Revealing Explosive Mass Loss Decades before Massive Star Explosions from Type IIn Supernova Light Curve Modeling

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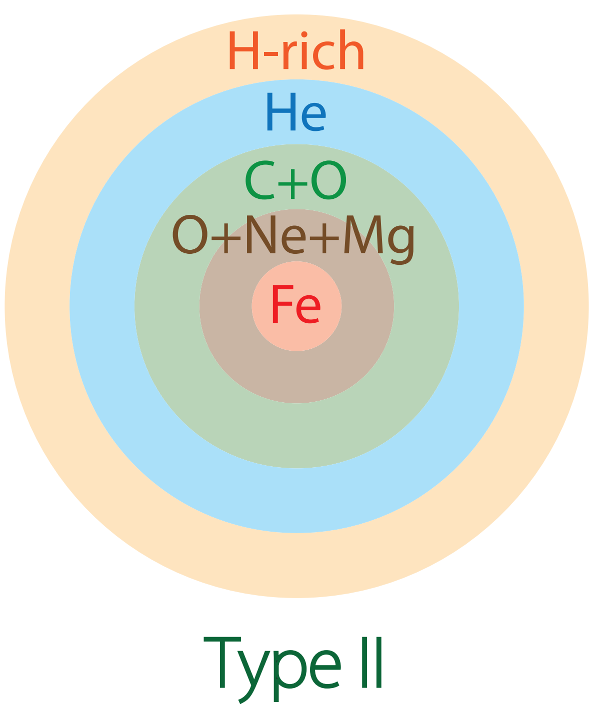
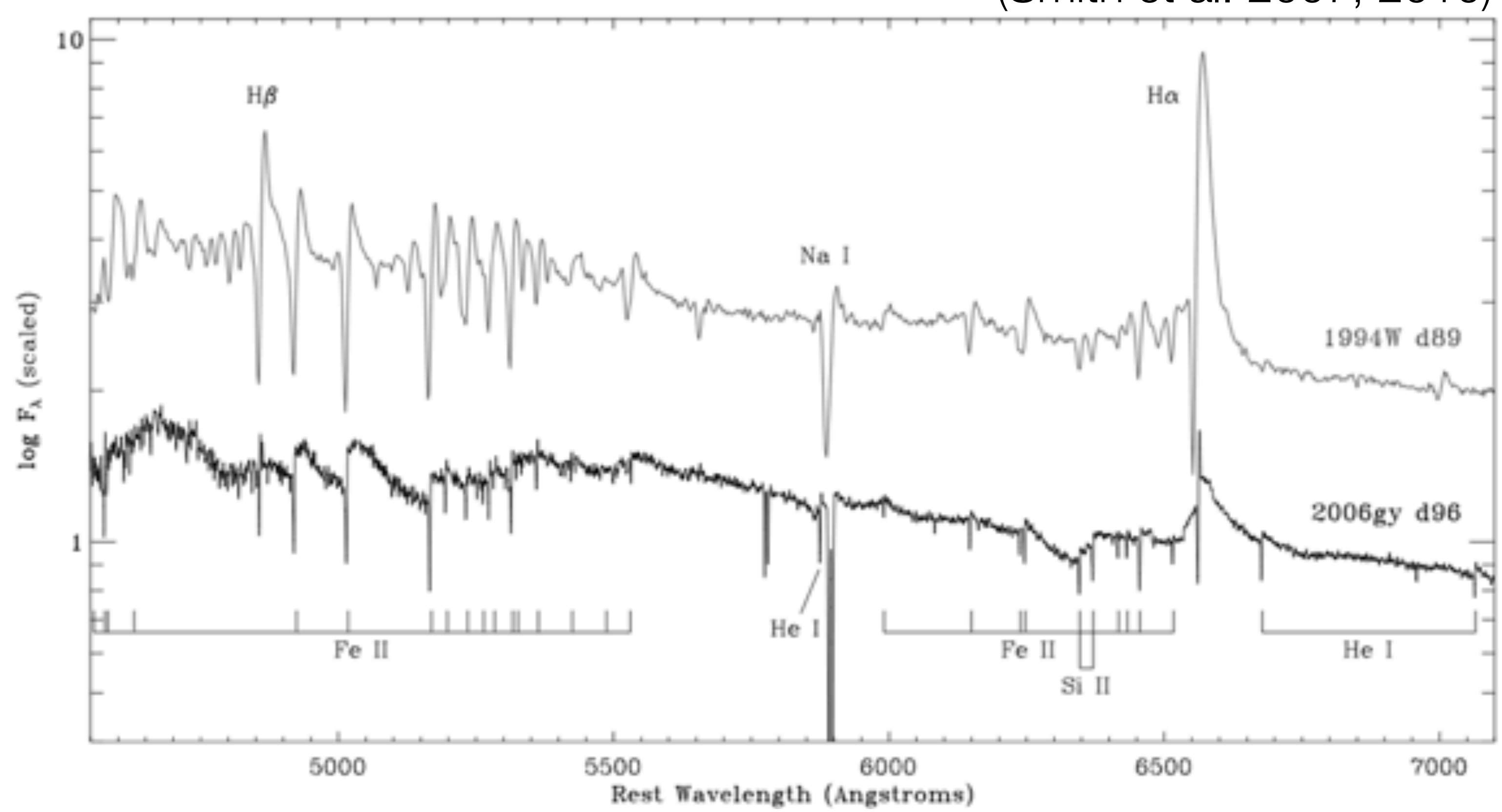
Type IIn Supernovae

- H lines + narrow emission lines

(Smith et al. 2007, 2010)





Type IIn Supernovae

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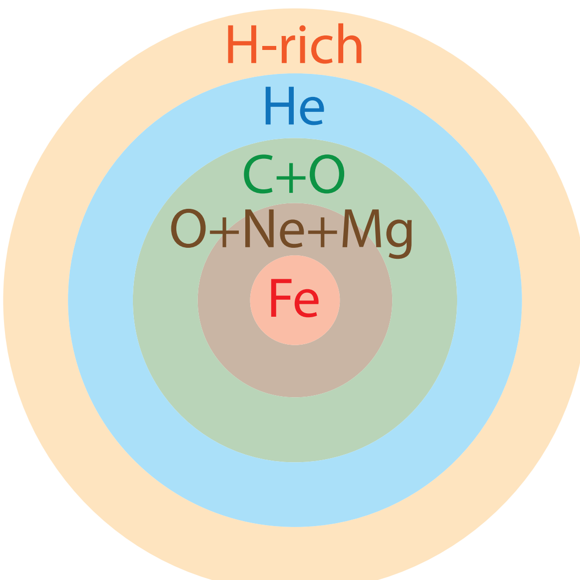
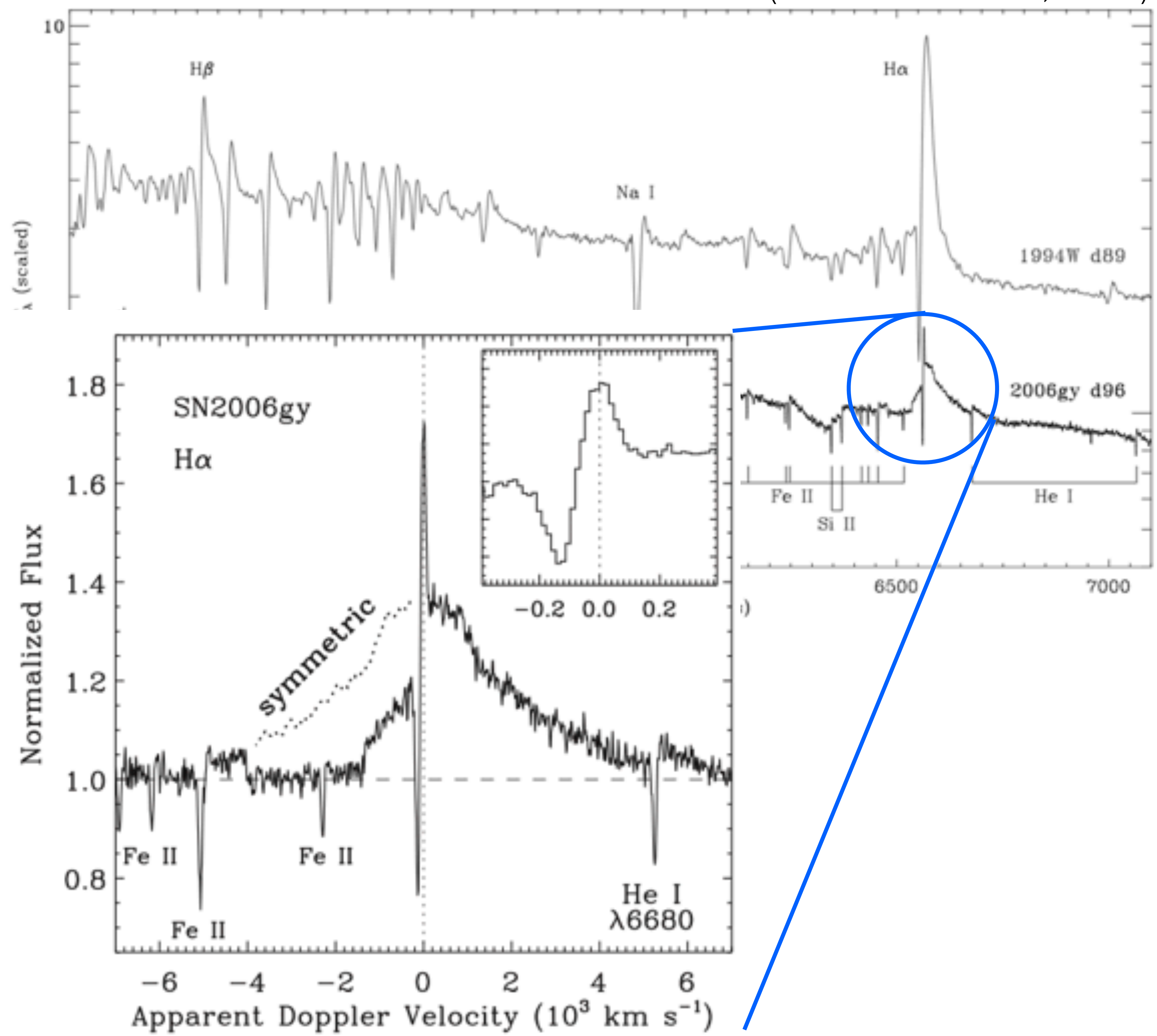


Type II

(Smith et al. 2007, 2010)



Type IIn Supernovae

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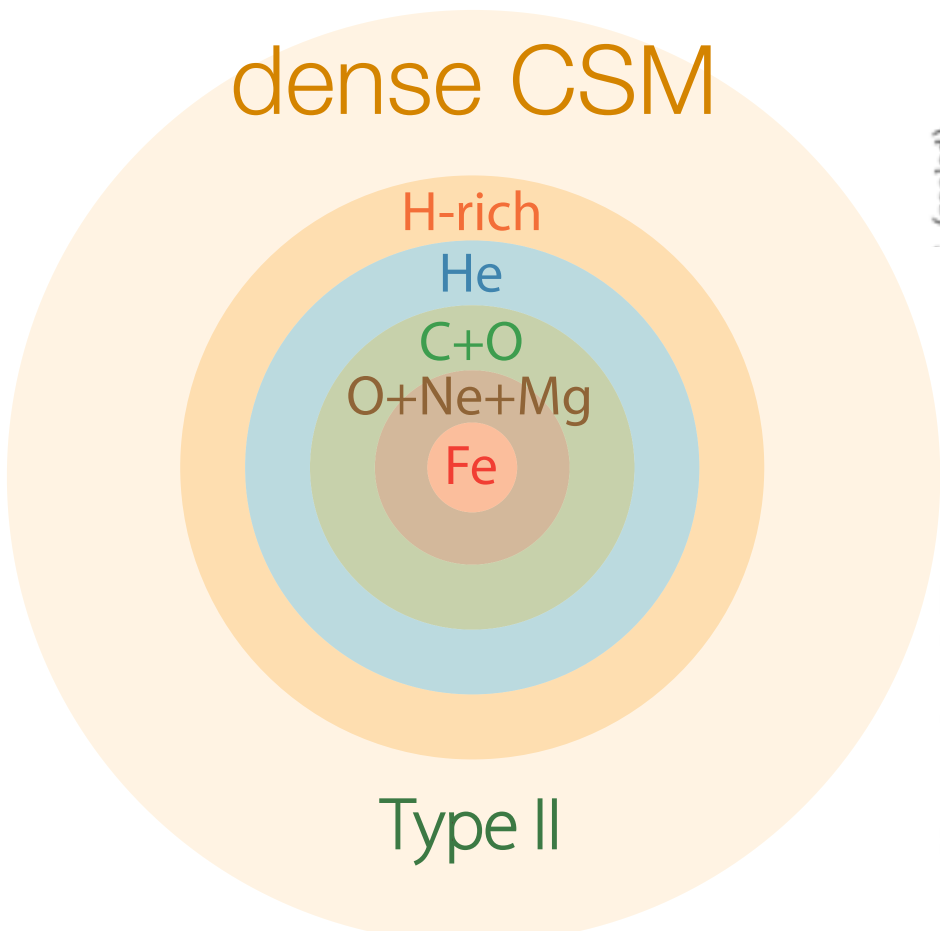
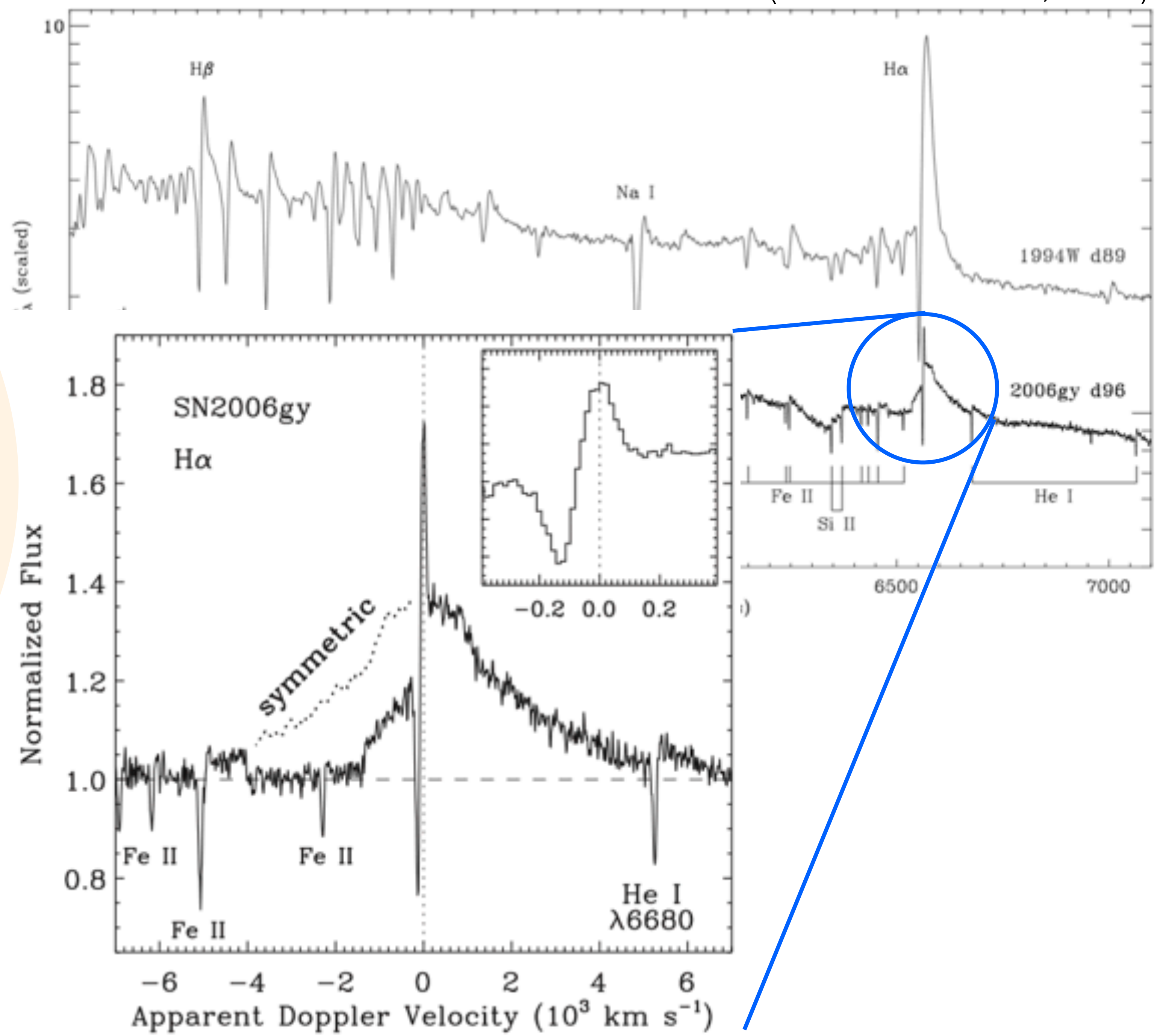


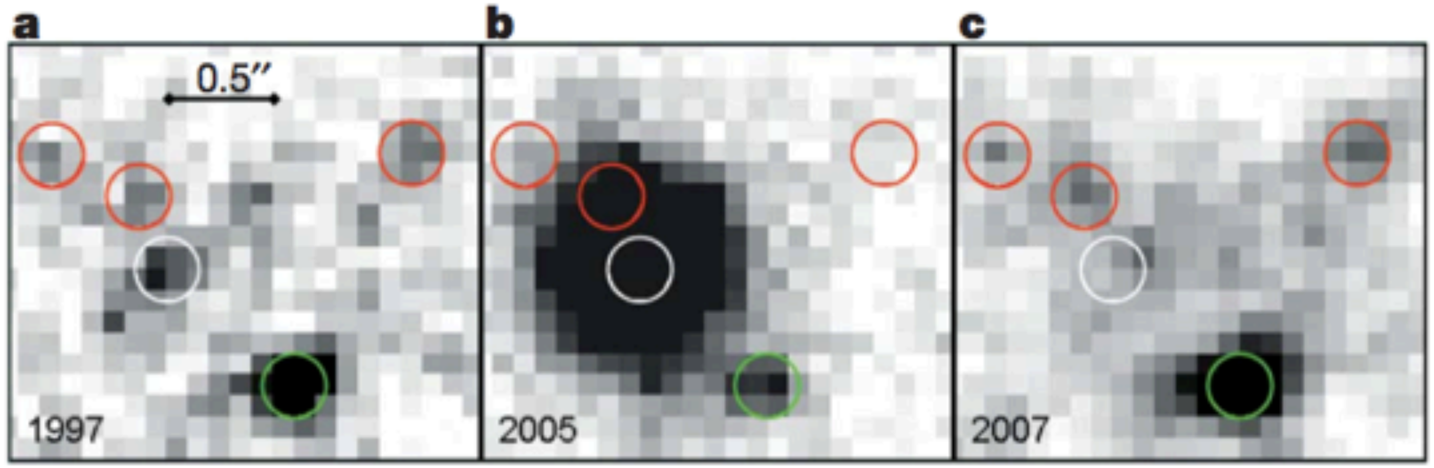
(Smith et al. 2007, 2010)



Progenitors of Type IIn Supernovae

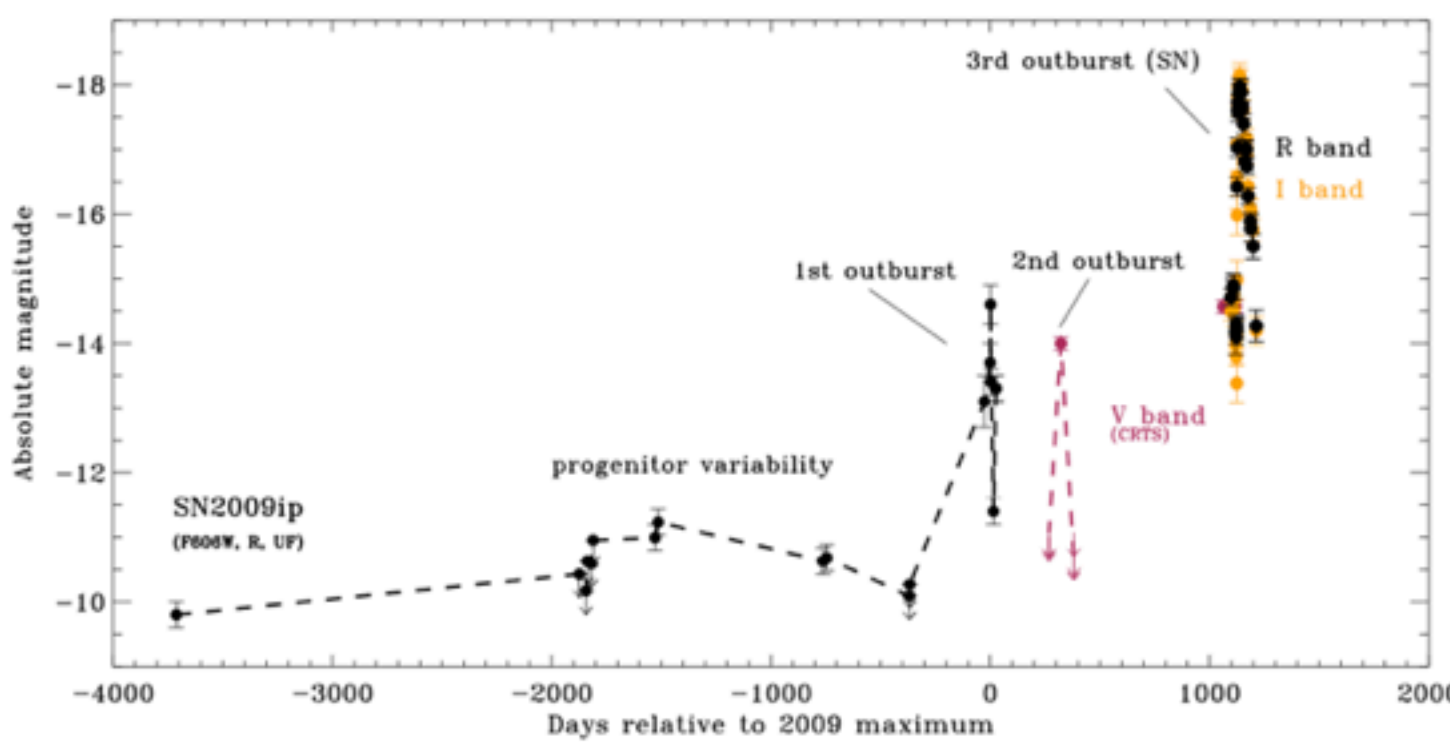
- Luminous Blue Variables (LBVs) detected in pre-explosion images?
  - SN 2005gl

    $M_V \simeq -10$ mag



(Gal-Yam & Leonard 2009)

  - SN 2009ip?

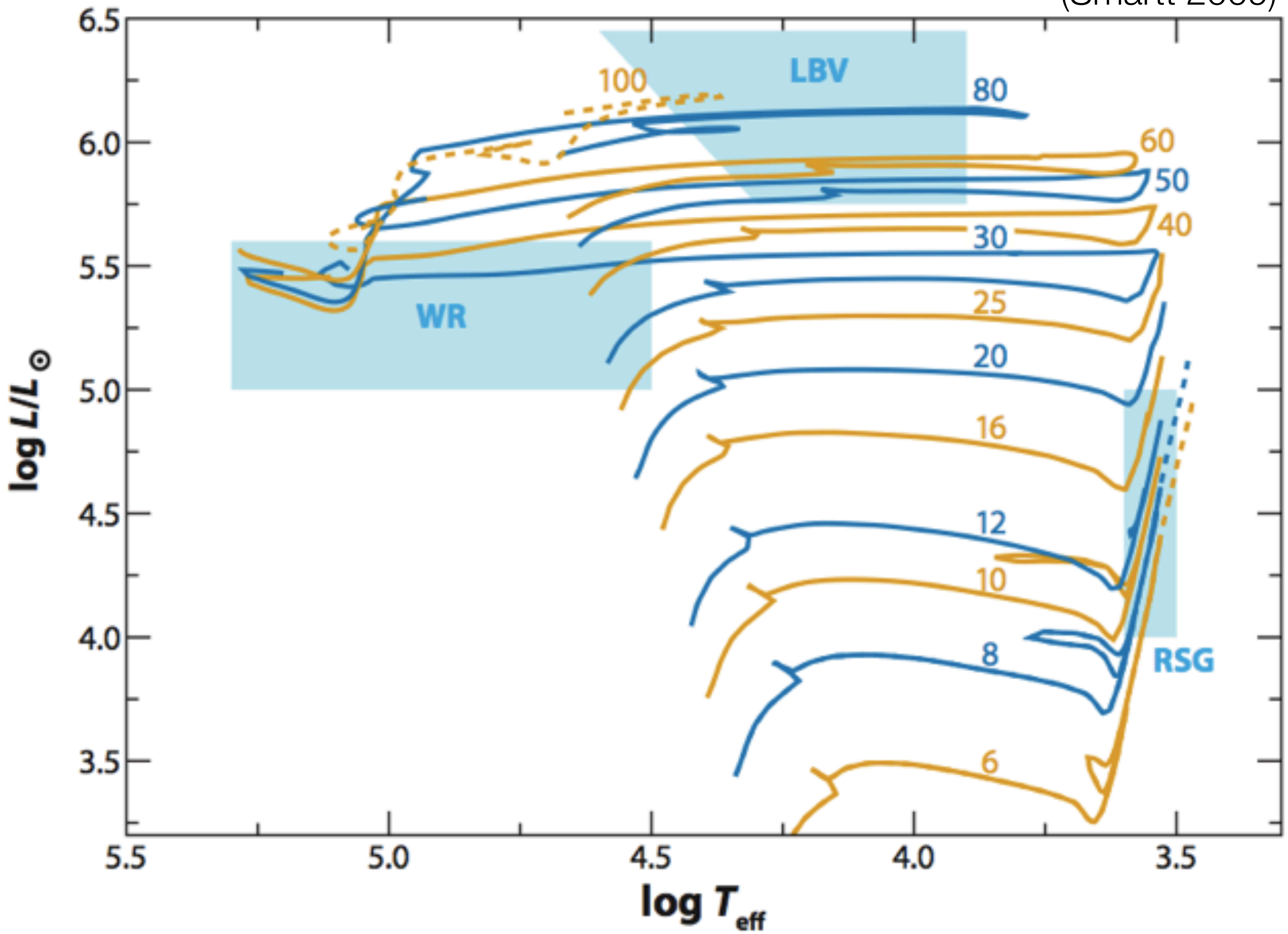


(Mauerhan et al. 2012)

Progenitors of Type IIn Supernovae

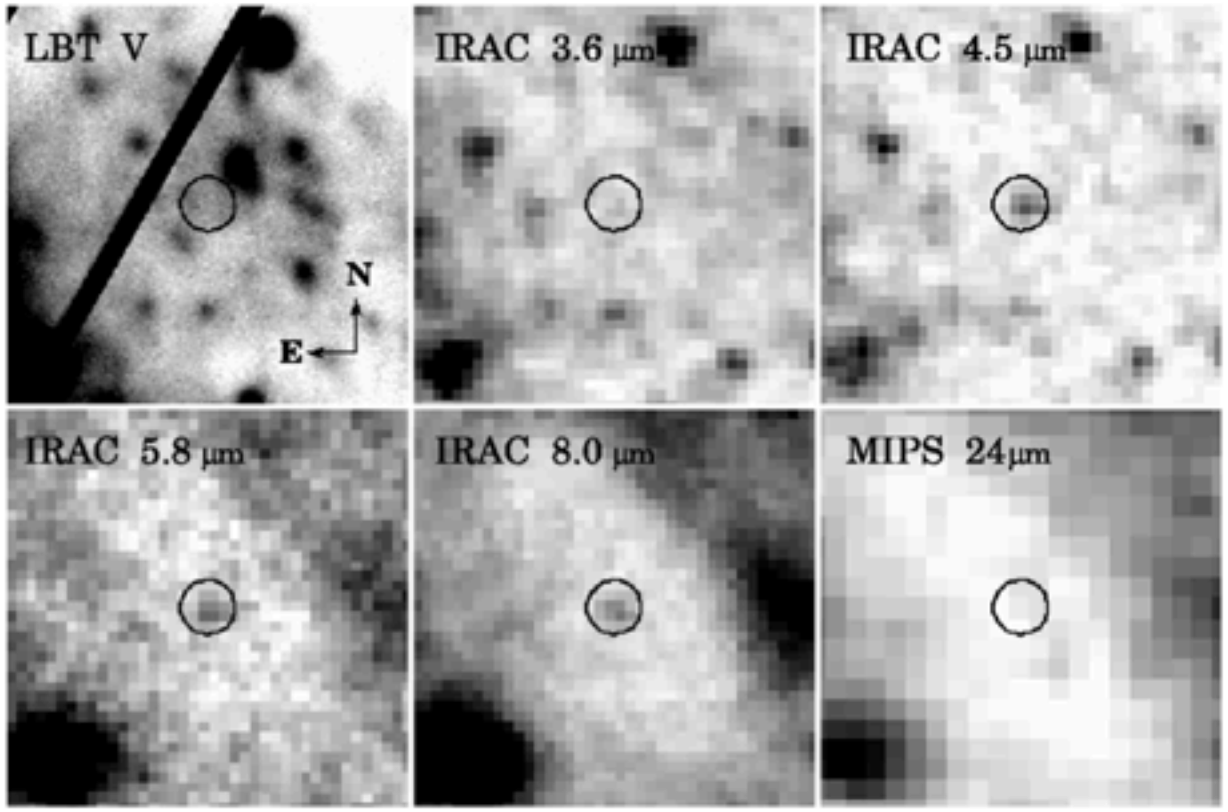
- LBVs as supernova progenitors?

(Smartt 2009)



Progenitors of Type IIn Supernovae

- Low-mass star detected in near-infrared pre-explosion image
  - SN 2008S
    - IR luminosity $\approx 3.5 \times 10^4\ L_\odot$
      - ~ 10 Msun
    - super-AGB star?
      - electron-capture SN inside?



(Prieto et al. 2008)

- SN Ia in dense CSM (e.g. Silverman et al. 2013)
  - How common are they? Can we always see the SN Ia signatures?

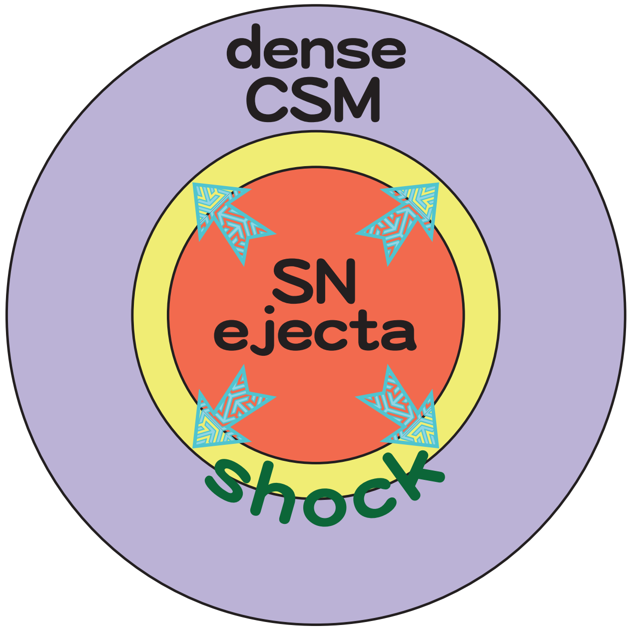
Constraining CSM Properties from LC modeling

Constraining CSM Properties from LC modeling

- Constraining CSM and SN properties in SNe IIn
    - mass-loss properties of SN IIn progenitors
    - hint to reveal the progenitors

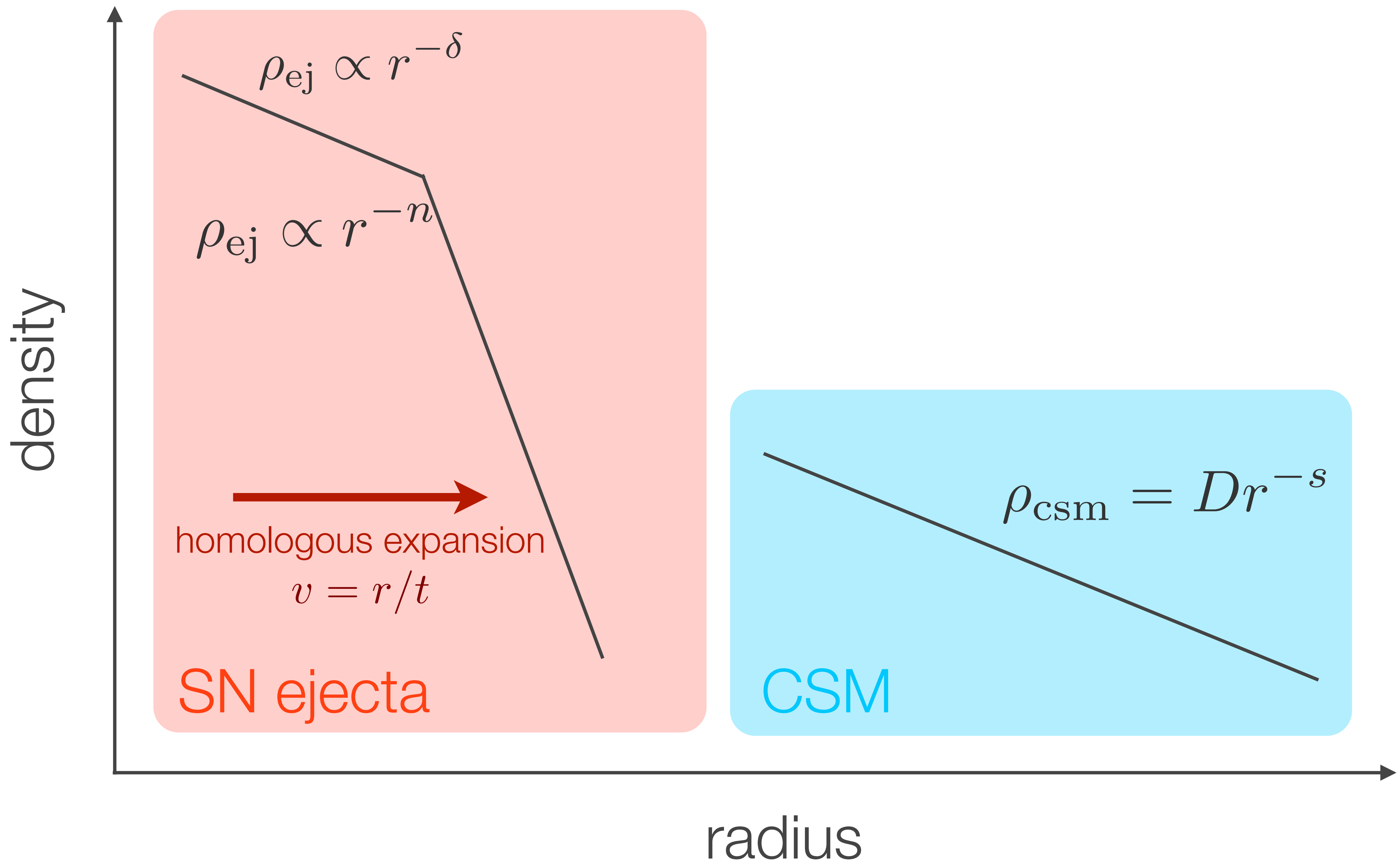
Constraining CSM Properties from LC modeling

- Constraining CSM and SN properties in SNe IIn
  - mass-loss properties of SN IIn progenitors
  - hint to reveal the progenitors
- Constraining CSM properties from LC modeling
  - Radiation energy source is SN kinetic energy
    - in principle, radiation hydrodynamics is required
    - can be simplified in some cases -- can be treated analytically!

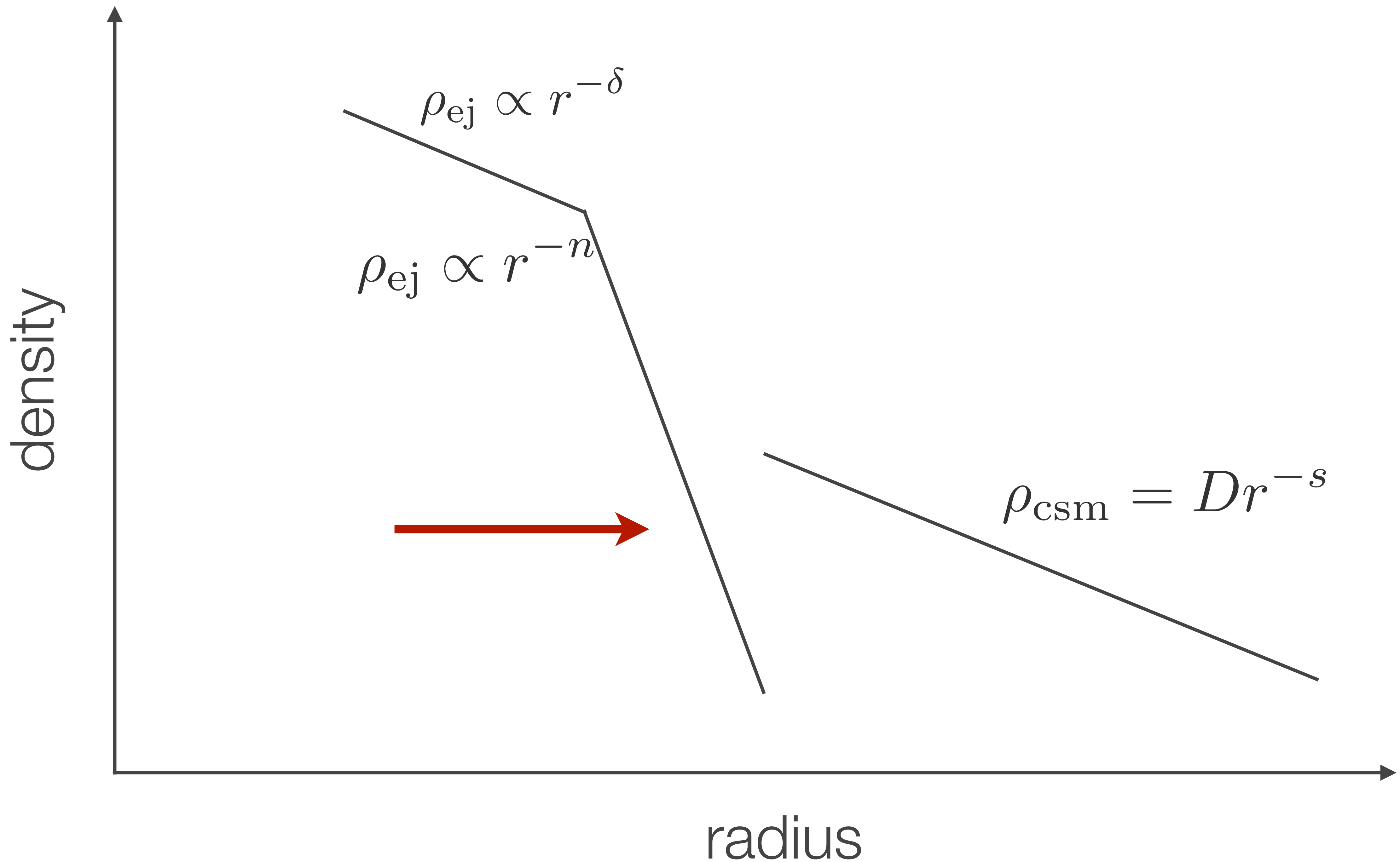


An Analytic Bolometric Light Curve Model

- Spherically symmetric model



An Analytic Bolometric Light Curve Model



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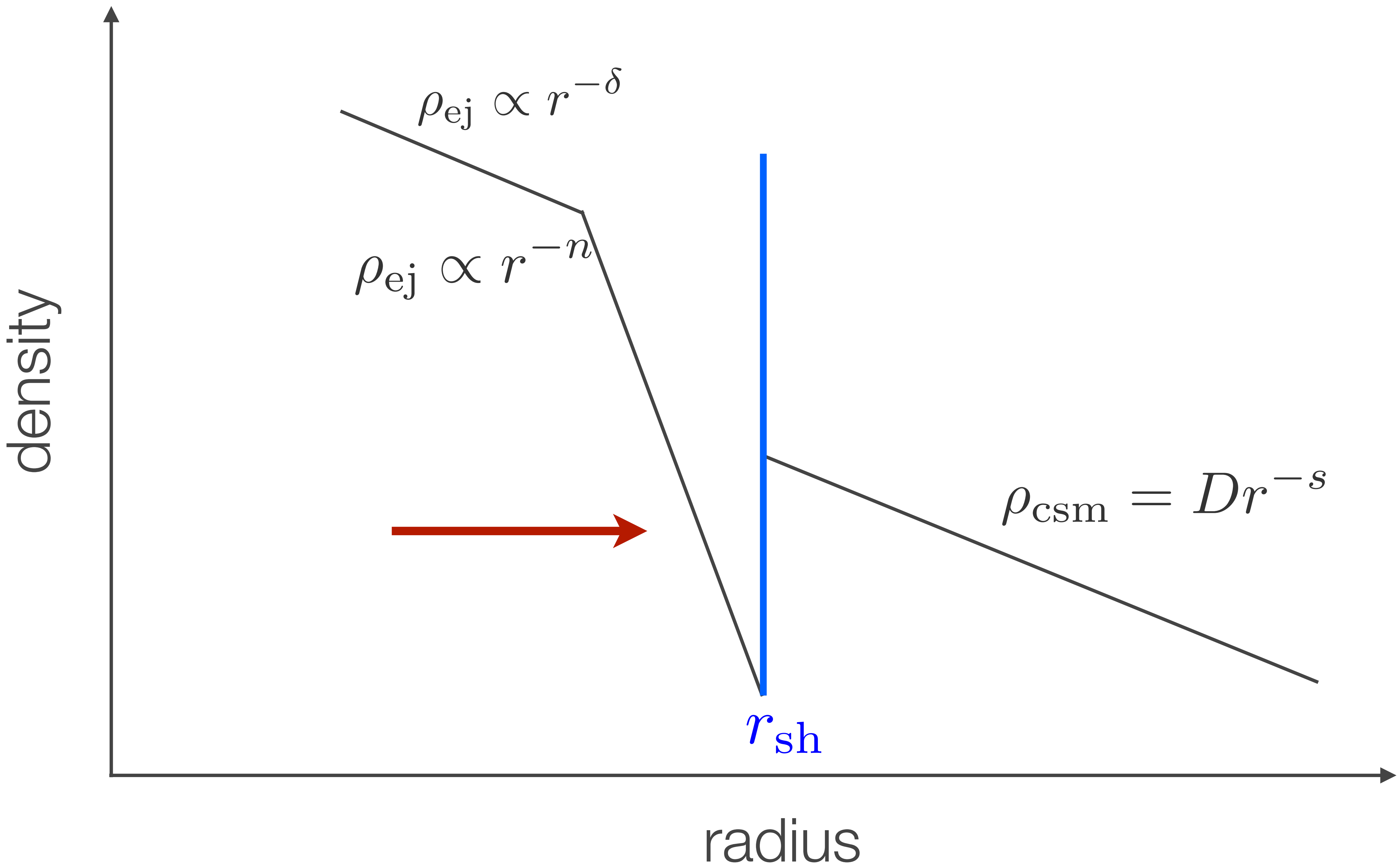

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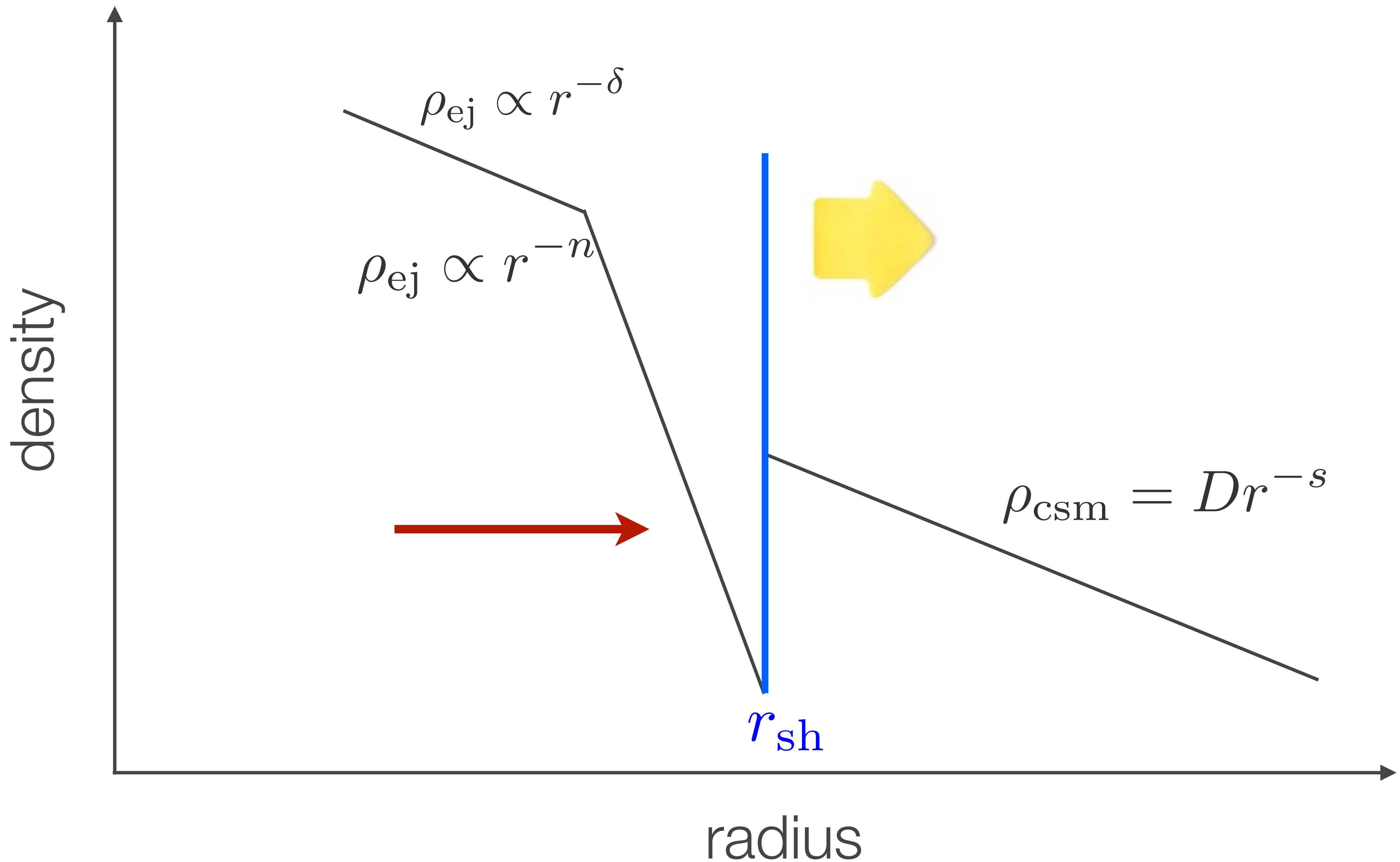
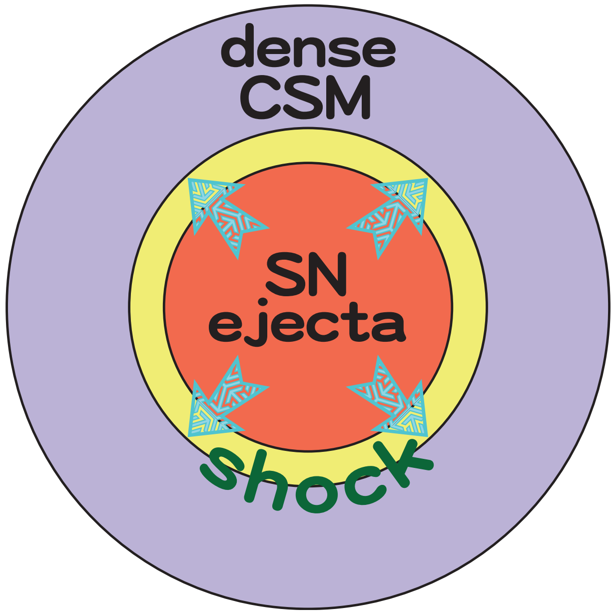


An Analytic Bolometric Light Curve Model

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

$$\downarrow$$

$$dE_{\rm kin} = 4\pi r_{\rm sh}^2\frac{1}{2}\rho_{\rm csm}v_{\rm sh}^2 dr$$

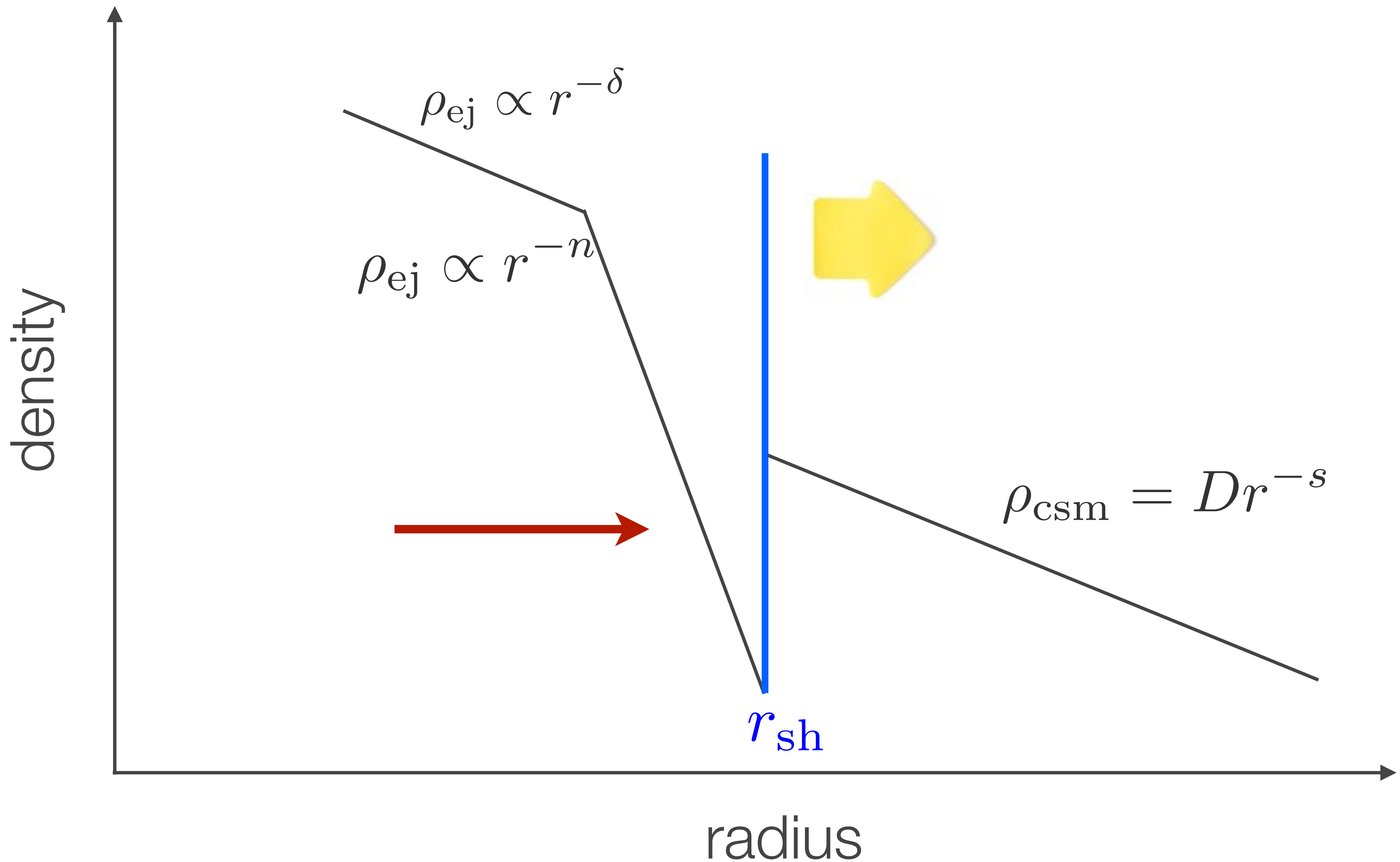


$$L = \epsilon\frac{dE_{\rm kin}}{dt} = 2\pi\epsilon\rho_{\rm csm}r_{\rm sh}^2 v_{\rm sh}^3$$

ϵ :conversion efficiency

(Moriya et al. submitted)

An Analytic Bolometric Light Curve Model



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↓

$$r_{\rm sh}(t) = \left[\frac{(3-s)(4-s)}{4\pi D(n-4)(n-3)(n-\delta)}\frac{[2(5-\delta)(n-5)E_{\rm ej}]^{(n-3)/2}}{[(3-\delta)(n-3)M_{\rm ej}]^{(n-5)/2}}\right]^{\frac{1}{n-s}} t^{\frac{n-3}{n-s}}$$

↓ $L = \epsilon\frac{dE_{\rm kin}}{dt} = 2\pi\epsilon\rho_{\rm csm}r_{\rm sh}^2 v_{\rm sh}^3$

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

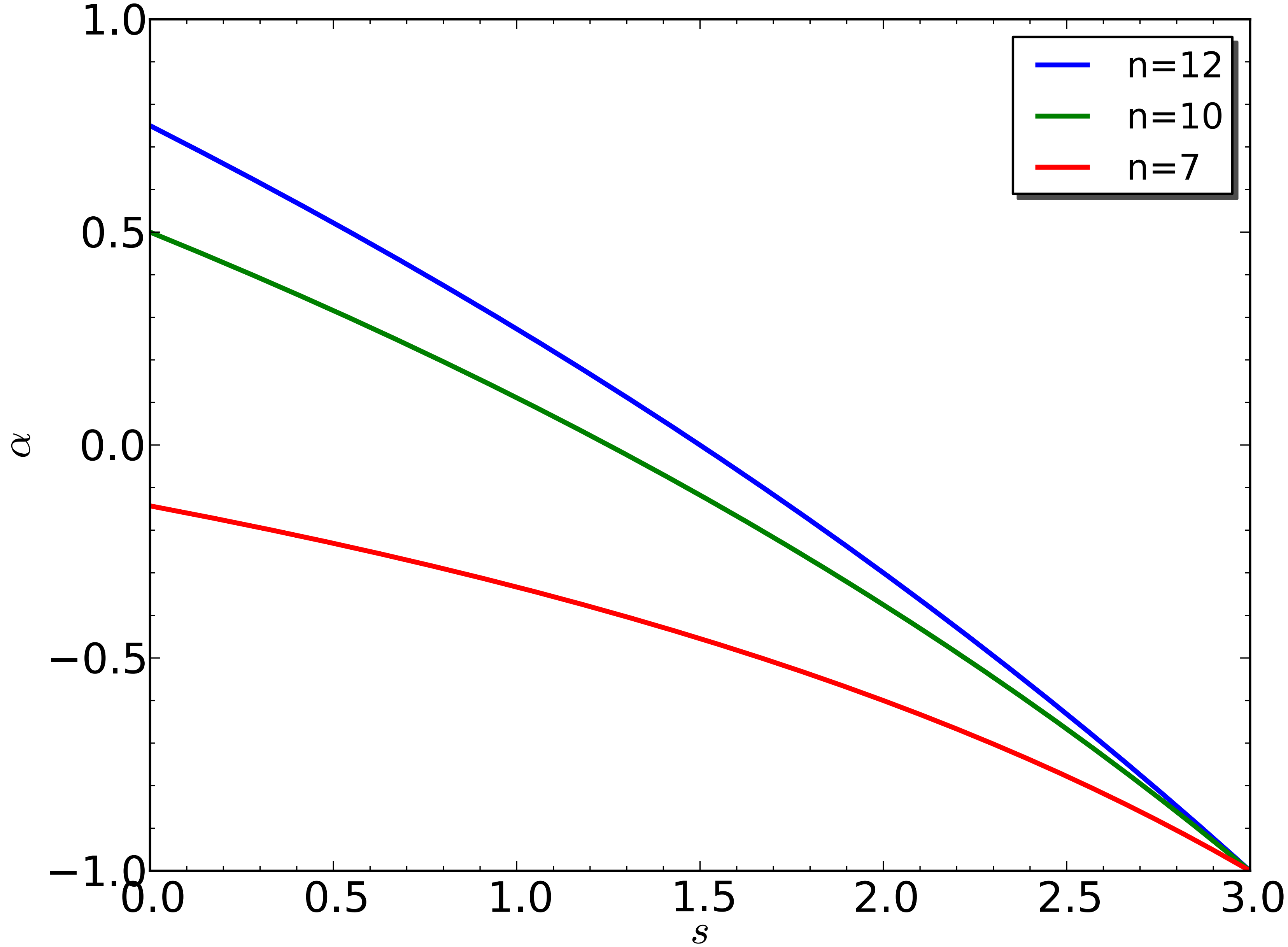
$$L_1 = \frac{\epsilon}{2}(4\pi D)^{\frac{n-5}{n-s}}\left(\frac{n-3}{n-s}\right)^3\left[\frac{(3-s)(4-s)}{(n-4)(n-3)(n-\delta)}\frac{[2(5-\delta)(n-5)E_{\rm ej}]^{(n-3)/2}}{[(3-\delta)(n-3)M_{\rm ej}]^{(n-5)/2}}\right]^{\frac{5-s}{n-s}}$$

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

(Moriya et al. submitted)

An Analytic Bolometric Light Curve Model

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



n depends on progenitors

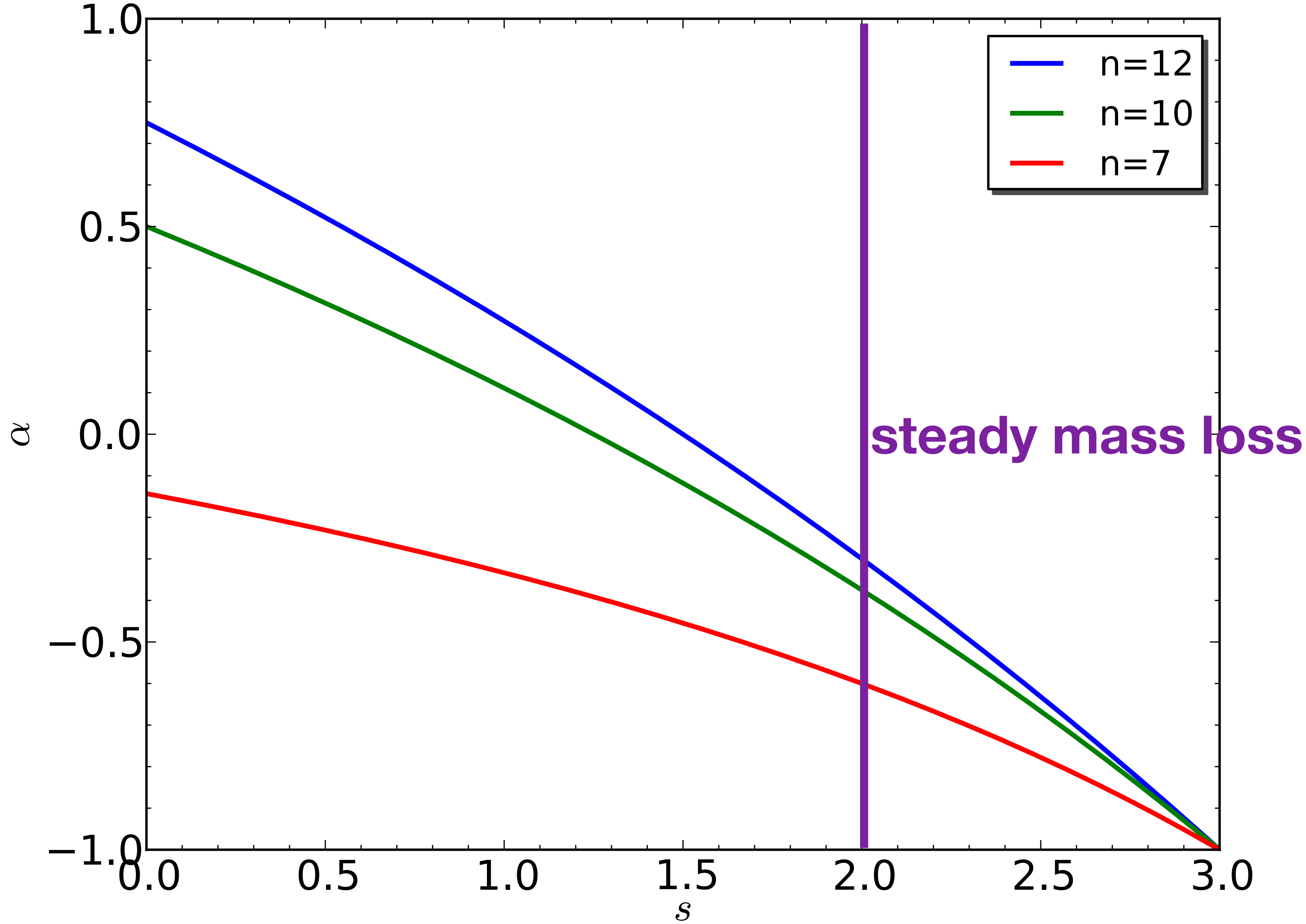
n=12: RSGs

n=10: compact stars, n=7: steepest possible

(Moriya et al. submitted)

An Analytic Bolometric Light Curve Model

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



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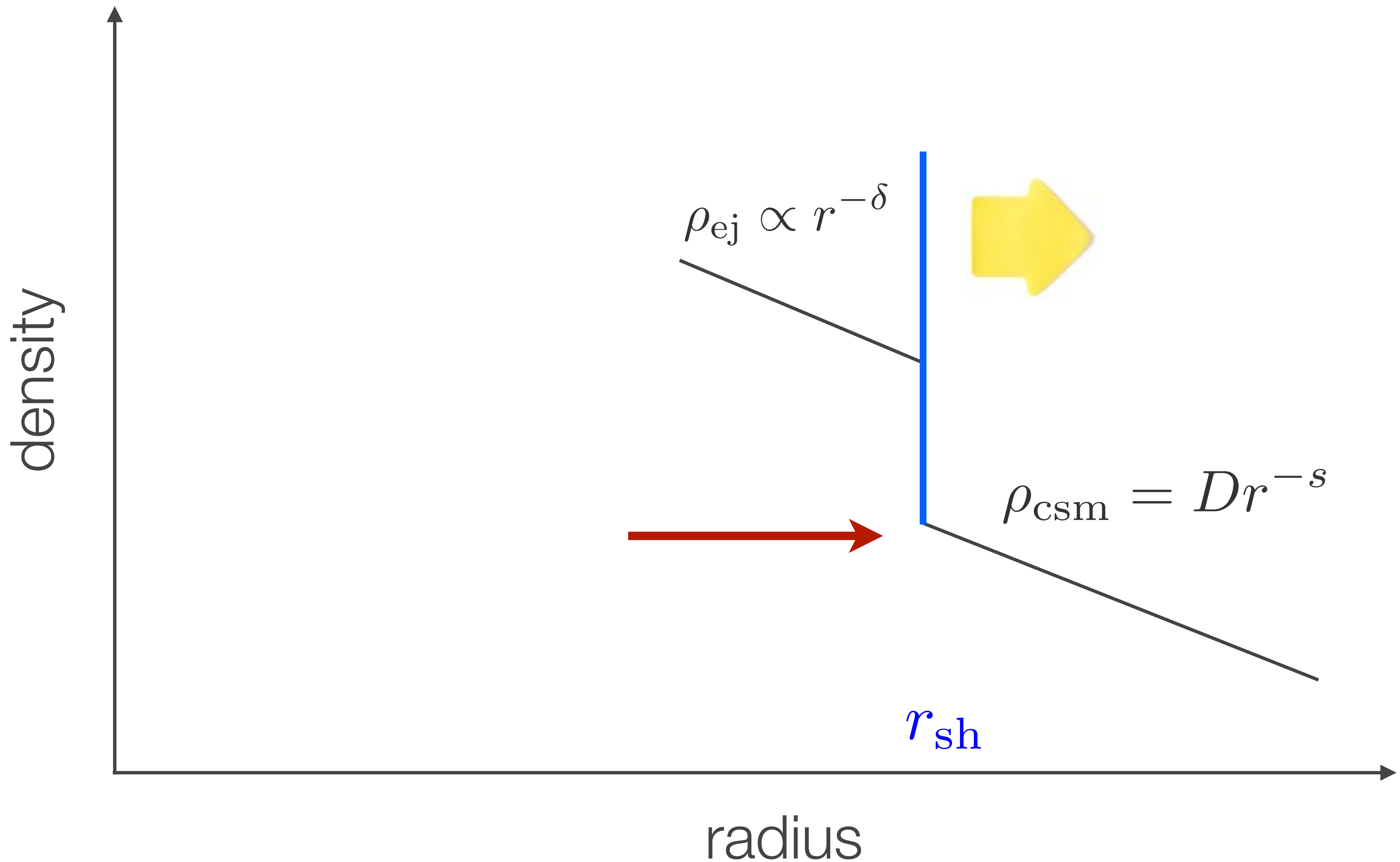


An Analytic Bolometric Light Curve Model

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

↓ approaches..

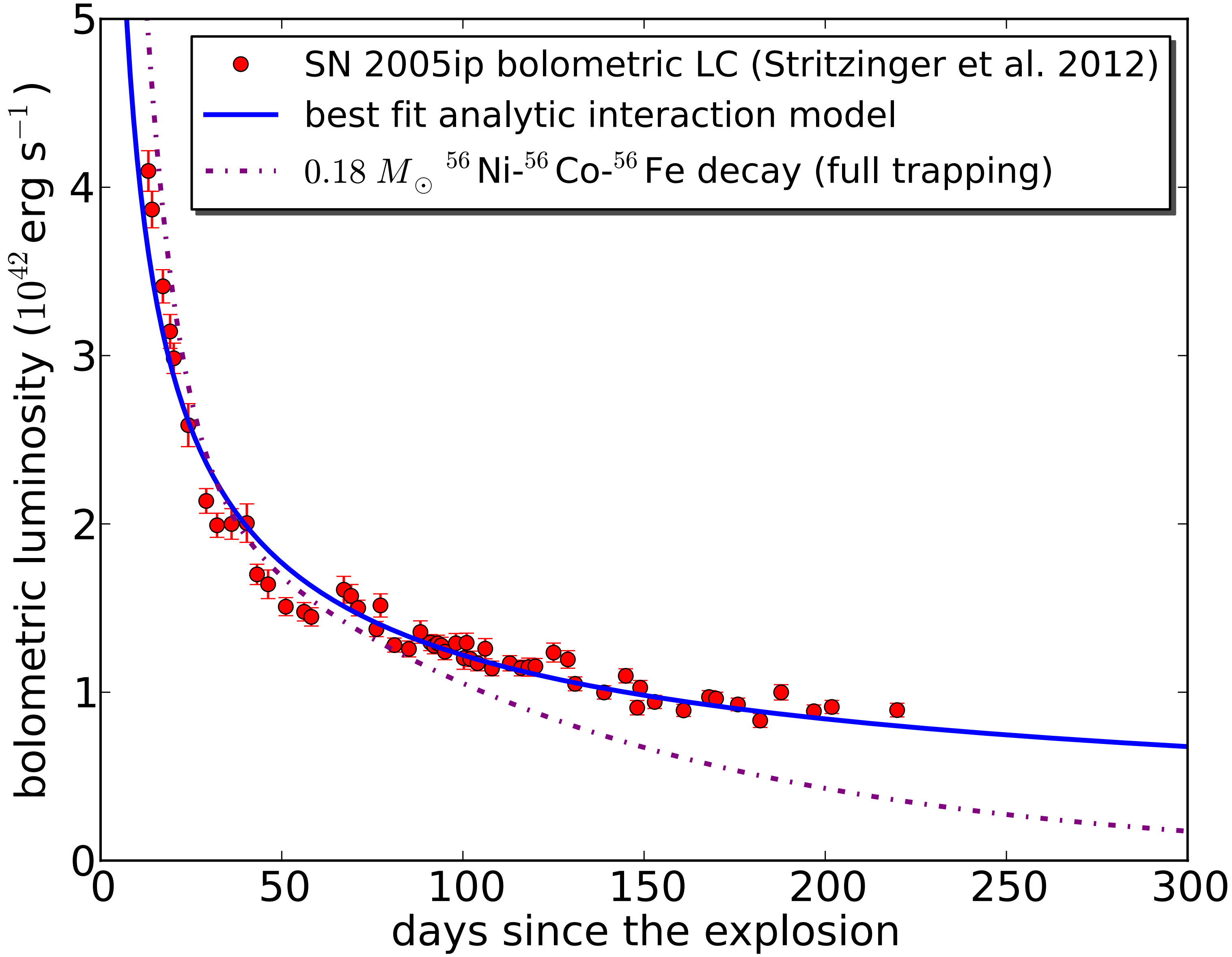
$$\frac{4\pi D}{4-s}r_{\rm sh}(t)^{4-s} + (3-s)M_{\rm ej}r_{\rm sh}(t) - (3-s)M_{\rm ej}\left(\frac{2E_{\rm ej}}{M_{\rm ej}}\right)^{\frac{1}{2}}t = 0.$$

↓ $L = \epsilon\frac{dE_{\rm kin}}{dt} = 2\pi\epsilon\rho_{\rm csm}r_{\rm sh}^2 v_{\rm sh}^3$

$$\begin{aligned} L &= 2\pi\xi\rho_{\rm csm}r_{\rm sh}^2 v_{\rm sh}^3, \\ &= 2\pi\xi D r_{\rm sh}^{2-s}\left[\frac{(3-s)M_{\rm ej}\left(\frac{2E_{\rm ej}}{M_{\rm ej}}\right)^{\frac{1}{2}}}{4\pi D r_{\rm sh}^{3-s} + (3-s)M_{\rm ej}}\right]^3. \end{aligned}$$

Application

- SN 2005ip



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

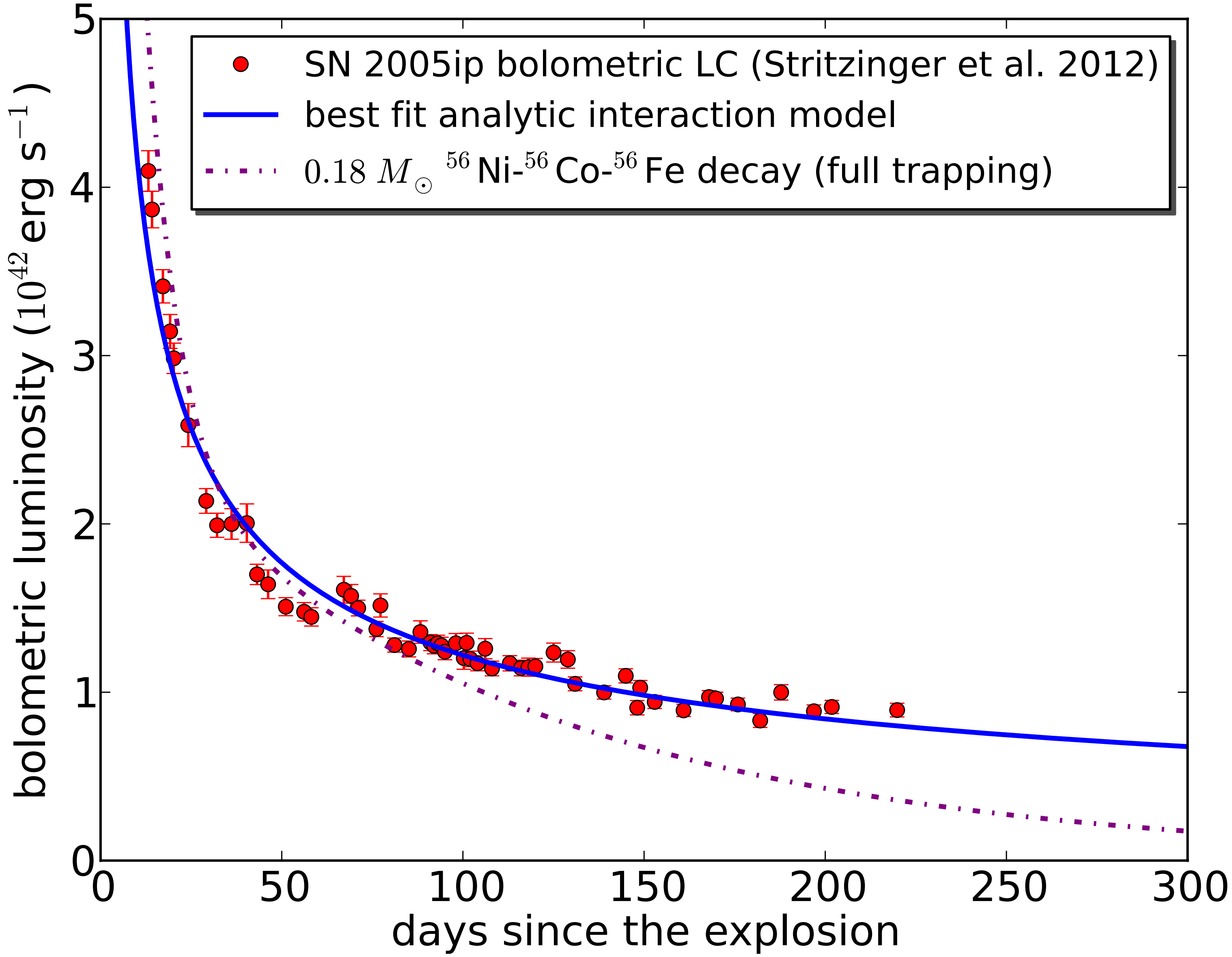
$\alpha = -0.536$

n=12 (RSGs): s=-2.28

n=10 (compact): s=-2.36

Application

- SN 2005ip



+ shell velocity evolution

$\epsilon = 0.1$

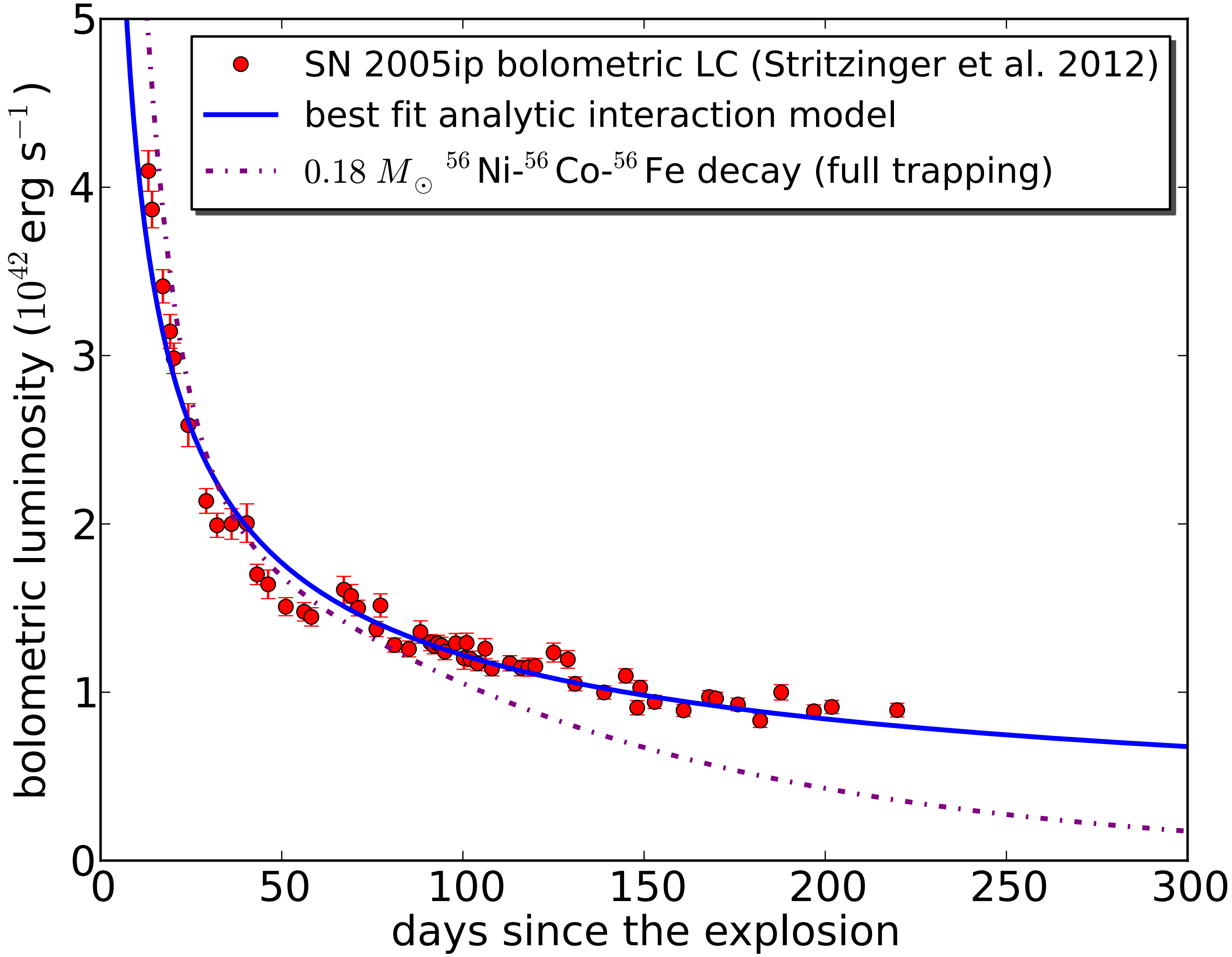
$$\langle \dot{M} \rangle = \begin{cases} 1.2 \times 10^{-3}\ M_\odot\ \mathrm{yr}^{-1} & (n = 10) \\ 1.4 \times 10^{-3}\ M_\odot\ \mathrm{yr}^{-1} & (n = 12) \end{cases}$$

*average rate obtained by CSM mass within 10^{16} cm and $v_\mathrm{w} = 100\ \mathrm{km\ s^{-1}}$

(Moriya et al. submitted)

Application

- SN 2005ip

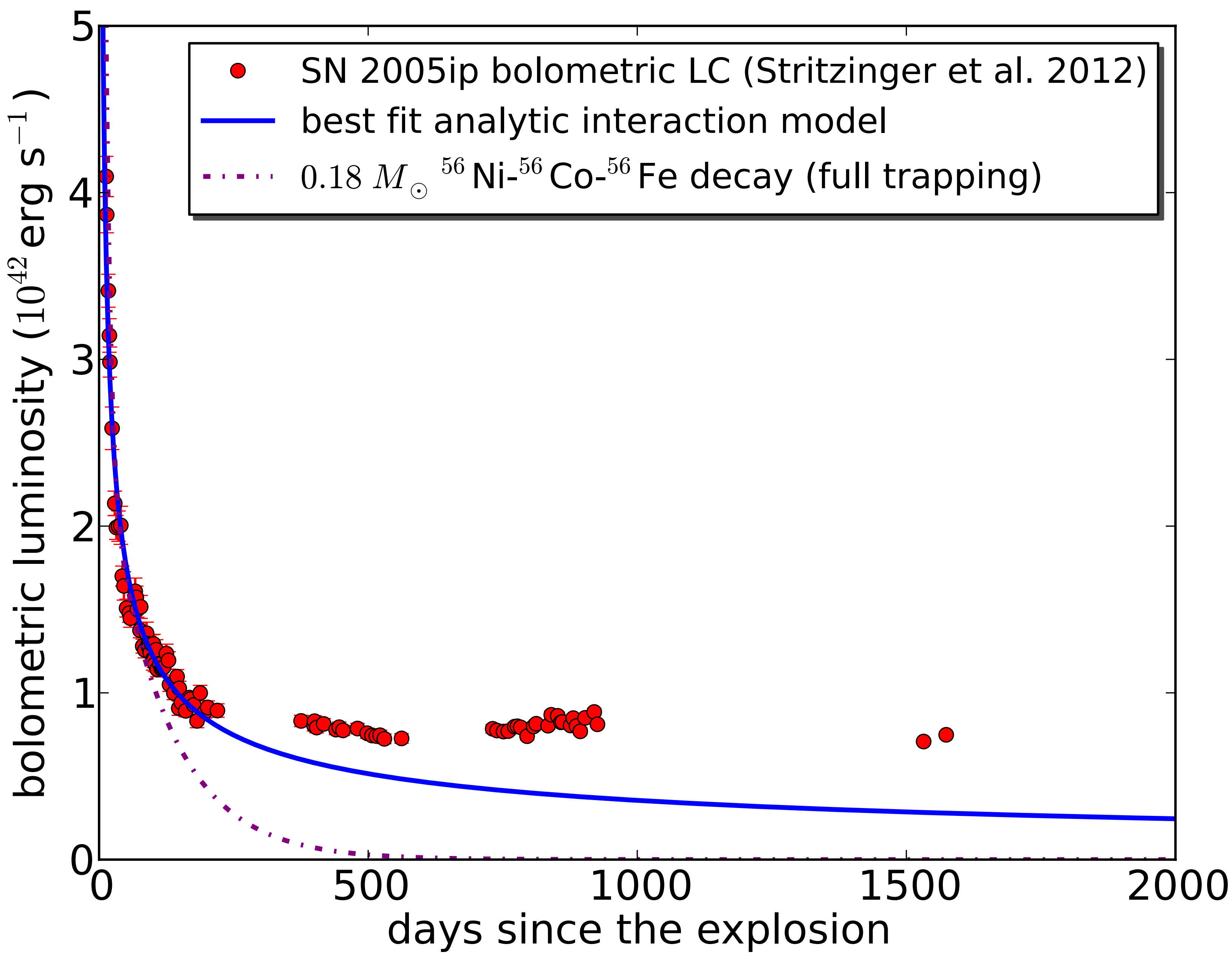


$+ M_{\rm ej} = 10\ M_\odot$

$$E_{\rm ej} = \begin{cases} 1.3 \times 10^{52}\ {\rm erg\ s^{-1}} & (n=10) \\ 1.5 \times 10^{52}\ {\rm erg\ s^{-1}} & (n=12) \end{cases}$$

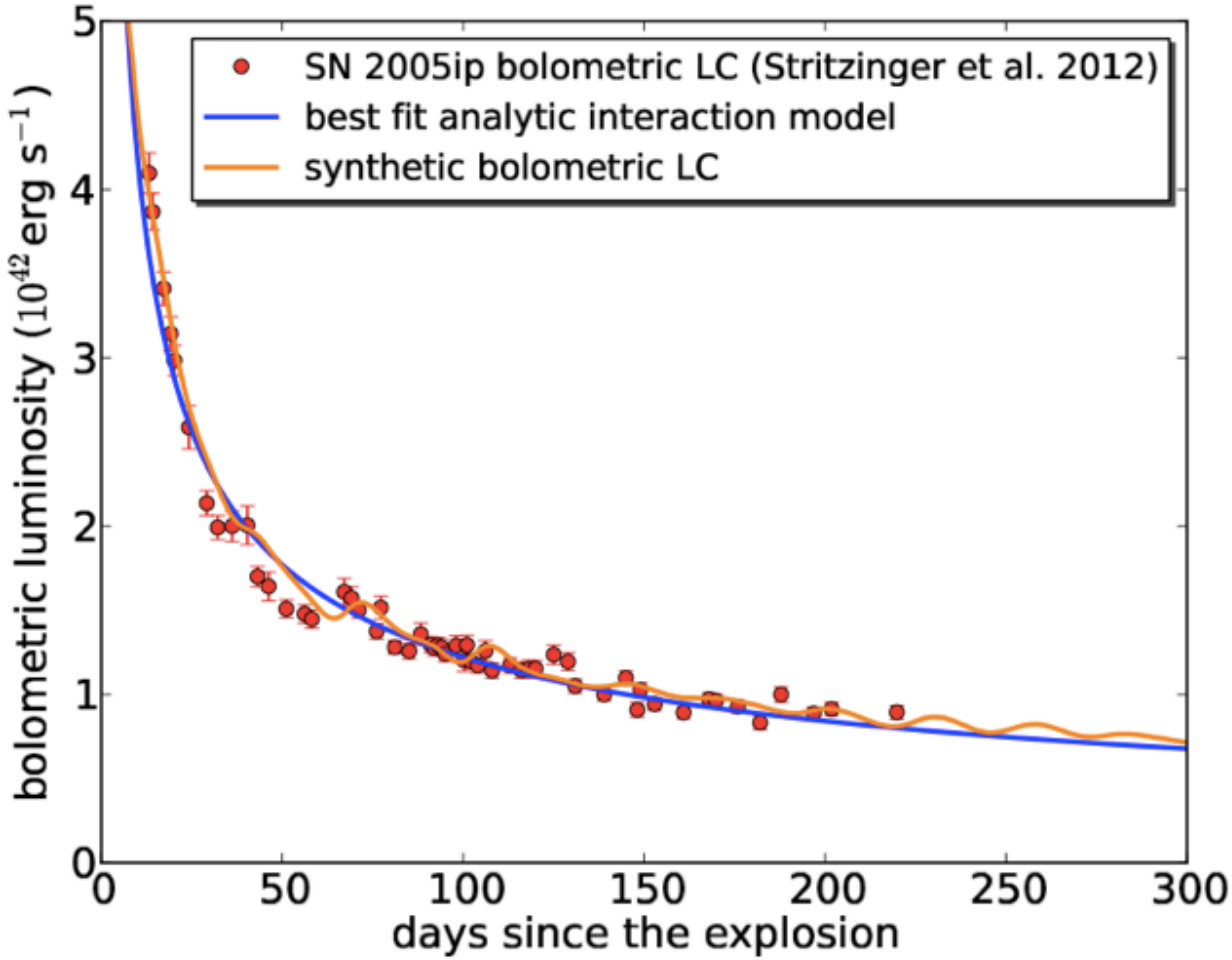
Application

- SN 2005ip



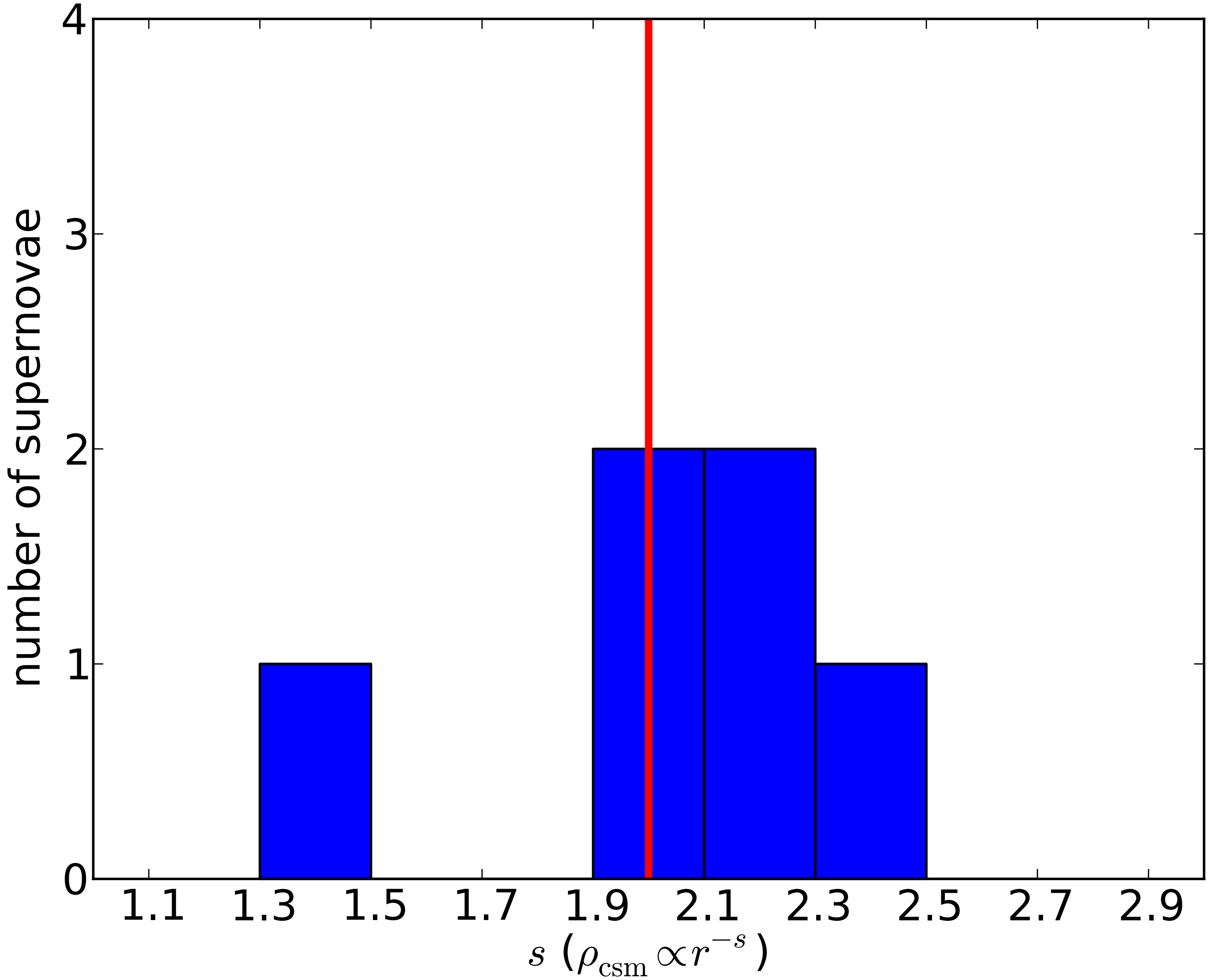
Comparison to Synthetic Light Curves

- STELLA code (one-dimensional radiation hydro. code, Blinnikov et al.)



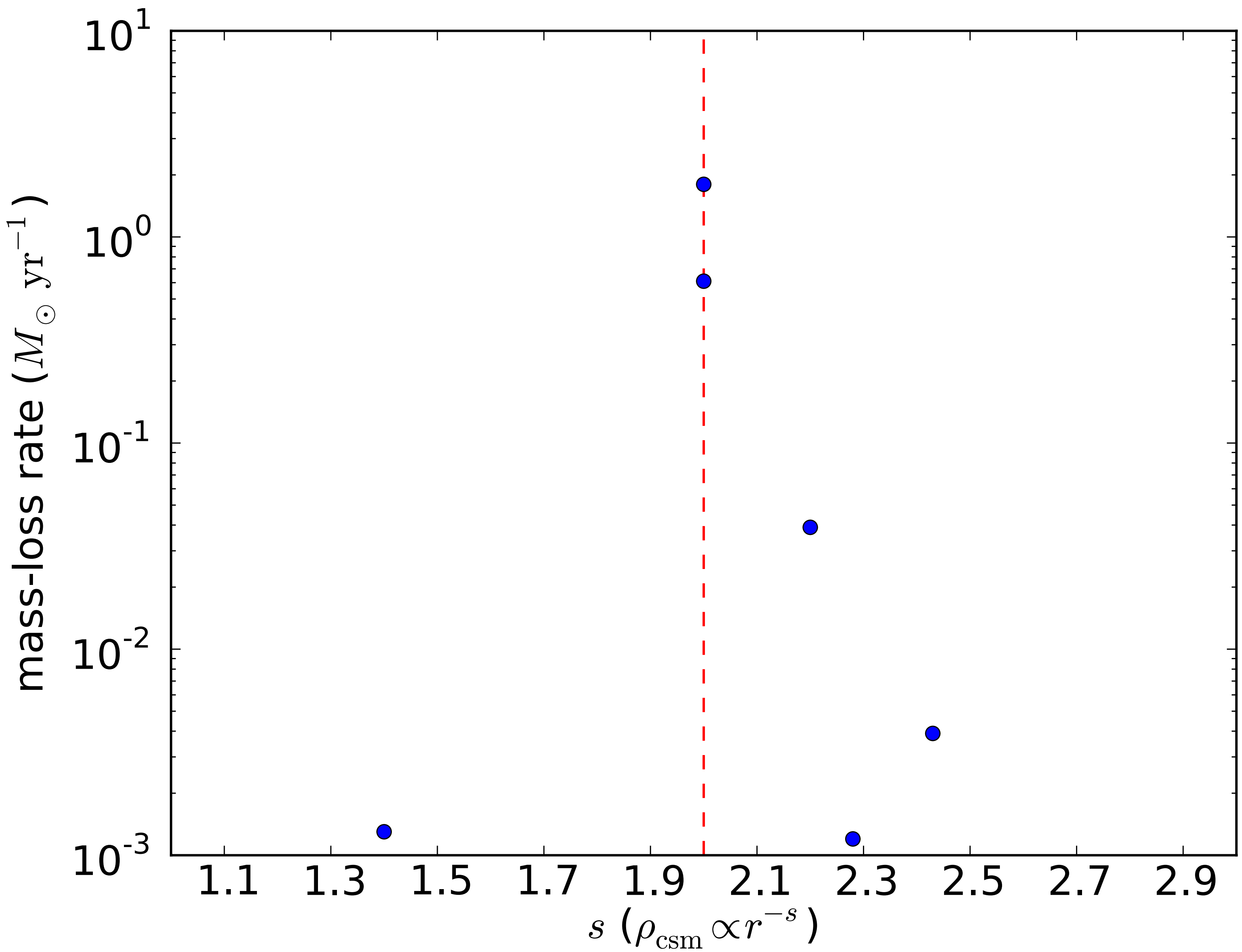
Circumstellar Medium Properties

- CSM slope
  - n=10

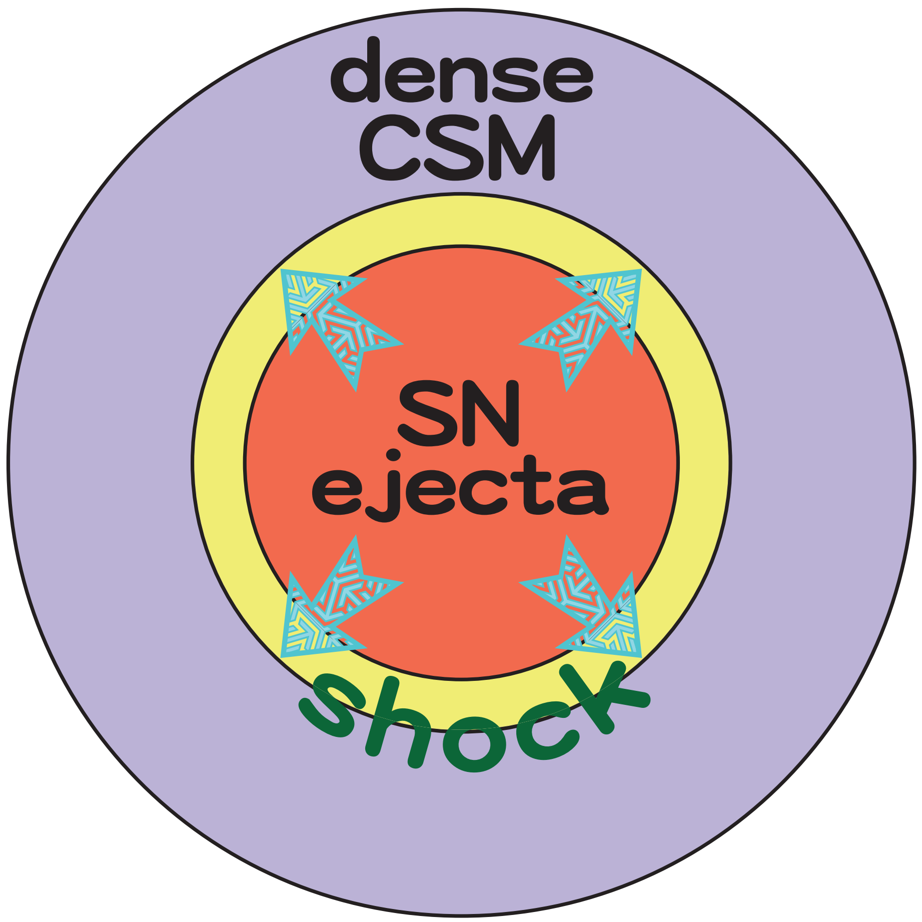


Circumstellar Medium Properties

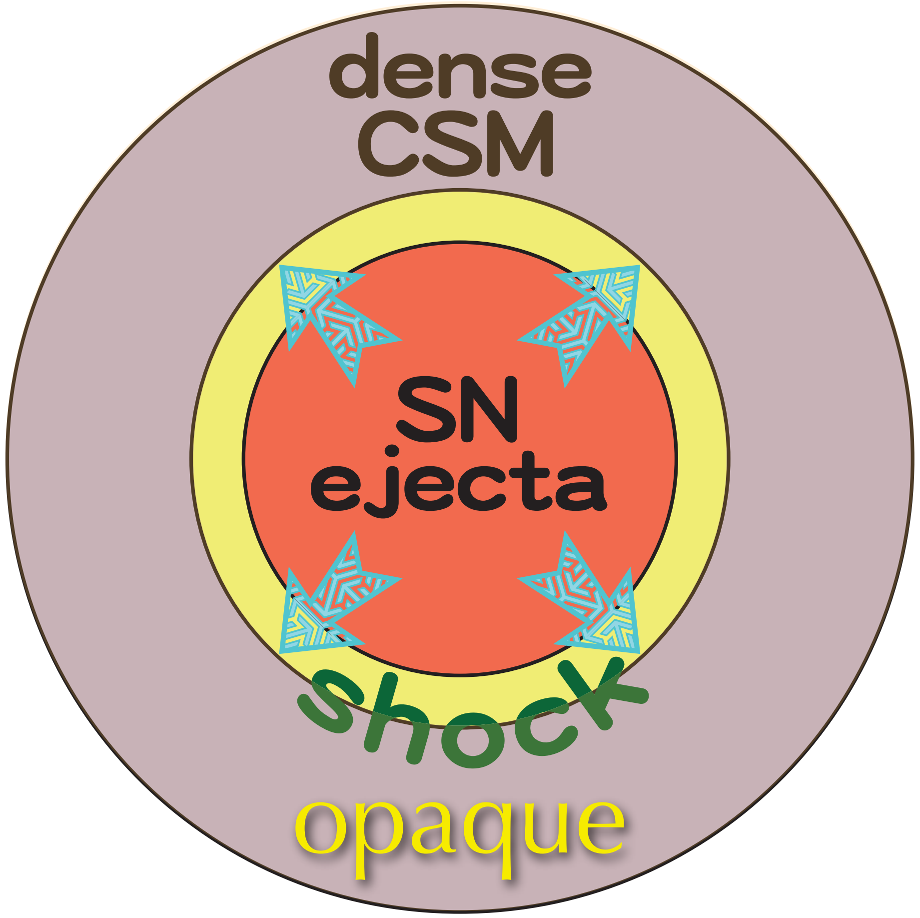
- Mass-loss rates
  - n=10
  - $M_{\mathrm{ej}} = 10\ M_\odot$
  - $v_{\mathrm{w}} = 100\ \mathrm{km\ s^{-1}}$
  - within 10^{16} cm
  - $\epsilon = 0.1$



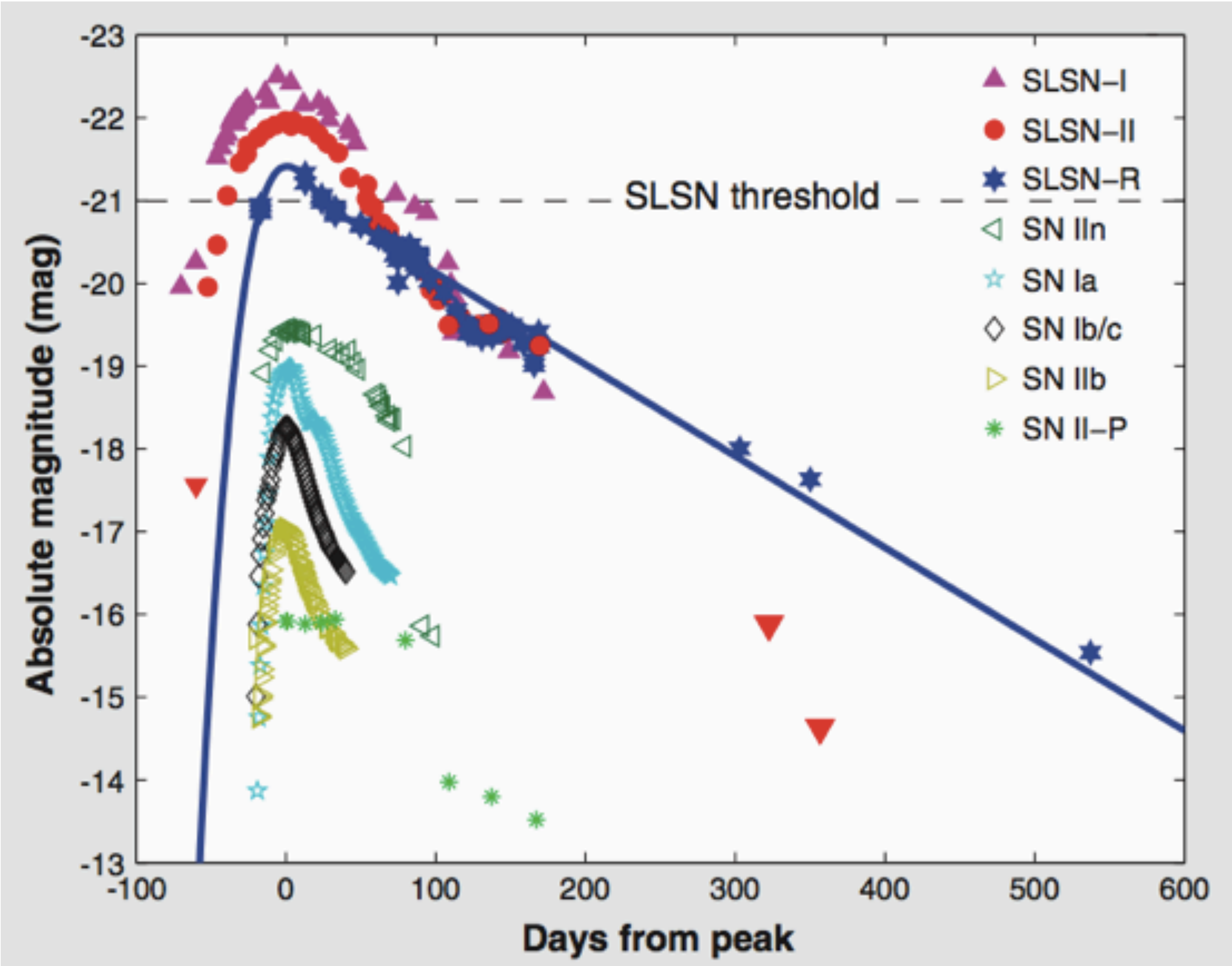
Light Curve Modeling of Interacting Supernovae



Light Curve Modeling of Interacting Supernovae



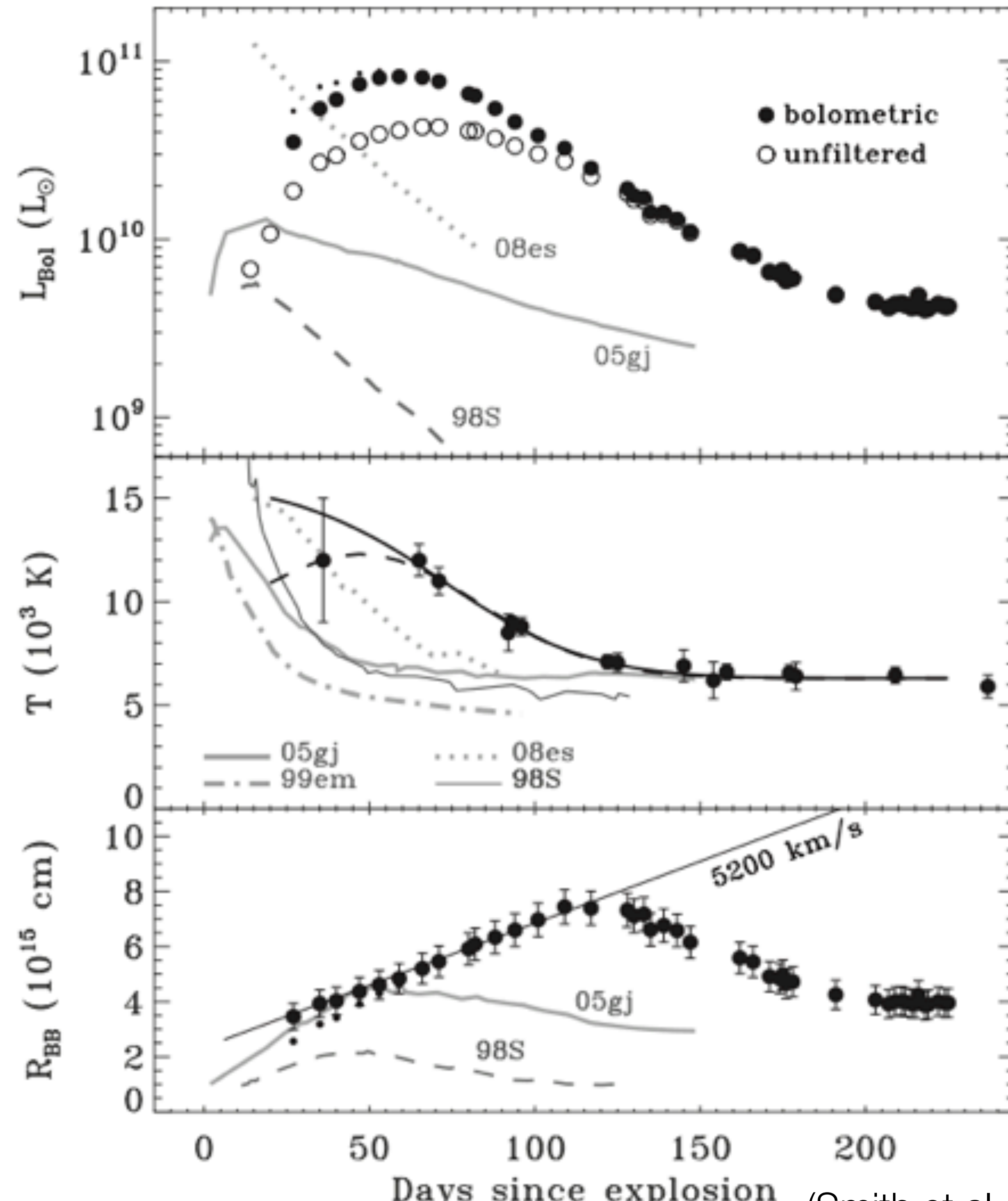
Superluminous Supernovae -- Extreme Cases



(Gal-Yam 2012)

SLSN 2006gy

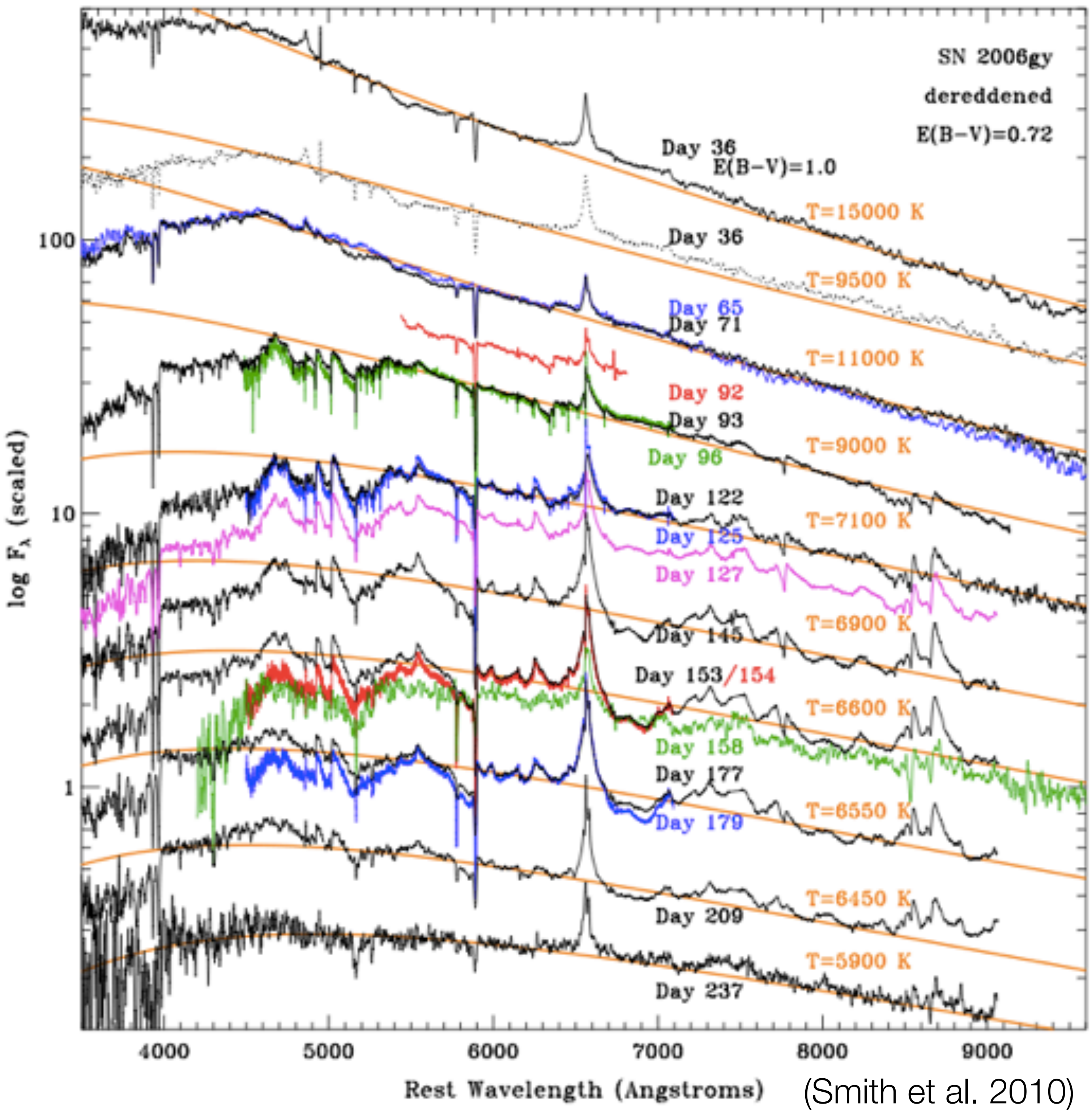
- Type IIn



(Smith et al. 2010)

SLSN 2006gy

- Type IIn

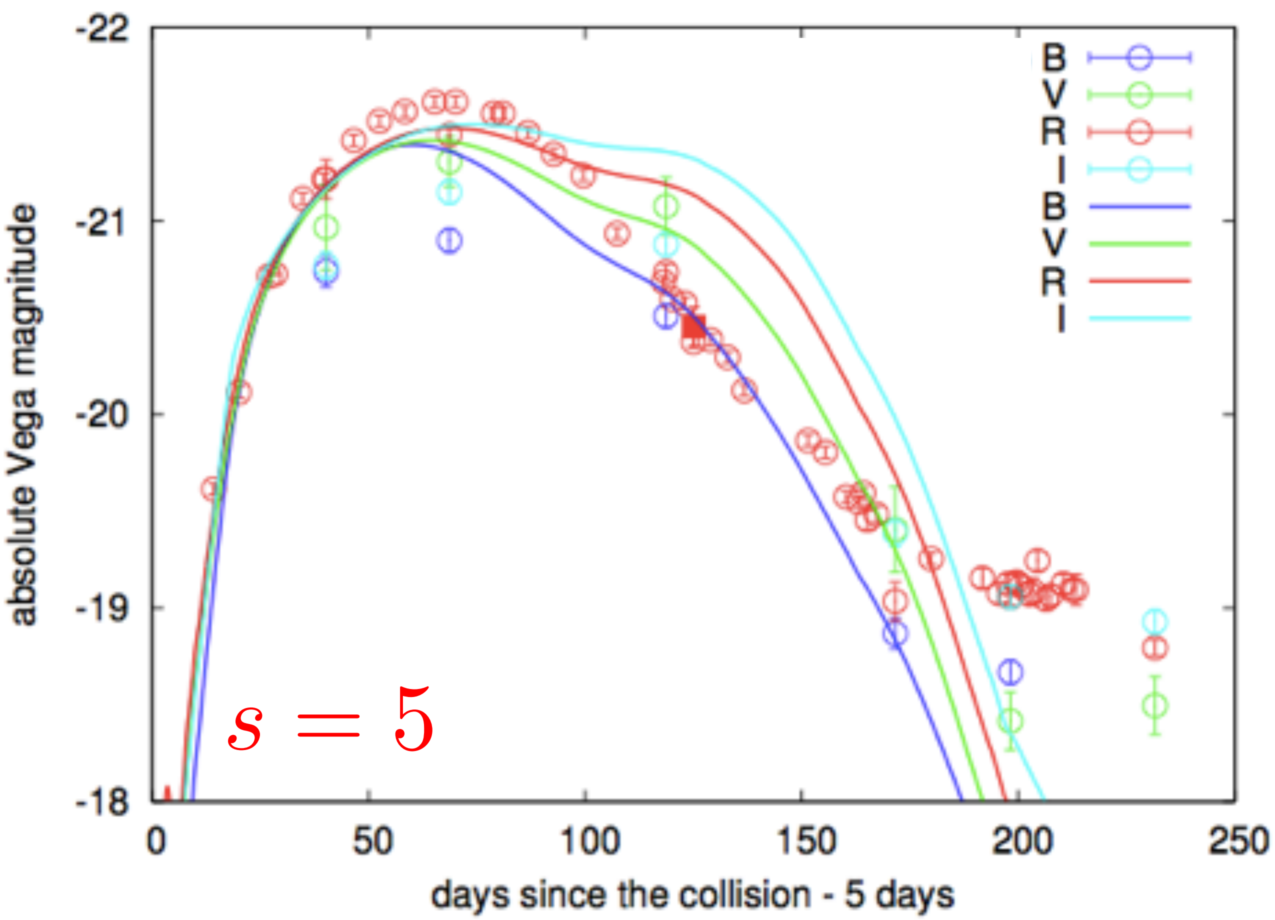


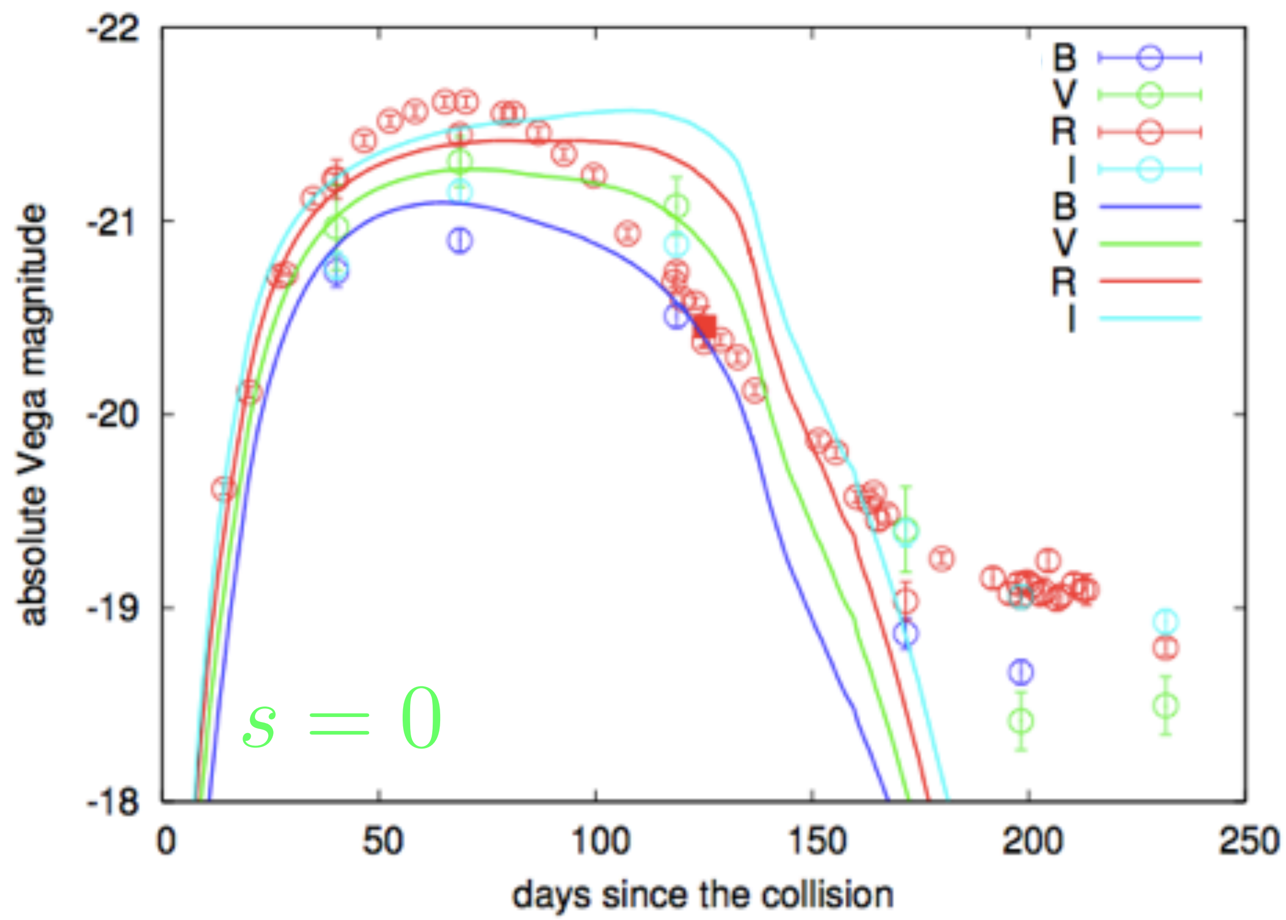
(Smith et al. 2010)

(Moriya et al. 2013)

Superluminous Type IIn SN 2006gy

- Numerical modeling
  - STELLA code (one-dimensional radiation hydro. code, Blinnikov et al.)
  - SN ejecta (20 Msun+1e52 erg) + dense CSM (15 Msun)
  - non-steady mass loss required

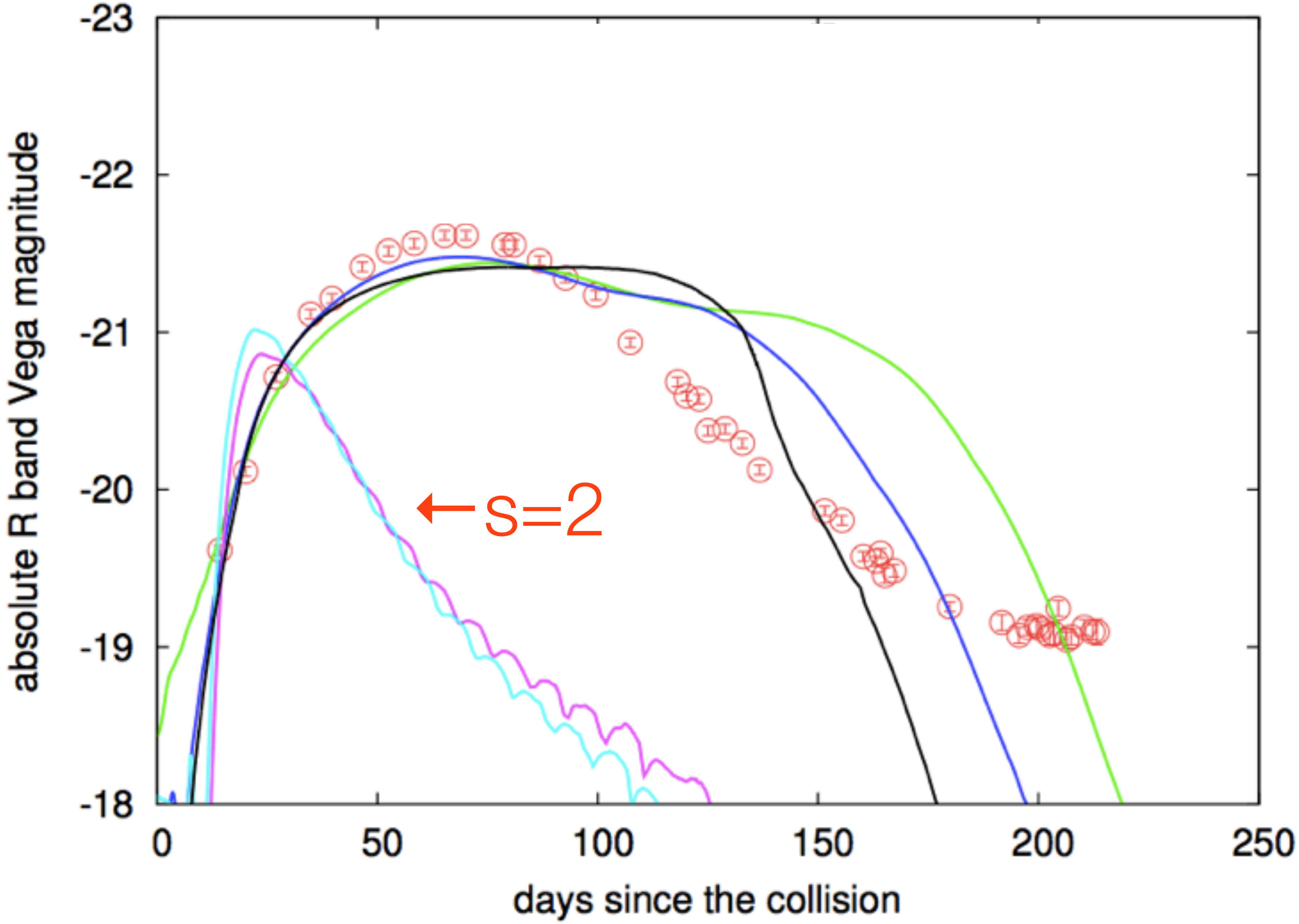




(Moriya et al. 2013)

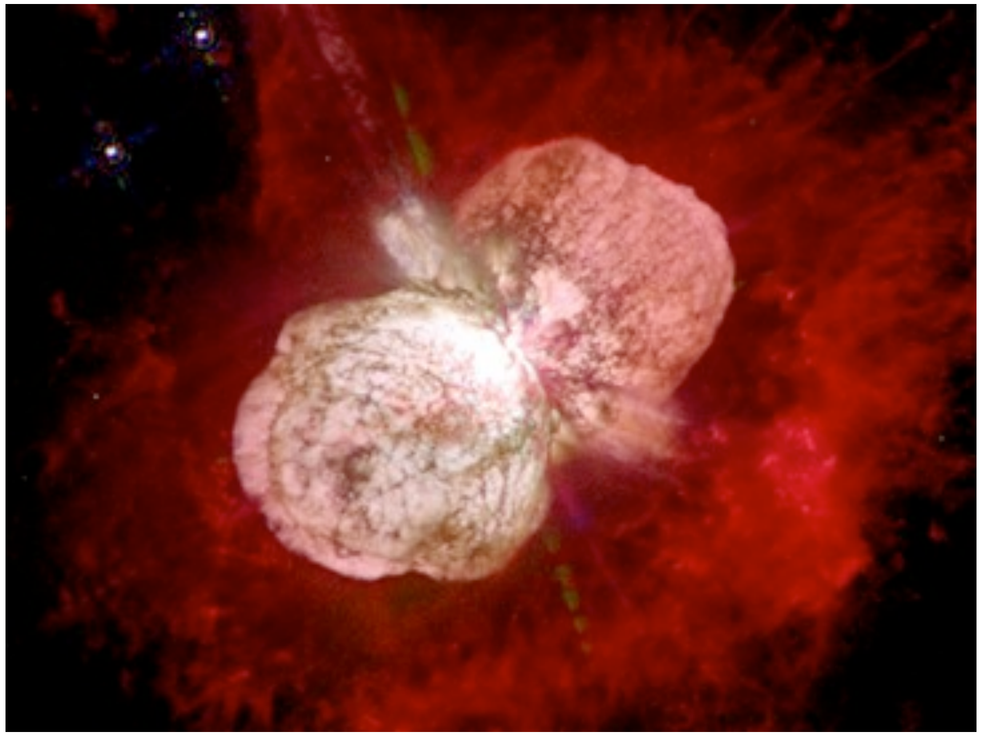
SLSN 2006gy

- steady mass-loss fails



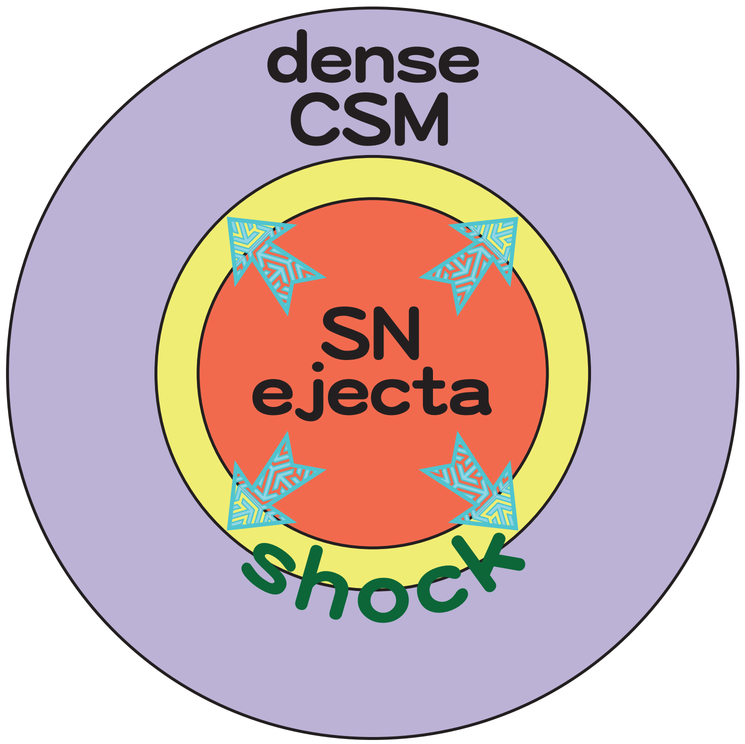
Superluminous Type IIn SN 2006gy

- CSM properties required:
  - CSM mass: $\sim 10\ M_\odot$
    - average mass-loss rate: $\simeq 0.5\ M_\odot\ \mathrm{yr}^{-1}$ (~ 30 years before explosion)
  - non-steady mass loss



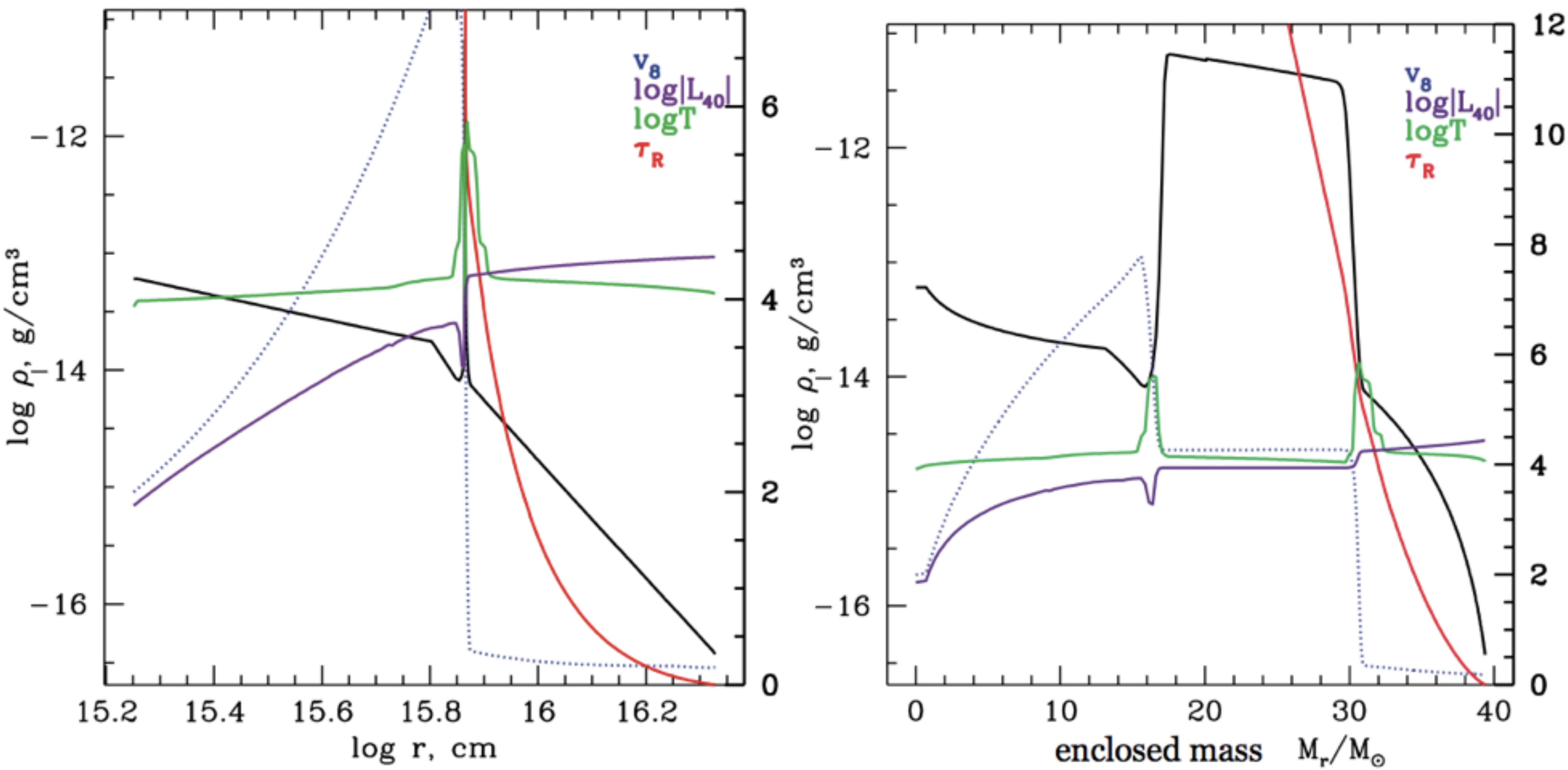
Summary

- (Non-superluminous) Type IIn supernovae
  - analytic LC model can be applied
  - consistent with s=2 (slightly higher?)
  - mass-loss rates: $\sim 0.001\ M_\odot\ \mathrm{yr}^{-1}$ (or higher)
- Superluminous supernovae
  - Type IIn SN 2006gy
    - dense CSM clearly exists.
    - requires $\sim 0.1\ M_\odot\ \mathrm{yr}^{-1}$ to explain the huge luminosity
- Future
  - gathering and applying to more samples
  - connecting to mass-loss mechanisms, progenitor scinarios



SLSN 2006gy

- Hydrodynamical structure



An Analytic Bolometric Light Curve Model

$$\left[\frac{4\pi D}{3-s} r_{\rm sh}^{3-s} + \frac{t^{n-3}}{(n-\delta)(n-3) r_{\rm sh}^{n-3}} \frac{[2(5-\delta)(n-5)E_{\rm ej}]^{(n-3)/2}}{[(3-\delta)(n-3)M_{\rm ej}]^{(n-5)/2}}\right] \frac{d^2 r_{\rm sh}}{dt^2} =$$

$$\frac{1}{(n-\delta)} \frac{[2(5-\delta)(n-5)E_{\rm ej}]^{(n-3)/2} t^{n-3}}{[(3-\delta)(n-3)M_{\rm ej}]^{(n-5)/2} r_{\rm sh}^{n-2}} \left(\frac{r_{\rm sh}}{t} - \frac{dr_{\rm sh}}{dt}\right)^2 - 4\pi D r_{\rm sh}^{2-s} \left(\frac{dr_{\rm sh}}{dt}\right)^2$$

$$r_{\rm sh}(t) = \left[\frac{(3-s)(4-s)}{4\pi D(n-4)(n-3)(n-\delta)} \frac{[2(5-\delta)(n-5)E_{\rm ej}]^{(n-3)/2}}{[(3-\delta)(n-3)M_{\rm ej}]^{(n-5)/2}}\right]^{\frac{1}{n-s}} t^{\frac{n-3}{n-s}}$$

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

$$L = L_1 t^\alpha$$

$$L_1 = \frac{\epsilon}{2} (4\pi D)^{\frac{n-5}{n-s}} \left(\frac{n-3}{n-s}\right)^3 \left[\frac{(3-s)(4-s)}{(n-4)(n-3)(n-\delta)} \frac{[2(5-\delta)(n-5)E_{\rm ej}]^{(n-3)/2}}{[(3-\delta)(n-3)M_{\rm ej}]^{(n-5)/2}}\right]^{\frac{5-s}{n-s}}$$

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

An Analytic Bolometric Light Curve Model

$$\left[\frac{4\pi D}{3-s}r_{\rm sh}^{3-s} + M_{\rm ej} - \frac{r_{\rm sh}^{3-\delta}}{(n-\delta)(3-\delta)t^{3-\delta}}\frac{[2(5-\delta)(n-5)E_{\rm ej}]^{(\delta-3)/2}}{[(3-\delta)(n-3)M_{\rm ej}]^{(\delta-5)/2}}\right]\frac{d^2 r_{\rm sh}}{dt^2} =$$
$$\frac{1}{(n-\delta)}\frac{[2(5-\delta)(n-5)E_{\rm ej}]^{(\delta-3)/2} r_{\rm sh}^{2-\delta}}{[(3-\delta)(n-3)M_{\rm ej}]^{(\delta-5)/2} t^{3-\delta}}\left(\frac{r_{\rm sh}}{t} - \frac{dr_{\rm sh}}{dt}\right)^2 - 4\pi D r_{\rm sh}^{2-s}\left(\frac{dr_{\rm sh}}{dt}\right)^2$$

approaches..

$$M_{\rm sh}\frac{d^2 r_{\rm sh}}{dt^2} = 4\pi r_{\rm sh}^2(-\rho_{\rm csm} v_{\rm sh}^2),$$

$$\left(\frac{4\pi D}{3-s}r_{\rm sh}^{3-s} + M_{\rm ej}\right)\frac{d^2 r_{\rm sh}}{dt^2} = -4\pi D r_{\rm sh}^{2-s}\left(\frac{dr_{\rm sh}}{dt}\right)^2$$

$$\frac{4\pi D}{4-s}r_{\rm sh}(t)^{4-s} + (3-s)M_{\rm ej}r_{\rm sh}(t) - (3-s)M_{\rm ej}\left(\frac{2E_{\rm ej}}{M_{\rm ej}}\right)^{\frac{1}{2}} t = 0.$$

$$L = 2\pi\xi\rho_{\rm csm} r_{\rm sh}^2 v_{\rm sh}^3,$$
$$= 2\pi\xi D r_{\rm sh}^{2-s}\left[\frac{(3-s)M_{\rm ej}\left(\frac{2E_{\rm ej}}{M_{\rm ej}}\right)^{\frac{1}{2}}}{4\pi D r_{\rm sh}^{3-s} + (3-s)M_{\rm ej}}\right]^3.$$