Supernova shock breakouts

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Early SN emission

- SN shock is radiation mediated at the envelope
- Outer ($10^{-3} M_{sun}$) heated to ~keV
- Shock emergence accompanied by thermal X-rays

[Colgate 74; Falk 78; Klein & Chevalier 78]

- Post breakout expansion → early UV emission

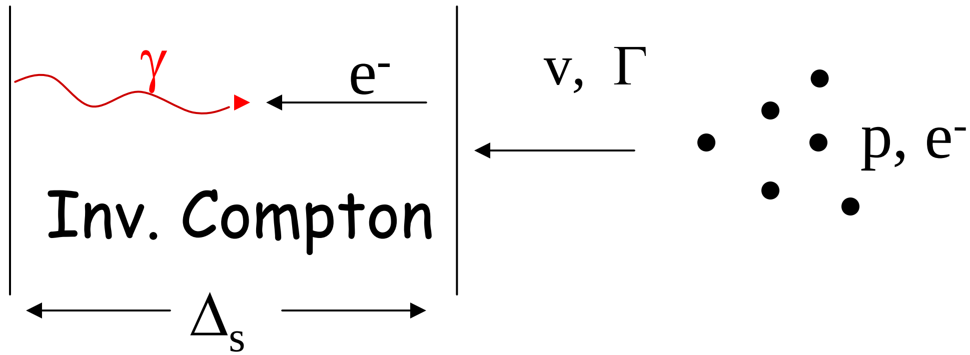
[Ensman & Burrows 92; Chevalier 92; Blinnikov et al. 00]

- Wind
  - Breakout may take place within the wind
  - Ejecta/wind interaction → non-thermal X, radio

Radiation mediated shocks: I

$$U_{\text{rad.}} >> U_{\text{part.}}$$

$$U_{\text{rad.}} \approx \Gamma^2 n m_p c^2$$



$$t_\gamma \approx \frac{\Delta_s}{\lambda_\gamma}\frac{\Delta_s}{c} \approx t_e \approx \frac{\Delta_s}{\text{v}} \Rightarrow \quad \frac{\Delta_s}{\lambda_\gamma} \approx \frac{c}{\text{v}}$$

- Radiation escapes when the shock reaches $\tau \sim c/\text{v}$,

$$\delta m \approx \frac{4\pi R^2}{\kappa}\tau \approx 10^{-8} R_{12}^2 \tau M_{\text{Sun}} .$$

- Optically thick wind,

$$\frac{\dot{M}}{v_w} \approx \frac{4\pi R}{\kappa}\tau \approx 5\dot{m}R_{12}\tau \; ; \quad \dot{m} \equiv 10^{-5}\frac{M_{\text{Sun}}/\text{yr}}{10^3\,\text{km/s}}.$$

Breakout X-rays: a simple model

- Envelope density $\rho \sim \delta^n$, $\delta = (1 - r/R)$
  (n=3, 3/2 for radiative, convective)

- Shock velocity (interpolating ST-Sakuri)

$$v_s \approx 0.8 \left(\frac{E}{M} \right)^{1/2} \delta^{-0.2n} .$$

[Matzner & McKee 99]

- Post-shock thermal energy

$$U_{rad} = (18/7) \rho v_s^2$$

Breakout X-rays: a simple model

- At $\tau = c/v_s$:

$$\beta_{\rm s,max} = {\rm v}_{\rm s,max}/c \approx 0.2 \frac{E_{51}^{0.6}}{(M/M_{\rm Sun})^{0.4}} R_{12}^{-0.3},$$

$$\beta_{\rm free} \approx 2\beta_{\rm s,max}$$

$$T_{\rm BO} \approx 0.2 \frac{E_{51}^{0.2}}{(M/M_{\rm Sun})^{0.05}} R_{12}^{-0.5} \ \ {\rm keV},$$

$$E_{\rm BO} \approx 2\times 10^{46} \frac{E_{51}^{0.6}}{(M/M_{\rm Sun})^{0.4}} R_{12}^{1.7} \ \ {\rm erg}.$$

[Matzner & McKee 99]

- Optically thick wind,
  mildly relativistic ($\Gamma\beta$~1) breakout:

$$T_{\rm BO} \approx 0.1 (\Gamma\beta)^3 R_{12}^{-1/4} \ \ {\rm keV},$$

$$E_{\rm BO} \approx 3\times 10^{46} (\Gamma\beta)^4 R_{12}^{2} \ \ {\rm erg}.$$

- E_X, T → R, v_s ;   Consistency: Δt~R/c.

[Waxman, Meszaros & Campana 07]

Ejecta/Wind interaction

- Deceleration:

$$t_{\rm dec} \approx 10 \frac{E_{k,47}}{\beta^3 \dot{m}} \, \text{min}, \quad \frac{\dot{M}}{\text{v}_w} = \dot{m} \frac{10^{-5} M_{\rm Sun} / \text{yr}}{10^3 \, \text{km/s}}.$$

- Collisionless shock L:

$$(\nu L_\nu)_{\rm synch.} \approx \frac{\varepsilon_e E_k / t}{2\Lambda} \approx 10^{40} \frac{\varepsilon_{e,-1} E_{k,47}}{t_{\rm day}} \frac{\text{erg}}{\text{s}},$$

$$\Lambda \equiv \log(\gamma_{e,\max} / \gamma_{e,\min}).$$

- IC of SN light:

$$R_s \approx 0.7 \left(\frac{E_k}{\dot{M} / 4\pi \text{v}_{\rm w}} t^2 \right)^{1/3}, \quad h\nu_{IC,T} \approx 1 \, \varepsilon^2_{e,-1} \left(\frac{E_{k,47}}{\dot{m} t_{\rm day}} \right)^{4/3} \text{keV}$$

$$(\nu L_\nu)_{\rm IC,T} \approx \min \left[10^{40} \varepsilon^2_{e,-1} \frac{E_{k,47} L_{SN,42}}{t^{2/3}_{\rm day}} \frac{\text{erg}}{\text{s}}, (\nu L_\nu)_{\rm syn} \right].$$

[Waxman, Meszaros & Campana 07]

XRO 080109-SN 2008D

- XRO: $E_X \sim 3\times10^{46}$erg, $R \sim c\Delta t \sim 10^{12}$cm ($\rightarrow \Gamma\beta \sim 1$)
  $R_* \sim 10^{11}$cm → Wind
  Wind transparency: $m_{dot} \sim$few (@ 10^{12}cm).

- Wind/Ejecta interaction vs. observed X-ray, radio:
  Late non-thermal X ($L_X \sim 10^{40} t_d^{-0.7}$erg/s)
  + non-thermal radio
  Consistent with
  $m_{dot} \sim 1$ (@ 10^{15}cm) wind + 10^{47}erg, $\beta \sim 0.3$ shell

- T=0.1keV? No! Non-thermal, $d\log n_\gamma / d\log E_\gamma \sim -2$

[Soderberg et al. 08]

SN 2008D: X-ray outburst spectrum

- T=0.1keV? No! Non-thermal, $d\log n_\gamma / d\log E_\gamma \sim -2$

[Soderberg et al. 08]

- What is the origin of the non-thermal emission?

  -- Let's pretend it's thermal

[Chevalier & Fransson 08]

  -- Breakout ruled out. Must be a Relativistic Jet

[Mazzali et al. 08, Li 08]

  However: VLBI (30d) → $v/c<0.6$

[Bietenholz, Soderberg & Bartel 08]

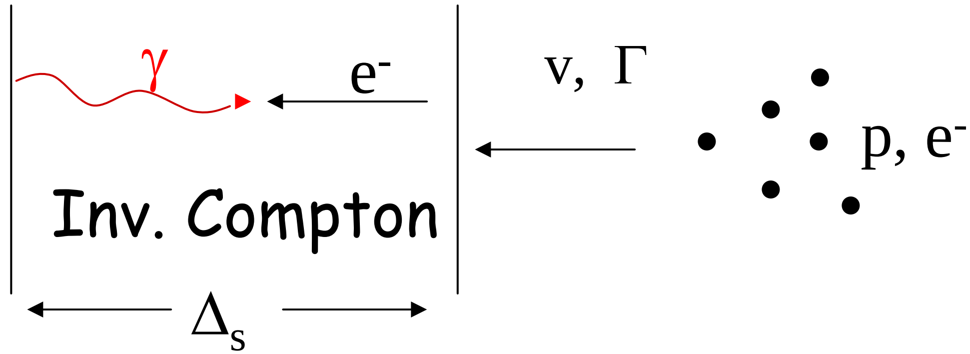
  -- Shock breakout physics?

[Campana et al. 06; Waxman, Meszaros & Campana 07; Wang et al. 07; Soderberg et al. 08]

Radiation mediated shocks: II

$$U_{\text{rad.}} >> U_{\text{part.}}$$

$$U_{\text{rad.}} \approx \Gamma^2 n m_p c^2$$



- Relativistic shock challenges

  Δ_s/λ_γ~c/v~1, $\Delta E_\gamma/E_\gamma$>=1 → Transport (not diffusion)

  Relativistic processes ($\gamma\gamma \to e^+e^-$, $\gamma e \to e\gamma\gamma$, $\gamma e \to ee^+e^-$ …)

  → Solutions (Weaver 76) exist only for NR shocks

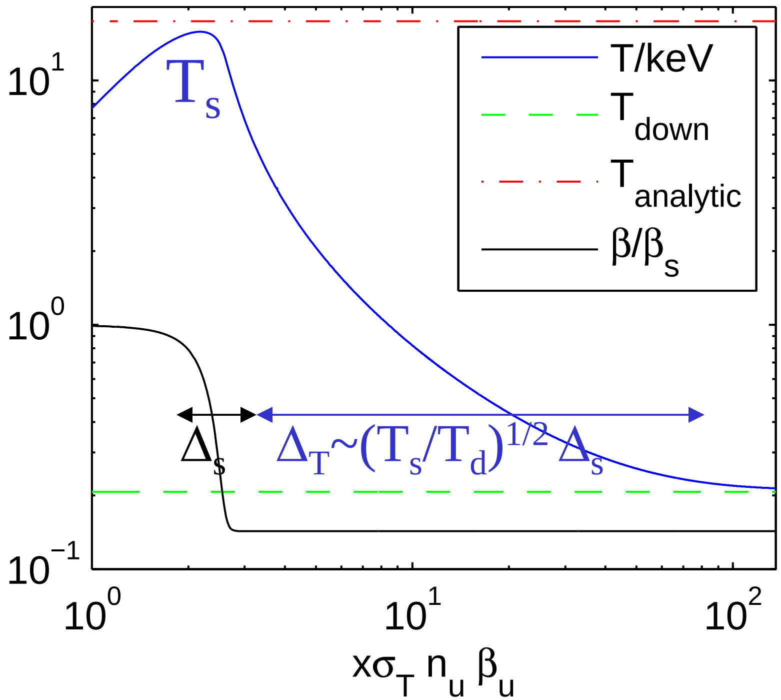
- $T_{e,tran} >> T_{down}$ → $T_{e,tran} \sim m_e c^2$ @ v/c~0.2

  → Existing solutions not valid for fast breakouts

Radiation mediated shocks: III

[Katz, Budnik & Waxman 09]

$v_s/c=0.25$, $n_u=10^{15}/cm^3$



$n_{\gamma s}$:Production/Diffusion

$$n_{\gamma,s} \approx Q_{Bremm.}(T_s, n_d)t_{Diff} \approx Q_{Bremm.}(T_s, n_d)\frac{1}{3n_d\sigma_T\beta_d^2 c}$$

$$Q_{Brem.} = \alpha\, n^2\sigma_T c\sqrt{\frac{m_e c^2}{T}}g_{ff}\Lambda$$

$$\Lambda \approx \log\left[\frac{T}{h\nu_a\left(@\ N_{coll.} = m_e c^2/4T\right)}\right]$$

T_s<50keV: $n_{\gamma s}T_s=U_{rad}$

→ $\beta_s=0.2\ (T_s/10keV)^{1/8}$

T_s independent of n_u

$T_s \gg T_d=0.2keV\ (\beta_s/0.2)^{1/2}(n_u/10^{15}cm^{-3})^{1/4}$

- Highly relativistic limit $\beta_d \rightarrow 1/3$:
  pair eq. (at $T<\sim m_e c^2$)

$$\frac{n_{\gamma,s}}{n_{\pm,s}} \approx \frac{m_e c^2}{2T}$$

  production/diffusion

$$\frac{n_{\gamma,s}}{n_{\pm,s}} \approx 2.5\left(\frac{\Lambda}{15}\right)^2\left(\frac{\beta_d}{1/3}\right)^{-2}$$

$\rightarrow$ $T_s<200$keV

- Thermalization tail: Production (no Diffusion)

$$\Delta_T \approx \beta c \frac{n_\gamma(T_d)}{Q_{Bremm.}(T_d, n_d)}$$

$$Q_{Brem.} = \alpha\, n_d^2 \sigma_T c \sqrt{\frac{m_e c^2}{T_d}}\, g_{ff} \Lambda$$

$$\Lambda \approx \log\left[\frac{T}{h\nu_a\left(@\, 4T/m_e c^2 \text{ coll.}\right)}\right]$$

Some implications

- XRO 080109 may be SN 2008D breakout

- For reasonable explosion parameters, WR & BSG progenitors produce fast breakouts → non-thermal XRO's up to 10's to 100's keV

[Katz, Budnik & Waxman 09]

Open issues

- At breakout shock-width~"scale height"
  Steady shock solution not strictly valid

- Transition to a collisional/collisionless shock
  → modifies electron spectrum

Collisional or Collisionless?

- If a transition occurs

  Radiation mediated → Collisionless (not collisional)

- For RSG- collisional shock structure would be

$$\Delta_s \approx \mathrm{v}_s / \nu_{ii} \approx 3\times10^8 \rho_{-10}^{-1}\ \mathrm{cm},$$

$$T_i \approx 100\ \mathrm{keV}, \quad T_r \approx 30\mathrm{eV}, \quad T_e \approx \nu_{ie} T_i / \nu_{\mathrm{Compt.}} \approx 30\ \mathrm{keV}\ .$$

- Under these conditions, EM instabilities

$$\nu_{EM} \approx \left(0.1\frac{m_e}{m_p}\right)^{1/2} \frac{\mathrm{v}_s}{c}\nu_{pi} \approx 3\times10^6 \rho_{-10}^{1/2}\ \mathrm{s}^{-1}\ .$$

- If a collisionless shock forms: p acceleration + inelastic nuclear collisions →

  10^{45}erg, 1 hr flash of TeV ν's and 10 GeV γ's

[Waxman & Loeb 01]

GRB-SNe: 060218/SN2006aj

- Thermal, T=0.2keV, + non-thermal emission
  $E_T \sim E_{NT} \sim 10^{49}$ erg, $\Delta t \sim 10^{3.5}$s
  Long term X-rays: $L_X \sim 2\times10^{42} t_d^{-1}$ erg/s ($t>10^4$s)

[Campana et al. 06, Pian et al. 06, Mazzali et al. 06]

- Inverting T,E_{NT}(R,β):
  R~8×10^{12}cm, β~0.8 → m_{dot}~30
  Long term X:

$$t_{\rm dec} \approx 10^4 \frac{E_{k,49}}{\beta^3 \dot{m}/10}\,{\rm s}, \quad L_{IC,T} \approx 10^{42.5} \frac{E_{k,49} L_{SN,42}}{t_{\rm day}^{2/3}} \frac{\rm erg}{\rm s}.$$

- Challenges: R/c~$10^{2.5}$s -- Anisotropic breakout?
  Too low predicted radio emission

[Waxman, Meszaros & Campana 07]

- Jet models- explain radio, but not X (+UV)

[Soderberg et al. 2006, Fan et al. 07]

GRB-SNe: 080425/1998bw

- E_{NT}~10^{48} erg (ε_{cut}~200keV)

[Pian 00]

- Long term X-ray & Radio monitoring:
  Decelerating shell, E_K~$10^{49.5}$ erg, β~0.8, m_{dot}~0.1
  No GRB jet

[Kulkarni et al. 98, Loeb & Waxman 99; Li & Chevalier 99; Frail et al. 2001; Kouveliotou et al. 04; Waxman 04]

- E_K~$10^{49.5}$ erg, β~0.8 shell common to low-L SN-GRBs?

  Challenge:
  Shock envelope acceleration $E_K(\beta\sim0.8)/E_{K,tot}\sim10^{-6}$

[Tan, Matzner & McKee 01]

Low-L GRB/SN

- Can these be due to fast breakouts?

- Expectations:

-- Smooth light curve

-- cutoff <~200keV

-- No energetic relativistic jets

- Consistent with properties of

  980425/SN1998b, 031203/SN2003lw, 060218/SN2006aj

- Challenges:

  $E_K(\beta\sim0.8)/E_{K,tot}\sim10^{-2}$ [Anisotropy, Failed Jet?]

Early UV/Optical emission

- Rapid post-breakout expansion
  → Adiabatic cooling, photosphere penetration

- Predictions:

$$\delta m_{\rm photo.}/M \approx 10^{-2.5}\frac{E_{51}^{0.8}}{(M/M_{\rm Sun})^{1.6}}t_{\rm day}^{1.6},$$

$$T_{\rm eff.} \approx 1(\kappa\sigma_T/m_p)^{0.27}R_{12}^{1/4}t_{\rm day}^{-1/2}\ {\rm eV},$$

$$T_{\rm diff.\text{-}depth}/T_{\rm eff.} \sim 1.2--1.3$$

$$L_{\rm bol.} \sim 10^{42}(\kappa\sigma_T/m_p)^{-0.8}\frac{E_{51}^{0.9}}{(M/M_{\rm Sun})^{0.7}}R_{12}t_{\rm day}^{-1/3}\ {\rm erg/s}.$$

[Waxman, Meszaros & Campana 07
Rabinak & Waxman 09]

- Measure R (from T), E_K (@ $\delta m/M$~0.003)

SNIIp- GALEX early UV

[Gezari et al. 08, Schawinski et al. 08]

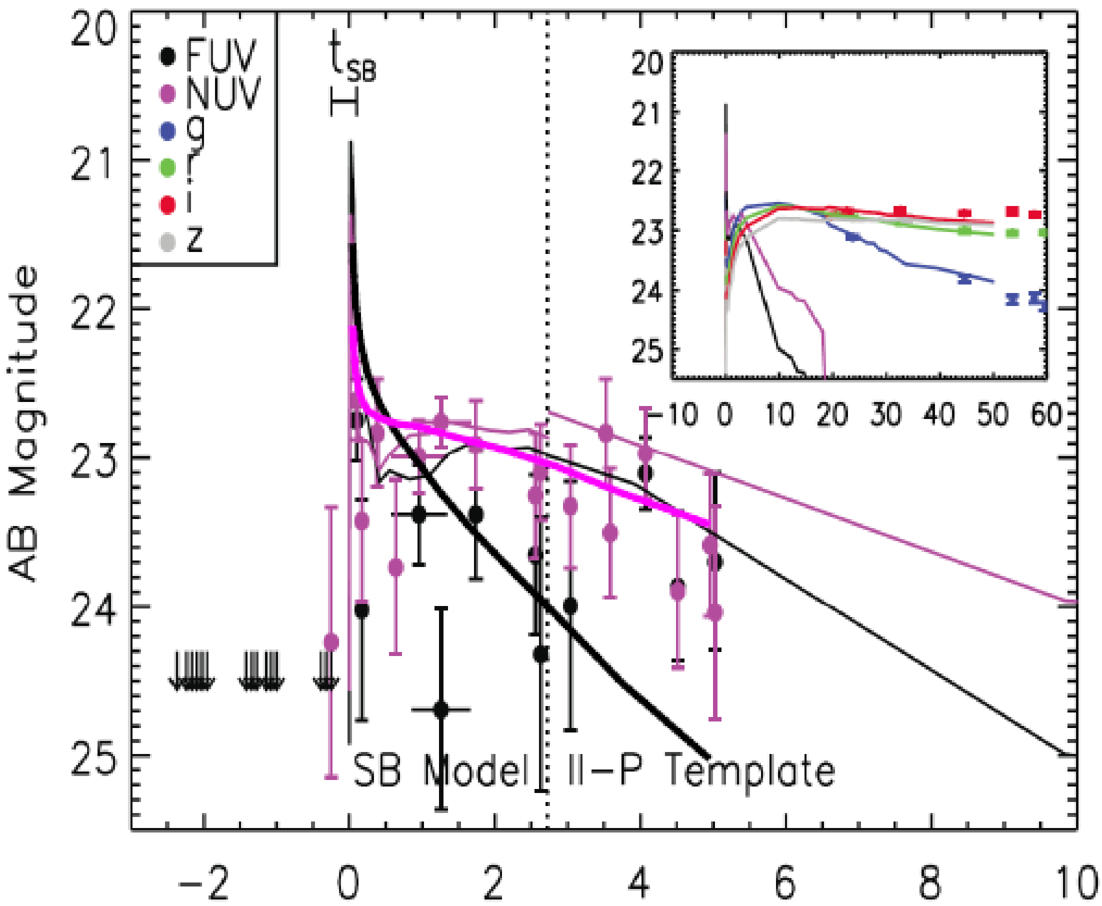
- $R=6\times10^{13}$cm
  $E=1.2\times10^{51}$erg
  $M=11M_{sun}M$

Solid: Rad-hydro numerics

[Gezari et al. 08]

Other: Simple model

[Rabinak & Waxman 09]



Open issues

- Simple model limited by simplified opacity (λ dependence)

- Smaller progenitors →
  Lower T (~1eV @ ~1d)
  Absence of H → modification of opacity
  (e.g. recombination)

Trans-relativistic SNe & CRs

- Origin of 10^{15}eV-10^{19}eV CRs unkown
  Likely Galactic (smooth steepening at 10^{15}eV)

- With pre-shock B amplification:
  $E_{CR}(Z\sim 10) < 10^{19}\beta_{-1}^{2}$ eV

- Normal SNe: $E_K(\Gamma\beta)\sim(\Gamma\beta)^{-4}$
  If the fast edge of normal SNe ejecta produce 10^{19}eV → Over-production at 10^{15}eV

- Trans-relativistic, $E_K(\Gamma\beta\sim 1)/E_{K,tot}\sim 10^{-2}$: Allow accleration to 10^{19}eV, no overproduction at 10^{15}eV, Rate consistent with observed flux

[Budnik, Katz & Waxman 08]

Summary

- Fast, v/c>0.1, breakouts are likely in WR/BSG progenitors
  Will produce non-thermal XRO's, up to 10's—100's keV
  XRO 080109/SN2008D- 1st (clean) example

* Open: Non-steady shock, collisional(less) transition

- Low-L, smooth light-curve, <~200keV SN-GRB/XRF/XRO
  Are all due to breakout, no energetic relativistic jet?
  $E_K \sim 10^{49.5}$ erg, $\beta \sim 0.8$ shells

* Open: For ordinary SNe $E_K(\beta \sim 0.8)/E_{K,tot} \sim 10^{-6}$

- Simple model for post-breakout UV/O
  Observations→ R_*; E/M @ $10^{-3}M_{sun}$ (XRO→ @ $10^{-7}M_{sun}$)
  1st detections: 2xIb/c (2006aj, 2008D); 2xIIp

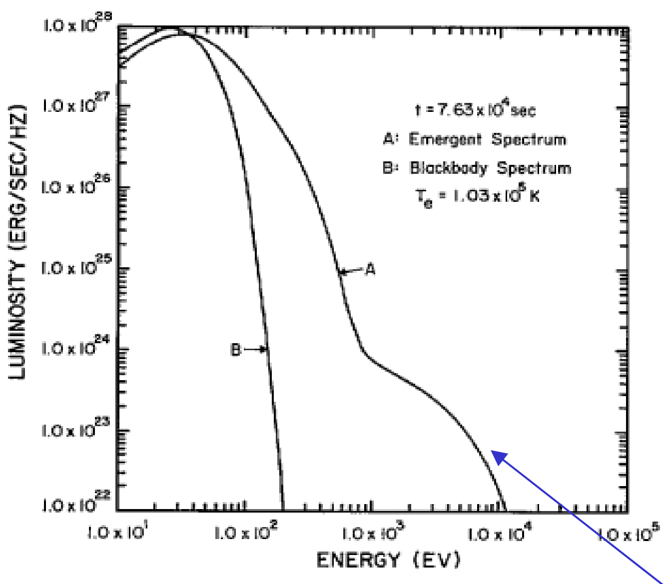
* Challenge & Opportunity: opacity → composition

* XRO SNe Triggering: Large sample, some o.w. undetected
  Constrain progenitor & environment

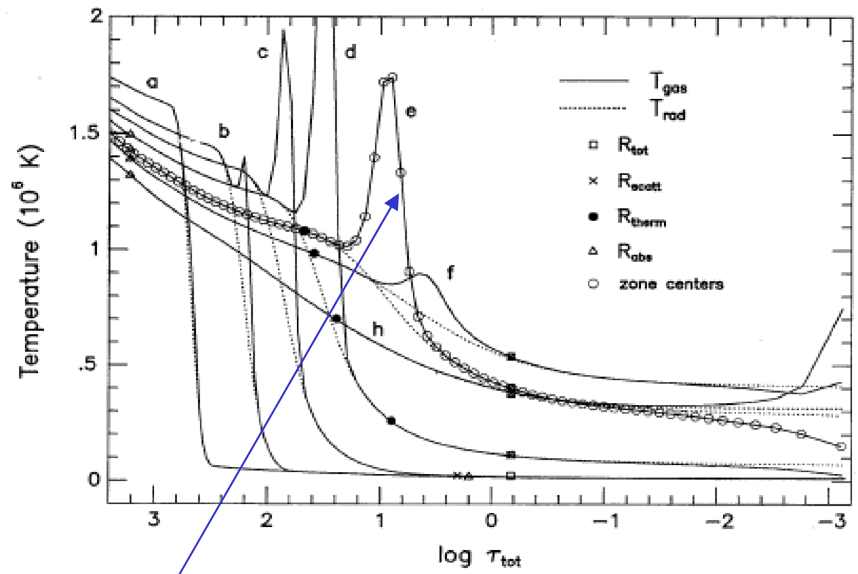
*XRO/UV timing: explosion models, GW & ν S/N enhancement

Transition to viscous shock?

- Viscous shock @ $\tau = c/v_s$ → $T_e \sim m_p v_s^2 \gg T_{rad}$



[Klein & Chevalier 78]



[Ensman & Burrows 92]

Purely numerical (viscosity, Compton cooling) effects

→ Caution required when inferring T_c from these simulations