GRBs, UHECRs, and the IGMF

Waxman 1995, 2000
Vietri 1995, 1998
Milgrom & Usov 1996
Waxman & Bahcall 1997
Waxman & Coppi 1998
Böttcher & Dermer 1998
Totani 1998, 1999
Rachen & Meszaros 1998
Zhang & Meszaros 2001
Dermer 2002
Wick et al. 2004
Wang et al. 2008
Murase et al. 2008
Murase & Takami 2009
Asano et al. 2009
Becker et al. 2010
…

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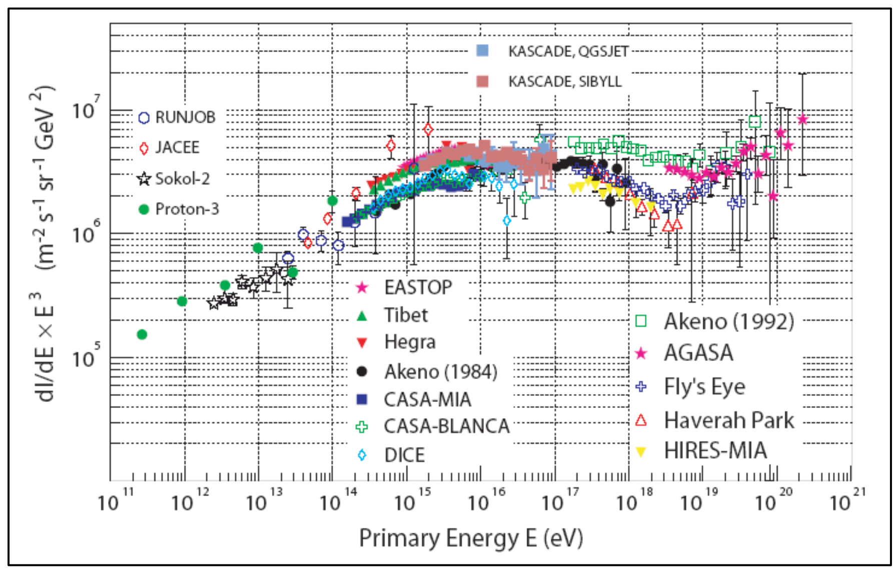
Chuck Dermer
United States Naval Research Laboratory
Washington, DC USA
charles.dermer@nrl.navy.mil

Critical review of the hypothesis that GRBs are the sources of the UHECRs



Acceptable UHECR source candidates

1. Sources are extragalactic

2. Mechanism to accelerate to ultra-high energies
   acceleration region smaller than Larmor radius (Hillas condition)

3. Adequate energy production rate within GZK volume

4. Sources within GZK radius

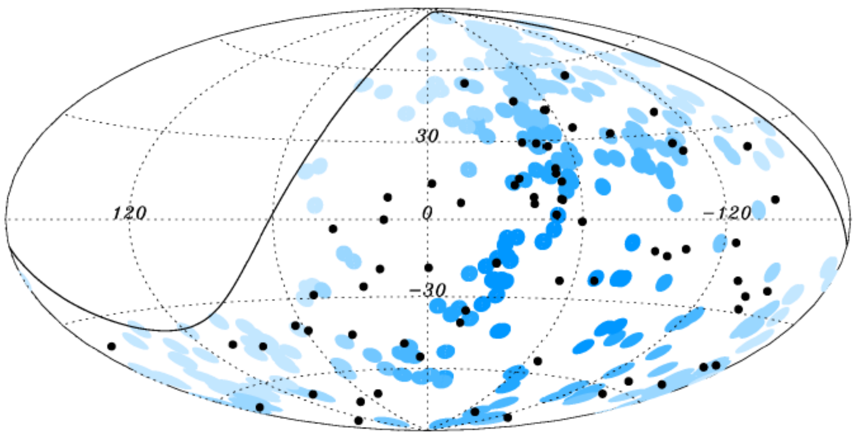
5. UHECRs can escape from acceleration region

Electromagnetic signatures of UHECRs

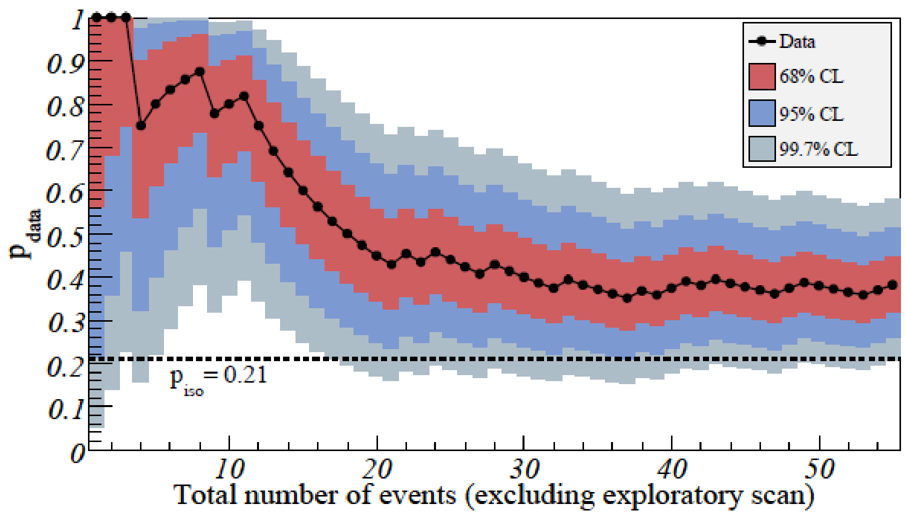
The goal of identifying hadronic signatures in the high-energy spectra of GRBs is ambiguous, and leptonic emission models are energetically favored.

Neutrino signatures of UHECRs in GRBs Waiting…

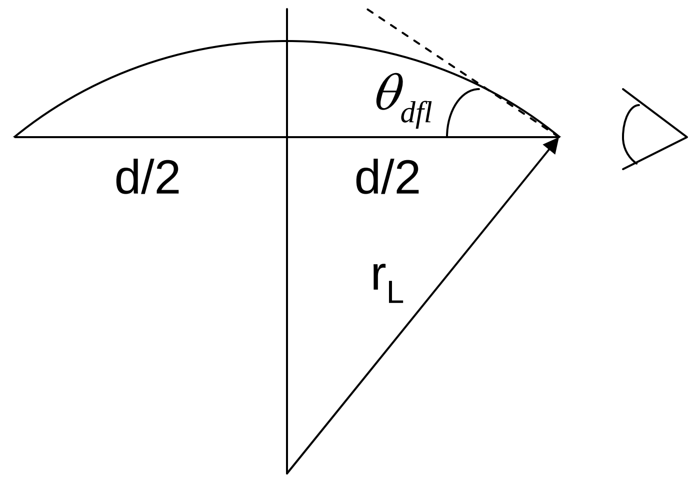
Intergalactic Magnetic Field Constraints from Auger Observations



Auger collaboration: 69 events
29 Sept 2010 (arXiv:1009.1855)



$$\theta_{dfl} \cong \frac{d}{2r_L\sqrt{N_{inv}}} \qquad r_L \cong \frac{E}{ZeB}$$



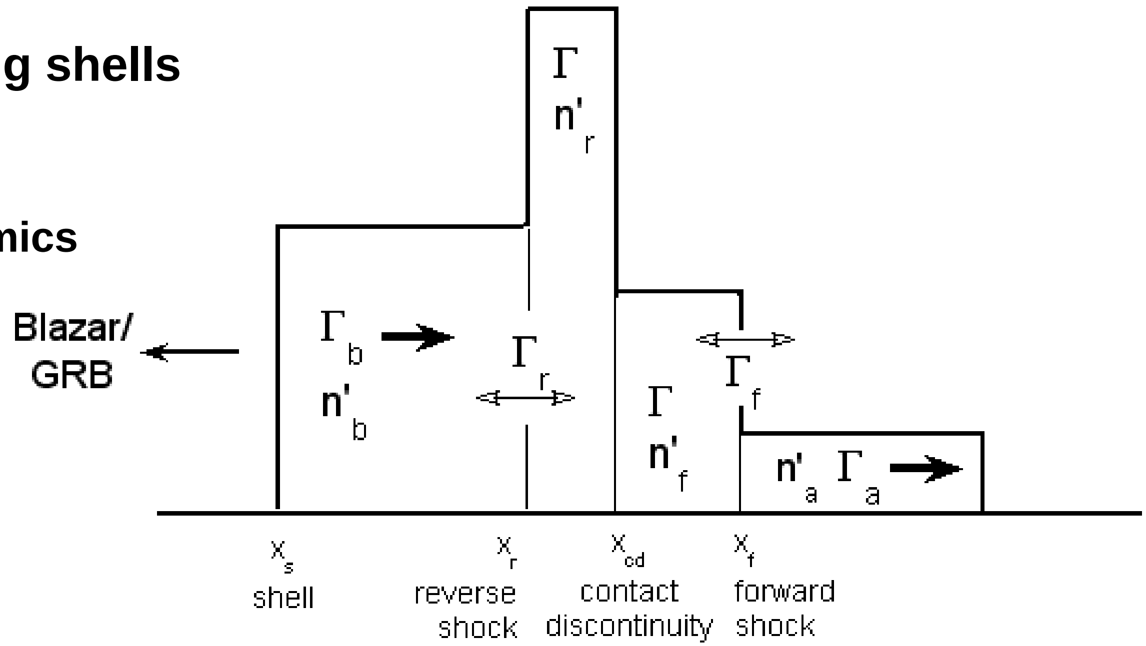
$$B(nG) < \frac{3(E/10^{20}eV)\sqrt{N_{inv}}}{Z(d/75Mpc)}$$

$$B(nG) < \frac{6(\theta_{dfl}/0.1)E_{20}\sqrt{N_{inv}}}{Z(d/3.5\,Mpc)}$$

2. Mechanism to accelerate to ultra-high energies

external shocks or colliding shells

Relativistic Shock Hydrodynamics



$$E_{\max} \approx \Gamma Z e B' R'$$

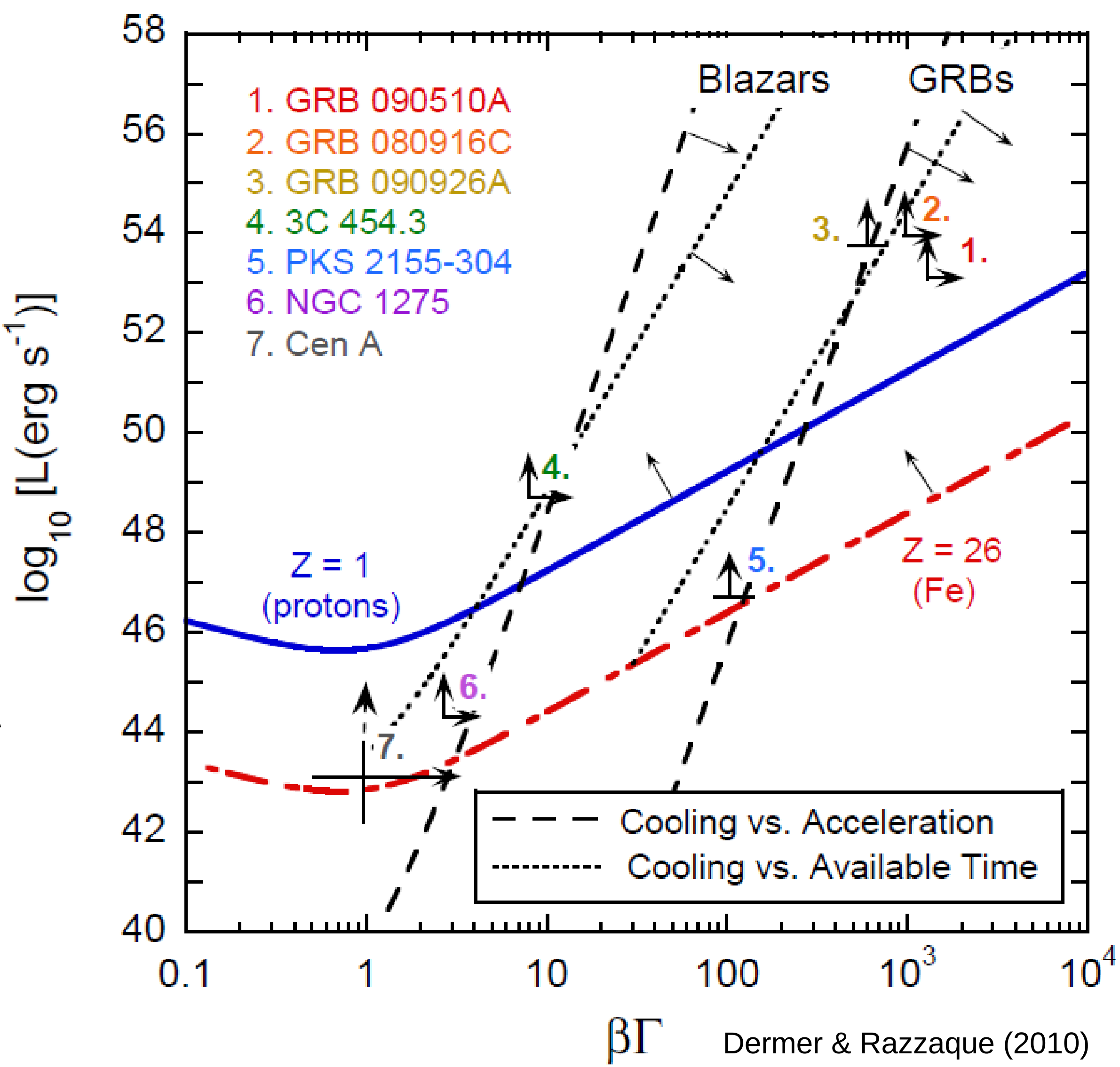
Requirement to accelerate to ultra-high energies by Fermi processes:

$$\Rightarrow E_{\max} \approx \left(\frac{Ze}{\Gamma}\right)\sqrt{\frac{2L}{c}} \times Factor\,(<1)$$

$$\Rightarrow L_{\gamma} > \frac{3\times 10^{45}}{Z^{2}}\Gamma^{2}\,(\frac{E}{10^{20}eV})\; erg\; s^{-1}$$

L – Γ diagram

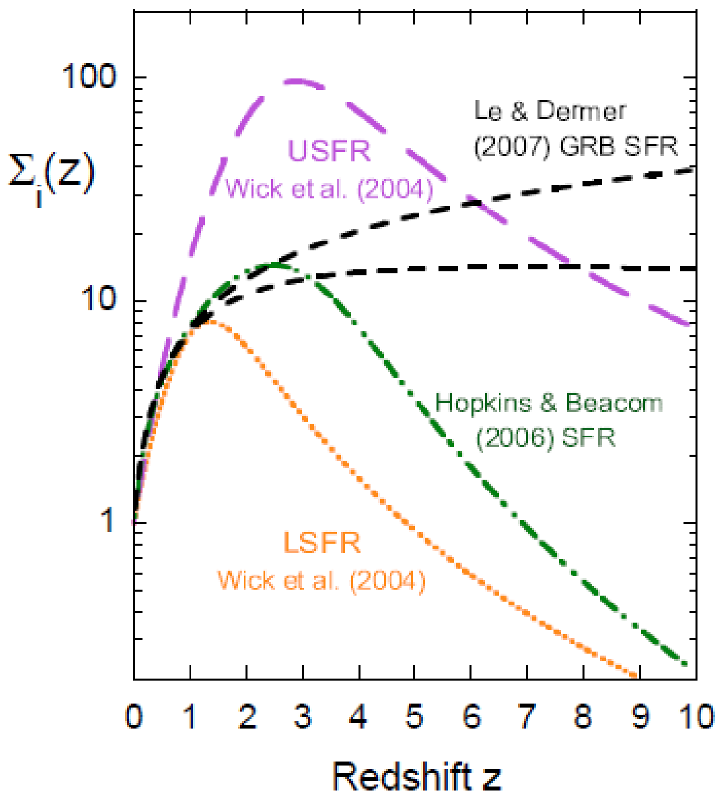
- Bulk Lorentz factor Γ from γγ opacity arguments
- Sources with jet Lorentz factor Γ must have jet power L exceeding heavy solid and dot-dashed curves to accelerate p and Fe respectively, to E = 10^{20} eV
- GRBs can easily accelerate p and Fe to >10^{20} eV

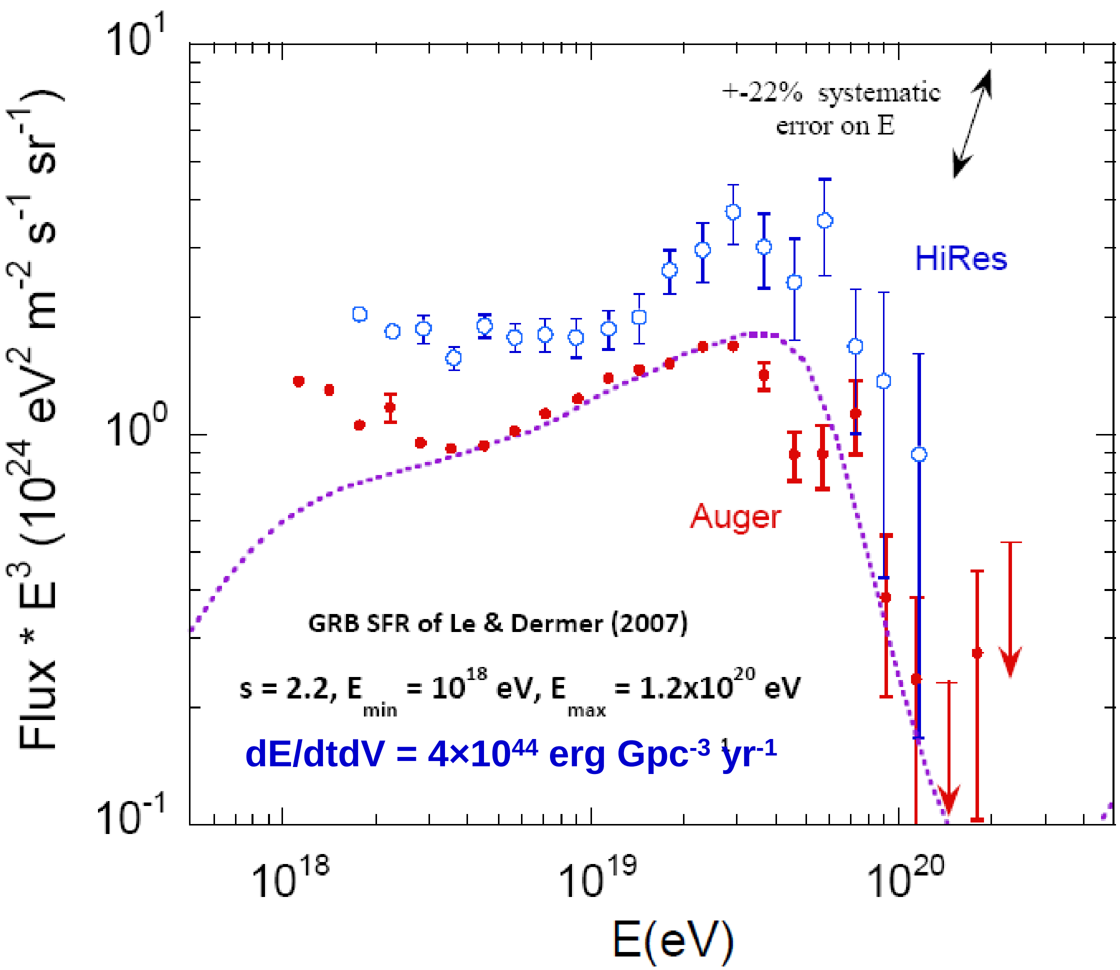


Dermer & Razzaque (2010)

3. Energy Production Rate within GZK Volume

- $u_{UHECR}/t_{GZK} \sim 10^{44}$ erg Mpc^{-3} yr^{-1}
- 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 ≥ 4×10^{44} erg Mpc^{-3} yr^{-1}

Luminosity Density from Long GRB Observations

(Nonthermal) Luminosity density ℓ (energy/ time/ volume)

- Luminosity function Φ(L): $\Rightarrow \ell = \langle \Delta t \rangle \int_0^\infty dL\, \Phi(L)$

$\ell\ (10^{44}\, erg\ Mpc^{-3}\ yr^{-1})$	
0.05 – 0.08	(Guetta et al. 2005; 50-300 keV)
0.3-0.4	(Le & Dermer 2007; all photon energies)
0.6	(Wanderman & Piran 2010; 1 keV – 1 MeV)

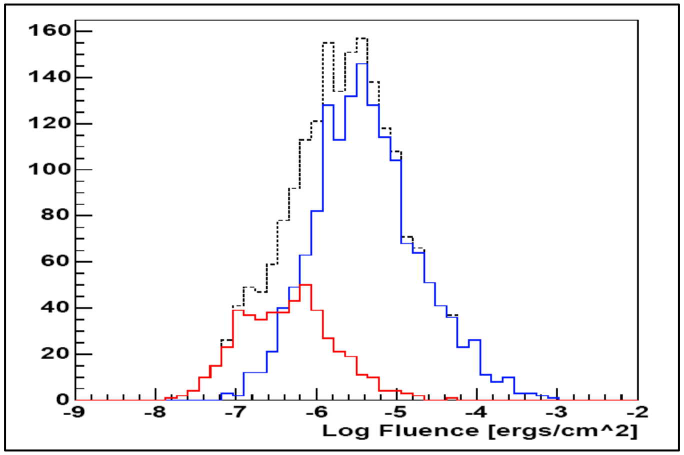
$\langle \Delta t \rangle = 10\, s$

- Mean GRB flux ϕ

$$\phi(>20\, keV) \approx 0.0075\, erg\ cm^{-2}\ yr^{-1}$$

BATSE data for long GRBs

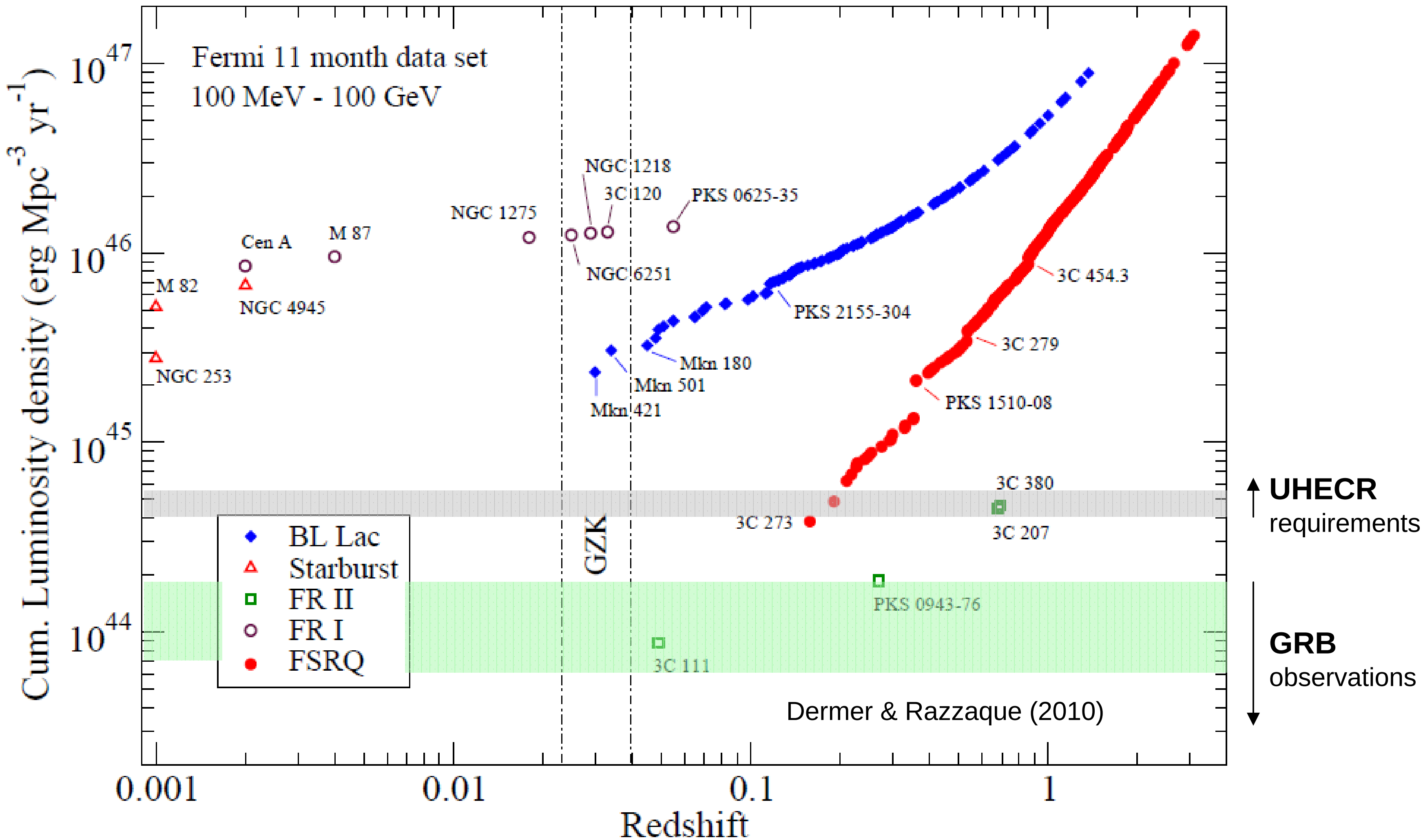
$$\Rightarrow \ell \approx \frac{H_0}{c}\phi \approx 10^{43}\, erg\ Mpc^{-3}\ yr^{-1}$$



- GRB flux ϕ at Fermi/LAT energies only

$$\Rightarrow \ell \approx 10^{42}\, erg\ Mpc^{-3}\ yr^{-1}$$ (Eichler et al. 2010)

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)

4. Sources within the GZK Radius

- Local GRB rate density ≈ (0.5 x 75) Gpc^{-3} yr^{-1} (Guetta et al. 2005)
  ≈ 10 Gpc^{-3} yr^{-1} (Le & Dermer 2007)
  ∴ GRB rate within GZK radius (≈100 Mpc): ~0.1 yr^{-1}
  GRB rate within GZK radius with jets pointing towards us: ~$10^{-3}\theta_{-1}^{2}$ yr^{-1}

- Deflection of 10^{20} E_{20} eV particles by $\theta_{dfl} \cong \dfrac{d}{2r_L\sqrt{N_{inv}}} < 10^{-6}\dfrac{ZB_{-15}d_{100}}{E_{20}}$

  in an Intergalactic Magnetic Field (IGMF) $B_{IGMF} = 10^{-15}B_{-15}$ G

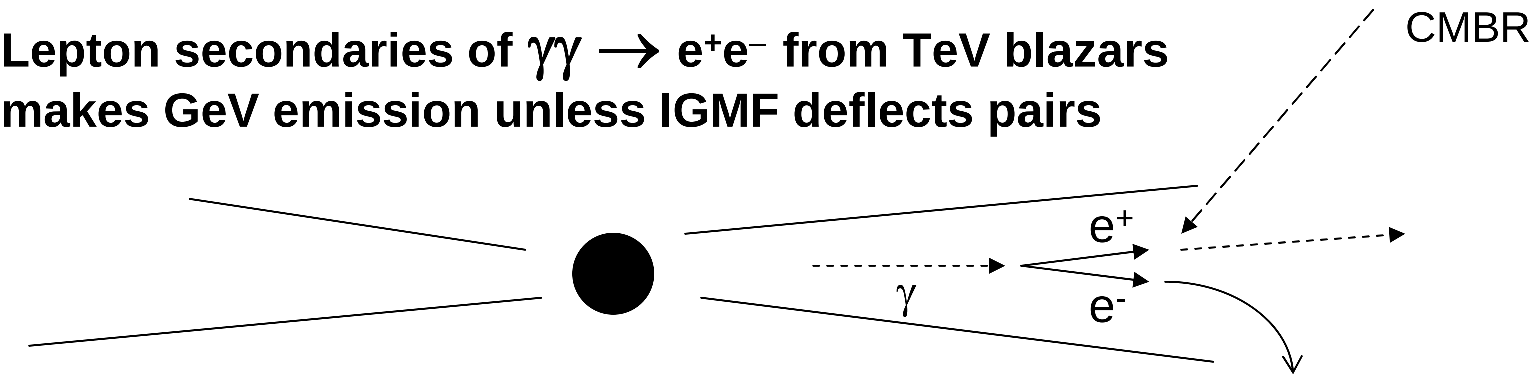
- Arrival times extended by $\Delta t \approx \dfrac{d}{6c}\theta_{dfl}^{2} \approx 400\dfrac{Z^2B_{-15}^2d_{100}^3}{E_{20}^2N_{inv}}\,s$

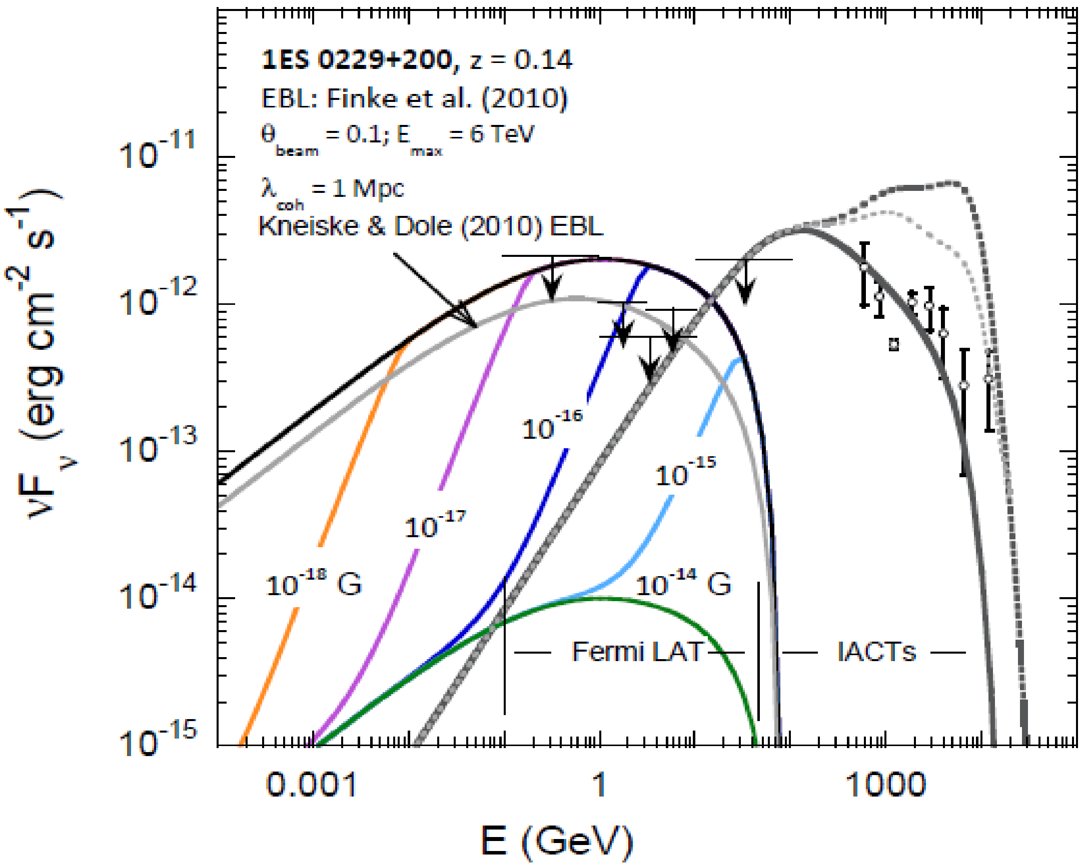
To extend arrival times over ~10^5 yr, require $B_{-15} > 10^5\dfrac{E_{20}\sqrt{N_{inv}}}{Zd_{100}^{3/2}}$

For UHECR/GRB hypothesis to be viable, B_{IGMF}(nG) > 0.1/Z

Intergalactic Magnetic Field

Lepton secondaries of $\gamma\gamma \rightarrow e^+e^-$ from TeV blazars makes GeV emission unless IGMF deflects pairs





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

Neronov & Vovk (2010)
Tavechhio et al. (2010a,b)

$B_{IGMF} \approx 10^{-15}$ G
and **$\lambda_{coh} \approx 1$ kpc**

from halos around stacked hard Fermi AGNs

Ando & Kusenko (2010)

Implications of Weak IGMF

- Model of UHECRs from GRBs not viable for weak IGMF

- Claims of Neronov & Vovk (2010), Tavecchio et al. (2010a,b) based on assumption about the constancy of TeV flux of blazars

(paper with Cavadini, Razzaque, Finke, Lott, in prepartion)

- Ando & Kusenko (2010) parameters contrary to spectral model

∴ **if $B_{IGMF}(G) > 0.1$ nG/Z, GRB model of UHECR origin remains viable**
$B_{IGMF}(G) <$ few nG/Z for clustering

Fine tuning?

5. UHECR escape from acceleration region

Depends on composition

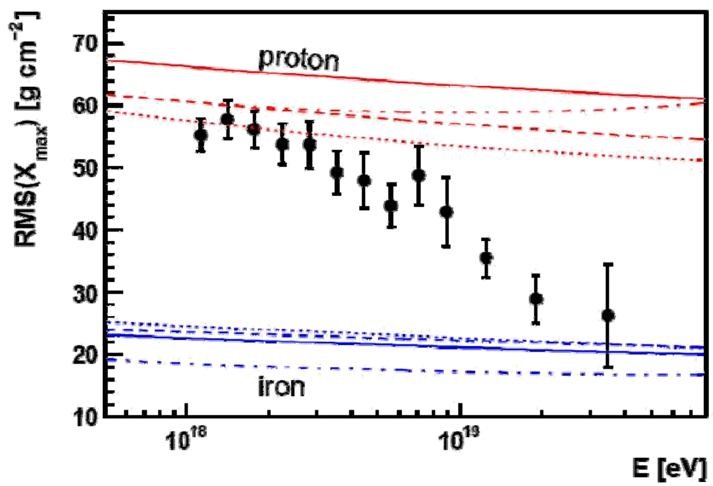
1. If p-dominated, claimed by HiRes

   Neutral beam model (Atoyan & Dermer 2003)

2. If Fe-dominated, claimed by Auger (at $\approx 4\times10^{19}$ eV)

   Impulsive production makes cosmic ray shock

   Escape from source region without photodisintegration



Scorecard: GRBs as UHECR sources

Sources are extragalactic ✓

Can accelerate to ultra-high energies ✓

Adequate energy production rate within GZK volume ?

Sources within GZK radius Need strong IGMF ?

UHECR escape Depends on composition ?

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Evidence favors (radio-loud) AGN hypothesis for UHECR origin