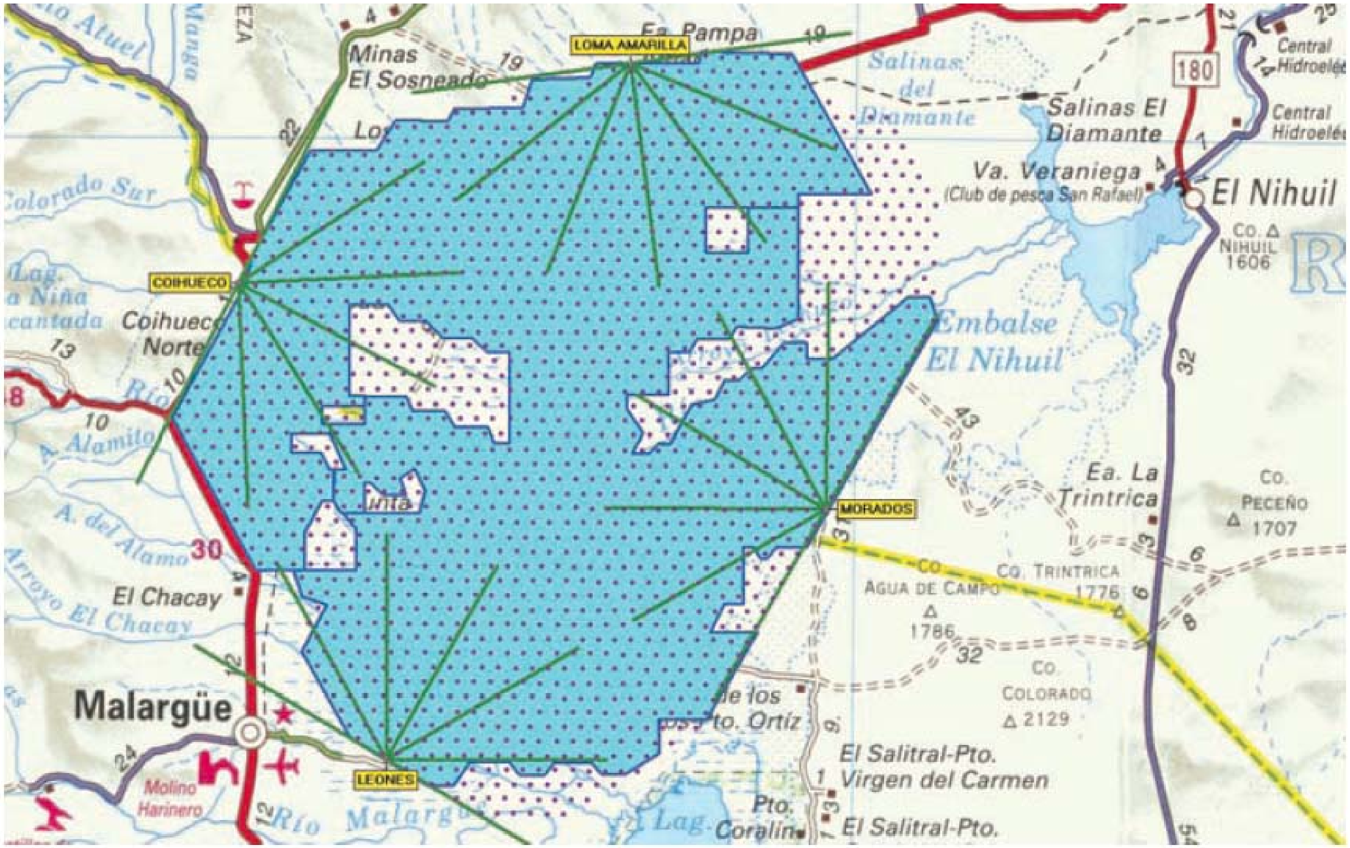
Hillas 1984

Larmor radius $$r_L \cong \frac{E}{QB} \cong 65 \frac{(E/60EeV)}{ZB(\mu G)} kpc$$

Particle with energy
E = 60 EeV = 60×10^{18} eV

- Hillas Condition: Sources of UHECRs must have r_L < source size
- Rules out many classes of potential UHECR sources: flare stars, white dwarfs, “normal” neutron stars, Galactic sources (if protons or light ions),…

Pierre Auger Observatory



Auger Observatory in Mendoza province in Argentina

(Auger Collaboration, Science Magazine, November 2007)

Flux (> 10^{20} eV):
1 particle/km^2/century

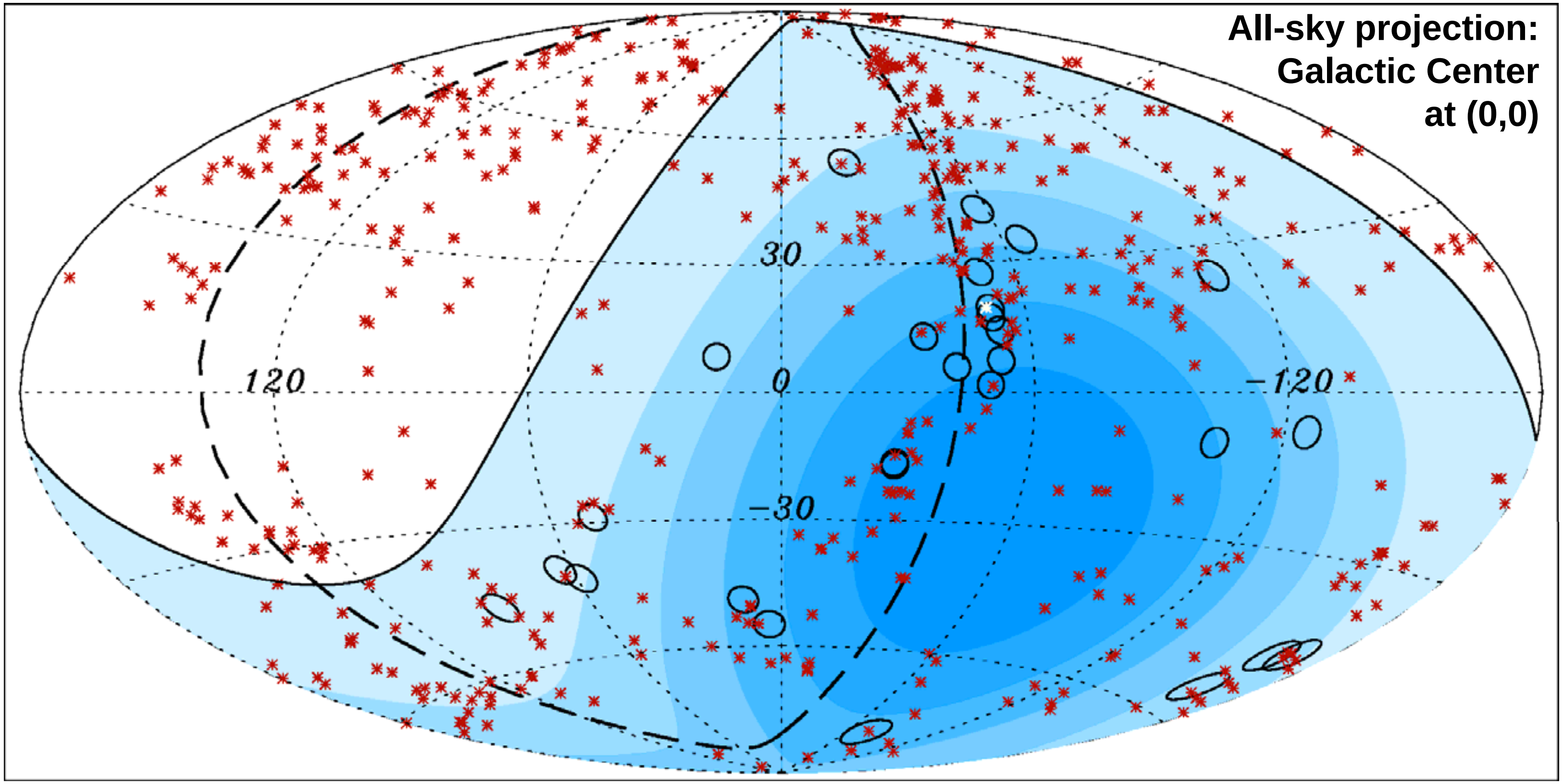
Ni Flurorescence Detectors

Spectroscopy Detectors (1600 SDs spaced 1.5 km apart)

Angular resolution: 1^o for E > 10 EeV

Energy uncertainty: 22% for E > 10 EeV

2007 — Birth of Charged Particle Astronomy



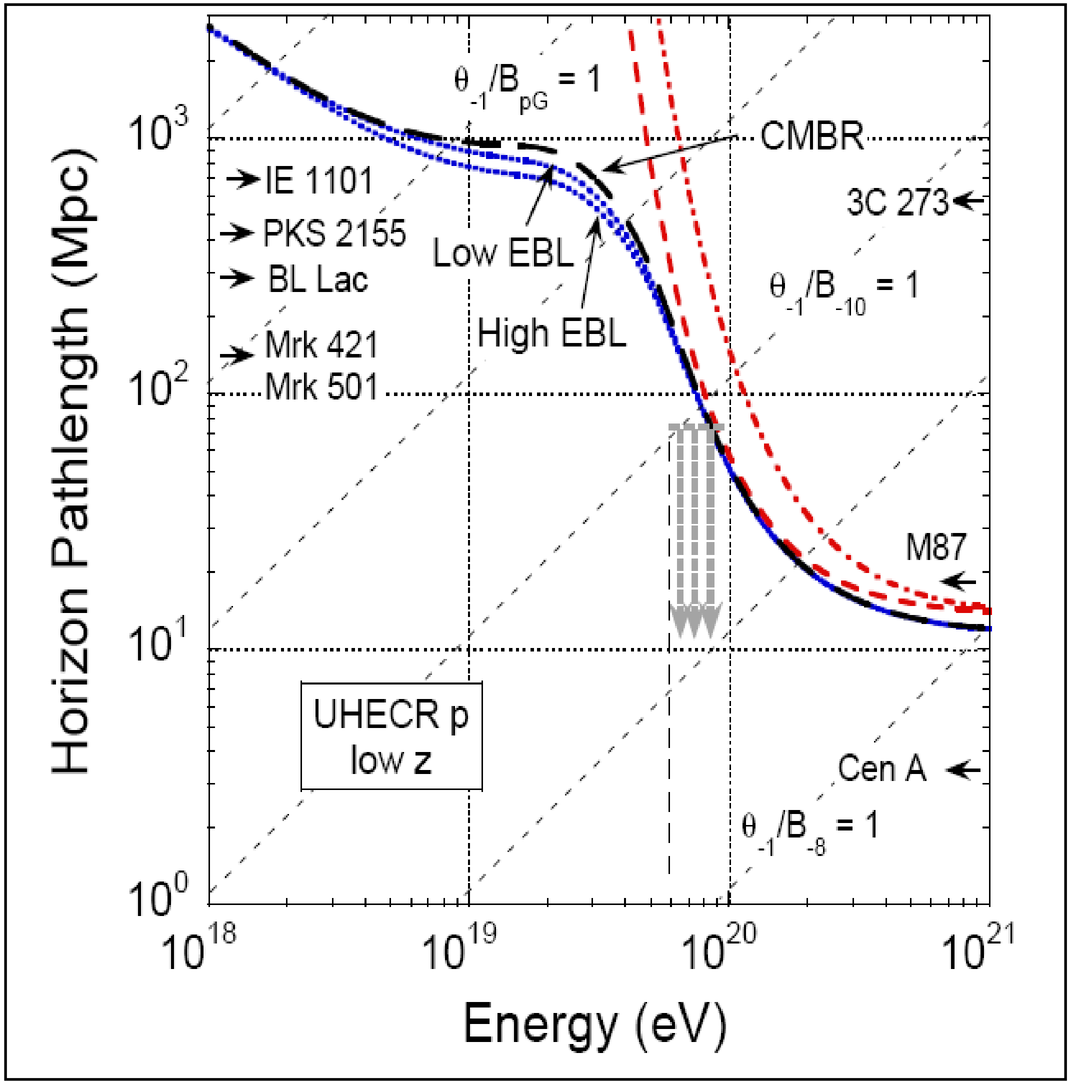
Arrival directions of highest energy cosmic rays (>6×10^{19} eV; open circles) correlated with active galaxies (AGNs) (×) within ~75 Mpc

Cen A, radio galaxies, also radio-quiet AGN

$$\theta_{dfl} \cong 1^\circ \frac{Z h_{md}(kpc) B(\mu G)}{\sin b (E/60 EeV)}$$

Deflection in Galactic magnetic field ⇒ protons or light nuclei

GZK Horizon Distance for Protons



Horizon distance:
Linear distance where proton with measured energy E had energy eE

CMBR only:

$$r_{hrz}(E_{20}) = \int_{E_{20}}^{eE_{20}} \frac{dx}{x} r_{\phi\pi}(x) \cong$$

$$13.7 \int_{E_{20}}^{eE_{20}} dx \frac{\exp(4/x)}{x(1+4/x)} \text{ Mpc} \cong$$

$$\frac{1.1 E_{20}^2 \exp(4/E_{20})}{1 + 1.6 E_{20}^2/13.7} \text{ Mpc}$$

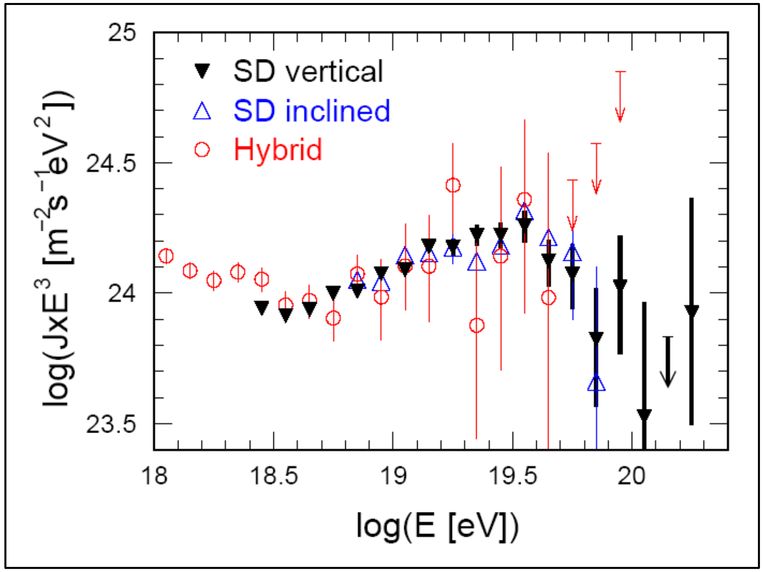
GZK cutoff consistent with UHECR protons

For model-dependent definition: Harari, Mollerach, and Roulet 2006

UHECR Emissivity

$$\dot{\varepsilon}_{CR}(dE/dVdt) \approx u_{UHECR}(dE/dV)/t_{loss}$$

$$t_{loss} = r_{horizon}/c$$



Yamamoto et al. (2007)

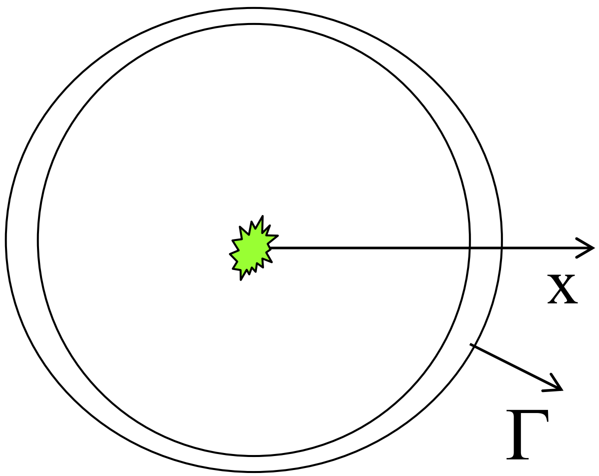
Sources of UHECRs need to have a local luminosity density (emissivity) of $\approx 10^{44}$ ergs/Mpc^3-yr (Waxman & Bahcall 1999)

$$\dot{\varepsilon}_{UHECR}\left(\frac{ergs}{Mpc^3 - yr}\right) \approx \frac{6\times 10^{45}\,(J\times E^3)_{24}}{r_{horizon}(Mpc)\,(E/10^{20}\,eV)}$$

$E_p(eV)$	$\dot{\varepsilon}_{UHECR}\left(\frac{10^{44}\ ergs}{Mpc^3 - yr}\right)$
10^{20}	0.4
10^{19}	0.8
10^{18}	3
10^{17}	40

UHECR Acceleration by Relativistic Jets

Proper frame (′) energy density of relativistic wind with apparent luminosity L



$$u' = \frac{L}{4\pi R^2 \beta c} \times \frac{1}{\Gamma^2} \qquad \frac{B'^2}{8\pi} \approx u' \Rightarrow B'$$

Maximum particle energy

$$E_{\max} \approx \Gamma Q B' R' \approx \Gamma Z e B' (R / \Gamma)$$

Lorentz contraction ⇒
$\Delta R' = \Gamma\ \Delta R$

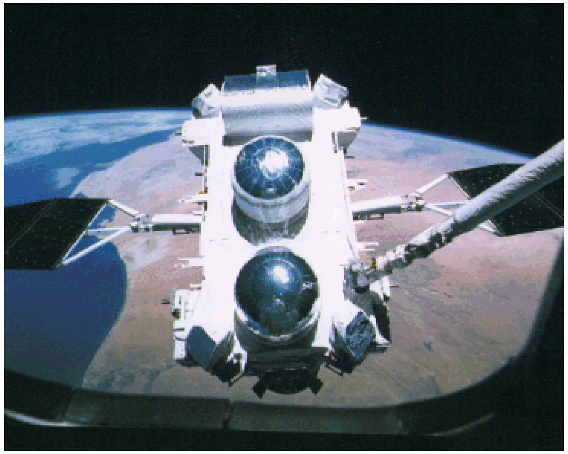
$R' = R/\ \Gamma$

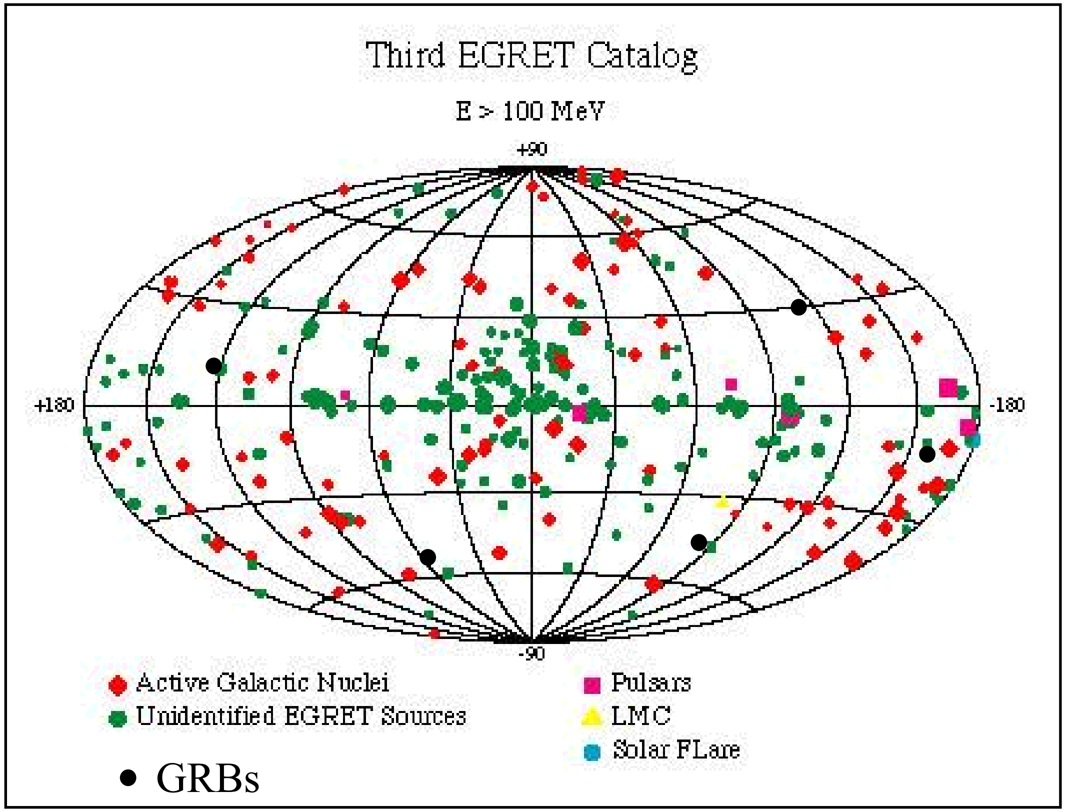
$$\Rightarrow E_{\max} \approx 2 \times 10^{20} Z \frac{\sqrt{L/(10^{46}\, ergs\ s^{-1})}}{\Gamma}\, eV$$

What extragalactic sources have (apparent isotropic) L >> 10^{46} ergs s^{-1}?

Those with (apparent isotropic) L_γ > 10^{46} ergs s^{-1}

Gamma Ray Sources





Compton Gamma-Ray Observatory: Pioneering γ-ray space observatory (1991 – 2000)

270 EGRET sources (3EG)
5 Spark Chamber Gamma Ray Bursts
70 High Confidence Blazars
LMC, Cen A

~25 blazars with ground-based TeV telescopes

Fermi Gamma-ray Space Telescope

- **International space mission devoted to the study of the high-energy gamma rays from the universe**
- **Launched on June 11, 2008 from Cape Canaveral**
- **Formerly, the Gamma ray Large Area Space Telescope (GLAST)**

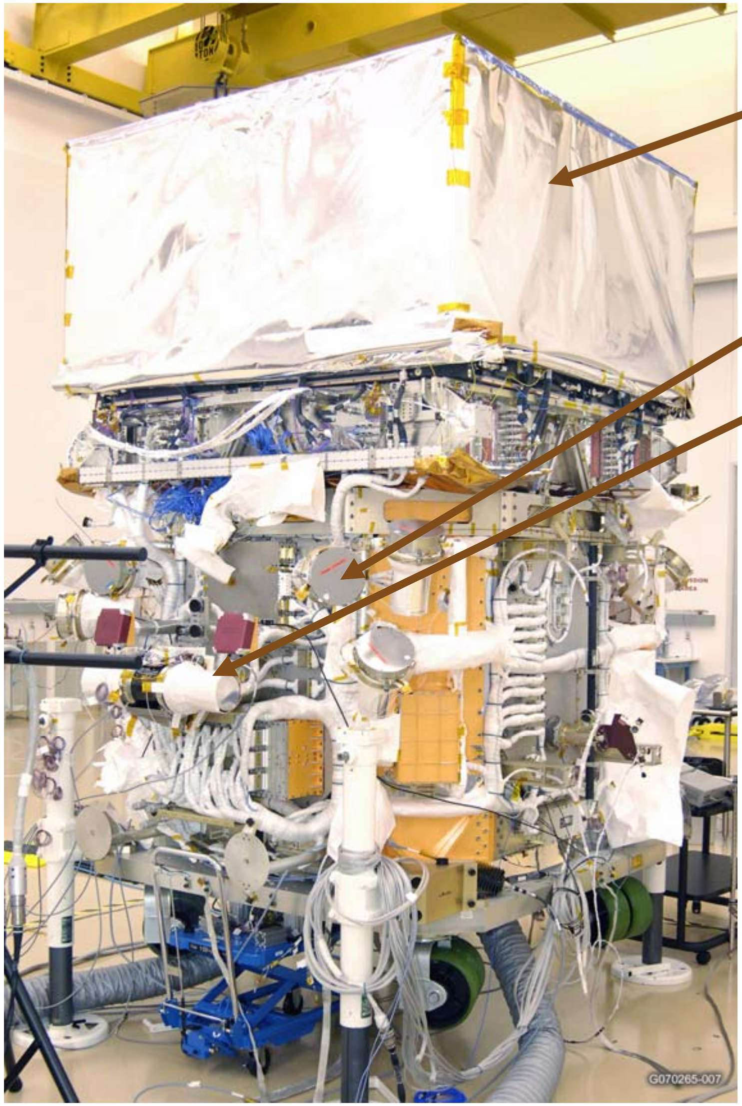
August 26, 2008 NASA renamed GLAST to Fermi

in honor of Enrico Fermi (1901-1954)

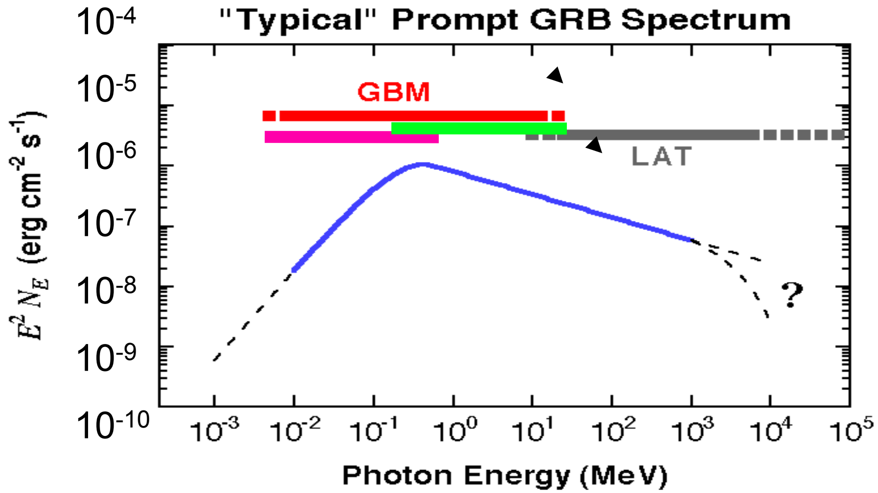
Circular orbit, 565 km altitude (96 min period), 25.6 deg inclination

Fermi
Gamma-ray Space Telescope

The Fermi Observatory

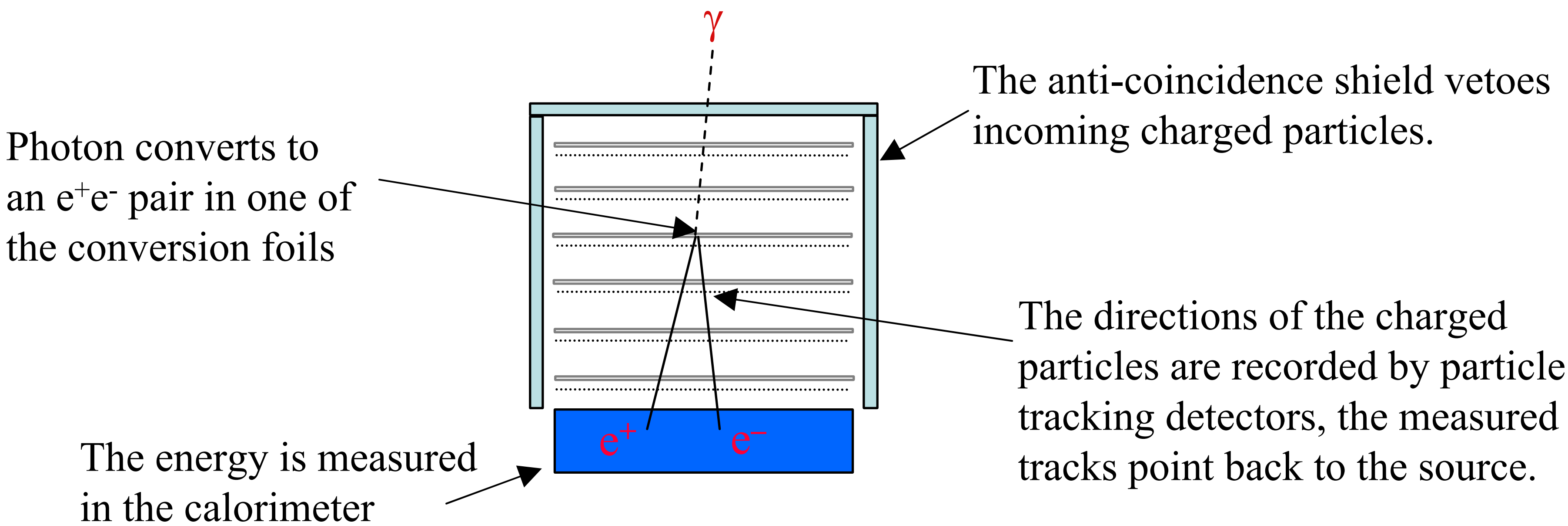


- Large Area Telescope (LAT)
  - 20 MeV to >300 GeV
  - onboard and ground burst triggers, localization, spectroscopy
- Gamma-ray Burst Monitor (GBM)
  - 12 NaI detectors (8 keV to 1 MeV)
    - onboard trigger, onboard and ground localizations, spectroscopy
  - 2 BGO detectors (150 keV to 30 MeV)
    - spectroscopy



Spectral observations over 7 orders of magnitude in energy

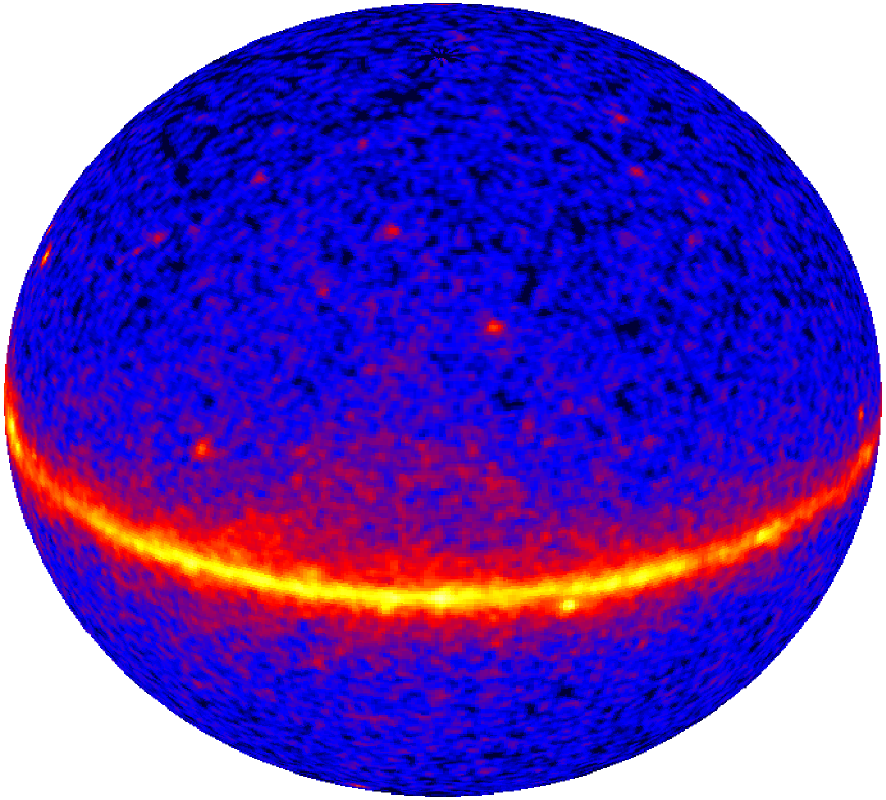
Pair Conversion Technique



Anti-coincidence detector:
Must have high efficiency for rejecting charged particles, but not veto gamma-rays
Tracker: angular resolution is determined by:
multiple scattering (at low energies) => Many thin layers
position resolution (at high energies) => fine pitch detectors
Calorimeter: (Sweden, France, USA)
Enough X_0 to contain shower, shower leakage correction.

First Light Sky Map (June 30 – July 4, 2008)

Equivalent to full year of data from EGRET on the Compton Observatory!



• Bright central band shows γ rays from (primarily) cosmic-ray interactions in our Galaxy

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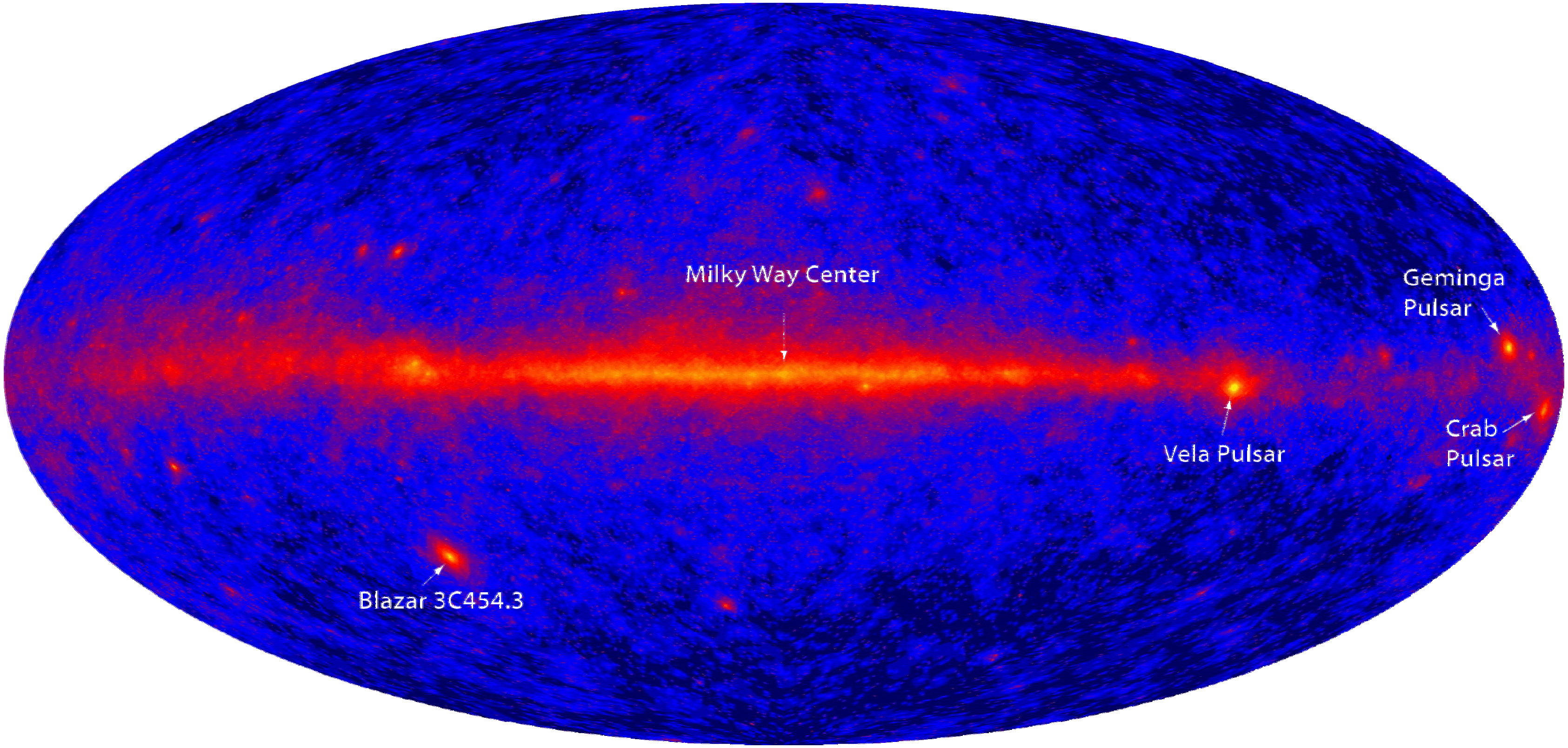

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Relativistic Jet Sources of UHECRs

Nonthermal γ rays ⇒ relativistic particles + intense photon fields

Leptonic jet model: radio/optical/ X-rays are nonthermal lepton synchrotron

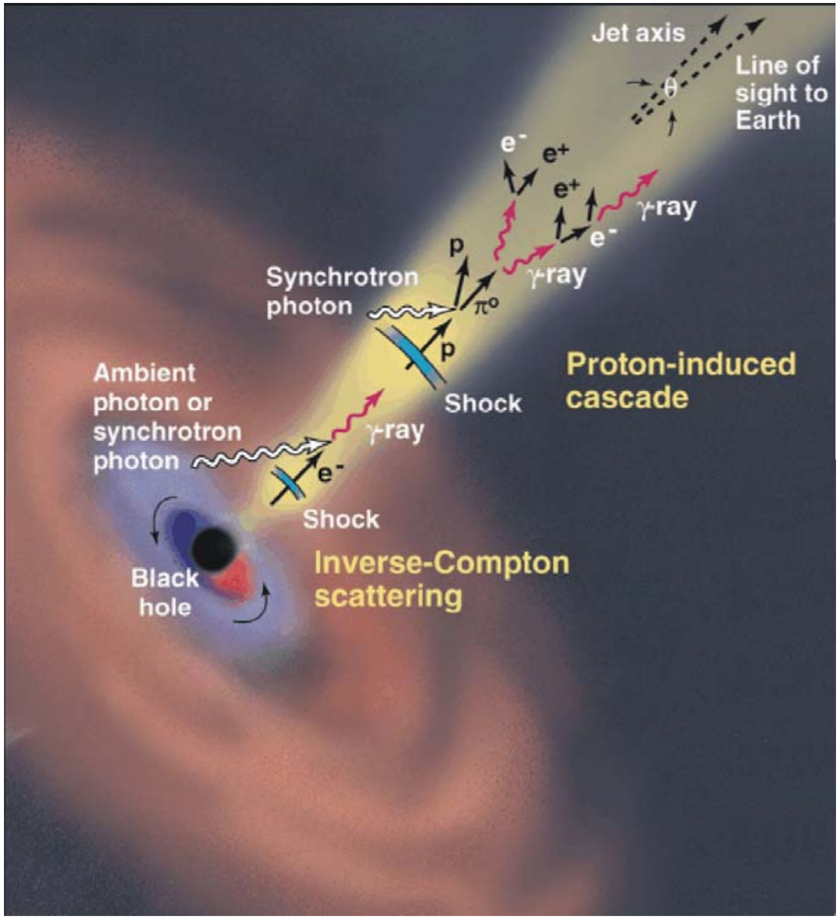
Hadronic jet model:
⇒ Photomeson production second γ-ray component

$$p + \gamma \rightarrow N + \nu, \gamma$$

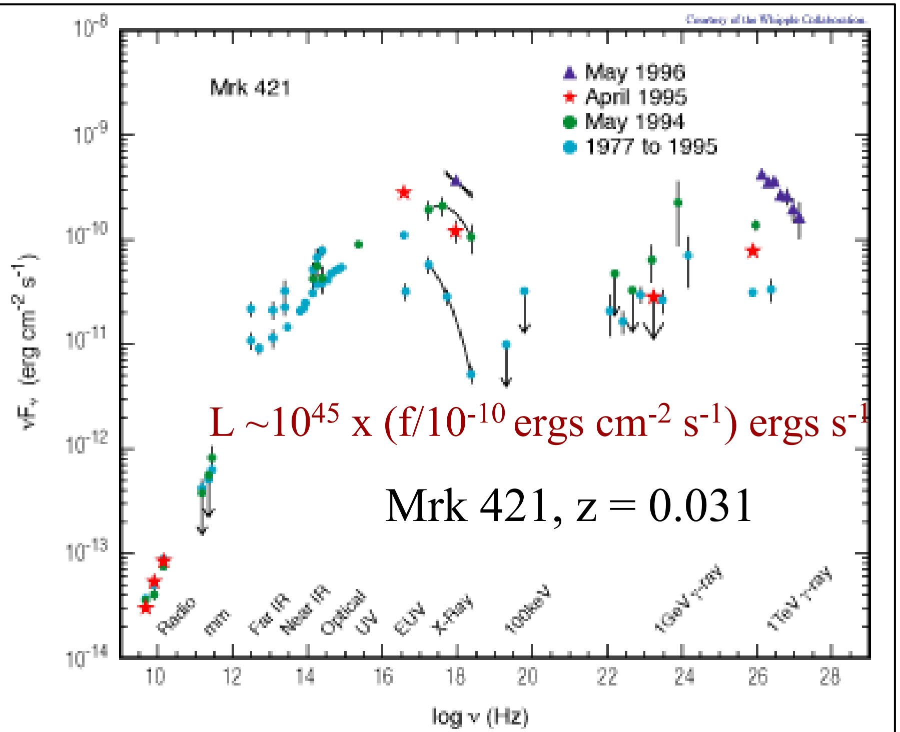
$$Doppler\ \ factor:$$

$$\delta_D = [\Gamma(1 - \beta\mu)]^{-1}$$

Large Doppler factors required for γ-rays to escape

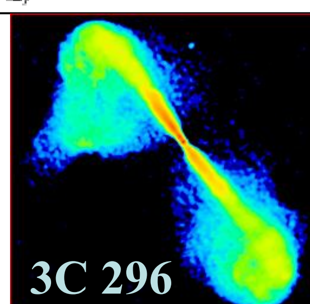


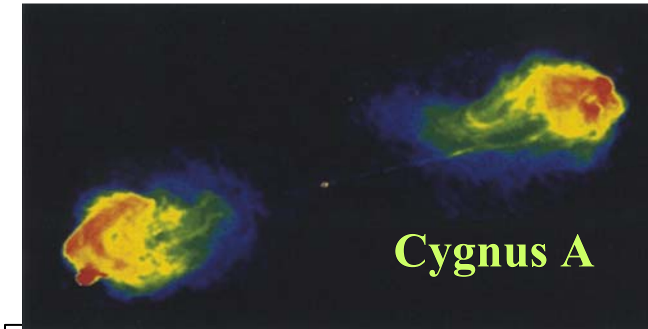
UHECRs from Radio Galaxies and Blazars

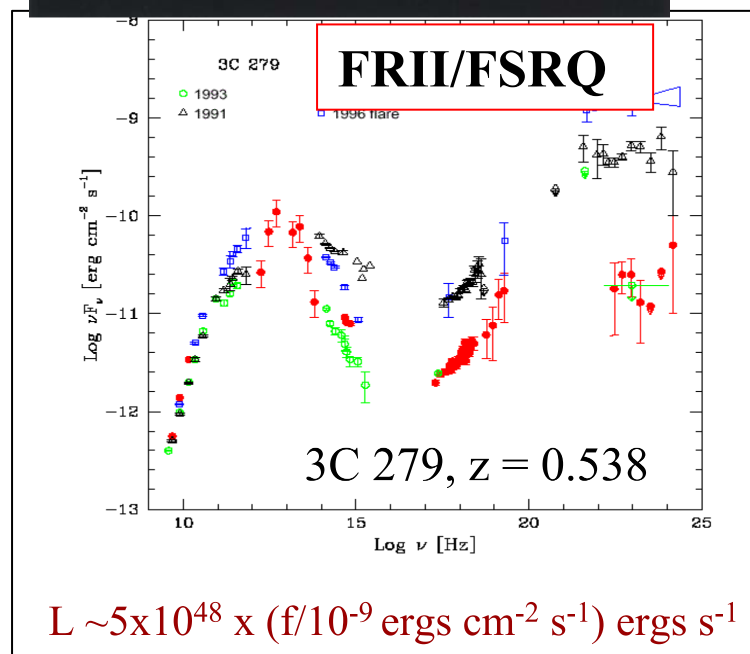


FRI/BL Lac

FRI/II dividing line at radio power ≅10^{42} ergs s^{-1}

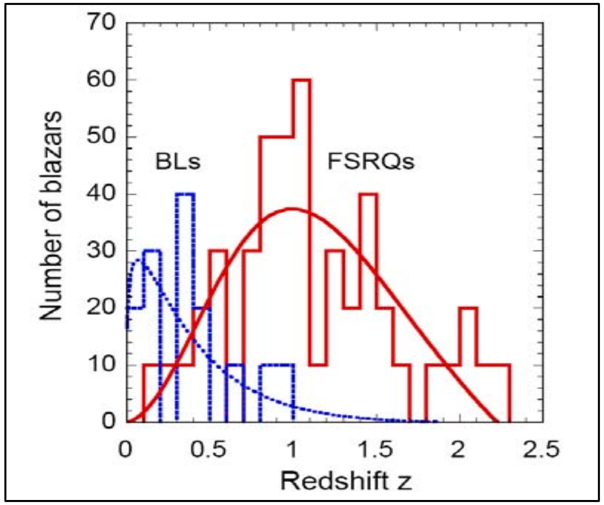


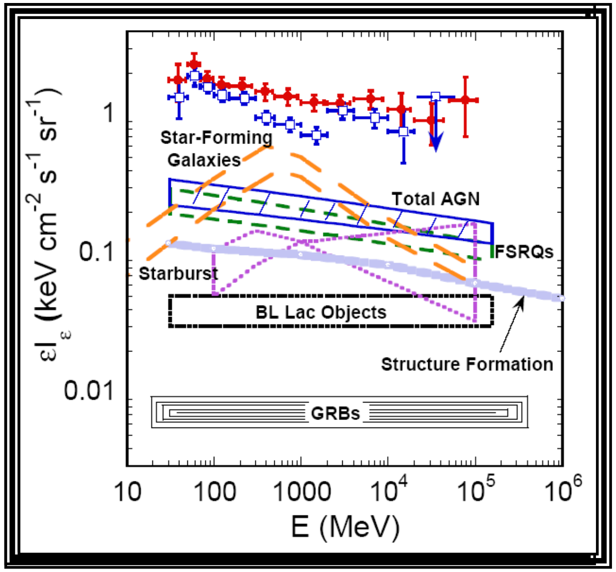




BL Lacs: optical emission line equivalent widths < 5 Å

Blazar γ-ray Emissivity





Dermer 2007

>100 MeV γ-Ray fluence:

$$\approx 1.5\, keV\ cm^{-2}\ s^{-1} sr^{-1}$$

$$\Rightarrow \approx 1\, erg\ cm^{-2}\ yr^{-1}$$

$$\dot{\varepsilon}_{FSRQ} \approx \frac{4\pi d^2 \times 0.2\ ergs\ cm^{-2}\ yr^{-1}}{4\pi d^3/3}$$

$$\approx 10^{45}\ ergs\ Mpc^{-3}\ yr^{-1}$$

$$(z \approx 1; d \approx 4000\ Mpc)$$

$$\dot{\varepsilon}_{BL\ Lac} \approx 10^{45}\ ergs\ Mpc^{-3}\ yr^{-1}$$

$$(z \approx 0.2; d \approx 800\ Mpc)$$

Fermi Bright Sources

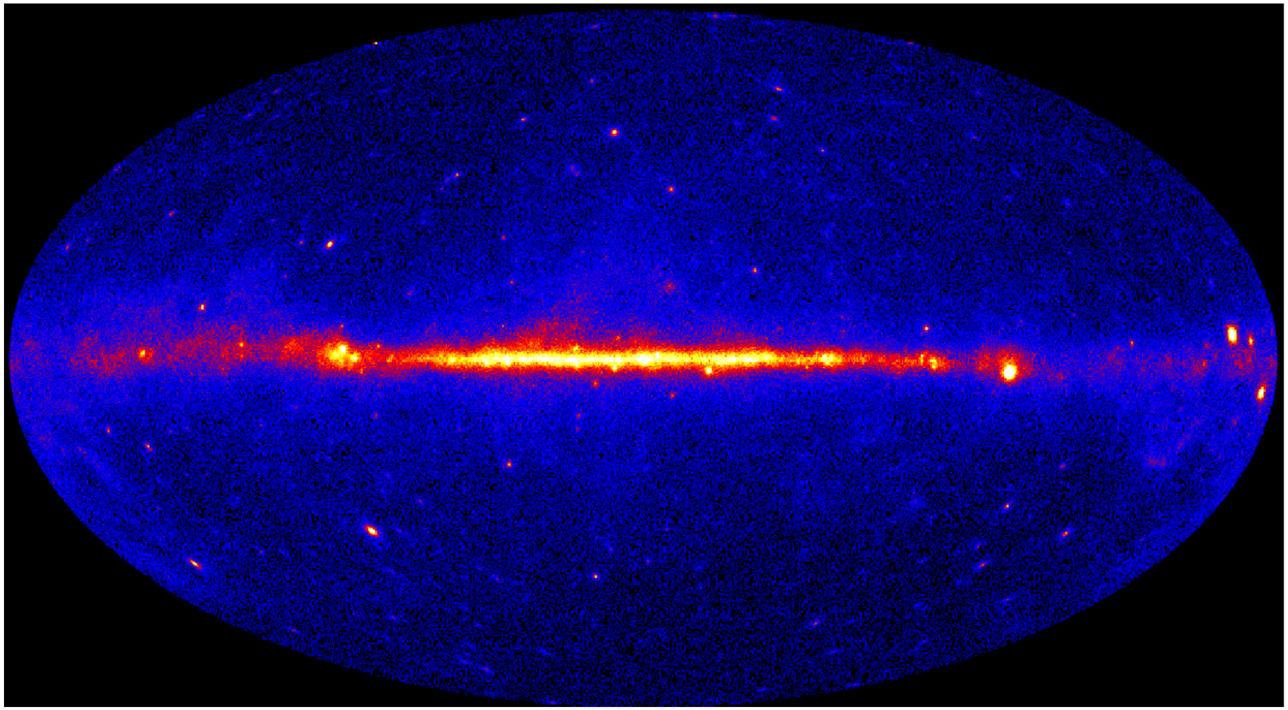
- Subset of LAT Bright Source List, 0FGL (**F**ermi **G**amma-ray **L**AT):
  Abdo et al. arXiv:0902.1340 (ApJ, in press)
- LAT Bright AGN Sample (LBAS): Abdo et al. arXiv:0902.1559 (ApJ, in press)

0FGL: 205 LAT Bright Sources

Test Statistic > 100
Significance > 10σ

132 |b|>10° sources
114 associated with AGNs

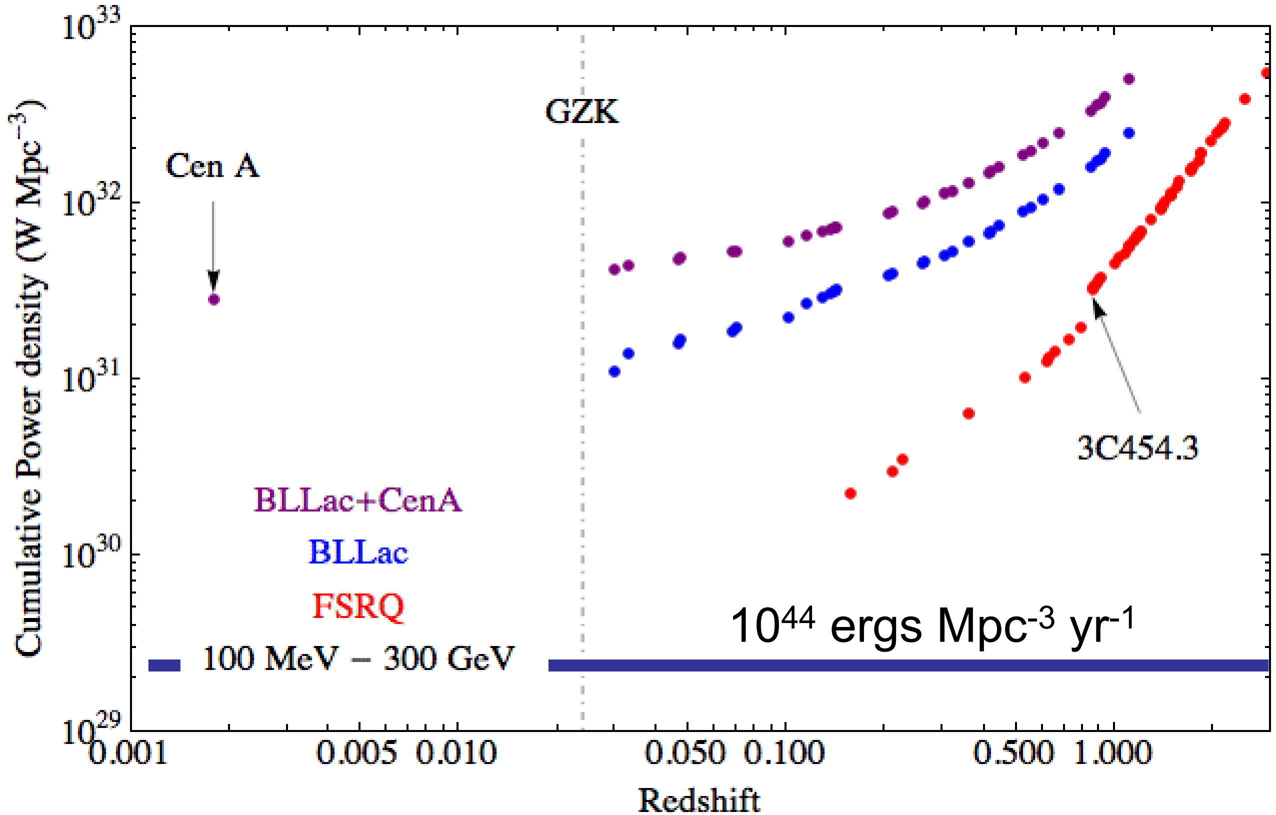
Compare EGRET:
31 >10σ sources (total)
(10 at |b|>10°)



August 4 – October 30, 2008

Luminosity Density of Blazars

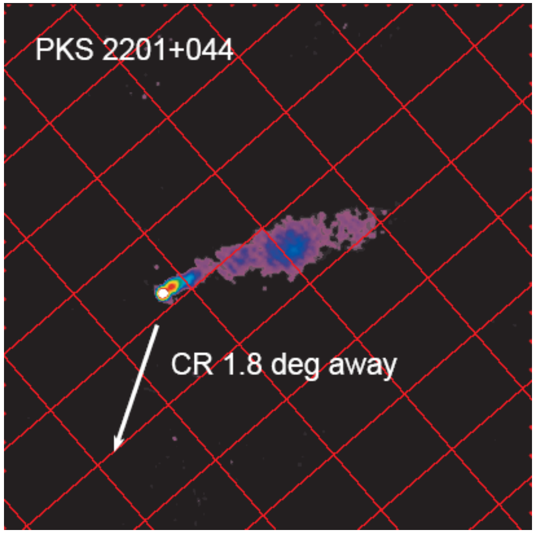
- Minimum luminosity density of Radio Galaxies from LBAS



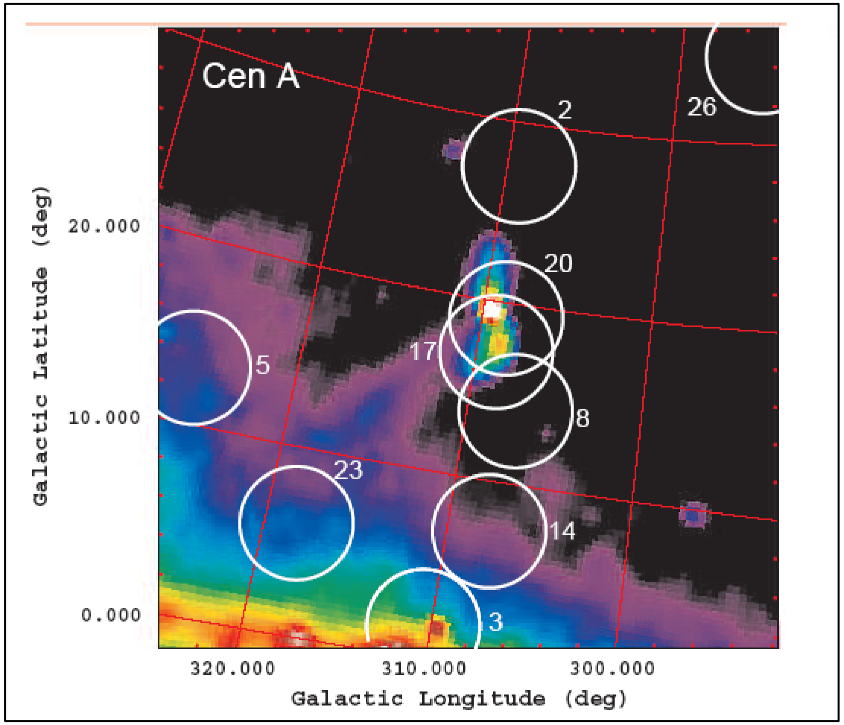
UHECRs from Radio Galaxies/AGNs

UHECR arrival directions are associated with Cen A, Cen B, an FR II radio galaxy and a BL Lac object within 140 Mpc.

IGR J21247+5058, an FR II broad-lined radio galaxy at $z = 0.02$ or $d \approx 80$ Mpc (INTEGRAL), is 2.1 degrees away from a HiRes Stereo event with $E > 56$ EeV.

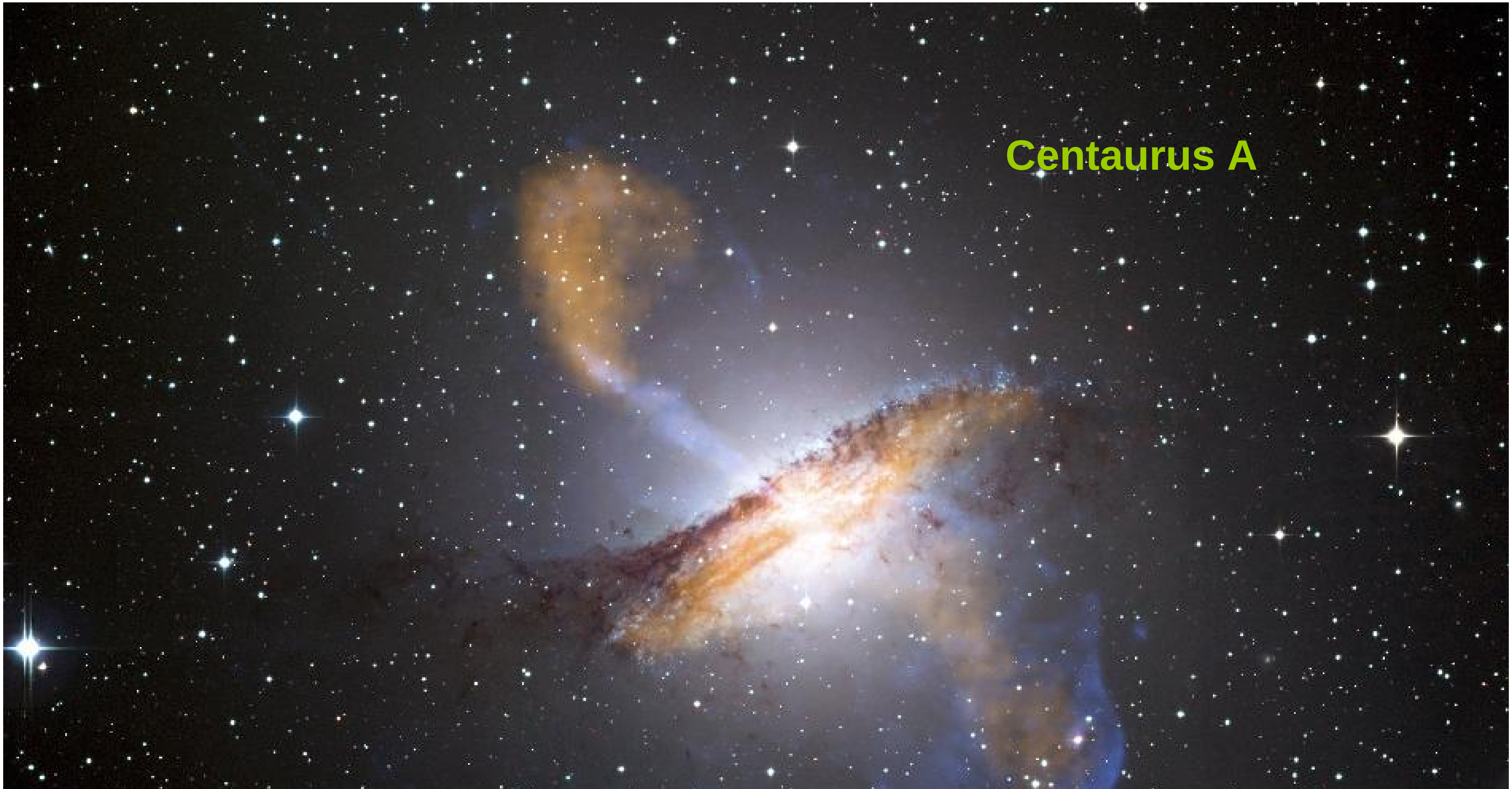


Moskalenko et al. 2009
Zaw et al. 2009



> 8 of the 27 UHECRs with $E > 56$ EeV are within 3.5° of nearby radio galaxies.

Seyfert 2, low ionization, radio-quiet galaxies closest to the UHECR arrival directions



Need > 10^{46} erg s^{-1} apparent power to accelerate UHECR protons by Fermi processes

Cen A power: Bolometric radio luminosity: 4×10^{42} erg s^{-1}
Gamma-ray power (from Fermi): 5×10^{41} erg s^{-1}
Hard X-ray/soft γ-ray power: 5×10^{42} erg s^{-1}
UHECR power: few $\times10^{40}$ erg s^{-1}

What is Average Absolute Jet Power of Cen A?

Total energy and lifetime:

Cocoon dynamics (Begelman and Cioffi 1989 for Cyg A)

New approach (Dermer et al. 2009):

Compton-synchrotron theory to infer minimum energy magnetic field, *absolute* jet power Pj

$$B_{minL} = \frac{0.57}{\delta_D} \left(\frac{f_{-12}}{d_{3.5} g \psi_0^3}\right)^{2/7} \left(\frac{\ln(\epsilon_2/\epsilon_1)(1+\zeta_{pe})}{\sqrt{\tilde{\epsilon}_{21}(1+z)}}\right)^{2/7}$$

$$P_j^*(B) = \frac{3}{7} P_j^*(B_{minL})(u^2 + \frac{4}{3u^{3/2}})$$

$$u \equiv B/B_{minL}$$

Jet/counter-jet asymmetry gives outflow speed

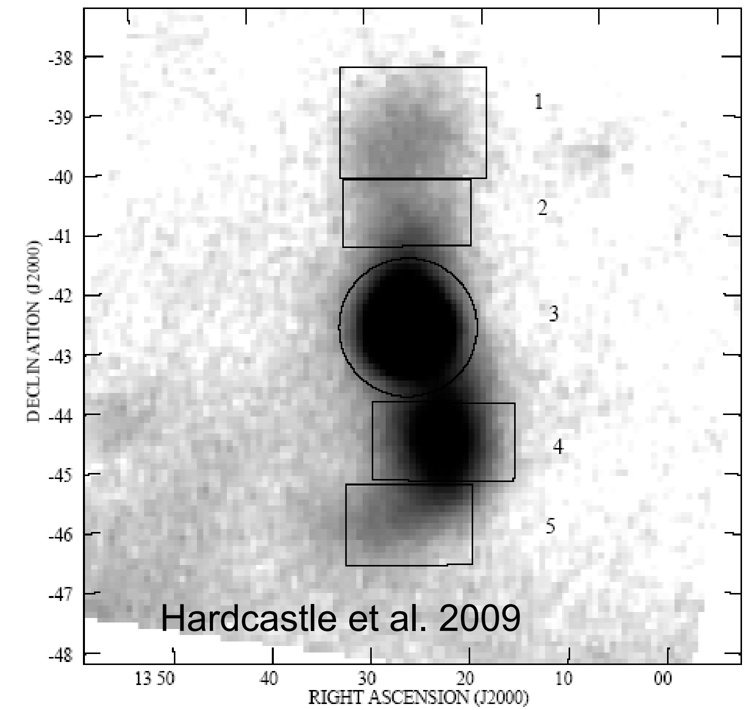


Figure 3. Spectral extraction regions used for Table 1 and Fig. 4. The greyscale shows the 20-GHz *WMAP* data.

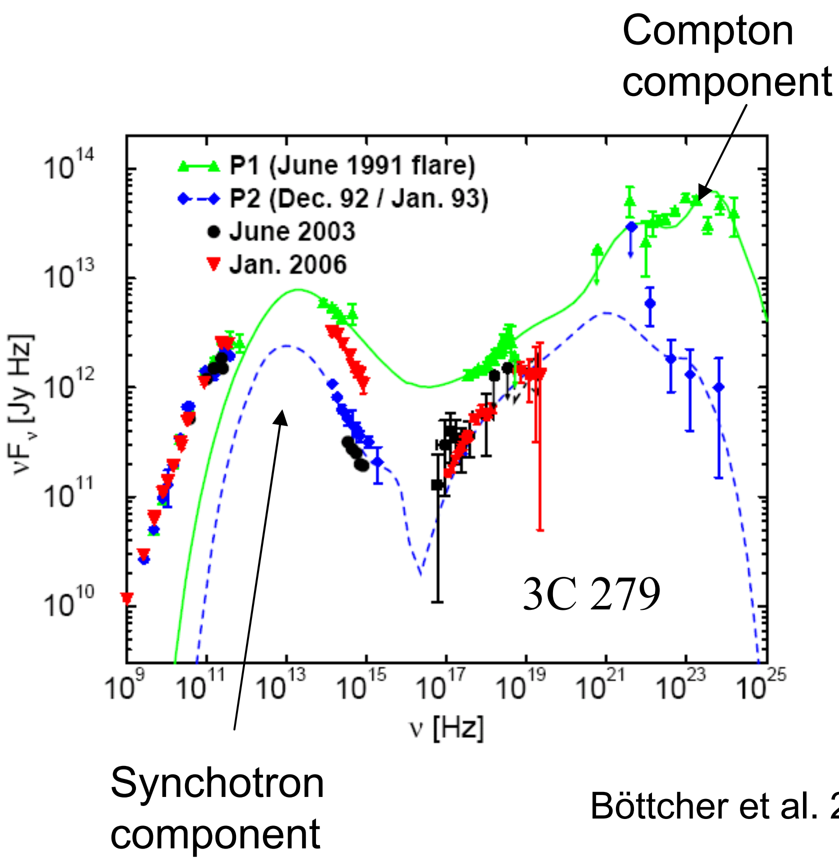
$$P_j^*(B_{minL}) = \frac{7}{3} \pi c \beta (\frac{\Gamma}{\delta_D})^2 r_b'^2 U_{cr} \left[\frac{27 d_L^2 m_e c^2 f_{\epsilon_2}^{syn} \ln(\epsilon_2/\epsilon_1)(1+\zeta_{pe})}{16 c \sigma_T U_{cr}^2 \sqrt{(1+z)\epsilon_2}}\right]^{2/7}$$

$\Rightarrow P_j(\text{Cen A}) \approx 10^{44}$ erg s^{-1}

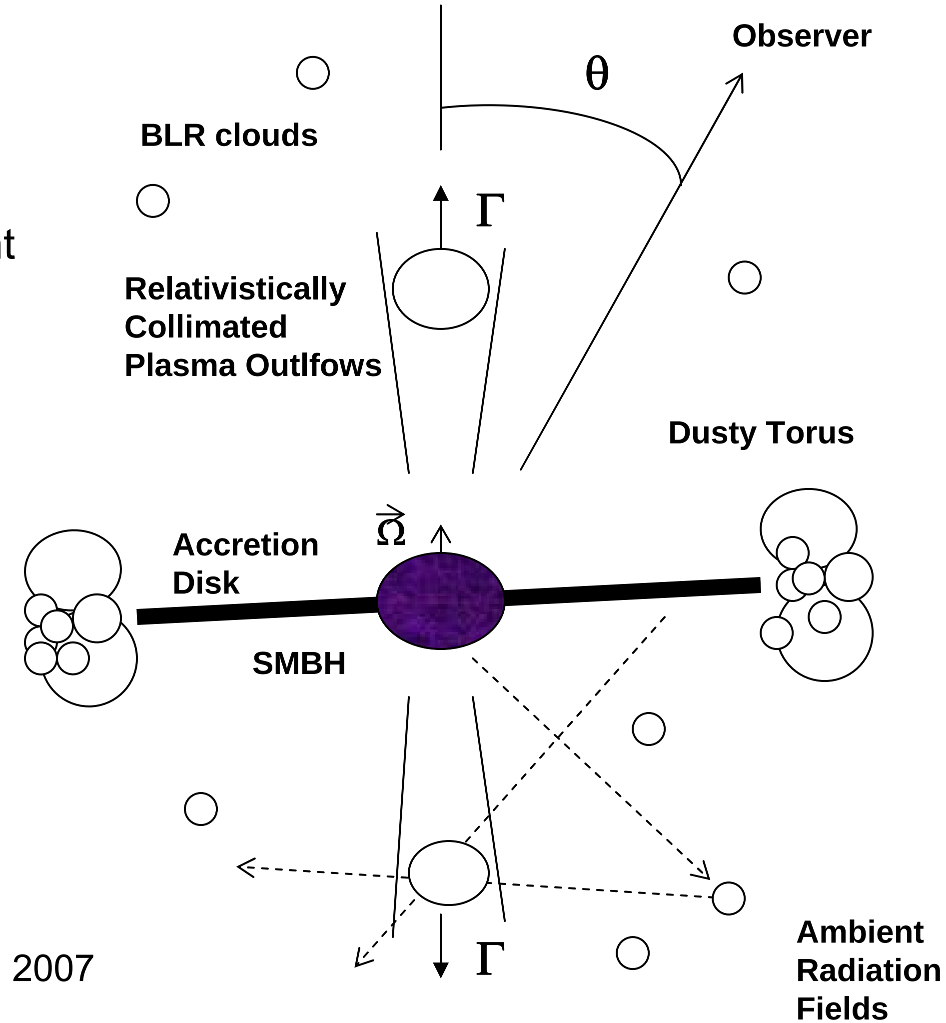
Apparent jet power 100 x larger?

Leptonic Blazar Modeling

Ejection of relativistic plasma from supermassive black hole



Böttcher et al. 2007



Neutral Beam Model for UHECRs in Blazars

Possible photon targets for **p + γ** :

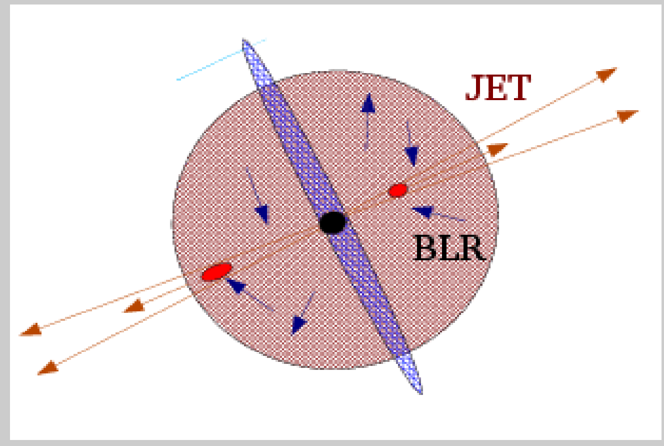
Internal: **synchrotron radiation**

External: **accretion disk radiation (UV)**

(i) direct accretion disk radiation:

(ii) accretion disk radiation scattered in the broad-line region **(Atoyan & Dermer 2001)**

quasi-isotropic, *up to R_{BLR}~ 0.1-1 pc*

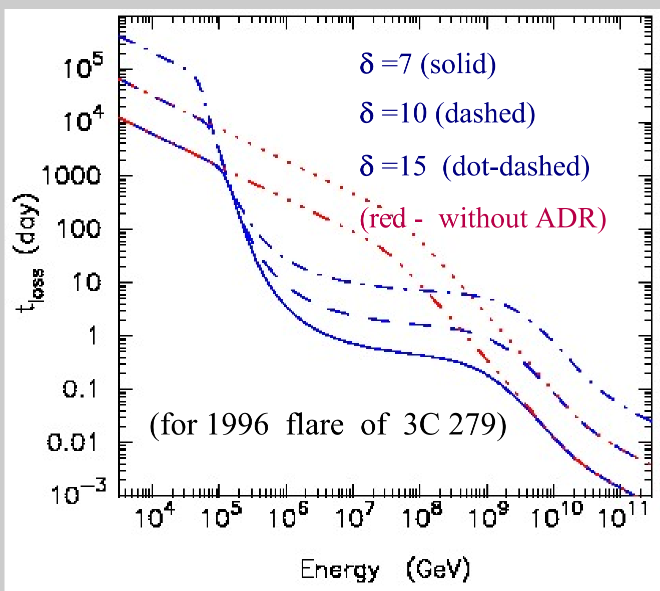


Impact of the external accretion-disk radiation component:

***high pγ-rates* & lower threshold energies:**

pγ →π →ν, γ, n

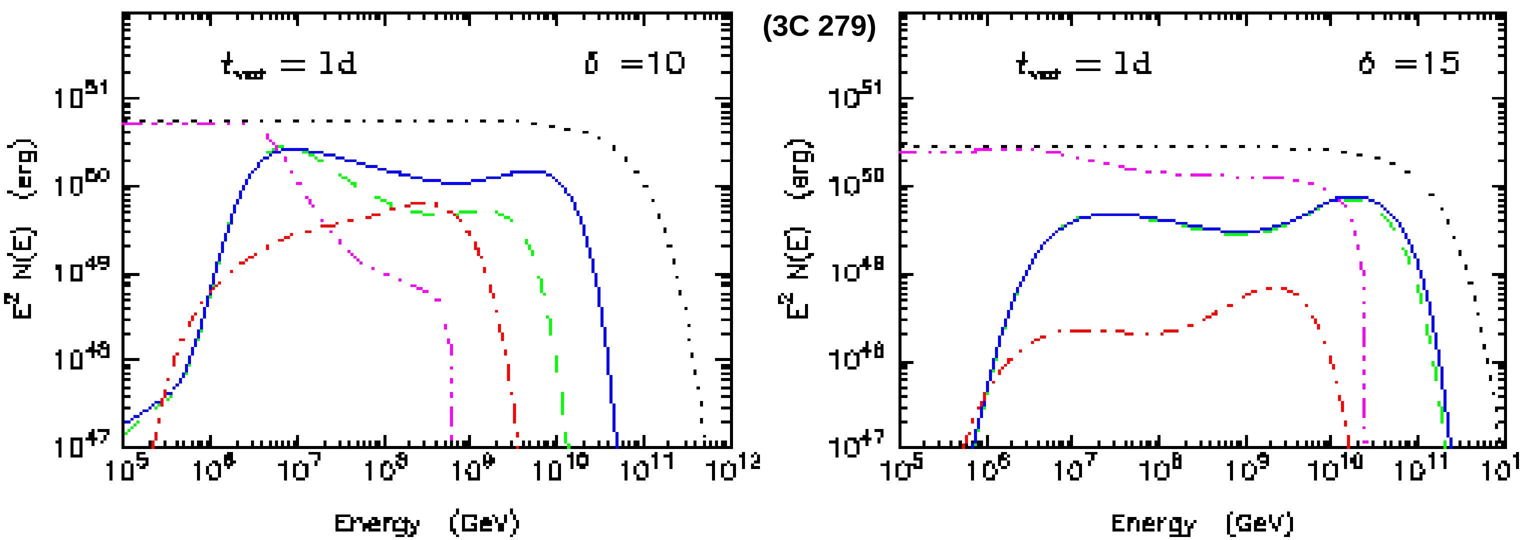
Neutrons escape to decay and become UHECRs (Atoyan & Dermer 2003)



Powerful blazars / FR-II

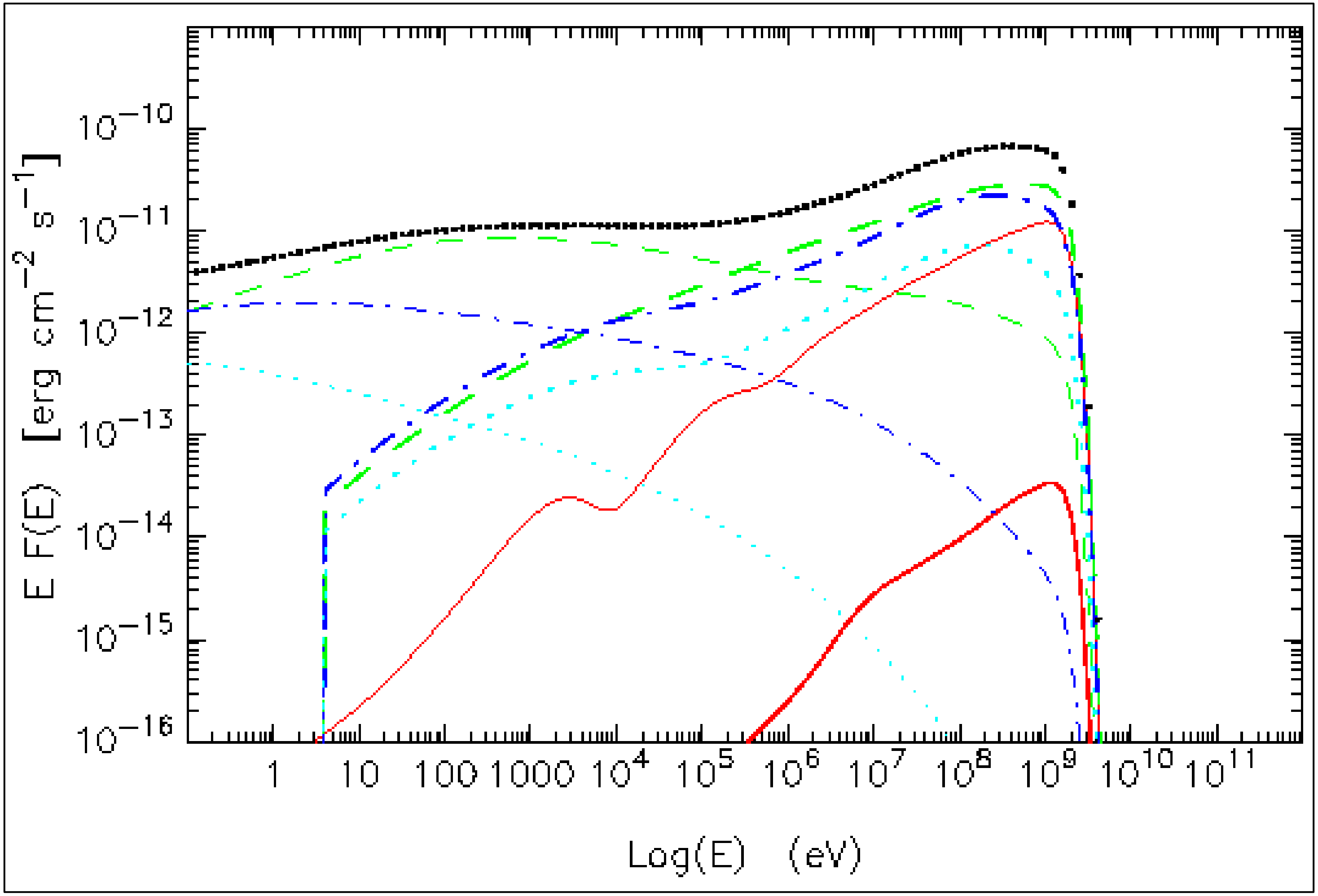
***Neutrons* with $E_n > 100$ PeV and *γ–rays* with $E_\gamma > 1$ PeV take away ~ 5-10 % of the total energy injected at $R<R_{BLR}$**

(3C 279)



dotted **-** CRs injected during the flare;
solid **-** neutrons escaping from the blob,
dashed **-** neutrons escaping from Broad Line Region (ext. UV)
dot-dashed **-** γ rays escaping external UV field (from *neutrons outside the blob*)
***3dot-dashed*-** Protons remaining in the blob at $l = R_{BLR}$

Hadronic γ-Ray Emission from Blazars



Gamma rays from hadron-induced cascades: Orphan γ-ray flares

UHE neutrons and γ rays

energy and momentum transport from AGN core

- **UHE γ-ray pathlengths in CMBR:**

$$l_{\gamma\gamma} \sim 10\ kpc\ \text{-}\ 1 Mpc$$

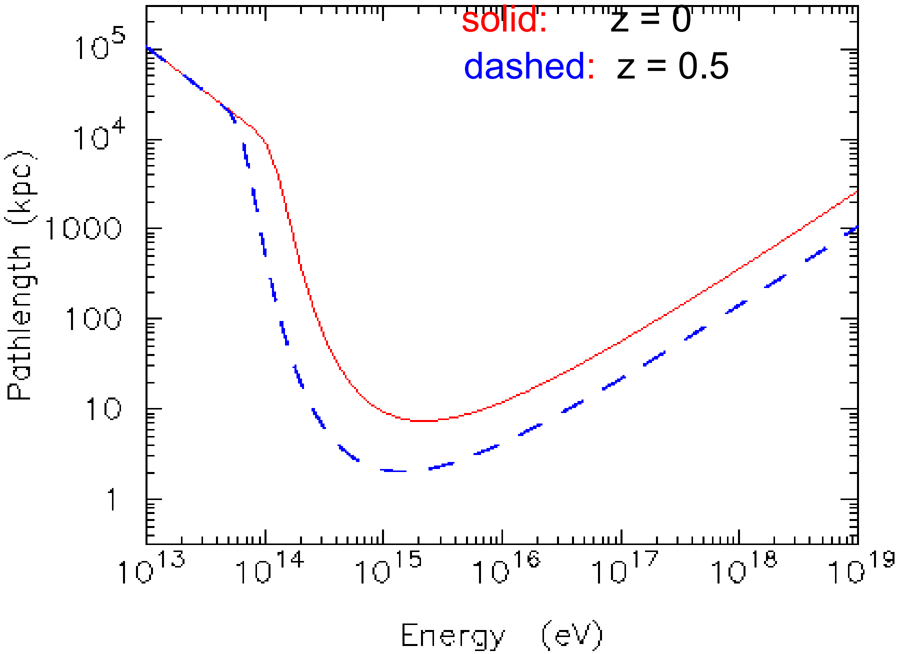
for $E_n \sim 10^{16}$ - 10^{19} eV

- **Neutron decay pathlength:**

$$l_d(\gamma_n) = \tau_0\, c\, \gamma_n\ (\tau_0 \sim 900\ \text{s})$$

$$\Rightarrow \quad l_d \sim 1\ kpc - 1\ Mpc$$

for $E \sim 10^{17}$ - 10^{20} eV



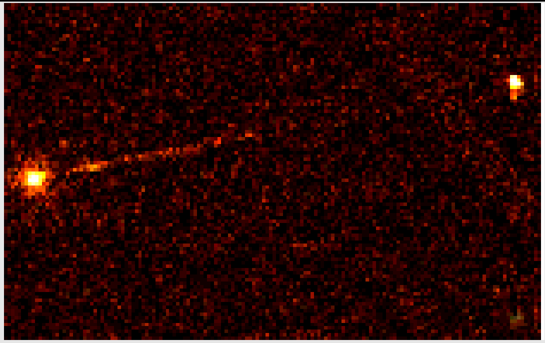
Pictor A

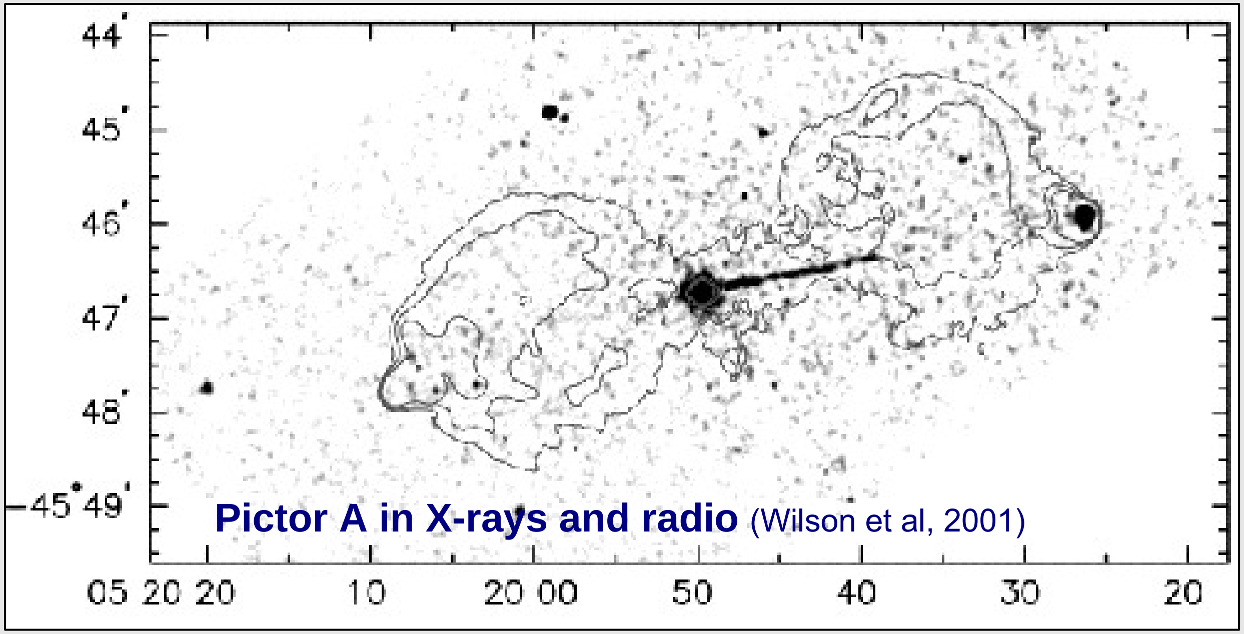
$d \sim 200$ Mpc

$l_{jet} \sim 1$ Mpc   ($l_{proj} = 240$ kpc)

Deposition of energy through ultra-high energy neutral beams

(Atoyan and Dermer 2003)



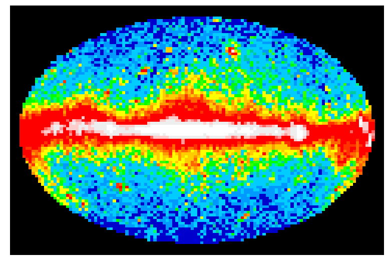


Pictor A in X-rays and radio (Wilson et al, 2001)

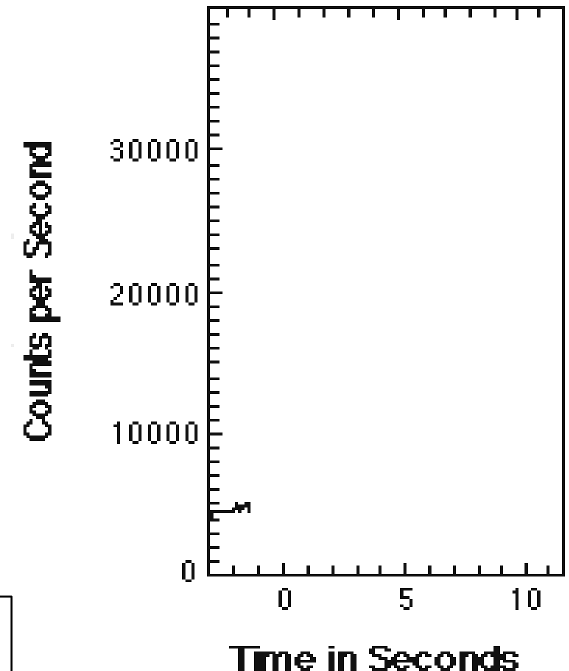
UHECRs from Gamma Ray Bursts

- GRB: Burst of γ rays accompanying black-hole formation
- Classes of GRBs
  - Long duration GRBs
    (collapse of massive stellar core)
  - Short hard class of GRBs
    (coalescence of compact objects)
  - Low luminosity GRBs

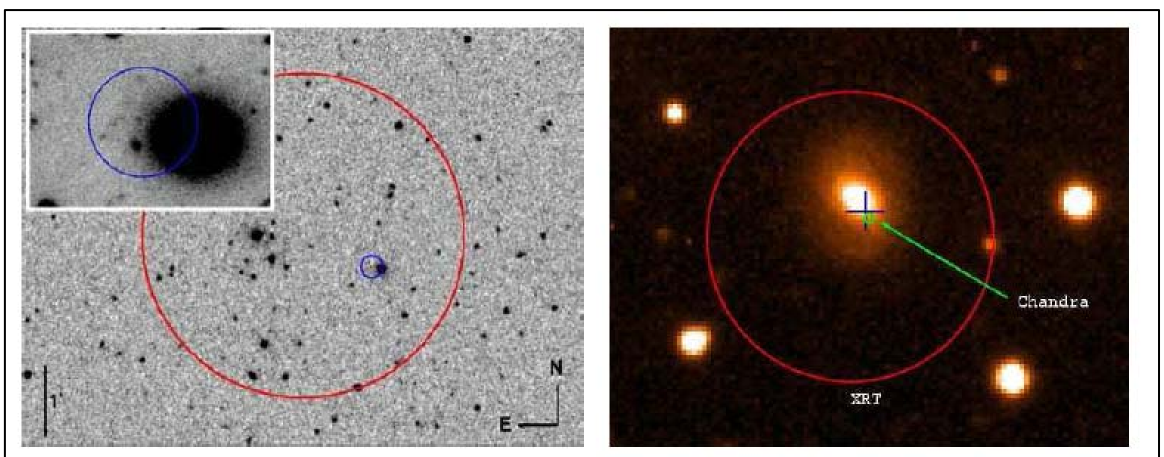
All-sky γ ray map
in Galactic coordinates



(Galactic coordinates)

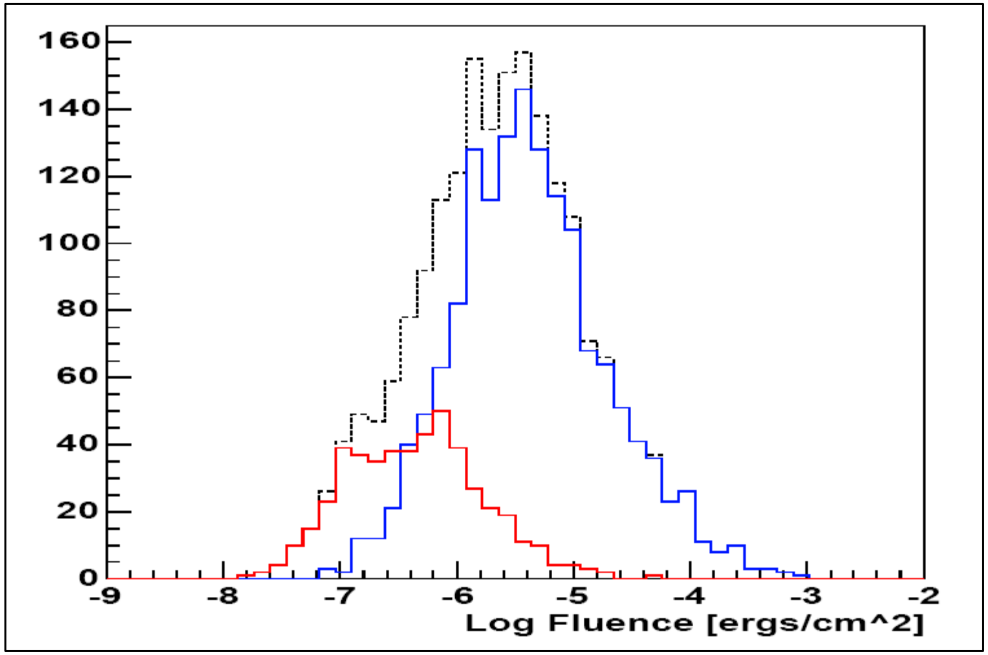


γ-ray Light Curve of GRB



Swift mission discovered that short hard class of GRBs are related to old stellar populations (Gehrels et al. 2005)

GRB X-ray/γ-ray Emissivity



> 20 keV fluence distribution of 1,973 BATSE GRBs (477 short GRBs and 1,496 long GRBs).

670 BATSE GRBs/yr (full sky) (Band 2001)

GRB fluence:

$$\approx 10^{-2}\ ergs\ cm^{-2}\ \ yr^{-1}$$

$$\Rightarrow \dot{\varepsilon}_{GRB} \approx$$

$$\frac{4\pi d^2 \times 10^{-2}\ ergs\ cm^{-2}\ \ yr^{-1}}{4\pi d^3/3}$$

$$\approx 0.75\times 10^{44}\ ergs\ Mpc^{-3}\ \ yr^{-1}$$

$$(d \approx 4000\ Mpc;\ z = 1)$$

$$\dot{\varepsilon}_{GRB} \approx \dot{\varepsilon}_{UHECR}(>10^{20}\,eV)$$

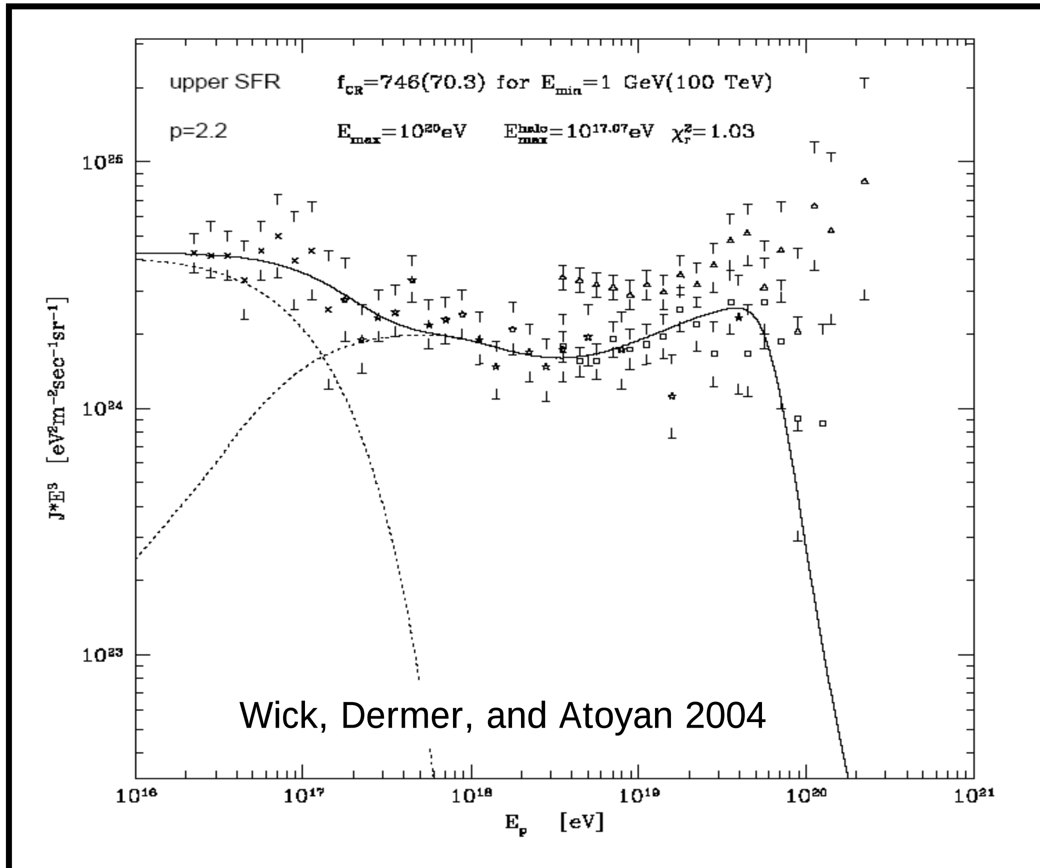
Vietri 1995; Waxman 1995

(independent of beaming)
Baryon loading

Ultra-high Energy Cosmic Rays from Gamma Ray Bursts

Proposed Solution to the Origin of Ultra-High Energy Cosmic Rays

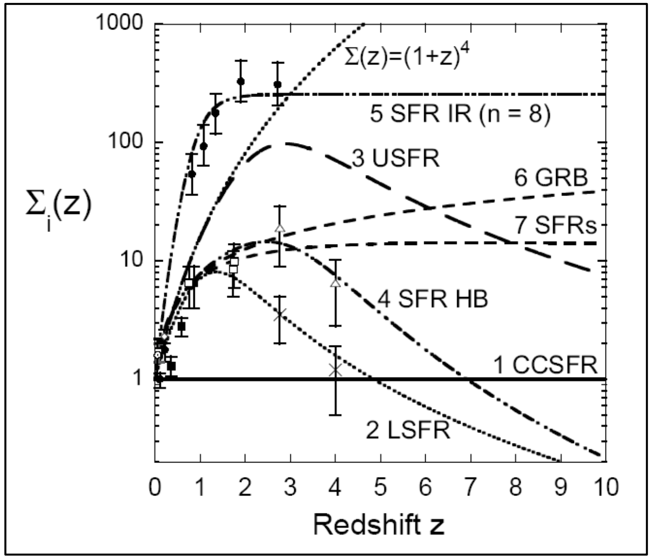
- Hypothesis requires that GRBs can accelerate cosmic rays to energies > 10^{20} eV
- Injection rate density determined by birth rate of GRBs early in the history of the universe
- High-energy (GZK) cutoff from photopion interactions with cosmic microwave radiation photons
- Ankle formed by pair production effects (Berezinsky)

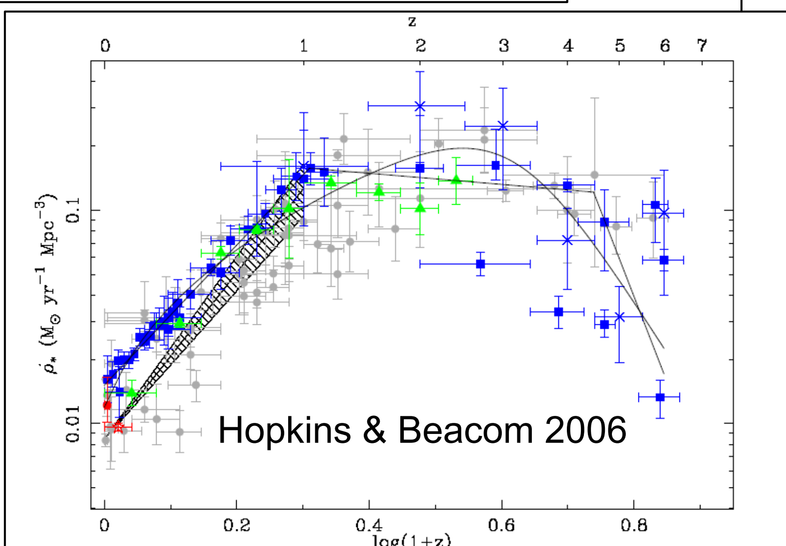


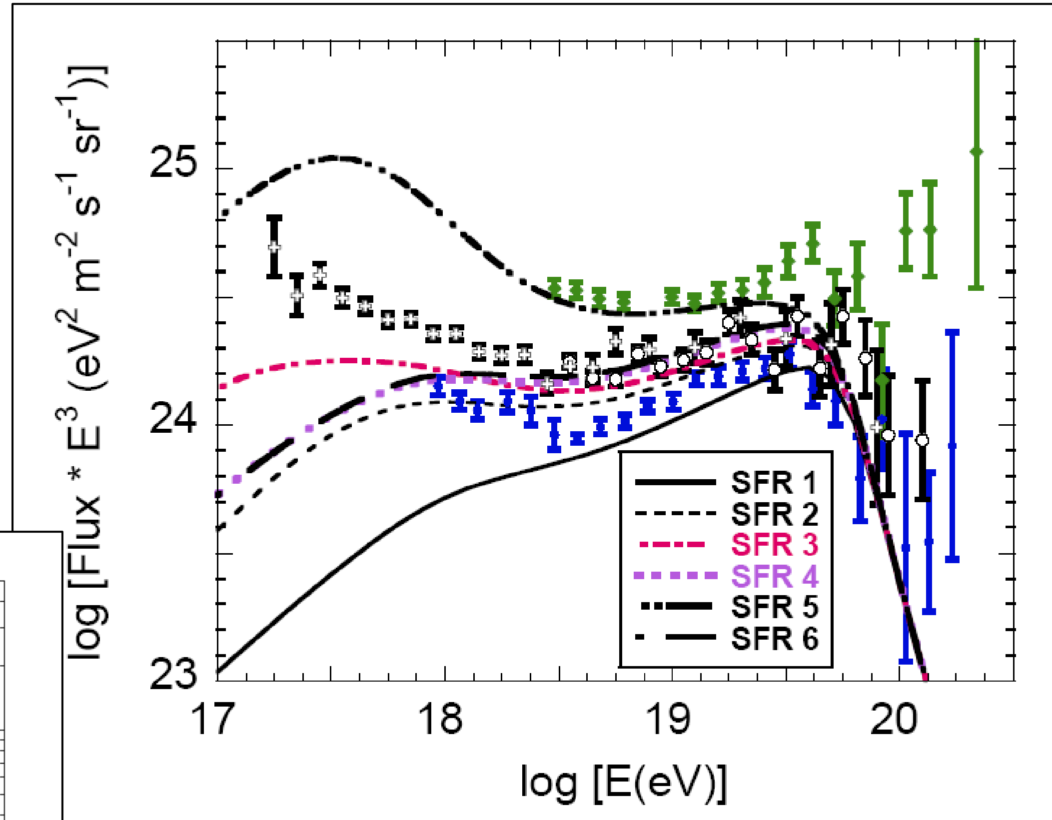
Wick, Dermer, and Atoyan 2004

Test UHECR origin hypothesis by detailed fits to measured cosmic-ray spectrum

Effects of Different Star Formation Rates







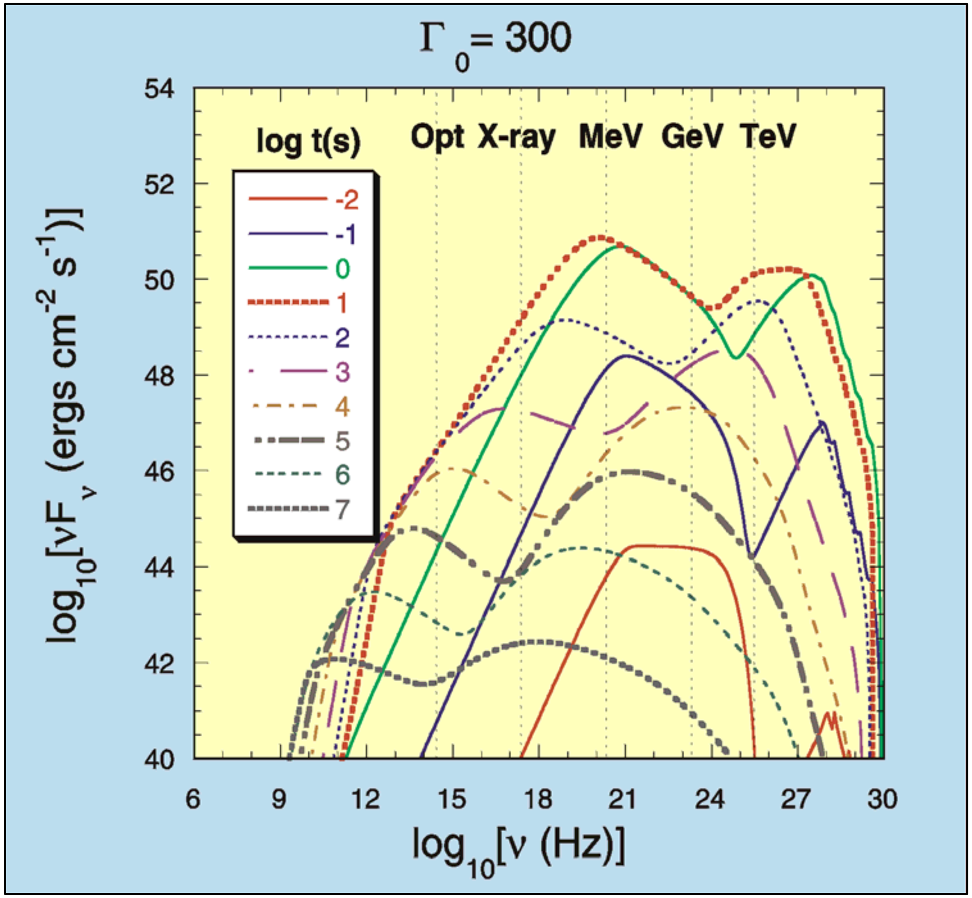
γ-ray signatures of UHECRs at source can confirm this hypothesis

Leptonic GRB Modeling

Simplest model (no photospheric Component; strong forward shock)

- ❑ Dominant synchrotron radiation at X-γ energies
- ❑ Two peaks in νF_ν distribution
- ❑ Power-law afterglow decay
- ❑ Generic rise in intensity followed by constant or decreasing flux with later appearance of a synchotron self-Compton component

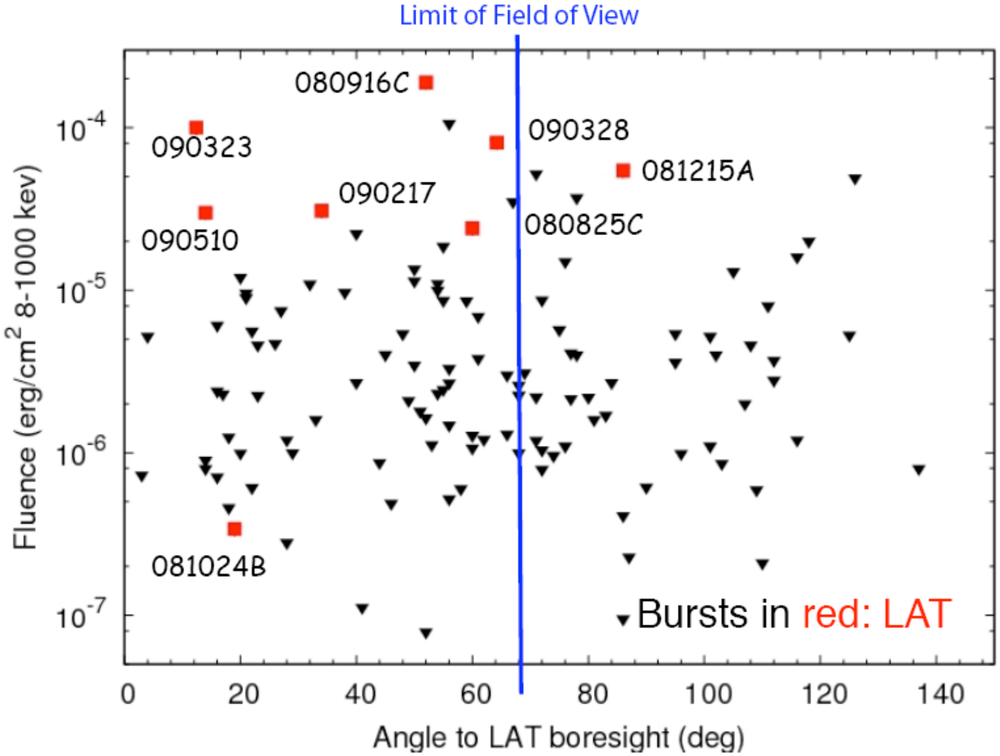
$E=10^{54}$ ergs
$n_0=100\ cm^{-3}$
$\varepsilon_B = 10^{-4}$



- νF_ν spectra shown at 10^i seconds after GRB
- $\gamma\gamma$ opacity included

Fermi GRBs as of 090510

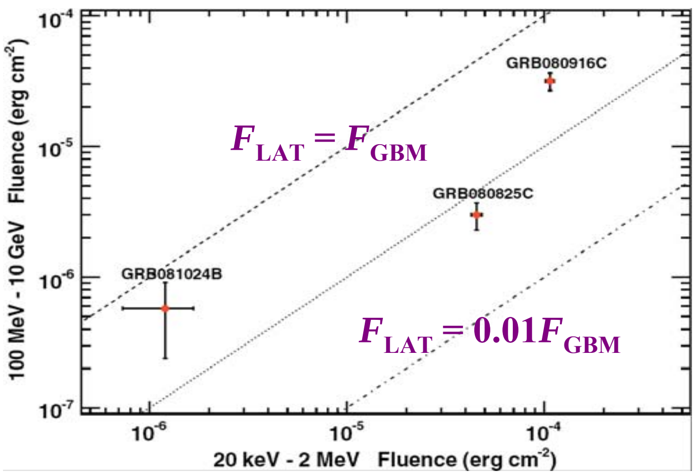
- GRB 080825C
- GRB 080916C – very strong, z=4.35
- GRB 081024B – short
- GRB 081215A – LAT rate increase
- GRB 090217
- GRB 090323 – ARR, z=3.6
- GRB 090328 – ARR, z=0.79
- GRB 090510 – short, intense, 1st LAT on-board trigger (GCN notice issued), z=0.9



192 GBM GRBs, ~30 short GRBs, 8 LAT GRBs

(Sinéad McGlynn, this program)

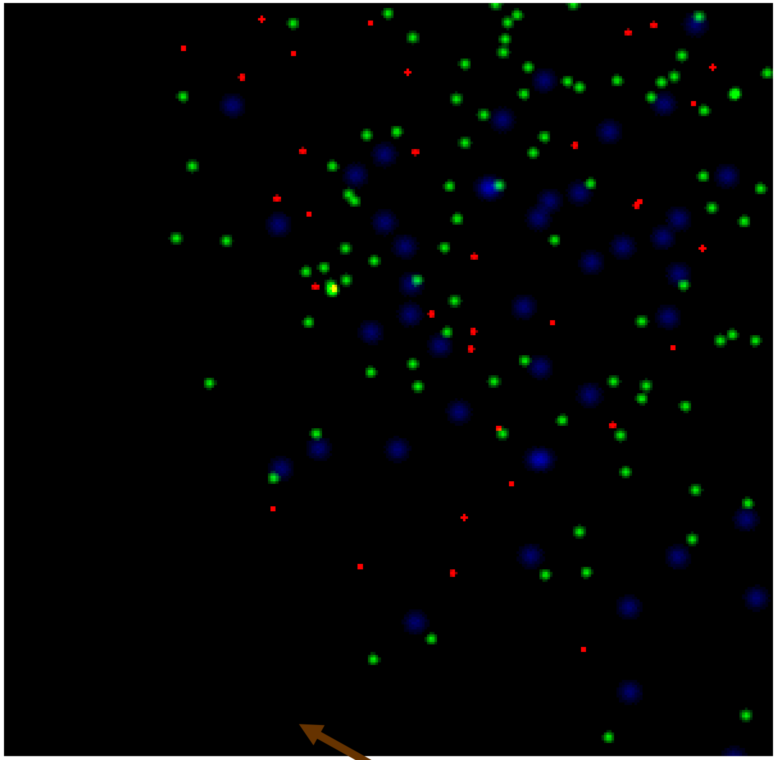
LAT vs GBM γ-ray fluence



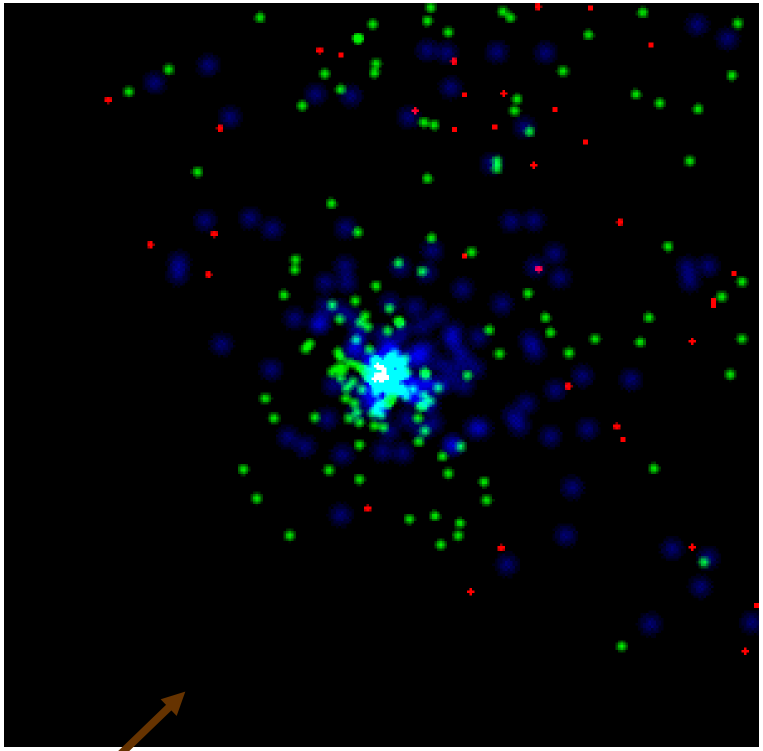
GRB 080916C: Luminous Fermi GRB

- ±30 deg region around GRB 080916C
  - GRB at 48° from the LAT boresight at T_0
- RGB= <100 MeV, 100 MeV - 1 GeV, >1 GeV

Before the burst (T_0-100 s to T_0)



During the burst (T_0 to T_0+100 s)



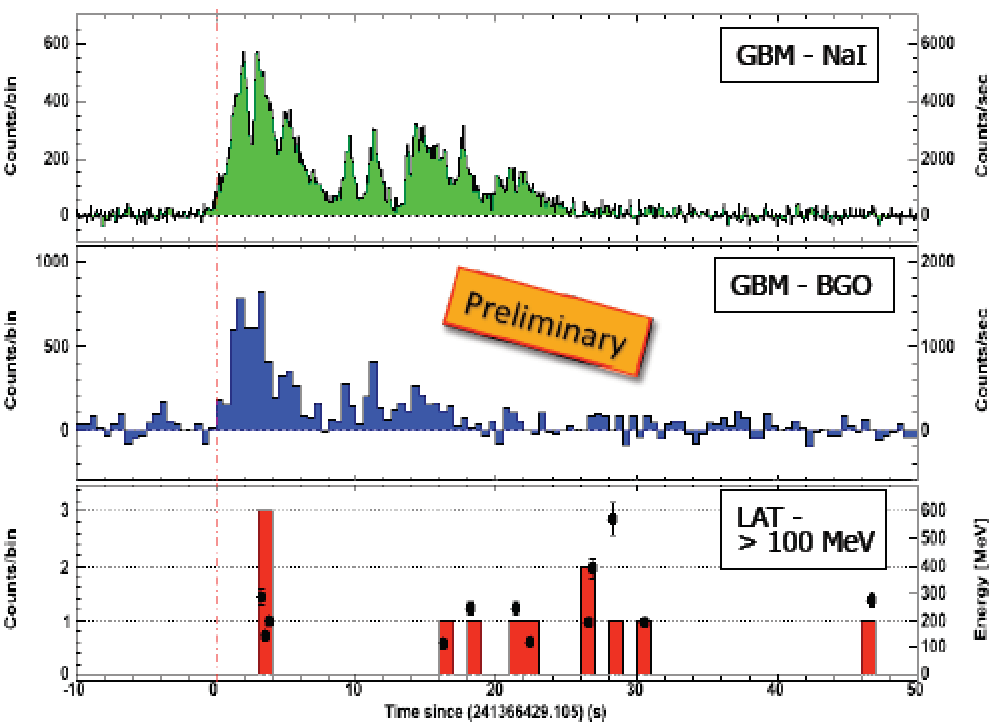
Black region = out of FoV

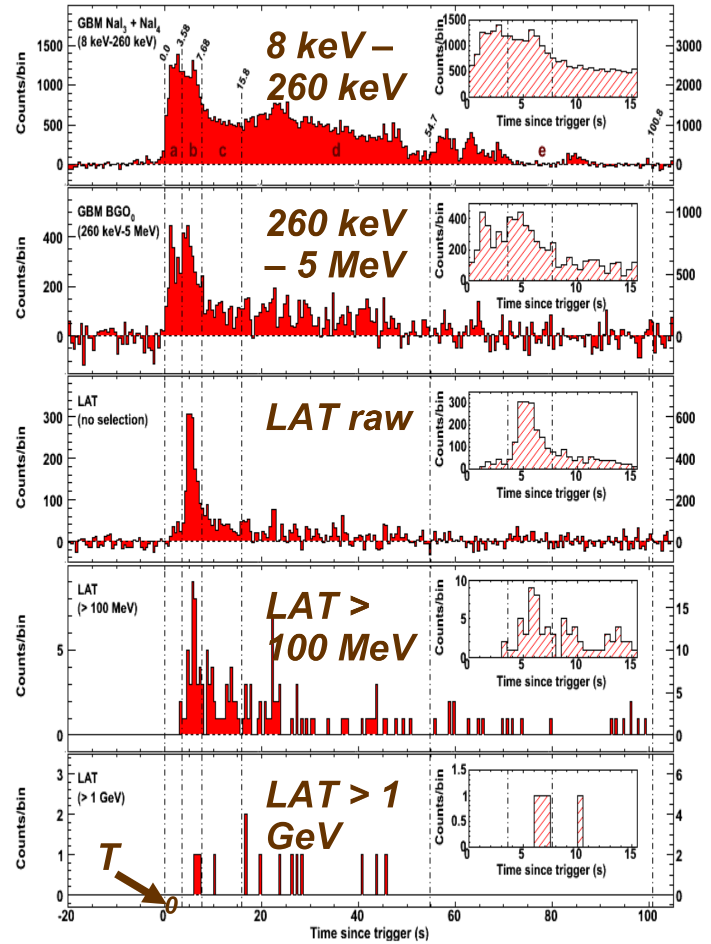
GRB 080916C: Notable Firsts

- Largest number, ~145, of >100 MeV photons from a GRB
  - ➔ Allows time-resolved spectral studies
- First high-energy 100 MeV – GeV detection of a GRB with known redshift z = 4.35±0.2 from GROND photometry on 2.2 m in La Silla, Chile (*Greiner et al. 2009*)
- Large fluence burst (2.4×10^{-4} ergs s^{-1}) at 10 keV – 10 GeV energies
  - ➔ Apparent isotropic energy release 8.8×10^{54} erg
  - ➔ Supports the black-hole jet paradigm of GRB
- Highest energy photon, $E = 13.22^{+0.70}_{-1.54}$ GeV from a GRB with measured redshift
  - ➔ Constraints on the jet Doppler factor/bulk Lorentz factor, emission region
  - ➔ Implications for Extragalactic Background Light (EBL) models
  - ➔ Limit on Quantum Gravity mass scale
- Significant ≅ 4s delay between onset of >100 MeV and 100 keV radiation
  - ➔ Implications for high-energy spectral modeling, leptonic/hadronic origin

Results published in Science (Abdo et al., vol. 323, issue 5922, page 1668, 2009)

Light Curves of GRBs 080825C, 080916C





Abdo et al. 2009, Science

Two notable features:

1. Delayed onset of high-energy emission
2. Extended ("long-lived") high-energy γ rays seen in both long duration and short hard GRBs

Interpretation of Delayed >100 MeV Emission

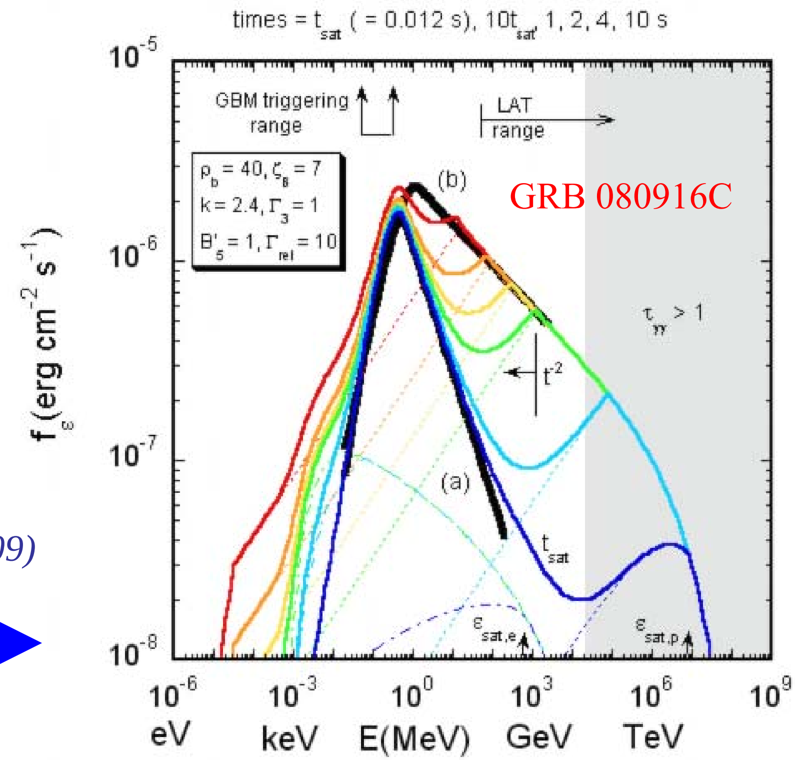
- Random collisions between plasma shells
  - ➔ Separate emission regions from forward/reverse shock systems
  - ➔ Second pair of colliding shells produce, by chance, a harder spectrum
  - ➔ Expect no time delays for >100 MeV in some GRBs, yet to be detected
- Opacity effects
  - ➔ Expansion of compact cloud, becoming optically thin to >100 MeV photons
  - ➔ Expect spectral softening break evolve to higher energy in time, not observed
- Up-scattered cocoon emission

  Synchrotron-self-Compton for < MeV

  External Compton of cocoon photons, arriving late from high-latitude, to >100 MeV

  Toma, Wu, Meszaros (2009)
- Proton synchrotron radiation

  Inherent delay to build-up proton synchrotron flux which sweeps into LAT energy range from high-energy end

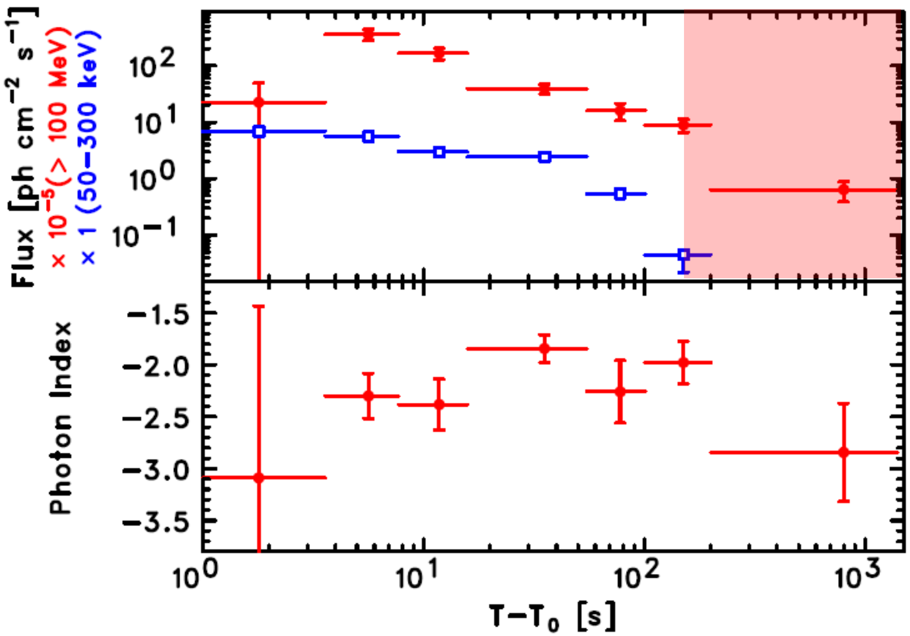


Razzaque, Dermer and Finke (2009)

Extended High Energy Emission

- All LAT detected GRBs show significant high energy emission extending after the low energy emission has (almost) disappeared below detectability (discovered originally with EGRET on Compton Observatory; *Hurley et al. 1994*)

GRB 080916C



Abdo et al., Science, 323, 1668 (2009)

- GRB080916C shows HE emission that extends more than 1000 sec. beyond the detectable keV-MeV emission
- Could be due to …
  - Delayed arrival of Compton-scattered synchrotron photons (SSC)
    Though no hard spectrum observed as expected from SSC, unknown reason for delay
  - Emission from >TeV γ-ray induced cascade in CMB (*e.g., Razzaque, Meszaros & Zhang 2004*)
    Requires very small (<10^{-16} G) intergalactic magnetic field
  - Long-lived hadronic emissions (Böttcher and Dermer 1998)

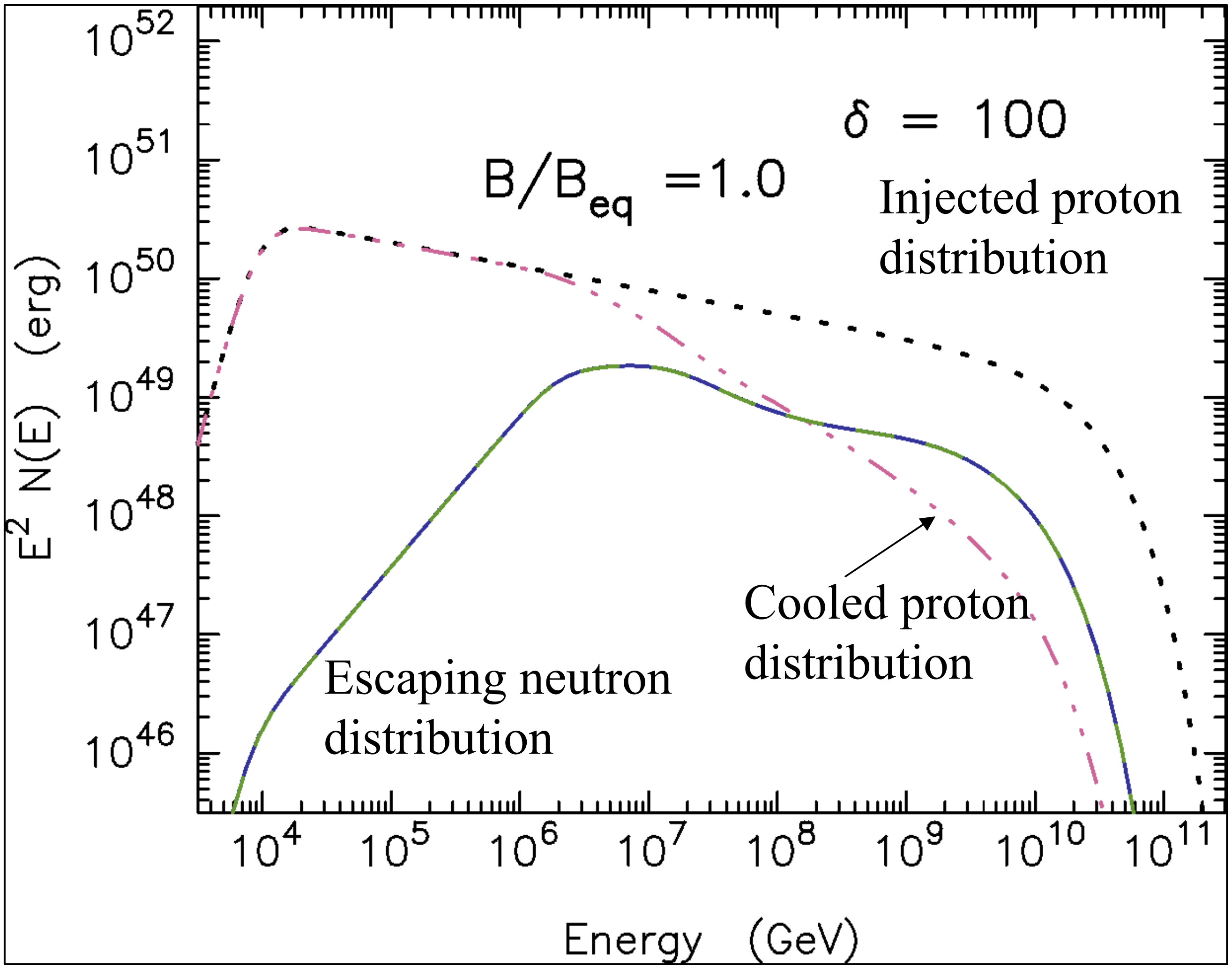
Hadronic GRB Modeling in Collapsar Scenario

Energy injected in protons normalized to GRB synchrotron fluence

$\Phi_{tot} = 3\times10^{-5}$ *ergs cm*$^{-2}$, 50 *one* sec *pulses*

Forms neutral beam of neutrons, γ rays, and neutrinos

Nonthermal Baryon Loading Factor f_b = 30

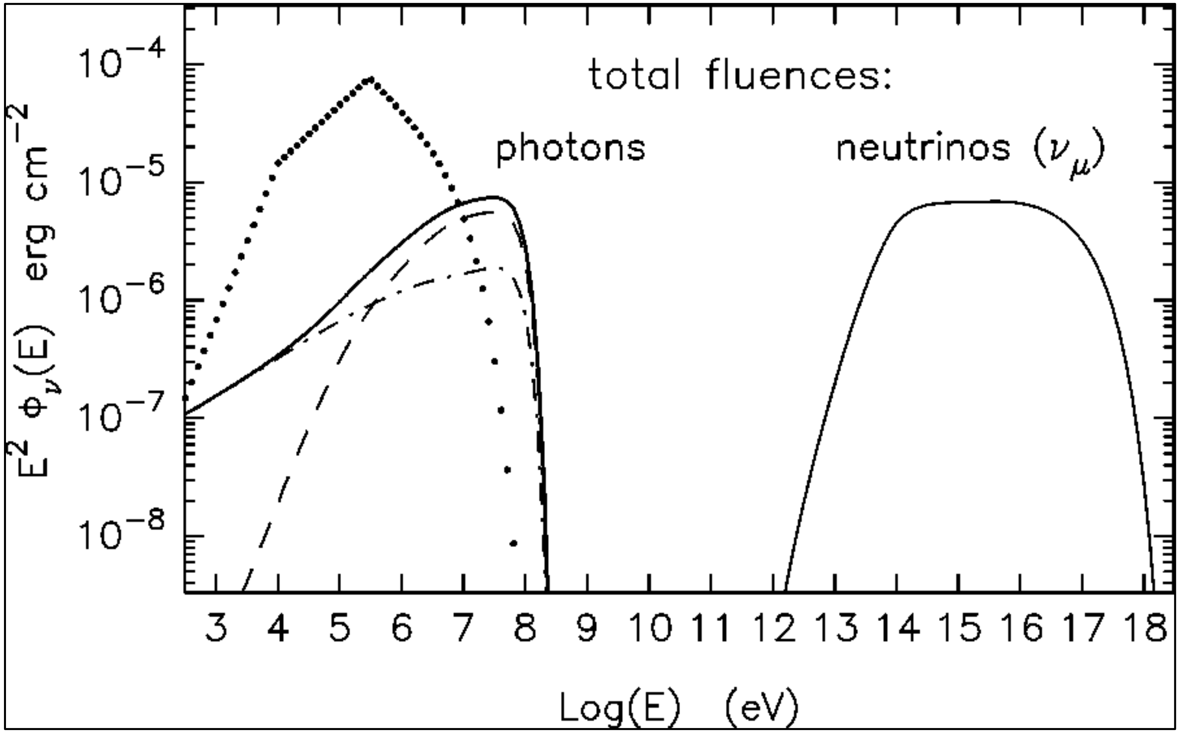


Photon and Neutrino Fluence during Prompt Phase

Nonthermal Baryon
Loading Factor $f_b = 1$

$\Phi_{tot} = 3\times10^{-4}$ ergs cm^{-2}

$\delta_D = 100$



Hard γ-ray emission component from hadronic-induced electromagnetic cascade radiation inside GRB blast wave

Second component from outflowing high-energy neutral beam of neutrons, γ-rays, and neutrinos

$$p\gamma \rightarrow \pi^{\pm} \rightarrow e^{\pm}\ (+n, p, \nu)$$
$$\rightarrow \pi^{0} \rightarrow 2\gamma \rightarrow e^{\pm}$$

Neutrinos from GRBs in the Collapsar Model

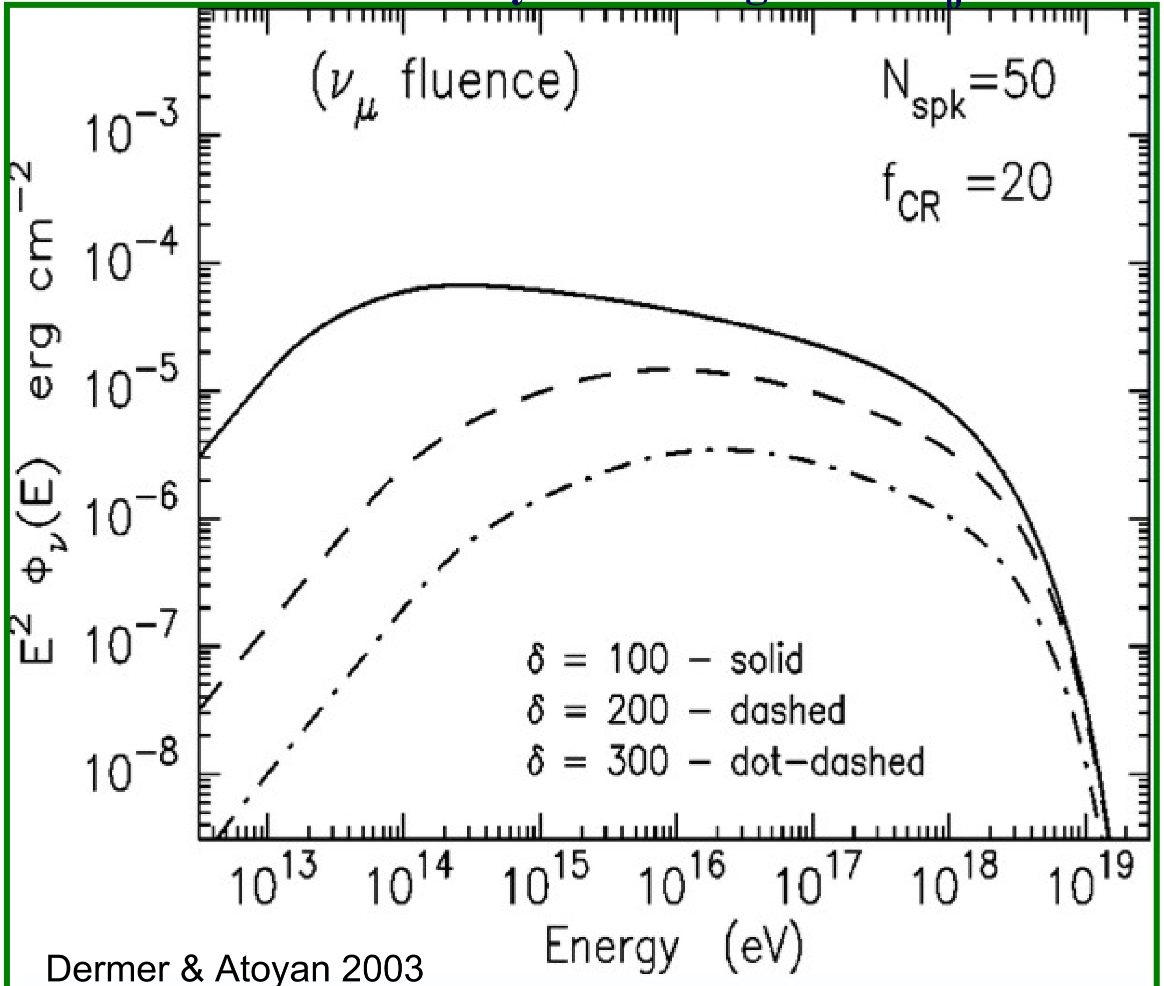
For a fluence of $3x10^{-4}$ ergs/cm^2, (~2/yr)

N_ν predicted by IceCube:

$N_\nu \approx$ 1.3, 0.1, 0.016 for δ = 100, 200, and 300, respectively in collapsar model for f_{CR} = 20

requires Large Baryon-Loading

Nonthermal Baryon Loading Factor f_b = 20



Dermer & Atoyan 2003

Origin of UHECRs

Ruled out: **Galactic sources**

young neutron stars or pulsars, black holes,
GRBs in the Galaxy

Particle physics sources

superheavy dark matter particles in galactic halo
top-down models, topological defects

Clusters of galaxies

Viable: **Jets of AGNs:** radio-loud or radio-quiet? Cen A!, M87?

GRBs: Requires nano-Gauss intergalactic magnetic field

Magnetars? **Others?**

UHECRs accelerated by black-hole jets

UHECRs from GRBs and Radio-Loud AGNs: Why (these) Black Holes?

1. Extragalactic
2. Powerful
3. Emissivity

How to confirm origin?

Association of arrival directions with sources
γ-ray signatures of UHECR acceleration
Neutrino emission from GRBs or Blazars