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Astrophysics of High-Energy Cosmic Rays, Photons, and Neutrinos

The Knee and Beyond

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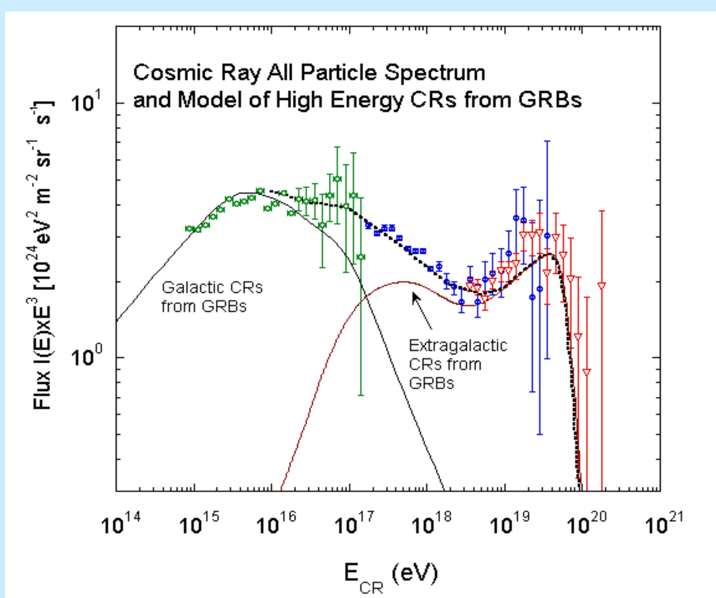
Simulations of cosmic ray transport in the Galaxy (this url)
(astro-ph/0504158, ApJL, submitted)

Model: GRB origin of CRs *at* and *above* the knee

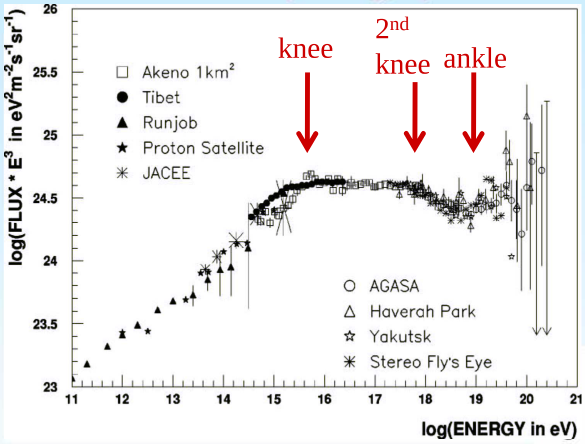
- Cosmic Rays below ≈ 10^{14} eV from SNe that collapse to neutron stars
- Cosmic Rays above ≈ 10^{14} eV from SNe that collapse to black holes
  - CRs between knee and ankle/second knee from GRBs in Galaxy
  - CRs at higher energy from extragalactic/ cosmological origin

Power-law transition at second knee



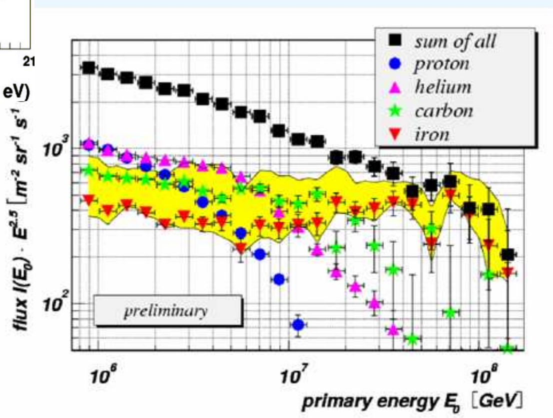
(Wick et al. 2004)

Cosmic Ray Energy Spectrum at High (> 10^{14} eV/nuc) Energies

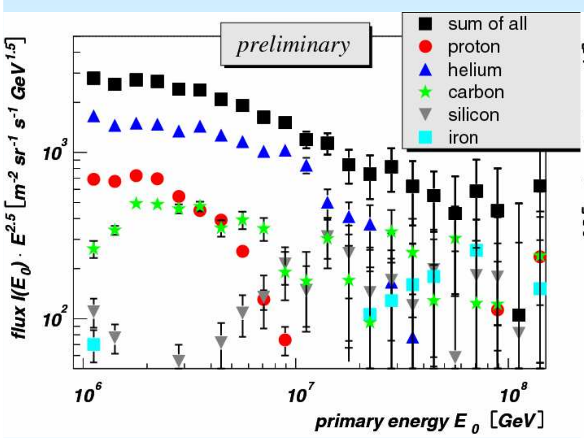


- Steepening above "knee" at ≈ **3×10^{15} eV**
- Second knee at ≈ **$10^{17.4}$ eV**
- Flattening above "ankle" at ≈ **5×10^{18} eV**
- Ultra-high energy cosmic rays (UHECRs) > **5×10^{18} eV**

- Preliminary (2001) KASCADE results on the Knee of the Cosmic Ray Spectrum
- Break in total energy $E \propto Z$ (rigidity; gyroradii $r_L = E/QB$)



KASCADE: Energy spectra for individual elemental groups



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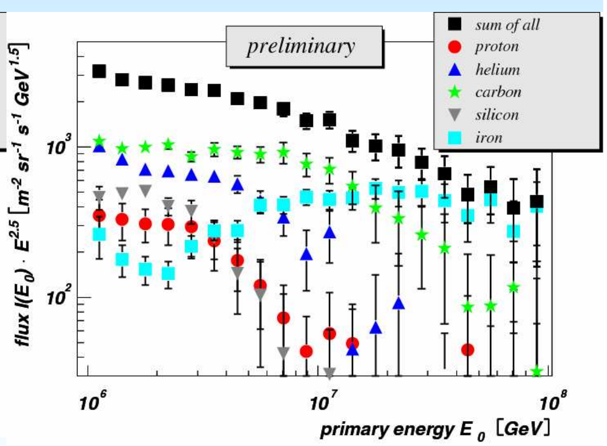


SIBYLL

Hoerandel (2005)

Origin of Cosmic Rays at and above Knee of the Cosmic Ray Spectrum is Unsolved Problem

- **Nonrelativistic first-order shock-Fermi mechanism has difficulties accelerating particles above knee**

$$E_{\max,I} \approx 10^{16} Z B_{\mu G} \beta_0^{2/3} (\frac{m_o}{n_{ISM}})^{1/3} eV$$

Lagage and Cesarsky (1979)

- **Obtain higher maximum particle energies for supernova remnants with faster initial speeds**

  $v_0 = \beta_0 c$ is initial speed of supernova remnant shell; ~10,000 km/s
- **Obtain higher maximum particle energies for supernova remnants with faster initial speeds, magnetic fields** (Völk and Biermann 1988)
- **What are speeds of supernova ejecta?**

Different Types of Supernovae

Type I: no H lines in spectra, Type II: H lines

White Dwarf Detonation

Supernova Ia: $\beta_0 = v_0/c \approx 0.02\text{-}0.1$

Core Collapse Supernova

Supernova II: $\beta_0 \cong 0.005\text{-}0.05$

Supernova Ib: $\beta_0 \cong 0.03\text{-}0.1$ (no H)

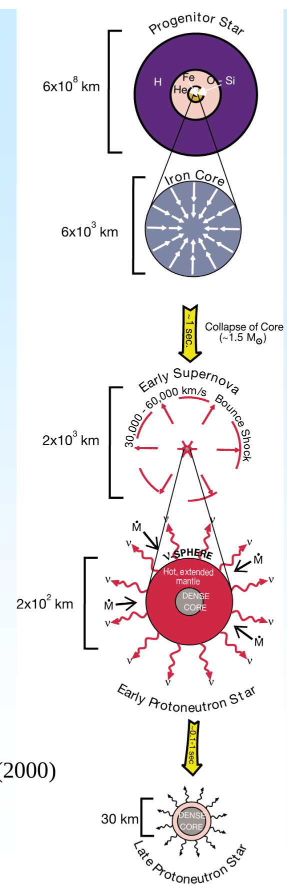
Supernova Ic: $\beta_0 \cong 0.05\text{-}0.5$ (no H, He)

Collapse to neutron star

GRBs: $\beta_0 \cong 1$, $\Gamma_0 \approx 100\text{-}1000$

Collapse to black hole?

- Second-order Fermi acceleration
- Colliding magnetized shells
- Converter mechanism



Burrows (2000)

GRBs in the Galaxy as CR sources:

- **Gamma Ray Bursts: *supernovae collapsing into black holes***
  - **for a beaming factor ~1/500** (Frail et al 2001)
  - **mean gamma-ray energy in X/γ-rays ~ 5×10^{50} *ergs***
  - **powerful accelerators of UHE cosmic rays**
    - (Vietri 1995, Waxman 1995; Dermer 2002)
  - **relativistic shocks/jets with Γ~100-1000 (*beaming*)**
  - **one of (*only*) 2 most probable sources for UHE CRs**

- **Likelihood of a recent (~Myr) GRB in our Galaxy**
  - **From BATSE rate *2 GRB/day***
  - **~ 0.3-1% of SNe collapse into black holes**
  - **⇒ ~1 GRB every ~10 kyrs in the Galaxy**
  - **Expected number of recent GRBs near Earth:**

$$\langle N_{GRB}\rangle \approx (0.45-1.3)\left(\frac{r}{1kpc}\right)^2\left(\frac{t}{1Myr}\right)$$

Implications of steep CR spectra: *propagation effects*

- **CR/proton energy losses:** mostly -dE/dt ∝ E (*below* 10^{18} *eV*),
  no effective radiative losses ∝ E^2 ⇒
  no spectral steepening due to E-losses
- ⇒ **Energy-dependent propagation (*diffusion*)** – the only possibility
  to steepen the source spectra α ~ 2.2 to α_{obs} ~ 2.7-3.0 observed
  Possible if the CR distribution is **non-uniform in space and time**

$$N_{CR.gal}(E) > N_{CR.IG}(E) \quad ; \quad N_{gal}(E) = N(E,t)$$

- **Steep spectra ⇒ local** (‘CR bubble’) , N(E,t) higher than ‘outside’
- For a diffusion coefficient **D(E) ∝ E^{δ} ⇒ N ∝ $E^{-(\alpha+\Delta)}$**

  impulsive source: **Δ = (3/2) δ ,** **δ = 2 –q**

  ***continuous source*:** **Δ = δ** **q is turbulence index**

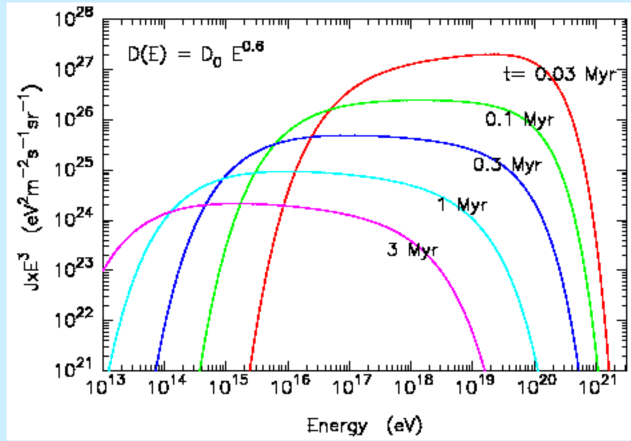
  (q = 5/3: Kolmogorov, q = 3/2; Kraichnan)

CR flux evolution from a local GRB: *simple power-low D(E)*

$$N(E,r,t) \propto r_{dif}^{-3} \exp\left(-\frac{r^2}{r_{dif}^2}\right)$$

$$r_{dif}(E,t) = \sqrt{2D(E)t}$$

(conserves the number of particles in r_{dif}^3)



Injected CR energy: 10^{52} ergs at 1 kpc

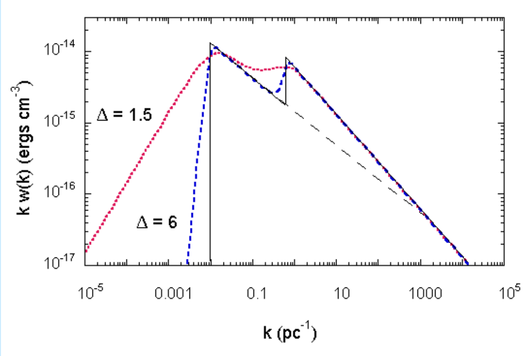
$E_{max}=10^{21}$ erg, $\alpha = 2.2$

D(1 PeV)= 10^{29} cm^2 s^{-1}, δ =0.6

Galactic halo size: 10 kpc

Diffusion of Cosmic Rays due to plasma turbulence

Turbulence injection scales:
~1pc (***SNR***) & **~100pc** (***G. disc***)



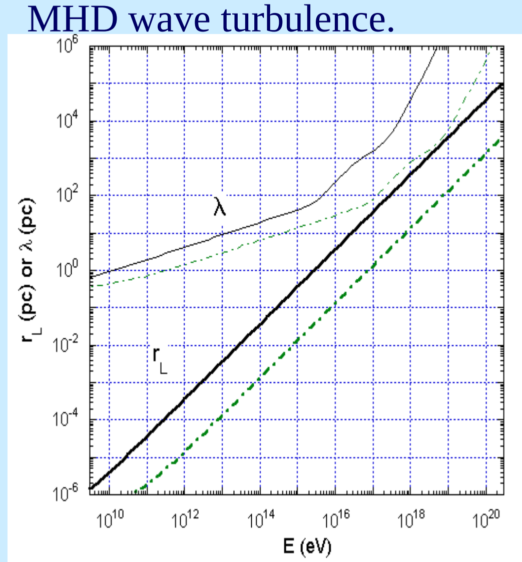
Larmor Radius: $r_L = \frac{mc^2\gamma}{qB} \cong \frac{(\gamma/10^6)}{ZB_{\mu G}}\, pc$

Mean free path λ for deflection by $\pi/2$:

$$\lambda = \frac{U_B}{\bar{k}w(\bar{k})} r_L ; \bar{k} = 1/r_L$$

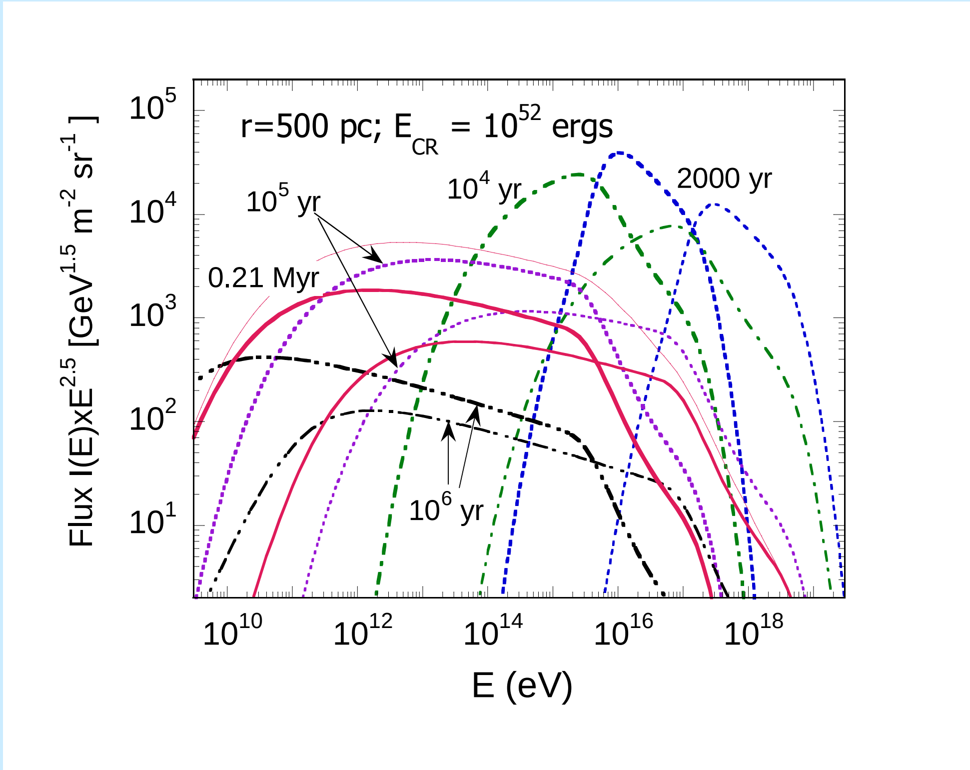
$$(\lambda \propto E^{2-q} \;\; for \;\; w \propto k^{-q})$$

Cosmic rays diffuse through stochastic gyro-resonant pitch-angle scattering with MHD wave turbulence.



(Wick, Dermer, Atoyan 2004)

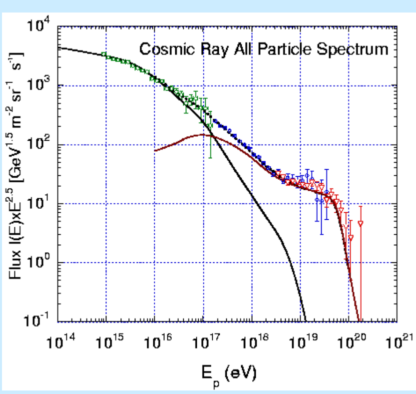
CR flux evolution from a local GRB: *model diffusion coefficient*

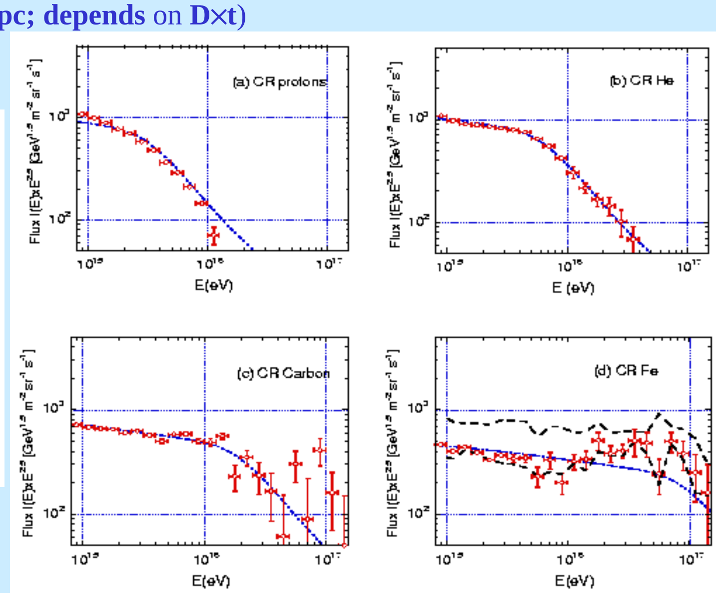


Fits to KASCADE data through the Knee

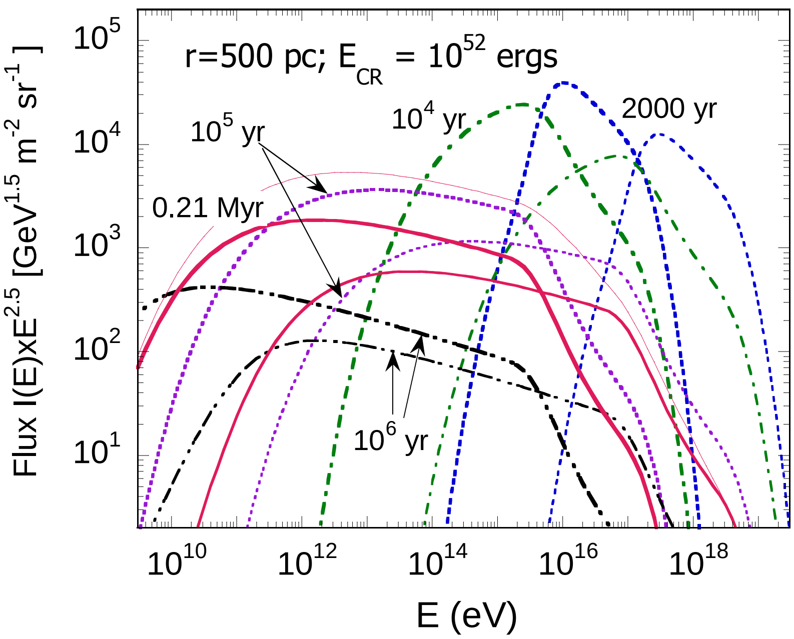
GRB occurred ~2x10^5 years ago at a distance of ~500 pc (Wick et al, 2004)

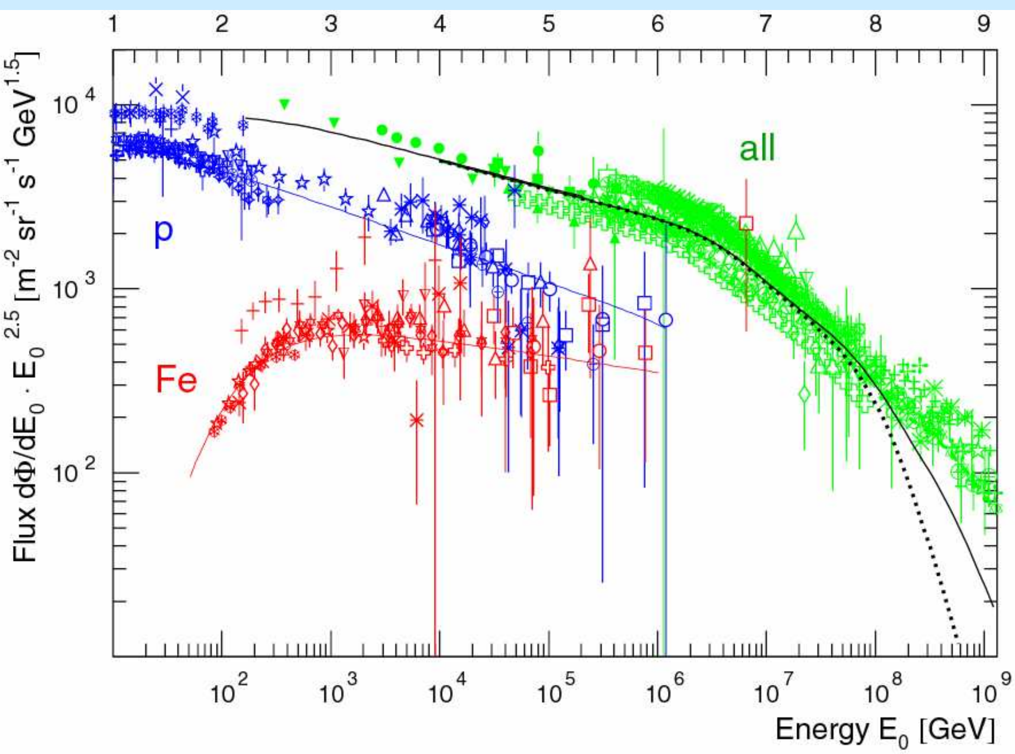
(**similar for t ~1 Myr, at r ~ 1 kpc; depends** on **D×t**)





CR flux evolution from a local GRB: *model diffusion coefficient*





Hoerandel (2005)

Anisotropy of CRs from a ‘single source’:

$$\omega = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \cong \frac{3D\,|grad_r\, N(r,E)\,|}{c\,N(r,E)}$$

(Ginzburg & Ptuskin 1976)

$\Rightarrow$ **for a ‘single-source’ diffusion**

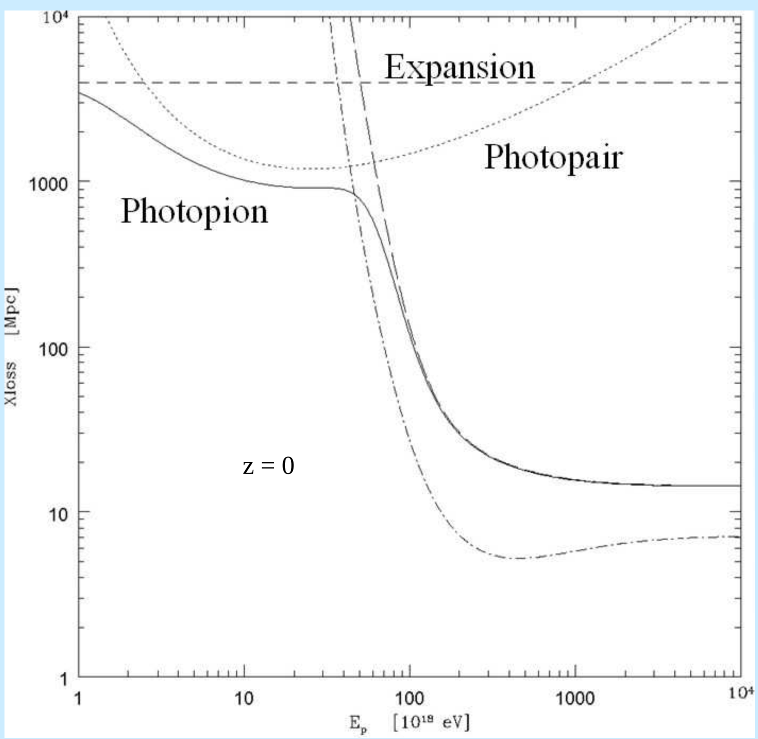
$$\omega = \frac{3r}{2ct} = 0.4\, r_{kpc}\, t_{Myr}^{-1}\,(\%)$$

r* ~0.1% for (e.g.) *r~500pc & t~2Myr

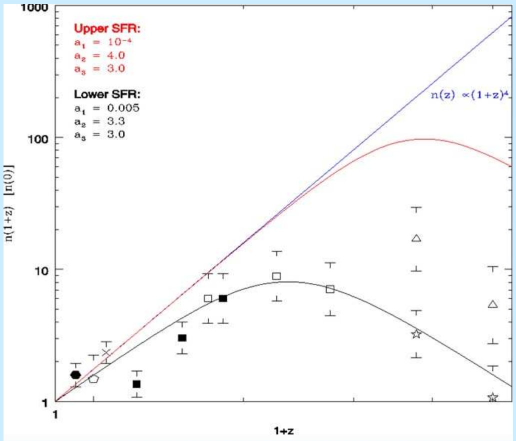
Energy-loss Mean Free Path of UHECR Protons on CMBR Photons

Energy Losses

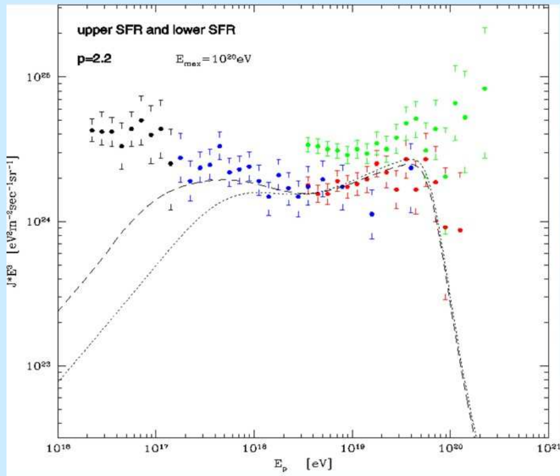
- Photopair
- Photopion
- Expansion



Effects of Star Formation Rate on UHECR Spectrum



Production of the ankle in extragalactic CR spectrum



Assume luminosity density of GRBs follows SFR history of Universe

Pair-production losses on cosmological scales
(also Berezinskii et al 2002)

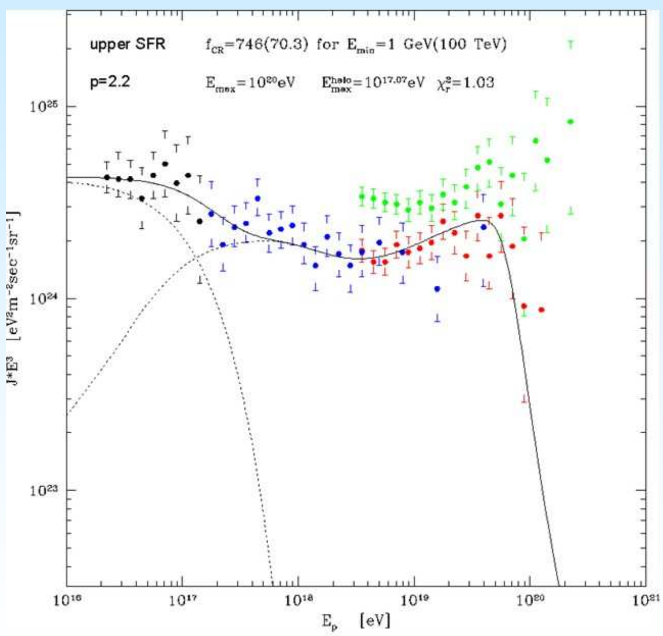
Best Fit to High Energy Cosmic Ray Data

Inject -2.2 spectrum (relativistic shock acceleration index)

Better fit with upper SFR

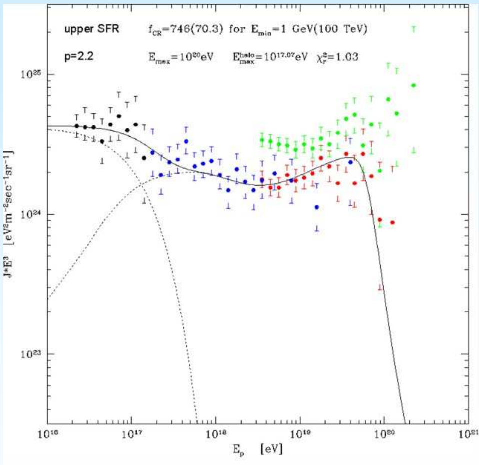
"Second knee" at transition between galactic and extragalactic components

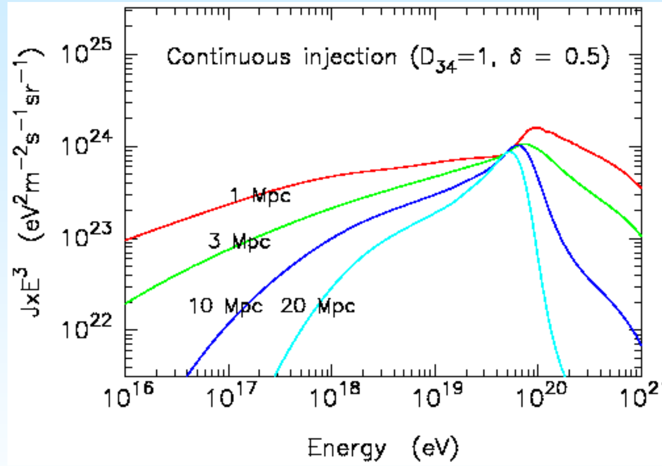
Fits to KASCADE and HiRes data imply local luminosity density of GRBs:



$$(50-200)\times 10^{44}\ ergs/(Mpc^3 - yr)$$

Contribution from *local extragalactic* GRBs (Virgo?) above GZK cutoff ?

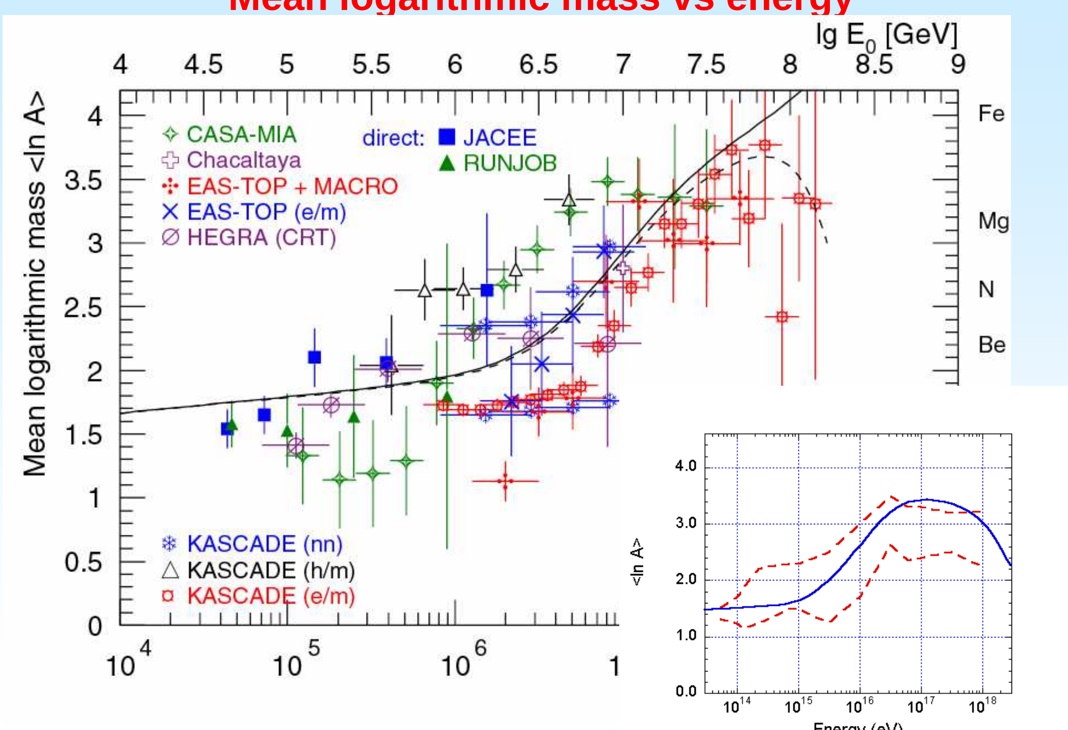




(assumes diffusive propagation)

(calculations by
Armen Atoyan)

Mean logarithmic mass vs energy



Hoerandel, Astropart. Phys. 19 (2003) 193

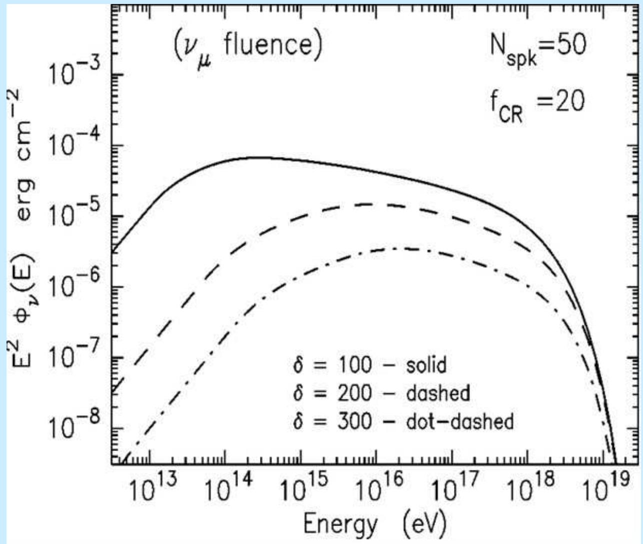
Neutrino Detection from GRBs with Large Baryon-Loading

For a fluence of 3×10^{-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

Nonthermal Baryon Loading Factor f_b = 20

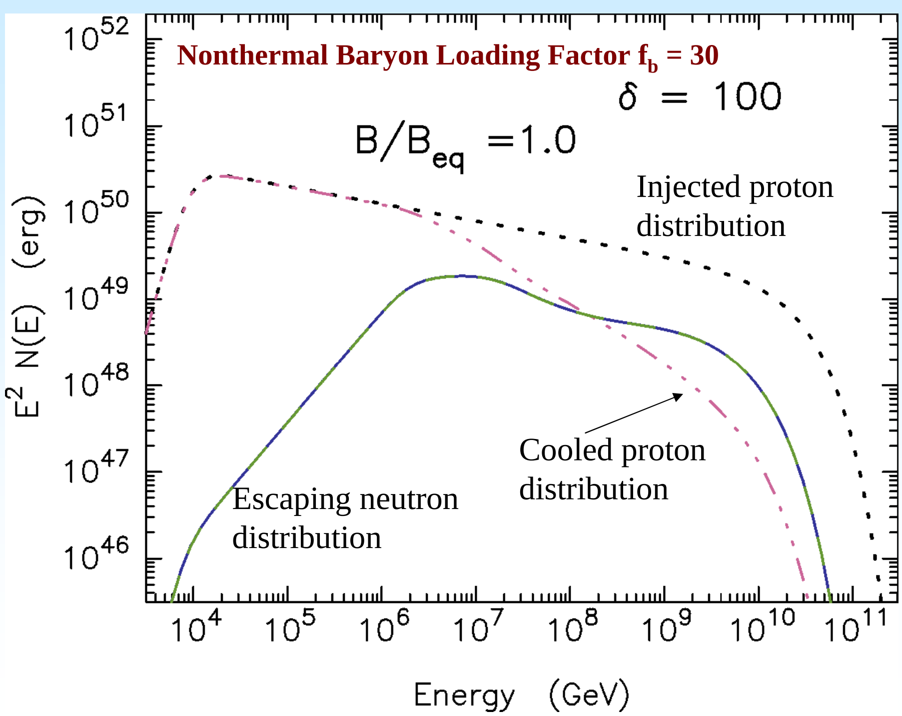


Proton Injection and Cooling Spectra

GRB synchrotron fluence

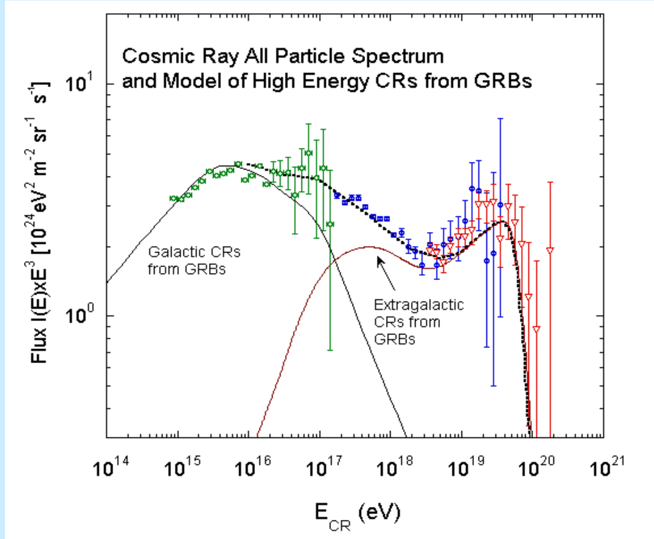
$\Phi_{tot} = 3 \times 10^{-5}$ *ergs cm*$^{-2}$, 50 *one* sec *pulses*

Forms neutral beam of neutrons, γ rays, and neutrinos



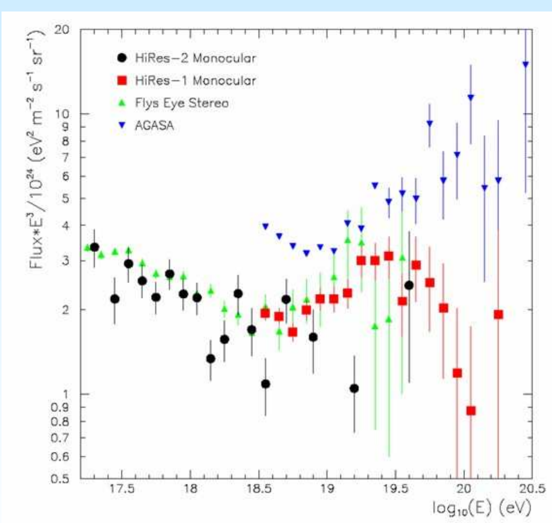
Explanation for High Energy Cosmic Ray Data:

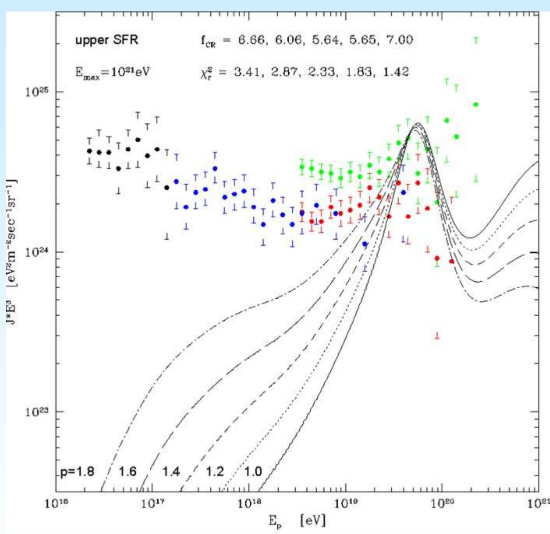
Inject -2.2 spectrum (relativistic shock acceleration); spectral modiffications due to CR scattering on the MHD turbulence



Knee in CR spectrum: results from the **knee** in the spectrum of MHD turbulence in the Galaxy, rigidity dependece of the knee due to interaction with the same spectrum of turbulence.
"Second knee": results from the decline of turbulence with wavelengths >100 pc
transition between galactic and extragalactic components occurs between the second knee and ankle.
Transition to CRs from Galactic SNR occurs at ~100 TeV (or lower)
Fits imply large baryon load: f_b ~ 10-100
Predict detectable neutrino flux from strong GRBs

Fits to AGASA Data





- Fit highest energy points with hard injection spectrum
- Requires other sources for lower energy cosmic rays

- GRB model implies AGASA results not valid
- If correct, points to new physics
- Will be resolved with Auger

Photomeson Cascade Radiation Fluxes

Photon index between −1.5 and −2

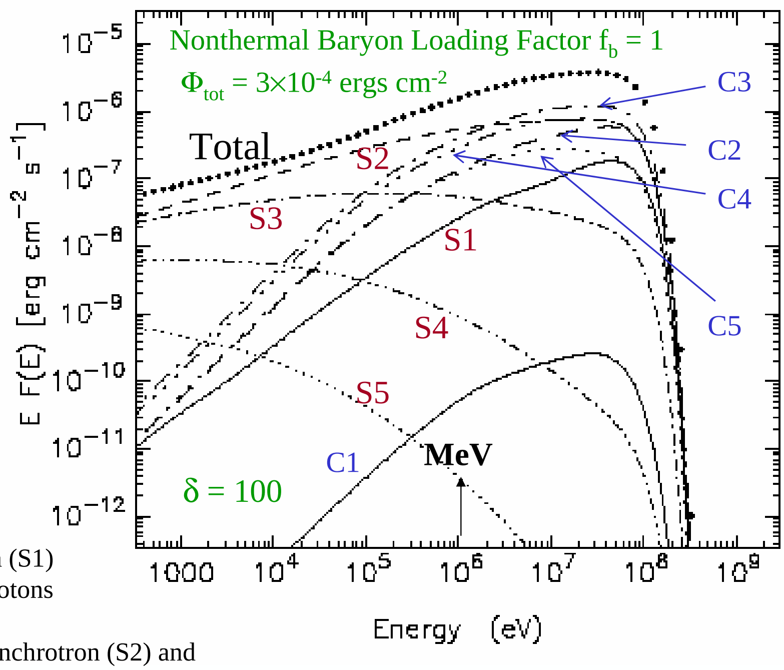
Fits data for GRB 941017 spectrum during prompt phase

Photomeson Cascade:

$p\gamma \to \pi^{\pm} \to e^{\pm}$

$e^{\pm}$ emits synchrotron (S1) and Compton (C1) photons

$\gamma\gamma' \to e^{\pm}$ emits synchrotron (S2) and Compton (C2) photons, etc.

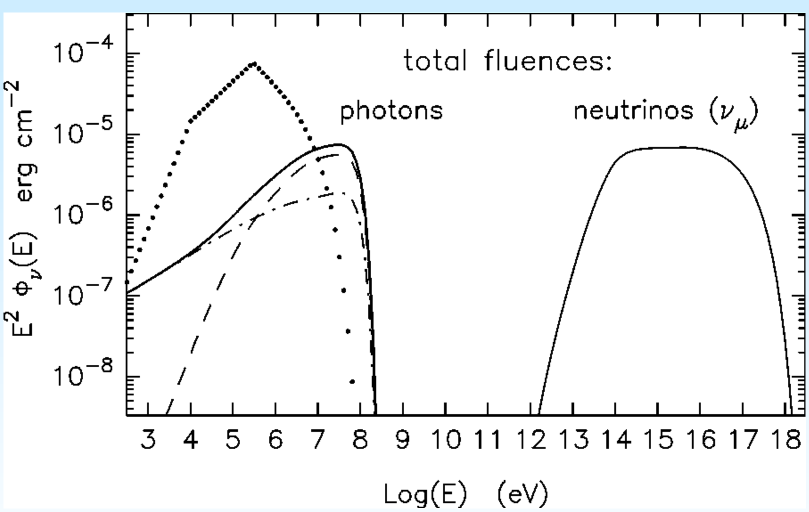


Photon and Neutrino Fluence during Prompt Phase

Nonthermal Baryon Loading Factor f_b = 1

Φ_{tot} = 3×10^{-4} ergs cm^{-2}

δ = 100



Hard γ-ray emission component from hadronic cascade radiation inside GRB blast wave with associated outflowing high-energy neutral beam of neutrons, γ-rays, and neutrinos

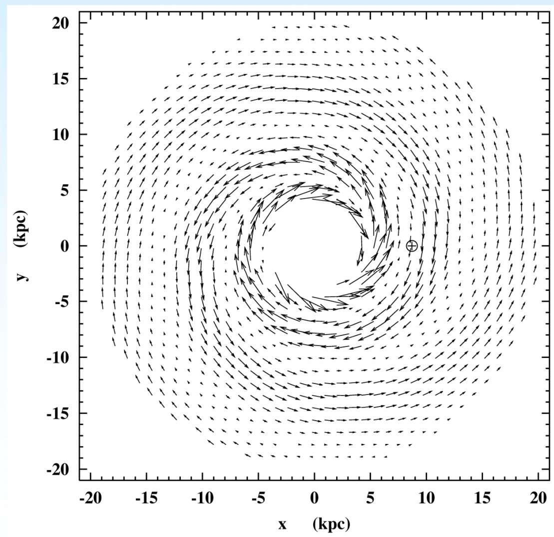
$$p\gamma \to \pi^{\pm} \to e^{\pm}\ (+n, p, \nu)$$
$$\to \pi^{0} \to 2\gamma \to e^{\pm}$$

Magnetic Field Model of the Galaxy

Disk magnetic field:

$$B(r,\phi) = B_o(\frac{R_\oplus}{r})\cos(\phi - \beta \ln \frac{r}{R_o})$$

Alvarez-Muniz, et al. (2000)



The typical Galactic magnetic field near Earth is 3-4 μGauss

Combined finite difference/Monte Carlo simulation for motion of cosmic ray protons and ions, and protons formed from neutron decay.

Rate of Irradiation Events by GRBs

Fluence referred to Solar energy fluence in one second

$$\varphi = S\varphi_\circ = 1.4\times 10^6 S\ ergs\ cm^{-2}$$

$$S > 10^2 - 10^3$$

for significant effects on biology. Using constant-energy reservoir result implies

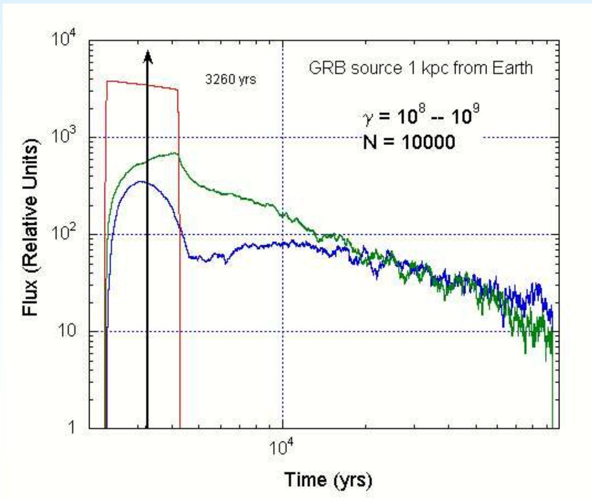
$$\dot{N}(>S) \approx \frac{0.3}{R_{15}^2}\frac{E_{51}}{(S/10^3)t_5}\,Gyr^{-1}\ ,$$

where $10^5 t_5$ yr is the mean time between galactic GRBs, and the GRB distance is

$$R_s(kpc) \approx \frac{1}{(\theta_j/0.1)}\sqrt{\frac{E_{51}}{(S/10^3)}}$$

Flux of Cosmic Rays from GRB Jet Pointed towards the Earth

Fluxes of cosmic ray neutrons, neutron-decay protons, and protons passing near Earth as a function of time for cosmic ray Lorentz factors between 10^8 and 10^9. The source of high-energy cosmic rays is located 1000 parsecs from the Earth, with the GRB jet pointed in our direction.

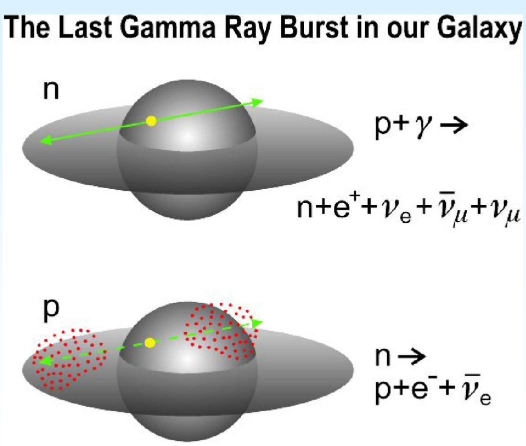


As many as three phases of cosmic ray irradiation are found:

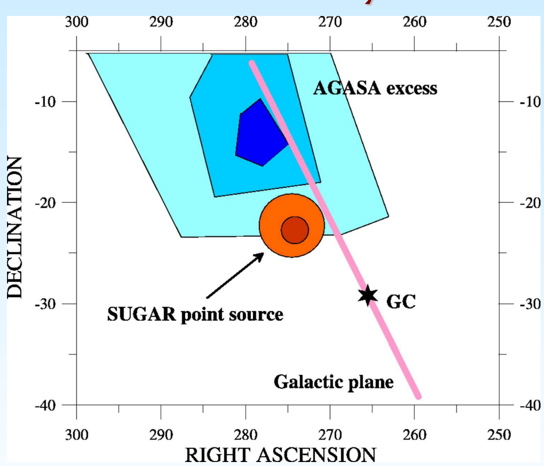
1. Prompt neutron (and gamma-ray) flux,
2. Neutron-decay protons,
3. Cosmic ray protons produced at the GRB source.

Cosmic Ray Sources in the Inner Galaxy

^{18} eV) cosmic ray sources towards the Galactic Center



Medina-Tanco, Biermann et al. (2004)



Duration of a cosmic-ray neutron event from a GRB is short compared to the mean lifetime between GRBs; therefore GRB/Cosmic Ray model predicts ***NO*** SUGAR excess

Summary

- Complete model where Cosmic Rays originate from
  1. SNe that collapse to neutron stars in the Galaxy ($E<\sim 10^{15}$ eV),
  2. SNe that collapse to black holes (GRBs) inject CRs with (10^{14} eV <~ E <~ 10^{20} eV)
     1. SNe that collapse to black holes (GRBs) in the Galaxy (10^{14} eV <~ E <~ 5×10^{17} eV),
     2. Extragalactic SNe that collapse to black holes (GRBs) (E >~ 5×10^{17} eV)
- Structure of Ionic Spectra at Knee consistent with power-law injection modified by propagation; predict composition change at second knee
- GRB/Cosmic Ray model requires that GRBs are hadronically dominated
- High-energy neutrino detection from GRBs only if GRBs are hadronically dominated
- UHECRs from CRs in the Milky Way inconsistent with SUGAR sourdce

Rate of GRBs into Milky-Way--Type (L*) Galaxies

- **BATSE obs. imply ~ 2 GRBs/day over the full sky**
- **Beaming factor increases that rate by factor ~500**
- **Volume of the universe ~ 4π(4000 Mpc)^3/3**
- **Density of L* galaxies ~ 1/(200-500 Mpc^3)**

Rate per L* galaxy

$$\approx \frac{250\ Mpc^3 / L^*}{\frac{4\pi}{3}(4000\ Mpc)^3}\frac{2}{day}\frac{365}{yr}\times 500\, f_{500}\times SFR\times K_{FT}$$

$$\approx \left(\frac{SFR}{1/6}\right)\times K_{FT}\times\frac{f_{500}}{6\times10^{-4}\,yr}\approx f_{500}K_{FT}\ /(18000\,yrs)$$

K_{FT} correction factor for XRFs

∴ 1 GRB in the Milky Way every 10,000 – 100,000 years