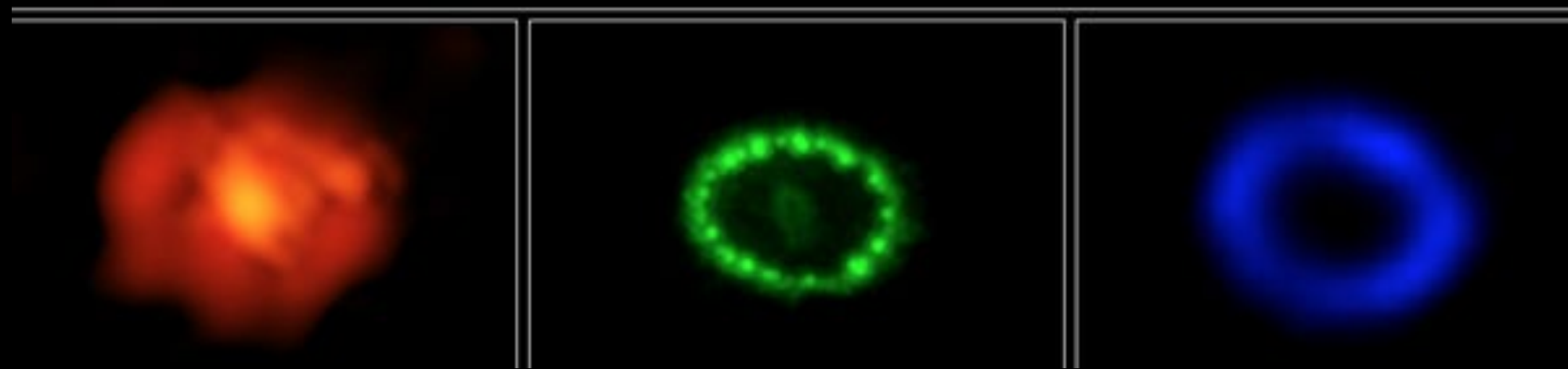


# CORE-COLLAPSE SUPERNOVAE: FROM NEUTRINO-DRIVEN 1D EXPLOSIONS TO LIGHT CURVES AND SPECTRA

**SANJANA CURTIS**  
**UNIVERSITY OF CHICAGO/KICP**

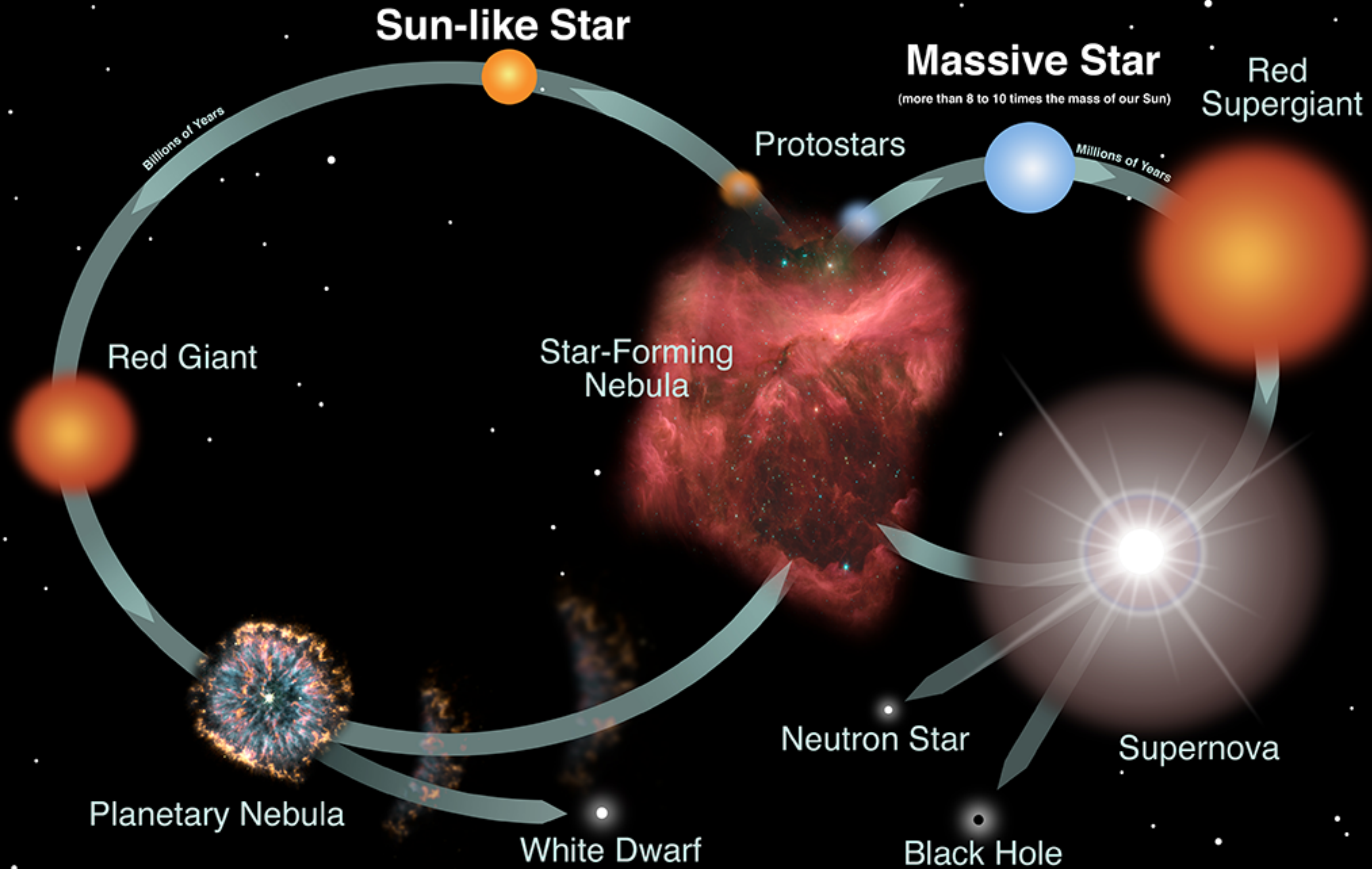
NOAH WOLFE (NC STATE/MIT)  
CARLA FRÖHLICH (NC STATE)  
JONAH MILLER (LANL)  
RYAN WOLLAEGER (LANL)  
KEVIN EBINGER (GSI)

**SNEWS MEETING, AUG 3, 2022**



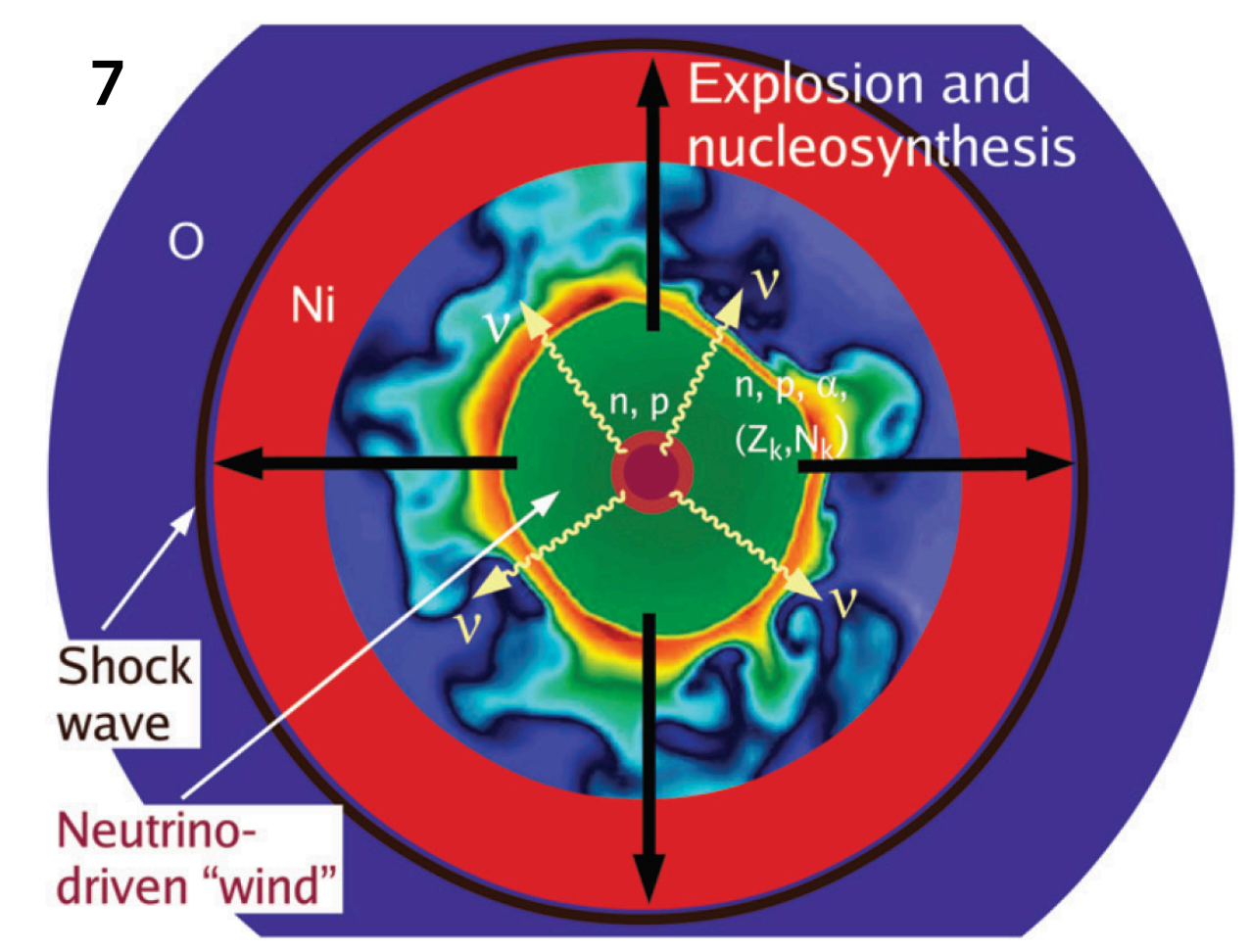
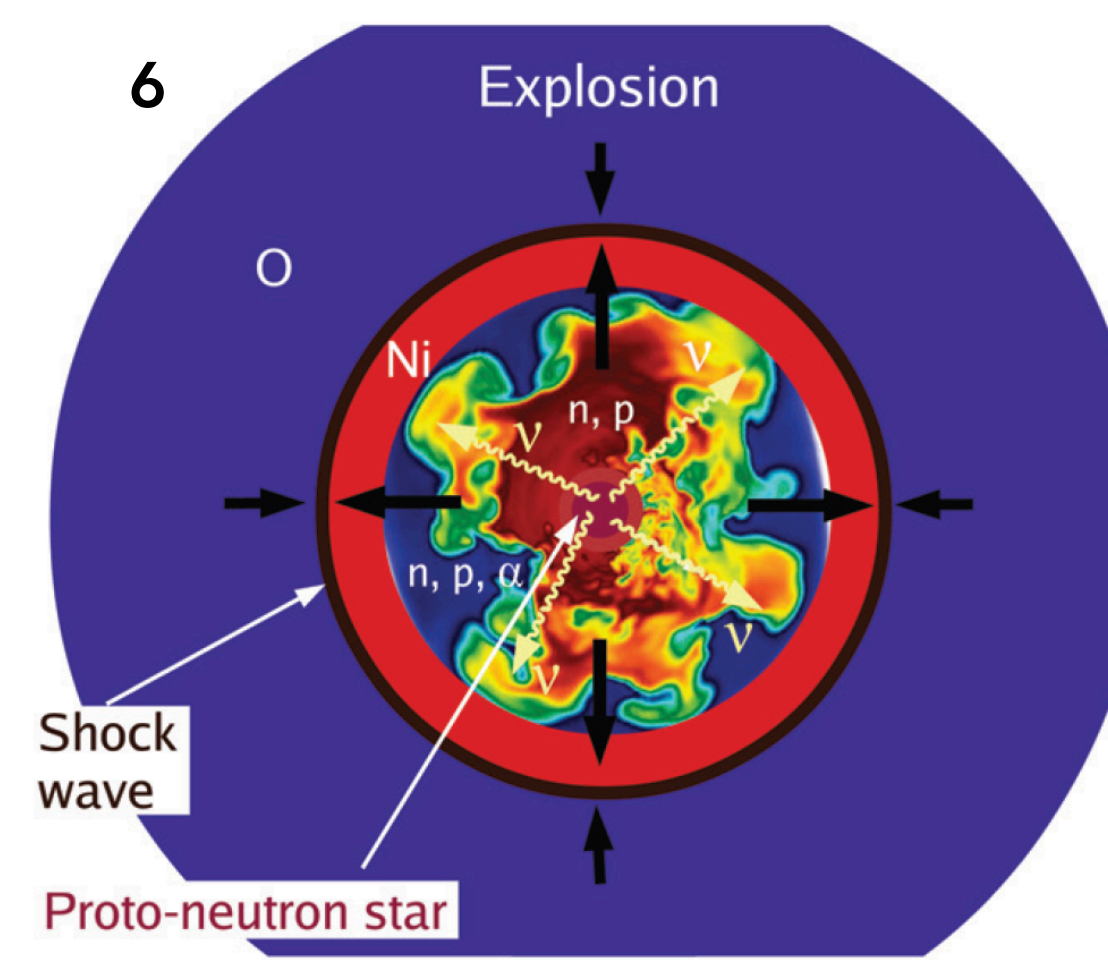
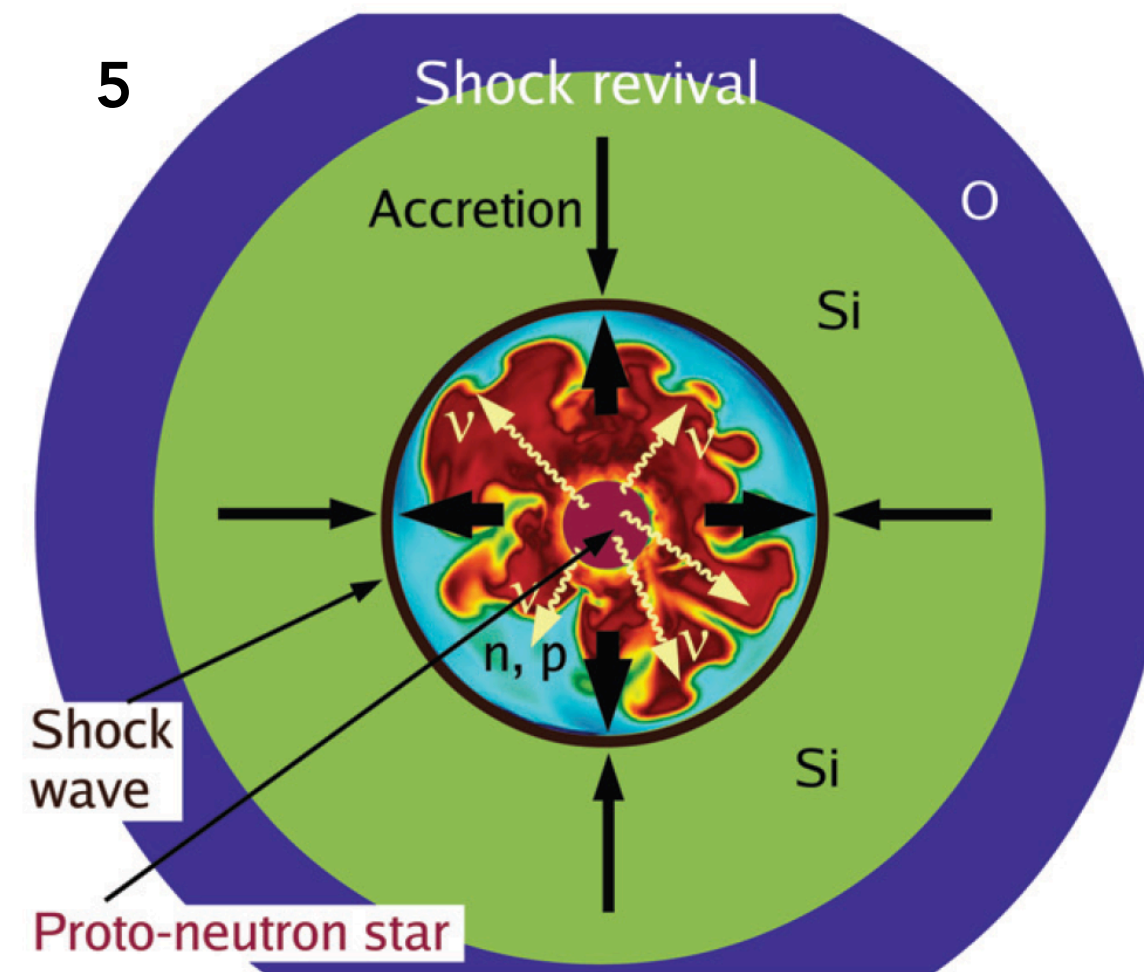
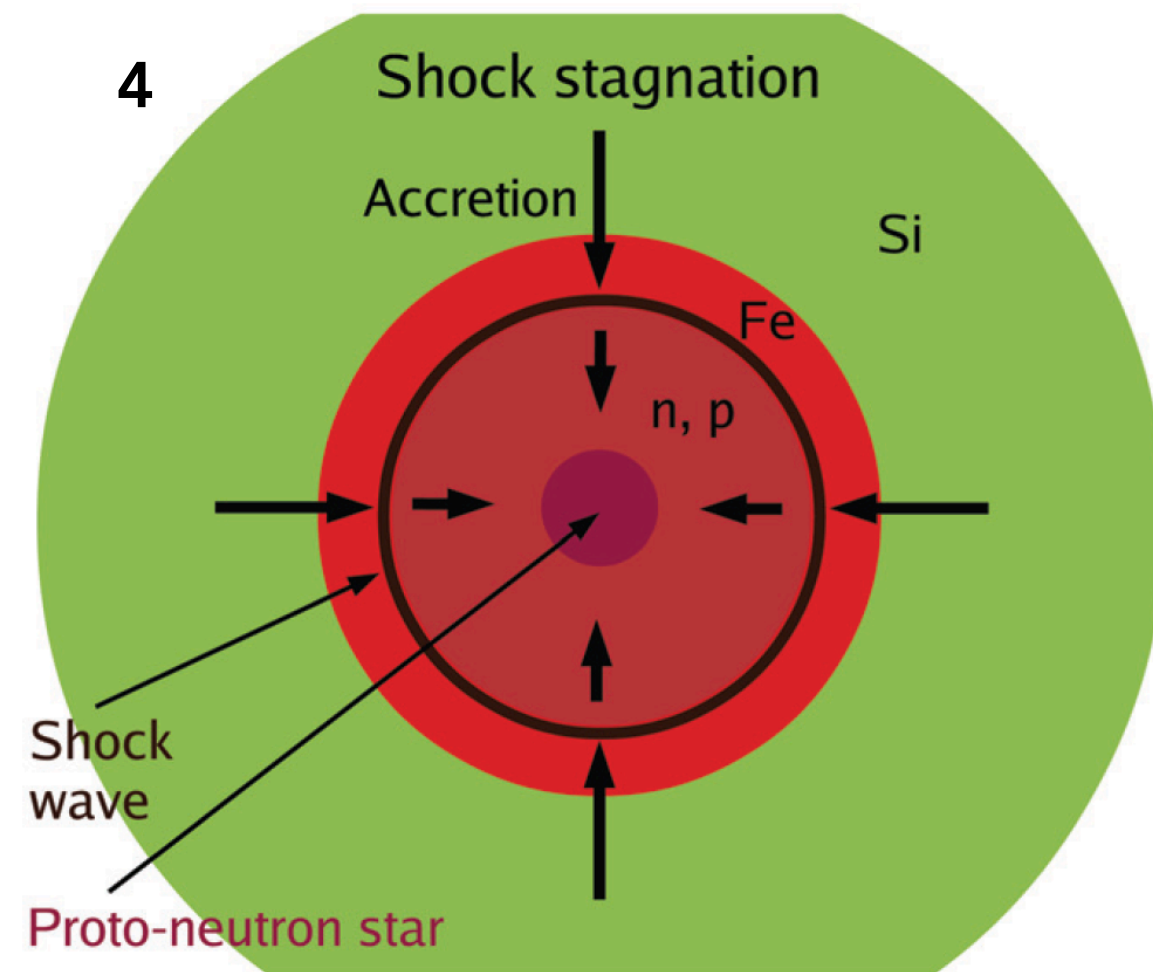
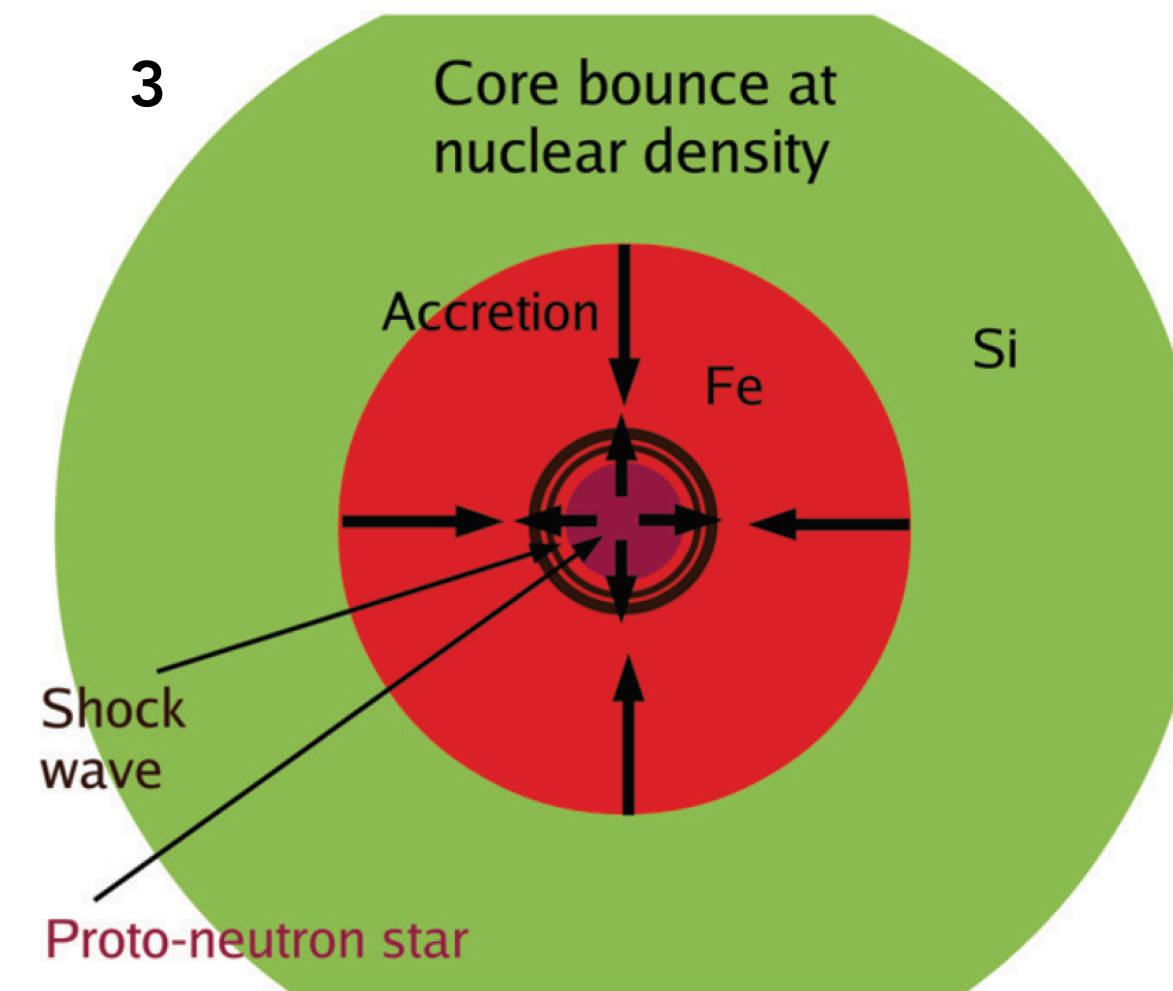
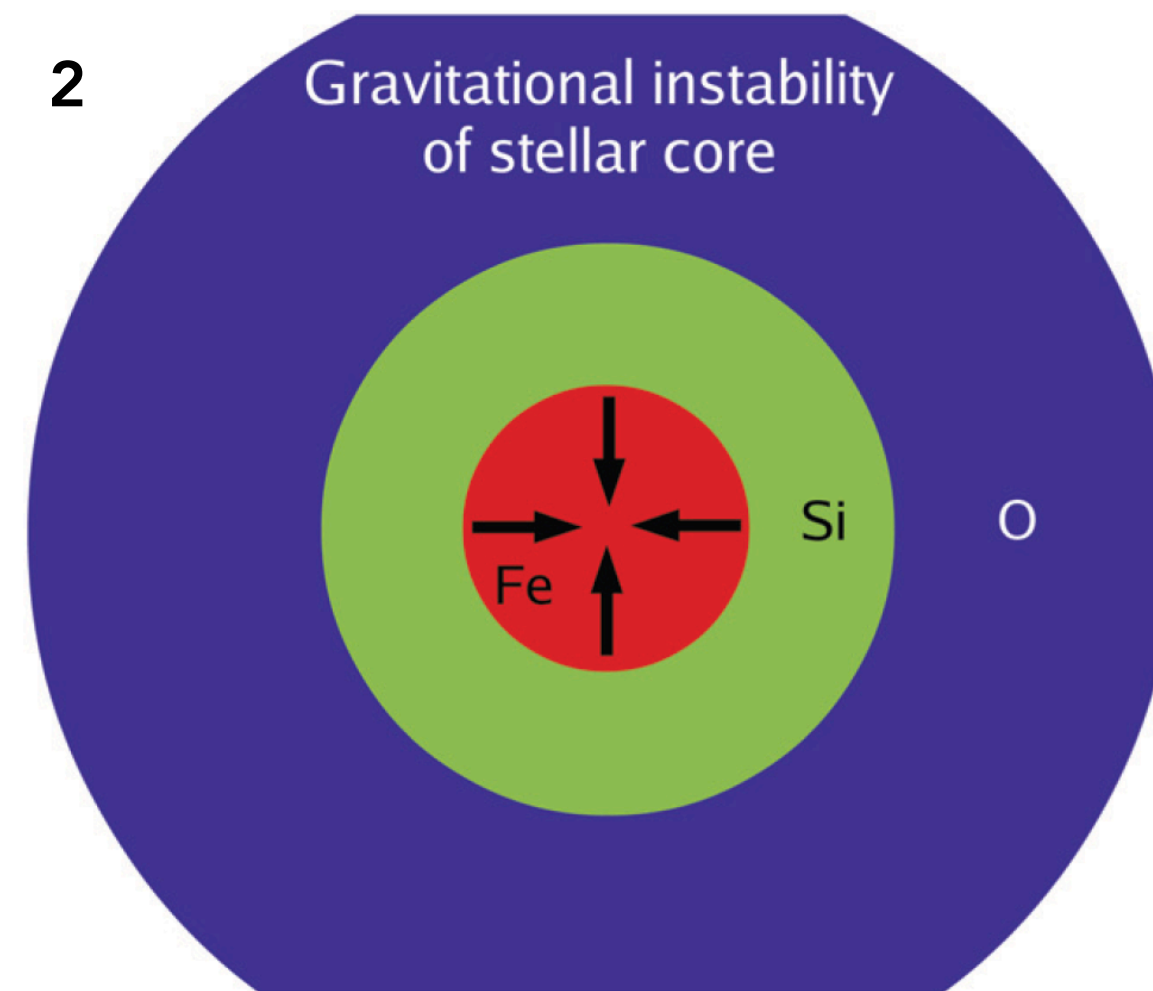
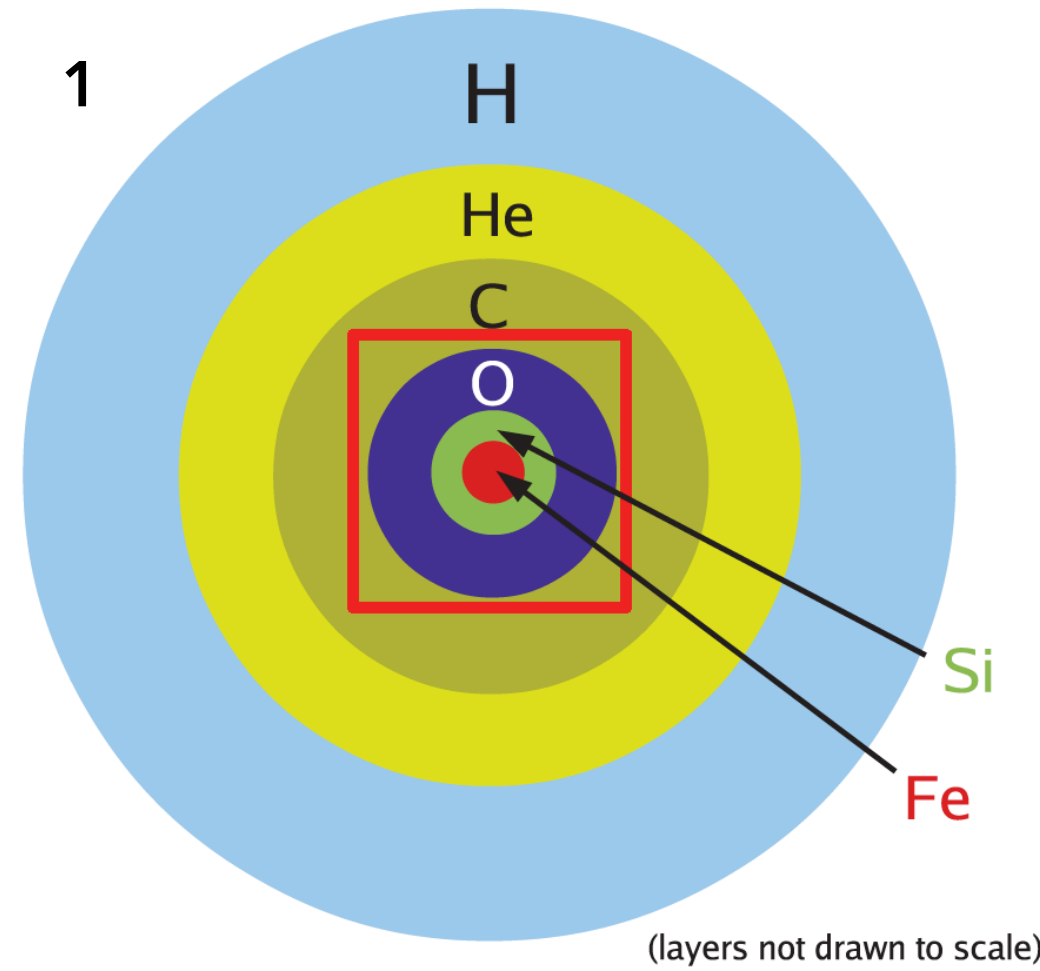
# OUTLINE

- **Introduction to Core-Collapse Supernovae**
- Motivation and Objectives
- From Explosions to Light Curves and Spectra
- Light Curves and Spectra
- Summary and Outlook





# WHAT MAKES A MASSIVE STAR EXPLODE?



(Janka+2012)

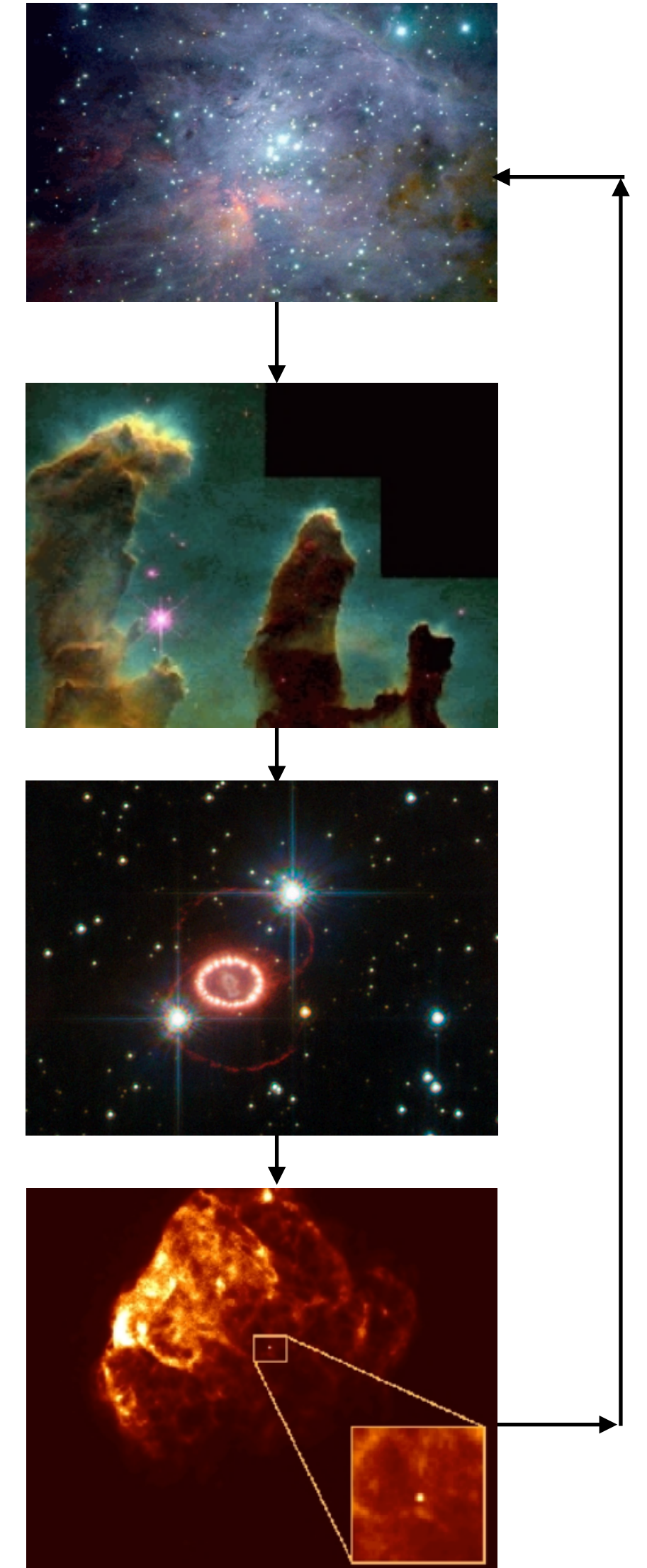


# OUTLINE

- Introduction to Core-Collapse Supernovae
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- Light Curves and Spectra
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# WHY STUDY CORE-COLLAPSE SUPERNOVAE?

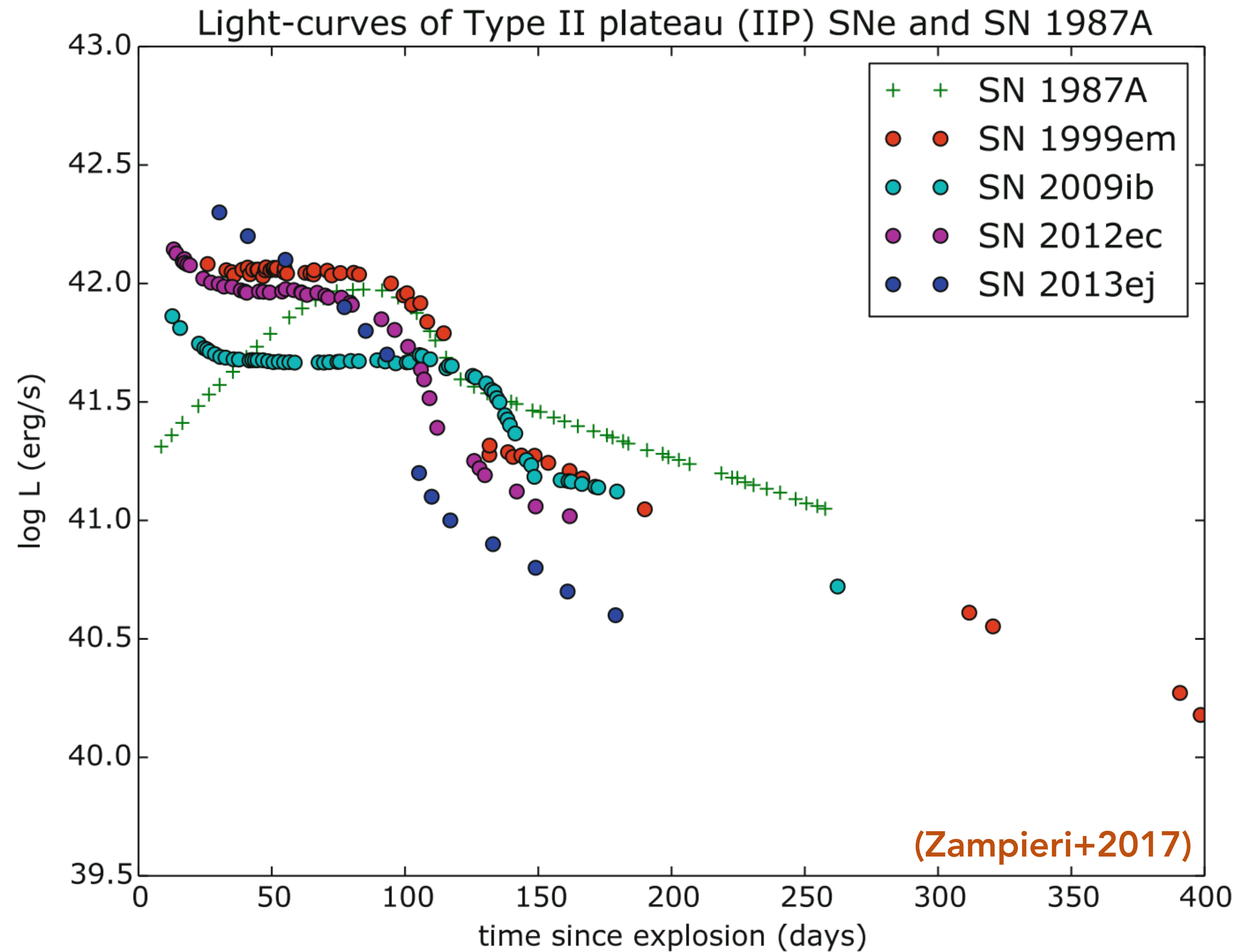
- Element factories
  - Alpha elements ( O, Ne, Mg, Si, S, Ar, Ca)
  - Fe-group elements (Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn)
  - Some heavier elements (Sr, Y, Zr, Mo, Ru, r-process?)
- Give birth to neutron stars and black holes
- Shape dynamical and chemical evolution of galaxies
- Probe matter at high densities and neutrino physics
- Multi-messenger sources: **light**, neutrinos, gravitational waves





# WHAT CAN WE LEARN FROM CCSN LIGHT CURVES?

- Diverse light curves
- Type I or Type II from spectrum
- Ni-56 amount and distribution
- Ejecta mass, explosion energy
- Constrain progenitor properties
- Measure cosmological distances



# WHAT CAN WE LEARN FROM CCSN SPECTRA?

- Photospheric temperature and velocity
- Line strengths: ionic masses, composition
- Line profiles: velocity, morphology, mixing

progenitor properties

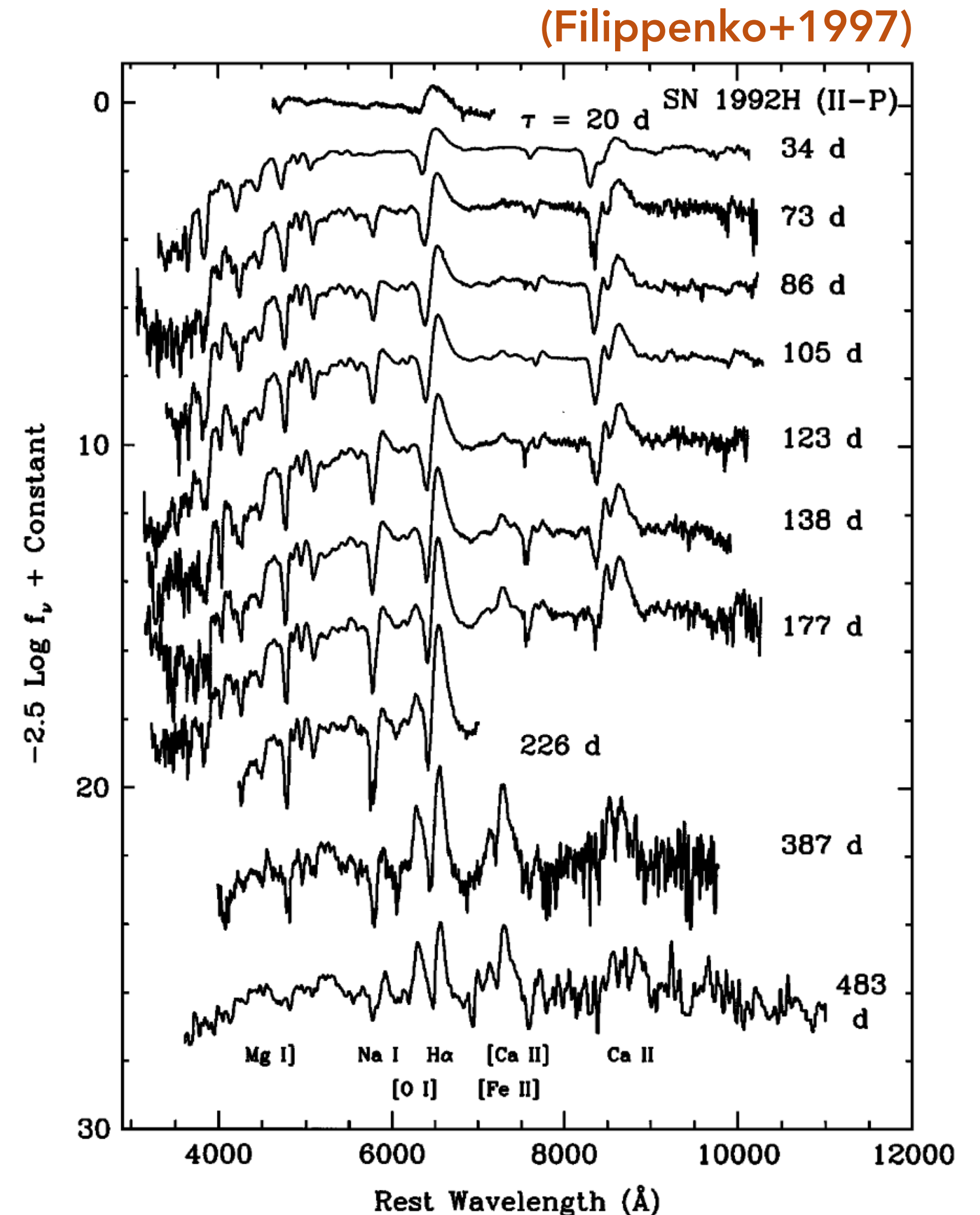
stellar evolution

explosion mechanism

nuclear equation of state

nucleosynthesis

formation of neutron stars and black holes





# OUR GOAL

- Multi-messenger database using the same set of models
- Previous work ranges from analytic scalings to detailed numerical work  
(Arnett 1980, Chugai 1991, Popov 1991, Chieffi+2003, Young 2004, Kasen & Woosley 2009, Bersten+2011, Dessart+2011, Dessart+2013, Jerkstrand+2014, Jerkstrand+2015)
- Self-consistent calculation from explosion models to light curves and spectra
- Comparison with observations and validation of the PUSH method
- Low computational cost to explore broad range of masses and metallicities

Curtis+2021 (*ApJ* 921 143, arXiv:2008.05498)

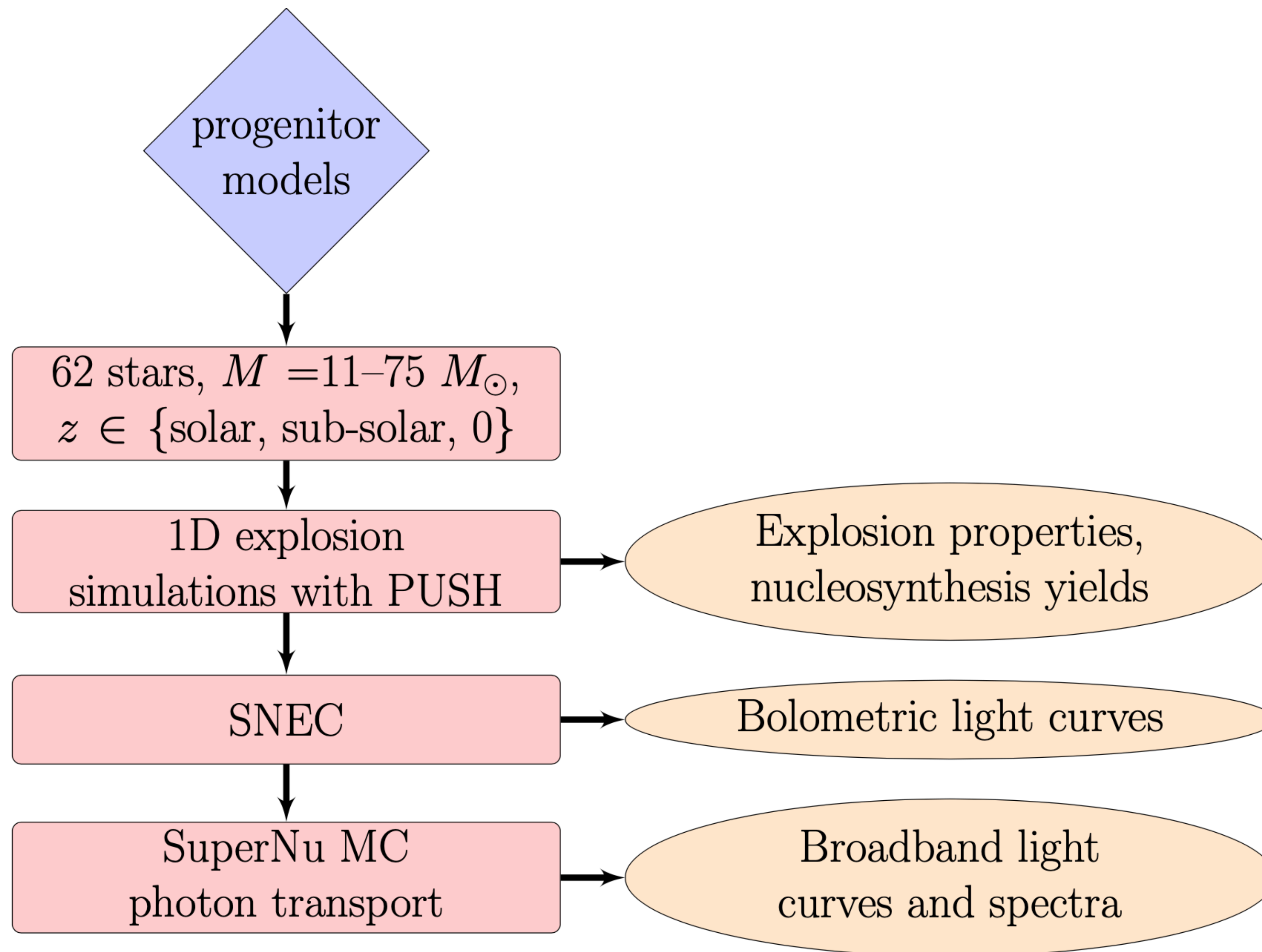
[http:// go.ncsu.edu/astrodata](http://go.ncsu.edu/astrodata)

# OUTLINE

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# FROM EXPLOSIONS TO LIGHT CURVES



# PROGENITOR MODELS

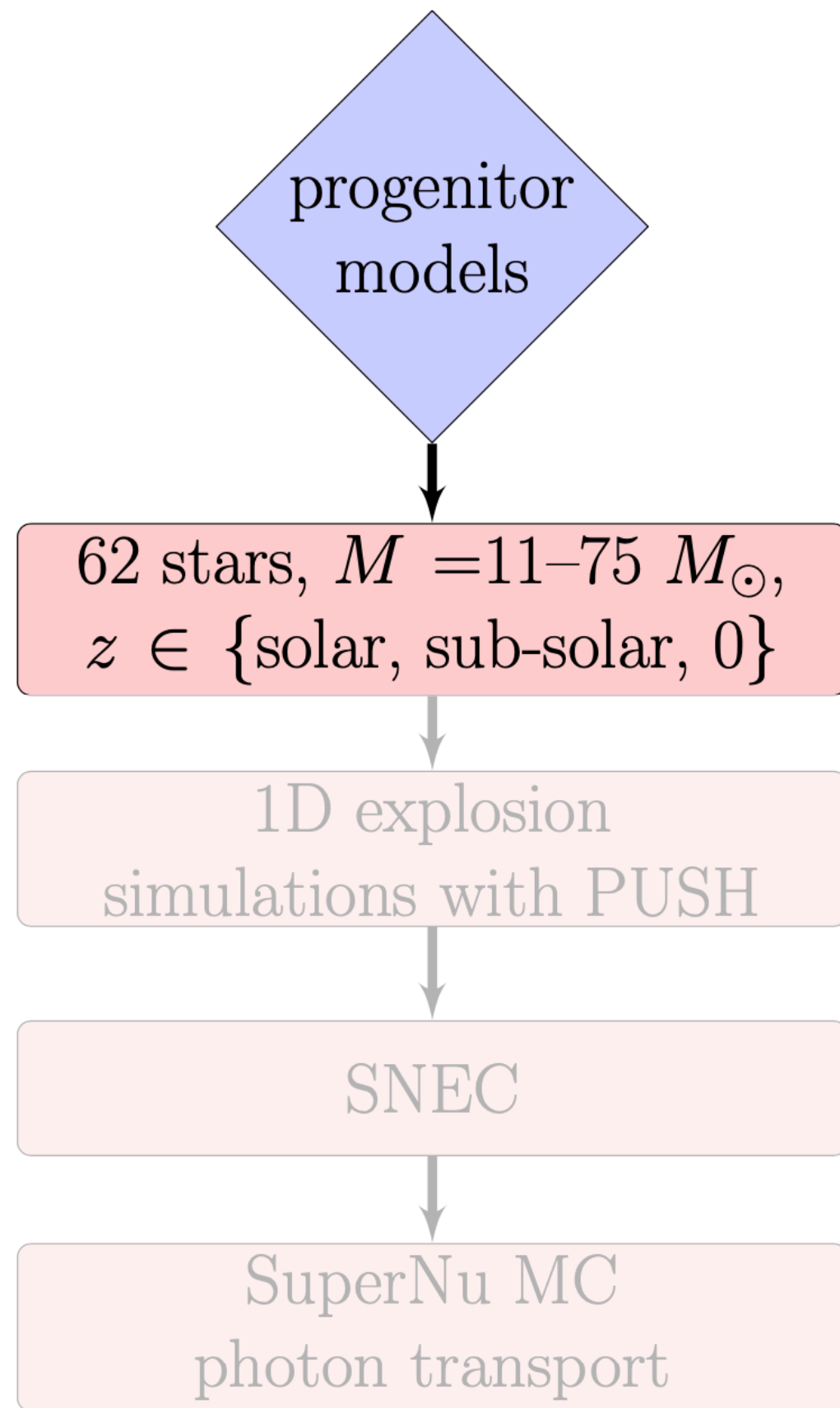
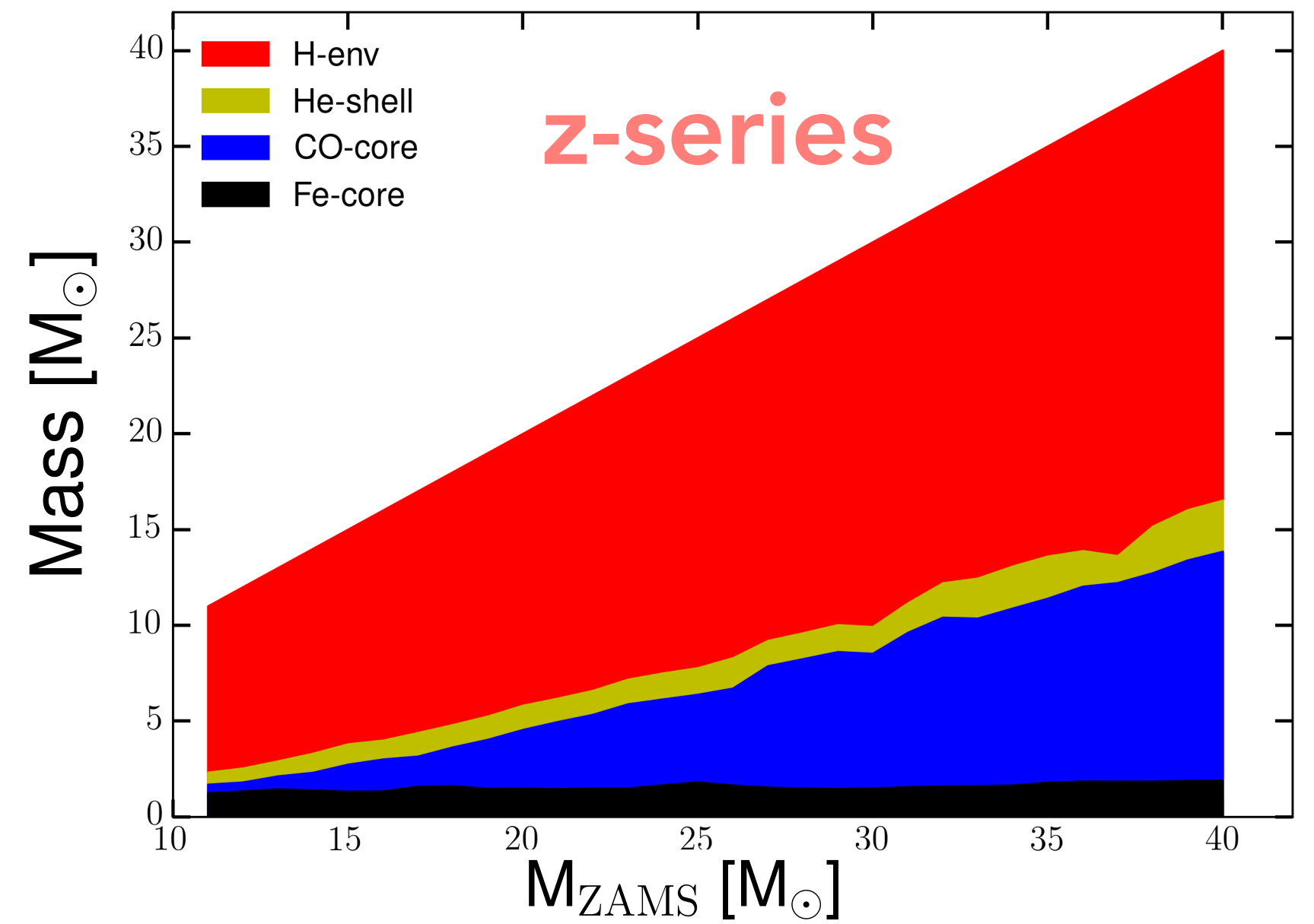
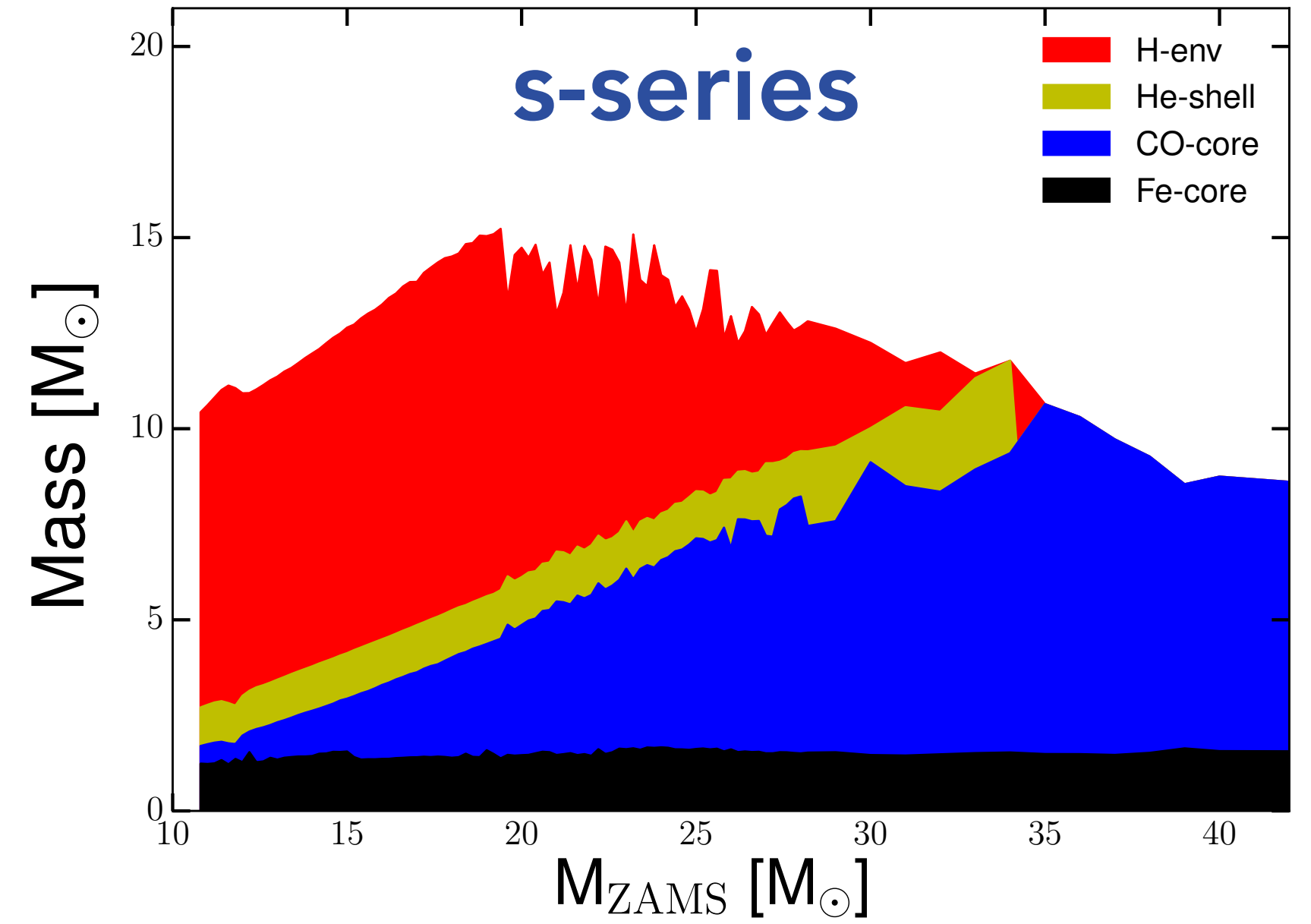
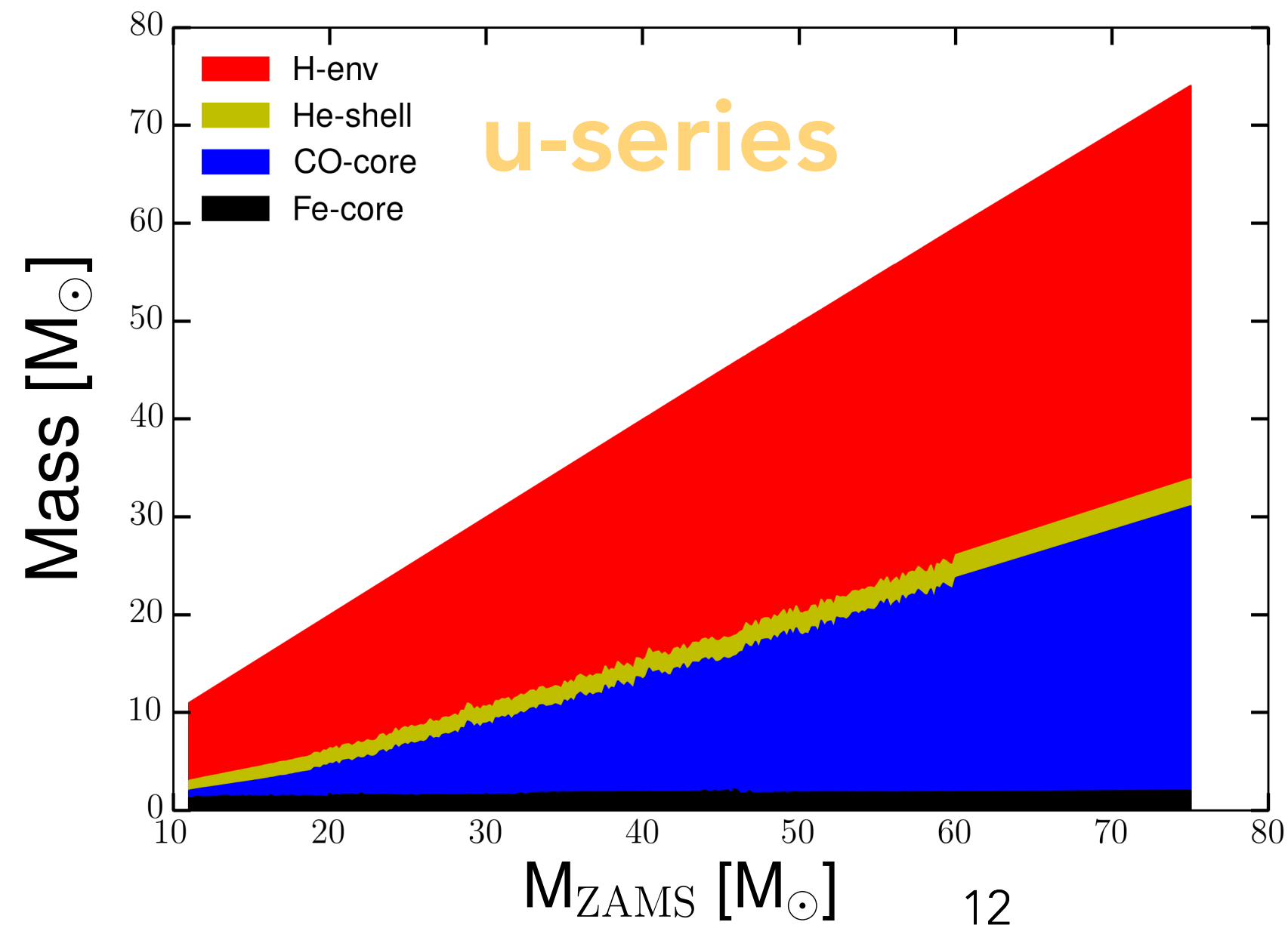
KEPLER stellar evolution code  
(Woosley+2002)

**s-series**  $Z=Z_{\odot}$

**u-series**  $Z=Z_{\odot} \times 10^{-4}$

**z-series**  $Z=0$

Different degrees of mass loss



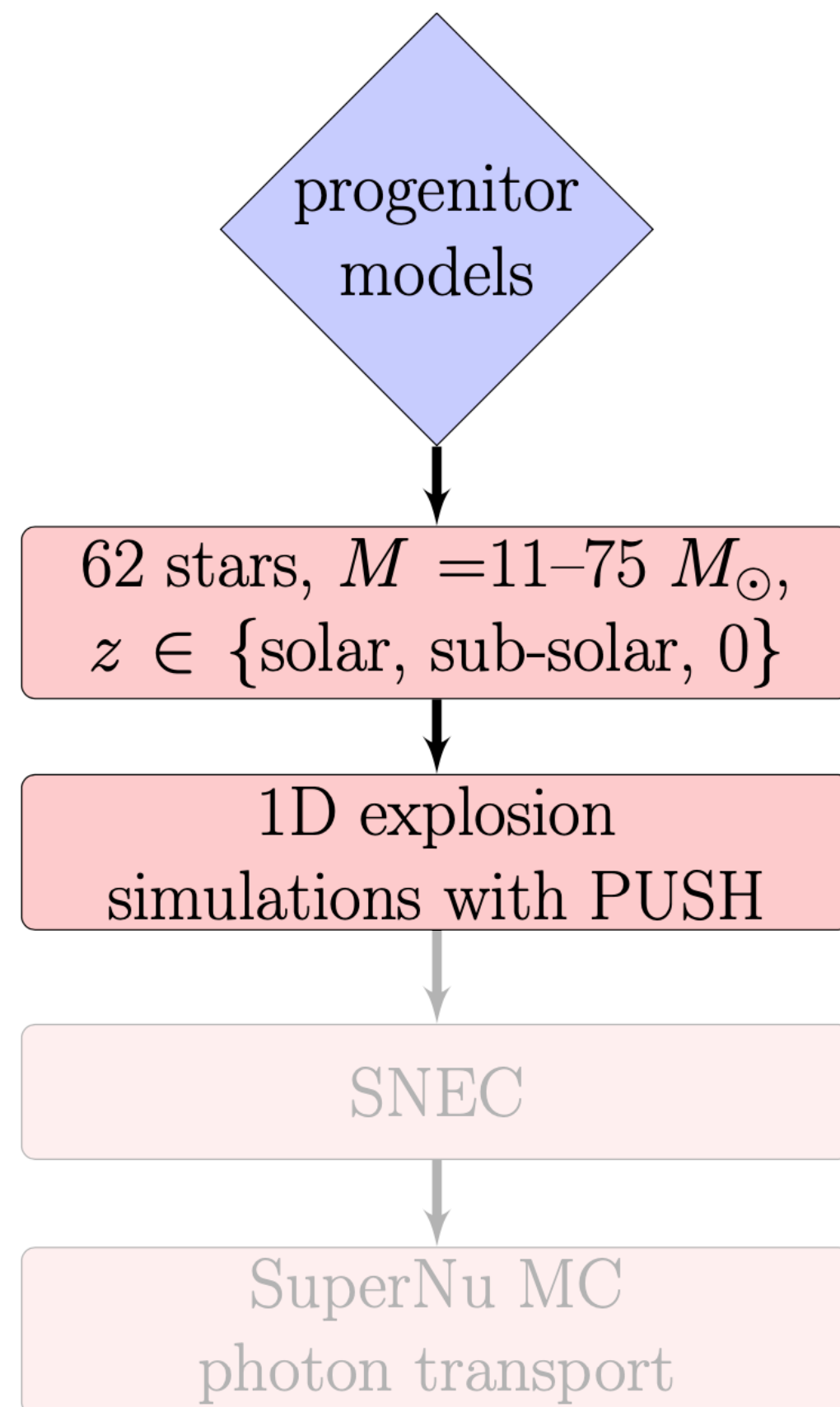
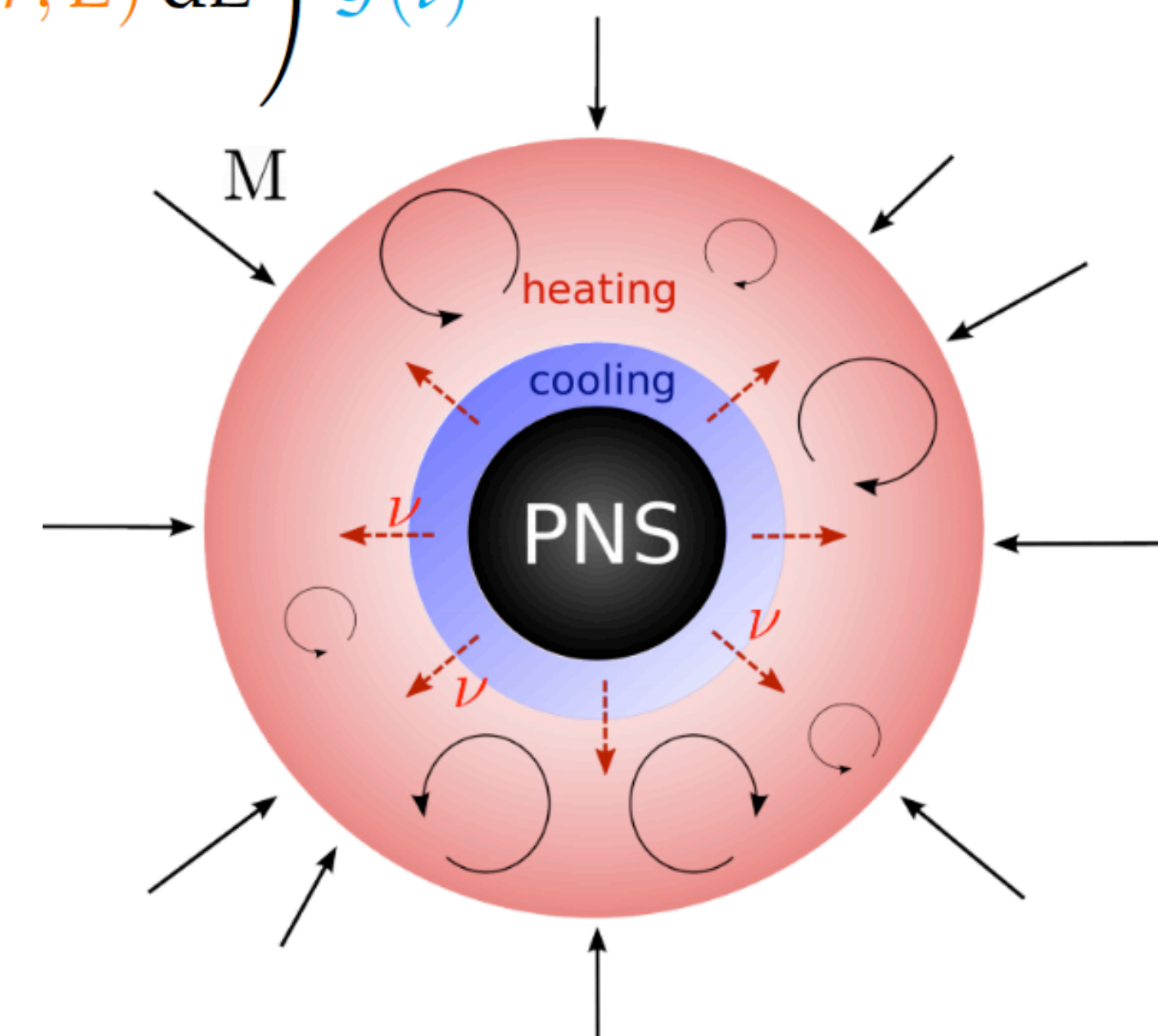


# 1D EXPLOSION SIMULATIONS WITH PUSH

- Parametrized neutrino heating in Agile-IDSA  
(Perego+2015, Ebinger+2019)
- Inspired by multi-d simulations, calibrated against SN1987A
- Deposits fraction of heavy-flavor  $\nu$  energy in the gain region

$$\dot{E}_{\text{push}}^+(t, r) \propto \left( \int_0^{+\infty} \sigma_0 \left( \frac{E}{m_e c^2} \right)^2 \left( \frac{1}{4\pi r^2} \frac{dL_{\nu_{\mu, \tau}}}{dE} \right) \mathcal{F}(t, r, E) dE \right) \mathcal{G}(t)$$

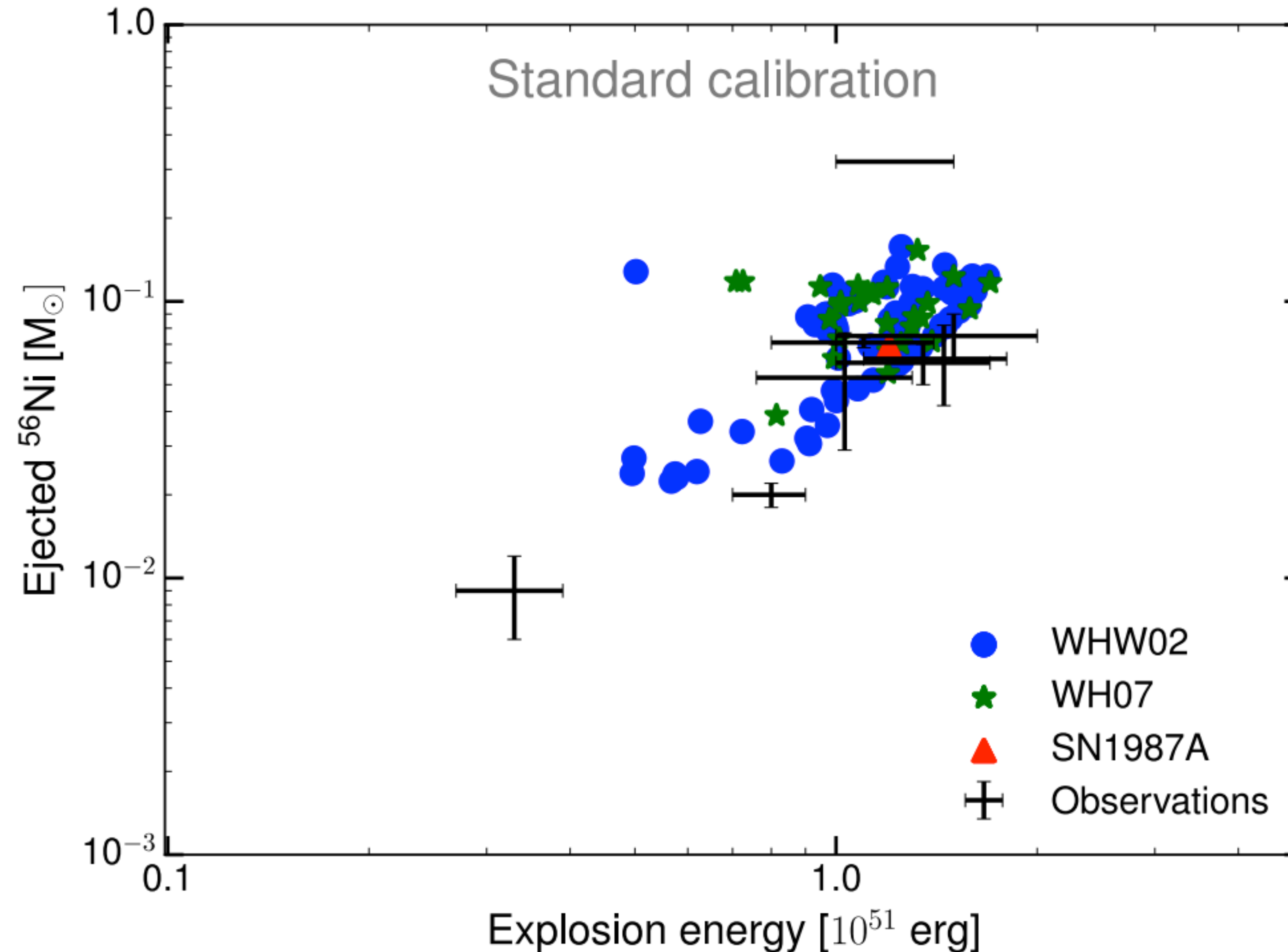
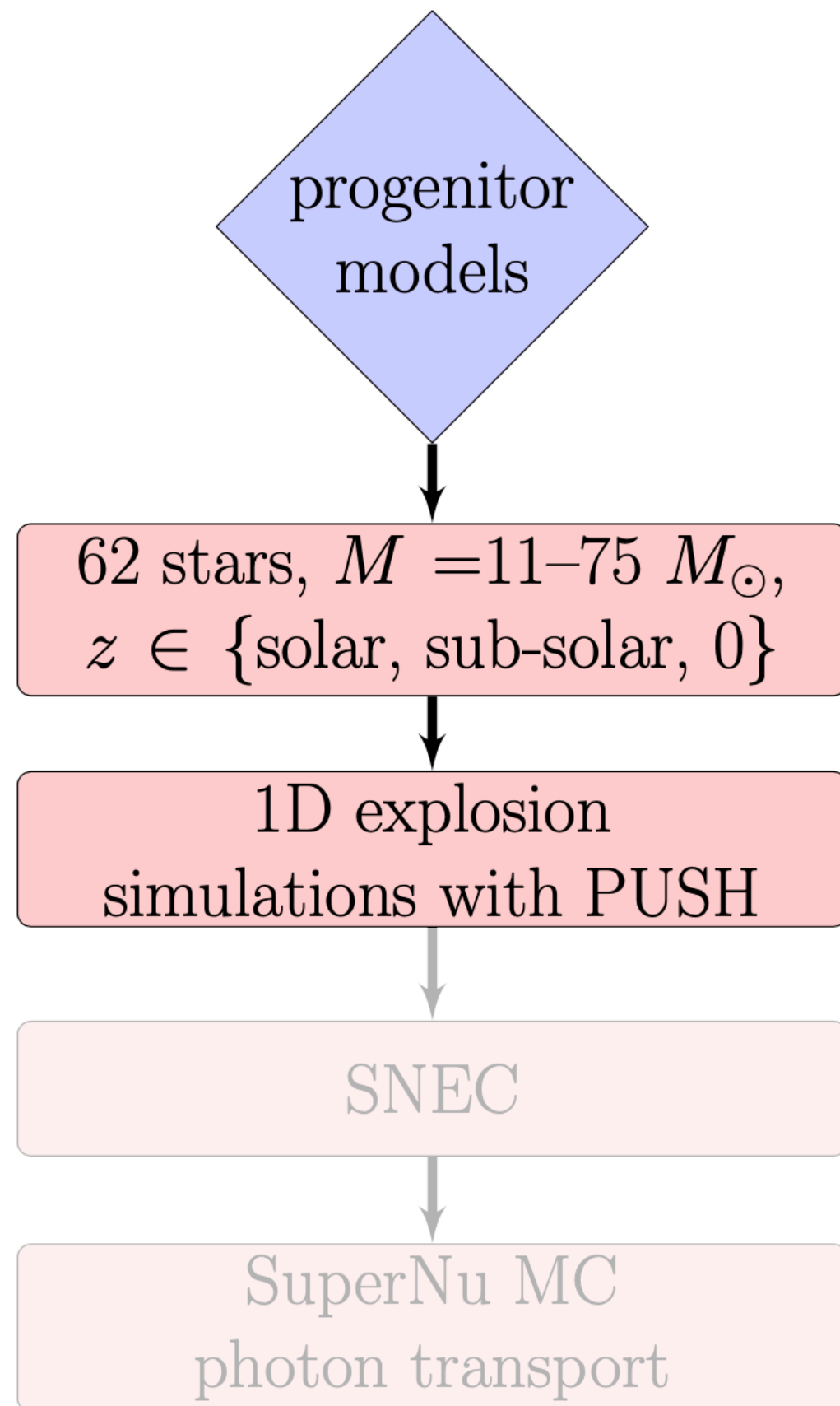
- ▶ spectral  $\nu_{\mu, \tau}$  energy flux
- ▶ temporal function
- ▶ typical  $\nu$  cross section
- ▶ space location function



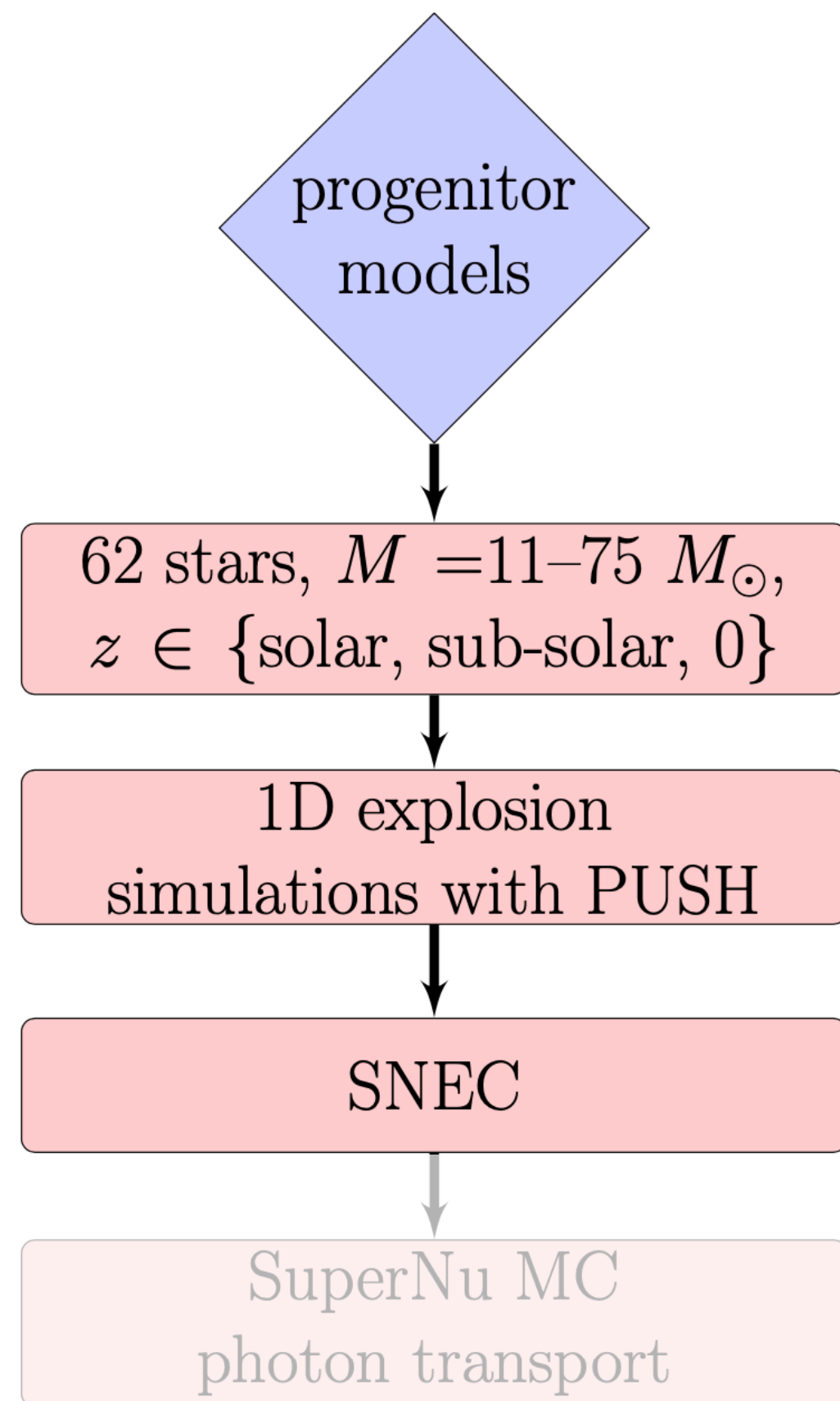
# 1D EXPLOSION SIMULATIONS WITH PUSH

Explosion properties and nucleosynthesis

[Ebinger+2019](#), [Curtis+2019](#), [Ebinger & Curtis+2020](#)



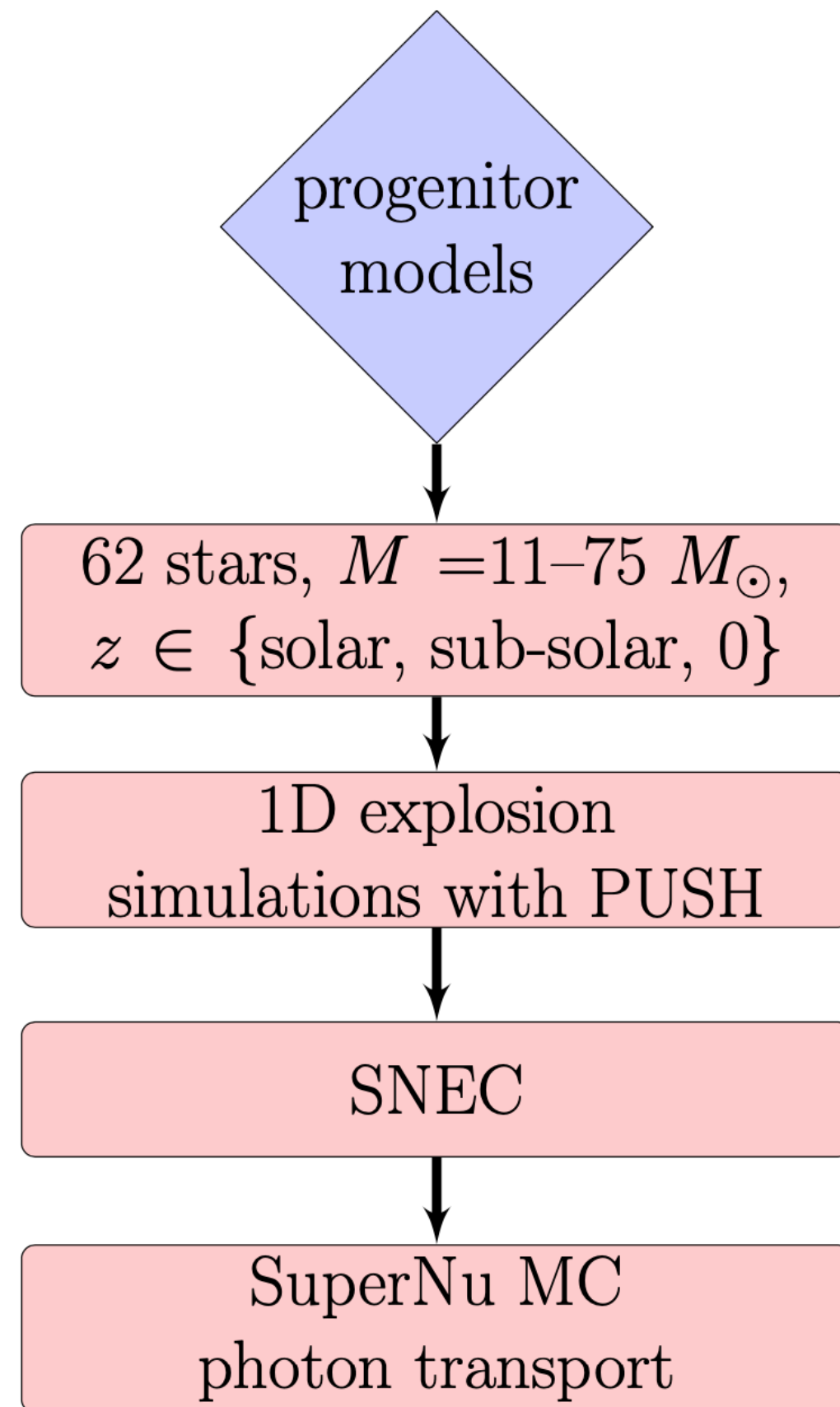
# RADIATION HYDRODYNAMICS WITH SNEC



- 1D Lagrangian hydrodynamics with flux-limited diffusion  
**(Morozova+2015)**
- Map at the end of PUSH simulations before shock leaves the grid
- Hydrodynamic and composition profiles from Agile-IDSA and CFNET
- Include radioactive heating by Ni-56, recombination up to Oxygen
- Boxcar smoothing to imitate mixing
- Thermal bomb effectively zero
- Bolometric and broadband light curves



# MC RADIATION TRANSPORT WITH SUPERNU



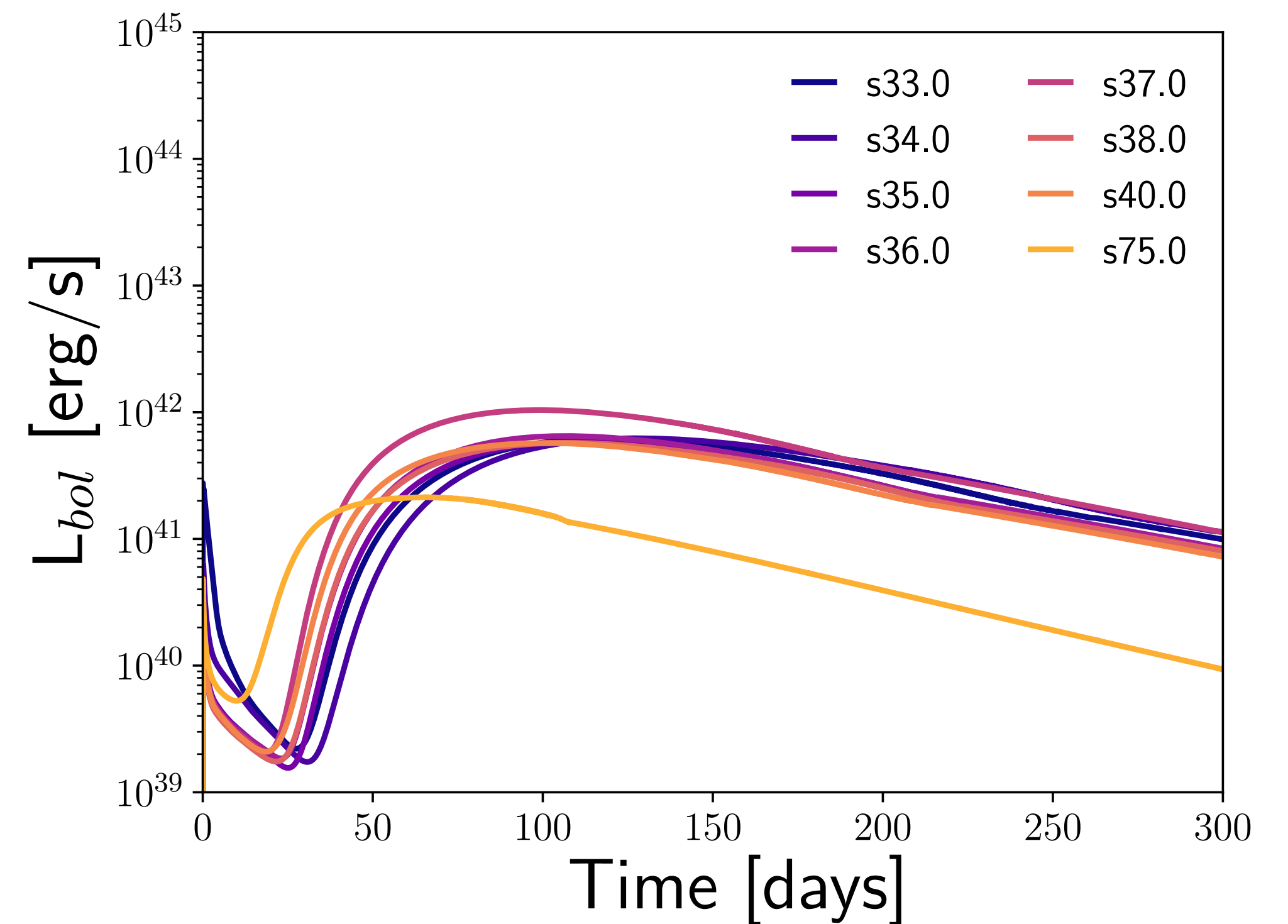
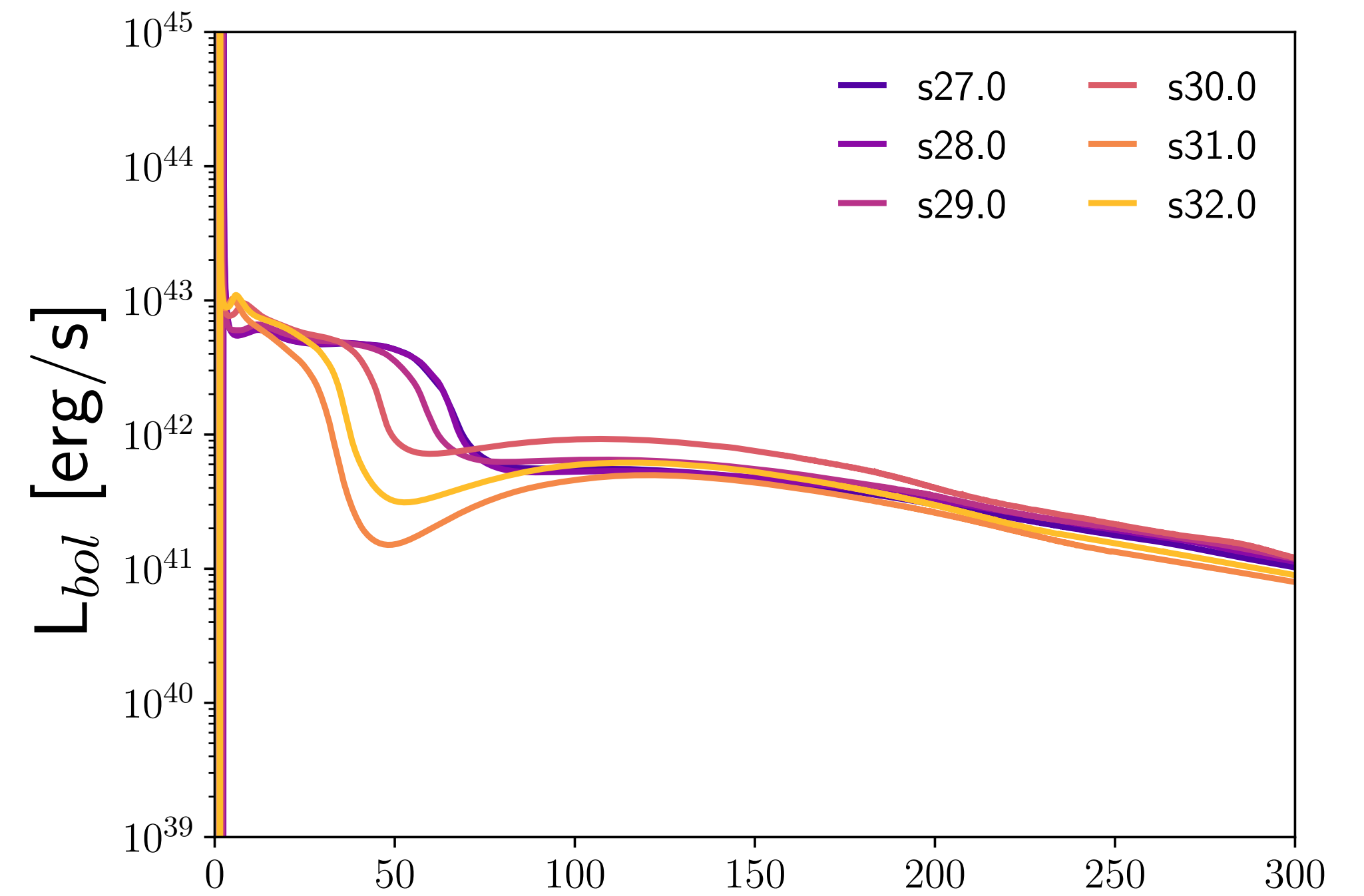
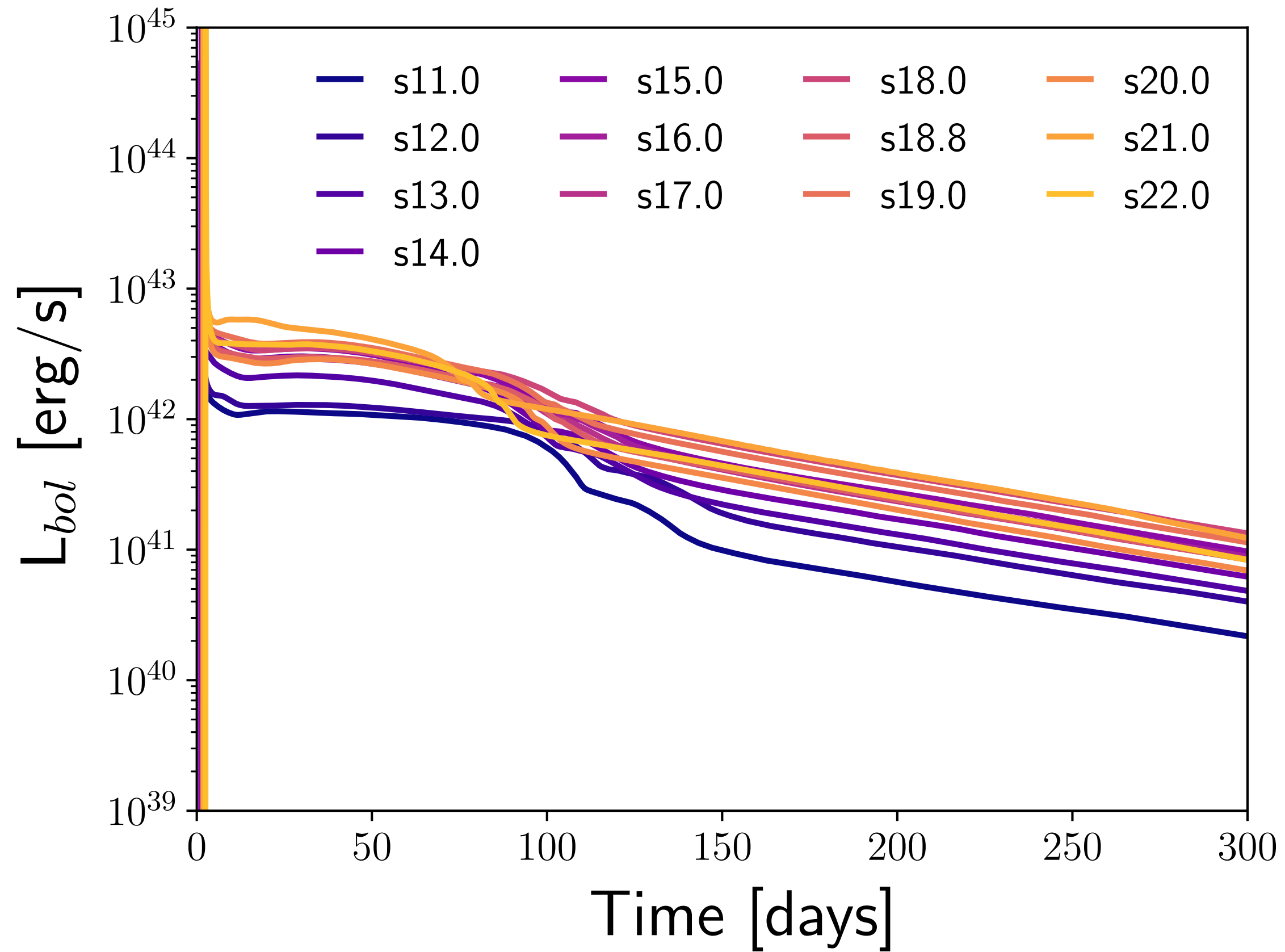
- Time-dependent IMC radiation transport with DDMC  
(Wollaeger+2013, Wollaeger+2014)
- Assumes homologous expansion and LTE
- Multi-group absorption opacities from H to Co
- Decay chains of Ni-56, Fe-52 and Cr-48
- Map from SNEC when outflow is homologous
- Bolometric light curves and synthetic spectra

# OUTLINE

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# SNEC: LIGHT CURVES

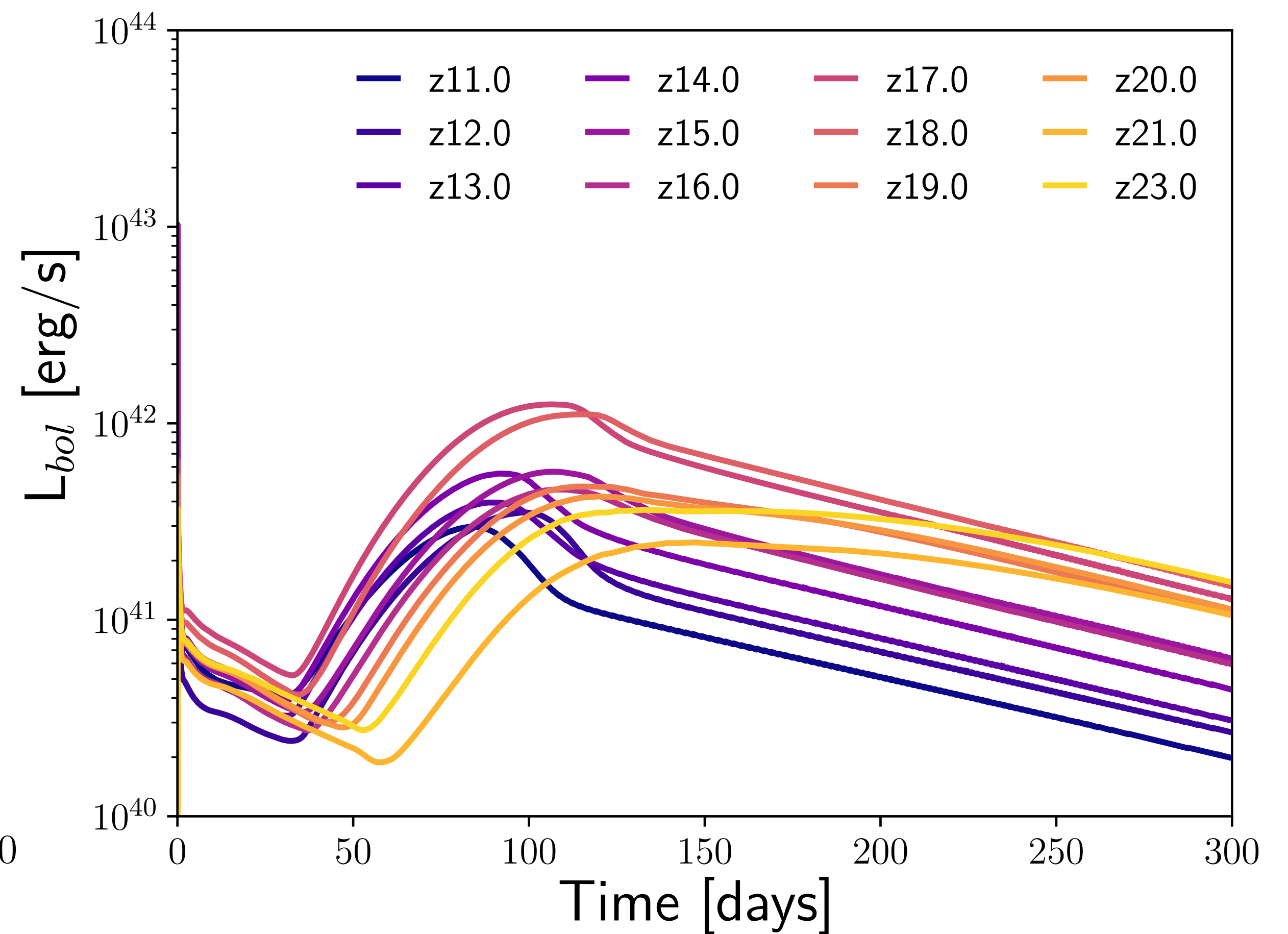
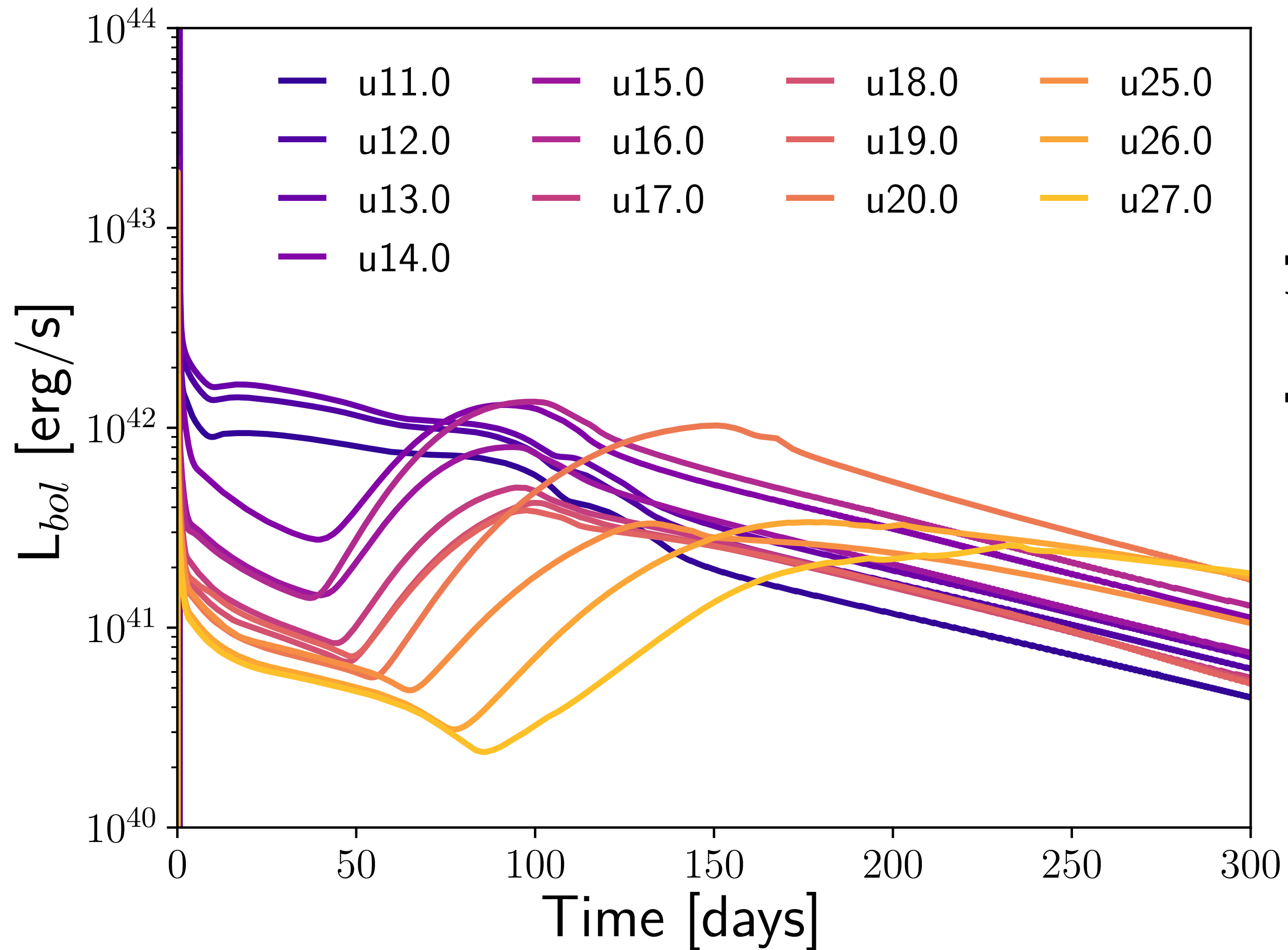
For **s-series**, standard Type IIp light curves transition to stripped envelope-like with increasing ZAMS mass



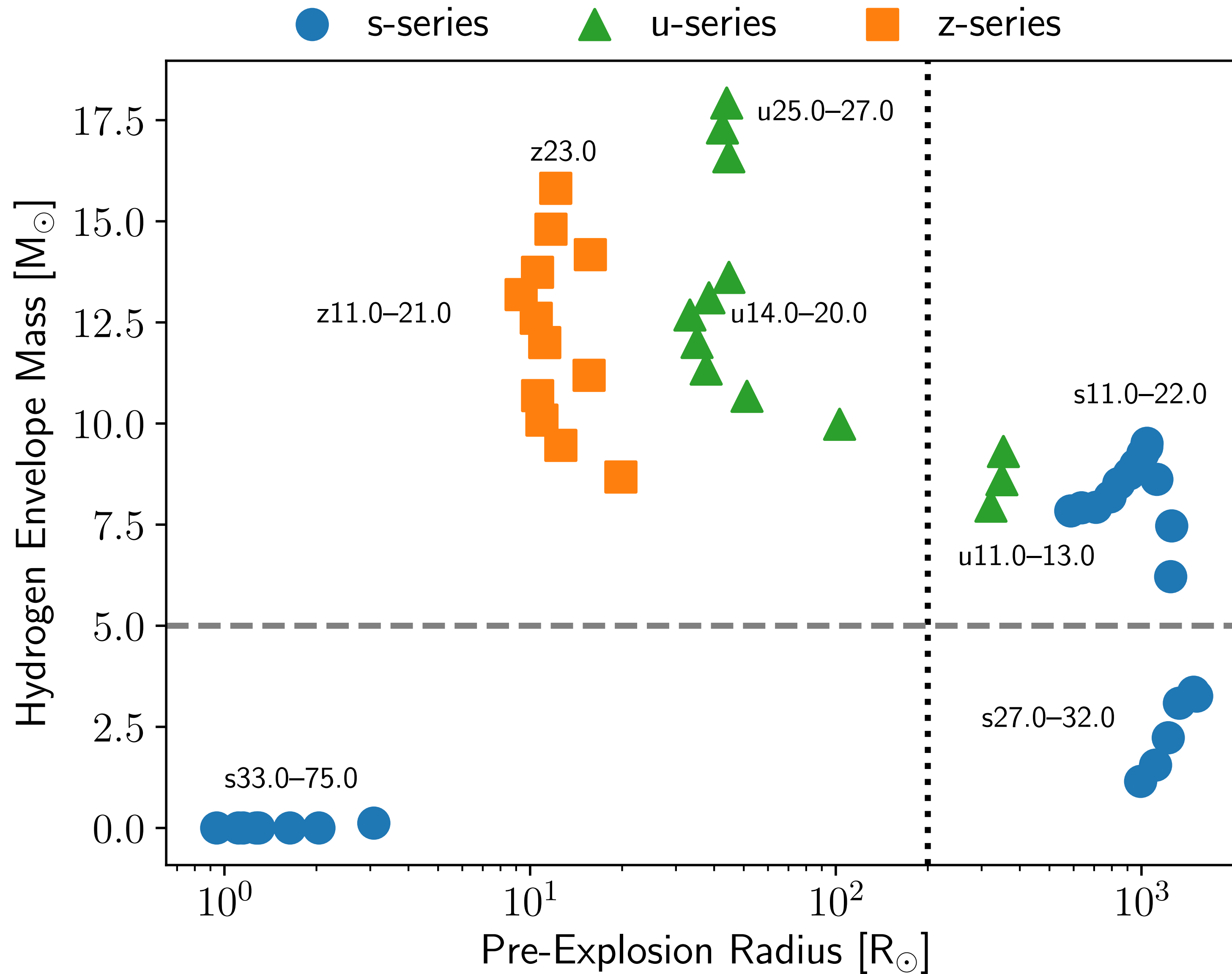


# SNEC: LIGHT CURVES

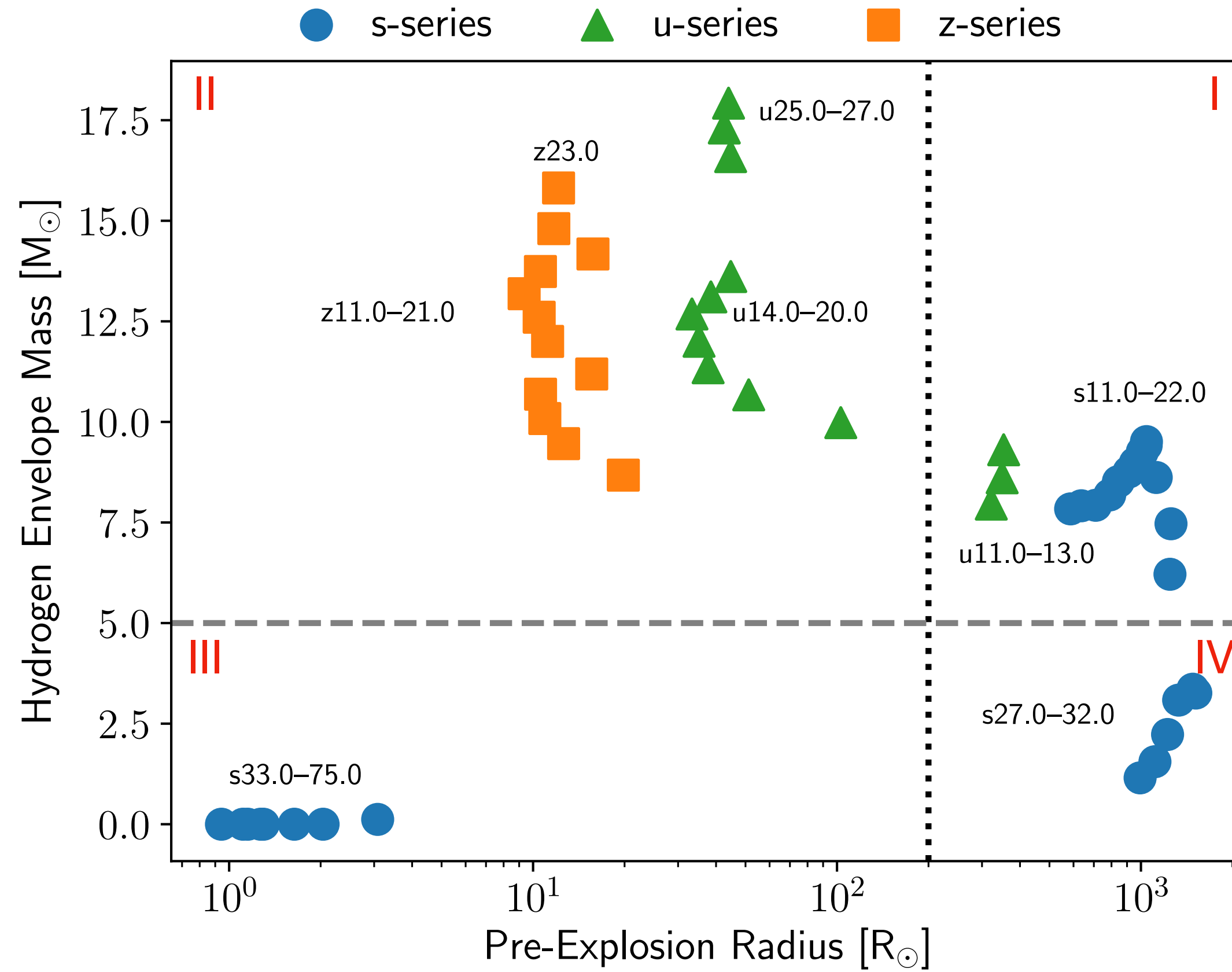
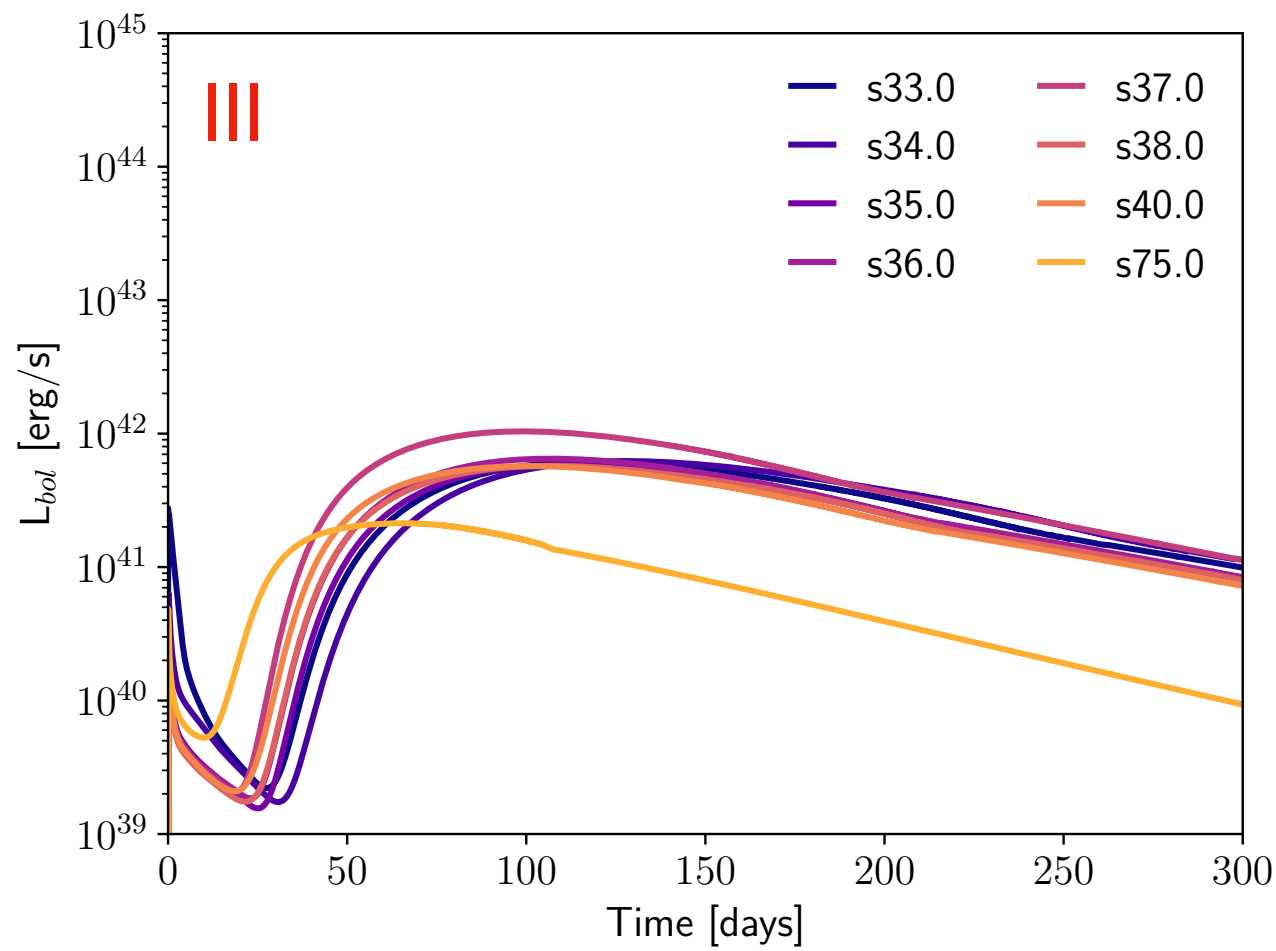
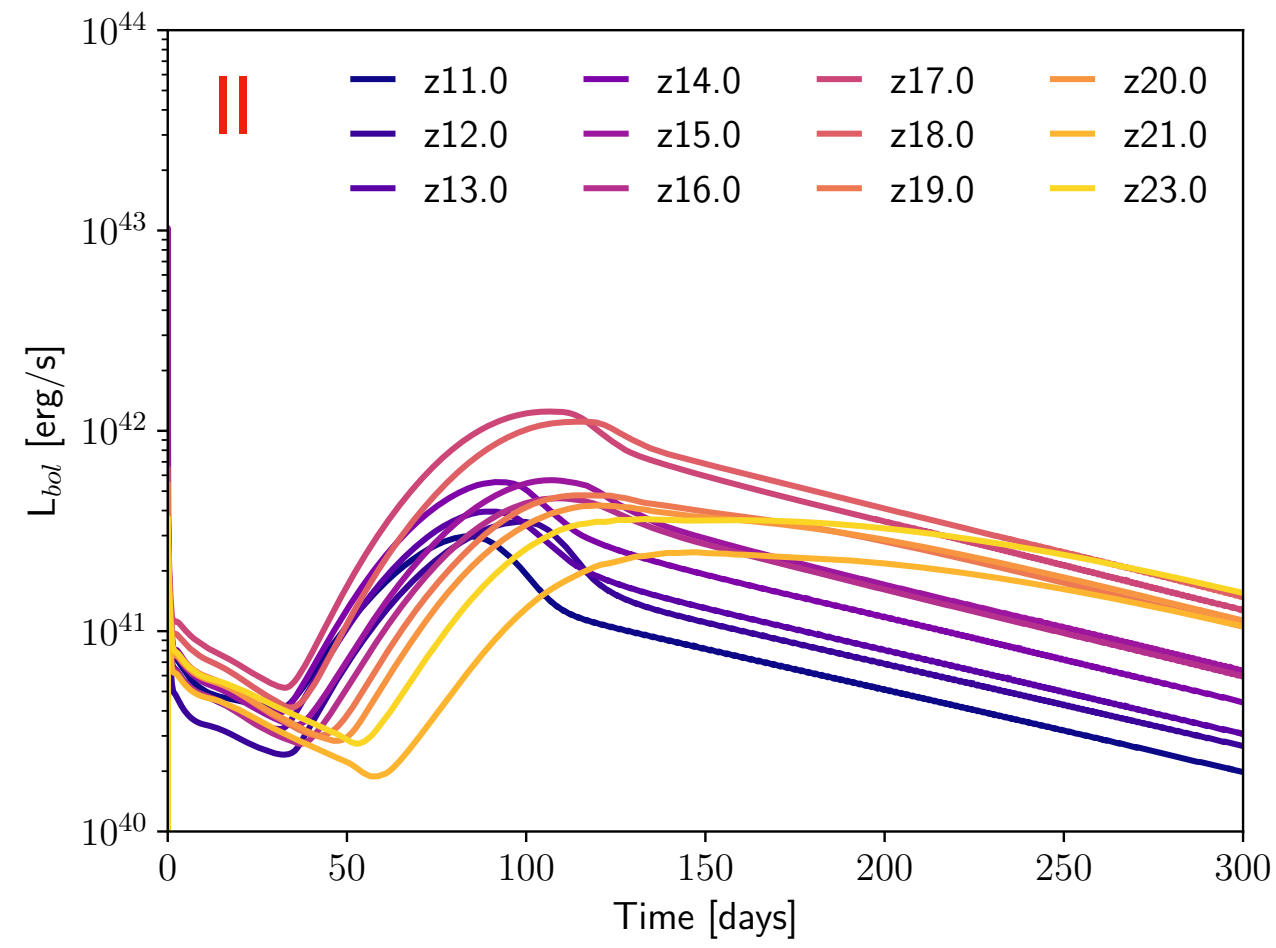
The **u-series** and **z-series** light curves are mostly 1987A-like



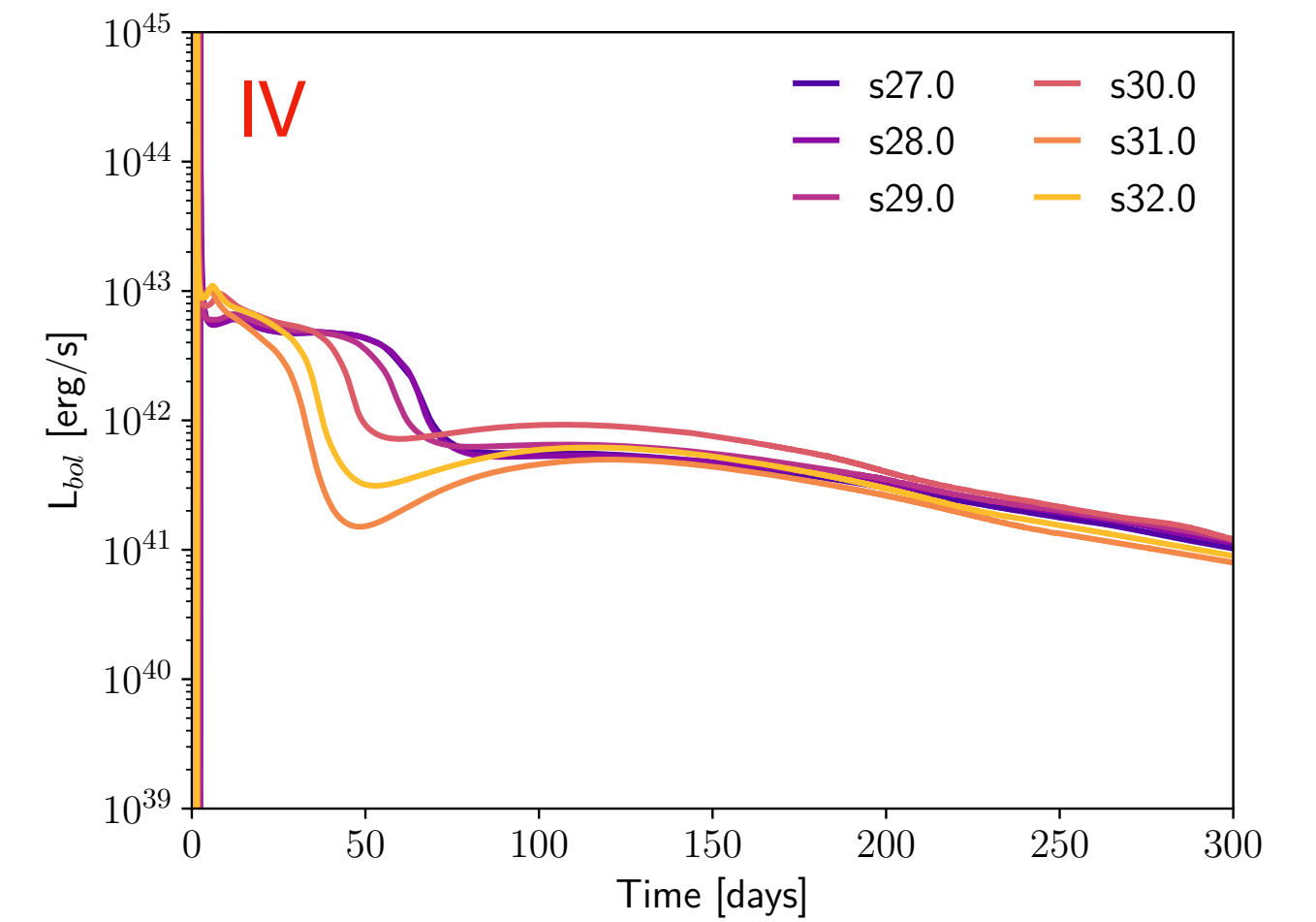
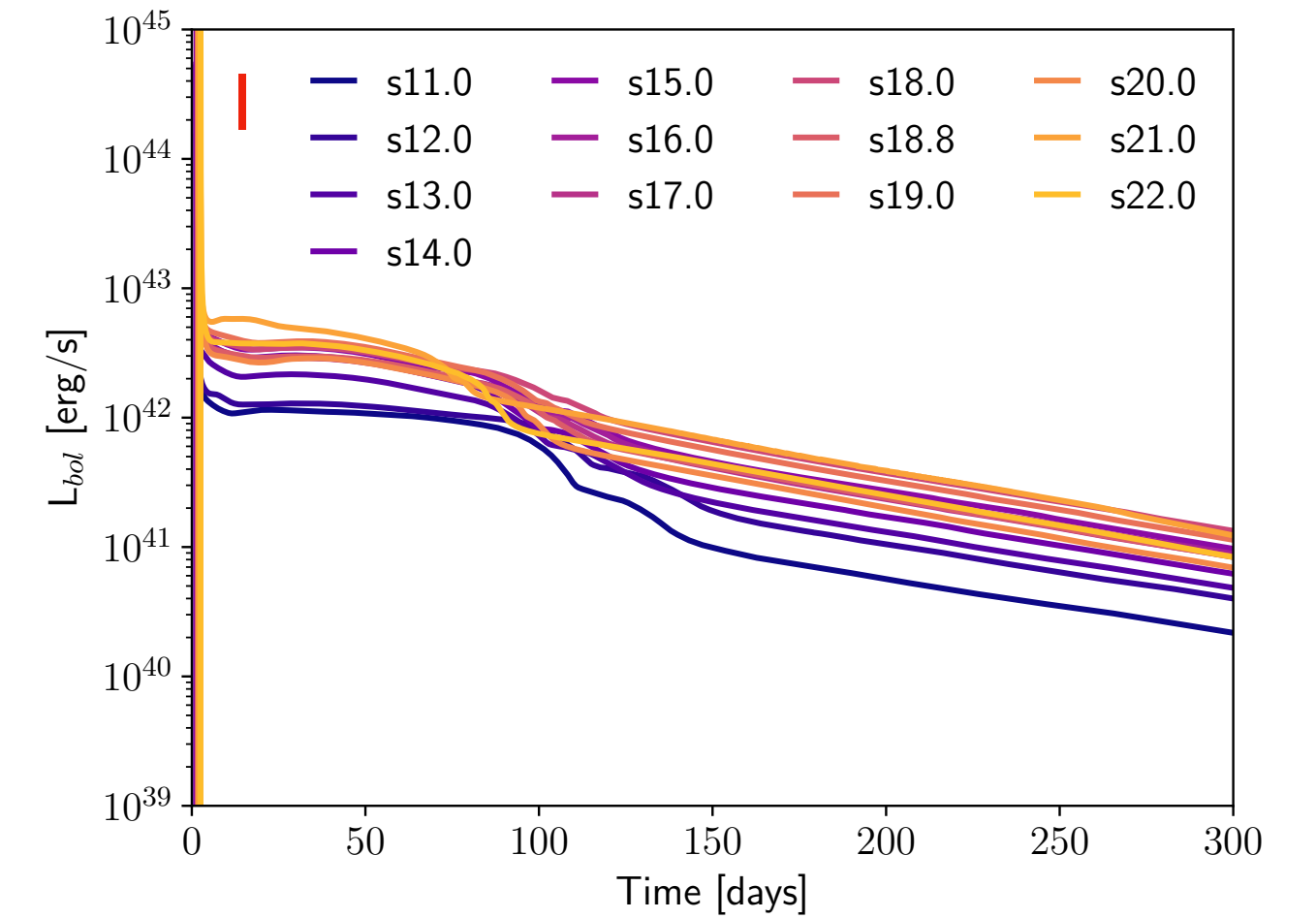
# SNEC: QUALITATIVE BEHAVIOR



# LIGHT CURVE CLASSES



- I - Normal Type IIP
- II - SN 1987A-like
- III - Stripped Envelope-like
- IV - Transition between Type IIP and Stripped Envelope-like



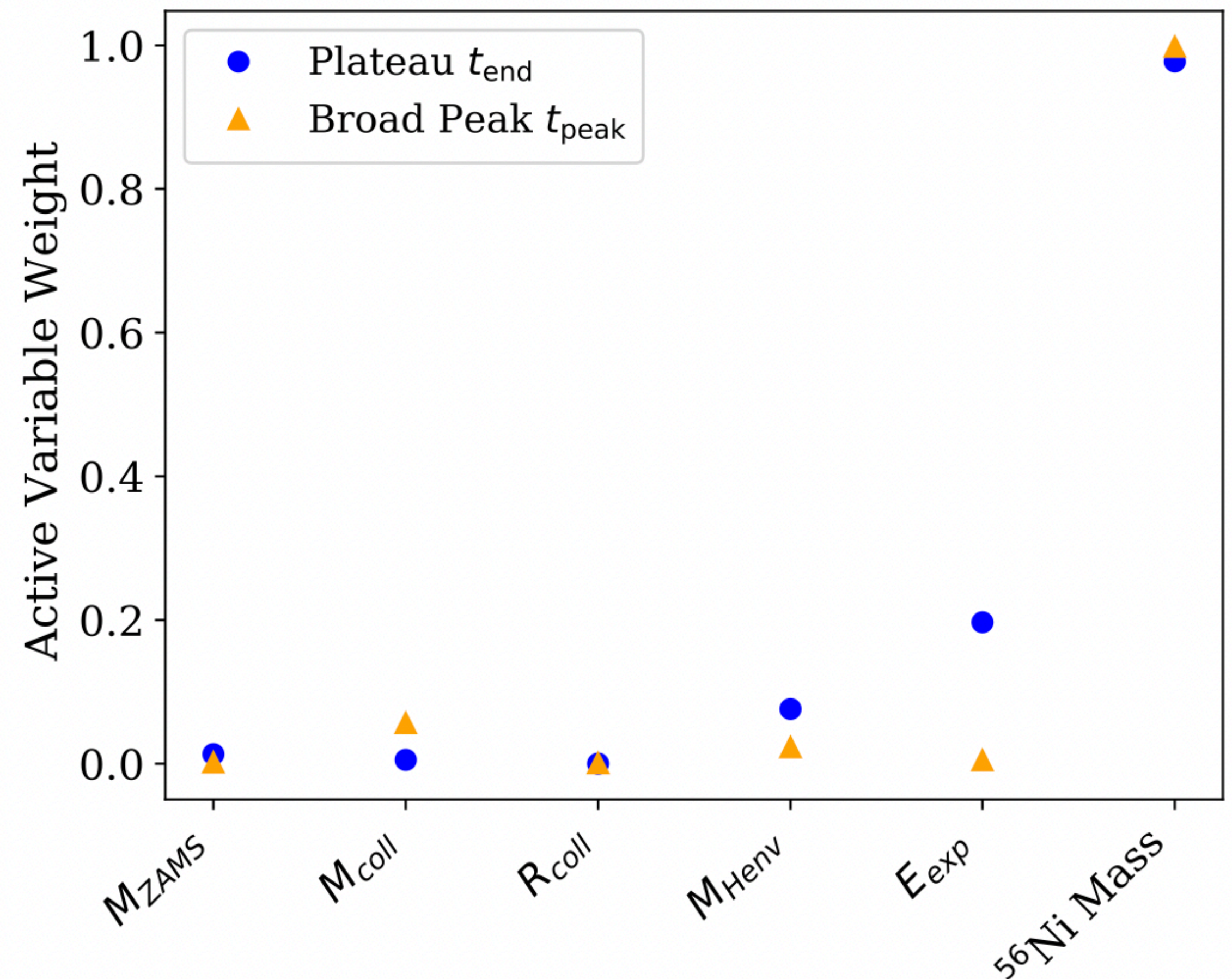
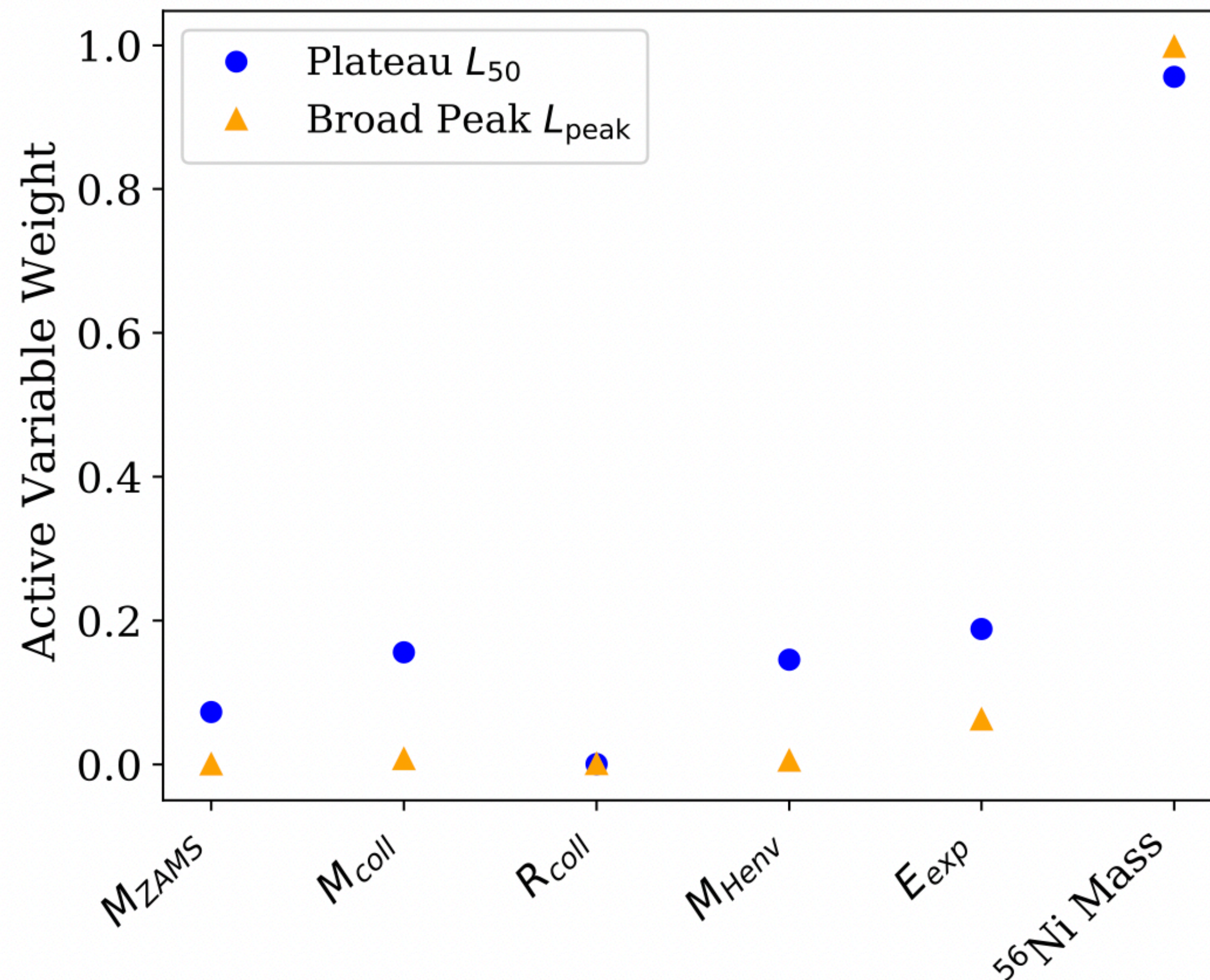


# SNEC: QUANTITATIVE BEHAVIOR

Noah Wolfe  
Incoming grad  
at MIT, previously  
NC State

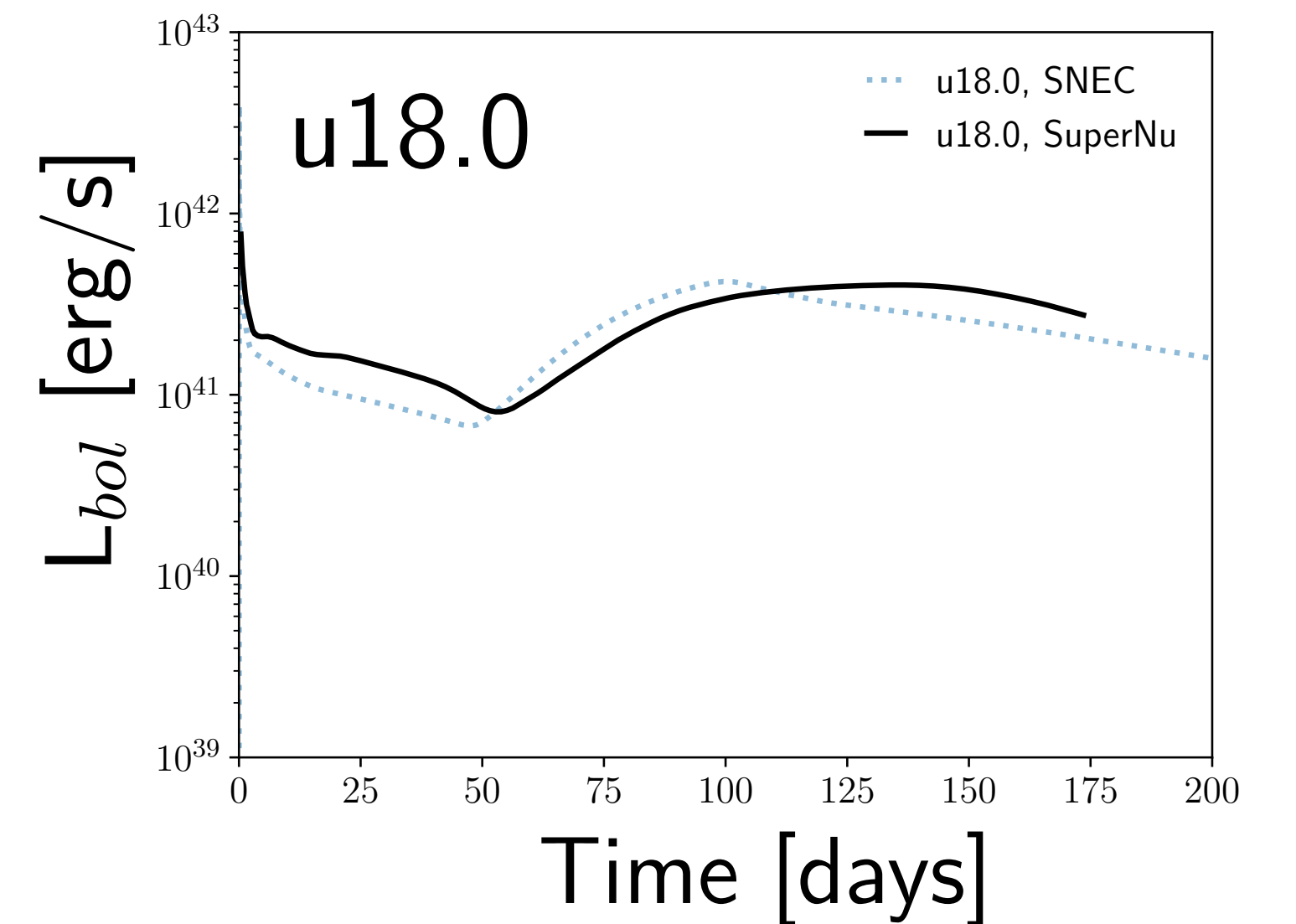
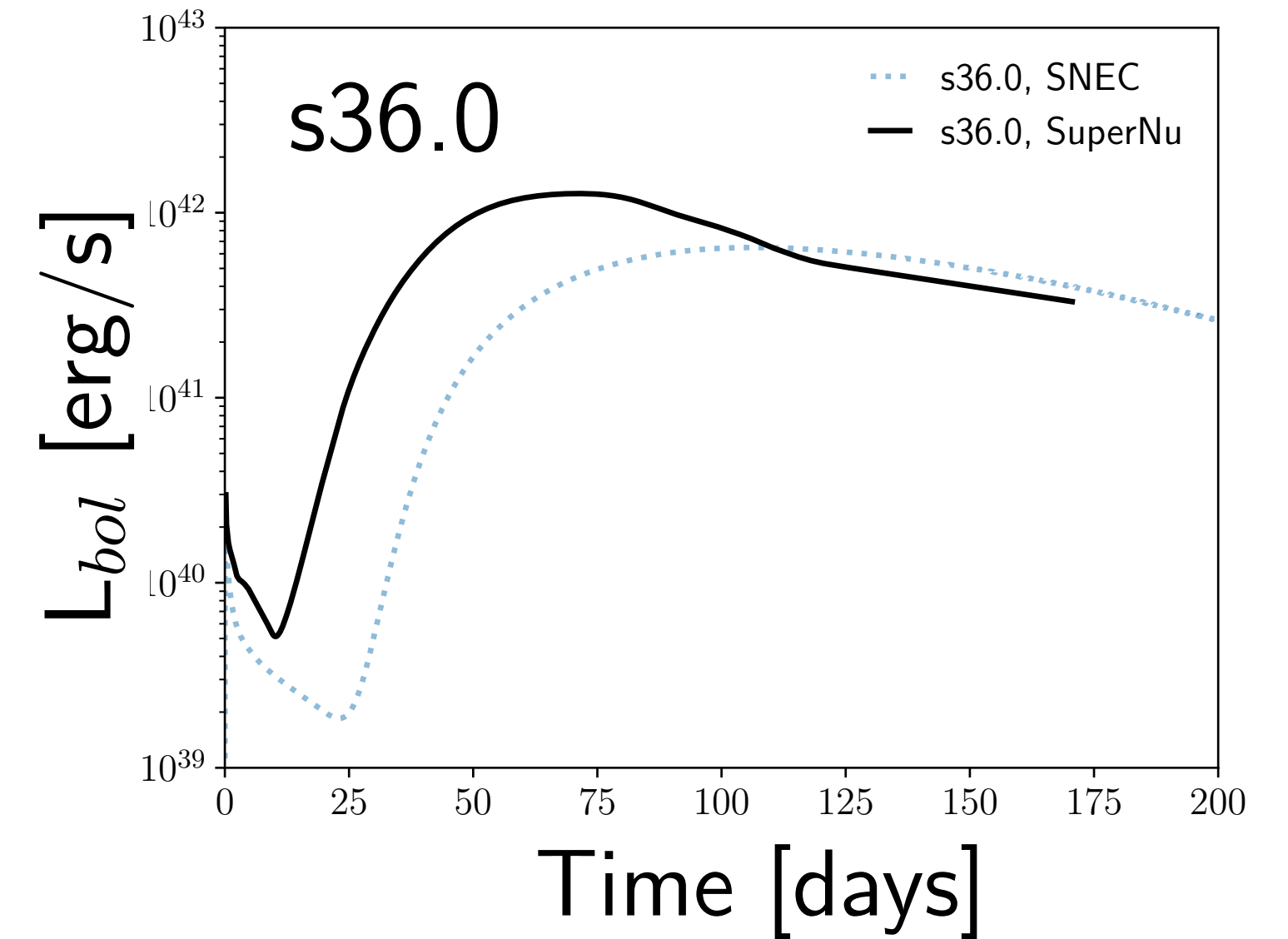
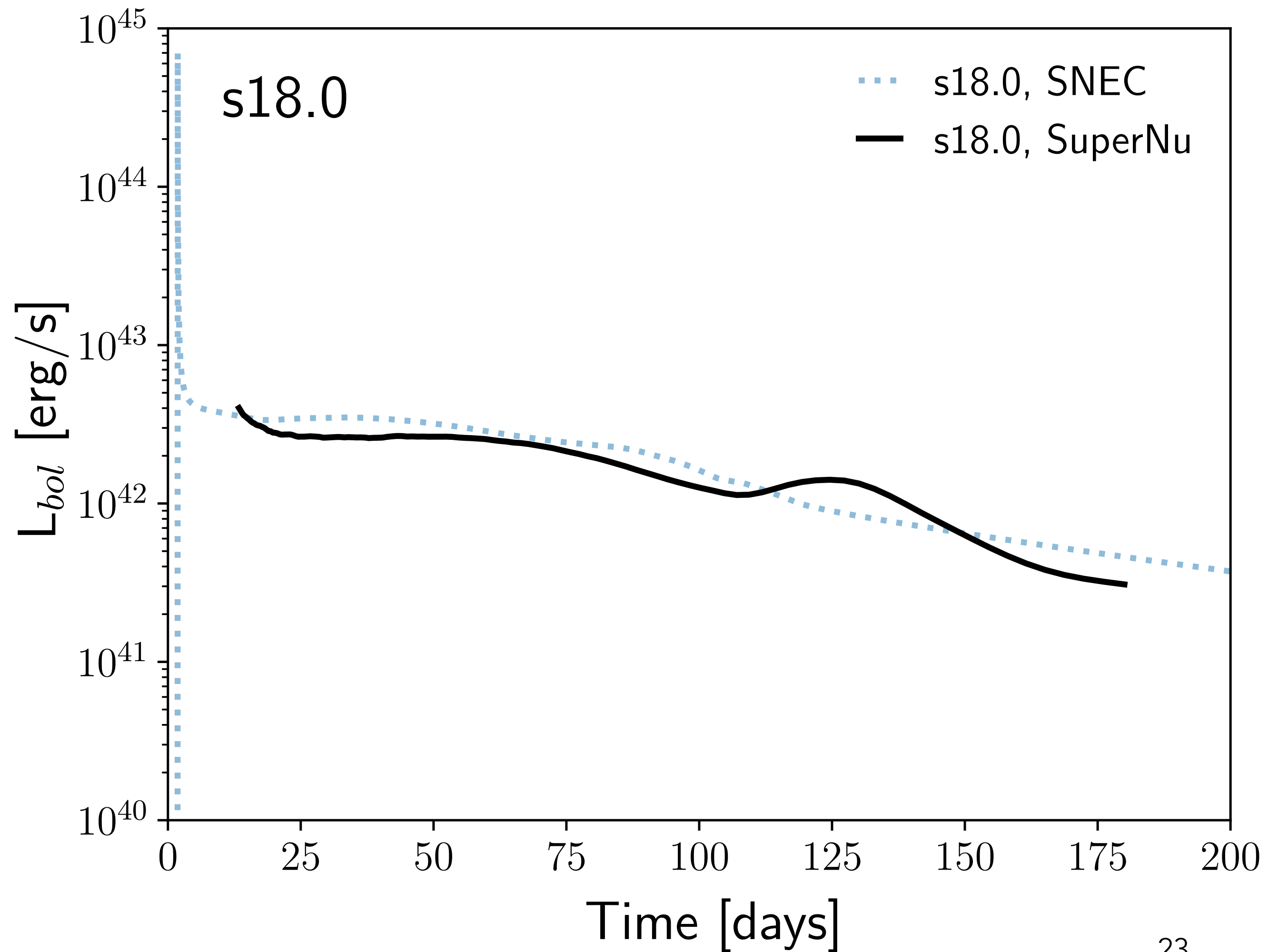


Active sub-space analysis identifies the most important input parameter for given quantity



# SUPERNU: BOLOMETRIC LIGHT CURVES

Quantitatively different but qualitatively same

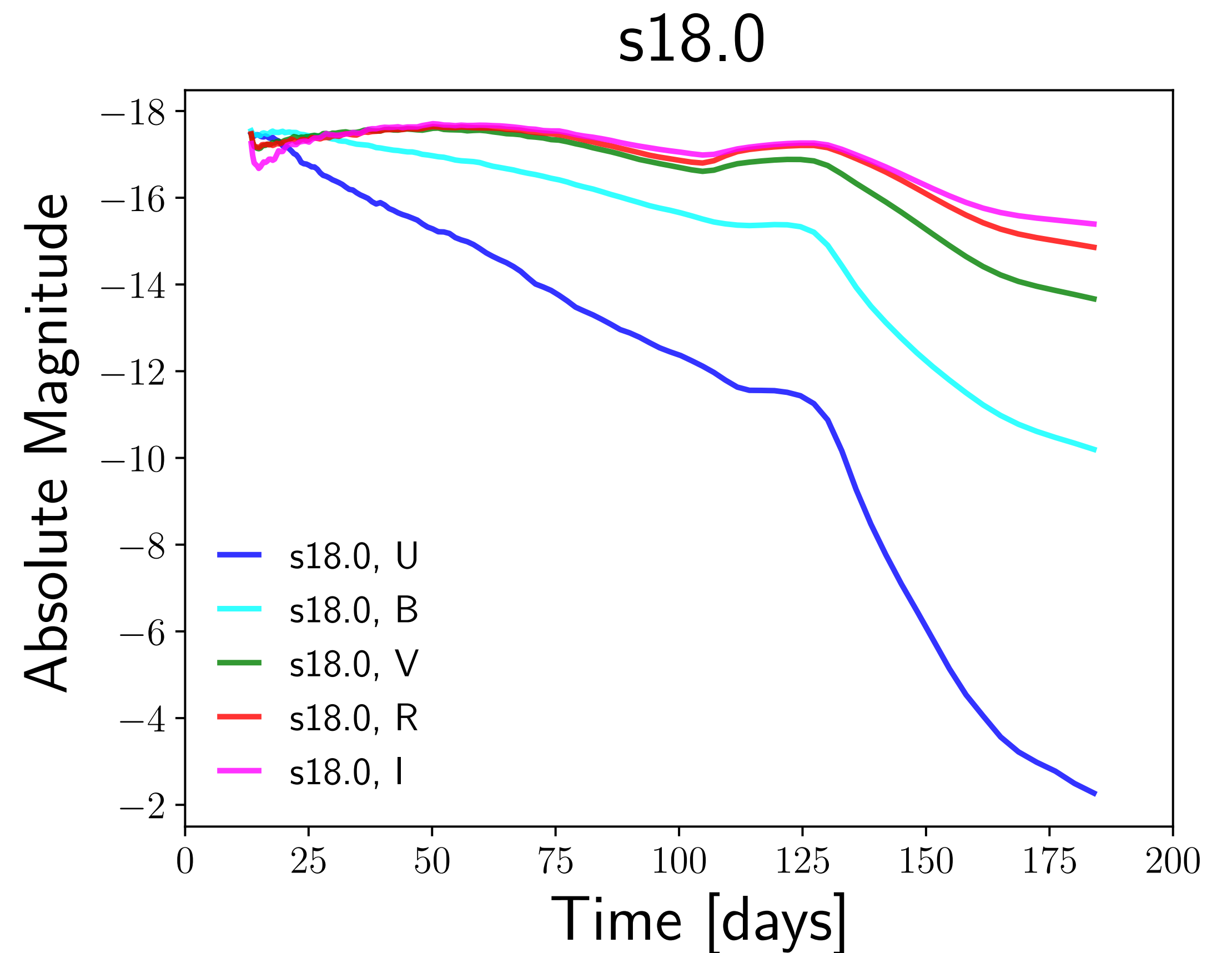
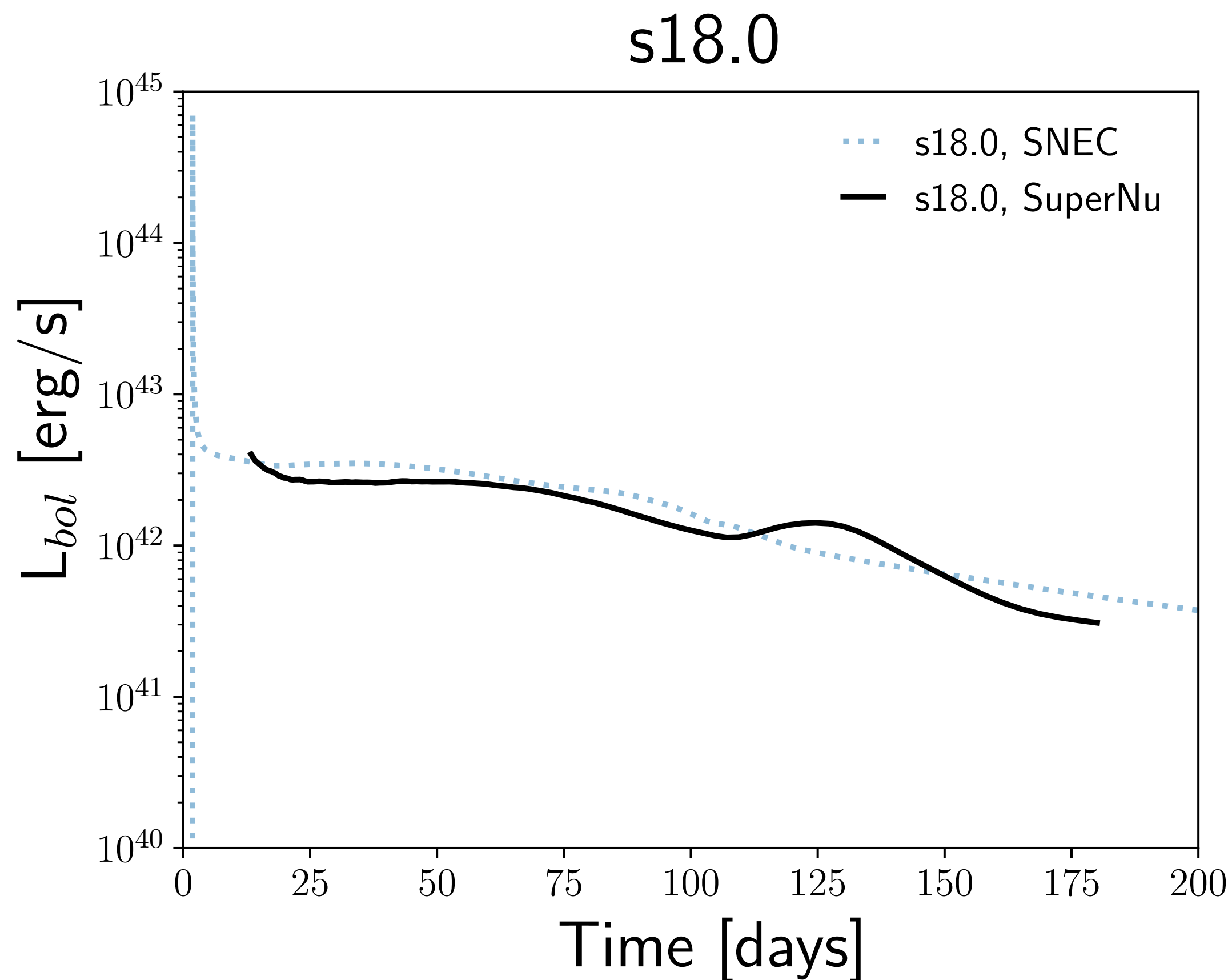


# SUPERNU: BROADBAND LIGHT CURVES

U and B bands magnitudes fall quickly

Bump at the end of the plateau is a known issue with 1D models

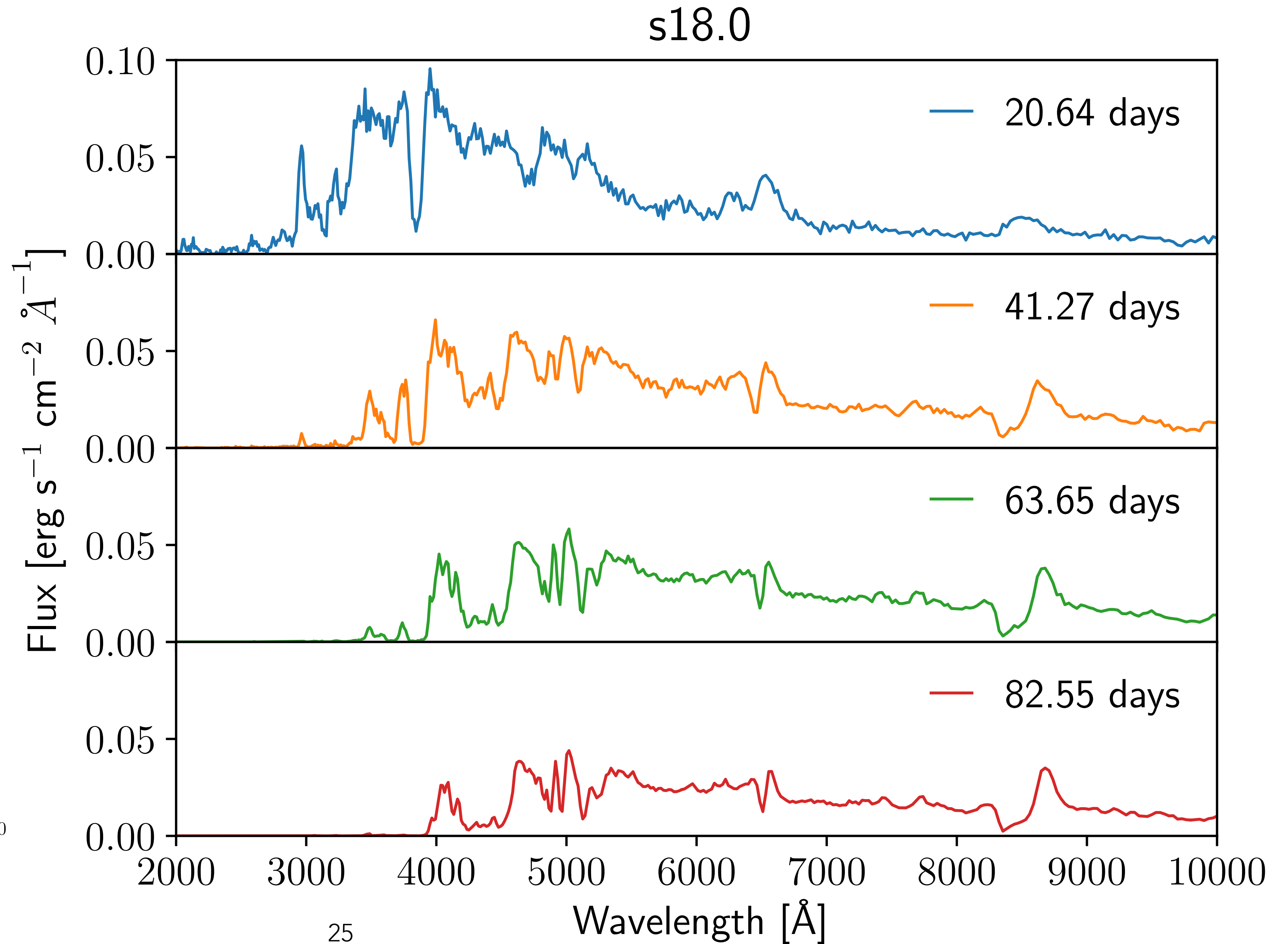
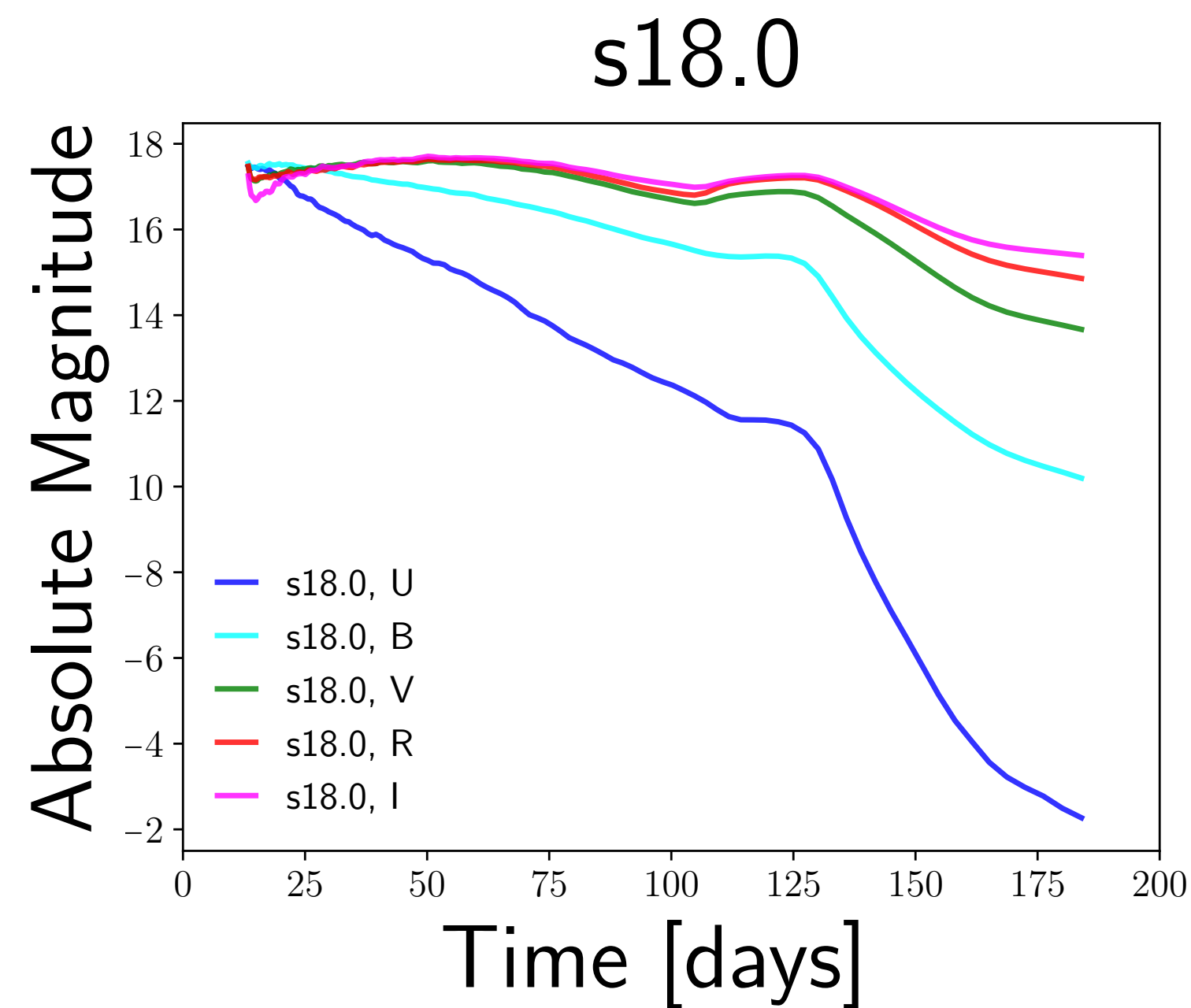
(Chieffi+2003, Young 2004, Utrobin+2007, Utrobin+2017)



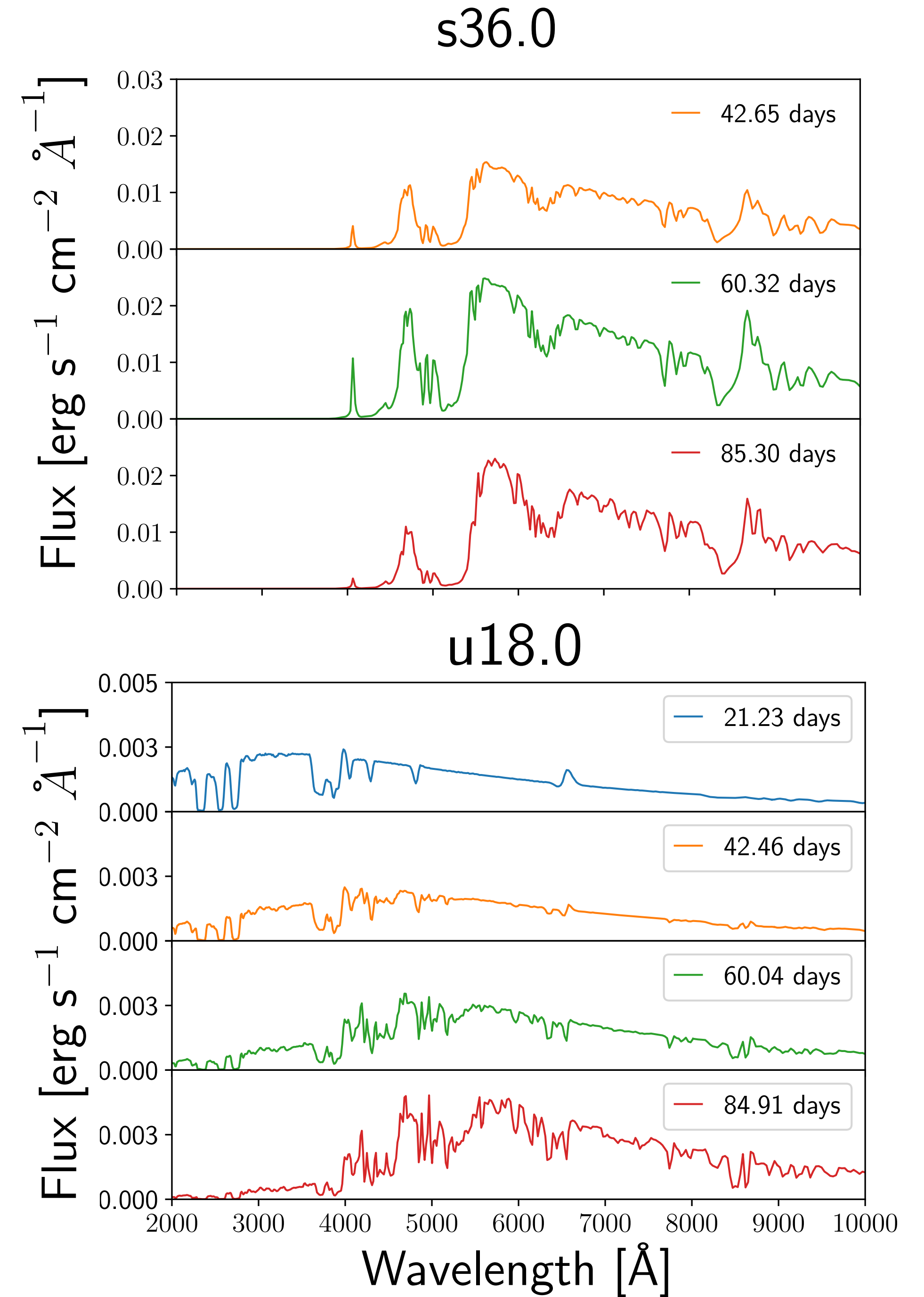
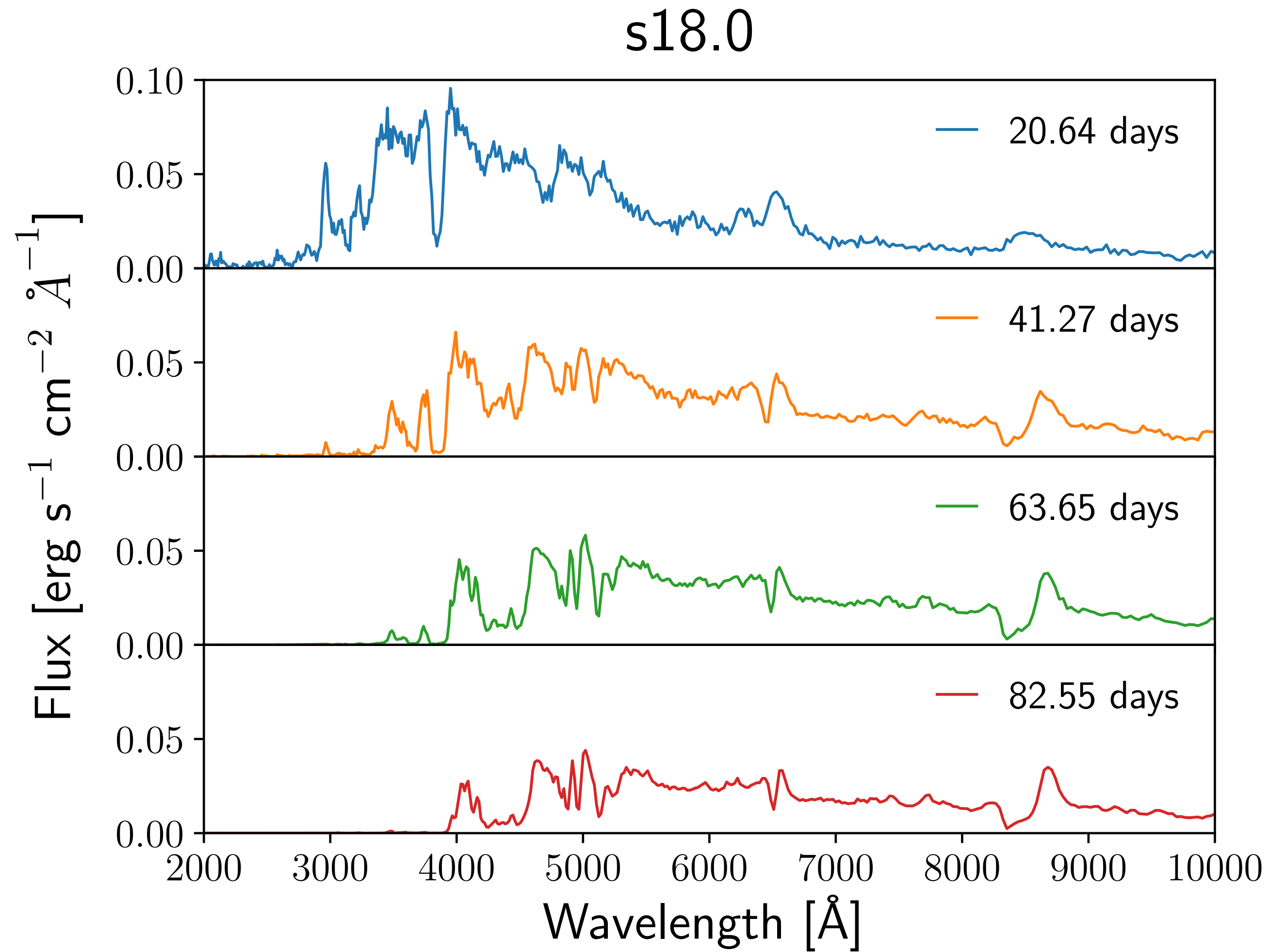


# SUPERNU: SPECTRA

Note line-blanketing  
at short wavelengths



# SUPERNU: SPECTRA



# SUMMARY AND OUTLOOK

- Light curves and spectra of 62 core-collapse supernovae across metallicities, connecting self-consistent PUSH explosion simulations to observations

Curtis+2021, ApJ 921 143, arXiv:2008.05498  
<http://go.ncsu.edu/astrodata>



sanjanacurtis@uchicago.edu

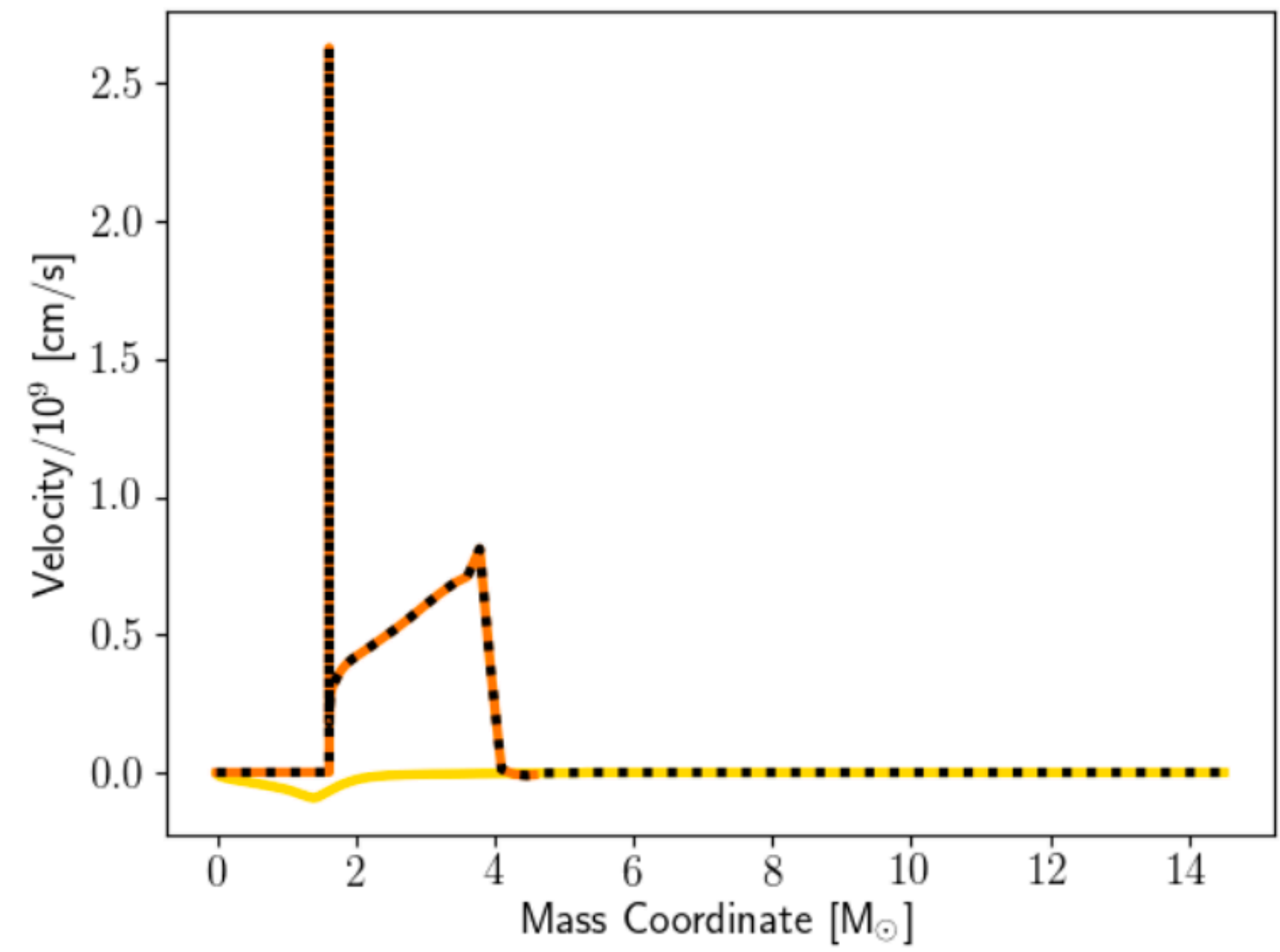
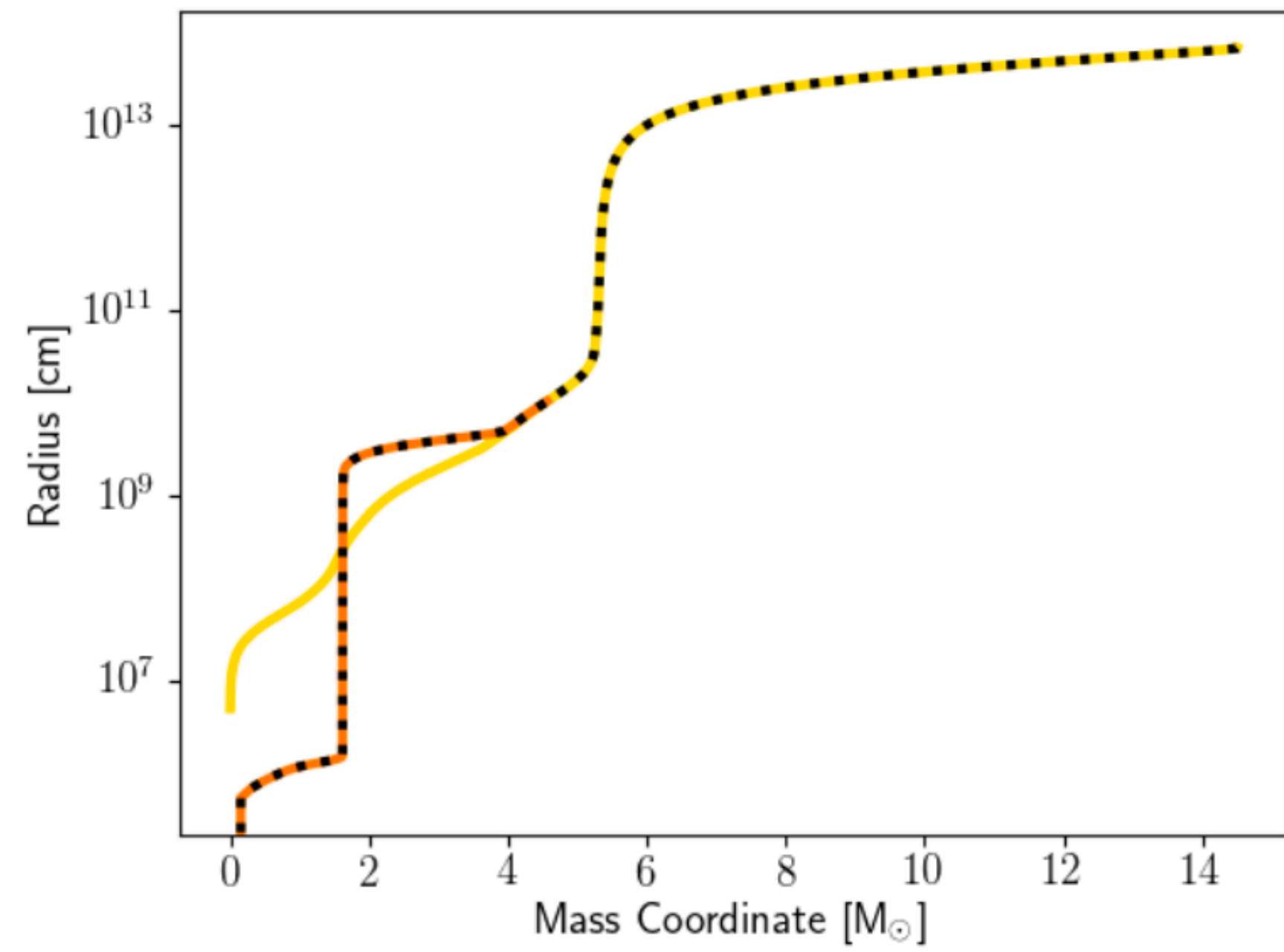
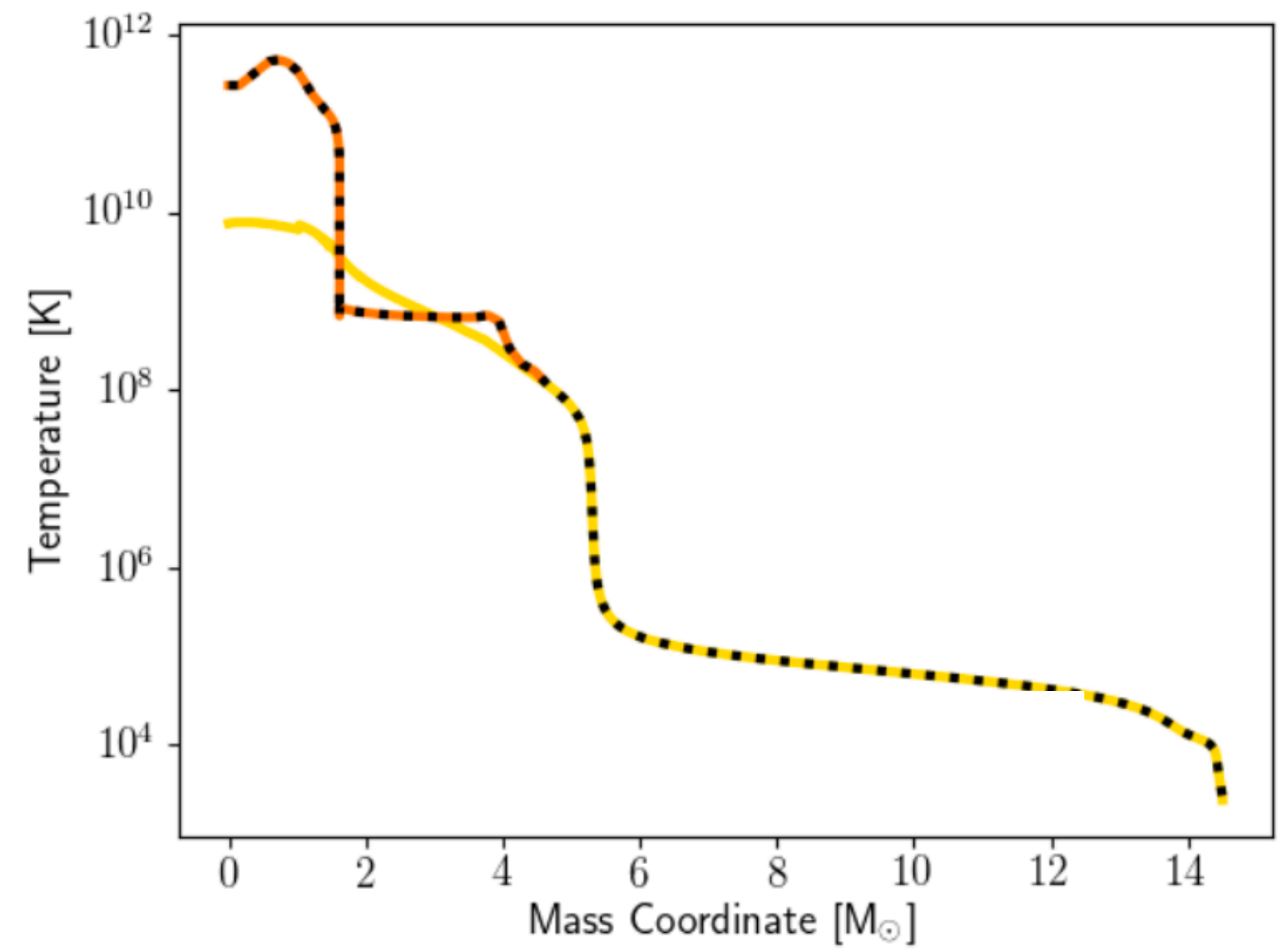
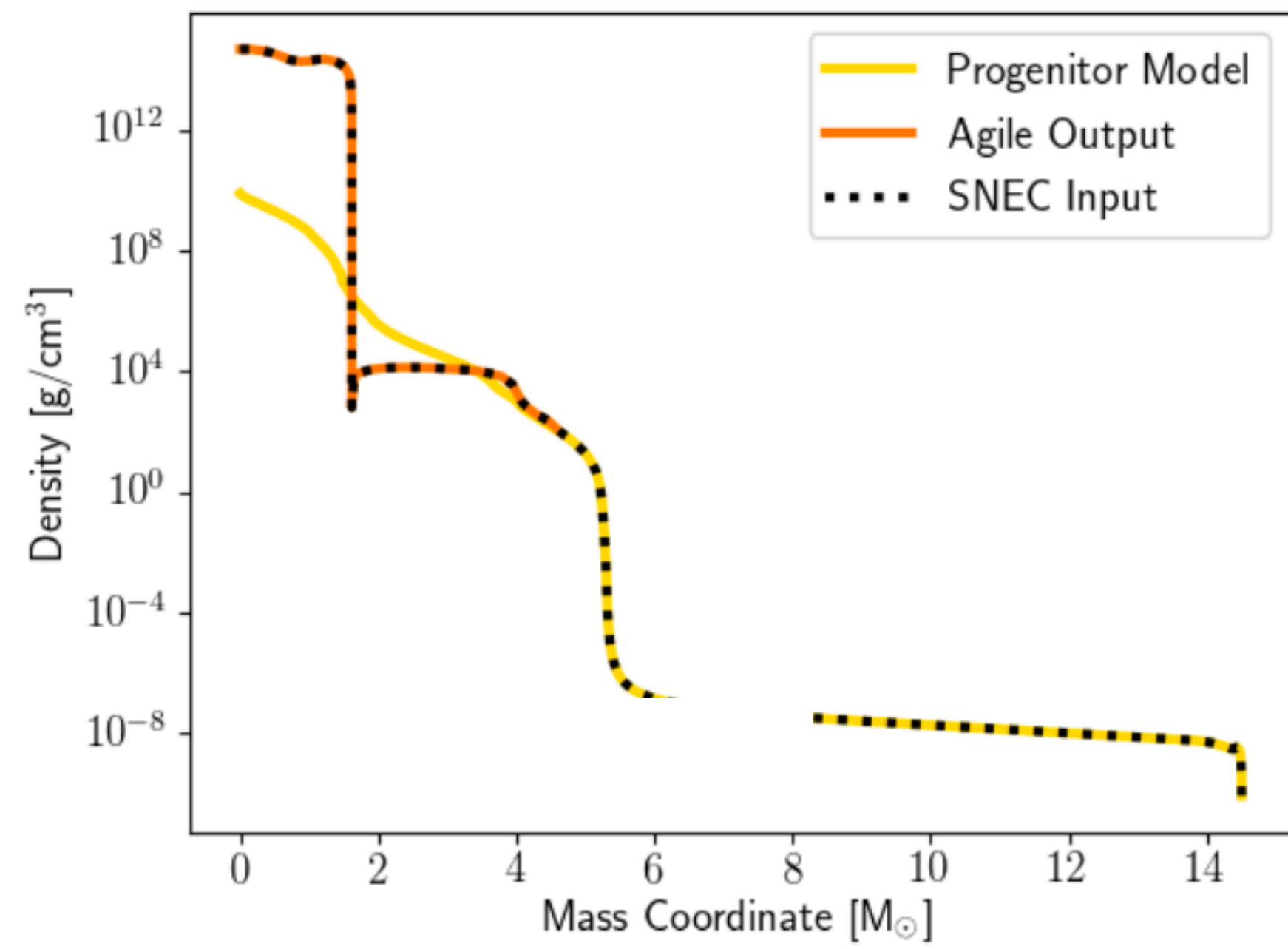


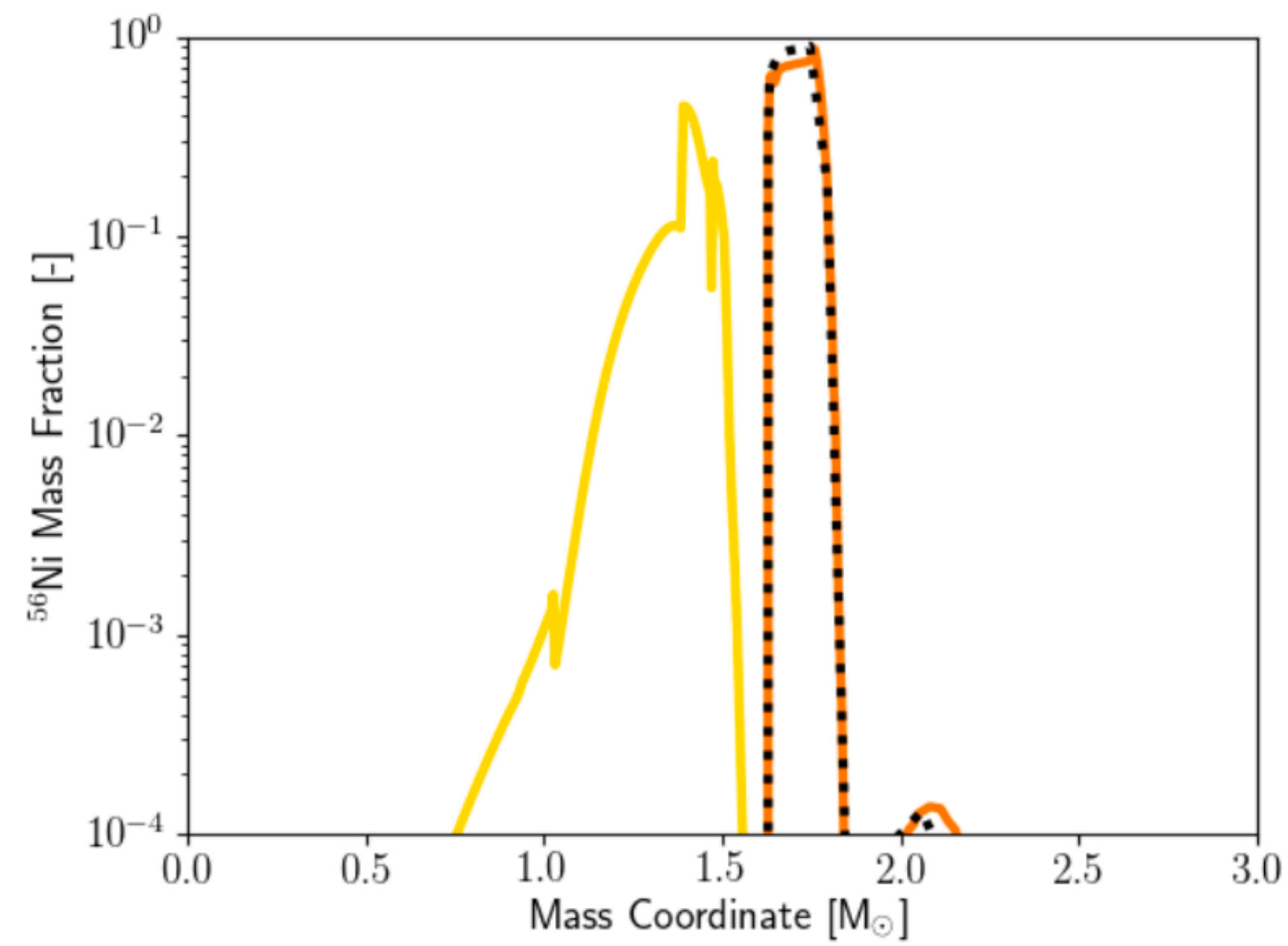
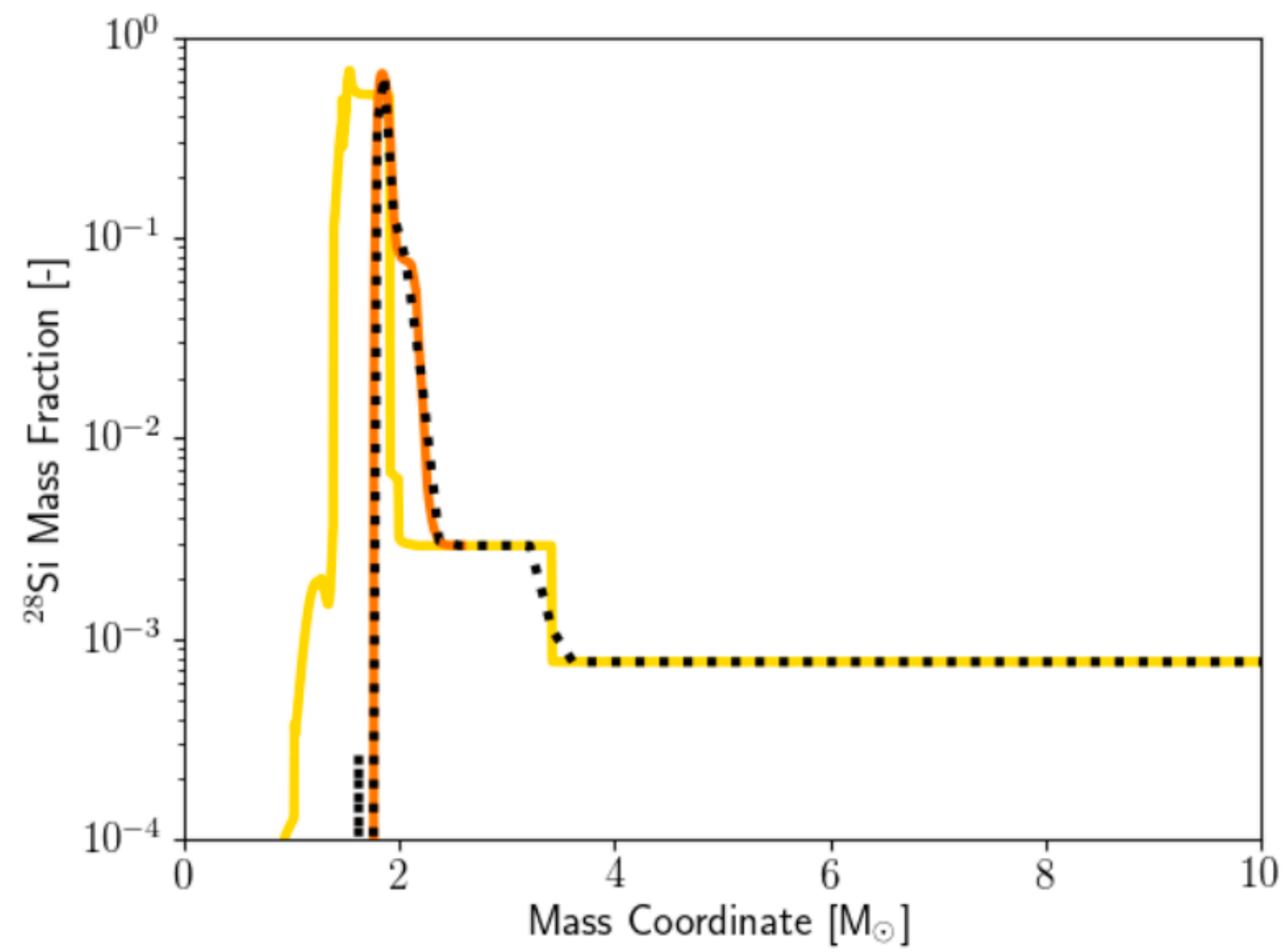
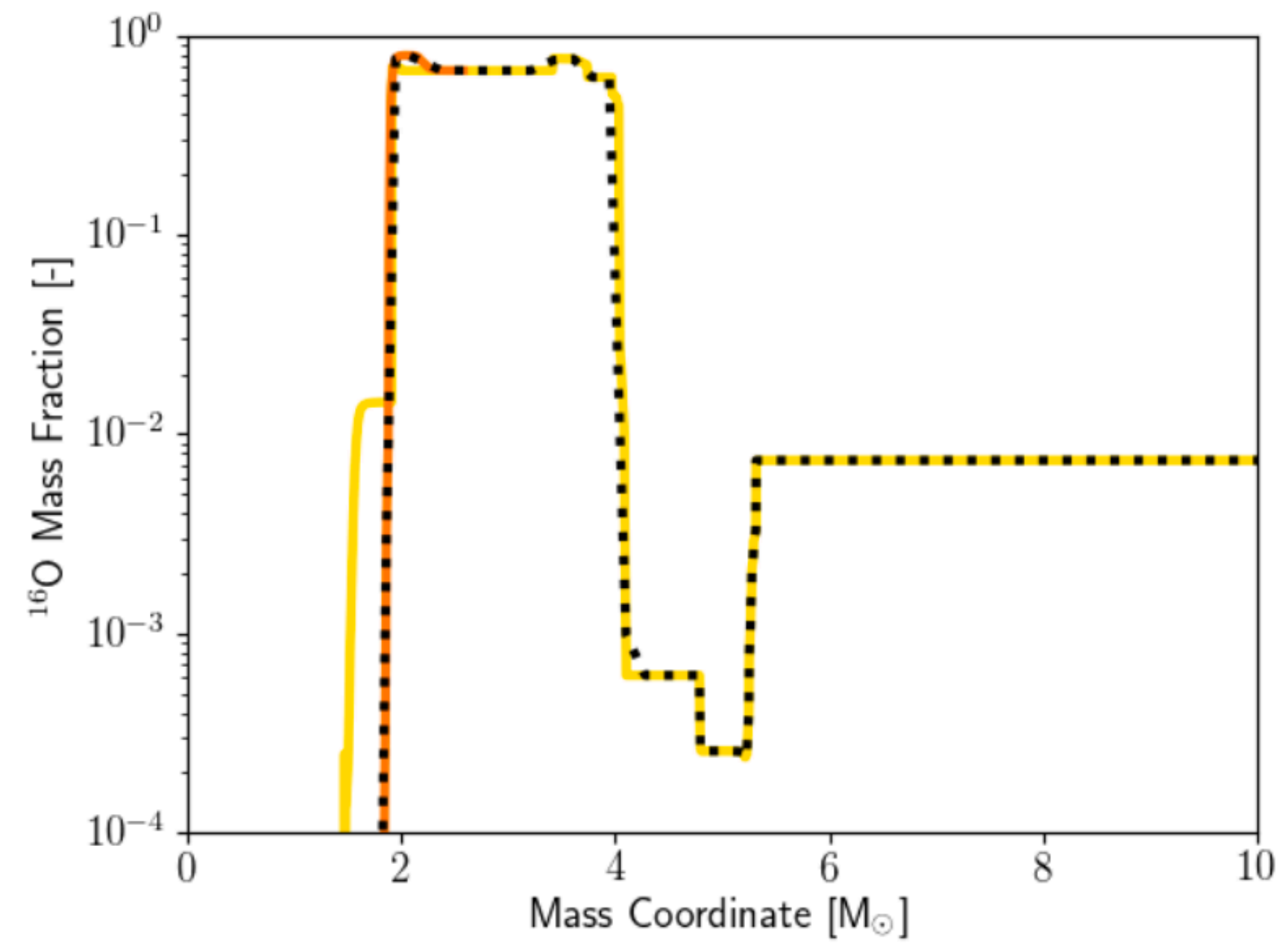
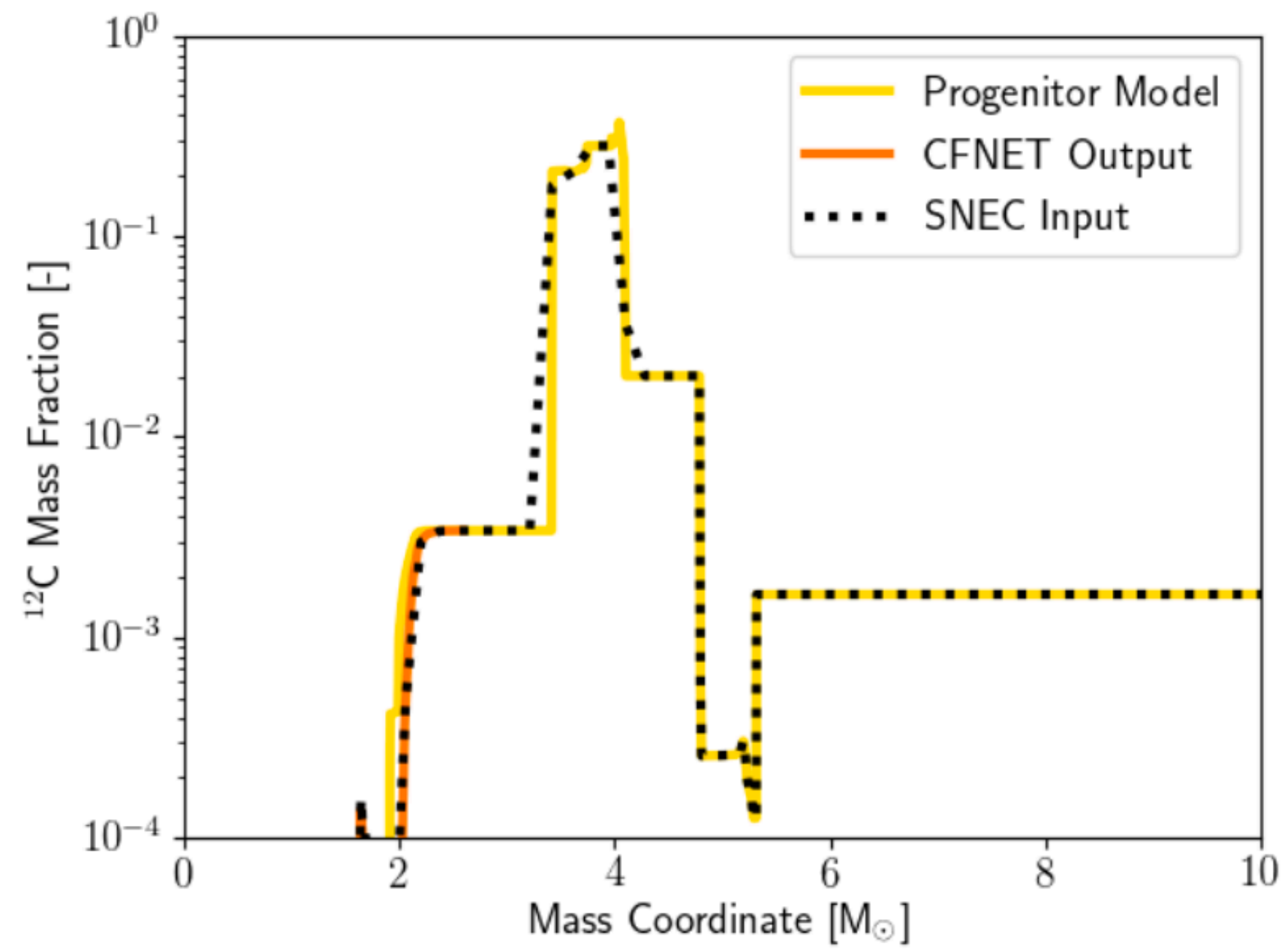
@sanjanacurtis

- Different qualitative classes depending on radius and H-envelope mass
- Active sub-space analysis of progenitor, explosion and light curve properties
- Part of multi-messenger database using the same set of models
- Potential for adding more models and extending to multi-dimensional simulations!



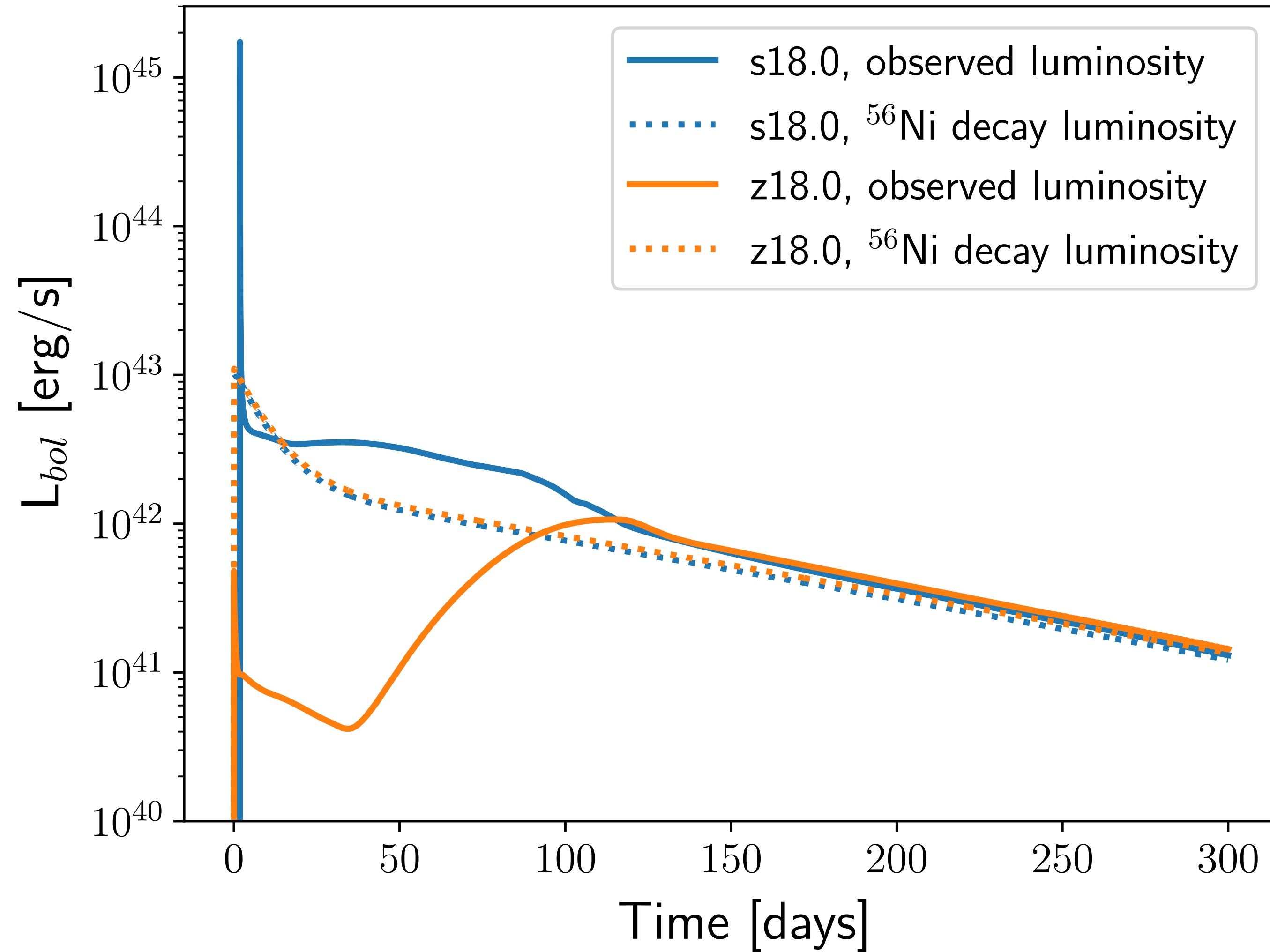






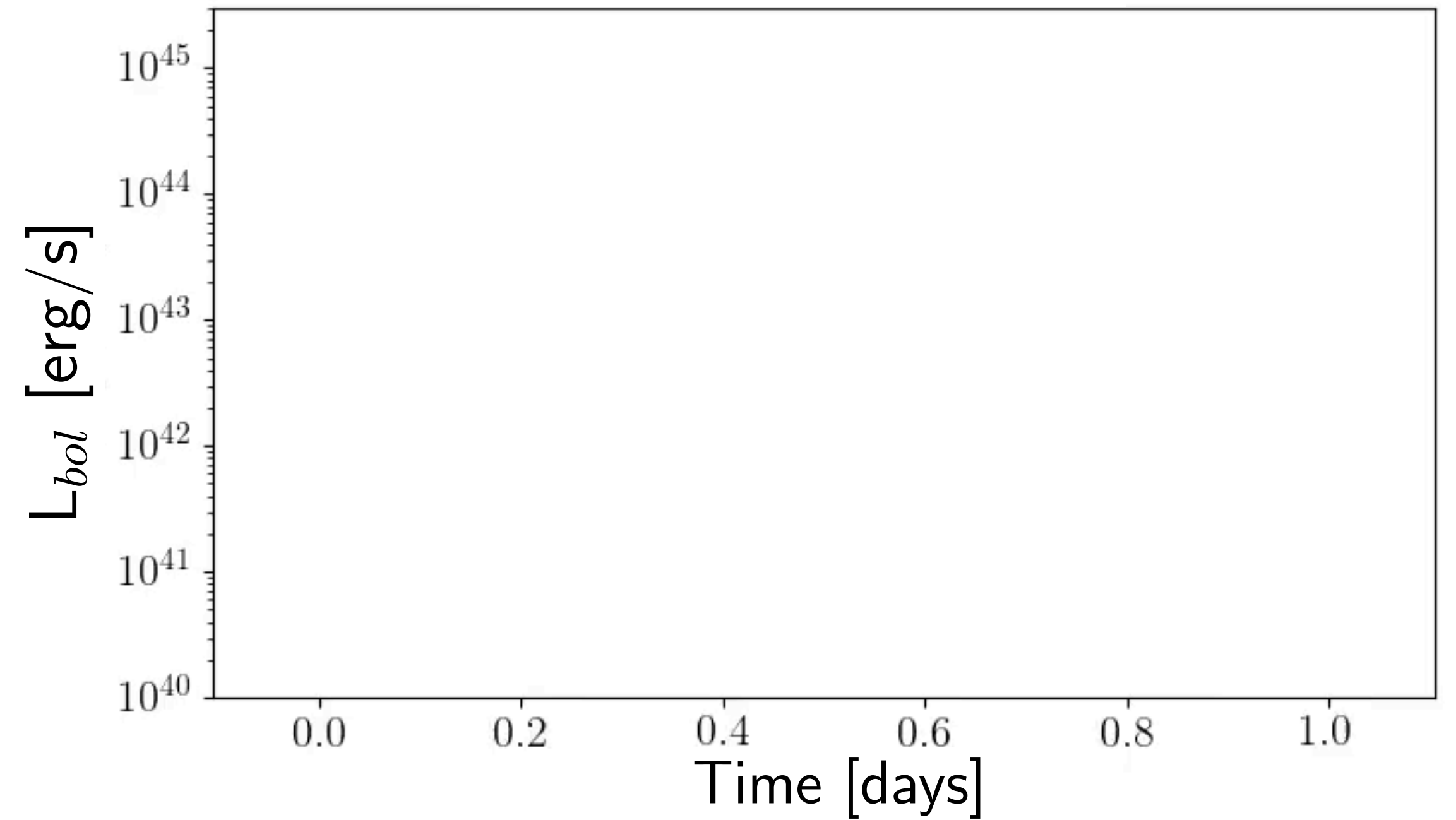
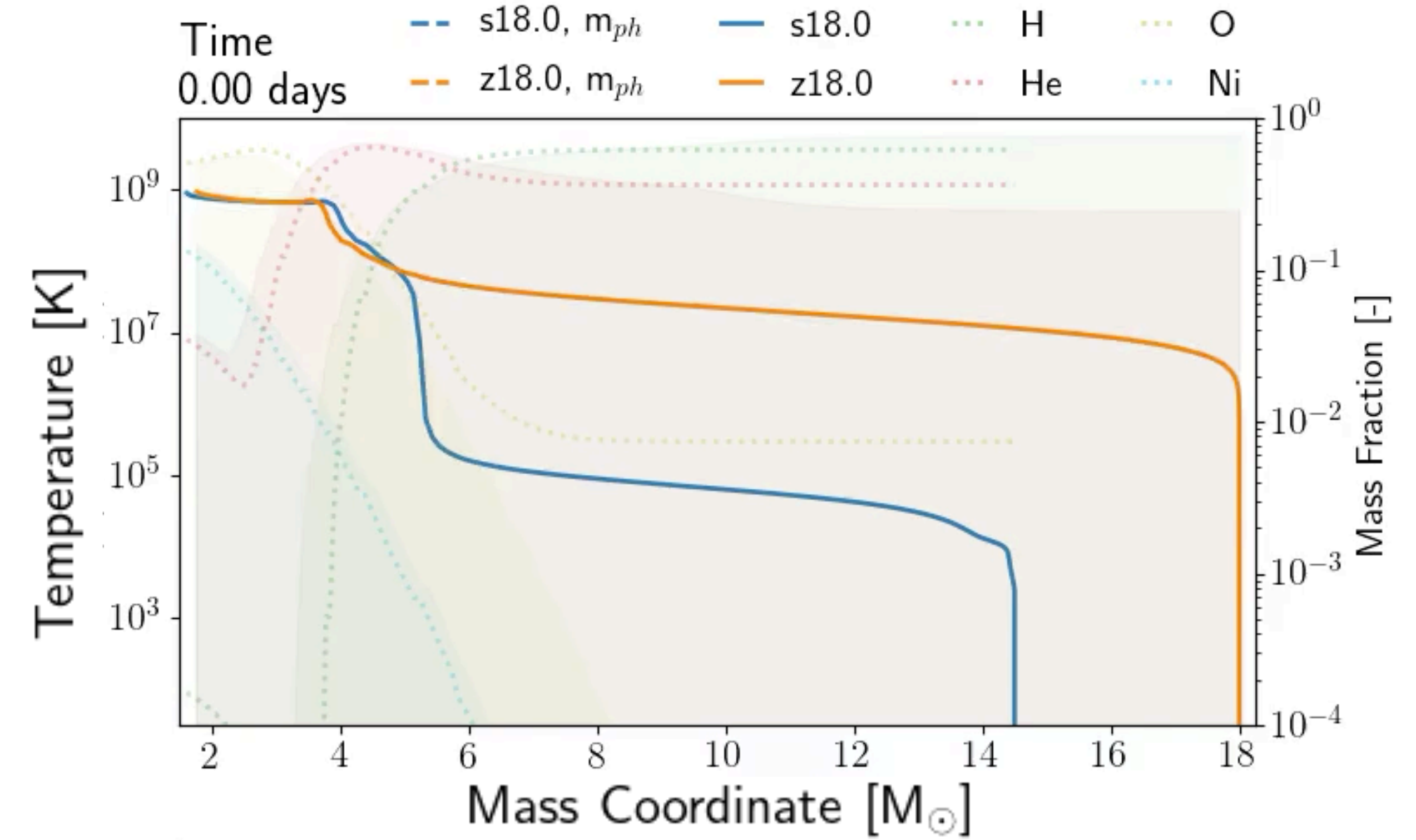
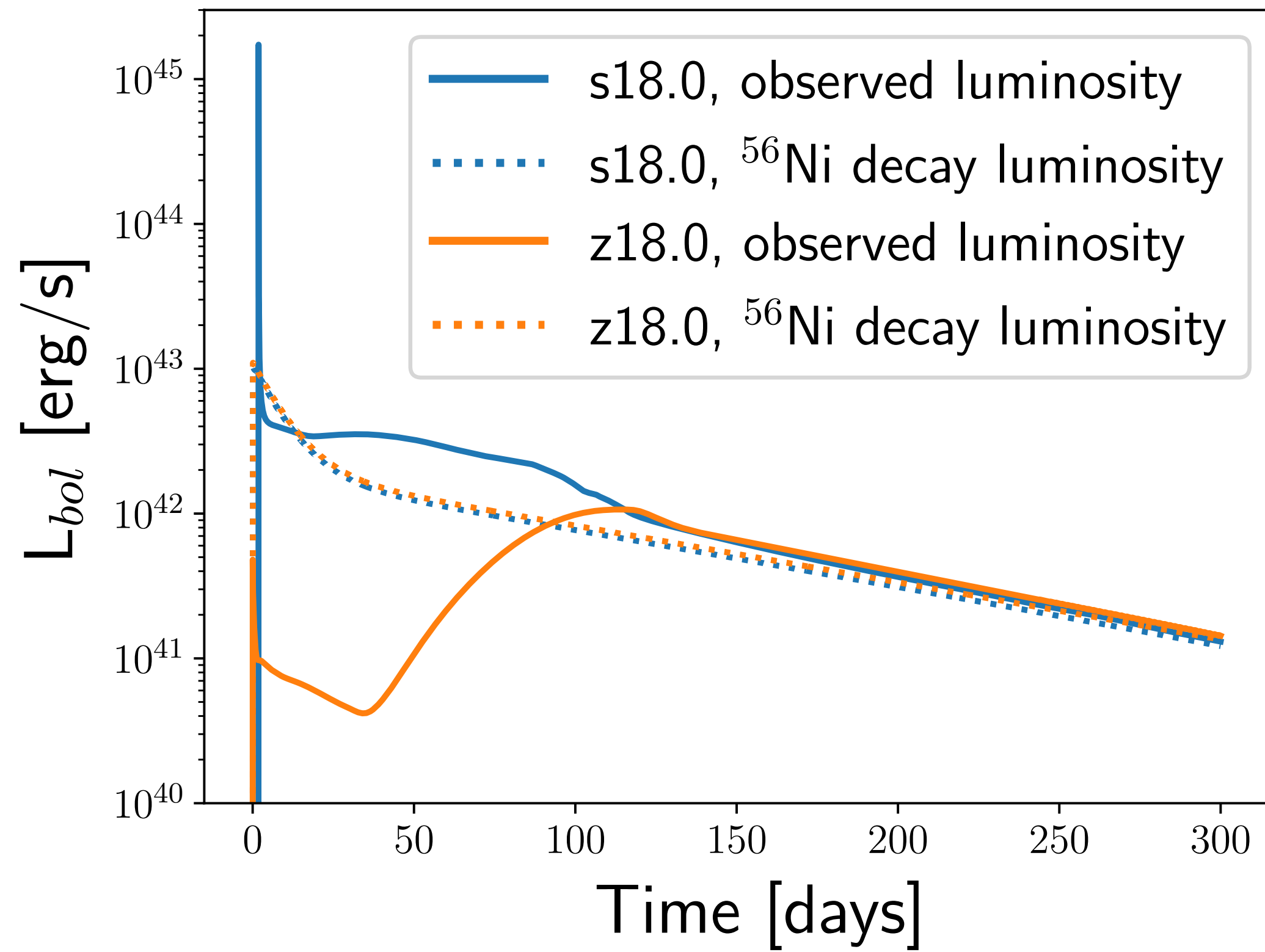


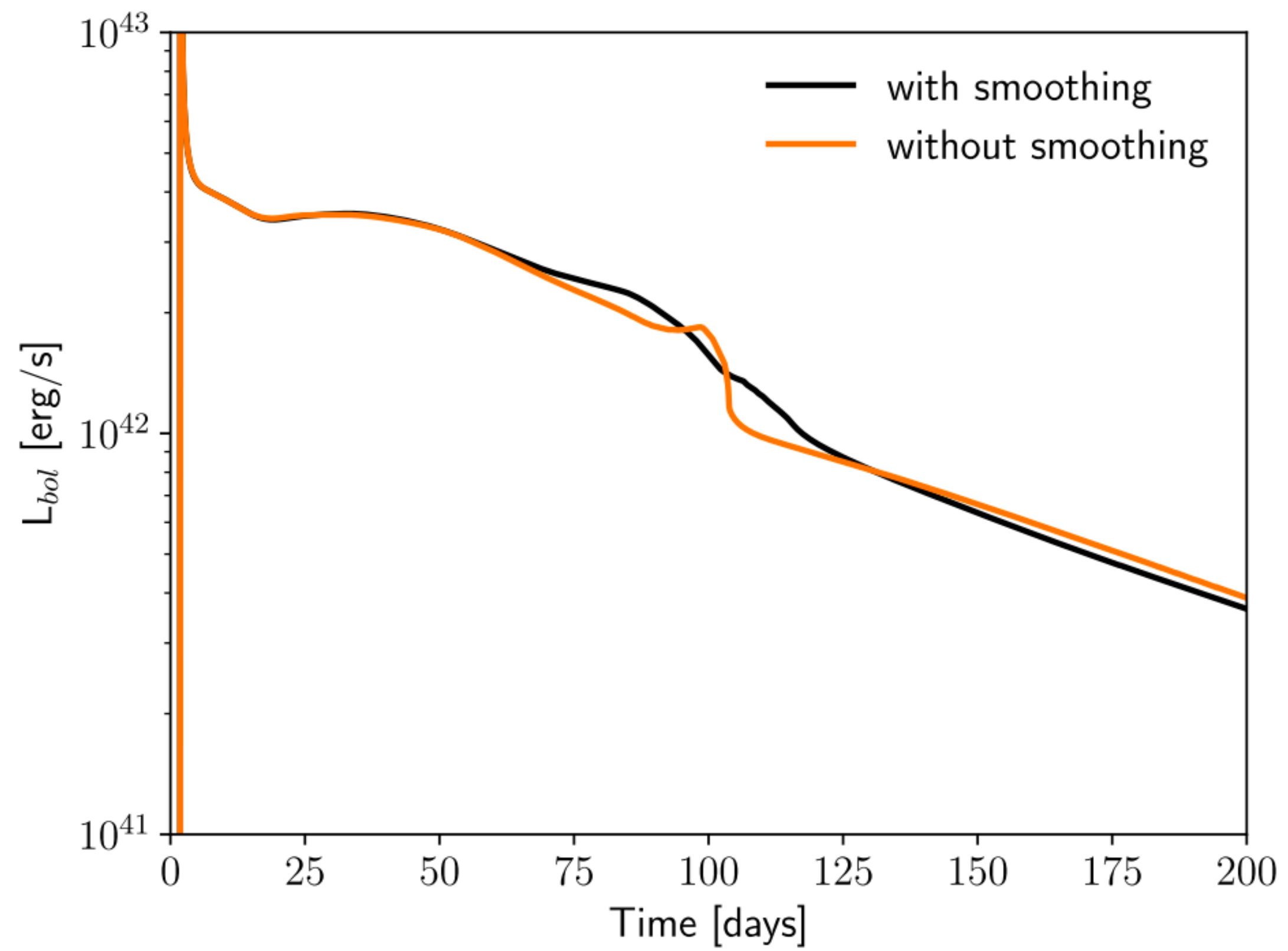
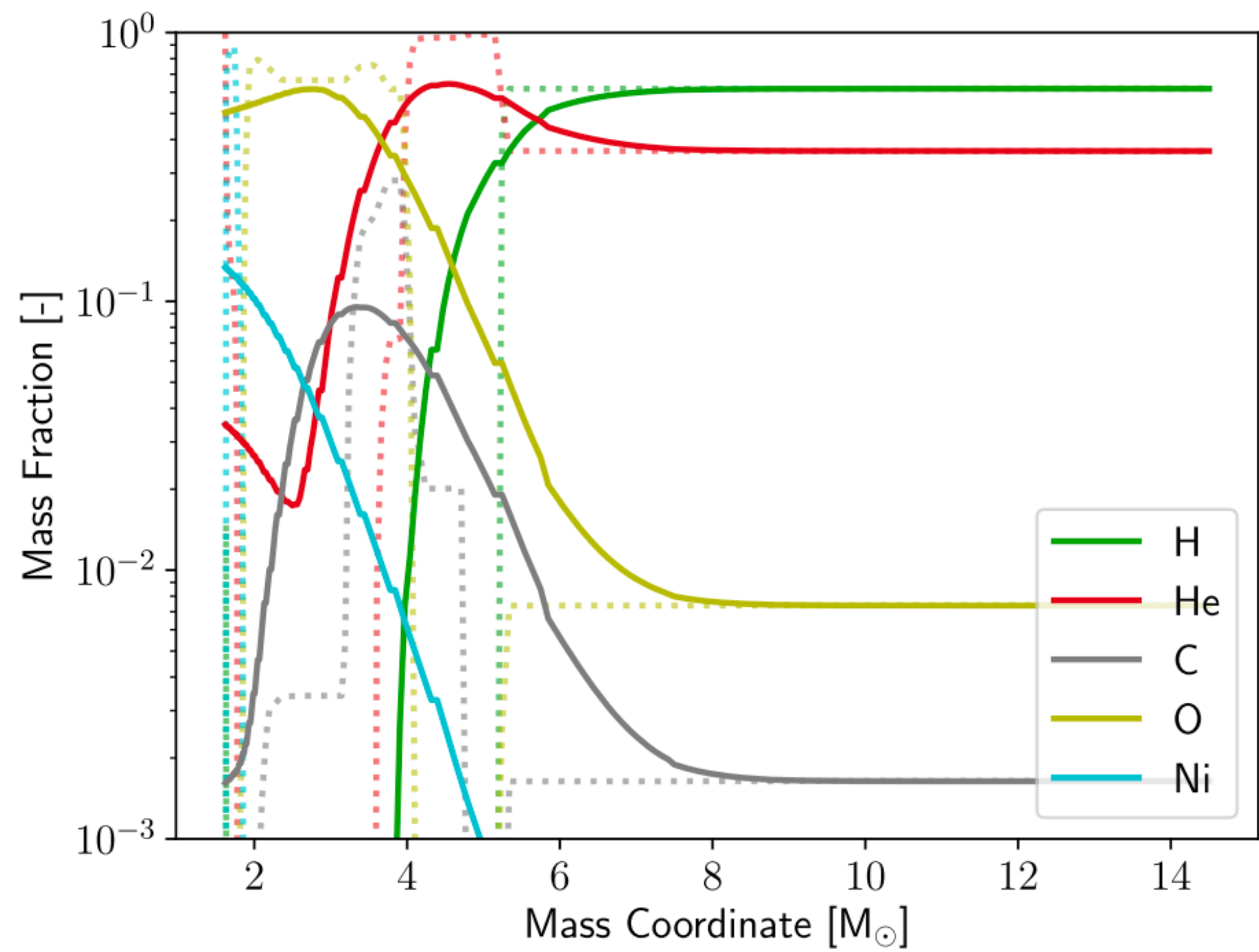
# SNEC: QUALITATIVE BEHAVIOR

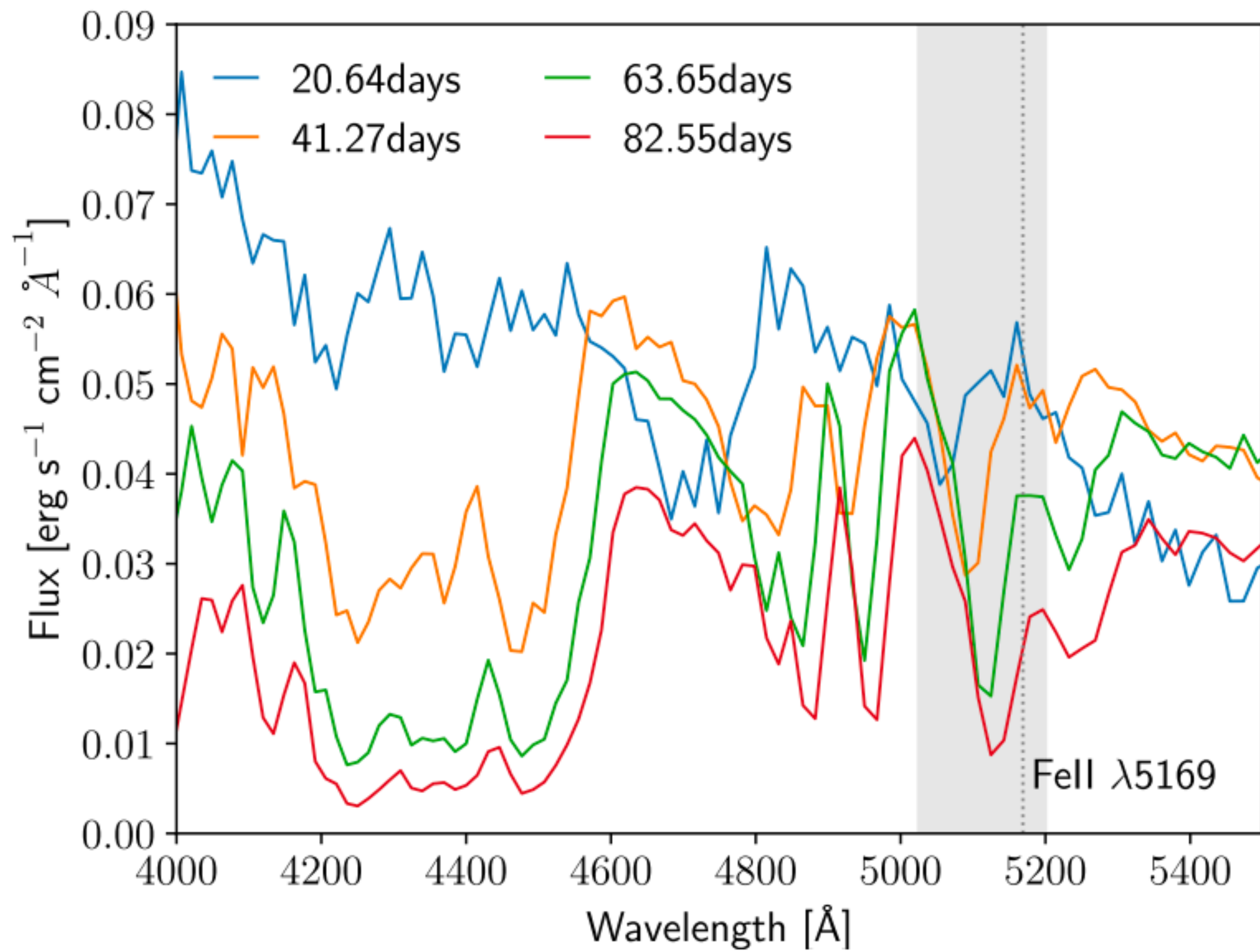


Properties	s18.0	z18.0
MASS [ $M_{\odot}$ ]	14,5	18,0
RADIUS [ $R_{\odot}$ ]	<b>1010</b>	<b>9,3</b>
EXP ENERGY [B]	1,45	1,54
NICKEL [ $M_{\odot}$ ]	1,12	1,34

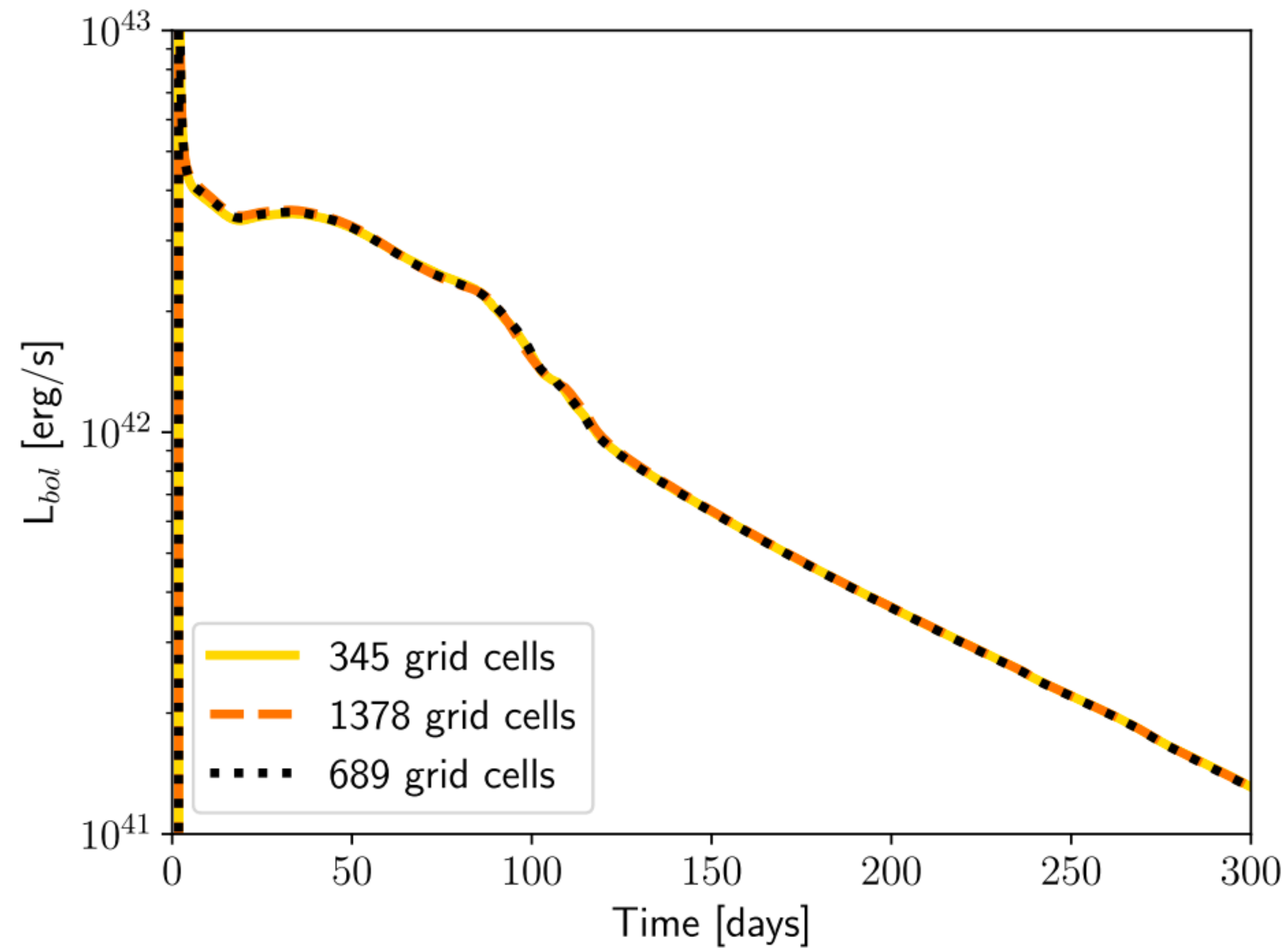
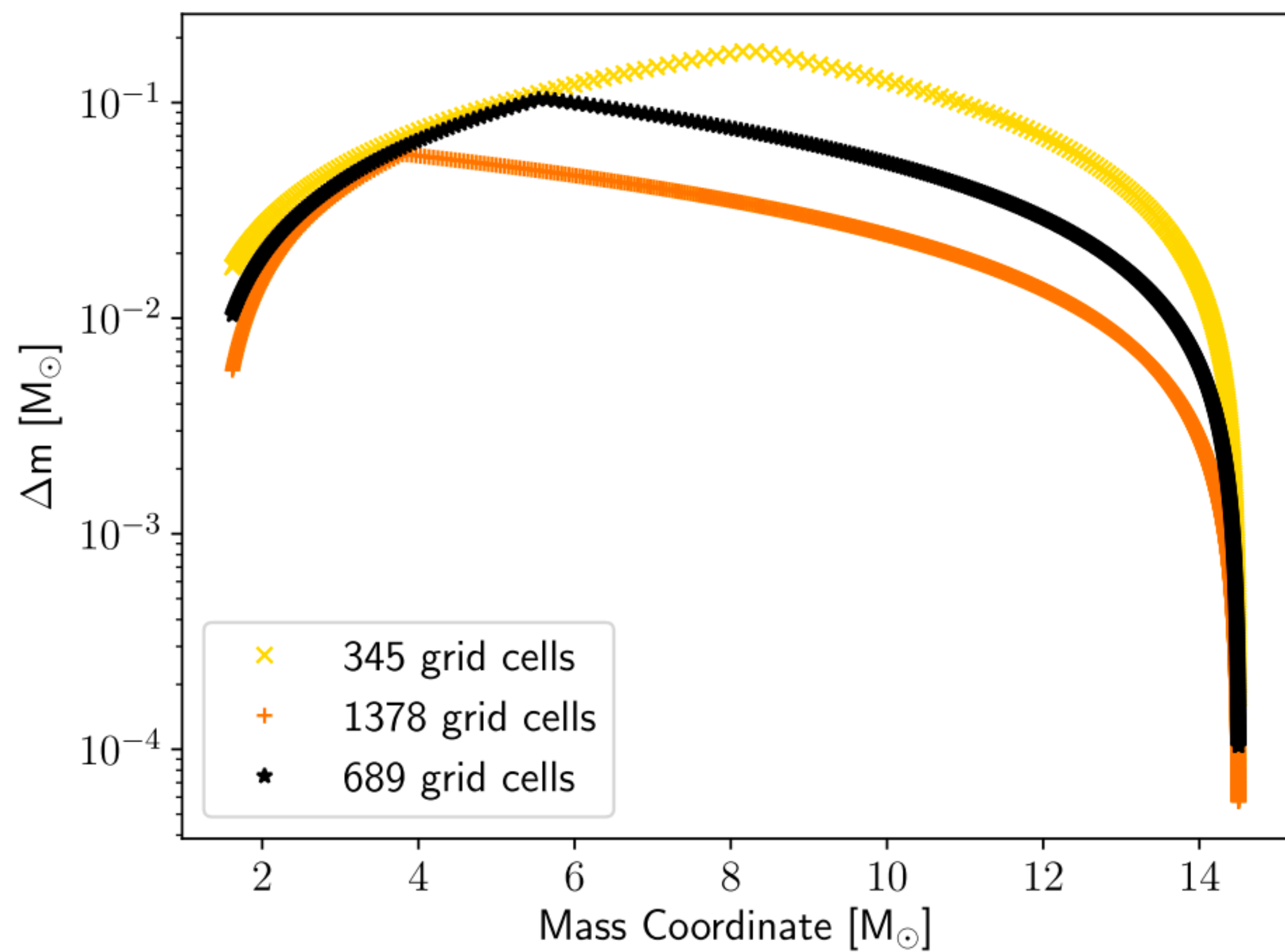
# Time-evolution of temperature profiles and light curves

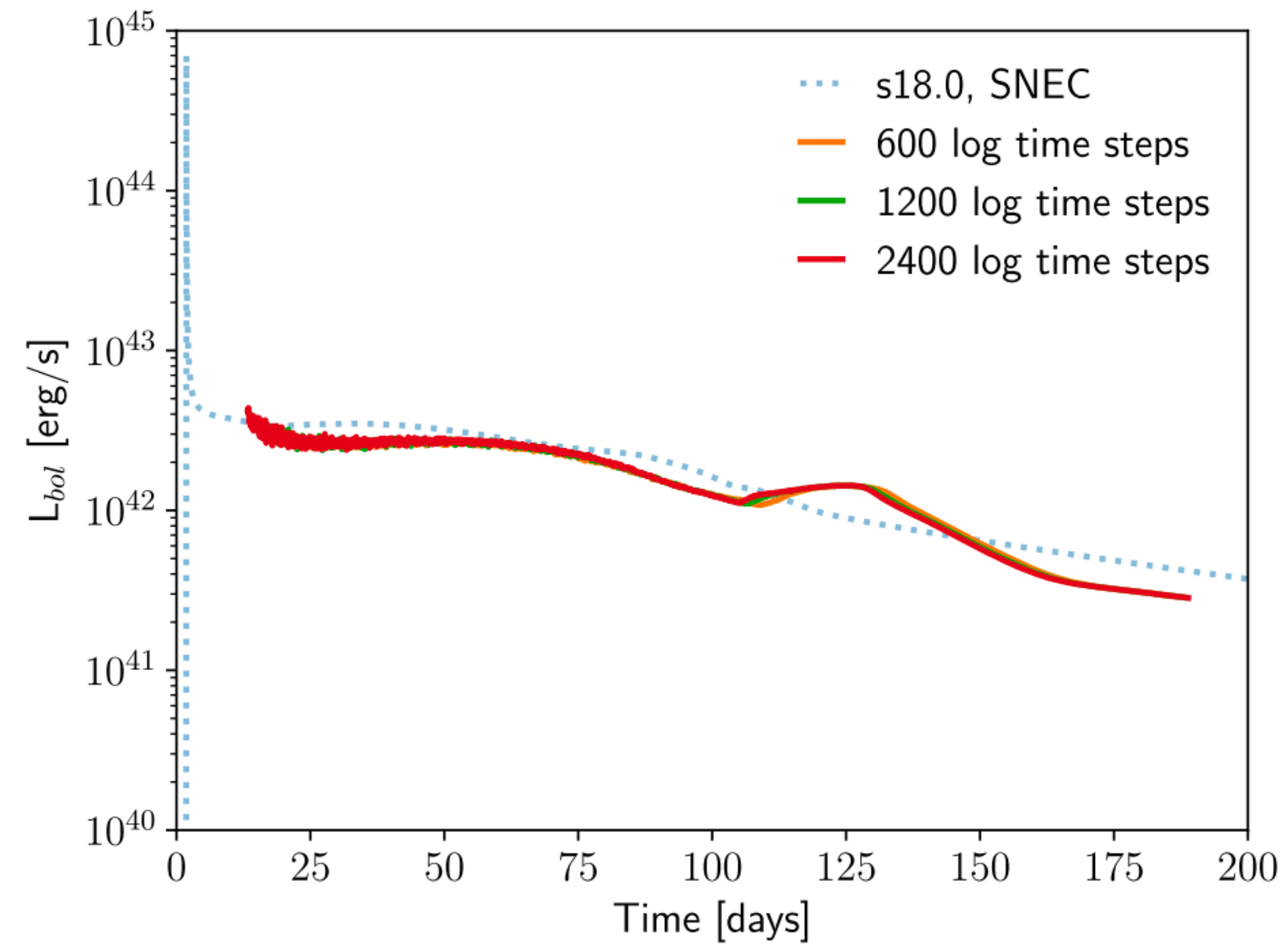
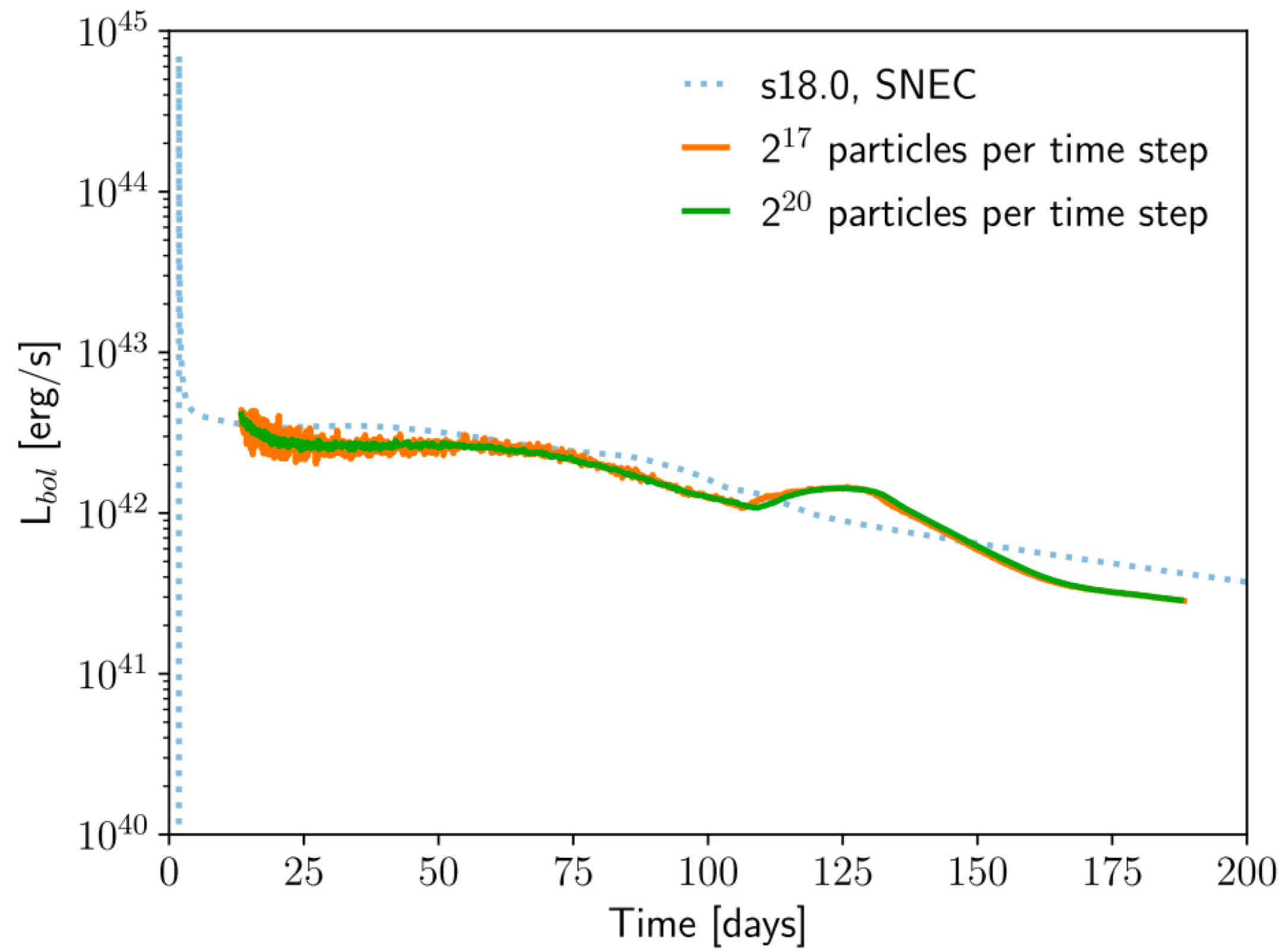




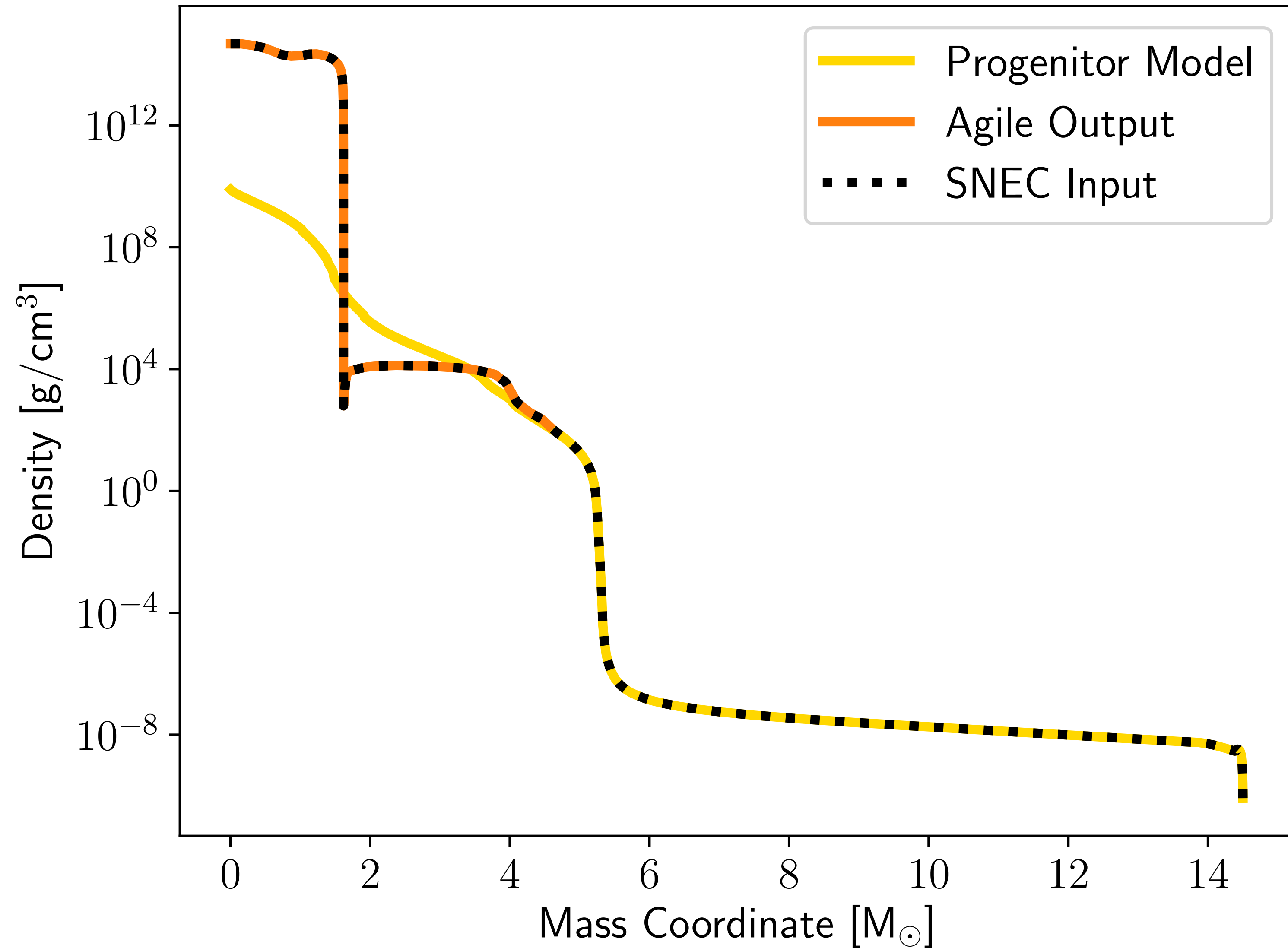
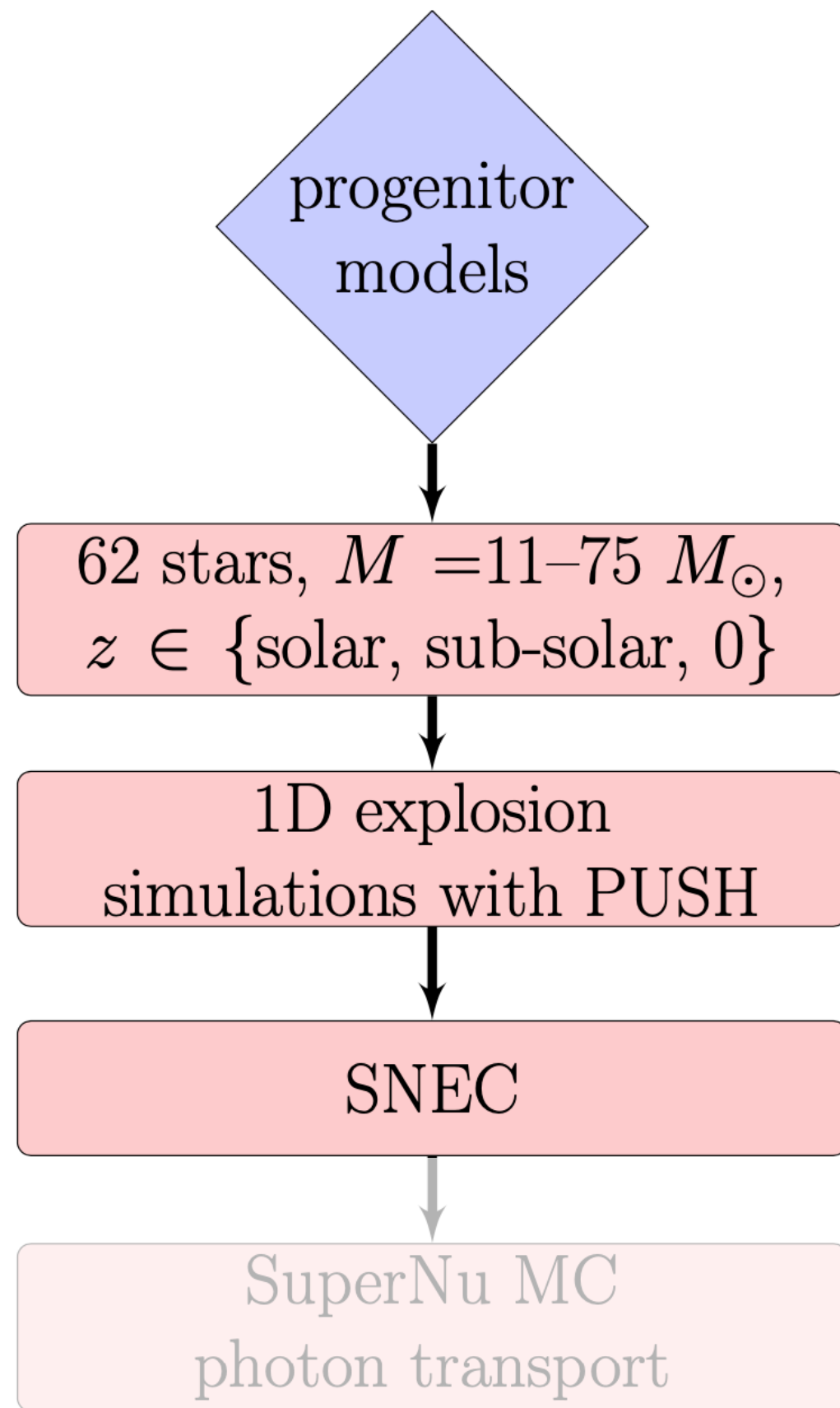




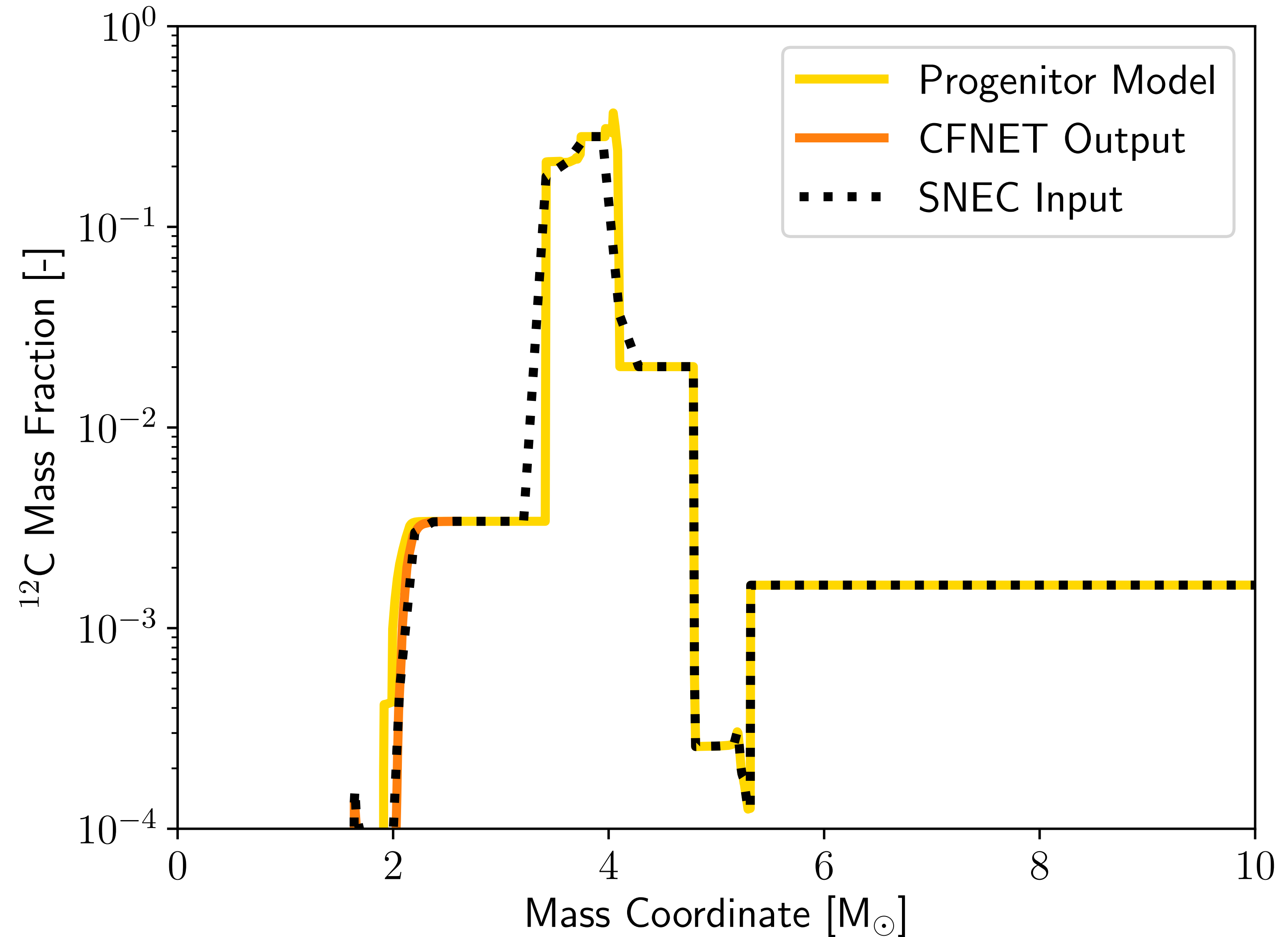
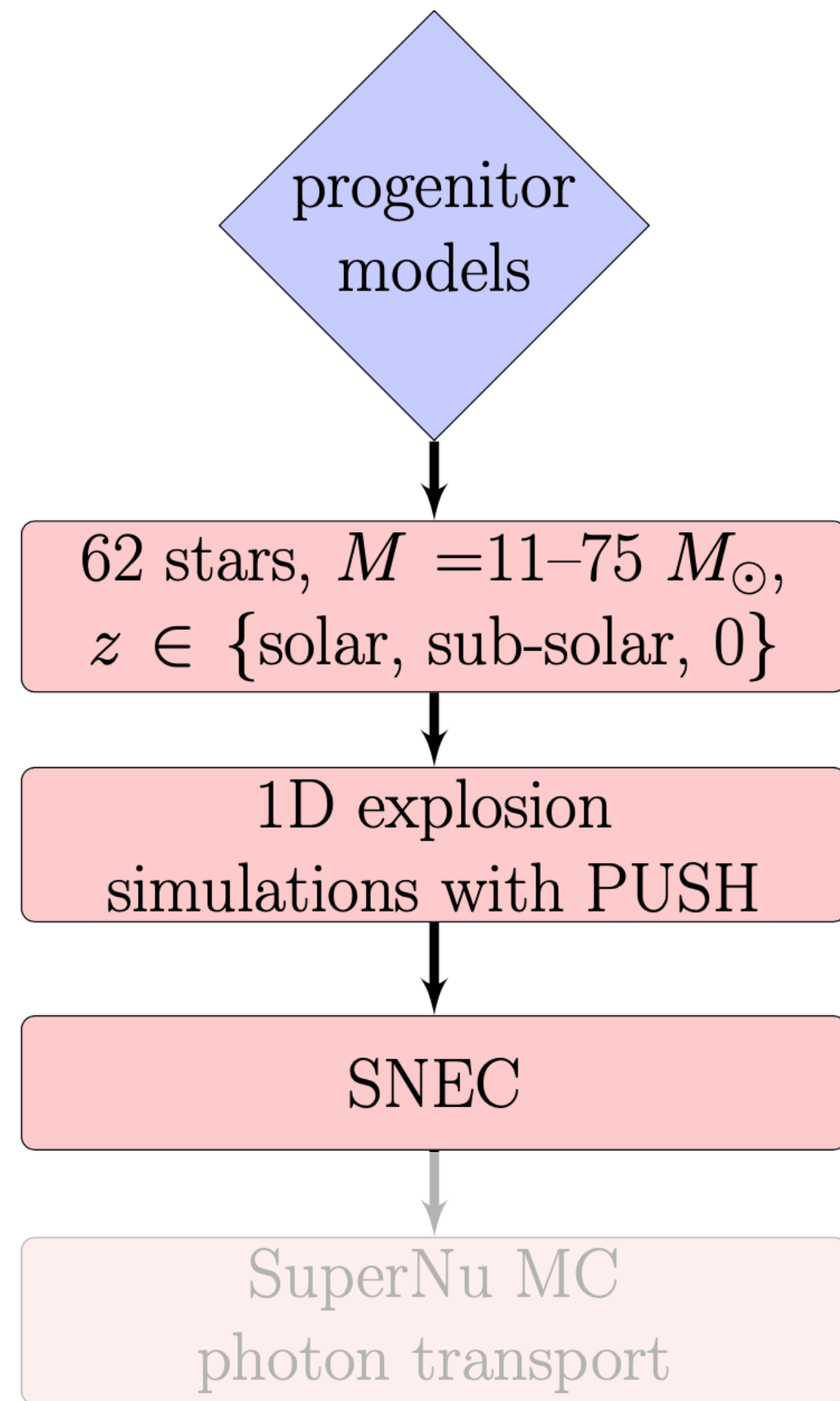




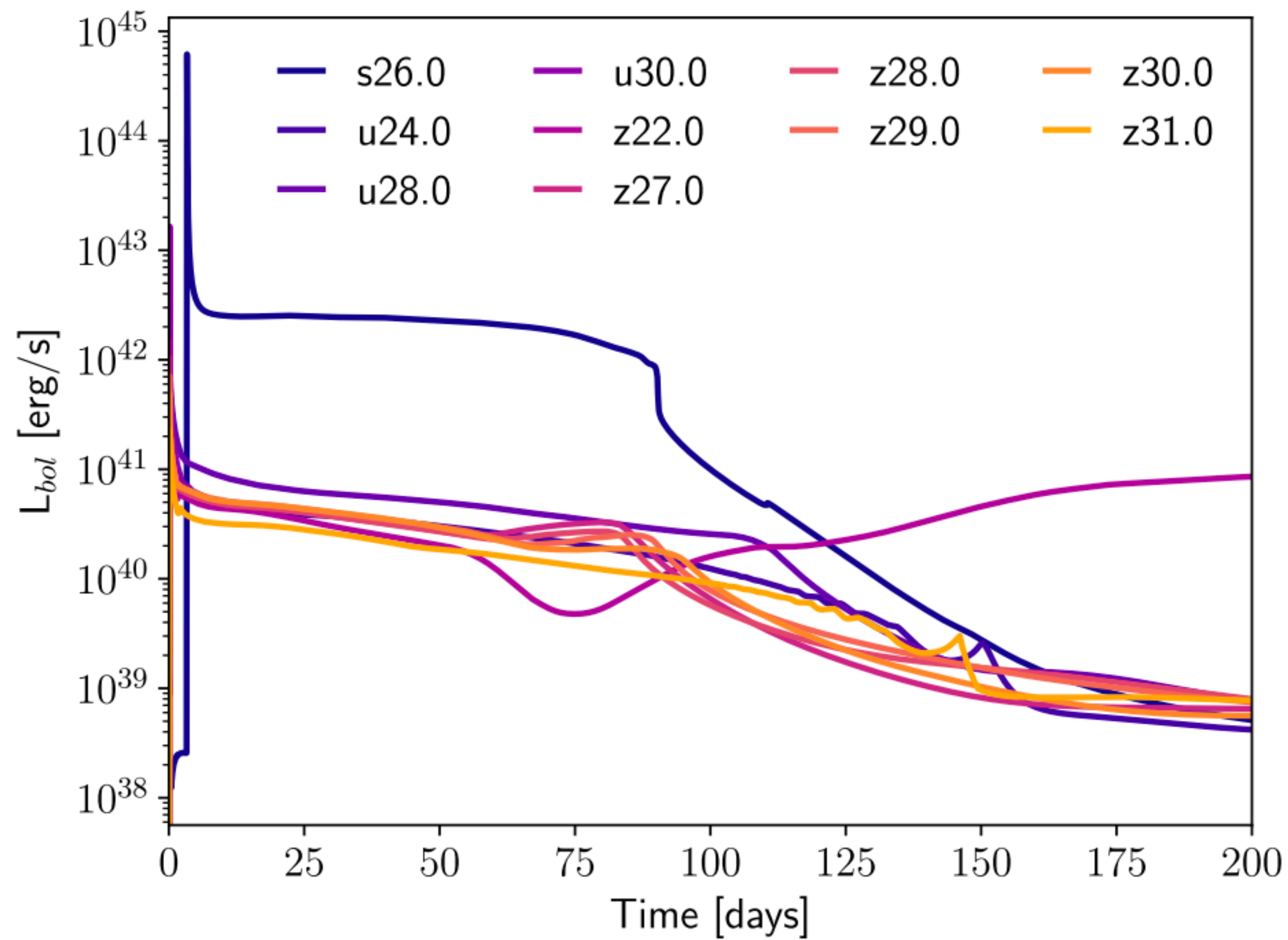
# RADIATION HYDRODYNAMICS WITH SNEC

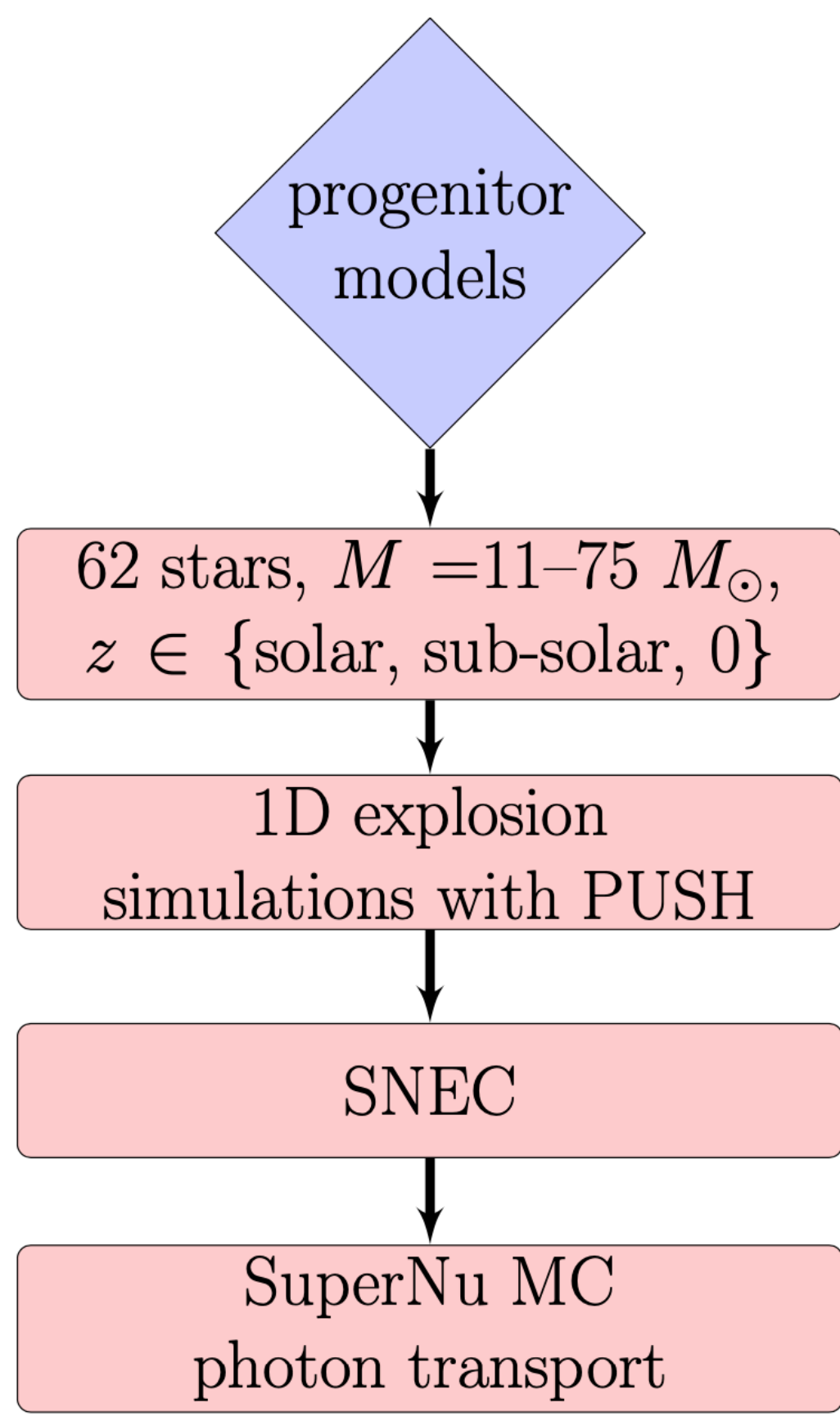


# RADIATION HYDRODYNAMICS WITH SNEC

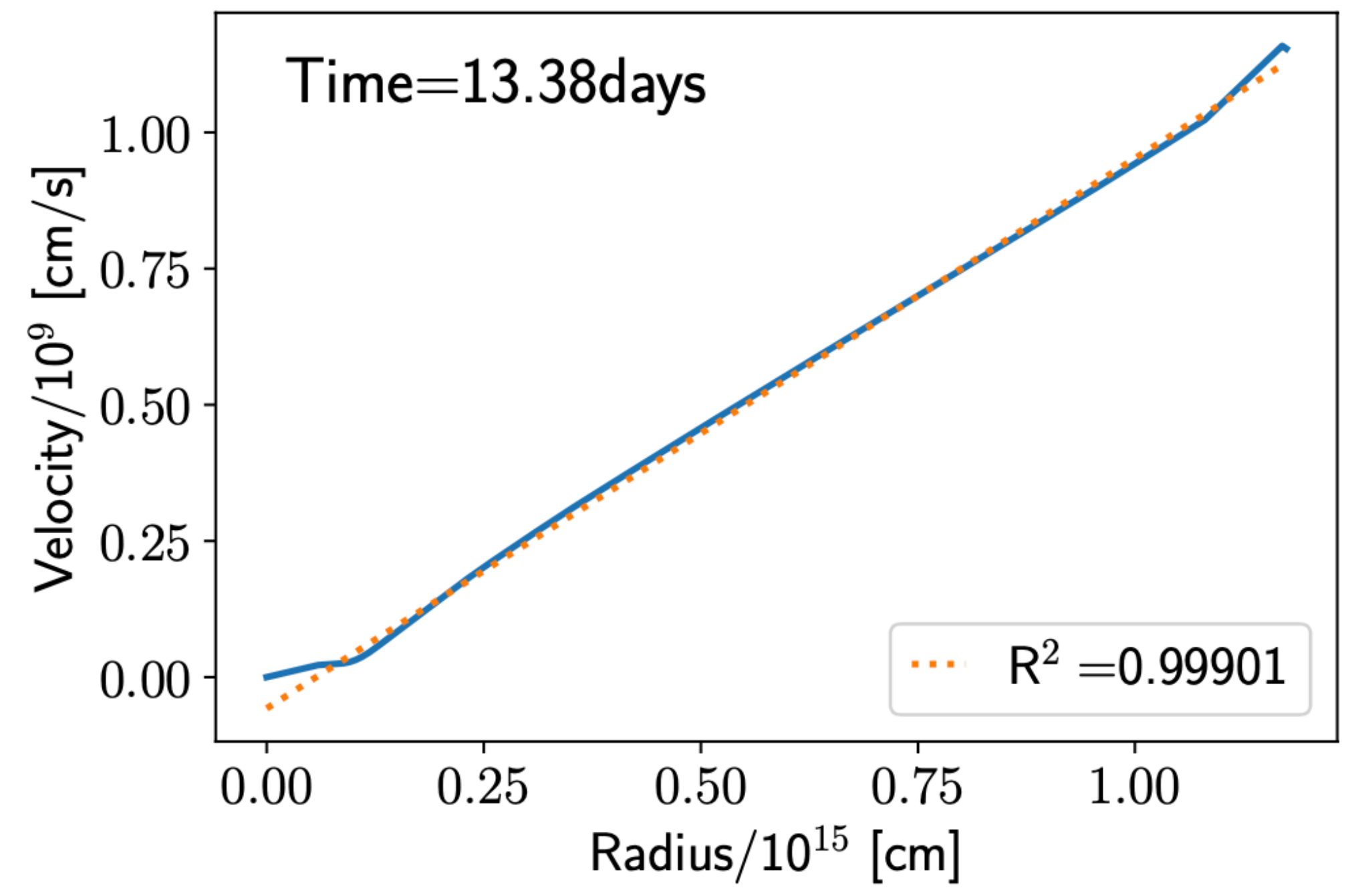








Check homologousness



Map to velocity grid

