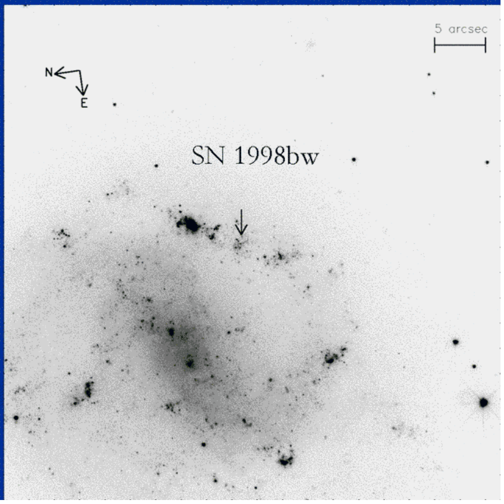
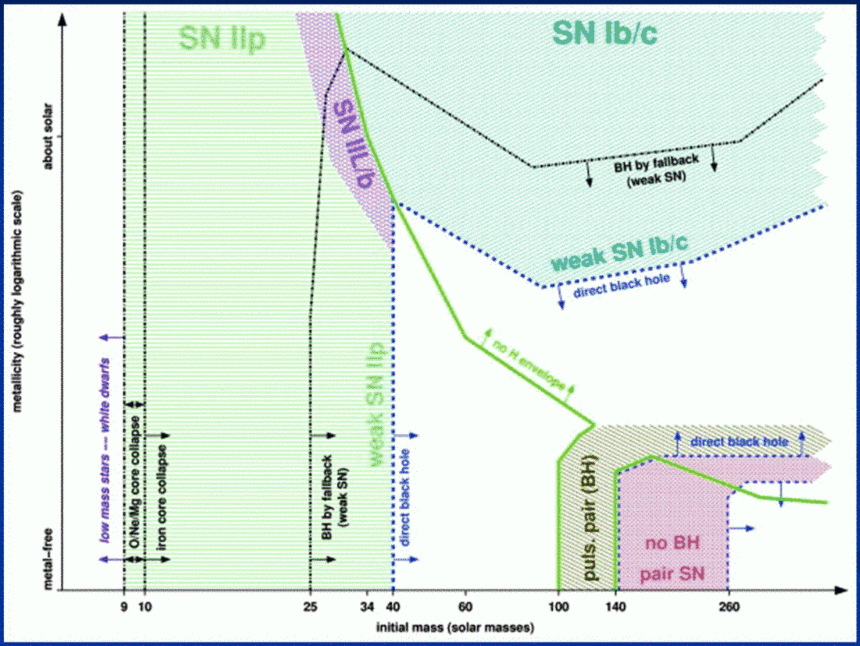
Circumstellar emission from Type Ib/c supernovae and the GRB connection

Roger Chevalier



Single massive star evolution



Heger et al. 2003

Shock breakout

- The radiation dominated shock breaks out when the radiation can freely stream
- Maximum velocity for WR explosion ~c/3
- The shock disappears and re-forms as a viscous shock when the radius has ~doubled

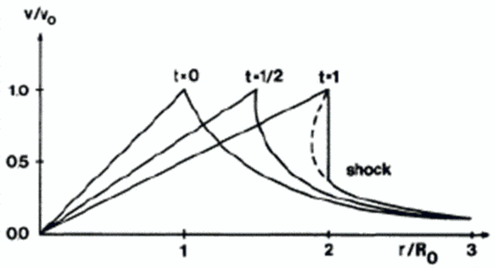


Fig. 2. Evolution of the initial velocity profile, $v = v_0(R_0/r)^2$, of the gas. The shock wave forms after a time $t = R_0/2v_0$ and quickly evolves to a strong shock

Fransson 82

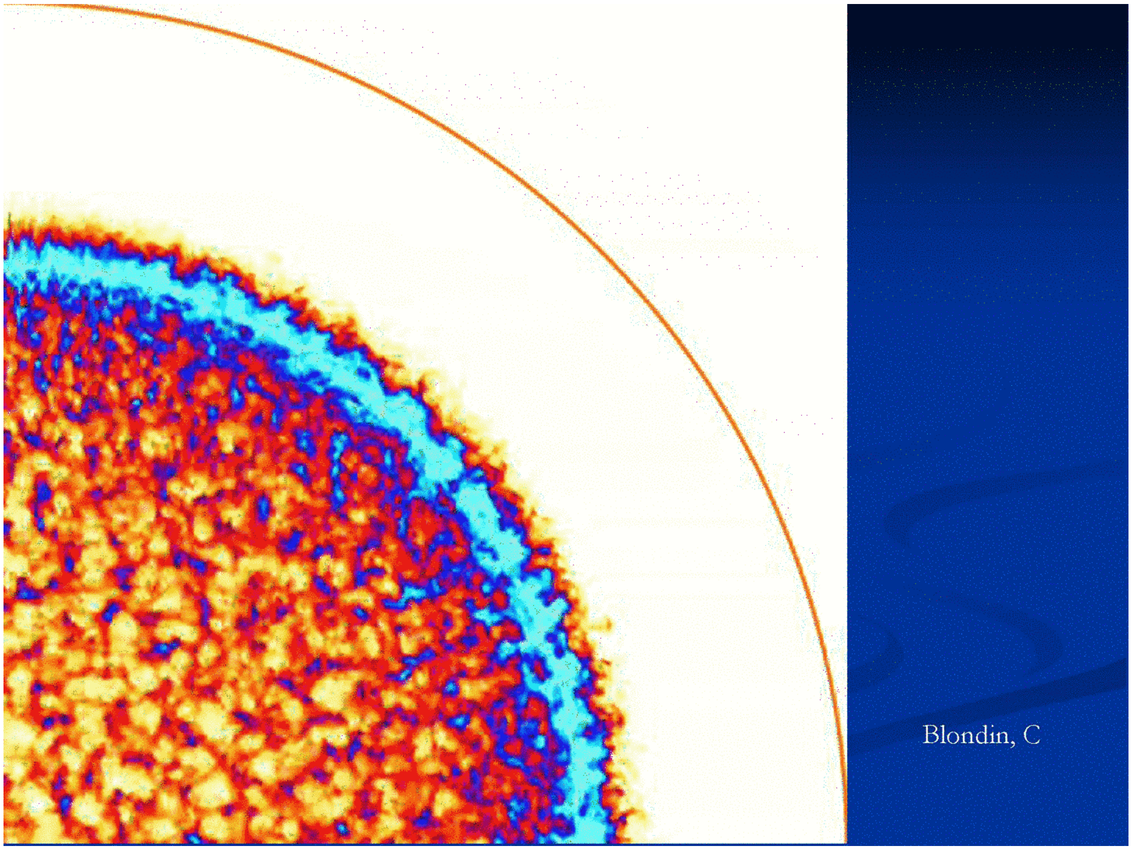
Interaction with surrounding wind

- Self similar solution

$$\rho_{sn} = B\left(\frac{r}{t}\right)^{-n} t^{-3} \qquad \rho_w = Ar^{-2}$$

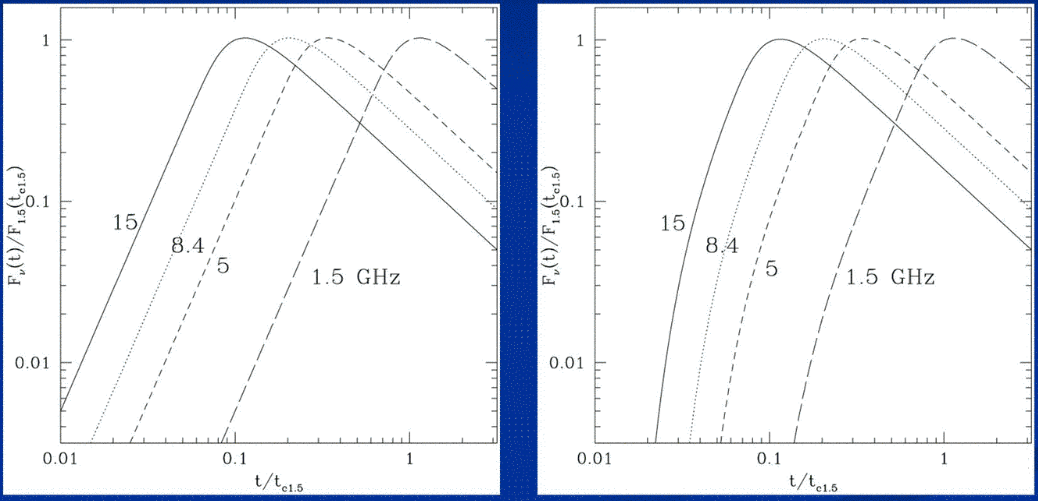
$$R = \left(\alpha\frac{B}{A}\right)^{1/(n-2)} t^{(n-3)/(n-2)}$$

For SN Ib/c, n~10, R~$t^{0.9}$



Blondin, C

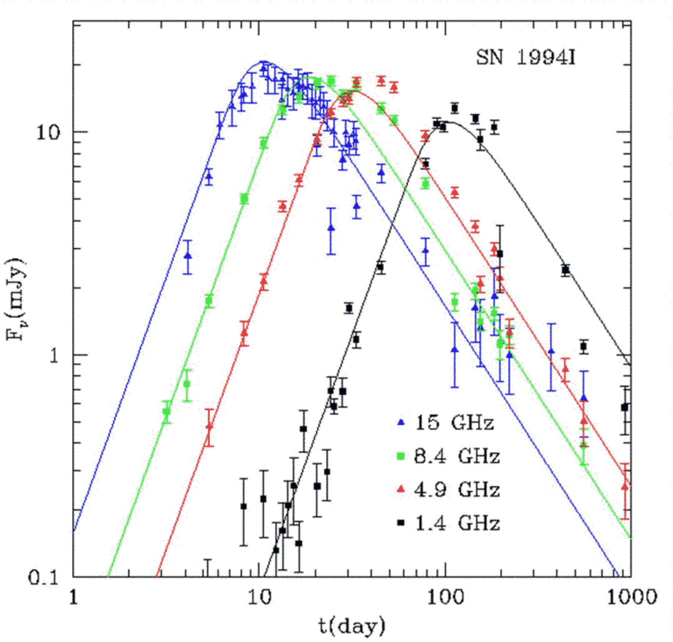
Model radio light curves



Pure SSA

SSA + external FFA

Type Ic SN 1994I in M51



- Model with synchrotron self-absorption and interaction of outer steep power law profile with a wind
- $\nu^{-1.0}$ spectrum, $R \sim t^{0.9}$

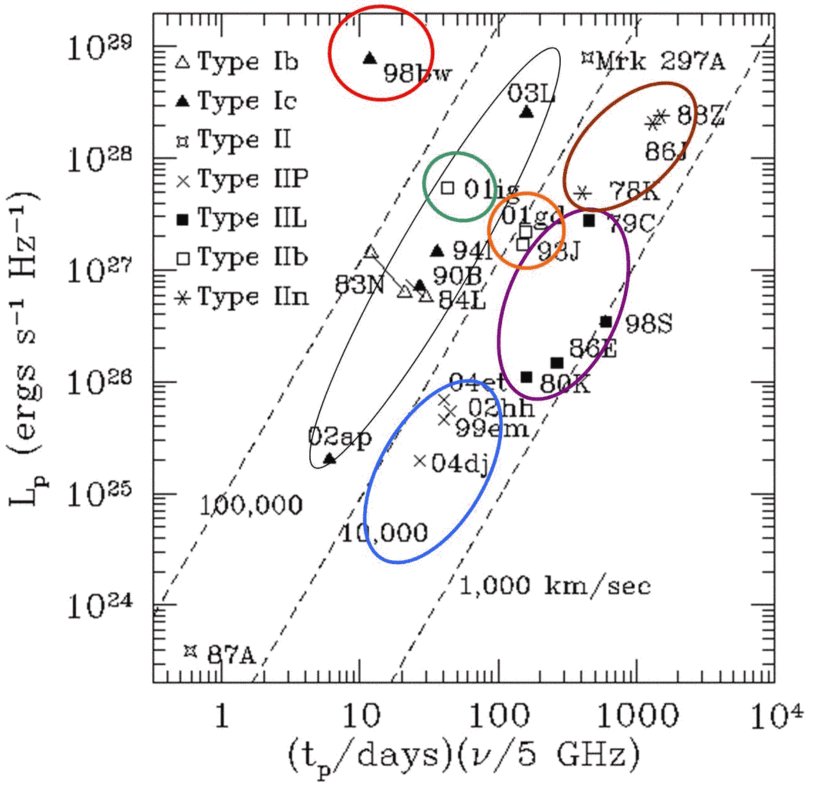
Data from Weiler, Stockdale,….

Synchrotron self-absorption

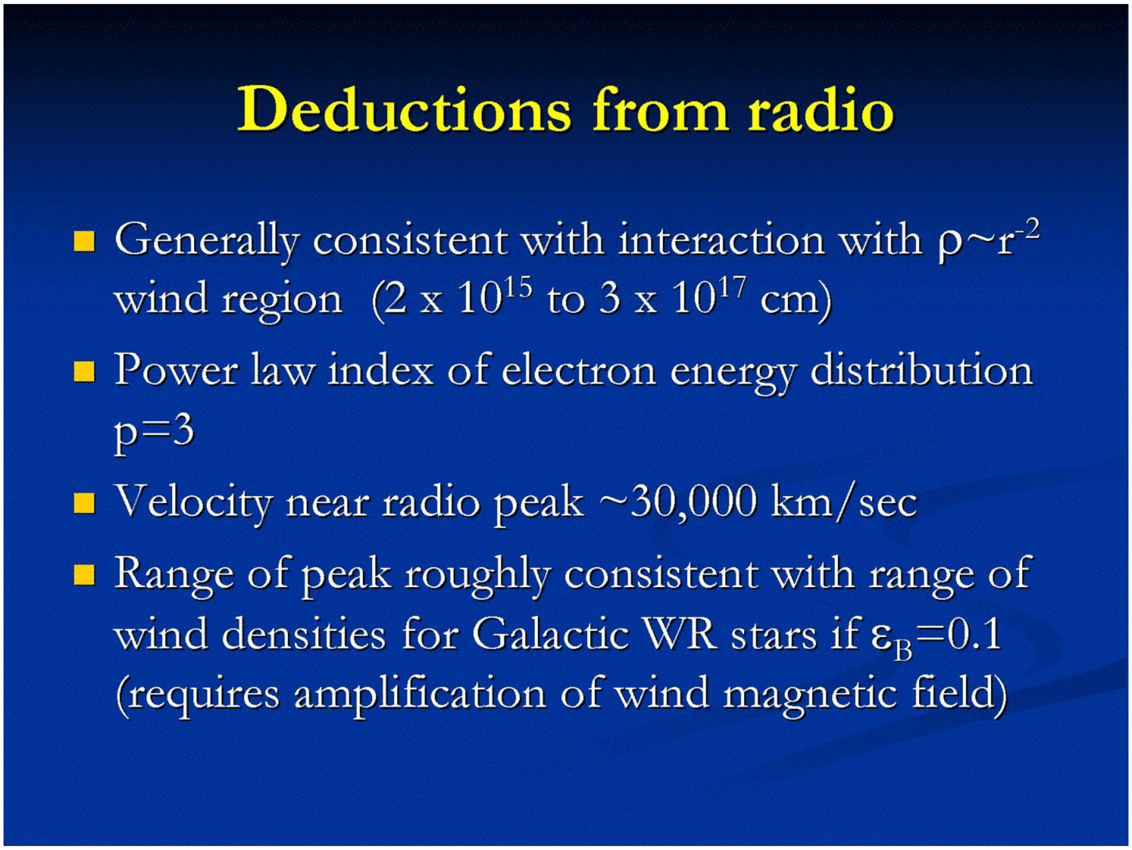
- At peak of light curve (and p=3)

$$R_p = 8.8 \times 10^{15} \left(\frac{u_e}{u_B}\right)^{-1/19} \left(\frac{f}{0.5}\right)^{-1/19} \left(\frac{F_p}{Jy}\right)^{9/19} \left(\frac{D}{Mpc}\right)^{18/19} \left(\frac{\nu}{5GHz}\right)^{-1} \quad cm$$

- Angular size (measurable by VLBI) only weakly dependent on D



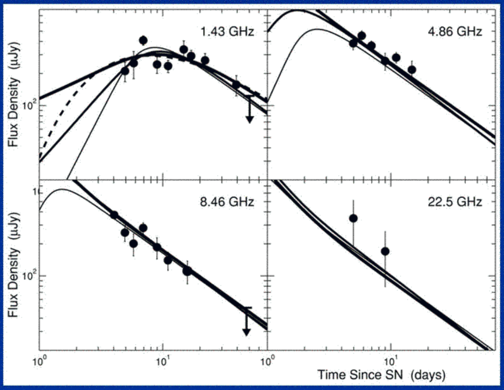
Type Ib/c, GRB
Relativistic
H env. – 0 M$_\odot$
Type Ib/c, no GRB
H env. - 0 M$_\odot$
Type IIb – WR
H env. - 0.01 M$_\odot$
Type IIb – RSG
H env. - 0.1 M$_\odot$
Type IIL
H env. - 1 M$_\odot$
Type IIP
H env. - 10 M$_\odot$



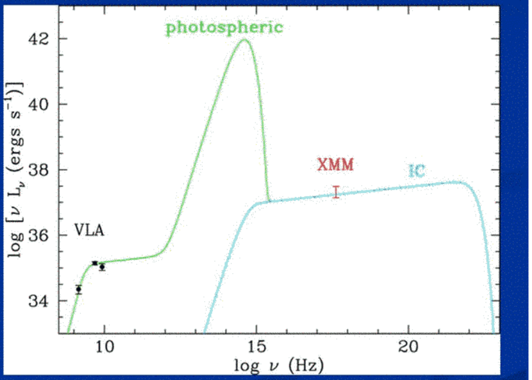
Deductions from radio

- Generally consistent with interaction with $\rho \sim r^{-2}$ wind region (2 x 10^{15} to 3 x 10^{17} cm)
- Power law index of electron energy distribution p=3
- Velocity near radio peak ~30,000 km/sec
- Range of peak roughly consistent with range of wind densities for Galactic WR stars if ε_B=0.1 (requires amplification of wind magnetic field)

Broad-lined Type Ic SN 2002ap



Radio: Berger, Kulkarni, RAC 02

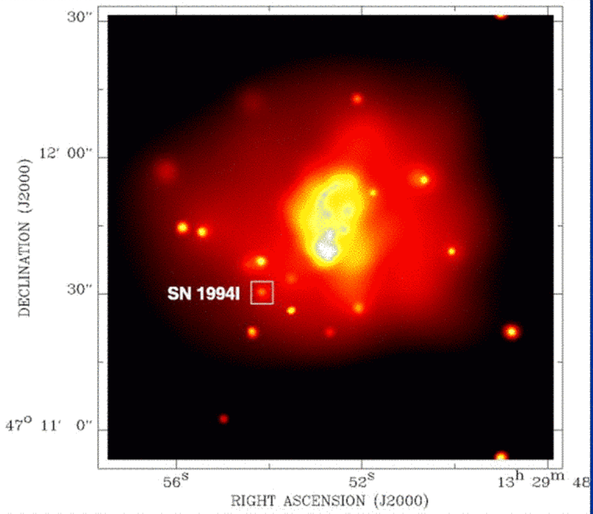


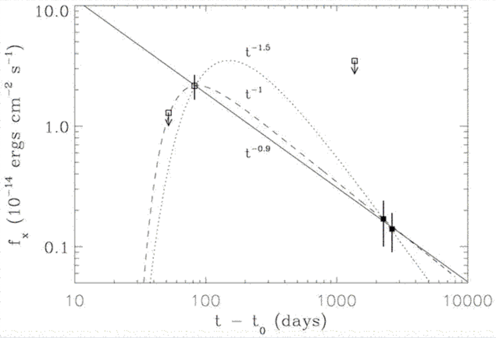
Bjornsson & Fransson 04

Low energy in high velocity ejecta; $A_* = 0.001\ \varepsilon_b^{-1}$

X-rays (age < 200 days)

- Thermal emission too low (if wind densities like WR wind density)
- Extrapolation of radio synchrotron to X-ray too low, especially when allow for synchrotron cooling
- Inverse Compton scattering of photospheric photons by relativistic electrons about right (with particle density from radio and approximate equipartition)

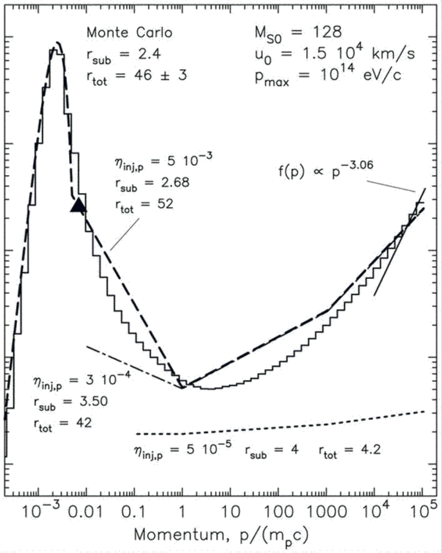


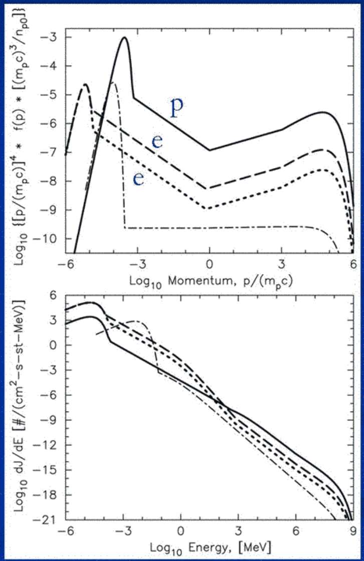


SN 1994I at 7 years

Chandra Immler et al. 02

Nonthermal particle distribution



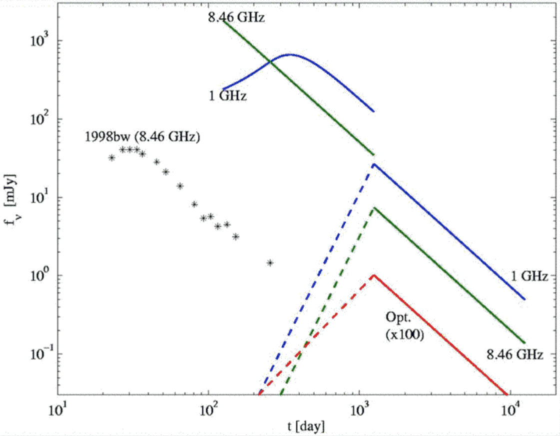


Ellison, Berezhko, Baring 00

Evidence for cosmic ray dominated shock

- Radio emitting particles have steeper spectrum than expected in the test particle limit
- Flattening of spectrum to high energies needed to explain X-rays

Late increase from an off-axis GRB



Waxman 04

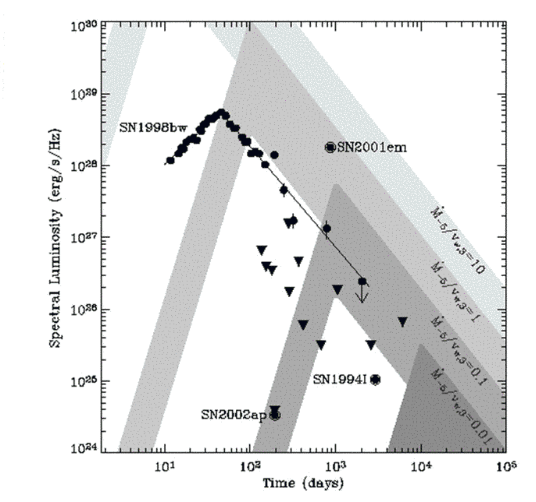
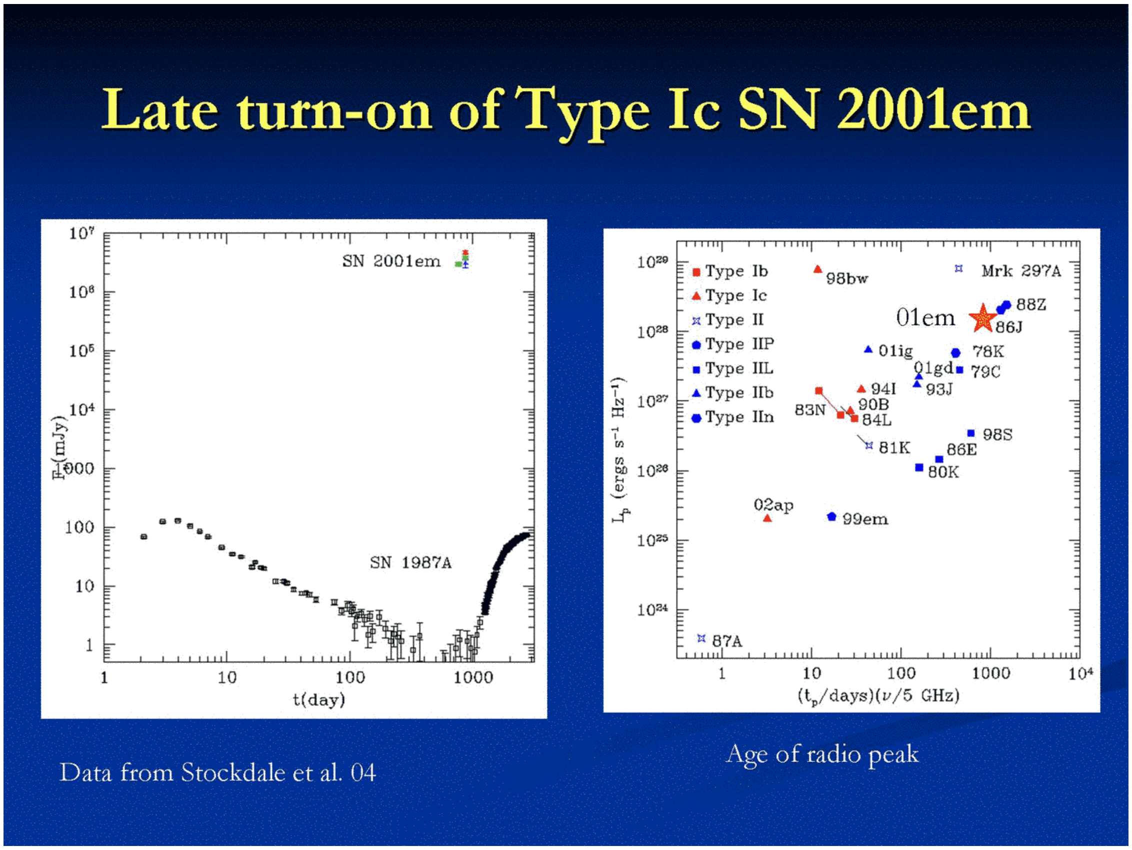


FIG. 1.— The radio luminosity evolution of SN 1998bw is shown with late-time detection limits for 12 nearby Ibc supernovae (triangles) and three late-time detections for SN 1994I, SN 2002ap and SN 2001em. The four shaded regions represent an off-axis GRB jet for $A_* = \dot M_{-5}/v_{w,3} = (0.01, 0.1, 1, 10)$ and assuming a range of values, $\epsilon_B = 0.002 - 0.25$. We have assumed typical values of $E_{51} = 1$ and $\epsilon_e = 0.1$. With the exception of SN 2001em, all of these late-time observations are significantly fainter than the $\dot M_{-5}/v_{w,3} = 1$ off-axis jet prediction and nine of the SNe constrain $\dot M_{-5}/v_{w,3} \leq 0.1$.

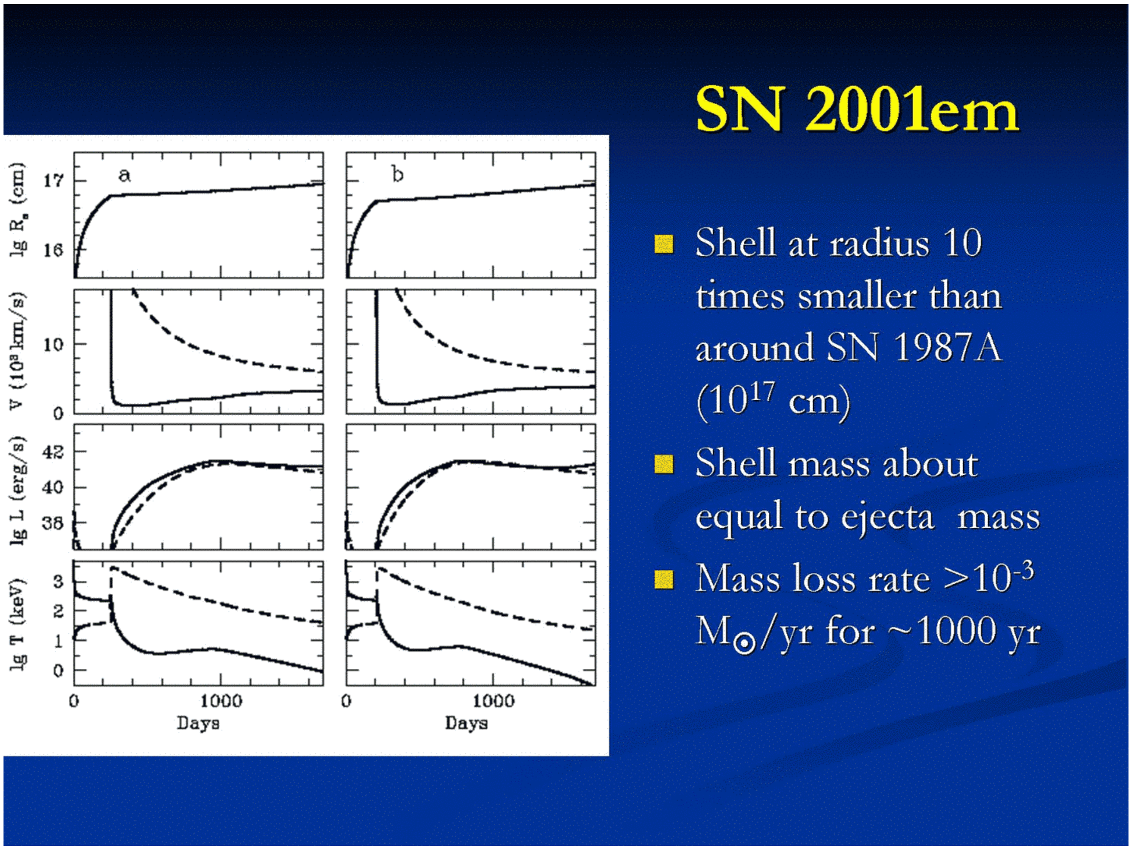
Soderberg et al. 04



Late turn-on of Type Ic SN 2001em

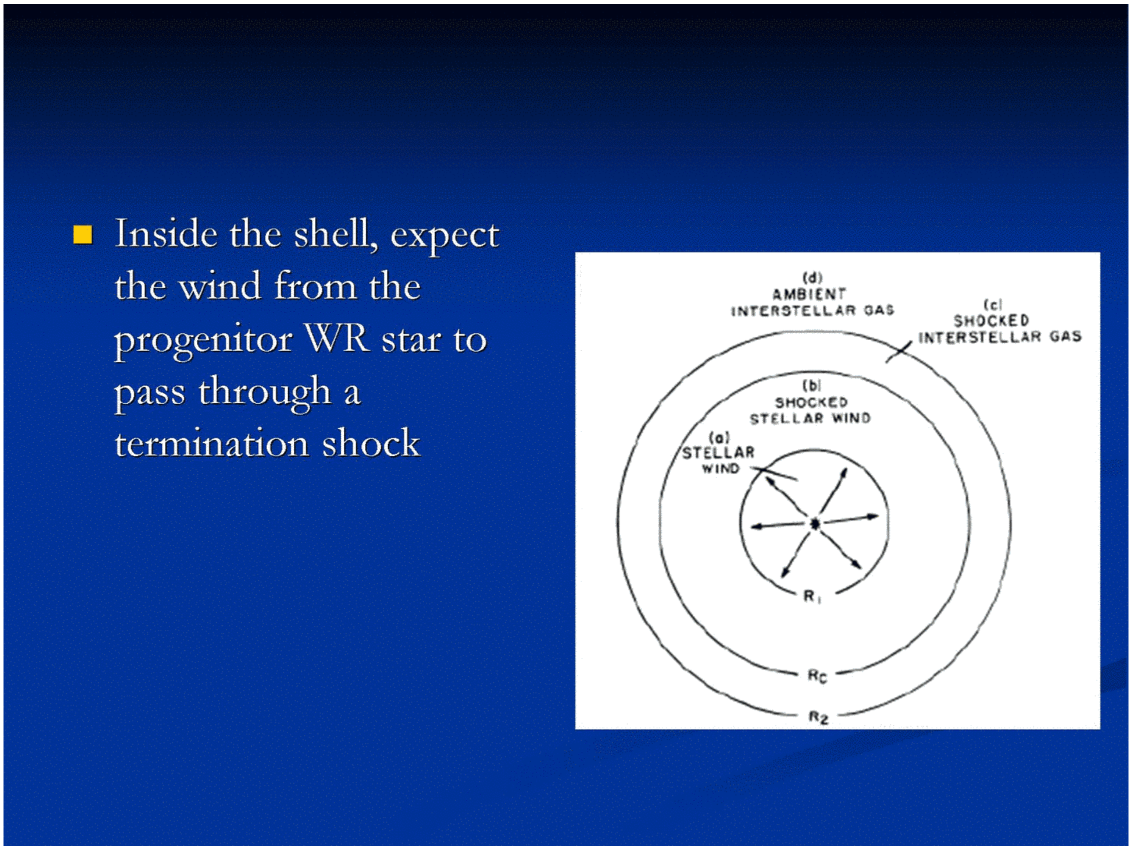
Data from Stockdale et al. 04

Age of radio peak

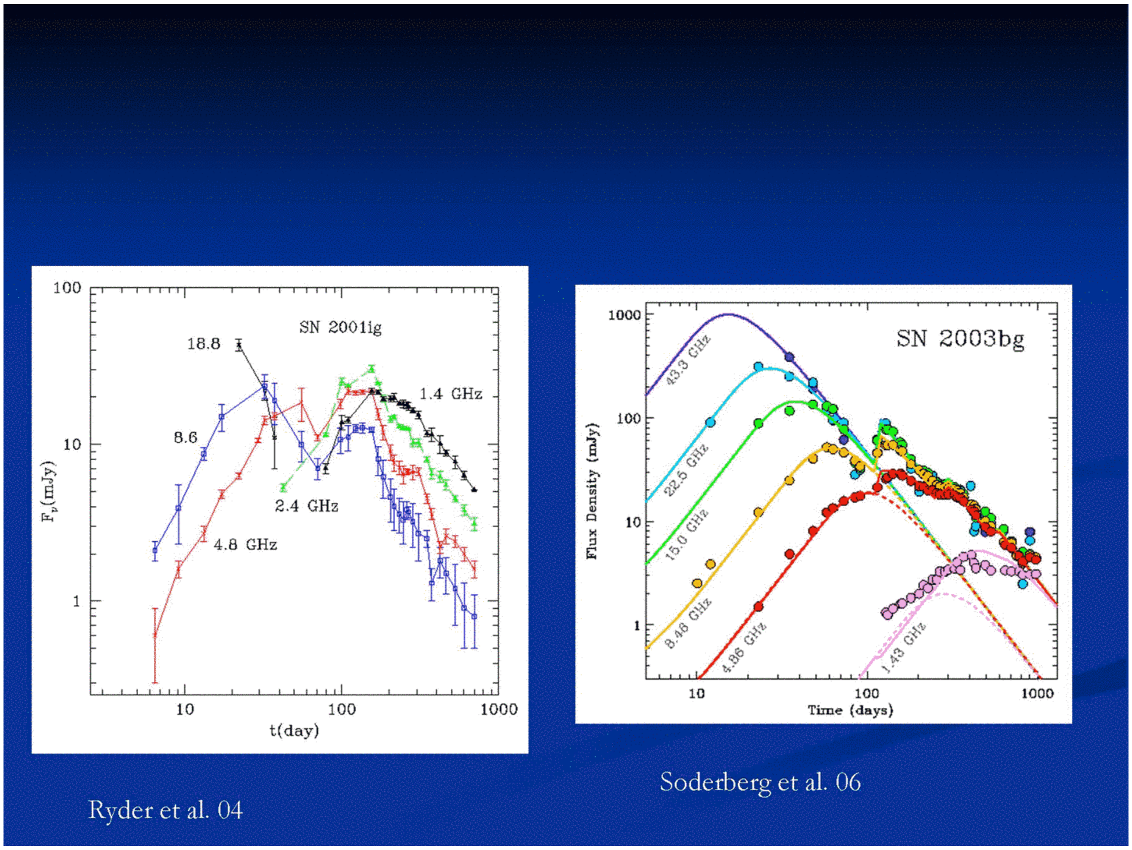


SN 2001em

- Shell at radius 10 times smaller than around SN 1987A (10^{17} cm)
- Shell mass about equal to ejecta mass
- Mass loss rate >10^{-3} $M_{\odot}$/yr for ~1000 yr

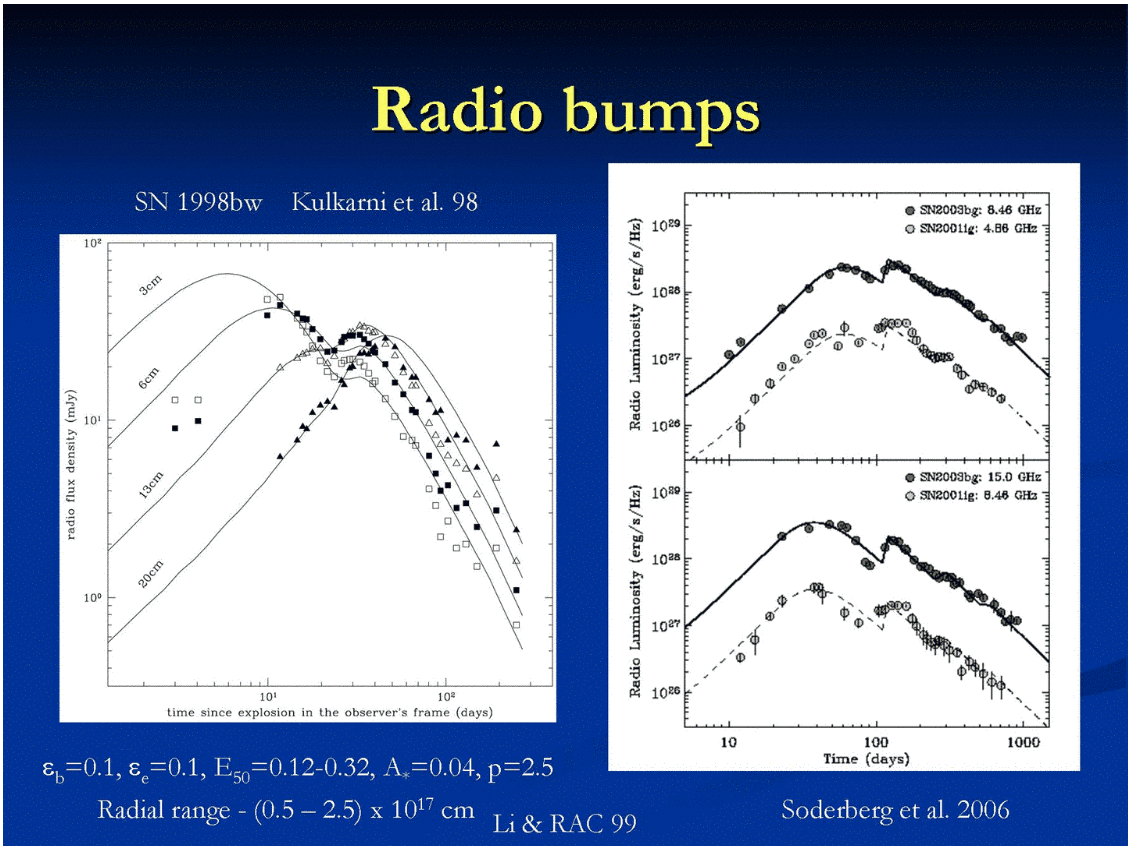


- Inside the shell, expect the wind from the progenitor WR star to pass through a termination shock



Ryder et al. 04

Soderberg et al. 06



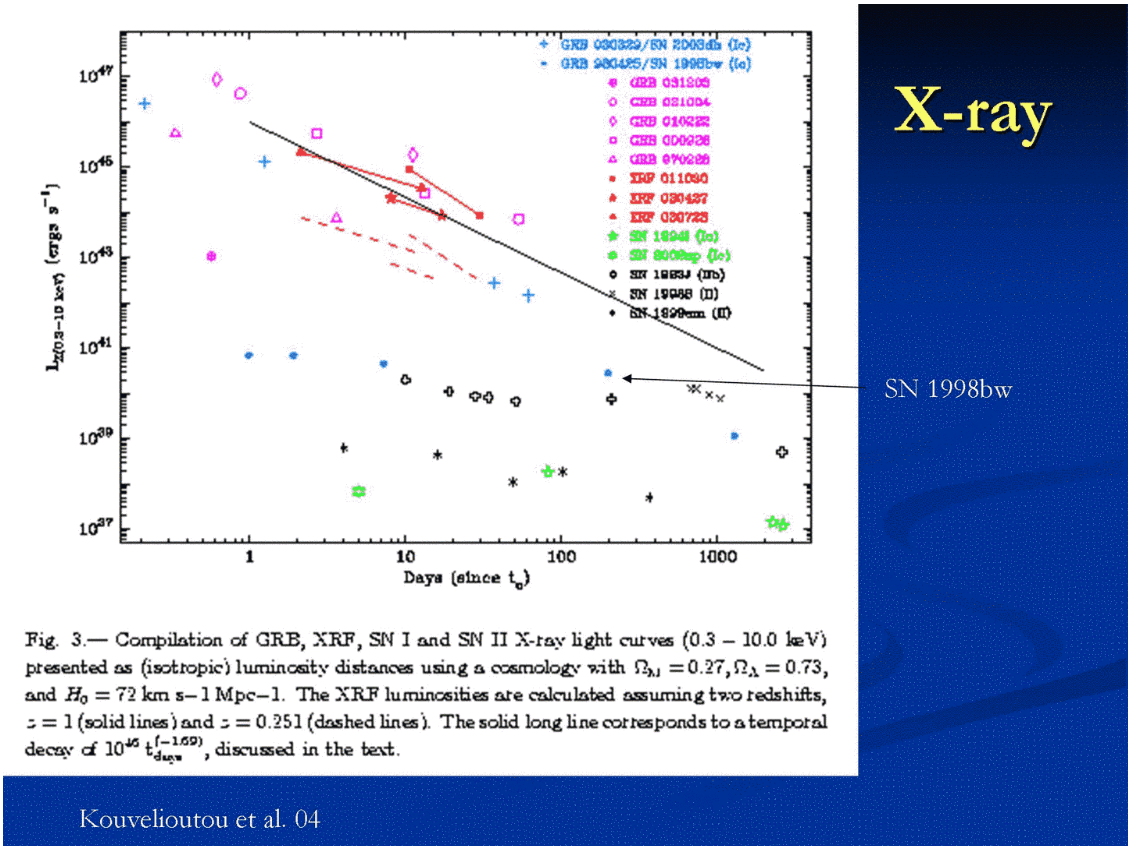
Radio bumps

SN 1998bw Kulkarni et al. 98

ε_b=0.1, ε_e=0.1, E_{50}=0.12-0.32, A_*=0.04, p=2.5

Radial range - (0.5 – 2.5) x 10^{17} cm Li & RAC 99

Soderberg et al. 2006



X-ray

SN 1998bw

Fig. 3.— Compilation of GRB, XRF, SN I and SN II X-ray light curves (0.3 – 10.0 keV) presented as (isotropic) luminosity distances using a cosmology with $\Omega_M = 0.27, \Omega_\Lambda = 0.73$, and $H_0 = 72$ km s−1 Mpc−1. The XRF luminosities are calculated assuming two redshifts, $z = 1$ (solid lines) and $z = 0.251$ (dashed lines). The solid long line corresponds to a temporal decay of $10^{45}\, t_{\rm days}^{(-1.59)}$, discussed in the text.

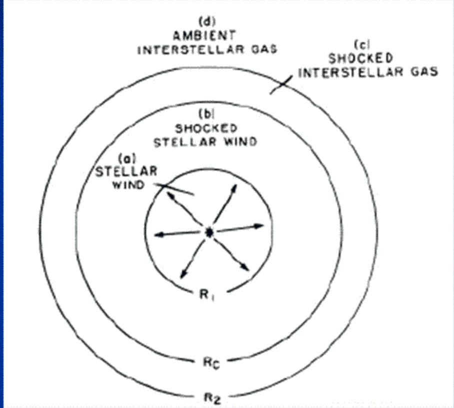
Kouveliotou et al. 04

Unlike SNe Ib/c, GRBs do not show evidence for interaction with progenitor wind

- Modeling of multiwavelength afterglow evolution
- Jet breaks

Termination shock of wind

- R_1 – termination shock radius. Beyond R_1, density ~ constant.

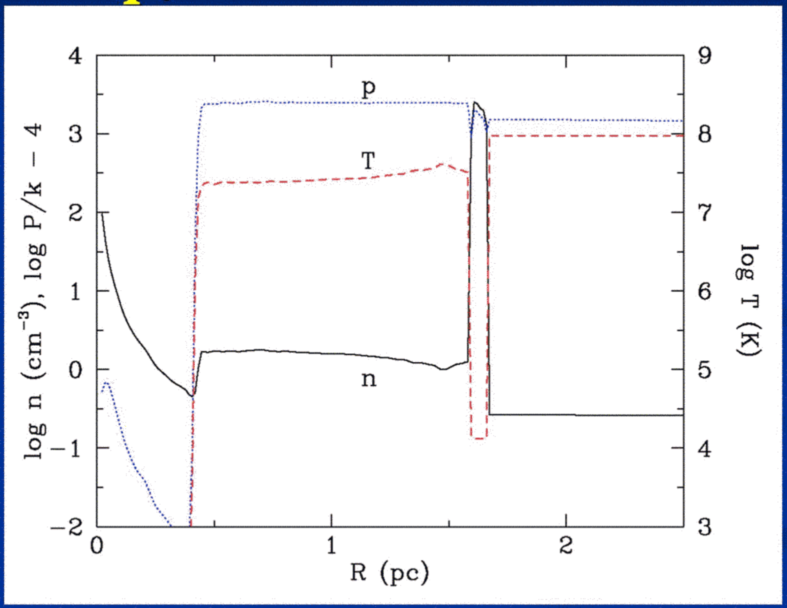


$$R_1 = 5.7\times10^{19}\left(\frac{v_w}{1000\ km/\sec}\right)\left(\frac{p/k}{10^4\ cm^{-3}\ K}\right)^{-1/2} A_*^{1/2}\,cm$$

Ways to reduce R_1 around a GRB

- Reduce stellar mass loss rate
  - Low metallicity $dM/dt \sim Z^{0.5}$
- Increase pressure
  - Star in very dense region of ISM
  - Stellar motion
  - High ISM pressure, as in a starburst
  - Recent transition to WR star, so WR wind contained by dense mass loss (e.g., SN 2001em)

Wind structure with ambient $p/k = 2 \times 10^7$ cm^{-3} K



(RAC, Li, Fransson 04)

GRB 021004 ($z=2.32$) possible circumstellar absorption lines

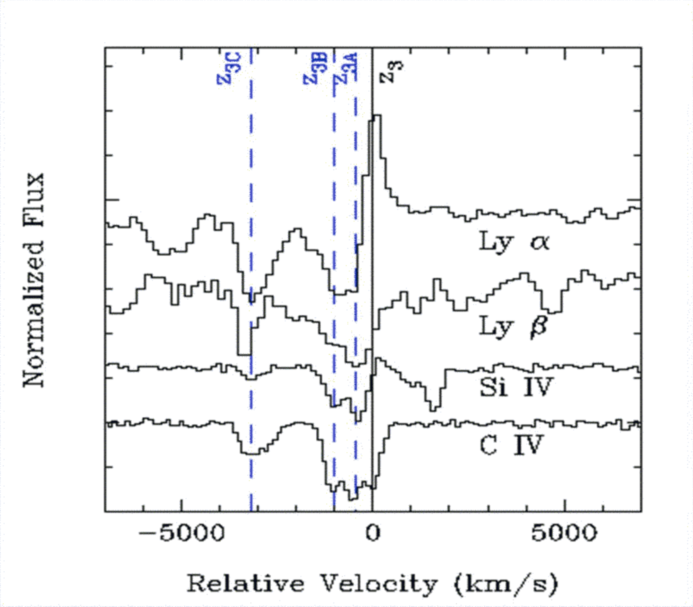
(Mirabal et al. 2003)

Similar lines seen in

GRB 020813

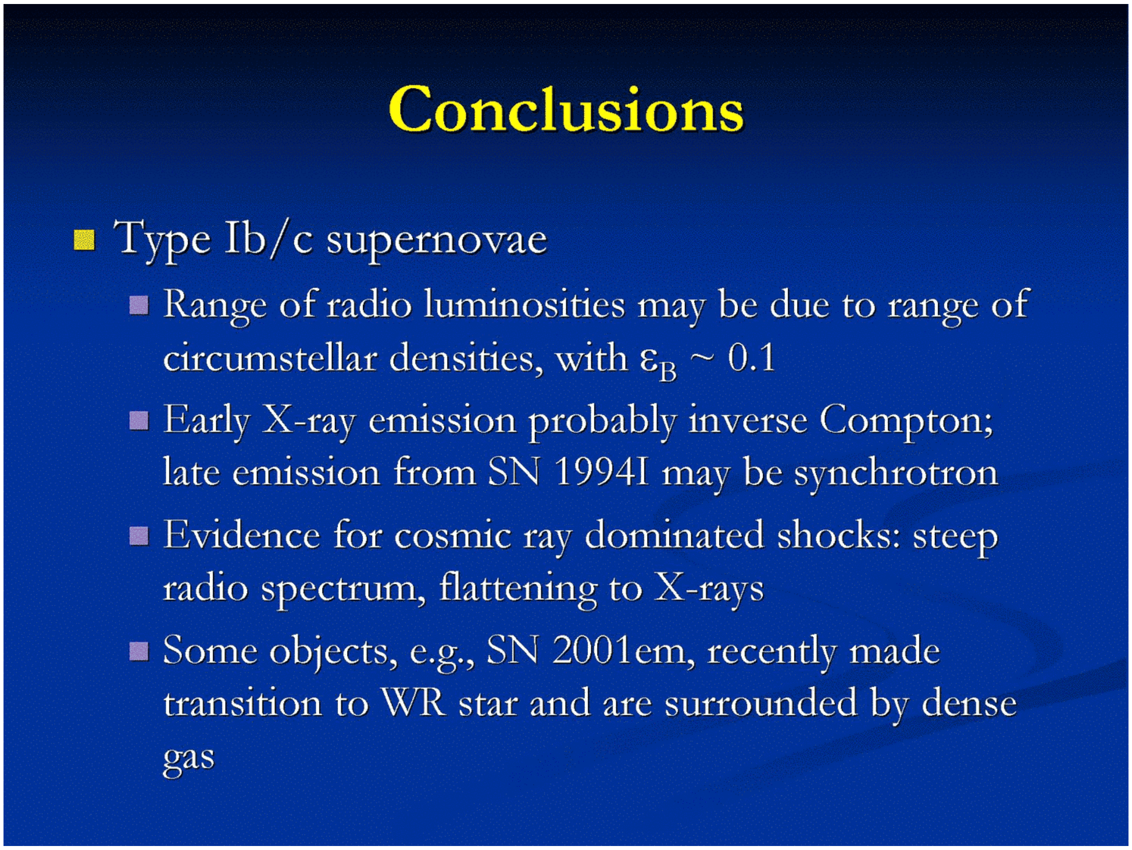
GRB 030226

GRB 050505



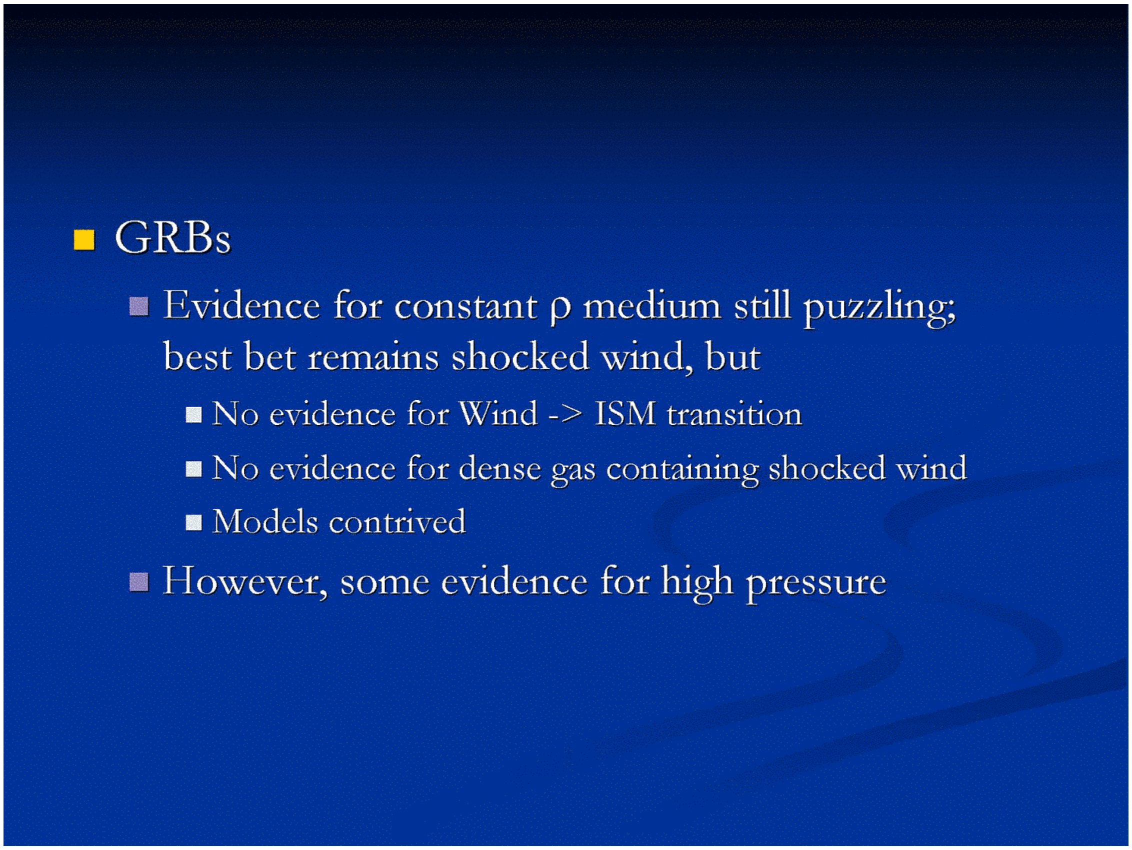
Absorption lines

- High velocities (1000 – 3000 km/sec) naturally explained by WR wind velocity, but..
  - Photoionization expected near GRB
  - Afterglow should be of Wind type
- Excited fine structure lines of Fe II, Si II (GRB 051111 and GRB 050730)
  - Require T ~ few 10^3 K, n > 10^5 cm^{-3} (Prochaska et al. 06)



Conclusions

- Type Ib/c supernovae
  - Range of radio luminosities may be due to range of circumstellar densities, with $\varepsilon_B \sim 0.1$
  - Early X-ray emission probably inverse Compton; late emission from SN 1994I may be synchrotron
  - Evidence for cosmic ray dominated shocks: steep radio spectrum, flattening to X-rays
  - Some objects, e.g., SN 2001em, recently made transition to WR star and are surrounded by dense gas



- GRBs
  - Evidence for constant ρ medium still puzzling; best bet remains shocked wind, but
    - No evidence for Wind -> ISM transition
    - No evidence for dense gas containing shocked wind
    - Models contrived
  - However, some evidence for high pressure