Ejecta-CSM interaction model for low-luminosity GRBs: application to llGRB 171205A

Akihiro Suzuki (NAOJ)

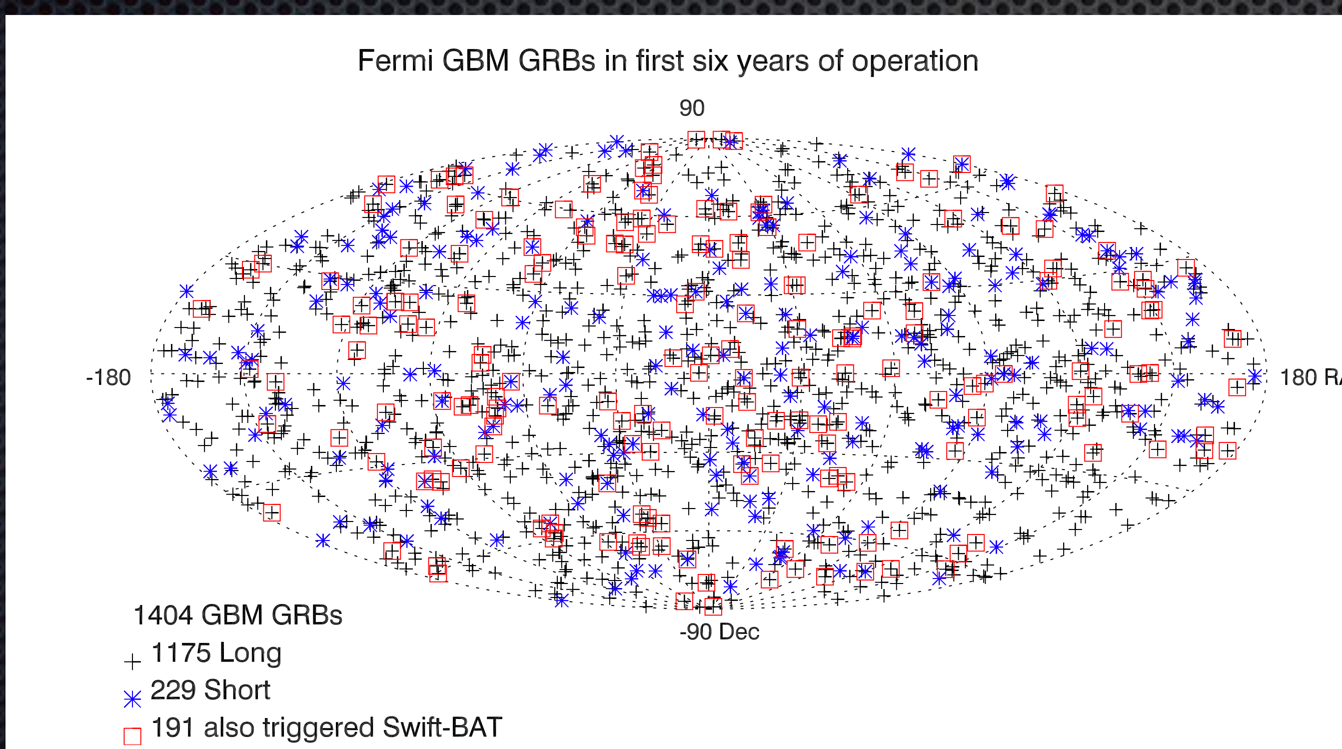
Suzuki, Maeda, & Shigeyama (2017), ApJ, 832,32

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

- Introduction
- Ejecta-CSM interaction
- Light curve fitting for GRB171205A
- Conclusion

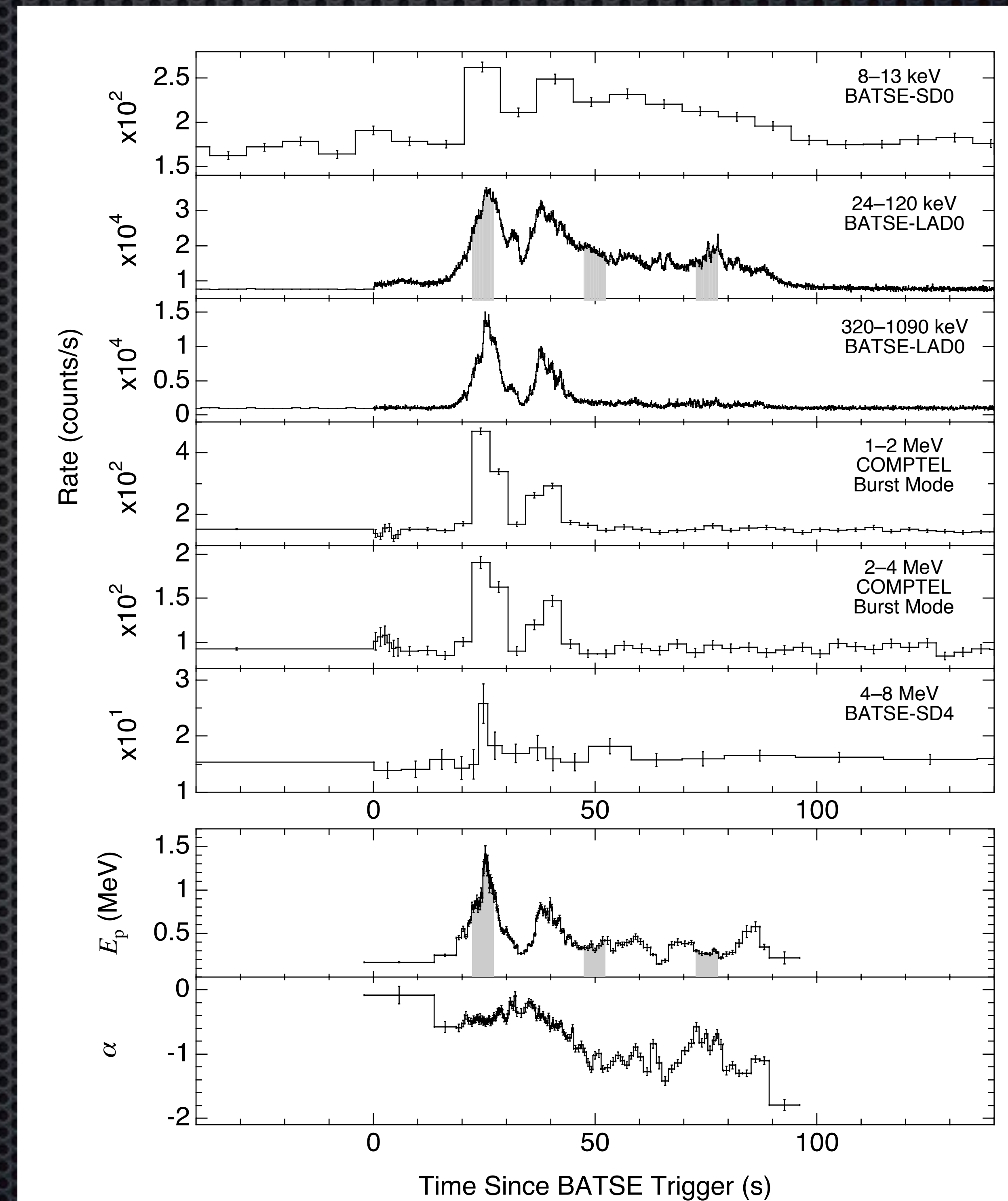
Gamma-ray bursts

- 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



distribution of Fermi GRBs on the celestial sphere

(3rd Fermi GBM catalog, 2016)



Briggs+ (1999)

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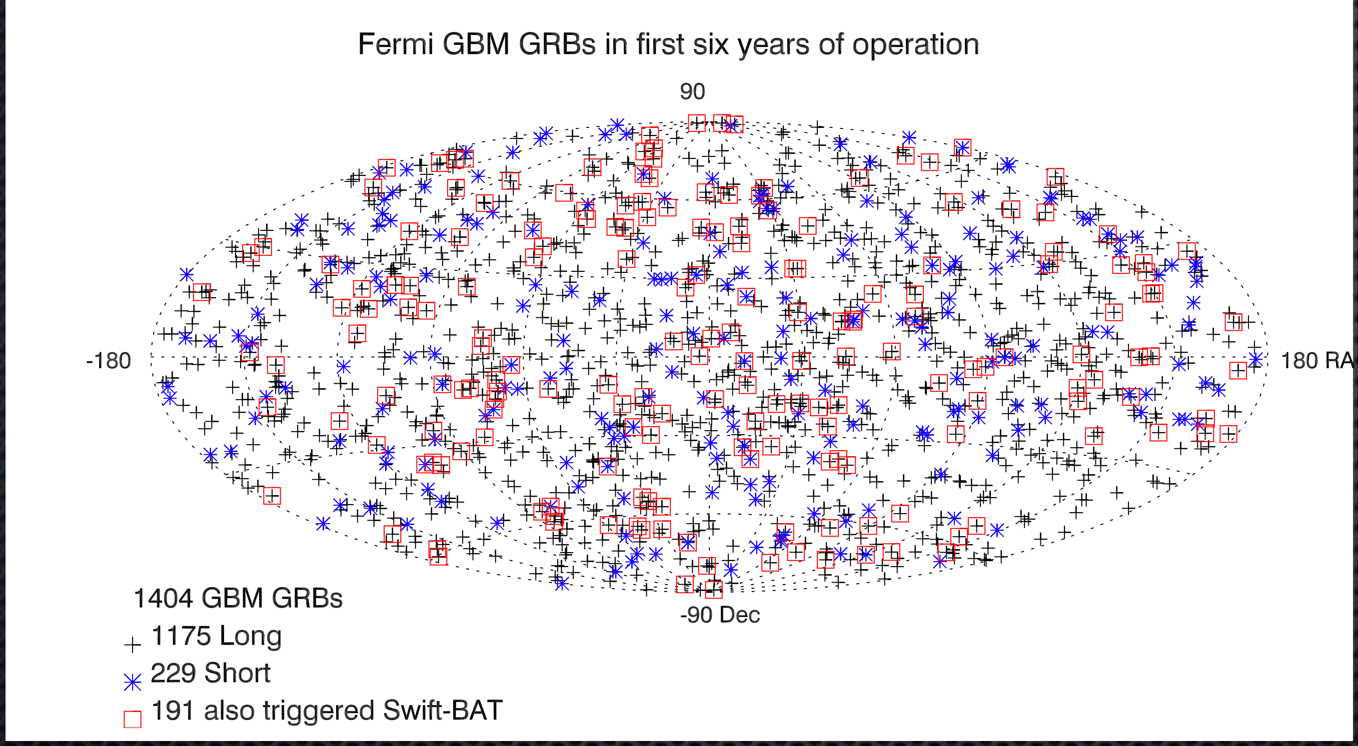

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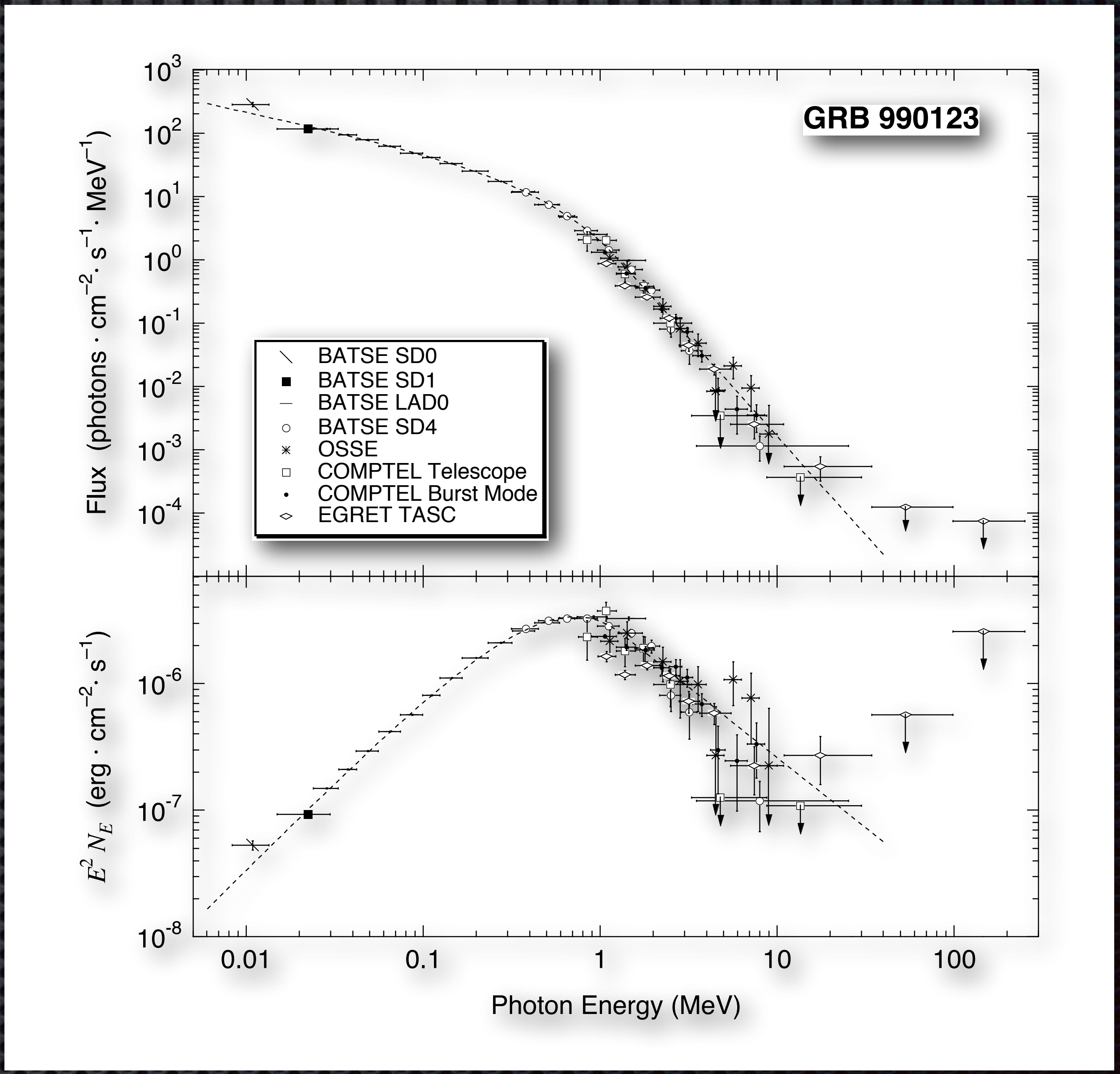

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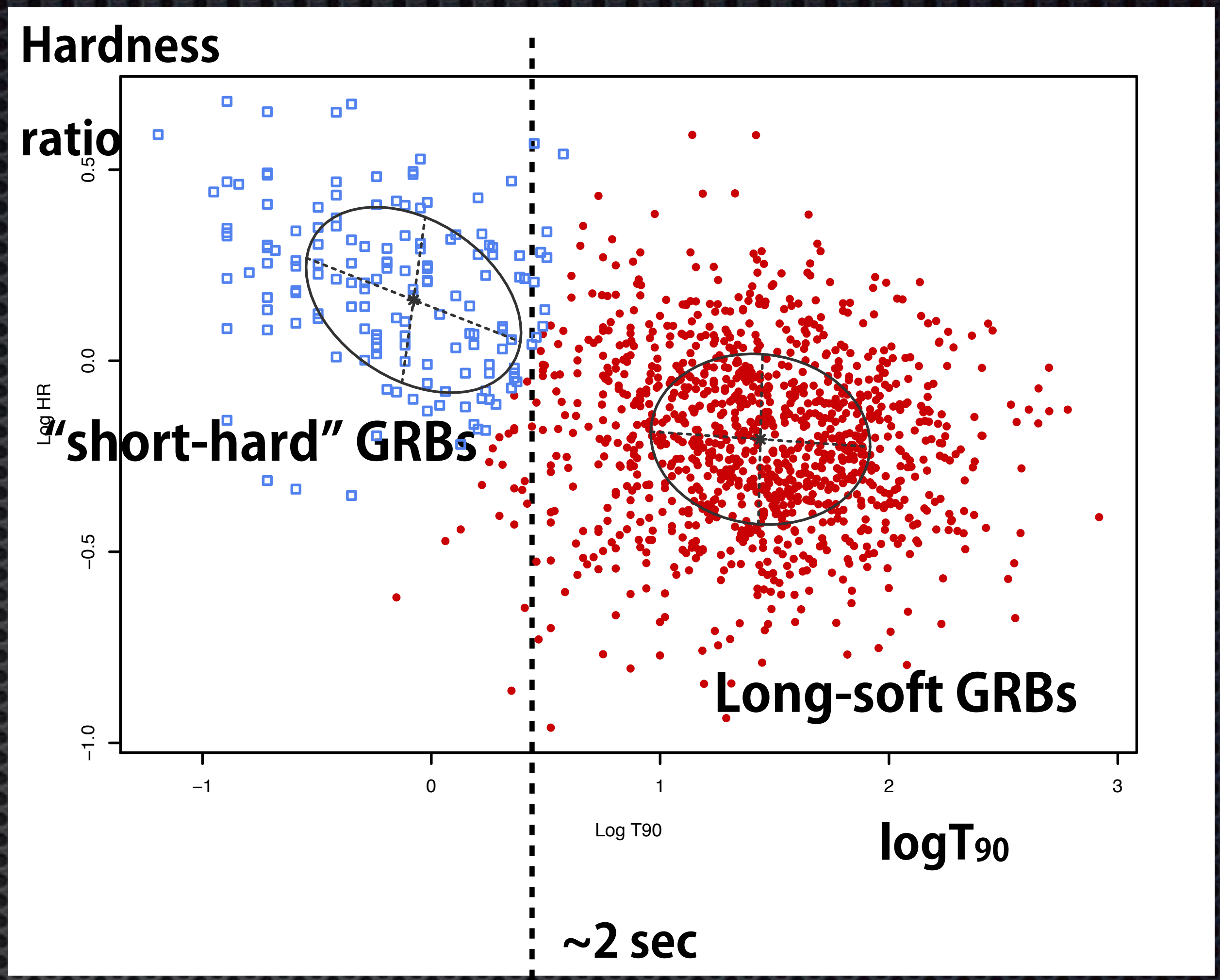
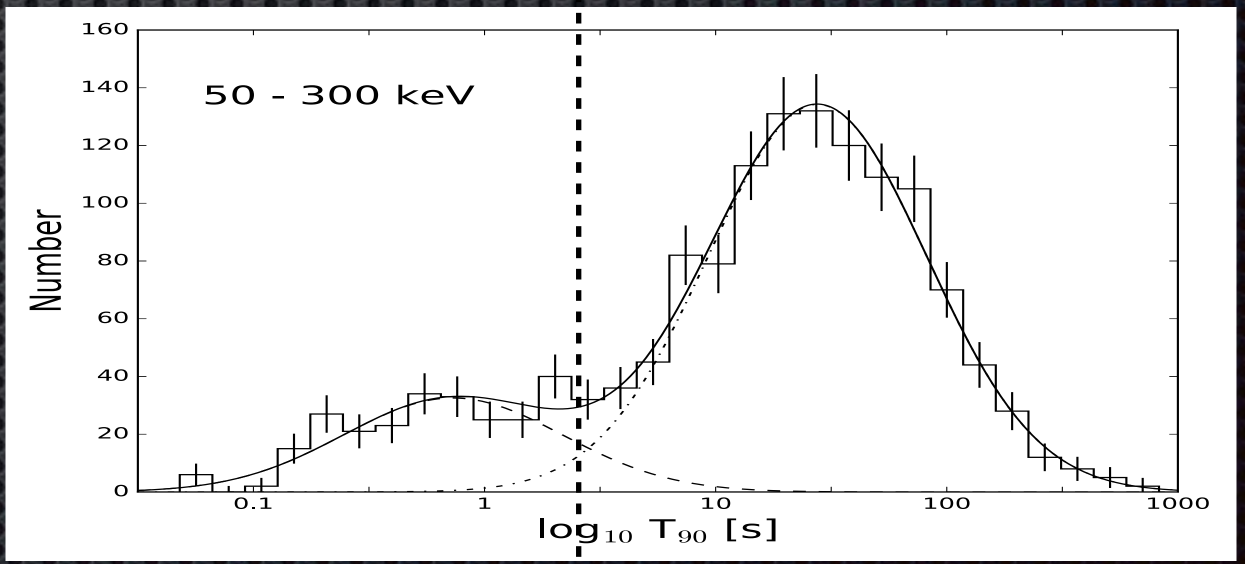
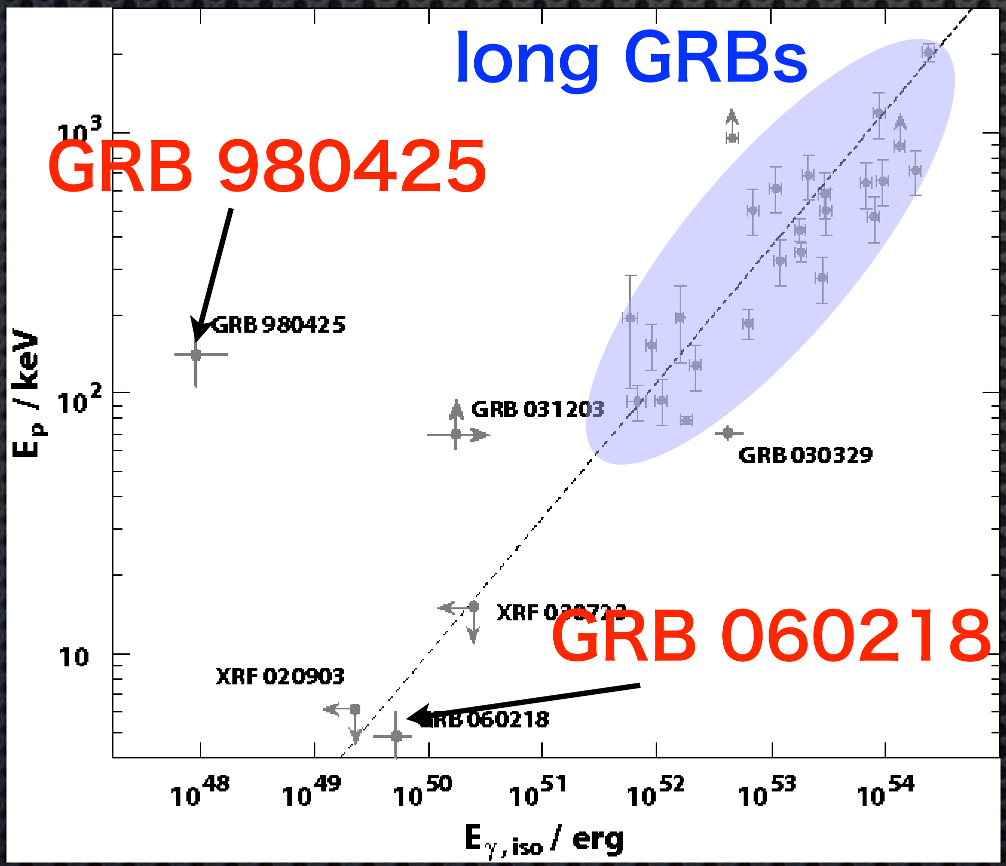
HR vs T90 plot(3rd Fermi GBM catalog, 2016)



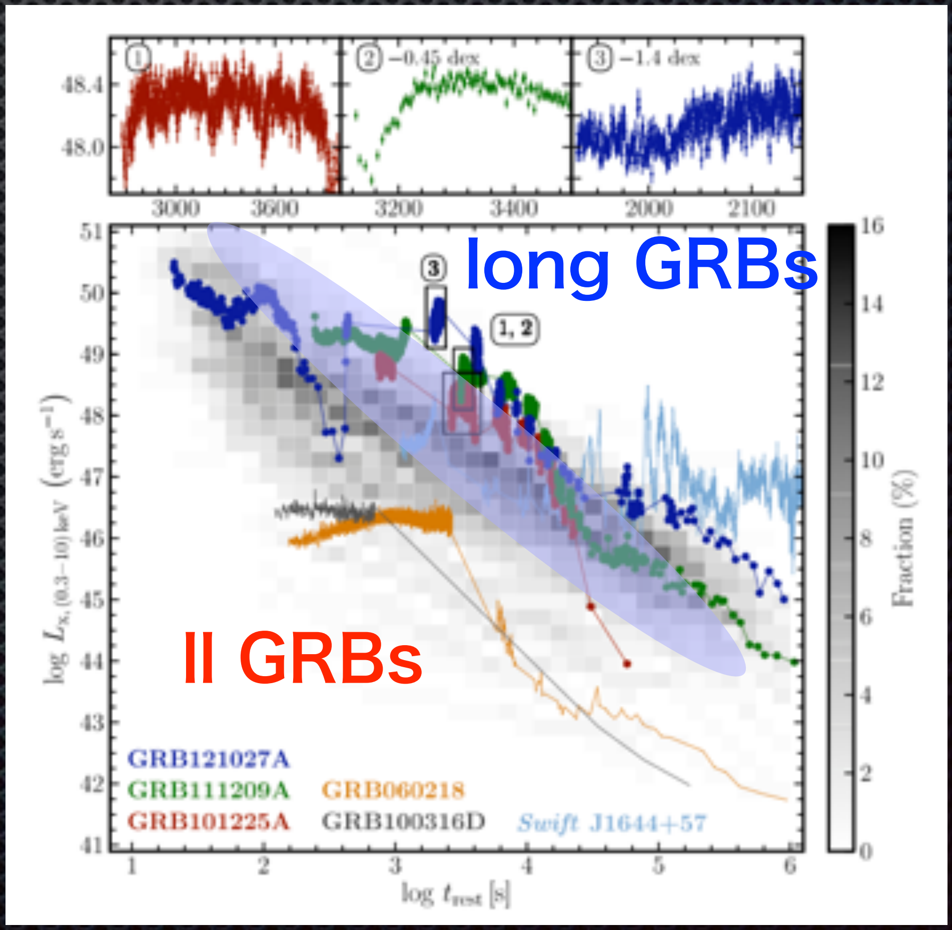


low-luminosity GRBs

- 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



Kaneko+ (2006)



Levan+ (2013)

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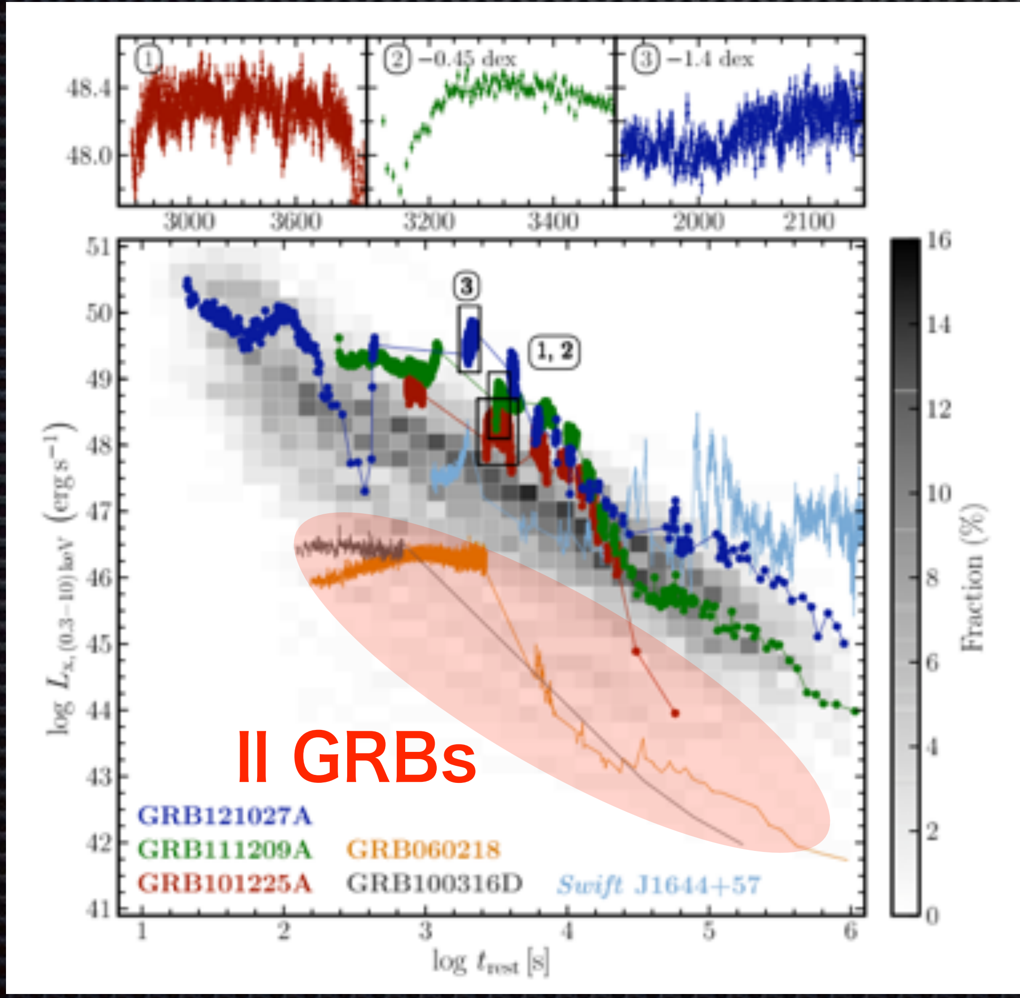

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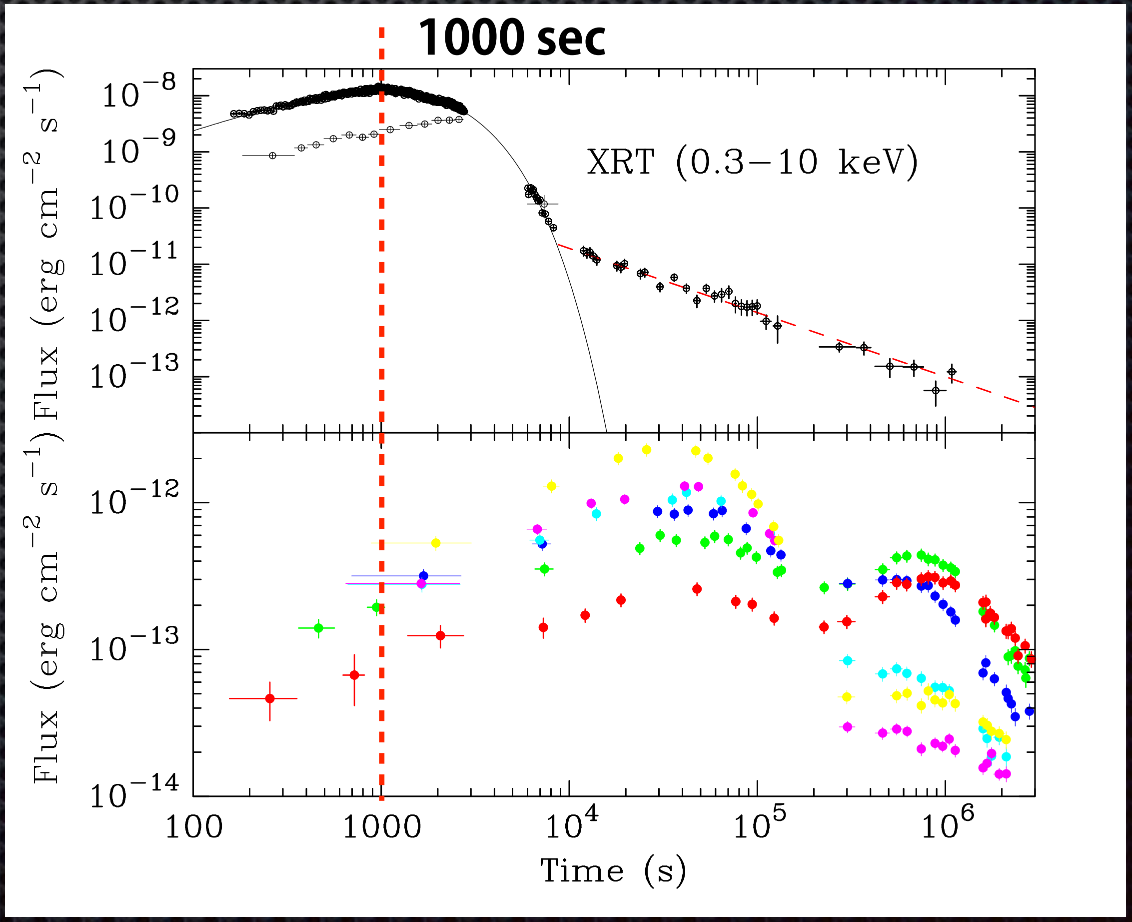


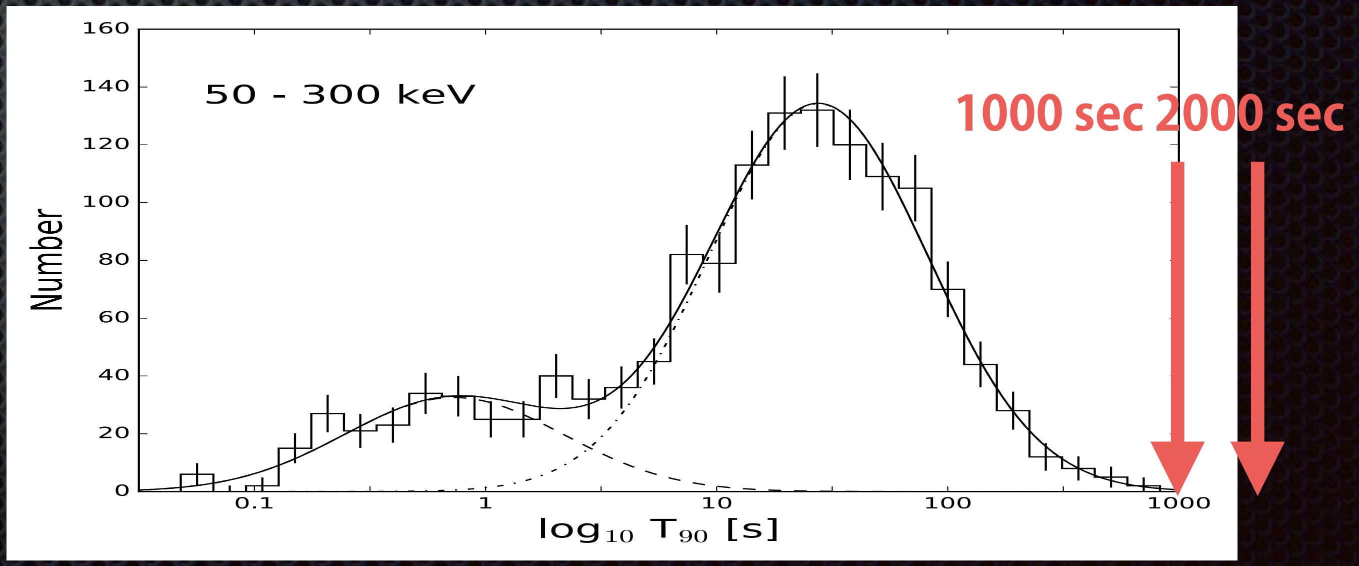
GRB 060218, Campana+ (2006)

low-luminosity GRBs

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

	Luminosity $L_{\gamma,iso}$	Isotropic energy E_{iso}	Duration T_{90}	peak energy E_p
GRB 980425 SN 1998bw	6×10^{46} erg/s	9×10^{47} erg	35 s	122 keV
GRB 060218 SN 2006aj	2×10^{46} erg/s	4×10^{49} erg	2100 s	4.7 keV
GRB 100316D SN 2010bh	5×10^{46} erg/s	6×10^{49} erg	1300 s	18 keV

cf. $L_{iso}\sim10^{51}$ erg/s, $E_{iso}\sim10^{52-53}$ erg for standard GRBs



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- ➡ GRB 980425/SN 1998bw, GRB 060218/SN 2006aj, GRB 100316D/SN 2010bh
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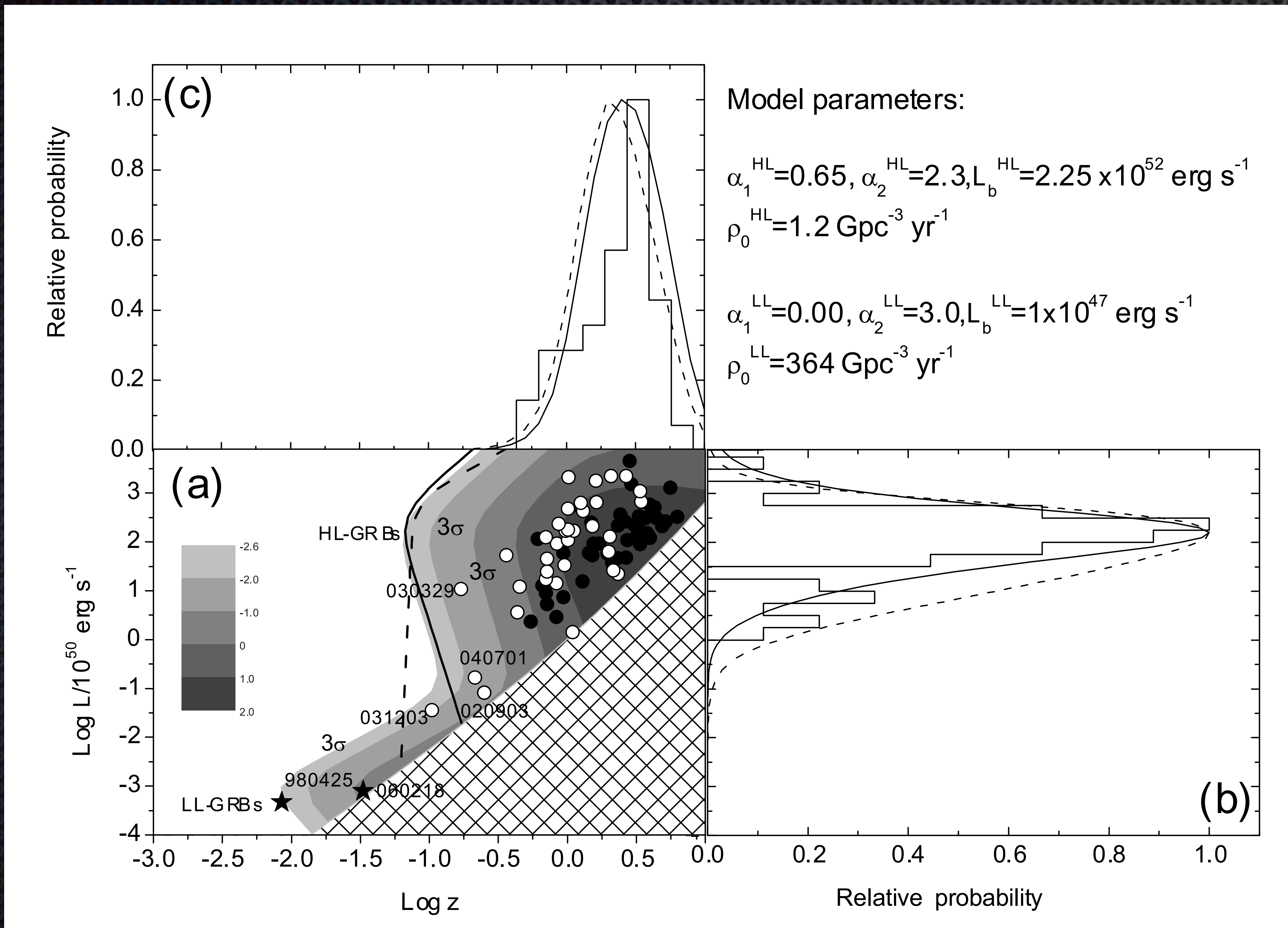
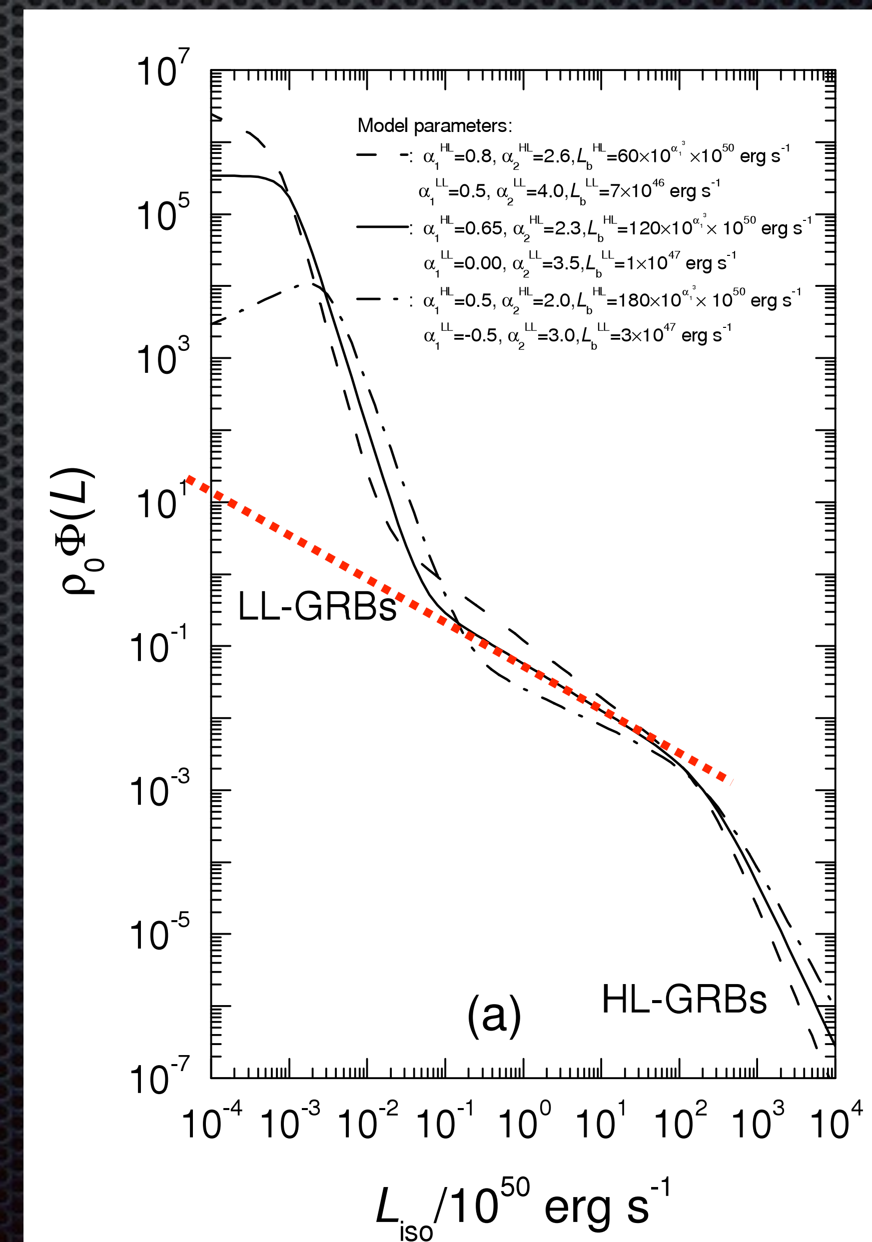
- ➡ luminosity function

Liang+ (2007)



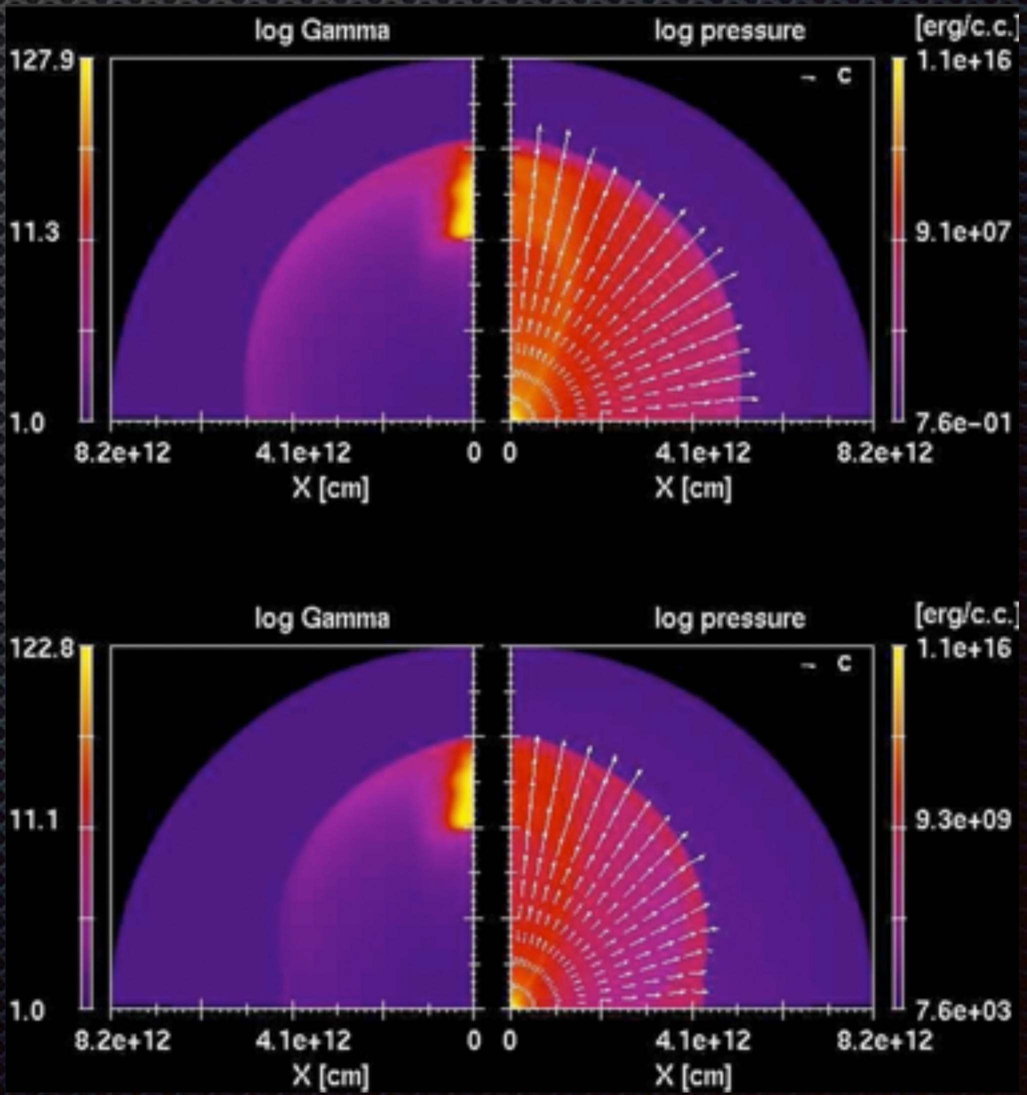


Origin of low-luminosity GRBs

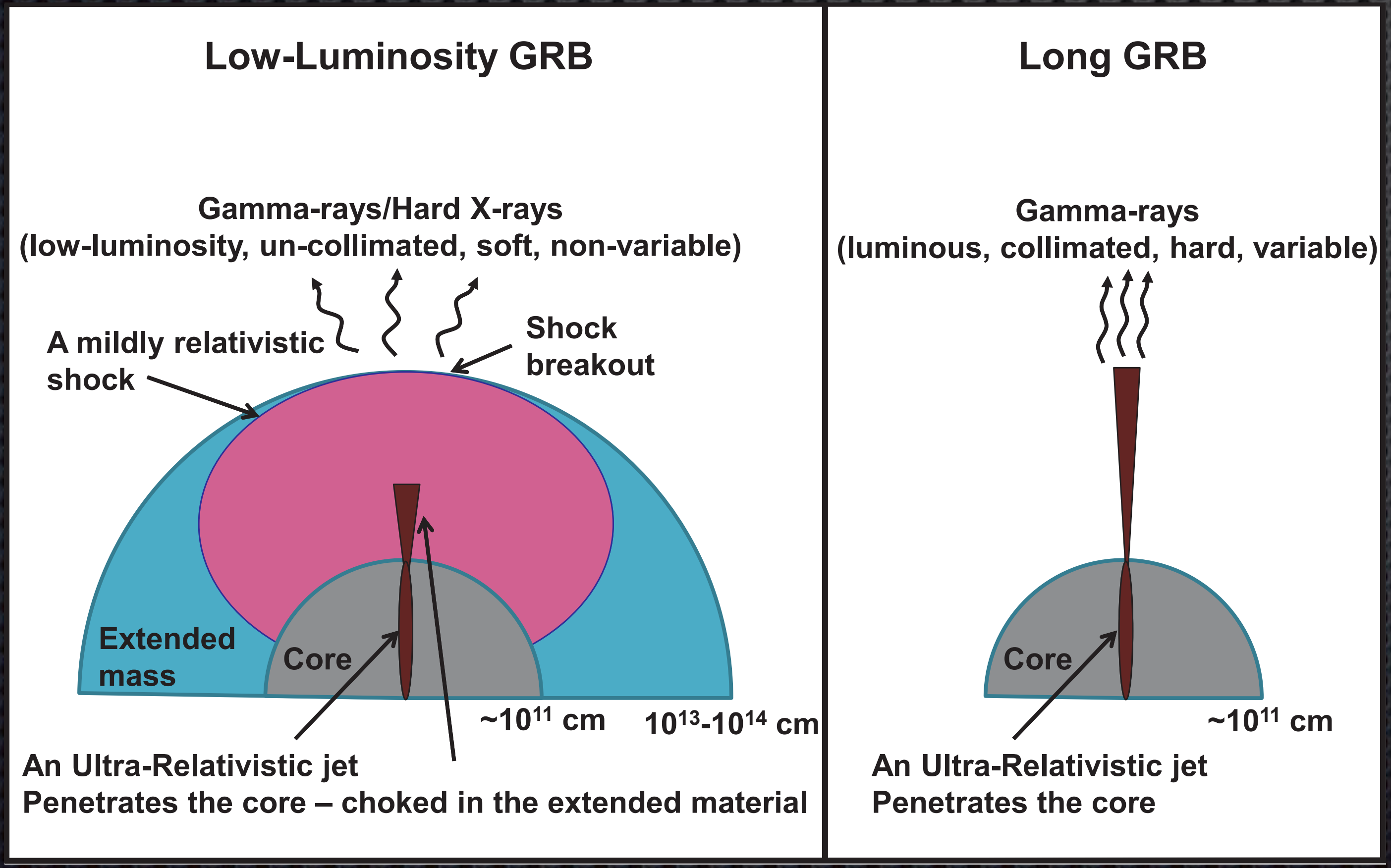
➡ central engine was a neutron star? (e.g., Mazzali+2006)

➡ 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)

Suzuki&Shigeyama (2013)



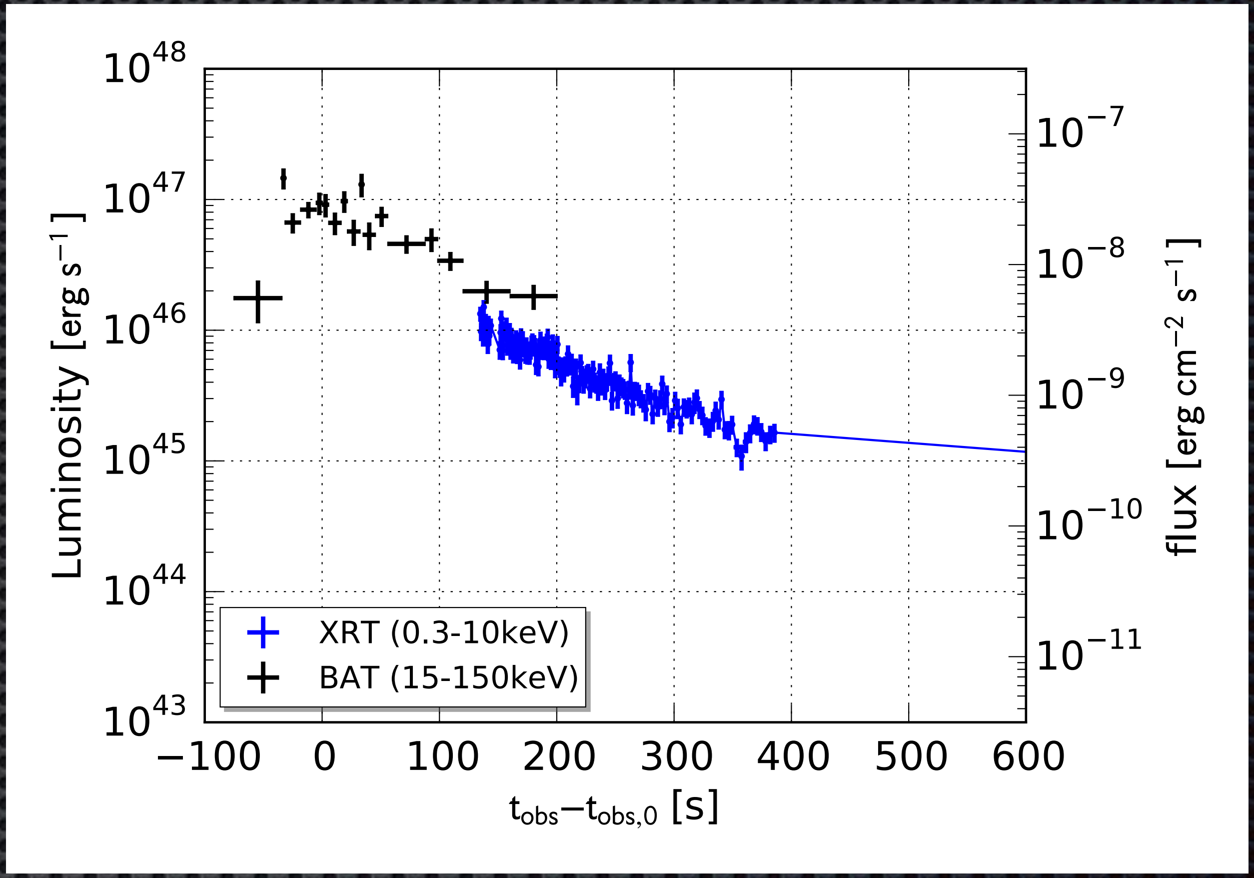
Nakar (2015)



New LLGRB 171205A @ 168Mpc

- Swift detection on 2017/12/05
  (D'Elia+2017, GCN circular 22177)
- E_{iso}~1.2×10^{49}[erg], T_{90}~190[s]
  (Lien+2017, GCN circular 22184)
- 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



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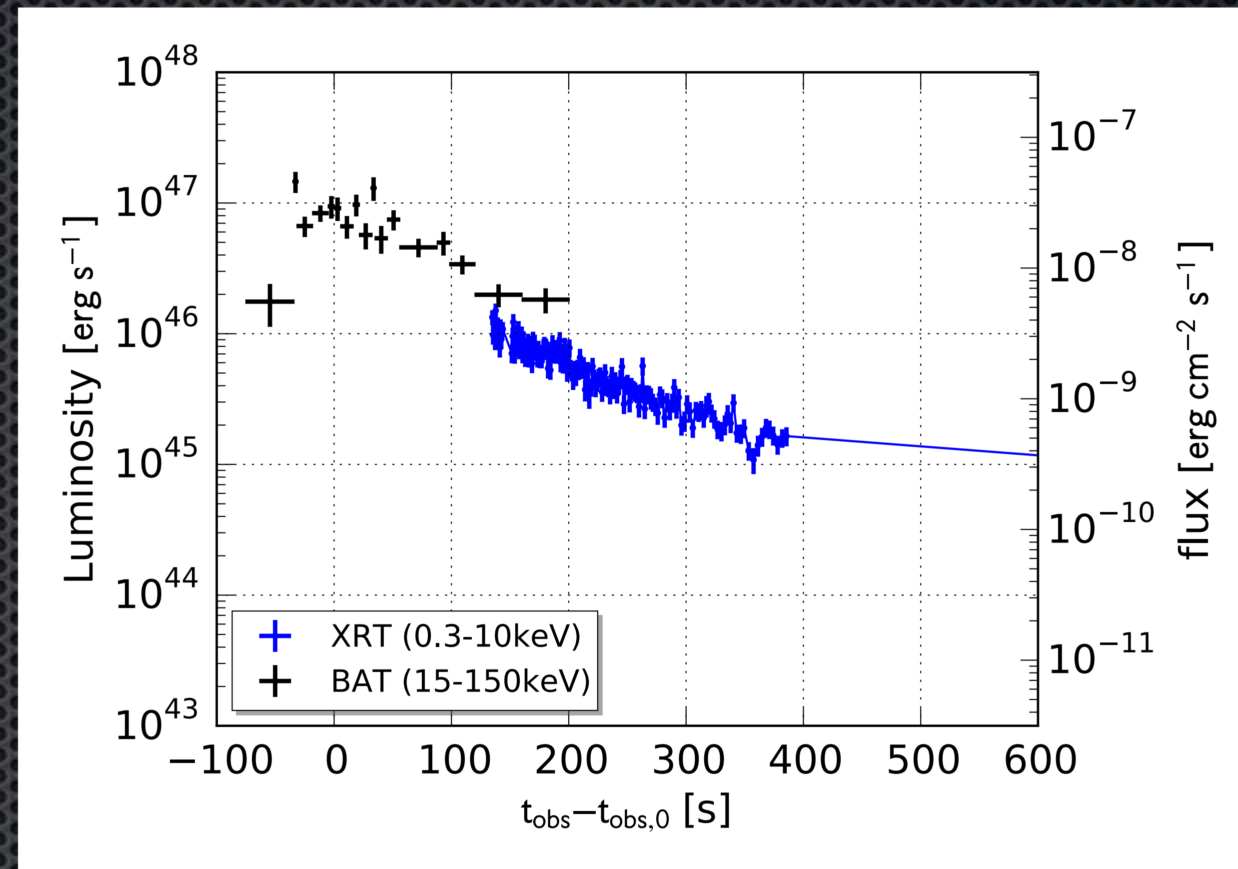

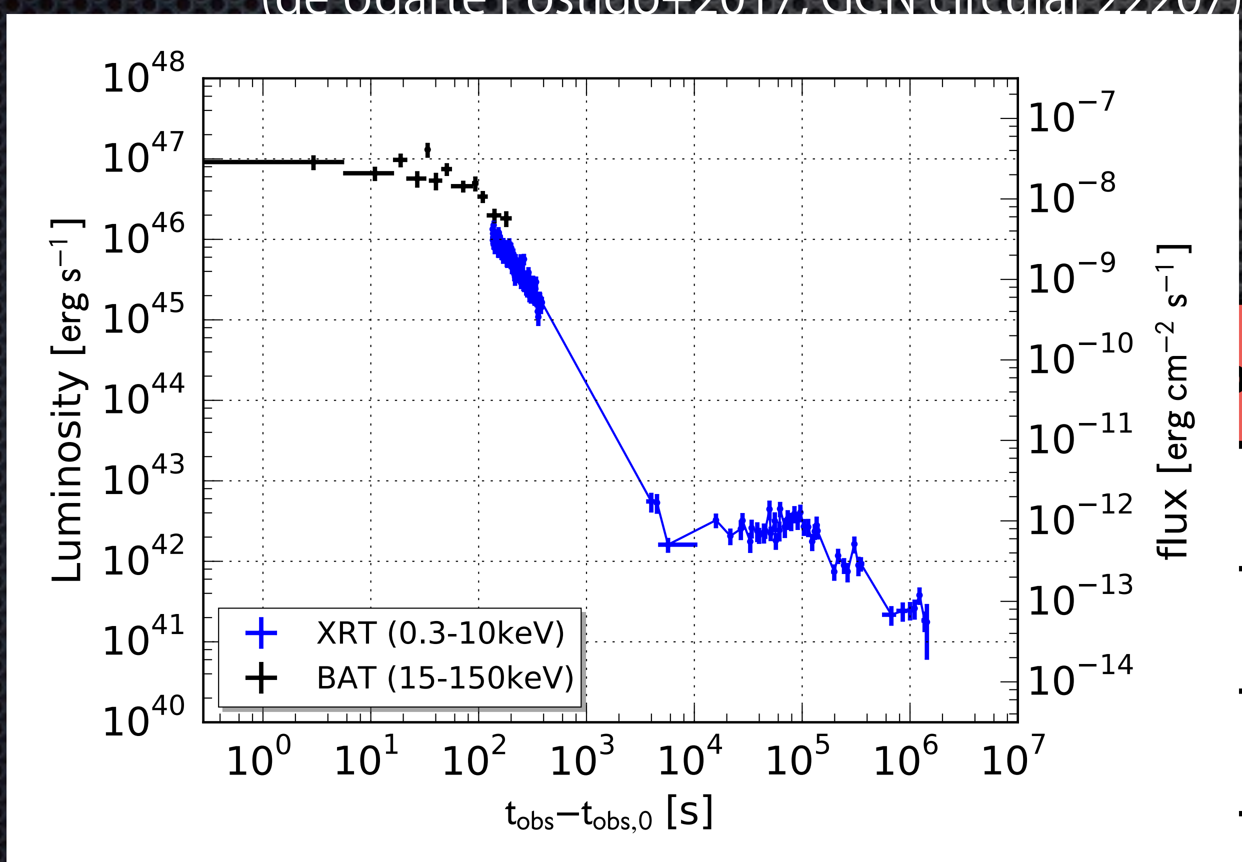

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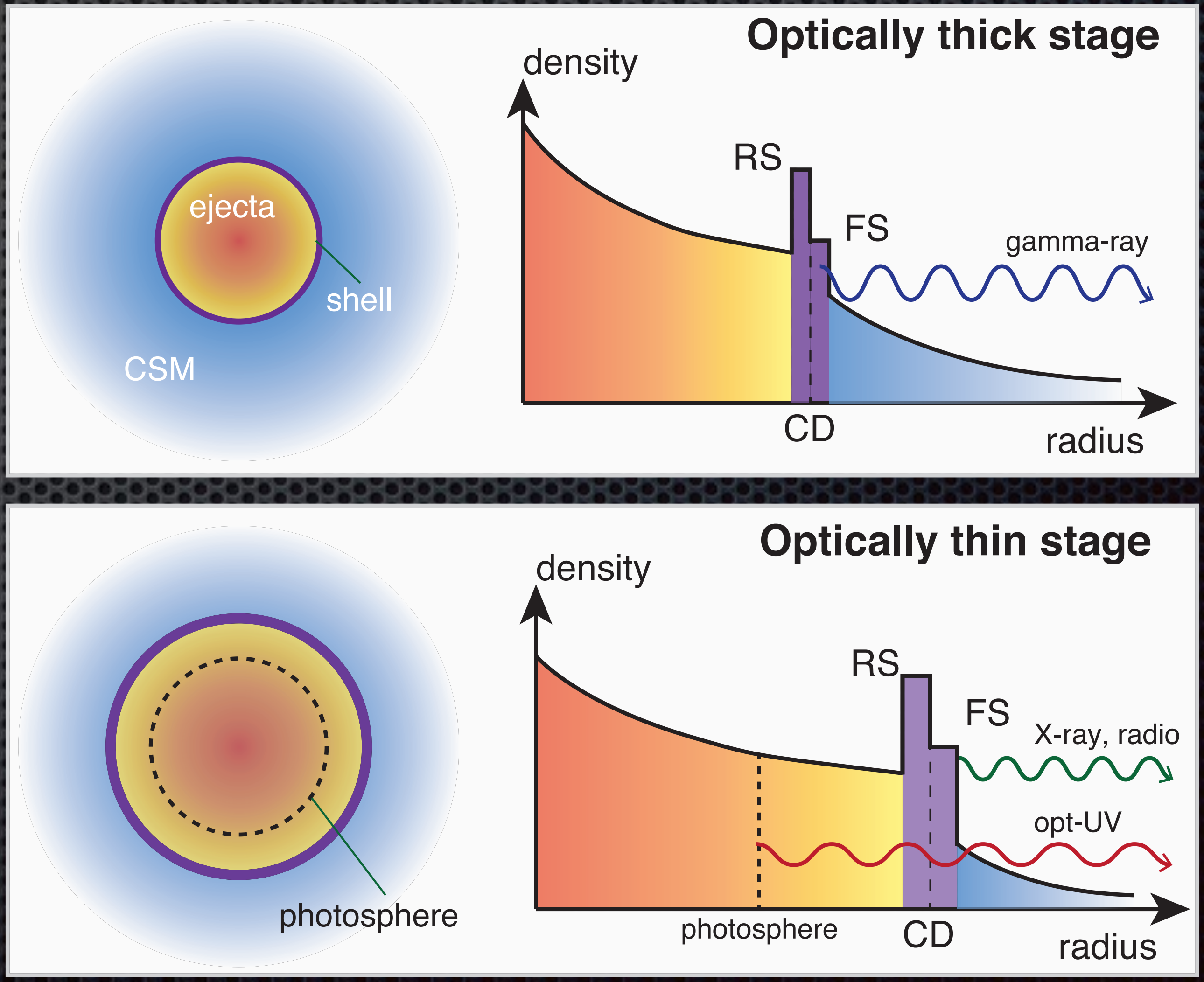
Ejecta with mildly relativistic speeds and CSM

➡ SN ejecta (with max Γ ~2-10) 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**



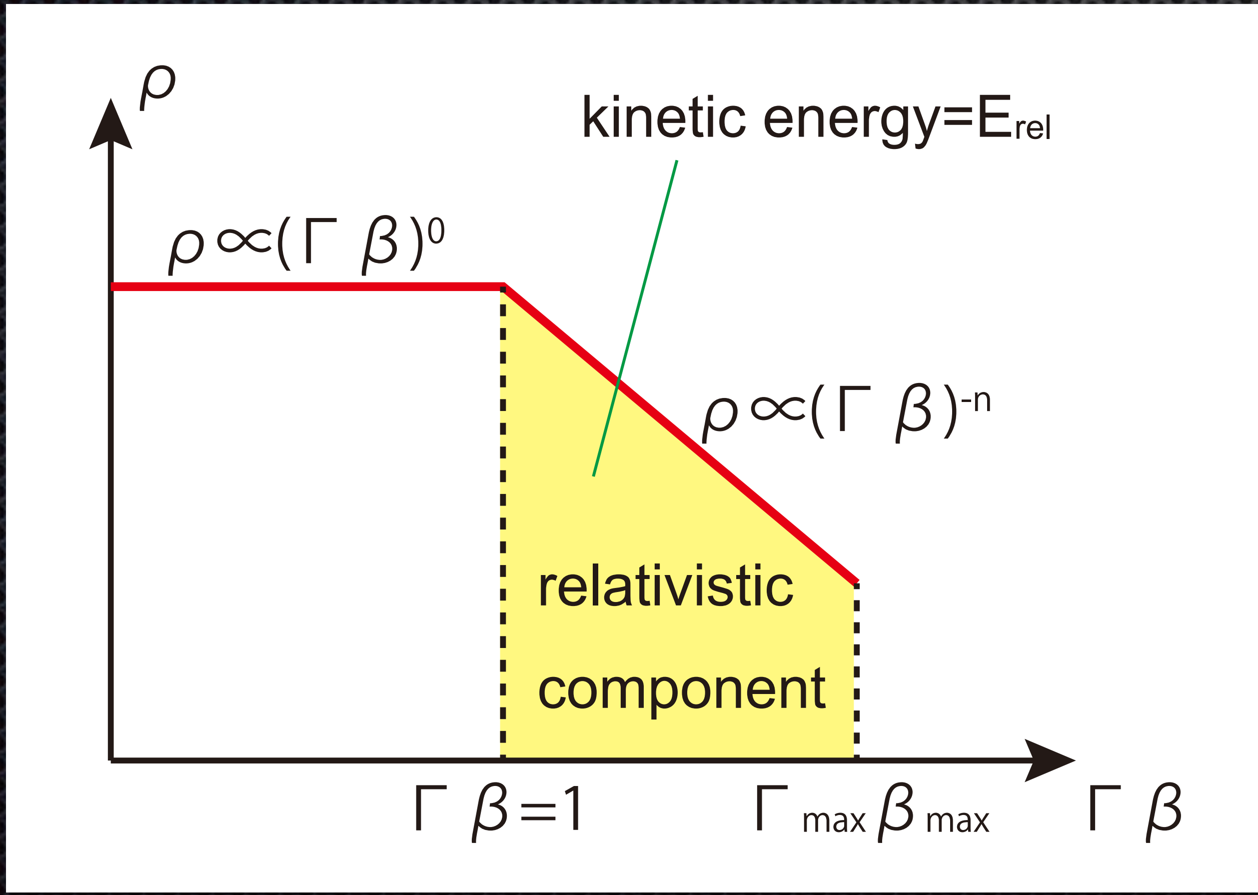
Suzuki, Maeda, Shigeyama (2018)

1D simulation with spherical symmetry

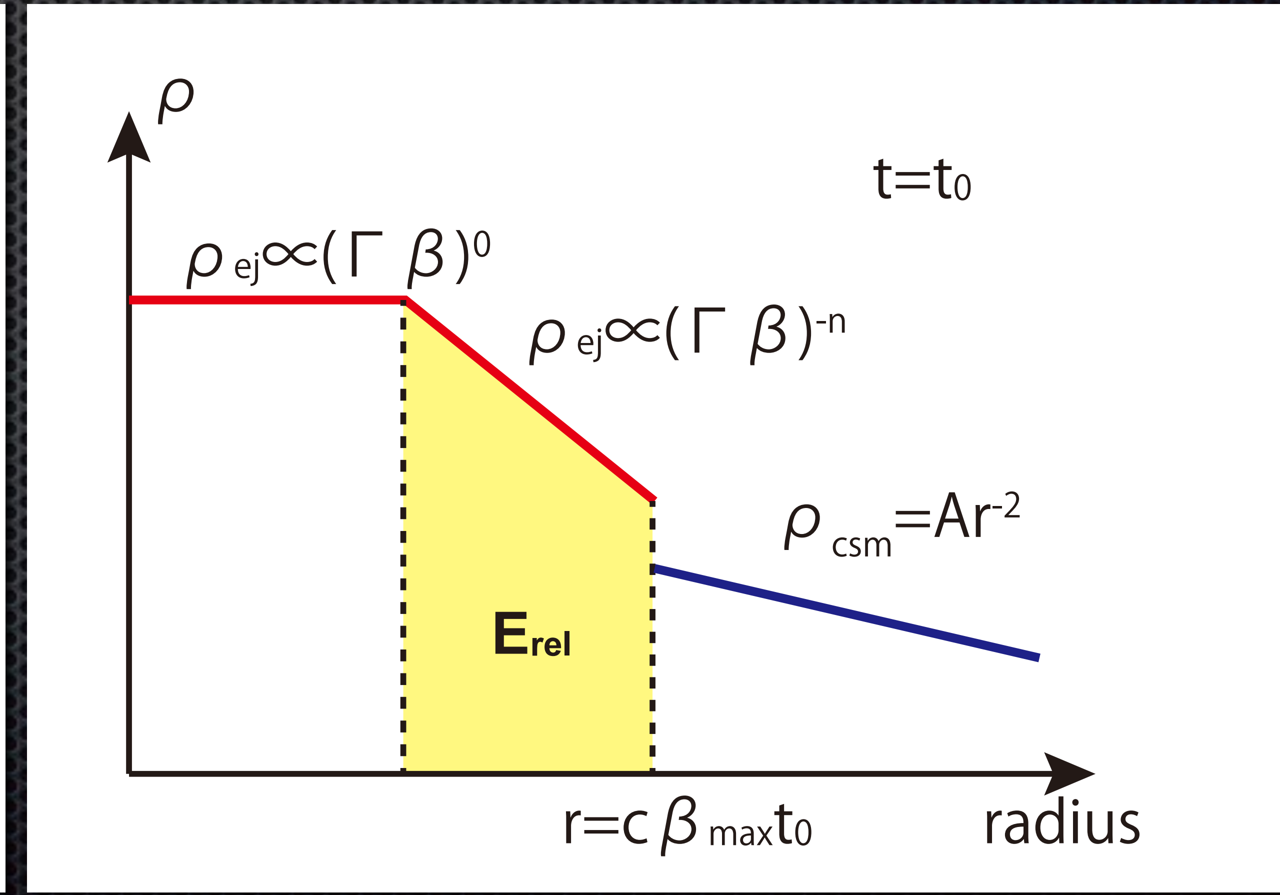
- steady wind: $\rho = Ar^{-2}$, $A_\star = A/(5\times10^{11}\ [g/cm]) = 10$
  ($dM/dt = 10^{-4} M_\odot/yr$, for $v_{wind} = 1000 km/s$)

- freely expanding trans-relativistic ejecta: $c\beta = r/t$,
  $\Gamma_{max} = 10$, $E_{rel} = 10^{51}$ [erg], $t_0 = 10$ [sec], $n=5$

Ejecta distribution in velocity space



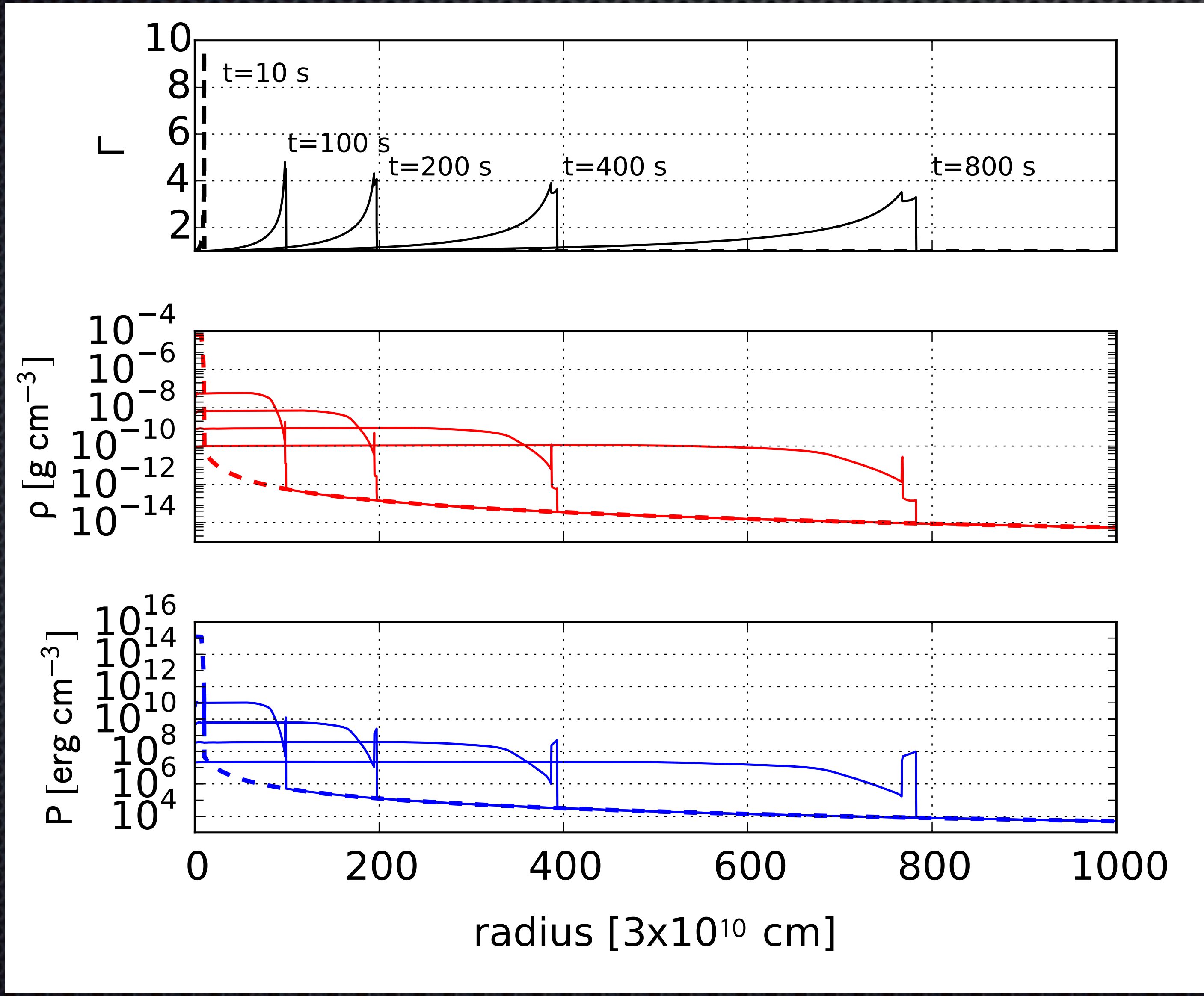
Ejecta distribution in physical space



1D simulation with spherical symmetry

➡ forward/reverse shock formation by ejecta-CSM interaction.

➡ geometrically thin shell between the shocks is expanding into the outer region.



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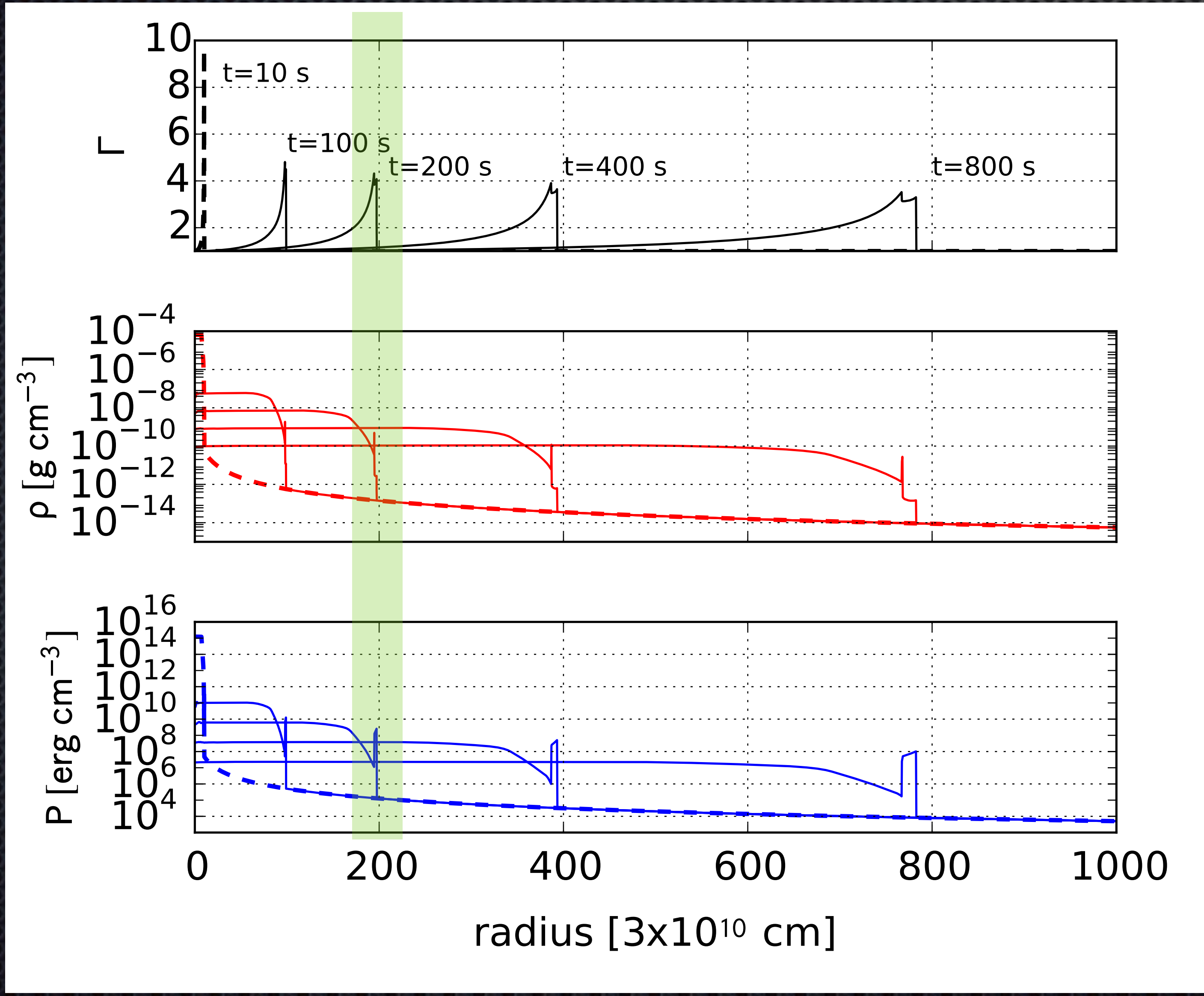

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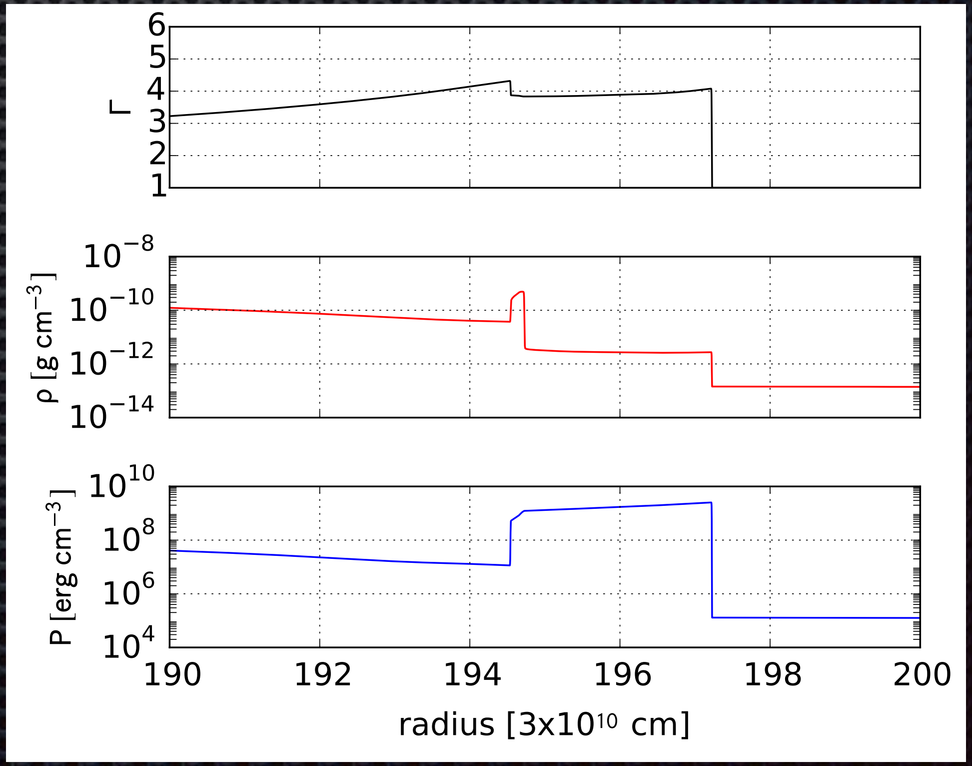

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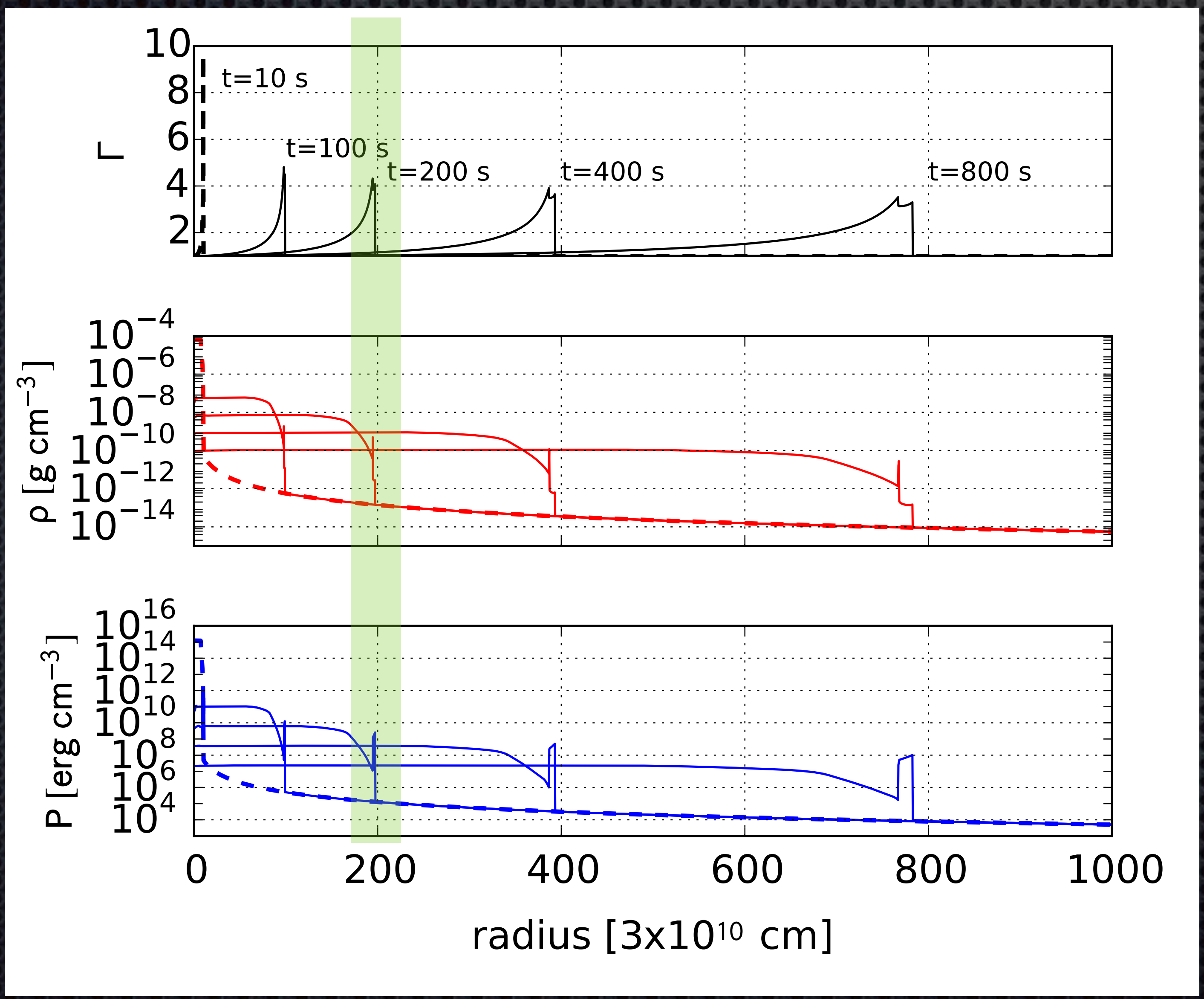

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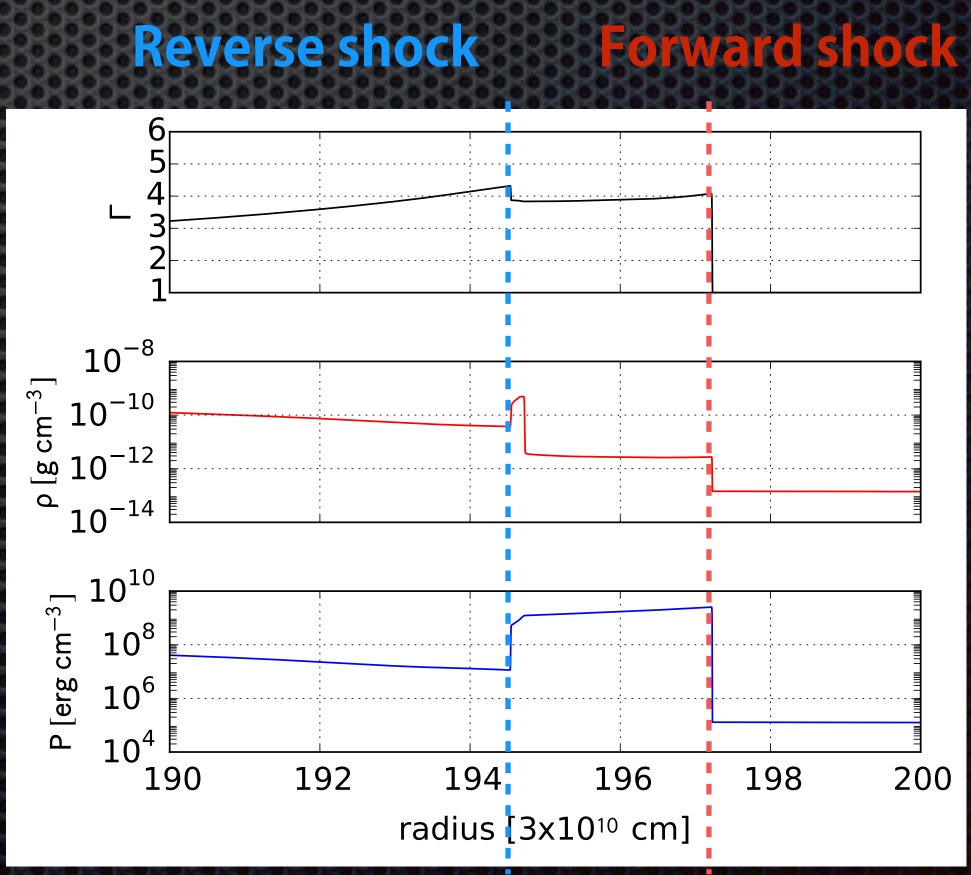
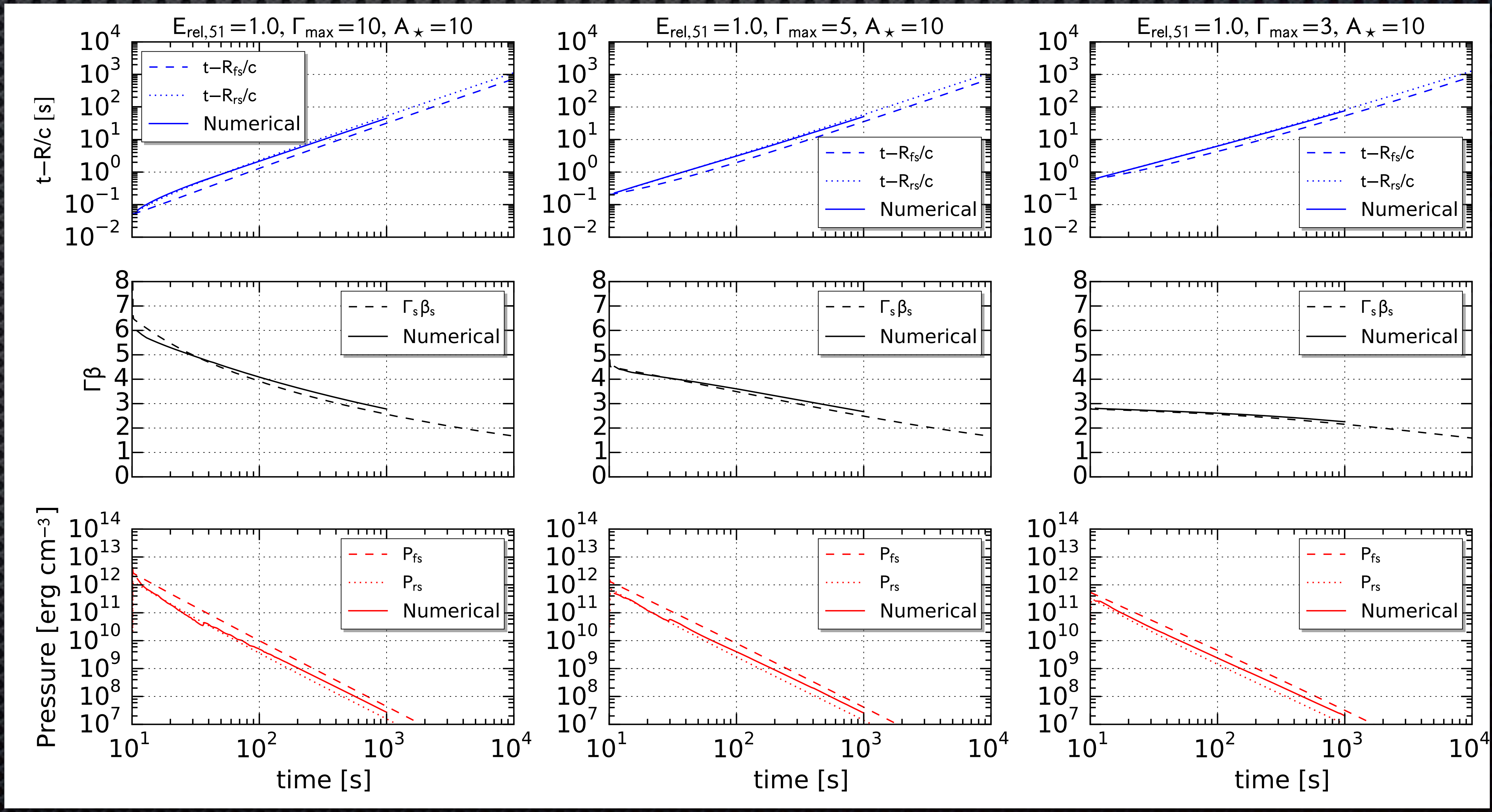


1D simulation with spherical symmetry

➡ shock radii R_{fs},R_{rs}, shell 4-velocity $\Gamma\beta$, and post-shock pressures.

Suzuki, Maeda, &Shigeyama(2017)

temporal evolution of shock radii, $\Gamma\beta$, pressure. simulation (solid line) and semi-analytic model (dashed line)



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

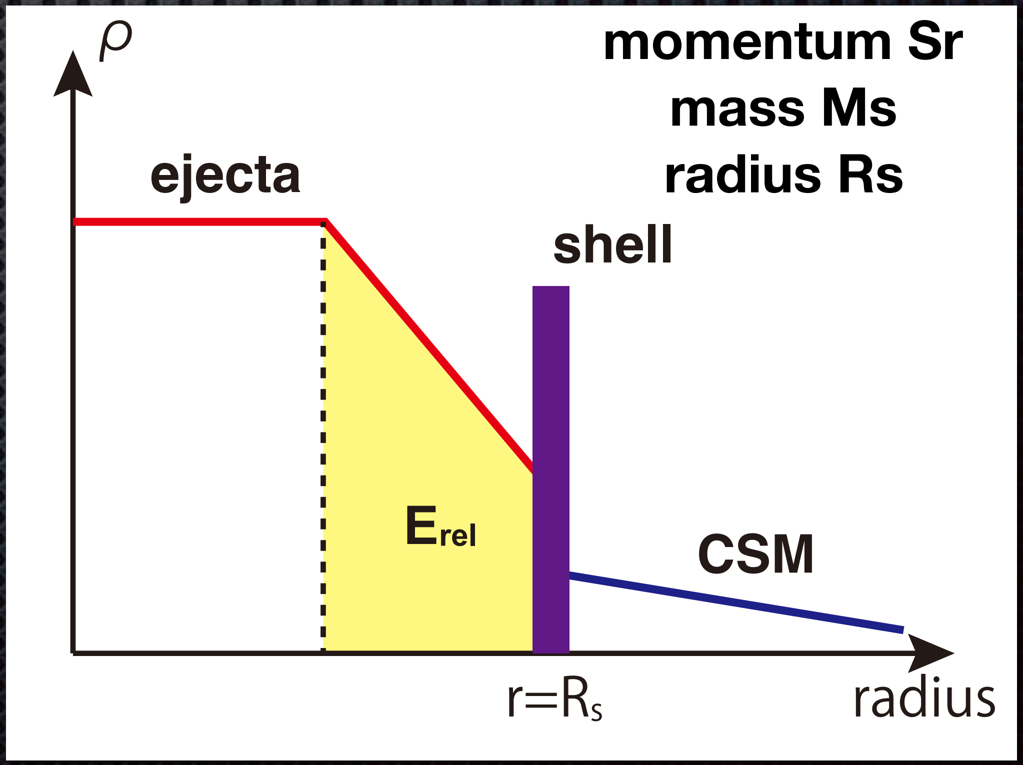
$$\frac{dS_r}{dt} + 4\pi R_{\rm fs}^2 F_{\rm fs} - 4\pi R_{\rm rs}^2 F_{\rm rs} = 4\pi R_{\rm fs}^2 p_{\rm rs,d} - 4\pi R_{\rm rs}^2 p_{\rm fs,d}$$

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

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

shell increases its mass
by sweeping CSM/ejecta

forward/reverse shock velocity
determined by shock jump condition



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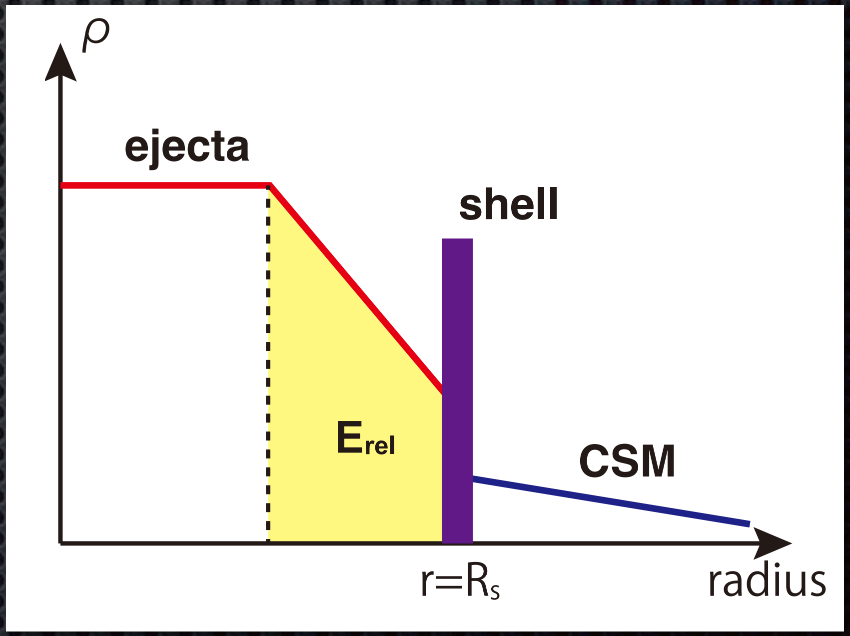
$$\frac{dS_r}{dt} + \cancel{4\pi R_{\rm fs}^2 F_{\rm fs}} - 4\pi R_{\rm rs}^2 F_{\rm rs} = 4\pi R_{\rm fs}^2 p_{\rm rs,d} - 4\pi R_{\rm rs}^2 p_{\rm fs,d}$$

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

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

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

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

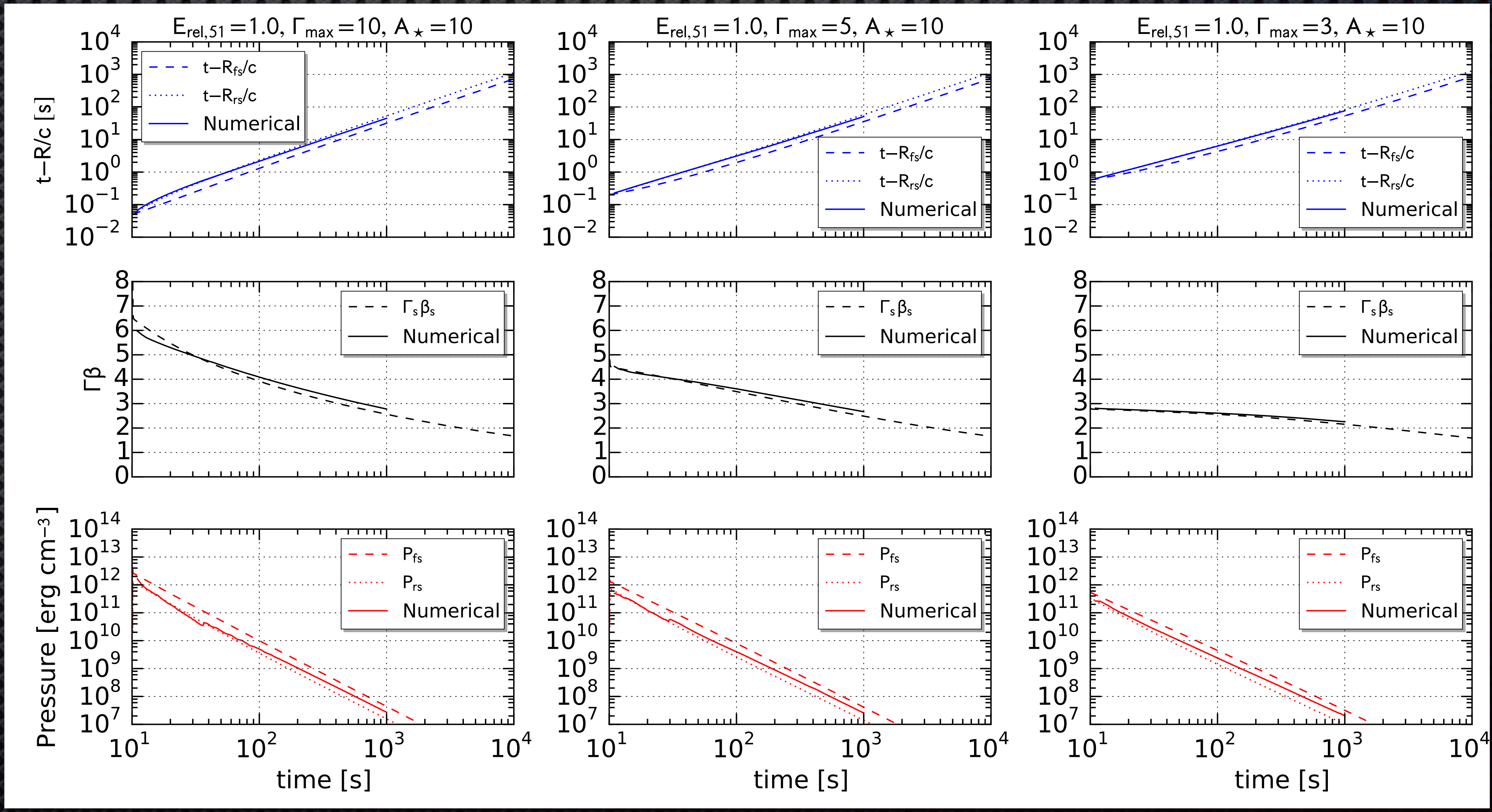


One-zone semi-analytical model

- ➡ 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
- ➡ consistent with numerical simulations

Suzuki, Maeda, &Shigeyama(2017)

temporal evolution of shock radii, Γ β, pressure. simulation (solid line) and semi-analytic model (dashed line)



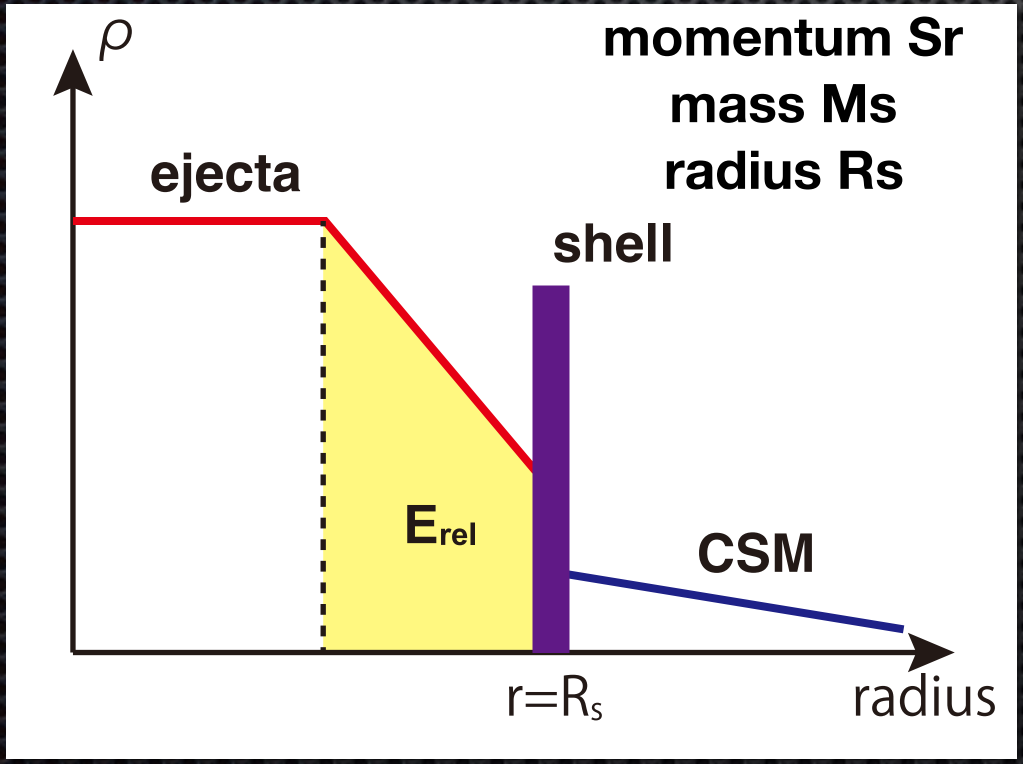
Emission model

Suzuki, Maeda, &Shigeyama(2017,2018 in prep)

- ➡ temporal evolution of the internal energy of the shell is soveld.
- ➡ the internal energy is lost by radiative diffusion and adiabatic cooling.
- ➡ radiative loss rate corresponds to the luminosity of the diffusive emission

adiabatic loss — radiative loss

$$\frac{dE_{\mathrm{s,rad}}}{dt} = \dot{E}_{\mathrm{fs}} + \dot{E}_{\mathrm{rs}} - \frac{E_{\mathrm{s,rad}}}{3V}\frac{dV}{dt} - \dot{E}_{\mathrm{diff}},$$



$$\dot{E}_{\mathrm{diff}} = 4\pi R_{\mathrm{s}}^2 u_{\mathrm{s,rad}} v_{\mathrm{diff}}$$

$$v_{\mathrm{diff}} = \frac{c(1-\beta_{\mathrm{s}}^2)}{(3+\beta_{\mathrm{s}}^2)\tau_{\mathrm{s}} + 2\beta_{\mathrm{s}}},$$

- ➡ diffusion approximation: optical depth τ (κ =0.2 cm^2/g), velocity β_s, and internal energy density u_{rad}

$$L_{\mathrm{diff}}(t_{\mathrm{obs}}) = c\int \frac{\dot{E}_{\mathrm{diff}}(t)}{R_{\mathrm{s}}(t)\Gamma_{\mathrm{s}}^3[1-\mu\beta_{\mathrm{s}}(t)]^3}dt,$$

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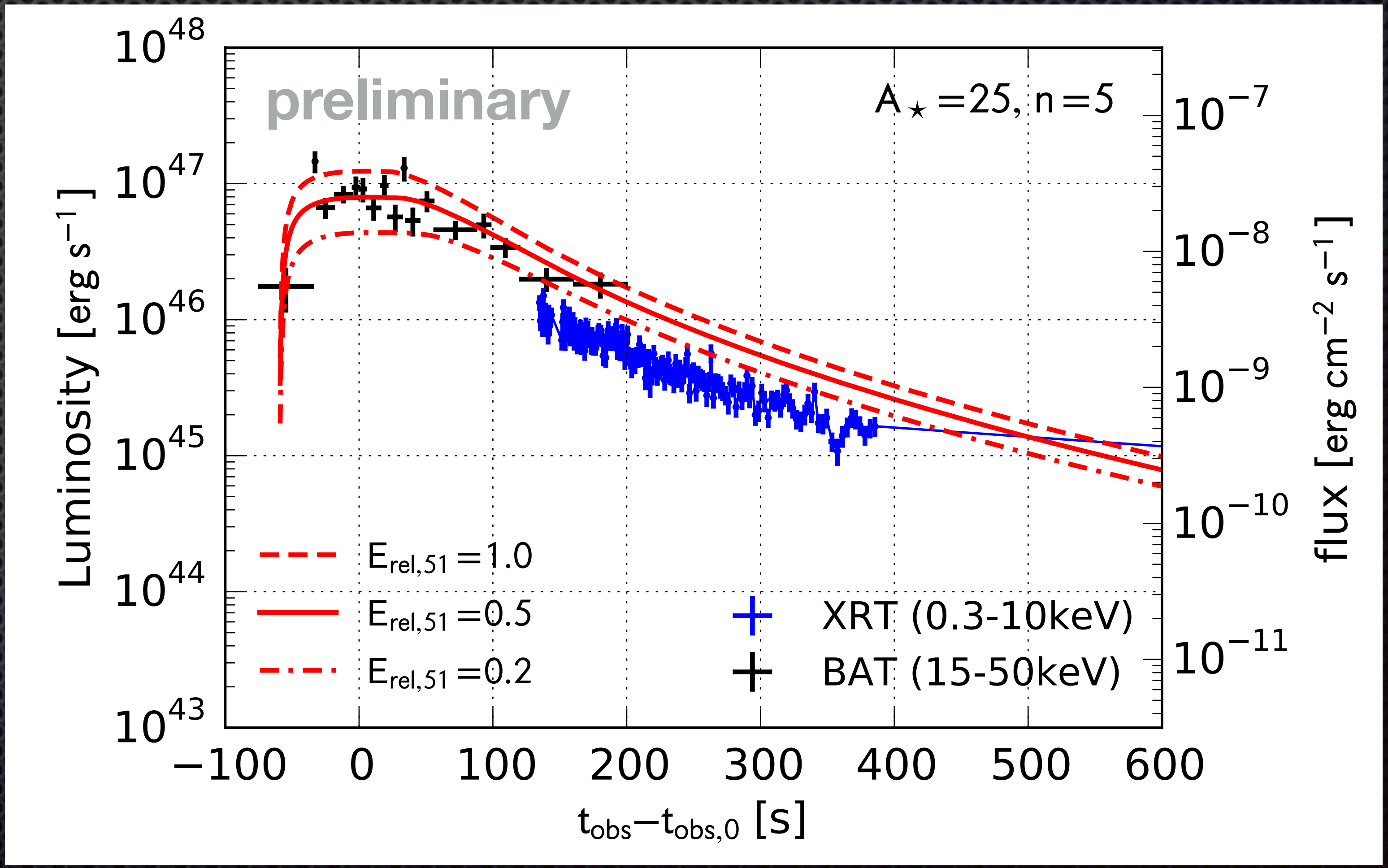
Bolometric LC for prompt emission

- fiducial model: $E_{rel,51}$=0.5, $A_\star$=25, n=5 (dM/dt=2.5x10^{-4}M$_\odot$/yr for v_w=10^3km/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

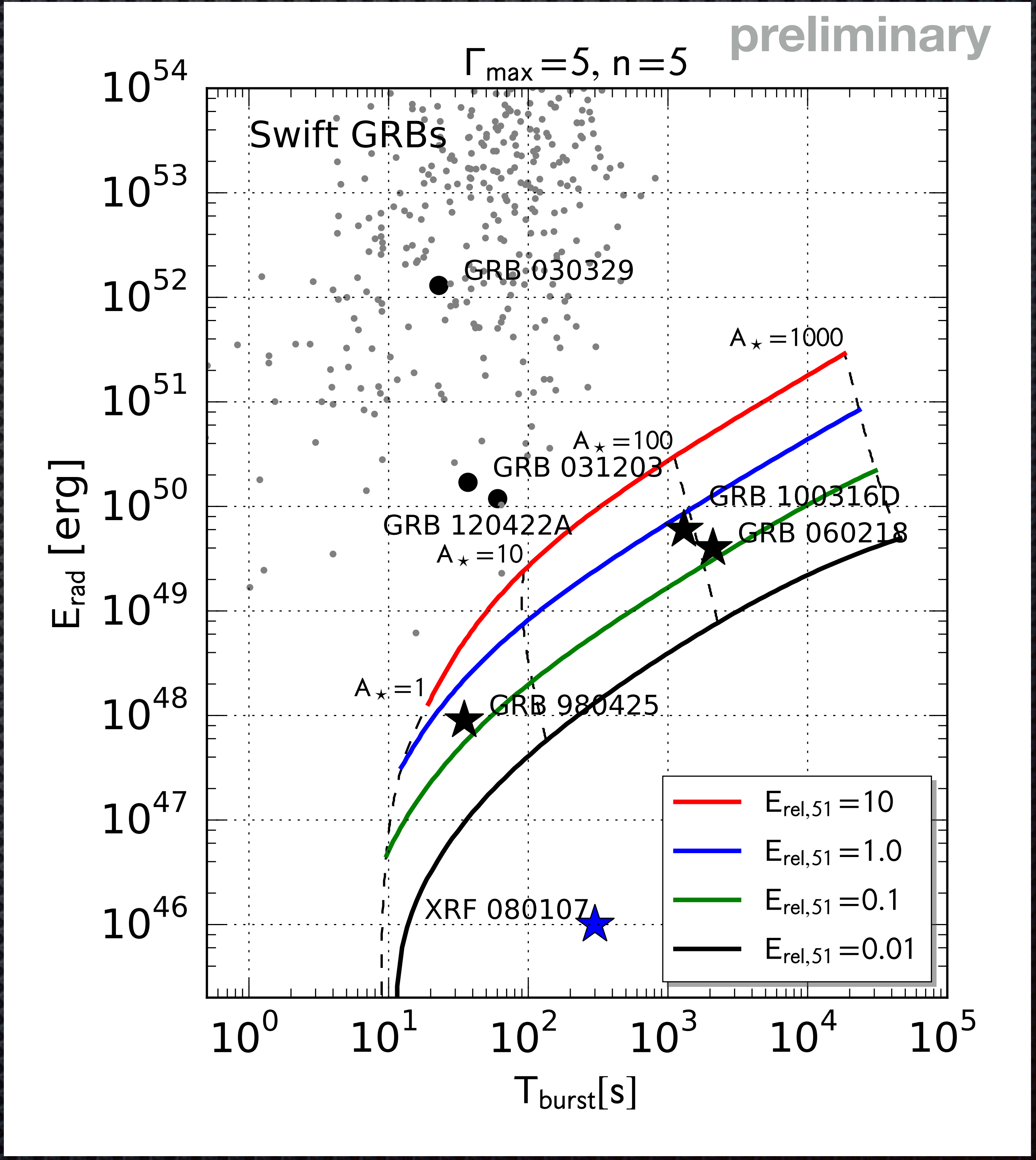
Suzuki, Maeda, & Shigeyama (2018, in prep)



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}~10^{51}[erg], $A_★$~ several 10

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



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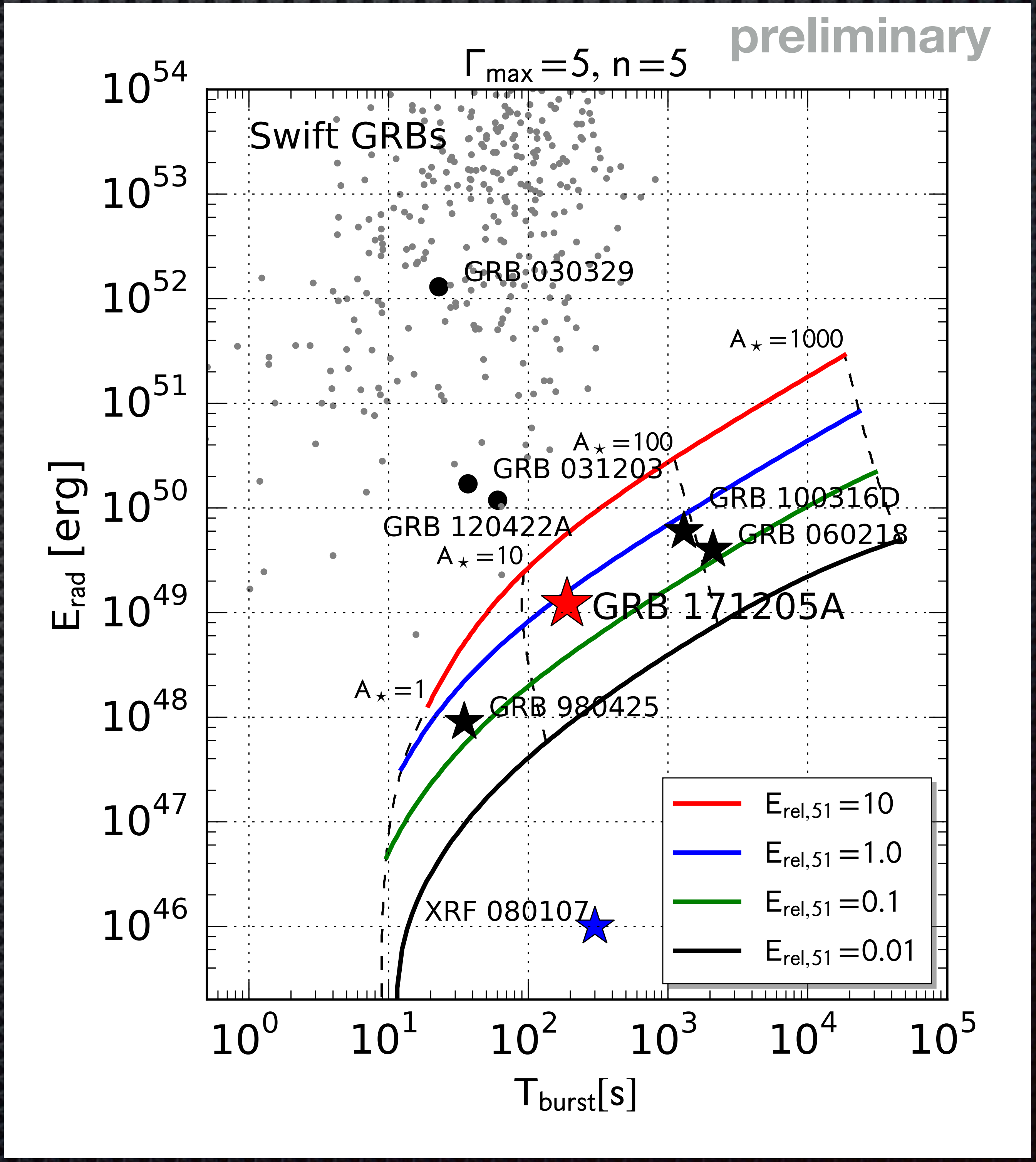
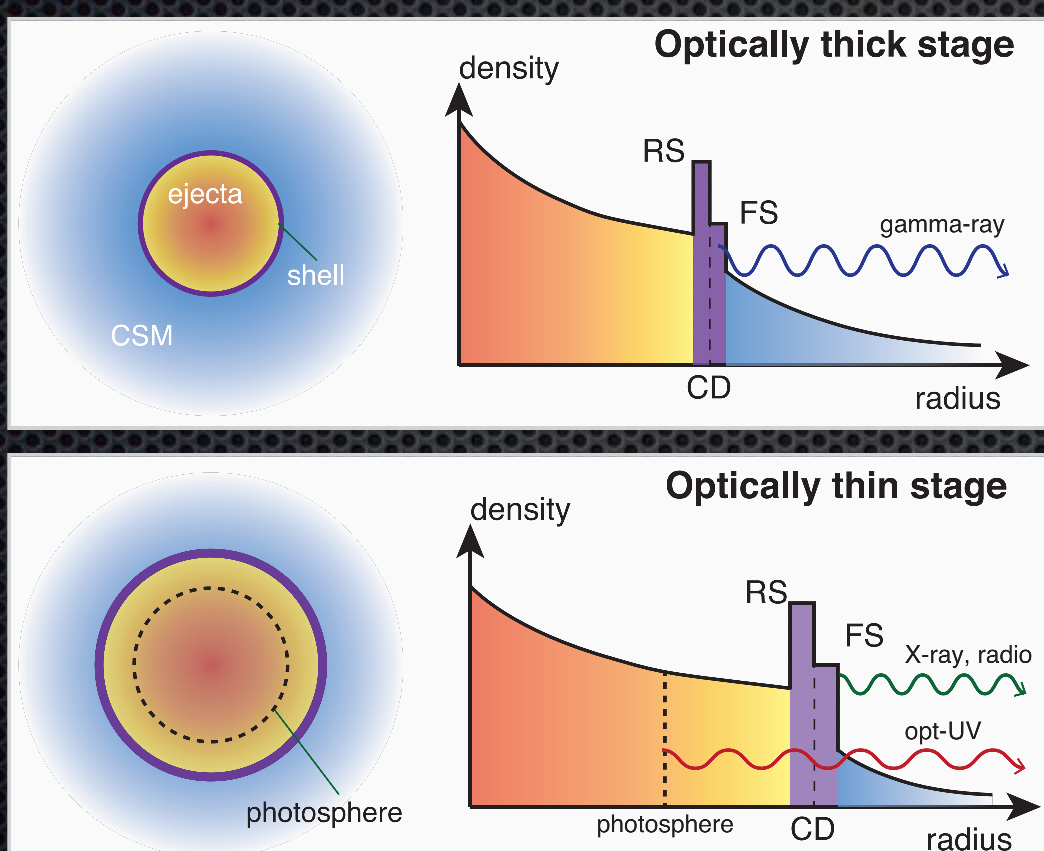


Optical-UV emission

- ➡ Swift UVOT observations
- ➡ a parameter f_{th}=0.03: radiation energy to kinetic energy ratio of the ejecta at $t=t_0$



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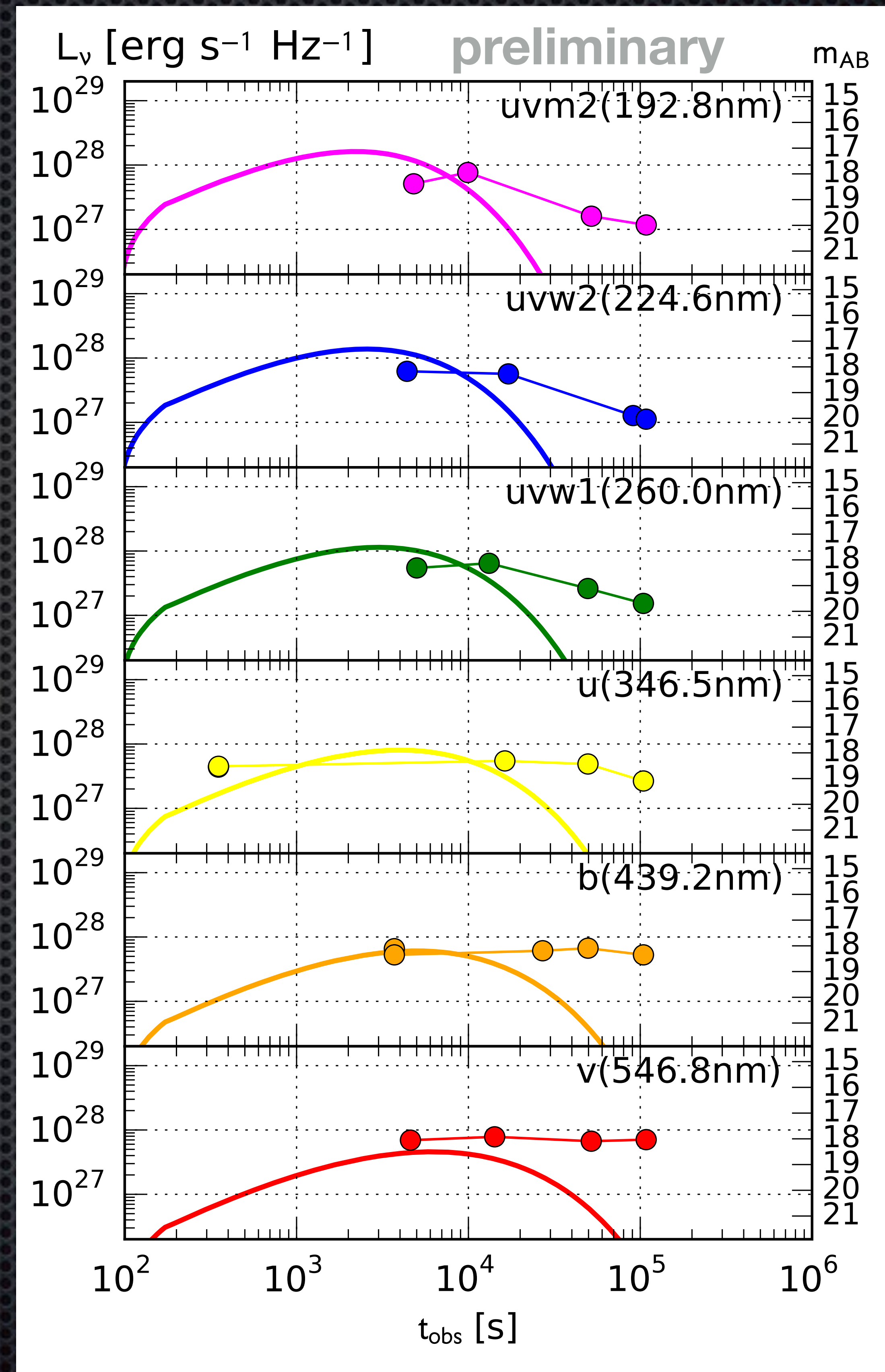
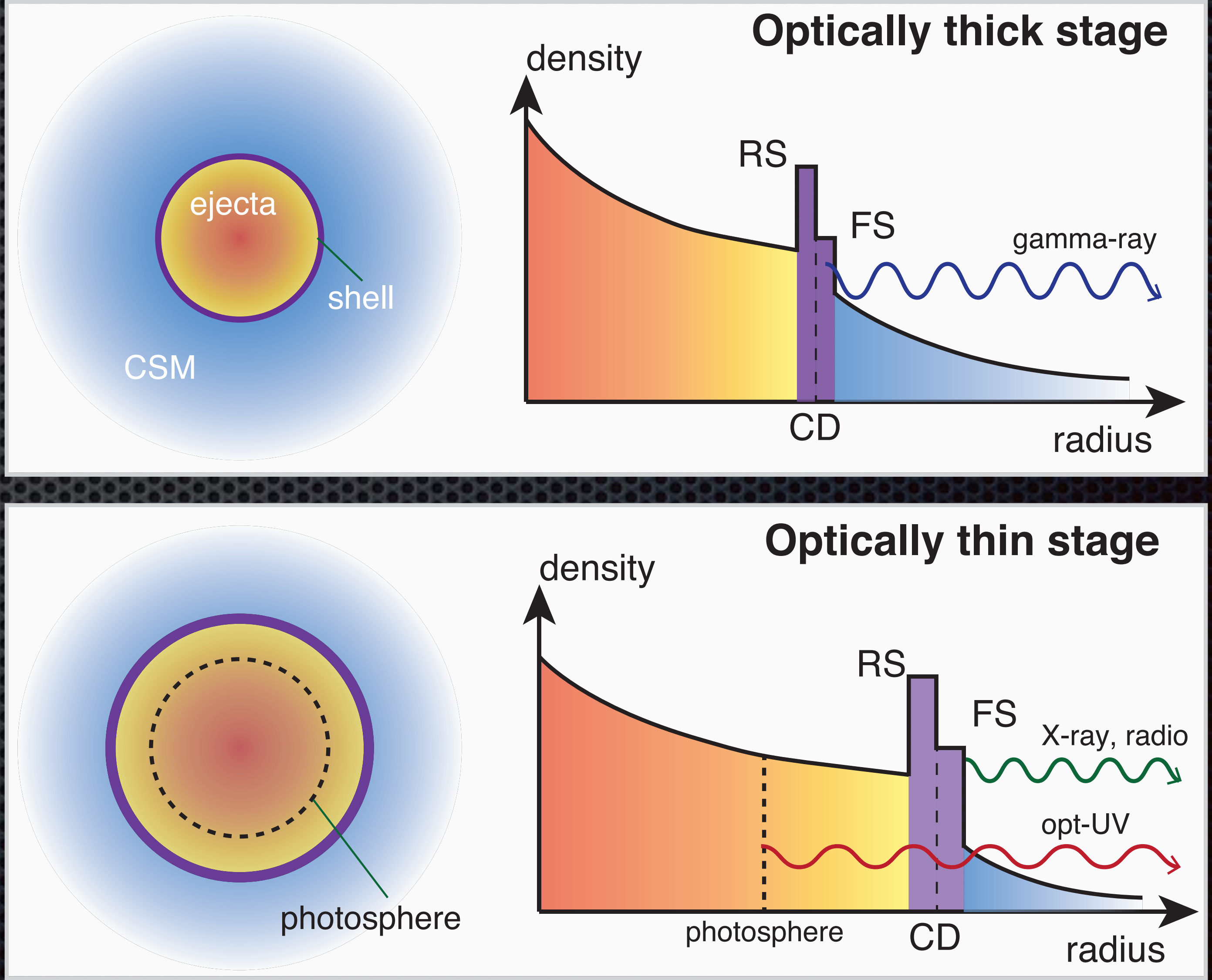


Multi-wavelength LC modeling

- ➡ prompt emission of GRB 171205A could be explained by mildly relativistic SN ejecta interacting with a dense CSM.
- ➡ What about other EM signals?
- ➡ opt-UV observations by UVOT
- ➡ radio, X-ray non-thermal emission



Non-thermal X-ray and radio emission

- ➡ electron distribution in momentum space
- ➡ parameters: p, ε_e, ε_B
- ➡ synchrotron, inverse Compton, and adiabatic cooling

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

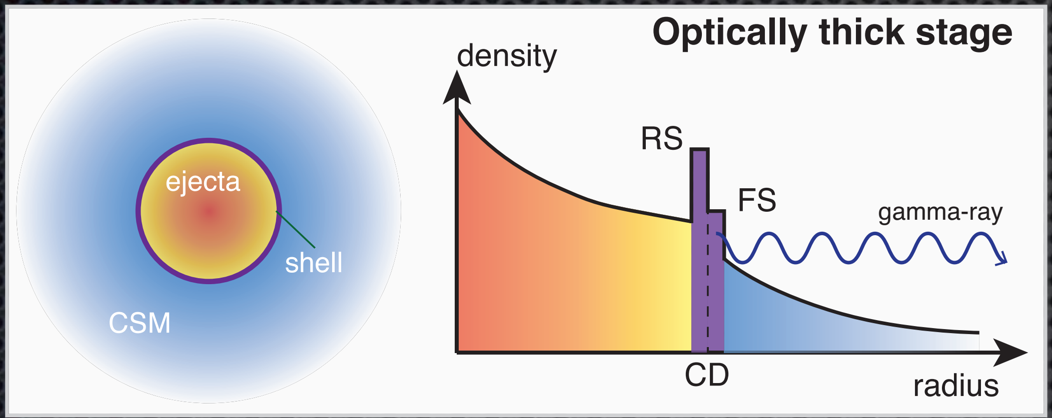
$$\frac{\partial}{\partial t}\left(\frac{dN}{dp_\mathrm{e}}\right) = \frac{\partial}{\partial p_\mathrm{e}}\left[(\dot{p}_\mathrm{syn} + \dot{p}_\mathrm{ic} + \dot{p}_\mathrm{ad})\frac{dN}{dp_\mathrm{e}}\right] + \left(\frac{d\dot{N}}{dp_\mathrm{e}}\right)_\mathrm{in}$$

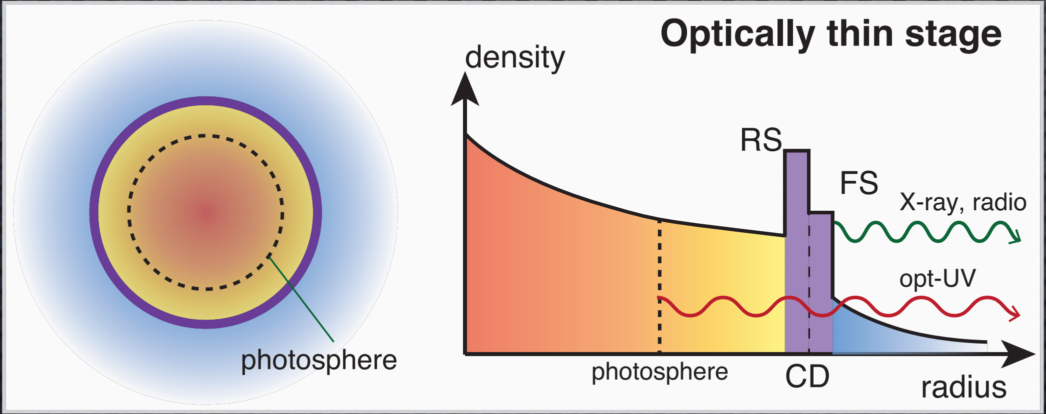
$$\left(\frac{d\dot{N}}{dp_\mathrm{e}}\right)_\mathrm{in} \propto \begin{cases} p_\mathrm{e}^{-p} & \text{for } p_\mathrm{in} \le p_\mathrm{e} \le p_\mathrm{max} \\ 0 & \text{otherwise} \end{cases}$$

$$\dot{p}_\mathrm{syn} = \frac{4\sigma_\mathrm{T} u_\mathrm{B}}{3m_\mathrm{e}^2 c^2} p_\mathrm{e}\sqrt{m_\mathrm{e}^2 c^2 + p_\mathrm{e}^2},$$

$$\dot{p}_\mathrm{ic} = \frac{4\sigma_\mathrm{T} u_\mathrm{rad}}{3m_\mathrm{e}^2 c^2} p_\mathrm{e}\sqrt{m_\mathrm{e}^2 c^2 + p_\mathrm{e}^2},$$

$$\dot{p}_\mathrm{ad} = \frac{p_\mathrm{e}}{3V}\frac{dV}{dt}.$$

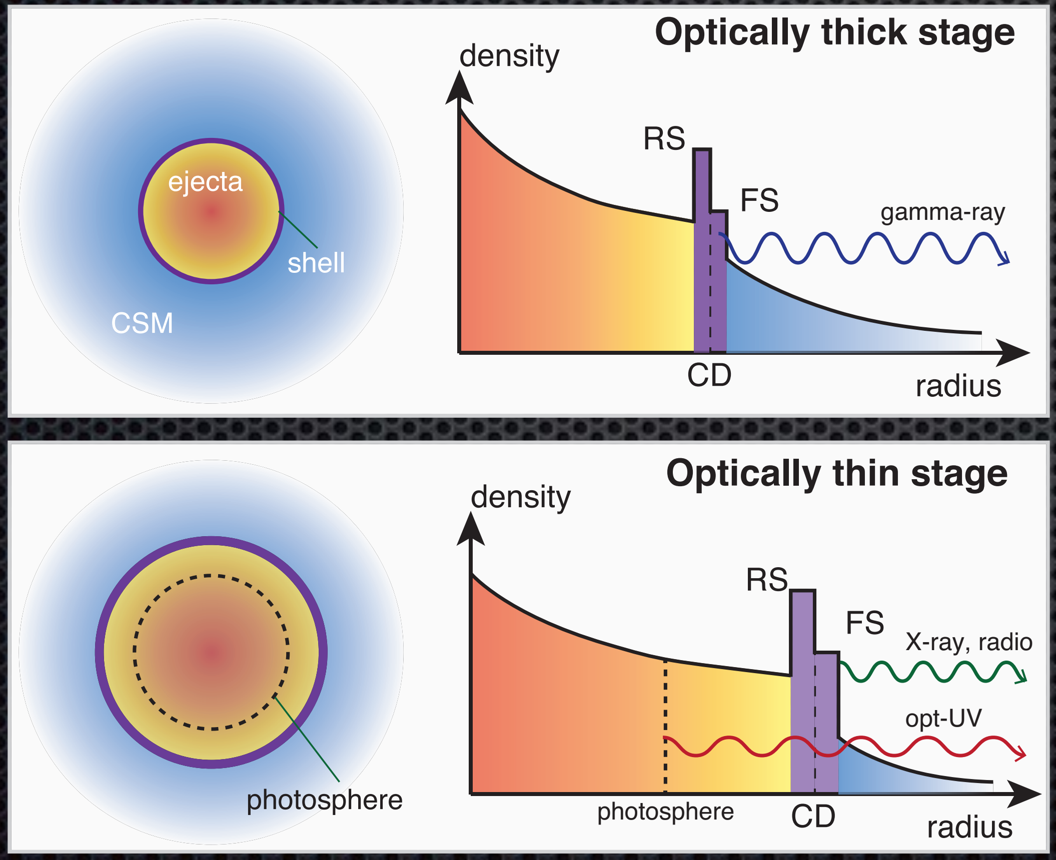




- ➡ u_{rad}: thermal photons+ synchrotron photons

Non-thermal X-ray and radio emission

- ➡ p=3.0, ε_e=0.08, ε_B=3x10^{-3}
- ➡ Swift XRT observations + radio (NOEMA, ALMA, VLA)
- ➡ too bright inverse Compton X-ray emission…
- ➡ too high $A_\star$ beyond r~3x10^{13}cm?



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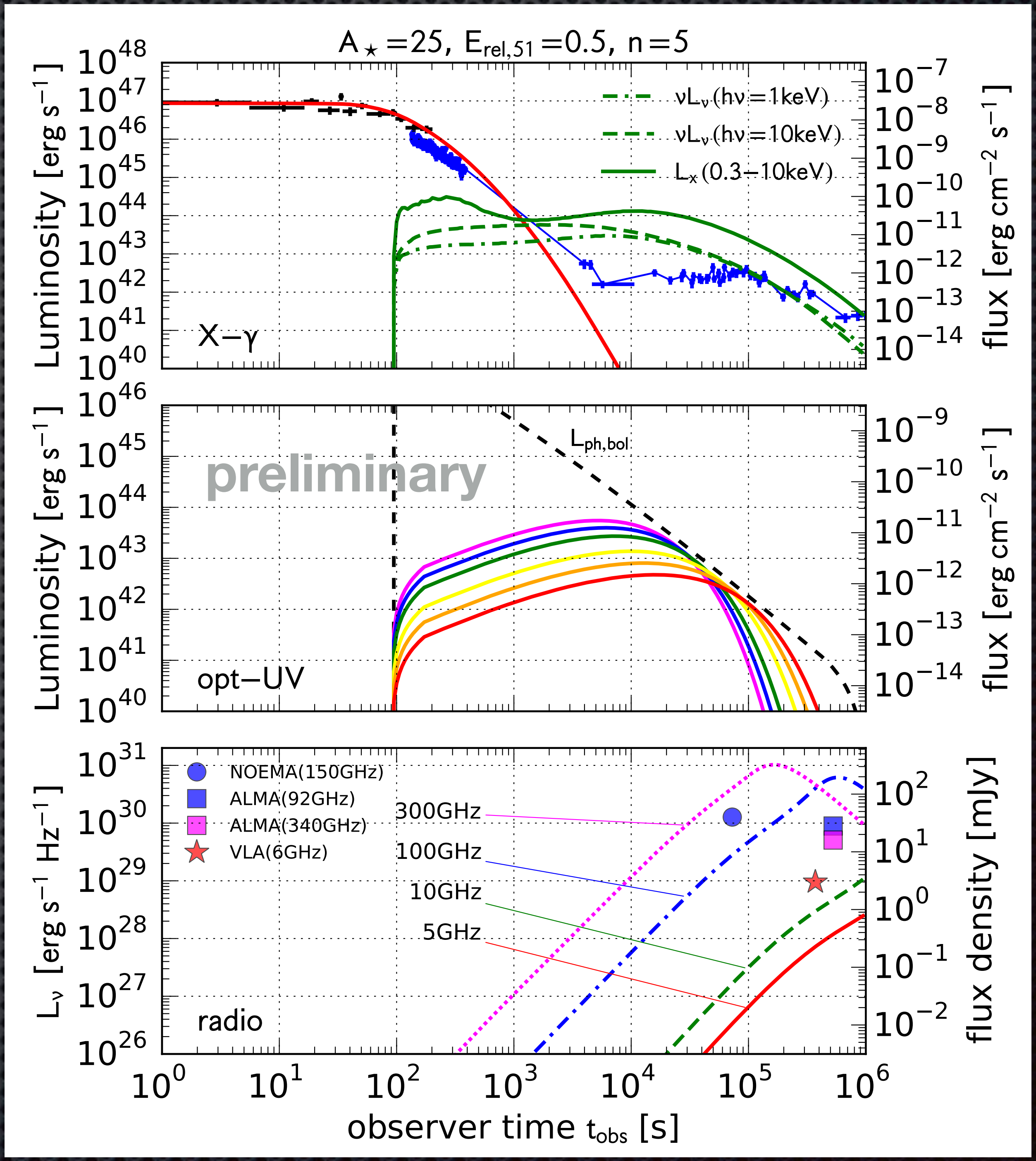

Non-thermal X-ray and radio emission

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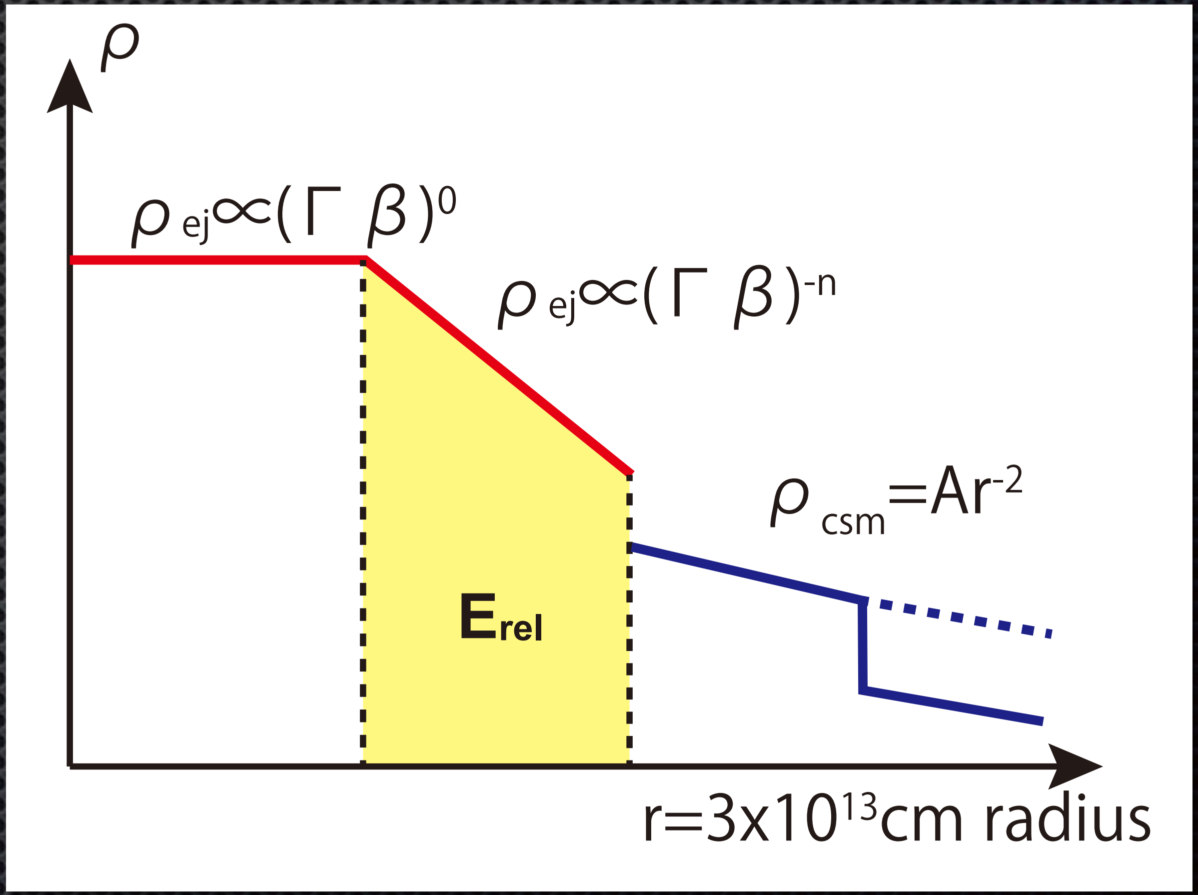
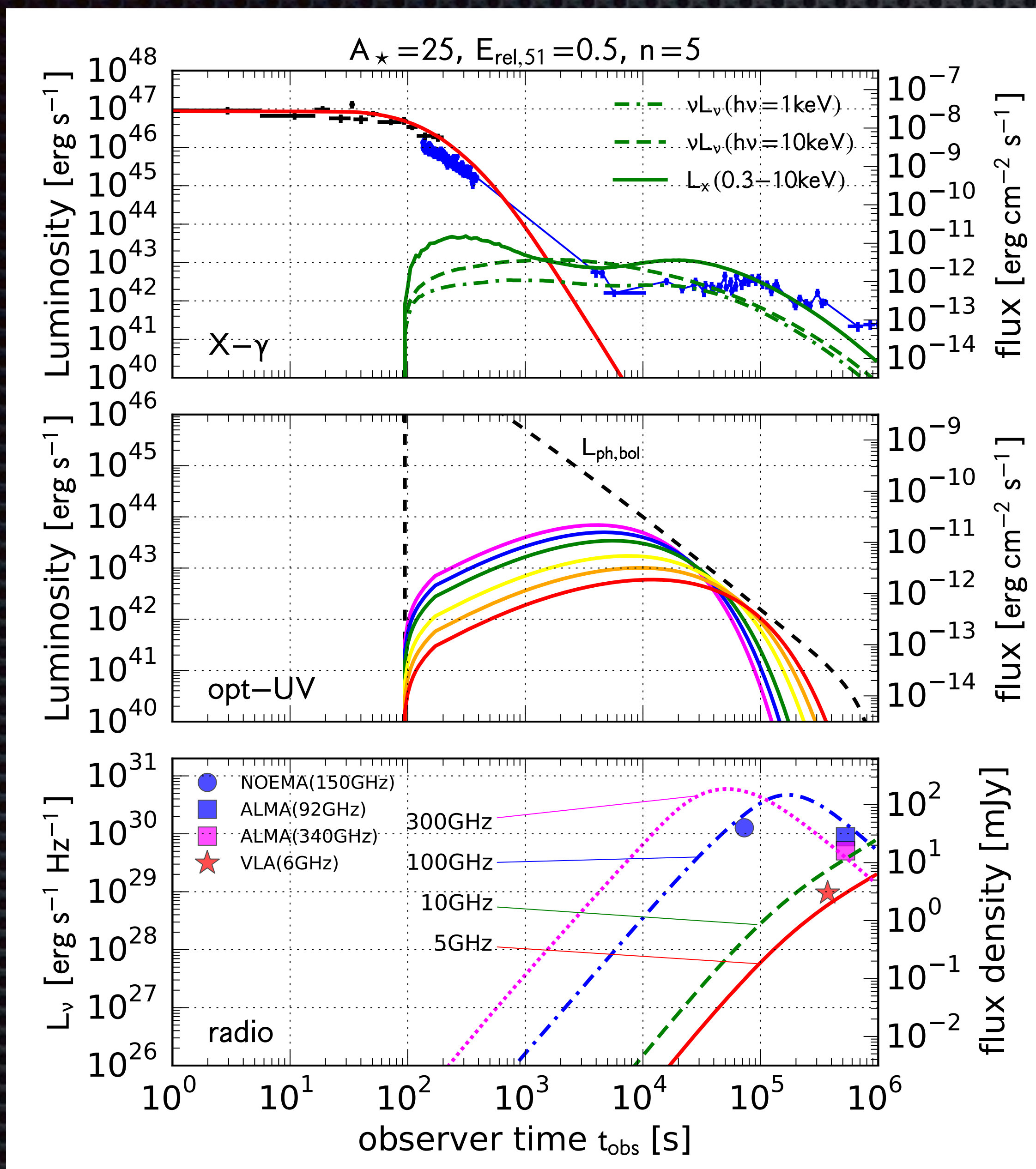


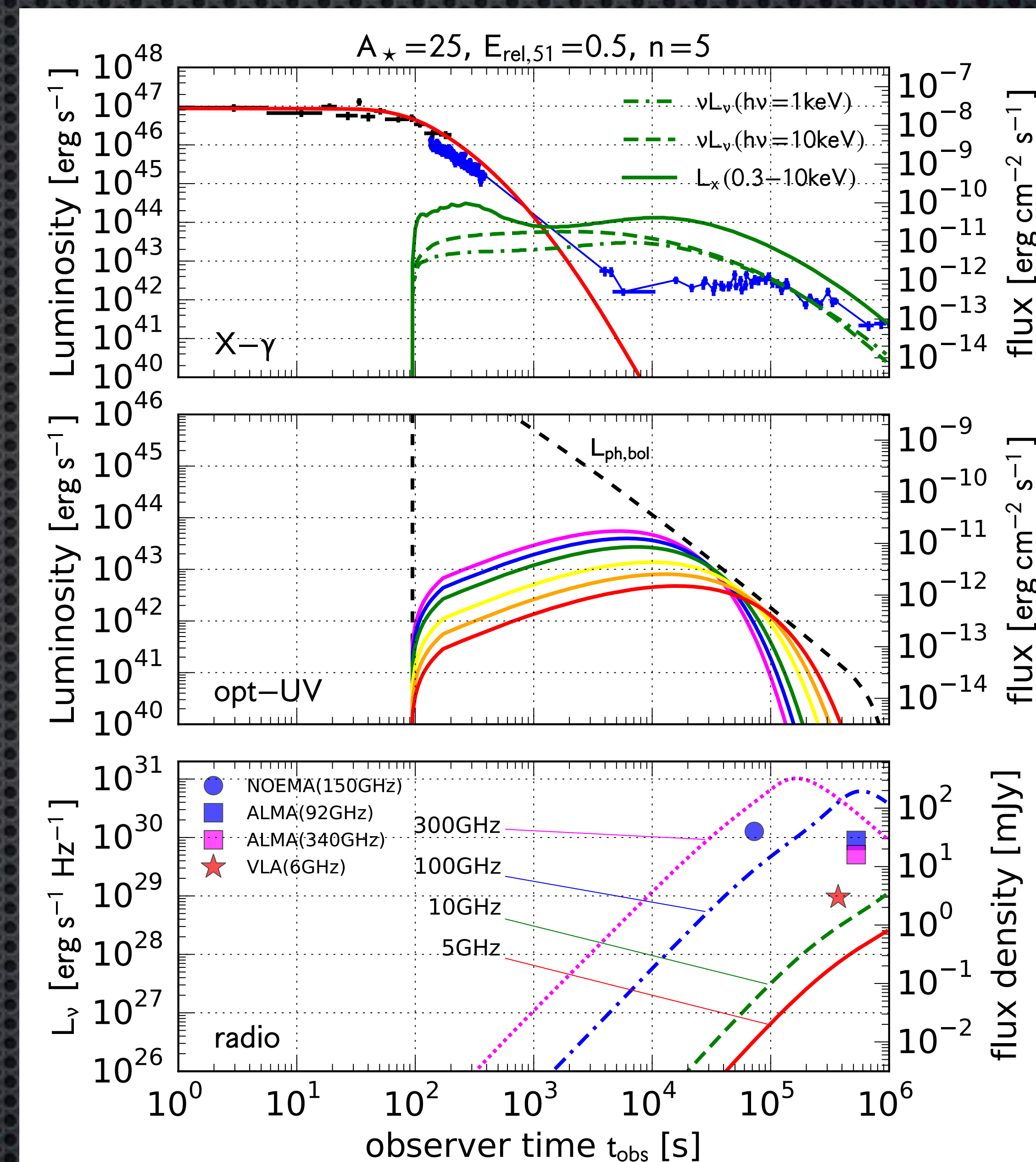
- ➡ reduced CSM density at $r>3\times10^{13}$cm : $A_\star=25 \rightarrow 0.5$

Non-thermal X-ray and radio emission

reduced A★ model

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

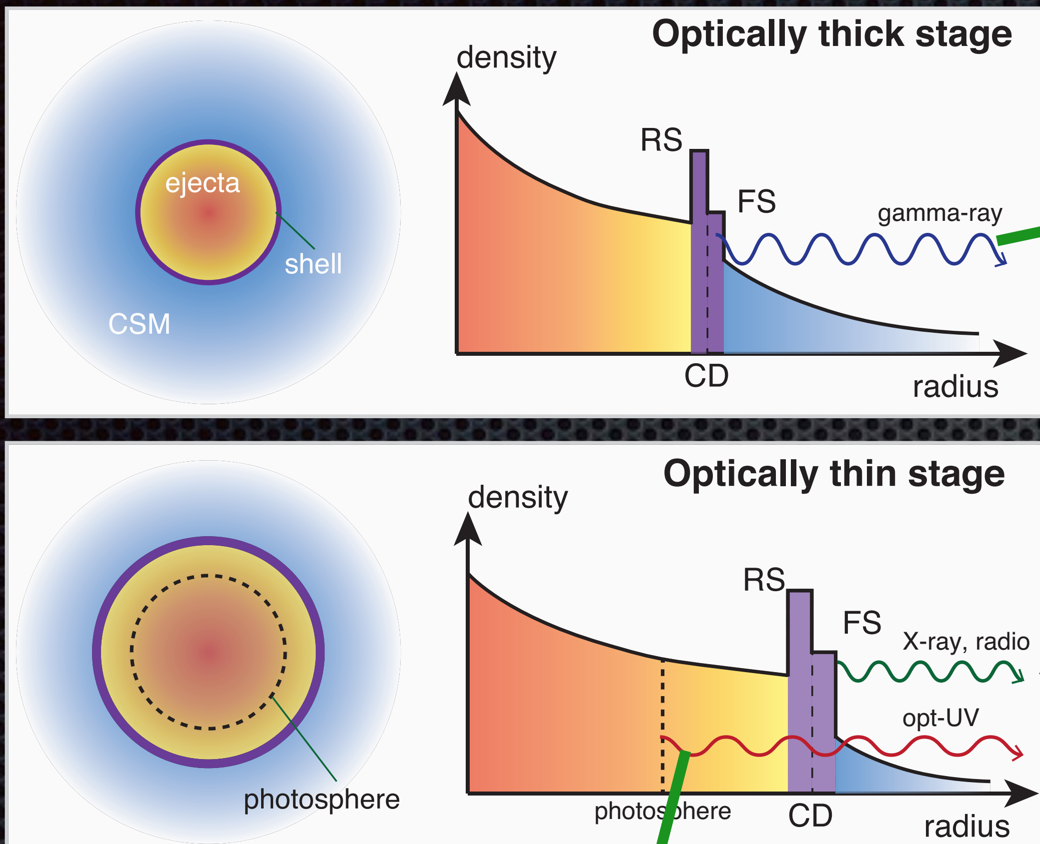


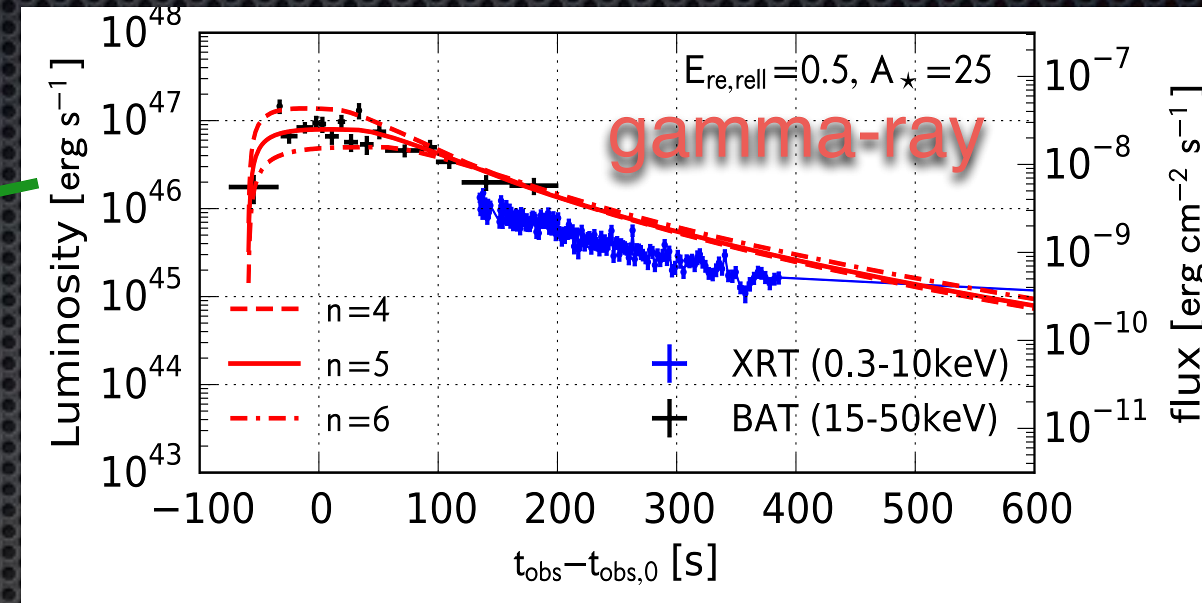


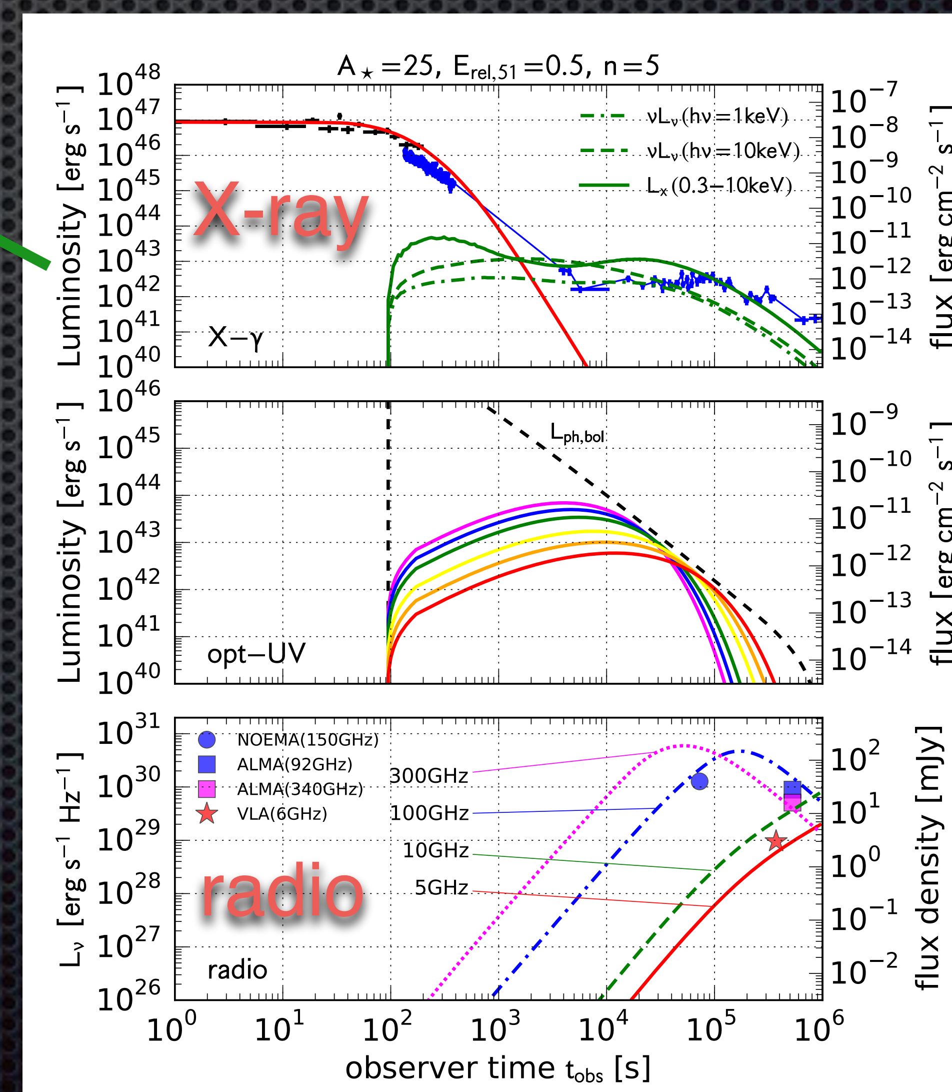
➡ reduced CSM density at $r>3\times10^{13}$cm : $A_\star=25 \rightarrow 0.5$

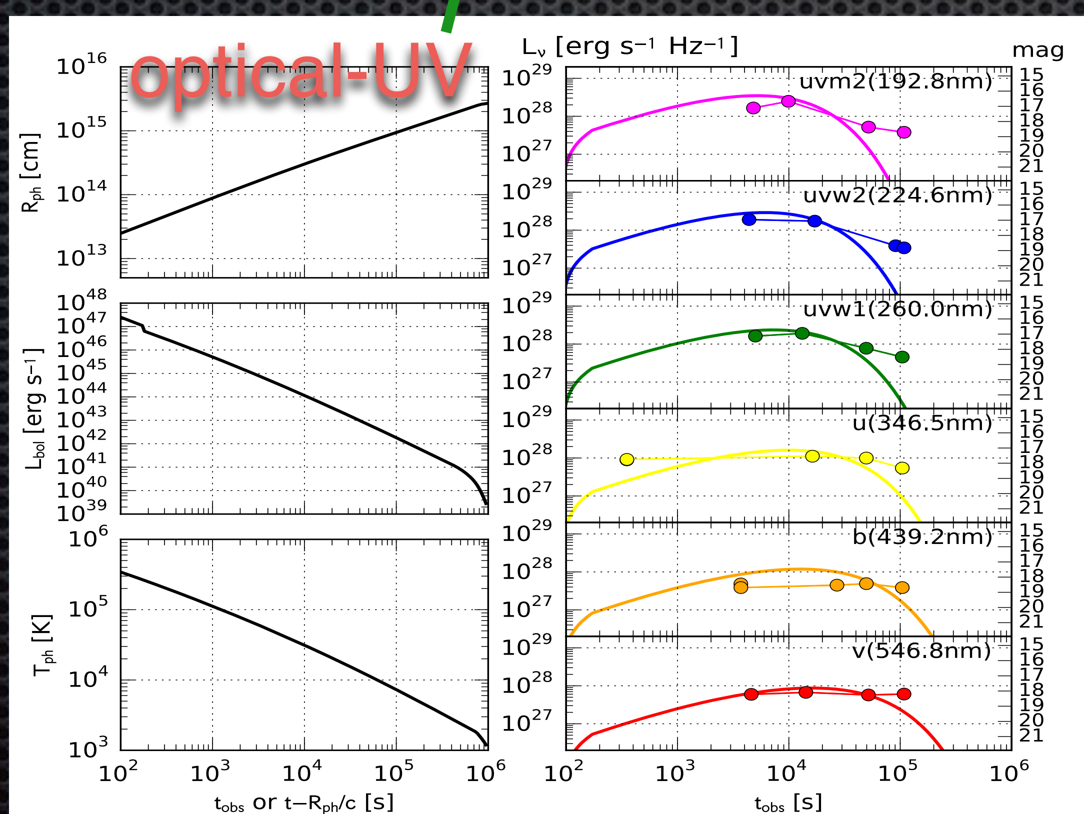
- Introduction
- Ejecta-CSM interaction
- Light curve fitting for GRB171205A
- Conclusion

Discussion and Conclusions

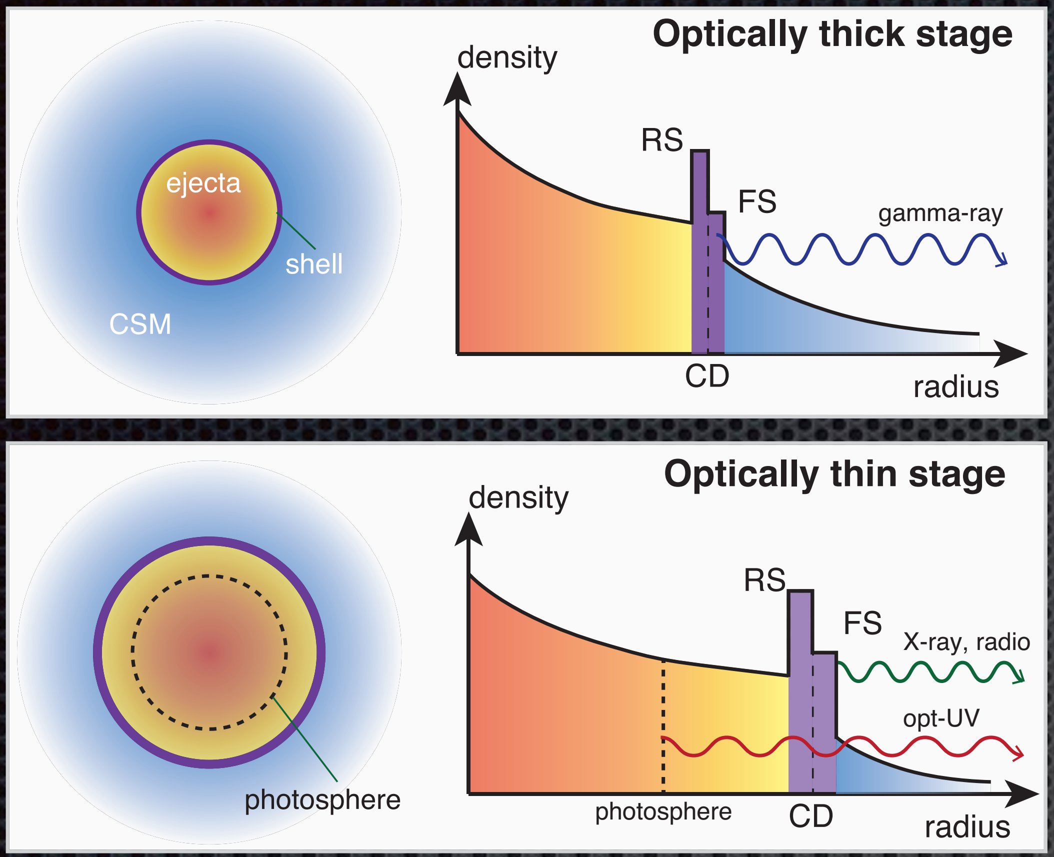


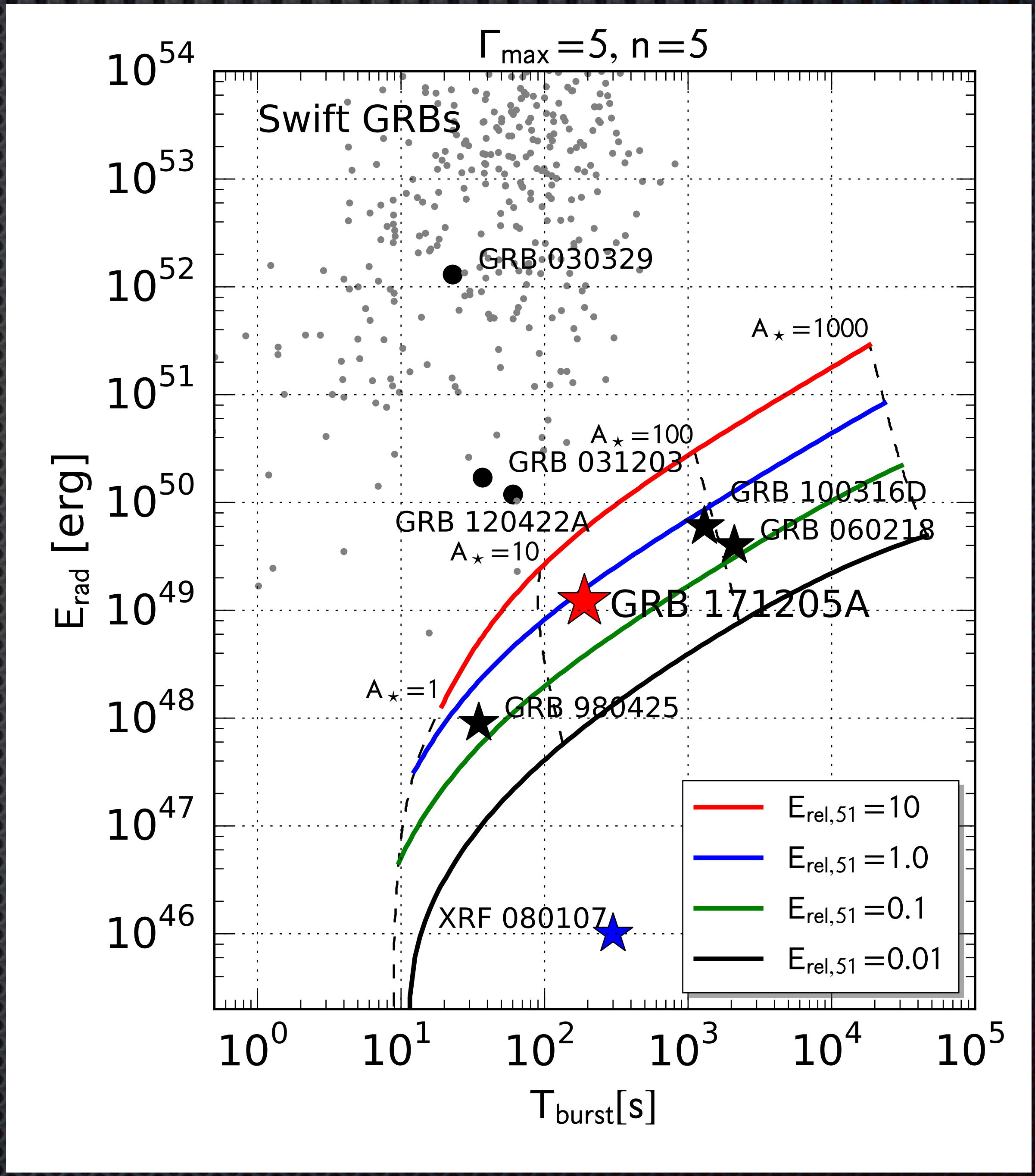






Discussion and Conclusions

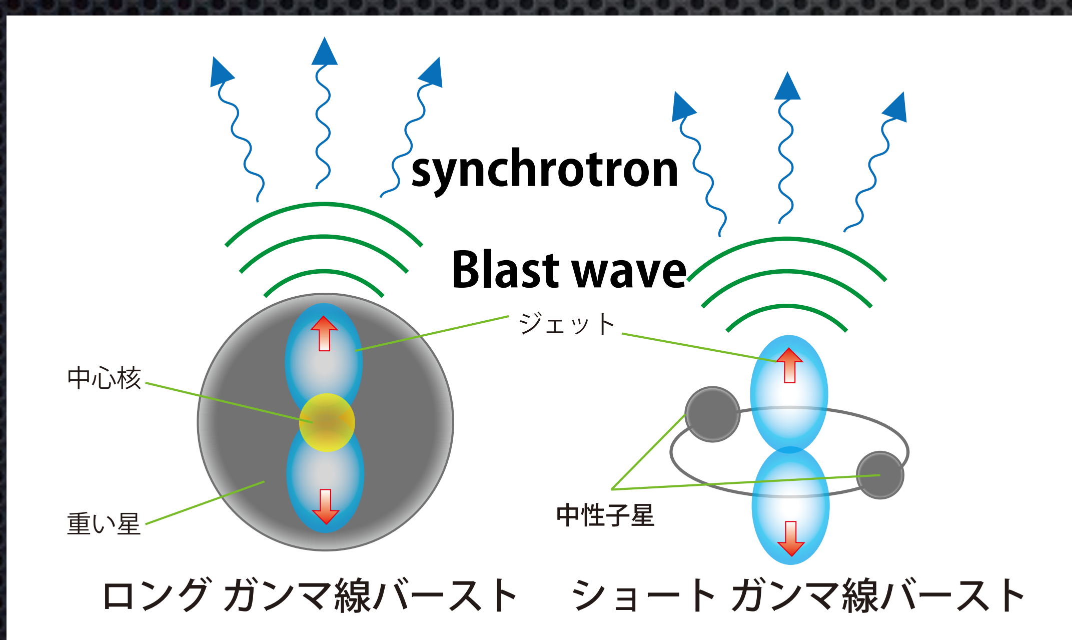


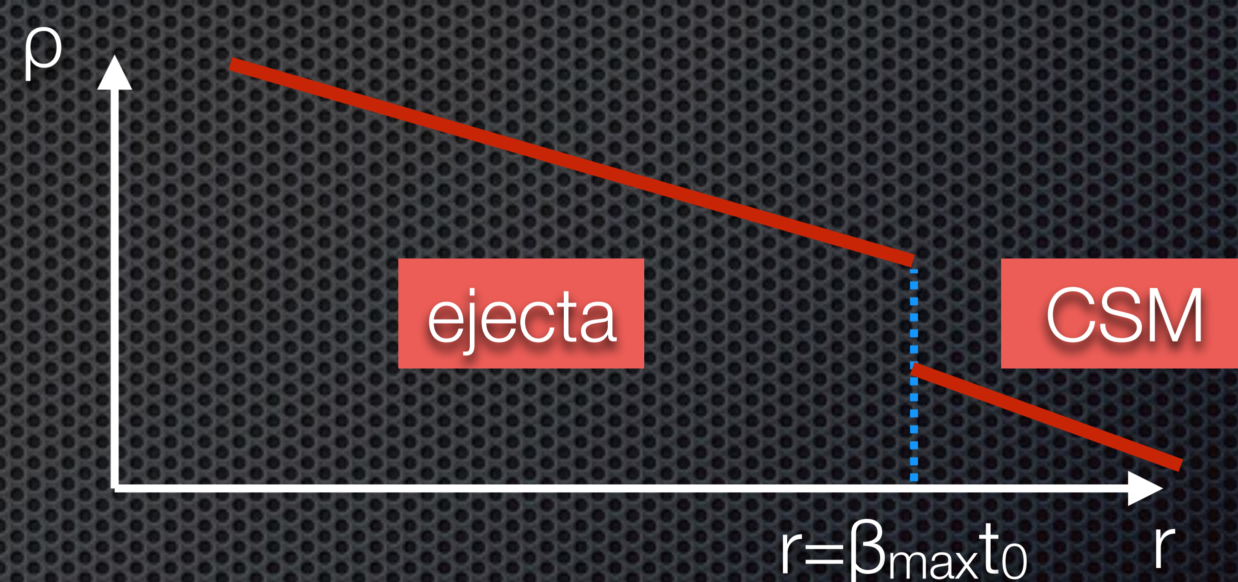


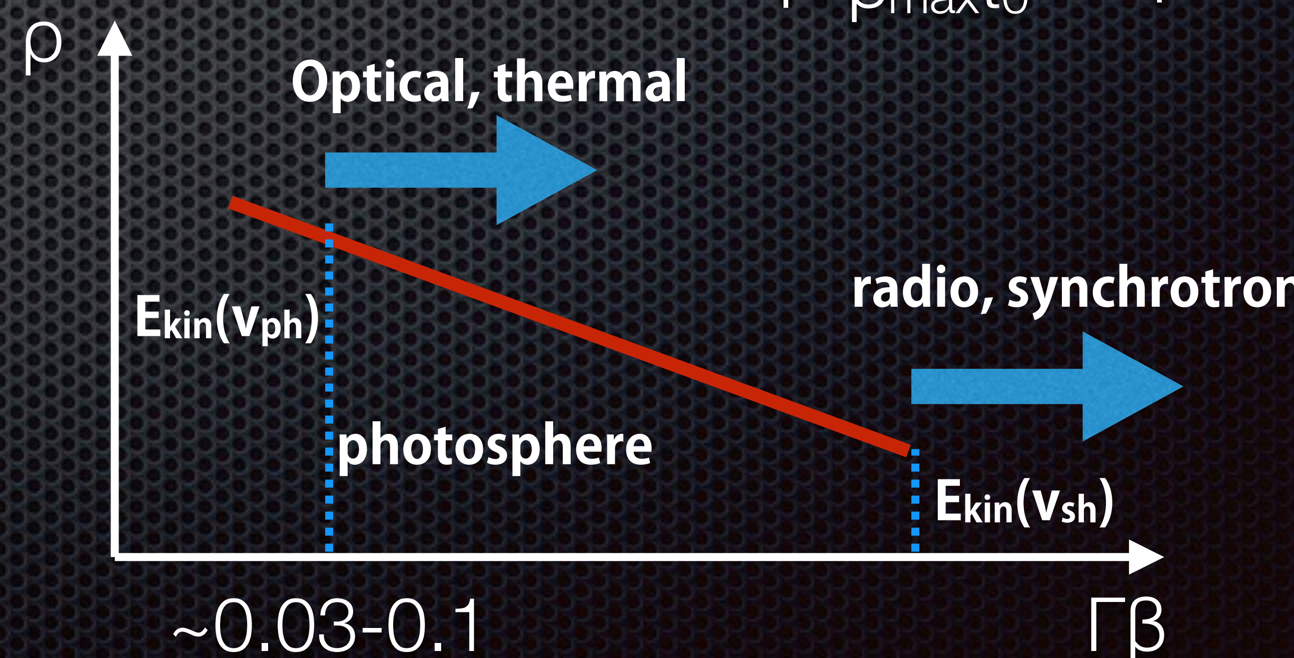
- ➡ multi-wavelength emission model based on relativistic ejecta-CSM interaction scenario
- ➡ what is the origin of relativistic ejecta? failed jet? cocoon?
- ➡ CSM structure?
- ➡ gamma-ray spectrum?

Radio observations of synchrotron emitting blast wave

- ➡ radio loud & radio quiet populations correspond normal GRBs and SNe
- ➡ 4-velocity of blast wave, $\Gamma\beta \sim 1\text{-}2$ for sub-energetic GRBs
- ➡ radio observations imply steeper kinetic energy distributions than normal GRBs







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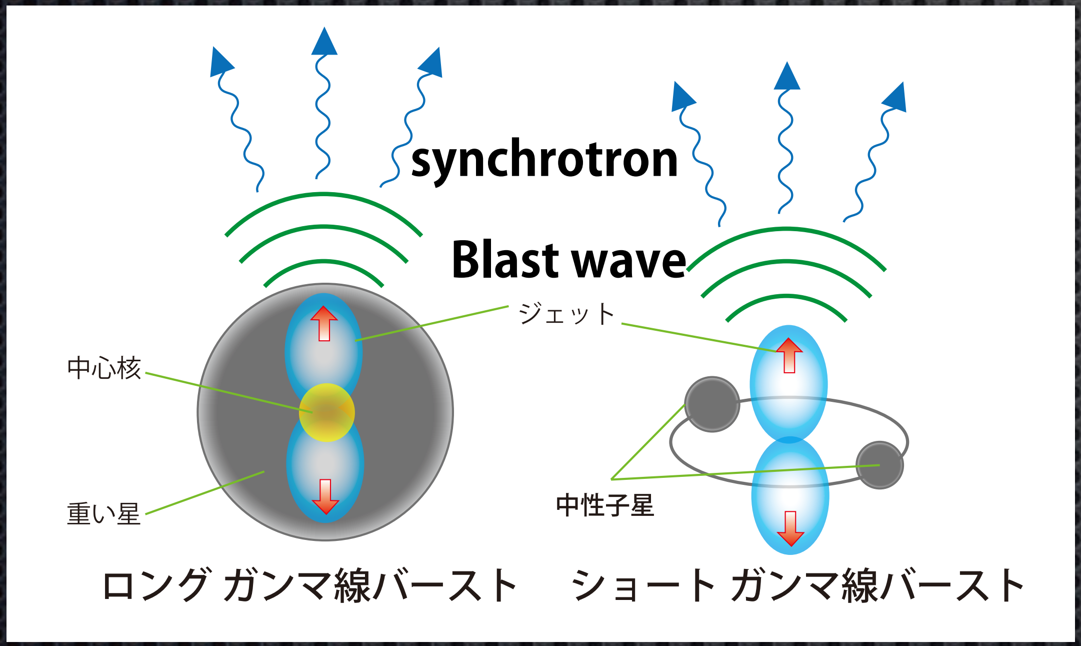
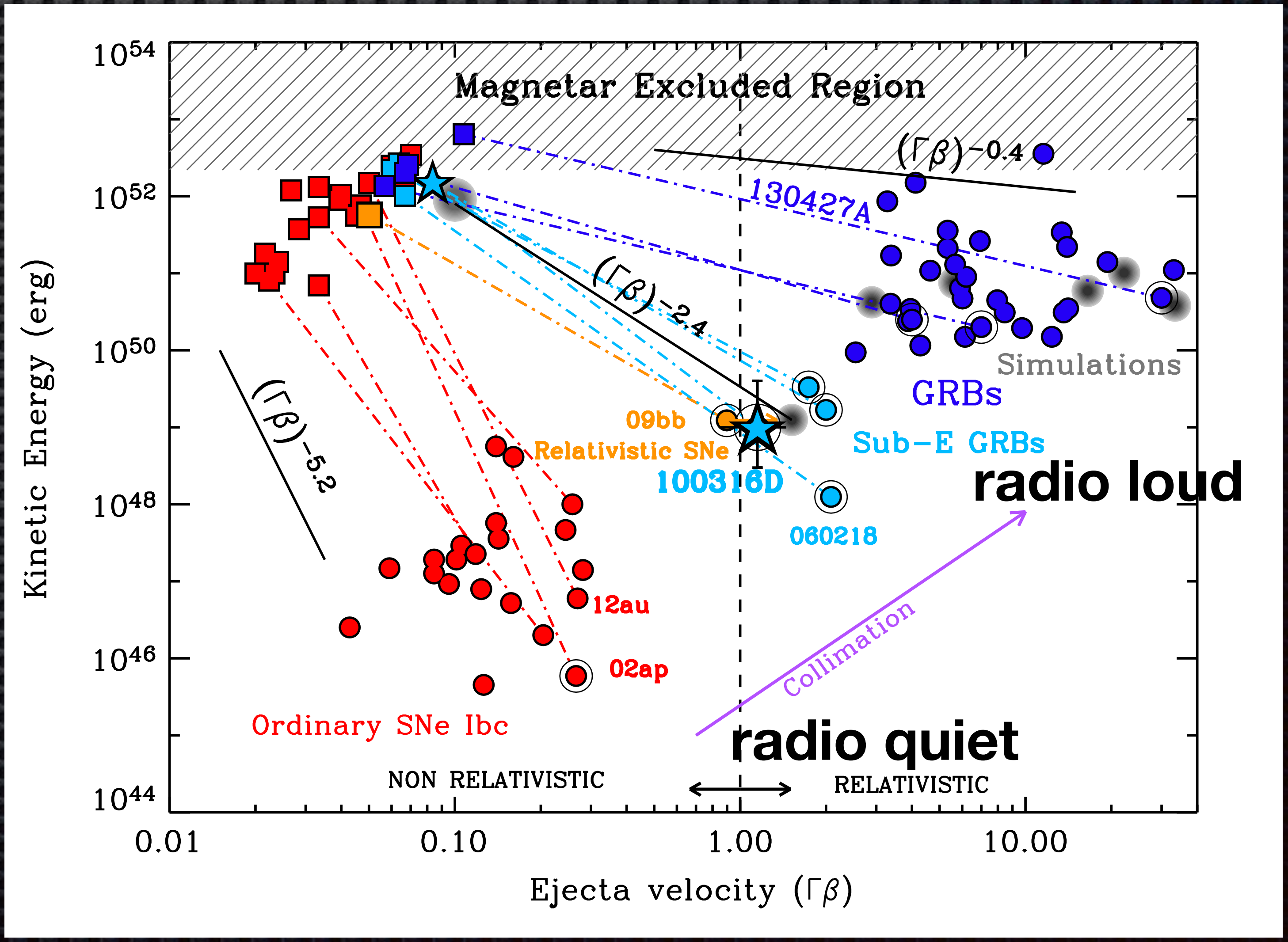
Margutti+ (2013)





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