Evidence for nonlinear diffusive shock acceleration of cosmic-rays in the 2006 outburst of RS Ophiuchi

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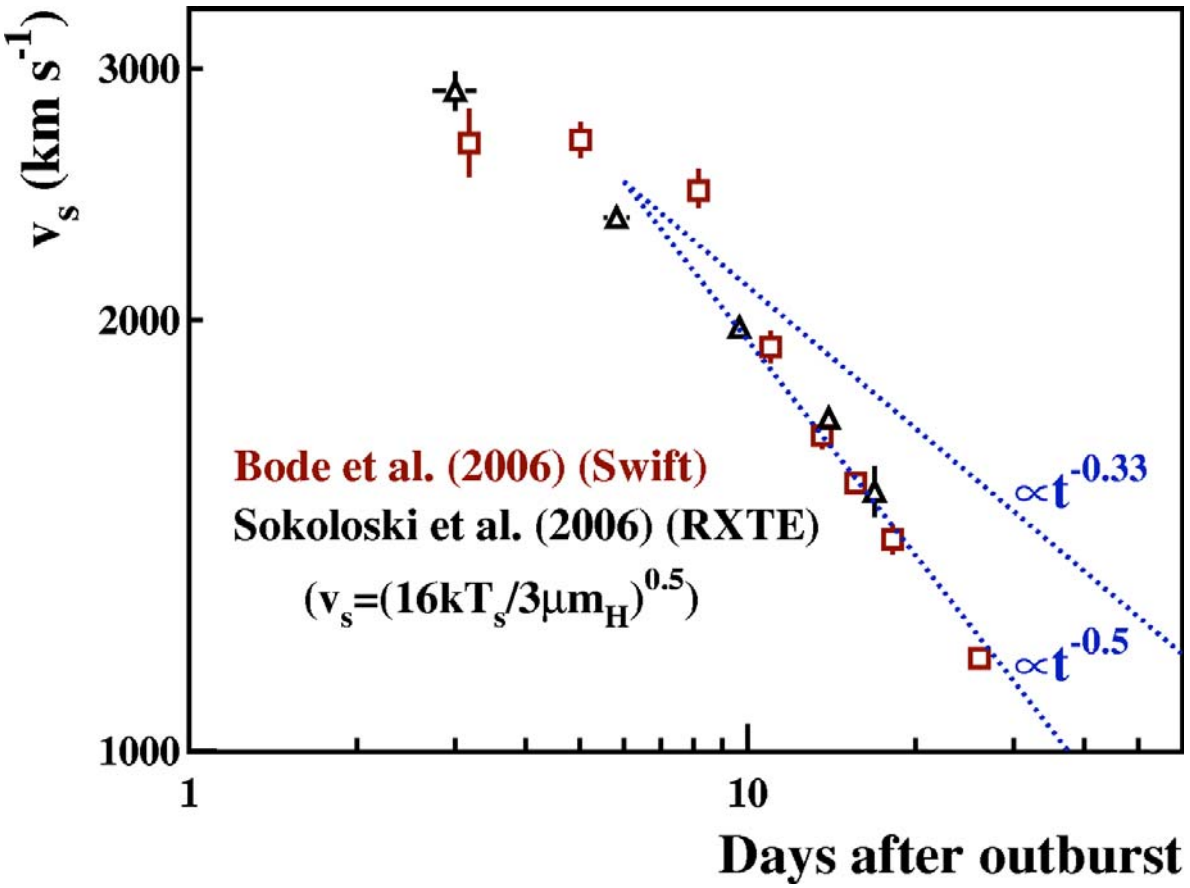
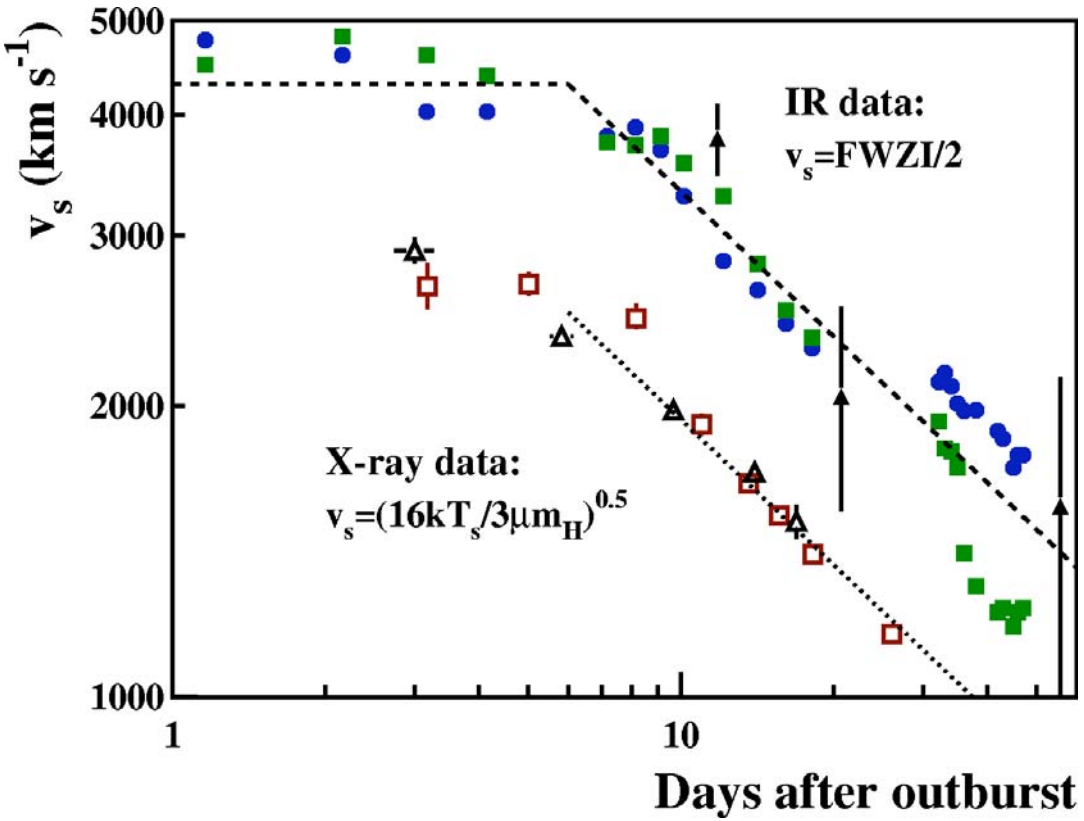
What's cooling the shock ?

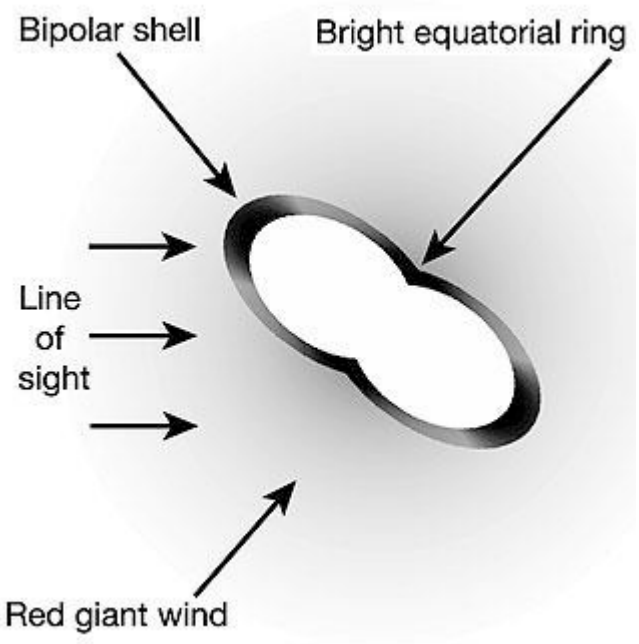


After ~6 days, the forward shock experienced significant cooling.

But T_s ~ 10^8 K at day 6 and radiative cooling was not important (?)

What makes the difference between the X-ray and IR measurements of shock velocities ?



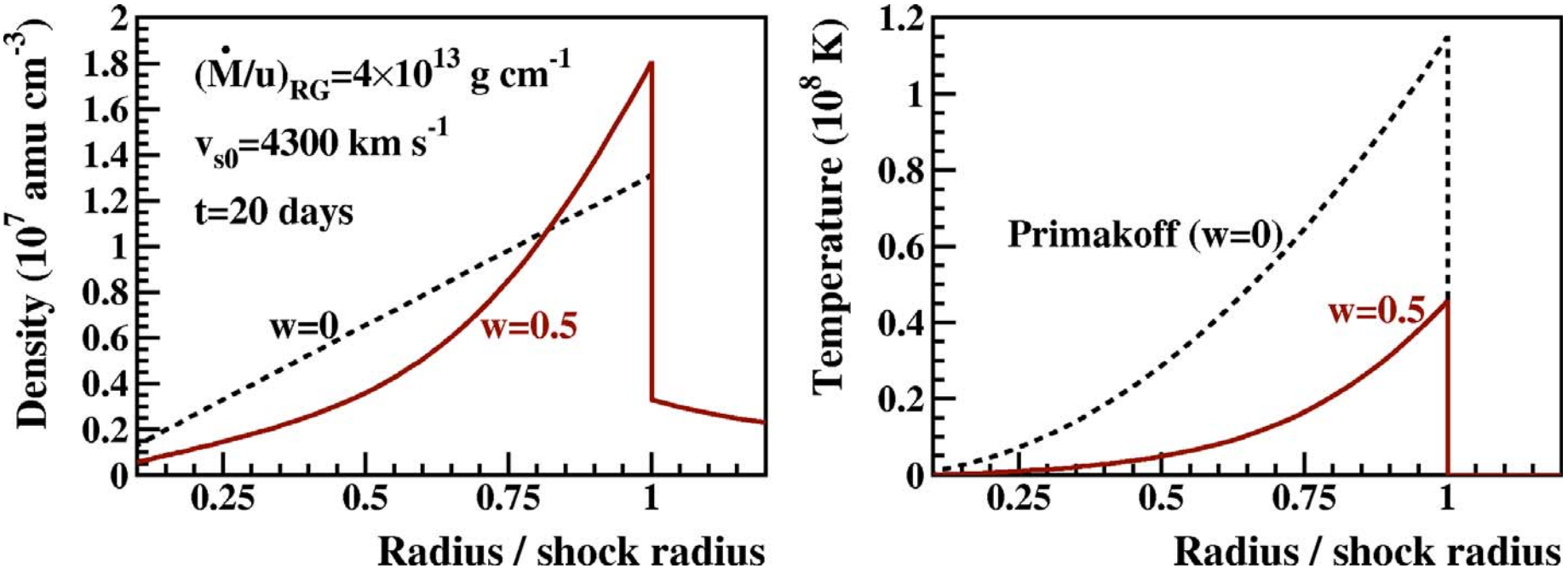


O'Brien et al. (2006)

FWZI of IR emission lines (Das et al. 2006; Evans et al. 2007)

⇒ largest blueshifted and redshifted velocities, which should be close to the mean expansion speed given θ_{sym} ~ 50-60°

Effects of cosmic-rays on the v_s-T_s relation



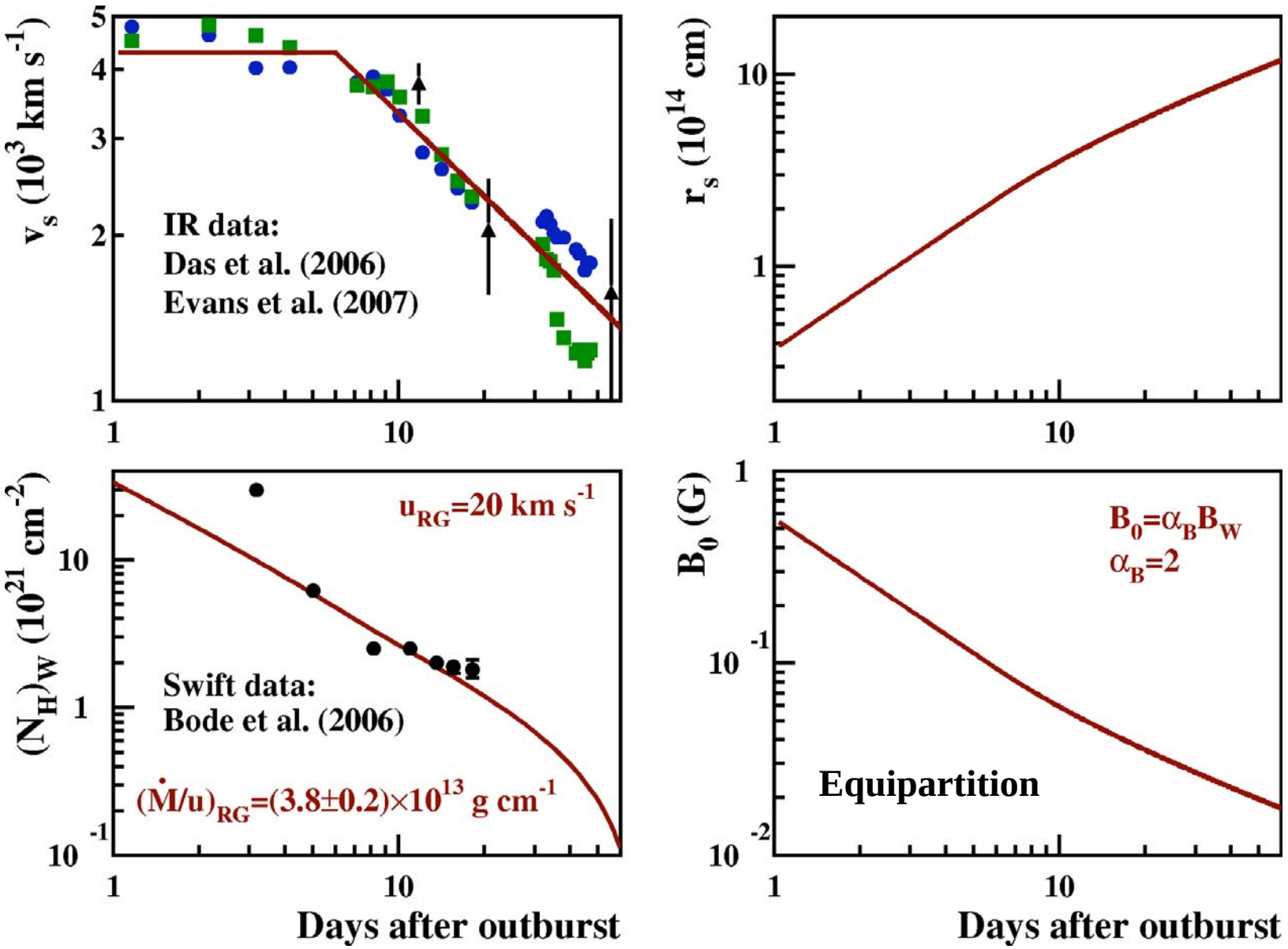
From the two-fluid, self-similar solutions of Chevalier (1983)

The well-known relation for a test-particle strong shock, $v_s = \sqrt{\frac{16}{3}\frac{kT_s}{\mu m_H}}$,

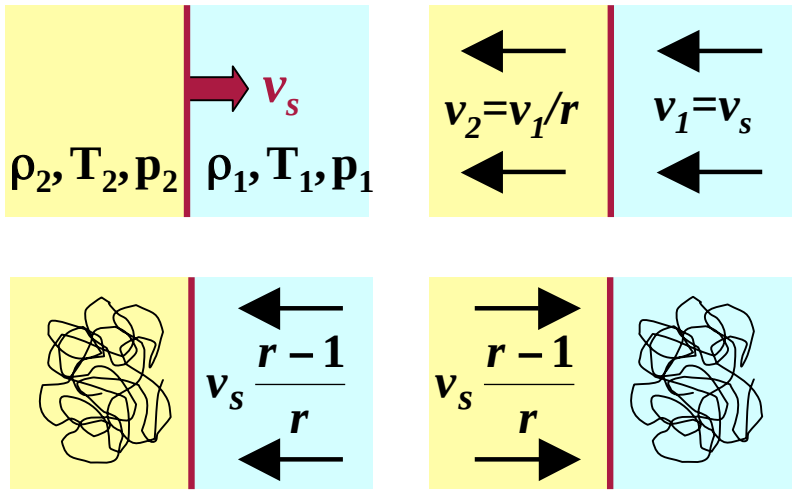
underestimates v_s when particle acceleration is efficient,

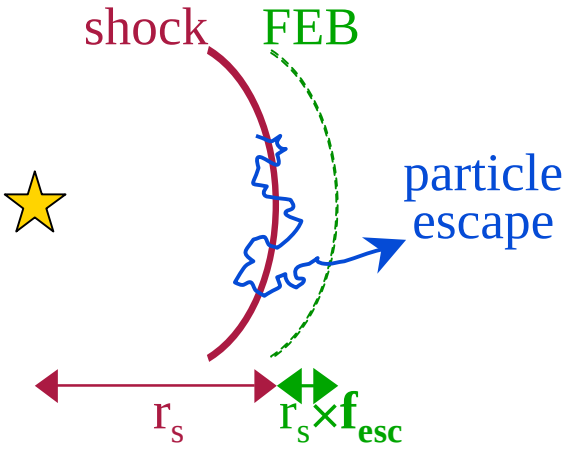
because T_s is lower (softer equation of state + particle escape)

Blast wave evolution



Shock-accelerated-particle maximum energy



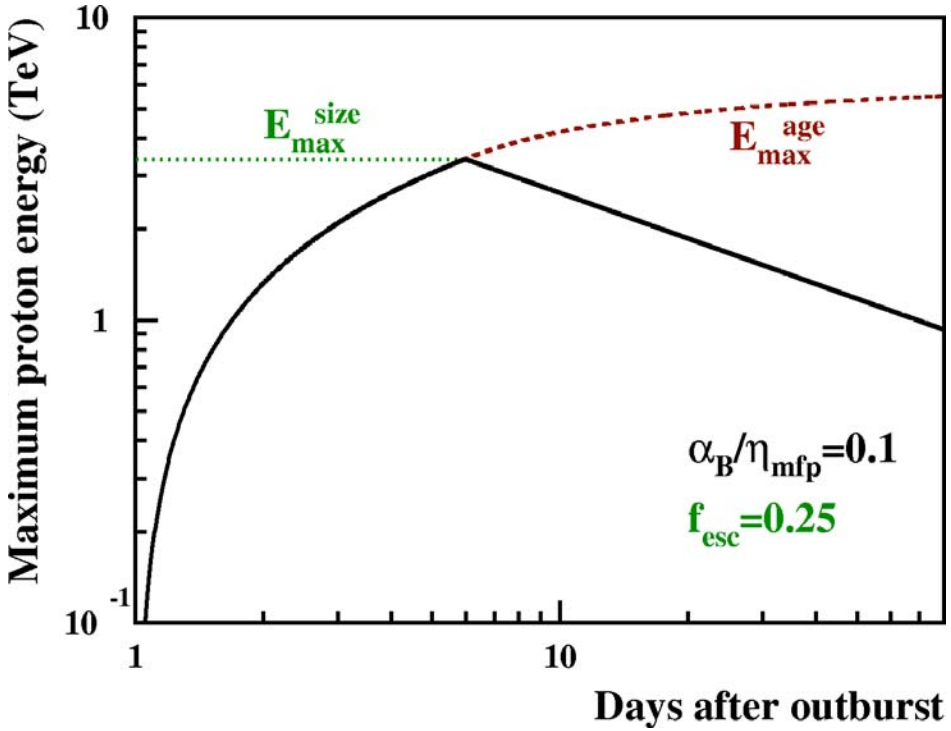


Acceleration rate:

$$\left(\frac{dp}{dt}\right)_{acc} = \frac{p}{3}\frac{r-1}{r}\frac{v_s^2}{\kappa_1(p)+r\kappa_2(p)}$$

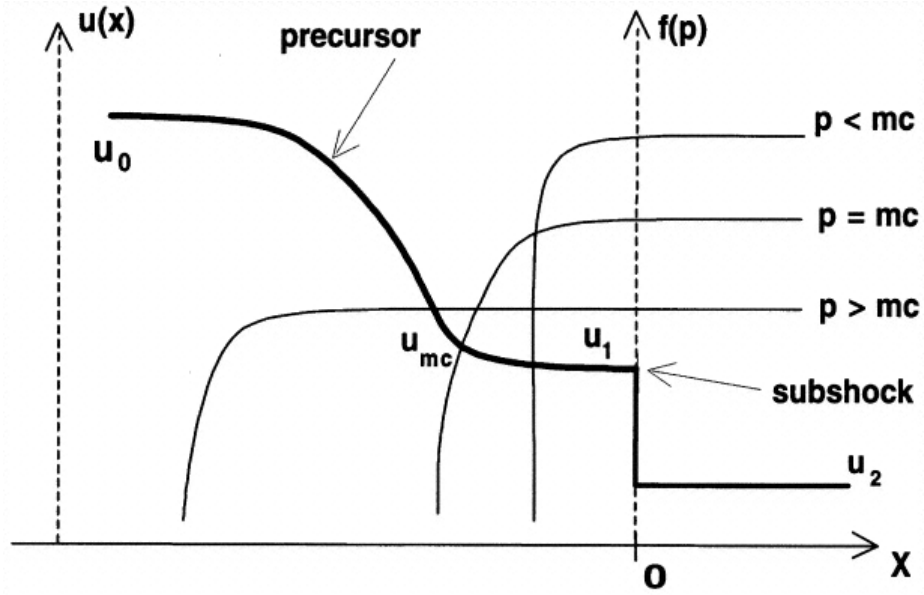
with $\kappa = \eta_{mfp} r_g v / 3$

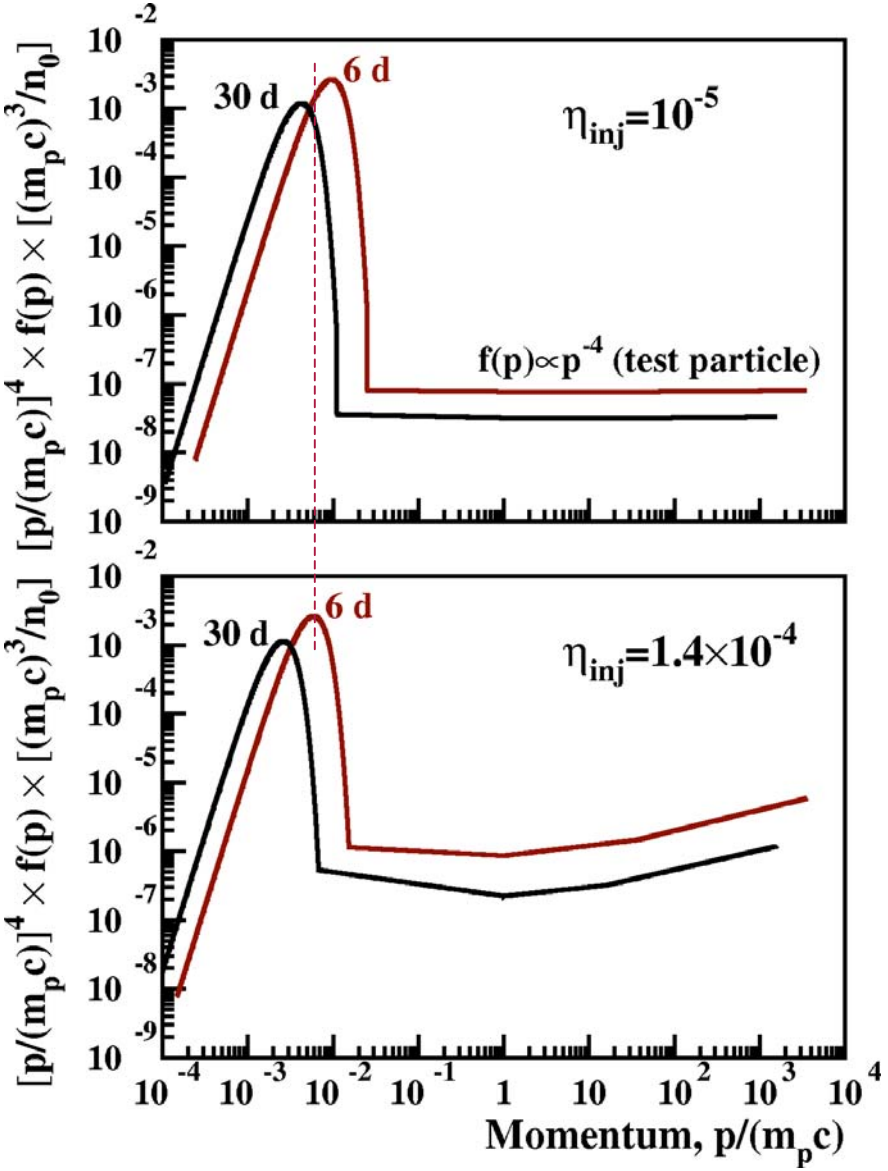
Limited by particle escape (free escape boundary; Baring et al. 1999)



Shock modification due to particle acceleration

Semi-analytic model of nonlinear diffusive shock acceleration (Berezhko & Ellison 1999) ⇒ accelerated proton spectrum + shock structure, as a function of η_{inj}: fraction of shocked protons injected into the acc. process





Properties of the cosmic-ray modified shock

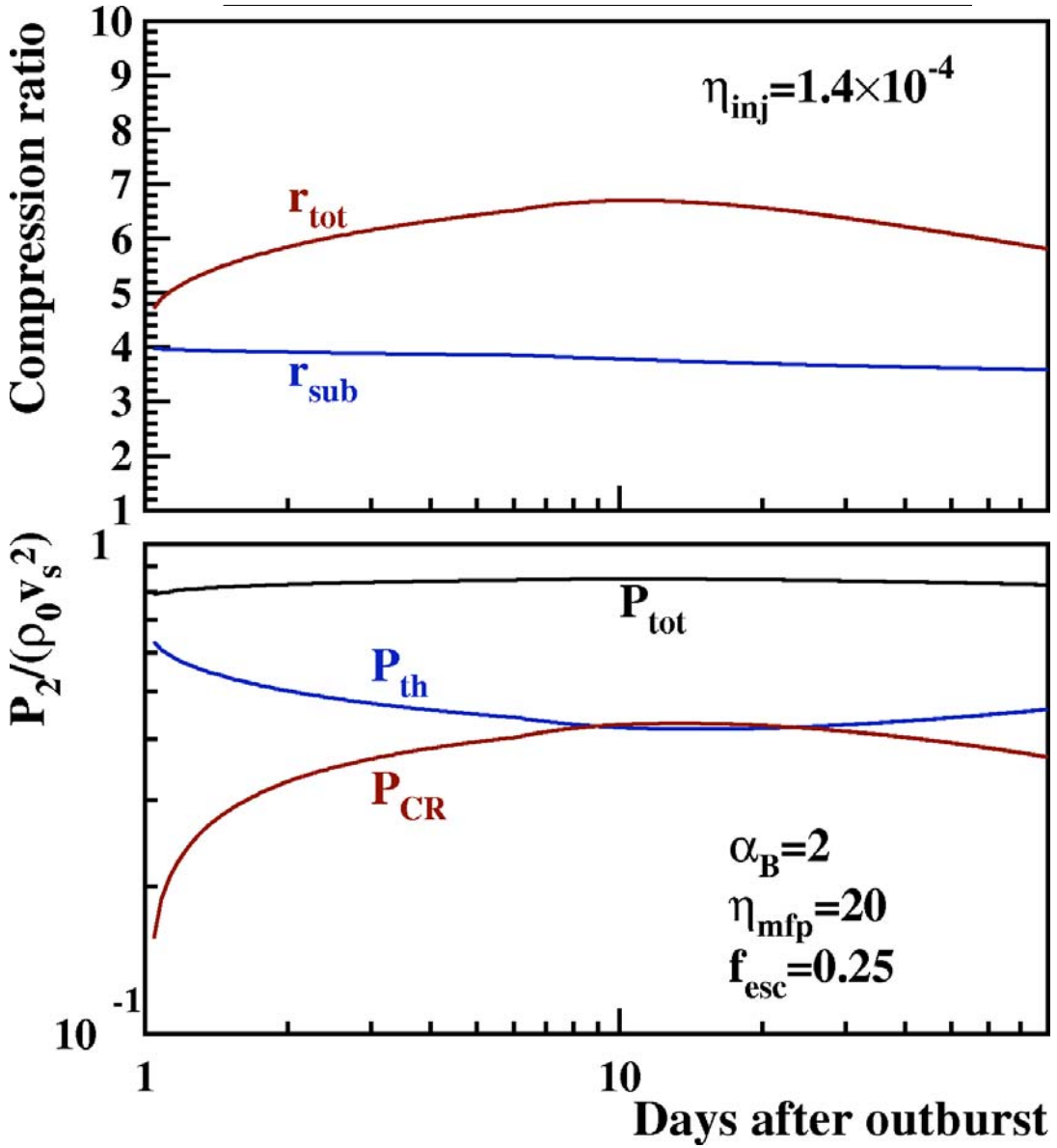
- Instant T_p–T_e equilibration

⇒ Good agreement with the *RXTE*/PCA and *Swift*/XRT measurements of T_s for $\eta_{inj} \gtrsim 10^{-4}$ and Alfvén wave heating of the precursor

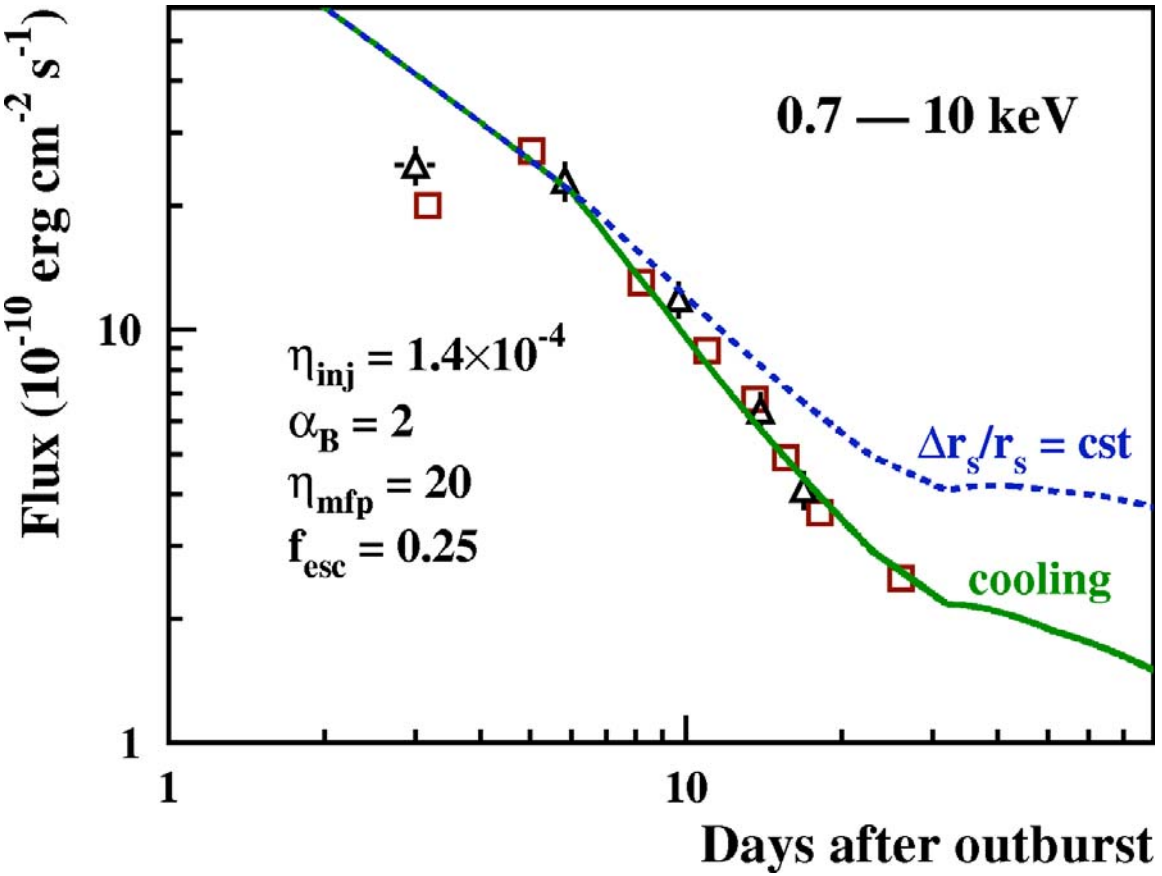
⇒ Energy loss rate due to particle escape:

$$2\times10^{38}\left(\frac{\varepsilon_{esc}}{0.15}\right)\left(\frac{t}{6\,\mathrm{days}}\right)^{-1.5}\ \mathrm{erg\ s^{-1}}$$

~200 times the bolometric luminosity of the postshock plasma at t = 6 days



Calculated X-ray flux



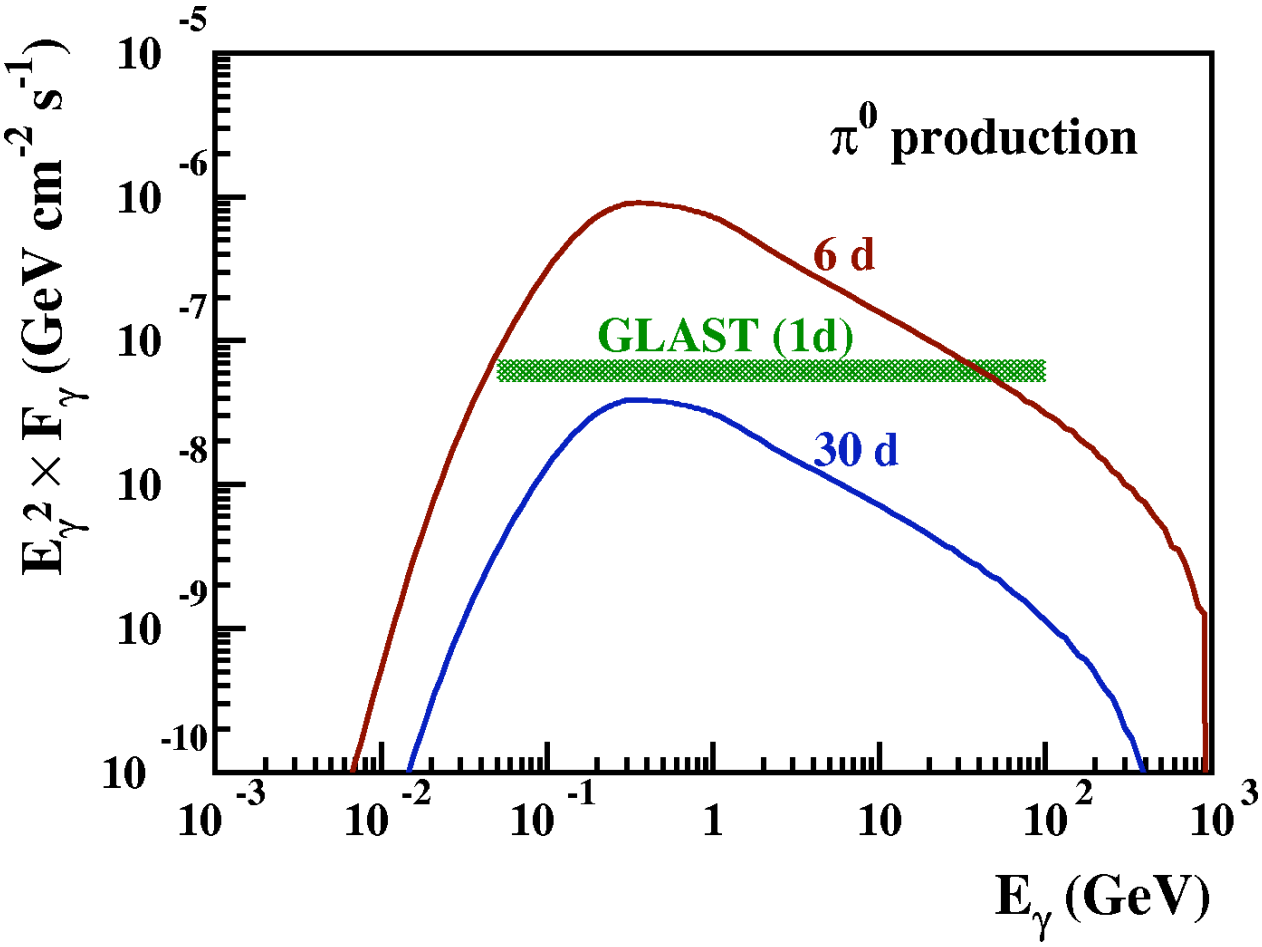
From postshock T_s and ρ_s + MEKAL emissivities ⇒ emission volume:

$$\frac{\Delta r_s}{r_s} = 1.7\%^{*}\left[2\left(\frac{t}{6\,\text{days}}\right)^{0.5} - 1\right]^{-0.5}$$

, consistent with SNR (e.g. Warren et al. 2005)

*for D = 1.6 kpc

Nonthermal gamma-ray emission



- RS Ophiuchi (2006) would have been probably detected by GLAST
- In preparation: accelerated electron contributions (brem., IC, sync.)