Hypernovae/sub-energetic GRBs as a possible source of UHE cosmic rays

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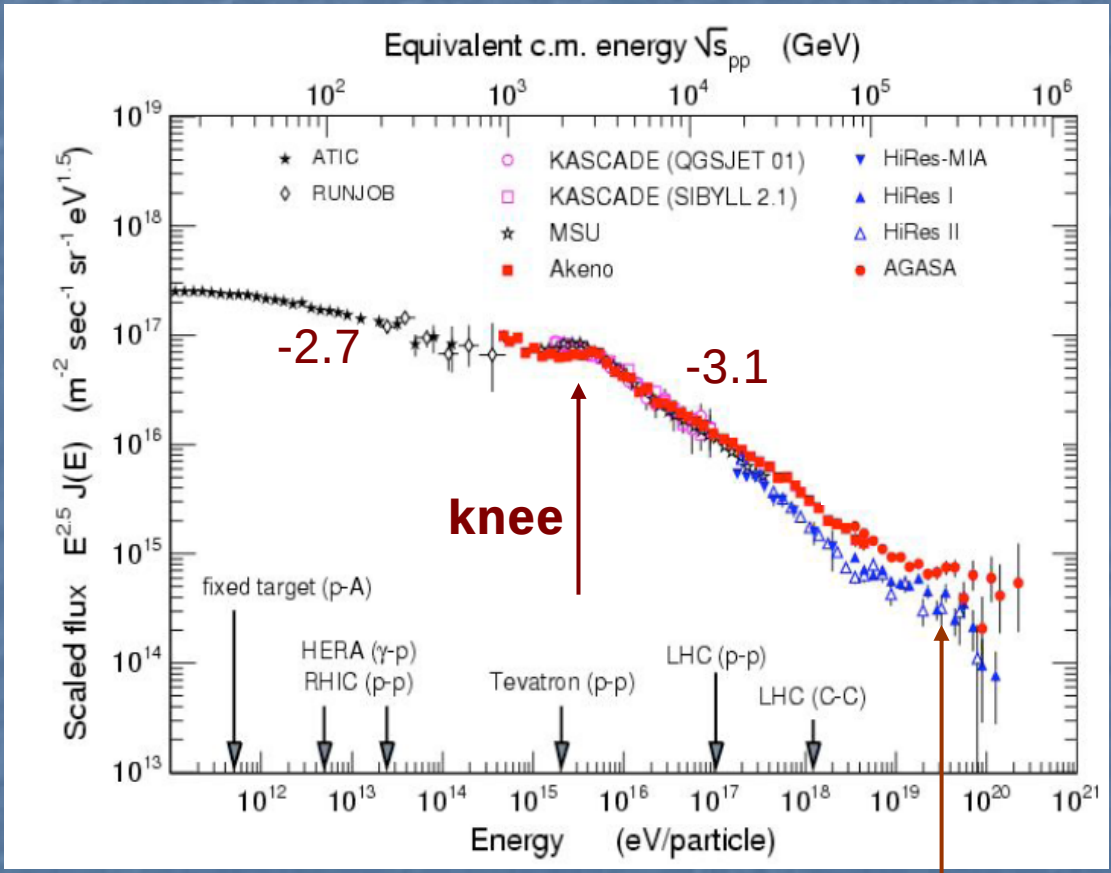
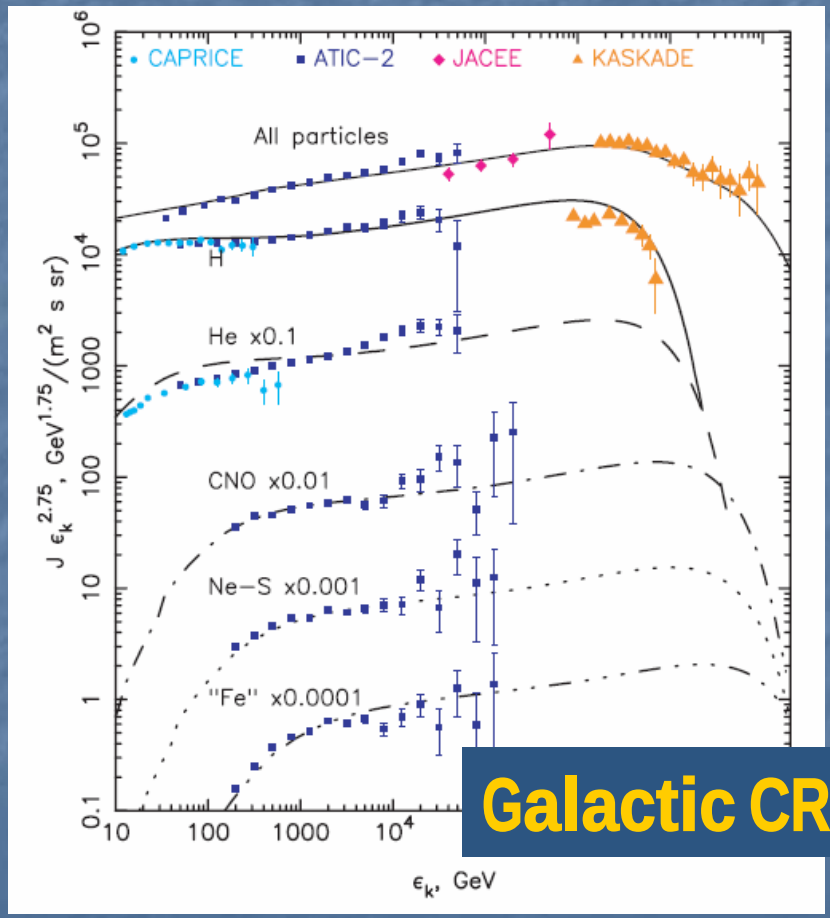
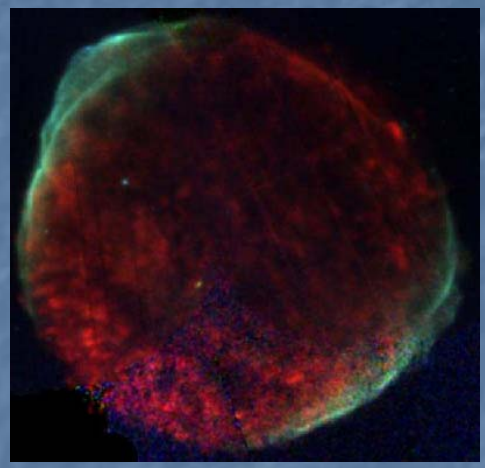
CR spectrum


Equivalent c.m. energy $\sqrt{s}_{pp}$ (GeV)
10^2
10^3
10^4
10^5
10^6
ATIC
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
MSU
Akeno
HiRes-MIA
HiRes I
HiRes II
AGASA
-2.7
-3.1
knee
ankle
fixed target (p-A)
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
LHC (C-C)
Scaled flux $E^{2.5}$ J(E) (m^{-2} sec^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
Energy (eV/particle)

CRs below the knee --- Galactic SN Remnants



Berezhko & Volk 07



SN1006

- Diffuse shock acceleration

a) CRs below the knee

Protons: $\varepsilon_{\max}(p) \sim 3\times10^{15}\,\mathrm{eV}$

b) CRs above the knee

Heavy nuclei: $\varepsilon_{\max}(Z) \sim 3Z\times10^{15}\,\mathrm{eV}$

Galactic CRs >~1e17 eV

KASCADE data: Progressively increasing contribution of heavy nuclei with increasing energy

Extra-galactic CRs

- Transition position from GCR to EGCR: still controversial

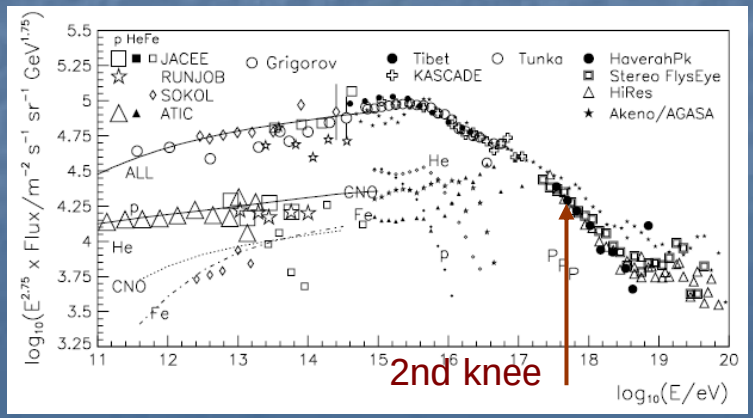
1) ankle: EGCRs start at E>1e19 eV

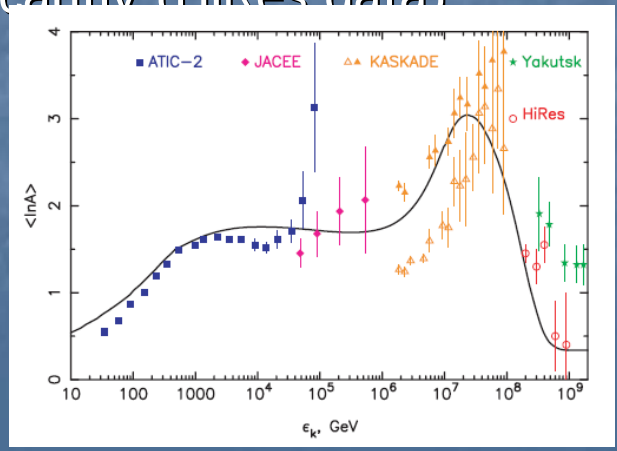
require GCRs extending to ~1e19 eV (e.g. Budnik et al. 07)

e.g. Berezinsky et al. 06

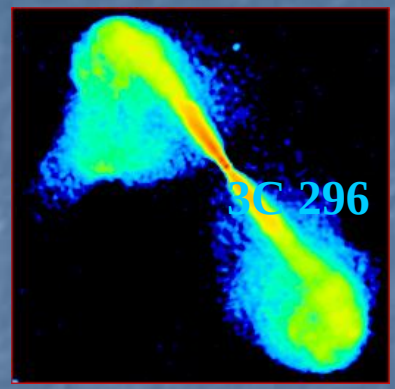
2) the second knee: E~6e17 eV

where the composition changes significantly (HiRes data)

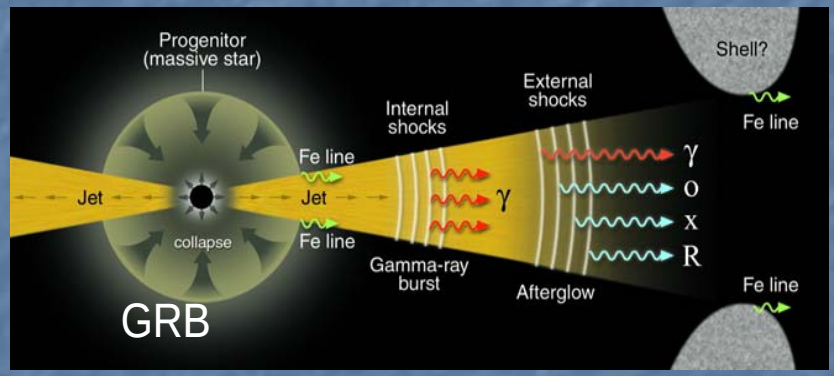




Source models for EGCRs



- AGNs, radio galaxies (Biermann….)
- GRBs (waxman 05; Vietri; Dermer)
- Cluster of galaxies
- …



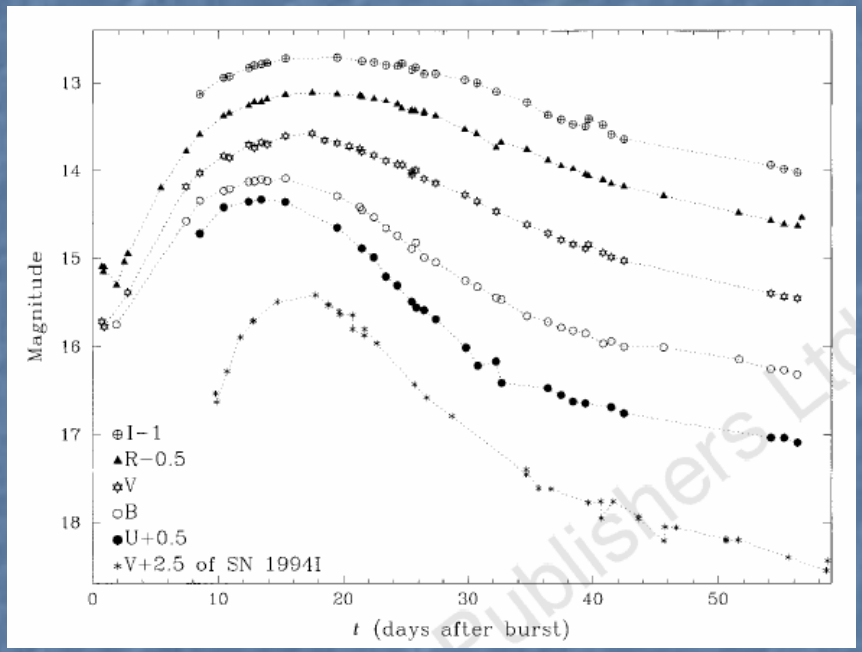
- Semi-relativistic Hypernovae: **?**

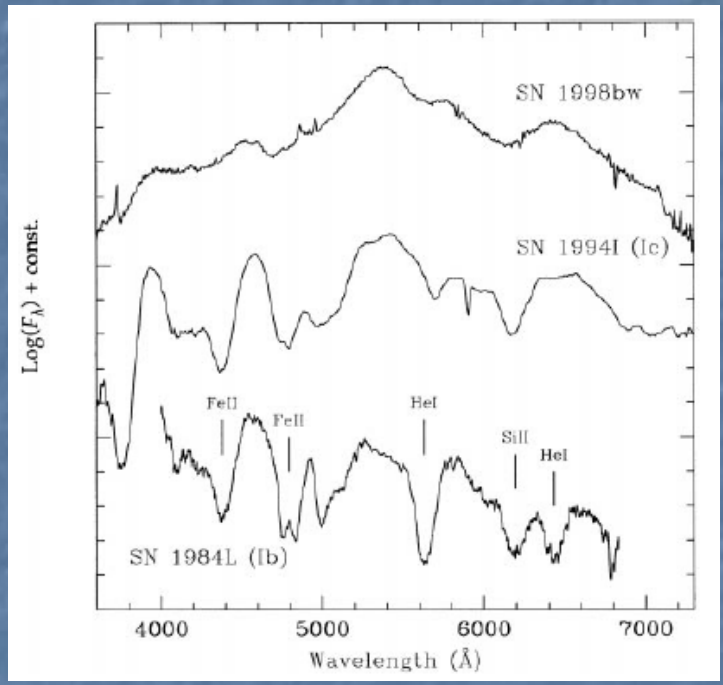
large explosion energy SN (E=3-5e52erg) with significant mildly-relativistic ejecta

Wang et al.,2007, arXiv:0705.0027 (astro-ph)

Hypernova prototype – SN1998bw: an unusual SN

In the error box of GRB980425





1) Type Ic SN
2) High peak luminosity, broad emission lines -> modelling require large explosion energy (E=3-5e52erg)

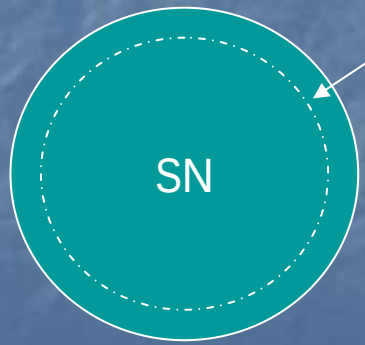
Normal SN: E=1e51 erg

Radio, x-ray & gamma-ray observations

- sub-energetic GRB—GRB980425: E~1e48 erg (d=38 Mpc)
- Radio afterglow modeling: E>1e49 erg, \Gamma~1-2
- X-ray afterglow: E~5e49 erg, \beta=0.8

Mildly relativistic ejecta component

E_SN=5e52 erg
V=0.1c



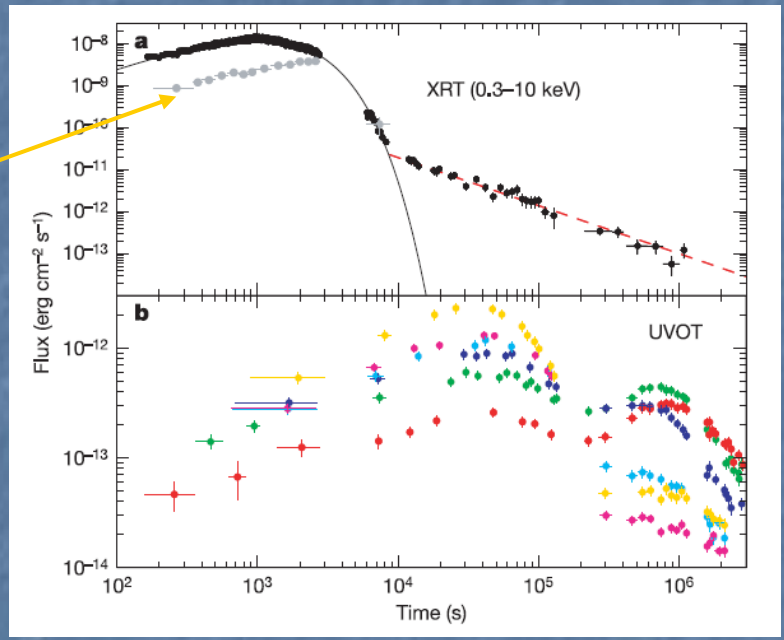
SN shock acceleration in the Envelope?

Tan et al. 01
Woosley et al. 99

Other hypernovae/sub-energetic GRBs

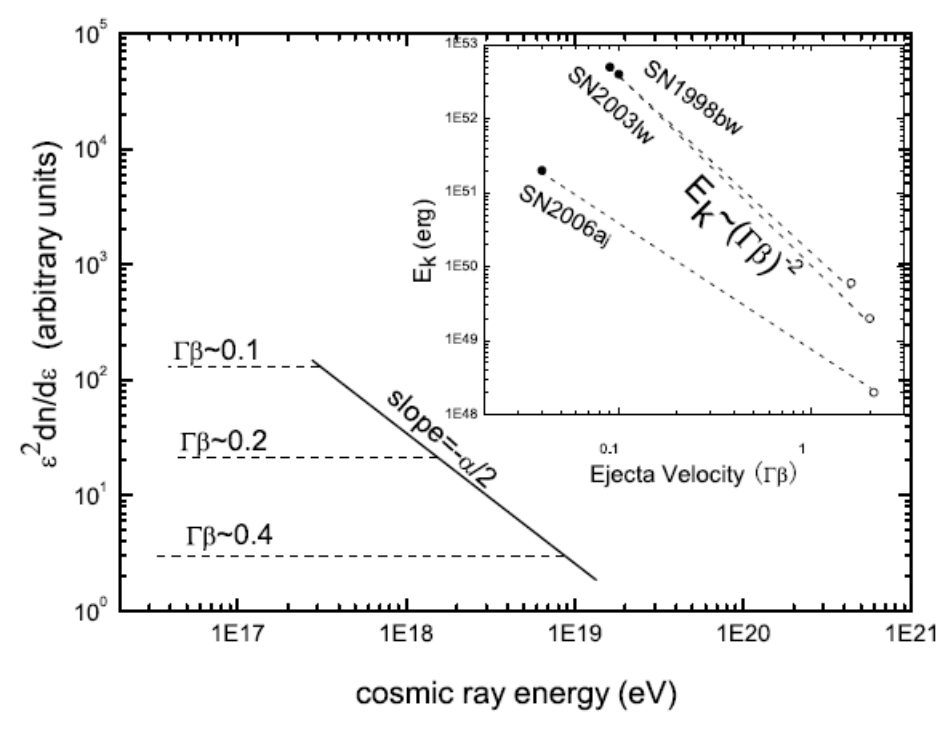
- SN2003lw/GRB031203
- SN2006aj/GRB060218

- prompt thermal x-ray emission—mildly relativistic SN shock breakout from stellar wind
  Waxman, Meszaros, Campana 07
- gamma-ray emission (repeatedly scattering of shock breakout photons by hypernova ejecta)
  Wang, Li, Meszaros, Waxman 07
- radio afterglow emission modelling: a continuous velocity distribution $r \propto t^{0.85}$



Campana et al. 06

Energy distribution with velocity



Wang, Soeb, Meszaros, Dai 07

- 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

$$E_k \sim (\Gamma\beta)^{-2}$$

The maximum energy of accelerated particles

1) Type Ib/c SN expanding into the stellar wind, Wolf-Rayet star

2) equipartition magnetic field B, both upstream and downstream

$$B^2/8\pi = 2\epsilon_B \rho_w(R) c^2 \beta^2 \qquad \rho_w(R) \propto R^{-2}$$

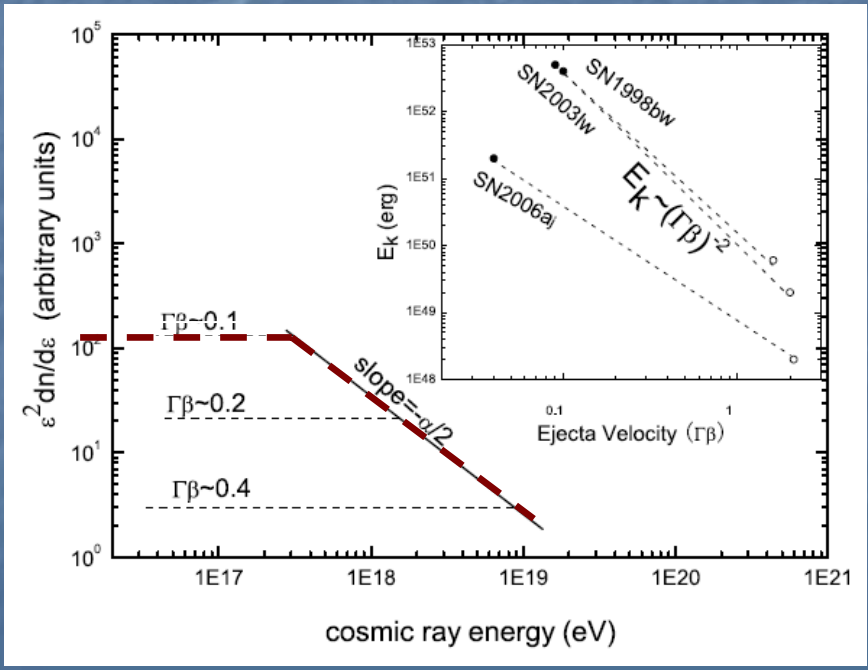
Maximum energy: Hillas 84

$$\varepsilon_{\rm max} \simeq ZeBR\beta = 4\times 10^{18} Z \times \epsilon_{B,-1}^{1/2} \left(\frac{v}{10^{10}{\rm cms}^{-1}}\right)^2 \left(\frac{\dot{M}}{3\times 10^{-5}{\rm M}_\odot{\rm yr}^{-1}}\right)^{1/2} v_{w,3}^{-1/2} {\rm eV}$$

Protons can be accelerated to >=1e19 eV

The spectrum

- Injection spectrum $dN/d\varepsilon \propto \varepsilon^{-\gamma}$ with $\gamma \simeq 2.0$



$\varepsilon_{\max} \propto (\Gamma\beta)^2$

$E_k \propto (\Gamma\beta)^{-\alpha}$

$E_k \propto \varepsilon_{\max}^{-\alpha/2}$

$\varepsilon^2(dN/d\varepsilon) \propto \varepsilon^{-\alpha/2}$

$\alpha \simeq 2$

The flux level--- energetics

1) Extra-galactic hypernova explosion rate
2) average energy per hypernova event

$$\dot{\epsilon}_k(z=0) = R_{\rm HN} E_{k,\rm HN}$$
$$= 2.5\times10^{46}\left(\frac{R_{\rm HN}}{500{\rm Gpc^{-3}yr^{-1}}}\right){\rm erg\ Mpc^{-3}\ yr^{-1}}$$

Compare with normal GRBs

	Hypernova (v=0.1c)	Normal GRBs
Rate (z=0)	~500 $\rm Gpc^{-3}\,yr^{-1}$	~1 $\rm Gpc^{-3}\,yr^{-1}$
kinetic energy	3-5e52 erg	1e53-1e54erg

The required rate :

$$R_{\rm HN} = 750 Z^{-1.2}(f_z/3)^{-1}{\rm Gpc^{-3}yr^{-1}}$$

Normal Ib/c SN rate:

$$\sim 2-5\times10^4\ {\rm Gpc^{-3}yr^{-1}}$$

sub-energetic GRB rate:

$$100-1800\ {\rm Gpc^{-3}yr^{-1}}$$

Soderberg et al. 06; Liang et al. 06

Open issues

- Low-metalicity host: no hypernovae in our Galaxy?
  Stanek et al. 06; Woosley & Bloom 06
- Hypernova ejecta velocity distribution profile
- CR composition: heavy nuclei in UHE CRs ?