Evolution & explosions of stars leading to type IIP-IIL supernovae* with MESA & SNEC

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*(e.g. SN 2013ej)

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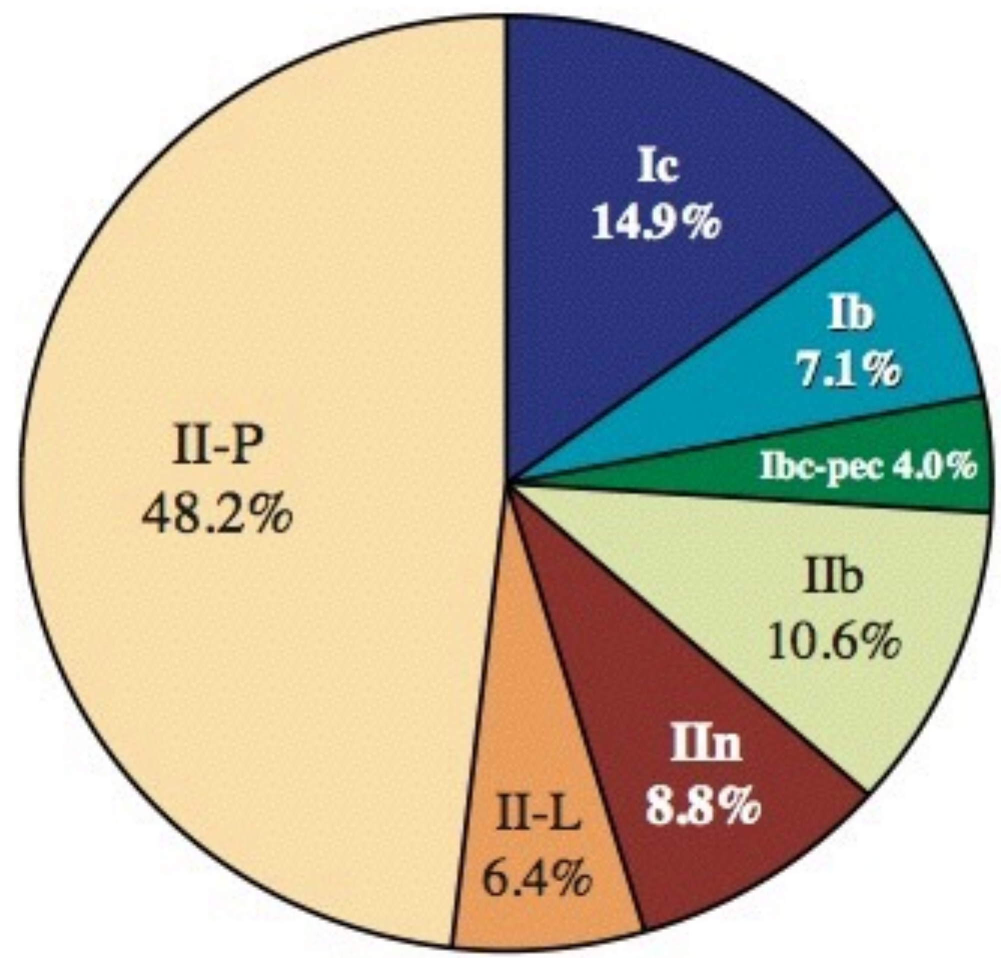
How are Supernovae distributed among different types?

Nathan Smith et al, MNRAS 2011

- Volume limited sample of 80 Core Collapse Supernovae up to 60 Mpc discovered and followed up by the UC Berkeley group.

Table 1. Volume-limited core-collapse SN fractions

SN Type	fraction (%)	error (%)
Ic	14.9	+4.2/−3.8
Ib	7.1	+3.1/−2.6
Ibc-pec	4.0	+2.0/−2.4
IIb	10.6	+3.6/−3.1
IIn	8.8	+3.3/−2.9
II-L	6.4	+2.9/−2.5
II-P	48.2	+5.7/−5.6
Ibc (all)	26.0	+5.1/−4.8
Ibc+IIb	36.5	+5.5/−5.4



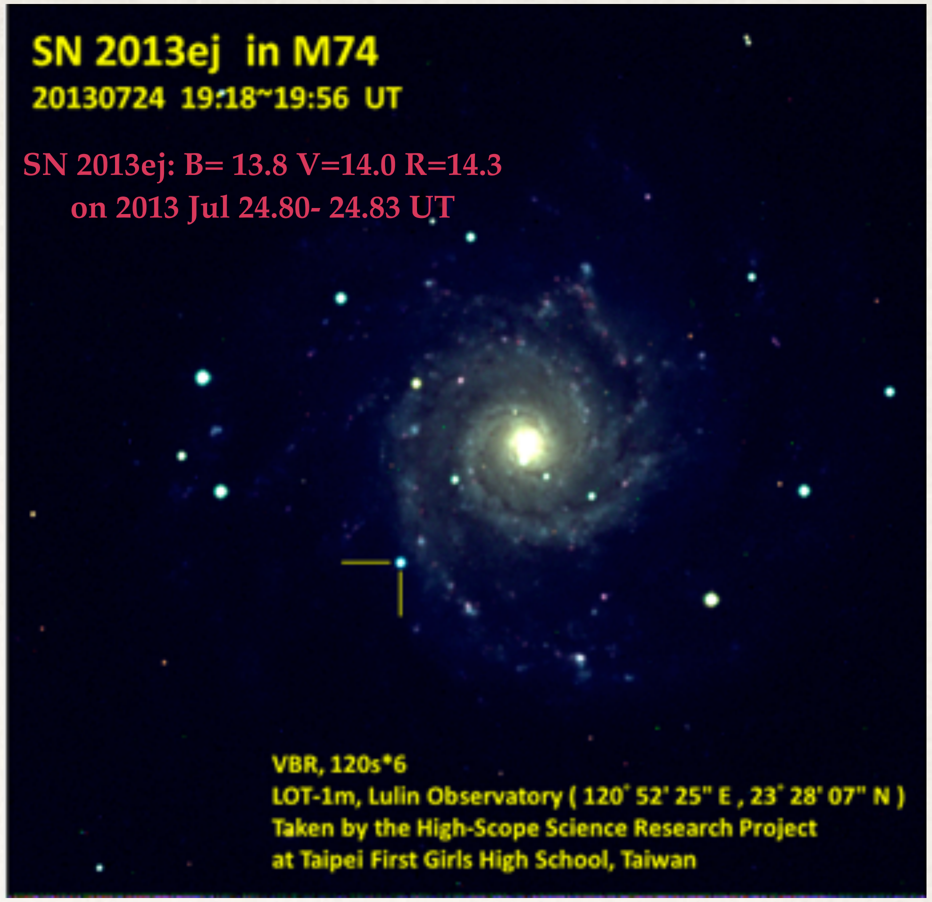
Core-Collapse SN Fractions

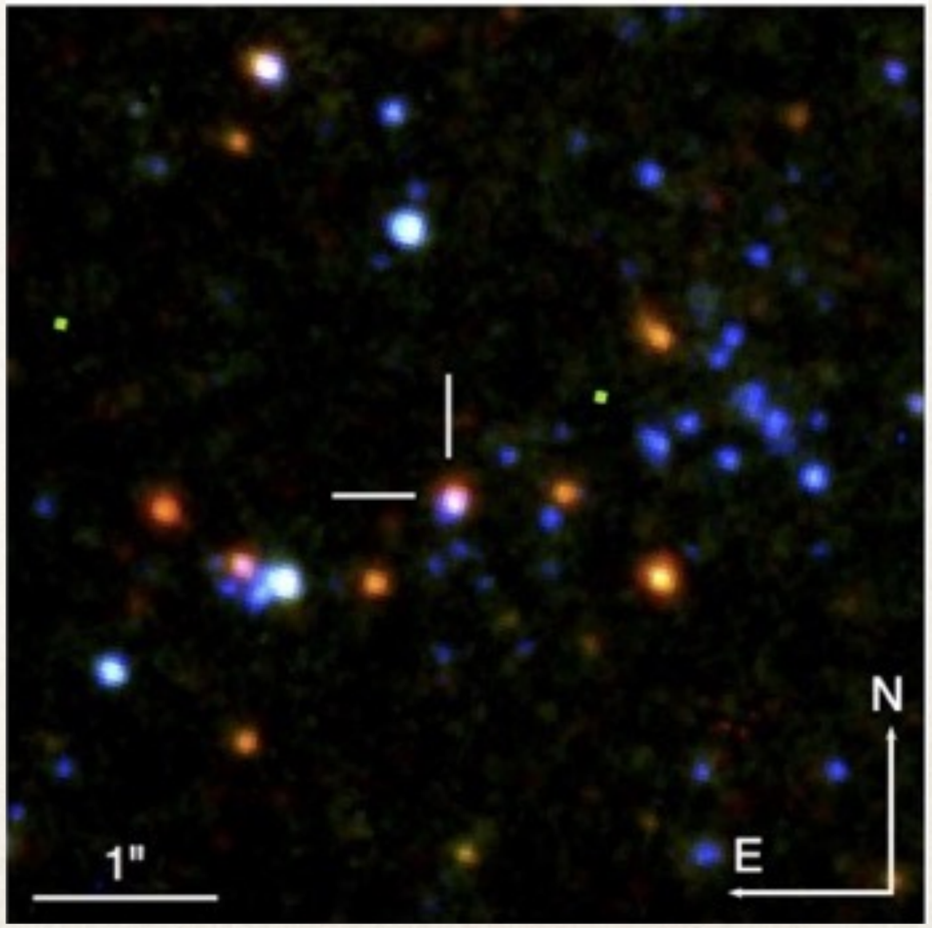
Strong SN interaction with recent dense & large mass loss from progenitor ?

- Supernovae of type IIn (e.g. SN 2010jl) may be explosions of stars that underwent strong mass loss (> 3 M_{sun}) before the event & the optical luminosity is powered by circumstellar int. (Chevalier 2013, Fransson et al 2014). 10 M_{sun} for SN 2006gy (Smith & McCray 2007) !
- Could even the type IIP + IIL SNe (e.g. SN 2013ej) that have long "plateaus" in their OIR light curves be partly powered by SN shock breakout interaction with dense CSM? The dense CSM may have been due to large mass loss just (~1 yr) before core collapse (e.g. Morozova et al 2016; Nagy & Vinko 2016).
- We investigate this in the context of SN 2013ej with pre supernova stars computed with MESA & exploded with SNEC, especially since X-ray data on SN 2013ej indicates the mass loss is well constrained on a timescale 40-400 years before core collapse (Chakraborti et al 2016).

SN 2013ej in spiral galaxy M74

- M74: 9.1 +/- 1 Mpc (Fraser et al 2013). d= 9.6 +/- 0.7 Mpc (Bose, Sutaria et al 2015).
- HST position of progenitor candidate F435W & F555W filters is significantly offset. Blue source likely unrelated to the SN. Red source likely have exploded as SN 2013ej.
- Fraser et al (2013): progenitor mass range of 8 - 15.5 Msun assuming F814W flux is dominated by the progenitor of SN and a bolometric correction for an M-type supergiant
- Originally it was classified as a type IIP but was later reclassified as a type IIL (Bose et al 2015) based on a fast decline rate the luminosity at intermediate stages (1.74 mag/100 days in V band and slow decline of Halpha , Hbeta profiles.
- Characteristics of explosion: 12 M_{SUN} progenitor star, 450 R_{SUN} progenitor radius, explosion energy 2.3 x 10^{51} erg (Bose et al 2015).





HST ACS image of the site of SN 2013ej prior to explosion

Chandra & *Swift* Observations of SN2013ej

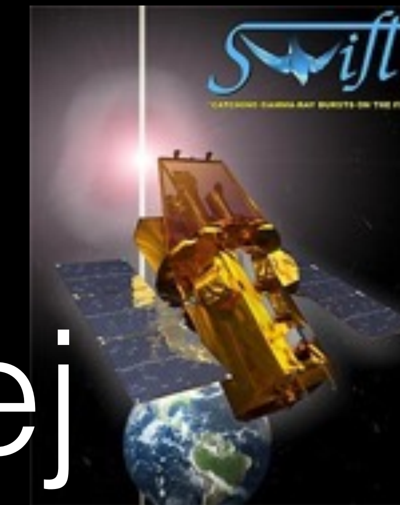


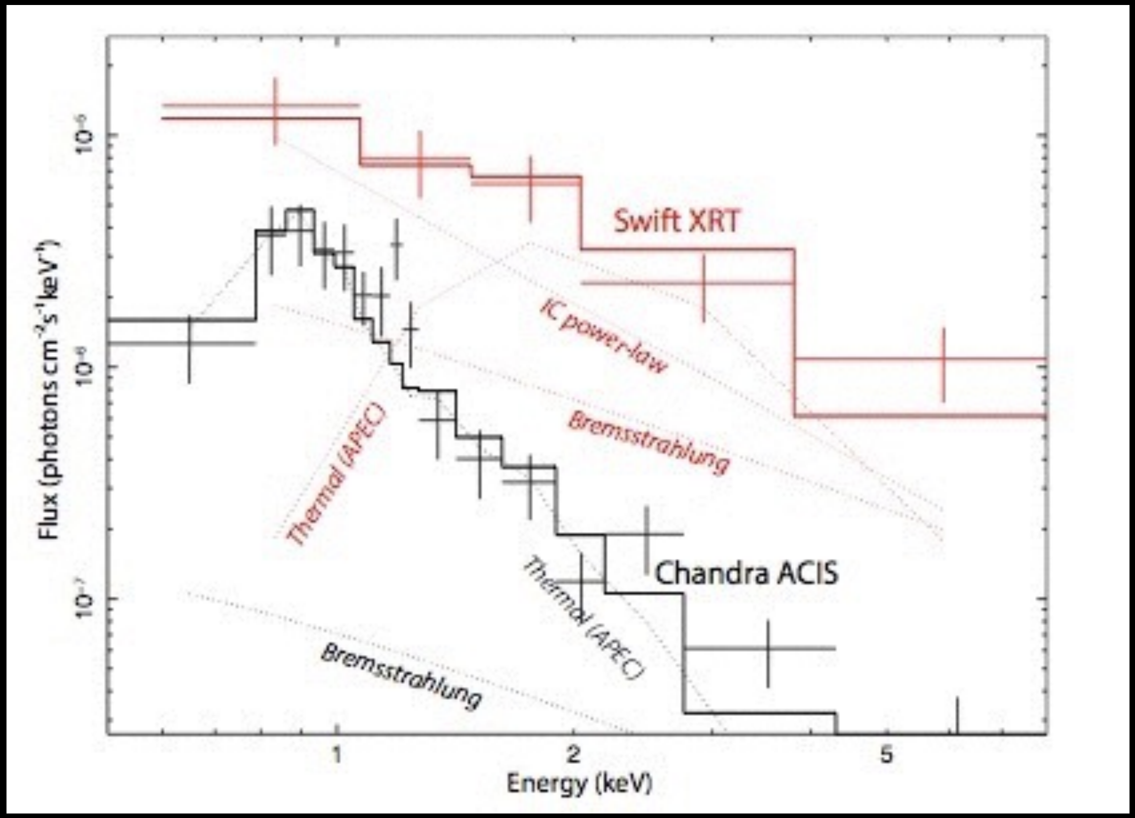
TABLE 1
SWIFT AND CHANDRA OBSERVATIONS OF SN 2013EJ

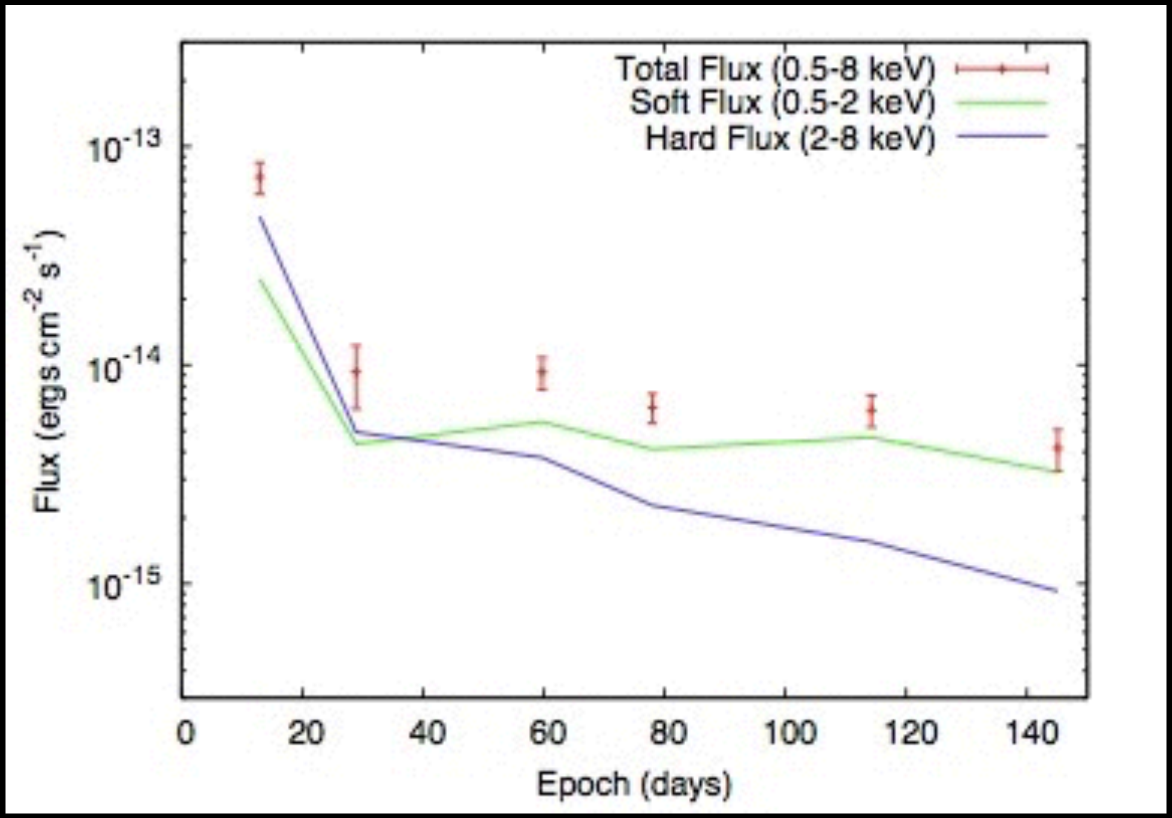
Dates (2013)	Age[a] (days)	$L_{\rm bol}$ (ergs s^{-1})	Telescope	Exposure (ks)	X-ray Flux (0.5-8 keV) (ergs cm^{-2} s^{-1})
Jul 30 - Aug 9	13.0	$(3.89 \pm 0.58) \times 10^{42}$	Swift	73.4	$(7.2 \pm 1.2) \times 10^{-14}$
Aug 21	28.9	$(2.19 \pm 0.27) \times 10^{42}$	Chandra	9.8	$(9.3 \pm 3.3) \times 10^{-15}$
Sep 21	59.7	$(1.29 \pm 0.03) \times 10^{42}$	Chandra	39.6	$(9.3 \pm 1.6) \times 10^{-15}$
Oct 7 - 11	78.0	$(1.00 \pm 0.02) \times 10^{42}$	Chandra	38.4	$(6.4 \pm 1.0) \times 10^{-15}$
Nov 14	114.3	$(8.13 \pm 0.38) \times 10^{40}$	Chandra	37.6	$(6.2 \pm 1.0) \times 10^{-15}$
Dec 15	145.1	$(5.13 \pm 0.24) \times 10^{40}$	Chandra	40.4	$(4.2 \pm 0.9) \times 10^{-15}$

NOTE. — The Chandra observations can be retrieved from the Chandra Data Archive using their Obs Ids of 14801, 16000, 16001 (with fragments in 16484 and 16485), 16002, and 16003.

[a] Age at the middle of an observation with an assumed explosion date 23.8 July 2013 (UT) (JD 2456497.3 ± 0.3) following Bose et al. (2015)

Chandra & *Swift* obs of SN 2003ej

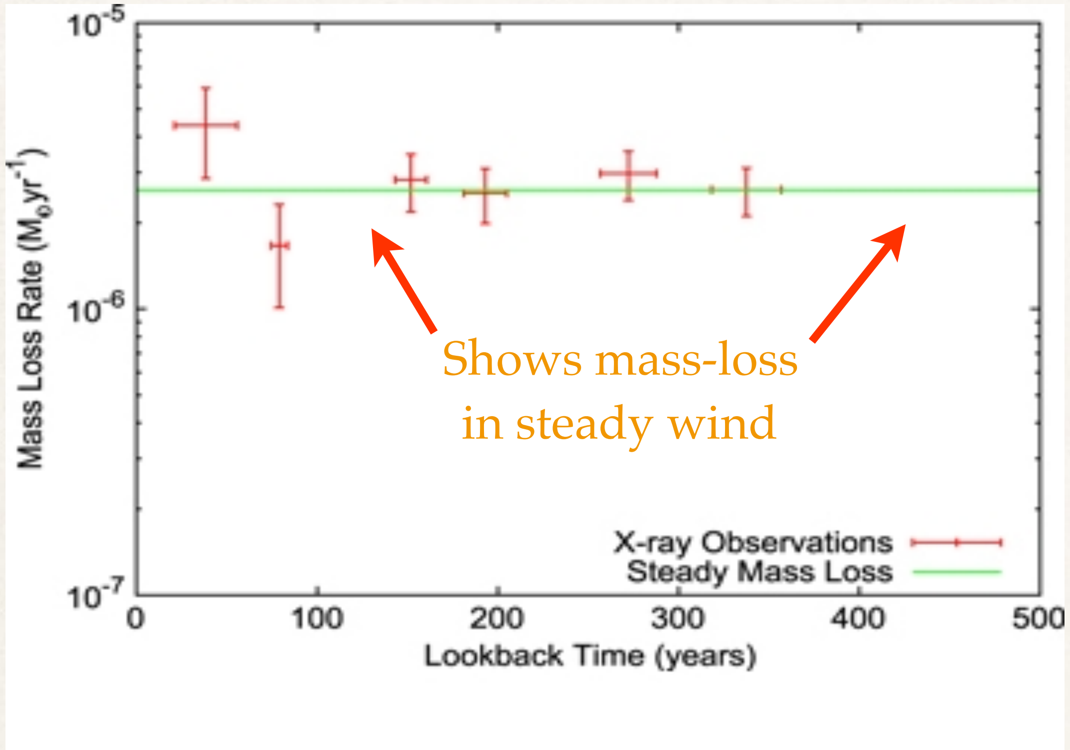


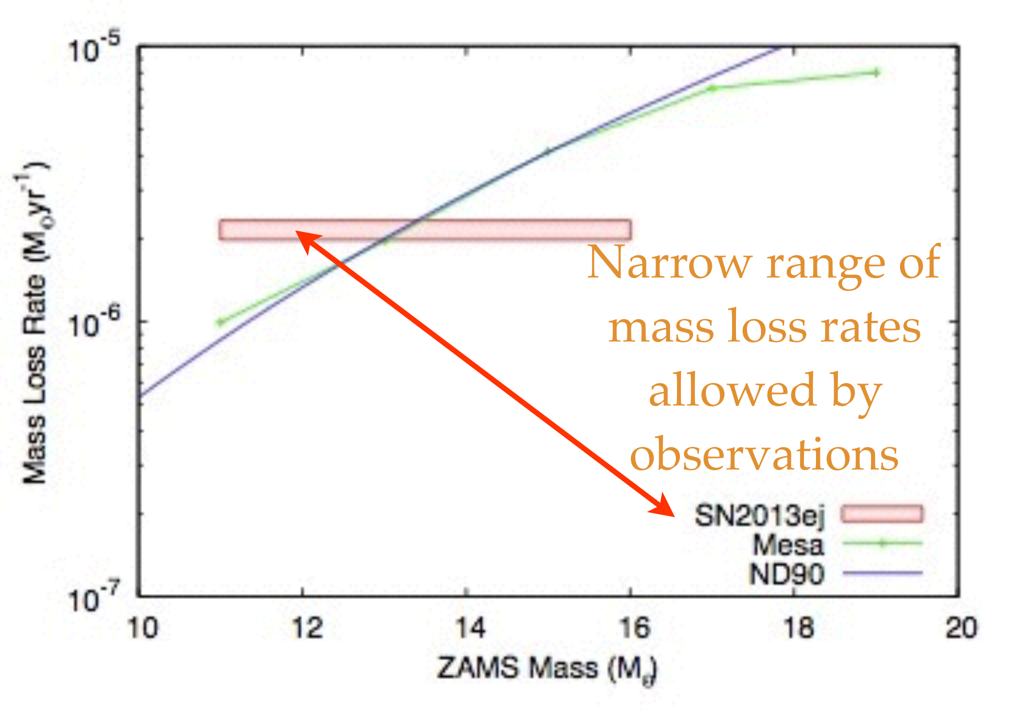


Chandra separates non-thermal from thermal components in SN emission

S. Chakraborti, A.R., et al, 2016 ApJ

SN 2013ej: Progenitor's mass loss





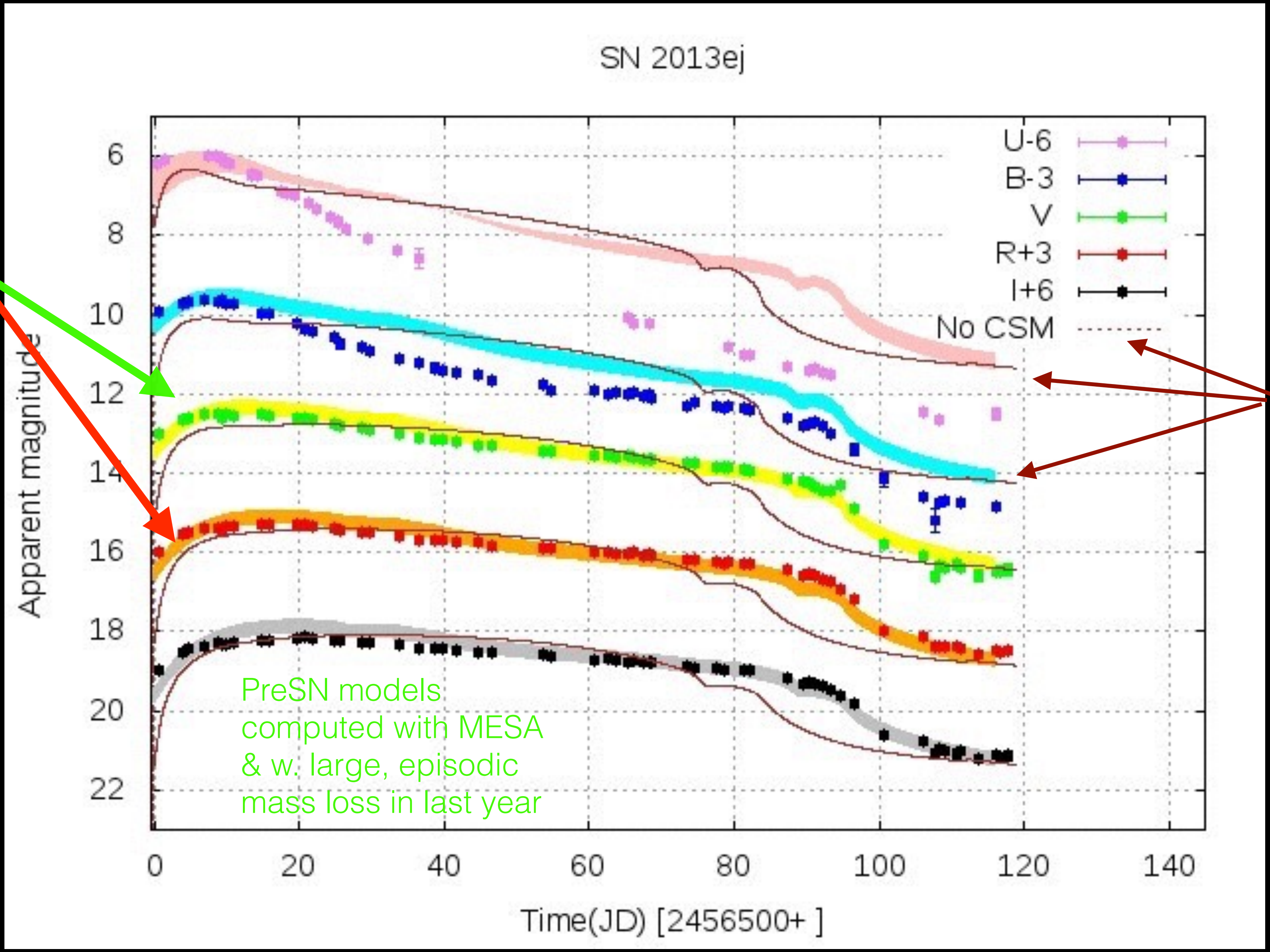
$$\dot{M} = 7.5 \times 10^{-7} \left(\frac{v_{\rm w}}{10\ {\rm km\ s^{-1}}}\right) \left(\frac{D_{\rm A}(1+z)}{10\ {\rm Mpc}}\right) \times \left(\frac{N_{\rm APEC}}{10^{-5}}\right)^{1/2} \left(\frac{R_{\rm cs}}{10^{15}\ {\rm cm}}\right)^{1/2} {\rm M_\odot\ yr^{-1}}.$$

$$N_{\rm APEC} = \frac{10^{-14}}{4\pi\,(D_{\rm A}(1+z))^2} \int n_e n_H dV,$$

S. Chakraborti, A.R., et al, ApJ 2015

SNEC Model fits to SN 2013ej multiband data with and without dense CSM

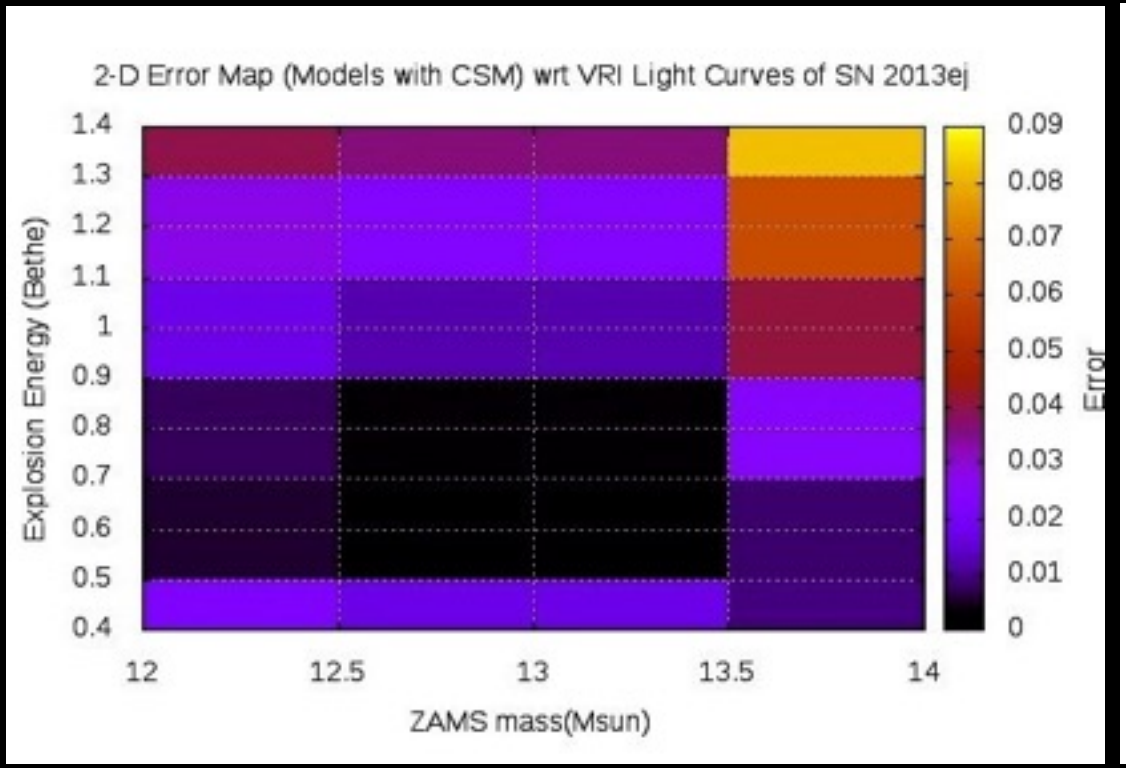
Coloured broad lines show best fit SNEC V,R, I outputs for 0.7 Msun CSM ejected ~ 1yr prior to SN & allows for uncertainty of distance and reddening.

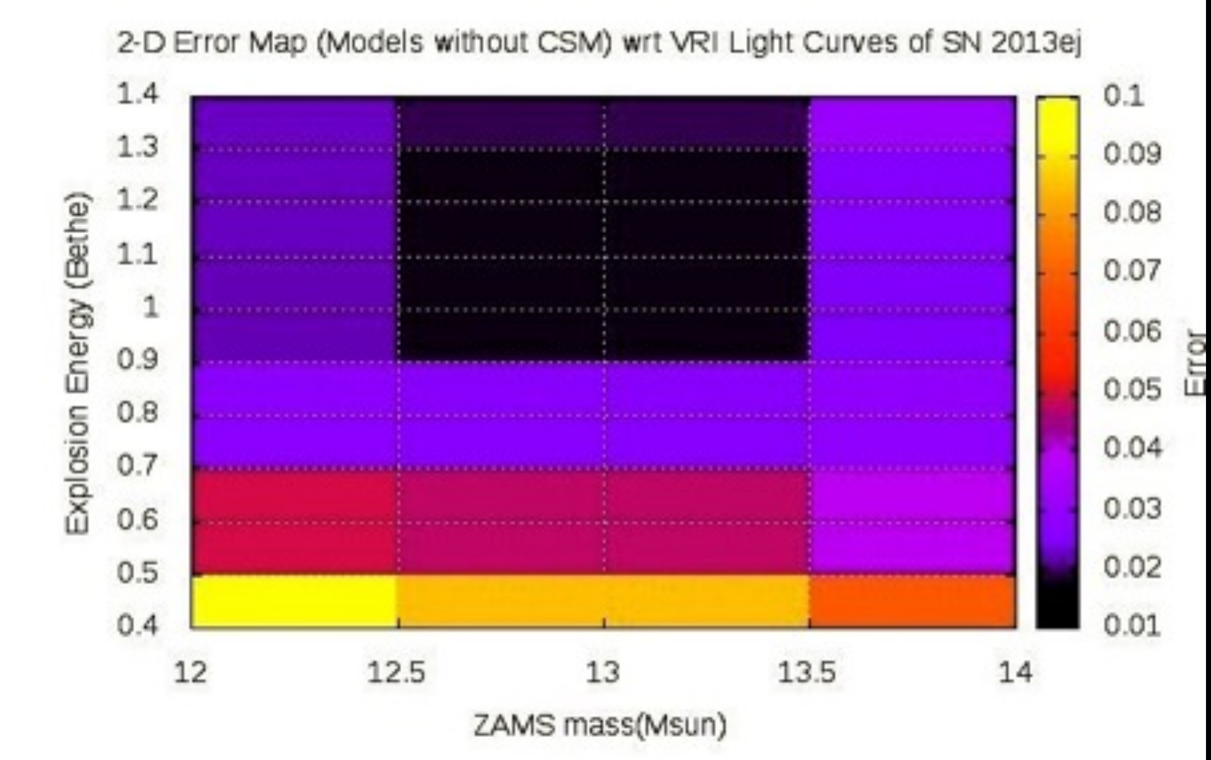


Thin brown lines for represent "best fit" SNEC outputs without strong preSN mass loss.

Multiwaveband data from Richmond et al (2014)

Comparison of data fits to models with and without recent strong mass loss from progenitor star





We compare only the V, R & I band data, because SNEC have limitations of modelling U and B light curves at late times (opacity from Iron line forest not modelled well)

Parameters of best fit model (with or without dense CSM)

ZAMS Mass	*Pre-SN Mass (Msun)*	Pre-SN Radius (Rsun)	Fe Core $ (Msun)	CSM Mass^ (Msun)	Time_ej* (year)	Energy (Bethe)	Ni56 (Msun)	Ni Boundary** (Msun)	Error
13	**11.6**	**667**	1.45	0.76	1	**0.6-0.8**	0.021	3.15	0.0034
13	**12.4**	**617**	1.47	- (No major mass ejection)	- (No major mass ejection in last year)	**1.0-1.4**	0.021	3.15	0.018

$ equal to the excised mass in SNEC.
^ lost mass in 1 year before collapse.
* time before collapse when the huge mass loss was triggered.
** Approximately the average of He and C core mass, i.e. Ni56 is roughly spread till the He boundary after boxcar smoothing in SNEC.

Model fit errors calculated using expression (Morozova et al 2016) and dividing by degrees of freedom

$$\chi^2 = \sum_{\lambda \in [g,\ldots,z]} \sum_{t^* < t_{PT}} \frac{(M^*_\lambda(t^*) - M_\lambda(t^*))^2}{M_\lambda(t^*)},$$

Compare model fits to SN 2013ej data with and without dense CSM due to Morozova et al using Kepler preSN models

Morozova et al
arXiv: 1610.08054v1

These models calculated with KEPLER & wind density ~ $1/r^2$

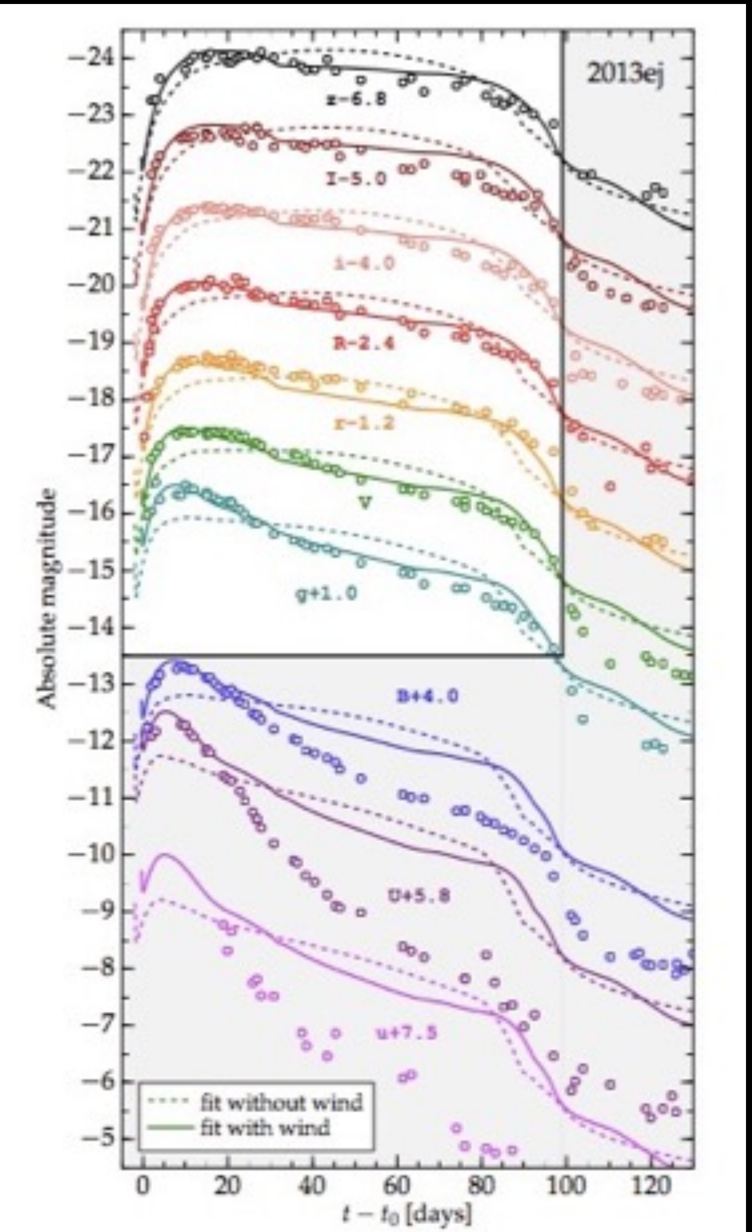
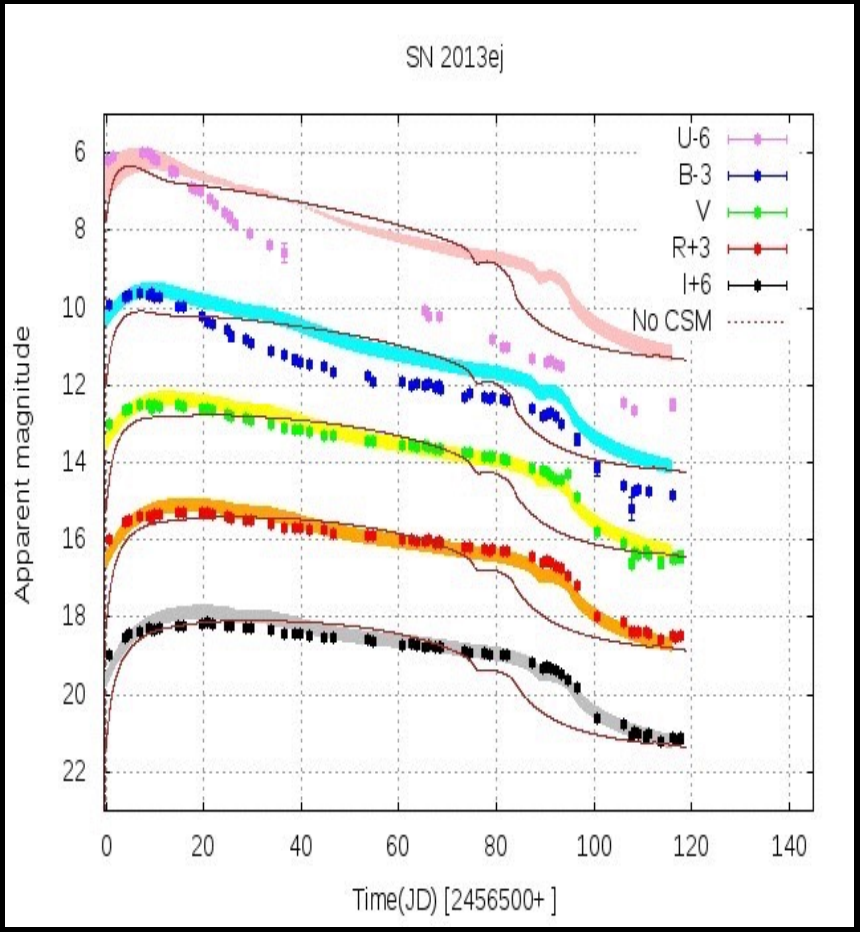
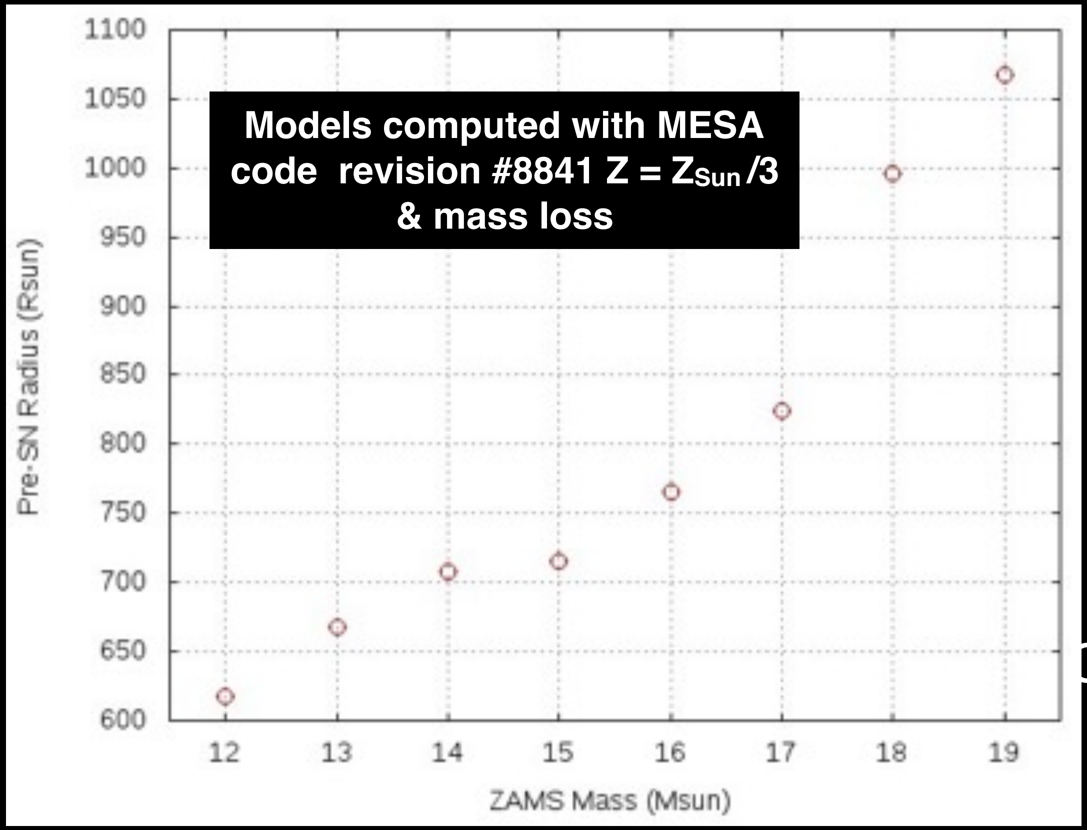


Figure 2. Best fits of the SN 2013ej data without (dashed lines) and with (solid lines) CSM.

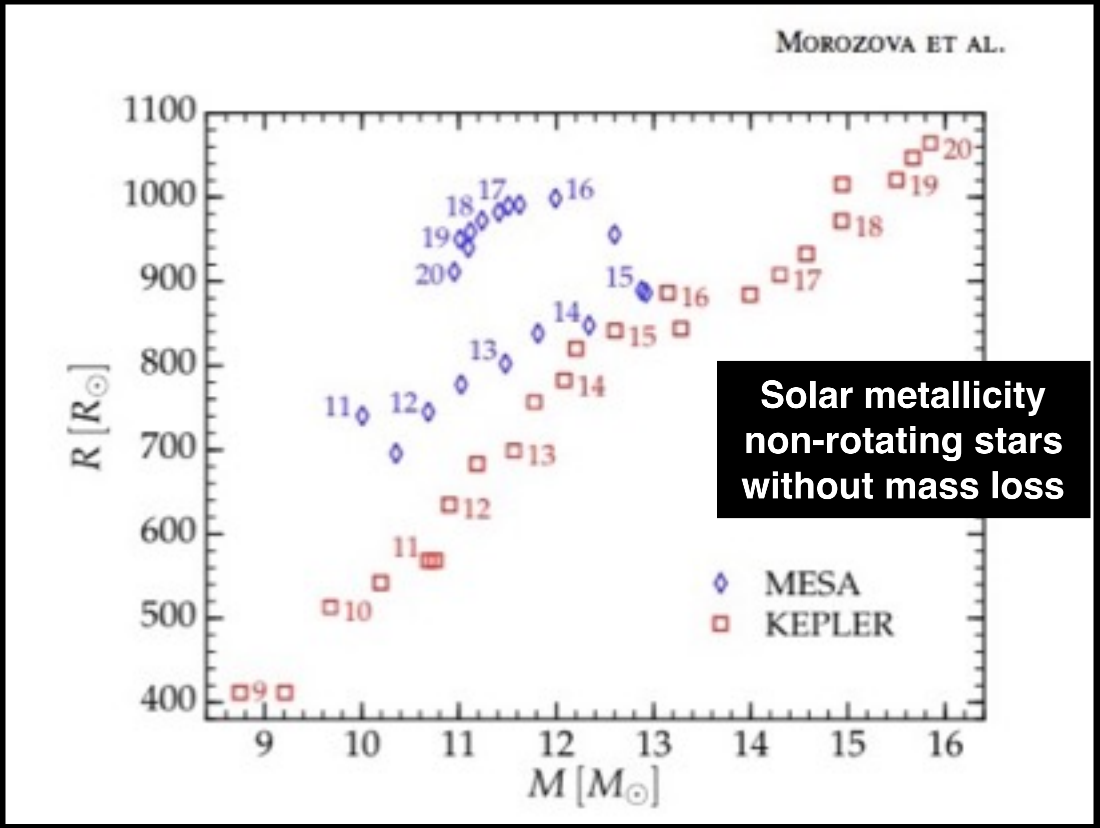


This work @ IAUS 331

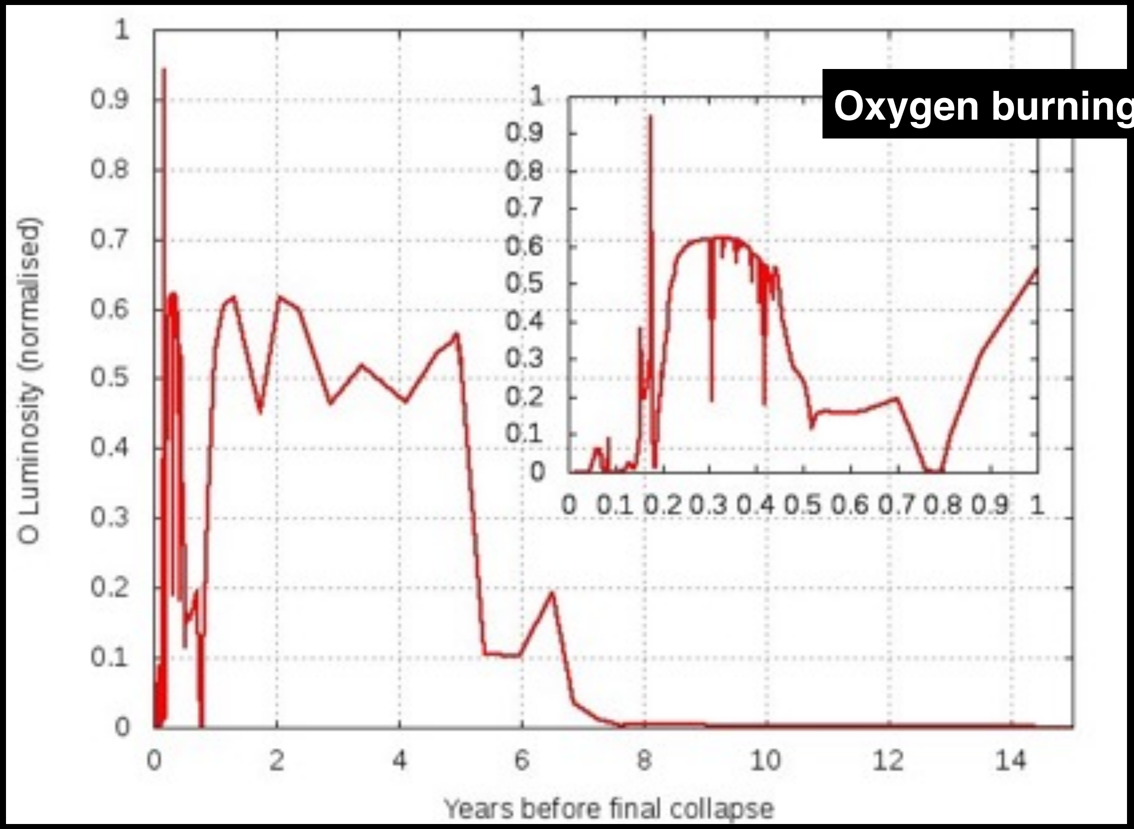
Pre-SN Stars

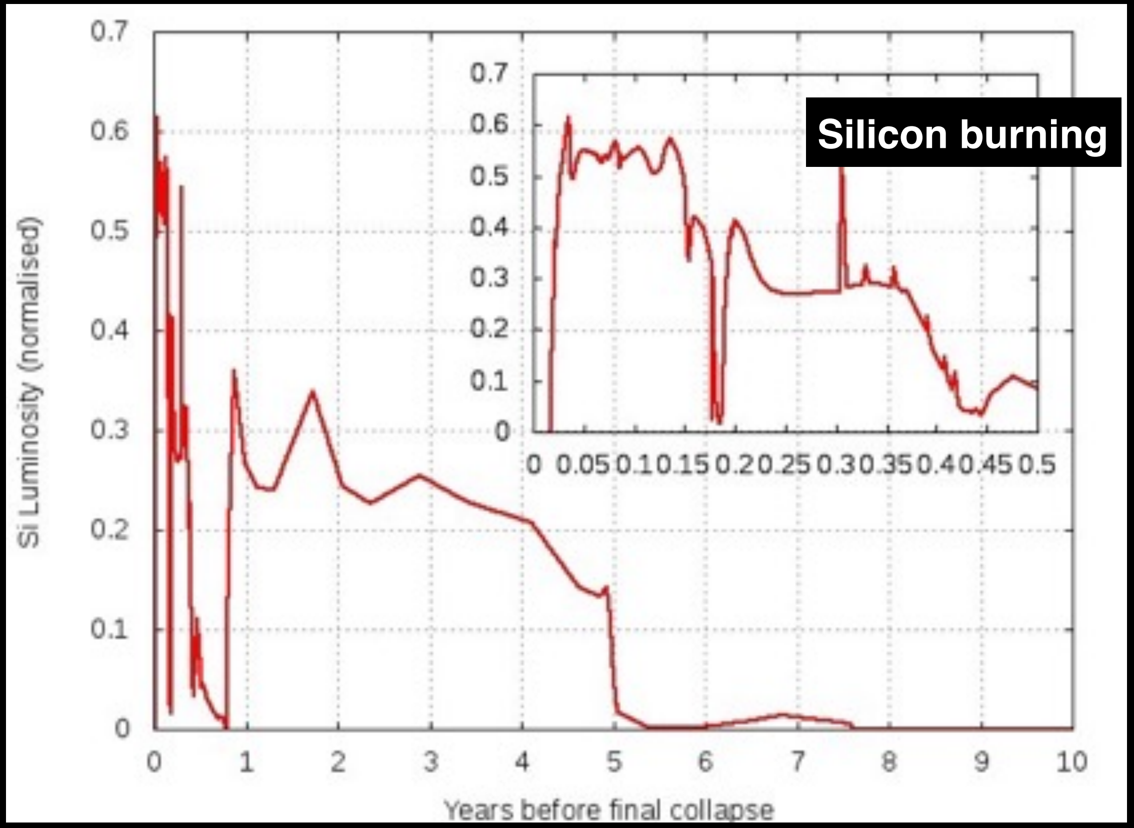


Compare with



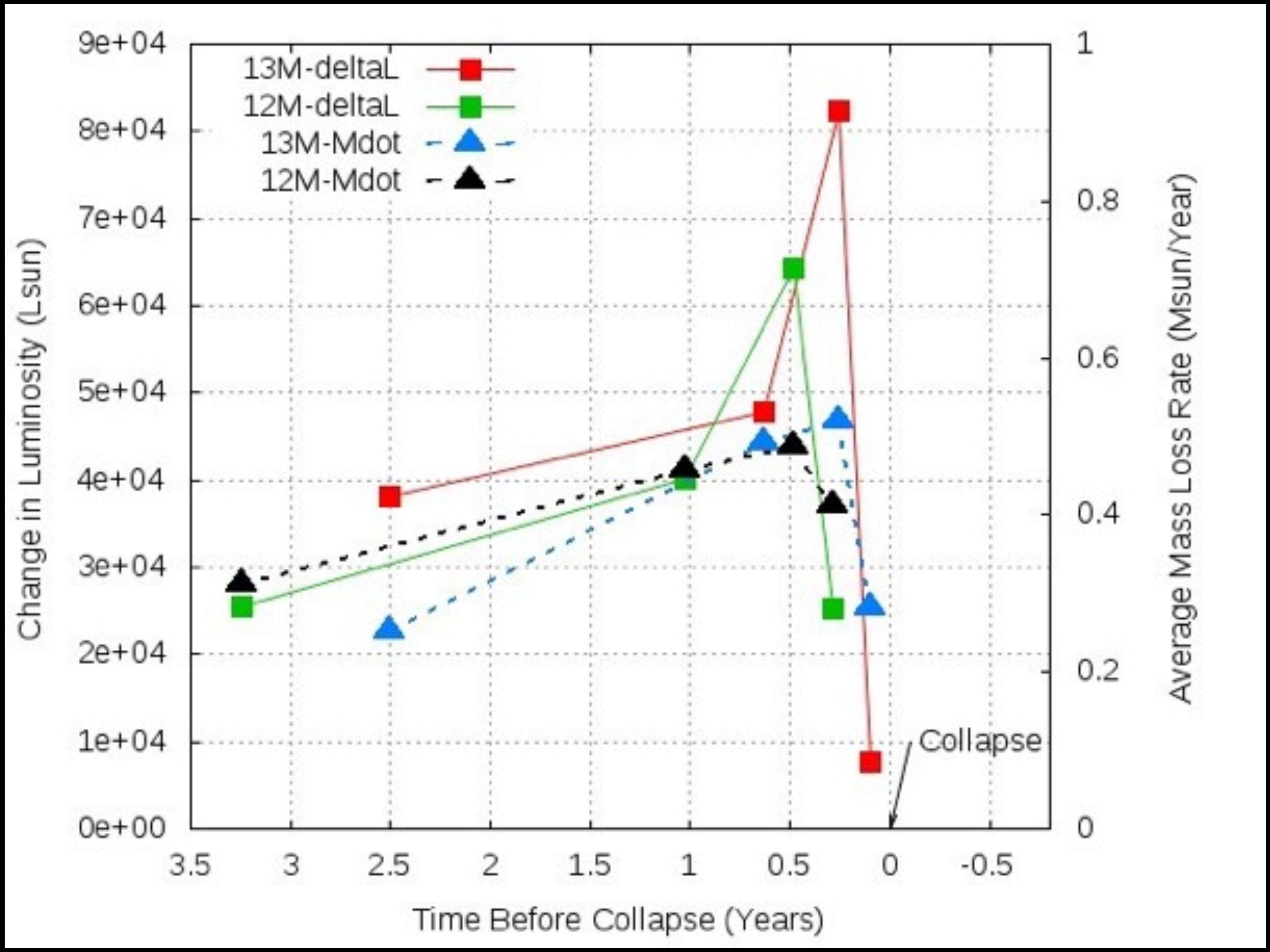
Pre-SN Stars



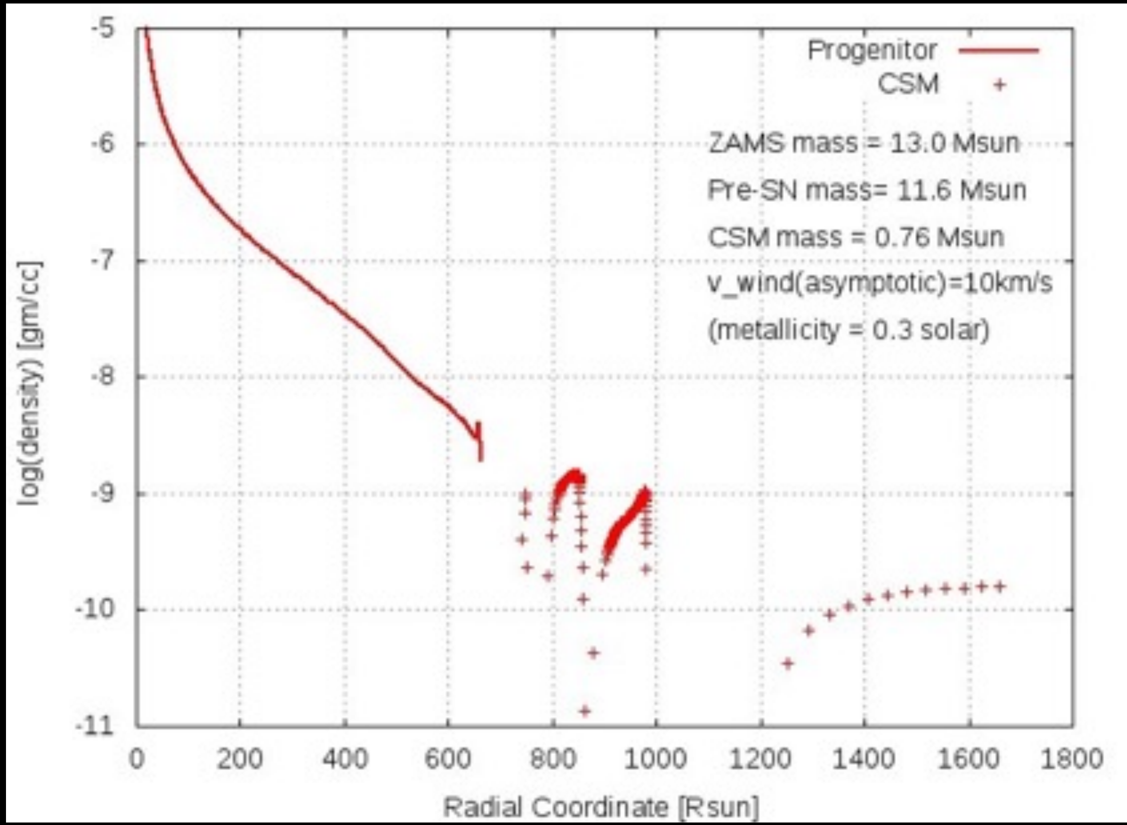


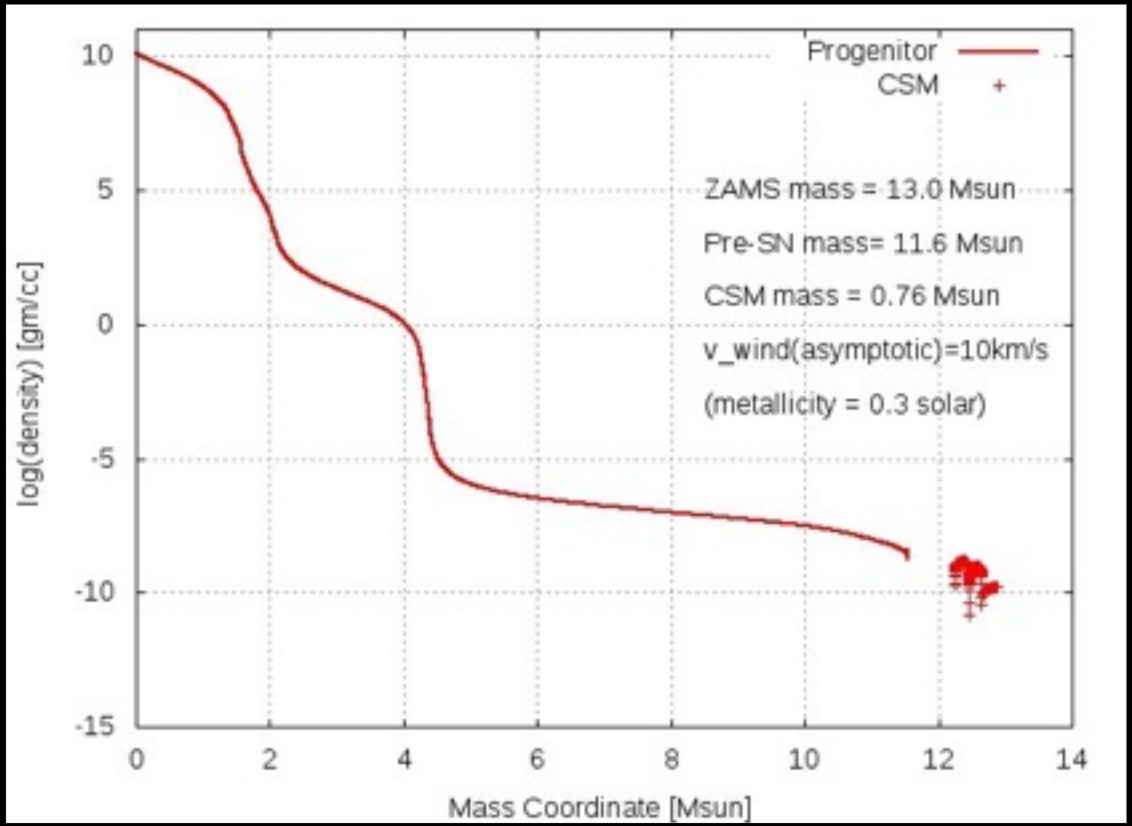
ZAMS Mass
13 M_{SUN}

Correlated mass loss & pre-SN luminosity



PreSN star & Circumstellar medium: Density vs Radius & Mass coordinates





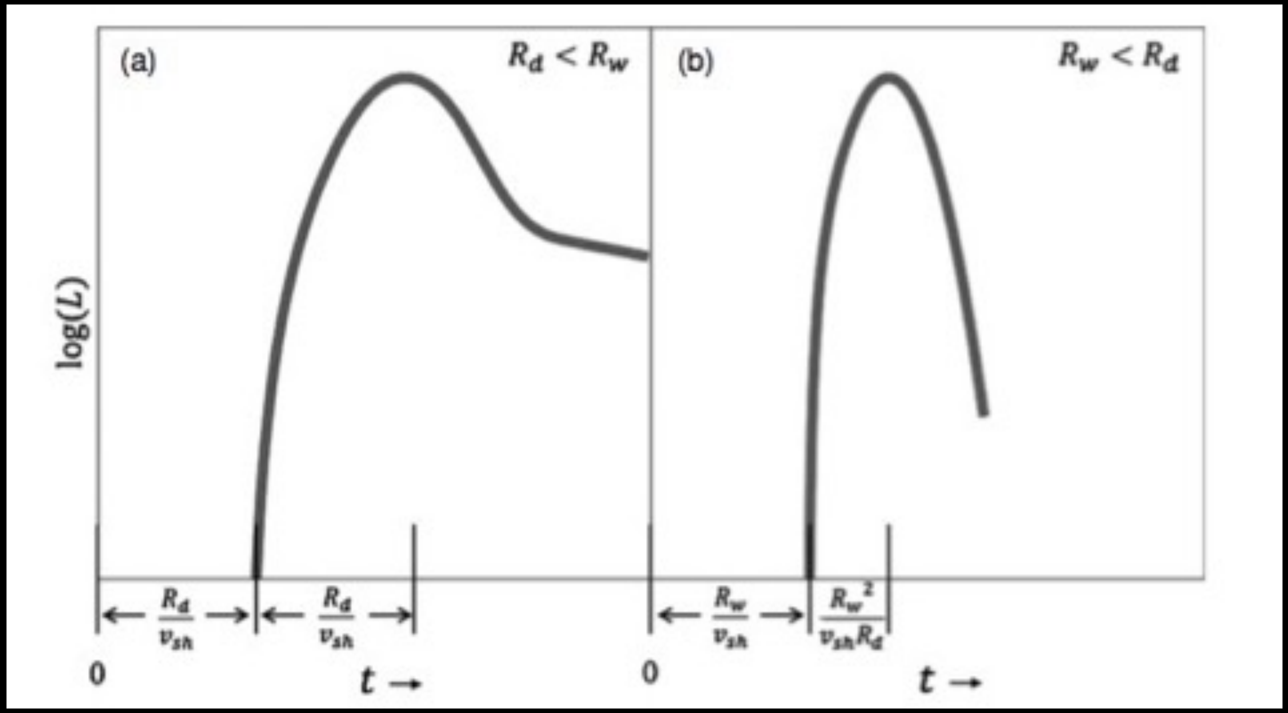
Example: Shell shocked diffusion model of type IIn supernovae (e.g. SN 2006gy)

- Smith & McCray (2007) explained SN light curve of type IIn SN 2006gy by invoking an opaque unbound massive (~10 M_{SUN}), circumstellar shell ejected before the SN event. When hit by the SN blast wave this shell has 10^{51} erg of kin energy (E_0) deposited in it that diffusively radiated $E_0 \times M_{shell}/[2(M_{SN} + M_{shell})]$ of the total SN energy.

- The key distinction of the shell-shocked diffusion model with the previous CSM-interaction models for type IIn SNe, was that the latter was optically thin, albeit dense CSM.

- The shell in SM (2007) model is so dense and opaque and large that it mimics a extremely large red supergiant envelope, even though the "envelope" is not bound to the star. Thermal energy deposited by the SN shock is deposited throughout this large envelope so that it is not adiabatically degraded and can radiatively escape from the boundary without suffering great loss.

From Chevalier & Irwin 2011: Dense mass loss & luminous SNe



Supernova interaction with dense mass loss: (a) wind extent R_W greater than the characteristic diffusion radius R_d and (b) $R_W < R_d$. There is a time from the explosion to the shock wave reaching a place where the radiation can escape and the luminosity rises. In the case $R_W > R_d$, there is a later, slower luminosity decline due to continued interaction of the shock wave (velocity v_{sh}) with slow wind material.

Summary & Conclusions

- *When the CSM densities are low,* in the initial interaction of the SN shock wave after emerging from the stellar surface, the *emission from the interaction is a small fraction of the SN's power.* Some of the emission comes out in radio and x-ray bands. This was *traditionally* how type IIP SNe where the inferred CSM density was low were *thought to have* behaved.

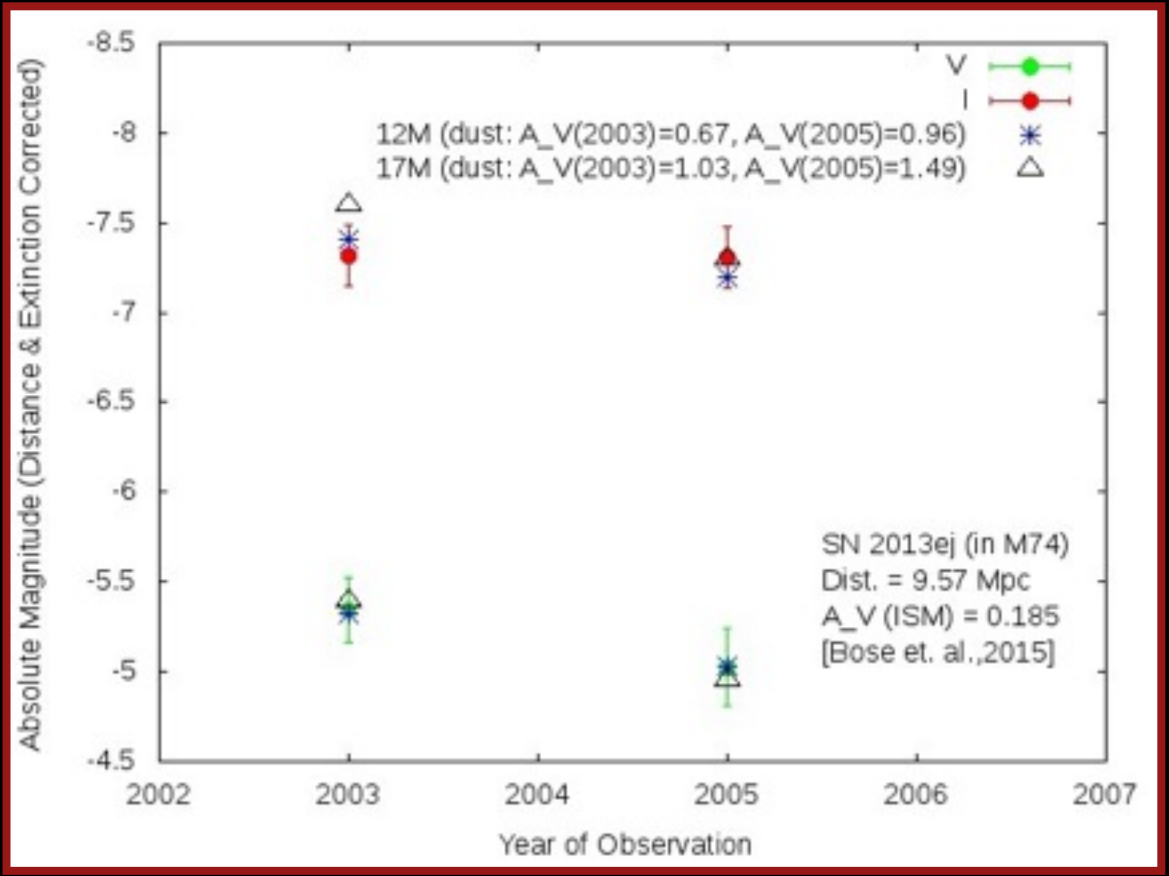
- Nevertheless more detailed modelling of optical+IR light curves of type IIP + IIL class (esp. the early rise part) suggests the presence of dense, massive envelope soon before the preSN star exploded. Presence of this dense envelope allows a lower energy of explosion than if the envelope was not present. The late part of the plateau and even into the radioactive tail is also better modelled at the same time.

- At the same time, observed X-ray by Chandra and Swift telescopes imply a roughly steady mass loss rate of the pre-SN star *on a longer timescale* of 40-400 yr.

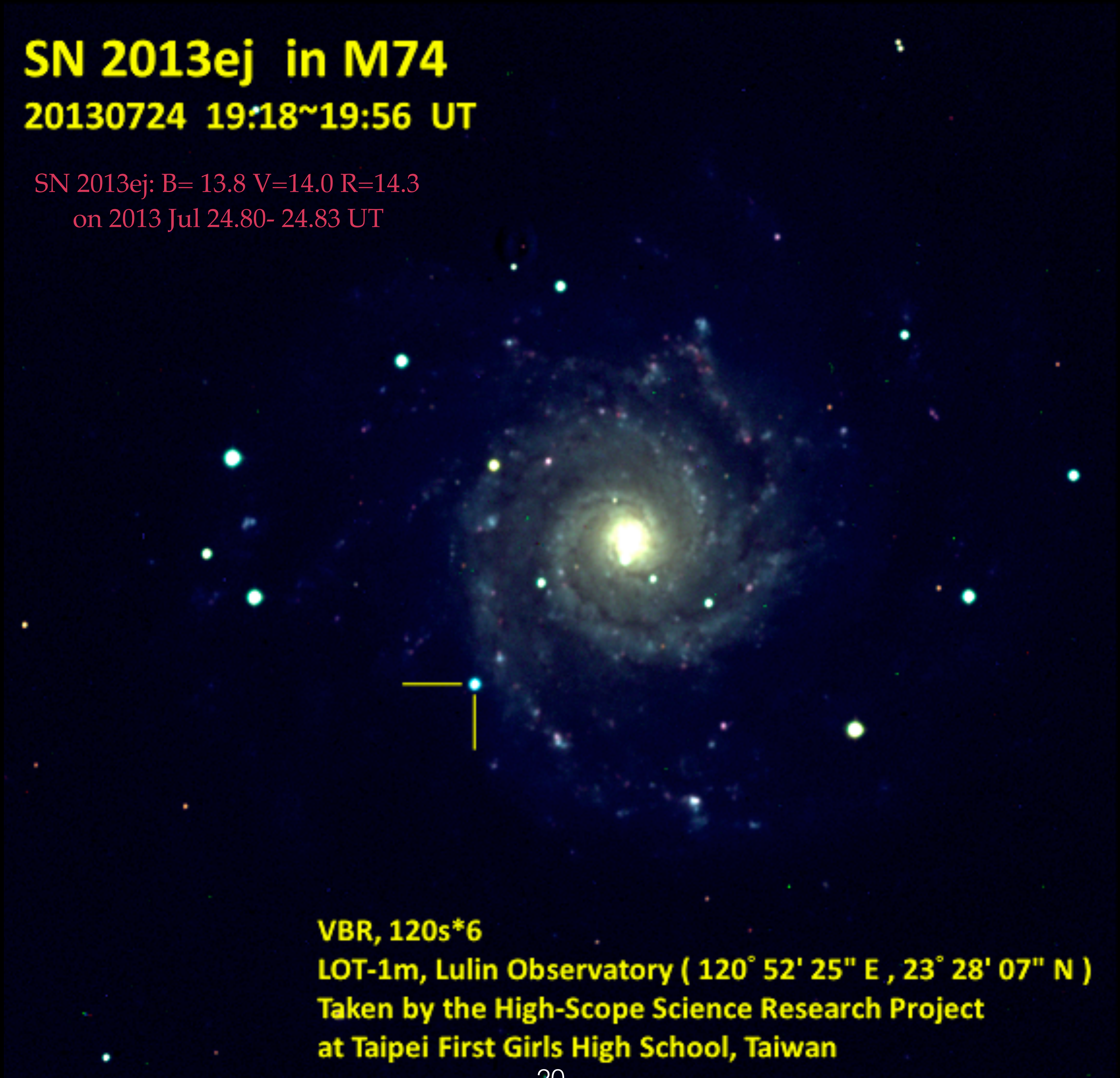
- X-ray flux measurement by Swift at 13 days shows that despite a possible strong mass loss at the very end stage of the star's evolution, the dense shell did not fully thermalise the X-rays. If the pre-shock CSM is largely recombined (see Smith & McCray 2007) then the resultant opacity would be lower than what is implied by Thompson scattering (which would otherwise be very large with the *implied* huge mass loss recently).

THANK YOU

Pre-SN V & I band observations with HST circa 2003 & 2005 & comparison with MESA models



ZAMS Mass	Mass lost :before 2003 (Msun)#	Mass lost :between 2003 and 2005 (Msun)#
12	0.0174	0.0090
13	0.0191	0.0159
14	0.0192	0.0139
15	0.0148	0.0207
16	0.0154	0.0238
17	0.0153	0.0294


SN 2013ej in M74
20130724 19:18~19:56 UT
SN 2013ej: B= 13.8 V=14.0 R=14.3
on 2013 Jul 24.80- 24.83 UT
VBR, 120s*6
LOT-1m, Lulin Observatory (120° 52' 25" E , 23° 28' 07" N)
Taken by the High-Scope Science Research Project
at Taipei First Girls High School, Taiwan