SN-GRB 2014 in Riken

Probing Relativistic Supernova Explosions with Multi-Band Synchrotron Emission

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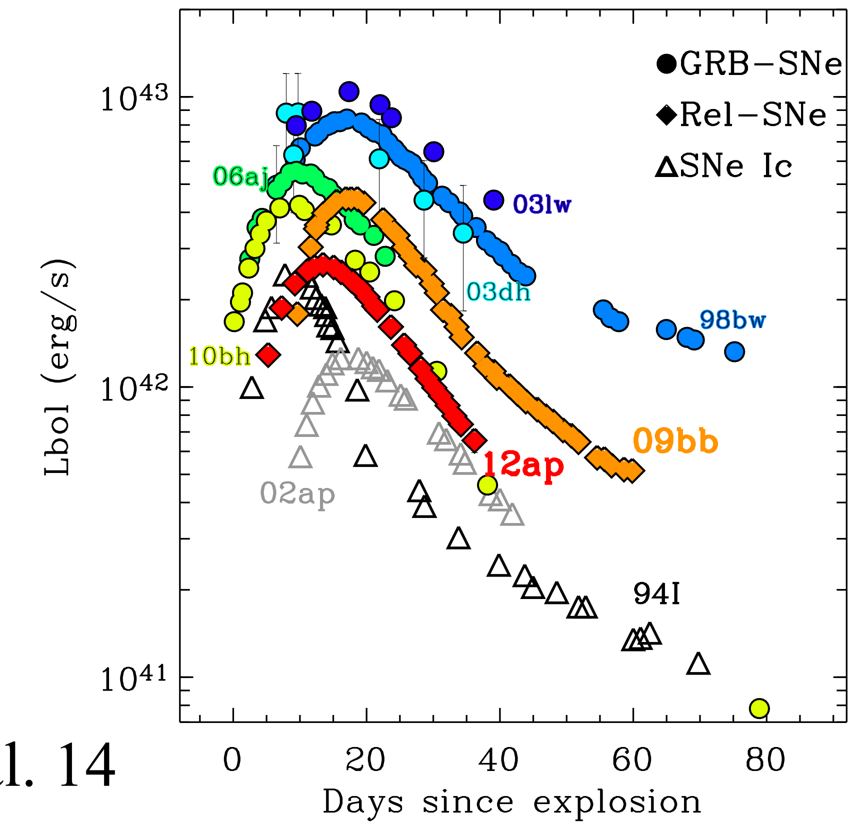
1. Introduction

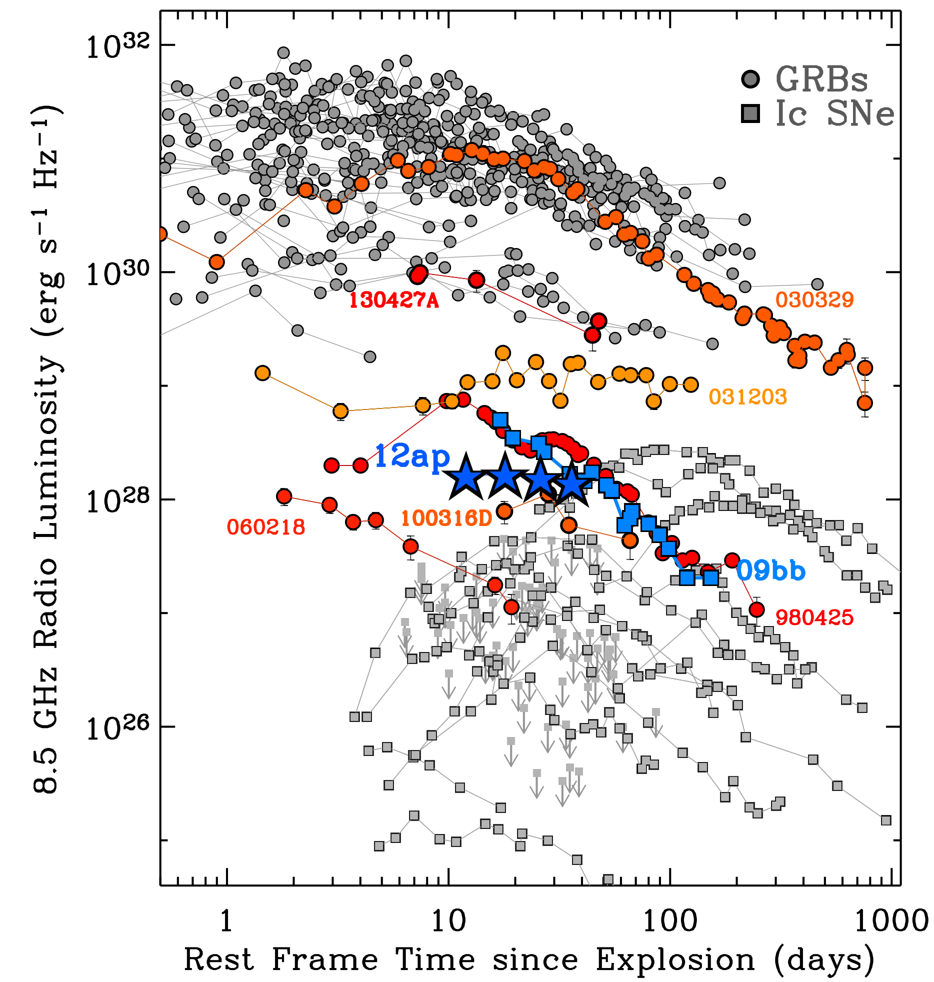
Relativistic SN (RSN) 09bb & 12ap

One of the key events to study the GRB-SN connection.

- Lack a GRB detection but,
- Broad-lined Type Ic SNe, hypernova

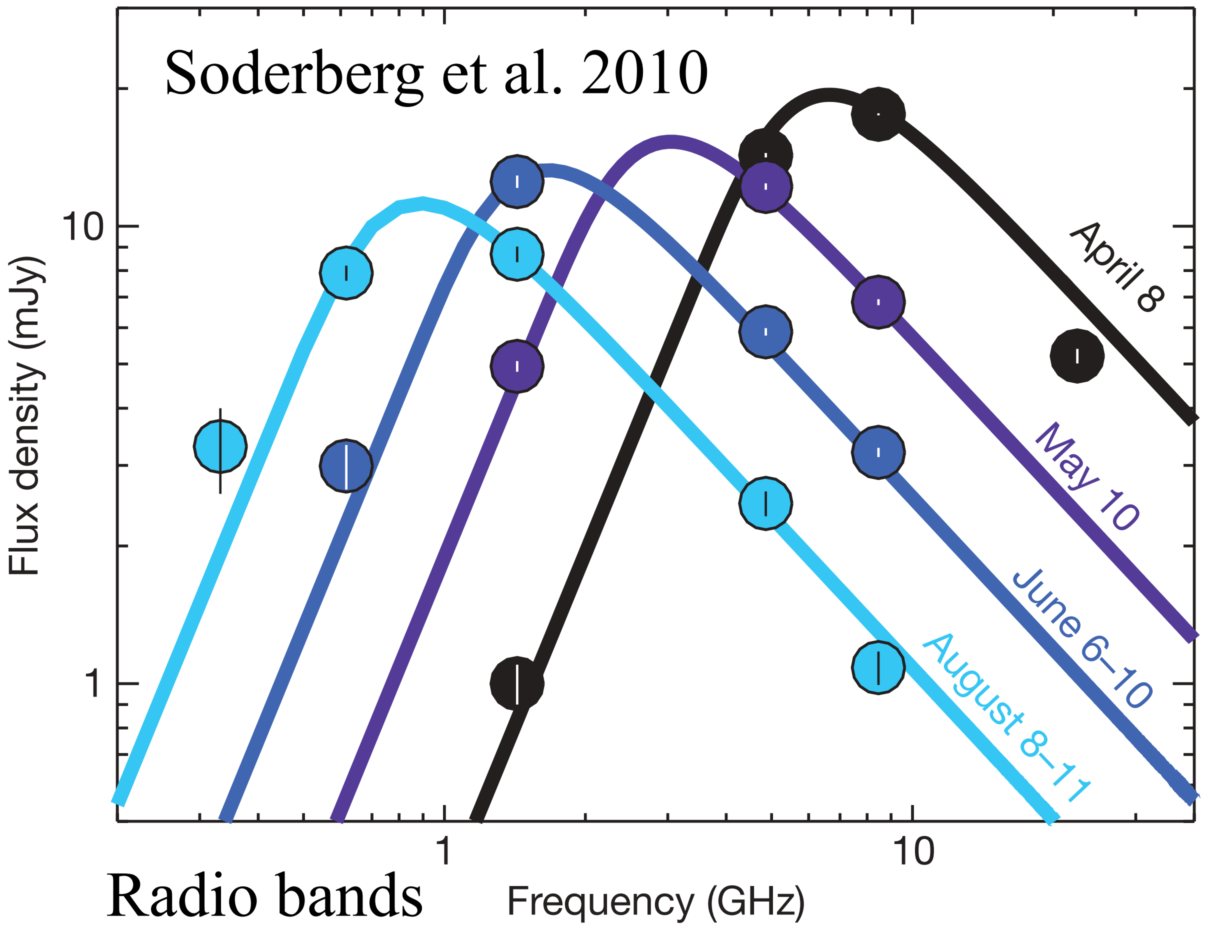
  $E_{\rm in} \sim 10^{52}$ erg $M_{\rm ej} \sim 3\text{-}4\ M_\odot$ Lyman et al. 14 Milisavljevic et al. 14
- Luminous radio emission comparable to LLGRBs. Margutti et al. 14
- They show intermediate features between a Type Ic SN and a GRB.





Radio Calorimetry

Chevalier 98



Radio bands

- Ejecta - CSM interaction.
- Synchrotron emission model.

➡ $v(t) \sim R(t)/t$

$R(t)$: ejecta radius

$E \sim R^3 B^2/\epsilon_B$: ejecta energy

$\dot{M} \sim v_{\rm wind} \frac{B^2}{\epsilon_B} \left(\frac{R}{\beta c}\right)^2$: wind density

*Within the uncertainty of ϵ_e ϵ_B

- Luminous radio emission comparable to LLGRBs. Soderberg et al. 10

➡ An energetic and mildly-relativistic ejecta may be present.

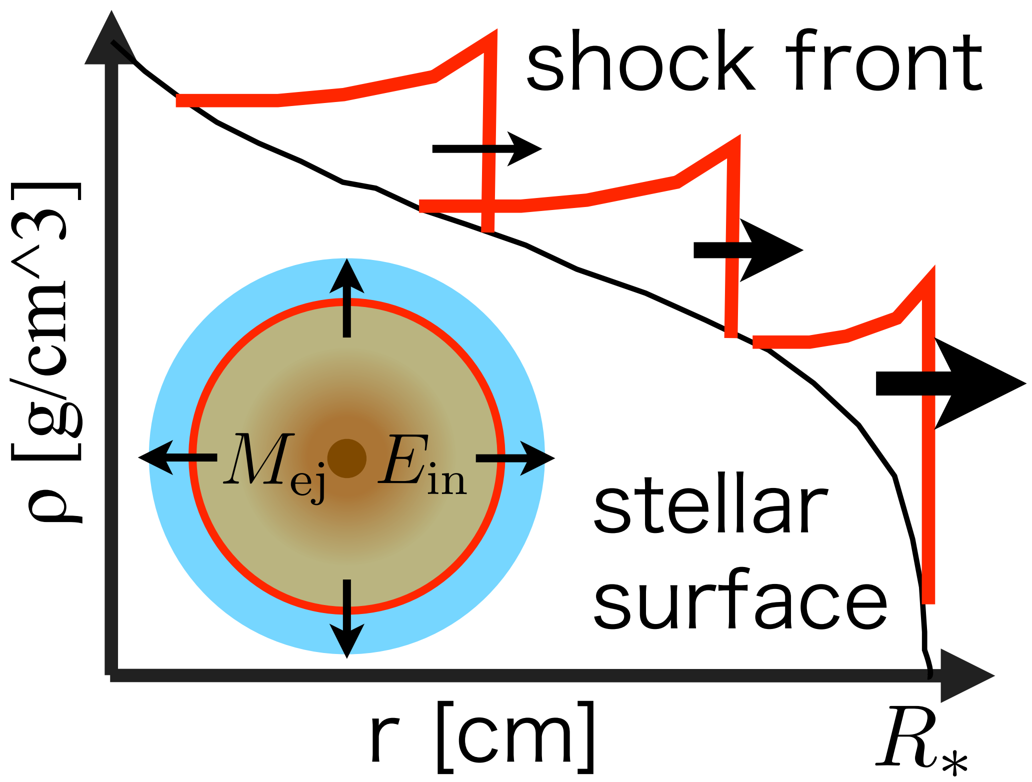
$$E_{\rm kin} \sim 10^{49}\ {\rm erg} \qquad \Gamma\beta \sim 1$$

- But their estimate is rough.

- We reconsider the radio emission of an RSN in more detail.

2. Model

The Dynamics of SN Shock Breakout



- Steep density decline $\rho(r) \propto (R_*/r - 1)^n$
- Shock front acceleration for k > 3.

  $k = |d \log \rho(r)/dr|$

  Sakurai 60
  Johnson&McKee 71
- Some part reaches relativistic speed.
- Shock breakout.

  Matzner&McKee 99
  Tan et al. 01

- After shock breakout, the shocked envelope is further accelerated by converting I.E. to K.E.
- Outer layers have larger velocity but less energy.

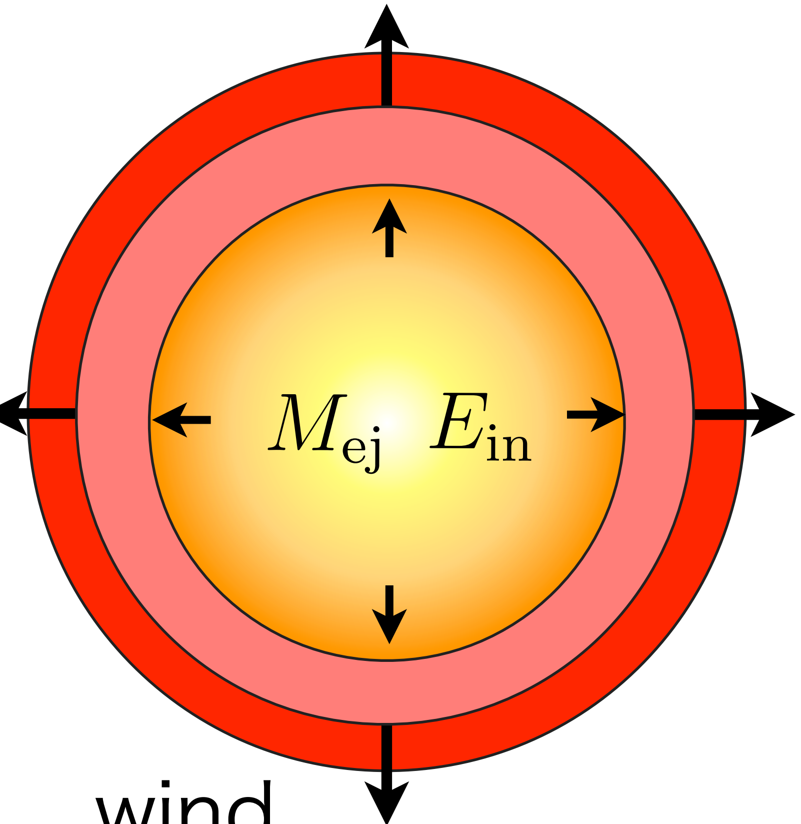
$$E_{\rm kin}(>\Gamma\beta) = \tilde{E}F(\Gamma\beta) \propto E_{\rm in}^{10.7/3} M_{\rm ej}^{-7.7/3}[(\Gamma\beta)^{-0.94} + (\Gamma\beta)^{-0.2}]^{5.5}.$$

- The above structured ejecta collides with the wind medium and contributes to the radio emission.

Deceleration of the Structured Ejecta

Refreshed shock model.

Sari et al. 98
Rees&Meszaros98
Sari&Meszaros00



wind
$n_{\rm CSM}(R) \propto R^{-2}$
$\propto \dot{M}$

- A faster and less energetic layer is decelerated earlier.
- Layers are decelerated in a successive way.
- Slower layers catch up with the decelerated ones and energize the forward shock.
- The FS velocity

$$E_{\rm kin}(>\Gamma\beta) \sim E_{\rm tot}(\Gamma\beta, R) \Rightarrow \Gamma\beta = \Gamma\beta(R)$$

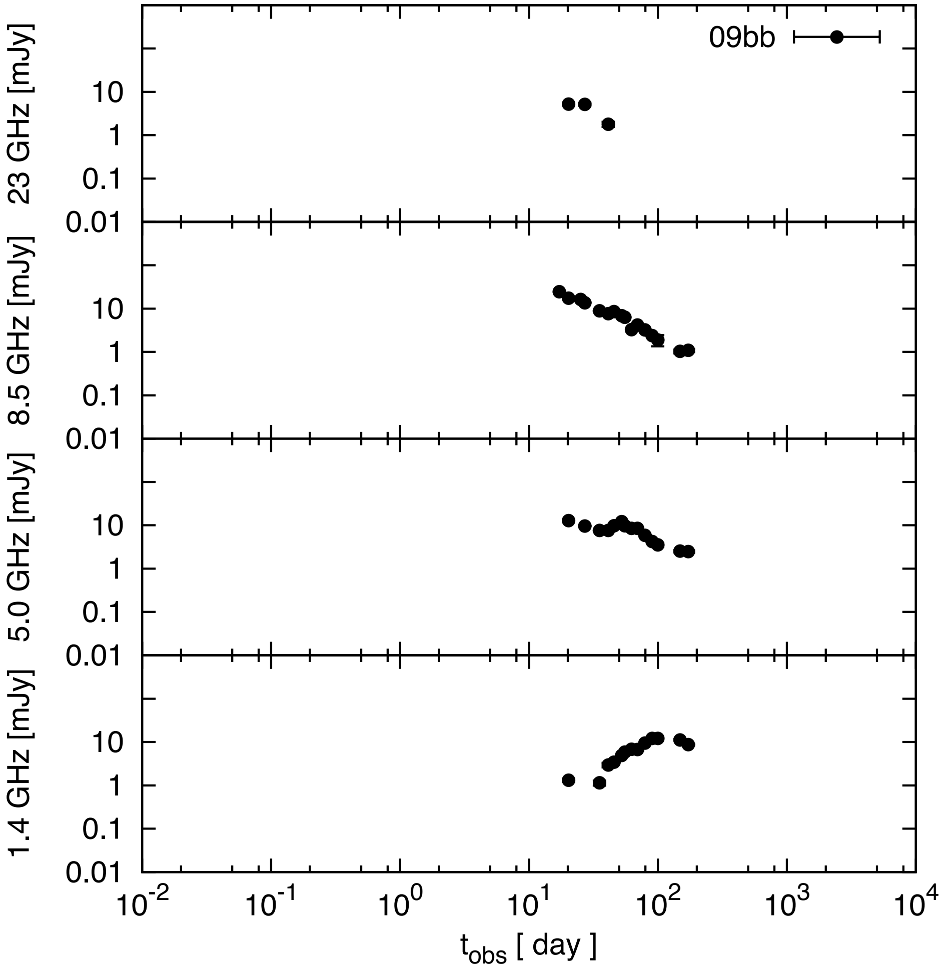
$$E_{\rm tot}(\Gamma\beta, R) = R^3(\Gamma\beta)^2\rho_{\rm w}(R)c^2\left[\frac{8\pi}{9}\beta^2 + \frac{9}{4\alpha_2}(1-\beta^2)\right]$$

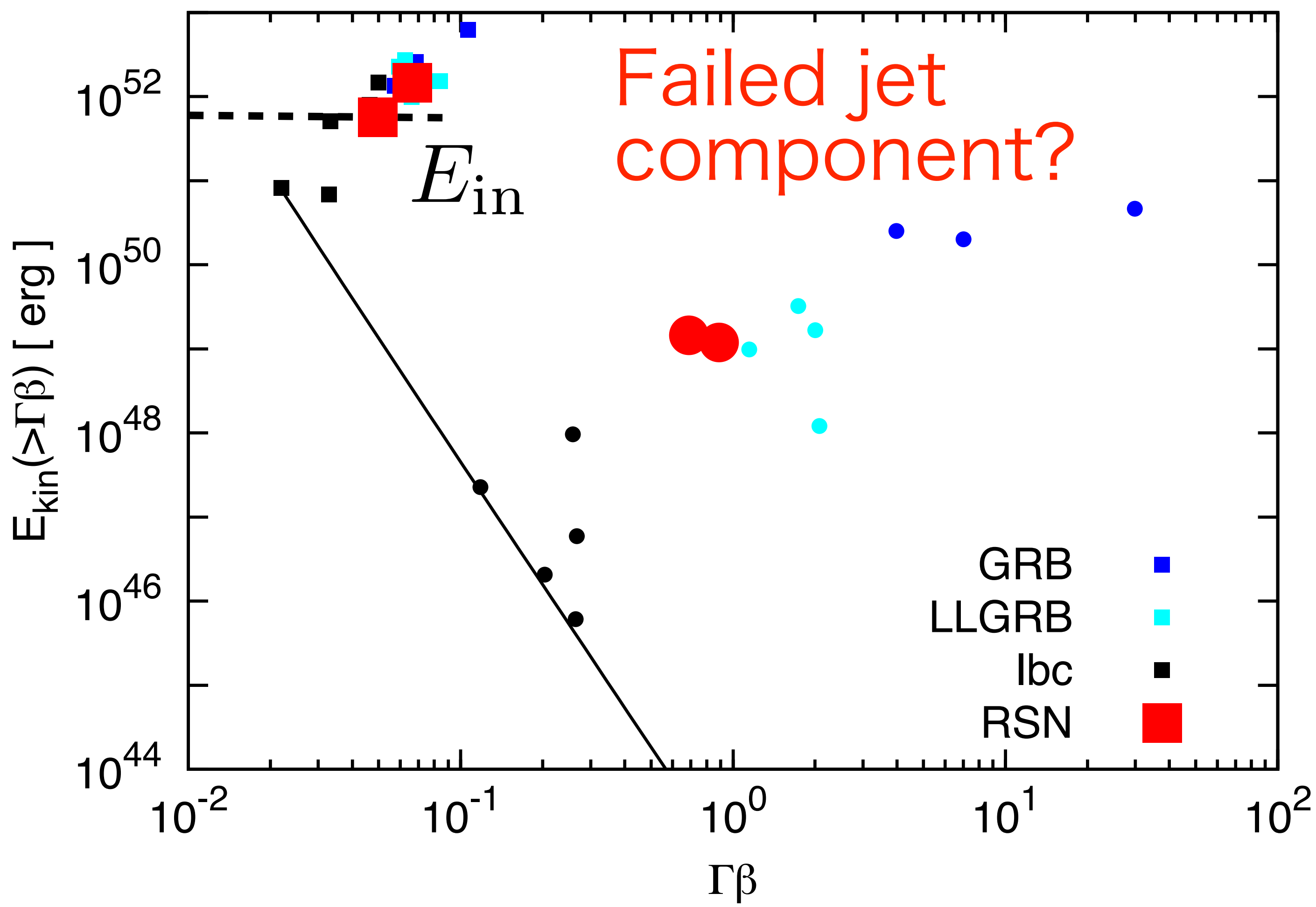
De Colle et al. 12

- Synchrotron emission from the shock-accelerated relativistic electrons contributes to the radio emission.

Radio Observation Fitting

Margutti et al. 2014
arXiv:1402.6344





- Radio observation fitting.

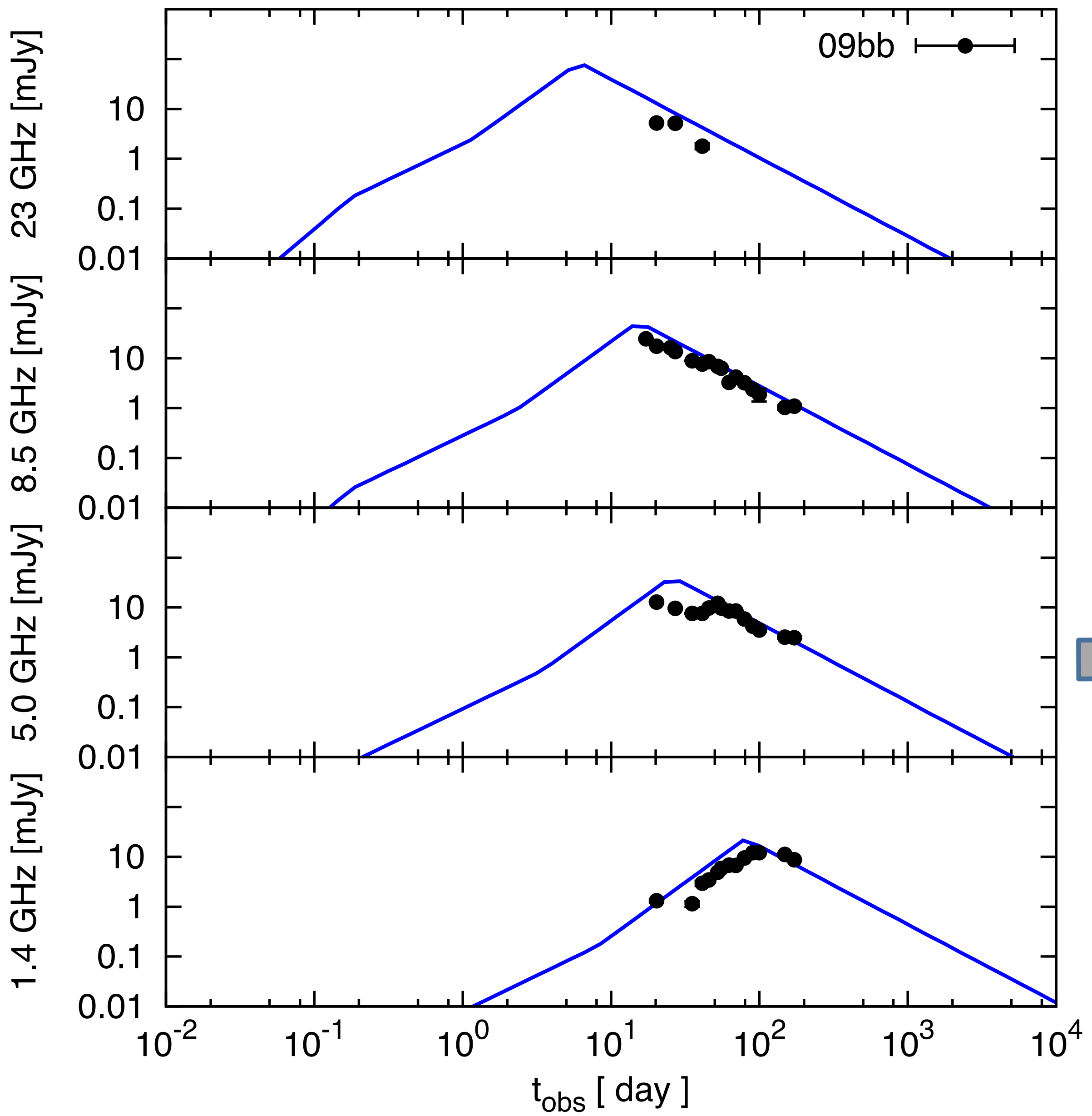
⇨ Energy distribution. $E_{\rm kin}(>\Gamma\beta)$ Mass loss rate. $\dot{M}$

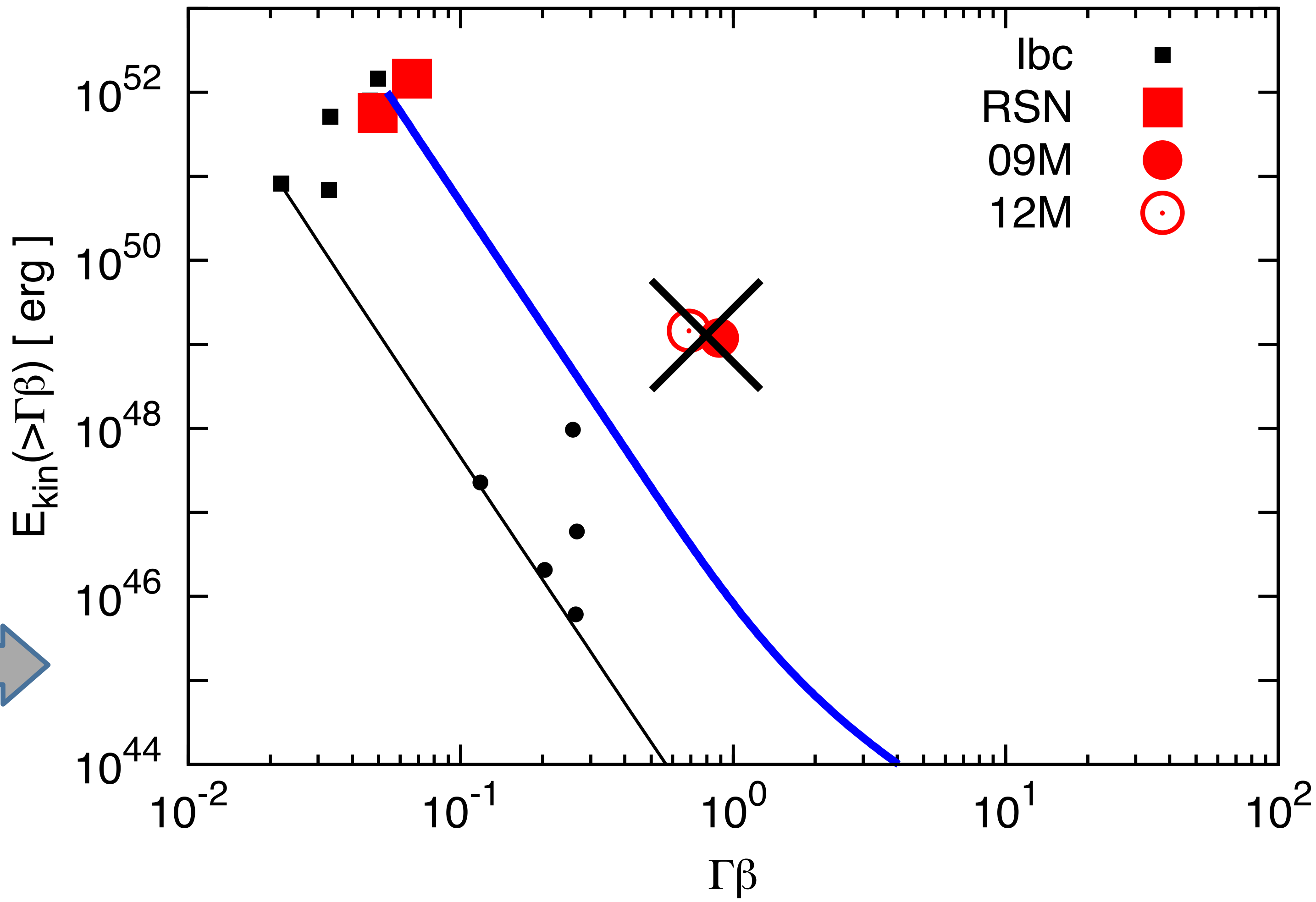
(The efficiency parameters are fixed.) $\epsilon_e = \epsilon_B = 0.33$ $p = 3$

- We reexamine the estimate of previous authors.

3. Results

Energy Distribution in the 09bb Ejecta

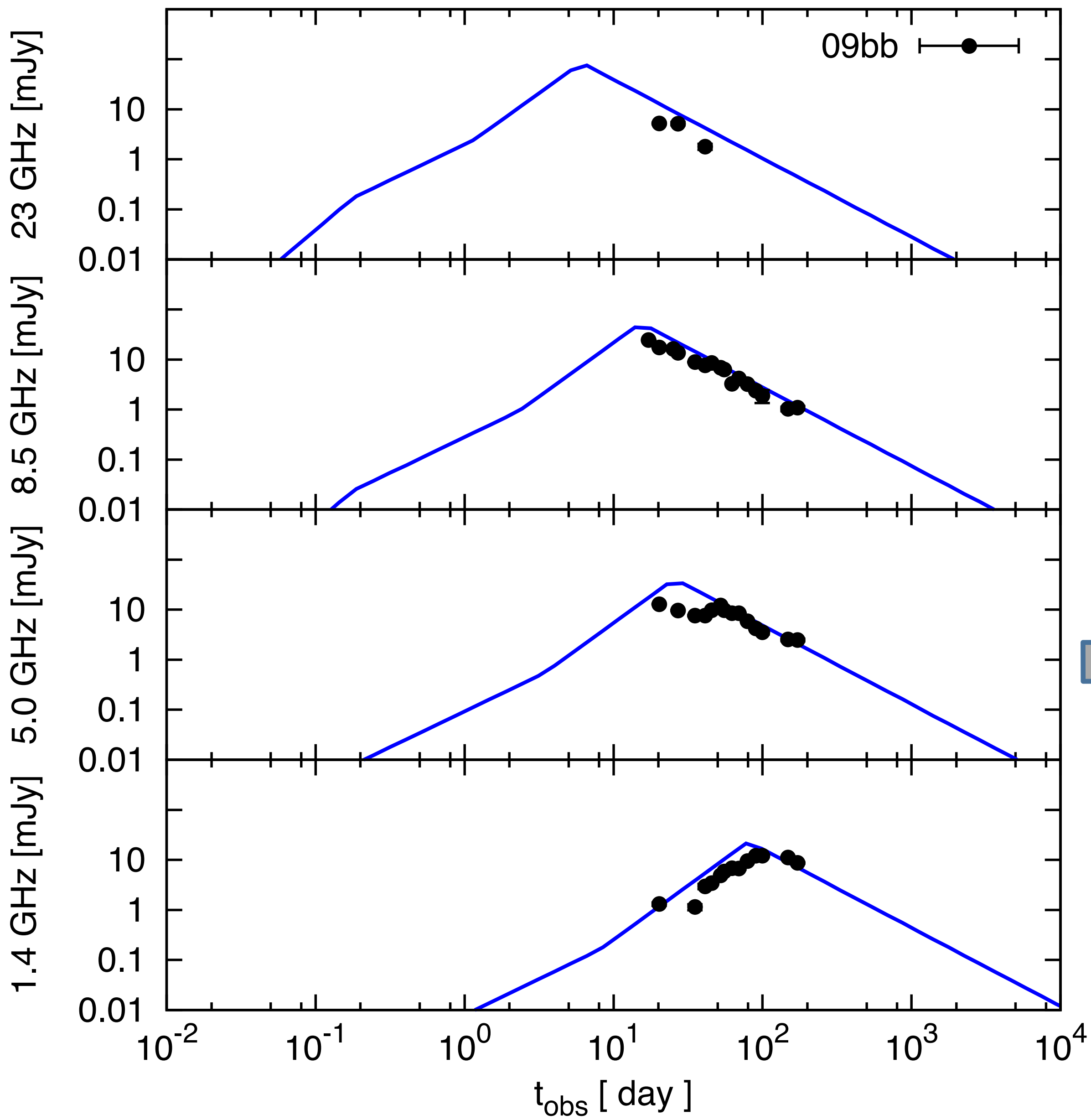


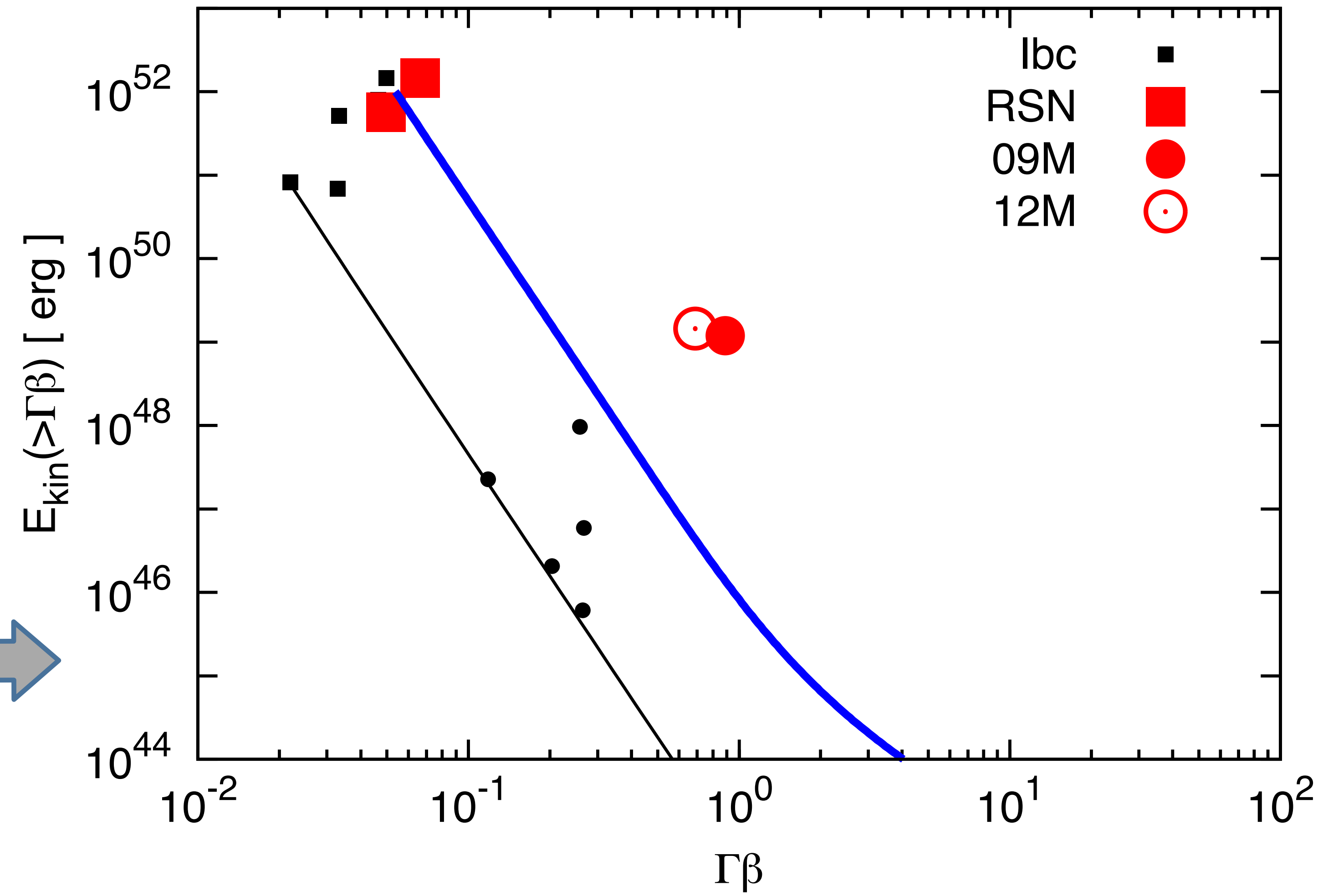


$$\dot{M} = 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$$

- The radio observation is consistent with the spherical hypernova explosion.

Energy Distribution in the 09bb Ejecta





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- The radio observation is consistent with the spherical hypernova explosion.

*The failed jet model is allowed within the model uncertainty.