# Light-curve properties of electron-capture SNe

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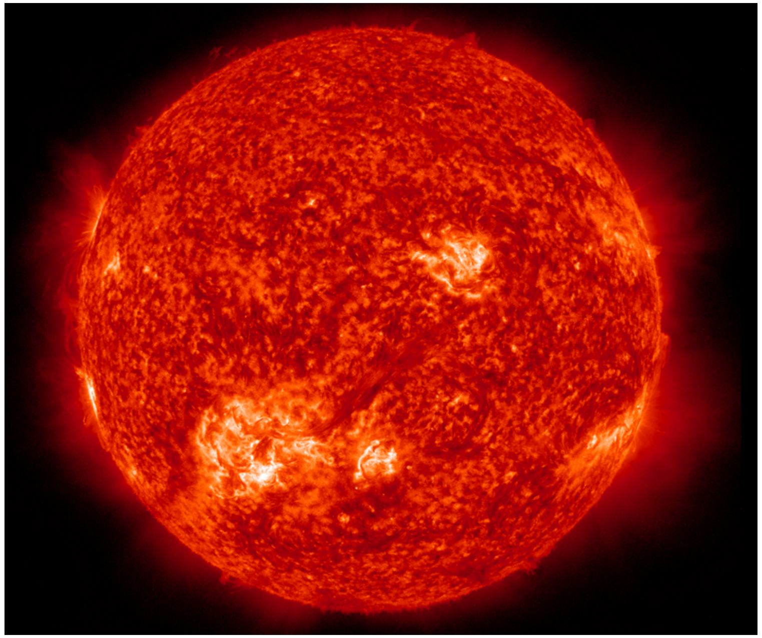
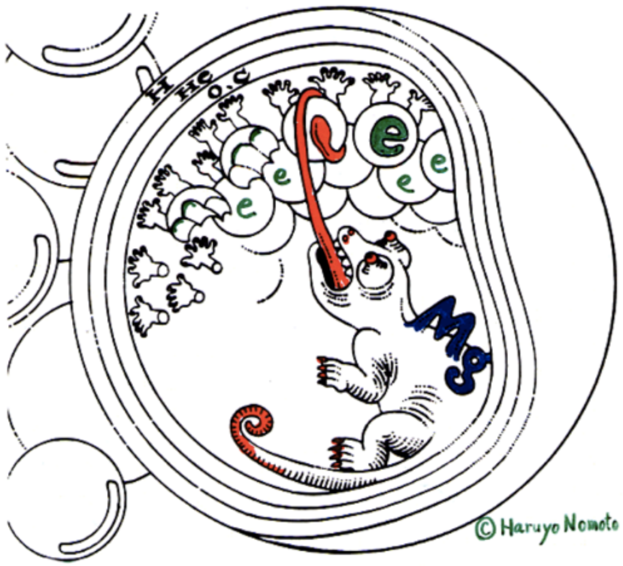
# What determines SN LC properties

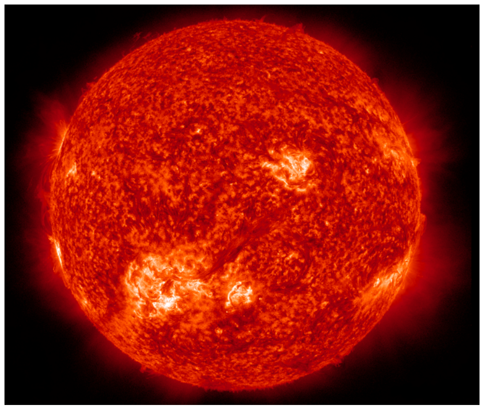
- progenitor properties
  - structure and composition
    - hydrogen-rich envelope mass
  - radius
  - mass-loss rate (CSM density)
- explosion properties
  - explosion energy
  - 56Ni mass





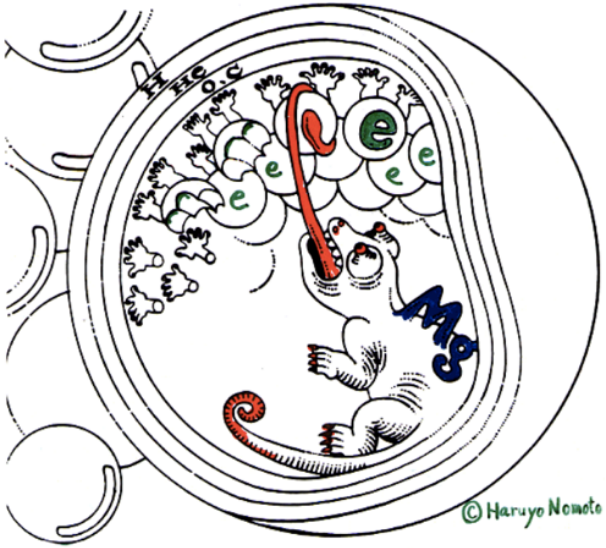
# Super-AGB star properties

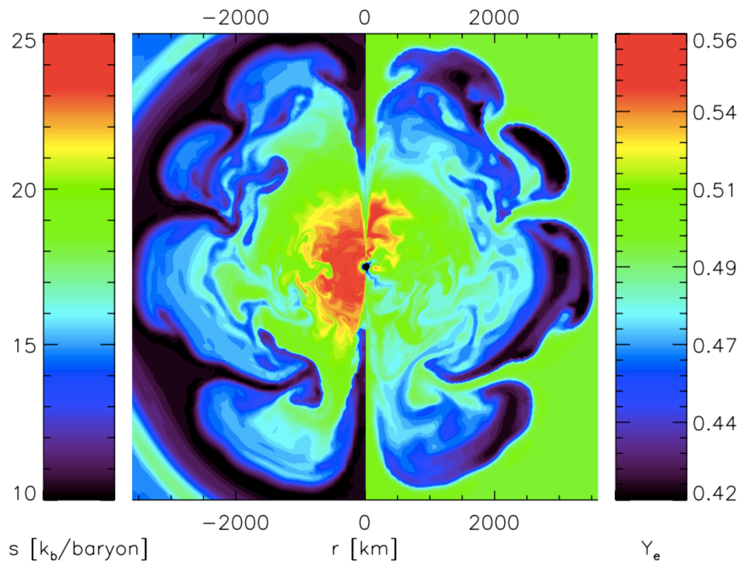
- structure and composition
  - super-AGB stars
  - about 1.37 Msun O+Ne+Mg core + H-rich envelope (several Msun)
  - expected SN type is Type II
- radius
  - about 1000 Rsun
- mass-loss rate
  - ~ 1e-4 Msun/yr with ~ 10 km/s (e.g., Poelarends et al. 2007)
    - wind is dense enough to affect SN properties



# Explosion properties

- explosion energy
  - ~ 1e50 erg
    - in both 1D and 2D neutrino-driven explosion simulations
    - about 10 times less than typical core-collapse SNe
- 56Ni mass
  - ~ 0.001 Msun
    - typical core-collapse SNe have more than about 0.05 Msun




Wanajo et al. (2009)

# Rough estimates for ecSN properties

- roughly 2-5 Msun hydrogen-rich envelope
- small explosion energy
    - presumably observed as Type IIP SNe
    - if explosion energy is high, Type IIL SNe are also possible

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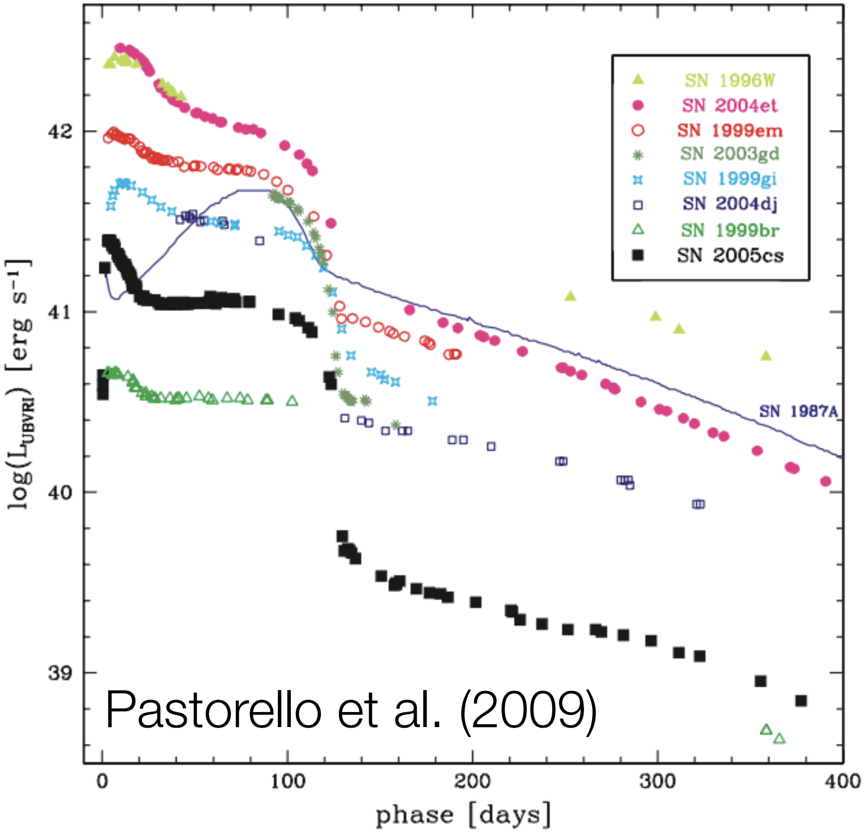
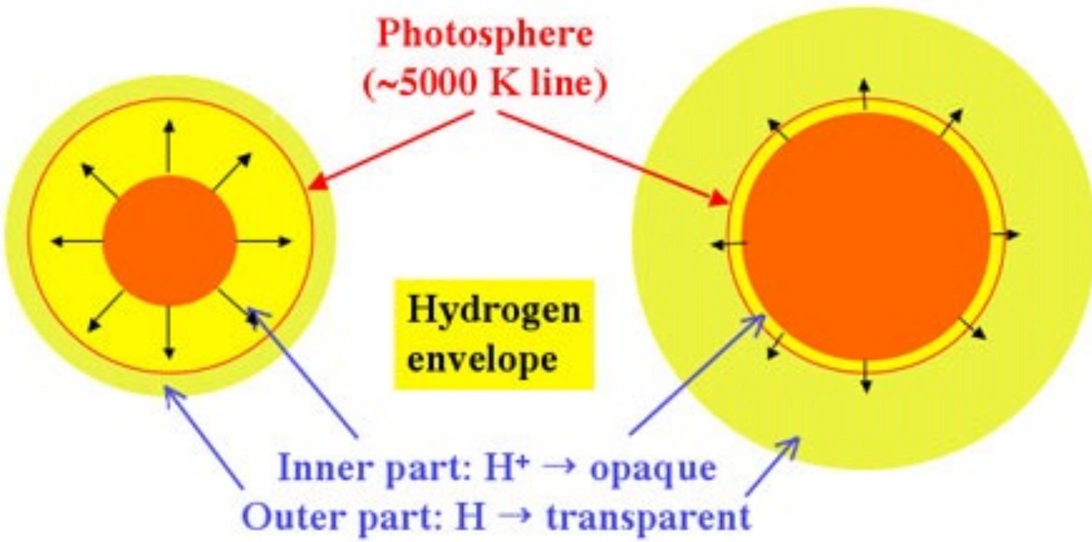


Pastorello et al. (2009)



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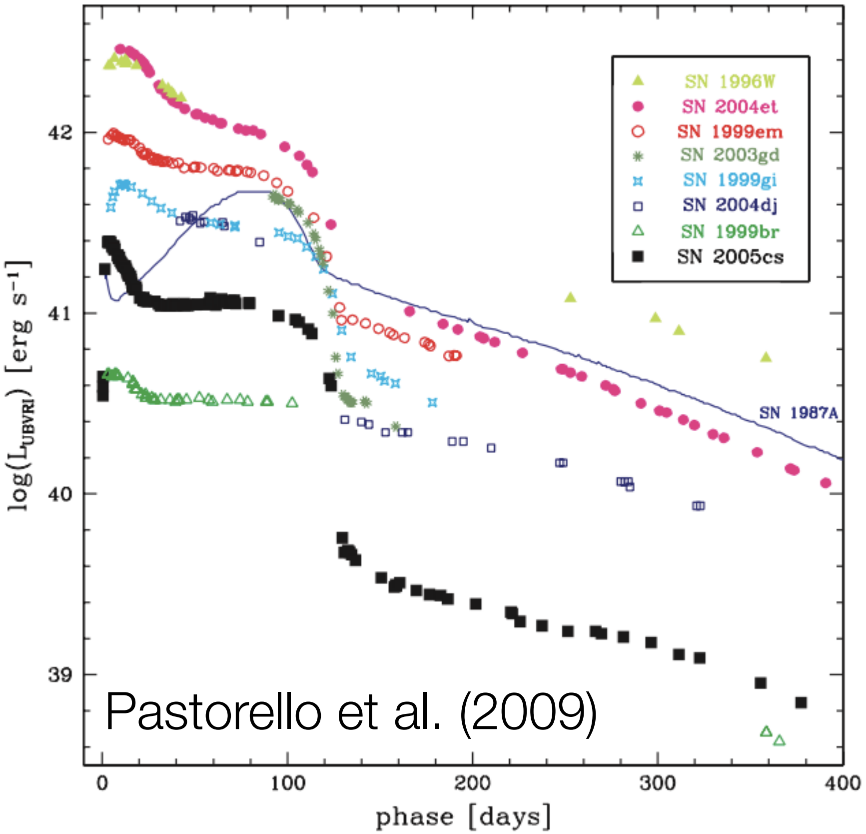


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$$t_{p,0} = 122 E_{51}^{-1/4} M_{10}^{1/2} R_{0,500}^{1/6} X_{\rm He}^{1/2} \text{ days},$$

Kasen & Woosley (2009)

- E = 1e50 erg, Menv = 3 Msun, R = 1000 Rsun, Xhe = 0.5
  - L ~ 3e41 erg/s
  - tp ~ 94 days

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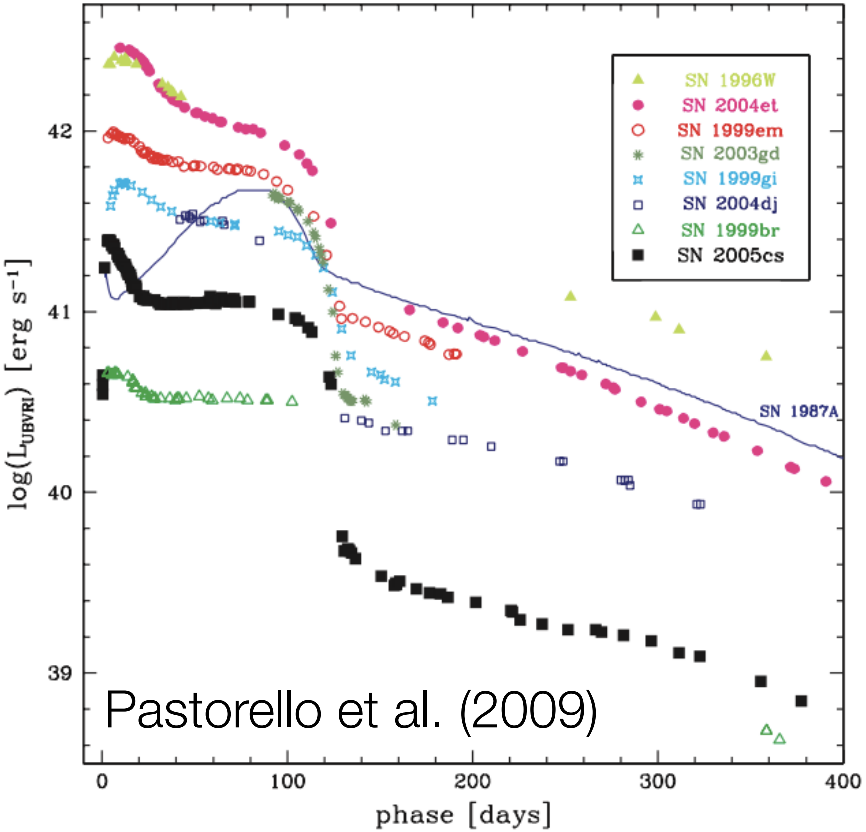


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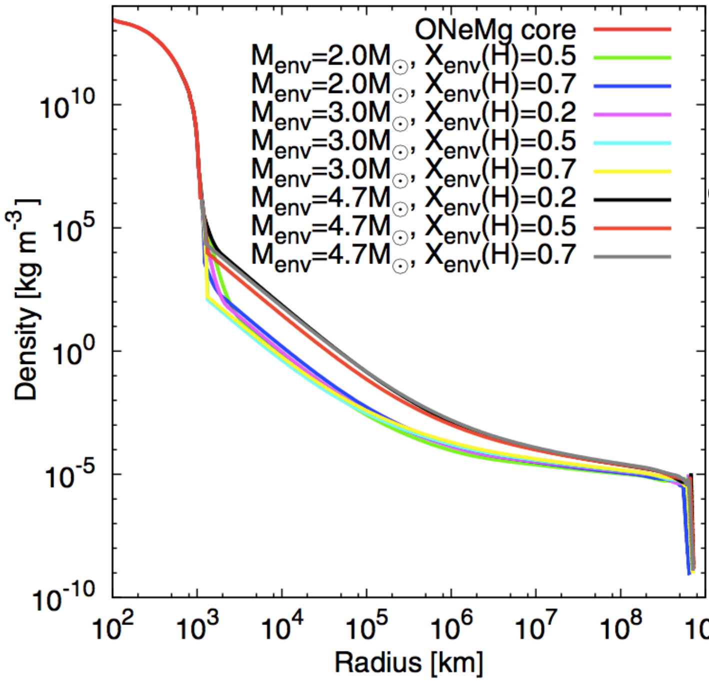
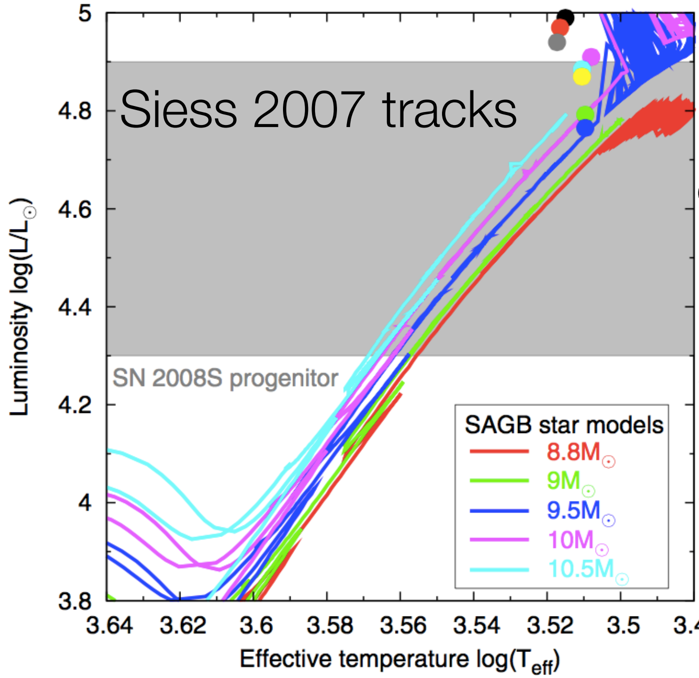
- E = 1e50 erg, Menv = 3 Msun, R = 1000 Rsun, Xhe = 0.5
  - L ~ 3e41 erg/s
  - tp ~ 94 days
- **ecSNe are not very faint!**

# Numerical LC investigation

- radiation hydrodynamics code STELLA (Blinnikov et al.)
  - one-dimensional
  - rough SED can be obtained
  - SN ejecta + dense wind interaction can be treated
- progenitor
  - Nomoto 1.377 Msun O+Ne+Mg core + several envelopes



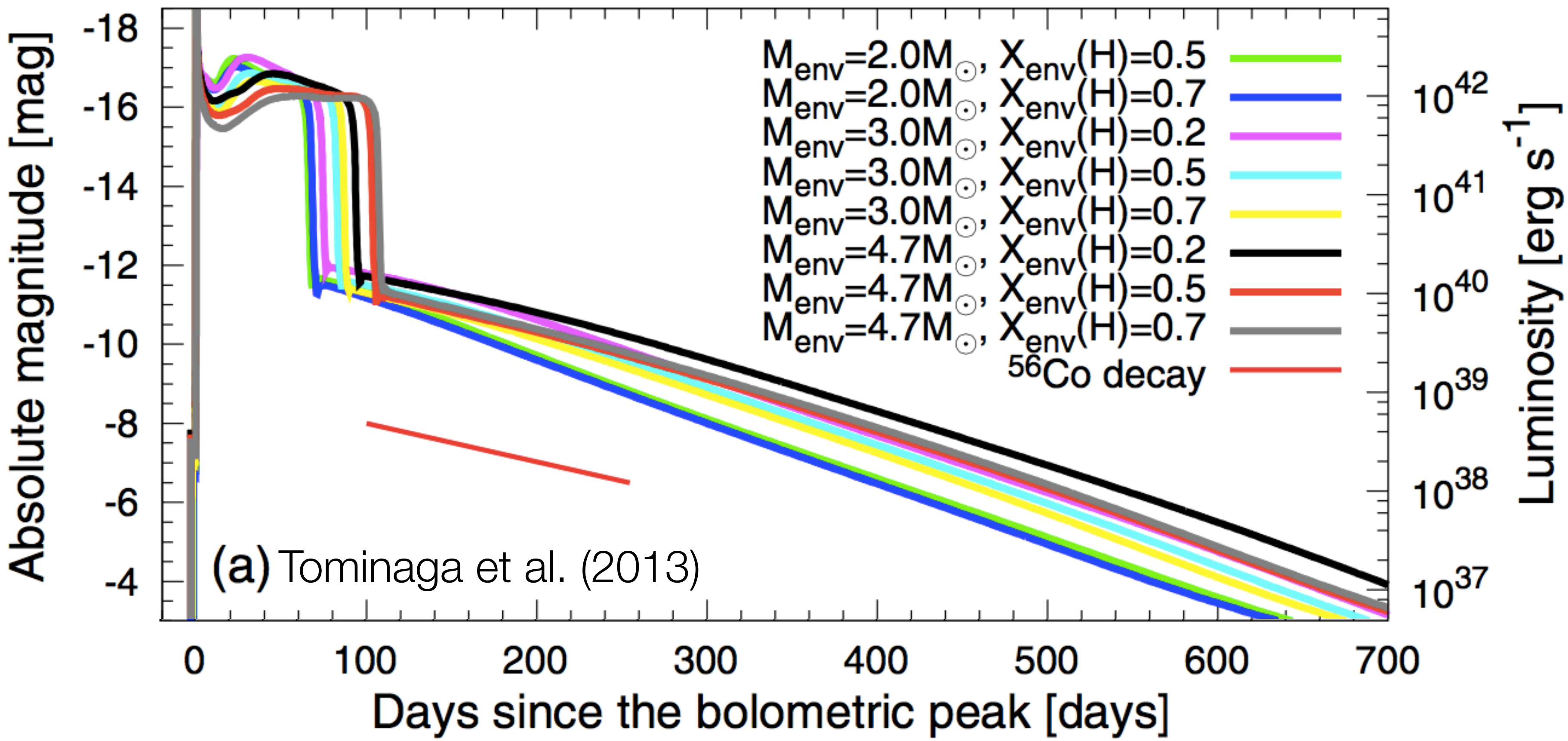

Tominaga et al. (2013)




Tominaga et al. (2013)

# Numerical ecSN LCs without CSM interaction

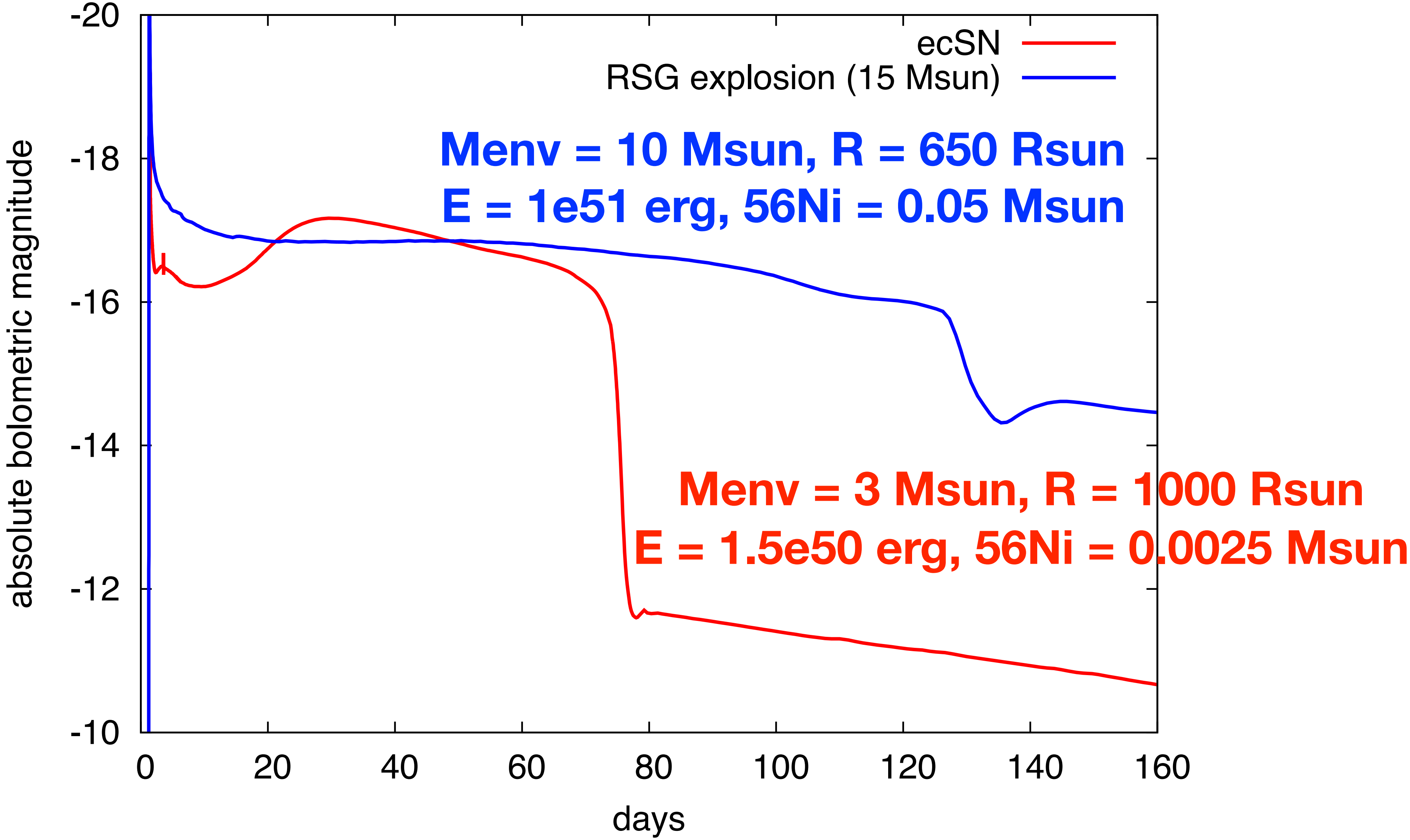
- explosion energy: 1.5e50 erg (Kitaura et al. 2006)
- 56Ni mass: 0.0025 Msun (Wanajo et al. 2009)




- rough analytic estimate: L ~ 3e41 erg/s, tp ~ 97 days
  - difference in density structure

# Numerical ecSN LCs without CSM interaction

- comparison with a RSG explosion



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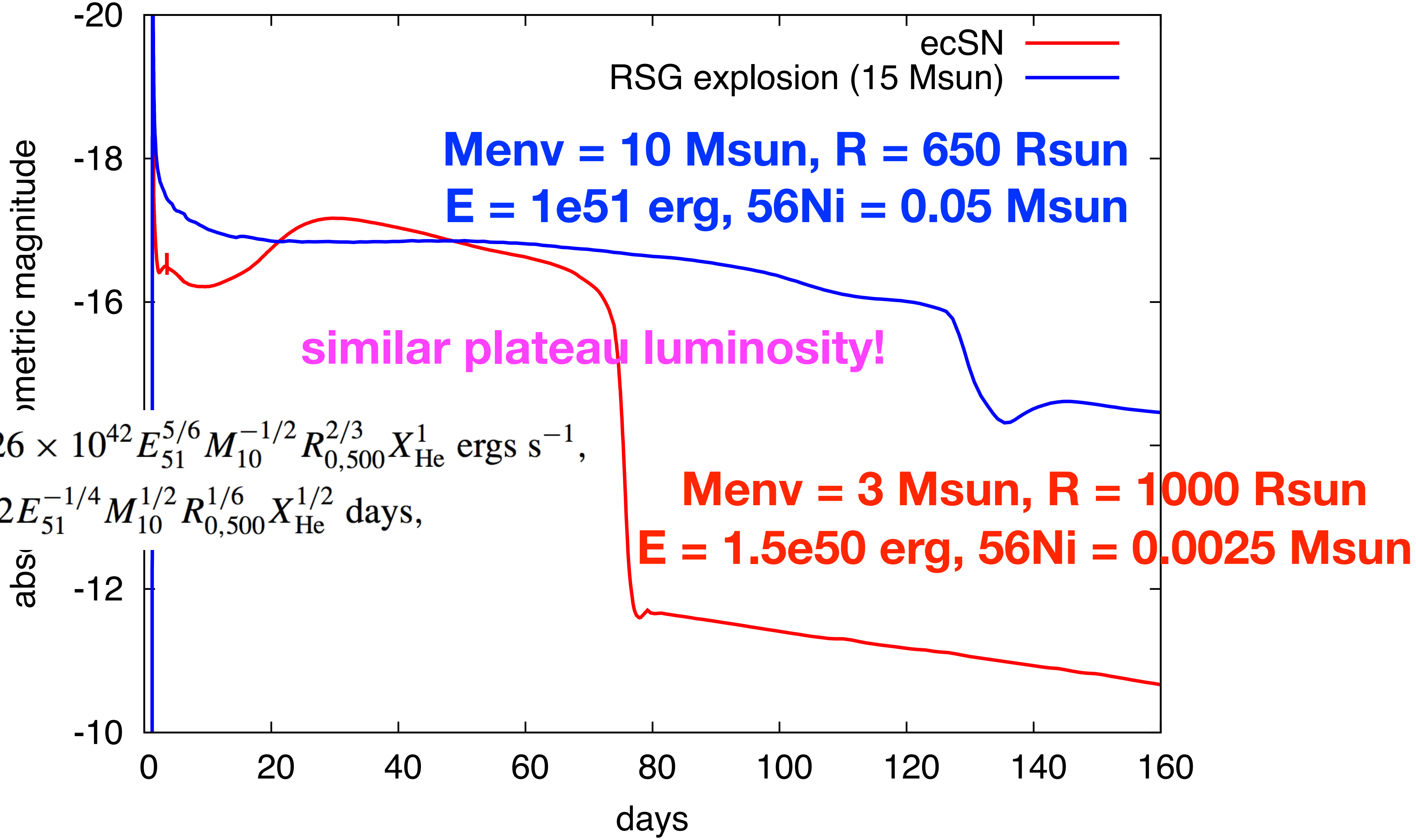


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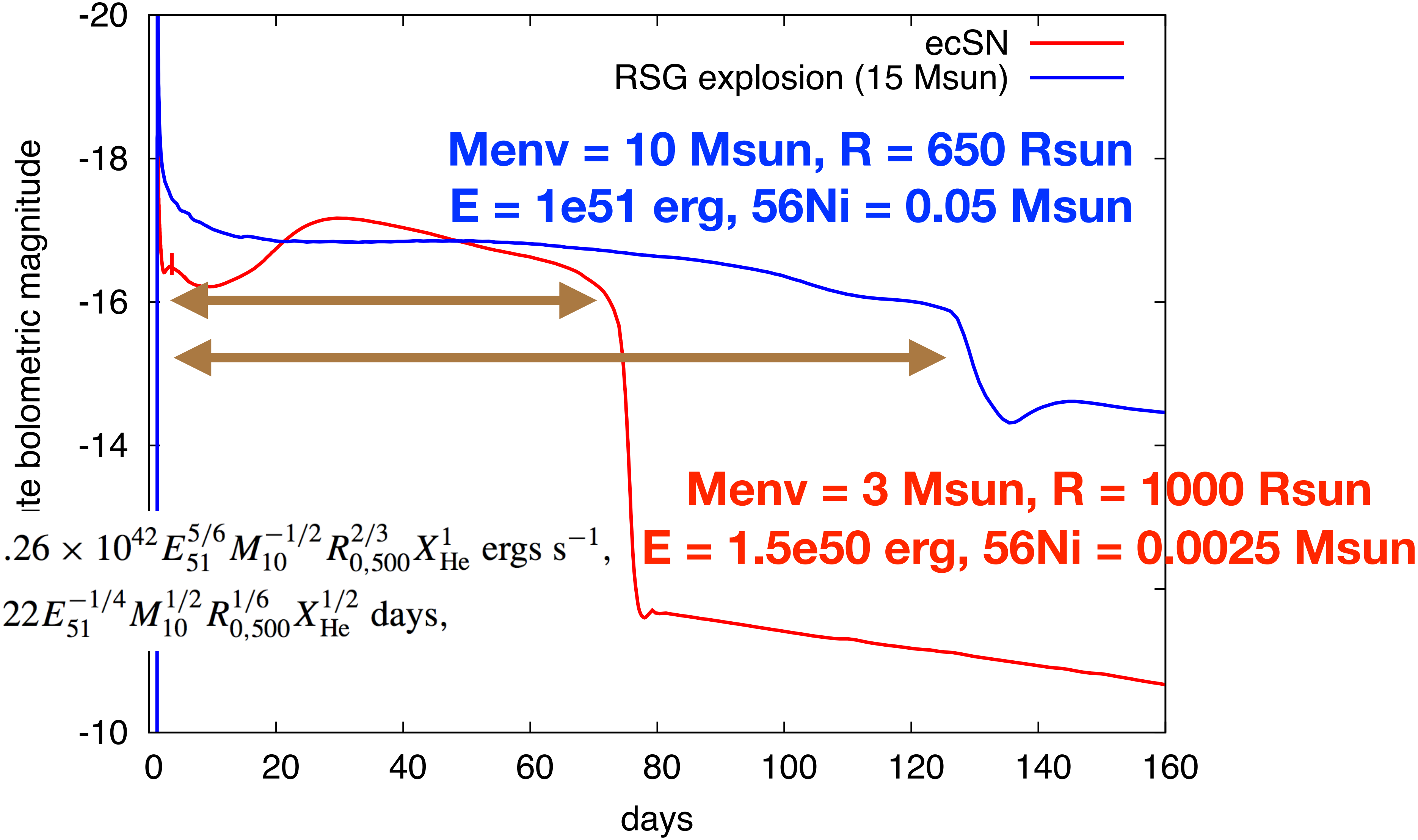


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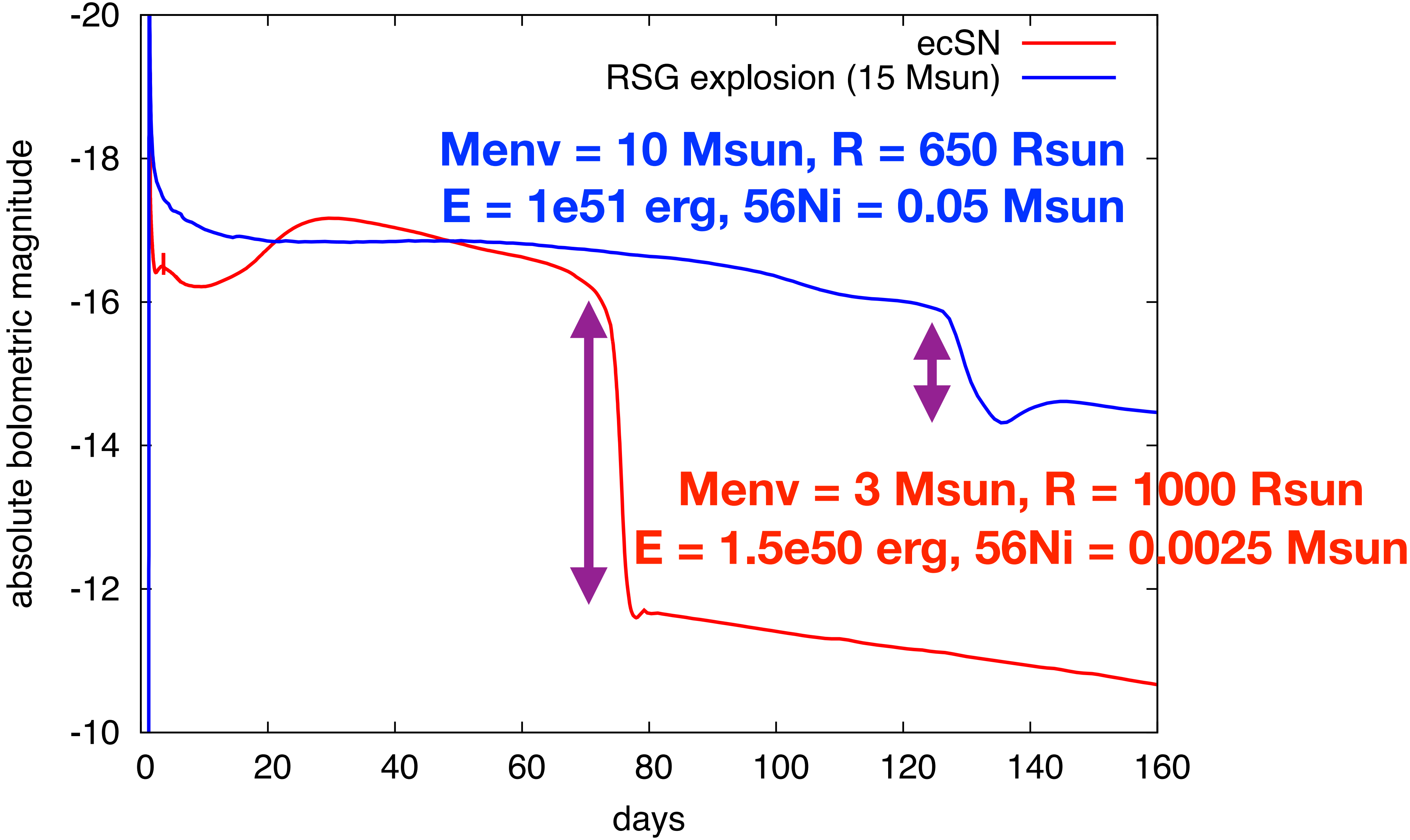
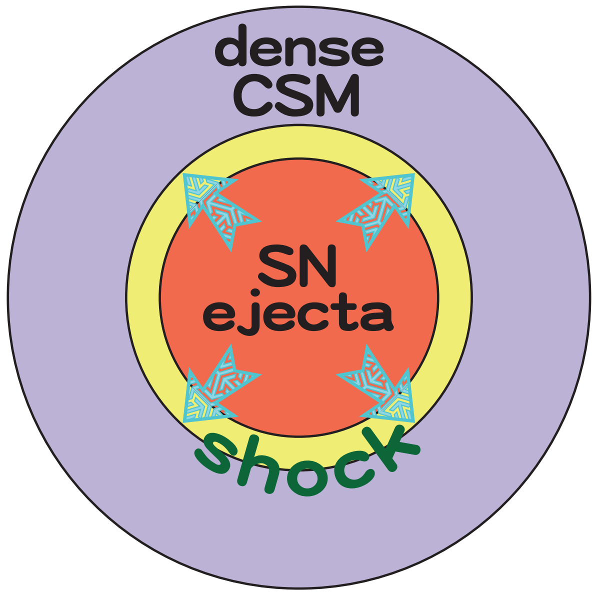


# Dense super-AGB wind affects late-phase LCs

- wind properties of super-AGB stars
  - ~ 1e-4 Msun/yr with ~ 10 km/s
- typical estimated wind properties of Type IIn SNe
  - ~ 1e-3 Msun/yr with ~ 100 km/s

$$\rho_{\rm csm}(r) = \frac{\dot{M}}{4\pi v_{\rm wind}} r^{-2}$$



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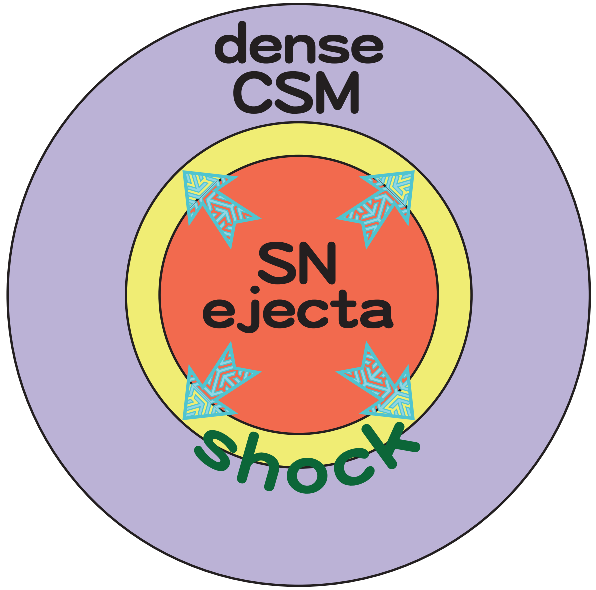


- ecSNe have smaller explosion energy
  - lower luminosity from interaction than typical Type IIn SNe

$$L_{\rm int} = \frac{\epsilon A}{2}\left(\frac{\dot{M}}{v_{\rm wind}}\right)^{\frac{5}{2}} E_{\rm ej}^{\frac{21}{16}} M_{\rm ej}^{-\frac{15}{16}} t^{-\frac{3}{8}}$$

Moriya et al. (2014)

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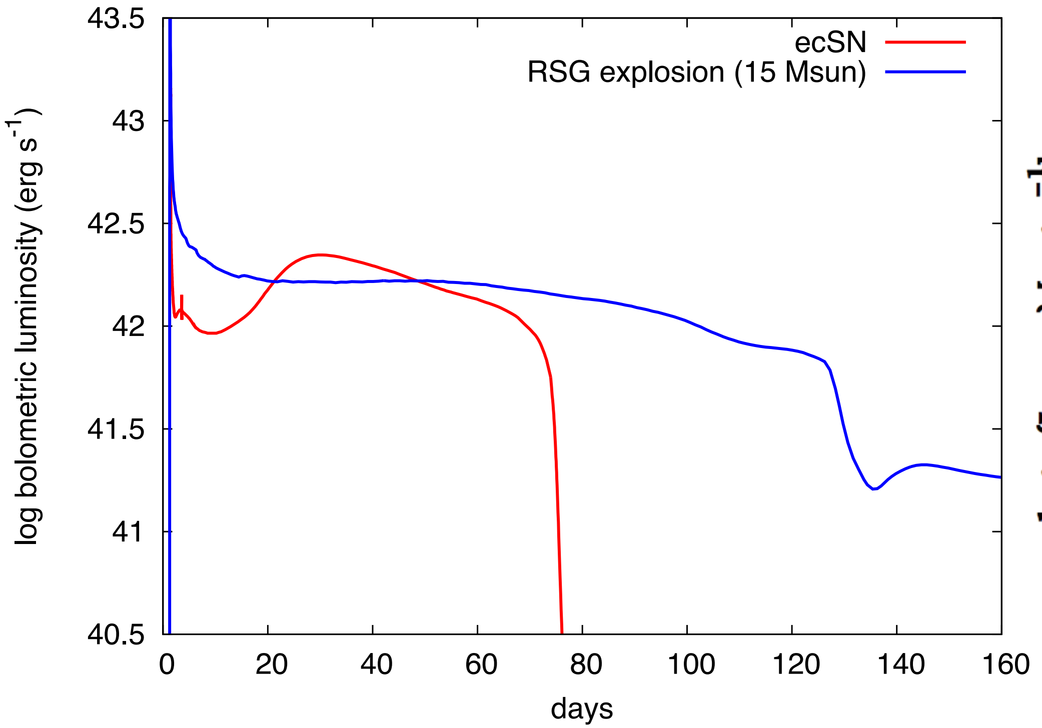


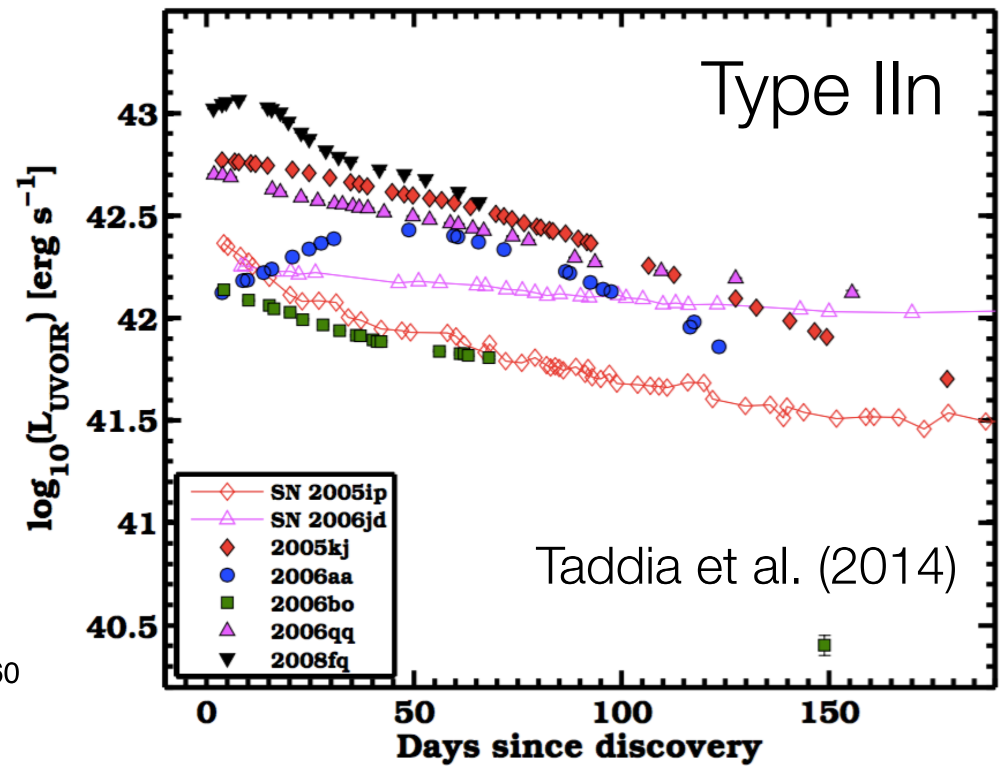

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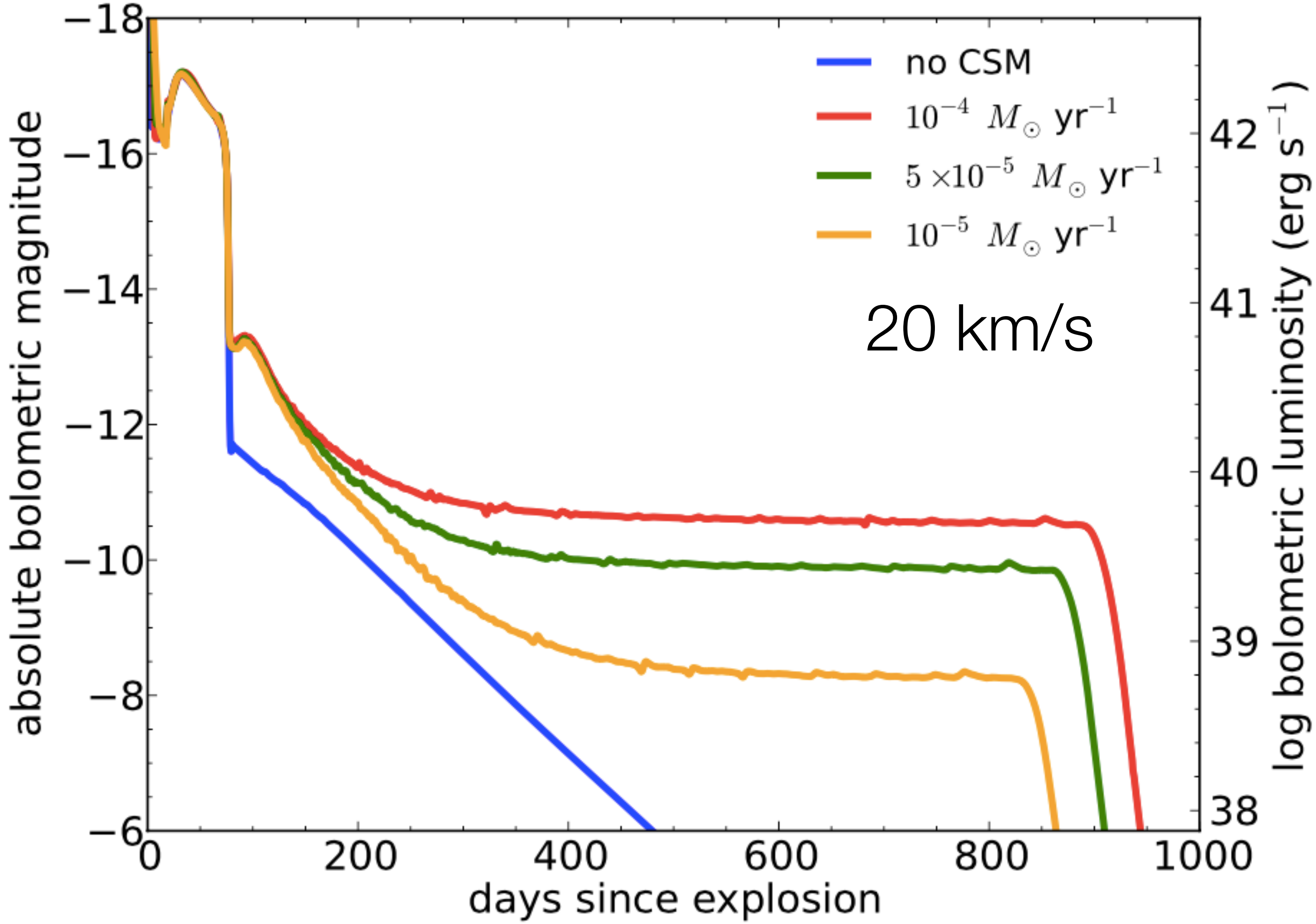


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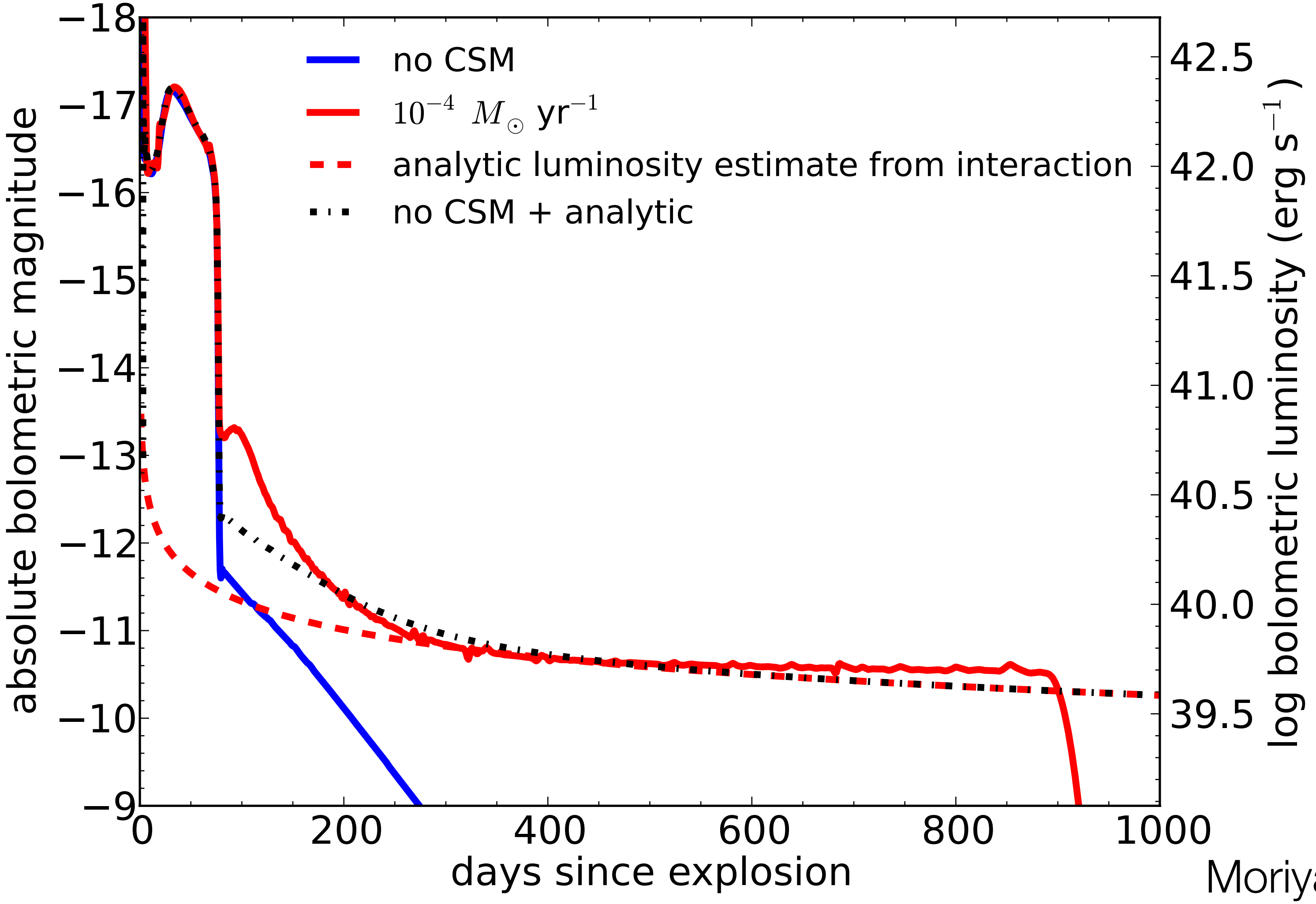
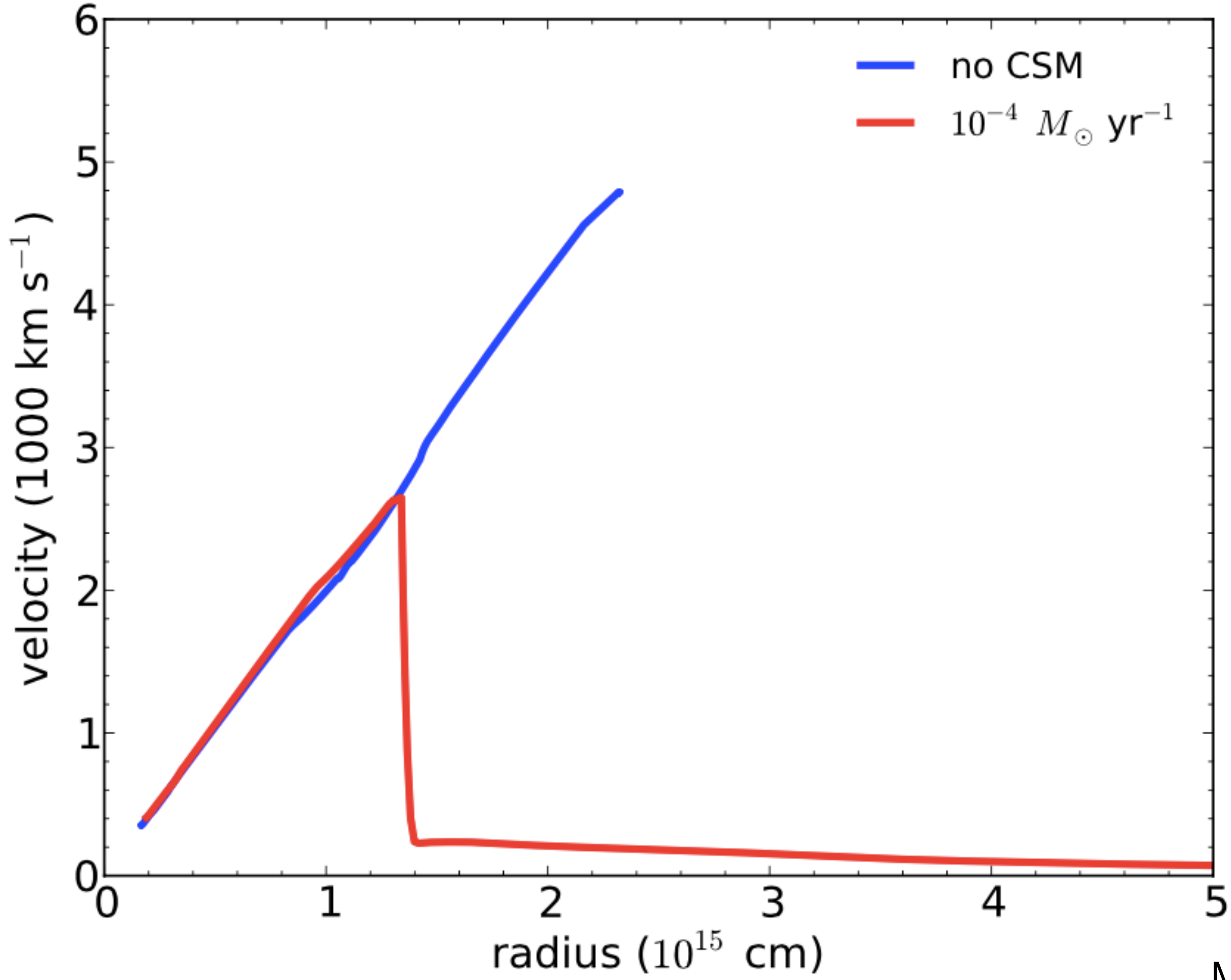



Moriya et al. (2014)

# Dynamical effect of dense wind

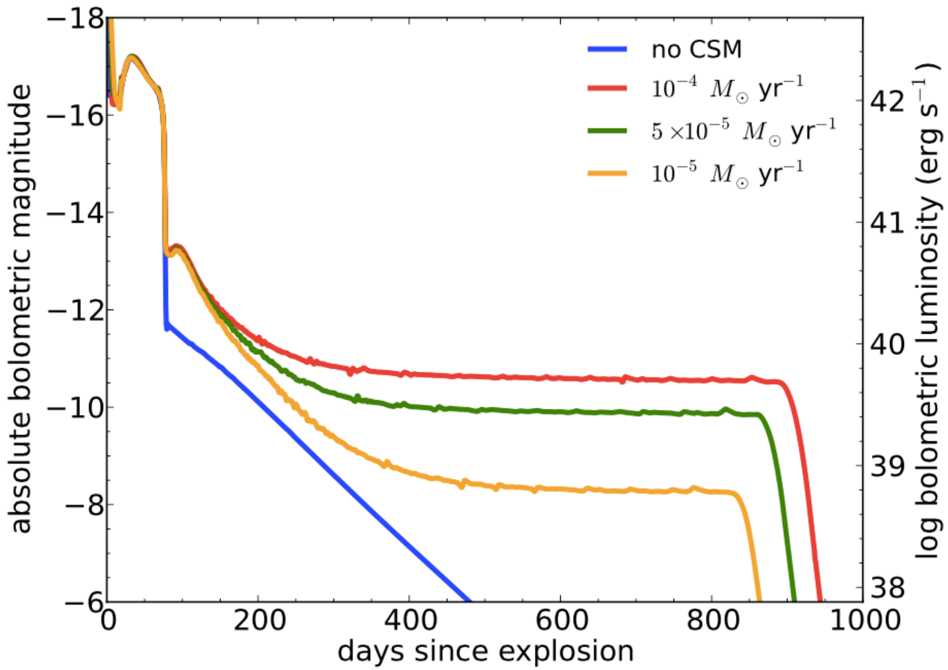
- velocity profile at 50 days after the explosion




Moriya et al. (2014)

# Summary of ecSN LC properties

- Type IIP SN-like LCs
  - ~ 1e42 erg/s plateau for about 100 days
  - sudden luminosity drop as seen in Type IIP
  - small amount of 56Ni (~ 0.001 Msun)
    - large luminosity drop after the plateau
- dense wind affects LCs and dynamics
  - wind is as dense as in Type IIn
  - but explosion energy is lower
  - likely to dominate after the drop



# Comparison with observations

- Crab SN (SN 1054)
- faint Type IIP and IIn SNe (e.g., SN 2008S)
- “Type IIn-P” SNe
- PTF11iqb-like SNe

# Crab SN (SN 1054)

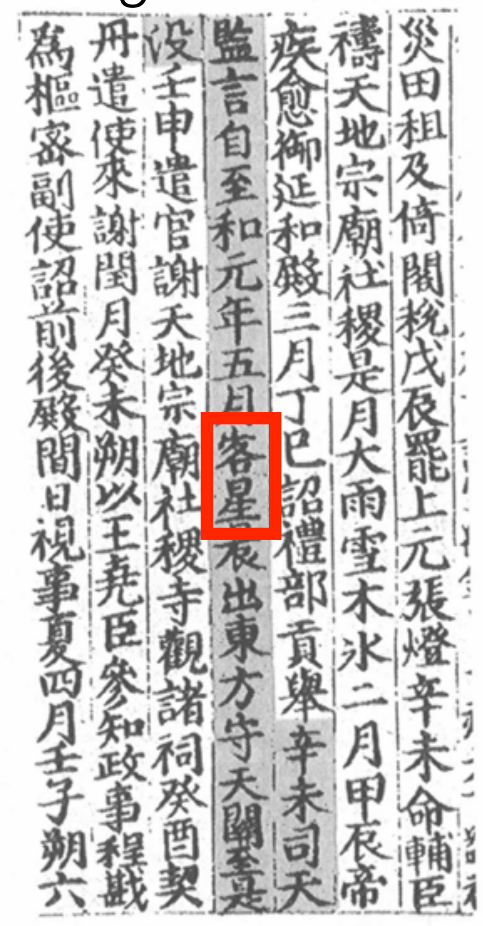
- ejecta mass: 4.6 ± 1.8 Msun (e.g., Fesen et al. ’97)
- kinetic energy: ~ 1e49 erg (e.g., Frail et al. ’95)
- abundances (e.g., Nomoto et al. ’82)

an ecSN candidate!

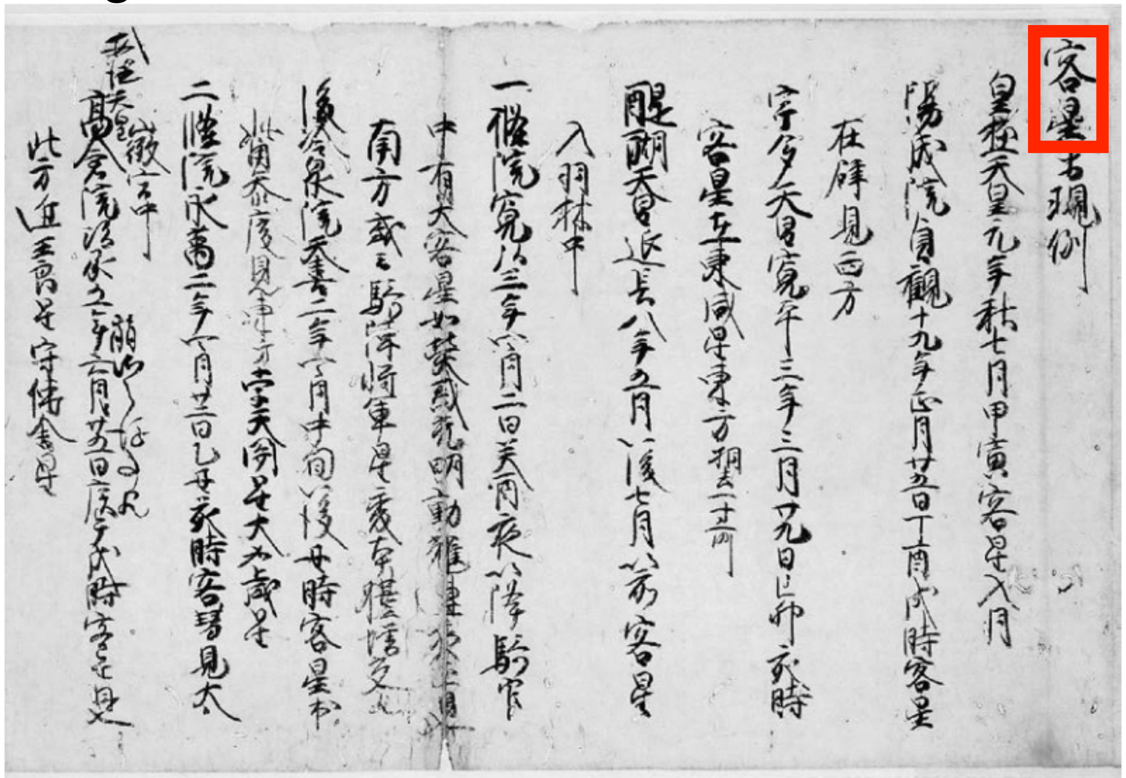
# Crab SN (SN 1054)

- light curve from ancient Chinese text (宋史, *Songshi*)
    - SN 1054 also appears in Japanese literature (明月記, *Meigetsuki*)

*Songshi*



*Meigetsuki*



客: guest, 星: star

Stephenson & Green (2002)

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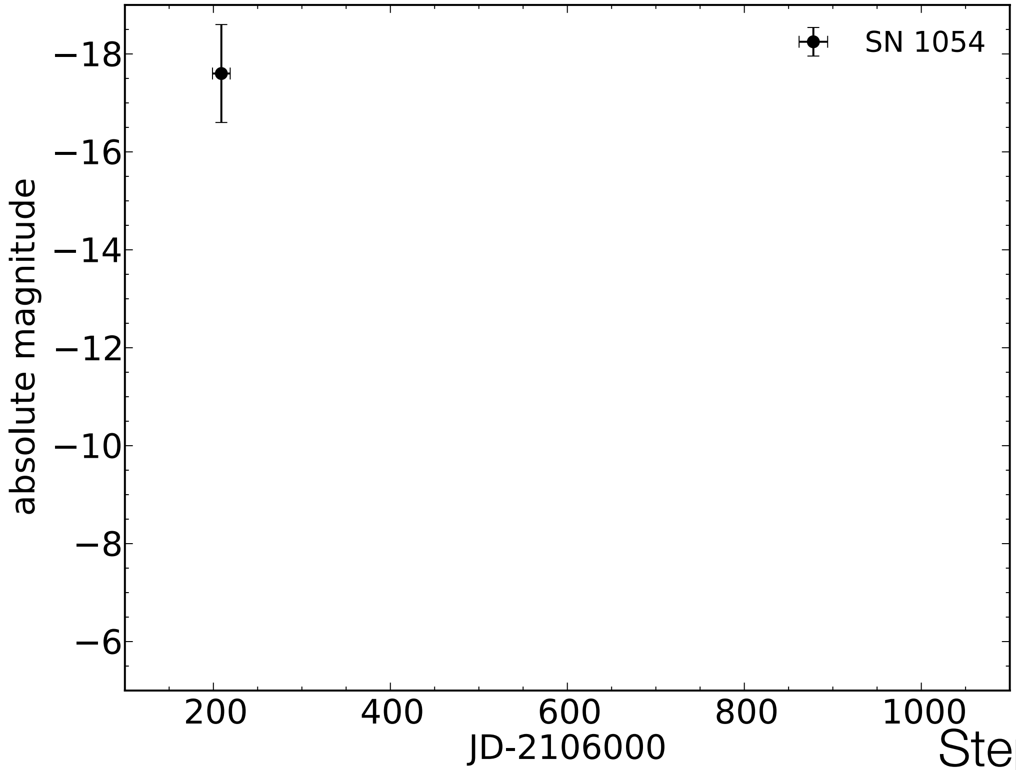
- according to the Chinese record..
    - the “guest star” appeared appeared on July 4 1054
        - it was as bright as Venus

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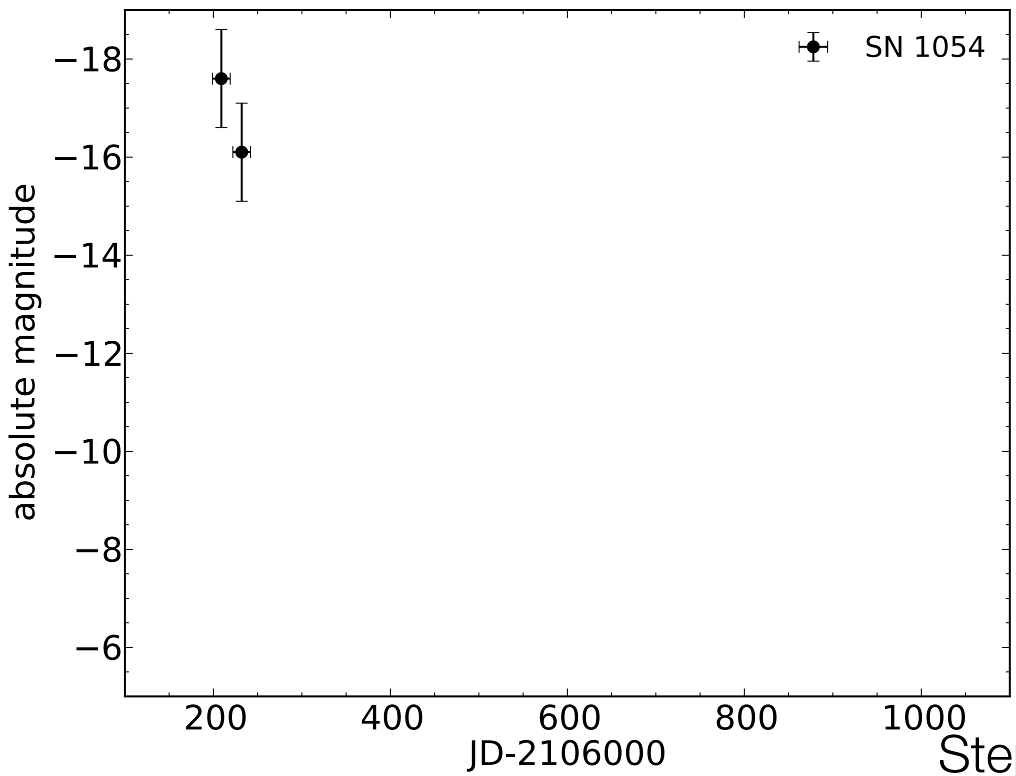


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  - the “guest star” appeared appeared on July 4 1054
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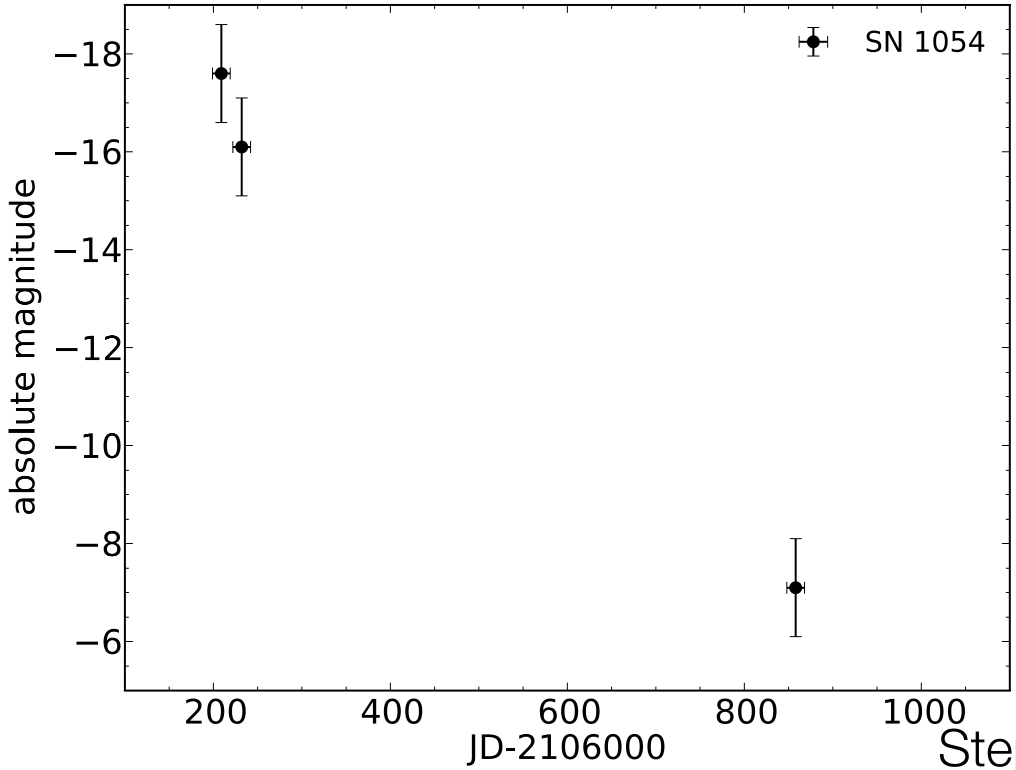
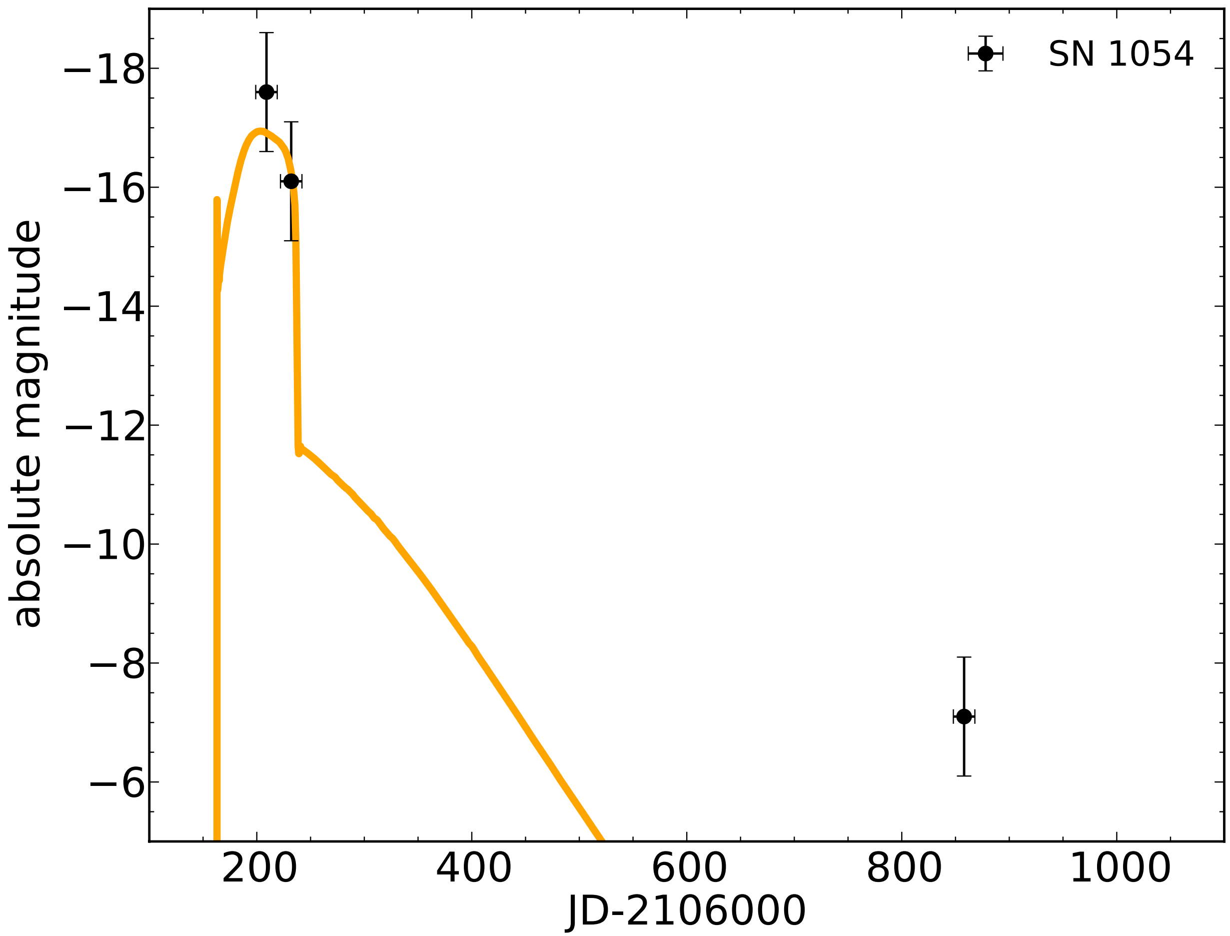
  - it was able to observe during day time for 23 days
  - it disappeared on April 6 1056




Stephenson & Green (2002)

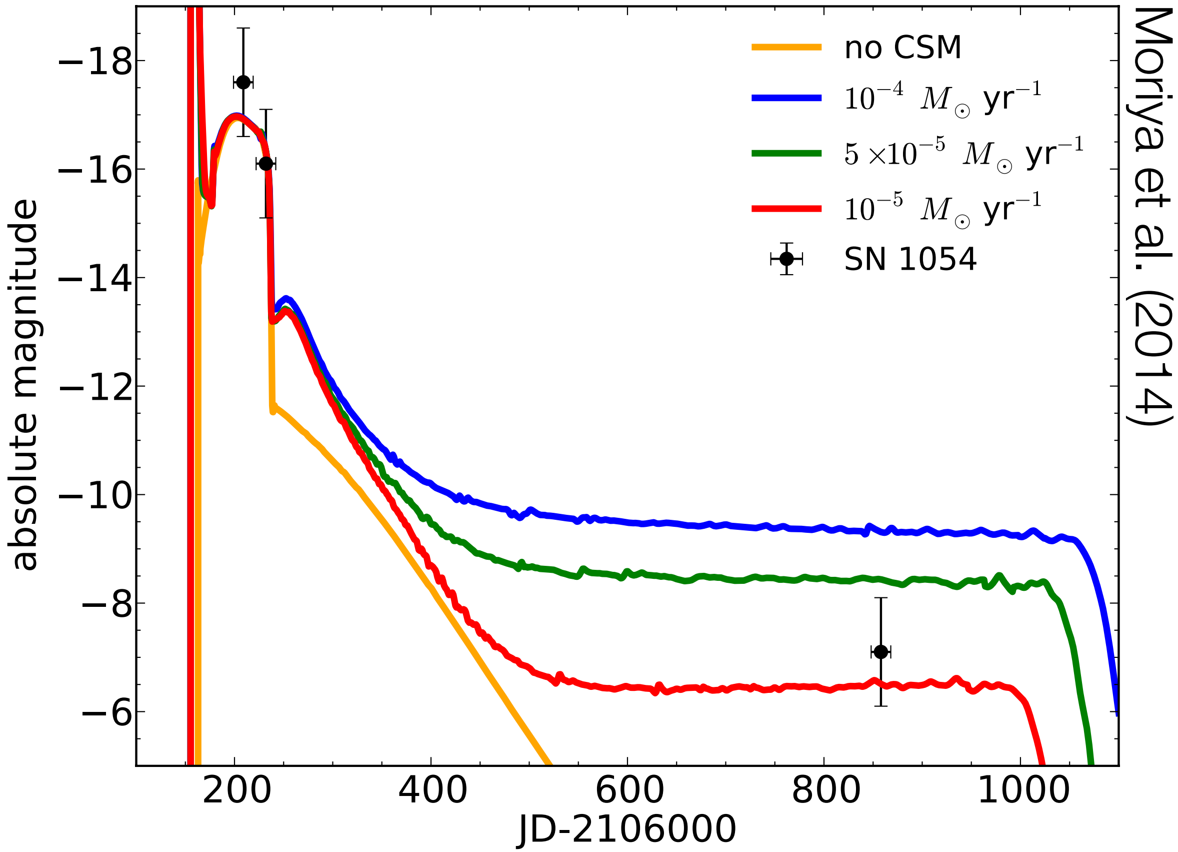
# Crab SN (SN 1054)

- early observations are consistent with ecSN LC models
  - very dense shell as suggested by Smith (2013) is not required
- the last record does not match (e.g., Sollerman et al. 2001)



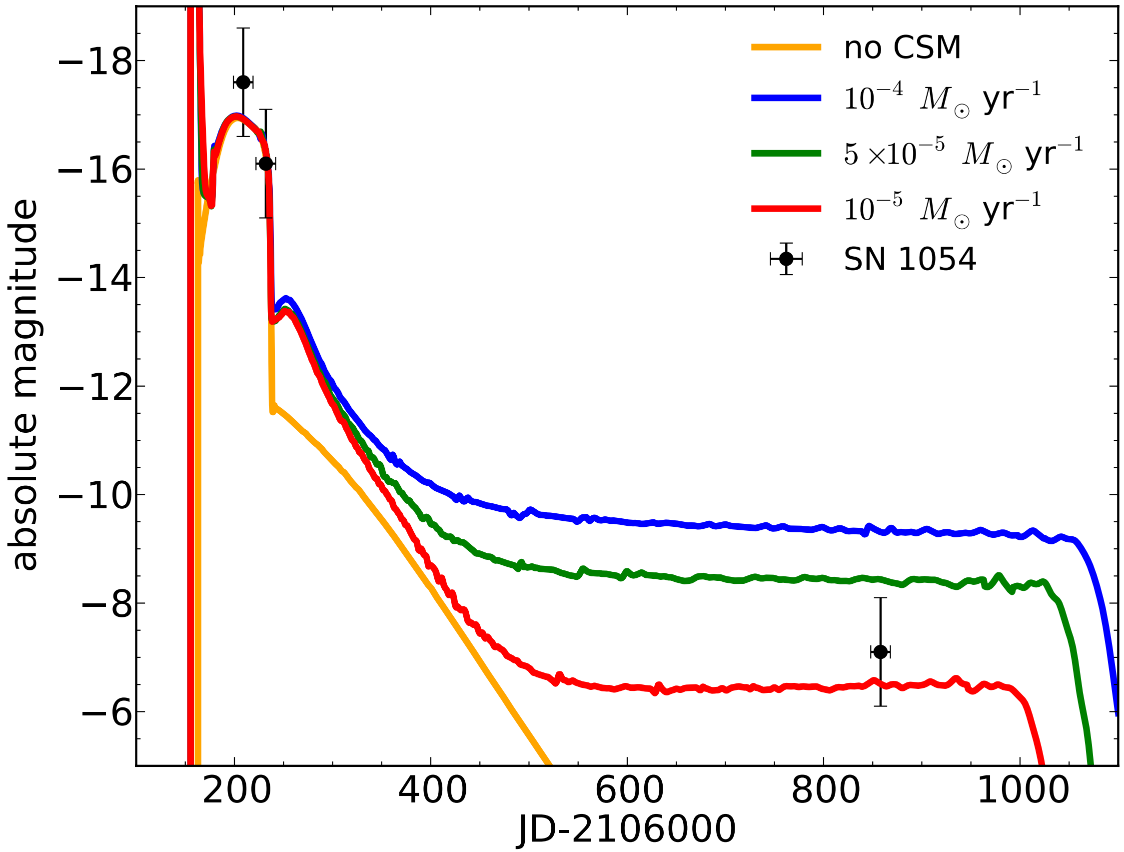
# Crab SN (SN 1054)

- ecSN + wind interaction



# Crab SN (SN 1054)

- ecSN + wind interaction
  - does not "disappear"
    - wind radius needs to be 1.5e16 cm
    - high mass-loss rate in 240 years before the explosion




Moriya et al. (2014)

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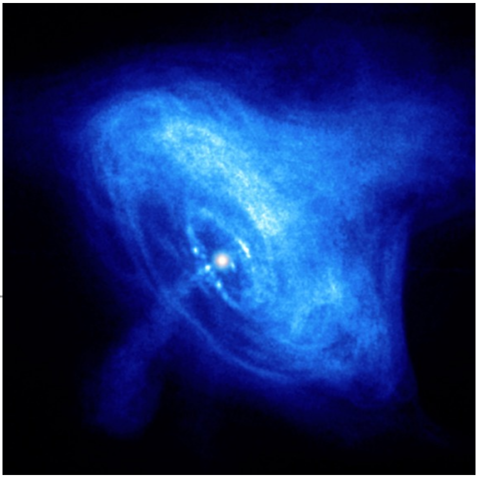
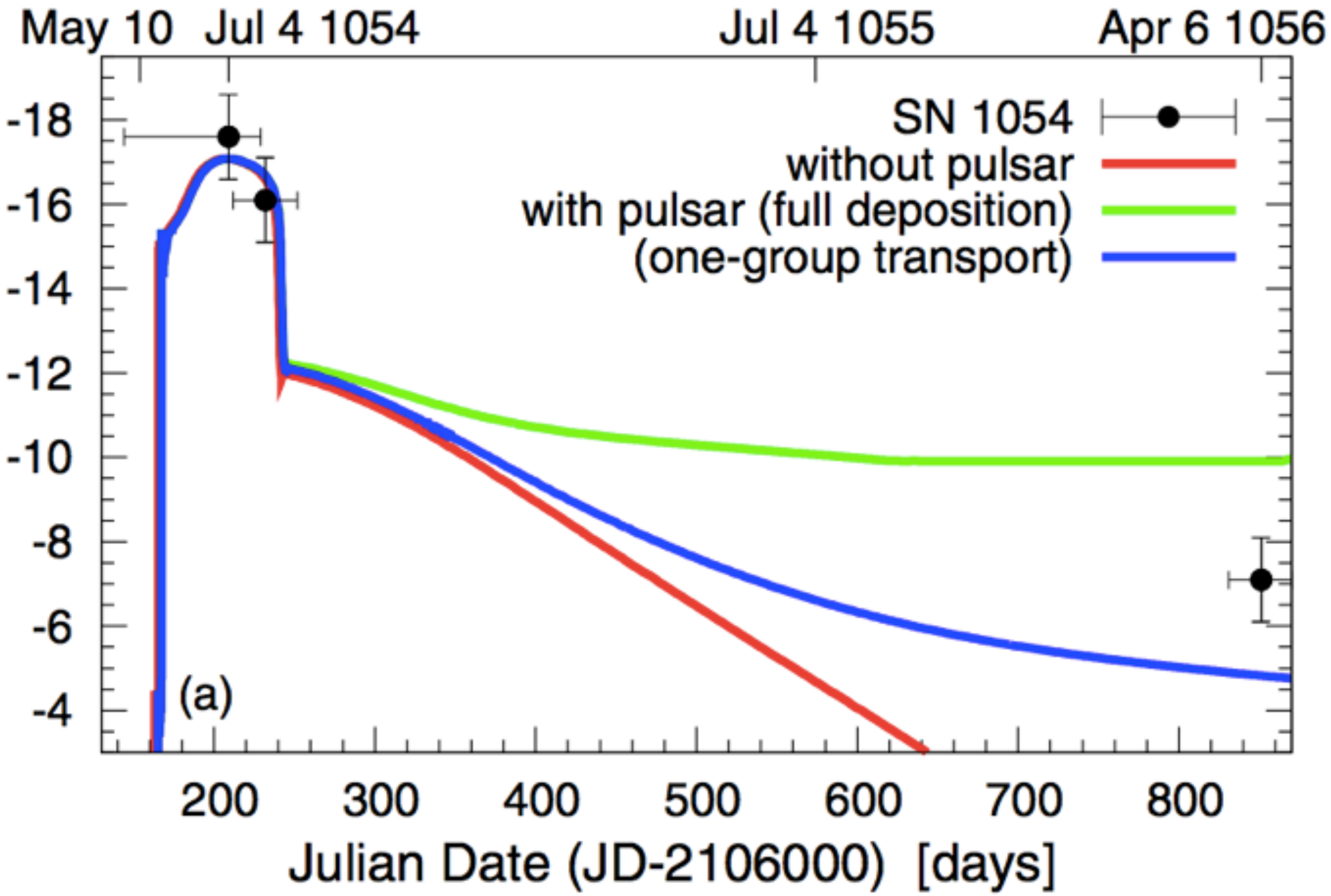


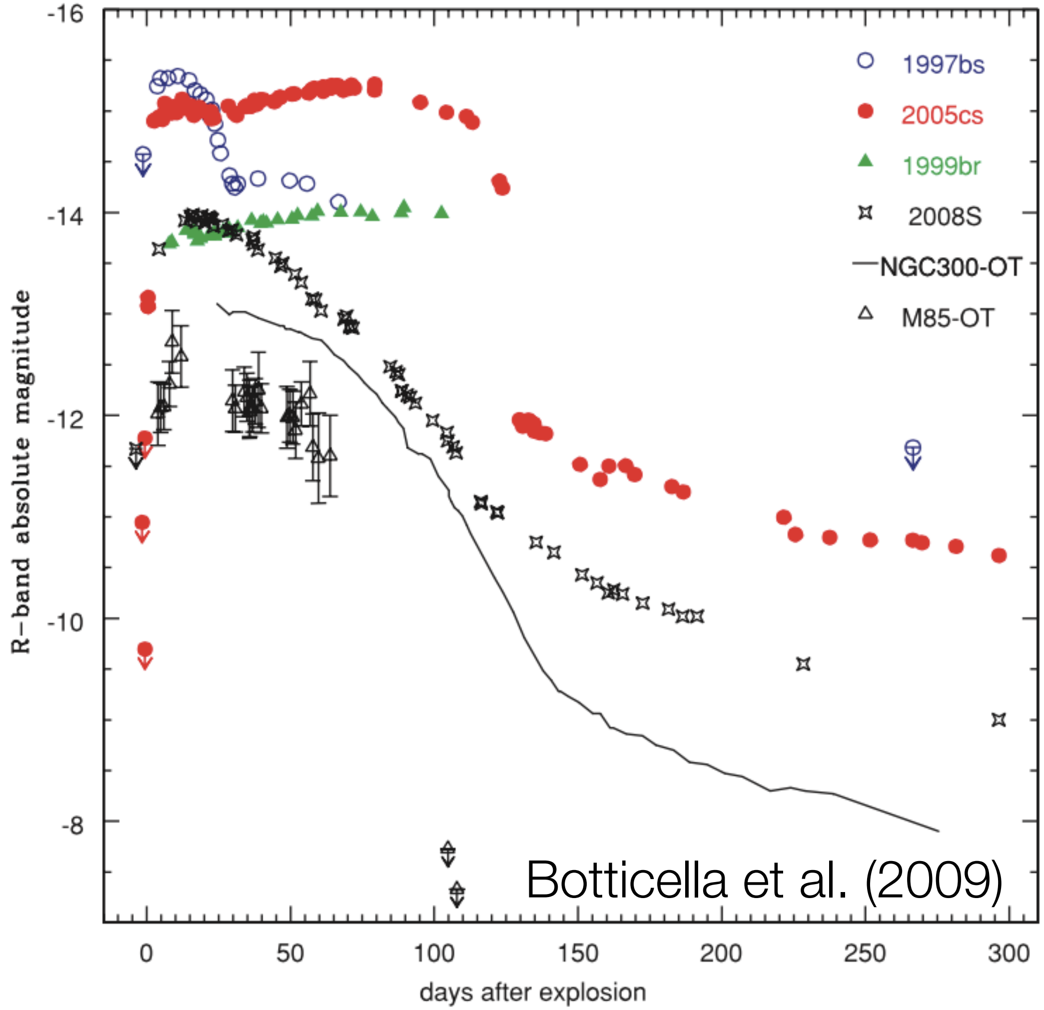
- ecSN + pulsar energy input




Tominaga et al. (2013)

# Faint Type IIP and IIn SNe

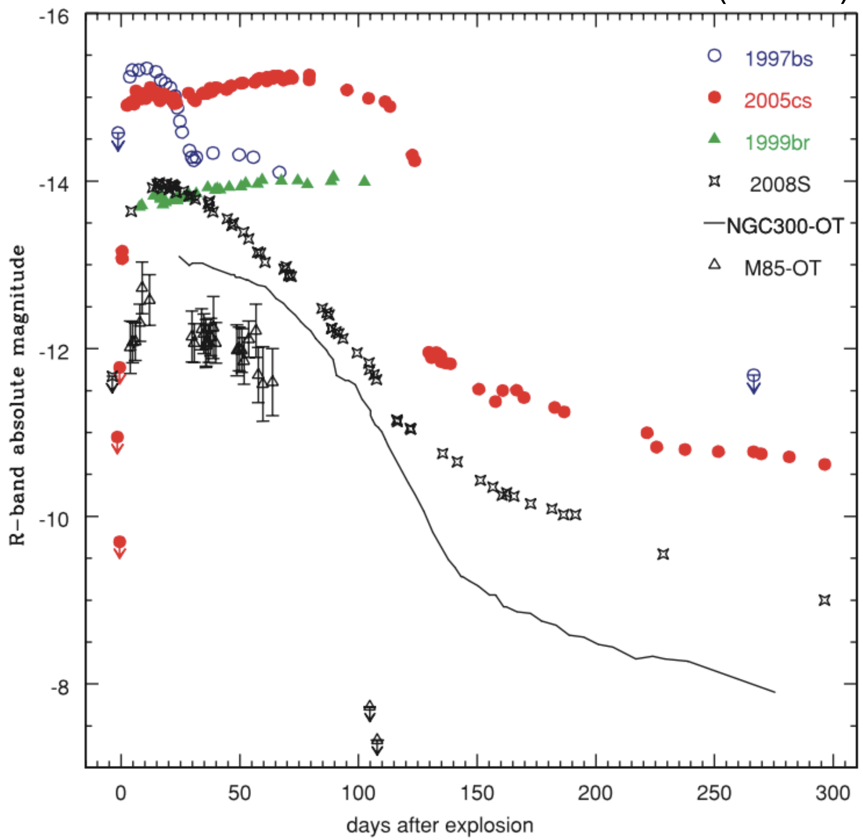
- faint SNe with small 56Ni production and small explosion energy
  - some of them have small progenitor mass

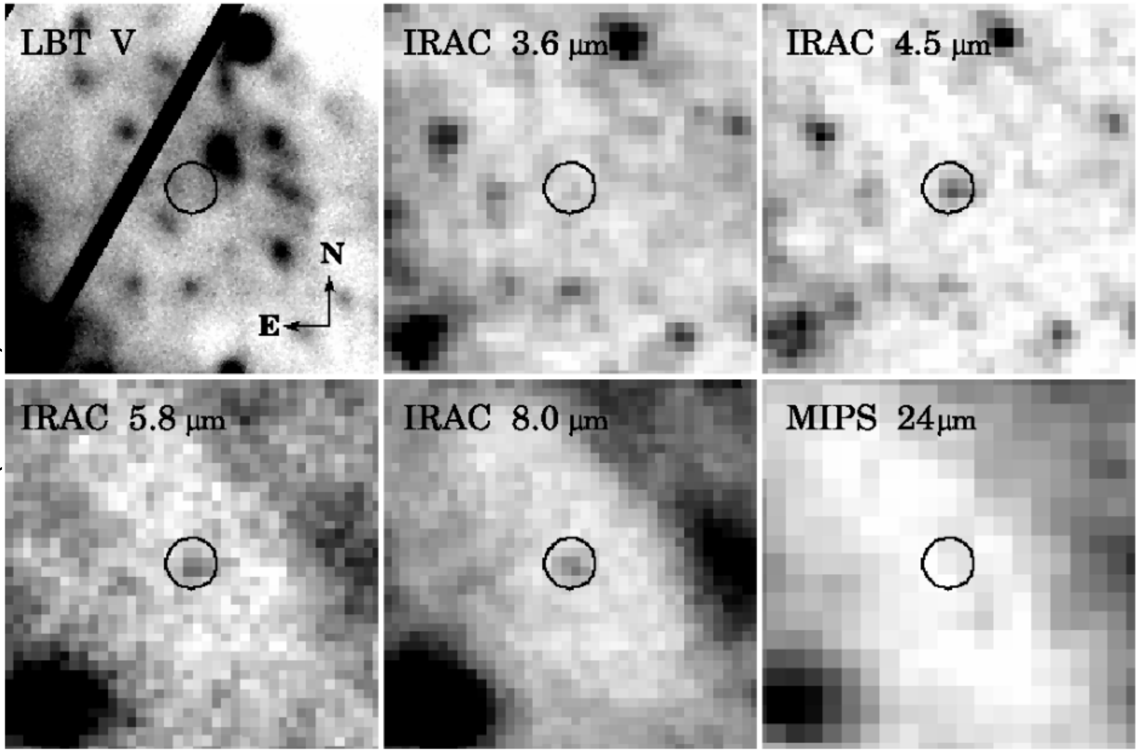


# Faint Type IIP and IIn SNe

- SN 2008S
  - faint Type IIn
    - ecSN explosion in a dense super-AGB wind?
  - progenitor is ~ 8 Msun with dusty CSM
    - super-AGB wind?

Botticella et al. (2009)



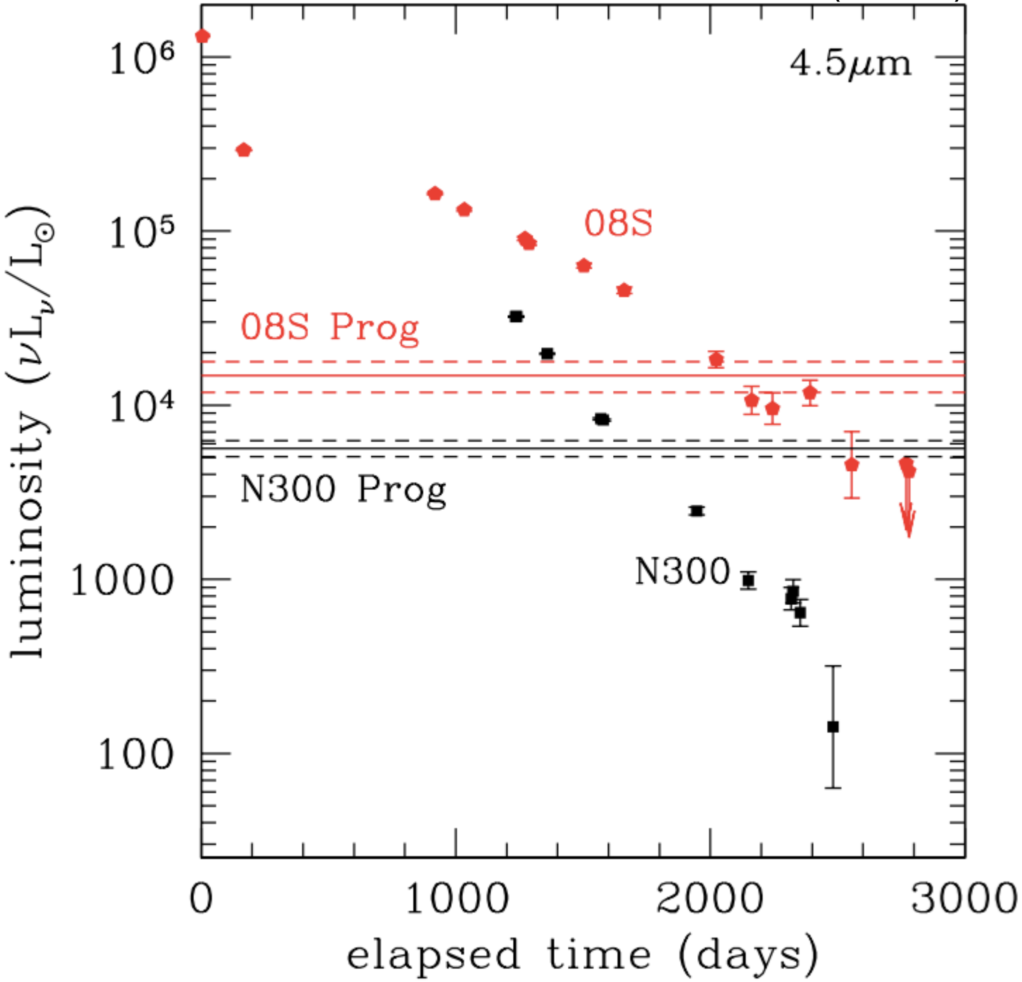




Prieto et al. (2008)

# Faint Type IIP and IIn SNe

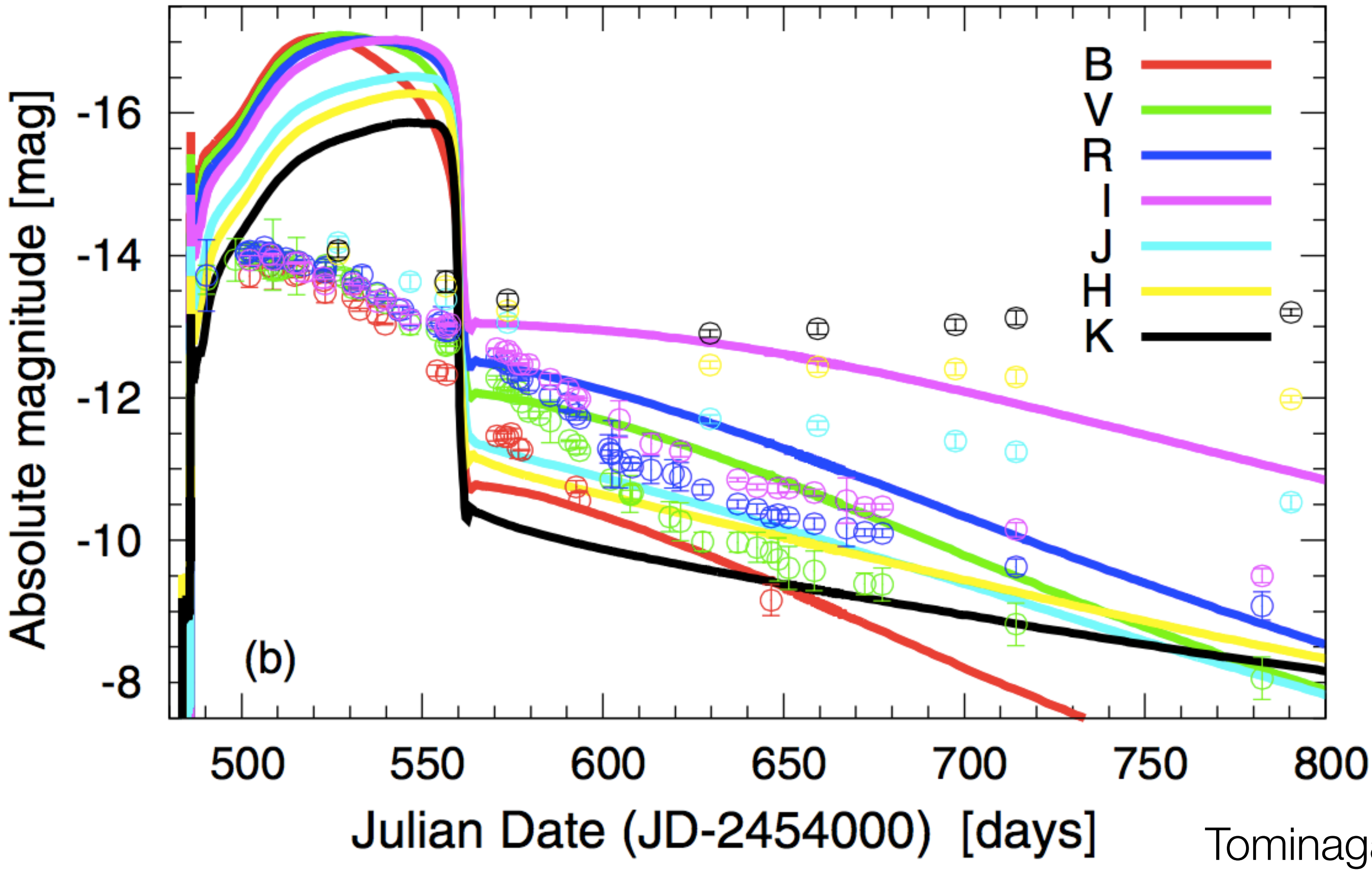
- SN 2008S
  - progenitor likely disappeared

Adams et al. (2015)



# Faint Type IIP and IIn SNe

- ecSNe are not faint, despite of their small explosion energy
  - SN 2008S




Tominaga et al. (2013)

# Faint Type IIP and IIn SNe

- ecSNe with E = 1e50 erg are not faint enough
  - SN 2008S
    - E = 2.5e48 erg
    - Menv = 3.4 Msun

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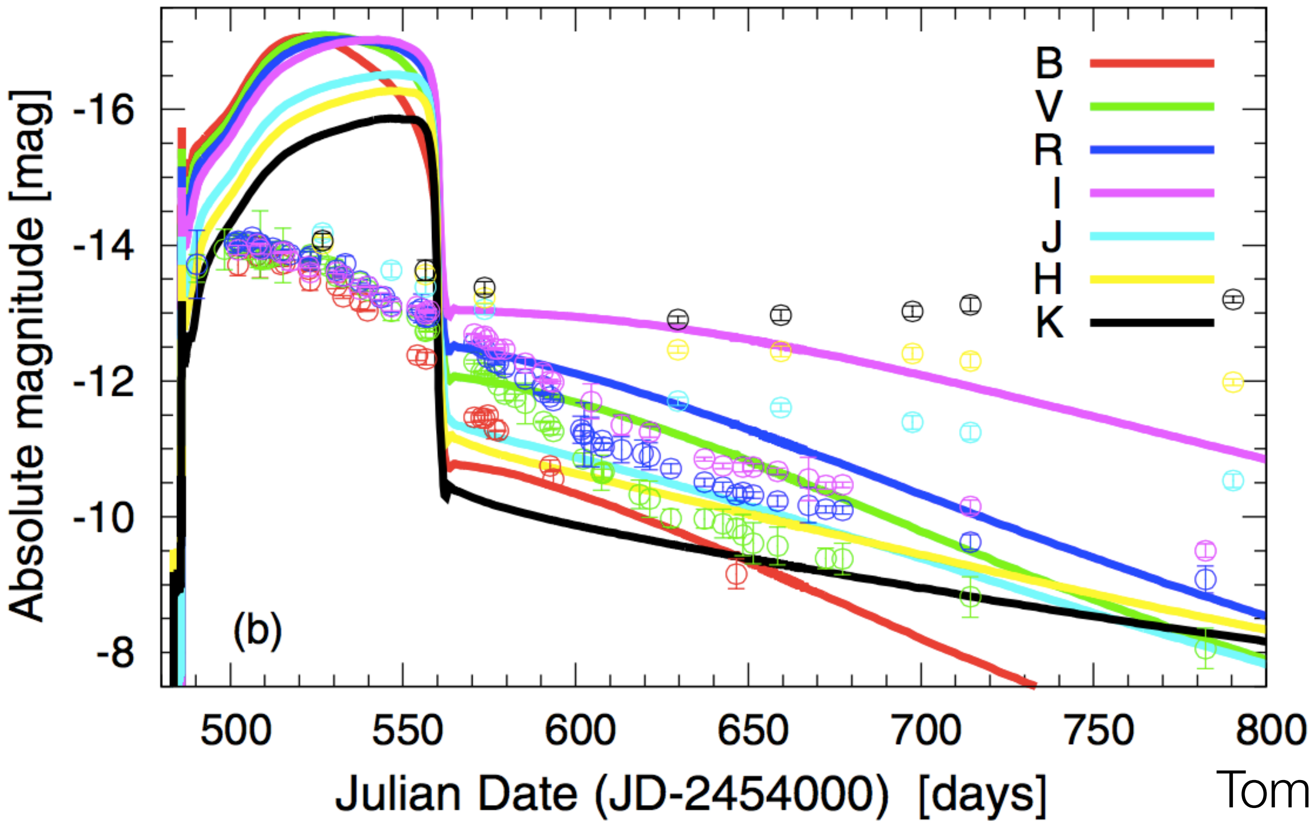
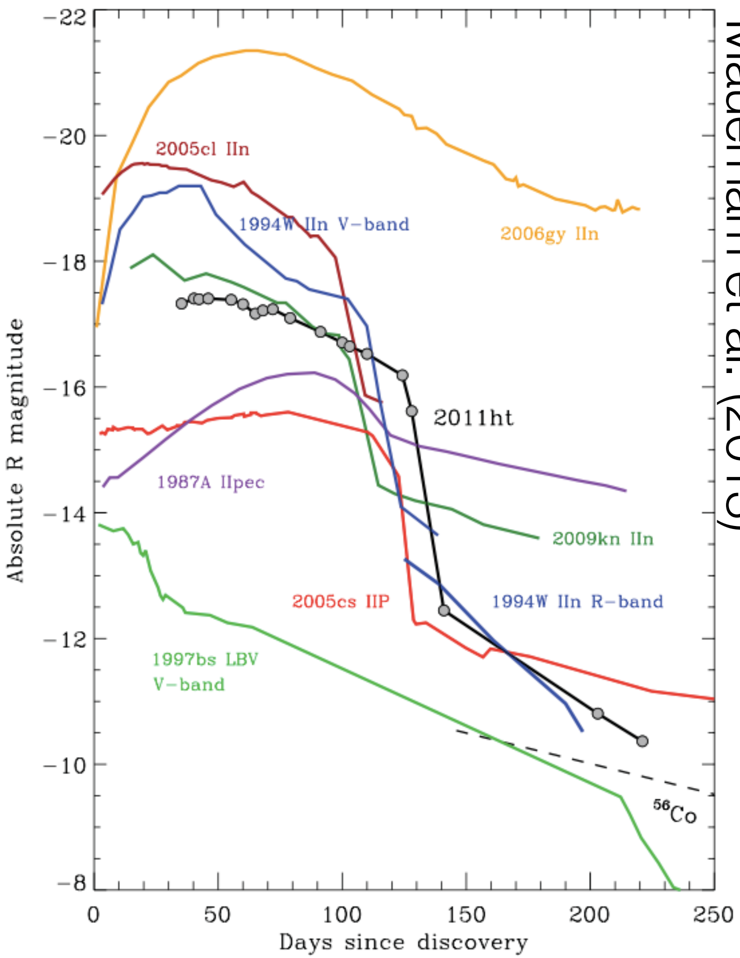


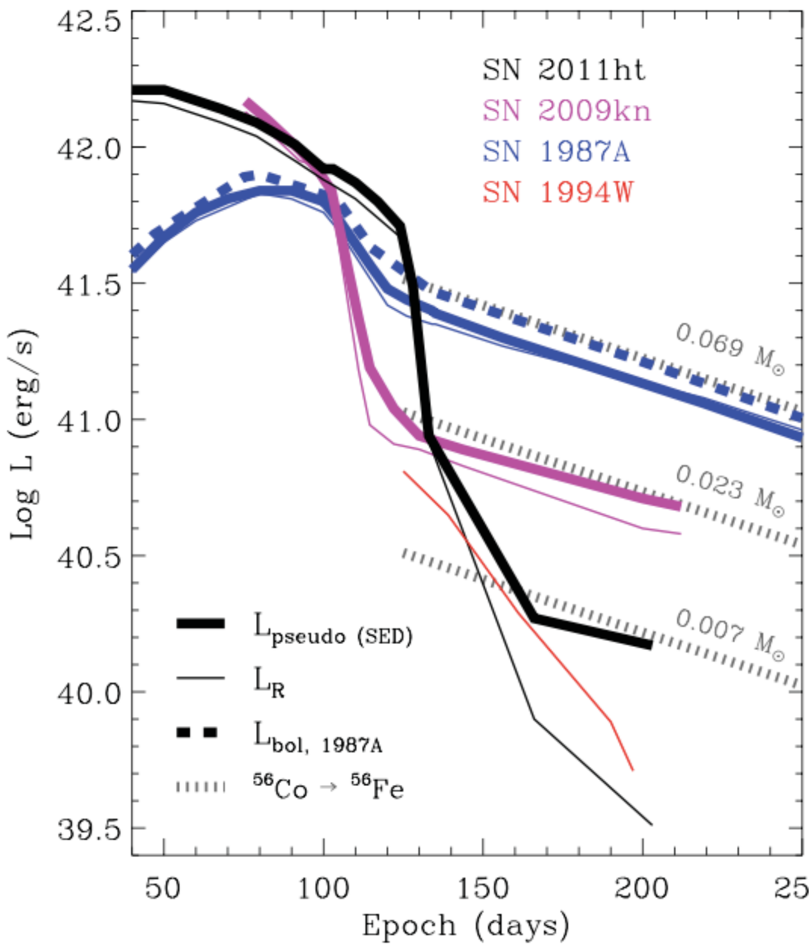

Tominaga et al. (2013)

# “Type IIn-P” SNe

- a sub-class of Type IIn SNe with a long LC plateau
  - SN 1994W, SN 2009kn, SN 2011ht, …




Mauerham et al. (2013)

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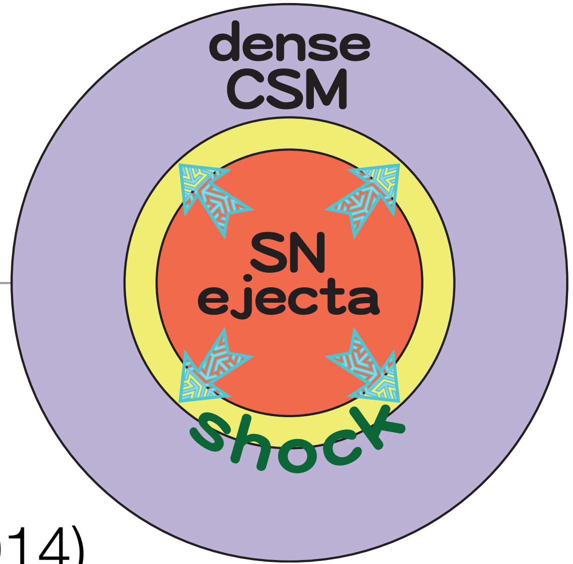
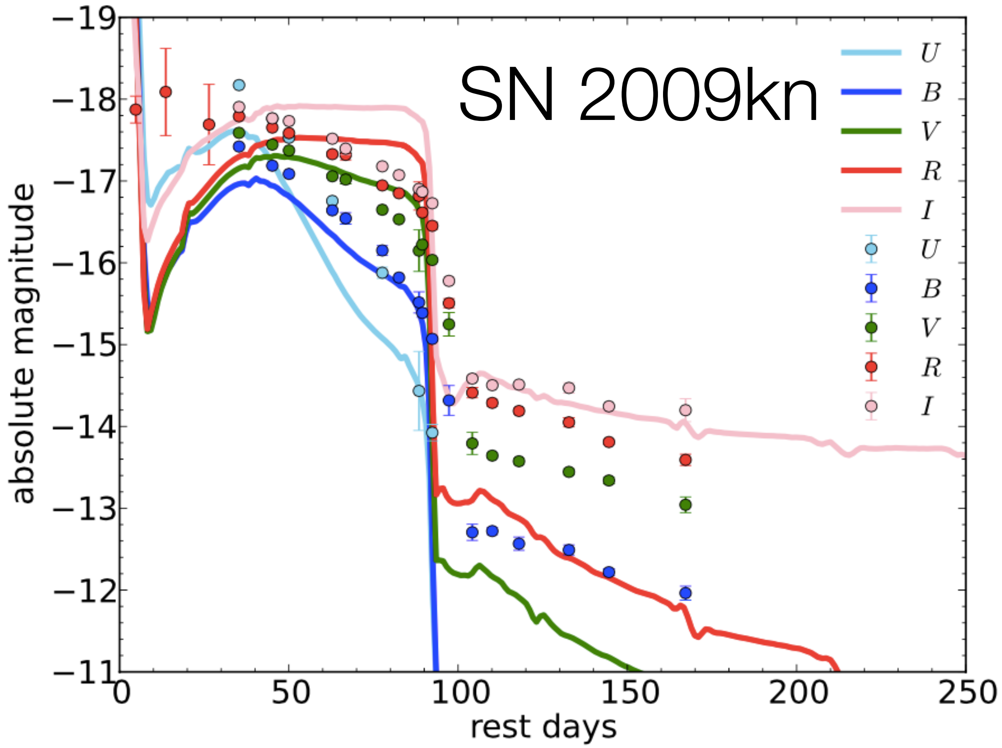
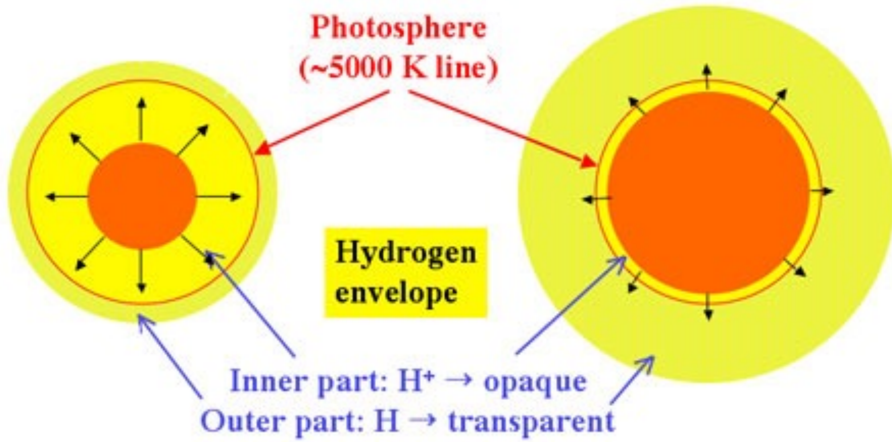



- origin of plateau and sudden luminosity drop
    - similar to Type IIP SNe, i.e., recombination?
        - recombination in SN ejecta (Moriya et al. 2014)
        - recombination in dense wind (Dessart et al. 2009)
    - termination of CSM interaction? (Chugai et al. 2004)

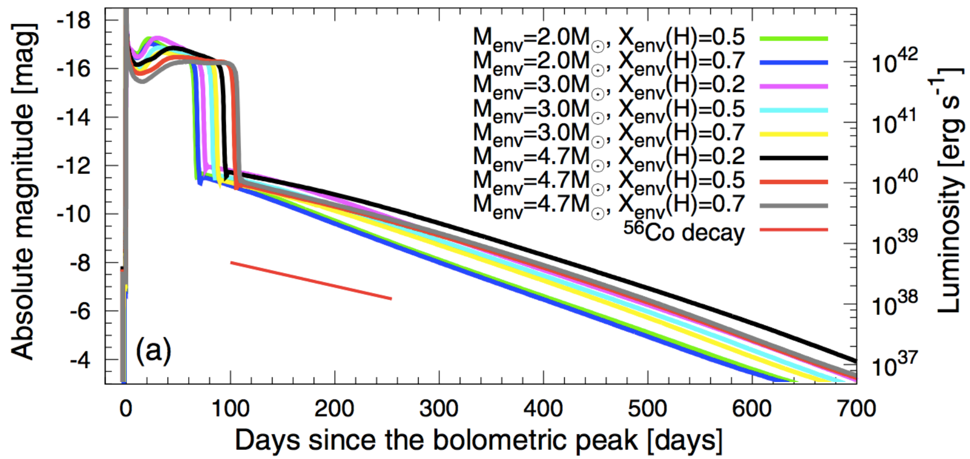


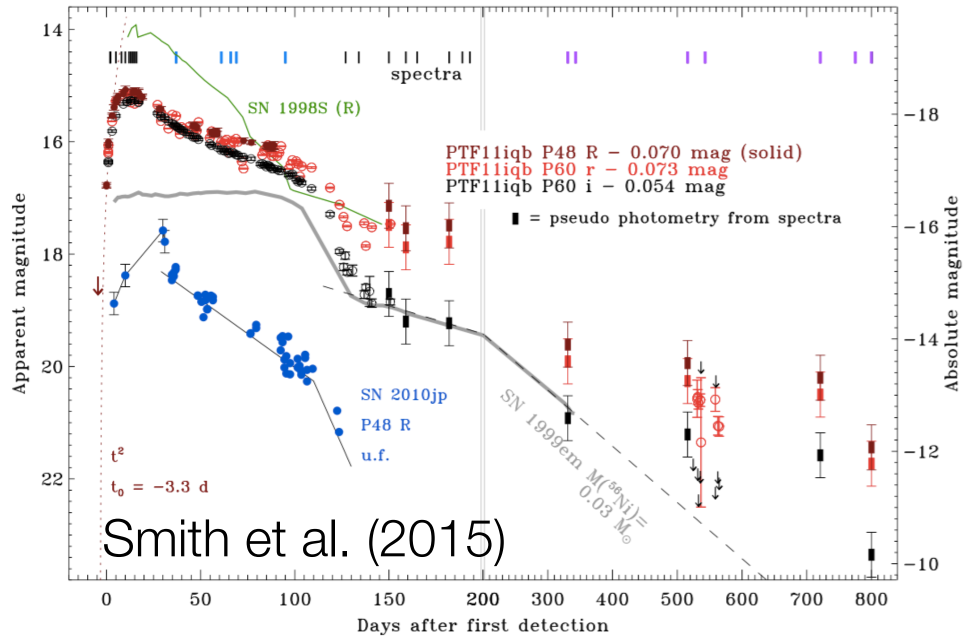




Moriya et al. (2014)

# Possible ecSN candidate features

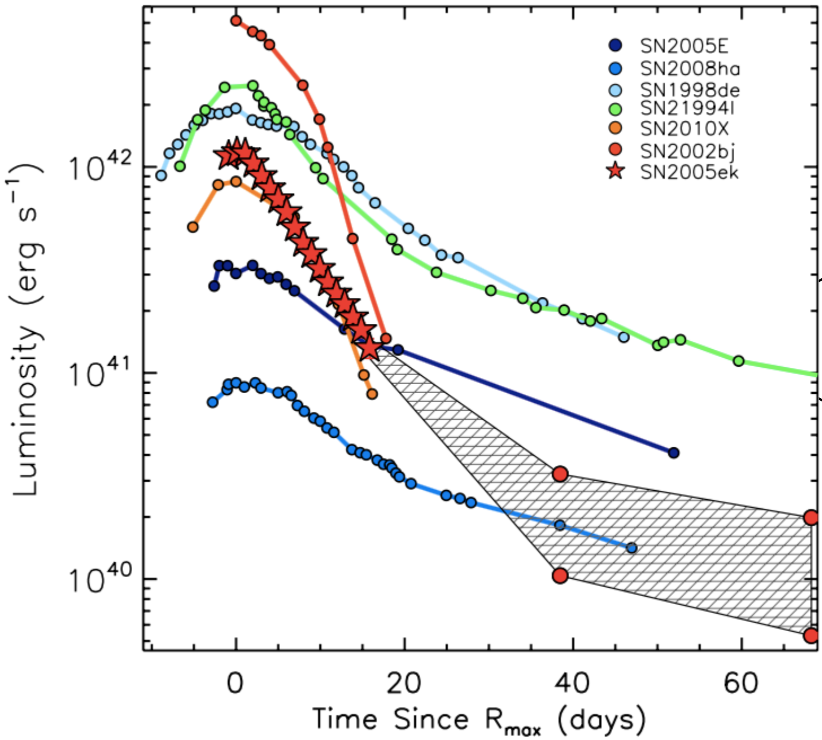
- SN IIP or IIL + weak SN IIn features
  - PTF11iqb (Smith et al. 2015)
    - weak SN IIn features
    - 1e-4 Msun/yr
    - enhanced N/H
  - YSG explosion?
    - super-AGB may result in similar SNe
      - similar envelope mass
      - similar radius
      - explosion energy??
        - CCSN: ~1e51 erg
        - ecSN: ~1e50 erg



# H-free electron-capture SNe

- ~ 0.1 - 0.01 Msun of ejecta?
- ~1e-3 Msun 56Ni
    - probably Type Ic
    - rise time of several days
    - peak luminosity of ~ 1e41 erg/s




Drout et al. (2013)

# Summary

- ecSN LCs are characterized by
  - LC plateau
    - ~ 1e42 erg/s lasts about 100 days
  - large luminosity drop follows
    - small 56Ni production (~1e-3 Msun)
  - CSM interaction powers late-phase LCs
- observational candidates
  - SN 1054 (Crab)
  - low luminosity SNe may not be related
    - unless exp. energy is ~ 1e48 erg
  - Type IIn-P SNe?
  - PTF11iqb-like SNe?
- H-free ecSN features are unexplored much