What does a Type IIP look like

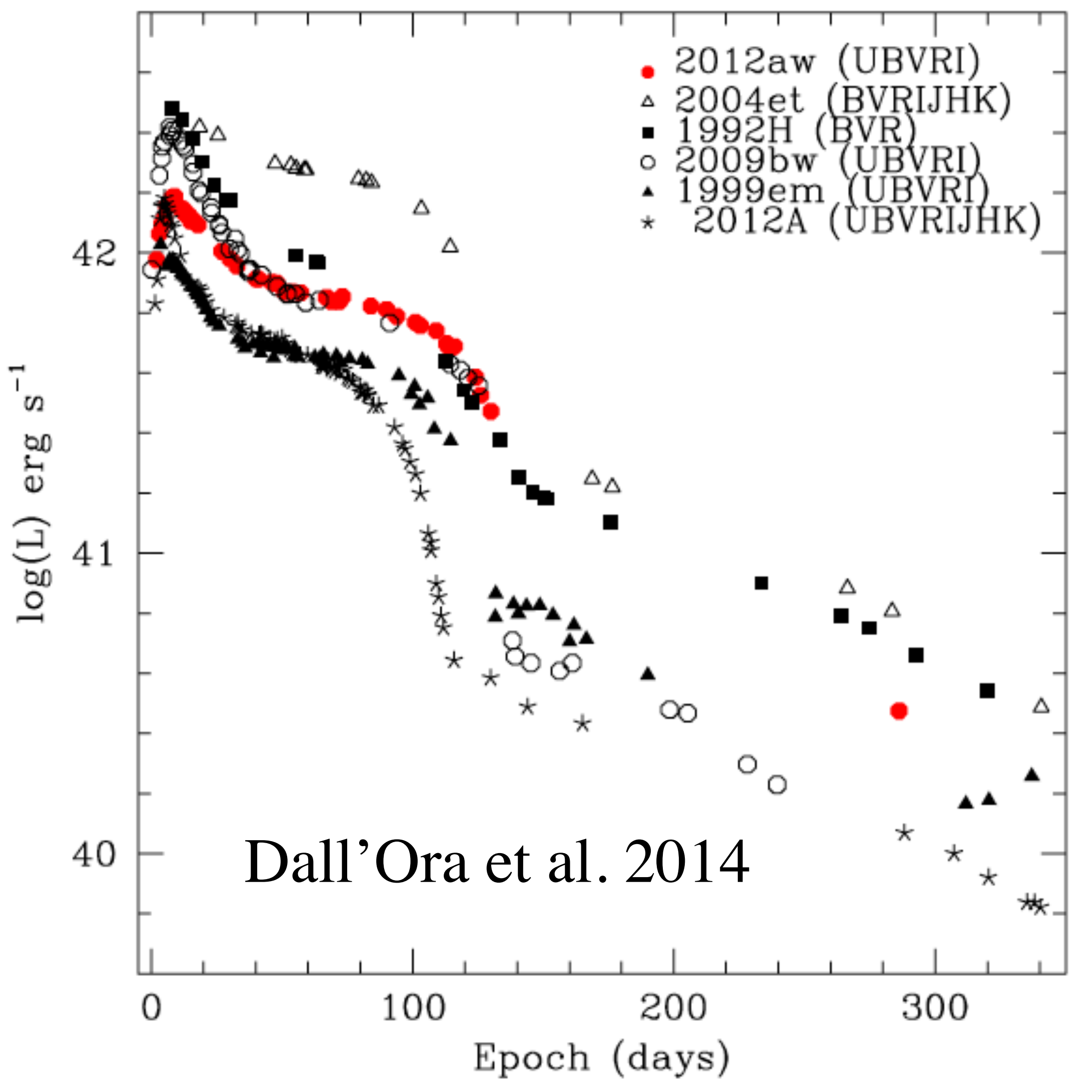
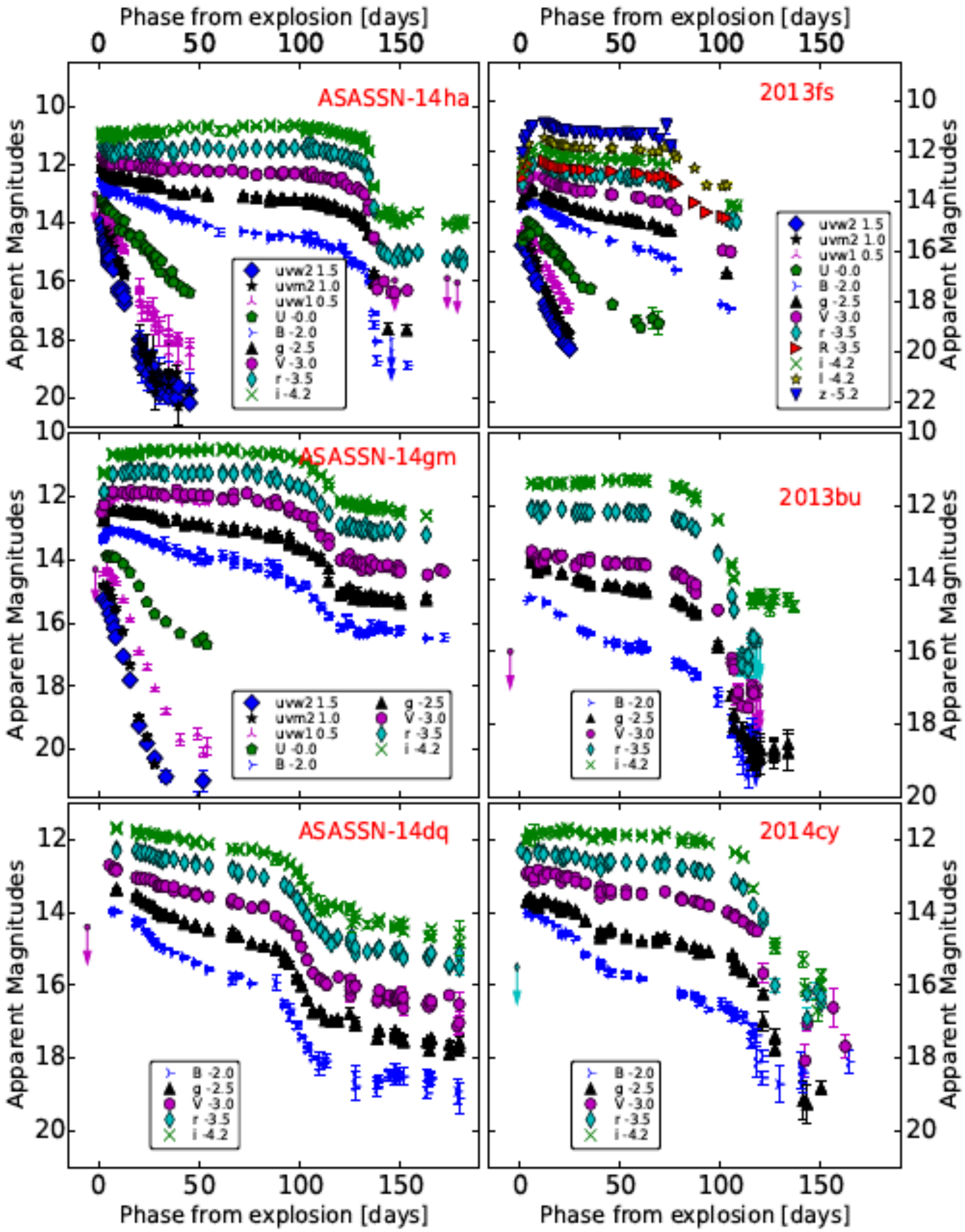


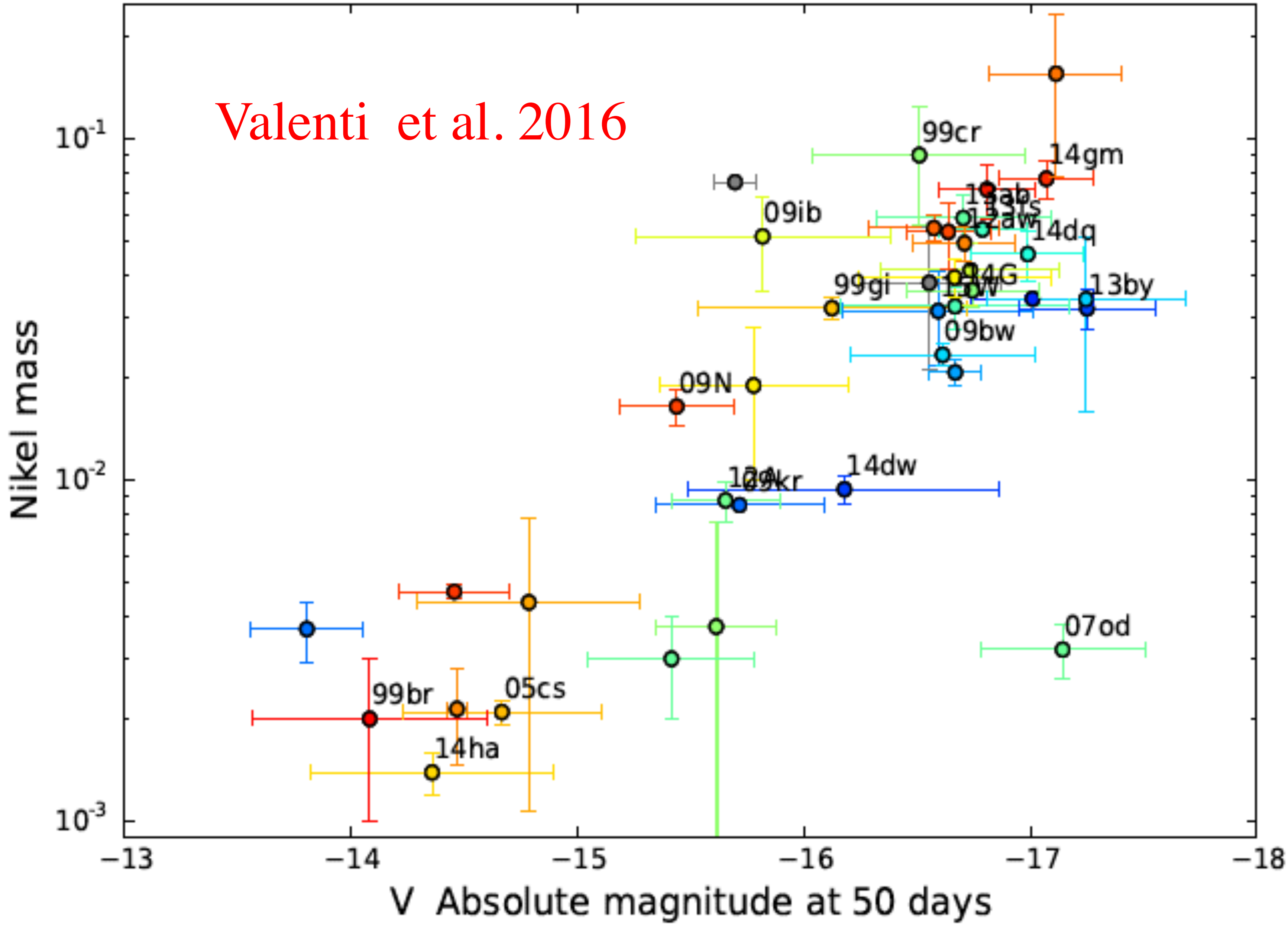
Figure 14. *UBVRI* Pseudo-bolometric light curve of SN 2012aw. The light curve is compared with the Type IIP SNe SN 1992H, SN 1999em, SN 2004et, SN 2009bw, and SN 2012A.

- Plateau phase that lasts ~100 days with H present at the photosphere
- Collapse to radioactive powered tail once the ejecta has thinned. => ^{56}Ni mass can be measured

LCO Lightcurves



Valenti et al. 2016


Valenti et al. 2016
Nikel mass
V Absolute magnitude at 50 days
10^-1
10^-2
10^-3
−13
−14
−15
−16
−17
−18
99cr
14gm
09ib
14dq
99gi
13by
09bw
09N
14dw
07od
99br
05cs
14ha

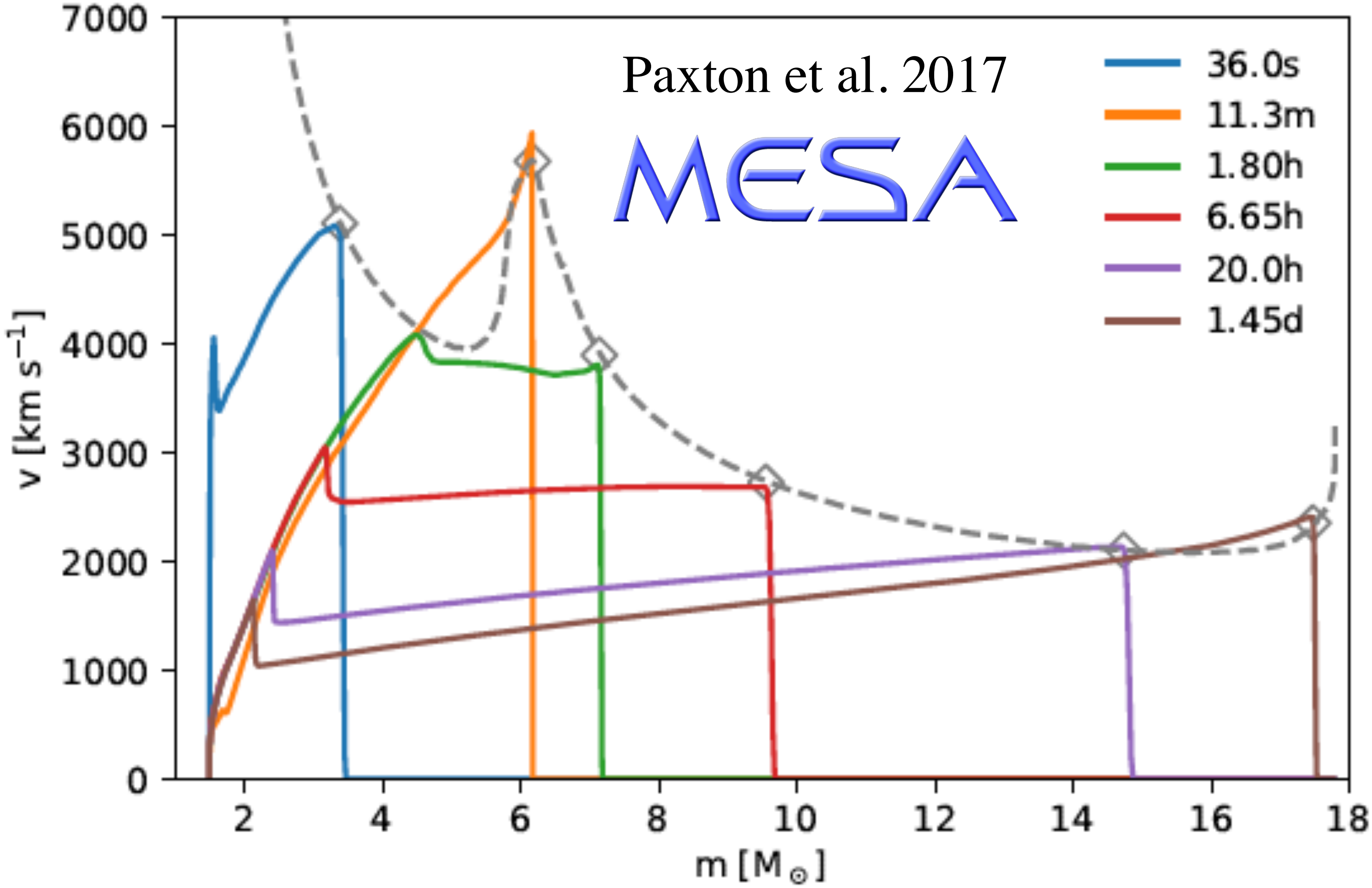
What we Wish to Learn from 100's of IIPs?

- Are the photometric and velocity data from Type IIP SNe consistent with the explosion of a red supergiant?
- Are the implied parameters (e.g. ejecta mass and radius) consistent with the expected 8-20 $M_\odot$ progenitors?
- Can reliable inferences be made of explosion energy and ^{56}Ni masses to test/probe the core collapse mechanism?

One challenging piece is modeling the impact of mixing within the ejecta due to Rayleigh-Taylor instabilities at compositional boundaries (Chevalier '76, Chevalier & Klein '78, Weaver & Woosley '80, Benz & Thielemann '90, Herant & Woosley '94; . .) Modern 3D modeling by Hammer et al. '10, and most recently by Wongwathanarat, Muller & Janka '15, and Utrobin et al. '17 yielding profound insights.

Paul Duffell (UC-Berkeley) & Bill Paxton (KITP)

Post-Shock Velocity in a Red Supergiant



Dashed line is the analytic work of Matzner & McKee ‘99

Instability and clumping in SN 1987A

E. Müller[1], B. Fryxell[2] and D. Arnett[2]

[1] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, W-8046 Garching bei München, Federal Republic of Germany
[2] Steward Observatory and Departments of Physics and Astronomy, University of Arizona, Tucson, AZ 85721, USA

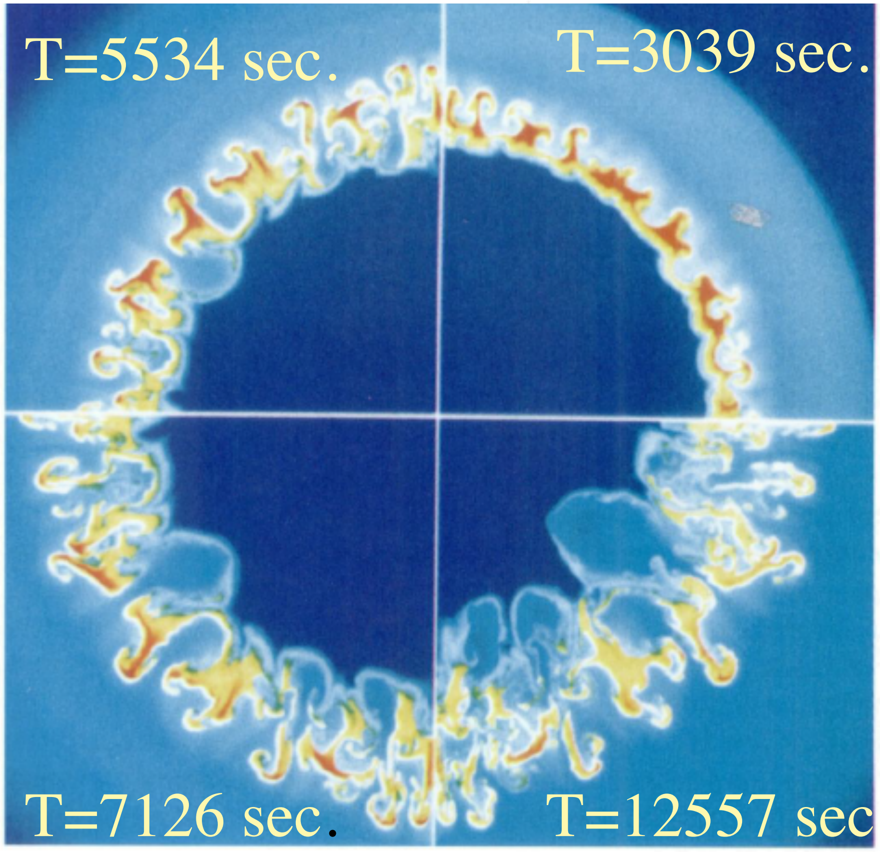


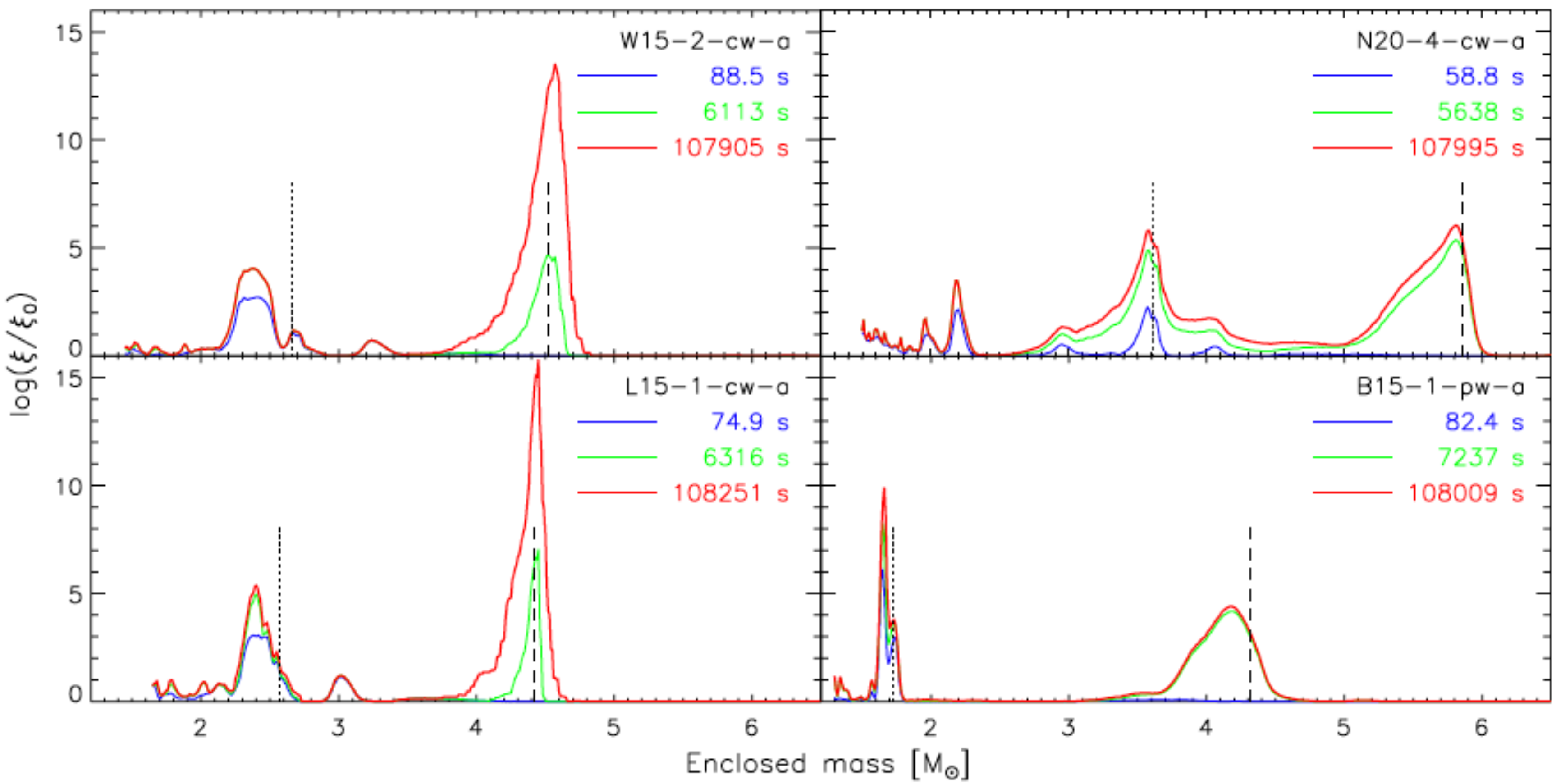
Fig. 11. Contours of partial density (total density time mass fraction) of ^{4}He at four instants during the explosion (see Table 1, which also indicates the sizes of the plots). At time t_1 (upper right), the originally spherical helium shell is beginning to break up into small clumps. At time t_2 (upper left), the helium are pushing their way outward into the hydrogen envelope, while low-density "bubbles" of hydrogen-rich material are being trapped between the fingers. These effects become even more pronounced at times t_3 (lower left) and t_4 (lower right)

- Plots show partial density of Helium in a 15 Msun star
- Penetration of Helium out into the H envelope and Hydrogen down into the interior are evident in 2D
- ^{56}Ni can be more extreme due to launching from the core. I will neglect that item today.

Unstable Profiles & Mixing

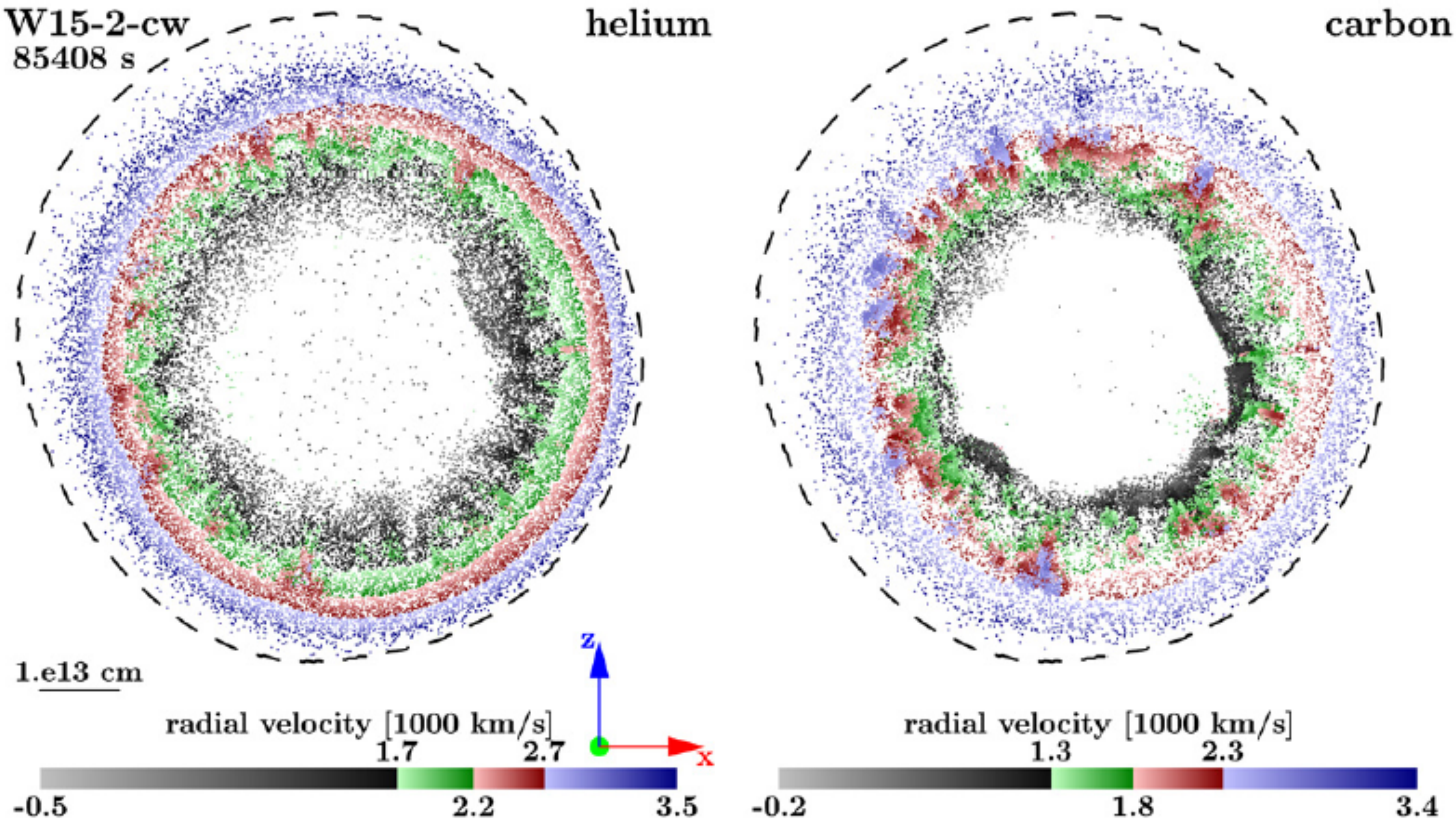
- The reverse shock leads to regions of dense Helium getting decelerated by light material.
- Many e-foldings, depending on H envelope mass

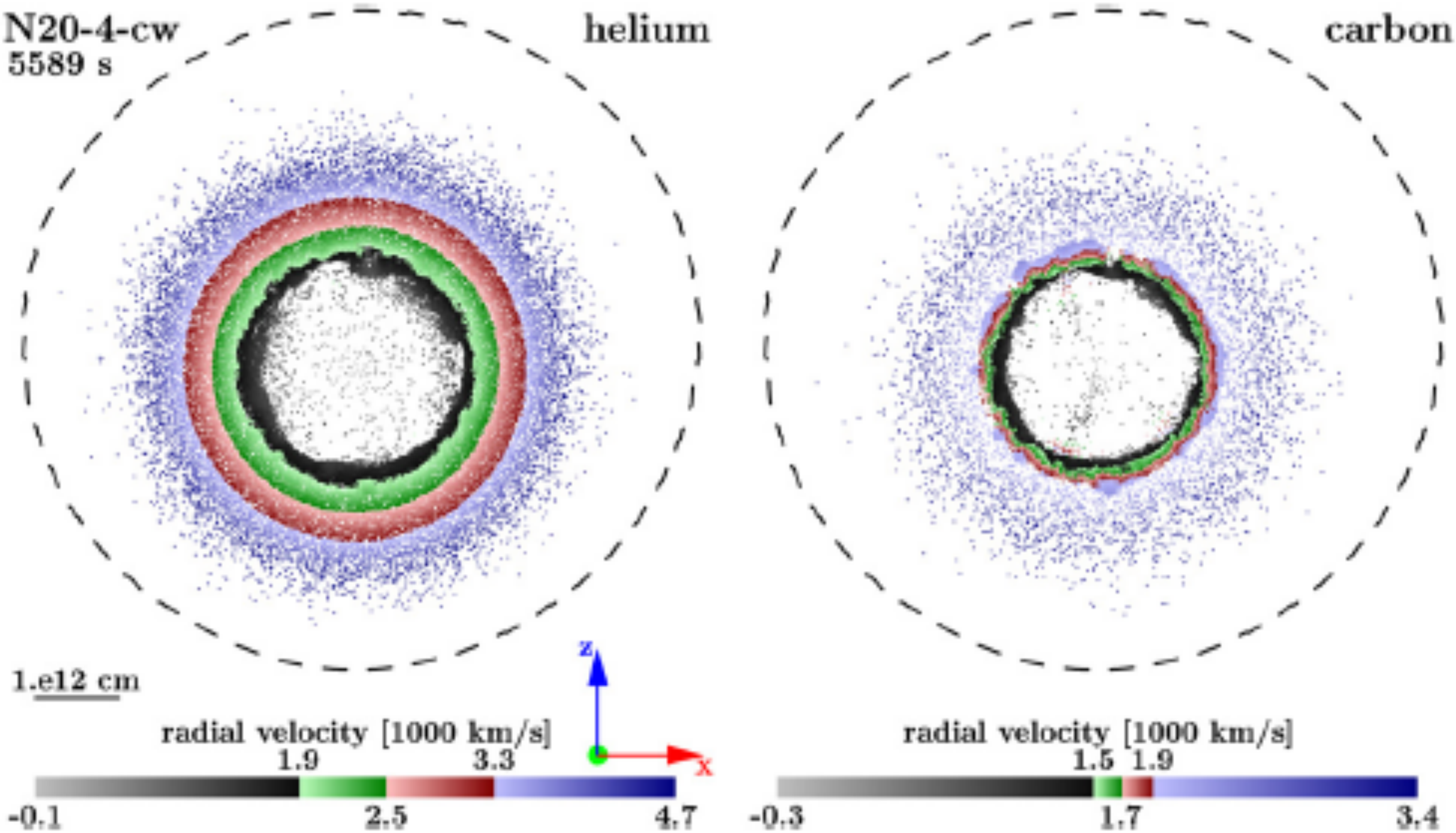
Wongwatharat et al. 2015



Three-dimensional simulations of core-collapse supernovae: from shock revival to shock breakout

A. Wongwathanarat*, E. Müller, and H.-Th. Janka

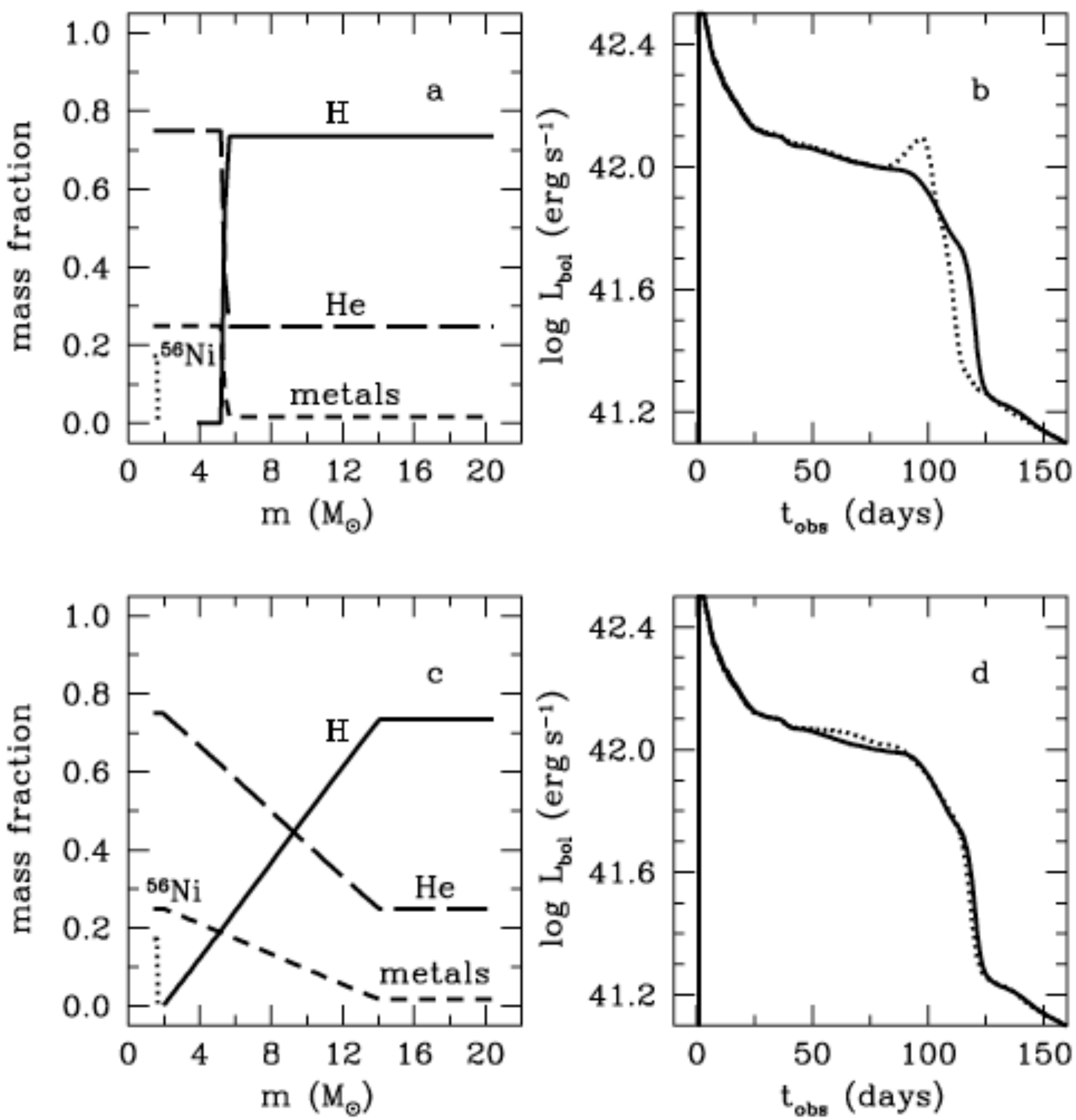




Material gets very mixed, but we can't afford a large series of 3D calculations for initial exploration of this physics for 100's of IIP SNE!

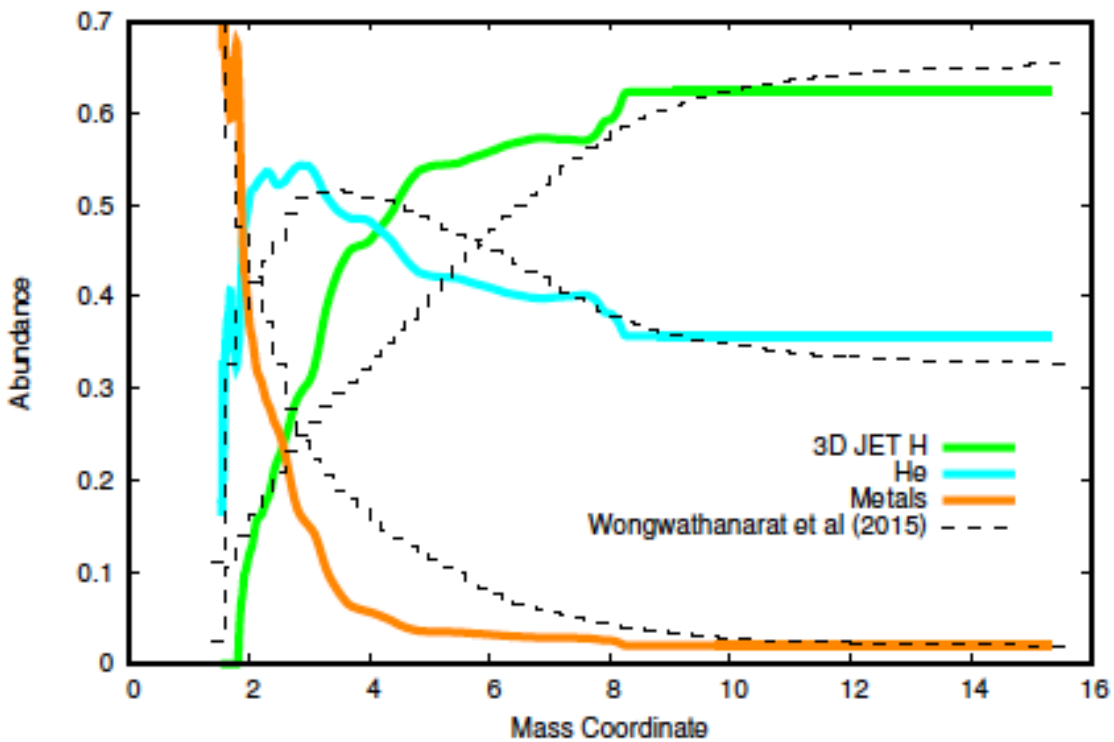
Impact of Mixing on Light-Curves

Utrobin ’07



- Tradition has been to mix ejecta composition only, guided by the numerics.
- However, no way to incorporate more or less intense mixing due to varying strength of RTI
- Density and velocities also get mixed and need to be handled in some reasonably physical manner.

Step One: Compare 3D where we Can



Duffell, LB & Paxton '17 (in prep).

- Start with 3D runs just with RTI via Duffell's JET code.
- Not exact match to progenitor, but close.
- Compare averaged quantities to Wongwathanarat's results.
- Just RTI, so metals will be off, as W15 had initial perturbations due to nickel.

Duffell's RTI in 1D (RT1D)

Duffell, 2016, ApJ, 821, 76

- Built on earlier work of Gull (1973) for supernovae remnants.
- Introduced an extra scalar variable that accounts for the strength of turbulence and is driven by the instantaneous measure of the RTI driving
- Turbulence leads to mixing and eventually decays when no RTI driving is occurring.
- Developed first for SNR, we are now applying it to ejecta evolution.

The model modifies these equations by adding an additional quantity to be evolved, α, which grows in unstable regions and provides diffusive fluxes to the hydrodynamical evolution:

$$\partial_t(\rho) + r^{-2}(r^2(\rho v - \eta\rho'))' = 0 \tag{8}$$

$$\partial_t(\rho v) + r^{-2}(r^2(\rho v^2 + P - \eta(\rho v)'))' = 2P/r \tag{9}$$

$$\partial_t(\epsilon_{\rm tot}) + r^{-2}(r^2((\epsilon_{\rm tot} + P)v - \eta\epsilon'_{\rm tot}))' = 0 \tag{10}$$

$$\partial_t(\rho X_i) + r^{-2}(r^2(\rho X_i v - \eta(\rho X_i)'))' = 0 \tag{11}$$

$$\partial_t(\rho\alpha) + r^{-2}(r^2(\rho\alpha v - \eta(\rho\alpha)'))' = S_\alpha. \tag{12}$$

The diffusion constant, η, is given by

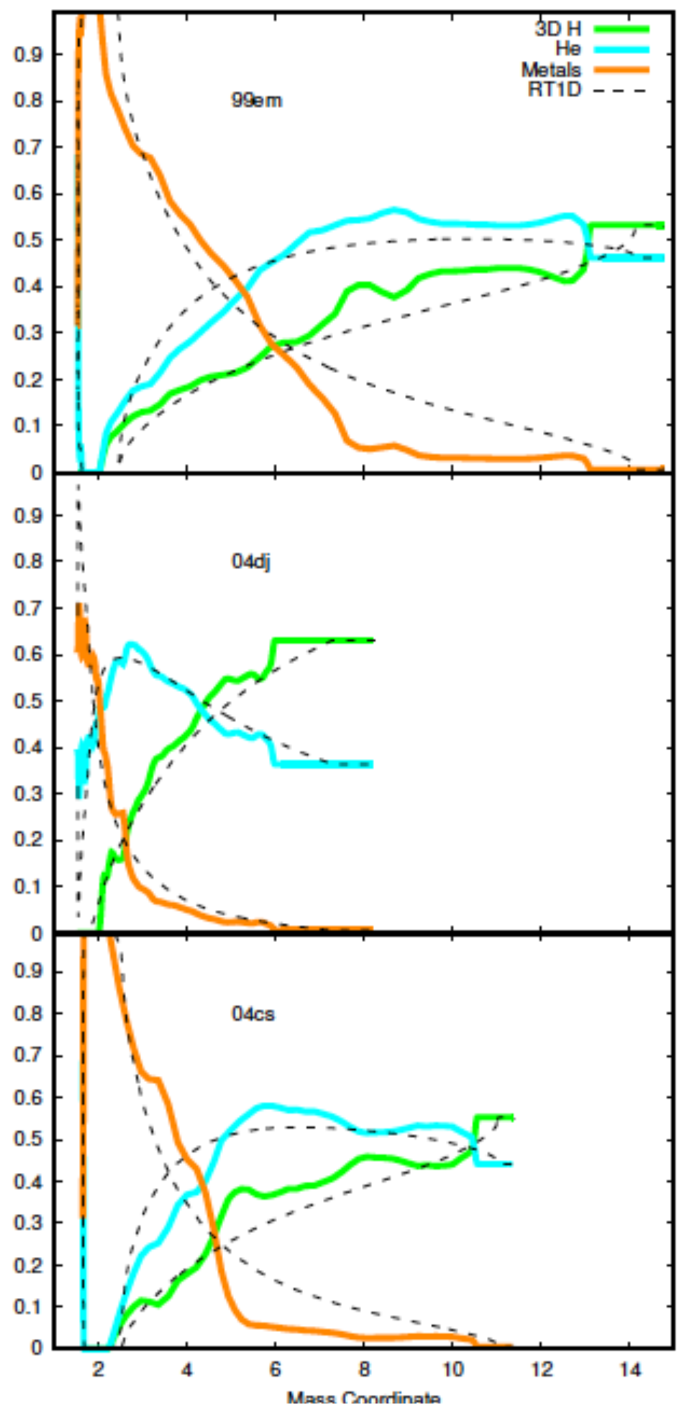
$$\eta = C\alpha c_s r, \tag{13}$$

where c_s is the local sound speed. The source/sink term for α is given by

$$S_\alpha = (A + B\alpha)\sqrt{\max(-P'\rho', 0)} - D\rho\alpha c_s/r. \tag{14}$$

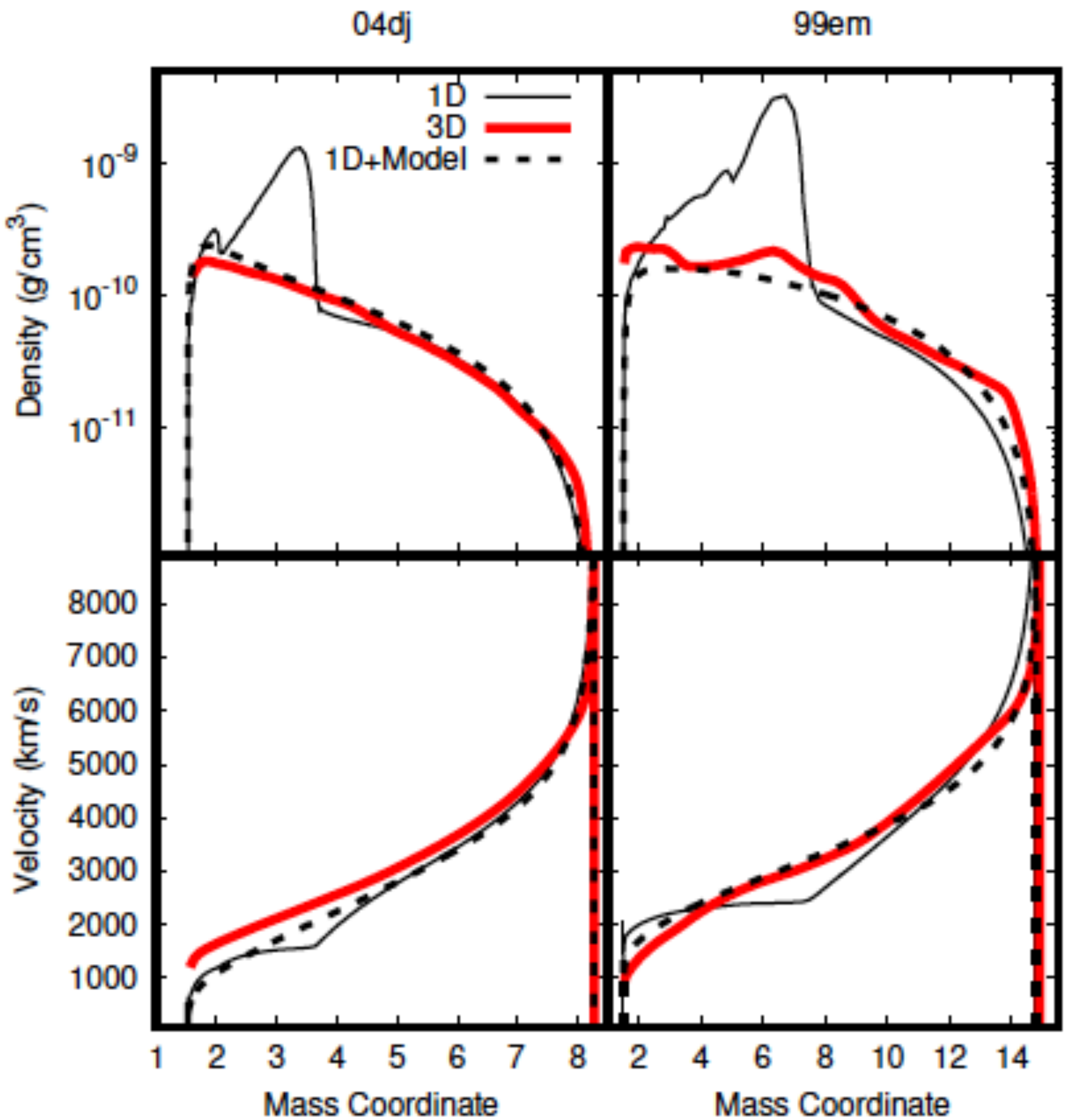
Duffell, LB & Paxton '17 (in prep).

Duffell, LB & Paxton '17 (in prep).



- Calibrate A,B,C,D on toy problem of explosion from Duffell '16
- Then check how well those frozen settings perform by doing full 3D runs of various SNe models.
- Plot on left shows the results, where the SNe name is really just indicative of different progenitor scenarios.

Density and Velocity Profiles at Breakout



Duffell, LB & Paxton ‘17 (in prep).

- 1D is the normal 1D model, no RTI
- 3D is the JET run
- 1D+Model is a 1D run including mixing from RTI.
- Also changes the density slope and hence can impact line shapes

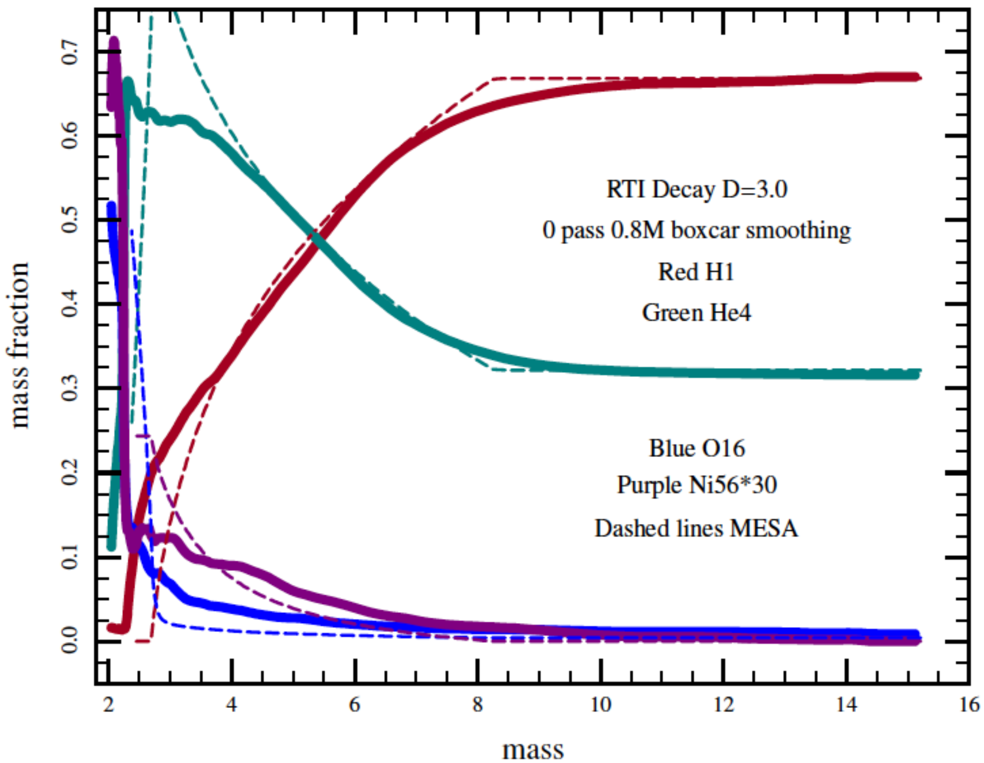
MESA Implementation of RTI

- Paxton developed the MESA implementation of RT1D for the Lagrangian code.
- Comparisons made between MESA and RT1D, and parameters then FIXED.
- Annop gave us more data, allowing for comparisons of MESA's 1D RTI to full 3D
- All of this is work underway, and preliminary.
- Goal is to incorporate 3D outcomes in a 1D code adequate for initial exploration of broad parameter space of Type IIPs

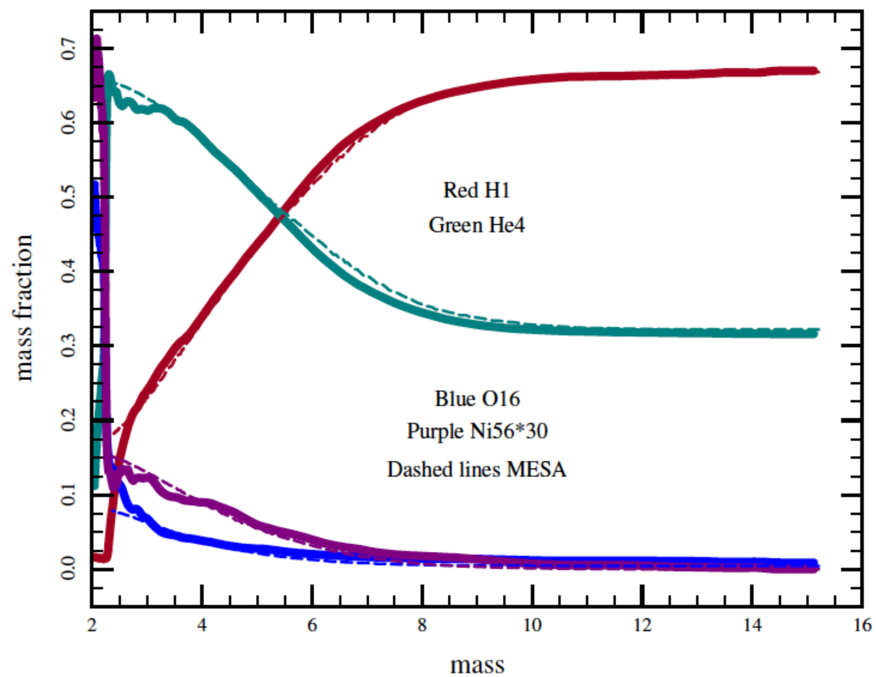
MESA Compare to Munich L15

Thanks Annop!!!

Straight comparison



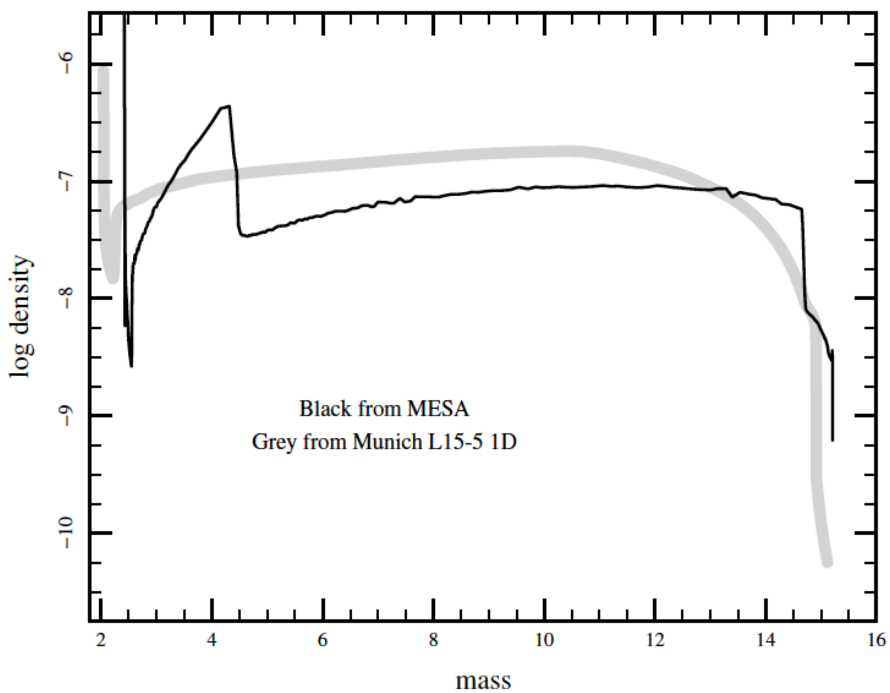
Boxcar Smooth MESA



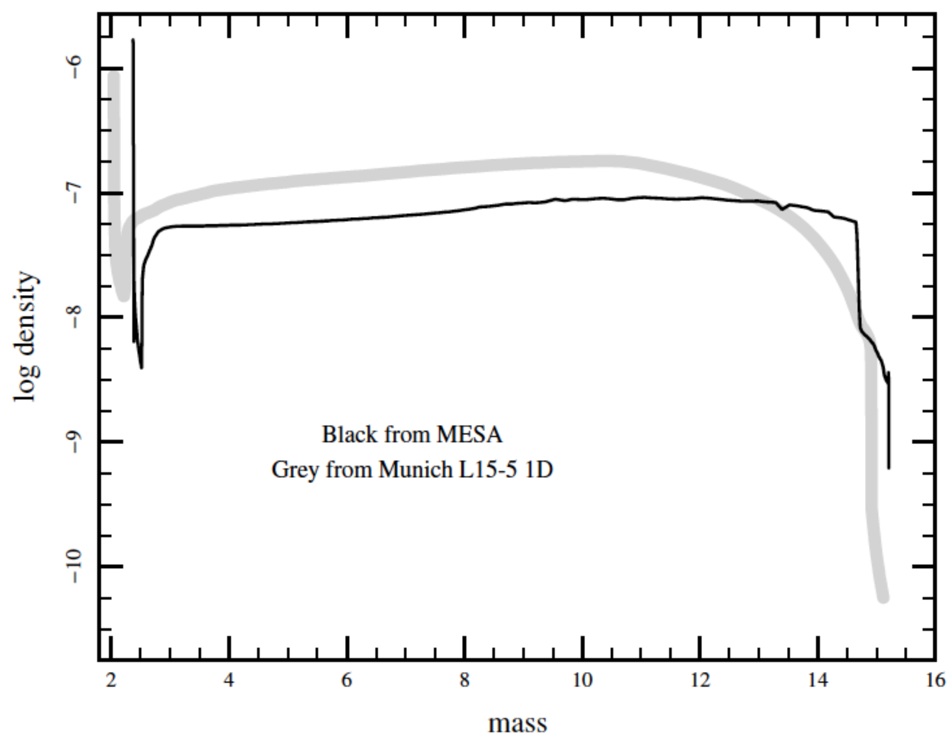
Density Profiles Near Breakout

Thanks Annop!!!

No RTI Implemented

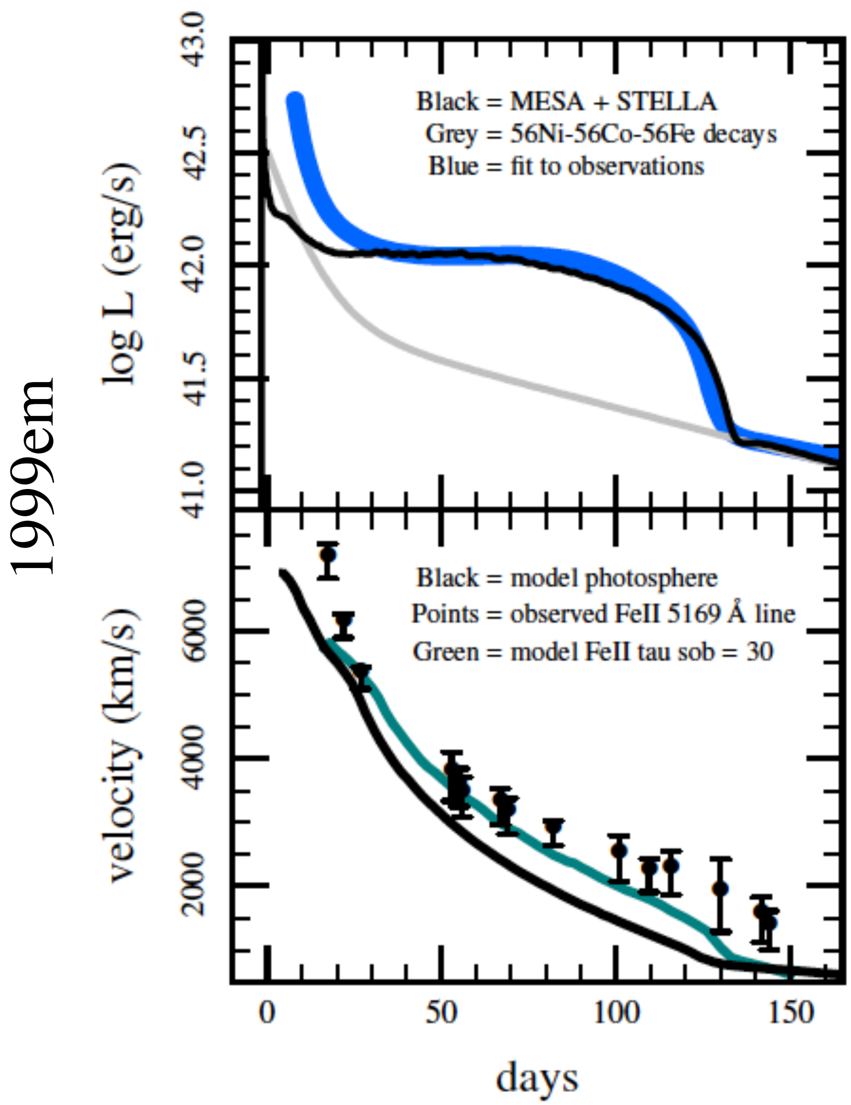


RTI Turned on. . No dials



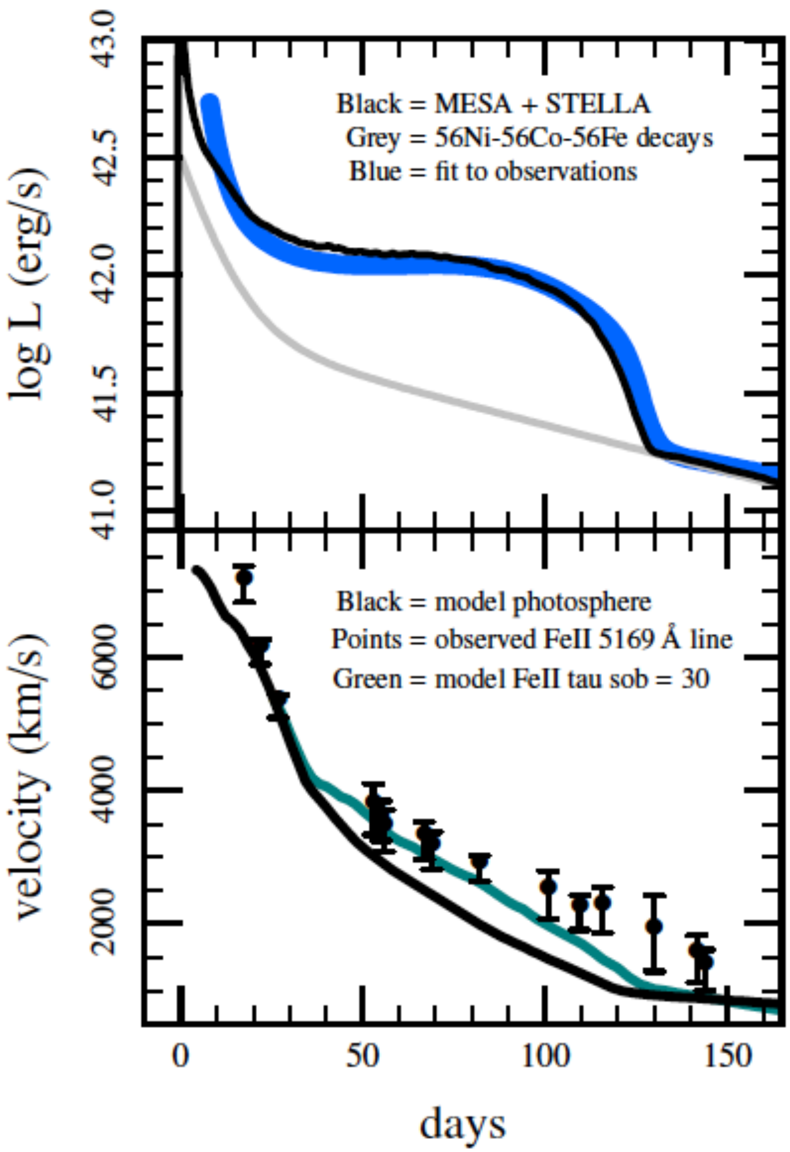
MESA+STELLA

Thanks Sergei and Elena !!!



- Handoff to STELLA done just before breakout
- That inhibits further RTI, but most mixing is complete by then.
- Advantage is that STELLA does not assume homology, and does far better radiative transfer than MESA simple diffusion.

Alternative 16 Solar Mass Model



- Previous model was built from Utrobin's original 19 solar mass model.
- Can also get a good fit with a 16 solar mass model, little bit less energy.
- Lack of progenitor implied < 15 Msun…
- CSM added to get early luminosity right.

Summary of new Capabilities

- Developed a new ability to incorporate the impact on 1D SNE ejecta of RTI mixing, both for composition as well as density and velocity
- Will continue to check 1D against all available 3D models as they are available. Doing same progenitors will help a lot! Thanks Annop!
- Lightcurves now obtained in 1D via a MESA handoff to STELLA. SEDONA (D. Kasen) comparisons coming
- GOAL is to use these MESA+STELLA capabilities to model Type IIP SNE lightcurves, initiating the process of diagnosing progenitors + explosions.
- Actively writing MESA IV paper. . . Stay tuned!