中性子星連星合体後の活動性

Activities after neutron star binary merger

Shota Kisaka

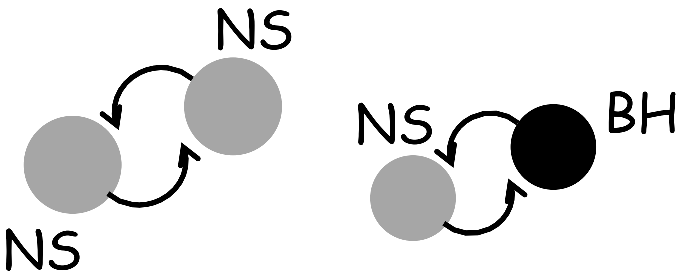
(Aoyama Gakuin Univ.)

Merger of Neutron Star Binaries

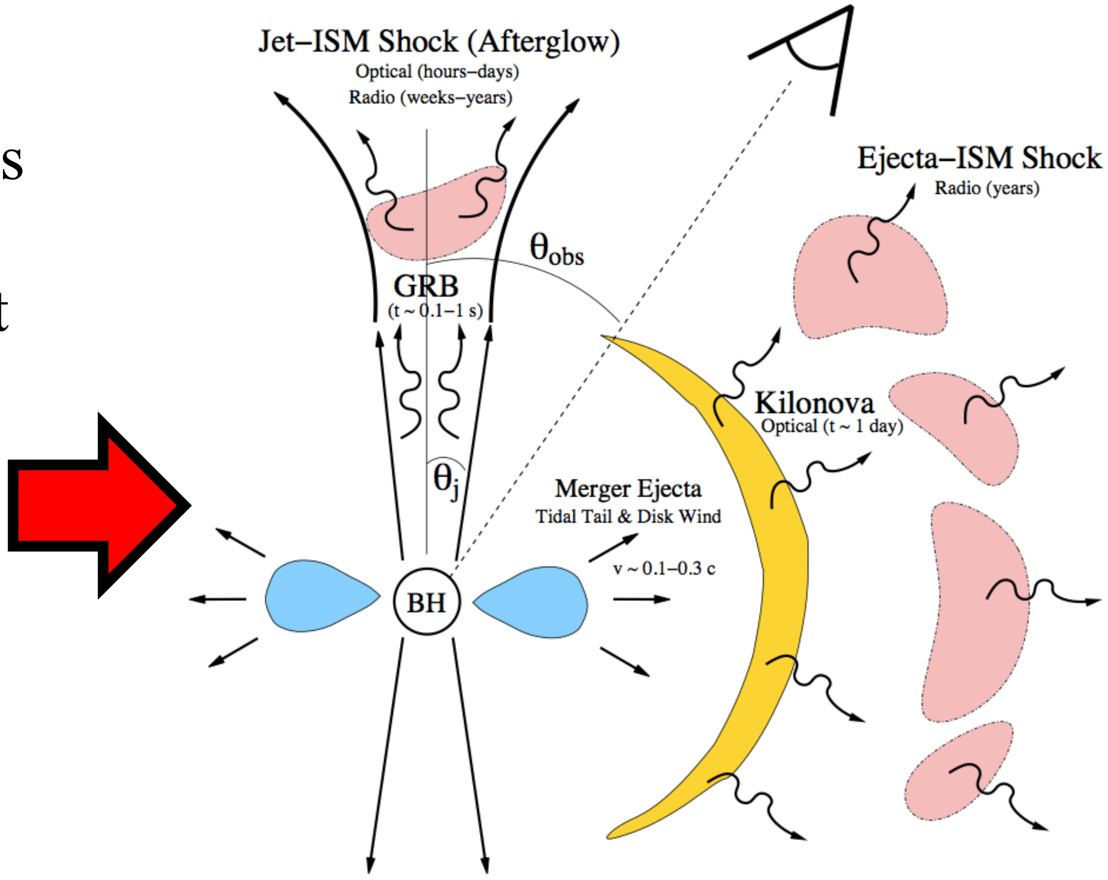
EM counterparts to GW sources are important to maximize scientific returns from the detection of GWs.

Metzger & Berger 12

e.g.,
- Localization
- Origin of short GRBs
- Equation of state
- r-process enrichment

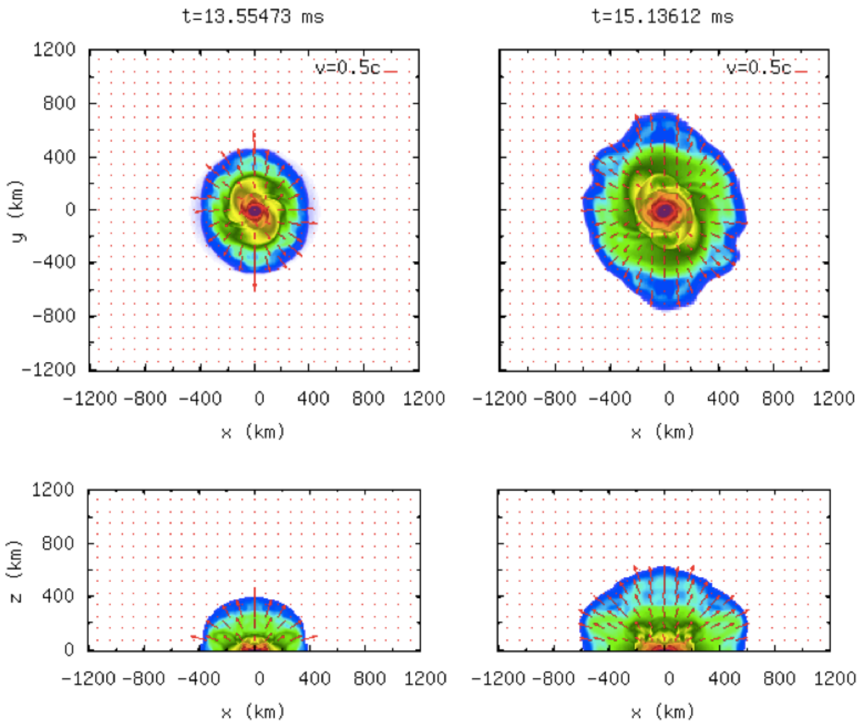


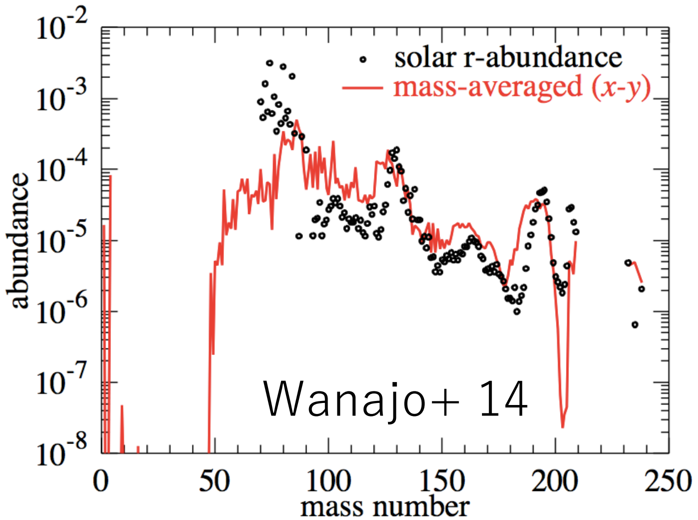
NS binary



Merger Ejecta

Hotokezaka+ 13





Bounded mass

$$M_{\rm d} \sim 10^{-1} M_\odot$$

Ejecta mass

NS-NS: $M_{\rm ej} \sim 10^{-4} - 10^{-2} M_\odot$

BH-NS: $M_{\rm ej} \lesssim 10^{-1} M_\odot$

Ejecta velocity

$$v_{\rm ej} \sim 0.1 - 0.3c$$

Homologous expansion

$$R_{\rm ej} \sim v_{\rm ej} t$$

r-process nucleosynthesis

Neutron-rich Ejecta

$\Rightarrow T_{\rm n-capture} < T_{\beta-{\rm decay}}$

Iron ejecta are also possible.

Energy Sources

- **Rotation energy:**

$$\sim 10^{53} \left(\frac{M_{\rm BH}}{3M_\odot}\right) \ {\rm erg} \qquad (a/M_{\rm BH} = 0.5)$$

- **Disk gravitational energy:**

$$\sim 10^{52} \left(\frac{M_{\rm d}}{10^{-1}M_\odot}\right) \ {\rm erg}$$

- **Ejecta kinetic energy:**

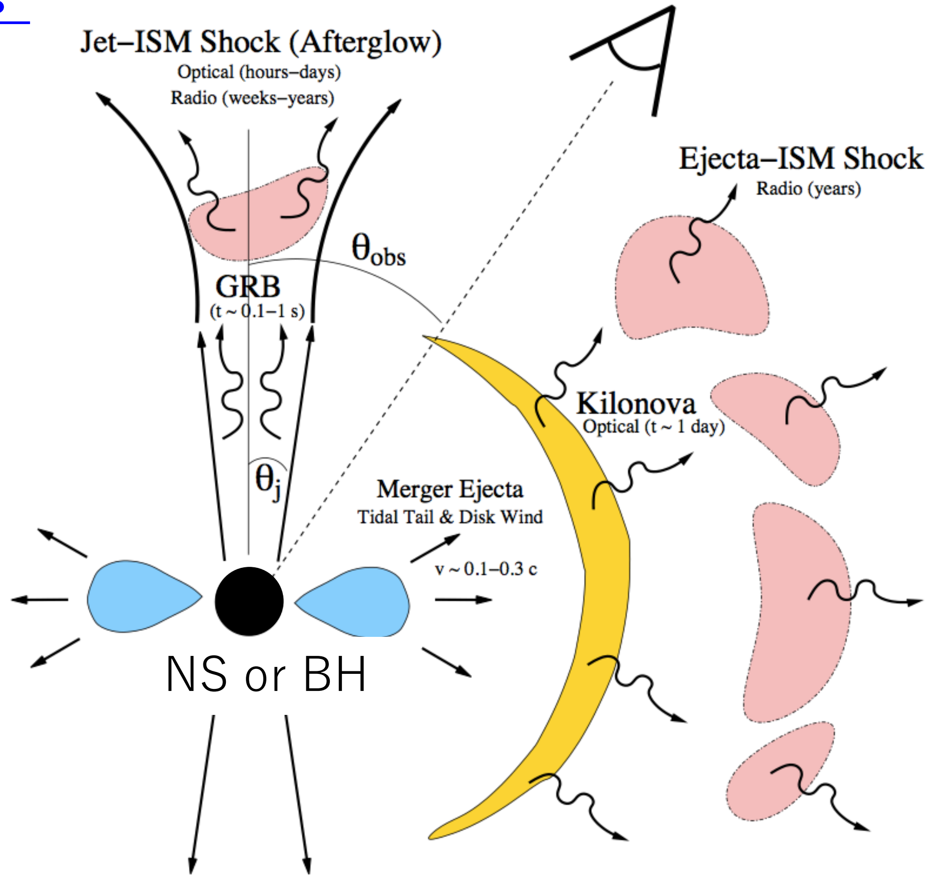
$$\sim 10^{51} \left(\frac{M_{\rm ej}}{10^{-2}M_\odot}\right) \left(\frac{v_{\rm ej}}{0.3c}\right)^2 \ {\rm erg}$$

- **Radioactivity:**

$$\sim 10^{49} \left(\frac{\epsilon}{10^{-3}}\right) \left(\frac{M_{\rm ej}}{10^{-2}M_\odot}\right) \ {\rm erg}$$

- Magnetic field:

$$\sim 10^{48} \left(\frac{B}{10^{15}{\rm G}}\right)^2 \ {\rm erg}$$



Metzger & Berger 12

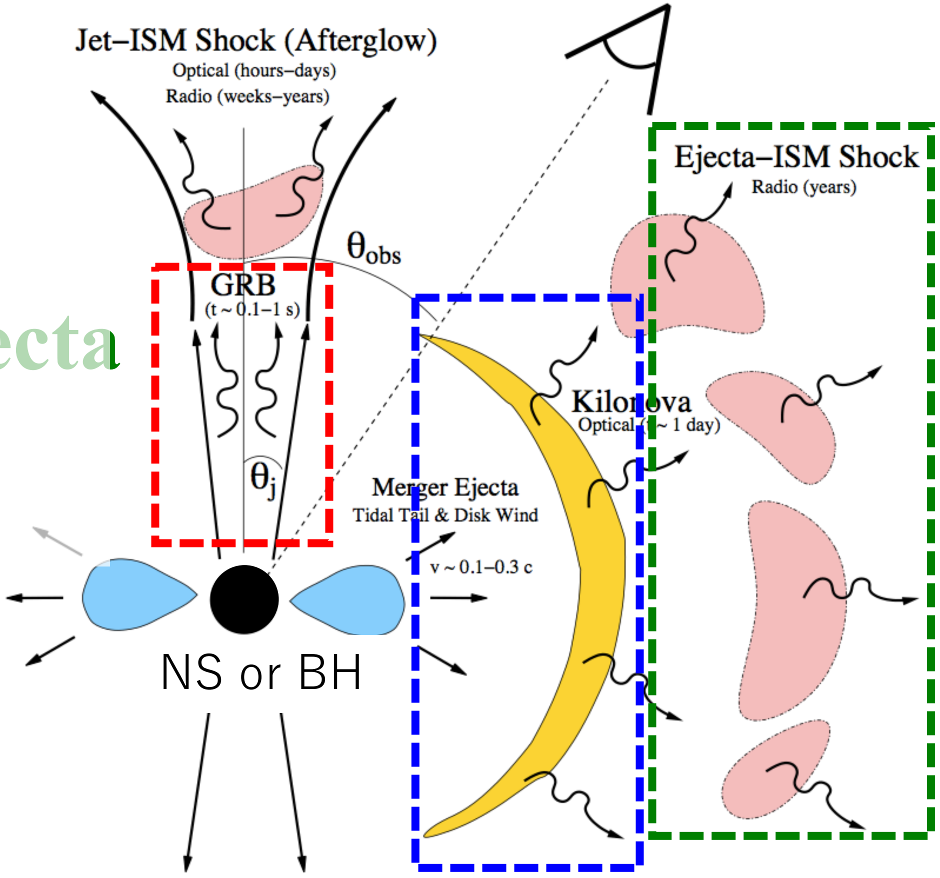
EM Counterparts

- **Gamma-ray Burst**
  $t < 10^6$ s
  Rotation/disk grav. energies

- **Macronova/Kilonova**
  t ~ 10 day
  Radioactivity (?)

- **Remnant of Merger Ejecta**
  t ~ yr
  Ejecta kinetic energy

- **Others**

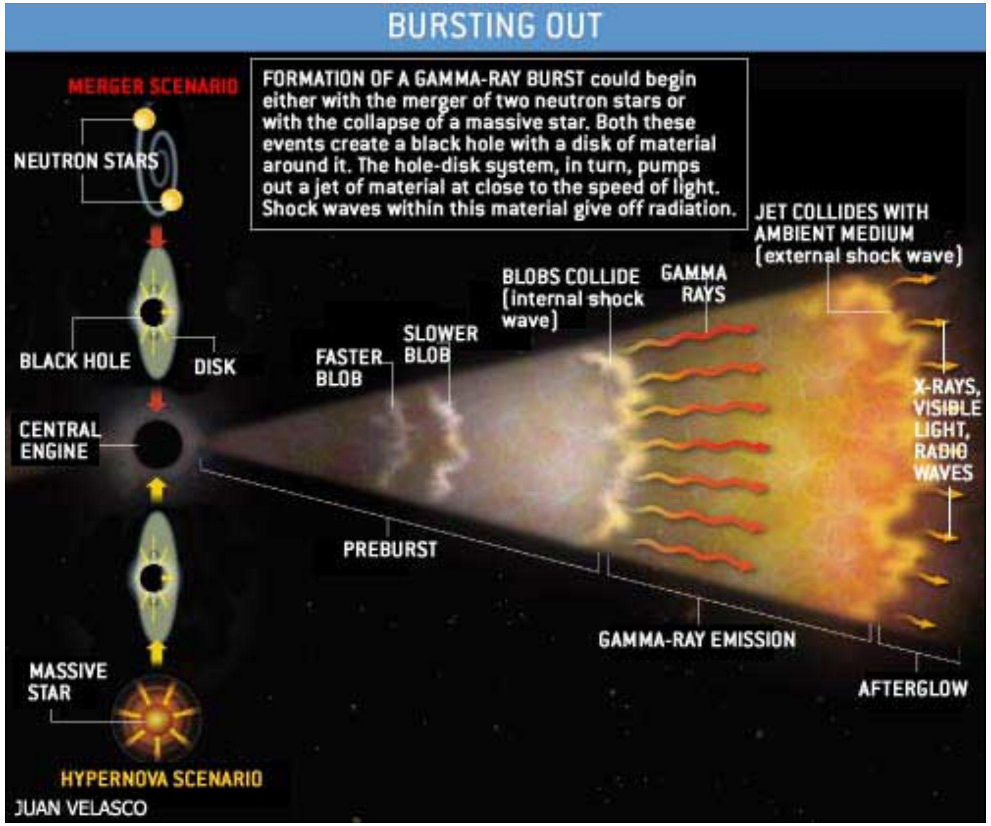


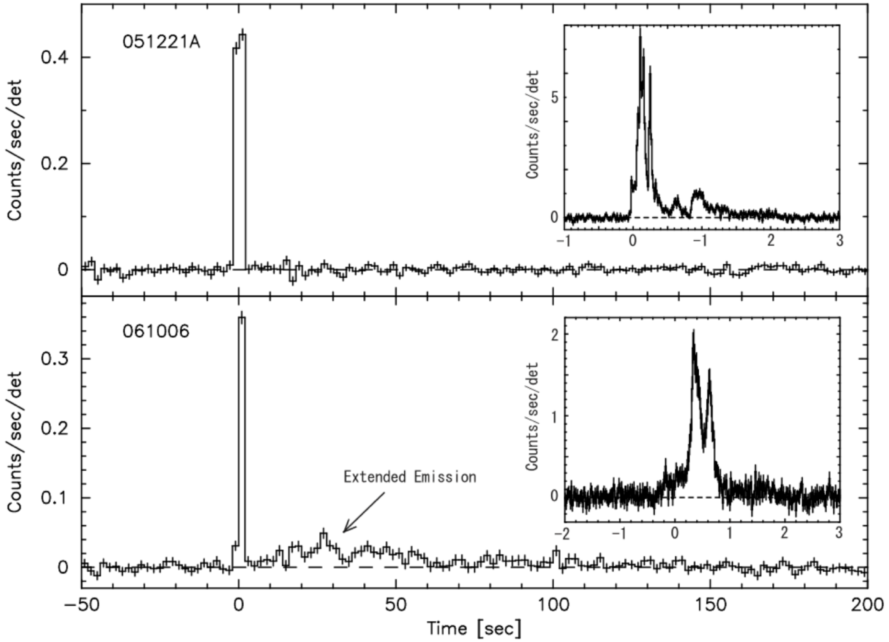
Metzger & Berger 12

Gamma-ray Burst

Short Gamma-Ray Bursts (GRBs)

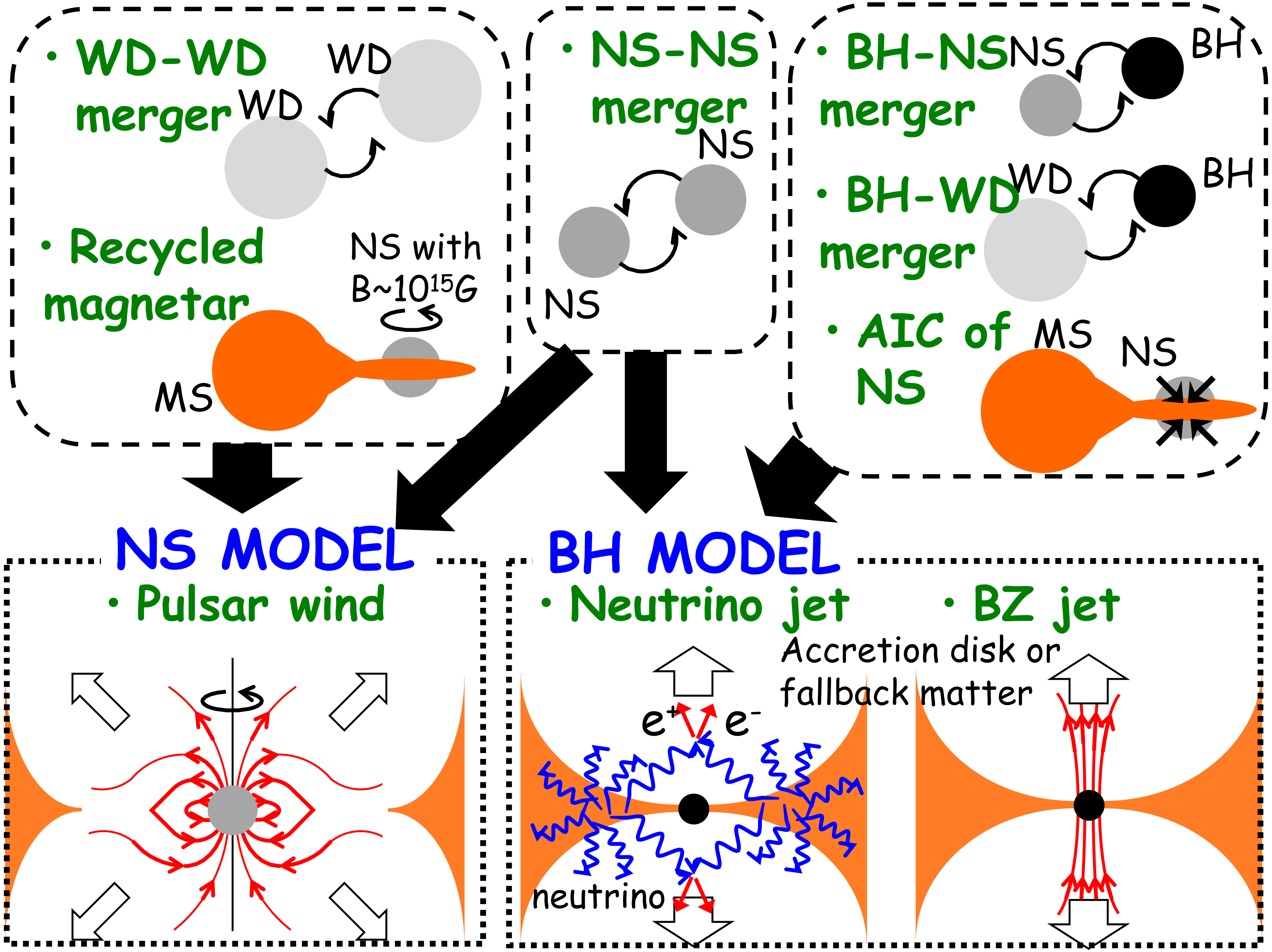
- Total energy : ~10^{50} – 10^{51} erg (isotropic)
- Duration : ~10^{-2} – 2 sec
- Event rate : ~10 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (observed; Nakar+ 06)
- Jet-like outflow (opening angle ~5-10° ; Fong+14)





Norris & Bonnell 06

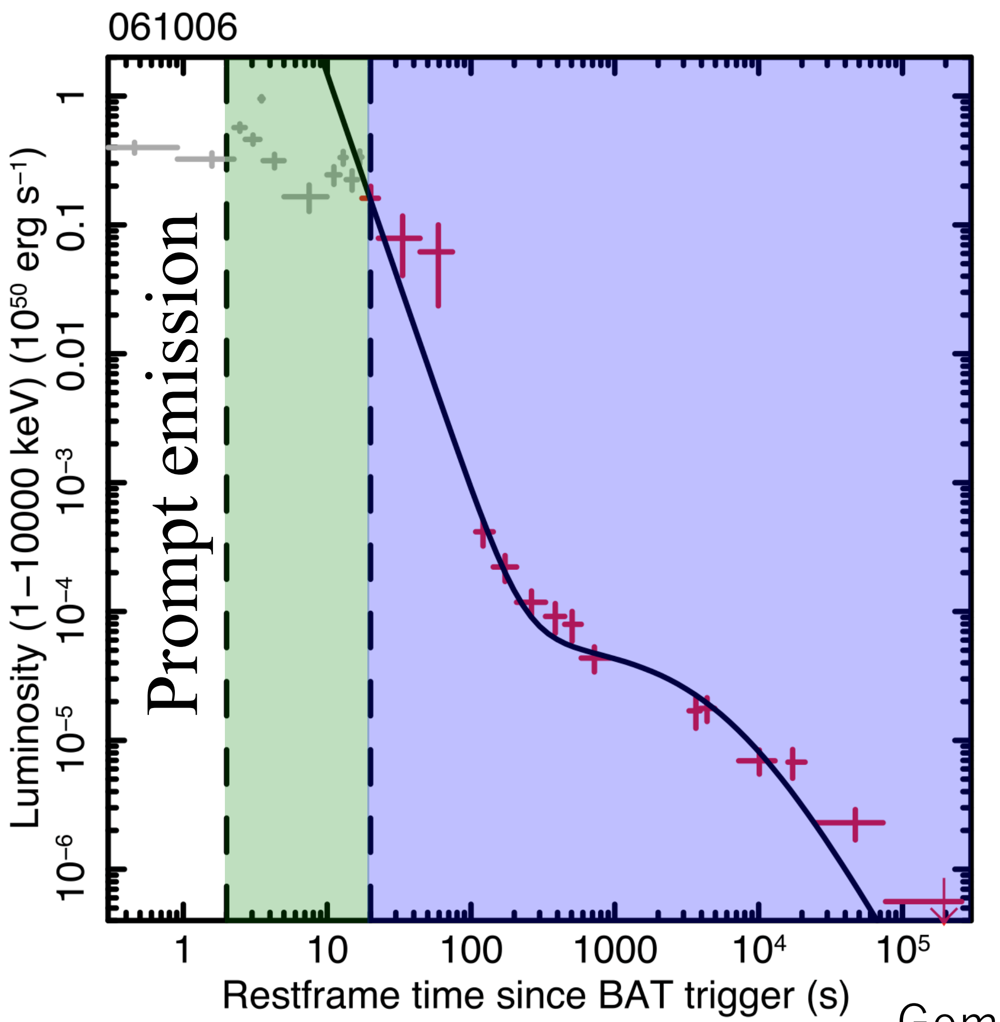
Diversity of short GRB models



Light curve

Plateau emission : L ~ 10^{45}-10^{47} erg/s, T ~ 10^3 – 10^4 s

Extended emission : L ~ 10^{48}-10^{49} erg/s, T ~ 10^2 s



Gompertz+ 13

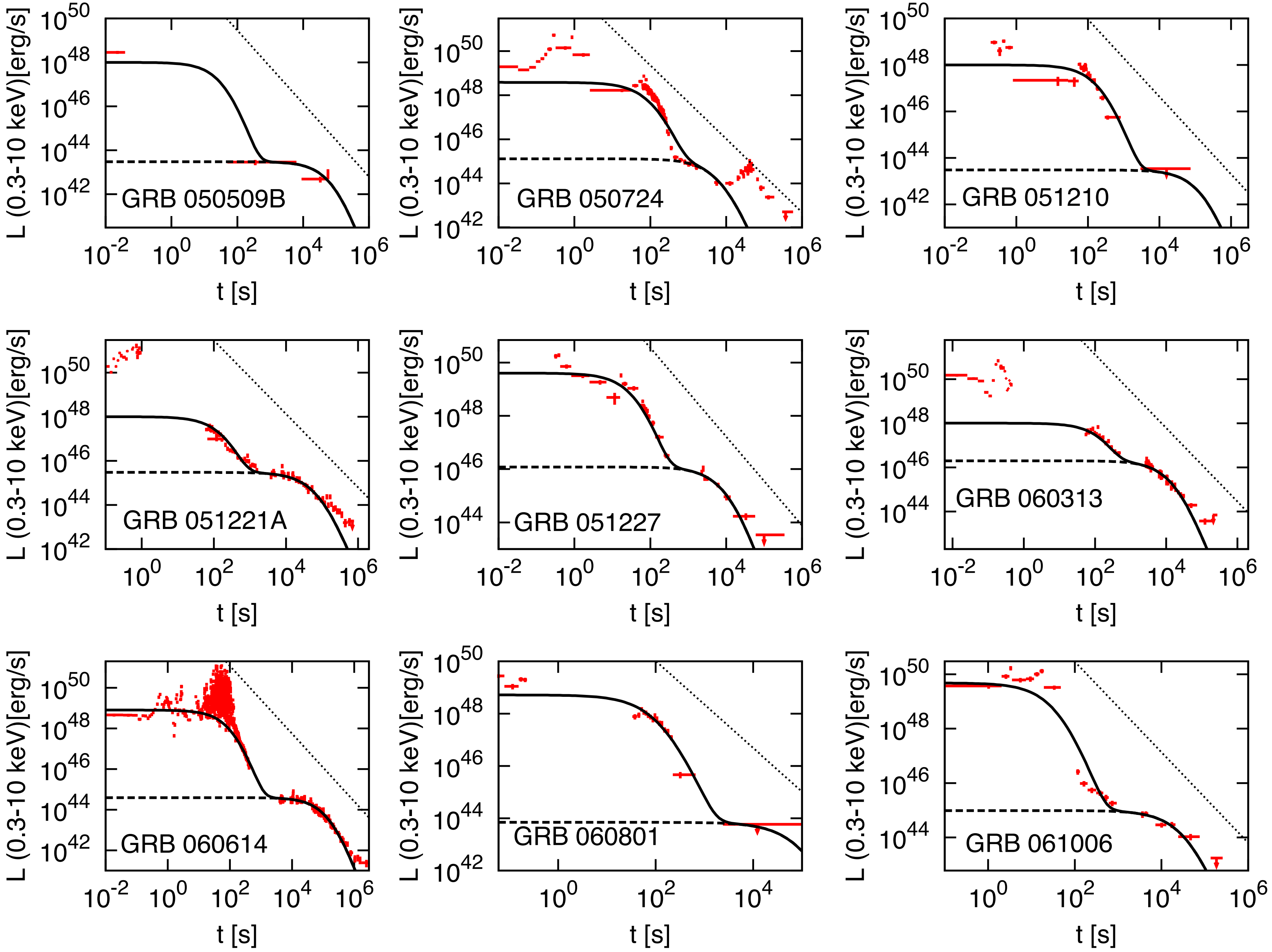
cf. Prompt emission
L ~ 10^{50} - 10^{51} erg/s
T ~ 0.1 – 1 s

Total energy is comparable
~ 10^{50} - 10^{51} erg

Activity of central engine ~ 10^3 - 10^4 s ?

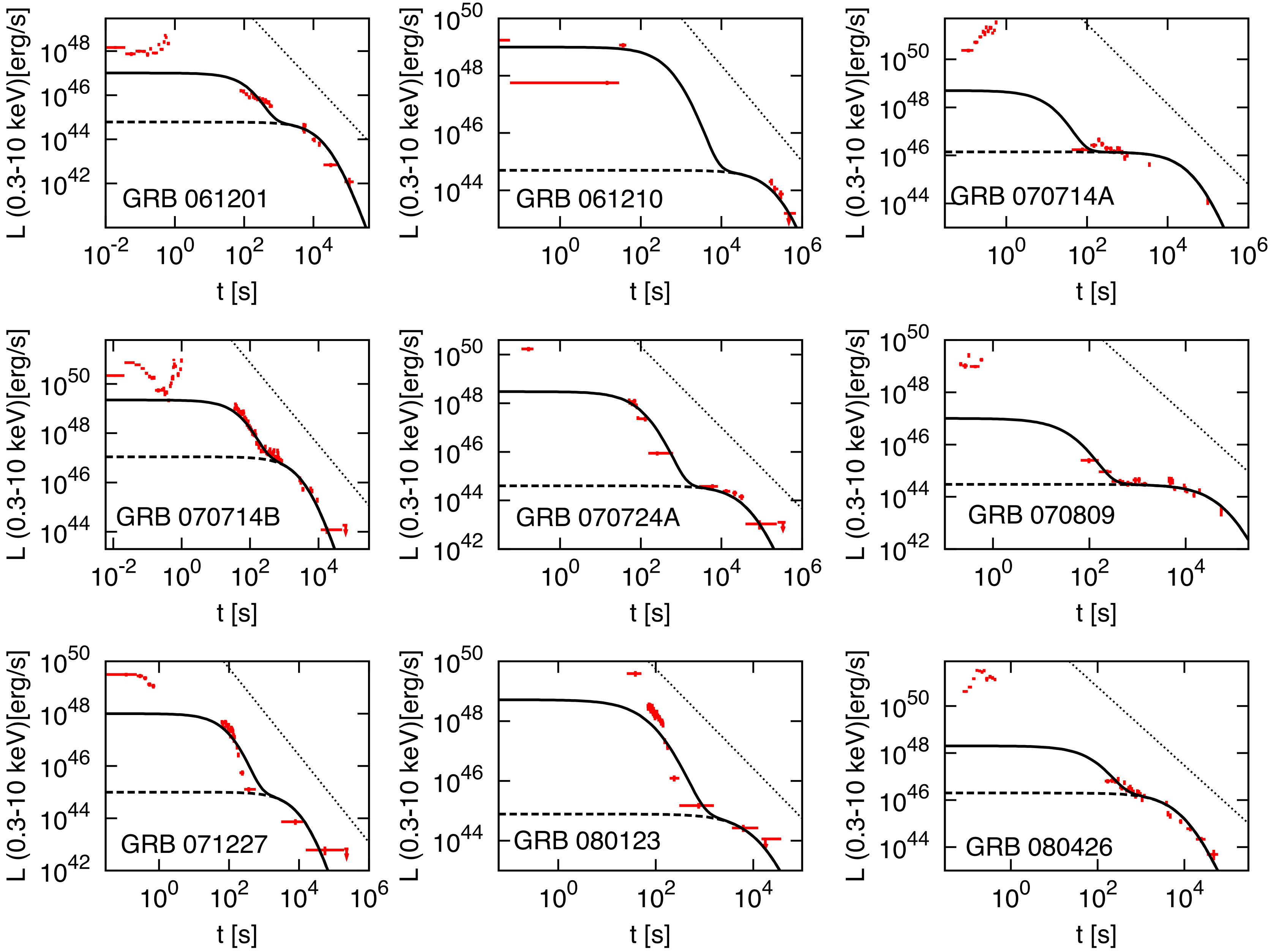
Light curves

Model : SK & Ioka 15



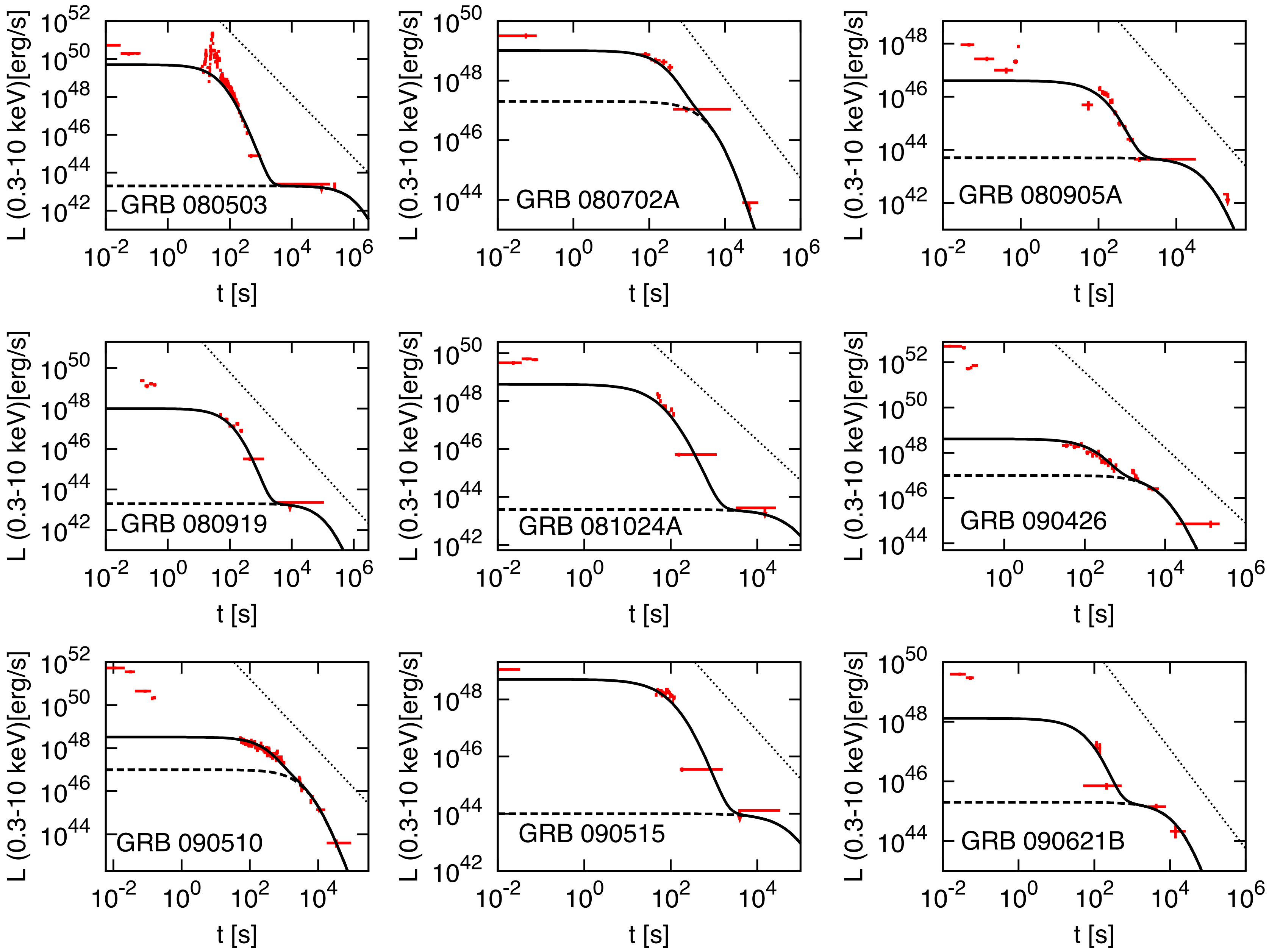
Light curves

Model : SK & Ioka 15



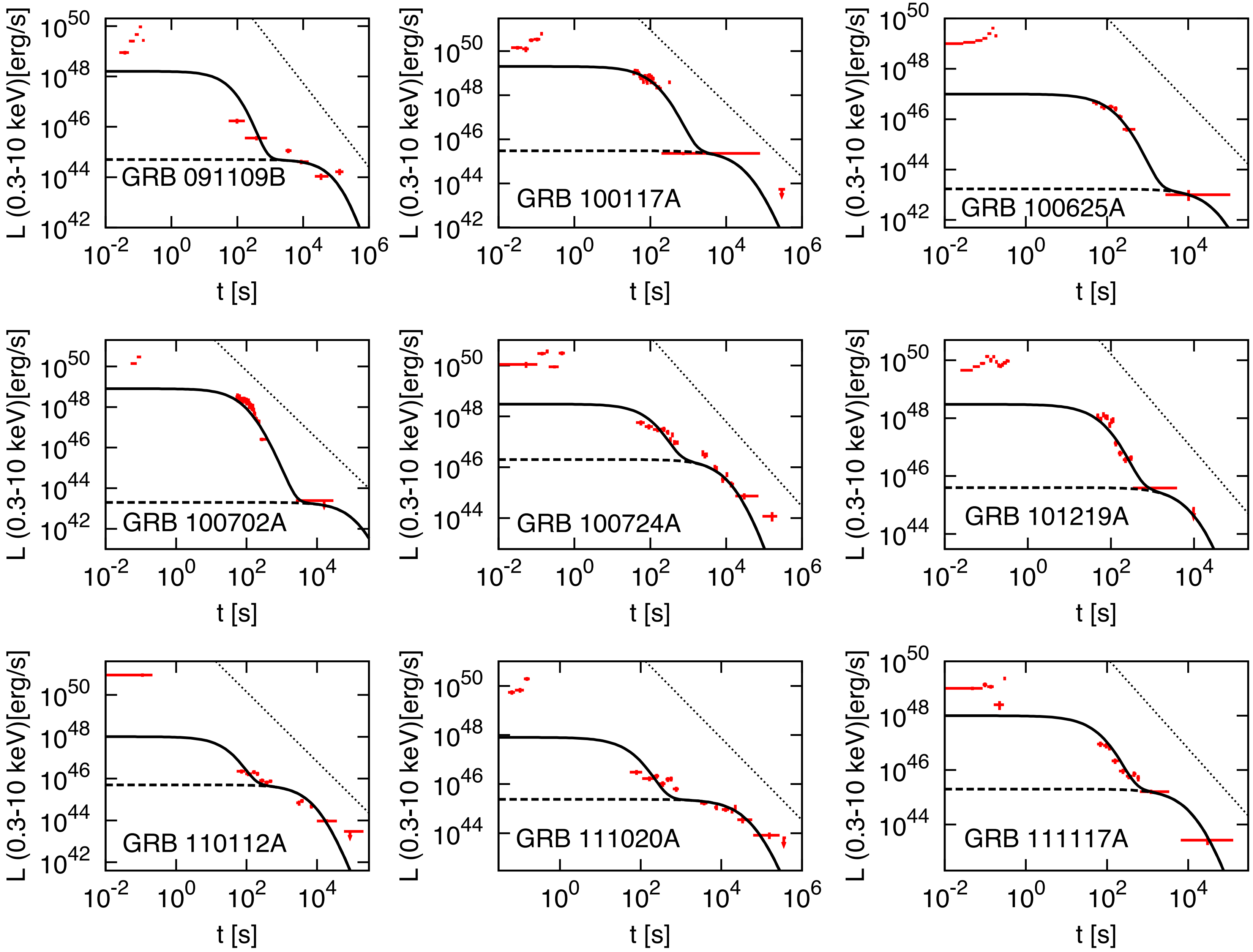
Light curves

Model : SK & Ioka 15



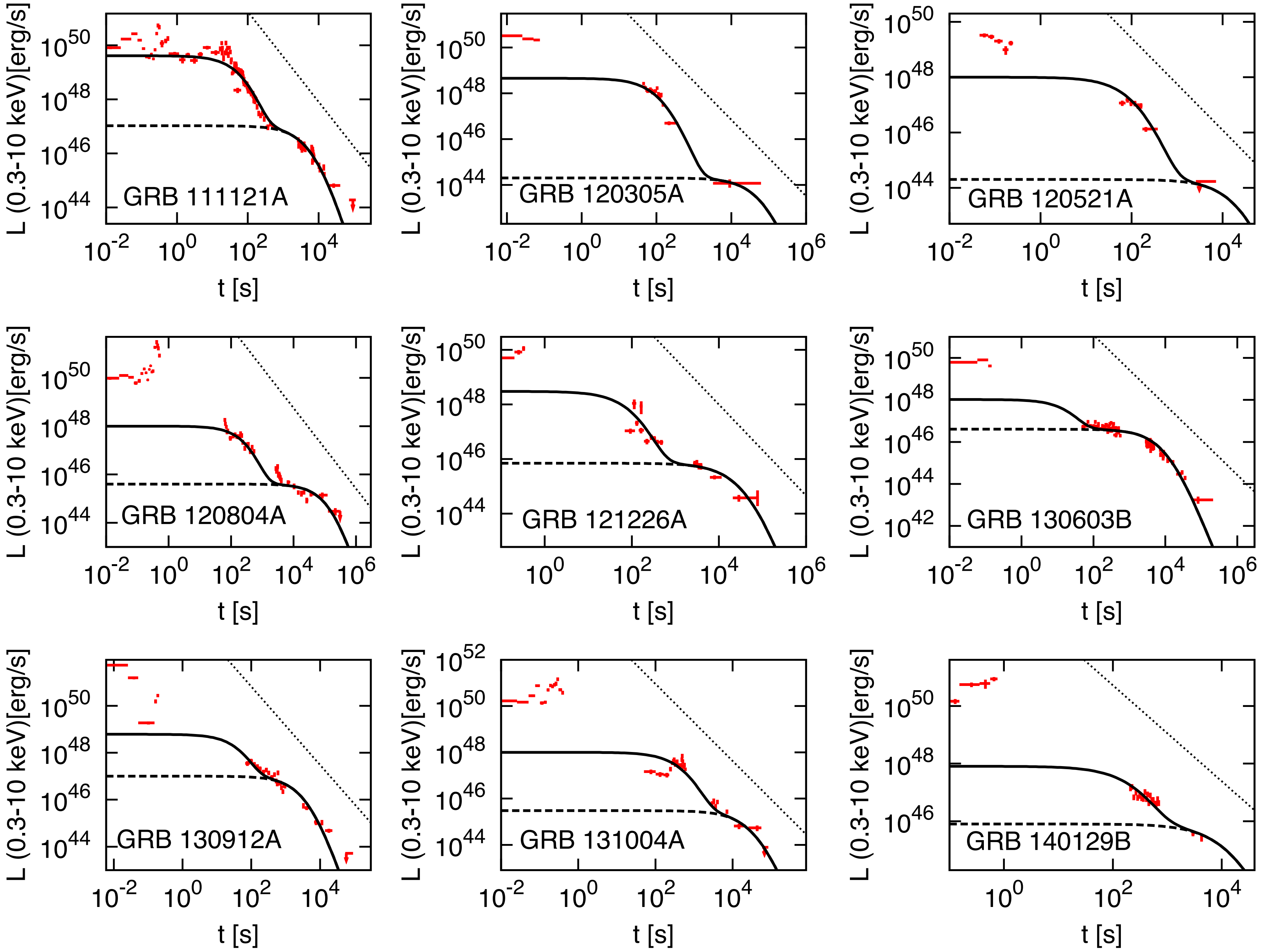
Light curves

Model : SK & Ioka 15



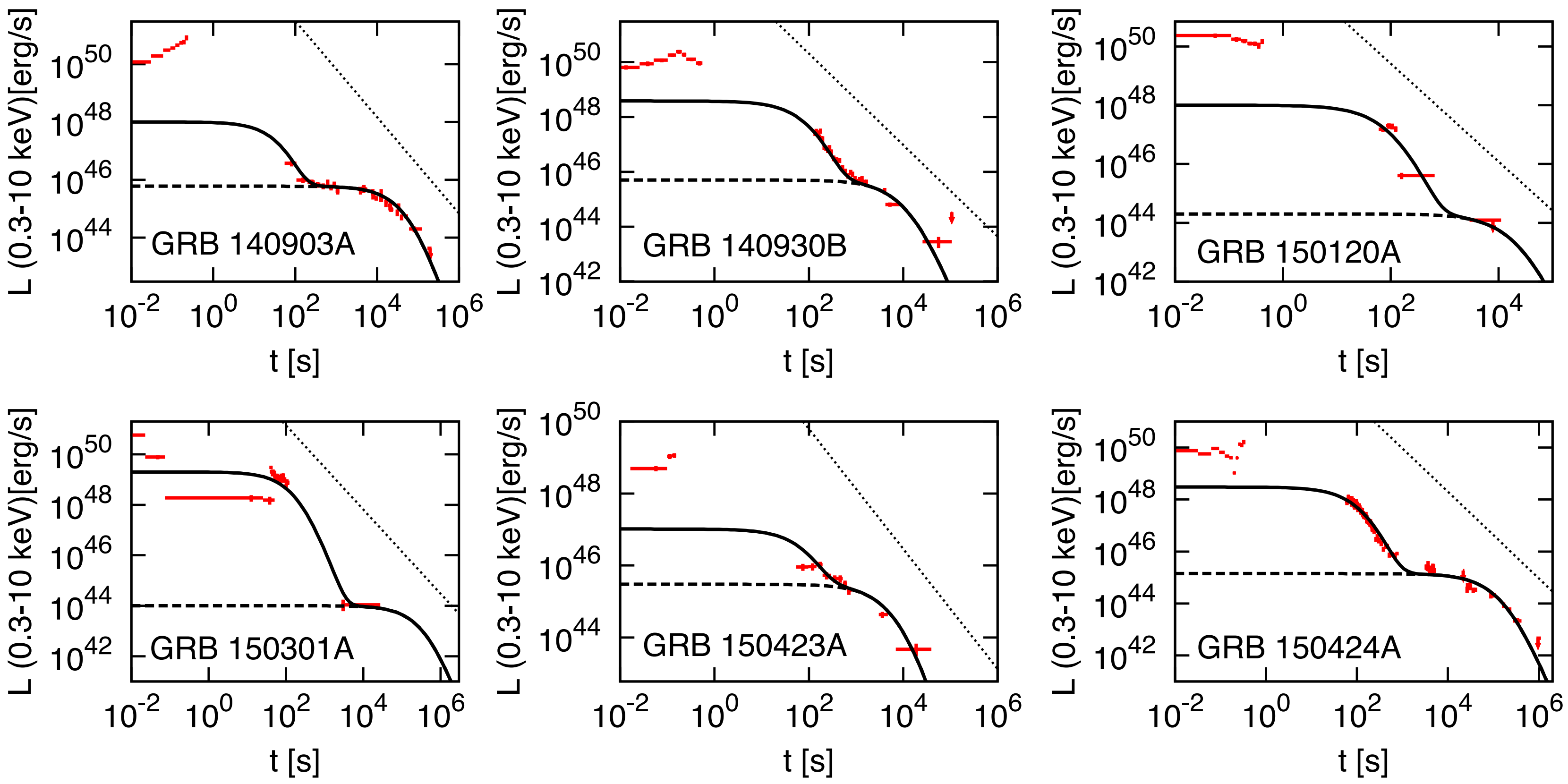
Light curves

Model : SK & Ioka 15



Light curves

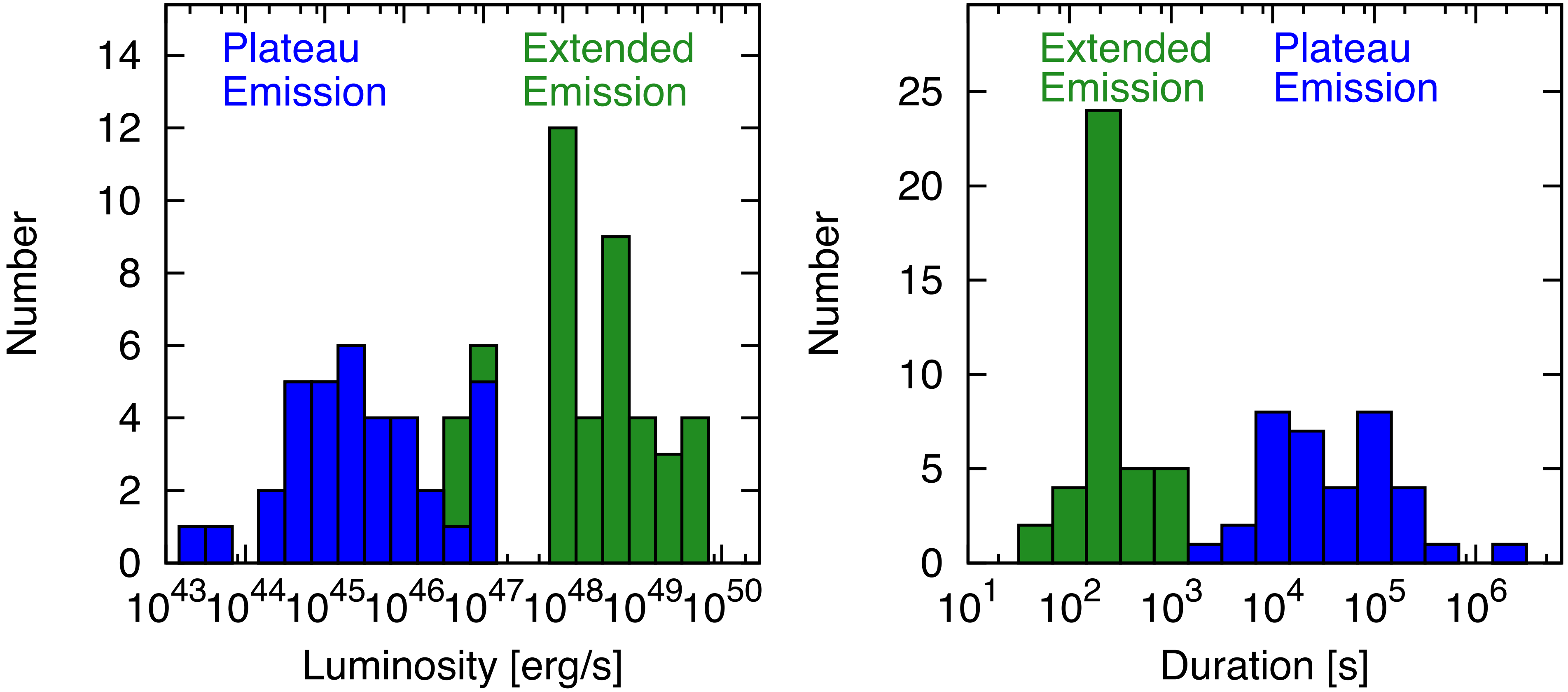
Model : SK & Ioka 15



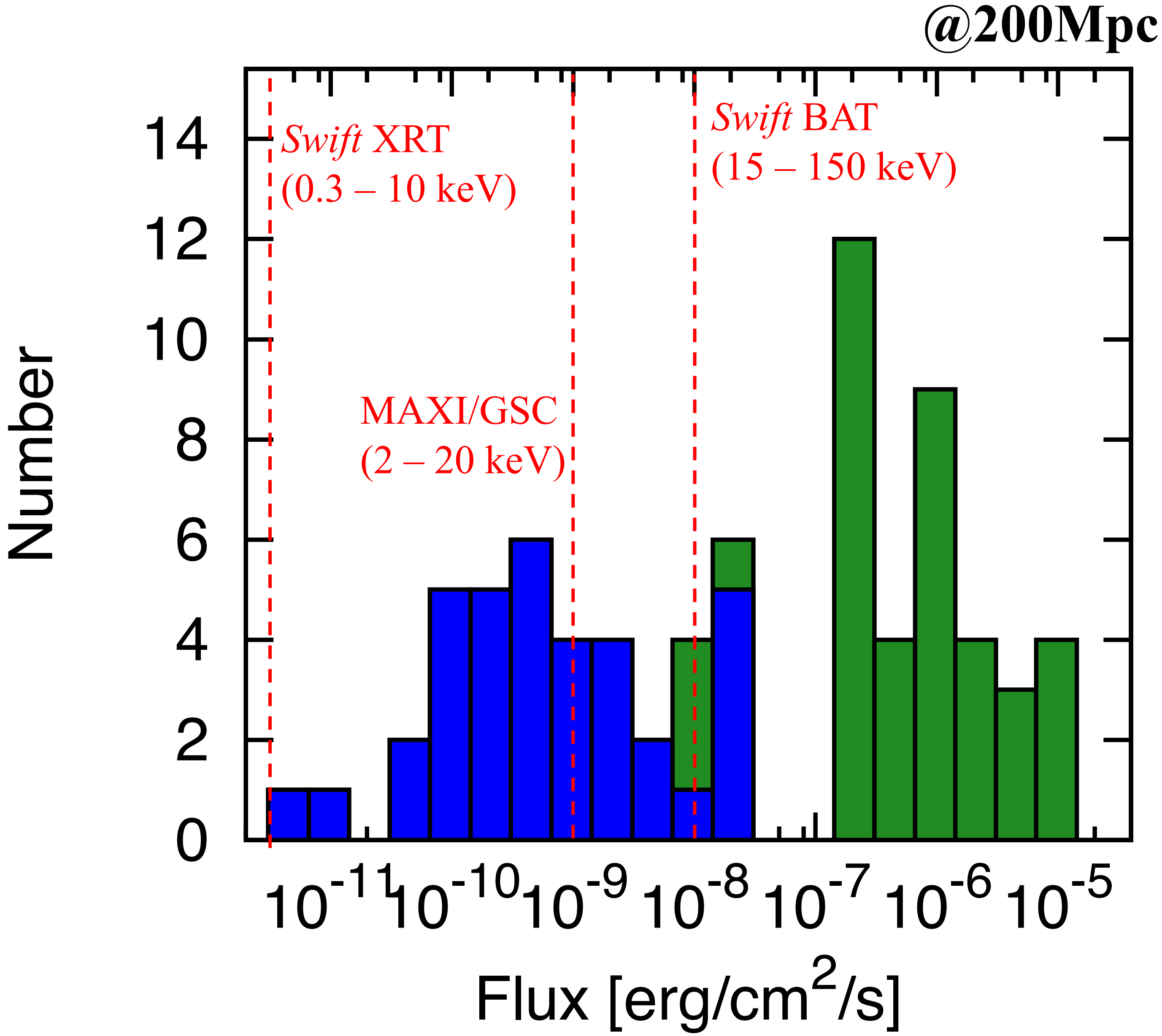
Luminosity and Duration

Plateau emission : L ~ 10^{45}-10^{47} erg/s, T ~ 10^{3} – 10^{4} s

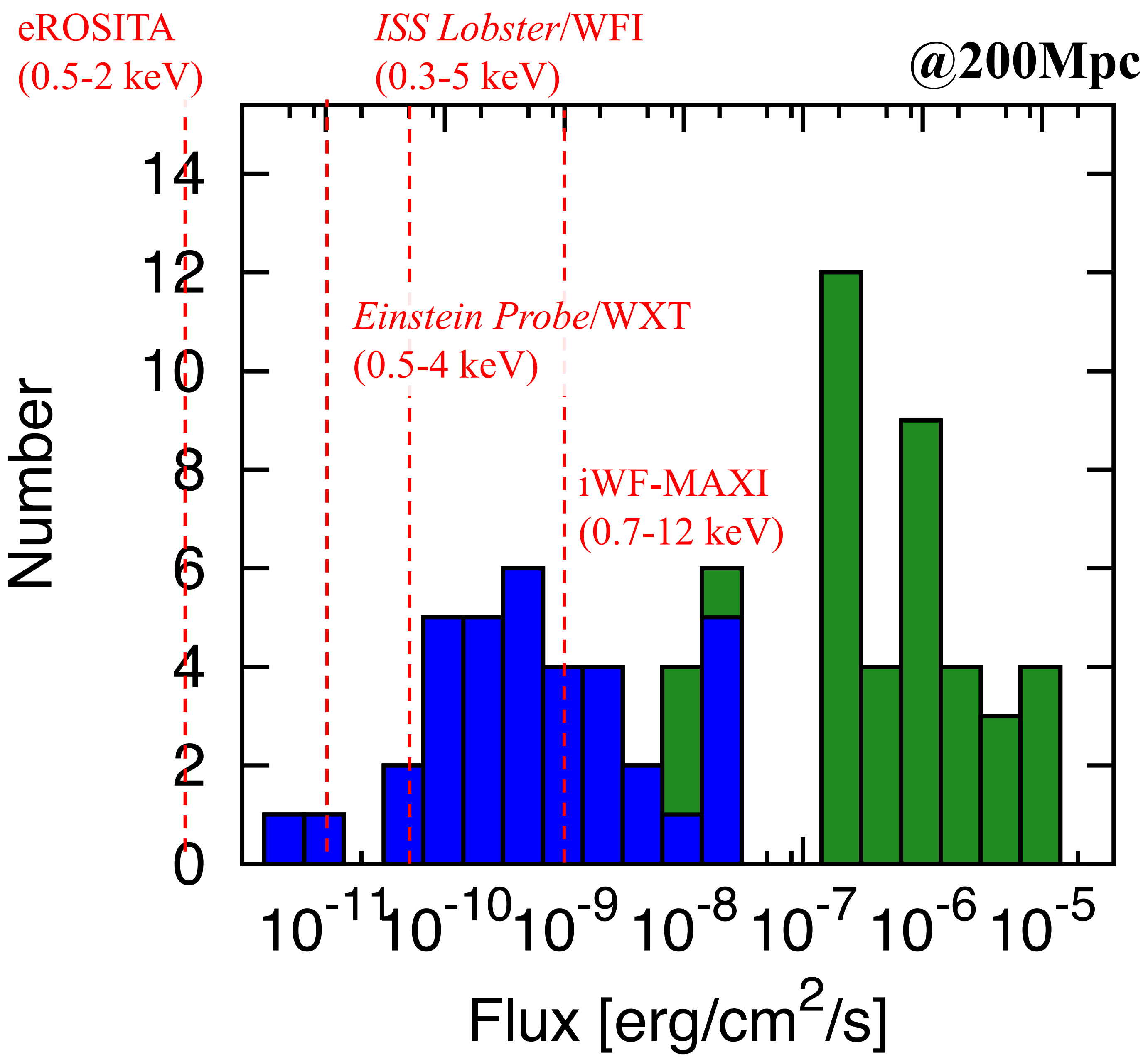
Extended emission : L ~ 10^{48}-10^{49} erg/s, T ~ 10^{2} s



Current Detectors

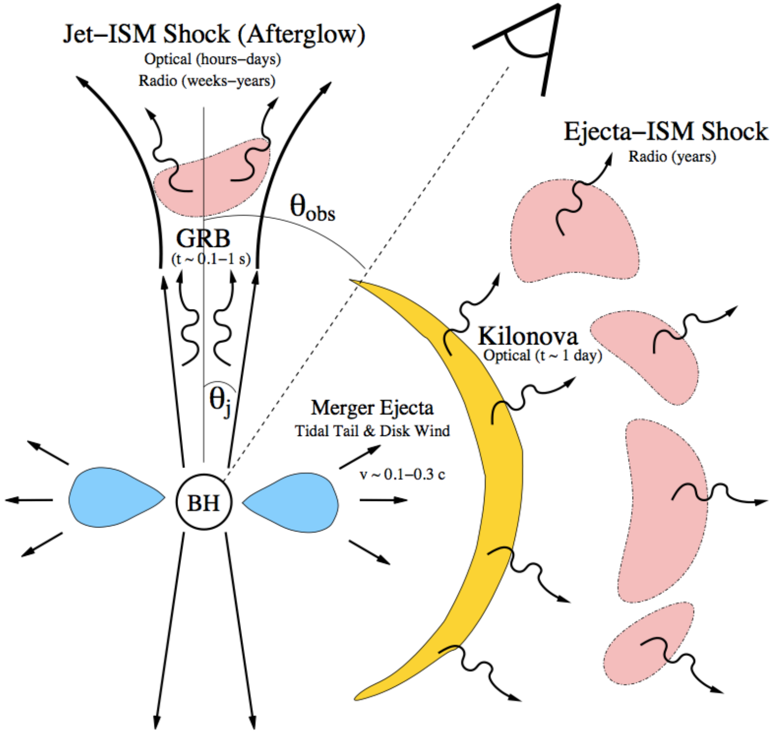


Planed Detectors

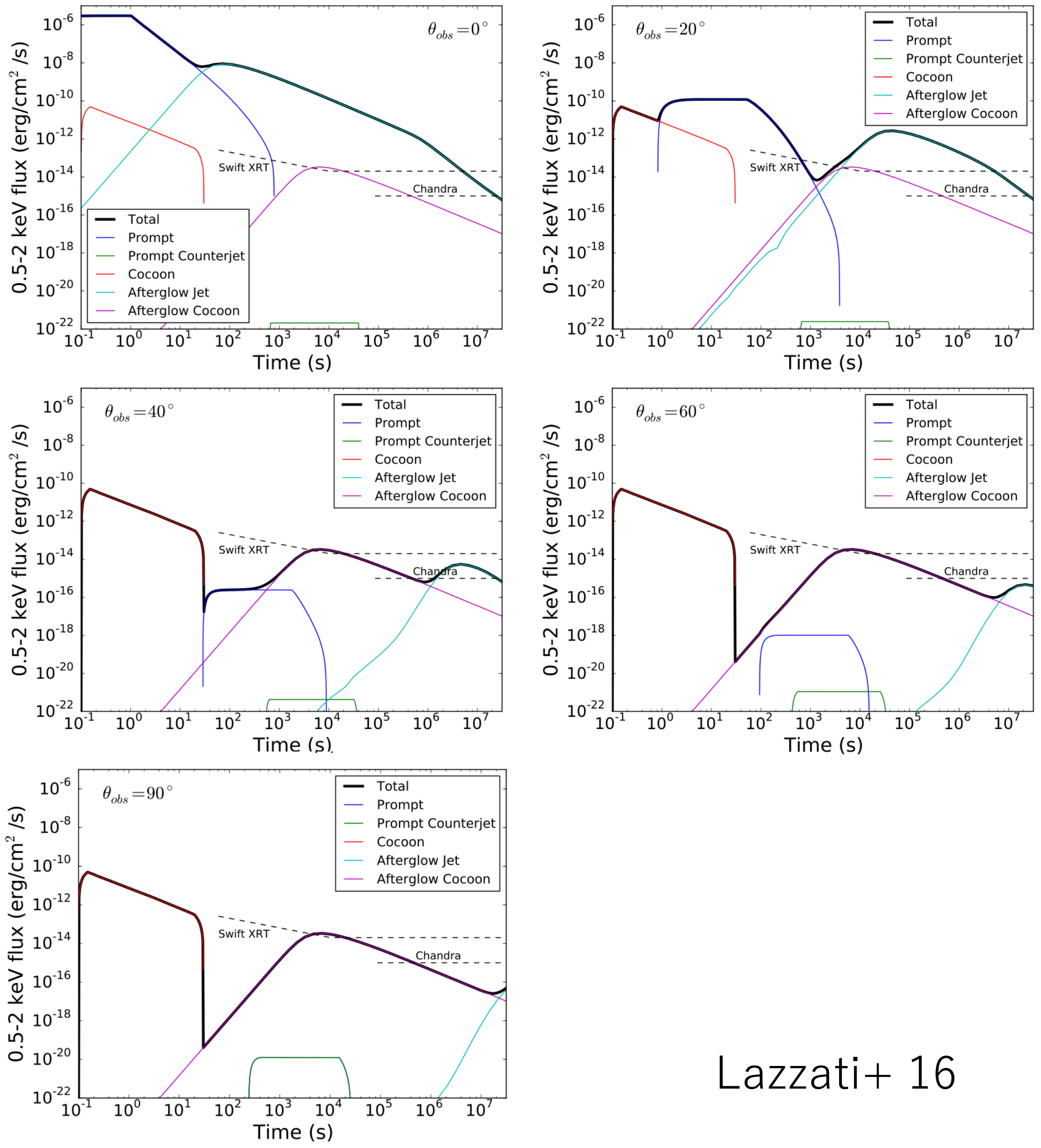


Viewing Angle Dependence

Low probability of the simultaneous detection with GW ?



Metzger & Berger 12



Lazzati+ 16

Scattering

- Emission region locates inside the ejecta, $r_e < r$.
- Optical depth $\tau >> 1$.

Emission region

$$r_e \sim \Gamma^2 c\Delta t$$
$$\sim 3\times 10^{12}\left(\frac{\Gamma}{10}\right)^2\left(\frac{\Delta t}{1\mathrm{s}}\right)\ \mathrm{cm}$$

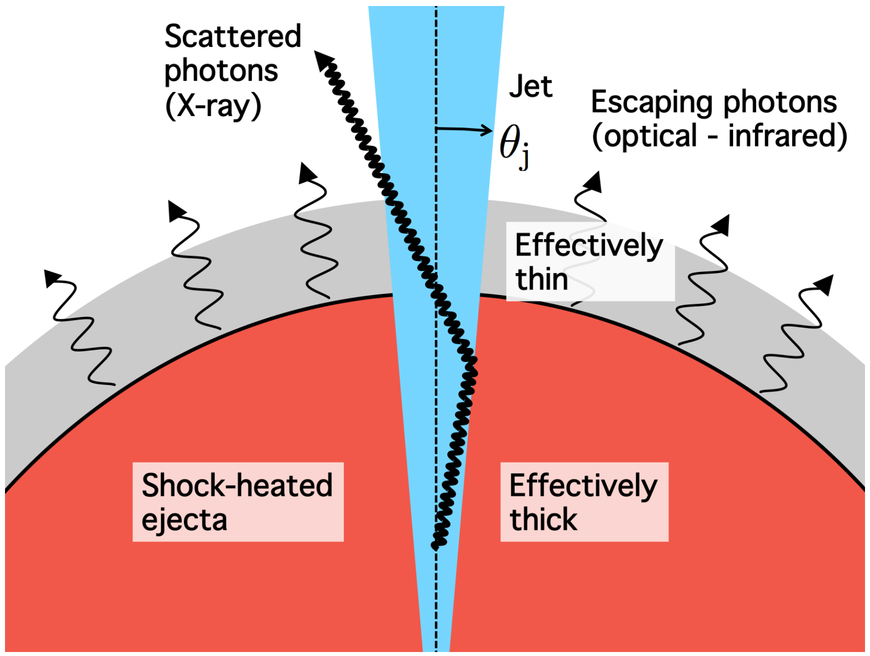
Ejecta

$$r \sim vt$$
$$\sim 3\times 10^{13}\left(\frac{v}{0.1c}\right)\left(\frac{t}{10^4\mathrm{s}}\right)\ \mathrm{cm}$$

Optical depth

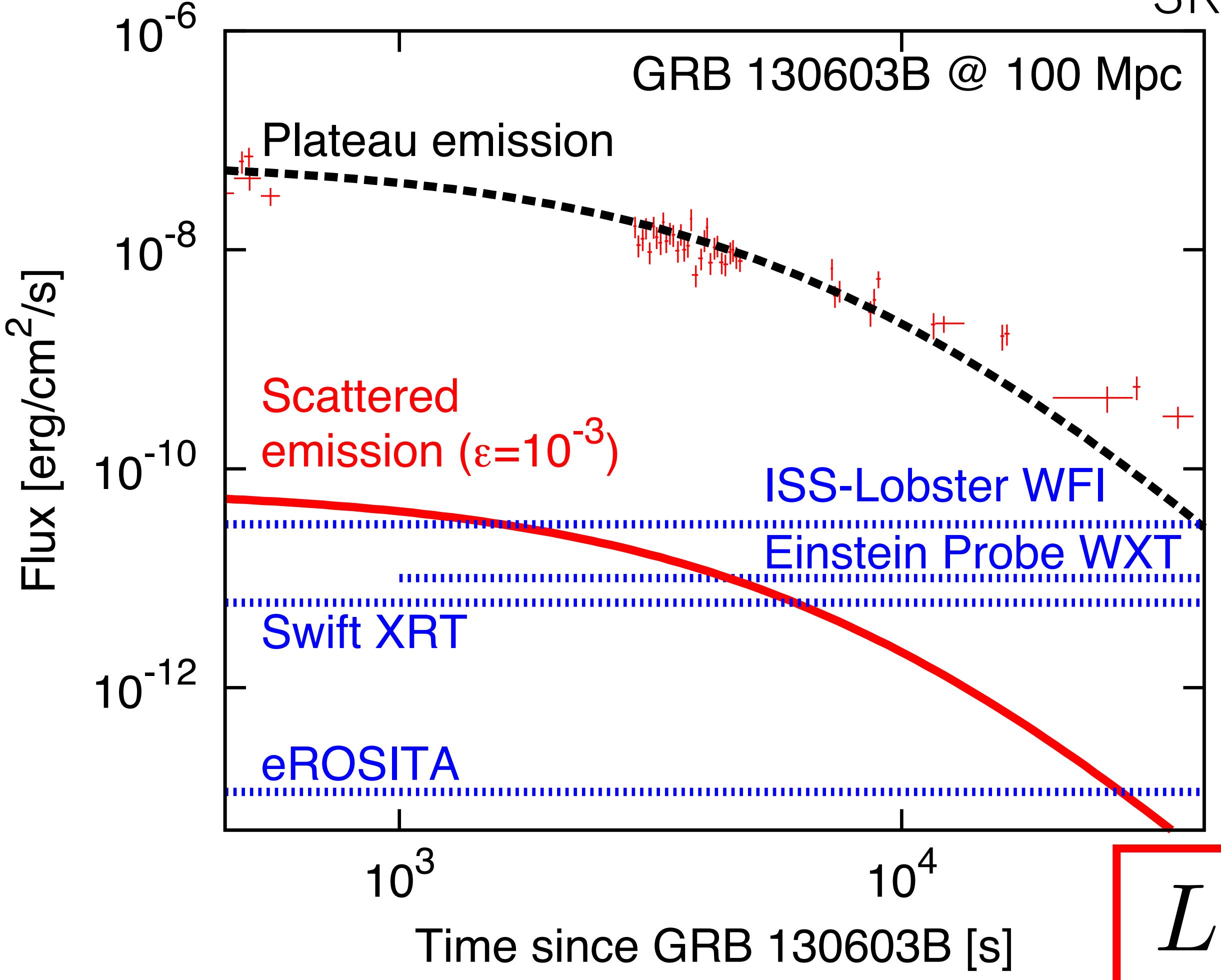
$$\tau \sim 10^2\left(\frac{t}{10^4\mathrm{s}}\right)^{-2}\left(\frac{\bar{A}}{10^2}\right)^{-1}\left(\frac{M_{\mathrm{ej}}}{10^{-2}M_\odot}\right)\left(\frac{v}{0.1c}\right)^{-2}$$

SK, Ioka & Nakamura 15



Light curve

SK, Ioka & Nakamura 15



$$\boxed{L_{\rm sc} \sim \epsilon L_{\rm obs}}$$

Isotropically scattered case : $\epsilon \sim 5 \times 10^{-3} (\theta_{\rm j}/0.1)^2$

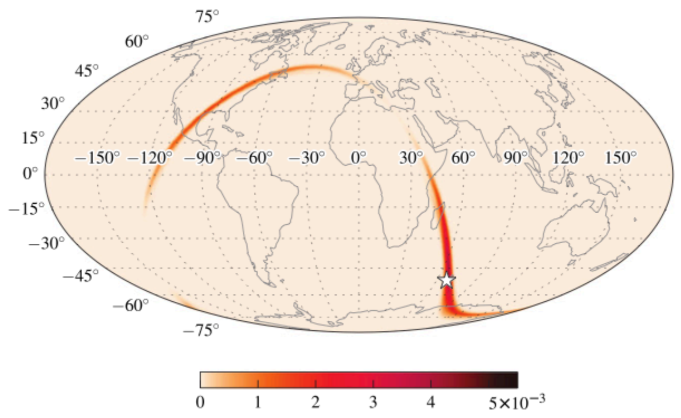
cf. $\epsilon \sim 3 \times 10^{-5} - 3 \times 10^{-4}$ (Eichler & Levinson 99)

Observation strategies

- ***ISS-Lobster WFI***: 900 deg^2
  $\Rightarrow$ Pointing to the error box
- ***Einstein Probe WXT***: 3,600 deg^2
  $\Rightarrow$ Pointing to the error box

GW error box: ~ 100 deg^2

$N_{gal}(< 100\ \mathrm{Mpc}) \sim 100$



Singer+ 14

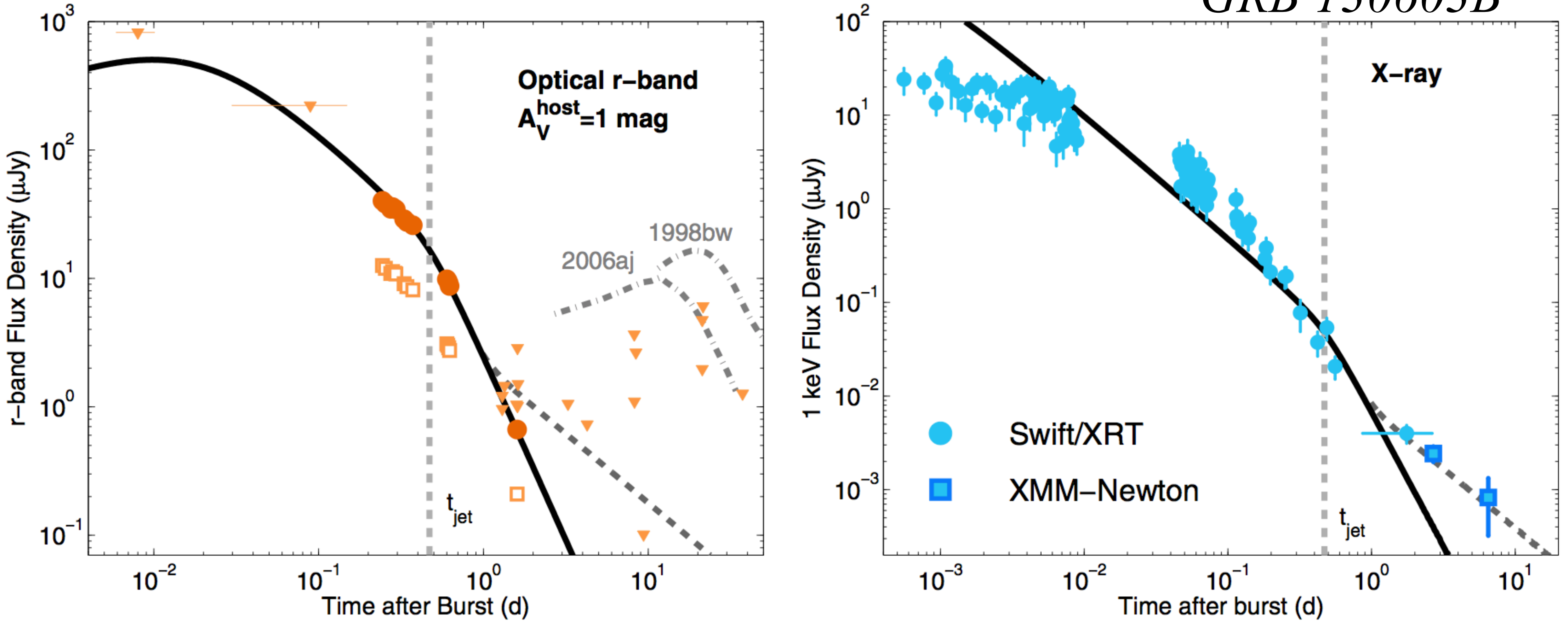
- ***Swift XRT***: 0.16 deg^2
  $\Rightarrow$ Pointing to the galaxies within 100 Mpc
- ***NICER***: 0.008 deg^2
  $\Rightarrow$ Pointing to the galaxies within 200 Mpc

Long-Lasting Component

The long-lasting mysterious X-ray component

(Fong+ 14)

GRB 130603B



Activity of central engine ~10 days ?

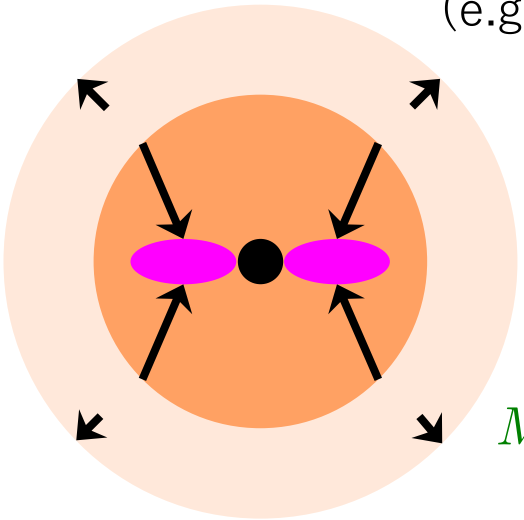
Long-Lasting Component

The long-lasting mysterious X-ray component

(Fong+ 14)

Emission from the disk around the BH?

(e.g., Rosswog 07;
Rossi & Begelman 09)

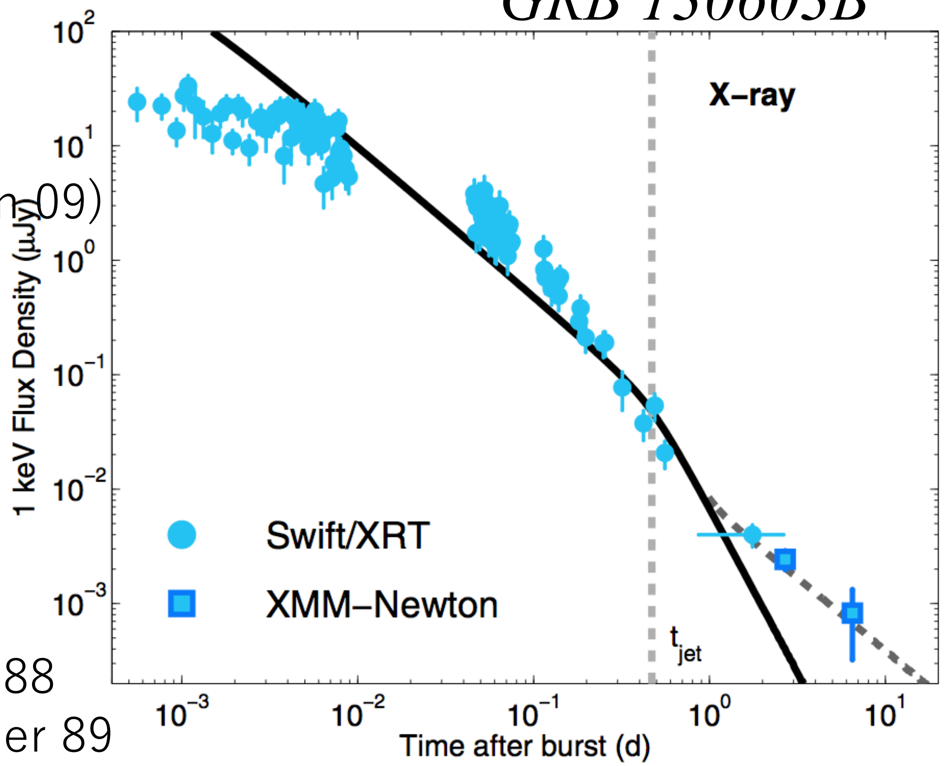


$$\dot{M} = \frac{M_{\rm f}}{t_0}\left(\frac{t}{t_0}\right)^{-5/3}$$

$t_0 \sim 0.1{\rm s}$ Michel 88
Chevalier 89

$M_f \sim 10^{-2}\ M_{sun}$

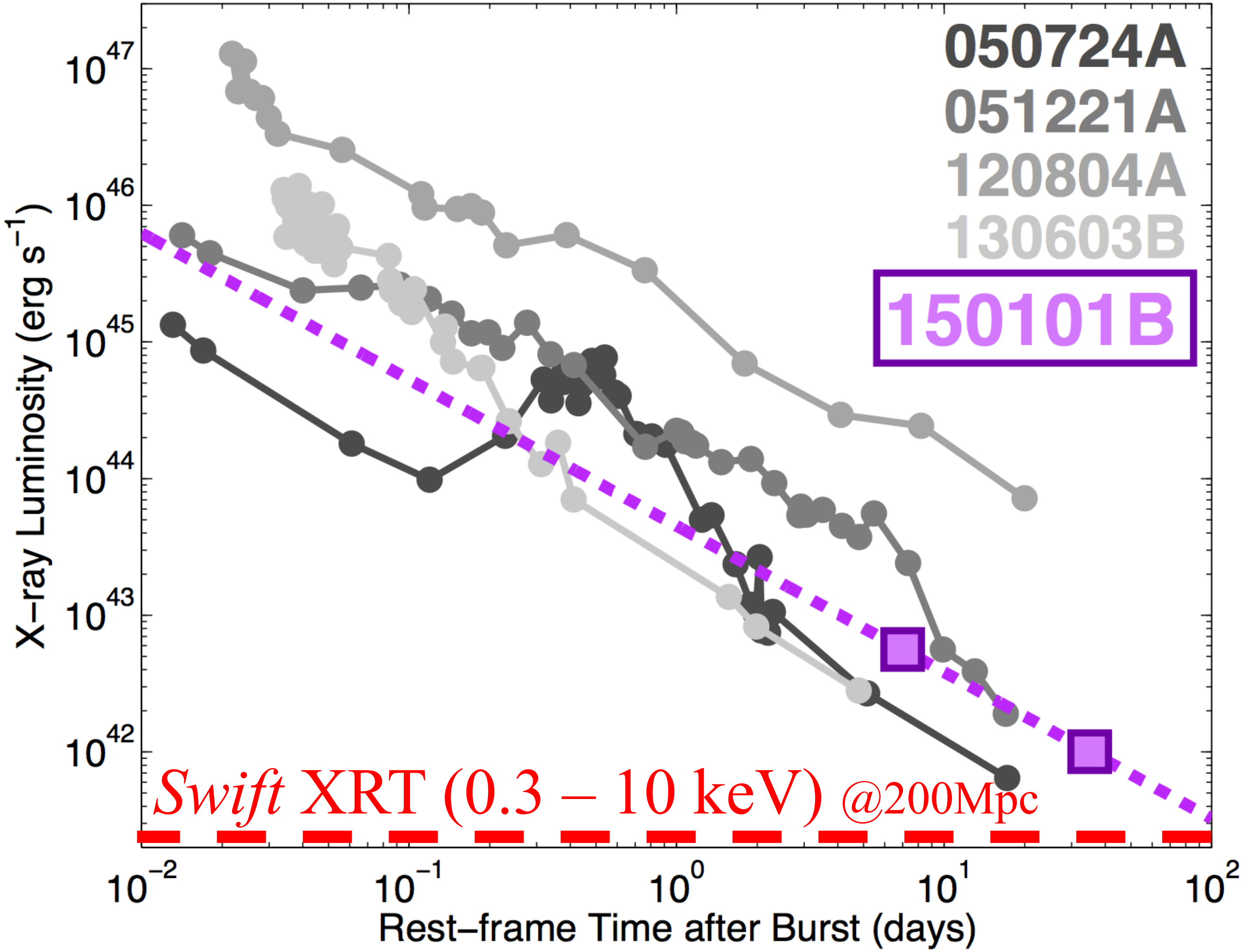
GRB 130603B



Activity of central engine ~10 days ?

Detectability

Long-Lasting component can be detectable by *Swift/XRT.*

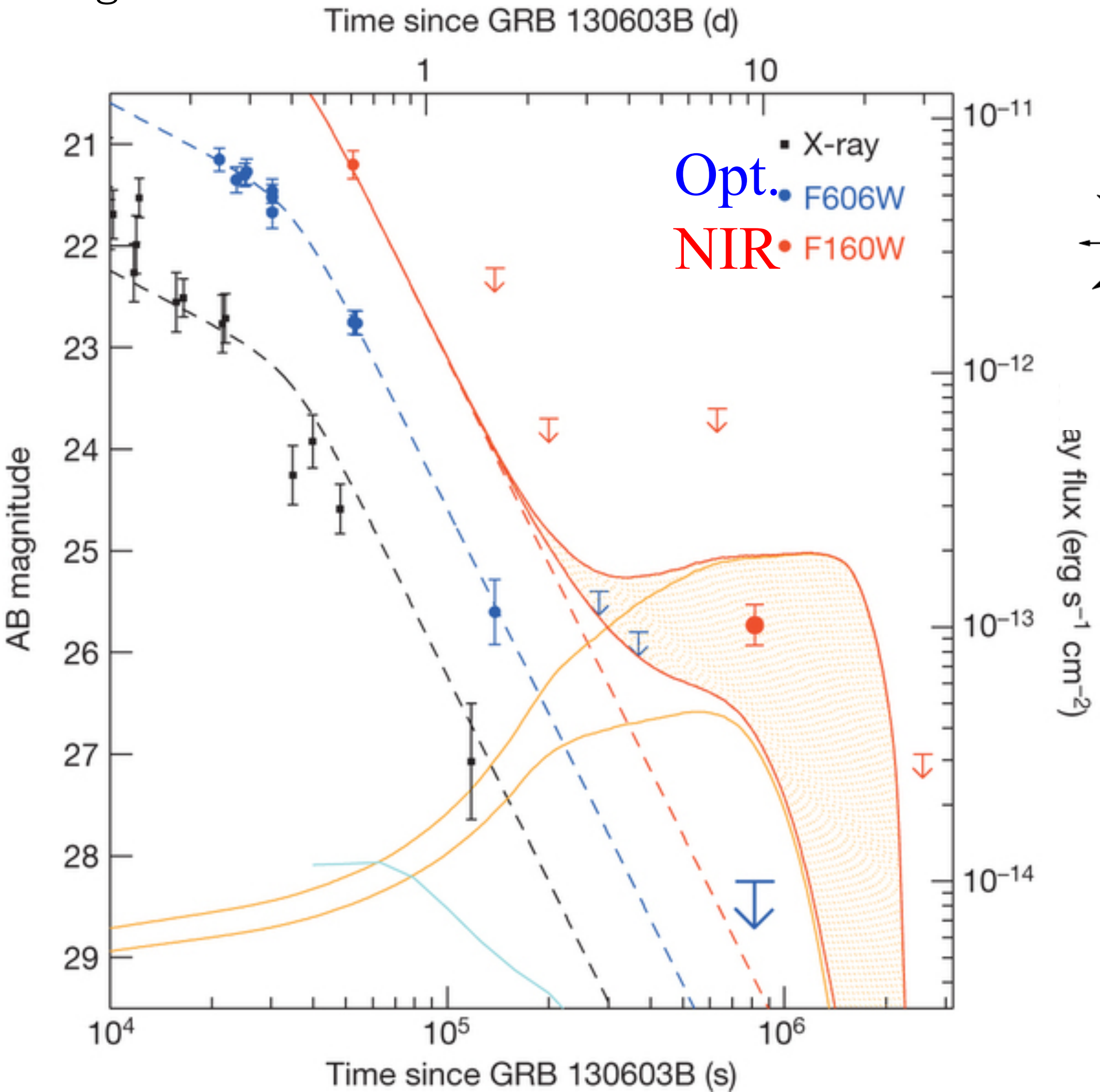


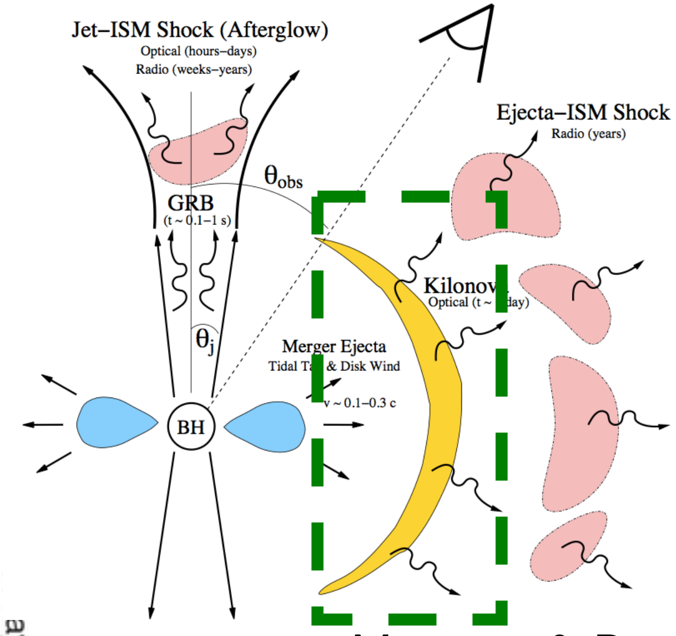
Fong+ 16

Macronova

Macronova Candidate

Tanvir+ 13
Berger+ 13





Metzger & Berger 12

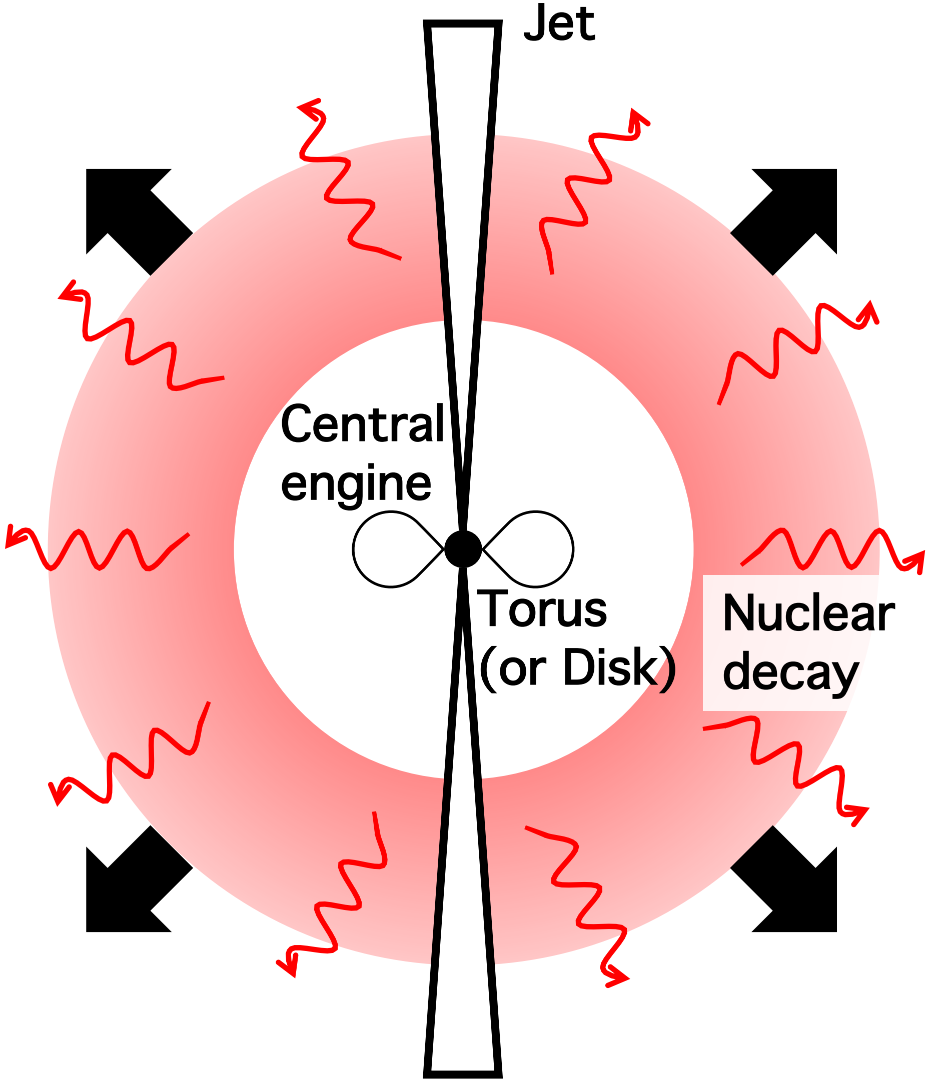
t ~ 7 day

L_{NIR} ~ 10^{41}erg/s

T < 4000 K

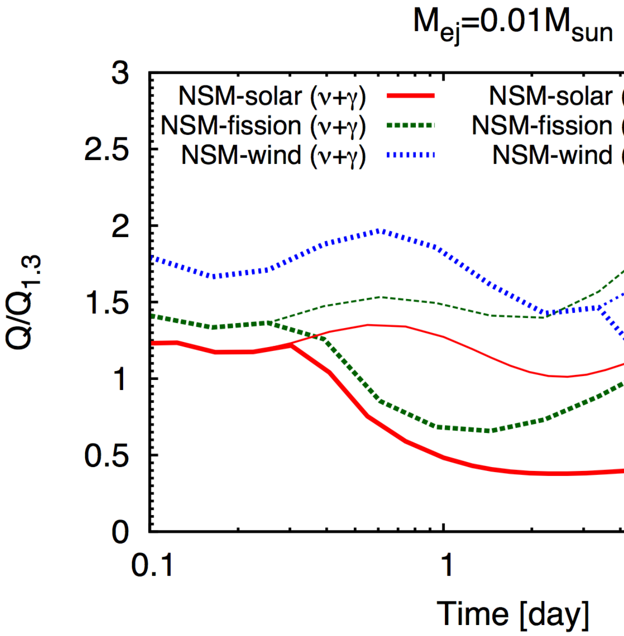
(m_r-$m_j \geq 2.5$)

r-process Heating Model



Nuclear heating rate

$$\dot{Q} \sim 10^{10} \left(\frac{t}{1\mathrm{day}}\right)^{-1.3} \mathrm{erg\ g^{-1} s^{-1}}$$

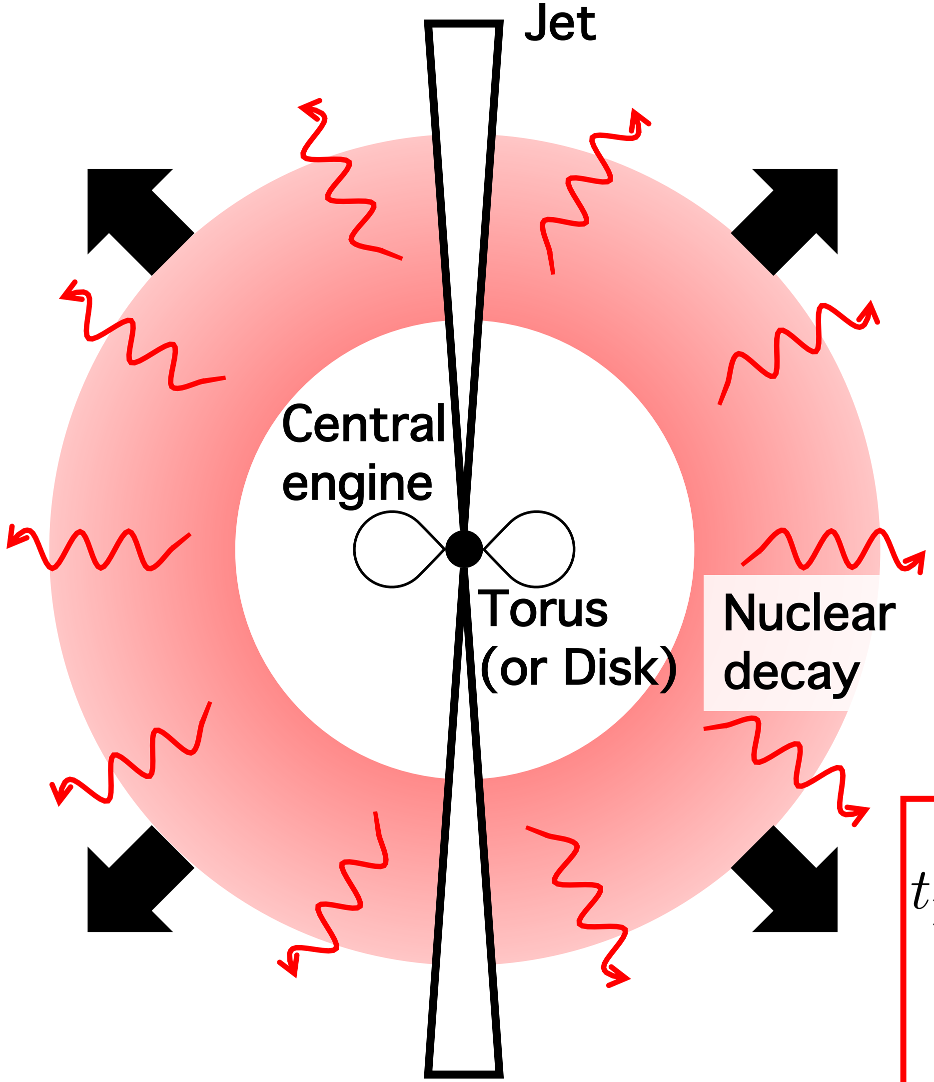


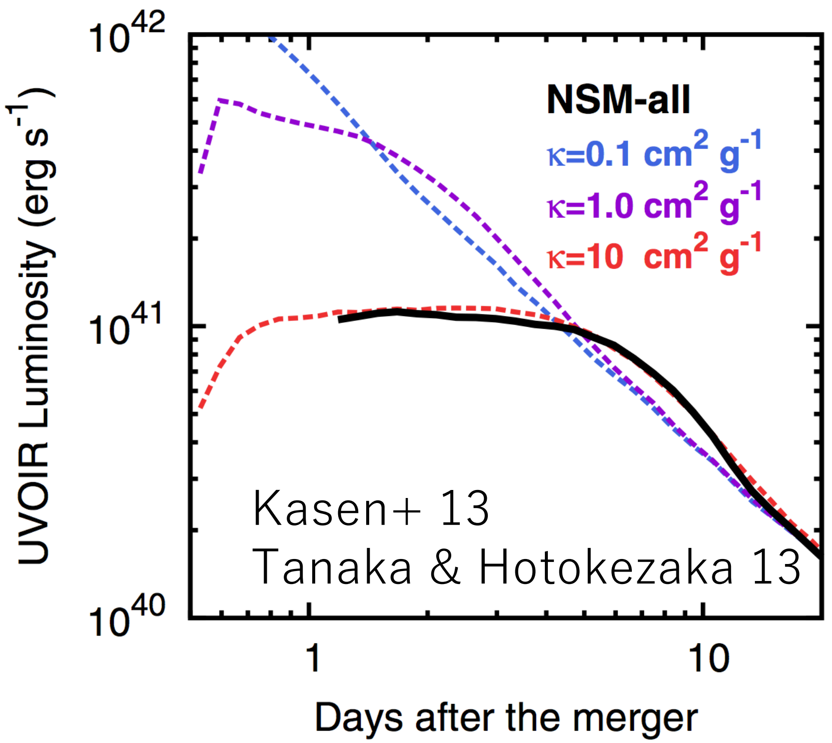
Hotokezaka+ 16

$$\boxed{L \sim 10^{41}\ \mathrm{erg\ s^{-1}} \left(\frac{M_{\mathrm{ej}}}{0.05 M_{\odot}}\right)}$$

r-process Heating Model

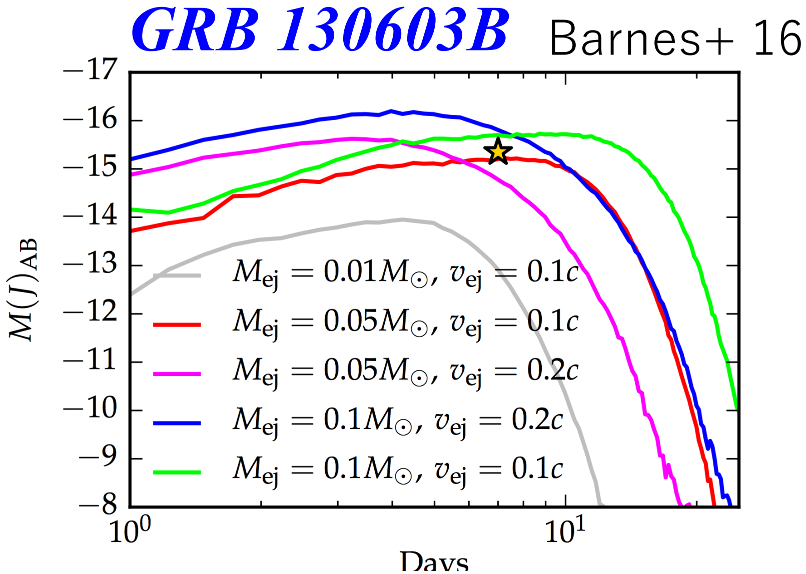
Opacity $\kappa \sim 10\mathrm{cm}^2\ \mathrm{g}^{-1}$

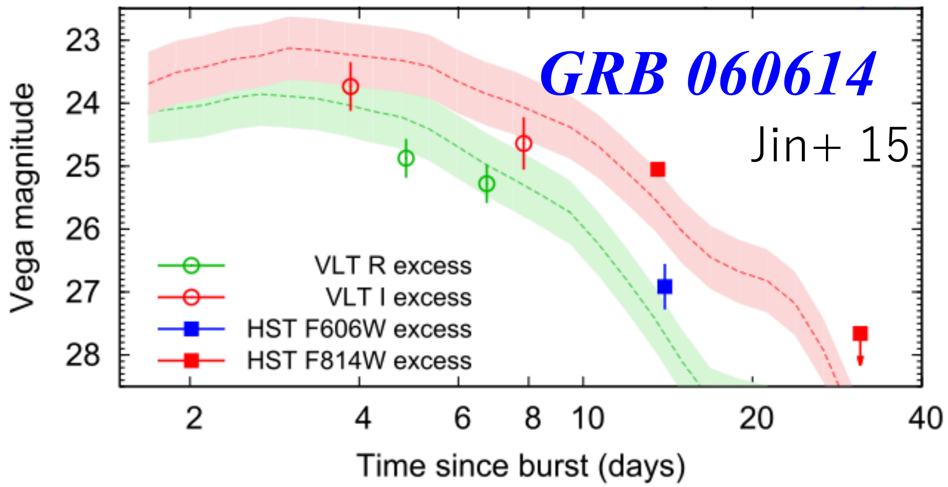


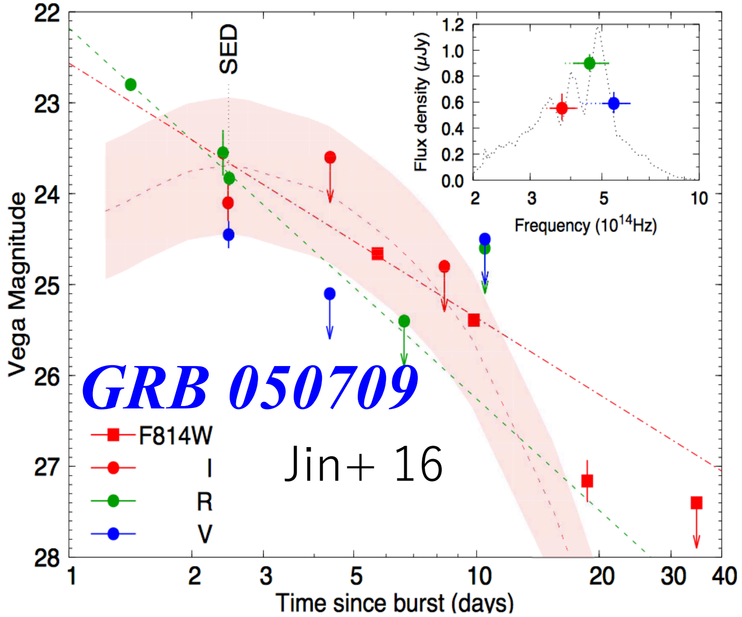


$$t_{\mathrm{peak}} \sim 7\mathrm{day}\left(\frac{M_{\mathrm{ej}}}{0.05M_{\odot}}\right)^{1/2} \times \left(\frac{\kappa}{10\mathrm{cm}^2\mathrm{g}^{-1}}\right)^{1/2}\left(\frac{v_{\mathrm{ej}}}{0.1c}\right)^{-1/2}$$

r-process Heating Model







Light curve fitting

$M_{ej}/M_\odot$

GRB 050709 : ~ 0.1 — Jin+ 16

GRB 060614 : ~ 0.25 — Jin+ 15, Yang+ 15

GRB 130603B : ~ 0.05 - 0.1 — Hotokezaka+ 16, Barnes+ 16

Simulation

NS-NS : ~ 10^{-4} – 10^{-2} — Hotokezaka+ 13

BH-NS : < 10^{-1} — Kyutoku+ 15

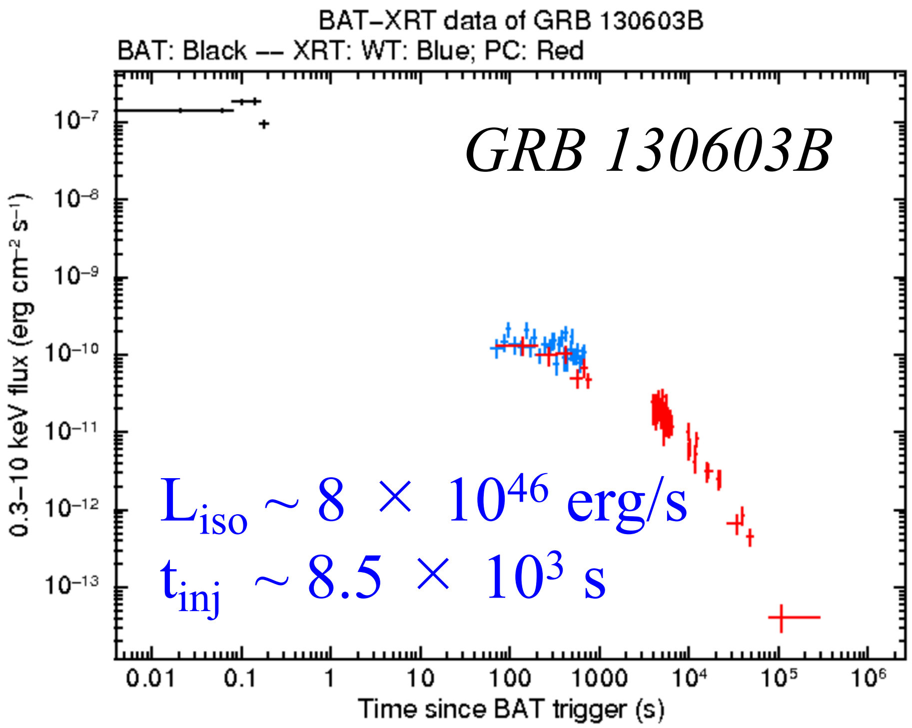
Shock Heating

Injection energy

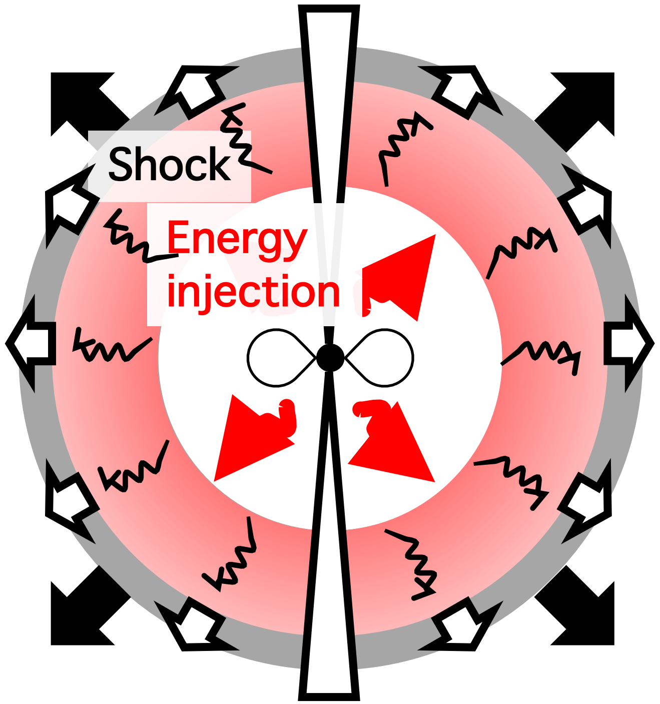
$$E_{\rm int0} \sim \left(\frac{\theta_{\rm j}^2}{2}\right) \eta^{-1} L_{\rm iso} t_{\rm inj}$$

$$\sim 10^{49} \left(\frac{\theta_{\rm j}}{0.1}\right)^2 \left(\frac{\eta}{0.1}\right)^{-1} \left(\frac{L_{\rm iso}}{10^{47}{\rm erg~s^{-1}}}\right) \left(\frac{t_{\rm inj}}{10^4{\rm s}}\right) {\rm erg}$$

Radiative efficiency η
Jet opening angle $\theta_{\rm j}$



the UK Swift Science Data Centre



SK, Ioka & Takami 15

Adiabatic Cooling

Luminosity: $L \sim E_{int}/t$, $E_{int} \propto r^{-1}$

Homologous expansion

$$r \sim vt$$

$$L \sim \frac{E_{\rm int0}}{t}\left(\frac{t}{t_{\rm inj}}\right)^{-1}$$

$$\sim 10^{41}\left(\frac{E_{\rm int0}}{10^{49}{\rm erg}}\right)\left(\frac{t_{\rm inj}}{10^{4}{\rm s}}\right)\left(\frac{t}{10^{6}{\rm s}}\right)^{-2}\ {\rm erg\ s^{-1}}$$

Temperature: $T \propto r^{-1}$

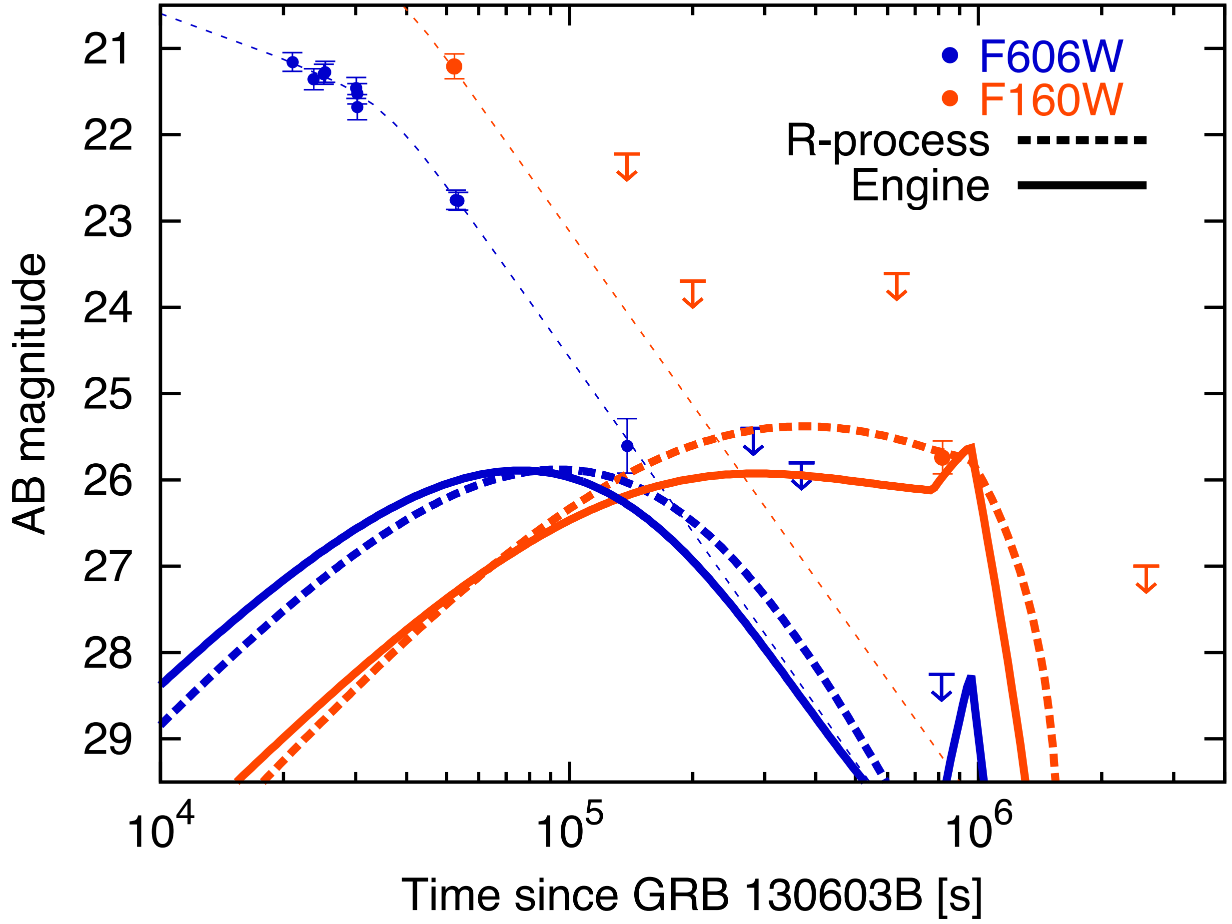
$$T \sim T_0\left(\frac{t}{t_{\rm inj}}\right)^{-1}$$

$$\sim 2\times 10^{3}\left(\frac{E_{\rm int0}}{10^{49}{\rm erg}}\right)^{1/4}\left(\frac{t_{\rm inj}}{10^{4}{\rm s}}\right)^{1/4}$$

$$\times\left(\frac{v}{10^{10}{\rm cm\ s^{-1}}}\right)^{-3/4}\left(\frac{t}{10^{6}{\rm s}}\right)^{-1}\ {\rm K}$$

Macronova Light Curve

SK, Ioka & Nakamura 15



Plateau emission parameters

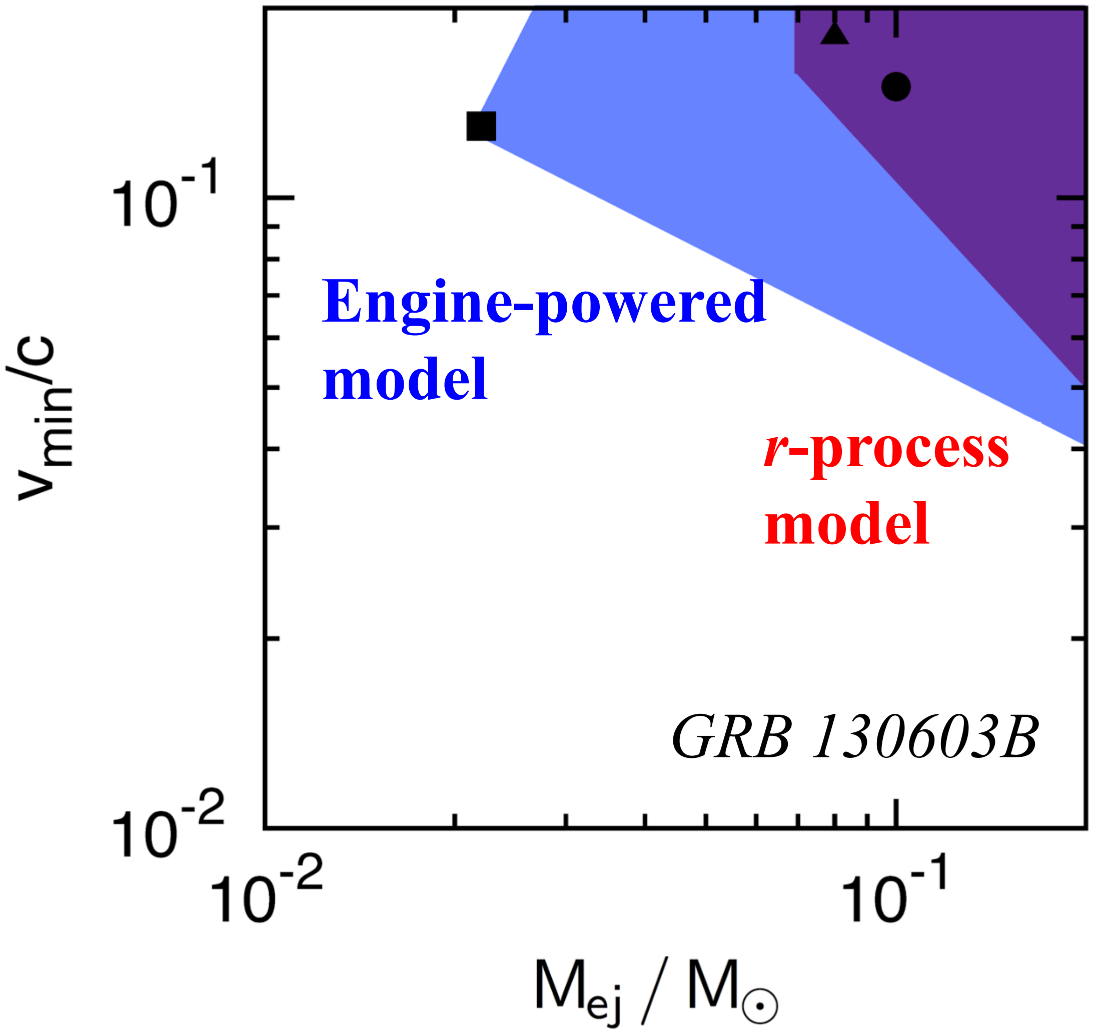
$\eta = 0.1$ (Zhang+ 07), $\theta_j = 4^\circ$ (Fong+ 14)

$L_{iso} = 8 \times 10^{46}$ erg/s, $t_{inj} = 8.5 \times 10^3$ s

Allowed Parameter Region

The required mass ($\sim 0.02 M_{\odot}$) is comparable to NS-NS merger (e.g., Hotokezaka+ 13).

SK, Ioka & Takami 15

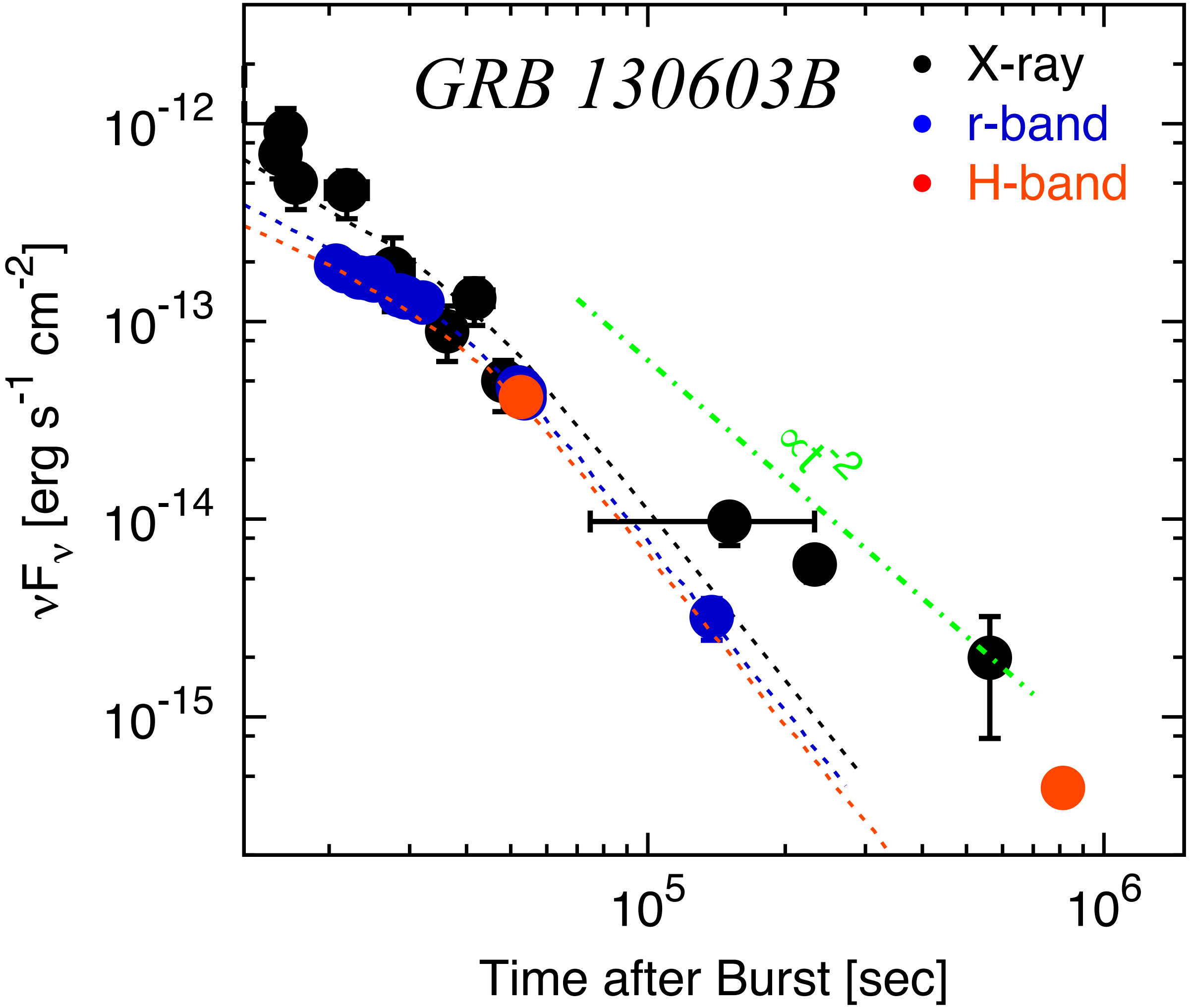


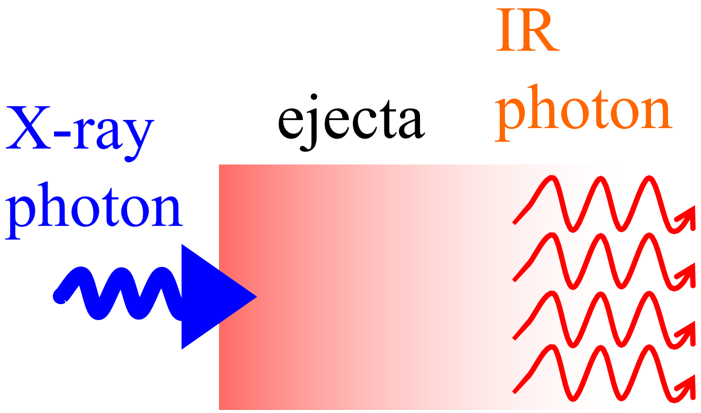
$v_{\rm max} = 0.4c$

$\kappa = 3 - 30 {\rm cm}^2 {\rm g}^{-1}$

X-ray-powered Macronova ?

Fluxes of the X-ray and IR excesses are comparable. ⇨ **A single energy source?**



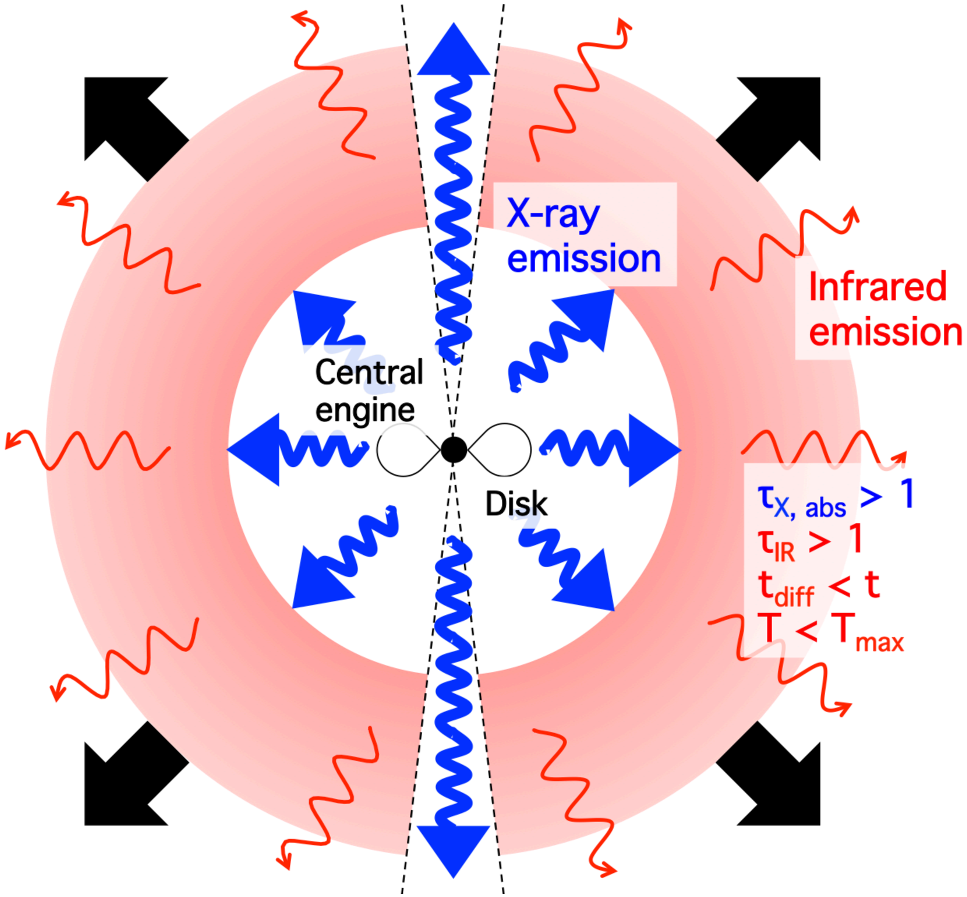


	F_{IR}/F_X
GRB 050709	~ 1
GRB 060614	~ 0.1
GRB 130603B	~ 0.4

Jin+ 16

X-ray-powered Macronova

The merger ejecta heated by the irradiation of X-ray emit thermal infrared radiation.



Physical setups

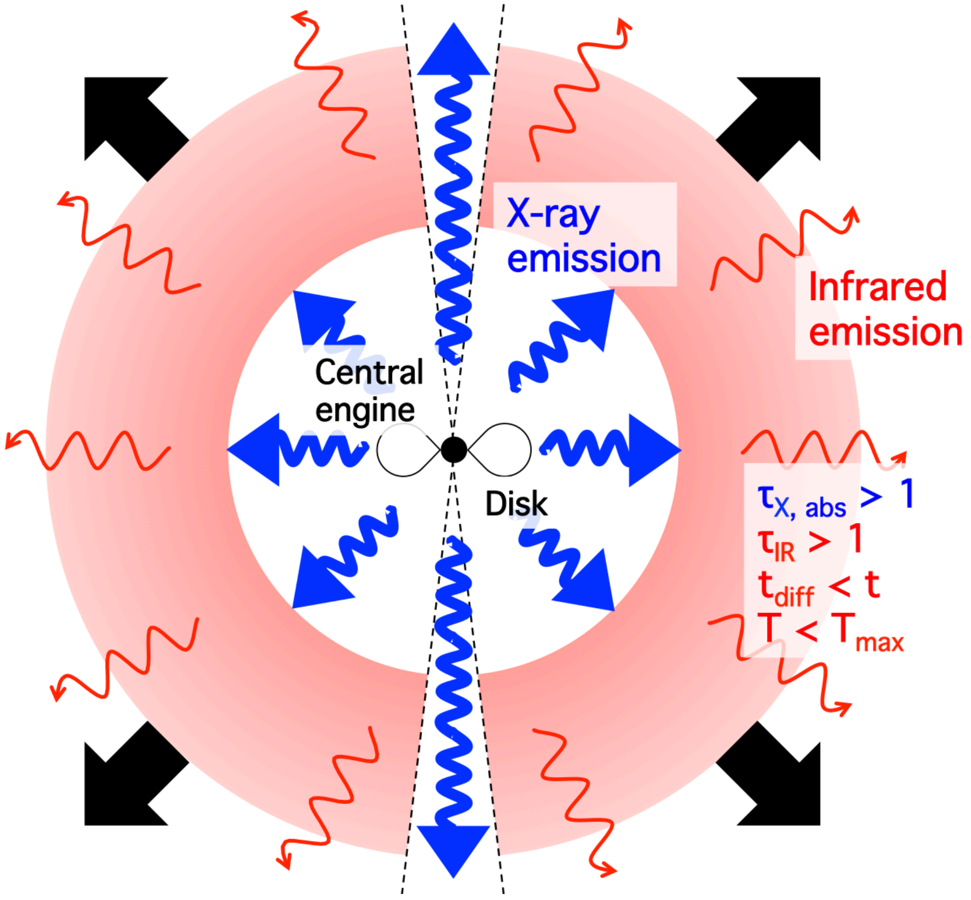
・Isotropic X-rays are generated near the central source.

・The ejecta cover a fraction of solid angle.

・The line-of-sight to the source is clean for the observers.

X-ray-powered Macronova

The merger ejecta heated by the irradiation of X-ray emit thermal infrared radiation.



Required conditions

・Absorption of X-ray photons

$\tau_X > 1$

・Thermalization

$\tau_{IR} > 1$

・Escaping thermal photons

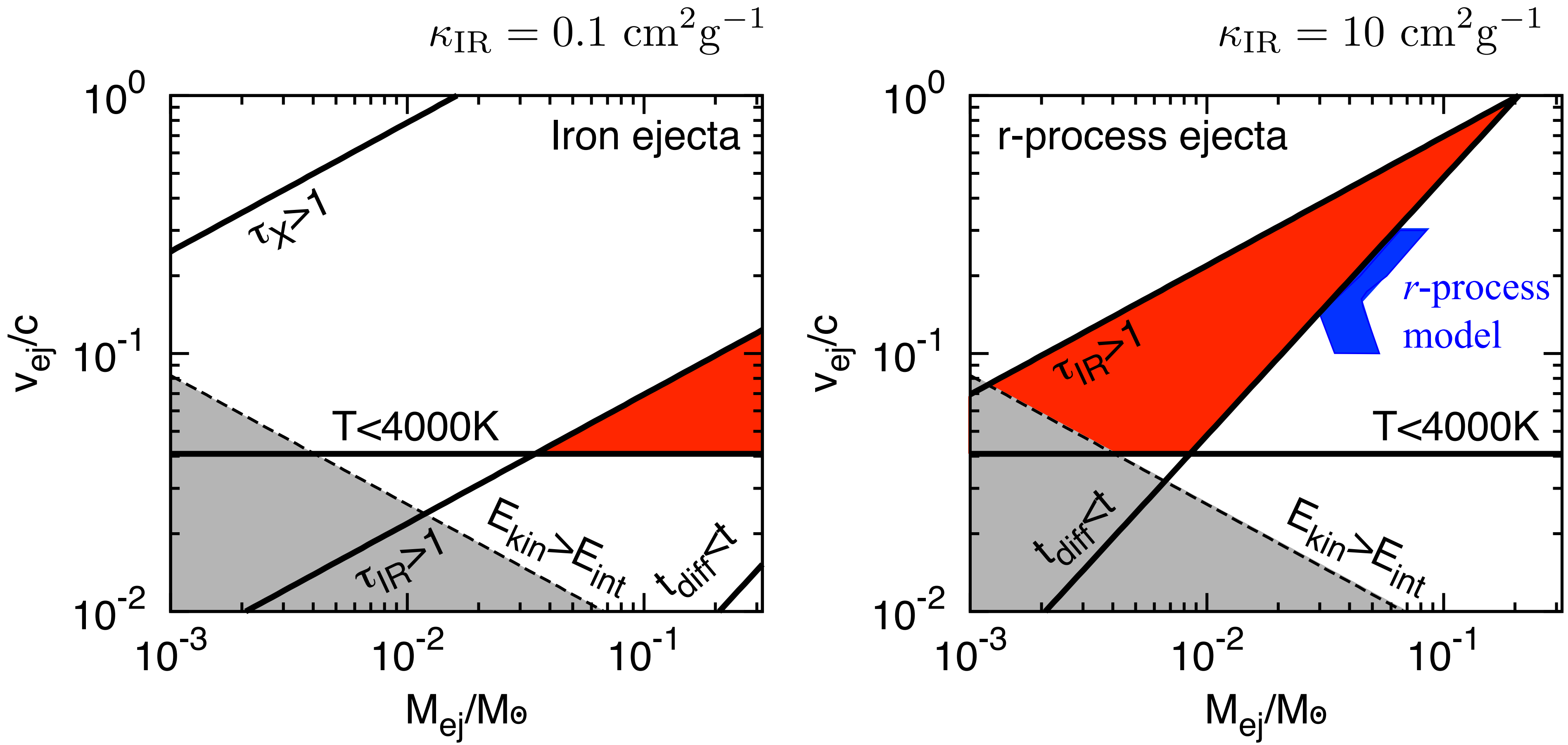
$t_{diff} < t$

・Temperature

$T < T_{max}$

Results

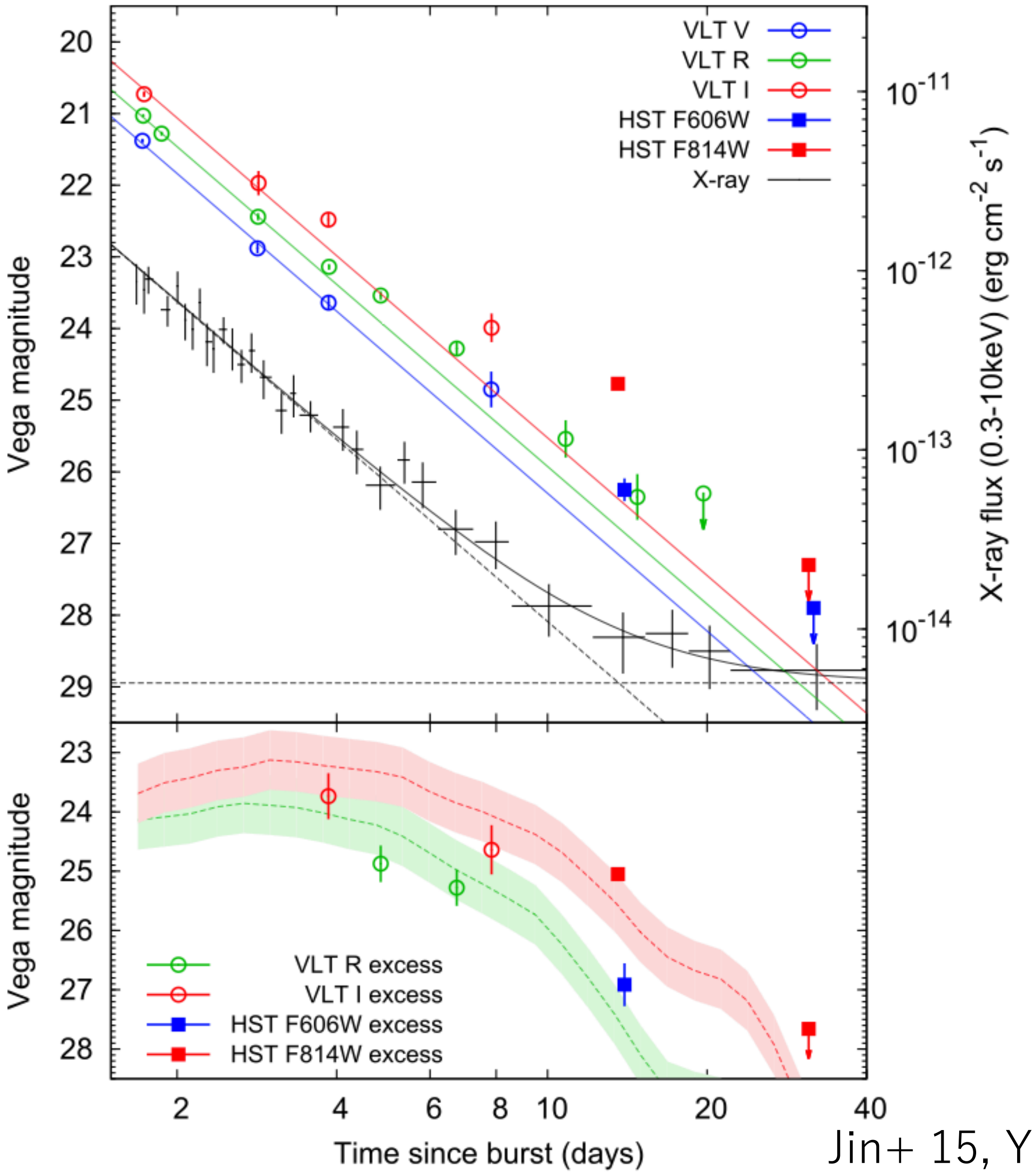
Broad ranges of the allowed parameter regions



Without r-process ejecta

$10^{-3} < M_{ej}/M_{sun} < 10^{-1}$

Other Macronova Candidate



GRB 060614

The long-lasting X-ray component was also detected.

t ~ 12 day

L_{NIR} ~ 10^{41}erg/s

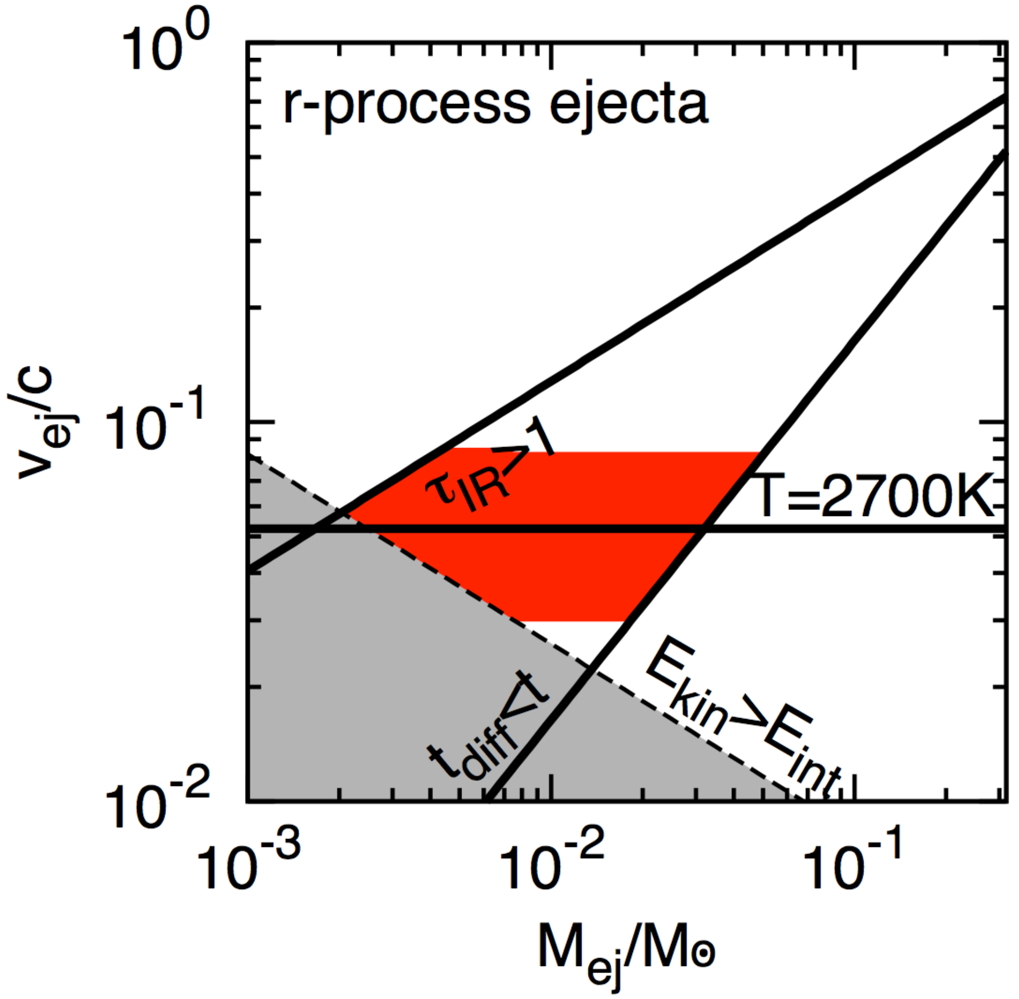
T ~ 2200 - 3400 K

***r*-process model**

$$M_{\rm ej} \gtrsim 0.25 M_\odot$$

Jin+ 15, Yang+ 15

Other Macronova Candidate



GRB 060614

Required mass

$0.002 \lesssim M_{ej}/M_\odot \lesssim 0.05$

Consistent with NS-NS merger ejecta

Late Phase X-ray Emission

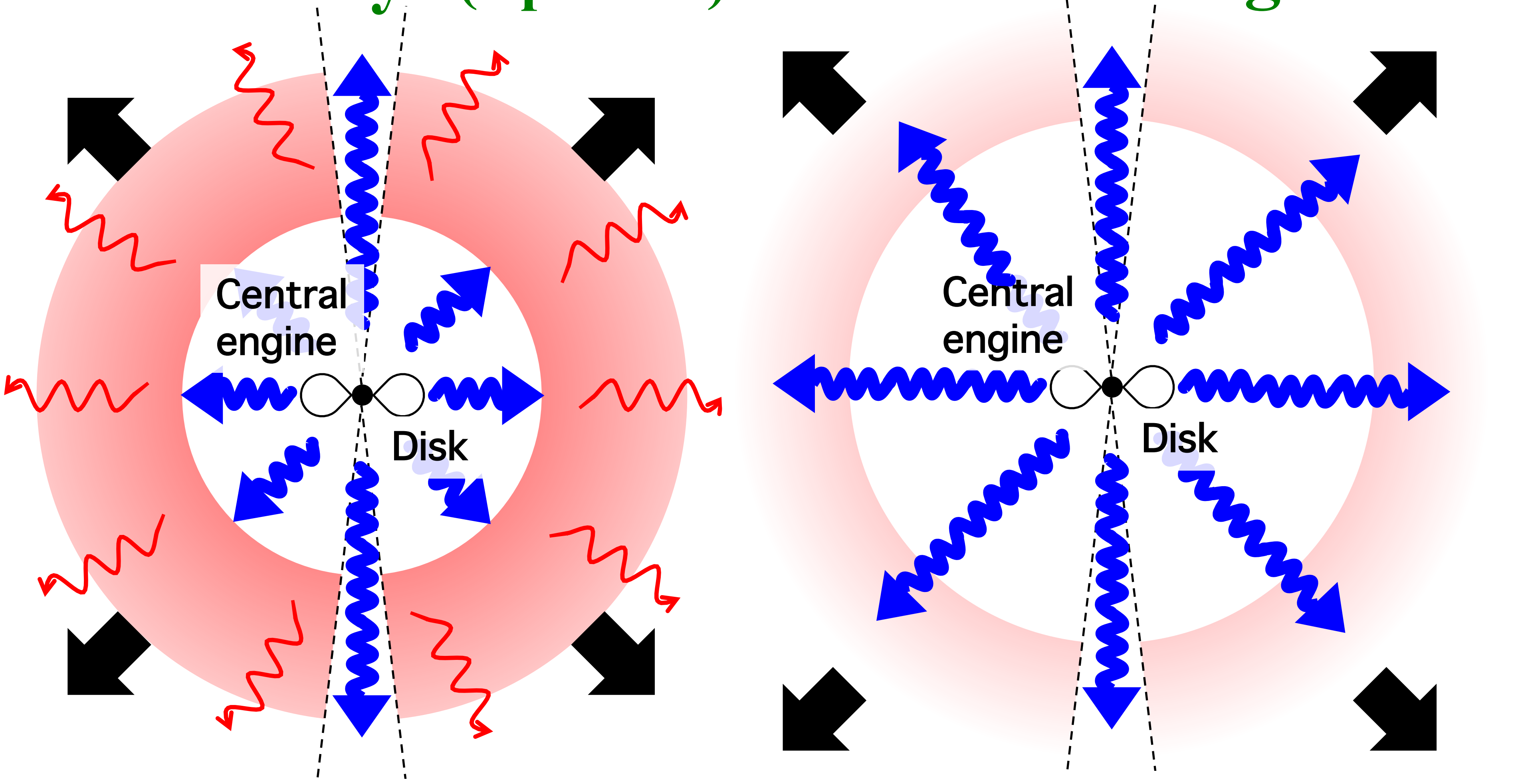
Ejecta become optically thin to the X-ray.

<10 days (Fe)

<100 days (*r*-process)

> 10 days (Fe)

$L \sim 10^{41}$ erg/s

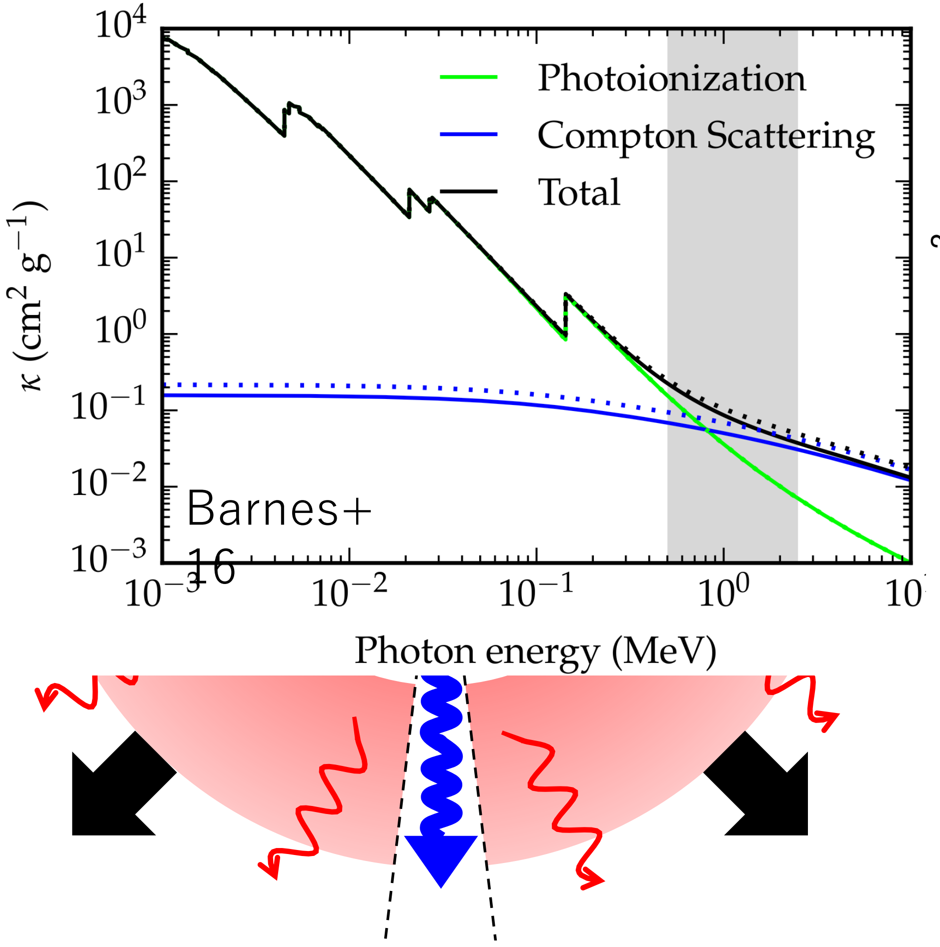


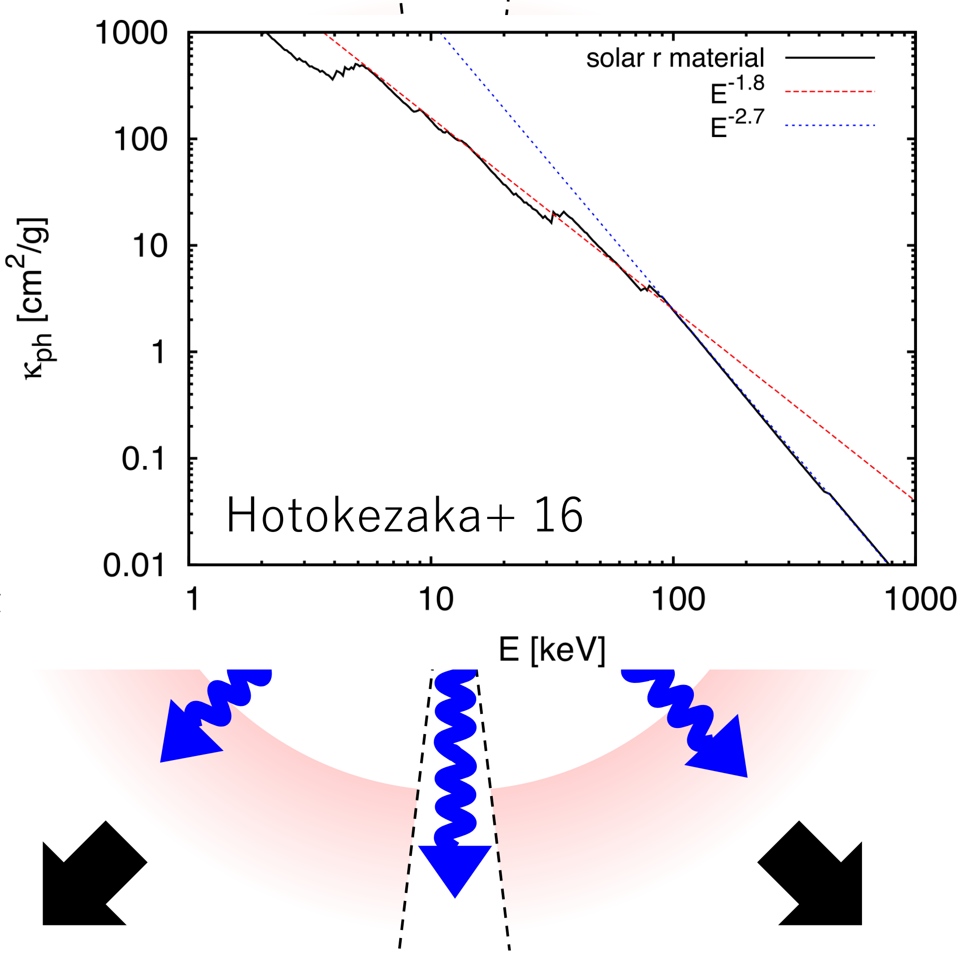
Late Phase X-ray Emission

Ejecta become optically thin to the X-ray.

<10 days (Fe)
<100 days (*r*-process)

> 10 days (Fe)
L ~ 10^{41} erg/s





Summary

Gamma-ray Burst

Scattering produces isotropic emission which can be detectable by current and planed detectors.

Macronova

Engine-powered model explains IR excess and allow for broader parameter region even if the ejecta are composed of iron.