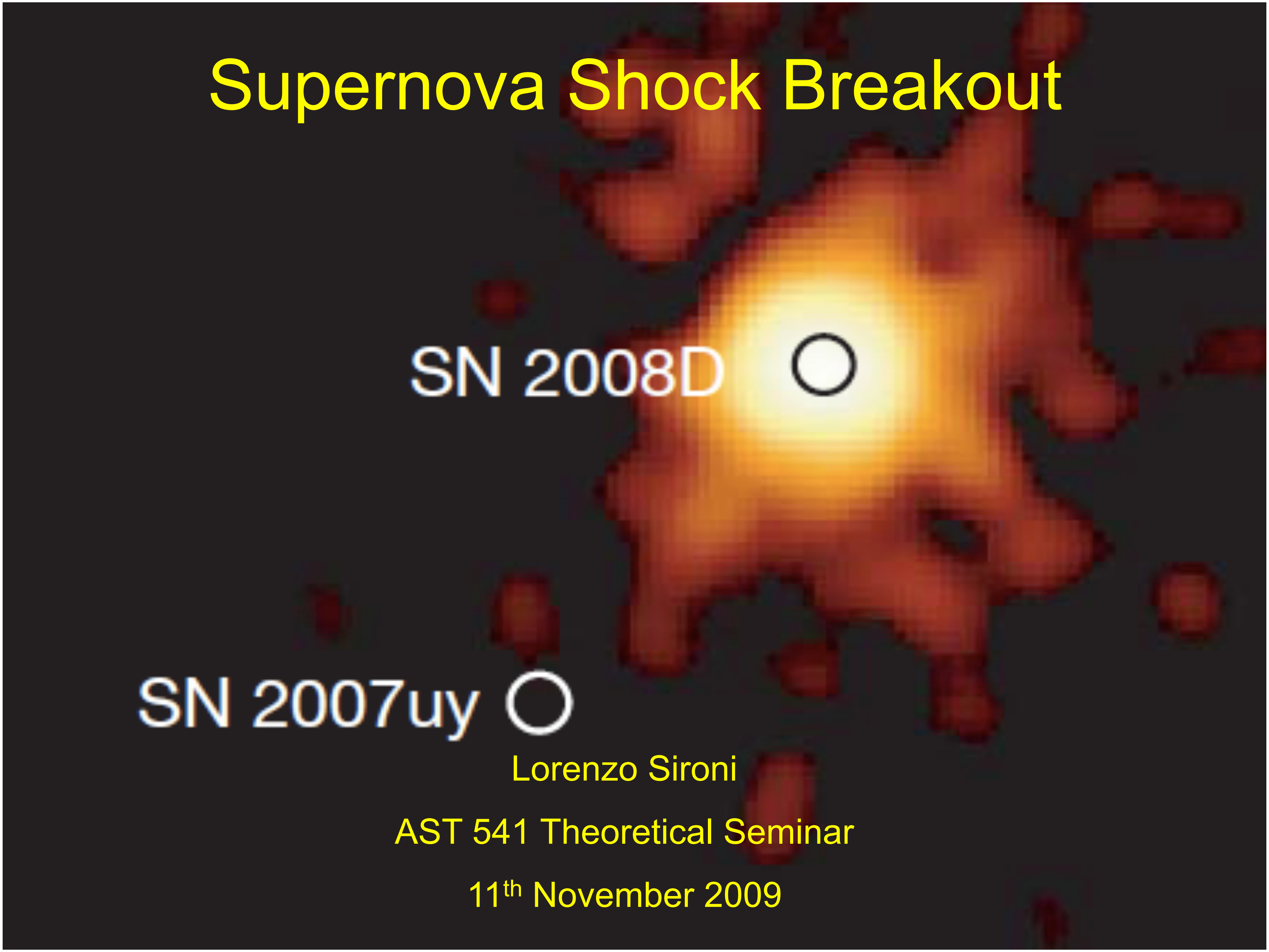
Supernova Shock Breakout



Lorenzo Sironi

AST 541 Theoretical Seminar

11th November 2009

SN Shock Breakout (SB)

• For any core-collapse SN, a flash of thermal UV (or soft X-ray) radiation is expected when the SN shock breaks out of the stellar surface (Falk & Arnett 1977, Klein & Chevalier 1978)

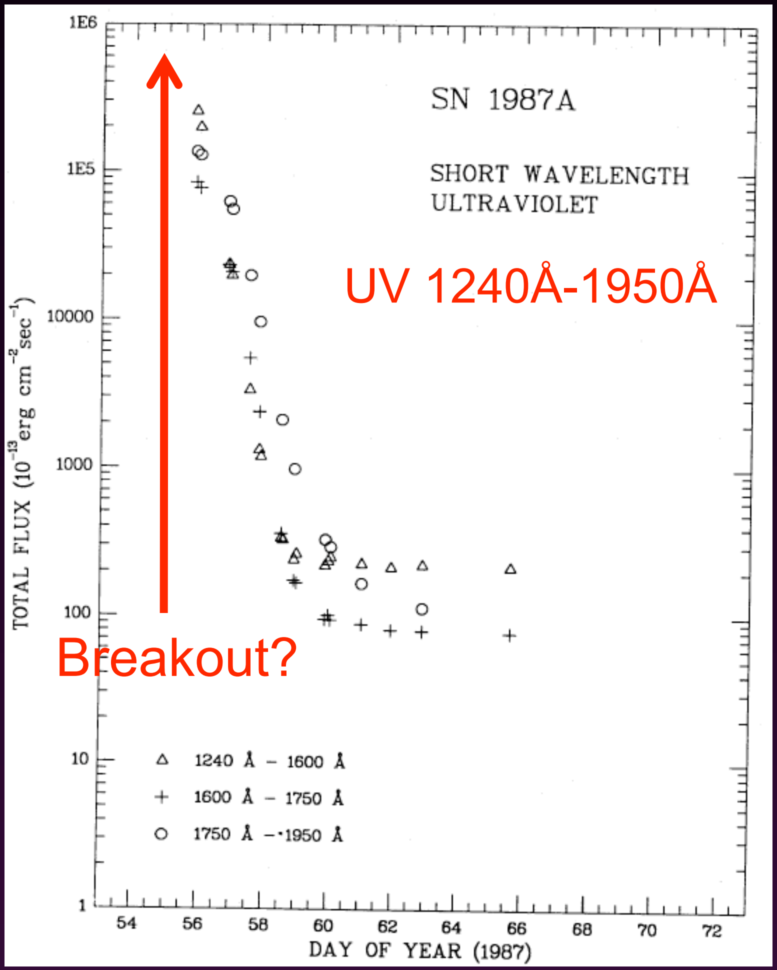
SN 1987A:

IUE missed the breakout by ~35 hrs

T_{eff}~15,000 K for earliest EUV observations, already declining from higher values…

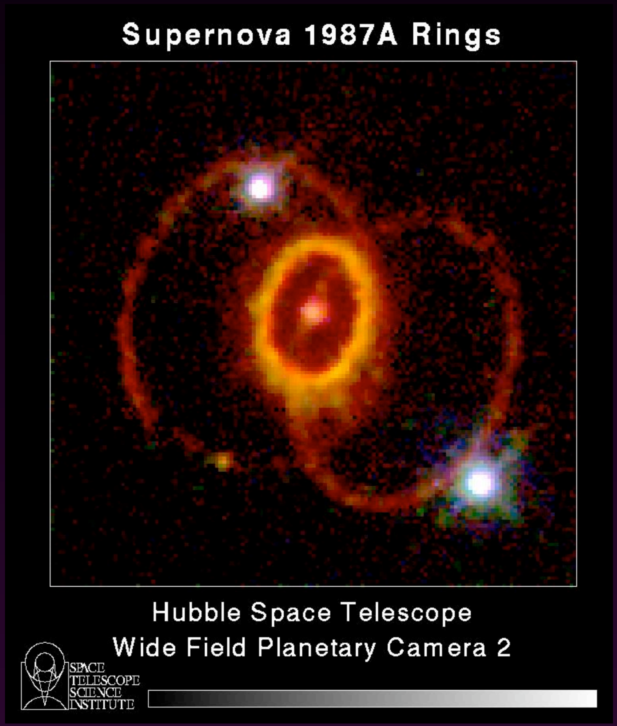
How can we determine the conditions at SB?

(Kirshner et al. 1987)

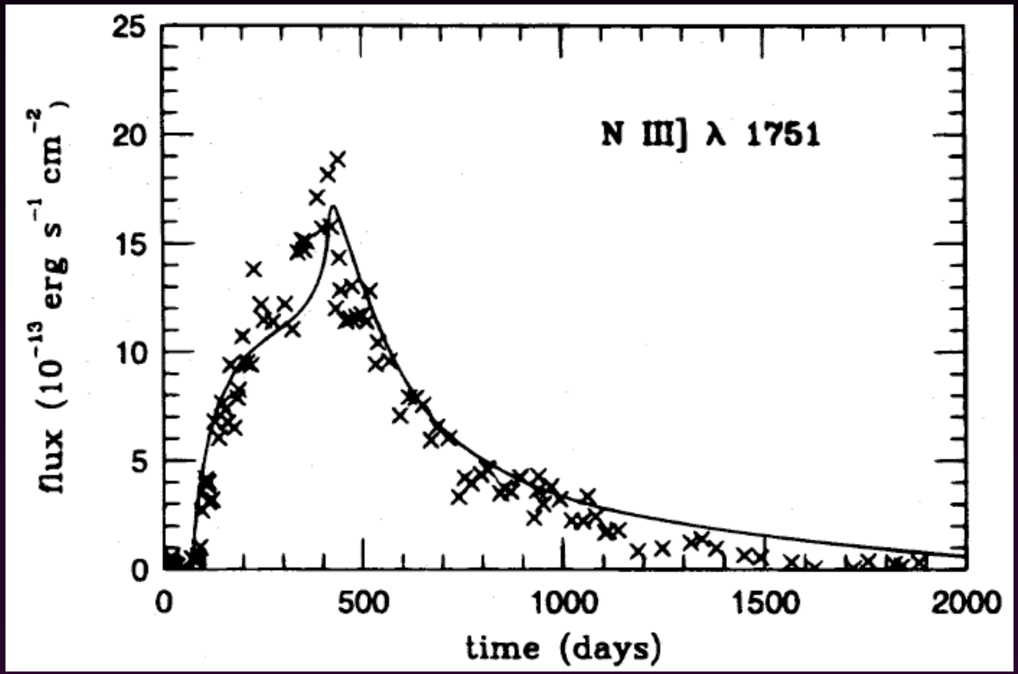


SN 1987A

• After ~1000 days, brightest narrow (UV & optical) emission lines come from a ring around the SN: recombination lines of gas that was photo-ionized by the SN breakout radiation



(Lundqvist & Fransson 1996)



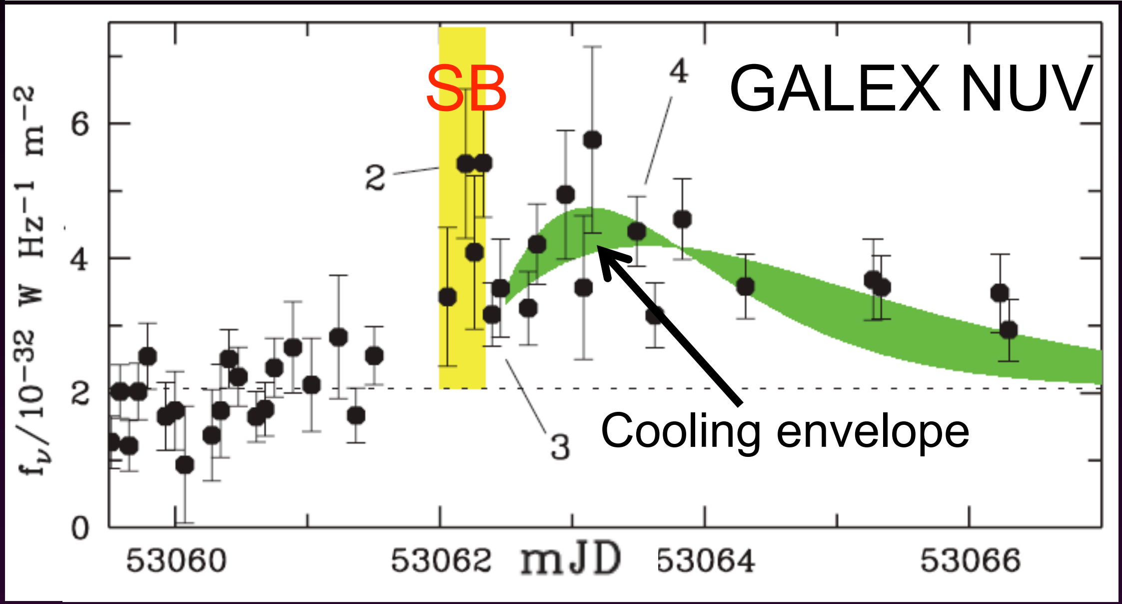
• Temperature and energy of the breakout flash can be reconstructed from the light curves of the lines: $T_C \sim 10^6$ K; number of ionizing photons (>100 eV) is ~10^{56} (~10^{46} ergs)

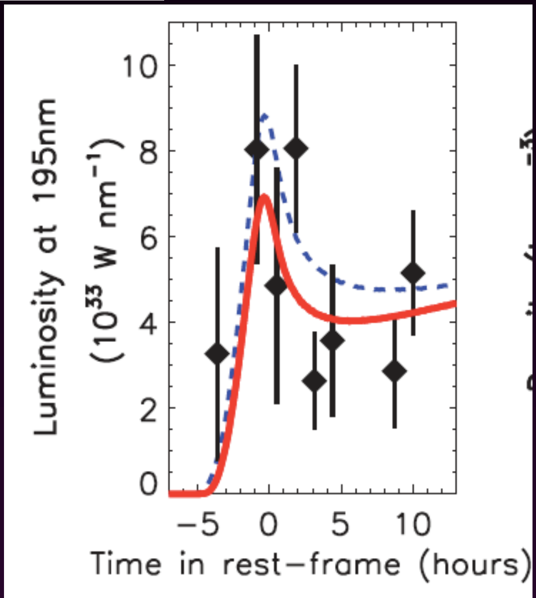
SNLS-04D2dc

Type II P (RSG progenitor)

GALEX NUV

(Schawinski et al. 2008)



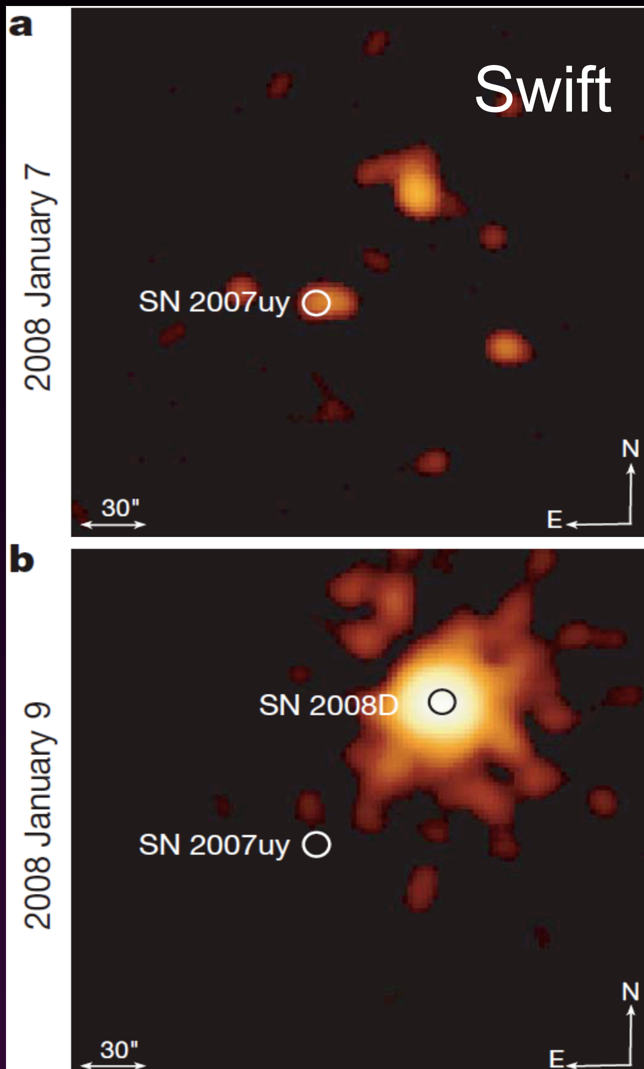


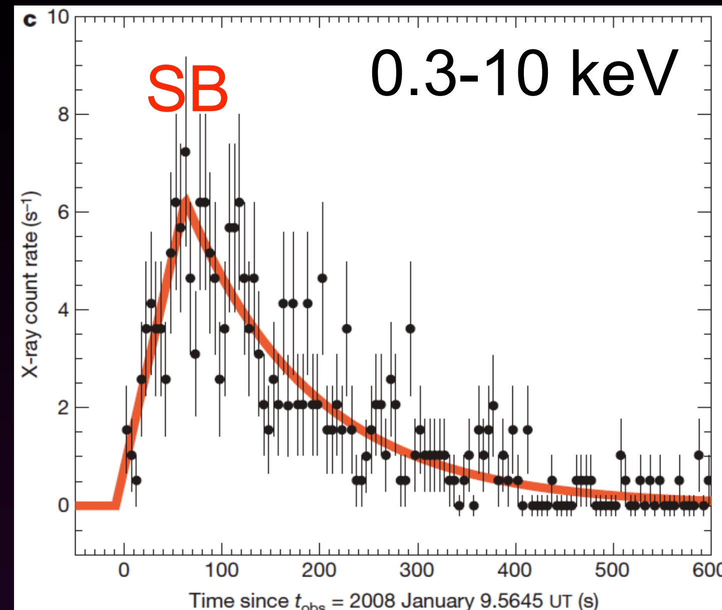
HIGH-SOFT CASE: high energy (E_{SB}~10^{48} ergs) - low temperature ($k_B T_{eff}$~10 eV) - long duration (Δt~6 hrs)

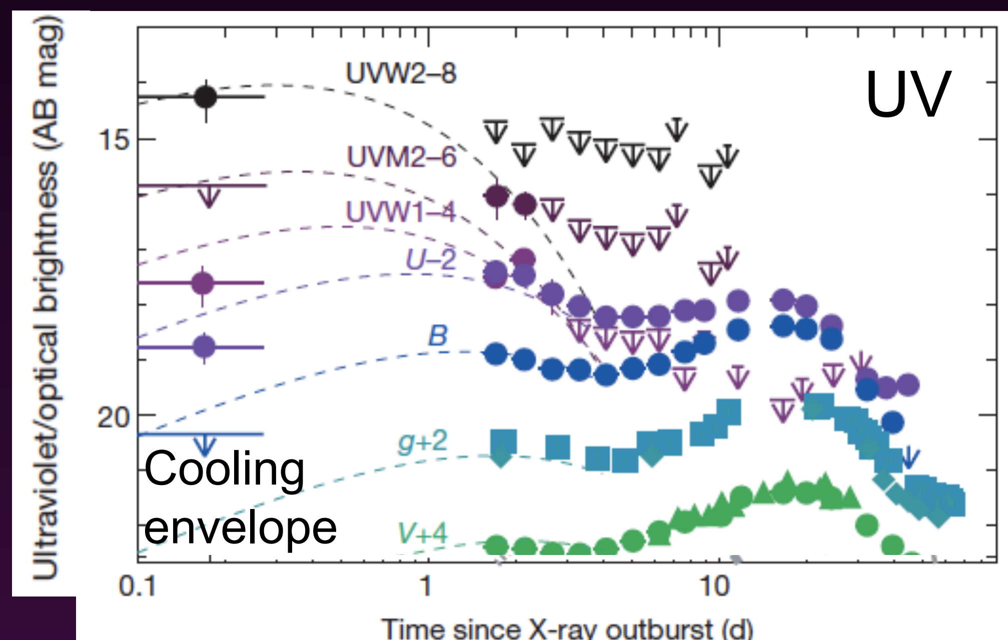
➔ extended progenitor ($R_\star$~1000 R_{sun}: RSG!)

SN 2008D (1/2)

Type Ibc (WR candidate progenitor)



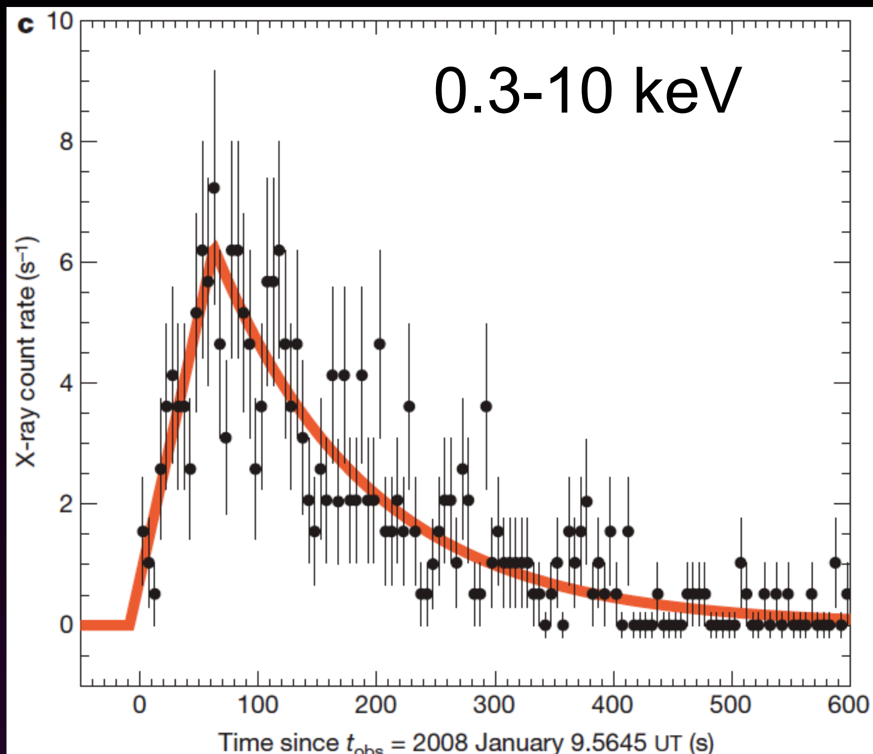


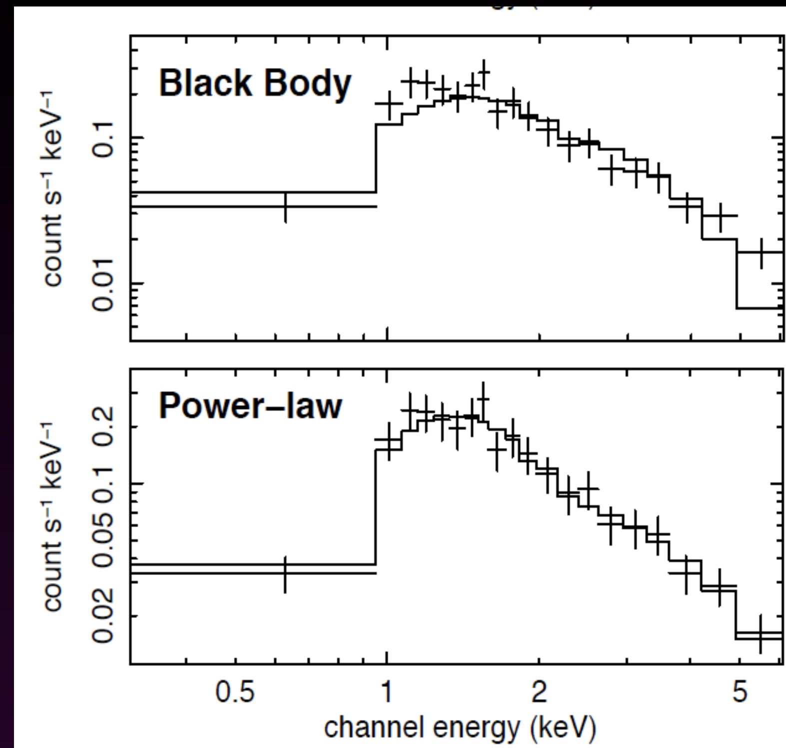


(Soderberg et al. 2008)

SN 2008D (2/2)

(Soderberg et al. 2008)





LOW-HARD CASE: low energy (E_{SB}~10^{46} ergs) - high temperature ($k_B T_{eff}$~5 keV, IF thermal) - short duration (Δt~100 s)

E_{SB} and T_{eff} → IF thermal, VERY compact progenitor ($R_\star$~0.1 R_{sun}), inconsistent with duration Δt~100 s → ???

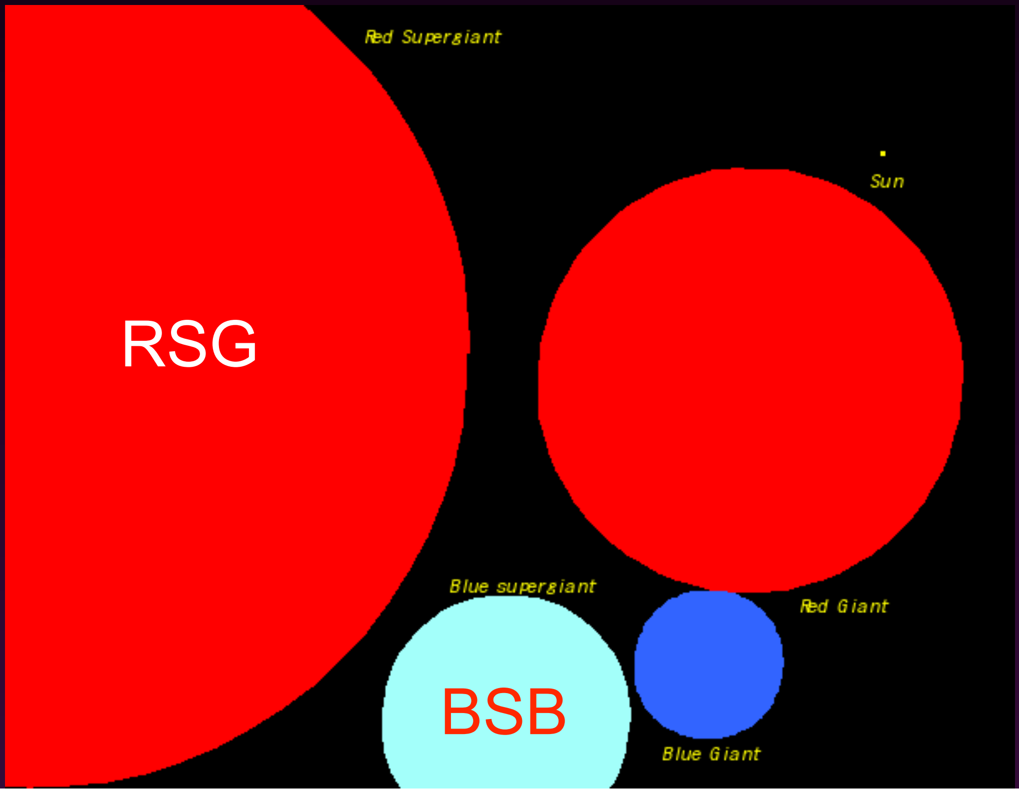
Candidate core-collapse SN progenitors

- RED SUPERGIANT (RSG): type II P
- BLUE SUPERGIANT (BSG): type II
- WOLF-RAYET (WR): type Ib/Ic (stripped hydrogen envelopes)

R_{RSG}=500-1000 R_{sun}

R_{BSG}=25-50 R_{sun}

R_{WR}=5-10 R_{sun}



SB for dummies

• SN shock in the stellar envelope is radiation-mediated (via Compton scattering) and radiation-dominated (post-shock energy dominated by radiation)

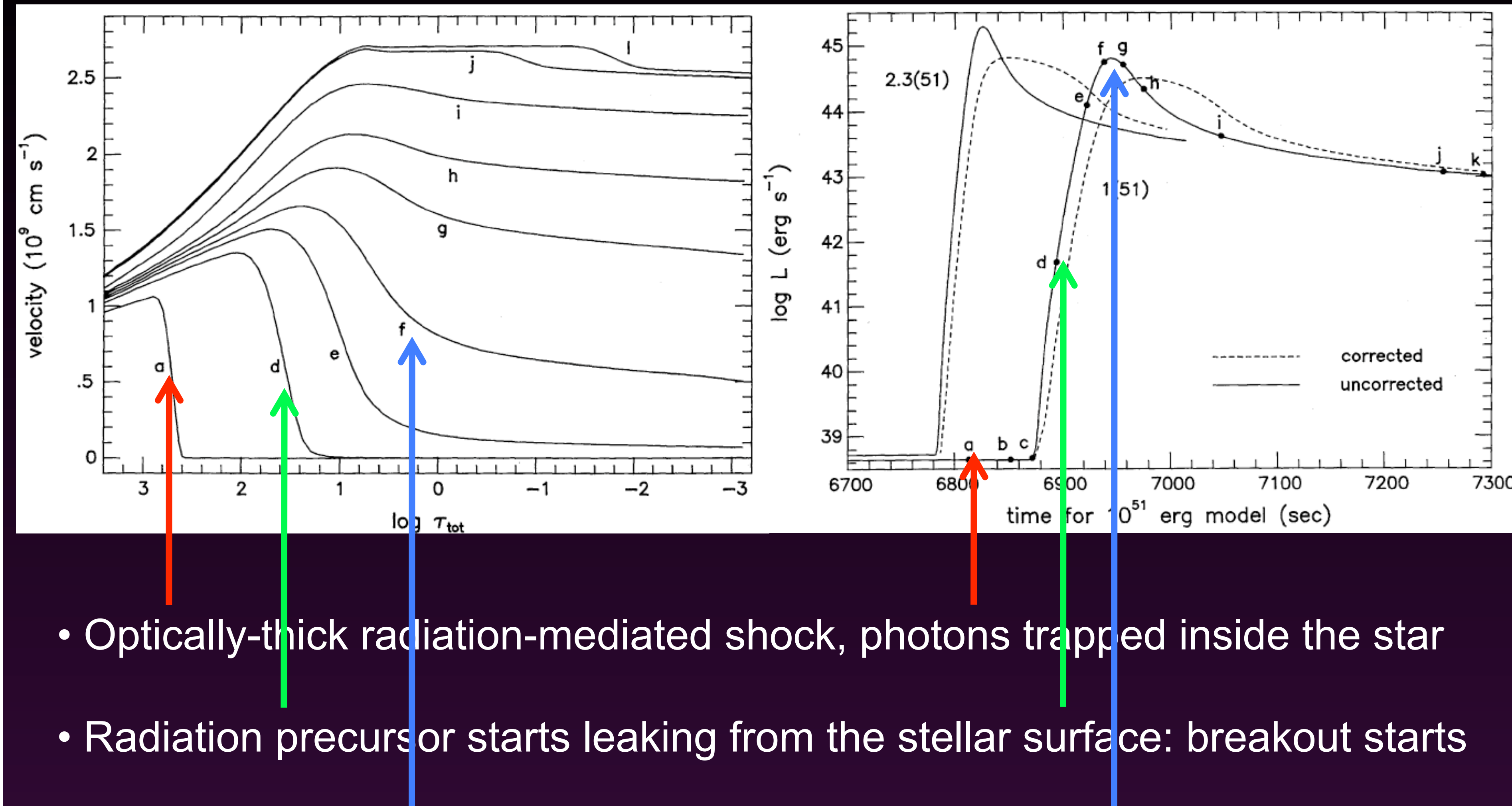
• Shock thickness is set by balance between advection time across the shock $\sim \Delta_s / v_s$ and diffusion time of photons $\simeq \tau_s \Delta_s / c$
➔ shock optical depth is $\tau_s \simeq c/v_s$

• As the shock propagates, the Thomson optical depth to the surface τ decreases faster than τ_s : radiation escapes when

$\tau < \tau_s$ ➔ BREAKOUT RADIATION

Shock propagation and SB (BSG)

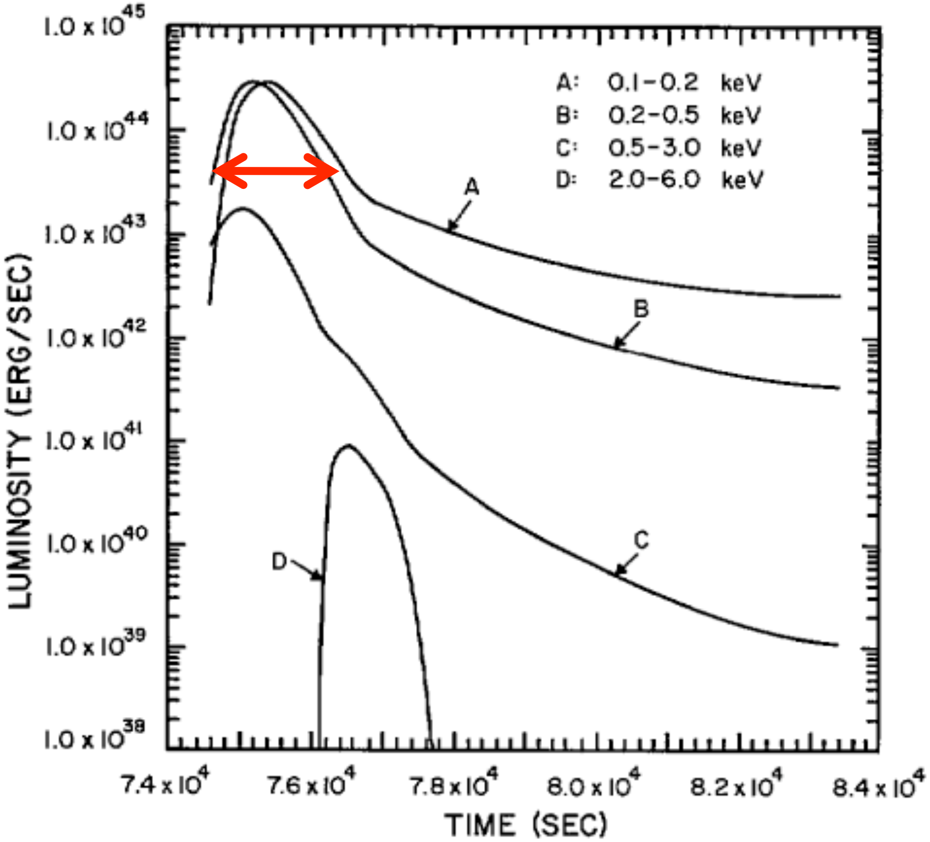
(Ensman & Burrows 2002)



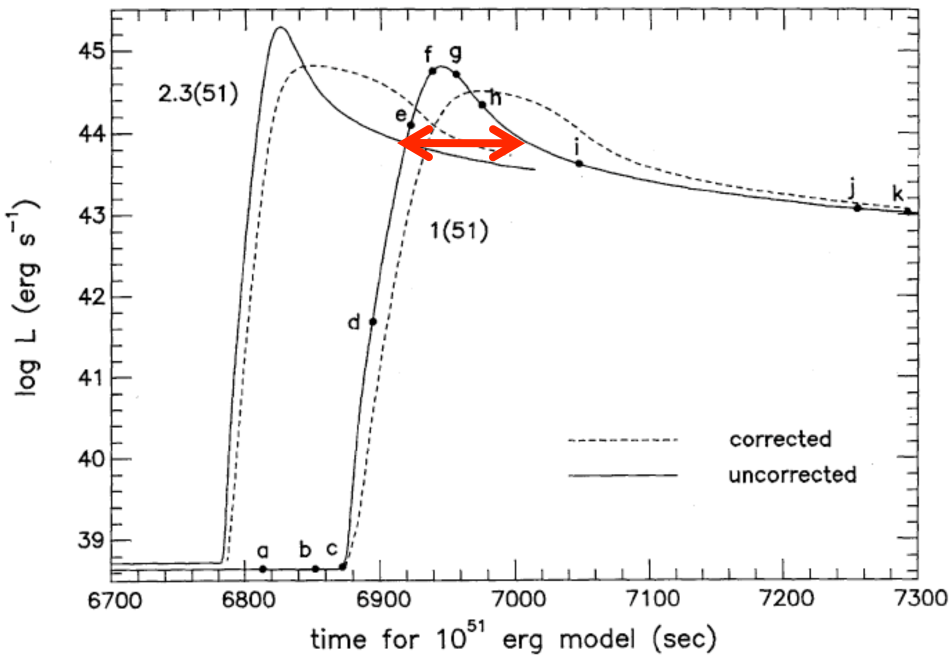
- Optically-thick radiation-mediated shock, photons trapped inside the star
- Radiation precursor starts leaking from the stellar surface: breakout starts
- Peak of breakout radiation, photons leaking out damp the shock

SB light curves

RSG



BSG



(Ensman & Burrows 2002)

(Klein & Chevalier 1978)

- Overall structure of light curve very similar, but different duration (Δt~2000 s for RSG vs Δt~100 s for BSG) : information on $R_\star$?

From SB to SN progenitors (1/3)

SB properties determined by the structure of the stellar envelope

Assumptions:

- If the shock flow before breakout is adiabatic, radiation-dominated and non-gravitating, the only scales are the explosion energy (E_{in}), ejected mass (M_{ej}) and initial stellar radius ($R_\star$)

- Mass density profile in the outer envelope is a polytrope:

$$\rho(r) = \rho_1 \left(\frac{R_\star - r}{r} \right)^n$$

  - RSG: convective envelope (n=3/2)
  - BSG: radiative envelope with constant opacity (n=3)

- SB when $\tau \simeq \tau_s$ ➔ v_s(SB) as a function of E_{in}, M_{ej}, $R_\star$

From SB to SN progenitors (2/3)

Results (Matzner & McKee 1999):

• Post-shock temperature T_{se} (~SB temperature?), assuming post-shock region is radiation-dominated:

$$T_{se} = 5.55 \times 10^5 \mathrm{K} \quad \left(n = \frac{3}{2}\right)$$
RSG

↑

$$T_{se} = 1.31 \times 10^6 \mathrm{K} \quad (n = 3)$$
BSG

• Breakout energy E_{se} (~SB energy?), i.e., all thermal energy in shock front at breakout:

$$E_{se} = 1.7 \times 10^{48} \mathrm{ergs} \quad \left(n = \frac{3}{2}\right)$$
RSG

↓

$$E_{se} = 7.6 \times 10^{46} \mathrm{ergs} \quad (n = 3)$$
BSG

• Photon diffusion time across the shock (~SB duration?):

$$t_{se} = 790 \mathrm{s} \quad \left(n = \frac{3}{2}\right)$$
RSG

↓

$$t_{se} = 40 \mathrm{~s} \quad (n = 3)$$
BSG

From SB to SN progenitors (3/3)

Parameter	RSG T_{se}	RSG E_{se}	RSG t_{se}	BSG T_{se}	BSG E_{se}	BSG t_{se}
10	6.28	46.49	0.74	6.12	46.88	1.60
$f\kappa/0.34\ \mathrm{cm^2\ g^{-1}}$	−0.10	−0.87	−0.58	−0.14	−0.84	−0.45
$\rho_1/\rho_\star$	0.070	−0.086	−0.28	0.046	−0.054	−0.18
$E_{in}/10^{51}$ erg	0.20	0.56	−0.79	0.18	0.58	−0.72
$M_{ej}/10\ M_\odot$	−0.052	−0.44	0.21	−0.068	−0.42	0.27
$R_\star/50\ R_\odot$	−0.54	1.74	2.16	−0.48	1.68	1.90

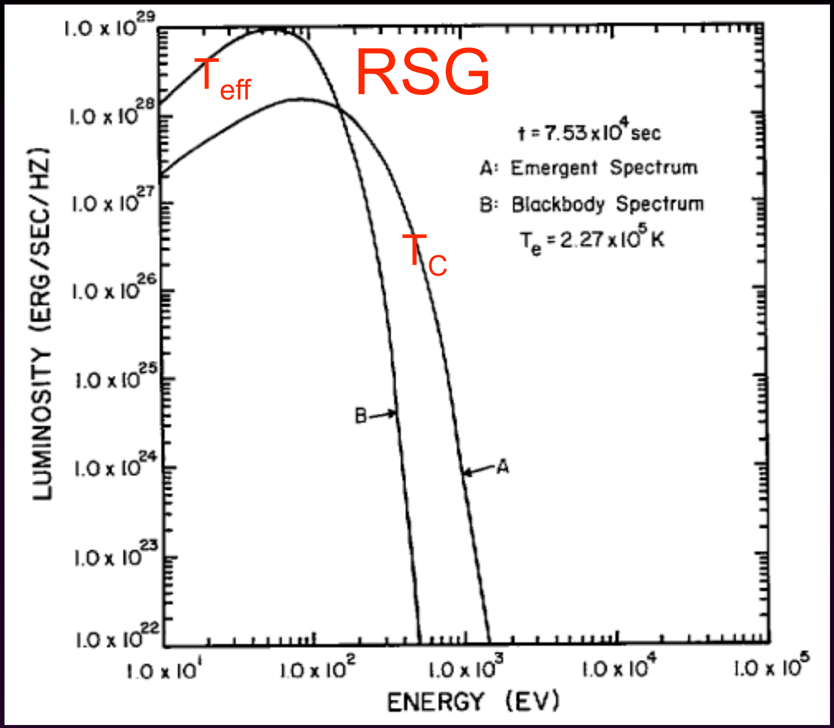
(Calzavara & Matzner 2004)

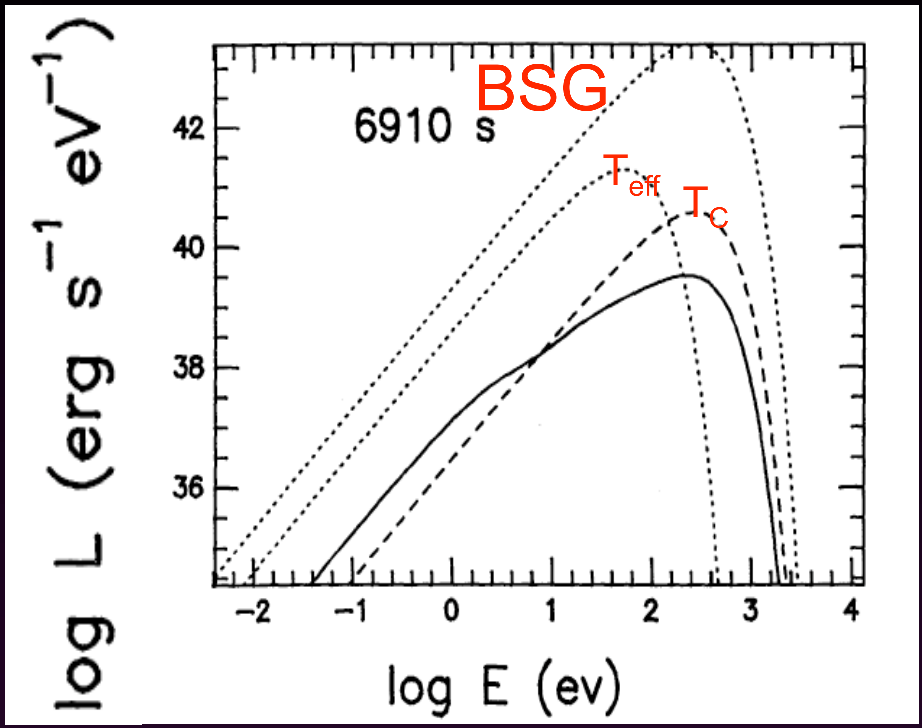
- Strongest dependence on $R_\star$
- Can we determine the SN progenitor properties? Caveats…

Caveat 1: SB spectrum is BB?

(Klein & Chevalier 1978)

(Ensman & Burrows 2002)

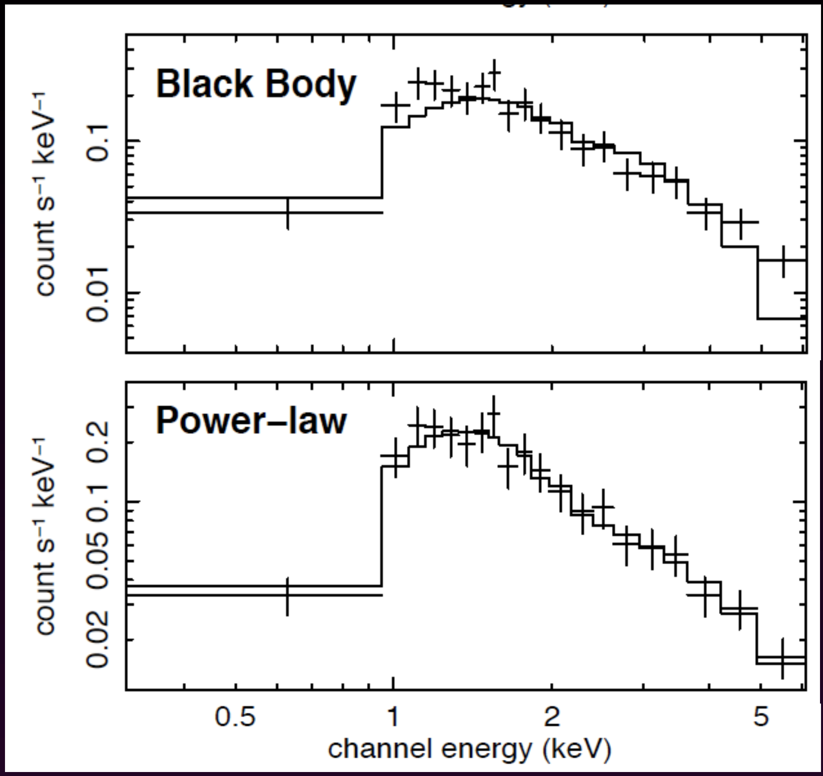




- SB spectrum is NOT BB, but dilute BB with T_C~2-3 T_{eff}
- Scattering-dominated atmosphere: photons retain the color at thermalization depth, but their energy density is diluted as they scatter towards the surface
- $h\nu_{peak}$~10-100 eV for RSG vs $h\nu_{peak}$~0.1-1 keV for BSG

Caveat 2: is SB spectrum always thermal?

SN 2008D



(Soderberg et al. 2008)

• Thermal fit is poor, and gives estimate for $R_\star$ not consistent with SB duration or candidate progenitor

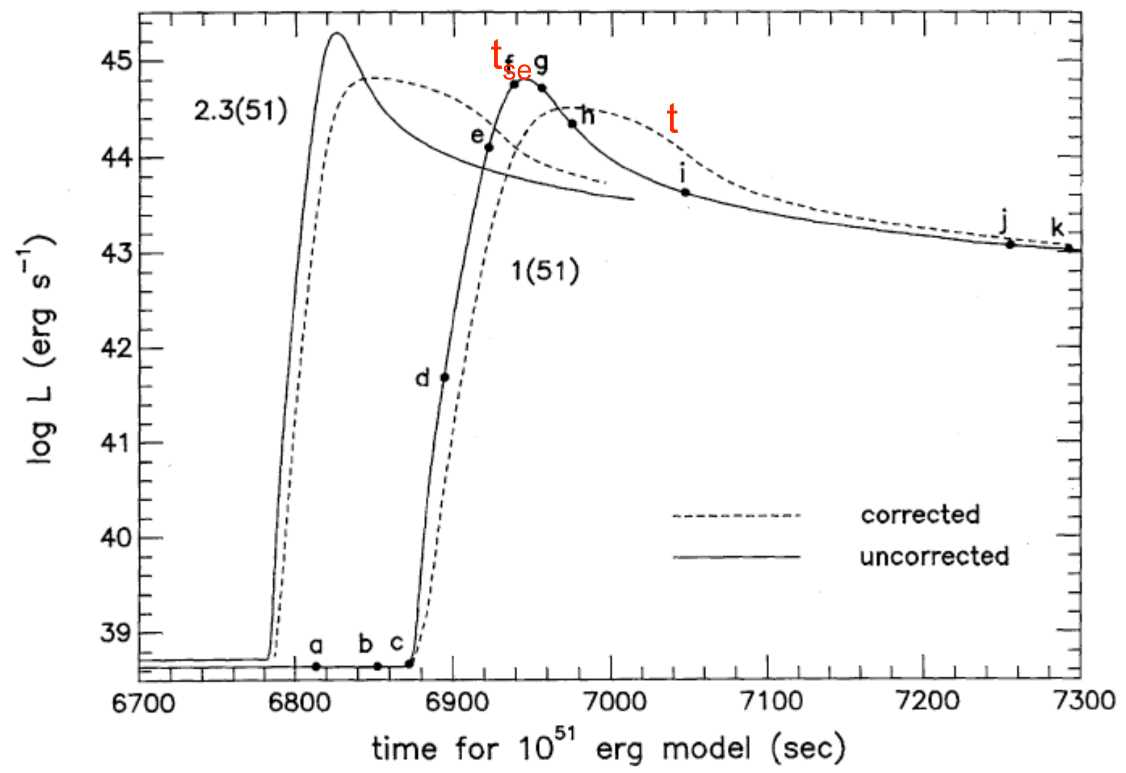
Solutions?

• Non-thermal emission by Fermi (Compton) scattering of SB photons (Wang 2007)

• For v_s>0.1 c, shock photons in Compton equilibrium with pairs at high T (Katz 2009)

Caveat 3: SB duration? (1/2)

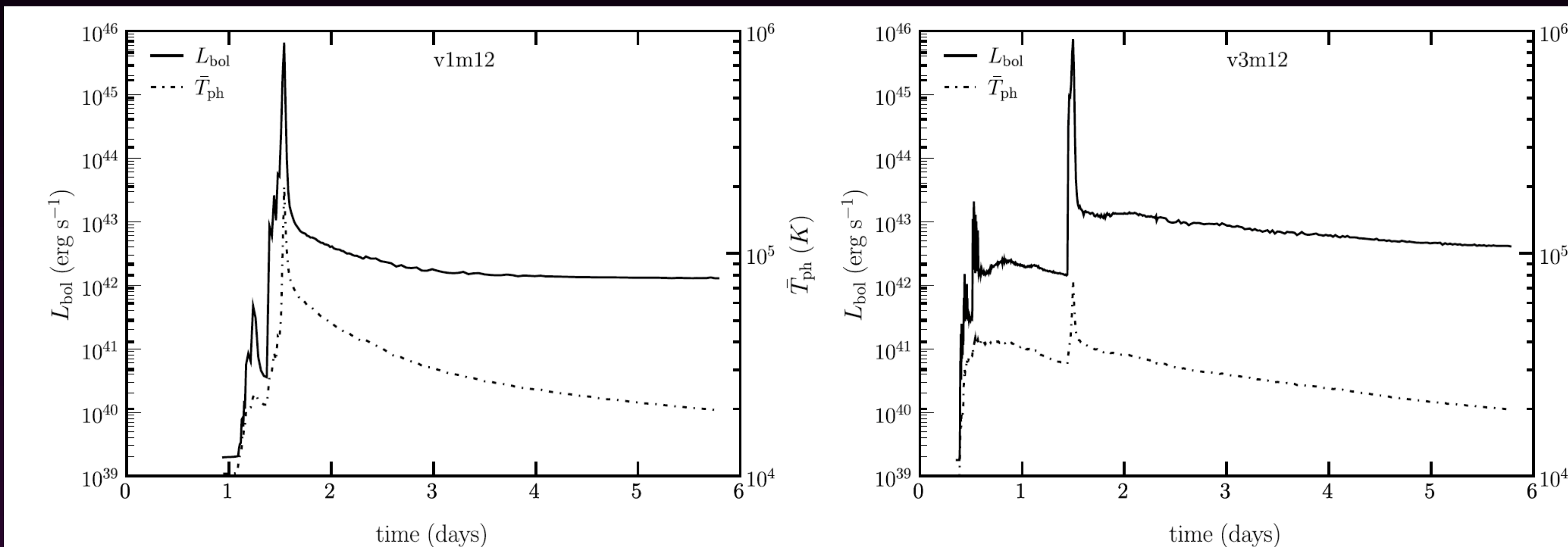
- Is SB duration set only by photon diffusion across the shock front? $t_{\rm se} \sim \Delta_s / v_s$
- What about light-travel time between center and limb of stellar disk? $t_{\rm c} \simeq \frac{R_\star}{c}$
- Observed duration should be larger, $t \simeq \left(t_{\rm se}^2 + t_{\rm c}^2\right)^{1/2}$
- …



(Ensman & Burrows 2002)

Caveat 3: SB duration? (2/2)

- Limb darkening
- Asphericity of the explosion can dramatically change the light curve!



(Couch et al. 2009)

- On the other hand, light curve can constrain asphericity

A gedankenexperiment

- Unknowns: E_{in} , M_{ej} , $R_\star$, D (distance) , N_H (obscuring column)
- Observables:

  counts C_1(0.10-0.33 keV), C_2(0.33-0.54 keV), C_3(0.54-3.5 keV)

  t (duration)

  (+ D from optical follow-up)

- C_1, C_2, C_3 are affected by interstellar absorption (bluening)
- Assuming dilute BB spectrum, spherical explosion, no limb darkening effects

Constraints from timing alone

- RSG: critical stellar radius in the transition between diffusion limited ($t \sim t_{se}$) and light-travel time limited ($t \sim t_c$) flash duration:

$$R_{\star TZ} = 697 \quad R_\odot \qquad t_{TZ} = 27.0 \quad \text{min}$$

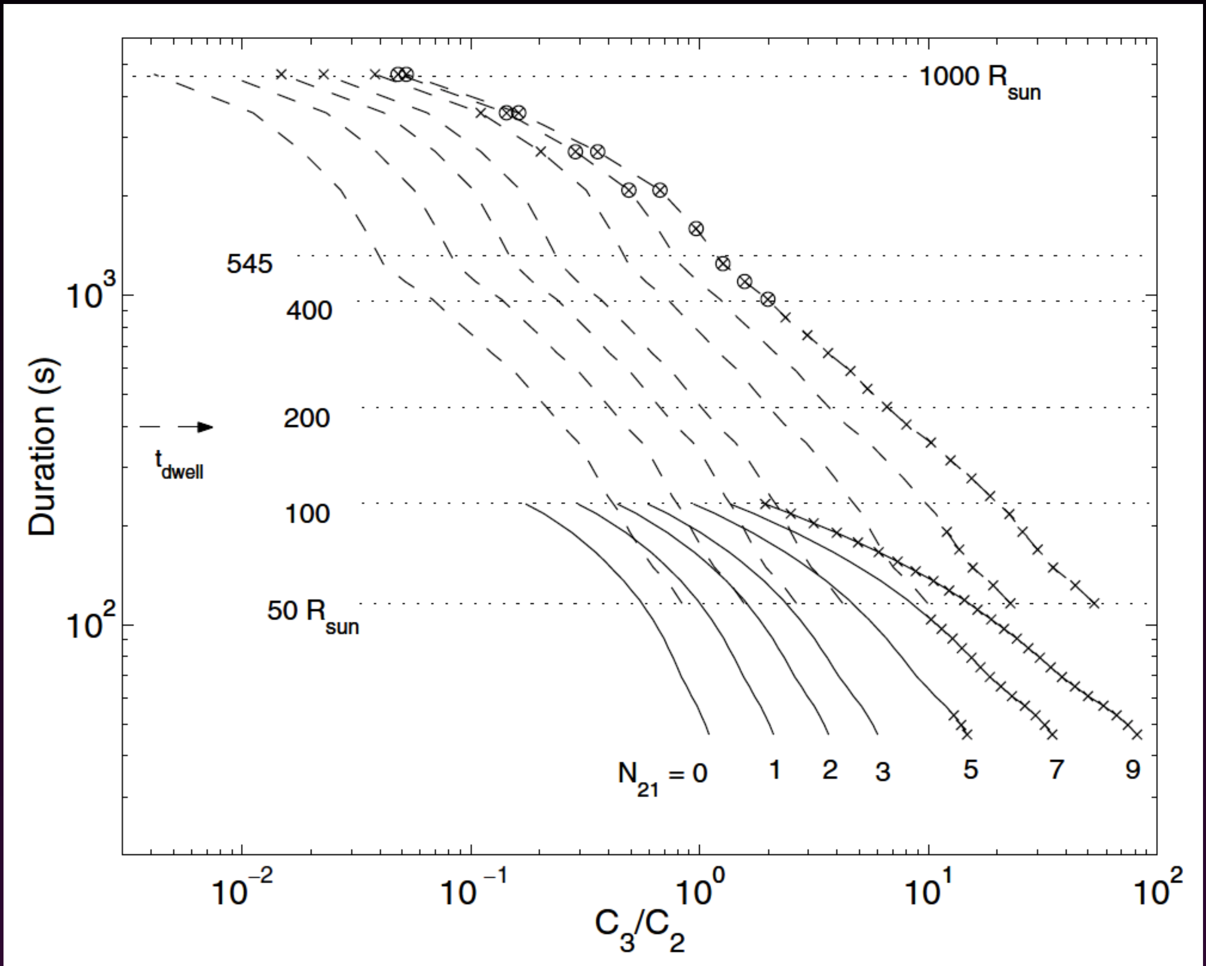
- BSG: $t \sim t_c$ always

t (s)	Progenitor type	$R_\star$
0–116	BSG	ct
116–230	need colour info	ct
230–1100	RSG	ct
1100–2080	RSG	near TZ
>2080	RSG	can constrain using t_{se}

(Calzavara & Matzner 2004)

Constraints from timing and color

- Larger progenitors (RSG) produce redder flashes



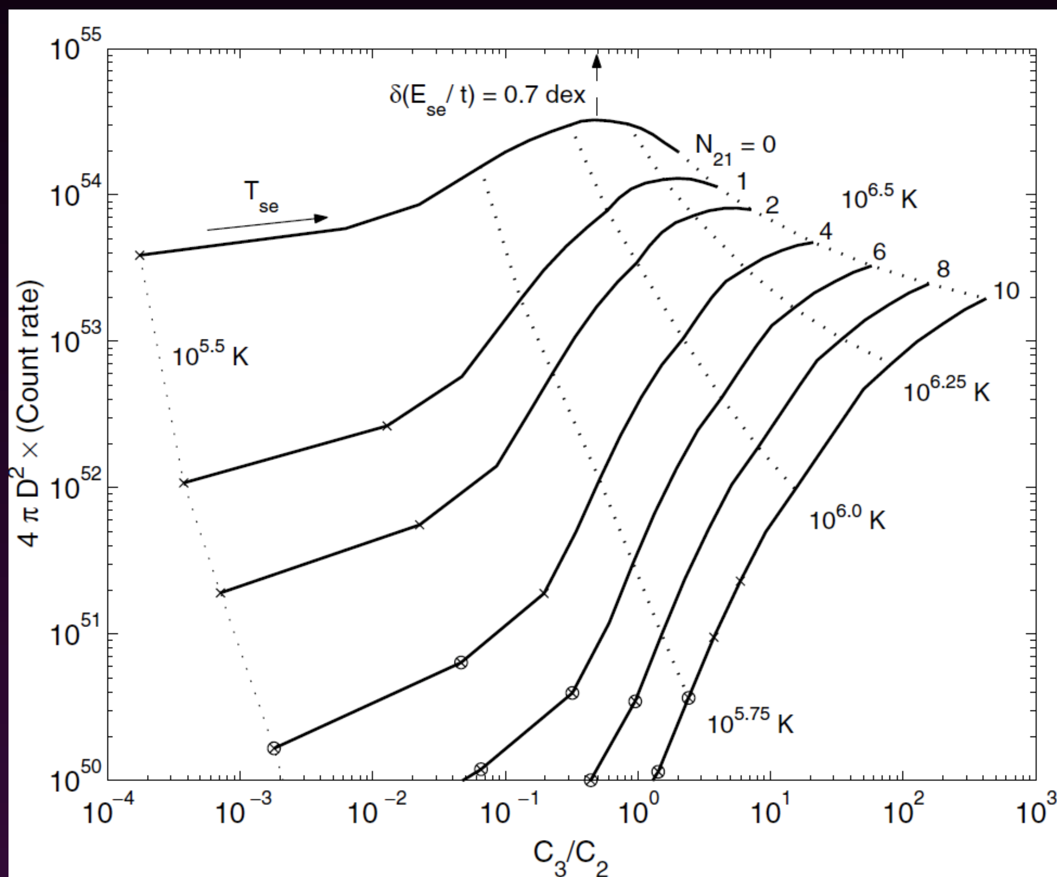
(Calzavara & Matzner 2004)

progenitor degeneracy for t~100-200 s can only be broken if N_H known

Constraints from luminosity and color

• Useful if duration cannot be determined (long flashes, RSG) and if D is given by optical follow-up

• X-ray HR diagram: RSG



(Calzavara & Matzner 2004)

Summary

- X-ray SB flashes can constrain the radius of the SN progenitor better than optical estimates (contaminated by radioactive decay, especially for small progenitors)

- But a lot of caveats…

- Where does the >1 keV emission in SN 2008D come from?

- Where does the SB happen in WR progenitors?

- More SB observations by UV telescopes (GALEX) or optical telescopes in the time domain (LSST, PTF) needed!