Extragalactic Sources of Neutrinos & Ultra-High Energy Cosmic Rays

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Likely Egal UHECR/NU Sources:

AGN

GRB

MGR
GRB: → Hyperaccreting Black Holes (via PNS?)

- NS - NS merger
- BH - NS merger
- BH - WD merger
- NS/BH - He core merger after common envelope
- Collapsar = rotating, collapsing "failed" supernova

Very, very fast jet

0.01 $M_\odot$ torus
0.1 $M_\odot$ torus
1 $M_\odot$ torus
Few $M_\odot$ torus

Short

Long

M. Ruffert, H.-Th. Janka, 1999
Fireball Model of GRBs

Internal Shock
- Collisions between different parts of the flow
- Photospheric thermal radiation
- \( n_p \) decouple

External Shock
- Flow decelerating into the surrounding medium
- Reverse shock
- Forward shock

Several shocks - also possible cross-shock IC

GRB
- \( \approx 10^{11} \) cm

Afterglow
- \( \approx 10^{13} \) cm
- \( > 10^{16} \) cm

\( Mészáros \)
Standard shock $\gamma$-ray components:
shock Fermi acc. of $e^- \rightarrow$ synchrotron and inv.Compton

- GRB 990123 $\rightarrow$ bright ($9^{th}$ mag)
  prompt opt. transient (Akerlof et al. 99).
  - 1st 10 min: decay steeper than forw.sh.
  - Interpreted as reverse shock .....
**SWIFT**

**Three instruments**
Gammaray, X-ray and optical/UV

**Slew time:** 20-70 s!

> 95% of triggers yield XRT det
> 50% triggers yield UVOT det.

**Mission Operations Center:** @ PSU
(Bristol Res. Park)

**BAT:** Energy Range: 15-150 keV
FoV: 2.0 sr
Burst Detection Rate: 100 bursts/yr

**UVOT:** Wavelength Range: 170-650 nm

**XRT:** Energy Range: 0.2-10 keV

Launched Nov 04
**Figure 4 | Schematic of Two-Component Jet Model.** Summary diagram showing spectral and temporal elements of our two-component jet model. The prompt γ-ray emission is due to the internal shocks in the narrow jet, and the afterglow is a result of the forward and reverse shocks from both the narrow and wide jets. The reverse shock from the narrow jet is too faint to detect compared to the bright wide jet reverse shock and the prompt emission. If X-ray observations had begun earlier, we would have detected X-ray emission during the prompt
UHE CRs & $\nu$, $\gamma$ from GRB

$p\gamma$, $pp \rightarrow$ UHE $\nu$, $\gamma$

- If protons present in (baryonic) jet $\rightarrow p^+$ Fermi accelerated (as are $e^-$)

- $p_\gamma \rightarrow \pi^\pm \rightarrow \mu^\pm \nu_\mu \rightarrow e^\pm, \nu_e, \nu_\mu$ (\(\Delta\)-res.: $E_p, E_\gamma \sim 0.3$ GeV$^2$ in jet frame)
  - $\rightarrow E_{\nu, br} \sim 10^{14}$ eV for MeV $\gamma$s (int. shock)
  - $\rightarrow E_{\nu, br} \sim 10^{18}$ eV for 100 eV $\gamma$s (ext. rev. sh.) $\Rightarrow$ ICECUBE

- $\rightarrow \pi^0 \rightarrow 2\gamma \rightarrow \gamma\gamma$ cascade $\Rightarrow$ GLAST, ACTs.. $\Rightarrow$ ICECUBE

- Test hadronic content of jets (are they pure MHD/$e^\pm$, or baryonic …?)

- Also (if dense): $p_\gamma \rightarrow \pi^\pm \rightarrow \mu^\pm, \nu_\mu \rightarrow e^\pm, \nu_e, \nu_\mu$

- Test acceleration physics (injection effic., $\varepsilon_e$, $\varepsilon_B$..)

- Test scattering length (magnetic inhomog. scale?..or non-Fermi?..)

- Test shock radius: $\gamma\gamma$ cascade cut-off:
  - $E_\nu \sim$ GeV (internal shock); $E_\gamma \sim$ TeV (ext shock/IGM)

- $\rightarrow$ photon cut-off: diagnostic for int. vs. ext-rev shock
Fermi

- Launched June 11 2008
- **LAT**: Pair-conv.modules + calorimeter
- 20 MeV-300 GeV, \( \Delta E/E \sim 10\% @ 1 \text{ GeV} \)
- FoV = 2.5 sr (2xEgret), ang.res. \( \sim 30'' - 5' \) (10GeV)
- Sensit. \( \sim 2.10^{-4}\text{ph/cm}^2/\text{s} \) (2 yr; > 50xEgret)
- GBM: FoV \( 4\pi \), 10keV-30MeV
- 2.5 ton, 518 W
- det. \( \sim 200 \text{ GRB/yr (GBM)} \); simult. w. Swift : 30/yr; det. w. LAT : \( \sim 20-25/yr \)

Also on Fermi: **GBM** (~BATSE range);
12 NaI: 10keV-3 MeV; 2 BGO: 150 keV-30 MeV
A bright **LONG** burst:

1) **All spectra approximate Band functions: same mechanism?**

- Could be Synchrotron. No obvious cutoff or a softening $\Gamma \approx 100$; expect also SSC, but this could be $>\rm{TeV}$, not observed
- Since no statistically significant higher energy component above Band, the latter must have either $E \approx \rm{TeV}$ or $Y \sim \varepsilon_e/\varepsilon_B \leq 0.1$

2) **GeV only in 2nd pulse or later, vs. MeV (1st pulse) - Why?**

- Could originate in different region, e.g. a 2nd set of internal shocks, with $\neq$ parameters or physics (possible)
- Or radiation from one set of shells up-scattered by another set of shells? (but no expected delay between 2nd LAT & GBM)
Notice:
GeV photons ← "lag" behind MeV!
GRB 080916C

Spectrum

- “Band” fits (joint GBM/LAT) for all the different time intervals
- Soft-to-hard, to “sort-of-soft-peak-but-hard-slope” afterglow
- No evidence for 2nd component
GRB 080916c
(the Fermi collaboration, 2009)

3) GeV only in 2nd pulse or later, vs. MeV (1st pulse) - Why?

• Hadronic? (the burning question)... natural delay since extra time for cascade to develop - but: expect hard to soft time evolution & distinct sp. component - not seen)

Upshot:
more analysis needed to test hadronic model and/or constrain variant of leptonic model

Future Fermi+Swift+ground observations will tell
GRB 090510

- Fermi LAT/GBM identified *SHORT* burst
- Shows (sim. to long bursts) time *LAG* between soft 1st pulse and hard 2nd pulse
- Shows an *EXTRA* spectral component, besides usual Band component (first clear!)
- *Hadronic?* Maybe...
GRB 090510

Spectrum: clear 2nd comp (5σ)

Abdo, et al. 09 (LAT/GBM coll.)
Nature, subm.
arXiv/0908.1832
Hadronic model: 090510

Asano, Guierec, Mészáros, 09
(arXiv:0909.0306)

Secondaries from photomeson cascades ✔
(but: need $L_{\gamma,\text{iso}} \sim 10^{55}$ erg/s !)

Secondary photons ↑
Secondary neutrinos →
(not detectable, for this burst)
UHE neutrinos from GRB

- Need baryon-loaded relativistic outflow
- Need to accelerate protons (as well as e⁻)
- Need target photons or nuclei with \( \tau \gtrsim 1 \)
  (generally within GRB itself or environment)
- Need \( E_{\text{rel,p}} \gtrsim 10-20 \ E_{\text{rel,e}} \)
- Might hope to detect individual GRB if nearby \( (z \lesssim 0.15) \), or else cumul. background
- If detected, can identify hadronic \( \gamma \) in GRB?
UHE $\nu$ in GRB

Various collapsar GRB $\nu$-sites

- 1) at collapse, similarly to supernova core collapse, make GW + thermal $\nu$ (MeV)
- 2) If jet outflow is baryonic, have p,n
  - $\rightarrow$ p,n relative drift, pp/pn collisions
  - $\rightarrow$ inelastic nuclear collisions
  - $\rightarrow$ VHE $\nu$ (GeV)
- 3) Int. shocks while jet is inside star, accel. protons $\rightarrow p\gamma$, pp/pn collisions
  $\rightarrow$ UHE $\nu$ (TeV)
- 4) Internal shocks below jet photosphere, accel. protons $\rightarrow p\gamma$, pp/pn collisions
  $\rightarrow$ UHE $\nu$ (TeV)
- 5) Internal shocks outside star accel. protons
  $\rightarrow p\gamma$ collisions $\rightarrow$ UHE $\nu$ (100 TeV)
- 6) $\leftarrow$ External rev. shock:
  $\rightarrow p\gamma \rightarrow$ EeV $\nu$ (10$^{18}$ eV)
"Hadronic" GRB Fireballs:
Thermal $p,n$ decoupling $\rightarrow$ VHE $\nu, \gamma$

- Radiation pressure acts on $e^-$, with $p^+$ coming along (charge neutrality)
- The $n$ scatter inelastically with $p^+$
- The $p,n$ initially expand together, while $t_{pn} < t_{exp}$ ($p,n$ inelastic)
- When $t_{pn} \sim t_{exp} \rightarrow p,n$ decouple
- At same time, $v_{rel} \geq 0.5c$ $\rightarrow p,n$ becomes inelastic $\rightarrow \pi^+$
- Decoupling important when $\Gamma \geq 400$, resulting in $\Gamma_p > \Gamma_n$
- Decay $\rightarrow \nu$, of $E_\nu \geq 30-40$ GeV
- Motivation for DEEP-CORE!
While jet is inside progenitor:

\[ \frac{E_p}{\Gamma} \geq 3 \text{ GeV}^2 \]
\[ \Rightarrow E_p \geq 100 \text{ TeV} \]

- \( e_v \geq 10^{12.5} \text{ eV} \)
- \( N_{\nu \rightarrow \mu} = 0.2 \text{ km}^{-2}/\text{Collapse} \) (10\(^3\) GRBs/yr)
- Both “Chocked” and “successful” jets

Meszaros & Waxman 01
GRB 030329: precursor (& pre-SN shell?) with ICECUBE

Burst of $L \sim 10^{51}$ erg/s, $E_{SN} \sim 10^{52.5}$ erg, @ $z \sim 0.17$, $\theta \sim 68^\circ$

Razzaque, Mészáros, Waxman 03 PRD 69, 23001

Razzaque, Mészáros, Waxman 03 PRD 69, 23001
**Internal shock ν’s, contemp. with γ’s**

Detailed ν in diffuse flux incl. cooling, using GEANT4 sim., integrate up to z=7, $U_p/U_\gamma=10$ (left); z=20, $U_p/U_\gamma=100$ (right)

GRB ‘Photospheric’ Neutrinos

- GRB relativistic outflows have a Thomson scattering $\tau_\text{T} \sim 1$ “photosphere”, below which photons are quasi-thermal
- Shocks and dissipation can occur below photosphere.
- Acceleration of protons occurs, followed by pp and pγ interactions → neutrinos
- Gas and photon target density higher than in shocks further out.
- Characteristics resemble precursor neutrino bursts, but contemporaneous with prompt gamma-rays

Wang, Dai 0807.0290

Murase 0807.0919
Crucial parameter for neutrino (and CR) flux is $U_p/E_e$.

Note that $\nu$'s from pion decay are good targets too (not just muon decay).

For typical values, $U_p/E_e \sim 30$ needed to make GRB “interesting” UHECR sources, the neutrino flux might be detectable from individual GRB sources at $z \sim 0.1$ with JEM-EUSO (K. Asano et al, 2008, in prep.)
Semi-relat. ("slow") jets in core-collapse SN?

- Maybe all core coll. (II or Ib/c) SN resemble (watered-down) GRB?
- Evidence for asymmetric expansion of c.c. (Ib/c) SNR:
  - asymmetric remnants
  - optical polarization
  - jets may help eject envelope
- $\rightarrow$ slow jets $\Gamma \sim$ few?
Core collapse SN: slow jets?

- Maybe all core coll. (or Ib/c) SN resemble (watered-down) GRB?
- Evidence for asymmetric expansion of c.c. (Ib/c) SNR: slow jets $\Gamma \sim \text{few}$?
- If so, accel protons while jet inside star, $p\gamma \rightarrow \pi, \mu \rightarrow \nu$ (TeV)
- Diffuse flux: negligible, but
- **individual SN** in nearby (2-3 Mpc) gals, e.g. M82, NGC253, detectable (if have slow jets), at a rate $\sim 1$ SN/5 yr, fluence $\sim 2$ up-muons/SN (hypernova: 1/50 yr, 20 up-$\mu$), negligible background, in $\text{km}^3$ detectors - ICECUBE

Spectrum and diffuse flux ↑

Razzaque, Mészáros, Waxman, 2004, PRL 93, 181101
Ando & Beacom, 2005, PRL 95, 1103
AUGER result:
UHECR spatial correlations with AGN/LSS

- Dashed line: supergalactic equator
- Circles (proton): Events $E > 4.5 \times 10^{19}$ eV
- Crosses: Veron-Cetty catalog AGNs

Science Nov 2007
Auger spatial correlation

Science, 07

- Found $3\sigma$ corr. with V.C. AGNs within 3.5 deg inside 75 Mpc, for 28 events $E > 4.5 \times 10^{19}$ eV
- The above correlation suggest protons
- But cannot say positively it is AGNs - could be correl. with underlying LSS
- Kashti-Waxman confirm correl. with LSS at >98% confidence level, via two-pt corr., ang. power spectr. and predicted-observed coincid.
- If heavy mix: many more gals. inside each event’s larger angular spread.
- **But: AGN significance now (09) weakened to $1.7\sigma$**
**CR Flux & spectrum - GRB**

**Protons**
- Particle spectrum:
  \[ \frac{dn_p}{d\varepsilon_p} \propto \varepsilon_p^{-2} \]
- p energy production:
  \[ \varepsilon_p^2 \frac{dn_p}{d\varepsilon_p} \approx 10^{44} \text{ erg Mpc}^{-3} \text{yr}^{-1} \]

**Electrons**
- \( \gamma \) spectrum
  \[ \frac{dn_\gamma}{d\varepsilon_\gamma} \propto \varepsilon_\gamma^{-2} \]
- \( \gamma \) energy production
  \[ \varepsilon_\gamma^2 \frac{dn_\gamma}{d\varepsilon_\gamma} = \frac{30}{\text{Gpc}^3 \text{yr}} \times 10^{51} \text{ erg} = 0.3 \times 10^{44} \text{ erg Mpc}^{-3} \text{yr}^{-1} \]

**Afterglow \( \longrightarrow \) z distribution**

\[ \varepsilon_\gamma^2 \frac{dn_\gamma}{d\varepsilon_\gamma} = \frac{0.5}{\text{Gpc}^3 \text{yr}} \times 500 \times 0.5 \cdot 10^{51} \text{ erg} = 1.3 \times 10^{44} \text{ erg Mpc}^{-3} \text{yr}^{-1} \]

[Waxman 95]

[Frail et al. 01
Schmidt 01]
GZK CR Sources

- Sources: GRB \(\checkmark\); AGN.... #?
- Rate: \(R_{\text{GRB}} (z=0) \approx 0.5 \text{ Gpc}^3 \text{ yr}^{-1}\)
  \(\approx 0.5 \times 10^{-3} (D/100 \text{ Mpc})^{-3} \text{ yr}^{-1}\)
- But, arrival time dispersion:
  \(t_{\text{disp}} \approx 10^7 \text{ yr} (B/10^{-8} \text{ G})^2 (\lambda_B/1 \text{ Mpc})\)
  \((D/100 \text{ Mpc})^2 (E_p/10^{20} \text{ eV})^{-2}\)
- \(N_{\text{GRB}(E>E_p, \ D<D_{\text{GZK}})} \sim R \cdot t_{\text{disp}}\)
  \(\approx 10^4 B_{-8}^2 \lambda_{B,0}^2 D_{100}^2 E_{p20}^{-2}\)
- GZK event rate: \(\sim 1 \text{ /Km}^2 \text{ /100 yr} \checkmark\)

[Waxman 95, 2005]

Meszáros grb-glast06
UHECR data vs. GRB model

Waxman 06
What about Magnetars?

Isolated neutron stars where the main source of energy is the magnetic field

[ most observed NS have $B = 10^9 - 10^{12}$ G and are powered by accretion, rotational energy, residual internal heat ]

In Magnetars external field: $B = 10^{14} - 10^{15}$ G
internal field: $B > 10^{15}$ G

[ arXiv:0804.0250 ]
Magnetars birthrate

~ a few every $10^4$ years

large uncertainties:

- small statistics (~10 persistent sources)
- uncertain lifetimes (~$10^4$ yrs?),
- number and duty cycle of transient magnetars

Birthrate of radio PSR and core collapse SN (1-3 / century) already in reasonable agreement $\Rightarrow$ no much room for other populations of NS

Magnetars $\sim 0.1$-0.3 / century i.e. up to $\sim 10\%$ of radio PSRs

See also:
Gill & Heyl 2007, MNRAS 381,52

(-0.22 / century + transients)
(-0.3 – 6 / century)
A different magnetar signature:

**Magnetar birth ν-alert?**

Murase, Mészáros & Zhang, PRD '09; arXiv: 0904.2509

- Magnetars (B~10^{14}-10^{15} G) may result from turbulent dynamo when born with fast (ms) rotation
- A fraction ≲0.1 of CC SNe may result in magnetars
- In PNS wind, wake-field acceleration can lead to UHECR energies \( E(t) \lesssim 10^{20} \text{ eV } Z \eta^{-1} \mu_{33}^{-1} t_4^{-1} \)
- Surrounding ejecta provides cold proton targets for \( pp \rightarrow \pi^\pm \rightarrow \nu \)
- \( \nu \)-fluence during time \( t_{\text{int}} \) first increases (strong initial \( \pi/\mu \) cooling), then decreases (with the proton flux)
Magnetar birth \( \nu \)-alert

Murase, Mészáros & Zhang 09

Magnetar fluence @ \( D=5 \) Mpc

- Can signal birth of magnetar
- Test UHECR acc. in magnetar

-BUT: Not an explanation for Auger, because a) UHECR flux not sufficient, and b) UHECR spectrum not like Auger obs.
AGN as UHE $\gamma$ sources

- Big brother of GRB: massive BH ($10^7$-$10^8 M_{\odot}$) fed by an accretion disk $\rightarrow$ jet –
- But, jet $\Gamma_{j,agn} \sim 10^{-30}$ (while $\Gamma_{j,grb} \sim 10^2 - 10^3$)
- UV photons from disk; in addition, line clouds provide extra photons (+back-scatter)
- Typical ("leptonic") model: SSC (sync-self-compton); SEC (sync-exter.compton)
HESS + Fermi: PKS 2155
Radio-loud hadronic Blazar models
(PSB-proton synchrotron blazar - γ-ray spectrum from cascades)

• Full : synchrotron γ SED (target photons)
• Dash: p-sync. casc.; Dash-3 dot: μ±-sync. casc;
  Dots: π0 casc;    Dash-dot: π± casc

(Muecke, et al, Apjh, astro-ph/0206164 )
Mrk 501: prototypical HBL

- a) - PSB: Quiet state $\gamma$
- b) - PSB: Flare state $\gamma$
  - $e$-sync $g$ targets + $p$-sync $g$ + $p,g$ cascades, pm cascades & sync
  (Muecke et al, a-ph/0206164)
- c) $\rightarrow$ LEP: Flare state $\gamma$
  - $e$-sync $g$ + $e$-Inv. Compton scatt (Ghisellini et al, e.g.
UHE $\nu$ spectra of indiv. AGN: SPB

- Generic neutrino spectra in LBL, HBL from $p, \gamma$ interact. with softer/harder target synchrotron spectra
- “Internal” synchrotron low hump assumed + proton sync contrib. to high hump
- “External+internal” target photons yields alternative models

[Muecke et al 02]
Radio-quiet (core) AGN vs

- AGN are powered by accretion on massive \(10^6-10^8 \, M_{\odot}\) BHs
- 90% of AGNs are radio-quiet (no jets), core X-ray
- Core emission model: aborted jet → cloud collisions → shocks → p accel. → pγ → π⁺ → ν
- ← Diffuse flux: already constrained by AMANDA
- \(\pi^0 \rightarrow GeV\gamma\) (soft photon density too high for TeV γ)

Alvarez-Muñiz & Mészáros, 2004, PRD 70, 123001

Mészáros TeV05
What about $E_\nu \gtrsim 10^{19}$ eV? from GZK CRs to GZK $\nu$ vs

2 $\neq$ CR models $\downarrow$ same GZK CR fit

\[ a \]
\[ b \]

But … lead to $\neq$ GZK $\nu$ flux $\downarrow$

Can infer GZK CR injection spectrum and/or source cosm. luminosity evolution via their GZK $\nu$s.

Seckel & Stanev astroph/050244
If GRB make the GZK UHECR, then:

- \( \nu \) flux dep. on GRB rate vs. \( z \)
- (from \( z \gg R_{\text{GZK}} \))
Potential of Cosmogenic $\nu$s for CR Composition

- If CRs have large fraction of heavies, depending on source distance, photodissociation opt. depth could be $<1 \rightarrow$ only some of them break up into p,n
- Implies smaller fraction contributes to $\pi^+$ and cosmogenic $\nu$ production (Anchordoqui et al 06)
- Cosmogenic $\nu$ flux vs. CR flux may help resolve discrepancy between Auger $X_{\text{max}}$ data and apparent correlation with AGN suggesting protons
Conclusions

- The sources of UHECR and potentially of UHENU are still unknown
- Will learn much about best candidates (GRB, AGN, MGR) from GeV and TeV photon observations; many with good photon statistics
- Will constrain particle acceleration / shock parameters, compactness of emission region (dimension, mag.field,)
- UHECR : chemical composition, angular correl.: sources?
- UHE ν will allow test of proton content of jets, proton injection fraction, test shock acceleration physics, magn. field
- If UHE ν NOT detected in GRB, AGN → jets are Poynting dominated!
- Probe ν interactions at ~ TeV CM energies
- Constraints on stellar birth & death rates @ high-z, first structures?
- Cosmogenic nus: probe CR origins, sources
Back-up slides

1st and 2nd order (n=1,2) energy dependent pulse time dispersion in effective field theory formulation of LIV effects, where leading order deviation is $E^2 - p^2 - m^2 \approx \pm E^2 (E/E_{QG})^n$

$$\Delta t = \frac{(1+n)}{2H_0} \frac{E_{r}^n - E_{r}^p}{(M_{QG,n}c^2)^n} \int_{0}^{z} \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_A}} dz' ,$$

Conservative lower limit on $E_{QG}$, taking $E_h/t$ ($E_h/t^{1/2}$) with $t$=pulse time since trigger

$$M_{QG,1} > (1.50 \pm 0.20) \times 10^{28} \left( \frac{E_h}{13.22^{+0.70}_{-1.54} \text{GeV}} \right) \left( \frac{t}{16.54 \text{ s}} \right)^{-1} \text{GeV}/c^2 ,$$

$$M_{QG,2} > (9.42 \pm 1.21) \times 10^{39} \left( \frac{E_h}{13.22^{+0.70}_{-1.54} \text{GeV}} \right) \left( \frac{t}{16.54 \text{ s}} \right)^{-1/2} \text{GeV}/c^2 .$$

These are the most stringent limits to-date via dispersion.
Hadronic GRB:
easier to look for secondary photons
from $p,γ$ interactions

Asano, Inoue & Mészáros

If GRB are UHECR sources, may need $\varepsilon_p/\varepsilon_e \gg 10 \rightarrow$ tends to give identifiable “hadronic” photon peak

Diagnostic for $\Uparrow$: high $\varepsilon_p/\varepsilon_e$
$\leftarrow$: high bulk $\Gamma$
$\rightarrow$: high $\varepsilon_B/\varepsilon_e$
2 sources of hot IC e⁻:
shocks- a: $\Gamma \sim 2$, b: $\Gamma \sim 10$
  a) rel. jet in SS stage
  b) semirelat. outflow

and

2 sources of seed photons:
  a) synchrotron (SSC)
  b) SN UV (SN IC), incl. early th. & late RI

LL GRB: GeV-TeV γs

arising from leptonic sy-IC origin

He, Wang, Yu & Mészáros 09
Radio, x-ray & gamma-ray observations of SN1998bw/GRB980425

- sub-energetic GRB—GRB980425: $E \sim 1 \times 10^{48}$ erg (d=38 Mpc)
- Radio afterglow modeling: $E > 1 \times 10^{49}$ erg, $\Gamma \sim 1-2$
- X-ray afterglow: $E \sim 5 \times 10^{49}$ erg, $\beta = 0.8$

**Mildly relativistic ejecta component**

- $E_{SN} = 3-5 \times 10^{52}$ erg
- $V = 0.1c$
- SN shock acceleration in the Envelope?
- SN2003lw/GRB031203
- SN2006aj/GRB060218

Origin of $10^{19}-10^{21}$ eV UHECR: may be GRB - but what about $10^{16}-10^{19}$ eV?

Other SN/GRB w. semi-relativistic ejecta:
- SN2003lw/GRB031203
- SN2006aj/GRB060218
The maximum energy of accelerated particles

1) Type Ib/c hypernovae expanding into the stellar wind of Wolf-Rayet star
2) equipartition magnetic field $B$, both upstream and downstream

\[ \frac{B^2}{8\pi} = 2\epsilon_B \rho_w(R) c^2 \beta^2 \quad \rho_w(R) \propto R^{-2} \]

**Maximum energy:**

\[
\varepsilon_{\text{max}} \simeq Z e B R \beta = 4 \times 10^{18} Z \\
\times \left( \frac{v}{10^8 \text{cm}^{-1}} \right)^2 \left( \frac{\dot{M}}{3 \times 10^{-9} \text{M}_\odot \text{yr}^{-1}} \right)^{1/2} \left( \frac{\nu_{\nu,3}}{1/2} \right)^{-1/2} \text{eV}
\]

Protons can be accelerated to $\sim 10^{19}$ eV
Heavy nuclei can be accelerated to $\sim Z \times 10^{19}$ eV
Flux level--- energetics

Kinetic energy generation rate:

\[
\dot{E}_k(z = 0) = R_{\text{HN}} E_{\text{HN}} \\
= 2.5 \times 10^{46} \left( \frac{\rho_{\text{SN}}}{500 \text{Gpc}^{-3} \text{yr}^{-1}} \right) \text{erg Mpc}^{-3} \text{yr}^{-1}
\]

Compare w. normal GRBs

<table>
<thead>
<tr>
<th></th>
<th>Hypernova (v=0.1c)</th>
<th>Normal GRBs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate (z=0)</td>
<td>(\sim 500) Gpc(^{-3}) yr(^{-1})</td>
<td>(\sim 1) Gpc(^{-3}) yr(^{-1})</td>
</tr>
<tr>
<td>Kinetic energy</td>
<td>(3-5 \times 10^{52}) erg</td>
<td>(1 \times 10^{53} - 1 \times 10^{54}) erg</td>
</tr>
</tbody>
</table>

The required rate:

\[
R_{\text{HN}} = 750 Z^{-1.2} (f_z/3)^{-1} \text{Gpc}^{-3} \text{yr}^{-1}
\]

Normal Ib/c SN rate:

\[
\sim 2 - 5 \times 10^4 \text{Gpc}^{-3} \text{yr}^{-1}
\]

Sub-energetic GRB rate:

\[
100 - 1800 \text{Gpc}^{-3} \text{yr}^{-1}
\]

Soderberg et al.
Energy distribution with velocity

- Normal SN: $E_k \propto (\Gamma \beta)^{-5}$
  Very steep distribution -> negligible contribution to high-energy CRs
  Berezhko & Volk 04

- Semi-relativistic hypernova: high velocity ejecta with significant energy is essential
  $E_k \sim (\Gamma \beta)^{-2}$

CR spectrum:
  $\epsilon^2 (dN/d\epsilon) \propto \epsilon^{-\alpha/2}$
  $\alpha \sim 2$

Data from Soderberg et al.

Wang, Razzaque, Meszaros, Dai 07
Transition from GCRs to EGCRs