Supernova Explosions in Dense Circumstellar Medium

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partly based on Moriya et al. 2011, MNRAS, accepted
arXiv:1009.5799 (will be replaced tomorrow)

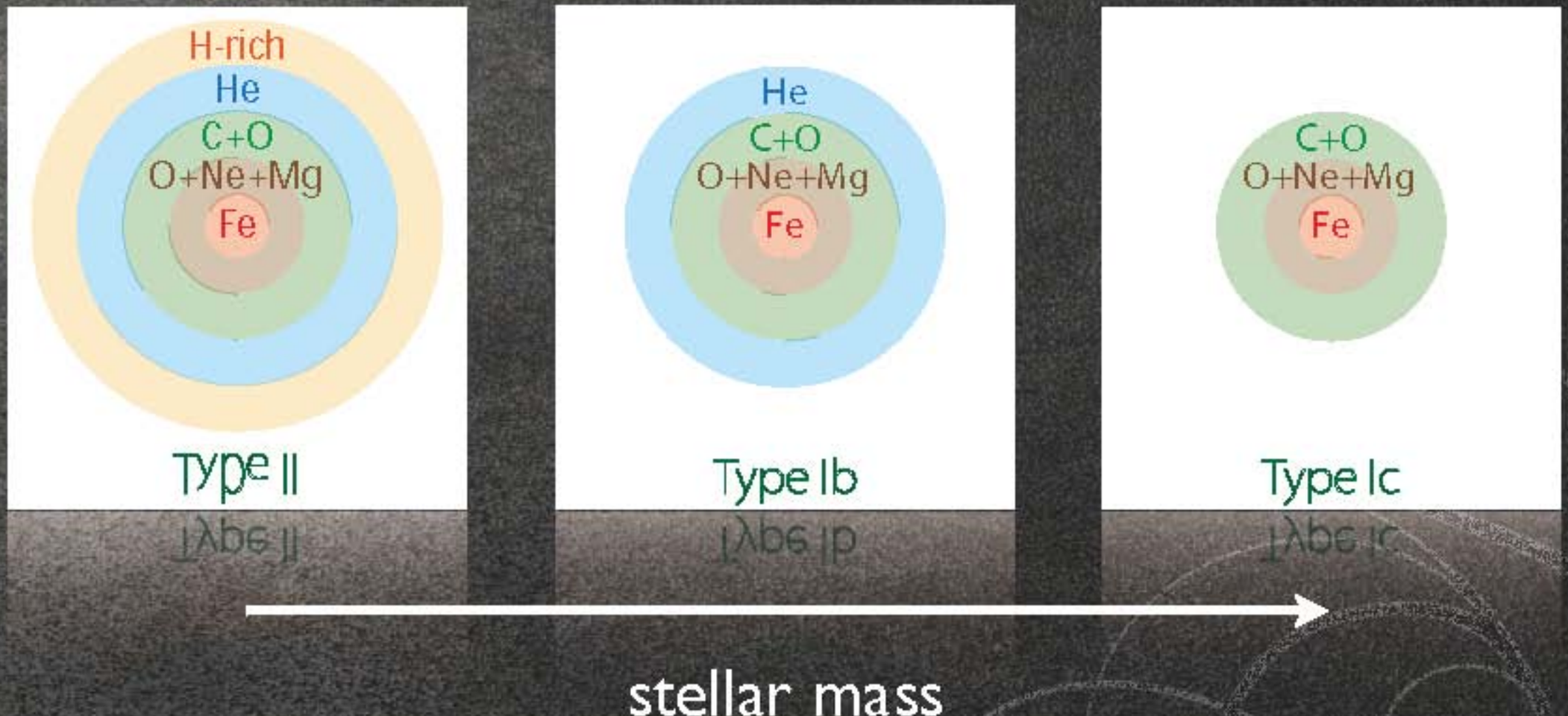
Contents

Supernovae

- Explosions of Stars
  - Type Ia: Explosions of white dwarfs
  - Other Types: Explosions of massive stars
    - Heavier than ~ 10 Msun

Explosions of Massive Stars

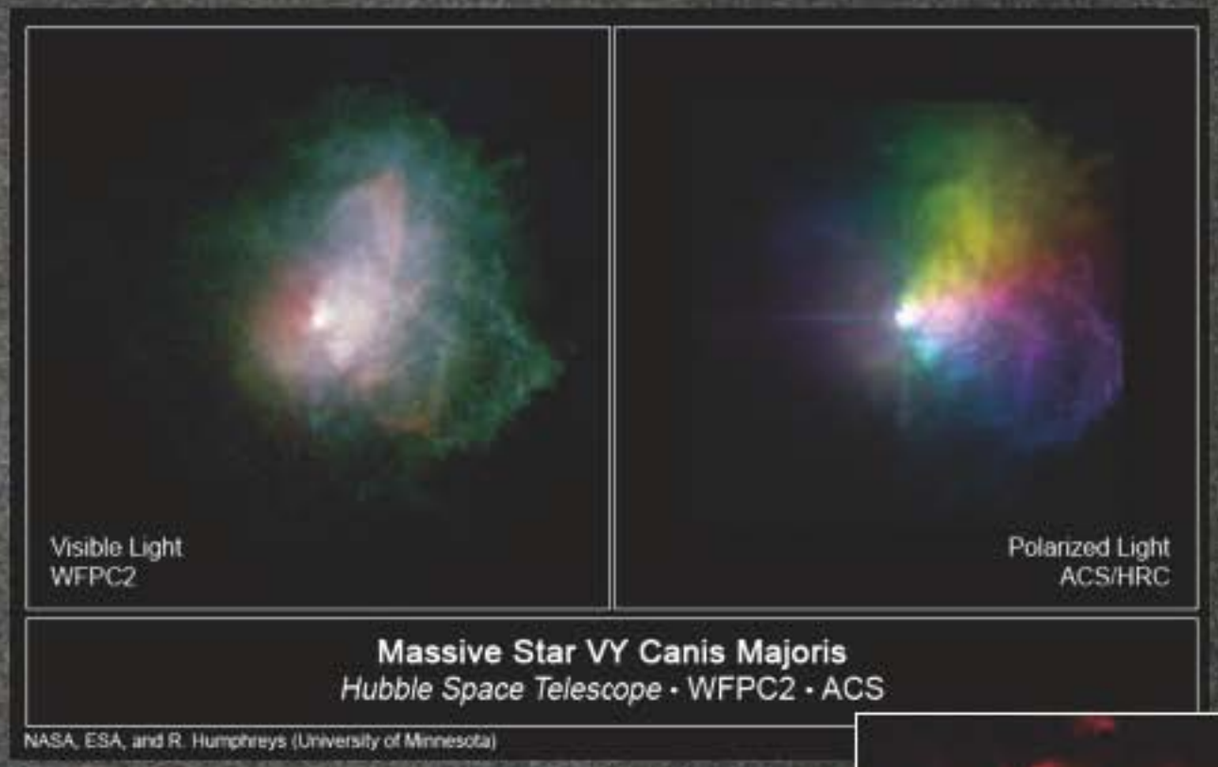
- Heavier stars lose more mass

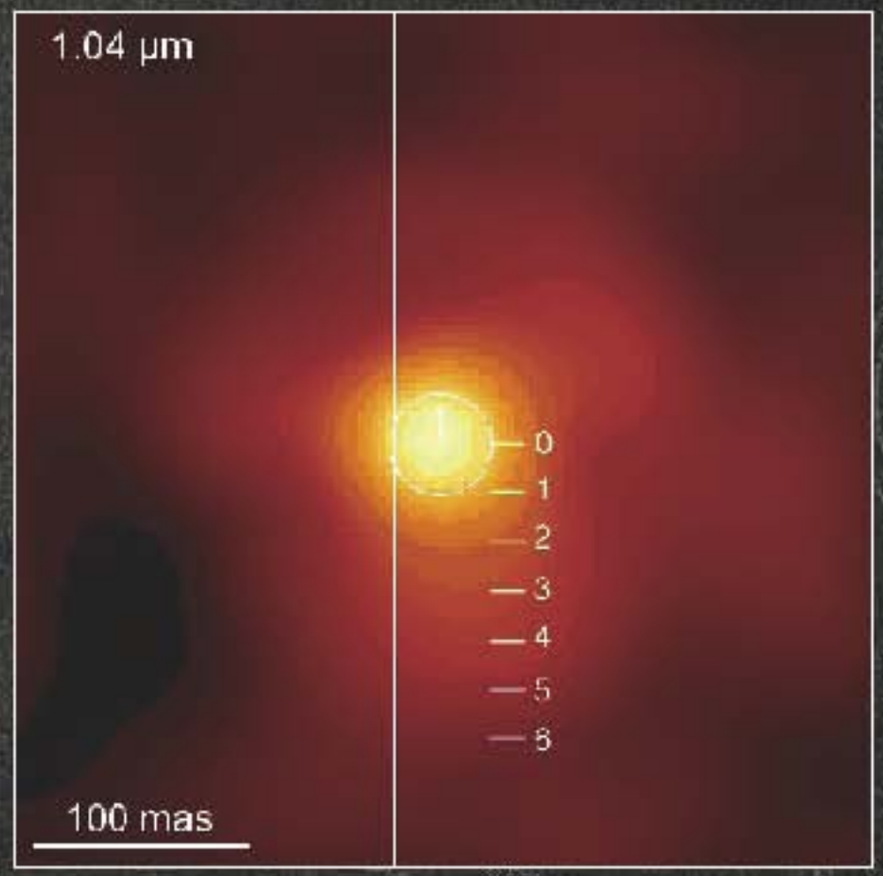


Mass Loss of Massive Stars

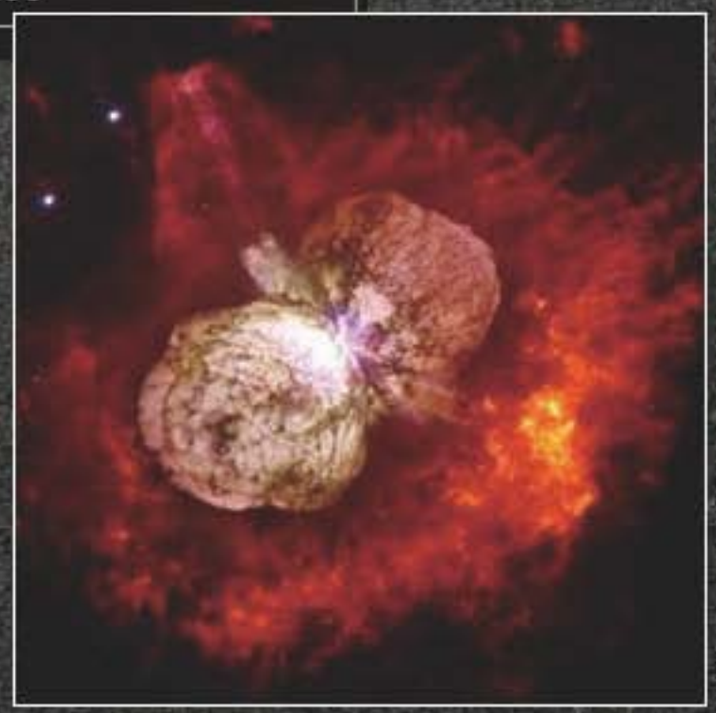
- Radiation Pressure
  - Line-driven winds
  - Dust-driven winds
- Kinetic Energy
  - Pulsations → Shock wave
- Rotation
- Magnetic Field
- ...

Circumstellar Medium (CSM)





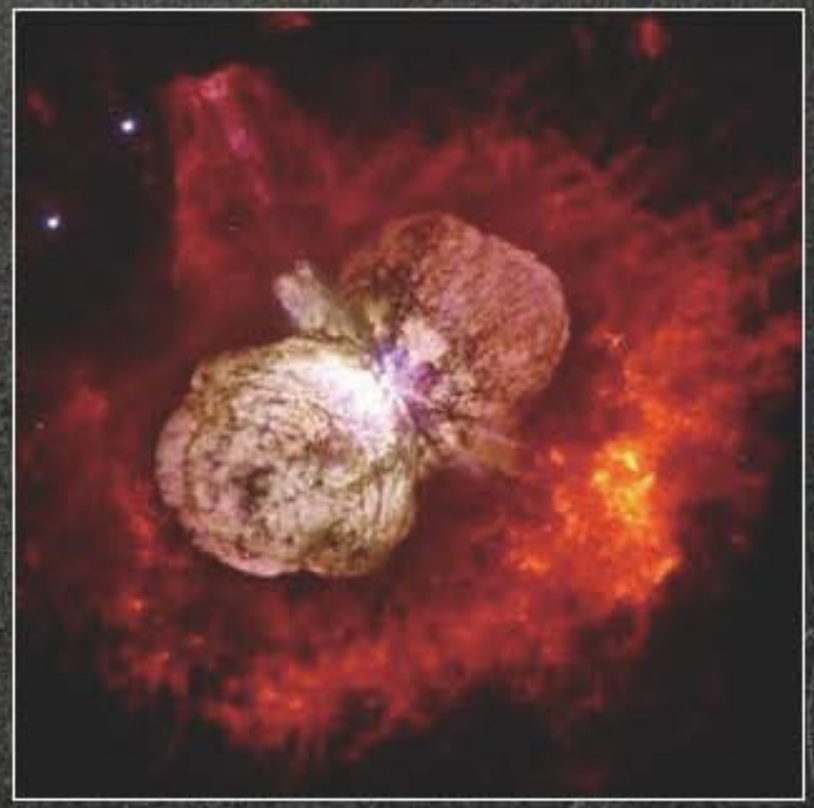
Betelgeuse



eta Carinae

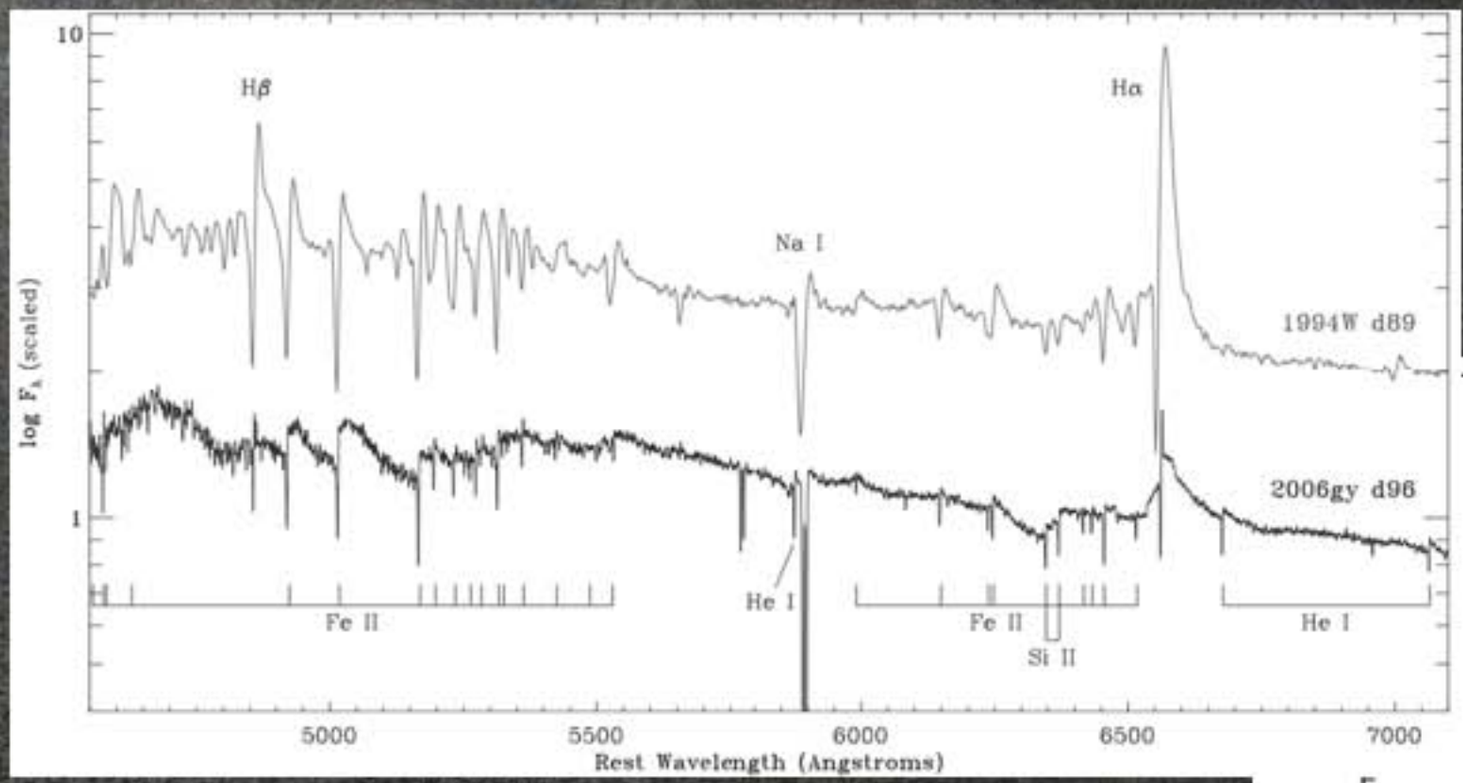
Effect on Supernovae

- SN ejecta collides to CSM
  - Usually, the effect is not big (small mass, thin)
- Some SNe show the effect



Effect on Supernovae

- P-Cygni profile (~ 100 km/s) of CSM
  - Type IIn



Smith et al. (2010)

Riess et al. (2004)

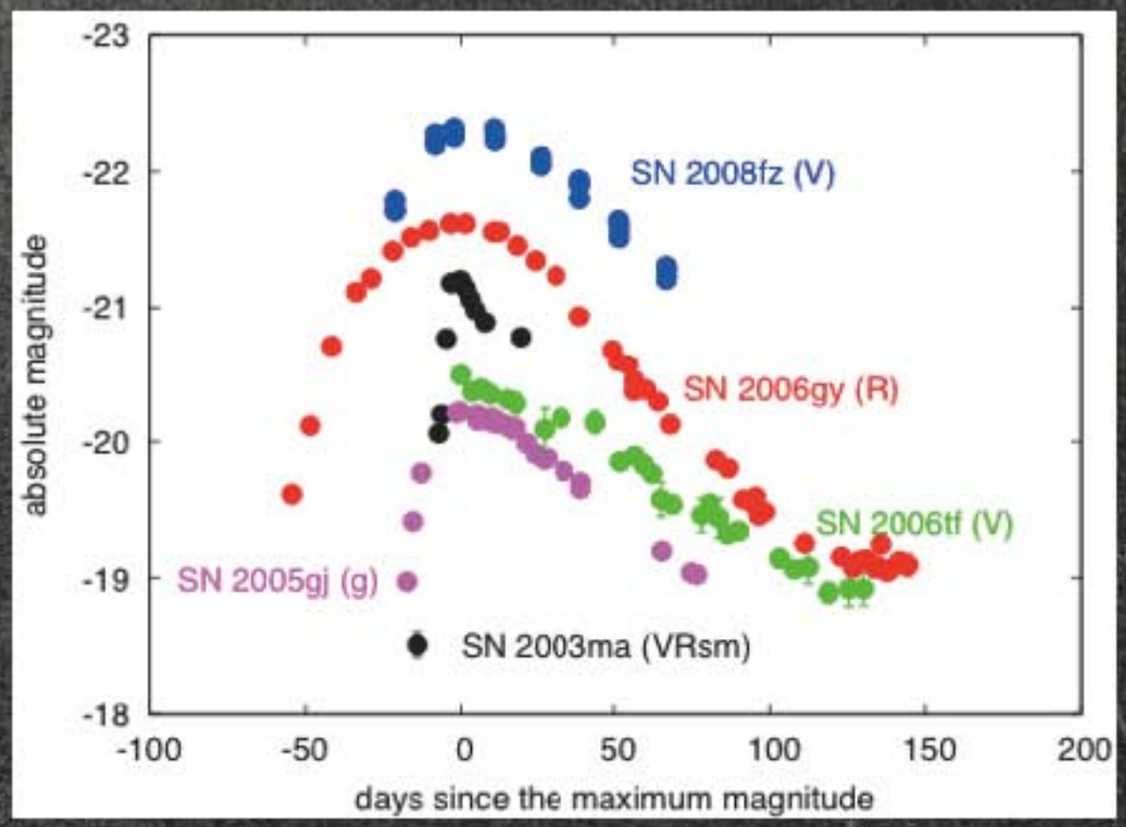
Effect on Light Curve

- Type IIn SNe are brighter than other Type II's on average

SN Type	$\overline{M}_{B,\mathrm{obs}}$	σ_{obs}	$\overline{M}_{B,\mathrm{int}}$	σ_{int}	Conf.	N
Bright II-L	-19.12 ± 0.12	0.23	-19.27	0.51	$\sim$1	4
Normal II-L....	-17.36 ± 0.12	0.43	-17.56	0.38	$\sim$1	12
II-P	-16.61 ± 0.23	1.23	-17.00	1.12	$\sim$1	29
IIn.....	-18.78 ± 0.31	0.92	-19.15	0.92	$\sim$1	9

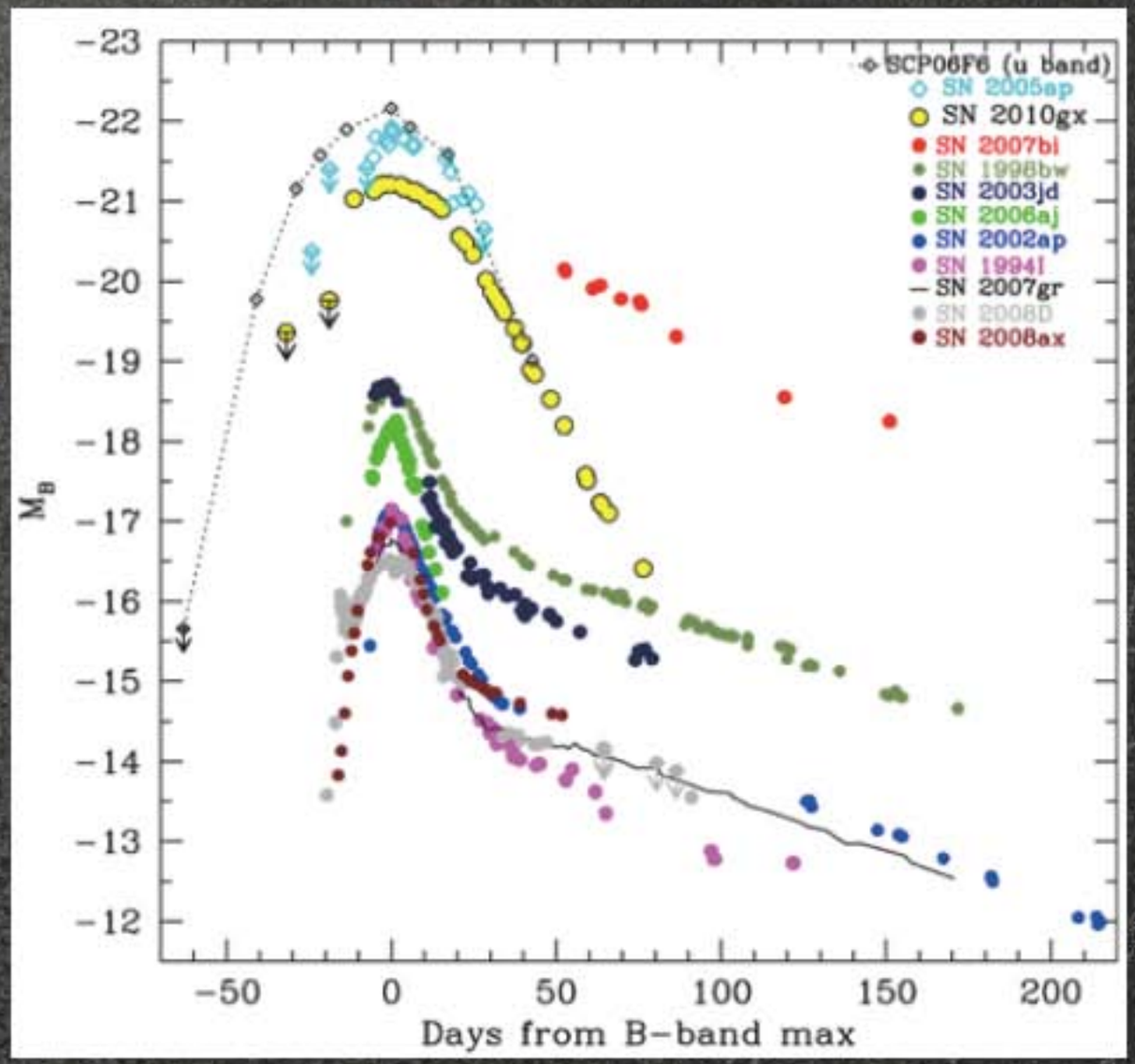
Richardson et al. (2002)

- Some of Type IIn are very bright

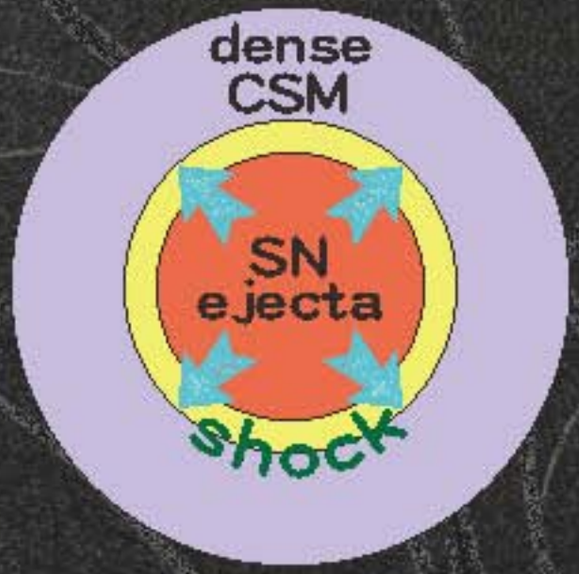


Luminous Supernovae

- Can be due to CSM (not 56Ni!)

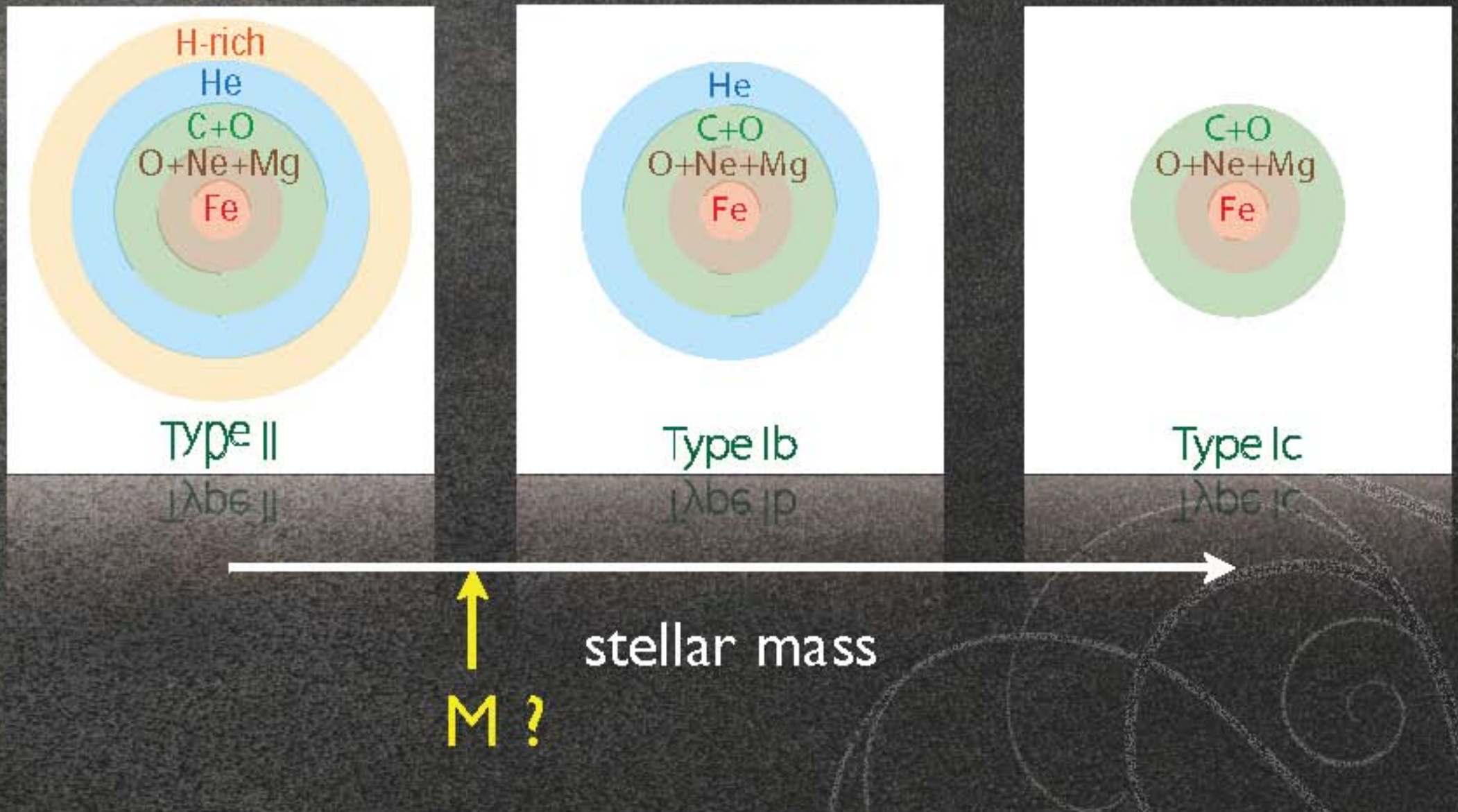


Pastorello et al. (2010)



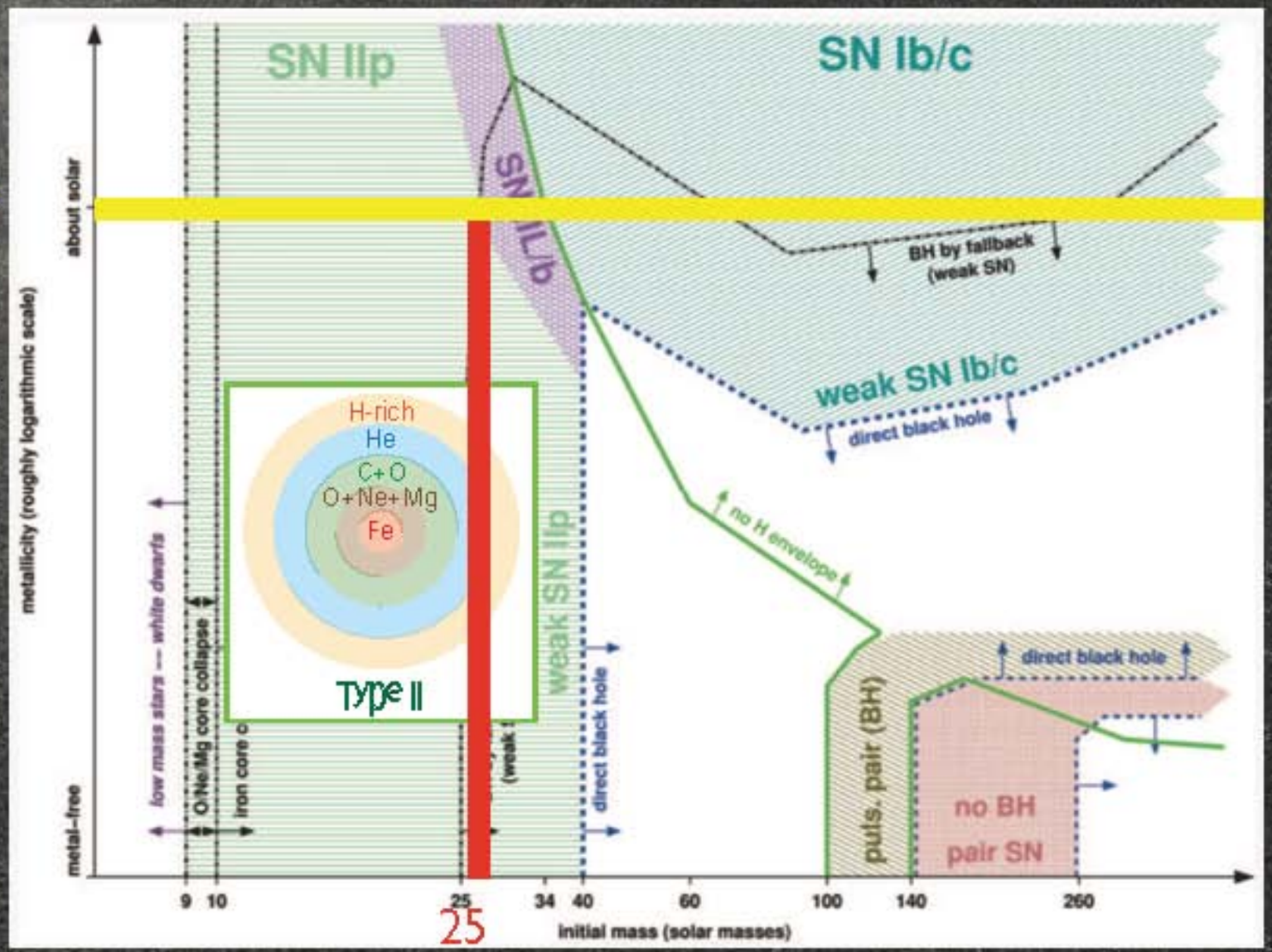
How much do they lose?

- Heavier stars lose more mass



Stellar Evolution

- Heger et al. (2003)



solar

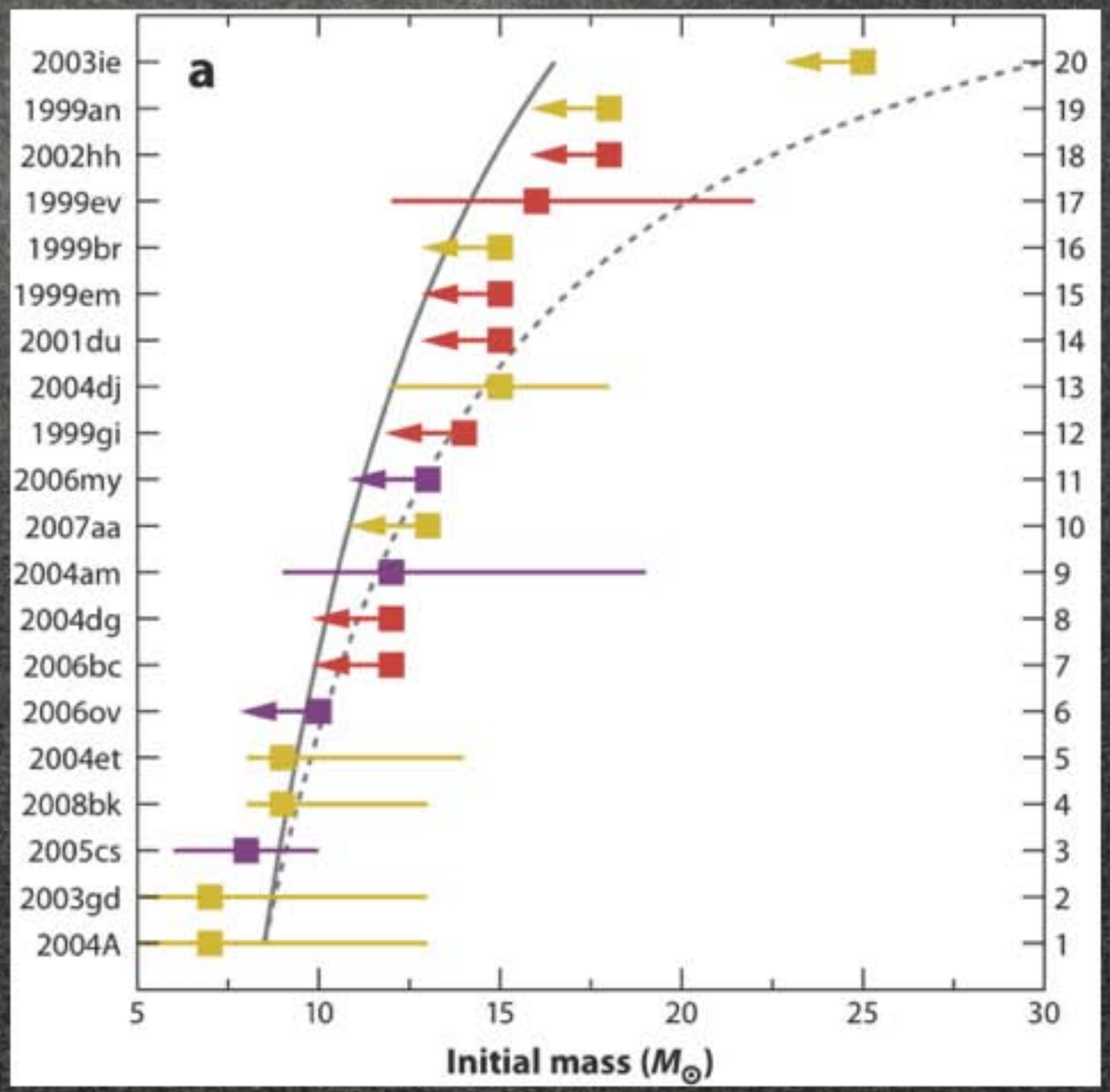
metallicity

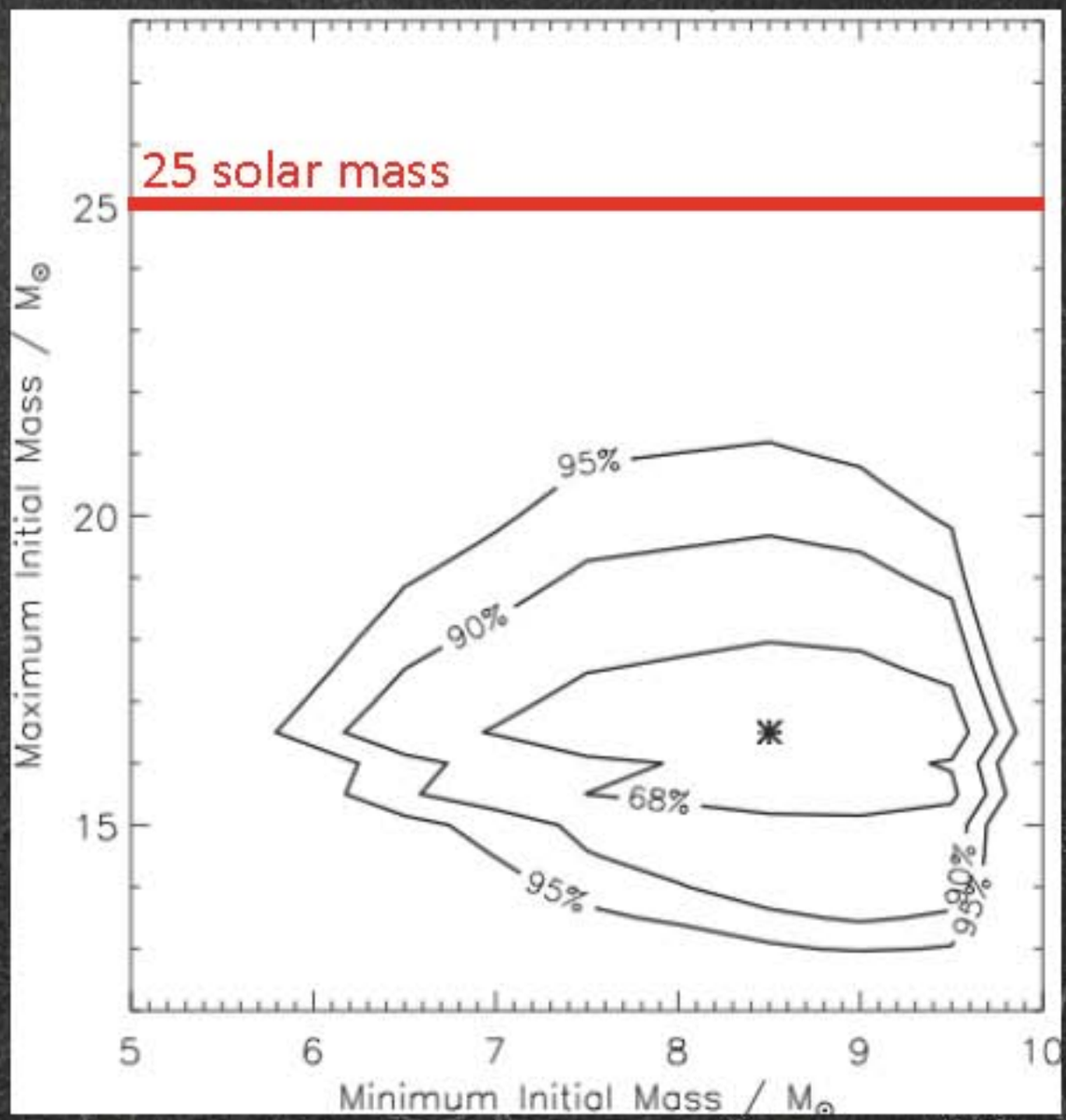
25

initial mass (solar masses)

Observations

- Direct detections of pre-supernova stars (Smart et al. 2009)





What's missing?

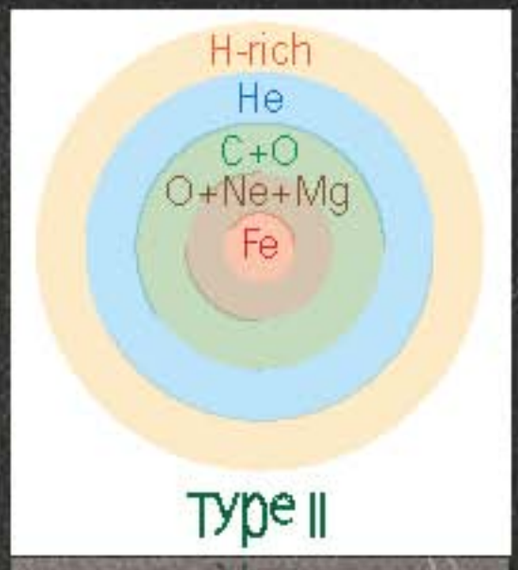
- Observational sample is too small
- Problems in theoretical stellar modeling
  - Missing mass-loss mechanisms
    - No rotation, no magnetic field, ...
    - Especially, no extensive mass loss
      - Nuclear flush
      - Pulsation-driven mass loss

Extensive Mass Loss of Red Supergiants (RSGs)

- Red Supergiant (RSG) ~ H-rich star before explosion
- Usual mass-loss rate: $\sim 10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$
- RSGs with very high mass-loss rates
  - VY CMa (Smith+ '09)

    $1 - 2 \times 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$
  - IRAS05280-6910 (Boyer+ '10)

    $\sim 10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$

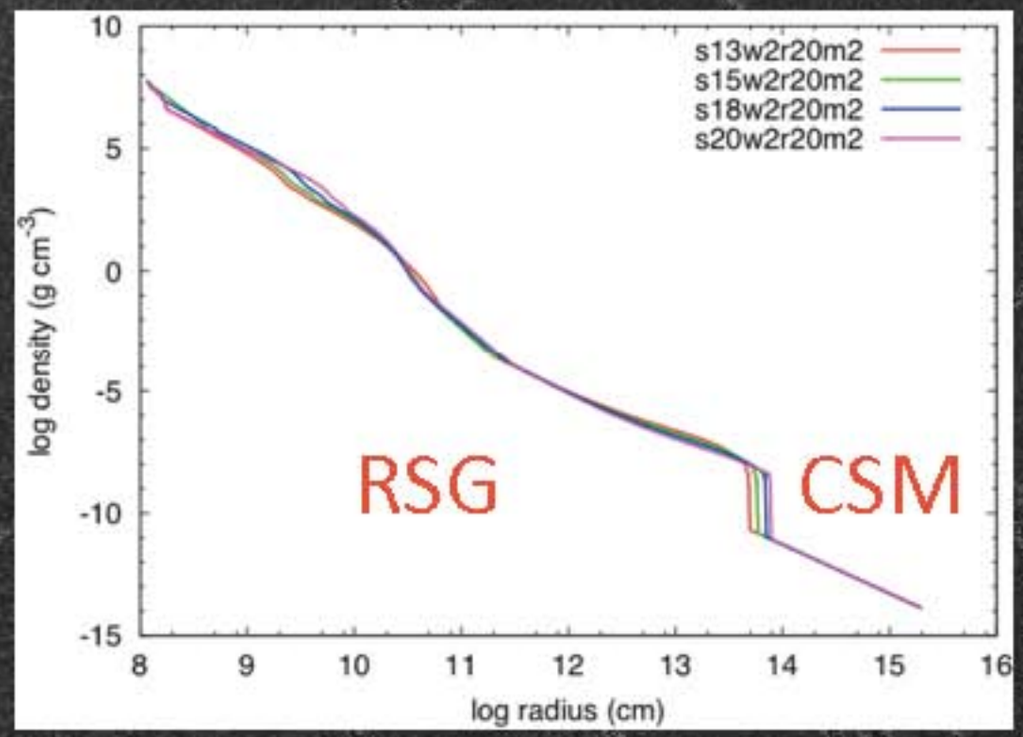


What happens if they remain at the time of explosion?

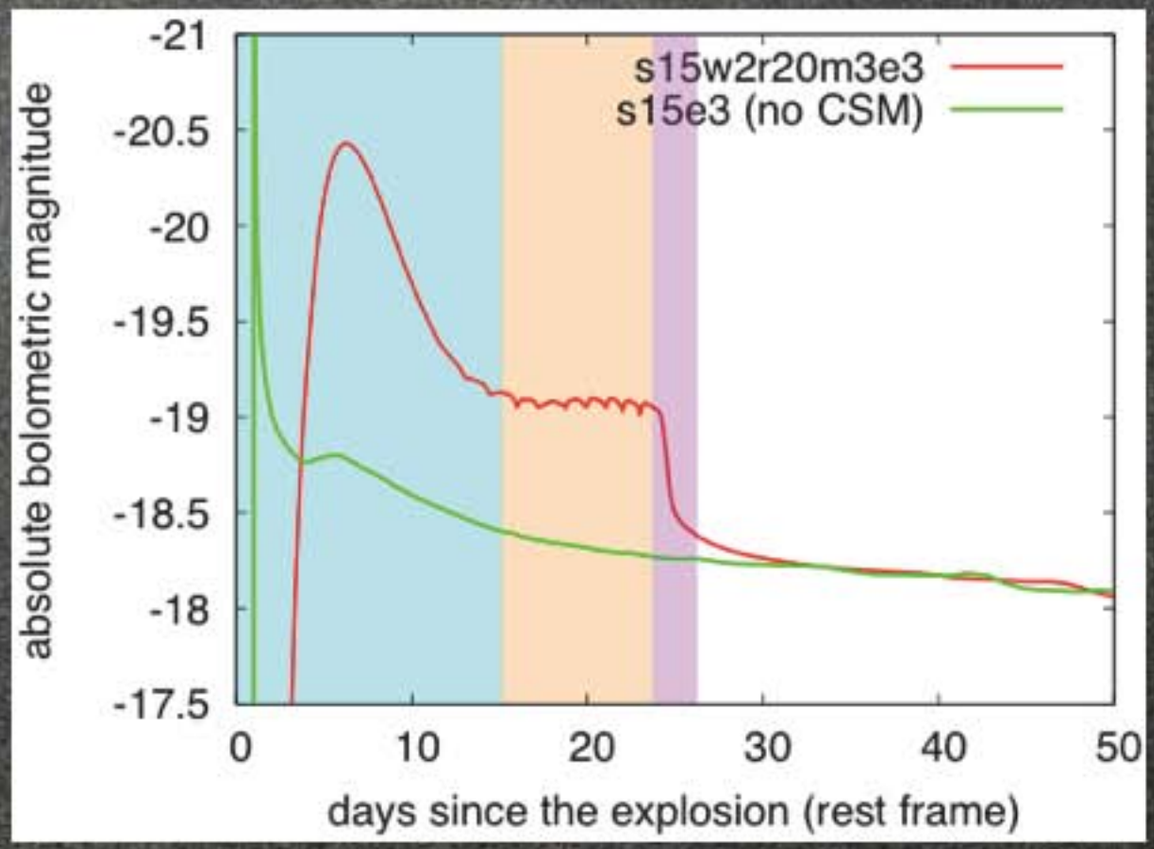
Numerical Modeling of CSM collision

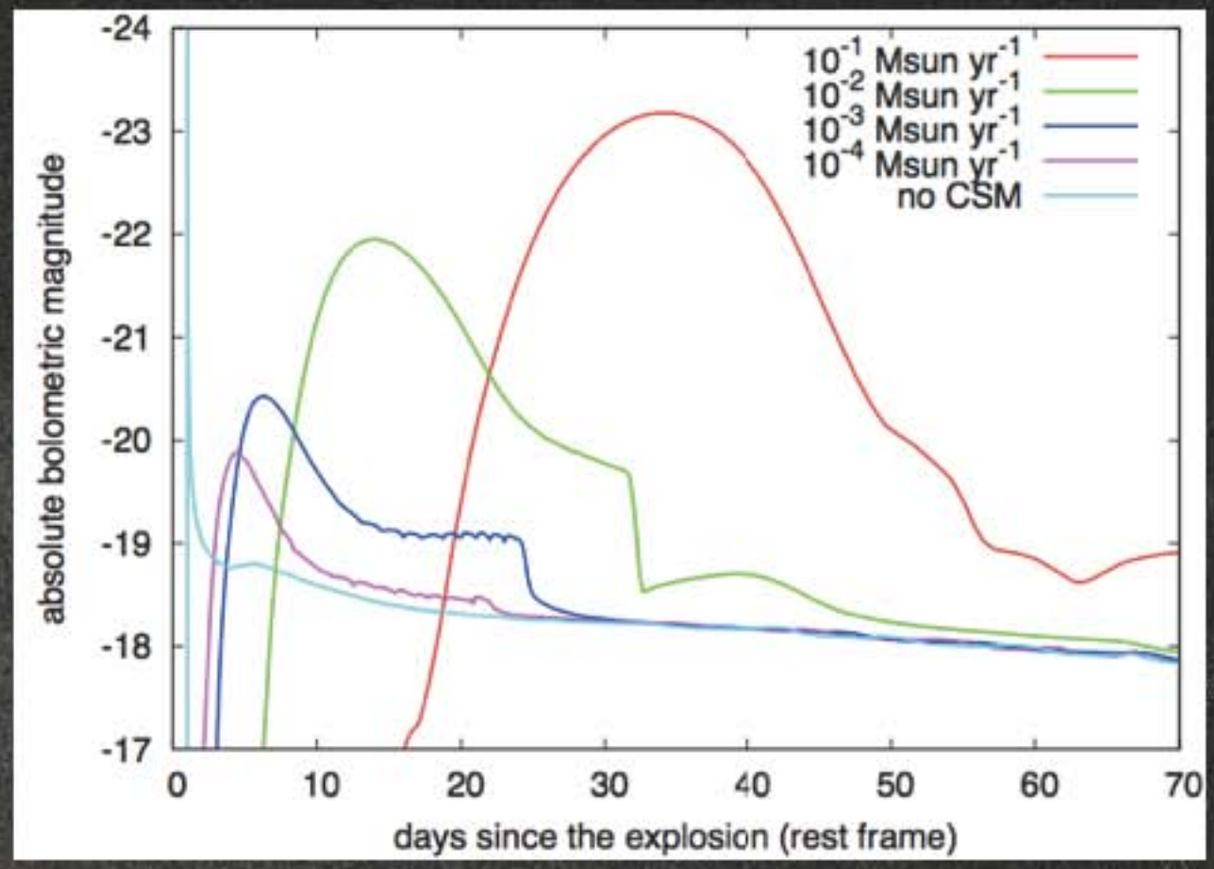
- Radiation energy source: kinetic energy of SN ejecta
  - Radiation hydrodynamics (STELLA code: e.g., Blinnikov+ '06)
- Initial conditions
  - RSG inside: s13, s15, s18, s20 of Woosley et al. (2002)
  - Explosion energy: $1 - 7 \times 10^{51}$ erg
  - CSM (10 km/s)
    - $\rho \propto r^{-2}, \rho \propto r^{-1.5}$
    - Mass-loss rate $(M_\odot\ \mathrm{yr}^{-1})$
      $10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}$
    - Radius $(10^{15}\ \mathrm{cm})$
      0.5, 1, 2, 3 (15, 30, 45, 60 yrs)

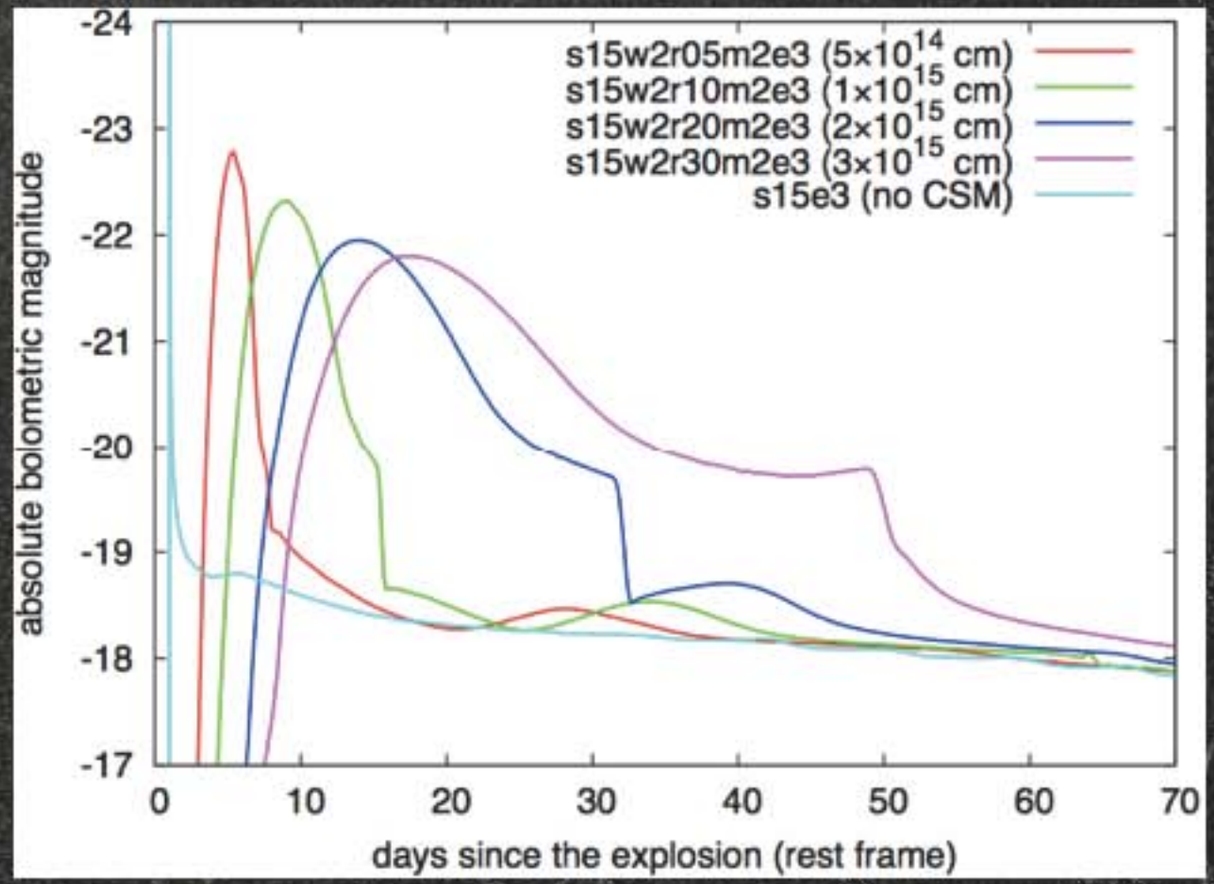
Example: s15, $10^{-2} M_\odot \mathrm{yr}^{-1}, 2 \times 10^{15} \mathrm{cm} \rightarrow 0.65 M_\odot, 60 \mathrm{yrs}$



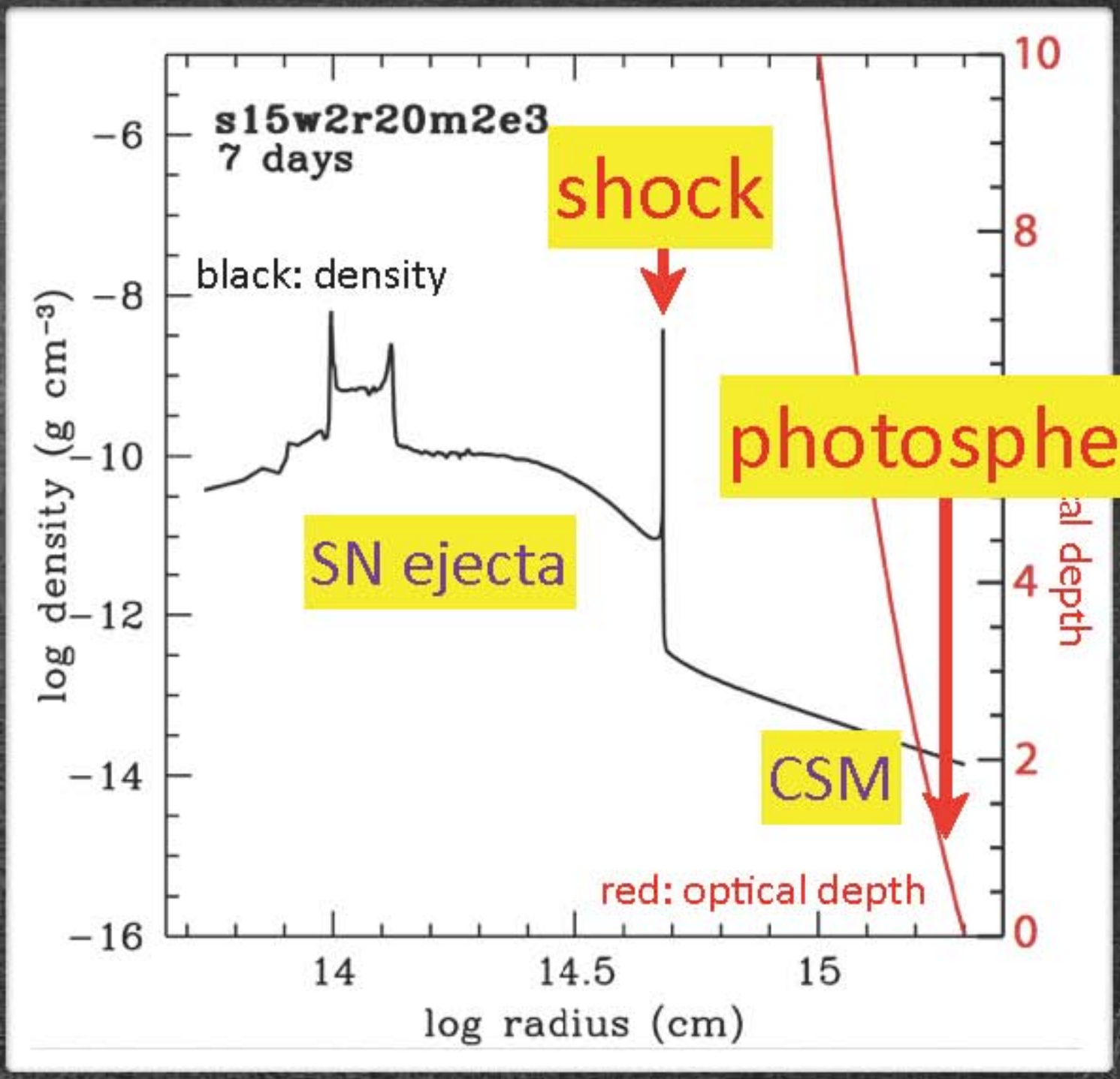
Results

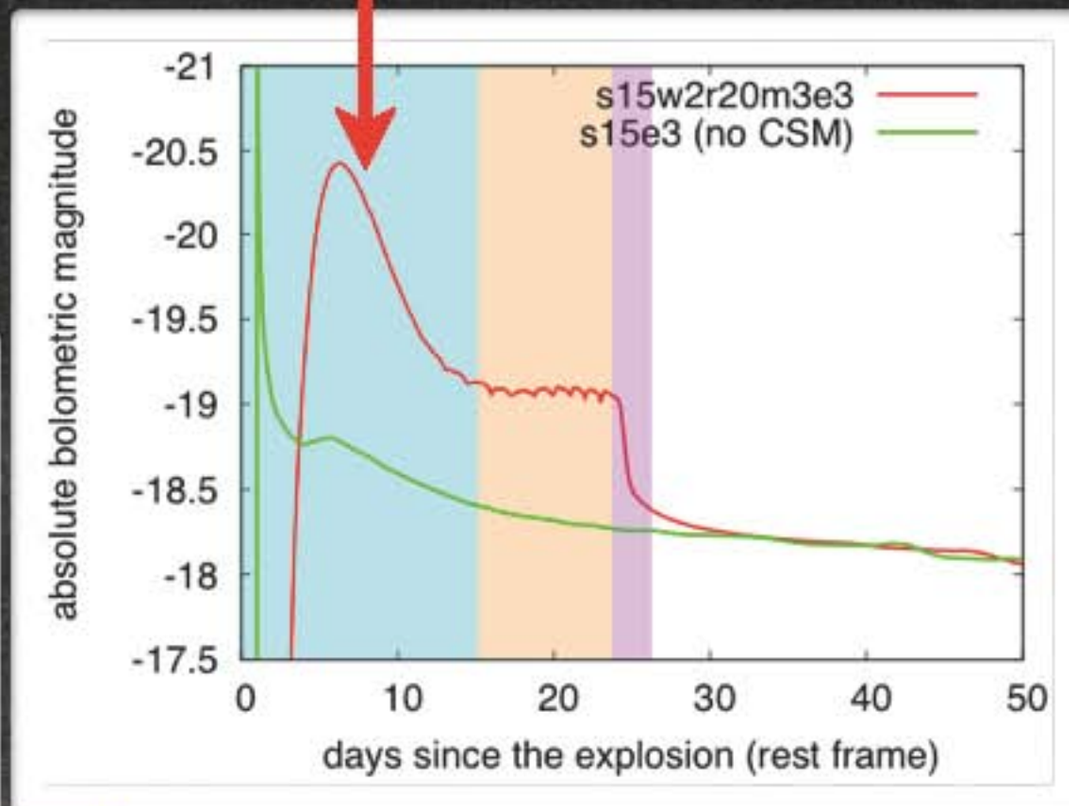

s15w2r20m3e3
s15e3 (no CSM)
absolute bolometric magnitude
days since the explosion (rest frame)
-21
-20.5
-20
-19.5
-19
-18.5
-18
-17.5
0
10
20
30
40
50

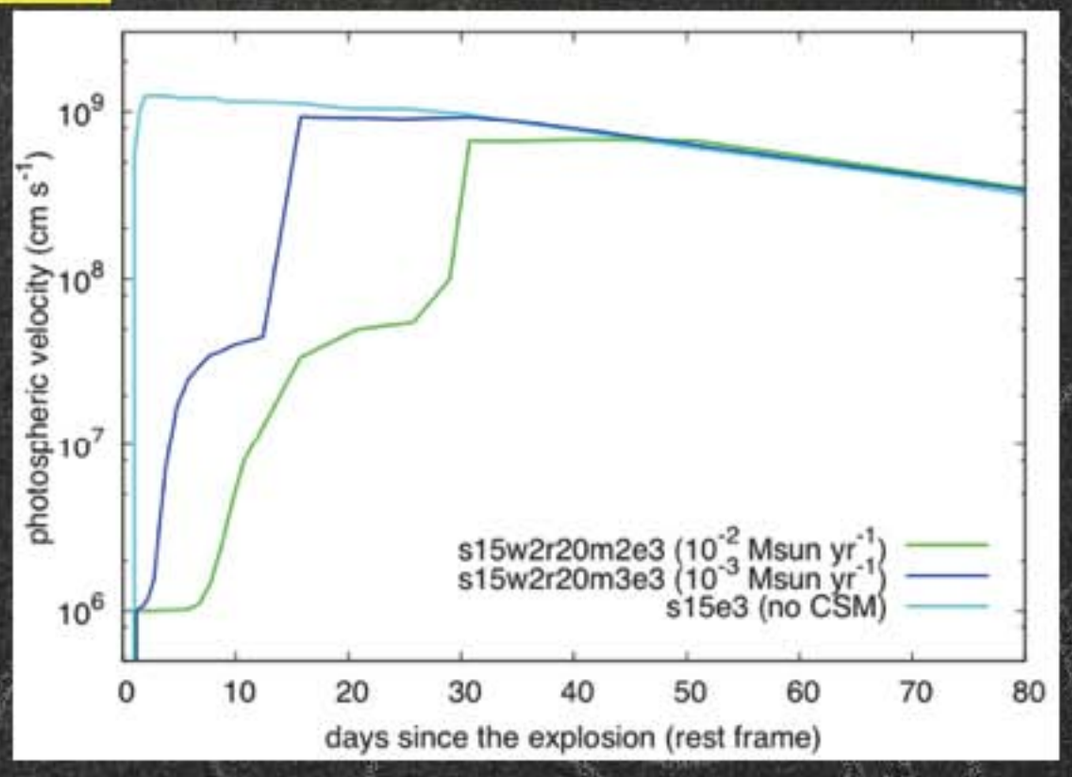

10^{-1} Msun yr^{-1}
10^{-2} Msun yr^{-1}
10^{-3} Msun yr^{-1}
10^{-4} Msun yr^{-1}
no CSM
absolute bolometric magnitude
days since the explosion (rest frame)
-24
-23
-22
-21
-20
-19
-18
-17
0
10
20
30
40
50
60
70


s15w2r05m2e3 (5×10^{14} cm)
s15w2r10m2e3 (1×10^{15} cm)
s15w2r20m2e3 (2×10^{15} cm)
s15w2r30m2e3 (3×10^{15} cm)
s15e3 (no CSM)
absolute bolometric magnitude
days since the explosion (rest frame)
-24
-23
-22
-21
-20
-19
-18
-17
0
10
20
30
40
50
60
70

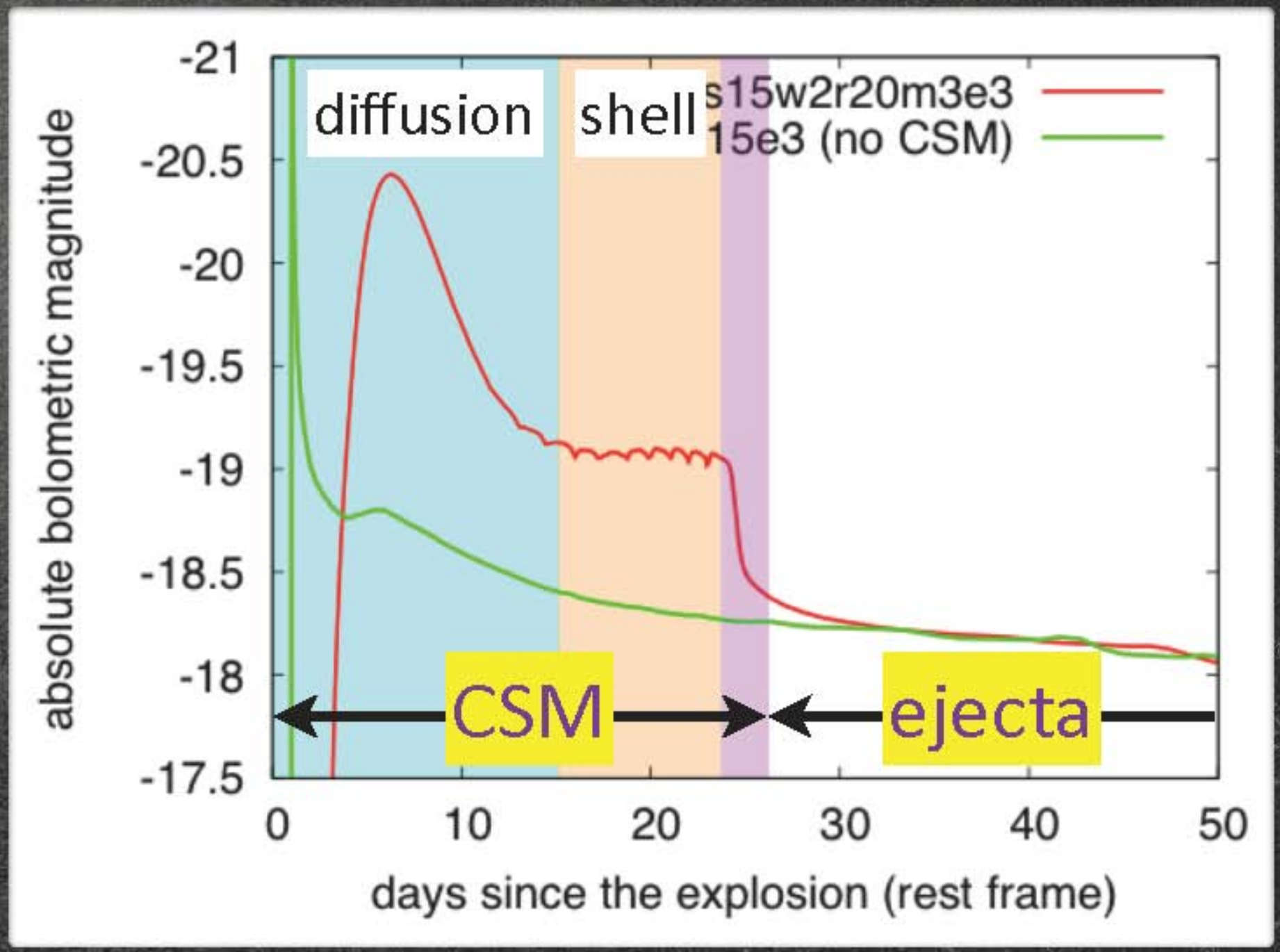
Results


s15w2r20m2e3
7 days
black: density
red: optical depth
shock
photosphere
SN ejecta
CSM
log density (g cm^{-3})
log radius (cm)
optical depth


s15w2r20m3e3
s15e3 (no CSM)
absolute bolometric magnitude
days since the explosion (rest frame)

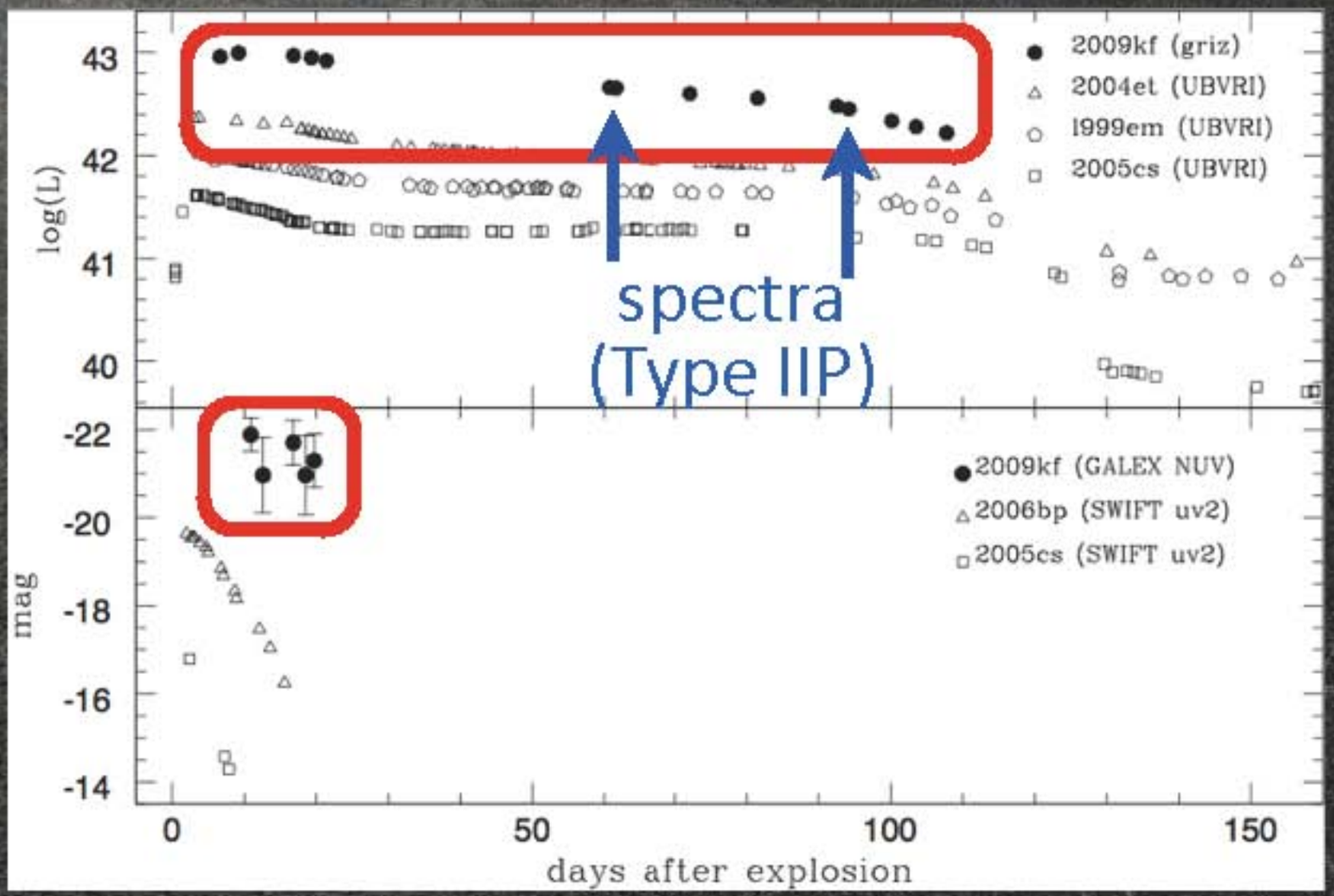

s15w2r20m2e3 (10^{-2} Msun yr^{-1})
s15w2r20m3e3 (10^{-3} Msun yr^{-1})
s15e3 (no CSM)
photospheric velocity (cm s^{-1})
days since the explosion (rest frame)

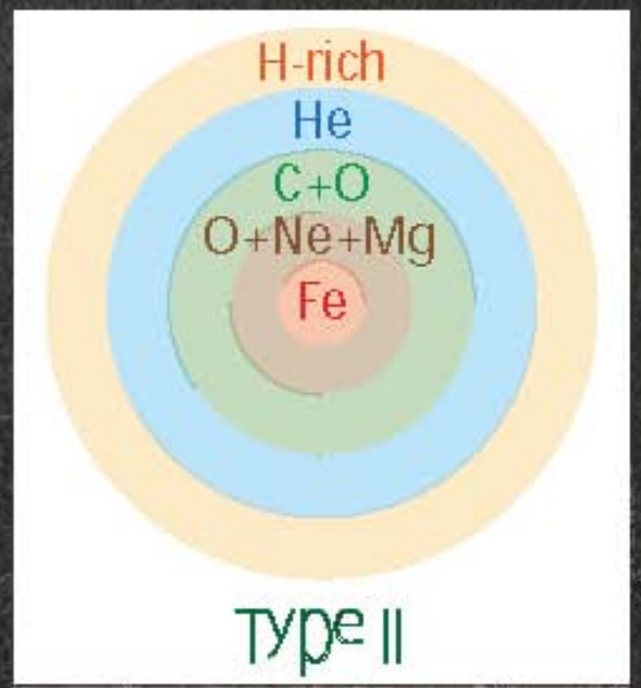
Results


diffusion
shell
s15w2r20m3e3
15e3 (no CSM)
CSM
ejecta
-21
-20.5
-20
-19.5
-19
-18.5
-18
-17.5
absolute bolometric magnitude
0
10
20
30
40
50
days since the explosion (rest frame)

Comparison with Observation

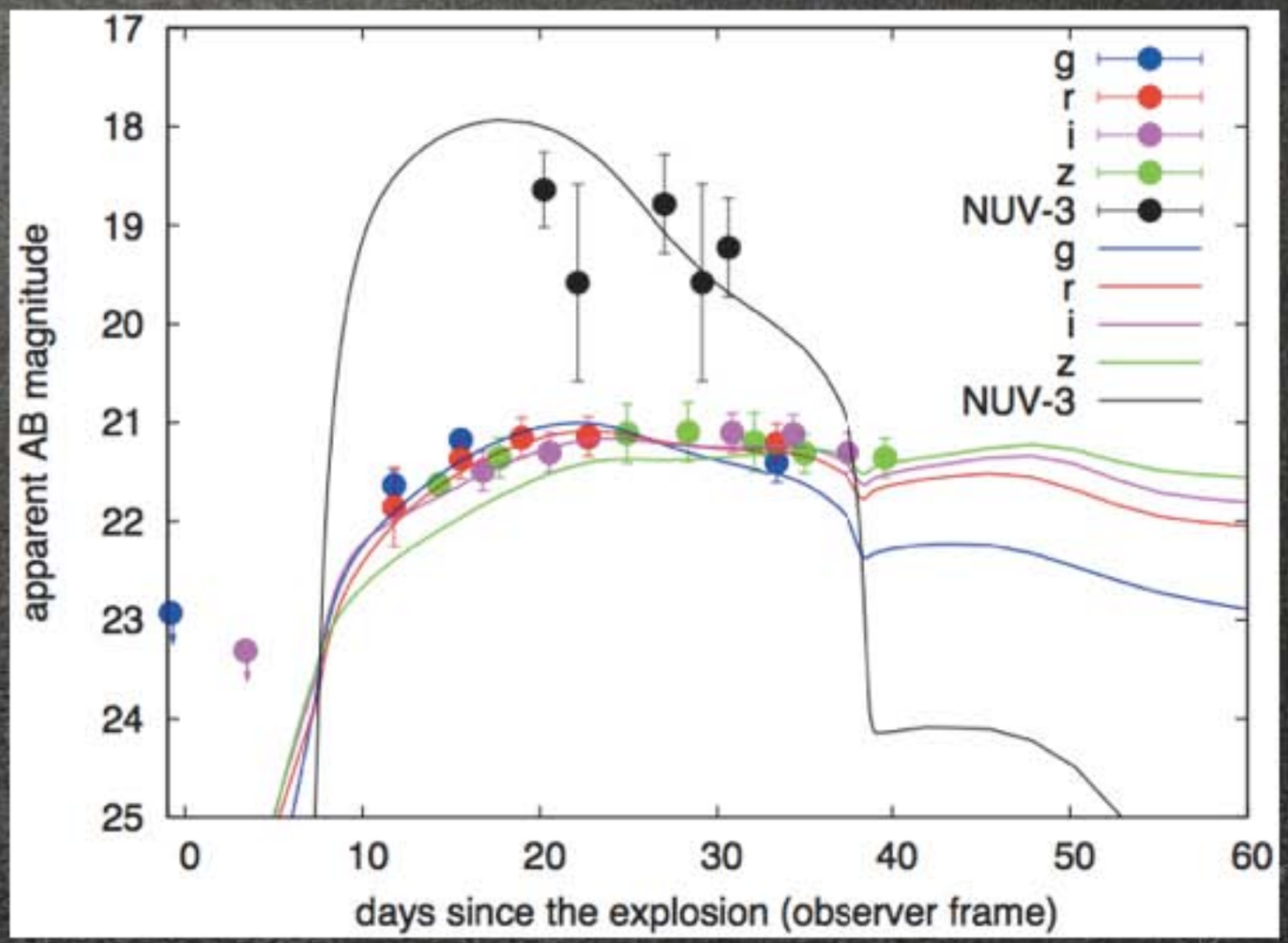
- SN 2009kf
  - Explosion of a RSG but unusually bright in UV at early epochs





Possible Feature of Dense CSM

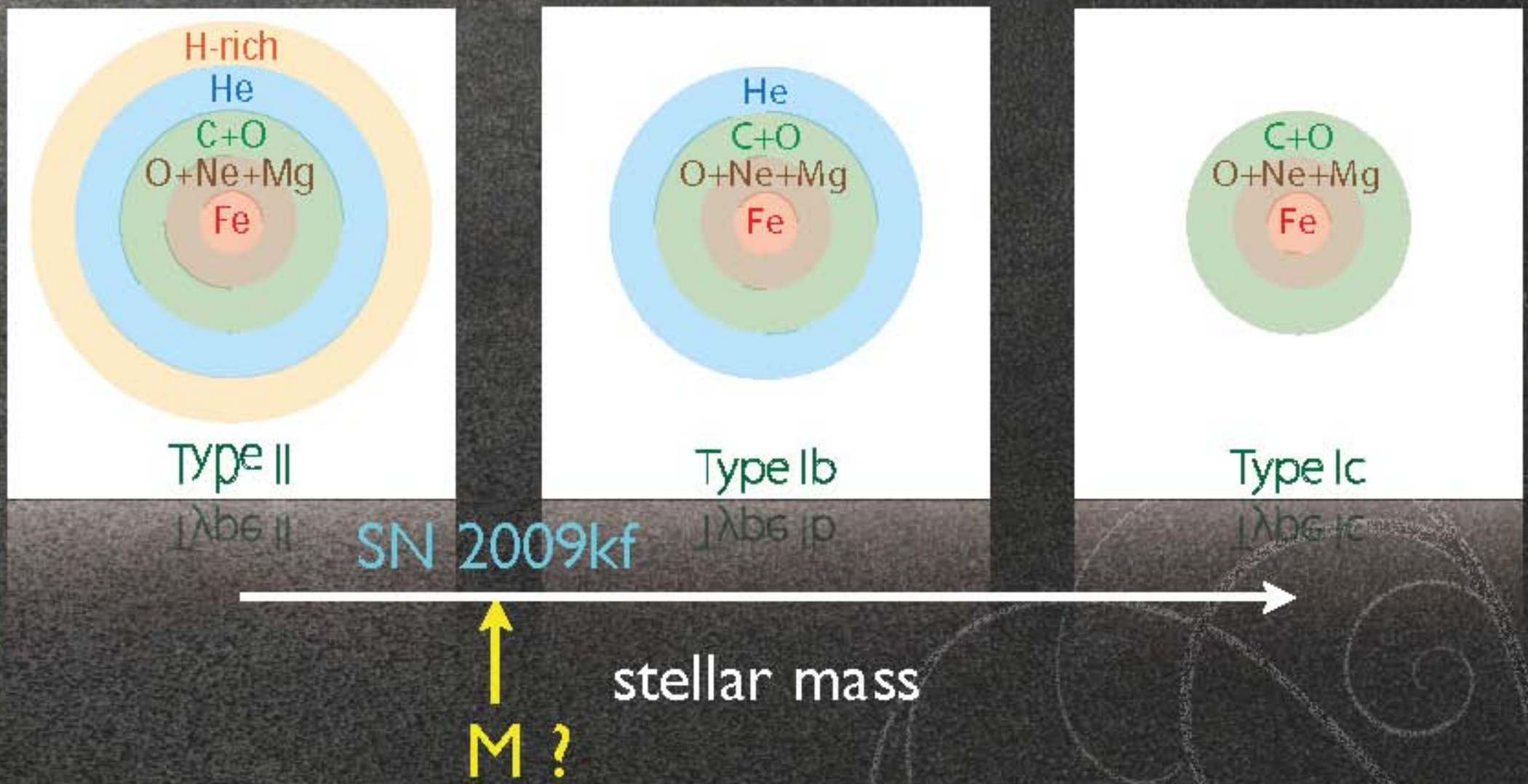
- Consistent with SN ejecta + CSM model



- Progenitor inside
  - s15
  - 3×10^{51} erg
- CSM
  - $\rho \propto r^{-2}$
  - 2×10^{15} cm
  - $10^{-2}\ M_\odot\ \mathrm{yr}^{-1}$ $(0.65\ M_\odot)$

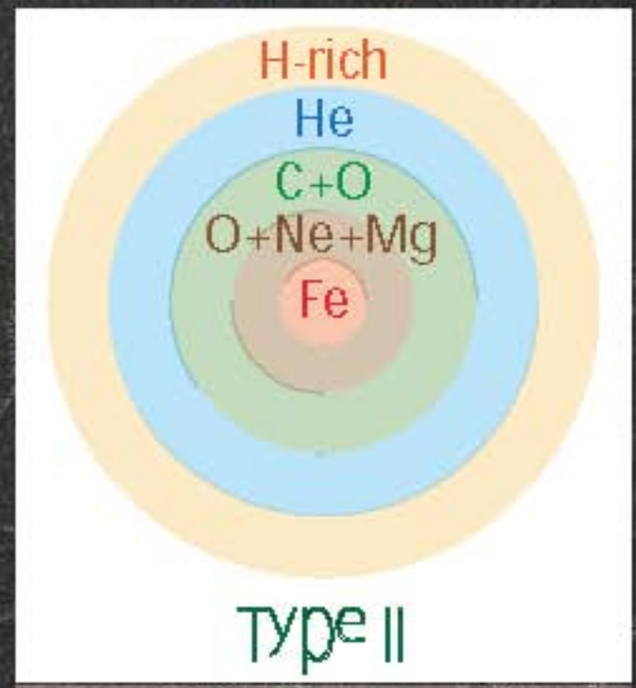
Progenitor is Massive!

- SN 2009kf: explosion energy is extremely high
  - Massive RSGs = Energetic Type II SNe (Hamuy 2003)



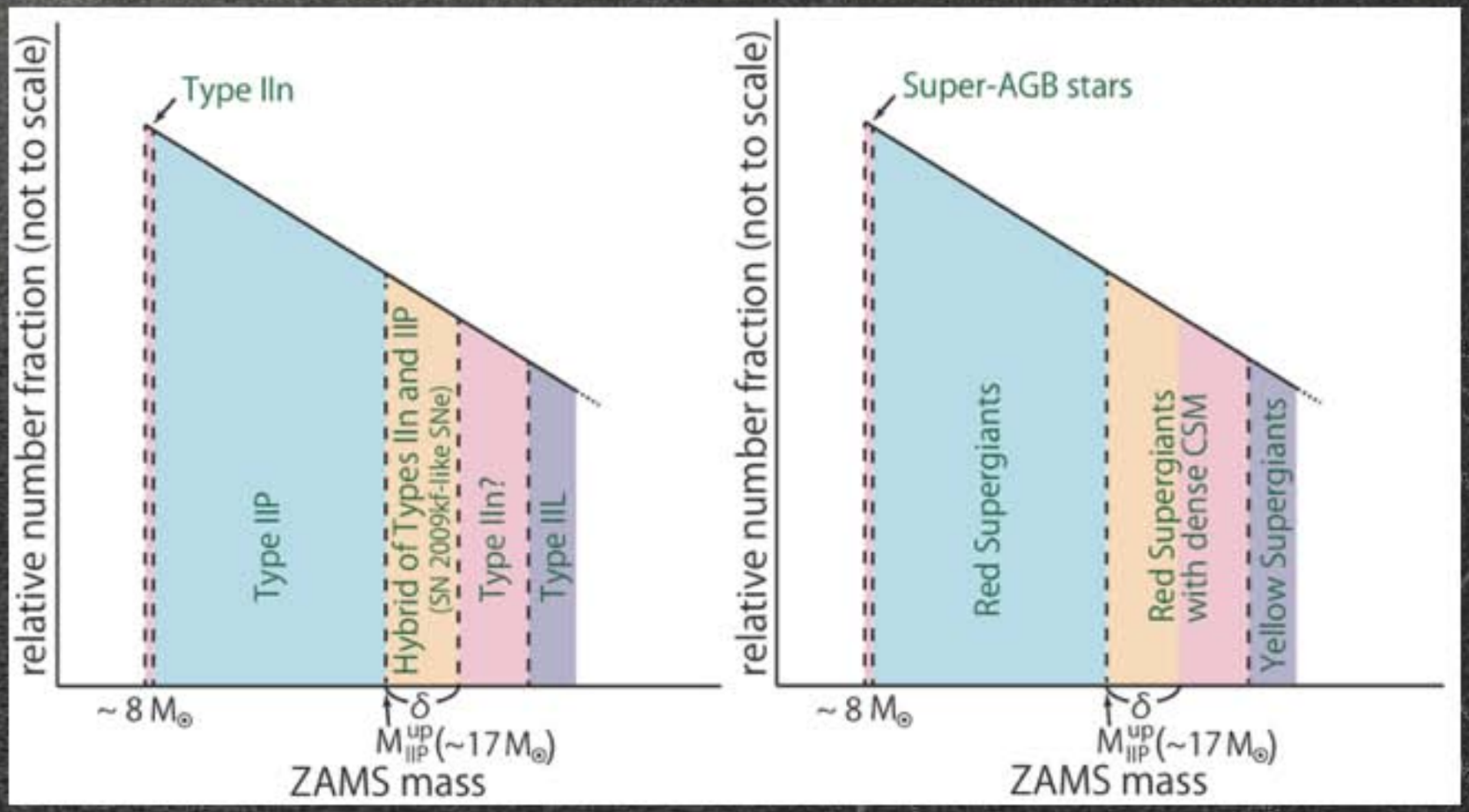
Possible Interpretation

- SN 2009kf is affected by dense CSM
  - Extensive mass loss just before the explosion?
  - Model suggests $10^{-2}\ M_\odot\ \mathrm{yr}^{-1}\,(0.65\ M_\odot)$
- SN 2009kf can be very massive RSGs
  - Close to the high mass end of Type IIP SNe?



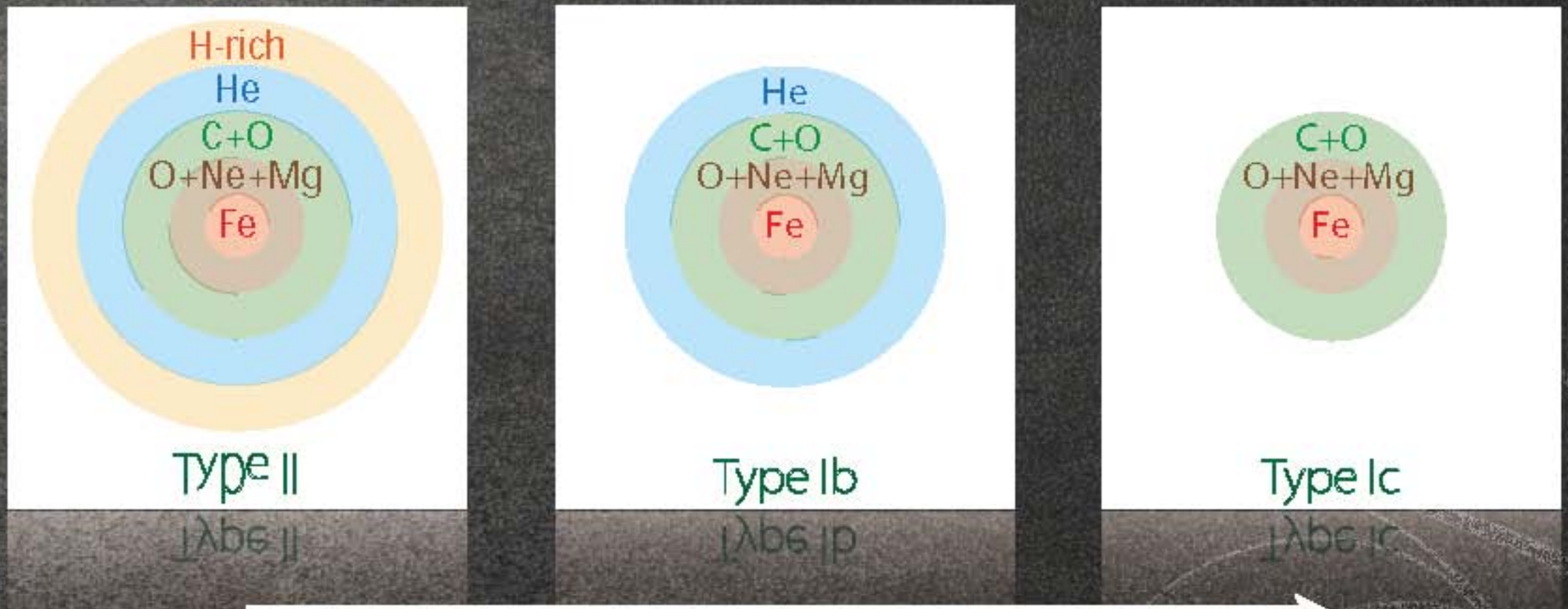
Key: Extensive Mass Loss

- Pulsational instability driven mass loss?
  - Suggested to work with massive RSGs (e.g., Heger+ '97)
  - For RSGs heavier than ~ 17 Msun (Yoon & Cantiello 2010)
    - Consistent with observations



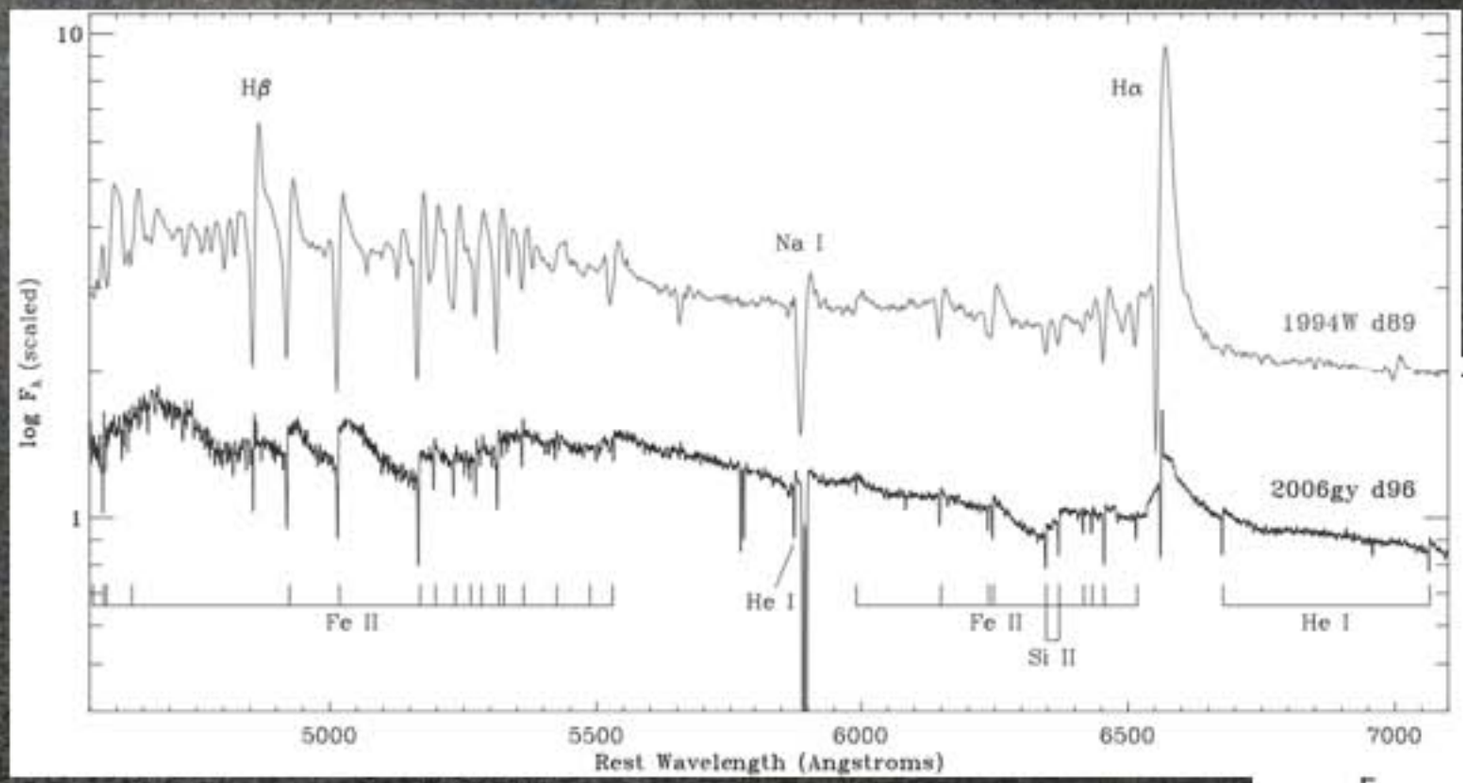
Type IIn Supernovae from Very Massive Stars

Type IIn Supernovae

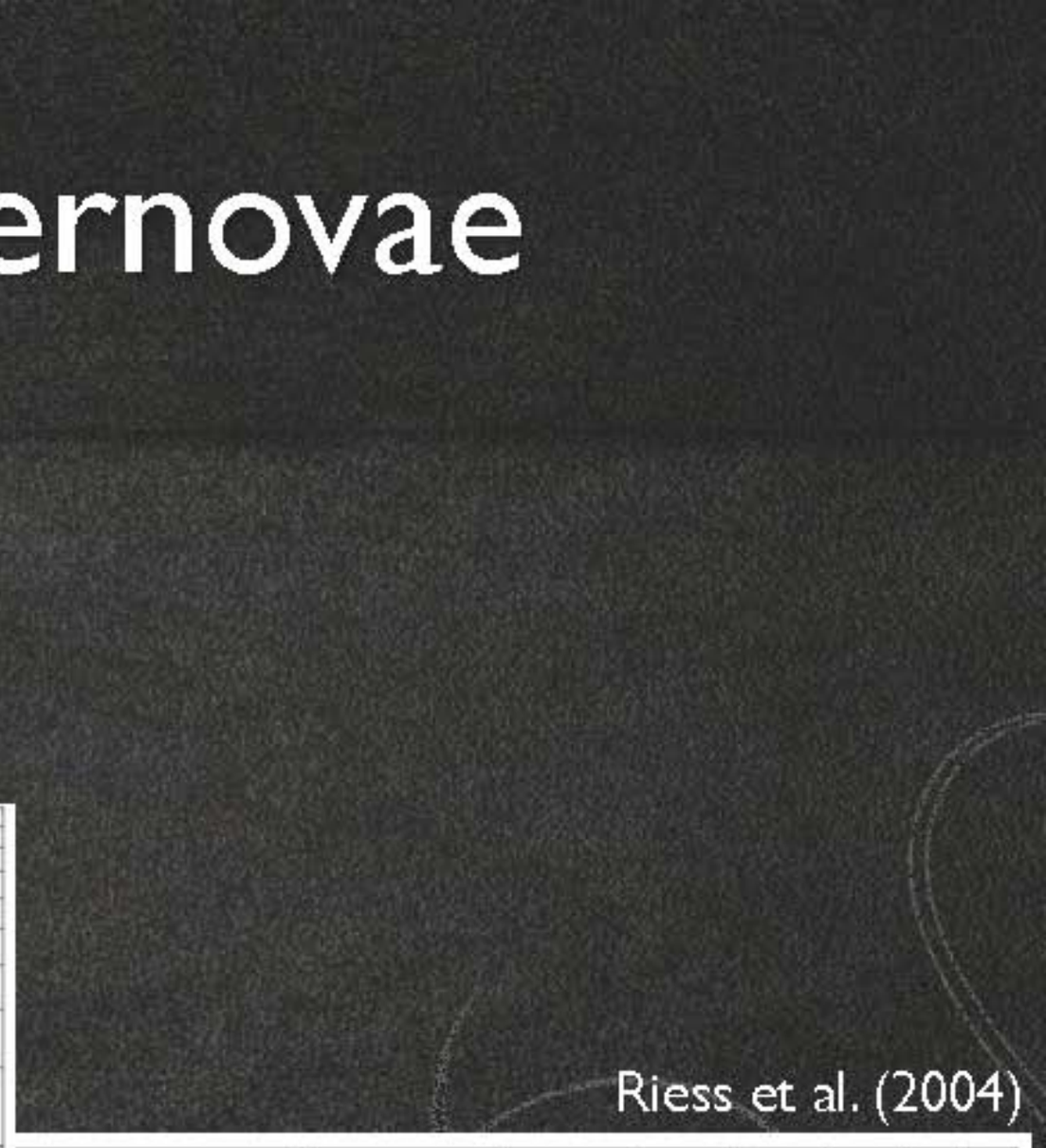


Type IIn Supernovae

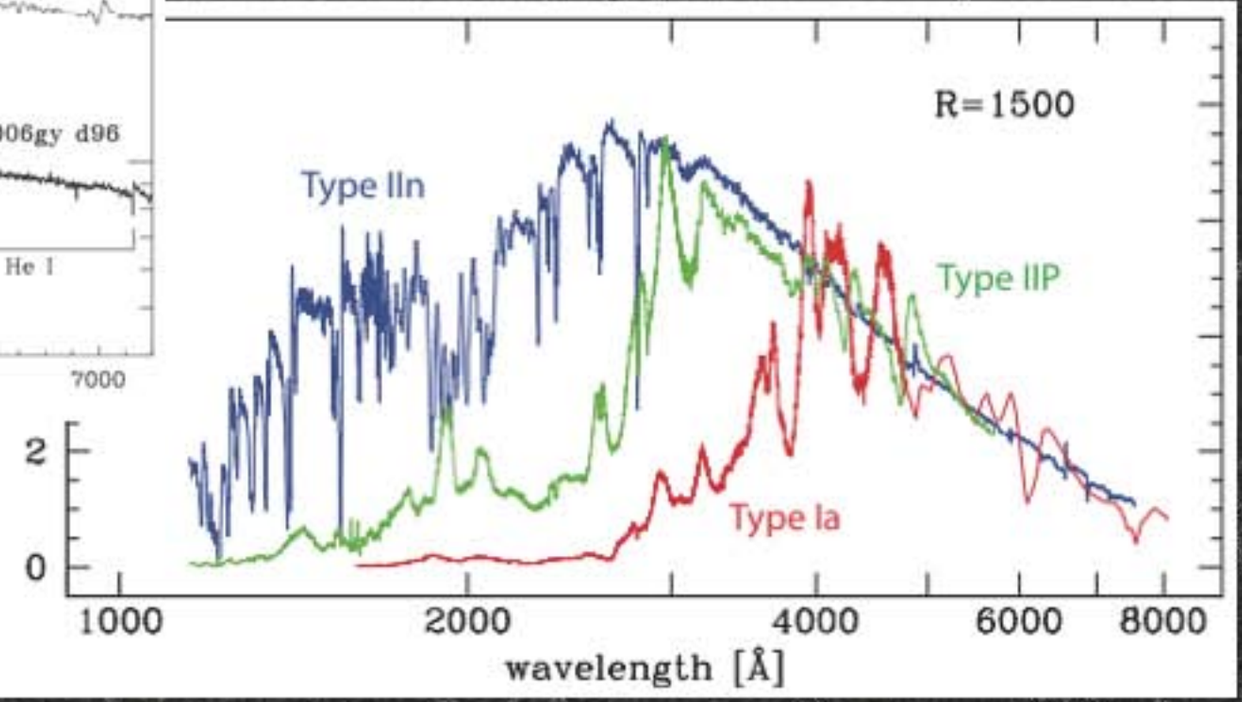
- P-Cygni profile (~ 100 km/s) of CSM
  - Type IIn



Smith et al. (2010)

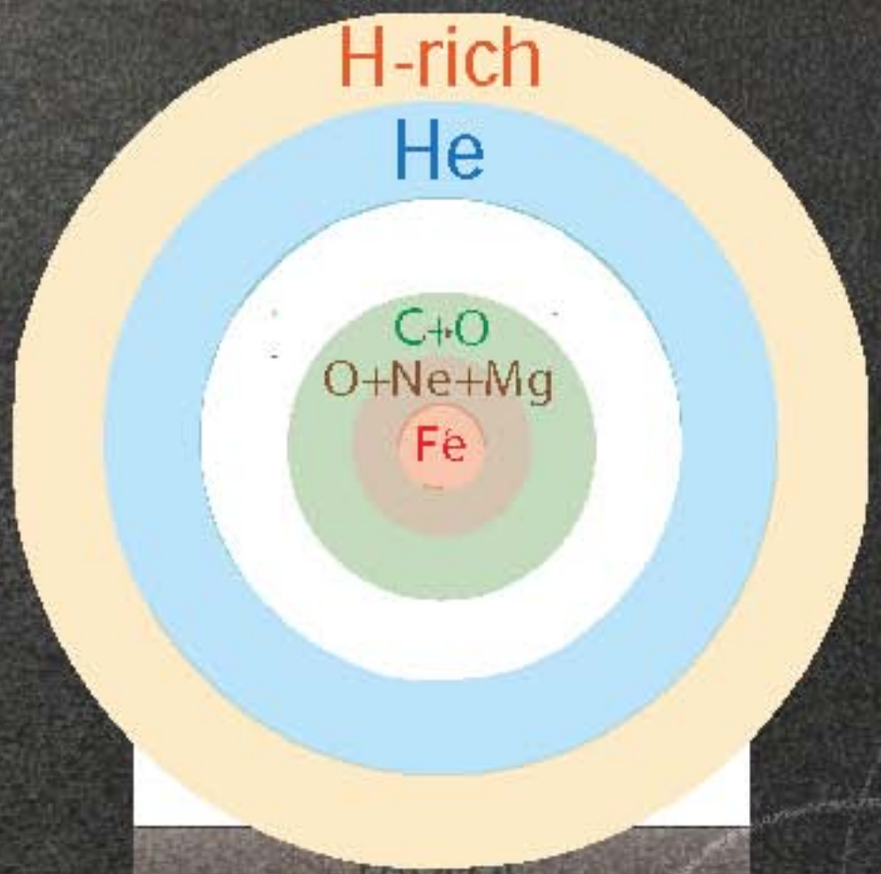


Riess et al. (2004)



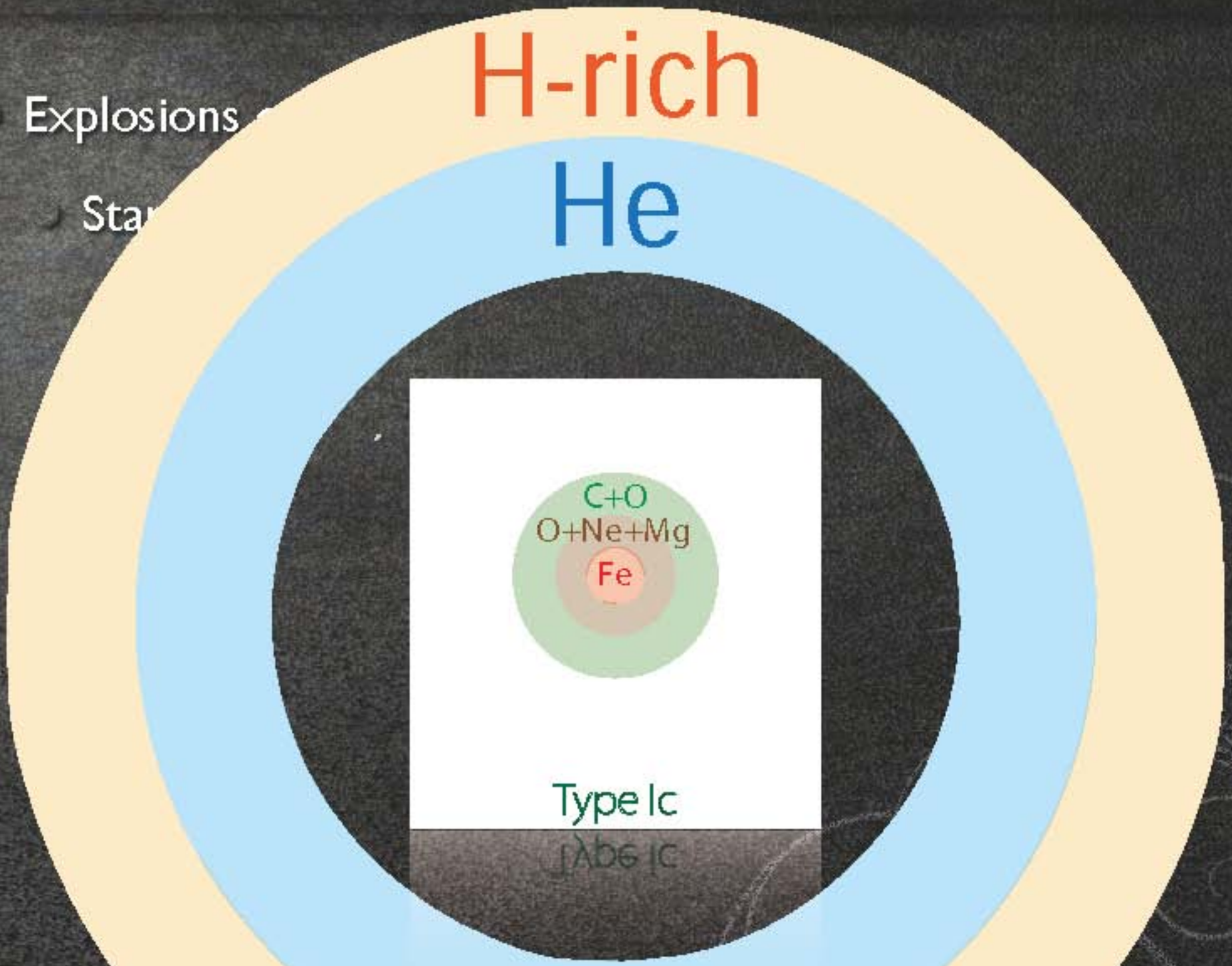
Explosions of very massive stars

- Explosions of Luminous Blue Variables (LBVs)
  - Stars heavier than ~ 80 Msun (Cooke 2008)



Explosions of very massive stars

- Explosions
- Star



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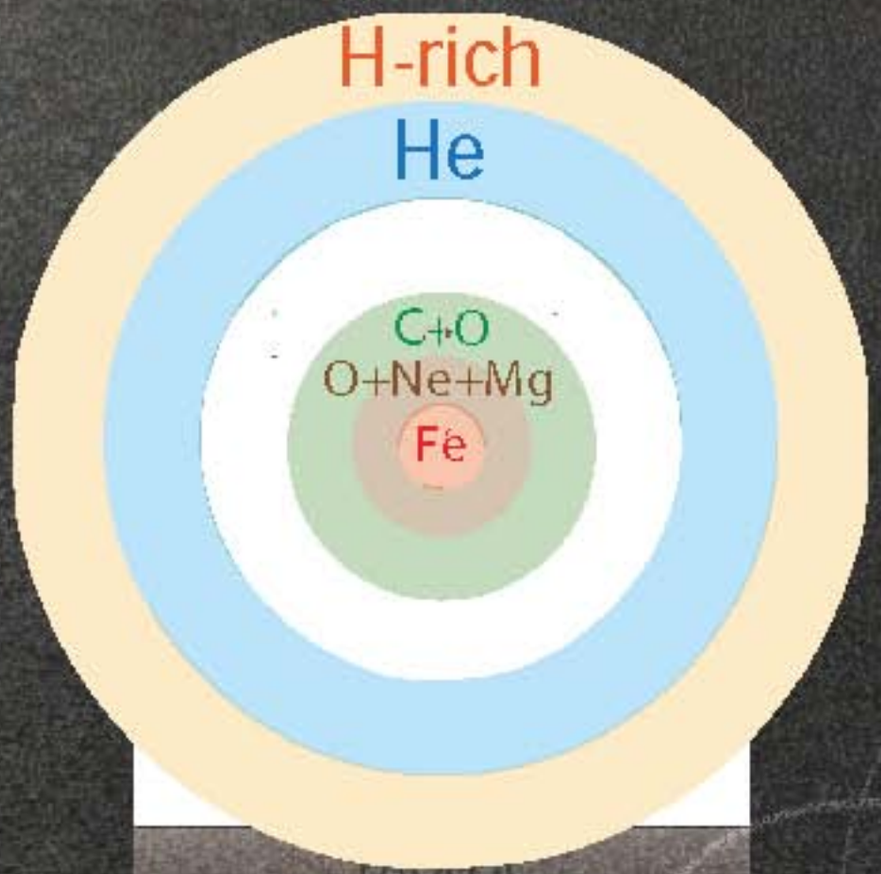
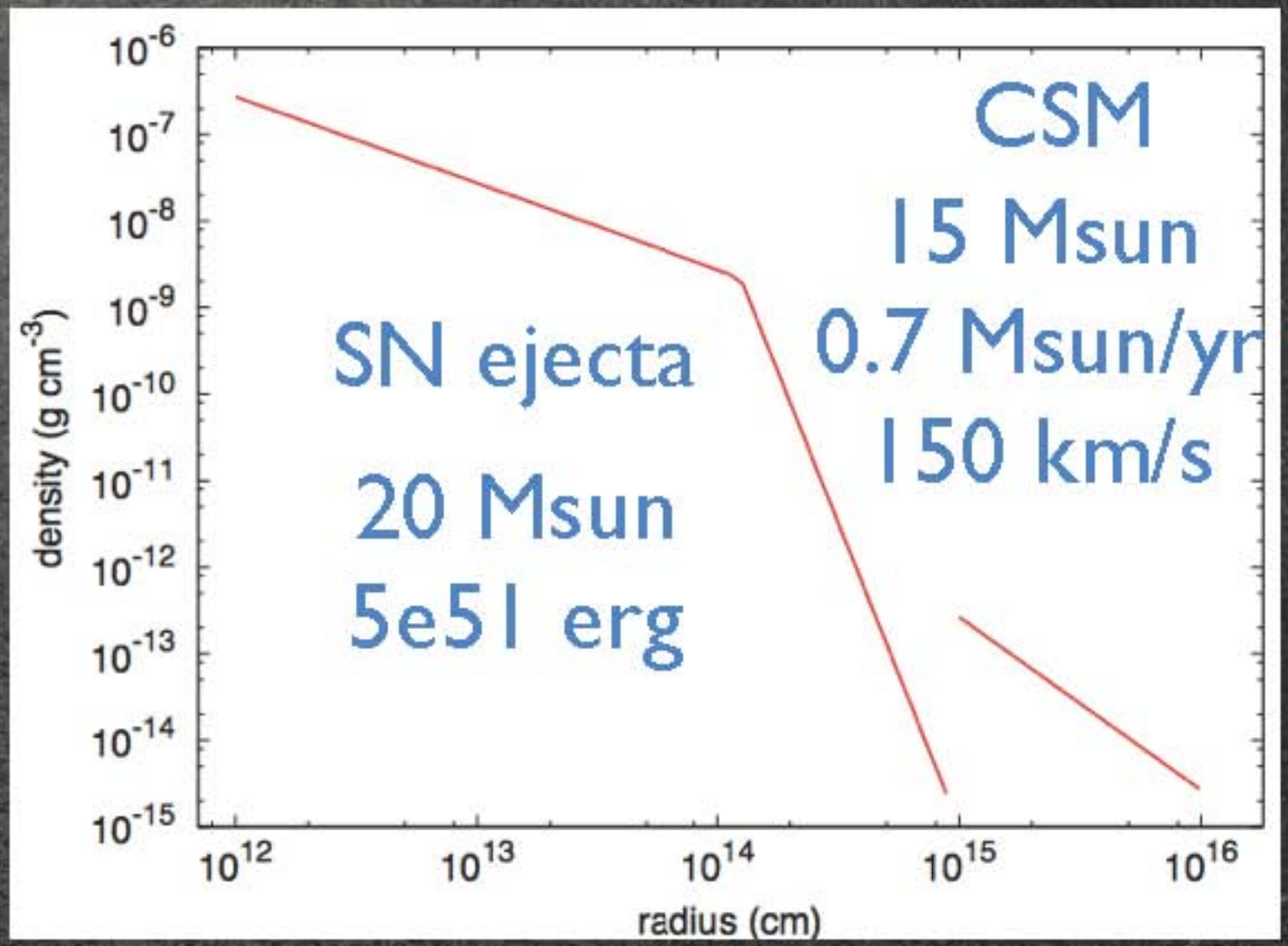
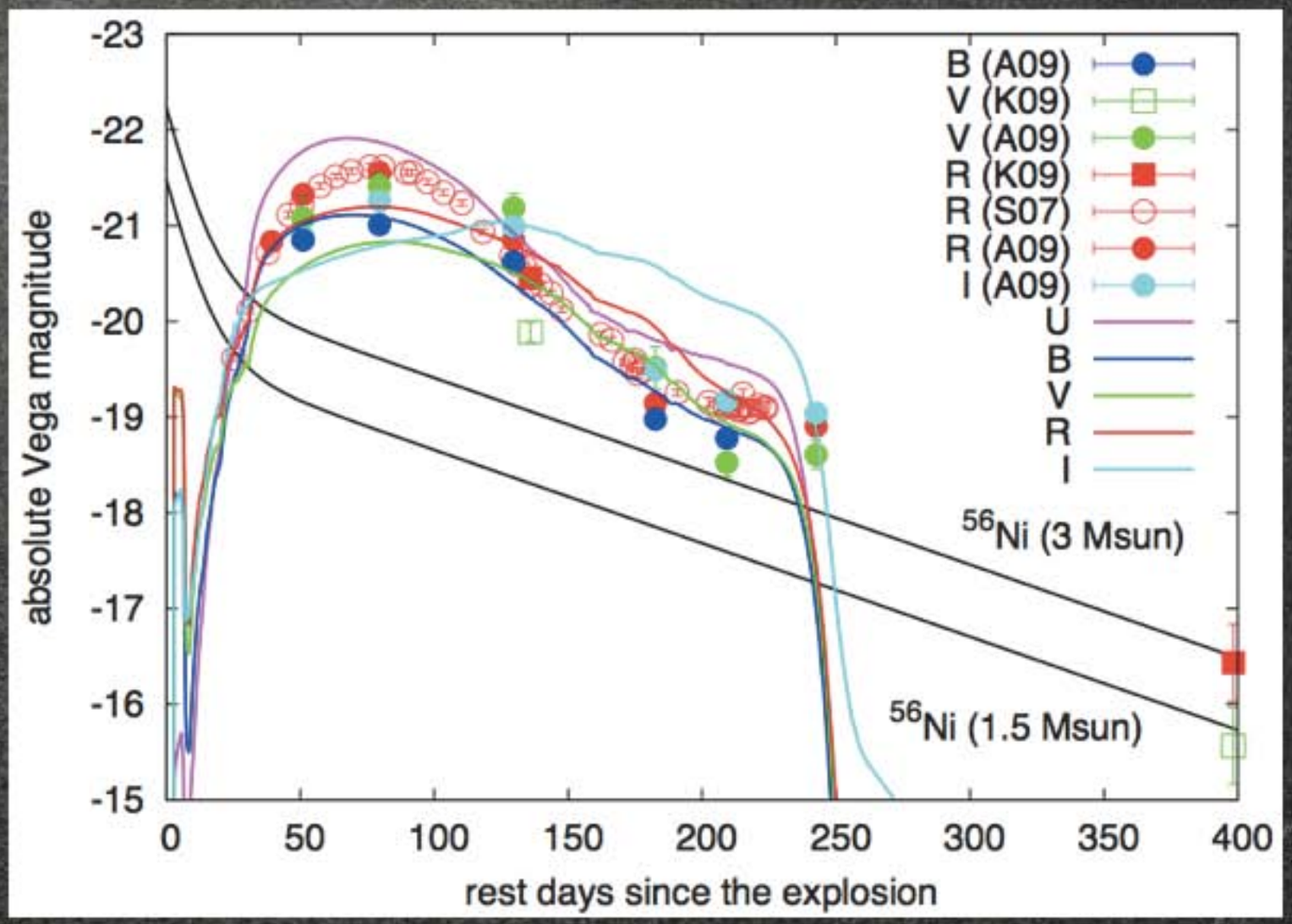


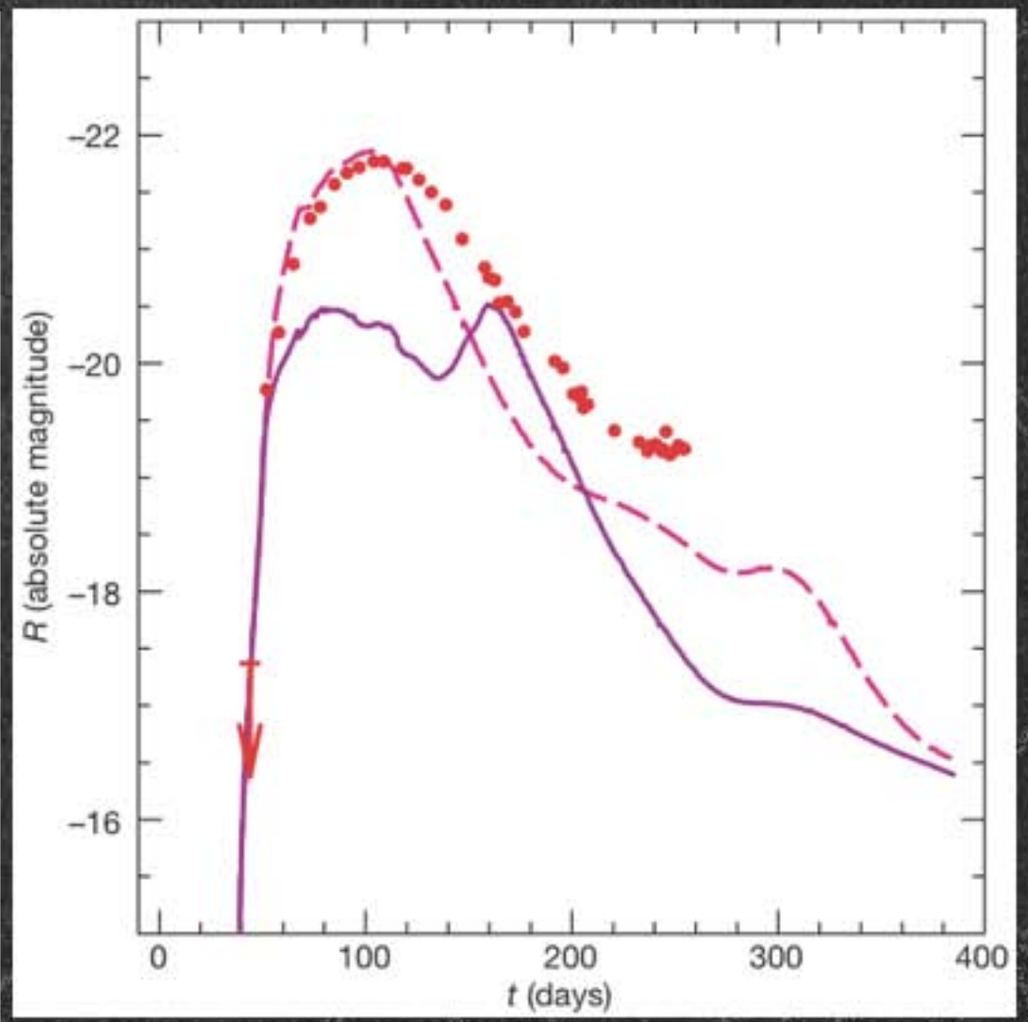
Simple Model



Simple Model

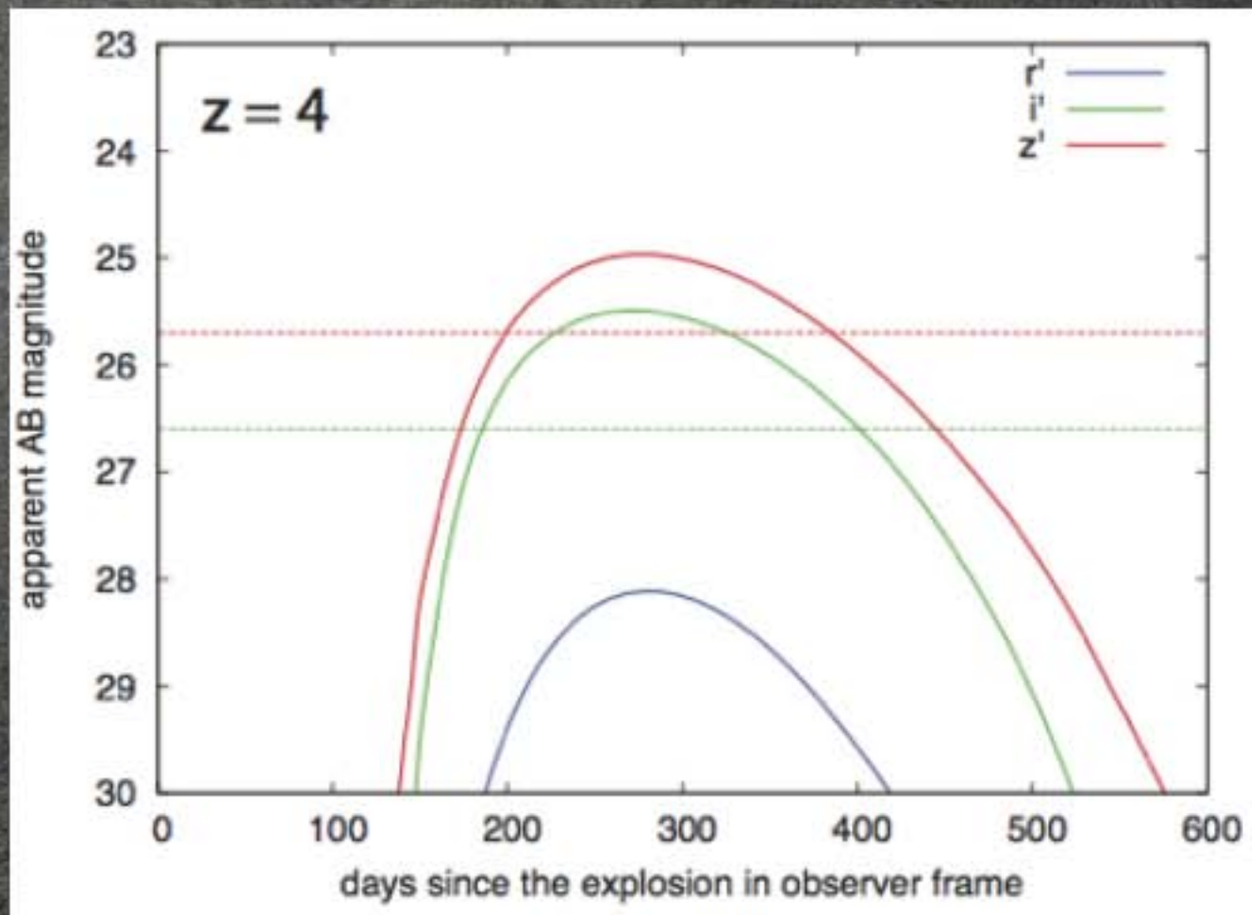
- Comparison with SN 2006gy

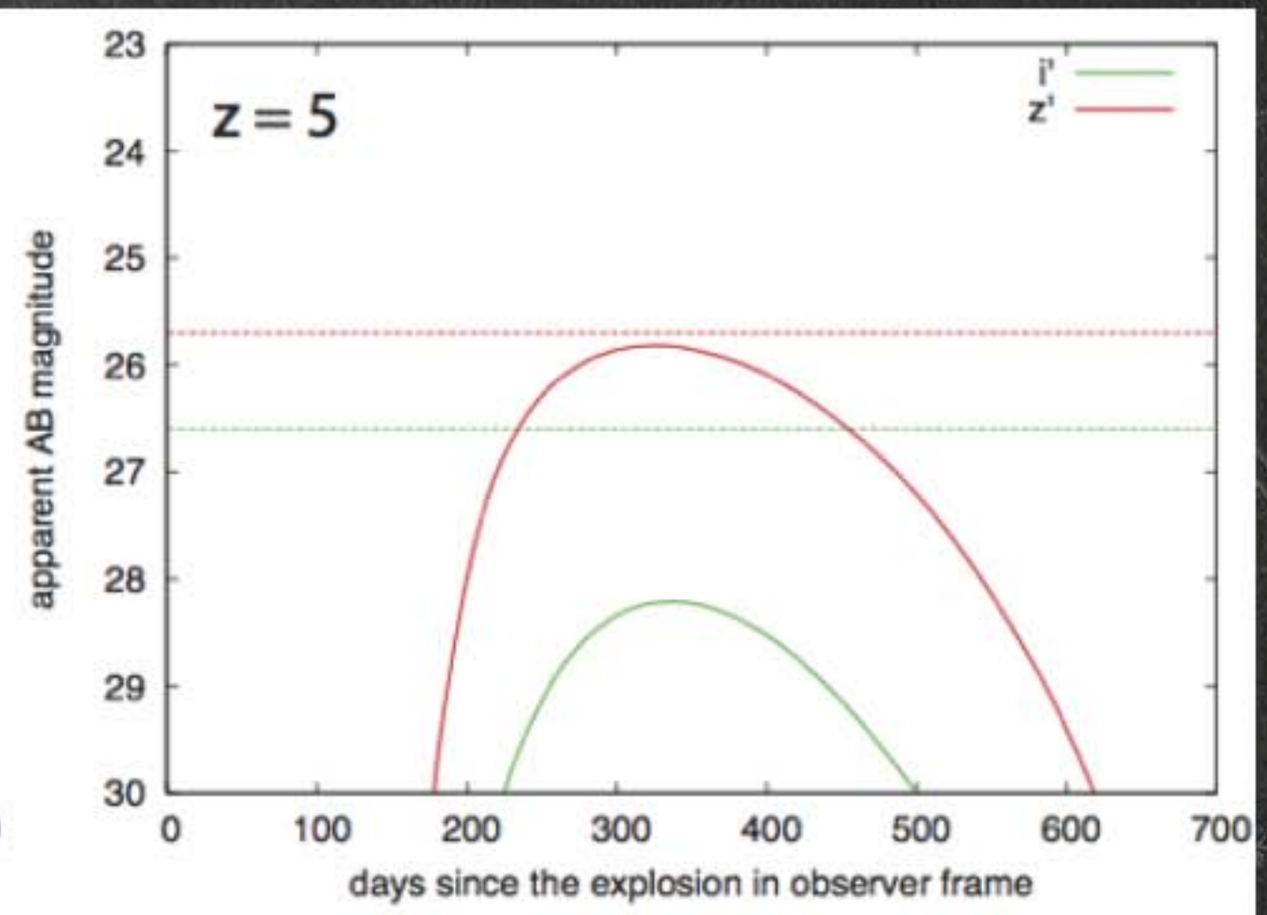




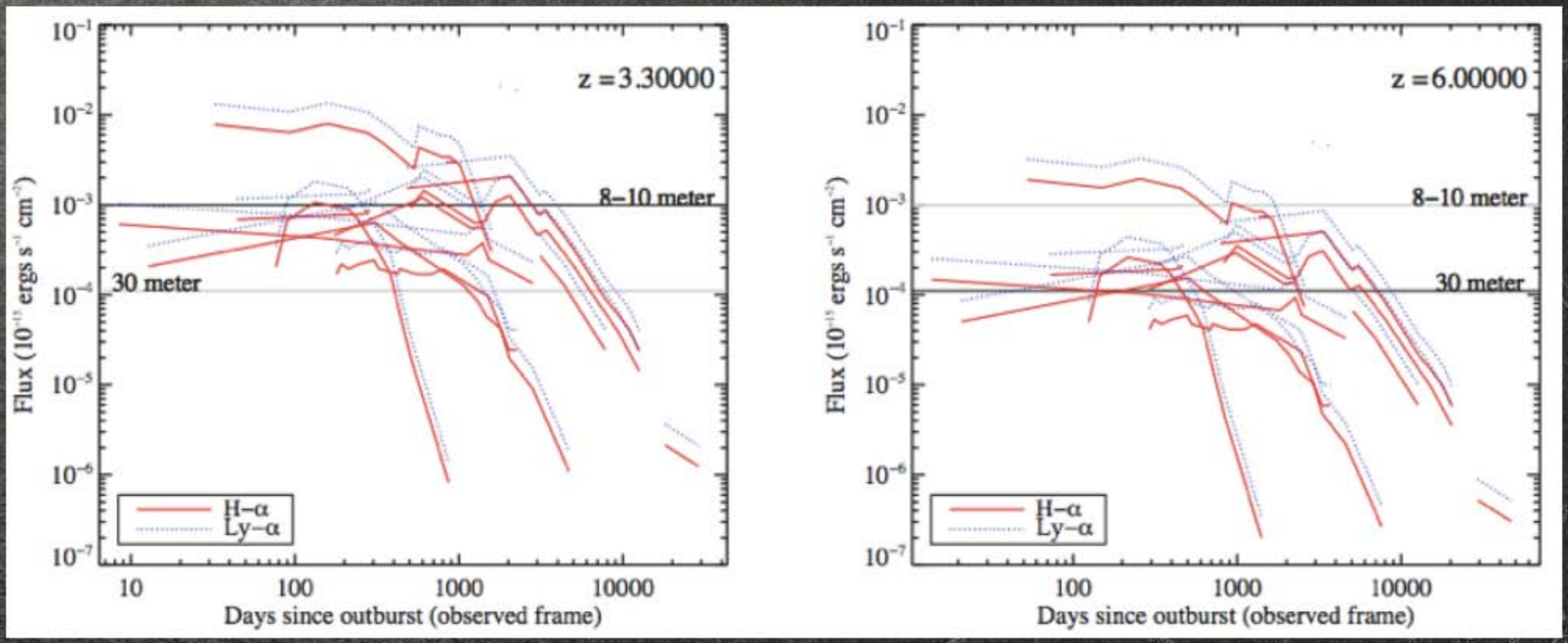
Woosley et al. (2007)

Subaru/HSC


z = 4
r'
i'
z'
apparent AB magnitude
23
24
25
26
27
28
29
30
0
100
200
300
400
500
600
days since the explosion in observer frame


z = 5
i'
z'
apparent AB magnitude
23
24
25
26
27
28
29
30
0
100
200
300
400
500
600
700
days since the explosion in observer frame

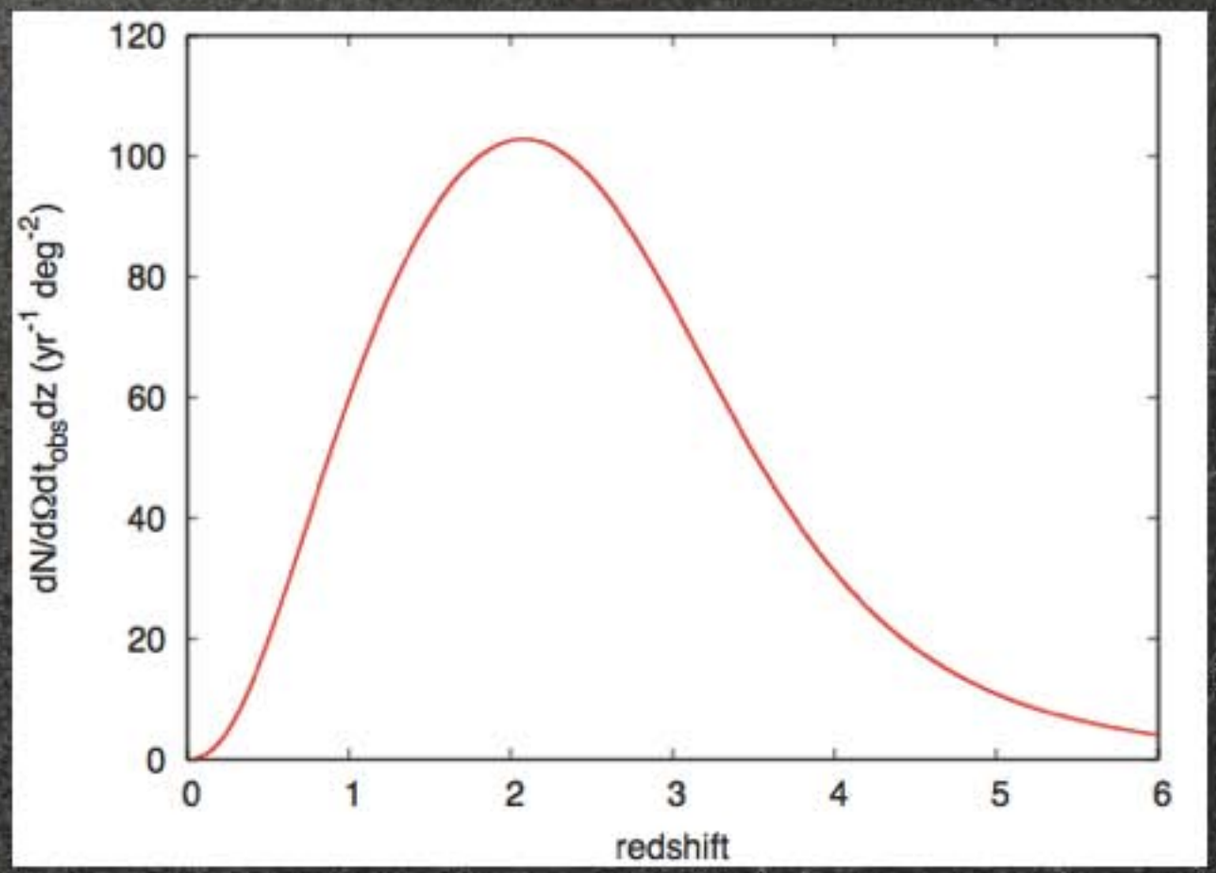
Spectroscopic follow-up



Cooke (2008)

Number Estimation

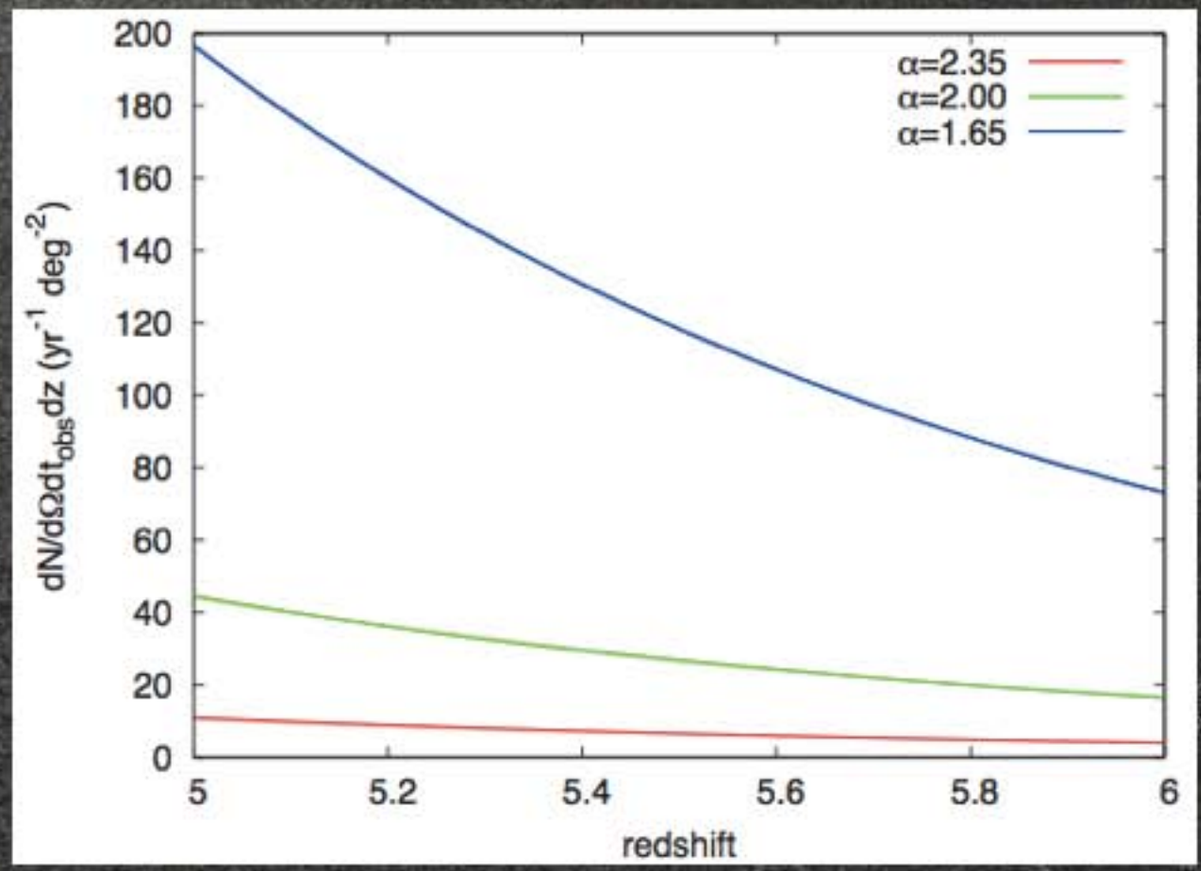
- Mzams > 80 Msun
  - Not all of them are luminous
- Current redshift record for SNe: z=2.36
  - Current HSC survey plan (deep, ultra-deep) can find higher-z one!



SFR:
Hopkins & Beacom (2006)
IMF:
Salpeter

Ultimate Goal

- Top-heavy IMF at the early Universe?
  - Type IIn are from the highest end of IMF
- Requires TMT for spectroscopic confirmation



Summary

- Mass loss is very important key for...
  - understanding the fate of massive stars
    - red supergiants & SN 2009kf
  - revealing the distant Universe
    - CSM makes supernovae luminous & blue
    - good probe for high mass end of the initial mass function