Scattered short gamma-ray bursts as electromagnetic counterparts to gravitational waves

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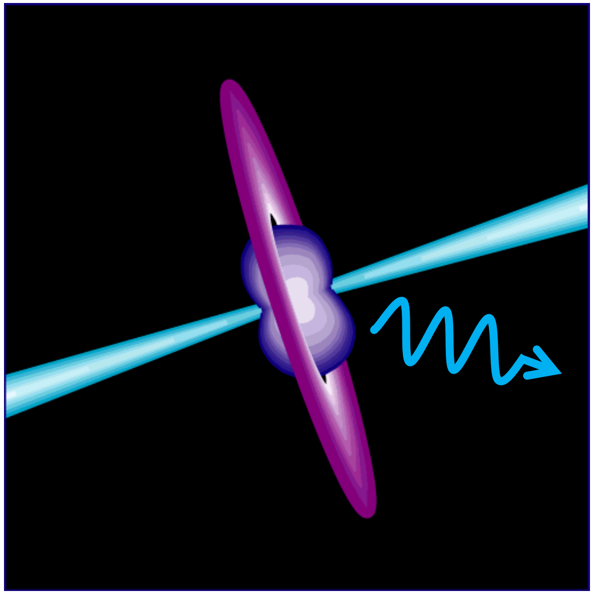
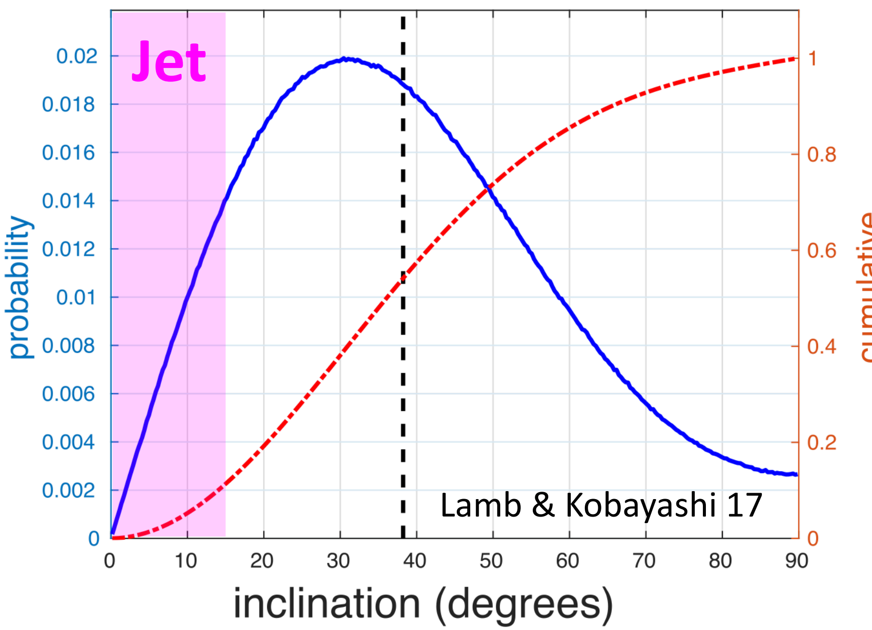
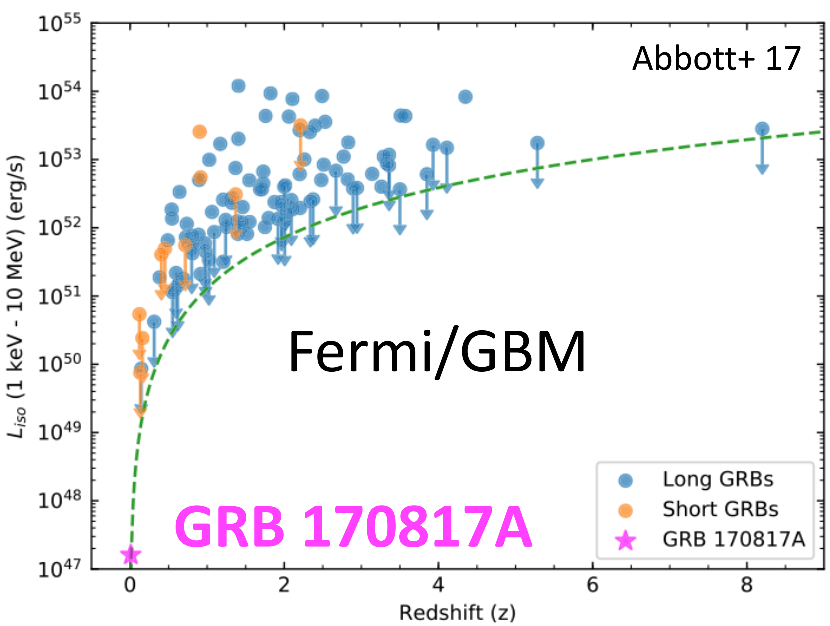


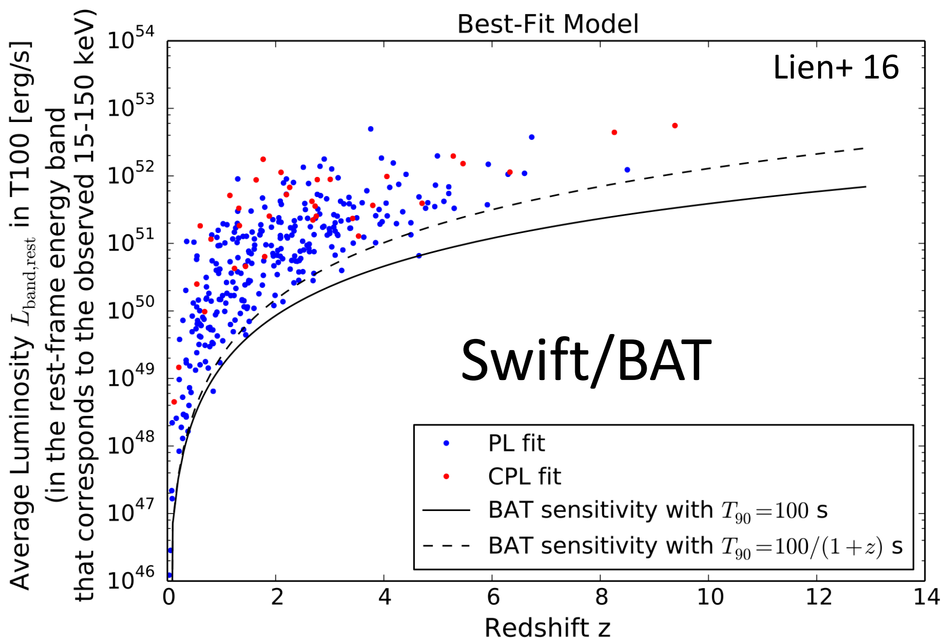
SK, Ioka, Kashiyama & Nakamura (2018) ApJ 867 39

Off-axis, low-luminosity population



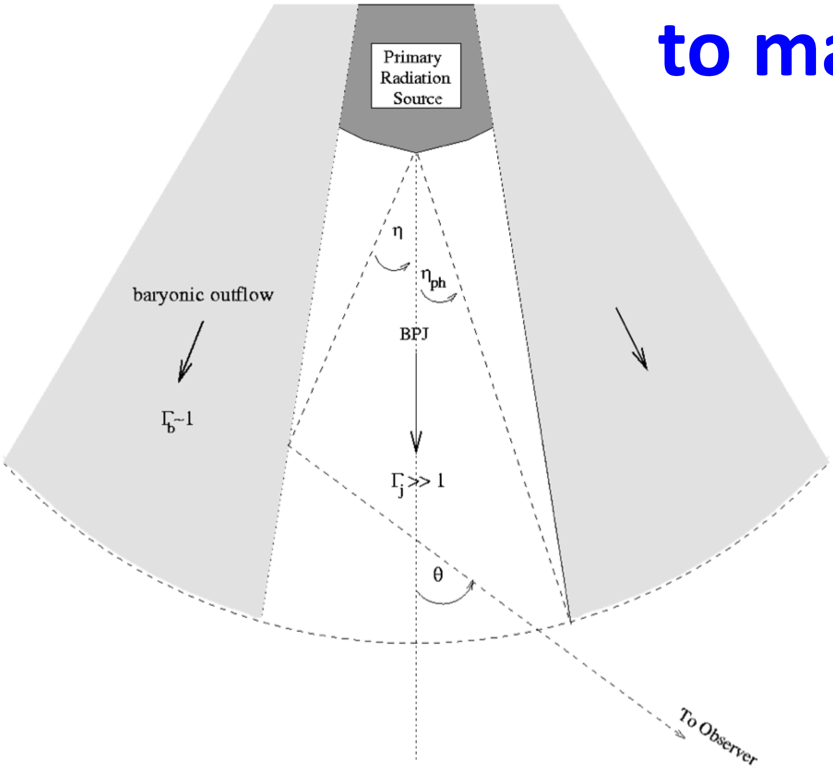
Most are off-axis event.
Low-L events may not be identified because of unknown-z.
Then, GW & EM observations will increase a number of the NS-NS merger origin γ-ray transients.





Scattered emission

Scattering in GRBs as a mechanism to make wide-angle emission.



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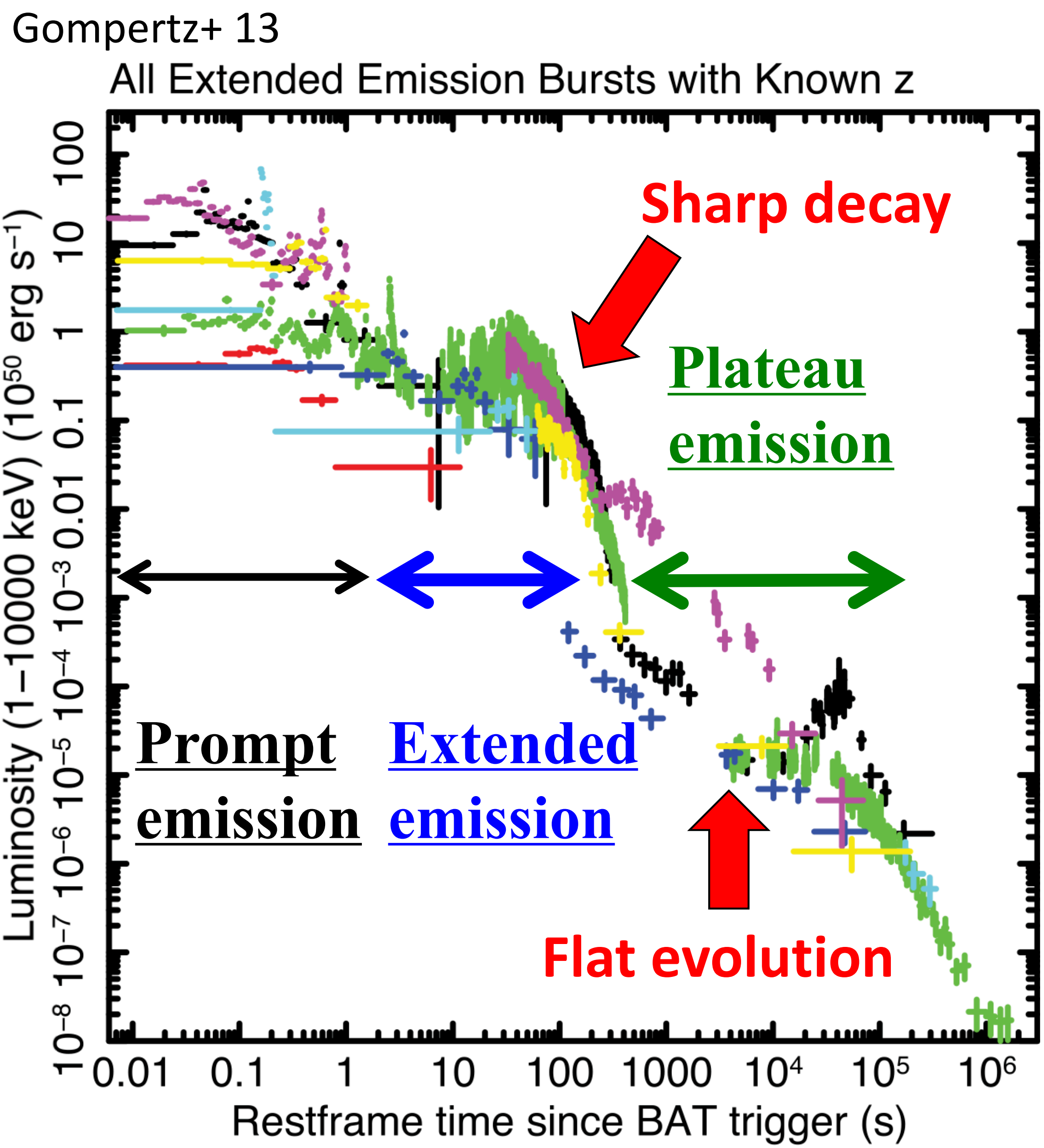
Scatterers

- relativistic scatterer
- sub-relativistic scatterer

Activities

- prompt emission
- extended emission
- plateau emission

Engine activities



Prompt emission

$$L_{\rm iso} \sim 10^{50} - 10^{51} {\rm erg\ s^{-1}}$$
$$T_{\rm dur} \sim 0.1 - 1\ {\rm sec}$$

Extended emission

$$L_{\rm iso} \sim 10^{47} - 10^{50} {\rm erg\ s^{-1}}$$
$$T_{\rm dur} \sim 10^2 - 10^3\ {\rm sec}$$

Plateau emission

$$L_{\rm iso} \sim 10^{43} - 10^{47} {\rm erg\ s^{-1}}$$
$$T_{\rm dur} \sim 10^4 - 10^5\ {\rm sec}$$

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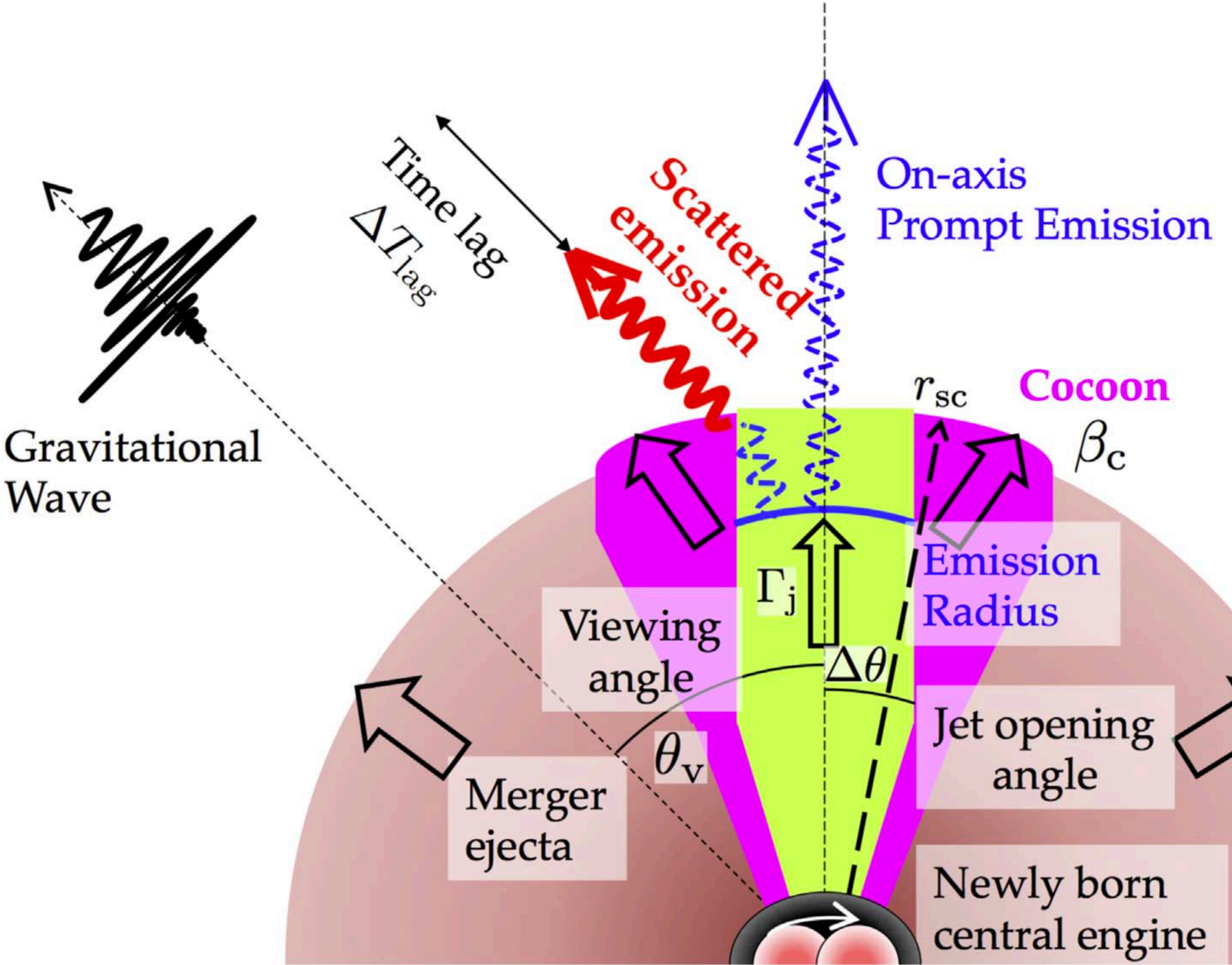
Conditions

- Emission region $r_{ph} < r_e < r_{sc}$
- Optical depth $\tau_c \sim 1$

$$r_{\rm ph} \sim \frac{L_{\rm iso}\sigma_{\rm T}}{4\pi m_{\rm p} c^3 \eta \Gamma_{\rm j}^2}$$



Conditions

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	Prompt emission $E_{\rm iso} \sim 10^{51}{\rm erg}$ $t_{\rm dur} \sim 1$ sec	**Extended emission** $E_{\rm iso} \sim 10^{51}{\rm erg}$ $t_{\rm dur} \sim 10^2$ sec	**Plateau emission** $E_{\rm iso} \sim 10^{50}{\rm erg}$ $t_{\rm dur} \sim 10^4$ sec
Relativistic scatterer $\Gamma_{\rm c} \sim 1 - 10$	$\Gamma_{\rm j}(\sim \eta) \gtrsim 10^2$ $r_{\rm e} \gtrsim 10^9{\rm cm}$ $M_{\rm c} \gtrsim 10^{-12} M_\odot$	$r_{\rm e} \gtrsim 10^{12}{\rm cm}$ $M_{\rm c} \gtrsim 10^{-6} M_\odot$	$M_{\rm c} \gtrsim 10^{-2} M_\odot$
Sub-relativistic scatterer $M_{\rm ej} \sim 0.01 M_\odot$ $\beta_{\rm ej} \sim 0.1 - 0.3$	$\Gamma_{\rm j}(\sim \eta) \gtrsim 10^3$ $r_{\rm e} \sim 10^9 - 10^{10}{\rm cm}$ $M_{\rm c} \lesssim 10^{-12} M_\odot$	$\Gamma_{\rm j}(\sim \eta) \gtrsim 20$ $r_{\rm e} \sim 10^{10} - 10^{12}{\rm cm}$ $M_{\rm c} \lesssim 10^{-6} M_\odot$	$r_{\rm e} \lesssim 10^{14}{\rm cm}$ $M_{\rm c} \lesssim 10^{-2} M_\odot$

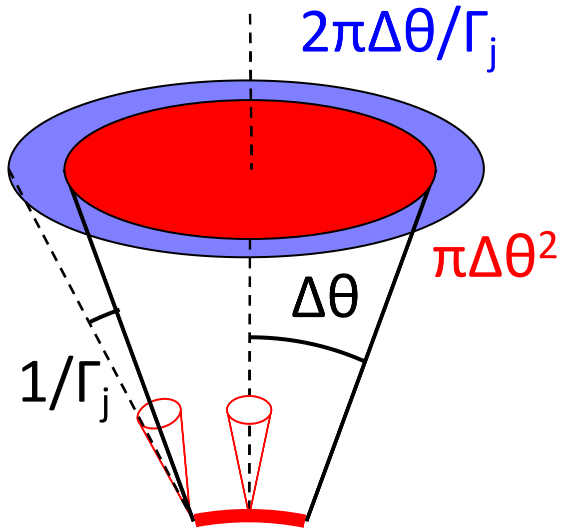
Isotropic radiation energy

$$\frac{E_{\rm iso,sc}}{E_{\rm iso}(\theta_{\rm v}=0)} \sim \frac{L_{\rm sc}T_{\rm dur,sc}}{L_{\rm iso}t_{\rm dur}}$$

$$\sim \frac{2}{\Gamma_{\rm j}\Delta\theta} \times \Gamma_{\rm c}^2 \times \epsilon_{\rm sc} \times \frac{\Delta\theta^2}{2}$$

$$(\Gamma_{\rm c}^{-1} > \theta_{\rm v} - \Delta\theta)$$

- Geometrical effect



$< \Delta\theta > \sim 0.3$ rad Fong+ 15

$T_{\rm dur,sc} \sim \max\{t_{\rm dur}, \Delta T\}$: Observed duration

$$\Delta T \sim \frac{r_{\rm sc}}{2c\beta_{\rm c}\Gamma_{\rm c}^2}$$

$t_{\rm dur}$: Intrinsic engine activity timescale

Isotropic radiation energy

$$\frac{E_{\rm iso,sc}}{E_{\rm iso}(\theta_{\rm v}=0)} \sim \frac{L_{\rm sc}T_{\rm dur,sc}}{L_{\rm iso}t_{\rm dur}}$$

$$\sim \frac{2}{\Gamma_{\rm j}\Delta\theta} \times \Gamma_{\rm c}^2 \times \epsilon_{\rm sc} \times \frac{\Delta\theta^2}{2}$$

$$(\Gamma_{\rm c}^{-1} > \theta_{\rm v} - \Delta\theta)$$

Sub-relativistic scatterer

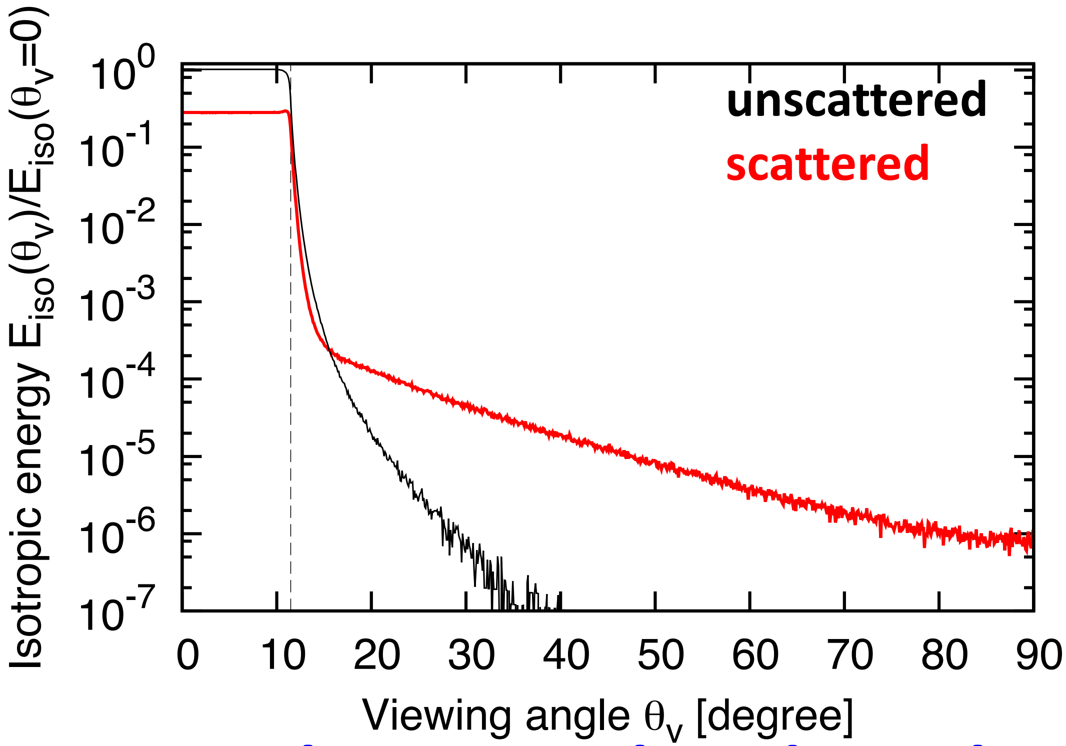
$$\frac{E_{\rm iso,sc}}{E_{\rm iso}(0)} \sim 3\times 10^{-6}\Gamma_{\rm j,3}^{-1}\Delta\theta_{-0.5}\epsilon_{\rm sc,-2}$$

Relativistic scatterer

$$\frac{E_{\rm iso,sc}}{E_{\rm iso}(0)} \sim 3\times 10^{-4}\Gamma_{\rm j,2}^{-1}\Delta\theta_{-0.5}\Gamma_{\rm c,0.5}^{2}\epsilon_{\rm sc,-2}$$

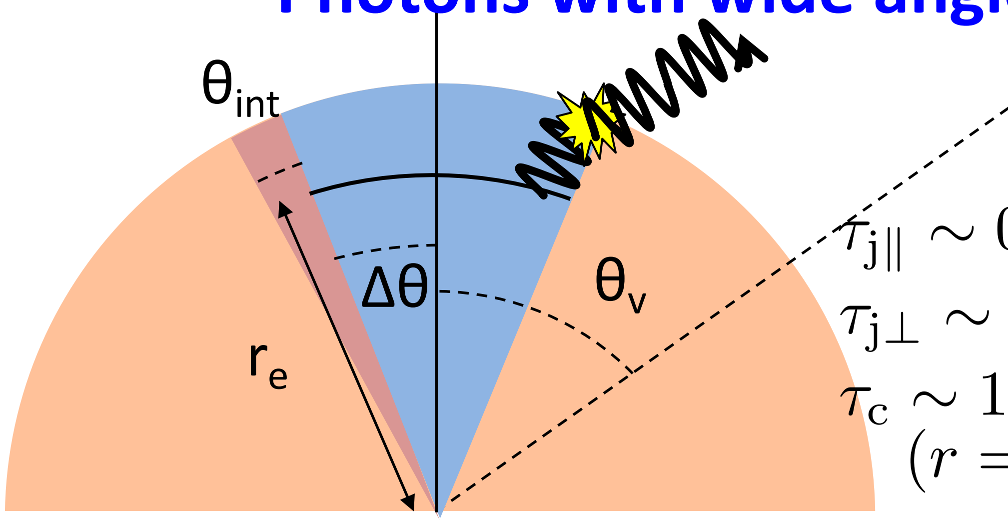
$$(\Gamma_{\rm c}^{-1} > \theta_{\rm v} - \Delta\theta)$$

Prompt emission (relativistic scatterer)



$\Delta\theta$ = 0.2 rad (~ 11°)
Γ_j = 200
$L_{iso} = 10^{51}$ erg s^{-1}
$r_e = 10^{12}$ cm
$M_c = 5 \times 10^{-8} M_{sun}$
Γ_c = 3
$\theta_{int} = \Gamma_j^{-1}$

Photons with wide angle could be detectable.



$\tau_{j\parallel} \sim 0.07$

$\tau_{j\perp} \sim 6 \times 10^3$

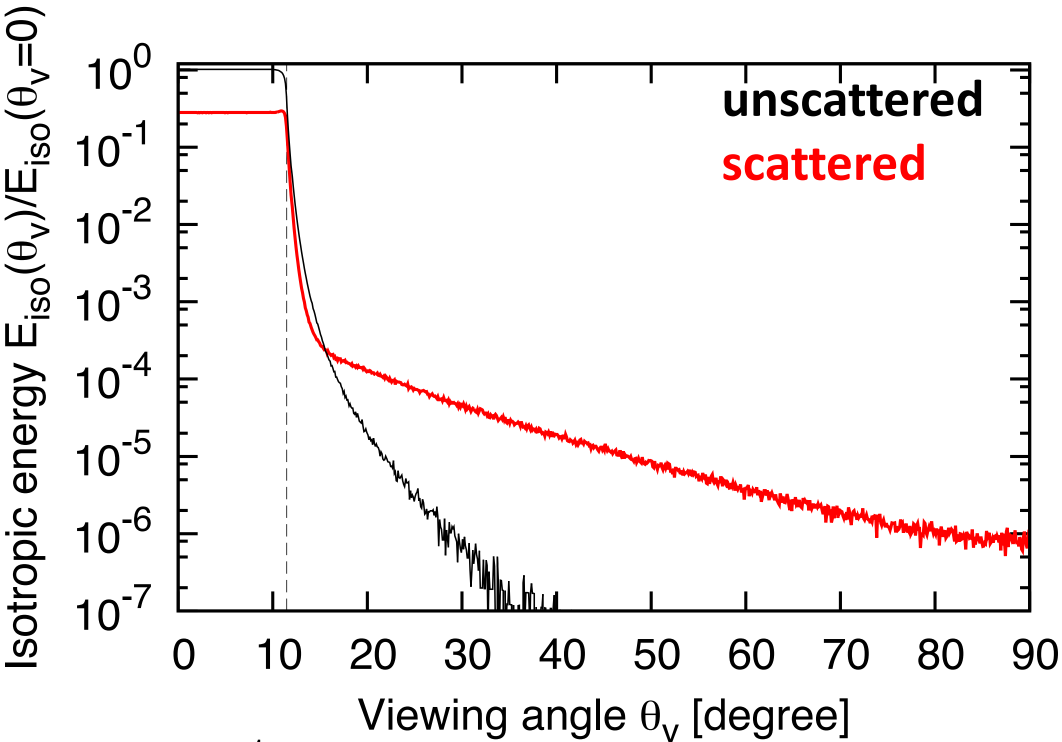
$\tau_c \sim 1.5$
$(r = r_e)$

$\epsilon_{sc} \lesssim 10^{-2}$

Isotropic energy

$$\frac{E_{iso,sc}}{E_{iso}(0)} \sim 3 \times 10^{-4} \epsilon_{sc,-2}$$

Prompt emission (relativistic scatterer)



$\Delta\theta = 0.2$ rad (~ 11°)

$\Gamma_j = 200$

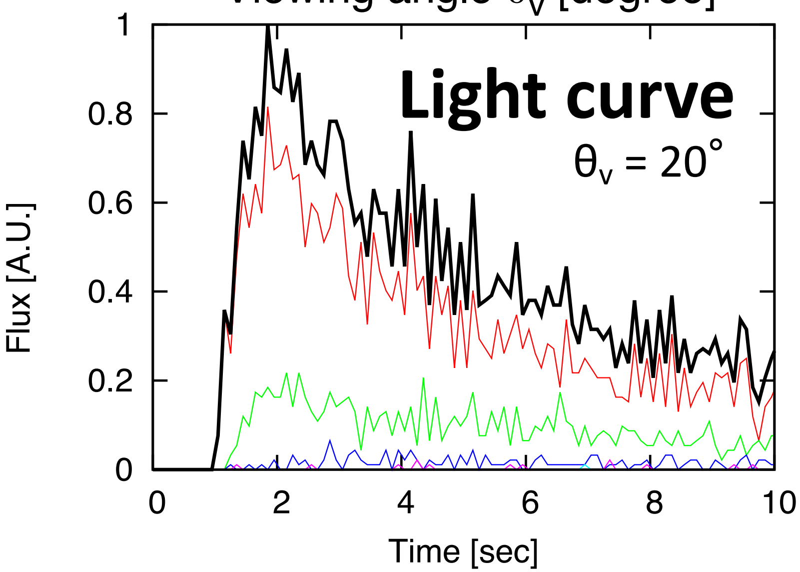
$L_{iso} = 10^{51}$ erg s^{-1}

$r_e = 10^{12}$ cm

$M_c = 5 \times 10^{-8} M_{sun}$

$\Gamma_c = 3$

$\theta_{int} = \Gamma_j^{-1}$



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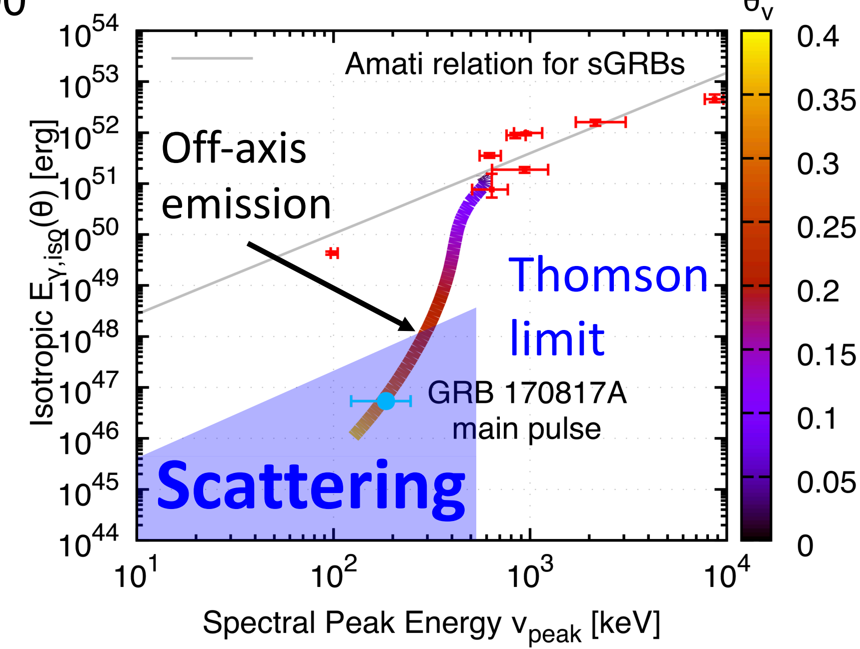
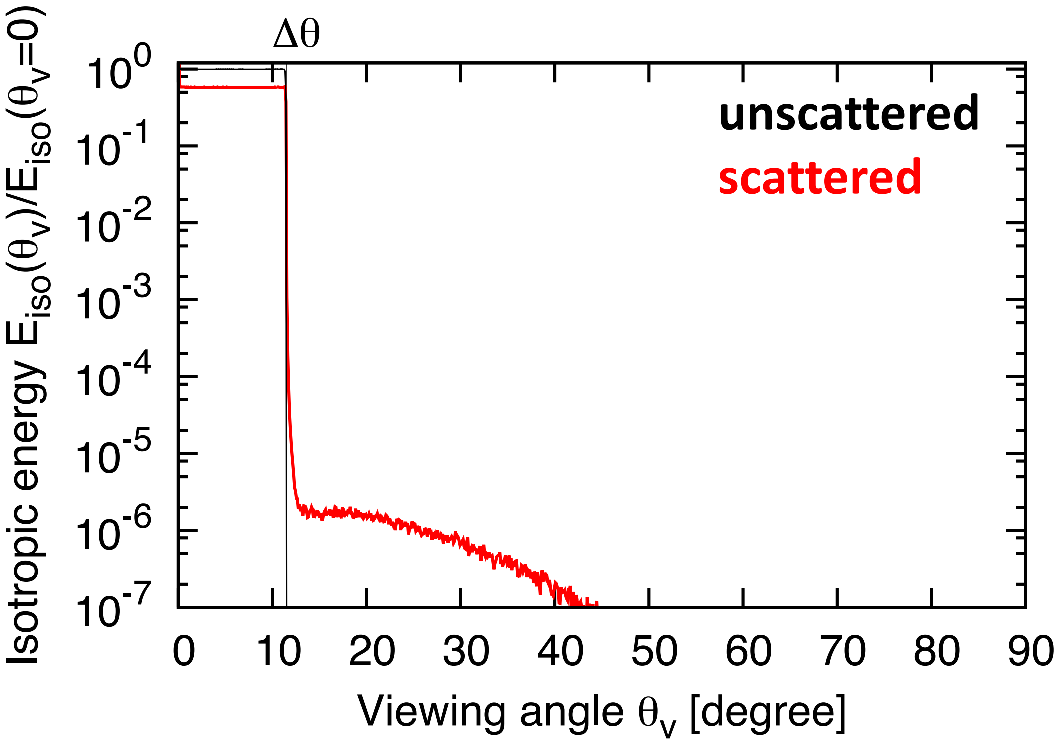


Prompt emission (sub-relativistic scatterer)



$\Delta\theta$ = 0.2 rad (~ 11°)

Γ_j = 1000

$L_{iso} = 10^{51}$ erg s^{-1}

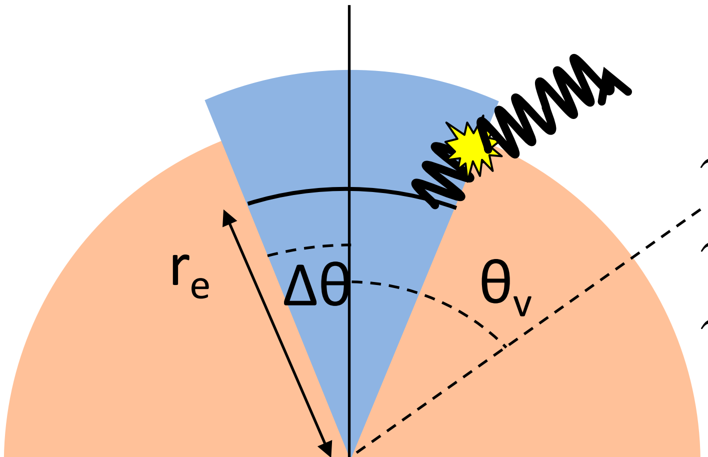
t_e = 1.0 sec

$r_e = 3 \times 10^9$ cm

$M_{ej} = 10^{-2} M_{sun}$ $(0.1 \leq \beta \leq 0.3)$

$\rho_{ej} \propto \beta^{-3}$

Photons scattered at the edge of the ejecta could be detectable.



$\tau_{j\parallel} \sim 0.4$

$\tau_{j\perp} \sim 8 \times 10^5$

$\tau_c \sim 7 \times 10^{10}$

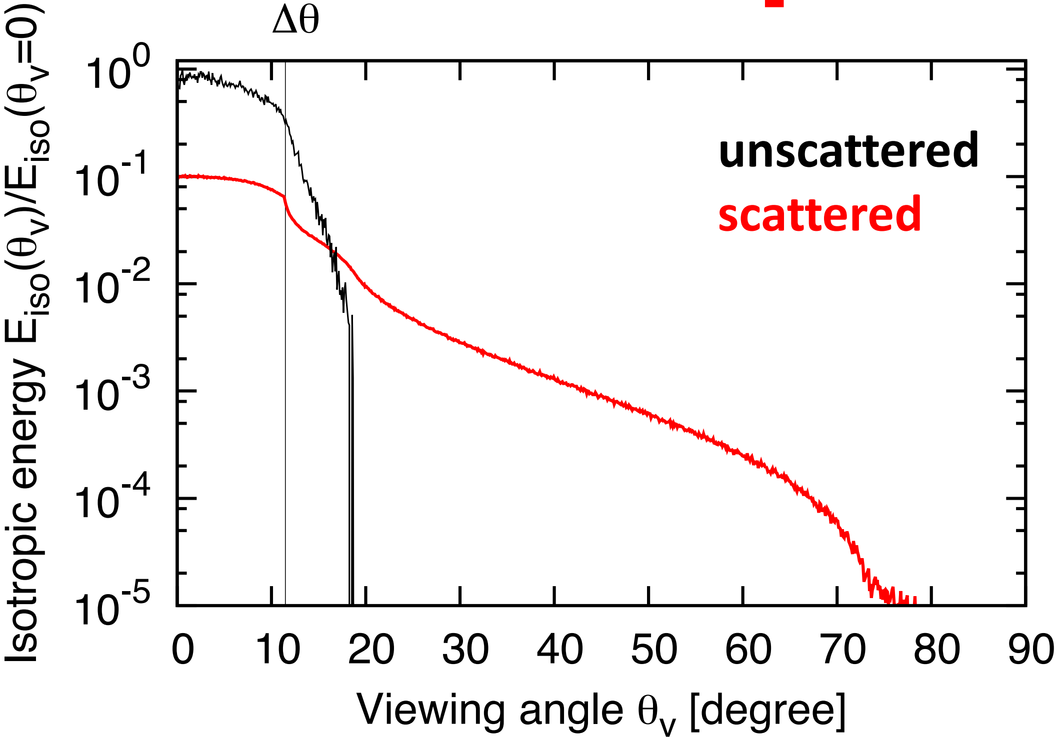
$(r = r_e)$

$\epsilon_{sc} \lesssim 10^{-2}$

Isotropic enetgy

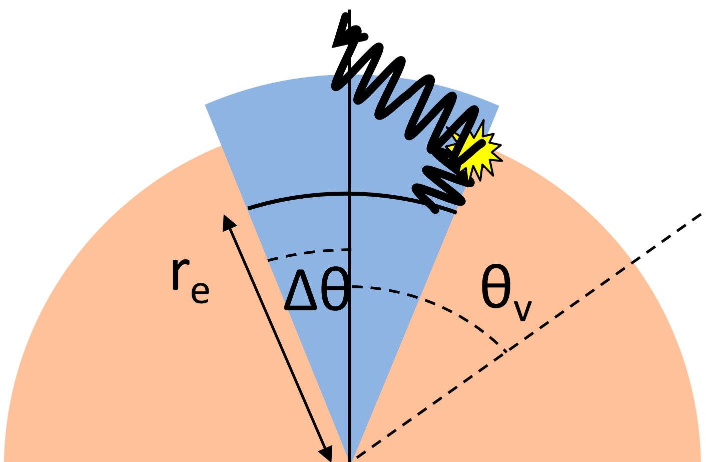
$$\frac{E_{iso,sc}}{E_{iso}(0)} \sim 3 \times 10^{-6} \epsilon_{sc,-2}$$

Scattered plateau emission



$\Delta\theta$ = 0.2 rad (~ 11°)
$\Gamma_j = 10$
$L_{iso} = 10^{46}$ erg s^{-1}
$t_e = 10^4$ sec
$r_e = 3 \times 10^{13}$ cm
$M_{ej} = 10^{-2} M_{sun}$ $(0.1 \le \beta \le 0.3)$
$\rho_{ej} \propto \beta^{-3}$

Photons can cross the jet.



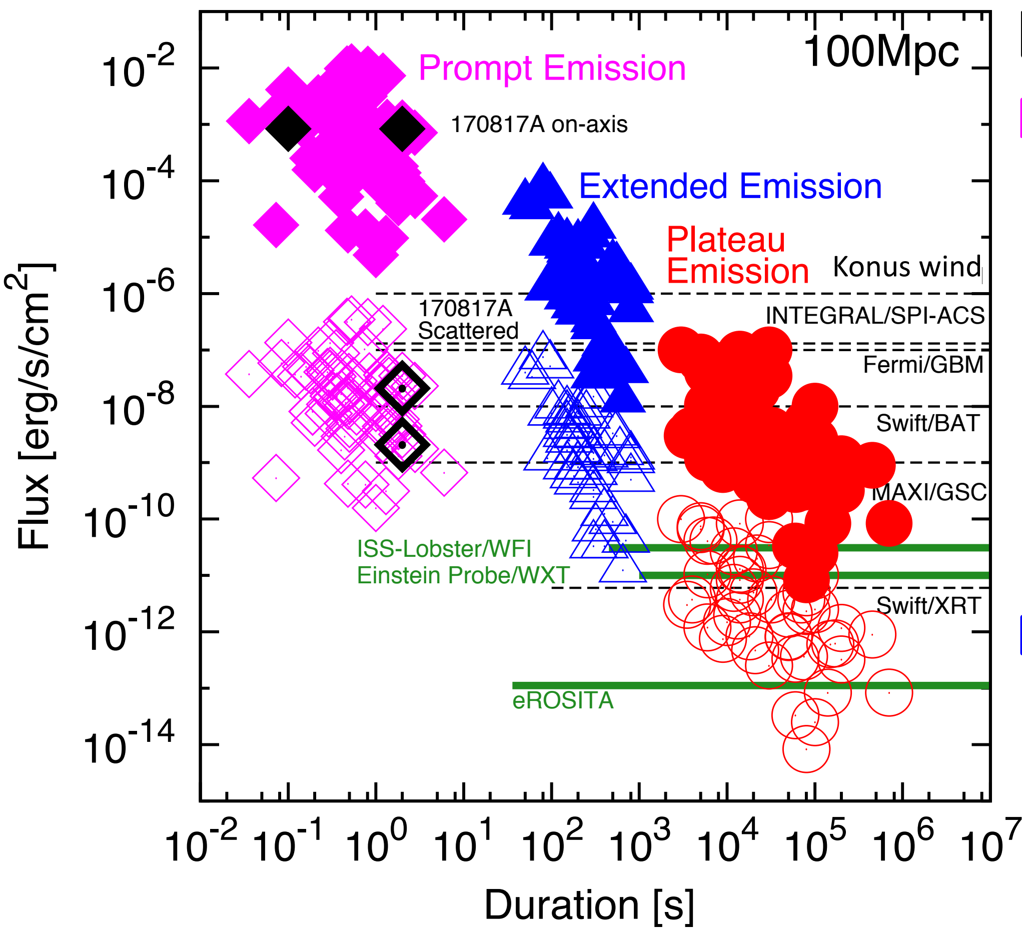
$\tau_{j\parallel} \sim 10^{-3}$
$\tau_{j\perp} \sim 0.2$
$\tau_c \sim 7 \times 10^3$

$\epsilon_{sc} \lesssim 10^{-1}$

Isotropic enetgy

$$\frac{E_{iso,sc}}{E_{iso}(0)} \sim 3 \times 10^{-3} \epsilon_{sc,-1}$$

Detectability



Detection rate (prompt, relativistic scatterer)

Swift/BAT $\mathcal{R} \sim 0.3 \ \mathrm{yr}^{-1}$

Fermi/GBM $\mathcal{R} \sim 0.1 \ \mathrm{yr}^{-1}$

Luminosity ($\Delta\theta$ = 0.3 rad)

Prompt Emission ($L_{iso} = 10^{51}$ erg s^{-1})

$$L_{\rm sc} \sim 3 \times 10^{45} \ \mathrm{erg\ s^{-1}} \Gamma_{\rm j,3}^{-1} \epsilon_{\rm sc,-2}$$

(Sub-relativistic scatterer)

$$L_{\rm sc} \sim 3 \times 10^{46} \ \mathrm{erg\ s^{-1}} \Gamma_{\rm j,2}^{-1} \epsilon_{\rm sc,-2} \times t_{\rm dur,-1} \Gamma_{\rm c,0.5}^{4} r_{\rm sc,12}^{-1}$$

(Relativistic scatterer)

Extended Emission ($L_{iso} = 10^{49}$ erg s^{-1})

$$L_{\rm sc} \sim 10^{45} \ \mathrm{erg\ s^{-1}} \Gamma_{\rm j,1.5}^{-1} \epsilon_{\rm sc,-2}$$

(Sub-relativistic scatterer)

$$L_{\rm sc} \sim 10^{46} \ \mathrm{erg\ s^{-1}} \Gamma_{\rm j,1.5}^{-1} \Gamma_{\rm c,0.5}^{2} \epsilon_{\rm sc,-2}$$

(Relativistic scatterer)

Plateau Emission ($L_{iso} = 10^{46}$ erg s^{-1})

$$L_{\rm sc} \sim 10^{43} \ \mathrm{erg\ s^{-1}} \Gamma_{\rm j,1.5}^{-1} \epsilon_{\rm sc,-1}$$

Summary

- GW observations will increase a number of NS-NS merger origin low-luminosity gamma-ray transients will be increased in near future.

- Scattering in short GRBs could wide angle emission with luminosities ~ 10^{45} - 10^{46} erg s^{-1} for prompt and extended emission, and ~10^{43} erg s^{-1} for plateau emission.

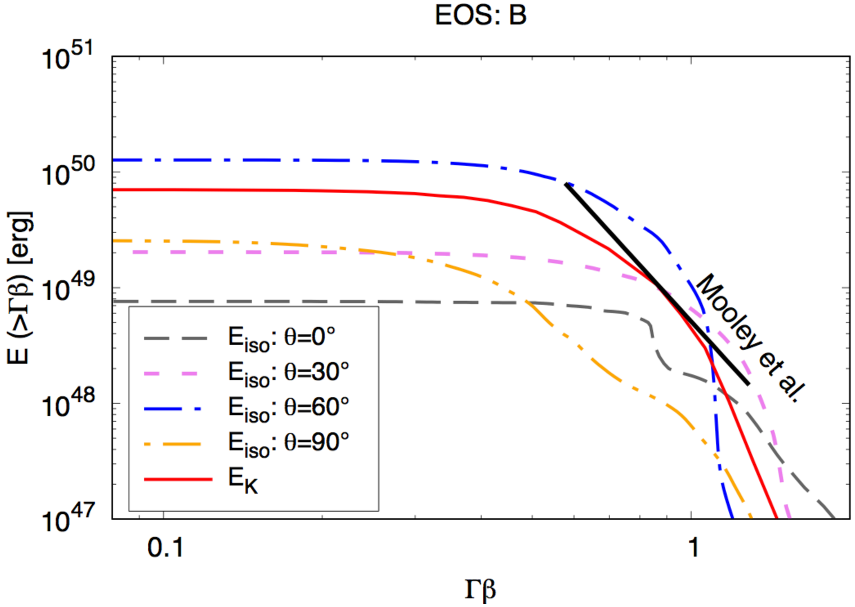
- The detection of the scattered emission could give constraints on the properties of the jet and the cocoon.

Surrounding materials

Relativistic component $M_c \sim 10^{-8} M_\odot ?$ $\Gamma_c \sim 1 - 10$

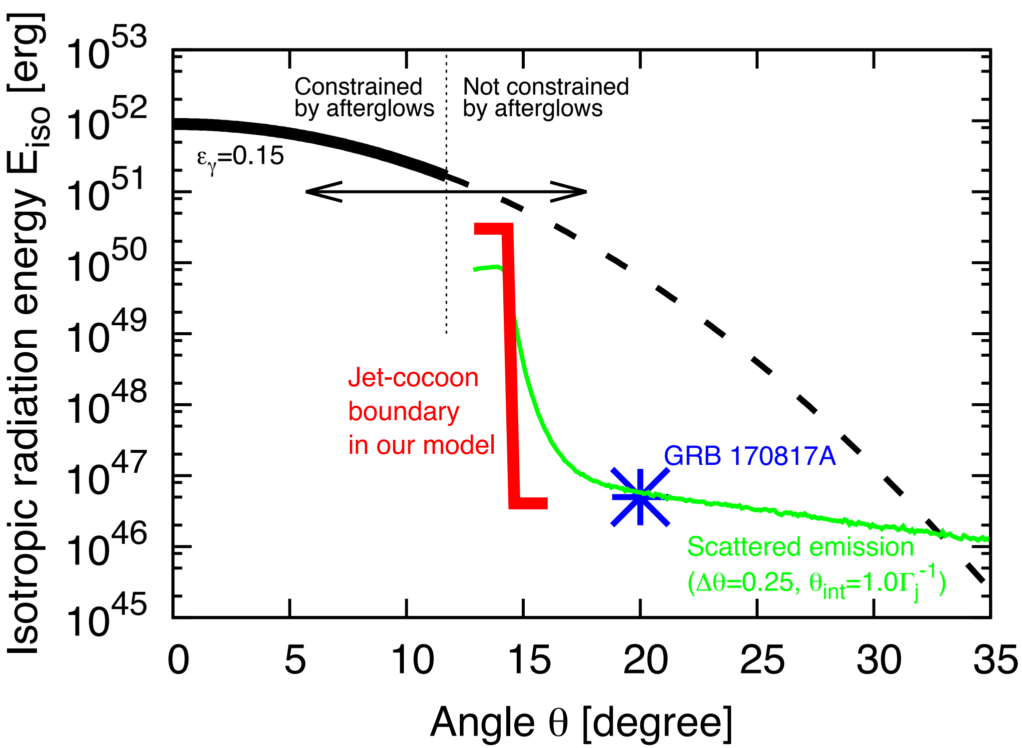
Sub-relativistic component $M_{ej} \sim 10^{-2} M_\odot$ $\beta_{ej} \sim 0.4$

Merger ejecta profile



Nagakura+ 14, Murguia-Berthier+ 14, 17
Nakar & Piran 17, 18, Bromberg+ 18,
Lazzati+ 17, Xie+ 18

Sharp boundary is still consistent with the afterglow observations.



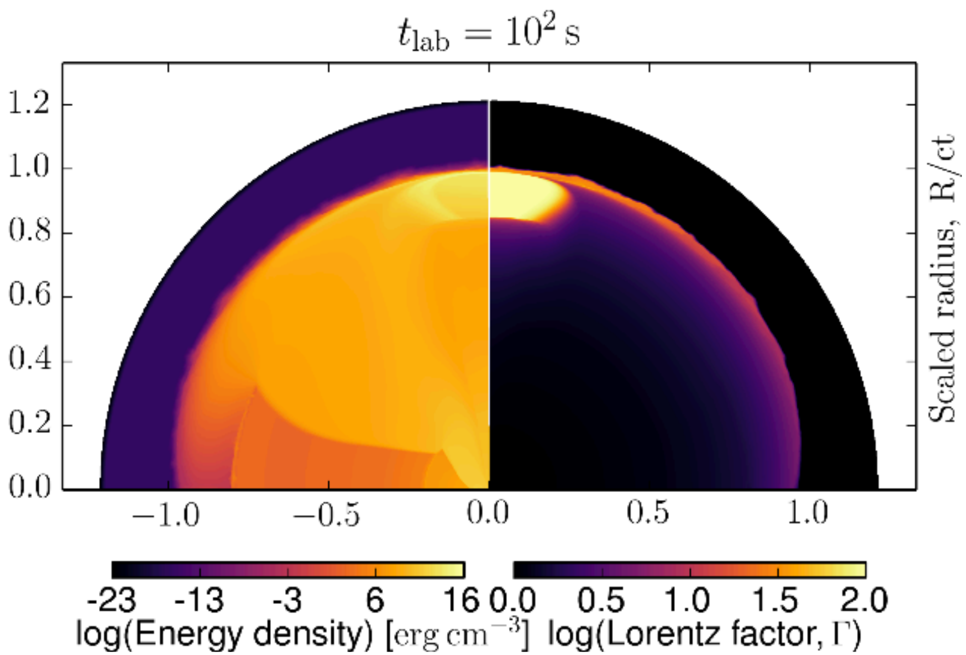
Surrounding materials

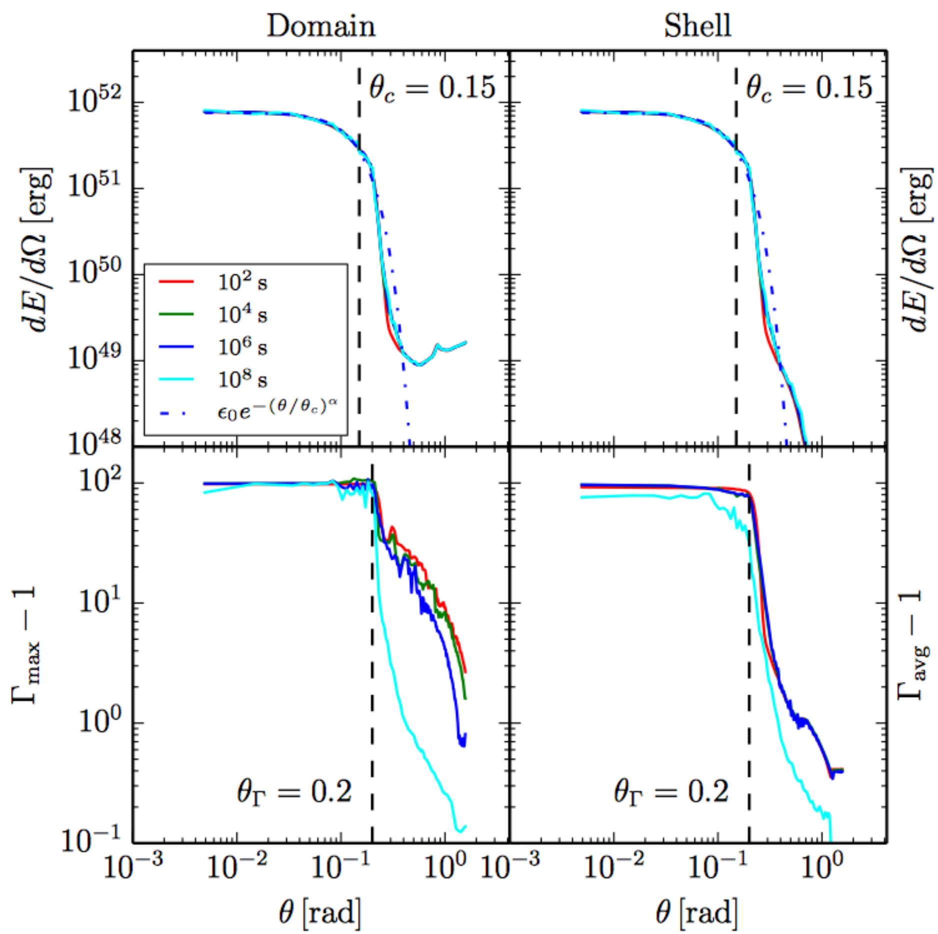
Cocoon is formed during the jet propagation.

Relativistic component $M_c \sim 10^{-8} M_\odot ? \; \Gamma_c \sim 1 - 10$

Sub-relativistic component $M_{ej} \sim 10^{-2} M_\odot \; \beta_{ej} \sim 0.4$

(Ioka & Nakamura 18)





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