2025/11/19
The third annual conference
@Naruko kanko hotel

Dust formation in confined circumstellar material: its impact on kilonova surveys

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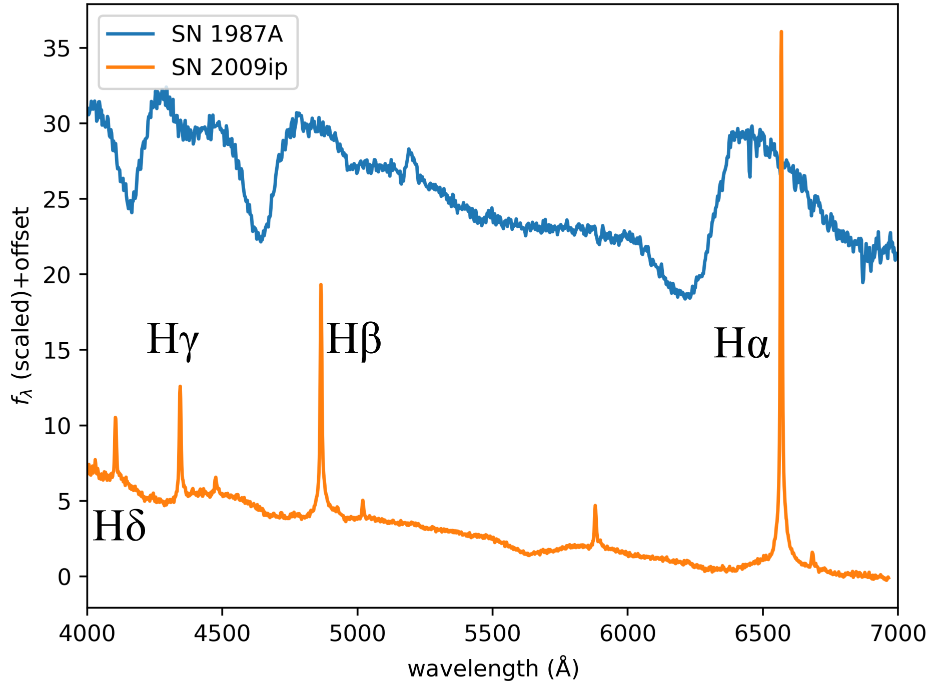
ApJ, 992, 137, arXiv: 2507.22763

Circumstellar material (CSM)

- SNe IIn show narrow hydrogen emission lines in their spectrum
  - ➢Indicate the presence of the slowly-moving dense gas around the progenitor
  - ➢Called CSM

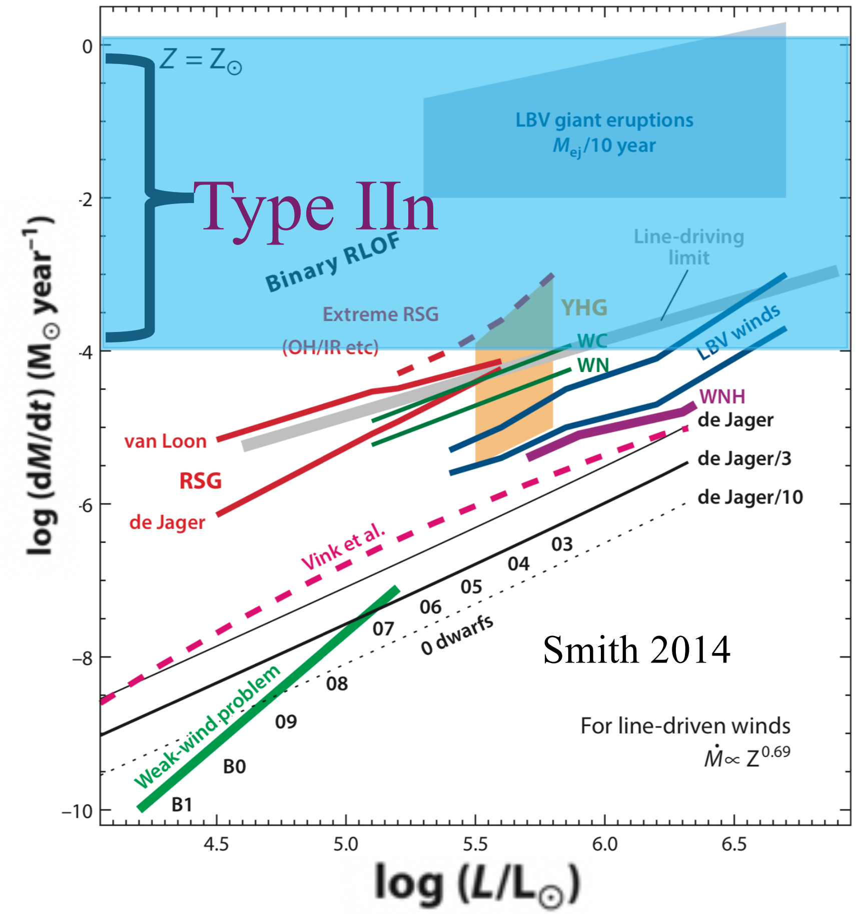


Why SNe IIn?

Conventional stellar evolution theory:
Hydrostatic equilibrium

Observations of SNe IIn have revealed
the dynamical evolution stage

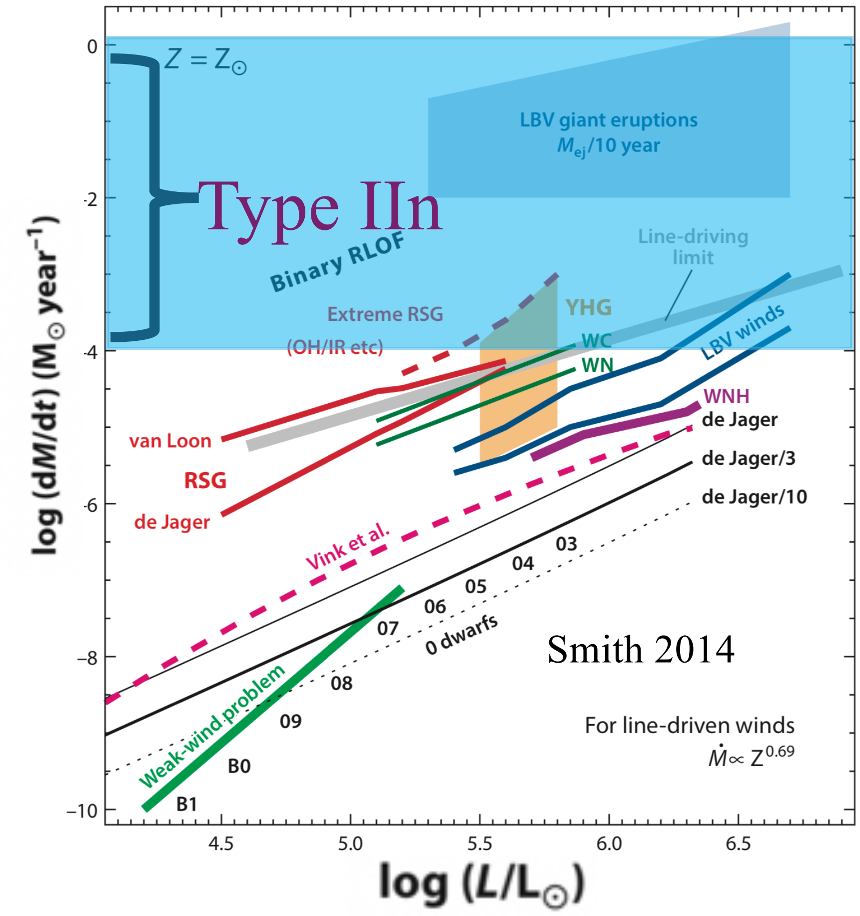
IIn: strong mass-loss!



Why SNe IIn?

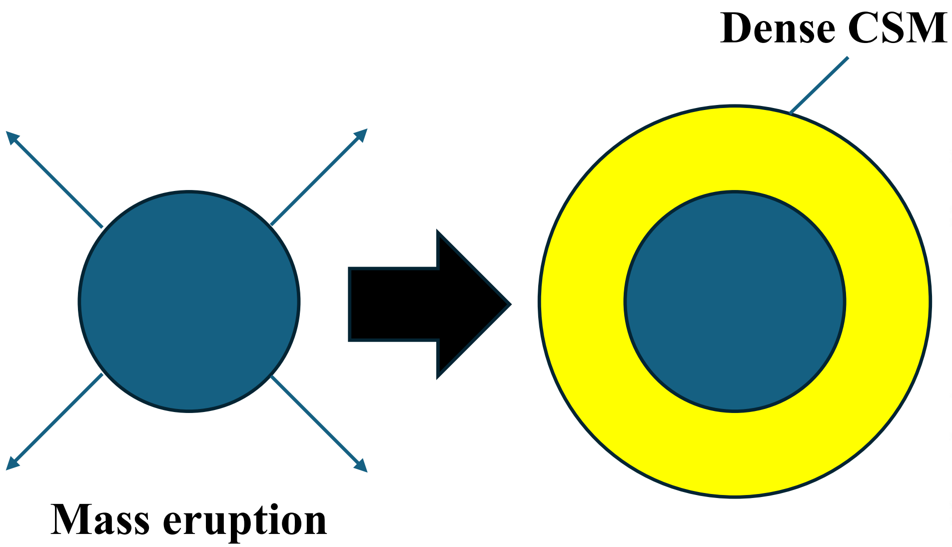
CSM studies can reveal the final stages of massive star evolution!

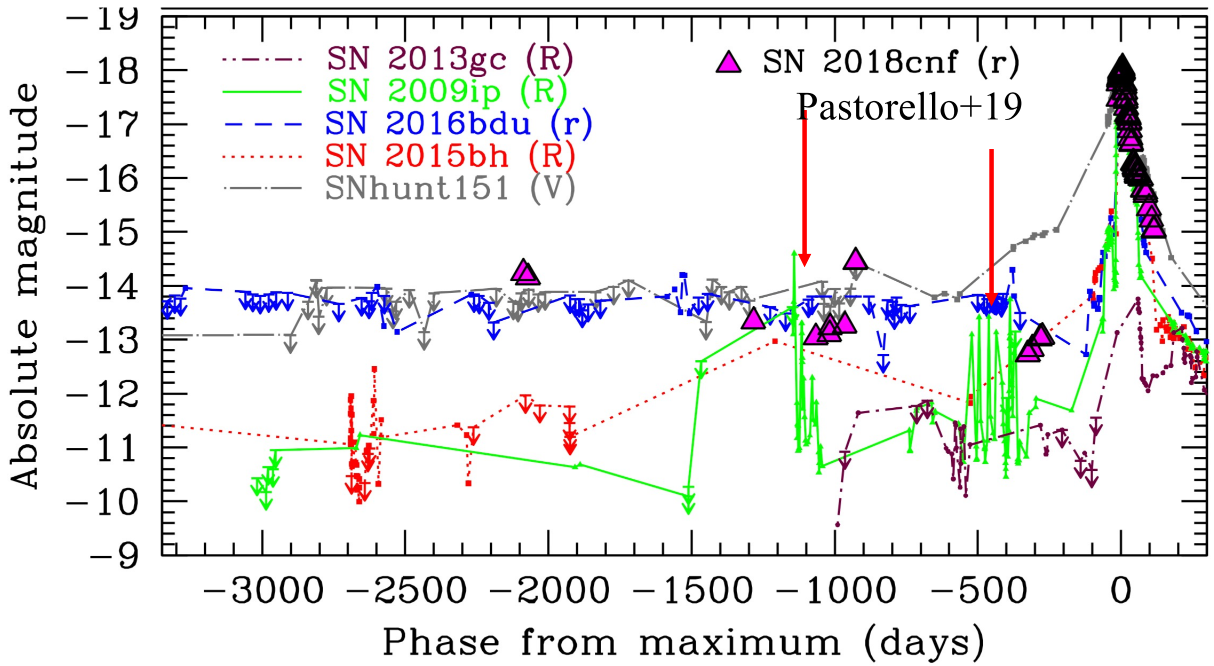
IIn: strong mass-loss!



Mass eruption prior to SN

- In some cases, outburst(s) are observed a few months – years before the SN explosion (e.g., Pastorello+07; Mauerhan+13)

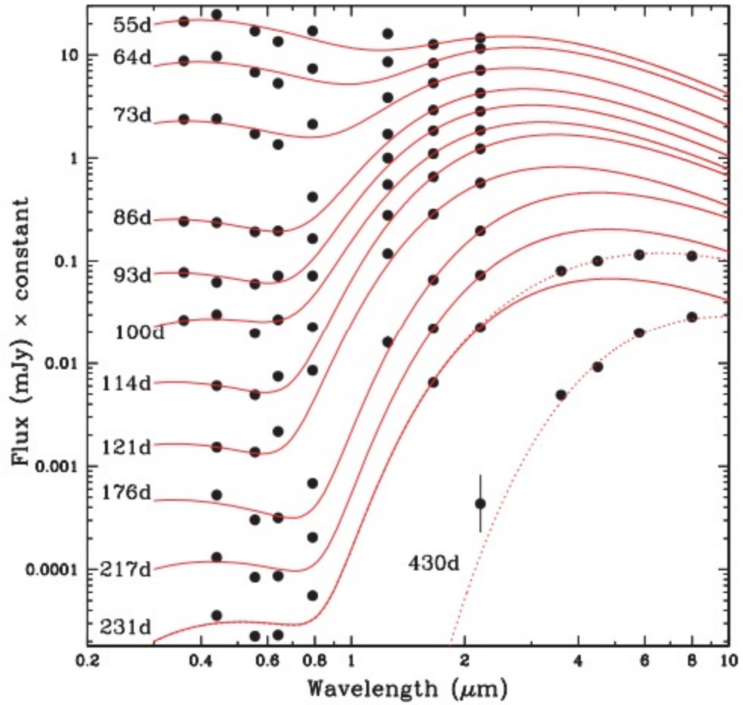




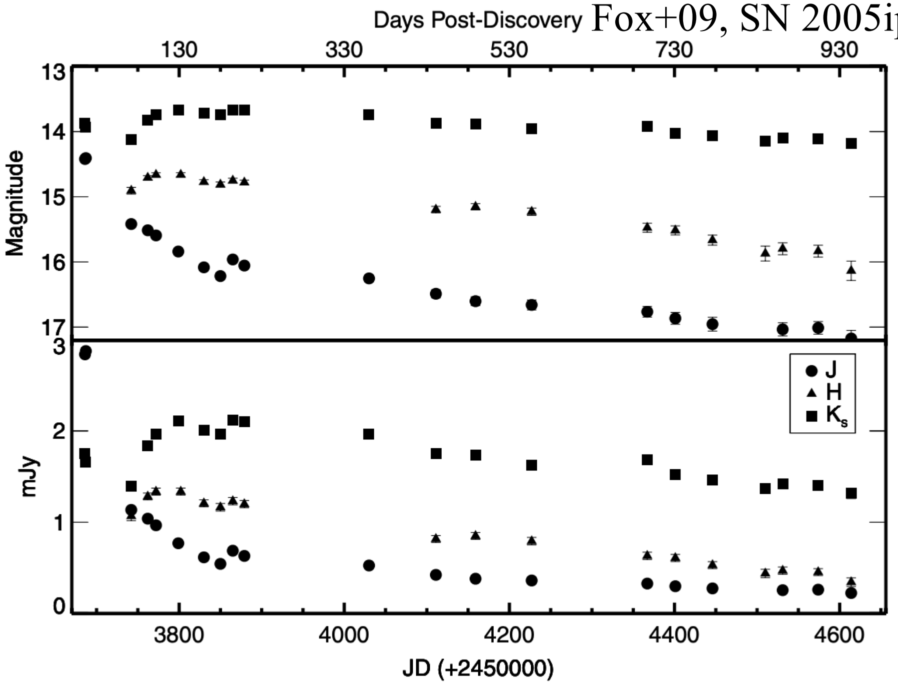
Dust formed in SNe IIn/Ibn

- IR excess is observed in some SNe IIn/Ibn
  - ➢IR excess indicates newly formed dust

Mattila+08, SN 2006jc (Ibn)



Fox+09, SN 2005ip (IIn)

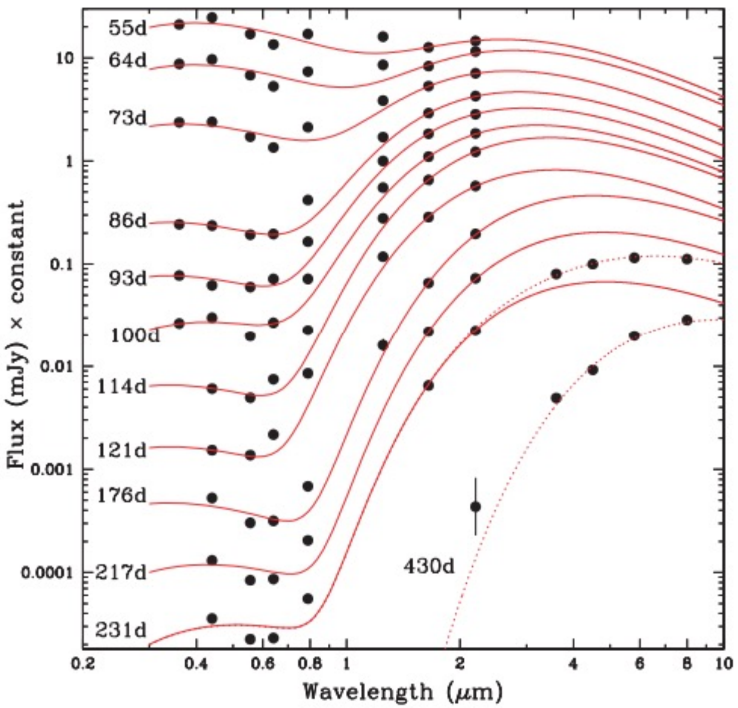


Dust formed in SNe IIn/Ibn

- IR excess is observed in some SNe IIn/Ibn
  - ➢IR excess indicates newly formed dust

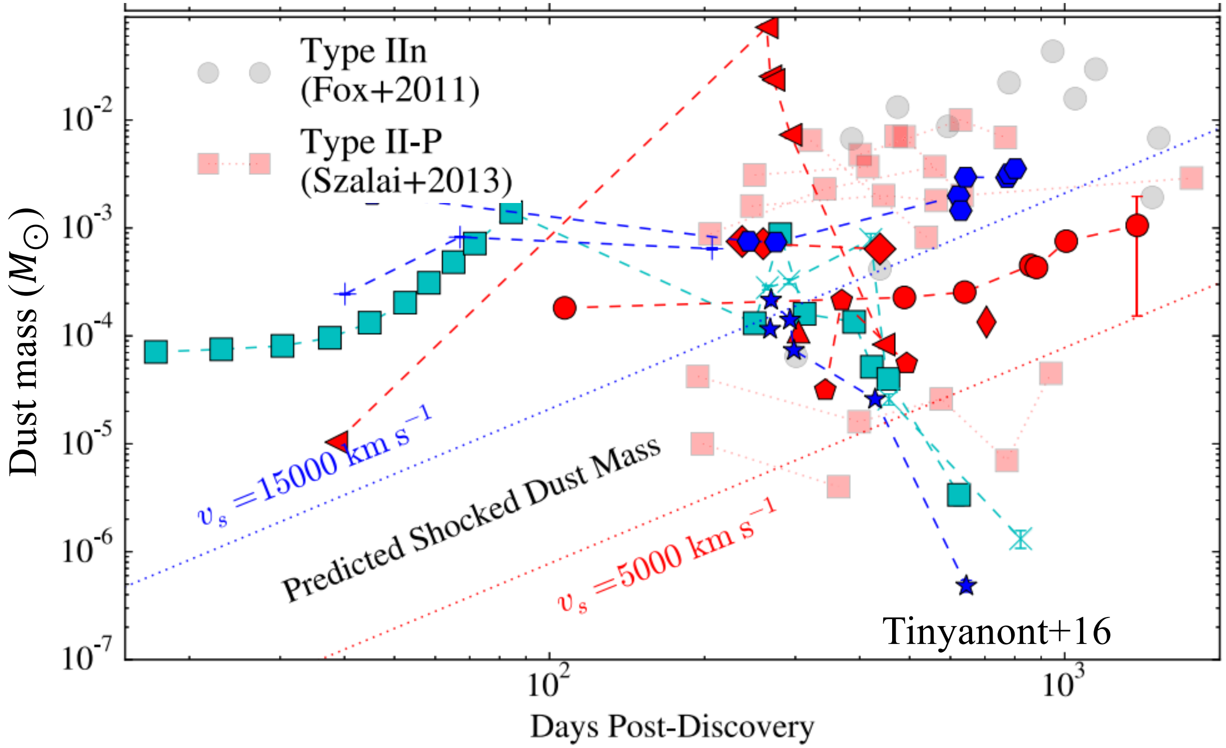
Does the presence of CSM make dust formation more likely?

Mattila+08, SN 2006jc (Ibn)



Comparison of observed dust

- Compared with other SNe (such as Type IIP), the observed dust mass is larger (e.g., Fox+11; Szalai+13)



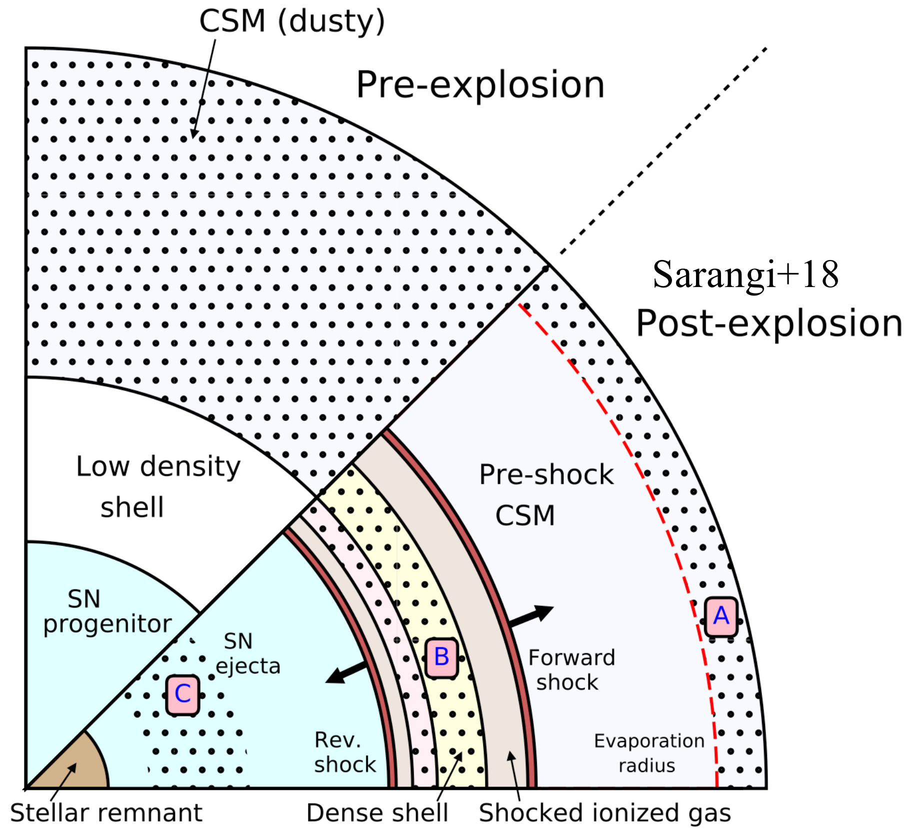
Dust formation site in SNe

- (A) Pre-existing dust in the stellar wind (e.g., Bode & Evans 80)

- (B) Dust formation in cold dense shell (CDS) formed in the shocked region between SN and CSM (e.g., Pozzo+04)

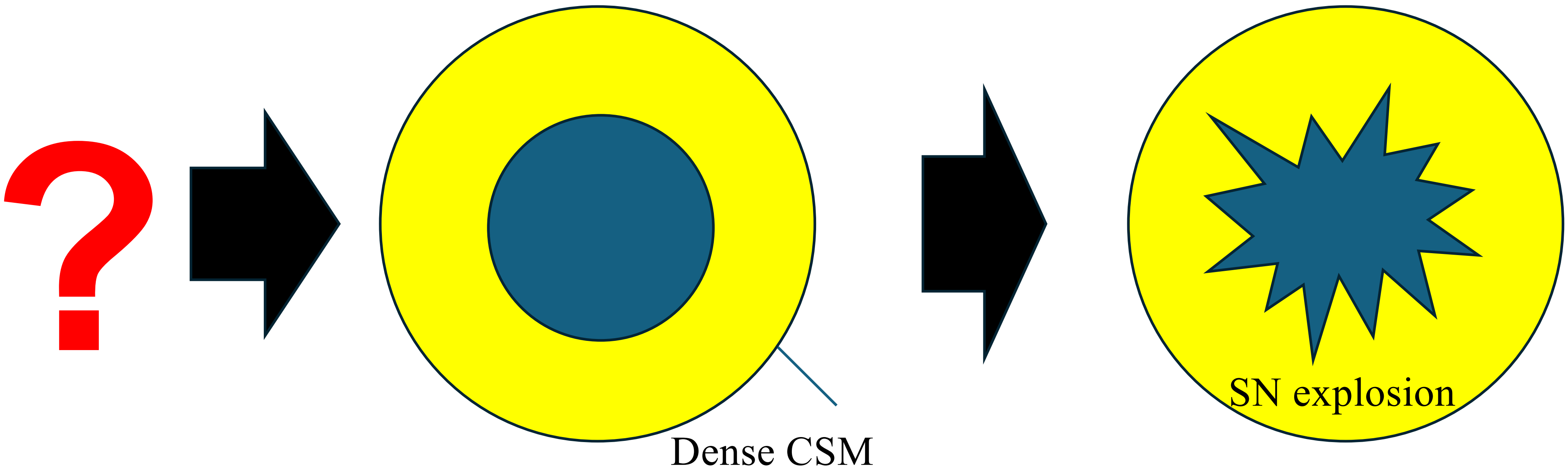
Very important!!

- (C) Dust formation in SN ejecta (e.g., Todini & Ferrara 2000)



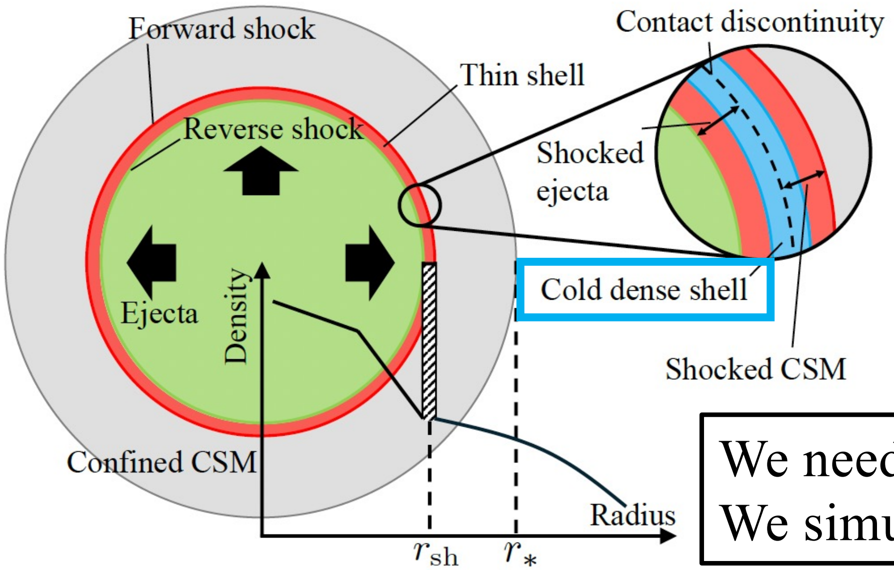
“Confined” CSM

- It has been revealed that many SN II progenitors are surrounded by compact CSM with a radius of $\lesssim 10^{15}$ cm (e.g., Förster+18; Bruch+23)
  - ➢More than ~40% of SNe II?? CSM is more universal than previously thought



New dust formation site in confined CSM

- Inspired by the dust formation in SNe IIn, we model the interaction between SN ejecta and confined CSM, and dust formation
- We do not solve the dust formation itself, but evaluate the density of the CDS at the temperature below which atoms can condense into dust



We need ejecta and CSM profiles!
We simulate CSM formation…

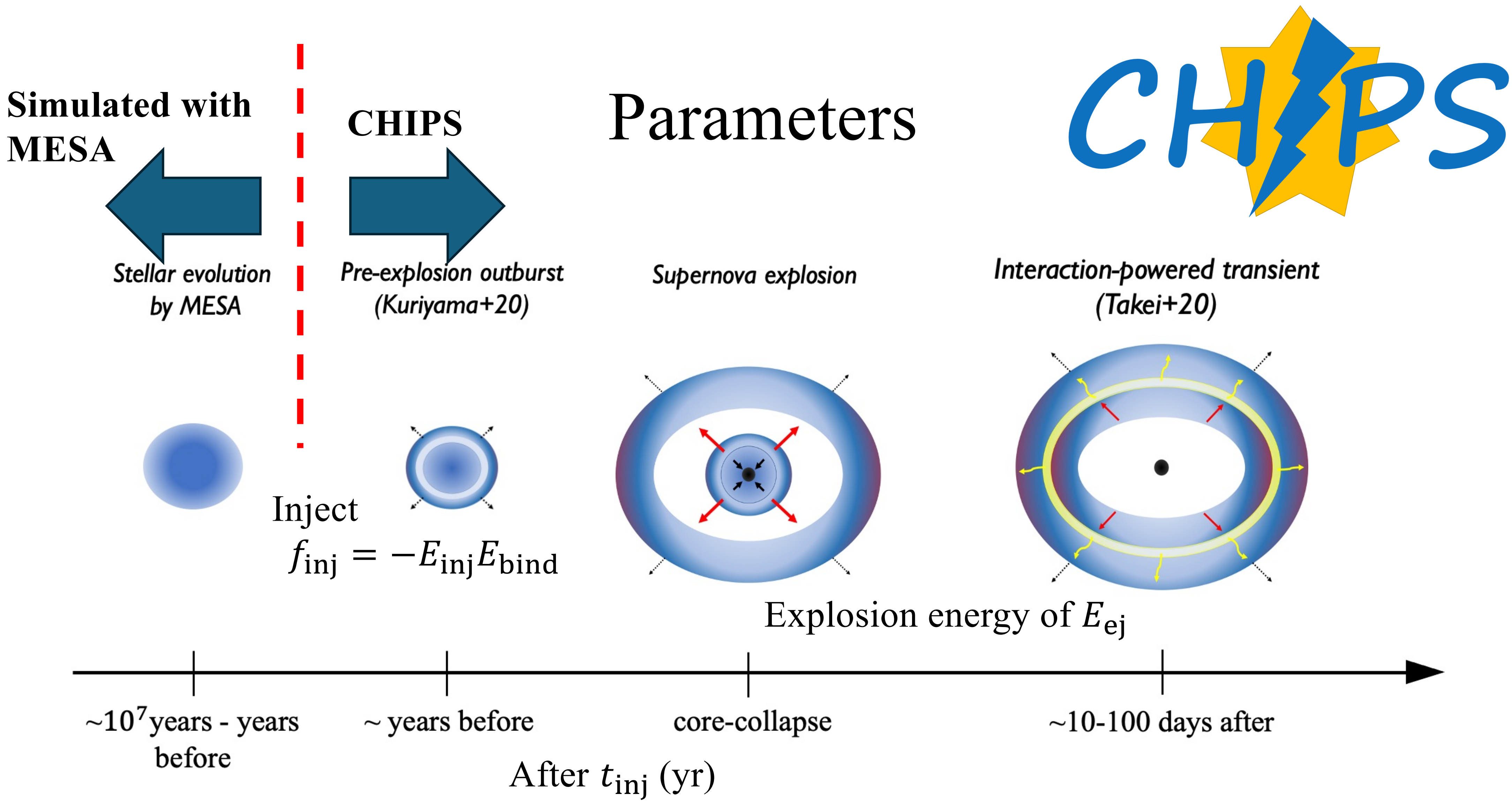
CHIPS project

YT, Tsuna, Kuriyama, Ko, Shigeyama 2022
YT, Tsuna, Ko, Shigeyama 2024
https://github.com/DTsuna/CHIPS

Open-source code aimed to unveil the
Complete History of Interaction-Powered Supernovae

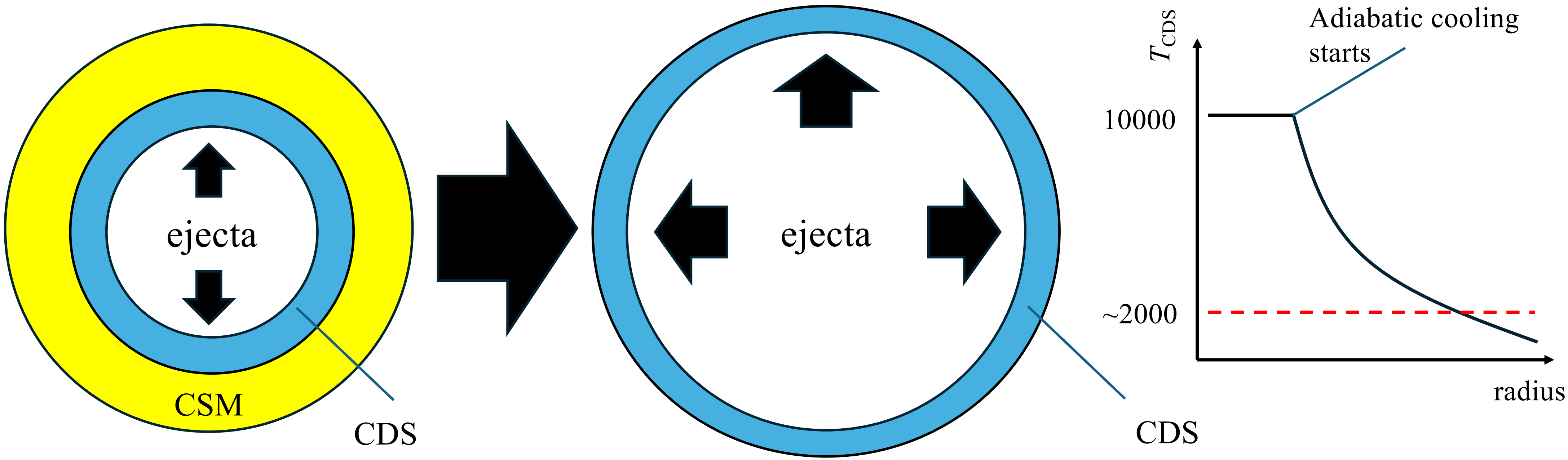
Parameters

- M_{ZAMS} ($M_{\odot}$): Initial mass (we have sample models of 13, 14, …, 26 solar masses)
- f_{inj}: Energy injected at the base of the stellar envelope, scaled with the envelope's binding energy (order of 0.1-1)
- t_{inj} (yr): Time from energy injection to core-collapse
- E_{ej} (erg): Explosion energy of supernova
- M_{Ni} ($M_{\odot}$): Nickel mass (newly implemented in ver. 2.0)


Simulated with MESA
CHIPS
Parameters
CHIPS
Stellar evolution by MESA
Pre-explosion outburst (Kuriyama+20)
Supernova explosion
Interaction-powered transient (Takei+20)
Inject
$f_{\rm inj} = -E_{\rm inj} E_{\rm bind}$
Explosion energy of $E_{\rm ej}$
$\sim 10^7$ years - years before
~ years before
core-collapse
~10-100 days after
After $t_{\rm inj}$ (yr)

Evolution of temperature/density of CDS

- During the interaction between the ejecta and the CSM, T_{CDS} rapidly drops to ~10^4K, following the cooling function (assumption)
- Adiabatic cooling starts after the shock passes through the CSM



Location and mass of CDS

- Determine the position by thin-shell approximation (e.g., Moriya+13)

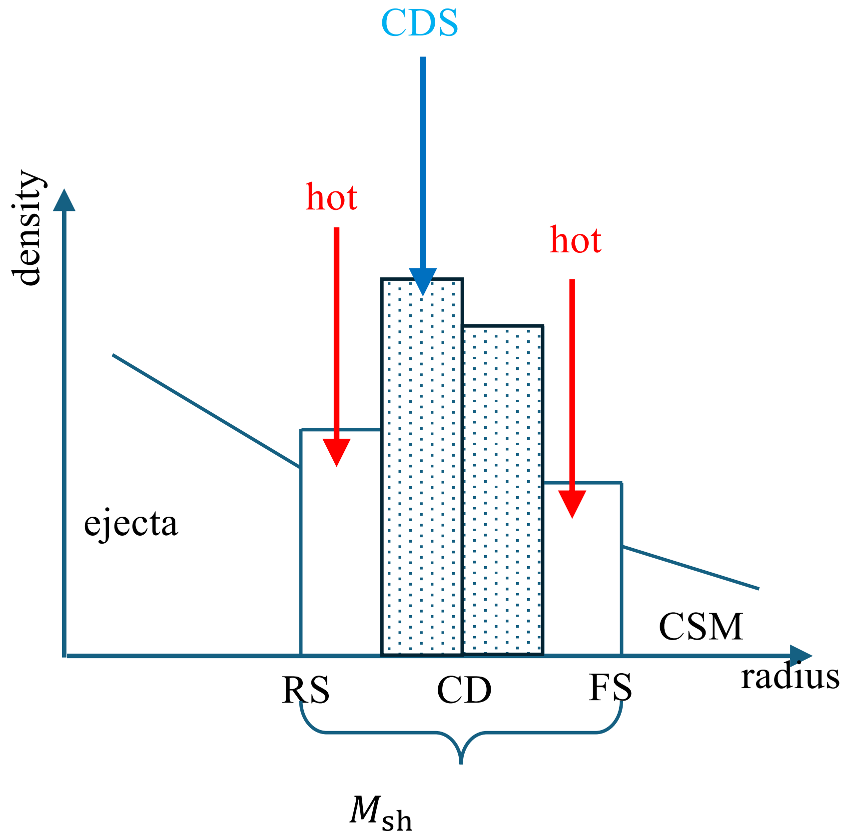
$$\frac{dM_{\rm sh}}{dt} = 4\pi r_{\rm sh}^2 \left[\rho_{\rm ej}(u_{\rm sh} - v_{\rm ej}) + \rho_{\rm CSM}(u_{\rm sh} - v_{\rm CSM})\right], \quad (6)$$

$$M_{\rm sh}\frac{du_{\rm sh}}{dt} = 4\pi r_{\rm sh}^2 \left[\rho_{\rm ej}(u_{\rm sh} - v_{\rm ej})^2 - \rho_{\rm CSM}(u_{\rm sh} - v_{\rm CSM})^2\right], \quad (7)$$

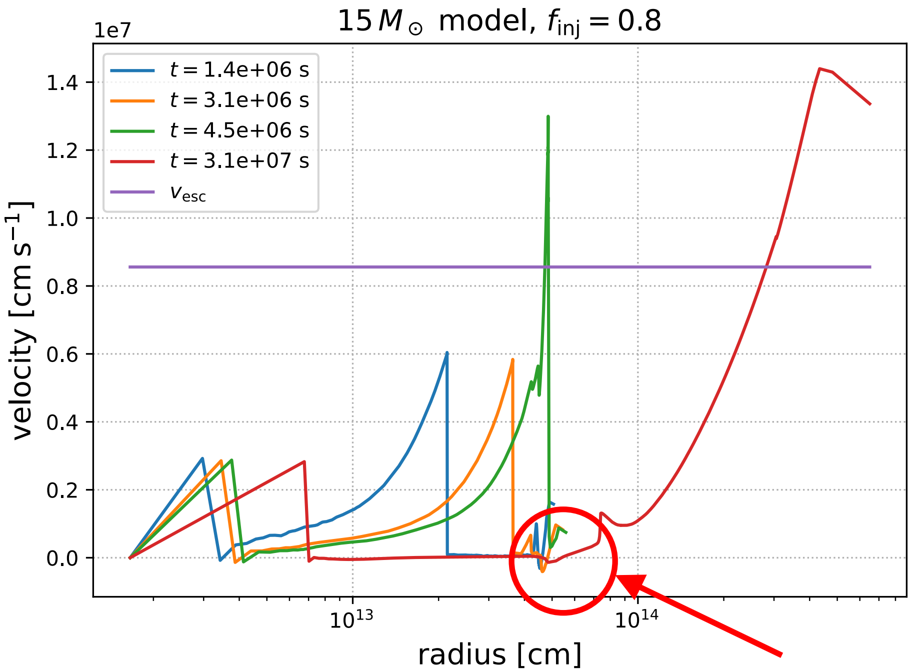
- We consider that the shock-heated shell settles into the CDS on the cooling timescale $\tau_{\rm cool}$

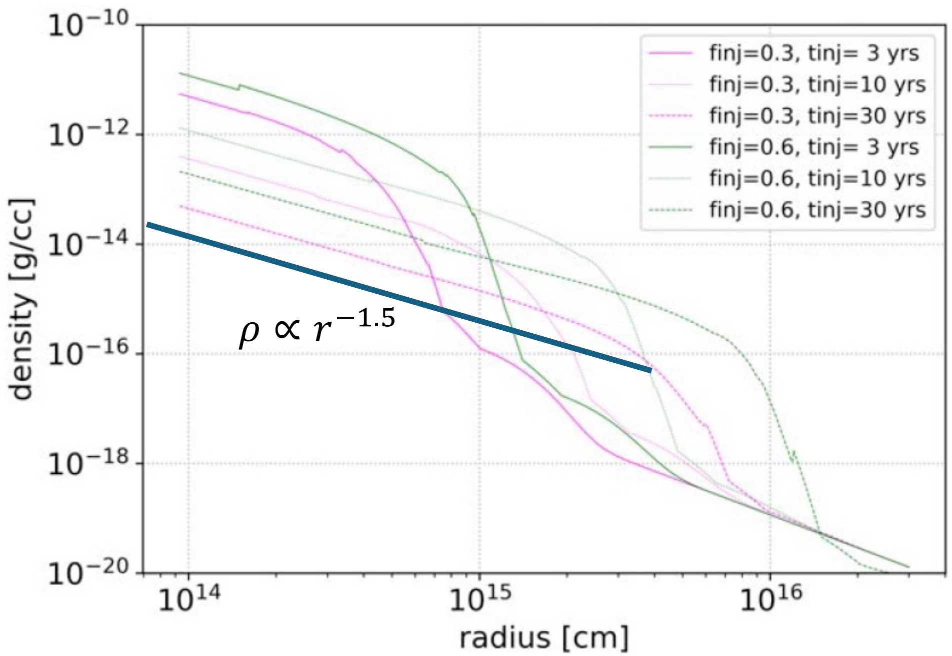
$$\frac{dM_{\rm CDS}}{dt} \sim \frac{M_{\rm hot}}{\tau_{\rm cool}},$$

$$M_{\rm CDS} = M_{\rm sh} - M_{\rm hot},$$



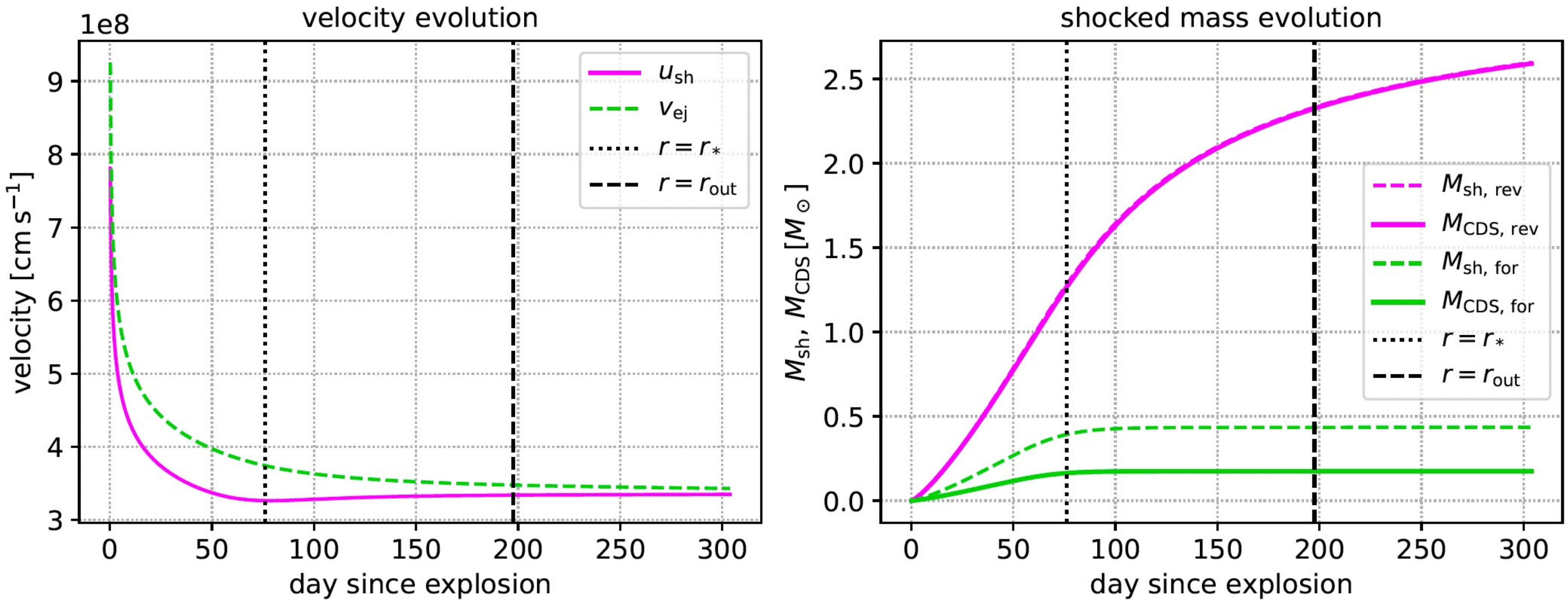
Simulation: Mass Eruption





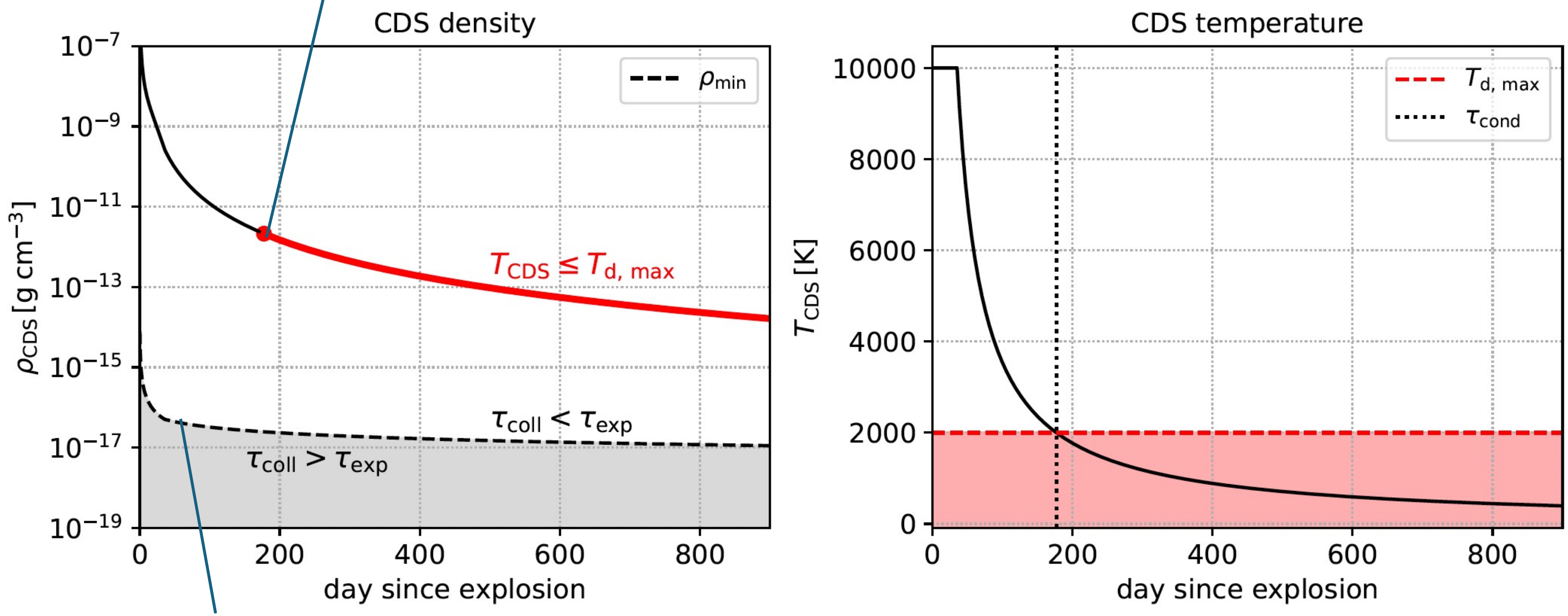
Partial ejection of the envelope results in the fallback of the inner CSM, which makes **the inner profile of $\boldsymbol{\rho \propto r^{-1.5}}$** (shallower profile compared to stellar wind, $\boldsymbol{\rho \propto r^{-2}}$) (Kuriyama & Shigeyama 20; Tsuna, YT+21)

The evolution of velocity and mass of CDS



Density/temperature evolution

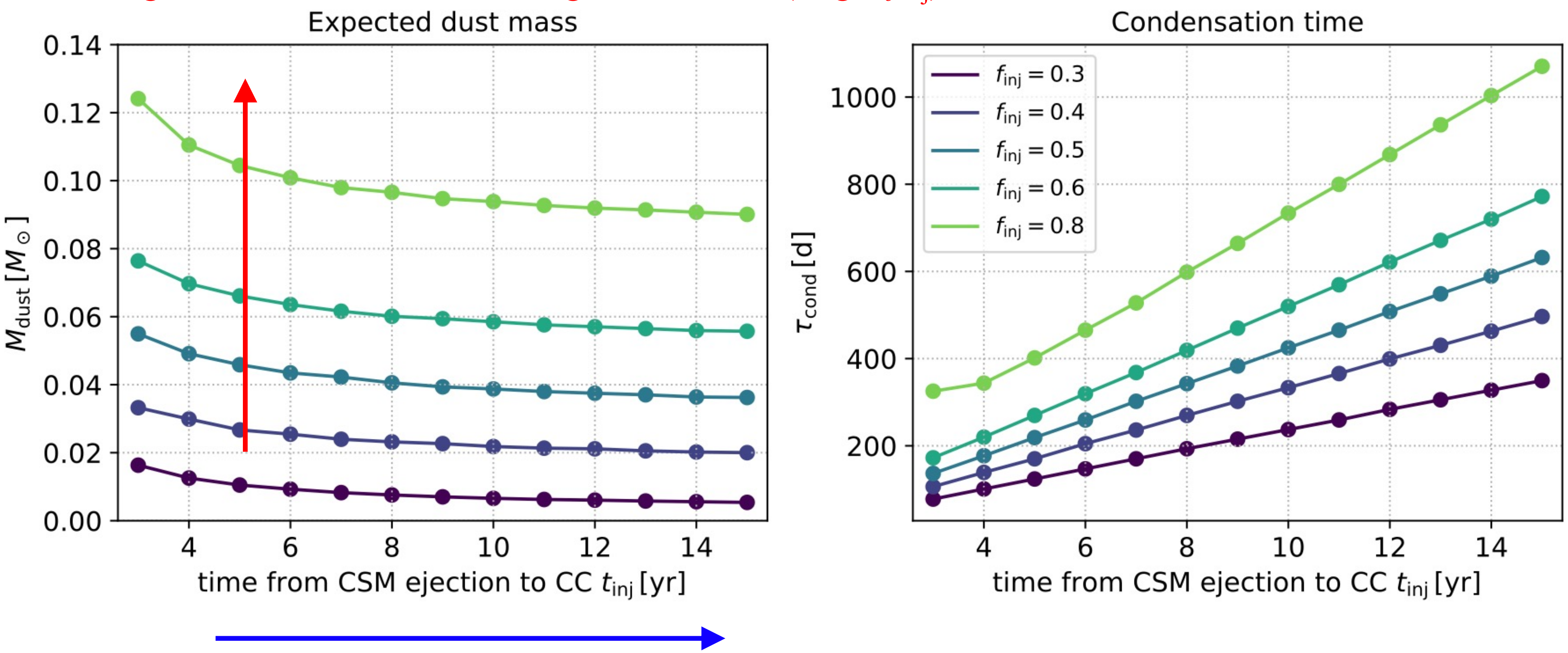
Assume that atoms condense into dust instantaneously here



The line where the expansion timescale equals to the atomic collision timescale
→If collisions occur on a short timescale, dust formation becomes possible

Expected dust mass

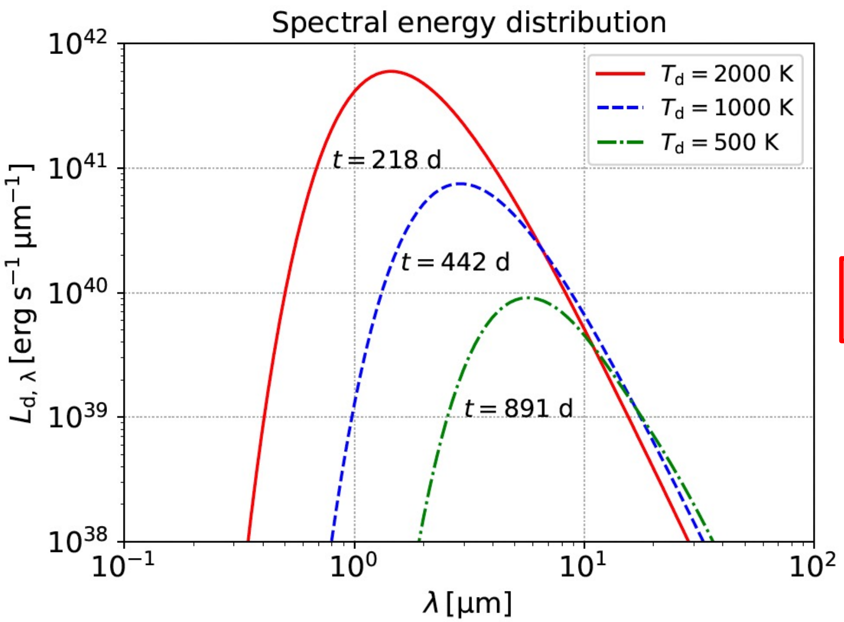
Larger CSM mass results in larger dust mass (larger f_{inj})

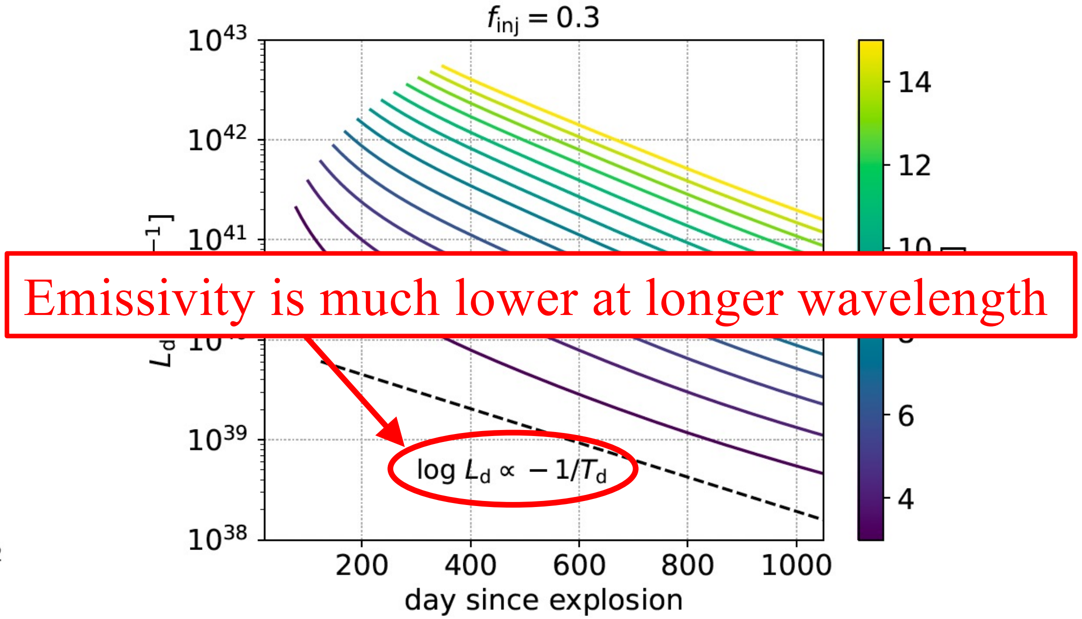


Longer t_{inj} → The reverse shock cannot sweep up larger ejecta mass before the interaction terminates

Light curves of dust emission

- Dust emission at IR bands
- Assuming $T_{\text{dust}} = T_{\text{CDS}}$, we calculate the dust light curves



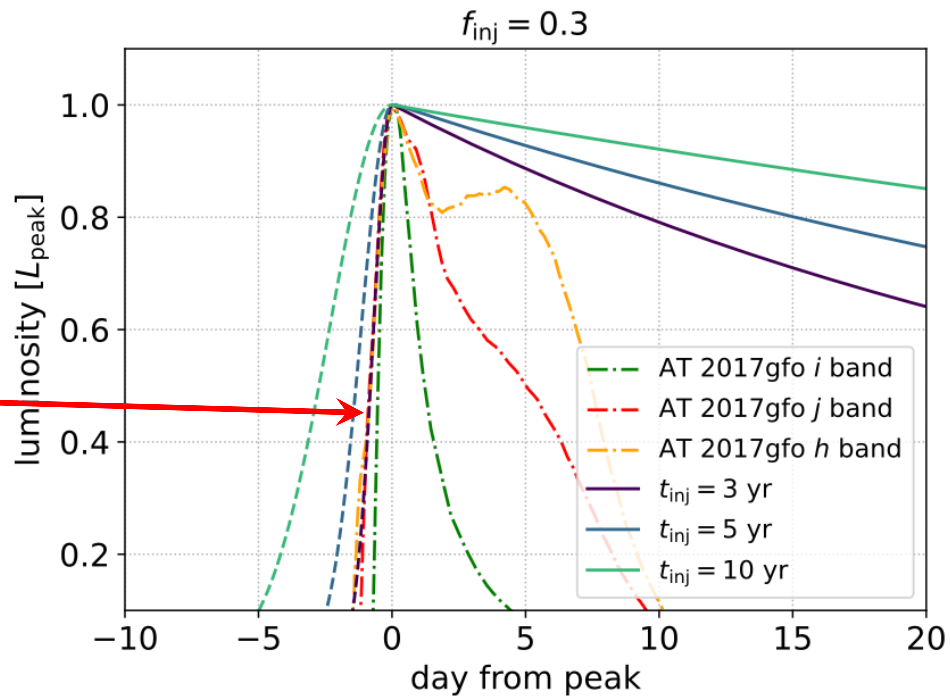


Implications for kilonova surveys

- The light curve of a kilonova (KN) exhibits a rapid rise within a timescale of a few days (e.g., Kasen+13, 17)

Dust emission light curves can mimic early KNe due to light-travel-time effects

$$t_{\rm rise} \sim \frac{r_{\rm sh}}{c}$$



Rise phase alone is insufficient; decay must also be examined.

Summary

- Interaction of the SN ejecta with CSM can promote the dust formation
- A new model that describes the temporal evolution of the density and temperature in the CDS is proposed
- Up to $\sim 0.1 M_{\odot}$ of dust can be newly formed in the CDS formed between the SN ejecta and confined CSM
- We should take into account the contamination by dust formed in the confined CSM