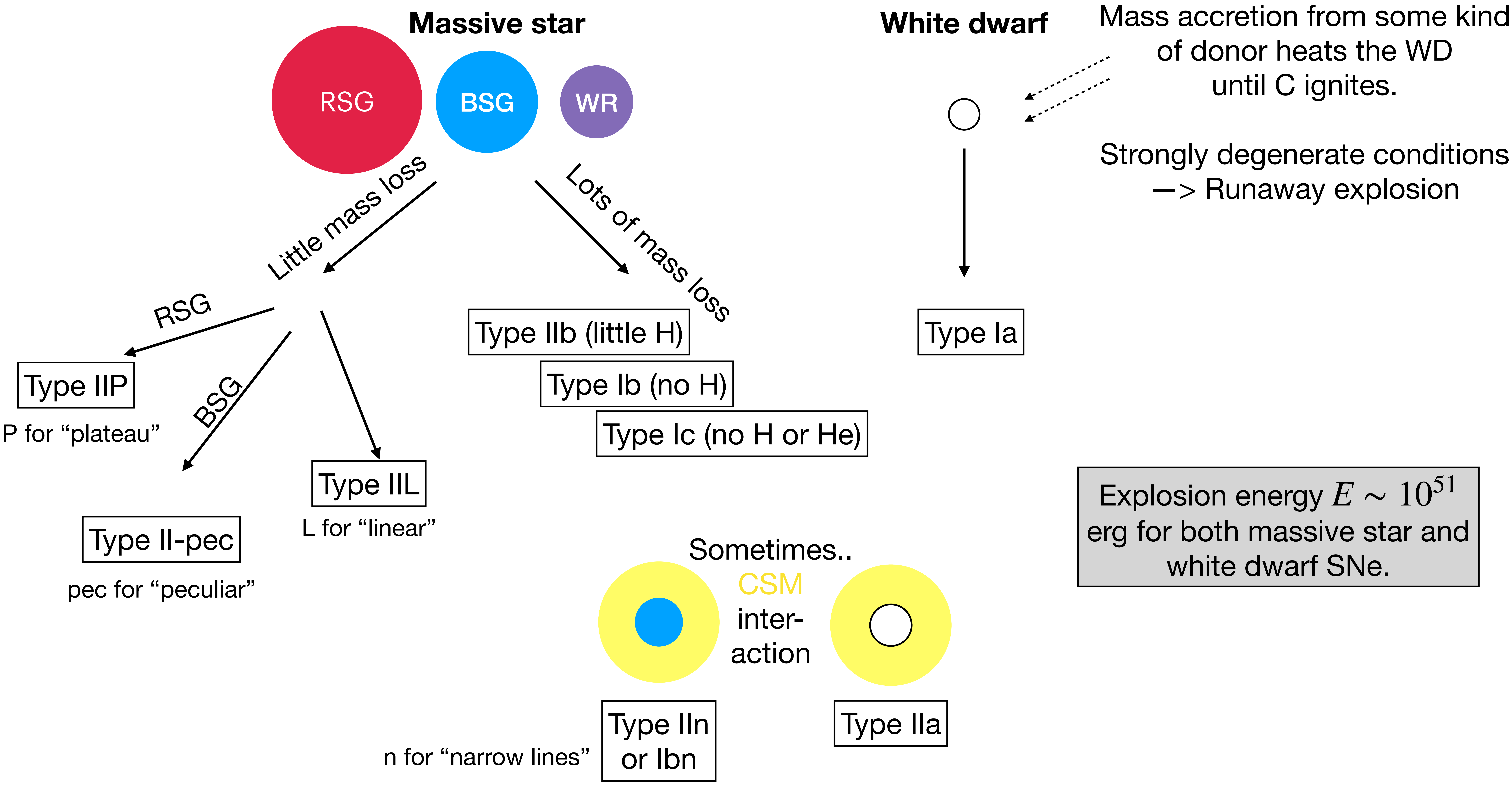
# Part F
# Supernova observations and analysis

## Section 1 : H-rich SNe

# Classification scheme



**Massive star**

RSG

BSG

WR

Little mass loss

RSG

Type IIP

P for “plateau”

BSG

Type II-pec

pec for “peculiar”

Type IIL

L for “linear”

Lots of mass loss

Type IIb (little H)

Type Ib (no H)

Type Ic (no H or He)

**White dwarf**

Mass accretion from some kind
of donor heats the WD
until C ignites.

Strongly degenerate conditions
—> Runaway explosion

Type Ia

Explosion energy $E \sim 10^{51}$ erg for both massive star and white dwarf SNe.

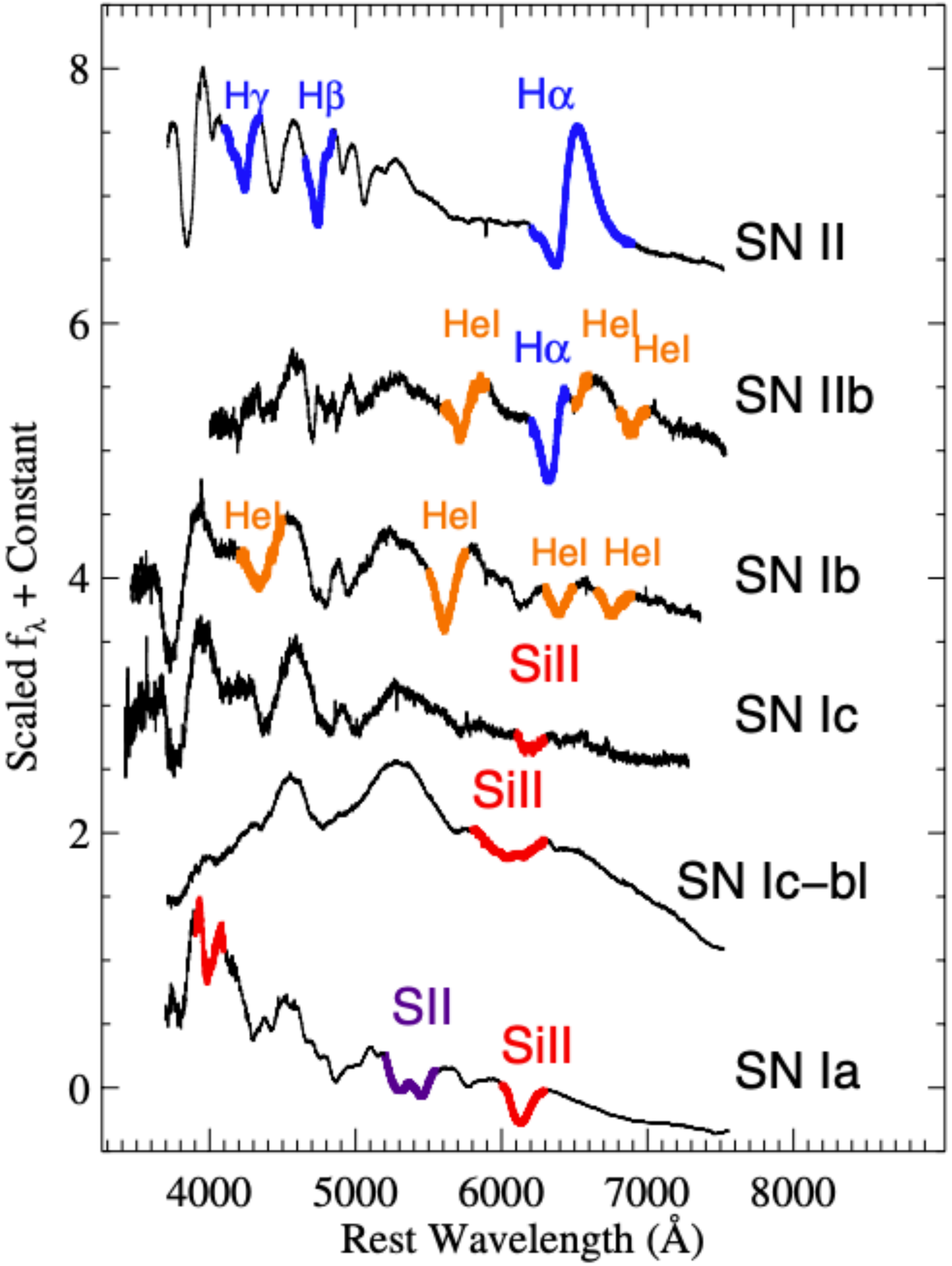
Sometimes..
CSM
inter-
action

Type IIn
or Ibn

n for “narrow lines”

Type IIa

# Spectral classification



Strong **H** lines

Weak **H** lines, distinct **He** lines

No **H** lines, distinct **He** lines

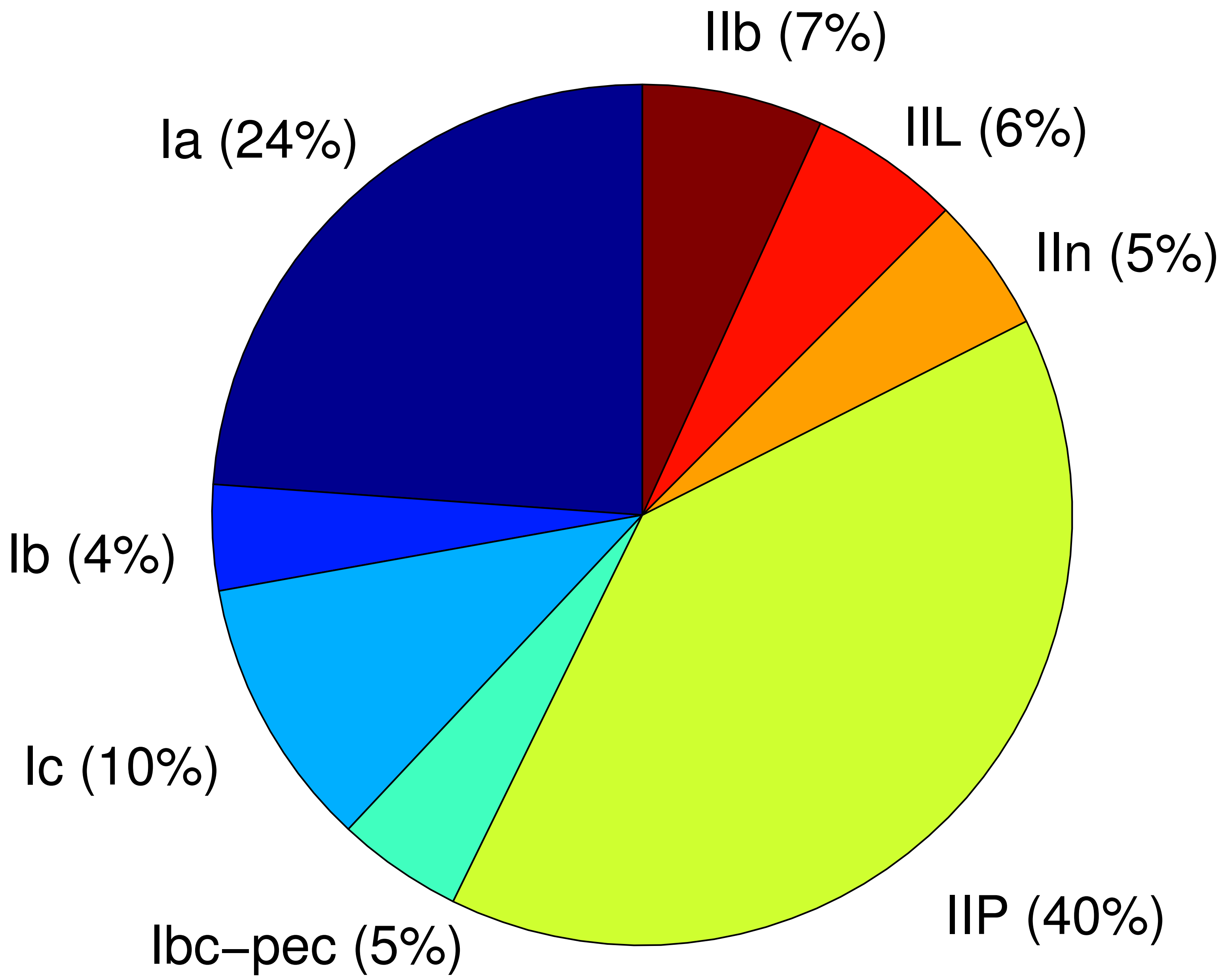
No **H** or **He** lines, no or weak **Si II** lines

Like Ic but broader features

No **H** or **He** lines, strong **Si II** lines

Modjaz 2014

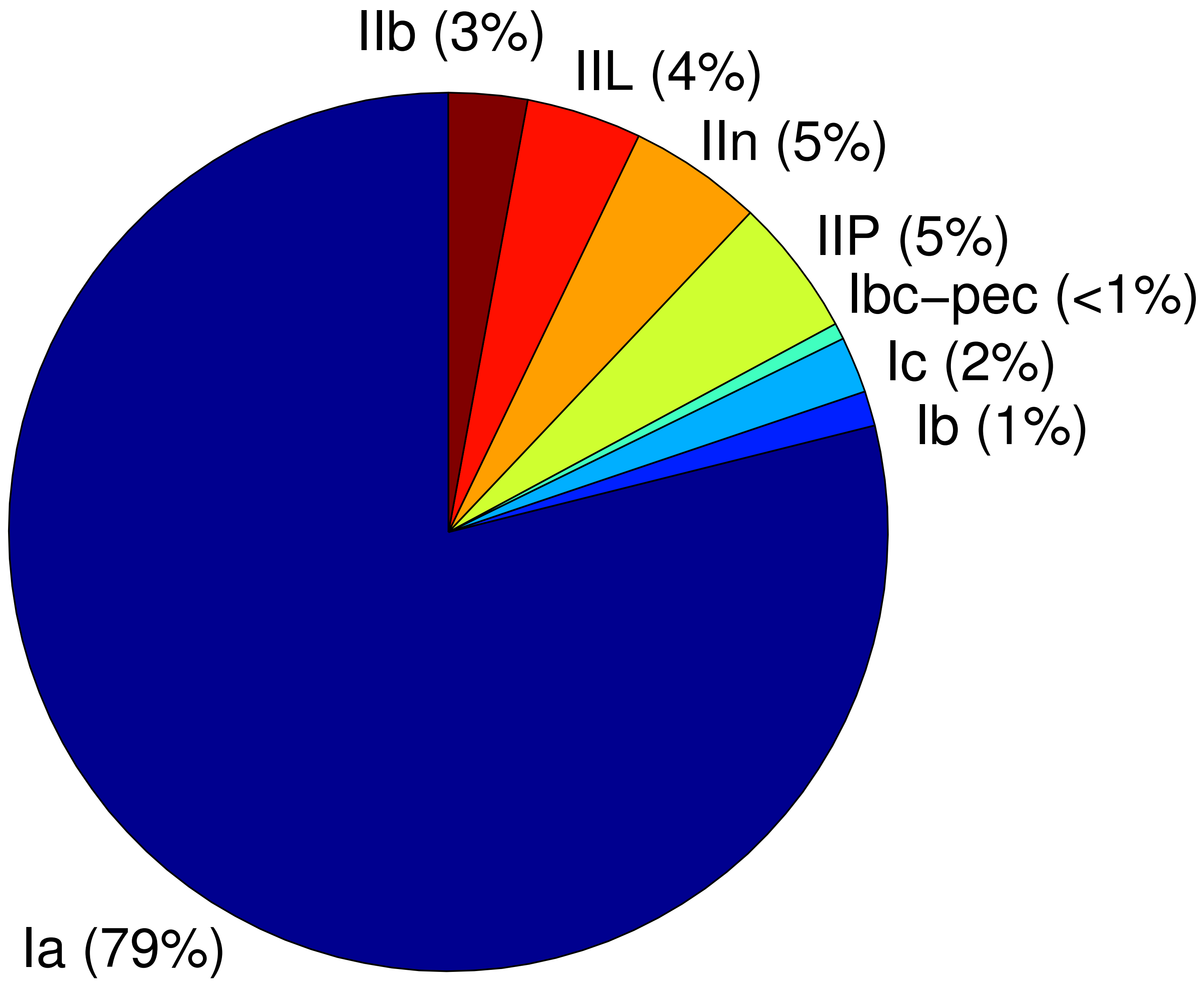
# Fraction of SNe in each class



Volume-limited

CCSNe: About 2/3 from H-rich stars, 1/3 from H-poor.

The intrinsic rate is highest for Type IIP SNe (~40%).



Magnitude-limited

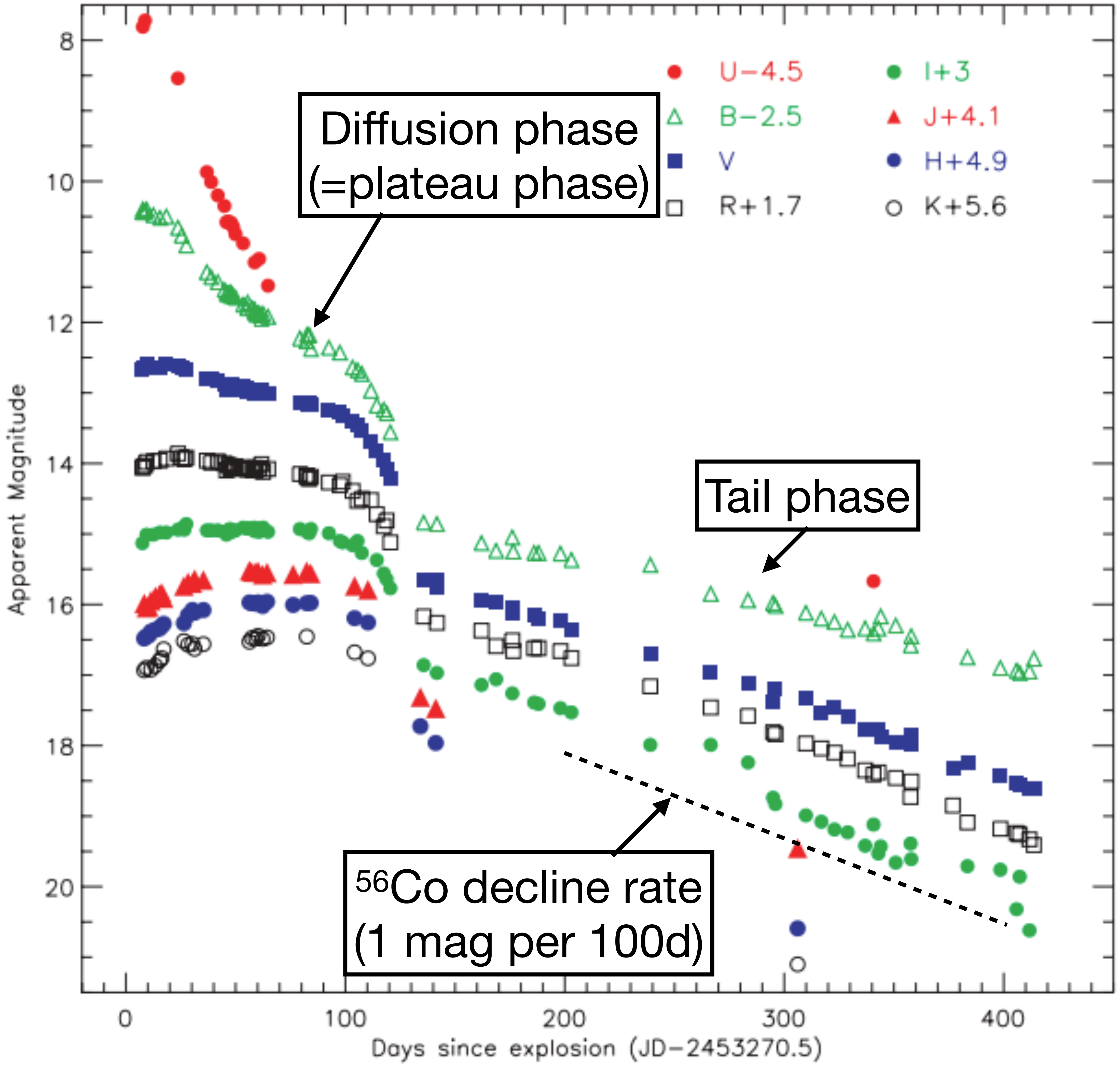
Type Ia SNe are the most commonly discovered because they are the **brightest** so can be seen to larger distances.

Li 2011

# Type IIP supernovae

# A Type IIP prototype : SN 2004et

Light curve in different photometric bands



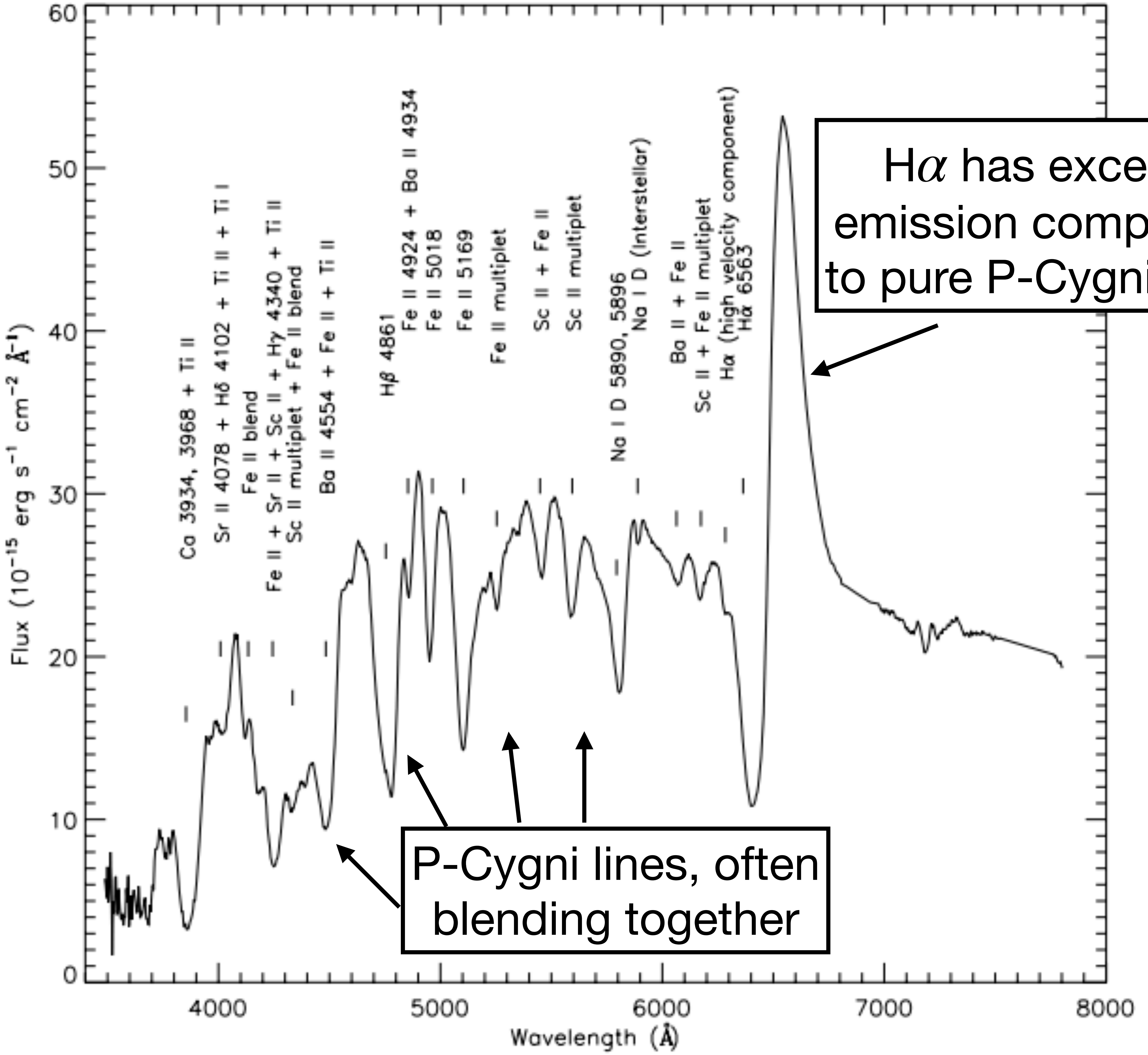
Diffusion phase
(=plateau phase)

Tail phase

$^{56}$Co decline rate
(1 mag per 100d)

Maguire 2010

Photospheric spectrum (at 50d)

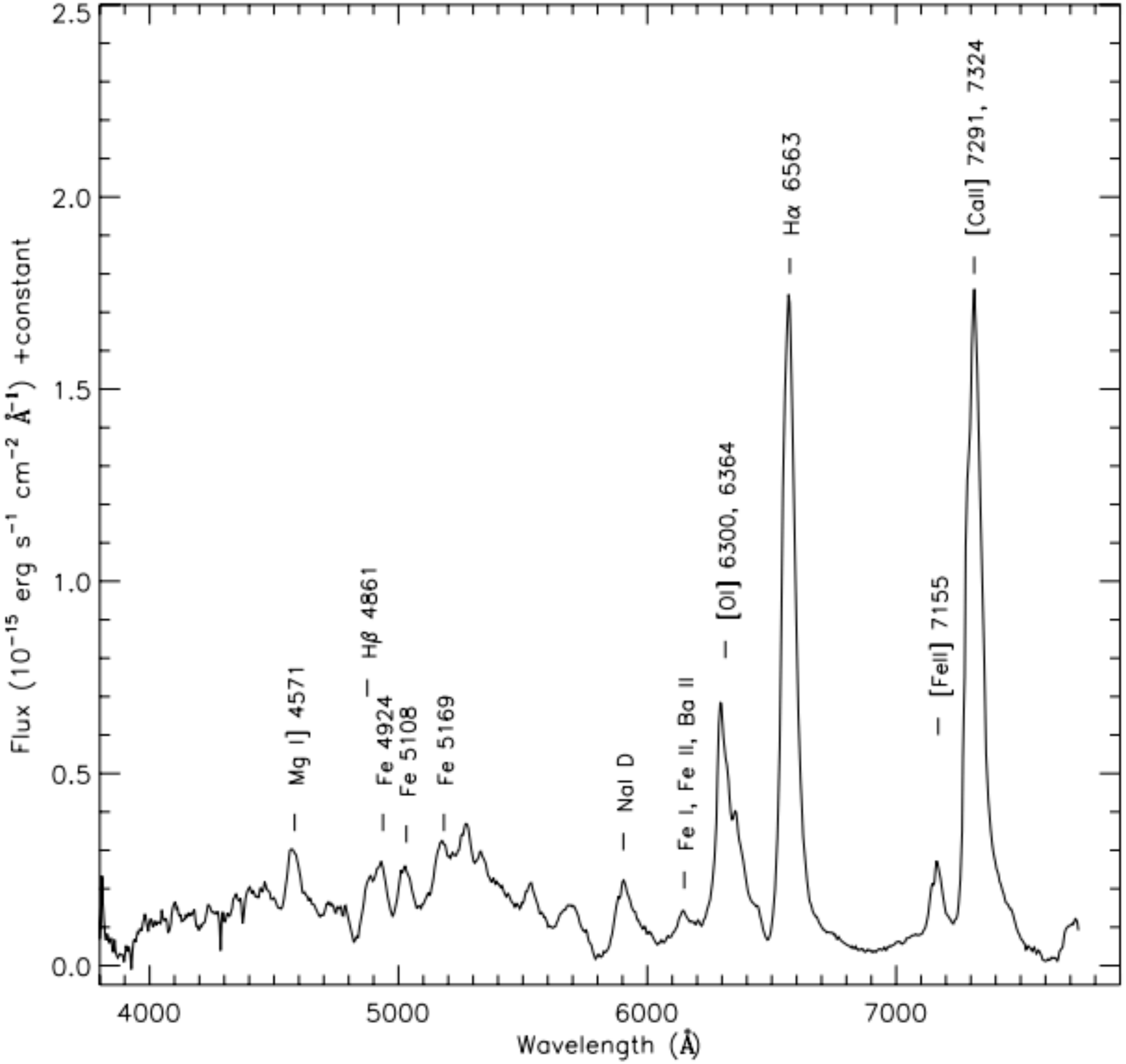


H$\alpha$ has excess emission compared to pure P-Cygni line.

P-Cygni lines, often blending together

# A Type IIP prototype : SN 2004et

Nebular spectrum, 400d

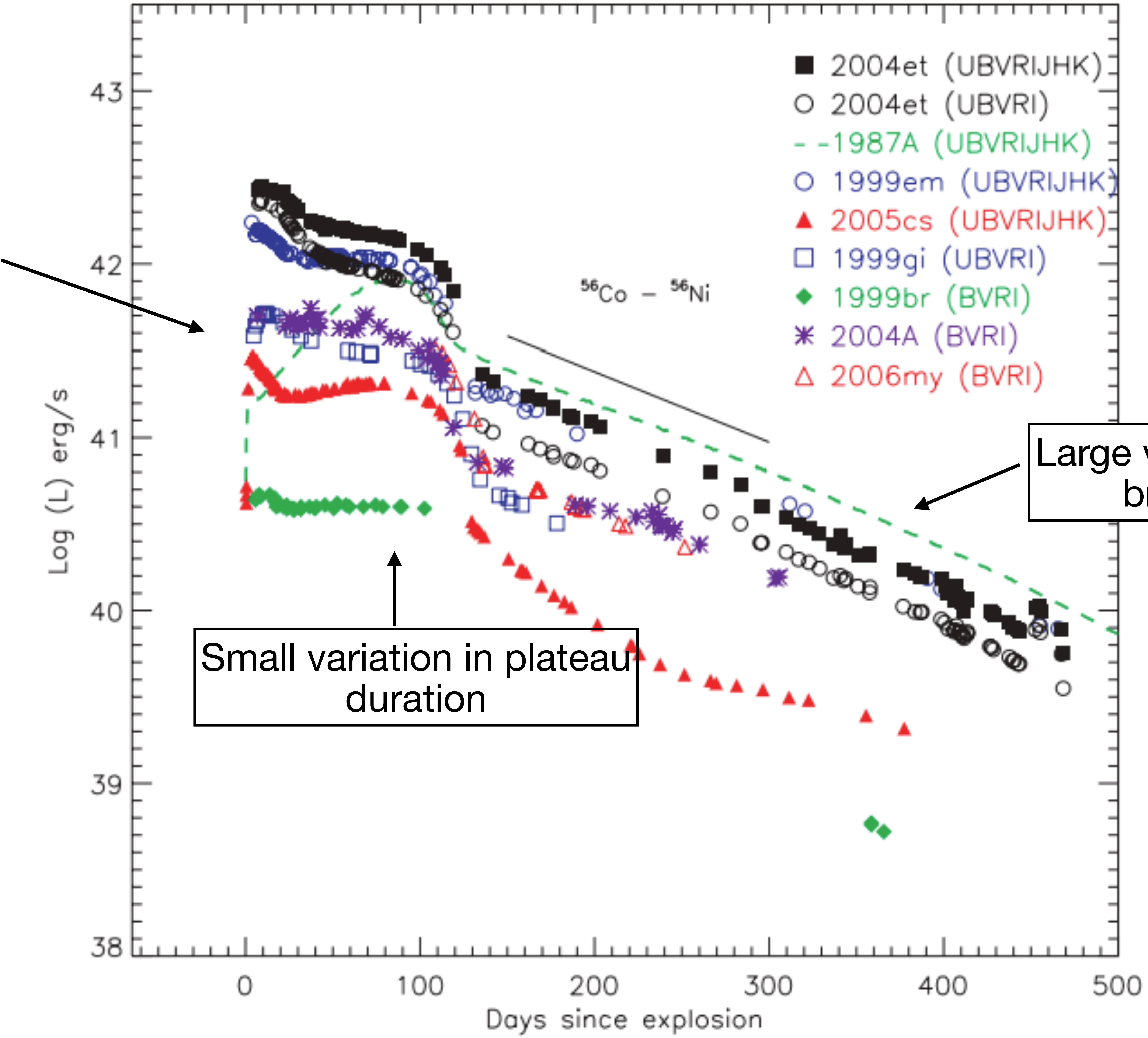


- Strong lines from **O, Mg, Na, Fe, Ca : *direct signatures of hydrostatic and explosive nucleosynthesis.***
- Expansion velocities of emission lines typically ~2000 km/s.
- A caveat: models show the strong [Ca II] 7291, 7324 line is not from newly synthesised calcium but from primordial calcium in the unprocessed H zone.
- Some lines, e.g. Na I 5890, 5896, can continue to absorb and have P-Cygni-like profiles as in the photospheric phase.

Maguire 2010

# Variety of IIP light curves

Large variation in plateau brightness

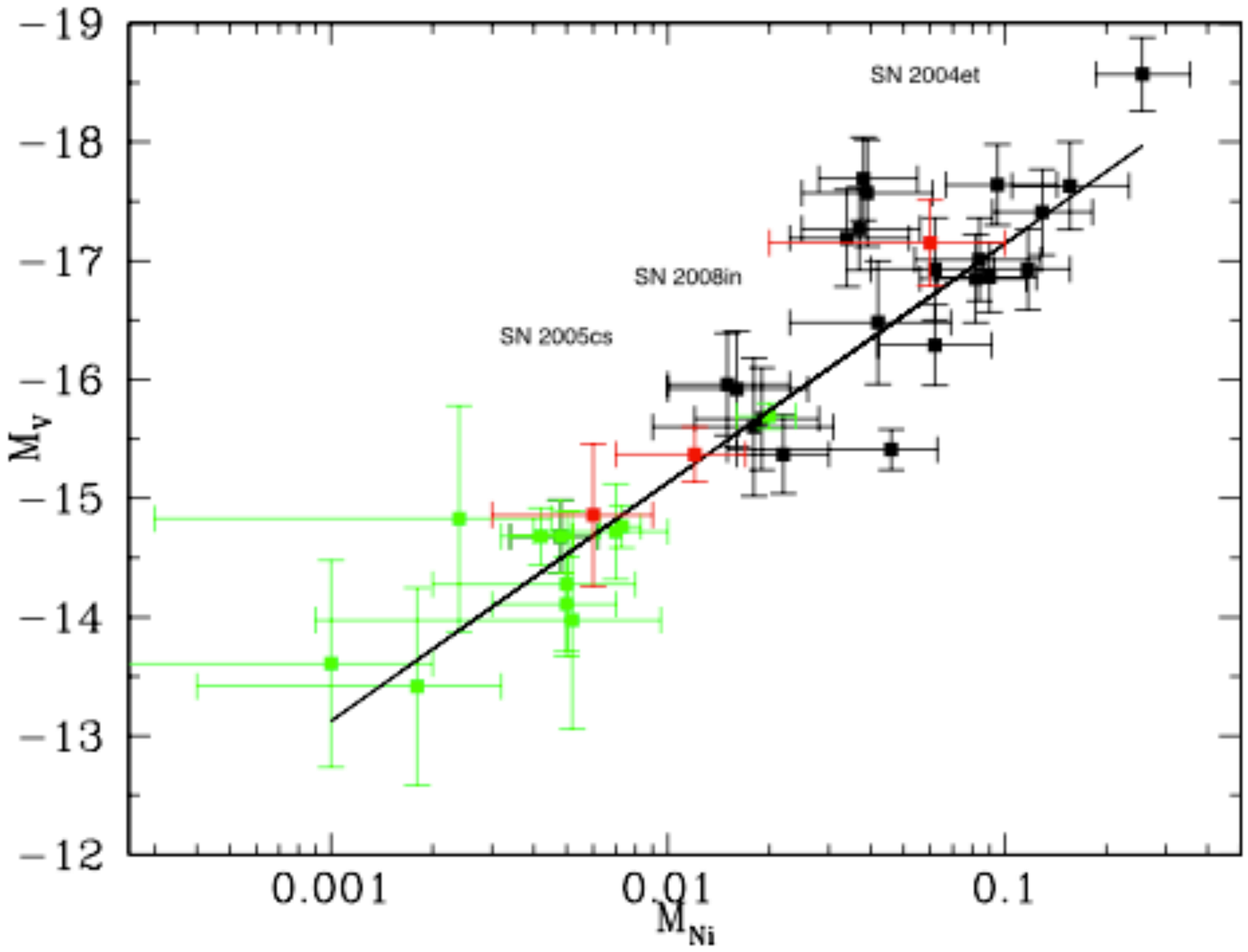


Small variation in plateau duration

Large variation in tail brightness

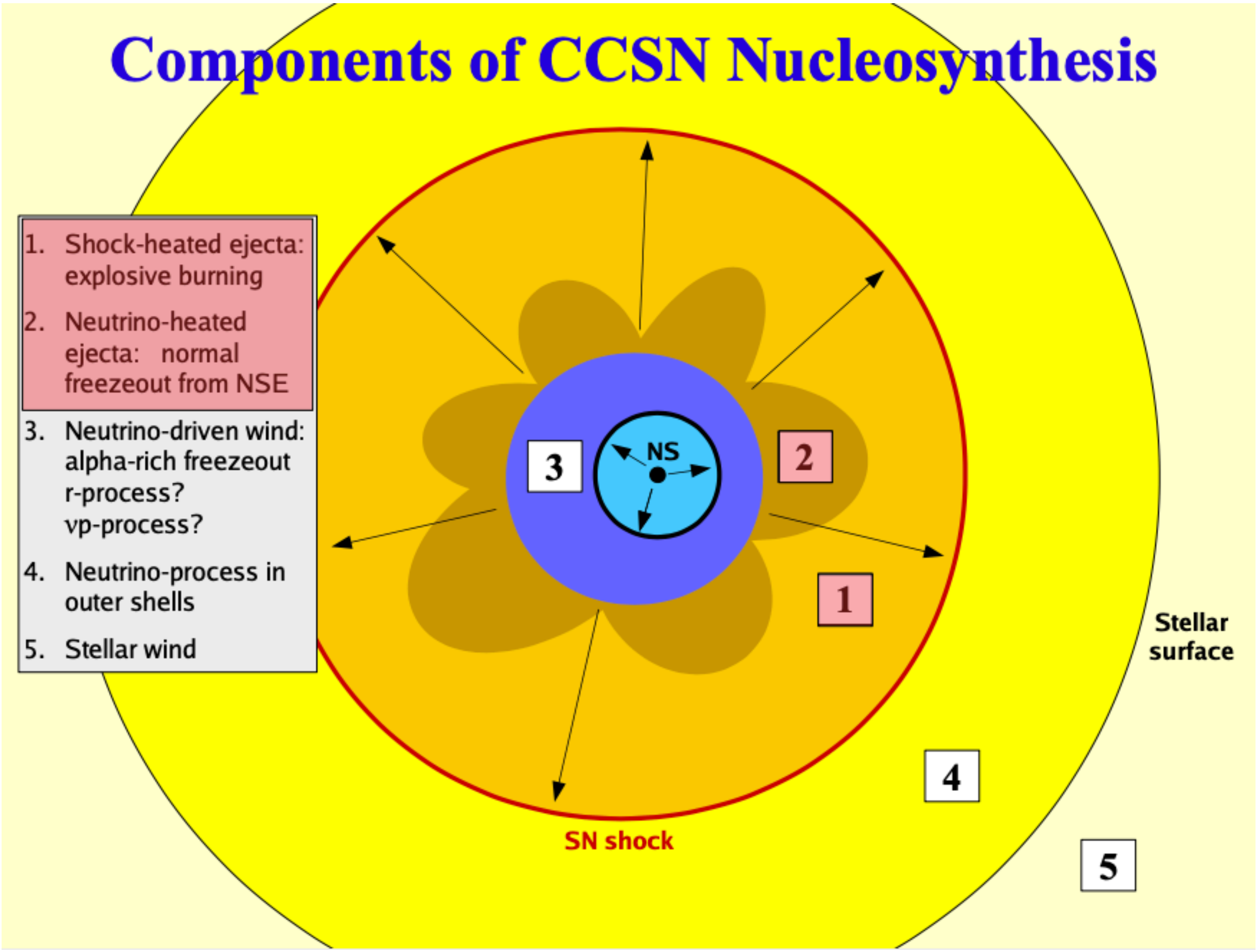
Maguire 2010

# Type IIP SNe with brighter plateaus make more $^{56}$Ni



Spiro 2014

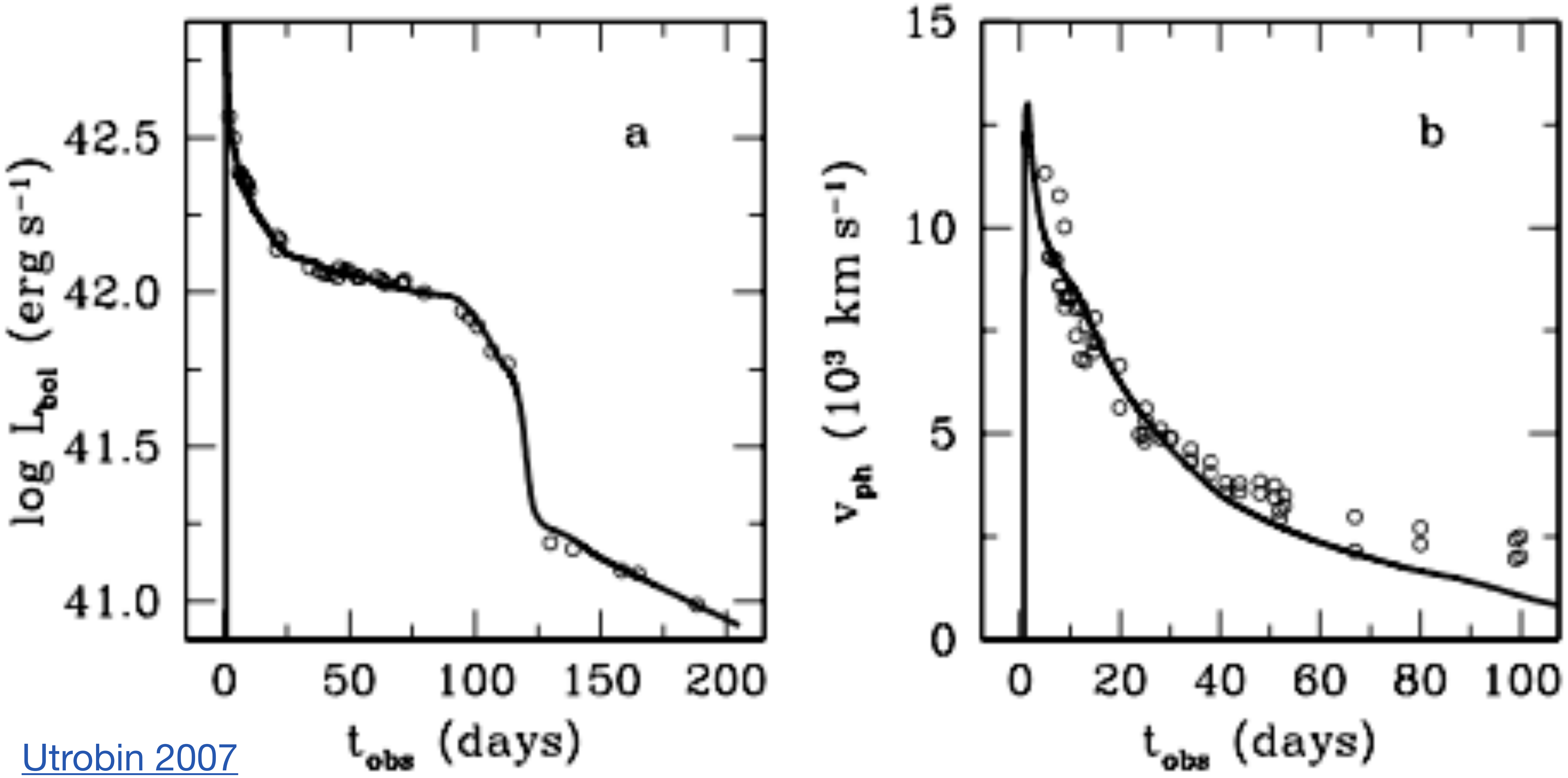
- $^{56}$Ni production varies in range 0.001 - 0.1 $M_\odot$



## Components of CCSN Nucleosynthesis

1. Shock-heated ejecta: explosive burning
2. Neutrino-heated ejecta: normal freezeout from NSE
3. Neutrino-driven wind: alpha-rich freezeout r-process? νp-process?
4. Neutrino-process in outer shells
5. Stellar wind

# Numerically modelling Type IIP light curves



Utrobin 2007

Here **polytropes** used for the RSG progenitor models.

Numerically solve 1st law of thermo-dynamics including treatment of radiative transport ($\frac{\partial l}{\partial m}$ term) and calculation of opacity $\kappa$ as function of $T, n_e$.

Compare models to observed $L_{bol}(t)$ and $v_{phot}(t)$.

$v_{phot}(t)$ estimated from P-Cygni line profiles.

Best model for SN 1999em:

$$M_{ZAMS} = 19\ M_{\odot}, R_0 = 500\ R_{\odot}, E = 1.3\ B$$

# Numerically modelling Type IIP light curves

Factor 2 larger $E$ —>

- Shortens plateau by 20%.
Our formula: 12%.

- Brightens factor ~2.
Our formula : factor 2.

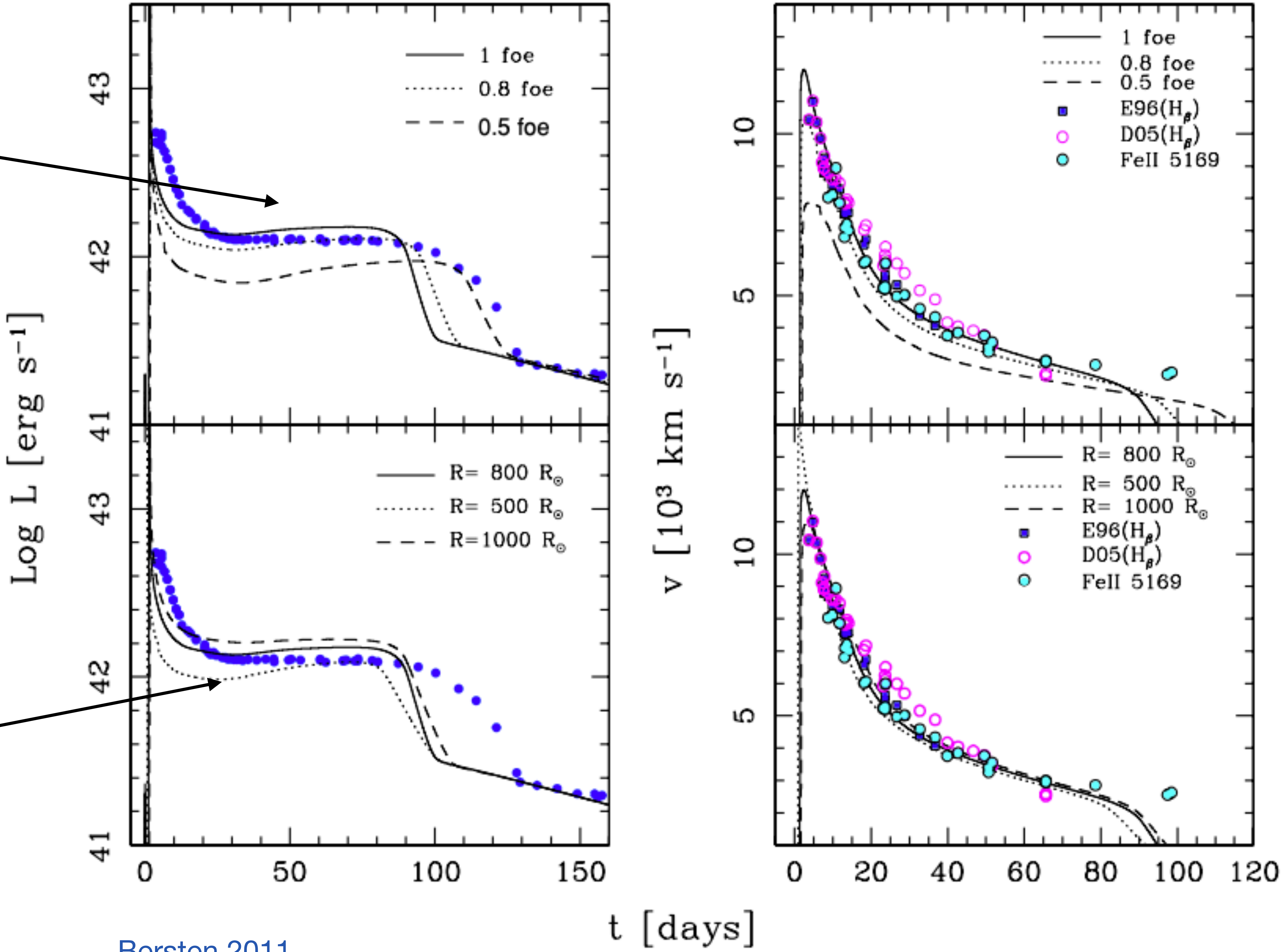
$$L \approx 6 \times 10^{42} E_{51} M_{M_\odot}^{-1} R_{0,500} \kappa_{0.2}^{-1}\ \mathrm{erg\ s^{-1}}$$

$$\Delta t_{IIP} = 81\mathrm{d}\ E_{51}^{-1/6} M_{10}^{1/2} R_{0,500}^{1/6} \kappa_{0.2}^{1/6}$$

Factor 2 larger $R_0$ —>

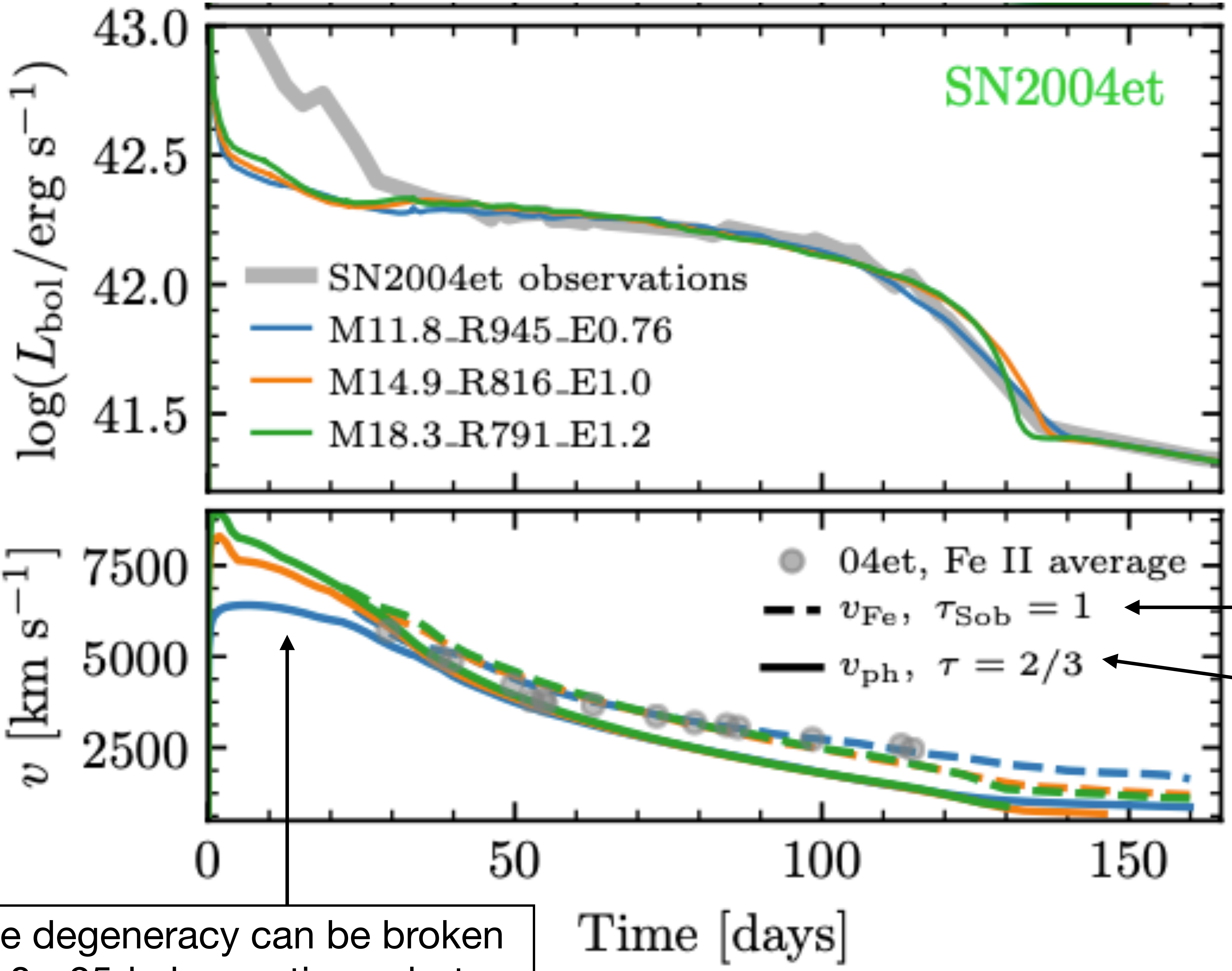
- Lengthens plateau by 10%.
Our formula : 12%.

- Brightens factor 1.6.
Our formula : factor 2.



Bersten 2011

# Numerically modelling Type IIP light curves



**Goldberg 2019** : Not so straightforward to determine $E, M$, and $R_0$ from observables $L, \Delta t$, and $v_{phot}$: there are degeneracies and $v_{phot}$ measurements in fact adds quite little new information between 25 - 120d.

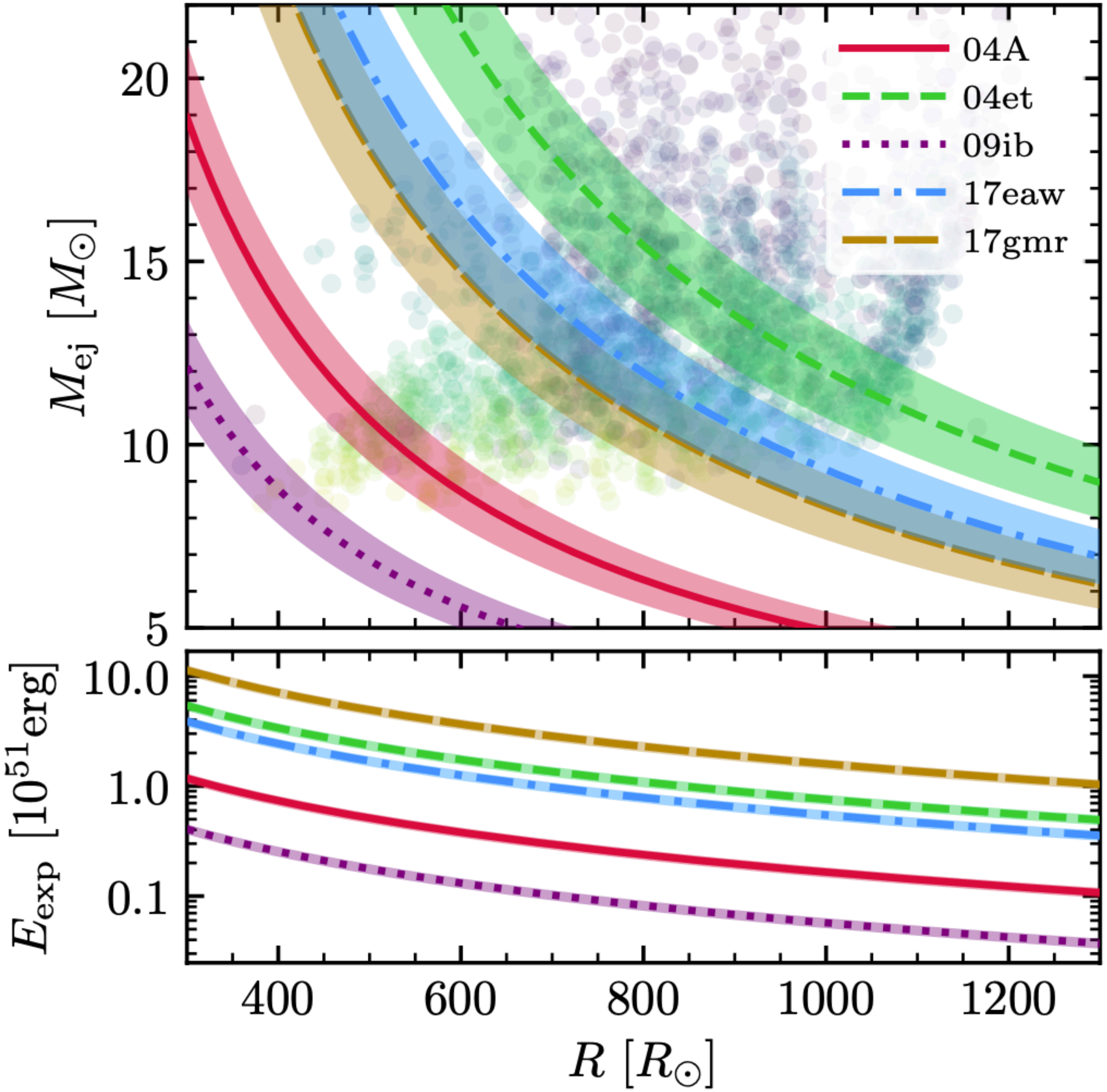
Measured $v_{max}$ from Fe II P-Cygni line

Model $v_{max}$

Model $v_{phot}$

The degeneracy can be broken by 0 - 25d observations : but other issues there (CSM interaction).

# Numerically modelling Type IIP light curves

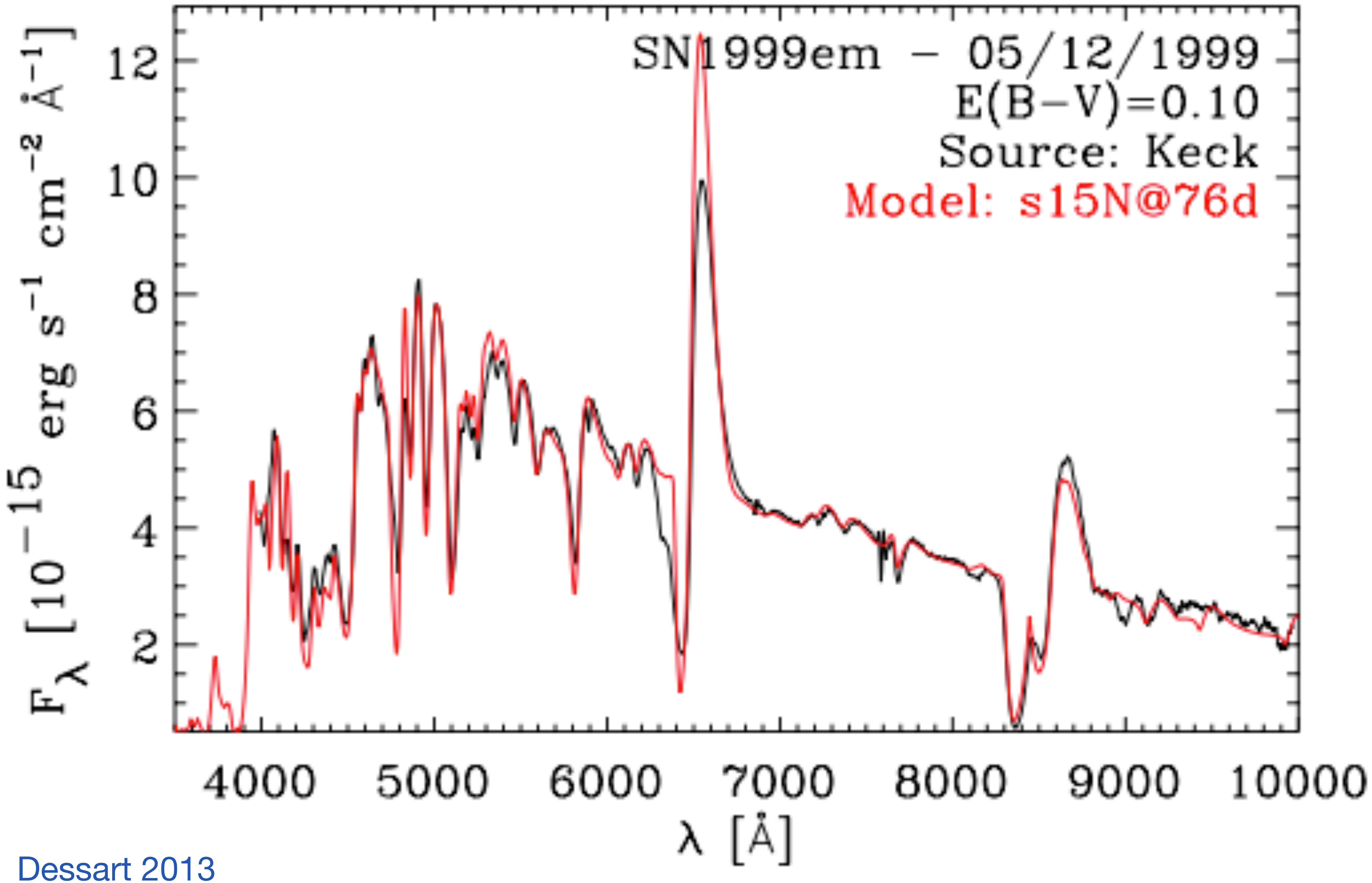


$M$ and $E$ can be most uniquely determined if $R_0$ can be determined by some other method (e.g. progenitor imaging).

Solution curves for measurements of $L_{plateau}$ (day 50) and $\Delta t$.

Goldberg 2019

# Modelling photospheric spectra



Dessart 2013

**Amazing fit?**

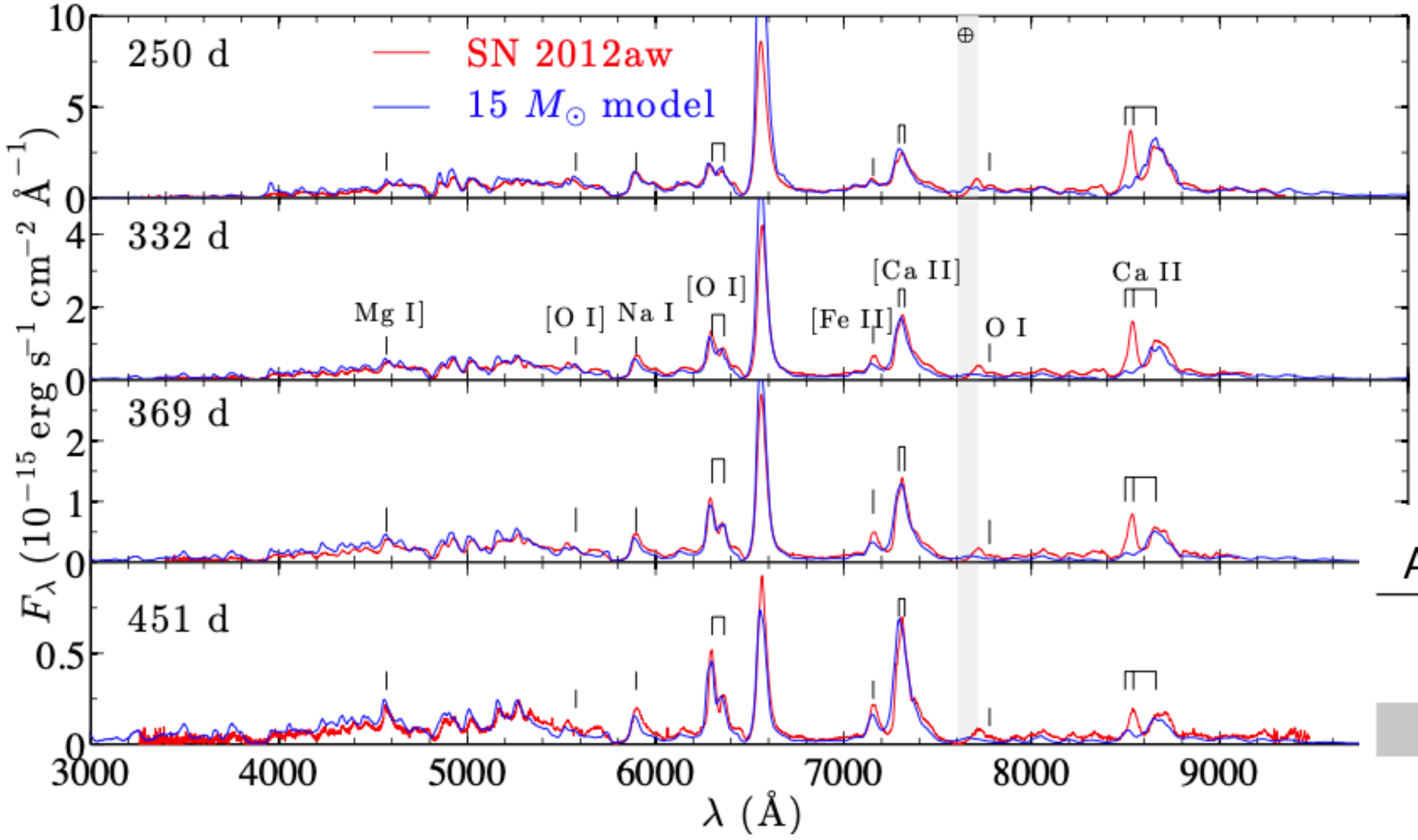
One should be aware that photospheric spectra probe the outermost layers : in a H-rich SNe this is unprocessed (~solar composition) material.

Also, LTE is a good approximation —> composition and physics is simple and known.

**This kind of analysis mainly useful to determine**

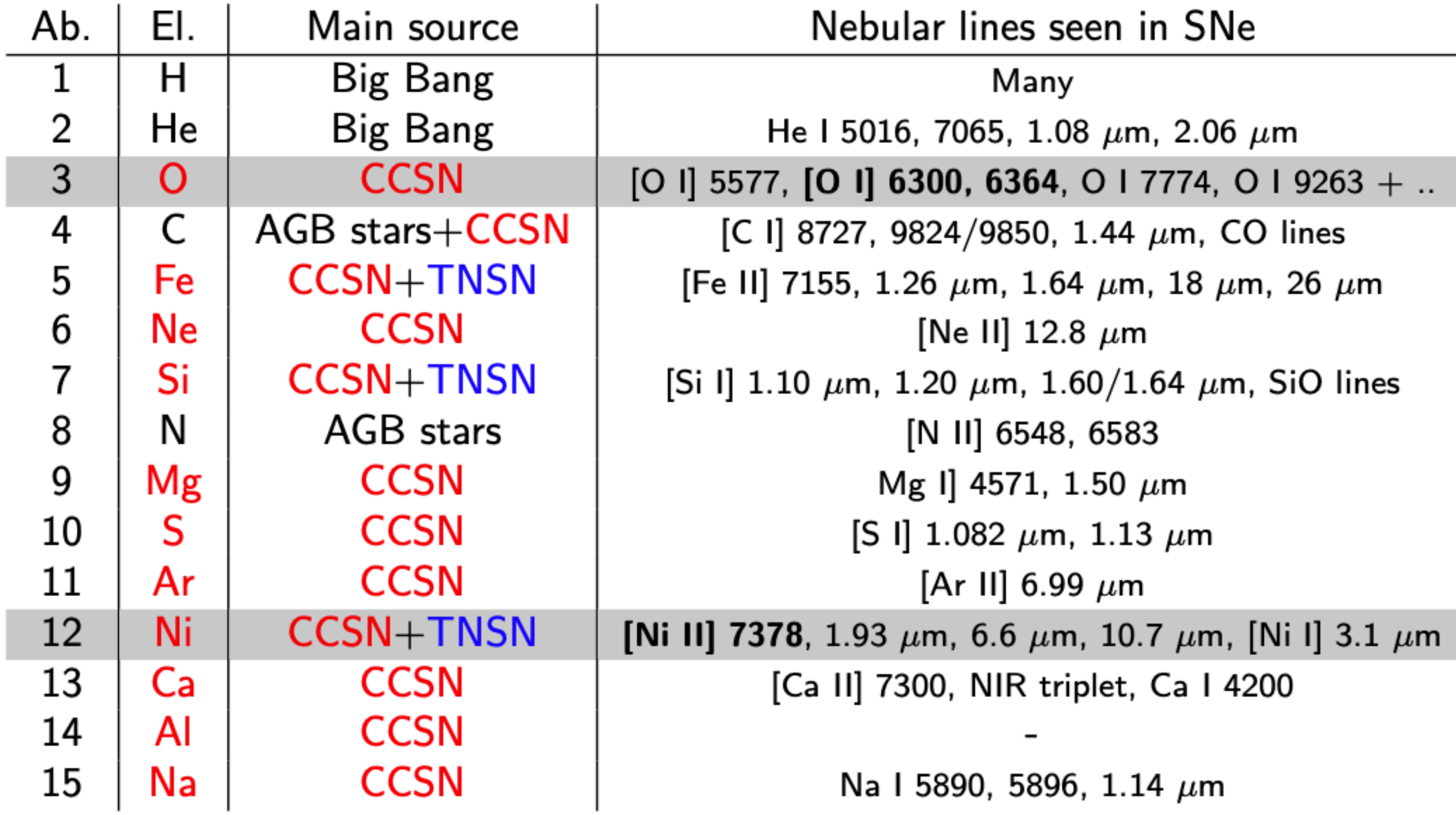
- **The SN density profile $\rho(v)$ in the outer layers.**
- **The metallicity.**

# Modelling nebular spectra



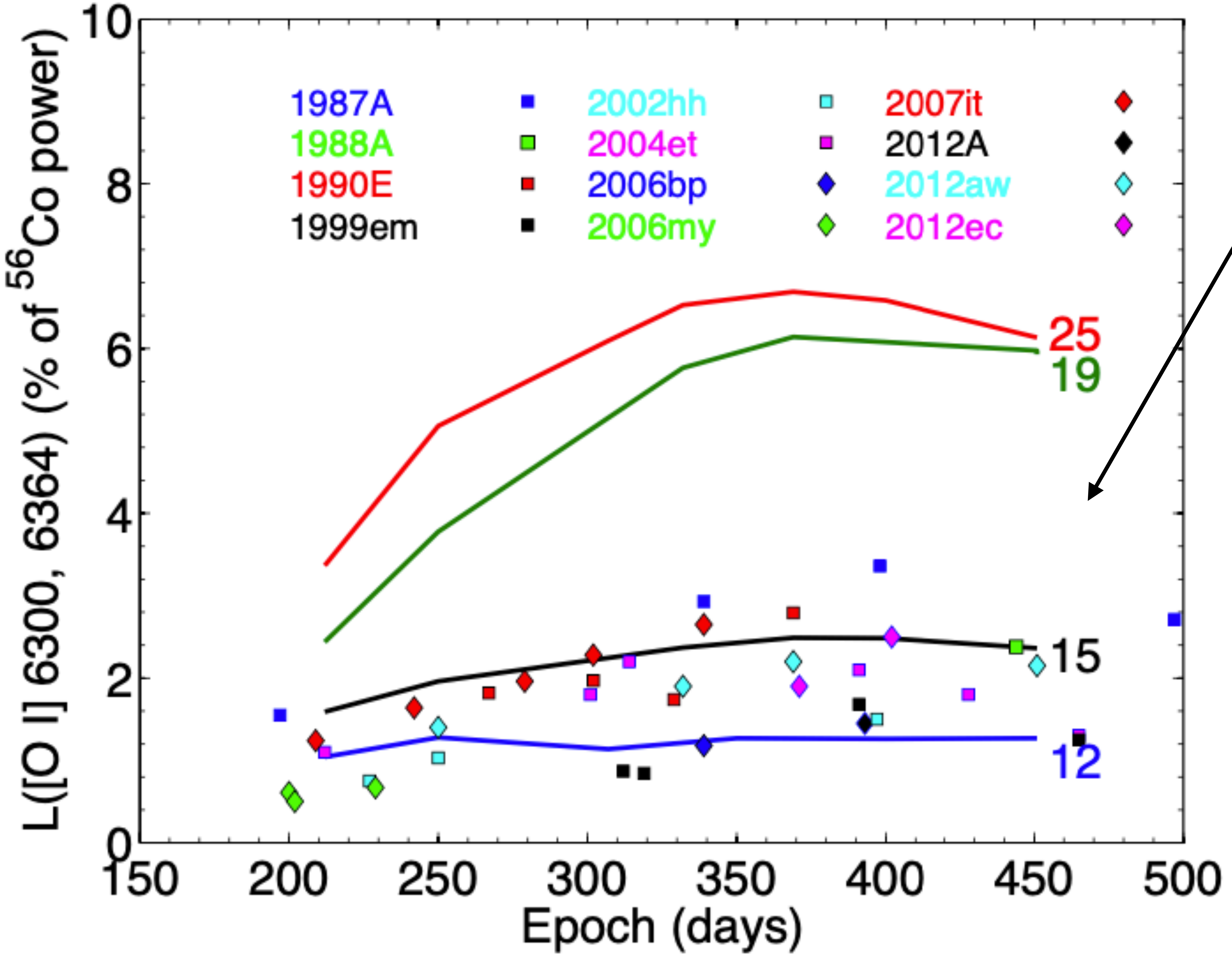
Jerkstrand 2014

CCSN = Core-Collapse Supernova
TNSN = Thermonuclear Supernova (=Ia)



| Ab. | El. | Main source | Nebular lines seen in SNe |
|---|---|---|---|
| 1 | H | Big Bang | Many |
| 2 | He | Big Bang | He I 5016, 7065, 1.08 $\mu$m, 2.06 $\mu$m |
| 3 | O | CCSN | [O I] 5577, **[O I] 6300, 6364**, O I 7774, O I 9263 + .. |
| 4 | C | AGB stars+CCSN | [C I] 8727, 9824/9850, 1.44 $\mu$m, CO lines |
| 5 | Fe | CCSN+TNSN | [Fe II] 7155, 1.26 $\mu$m, 1.64 $\mu$m, 18 $\mu$m, 26 $\mu$m |
| 6 | Ne | CCSN | [Ne II] 12.8 $\mu$m |
| 7 | Si | CCSN+TNSN | [Si I] 1.10 $\mu$m, 1.20 $\mu$m, 1.60/1.64 $\mu$m, SiO lines |
| 8 | N | AGB stars | [N II] 6548, 6583 |
| 9 | Mg | CCSN | Mg I] 4571, 1.50 $\mu$m |
| 10 | S | CCSN | [S I] 1.082 $\mu$m, 1.13 $\mu$m |
| 11 | Ar | CCSN | [Ar II] 6.99 $\mu$m |
| 12 | Ni | CCSN+TNSN | **[Ni II] 7378**, 1.93 $\mu$m, 6.6 $\mu$m, 10.7 $\mu$m, [Ni I] 3.1 $\mu$m |
| 13 | Ca | CCSN | [Ca II] 7300, NIR triplet, Ca I 4200 |
| 14 | Al | CCSN | - |
| 15 | Na | CCSN | Na I 5890, 5896, 1.14 $\mu$m |

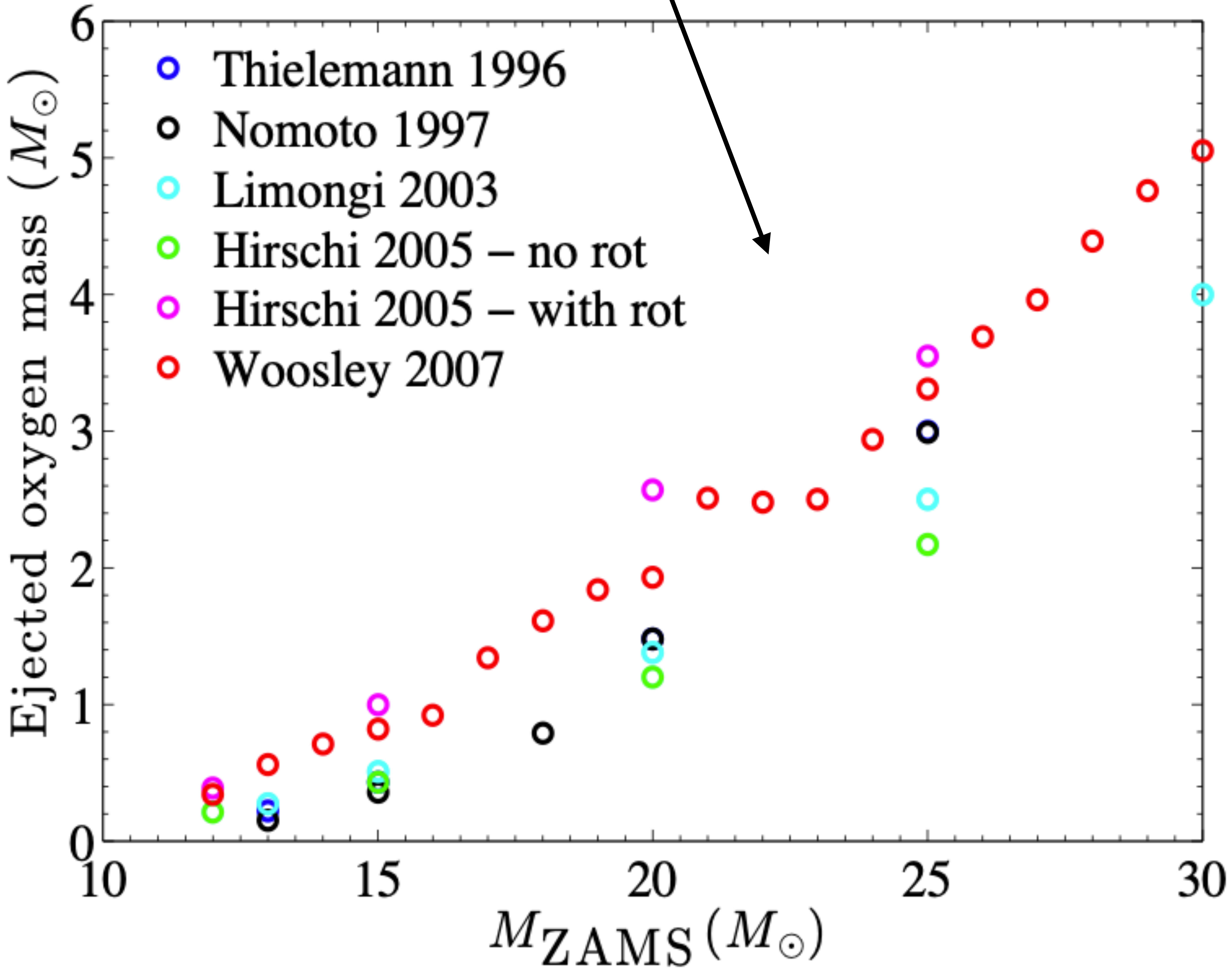
# Modelling nebular spectra



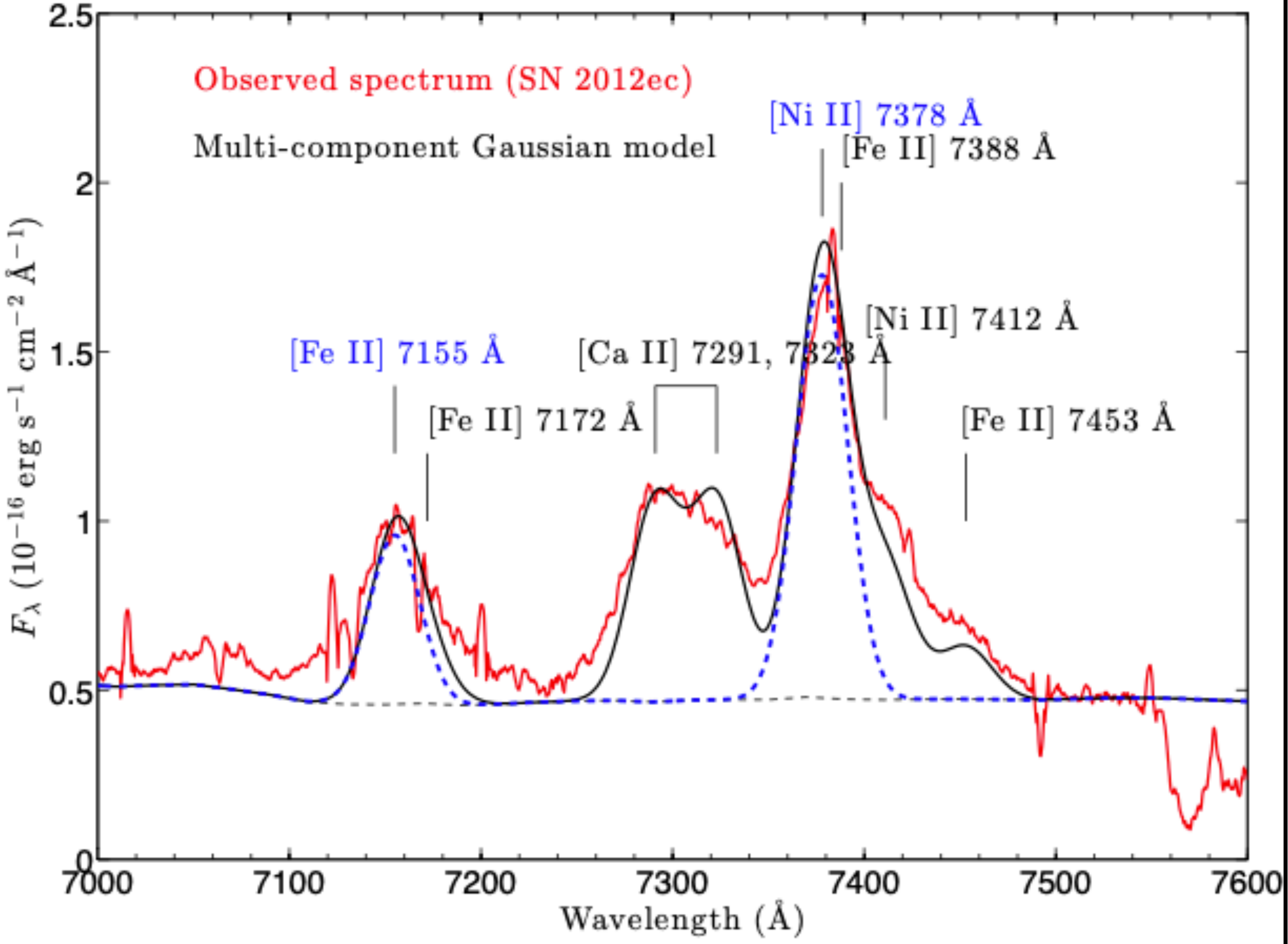
Jerkstrand 2015a

Observed [O I] lines in Type IIP SNe best fit models of $M_{ZAMS} = 8 - 17\ M_\odot$ stars.

Oxygen production is most sensitive to $M_{ZAMS}$ of all elements.



# An example of abundance determination in the nebular phase



Jerkstrand 2015b

Advanced NLTE model used to determine the physical regime : for **[Fe II] 7155** and **[Ni II] 7378** **LTE** and **optically thin** limits ok.

Then

Excitation energies

$$\frac{L_{7378}}{L_{7155}} = \frac{n_u^{7378} A_{7378} h\nu_{7378}}{n_u^{7155} A_{7155} h\nu_{7155}} = C\frac{n_{\mathrm{NiII}}}{n_{\mathrm{FeII}}} \times \exp - \left( \frac{1.69\ \mathrm{eV} - 1.96\ \mathrm{eV}}{kT} \right)$$

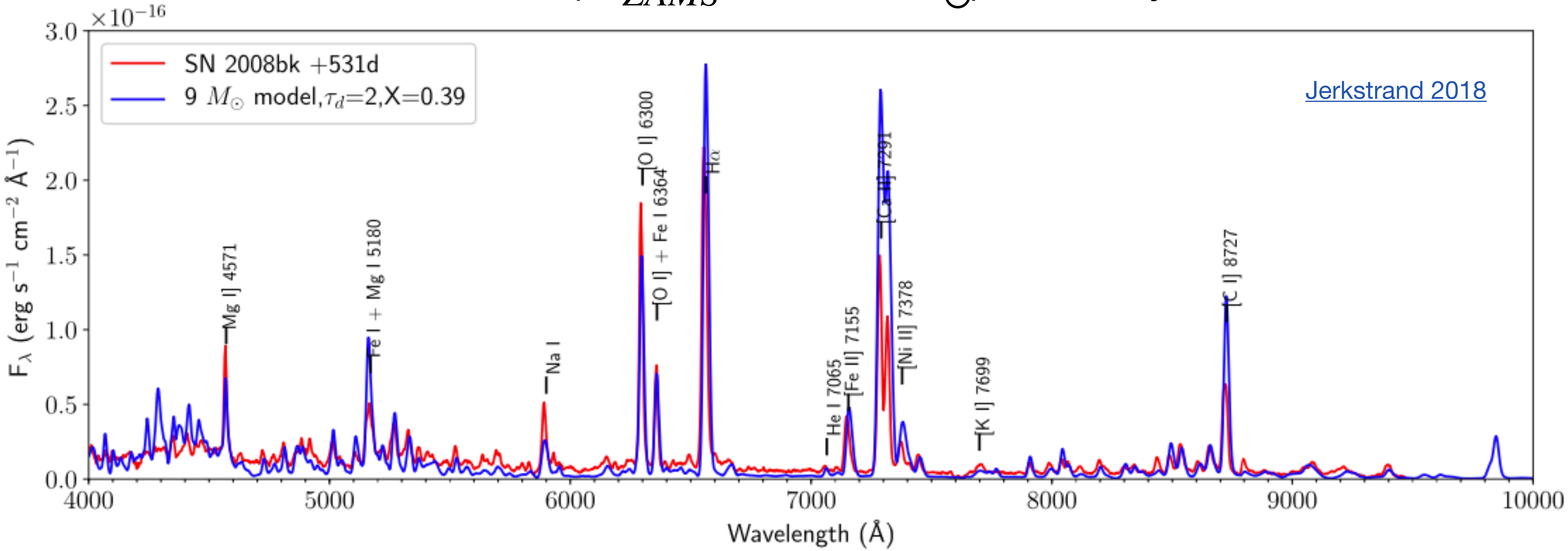
Only weak *T* dependency —> $\frac{n_{\mathrm{NiII}}}{n_{\mathrm{FeII}}}$ can be *accurately* determined.

Then, again use the advanced model, or basic physical argument (Ni and Fe have almost the same ionization potentials and cross sections) to conclude that

$$\frac{n_{\mathrm{Ni}}}{n_{\mathrm{Fe}}} \approx \frac{n_{\mathrm{NiII}}}{n_{\mathrm{FeII}}}$$

Then, the abundance ratio of Ni and Fe can be determined.

# The lowest-mass CCSNe ($M_{ZAMS}$ ~ 8 - 12 $M_{\odot}$) relatively well understood



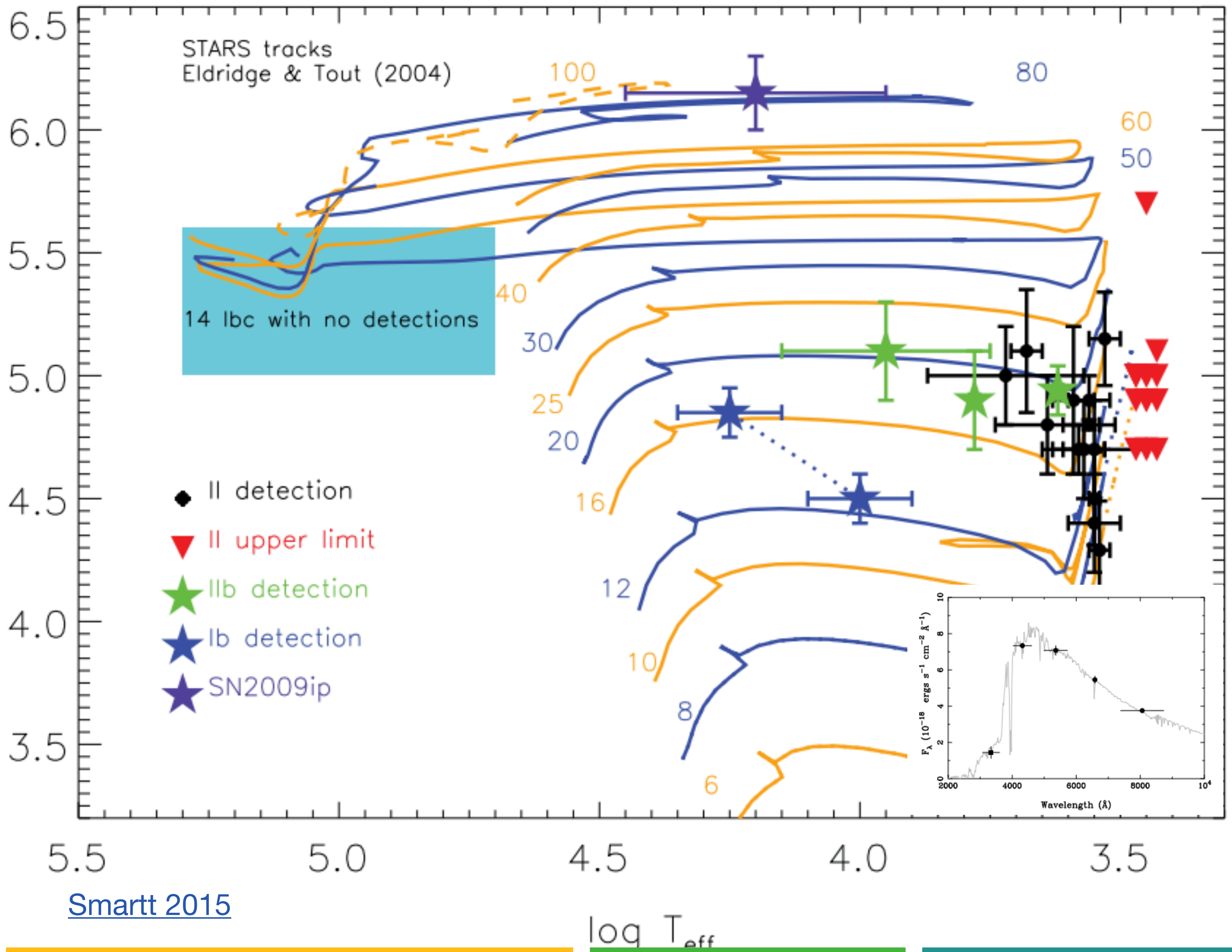
Jerkstrand 2018

- E ~ $10^{50}$ erg is a firm prediction from explosion modelling —> quite narrow lines.

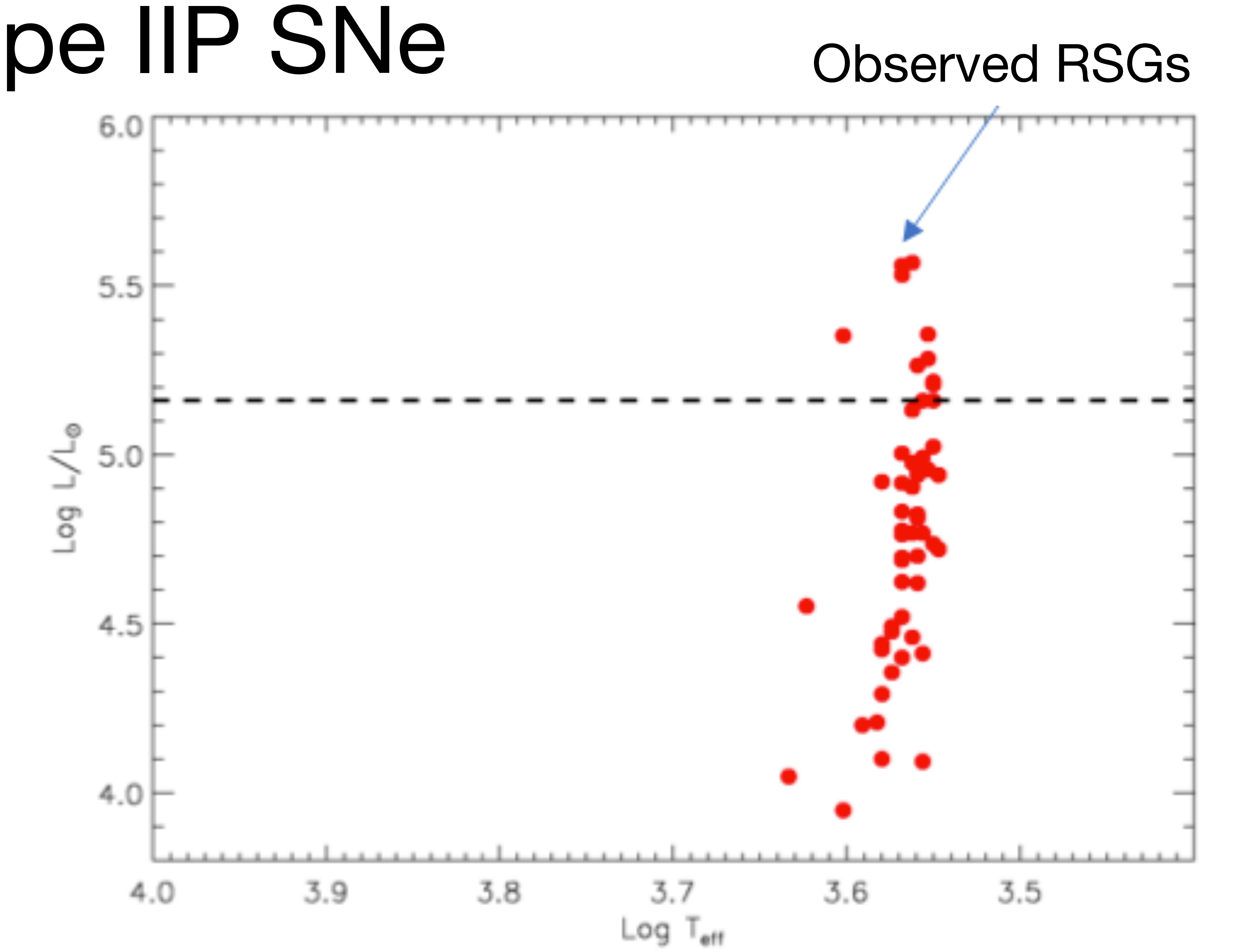
- Nebular model spectra of self-consistent neutrino-driven explosions in good agreement with observed spectra of SNe in the **subluminous Type IIP class.** Also fraction (20-30%) in good agreement.

- No electron-capture SNe clearly detected yet - current limit on possible progenitor mass range $\Delta M_{ZAMS} \lesssim 1\ M_{\odot}$.

# Direct progenitor detections of Type IIP SNe



[Smartt 2015](#)



Levesque 2005

For a nearby SN, good chance of finding an image of the progenitor in HST archives.

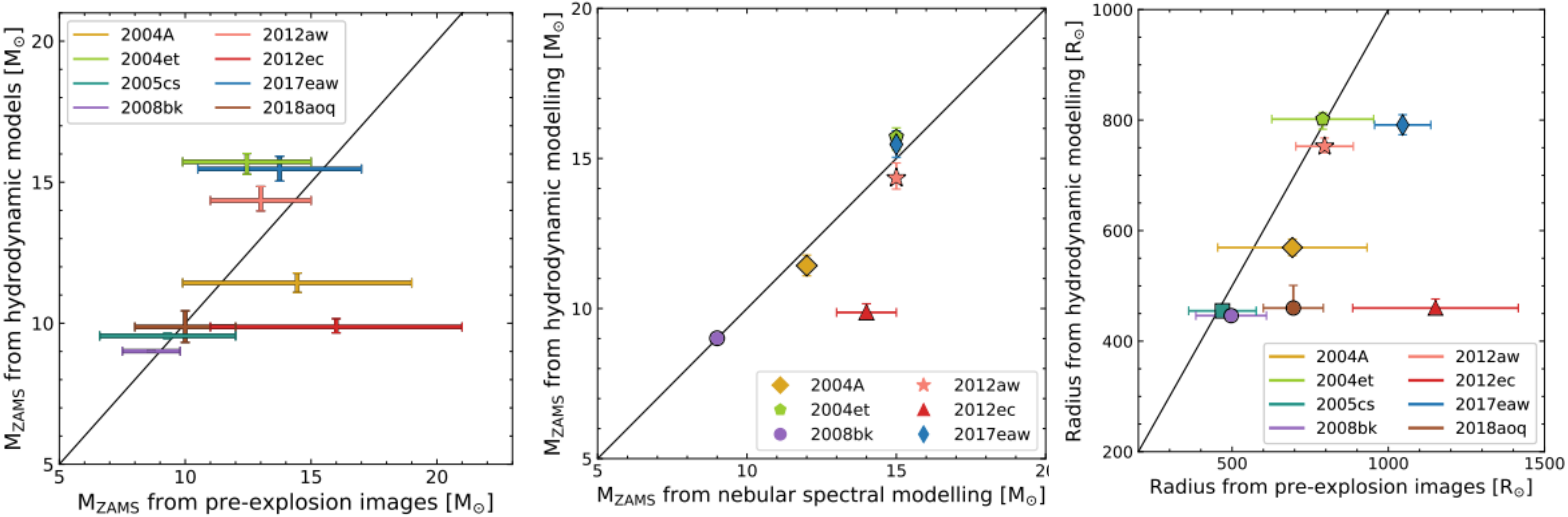
*No RSGs with log L > 5.0 so far seen to explode as IIP SNe, whereas RSGs up to log L = 5.5 are known —>* ***"Red supergiant problem"***

Most massive RSGs fail to explode?

Evolve to WR stars?

Get dust shrouded at end?

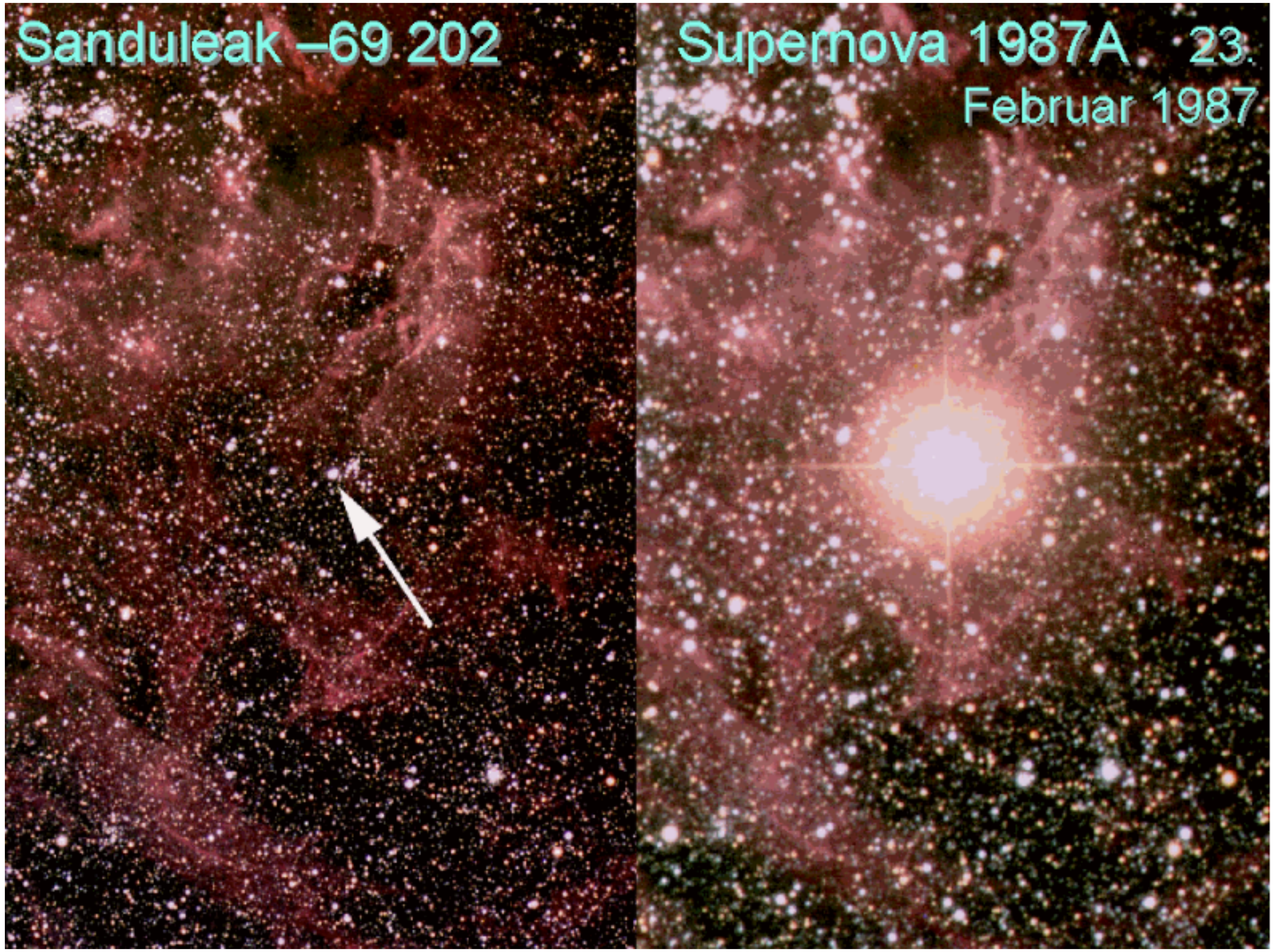
# Comparing results from progenitor imaging, light curve modelling, and nebular spectral modelling

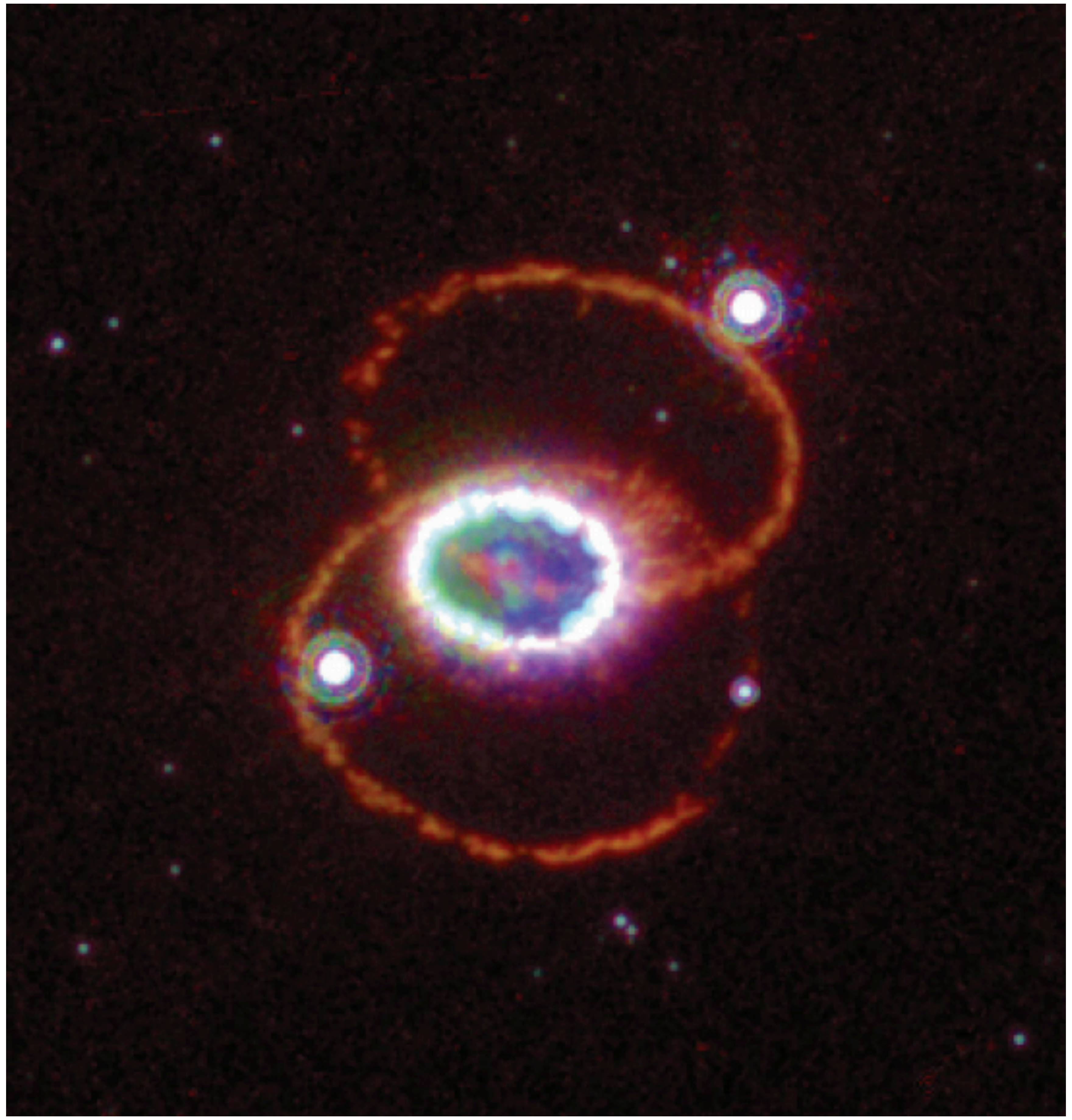


Martinez 2020

Biggest current issue is disagreement for RSG radii

# Type II-pec SNe
(e.g. SN 1987A)

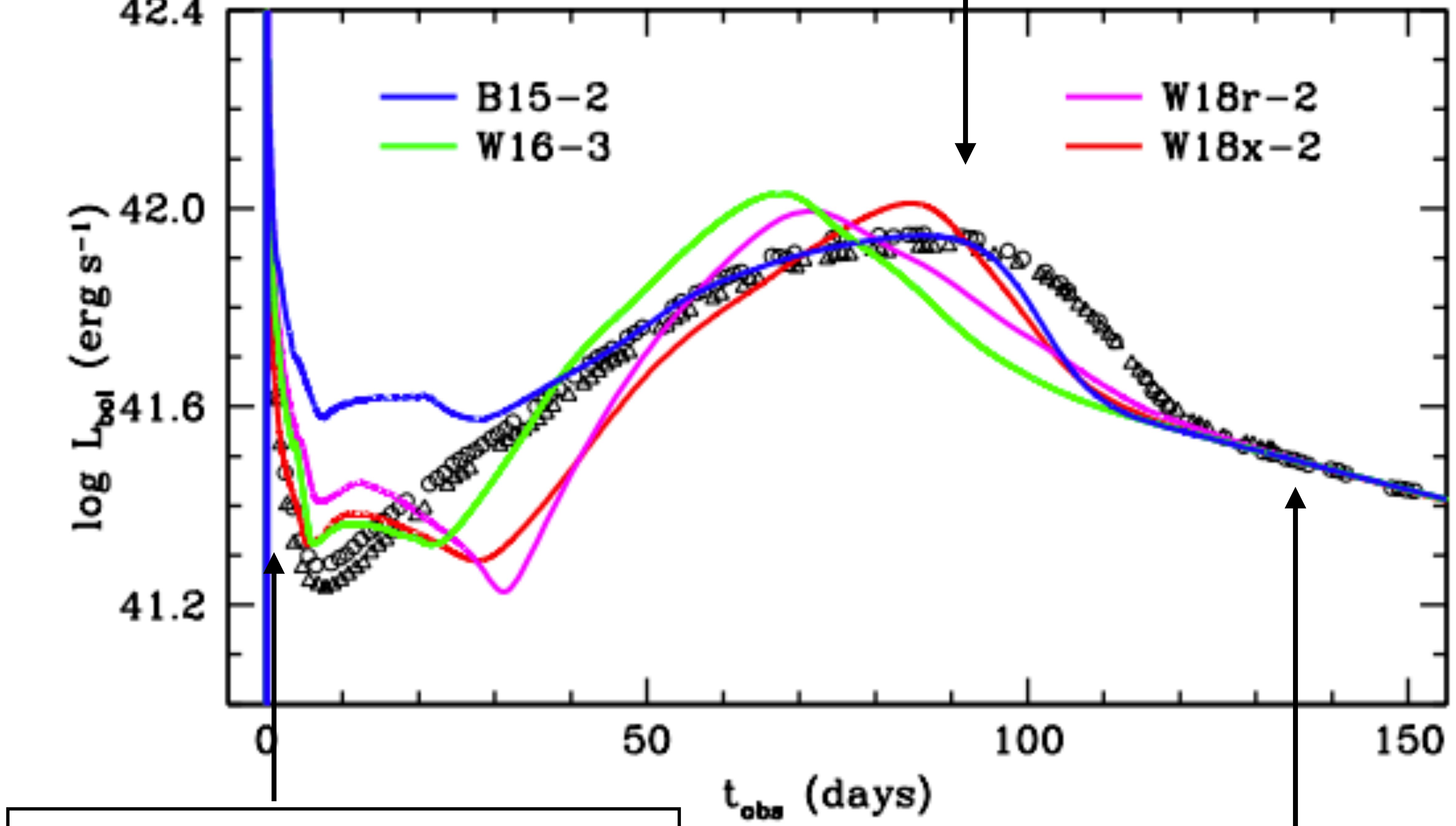



McCray & Fransson 2016

# SN 1987A light curve modelling

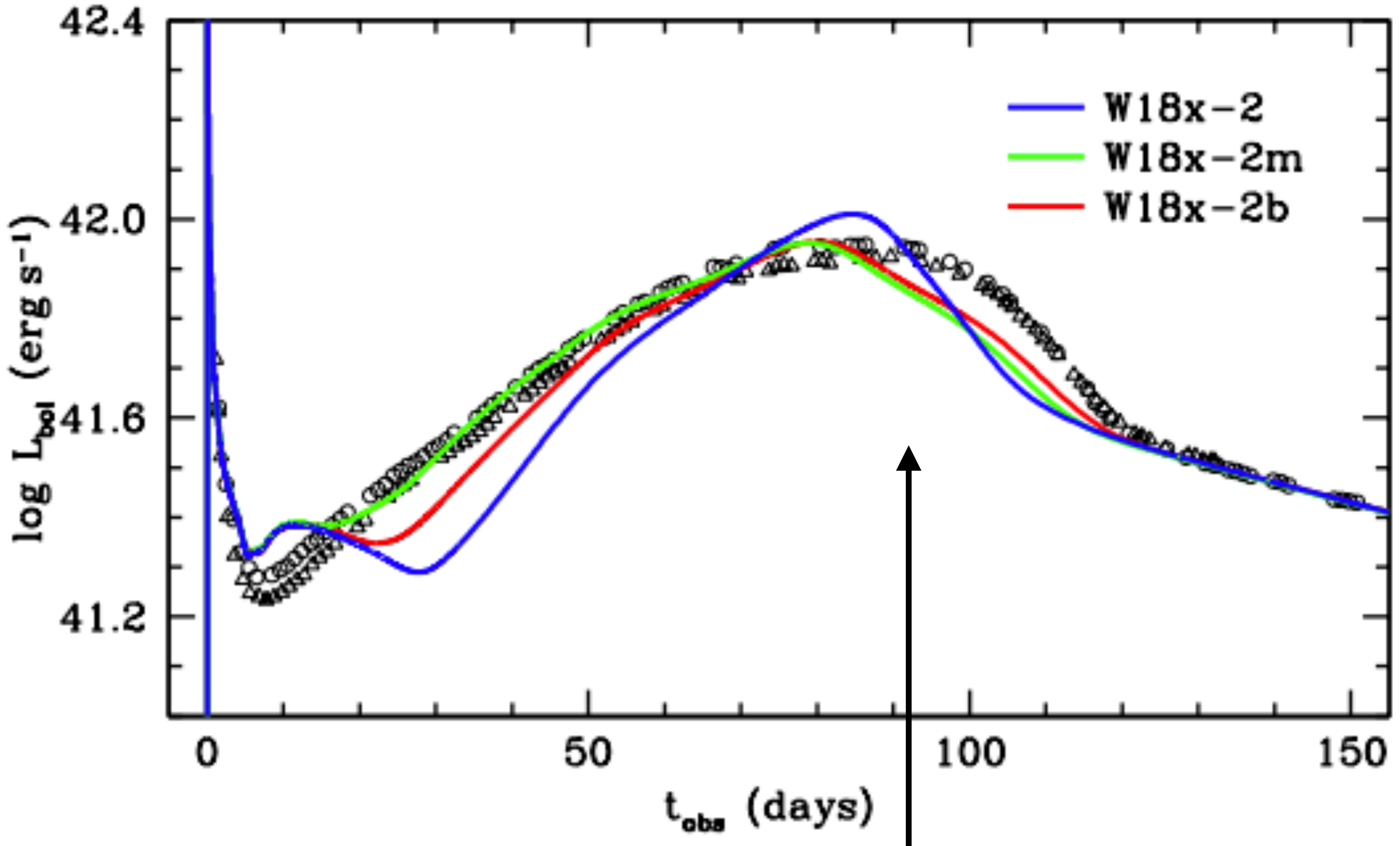
Utrobin 2017

Arnett's law gives $M(^{56}\text{Ni}) \approx 0.1\ M_\odot$



Shock-deposited energy can provide bright emission only for a week or so for a BSG: expanding from <~ $50\ R_\odot$ gives too strong adiabatic degradation for later contribution (Part E).

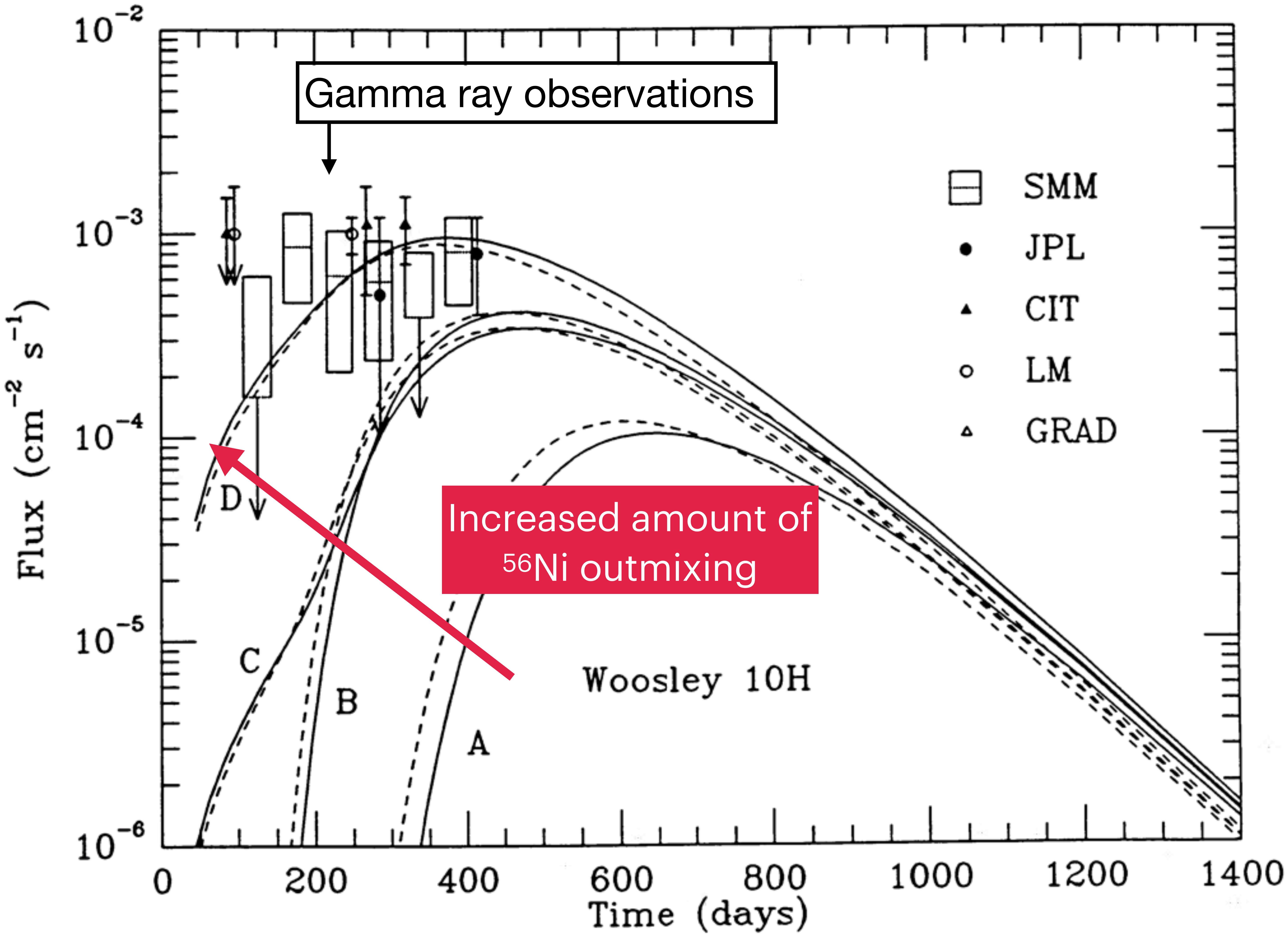
Early tail luminosity ==> $M(^{56}\text{Ni}) = 0.075\ M_\odot$



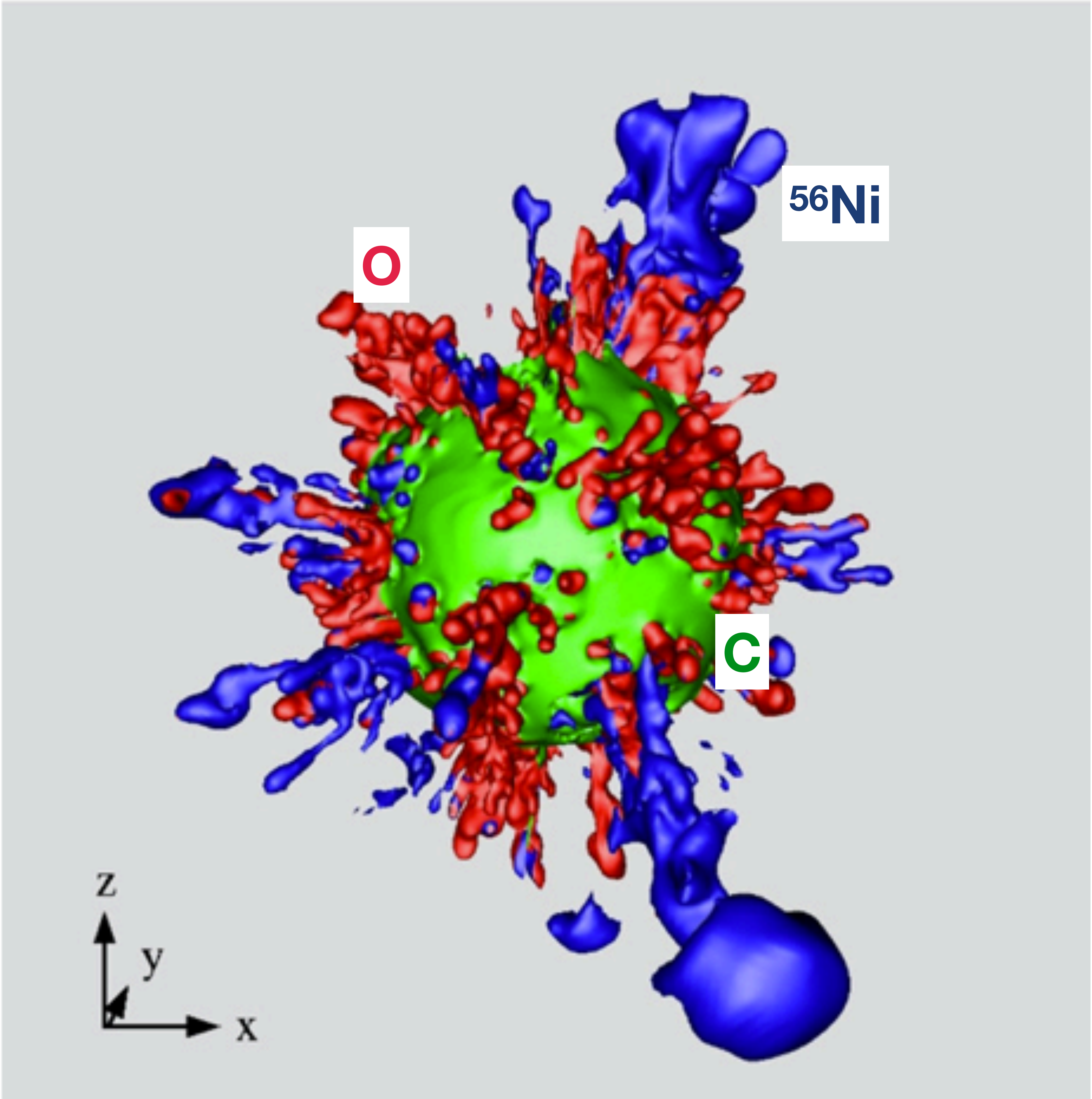
**Significant outmixing** of $^{56}$Ni (W18x-2m and W18x-2b) needed to make model light curves agree with observations.

Best models for 1987A:
$M_{ZAMS} = 15 - 20\ M_\odot$ progenitor, $E \sim 1\ B$ explosion.

# SN 1987A : Gamma rays escaped earlier than expected: **significant outmixing** of the $^{56}$Ni inferred also here



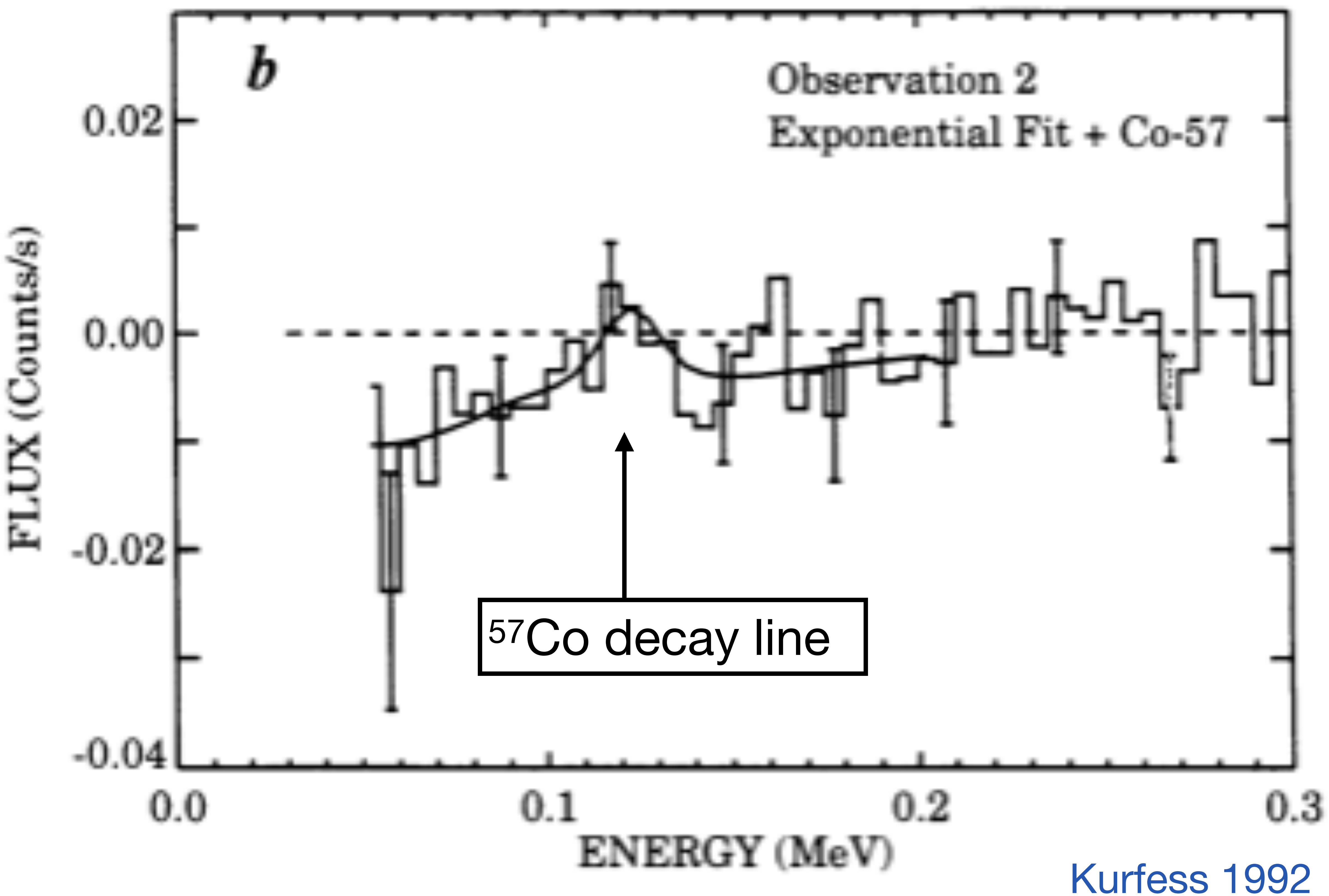
Bussard 1989



Hammer, Janka & Muller 2010:
**$^{56}$Ni fragments** fly far out into the envelope.

# First detection of other radioactive species than $^{56}$Ni

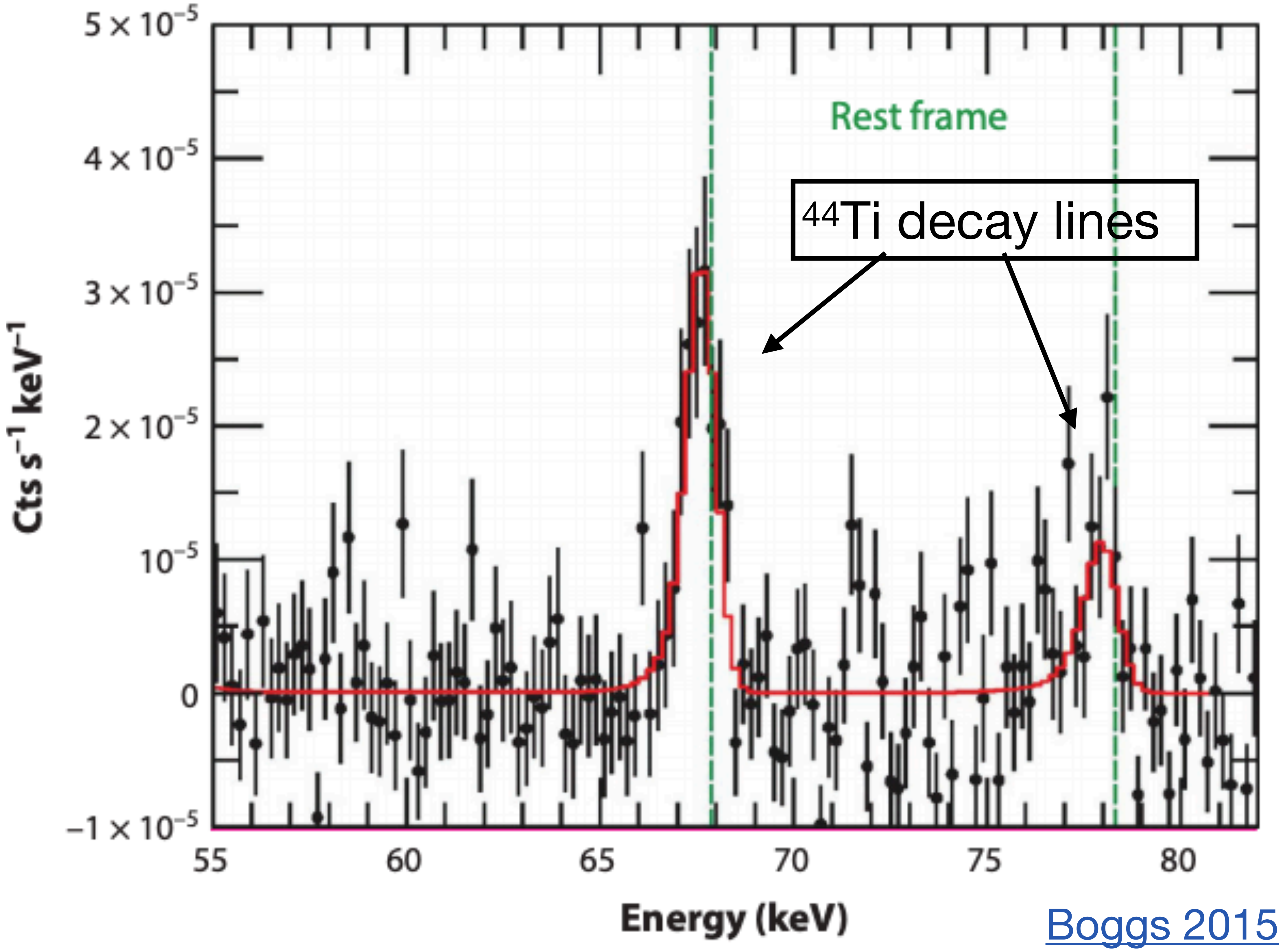
$^{57}$**Co** Constrains the **neutron excess** of the burning region.



$^{57}$Co decay line

Kurfess 1992

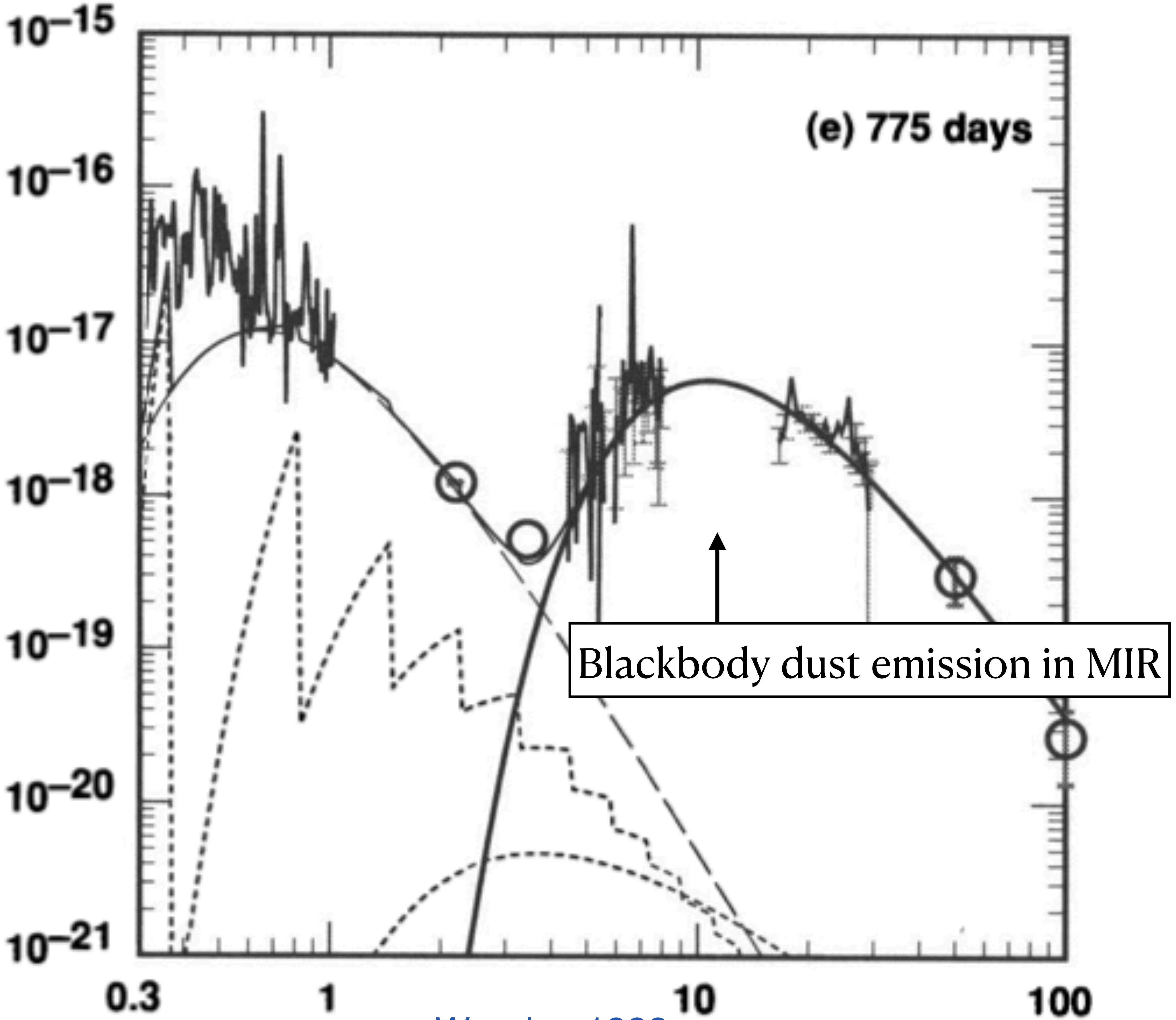
$^{44}$**Ti** Constrains the **entropy** of the burning region.



$^{44}$Ti decay lines

Boggs 2015

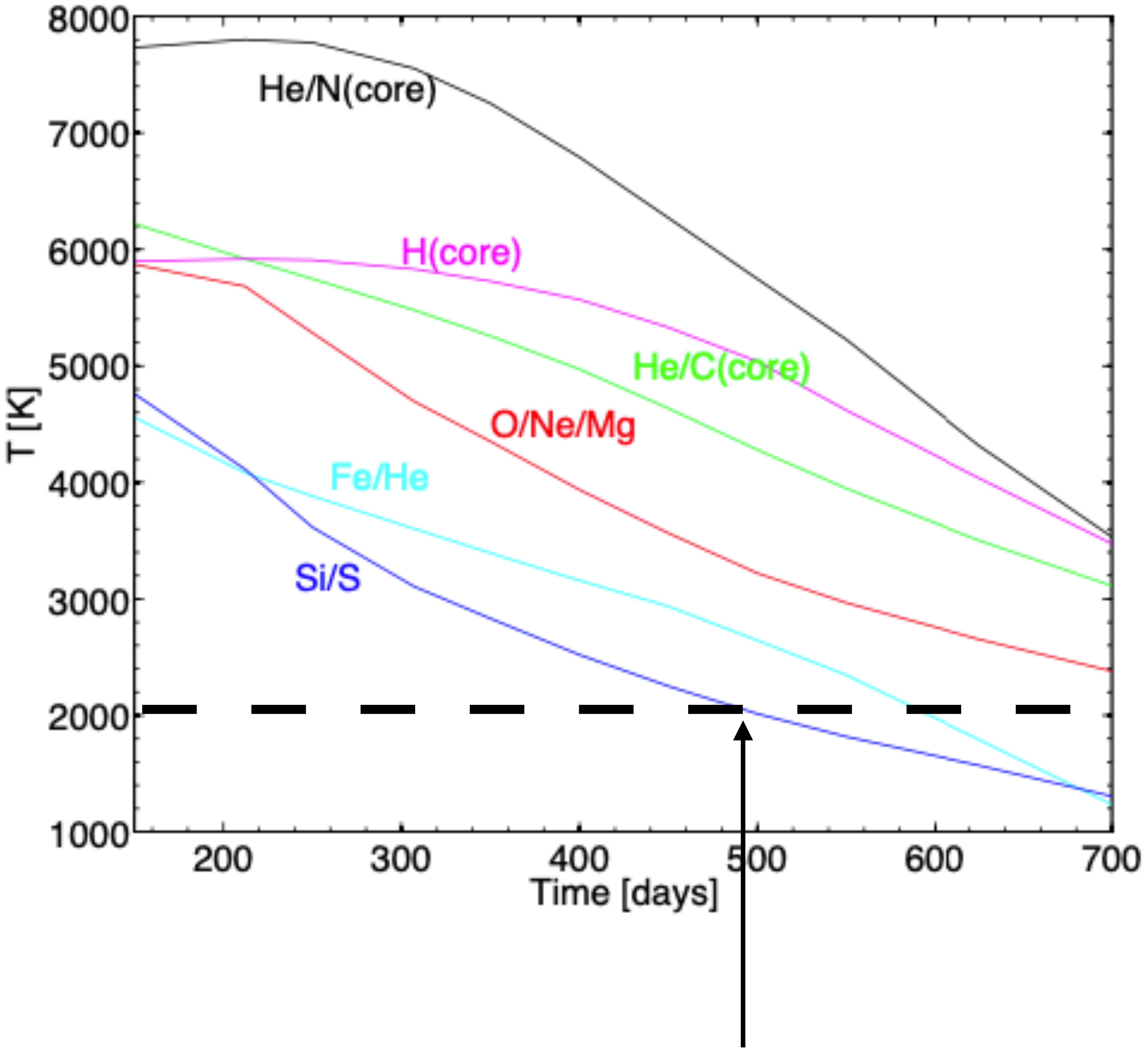
# Dust formed in the ejecta at around 500d



Blackbody dust emission in MIR

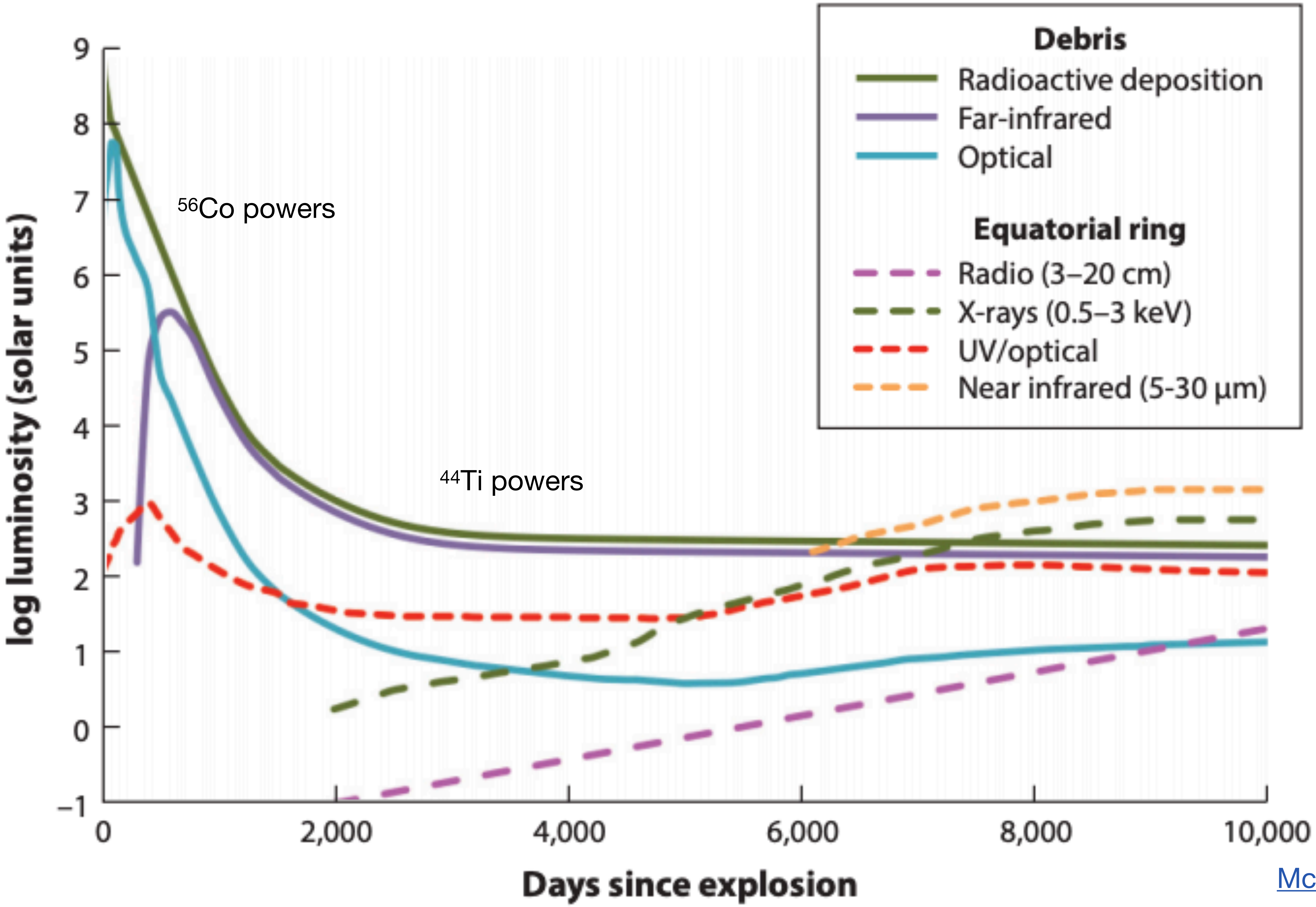
Wooden 1993

Jerkstrand 2012



Zone temperatures need to reach <~ 2000 K for dust to form.
Molecules will accelerate the cooling.

# Unique data at years/decades after explosion



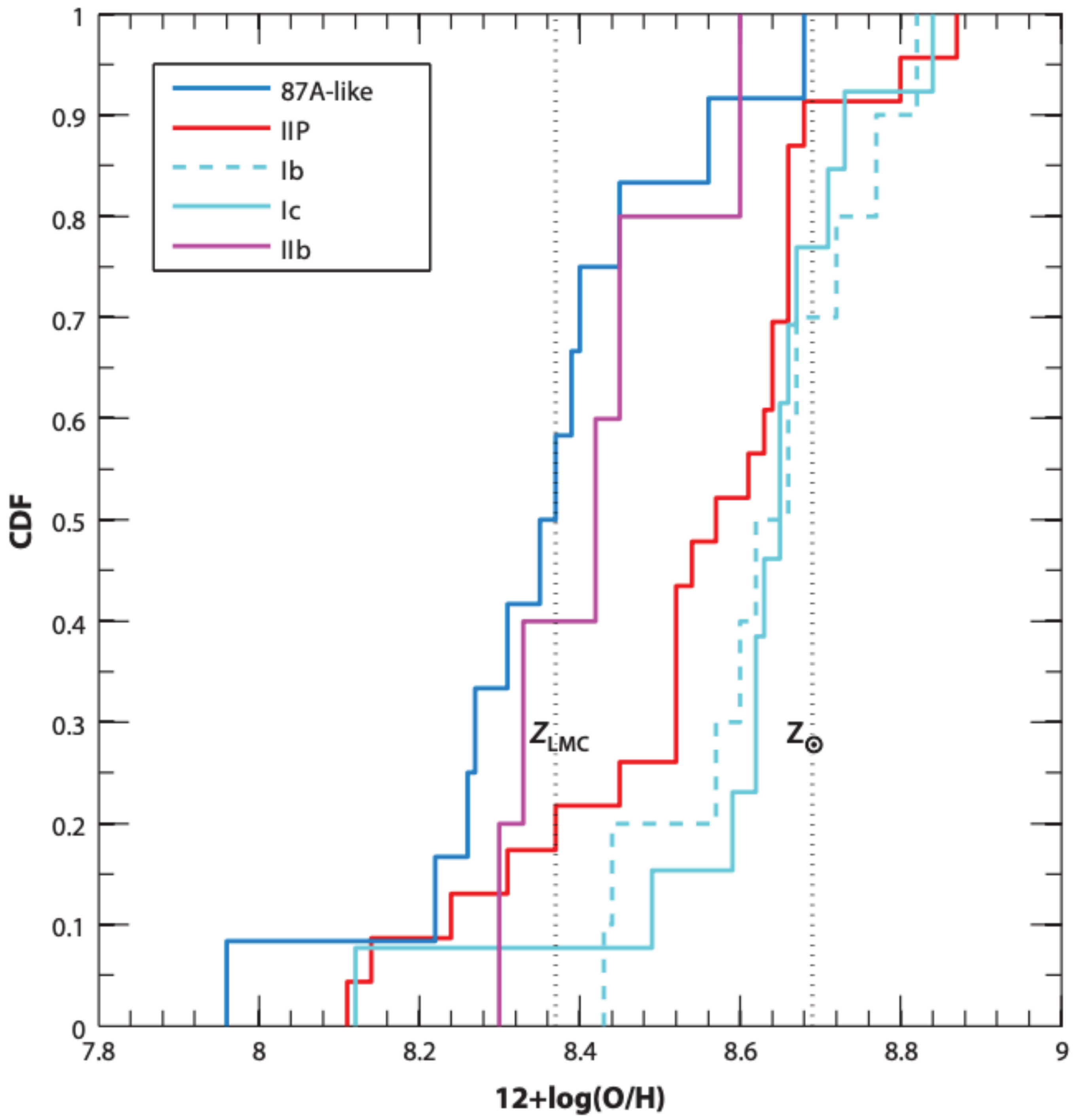
$^{56}$Co powers

$^{44}$Ti powers

McCray & Fransson 2016

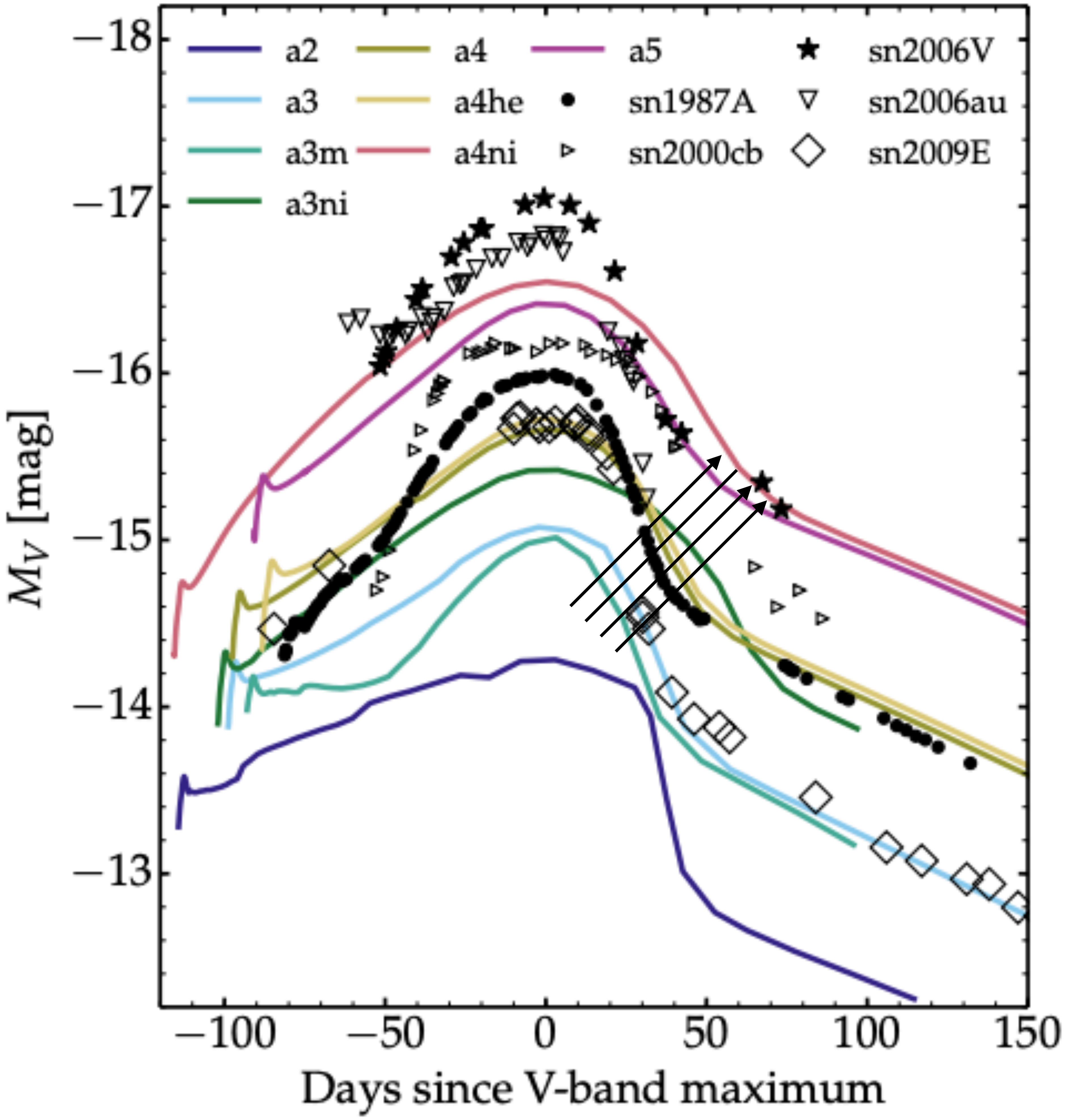
# Other Type II-pec SNe

Preference for low metallicity.



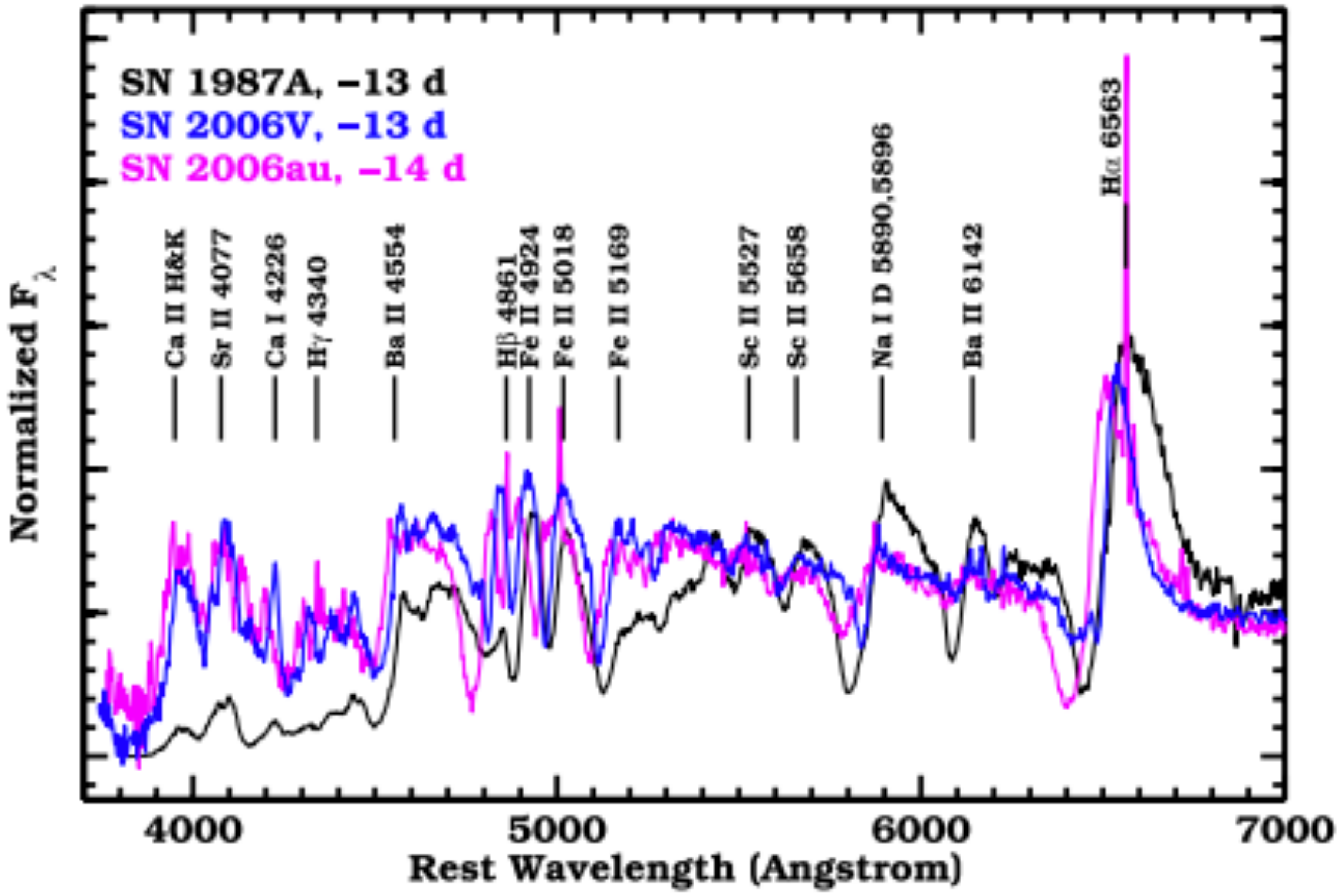
McCray & Fransson 2016

Significant variety in light curves..



Dessart 2019

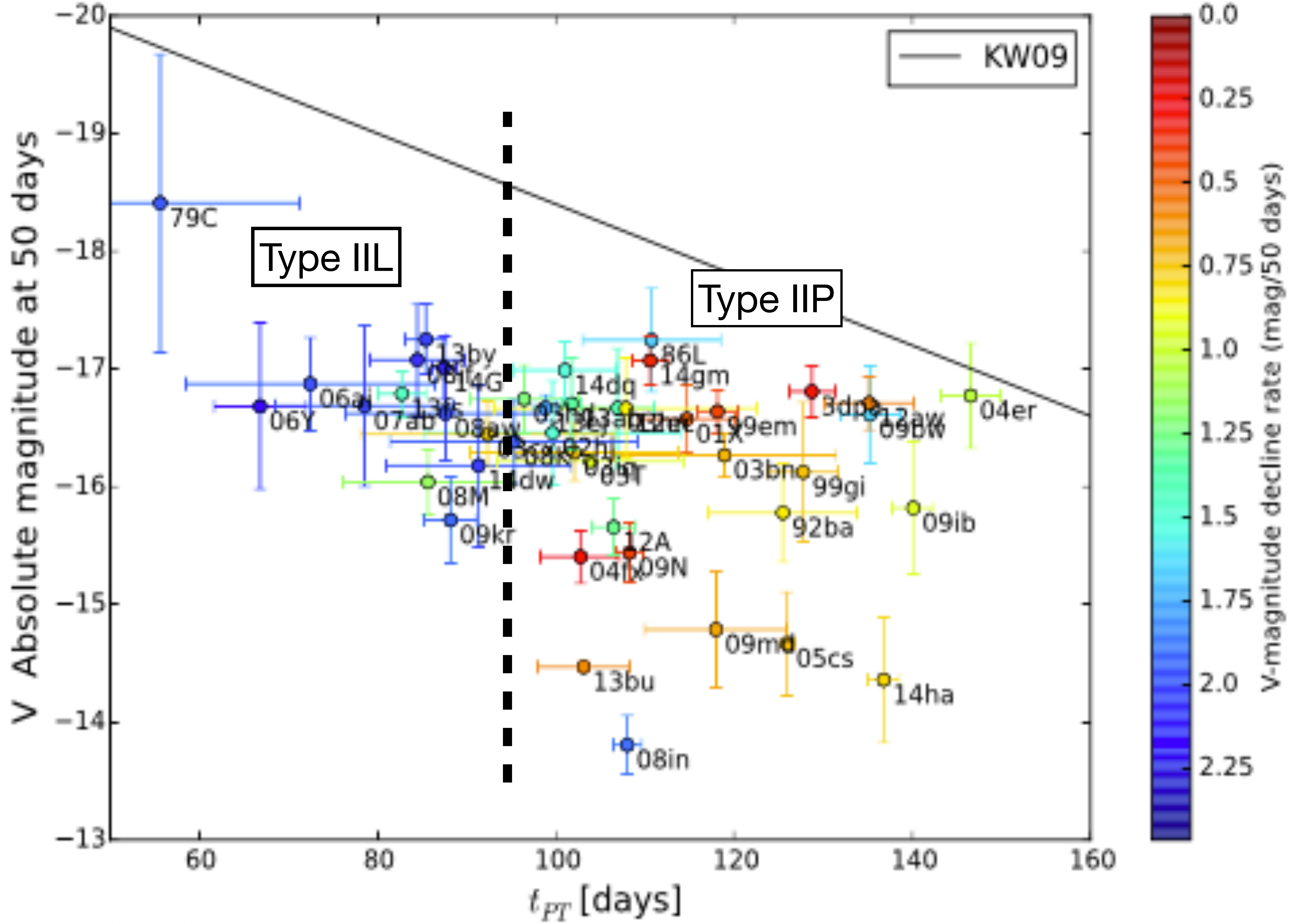
..and spectra.



Taddia 2012

# Type IIL supernovae

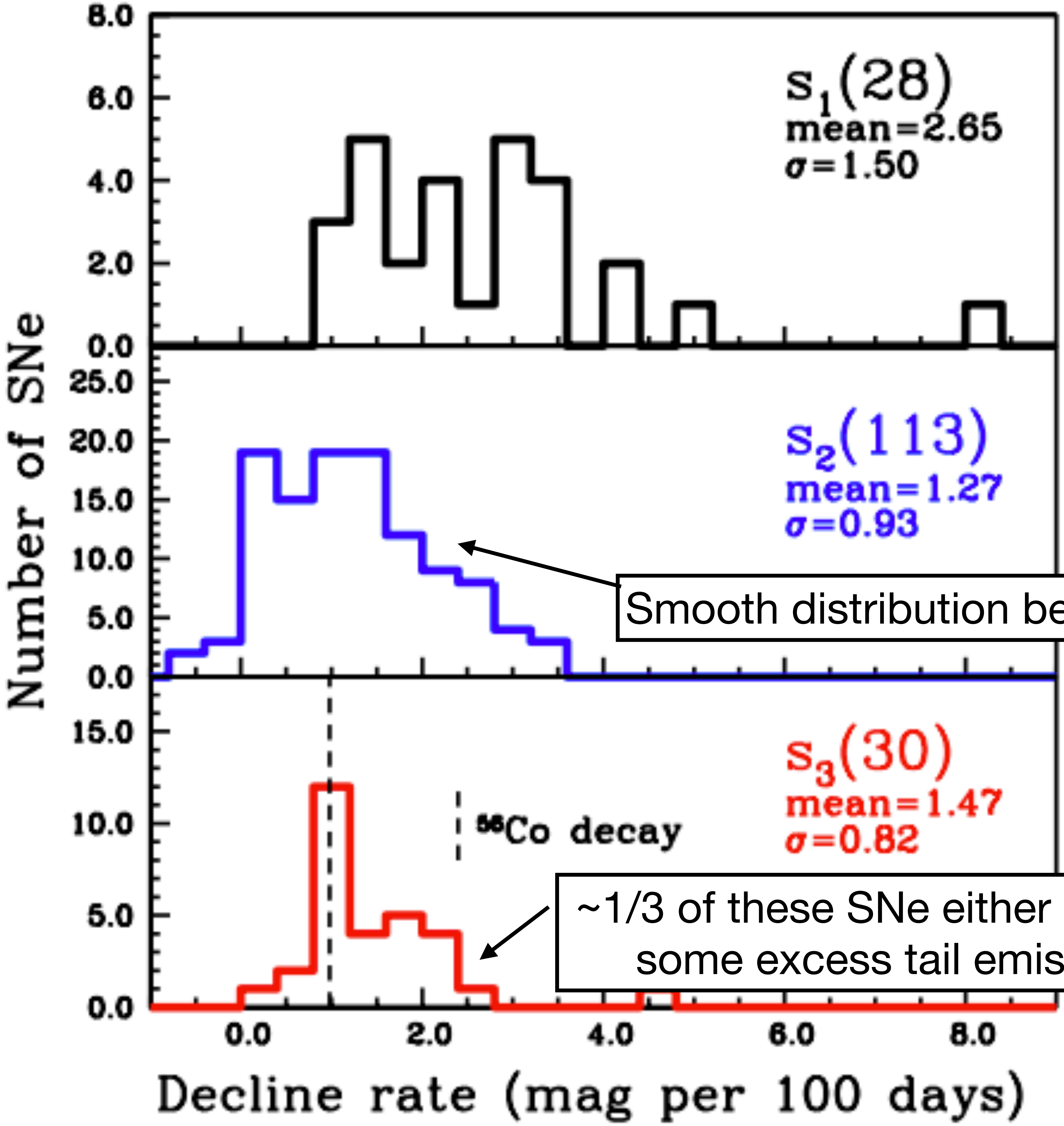
# Type IIL SNe have shorter diffusion phases than the IIPs



Light curves not well understood.

Valenti 2016

# Decline rates, Type IIP and IIL SNe together



s1 : Decline rate in early cooling phase (first 20d)

s2 : Decline rate on plateau

Smooth distribution between IIP and IIL SNe

s3: Decline rate early tail phase

~1/3 of these SNe either leak gamma rays early or have some excess tail emission that declines with time

Anderson 2014