Supernovae Interacting with Dense CSM

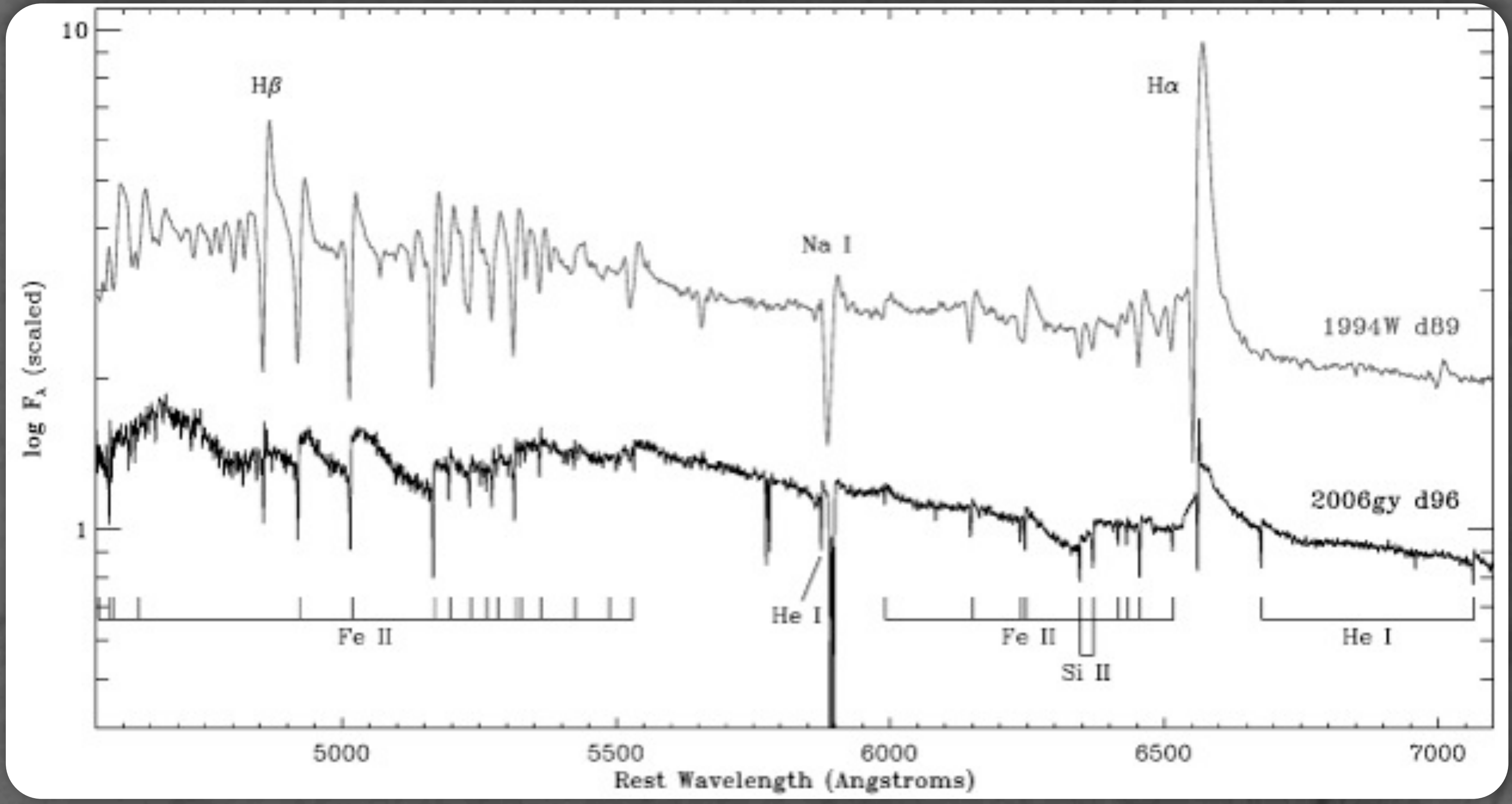
Takashi José Moriya Sierra (Kavli IPMU)

S. I. Blinnikov, N. Tominaga, K. Maeda, J. Sollerman,

F. Taddia, D. Kasen, N. Yoshida, M. Tanaka, K. Nomoto

Many interacting SNe

- ‘narrow’ line in SN spectra due to dense CSM
  - Type IIn
  - Type Ibn
  - Type Ian

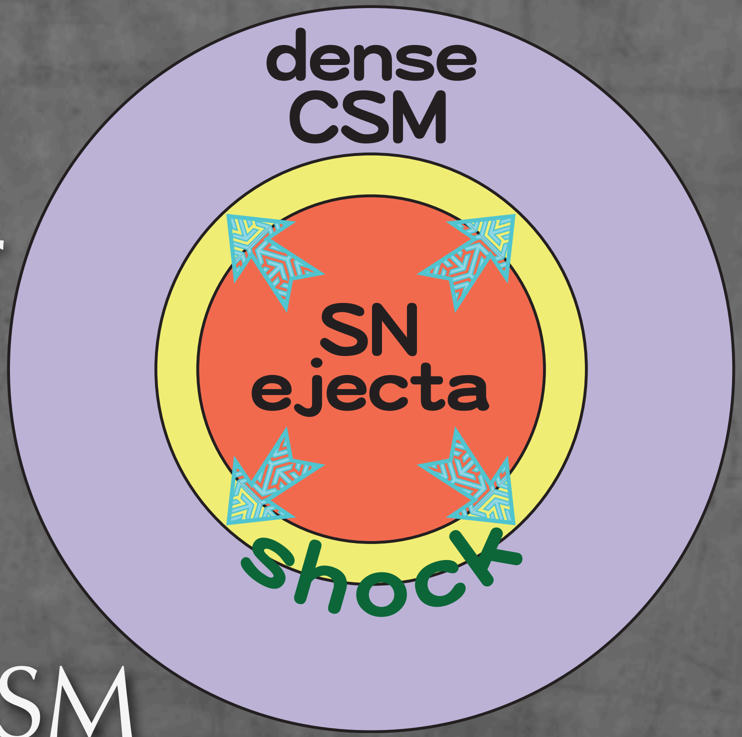


Smith et al. (2010)

‘dense’ CSM

- narrow lines from a dense shell
- how dense CSM should be?
    - more than ~ 1e-5 - 1e-4 Msun/yr
- temperature can get high but..
    - X-ray/radio absorbed by dense CSM
    - if it is very dense, temperature gets low

$$aT^4 \simeq \frac{1}{2}\rho v_s^2 \quad \rightarrow \quad T \sim 10^4 \text{ K}$$



Motivation for SNe IIn study

- What are they?
  - SN ejecta-CSM really works?
  - What are SN properties and CSM properties?
- What were they?
  - Progenitors: which stars can have such CSM?
  - Mass-loss mechanisms: how to have very high mass-loss rates?

SNe IIn tell us about the mass loss just before SN explosions

contents

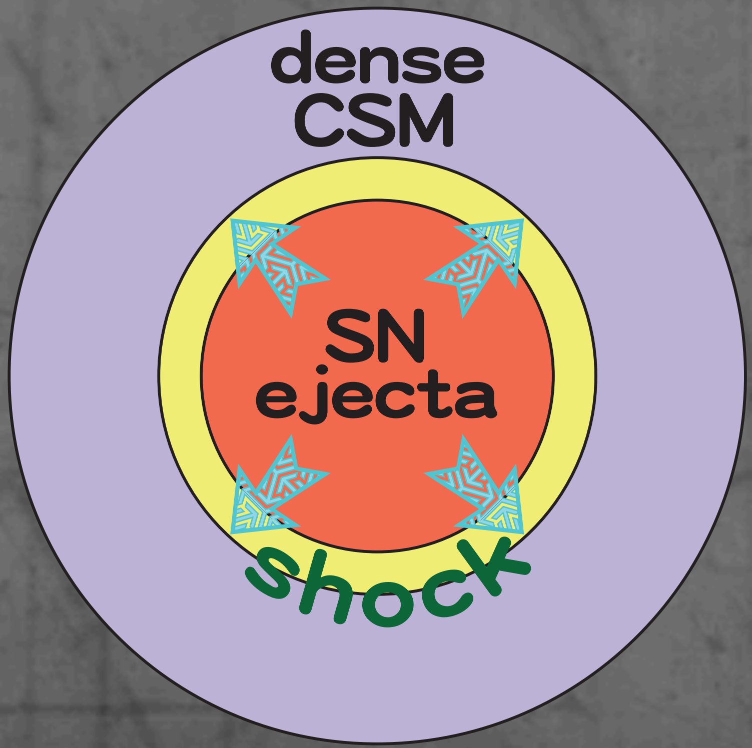
- Type IIn Supernovae
  - Non-superluminous
  - Superluminous

Non-Superluminous SNe IIn

LCs of Interacting SNe

- luminosity source = ejecta kinetic energy

$$dE = 4\pi r^2 \frac{1}{2}\rho_{CSM} v_s^2 dr \rightarrow L = \xi \frac{dE}{dt} = 4\pi\xi r^2 \frac{1}{2}\rho_{CSM} v_s^3$$



$$\rho_{SN} \propto r^{-n} \quad \rho_{CSM} \propto r^{-s}$$

↓ self-similar solution

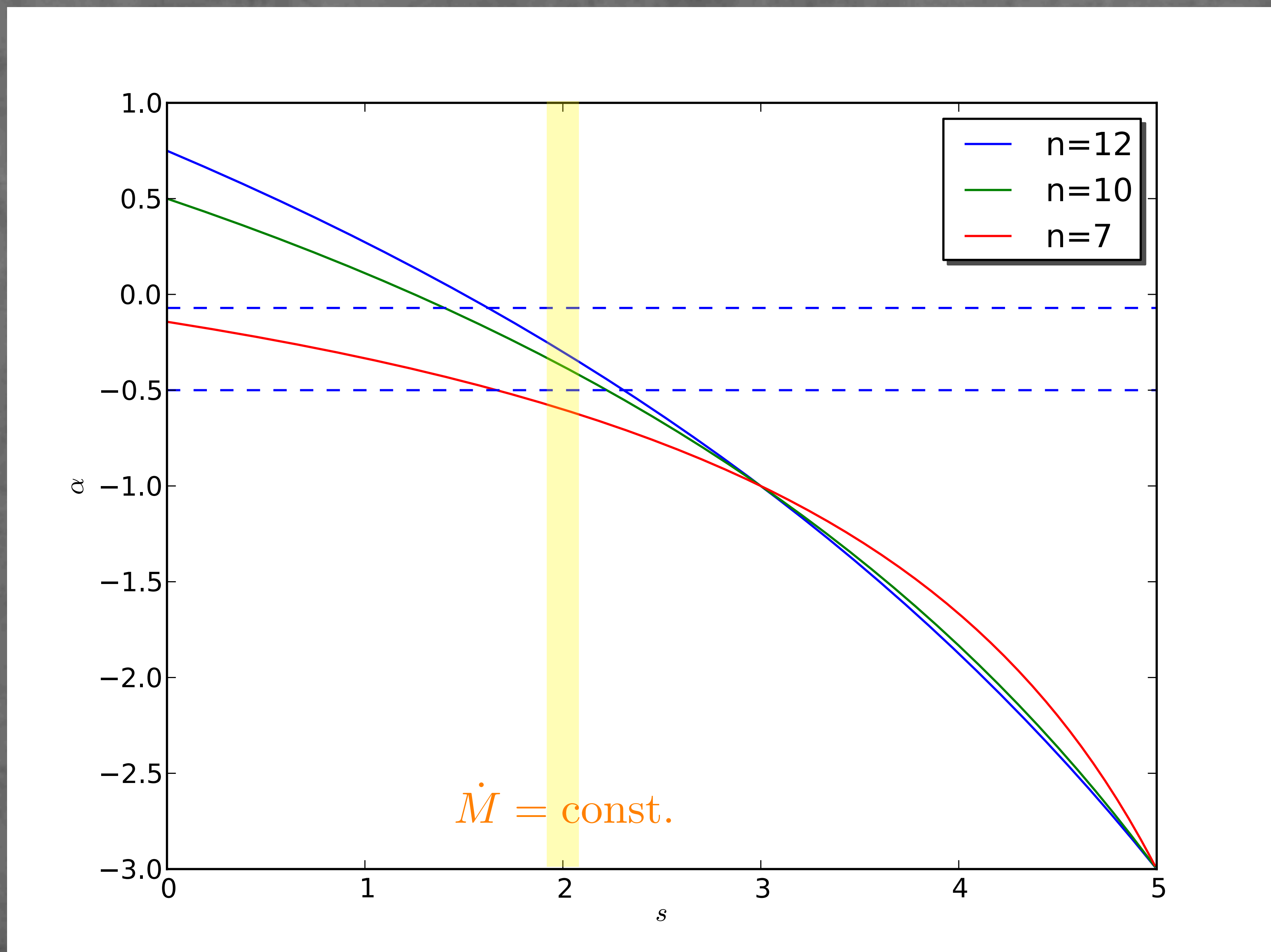
$$r \propto t^{\frac{n-3}{n-s}} \quad v_s \propto t^{\frac{s-3}{n-s}}$$

↓

$$L \propto t^{\alpha} \quad \alpha = \frac{n(2-s)+6s-15}{n-s}$$

$$L \propto t^{\alpha}$$

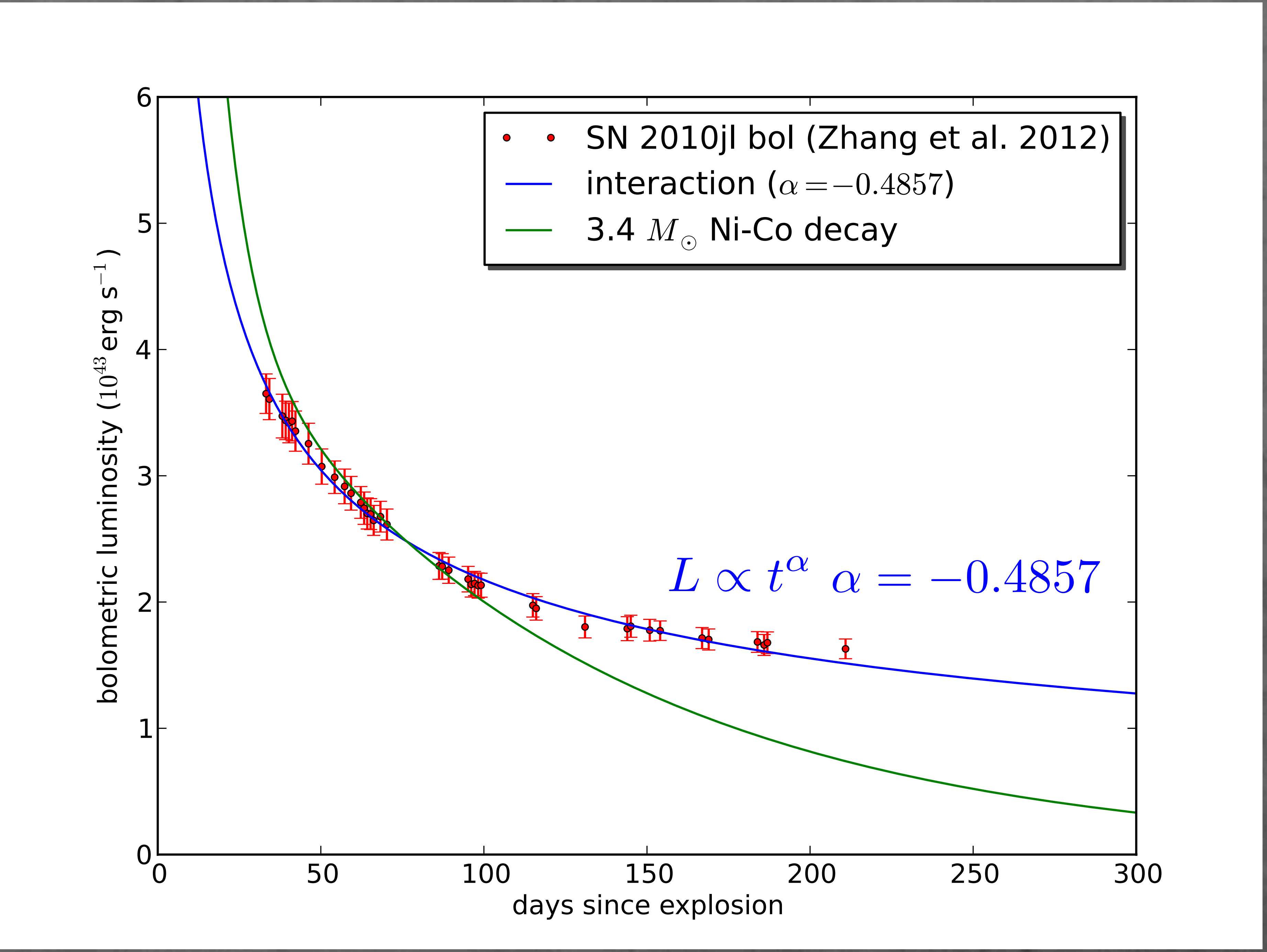
$$\alpha = \frac{n(2-s) + 6s - 15}{n - s}$$



n=12: RSG
n=10: IIb/Ib/Ic
n=7 : compact

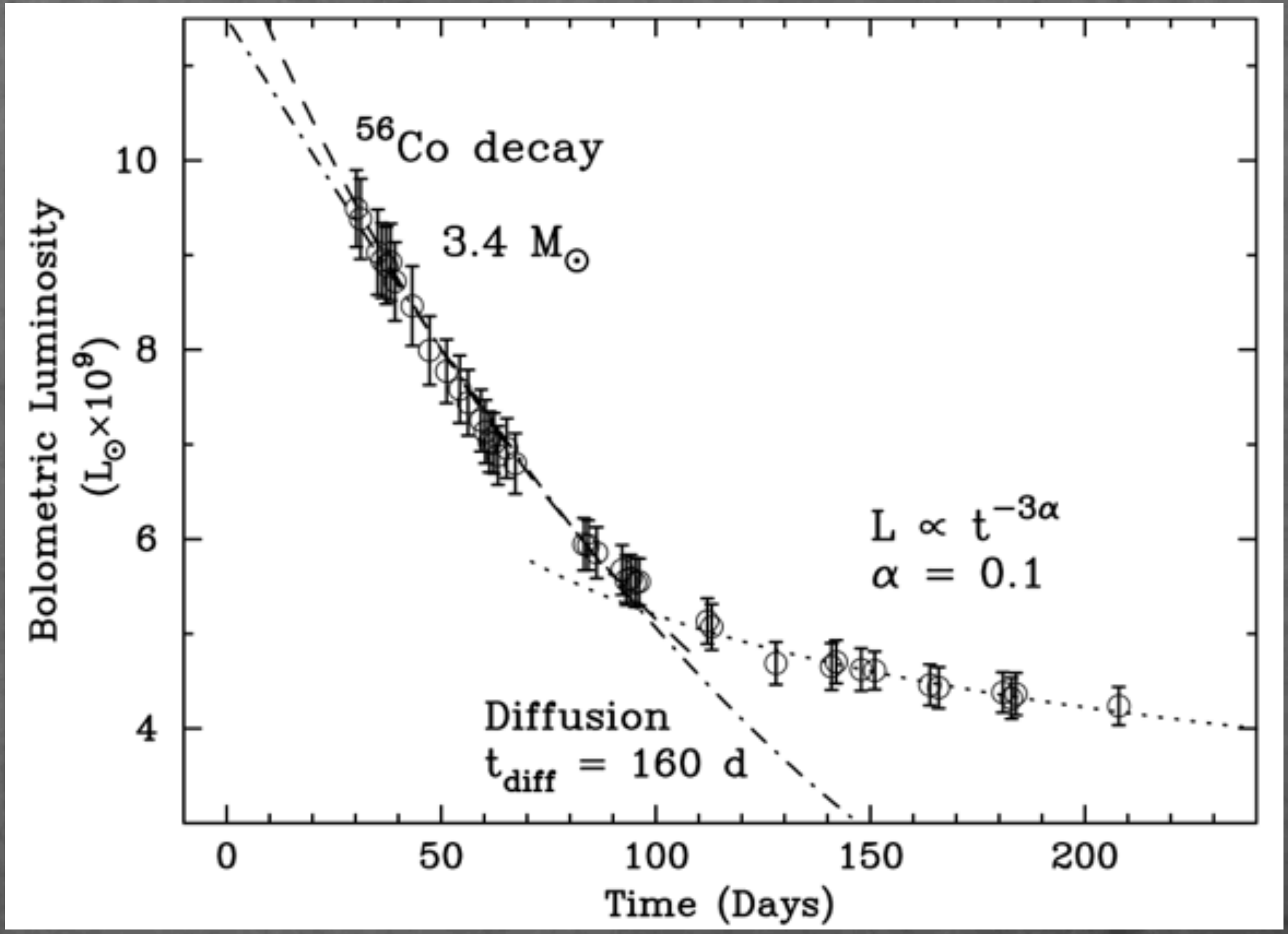
$$\rho_{\mathrm{CSM}} \propto r^{-s}$$

Type IIn SN 2010jl



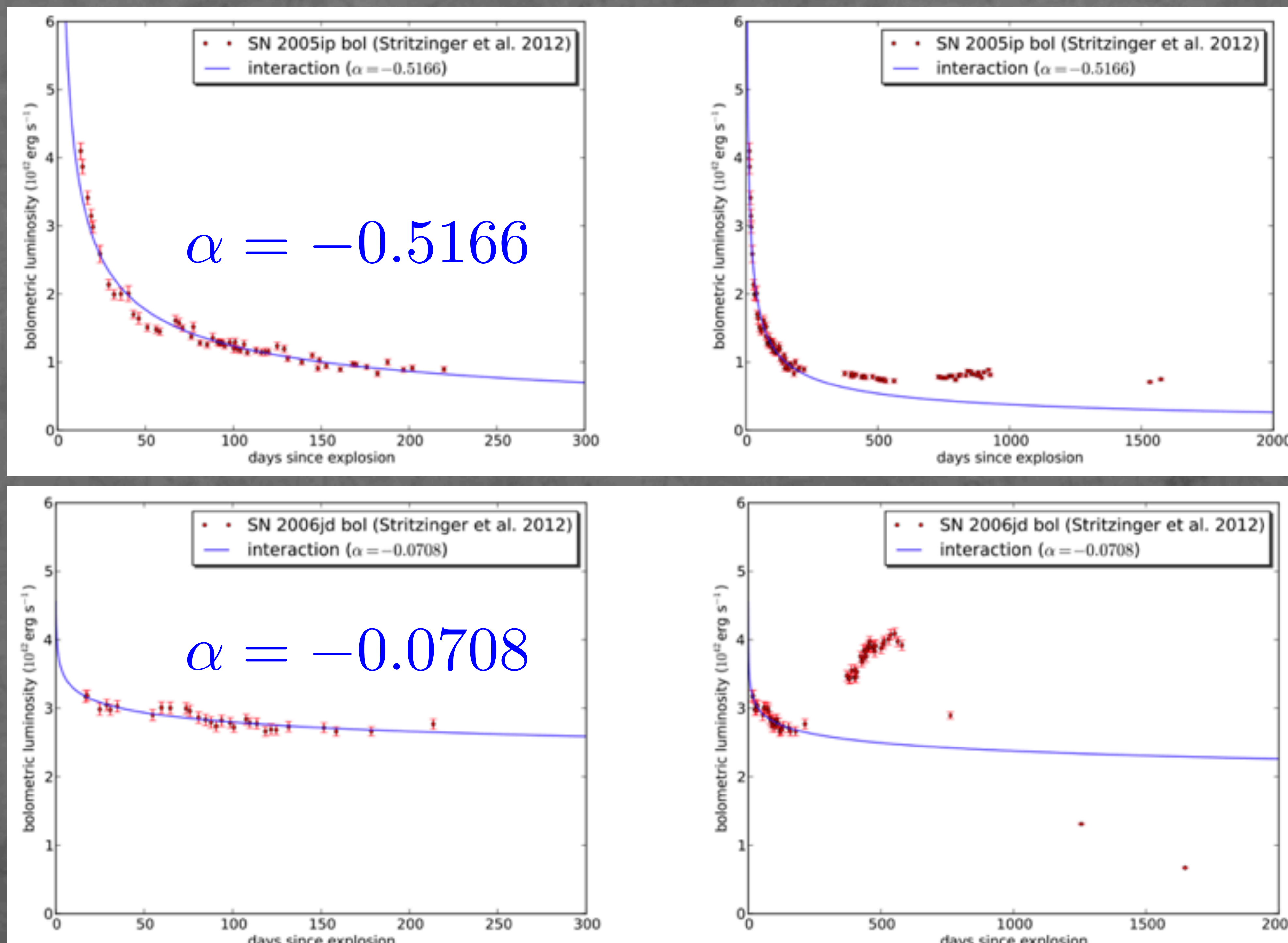
Type IIn SN 2010jl

- s=2 luminosity evolution ~ Ni-Co decay up to ~ 100 days since the explosion



Zhang et al. (2012)

SN 2005ip & SN 2006jd (IIn)

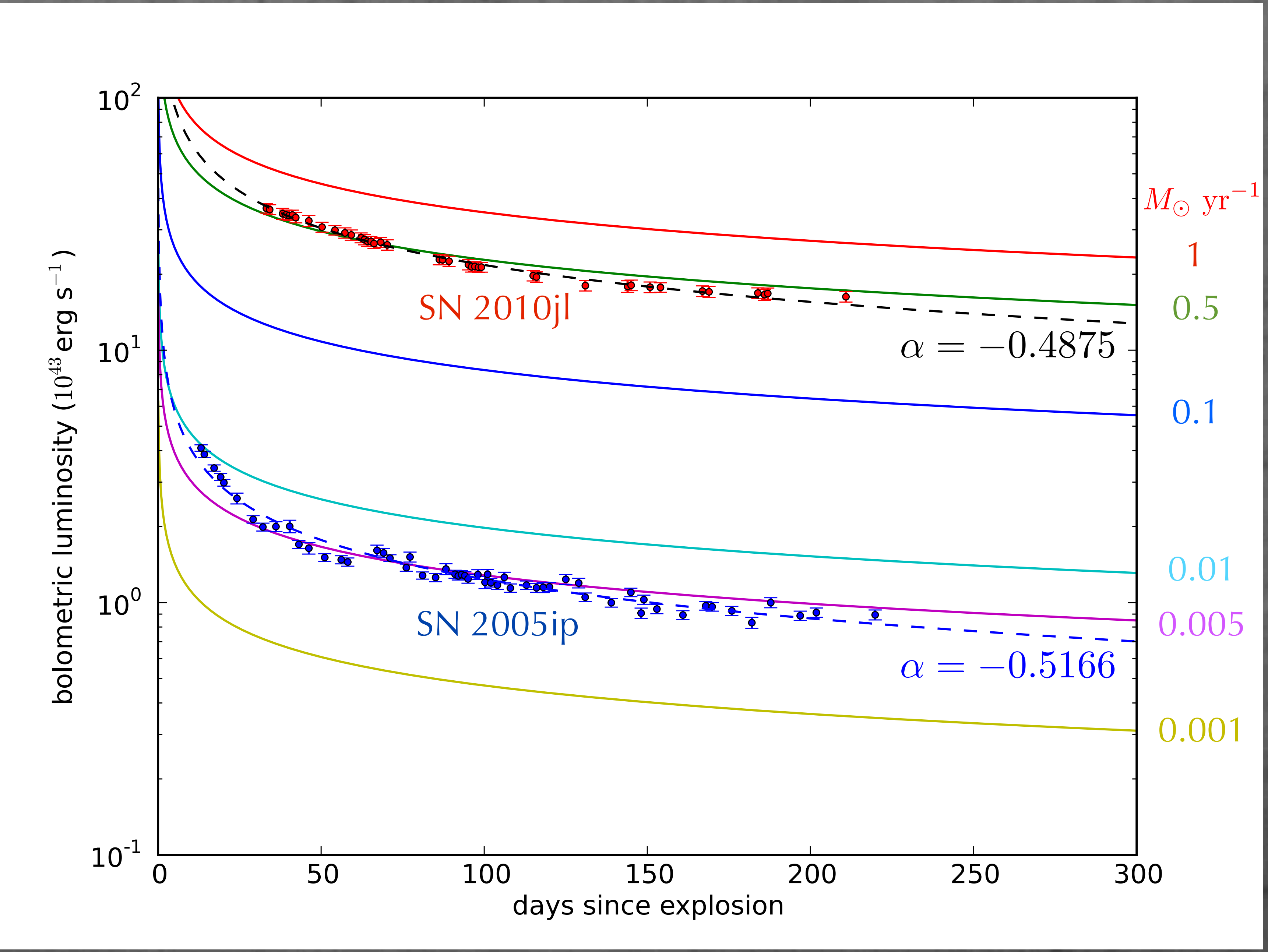


Mass-Loss Rates

- comparison to s=2 models

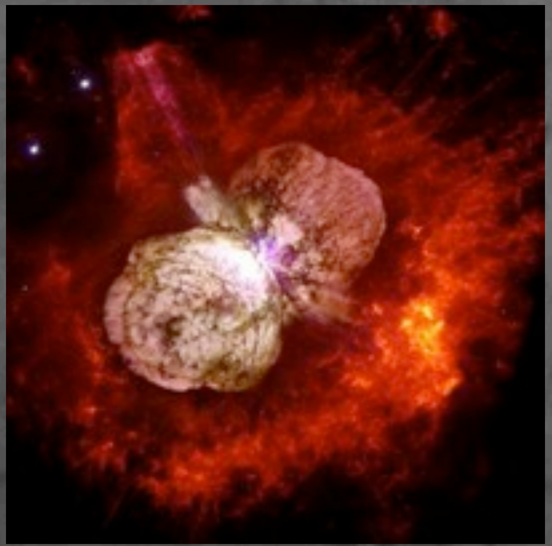
$$L = 4.69 \times 10^{43} \left(\frac{\xi}{0.1}\right) \left(\frac{E_{\rm kin}}{5\times10^{51}{\rm erg}}\right)^{1.3125} \left(\frac{M_{\rm ej}}{10M_\odot}\right)^{-0.9375} \left(\frac{\dot{M}}{0.1M_\odot{\rm yr}^{-1}}\right)^{0.625} \left(\frac{v_w}{100{\rm km\ s}^{-1}}\right)^{-0.625} \left(\frac{t}{1{\rm day}}\right)^{-0.375} {\rm erg\ s}^{-1}$$

$\alpha = -0.375$



Progenitors of Type IIn SNe

- Many SNe IIn is consistent with steady mass loss model up to ~ 300 days
  - steady mass loss ~ 10 years before explosions
- Are they really LBVs?
  - ↓ SN 2005ip
  - mass-loss rate in 'quiet' phase: <~1e-3 Msun/yr
  - ↓ SN 2010jl
  - 0.1 Msun/yr from LBV is from short 'eruptive' (non-steady) event



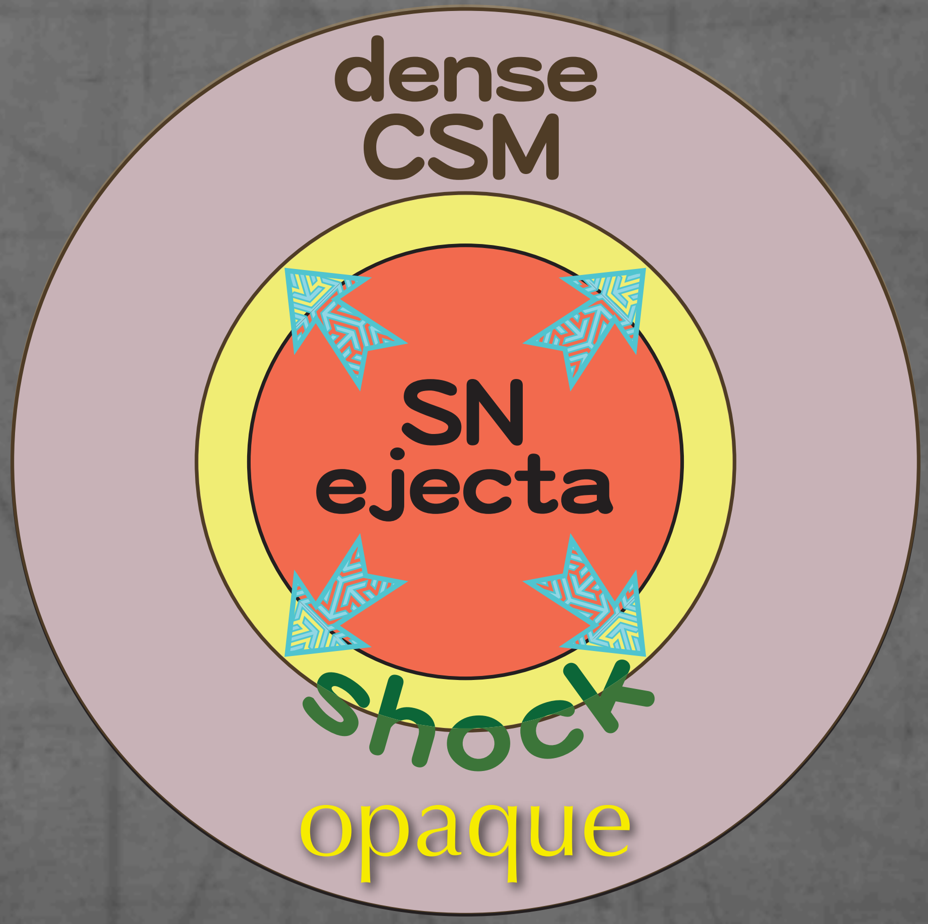
non-SL SNe Type IIn

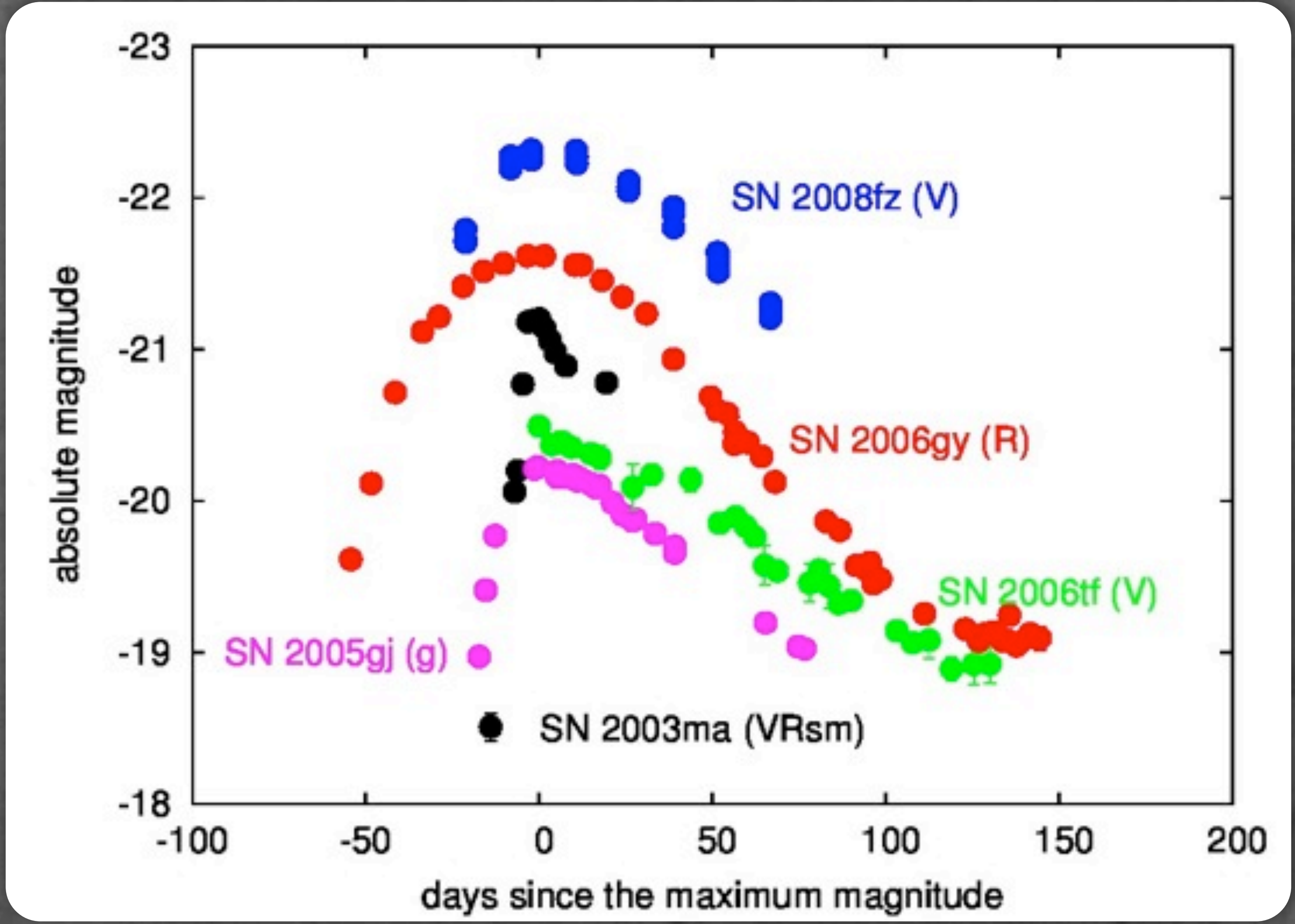
- SN 2010jl
  - steady mass-loss with ~ 1e-1 Msun/yr
  - difficult for LBV?
- SN 2005ip
  - steady mass-loss with ~ 1e-3 Msun/yr
  - consistent with LBV
- SN 2006jd
  - non-steady mass loss? CSM density flatter than the above two

Superluminous SNe IIn

Superluminous SNe

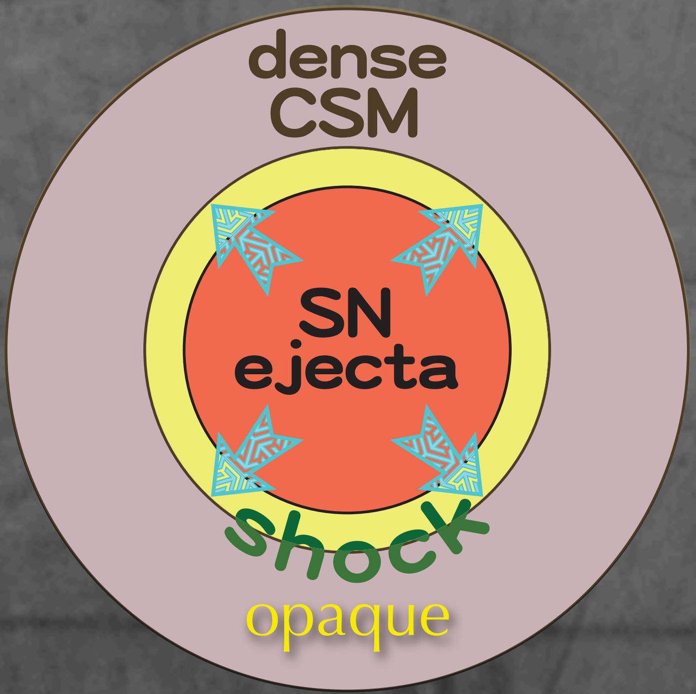
- Interaction + diffusion in CSM





Shock Breakout in Dense CSM

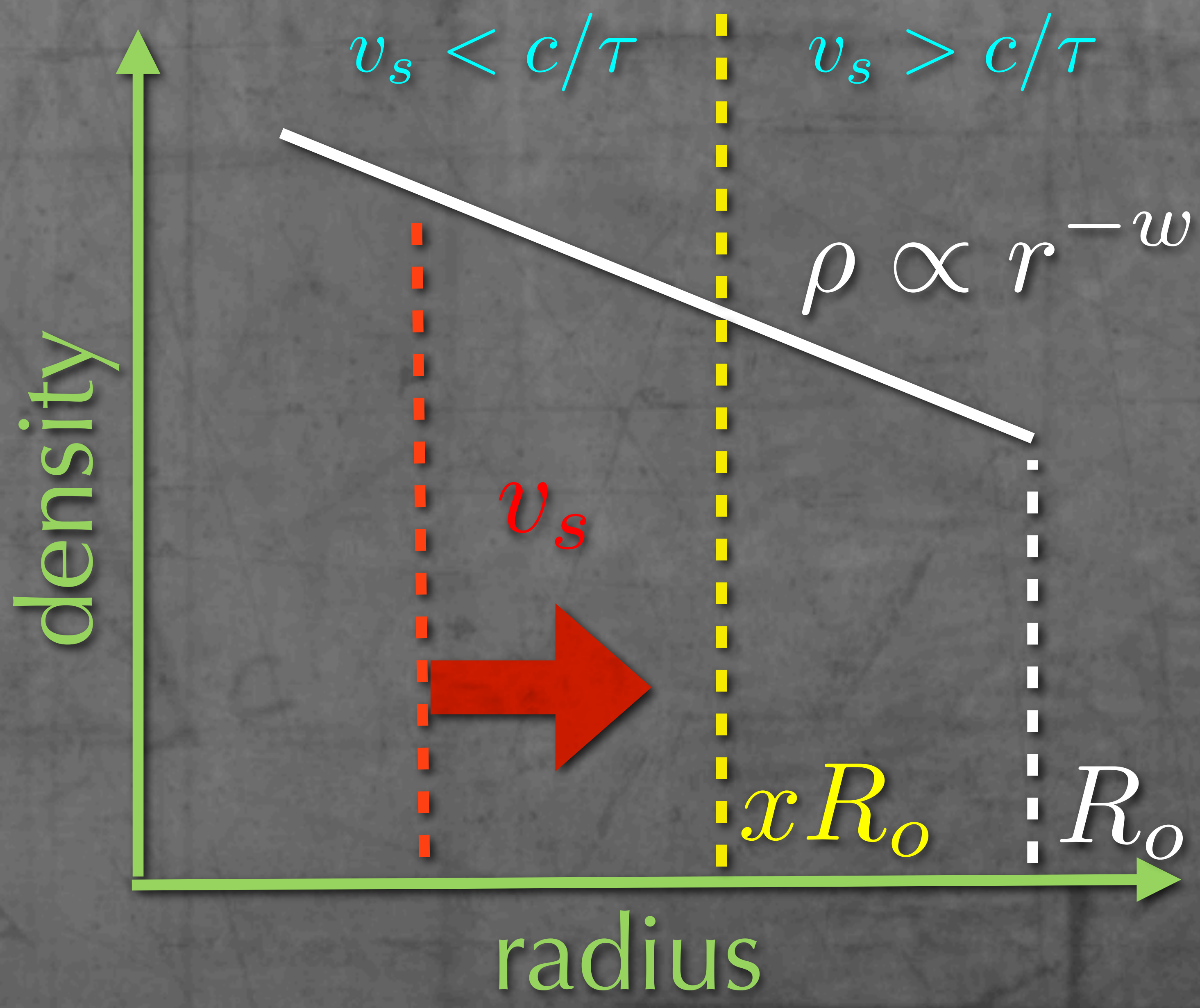
- Shock breakout
  - CSM optical depth: τ_w → photon velocity: c/τ_w
  - Typical SN shock velocity: $v_s \simeq 10,000 \text{ km s}^{-1}$
  - v_s wins if $\tau_w \gtrsim 30$
- CSM becomes $\tau_w \gtrsim 30$ to get the huge luminosity
  - $v_s > c/\tau_w$: no photon emission
  - $v_s \simeq c/\tau_w$: **shock breakout**
  - $v_s < c/\tau_w$: photon release



e.g., Chevalier & Irwin (2011)

Expected CSM Properties from Observations

- From the shock breakout



Moriya & Tominaga (2012)

Expected CSM Properties from Observations

- two timescales estimated from shock breakout
  - diffusion timescale in CSM after shock breakout = rising time of LC

$$t_d = \begin{cases} \frac{R_o}{v_s}\left[\left(\frac{c/v_s + x^{1-w}}{c/v_s + 1}\right)^{\frac{1}{1-w}} - x\right] & (w \neq 1), \\ \frac{R_o}{v_s}\left(x^{\frac{1}{1+c/v_s}} - x\right) & (w = 1). \end{cases}$$

  - timescale for forward shock to go through CSM

$$t_s = \frac{R_o - xR_o}{v_s}.$$

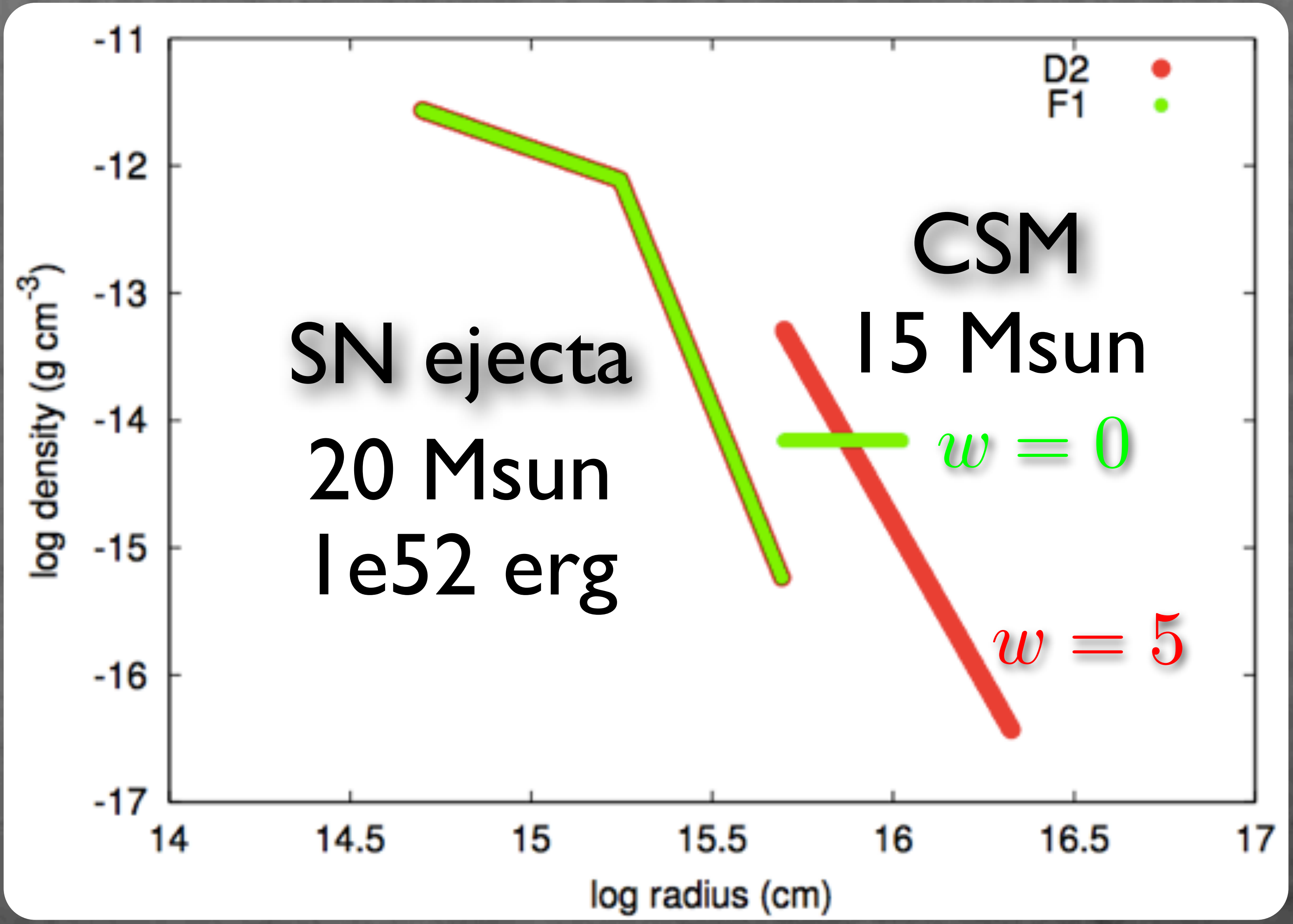
for a given w and v_s, we can get CSM properties

Moriya et al. (2012)

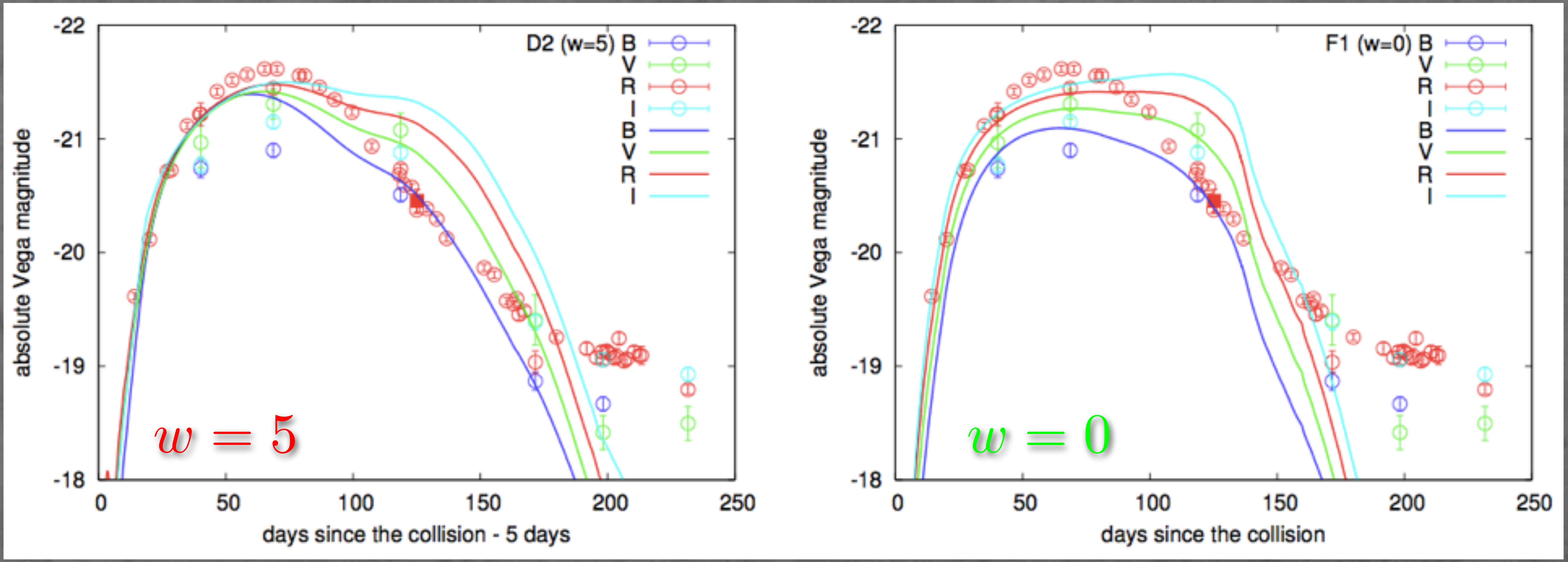
Expected CSM Properties from Observations

- SN 2006gy ($v_s = 10,000 \text{ km s}^{-1}$)

  $t_d \simeq 70$ days $t_s \simeq 193$ days (Smith et al. 2010)



Numerical LCs

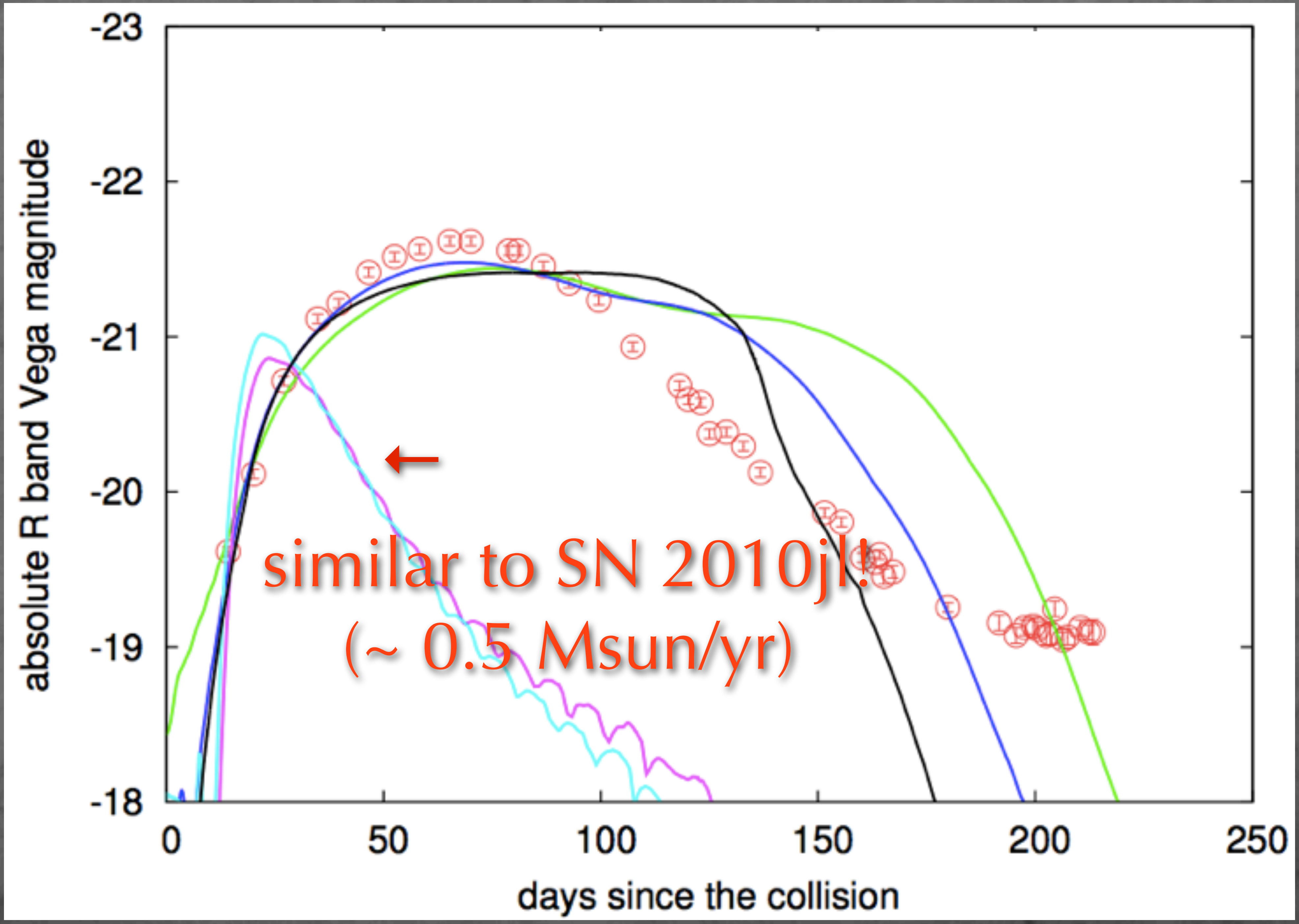


- No 'adjustment by hand'
  - simply from what is expected from shock breakout model
  - SN ejecta parameters (Mej & Ekin) are chosen

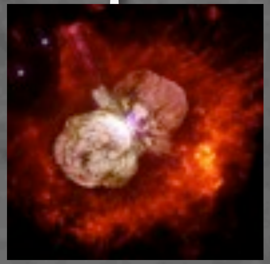
Moriya et al. (2012)

Steady Wind Does Not Work

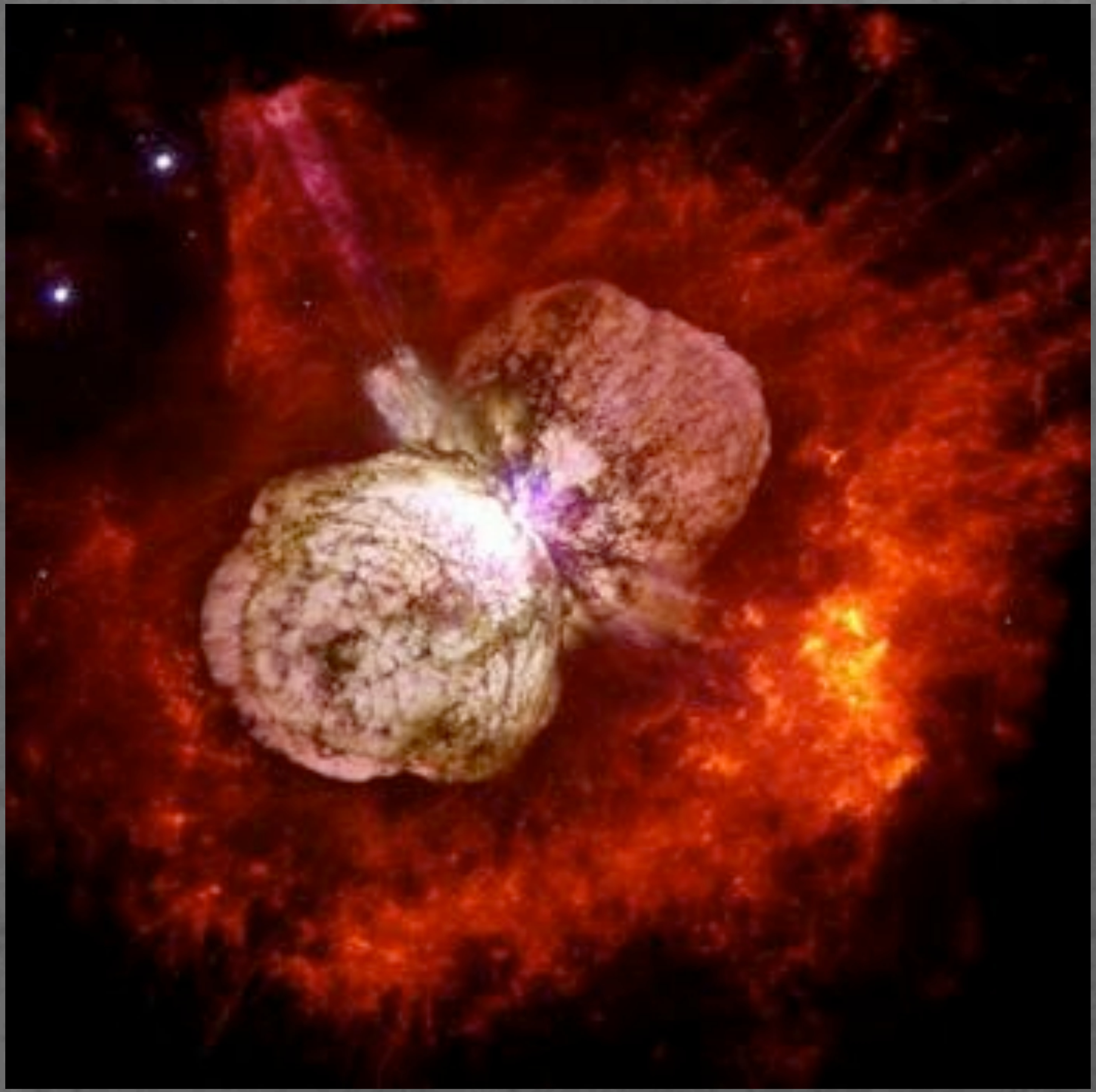
- Shock breakouts in steady winds $(w = 2)$ fail



Superluminous SNe

- Interaction model works to explain LCs
  - shock breakout in CSM
    - SN ejecta (1e52 erg, 20 Msun)
    - ~ 20 Msun CSM (0.5 Msun/yr)
- steady mass-loss does not work
  - from eruptive mass-loss of the progenitor
  - LBVs? 
  - SN 2010jl has a similar mass-loss rate but from steady mass loss

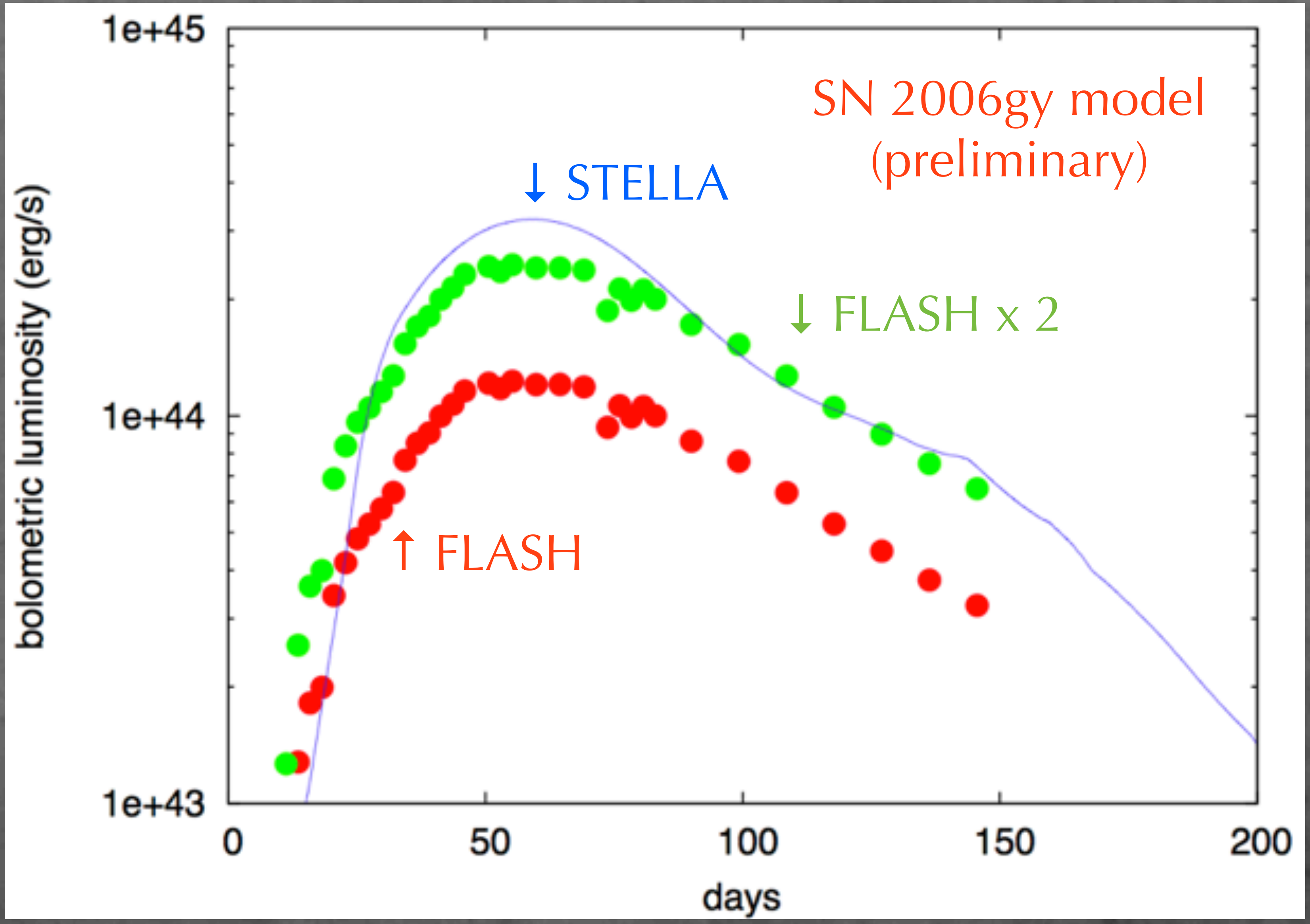
Multi-Dimensions



Moriya & Kasen

Multi-Dimensions

- FLASH rad. hydro. works well so far
  - 1D calculations from FLASH and STELLA



Summary

- non-SL SNe IIn
  - interaction model works well up to ~ 300 days
  - many of them consistent with steady mass loss
  - some require ~ 1e-1 Msun/yr
- SLSNe IIn
  - shock breakout in CSM
  - from non-steady ~ 1e-1 Msun/yr mass loss?