Energy dissipation of relativistic outflow

〜Internal and External Shocks〜

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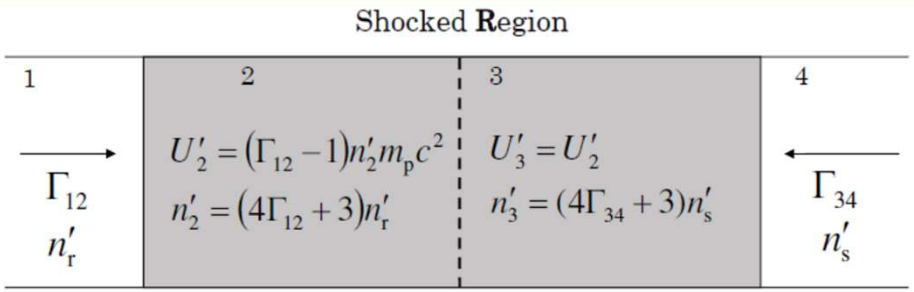
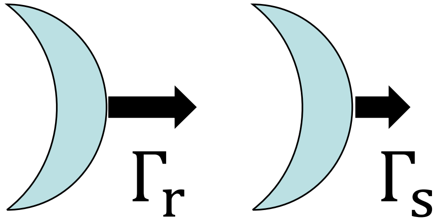
Prompt Emission

- Eiso= 10^{52}– 10^{55} erg may require high efficiency of energy dissipation.
- Several gamma-ray polarization reports imply synchrotron emission. (Some can be photospheric)
- Jets are driven by Blandoford-Znajek process?
- Then, magnetically dominated jets?
- The classical internal shock model works?

Objection to Internal Shock Model



Classical picture



collide of two shells → merge

$$\Gamma_m \approx \sqrt{\frac{M_r\Gamma_r+M_s\Gamma_s}{M_r/\Gamma_r+M_s/\Gamma_s}}$$

Energy dissipation efficiency

$$f \equiv \frac{\Gamma_{\mathrm{m}}E_{\mathrm{int}}}{(M_{\mathrm{r}}\Gamma_{\mathrm{r}}+M_{\mathrm{s}}\Gamma_{\mathrm{s}})c^2} = 1-\frac{2\sqrt{\Gamma_{\mathrm{r}}/\Gamma_{\mathrm{s}}}}{1+\Gamma_{\mathrm{r}}/\Gamma_{\mathrm{s}}} \approx 1-2\sqrt{\Gamma_{\mathrm{s}}/\Gamma_{\mathrm{r}}}$$

Equal mass

$\Gamma_{\mathrm{r}} \gg \Gamma_{\mathrm{s}}$

If $\Gamma_r/\Gamma_s=2$ **⇒f=0.057**

$\Gamma_r/\Gamma_s=10$ **⇒f=0.43**

Large dispersion in Γ is required for high f.

Objection to Internal Shock Model

Typical Synchrotron Photon Energy $\varepsilon_{\mathrm{pk}} = \frac{\hbar e B}{m_{\mathrm{e}} c} \gamma_{\mathrm{m}}^2 \Gamma_{\mathrm{m}}$

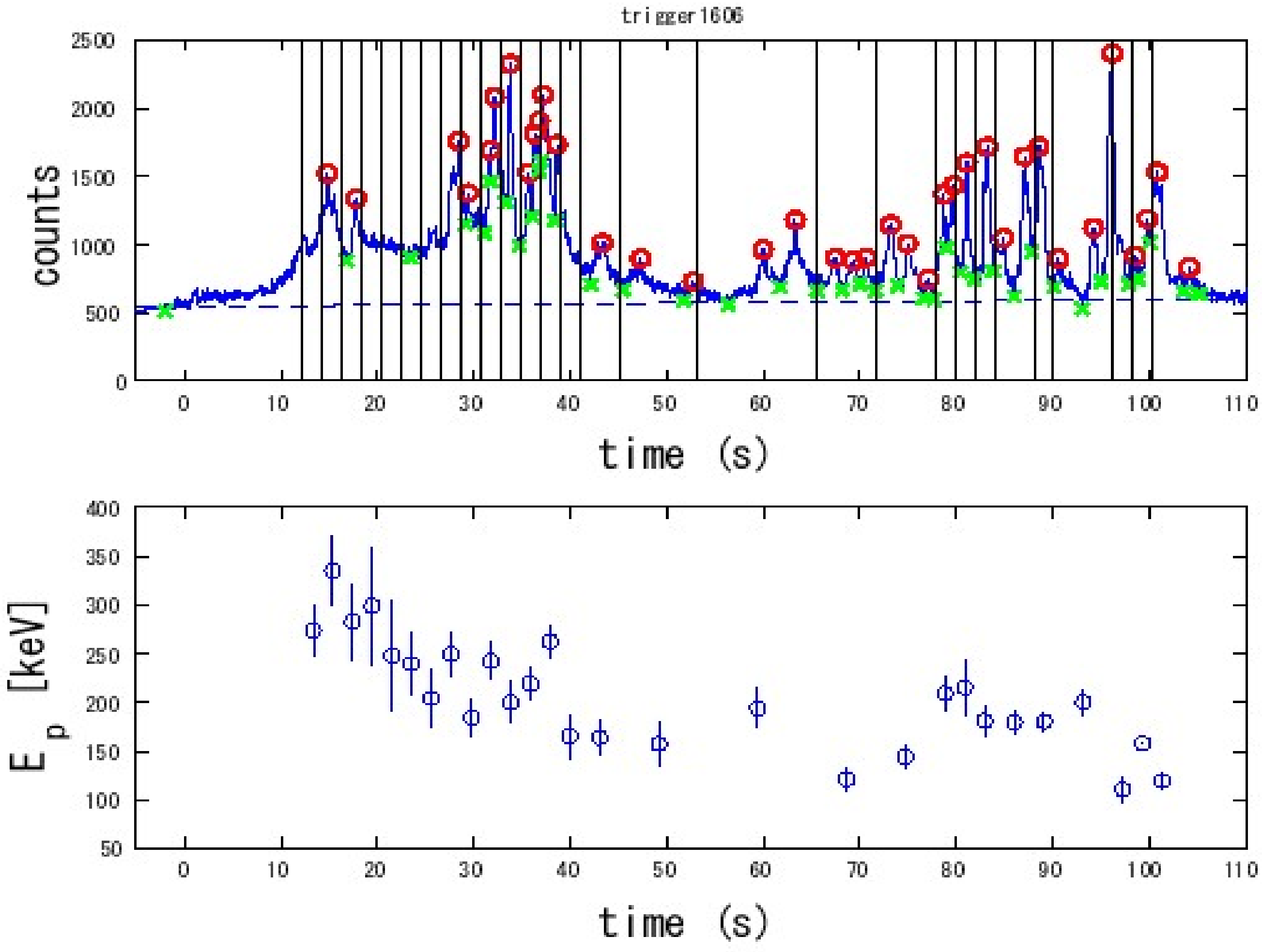
$$\frac{\Gamma_r}{\Gamma_s} = 10 \rightarrow \Gamma_{\mathrm{sh}} = 2.57$$

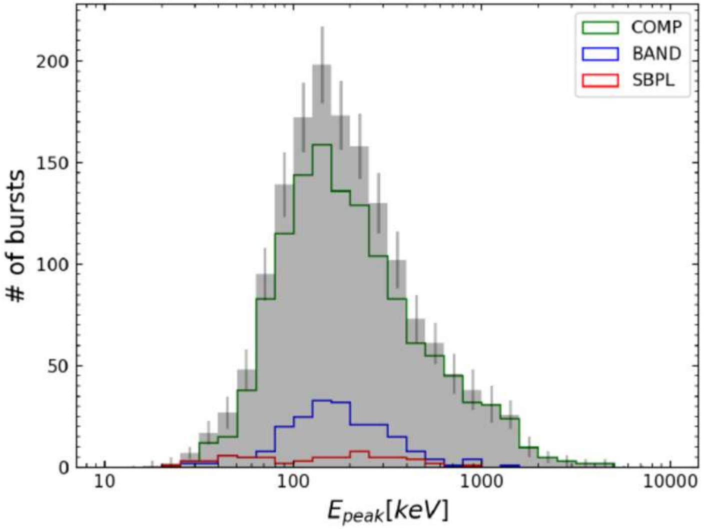
$$\frac{\Gamma_r}{\Gamma_s} = 2 \rightarrow \Gamma_{\mathrm{sh}} = 1.08$$

$$\gamma_{\mathrm{m}} \propto \epsilon_{\mathrm{e}} (\Gamma_{\mathrm{sh}} - 1) \frac{m_{\mathrm{p}}}{m_{\mathrm{e}}} \rightarrow \varepsilon_{\mathrm{pk}} \propto (\Gamma_{\mathrm{sh}} - 1)^2$$

For large dispersion in Γ, large dispersion in $\varepsilon_{\mathrm{pk}}$

Small Dispersion in typical photon energy





Fermi GBM GRB Spectral Catalog 21

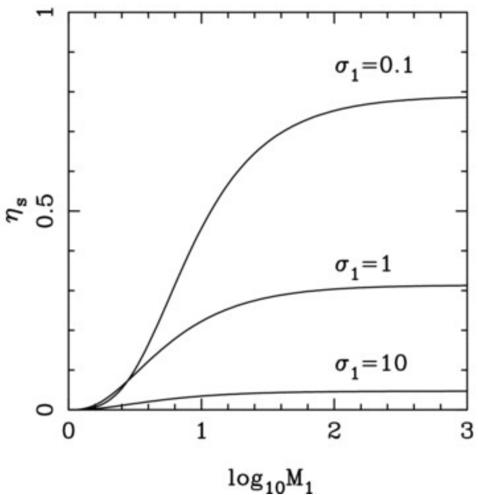
Magnetically dominated case

$$\sigma \equiv \frac{B^2}{4\pi\rho c^2}$$

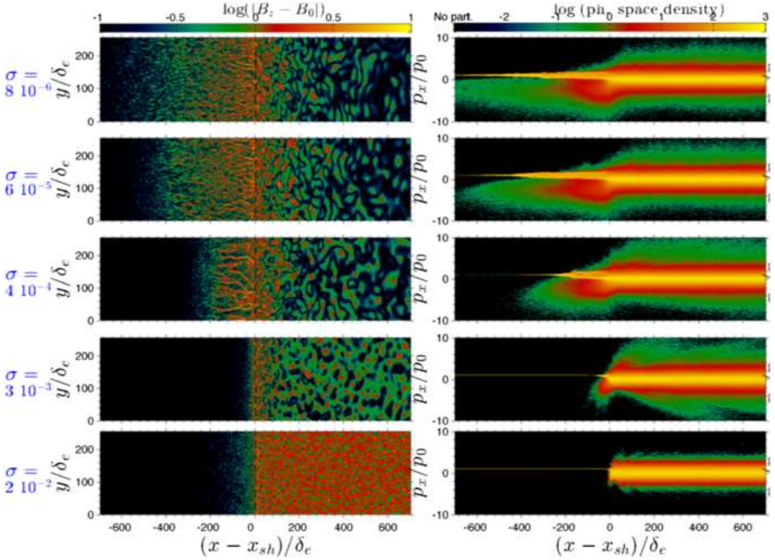
- **High-sigma case,** $\Gamma_{\mathrm{sh}} \simeq \sqrt{\sigma}$.
- **Energy dissipation due to shocks becomes small.**

Thermal energy fraction in the downstream $\frac{3}{8\sigma}$

Dissipation Efficiency



Komissarov 12



Plotnikov+ 18

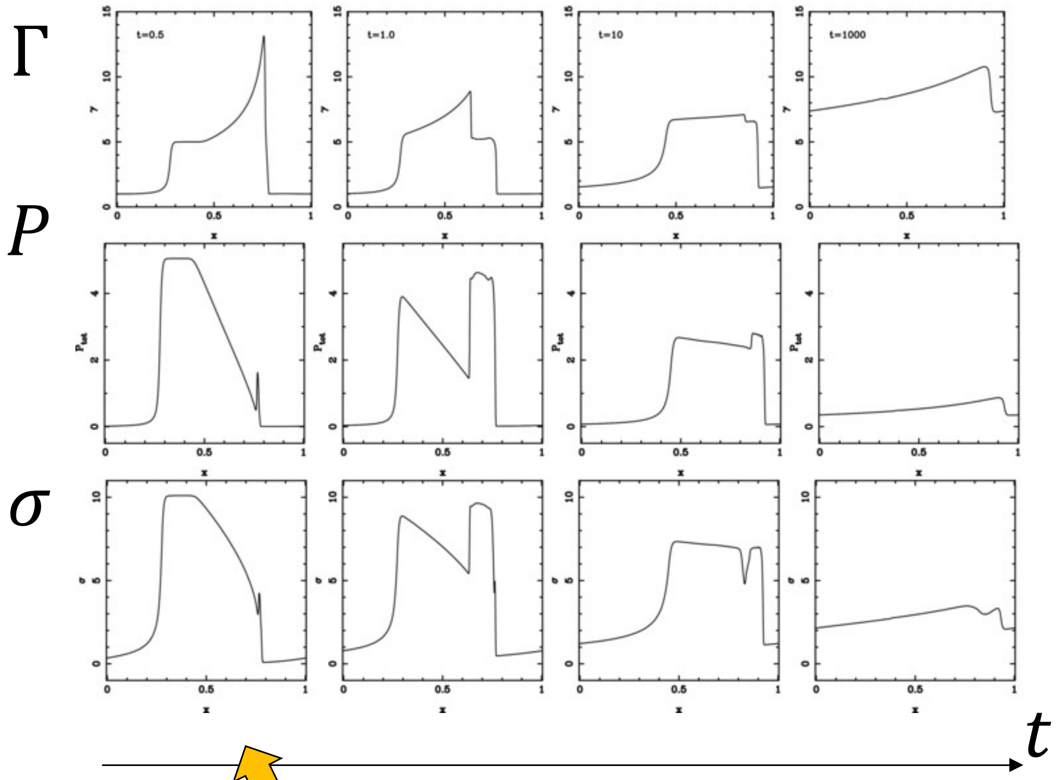
In addition, shock acceleration is hard for high sigma.

Need Reconnection?

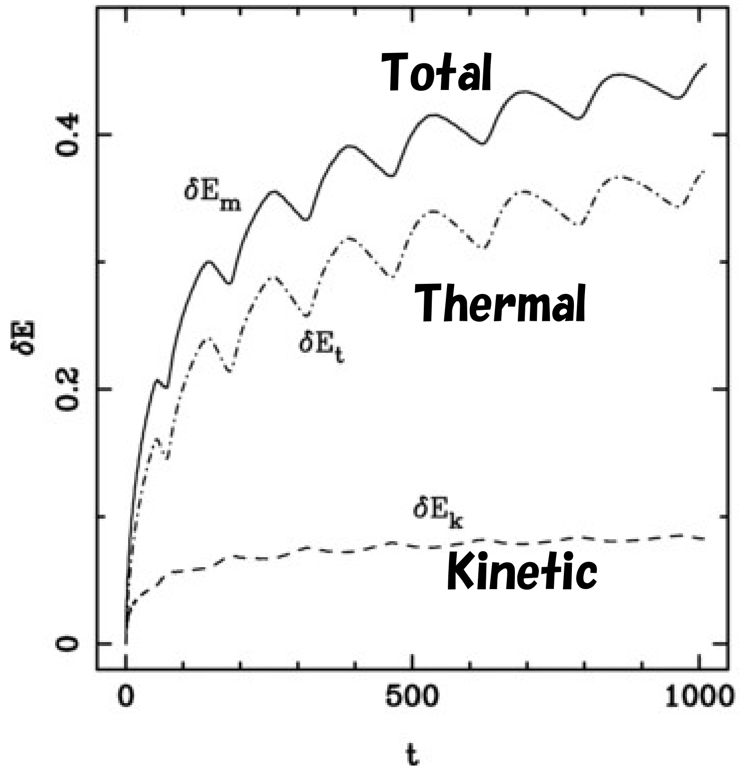
Shock dissipation of high-sigma flows

Komissarov 12

Periodic Boundary



Impulsive acceleration see Granot+ 11

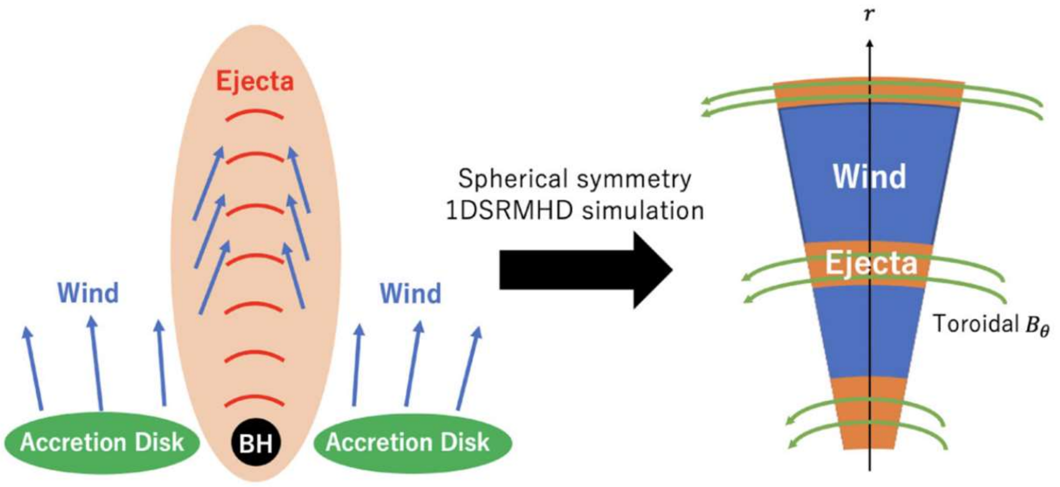


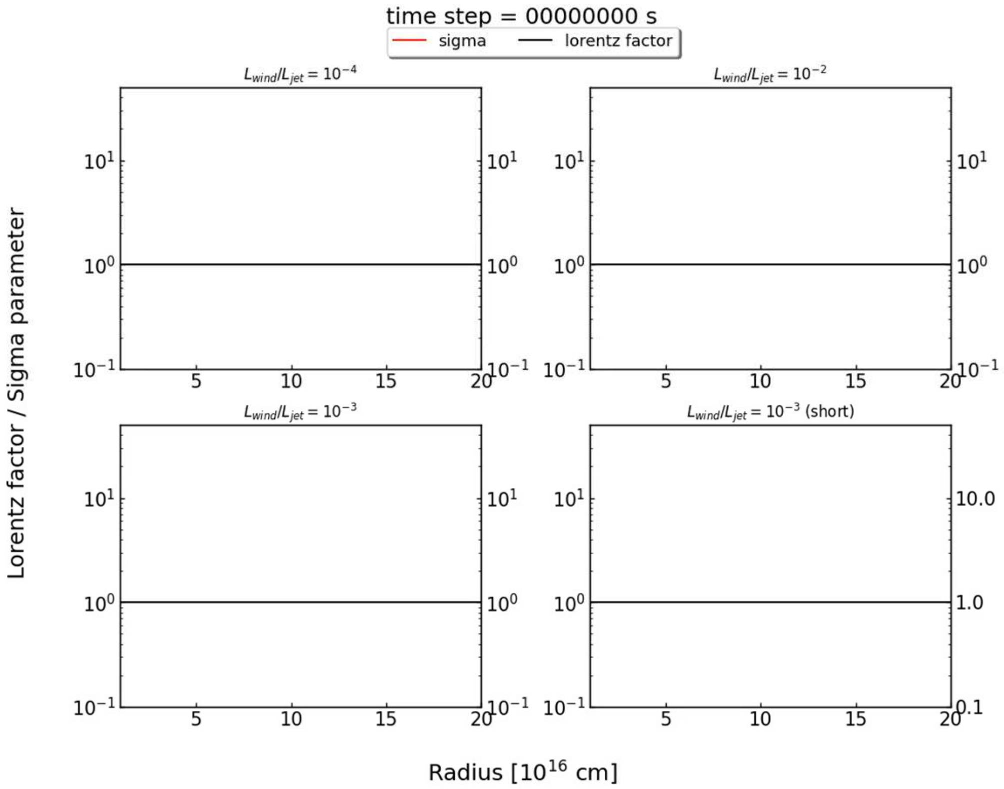
Dissipated Magnetic Energy

1D-spherical simulations

Kusafuka, KA+ 23

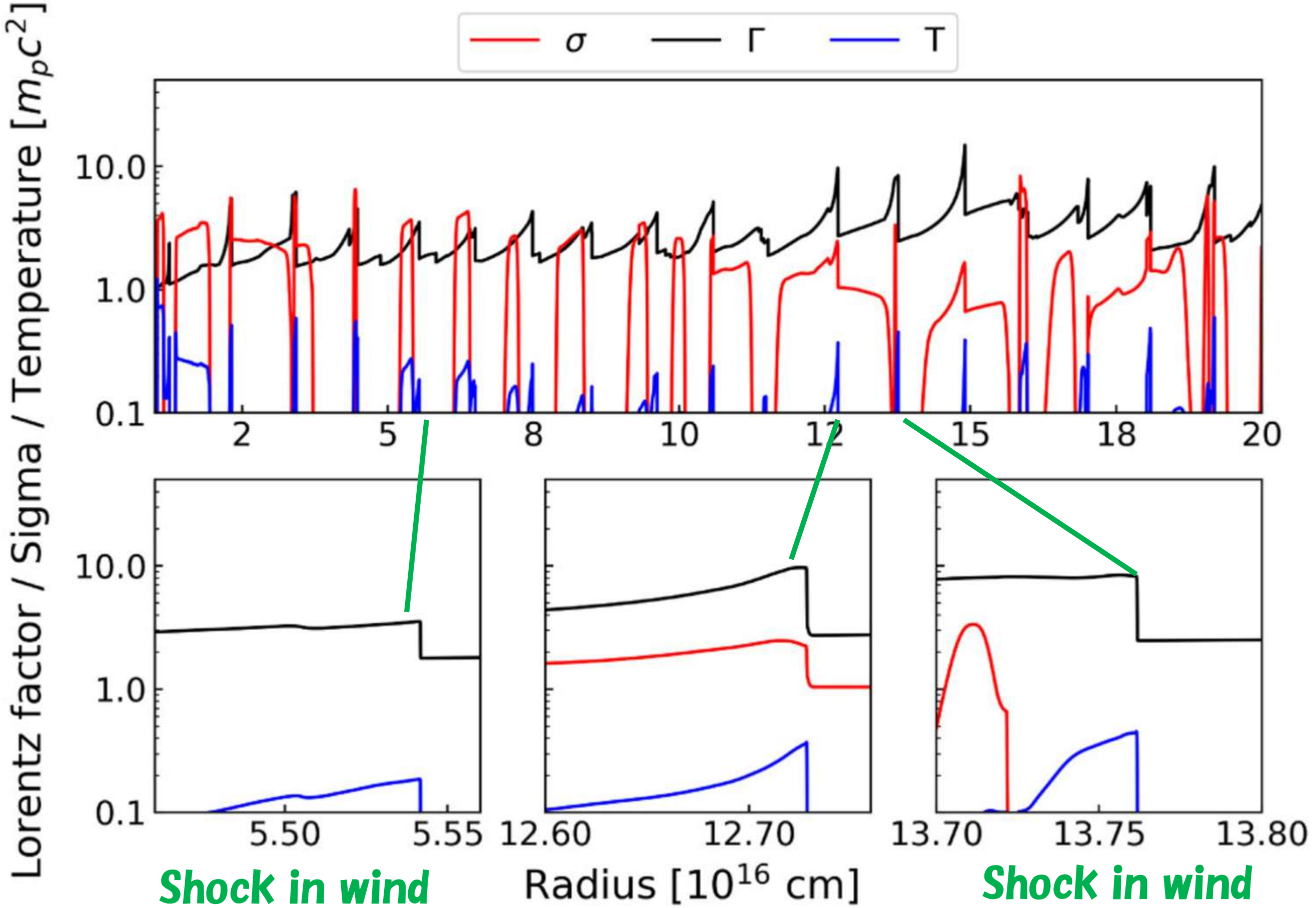
Intermittent ejection





Shocks in wind

$$L_{\mathrm{w}} = 10^{-2} L_{\mathrm{j}}$$



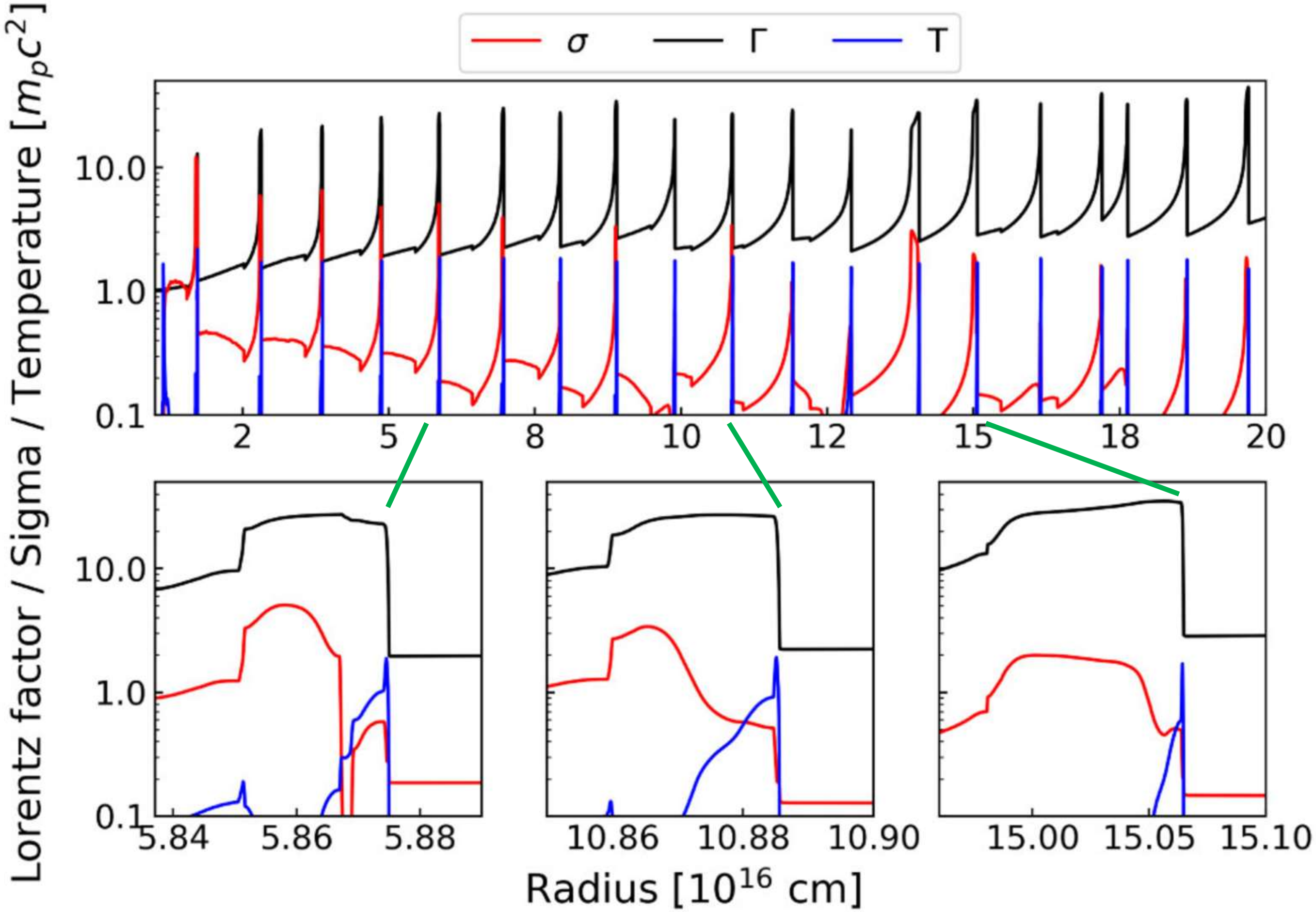
Shock in wind

Shock in rarefaction wave

Shock in wind

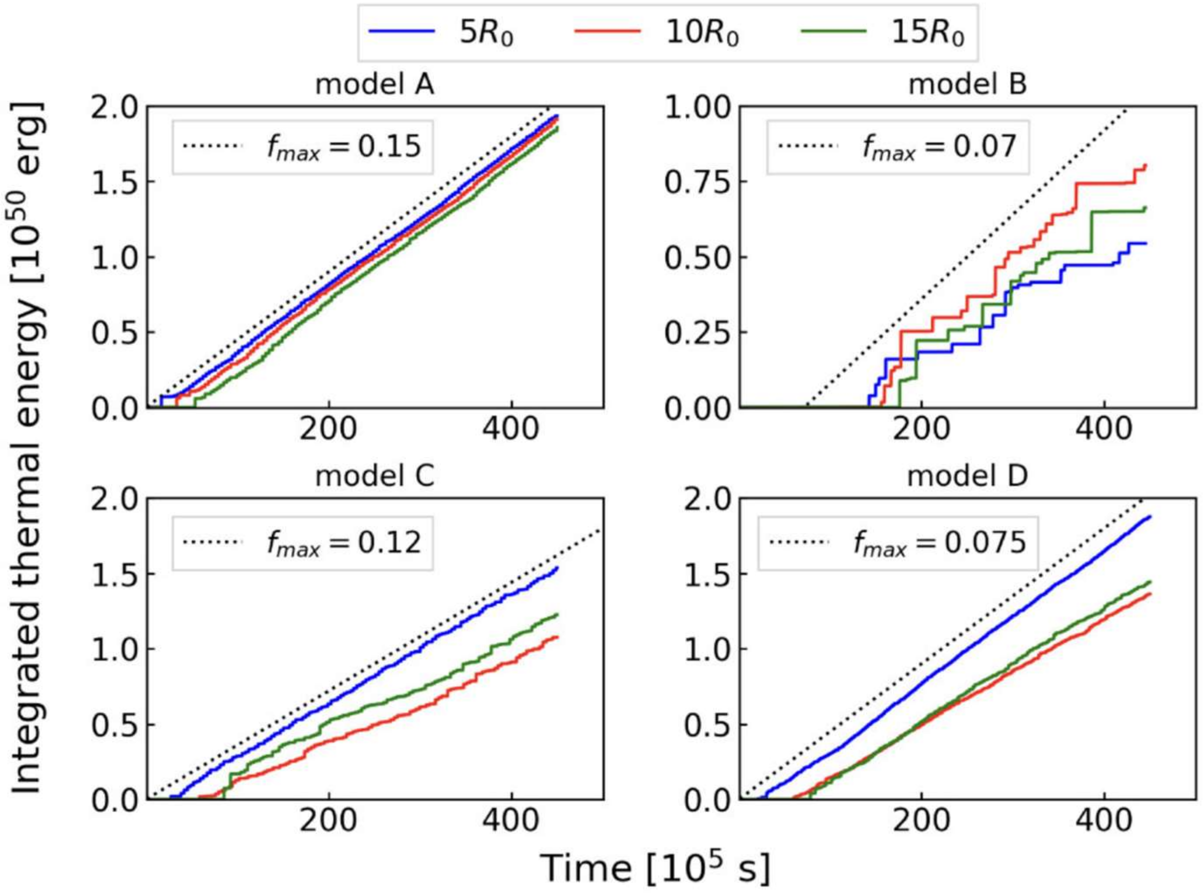
Shocks in rarefaction wave

$L_{\mathrm{w}} = 10^{-4} L_{\mathrm{j}}$



Jet compresses wind to be crushed.

Energy Dissipation



$\sim 10\%$

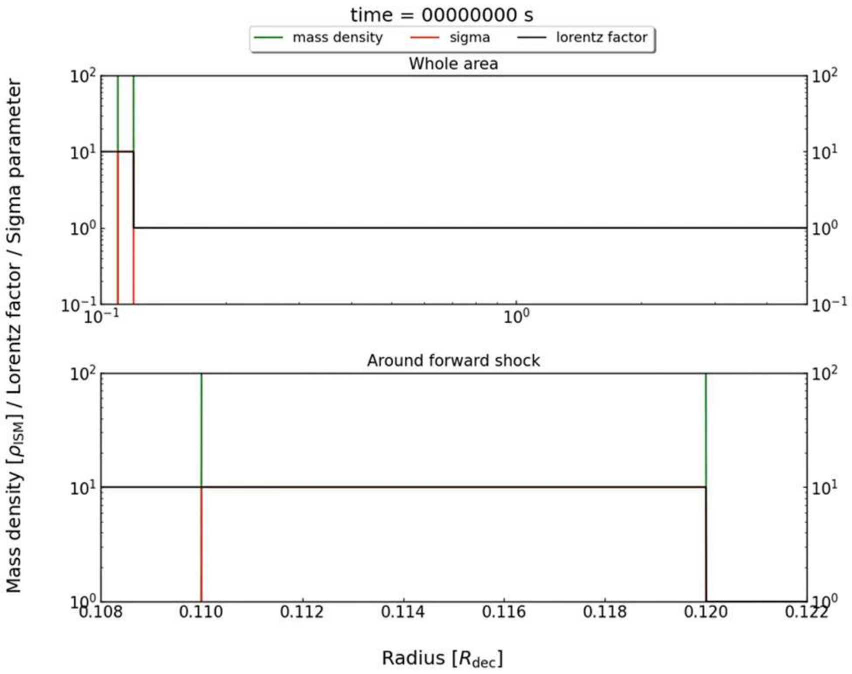
No need for
large dispersion in Γ

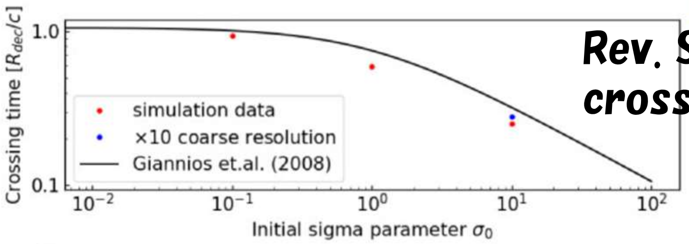
Moderate dispersion in $\Gamma_{\rm sh}$
→ small dispersion in $\varepsilon_{\rm pk}$

$\Gamma > 100$ in GRBs,
which may enhance efficiency

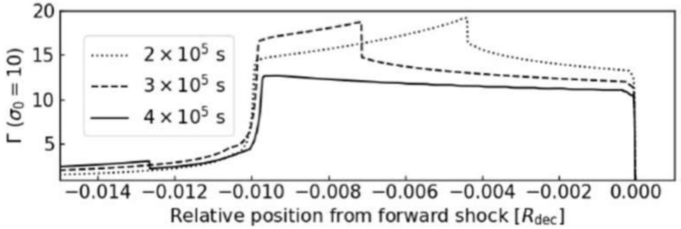
External Shock (Sorry despite session for prompt emission …)

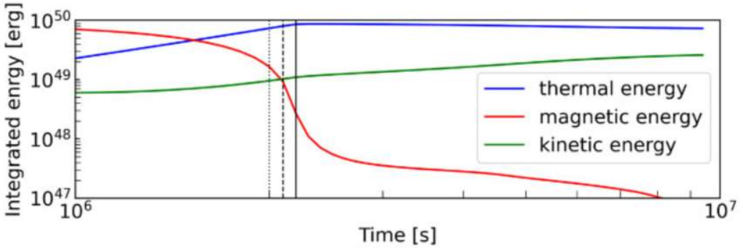
- **External shock is also a way to dissipate the magnetic energy.**

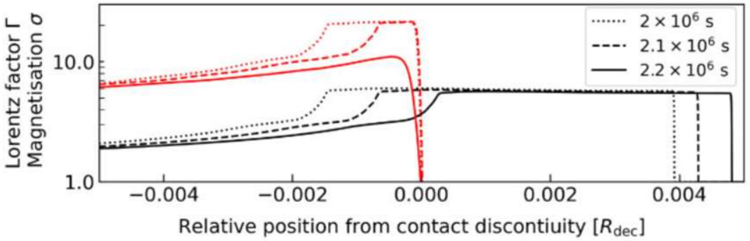




Rev. Shock crossing time







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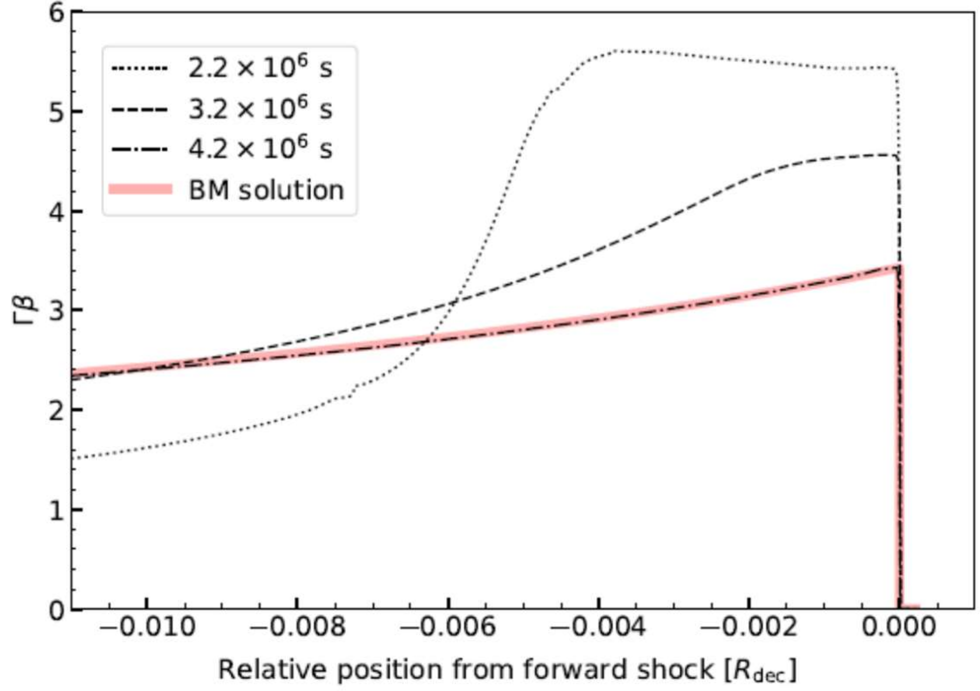
Transition Phase=Energy Injection Phase

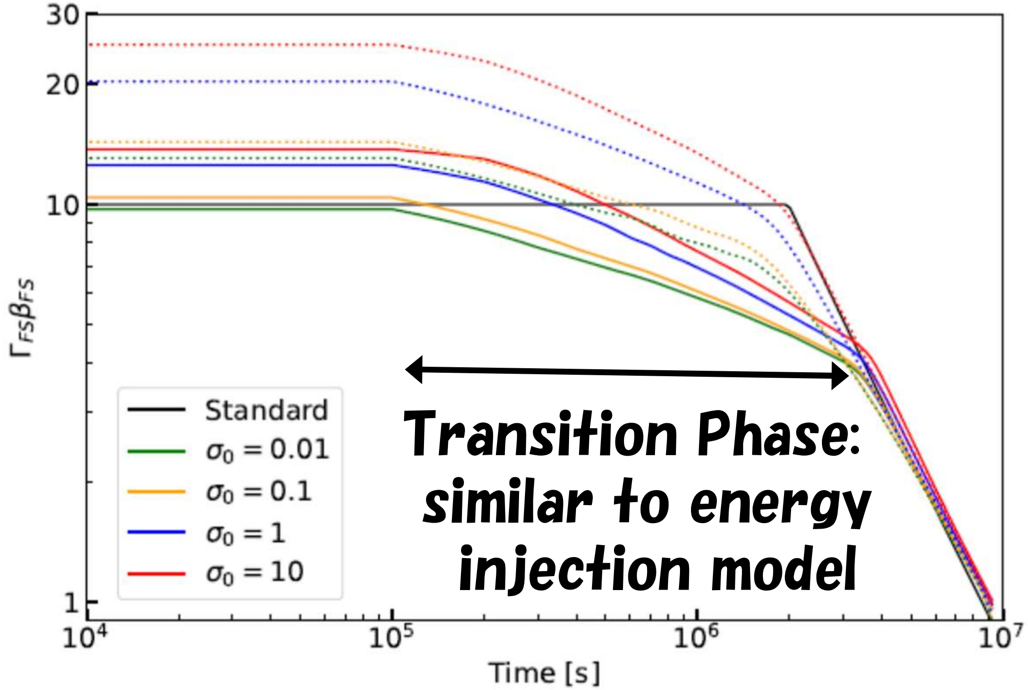
Kusafuka & KA 24

See also Kobayashi & Sari 2000; Mimica et al. 2009

Evolution of $\Gamma\beta$-Profile



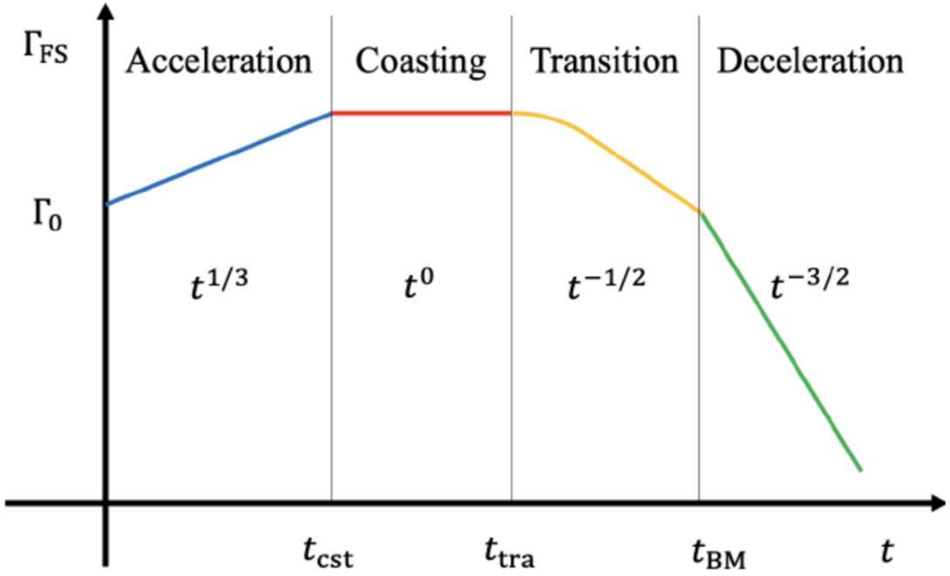
Forward Shock $\Gamma\beta$



Transition Phase: similar to energy injection model

Finite width of ejecta: delay of transition to BM solution.
The transition phase lasts longer than the reverse shock crossing time.

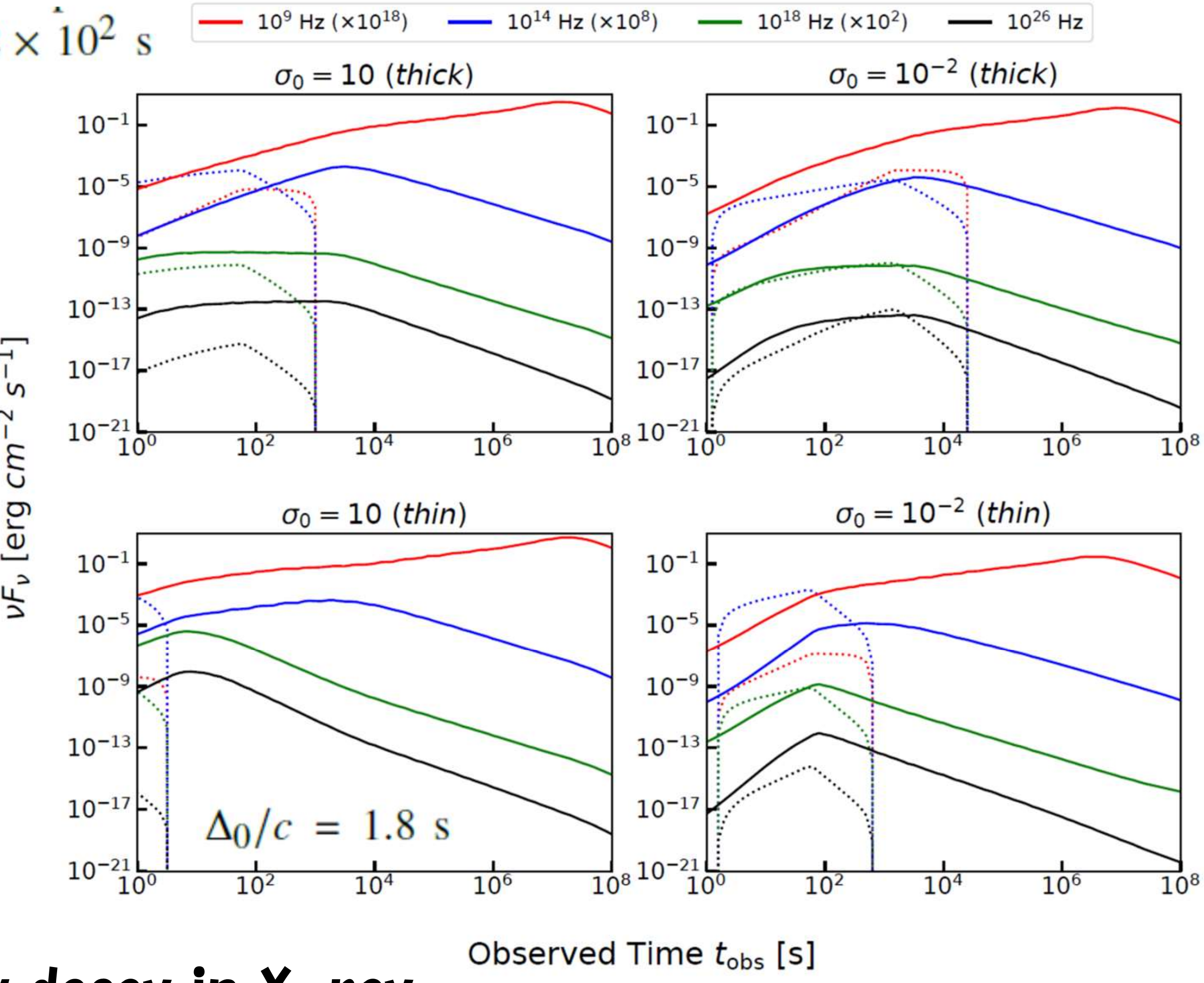
Afterglow lightcurve



$E_0 = 10^{52}$ erg, $\Gamma_0 = 100$, and $n_0 = 1\ \mathrm{cm}^{-3}$.

$\epsilon_e = 0.1$ $\epsilon_B = 0.01$ $p = 2.2$

$\Delta_0/c = 7.2 \times 10^2$ s

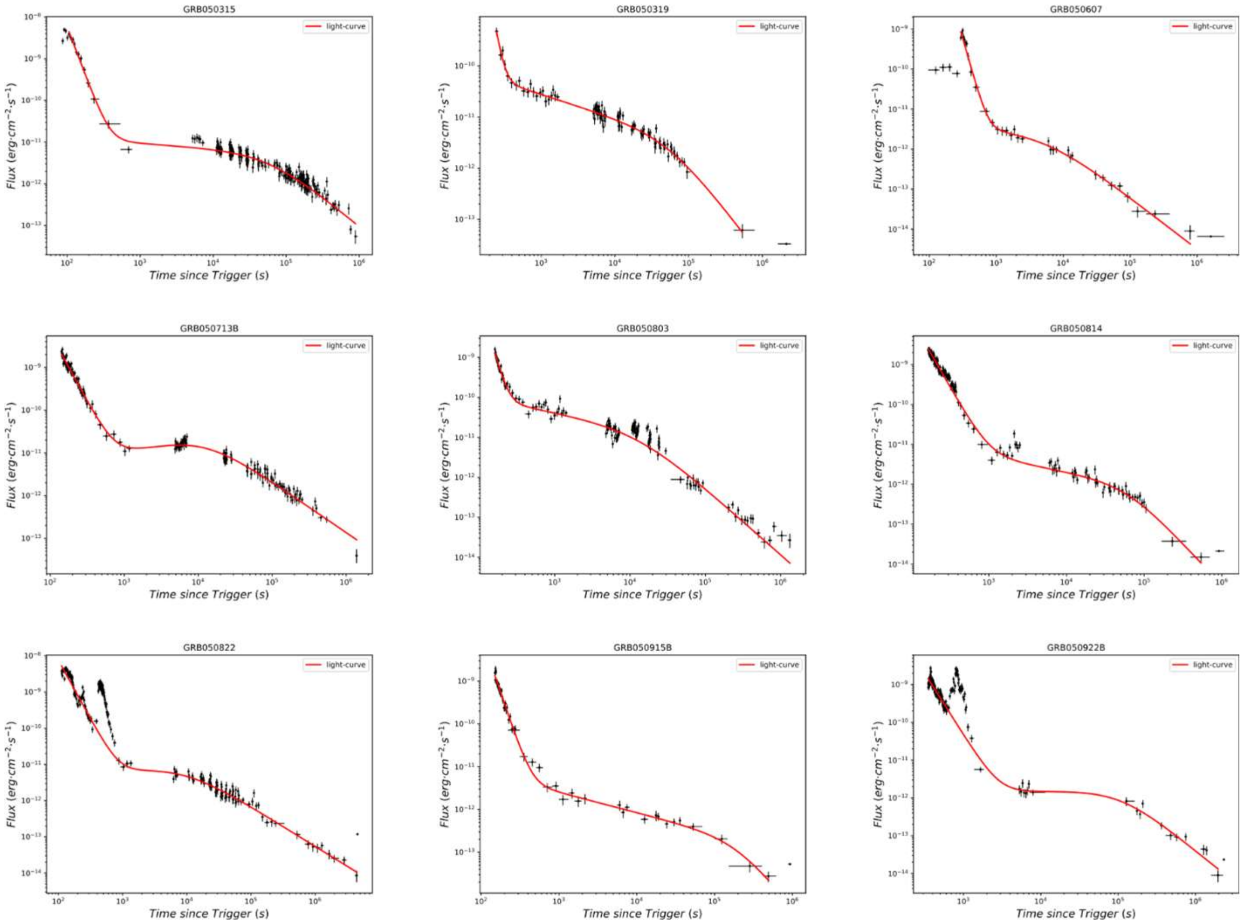


$\Delta_0/c = 1.8$ s

Transition phase leads to shallow decay in X-ray

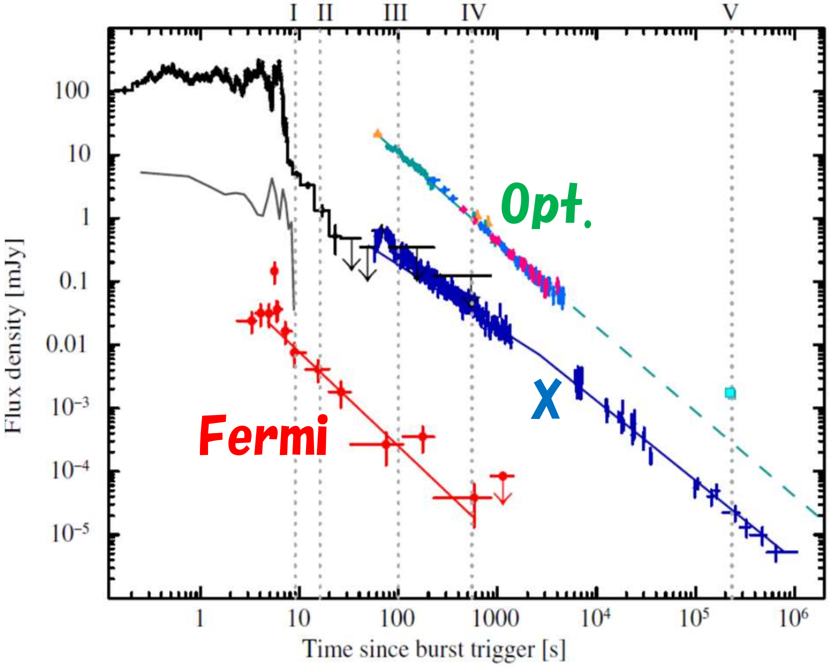
Shallow Decay Phase

X-ray LCs



X.-K. Ding+ 22

GRB 110731A (Ackerman+13)



Fermi-LAT GRBs tend to show no shallow decay.

See Yamazaki+ 20

1D time-dependent calculation

Fukushima, KA+ 2017

Mass:

$$\frac{dM}{dt} = \frac{1}{\Gamma}\frac{dM}{dt'} = 4\pi R^2 c\beta_{\rm sh} n_{\rm ISM} m_{\rm p},$$

Energy (Lorentz factor):

$$\frac{dE'_{\rm sh}}{dt'} = \Gamma c^2 \frac{dM}{dt'} - \frac{dE'_{\rm rad}}{dt'} - \frac{dE'_{\rm ad}}{dt'},$$

$$E_{\rm sh} = \Gamma E'_{\rm sh} = E_0 + Mc^2 - E_{\rm rad}.$$

Density and Volume:

$$n' = \frac{\hat{\gamma}\Gamma + 1}{\hat{\gamma} - 1} n_{\rm ISM},$$

$$V' = M/(m_{\rm p} n').$$

Magnetic Field:

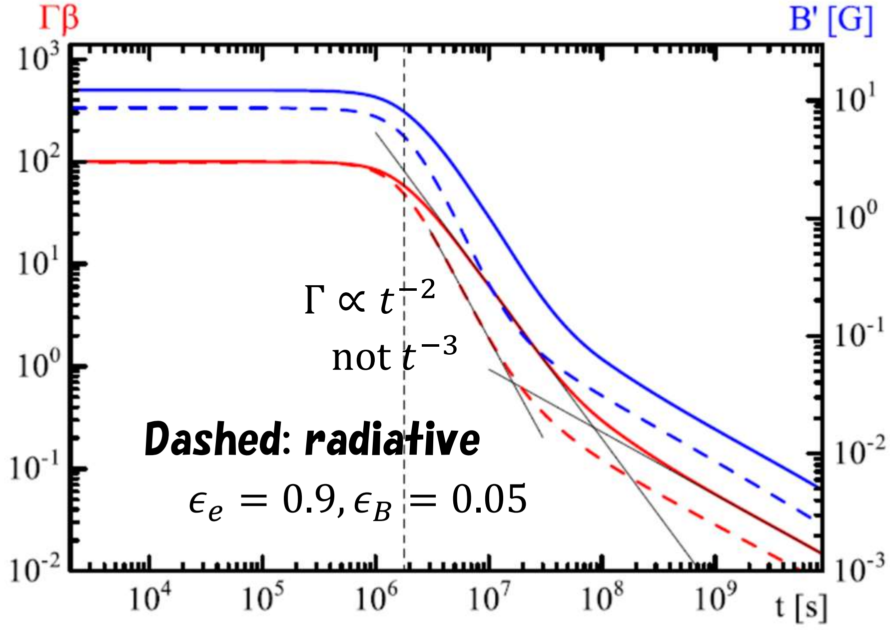
$$\frac{dE'_B}{dt'} = \epsilon_B(\Gamma - 1)c^2 \frac{dM}{dt'}.$$

$$B' = \sqrt{\frac{8\pi E'_B}{V'}}.$$

Non-thermal electrons:

$$\frac{dN'_{\rm e}}{dt'} = \frac{\eta}{m_{\rm p}}\frac{dM}{dt'} = \int_{\varepsilon'_{\rm min}}^{\infty} d\varepsilon' \dot{N}'_{\rm e}(\varepsilon'_{\rm e}),$$

$$\frac{dE'_{\rm e}}{dt'} = \epsilon_{\rm e}(\Gamma - 1)c^2 \frac{dM}{dt'} = \int_{\varepsilon'_{\rm min}}^{\infty} d\varepsilon' \varepsilon_{\rm e}{}' \dot{N}'_{\rm e}(\varepsilon'_{\rm e}).$$



$\Gamma \propto t^{-2}$

not t^{-3}

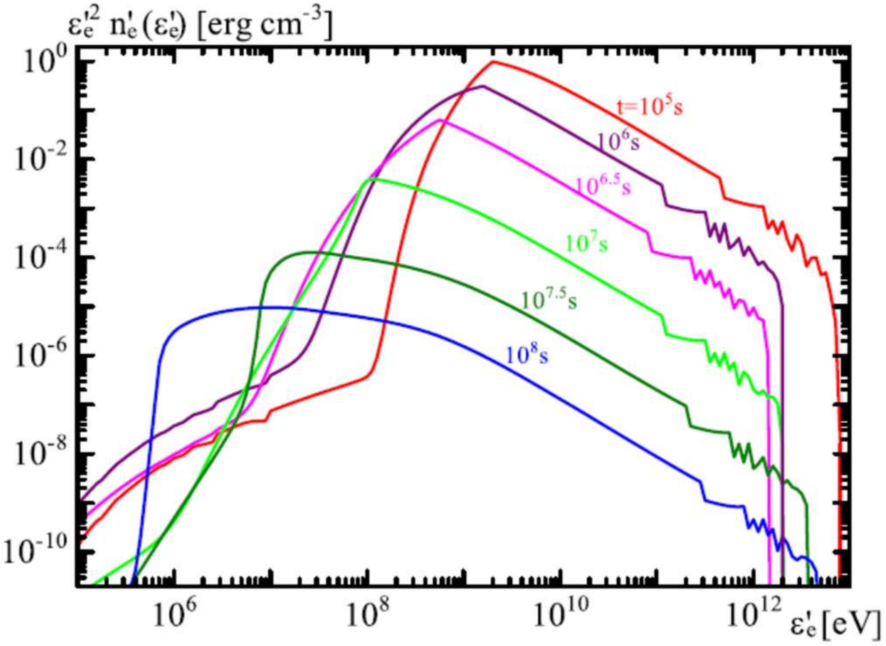
Dashed: radiative

$\epsilon_e = 0.9, \epsilon_B = 0.05$

$E_0 = 10^{52}\text{erg}, \Gamma_0 = 100, n_{\rm ISM} = 1\text{cm}^{-3}, p = 2.2,$
$\epsilon_e = \epsilon_B = 0.1$

1D time-dependent calculation

Electron energy distribution



Taking into account the theta-dependence on observables.

$$\varepsilon_{\rm obs} = \frac{\varepsilon'}{\Gamma(1-\beta\cos\theta)(1+z)},$$

$$t_{\rm obs} = (1+z)\left[\left(t - \frac{R-R_0}{c}\cos\theta\right) + \frac{R_0}{c}(1-\cos\theta)\right]$$

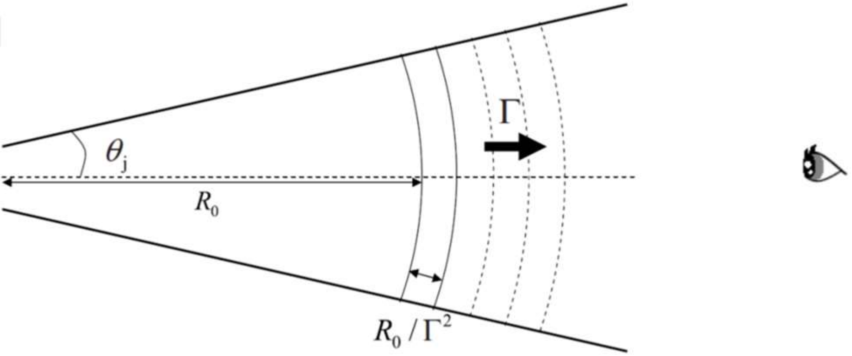
$$\Phi(\varepsilon_{\rm obs}, t_{\rm obs}) = \frac{dN_\gamma}{dS_{\rm obs}\,dt_{\rm obs}\,d\varepsilon_{\rm obs}}$$

$$= \int d\theta \left(\frac{R(t'_\theta)}{D}\right)^2 \frac{\sin\theta|\cos\theta'|cn'_\gamma(\varepsilon'_\theta, t'_\theta)}{2\Gamma^2(1-\beta\cos\theta)(1-\beta_{\rm sh}\cos\theta)},$$

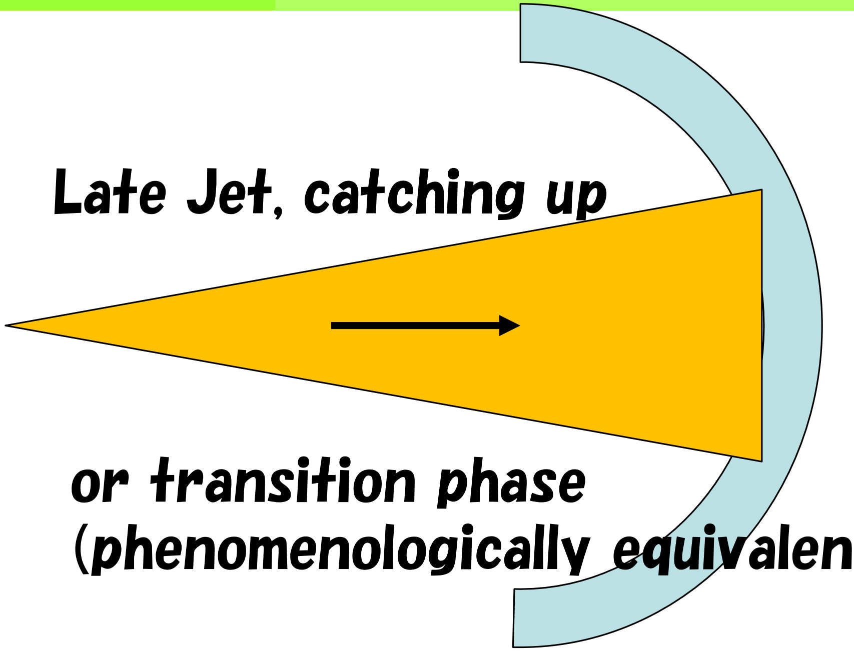
以下では基本的に

$$E_0 = 10^{53}\ \mathrm{erg},\ \epsilon_e = 0.1,\ \ \epsilon_B = 10^{-3}$$

$$\Gamma_0 = 300,\ n_0 = 1\ \mathrm{cm}^{-3},\ \text{and}\ p = 2.2$$



Energy Injection Model



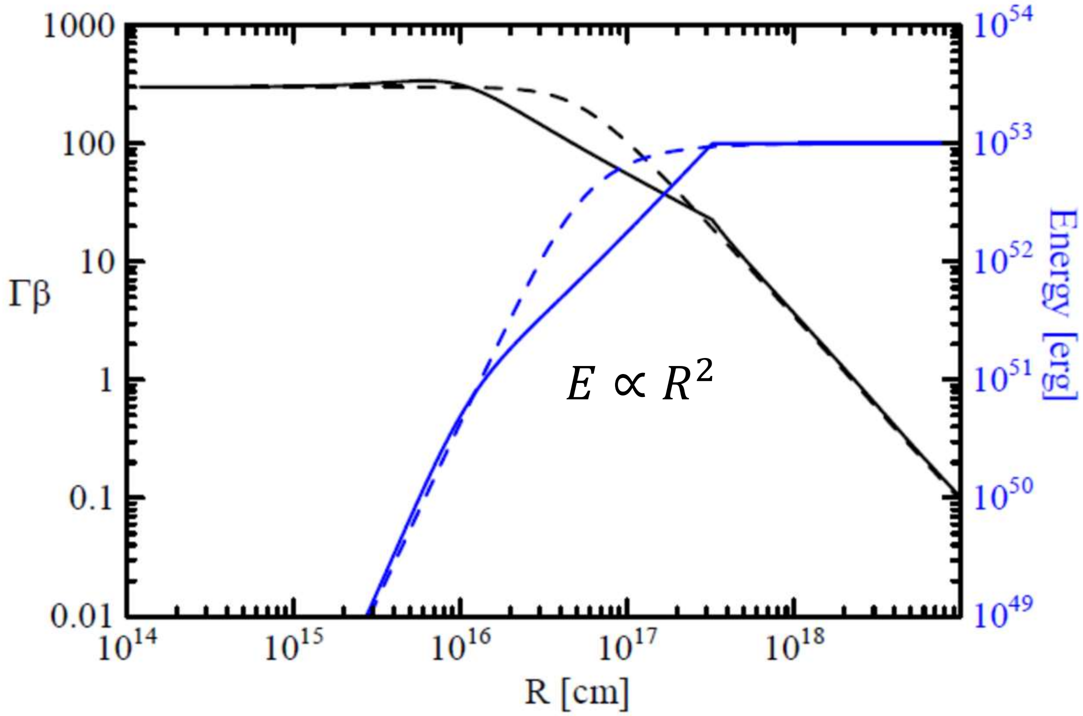
Late Jet, catching up

or transition phase
(phenomenologically equivalent)

Shock Front

$$E = E_{\rm i} + (E_0 - E_{\rm i}) \left(\frac{R}{R_{\rm e}}\right)^2, \quad \text{for} \quad R < R_{\rm e}.$$

$R_{\rm e} = 3.2 \times 10^{17}$ cm $\quad E_{\rm i} = 10^{51}$ erg



$E \propto R^2$ leads to $\Gamma \propto R^{-1/2}$

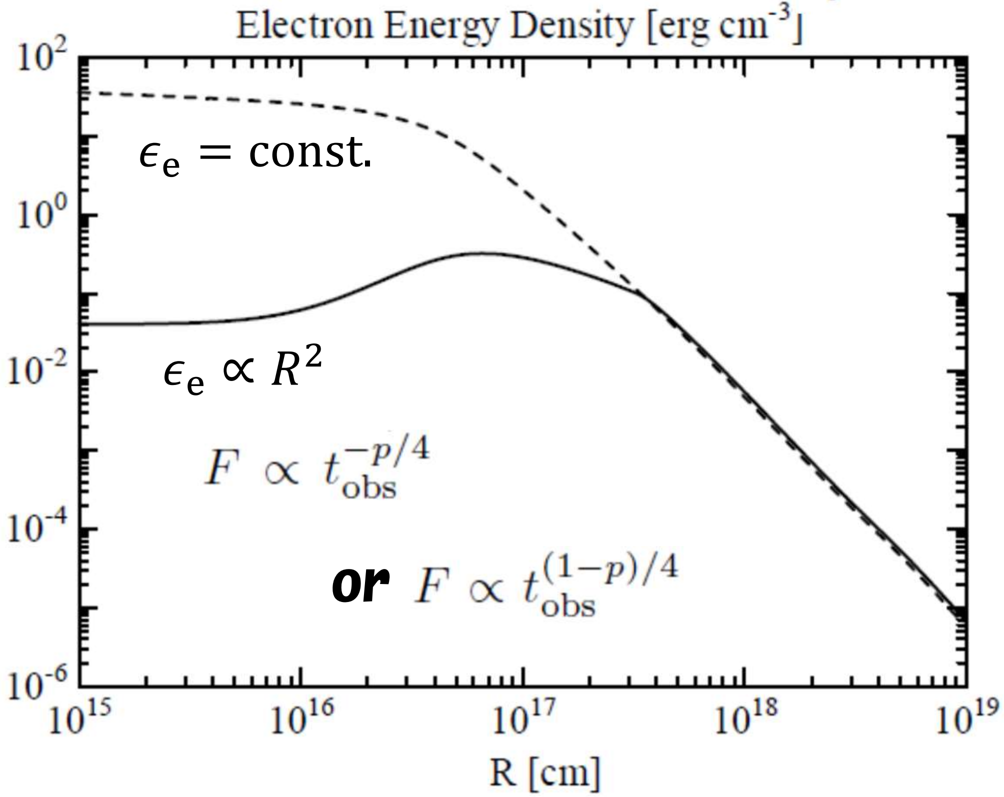
but $\Gamma \propto R^{-0.8}$ for $R < R_{\rm e}$.

Phenomenological Model

Evolving ϵ_e

$$\epsilon_e = \epsilon_i + (\epsilon_f - \epsilon_i)\left(\frac{R}{R_e}\right)^2, \quad \text{for} \quad R < R_e.$$

$$\epsilon_i = 10^{-4}$$



$\epsilon_e = \text{const.}$

$\epsilon_e \propto R^2$

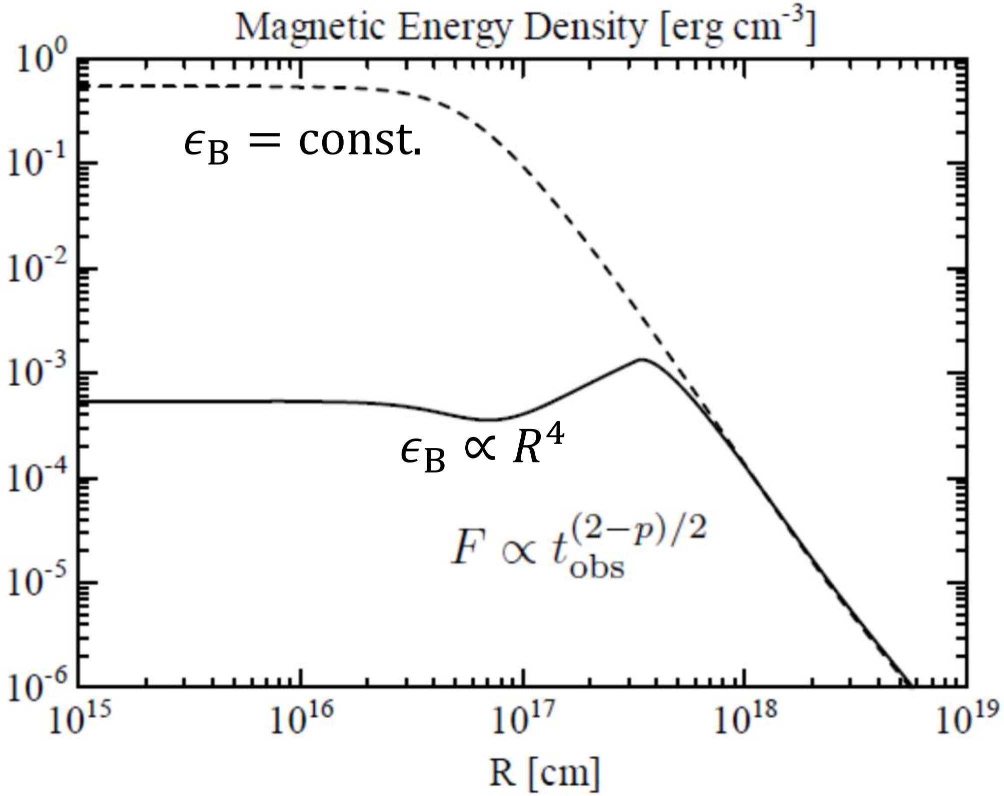
$F \propto t_{\text{obs}}^{-p/4}$

or $F \propto t_{\text{obs}}^{(1-p)/4}$

Evolving ϵ_B

$$\epsilon_B = \epsilon_i + (\epsilon_f - \epsilon_i)\left(\frac{R}{R_e}\right)^4, \quad \text{for} \quad R < R_e$$

$$\epsilon_i = 10^{-6}$$



$\epsilon_B = \text{const.}$

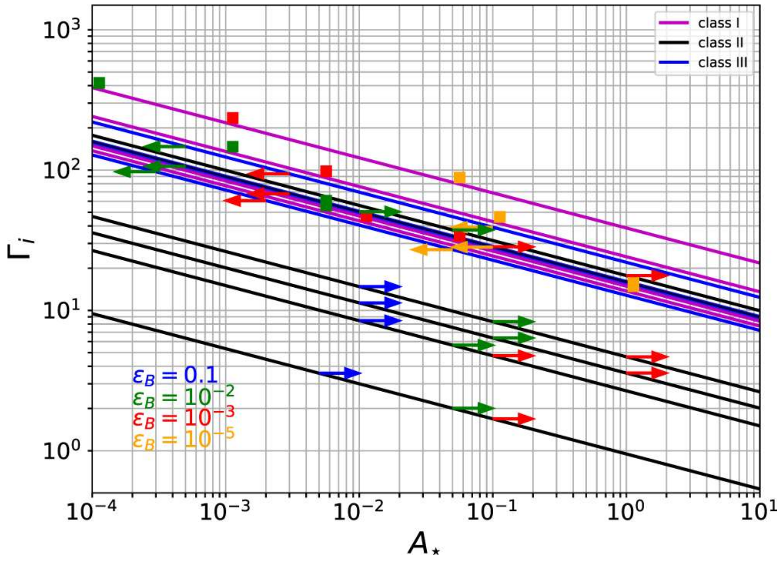
$\epsilon_B \propto R^4$

$F \propto t_{\text{obs}}^{(2-p)/2}$

Low-Γ + Wind

Wind Model

See Dereli-Bégué +22



$$\rho = 5.0 \times 10^{11} A_* \left(\frac{R}{1\ \mathrm{cm}}\right)^{-2}\ \mathrm{g\ cm^{-3}}$$

$A_* = 1$ corresponds to $10^{-5} M_\odot\ \mathrm{yr}^{-1}$

$$E_0 = \Gamma_0^2 M(R_{\mathrm{dec}}) c^2$$

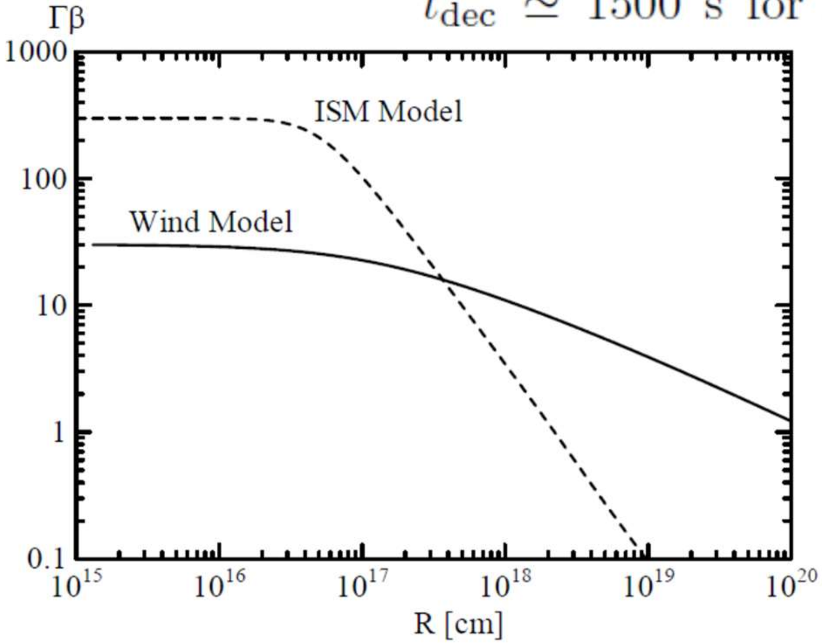
$$t_{\mathrm{dec}} \simeq (1+z)\frac{R_{\mathrm{dec}}}{5c\Gamma_0^2}$$

$$\simeq 150(1+z) A_*^{-1} \left(\frac{E_0}{10^{53}\ \mathrm{erg}}\right)\left(\frac{\Gamma_0}{30}\right)^{-4}\ \mathrm{s}$$

coasting phase, $F \propto t_{\mathrm{obs}}^{(2-p)/2}$

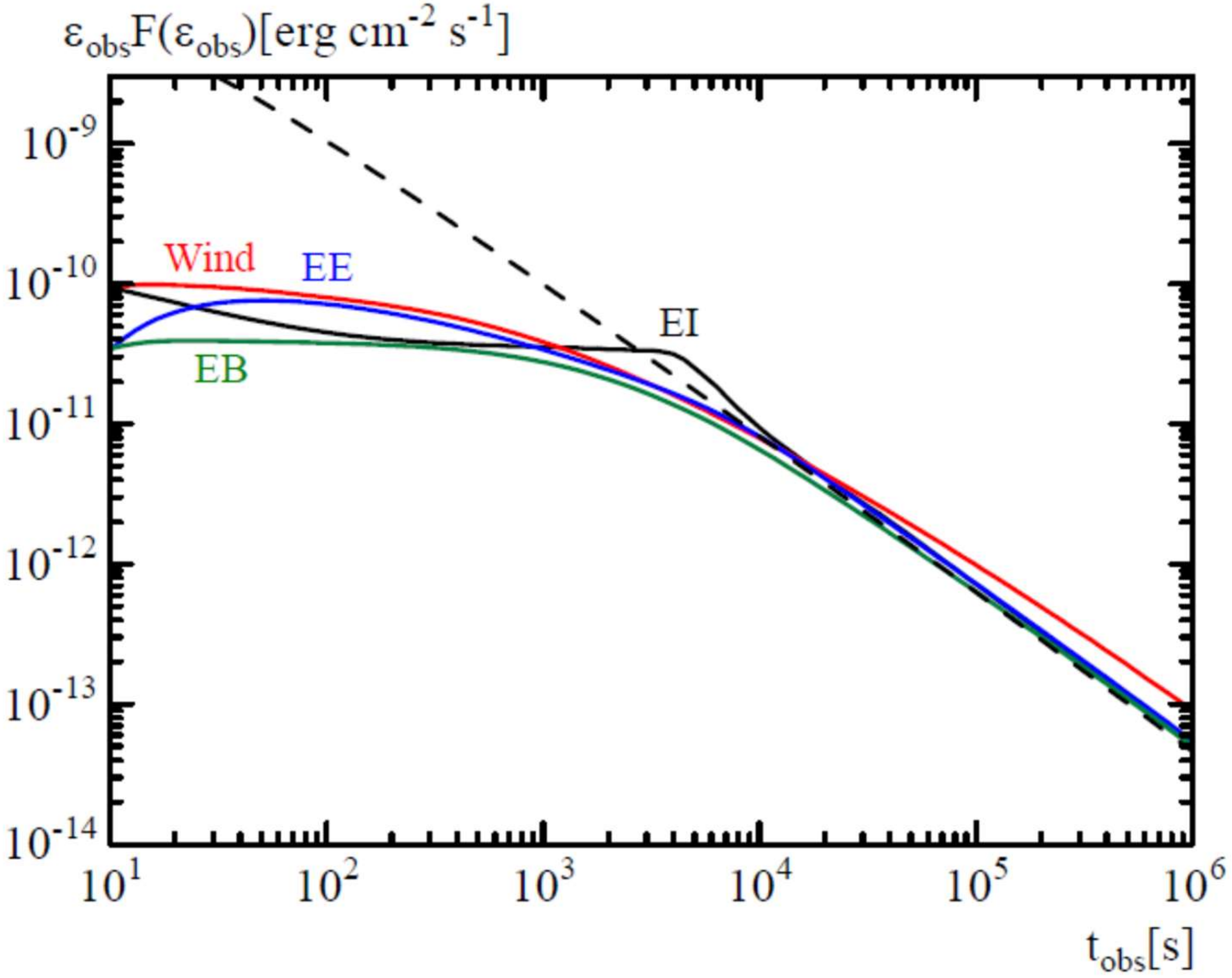
$A_* = 0.3,\ E_0 = 2 \times 10^{53}$ erg, and $\Gamma_0 = 30$

$t_{\mathrm{dec}} \simeq 1500$ s for $z = 0.5$.

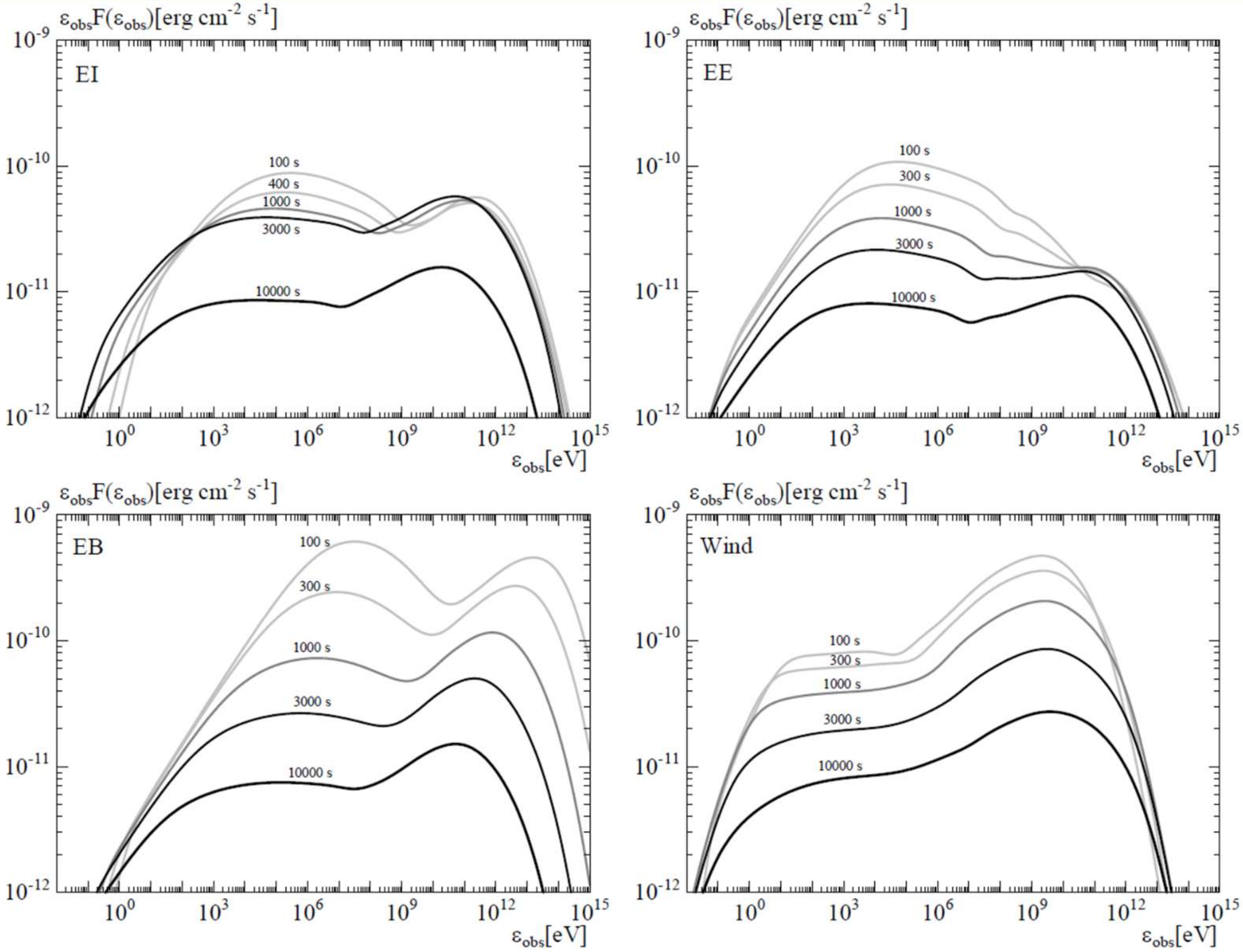


Lightcurves

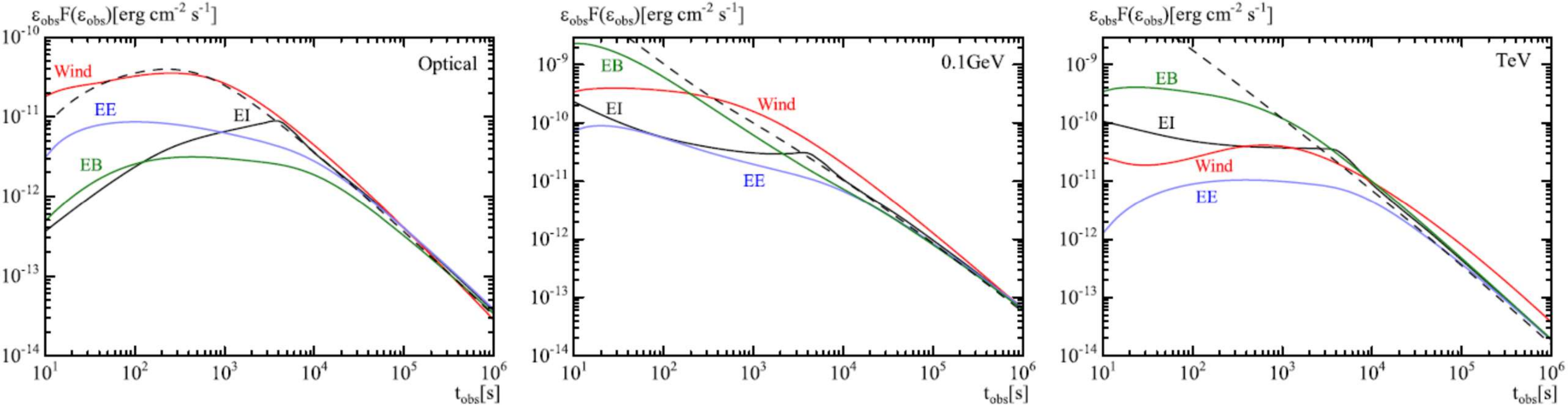
X-ray (1keV)



Spectrum Evolution



Multi-wavelength Lightcurves



Optical can be polluted by reverse shock component.
Variety in TeV lightcurves.

Summary

- **Internal Shock**. High sigma outflow can be dissipated via interaction with winds or rarefaction waves.
- **External Shock**. Transition phase before catch-up of rarefaction wave=Energy injection phase. Relevant for Shallow-decay phase?
- **GRB 240529A**. Shallow decay with gamma-rays.
- **BOAT GRB**. Model without early jet break