

# Scattered Short Gamma-ray Bursts

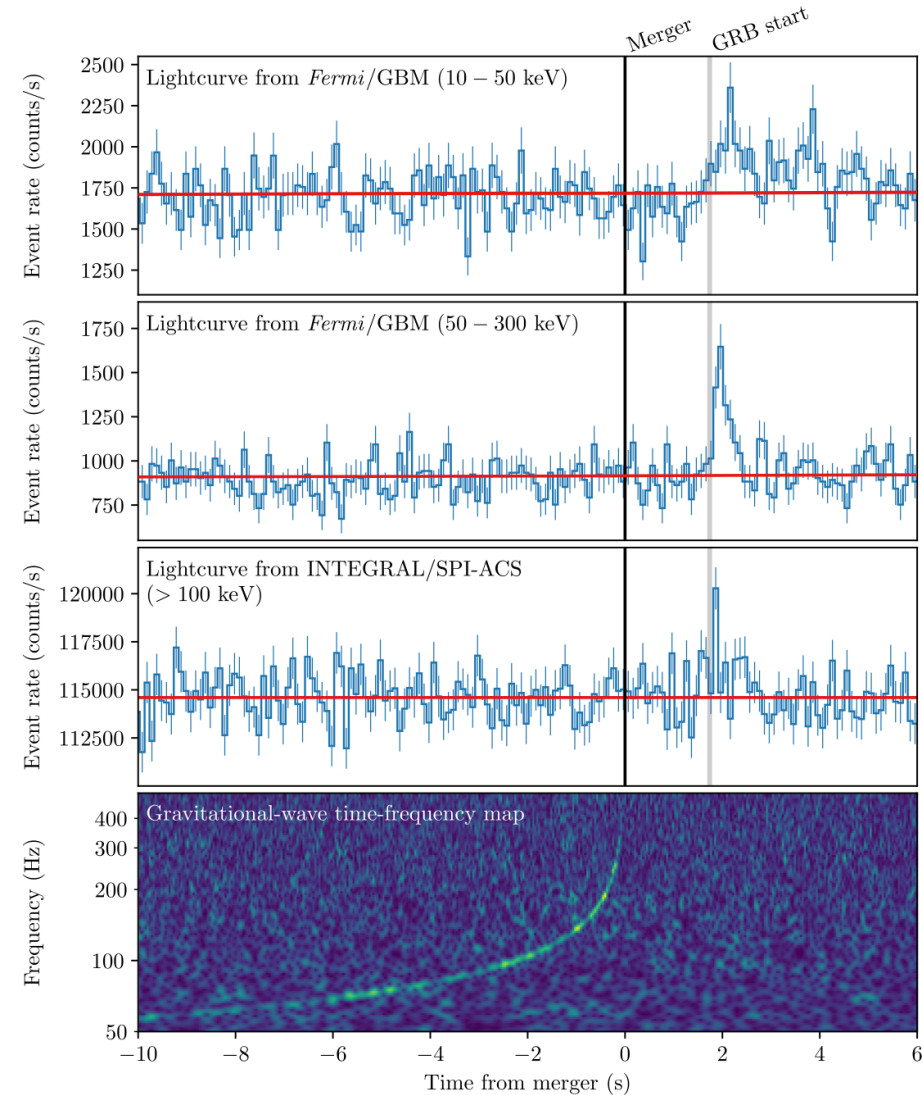
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# GW170817 / GRB 170817A

Abbott+ 17  
Goldstein+ 17  
Savchenko+ 17

## Detection of GW and EM signals.

### NS-NS merger = $\gamma$ -ray transient ( $L \sim 10^{46}$ erg s $^{-1}$ )



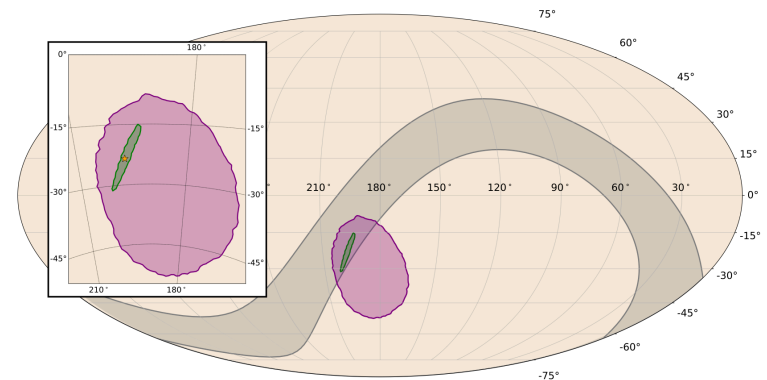
Duration ( $T_{90}$ ) :  $\sim 2 \pm 0.5$  sec

Time delay :  $\sim 1.7$  sec

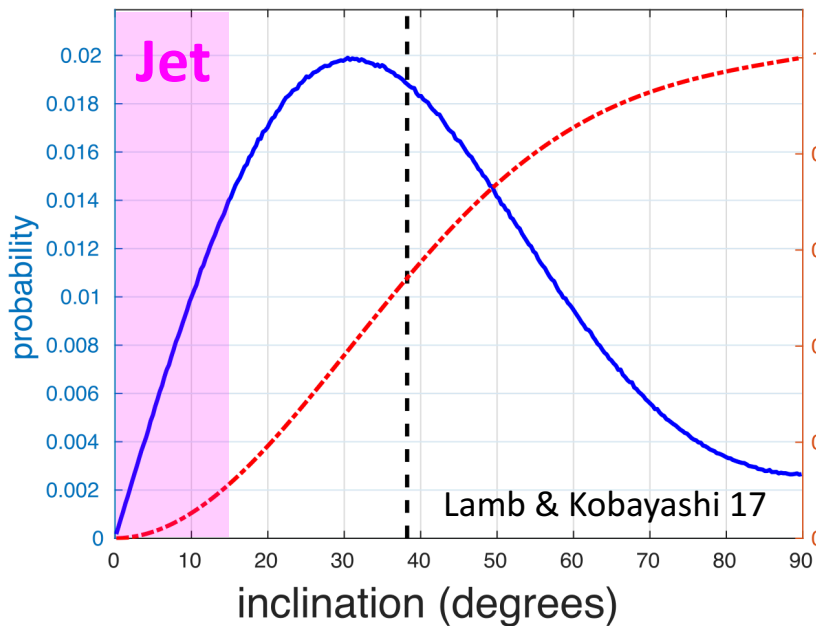
Distance :  $\sim 40$  Mpc

Viewing angle :  $< \sim 30^\circ$

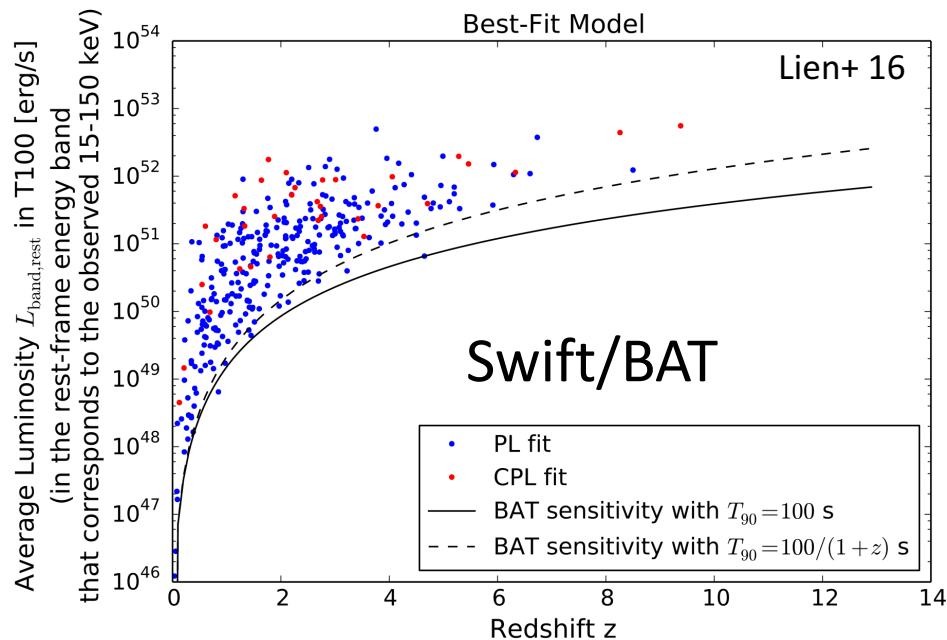
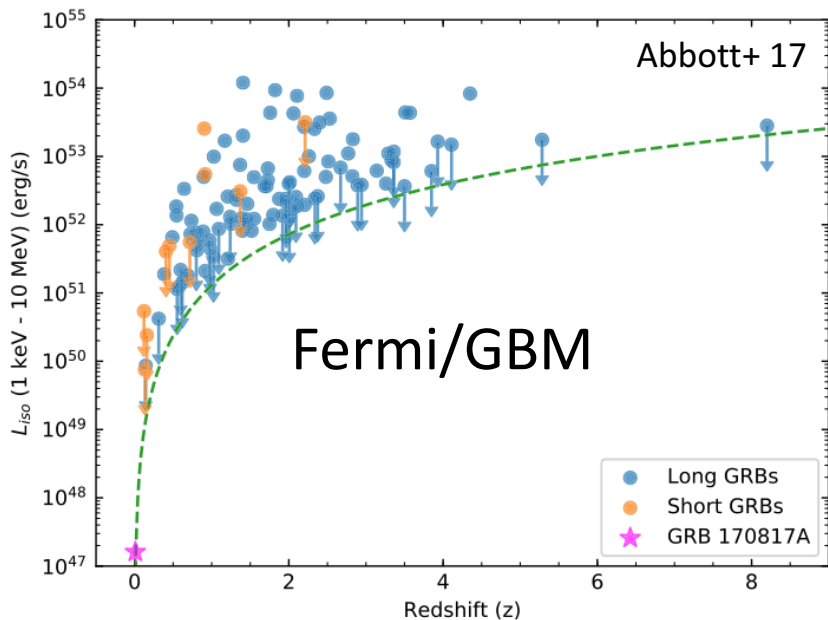
Association probability :  $\sim 5.0 \times 10^{-8}$



# 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  $\gamma$ -ray transients.



# $\gamma$ -ray emission scenarios

- **Short GRB off-axis emission**

Ioka & Nakamura 01, 17, Murguia-Berthier+ 17b,  
Abbott+ 17, Kim+17, Lamb & Kobayashi 17, Granot+ 17

- **Scattered short GRB**

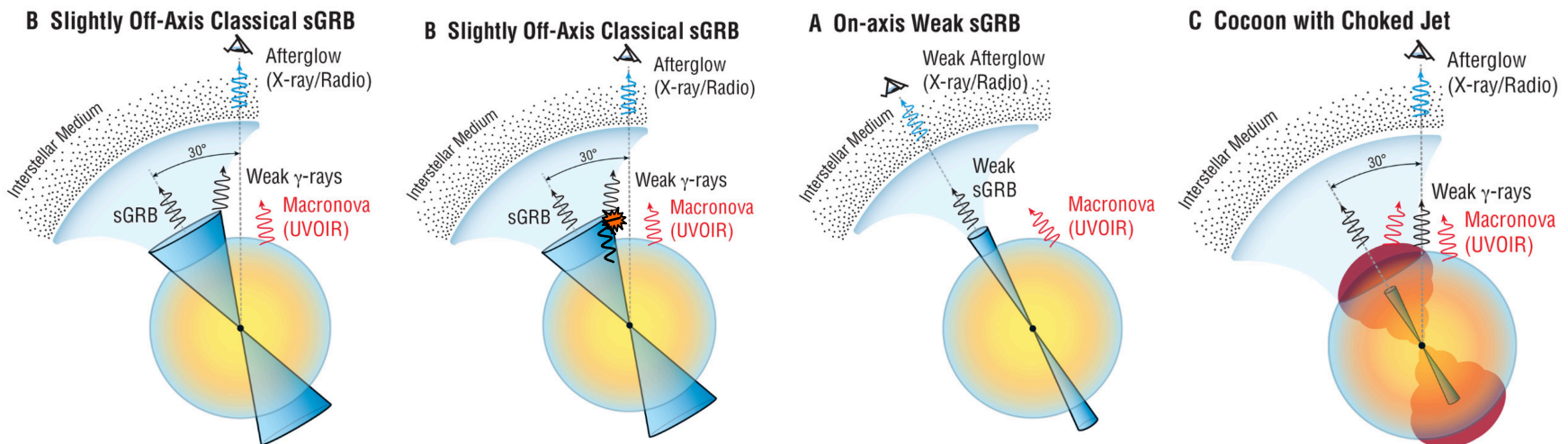
SK+ 17

- **Low-luminosity short GRB**

Murguia-Berthier+ 17b, Zhang+ 17

- **Cocoon shock breakout**

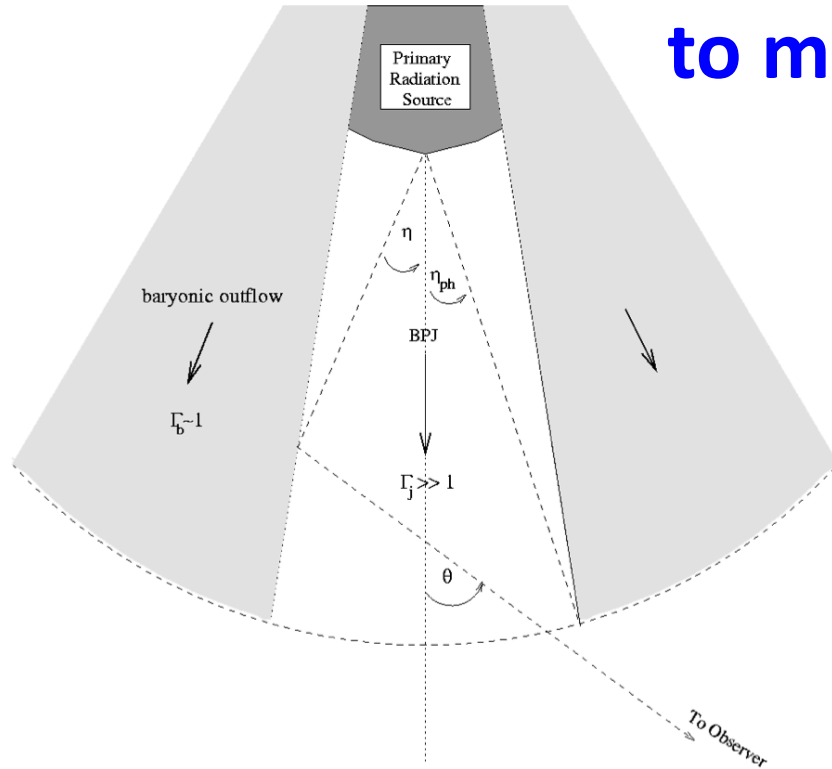
Kasliwal+ 17, Gottlieb+ 17, Bromberg+ 17



Kasliwal+ 17

# Scattered emission

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



Eichler & Levinson 99

Nakamura 98

Eichler & Levinson 99

SK, Ioka & Nakamura 15

SK, Ioka, Kashiyama & Nakamura 17

## Scatterers

- relativistic scatterer
- sub-relativistic scatterer

## Activities

- prompt emission
- extended emission
- plateau emission

# Surrounding materials

Cocoon is formed during the jet propagation.

Relativistic component

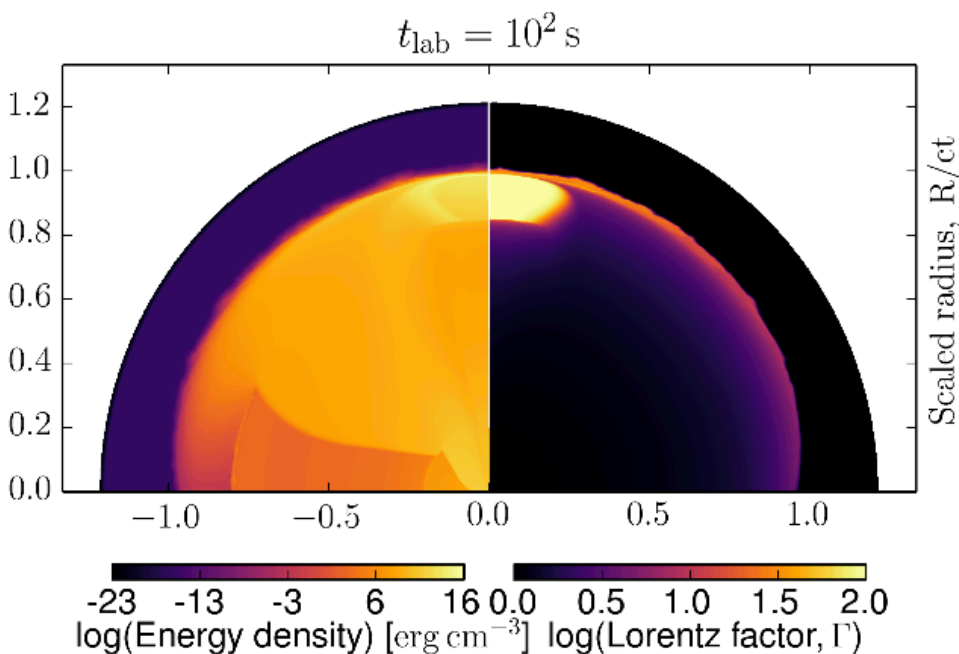
$$M_c \sim ?$$

$$\Gamma_c \sim 1 - 10$$

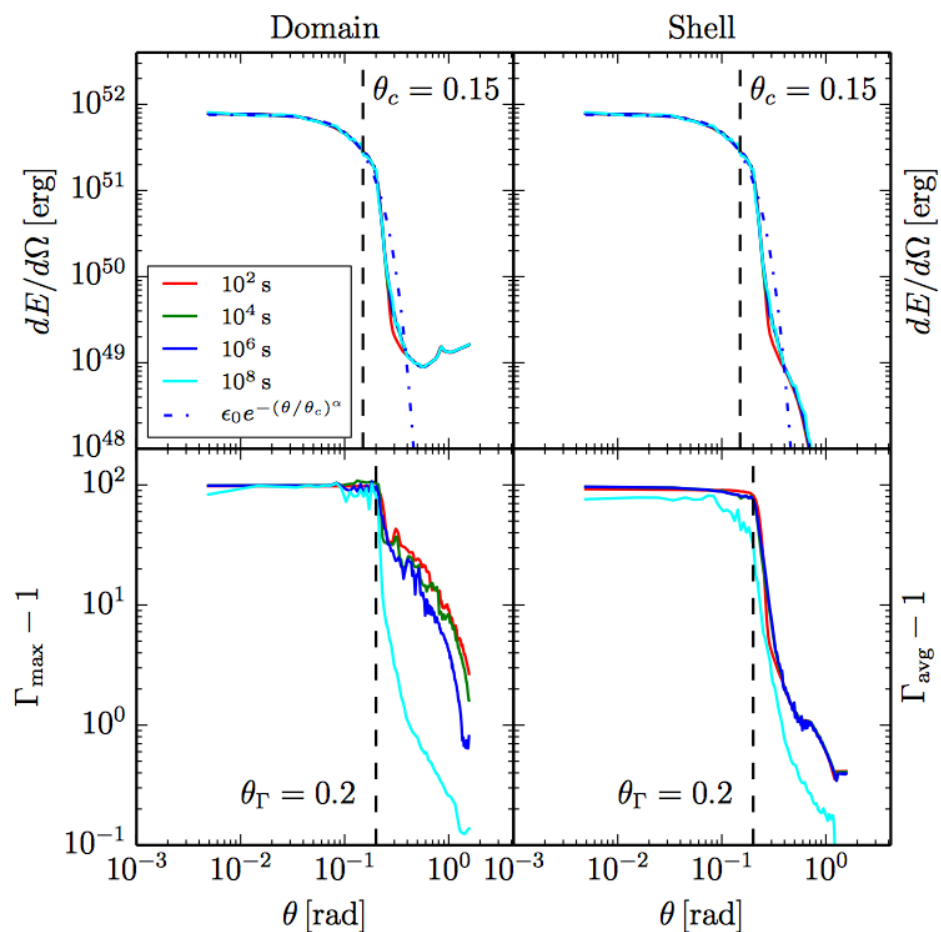
Sub-relativistic component

$$M_{\text{ej}} \sim 10^{-2} M_{\odot} \quad \beta_{\text{ej}} \sim 0.4$$

(Ioka & Nakamura 17)



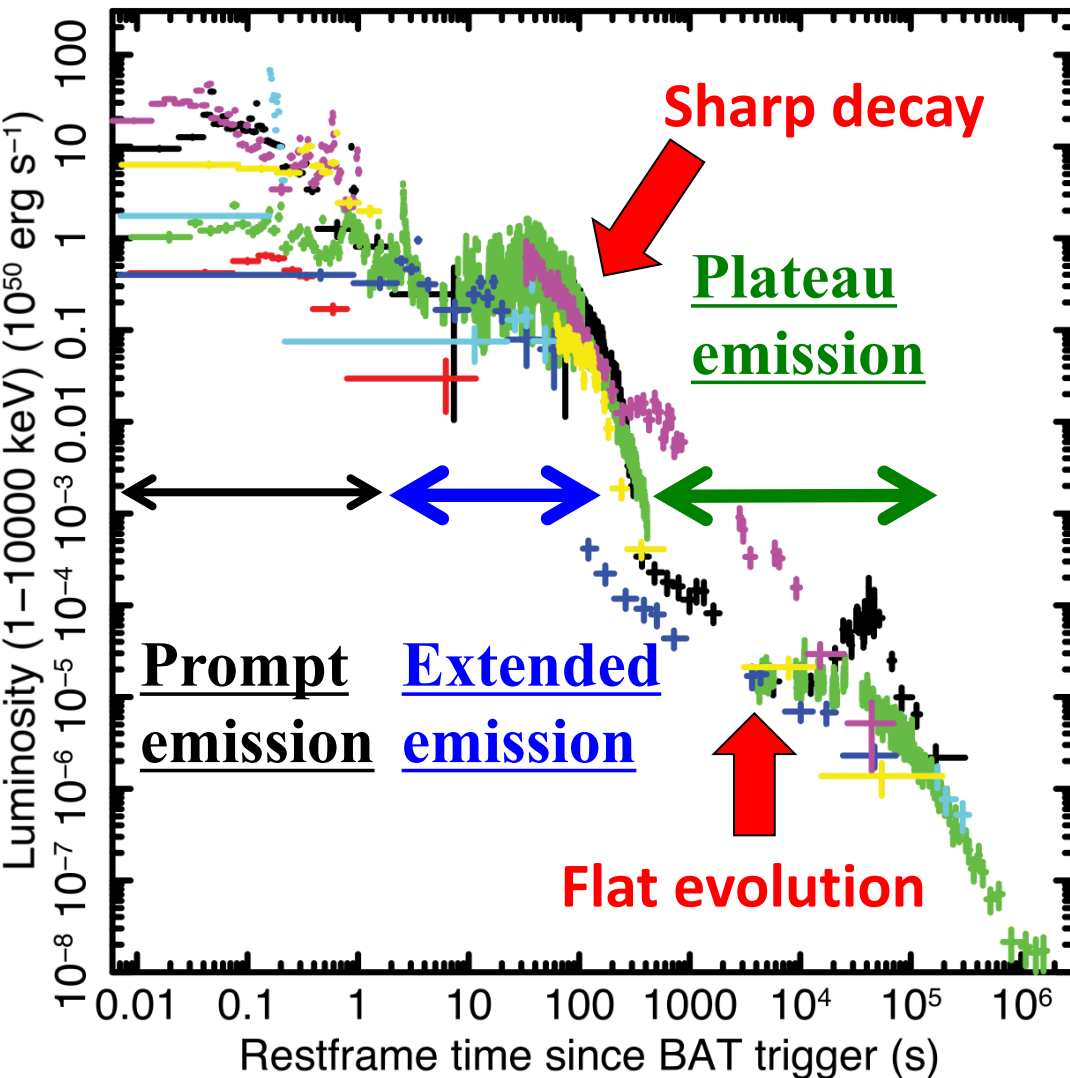
Nagakura+ 14, Murguia-Berthier+ 14, 17  
 Nakar & Piran 17, 18, Bromberg+ 18,  
 Lazzati+ 17, Xie+ 18



# Engine activities

Gompertz+ 13

All Extended Emission Bursts with Known z



## Prompt emission

$$L_{\text{iso}} \sim 10^{50} - 10^{51} \text{ erg s}^{-1}$$

$$T_{\text{dur}} \sim 0.1 - 1 \text{ sec}$$

## Extended emission

$$L_{\text{iso}} \sim 10^{47} - 10^{50} \text{ erg s}^{-1}$$

$$T_{\text{dur}} \sim 10^2 - 10^3 \text{ sec}$$

## Plateau emission

$$L_{\text{iso}} \sim 10^{43} - 10^{47} \text{ erg s}^{-1}$$

$$T_{\text{dur}} \sim 10^4 - 10^5 \text{ sec}$$

SK, Ioka & Sakamoto 17

# Conditions

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

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

	Prompt emission	Extended emission	Plateau emission
	$E_{\text{iso}} \sim 10^{51} \text{ erg}$ $t_{\text{dur}} \sim 1 \text{ sec}$	$E_{\text{iso}} \sim 10^{51} \text{ erg}$ $t_{\text{dur}} \sim 10^2 \text{ sec}$	$E_{\text{iso}} \sim 10^{50} \text{ erg}$ $t_{\text{dur}} \sim 10^4 \text{ sec}$
<b>Relativistic scatterer</b> $\Gamma_c \sim 1 - 10$	$\Gamma_{\text{j}} (\sim \eta) \gtrsim 10^2$ $r_e \gtrsim 10^9 \text{ cm}$ $M_c \gtrsim 10^{-12} M_{\odot}$	$r_e \gtrsim 10^{12} \text{ cm}$ $M_c \gtrsim 10^{-6} M_{\odot}$	$M_c \gtrsim 10^{-2} M_{\odot}$
<b>Sub-relativistic scatterer</b> $M_{\text{ej}} \sim 0.01 M_{\odot}$ $\beta_{\text{ej}} \sim 0.1 - 0.3$	$\Gamma_{\text{j}} (\sim \eta) \gtrsim 10^3$ $r_e \sim 10^9 - 10^{10} \text{ cm}$ $M_c \lesssim 10^{-12} M_{\odot}$	$\Gamma_{\text{j}} (\sim \eta) \gtrsim 20$ $r_e \sim 10^{10} - 10^{12} \text{ cm}$ $M_c \lesssim 10^{-6} M_{\odot}$	$r_e \lesssim 10^{14} \text{ cm}$ $M_c \lesssim 10^{-2} M_{\odot}$

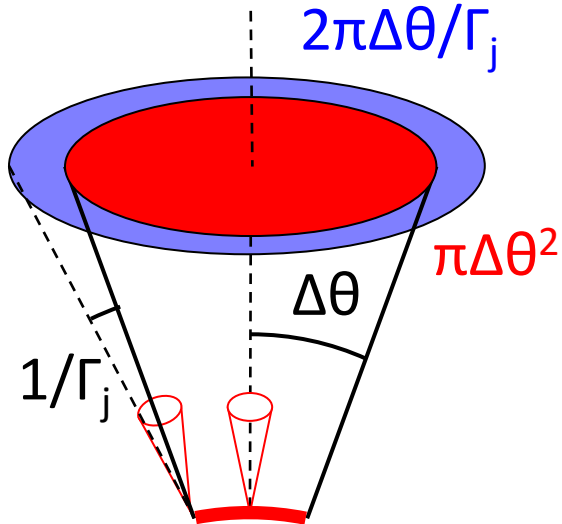


# Isotropic radiation energy

$$\frac{E_{\text{iso,sc}}}{E_{\text{iso}}(\theta_v = 0)} \sim \frac{L_{\text{sc}} T_{\text{dur,sc}}}{L_{\text{iso}} t_{\text{dur}}} \sim \frac{2}{\Gamma_j \Delta\theta} \times \Gamma_c^2 \times \epsilon_{\text{sc}} \times \frac{\Delta\theta^2}{2}$$

$(\Gamma_c^{-1} > \theta_v - \Delta\theta)$

▪ Geometrical effect  $\langle \Delta\theta \rangle \sim 0.3$  rad Fong+ 15



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

$$\Delta T \sim \frac{r_{\text{sc}}}{2c\beta_c \Gamma_c^2}$$

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

# Isotropic radiation energy

$$\frac{E_{\text{iso,sc}}}{E_{\text{iso}}(\theta_v = 0)} \sim \frac{L_{\text{sc}} T_{\text{dur,sc}}}{L_{\text{iso}} t_{\text{dur}}} \\ \sim \frac{2}{\Gamma_j \Delta\theta} \times \Gamma_c^2 \times \epsilon_{\text{sc}} \times \frac{\Delta\theta^2}{2} \\ (\Gamma_c^{-1} > \theta_v - \Delta\theta)$$

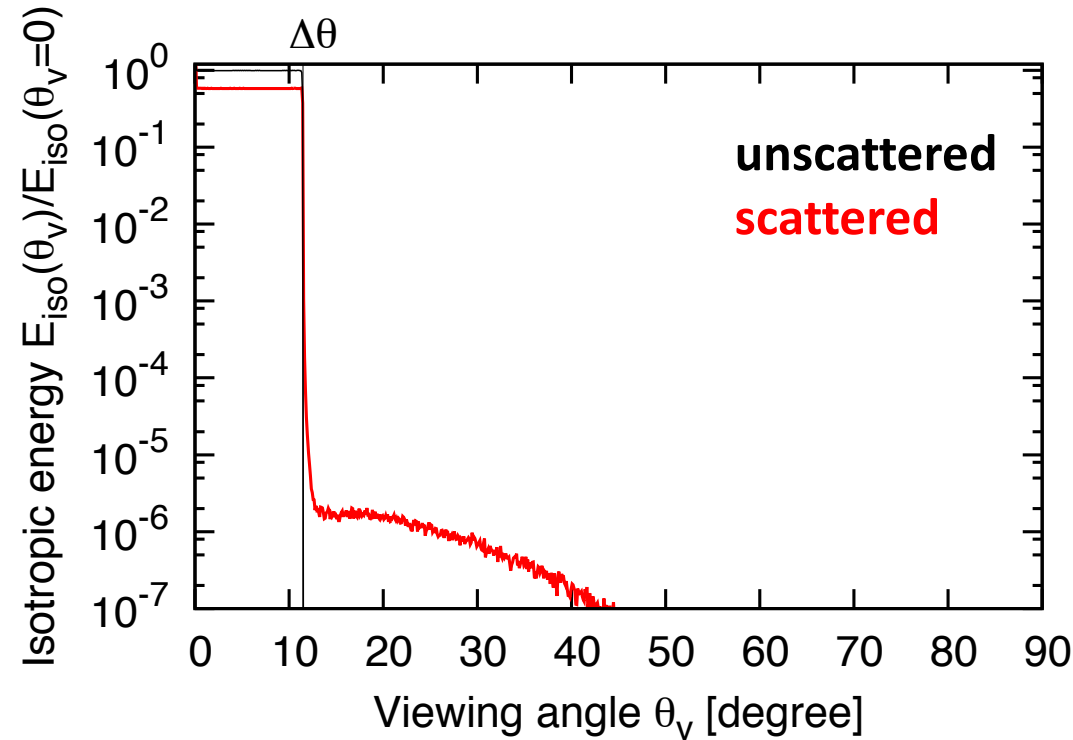
## Sub-relativistic scatterer

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

## Relativistic scatterer

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

# Sub-relativistic scatterer



$$\Delta\theta = 0.2 \text{ rad } (\sim 11^\circ)$$

$$\Gamma_j = 1000$$

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

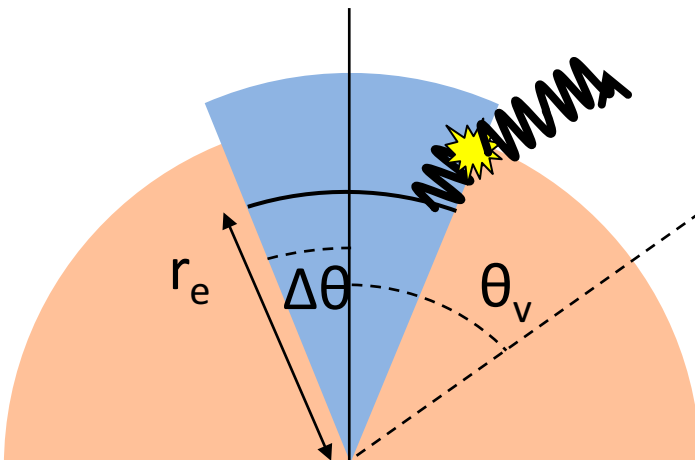
$$t_e = 1.0 \text{ sec}$$

$$r_e = 3 \times 10^9 \text{ cm}$$

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

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

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



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

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

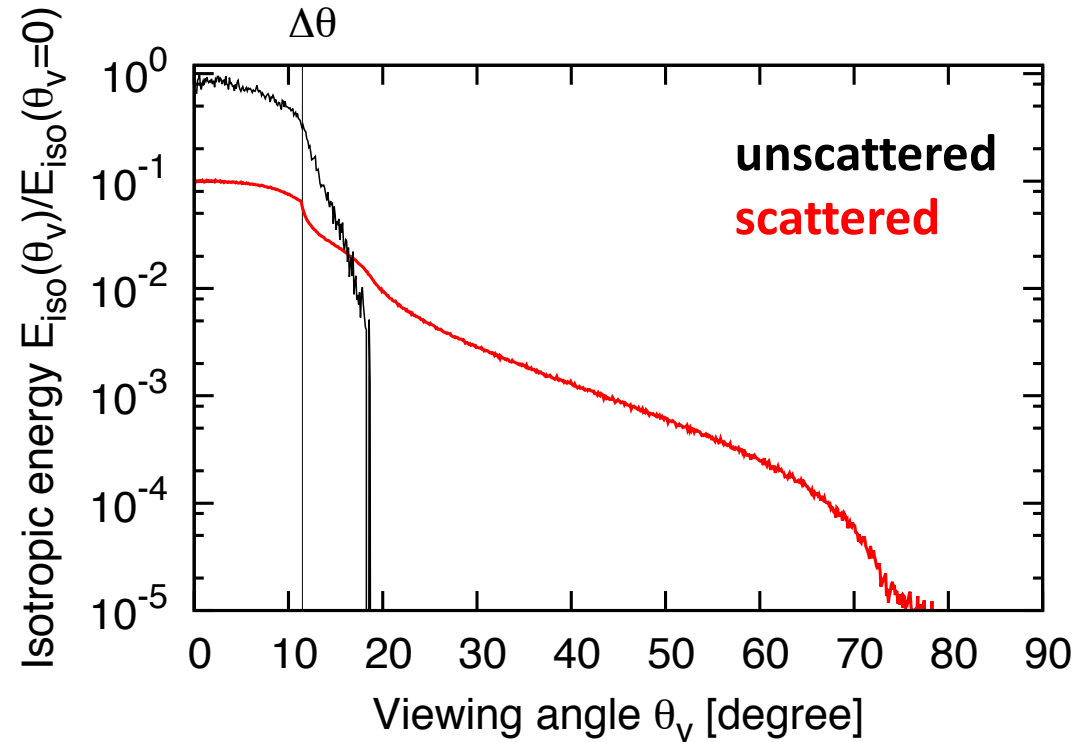
$$\tau_c \sim 7 \times 10^{10}$$

( $r = r_e$ )

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

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

# Sub-relativistic scatterer



$$\Delta\theta = 0.2 \text{ rad } (\sim 11^\circ)$$

$$\Gamma_j = 10$$

$$L_{\text{iso}} = 10^{46} \text{ erg s}^{-1}$$

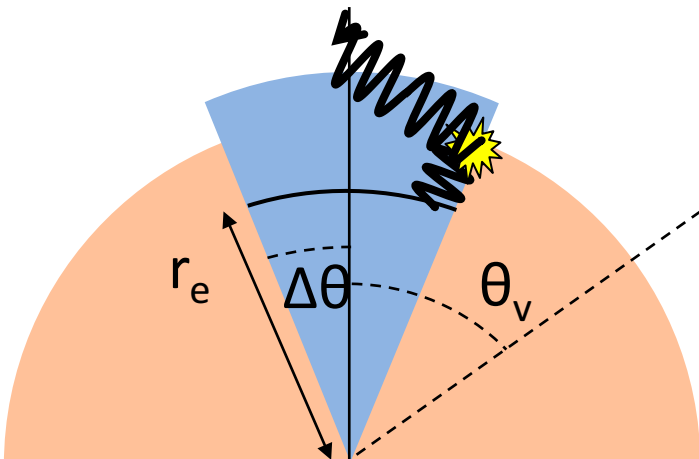
$$t_e = 10^4 \text{ sec}$$

$$r_e = 3 \times 10^{13} \text{ cm}$$

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

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

Photons can cross the jet.



$$\tau_{j\parallel} \sim 10^{-3}$$

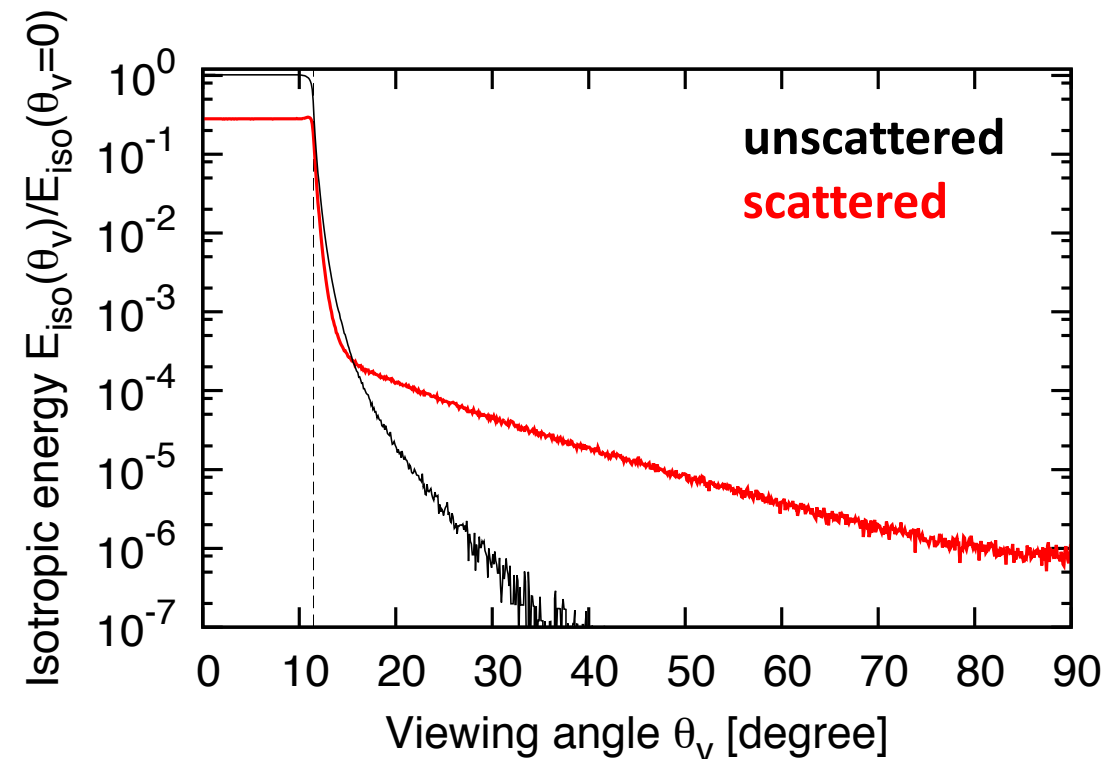
$$\tau_{j\perp} \sim 0.2$$

$$\tau_c \sim 7 \times 10^3$$

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

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

# Relativistic scatterer



$$\Delta\theta = 0.2 \text{ rad } (\sim 11^\circ)$$

$$\Gamma_j = 200$$

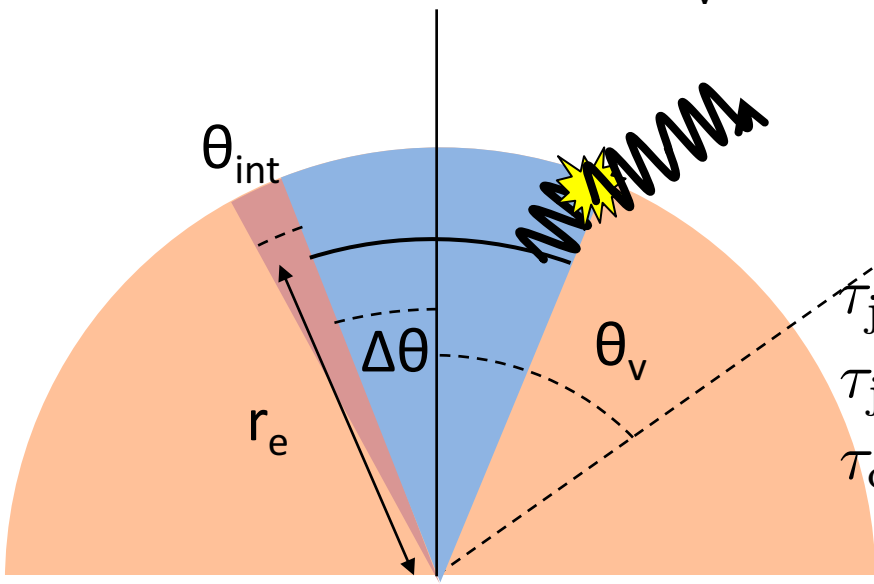
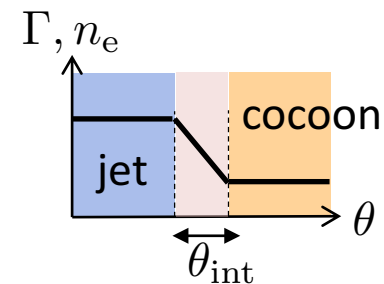
$$L_{\text{iso}} = 10^{51} \text{ erg s}^{-1}$$

$$r_e = 10^{12} \text{ cm}$$

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

$$\Gamma_c = 3$$

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



Photons with wide angle could be detectable.

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

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

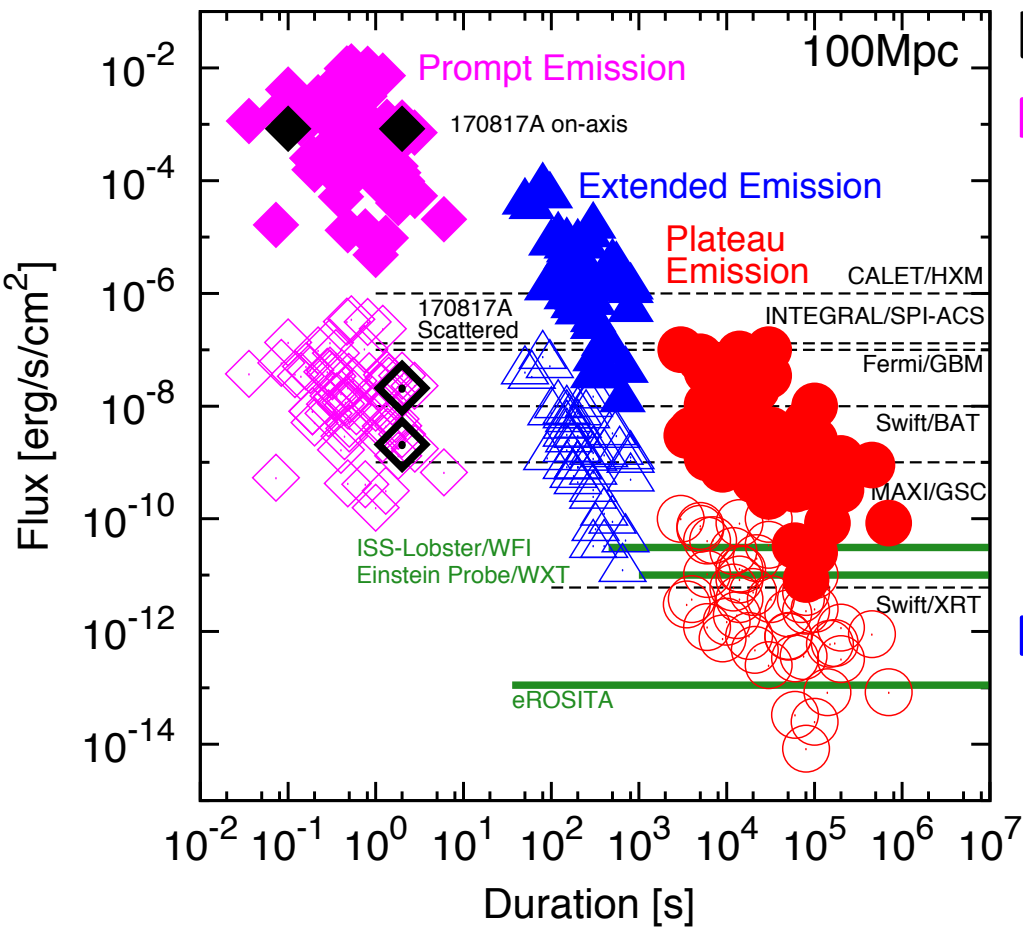
$$\tau_{j\parallel} \sim 0.07$$

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

$$\tau_c \sim 1.5$$

( $r = r_e$ )

# Detectability



**Luminosity** ( $\Delta\theta=0.3\text{rad}$ )

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

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

(Sub-relativistic scatterer)

$$L_{\text{sc}} \sim 3 \times 10^{46} \text{ erg s}^{-1} \Gamma_{j,2}^{-1} \epsilon_{\text{sc},-2}$$

$$\times t_{\text{dur},-1} \Gamma_{c,0.5}^4 r_{\text{sc},12}^{-1}$$

(Relativistic scatterer)

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

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

(Sub-relativistic scatterer)

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

(Relativistic scatterer)

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

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

**Detection rate**

**(prompt, relativistic scatterer)**

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

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

# 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  $\sim 10^{45} - 10^{46}$  erg s<sup>-1</sup> for prompt and extended emission, and  $\sim 10^{43}$  erg s<sup>-1</sup> for plateau emission.
- The detection of the scattered emission could give constraints on the properties of the jet and the cocoon.