A Light Curve Model for Interaction-Powered Supernovae (in progress)

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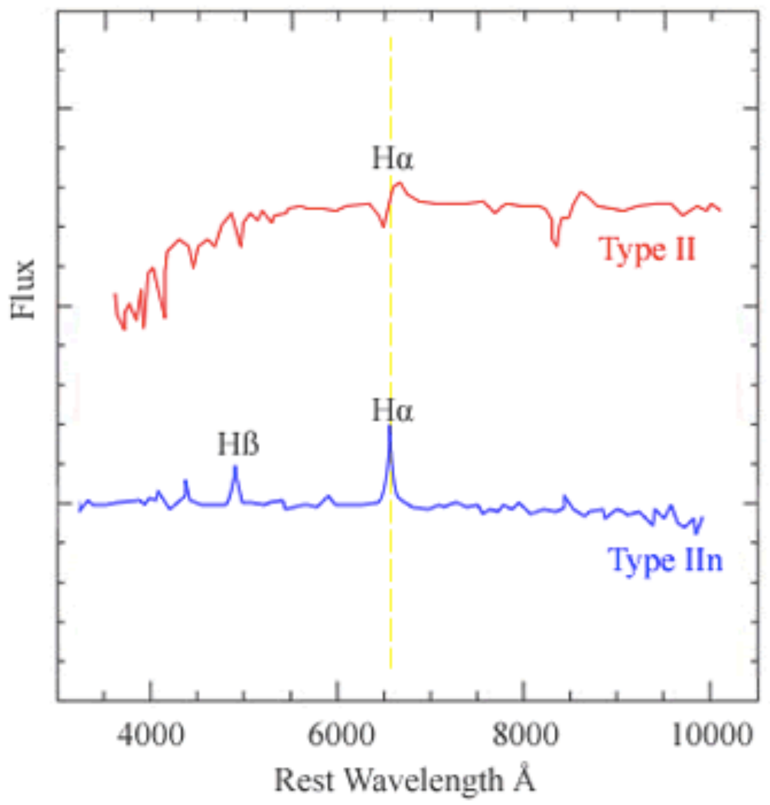
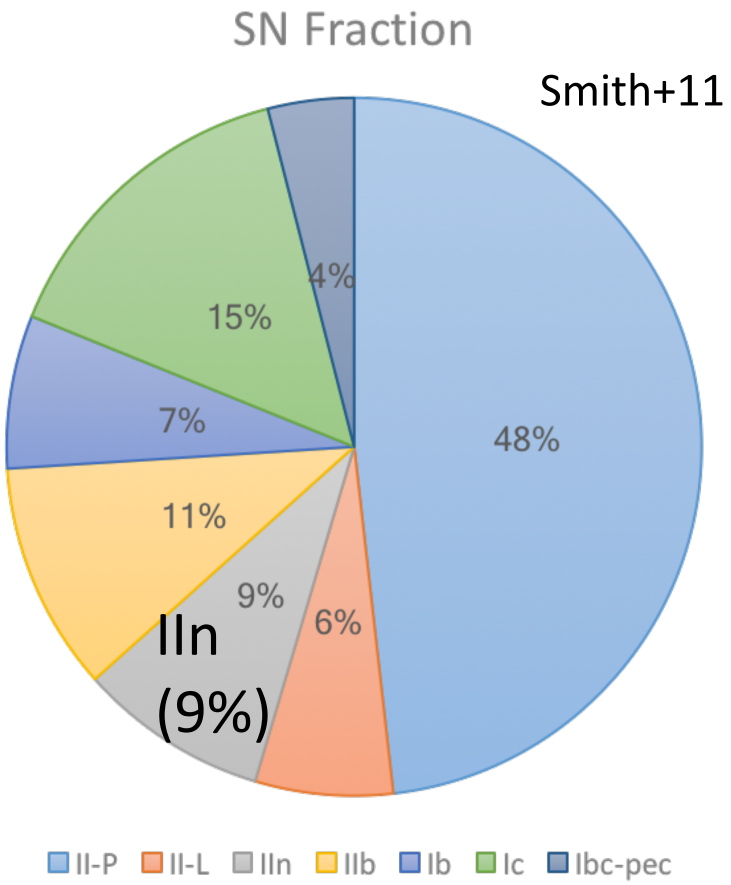
Interaction-powered Supernovae (Type IIn)



http://astronomy.swin.edu.au/cosmos/T/Type+IIn+Supernova



<u>~10% of SNe that have 'n'-arrow hydrogen line feature(s) in the spectrum</u>

Huge mass loss (probably) needed

$10^{-3} - 1 M_{\odot}$/yr

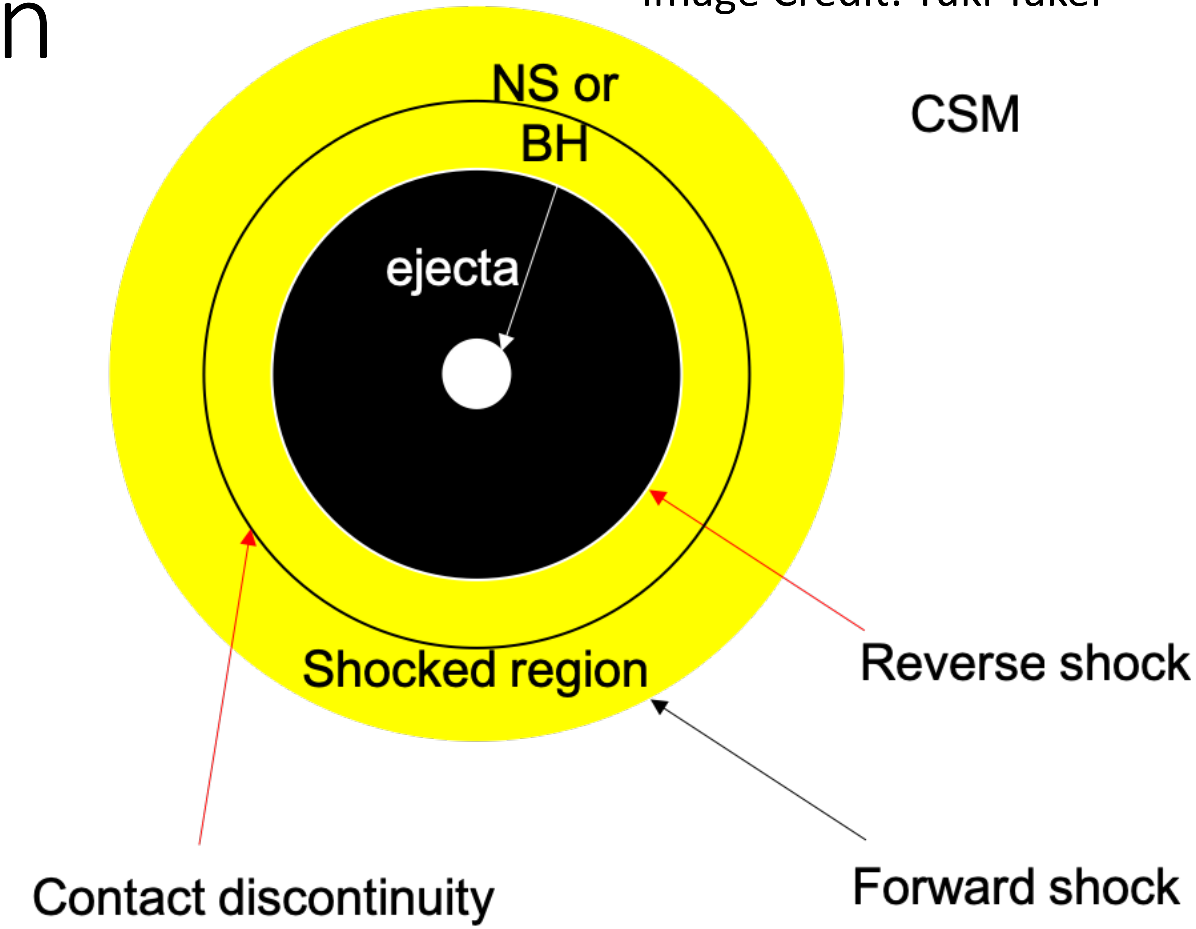
Table 9
Wind Velocities, Mass-loss Rates, and References for SNe IIn in the Literature

Supernova	Unshocked Wind Velocity (km s^{-1})	Shocked Wind Velocity (km s^{-1})	Mass-loss Rate ($M_{\odot}$ yr^{-1})	References
SN 1987F	150	6000	10^{-2}	[1] [2]
SN 1988Z	<200	1200–1800	7×10^{-4}–1.5×10^{-2}	[3] [4]
SN 1994W	1000	~4000	0.3	[5] [6]
SN 1994aj	1000	~3700	10^{-3}	[7]
SN 1995G	~1000	3000–4000	0.1	[8] [9] [10]
SN 1995N	<500	2500–5000	2×10^{-4}	[11] [12]
SN 1996L	1600	4800	10^{-3}	[13]
SN 1997ab	90	6600	10^{-2}	[14]
SN 1997eg	160	7000	8.3×10^{-3}	[15]
SN 1998S	30–100	N/A	10^{-4}–10^{-3}	[16]–[20]
SN 2005gl	420	1500	0.03	[21]
SN 2005ip	100–200	1100	2.2×10^{-4}	[22]
SN 2006gy	200	4000	0.1–1	[23] [24]
SN 2006tf	190	2000	0.1–4.1	[25]
SN 2008iy	100	5000	1–2×10^{-2}	[26]

Kiewe+ 12

Mechanism for Radiation

Image Credit: Yuki Takei



Fast SN ejecta and slow CSM collide

↓

Shock forms, which heats the ejecta and CSM

↓

Radiation is made in shock-heated region, propagates the CSM, and reaches the observer

- How to model these processes?
- Are current theoretical models consistent with observations?

Previous works

- Moriya+ (2013)

Analytical (phenomenological) model of the light curve

Simple model & easy to estimate ejecta & CSM parameters from observation

- Dessart+ (2015)

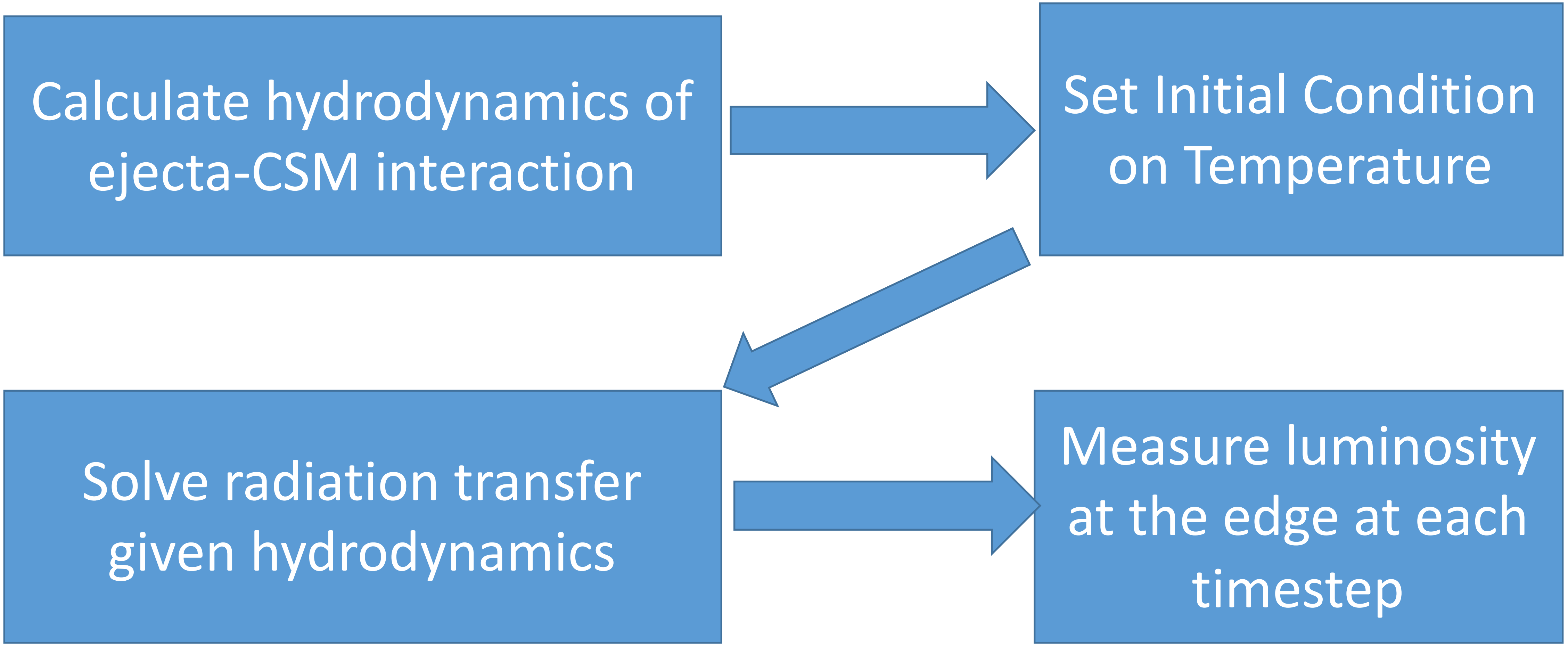
Non-LTE radiation hydrodynamics calculations

Roughly reproduces observational features of superluminous supernovae

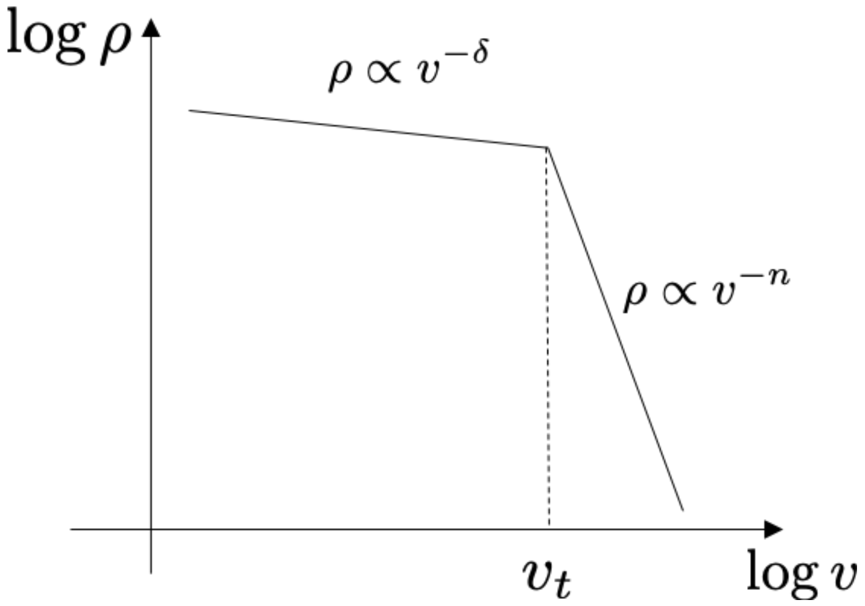
Both did not resolve the structure of the shocked region

➢A better model can be obtained by resolving shocked region? (Our work)

Methods: Overview



Methods (0): Parameters



Tested typical(?) parameter sets for Type IIn

Ejecta

- Mass $10M_{\odot}$, energy 10^{51}erg
- Density profile: broken power-law of velocity ($\delta = 1, n = 10$)

Matzner & McKee 99

CSM

- Stable wind mass-loss (rate $1\times10^{-3}M_{\odot}$/yr, wind velocity 10 km/s)
- Inner edge: 10^{14}cm、 Outer edge: 10^{16}cm (-> total mass ~ 0.3 $M_{\odot}$)

Methods (1): Hydrodynamics

- Self-similar solution by Chevalier (1982)

➢ p, ρ, v can be obtained as function of time

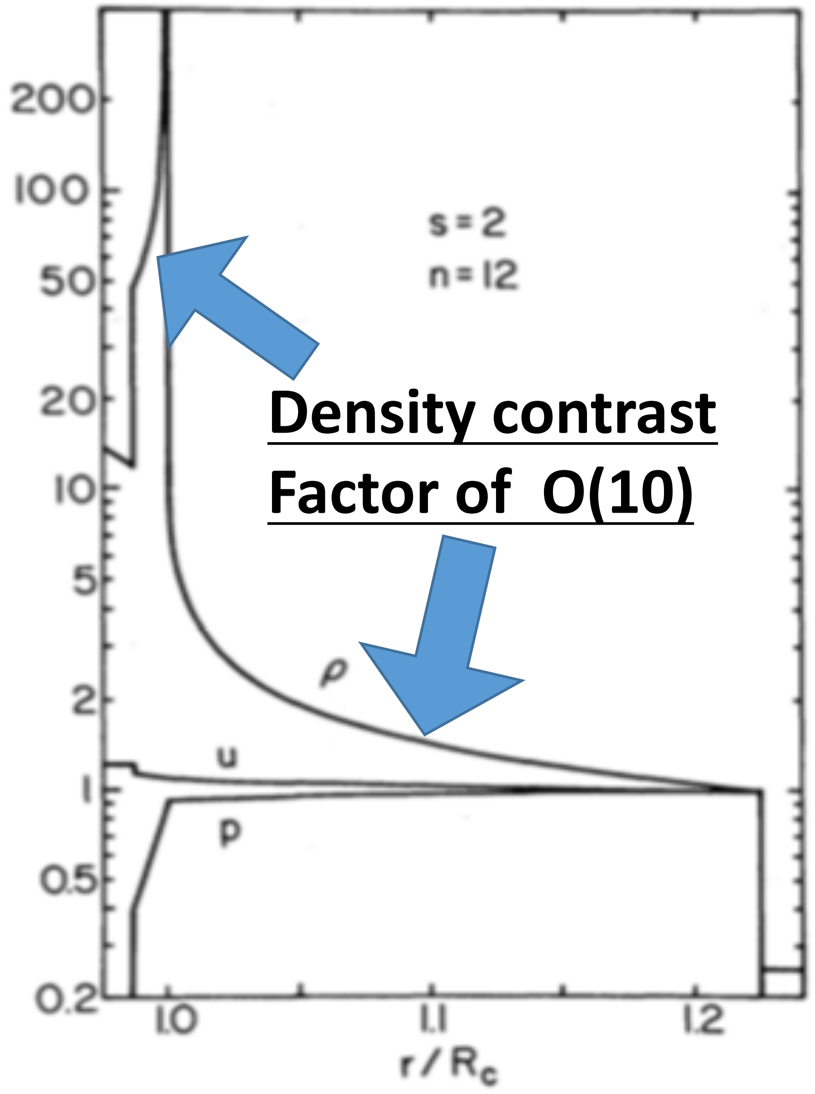
➢ Adiabatic solution, so can't fully incorporate radiation feedback onto hydrodynamics

(We *try*, by setting $\gamma = 1.2 < 4/3$)

- Inner shocked ejecta (HIGH density)

+ Outer shocked CSM (LOW density)

- The density contrast depends on the exact profile of ejecta & CSM, and adiabatic index



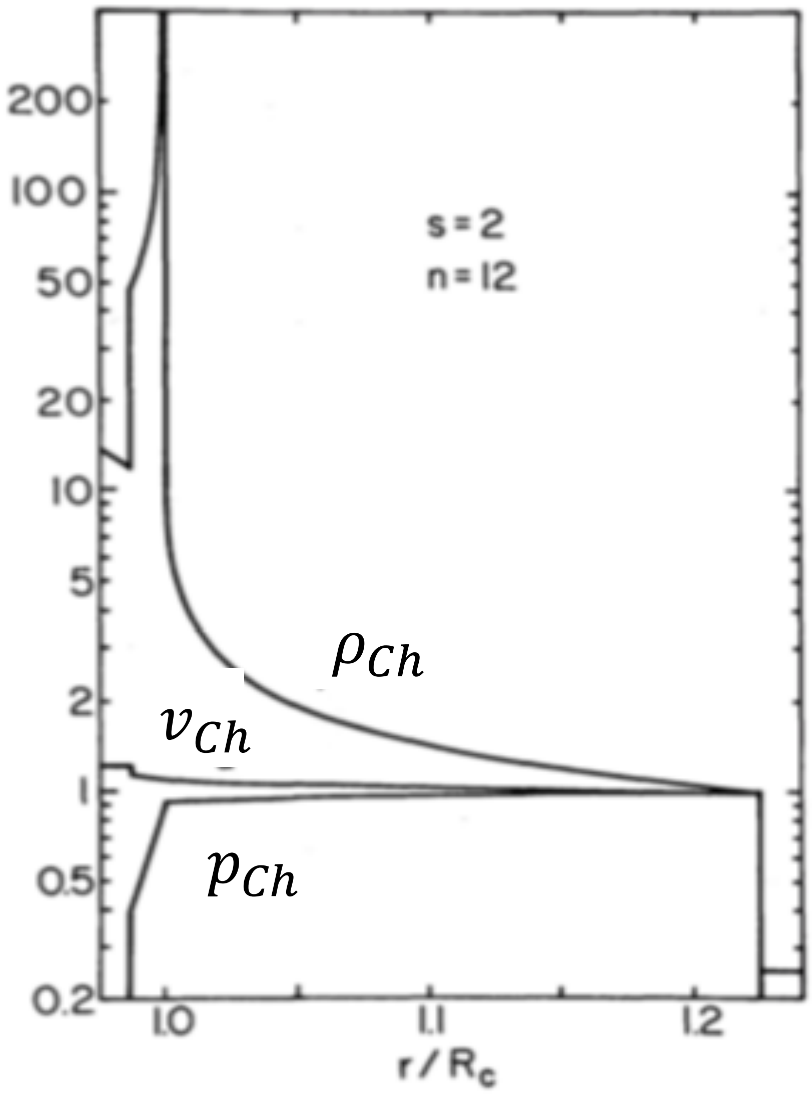
Chevalier (1982)

Methods (2): Initial Condition

Use Chevalier's solution for pressure, density, and velocity

Give (radiation) temperature from pressure by

$$p_{Ch} = \frac{1}{3} a T^4 + \frac{\rho_{Ch}}{\mu m_p} k_B T$$



μ:set to ≈ 0.62 assuming ionized gas of solar abundance

Methods (3): Radiation transfer

Flux-limited radiation transfer

- Optically thick case:

$$F = -\frac{c}{3\kappa\rho}\frac{\partial(aT^4)}{\partial r}$$

(Opacity κ comes from OPAL table assuming solar abundance)

- Optically thin case:

$$F = -acT^4 \, \mathrm{sign}(\partial T/\partial r)$$

- Obtain flux by interpolation of two cases (Levermore & Pomraning 81)

$$\lambda = \frac{2+|R|}{6+3|R|+|R|^2}$$

$$R = -\frac{1}{\kappa\rho}\frac{\partial(aT^4)/\partial r}{aT^4}.$$

→

$$F = -\frac{\lambda c}{\kappa\rho}\frac{\partial(aT^4)}{\partial r}$$

Methods (4): Radiation production at shock

Radiation from Shock heating:

- First the gas temperature increases

$$T_{gas} = \frac{\mu m_p p_{Ch}}{k_B \rho_{Ch}}$$

- Then photons are made by free-free emission within diffusion timescale

$$E_{rad} \sim aT_{rad}^4 \sim \epsilon_{ff} \cdot \frac{\min(\tau, 1)\, r}{c} \propto \rho^2\, T_g^{\frac{1}{2}}\, r \cdot \min(\tau, 1)$$

(Free-free emissivity)

★ Forw shock (low density) should be much less efficient at photon production than rev shock (high density)

Gas -> radiation efficiency

At reverse shock, free-free emission is strong enough that radiation & gas reach equilibrium

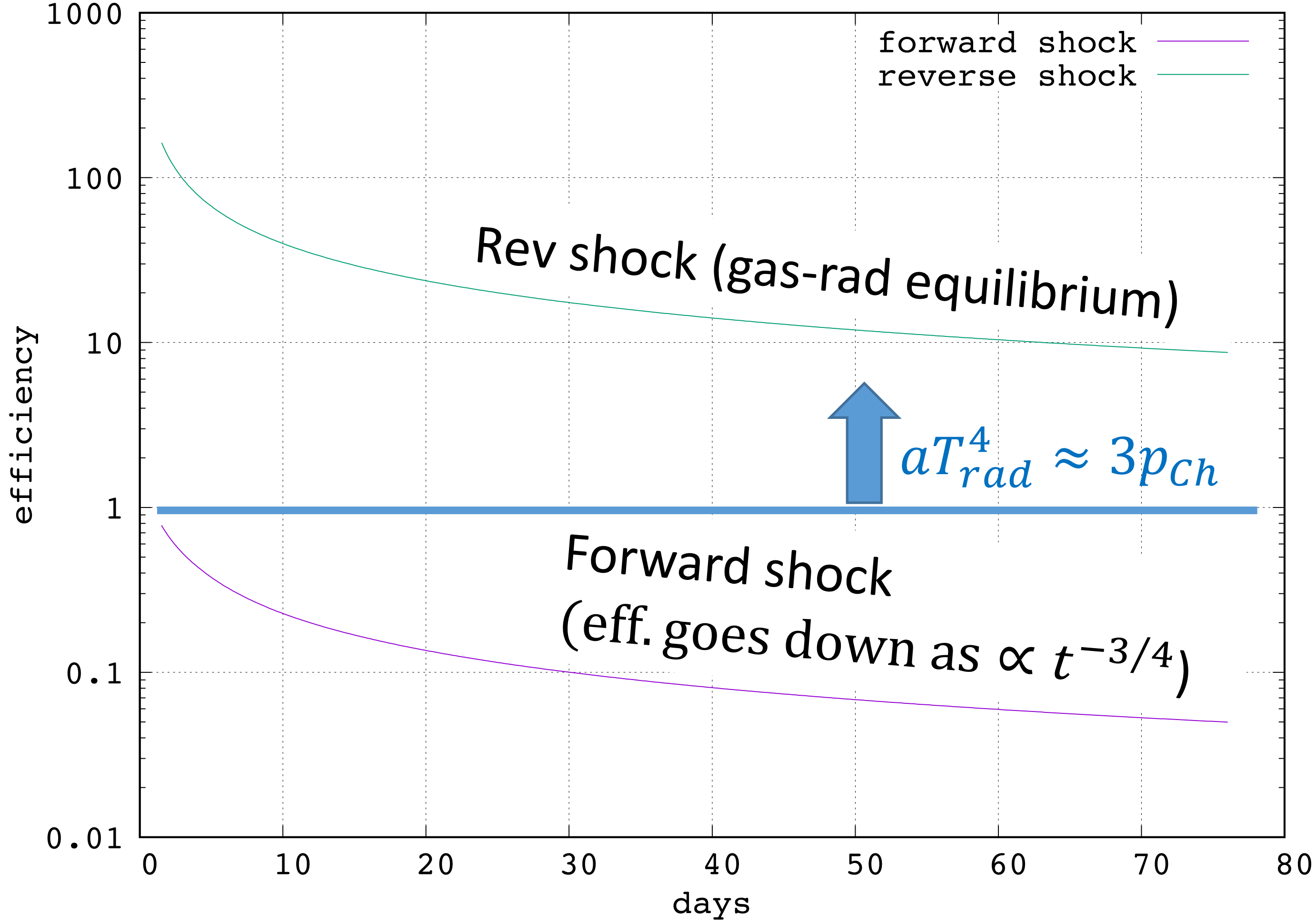
$$p_{Ch} \approx \frac{1}{3} a T_{rad}^4$$

gives temperature T_{rad}

@forward shock, radiation energy is limited by free-free emission within diffusion timescale

$$a T_{rad}^4 = \epsilon_{ff} \cdot \frac{\min(\tau, 1)\, r}{c}$$

$$\frac{\text{(Rad. density that can be supplied by free–free within diff time)}}{\text{(Rad. density assuming equilibrium } e_{\text{rad}} = aT_{rad}^4 \approx 3p_{Ch}\text{)}}$$



Result (Light curve)

<u>Early phase</u>

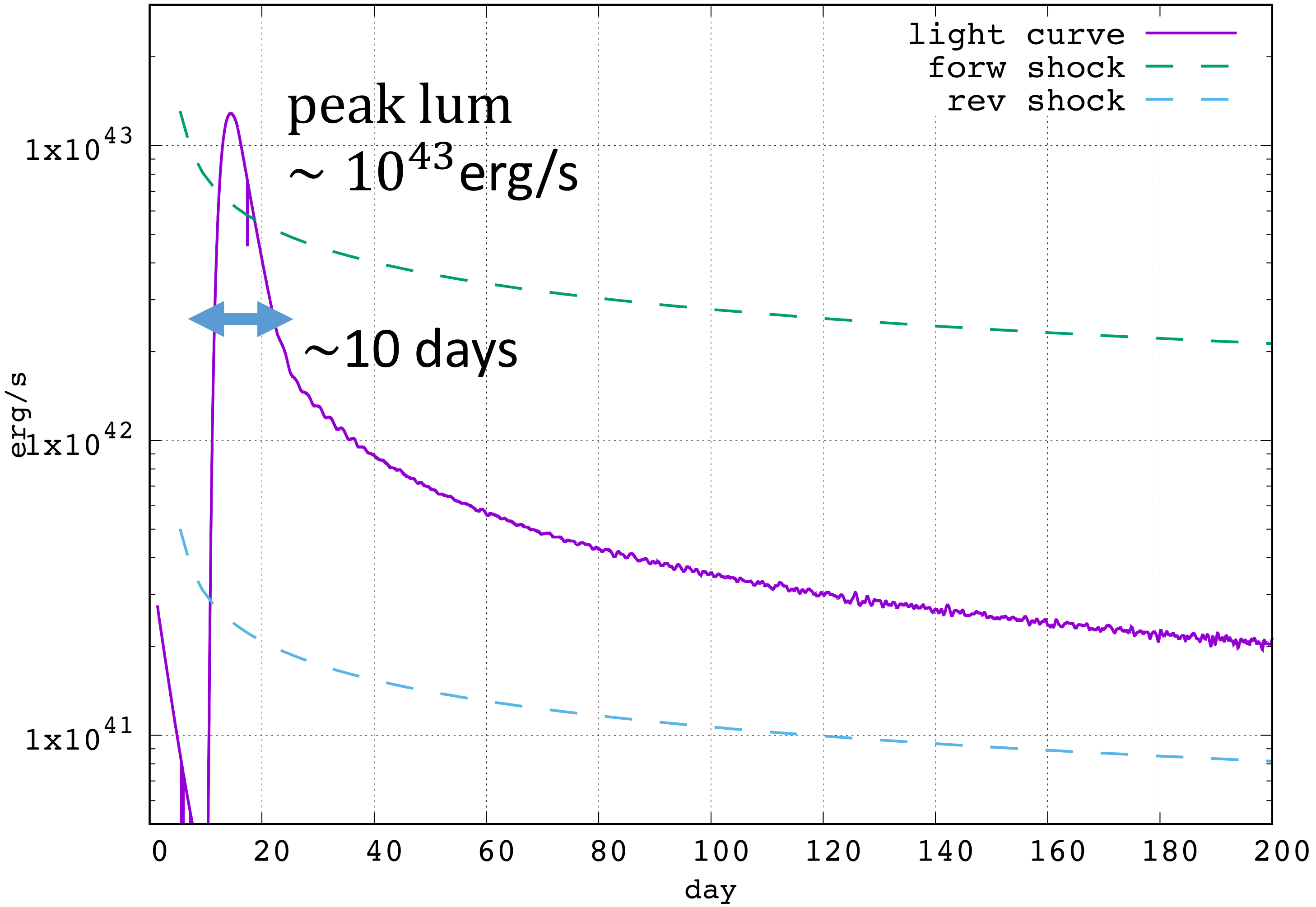
Photons diffusing out CSM makes a sharp rise in the light curve

- Peak luminosity $\approx 10^{43}$erg/s
- Timescale ~ 10 days

Timescale roughly consistent w/ diffusion timescale in CSM

$$t_d \sim \frac{\kappa M_{CSM}}{4\pi R_{Sh}\, c}$$

$$\sim 8\ \mathrm{day}\,\frac{\kappa}{0.3}\,\frac{M_{CSM}}{0.3 M_\odot}\left(\frac{R_{Sh}}{10^{15}\mathrm{cm}}\right)^{-1}$$



(R_{Sh}: radius of shock at peak)

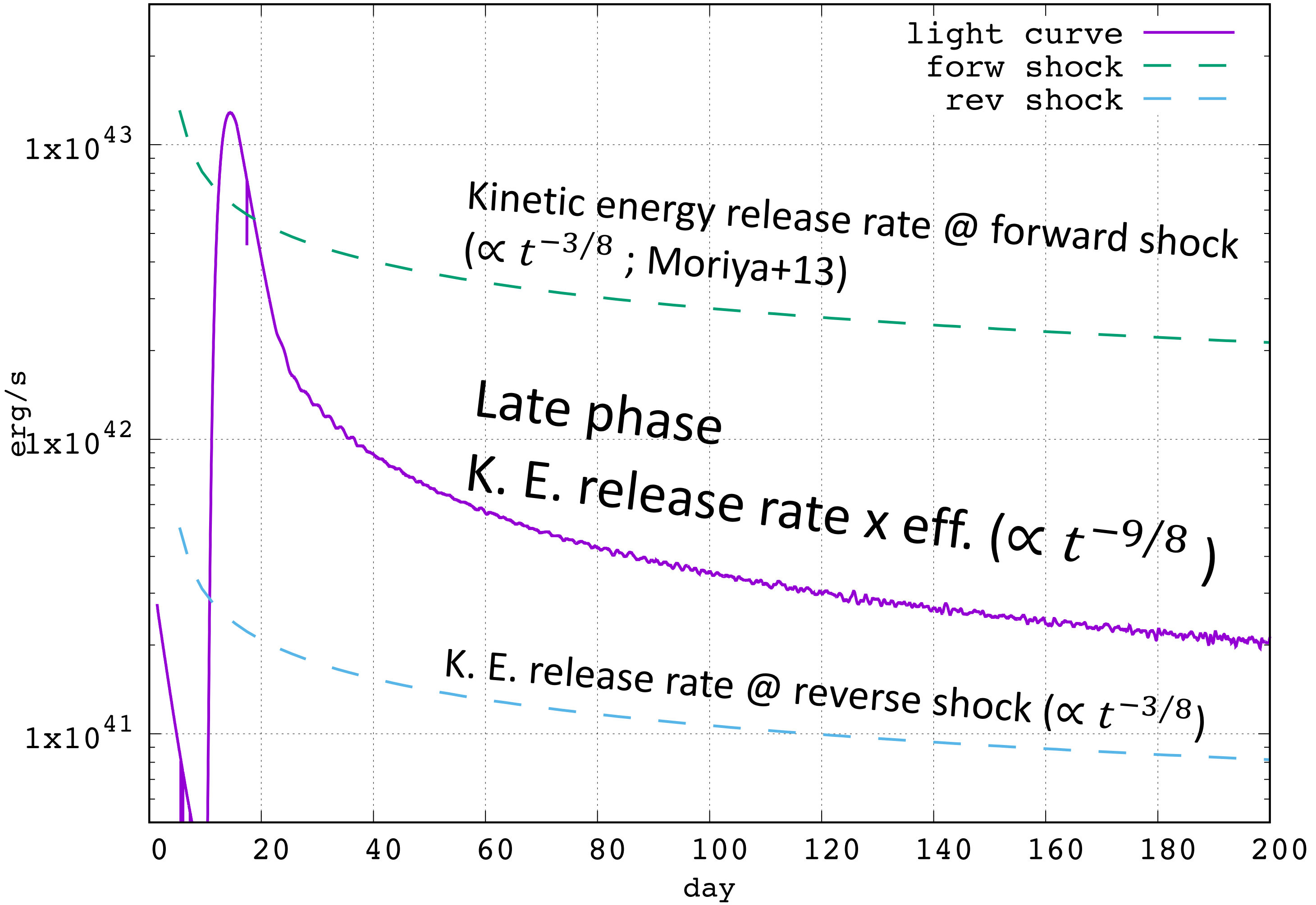
Result (Light curve)

Late phase

Light curve monotonically decays
(With time dependence given by
Energy release rate @ fwd shock &
radiation efficiency @ fwd shock)

- Energy release rate $\propto t^{-3/8}$
- Radiation efficiency $\propto t^{-3/4}$

$\Longrightarrow L \propto t^{-9/8}$



Conclusion

- We calculated the light curve of interaction-powered supernovae, resolving the radial profile inside the shocked region.

- At the early phase we find the luminosity peak that comes from photons created in the shocked region, diffusing out the CSM.

- At the late phase the luminosity comes from photons generated at the forward (and reverse) shock front, reflecting the decreasing efficiency at the forward shock.

Future work

- We have only tested a small number of parameter set, and results should vastly depend on parameters

➢ Parameter survey & comparison with observations important

- Our better treatment of the forward shock may have some applications, e.g.

➢ Calculating non-thermal emission from shock-heated electrons

➢ Collision-less shock acceleration -> hadronic process (-> high-energy neutrino)

May give multi-wavelength (messenger?) observational predictions of Type IIn SNe