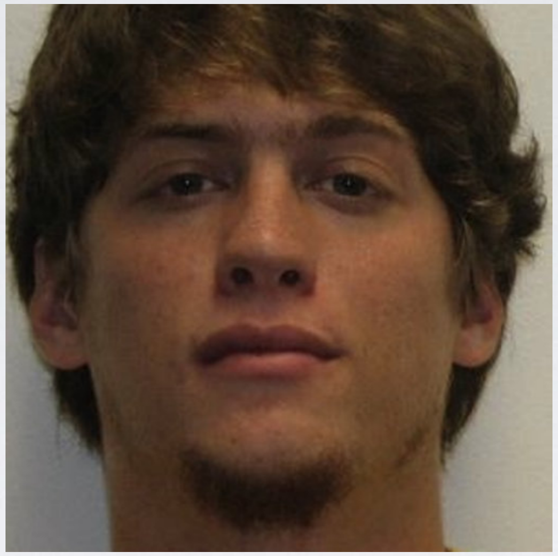
LOUISIANA STATE UNIVERSITY

PAIR-INSTABILITY SUPERNOVA SPECTRA IN 3D

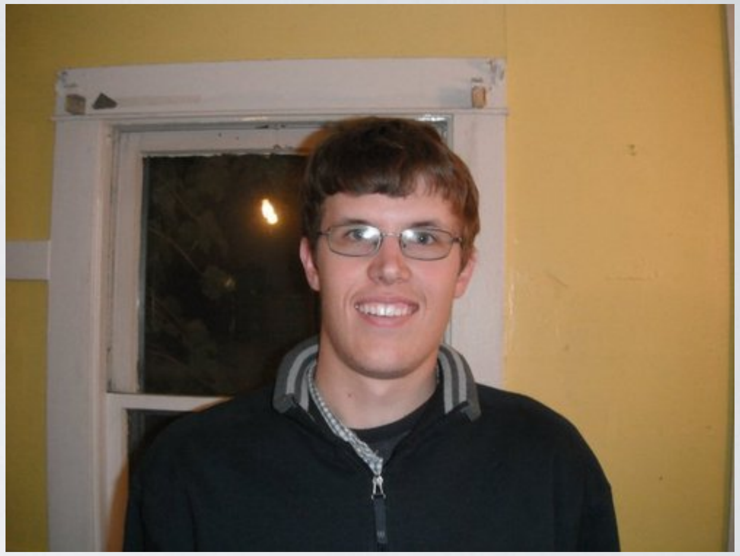
Manos Chatzopoulos
Louisiana State University

Collaborators & Sponsors

Carla Fröhlich (NCSU)



Matt Gilmer (LANL)



Ryan Wollaeger (LANL)

Wes Even (LANL)

LSU
LOUISIANA STATE UNIVERSITY

NC STATE UNIVERSITY

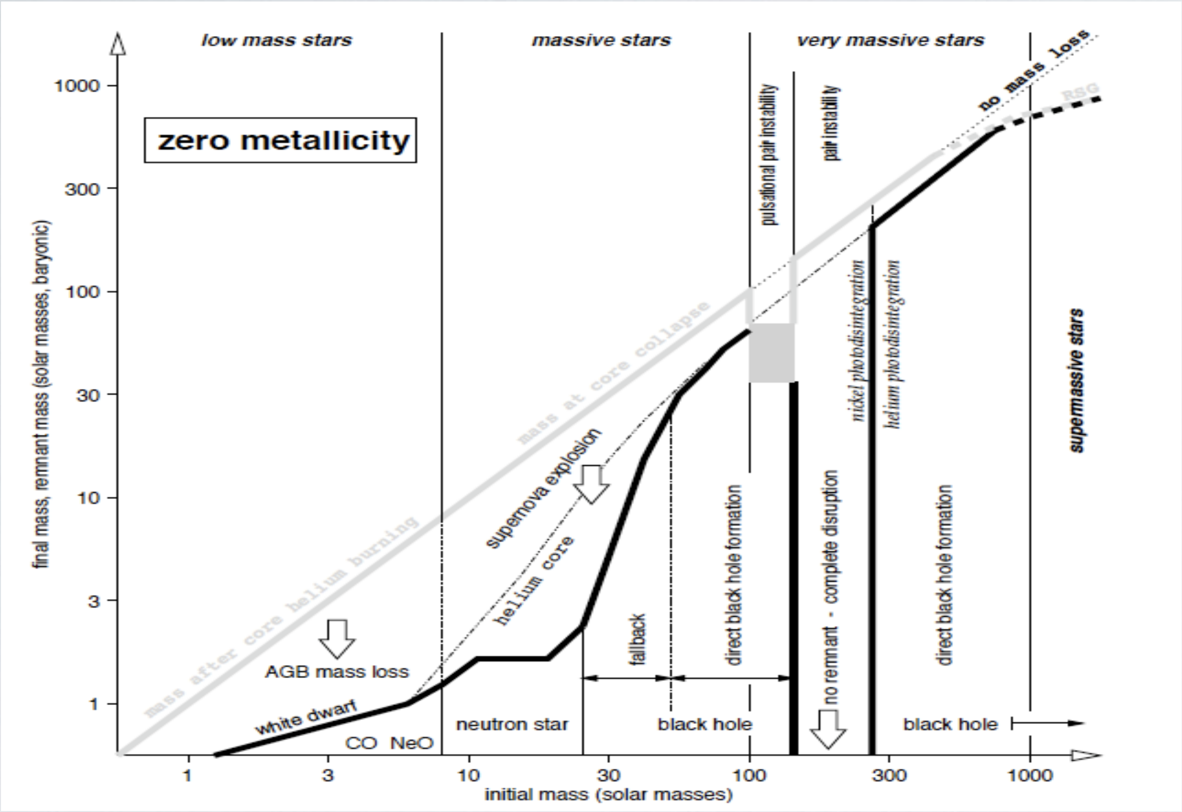
Los Alamos NATIONAL LABORATORY EST. 1943

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

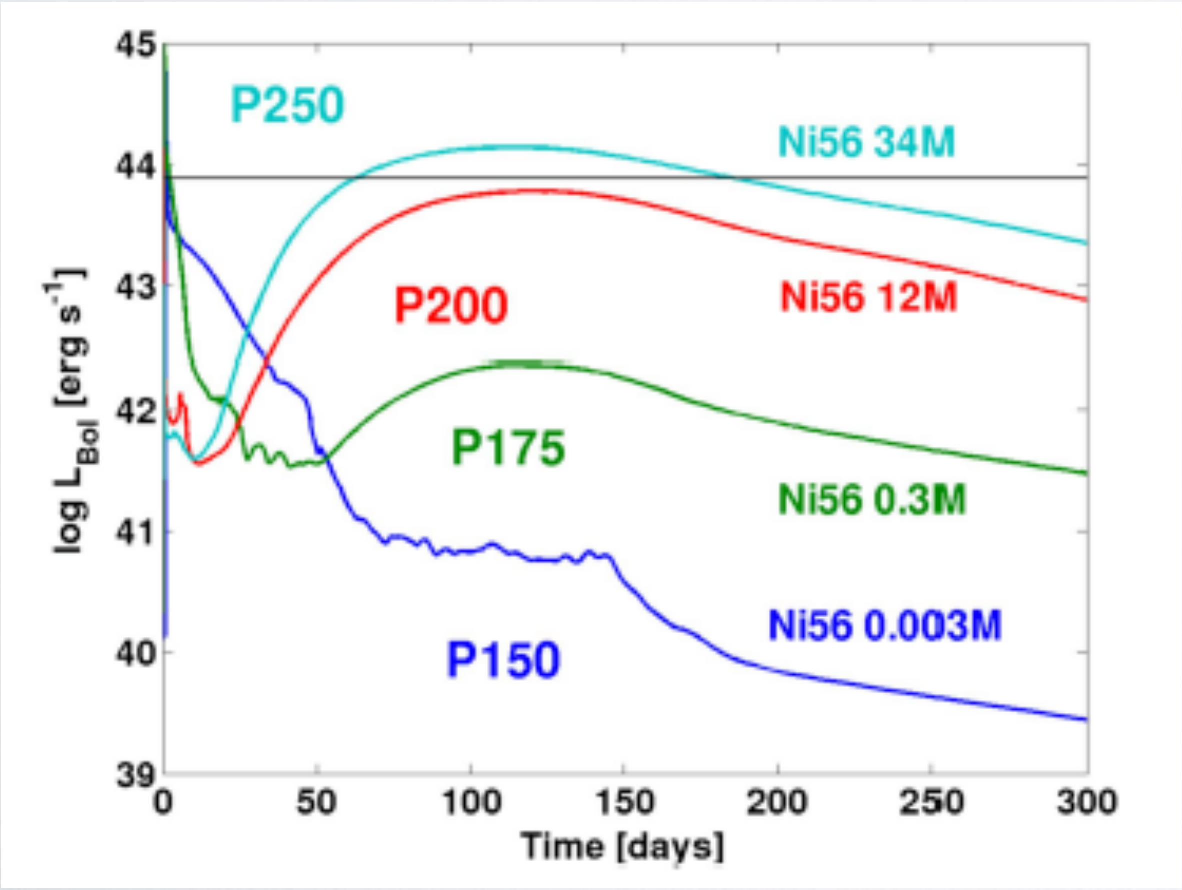
Outline

1. Introduction to PISNe (Pair-Instability Supernovae)
2. The progenitor model
3. Mixing in 2D/3D PISN simulations
4. Effects of mixing on PISN light curves, spectra & colors
5. Synthetic spectra of PISNe in 3D
6. Conclusions & Summary

Pair-Instability Supernovae (PISNe)



Heger & Woosley (2002)

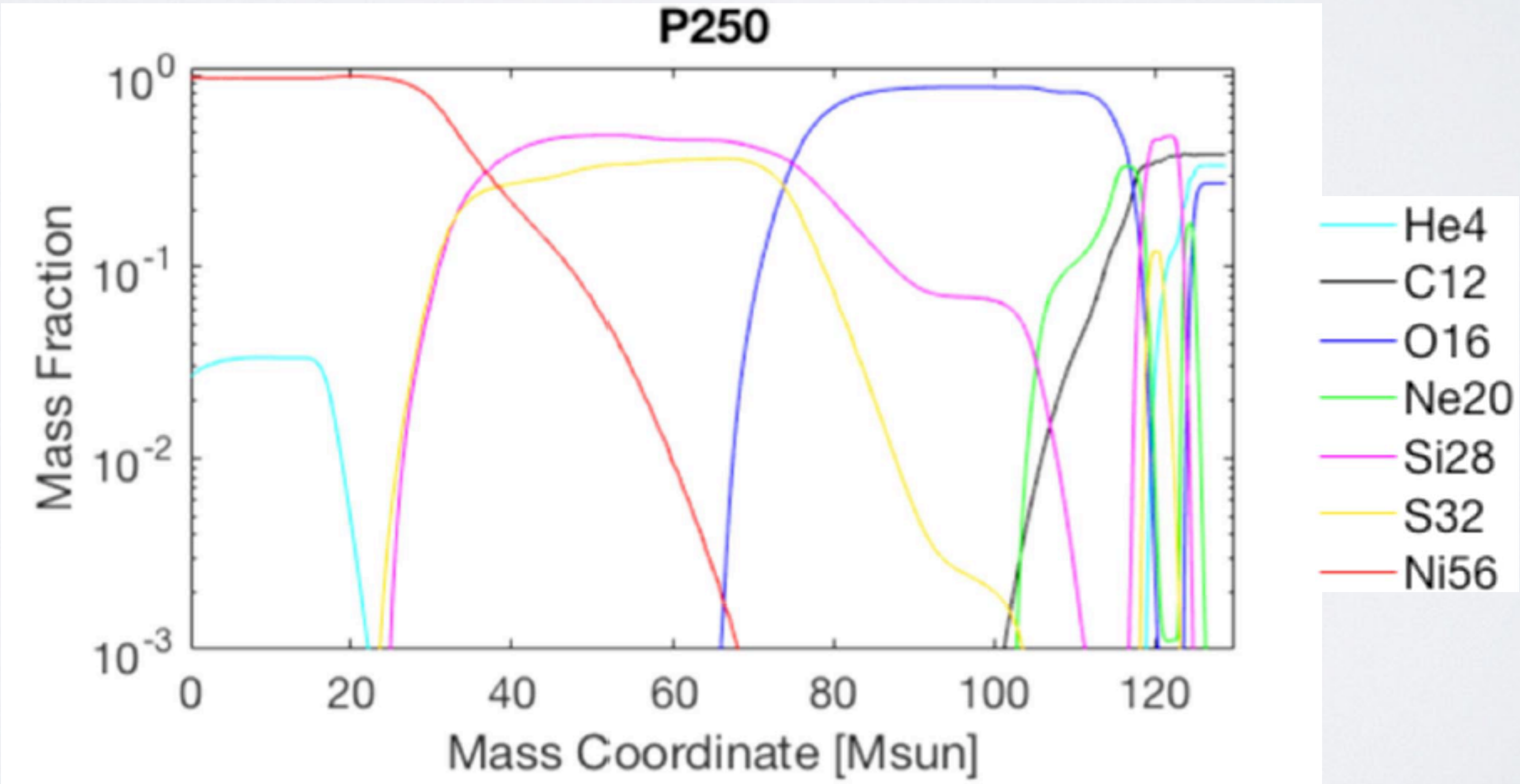


Gilmer et al. (2017)

- Very large progenitors (>200 $M_\odot$), down to ~ 80 $M_\odot$ for rapid rotation
- Collapse of massive C/O core
- Production of several solar masses of radioactive ^{56}Ni and ^{56}Co
- Slowly-evolving, red spectra
- May produce SLSNe but current sample implies host metallicities > 0.1 $Z_\odot$ favoring strong M.L.
- Could be more relevant to primordial (Pop III) massive progenitors (but see Kozyreva & Blinnikov (2015) and SN 2016iet; Gomez et al. 2019)

The PISN progenitor model

- Model **P250** from Gilmer et al. (2017)
- 250 $M_\odot$, 0.07 $Z_\odot$, at ZAMS computed with the *GENEC* code
- Pre-PISN mass: 127 $M_\odot$, CO-rich (He-layer mass ~2 $M_\odot$)
- PISN explosion & nucleosynthesis done in1D spherical, 2D cylindrical and 3D cartesian geometry using the Adaptive-Mesh Refinement (AMR) code *FLASH* (Gilmer et al. 2017).



Gilmer et al. (2017)

Motivation

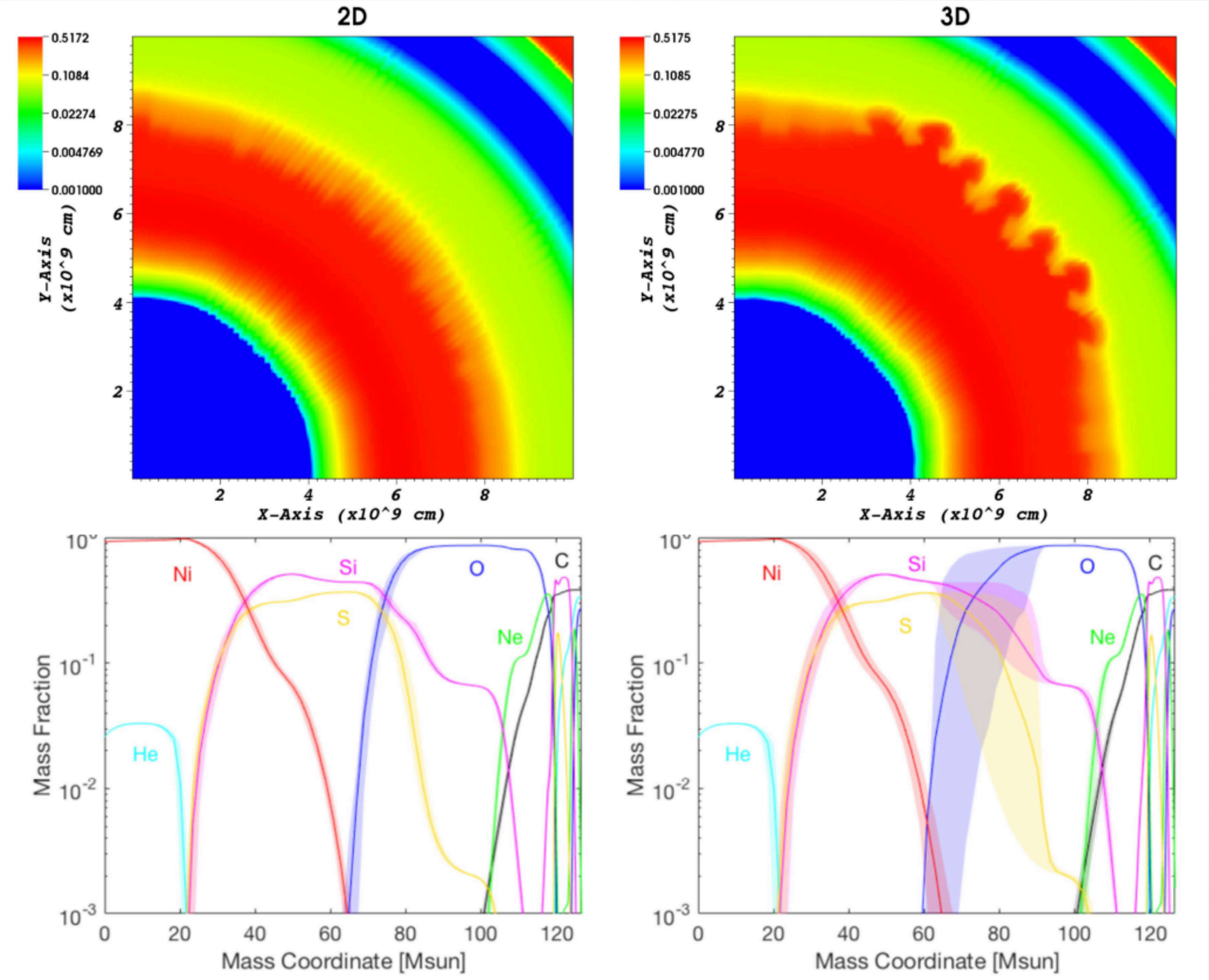
1) Explore effects of multi-D mixing on PISN observables

2) Explore 3D, viewing-angle effects on PISN spectra

3) Implications for future surveys (*JWST*, *WFIRST**)

4) Test capabilities of new radiation transport code *SuperNu*

Model P250 density/composition profiles in 2D and 3D



Gilmer et al. (2017)

The 1D mixing profiles

1) 1D (spherical) profile is kept as is
2) 1D line-out profiles from the 2D & 3D FLASH simulations are extracted for different angles (θ/φ) corresponding to different degrees of mixing in the Si/O interface ("outward/inward Si-mixing")
3) Mixing in the Si/O (and, to less extent, in the Ni/Si) interface is driven by Rayleigh-Taylor (RT) instability after the explosion (Chardonnet et al. 2010, Joggerst & Whalen 2011, Chatzopoulos et al. 2013, Chen et al. 2014a,b, Gilmer et al. 2017)
4) We also consider a complete 3D PISN explosion profile ("3D_FULL" run).

Table 1. Basic properties of the PISN (P250) models presented in this work.

1D
3D

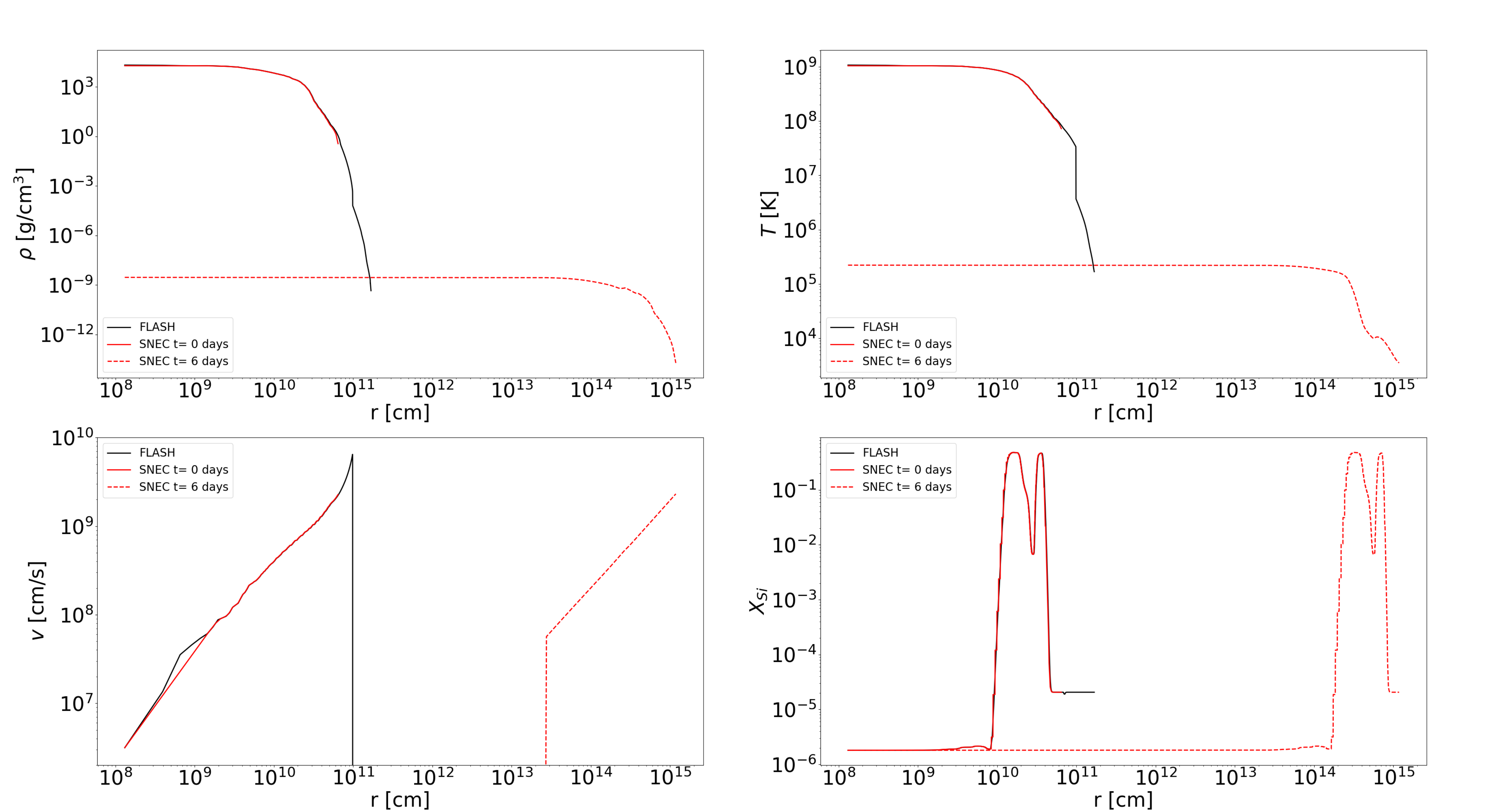
Model	E_{SN} (B)	M_{Ni} ($M_\odot$)	$\theta^\dagger$ (°)	$\phi^\dagger$ (°)	$L_{max,D}$ (10^{44} erg s^{-1})	$t_{max,D}$	L_{max} (10^{44} erg s^{-1})	t_{max}	$t_{Si/O}$	$t_{Ni/Si}$
1D	81.9	34.0	–	–	1.06	185.7	1.79	159.5	181.0	216.4
2D_AA	81.9	34.0	–	–	1.06	190.0	1.81	178.7	185.0	220.4
2D_MI	81.9	34.0	18–19	–	1.09	188.7	1.84	176.0	200.7	224.3
2D_MO	81.9	34.0	37–38	–	1.05	182.8	1.78	168.4	169.2	216.4
3D_AA	81.8	33.8	–	–	1.05	185.4	1.74	165.3	181.0	220.4
3D_MI	81.8	33.8	17–18	73–74	0.94	186.9	1.57	171.7	246.0	251.9
3D_MO	81.8	33.8	21–22	69–70	1.00	171.2	1.61	165.9	153.5	202.7
3D_FULL‡	81.8	33.8	–	–	–	–	1.23	185.0	N/A	N/A

NOTE—† θ and ϕ correspond to the polar and the azimuthal angle, accordingly, in 3D spherical coordinates. For the 2D models, the polar angle θ is the only coordinate used. The peak luminosity ($L_{peak,D}$) and time of peak luminosity ($t_{peak,D}$) values as computed in *SNEC* using equilibrium–diffusion radiation transport are also quoted. ‡ The values quoted for L_{max} and t_{max} in model 3D_FULL correspond to a viewing angle of $\Omega \simeq 0°$ ("edge–on" view). These values vary only by a small amount for different choices of Ω. We do not provide $t_{Si/O}$ and $t_{Ni/Si}$ estimates for the 3D_FULL model because there is not a unique time when the photosphere crosses the Si/O and Ni/Si compositional interfaces in the 3D simulations due to the large extent of the RT mixing. All timescales are expressed in units of days.

Chatzopoulos et al. (2019)

Homologous expansion by *SNEC*

- We use the equilibrium - diffusion *SNEC* code to expand the pre-shock break-out P250 profiles out to ~6 days (until SN ejecta is characterized by homologous flow)
- Step needed in order to map to homologous *SuperNu* code.
- Also an opportunity to perform code-to-code comparison (at least in term of computed LCs)



Chatzopoulos et al. (2019)

SuperNu radiation transport

- Radiation transport code that utilizes Implicit Monte-Carlo (IMC) - Direct Diffusion Monte Carlo (DDMC) schemes to compute time-series of synthetic spectra for explosive outflows

- Can be run in 1D, 2D and 3D geometries

- Assumes homologous expansion, LTE

- Includes Multi-Group absorption opacity data from H up to Co and line data for bound-bound opacities from Kurucz & Bell (1995)

- Features an improved implementation of opacity-regrouping to non-contiguous frequency groups that leads to enhanced performance and computing efficiency

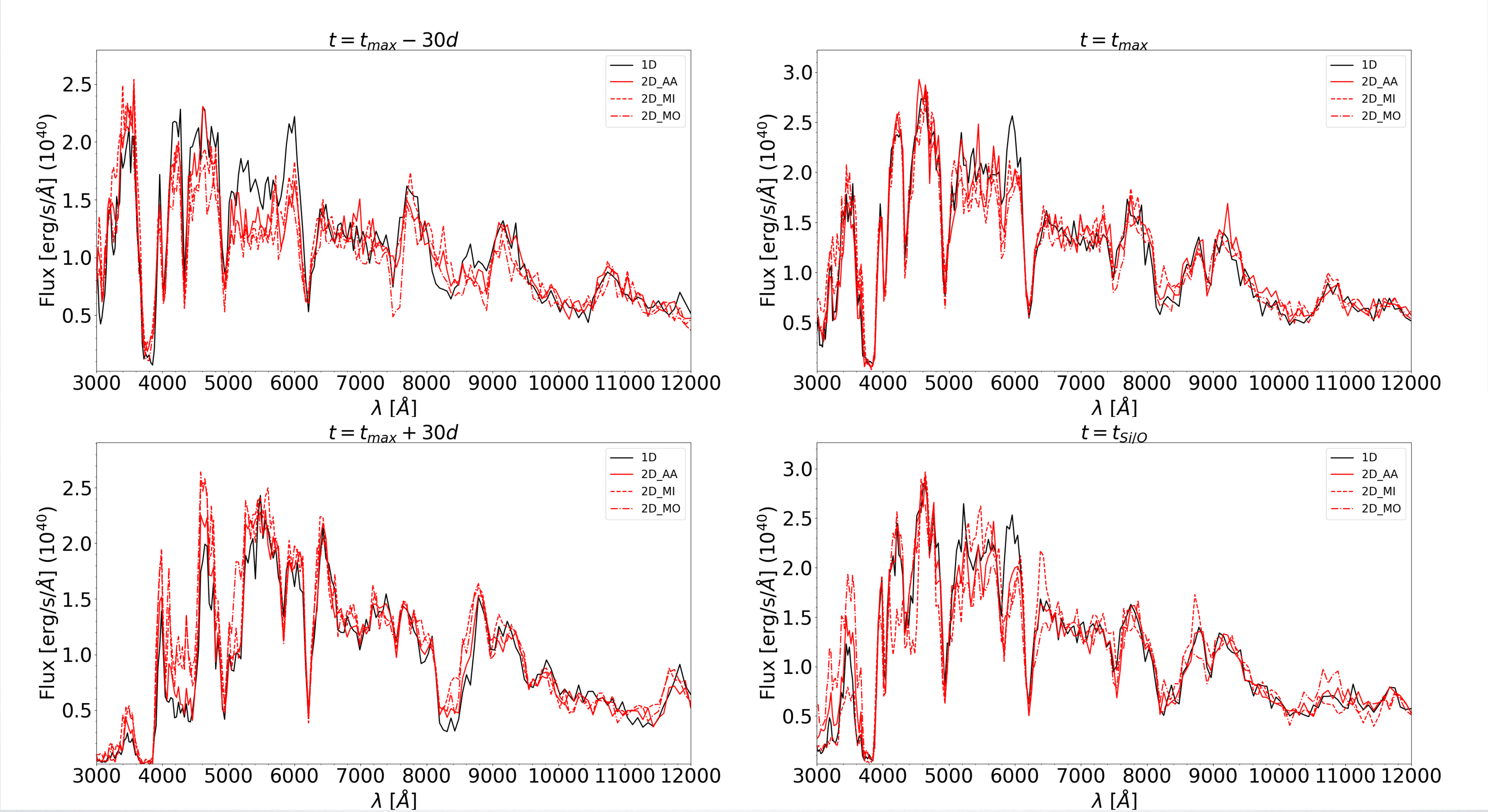
- Fully parallelized (MPI)

- Developed by Los Alamos National Lab collaborators (R. Wollaeger)

- Public release available at online repo: *https://bitbucket.org/drrossum/supernu/wiki/Home*

Spectra: 1D vs 2D

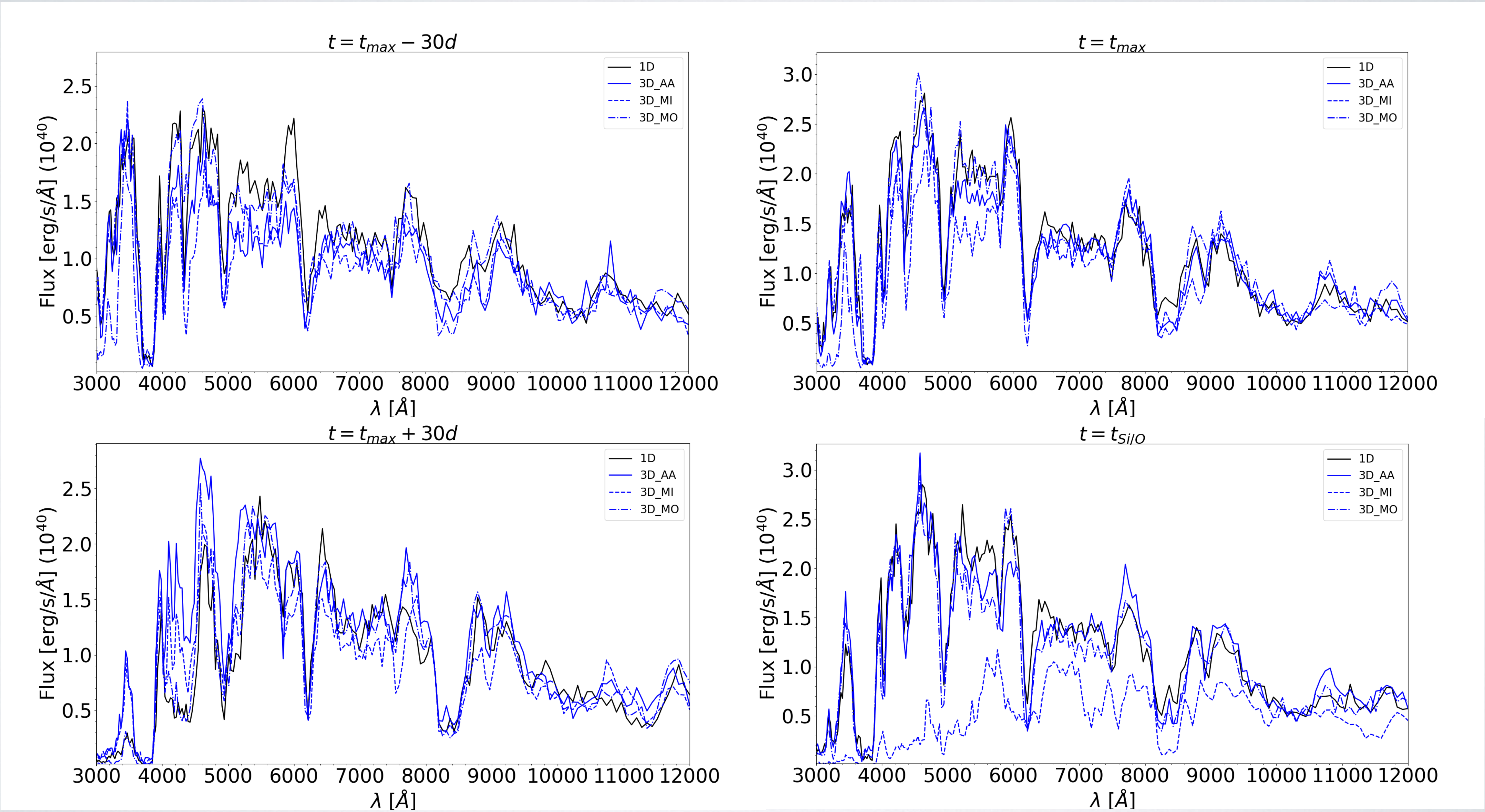
- Outward Si-mixing captured in 2D slightly affect spectra at contemporaneous epochs
- Faster evolution (features appear at somewhat earlier phases in 2D as compared to 1D)
- Opposite behavior is seen for the inward Si-mixing 2D profile



Chatzopoulos et al. (2019)

Spectra: 1D vs 3D

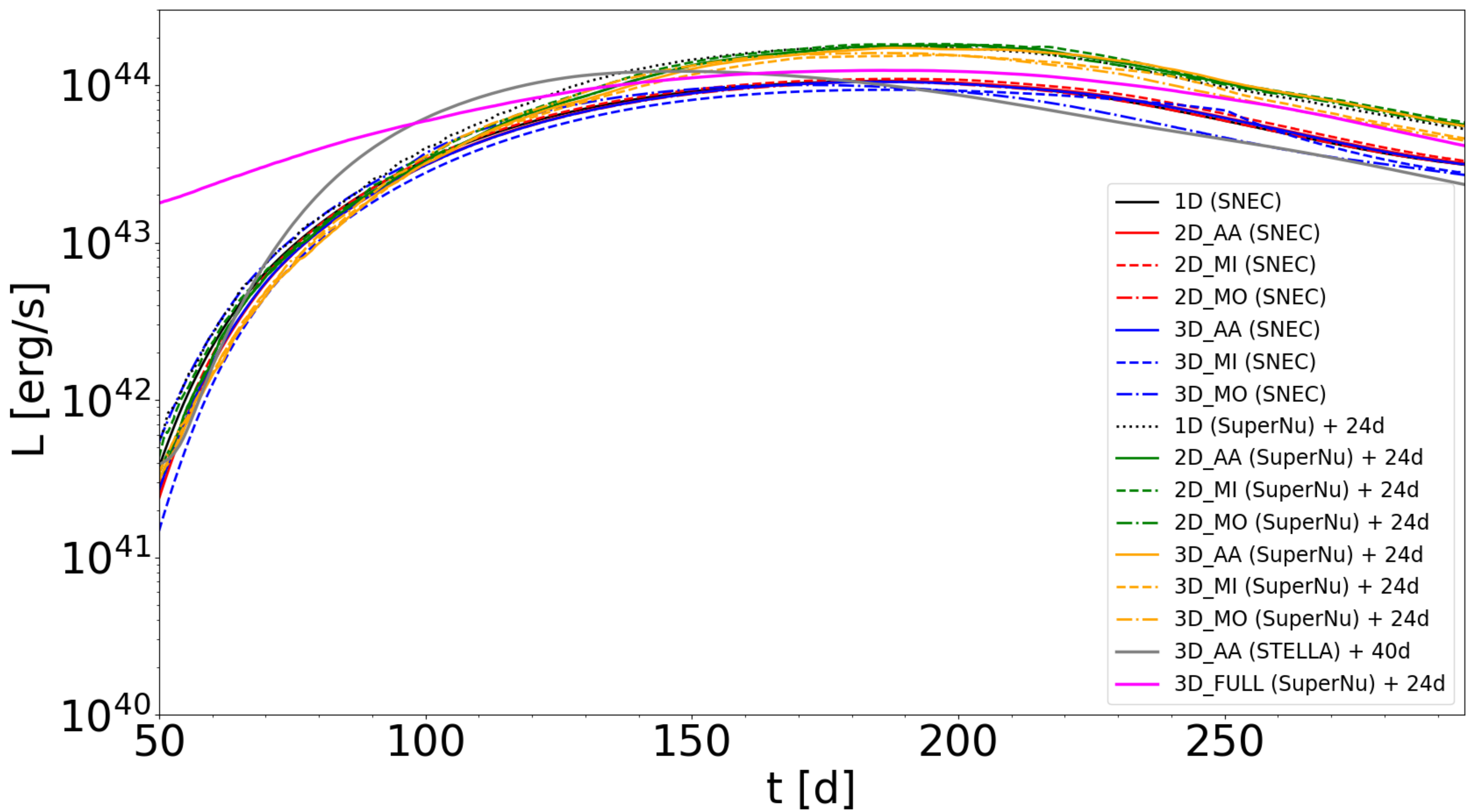
- Effects have the same sign as in the 2D case but much higher magnitude, especially at late times
- Stronger 3D RT-induced mixing implies a faster spectroscopic evolution.



Chatzopoulos et al. (2019)

1D/2D/3D Lightcurves

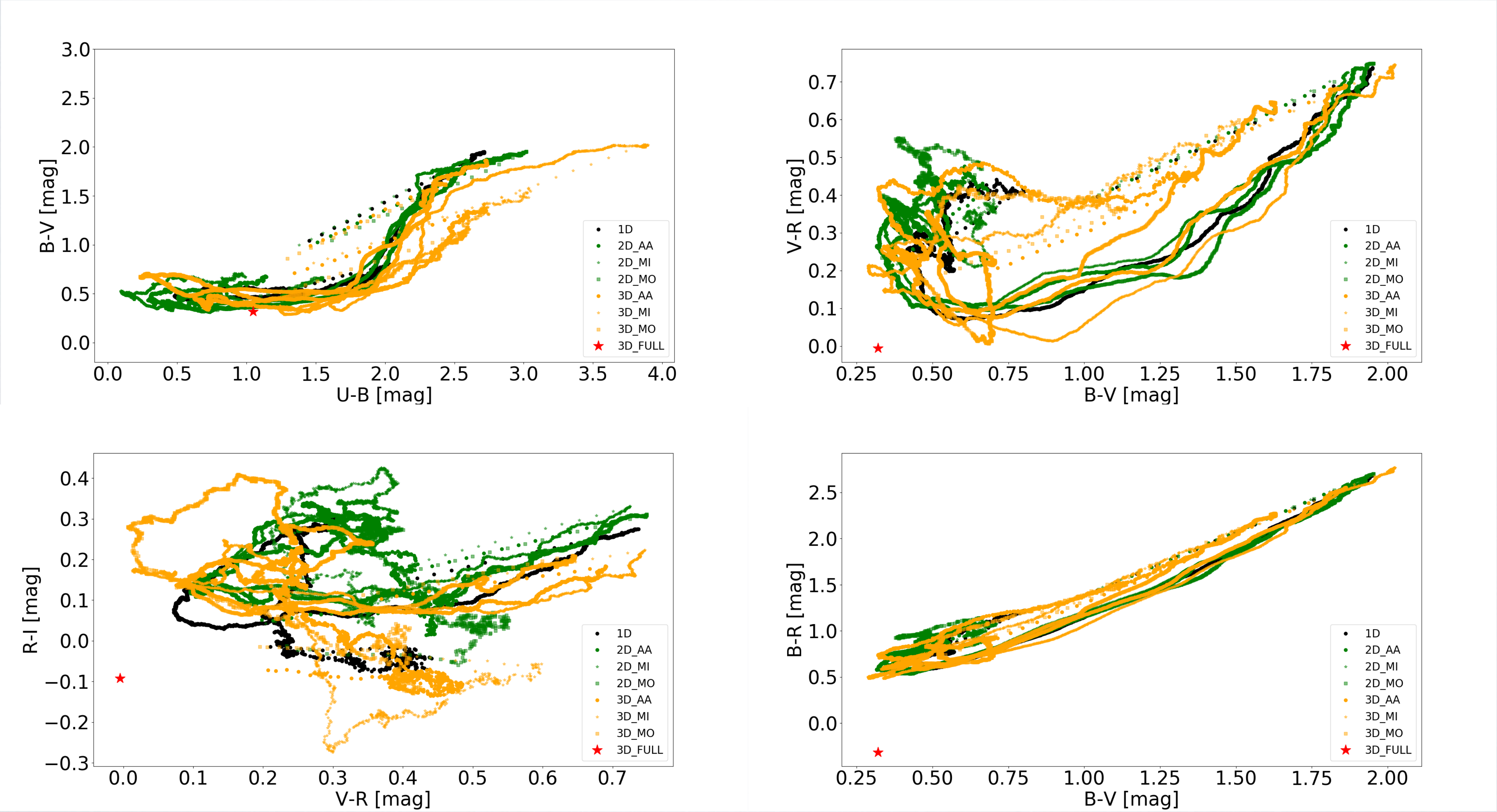
- The *SuperNu* LCs of the mixing profiles do not appear to differ significantly
- The Full 3D model LC, however, exhibits a slower evolution.



Chatzopoulos et al. (2019)

1D/2D/3D Color-Color plots

- Color-Color evolution is affected by mixing
- Best distinction between different degrees of mixing is captured for the R-I vs V-R color-color plot
- The Full 3D model colors at peak luminosity significantly bluer than all the 1D profiles (regardless of degree of mixing). The culprit? γ-ray leakage through areas of low density

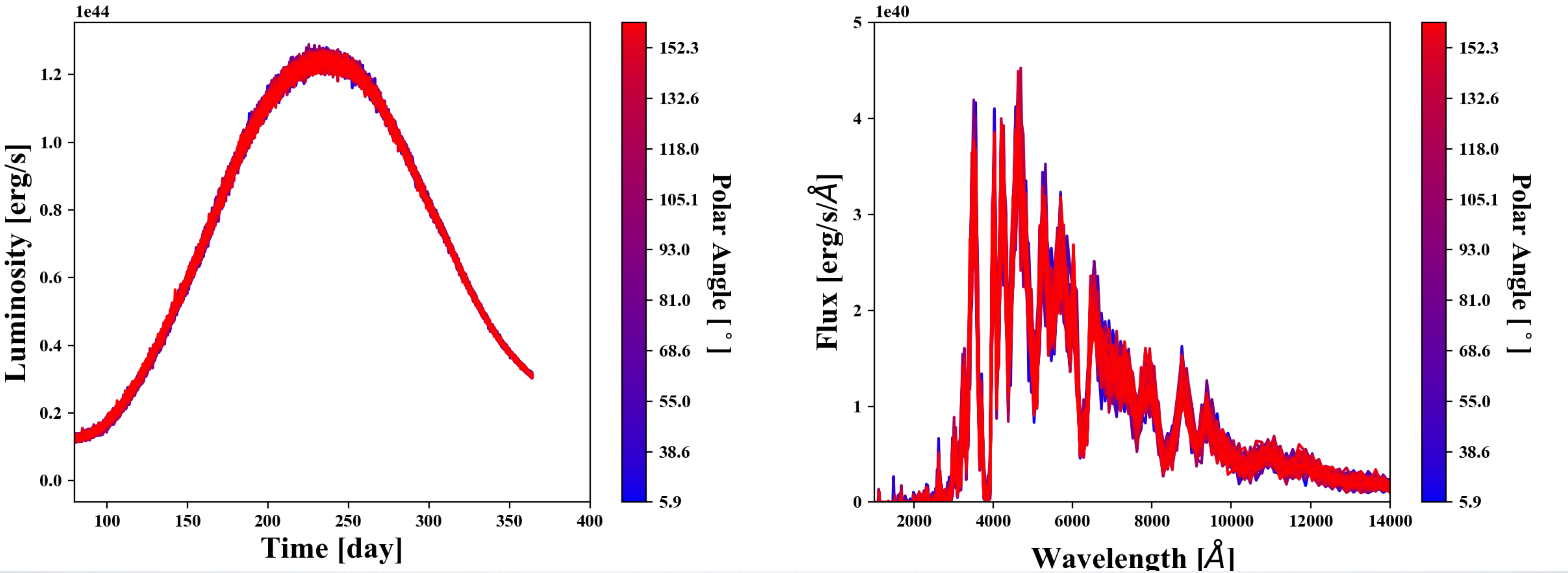


Chatzopoulos et al. (2019)

The first 3D PISN spectra - I

- Viewing-angle effects do not affect the observed LCs/spectra of PISN in 3D (as expected)

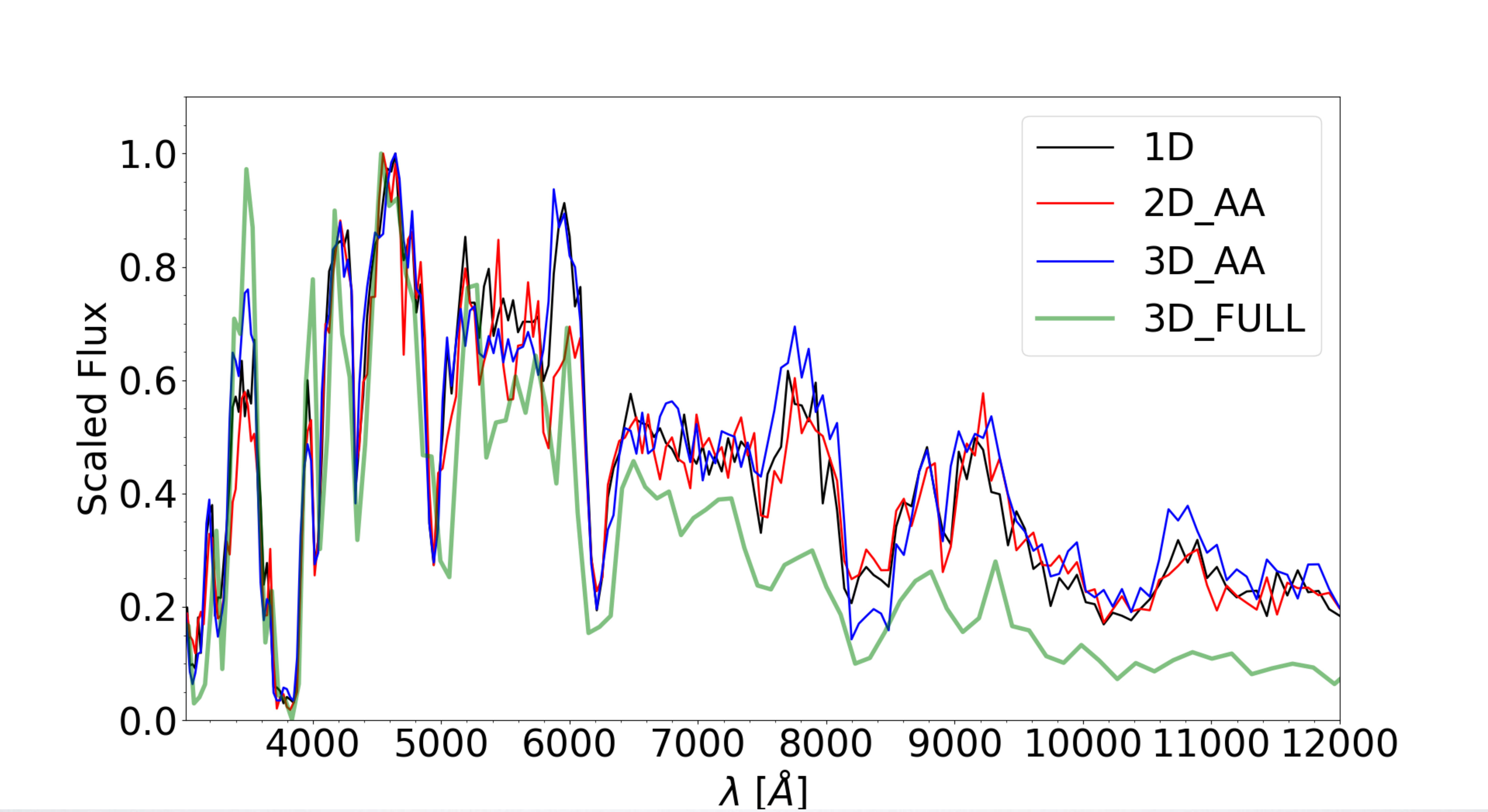
- However, our full 3D calculation yields a LC that is slower-evolving than in the 1D profiles and spectra that imply a bluer color evolution for the PISN.



Chatzopoulos et al. (2019)

The first 3D PISN spectra - II

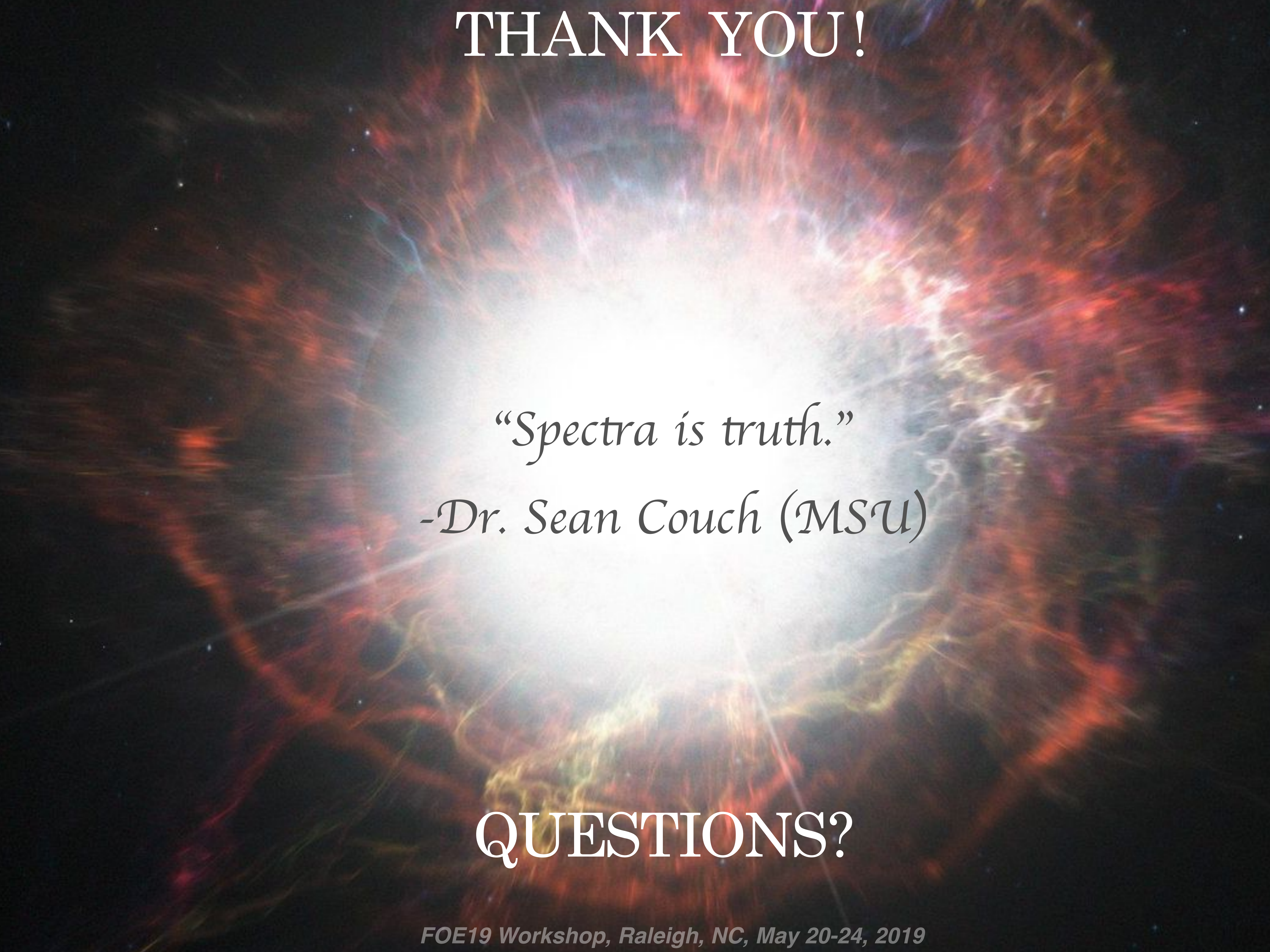
3D synthetic spectra of PISN at contemporaneous epochs with the 1D models show less flux in redder wavelengths.



Chatzopoulos et al. (2019)

Conclusions & Summary

- 2D/3D mixing does not significantly affect the bolometric LCs of PISNe, but it does impact their spectroscopic evolution.
- As a result, 2D/3D mixing affects the color evolution of PISNe.
- PISN spectroscopic evolution is faster for outward Si-mixing in the Si/O interface, more so in 3D than in 2D.
- 3D radiation transport modeling of PISN reveals that their LCs and spectra are practically unchanged as a function of viewing-angle.
- Leakage of γ-rays through areas of low density in 3D leads to bluer PISN spectra as compared to those corresponding to 1D models. Future surveys (i.e. JWST) may exploit that property to identify PISNe.
- SuperNu is shown to be a powerful software instrument for the study of explosive outflows in 1, 2 and 3D geometry.



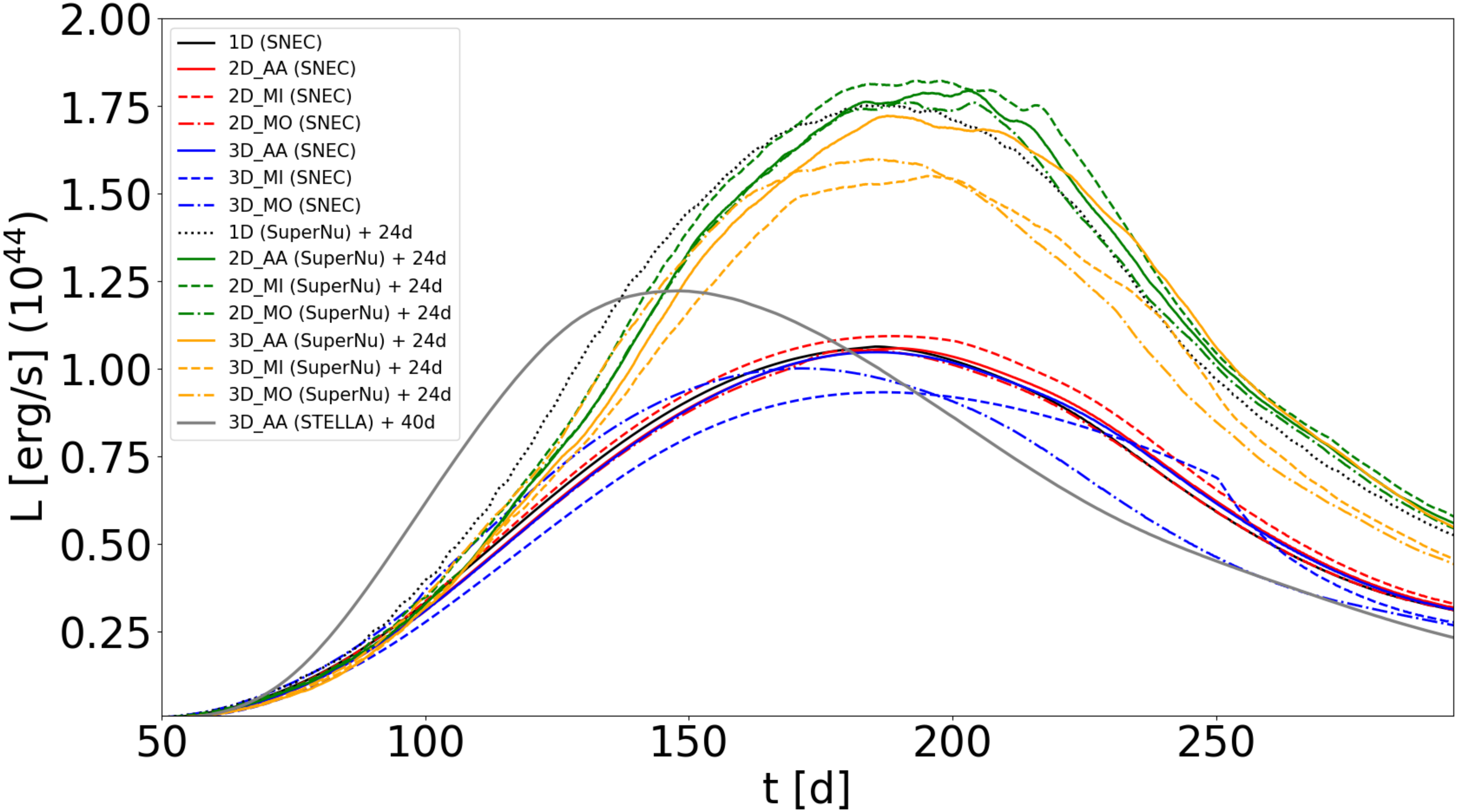
THANK YOU!

"Spectra is truth."

-Dr. Sean Couch (MSU)

QUESTIONS?

Auxiliary Slide 1



Chatzopoulos et al. (2019)