Shock Breakout

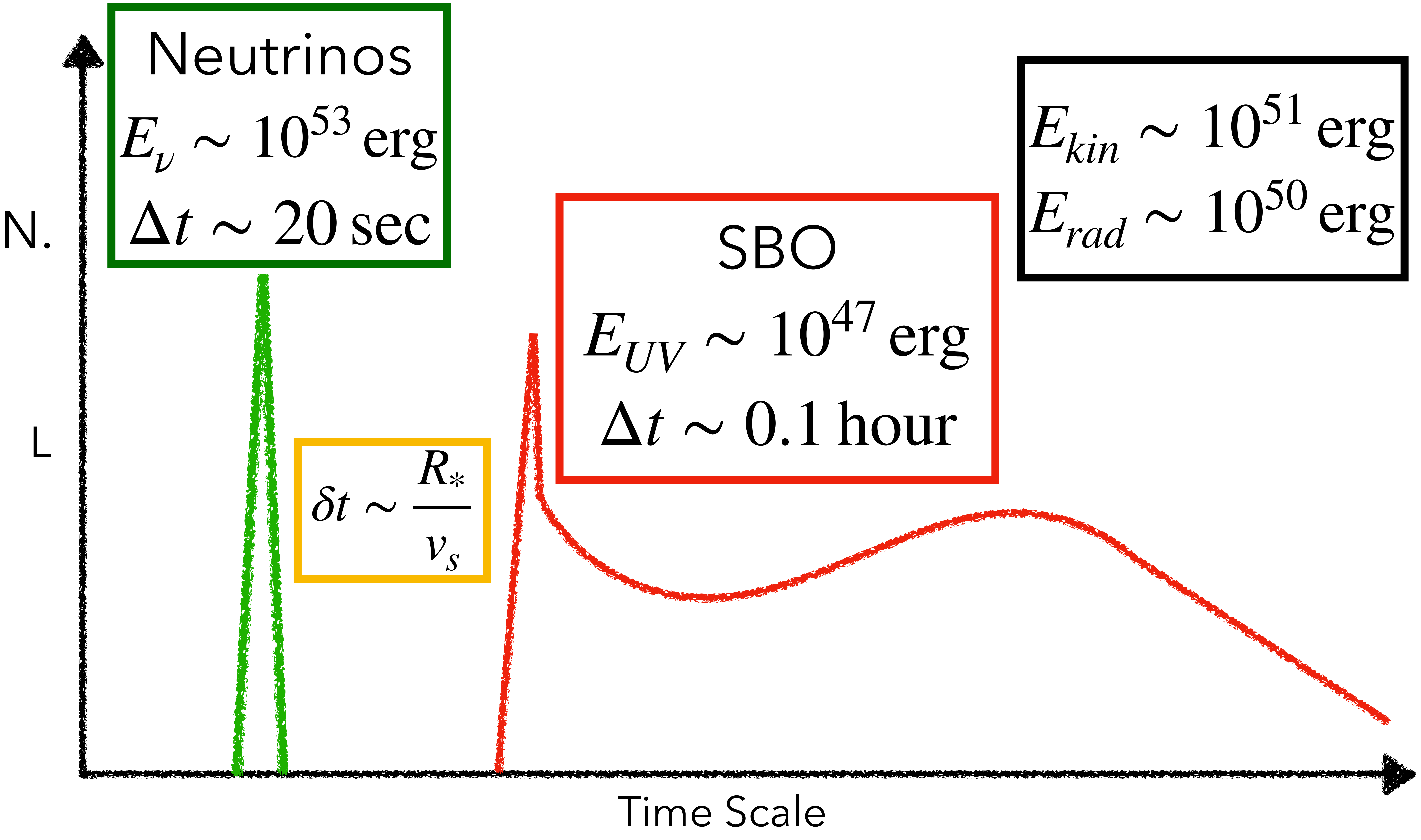
SN1987A/ RSG/ Sedona

15.09.25 wychen

Shock Breakout

Reasoning

- First Electromagnetic Signals of SN.
- Shocks propagate from optically thick to optically thin.
- Need Rad-Hydro+Shock



- D. Nadyozhin and V. S.imshennik. Physics of supernovae. *International Journal of Modern Physics A*, 20, 01 2012.
- Waxman, E., & Katz, B. 2017, in Handbook of Supernovae, ed. A. W. Alsabti & P. Murdin (Springer, Cham)

Progenitor

Explosion

Shock Breakout

CSM Interaction

Observer

Progenitor

Shock Breakout

Observer

BSG SN1987a

2D

UV Tail

SN1987a Shock Breakout

Chen W.-Y., Ke-Jung Chen, Masaomi Ono, 2024,

ApJ, 976, 147.

CASTRO

Almgren, Beckner, Zhang, Howell, Katz, Zingale. 2010-2020

- AMR-based, compressible hydrodynamics code. Support MHD, general equations of state, full Poisson equation, and reactive networks.
- MPI + OpenMP for CPU architectures, MPI + CUDA for NVIDIA GPUs, and MPI + HIP for AMD GPUs
- MGFLD:
  - In optically thick regimes, MGFLD reduces to classical diffusion.
  - In optically thin regions, radiation behaves as free-streaming.
  - In the intermediate regime flux limiters.
  - Frequency-dependent.

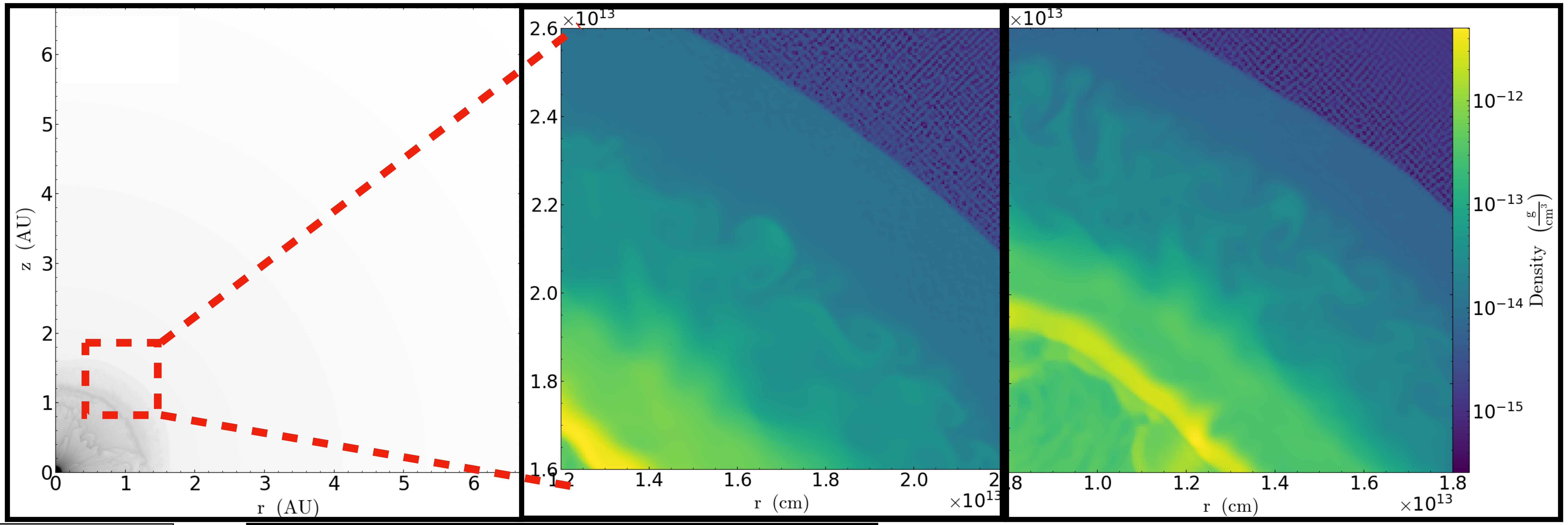
MGFLD

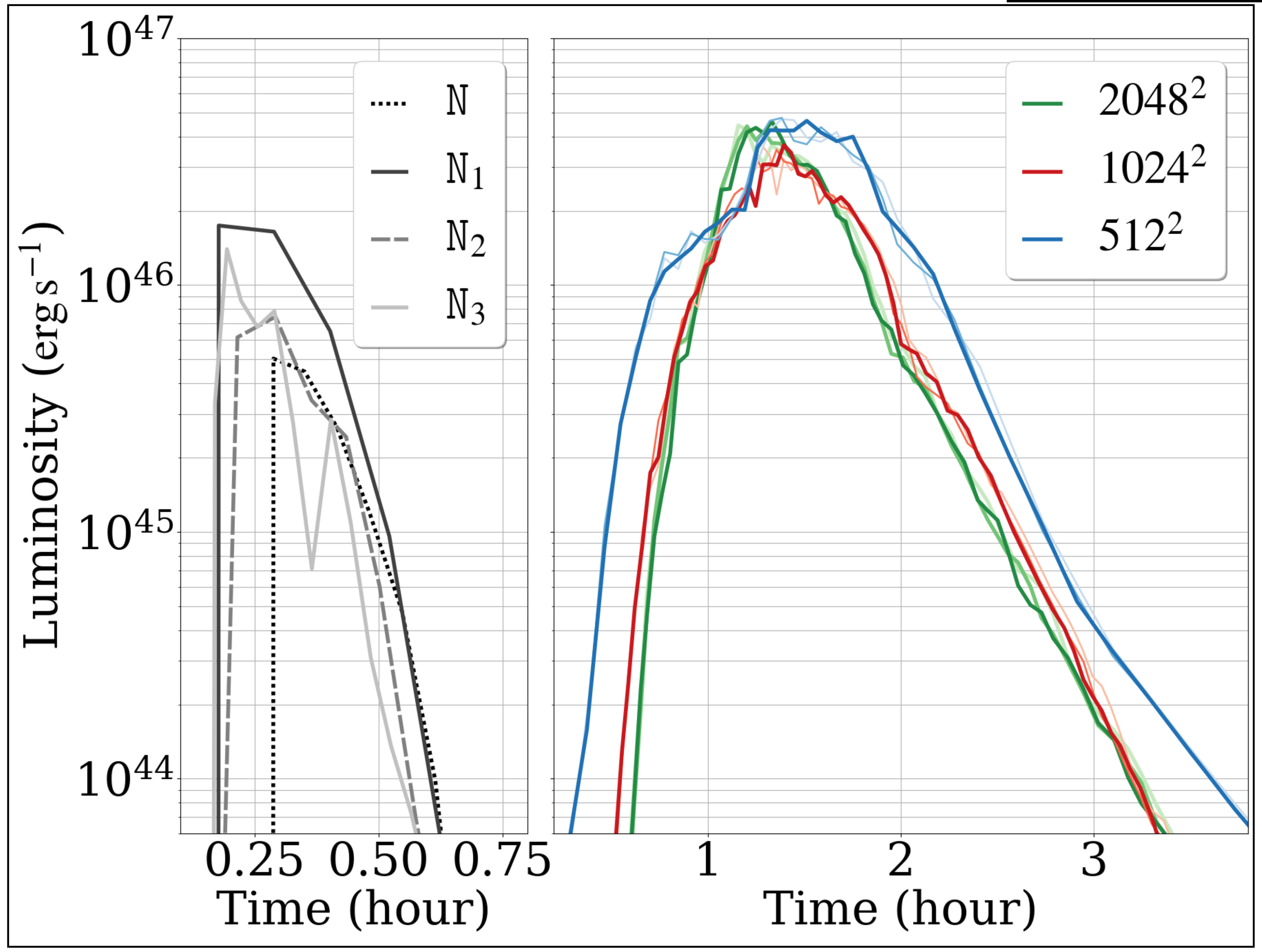
Almgren, Beckner, Zhang, Howell, Katz, Zingale. 2010-2020

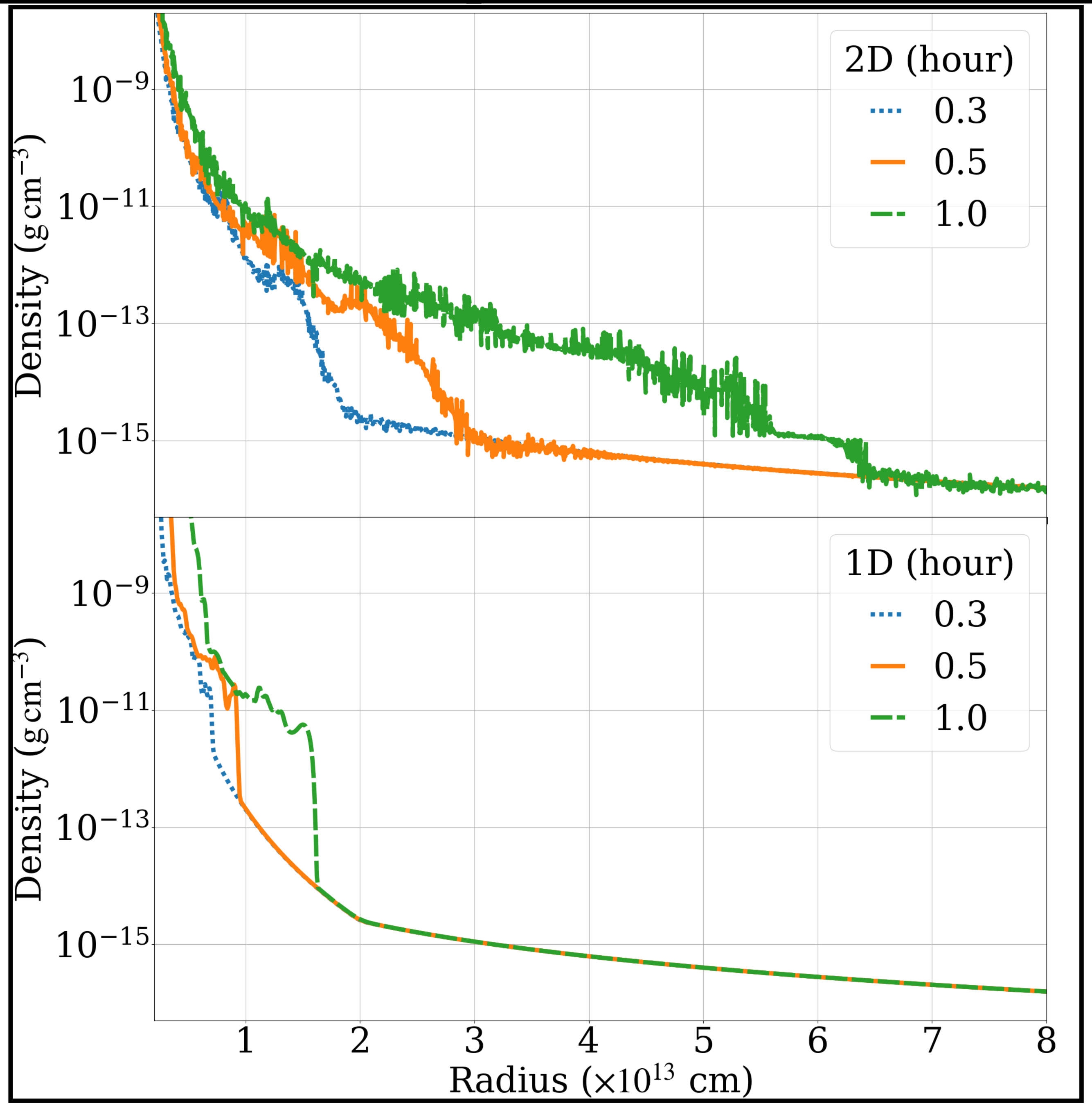
- $\frac{\partial E_r}{\partial t} + \nabla \cdot \mathbf{F}_r = c\kappa_P \left(a_r T^4 - E_r\right) + S_r$
- $F_r = -D \nabla E_r$, $D = \frac{c\lambda(R)}{\kappa_R}$, and $R = \frac{|\nabla E_r|}{\kappa_R E_r}$
- $\lambda(R) = \frac{1}{R}\left[\coth(R) - \frac{1}{R}\right]$ (Levermore & Pomraning)
- Diffusion: $R \to 0 : \lambda \to \frac{1}{3}$
- Free Streaming: $R \to \infty : \lambda \to \frac{1}{R}$

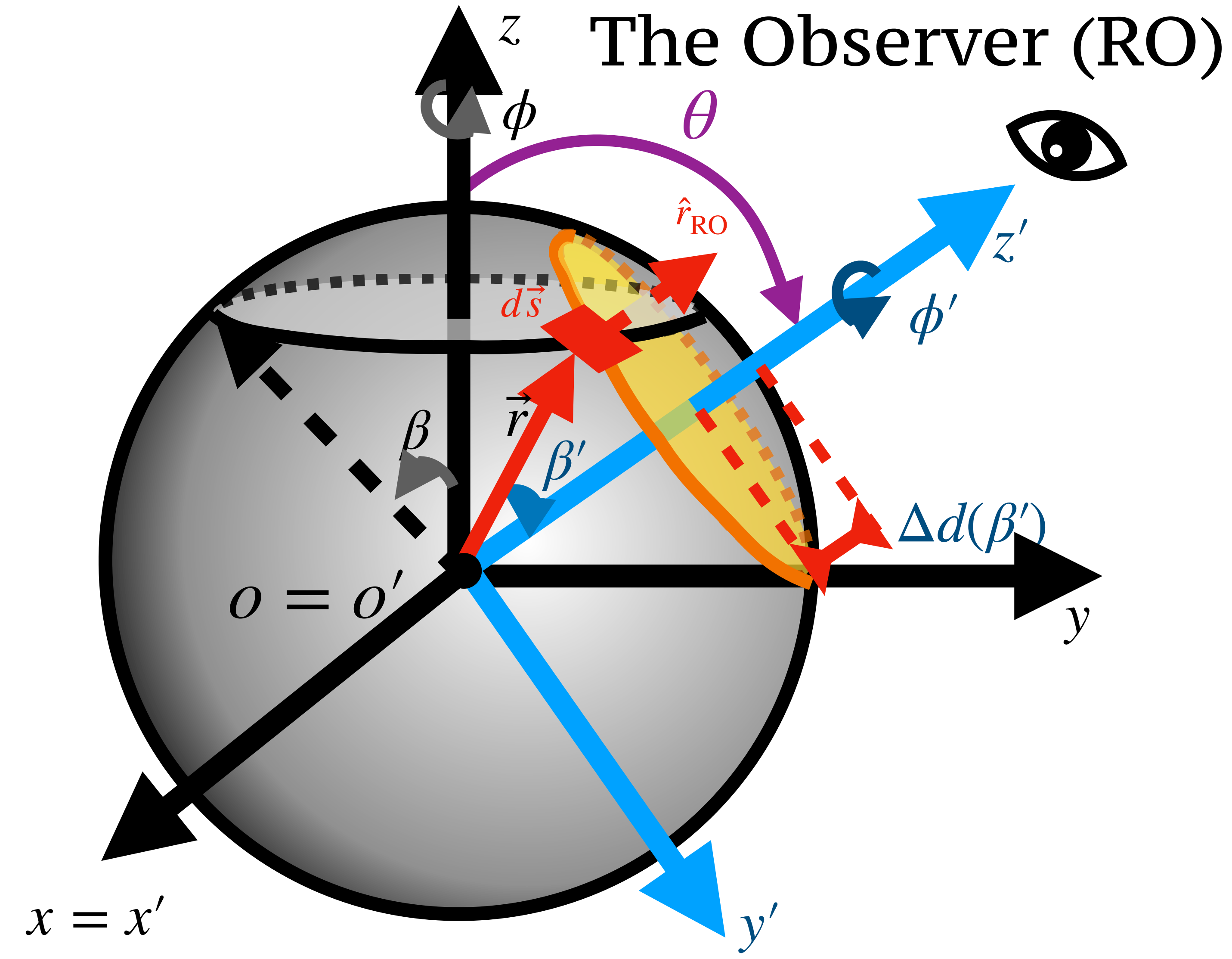
2D 1987a

- Chen W.-Y., Ke-Jung Chen, Masaomi Ono, 2024, ApJ, 976, 147.
- Structures and LC
- Spherical Progenitor





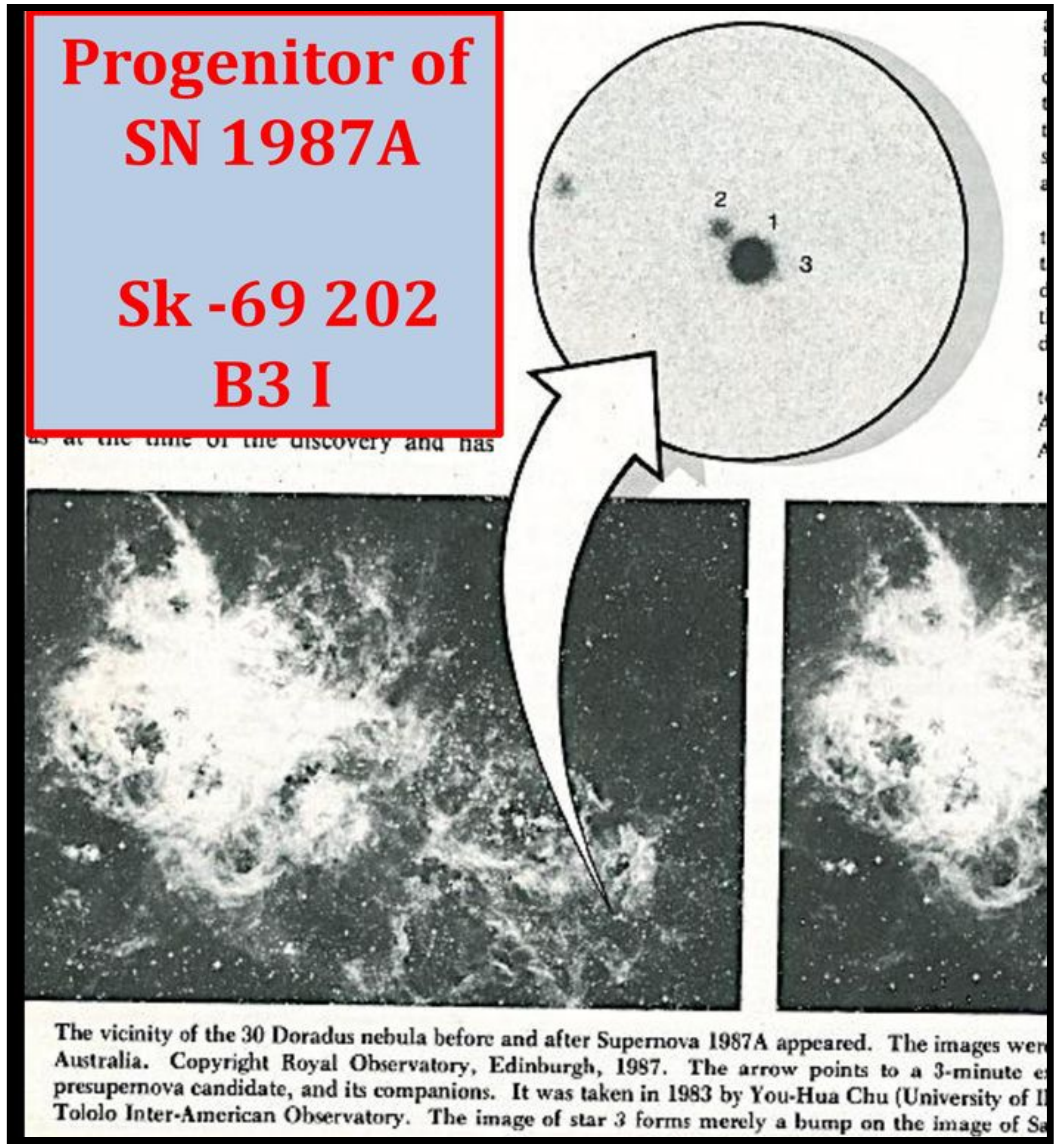


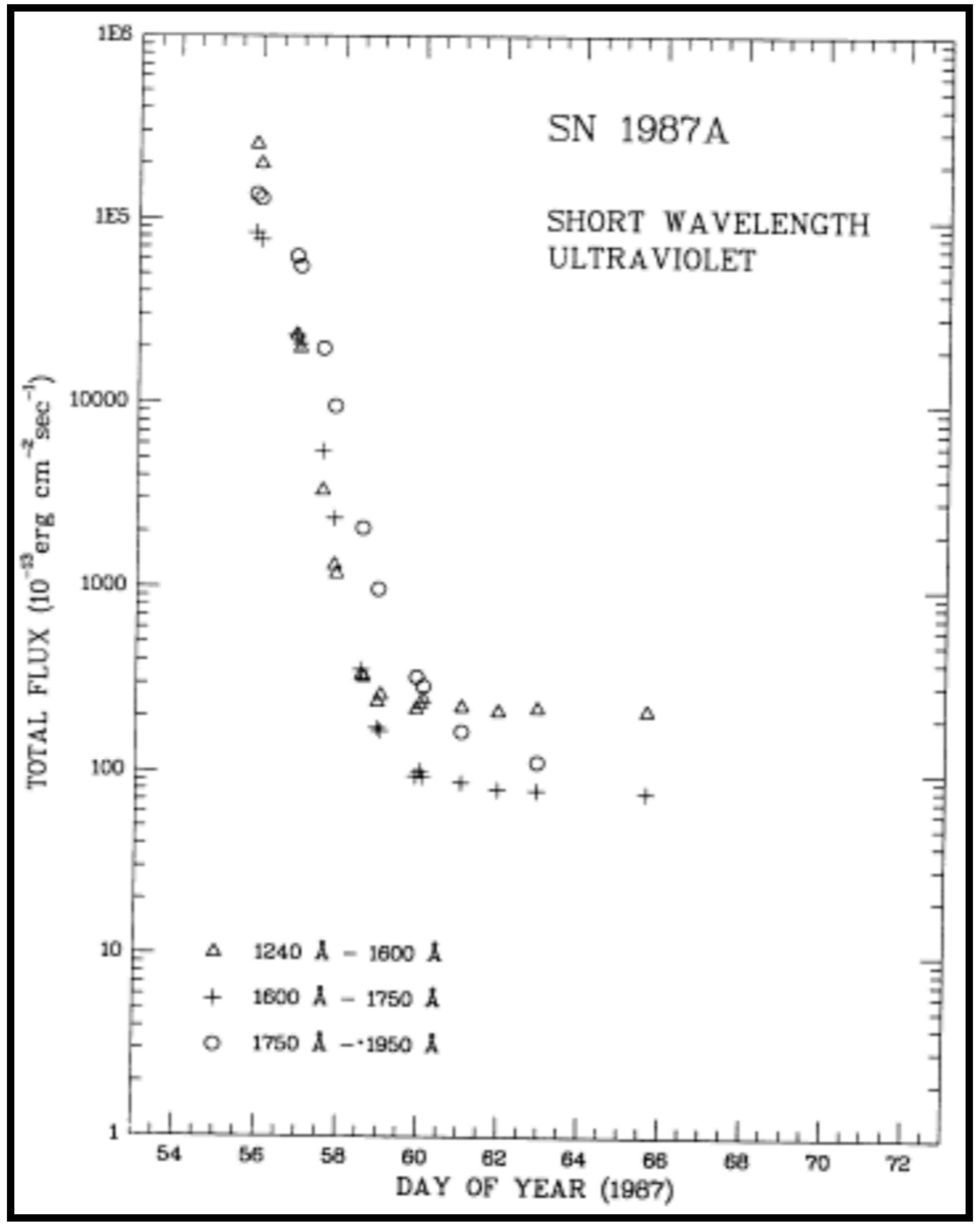


At $|\vec{r}| = r_s = 8 \times 10^{13}$ cm

Early Observation

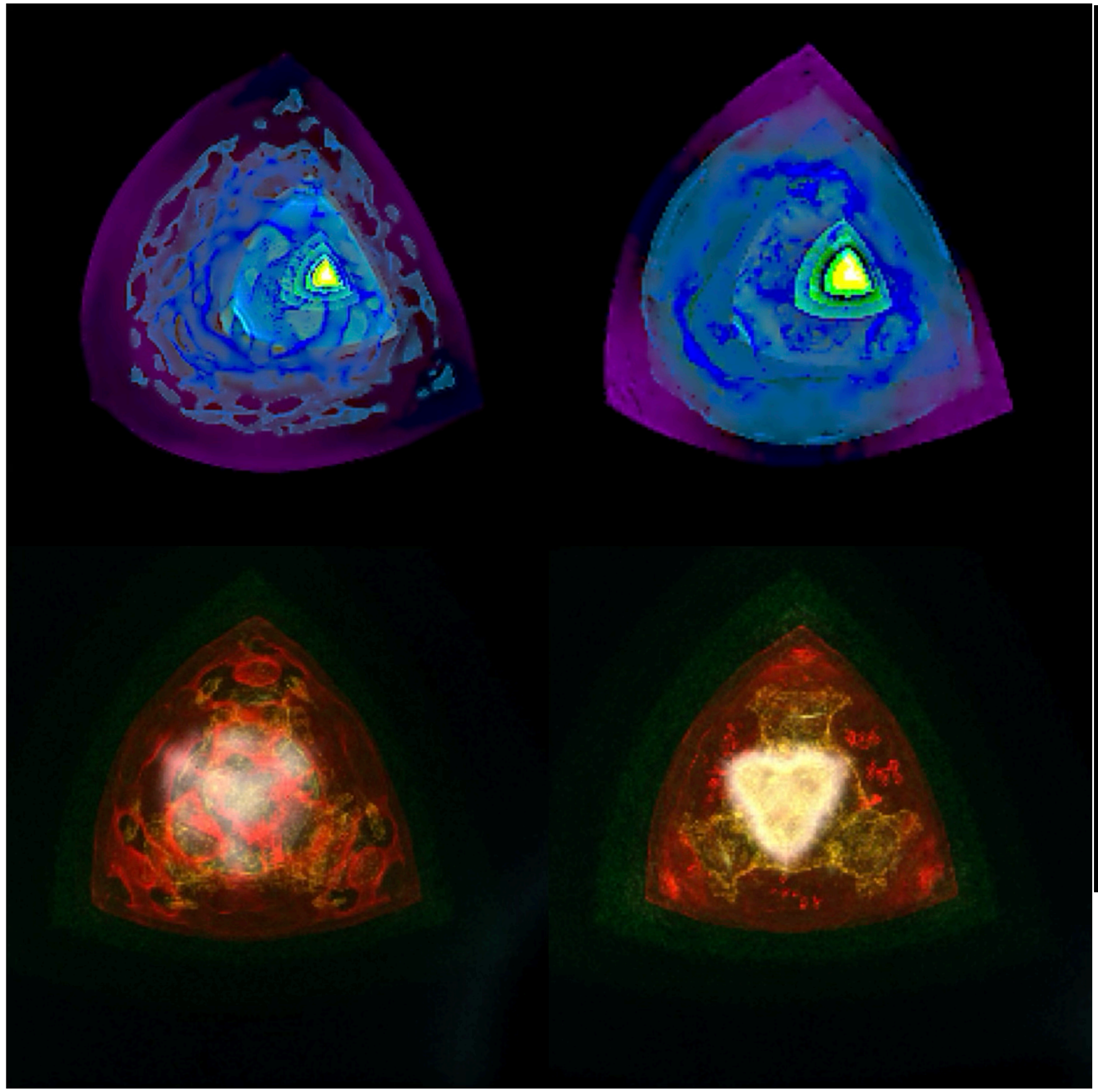
- You-Hua Chu: SK -69 202 B31
- Sonneborn and Kirshner (1987);
  Wamsteker (1987)
- The earliest most observation of UV is done after 13 hours of the discovery.
- Only the “tail” of shock breakout in UV can be compared: that drop from 10^7 K to 10^4 within 1-2 days.

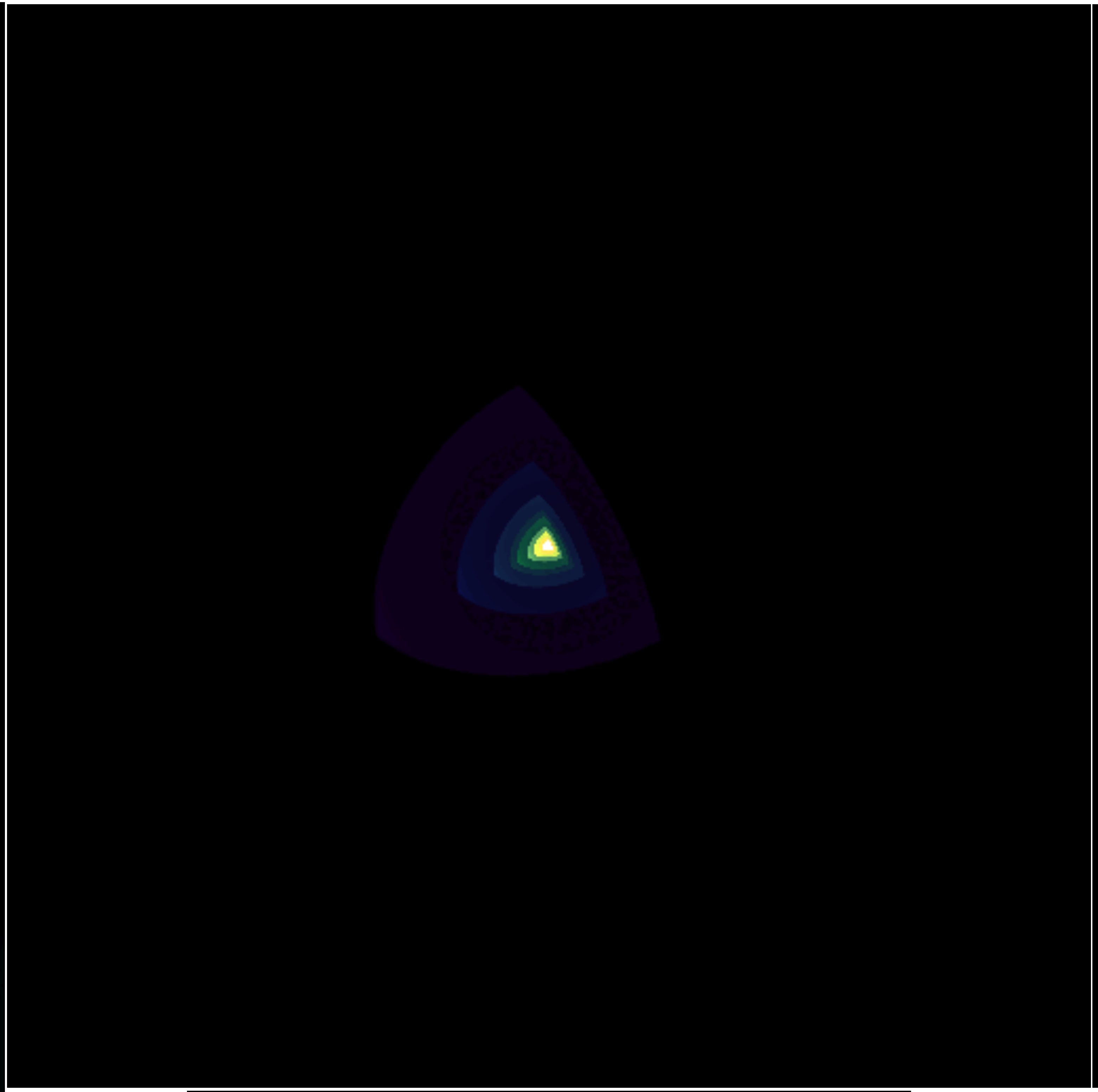




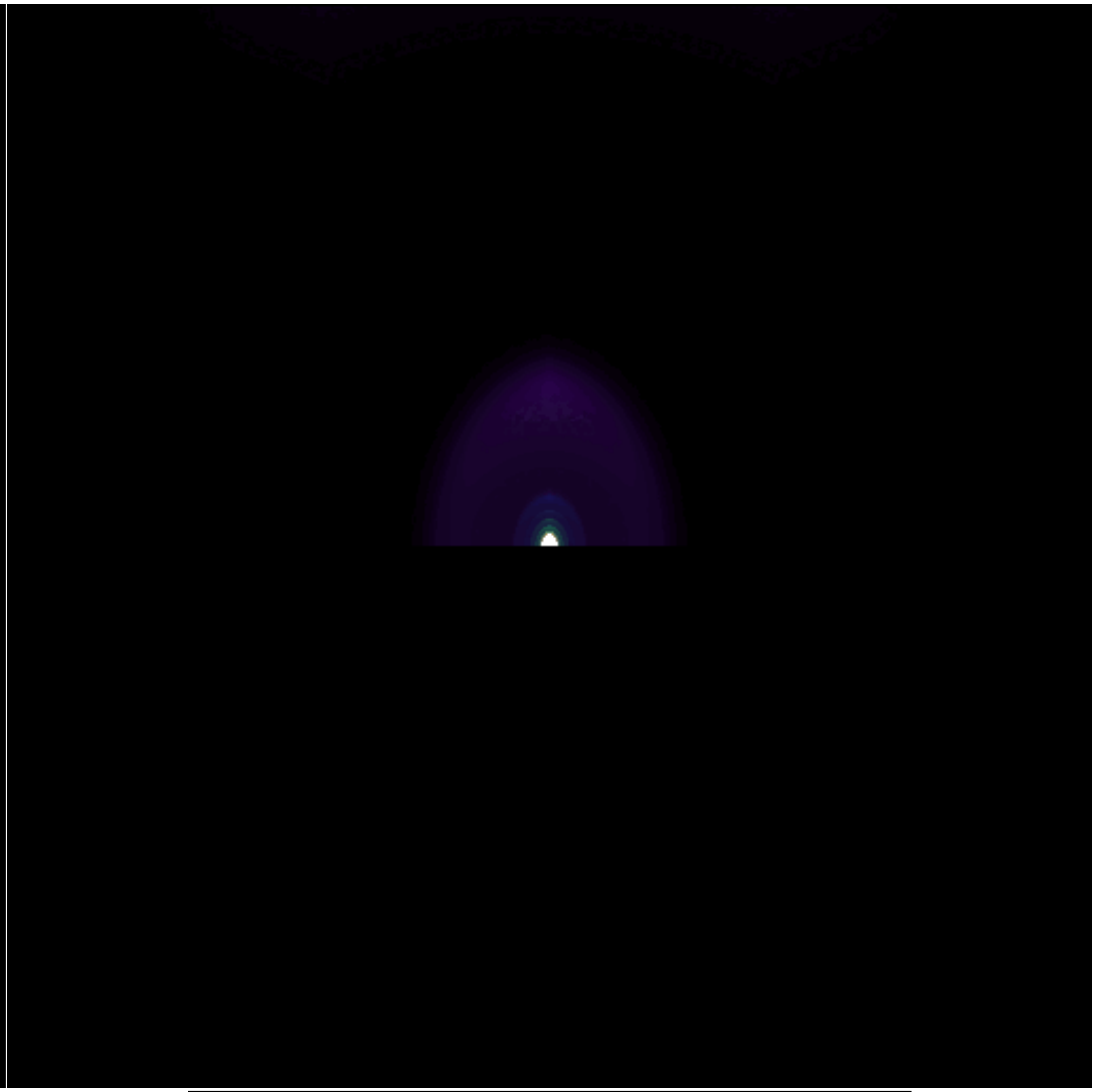
3D SN1987a

- 3D -> Bubbles ahead of stellar surface
- LCs -> Smoother than that of 2D





Density



Temperature

Progenitor

BSG
SN1987a

Shock
Breakout

2D
20s - 5hr

Observer

UV
Tail

Progenitor

Explosion

Shock Breakout

CSM Interaction

Observer

Progenitor	Shock Breakout	Observer
RSG 20 & 25	2D hour-day	Stronger Mass Loss

RSG Shock Breakout

In Prep.

Shock Breakout

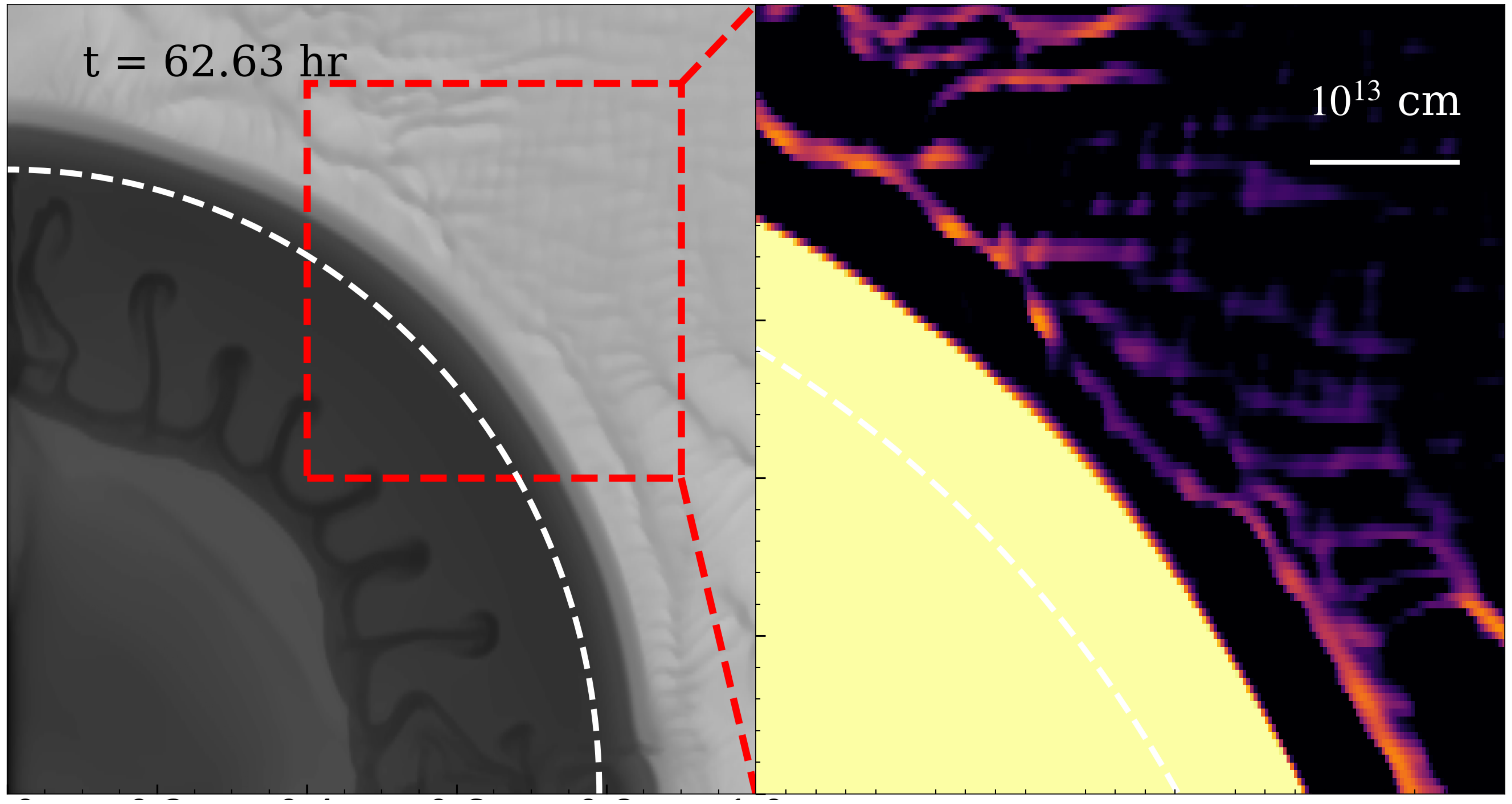
RSG

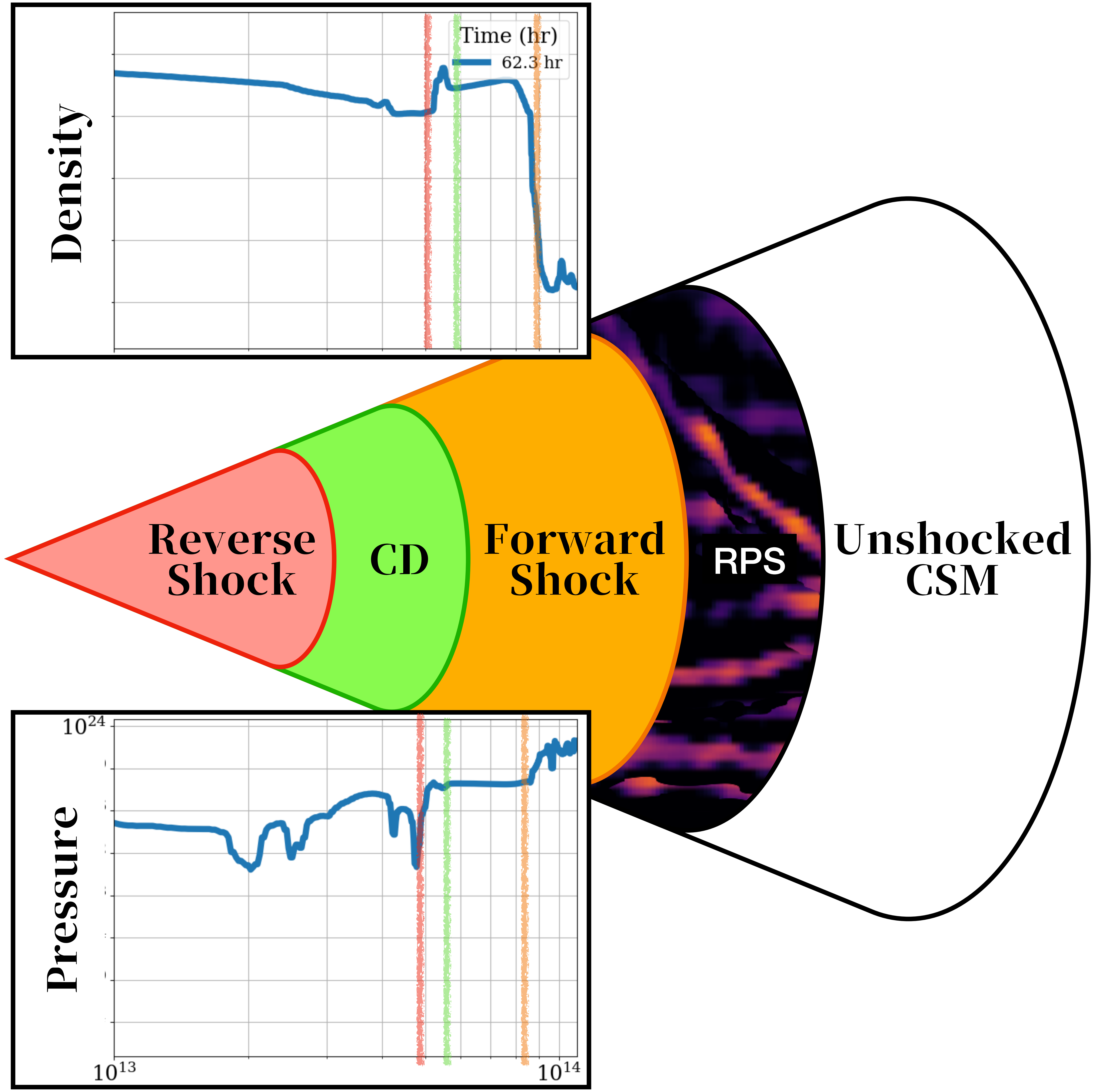
- Longer than BSG and Thicker CSM profile
- Aim at distinguishing the effects from multi-D, radiation precursors, progenitors, and the CSM profile.
- Shock Breakout structures revisited

Rad-Precursor

CSM Interaction

- RS/ FS: Pressure Rise.
- CD: Density gradient without pressure rise/ drop.
- RPS: Infront of FS (C-shock)

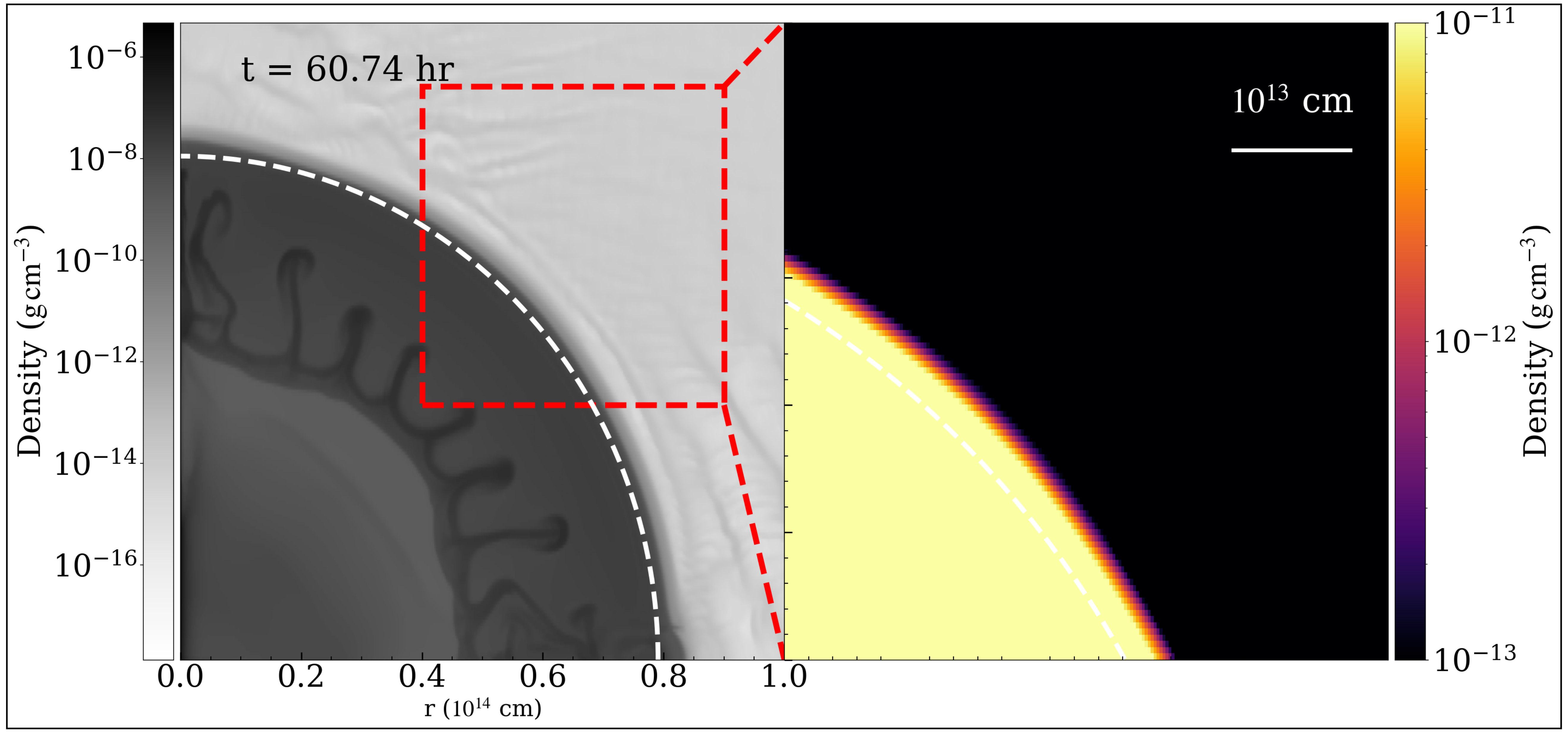


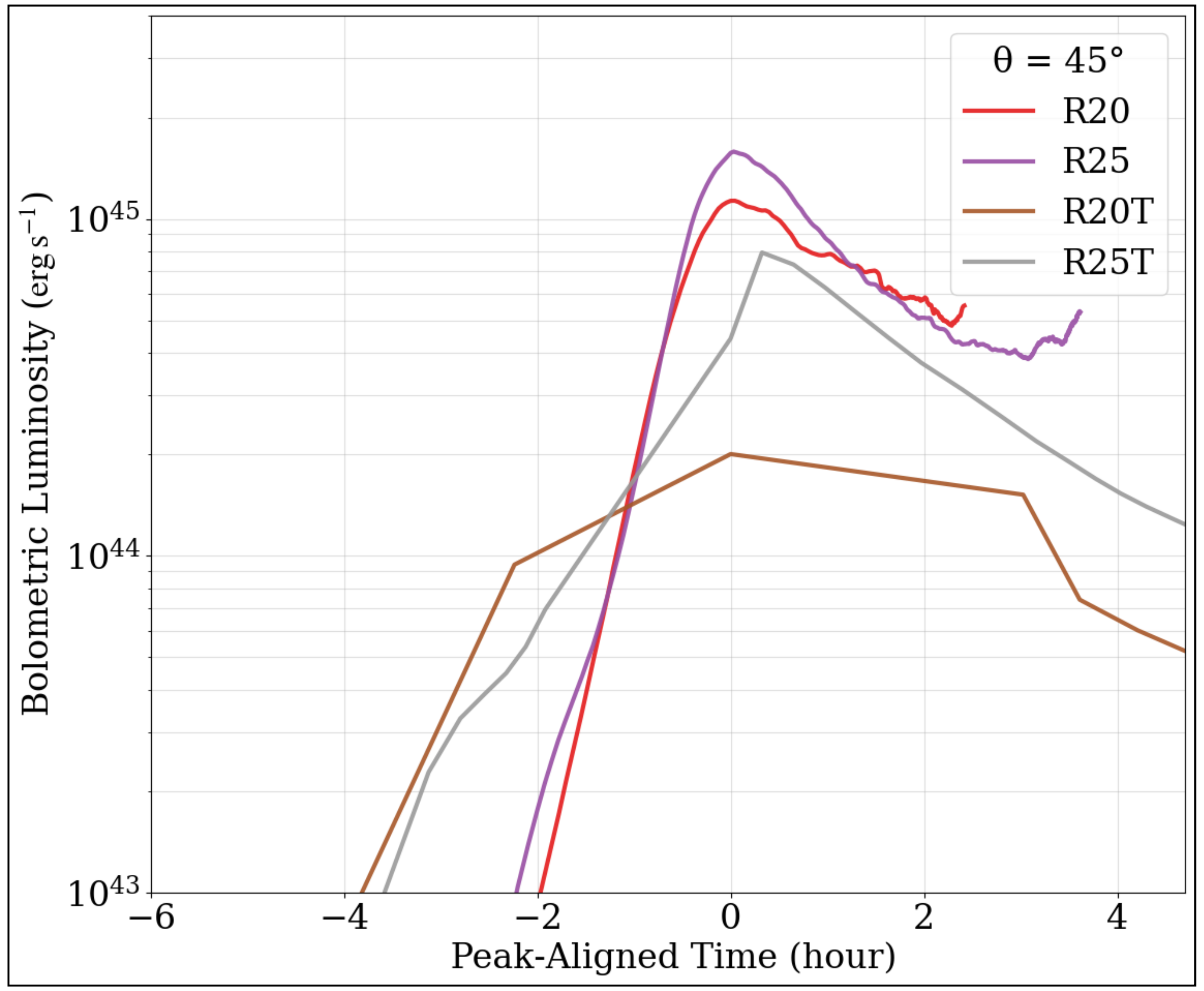


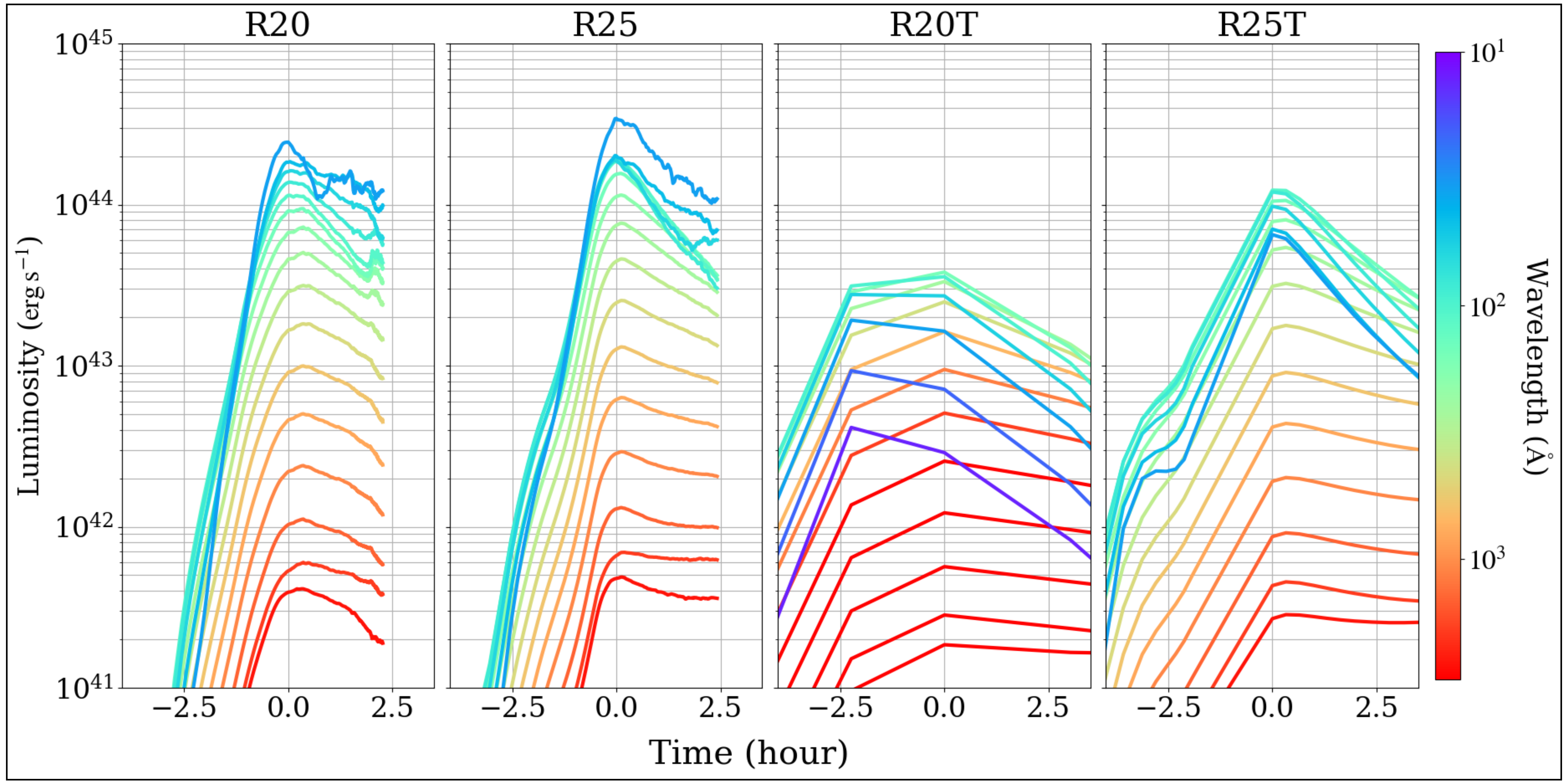
Shock Breakout

Later Time

- Double Peak
- Shock Breakout (RPS) always Interacting SNe?







Atmosphere

XRT 080109/ SN 2008D

- Takashi, Debashis, **Norbert.** 2015
  - Eddington Limit and inflated envelopes.
  - Diffusion > Light Crossing Time

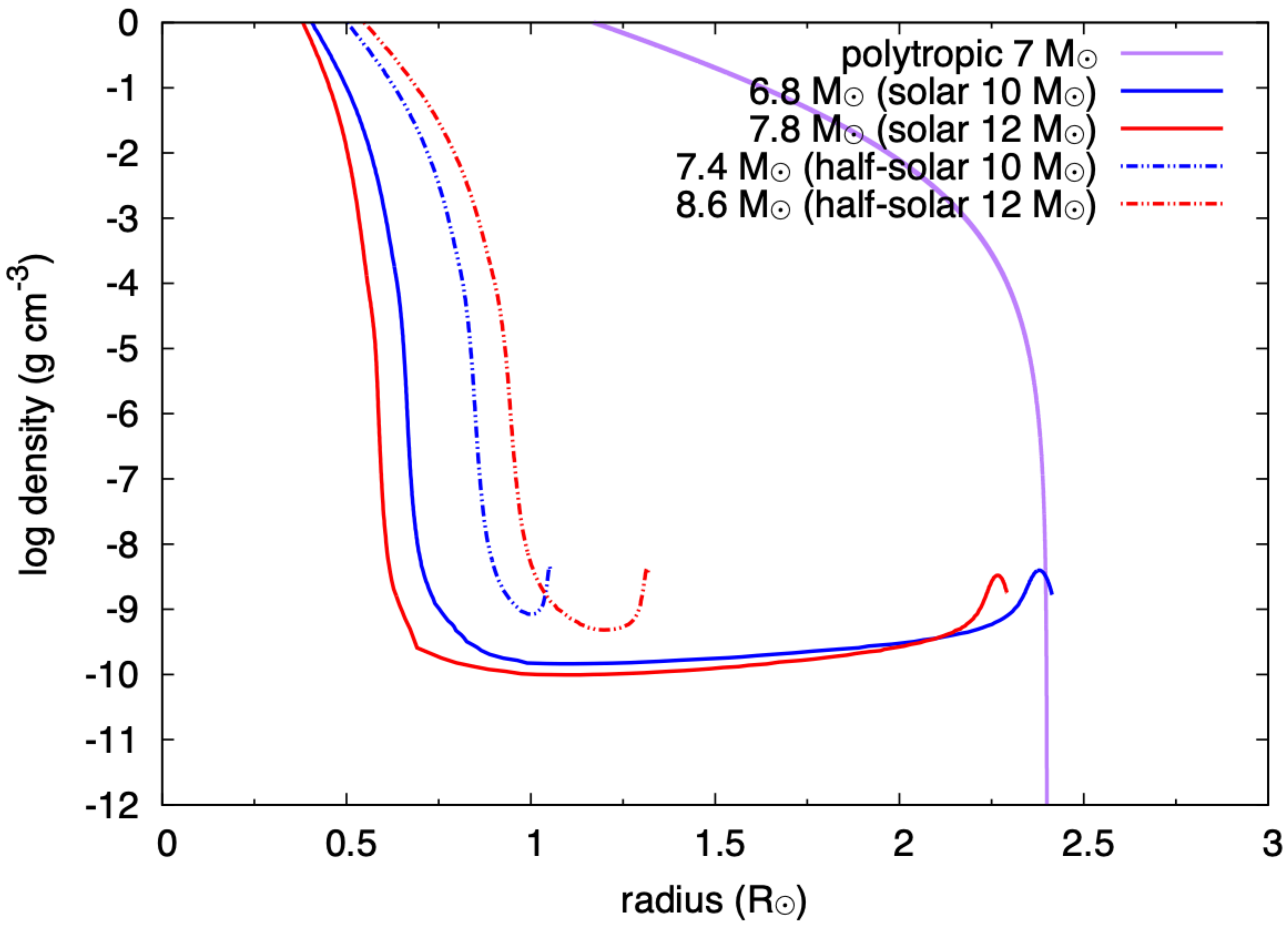
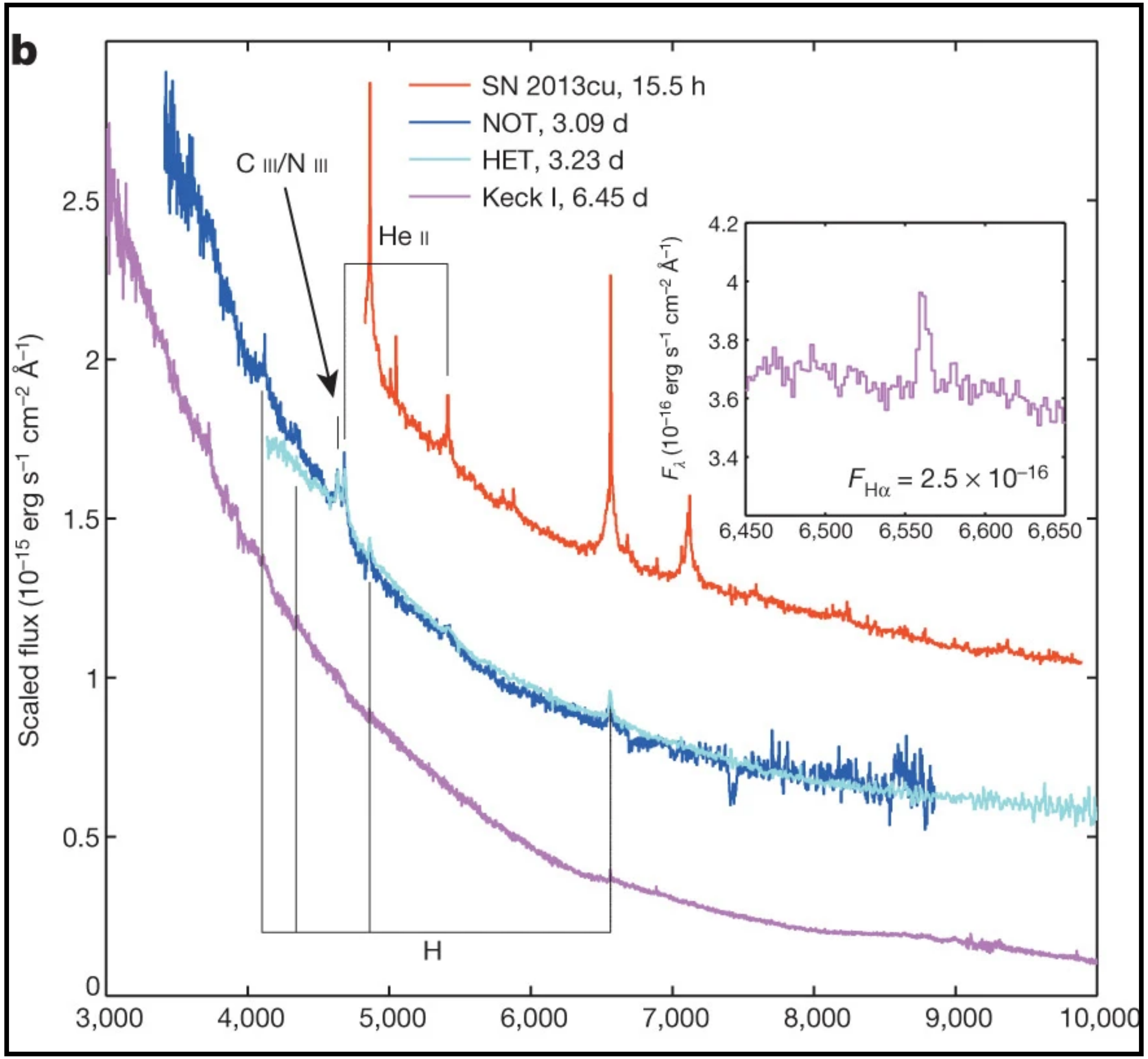


Fig. 2. Final density structure of our stellar models. We also show the structure of a star without the envelope inflation, which is a polytiropic star of 7 $M_\odot$ and 2.4 $R_\odot$ with the polytropic index of 3. The inflated stellar models have the extended low-density regions on top of the core structure.

Stellar Wind

SN 2013cu

- Gal-Yam, A., Arcavi, I., Ofek, E…, 2014
    - WR signals becomes featureless after ~ 6 days of explosion.
- Graefener and Vink 2016
    - Not a WR wind if include LTT effects
    - After 15.5 hours of explosion



Shock Breakout

Take Home Messages

- Shock Breakout ~ Instead of the light traveling time, it is a continuous process that starts at radiation precursor and ends by releasing radiation.
- Multi-D effects + RHD ~ Radiation Precursor that signals the beginning of shock breakout.
- MGFLD ~ Separate the progenitors and CSM impacts on the LCs.

Progenitor

Shock
Breakout

Observer

RSG
20 & 25

2D
hour-day

Stronger
Mass Loss

Progenitor

Explosion

Shock Breakout

CSM Interaction

Observer

Progenitor	Shock Breakout	CSM Interaction	Observer
RSG 20 & 25	2D hour-day	Confined-Shell CSM	Yaron 2017

Confined-Shell CSM

HITS Summer Institute Programme

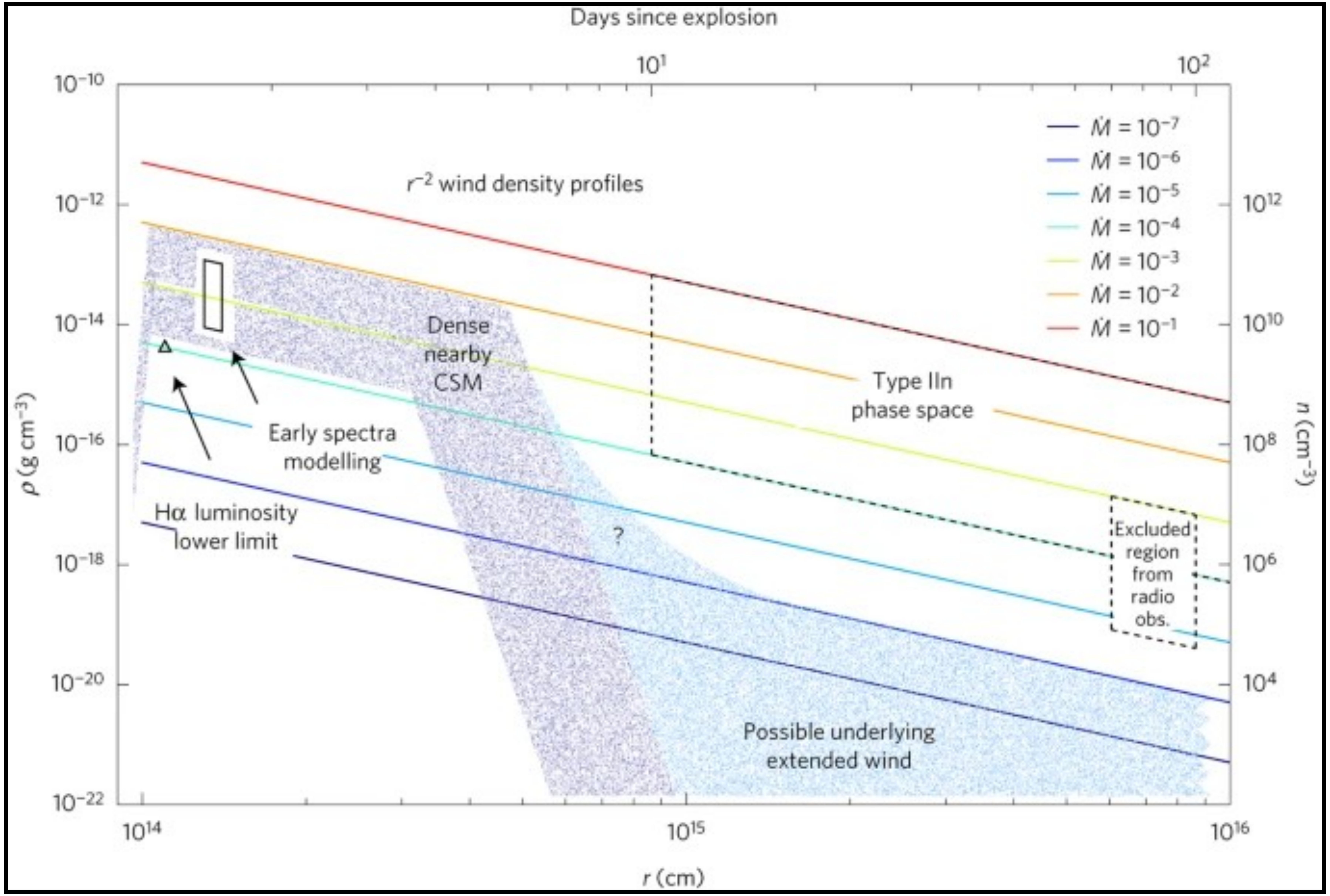
Conference in EAMA 11, Japan

Shock Breakout

Confined-Shell CSM

- Can constraint Mass Loss Rate?
- Need HD simulations on CSM formation
- Common Envelope?

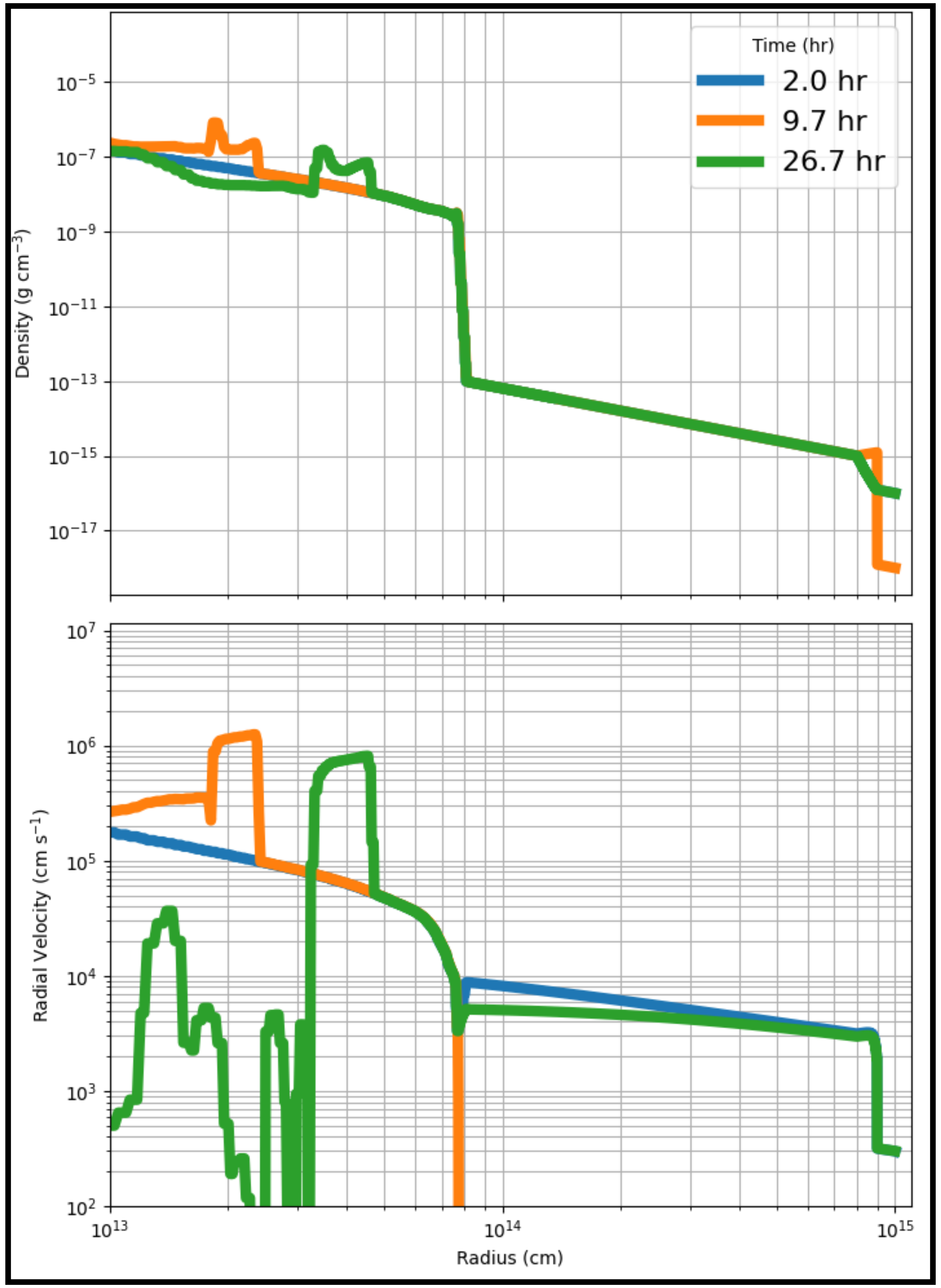
Rad-Precursor



Yaron, O., Perley, D., Gal-Yam, A. *et al.* Confined dense circumstellar material surrounding a regular type II supernova. *Nature Phys* **13**, 510–517 (2017). https://doi.org/10.1038/nphys4025

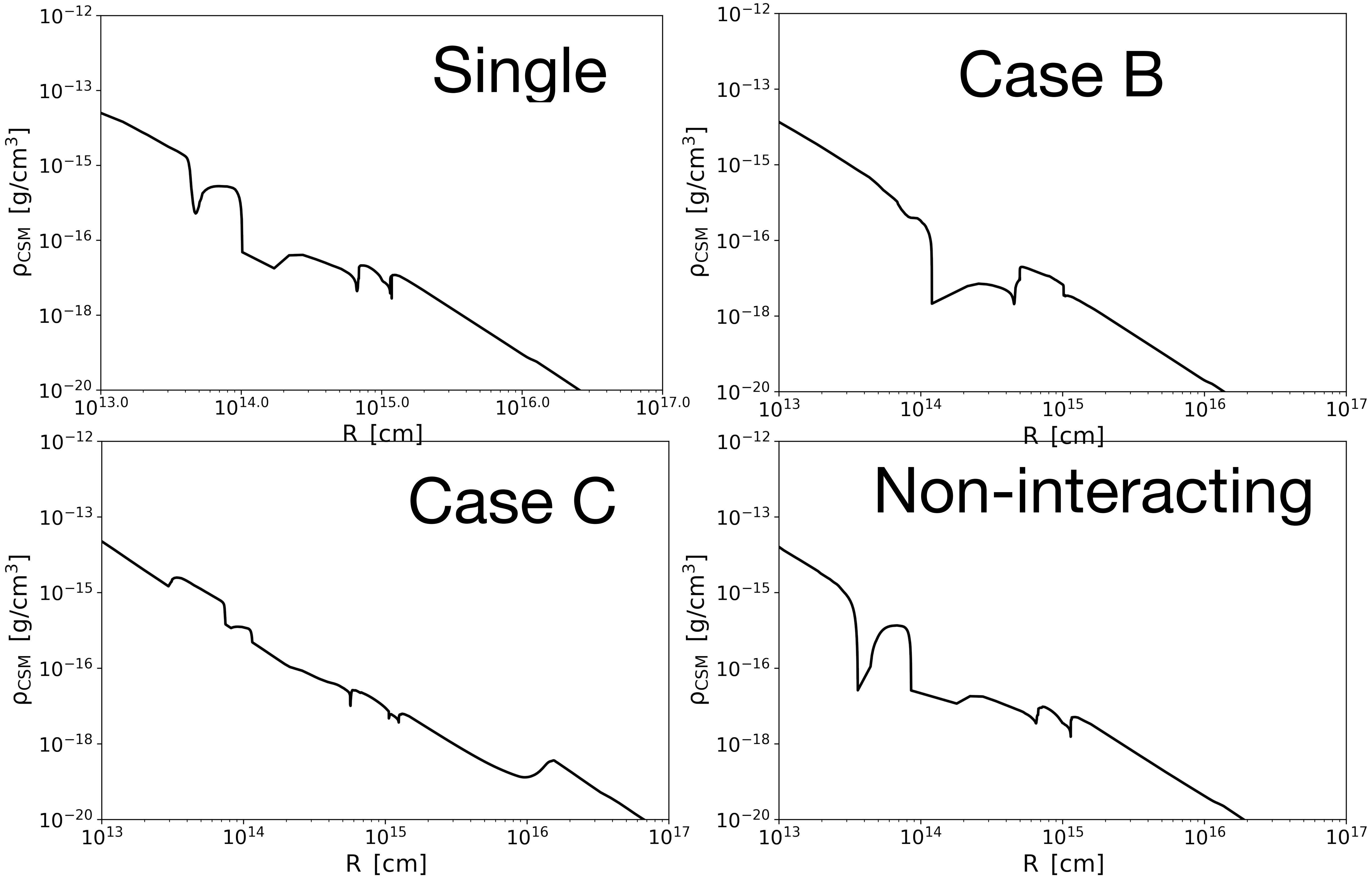
1. Observation

- Setup from Yaron 2017
- Use density ~ $\rho \approx \dfrac{\dot{M}}{4\pi r^2 v}$
- Have degeneracy of mass loss rate and wind velocity
- Time evolution is also degenerate.
- Testing other smoothing.



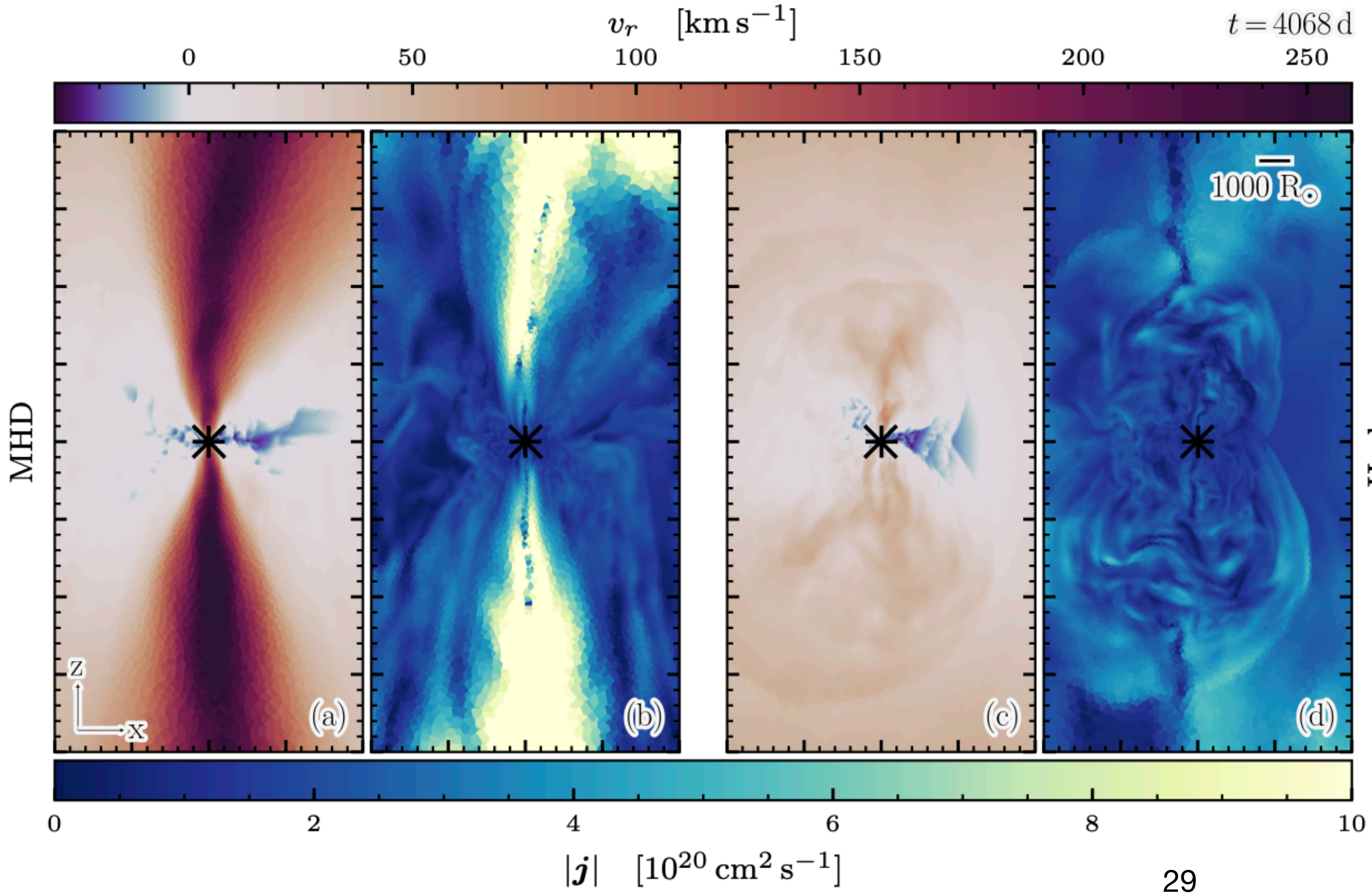
2. Sung-Han's

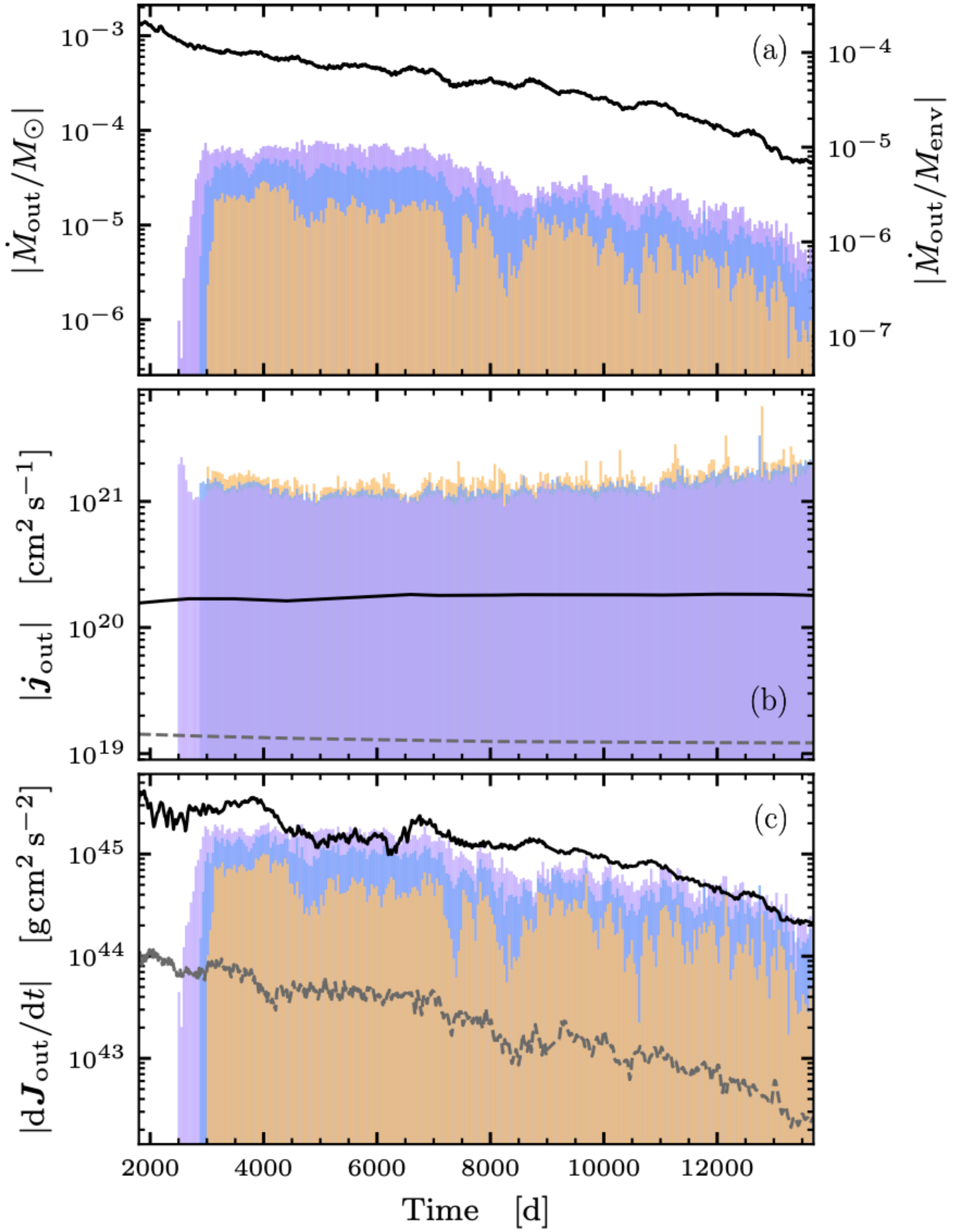
- Setup from Sung-Han's Model
- Use density ~ $\rho \approx \dfrac{\dot{M}}{4\pi r^2 v}$
- Weird Cut, Require Binning
- Depends on ExplpoSion Timing



3. 3D Common Envelope

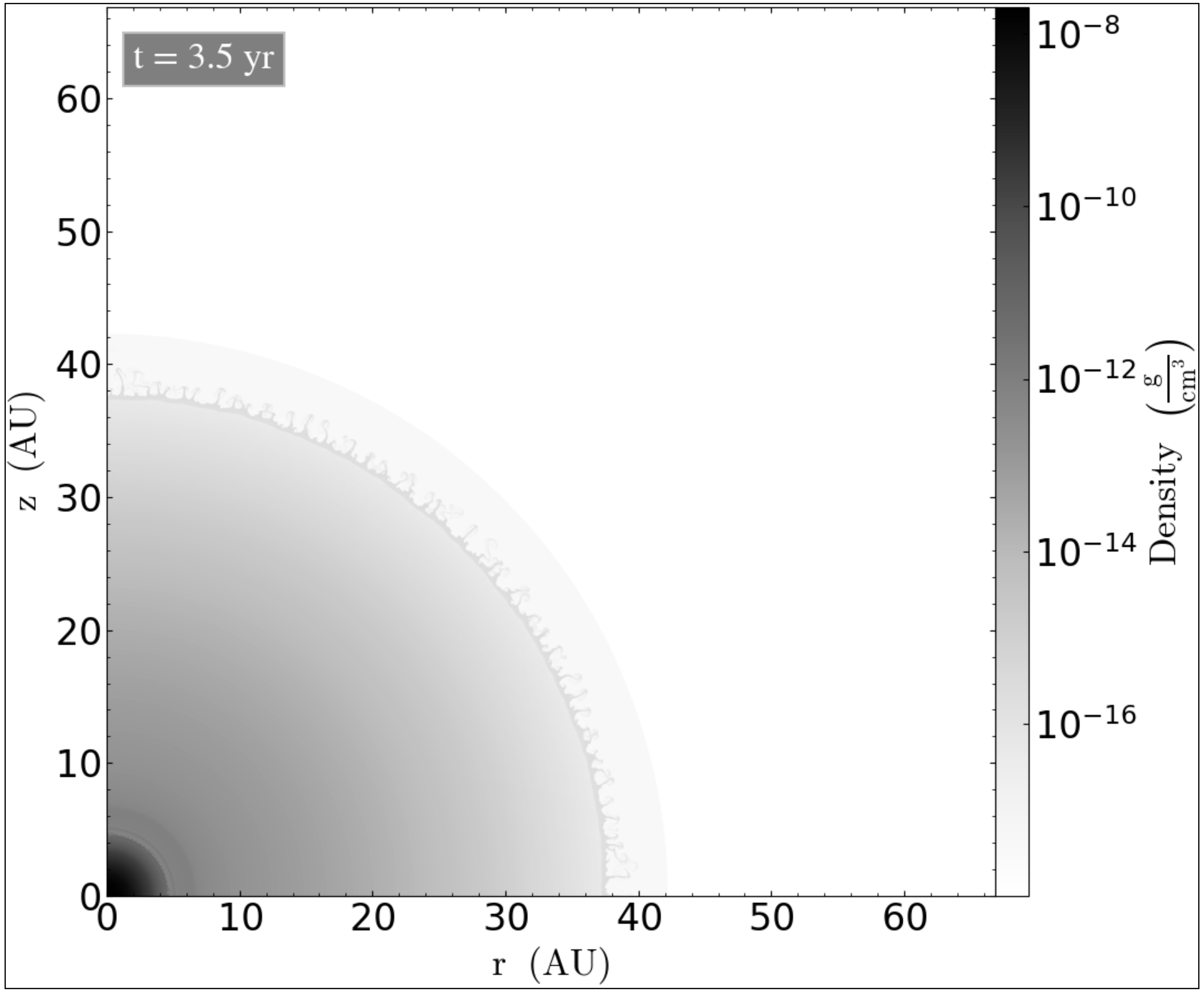
- HITS Group (Mike, Vetter …)
- MHD driven outflows
- Need Recombination Effects





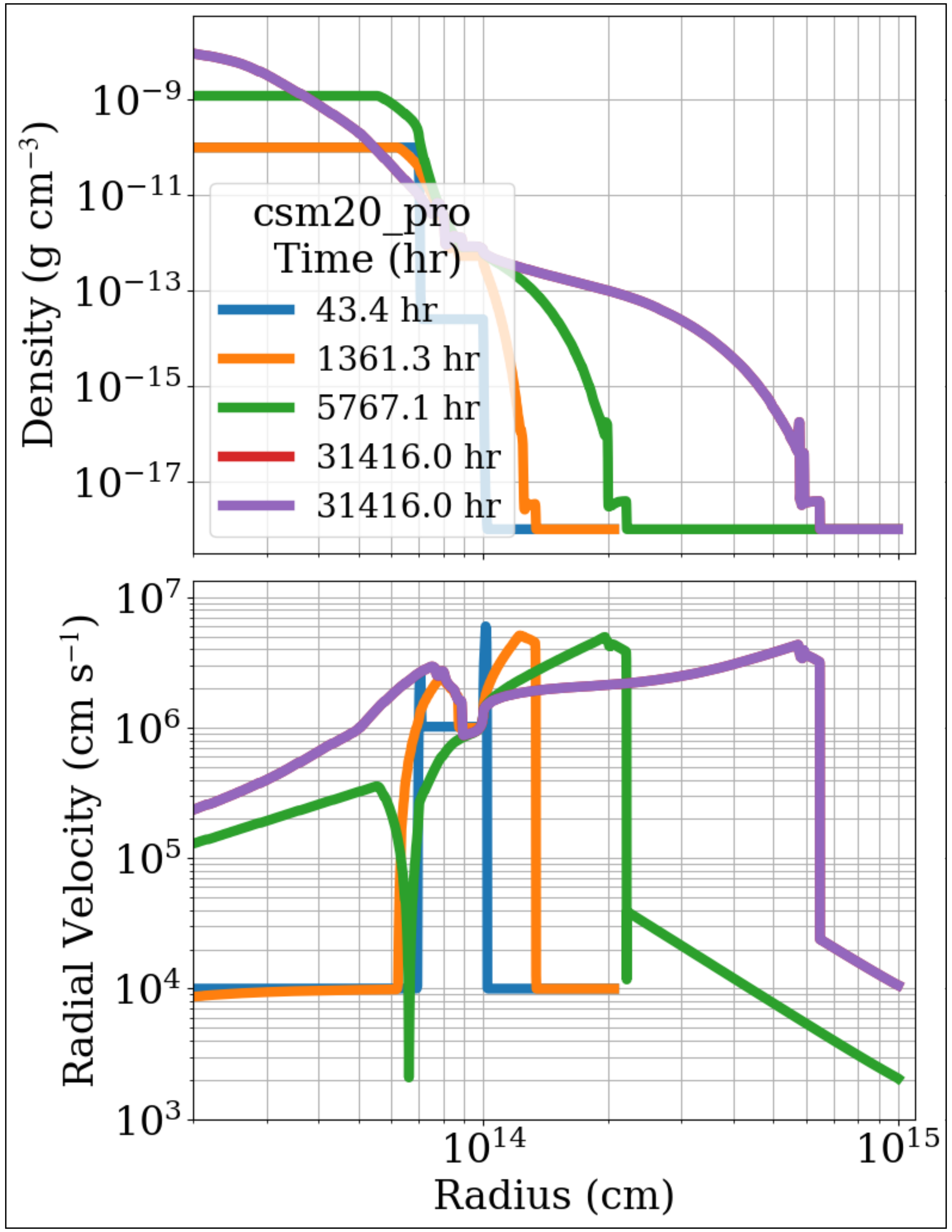
4. HD CSM formation

- Input mass flux from stellar radii
- Crop 3yr/ 10yr/ 100yr before SN till the wind blows to > 60 AU
- All outflow are spherical.



4. HD CSM formation

- Input from observation inferred
- From SH
- From others…



Progenitor	Shock Breakout	CSM Interaction	Observer
RSG 20 & 25	2D hour-day	Confined-Shell CSM	Yaron 2017

Progenitor

Explosion

Shock Breakout

CSM Interaction

Observer

Explosion

Shock Breakout

Observer

SN1987a

3D HD

SEDONA

SEDONA

Monte-Carlo with 3D SN1987a

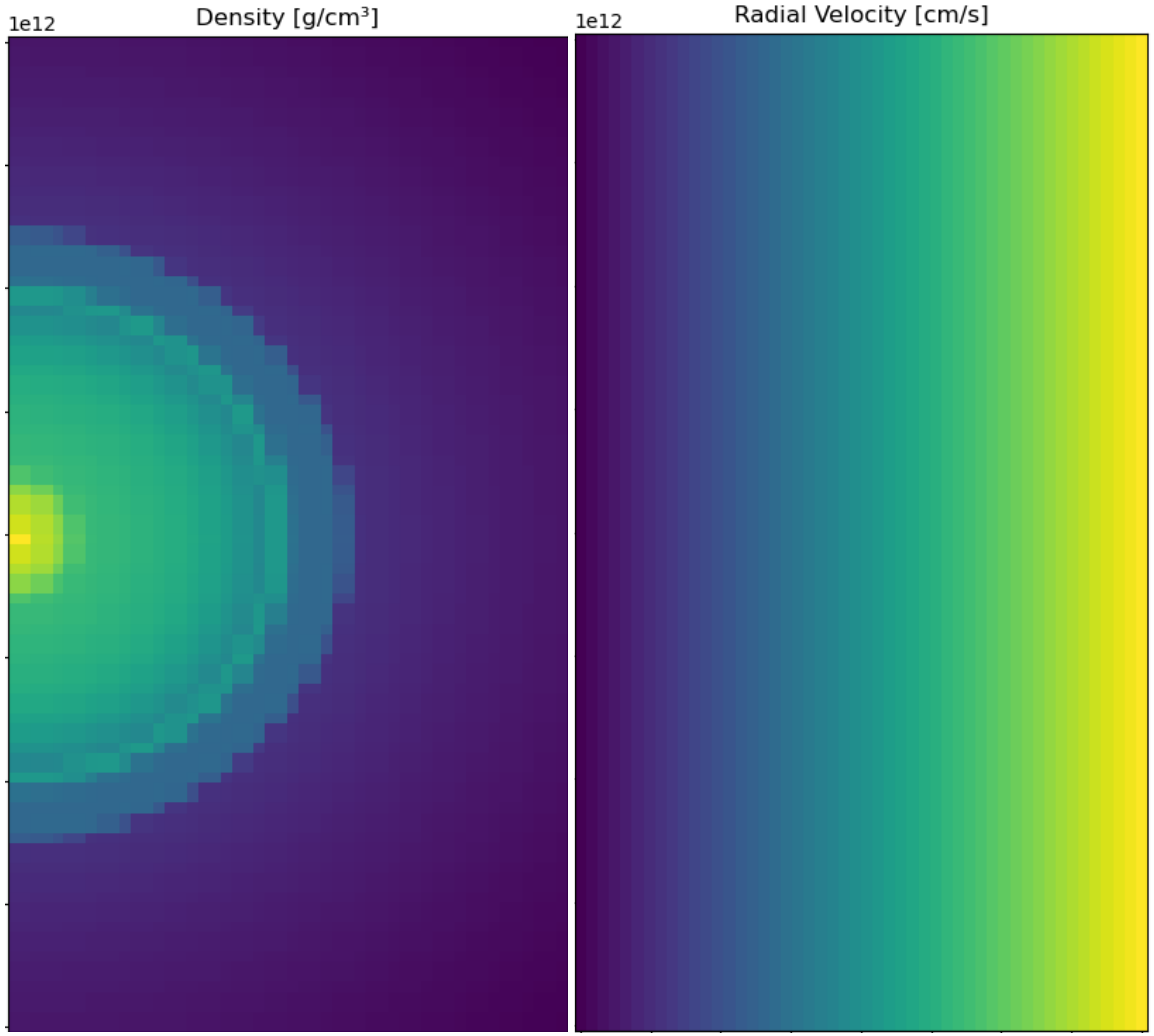
SEDONA

Kasen et al. (2006), Roth & Kasen (2014)

- Daniel Kasen, R.C. Thomas, Peter Nugent. “Time-dependent Monte Carlo Radiative Transfer Calculations for Three-dimensional Supernova Spectra, Light Curves, and Polarization.” 2006
- Sedona calculate the radiation signatures of supernovae and other transient phenomena. It has functionality for hydrodynamic calculations via various solvers. Its radiation transport calculation is via an implicit Monte Carlo algorithm, which works fastest in non-diffusive regimes.

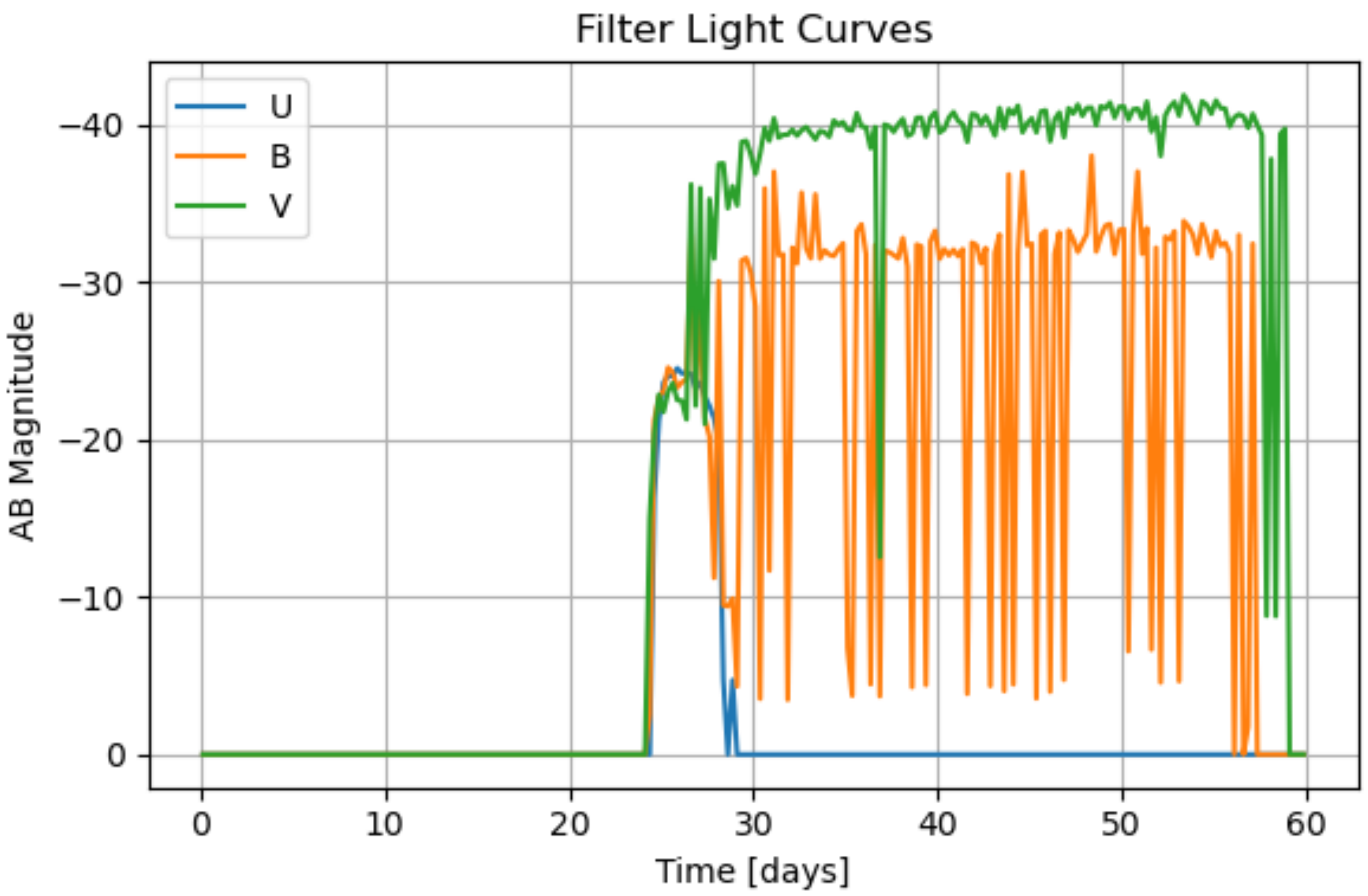
Homologous

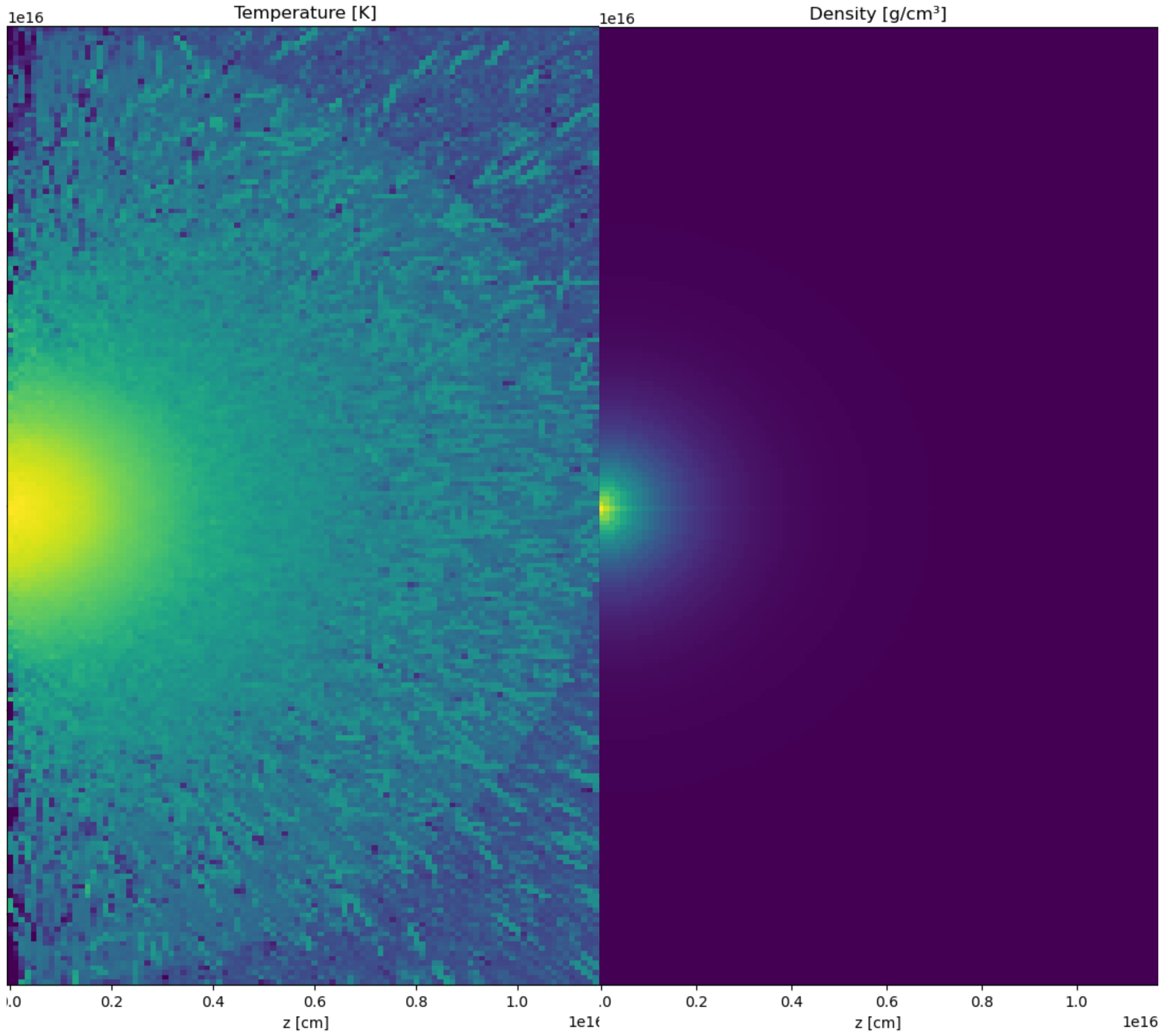
- Mapping from CASTRO (2D)
- Homologous
- Mock Species



Test SN Ia

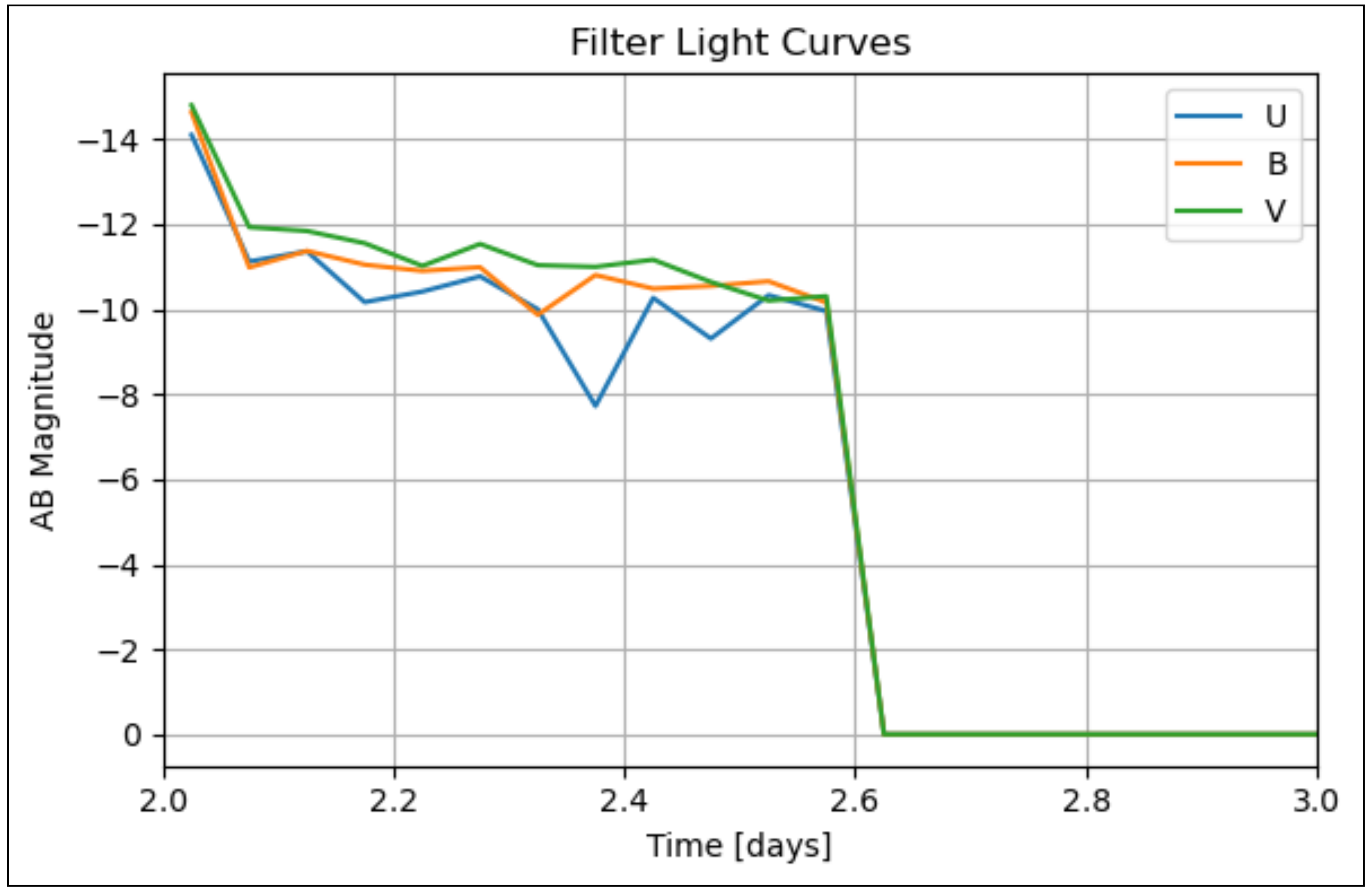
- Particles on Grids = Resolutions
- Toy model: SN Ia

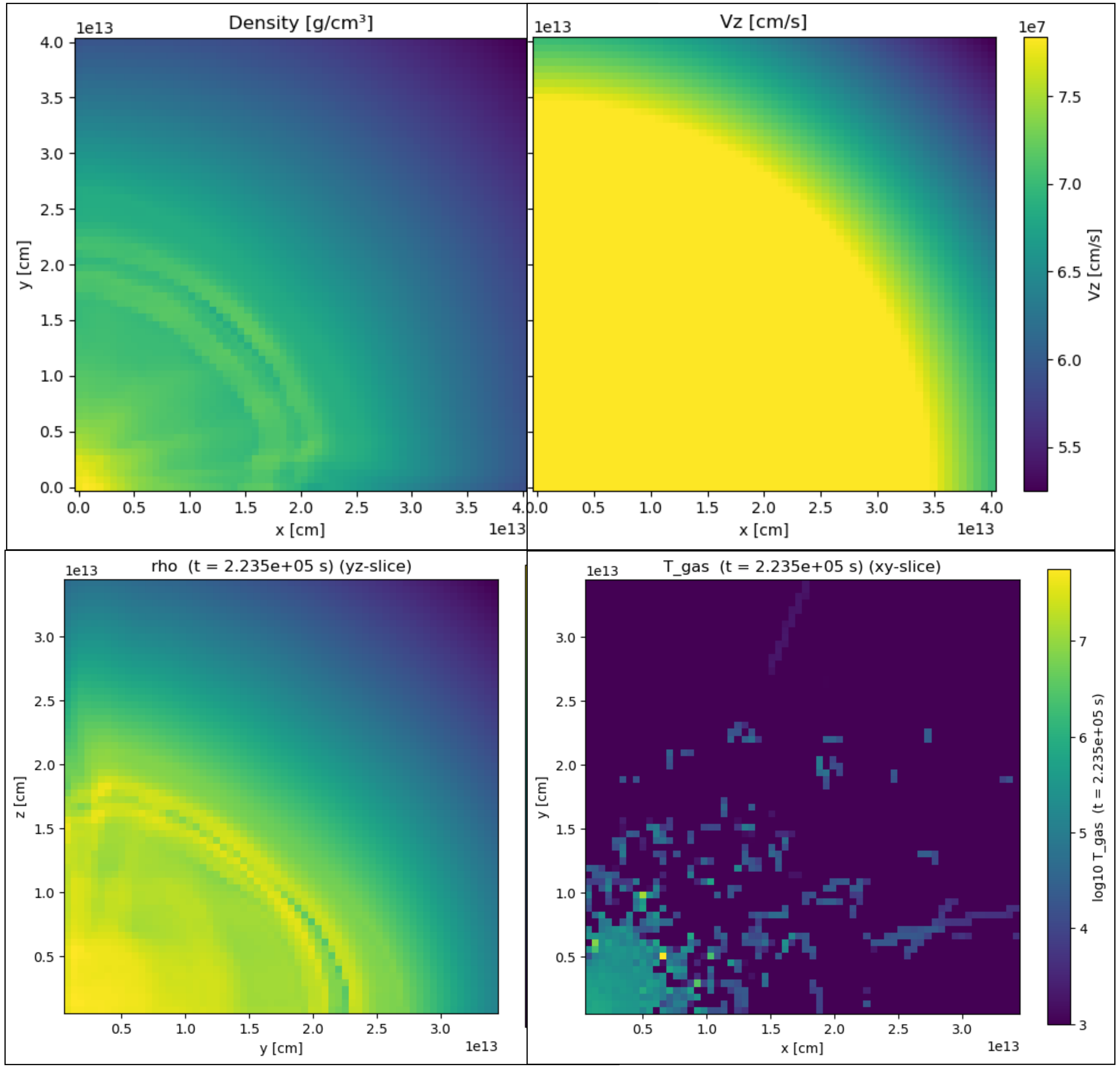




3D SN1987a

- HD 3D SN1987a
  One day after Shock Breakout.
- Mapped and Results





END NOTE

Remarks: Limitations

- Opacity:
  - Constant electron scattering
  - Adapted OPAL table (MESA)
- RHD:
  - FLD
  - Compare with VET, M1 …?