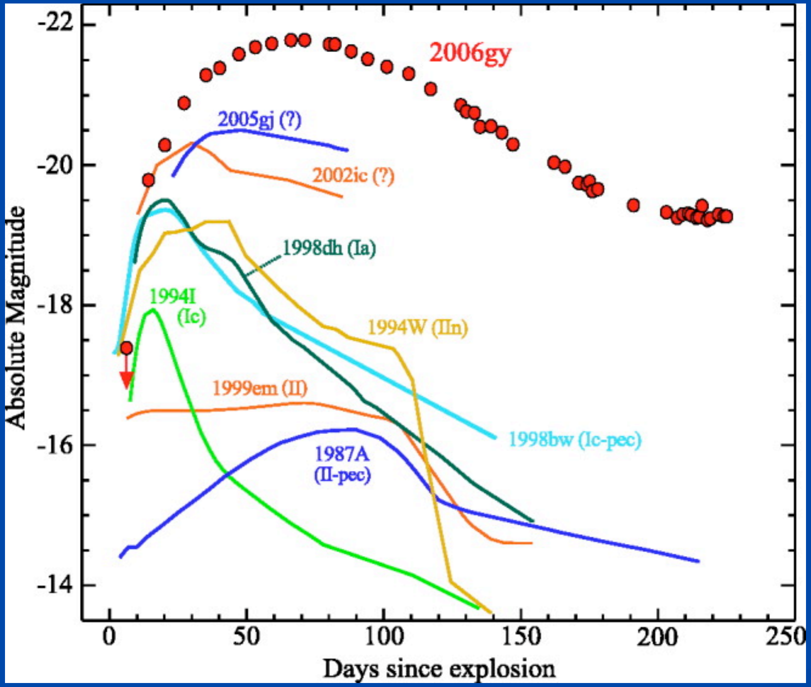
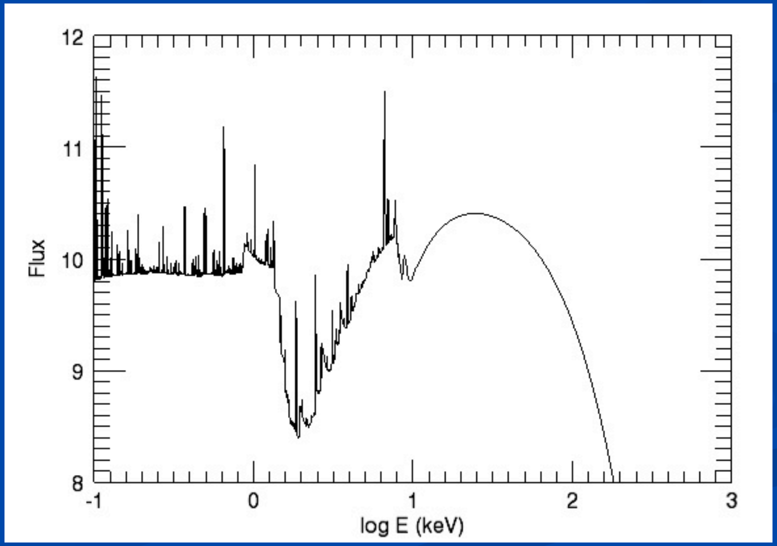
# Theory of Circumstellar Interaction: Dense mass loss and luminous SNe

Roger Chevalier



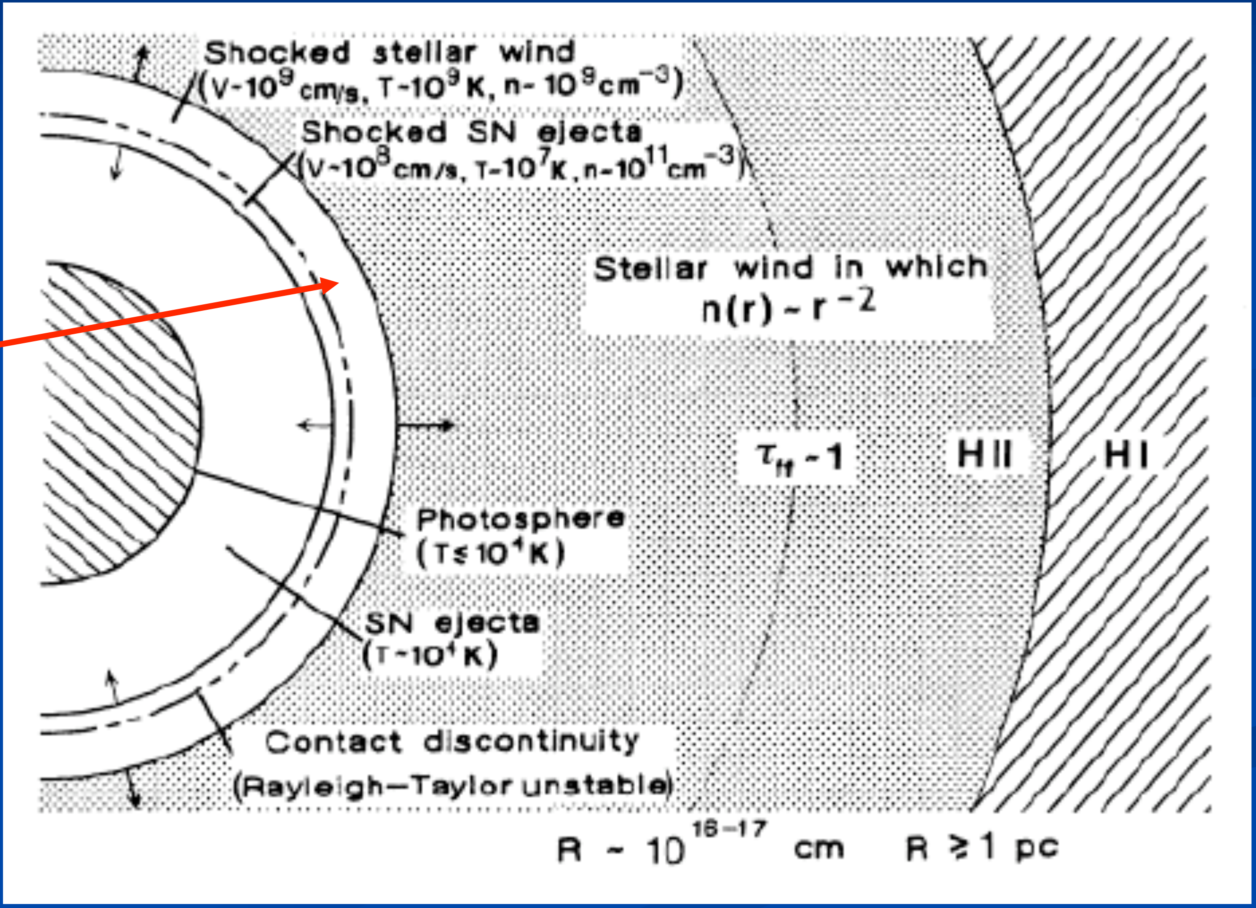

Smith et al. 2007




X-rays

- Circumstellar interaction – normal case

X-ray and
radio emission




CF

# Circumstellar density ($\rho_w = D/r^2$)

- $D = \dot{M}/4\pi v_w$ (D=Mdot/4πv_w)
  - WR star: $10^{-5}\ M_\odot$/yr, 1000 km/s   $D=5\times10^{11}$
  - Extreme RSG: $10^{-4}\ M_\odot$/yr, 10 km/s   $D=5\times10^{14}$
  - Optical depth effects: $10^{-2}\ M_\odot$/yr, 10 km/s $D=5\times10^{16}$   $D_*$ is scaled to this value

- $\tau_w \sim 17\ D_*\ (v_{sh}/10{,}000\ \mathrm{km/s})^{-1}(t/10\ \mathrm{day})^{-1}$

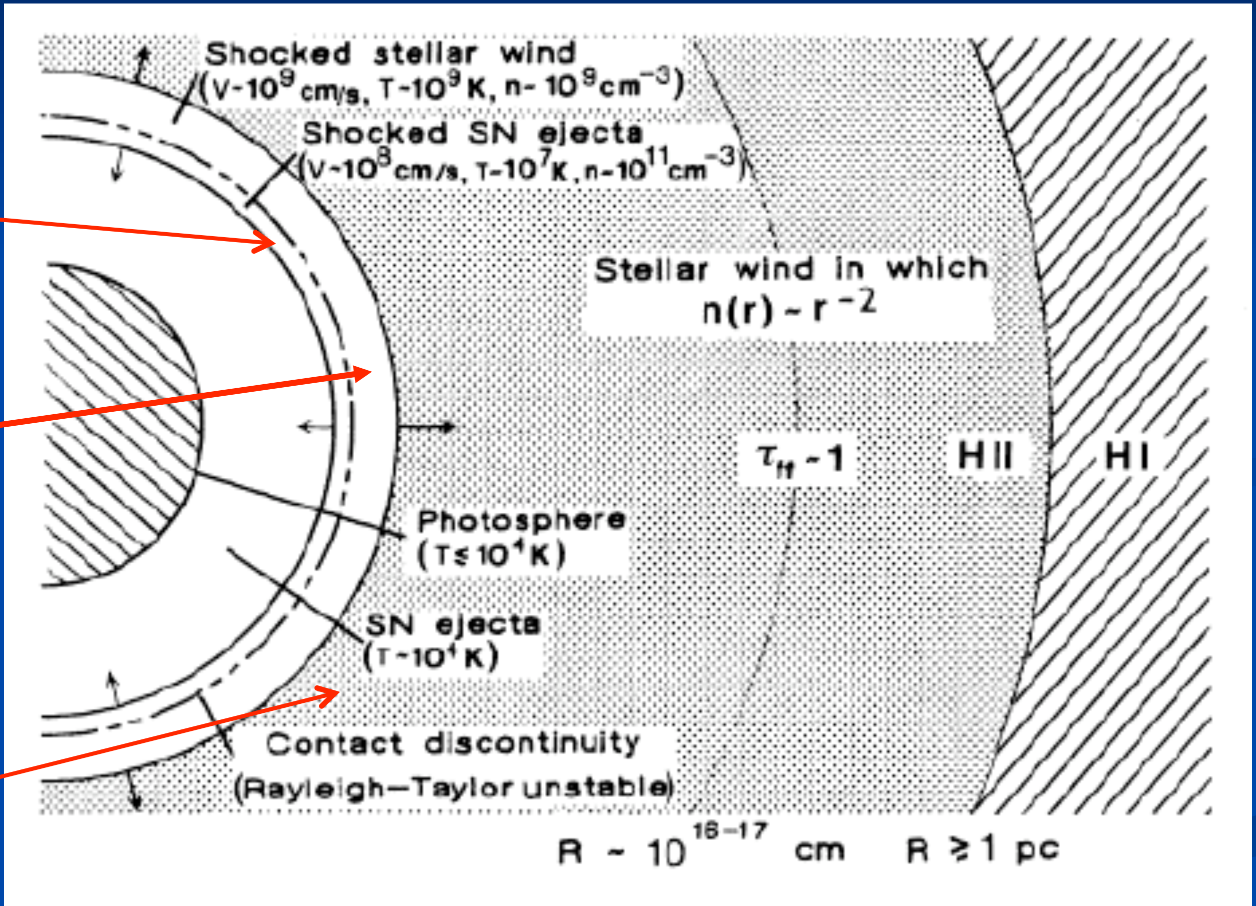
# High density interaction

Optically thick dense shell

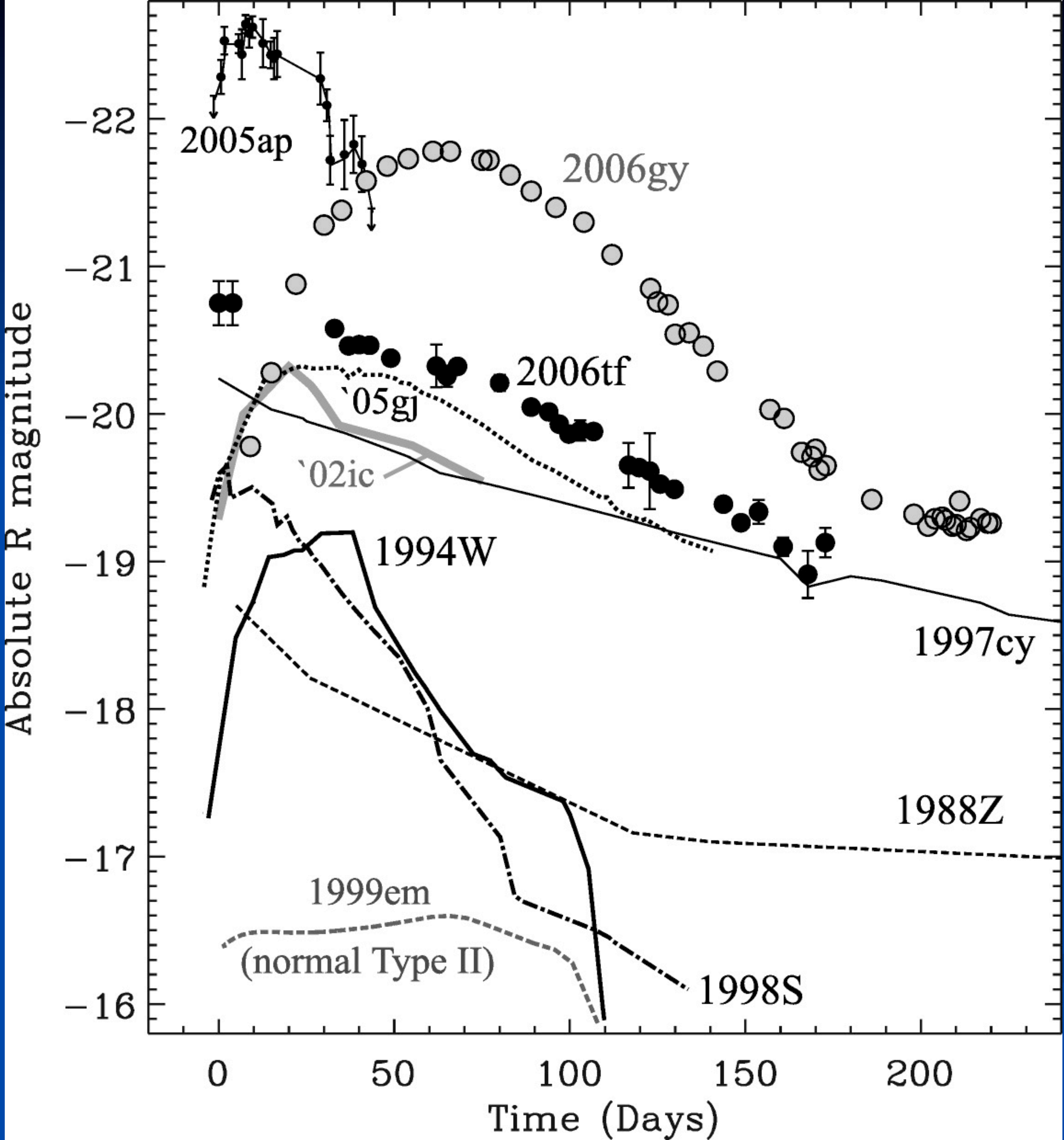
X-ray emission (radio absorbed)

X-ray photoionized region

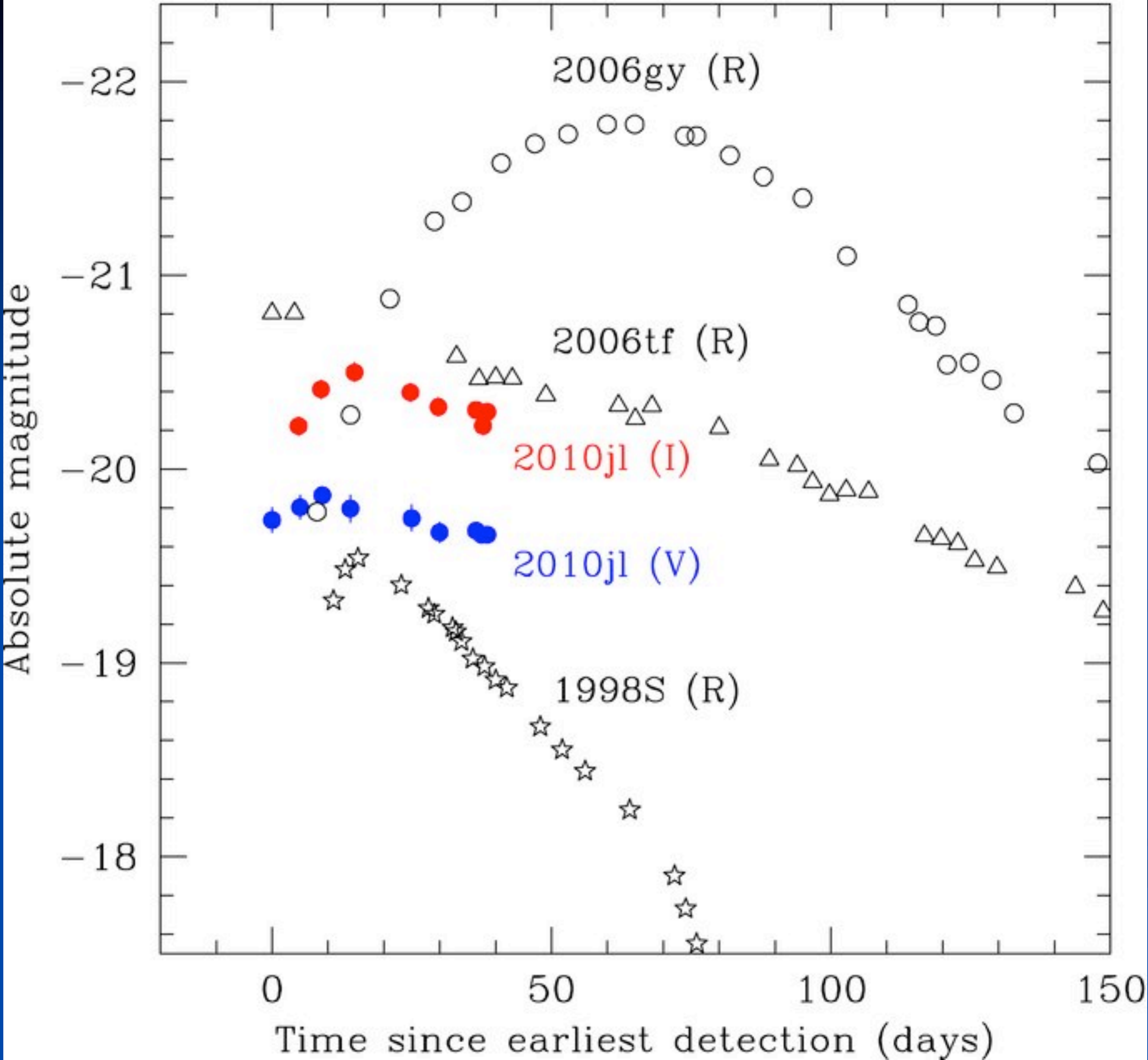
Wind possibly optically thick



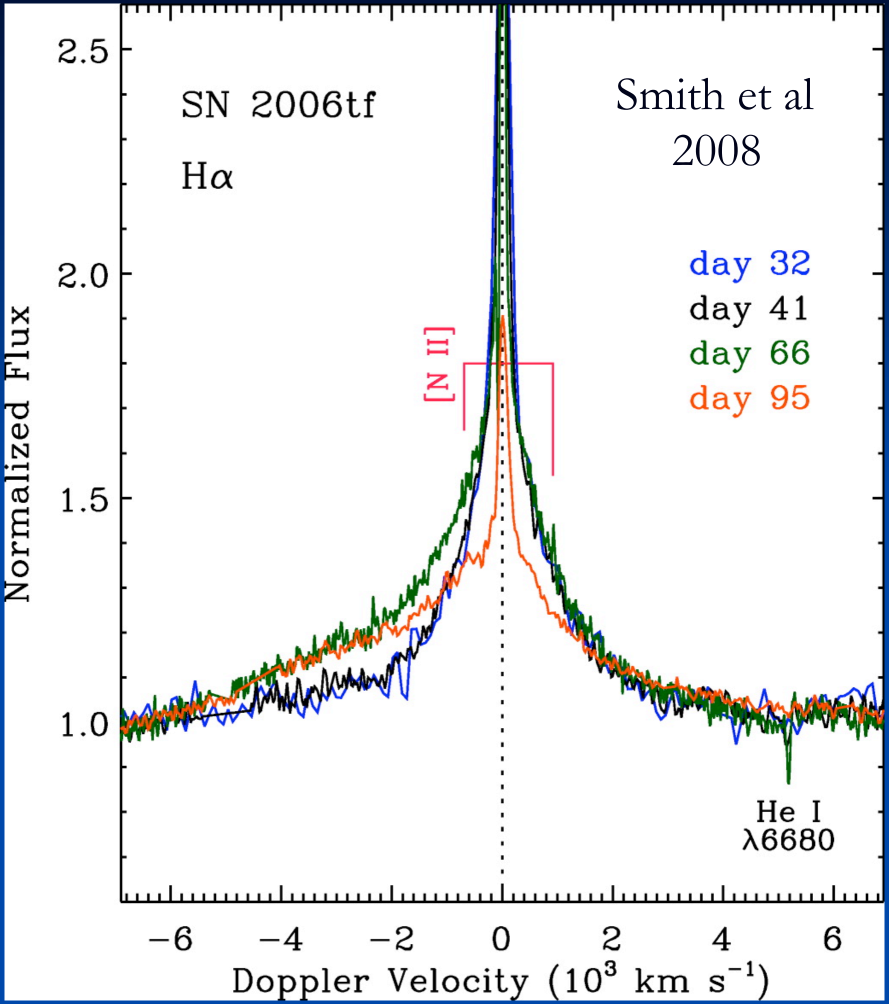

At high densities, the hard, forward shock X-ray emission dominates

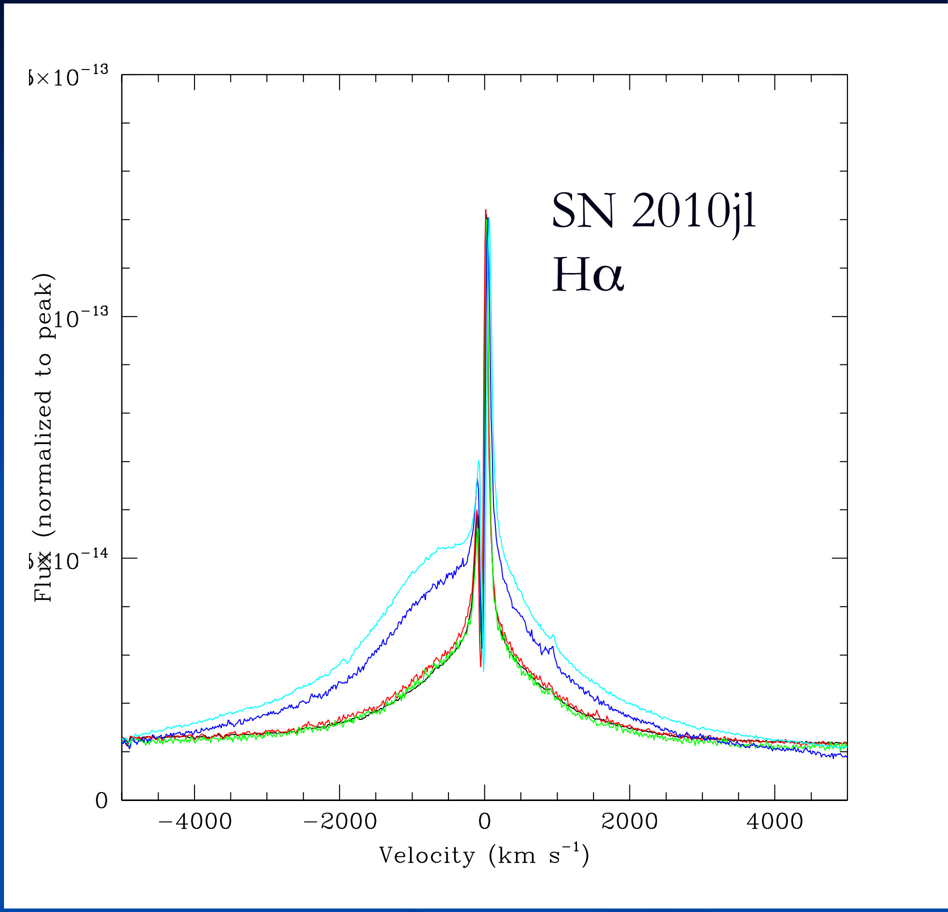


2005ap
2006gy
2006tf
`05gj
`02ic
1994W
1997cy
1988Z
1999em
(normal Type II)
1998S
Absolute R magnitude
Time (Days)
−22
−21
−20
−19
−18
−17
−16
0
50
100
150
200




Stoll et al. 2011

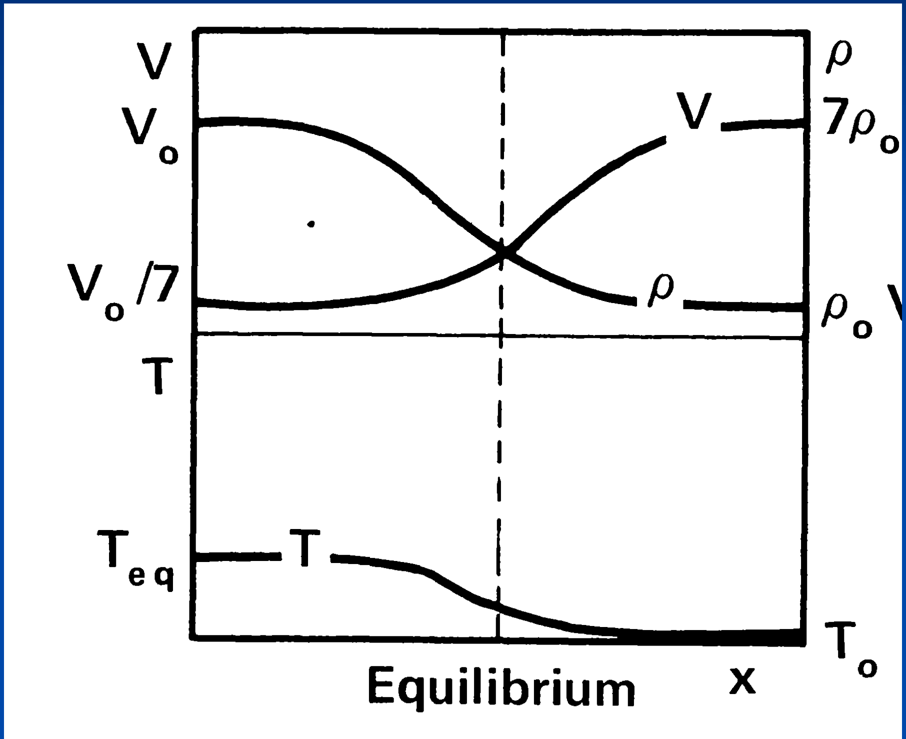



NOT: Ergon, Sollerman, Fransson

Broad Hα formed by electron scattering in the wind
(Chugai 2001 on SN 1998S)
Requires Thomson optical depth of a few in the wind

# Radiation dominated shock



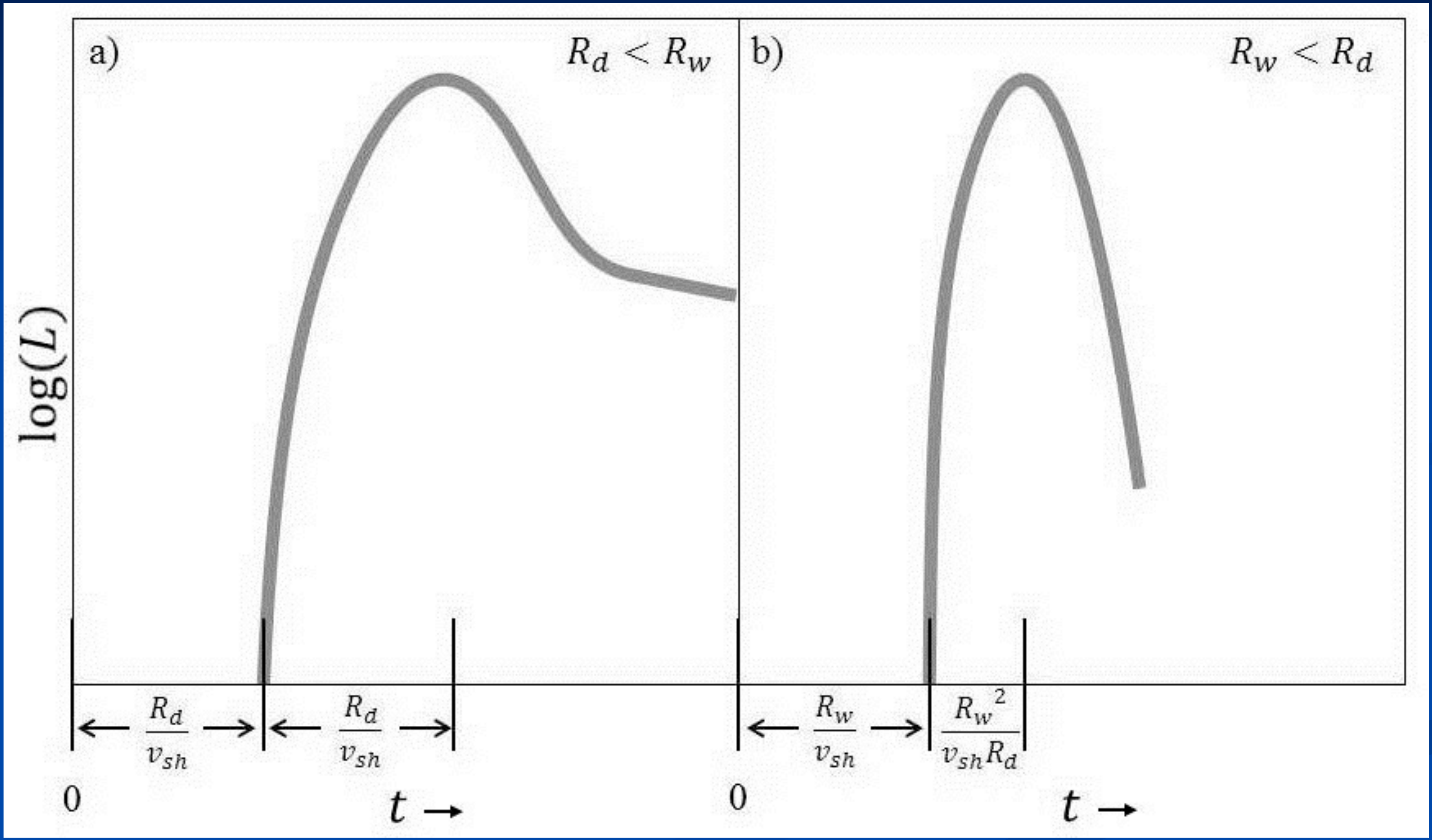

Weaver 76

Optical depth through the transition zone

$\tau \sim c/v_{sh}$

# Supernova in dense wind ($\rho_w = D/r^2$ to $R_w$)

- $\tau_w < 1$
  - Shock breakout unaffected
  - May have radiation from interaction
- $1 < \tau_w < c/v_{sh}$
  - Shock breakout energy same, longer time
  - Interaction power, broad line wings
- $\tau_w > c/v_{sh}$
  - Radiation dominated shock propagates into wind
  - Radiation breakout when $R_{sh} = R_d = \kappa D v_{sh}/c$, characteristic diffusion radius in the wind
  - Viscous shock at larger radii

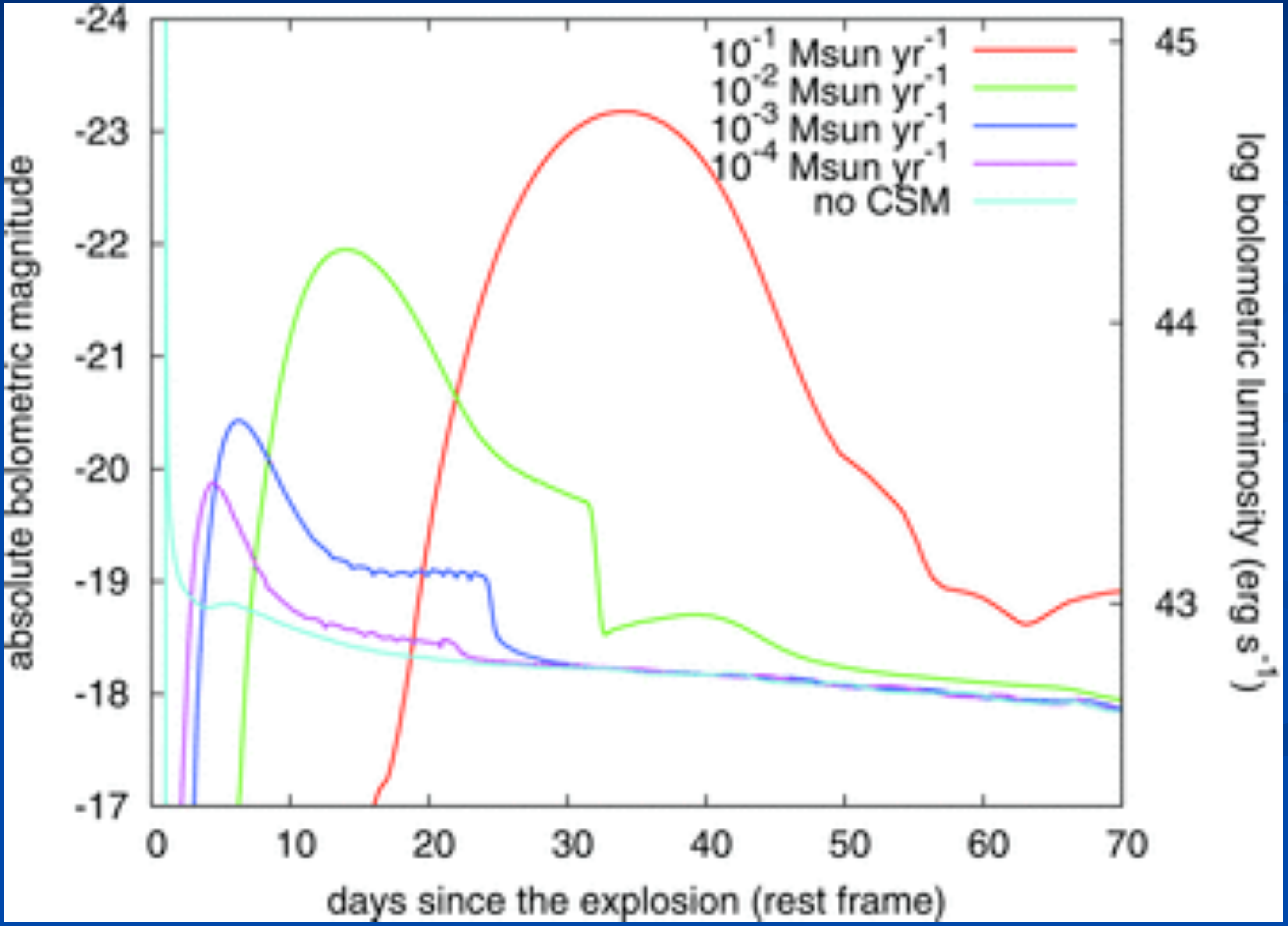



Chevalier & Irwin 2011

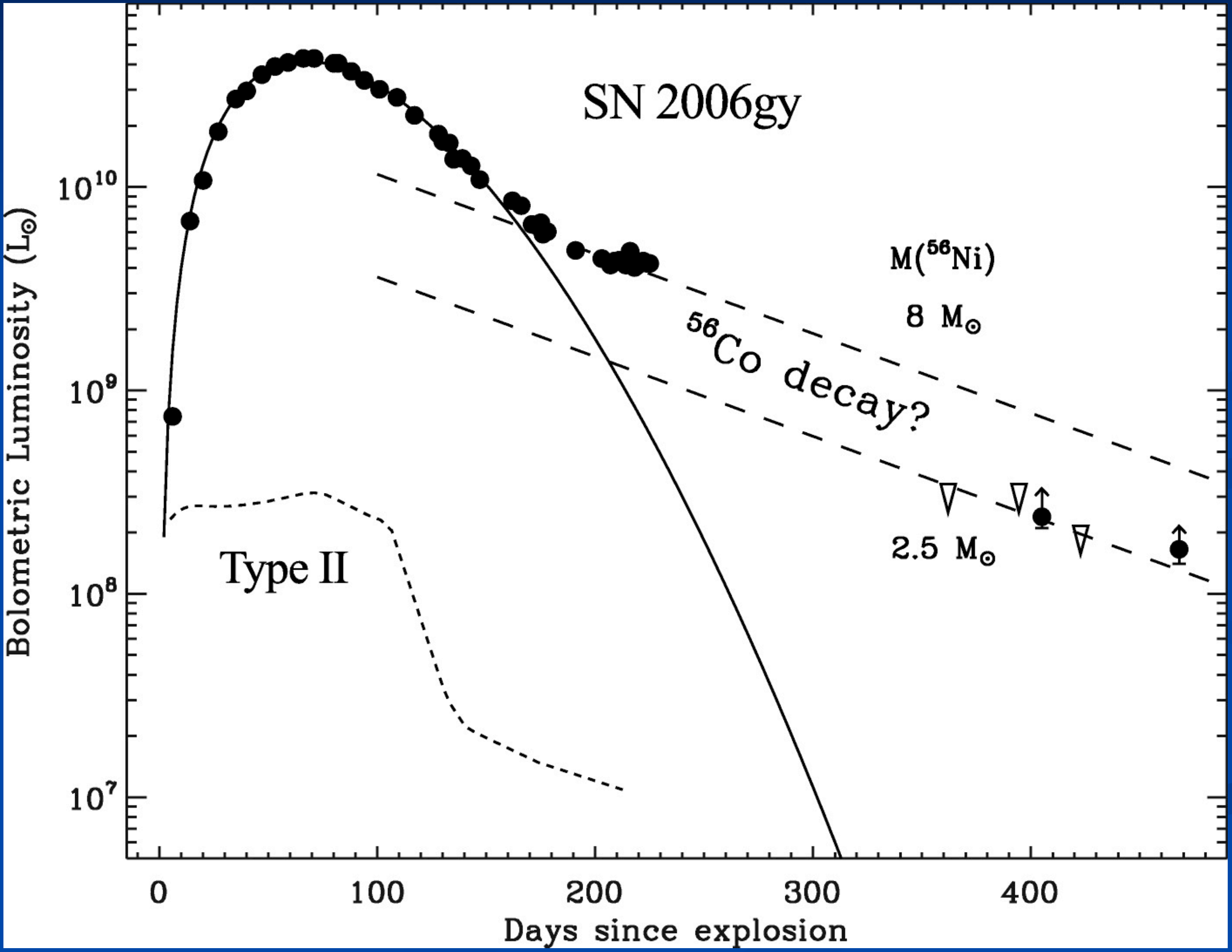
| $R_w > R_d$ | $R_w < R_d$ |
| --- | --- |
| Rise to max light $\sim R_d / v_{sh}$ | Rise to max light $R_w / v_{sh}$ |
| Duration of the rise also $\sim R_d / v_{sh}$ | Duration of the rise is $R^2_w / v_{sh} R_d$ |
| Outer parts of the opaque medium are extended and at low velocity at the time of peak luminosity | Outer parts of the opaque medium are not extended and are accelerated to high velocity by radiation pressure |
| A dense shell forms - continued interaction with the dense mass loss | A dense shell forms but does not affect the light curve near maximum |

Chevalier & Irwin 2011

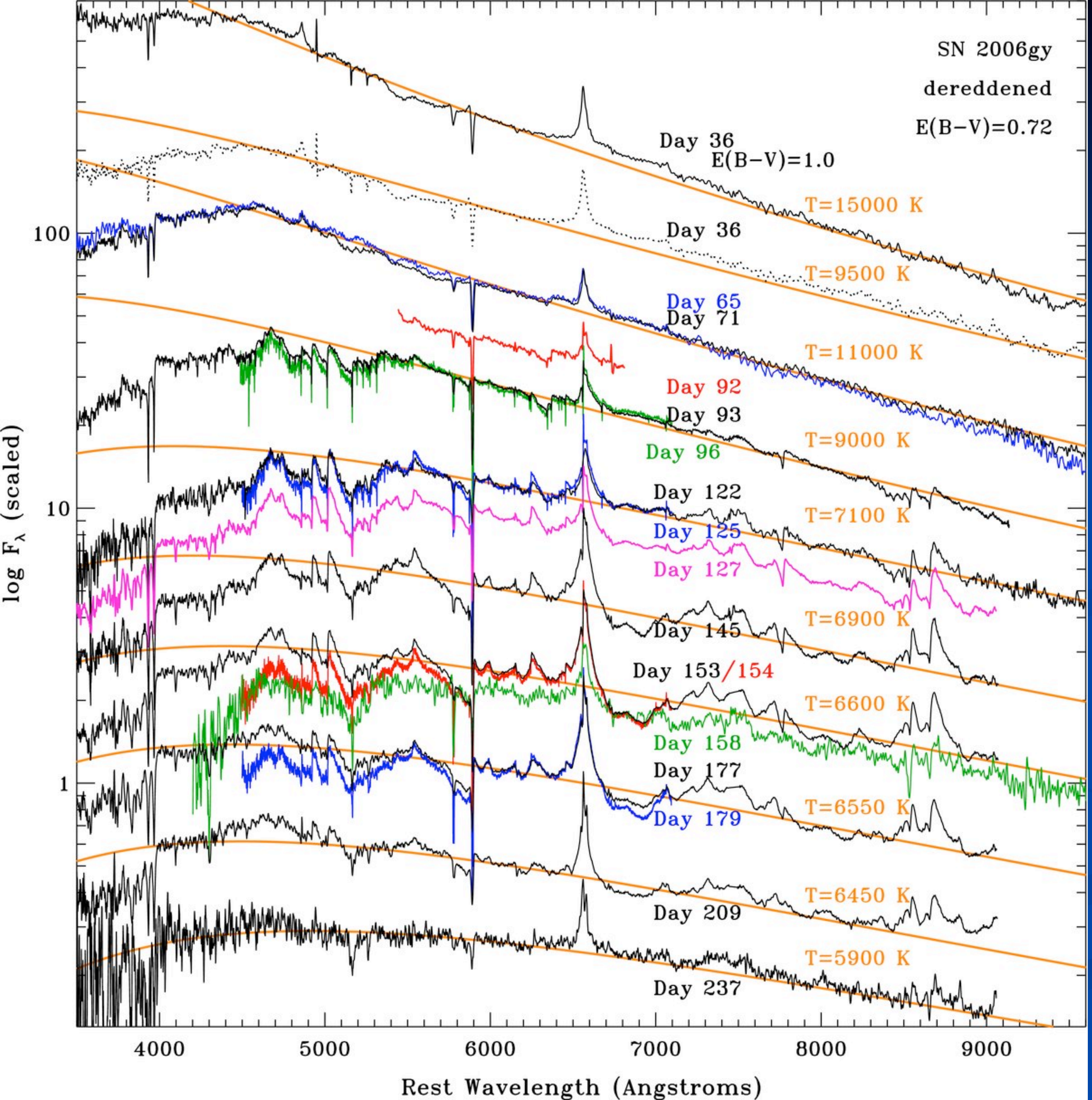
# Simulation of Type IIP in a dense CSM (Moriya et al. 2011)



# SN 2006gy: $R_w > R_d$

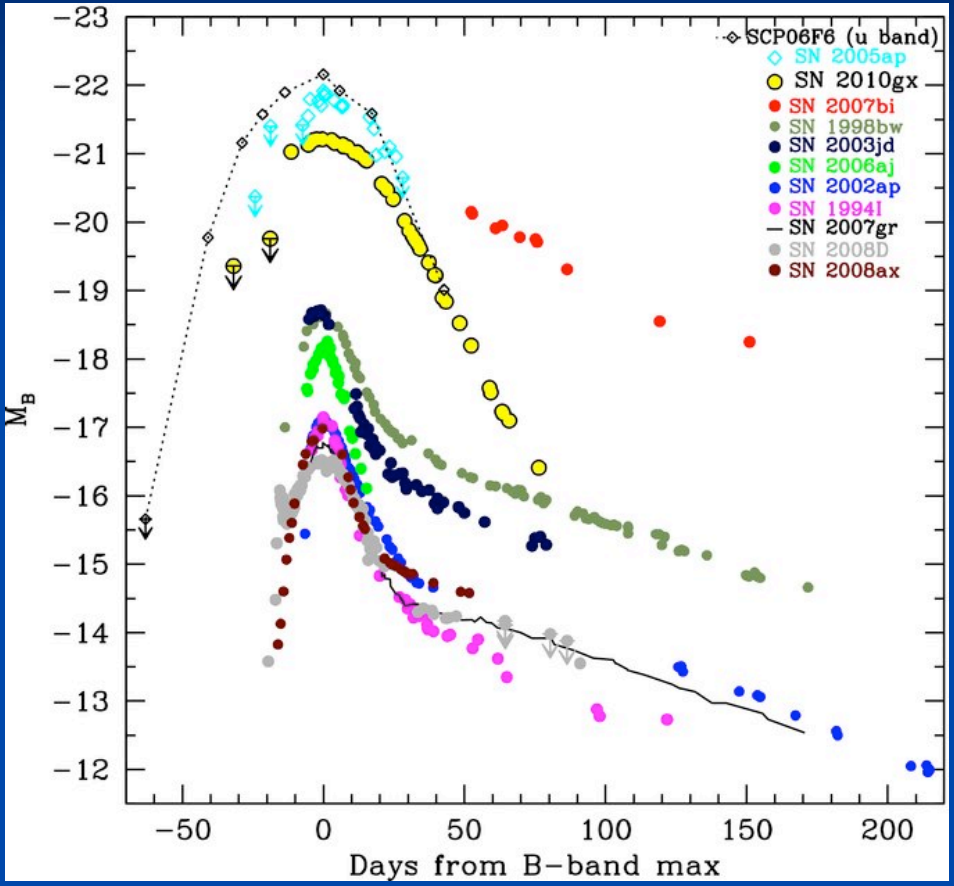


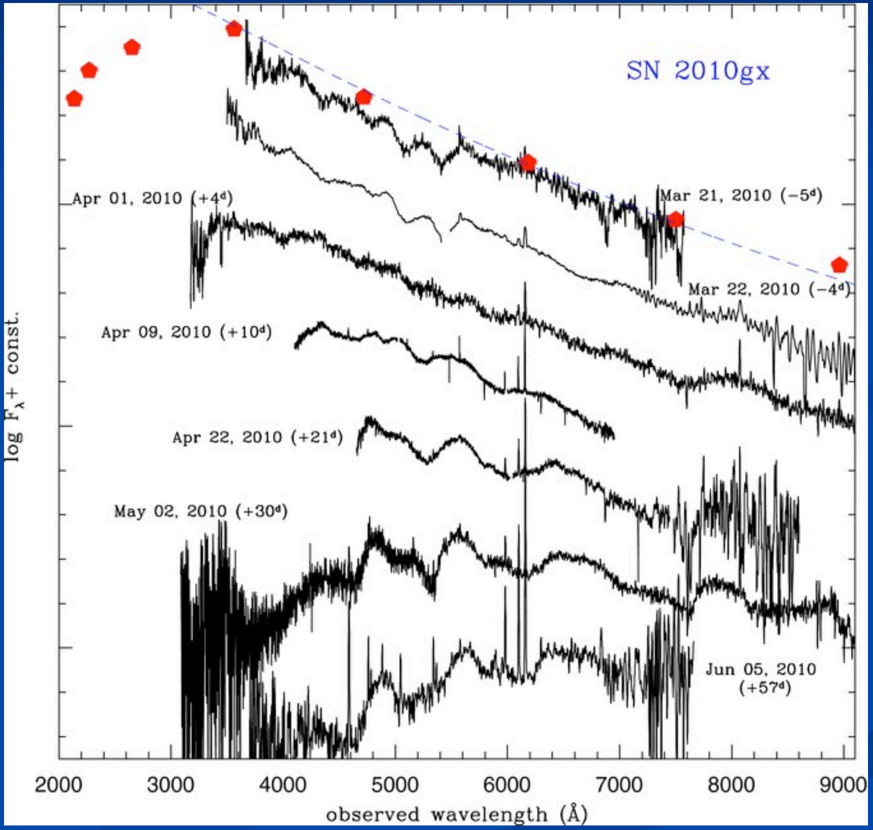

Smith et al. 2008




Smith et al. 2010

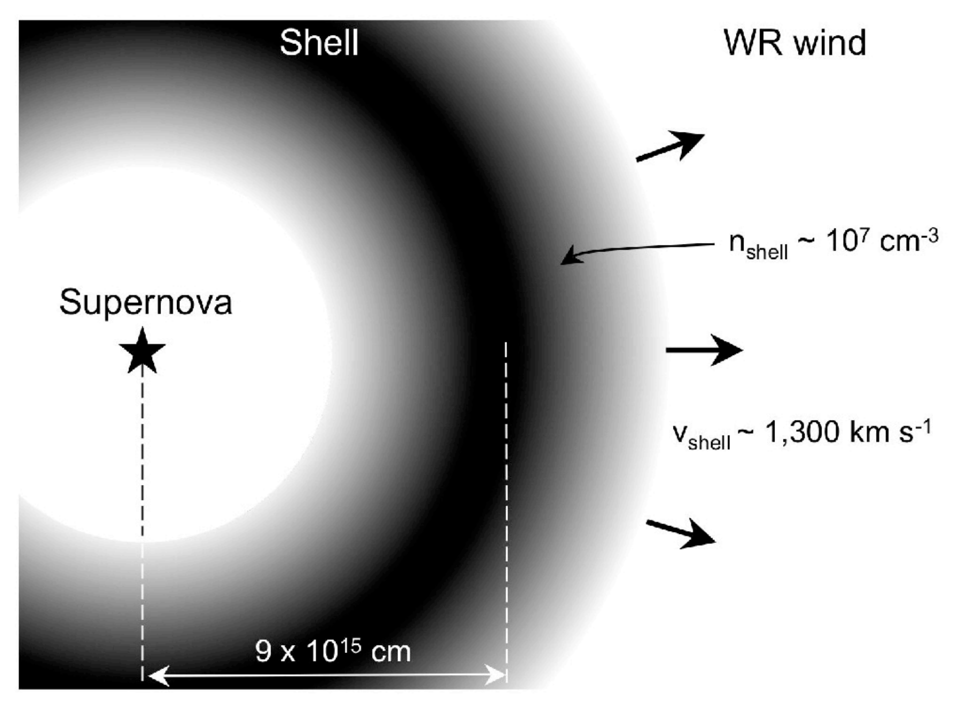
# SN 2010gx and related objects: $R_w < R_d$




Pastorello et al. 2010

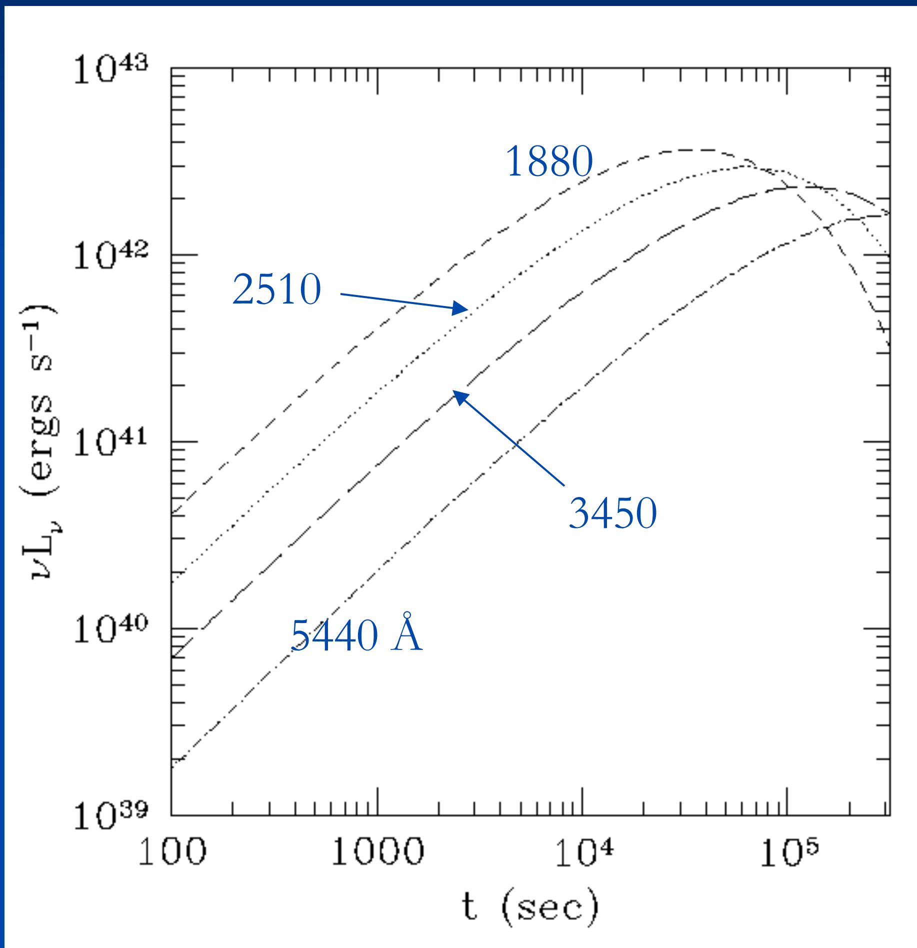
# SN 2006jc – Type Ib



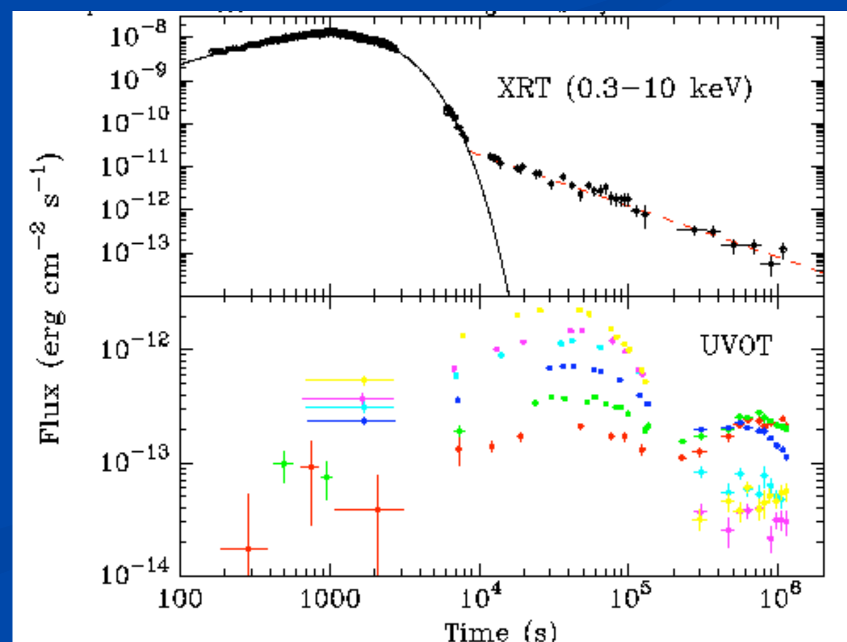

- Observed to erupt in 2004
- Interaction seen in X-ray/radio/optical/IR
- $M \sim 0.01\ M_{\odot}$

Immler et al. 2008

# Optical/uv from young Ic – GRB



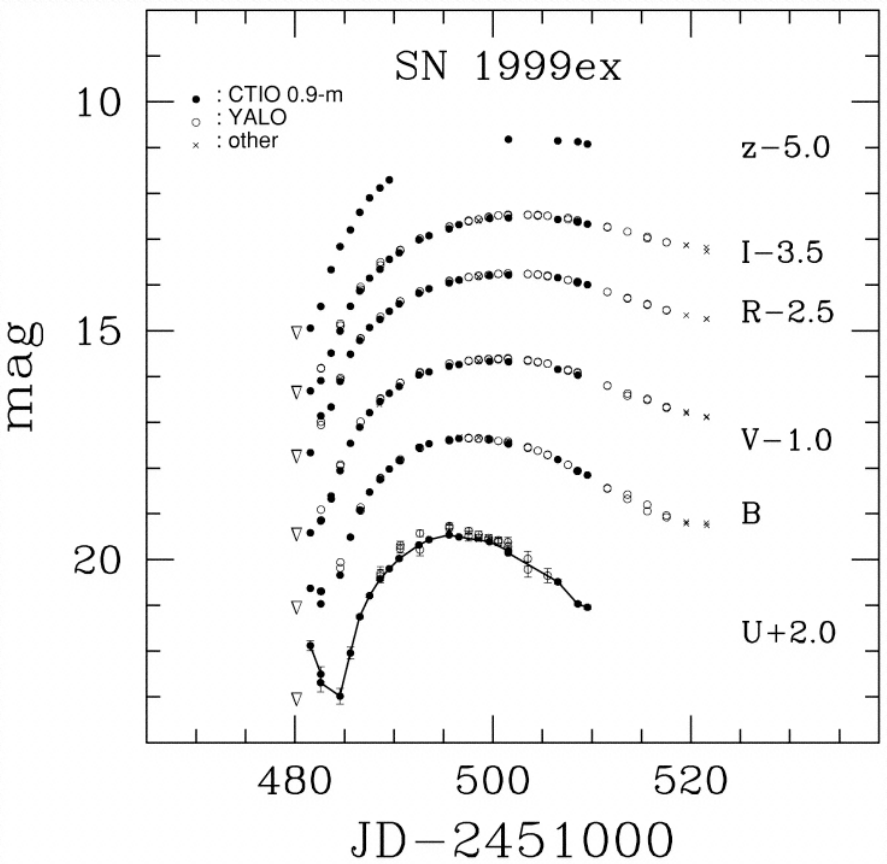

- Simple model for diffusion wave moving into power law density profile

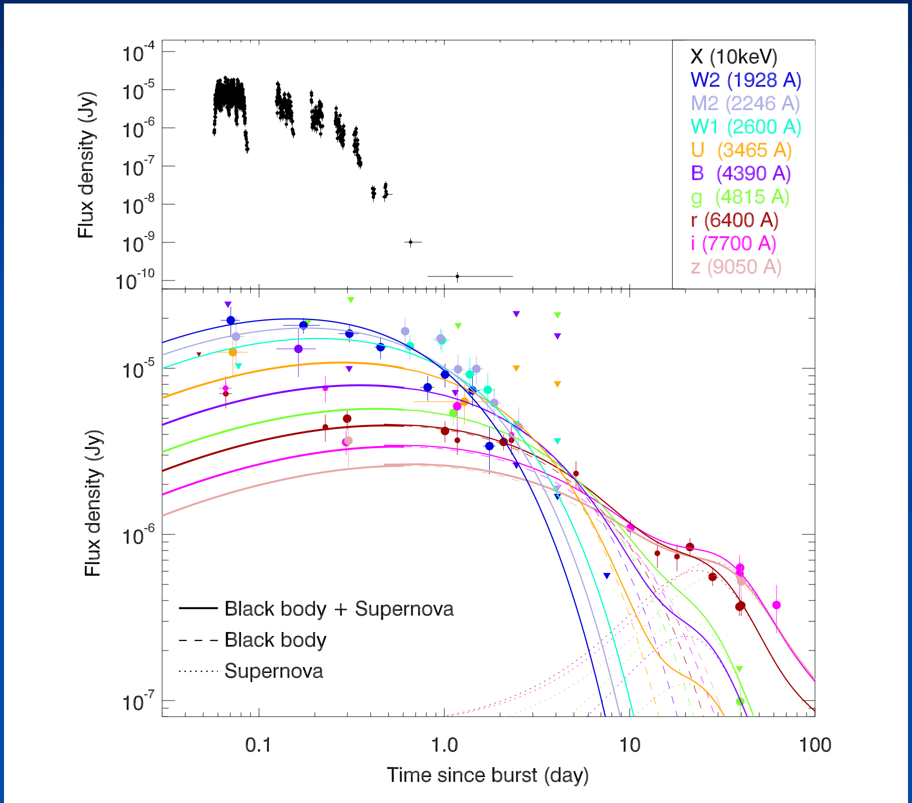



SN 2006aj Campana et al. 06

# Type Ic

GRB 101225A




Stritzinger et al. 02

Thone et al. 2011

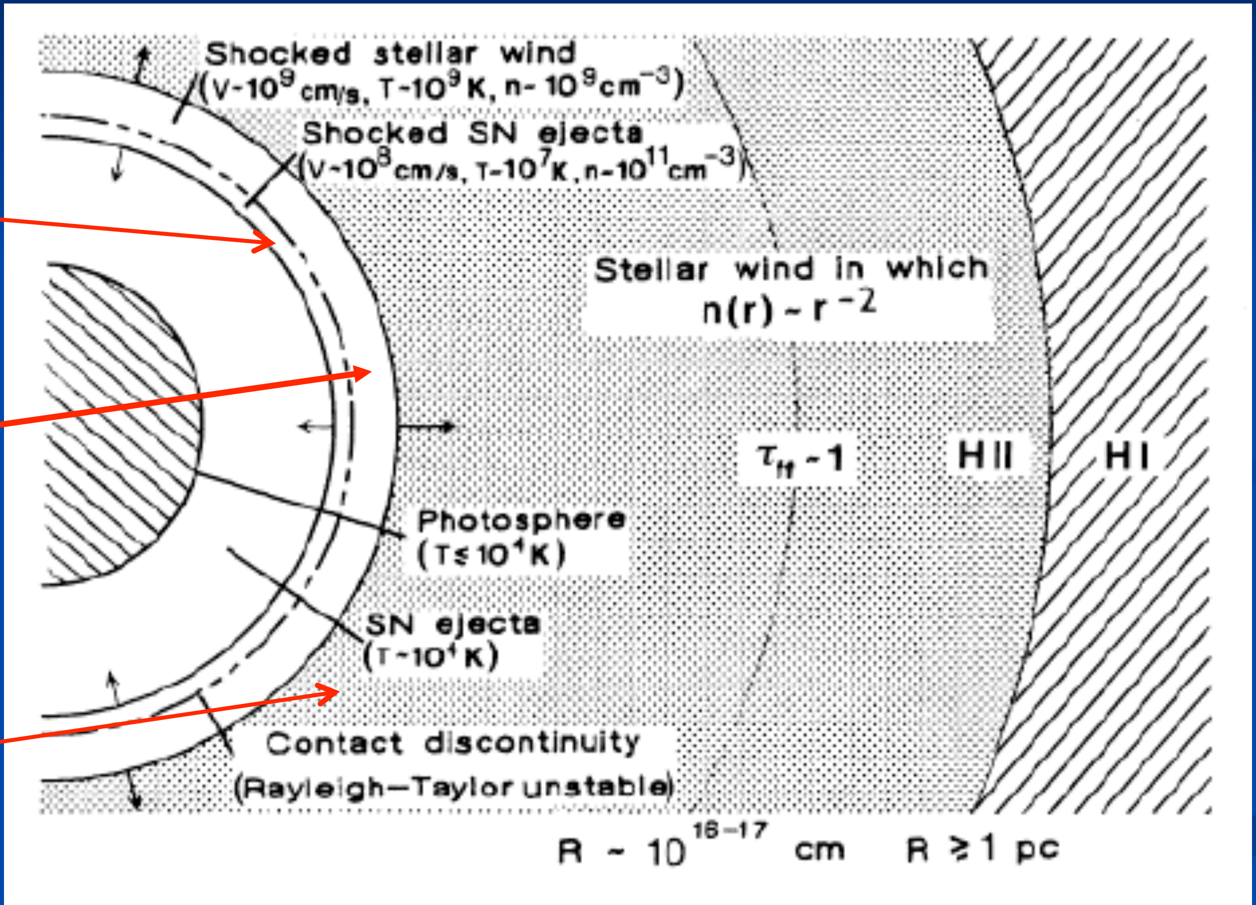
Also, Balberg & Loeb (2011) suggest a radiation dominated shock propagates into wind in SN2008D

# High density interaction

Optically thick dense shell

X-ray emission (radio absorbed)

X-ray photoionized region

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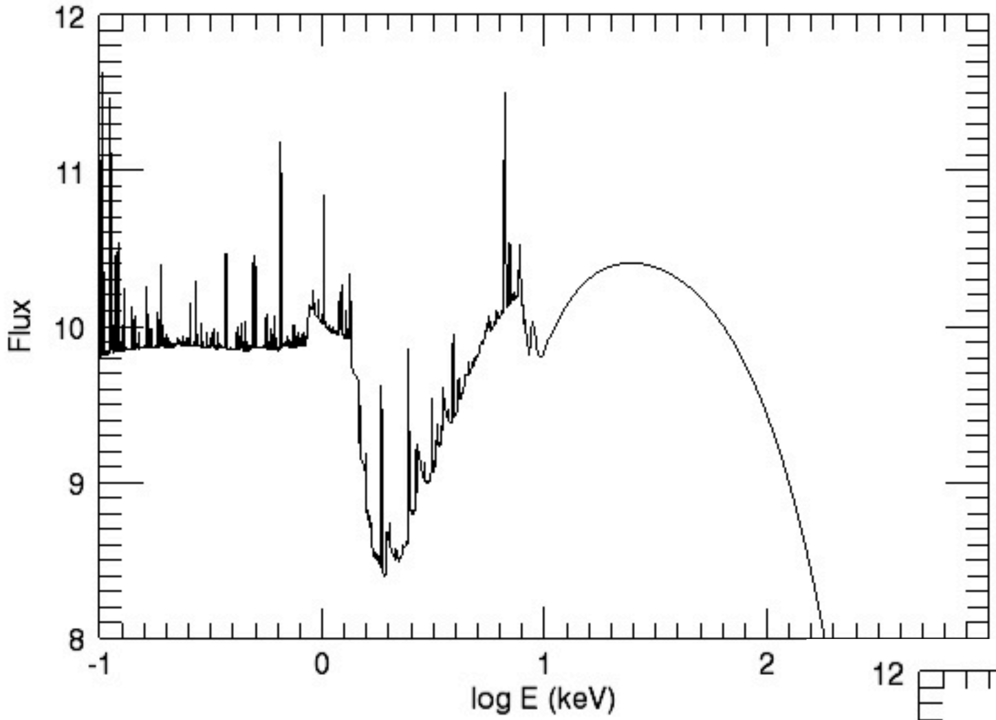
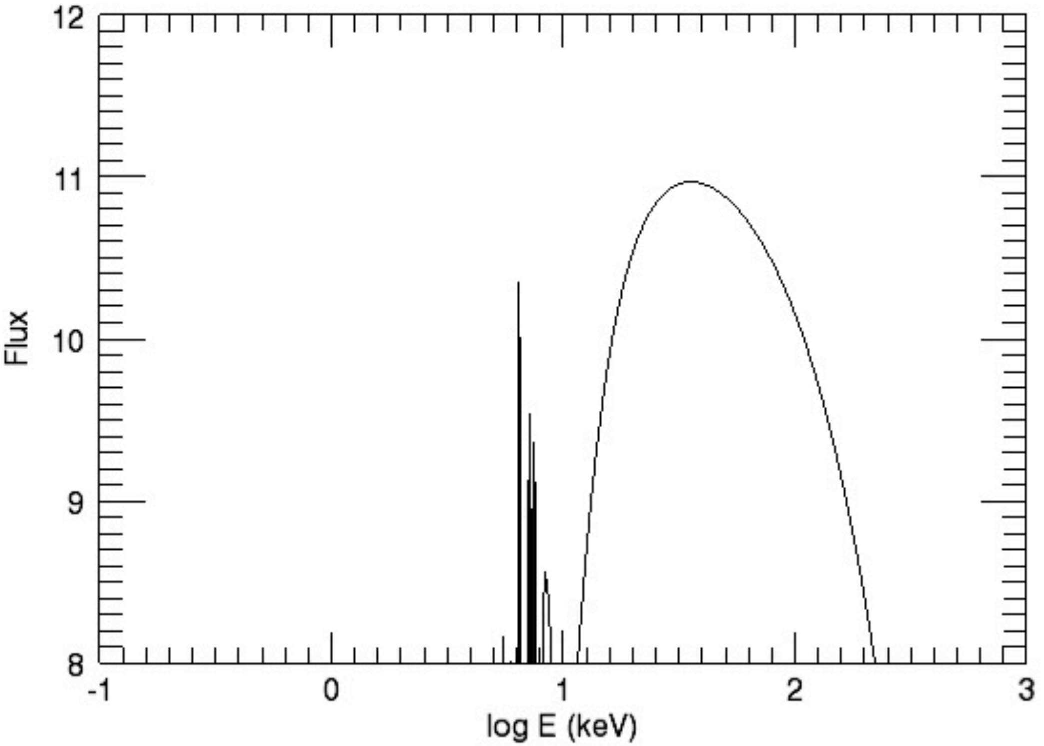


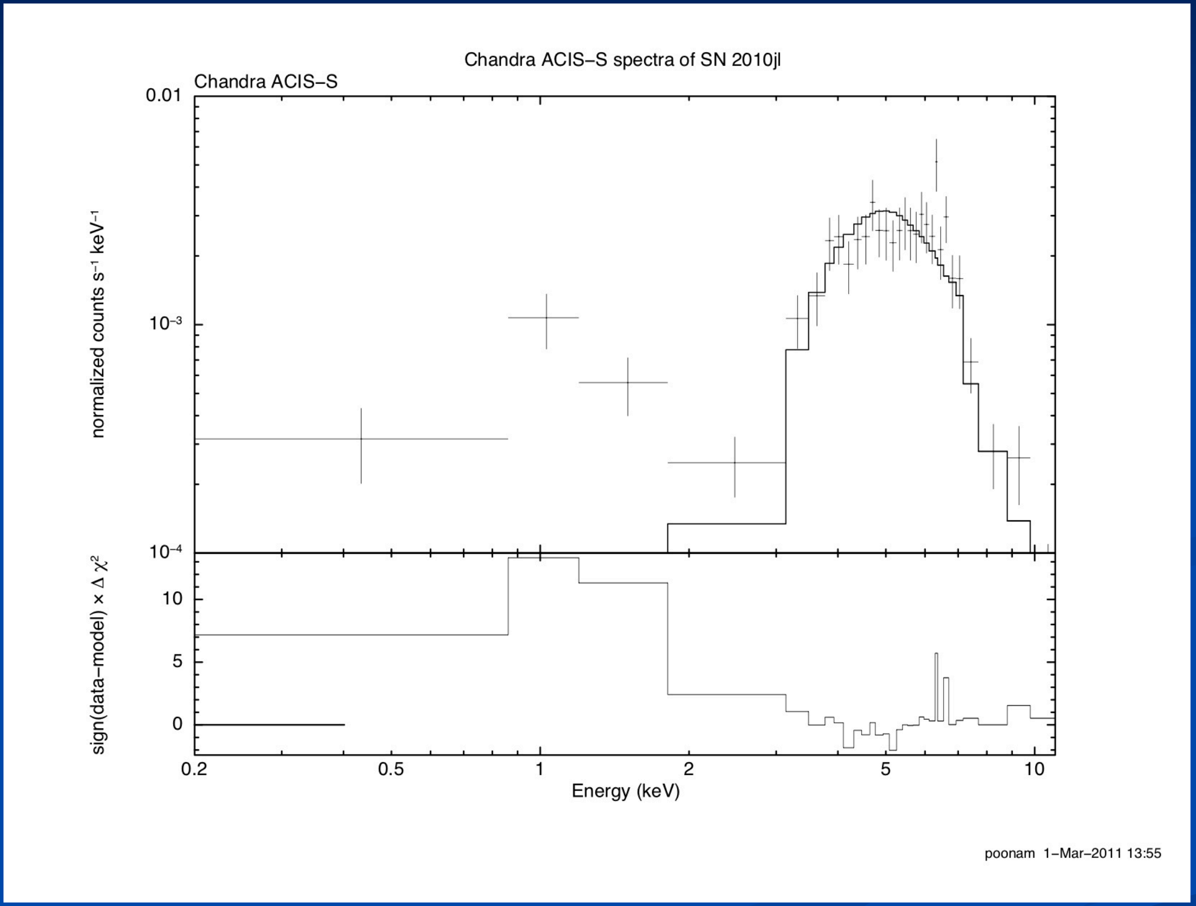

Reduced absorption due to photoionization of CNO

1. Ionization parameter ($L/nr^2$)
2. "Stromgren sphere" effects

Full absorption

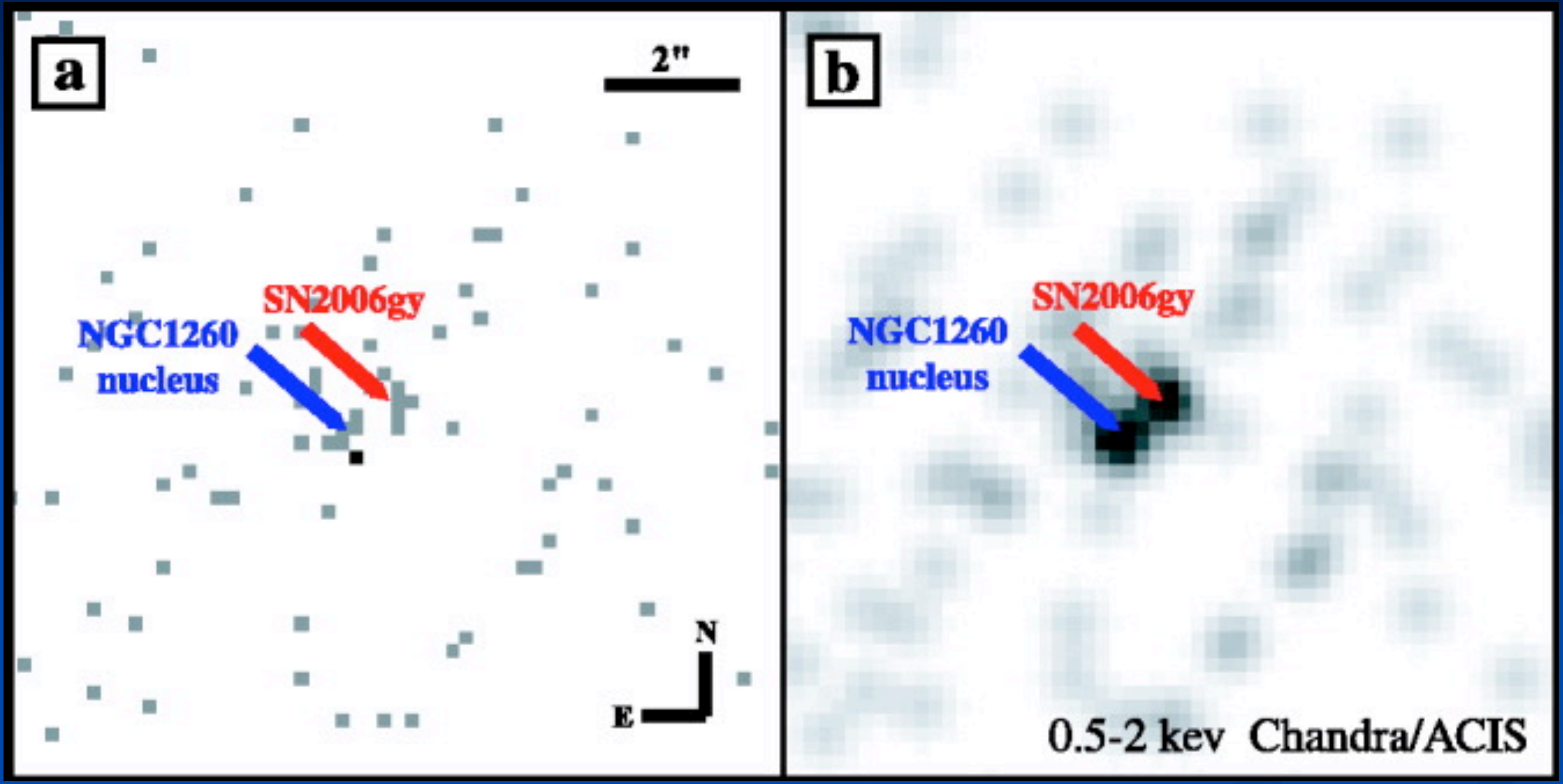


SN 2010jl, Dec 2010
Chandra X-ray




$N_H$ ~ 3e23 $cm^{-2}$
kT ~ 75 keV
6.3e41 ergs/s
(0.2-10 keV unabs.)

P. Chandra,…




Smith et al. 2007

SN2006gy X-rays $1.5 \times 10^{39}$ erg/s soft (upper limit)

Need full absorption

# Final comments

- Extent of dense mass loss

| | | | |
|---|---|---|---|
| $10^{14}$ cm | $10^{15}$ cm | $10^{16}$ cm | $10^{17}$ cm |
| SN 2006aj | SN 2010gx | SN 2006gy | SN IIn |
| 0.3 yr | | | 300 yr |
| (if $v_w$=100 km/s) | | | |

- Question of coincidence
  - Binary?