Type IIP Supernovae: Inferring Explosion Energies and Ejecta Masses

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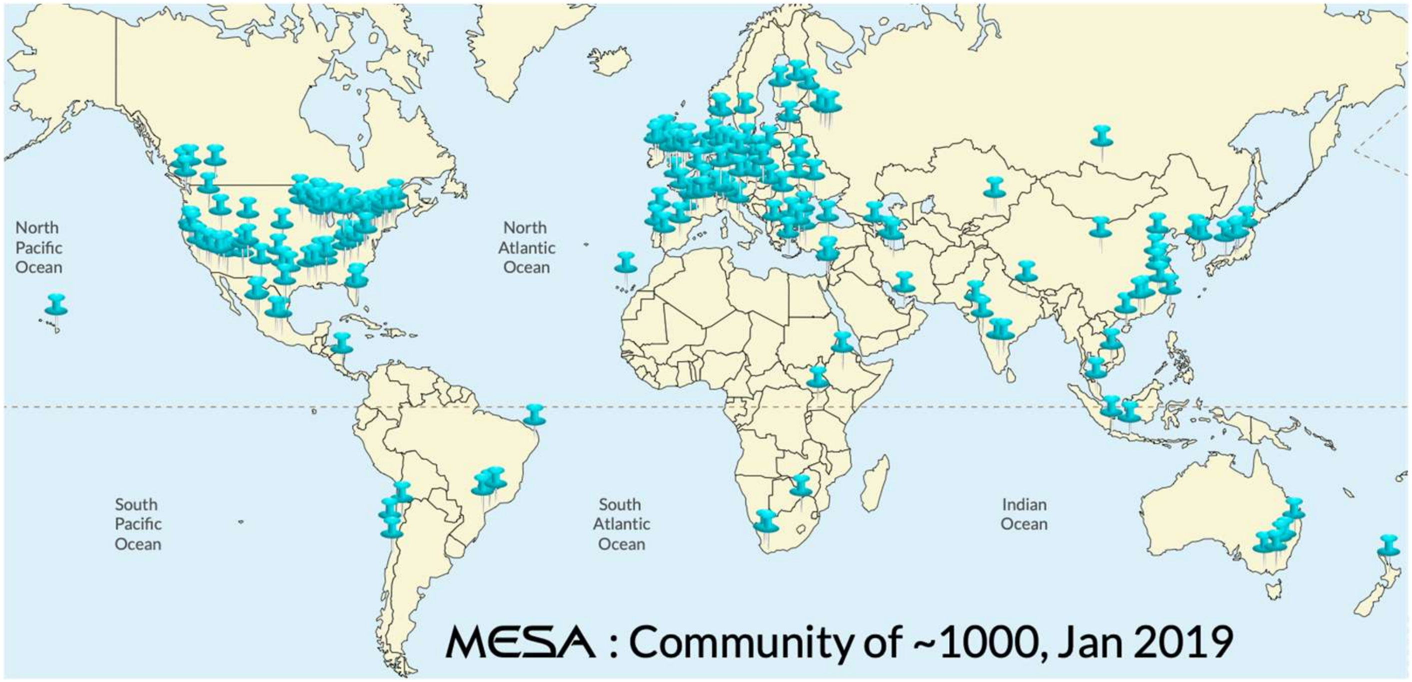

MESA : Community of ~1000, Jan 2019

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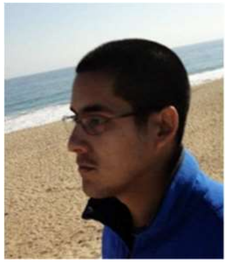

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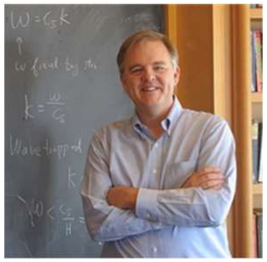

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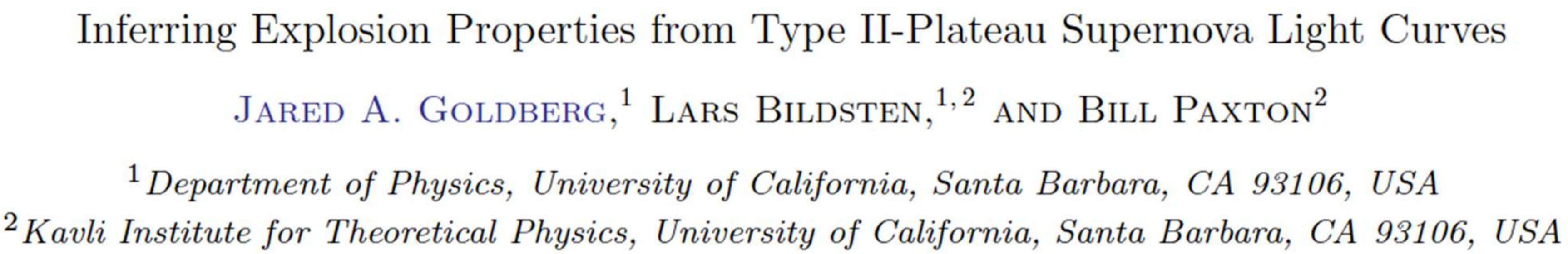
Three Recent Papers

- Two MESA ``Instrument" papers (Paxton et al. 2018 and Paxton et al. 2019)
- Recent paper led by Jared Goldberg (Ap J, accepted, on Arxiv)



Inferring Explosion Properties from Type II-Plateau Supernova Light Curves

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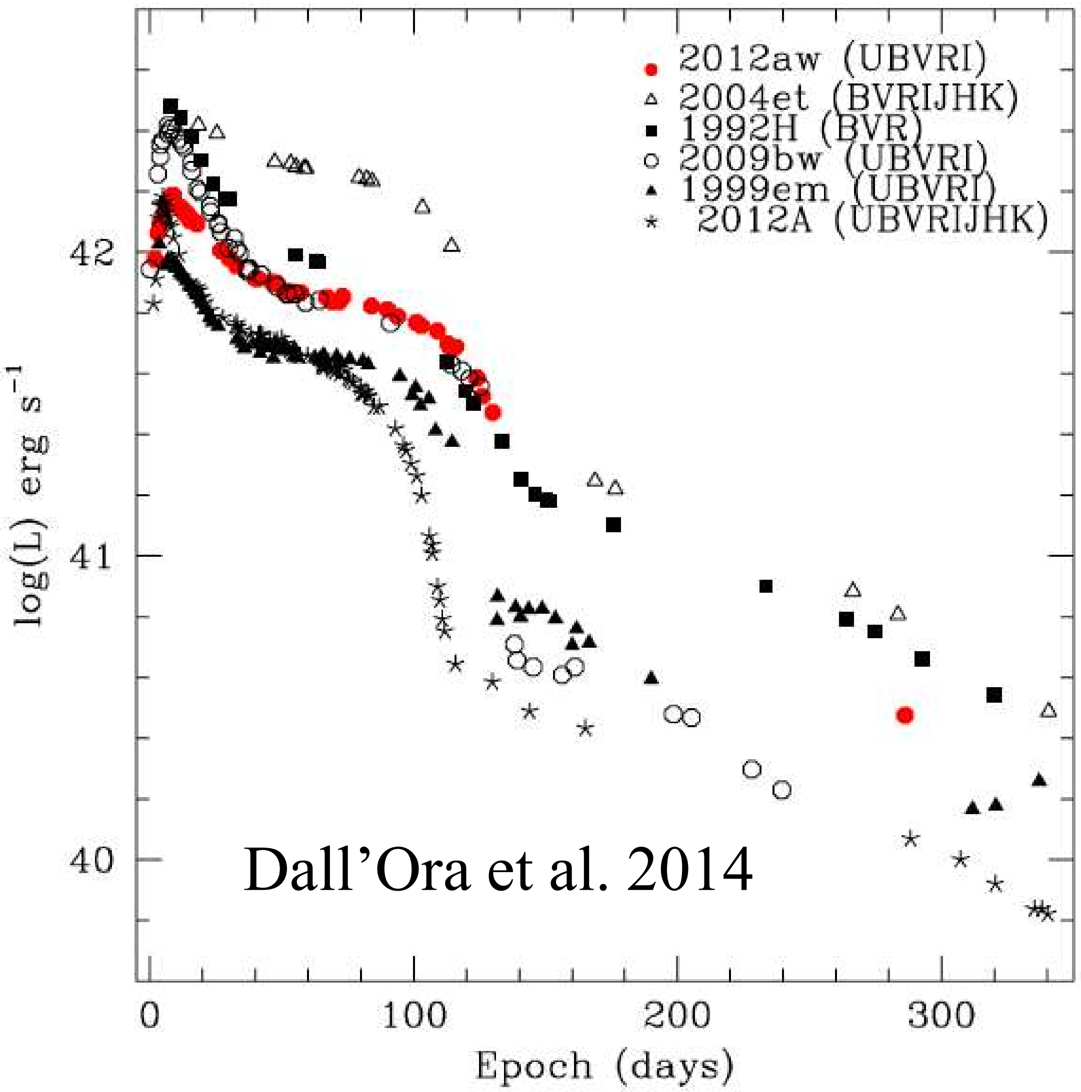
What does a Type IIP look like?

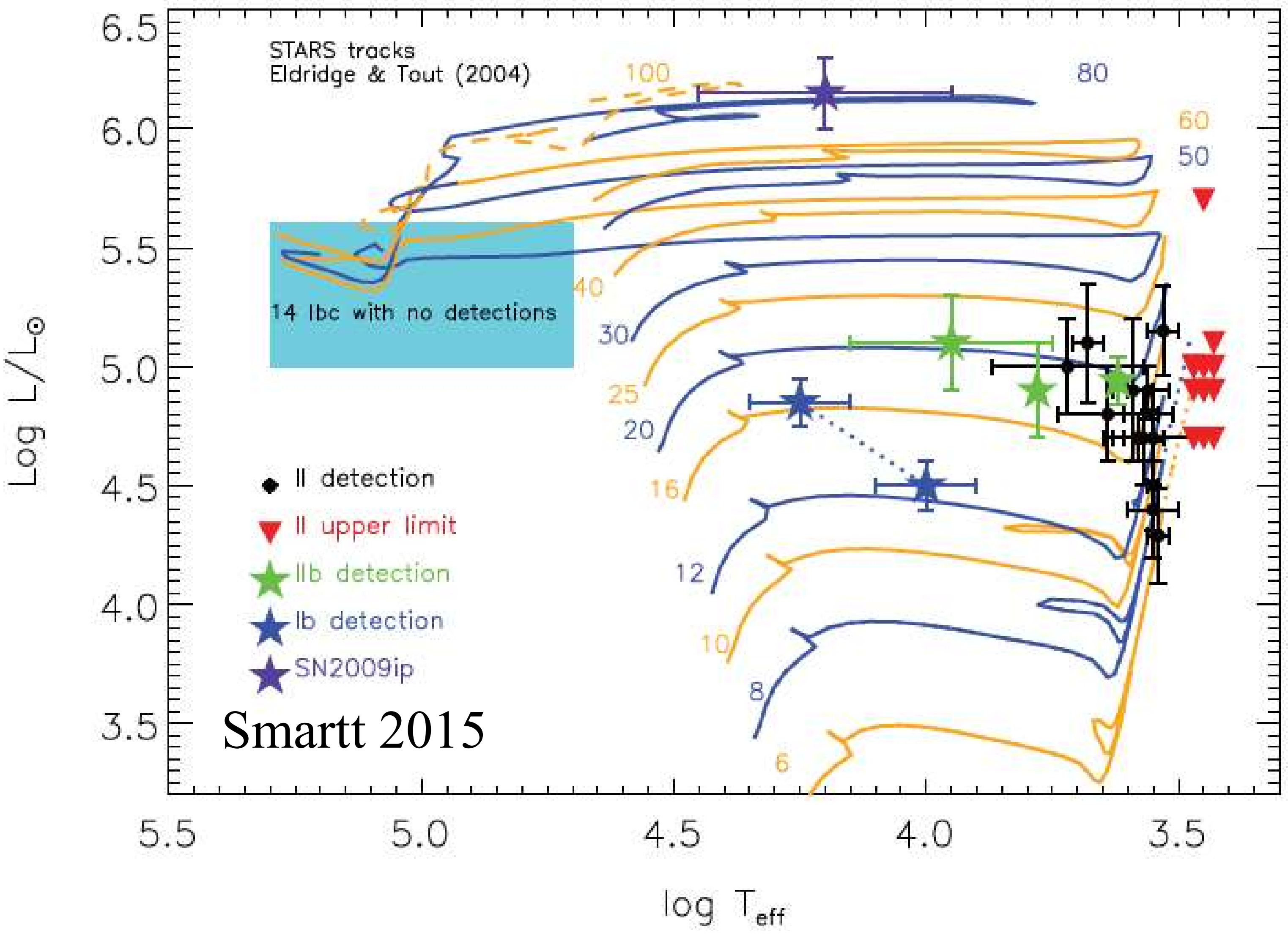


Dall'Ora et al. 2014

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

Progenitors studied in Nearby Galaxies



Smartt 2015

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

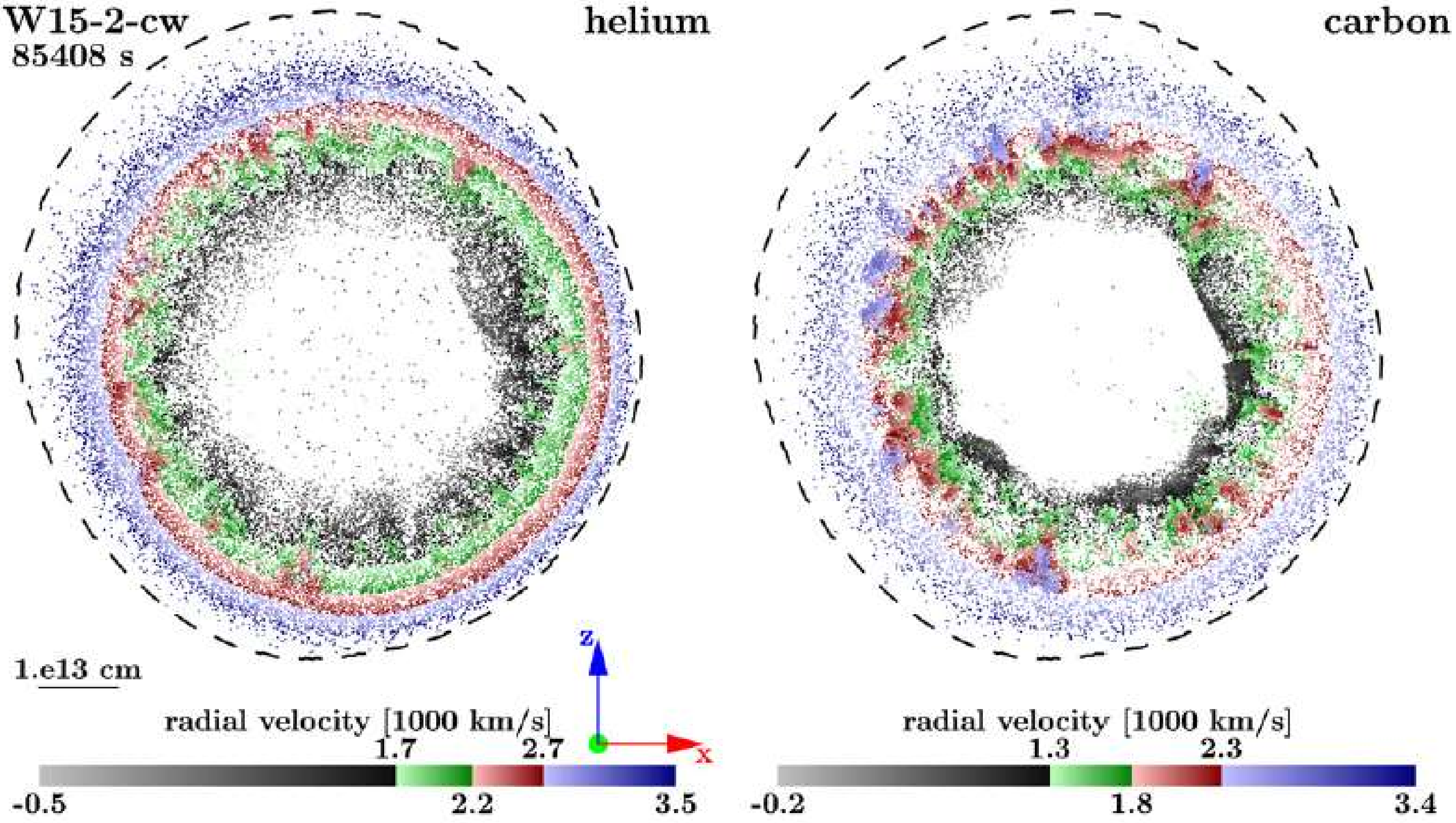
- Are the photometric and velocity data consistent with the explosion of a red supergiant?
- Are the implied parameters (e.g. ejecta mass and radius) consistent with the expected 8-20 $M_\odot$ progenitors?
- Can reliable inferences be made of explosion energy and ^{56}Ni masses to test/probe the core collapse mechanism?
- For any given event, can we uniquely determine the explosion energy, ejecta mass and progenitor radius just from the light-curve?

Type IIP Supernovae Modeling

- Accurate modeling of the shock wave propagation in the progenitor structure and subsequent expansion, light curves and velocities now possible with MESA+STELLA (Paxton et al 2018, 2019).
- One challenging piece was modeling the impact of mixing within the ejecta due to Rayleigh-Taylor Instabilities (RTI) 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.

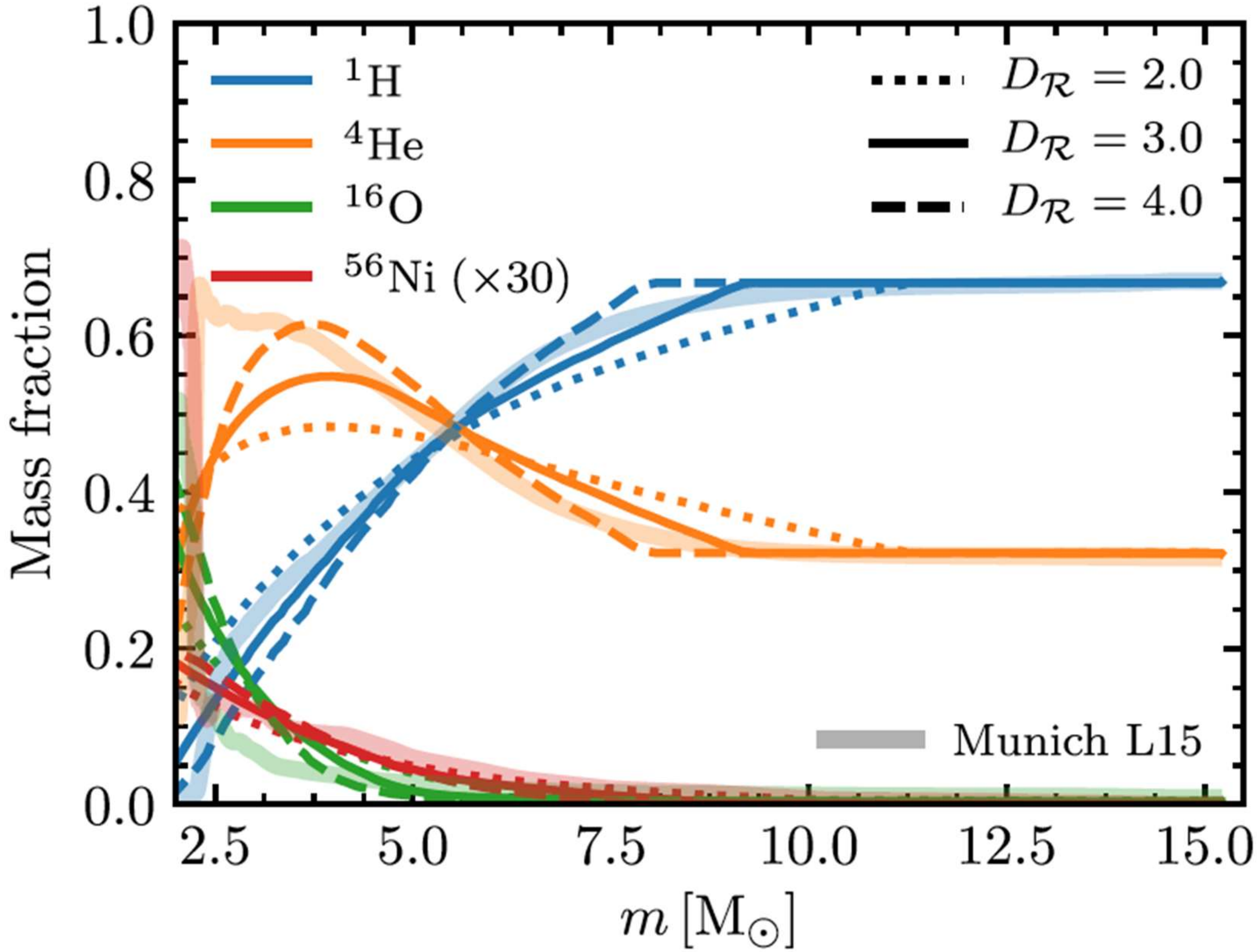
Three-dimensional simulations of core-collapse supernovae: from shock revival to shock breakout

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



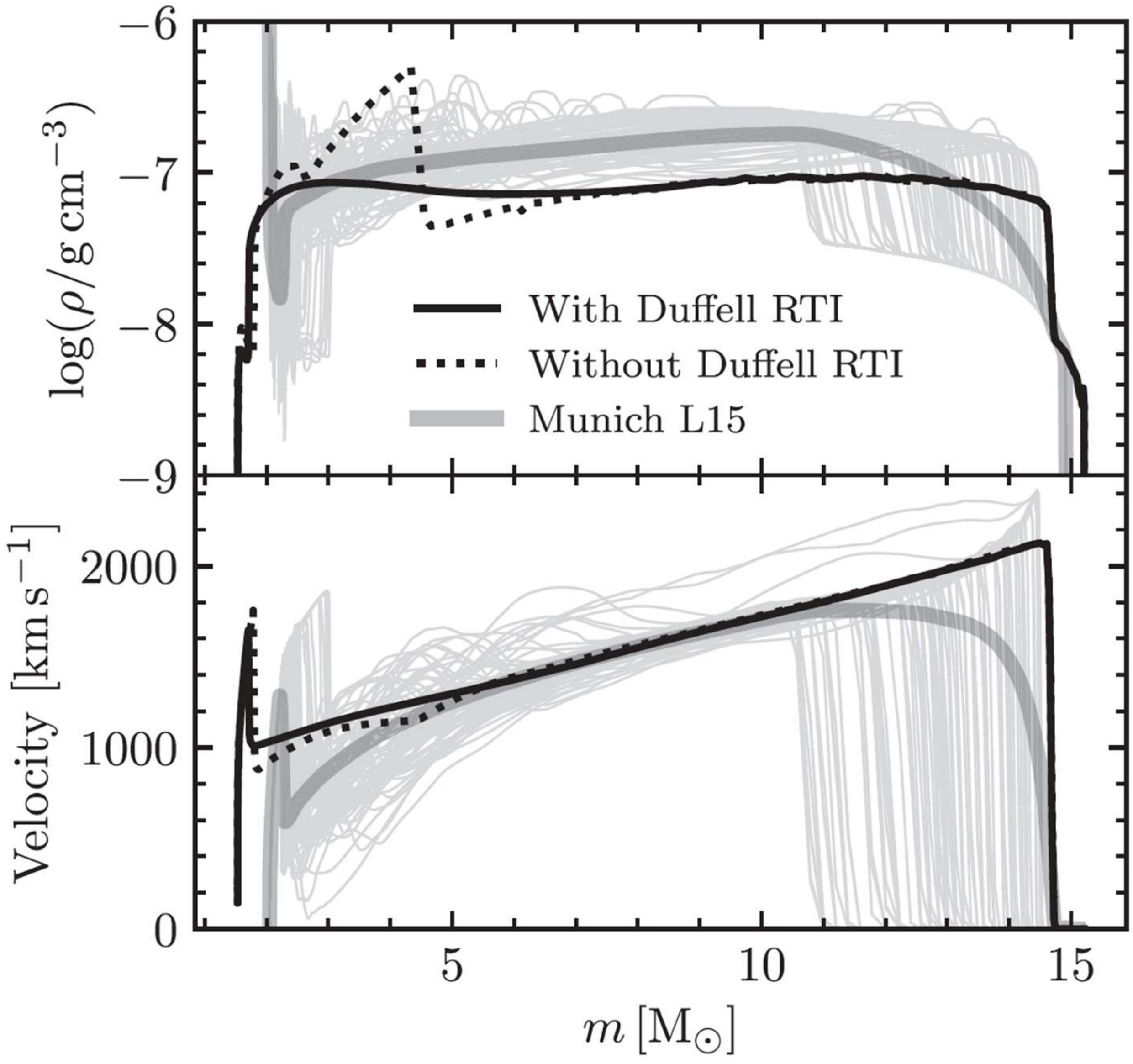
Duffell RTI in MESA

Paxton et al. 2018



Mixing Reshapes the Ejecta!

Paxton et al. 2018



Why MESA+STELLA?

- 1D models allow us to simulate an **ensemble of events** across parameter space in a reasonable amount of time.

- MESA now contains a prescription for mixing via the **Rayleigh-Taylor instability** (Duffell 2016) calibrated to 3D simulations.

- STELLA (Blinnikov+ ‘98, Blinnikov & Sorokina ‘04, Baklanov+ ‘05; Blinnikov+’06) employs multi-group (**frequency-dependent**) radiative transfer, so we can produce more accurate bolometric light curves.

- **Open source code** allows for widespread access, collaboration, transparency, and reproducibility of results.

What can we infer from Observations?

- Detailed analytics with simplified ejecta models (Popov ‘93) give scaling relationships between explosion properties and observables (See also: Kasen & Woosley ‘09, Sukhbold et al. ‘16, etc.)
- Luminosity at Day 50

$$L_{50} \propto M_{\rm ej}^{-1/2} E_{\rm exp}^{5/6} R^{2/3}$$

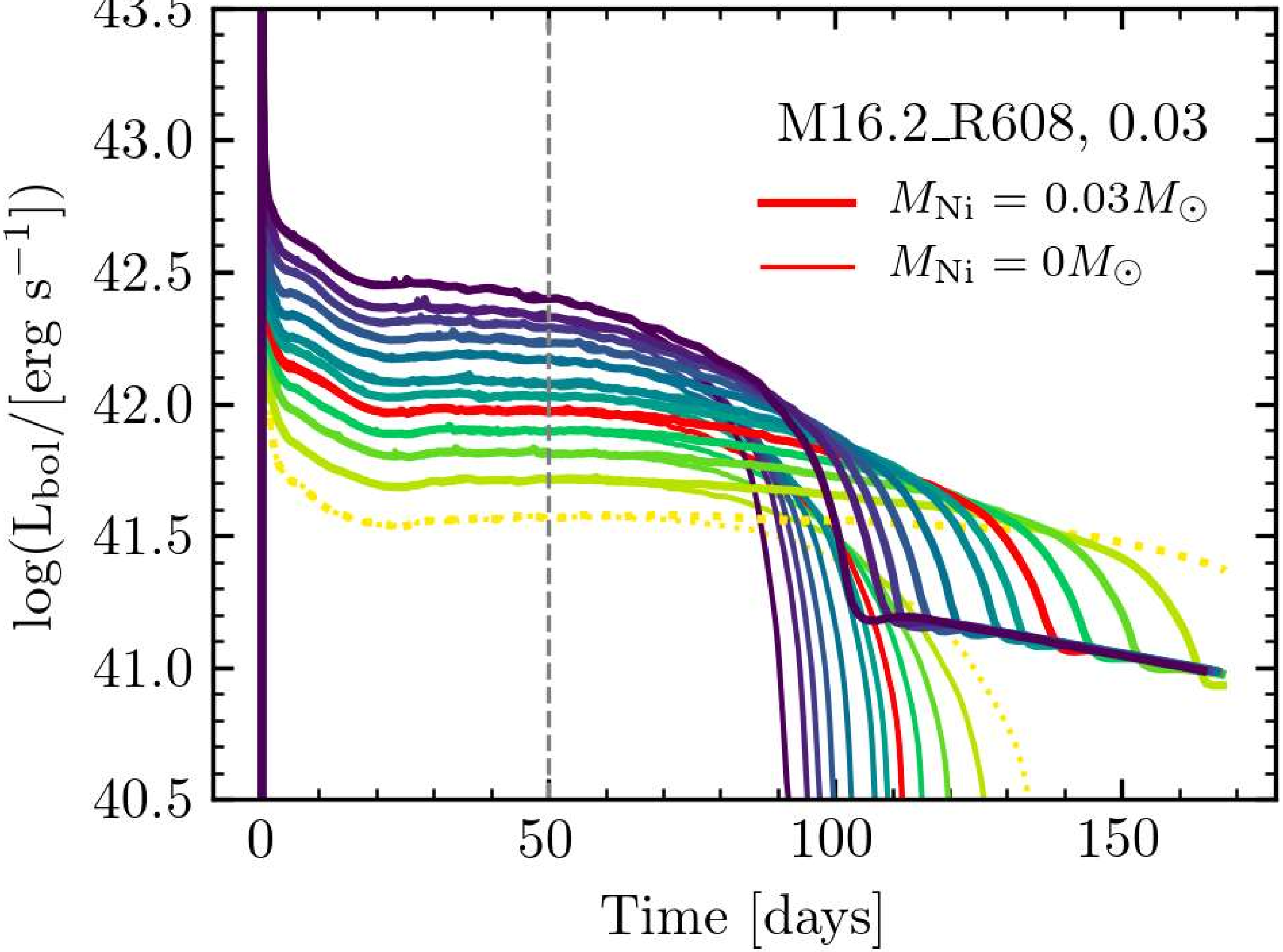
- Duration of plateau (without Nickel)

$$t_{\rm p} \propto M_{\rm ej}^{1/2} E_{\rm exp}^{-1/6} R^{1/6}$$

Our models

- Modeling these events is done in 3 steps:
  - 1) **Build the progenitor star** using MESA
  - 2) Blow up the progenitor star in MESA and **run until shock breakout.**
  - 3) **Model light curves** using the radiation hydro code STELLA (public version).
- (See Section 6 of the 4th MESA paper (Paxton et al 2018))
- We constructed a number of progenitor models, choosing 6 unique progenitors as our "standard suite" to attain sufficient dynamic range in radius and ejecta mass, and exploded them with many explosion energies and nickel masses.

Luminosity at Day 50



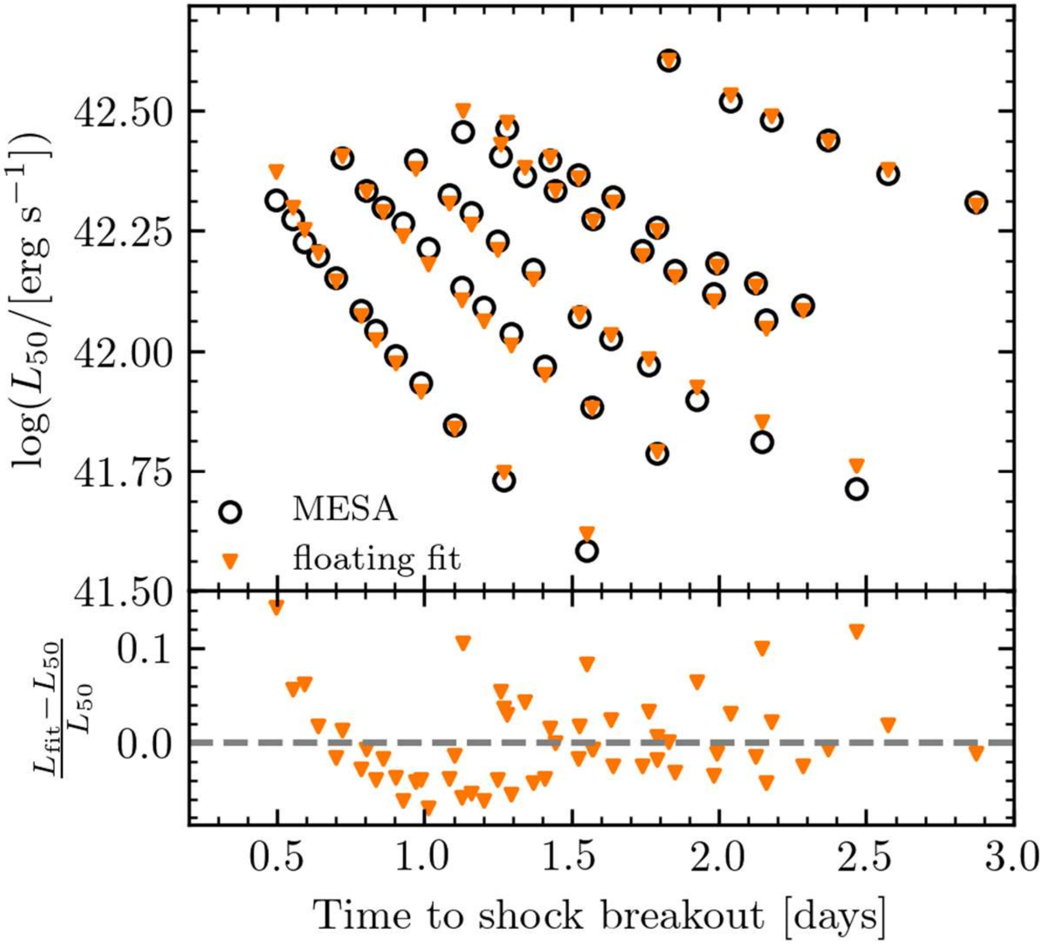
Goldberg, LB & Paxton 2019

Recovering Scaling Relations

- Assuming a power law and letting the exponents float, we get $L_{50} = 10^{42.16}\, M_{10}^{-0.40} E_{\rm foe}^{0.74} R_{500}^{0.76}\ {\rm erg/s}$

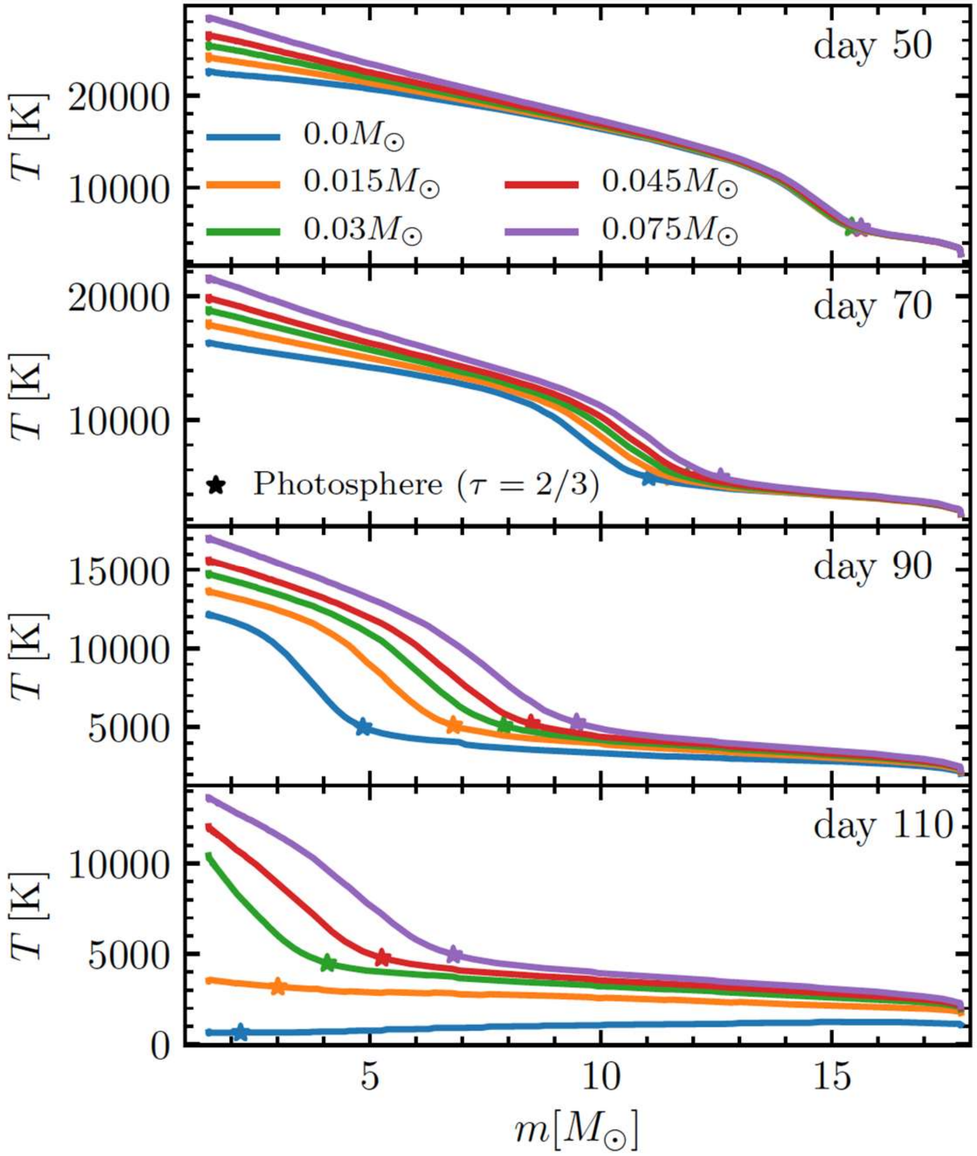
- RMS errors are 5%
- Popov had:

$$L_{50} \propto M_{\rm ej}^{-1/2} E_{\rm exp}^{5/6} R^{2/3}$$



Nickel Heating

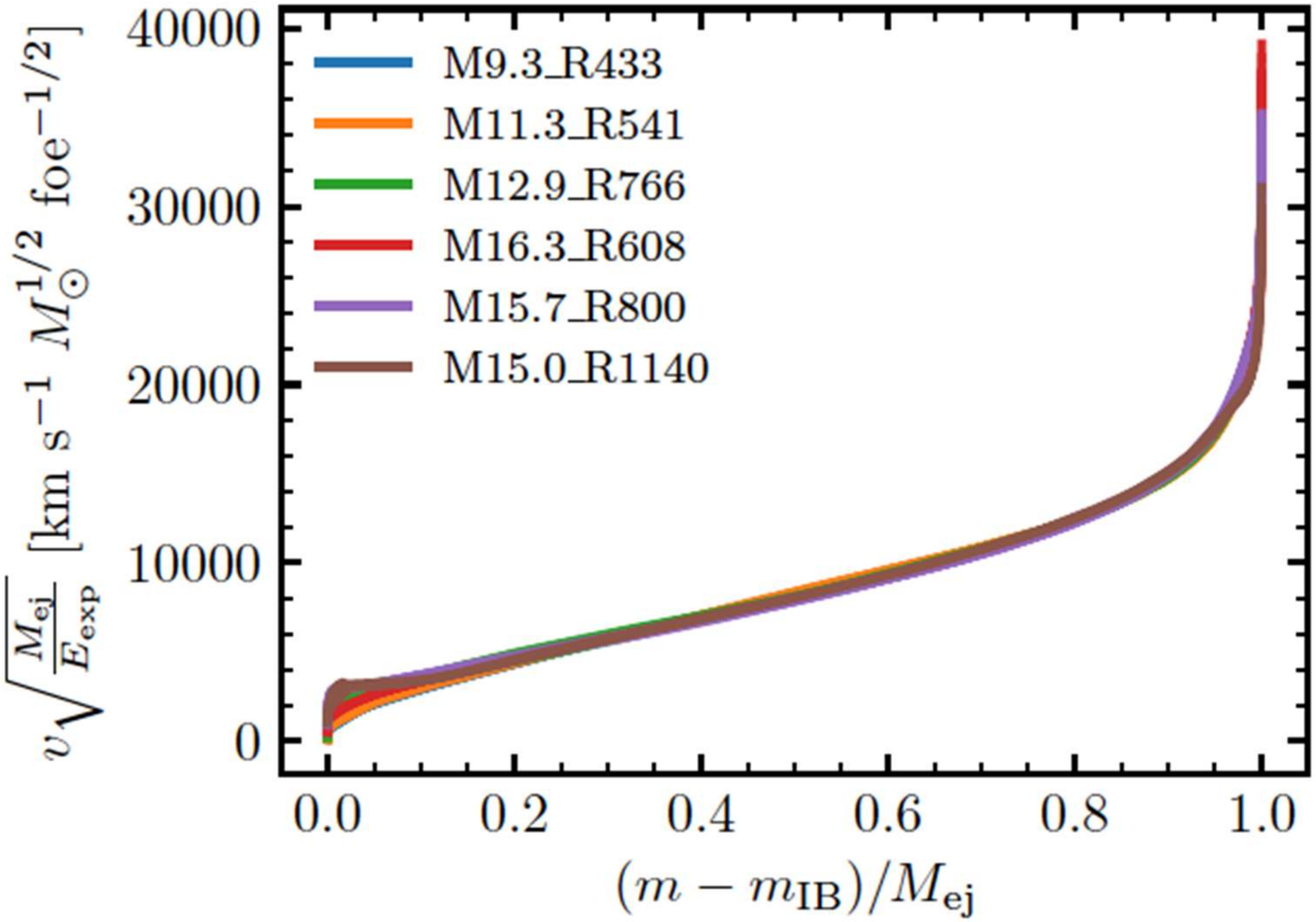
- Accumulated heating from ^{56}Ni decay gets trapped within the inner ejecta, raising its temperature and extending the plateau.
- This can be expressed analytically as in Kasen & Woosley 2009; Sukhbold+2016; Nakar+16; Kozyreva+18
- Our new fit for ^{56}Ni rich (>0.03 $M_\odot$) events is



$$t_{\rm p} \approx 112\,{\rm days}\left(\frac{M_{\rm Ni}}{0.1M_\odot}\right)^{0.14}\left(\frac{M_{\rm ej}}{10M_\odot}\right)^{0.41}\left(\frac{E_{\rm exp}}{10^{51}{\rm ergs}}\right)^{0.28}$$

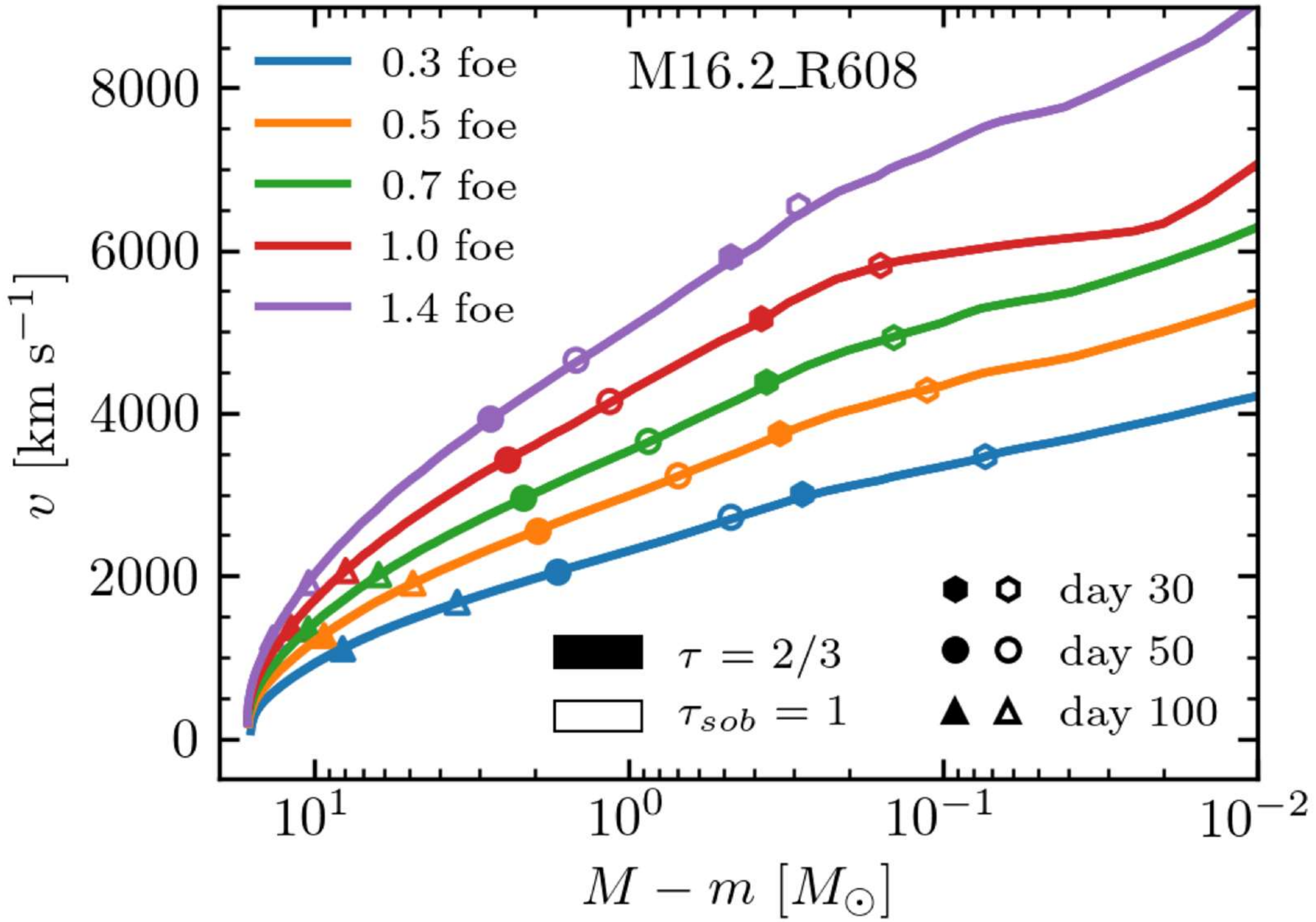
Velocity Scalings. . .?????

$$v_{50} \propto \sqrt{E/M}$$



Goldberg, LB & Paxton 2019

Faster moving lets you see in deeper sooner!



Goldberg, LB & Paxton 2019

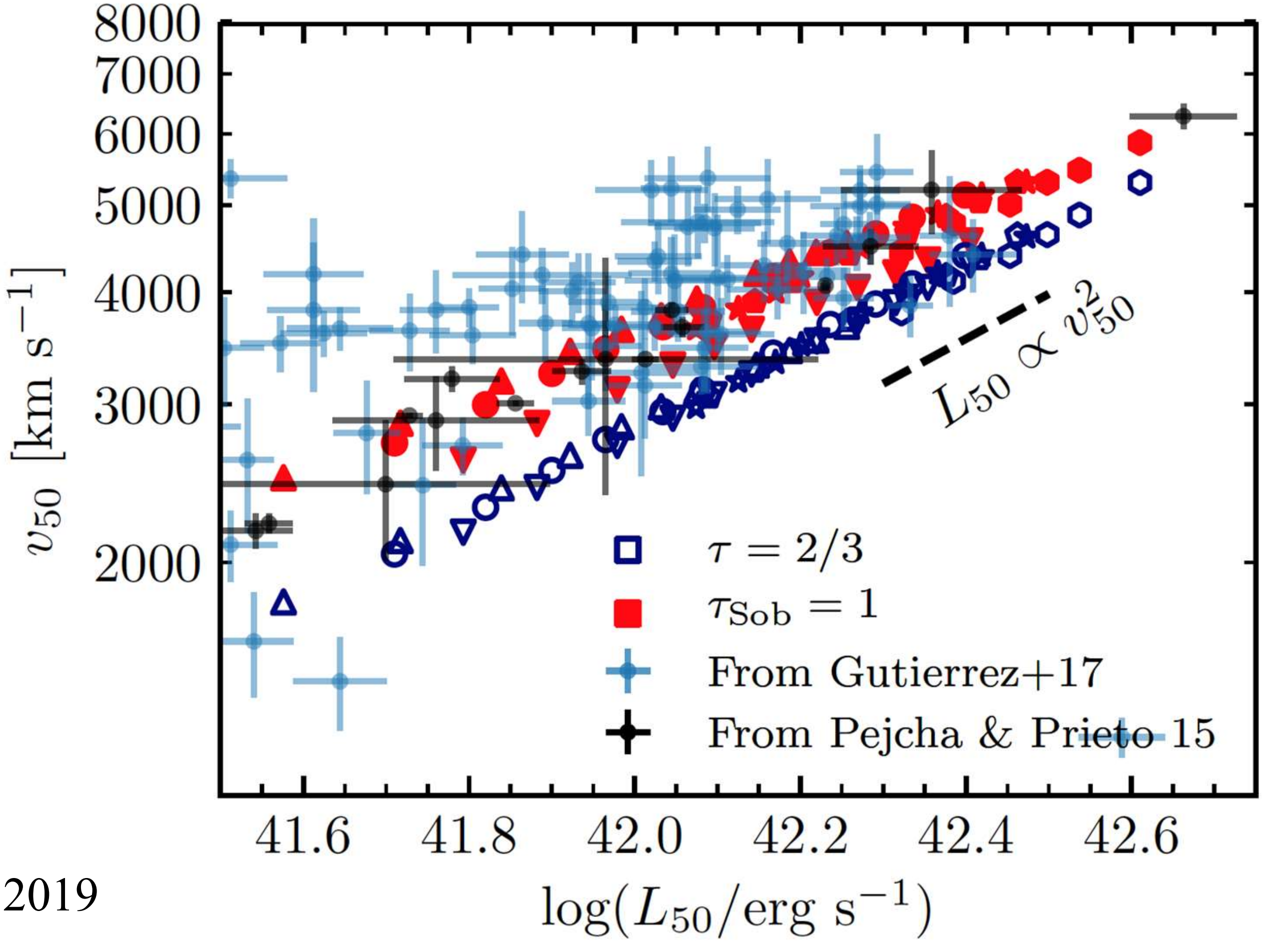
At fixed $E_{exp,}$ v_{50} is not monotonic in ejecta mass!

``Standard Candle” Relationship Known

- The velocity at day 50 is redundant with other measurements. Known observationally (Hamuy ‘03) and explained (Kasen & Woosley ‘09) $L_{50} \sim 4\pi R^2 \sigma (T_{ph})^4$

$$R \sim vt$$

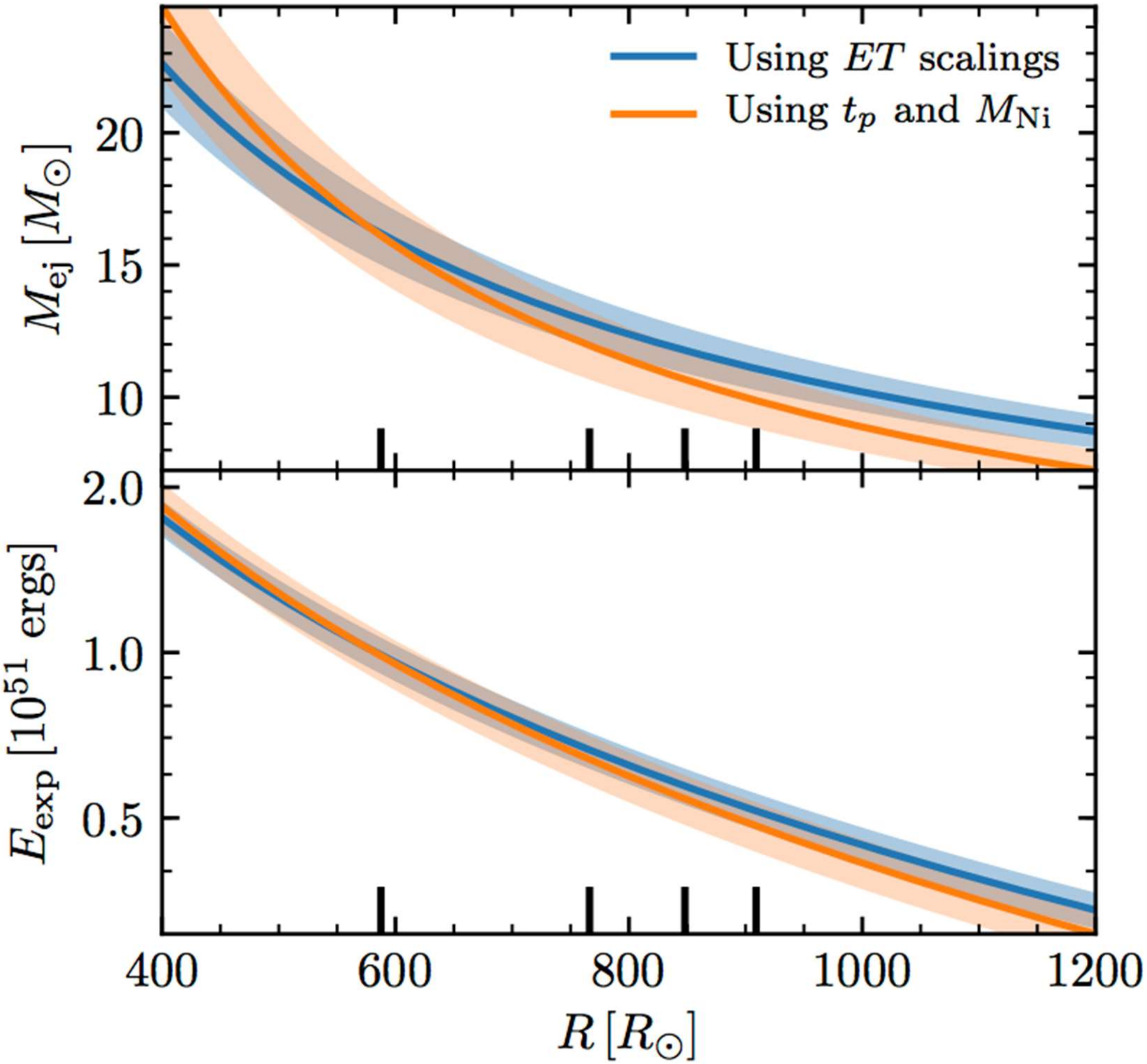
$$L_{50} \propto v_{50}^2$$



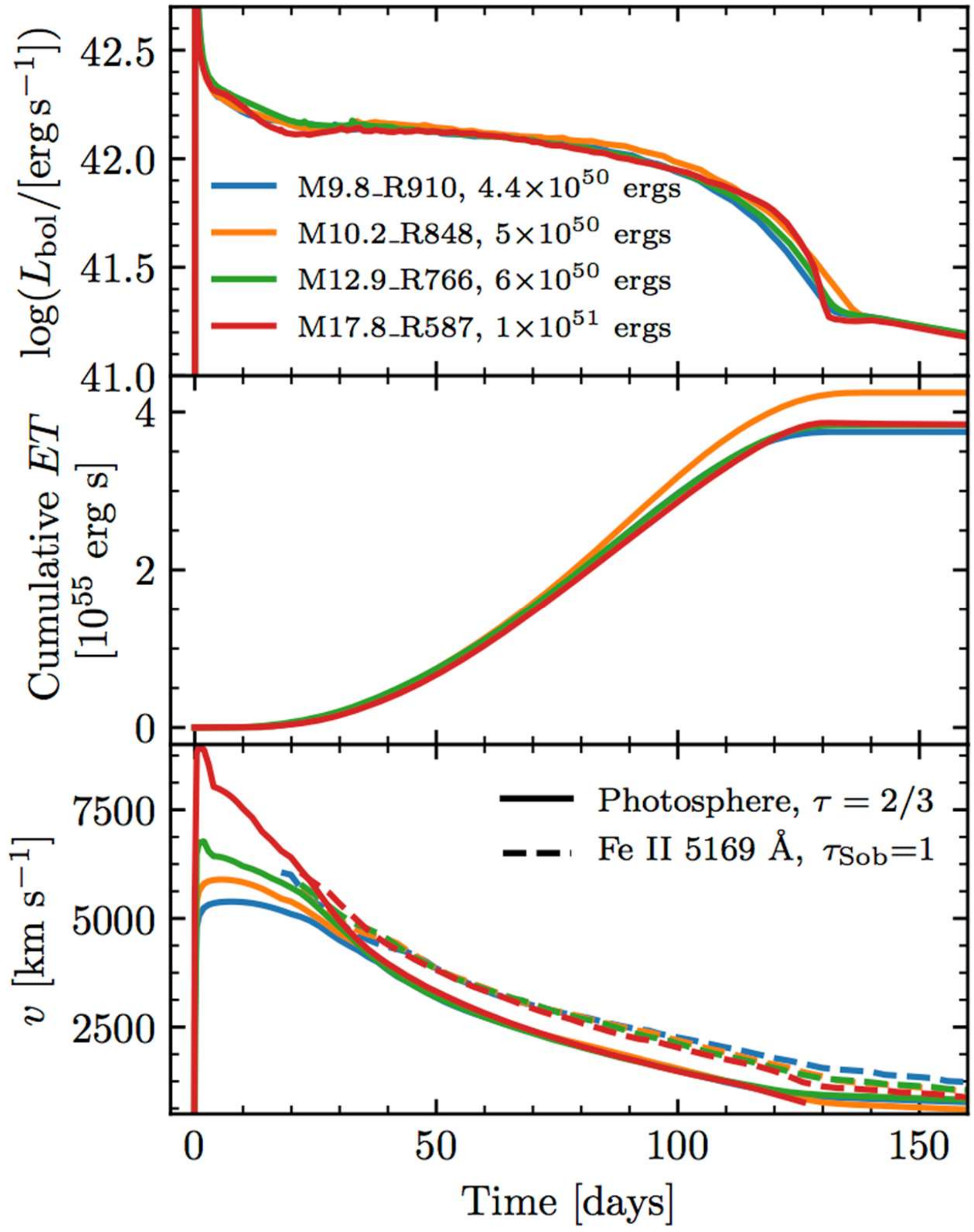
Goldberg, LB & Paxton 2019

You Can’t use Velocity at Day 50 to add a third equation.

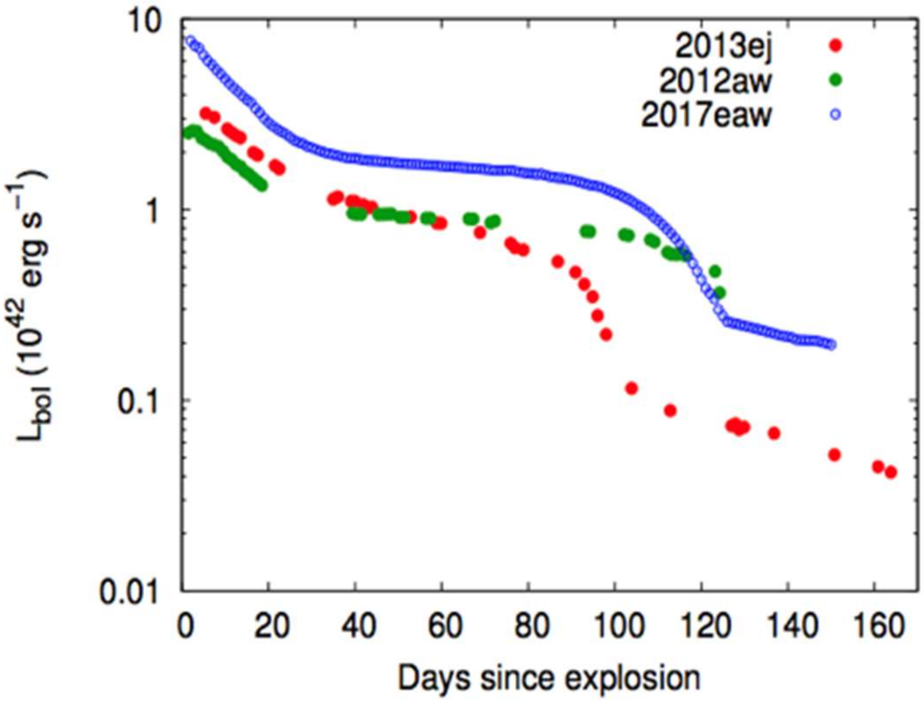
- This was the extra assumption that allowed Pejcha and Prieto to infer explosion energies and ejecta masses. . . But…
- Rather, the plateau duration, luminosity at day 50 and Nickel mass allows for a construction of a ``family” of solutions. ONLY if you know the progenitor radius can you break the degeneracy and infer the explosion energy and ejecta mass.

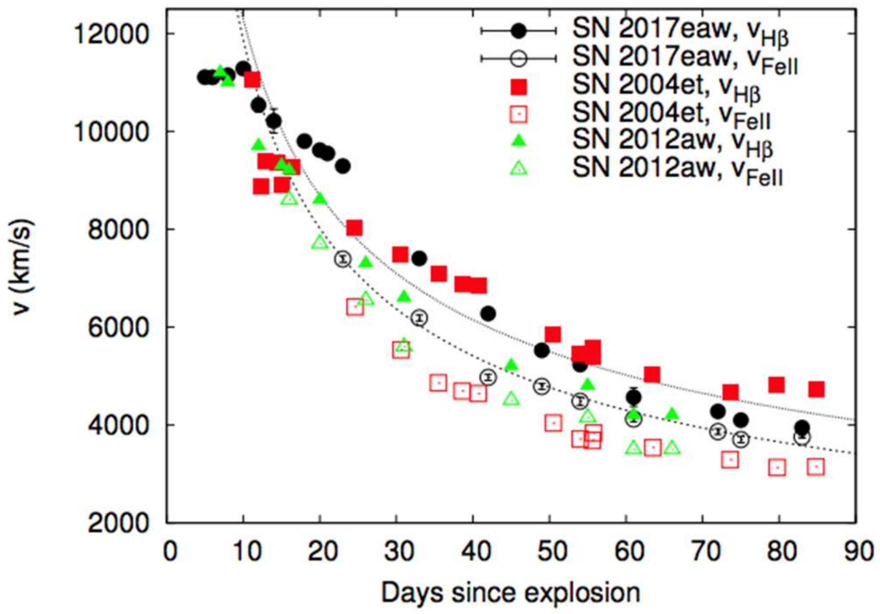

Using ET scalings
Using t_p and $M_{\rm Ni}$
$M_{\rm ej}\,[M_\odot]$
20
15
10
$E_{\rm exp}\,[10^{51}$ ergs]
2.0
1.0
0.5
400
600
800
1000
1200
$R\,[R_\odot]$

- 4 models with nearly a factor of 2 dynamic range in all explosion properties produce lightcurves with comparable L_{50}, t_p, and velocities.



Recent Nearby SNe 2017eaw

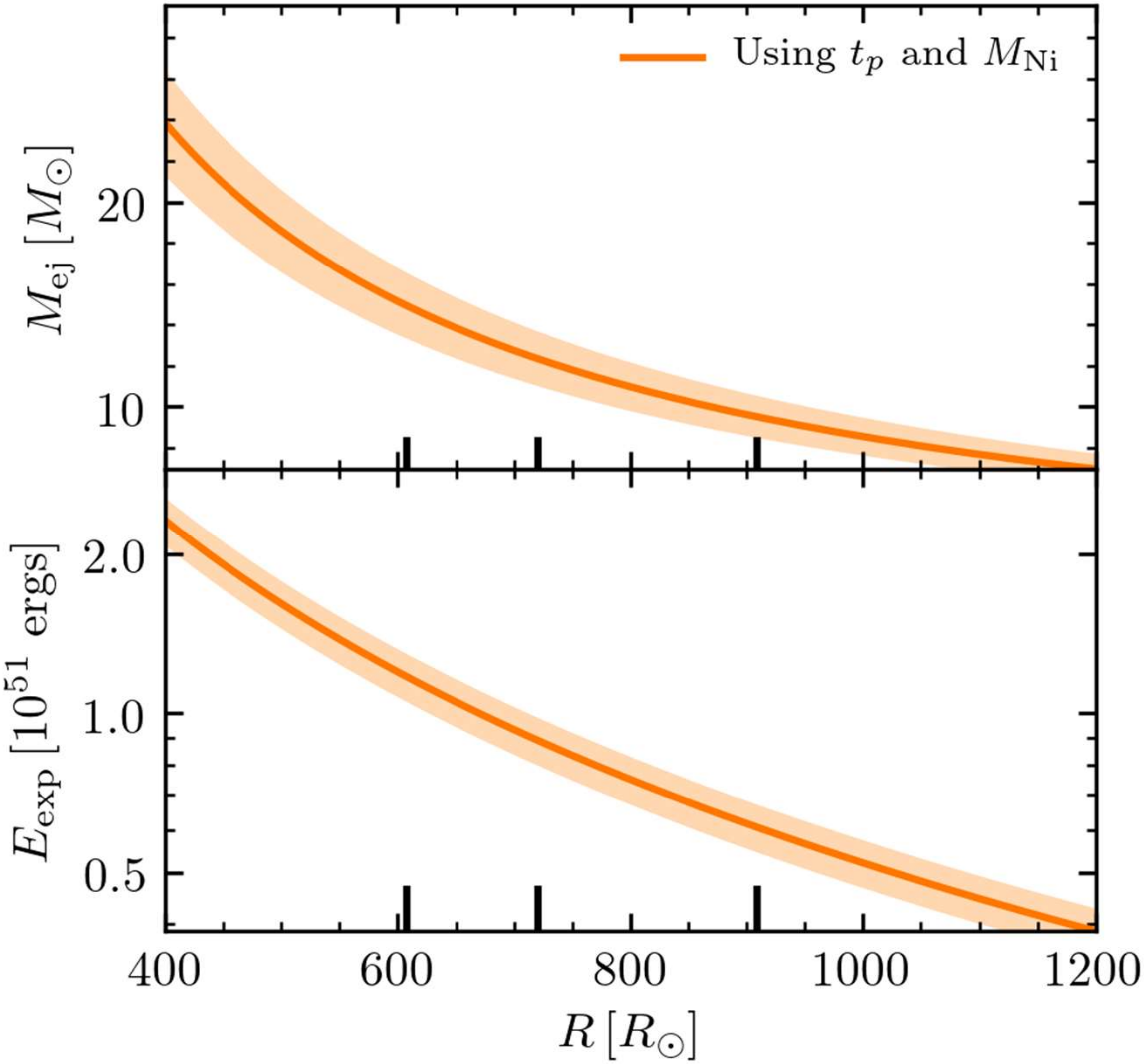




- Bolometric light curves and photospheric velocities of SN 2017eaw and other Type II-P SNe (global supernova project; Szalai et al., Submitted to ApJ)

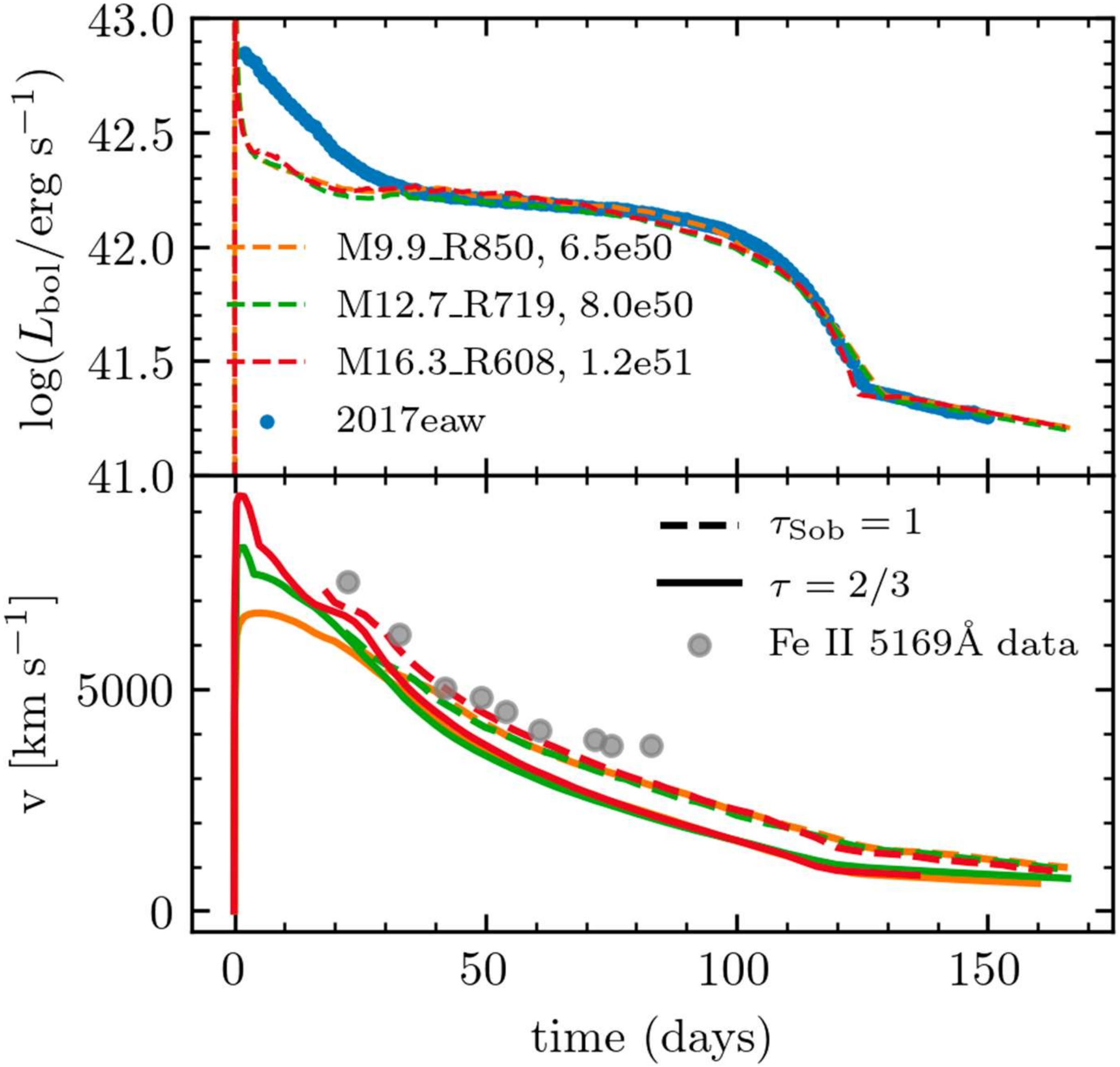
SNe 2017eaw

- Calculated families of possible explosions using our t_p scaling for Nickel-rich SNe, with $M_{Ni} \sim 0.05 M_\odot$ extracted from the lightcurve tail.



SNe 2017eaw

- We created 3 models within this family of possible explosions
- Produced lightcurves consistent with the given bolometric data for L_{50} and t_p



Summary

- We can model ensembles of type IIP Supernovae using MESA+STELLA
- Luminosity at day 50 and plateau duration roughly scale as power laws in M_{ej}, E_{exp}, $R_{progenitor}$ within ~15%.
- Velocity at day 50 provides no information above and beyond Luminosity, but measurement of one parameter (e.g. progenitor radius) allows extraction of the other two.
- This work provides a tool to guide modeling efforts, and the hope for a robust progenitor sample in the era of ZTF/LSST!