3/19 (Tue.) RIKEN-RESCEU Joint Seminar
@U-Tokyo, Science building 4, 1st floor

Constructing a Model for Interaction-Powered Supernovae

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Classification of Supernovae

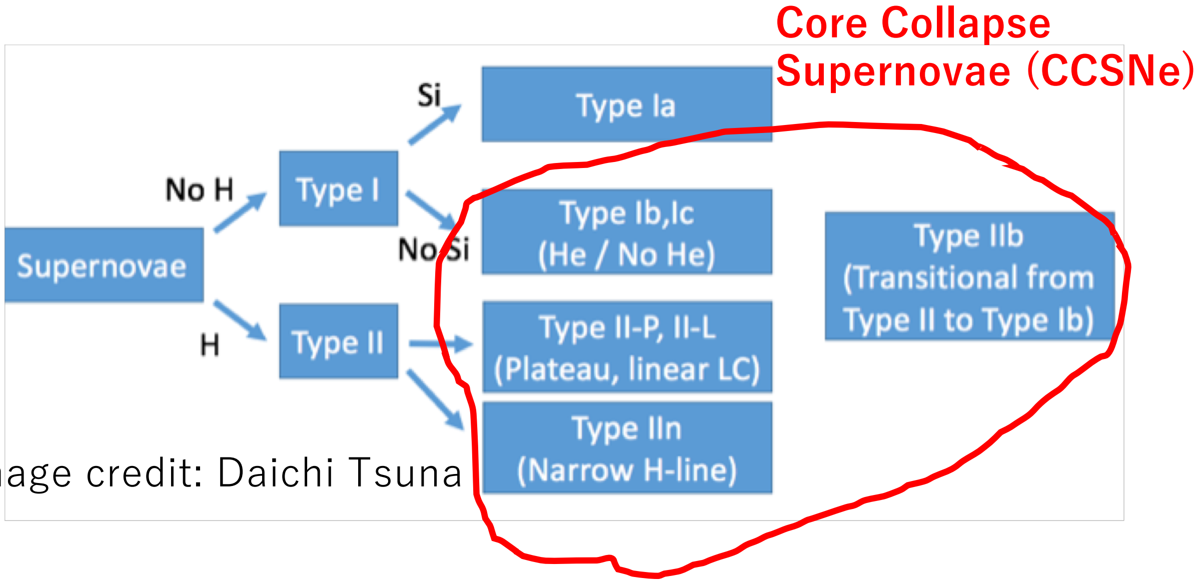
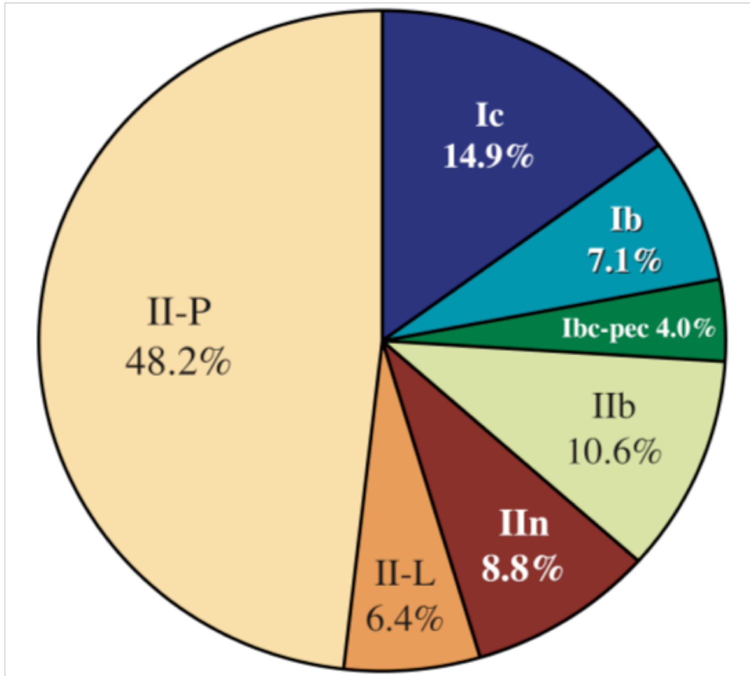


Image credit: Daichi Tsuna



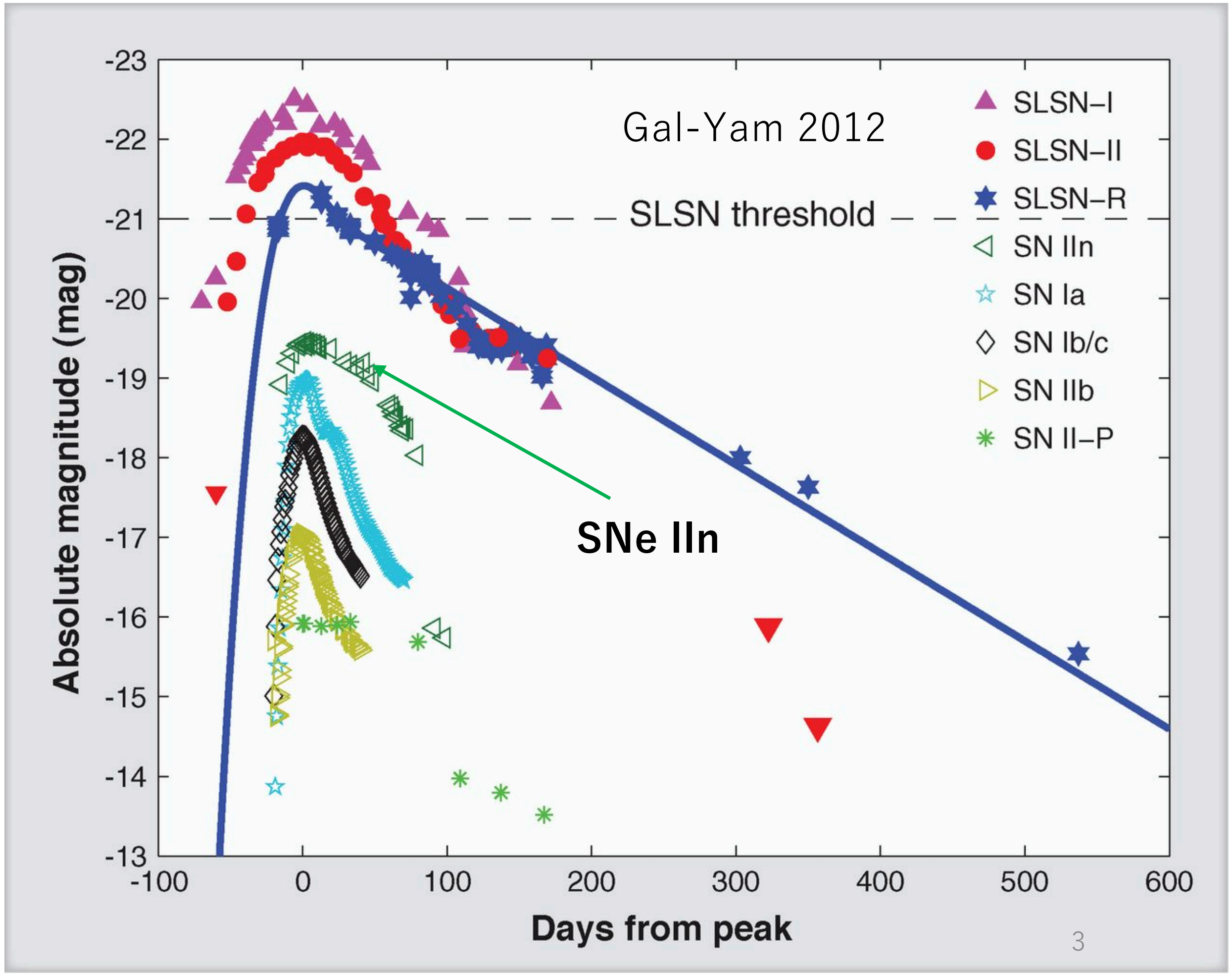
Fraction of CCSNe

Smith et al. (2011)

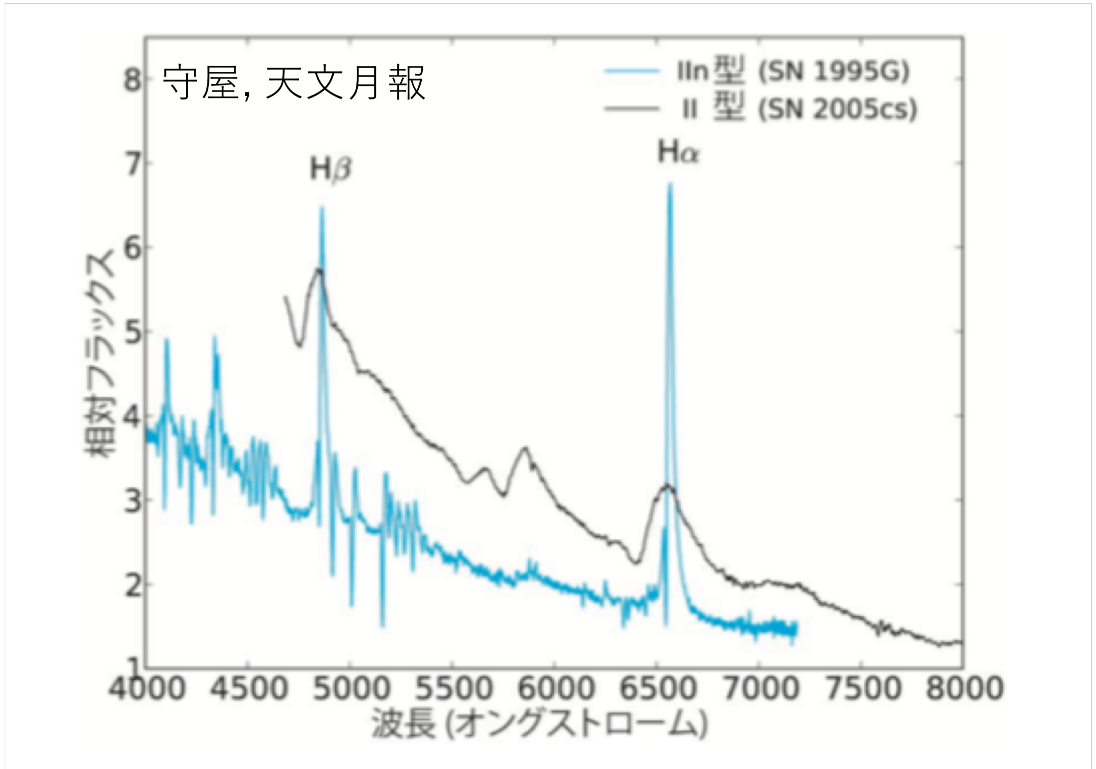
- Supernovae (SNe) brighten by the β decay of ^{56}Ni and ^{56}Co.
- Total radiated energy: ~ 1% of the kinetic energy of ejecta.

Light Curve of Various SNe

- SNe IIn is most luminous except Super Luminous Supernovae (SLSNe).



Type IIn Supernovae



- SNe IIn brighten by the interaction between ejecta and circumstellar medium (CSM) released by their progenitor.
- ~10% of the kinetic energy of ejecta is converted into the luminosity. (e.g., van Marle et al. 2010)

High Mass Loss Rate

- Narrow hydrogen emission lines mean that the radiation is affected by CSM.

→High density CSM

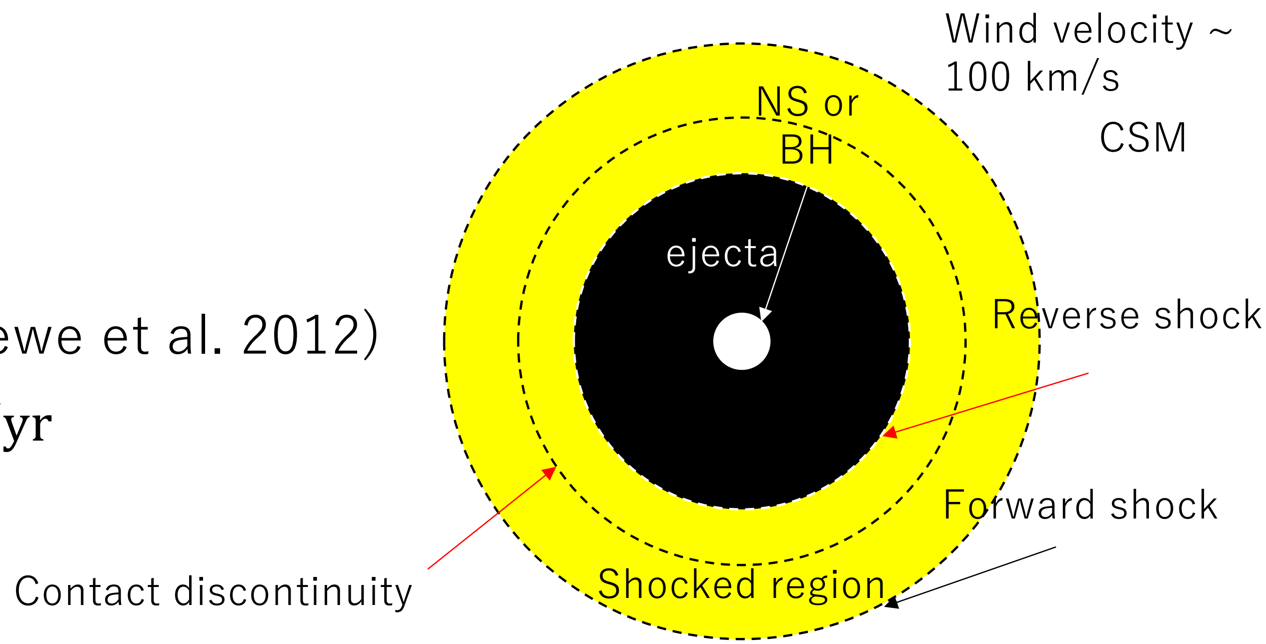
- High mass loss rate

  $\sim 10^{-4} - 0.3 M_{\odot}/\mathrm{yr}$ (e.g., Kiewe et al. 2012)

  Wolf Rayet star:$\sim 10^{-5} M_{\odot}/\mathrm{yr}$

  (e.g., Crowther 2007)

→High density CSM

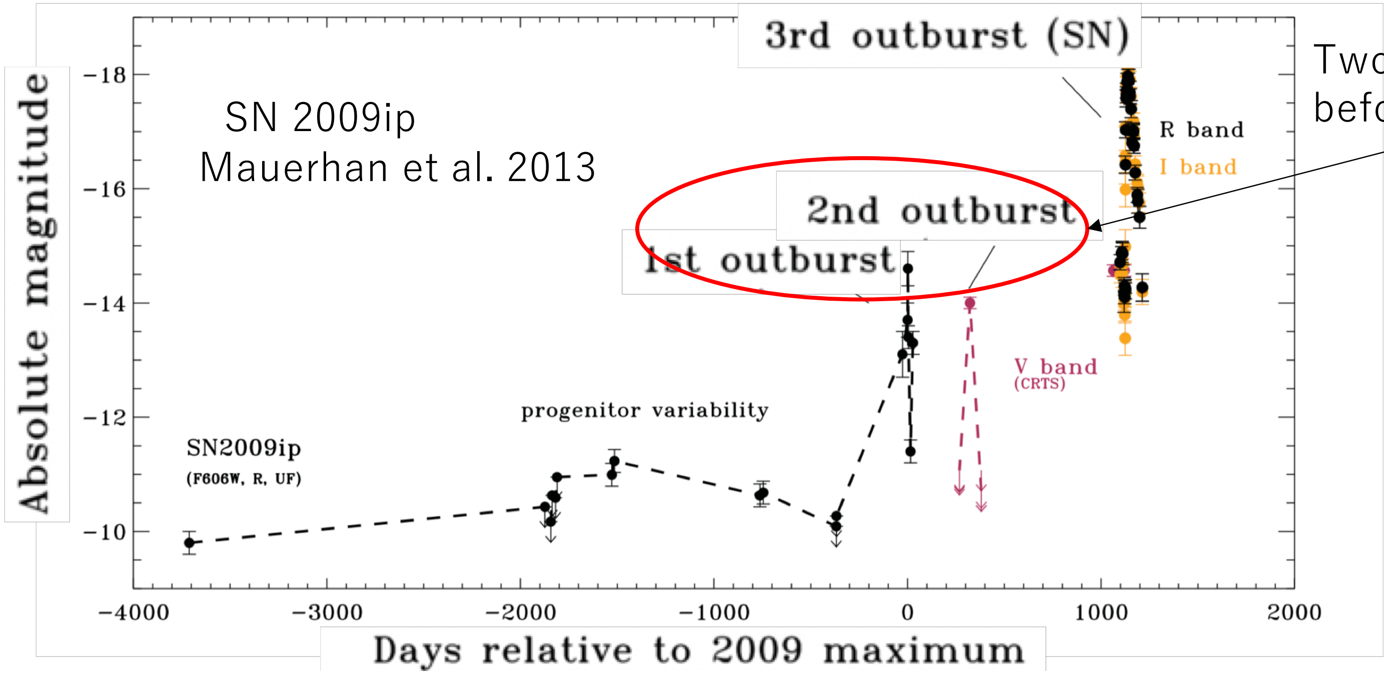


Because of the dense CSM, ejecta collides with CSM and SNe IIn become luminous.

Observational Sign of Dense CSM

- Outburst of Luminous Blue Variables(e.g., Smith & Owocki 2006; Smith et al. 2008)
- Outburst luminosity > Eddington luminosity

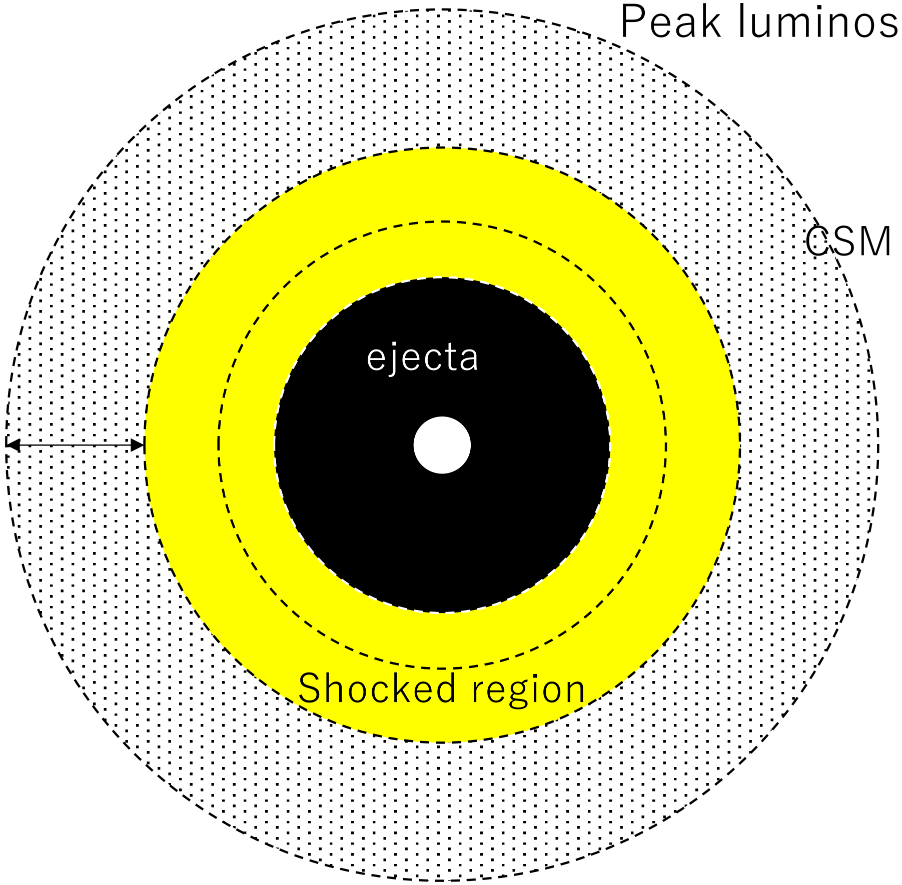
→It is considered that mass loss has occurred.



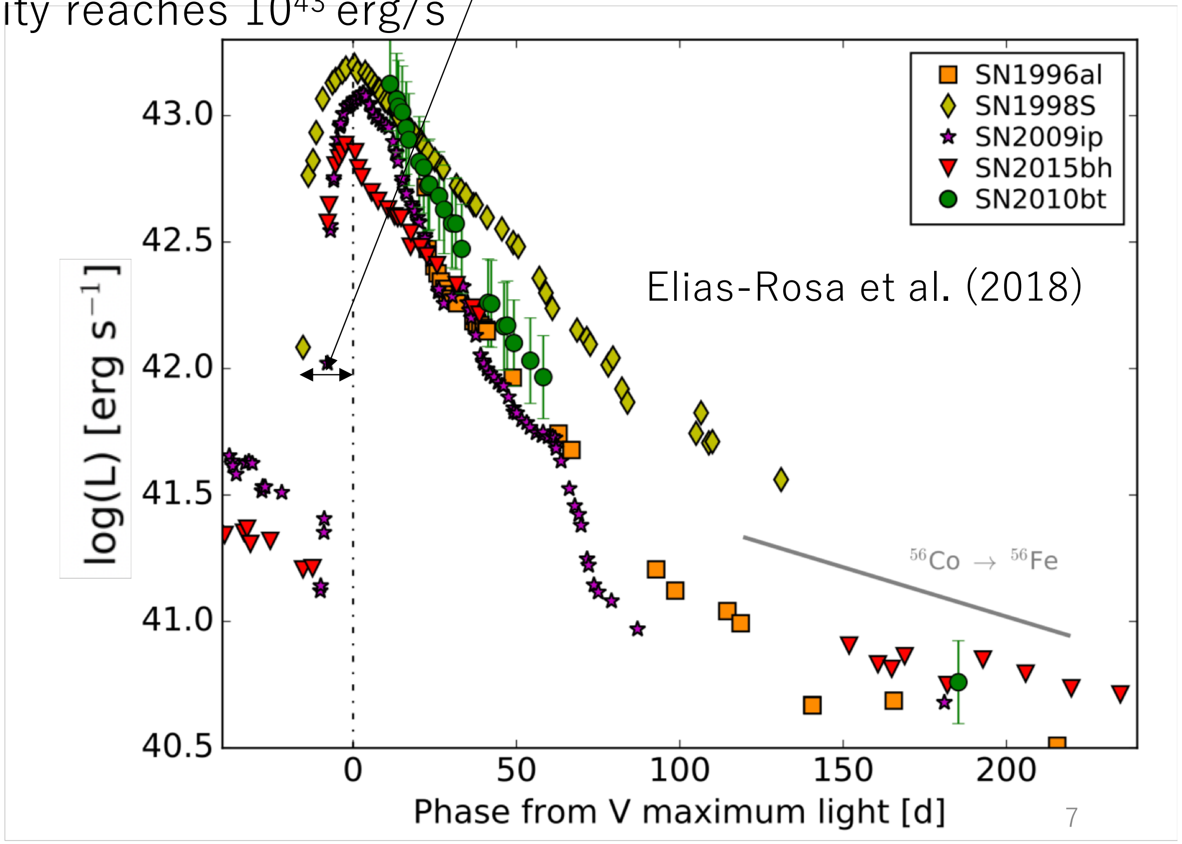
Two outbursts are observed before true SN

Sharp Rising Light Curve at the Early Epoch

- Shock breakout through dense CSM



Peak luminosity reaches 10^{43} erg/s



Previous work (1): Moriya et al. (2013)

➢Thin shell approximation: Radiative cooling

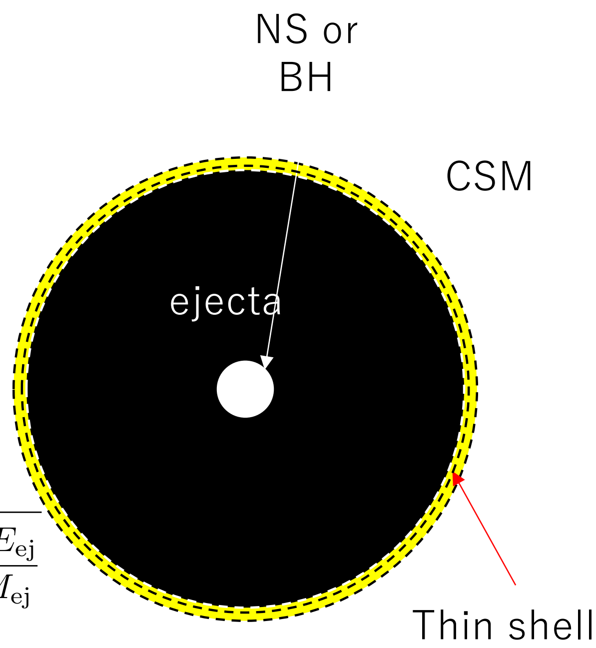
$$M_{\rm sh}\frac{dv_{\rm sh}}{dt} = 4\pi r_{\rm sh}^2\left[\rho_{\rm ej}(v_{\rm ej}-v_{\rm sh})^2 - \rho_{\rm CSM}(v_{\rm sh}-v_{\rm w})^2\right]$$

$$M_{\rm sh} \simeq \int_0^{r_{\rm sh}} 4\pi r^2\rho_{\rm CSM}dr + \int_{v_{\rm sh}t}^{\infty} 4\pi r^2\rho_{\rm ej}dr$$

- Ejecta density profile:

$$\rho_{\rm ej}(v_{\rm ej},t) = \begin{cases} \frac{1}{4\pi(n-\delta)}\frac{[2(5-\delta)(n-5)E_{\rm ej}]^{(n-3)/2}}{[(3-\delta)(n-3)M_{\rm ej}]^{(n-5)/2}}t^{-3}v_{\rm ej}^{-n} & (v_{\rm ej} > v_t) \\ \frac{1}{4\pi(n-\delta)}\frac{[2(5-\delta)(n-5)E_{\rm ej}]^{(\delta-3)/2}}{[(3-\delta)(n-3)M_{\rm ej}]^{(\delta-5)/2}}t^{-3}v_{\rm ej}^{-\delta} & (v_{\rm ej} < v_t) \end{cases}$$

$$v_t = \sqrt{\frac{2(5-\delta)(n-5)E_{\rm ej}}{(3-\delta)(n-3)M_{\rm ej}}}$$



- E_{ej} : Kinetic energy of ejecta、M_{ej}: Ejecta mass
- Luminosity

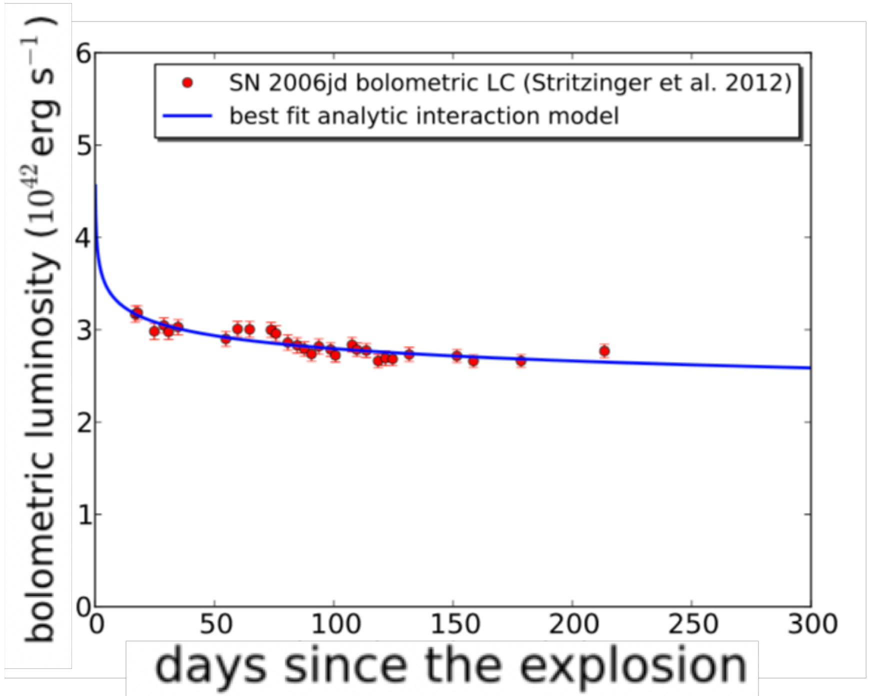
$$L = \epsilon\frac{dE_{\rm kin}}{dt} = 2\pi\epsilon\rho_{\rm CSM}r_{\rm sh}^2 v_{\rm sh}^3$$

- ϵ: Conversion efficiency~0.1

Previous work (1): Discussing Points

➢SN 2006jd: Ejecta kinetic energy

$E_{\mathrm{ej}} \sim 10^{52}$ erg



- E_{ej} ~ 10^{53} erg is needed to explain the luminosity of >10^{43} erg/s

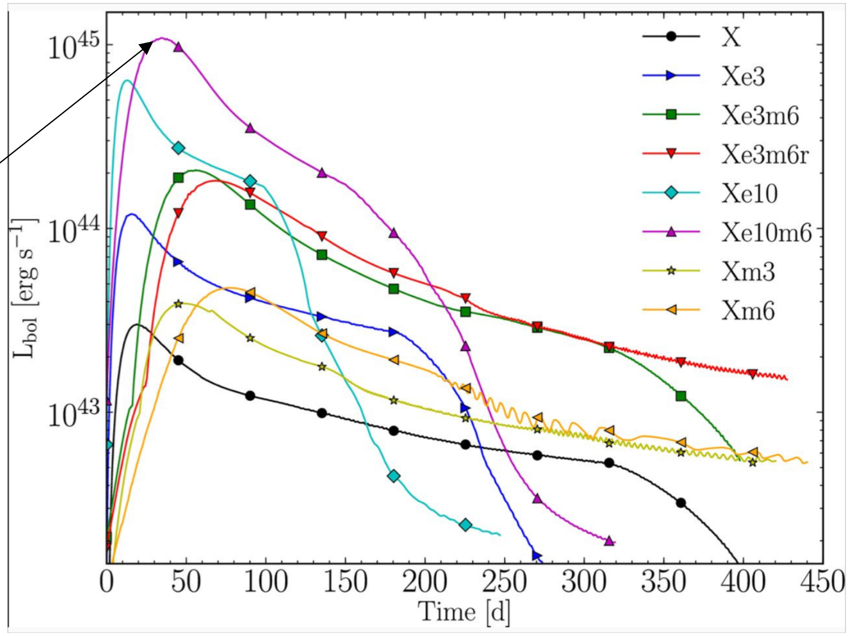
cf. Gravity potential of CCSNe is ~10^{53} erg and ~99% of that is taken out by neutrinos.

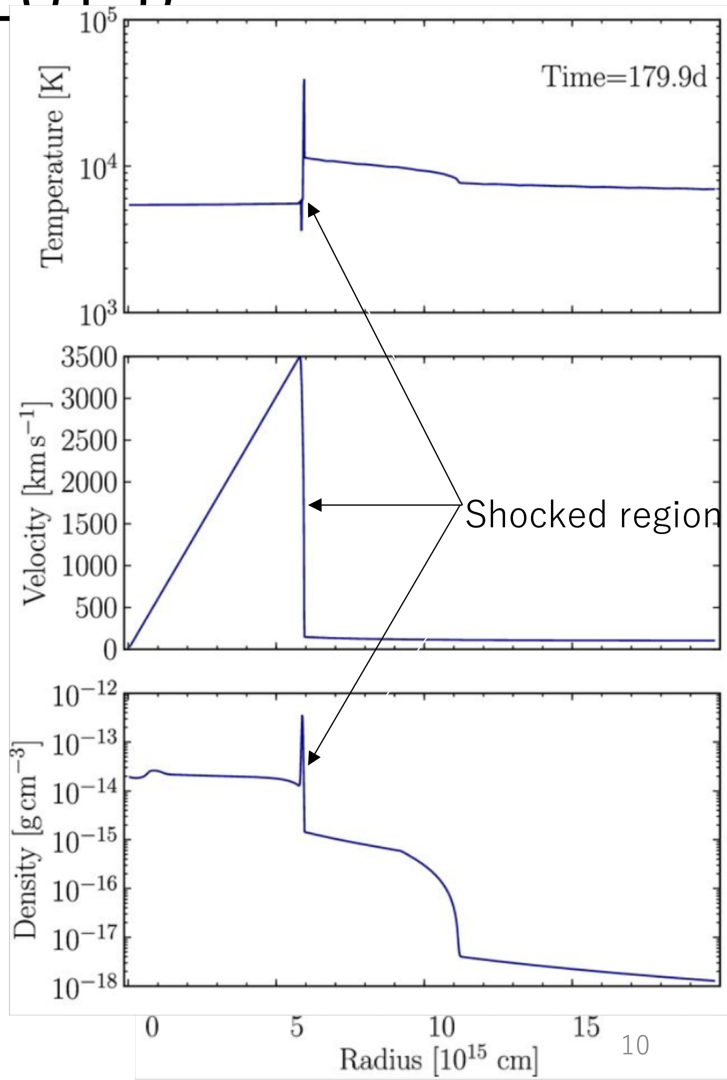
Previous work (2): Dessart et al. (2015)

- Reproducing the feature of SNe IIn by numerical simulations.
  - ➢ Solving the radiative transfer equations under non local thermodynamic equilibrium.
  - ➢ Initial rising of light curve is reproduced successfully
- Shocked region is not resolved.

$E_{\rm ej} = 10^{52}$ erg

$\dot{M} = 0.6 M_\odot$ yr^{-1}





Objectives of Our Research

- **Discussing points**
- Shocked region has not been resolved.
- Too much kinetic energy of ejecta.

- **Objective: Construct a Light Curve Model for Type IIn SNe**
- Calculations of luminosity based on the inside structure of shocked region
- Reproduce the sharp rising light curve

- **Methods**
- Calculation of radiation hydrodynamics in shocked region
- Calculation of radiative transfer equations in CSM

Method

- Spherical symmetry, stationary on shock rest frame
- Integrating by Runge-Kutta method: Shocked region is divided by 10^6
- Hydrodynamics：

$$\frac{1}{r^2}\frac{\partial(r^2\rho(v-u))}{\partial r}=0 \quad \text{(equation of continuity)}$$

$$\rho(v-u)\frac{\partial v}{\partial r}+\frac{\partial p}{\partial r}=0 \quad \text{(Euler equation)}$$

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\left\{\rho(v-u)\left(\frac{1}{2}(v-u)^2+\frac{e+p}{\rho}\right)+F\right\}\right]=0 \quad \text{(Equation of energy)}$$

Flux

- u: shock velocity, e: internal energy
- Assume local thermodynamic equilibrium
- Equation of state： $p=\frac{\rho}{\mu m_{\mathrm{u}}}kT+\frac{1}{3}aT^4 \qquad e=\frac{3}{2}\frac{\rho}{\mu m_{\mathrm{u}}}kT+aT^4$

Flux

- Using Flux-Limited Diffusion approximation

$$F^{-1} = \left(-\frac{ac}{3\kappa\rho}\frac{\partial T^4}{\partial r}\right)^{-1} + (acT^4)^{-1}$$

- Opacity: Rosseland mean opacity (well approximated in the optically thick region)

$$\frac{1}{\kappa_{\mathrm{R}}} \equiv \frac{\int_0^\infty \frac{1}{\kappa_\nu}\frac{\partial B_\nu(T)}{\partial T} d\nu}{\int_0^\infty \frac{\partial B_\nu(T)}{\partial T} d\nu}$$

- OPAL Opacity code

Initial Conditions

- Ejecta density broken power-law profile (e.g., Matzner & McKee 1999)

$$\rho_{\rm ej}(v_{\rm ej},t) = \begin{cases} \frac{1}{4\pi(n-\delta)}\frac{[2(5-\delta)(n-5)E_{\rm ej}]^{(n-3)/2}}{[(3-\delta)(n-3)M_{\rm ej}]^{(n-5)/2}} t^{-3} v_{\rm ej}^{-n} \ (v_{\rm ej} > v_t) \\ \frac{1}{4\pi(n-\delta)}\frac{[2(5-\delta)(n-5)E_{\rm ej}]^{(\delta-3)/2}}{[(3-\delta)(n-3)M_{\rm ej}]^{(\delta-5)/2}} t^{-3} v_{\rm ej}^{-\delta} \ (v_{\rm ej} < v_t) \end{cases}$$

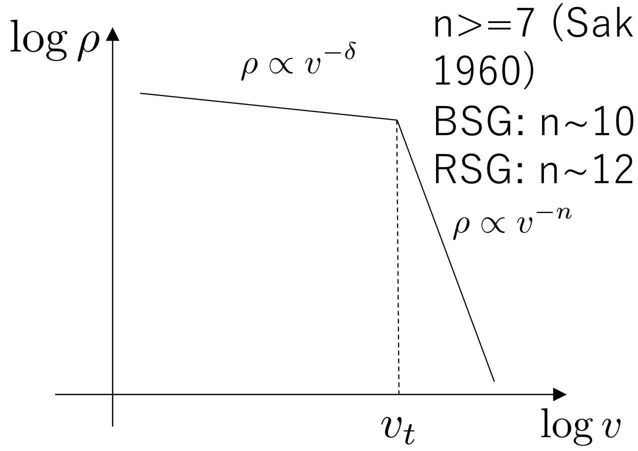
$$v_t = \sqrt{\frac{2(5-\delta)(n-5)E_{\rm ej}}{(3-\delta)(n-3)M_{\rm ej}}}$$

- Free expanding ($v_{\rm ej} = r/t$); p: negligible

- CSM density profile(v, p: negligible)

$$\rho_{\rm CSM} = Dr^{-s}$$

- Input parameters：n, s, E_{ej}, D



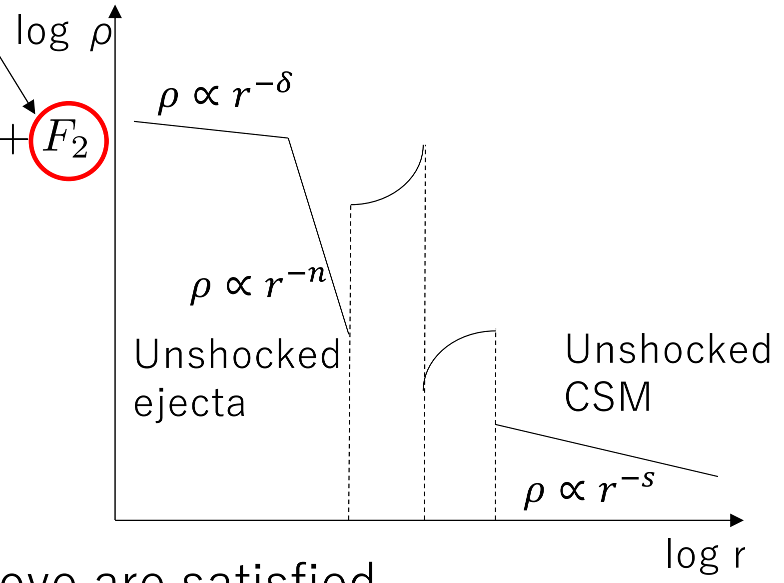
n>=7 (Sakurai 1960)
BSG: n~10
RSG: n~12

Boundary Conditions

- Reverse shock: 0
- Forward shock: F_{fs}

- Rankine-Hugoniot relations

$$\rho_1(v_1 - u) = \rho_2(v_2 - u)$$
$$\rho_1(v_1 - u)^2 + p_1 = \rho_2(v_2 - u)^2 + p_2$$
$$\frac{1}{2}(v_1 - u)^2 + \frac{e_1 + p_1}{\rho_1} + F_1 = \frac{1}{2}(v_2 - u)^2 + \frac{e_2 + p_2}{\rho_2} + F_2$$



- Boundary conditions at the contact surface:

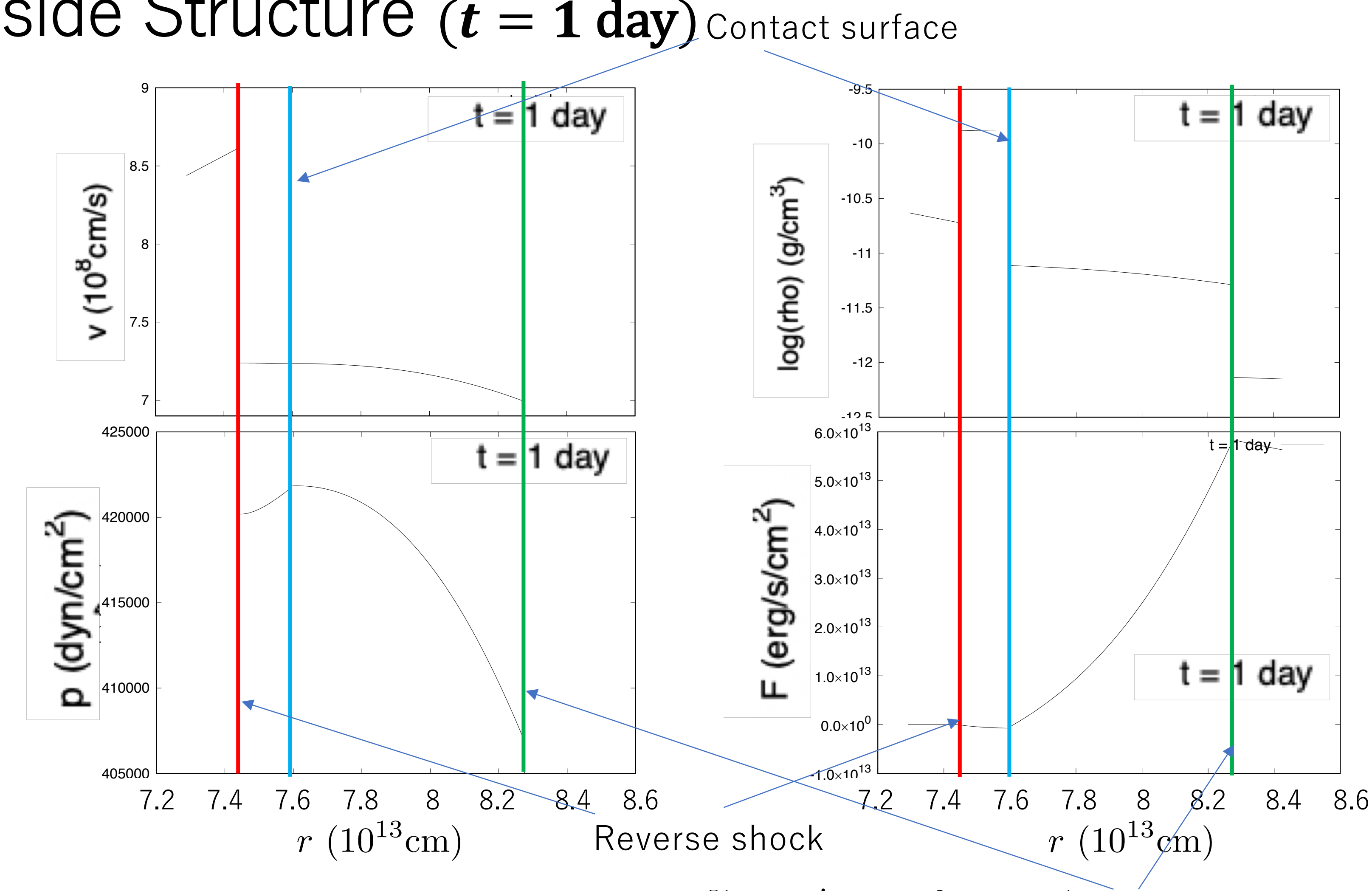
$$v^{\rm in} = v^{\rm out}$$
$$p^{\rm in} = p^{\rm out}$$
$$F^{\rm in} = F^{\rm out}$$

Determine u_{rs}, u_{fs}, F_{fs} so that three conditions above are satisfied.

u_{rs}, u_{fs} are velocities of reverse shock, forward shock

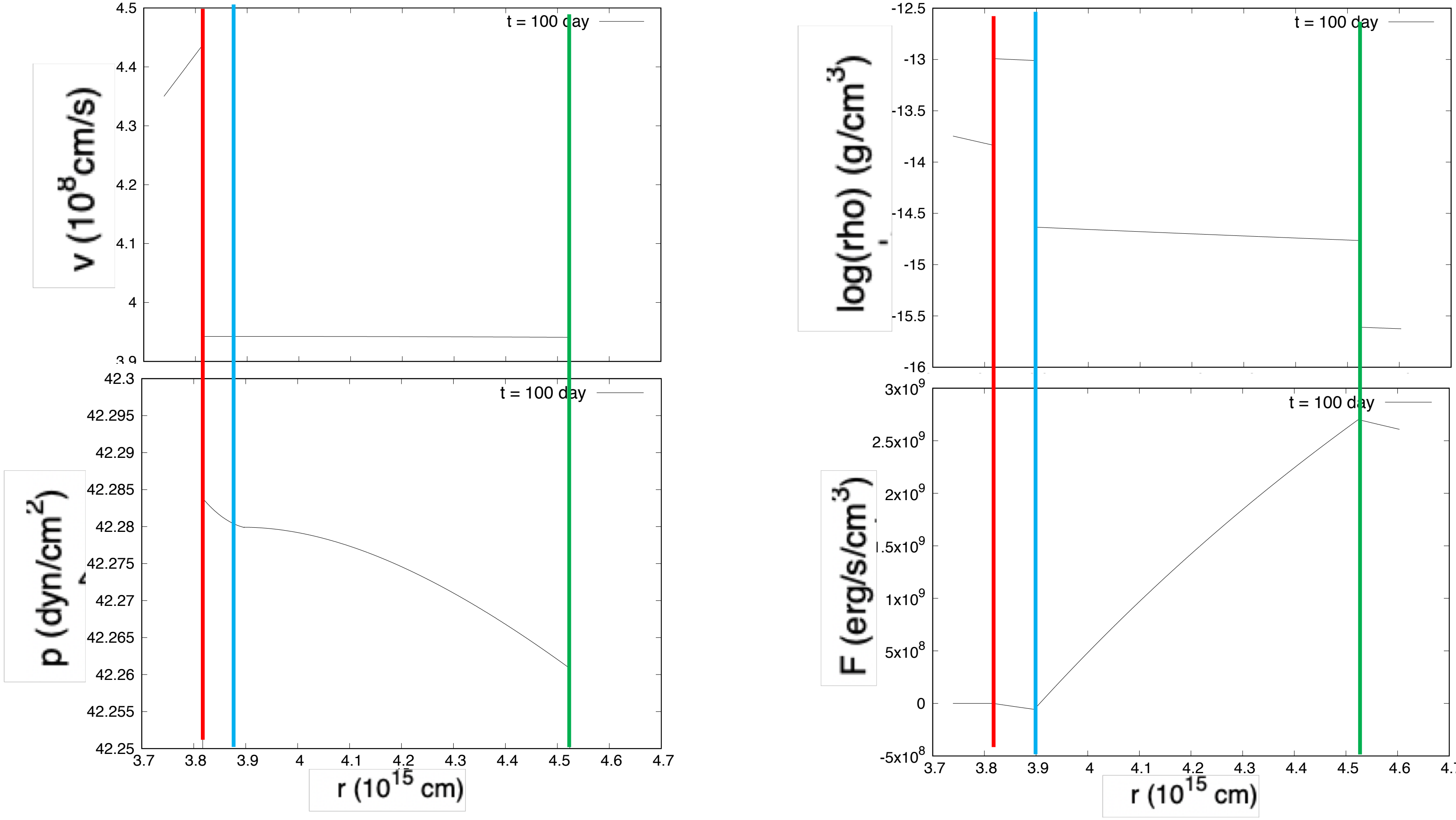
F_{fs} is flux at forward shock front

Inside Structure ($\boldsymbol{t} = \mathbf{1}$ day)



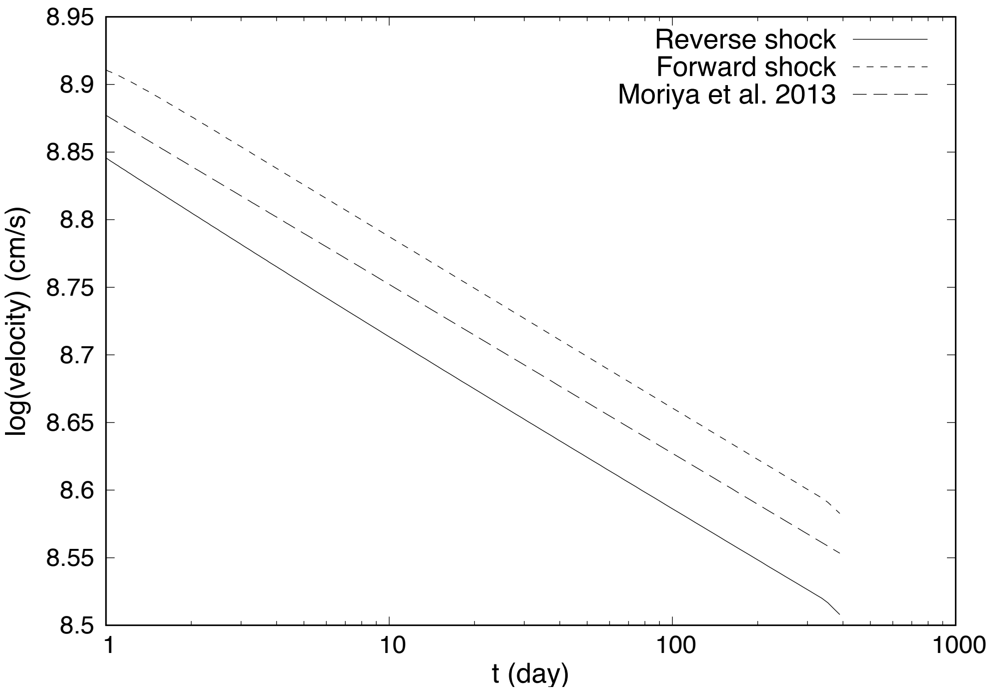
$n = 10, s = 2, E_{\rm ej} = 10^{51}$ erg, $\dot{M} = 10^{-2} M_\odot$ yr^{-1}

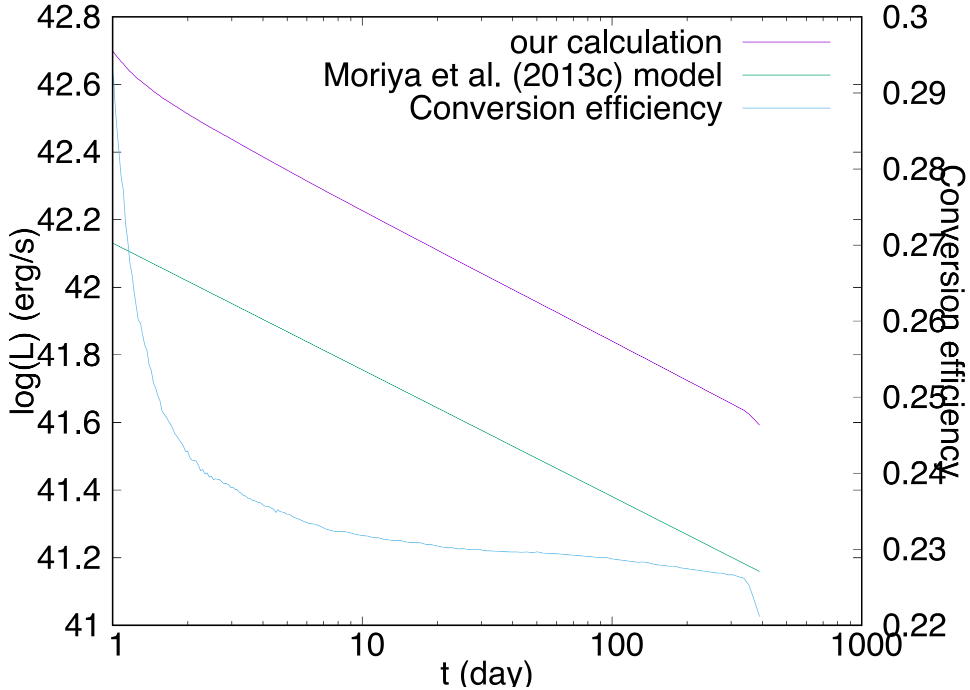
Inside Structure ($\boldsymbol{t} = \mathbf{100\ day}$)



$$n = 10, s = 2, E_{\rm ej} = 10^{51}\ {\rm erg}, \dot{M} = 10^{-2} M_\odot\ {\rm yr}^{-1}$$

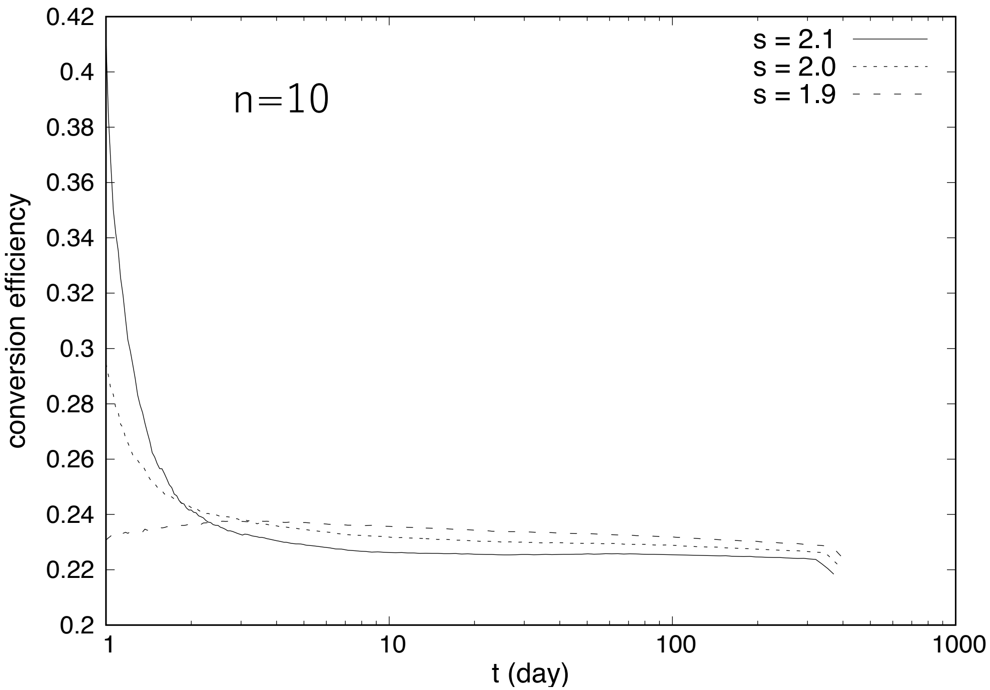
Comparing with Moriya et al. (2013)

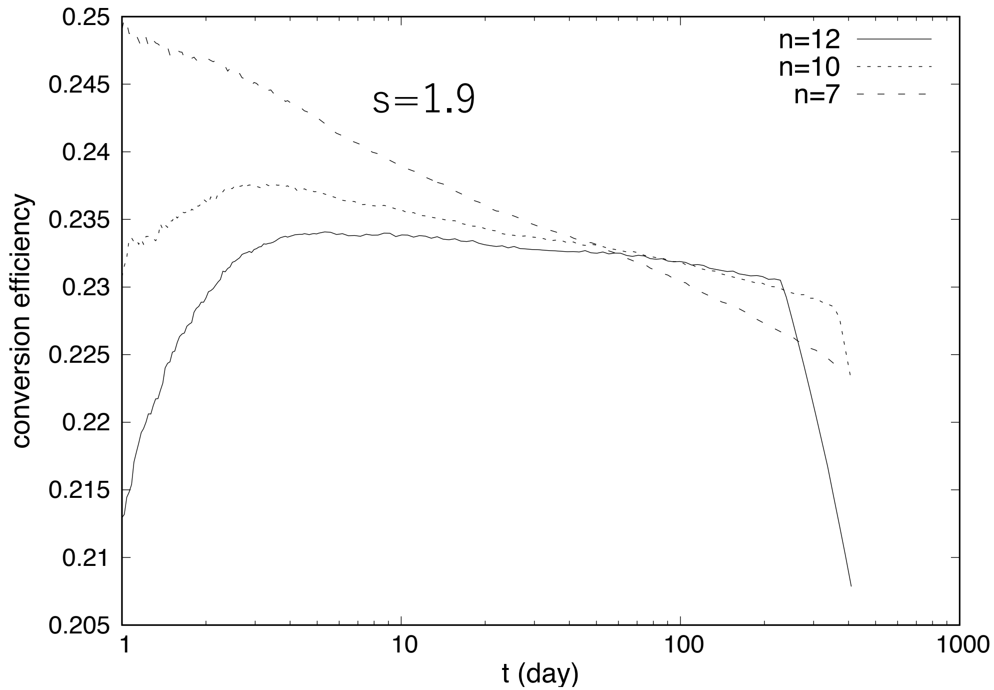




- This model is ~3-4 times brighter than that of Moriya et al. (2013)
- Forward shock velocity is larger than velocity obtained by Moriya et al. (2013), so $\epsilon = \frac{L}{2\pi\rho_{\rm CSM} r_{\rm fs}^2 v_{\rm fs}^3}$ become small.

Conversion Efficiency $(E_{\mathrm{ej}} = 10^{51}\ \mathrm{erg},\ \dot{M} = 10^{-2} M_{\odot}/\mathrm{yr})$

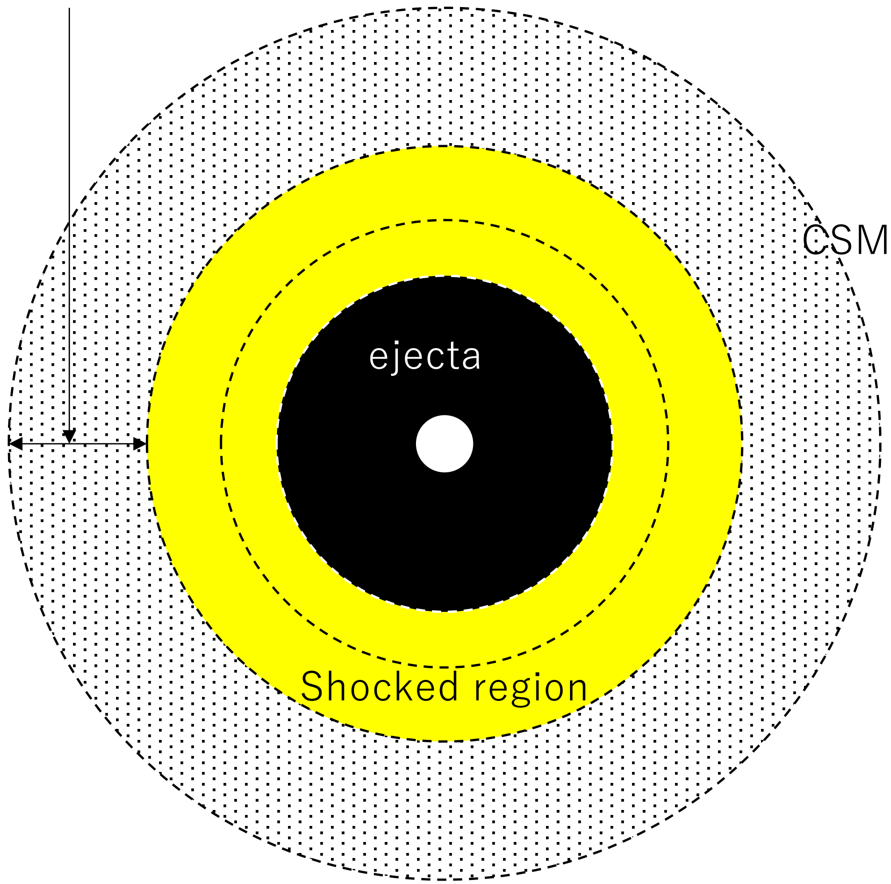




- Conversion efficiency is dependent on time, ejecta, CSM density profile.

Radiative Transfer Equations in CSM

- Radiation from forward shock goes through dotted black circle in the right picture and reaches observers.
- Solve radiative transfer equations in CSM



Radiative Transfer Equations in CSM

- Radiative transfer equations

$$\frac{\partial E}{\partial t} + \frac{\partial (r^2 F)}{r^2 \partial r} = 4\pi\eta_{\rm ff} - \kappa\rho c E$$

$$F = -\frac{c}{(\kappa+\sigma)\rho}\lambda\frac{\partial E}{\partial r}$$

$$\lambda = \frac{2+R}{6+3R+R^2},\ R = \frac{|\partial E/\partial r|}{(\kappa+\sigma)\rho E}$$ Levermore & Pomraning 1981

$$\rho\frac{\partial U}{\partial t} + \rho v_{\rm w}\frac{\partial U}{\partial r} + p v_{\rm w}\rho\frac{\partial \rho^{-1}}{\partial r} = \kappa\rho c E - 4\pi\eta_{\rm ff}$$

$$U = \frac{3}{2}\frac{kT_{\rm CSM}}{\mu m_{\rm p}}$$

Boundary conditions

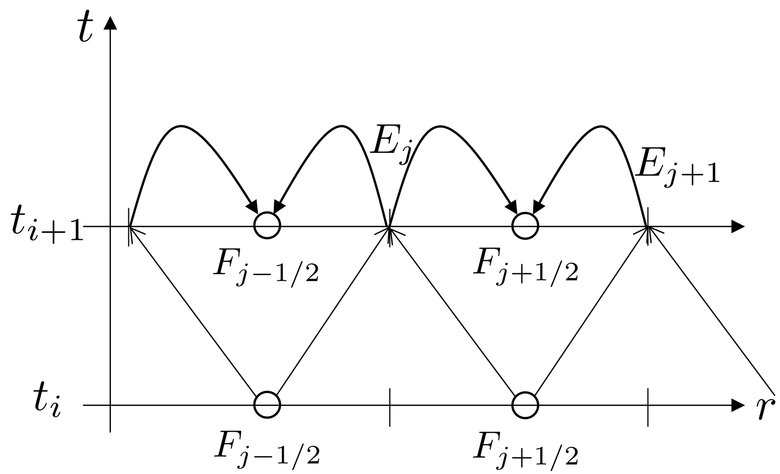
$$F(r_{\rm fs}) = F_{\rm fs}$$

$$E(r, t_{\rm ini}) = aT_{\rm CSM}^4$$

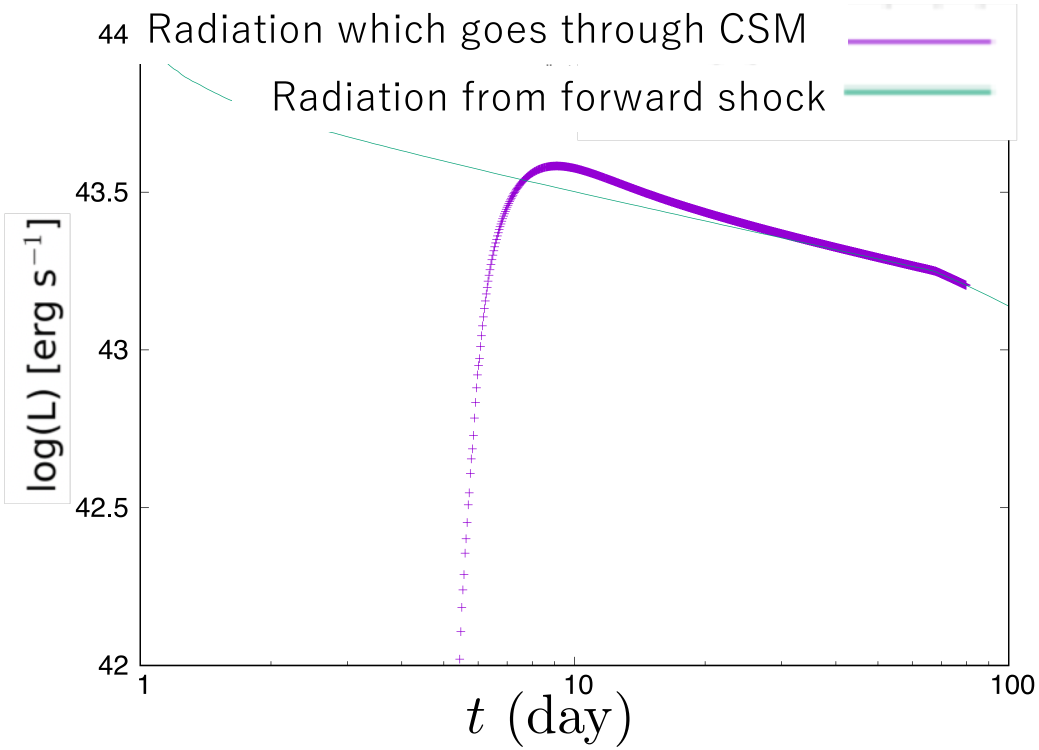
$$F(r < r_{\rm fin}, t_{\rm ini}) = 0$$

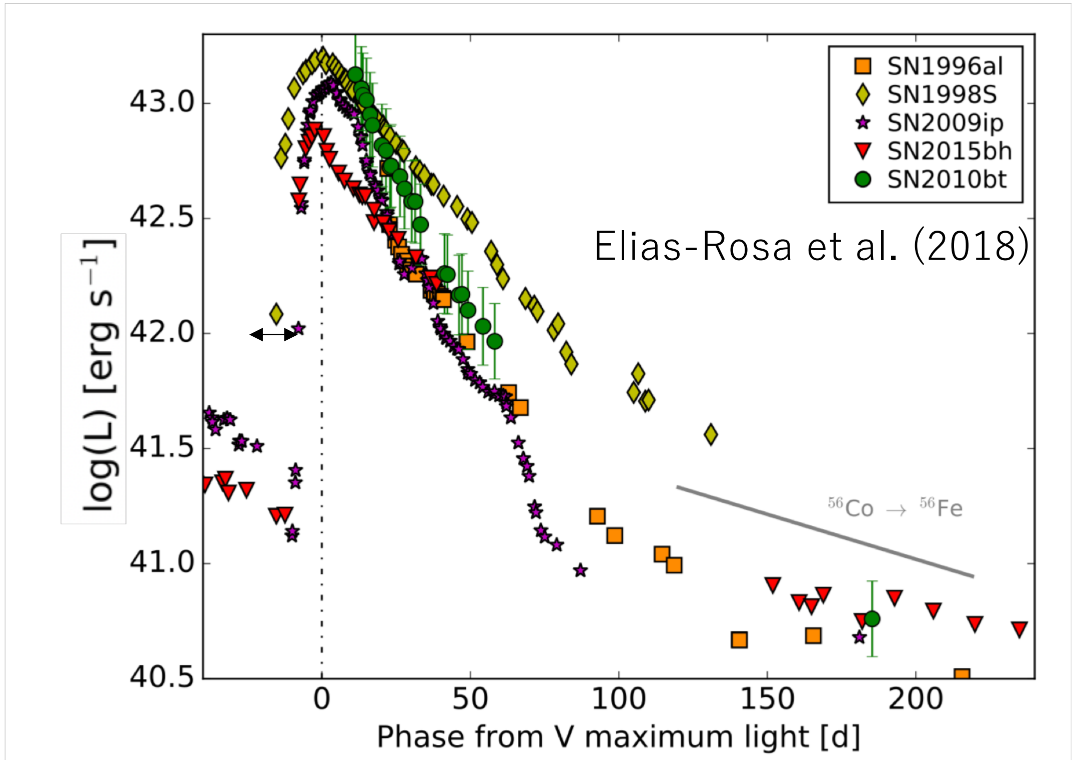
$$F(r_{\rm fin}, t) = cE$$

$$T_{\rm CSM} = 2000\ {\rm K}$$



Light Curve





n=12, s=2, $E_{ej}=10^{52}$ erg, $\dot{M} = 10^{-2}$/yr : peak luminosity~4×10^{43} erg/s

Conclusion and Future work

- **Conclusion**
- Luminosity can be explained by calculating the inside structure of SNe IIn between two shock fronts

➢ As a result, the calculated luminosity is ~3-4 times brighter than the calculation of Moriya et al. (2013)

- This research can explain the sharp rising light curve at early epoch.
- This realistic kinetic energy of 10^{52} erg can explain peak luminosity of $>10^{43}$ erg/s

- **Future work**
- Light curve model obtained by this work will be applied to the observed data of SNe IIn.
- Assuming that CSM density profile will be changed by outburst and CSM has broken power-law density profile, the calculation will be carried out.