# 低光度GRBの星周物質相互作用モデル

# Circumstellar medium (CSM)- interaction model for low-luminosity GRBs

Akihiro Suzuki (NAOJ)

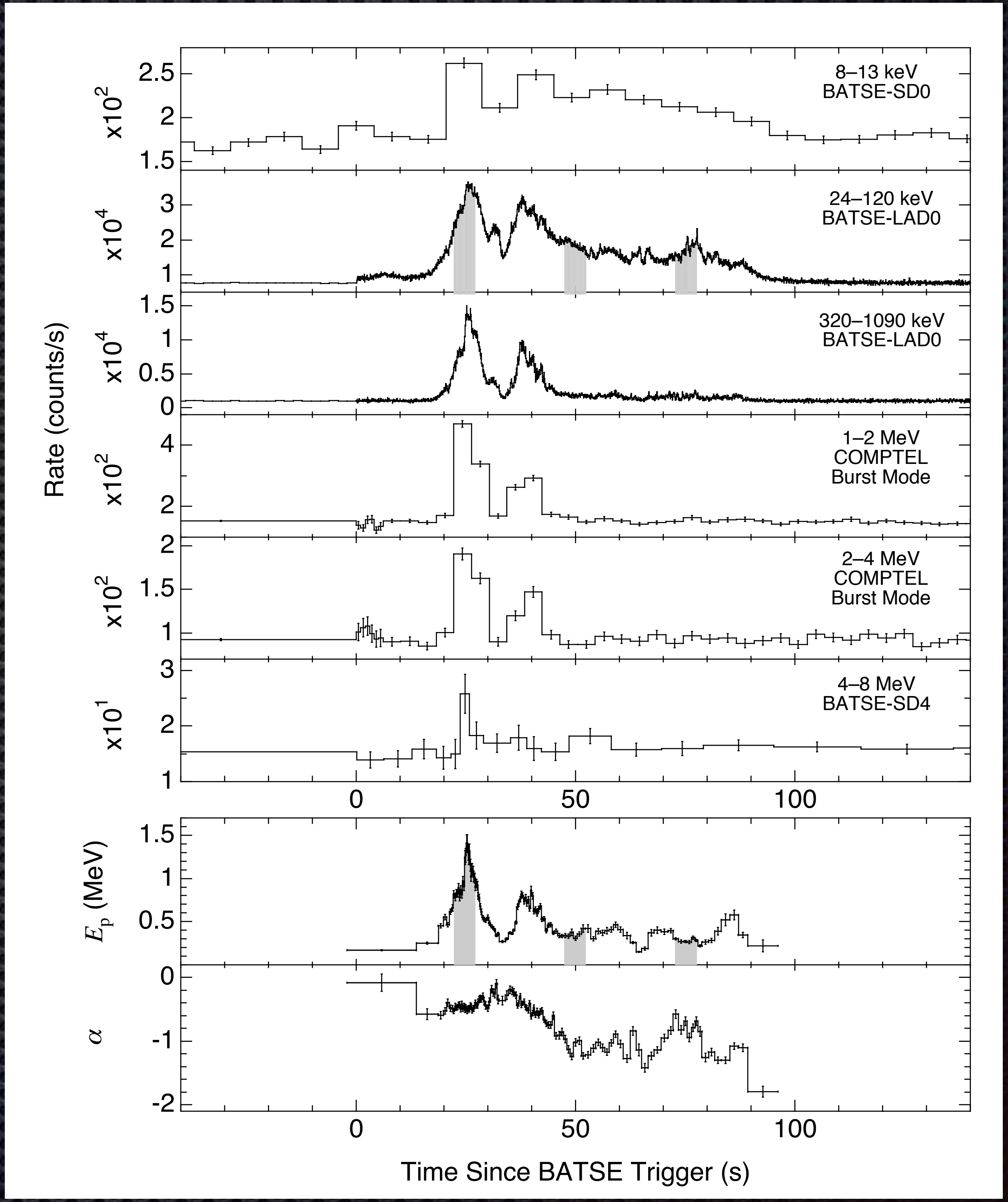
Suzuki, Maeda, & Shigeyama (2017), ApJ, 832,32

Suzuki, Maeda, & Shigeyama (2018), in press

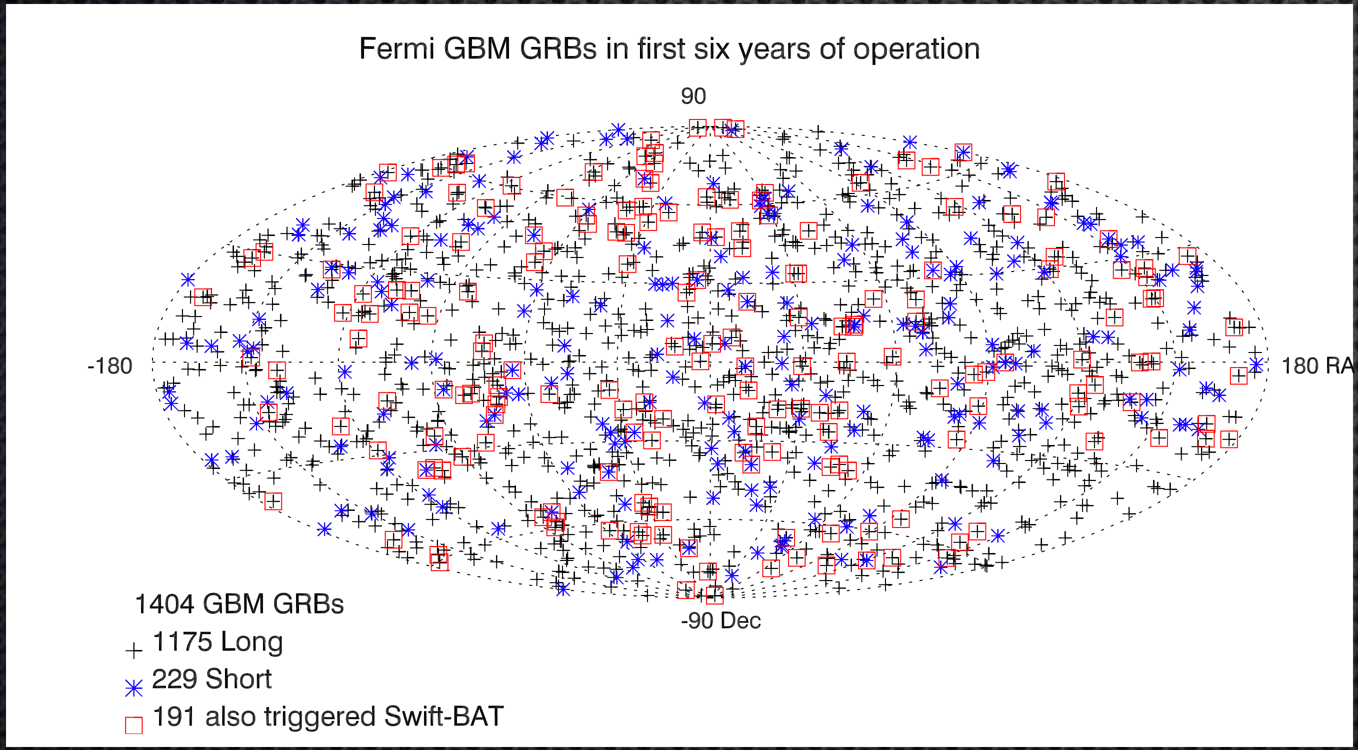
理論懇シンポジウム2018, 京都大学基礎物理学研究所, 2018/12/19

# Gamma-ray bursts

- ➡ bursts of gamma-ray photons: ~1 event/day, isotropic
- ➡ spectrum well represented by a "Band function" (Band et al. 1993)
- ➡ classification: long-soft/short-hard



Briggs+ (1999)

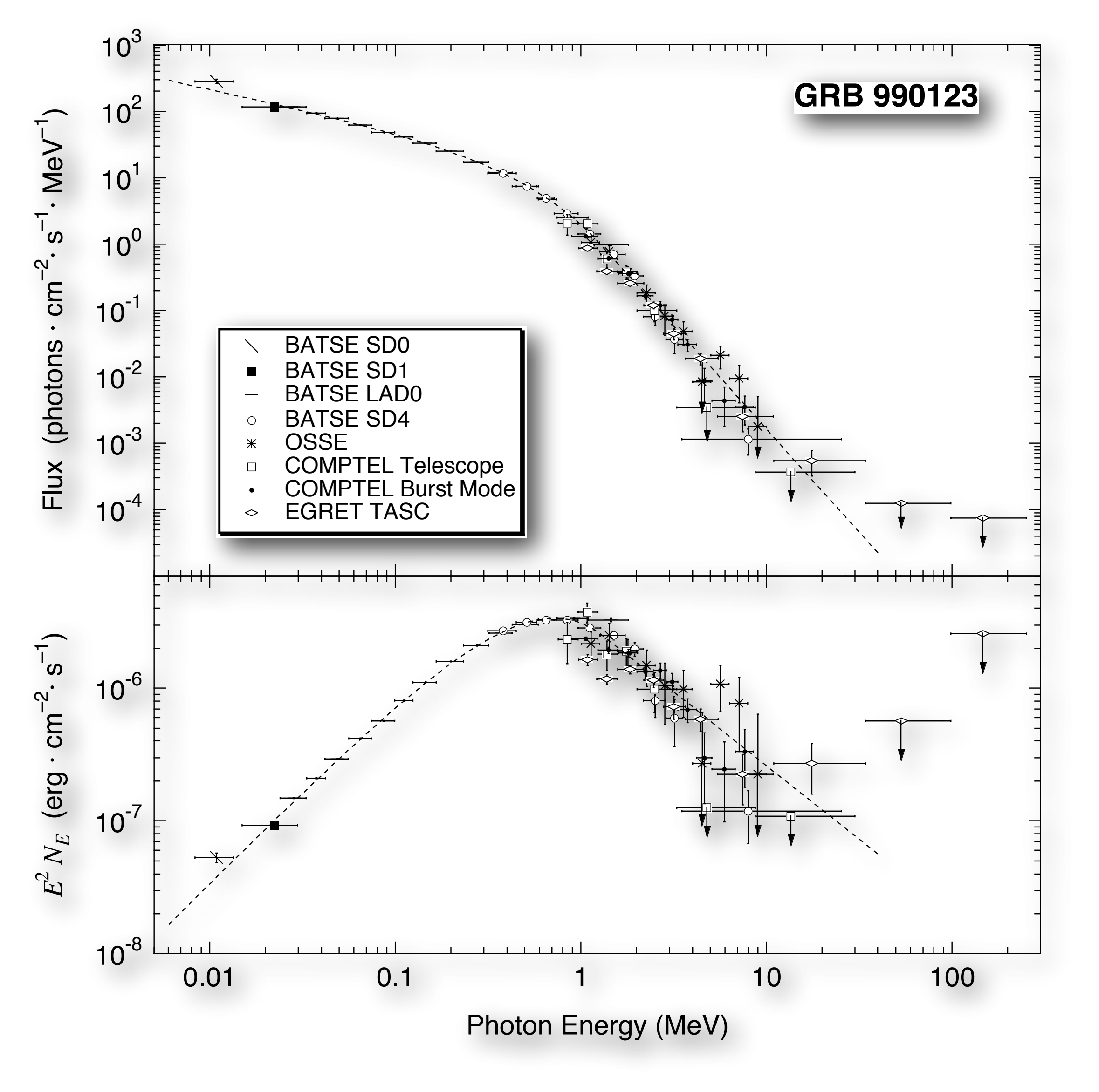


**distribution of Fermi GRBs on the celestial sphere**

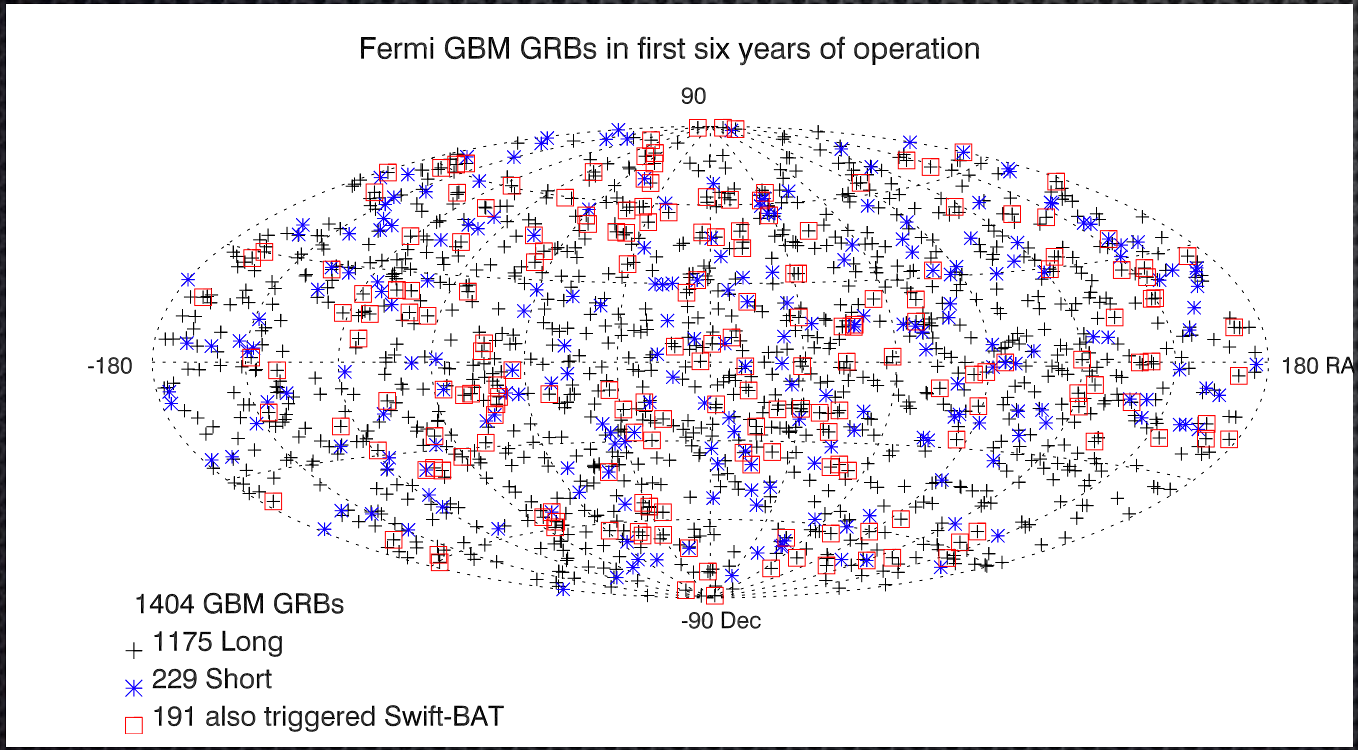
**(3rd Fermi GBM catalog, 2016)**

# Gamma-ray bursts

- bursts of gamma-ray photons: ~1 event/day, isotropic
- spectrum well represented by a "Band function" (Band et al. 1993)
- classification: long-soft/short-hard



**Briggs+ (1999)**



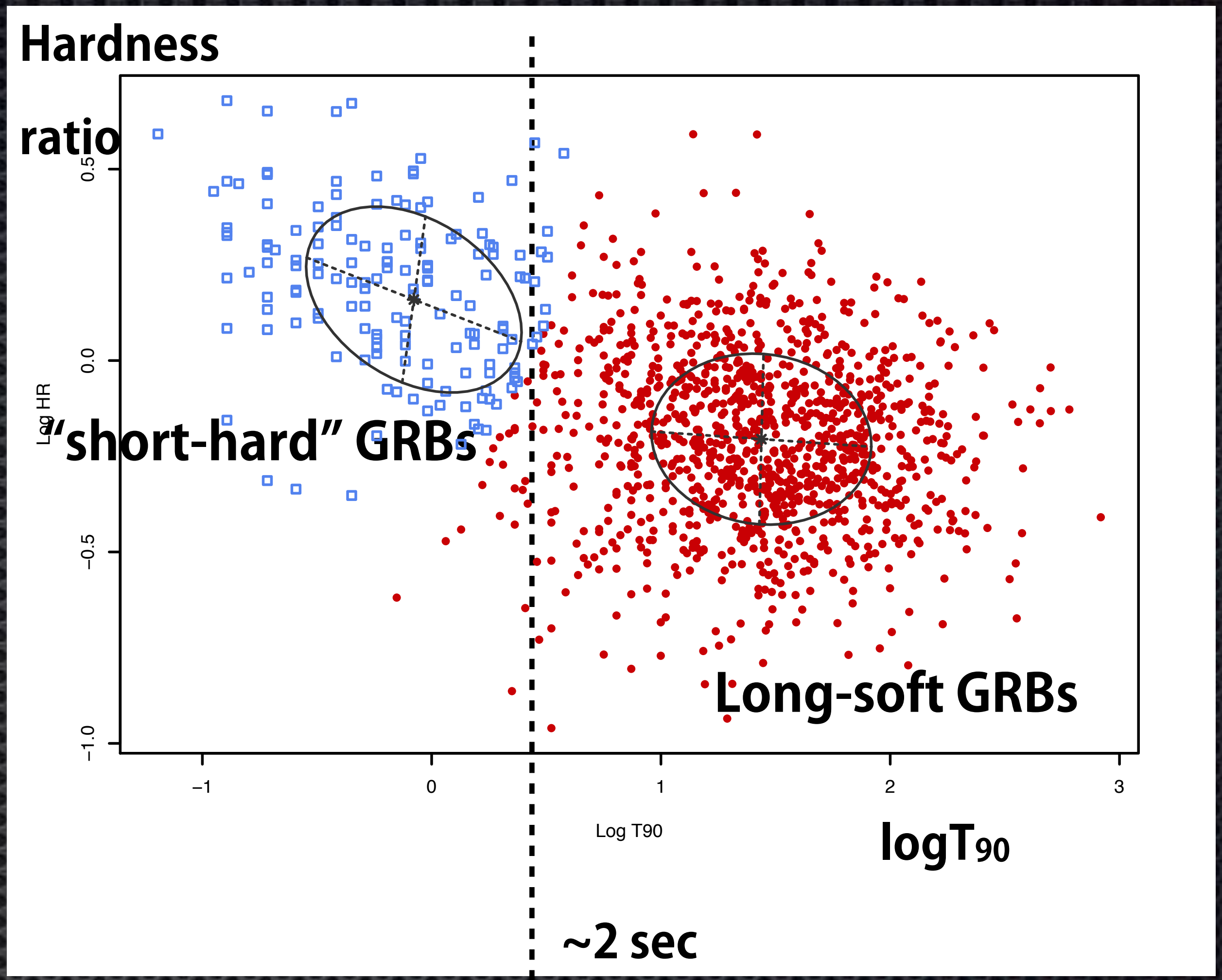
**distribution of Fermi GRBs on the celestial sphere**

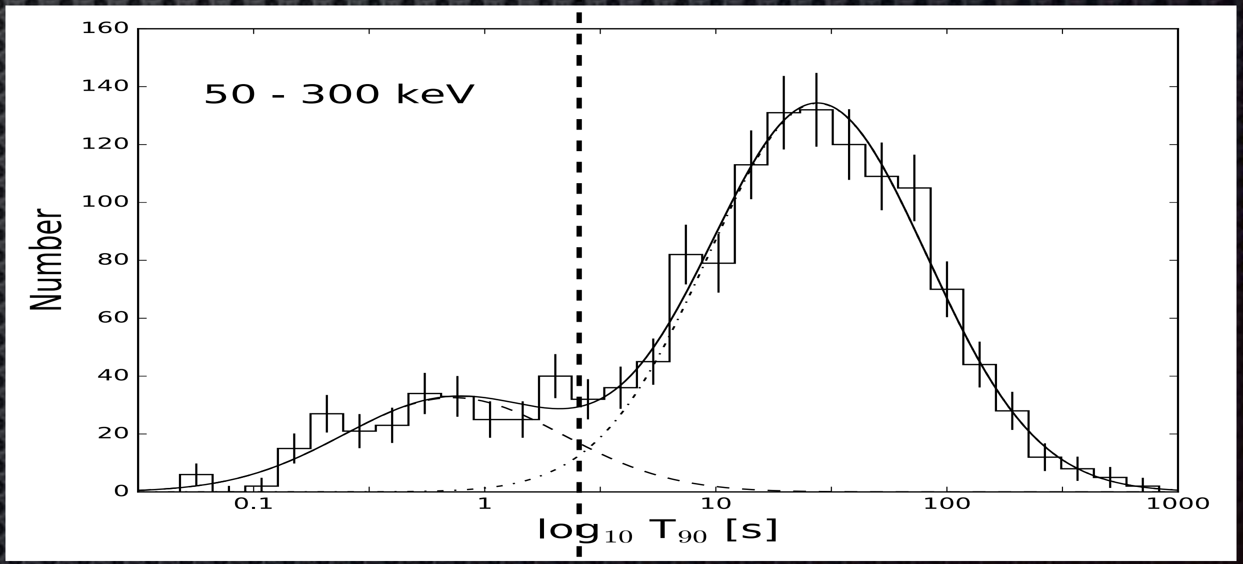
**(3rd Fermi GBM catalog, 2016)**

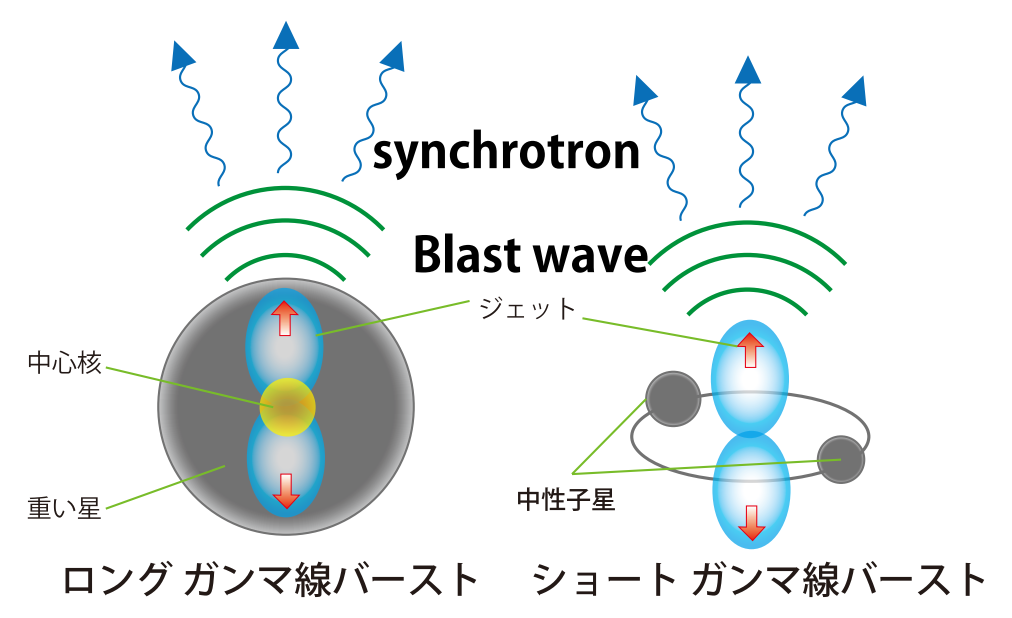
# Gamma-ray bursts

- ➡ bursts of gamma-ray photons: ~1 event/day, isotropic
- ➡ spectrum well represented by a "Band function" (Band et al. 1993)
- ➡ classification: long-soft/short-hard

HR vs T90 plot(3rd Fermi GBM catalog, 2016)







# low-luminosity GRBs

- ➡ sub-energetic class of long GRBs
- ➡ only nearby events are detected, but event rate is high

  e.g., $230^{+490}_{-190}$ Gpc$^{-3}$ yr$^{-1}$ (Soderberg+ 2006 ), 100-1800 Gpc$^{-3}$ yr$^{-1}$ (Guetta&Della Valle 2007)
- ➡ They accompany broad-lined Ic SNe
- ➡ Ex. GRB 980425/SN 1998bw, GRB 060218/SN 2006aj, GRB100316D/ SN2010bh

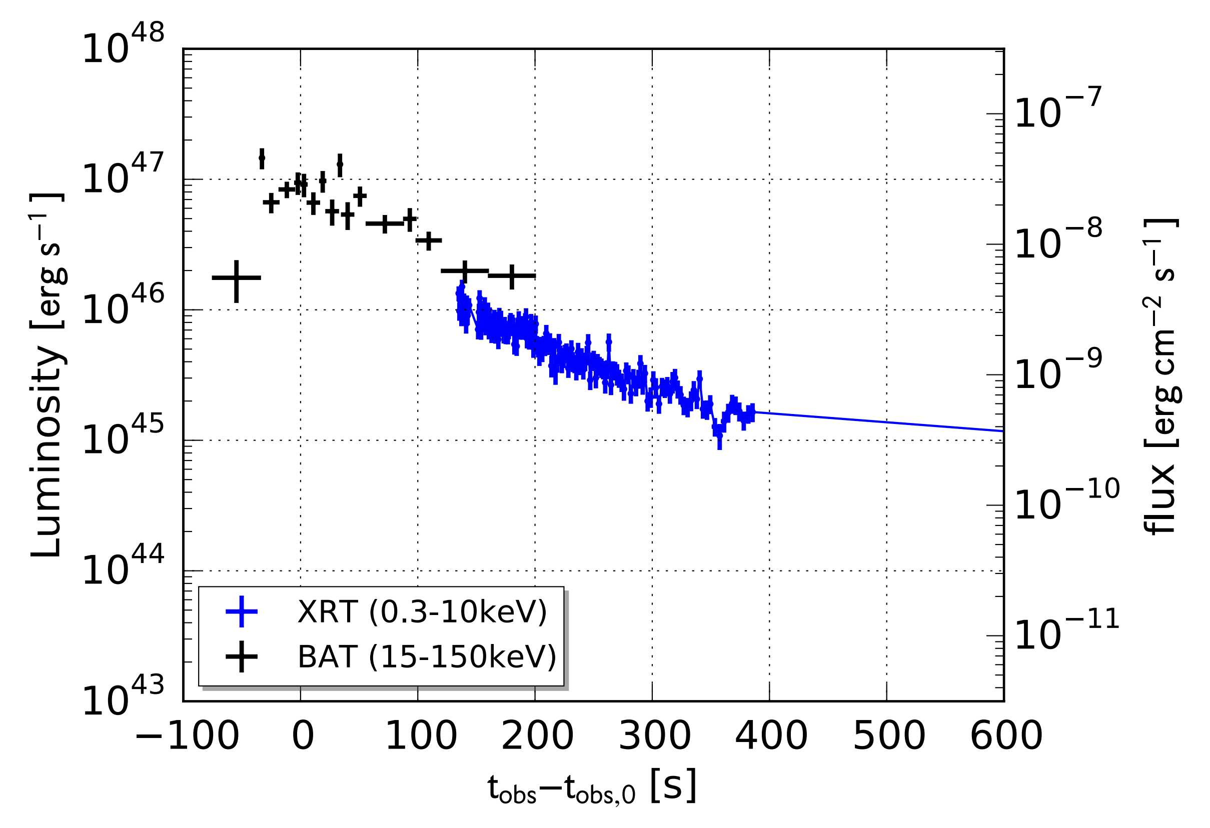
| | **Luminosity $L_{\gamma,\mathrm{iso}}$** | **Isotropic energy $E_{\mathrm{iso}}$** | **Duration $T_{90}$** | **peak energy $E_p$** |
|---|---|---|---|---|
| **GRB 980425**<br>**SN 1998bw** | **$6\times10^{46}$ erg/s** | **$9\times10^{47}$ erg** | **35 s** | **122 keV** |
| **GRB 060218**<br>**SN 2006aj** | **$2\times10^{46}$ erg/s** | **$4\times10^{49}$ erg** | **2100 s** | **4.7 keV** |
| **GRB 100316D**<br>**SN 2010bh** | **$5\times10^{46}$ erg/s** | **$6\times10^{49}$ erg** | **1300 s** | **18 keV** |

**cf. Liso~$10^{51}$ erg/s, Eiso~$10^{52\text{-}53}$ erg for standard GRBs**

# New LLGRB 171205A @ 168Mpc

- ➡ Swift detection on 2017/12/05
  (D'Elia+2017, GCN circular 22177)
- ➡ $E_{iso}$~$2.2 \times 10^{49}$[erg], $T_{90}$~190[s]
  (D’Elia+2018)
- ➡ follow-up optical, radio observation
- ➡ SN bump after a few days
  (de Ugarte Postigo+2017, GCN circular 22207)

Obs. Data provided by Swift UK Data Centre

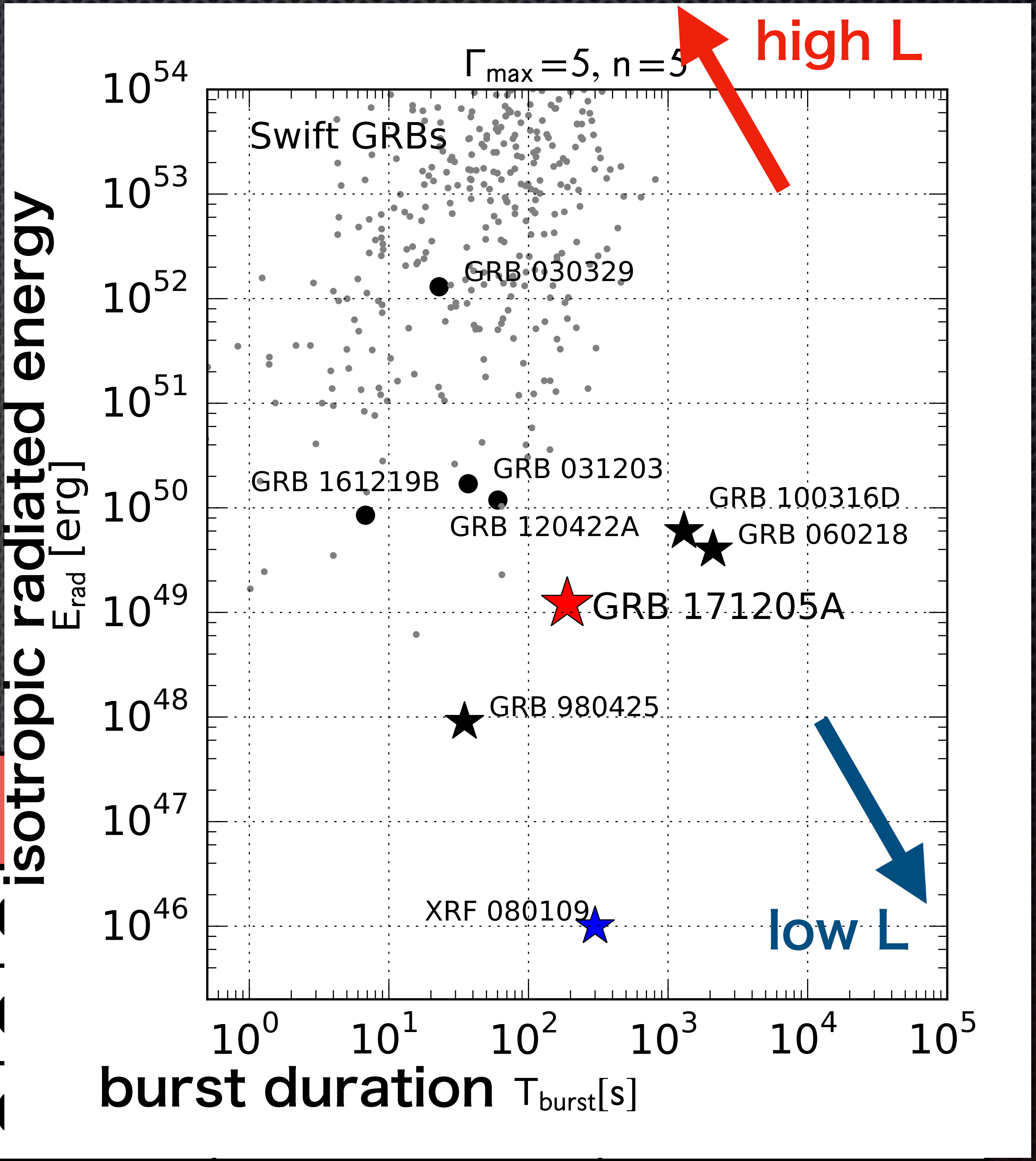


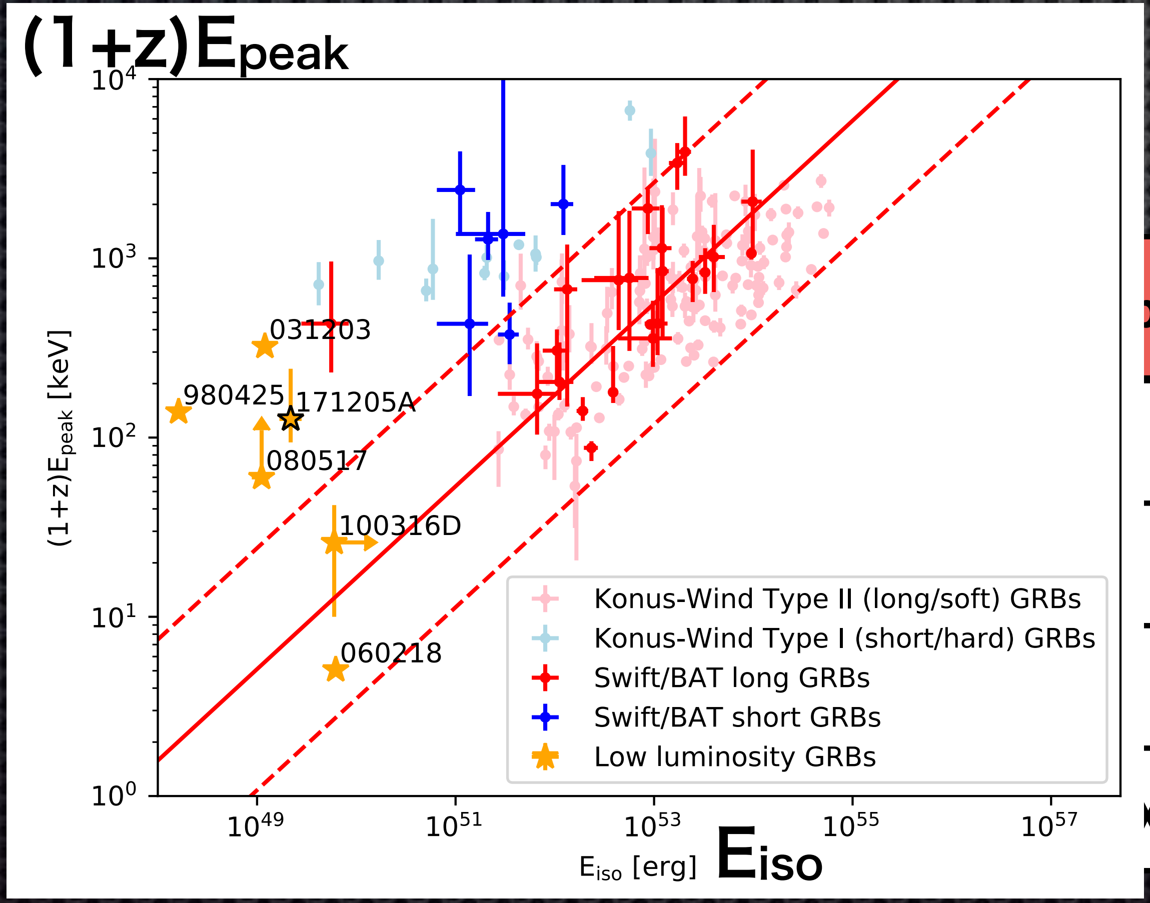
| | Luminosity $L_{\gamma,iso}$ | Isotropic energy $E_{iso}$ | Duration $T_{90}$ | peak energy $E_p$ |
|---|---|---|---|---|
| GRB 980425<br>SN 1998bw | $6 \times 10^{46}$ erg/s | $9 \times 10^{47}$ erg | 35 s | 122 keV |
| GRB 060218<br>SN 2006aj | $2 \times 10^{46}$ erg/s | $4 \times 10^{49}$ erg | 2100 s | 4.7 keV |
| GRB 100316D<br>SN 2010bh | $5 \times 10^{46}$ erg/s | $6 \times 10^{49}$ erg | 1300 s | 18 keV |
| GRB 171205A<br>SN 2017iuk | $1 \times 10^{47}$erg/s | $2.2 \times 10^{49}$ erg | 190 s | 125keV |

cf. $L_{iso}$~$10^{51}$ erg/s, $E_{iso}$~$10^{52\text{-}53}$ erg for standard GRBs

# New LLGRB 171205A @ 168Mpc

- ➡ Swift detection on 2017/12/05
  (D'Elia+2017, GCN circular 22177)
- ➡ $E_{iso}$~$2.2\times10^{49}$[erg], $T_{90}$~190[s]
  (D'Elia+2018)
- ➡ follow-up optical, radio observation
- ➡ SN bump after a few days
  (de Ugarte Postigo+2017, GCN circular 22207)





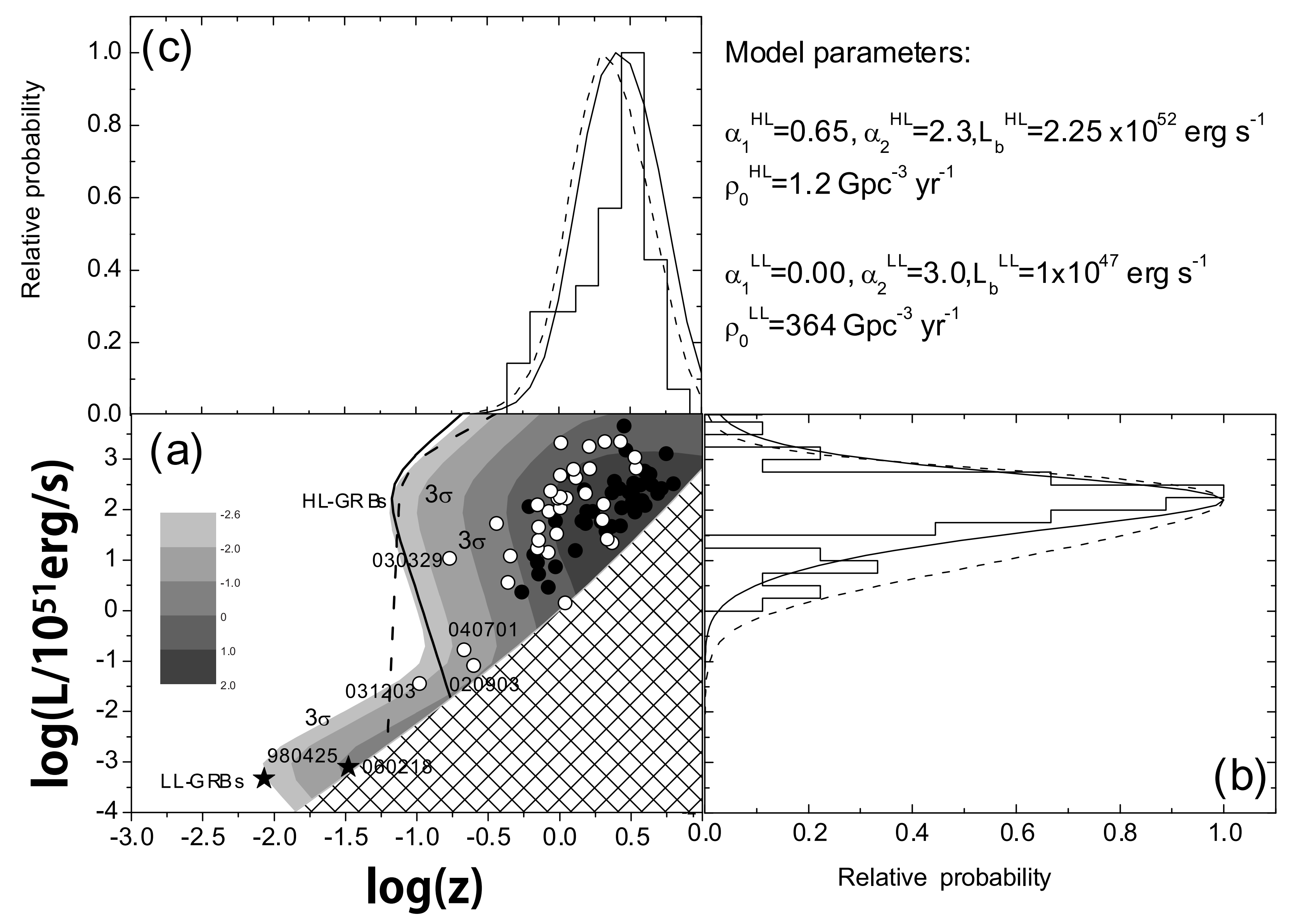
D'Elia+2018

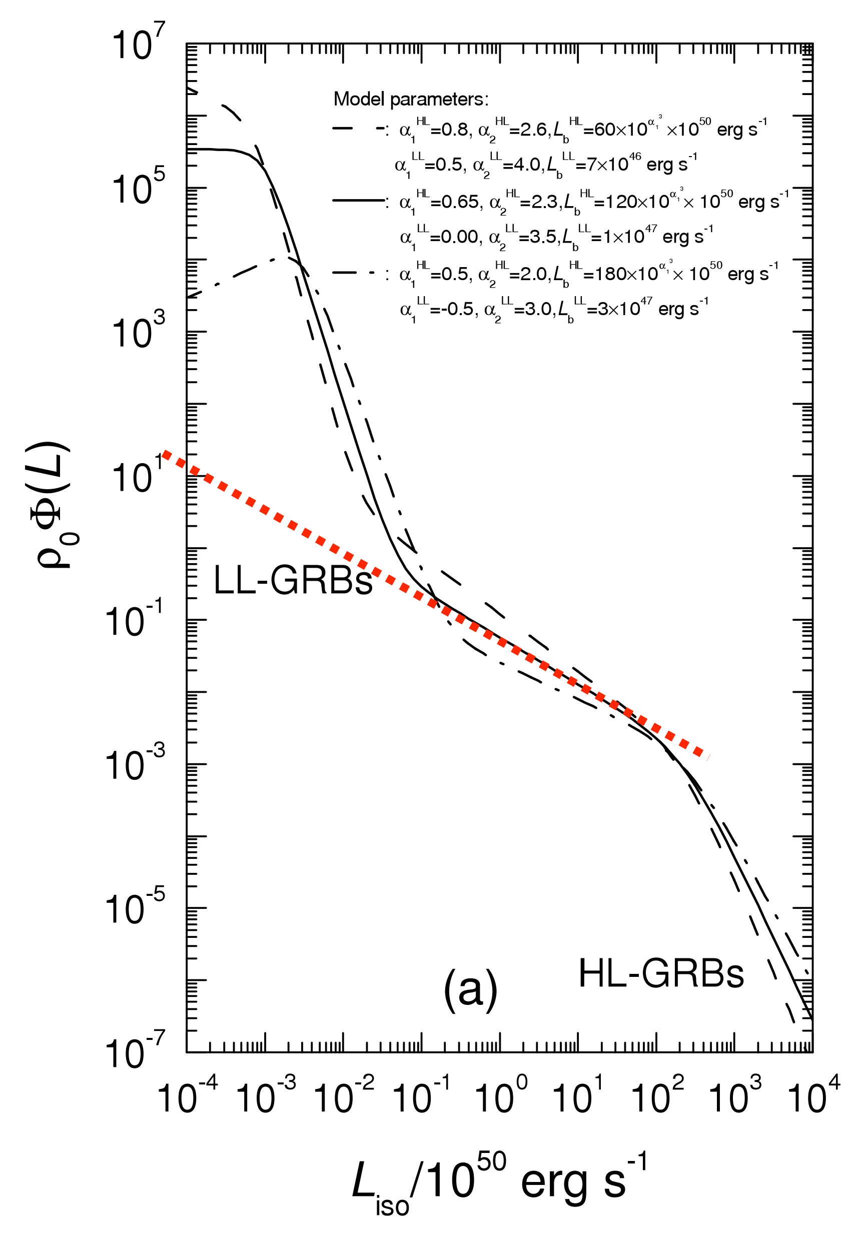
| | | |
|---|---|---|
| x $10^{49}$ erg | 190 s | N/A (single PL) |

# low-luminosity GRBs

- GRB 980425/SN 1998bw, GRB 060218/SN 2006aj, GRB 100316D/SN 2010bh
- low $L_{iso}$, low $E_{peak}$
- luminosity function

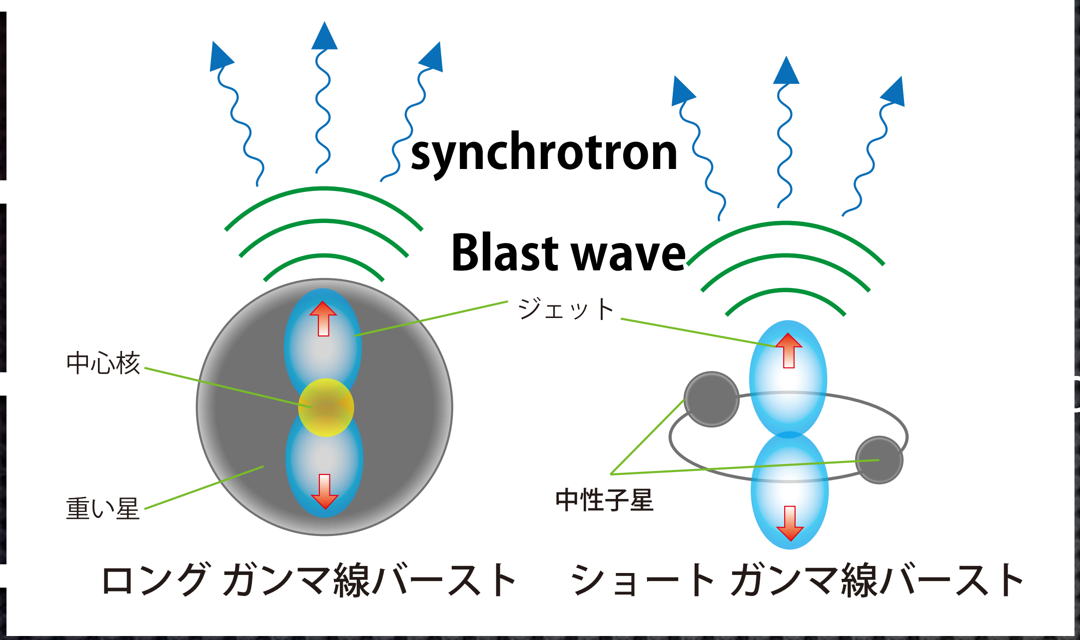
Liang+ (2007)





# New LLGRB 171205A @ 168Mpc

- Swift detection on 2017/12/05

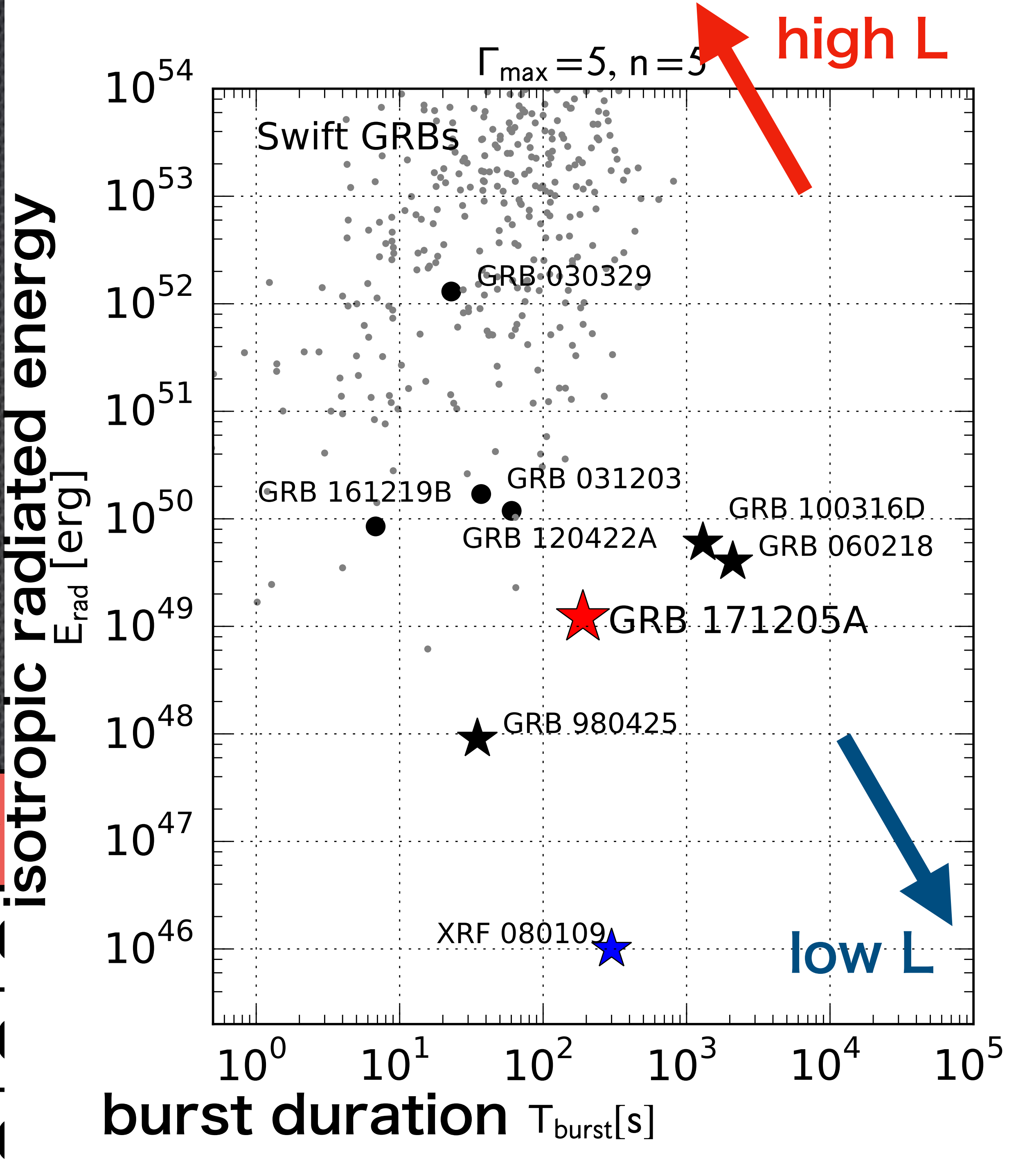


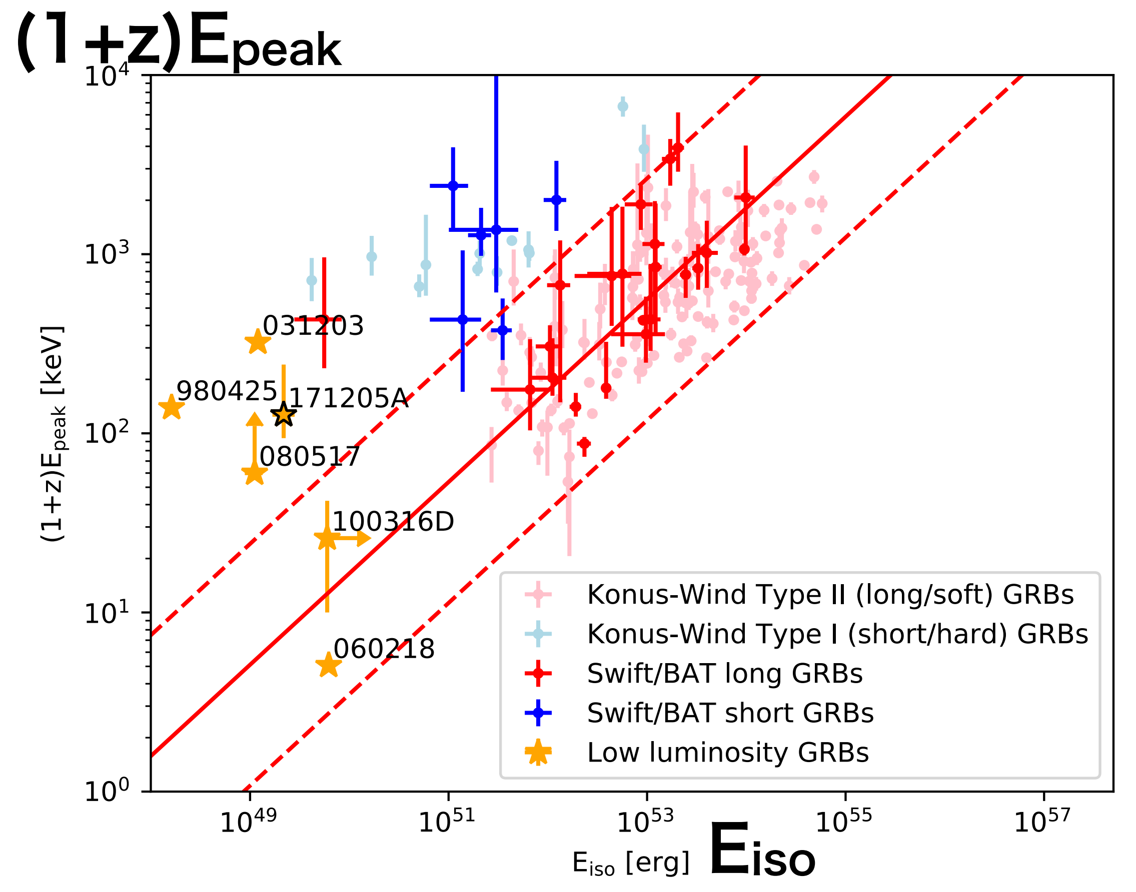
(de Ugarte Postigo+2017, GCN circular 22207)

on

pic

| | | |
|---|---|---|
| x $10^{49}$ erg | 190 s | N/A (single PL) |



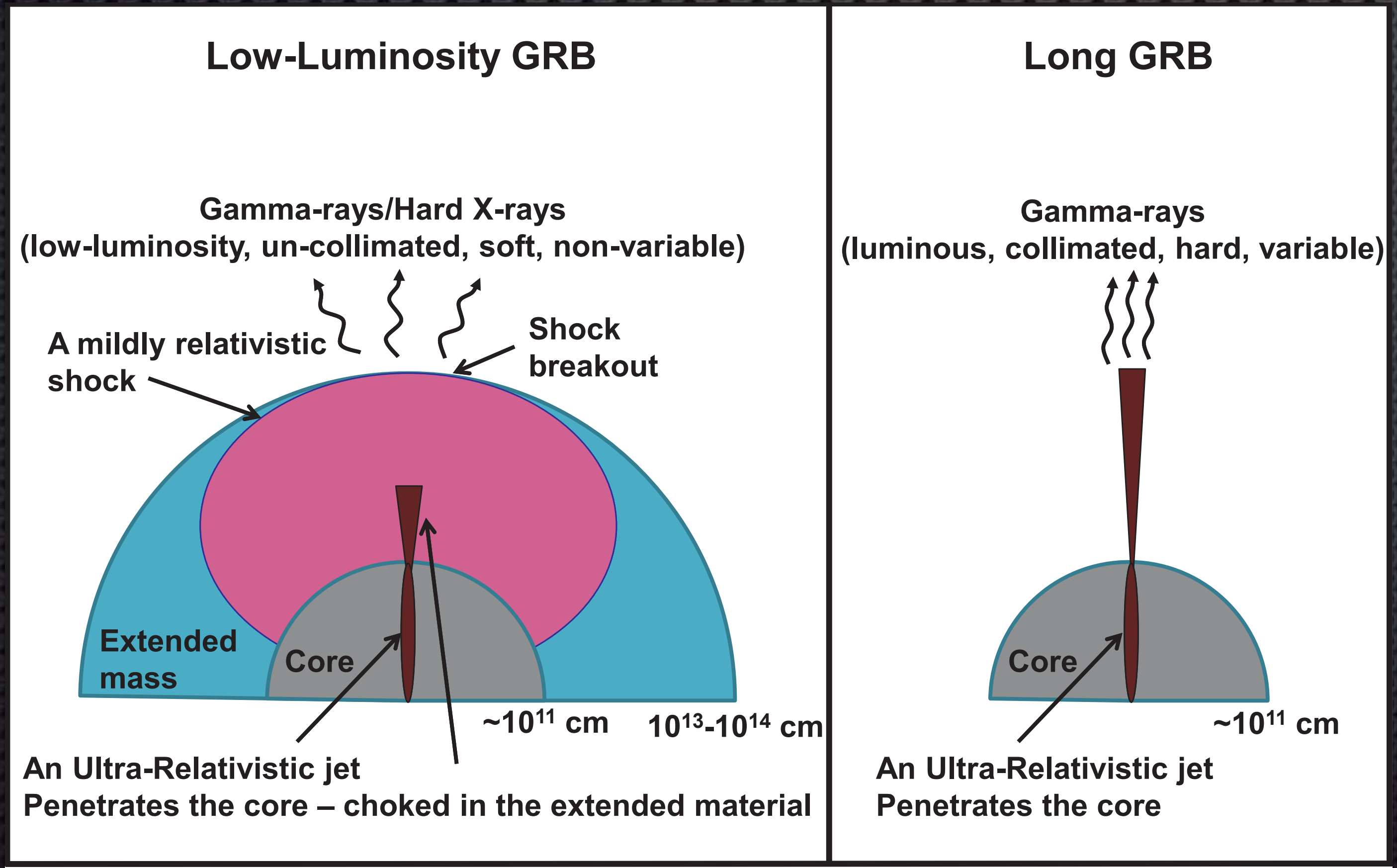


D'Elia+2018

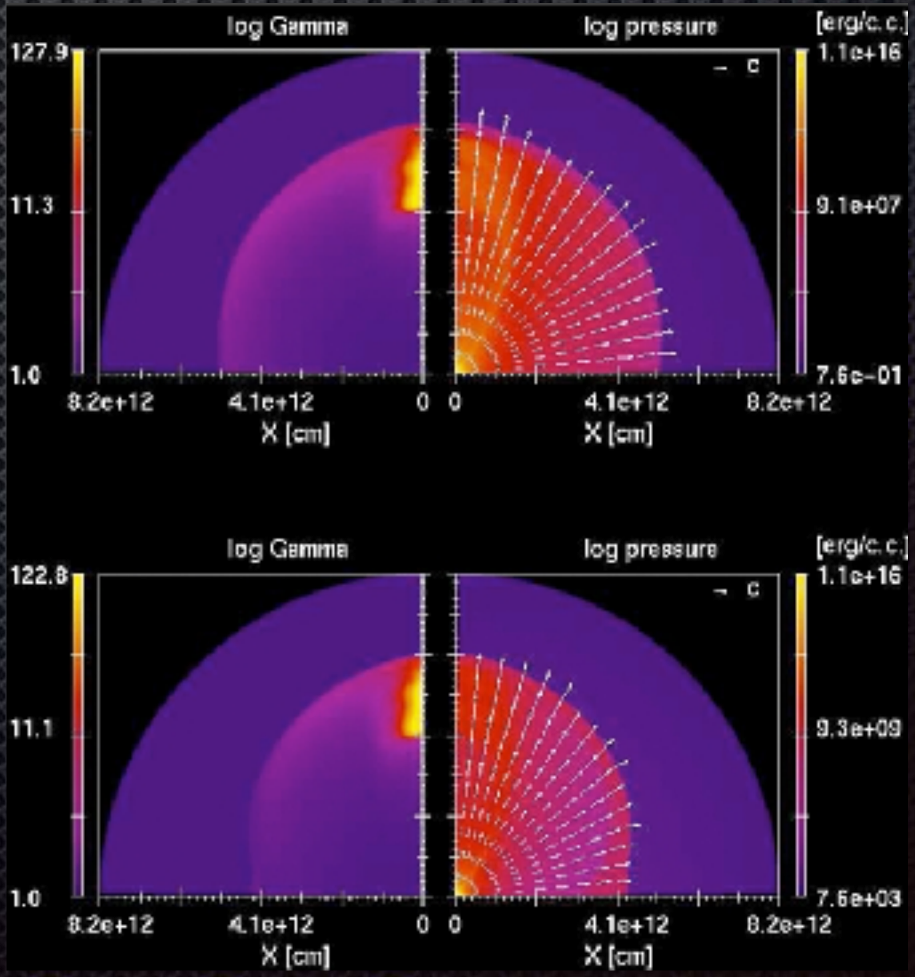
# Origin of low-luminosity GRBs

- ➡ central engine was a neutron star? (e.g., Mazzali+2006)
- ➡ off-axis GRB?
- ➡ relativistic shock breakout with dense CSM, off-axis/weak/failed jet, cocoon-CSM interaction(Kulkarni+1998, Tan+2001, Campana+2006, Li 2007; Toma+2007; Wang+ 2007; Waxman+ 2007,Suzuki&Shigeyama 2012, Nakar 2015, Irwin&Chevalier 2016 )

**Nakar (2015)**

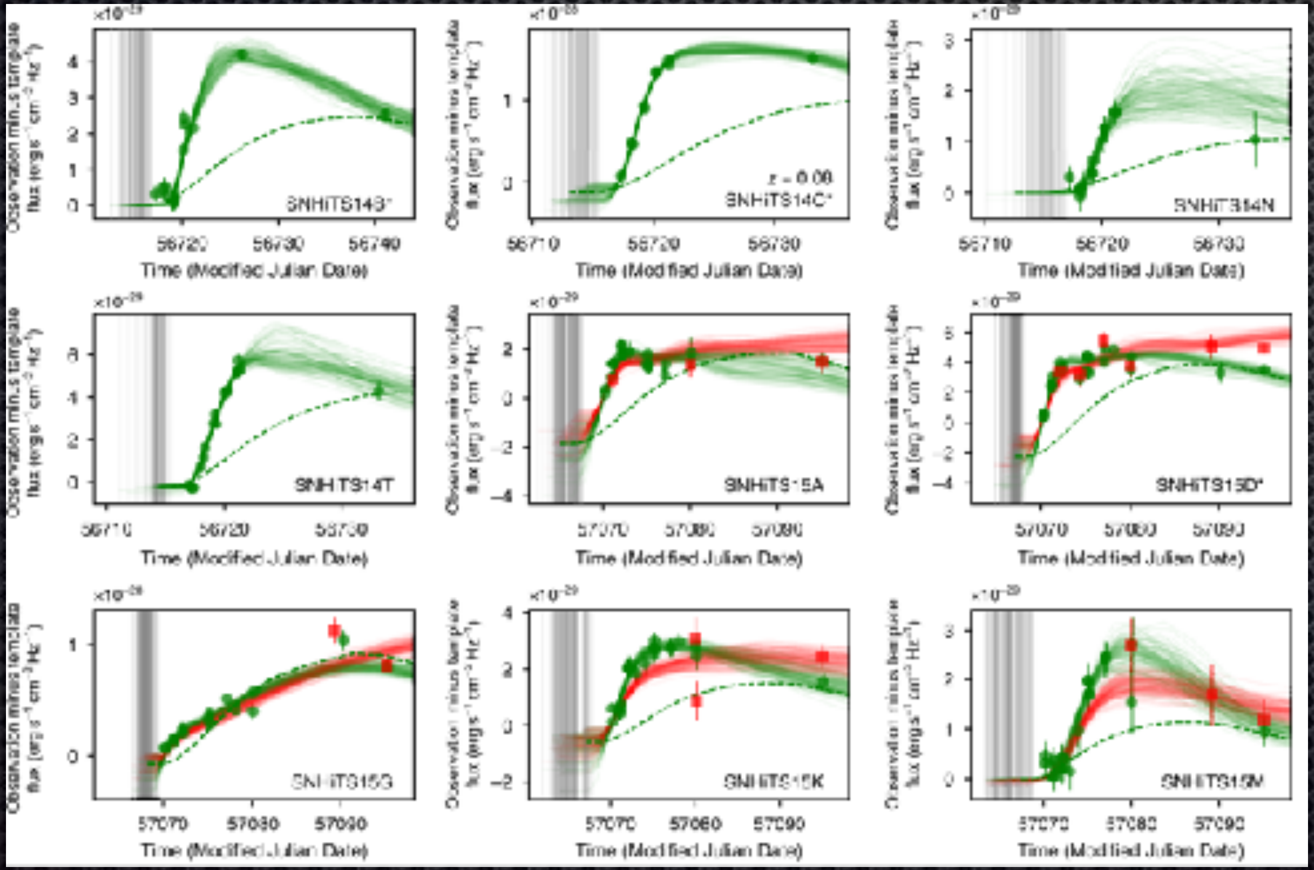


**Suzuki&Shigeyama (2013)**

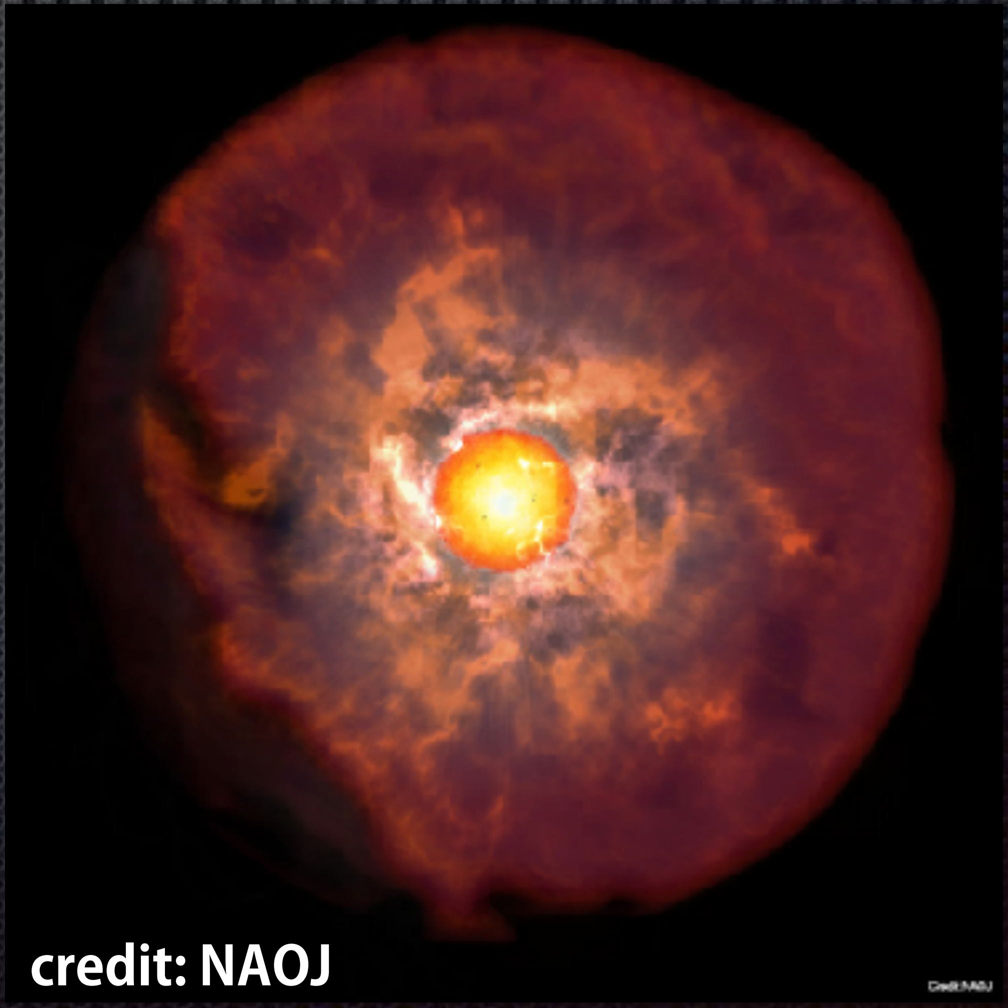


# dense CSM around massive stars?

- ➡ “Non-detection” of fast, bright shock breakout signals from type II SNe
- ➡ shock breakout emission can be smeared out or “delayed” by optically thick gas.
- ➡ SN progenitor surrounded by dense CSMs?
- ➡ we do not know if such CSMs are ubiquitously present for all types of CCSNe



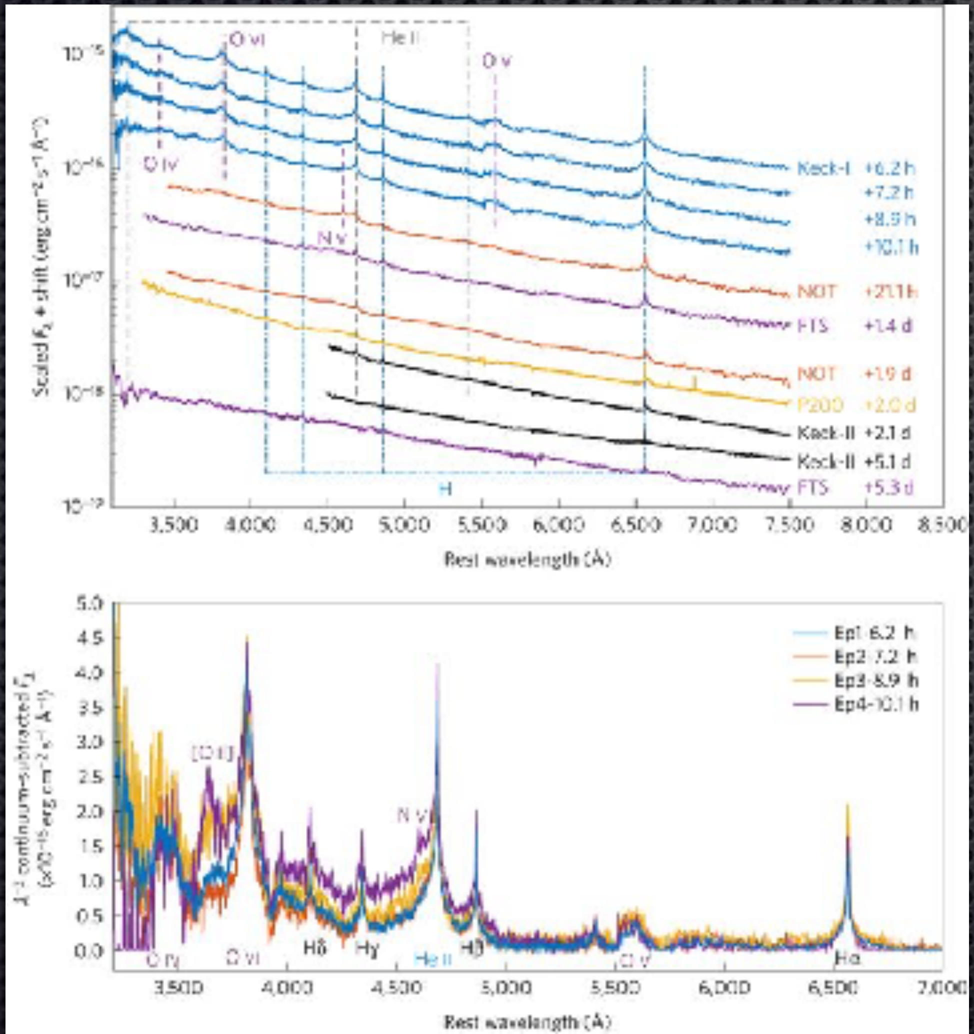
Forster, Moriya + (2018)

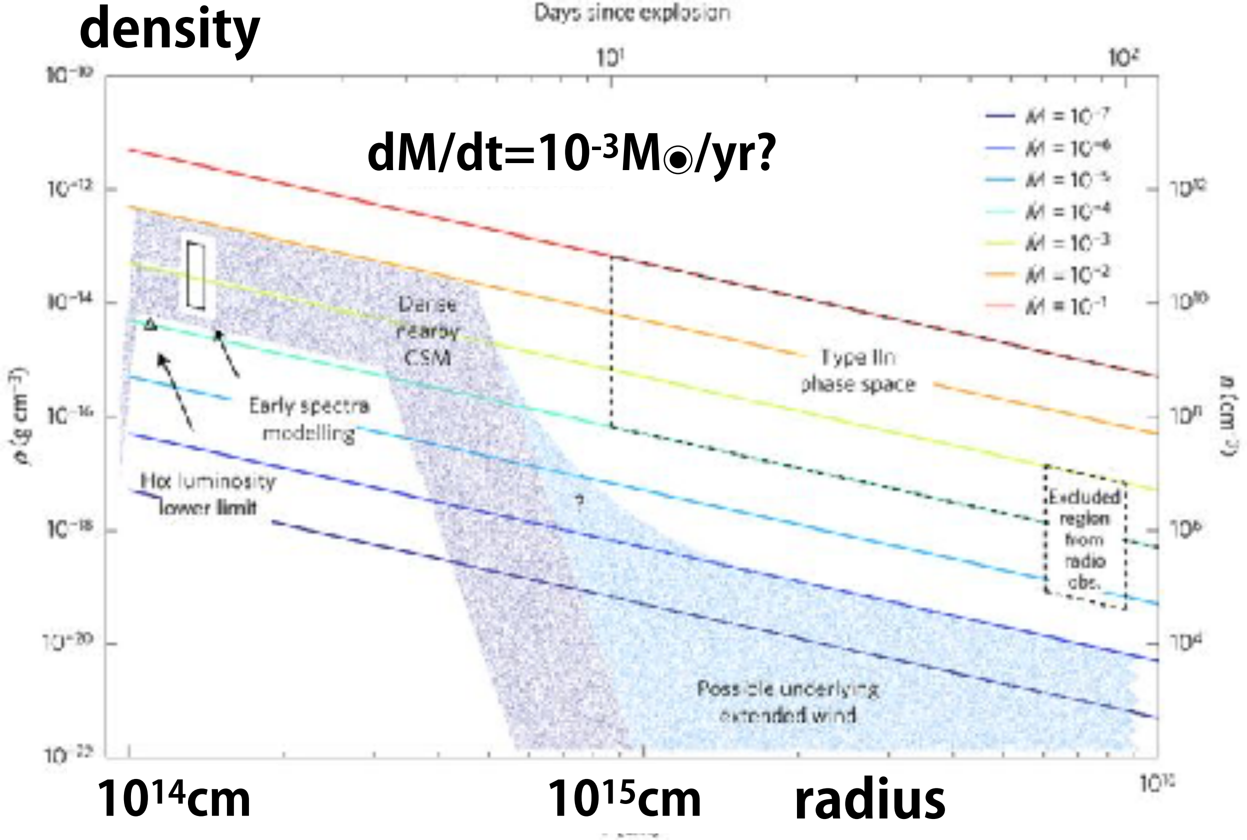


credit: NAOJ

# dense CSM around massive stars?

- ➡ “flash spectroscopy”, right after SN discovery
- ➡ CSM illuminated by the SN shock breakout light
- ➡ centrally confined CSM with a density much larger than normal stellar wind





SN 2013fs(=iPTF13dqy) Yaron + (2017)

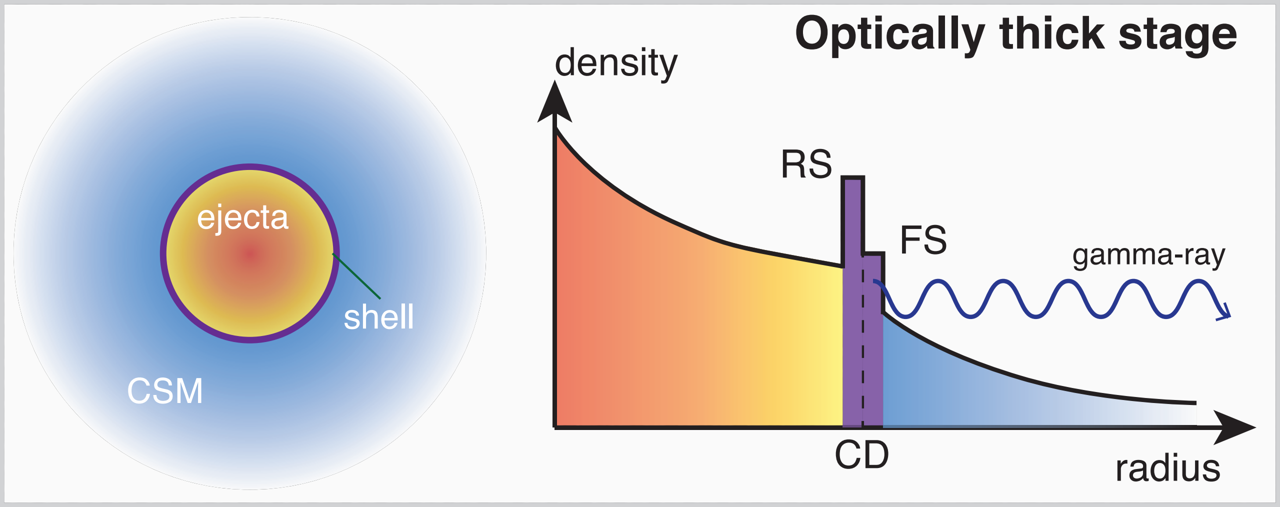
# Ejecta with mildly relativistic speeds and CSM

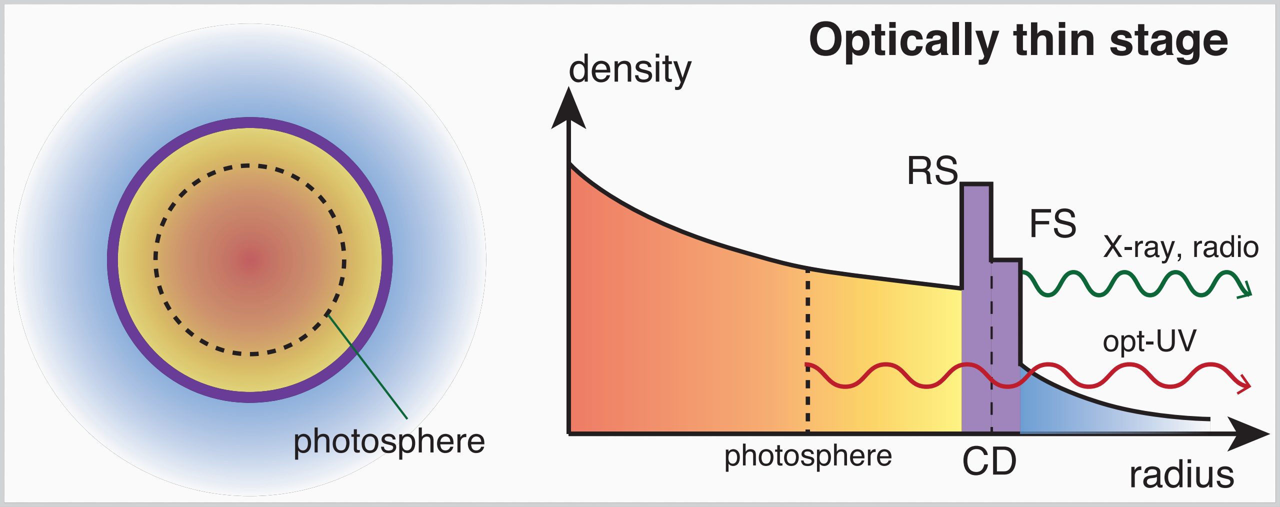
- ➡ SN ejecta (with max $\Gamma \sim 2\text{-}10$) colliding with circum-stellar medium (CSM), leading to the dissipation of the kinetic energy into the thermal energy of the shocked gas.
- ➡ the thermal energy diffusing out through the shell is responsible for the prompt emission

**How much energy can be released in ejecta-CSM interaction?**

- **kinetic energy of SN ejecta**
- **density structure**
- **CSM density**

**Suzuki, Maeda, Shigeyama (2018)**



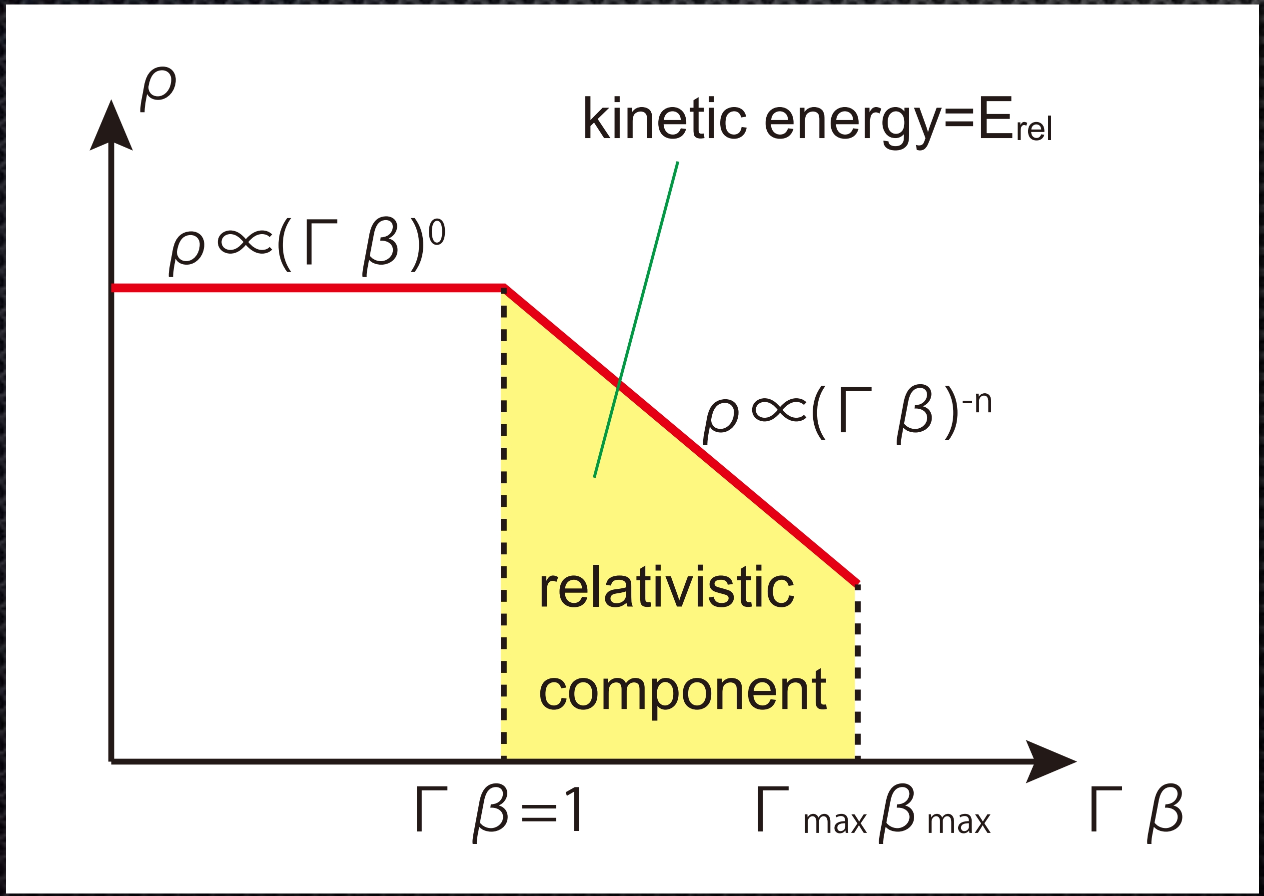


# One-zone semi-analytical model

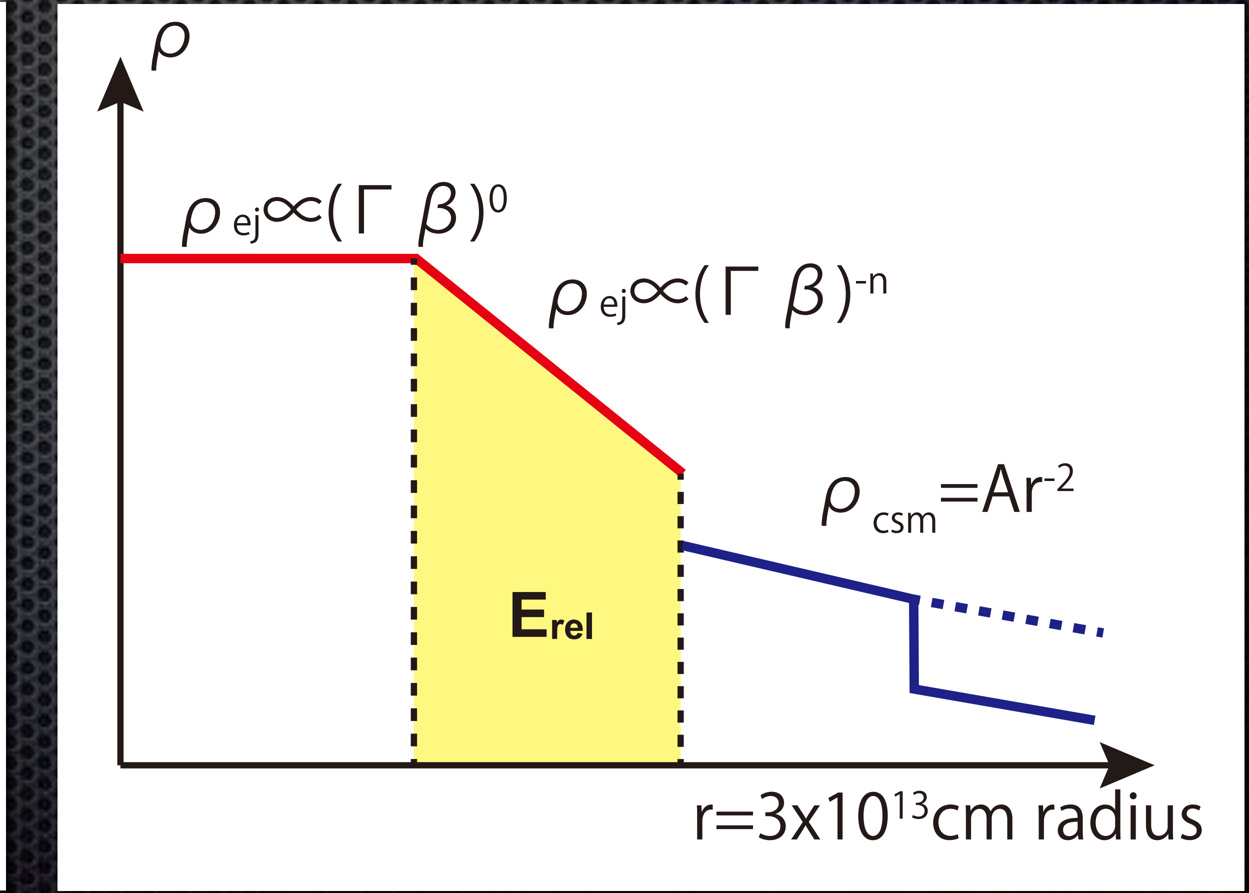
- steady wind: $\rho = Ar^{-2}$, $A_\star = A/(5\times10^{11}\ [\mathrm{g/cm}])$
  $(dM/dt = 10^{-4} M_\odot/\mathrm{yr}$, for $v_\mathrm{wind} = 1000\,\mathrm{km/s})$

- freely expanding trans-relativistic ejecta: $c\beta = r/t$,

**Ejecta distribution in velocity space**



**Ejecta distribution in physical space**



# One-zone semi-analytical model

➡ we approximate the shocked region as a thin shell and solve the EOM.

➡ shock radii $R_{\rm fs}$,$R_{\rm rs}$, shell mass Ms, shell momentum Sr, and so on

**momentum influx from ejecta**

**deceleration by pressure gradient force**

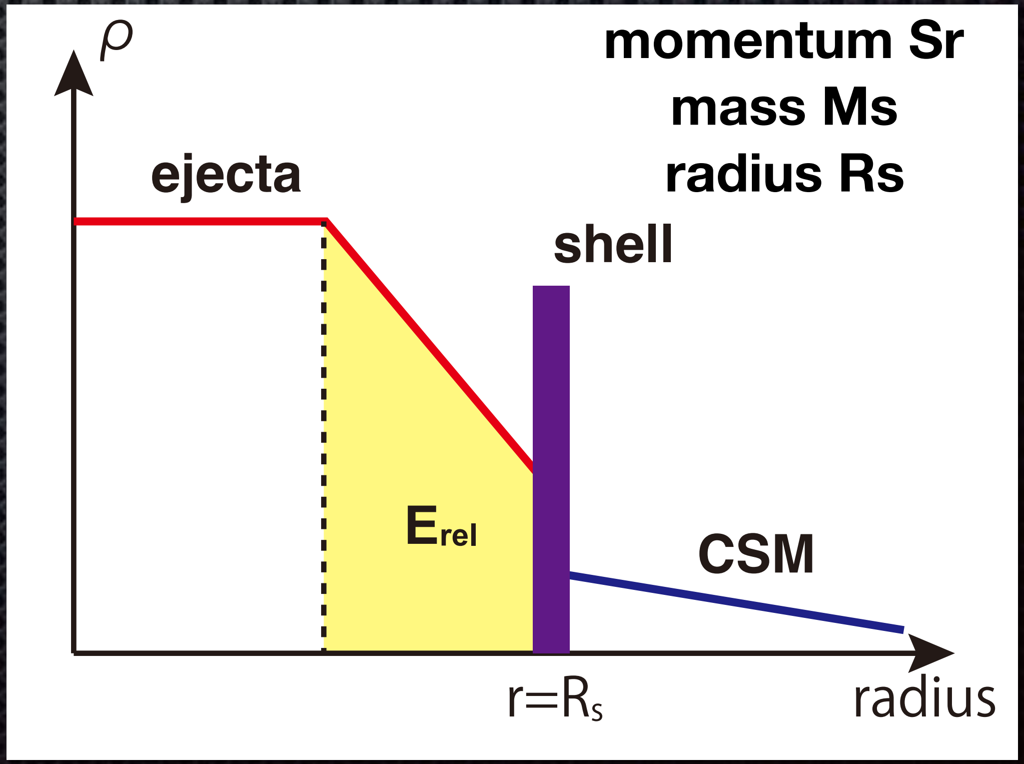
$$\frac{dS_r}{dt} + \cancel{4\pi R_{\rm fs}^2 F_{\rm fs}} - 4\pi R_{\rm rs}^2 F_{\rm rs} = 4\pi R_{\rm fs}^2 p_{\rm rs,d} - 4\pi R_{\rm rs}^2 p_{\rm fs,d}$$

$$\frac{dM_{\rm s}}{dt} + 4\pi R_{\rm fs}^2 F_{\rm m,fs} - 4\pi R_{\rm rs}^2 F_{\rm m,rs} = 0$$

$$\frac{dR_{\rm s}}{dt} = \beta_{\rm s},$$

**shell increases its mass by sweeping CSM/ejecta**

**forward/reverse shock velocity determined by shock jump condition**



# One-zone semi-analytical model

- ➡ we approximate the shocked region as a thin shell and solve the EOM.
- ➡ shock radii $R_{fs}$,$R_{rs}$, shell mass Ms, shell momentum Sr, and so on

momentum influx from ejecta

deceleration by pressure gradient force

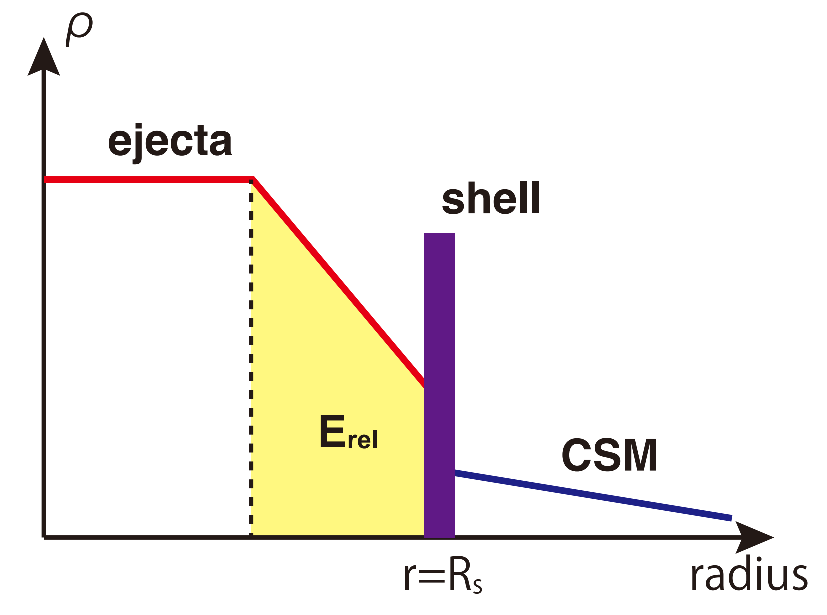
$$\frac{dS_r}{dt} + \cancel{4\pi R_{\rm fs}^2 F_{\rm fs}} - 4\pi R_{\rm rs}^2 F_{\rm rs} = 4\pi R_{\rm fs}^2 p_{\rm rs,d} - 4\pi R_{\rm rs}^2 p_{\rm fs,d}$$

$$S_r = M_{\rm s}\Gamma_{\rm s}\beta_{\rm s} \qquad \Gamma_{\rm s} = \sqrt{1 + \frac{S_r^2}{M_{\rm s}^2}}.$$

$$\beta_{\rm sh}(\beta_{\rm u}, \beta_{\rm d}) = \frac{\gamma\Gamma_{\rm u}\Gamma_{\rm d}^2(\beta_{\rm u} - \beta_{\rm d})\beta_{\rm d} - (\gamma - 1)(\Gamma_{\rm u} - \Gamma_{\rm d})}{\gamma\Gamma_{\rm u}\Gamma_{\rm d}^2(\beta_{\rm u} - \beta_{\rm d}) - (\gamma - 1)(\Gamma_{\rm u}\beta_{\rm u} - \Gamma_{\rm d}\beta_{\rm d})}$$

$$\beta_{\rm rs} = \beta_{\rm sh}(\beta_{\rm ej}, \beta_{\rm s}). \quad \rho_{\rm rs} = \rho_{\rm ej}\frac{\Gamma_{\rm ej}(\beta_{\rm ej} - \beta_{\rm rs})}{\Gamma_{\rm u}(\beta_{\rm s} - \beta_{\rm rs})}, \quad p_{\rm rs} = \frac{\rho_{\rm ej}\Gamma_{\rm ej}^2(\beta_{\rm ej} - \beta_{\rm rs})(\beta_{\rm ej} - \beta_{\rm s})}{1 - \beta_{\rm s}\beta_{\rm rs}}$$

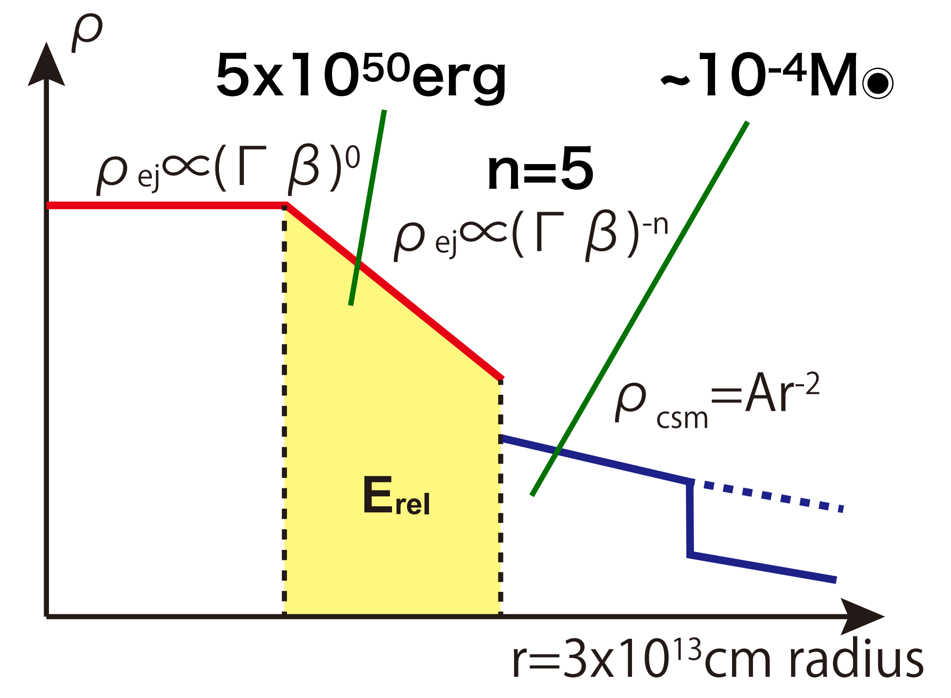
$$F_{\rm rs} = \rho_{\rm ej}\Gamma_{\rm ej}^2\beta_{\rm ej}(\beta_{\rm ej} - \beta_{\rm rs}),$$

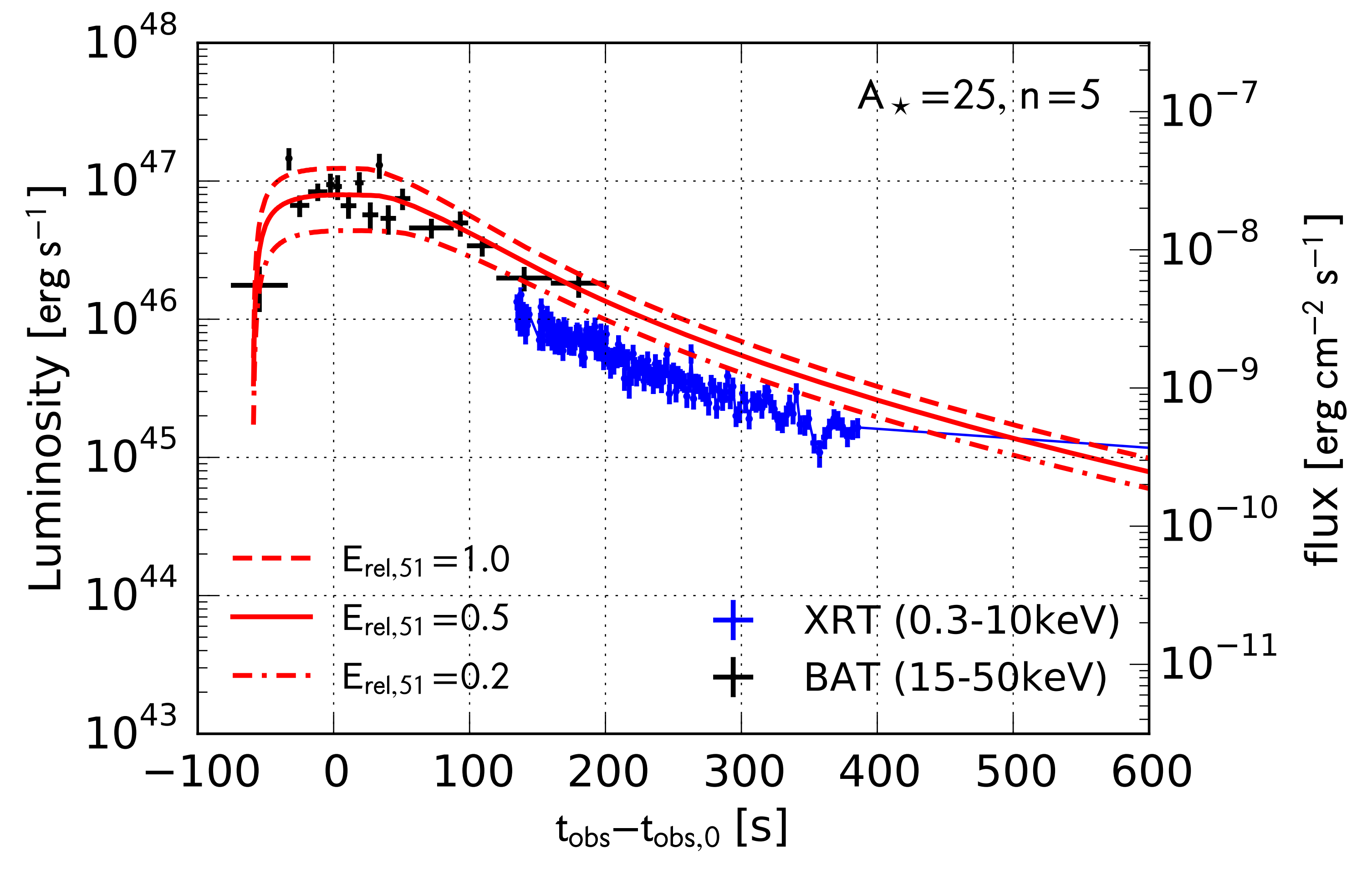


# Bolometric LC for prompt emission

- fiducial model: $E_{rel,51}$=0.5,$A_{\star}$=25,n=5 ($dM/dt$=2.5x$10^{-4}M_{\odot}$/yr for $v_{w}$=$10^{3}$km/s)
- theoretical emission model is consistent with observed prompt gamma-ray and X-ray light curves
- note: theoretical model produce bolometric light curves
- spectral evolution is the next step

**Suzuki, Maeda, & Shigeyama (2018)**

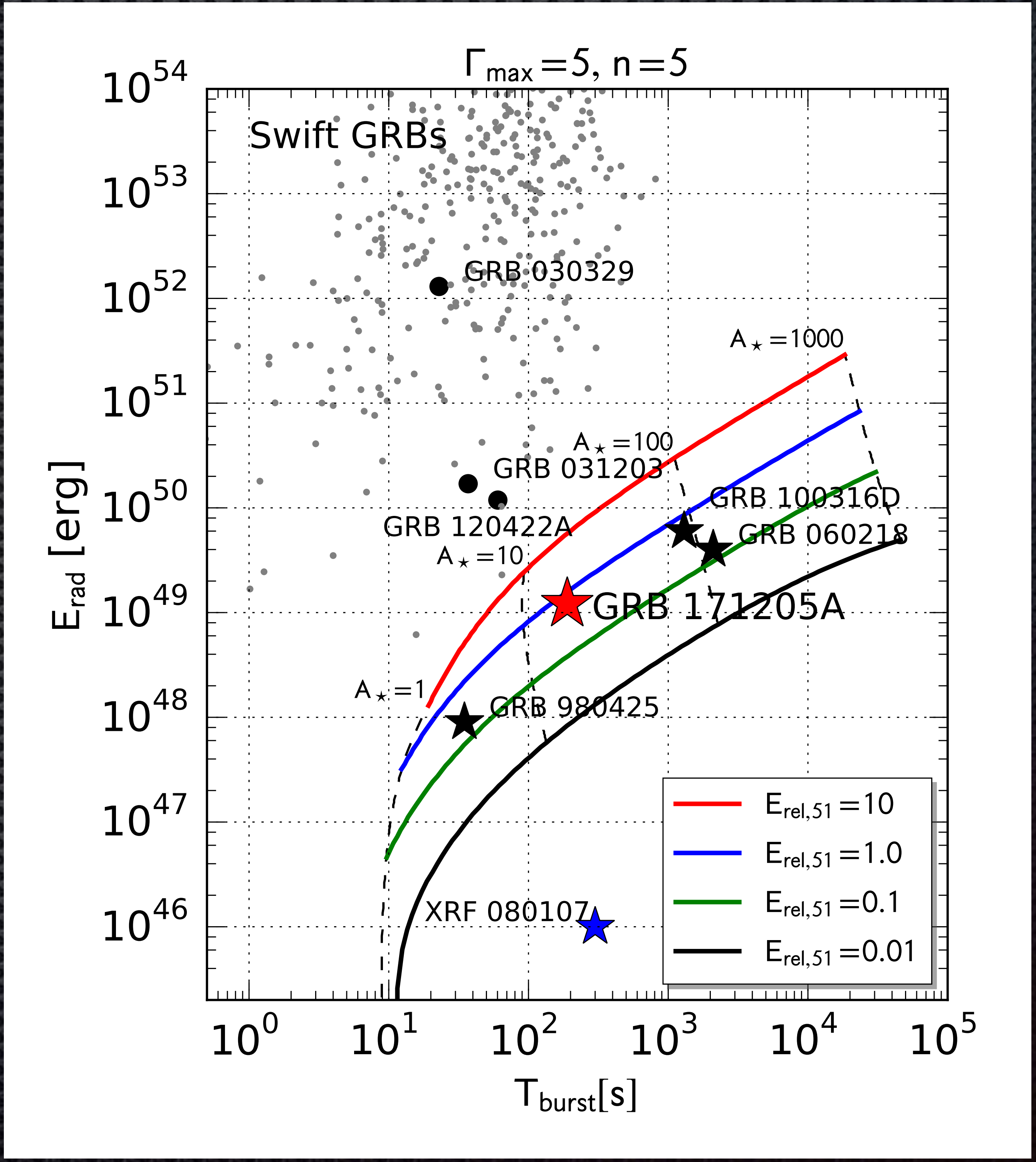




# $E_{rad}$ vs $T_{burst}$

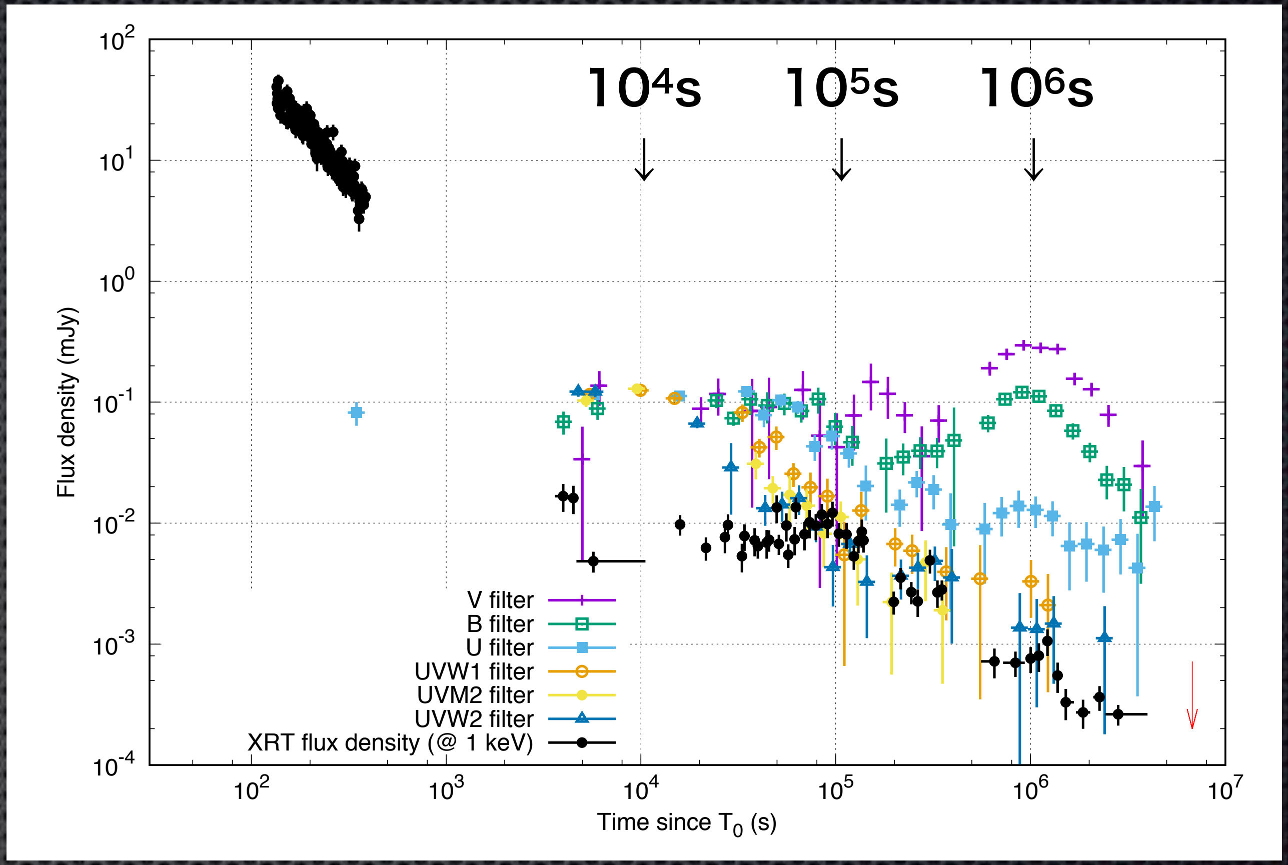
- $E_{rad}$-$T_{burst}$ diagram
- longer bursts show larger radiated energies
- in ejecta-CSM interaction model, this trend can be explained by increasing CSM density (or mass)
- GRB 171205A is consistent with the trend.
- GRB171205A: $E_{rel} \sim 10^{51}$[erg], $A_\star \sim$ several 10

Suzuki, Maeda, & Shigeyama (2018)

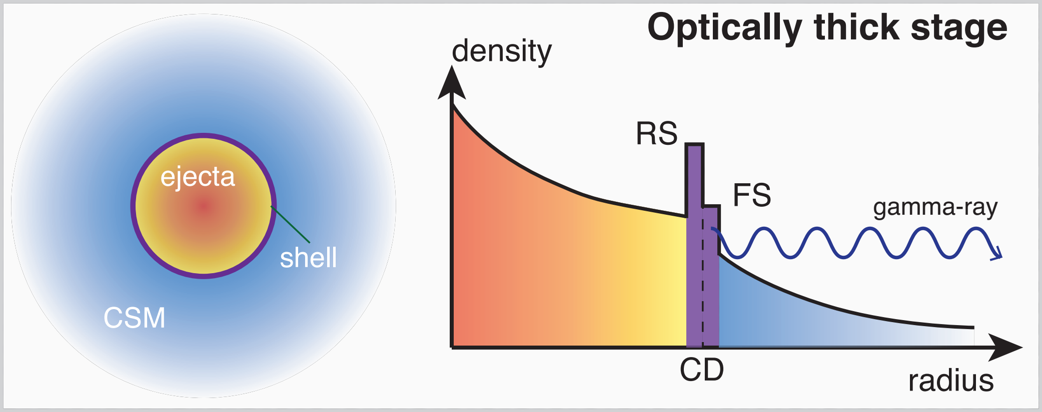


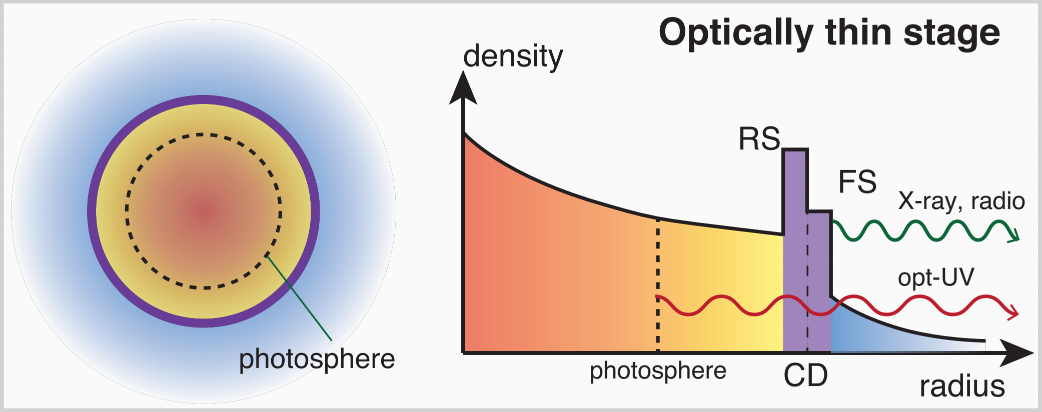
# Non-thermal X-ray and radio emission

- ➡ Afterglow emission following the prompt gamma-ray
- ➡ Swift XRT observations + radio (NOEMA, ALMA, VLA )



**XRT & UVOT obs. (D’Elia+2018)**





# Non-thermal X-ray and radio emission

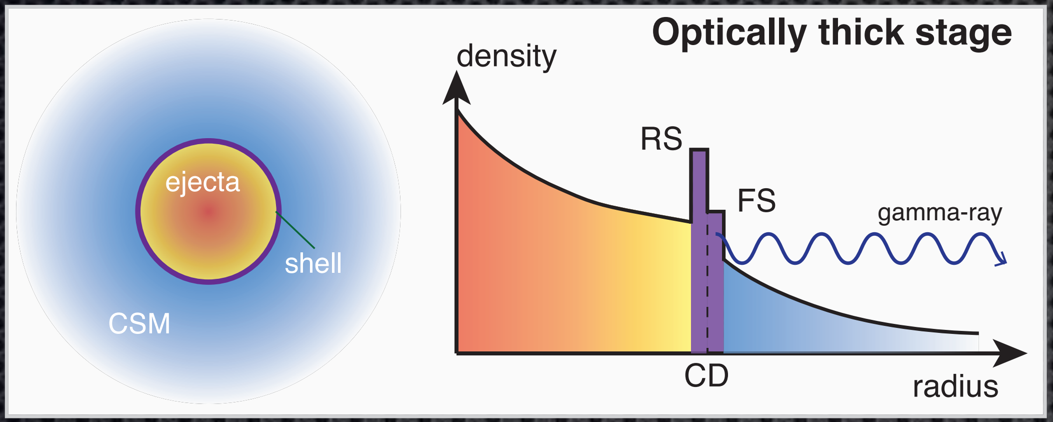
- ➡ electron distribution in momentum space
- ➡ parameters: $p$, $\varepsilon_{\rm e}$, $\varepsilon_{\rm B}$
- ➡ synchrotron, inverse Compton, and adiabatic cooling

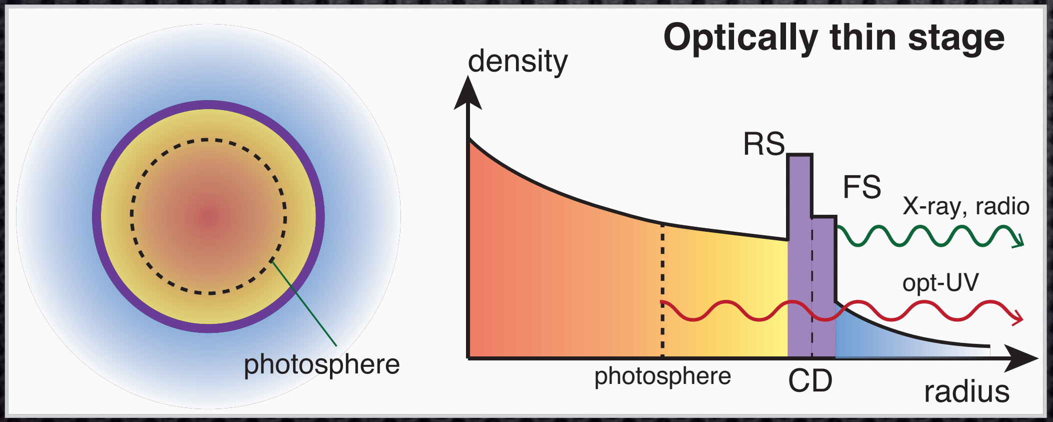
**Suzuki, Maeda, & Shigeyama (2018)**

$$\frac{\partial}{\partial t}\left(\frac{dN}{dp_{\rm e}}\right)=\frac{\partial}{\partial p_{\rm e}}\left[(\dot{p}_{\rm syn}+\dot{p}_{\rm ic}+\dot{p}_{\rm ad})\frac{dN}{dp_{\rm e}}\right]+\left(\frac{d\dot{N}}{dp_{\rm e}}\right)_{\rm in}$$

$$\left(\frac{d\dot{N}}{dp_{\rm e}}\right)_{\rm in}\propto\left\{\begin{array}{ll} p_{\rm e}{}^{-p} & \text{for } p_{\rm in}\leq p_{\rm e}\leq p_{\rm max} \\ 0 & \text{otherwise}\end{array}\right.$$

$$\dot{p}_{\rm syn}=\frac{4\sigma_{\rm T}u_{\rm B}}{3m_{\rm e}^2c^2}p_{\rm e}\sqrt{m_{\rm e}^2c^2+p_{\rm e}^2},$$
$$\dot{p}_{\rm ic}=\frac{4\sigma_{\rm T}u_{\rm rad}}{3m_{\rm e}^2c^2}p_{\rm e}\sqrt{m_{\rm e}^2c^2+p_{\rm e}^2},$$
$$\dot{p}_{\rm ad}=\frac{p_{\rm e}}{3V}\frac{dV}{dt}.$$



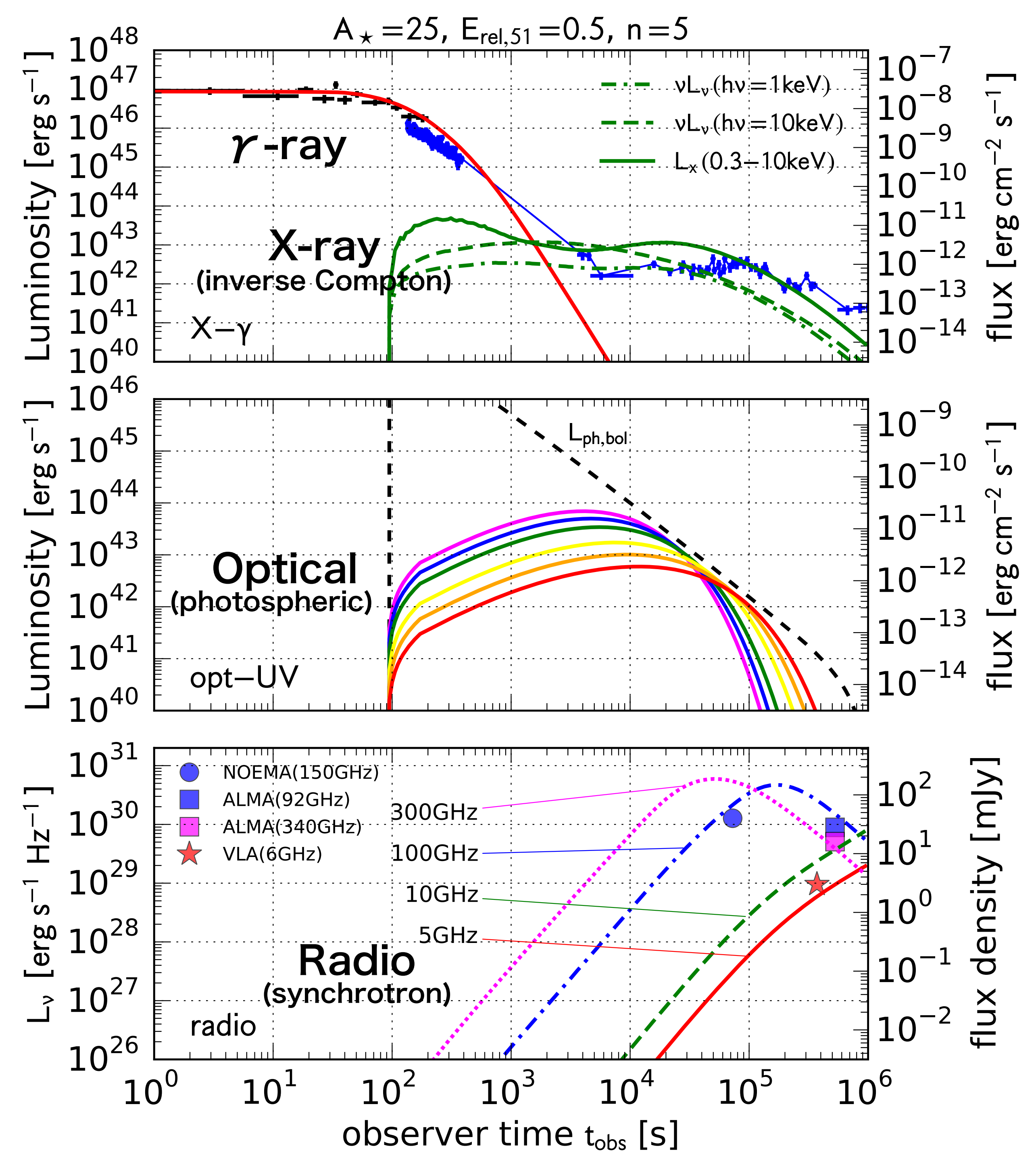


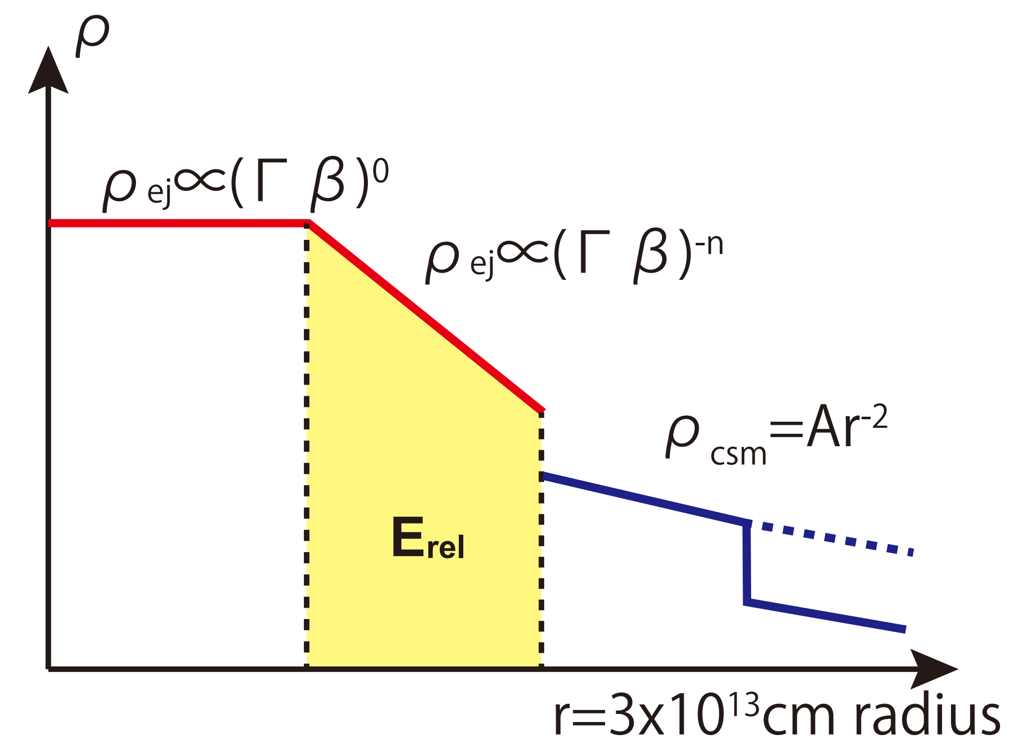
- ➡ $u_{\rm rad}$: thermal photons+ synchrotron photons

# Non-thermal X-ray and radio emission

- ➡ $p=3.0,\ \varepsilon_{e}=0.08,\ \varepsilon_{B}=3\mathrm{x}10^{-3}$
- ➡ Swift XRT observations + radio (NOEMA, ALMA, VLA )
- ➡ $A_{\star,\mathrm{out}}=0.5$ (normal stellar wind)

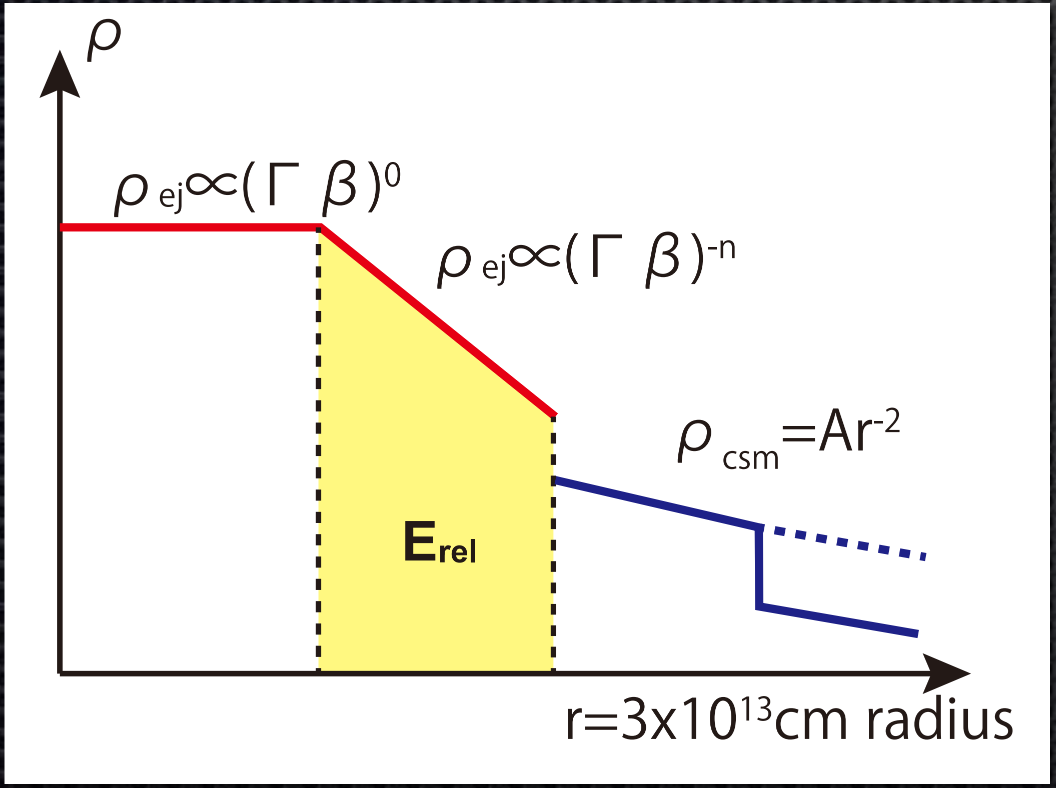
**Suzuki, Maeda, & Shigeyama (2018)**



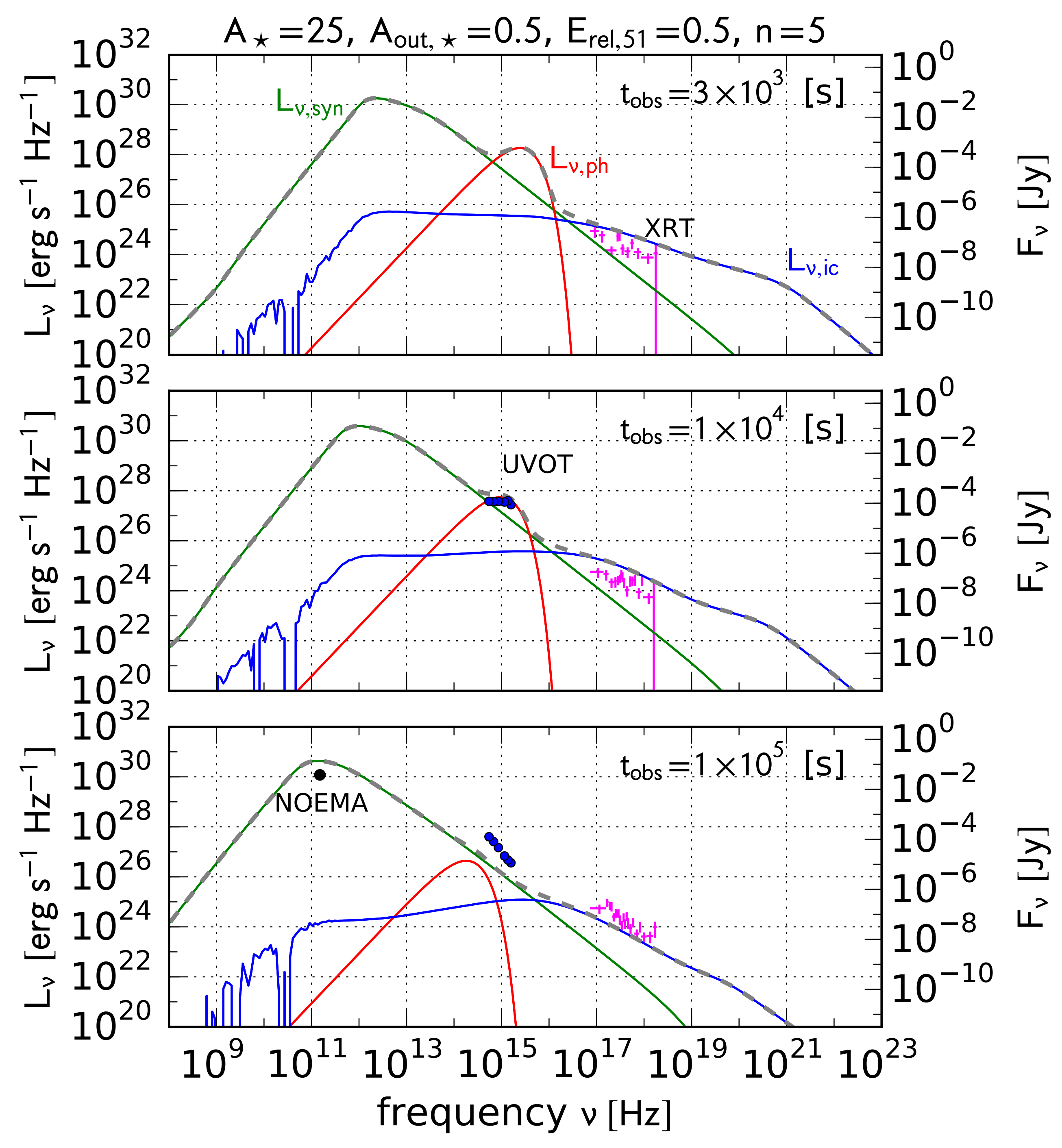


# Non-thermal X-ray and radio emission

- ➡ $p=3.0$, $\varepsilon_e=0.08$, $\varepsilon_B=3\times10^{-3}$
- ➡ Swift XRT observations + radio (NOEMA, ALMA, VLA )
- ➡ $A_{\star,\mathrm{out}}=0.5$ (normal stellar wind)



**Suzuki, Maeda, & Shigeyama (2018)**



# Summary

- low-luminosity GRBs: a sub-energetic population of long GRBs
- A part of them are really a distinct population powered by CSM interaction.
- origin of (sub-)relativistic ejecta?
- There should be more llGRBs, but how to distinguish between off-axis GRBs and CSM-powered transients.
- Future deep and/or wide X-ray surveys will unveil the hidden population.

**Suzuki, Maeda, & Shigeyama (2018)**