Insights into core-collapse supernovae from spectral modeling

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https://www.eso.org/sci/publications/messenger/archive/no.173-sep18/messenger-no173-58-59.pdf

What powers the Light Curve of SN?

1. Radioactive decay

   ^{56}Ni → ^{56}Co; Half-life = 6.08 days

   ^{56}Co → ^{56}Fe; Half-life = 77.27 days

   ^{57}Co → ^{57}Fe; Half-life = 271.8 days

   ^{44}Ti → ^{44}Sc (→ ^{44}Ca); Half-life = 60.0 years

2. Shock deposited energy

   Small progenitors

      Rapid expansion => large adiabatic cooling

      Shock energy less important.

   Large progenitors

      Powers pre-nebula phase l.c. of RSG progenitors

      Recom. energy NOT important, but recombination controls the light curve evol.

3. Interaction – conversion of kinetic to thermal energy.

   Fluff, wind, CSM

4. Magnetar powered

Type IIP SN

- RSG progenitor
  - Large progenitor
- Triggered by core collapse
  - Most of energy emitted as neutrinos. Neutron star remnant.
  - Still unclear what “powers” ejecta.
  - Aspherical explosion (hidden by H rich envelope?)
- Light curve
  - Powered by shock deposited energy, and then decay (^{56}Ni -> ^{56}Co -> ^{56}Fe).
- Spectra dominated by H, He I at early times
  - True continuum seen until nebular phase.
  - H, Ca II etc seen at late times

Type IIpec SN

BSG progenitor

- Adiabatic cooling very important
- 1987A was much fainter than “expected”

Fundamental Questions

(1) What are the progenitors of Ib, Ic, broad-lines Ic SN?

  a) Classic Wolf-Rayet stars?
  b) He stars resulting from binary evolution ($M_{pro} < 20$)

(2) What is the mass of the ejecta?

  a) H mass –controls the light curve in IIP
  b) He core mass

(3) What is the progenitor mass?

  a) Mass loss history
  b) Binarity
  c) Oxygen mass?

(4) How much mixing occurs and inhomogeneities?

  (1) Macroscopic versus microscopic mixing
  (2) When does it occur?

(5) Constraints on the nucleosynthesis

  (1) Abundance tomography (Paolo)

(6) Asymmetries?

Explosion physics

(7) Evolution as a function of z & Z

Spectral Modeling

Monte Carlo

Trace photon packets through the ejecta.

Treats absorption, scattering, and emission.

3D is not much more complex than 1D (but very computational).

Full-non LTE possible, but many codes are pseudo non-LTE.

Exceptions -- codes of Anders Jerkstrand, Mattias Ergon

Solve Radiative Transfer Equation (ray-tracing)

Fully non-LTE.

Not subject to statistical errors (but discretation errors).

3D is much more expensive than 1D (by factor of 10^5!)

CMFGEN: 1D time dependent radiative transfer code.

e.g., Hillier & Miller (1998), Hillier & Dessart (2012)

(cf. codes of Peter Hoeflich; PHOENIX – Peter Hauschildt).

Spectral Modeling Difficulties

Initial value problem

At many phases (primarily pre-nebula) need to run a time sequence.
Need a pre-SN model (i.e., progenitor model).
Mass, H-envelope mass, radius, core mass, full composition profile.
Core collapse SNe cannot (generally) be exploded from first principles.
^{56}Ni mass and explosion energy are “free” parameters.

Time dependent radiative transfer and energy equation

SNe are expanding. Diffusion time is long.
Flux is not conserved.

Non-LTE -- time dependent kinetic equations

Potentially affects ionization structure.
Crucial for explaining Hα in Type IIP Sne .

Additional complexities

Gamma ray transport & non thermal ionization.
Mixing / clumping / non-sphericity.

Homologous (Hubble) Expansion Law

$$r = Vt$$

(Broken) Power Law Density distribution

$$\rho(r,t) = \rho_{ot}(t)\left(\frac{r_o}{r}\right)^n$$

with n = 0 to 20

or

$$\rho(t) = \rho_o\left(\frac{t_o}{t}\right)^3\left(\frac{V_o}{V}\right)^n$$

where

r_o = radius at $v = v_o$

ρ_{ot} = density at $r = r_o$ at time t

ρ_o = density at $v = v_o$ at time t_o

$$\tau \propto t^{-2}$$

Atomic Data

Opacity Project:

Seaton 1987; Hummer et al. 1993

Bob Kurucz

Bell and Kurucz (1995)

http://kurucz.harvard.edu

Keith Butler (Munich)

Sultana Nahar / Anil Pradhan

http://www.astronomy.ohio-state.edu/~nahar/nahar_radiativeatomicdata/index.html

NIST

http://www.nist.gov/pml/data/asd.cfm (Energy levels, f values, bib)

http://www.nist.gov/pml/pubs/atspec/index.cfm (Introduction to Atomic Spectroscopy)

CLOUDY (Ferland/Verner)

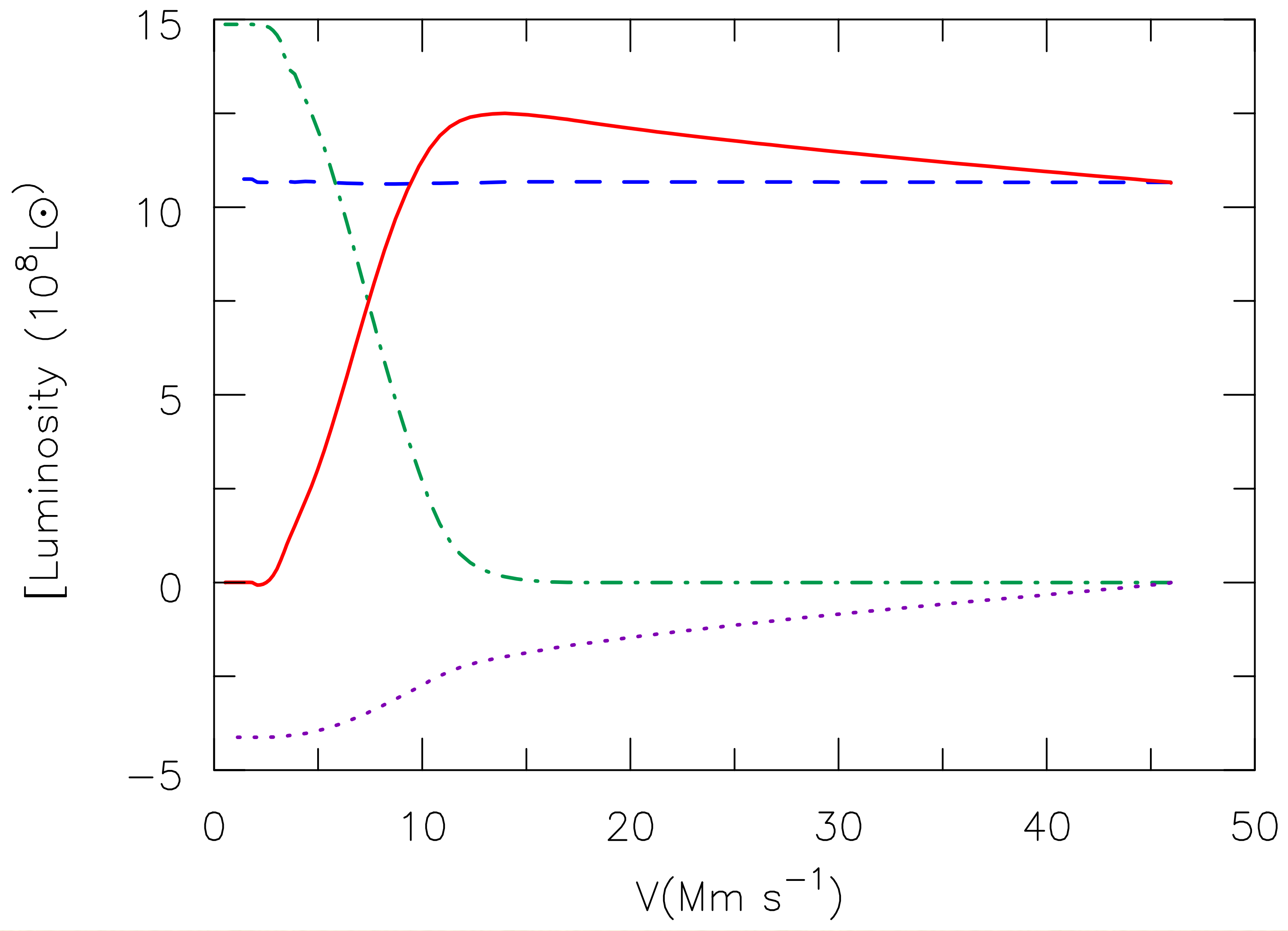
Charge exchange rates

Ground state photoionization cross-sections

+ many others

Energy Conservation (in CMF)

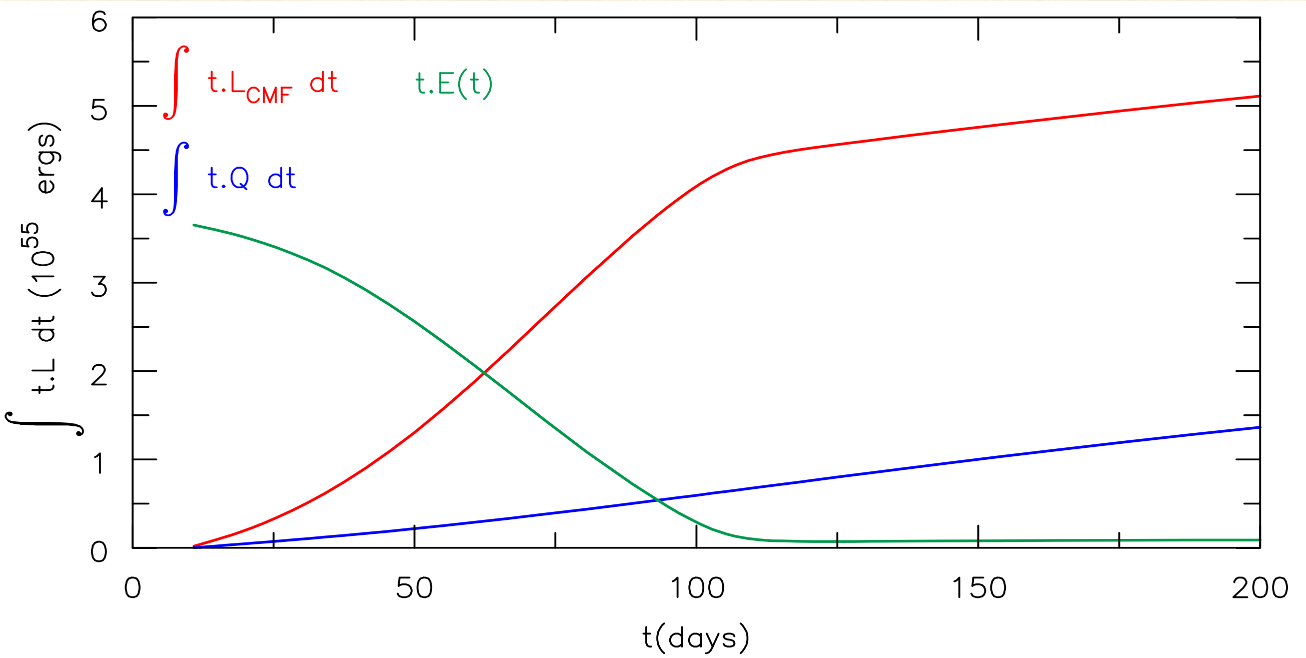
$$r_{\max}^2 H(r_{\max}) = r^2 H(r) + \int_r^{r_{\max}} \frac{r^2}{4\pi} \left(\dot{e}_{\rm decay} - \rho \frac{De}{Dt} + \frac{P}{\rho} \frac{D\rho}{Dt} \right) - \frac{1}{cr^2} \frac{D(r^4 J)}{Dt} \, dr$$



Energy Conservation

$$\int_{t_0}^{t} tL(t)\,dt = \int_{t_0}^{t} [tQ(t)\,dt - tI(t)]\,dt + t_oE(t_o) - tE(t)$$

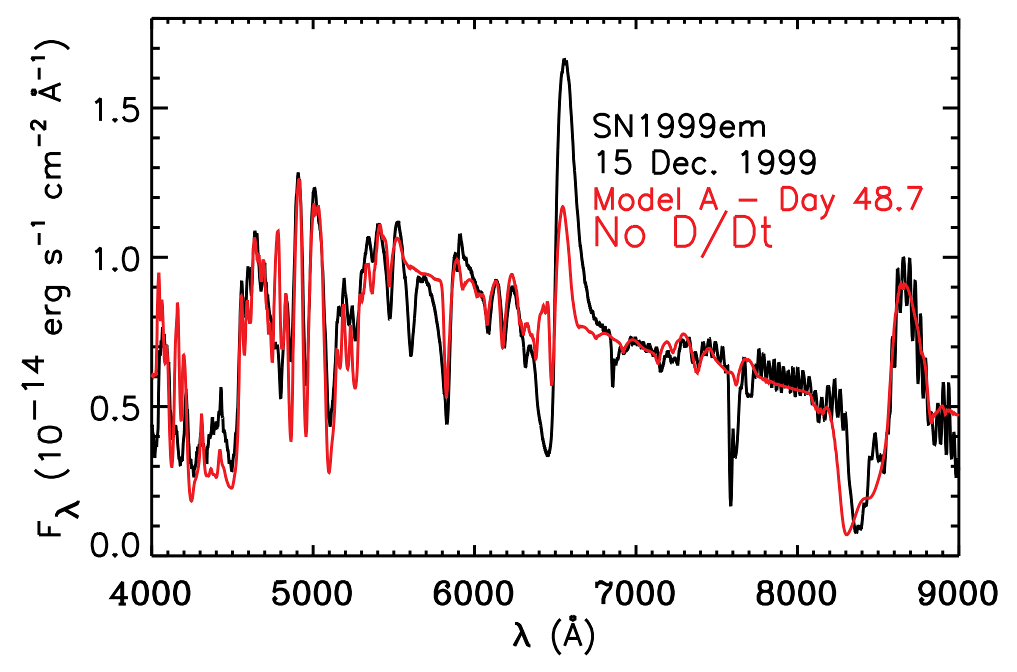
L_{cmf} – Luminosity in the comoving frame
Q – Energy from radioactive decay
E(t) – Radiative energy in envelope



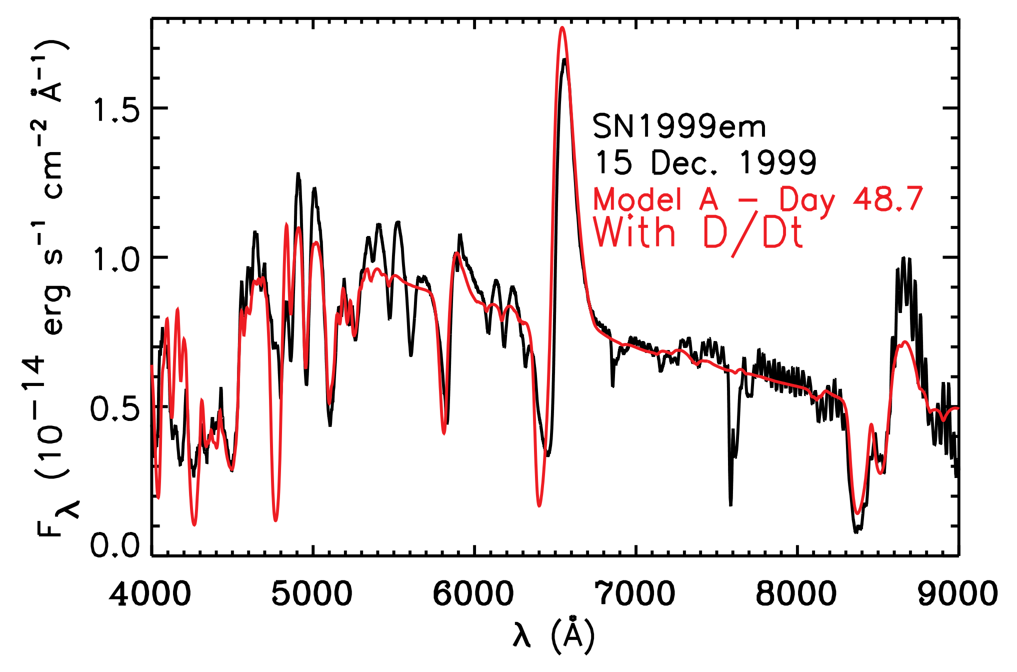
see also, Katz (2013), Nakar et al. (2016)

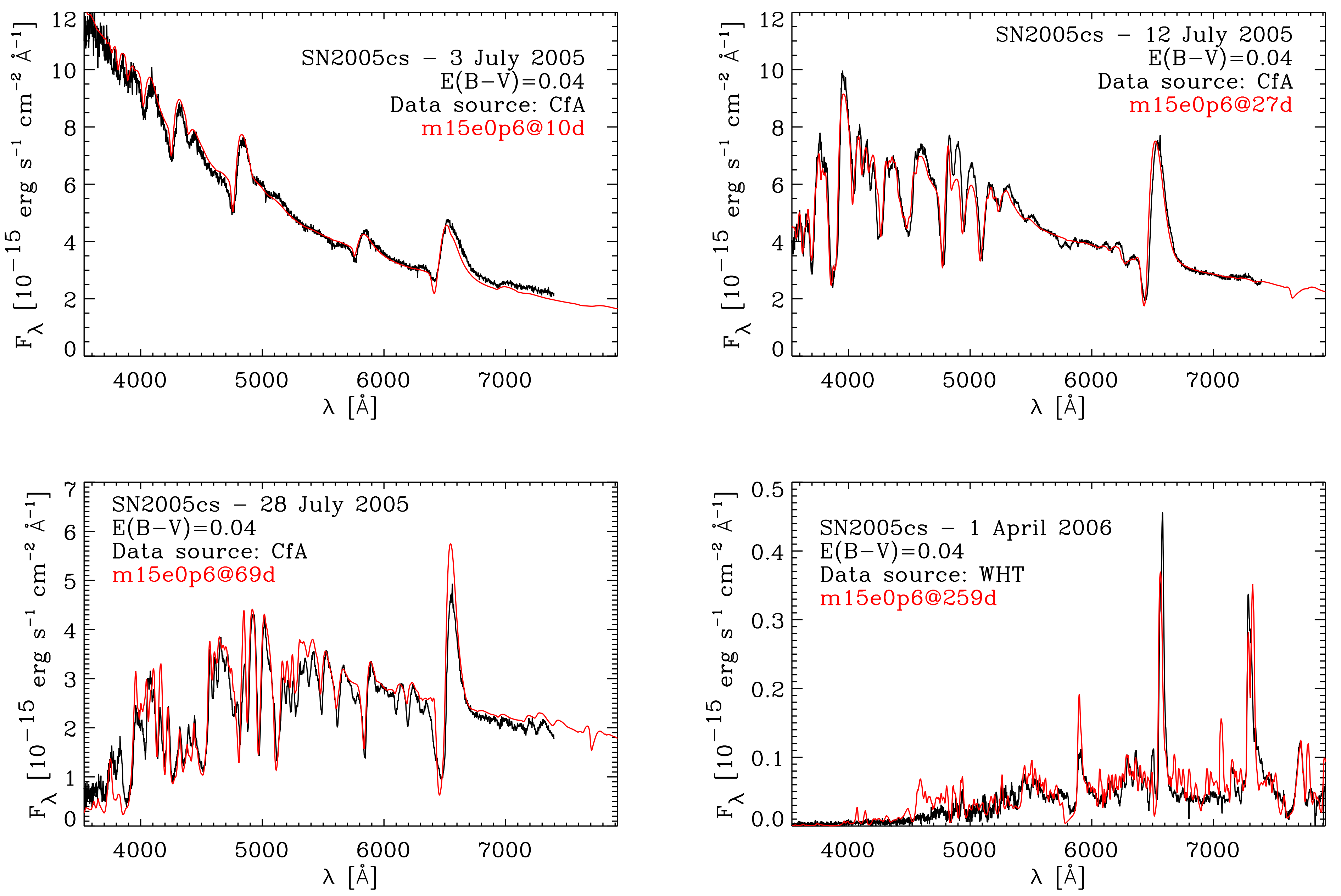
Why D/Dt in SEEs?

Utrobin & Chugai
2005, A&A, 441, 271



Dessart & Hillier
2008, MNRAS, 385, 57



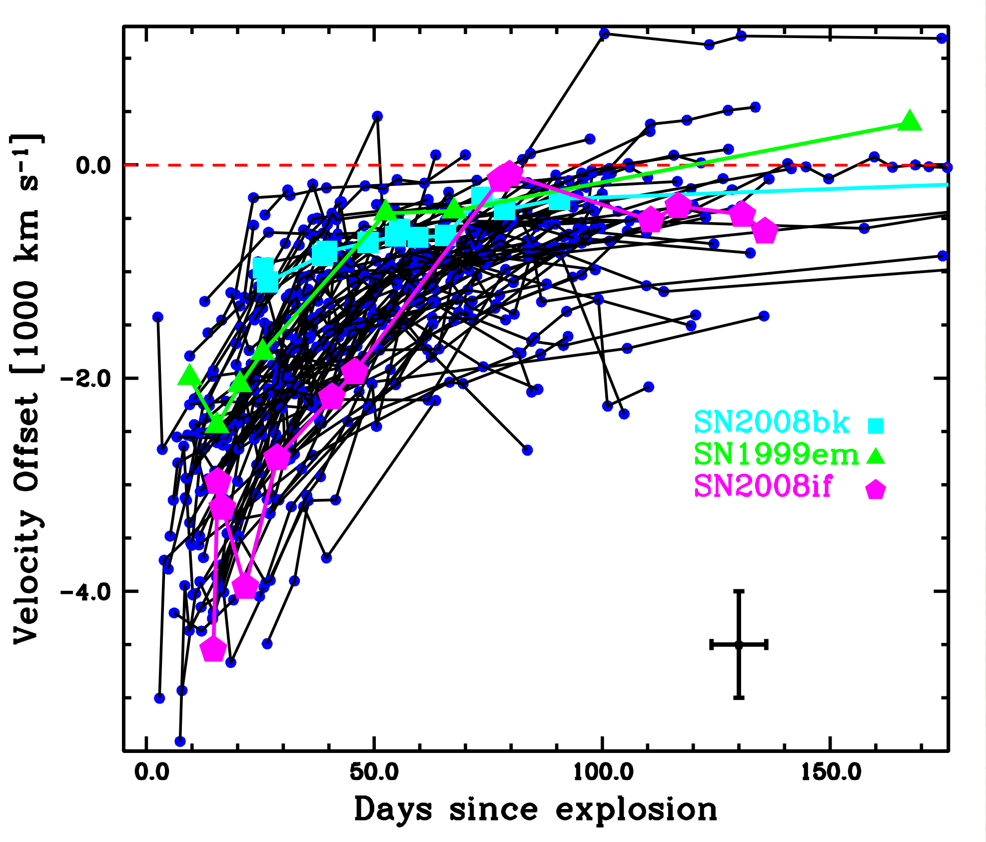


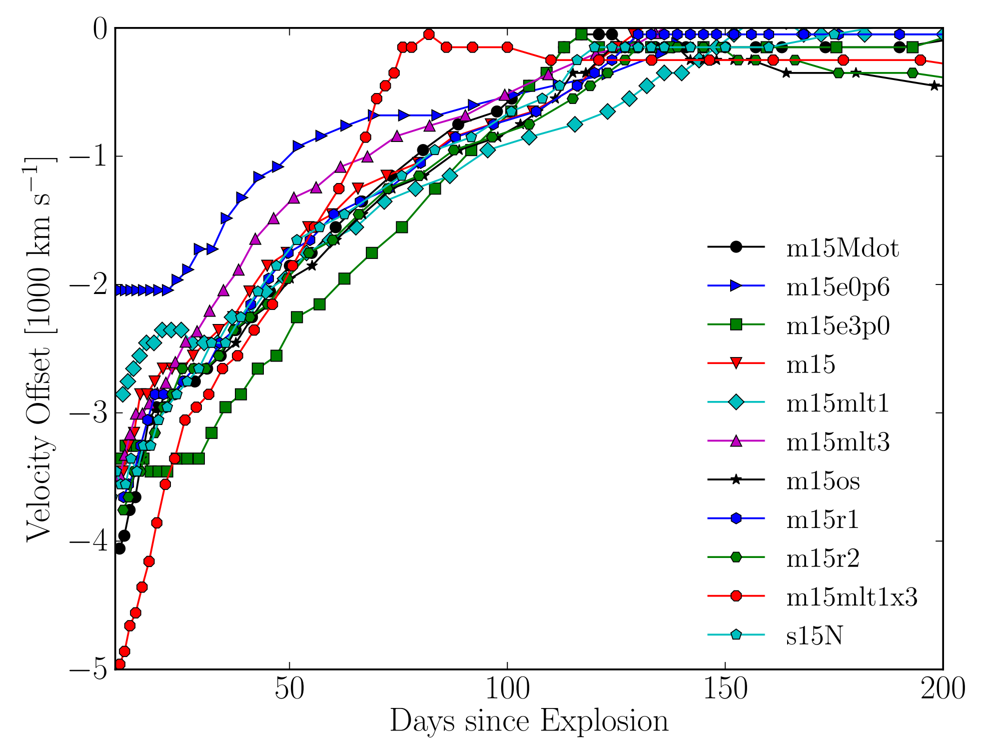
Spectra compared at same color!

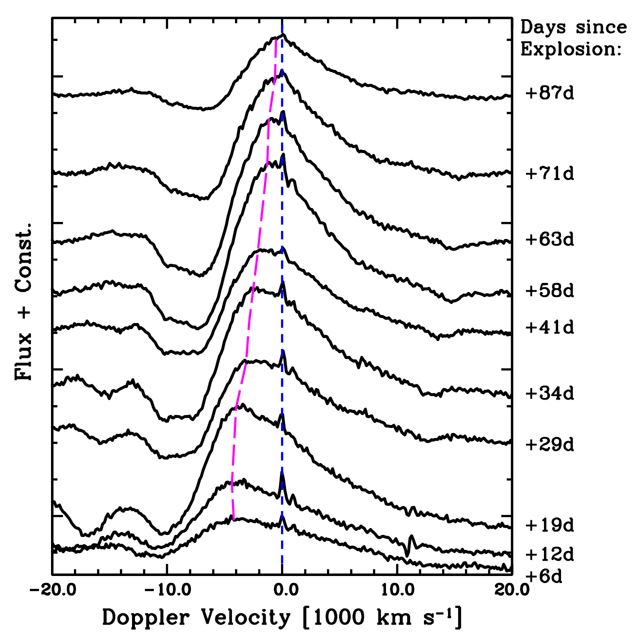
Dessart, Hillier, Waldman, Livne, 2013, MNRAS, 433,1745

Hα velocity evolution

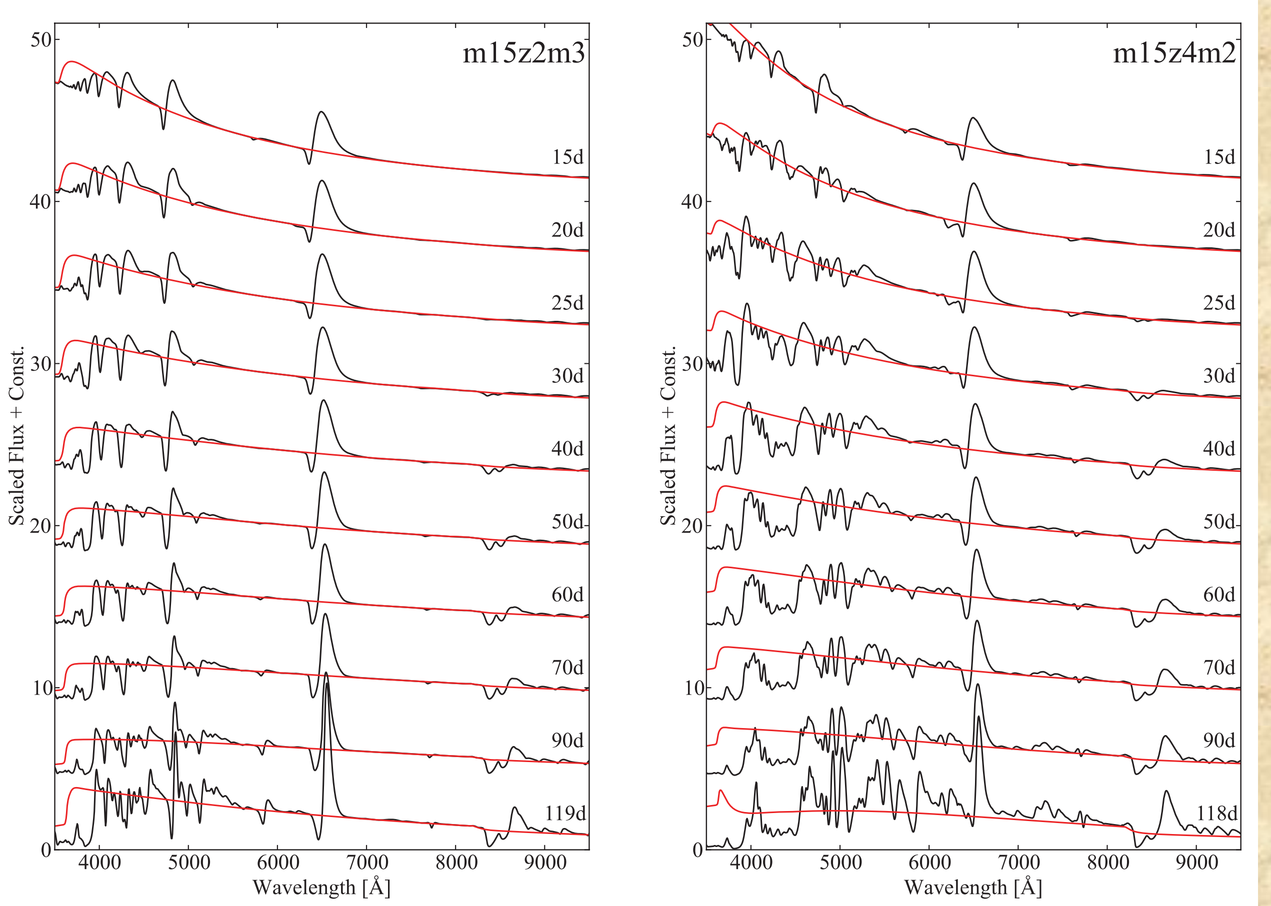
Anderson et al., 2014,
MNRAS, 441, 671







Measuring metallicity

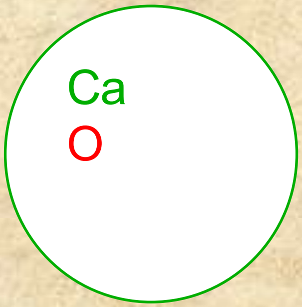


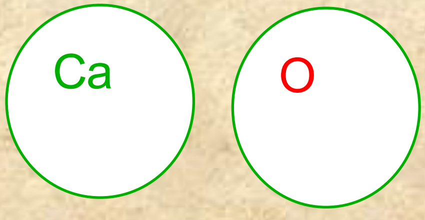
Dessart et al, 2014, MNRAS, 440, 1856

Anderson et al, 2016, A&A, 589, 110 -- correlation wit Z(O)
Anderson et al, 2018, NatAS,2, 574 -- <0.1 $Z_{\odot}$
Yan et al. , 2017, ApJ 840, 57 -- Sub –solar SLSLN-I:

Clumping and Mixing

Is the mixing mixing microscopic or macroscopic?





Microscopic – O I lines “weak”
as Ca II more efficient coolant.

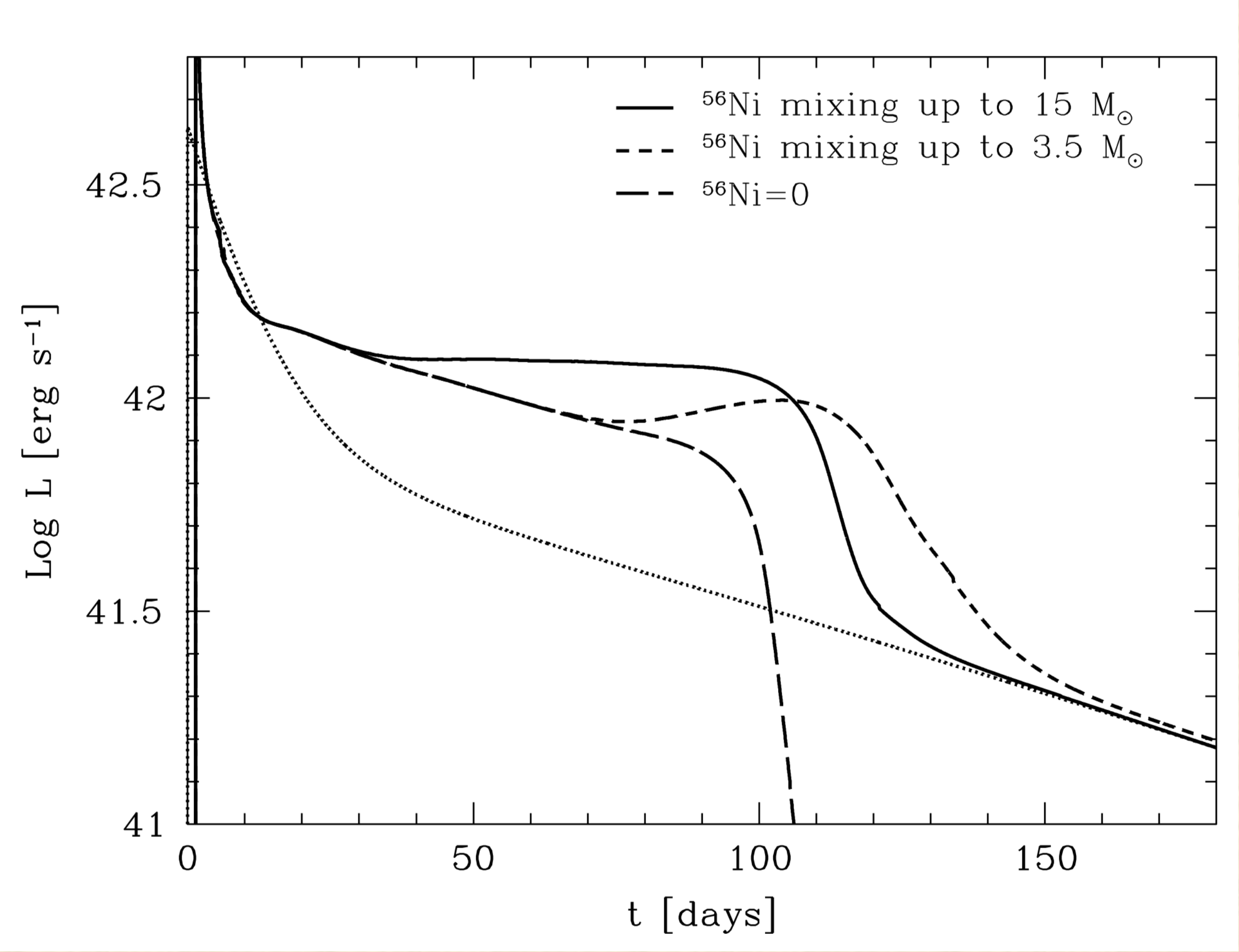
Macroscopic – O I lines “strong”

Clumping – scale and magnitude?

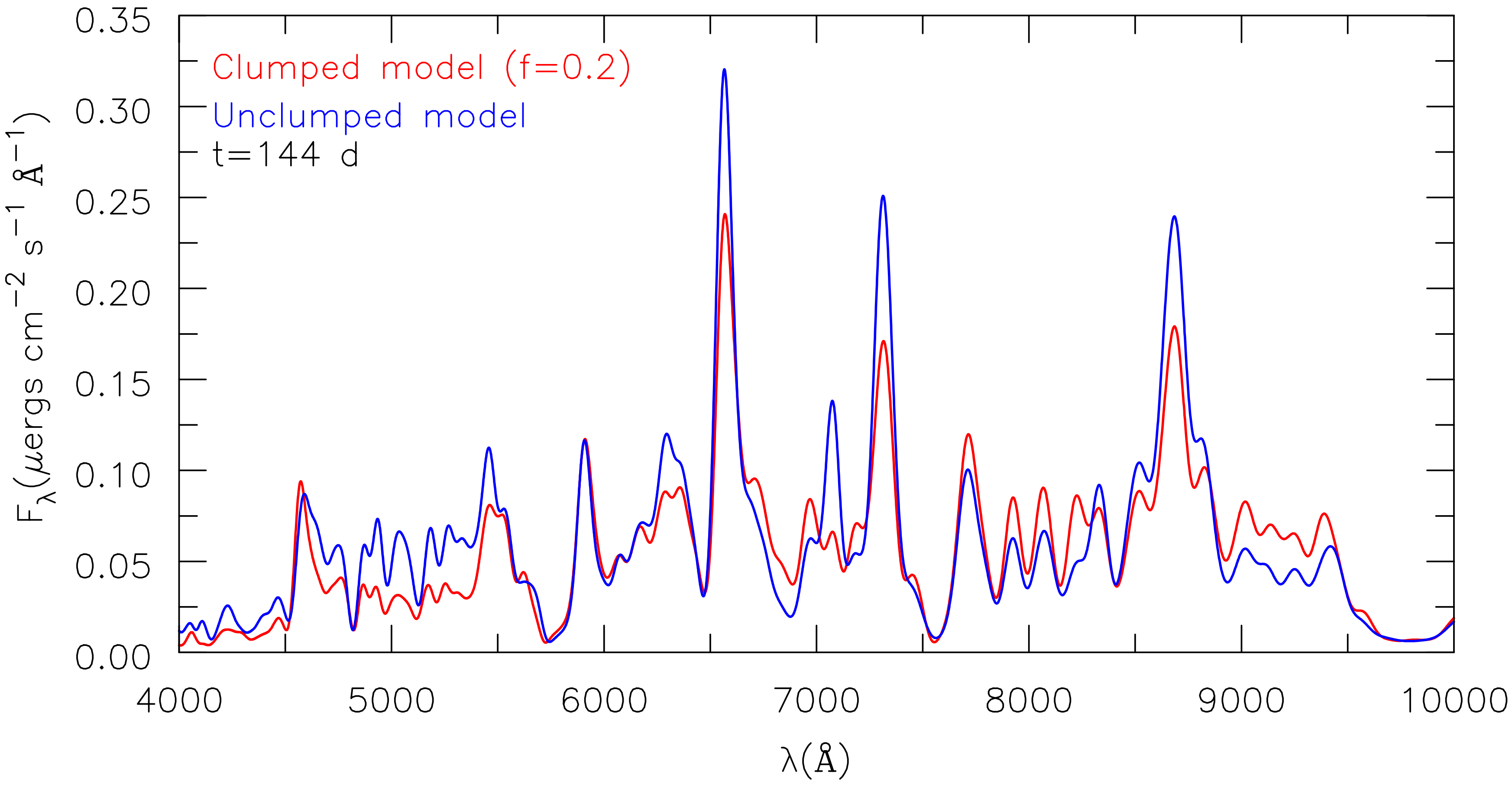
a) SN photosphere 10^{14} cm
b) Clump ~ R_{sun}
c) Sobolev length ~ rV_{th}/V ~ r /100 (V_{th}=10 km/s, V=10,000 km/s)

Lowers ionization!

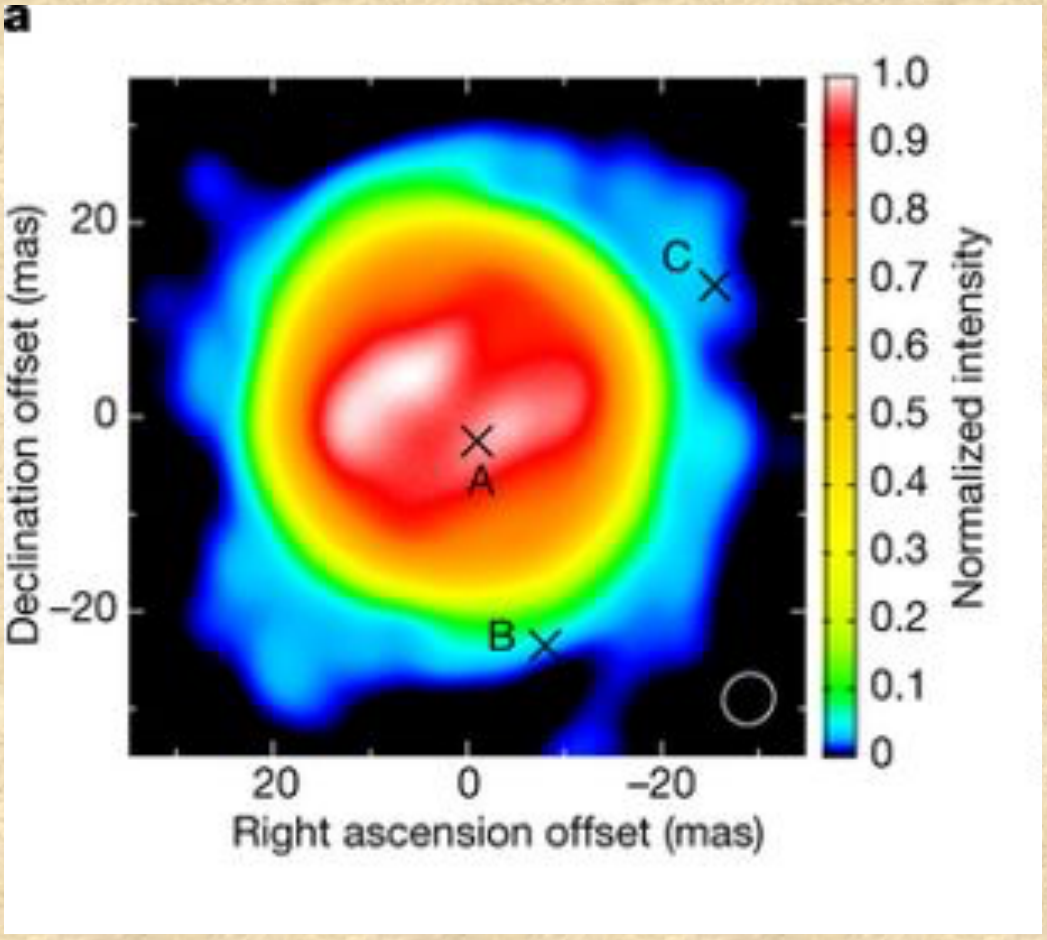
^{56}Ni mixing influences the light curve.

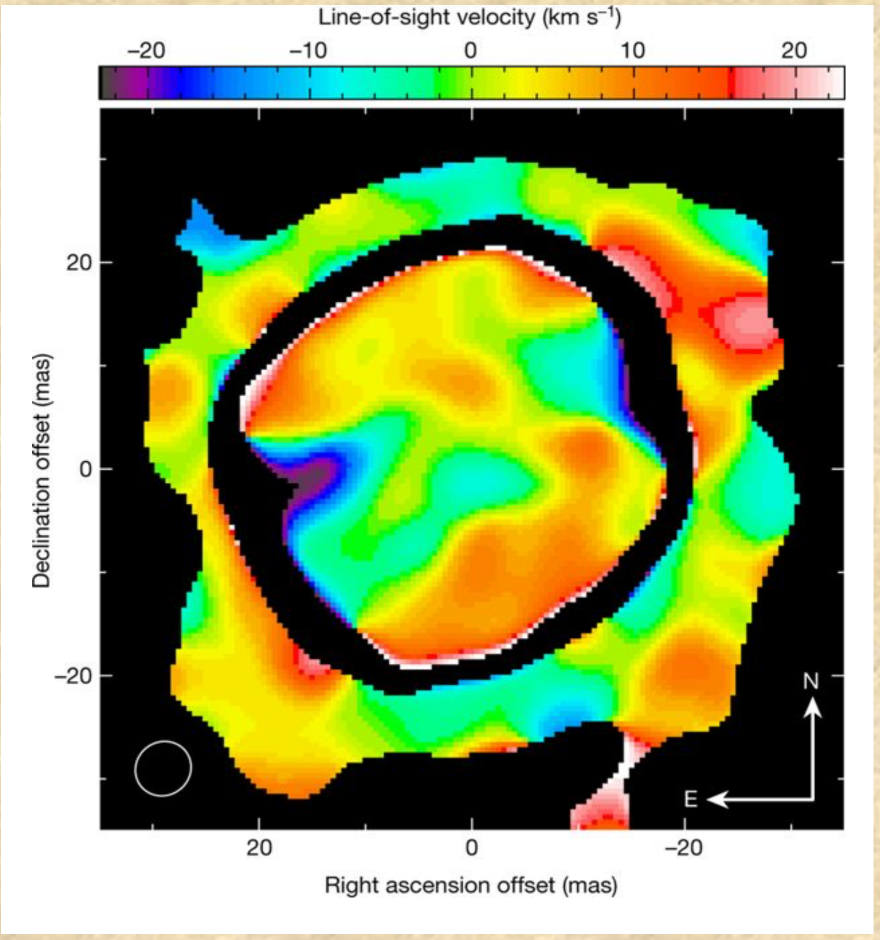


Bersten et al, 2011, ApJ, 729, 61


Clumped model (f=0.2)
Unclumped model
t=144 d
$F_\lambda(\mu ergs\ cm^{-2}\ s^{-1}\ Å^{-1})$
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
4000
5000
6000
7000
8000
9000
10000
λ(Å)

Imaging of Antares

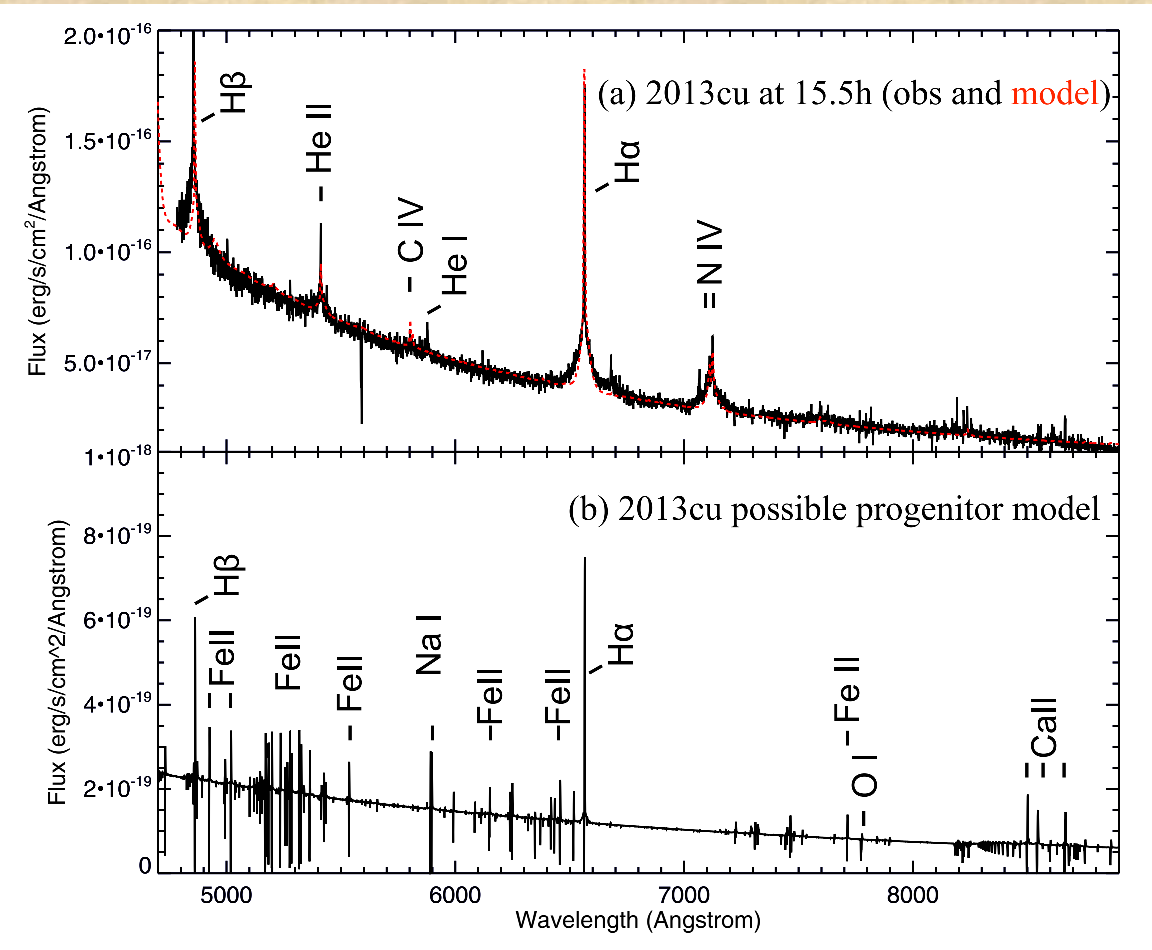




Ref: Vigorous atmospheric motion in the red supergiant star Antares.
Ohnaka, Weigelt, Hofmann, Nat. 2017, 548, 310

Flash Spectroscopy

SN 2013cu (Type IIb)

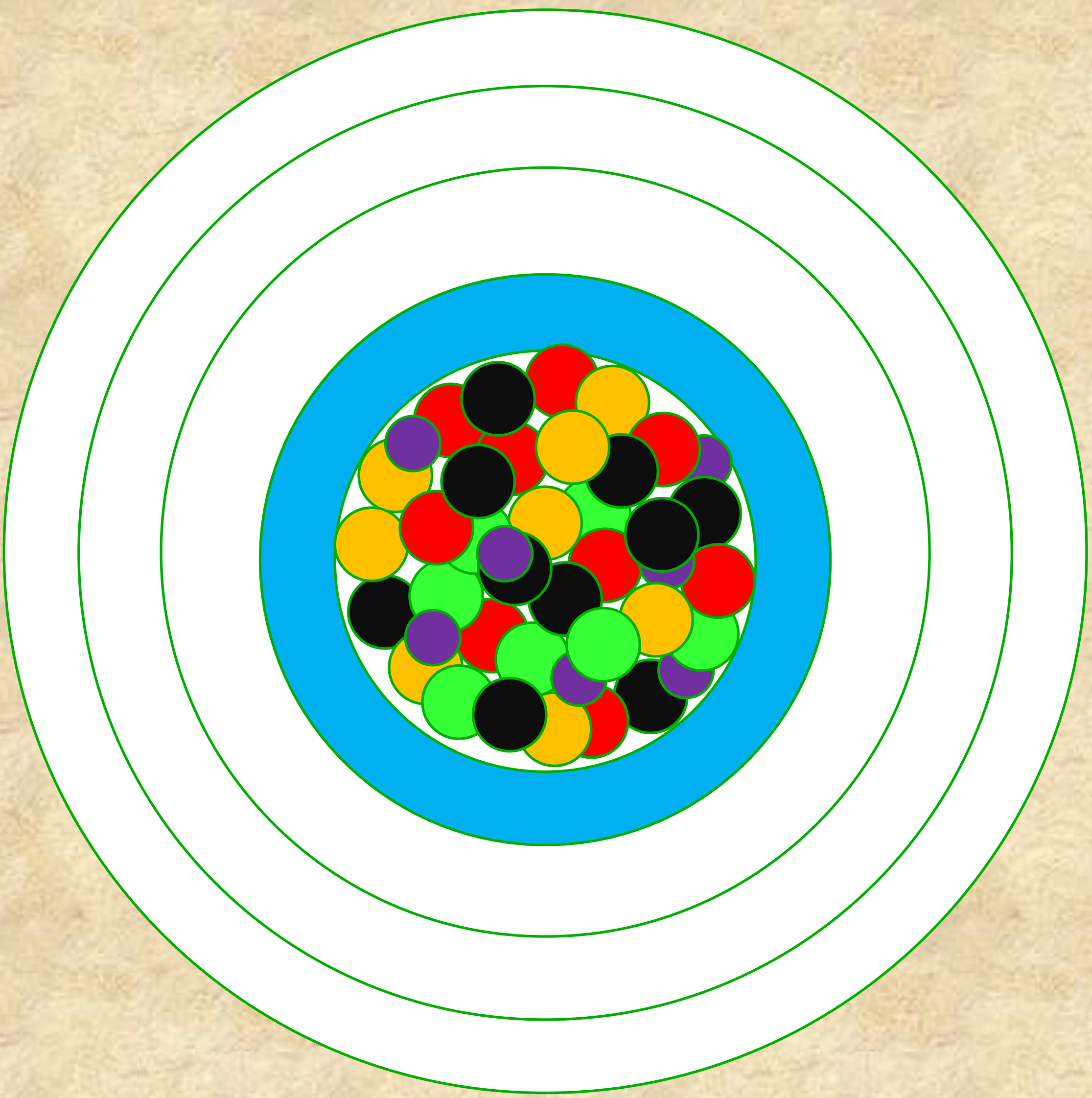


$\dot{M} \sim 3 \times 10^{-3}\ M_{\odot}/yr$; V ~ 100km/s, X=0.46,Y=0.52

Groh, A&A, 2014, 572, L11

Macroscopic Mixing

See Jerkstrand et al. 2011, A&A, 530, A45



Hydrogen

Helium

O/C

O/Ne/Mg

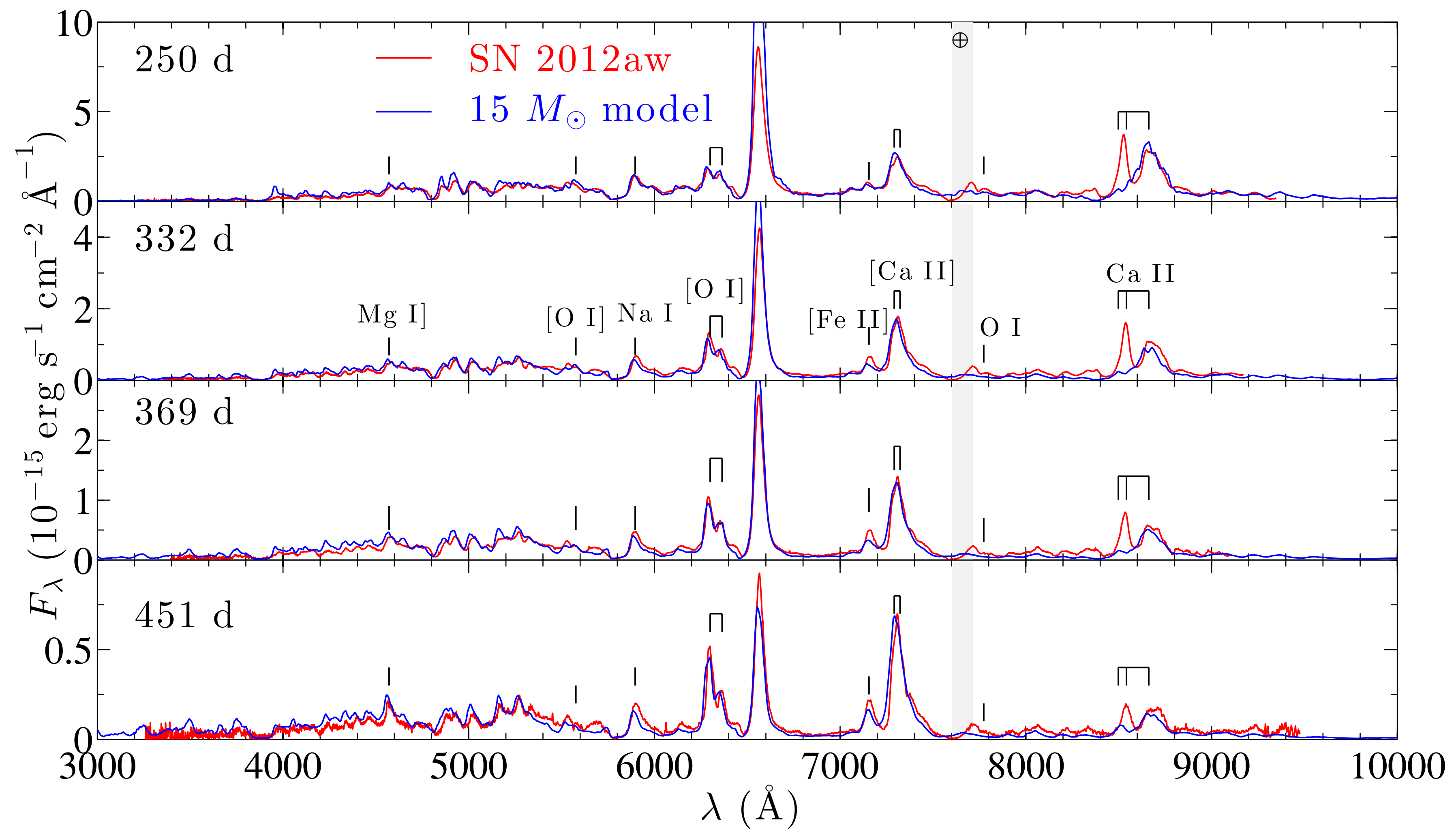
O/Si/S

Si/S

Fe/He

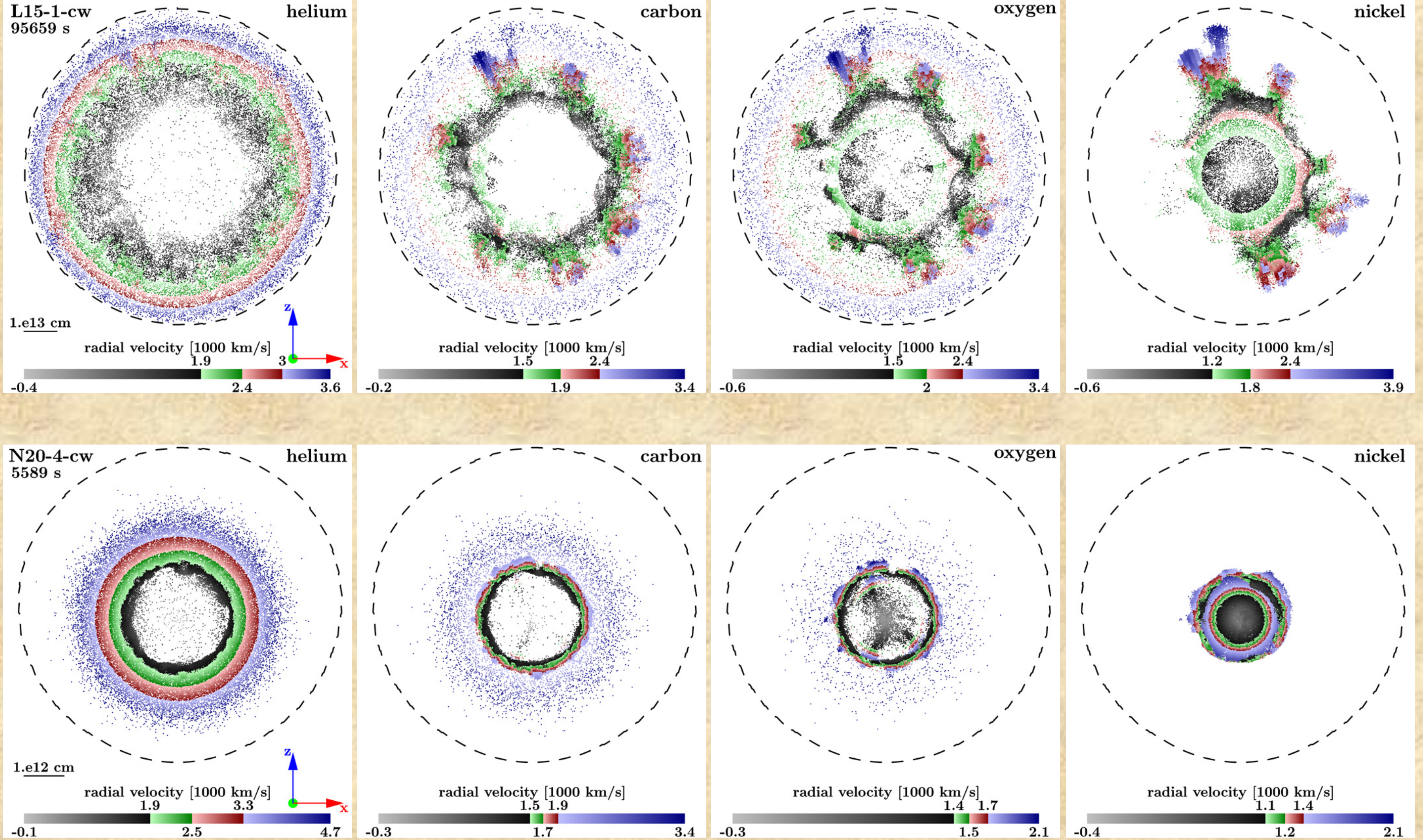
Not to Scale!

Jerkstrand et al. 2014
2012aw (Type IIP)



Transfer effects still important!

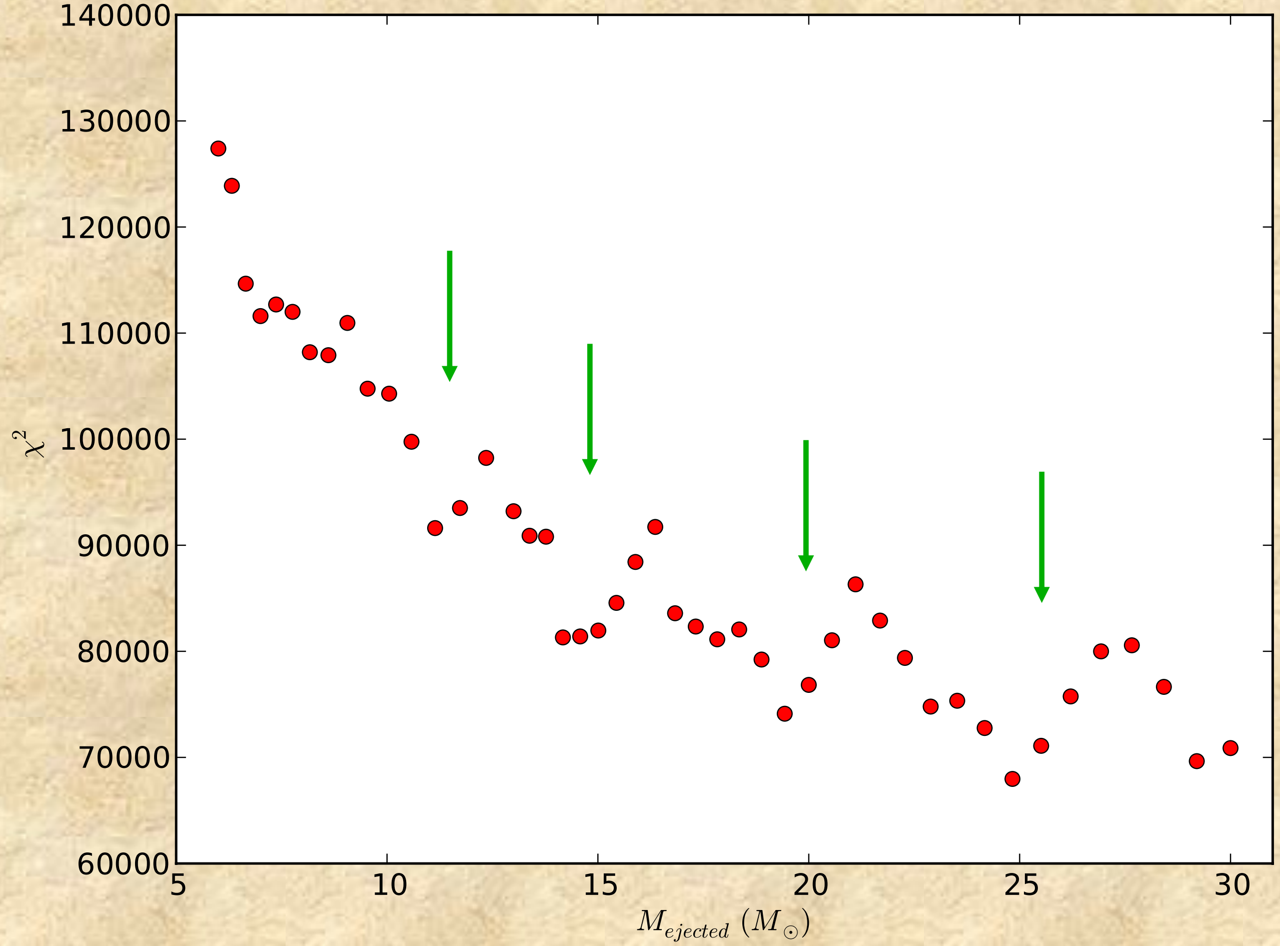
Helium **Carbon** **Oxygen** **Nickel**



From: Wongwathanarat et al. 2015, A&A, 577, A48

25% mass bins: blue - fastest 25%, black - slowest 25%

20012aw



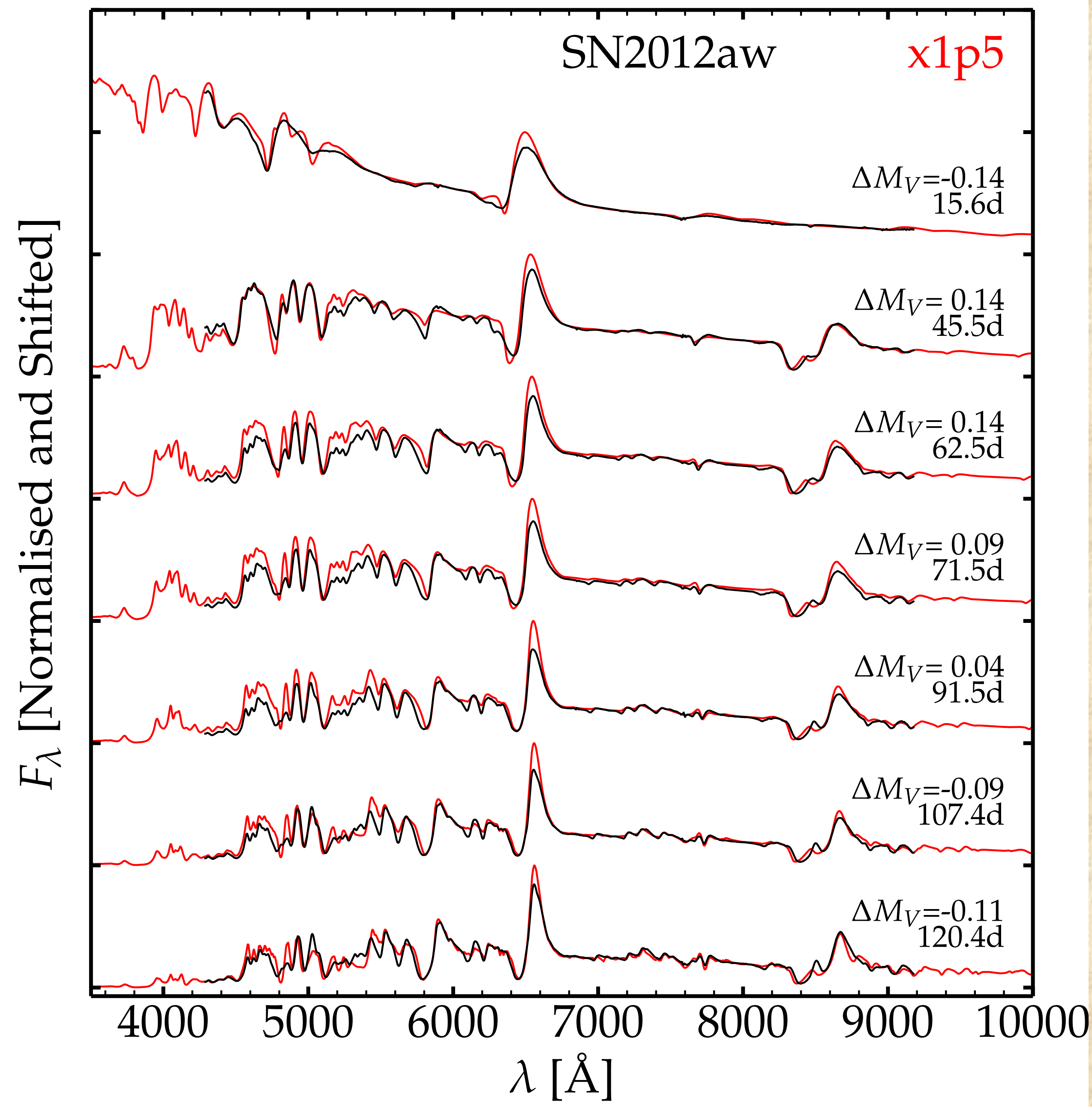
Semi-analytic and hydrodynamical models

M_{env}=20 $M_\odot$, R=430 $R_\odot$, E=1.5foe, ^{56}Ni=0.06

Dall'Ora et al. , 2014, ApJ, 787, 139

Fraser (2016, MRAS)

RSG photometry ->
M(proj)= 12.5 pm 0.5



M(proj) = 15 $M_\odot$, M(eject) = 12.2 $M_\odot$.   R = 587$R_\odot$, M(^{56}Ni) = 0.056 $M_\odot$

Polarization

Point source:
Optically thin, axisymmetric.

Define:

$$\gamma = \frac{\int \rho \mu^2 \, d\mu}{\int \rho \, d\mu}$$

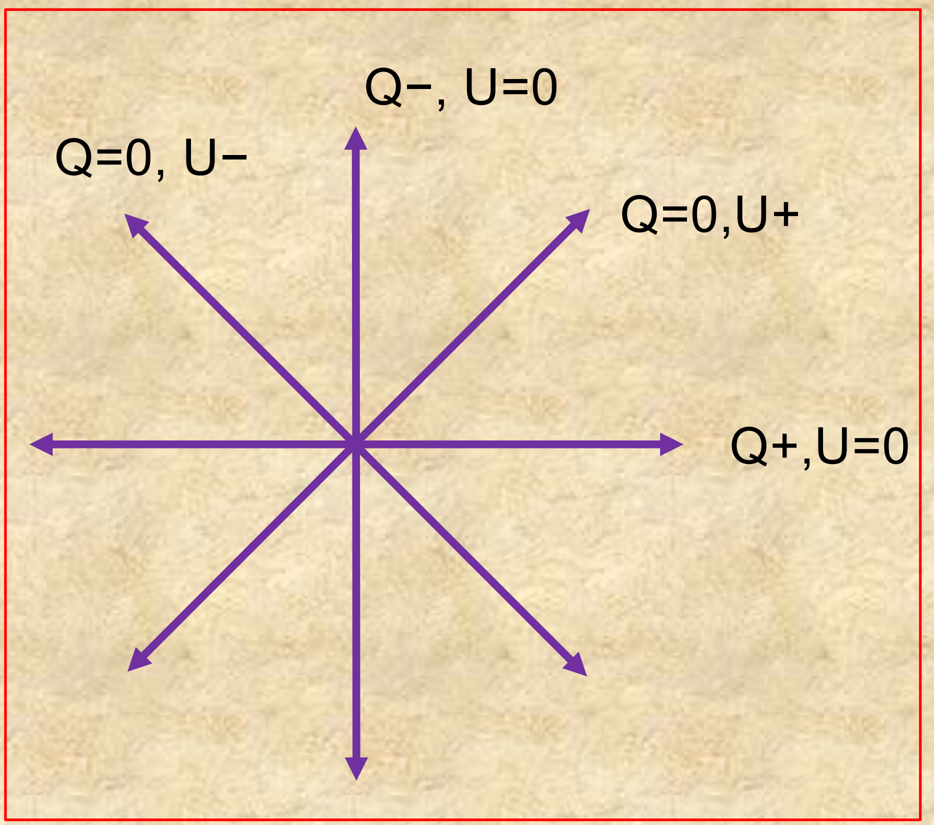
Then

γ=1/3 for sphere
γ<1/3 for oblate spheroid
γ>1/3 for prolate spheroid

Then

$$P \propto \tau (1 - 3\gamma) \sin^2 i$$

P [Q] is +ve when electric vector parallel to symmetry axis.

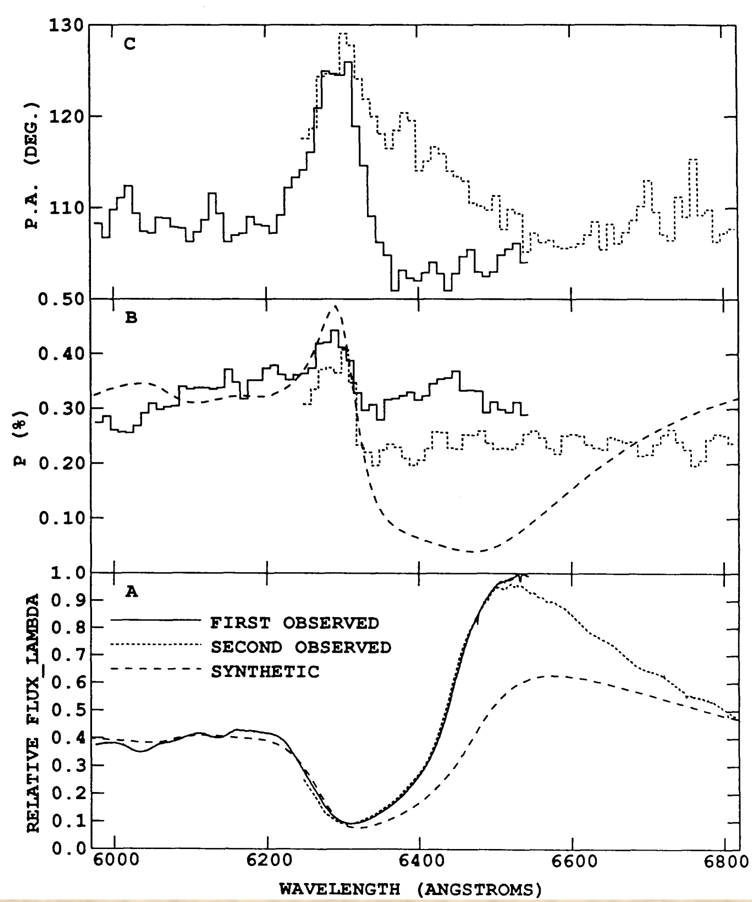


$$P = \sqrt{Q^2 + U^2}/I$$
$$\theta = 0.5 \arctan(U/Q)$$

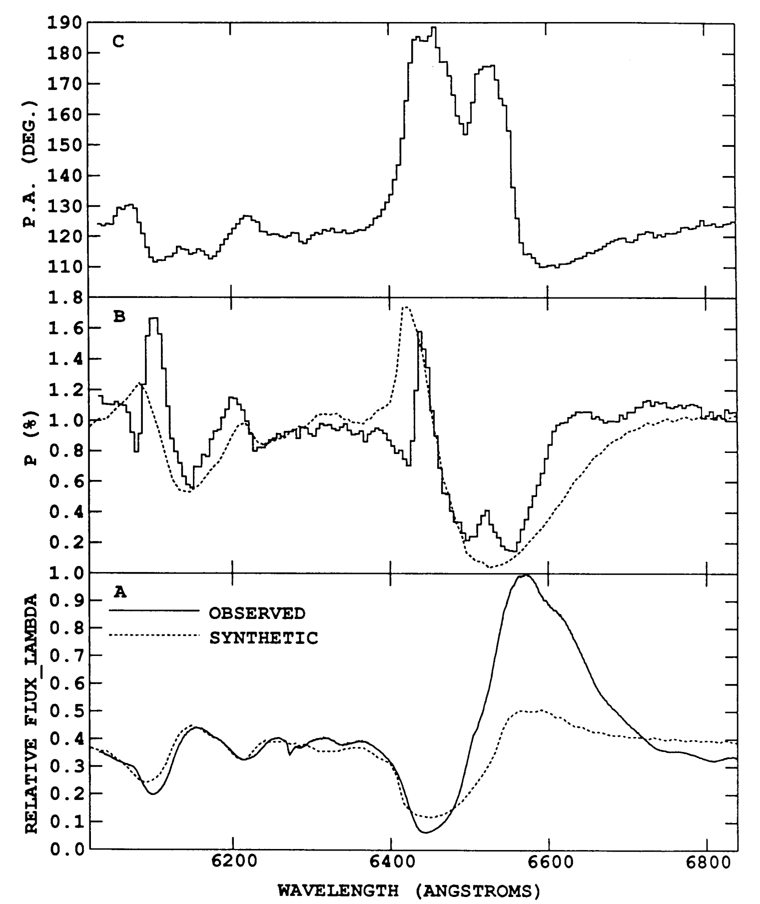
See: Brown and Mclean, 1977, A&A, 57, 141

SN 1987A

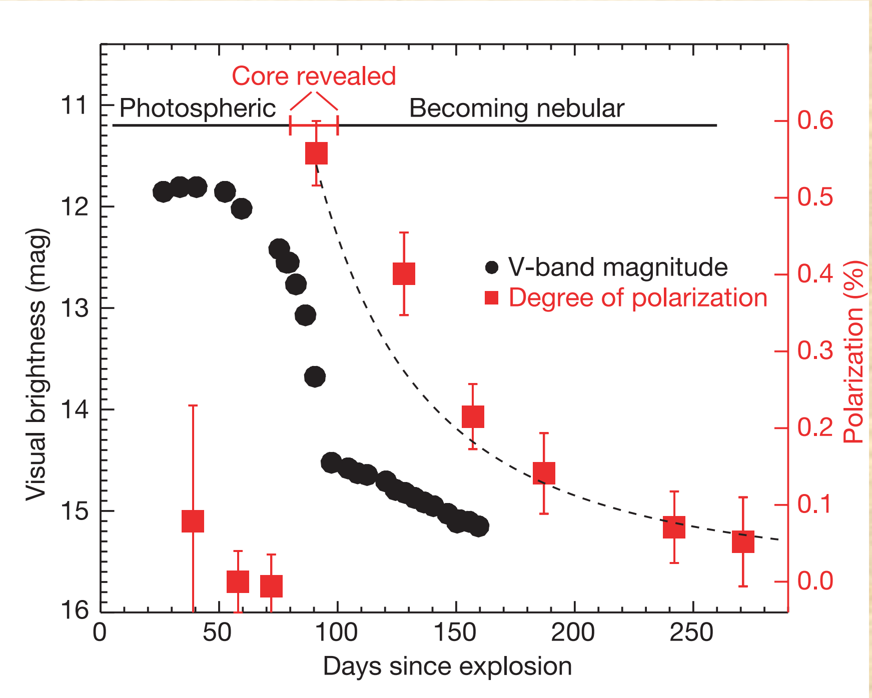
Day 12



Day 100

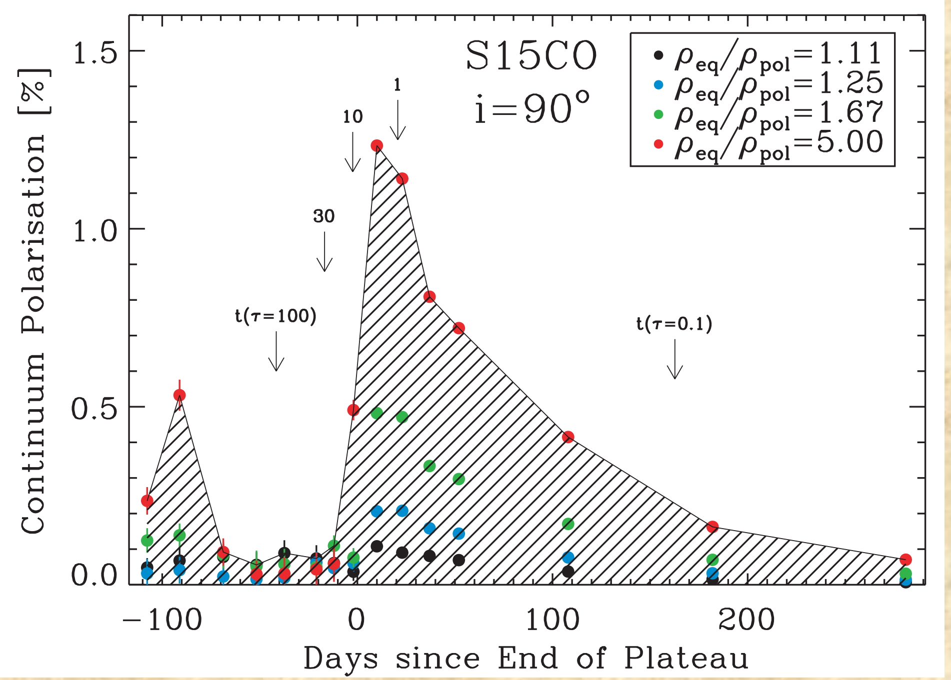


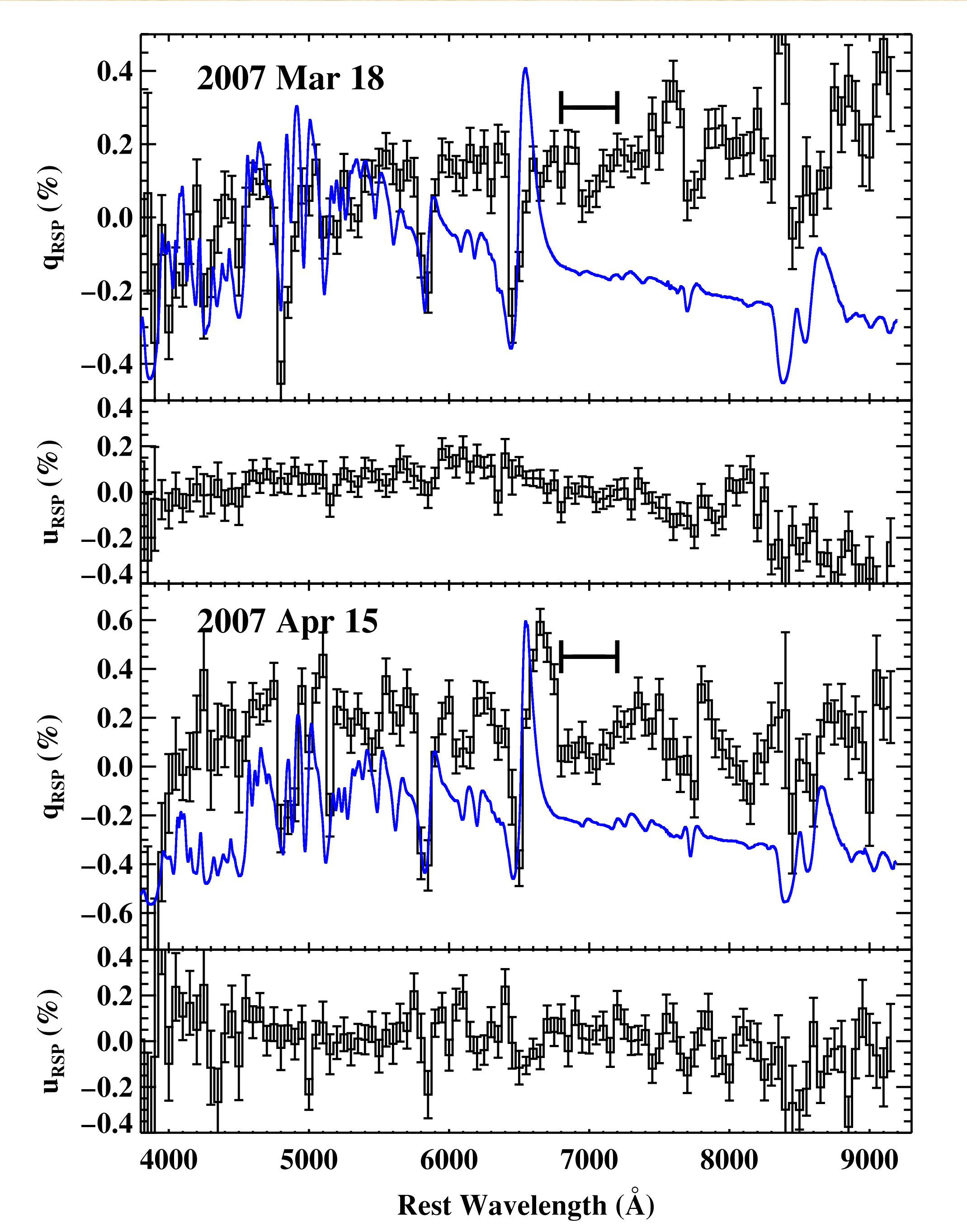
Jeffery 1991, ApJ, 375, 274



2004dj
Leonard et al, 2006,
Nat., 440, 505

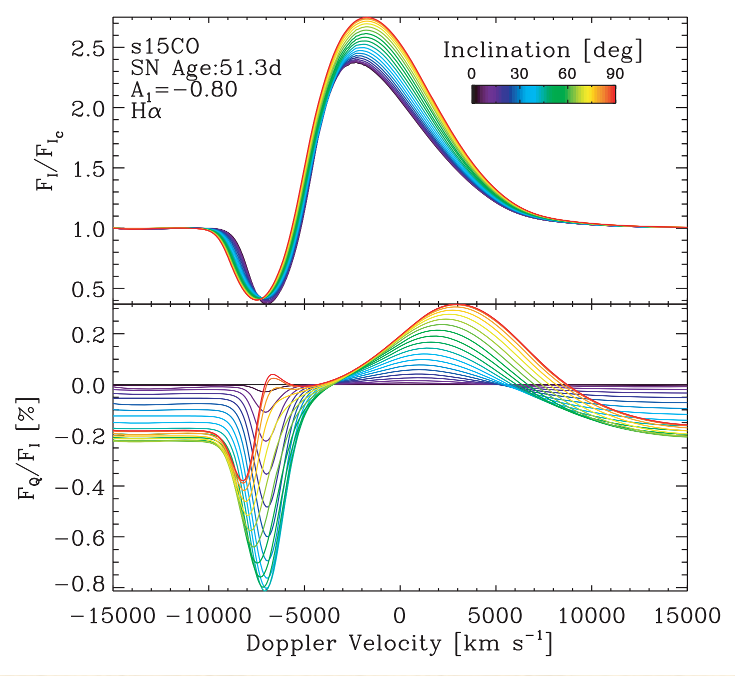
Dessart & Hillier, 2011
MNRA, 415, 3497





Chornock et al,
2010, ApJ, 713, 1363
SN 2007aa

Dessart & Hillier, 2011
MNRA, 415, 3497



Polarization Codes

Two transfer codes

Monte Carlo – can, in principal, be 3D.

Ray tracing – limited to axisymmetric geometries.

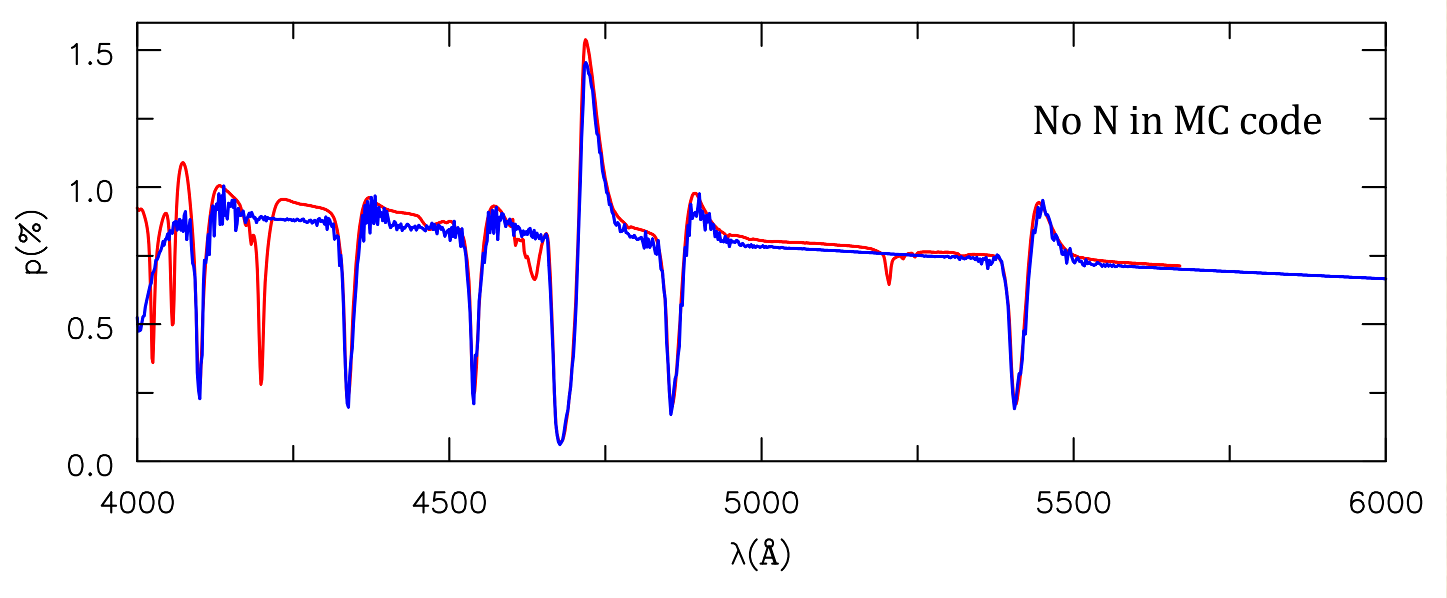
Generate model that depends on colatitude using CMFGEN 1D model.

(a) Shift structure in r

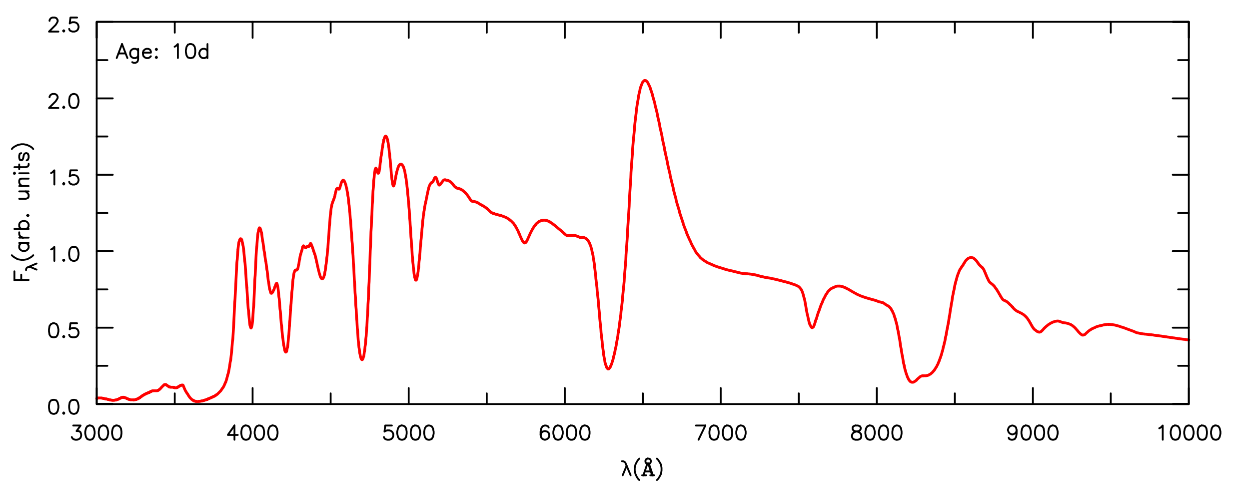
(b) Scale structure with angle

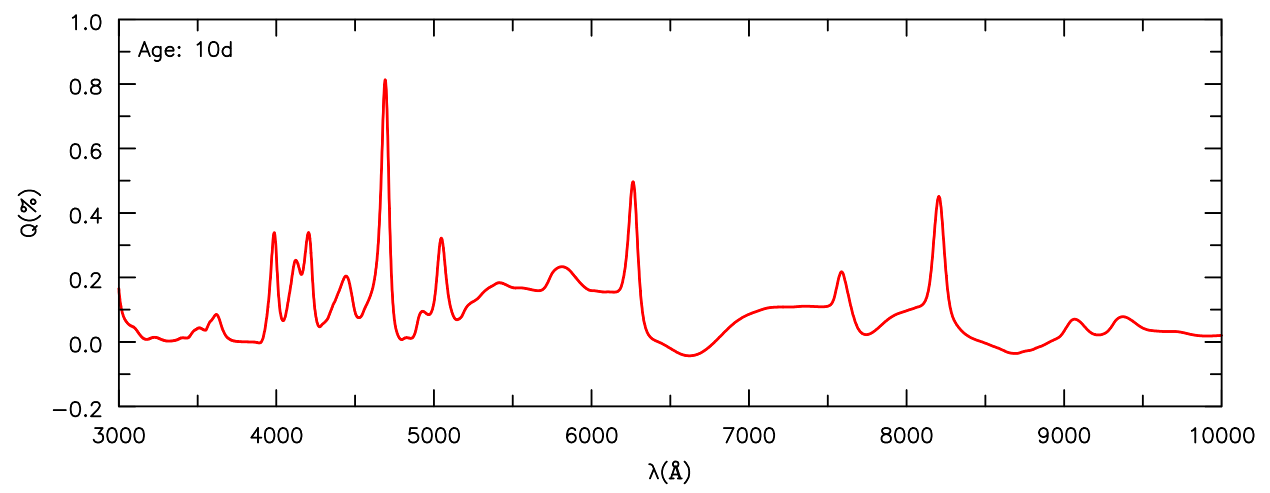
(c) Combine several CMFGEN models.

(d) (Alternatively could read in 2D or 3D model)

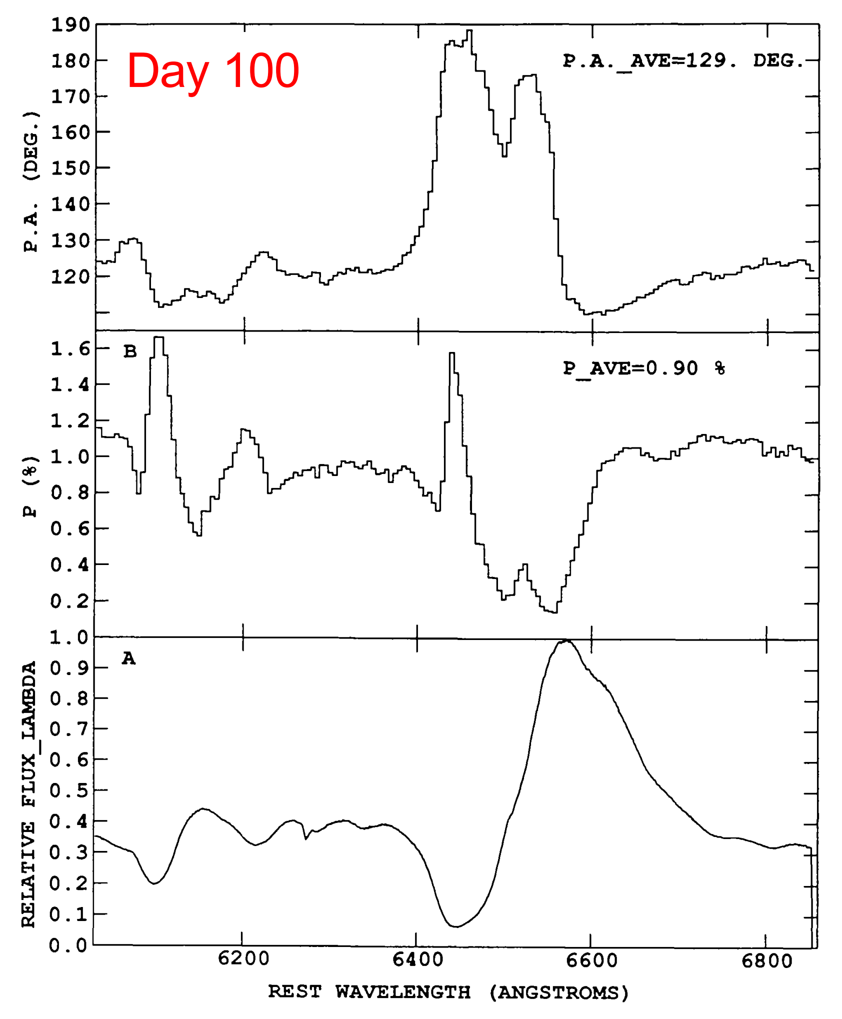


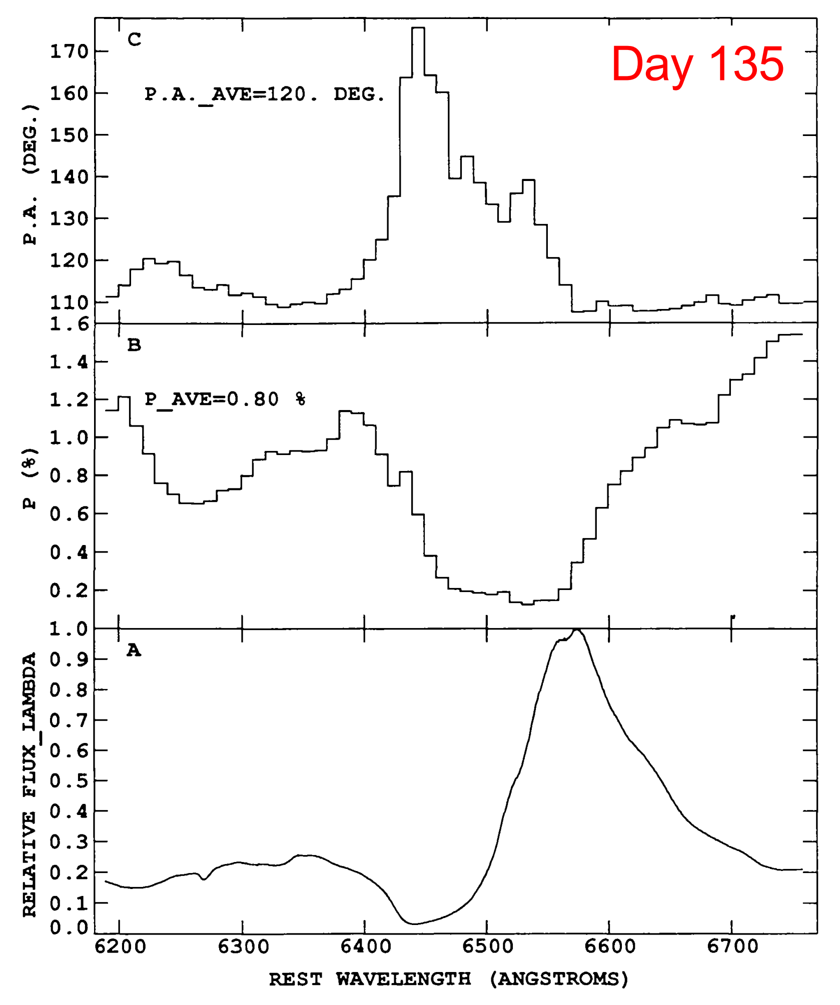
Model calculations
Prolate: 50% density enhancement at pole.





SN 1987A





From: Jeffery, 1991, ApJS, 77, 405

Conclusions

Tremendous advances in the last 30 years - 1987A

New surveys are going to reveal thousands of transits

- Which will get spectroscopic obs?

Need benchmark studies for IIP

Still fundamental questions :

- Origin of Ib, Ic & broad lined Ic SN
- Existence of PISN & PPISN
- pre-SN eruptions
- progenitor masses
- abundance yields

Multi–D effects are crucial.

- Less so for IIP?

THE
END