High-Energy Astronomy with Fermi

Overview: Fermi Summer School, Lewes, Delaware

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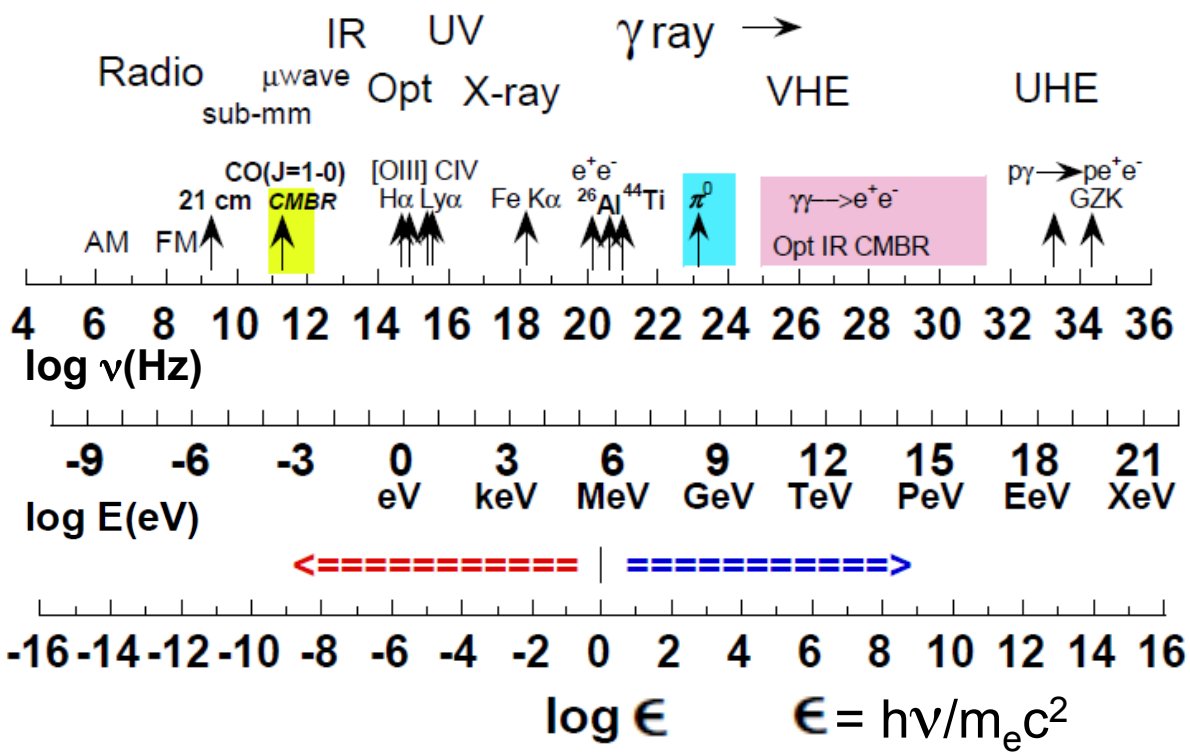
Outline: Big Picture Fermi Physics

1. Fermi Gamma ray Space Telescope
2. Some Results from Fermi
3. What are the UHECR sources?

Multiwavelength Astronomy

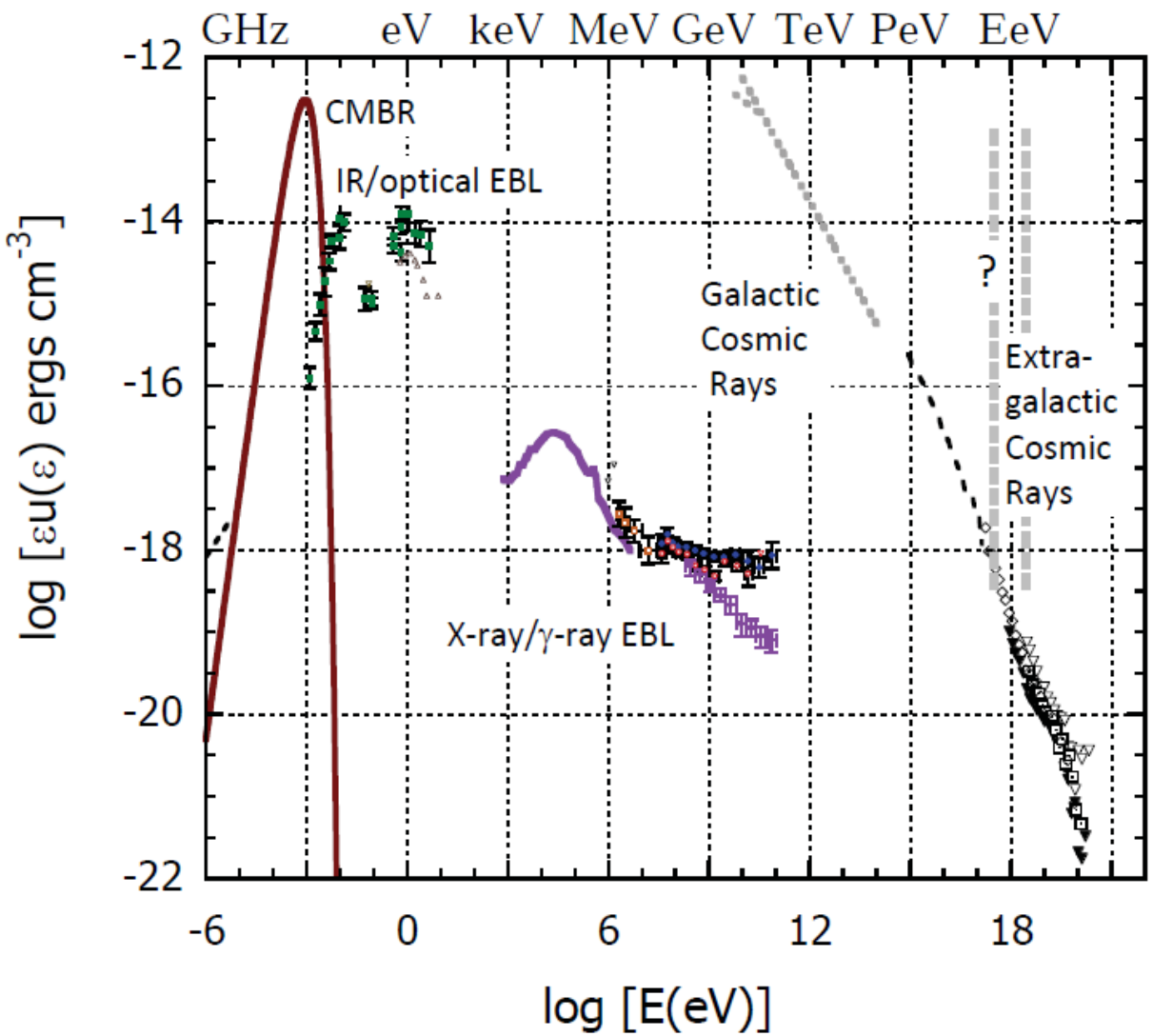


thermal vs. nonthermal

γ rays: particle acceleration or dark matter signatures

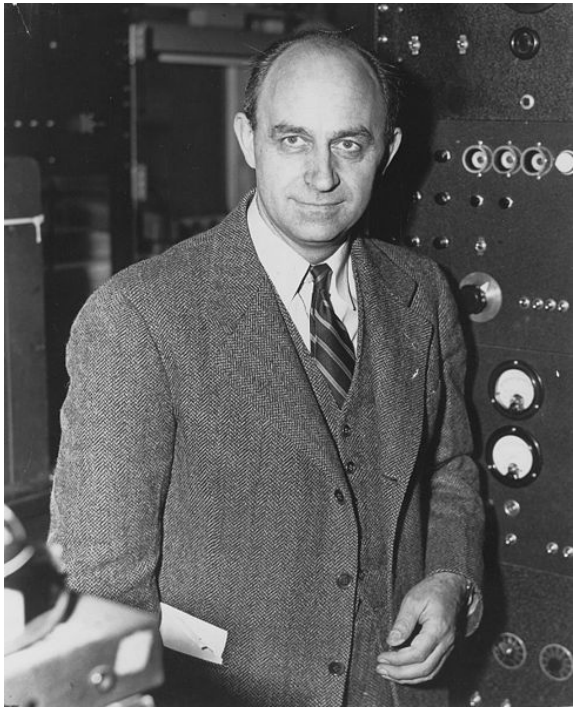
GeV vs. TeV astronomy

Diffuse Radiations

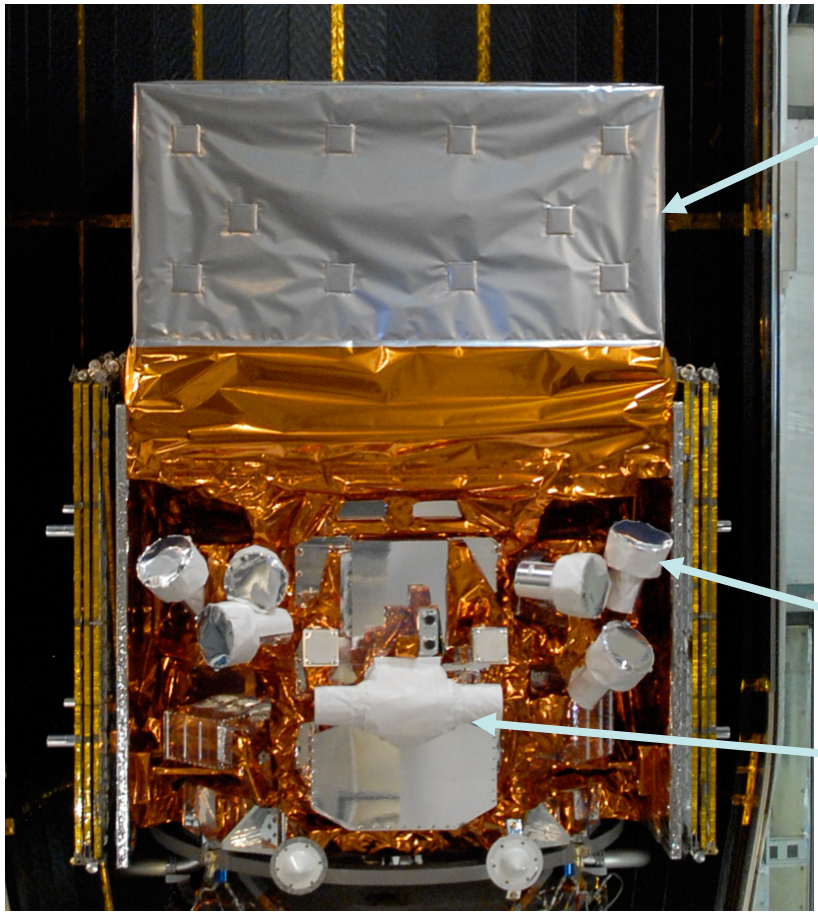


GLAST and Fermi

- Launch from Cape Canaveral Air Station 11 June 2008, 12:05PM EDT
- Circular orbit, 565 km altitude (96 min period), 25.6 deg inclination
- Gamma ray Large Area Space Telescope (GLAST) becomes the Fermi Gamma-ray Space Telescope



Fermi's Instruments



Large Area Telescope (LAT):

20 MeV → 300 GeV (including unexplored 10-100 GeV range)

2.4 sr FoV (scans entire sky every ~3 hrs)

Gamma-ray Burst Monitor (GBM)

8 keV - 40 MeV

12 NaI detectors (8 keV - 1 MeV)

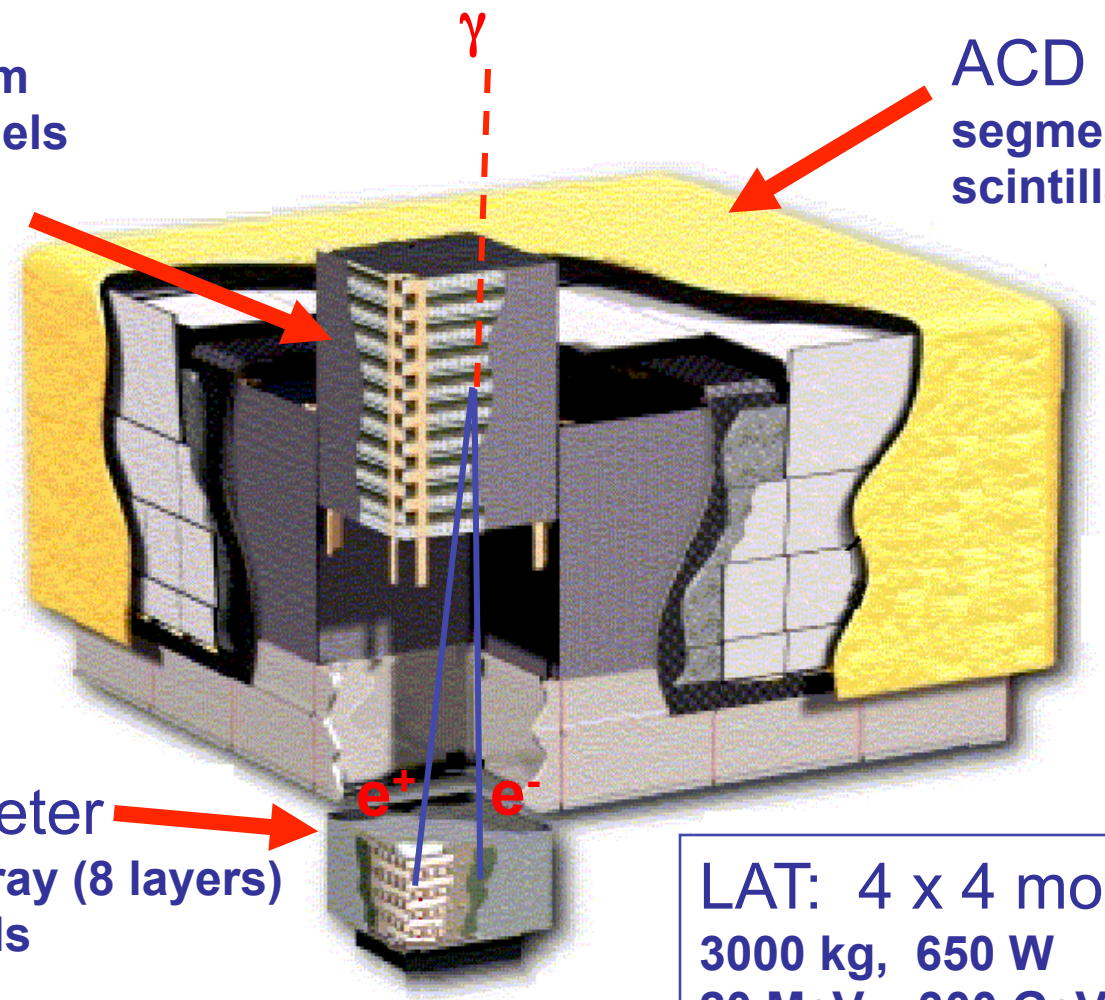
2 BGO detectors (0.15 - 40 MeV)

views entire unocculted sky

The Large Area Telescope

Si Tracker
pitch = 228 μm
8.8 10^5 channels
18 planes

ACD
segmented scintillator tiles

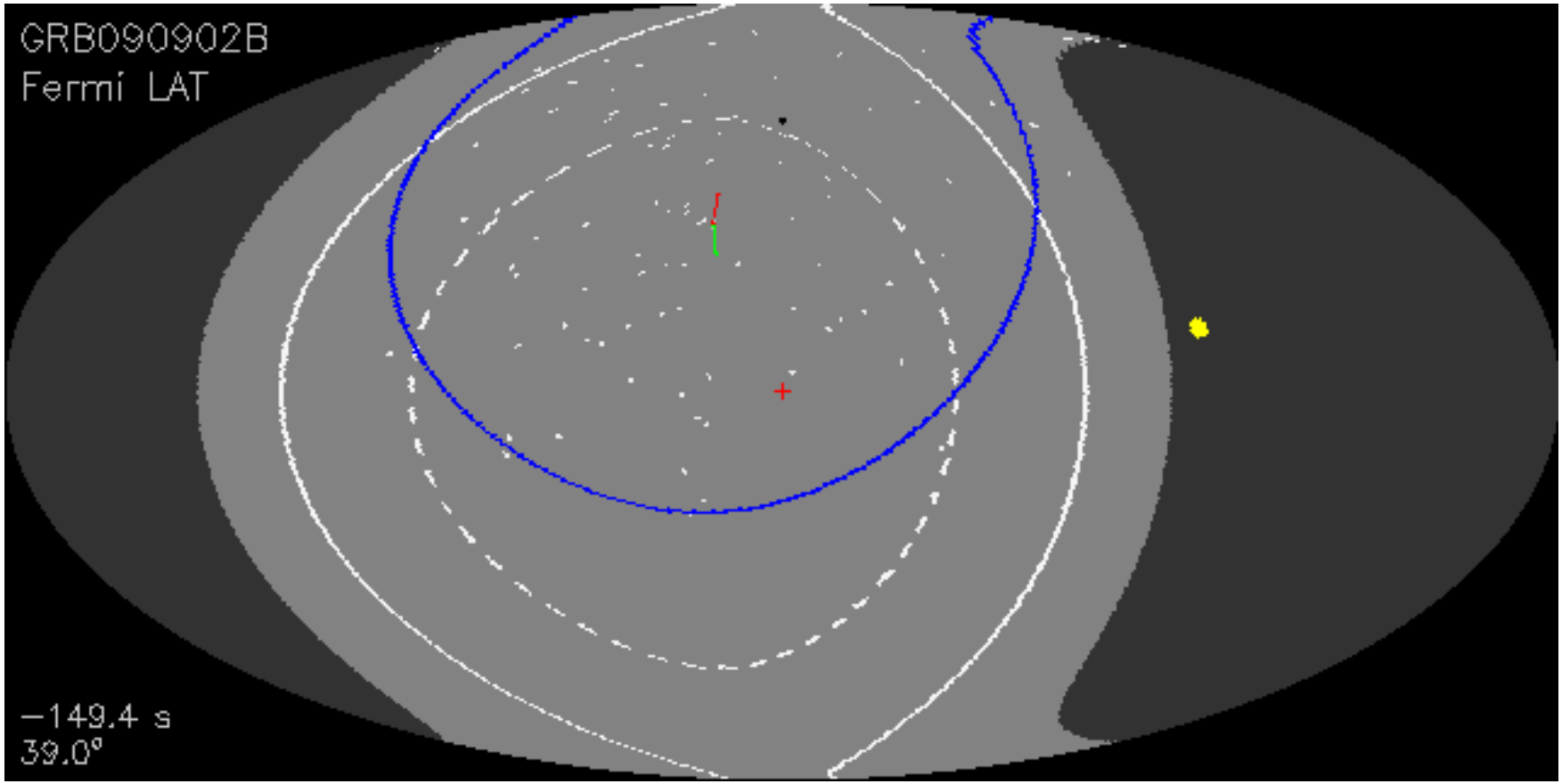


CsI Calorimeter
hodoscopic array (8 layers)
6.1 10^3 channels

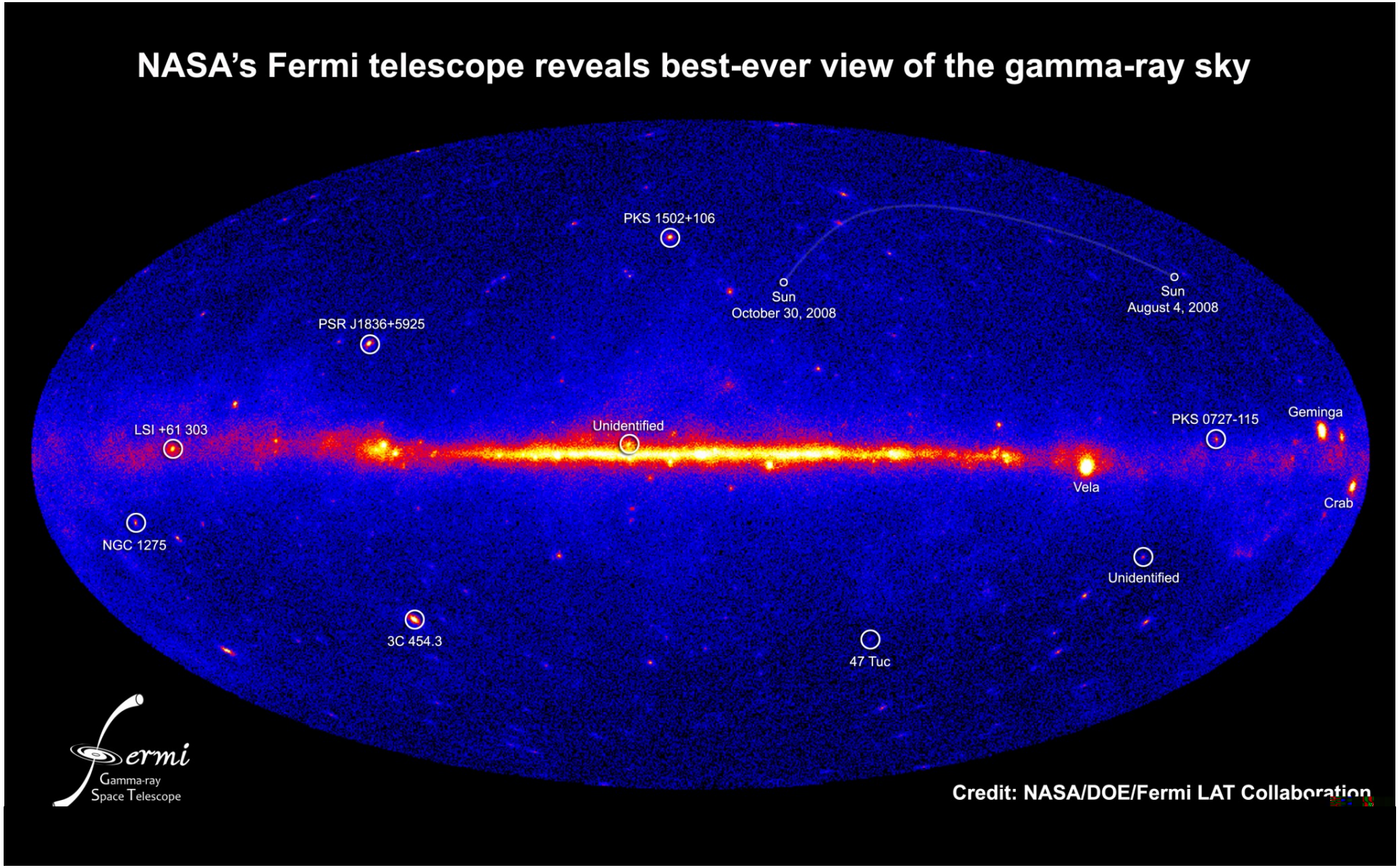
LAT: 4 x 4 modular array
3000 kg, 650 W
20 MeV – 300 GeV

GBM + LAT - Autonomous repoints

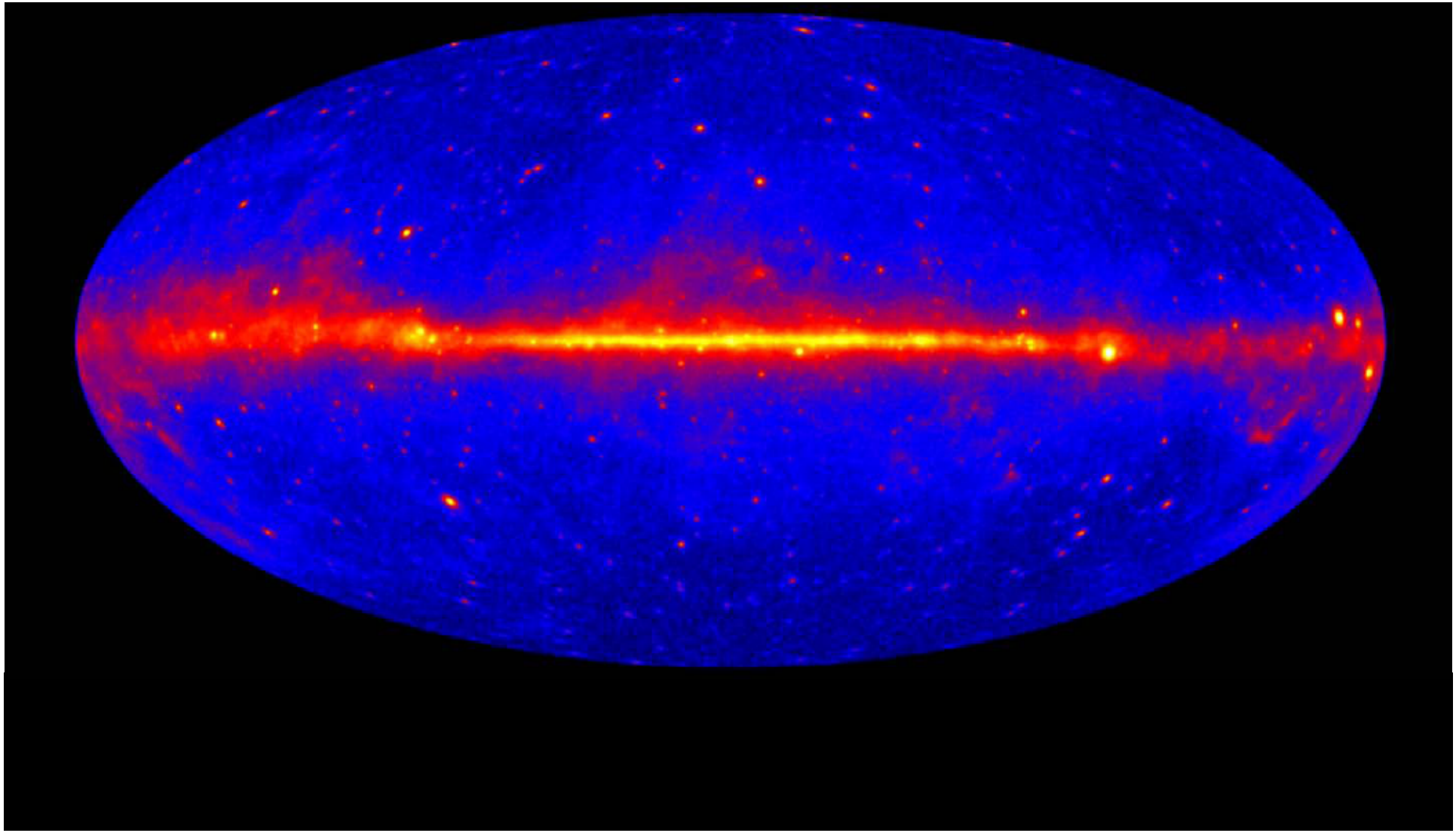
- **LAT pointing in celestial coordinates from -120 s to 2000 s**
  - **Red cross = GRB 090902B**
  - **Dark region = occulted by Earth**
  - **Blue line = LAT FoV (±66°)**
  - **White points = LAT events (no cut on zenith angle)**
  - **Yellow dot: Sun**



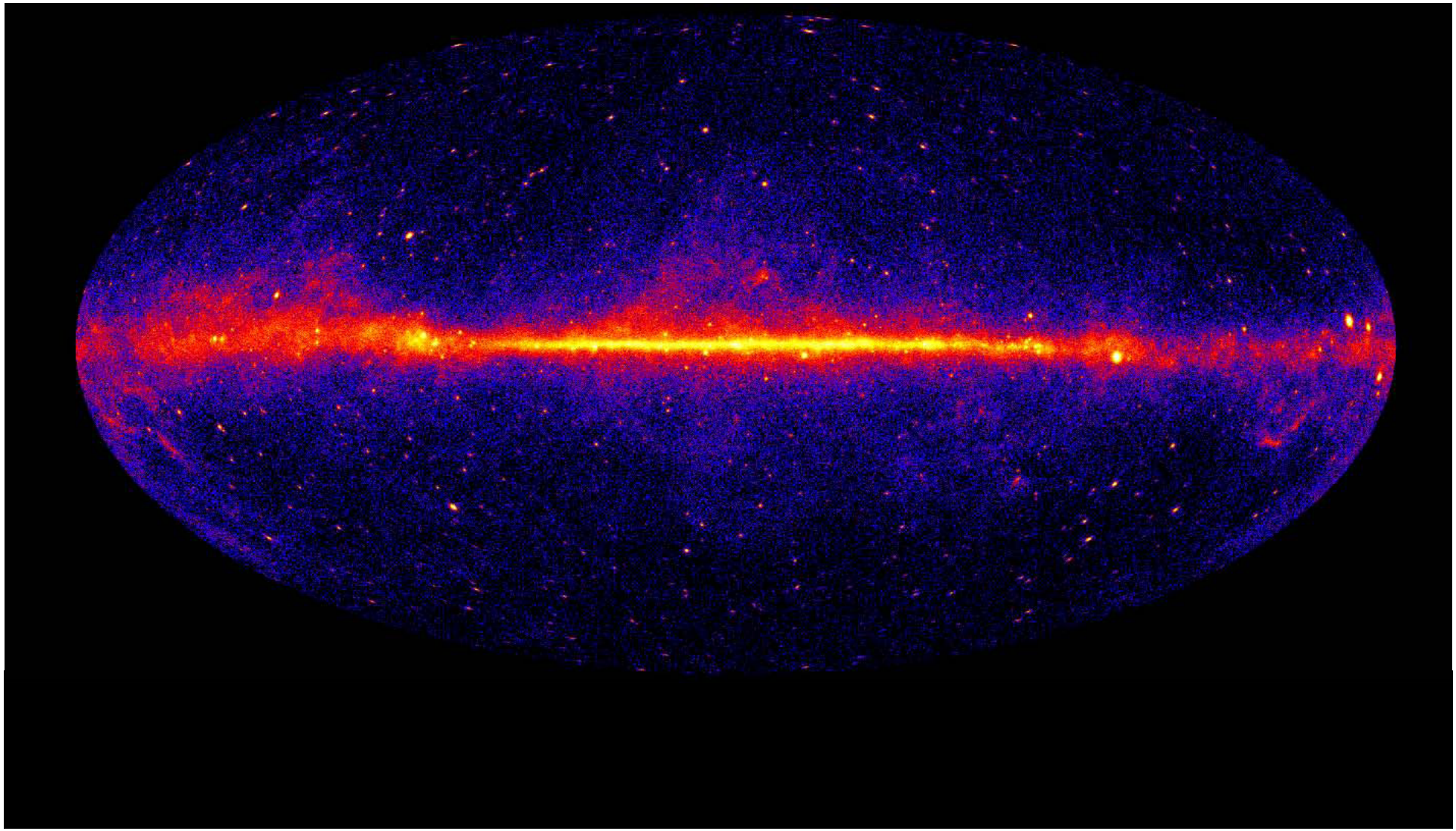
The Fermi LAT (3 month) Sky



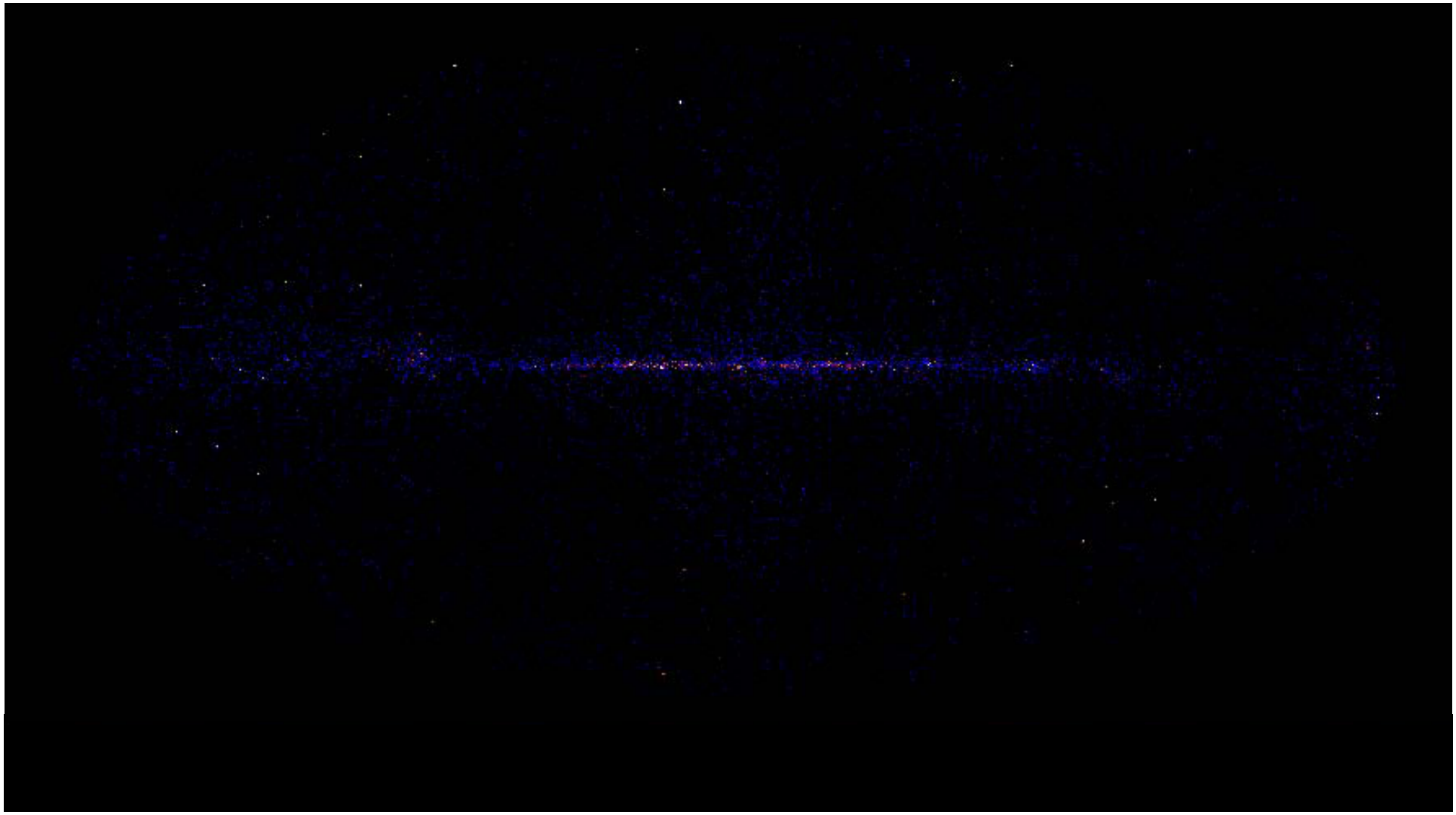
The Fermi LAT (2 yr, > 300 MeV) Sky



The Fermi LAT (2 yr, > 1 GeV) Sky

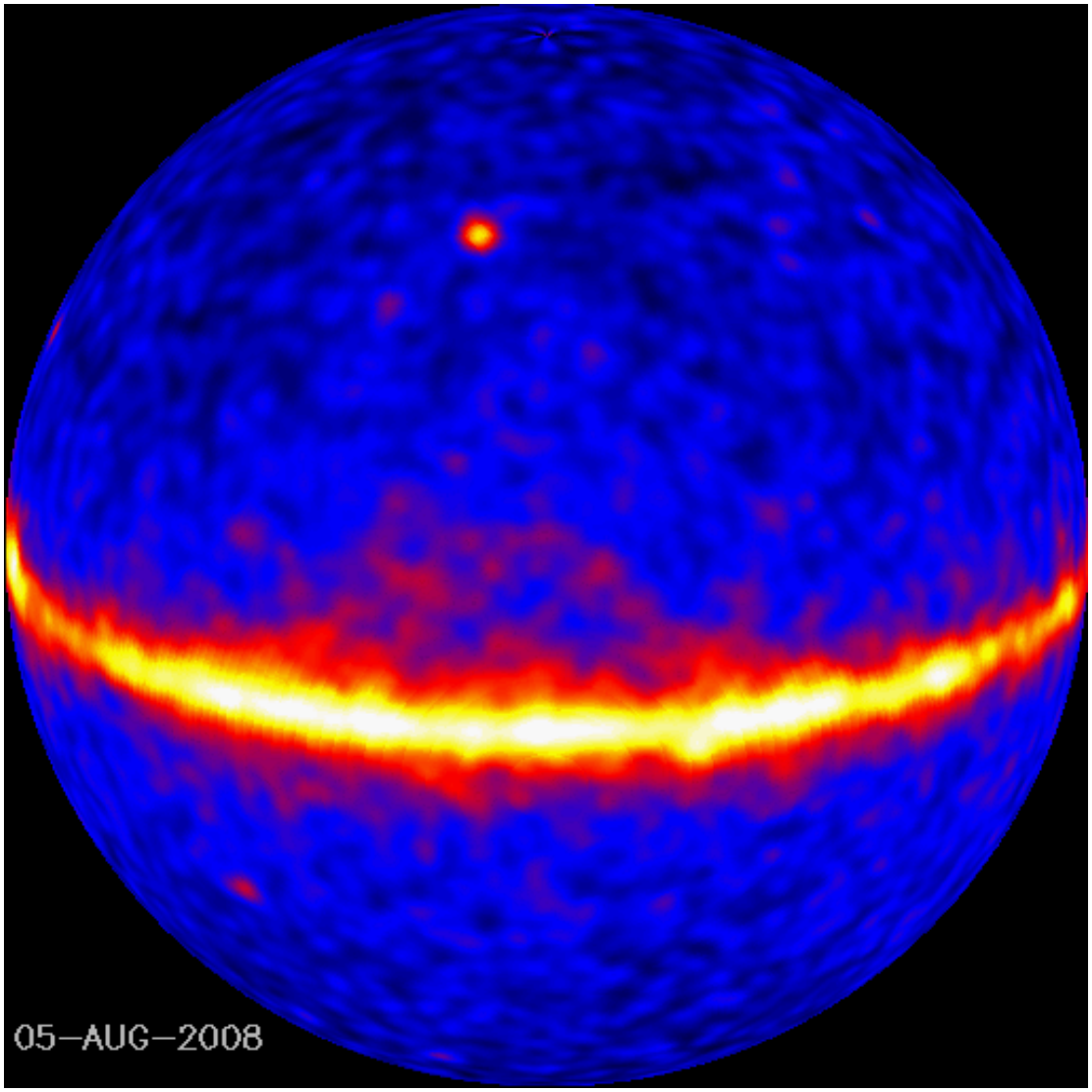


The Fermi LAT (2 yr, > 31 GeV) Sky



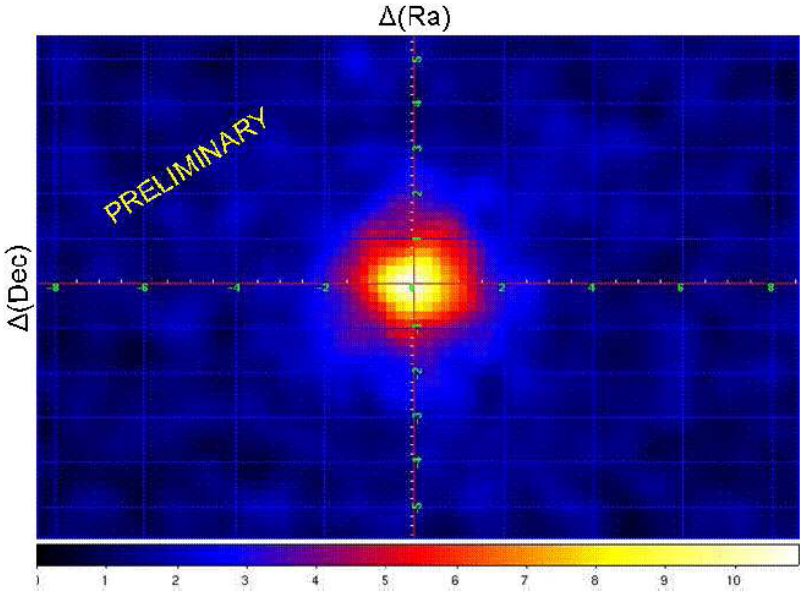
First Fermi Source List (1FGL)

- 11 months of data 100 MeV to 100 GeV, 23.3 Ms livetime
- Very uniform exposure (factor 1.25 between north and south)
- Detection based on integrated data (not on flares)
- 1451 Sources, TS >25 ($\gtrsim 4\sigma$)



One Year Catalog: 1FGL

- Sources/ Source Classes Detected with Fermi
  - Sun, Moon, Earth
  - 3 High Mass X-ray Binaries
  - Rotation-powered and millisecond pulsars
  - Supernova remnants
  - Globular clusters
  - > 600 blazars
  - At least 11 Radio Galaxies
  - Dozens of other AGNs
  - 3 Starburst Galaxies



Fermi observations of the Moon
Giglietto, N., for the Fermi Large Area Telescope Collaboration 2009, arXiv:0912.3734

LAT 1FGL Source Classes

Abdo et al. 2010, ApJS, 188, 405

Description	Designator	Number Assoc. (ID)
Pulsar, X-ray or radio, identified by pulsations	psr (PSR)	7 (56)
Pulsar, radio quiet (LAT PSR, *subset of above*)	PSR	24
Pulsar wind nebula	pwn (PWN)	2 (3)
Supernova remnant	† (SNR)	41 (3)
Globular Cluster	glc (GLC)	8 (0)
Micro-quasar object: X-ray binary (black hole or neutron star) with radio jet	mqo (MQO)	0 (1)
Other X-ray binary	hxb (HXB)	0 (2)
BL Lac type of blazar	bzb (BZB)	295 (0)
FSRQ type of blazar	bzq (BZQ)	274 (4)
Non-blazar active galaxy	agn (AGN)	28 (0)
Active galaxy of uncertain type	agu (AGU)	92 (0)
Normal galaxy	gal (GAL)	6 (0)
Starburst galaxy	sbg (SBG)	2 (0)
Unassociated		630

- Associations vs. identifications (in parentheses) based on temporal variability or source morphology

Pulsars with Fermi

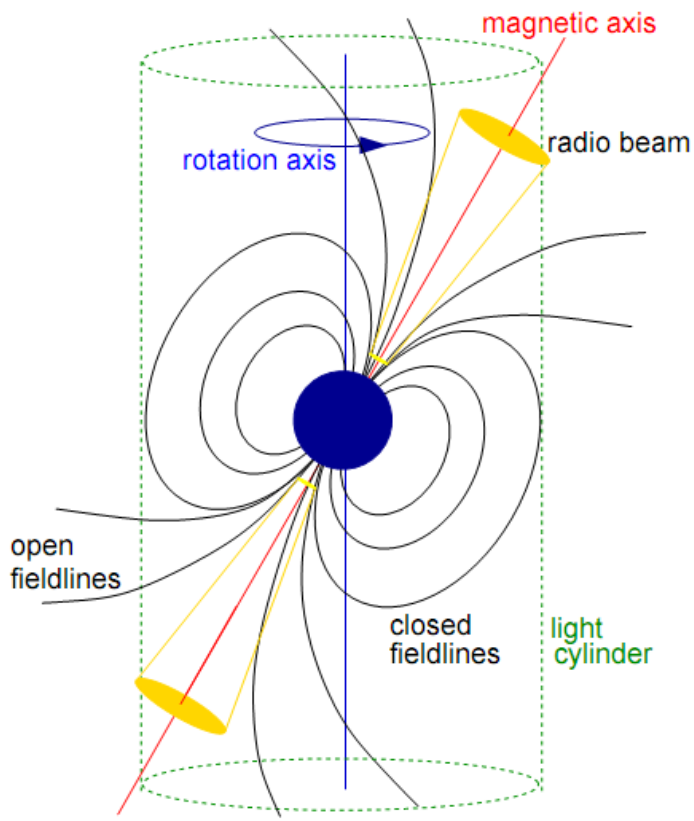
Pulsars: rapidly rotating, highly magnetized neutrons stars, born in supernova explosions of massive stars or accretion-induced collapse of white dwarfs.

Typically, M ~ 1.4 M_{sun} and R ~ 10 km

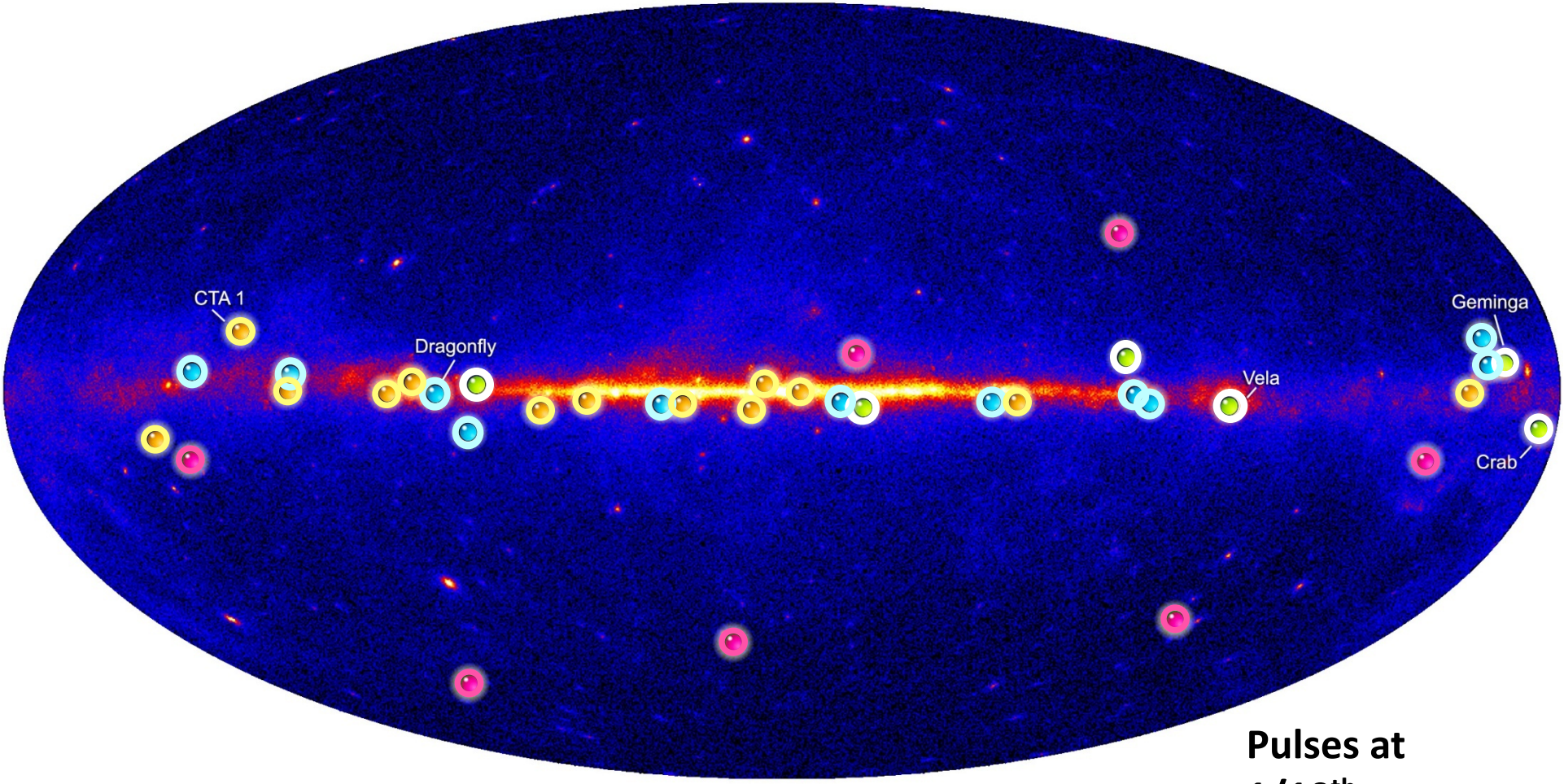
A dense plasma is found in the closed-field lines co-rotating with the star. The magnetosphere extends to the "light cylinder", where the rotation reaches the speed of light.

Emission (radio, optical, X-ray …) can be produced in beams around the pulsar, which acts like a cosmic light-house, probably accelerated on field-lines open to the light cylinder.

~ 1900 pulsars known today, most in radio



The Pulsing γ-ray Sky



Pulses at 1/10th true rate

Early Fermi Pulsar Detections

Solution to the unidentified EGRET sources?

- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Pulsars seen by Compton Observatory EGRET instrument

Pulsar Properties from Observations: Elementary Concepts

- Observations give $P, \dot{P}$. Theory gives M_{ns}, R_{ns}
- Characteristic age $\tau \sim P / \dot{P}$
- Light cylinder radius: $\vec{v} = \vec{\Omega} \times \vec{R}$, $\Omega = 2\pi/P \Rightarrow R_{LC} = Pc / 2\pi$
- Magnetic field at the neutron star surface (equating rotational spindown energy with magnetic dipole radiation):

$$-\frac{dE_{rot}}{dt} = \frac{d}{dt}(\frac{1}{2} I\Omega^2) \propto \frac{\dot{P}}{P^3} \qquad -\frac{dE_{md}}{dt} = \frac{B^2(R_{LC})}{8\pi} 4\pi R_{LC}^2 c \propto \frac{B_{NS}^2}{R_{LC}^4}$$

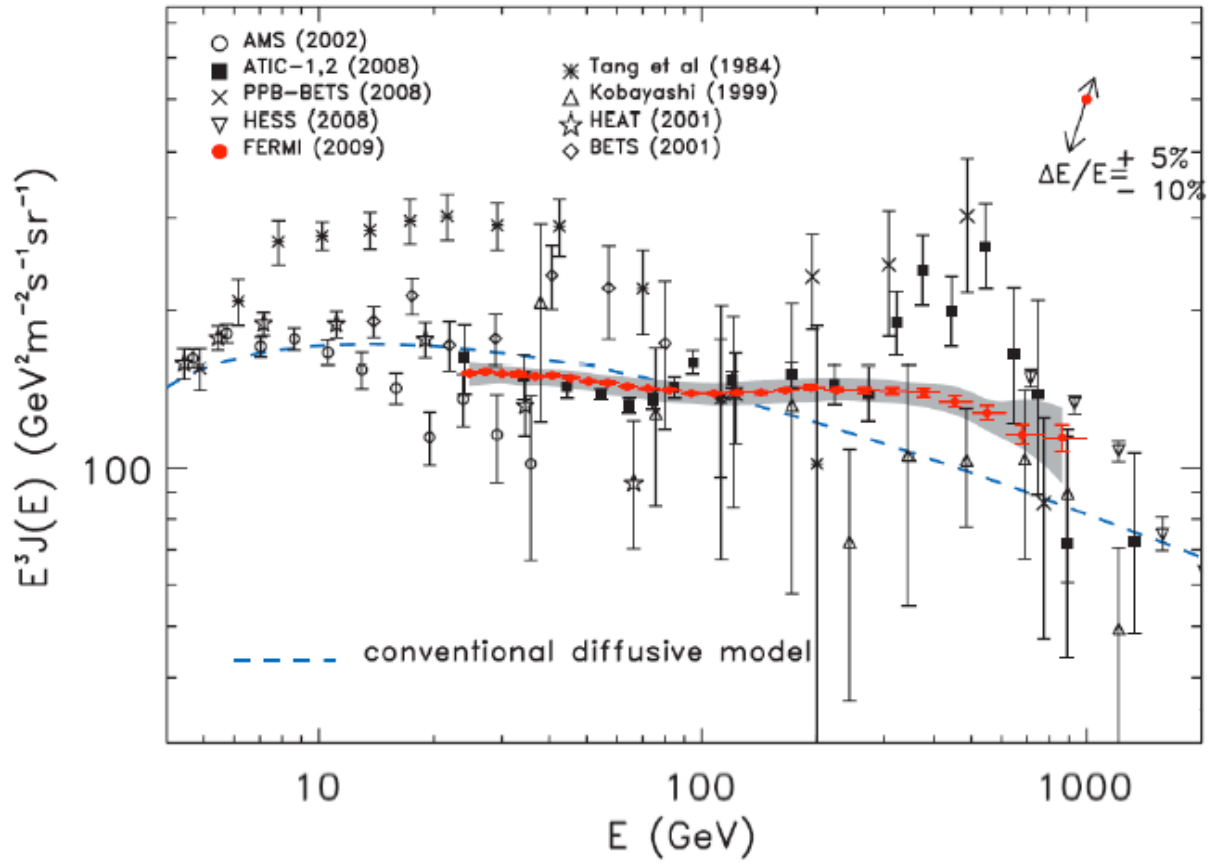
$$B(R) \approx B_{NS} / R^3 \qquad \Rightarrow B_{NS} \propto \sqrt{P\dot{P}}$$

- Goldreich-Julian density for a force-free magnetosphere:

$$\vec{F} = q(\frac{\vec{v}}{c} \times \vec{B} + \vec{E}) = 0 \qquad \rho_{GJ} = -\vec{\Omega} \cdot \vec{B} / 2\pi$$

Cosmic Ray Electron Spectrum

- ❑ >2 m^2-sr acceptance at 300 GeV (need to reject CR proton background)
- ❑ Spectrum $\propto E^{-3.04}$ from ~25 and 900 GeV
- ❑ Nearly featureless; consistent with power law
- ❑ CR electron spectrum harder than predicted by standard CR propagation models
  - **– Local sources?**
  - **– Dark matter?**
  - **– Propagation?**



Abdo, et al. 2009, PRL, 102, 181101

Tests of Lorentz Invariance Violation

- Planck mass $m_{Pl} = \sqrt{\frac{\hbar c}{G}} = 1.2 \times 10^{19}\ GeV \approx M_{QG}\ (?)$

- Some quantum gravity models allow Lorentz symmetry violation

  (e.g., Amelino-Camelia et al.1998, Ellis et al. 2003)

  – Speed of light becomes energy dependent

  – Time dispersion between low and high-energy photons from same source

Leading term in classical photon dispersion relation

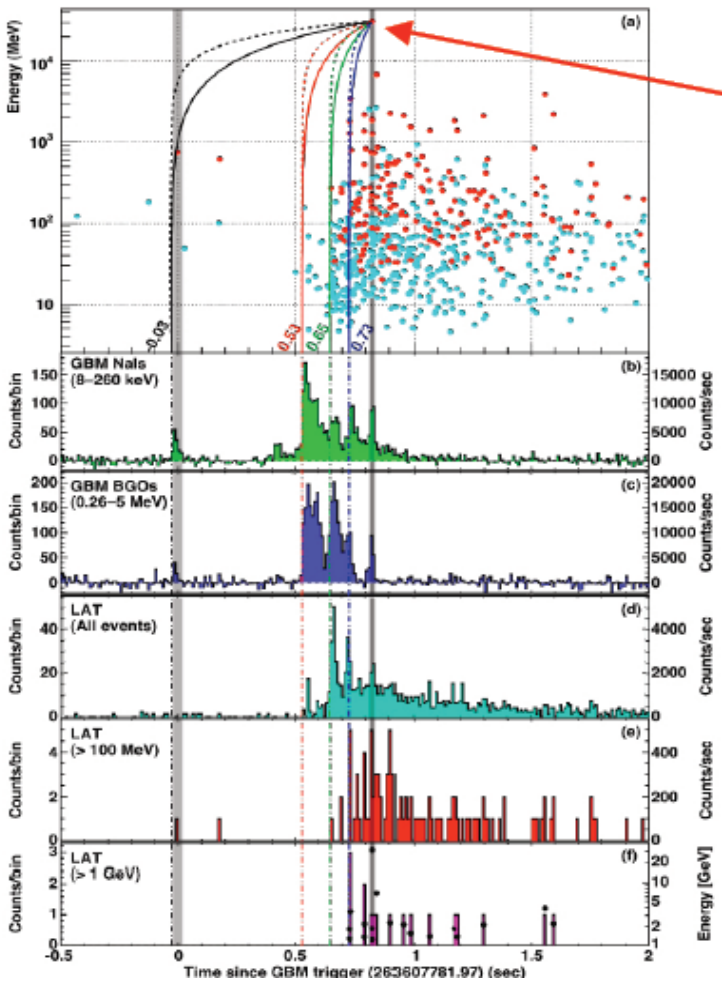
$$|1 - \frac{v_{ph}}{c}| \approx (\frac{E_{ph}}{M_{QG,n}})^n \Rightarrow \Delta t = \pm(\frac{\Delta E}{M_{QG,1} c^2})\frac{D}{c} \qquad \text{(linear)}$$

Does quantum nature of space-time cause variation of speed of light with energy?

Constraints on Quantum Gravity Time Delay

Abdo et al. 2009, Nature, 462, 331

GRB 090510



- Short hard GRB with many "spikes"
- High redshift, z = 0.903 +/- 0.003
- 31 GeV photon (27.97, 36.32 GeV 1s CL) 0.829 s after the GRB trigger
- Constraint on QG mass depends on Δt

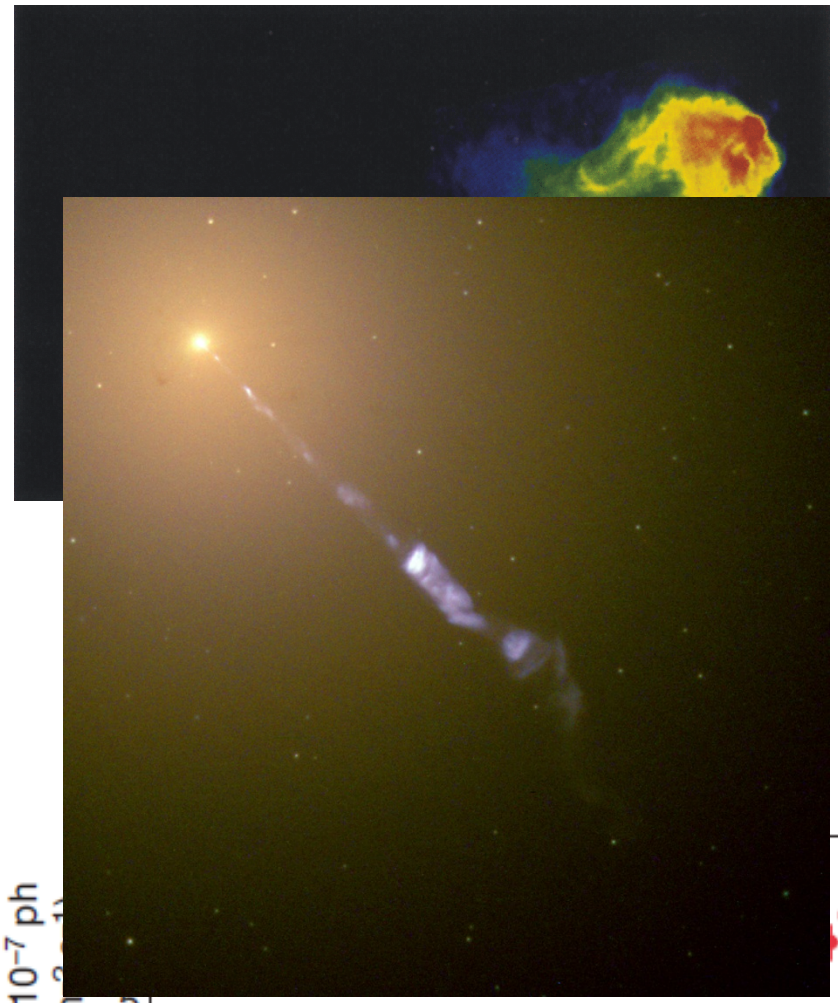
The most conservative constraint comes from $\Delta t < 0.859$ s, time from precursor

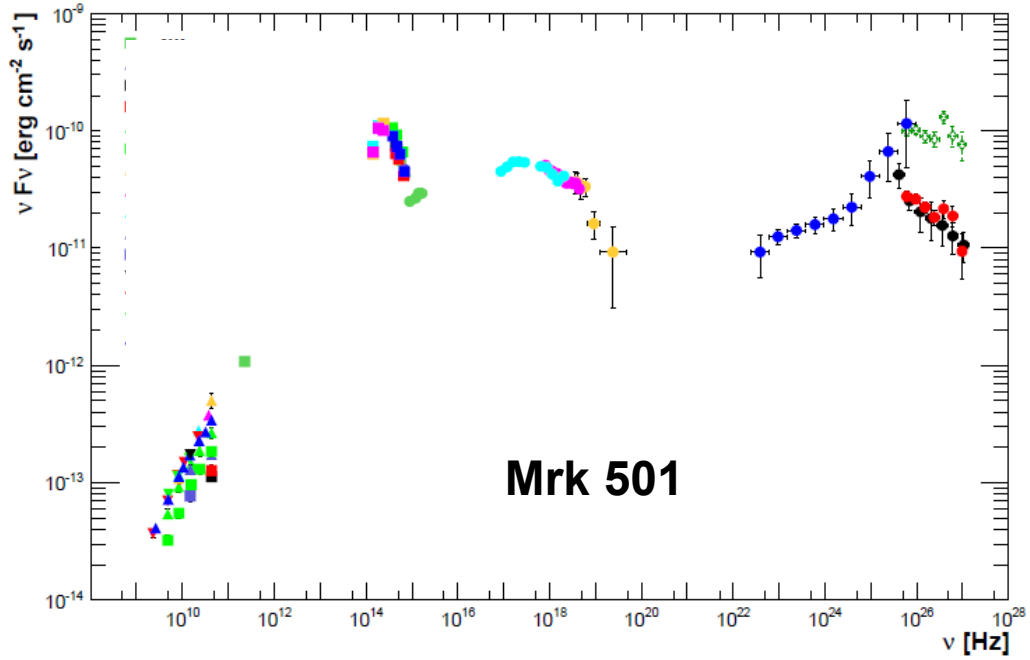
$$M_{QG,1} > 1.19\, M_{Pl}$$

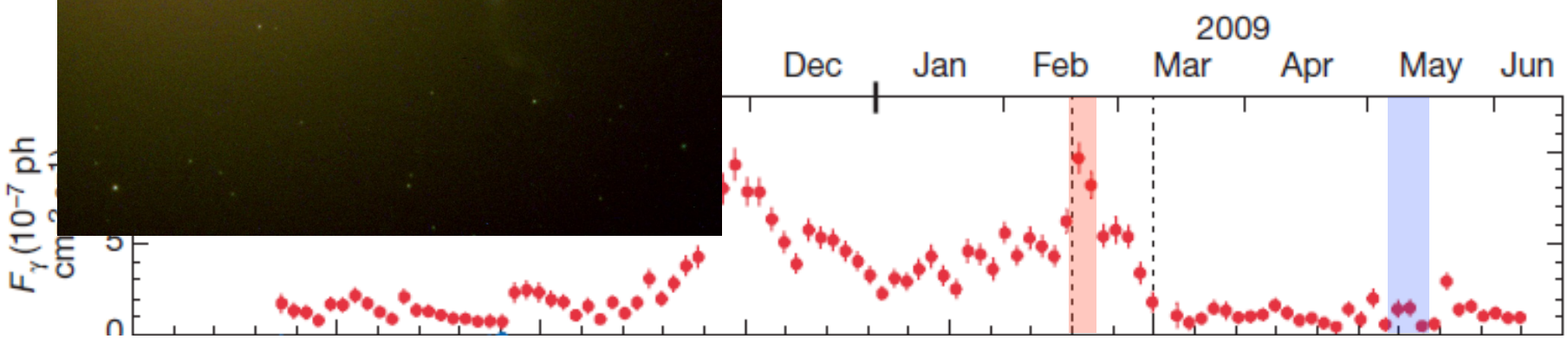
Table 1 | Limits on Lorentz invariance violation

	Limit on $\lvert\Delta t/\Delta E\rvert$ or $\lvert\Delta t\rvert$	Limit on $M_{QG,1}/M_{Planck}$	Valid for s_n
Limit a:	$\lvert\Delta t/\Delta E\rvert < 30\ \mathrm{ms\,GeV^{-1}}$	>1.22	± 1
Limit b:	$\lvert\Delta t\rvert < 859$ ms	>1.19	1

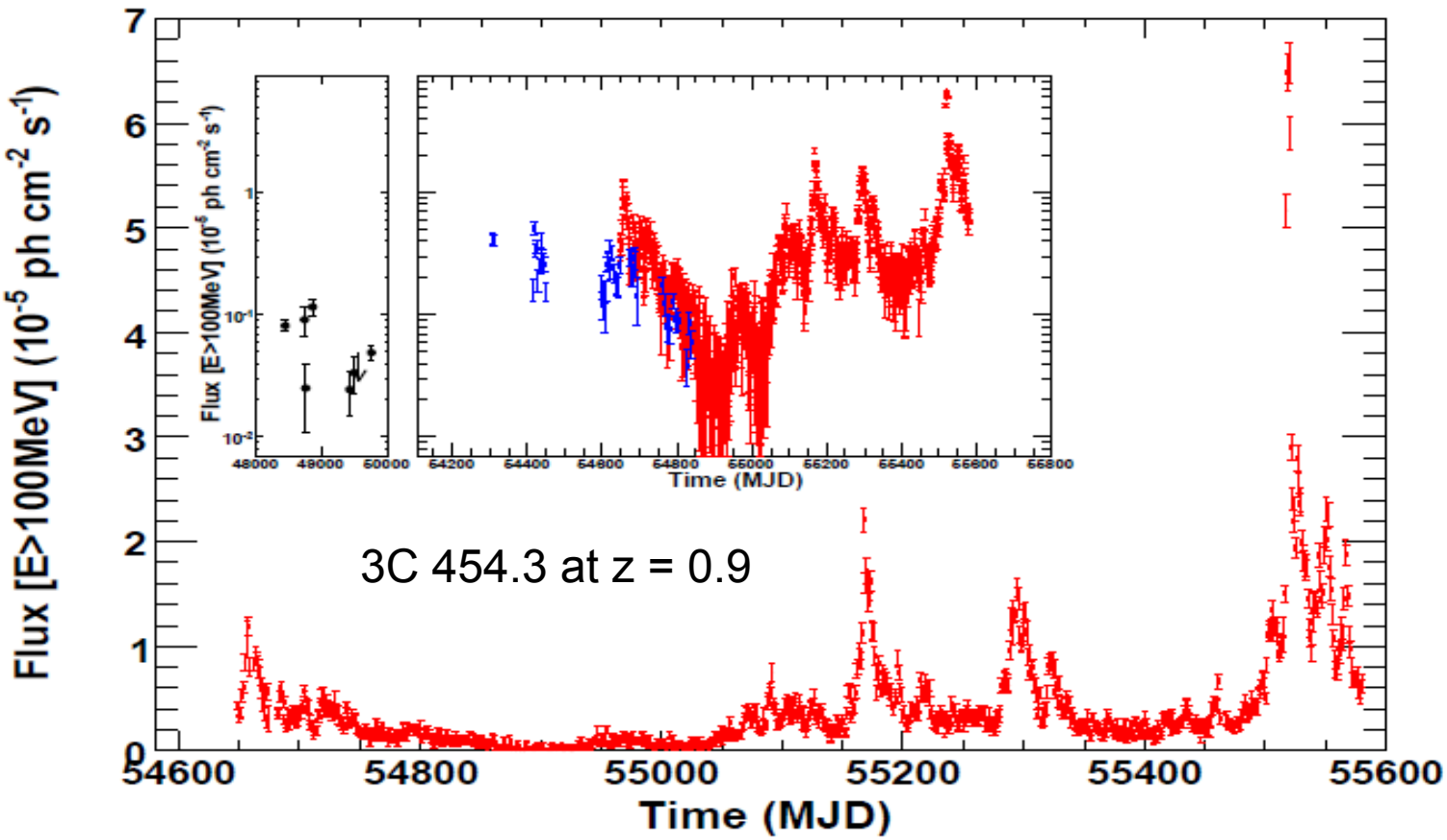
Black-hole Jet Physics







Peak Blazar Apparent Luminosity



$L_{max} \sim 10^{50}$ erg s^{-1} $\Delta t_{var} \sim 0.2$ d $\Rightarrow (\Delta L/\Delta t)_{obs} \approx 10^{46}$ erg/s^2

$L_{Edd}/(R_g/c) = 2.5\times10^{43}$ erg/s^2 << $(\Delta L/\Delta t)_{obs}$ << $c^5/G = 3.6\times10^{59}$ erg/s^2

Upper Limits on Extragalactic Background Light

γγ opacity

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

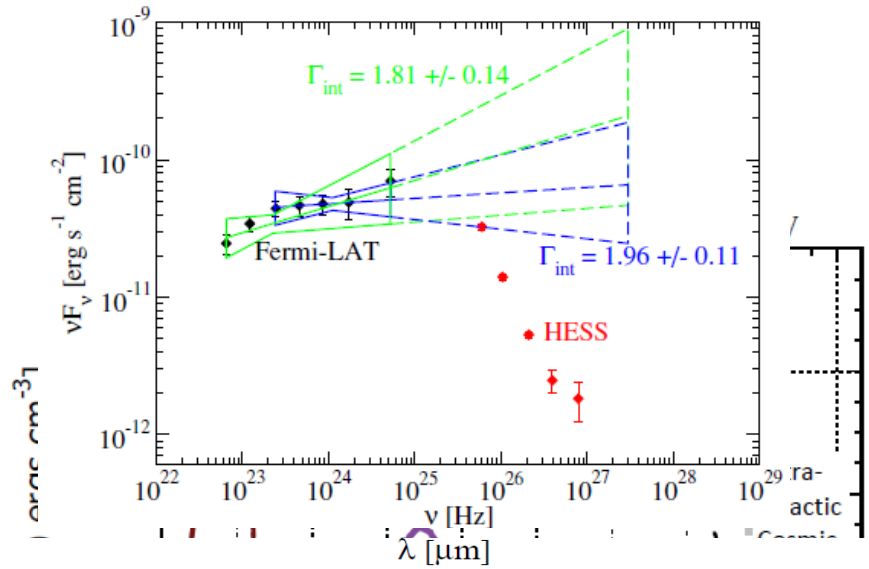
(in intergalactic space)

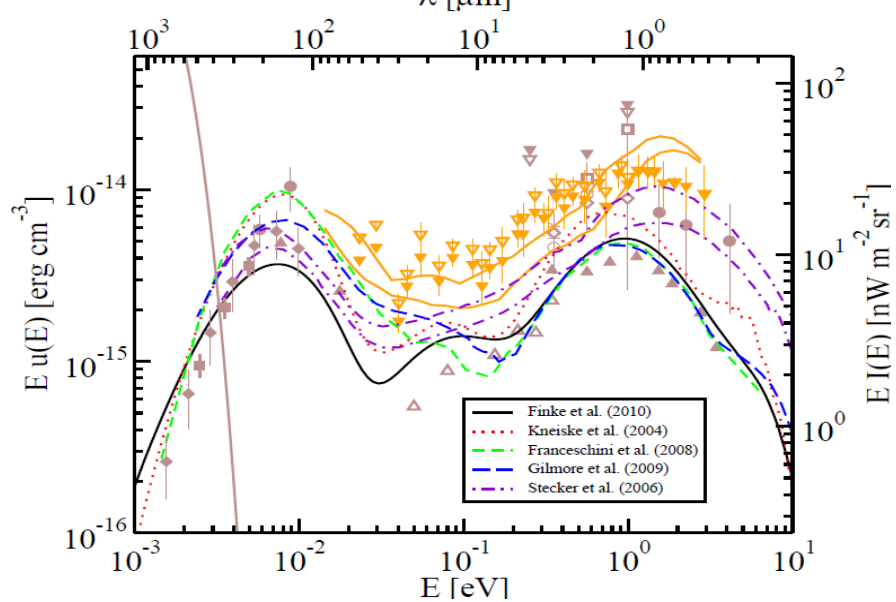
Infrared/optical EBL from past stellar activity and dust absorption and re-radiation
(attenuates TeV radiation)

Difficult to directly measure

Fermi spectrum extrapolated into TeV range bounded by deabsorbed TeV spectrum-depending on EBL model

Cosmic-ray contribution
(Essey, Kusenko et al. 2010, 2011)

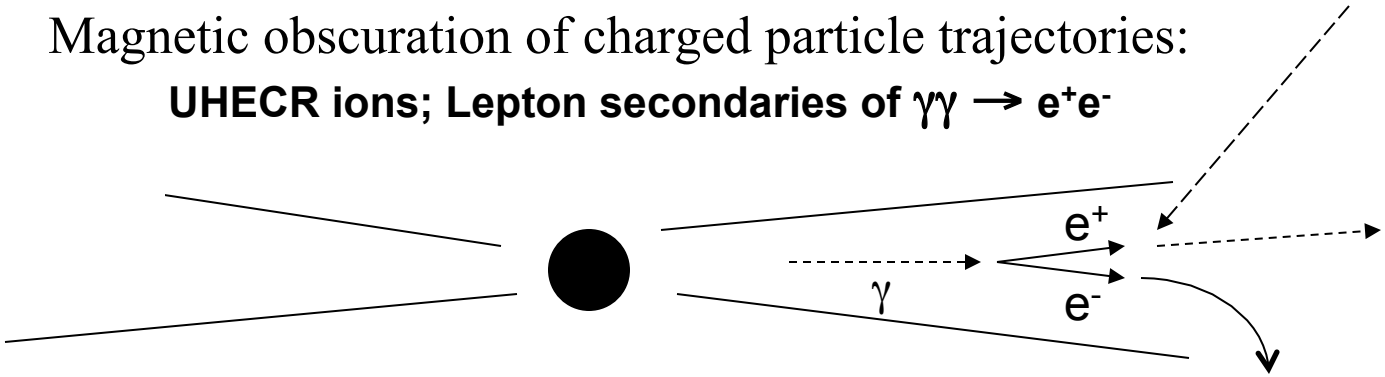


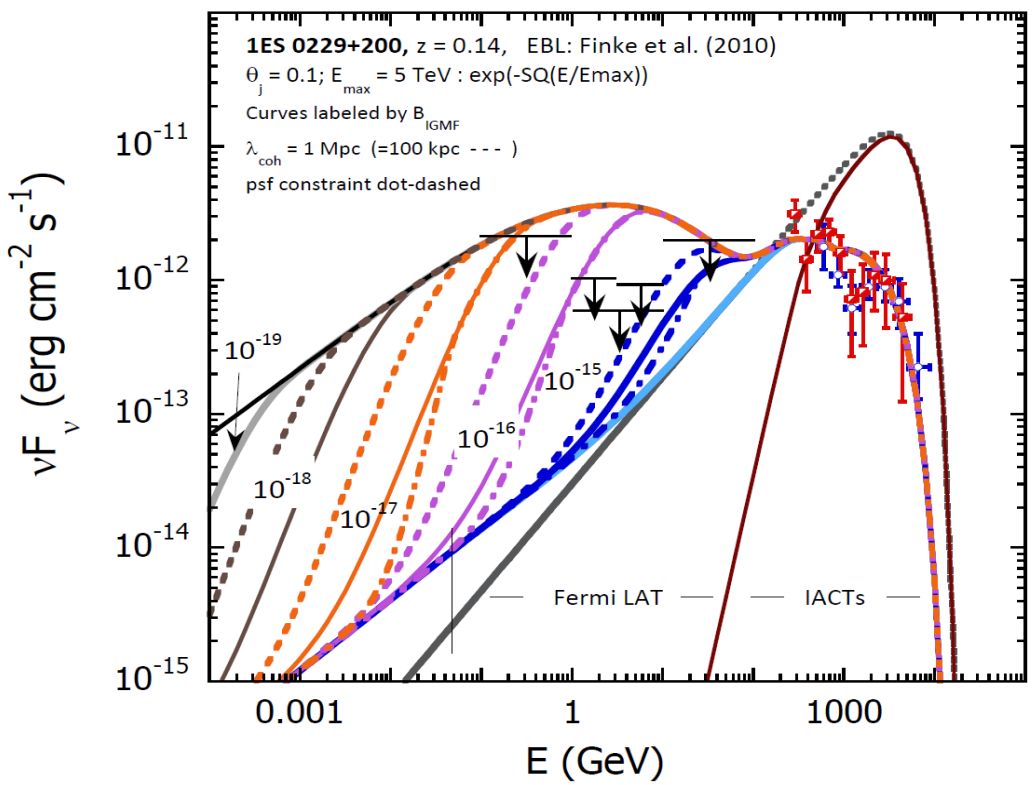


Lower Limits on the Intergalactic Magnetic Field

- Magnetic obscuration of charged particle trajectories:

  UHECR ions; Lepton secondaries of $\gamma\gamma \rightarrow e^+e^-$





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

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

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

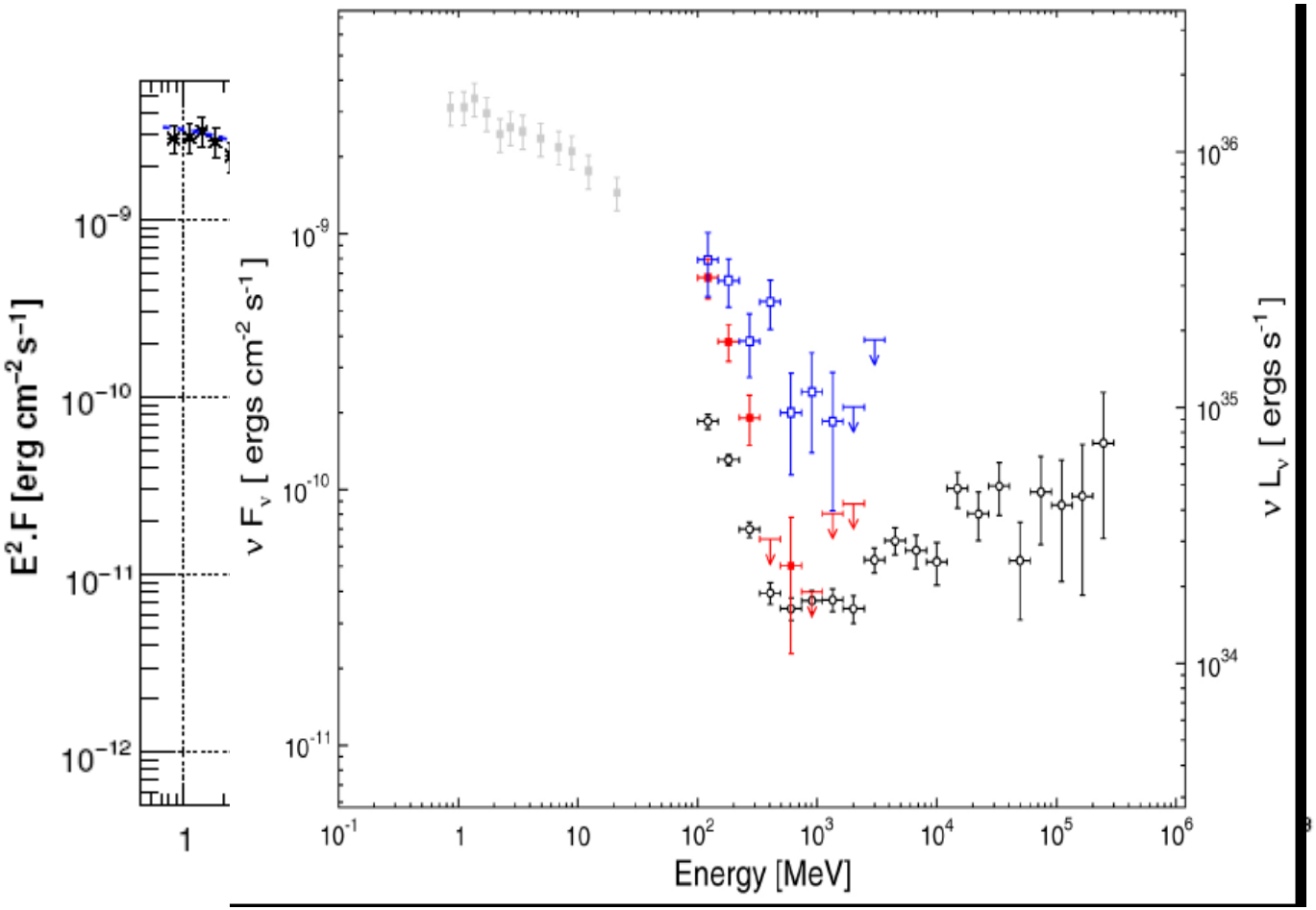
(relaxing assumption of extended TeV emission)

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

Particle Acceleration in the Crab Nebula

Crab Nebula (M1) with HST

Crab Nebular Spectrum and Flares



Abdo et al. (2010, 2011)

Maximum Electron Synchrotron Photon Energy

Electron synchrotron energy-loss rate: $$-\frac{dE_e}{dt}\Big|_{syn} = \frac{4}{3} c\sigma_T \left(\frac{B^2}{8\pi}\right)\gamma^2$$

$$E_e = m_e c^2 \gamma \quad \Rightarrow \quad t_{syn} = \left|\frac{\dot{E}}{E}\right|^{-1} = \frac{6\pi m_e c}{\sigma_T B^2 \gamma}$$

In Fermi acceleration scenarios, **acceleration time $\lesssim$ Larmor timescale**

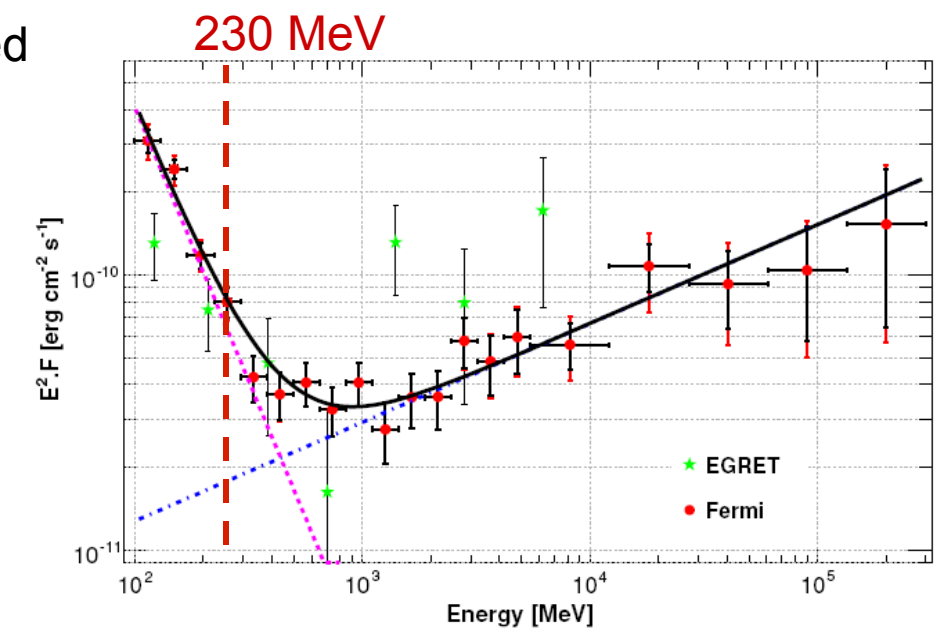
$$\therefore\ t_{acc} < t_L = \frac{E}{QBc} = \frac{m_e c\gamma}{eB} \qquad t_{syn} = t_{acc} \Rightarrow \gamma^2 < \frac{6\pi e}{\sigma_T B}$$

Mean synchrotron photon energy radiated by electron with Lorentz factor γ in a magnetic field of strength B:

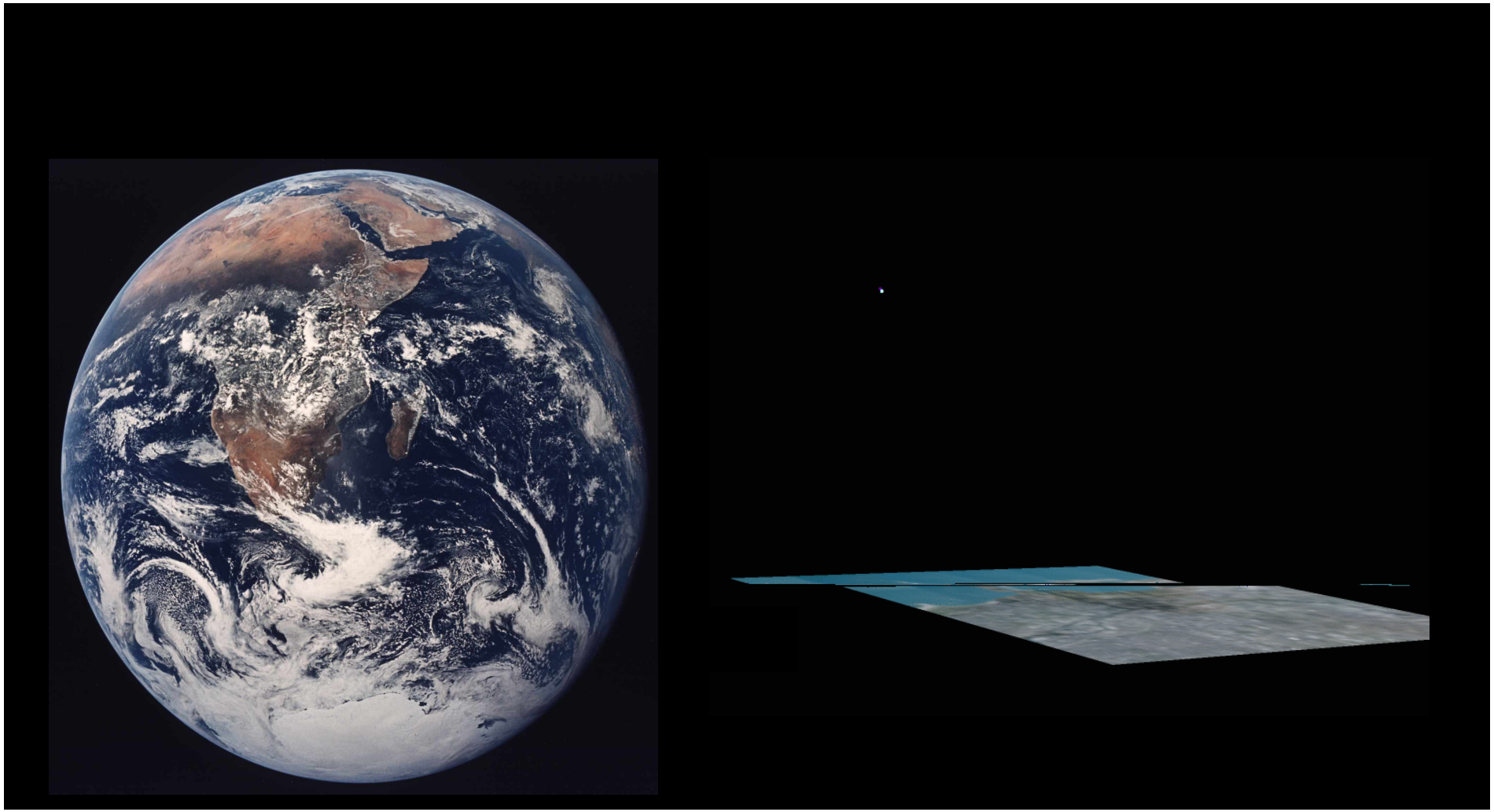
$$\varepsilon_{syn} = \frac{3}{2}\frac{B}{B_{cr}}\gamma^2 < \frac{27}{8\alpha_f} \cong 460 \qquad B_{cr} = \frac{m_e^2 c^3}{e\hbar} \qquad \alpha_f = \frac{e^2}{\hbar c}$$

$$or\ E_{syn} \cong 230\ MeV$$

$\Rightarrow$ efficient particle acceleration by Fermi Processes

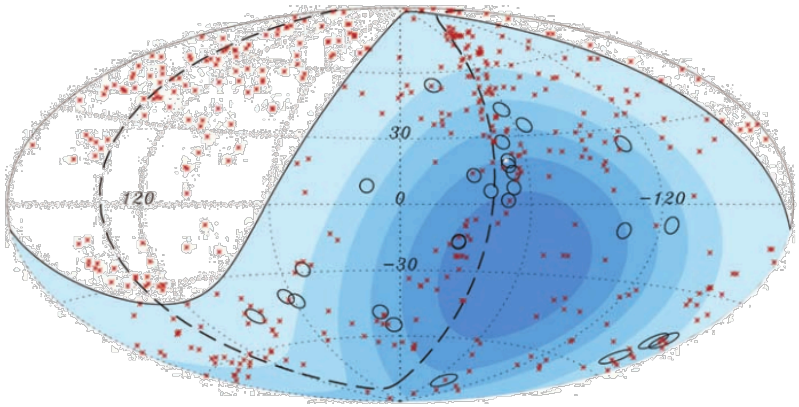


Ultrahigh Energy Cosmic Rays

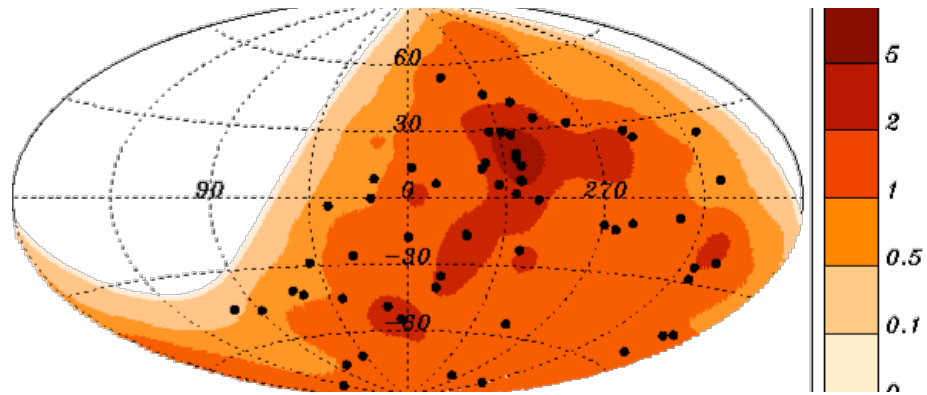


Extensive air showers discovered by Rossi and Auger in the 1930s

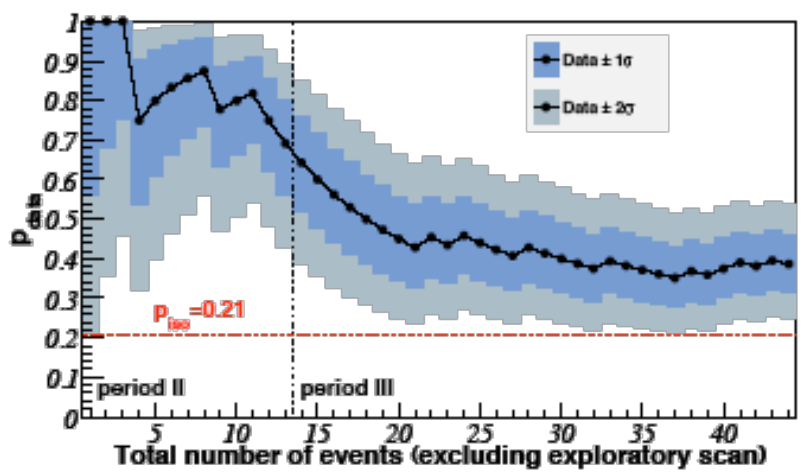
Charged Particle Astronomy with Auger



27 events as of November 2007



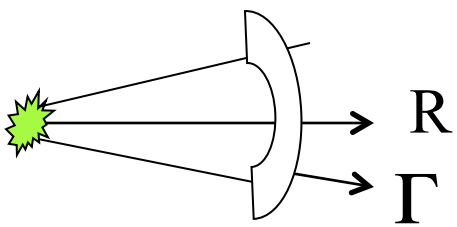
58 events: July, 2009 (with Swift-BAT AGN density map)



Particle Acceleration to Ultra-High Energies in Relativistic Outflows

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

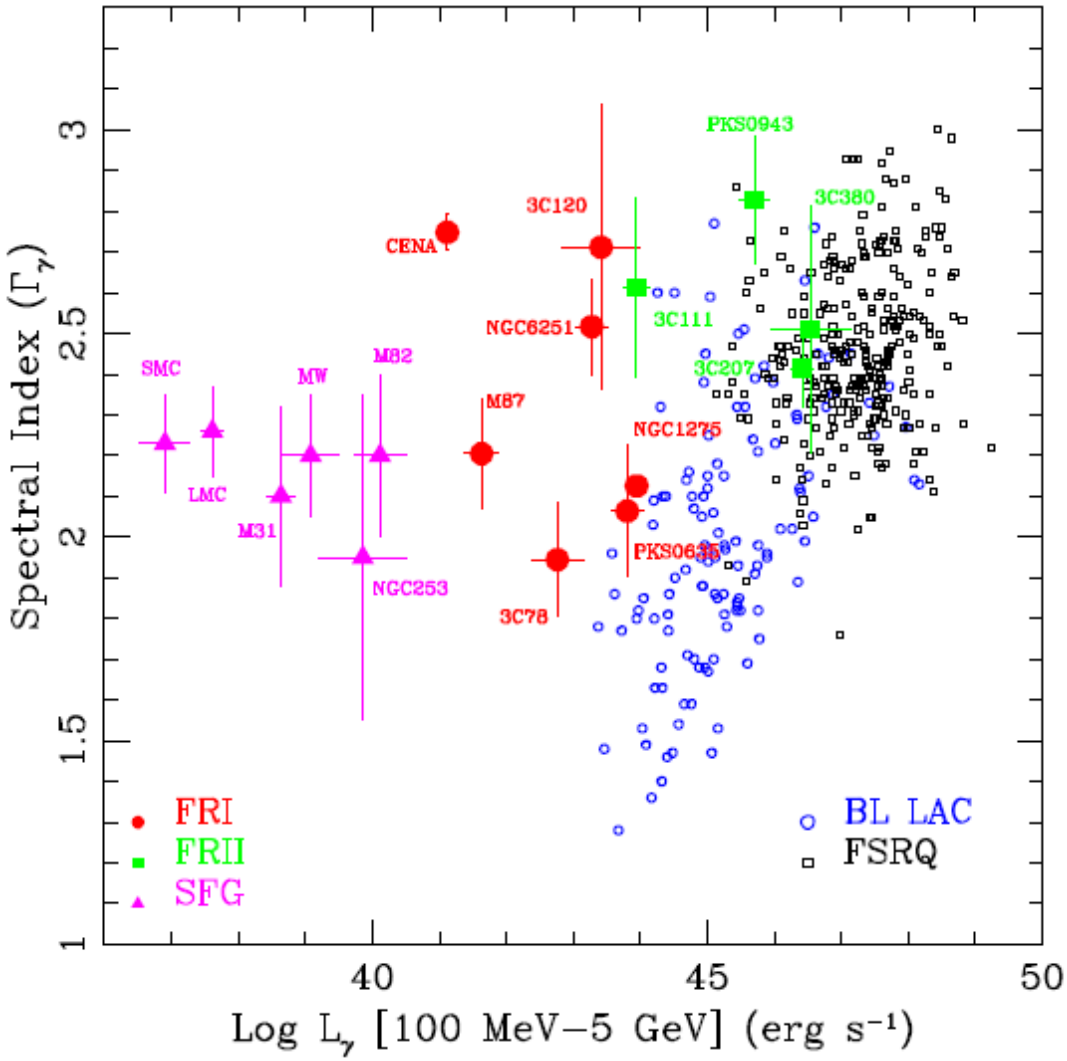
$$E_{\max} \approx \Gamma Q B' R' \approx \Gamma Z e B' (R/\Gamma)$$

Lorentz contraction: $R' \approx R/\Gamma$

$$L > L_\gamma$$

$$\Rightarrow E_{\max} \approx \left(\frac{Ze}{\Gamma}\right)\sqrt{\frac{2L_\gamma}{c}} \approx 6\times 10^{19} Z \frac{\sqrt{L_\gamma/(10^{46} erg\ s^{-1})}}{(\Gamma/10)} eV$$

γ-Ray Galaxy Luminosity



Fermi blazar divide
(Ghisellini et al. 2009)

Misaligned AGNs
(host galaxies of blazars)

Star forming galaxies
(not powerful enough to accelerate UHECRs)

Relativistic Outflows

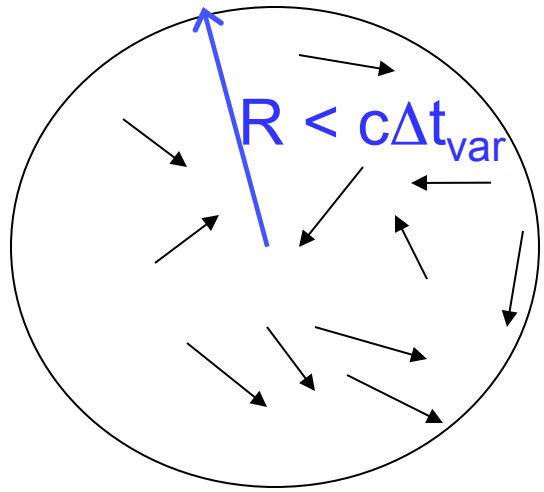
$\gamma\gamma$ opacity

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

(in source)

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

Threshold: $\varepsilon\varepsilon_1 > 2$



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

(superluminal motion In 3C 120)

$$\tau_{\gamma\gamma} \approx \frac{\sigma_T L_\gamma}{4\pi m_e c^4 \Delta t_{\rm var}} \approx 1000 \frac{L_\gamma / (10^{48} erg/s)}{\Delta t_{\rm var}(day)}$$

To be optically thin to $\gamma\gamma$ absorption,

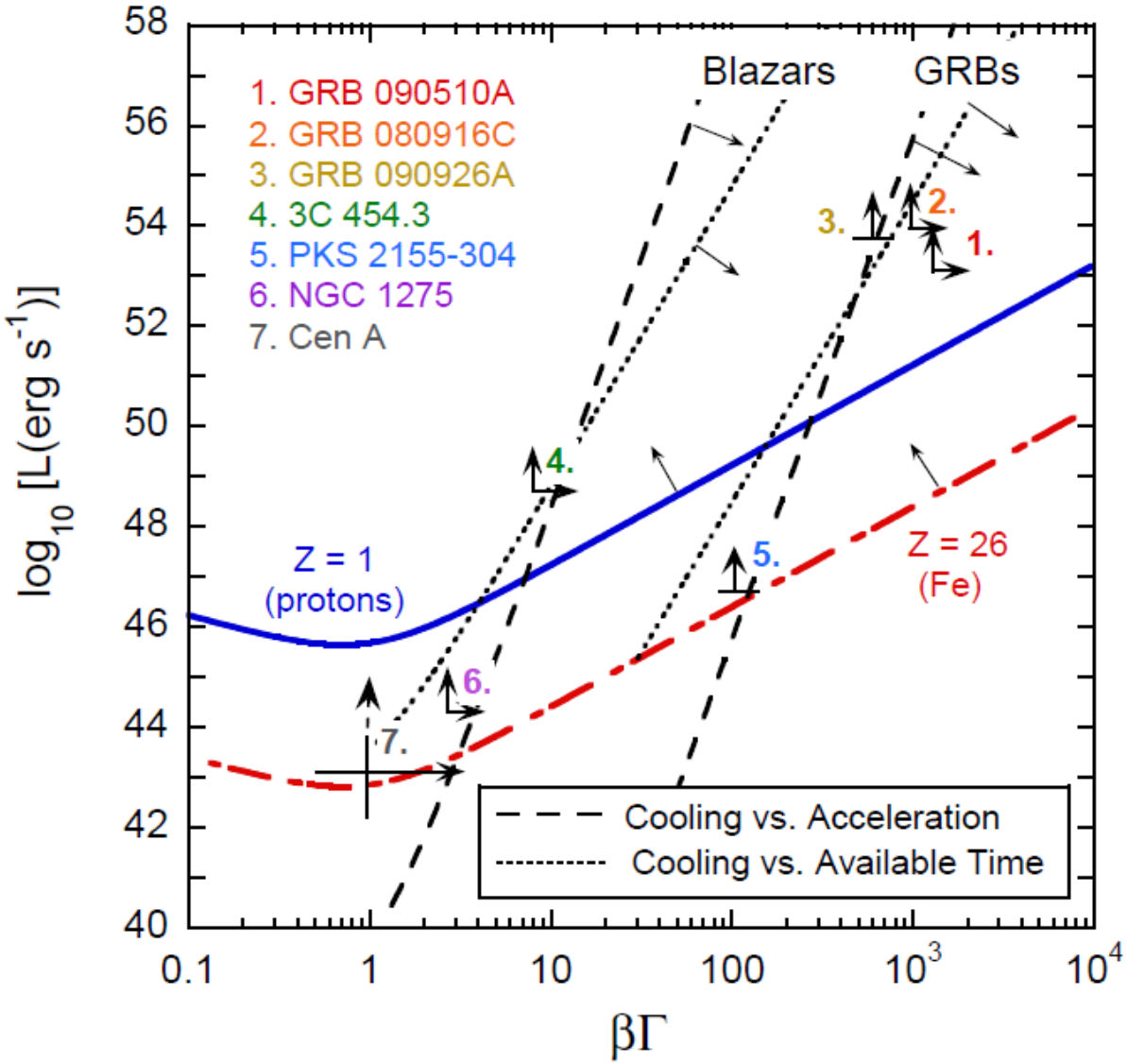
outflow Lorentz factor $\Gamma \gtrsim 10$ in blazar jets

$\Gamma \gtrsim 1000$ in GRBs

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

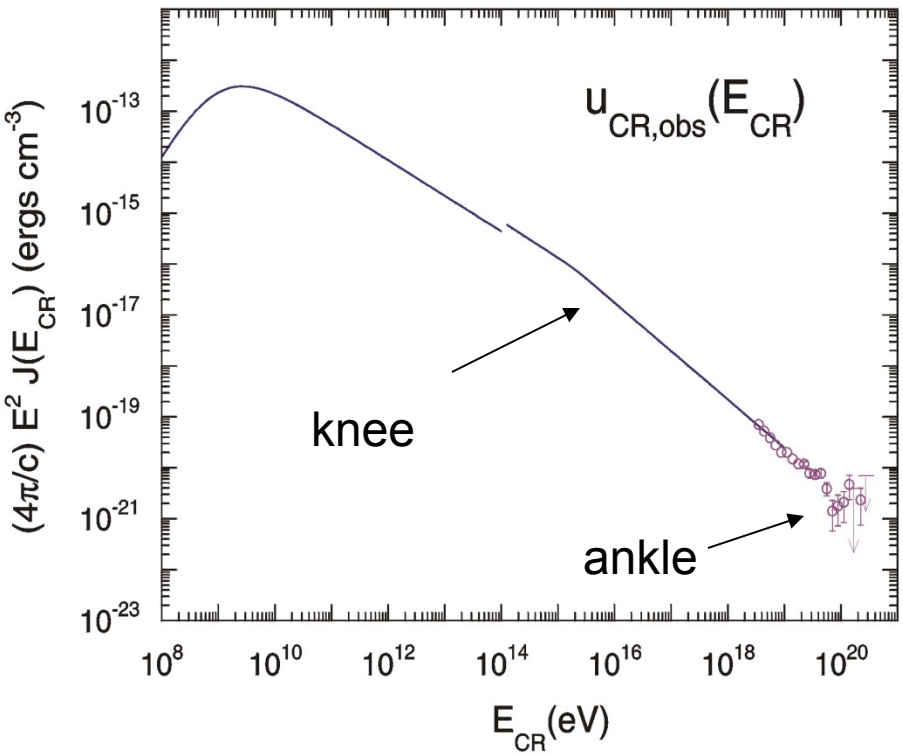
L - Γ diagram

- **Bulk Lorentz factor Γ from γγ opacity arguments**
- **Sources with jet Lorentz factor Γ must have jet power L exceeding heavy solid and dot-dashed curves to accelerate p and Fe respectively, to E = 10^{20} eV**
- **GRBs can easily accelerate p and Fe to >10^{20} eV**
- **Radio-loud AGNs can accelerate Fe to >10^{20} eV**



Energy Production Rate within GZK Volume

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



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

$$\dot{\varepsilon}_{UHECR} \approx \frac{10^{-21} erg\ \ cm^{-3}}{r_{GZK}/c}$$

$$\approx 10^{44} \frac{erg}{Mpc^3 - yr}$$

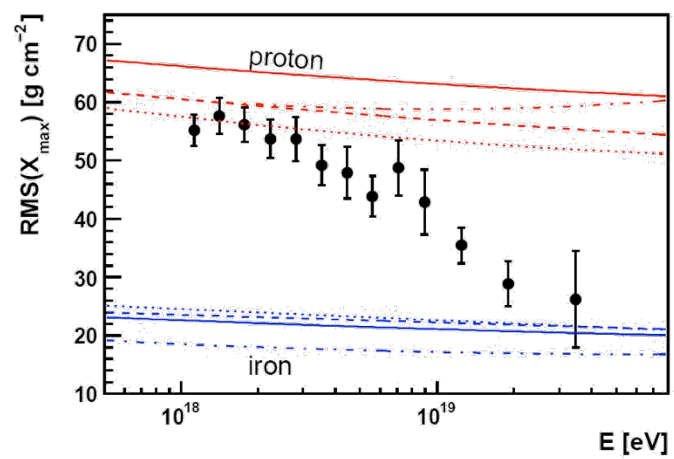
(Waxman 1995, Vietri 1995)

Sources of ~10^{20} eV UHECRs must have (local)

luminosity density $\gtrsim 10^{44}$ erg /(Mpc^3-yr)

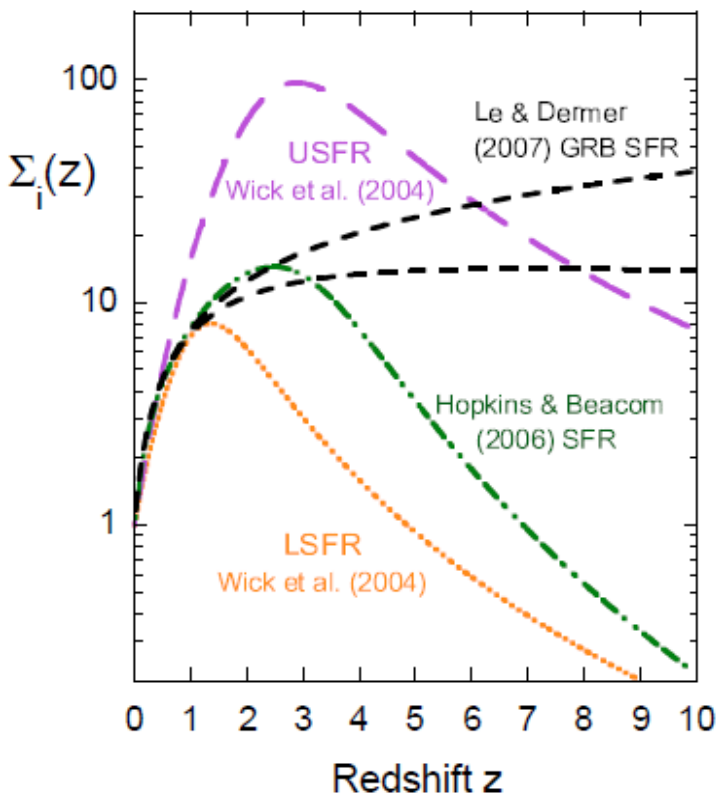
Conditions for acceptable UHECR source candidates

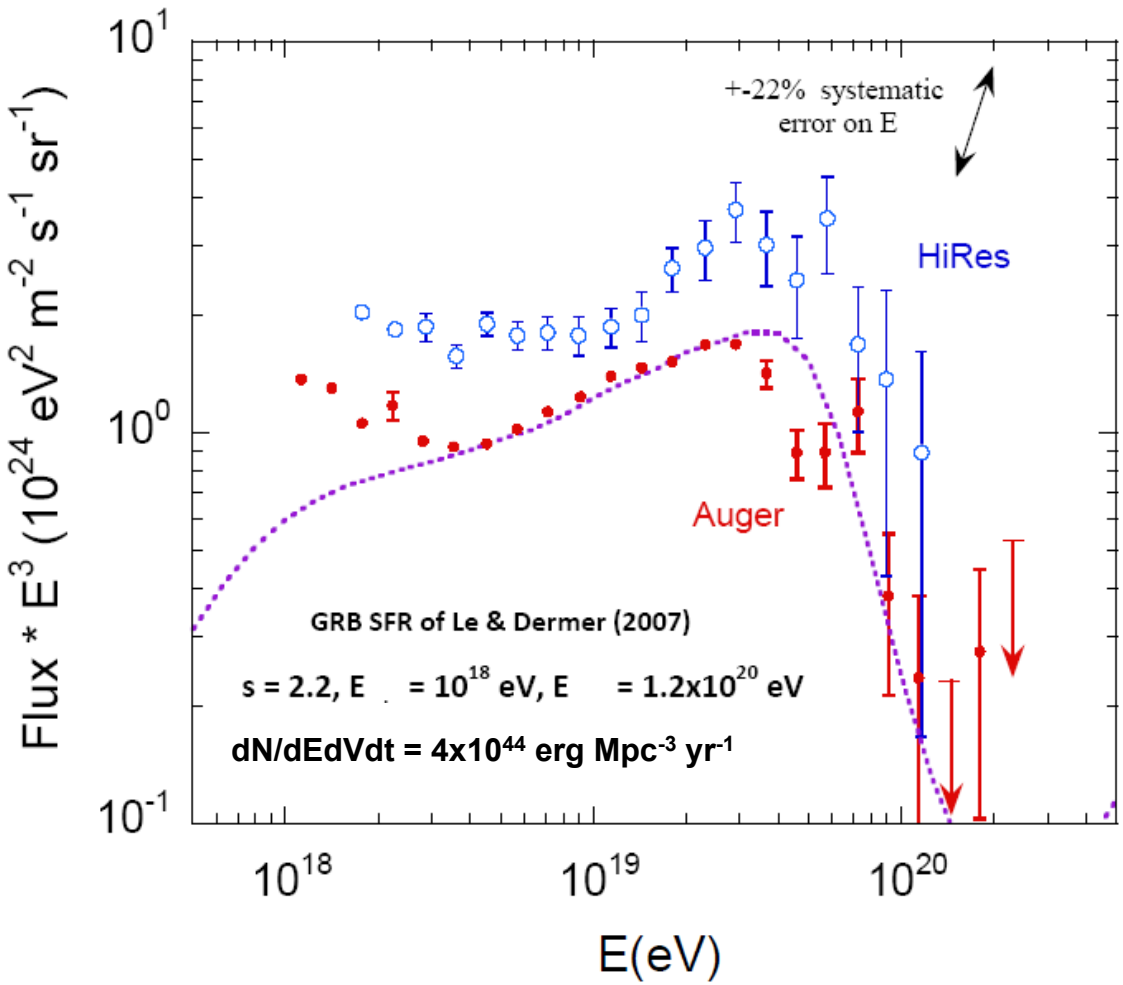
1. Sources are extragalactic
2. Sources within GZK radius
3. Source size smaller than Larmor radius
4. Adequate energy production rate within GZK volume
5. (Fermi) mechanism to accelerate to ultra-high energies
6. Composition is dominated by Fe (?)



Model Fits for Luminosity Density

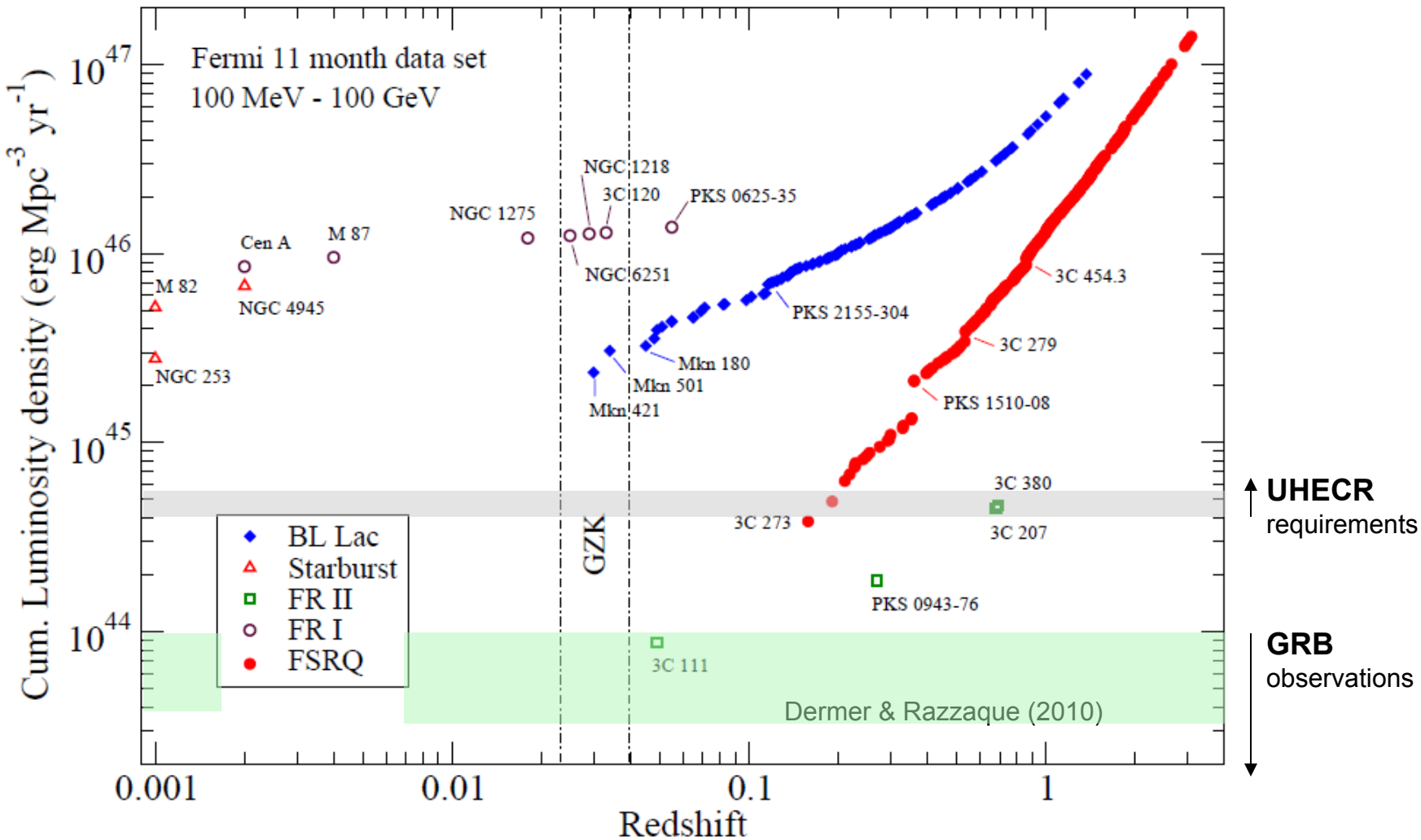
- Inject -2.2 spectrum of UHECR protons to E > 10^{20} eV
- Injection rate density determined by star formation rate of GRBs
- GZK cutoff and ankle from photohadronic processes





Requires luminosity density $\gtrsim 4\times10^{44}$ erg Mpc^{-3} yr^{-1}

Luminosity Density of UHECR Candidates from Fermi Data



GRBs have adequate energy production rate only if baryon loading large

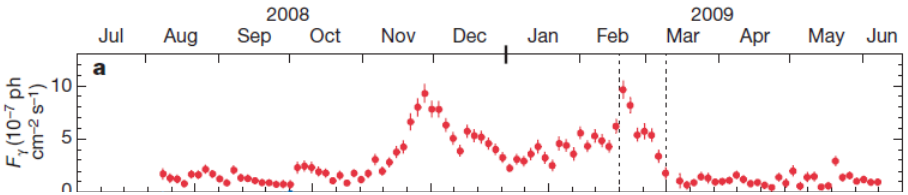
Fermi data favors ion acceleration by BL Lacs/FR1 radio galaxies

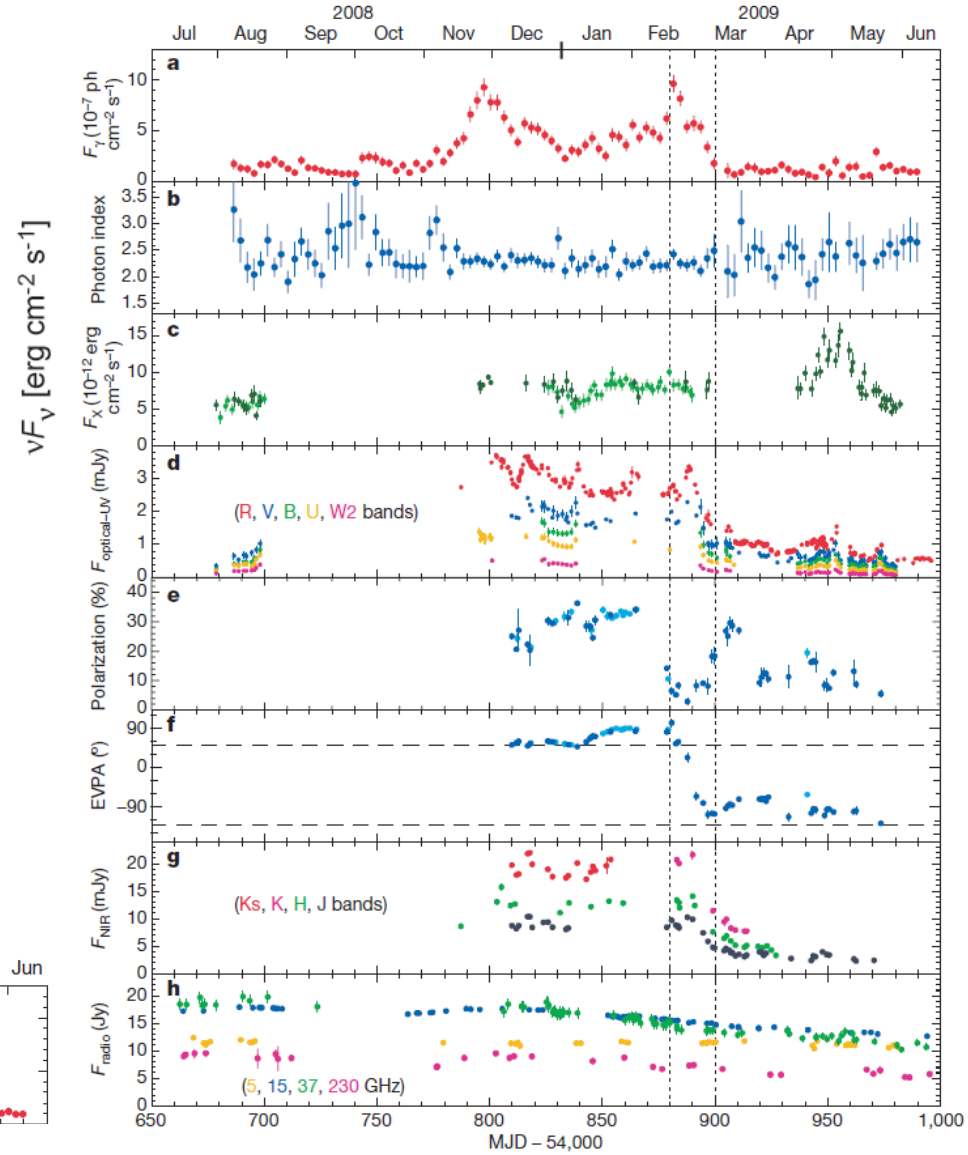
Location of Emission Region

- Coherent optical polarization signature
- EVPA swings over long timescales
- Correlation of gamma ray and optical
- γ rays from FSRQs

Black hole or antimatter factory?

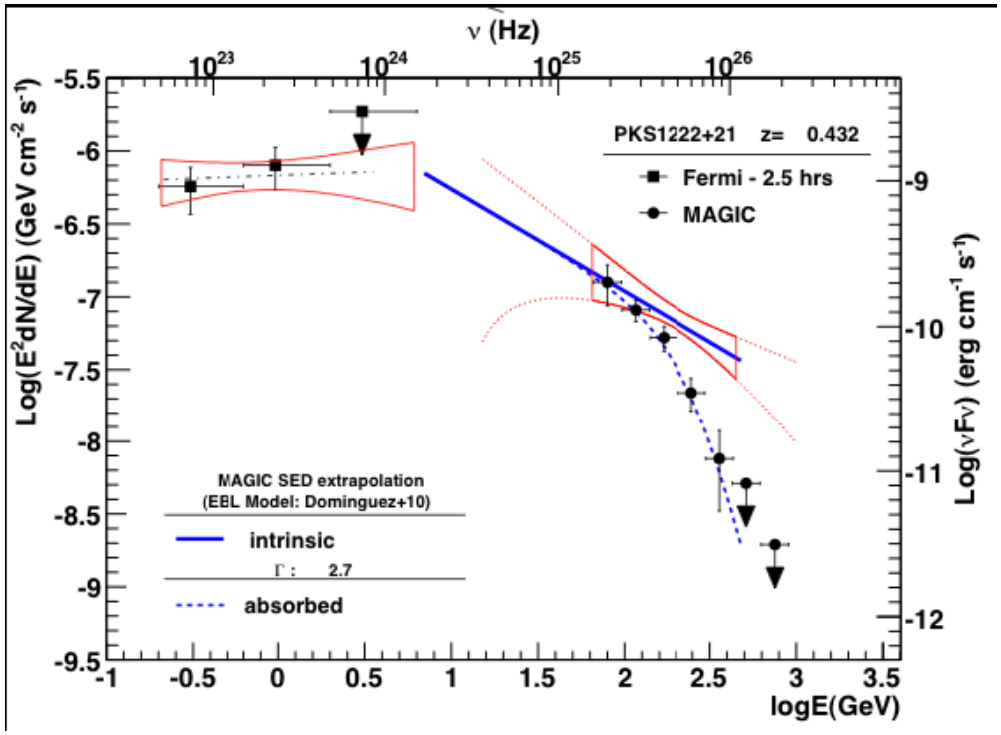
Abdo et al. 2010, Nature, 463, 920





VHE γ rays from Flat Spectrum Quasars

- 3C 279 (z = 0.536) with MAGIC
- PKS 1510-089 (zz = 0.361) with HESS
- PKS 1222+216 (z = 0.432) with Fermi, HESS, VERITAS



Aleksic et al. (2011)

Variability of 70 – 400 GeV radiation on 10 min timescale

Two-zone scenario
(Tavecchio et al. 2011)

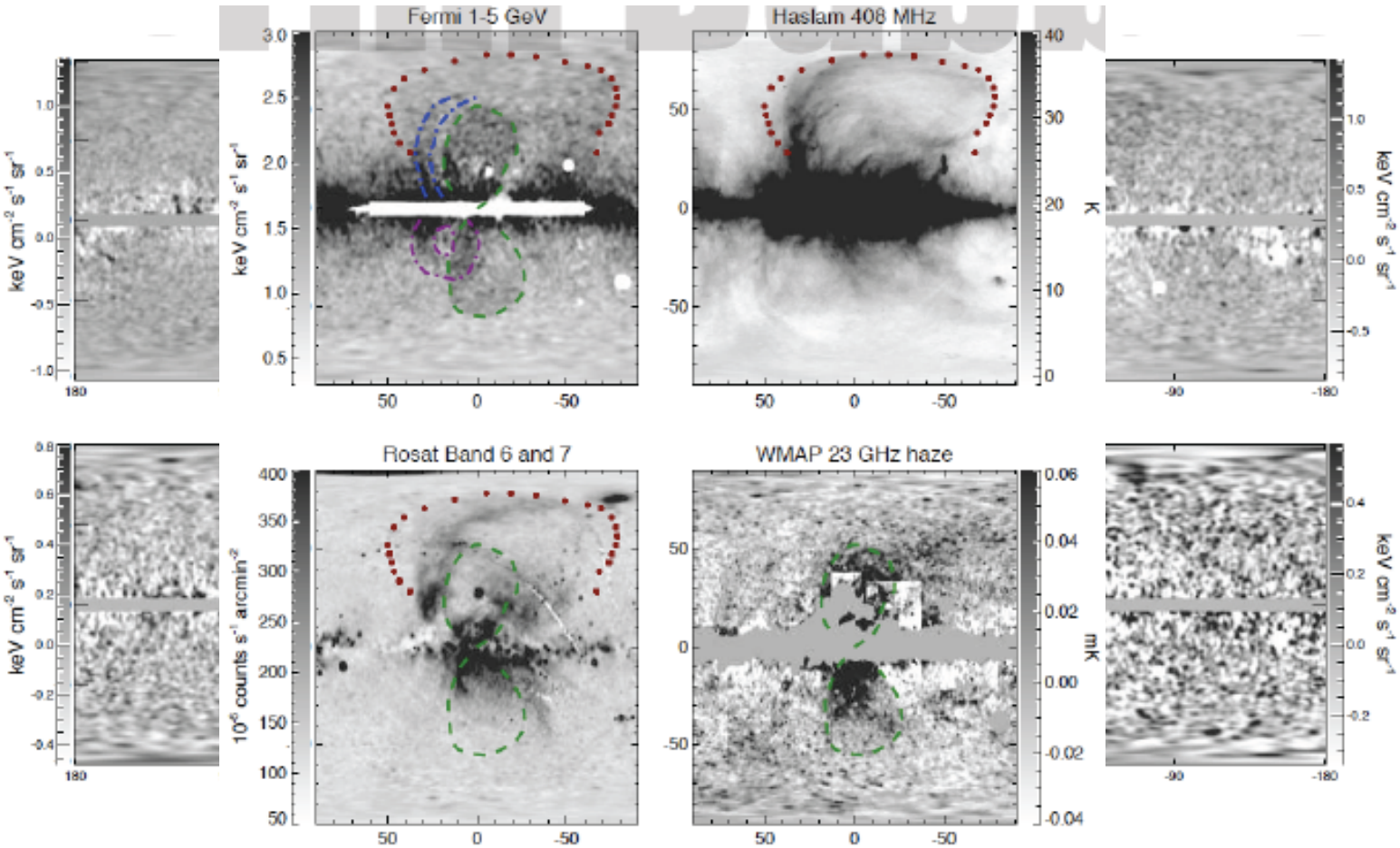
Strong nuclear pc-scale IR emission
(T = 1200 K, L_{IR} = 8x10^{45} erg/s)
Malmrose et al. (2011)

Cosmic-ray induced emission on pc scale

FSRQs favored for PeV/IceCube neutrino detection
(Atoyan & Dermer 2001)

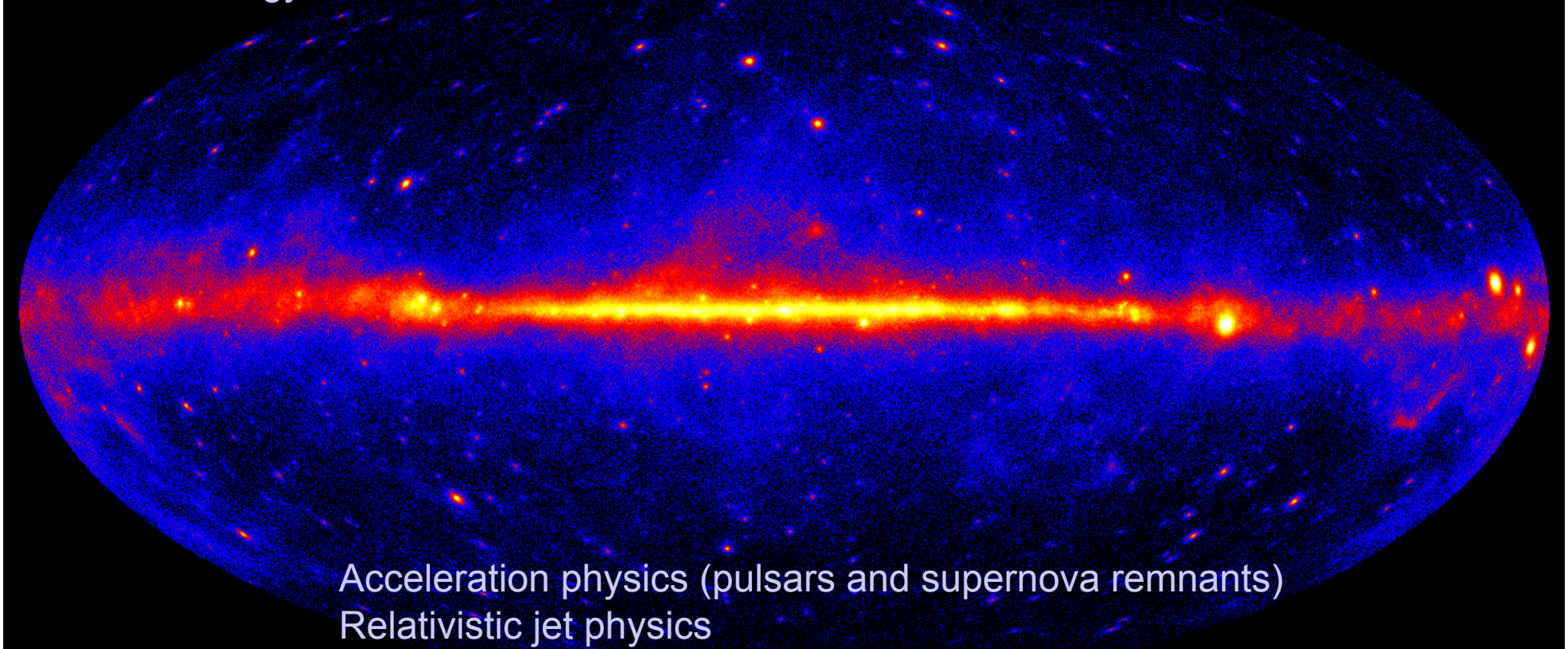
Fermi Bubbles

- Data minus diffuse Fermi emission model



Summary

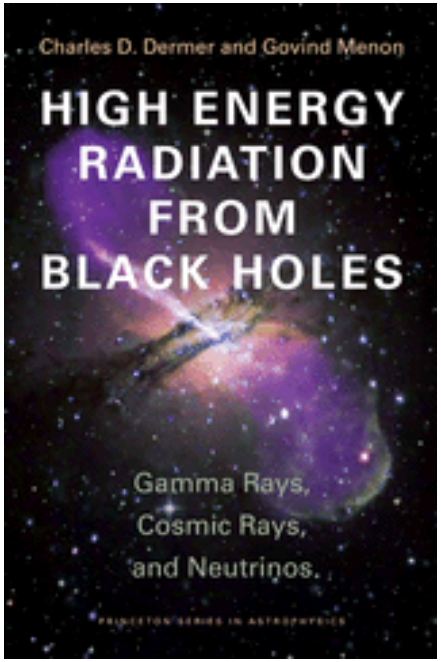
Fermi LAT provides uniform spectral, temporal GeV database of high energy radiation sources



Acceleration physics (pulsars and supernova remnants)
Relativistic jet physics
New physics: search for dark matter, LIV, magnetogenesis
Cosmic ray and UHECR origin

UHECRs from Black Holes: GRBs and Blazars

The most energetic and powerful radiations in nature are made by particles accelerated through Fermi processes in black-hole jets powered by rotation.



Possibilities:

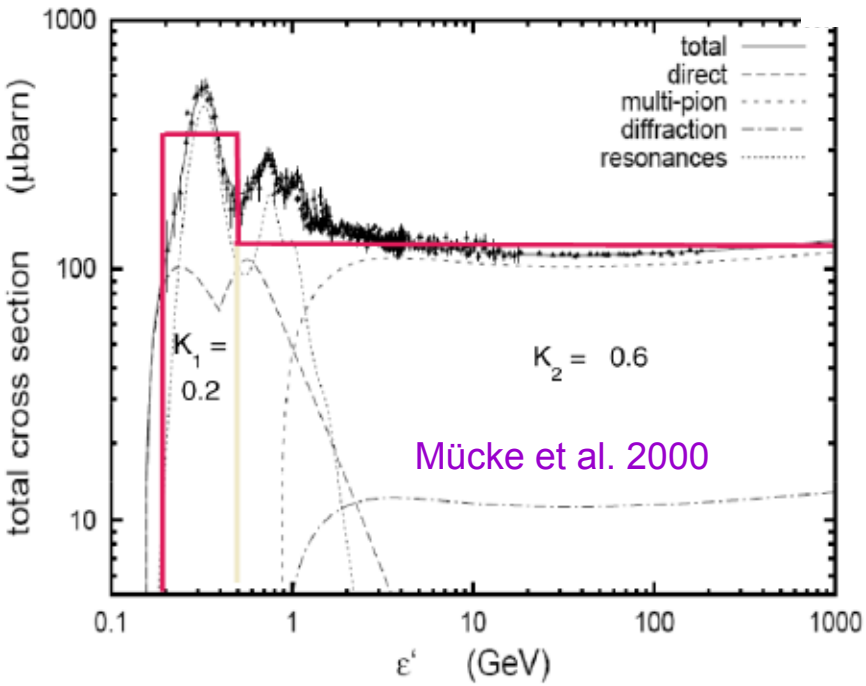
Pulsars/magnetars
Galaxy cluster shocks
Particle physics candidates
Radio-quiet AGNs
Dormant black holes
Others

Evidence favors (radio-loud) AGN hypothesis for UHECR origin; though GRB origin not ruled out

Photopion Production Cross section

- Photopion pγ production cross section

$$p+\gamma \to \Delta^+ \to \begin{cases} p+\pi^0 \to p+2\gamma \\ n+\pi^+ \to n+e+3\nu \to p+2e+4\nu \end{cases}$$



$$\sigma_{\phi\pi}(\epsilon_r) = \begin{cases} 340\ \mu\text{b}, & \epsilon_{thr} = 390 \le \epsilon_r \le 980 \\ 120\ \mu\text{b}, & \epsilon_r \le 980 \end{cases}$$

$$K_{\phi\pi}(\epsilon_r) = \begin{cases} 0.2, & 390 \le \epsilon_r \le 980 \\ 0.6, & \epsilon_r \le 980 \end{cases}$$

$$\hat{\sigma}_{\phi\pi} \equiv \sigma_{\phi\pi}(\epsilon_r) K_{\phi\pi}(\epsilon_r) \equiv$$

$$\sigma_1 K_1 H(\epsilon_r - 390) \cong 70 H(\epsilon_r - 390)\ \mu\text{b}$$

Atoyan & Dermer (2003)

$$t_{\gamma p}^{-1}(\gamma_p) = \frac{1}{\gamma_p}\left|\frac{d\gamma_p}{dt}\right|_{\gamma p} = c\int_0^{\infty} d\epsilon \int_0^{2\pi} d\phi \int_{-1}^{+1} d\mu\ n_{ph}(\epsilon,\Omega)(1-\beta_p\mu)\sigma_{\gamma p}(\epsilon_r)K_{\gamma p}(\epsilon_r)$$

- Crab Flares
- Extended SNRs and Cen A
- TGFs
- SGRs
- GC and MSPs
- η Carinae
- γ Cygni