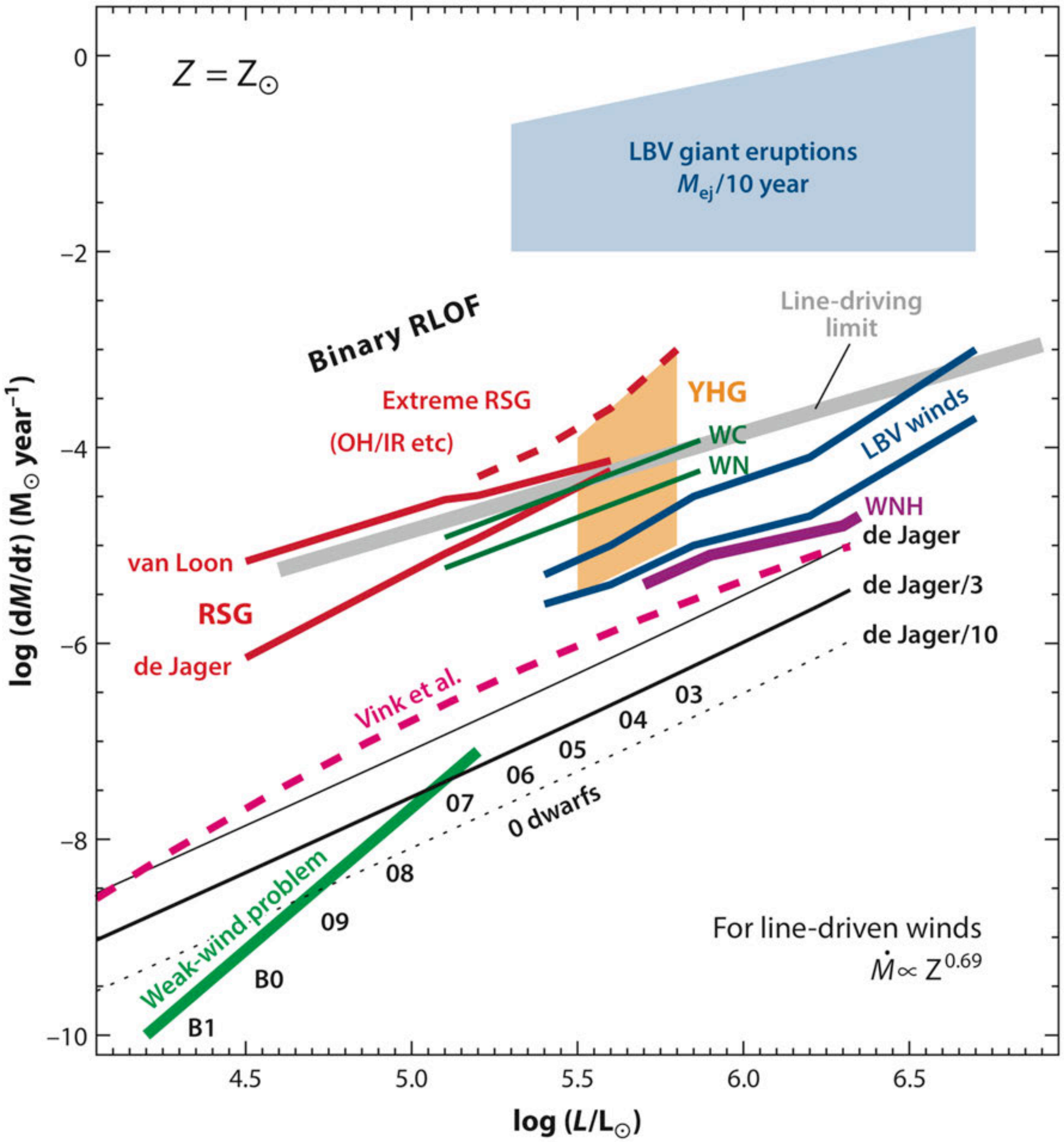
End point of stars revealed by supernovae

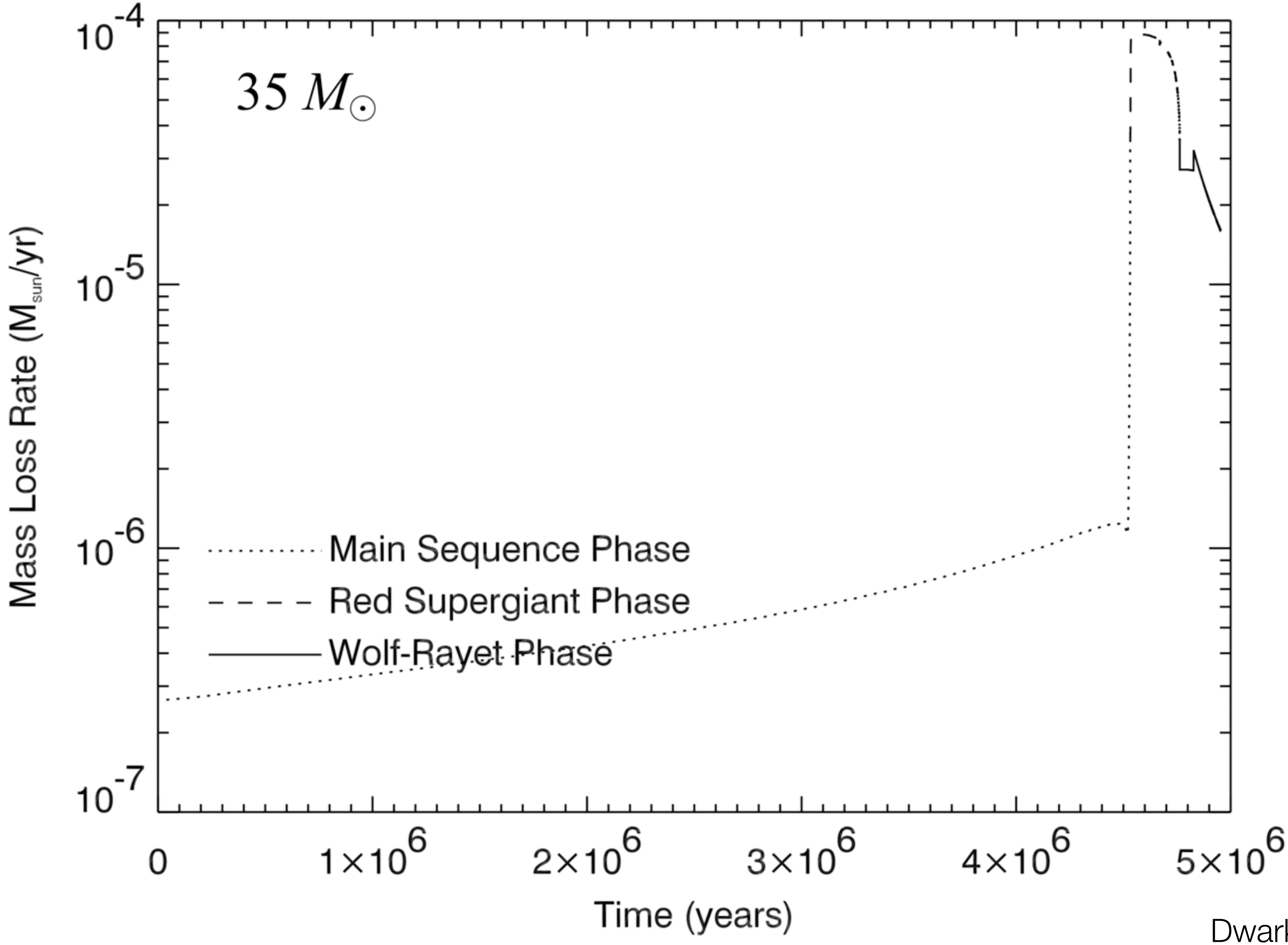
Takashi Moriya
National Astronomical Observatory of Japan

Mass loss from massive stars



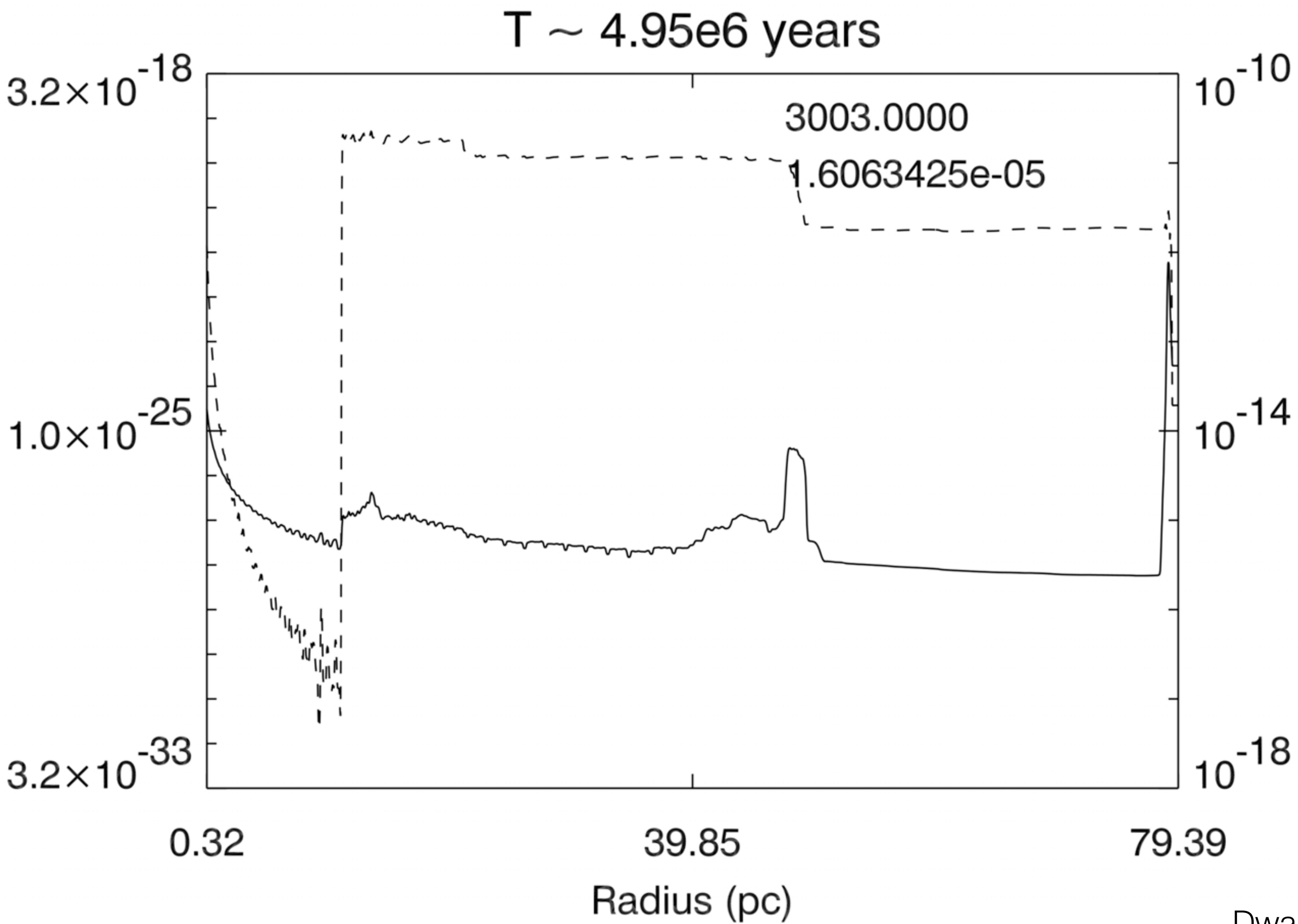
Smith (2014)

Mass-loss rate of a massive star



Dwarkadas (2007)

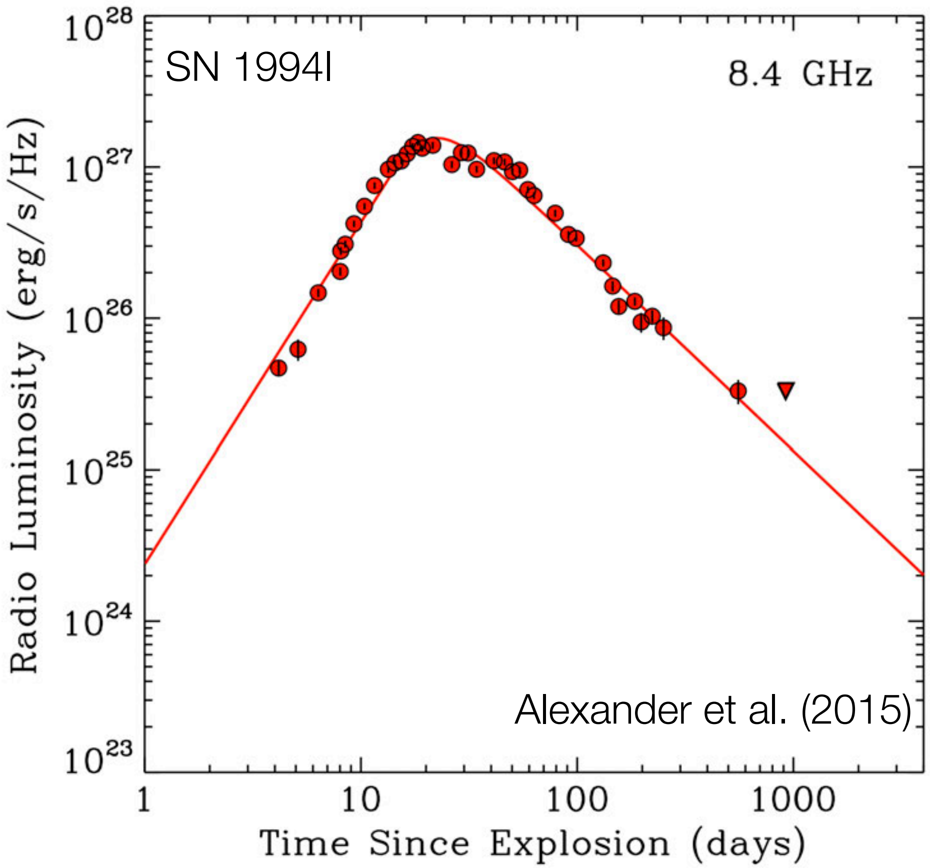
Circumstellar properties at the time of explosion

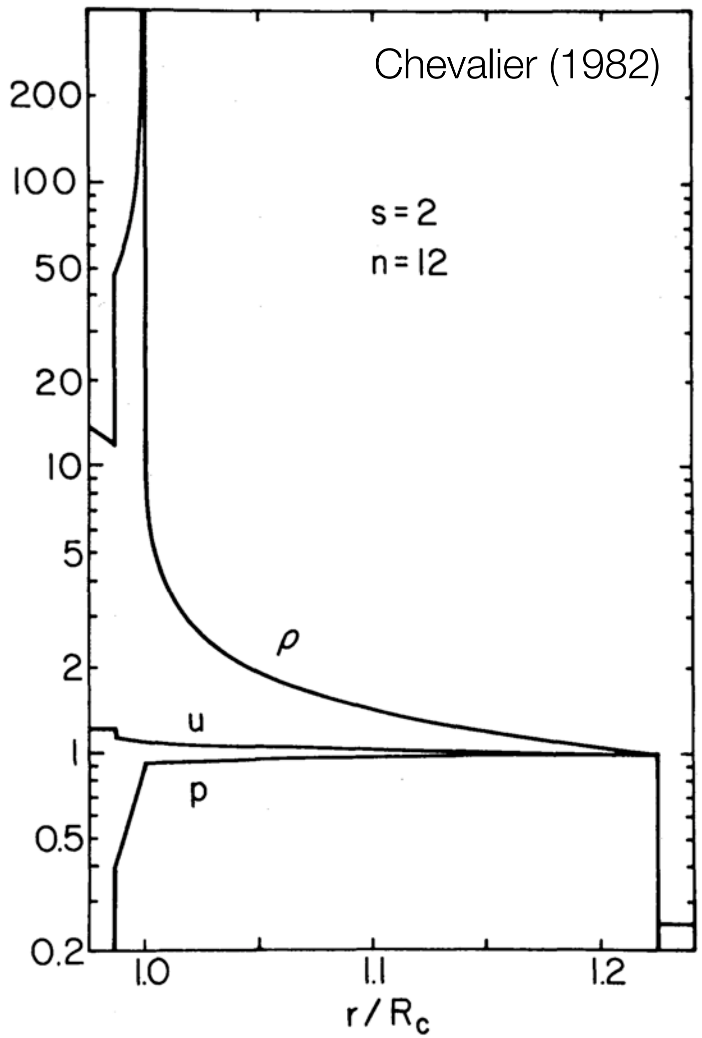


Dwarkadas (2007)

Strong shock between SN ejecta and CSM

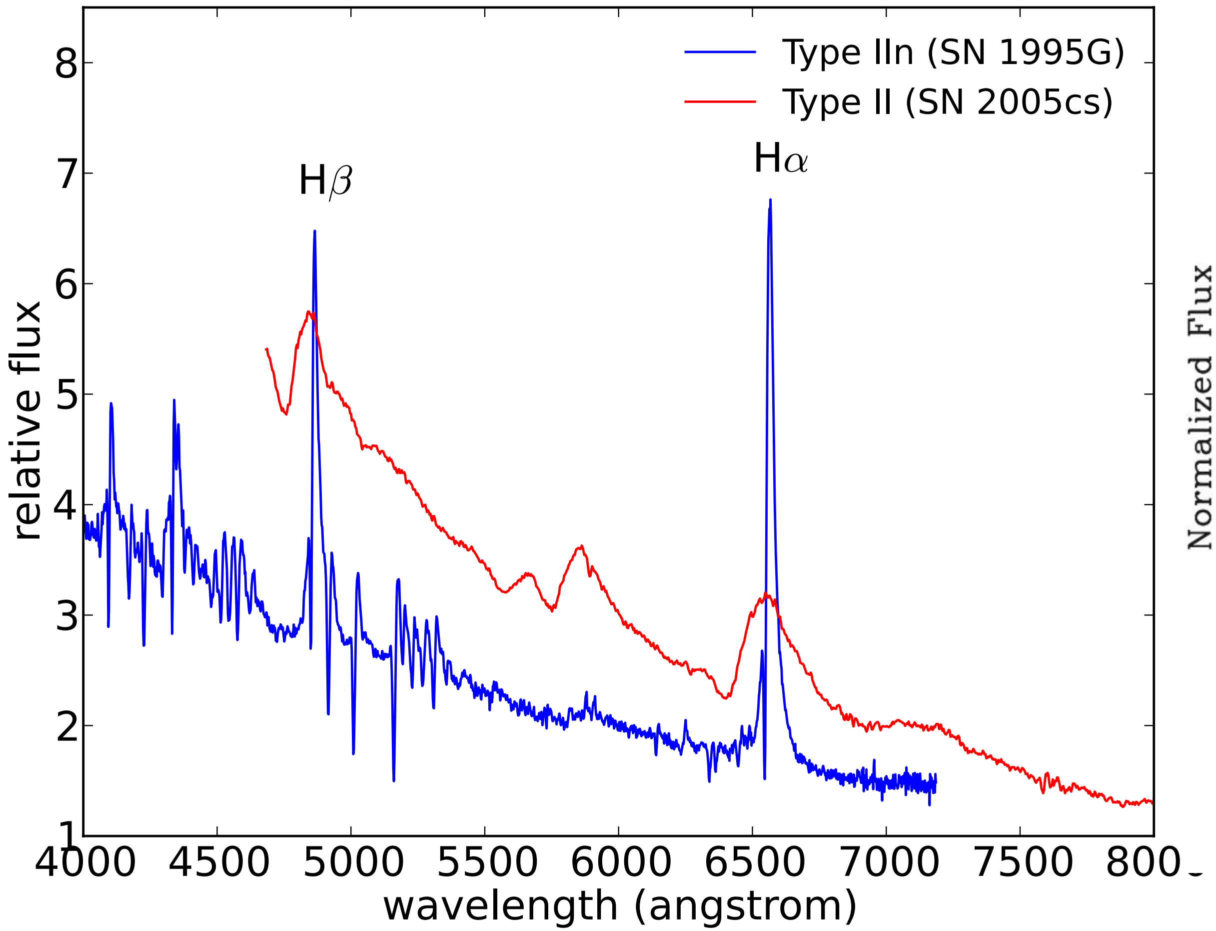
- dynamics is usually not affected at the beginning (at SN phase)
- electron acceleration at the shock
  - synchrotron emission



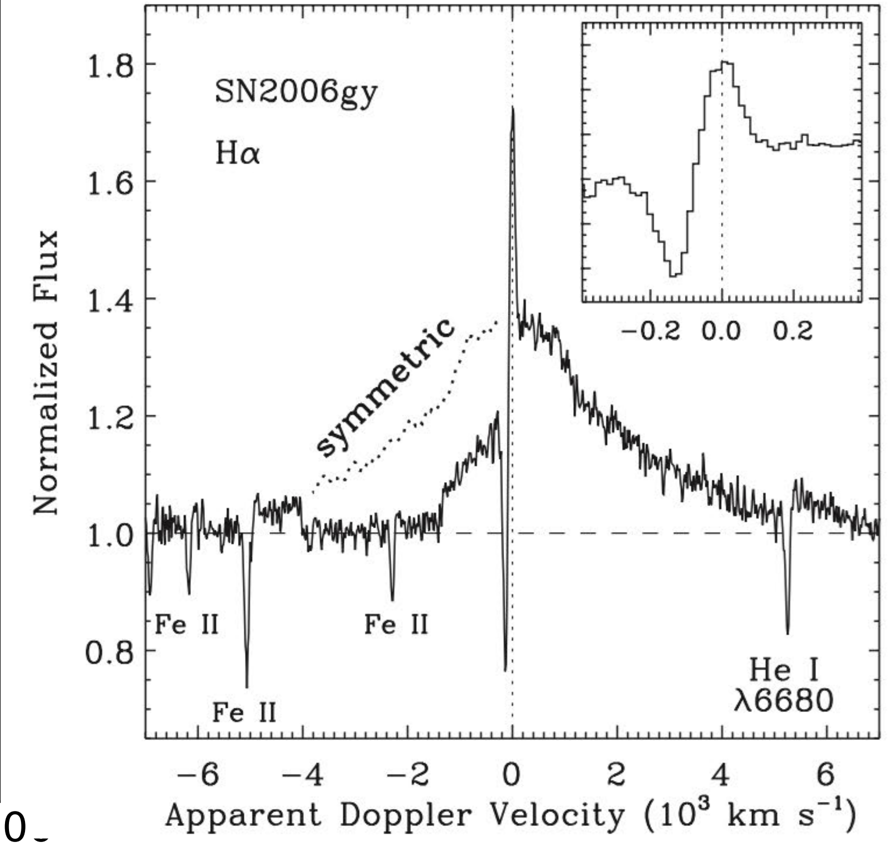


Type IIn supernovae

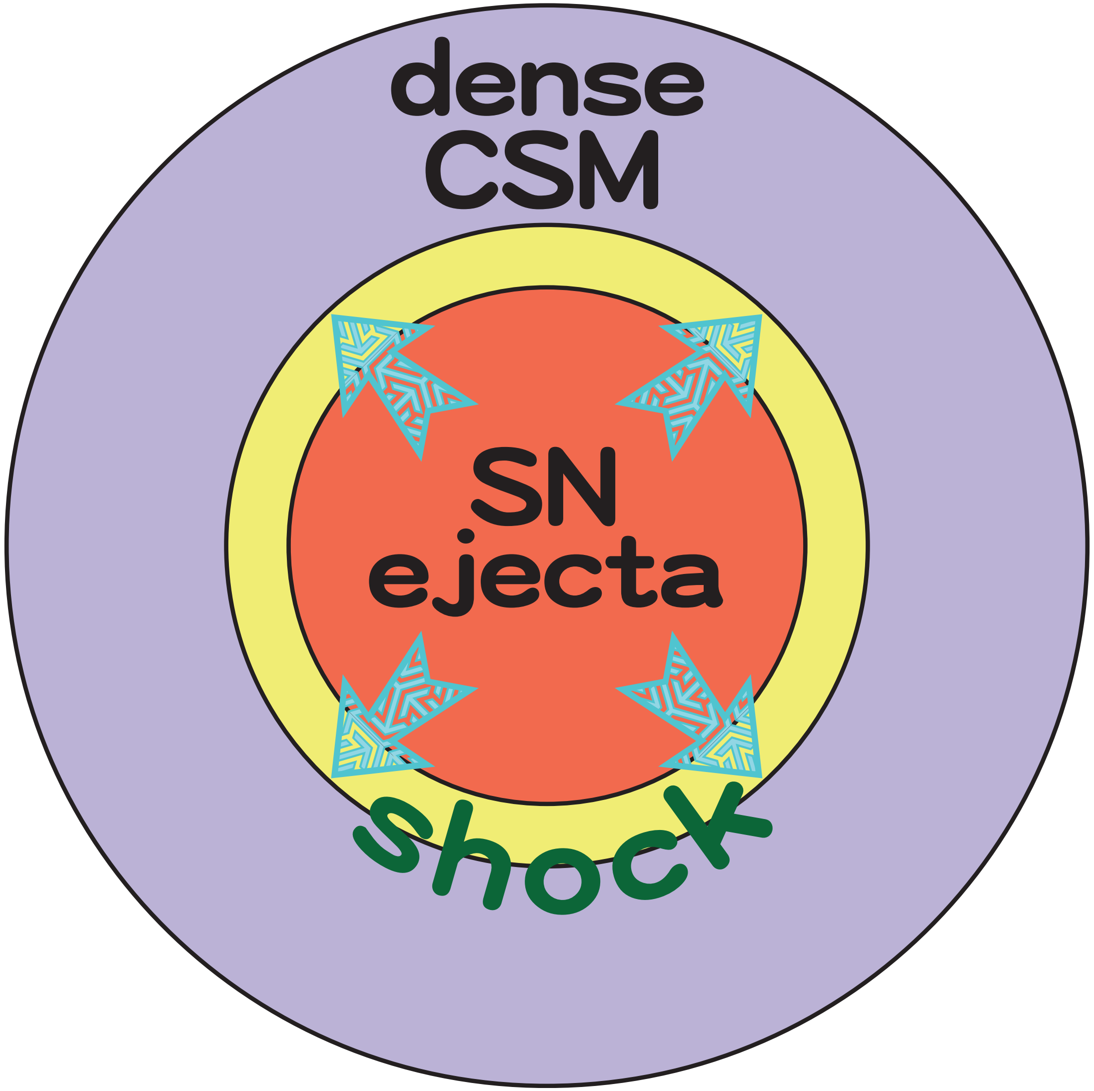
- outflow with ~ 100 km/s
  - too slow to be from SN ejecta (~ 10000 km/s)



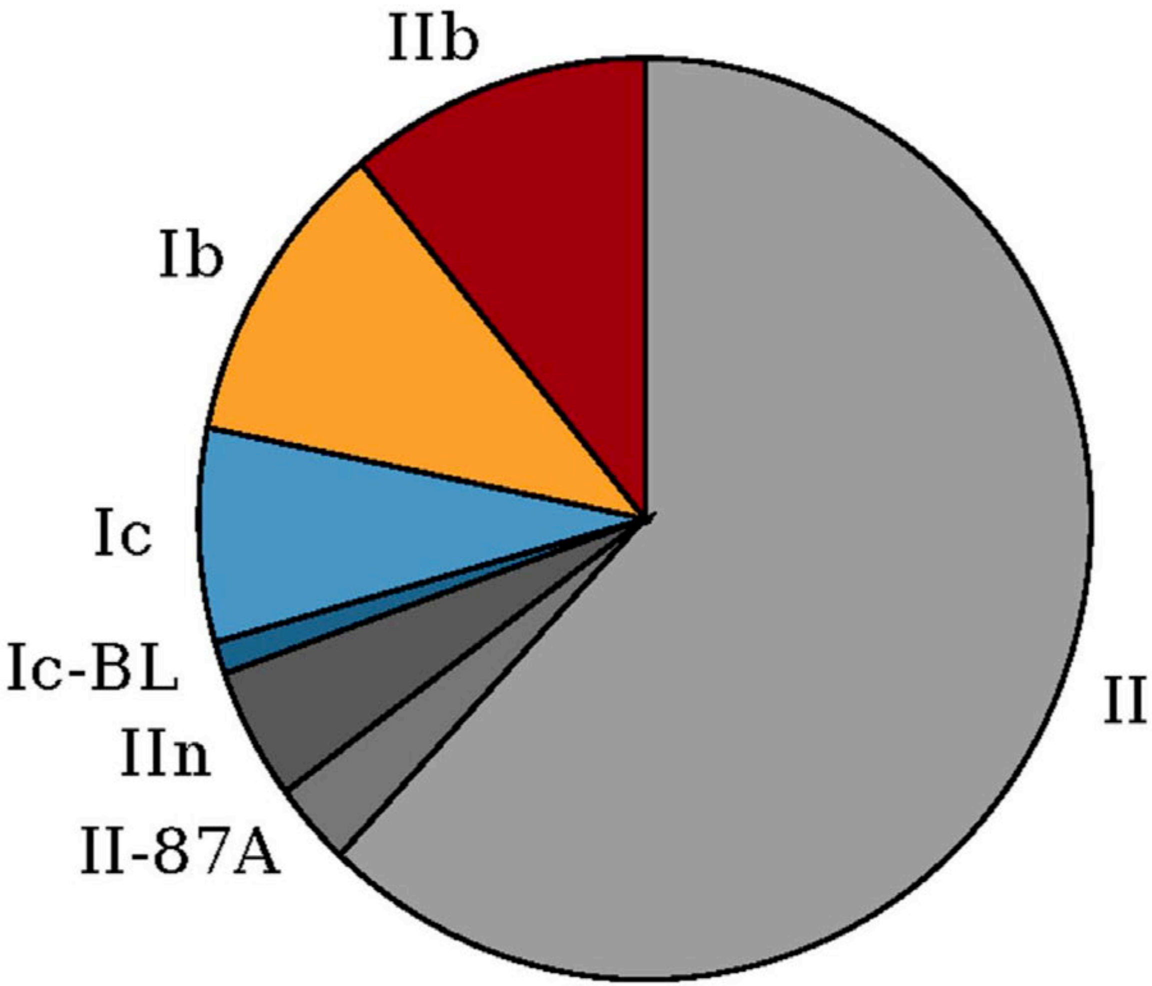
Smith et al. (2007)



Supernovae powered by circumstellar interaction

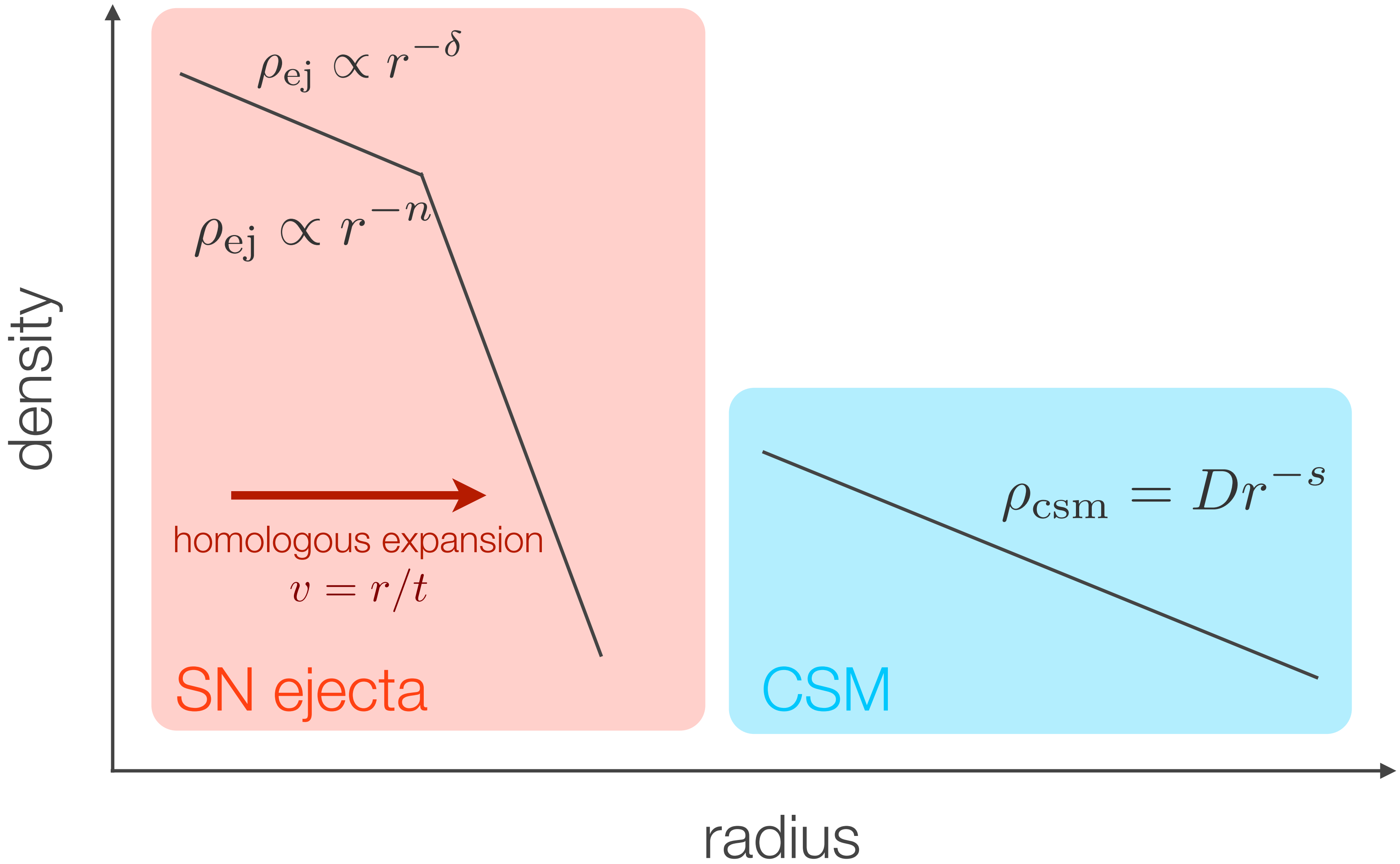


Type IIn supernova fraction



Shivvers et al. (2017)

Interaction between SN ejecta and dense CSM



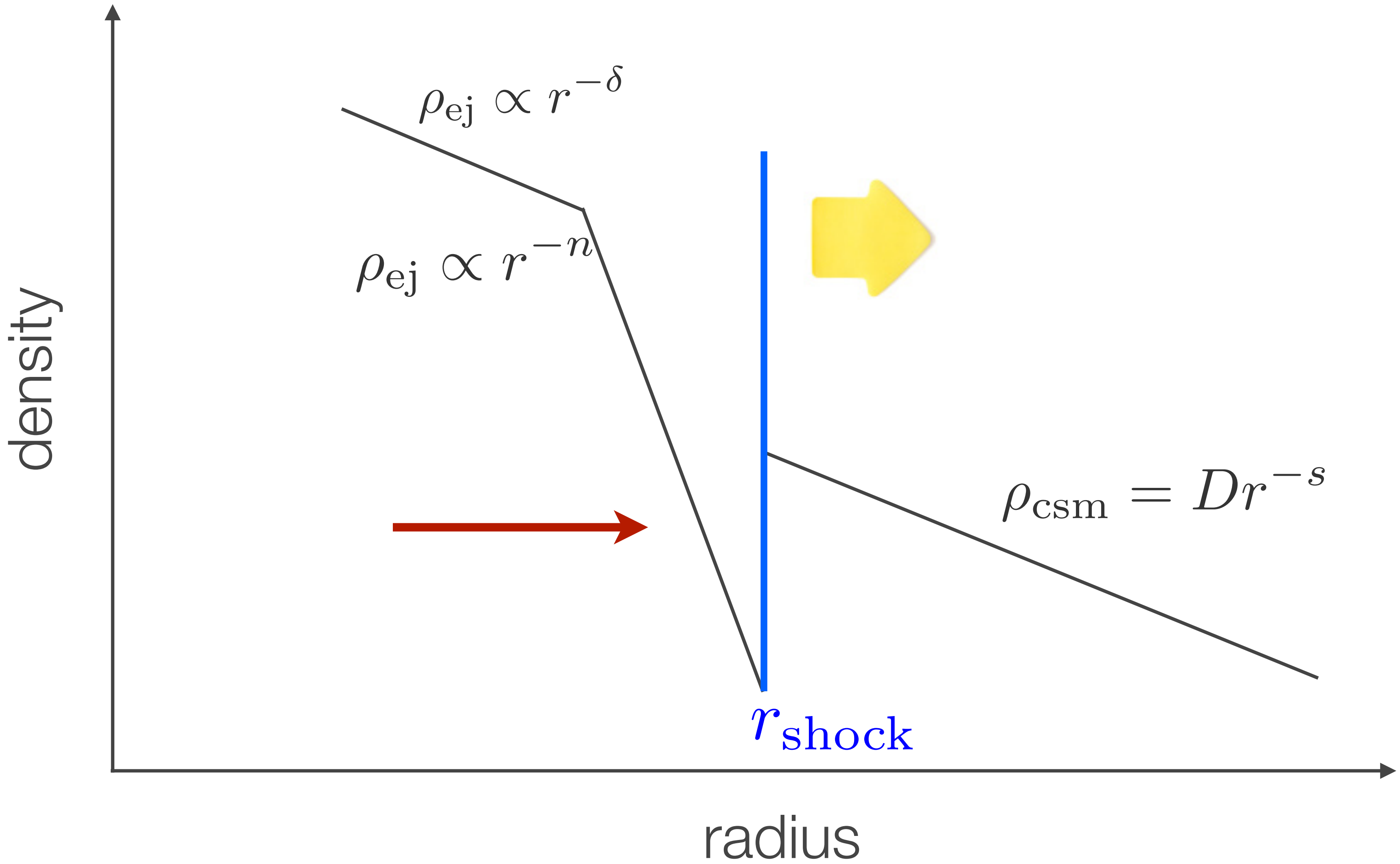
CSM density profile

$$dM = 4\pi r^2 \rho_{\mathrm{CSM}} dr$$

$$\dot{M} = 4\pi r^2 \rho_{\mathrm{CSM}} v_{\mathrm{wind}}$$

$$\rho_{\mathrm{CSM}} = \frac{\dot{M}}{4\pi v_{\mathrm{wind}}} r^{-2}$$

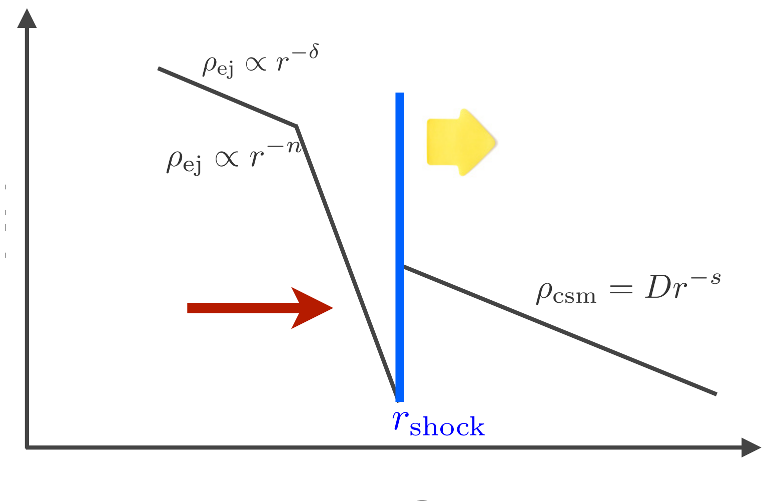
Interaction between SN ejecta and dense CSM



Analytic LC model for interaction-powered SNe

- conservation of momentum

$$M_{\mathrm{shock}} \frac{dv_{\mathrm{shock}}}{dt} = 4\pi r_{\mathrm{shock}}^2 \left[\underbrace{\boxed{\rho_{\mathrm{ej}} \left(v_{\mathrm{ej}} - v_{\mathrm{shock}}\right)^2}}_{\text{momentum injection from SN ejecta}} - \underbrace{\boxed{\rho_{\mathrm{csm}} \left(v_{\mathrm{shock}} - v_{\mathrm{w}}\right)^2}}_{\text{momentum injection from CSM}} \right]$$



Moriya et al. (2013a)

Analytic LC model for interaction-powered SNe

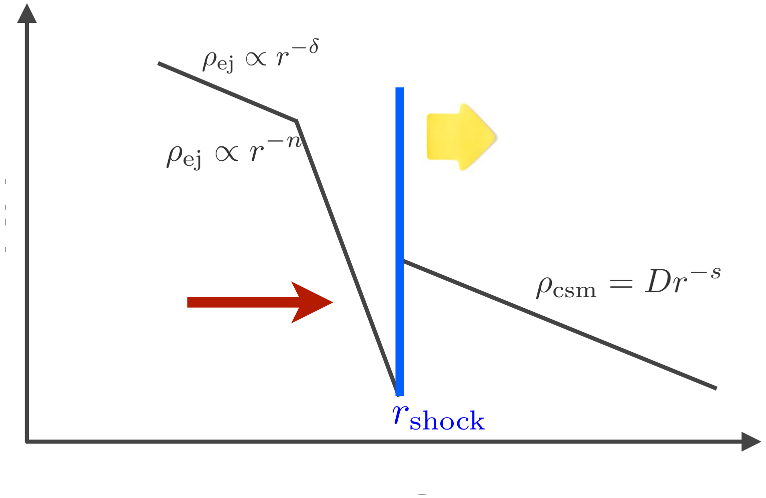
- conservation of momentum

$$M_{\rm shock}\frac{dv_{\rm shock}}{dt} = 4\pi r_{\rm shock}^2 \left[\boxed{\rho_{\rm ej}\left(v_{\rm ej}-v_{\rm shock}\right)^2} - \boxed{\rho_{\rm csm}\left(v_{\rm shock}-v_{\rm w}\right)^2}\right]$$

momentum injection from SN ejecta

momentum injection from CSM

$$r_{\rm shock}(t) = At^{\frac{n-3}{n-s}}$$



Moriya et al. (2013a)

Analytic LC model for interaction-powered SNe

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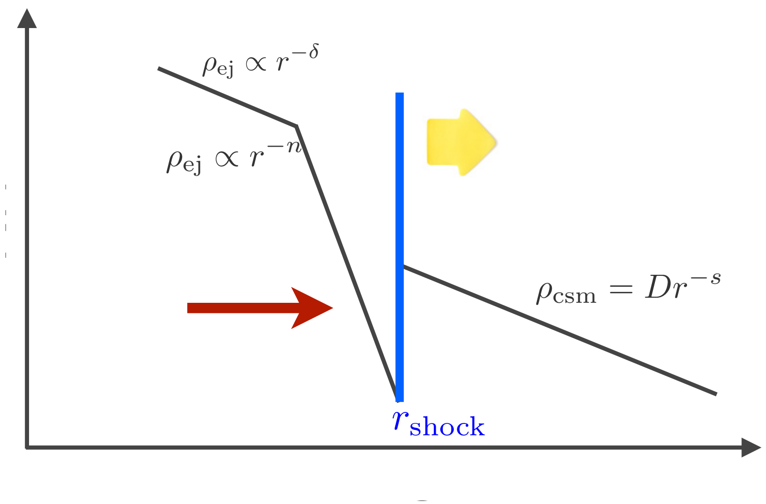
momentum injection from SN ejecta

momentum injection from CSM



$$\downarrow$$

$$r_{\mathrm{shock}}(t) = At^{\frac{n-3}{n-s}}$$

$$\downarrow \quad L = \epsilon\frac{dE_{\mathrm{kin}}}{dt} = 2\pi\epsilon\rho_{\mathrm{csm}} r_{\mathrm{shock}}^2 v_{\mathrm{shock}}^3$$

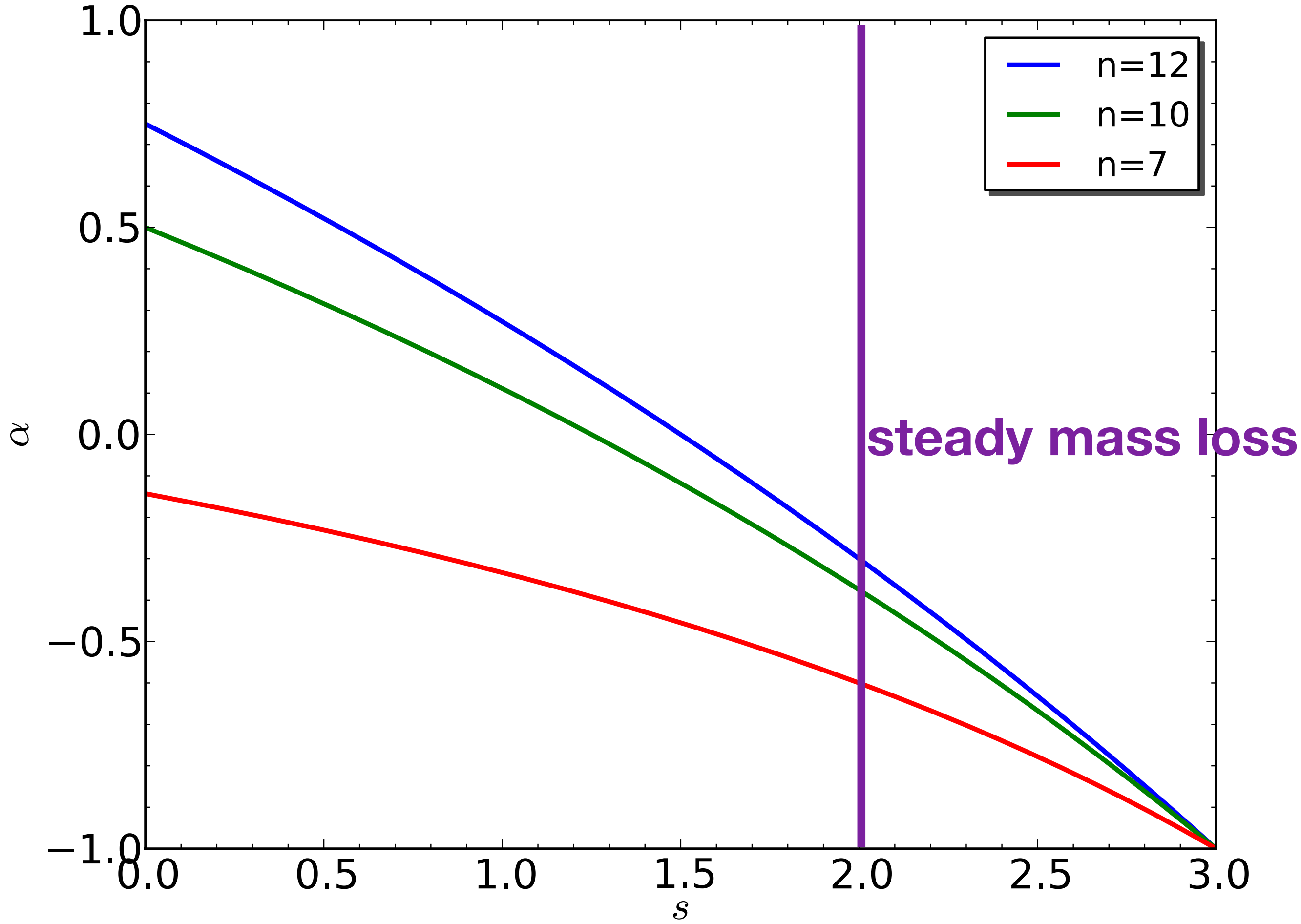
$$L = L_1 t^{\alpha}$$

$$\alpha = \frac{6s - 15 + 2n - ns}{n - s}$$

Moriya et al. (2013a)

Analytic LC model for interaction-powered SNe

$$L = L_1 t^{\alpha} \quad \alpha = \frac{6s - 15 + 2n - ns}{n - s}$$

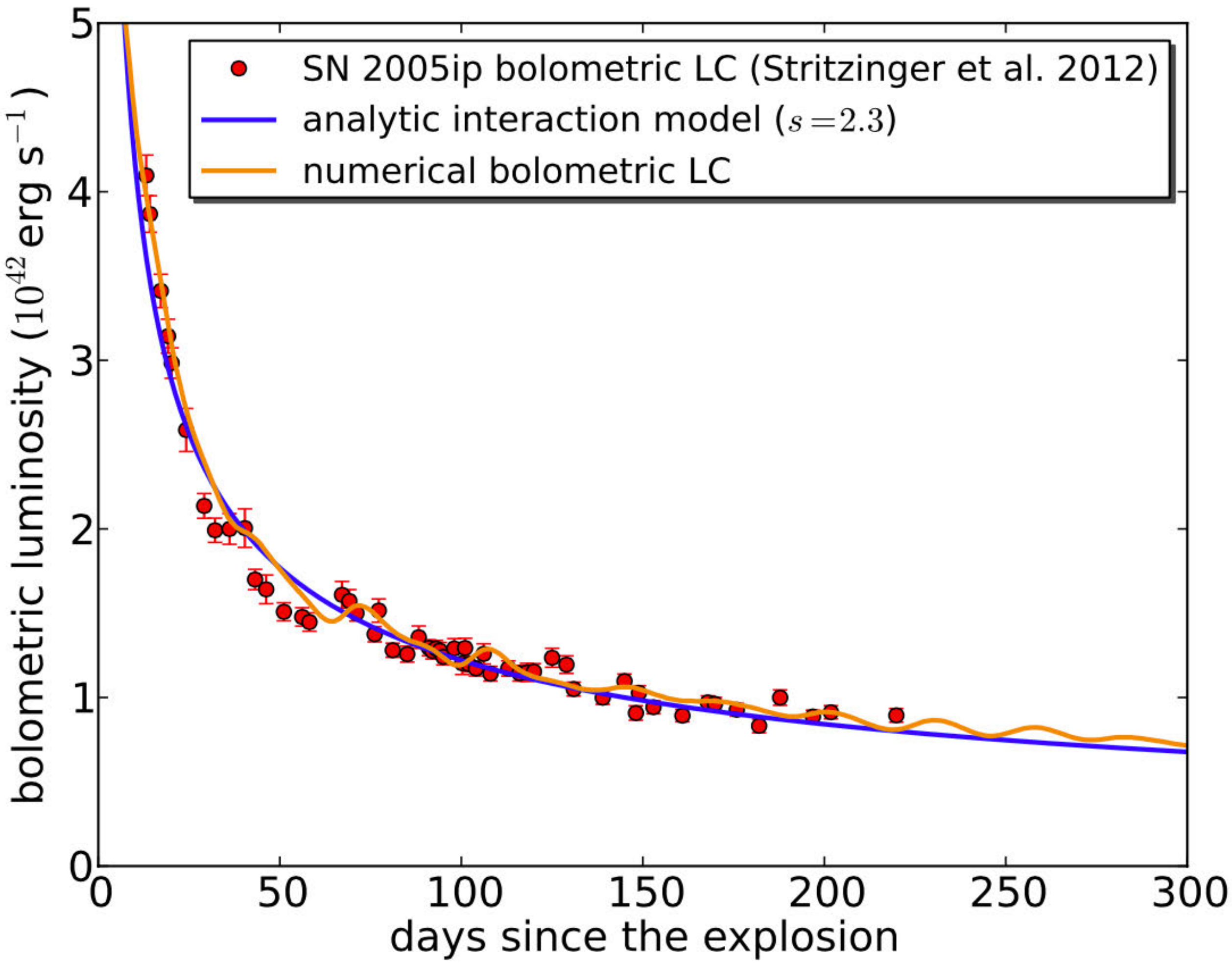


n = 9 (WR explosions), n = 12 (RSGs)

Moriya et al. (2013a)

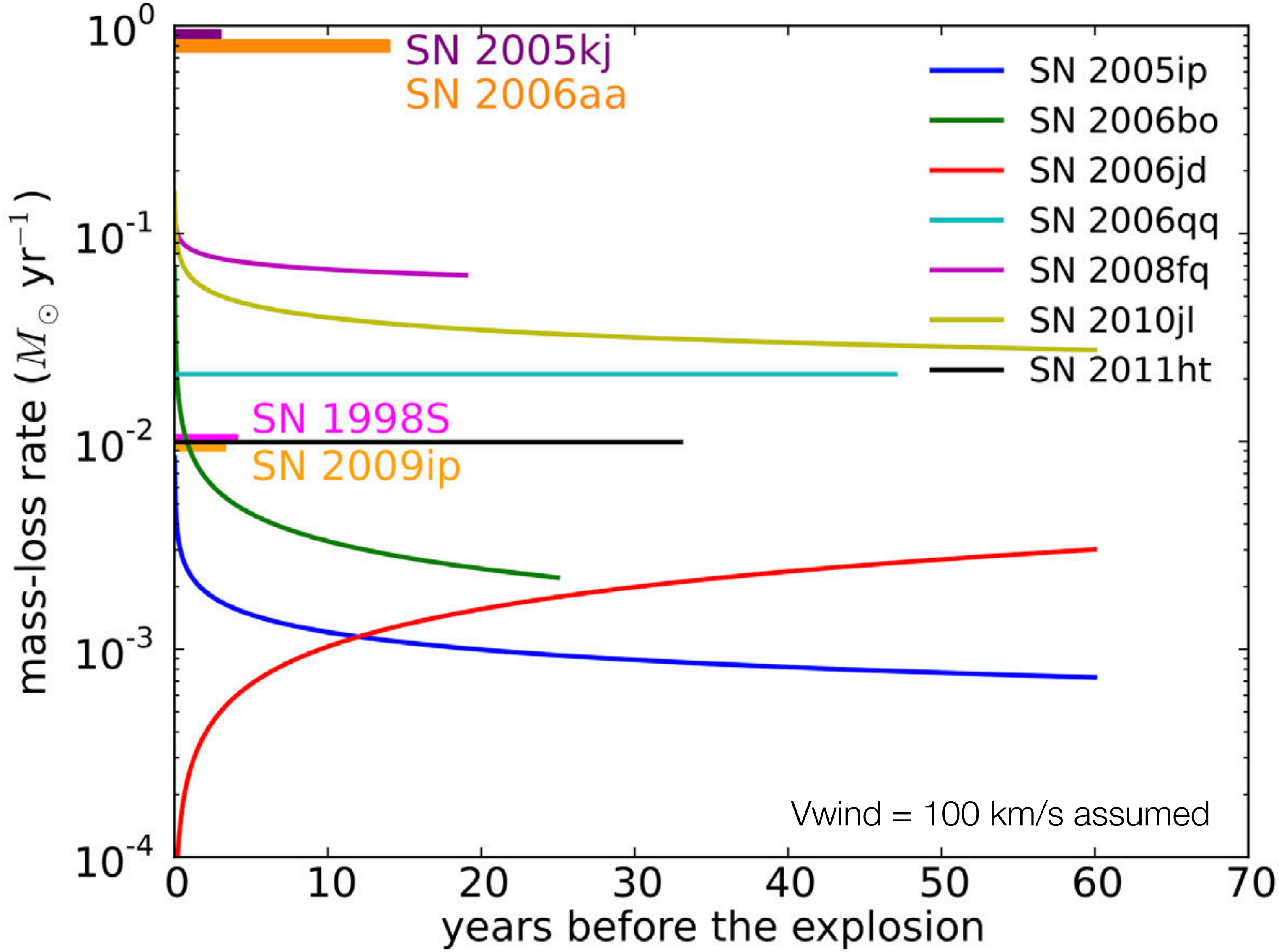
Light curve of Type IIn SNe

$$L = 1.44 \times 10^{43} \left(\frac{t}{1\,\mathrm{day}} \right)^{-0.536} \ \mathrm{erg\,s^{-1}}$$



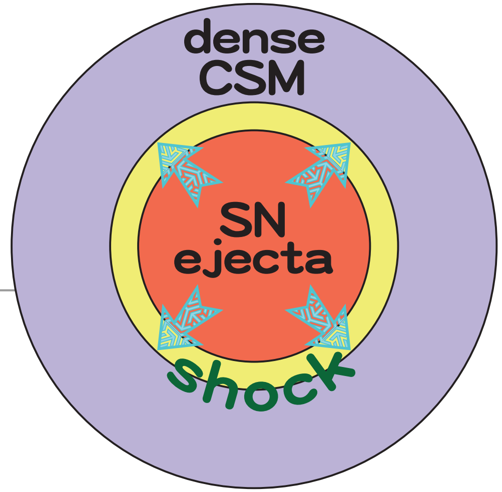
Moriya et al. (2013a)

Type IIn SNe

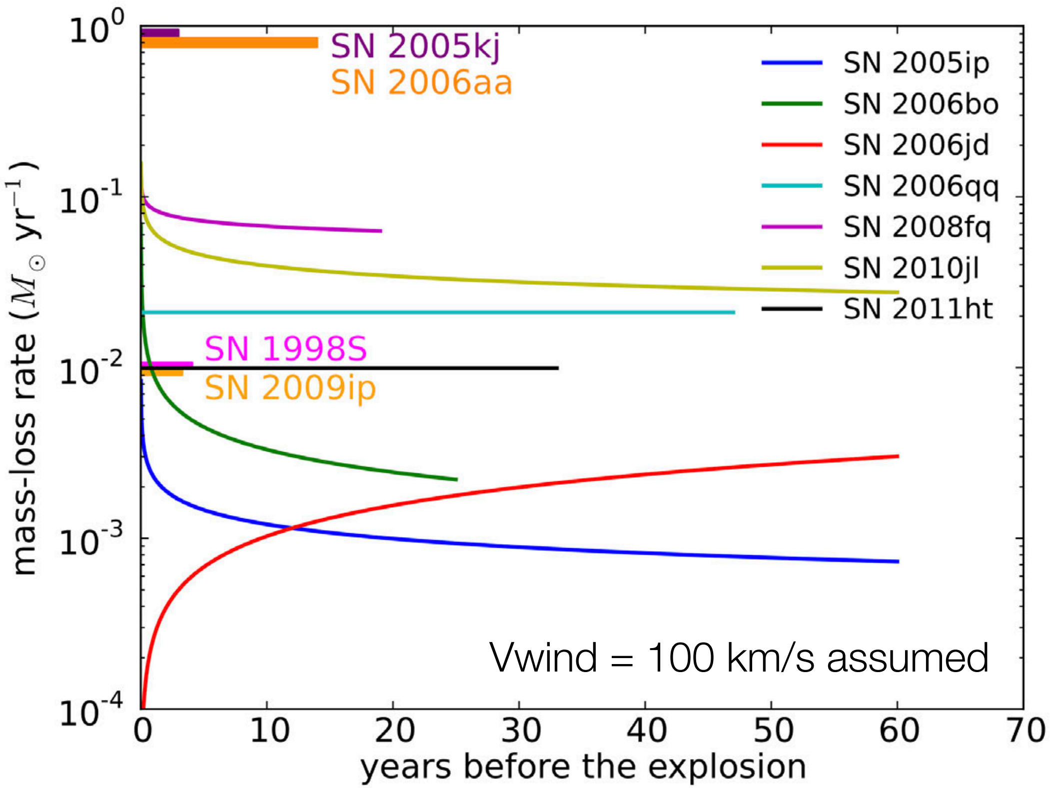


Moriya et al. (2014)

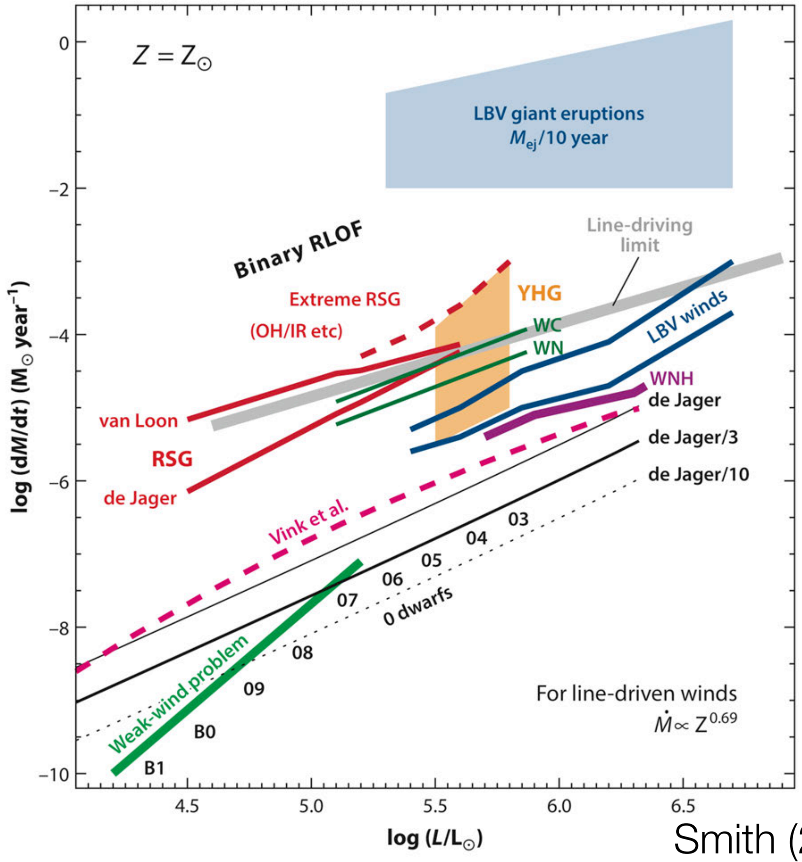
Type IIn SNe



- interaction often continues more than several years
  - extended dense CSM
- mass-loss increase of the progenitors should continue for at least several decades before the explosions: how?



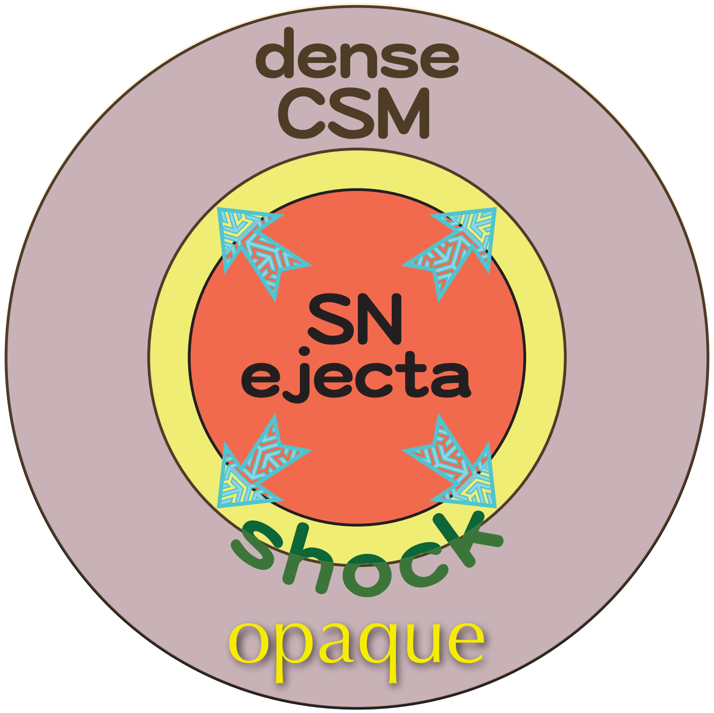
Moriya et al. (2014)



Smith (2014)

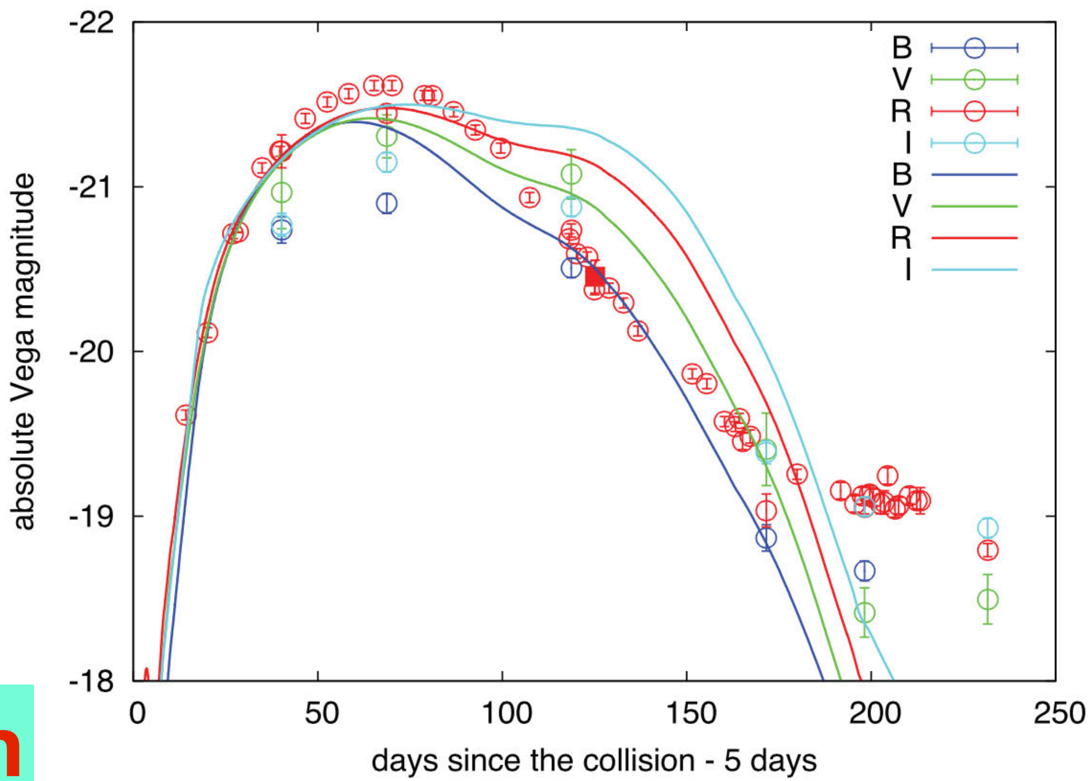
Photon diffusion in dense CSM

- photon diffuses in dense CSM



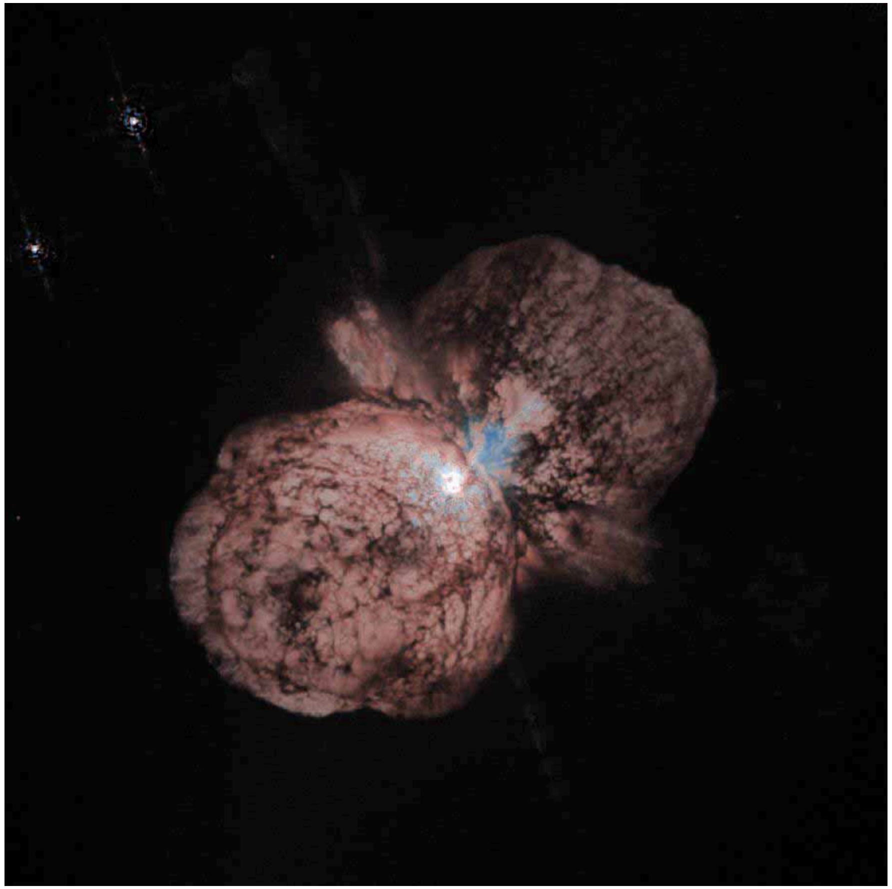
SN 2006gy

- Moriya et al. (2013b), Chatzopoulos et al. (2013), etc.



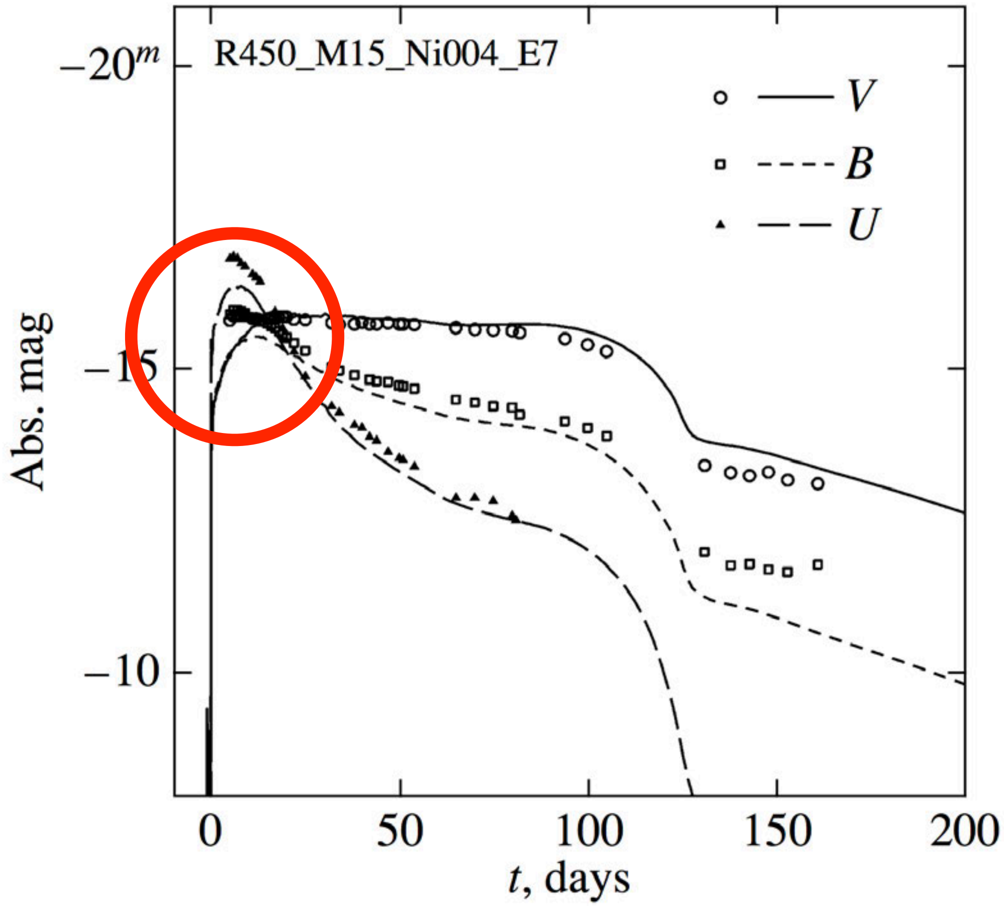
Mysteries

- How can we obtain such large mass loss?
  - only known star with ~ 0.1-1 Msun/yr: eta Carinae
    - during the Great Eruption for about 10 years



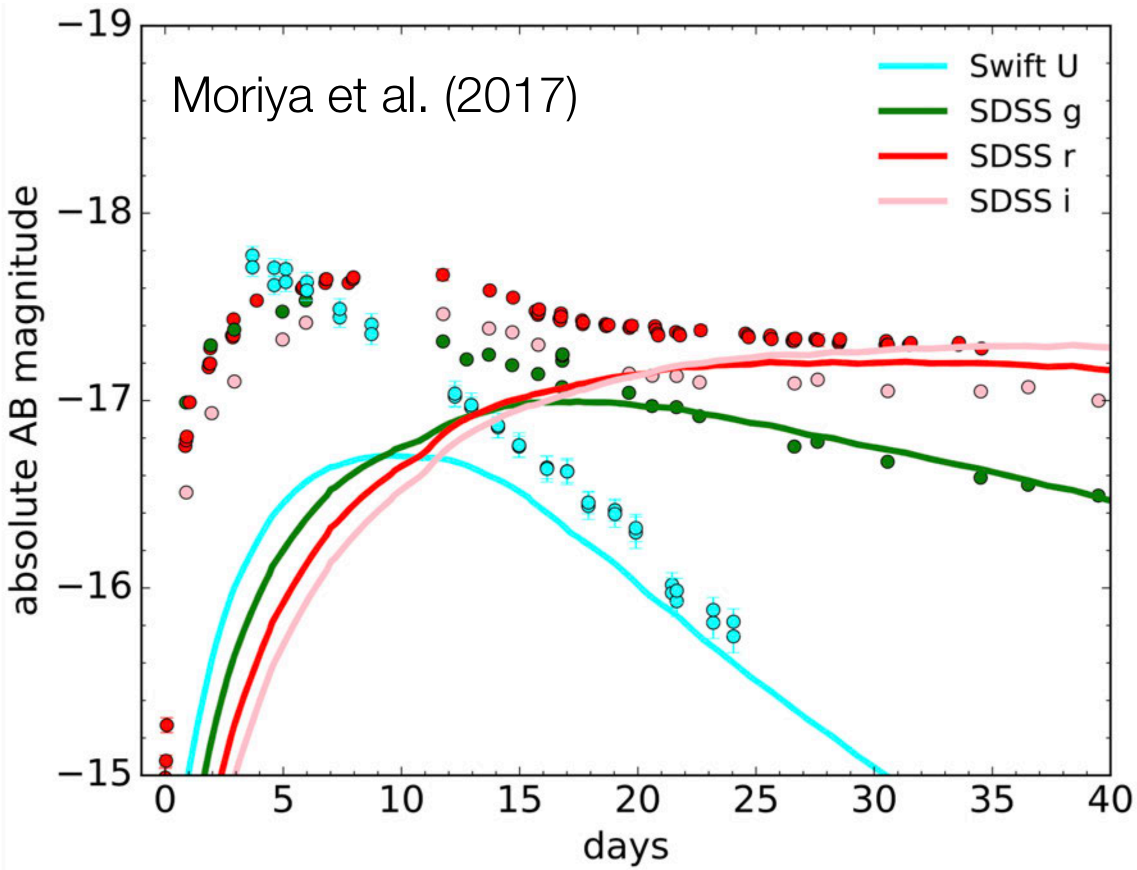
Ordinary Type II supernova light curves

Baklanov et al. (2005)



Optical rise time of Type II supernovae

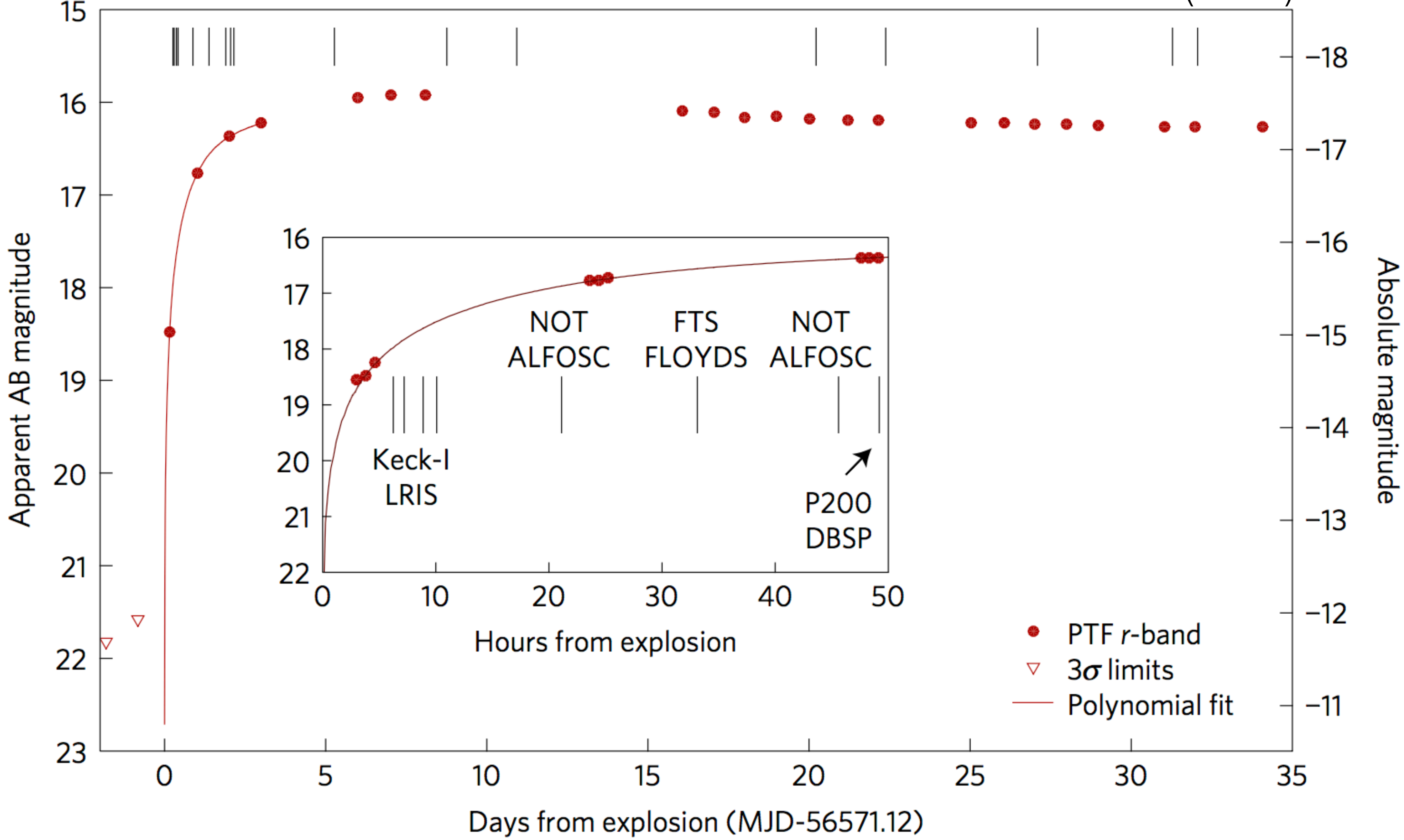
- observed optical rise time is short (~ 10 days, Gonzales+'15, Rubin+'16)
  - optical rise time is determined by the adiabatic cooling timescale
  - rise times obtained from RSG progenitor models are > 10 days
    - RSG radii are more than 500 Rsun



SN 2013fs: SN II discovered shortly after explosion

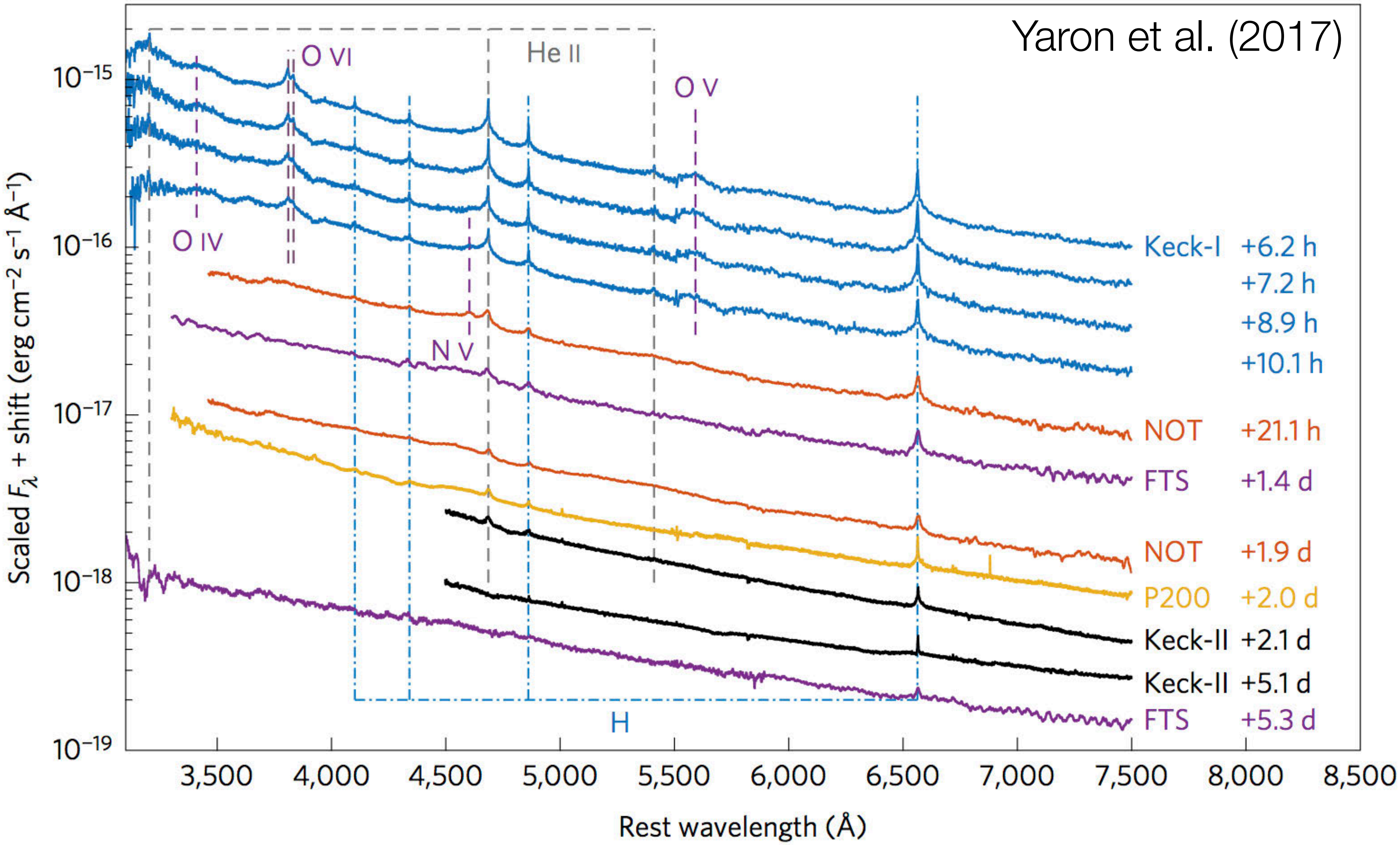
- discovered at ~ 3 hours after the explosion

Yaron et al. (2017)

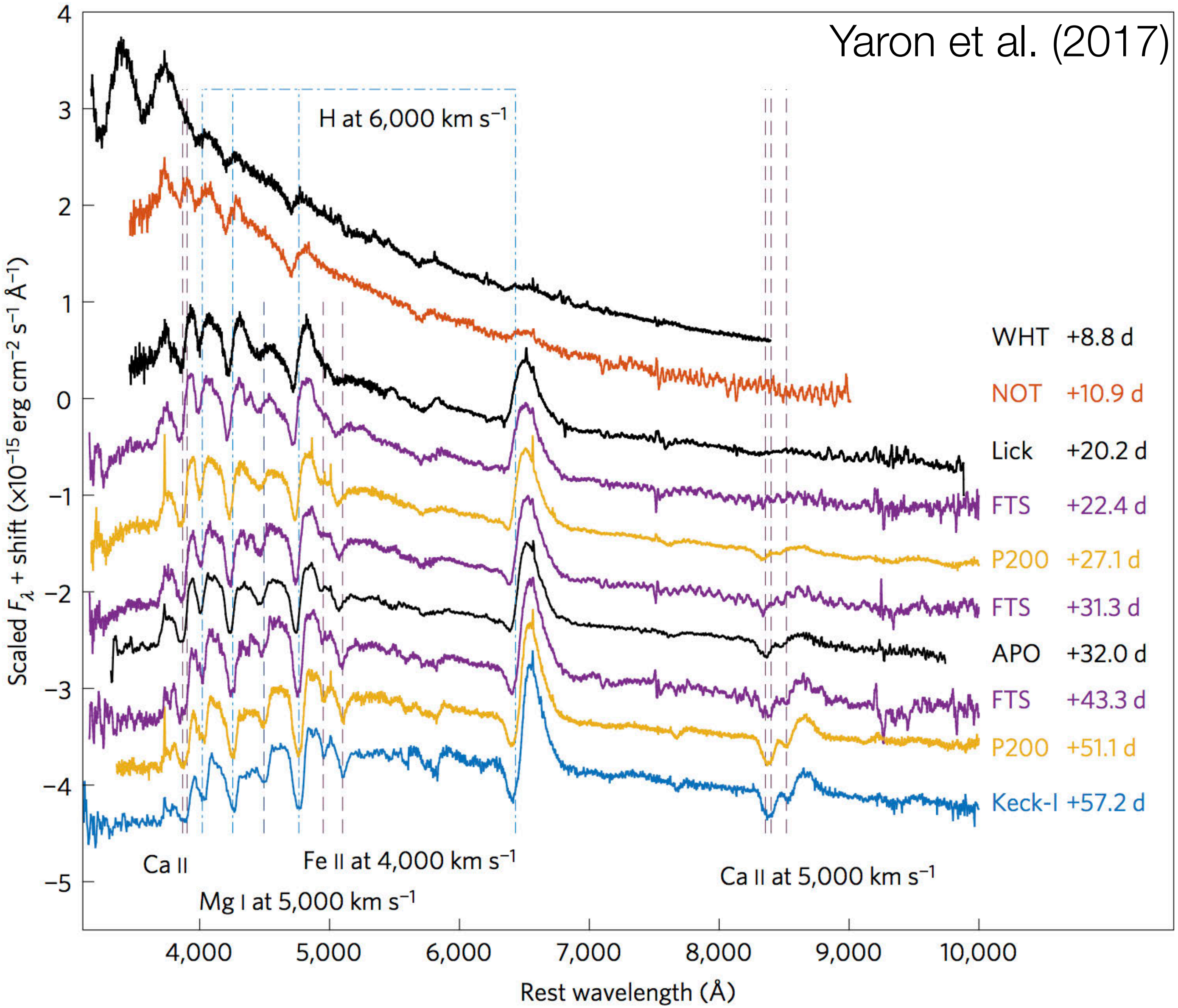


SN 2013fs: SN II discovered shortly after explosion

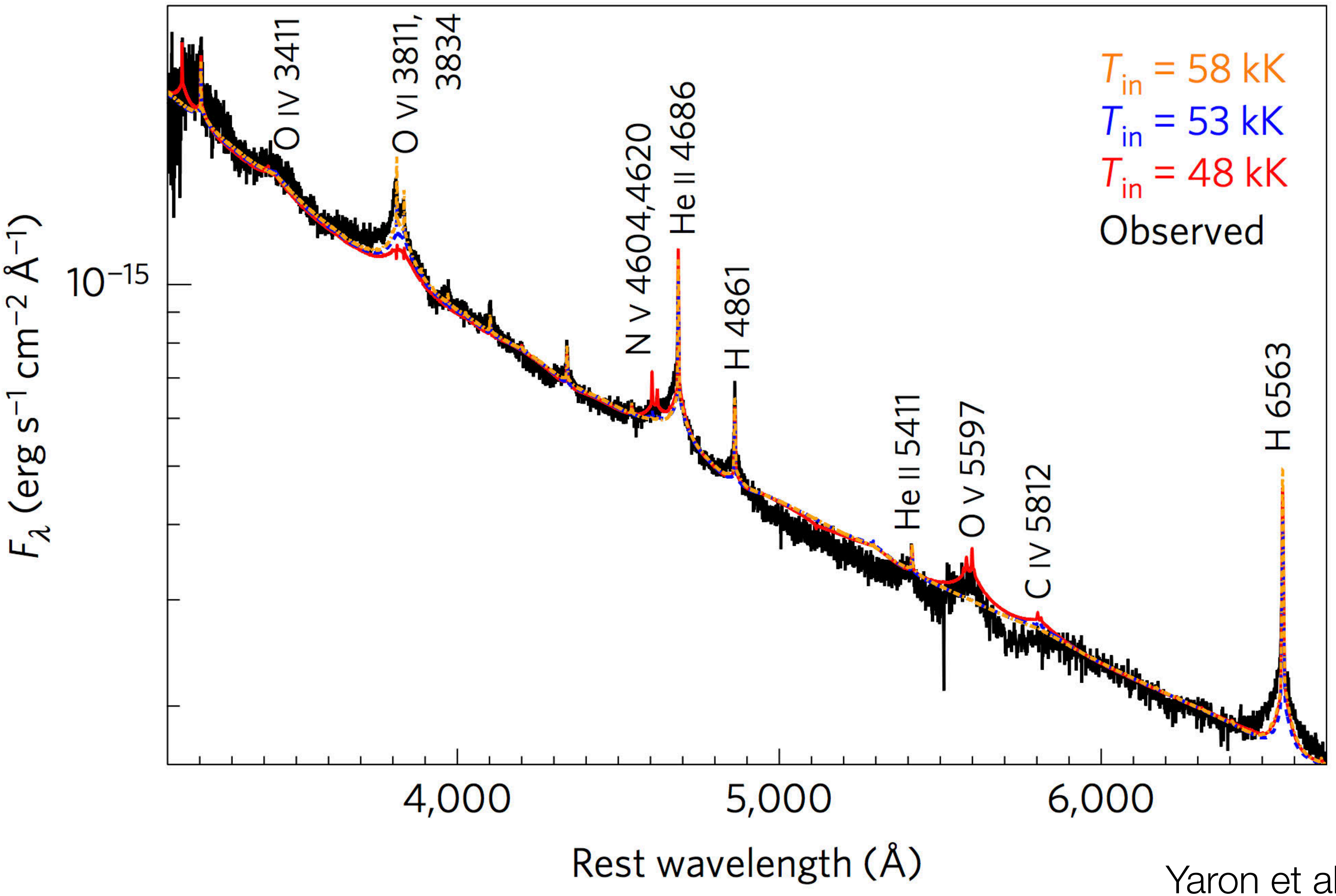
- first spectrum taken at ~ 6 hours after the explosion
  - very narrow hydrogen lines are observed



Early spectra of SN 2013fs

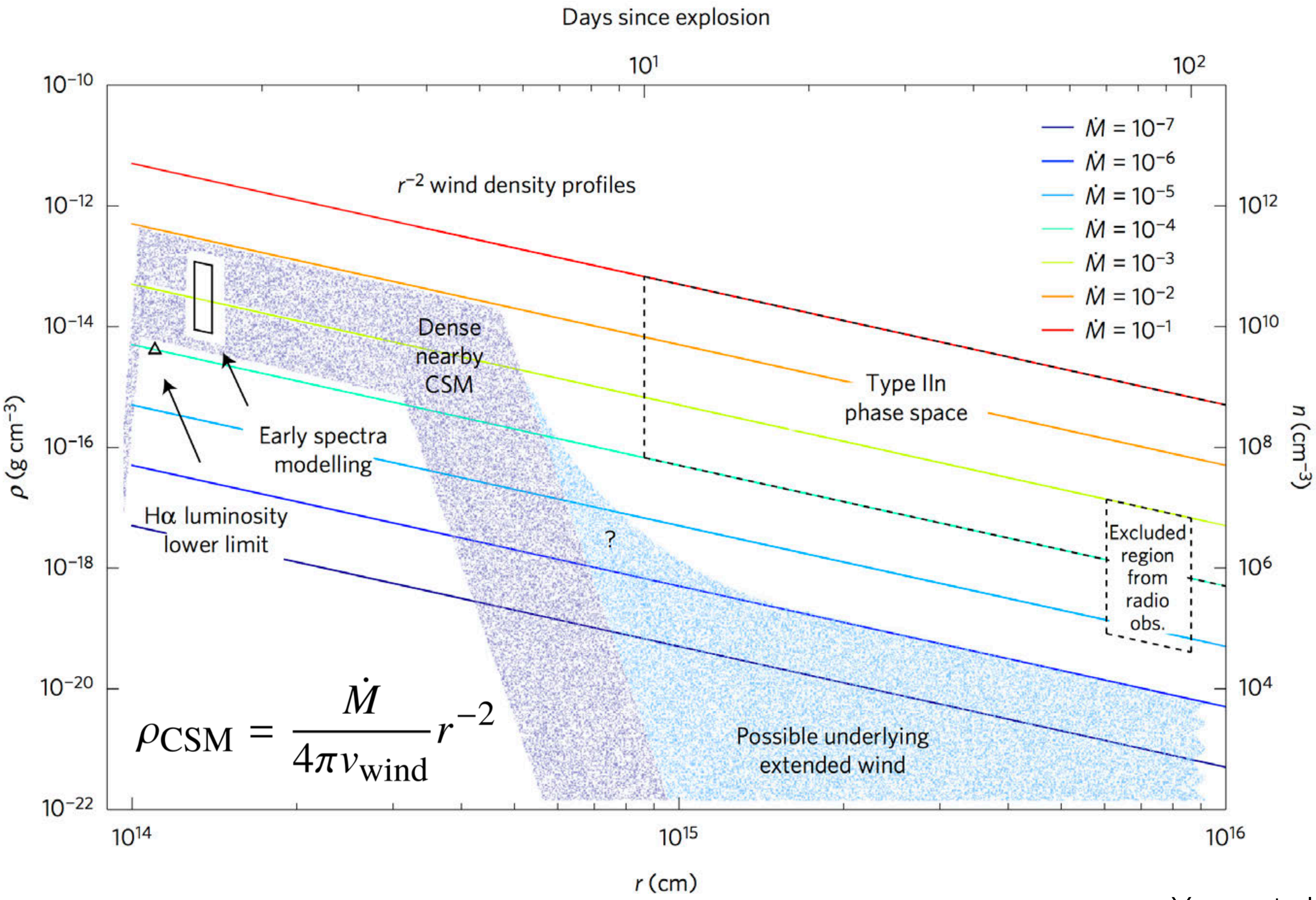


Modeling of the early spectrum



Yaron et al. (2017)

Dense CSM should exist just above the progenitor



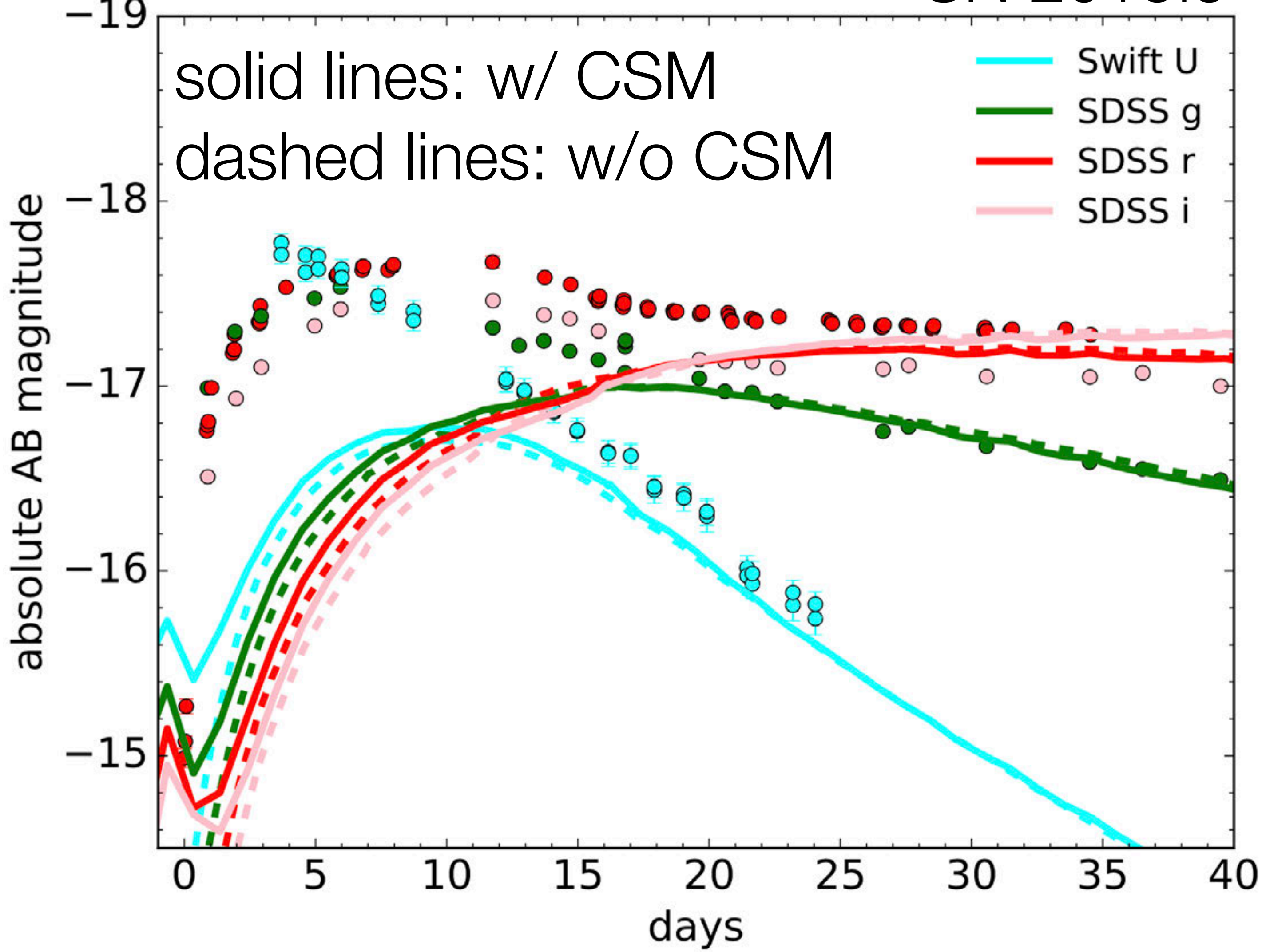
Yaron et al. (2017)

Circumstellar media (CSM)

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

- 10^{-5} Msun/yr, $v_{\rm wind}$ = 10 km/s, up to 10^{15} cm

SN 2013fs

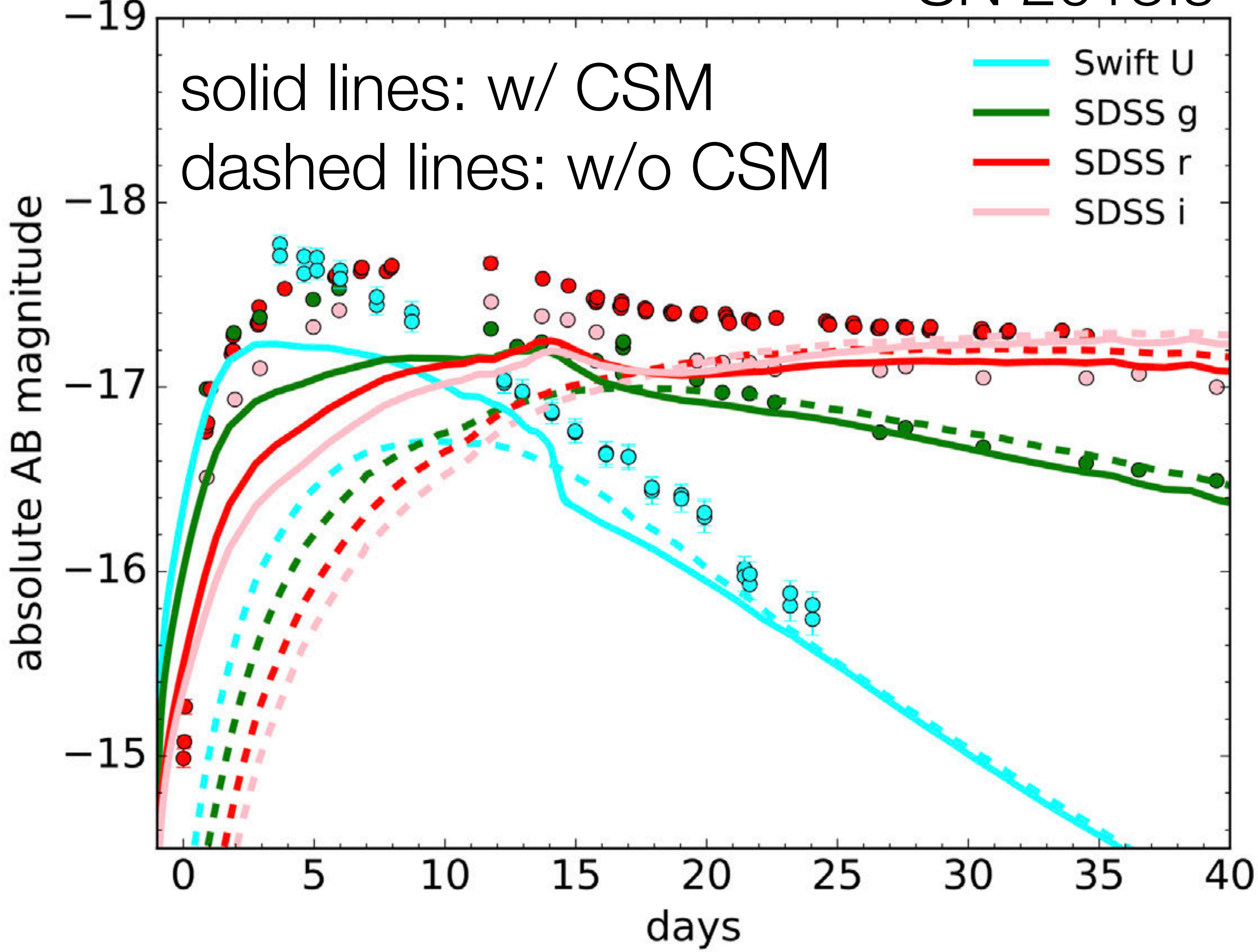


Circumstellar media (CSM)

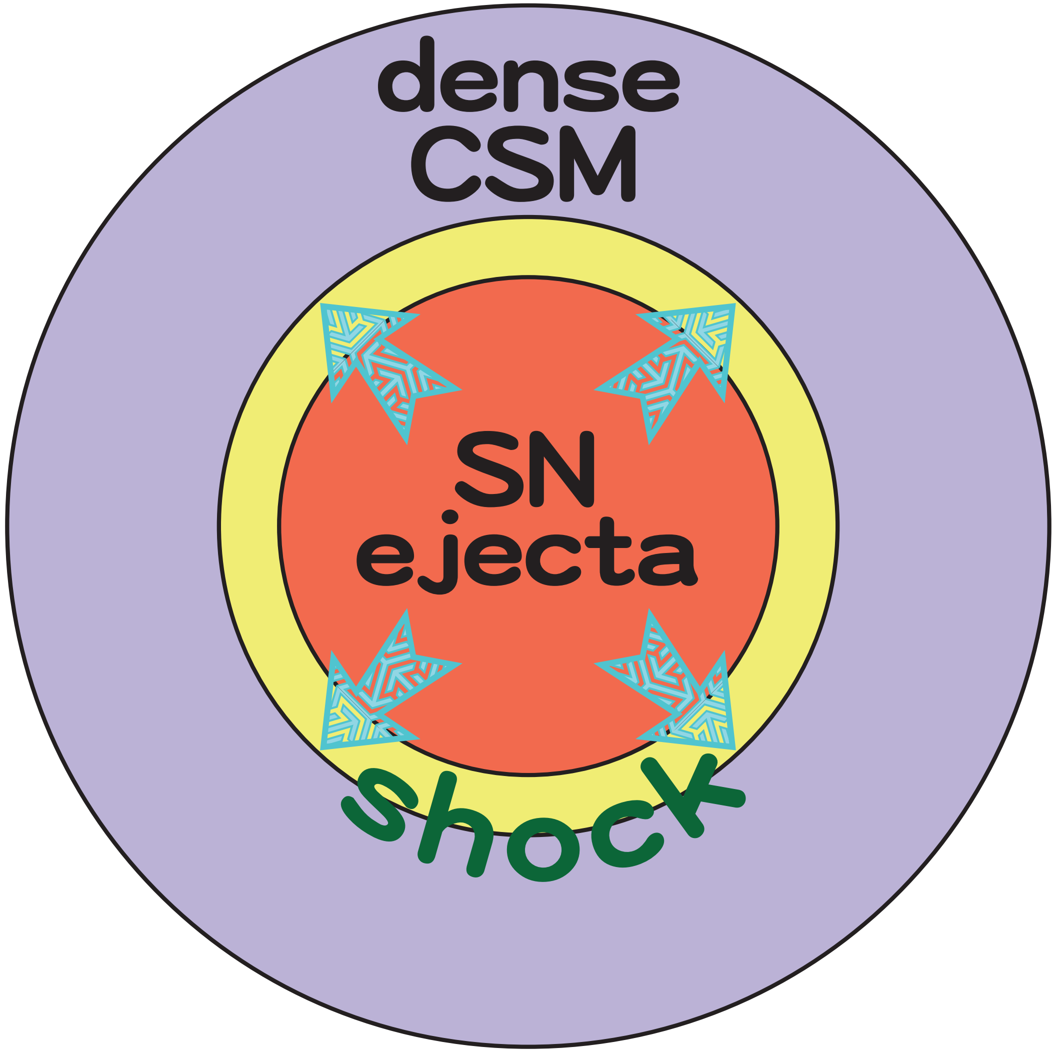
$$\rho_{\rm CSM} = \frac{\dot{M}}{4\pi v_{\rm wind}} r^{-2}$$

- 10^{-3} Msun/yr, $v_{\rm wind}$ = 10 km/s, up to 10^{15} cm

SN 2013fs



Interaction between SN ejecta and dense CSM

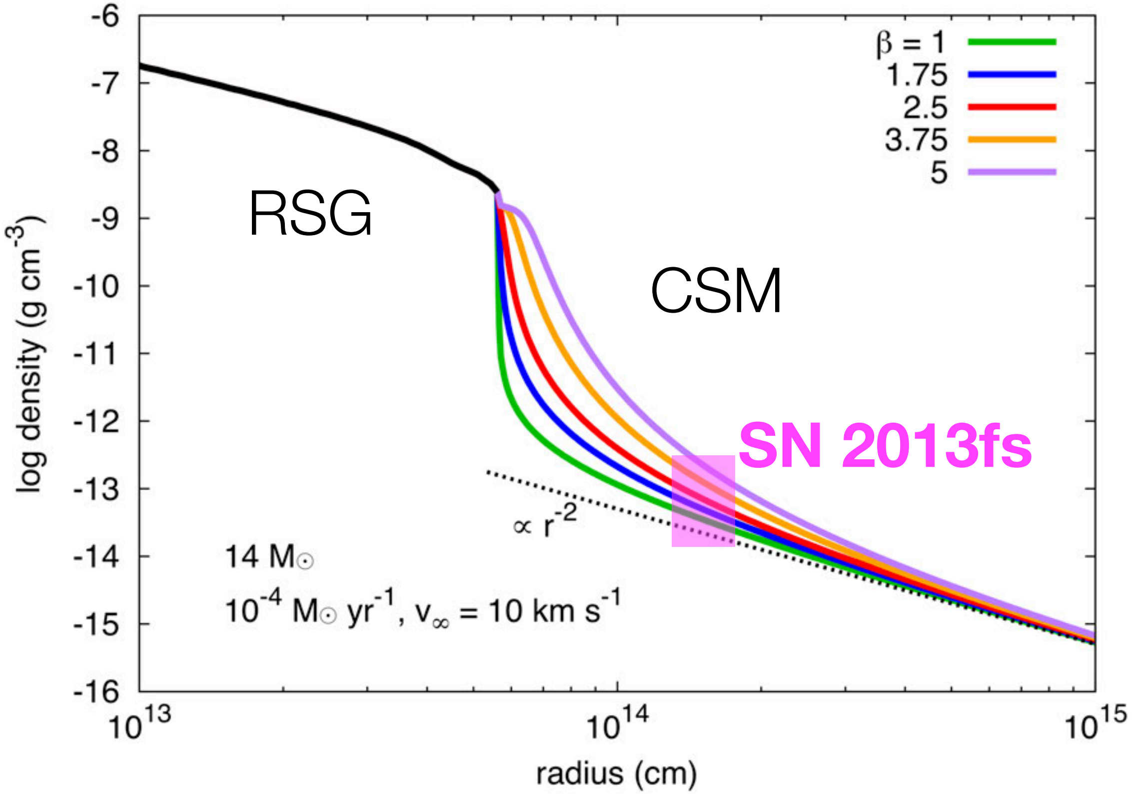


Shortly after explosion = progenitor vicinity

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

$$v_{\mathrm{wind}}(r) = v_0 + (v_\infty - v_0)\left(1 - \frac{R_\star}{r}\right)^{\beta}$$

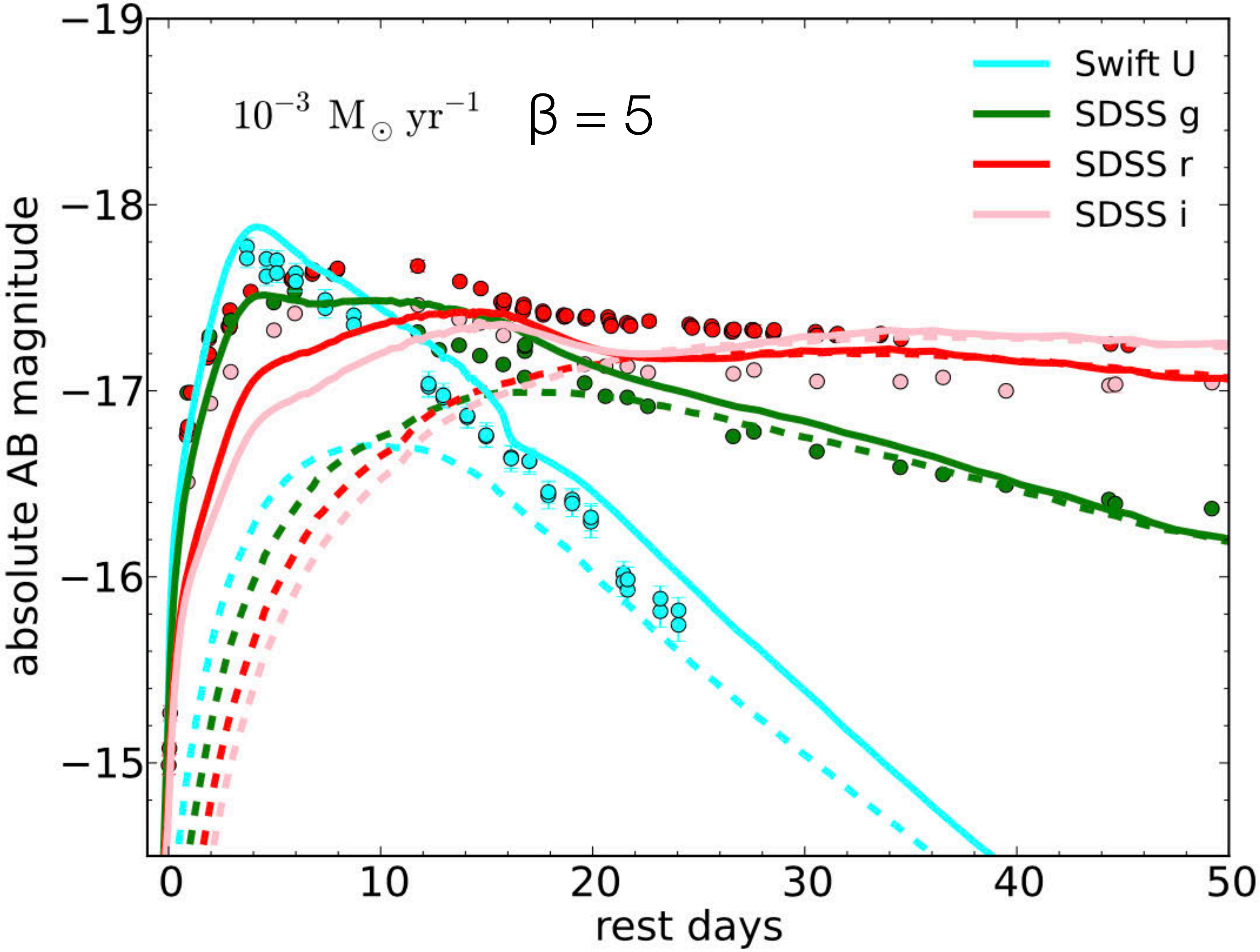
wind acceleration



Moriya et al. (2018)

Optical rise time of Type II supernovae

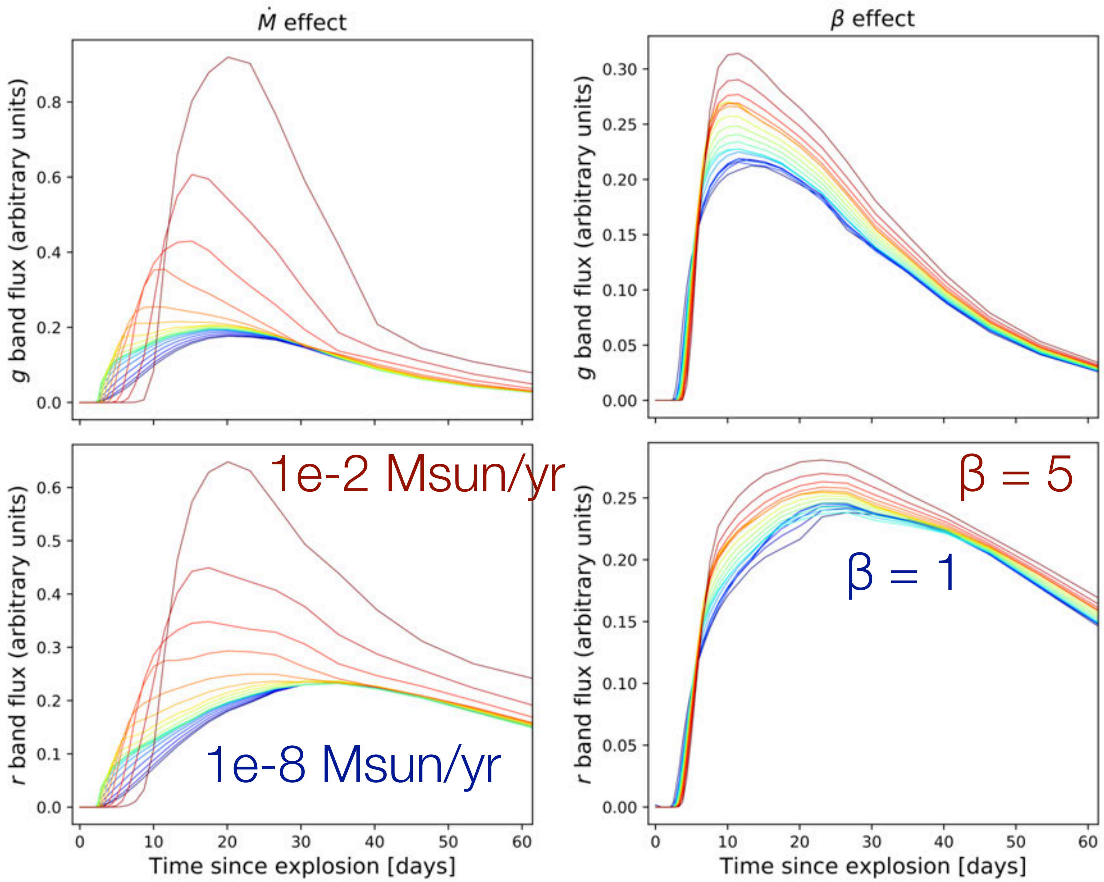
- rapid rise due to dense CSM



Moriya et al. (2017)

Systematic study of early Type II SN light curves

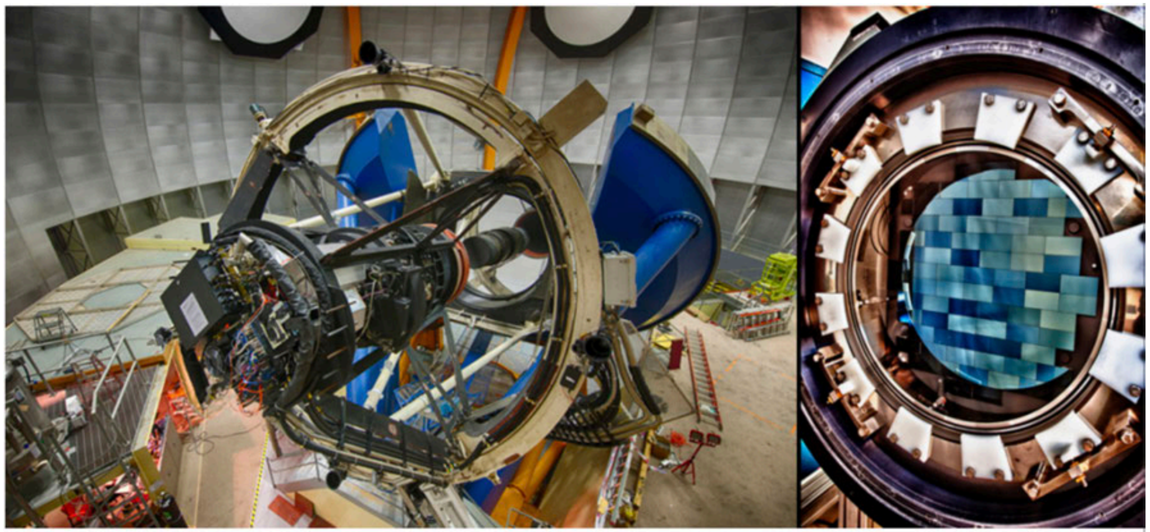
- calculations of early SN light curves with different mass loss rates and β
- progenitors and energies are also changed: about 600 models in total

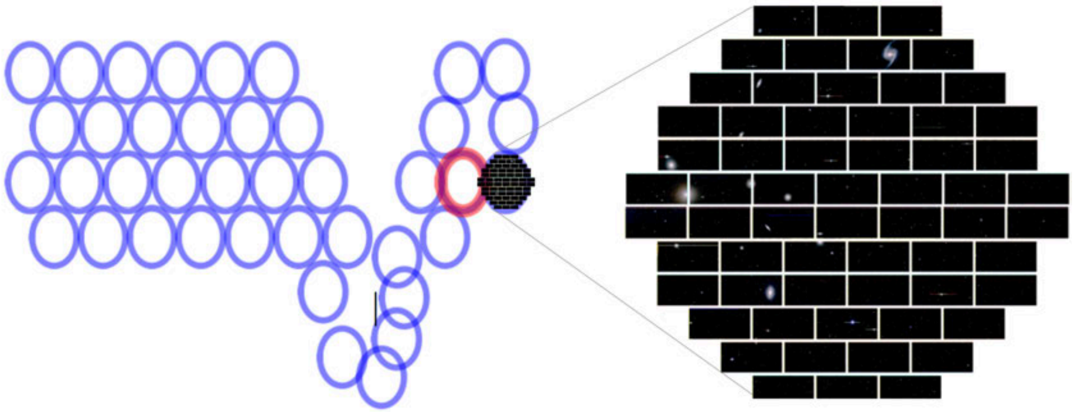


Förster, Moriya, et al. (2018)

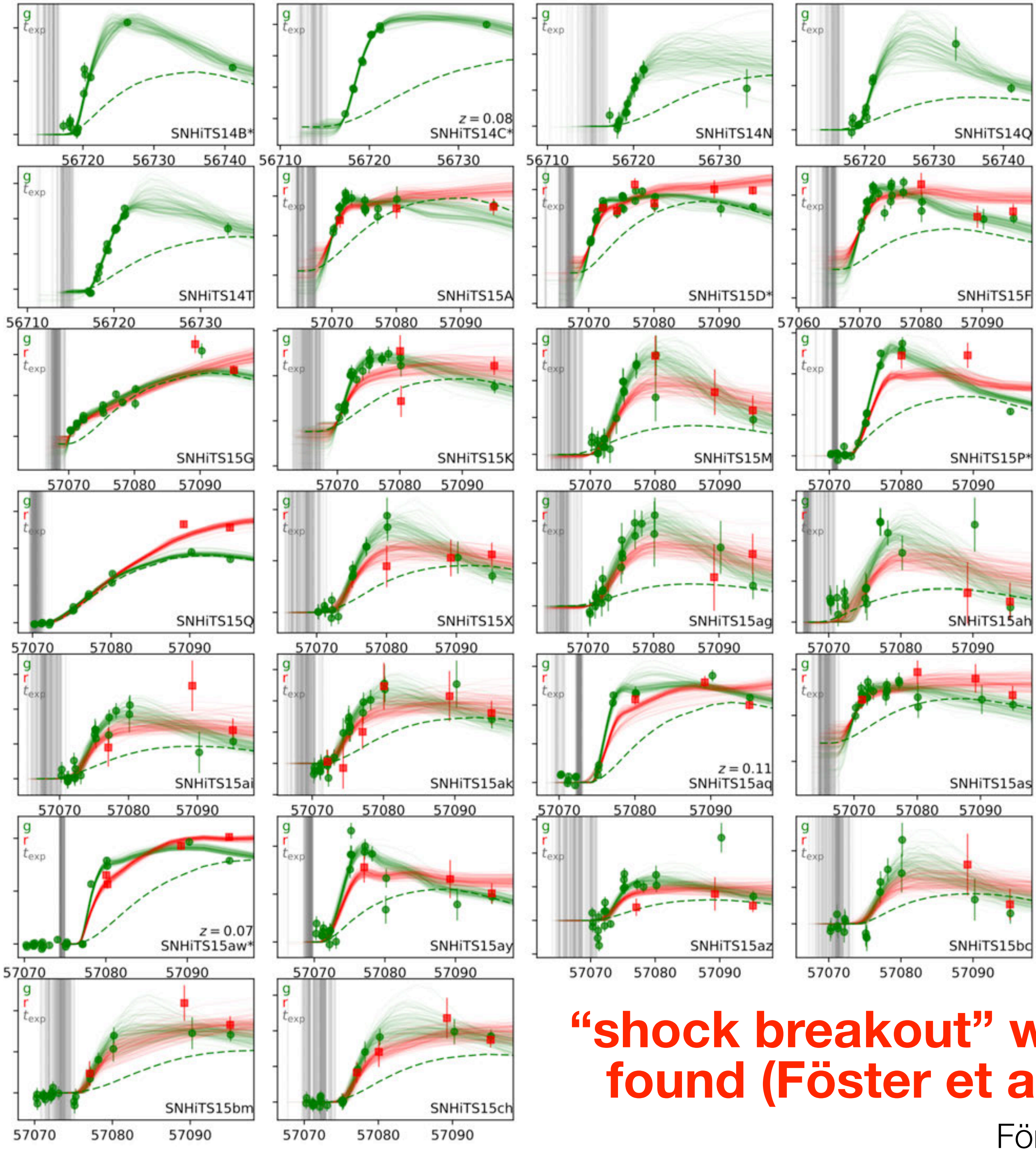
High cadence Transient Survey (HiTS)

- transient survey to find SNe just after the explosions using DECam
    - led by F. Förster in U. Chile
    - many Type II SNe shortly after the explosion are discovered





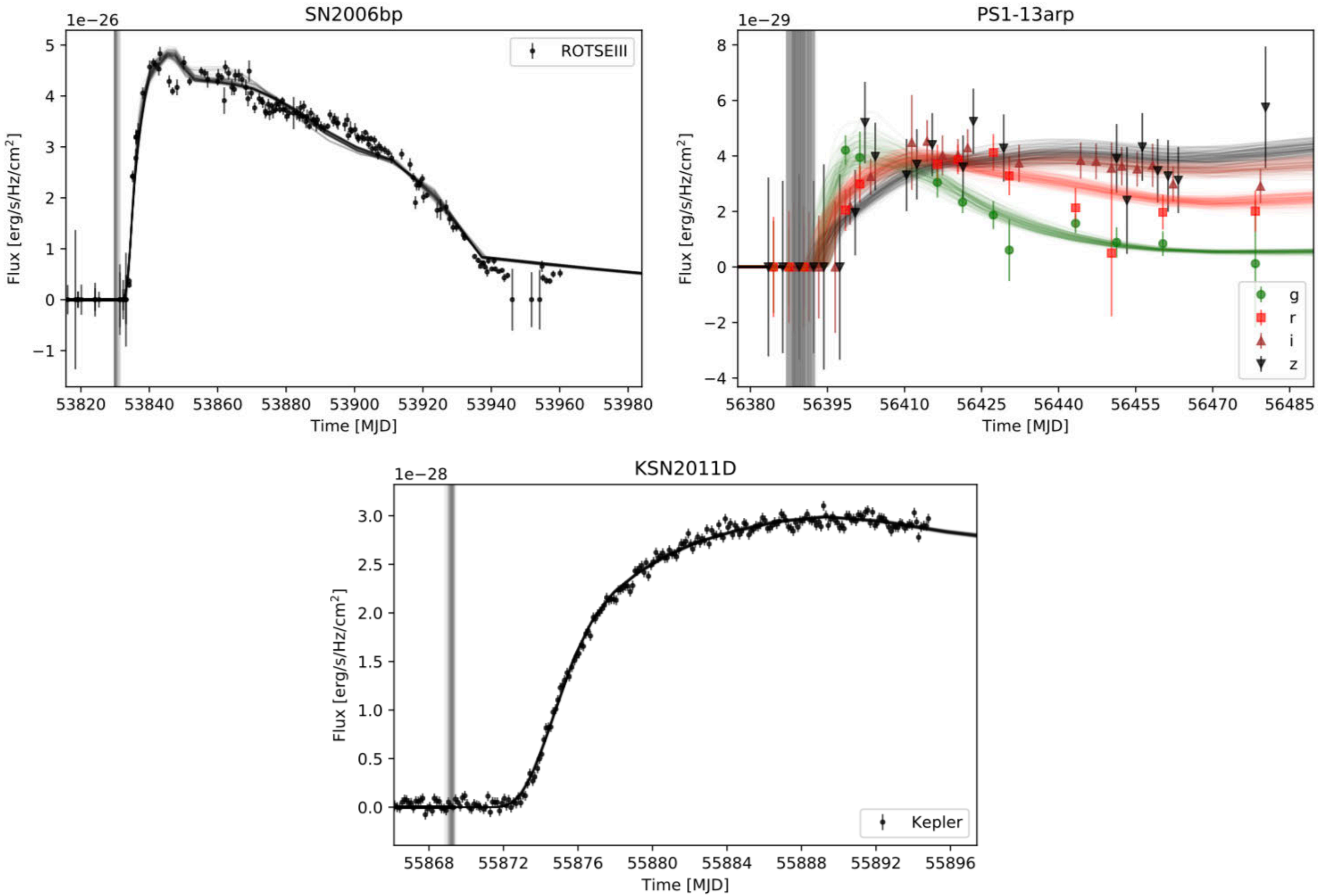
26 Type II SNe with rising light curves from HiTS



“shock breakout” was not found (Föster et al. ’16)

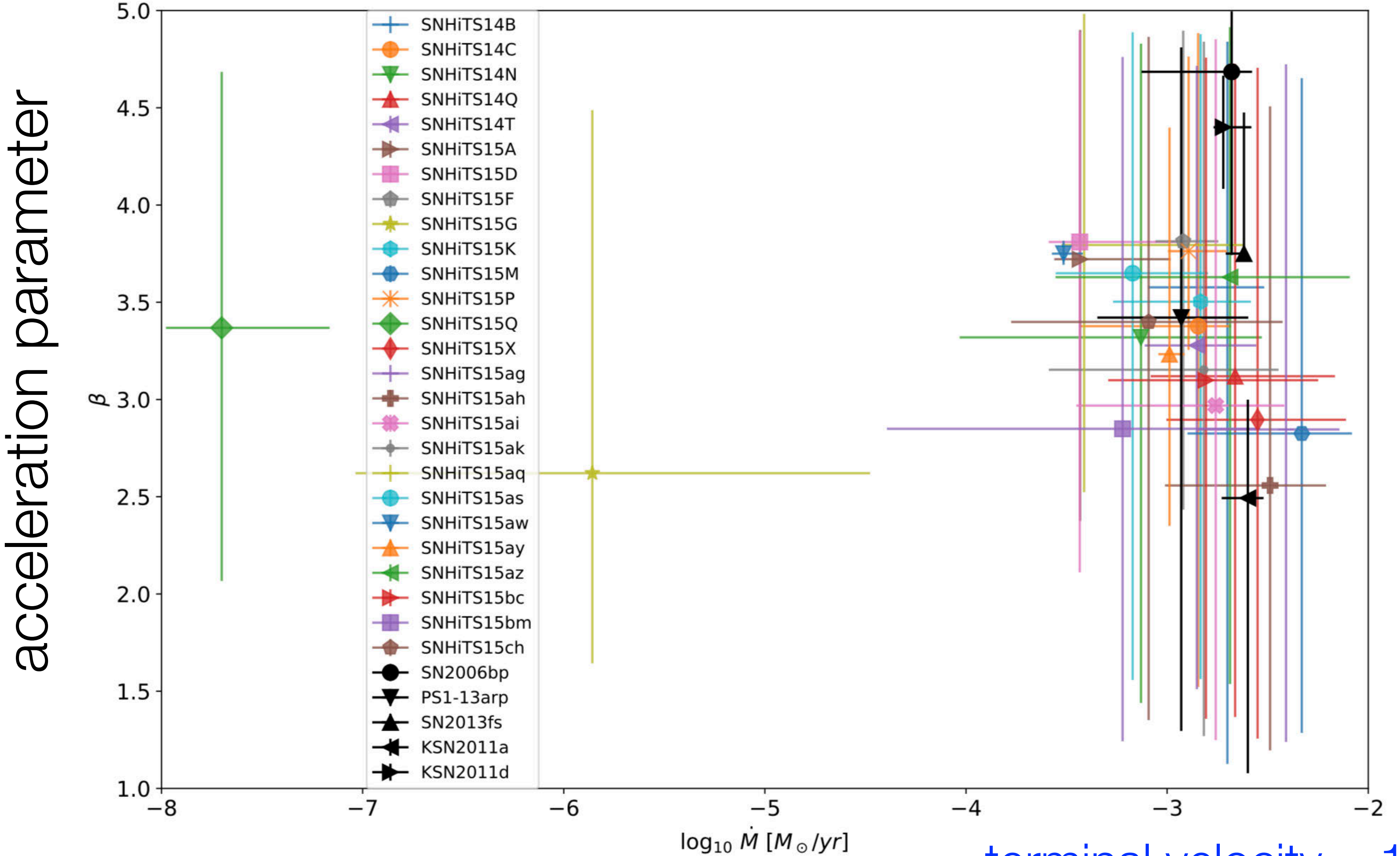
Förster, Moriya, et al. (2018)

Other Type II SNe with early discoveries



Förster, Moriya, et al. (2018)

RSG mass loss parameters estimated from SNe

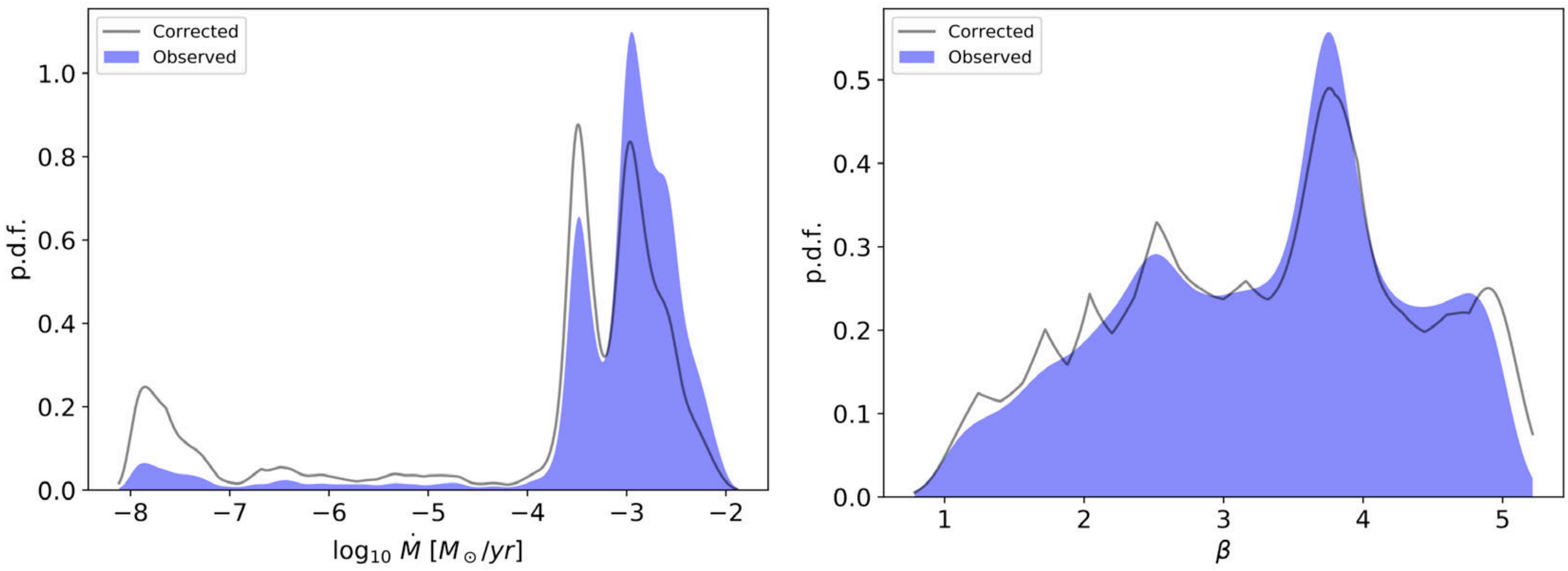


mass loss rate

terminal velocity = 10 km/s

Förster, Moriya, et al. (2018)

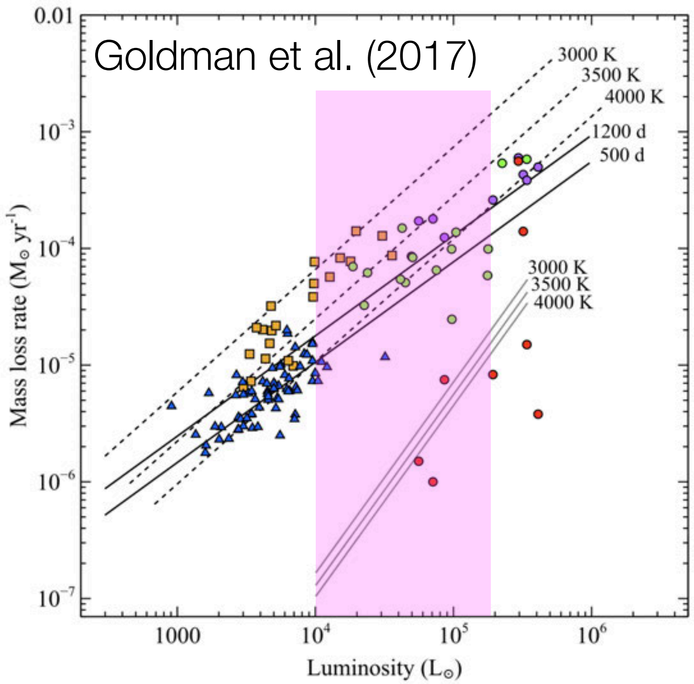
RSG mass loss parameters estimated from SNe

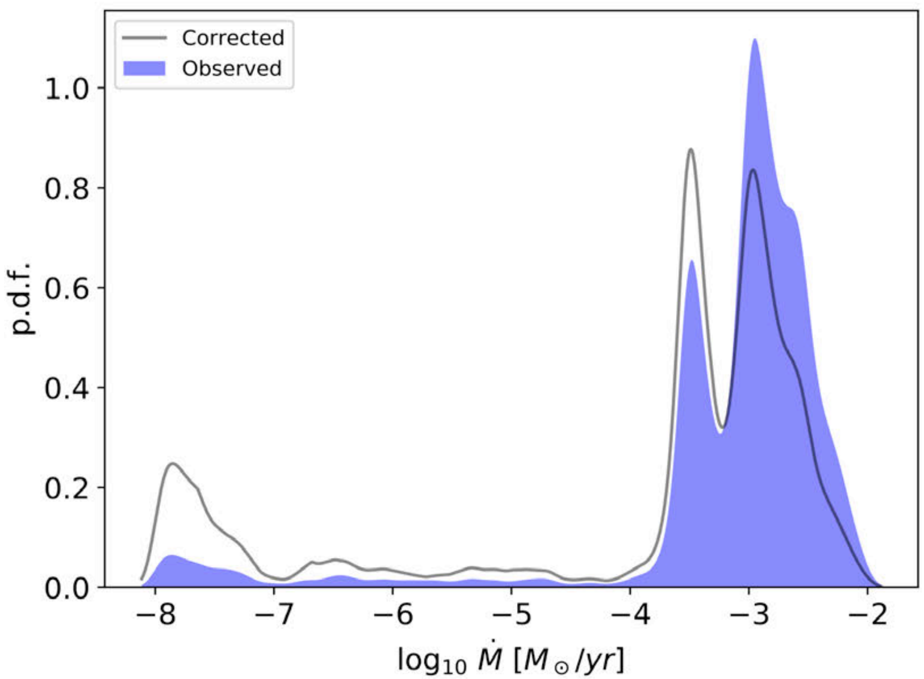


Förster, Moriya, et al. (2018)

RSG mass loss shortly before explosion

- RSG mass loss rate shortly before explosion is more than 1e-4 Msun/yr
    - RSGs may somehow increase mass loss rates shortly before explosion
    - difference from usual RSG mass loss mechanism is not clear

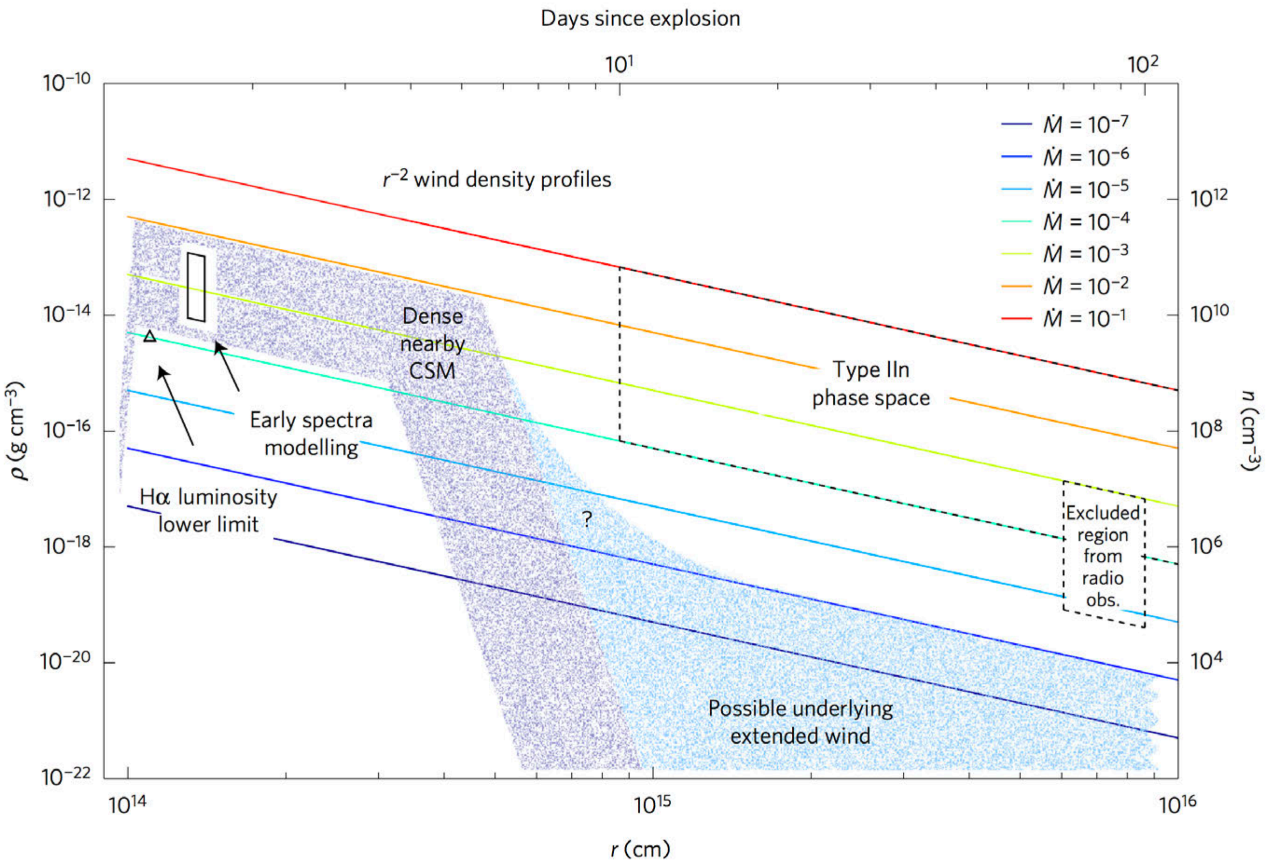




- it is hard to measure β in usual RSGs
    - ζ Aur: β ~ 3.5 (Baade et al. 1996)

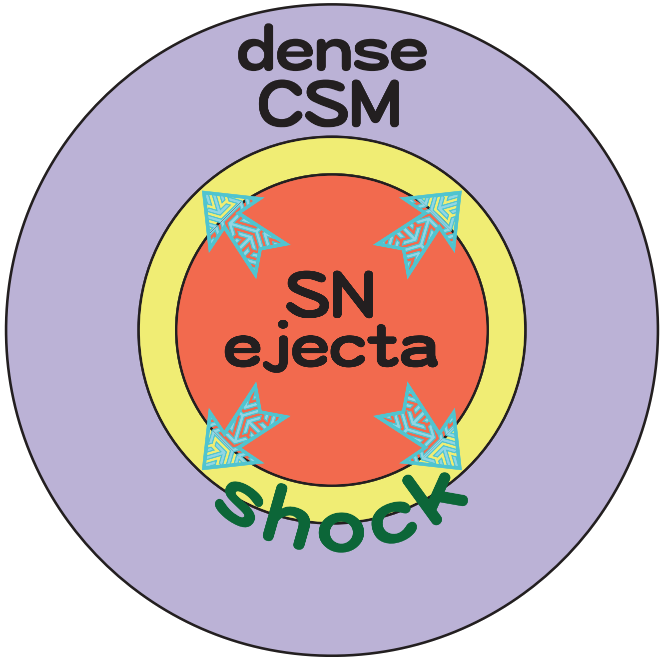
Mass loss enhancement in ordinary Type II SNe

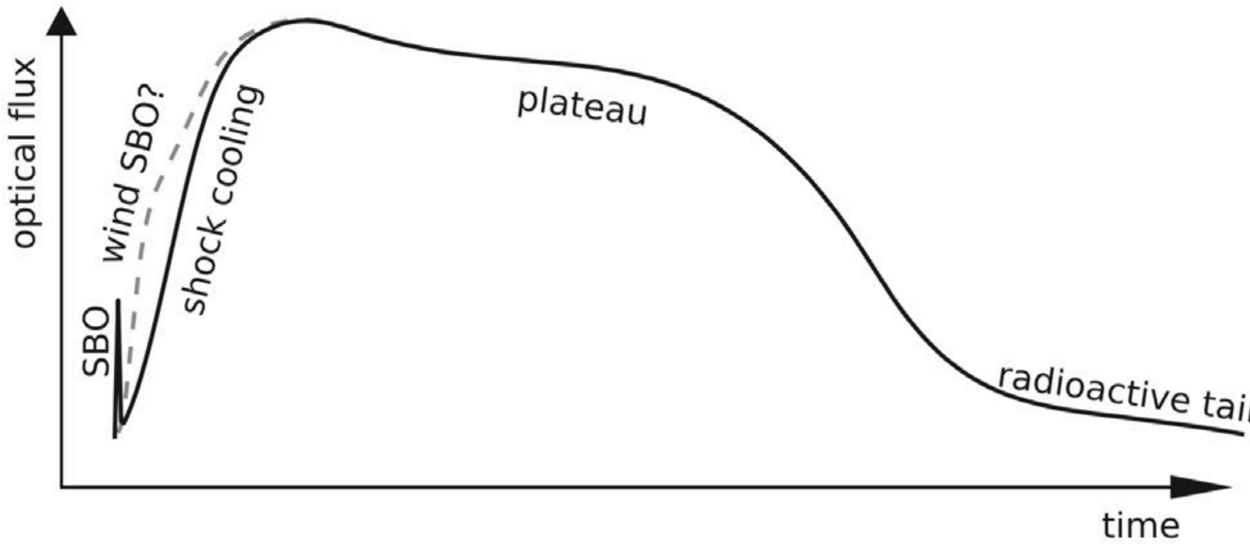
- Type IIn supernovae
  - mass-loss enhancement for more than 100 years before explosion
- ordinary Type II supernovae
  - mass-loss enhancement within ~ 100 years before explosion



Yaron et al. (2017)

Shock breakout

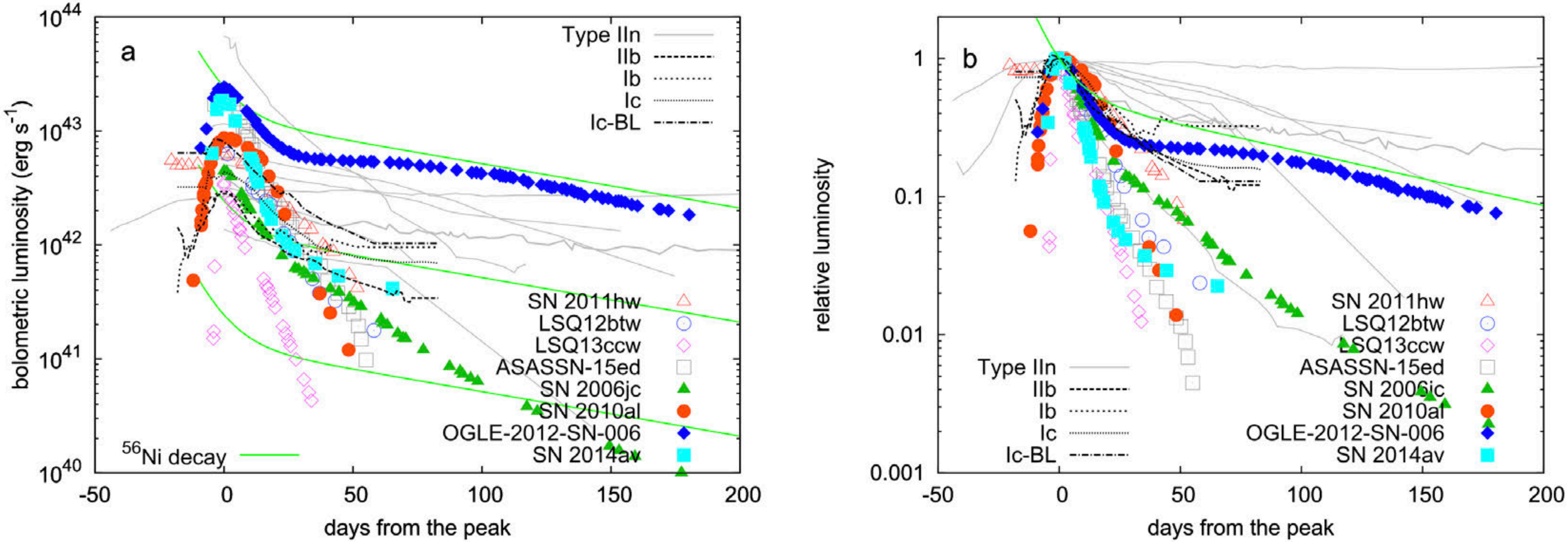




Förster et al. (2016)

Type Ibn supernovae

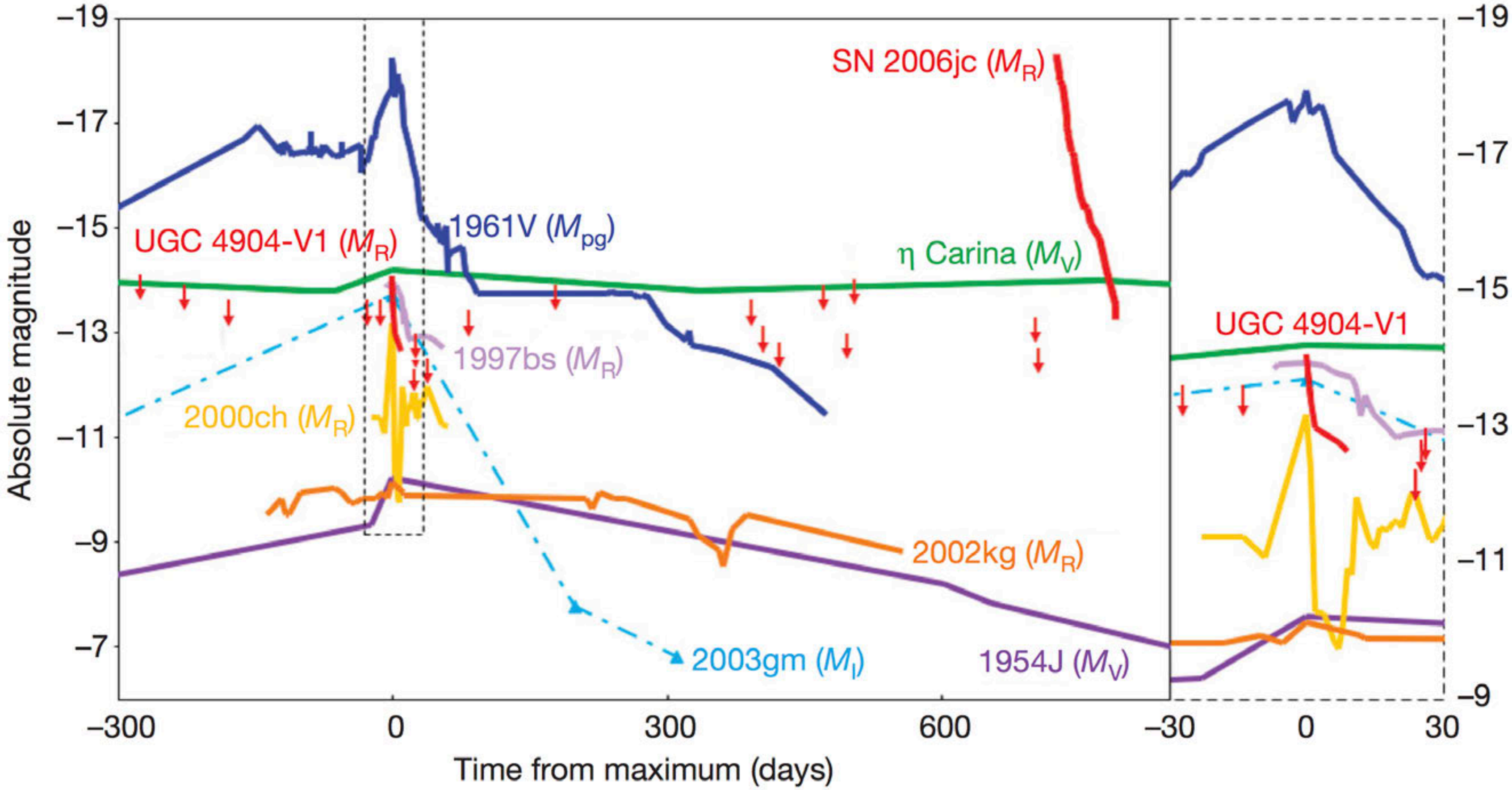
- SNe with narrow He lines
  - interaction between SN ejecta and He-rich CSM (sometimes with H)
  - ~ 1e-2 Msun/yr (1000 km/s): CSM density similar to Type IIn SNe



Moriya & Maeda (2016)

Type Ibn supernovae

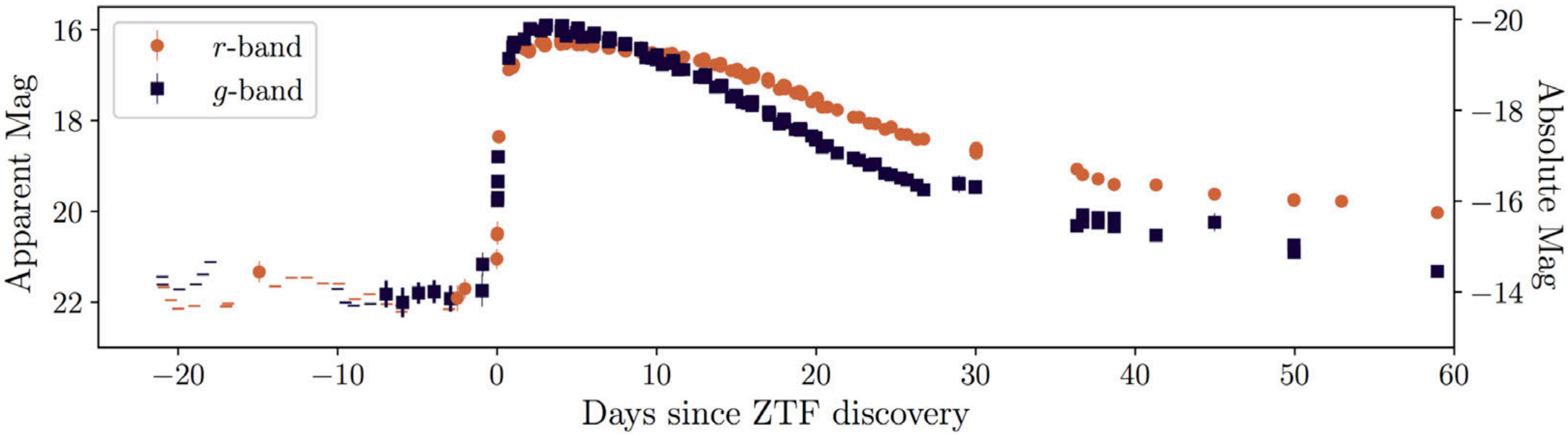
- SN 2006jc
  - progenitor got bright ~ 2 years before the explosion (psnLBV?)



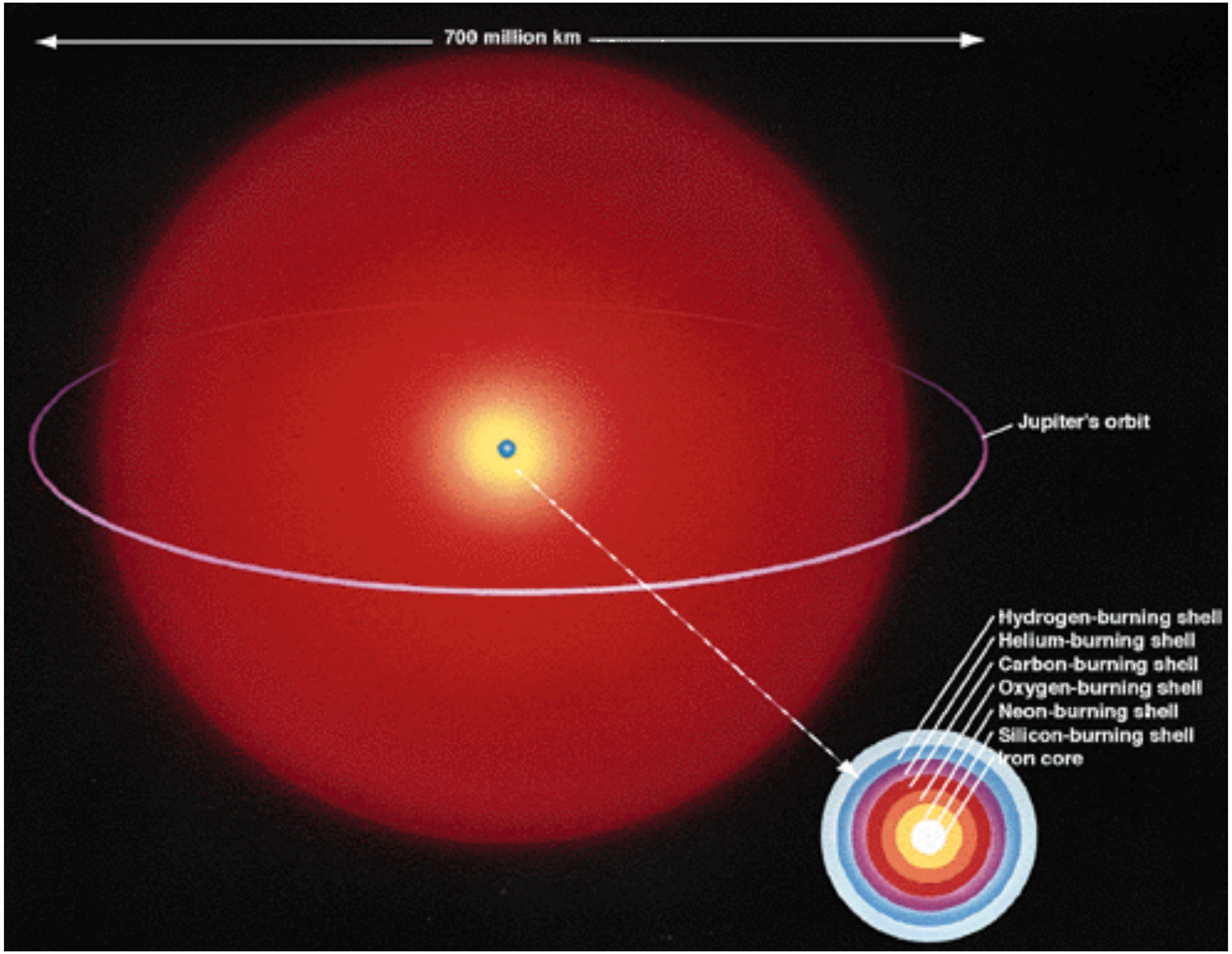
Pastorello et al. (2007)

Broad-line Type Ic supernova with dense CSM

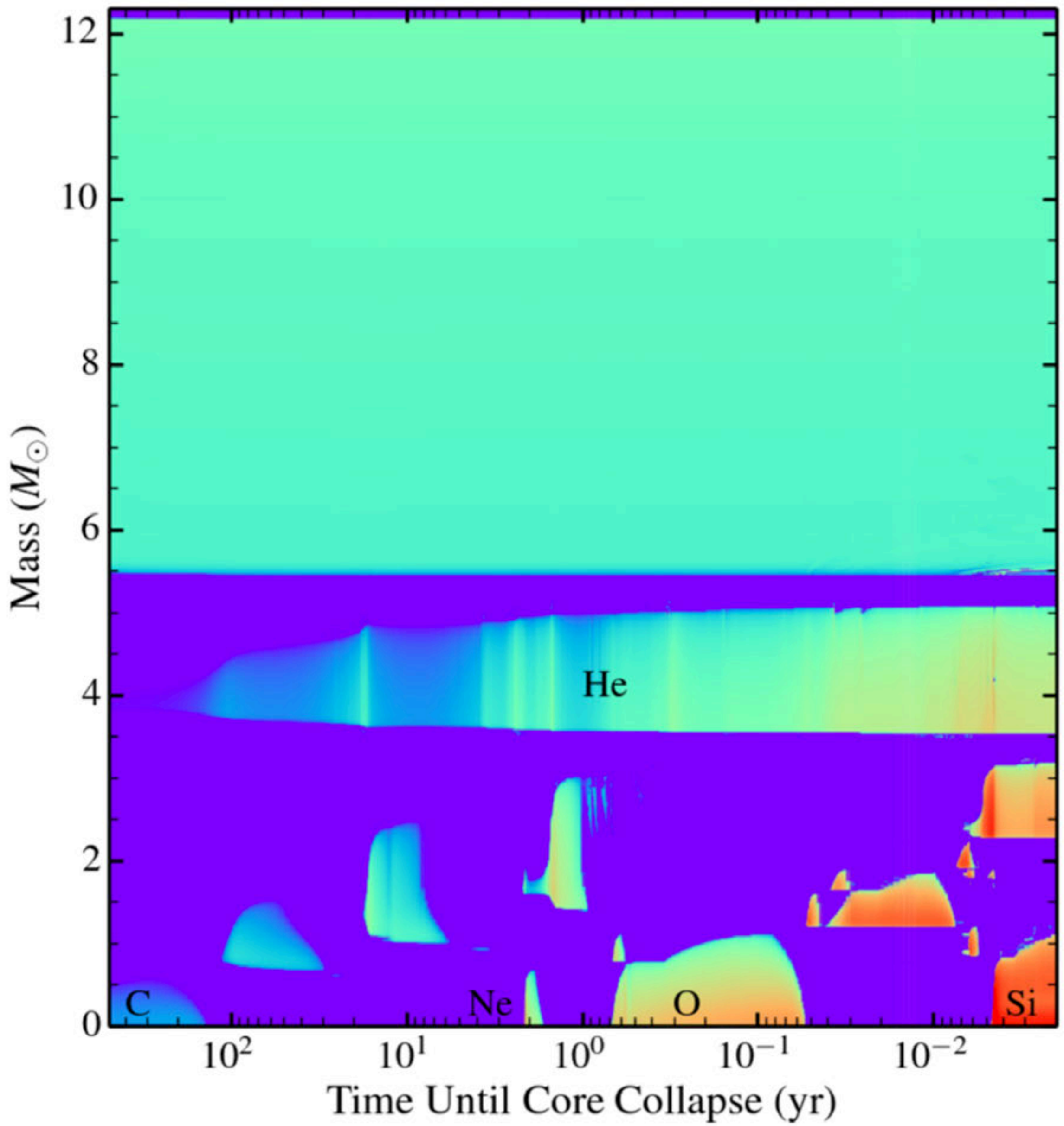
- SN 2018gep (Ho et al. 2019)



Connecting explosion and mass loss



Connecting explosion and mass loss



Fuller (2017)

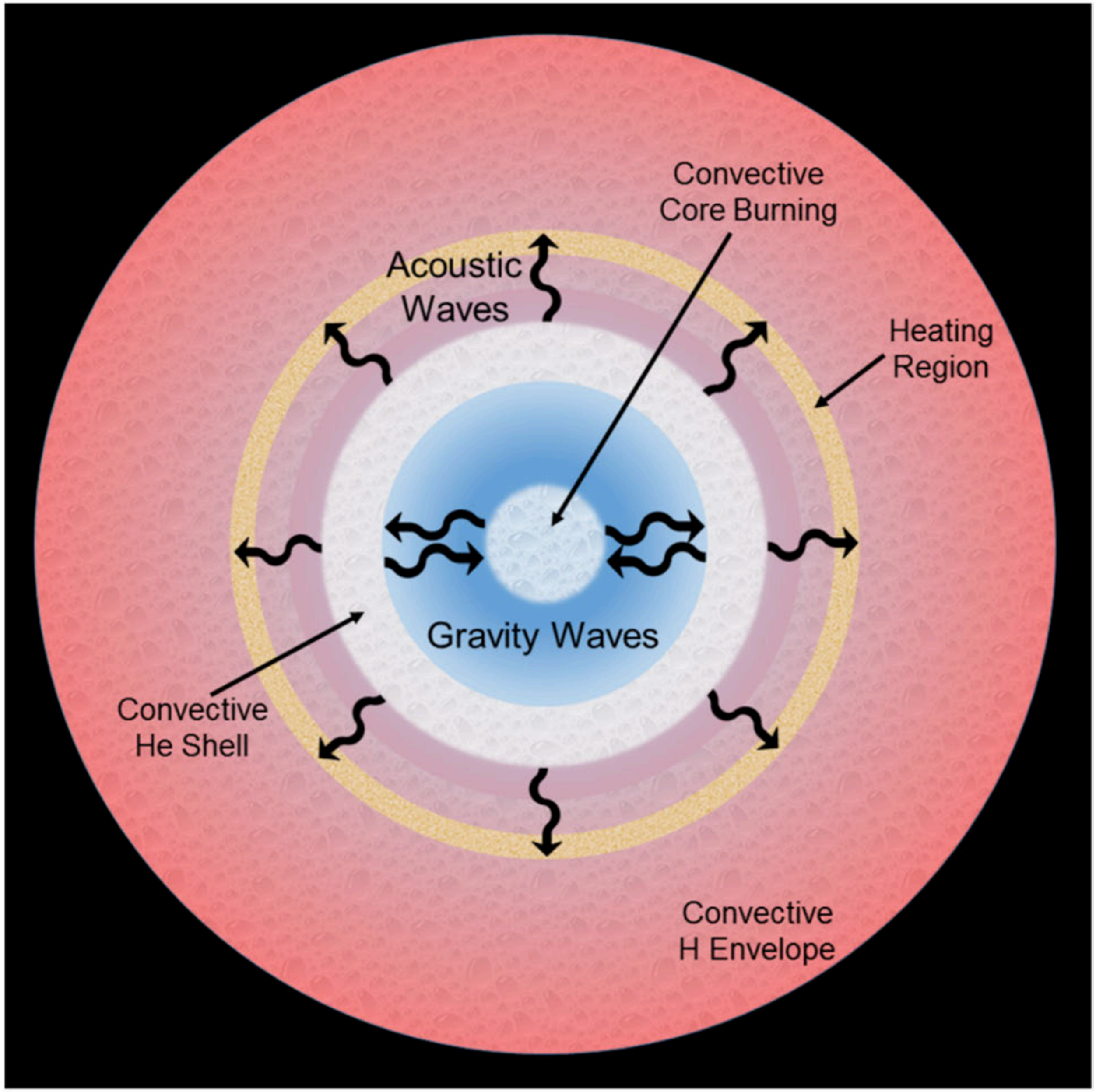
Timescales

$$\tau_{\rm dyn} \sim 4 \left(\frac{R}{100\ R_\odot} \right)^{3/2} \left(\frac{M}{10\ M_\odot} \right)^{-1/2} \ \text{days}$$

$$\tau_{\rm th} \sim 300 \left(\frac{M}{10 M_\odot} \right)^{2} \left(\frac{R}{100 R_\odot} \right)^{-1} \left(\frac{L}{10^5\ L_\odot} \right)^{-1} \ \text{yr}$$

$$\tau_{\rm nuc} \sim 10^6 \left(\frac{\varepsilon}{10^{-3}} \right) \left(\frac{M}{10\ M_\odot} \right) \left(\frac{L}{10^5\ L_\odot} \right)^{-1} \ \text{yr}$$

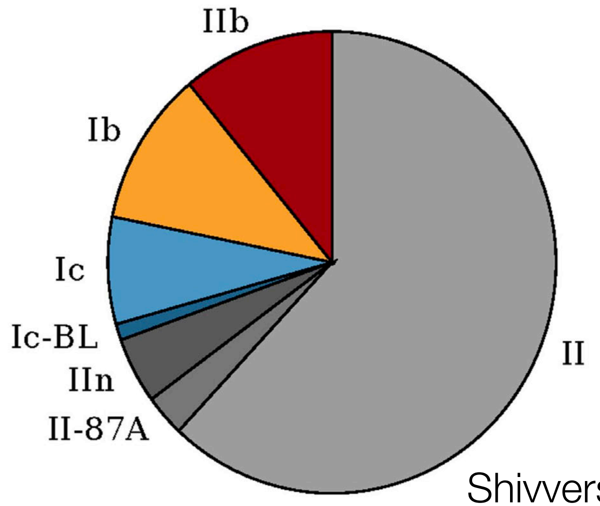
Connecting explosion and mass loss



Fuller (2017)

Summary

- A significant fraction of core-collapse SN progenitors enhance their mass-loss rates shortly before their explosion
  - Type IIn: more than 100 years before the explosion
  - others: ~ 100 years or less before the explosion
- the mass-loss rates exceed ~ 10^{-3} Msun/yr
- how to connect explosions and mass-loss is not yet clear



Shivvers et al. (2017)