γ rays, cosmic rays and ν's from Astrophysical Sources

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Ultra-High Energy Cosmic Ray Power

The energy spectrum measured by Auger and HiRes

Phenomenological fits

Confirm spectral cutoff
GZK or source feature?

Nature of Primaries

Debated, p or Fe?

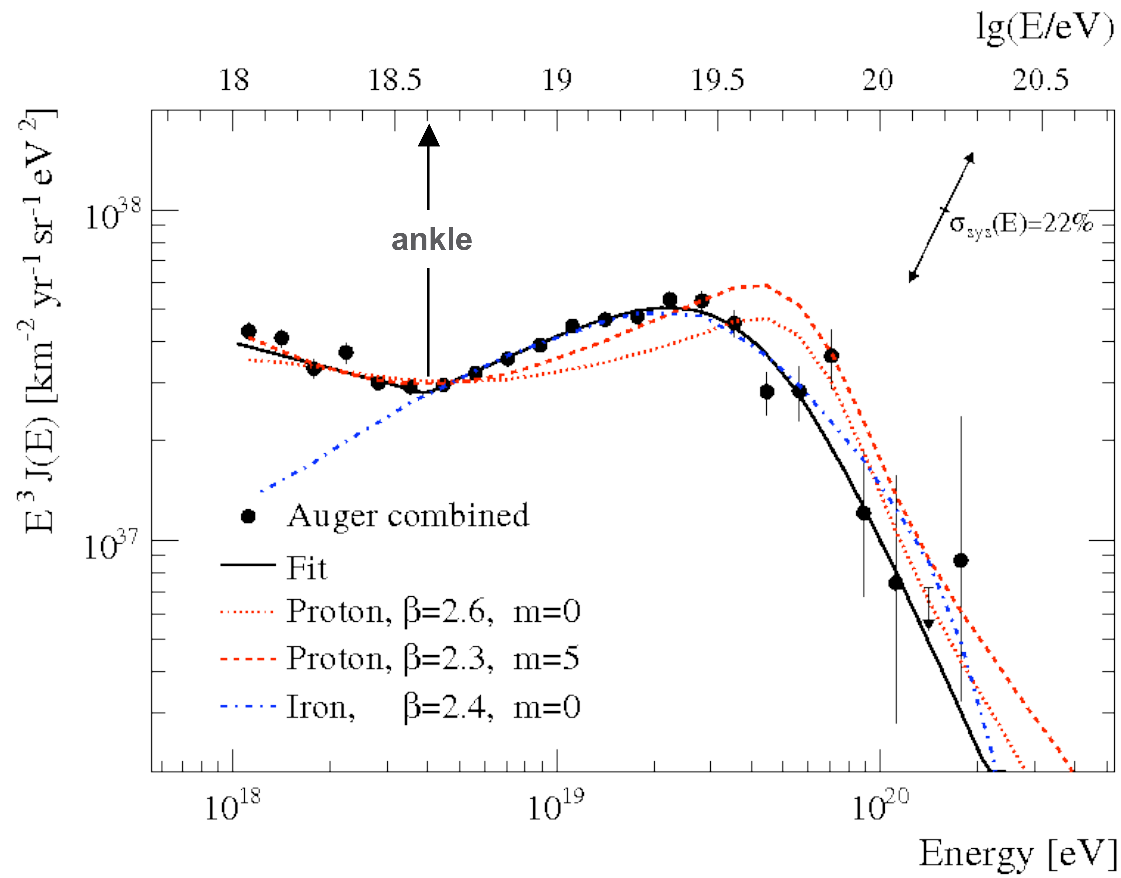
Galactic/extragalactic

Where is the transition?

Local power output by extragalactic sources

Depends on threshold

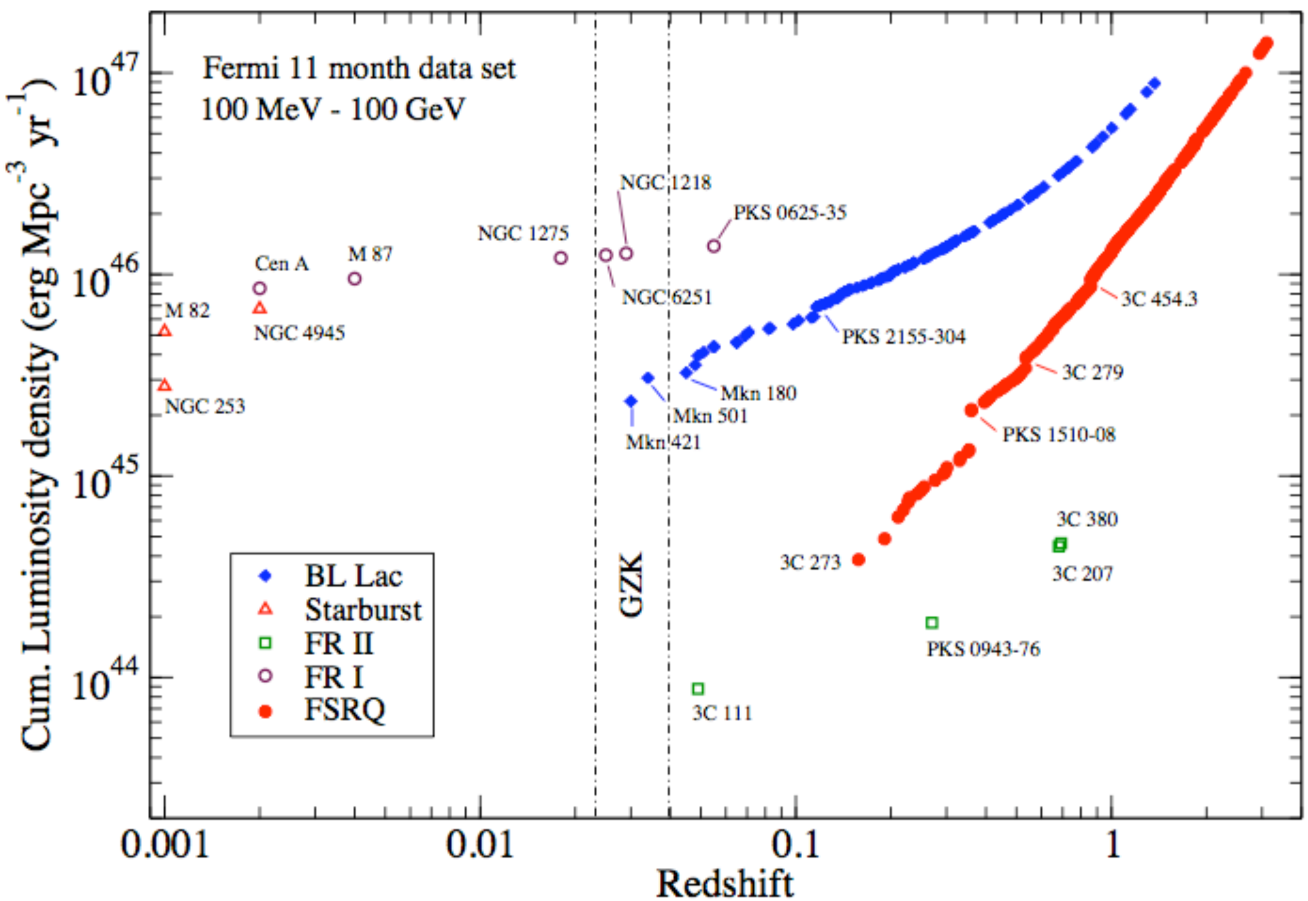
$f \times 10^{44}$ erg Mpc^{-3} yr^{-1} ; $f \sim 1$



Auger Collaboration 2010

Astrophysical Source Candidates - I

Non-thermal (>100 MeV) power output measured by Fermi LAT



Starburst Galaxies
Within GZK

FR I Radio Galaxies
Mostly within GZK

FR II Radio Galaxies
Outside GZK

BL Lacs
Barely within GZK

Flat Spectrum Radio Quasars
Outside GZK

Dermer & Razzaque, arXiv:1004.4249

Astrophysical Source Candidates - II

Cumulative power (> 10 keV) output from Gamma Ray Bursts

Back of the envelope calculation

- Total electromagnetic energy release per GRB: $10^{51}E_{51}$ erg
- Observed GRB rate ~ 2 $\mathrm{Gpc^{-3}\ yr^{-1}}$ at z ~ 1-2 ➔ ~ 0.2 $\mathrm{Gpc^{-3}\ yr^{-1}}$ at z ~ 0
  beaming corrected rate ~ 100 f_b times higher
- γ ray power output ~ $10^{51}E_{51}$ erg × 100 f_b × 0.2 $\mathrm{Gpc^{-3}\ yr^{-1}}$ ~ $2\times10^{43}E_{51}f_b$ erg $\mathrm{Mpc^{-3}\ yr^{-1}}$
- *Detail calculation using luminosity density function gives ~1-10 times this number*

Dermer & Razzaque, arXiv:1004.4249

A few caveats

- Total non-thermal power output may be smaller if most keV - MeV emission is thermal, and Fermi LAT is dominated by non-thermal emission

Eichler, Guetta & Pohl, arXiv:1004.4249

- Time delay due to scattering by intergalactic magnetic field

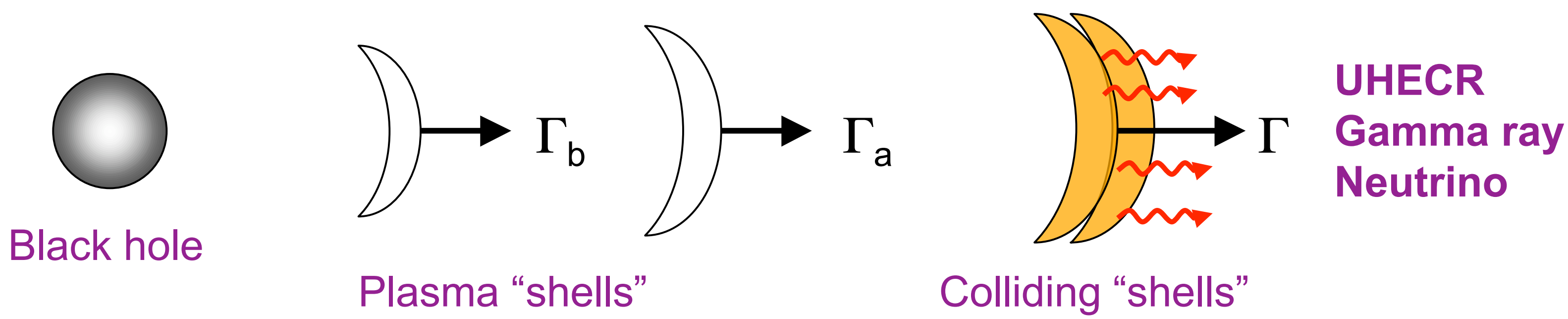
$$\Delta t_{CR} \approx 2\times10^{5} Z^2 B_{n\mathrm{G}}^2 E_{40\mathrm{EeV}}^{-2} d_{200\mathrm{Mpc}}^{3/2} \lambda_{1\mathrm{Mpc}}^{3/2} \text{ year}$$

Effectively increases the GRB rate within GZK volume by $(0.2)^3\Delta t_{CR}$

Large baryon loading, 10-1000, seems required for GRBs to be UHECR sources

Acceleration to 10^{20} eV

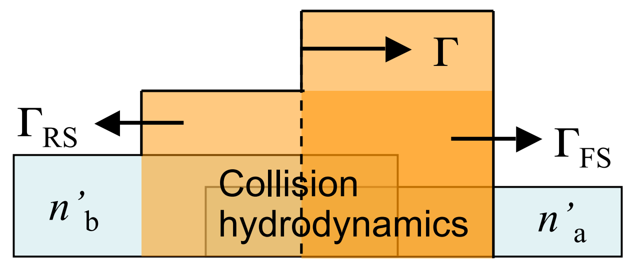
- Acceleration to 10^{20} eV requires large magnetic field - Fermi mechanism
- Collision between two plasma "shells" ejected by a black hole "central engine"
  - ➔ Relativistic forward & reverse shockwaves plough through the "shells"
  - ➔ Plasma instabilities, turbulent motion generate magnetic field
  - ➔ Charged particles (*test particle*) are accelerated in the induced electric field



Non-thermal γ-ray luminosity

Particle energy density in the shocked fluid

$$u_p = \frac{\varepsilon_e^{-1} L_\gamma}{4\pi R^2 \beta \Gamma^2 c} \Rightarrow \frac{B^2}{8\pi} = \varepsilon_B u_p$$



Maximum CR energy

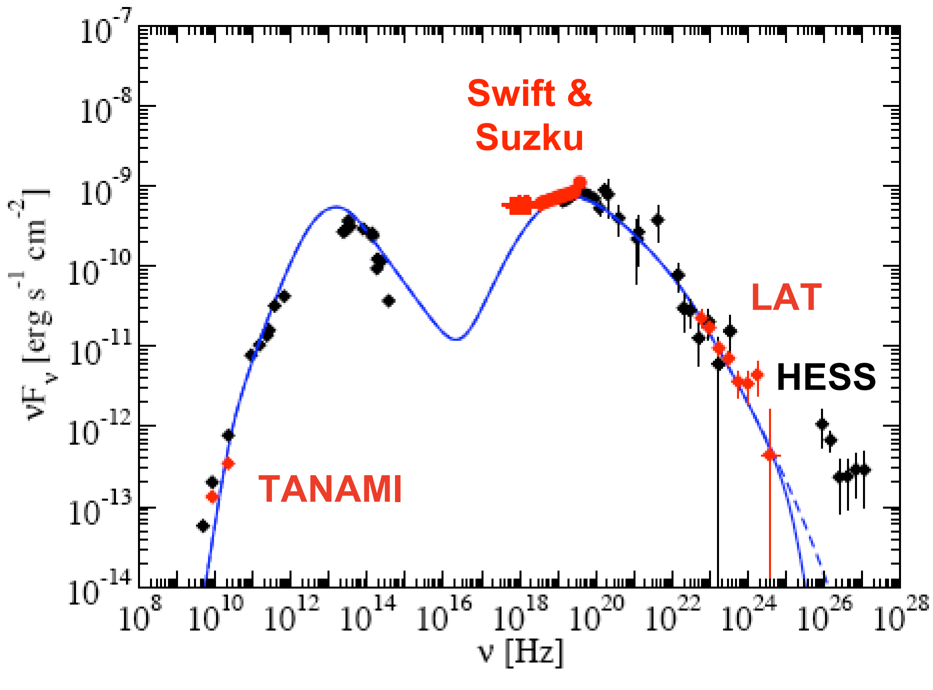
$$E_{\max} = \beta Q B' r = \left(\frac{Ze}{\Gamma}\right)\sqrt{\frac{2\beta\varepsilon_B L_\gamma}{\varepsilon_e c}} \cong 2\times 10^{20}\,\frac{Z}{\Gamma}\sqrt{\frac{\beta\varepsilon_B}{\varepsilon_e}}\sqrt{\frac{L_\gamma}{10^{46}\,\text{ergs s}^{-1}}}\ \text{eV}$$

Power requirement to Produce 10^{20} eV CRs

Which sources can accelerate to 10^{20} eV?

Radio galaxies, blazars

Broadband SED model of *Cen A*
Nearest (3.7 Mpc) radio galaxy



Abdo et al. 2010, ApJ

One-zone SSC model of the SED

Extract model parameters

Jet Doppler factor, bulk Lorentz factor

Magnetic field, jet power

Use these parameters to calculate maximum cosmic ray energy

Acceleration time
= variability (dynamic) time

$$E_{\max} \cong 4\times 10^{19}\,\frac{Z}{\phi}\left(\frac{B}{6.2\,\mathrm{G}}\right)\left(\frac{t_v}{10^5\,\mathrm{s}}\right)\delta_D\left(\frac{\Gamma_j}{7.0}\right)\,\mathrm{eV}$$

Acceleration time
= synchrotron cooling time

$$E_{\max} \cong 6\times 10^{20}\sqrt{\frac{Z}{\phi}\left(\frac{A}{Z}\right)^2\left(\frac{B}{6.2\,\mathrm{G}}\right)^{-1/2}}\left(\frac{\Gamma_j}{7.0}\right)\,\mathrm{eV}$$

Which sources can accelerate to 10^{20} eV?

Gamma Ray Bursts

***Fermi* has discovered/confirmed exciting new features**

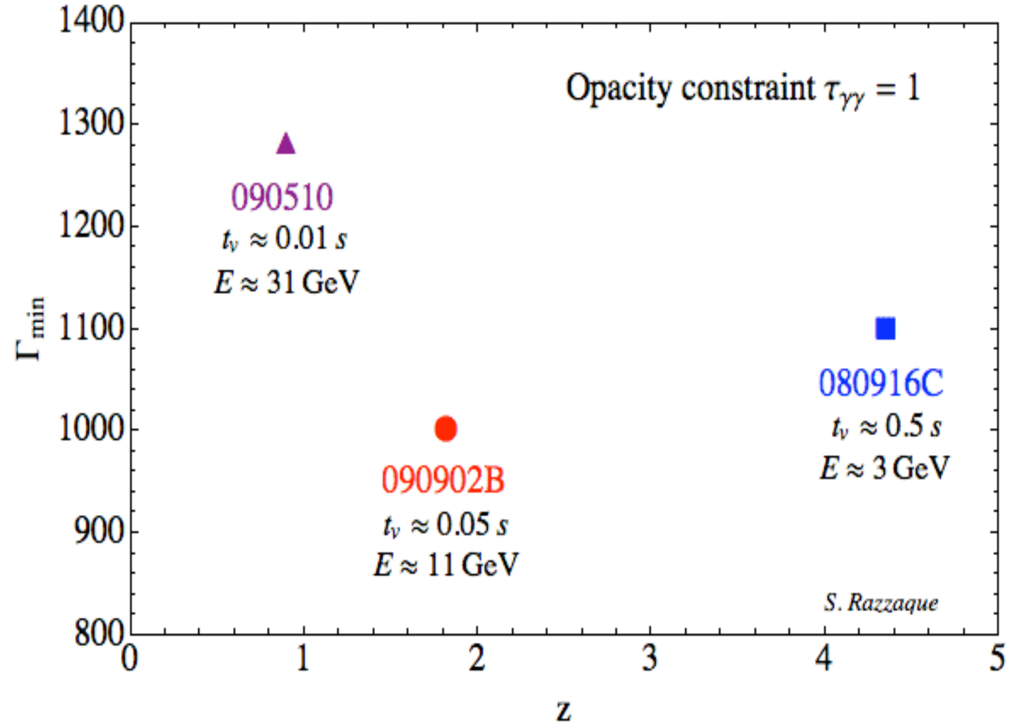
- *Delayed onset of high-energy emission*
- *Additional hard power-law component*
- *Extended high-energy emission*

Profound effects on emission modeling

Very high jet bulk Lorentz factor

Calculated from $\gamma\gamma \rightarrow e^+e^-$ pair production opacity argument for ≥10 GeV photons from GRBs detected with Fermi LAT

Minimum jet bulk Lorentz factors of bright Fermi LAT GRBs



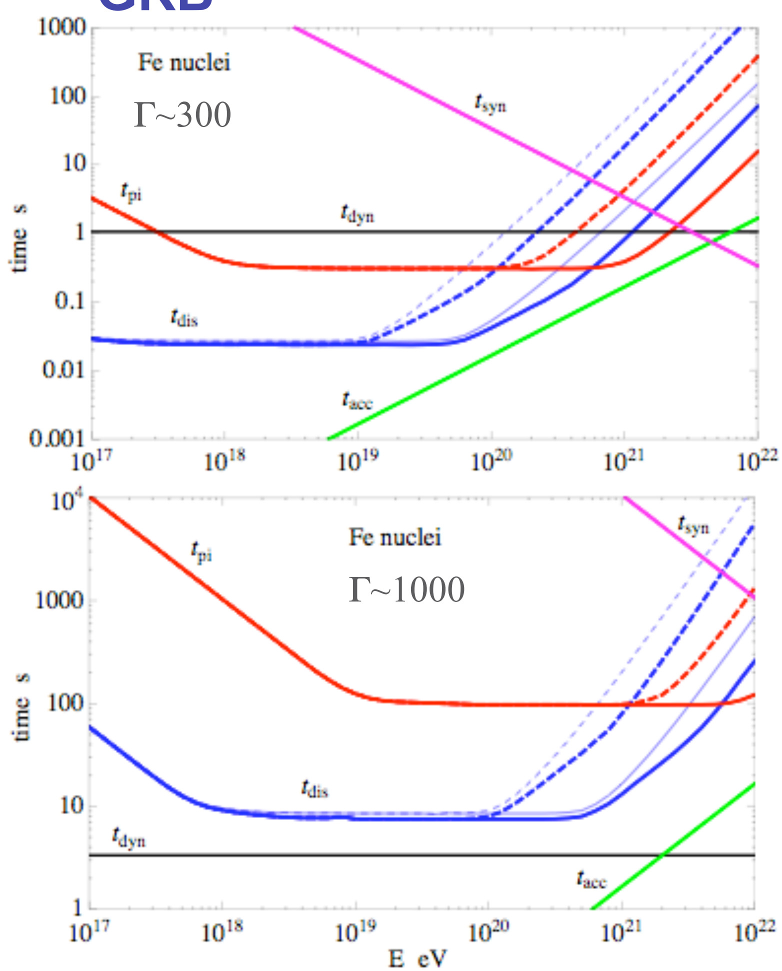
$$\tau_{\gamma\gamma}(E) = \frac{3}{4}\frac{\sigma_T d_L^2}{t_v \Gamma}\frac{m_e^4 c^6}{E^2(1+z)^3}\int_{\frac{m_e^2 c^4 \Gamma}{E(1+z)}}^{\infty} \frac{d\epsilon'}{\epsilon'^2}\, n\left(\frac{\epsilon' \Gamma}{1+z}\right) \varphi\left[\frac{\epsilon' E(1+z)}{\Gamma}\right]$$

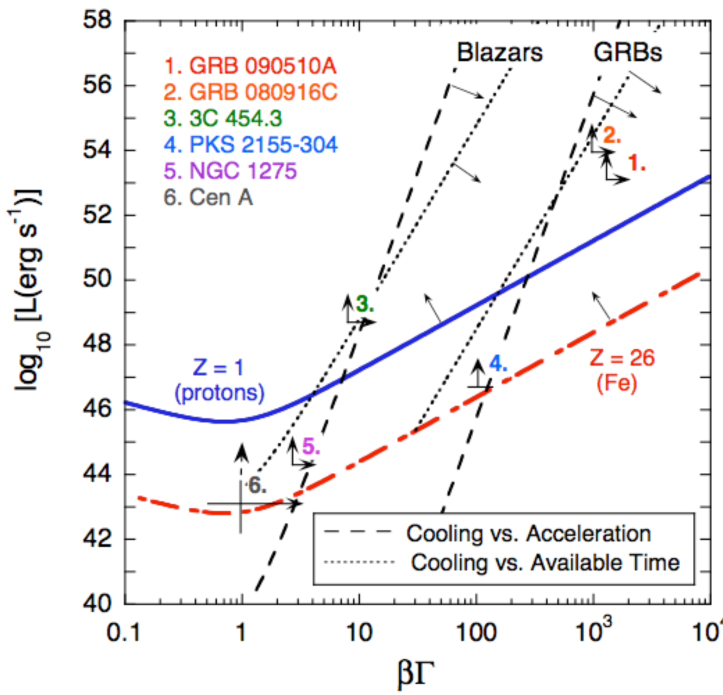
Which sources can accelerate to 10^{20} eV?

Available (dynamic) time and/or energy losses limit acceleration

GRB

Wang, Razzaque & Meszaros, 2008



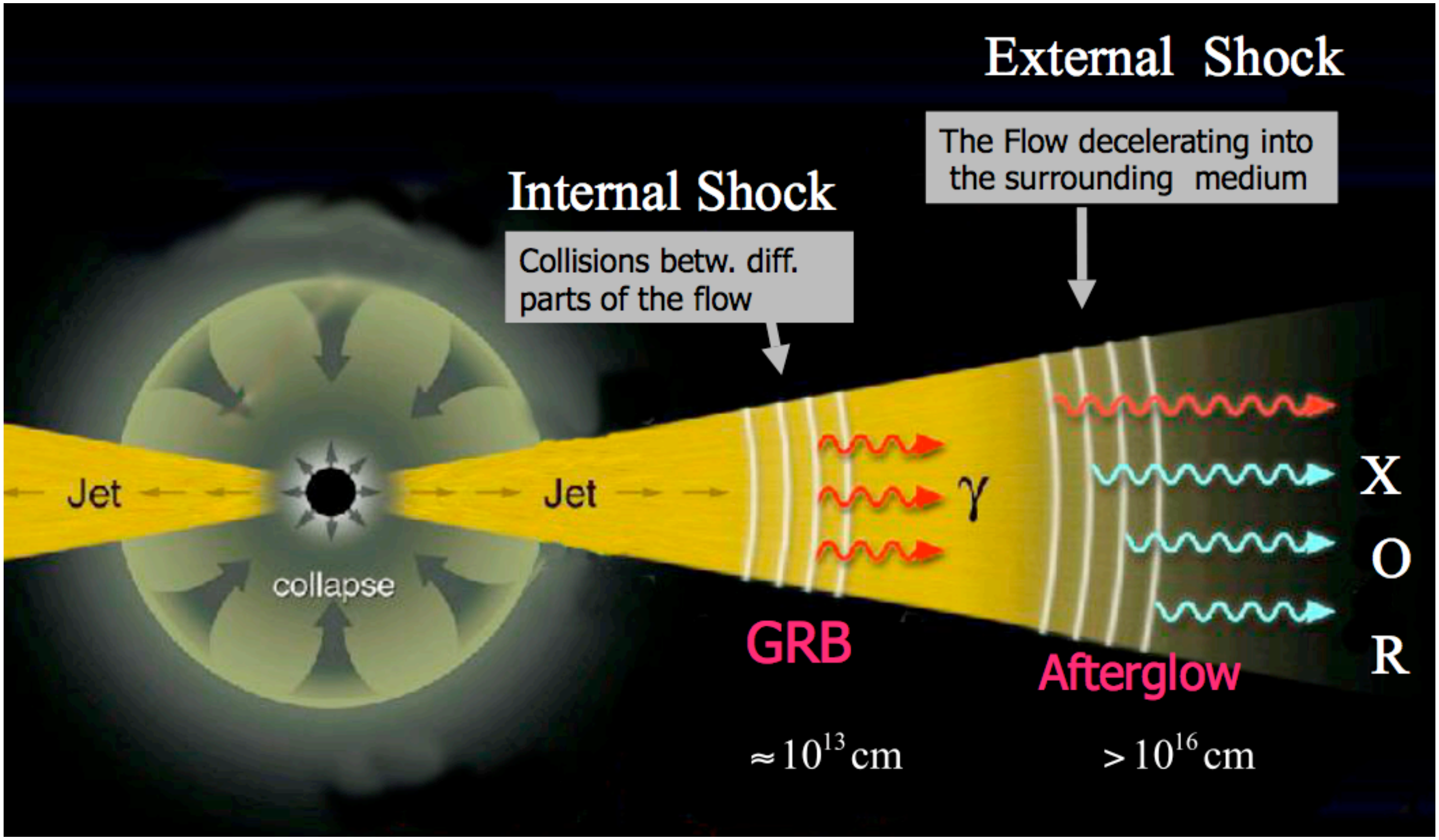


Dermer & Razzaque, arXiv:1004.4249

- GRBs can most easily accelerate *p* and/or Fe
- Powerful blazars can easily accelerate Fe, and *p* in some cases
- Radio Galaxies may only accelerate Fe

UHECR signatures in GRB emission

Rees, Meszaros, Piran and others … "standard GRB model"



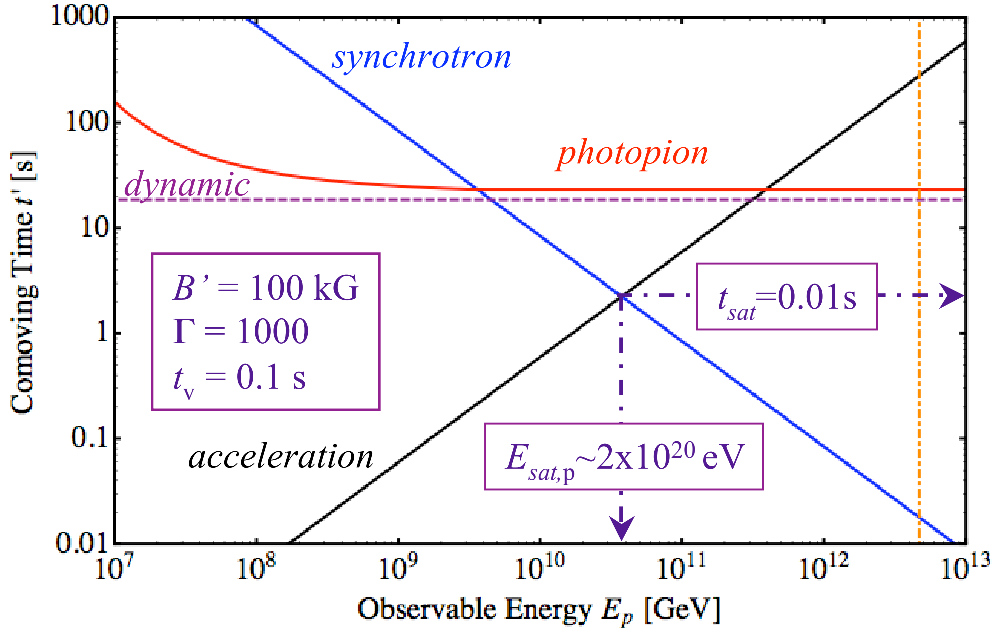
Synchrotron emission by shocked electrons for prompt and afterglow emission

UHECR signature in GRB emission

UHECR acceleration in magnetic field and interactions may provide γ ray signature from GRBs, specially in *Fermi* LAT

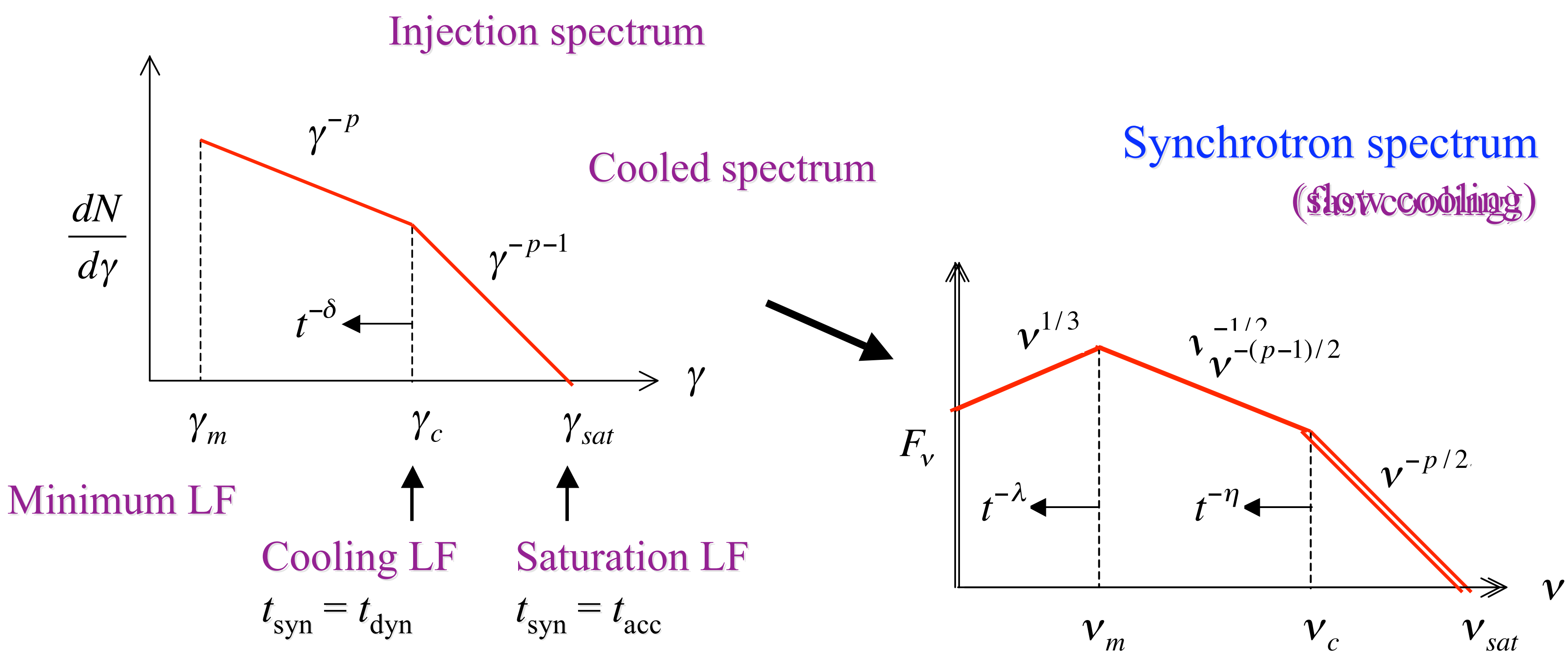
- *Synchrotron radiation and associated e^+e^- cascade radiation*
- *Photohadronic interactions with observed keV - MeV γ rays and cascade emission*

Very high jet bulk Lorentz factor reduces photohadronic cooling



Synchrotron Radiation from GRB Jets

- Particle acceleration in the forward shock B field
- Cooling is dominated by synchrotron radiation in the same B field



- Fast cooling $\gamma_m > \gamma_c$ or $\nu_m > \nu_c$; Slow cooling $\gamma_m < \gamma_c$ or $\nu_m < \nu_c$
- All break frequencies evolve with time as the B field (and Γ) does

Synchrotron radiation in GRB prompt phase

Fermi LAT emission (>100 MeV) modeled by proton-synchrotron radiation from a coasting (constant bulk Lorentz factor) GRB fireball

- *Synchrotron radiation by proton and associated e^+e^- cascade from $\gamma\gamma$*
- *Accumulation of protons cooling in time build-up flux in LAT*

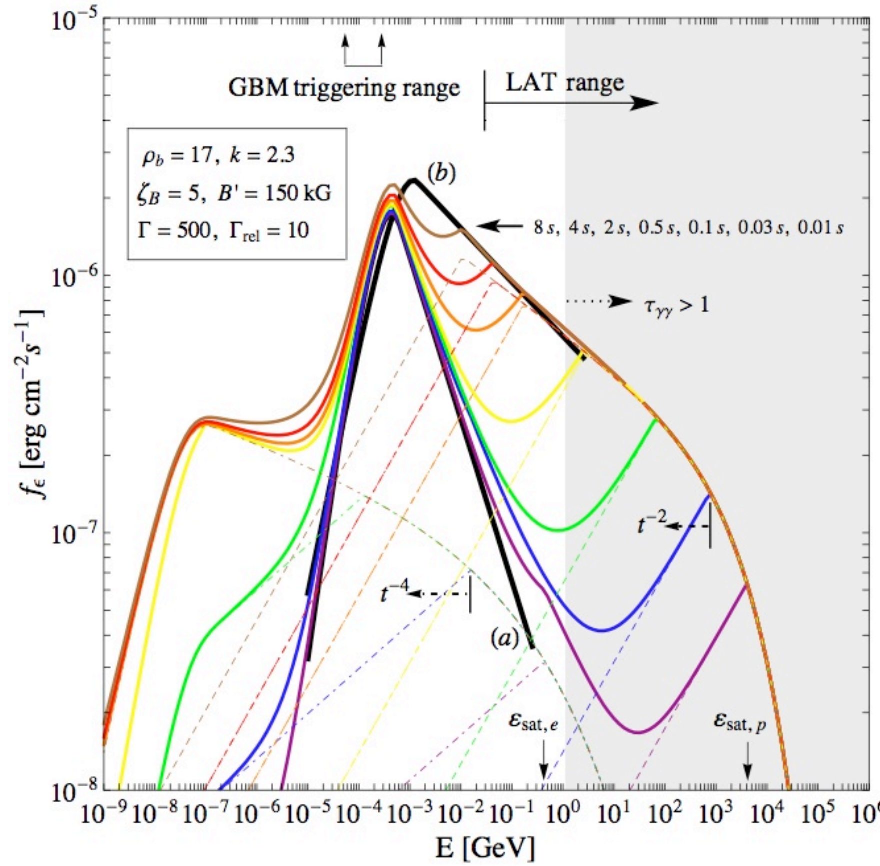
Can explain delayed emission in LAT

- *Requires large (~10^2-10^3 × γ rays) energy budget*

Consistent with large baryon load requirement for UHECRs from GRBs

- *Narrow (1/Γ) jet opening angle can help by reducing actual energy release*

GRB 080916C



Razzaque, Dermer & Finke, arXiv:0908.0513

GRB Afterglow

Adiabatic blast wave decelerating in uniform density medium

Blandford & McKee 1976

- Relationship between t, Γ and R : $R = 2\Gamma^2 act(1+z)^{-1}$

$a = 1$ for coasting
$a = 4$ after decel.

- Deceleration time: $t_{dec} \approx 1.9(1+z)(E_{55}/\mathrm{n})^{1/3}\Gamma_3^{-8/3}$ s

  Total KE in blast wave = swept-up material

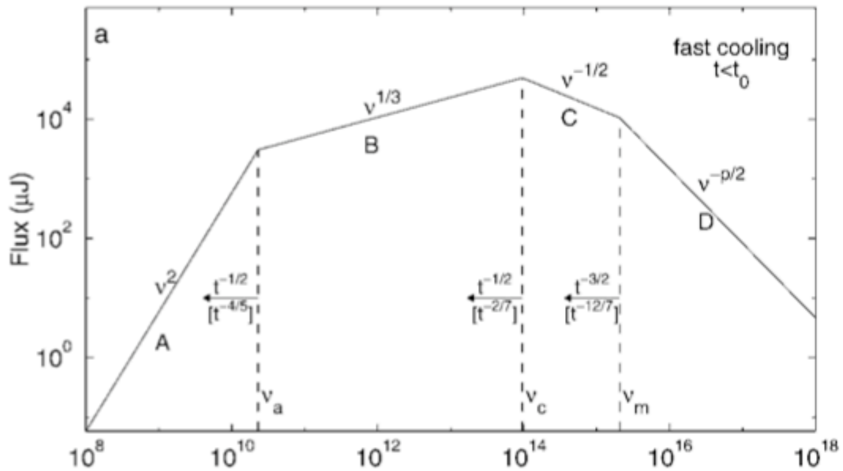
- Bulk Lorentz factor: $\Gamma \approx 763(1+z)^{3/8}(E_{55}/\mathrm{n})^{1/8} t_s^{-3/8}$

- Blast wave radius: $R \approx 1.4 \times 10^{17}(1+z)^{-1/4}(E_{55}/\mathrm{n})^{1/4} t_s^{1/4}$ cm

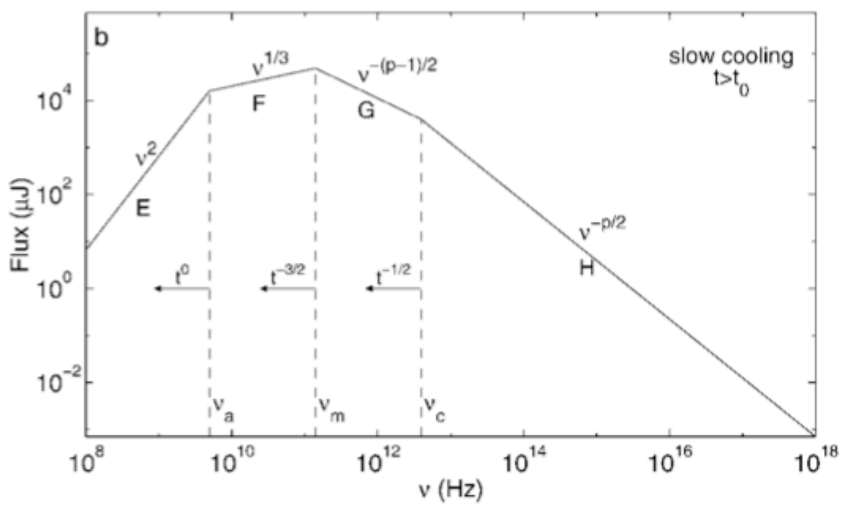
- Energy injection rate in the forward shock: $e_{shock} = 4\pi n m_p c^2 \Gamma^2$

- Magnetic field in the FS: $B' \approx 300(1+z)^{3/8} \varepsilon_B^{1/2} (E_{55}\mathrm{n}^3)^{1/8} t_s^{-3/8}$ G

Synchrotron Radiation in Afterglow Phase



Sari, Piran & Narayan 1998



Fast cooling : $\nu_m > \nu_c$

$F_\nu \propto \nu^{-\beta} t^{-\alpha}$ closure relations

$$\nu_c < \nu < \nu_m : F_\nu \propto \nu^{-1/2} t^{-1/4}$$

$$\nu > \nu_m > \nu_c : F_\nu \propto \nu^{-p/2} t^{-(3/4)(p-2/3)}$$

p-particle spectral index : $\dfrac{dN}{dE} \propto E^{-p}$

Slow cooling : $\nu_c > \nu_m$

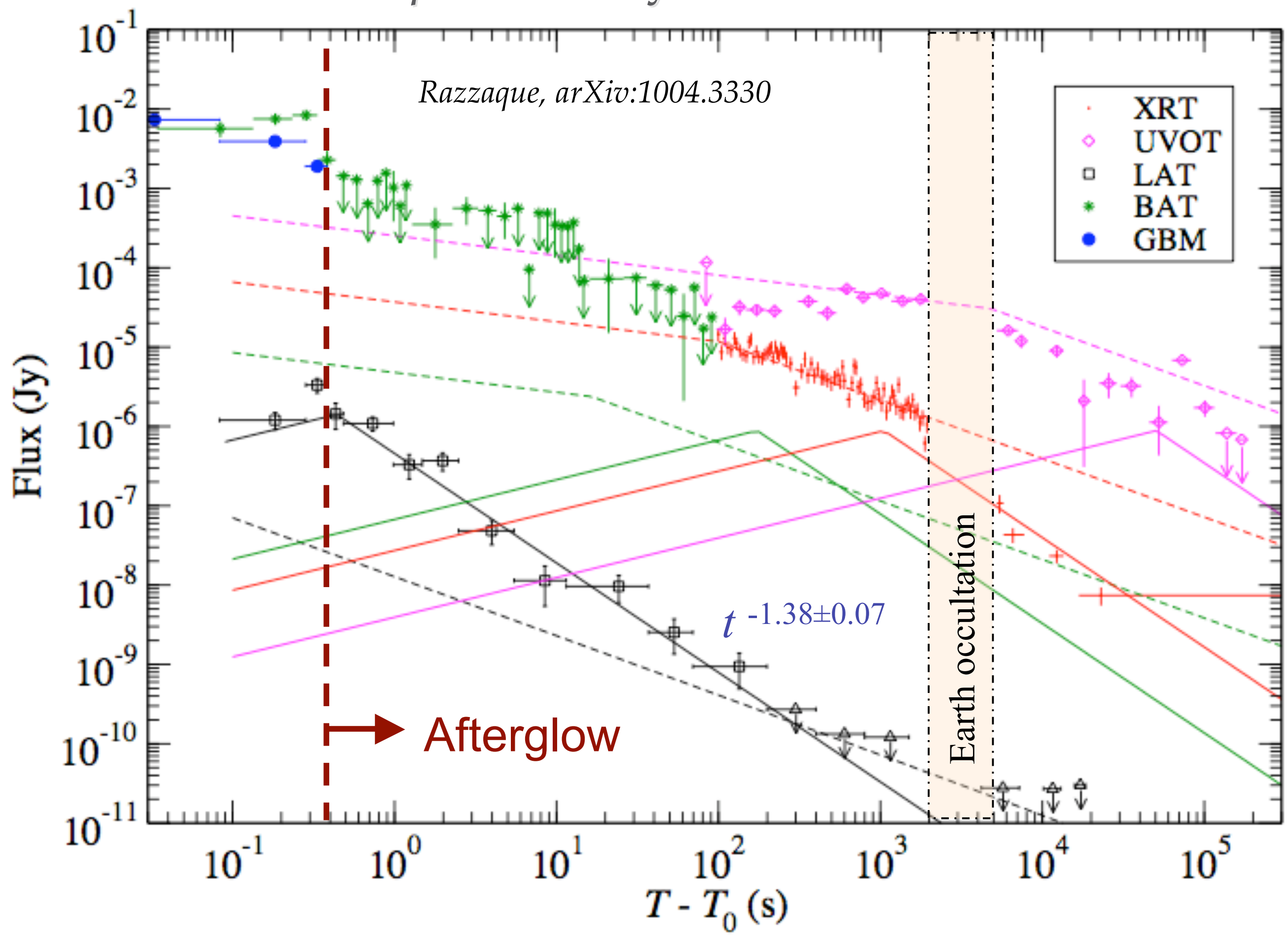
$F_\nu \propto \nu^{-\beta} t^{-\alpha}$ closure relations

$$\nu_m < \nu < \nu_c : F_\nu \propto \nu^{-(p-1)/2} t^{-(3/4)(p-1)}$$

$$\nu > \nu_c > \nu_m : F_\nu \propto \nu^{-p/2} t^{-(3/4)(p-2/3)}$$

GRB 090510: Leptonic-Hadronic Model

Multi wavelength light curve in γ ray, x ray and UV fitted with *p*- and *e*- synchrotron radiation from afterglow



Smooth power-law evolution of the fluxes indicate their origin from afterglow

p-synchrotron radiation (solid) produces >100 MeV LAT data

e-synchrotron radiation (dashed) produces XRT and UVOT data

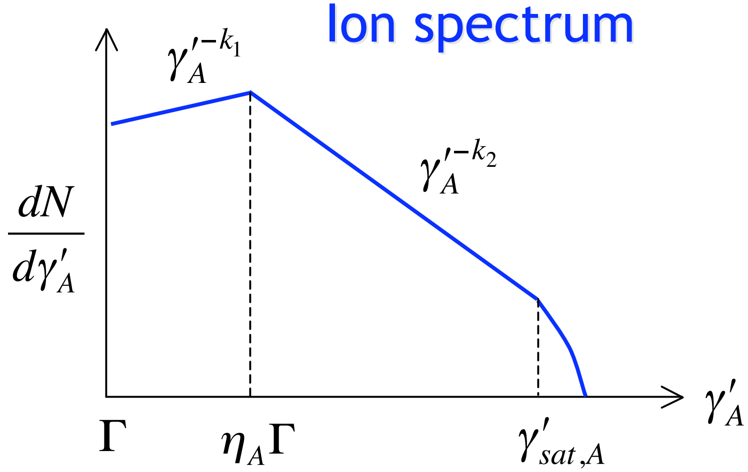
Requires ~100 times more energy in the jet than in observed g rays

Leptonic-Hadronic Synchrotron Model

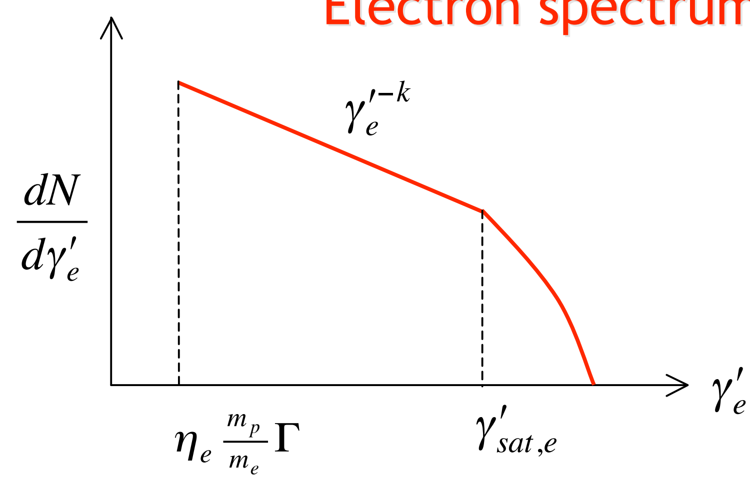
Both electrons and ions are accelerated in the Forward shock

- Total isotropic-equivalent jet energy : $E_{\rm k,iso} > E_{\gamma,\rm iso} \cong 10^{53}$ ergg
- Constant density surrounding medium : $n_{\rm ISM} \cong 1\ {\rm cm}^{-3}$
- Jet deceleration time scale : $t_{\rm dec} \leq 1$ s and $\Gamma_0 \geq 1000$ ← $\geq \Gamma_{\rm min}$ (from $\gamma\gamma$ Opacity calculation)

Ion spectrum



Electron spectrum



- Crucial parameters: ε_B; η_A, η_e, k and k_2 are fitted from data
- Fraction of jet energy: ε_A and ε_e are calculated from required spectra

Modeling GRB 090510 Multiwavelength Data

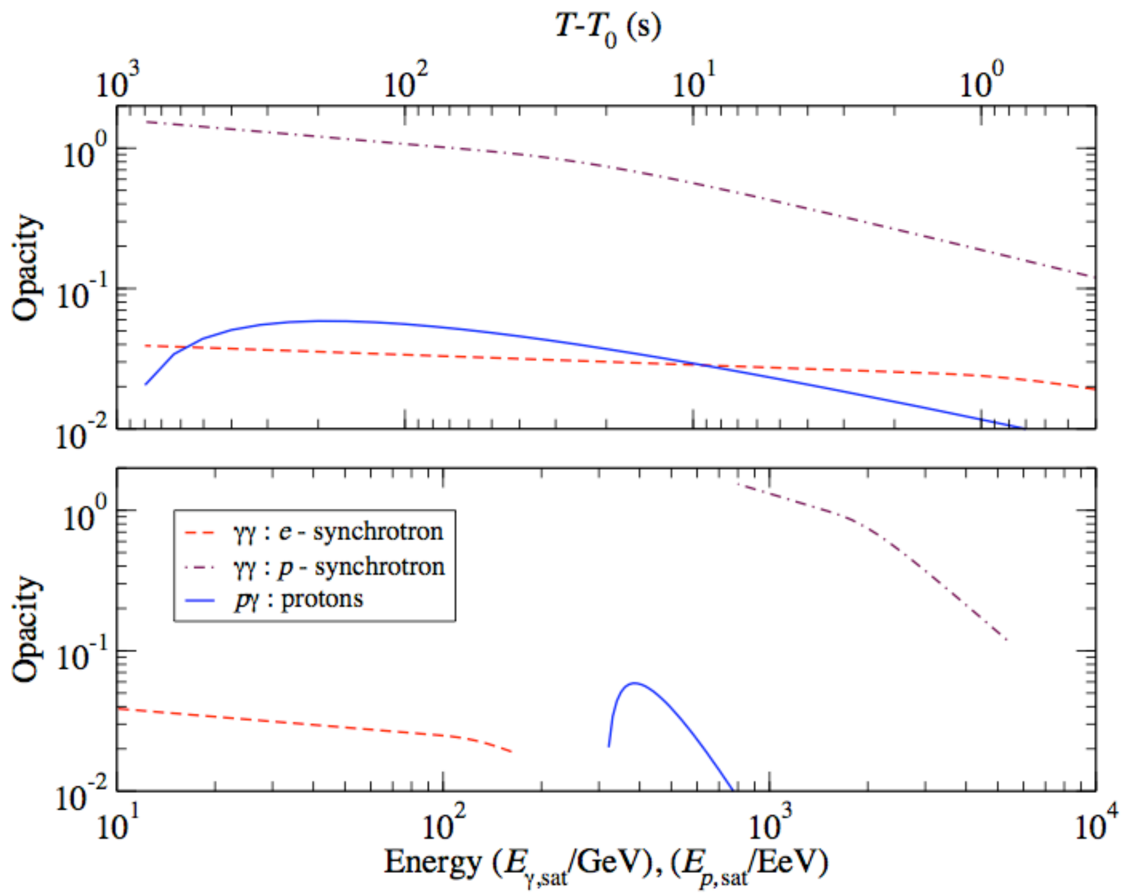
Use closure relations $F_\nu \propto \nu^{-\beta} t^{-\alpha}$ to determine β and k or k_2

Note: e-synchrotron model alone cannot satisfy the closure relations

- XRT light curve: $t^{-0.74\pm0.03}$ in between ~100 s and 1.4 ks
  - Model with e-synchrotron in the fast-cooling and for $\nu_{XRT} > \nu_{m,e} > \nu_{c,e}$
  - $k = (4/3)\alpha_{XRT} + 2/3 = 1.65 \pm 0.04$; $\beta_{XRT} = k/2 = 0.83 \pm 0.02$
- LAT light curve: $t^{-1.38\pm0.07}$ in between ~0.3 s and 100 s
  - Model with p-synchrotron in the slow-cooling and for $\nu_{m,p} < \nu_{LAT} < \nu_{c,p}$
  - $k_2 = (4/3)\alpha_\gamma + 1 = 2.84 \pm 0.09$; $\beta_\gamma = (k_2 - 1)/2 = 0.92 \pm 0.05$
  - β_γ needs to be compatible with measured LAT photon index (and it is)
- Parameters such as n_{ISM} and Γ_0 are mainly constrained by $t_{dec} \leq 0.3$ s
- Parameters such as $E_{k,iso}$, ε_B , η_e , η_p are set to produce required fluxes
- Parameters ε_e , ε_p are calculated from other parameters and constrained <1
- UVOT light curve is constrained by XRT (e-synchrotron)
- BAT light curve can not be fitted ➔ continued central engine activity

GRB 090510: TeV Signature

Opacities for γγ pair production and photopion production for maximum energy particles

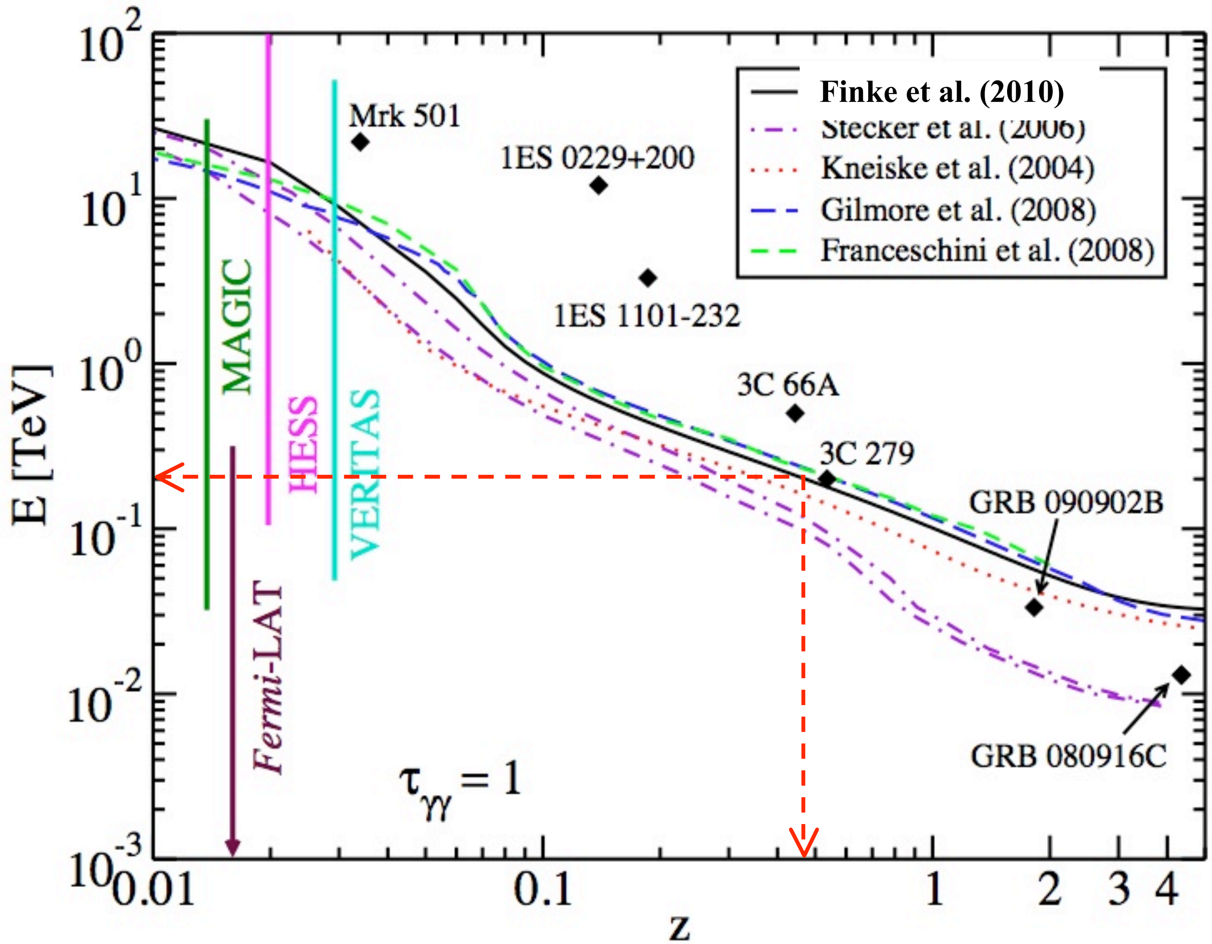


- ➔ synchrotron photons are targets for γγ and $p\gamma$
- ➔ maximum e-sync. photon ~100 GeV
- ➔ maximum p-sync. photon >1 TeV
- ➔ γγ pair production can only be marginally important

Ground-based detectors can probe p-synchrotron model

Detectability of >100 GeV γ rays

Extragalactic Background Light (EBL) limits distance of the source



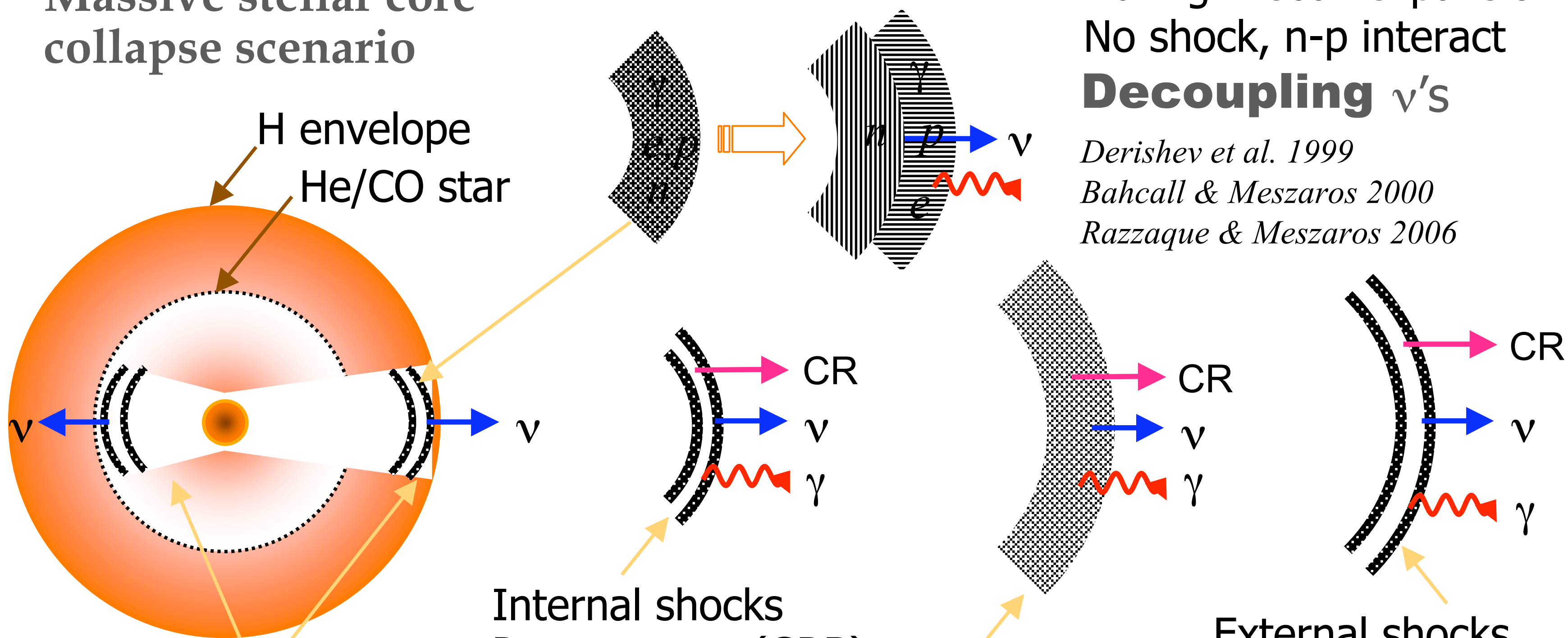
GRBs up to z ~ 0.5 can be detected at ≤ 200 GeV

See talk by Luis Reyes and poster by Silvia Raino for *Fermi* LAT constraints on EBL

Finke, Razzaque & Dermer 2010

High-energy Neutrinos from GRBs

Massive stellar core collapse scenario



During fireball expansion
No shock, n-p interact
Decoupling ν′s

Derishev et al. 1999
Bahcall & Meszaros 2000
Razzaque & Meszaros 2006

Buried shocks
No γ-ray emission
Precursor ν′s

Razzaque, Meszaros & Waxman 2003

Internal shocks
Prompt γ-ray (GRB)
Burst ν′s

Waxman & Bahcall 1997
Dermer & Atoyan 2003

Supernova shell
GRB after SN
Supranova ν′s

Razzaque, Meszaros & Waxman 2003

External shocks
Afterglow X,UV,O
Afterglow ν′s

Waxman & Bahcall 2000
Dai & Lu 2000

High Energy GRB ν Detection Prospects

- Neutrinos are very weakly interacting ➔ only 10^{-6} probability at ~TeV energy
- UHECRs need to interact with soft photons in the GRB to make ν's ➔ high opacity

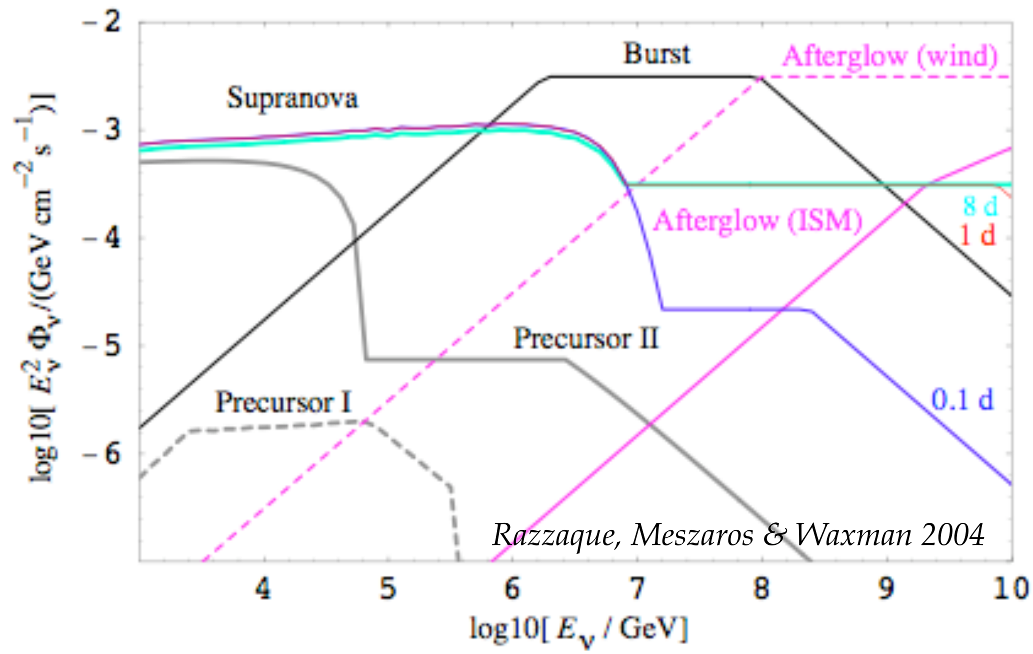
Nearby (z<0.5) bright GRBs with high variability (~1 ms) are the best bet candidates for neutrino telescopes

Projected ν events for IceCube		
Flux model	ν_μ	$\nu_e+\nu_\tau$
Precursor II (H)	4.1	1.1
Burst/prompt	3.2	0.3
Afterglow (ISM)	-	-
Afterglow (wind)	0.1	-
Supranova (~1 d)	13	2.4

GRB 030329/SN 2003dh

Typical long duration GRB with bright SN

~10^{51} ergs/s luminosity at redshift $z = 0.17$



Neutrino flux models:

Dai & Lu 2000 (afterglow wind)

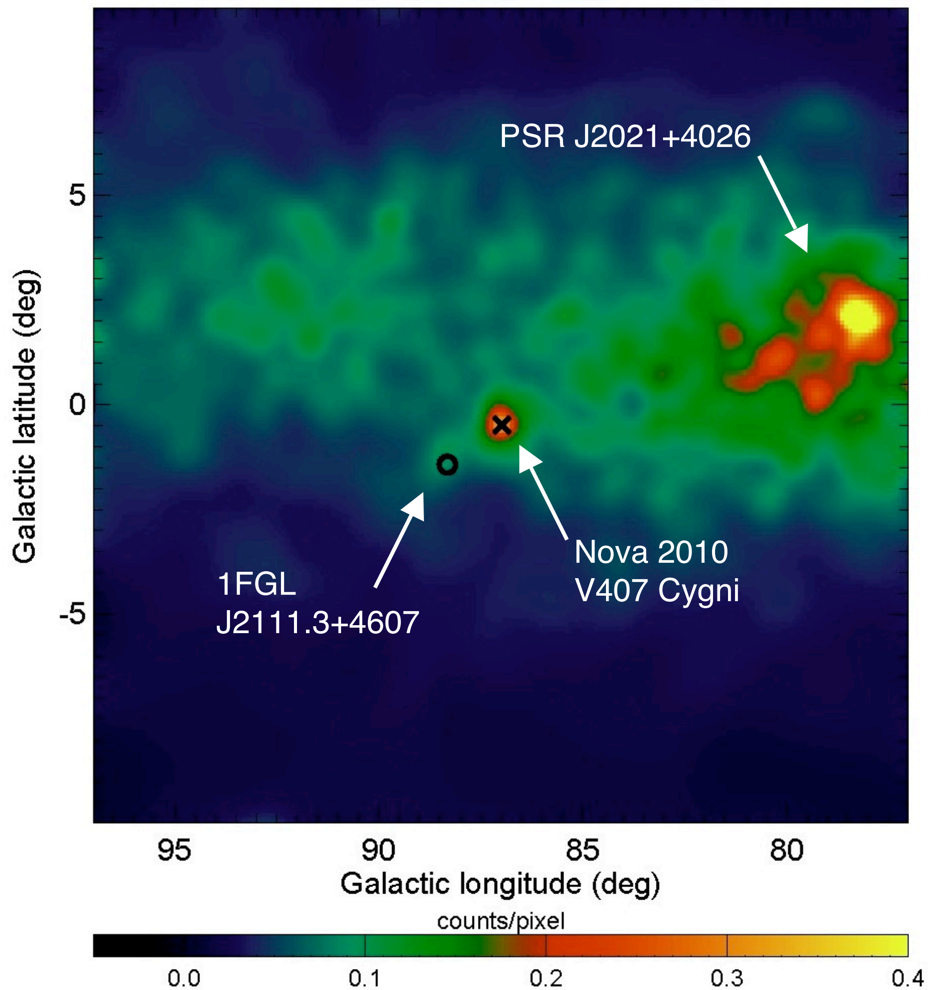
Razzaque, Meszaros & Waxman, PRL 2003 (supranova)

Razzaque, Meszaros & Waxman, PRD 2003 (precursor)

Waxman & Bahcall 2000 (afterglow ISM)

Waxman & Bahcall 1997 (burst/prompt)

Fermi LAT Discovery of Nova in V407 Cygni



March 10, 2010

- *Fermi* LAT found the nova in routine LAT processing for transients
- Initially, counterpart was unknown
- Later developments established:
  - First γ-ray detection of any nova
  - First clear γ-ray detection of *any* source associated with a white dwarf (in binary system)

Cheung *et al*, ATEL 2487

Fermi LAT publication:
Science, **329**, 817 (2010)

See talk by Teddy Cheung for details of *Fermi* LAT γ-ray data

10 GeV ν's from V407 Cygni?

Adopt the π^0 model for γ rays

- $\pi^{\pm}$ are also produced in *pp* interactions
- Neutrinos are produced through decays

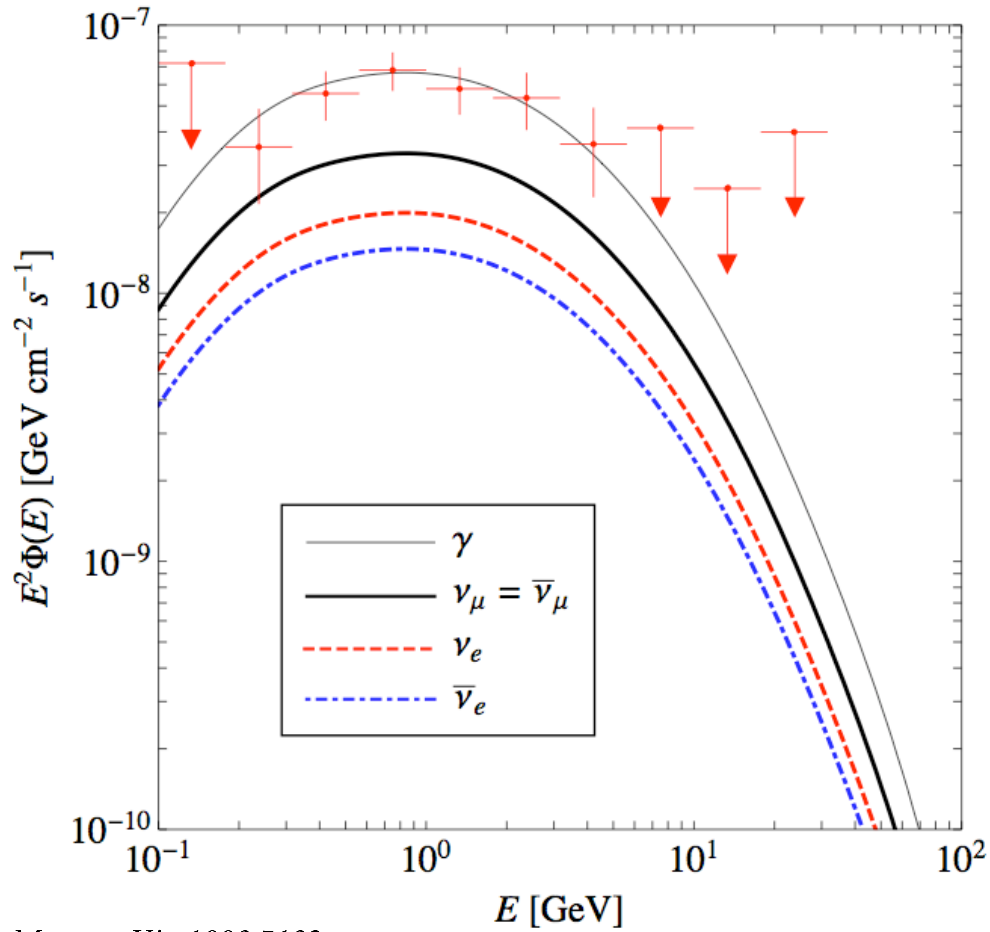
  $\pi \rightarrow \nu + \mu$

  $\rightarrow e + \nu + \nu$
- Expected ν fluxes of different flavors can be calculated using observed γ-ray flux
- 10 GeV ν fluence over the transient lifetime $\sim 10^{-4}$ erg

  $\geq$100 MeV γ ray fluence

  $\sim 3\times10^{-3}$ erg cm^{-2}

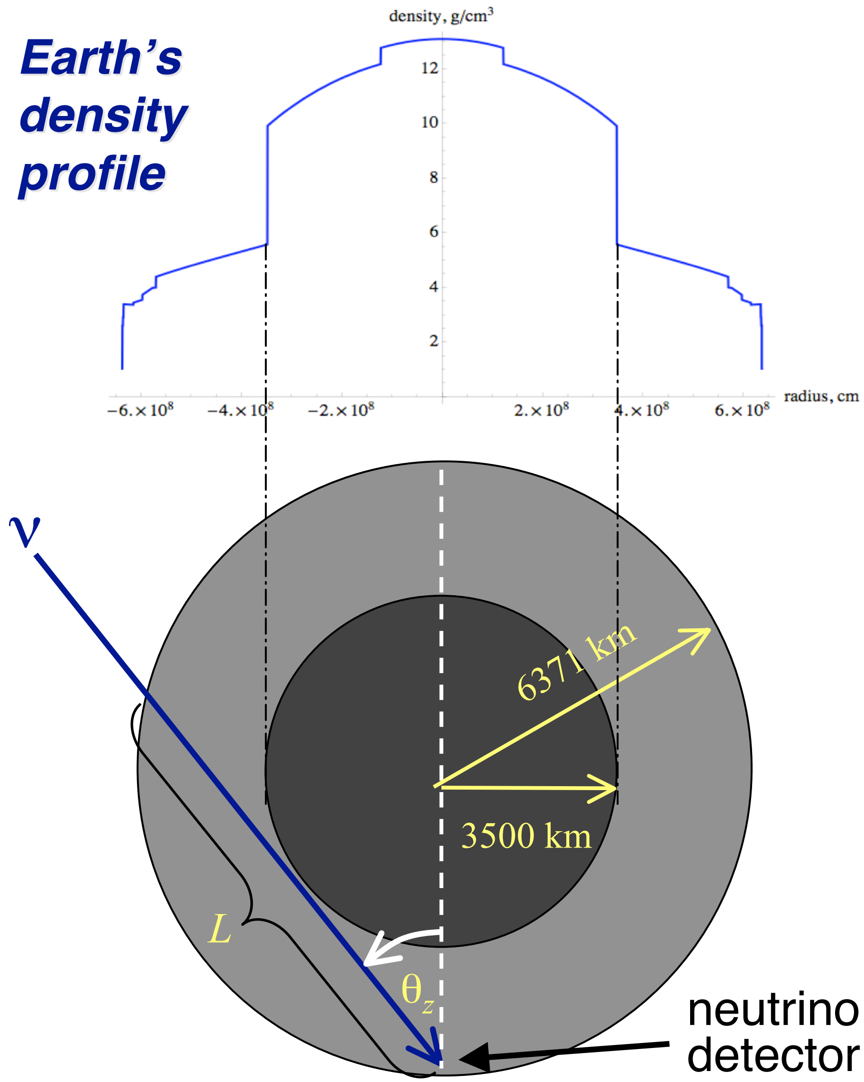
γ ray and ν spectra (15 day average)



Razzaque, Jean & Mena, arXiv:1008.5193

Neutrino Oscillation

Earth's density profile



Creation and detection of ν's at separate places allow them to change their "flavors" from creation to detection

- ν's are created with definite flavors $\alpha = e, \mu, \tau$
- ν's propagate with definite mass states $i = 1, 2, 3$
- α and i states are mixed while propagation in vacuum and in matter (*Mikheyev-Smirnov-Wolfenstein effect*)
- neutrinos are mostly affected by matter for normal mass hierarchy $m_1/m_2 < m_3$
- antineutrinos are mostly affected by matter for inverted mass hierarchy $m_1/m_2 > m_3$

Conversion of ν fluxes at Detectors

ν flavor conversion probability
in vacuum and inside the Earth

$$P_{\nu_\alpha \to \nu_\beta} = \sum_i P^{\rm src}_{\nu_\alpha \to \nu_i} P^{\oplus}_{\nu_i \to \nu_\beta}$$
$$= \sum_i |U_{\alpha i}|^2 |\sum_\eta A^{\oplus}_{\beta\eta} U_{\eta i}|^2$$

e.g., Razzaque & Smirnov 2010

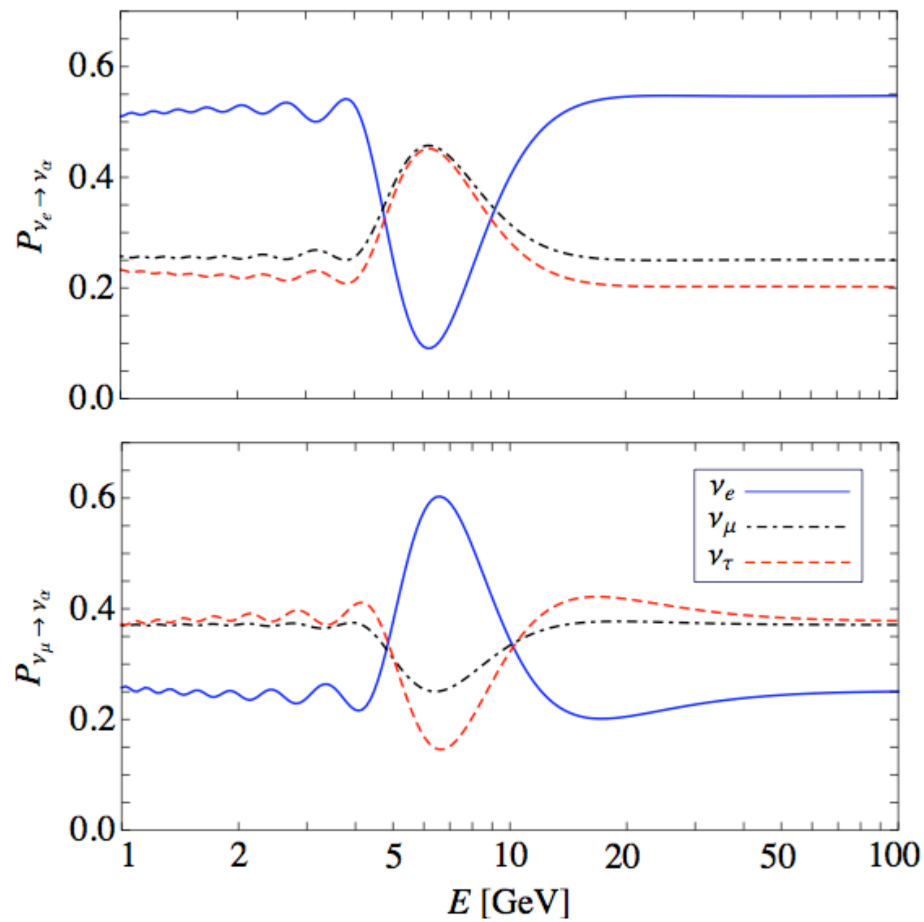
Detail calculation depends on

- V407 Cygni direction (*DEC* = 45.7°)
- ν oscillation parameters
- Earth's density profile model

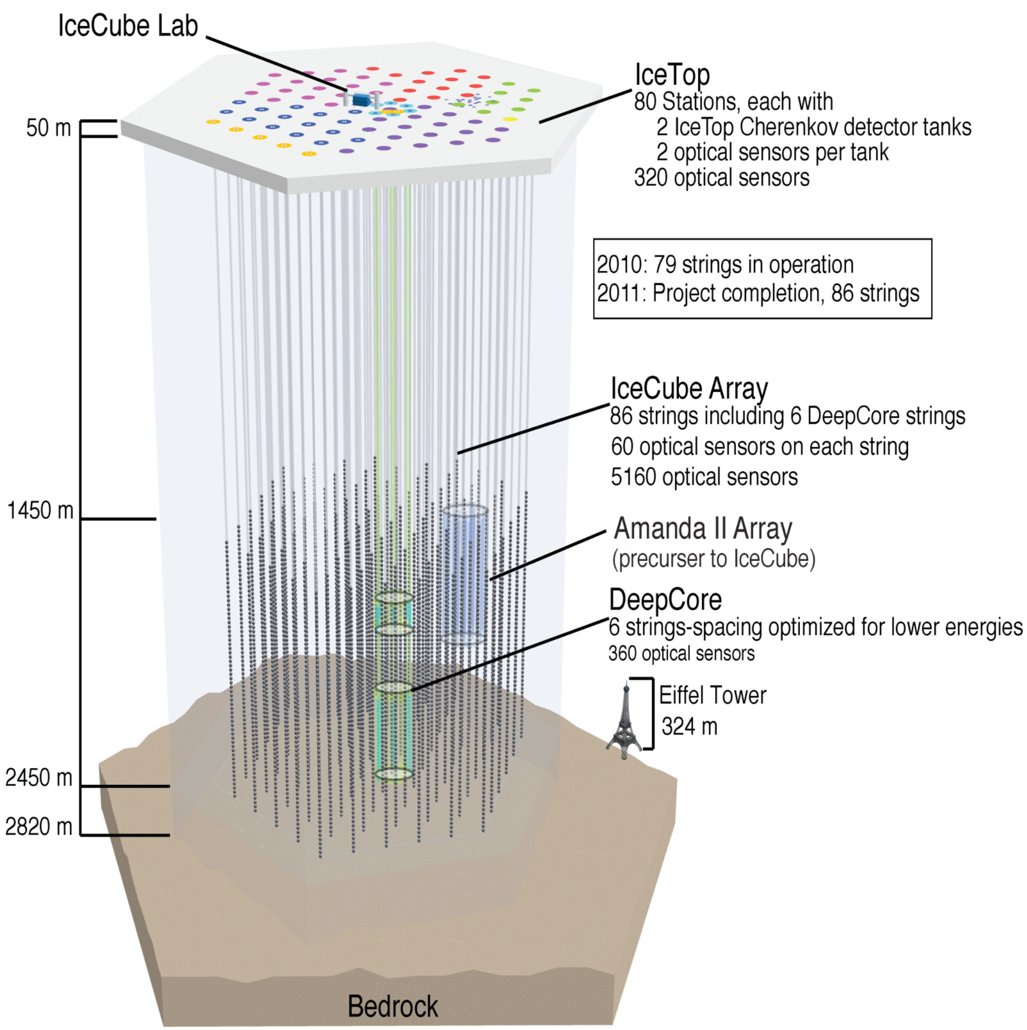
ν flux at a detector at the
South Pole looking "down"

$$\Phi^{\rm det}_{\nu_\alpha} = \Phi^{\rm src}_{\nu_\mu} P_{\nu_\mu \to \nu_\alpha} + \Phi^{\rm src}_{\nu_e} P_{\nu_e \to \nu_\alpha}$$

Numerical calculation



IceCube Deep Core Sub Array



≥10 GeV ν Detector at the South Pole

- 13 “strings” at the core of the IceCube array
- 6 strings with closely spaced (7-10 m) HQE digital optical modules
- allow detection of ν’s down to ~10 GeV
- Detection volume ~10 Mt

Fully operational and taking data since ~31st March, 2010

ν events at 10 Mt Deep Core from V407 Cyg

Neutrino-nucleon interactions in the detector volume produce a detectable muon (electron and tau as well)

$$N_{\nu_\alpha} = \frac{N_{\rm T} t}{V_{\rm det}} \int dE_\nu \int d\Omega \; V_{\rm eff}(E_\nu, \Omega) \times \left[\sigma_\nu^{\rm cc}(E_\nu)\Phi_{\nu_\alpha}^{\rm det}(E_\nu,\Omega) + \sigma_{\bar\nu}^{\rm cc}(E_\nu)\Phi_{\bar\nu_\alpha}^{\rm det}(E_\nu,\Omega)\right]$$

$$N_{\nu_\mu} \approx 0.5^{+4.4}_{-0.4} \;,\; N_{\bar\nu_\mu} \approx 0.3^{+2.3}_{-0.2} \;; \quad 10 \le E_\nu/{\rm GeV} \le 100$$

Atmospheric background in ~15 days

$$N(\nu_\mu) + N(\overline{\nu}_\mu) \sim 60 \; (\Delta\theta \sim 10^{\rm o})$$
$$\sim 160 \; (\Delta\theta \sim 30^{\rm o})$$

- Depends on angular resolution
- Can be smaller if most ν's come within <15 days

Summary

- We have explored best-bet sources of UHECRs
  - Total power output in local universe within GZK volume required for observed spectrum
    - *Radio galaxies, BL Lacs and Starburst galaxies*
    - *Gamma Ray Bursts with large baryon loading*
  - Total power per source for acceleration to 10^{20} eV
    - *Gamma Ray Bursts easily accelerates p and Fe*
    - *Most blazars can accelerate p and Fe*
    - *Radio galaxies may only accelerate Fe*
- We also explored γ ray emission from UHECRs from GRBs
  - May explain >100 MeV radiation detected with Fermi LAT
  - Requires large baryon loading, energetically less favorable
- High-energy neutrinos from UHECRs in GRBs
  - May be detectable from nearby GRBs
  - > 0.1 GeV neutrinos are expected from the Nova 2010 in V407 Cygni
  - *If* observed γ rays are created by π^0 decays
  - Test of leptonic vs. hadronic model of γ ray production