Modeling Rapidly Fading Supernovae as Nickel-Free Core-Collapse Explosions of Extended Helium Stars

Io Kleiser (Caltech)

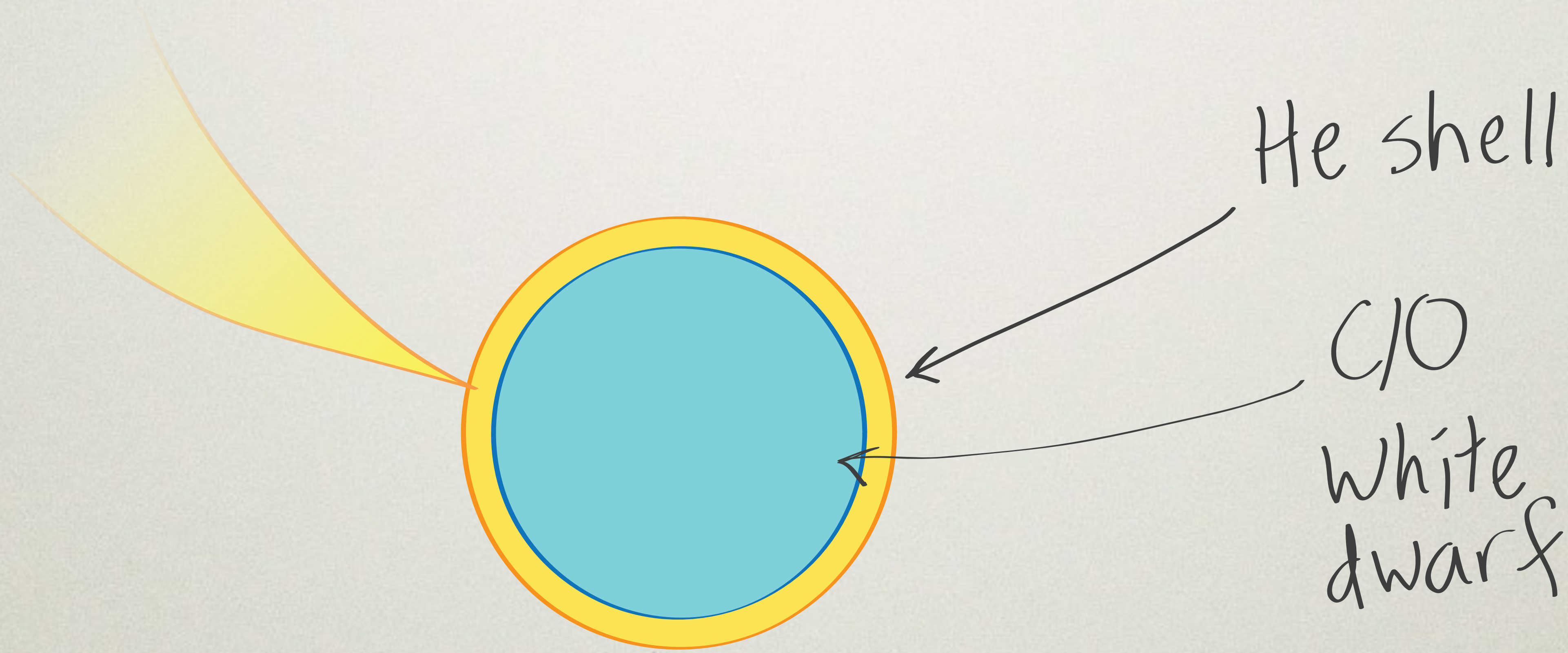
Advisors: Dan Kasen (UCB), Sterl Phinney (Caltech)

SSGF Annual Review · June 2018

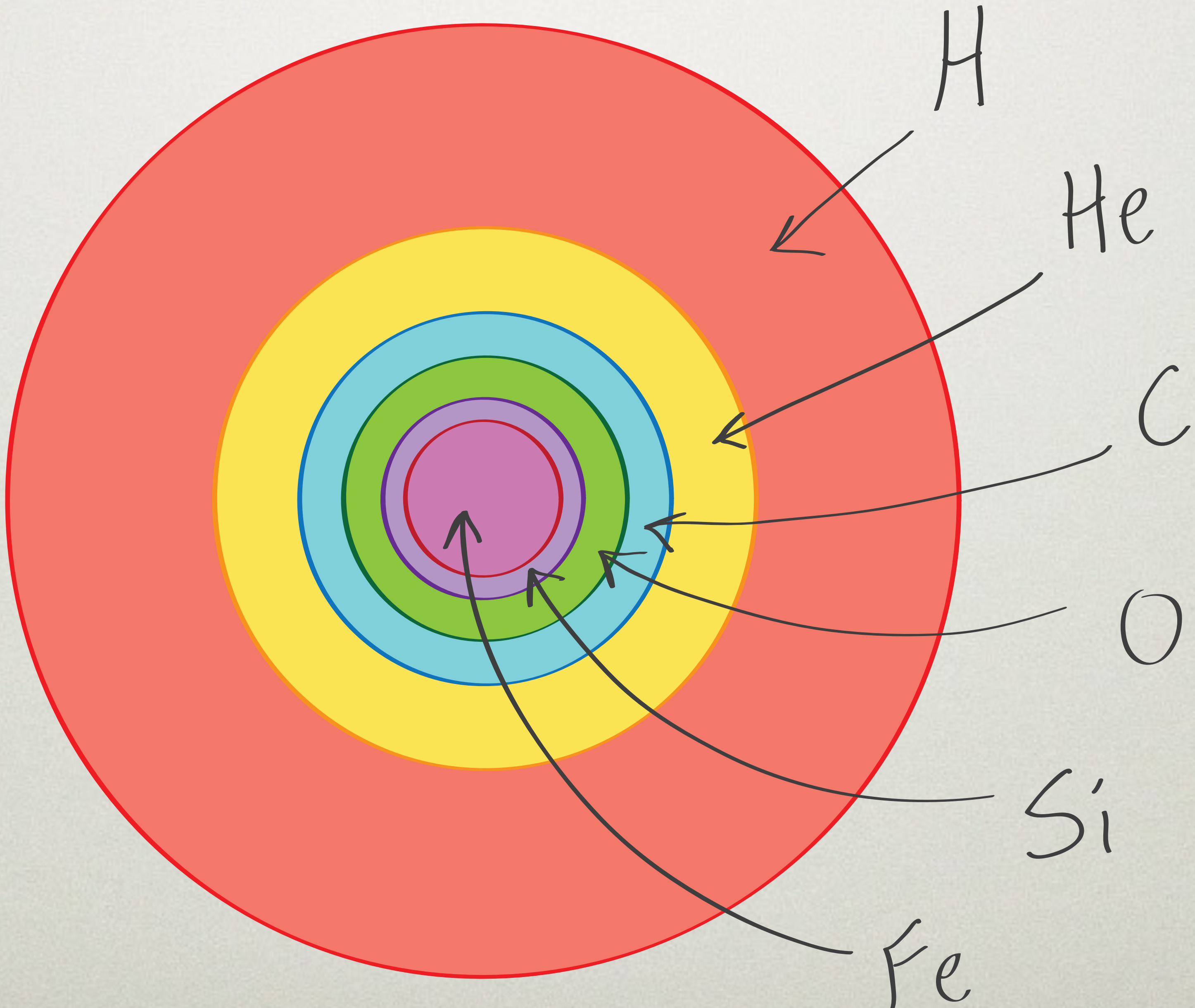
Outline

- Types of supernovae & their progenitor stars
- Supernova power sources
- Rapidly fading supernovae
- Model results
- Future work & implications

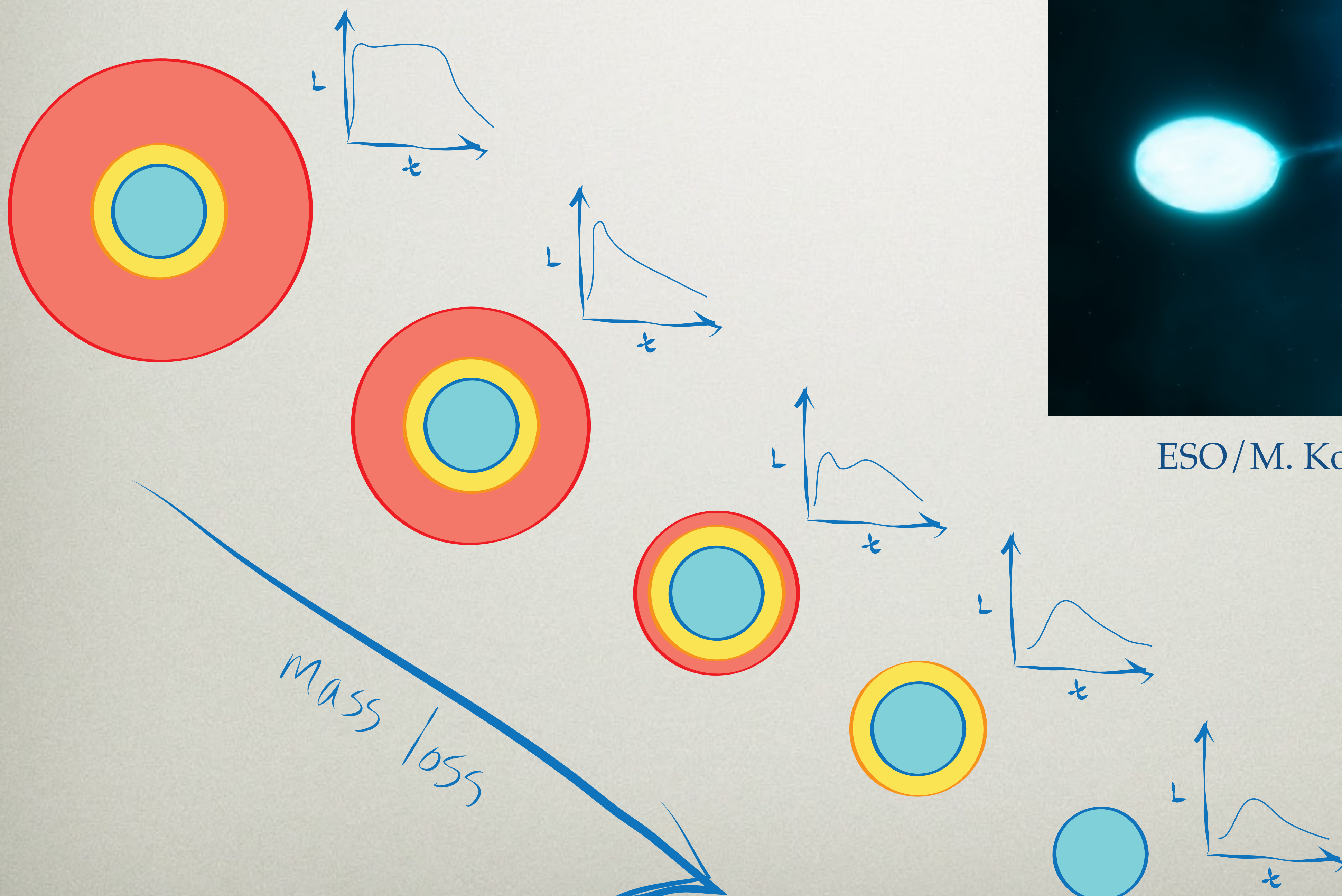
Thermonuclear Supernovae

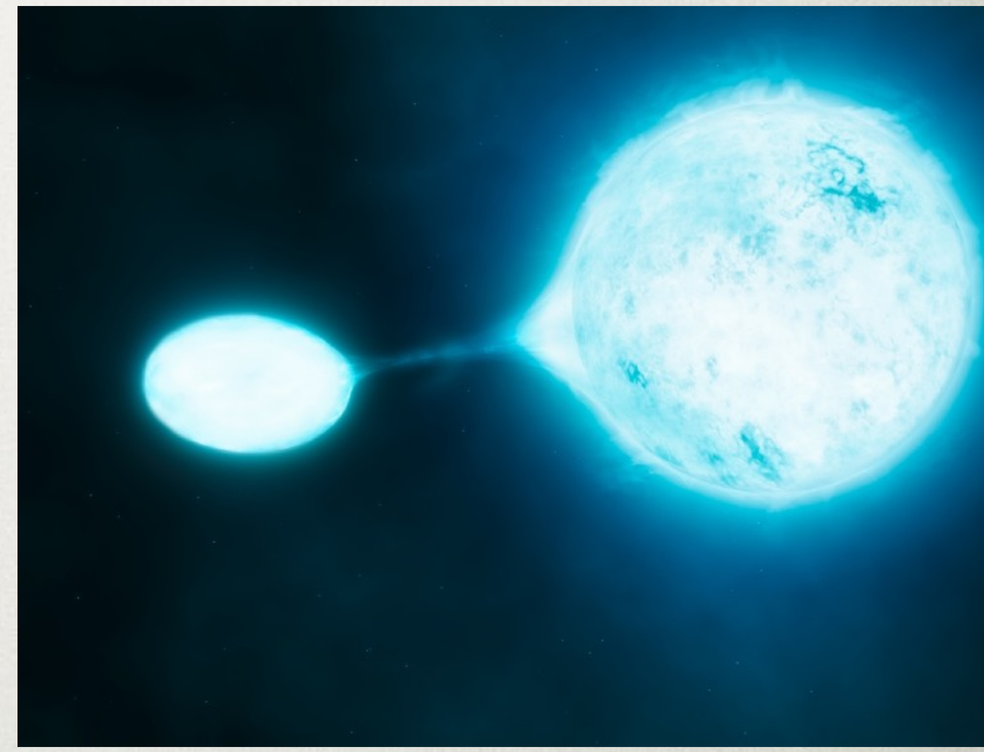


Core-Collapse Supernovae



Core-Collapse Supernovae





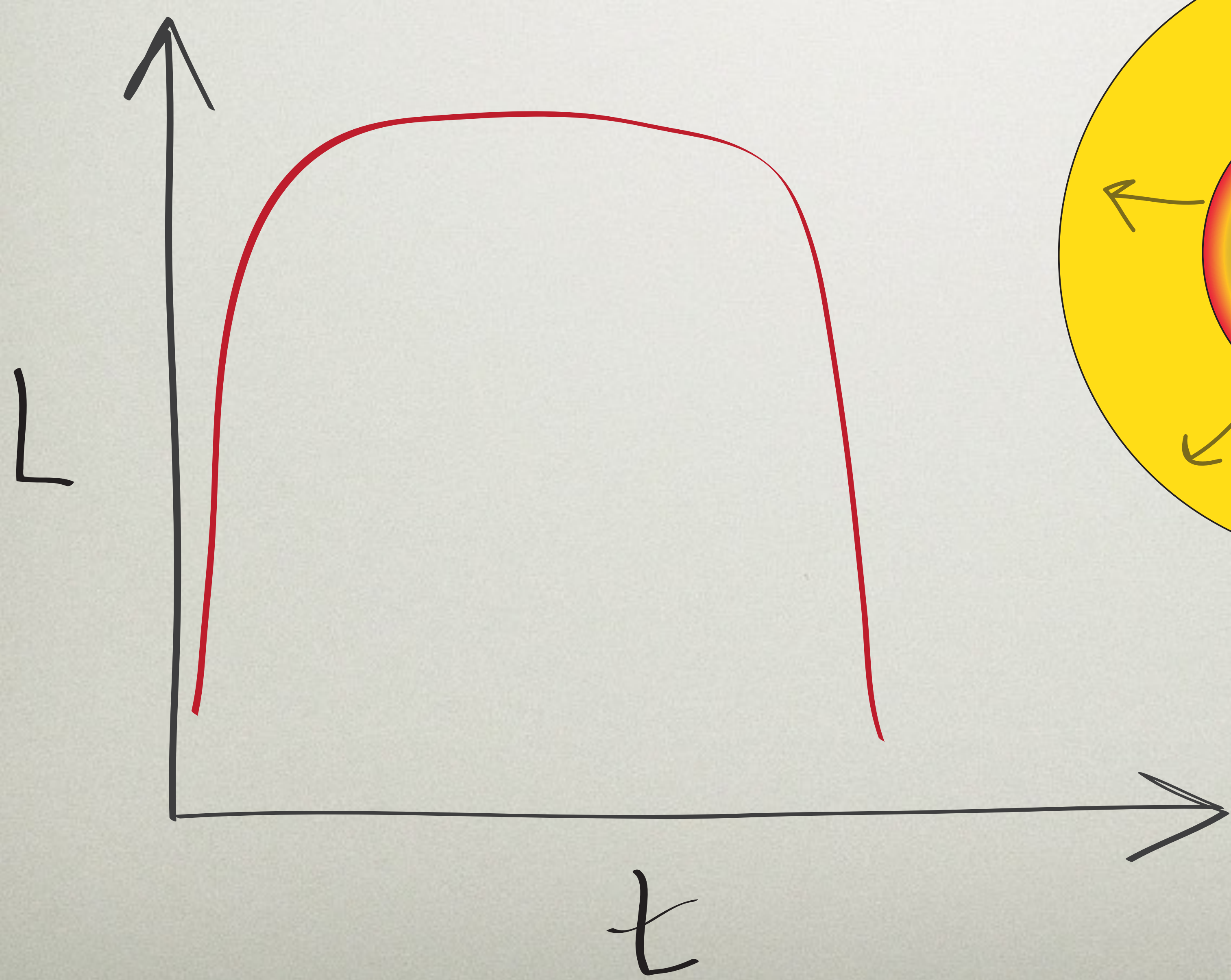
ESO / M. Kornmesser / S.E. de Mink

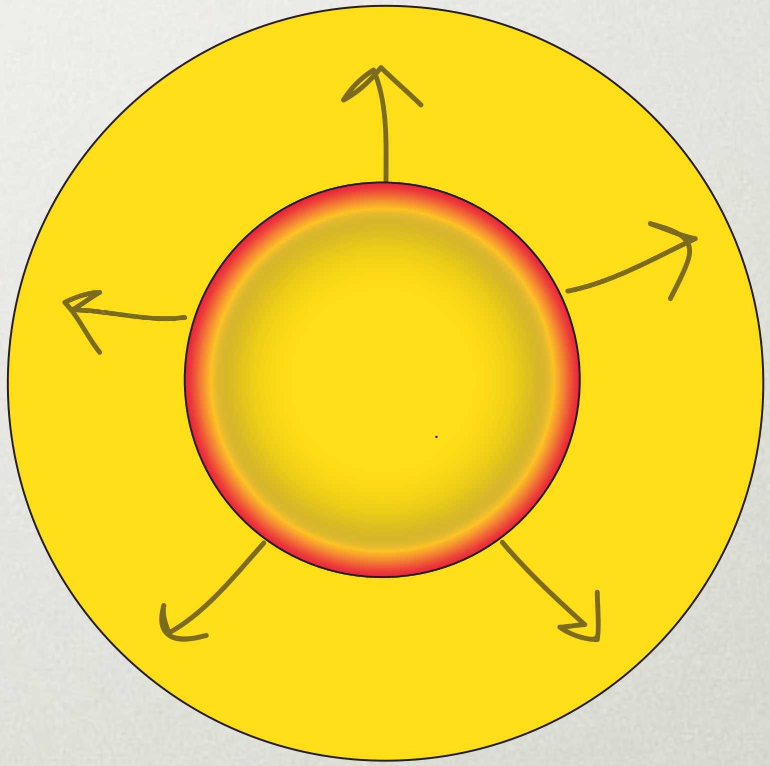
SN Power Sources

- SN shock energy - most important for large-radius stars
- Radioactive nickel - most important for small-radius stars

SN Power Sources

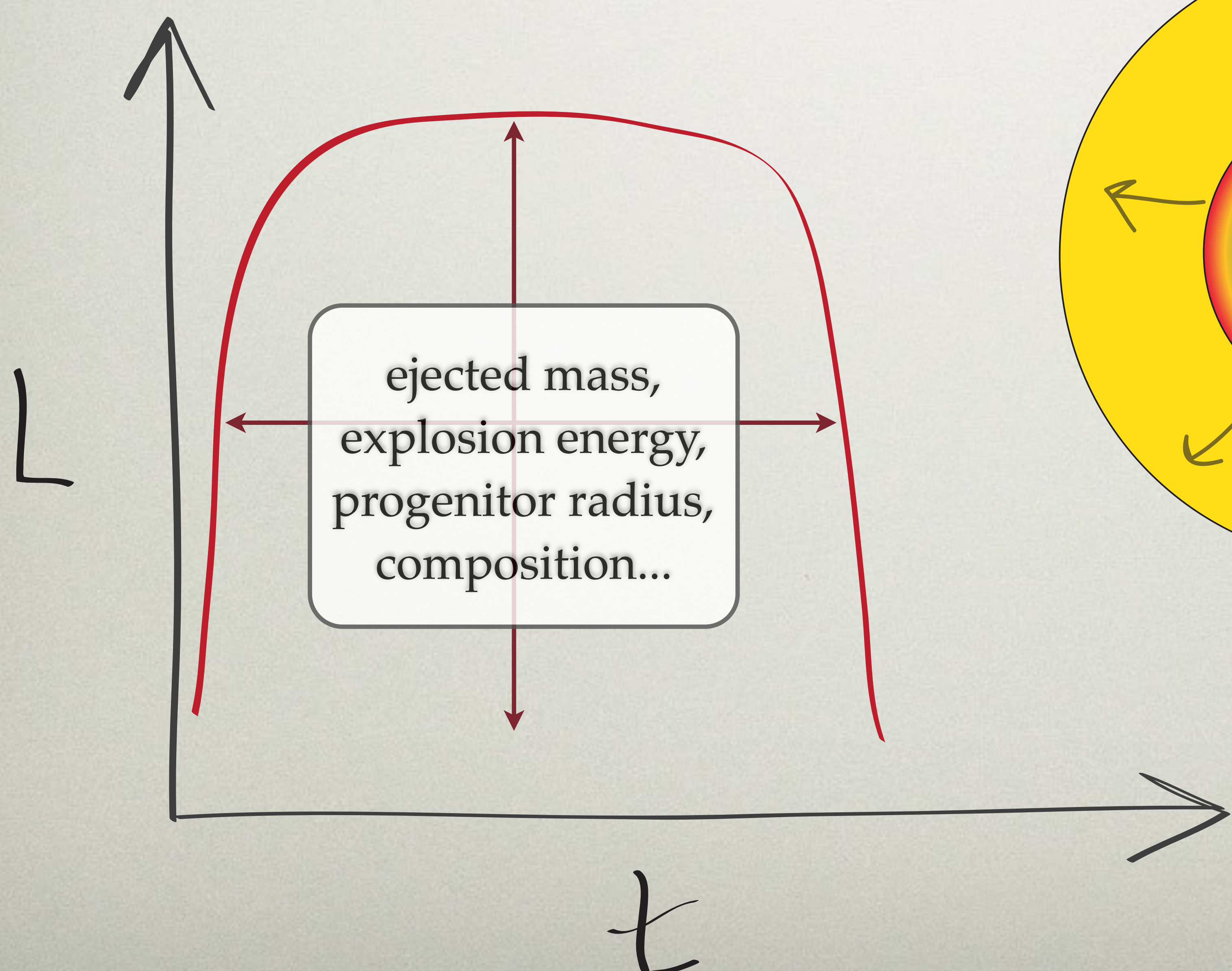
Energy deposited in SN shock

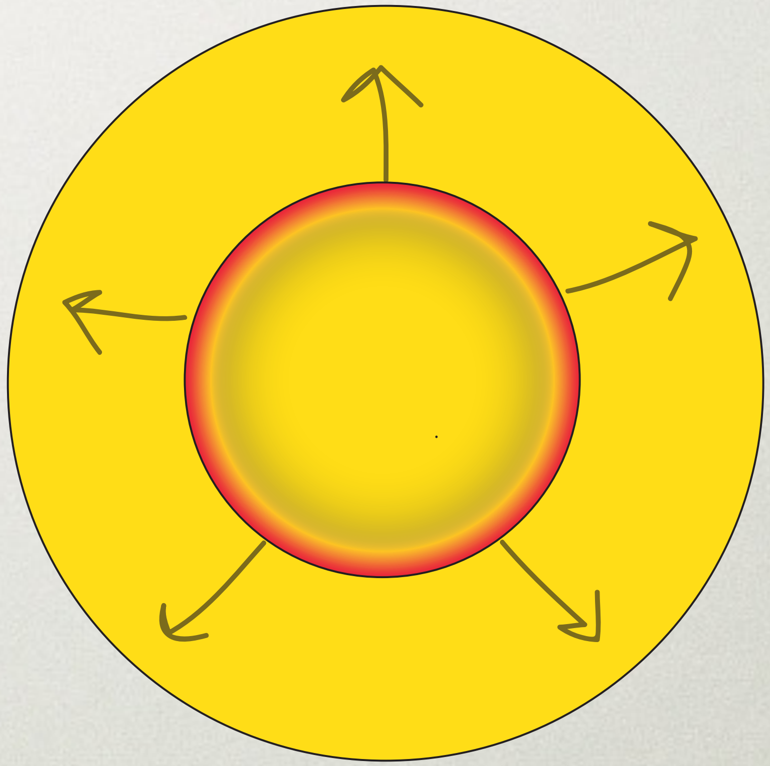




SN Power Sources

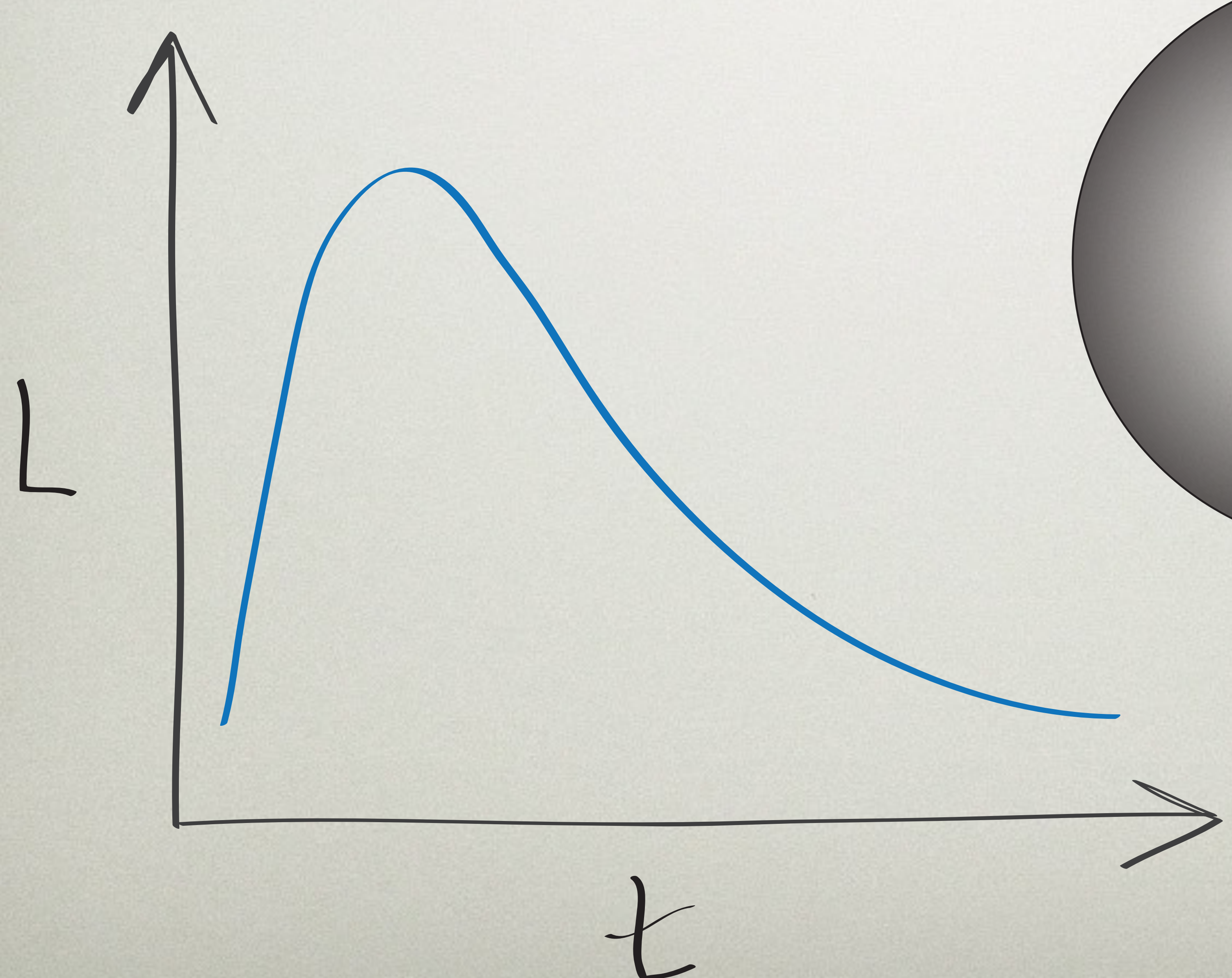
Energy deposited in SN shock

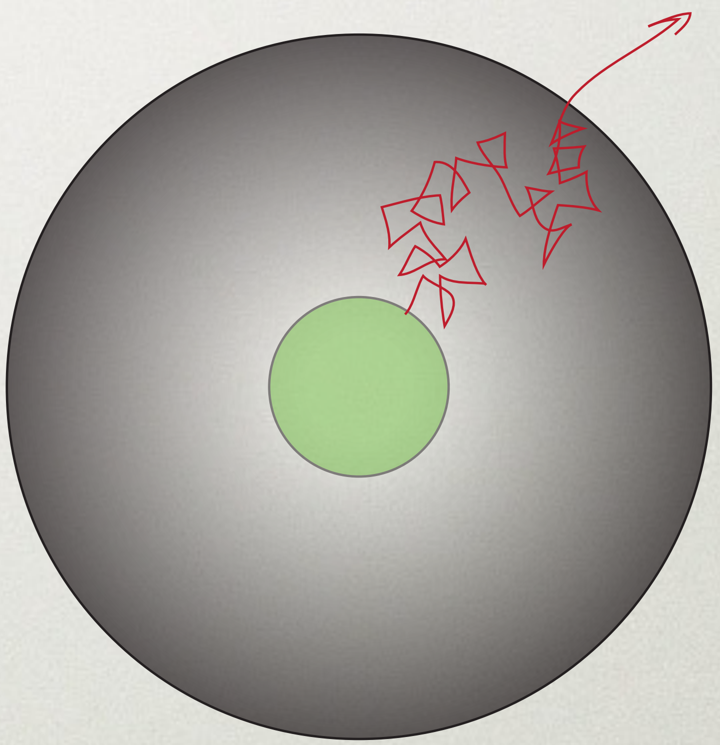




SN Power Sources

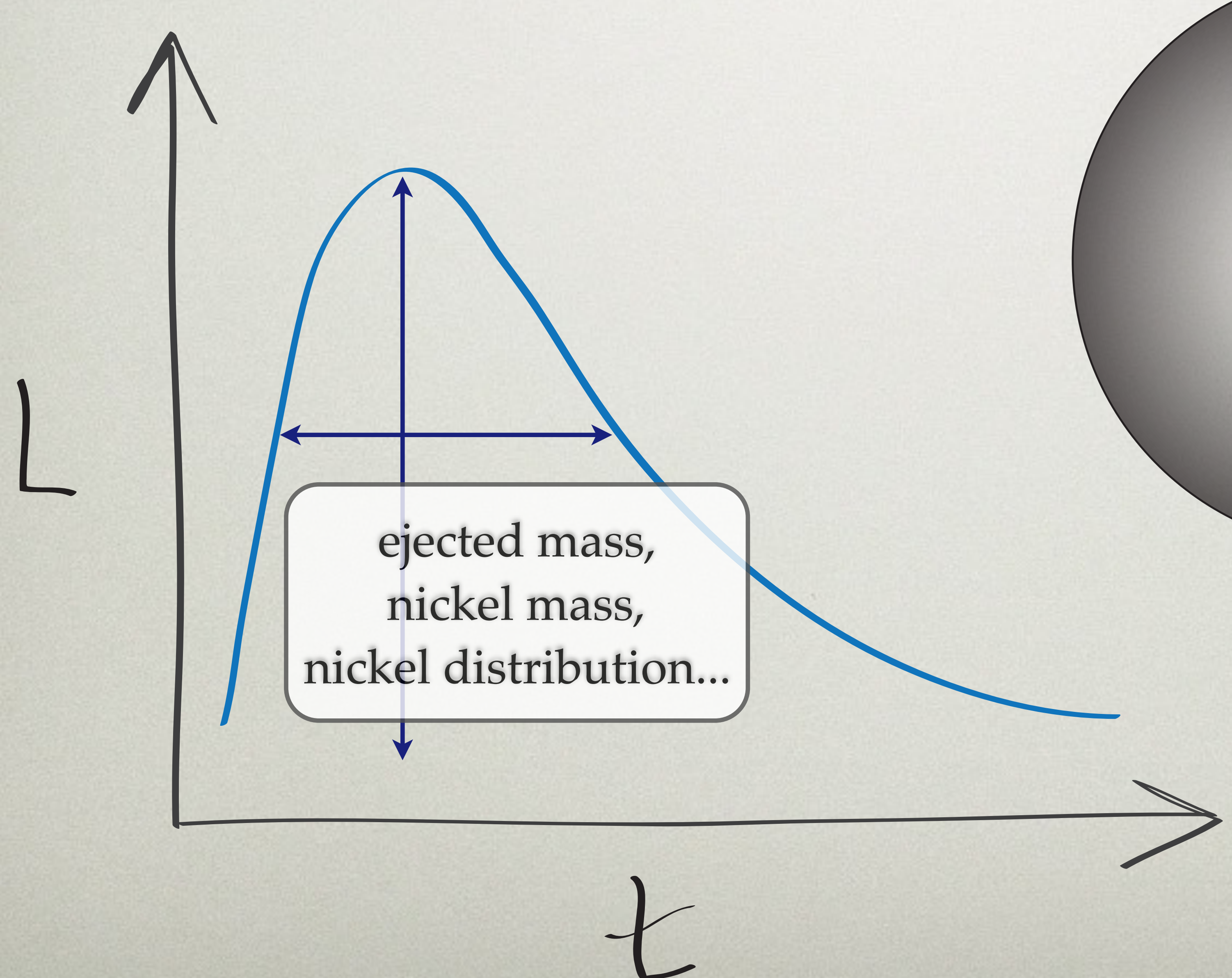
Radioactive nickel

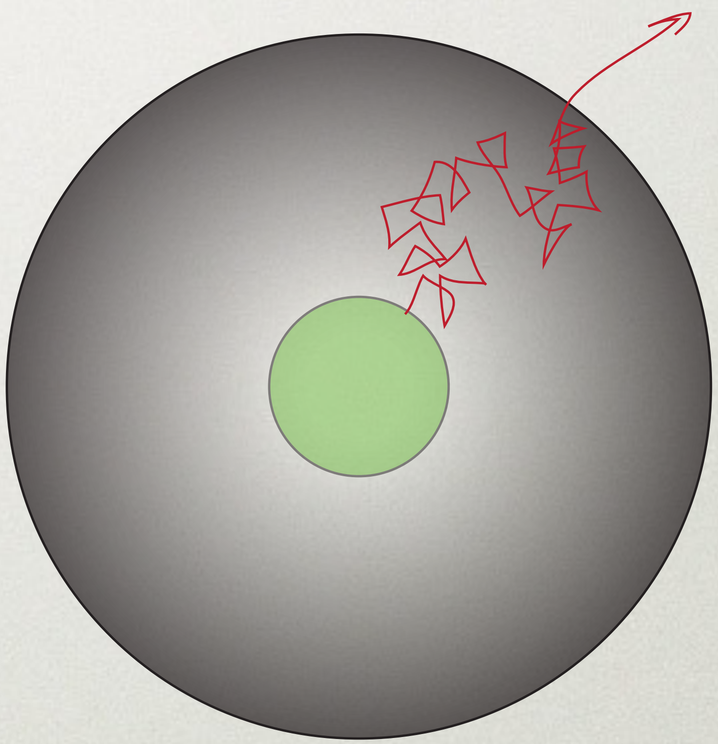




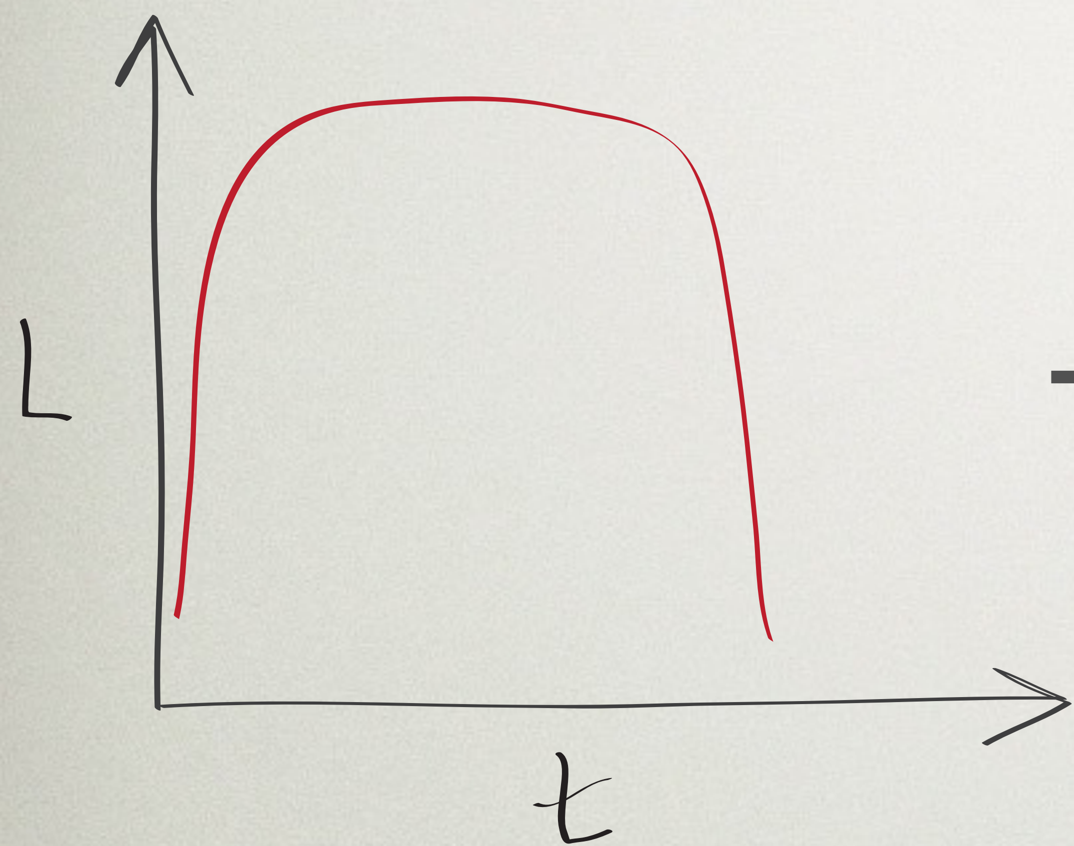
SN Power Sources

Radioactive nickel

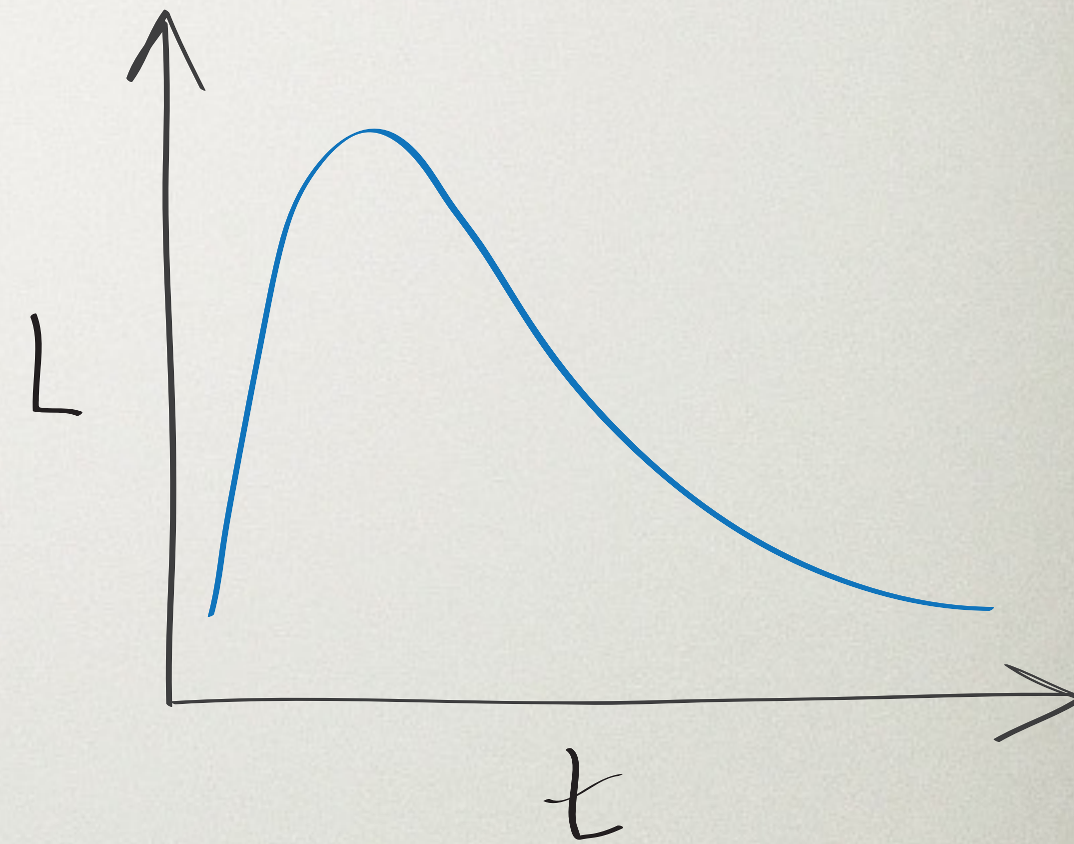




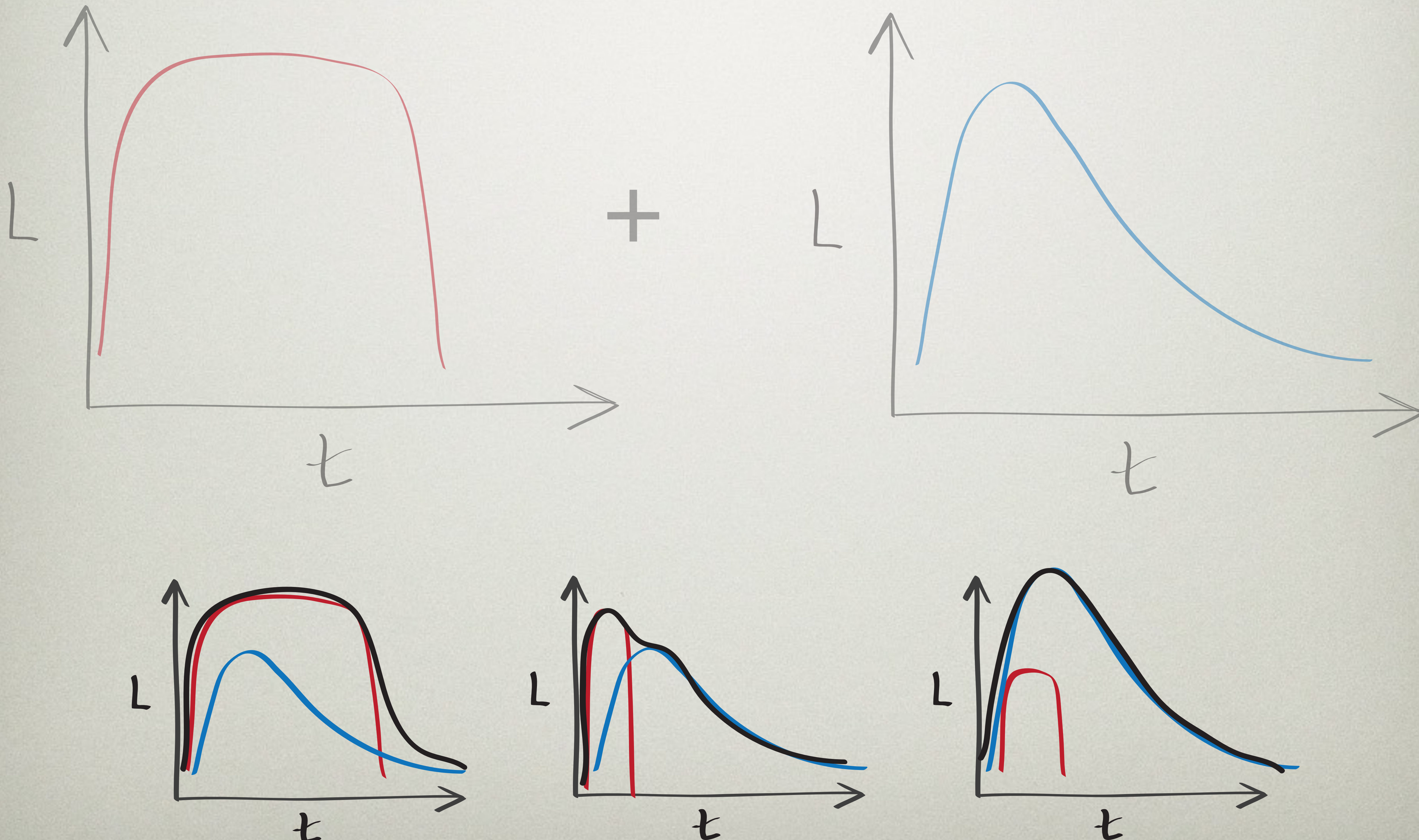
SN Power Sources



+



SN Power Sources

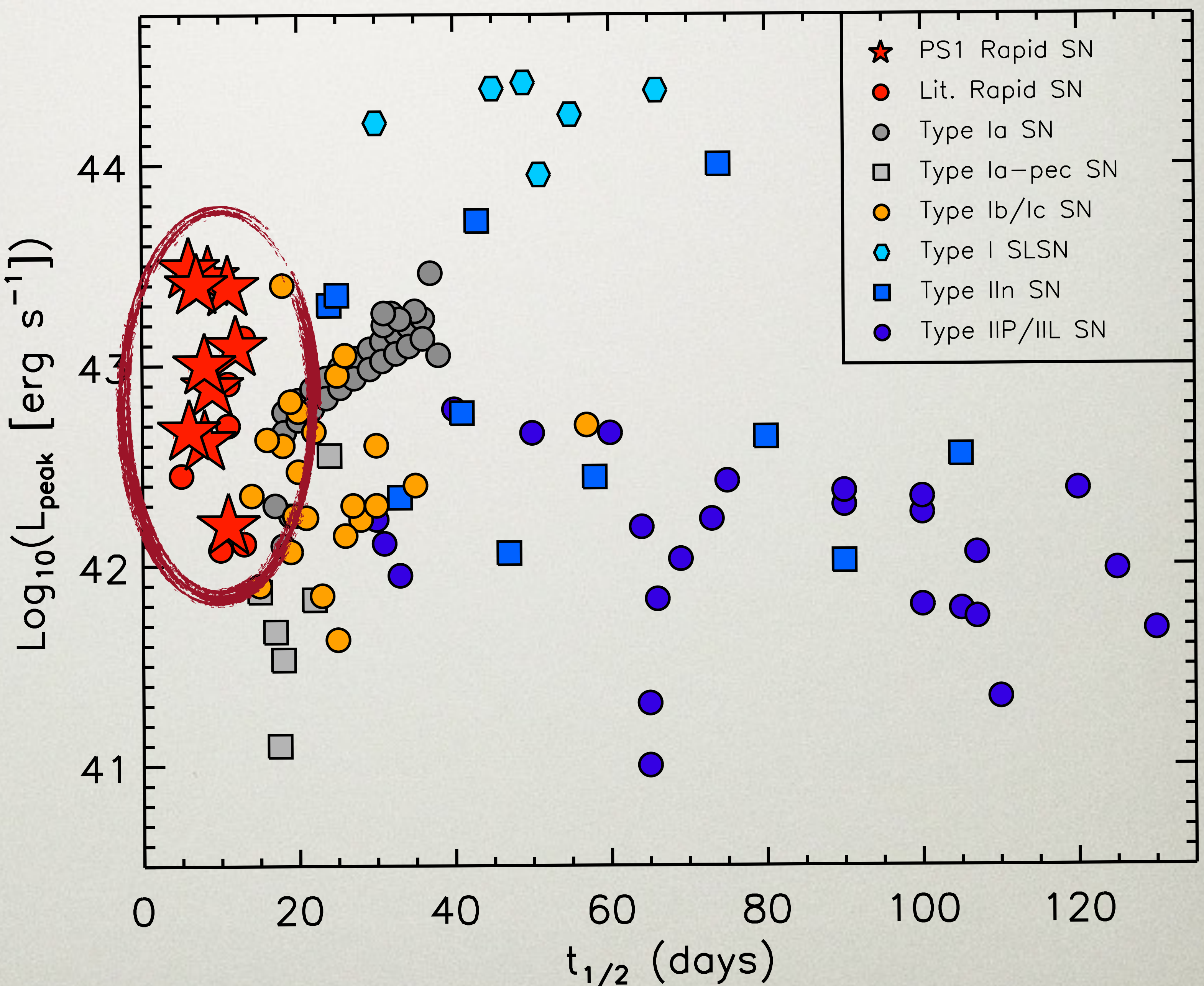


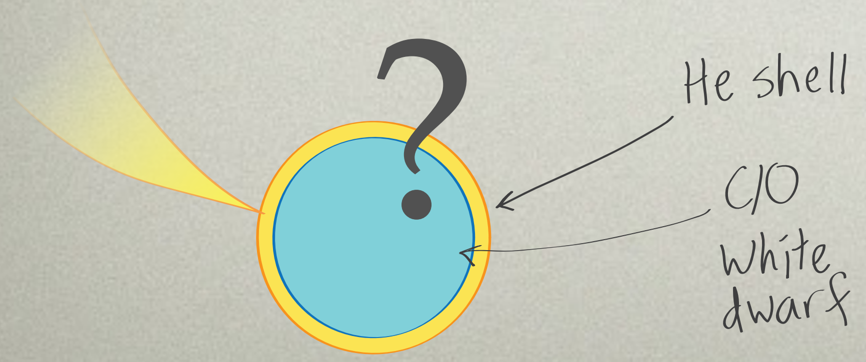
Rapidly Fading Supernovae

Diffusion time (Arnett 1979):

$$t_{\rm sn} \propto M_{\rm ej}^{1/2} \kappa^{1/2} v^{-1/2}$$

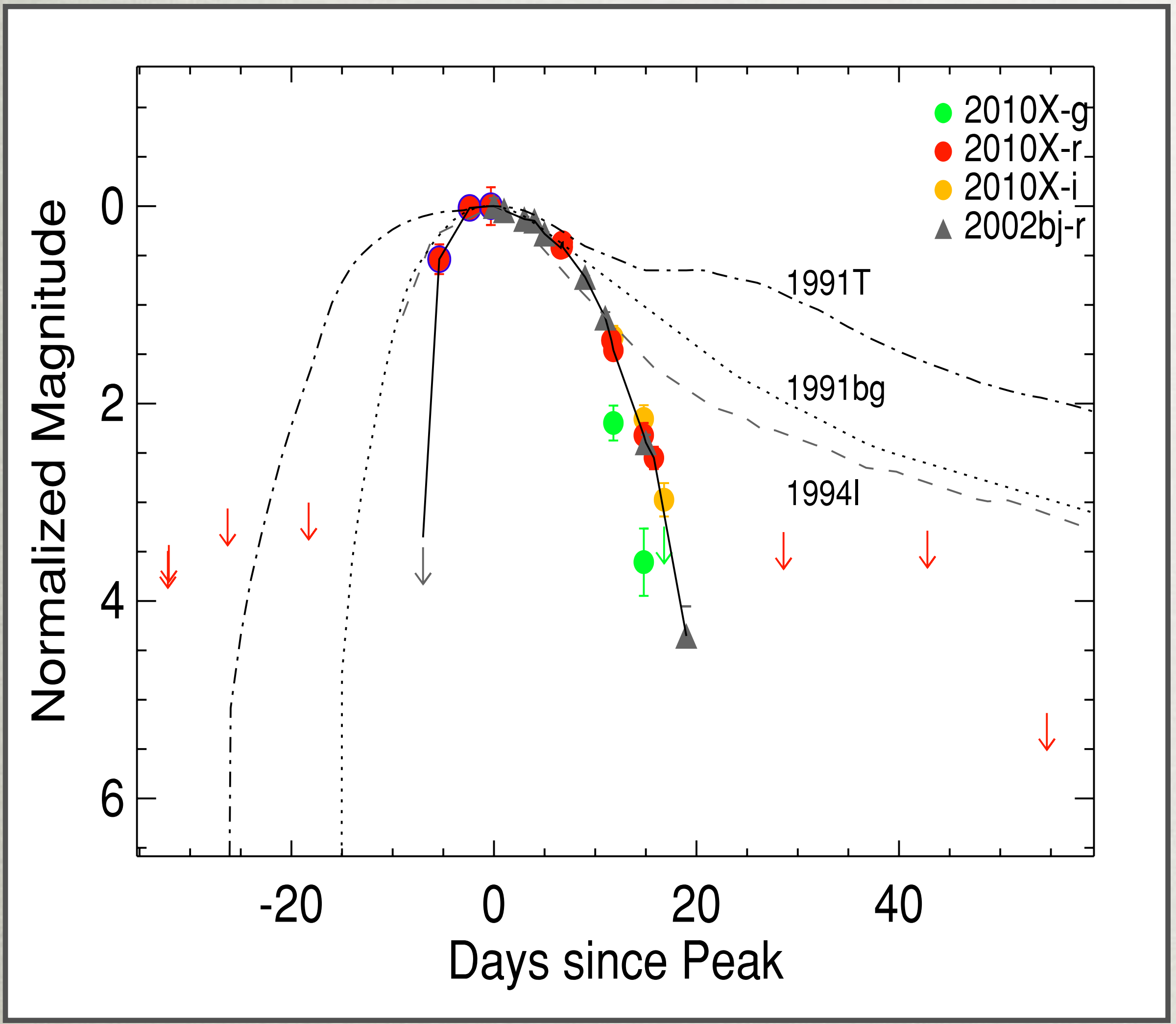
suggests a small ejected mass ($\sim 0.1\ M_\odot$) as in some thermonuclear models





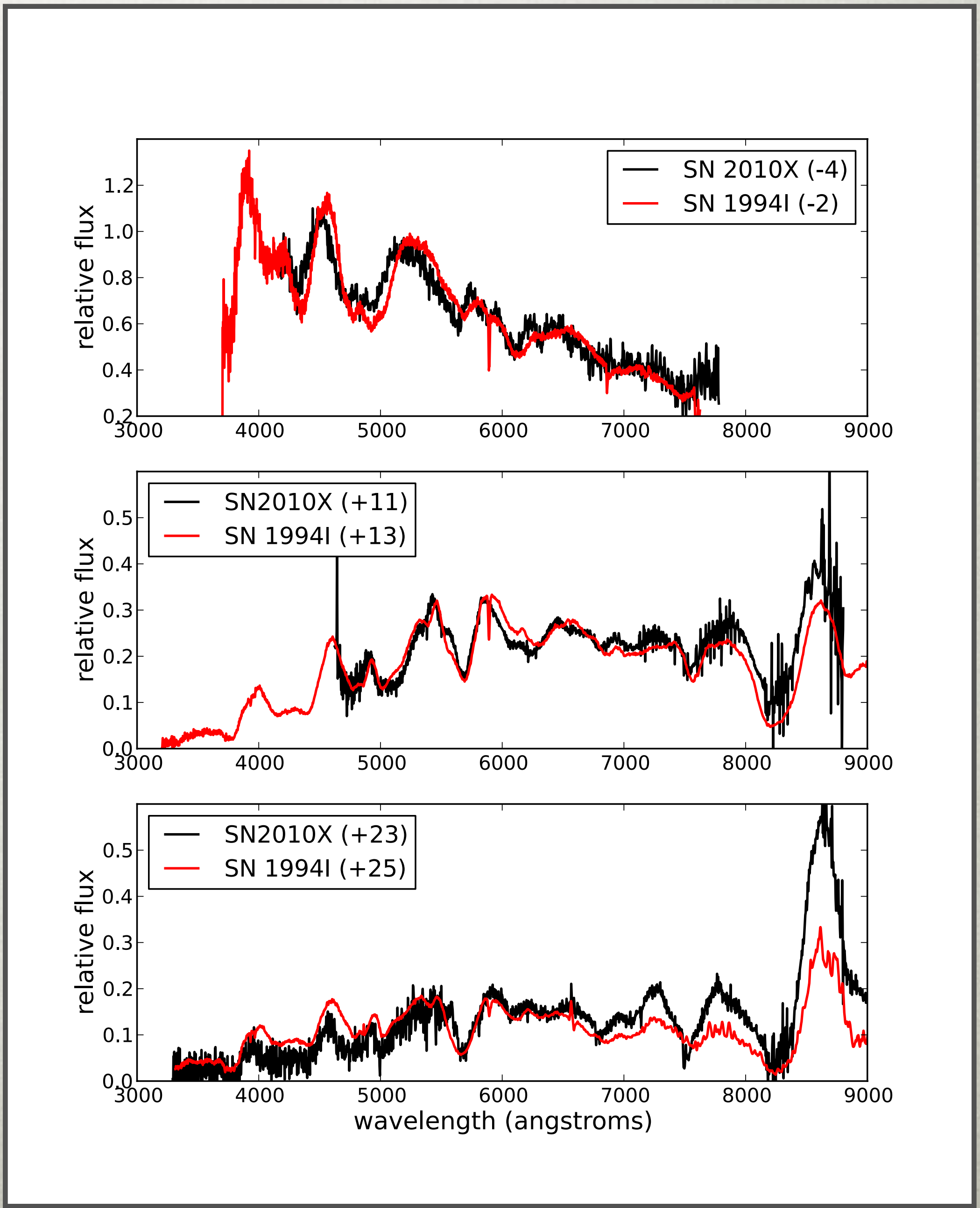
Drout et al. 2014

SN 2010X

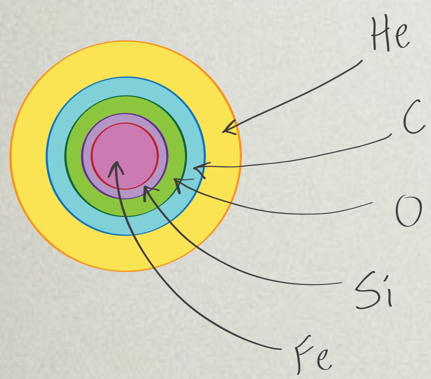


Kasliwal et al. 2010

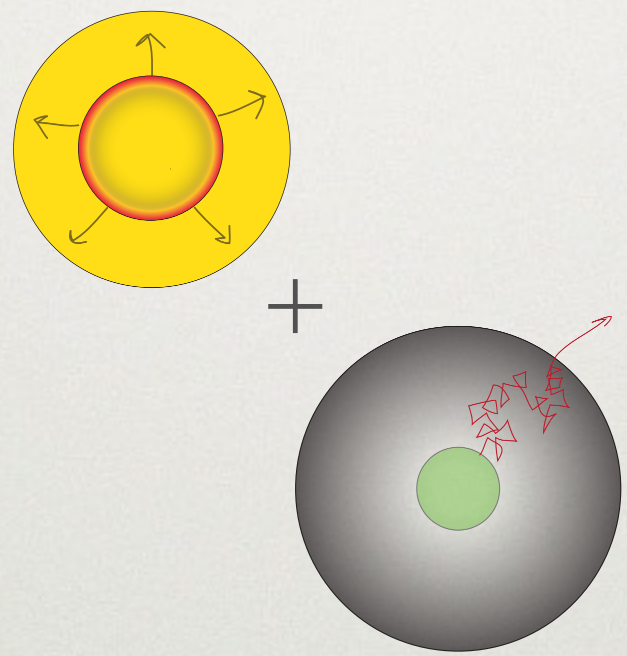
Kleiser & Kasen 2014



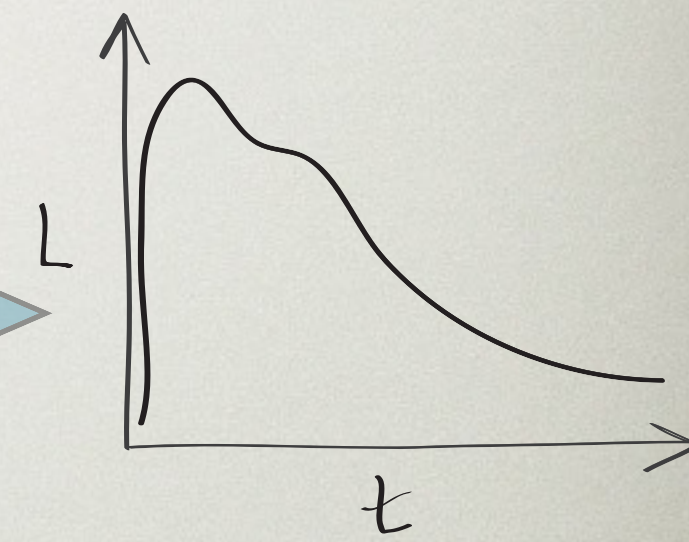
Connecting SNe to Their Progenitors



progenitor models
(MESA)

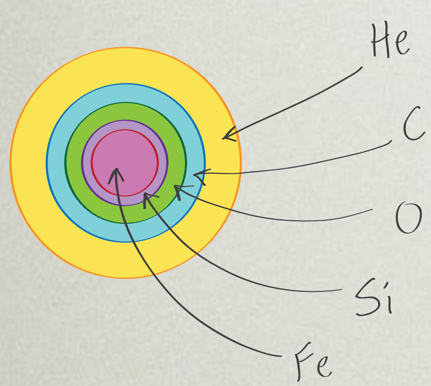


ejecta models
(in-house hydro code)

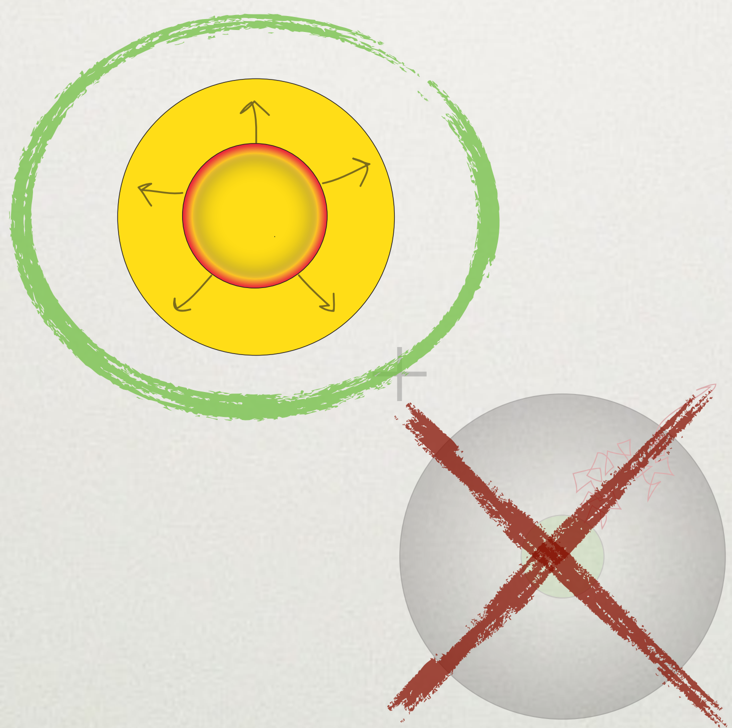


light curves & spectra
(SEDONA)

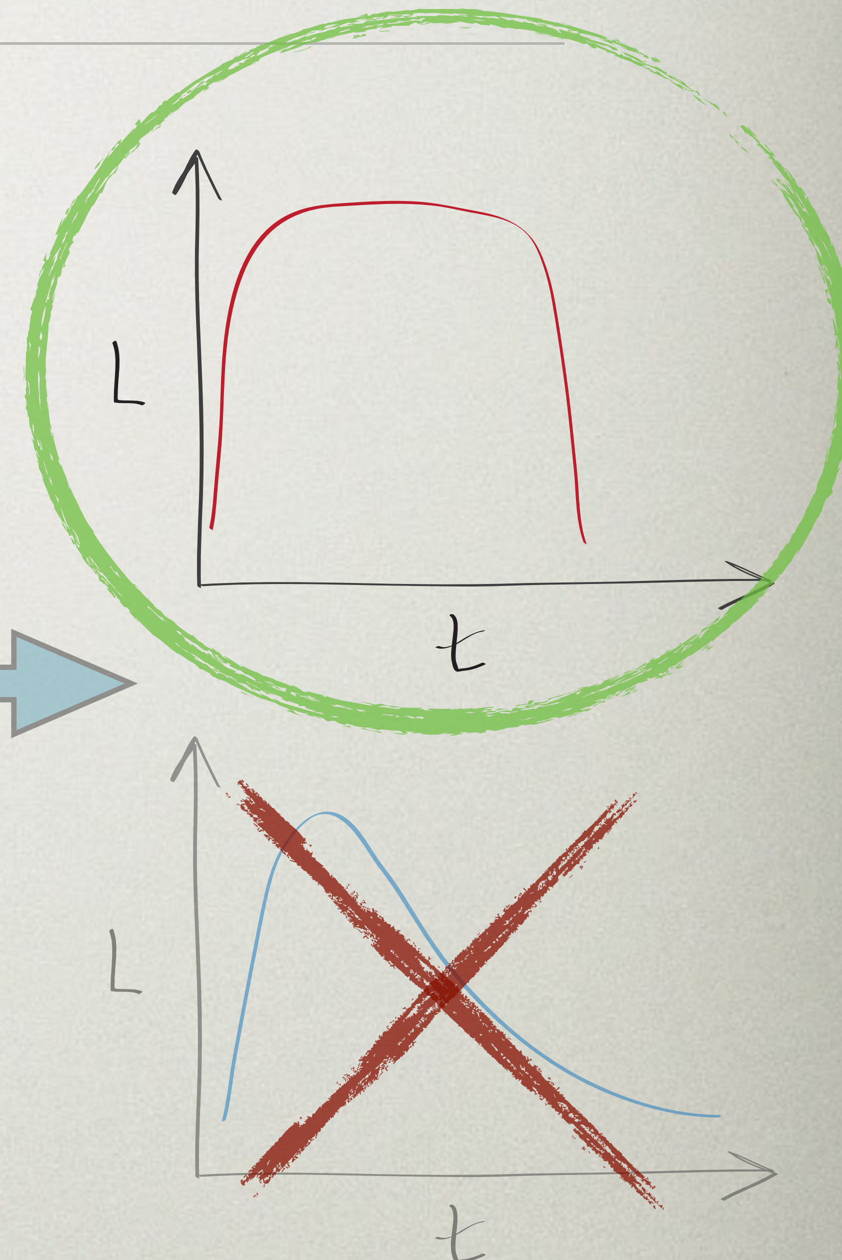
Rapidly Fading Supernovae



stripped massive star



shock cooling only,
no nickel

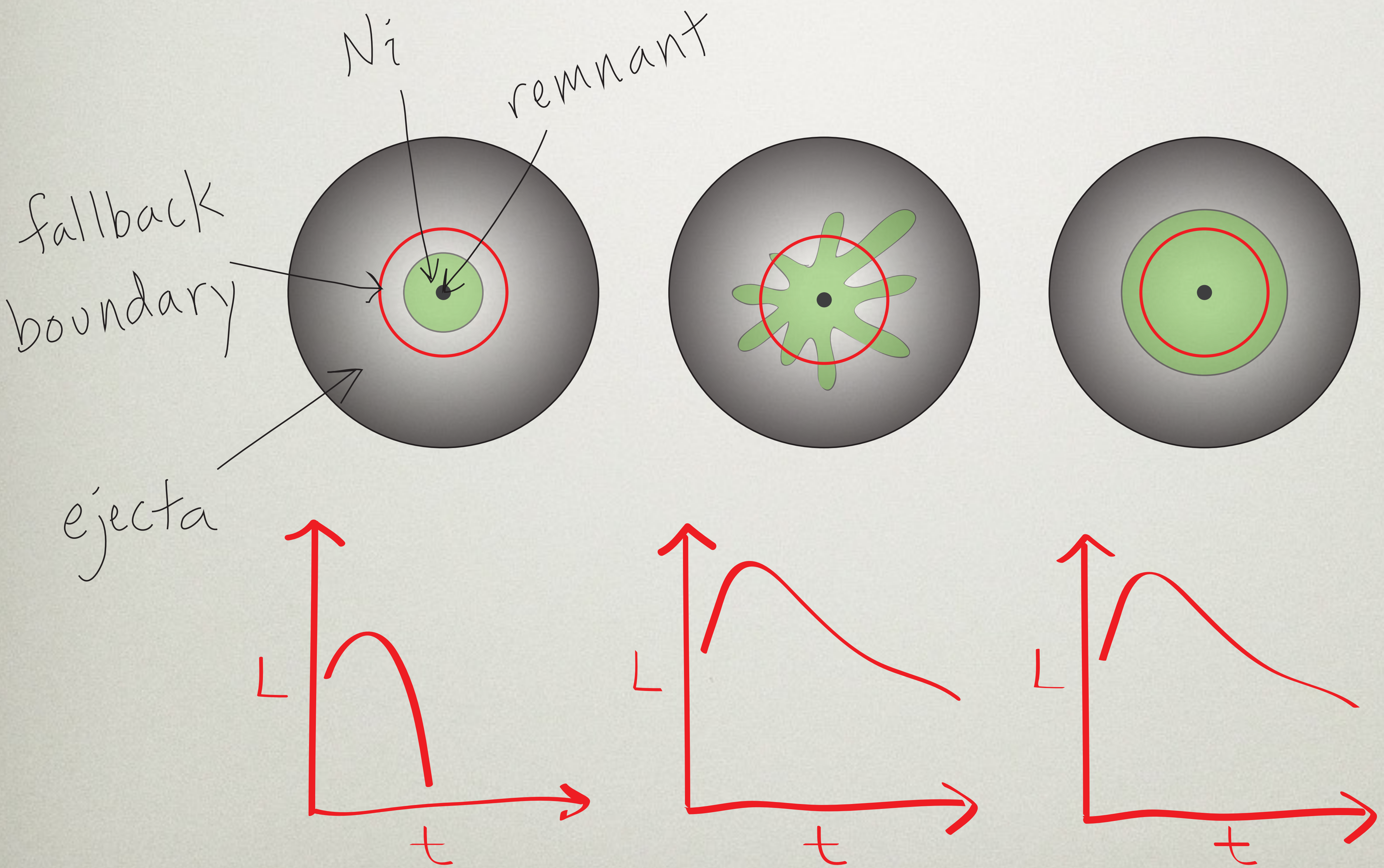


shock cooling light curve with no radioactive tail

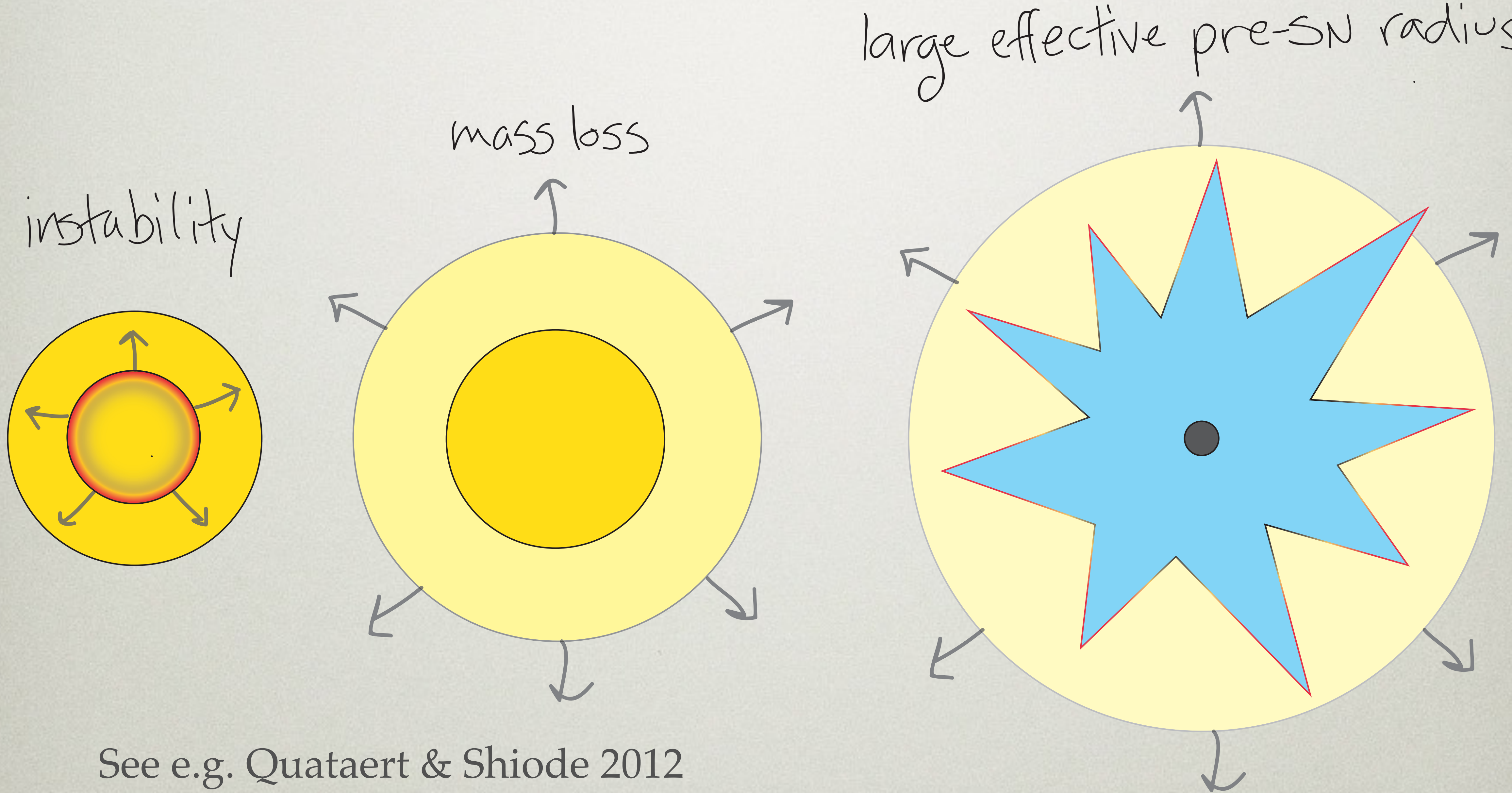
What We Need for This Model

- Little or no radioactive material ejected
- Large (effective) pre-supernova radius

Hiding Radioactive Nickel

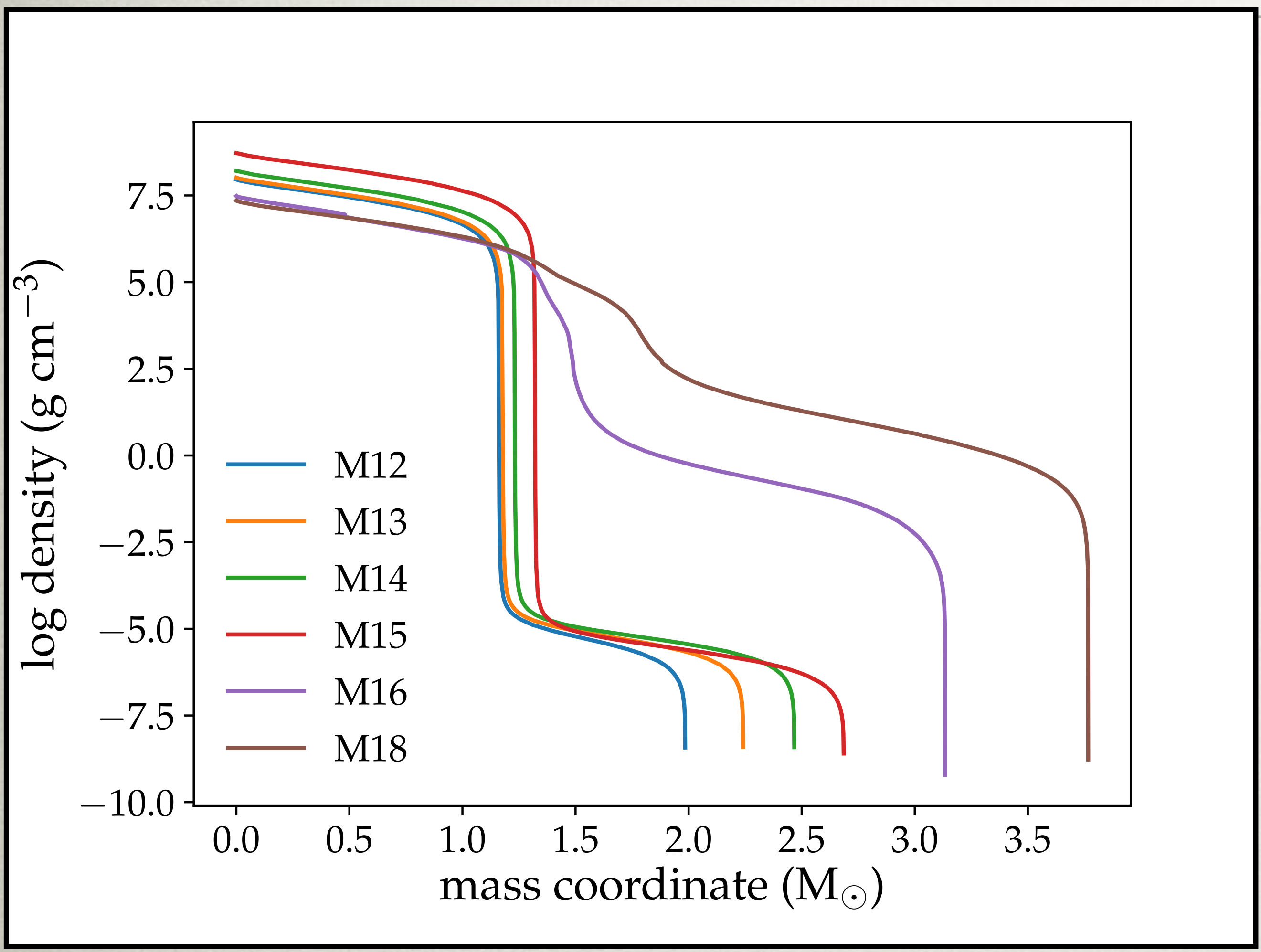


Large Presupernova Radii



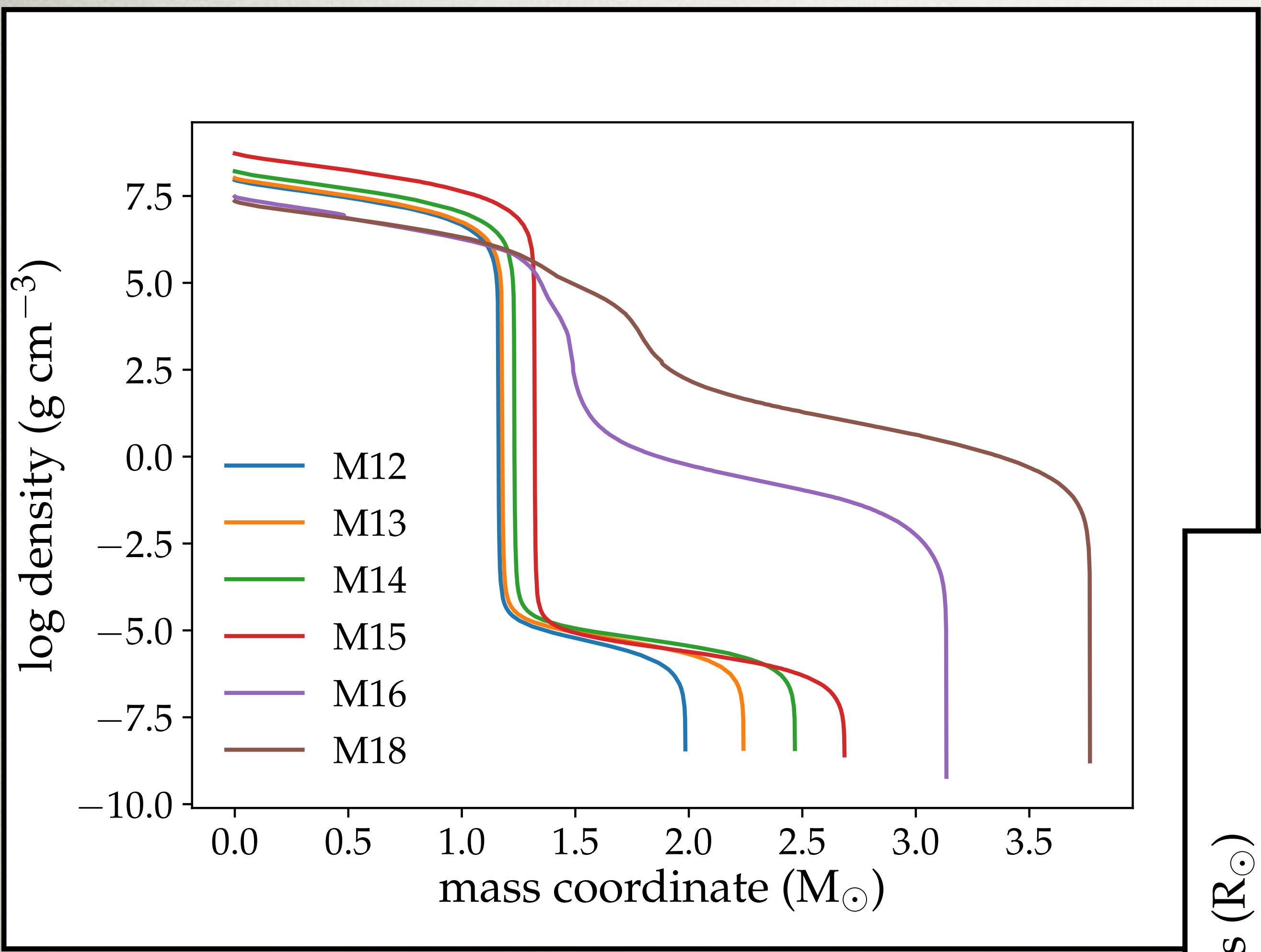
See e.g. Quataert & Shiode 2012

Large-Radius He Stars

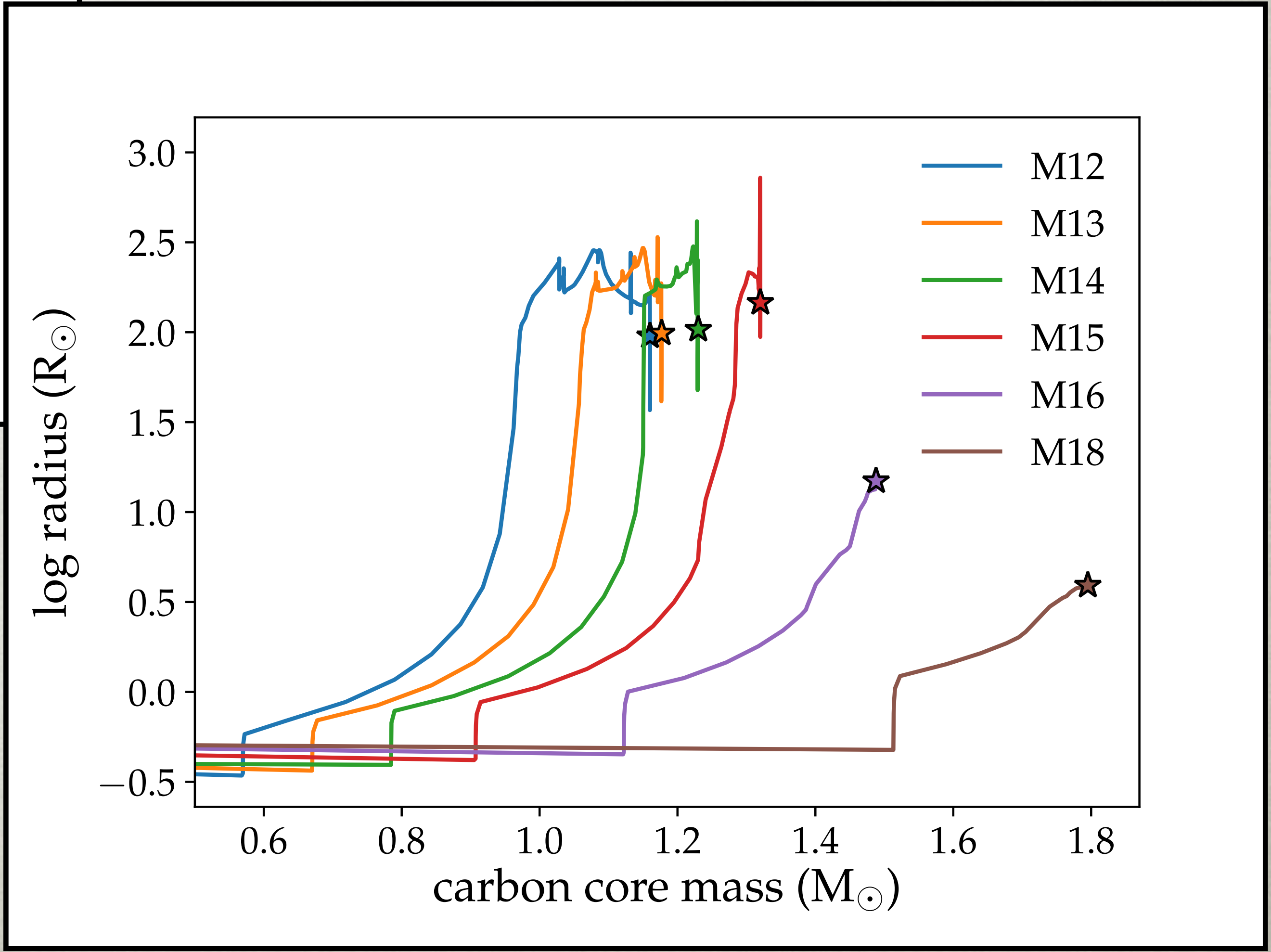


Kleiser et al. in press.

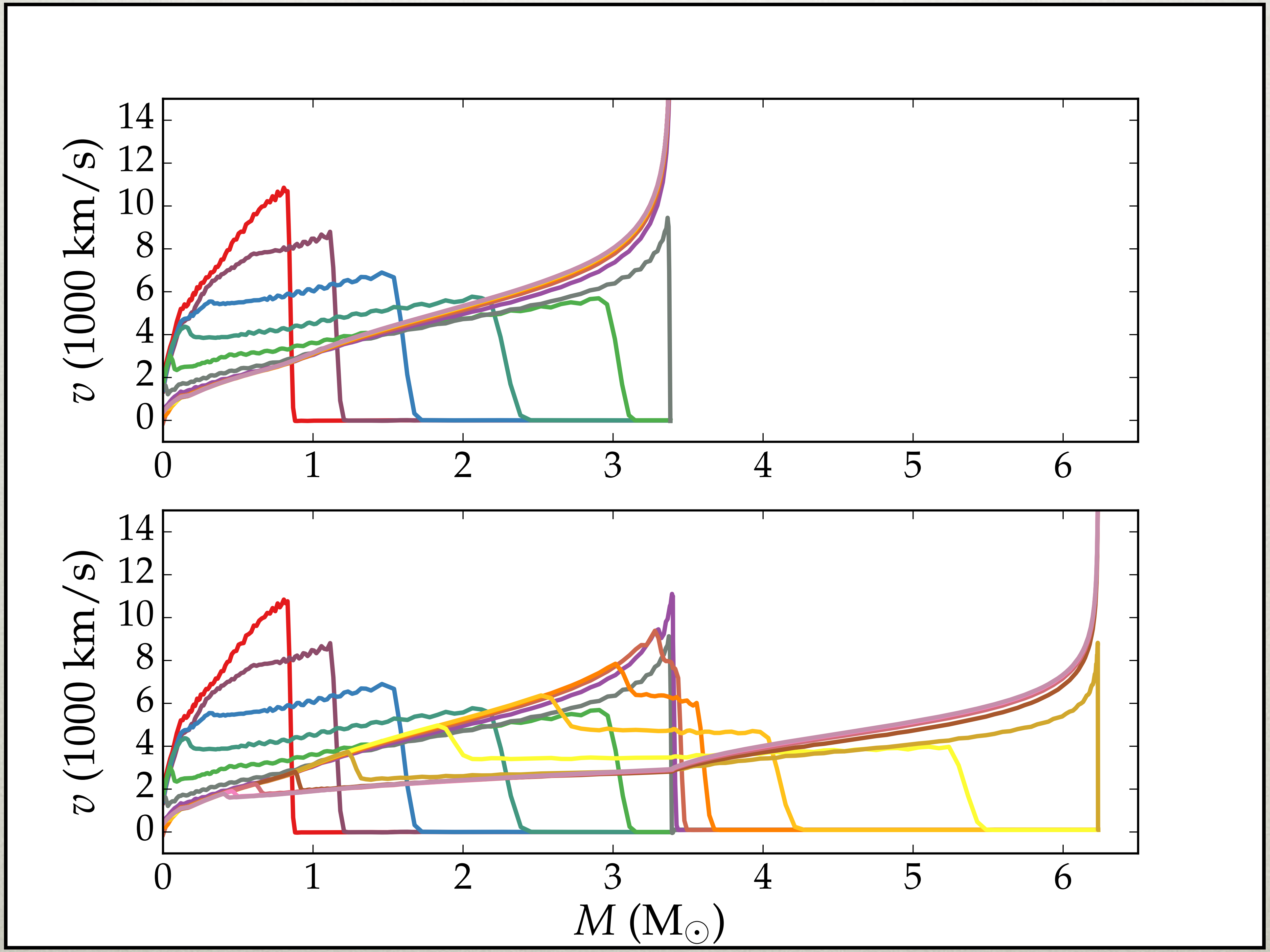
Large-Radius He Stars



Kleiser et al. in press.

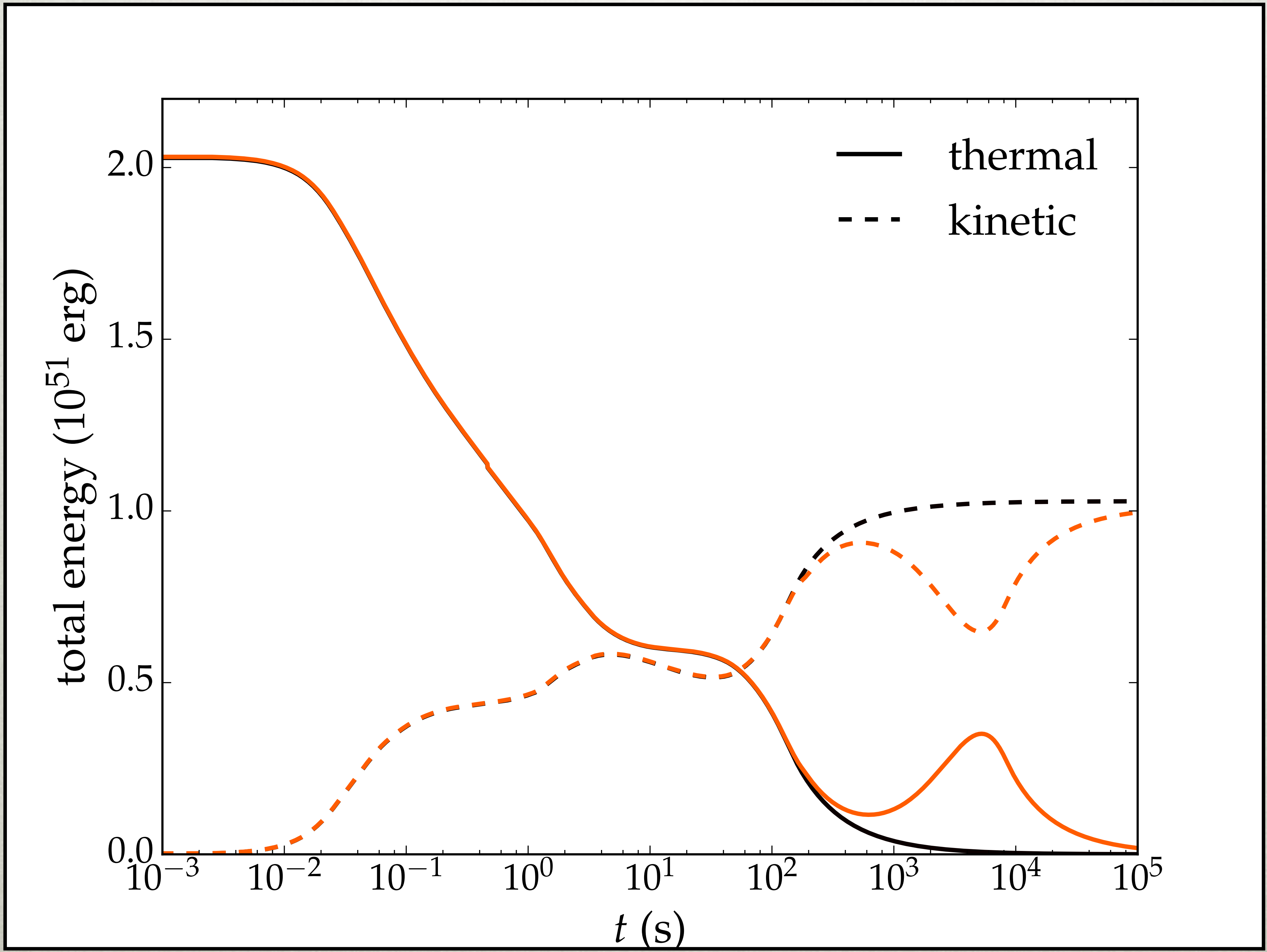


Collision with Shell/Envelope



Kleiser & Kasen 2018

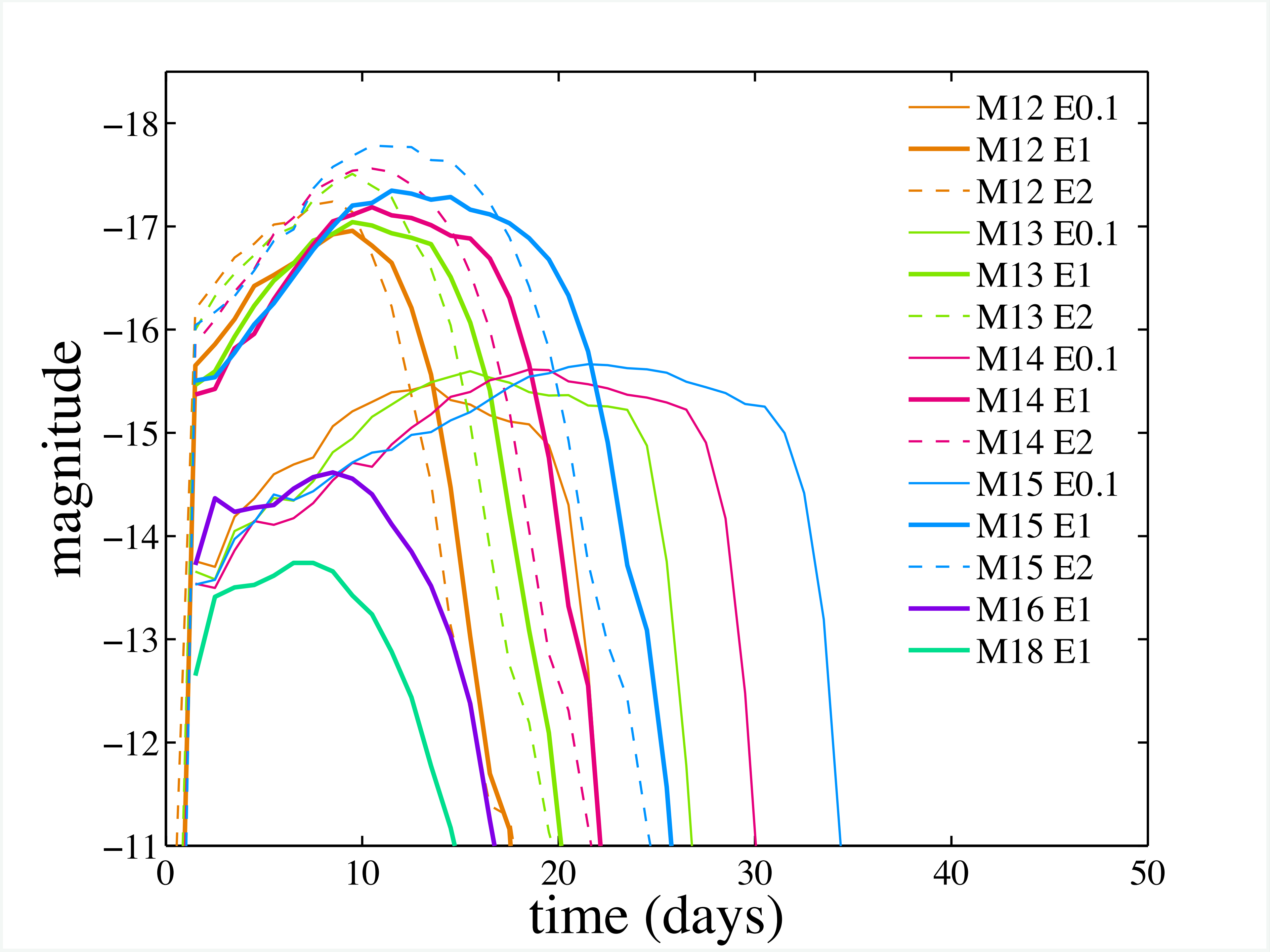
Collision with Shell/Envelope



Kleiser & Kasen 2018

A Self-Consistent Model?

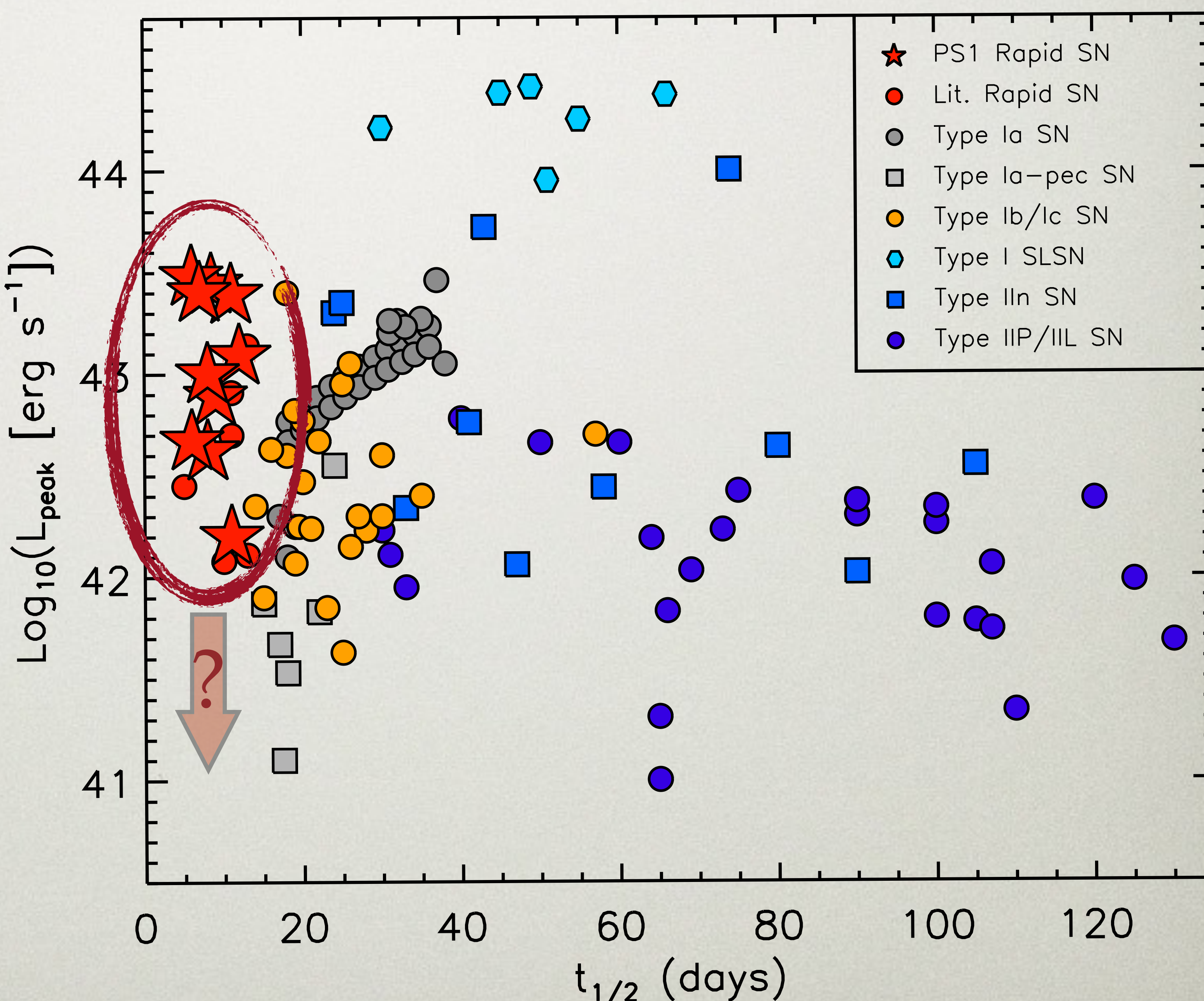
Kleiser et al. in prep.



Rapidly Fading Supernovae

RFSNe have ~4-7% of core-collapse rate

if these are massive ejections, they can impact the evolution of their galaxies



Drout et al. 2014

Summary

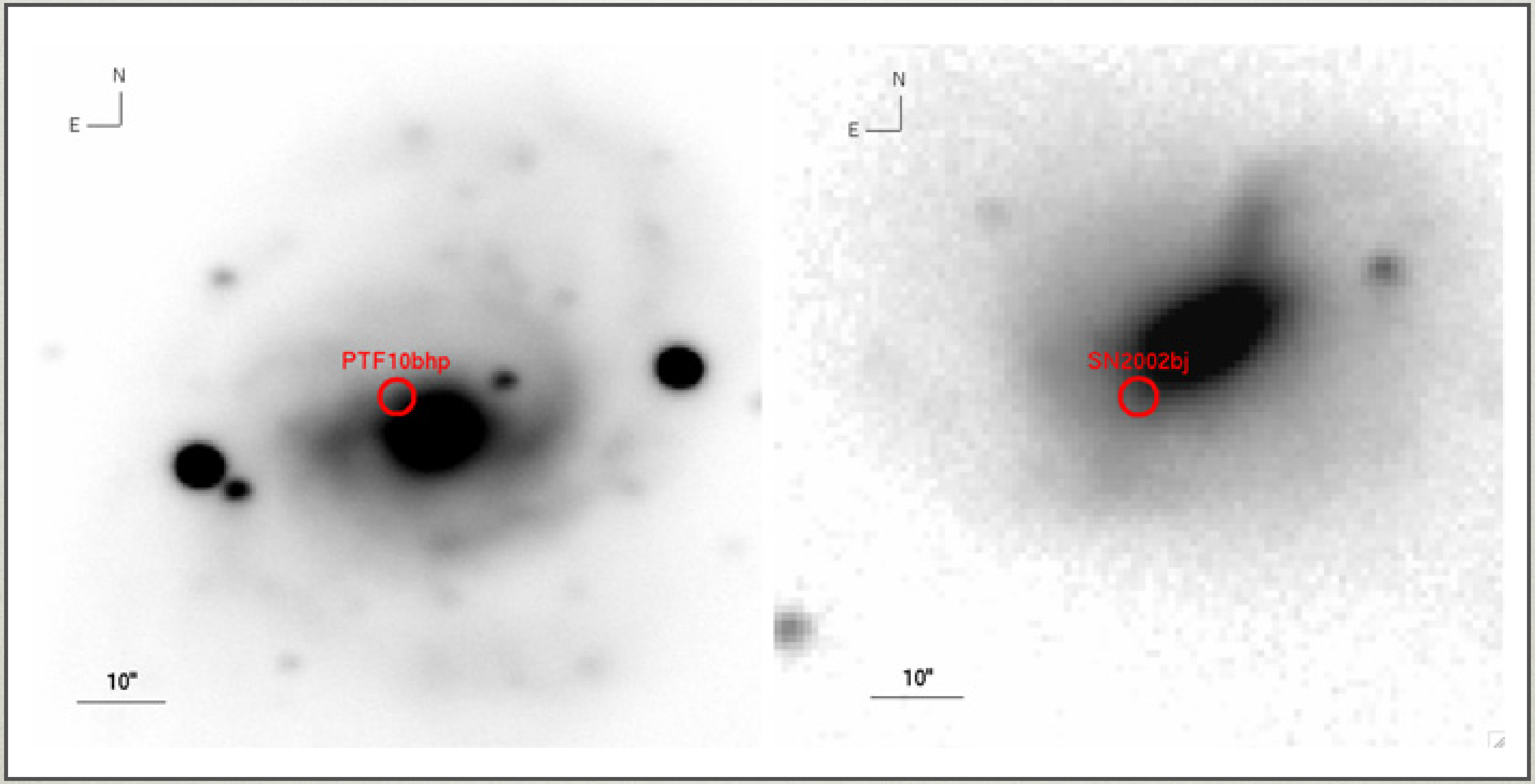
- **Rapidly fading supernovae** represent a new class of relatively poorly understood astronomical transients
- We found that a **large ejected mass** may be needed
- We explore **explosions of massive stars** in which **little or no radioactive material** is present in the ejecta
- To get nickel-free supernovae this bright would **require large pre-supernova radii**
- Model results show that **certain mass ranges of helium stars can naturally grow to large radii** and produce rapidly fading supernovae

Thank you!

Sterl Phinney

Dan Kasen

Host Galaxies

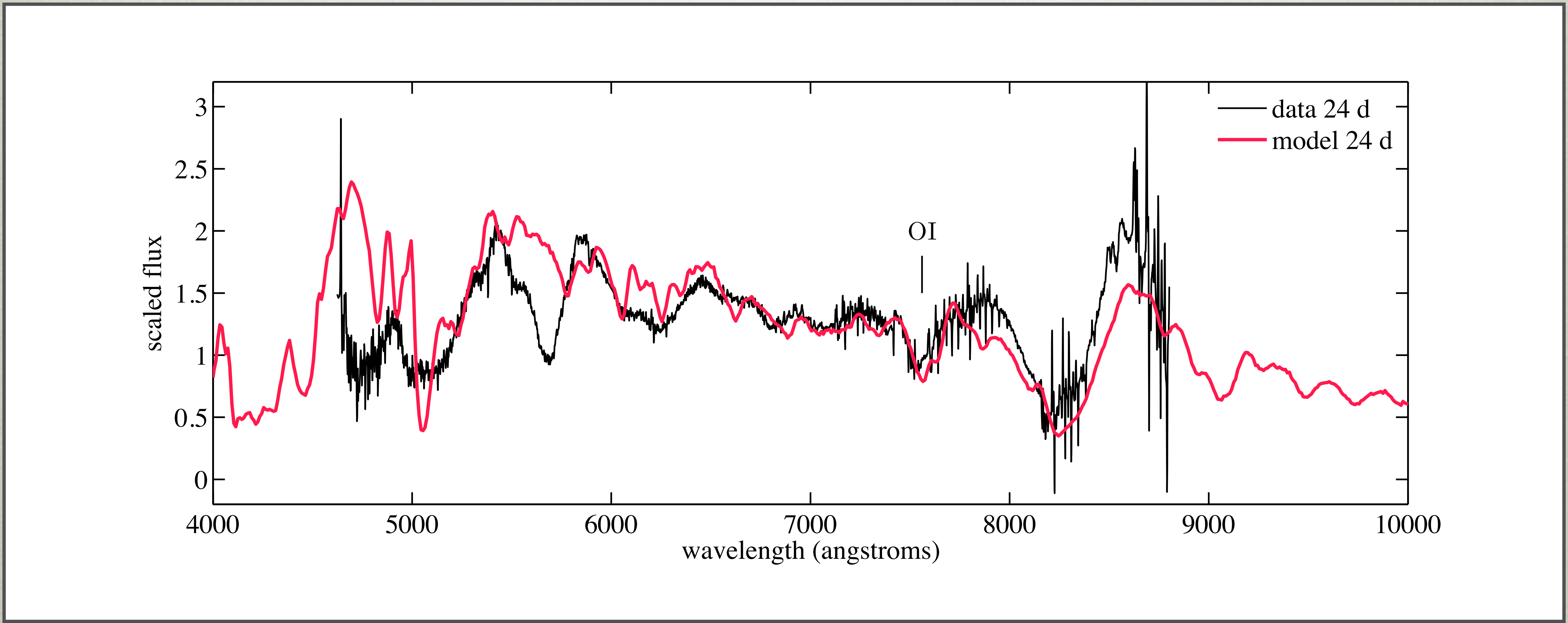


Hosts of SN 2010X (left) and SN 2002bj (right) are both star-forming galaxies and do not constrain the progenitors

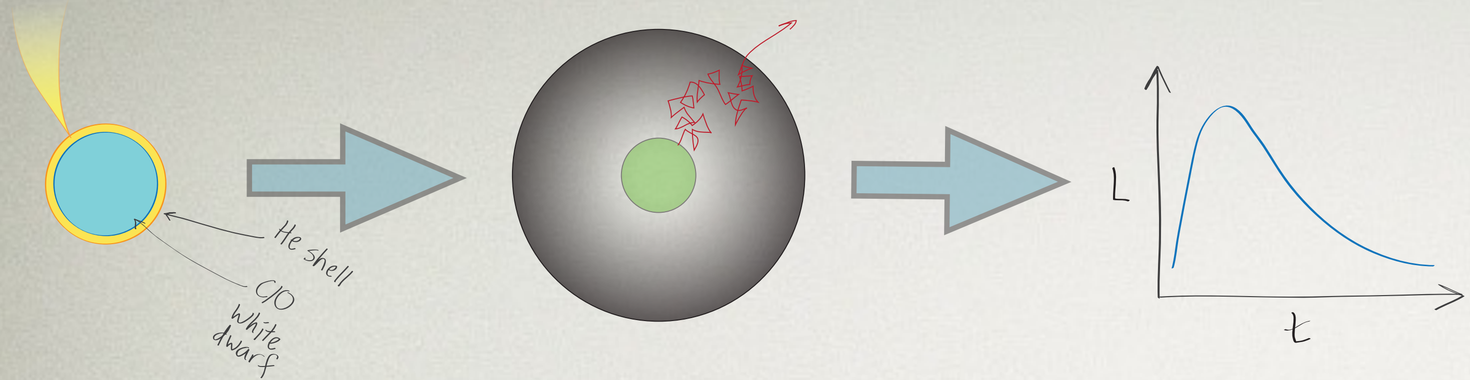
Kasliwal et al. 2010

SN 2010X Model Spectrum

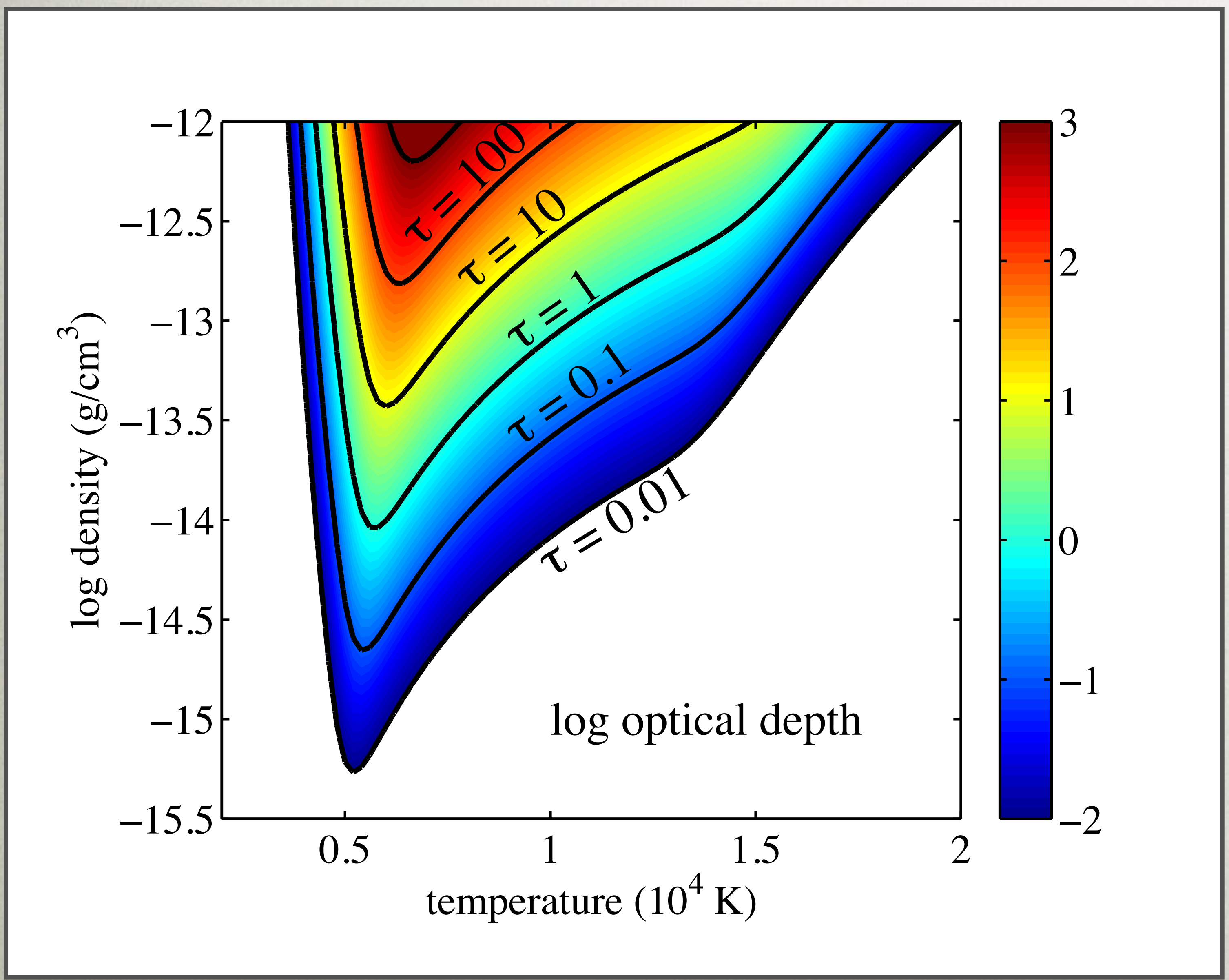
Kleiser & Kasen 2014



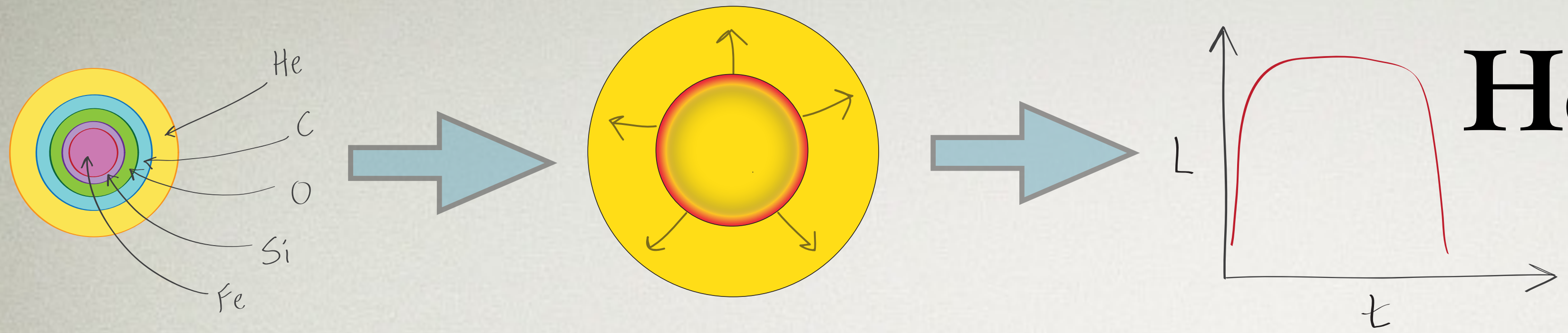
Strong oxygen feature in the spectra indicates more mass than possible in previous models



Problems with the ".Ia" Model



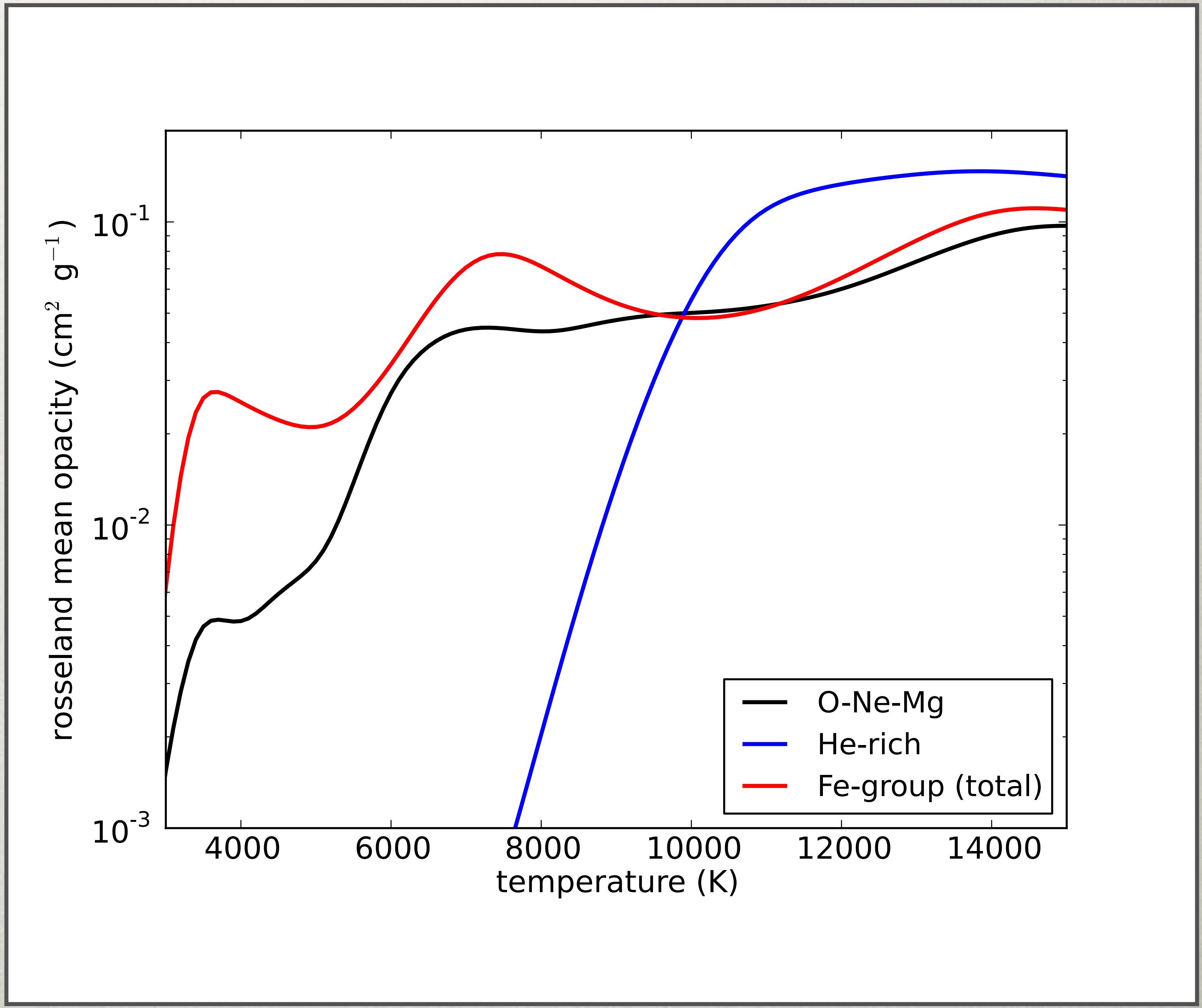
- No radioactive tail seen (could be below limits; could be little γ-ray trapping)
- Deep oxygen features require a large O mass ($\sim 0.3\ M_\odot$), larger than the total ".Ia" ejected mass of $\sim 0.1\ M_\odot$



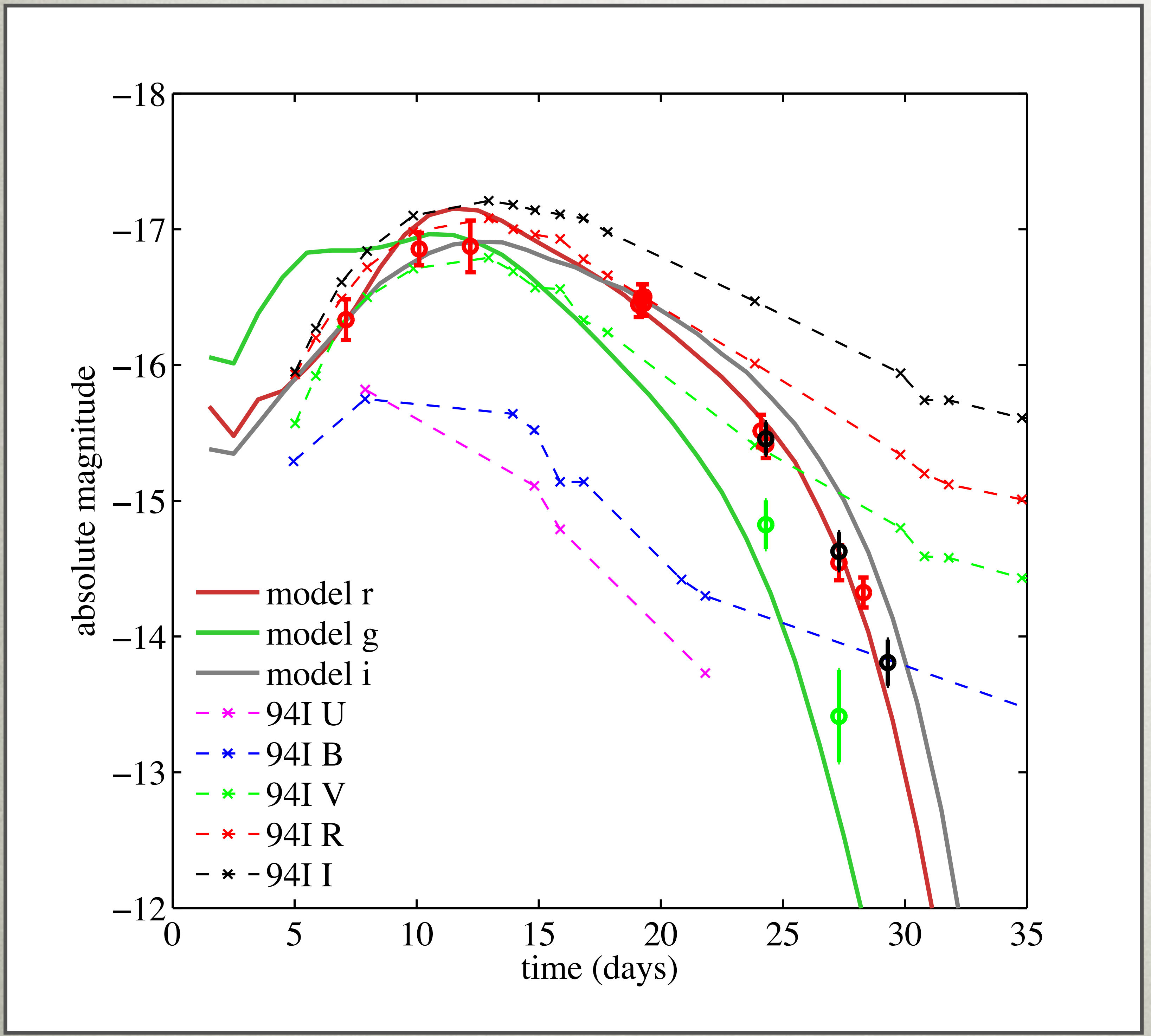
Helium Plateau SNe

- With little or no nickel, luminosity comes from diffusion of thermal energy deposited in the explosion shock
- Analogous to a Type II "plateau"
- O recombination allows radiation to be released more rapidly

(see Ensman & Woosley 1988, Dessart et al. 2011)



Model Light Curves



Representative model fit; Type Ic SN 1994I for comparison

Model parameters:

$M = 3.5\ \mathrm{M}_\odot$

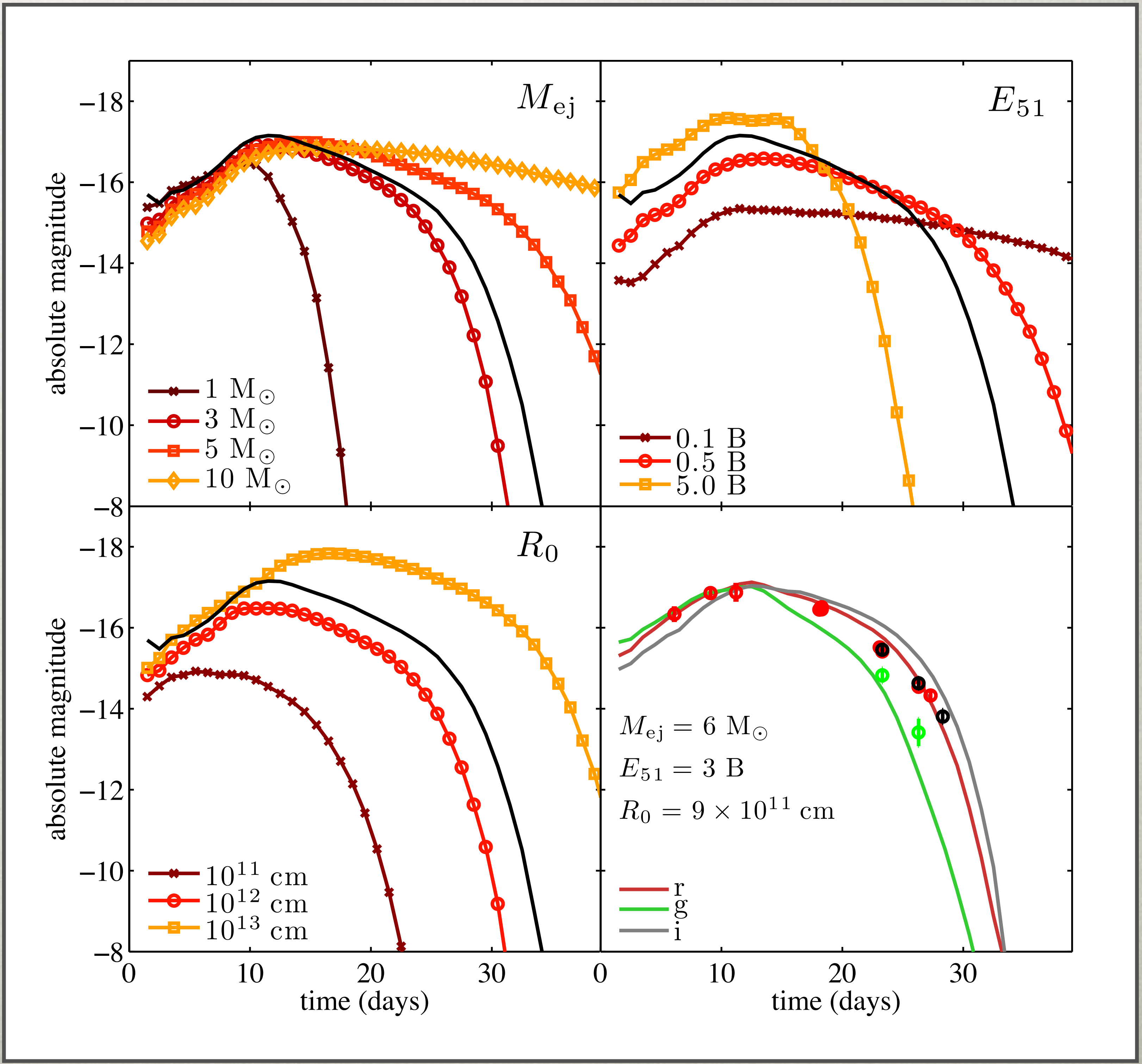
$E = 1\ B$

$R = 2 \times 10^{12}\ \mathrm{cm}$

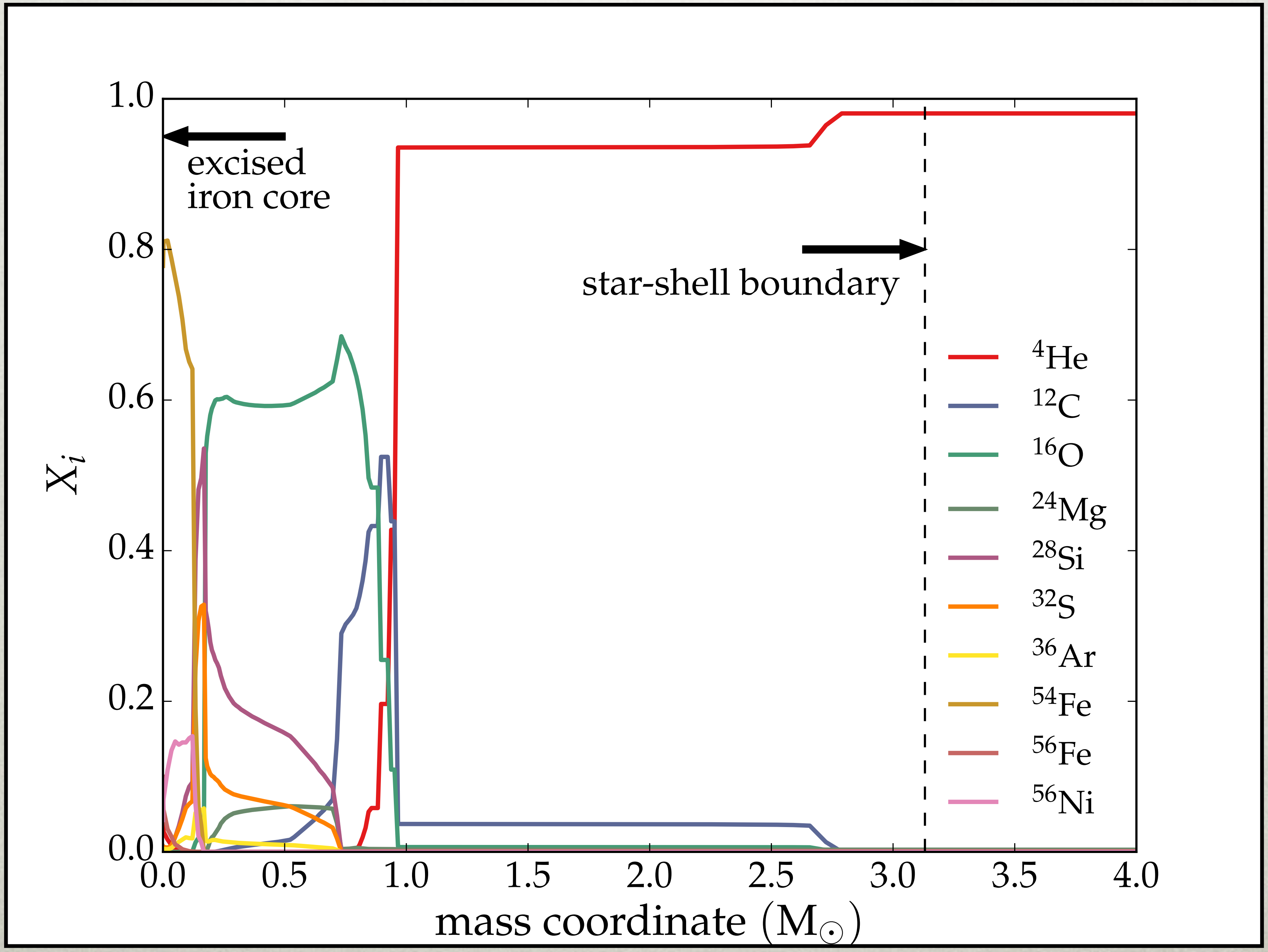
Dominantly O, Ne, Mg in composition

Degeneracy & Model Grids

- Parameters can be adjusted to fit a wide range of light curves
- Some degeneracy among them
- Adding nickel as a fourth parameter would allow us to explore connection to normal SNe Ibc

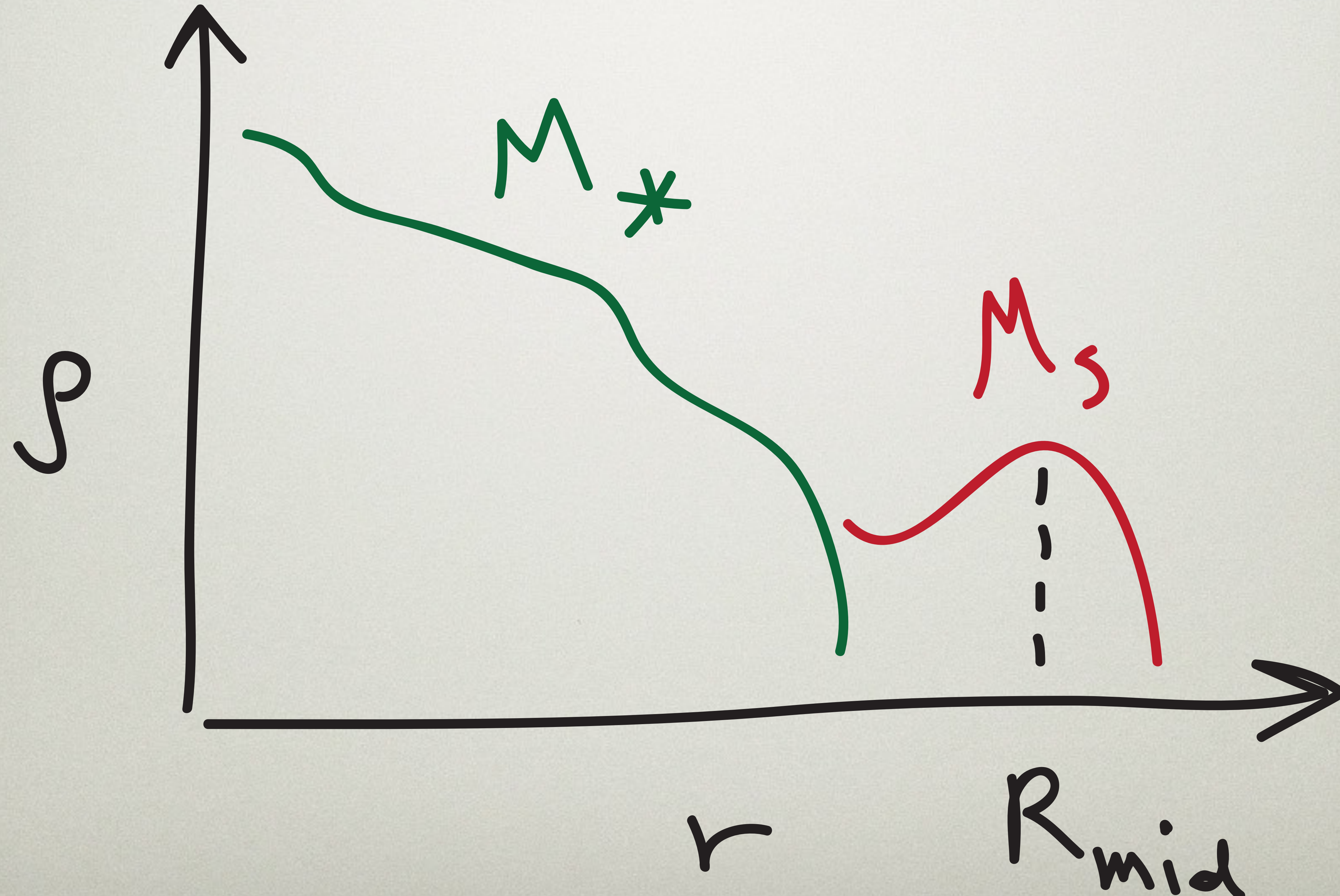


Composition



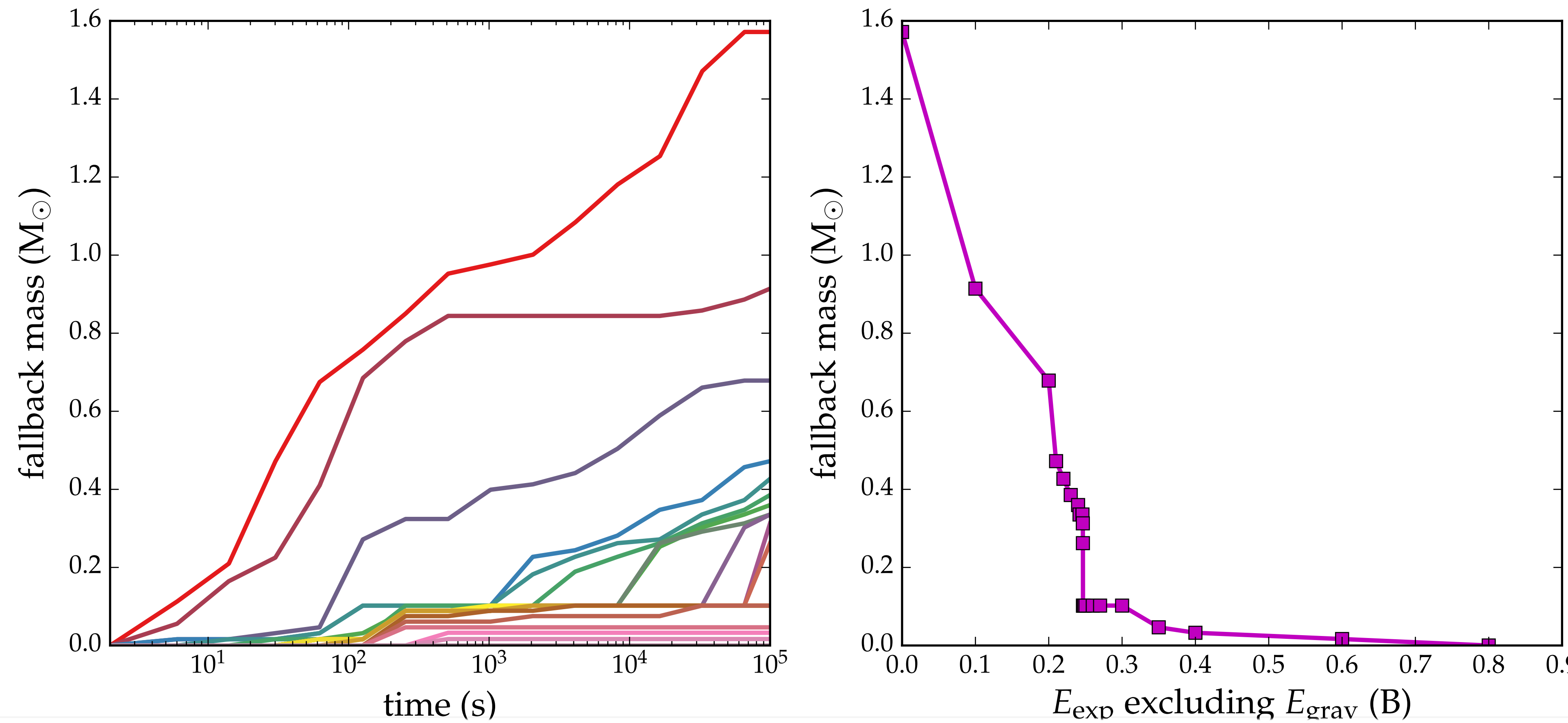
Kleiser & Kasen 2018

Adding a Toy Mass Shell



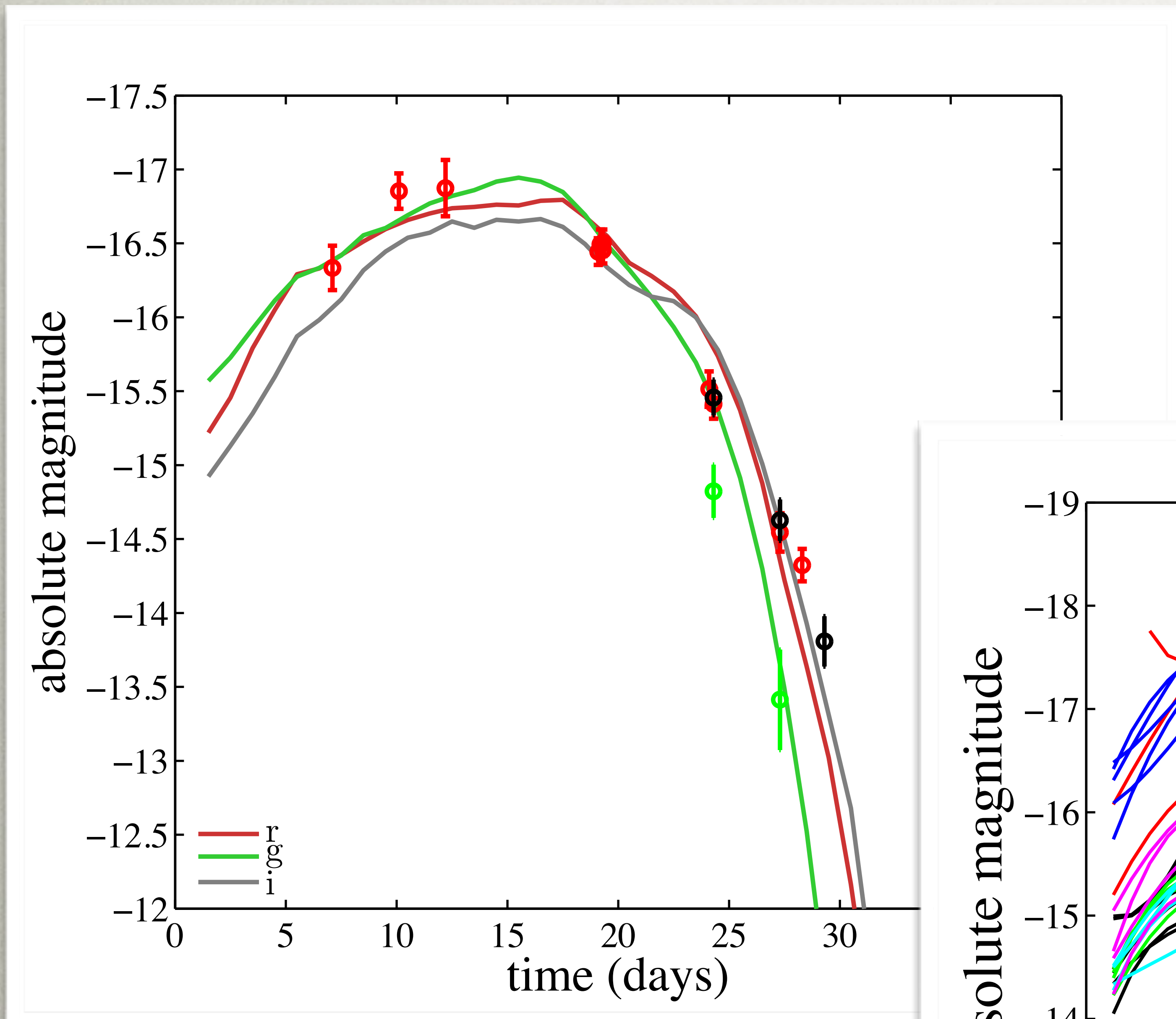
Fallback

Kleiser & Kasen 2018

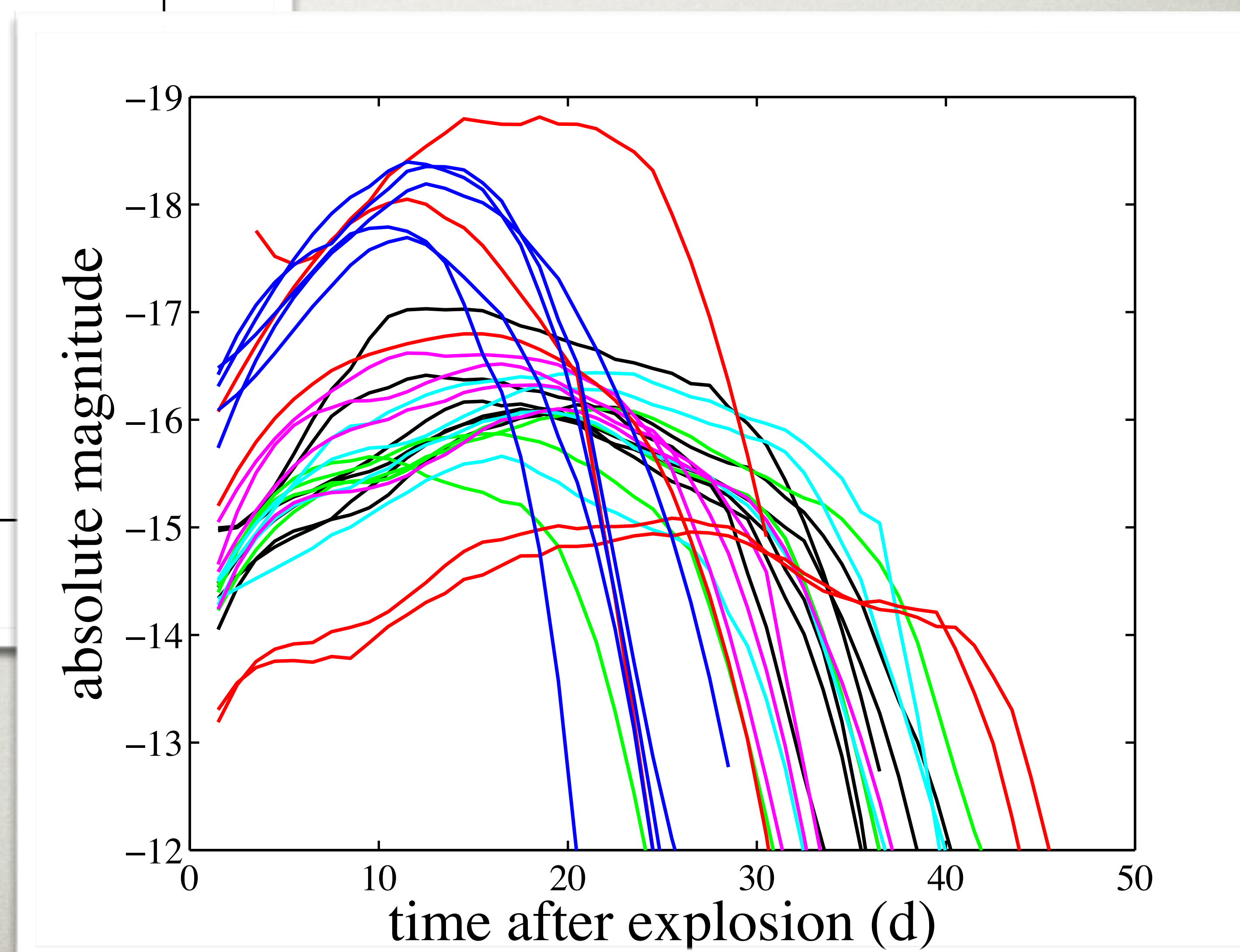


Lower explosion energies allow some of the innermost layers to fall back onto the remnant

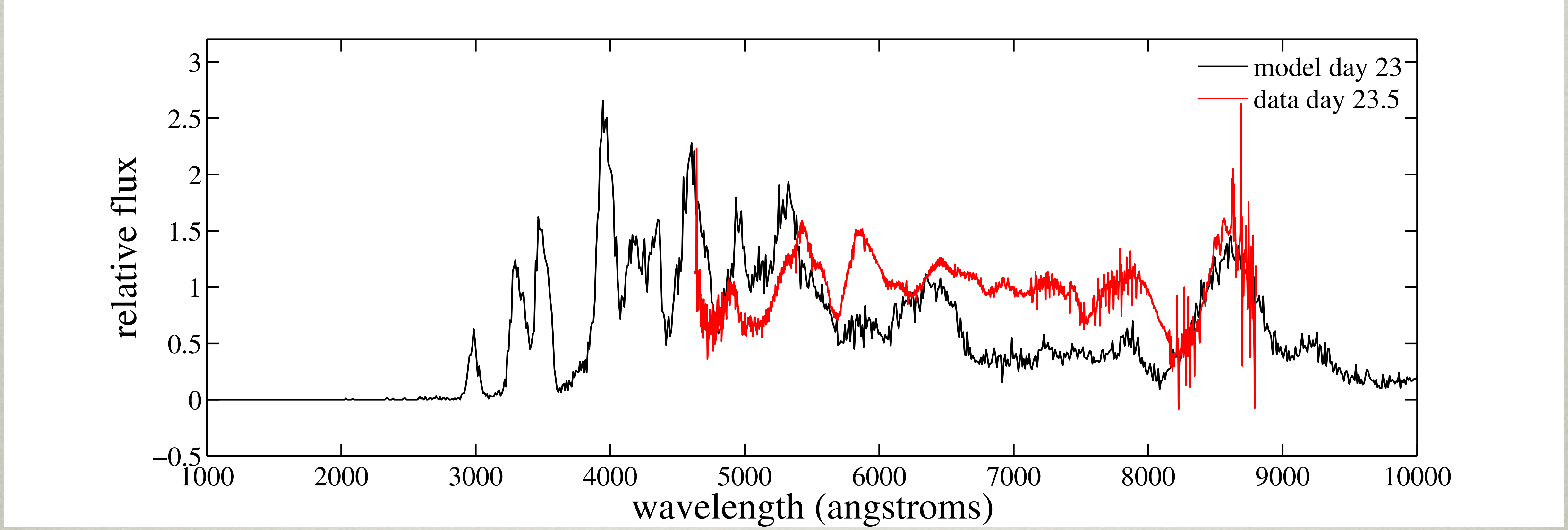
Model Light Curves



Kleiser & Kasen 2018

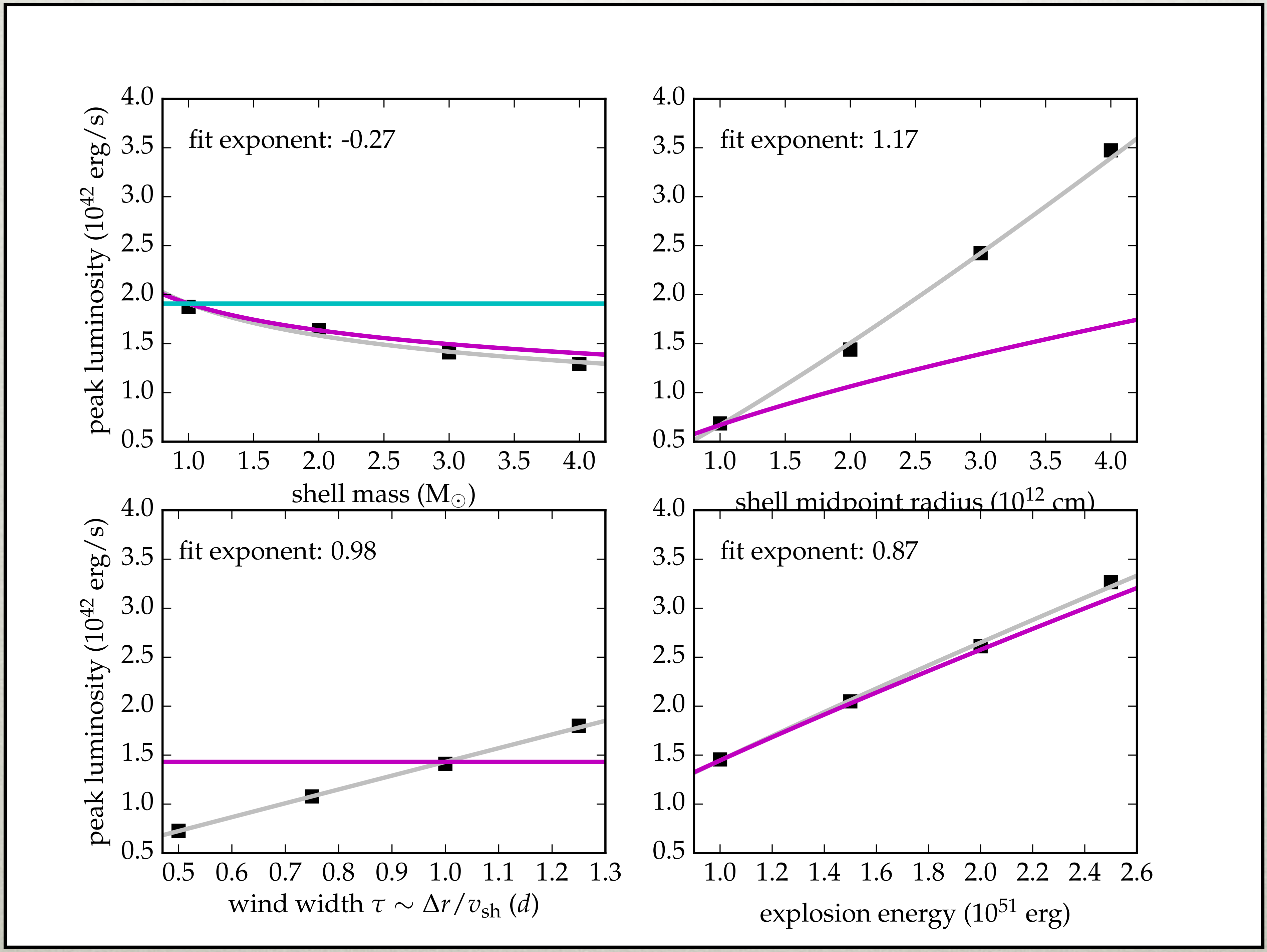


Example Spectrum: 2010X



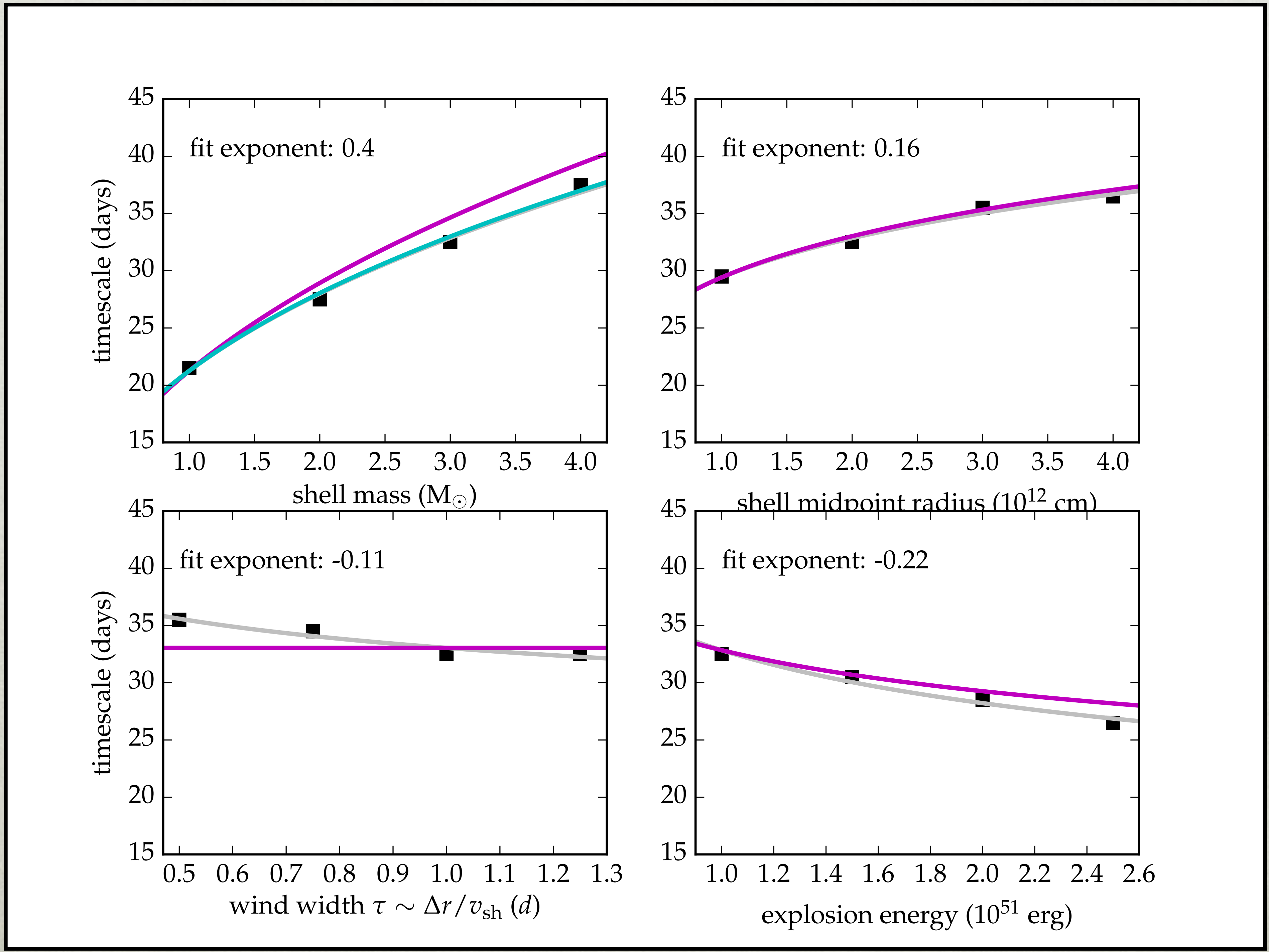
Kleiser & Kasen 2018

Parameter Study: Peak Luminosity



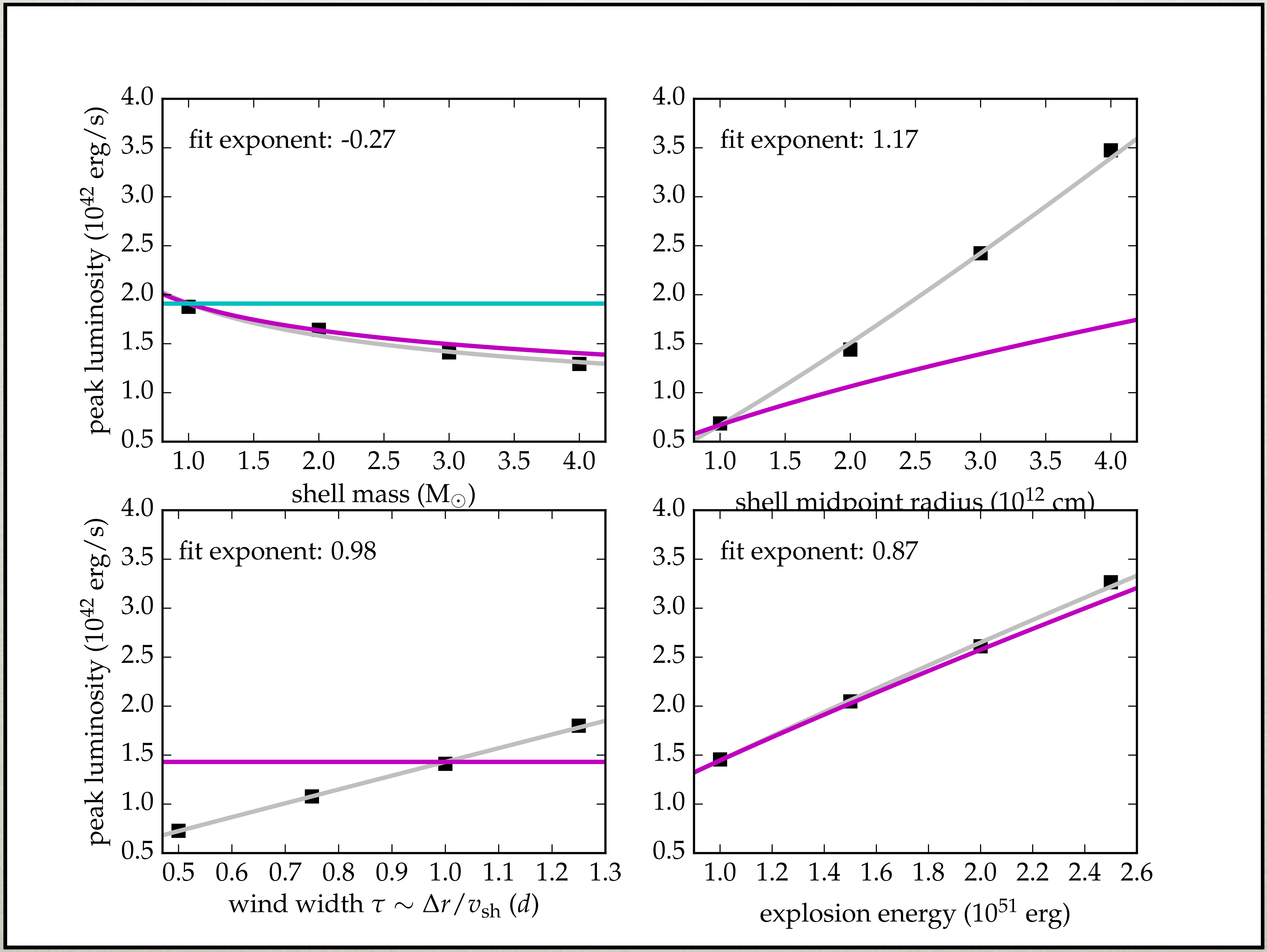
Kleiser & Kasen 2018

Parameter Study: Timescale



Kleiser & Kasen 2018

Parameter Study: Thermal Energy



Kleiser & Kasen 2018

Analytical Estimates

$$L_{\rm sn} \propto E_{\rm exp}^{5/6} M_{\rm CSM}^{\frac{5(n-5)}{6(n-3)}-\frac{1}{2}} R_{\rm CSM}^{2/3} \kappa^{-1/3} T_I^{4/3}$$

$$t_{\rm sn} \propto E_{\rm exp}^{-1/6} M_{\rm CSM}^{\frac{-(n-5)}{6(n-3)}+\frac{1}{2}} R_{\rm CSM}^{1/6} \kappa^{1/6} T_I^{-2/3}$$

Analytic Fits

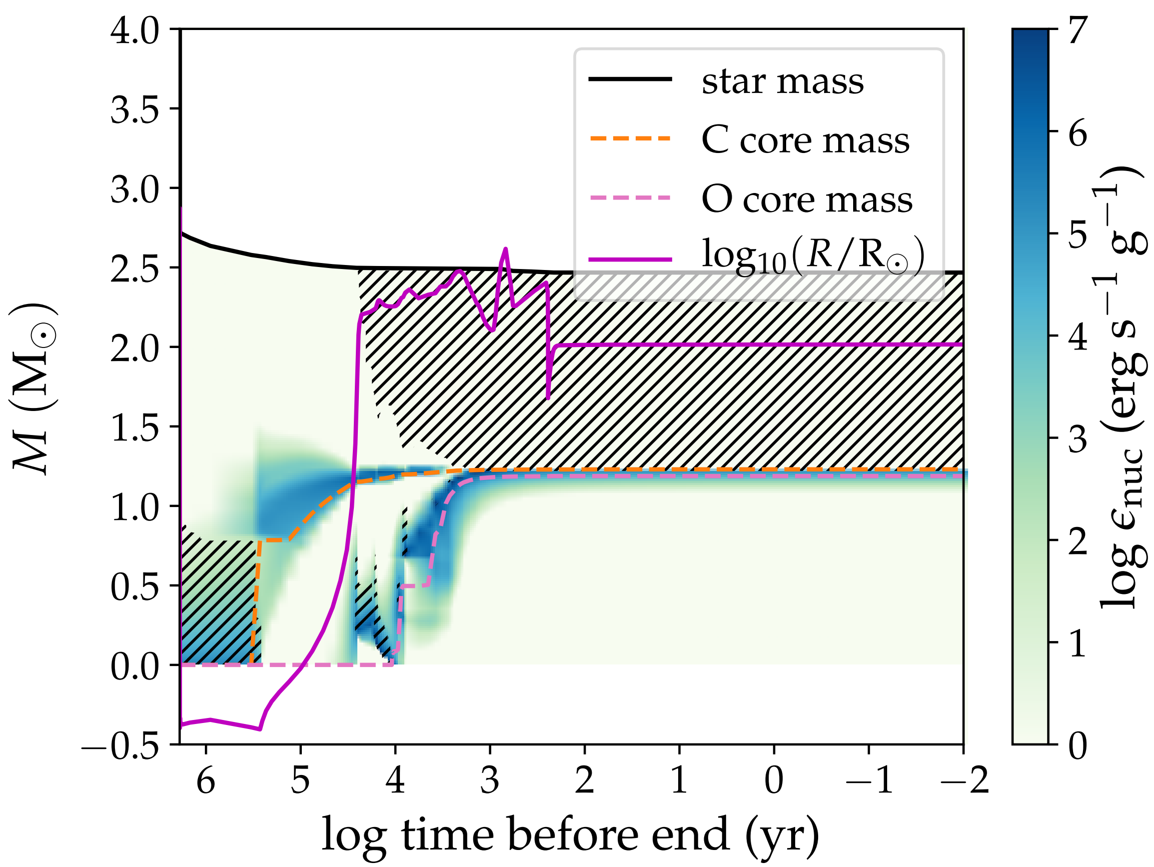
$$L_{\mathrm{sn}} \approx (1.3 \times 10^{42}\ \mathrm{erg/s})\ M_{\mathrm{CSM}}^{-0.27} R_0^{1.17} \tau^{0.98} E_{\mathrm{exp}}^{0.87}$$

$$t_{\mathrm{sn}} \approx (29\ \mathrm{days})\ M_{\mathrm{CSM}}^{0.4} R_0^{0.16} \tau^{-0.11} E_{\mathrm{exp}}^{-0.22}$$

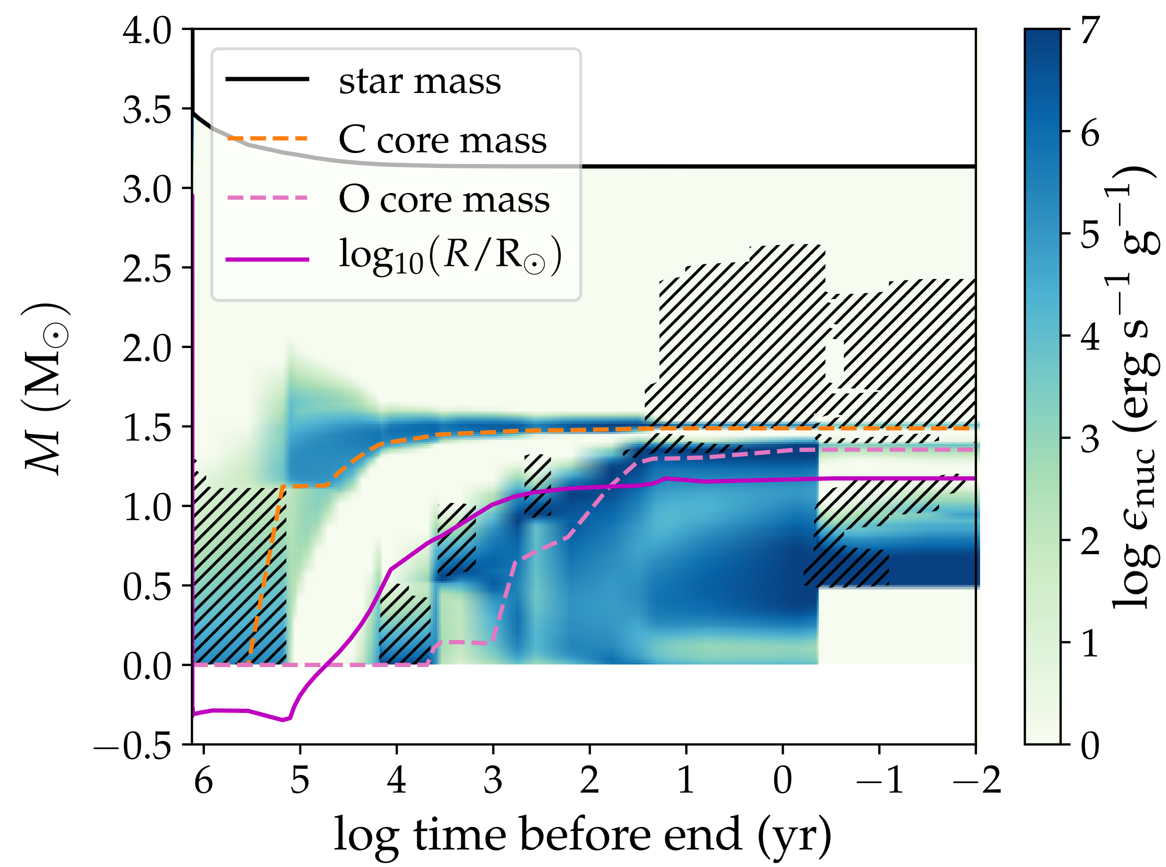
Large-Radius He Stars

Kippenhahn diagrams

14 solar mass



16 solar mass

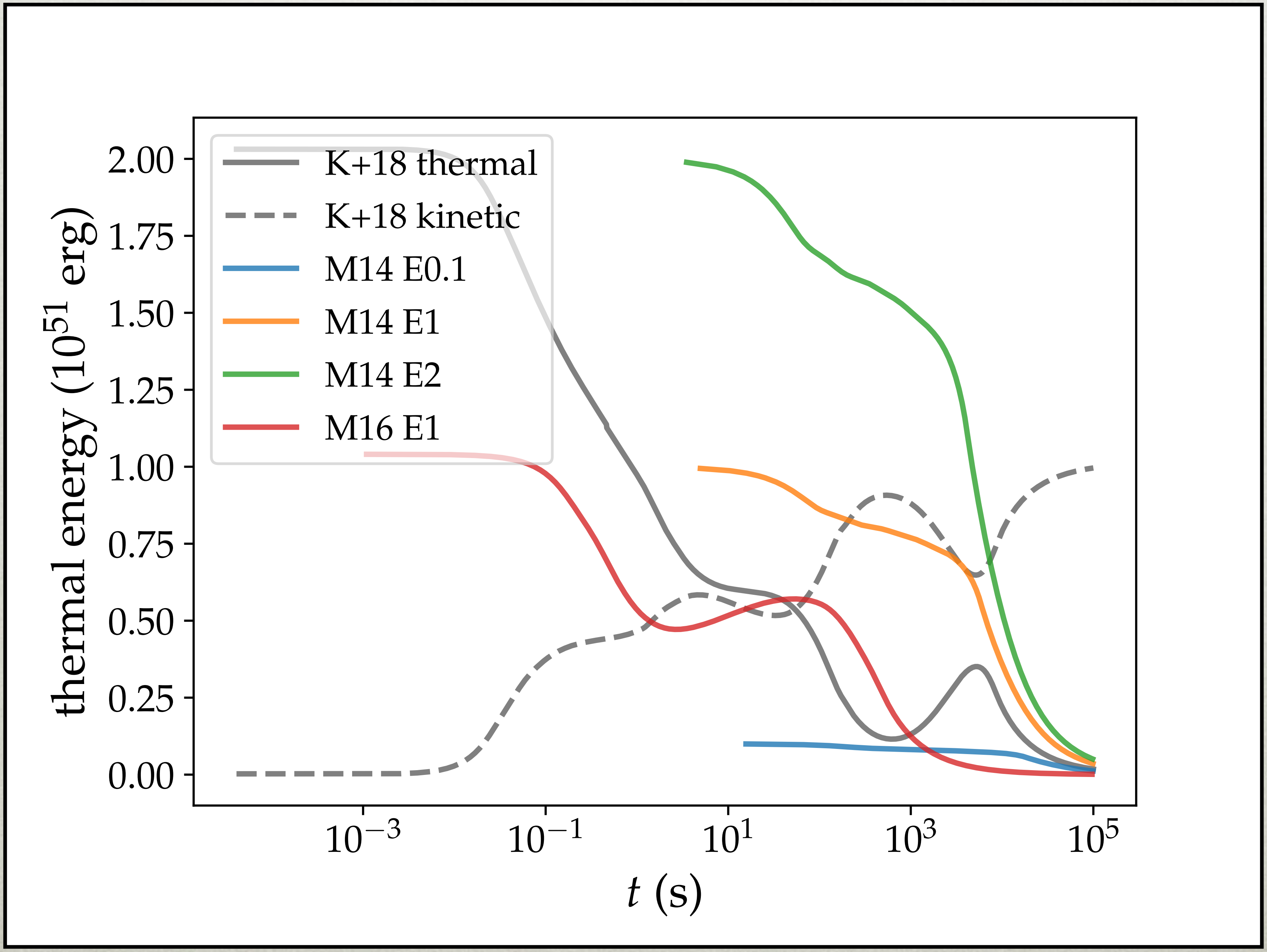


Kleiser et al. in prep.

hatches = convective

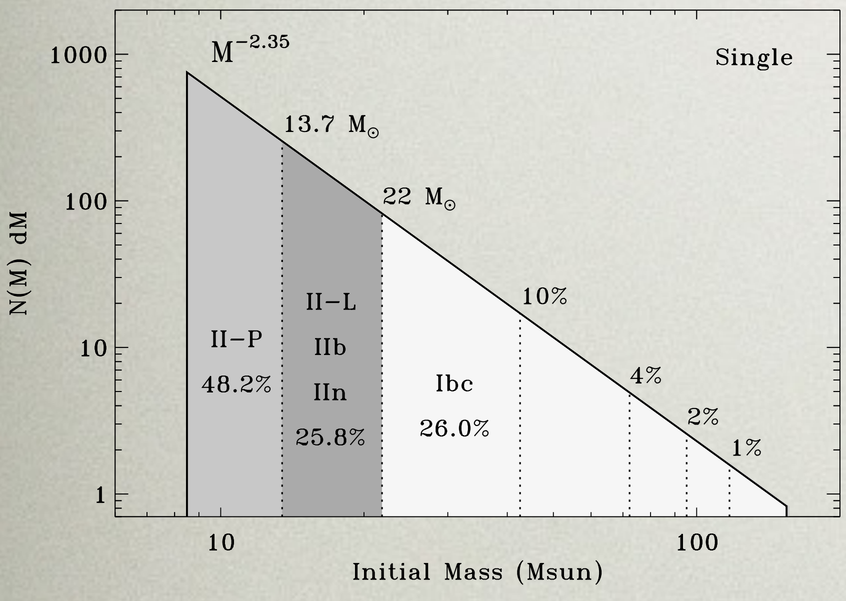
A Self-Consistent Model?

Kleiser et al. in prep.

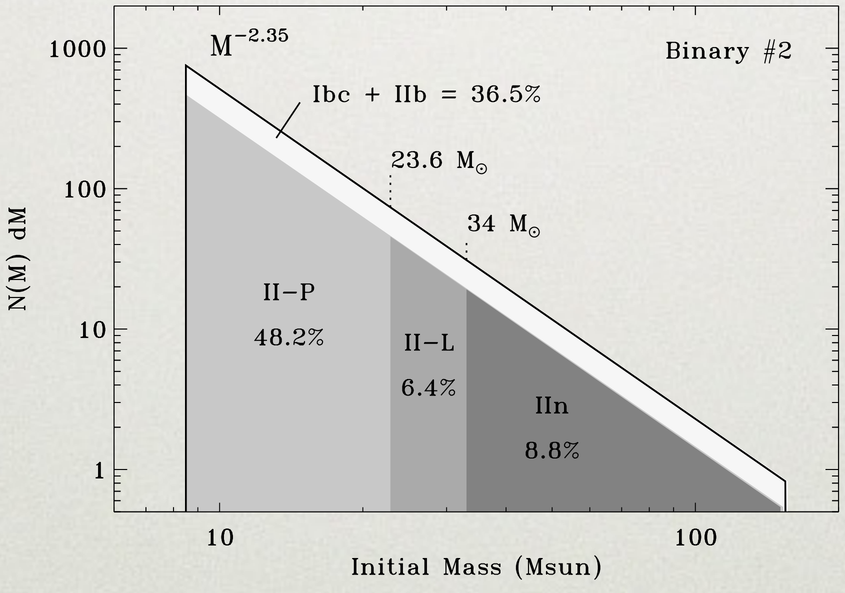


Deficiency of High-Mass Stars

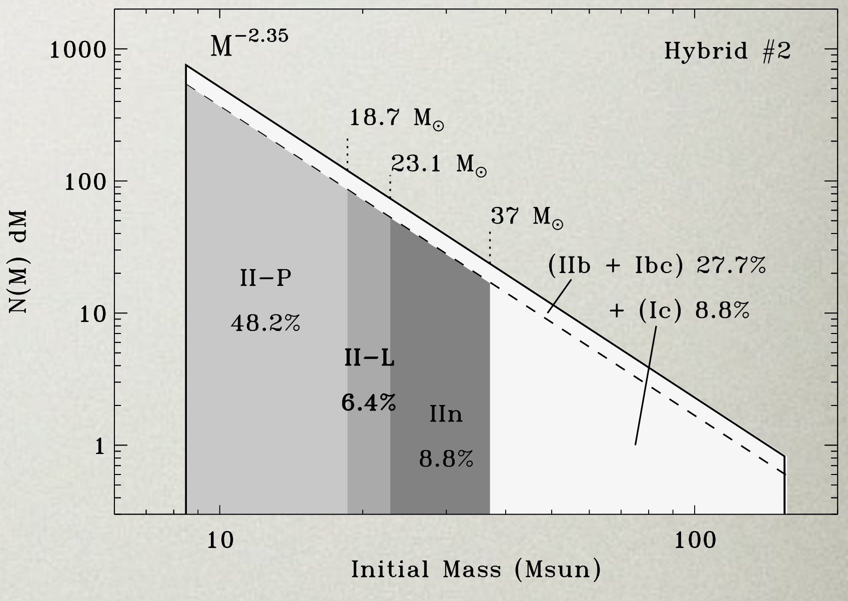
single stars only



binary systems only

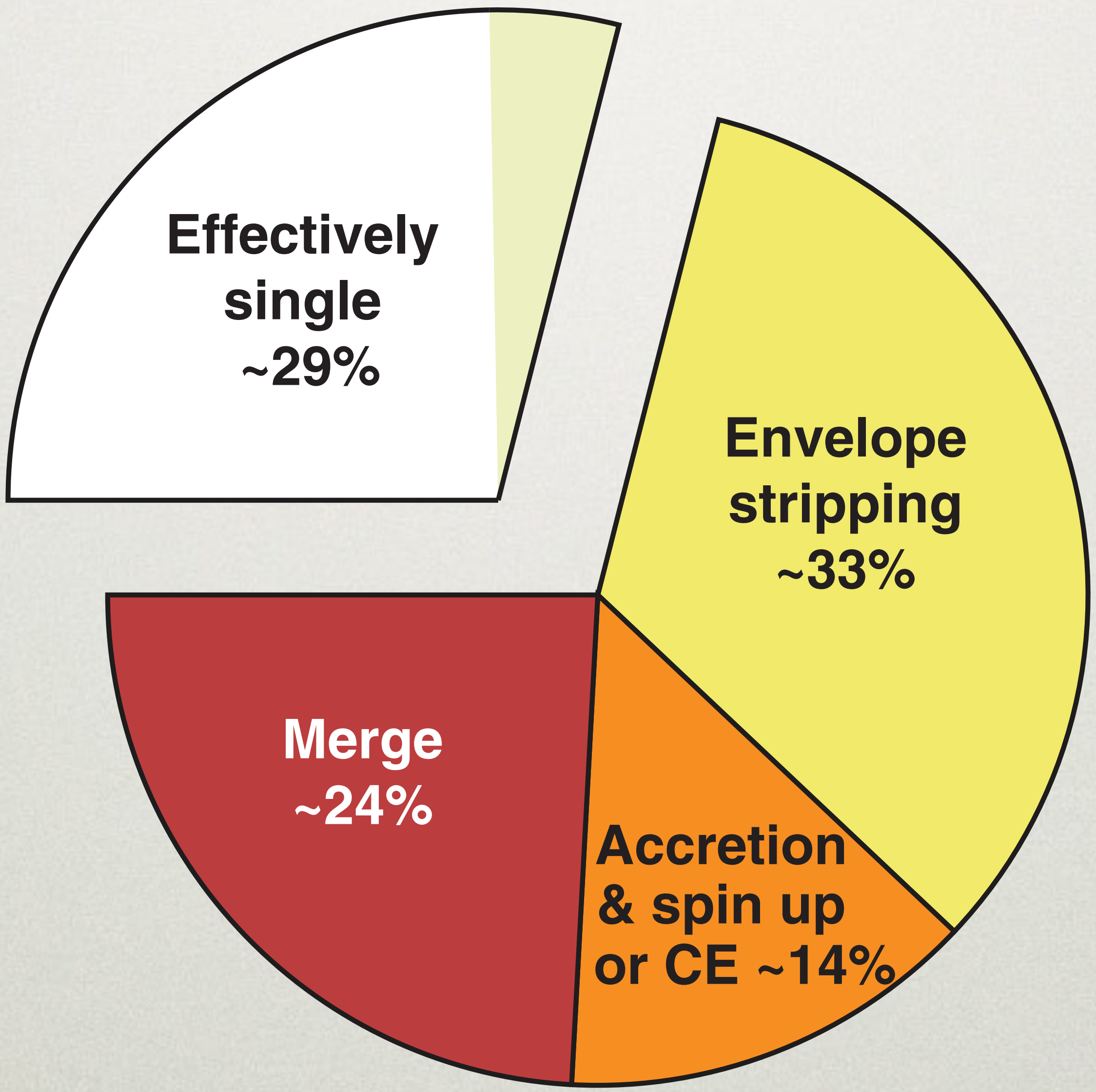


hybrid models



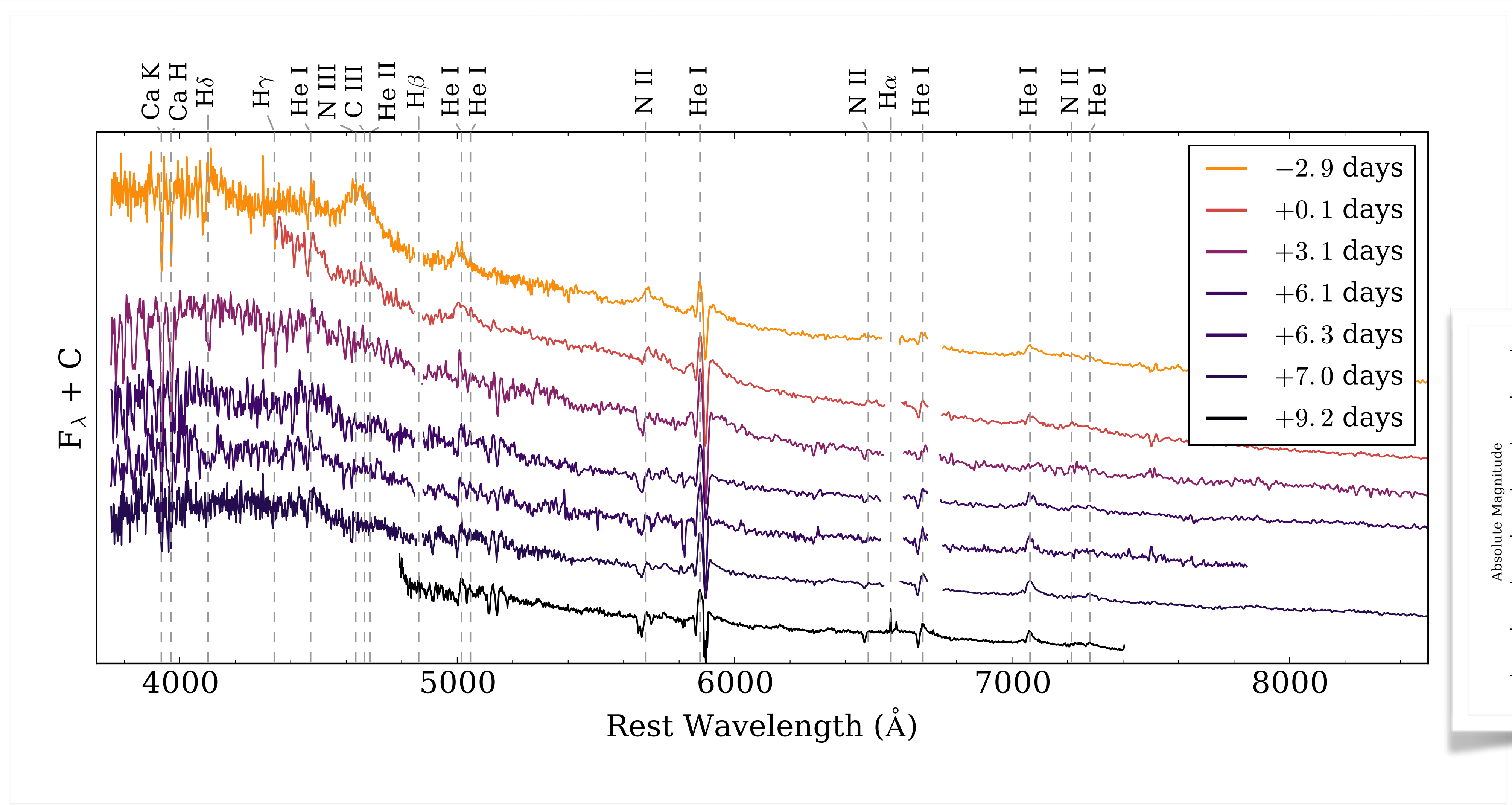
Smith et al. 2011

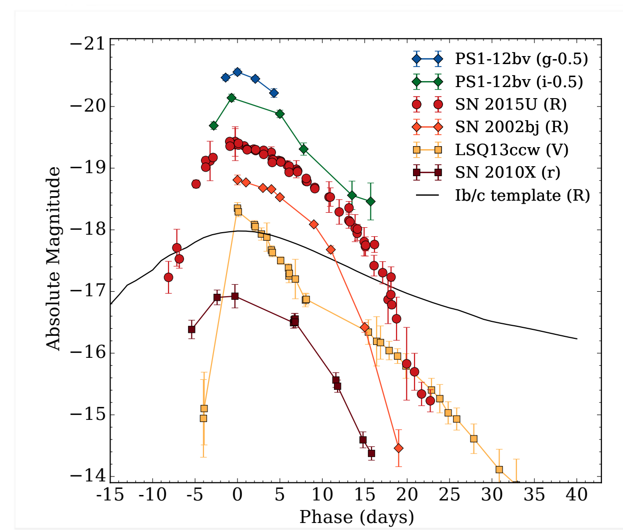
Frequency of Binarity



Sana et al. 2012

SN 2015U He Narrow Lines

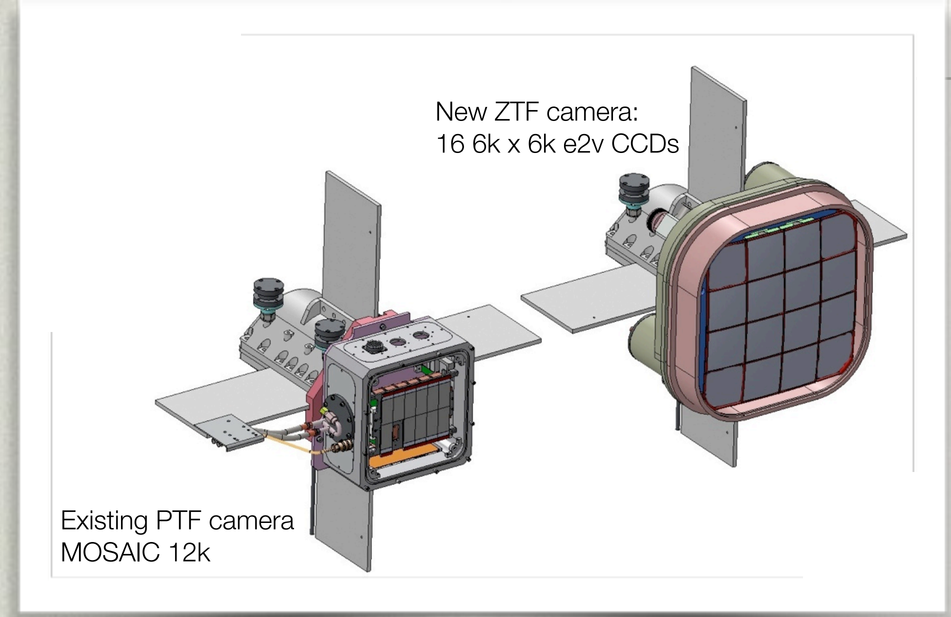


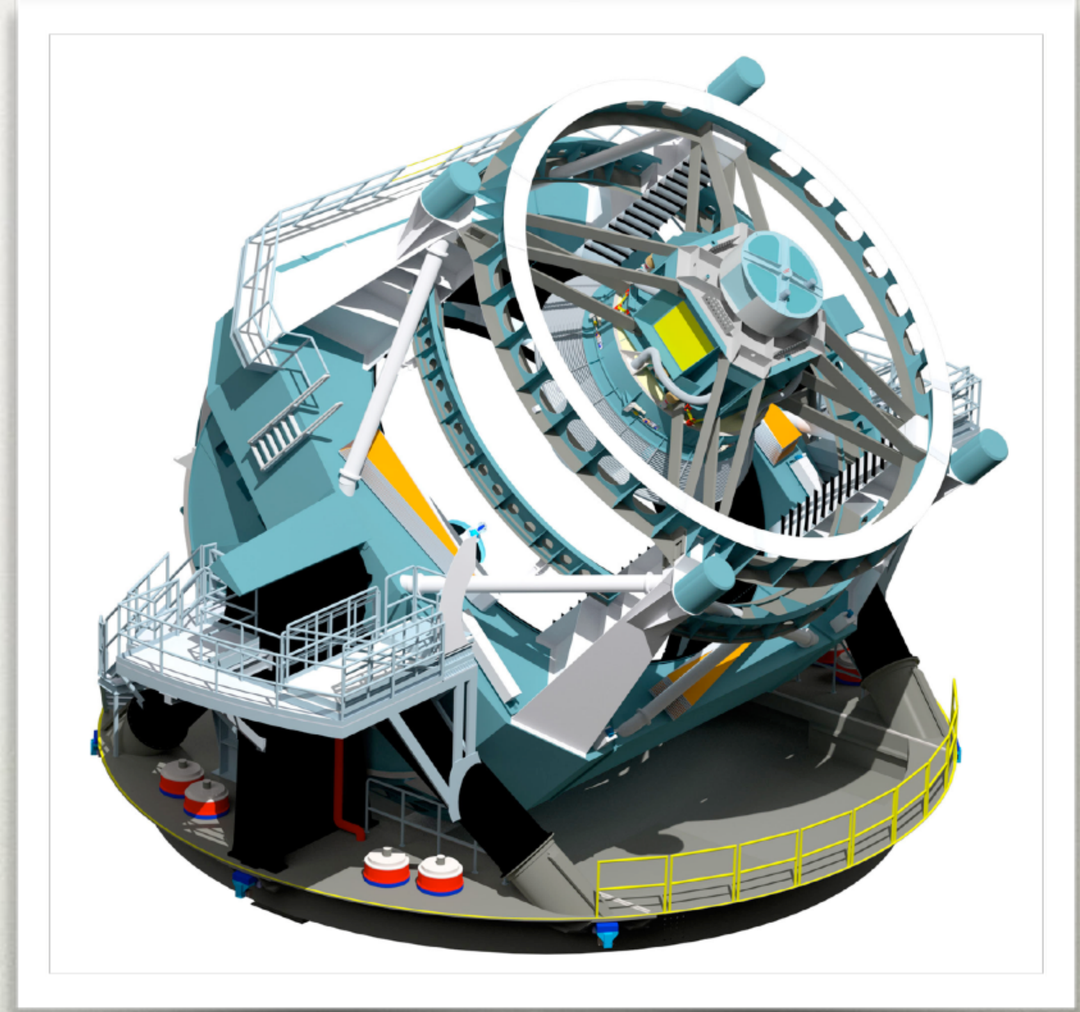


Shivvers et al. 2016, see also Pastorello et al. 2016

The Era of ZTF, LSST, and Other Surveys

Presentation by Eric Bellm



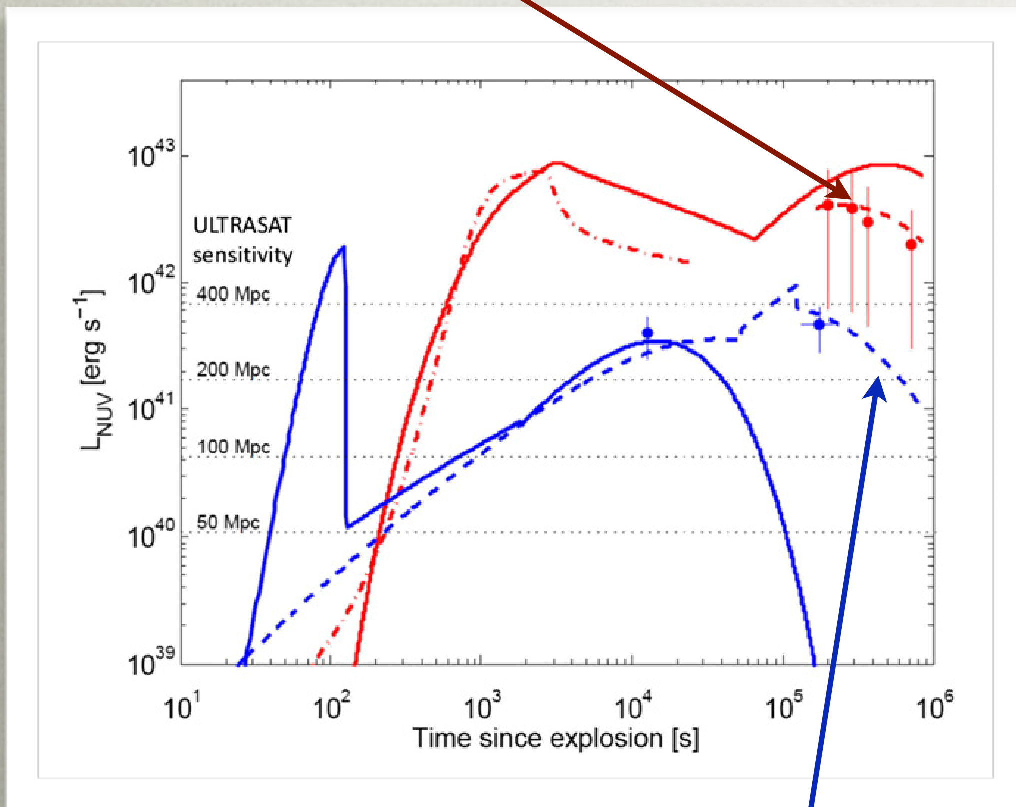


SLAC Today

- iPTF found 14 SNe Ibc in 2014; ZTF should scale discovery up by the field of view, ~90 SNe Ibc per year
- LSST will discover hundreds of thousands of SNe Ibc per year

Ni-free SN Rates with ULTRASAT

RSG shock cooling



WR star shock cooling

Sagiv et al. 2014

Rate	SN Ia	SN Ibc	SN II
Early (fiducial; SNuK)	$0.064^{+0.008}_{-0.007}$ $\left(^{+0.013}_{-0.013}\right)$	$0.008^{+0.006}_{-0.004}$ $\left(^{+0.002}_{-0.002}\right)$	$0.004^{+0.003}_{-0.002}$ $\left(^{+0.001}_{-0.001}\right)$
Late (fiducial; SNuK)	$0.074^{+0.006}_{-0.006}$ $\left(^{+0.012}_{-0.012}\right)$	$0.096^{+0.010}_{-0.009}$ $\left(^{+0.018}_{-0.018}\right)$	$0.172^{+0.011}_{-0.011}$ $\left(^{+0.045}_{-0.036}\right)$
Early (LF-average; SNuK)	$0.048^{+0.006}_{-0.005}$ $\left(^{+0.010}_{-0.010}\right)$	$0.006^{+0.004}_{-0.003}$ $\left(^{+0.002}_{-0.002}\right)$	$0.003^{+0.002}_{-0.001}$ $\left(^{+0.001}_{-0.001}\right)$
Late (LF-average; SNuK)	$0.065^{+0.006}_{-0.005}$ $\left(^{+0.010}_{-0.010}\right)$	$0.083^{+0.009}_{-0.008}$ $\left(^{+0.016}_{-0.016}\right)$	$0.149^{+0.010}_{-0.009}$ $\left(^{+0.039}_{-0.031}\right)$
Vol-rate (10^{-4} SN Mpc^{-3} yr^{-1})	$0.301^{+0.038}_{-0.037}$ $\left(^{+0.049}_{-0.049}\right)$	$0.258^{+0.044}_{-0.042}$ $\left(^{+0.058}_{-0.058}\right)$	$0.447^{+0.068}_{-0.068}$ $\left(^{+0.131}_{-0.111}\right)$

Li et al. 2011

$$\boxed{R_{\rm RFSNe}\ (0.705\times10^{-4}\ {\rm Mpc^{-3}\ yr^{-1}})\left(\frac{210\ {\rm deg}^2}{41253\ {\rm deg}^2}\right)\left(\frac{4\pi}{3}(200\ {\rm Mpc})^3\right)\approx 0.84\ {\rm yr}^{-1}\left(\frac{R_{\rm RFSNe}}{7\%}\right)}$$

fraction of CCSNe

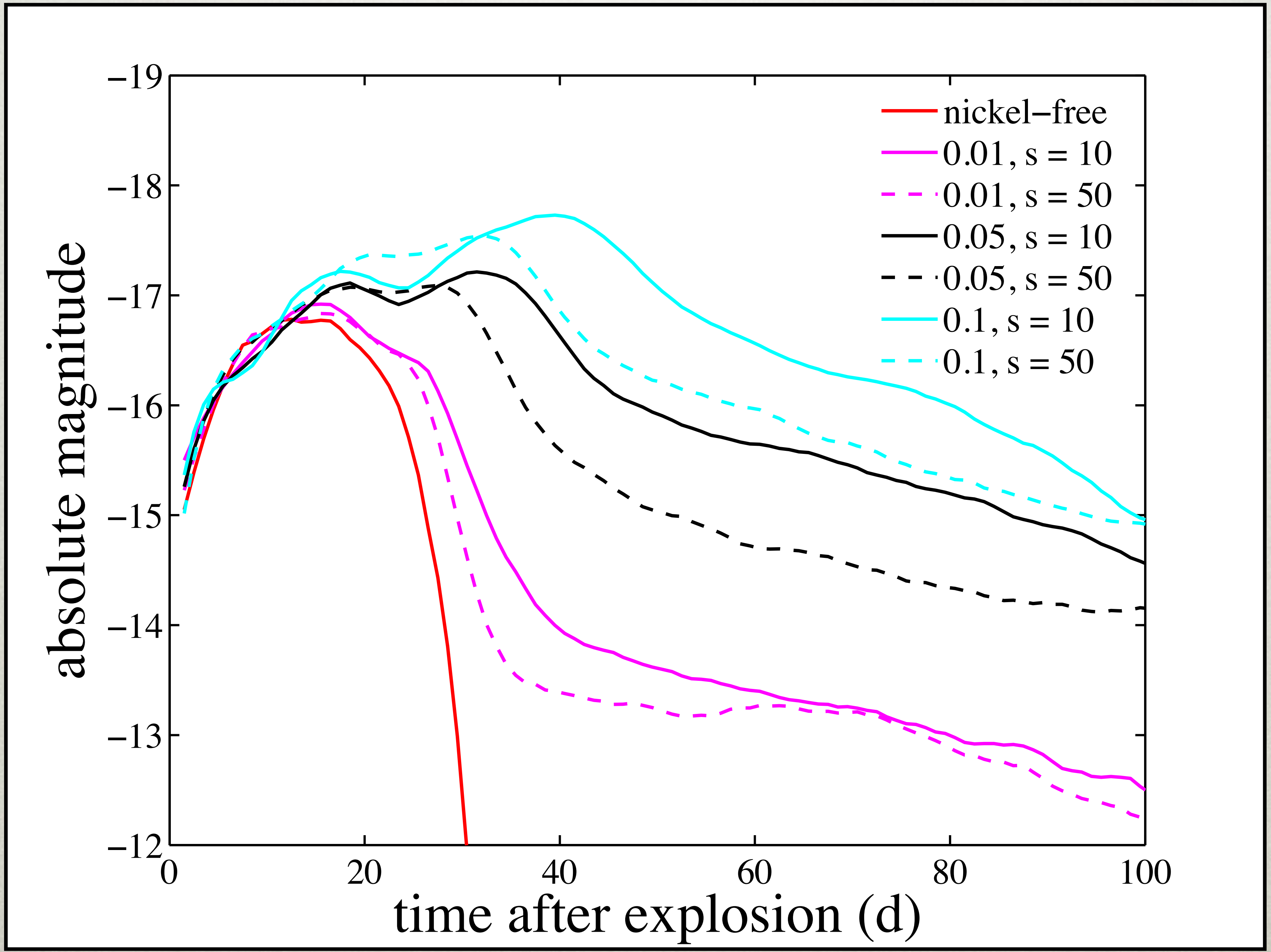
volume rate of CCSNe

fraction of sky

volume

expected discovery rate

Adding Nickel



Kleiser & Kasen 2018

Adding Nickel

Kleiser et al. in prep.