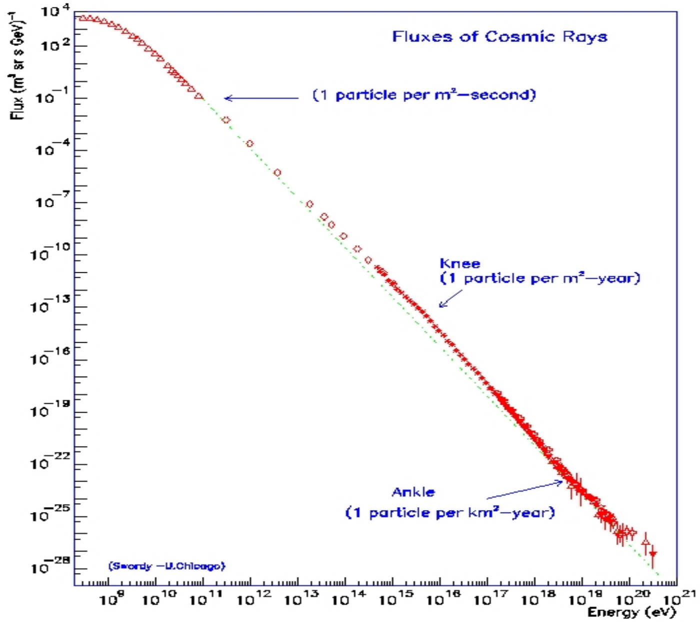
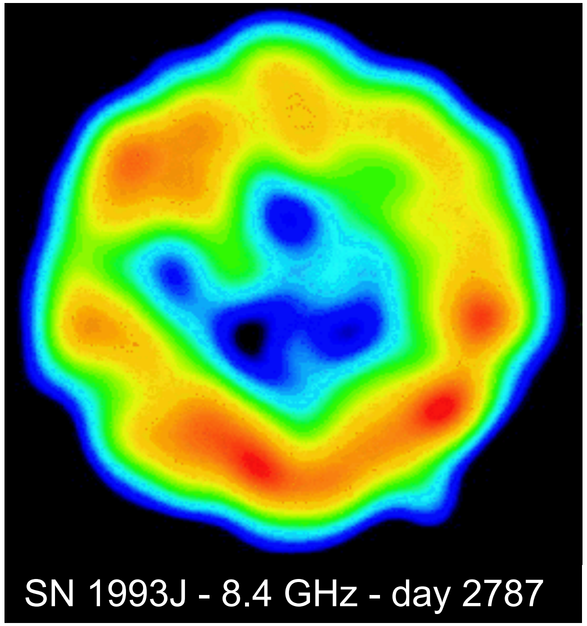
On the origin of cosmic rays. What can we learn from radio supernovae and symbiotic novae?

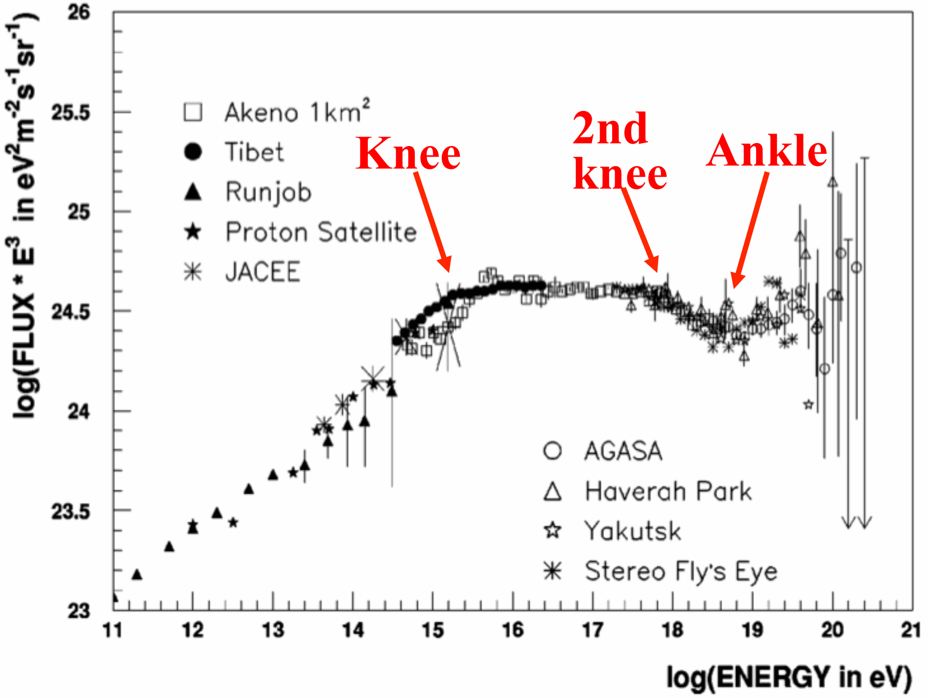


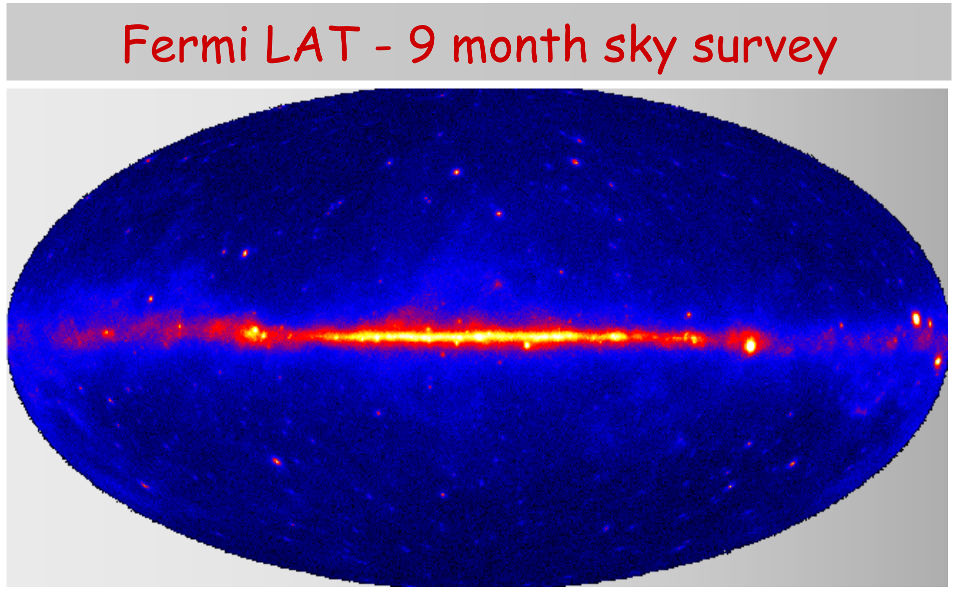
V. Tatischeff
CSNSM, Orsay



Galactic and extragalactic diffuse emissions, IAS, June 8th 2010

Galactic cosmic-ray and supernova energetics





- Galactic origin below ~10^{18} eV
- Extrag. from AGNs (Auger 2007)

- Galactic diffuse γ-ray emission: CR + ISM $\rightarrow$ pion $\rightarrow \gamma$
- CR source power: $5\text{x}10^{40}$ erg/s

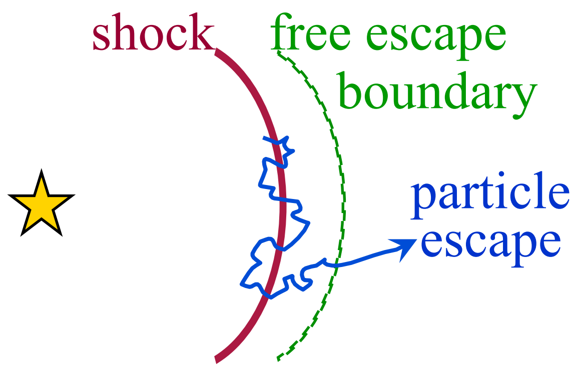
- Total power supplied by SNe: L_{SN} ~ $1.5\text{x}10^{51}$ erg x 50 yr^{-1} ~ 10^{42} erg/s

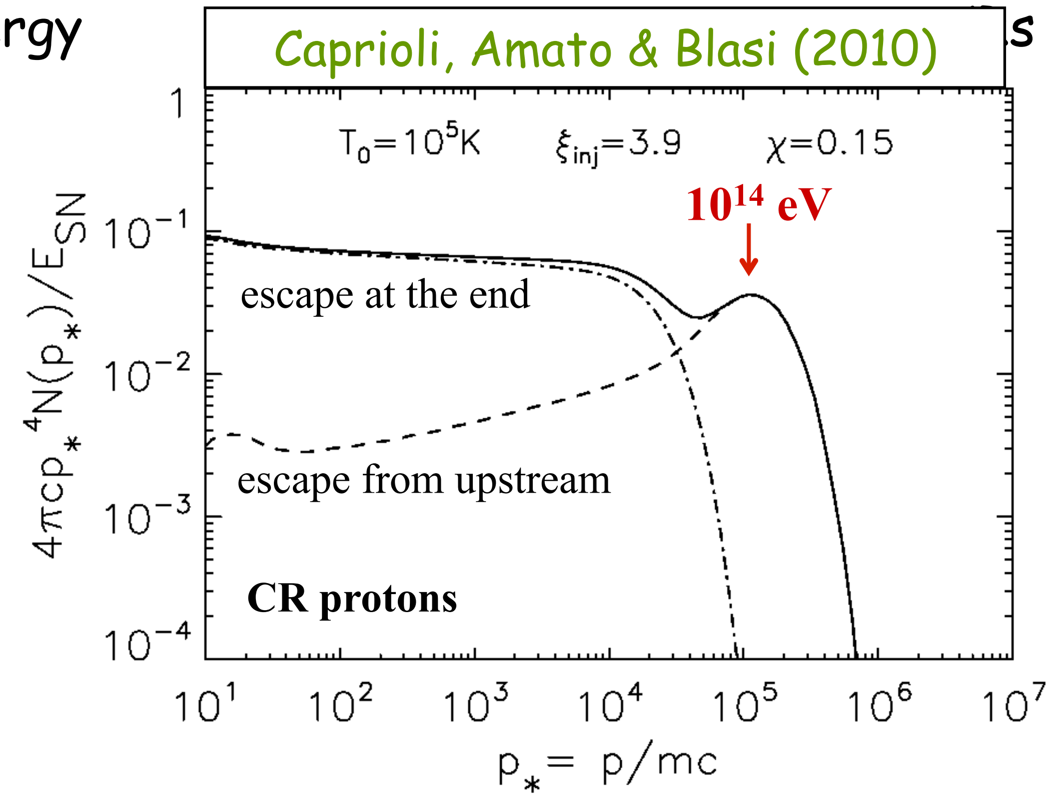
$\Rightarrow$ SN acceleration efficiency ~ 5%

Cosmic-ray production and SNR evolution

- Most of the GCRs are produced in SNRs at the beginning of the Sedov-Taylor stage ($t \sim 10^3$ yr for $n_{\rm ISM} = 1$ cm^{-3}) and released in the ISM at the end ($t > 2\times10^4$ yr) $\Rightarrow$ adiabatic deceleration during the SNR expansion

- Continuous escape of high-energy ... s from th

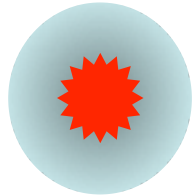




- What is the origin of GCRs above ~3x10^{15} eV ?

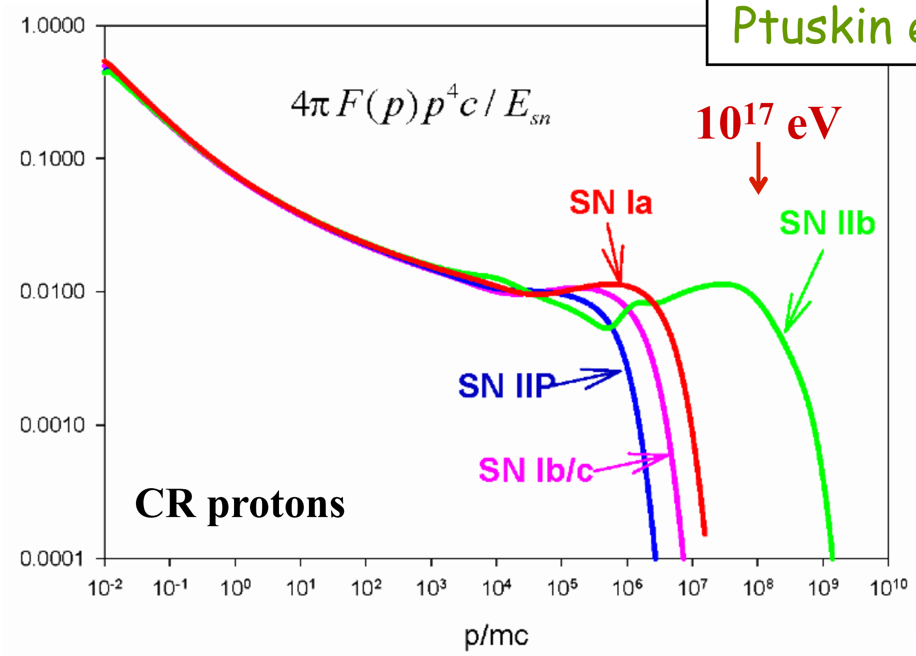
Importance of the progenitor's stellar wind

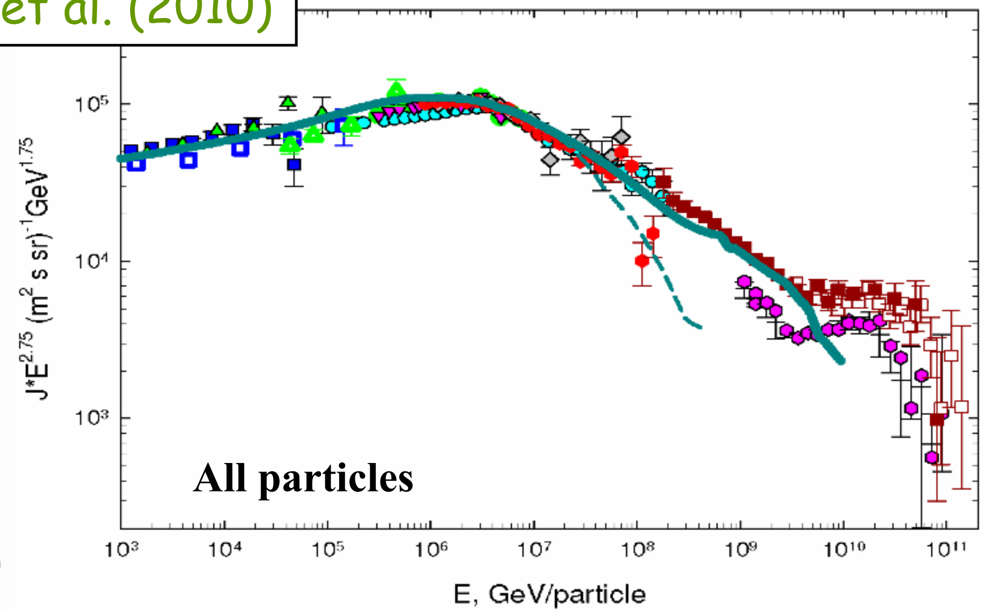
- In CC SNe, the shock initially runs through the progenitor's stellar wind
- High density ρ_{CSM} and $V_s \Rightarrow$ high amplified B ($B^2/8\pi \propto \rho_{CSM} V_s^2$) $\Rightarrow$ high E_{max} (Völk & Biermann 1988: $E_{max} \rightarrow 10^{19}$ eV)



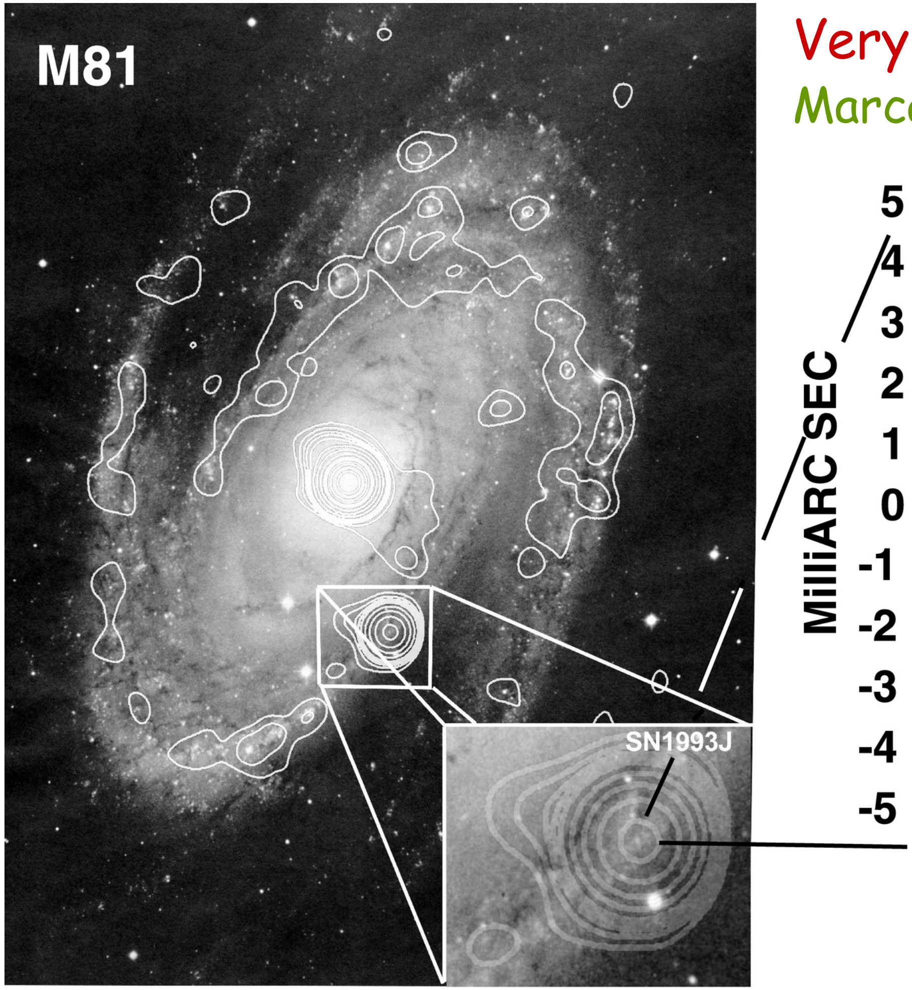
- SN IIb: explosion of a red supergiant (type eIIb, Chevalier et al. 2010) which has a slow and dense wind, $(dM/dt)_{RSG} > \sim 3\times10^{-5}\ M_\odot \mathrm{yr}^{-1}$ $\sim 25\ M_\odot < M_{ZAMS} < \sim 35\ M_\odot$ (single star) $\Rightarrow$ rare events $f \sim f$(SN IIP) / 10

Ptuskin et al. (2010)

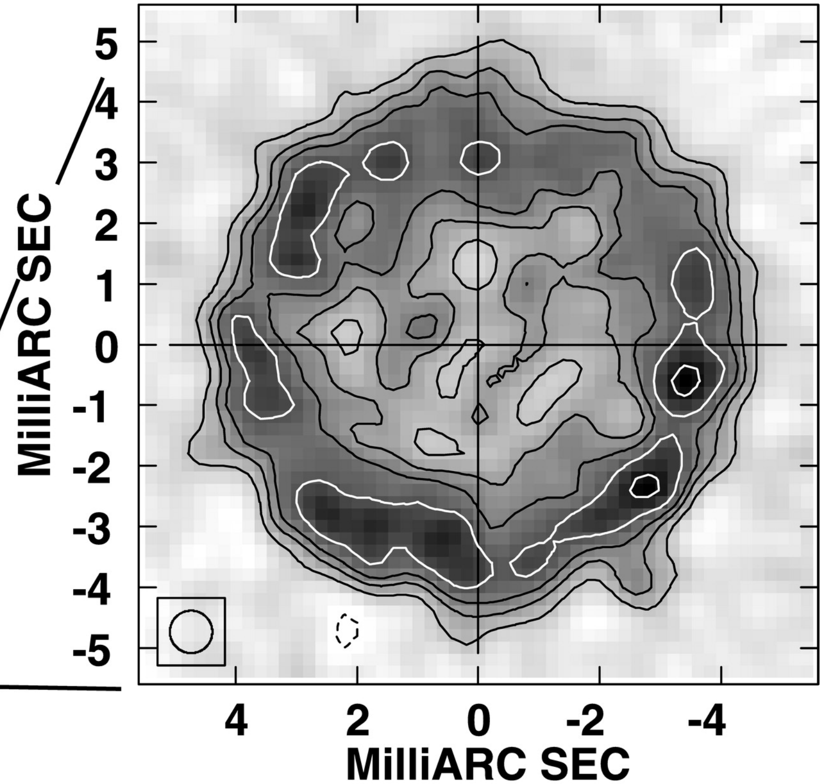




SN 1993J — One of the best observed radio SN

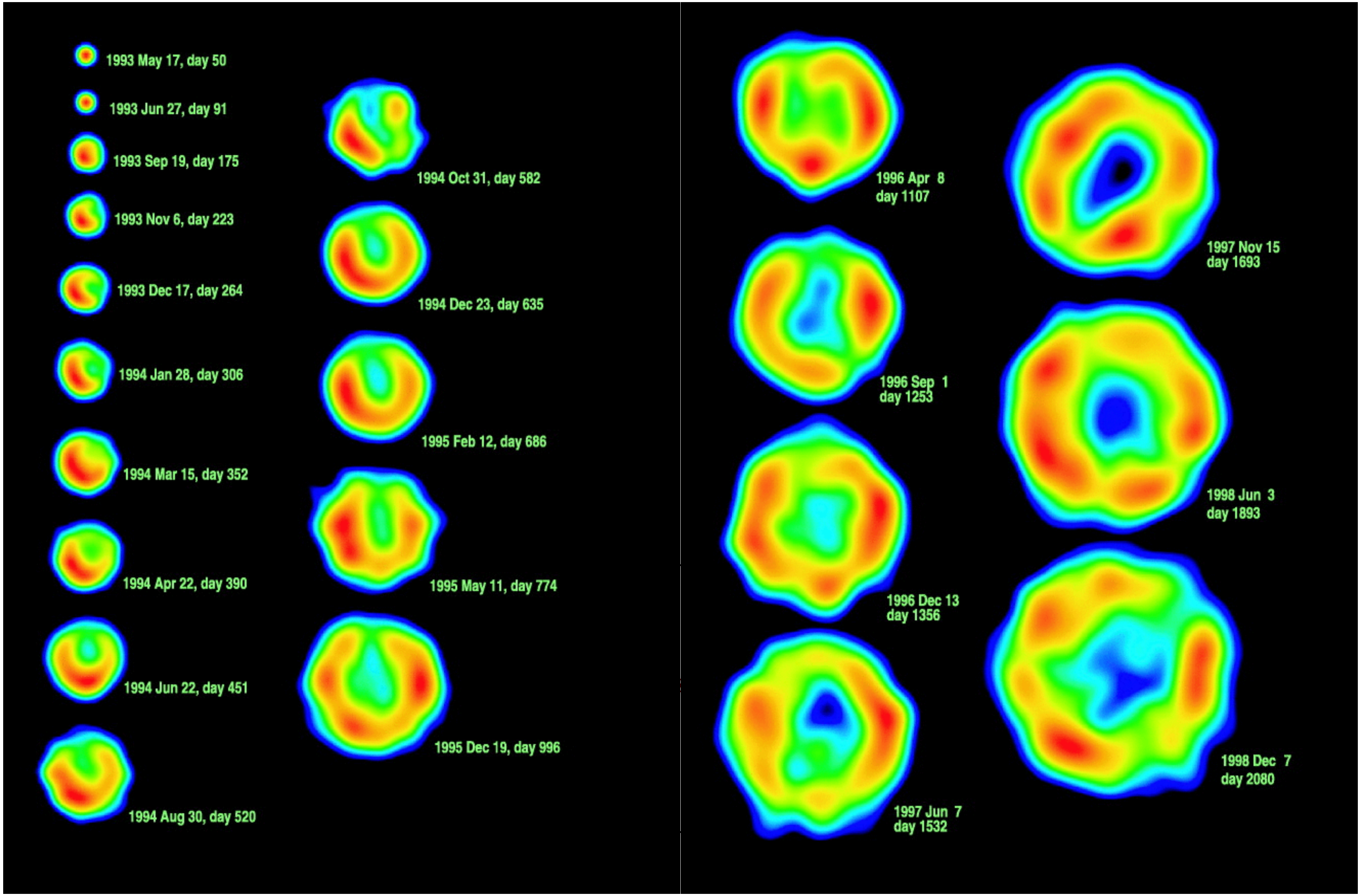


Very long baseline interformetry (e.g. Marcaide et al. 1997; Bartel et al. 2007)



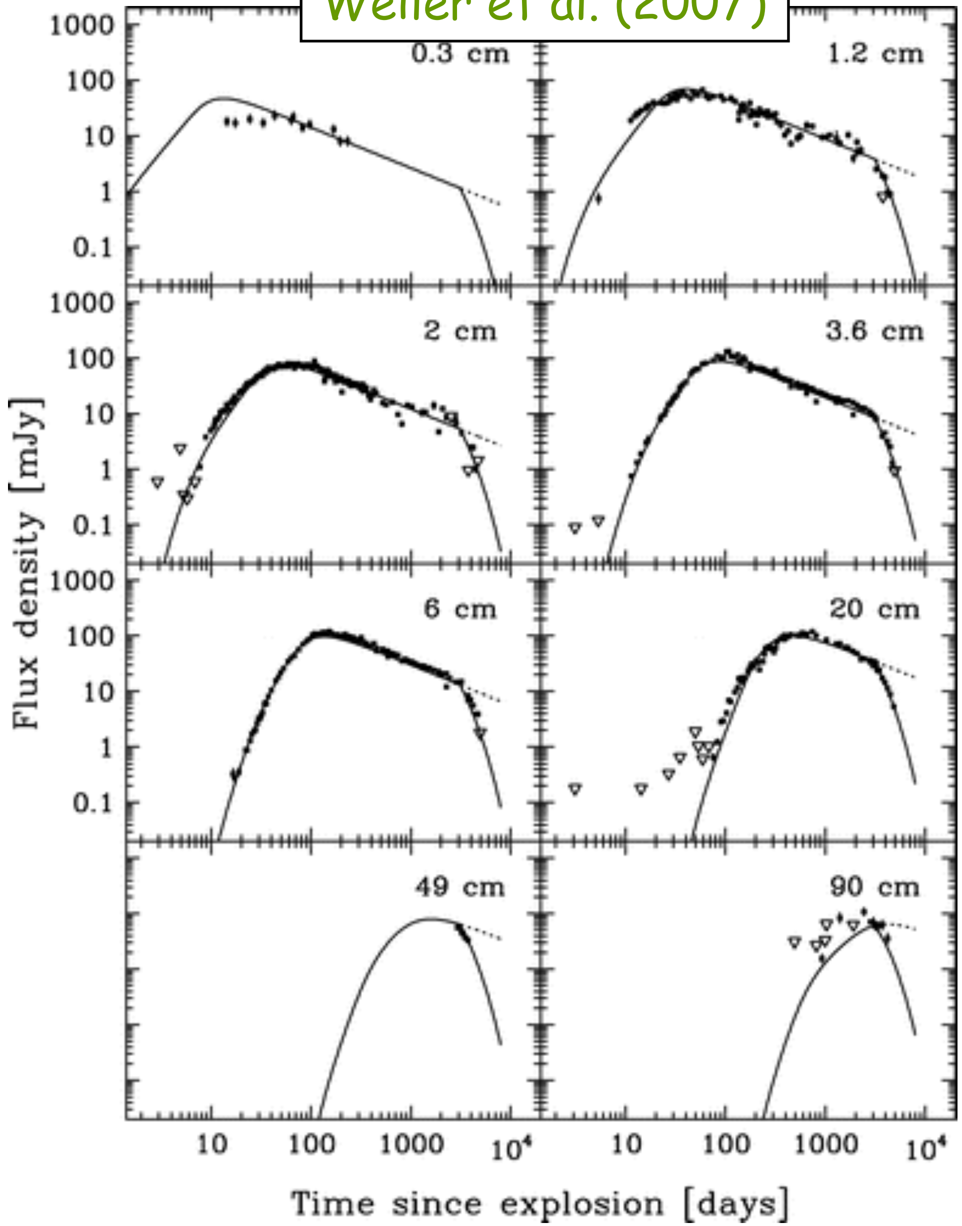
- Type IIb. Discovered on 1993 March 28 in M81 (D=3.63±0.34 Mpc)
- Explosion of a ~17 $M_\odot$ K0 I supergiant in a binary system

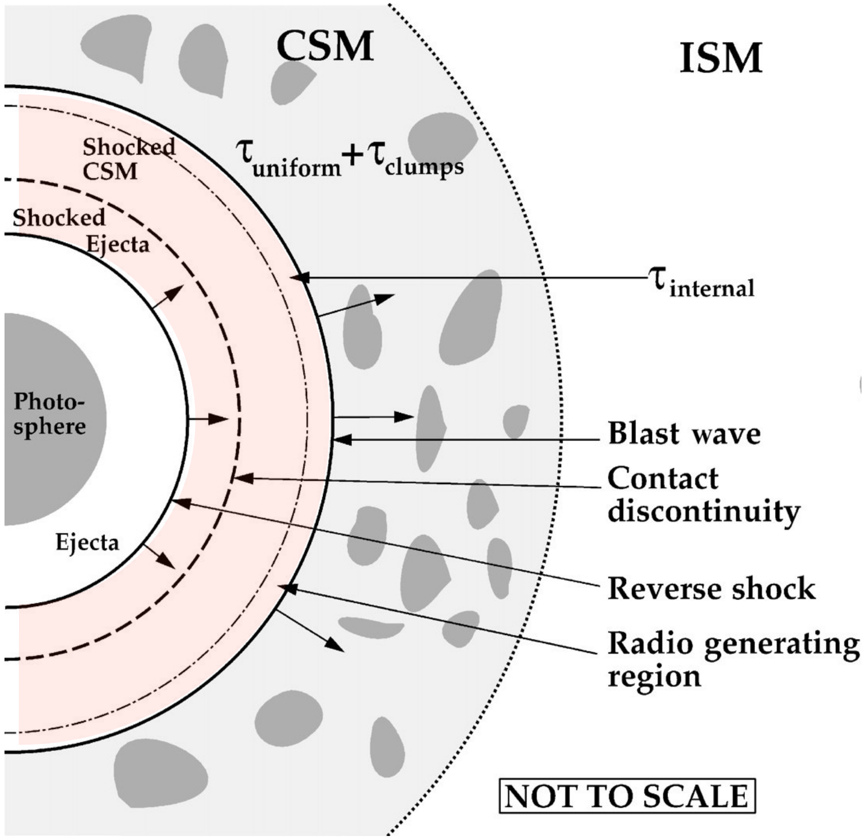
SN 1993J VLBI observations



SN 1993J radio light curves

Weiler et al. (2007)





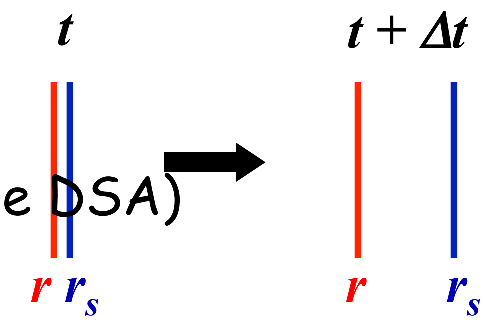
- Early absorption : free-free + synchrotron self-absorption $\Rightarrow B$
- Abrupt decline after day ~3100 as the shock has reached the outer limit of the dense CSM

Radio SN model (1)

- Nonlinear diffusive shock acceleration (NDSA) model (Berezhko & Ellison 1999) $\Rightarrow f_p(p,r_s)$ and $f_e(p,r_s)$

  f_e depends on the proton injection parameter η_{inj}^{p}

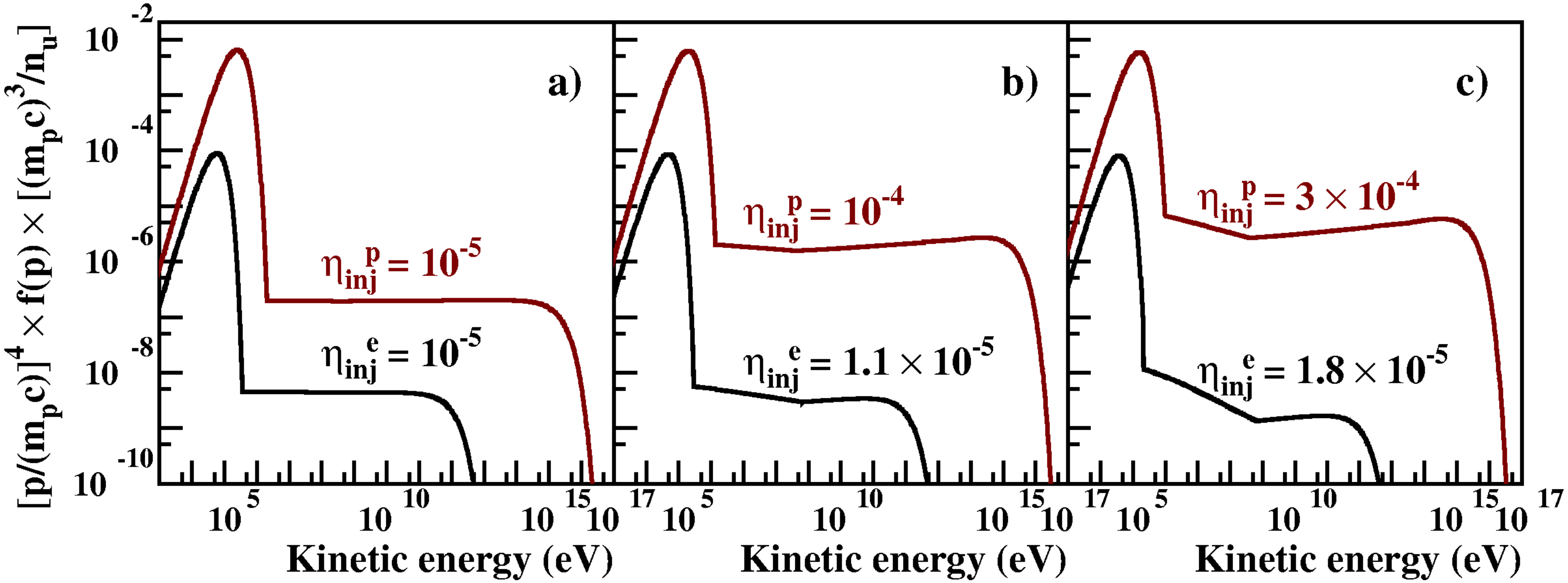
  (fraction of shocked protons injected into the DSA)



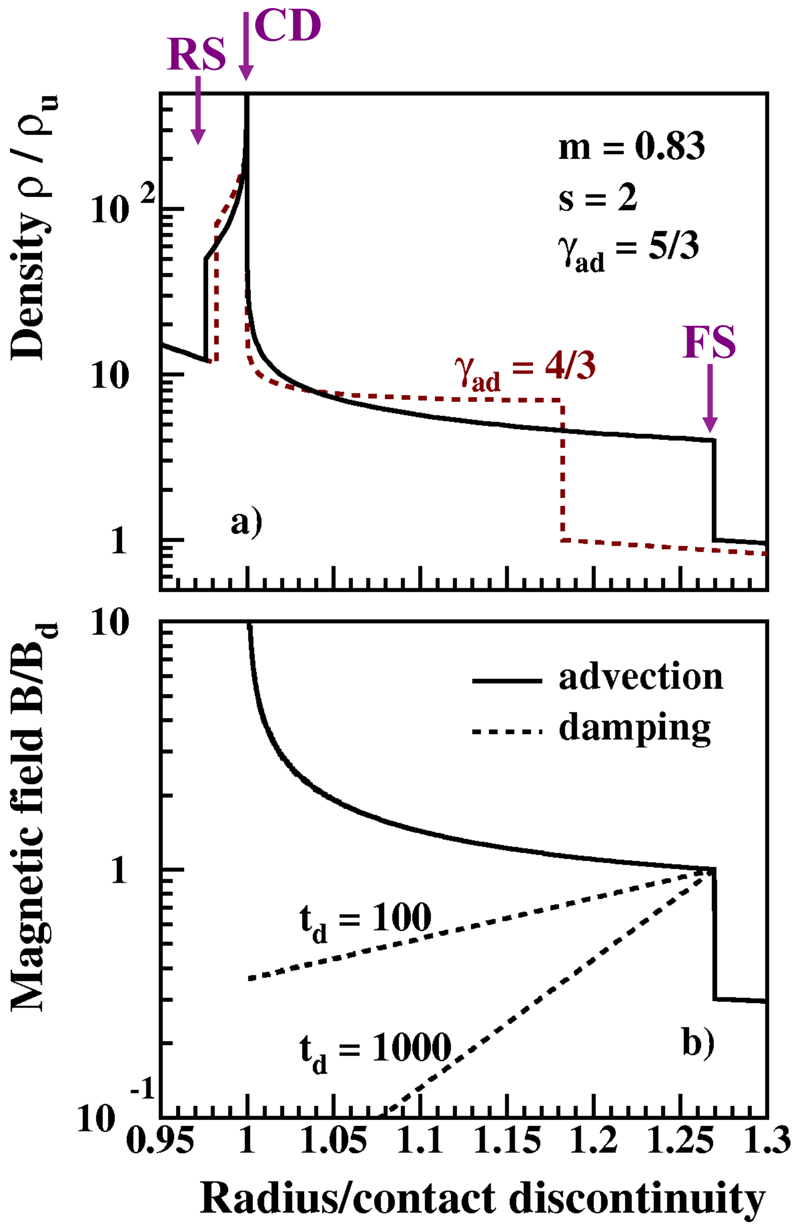
- Electron energy losses during the expansion:

  adiabatic, synchrotron and inverse Compton cooling (Reynolds 1998)

  (radiation density dominated by the ejecta; Fransson & Björnsson 1998)



Radio SN model (2)

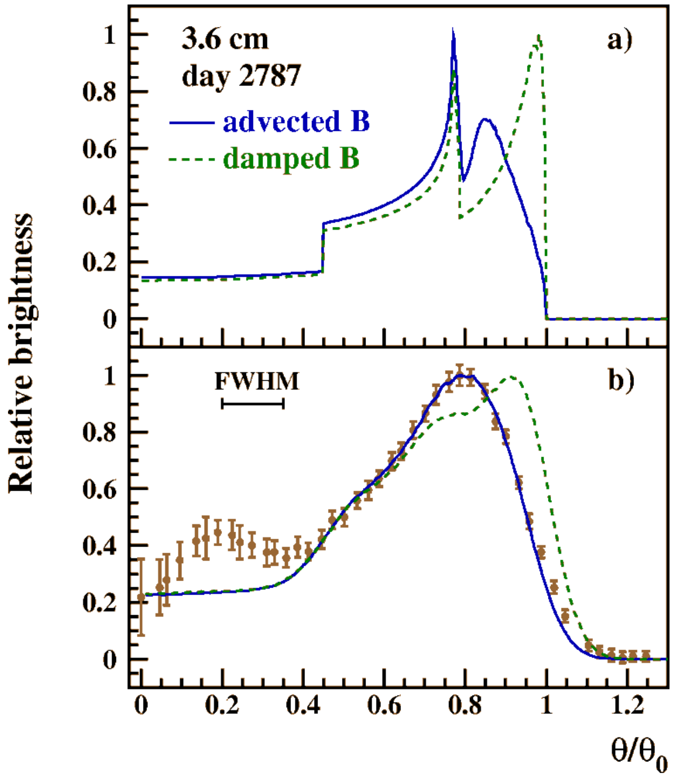


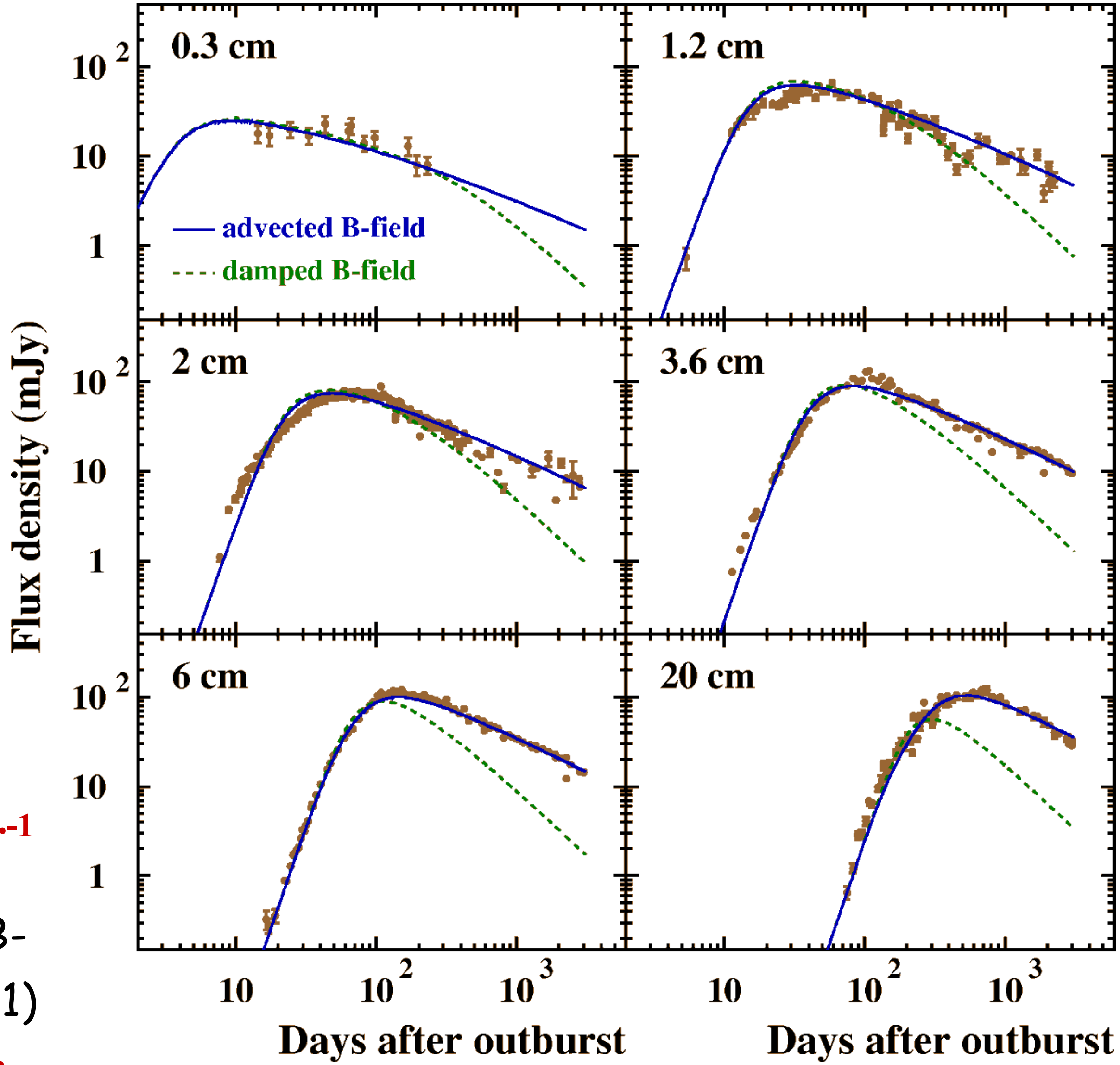
- Hydrodynamic of the postshock plasma: self-similar solutions (Chevalier 1983)
- Postshock magnetic field evolution:
  - advected in the plasma flow or
  - damped by cascading of MHD wave energy (Pohl et al. 2005)
- Synchrotron emission: radiative transfer calculations including synchrotron self-absorption
- Free-free absorption in the clumpy wind lost from the progenitor star

⇒ 4 free parameters:

$(\mathrm{d}M/\mathrm{d}t)_{\mathrm{RSG}}$, B_{u0}, $\eta_{\mathrm{inj}}^{\mathrm{p}}$, and K_{ep}

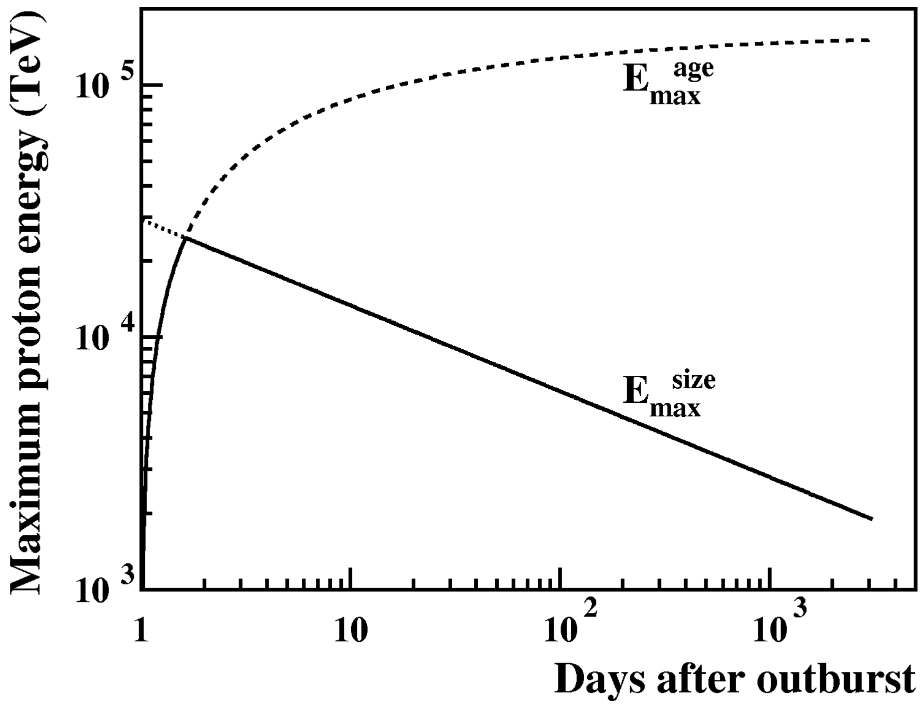
SN 1993J model results

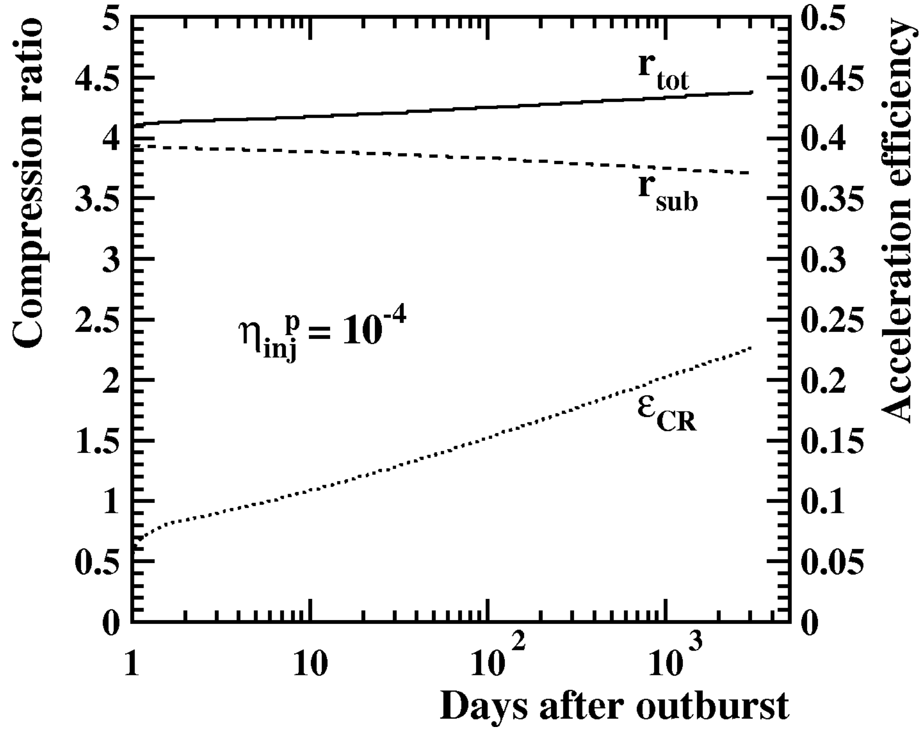




- <u>Best parameter values</u>:
  - $(dM/dt)_{RSG} \approx 3.8\times10^{-5}\ M_{\odot}\,\mathrm{yr}^{-1}$
  - $B_{u0} = 50 \pm 20$ G (amplified B-field in the precursor at day 1)
  - $\eta_{inj}^{p} \approx 10^{-4}$ and $K_{ep} \approx 2\times10^{-3}$

SN 1993J and the origin of cosmic rays

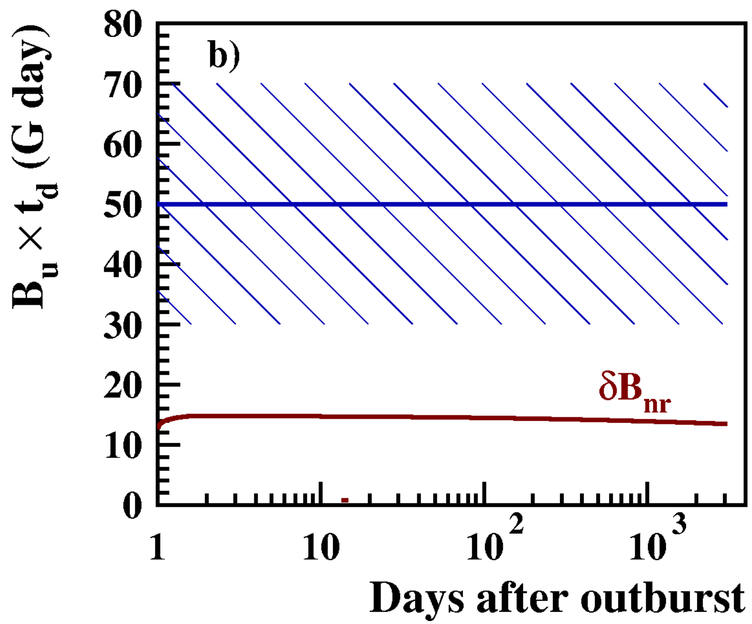




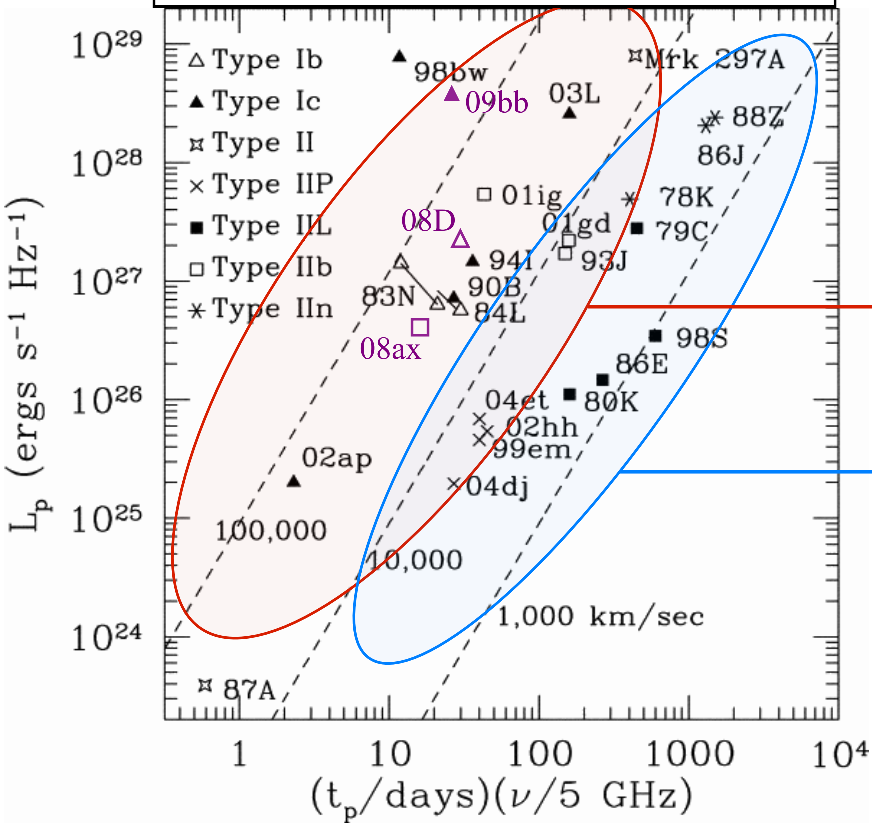
- Rapid acceleration above the “knee” energy of 3×10^{15} eV
- Total CR energy: $E_{CR} \cong \int_{\text{day }1}^{\text{day }3100} \varepsilon_{CR}(t) \times 0.5 \rho_{CSM} v_s^3 \times 4\pi r_s^2 dt = 7.4 \times 10^{49}$ erg
- Escape of high-energy CRs after day ~3100 as $\rho_{CSM} \searrow \Rightarrow B_u \searrow \Rightarrow l_{diff} \nearrow$

Radio supernovae and the origin of cosmic rays

- B-field amplification in SN 1993J, possibly by the Bell's nonresonant CR streaming instability ⇒ CR production above 3×10^{15} eV (Tatischeff 2009)



Chevalier et al.(2006,2010)



- Synchrotron self absorption ⇒ B-field amplification
- Free-free absorption ⇒ progenitor mass-loss rate

+ B-field damping, CR injection...

Symbiotic novae

- Binary systems with a white dwarf and a red giant star (symbiotic)
- Best-known object: RS Ophiuchi
- Massive white dwarf (M_{WD}~$1.35\ M_\odot$) - maybe a SN Ia in ~10^5-10^7 yrs
- Thermonuclear runaway outbursts: 1898, 1907, 1933, 1945, 1958, 1967, 1985, and 2006

$\Rightarrow$ ~20 years recurrence period, as compared to 10^4-10^5 yrs for classical novae, due to the higher $(dM/dt)_{acc}$ and M_{WD}

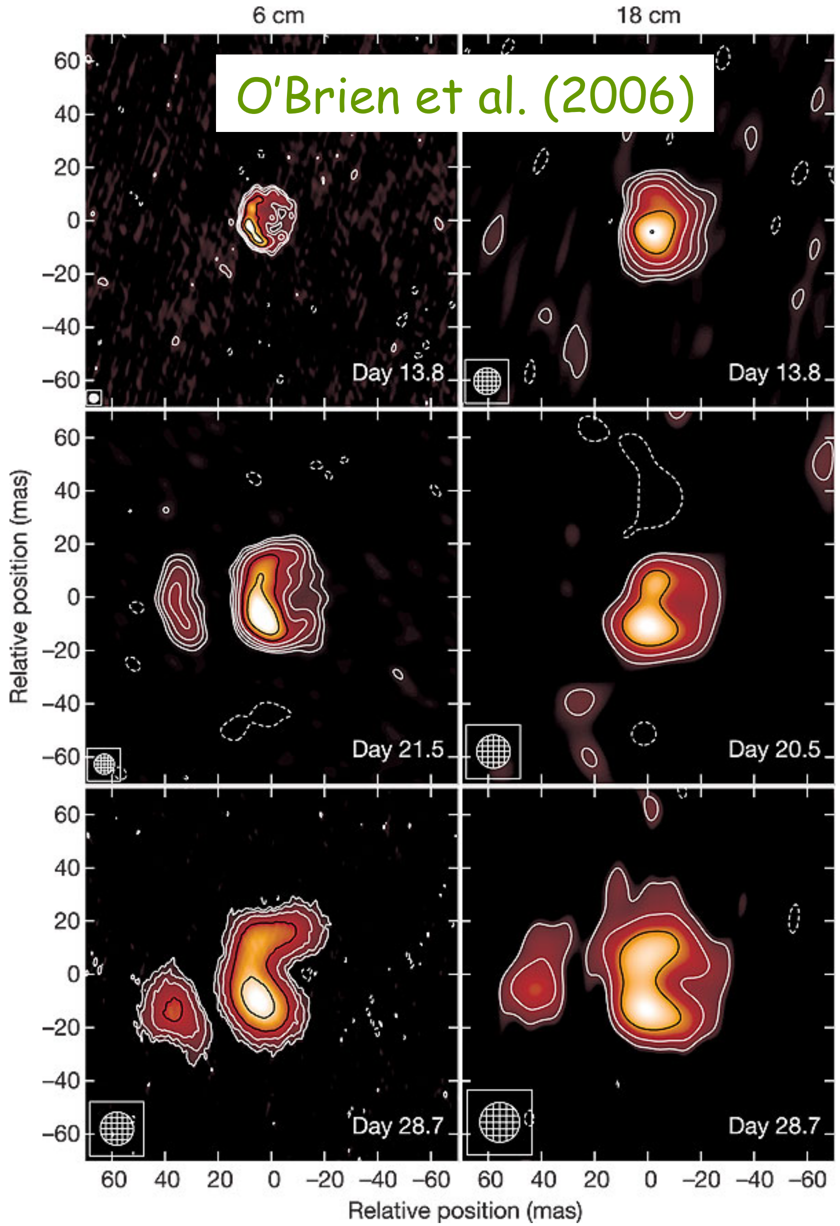
Symbiotic novae as fast "miniature supernovae"

Char. time of evolution: $t_c \propto \dfrac{M_{\rm ej}^{3/2} v_w}{E_{\rm out}^{1/2} \dot{M}_w}$

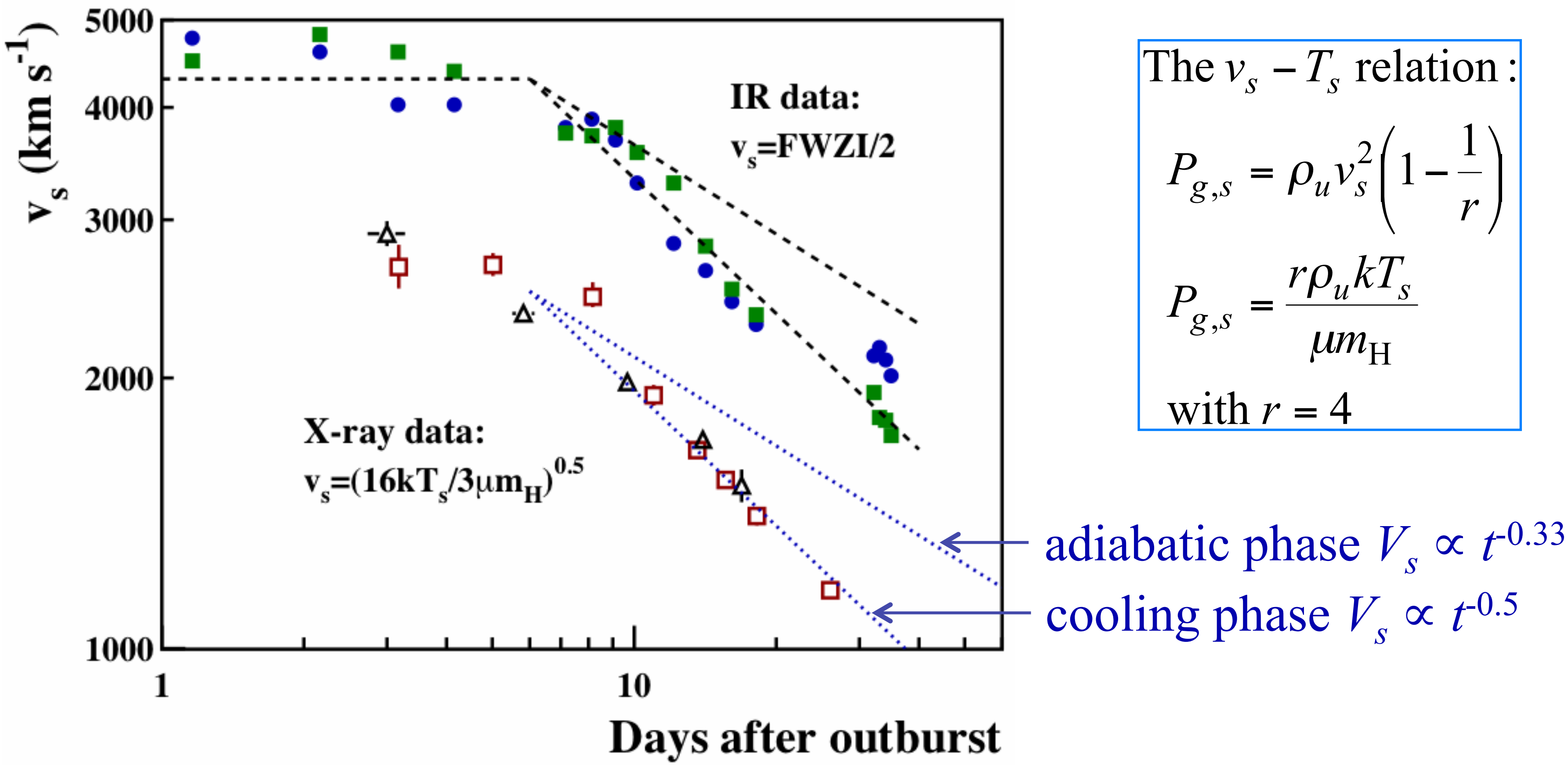
RS Oph	SN II
$M_{\rm ej} \sim 3\times10^{-6}\, M_\odot$	$M_{\rm ej} \sim 10\, M_\odot$
$E_{\rm out} \sim 10^{44}$ erg	$E_{\rm out} \sim 10^{51}$ erg
$\dot{M}_{\rm RG} \sim 10^{-6} M_\odot\ {\rm yr}^{-1}$	$\dot{M}_{\rm RSG} \sim 10^{-5} M_\odot\ {\rm yr}^{-1}$

$\Rightarrow$ t_c(RS Oph) ~ 10^{-5} t_c(SN II)

- free expansion phase: days
- adiabatic phase: ~2 months
- then radiative cooling phase



Blast wave evolution in RS Oph (2006)



The $v_s - T_s$ relation:

$$P_{g,s} = \rho_u v_s^2 \left(1 - \frac{1}{r}\right)$$

$$P_{g,s} = \frac{r \rho_u k T_s}{\mu m_{\mathrm{H}}}$$

with $r = 4$

- What cooled the shock after ~6 days (T_s ~ 10^8 K at day 6 and radiative cooling was not important)? ⇒ Cosmic-rays
- What makes the X-ray measurements of V_s lower than the IR data? CRs

Cosmic-ray acceleration in RS Oph (2006)

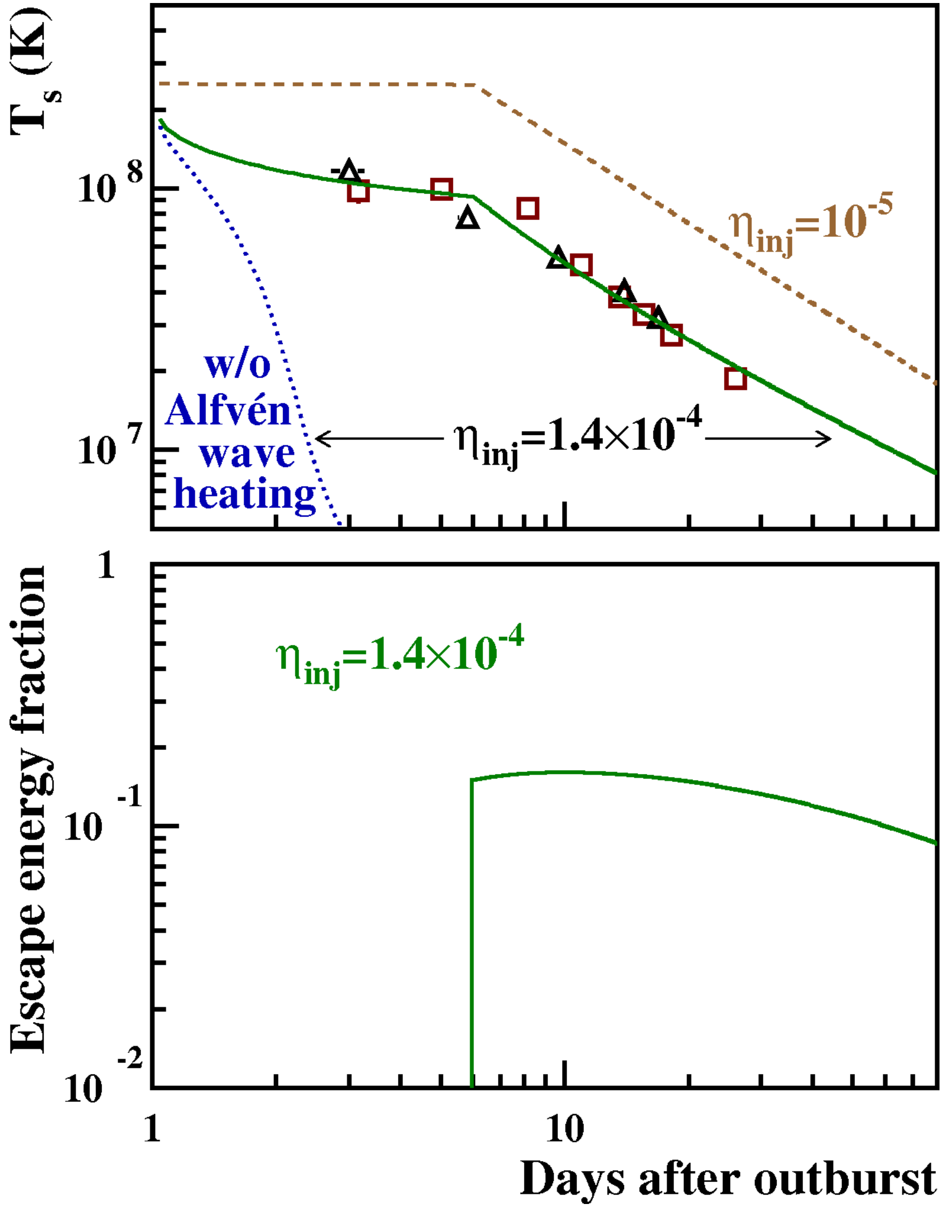
- Good agreement between the IR data and the X-ray measurements of T_s for moderate CR acceleration efficiency, $\eta_{inj} \sim 10^{-4}$

$\Rightarrow$ Energy loss rate due to accelerated particle escape:

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

~100 times the bolometric luminosity of the postshock plasma at $t = 6$ days

(Tatischeff & Hernanz 2007)

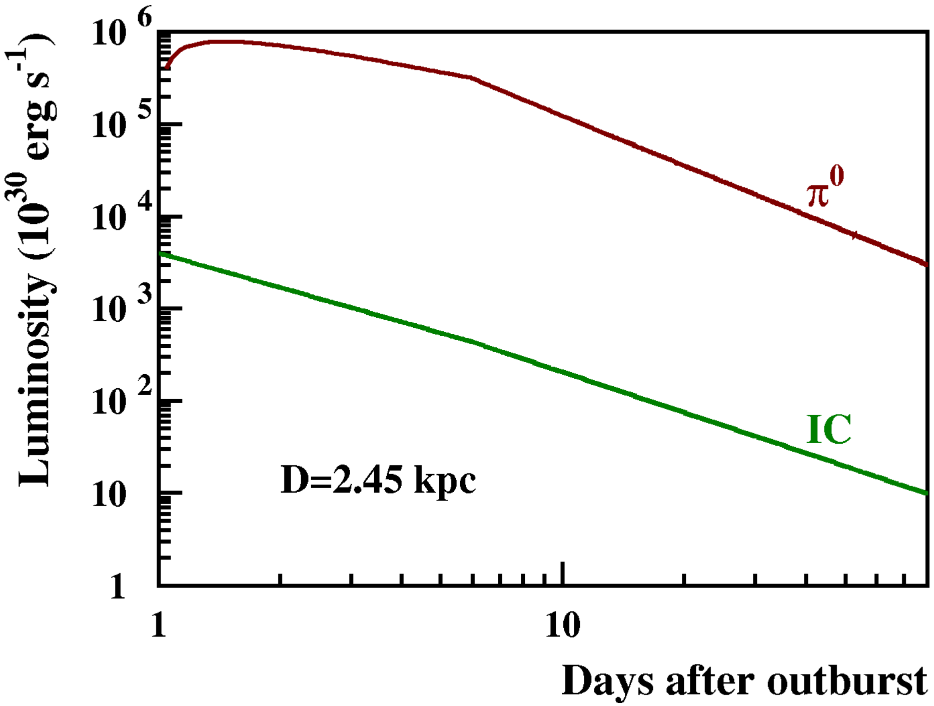


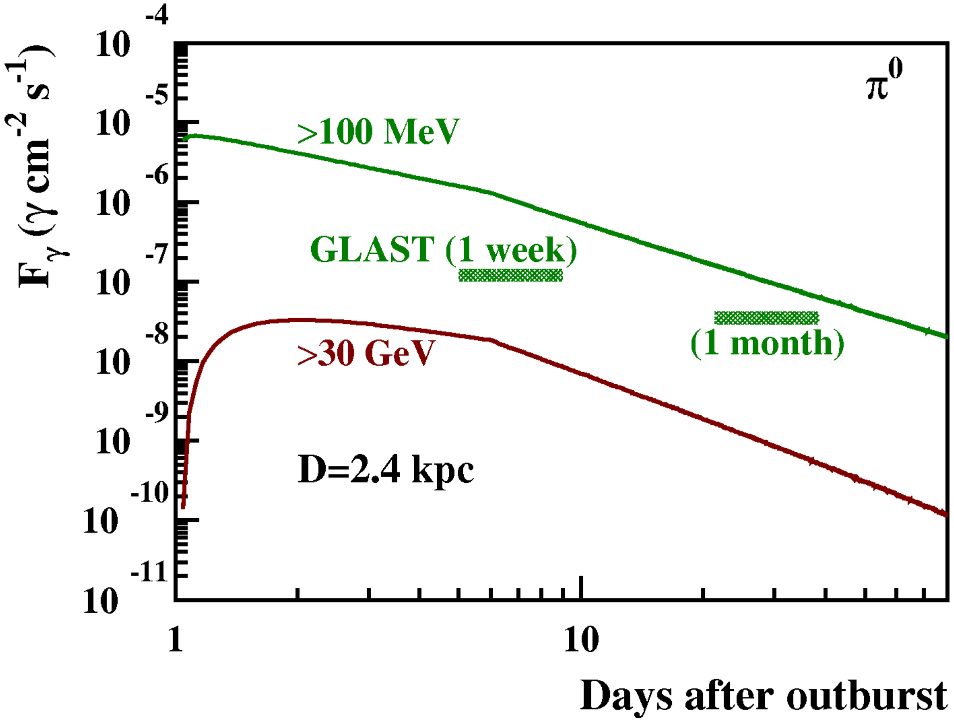
Predicted γ-ray emission from RS Oph (2006)

- π^0 production calculated from ε_{CR} and $(dM/dt)_{RG}$
- IC contribution estimated from the nonthermal synchrotron luminosity, $L_{syn} \sim 5\times10^{33}\, t_d^{-1.3}$ erg s^{-1} (Kantharia et al. 2007) and the ejecta luminosity, $L_{ej} \sim L_{Edd} = 2\times10^{38}$ erg s^{-1} $\Rightarrow L_{IC} = L_{syn} \times U_{rad}/(B^2/8\pi) \sim L_{syn}$

$\Rightarrow$ γ-rays mainly from π^0 production

$\Rightarrow$ RS Oph (2006) would have been detected by Fermi LAT





Known or suspected symbiotic recurrent novae

	m_{max}	m_{min}	Dist (kpc)	Sec. type	Outburst (years)
T CrB	2.0p	10.2v	1.3	M3III	1866, 1946
RS Oph	5.0v	11.5v	2.4	M0/2III	1898, 1907, 1933, 1945, 1958, 1967, 1985, 2006
V3890 Sgr	8.2v	17.0:	5.2	M5III	1962, 1990
V745 Sco	9.6v	19.0:	4.6	M6III	1937, 1989
V723 Sco	9.8p	19.0j		NIR ph. [1]	1952
EU Sct	8.4p	18p		− [2]	1949
V3645 Sgr	12.6p	18.0p		− [2]	1970
V1172 Sgr	9.0p	18.0j		− [2,3]	1951

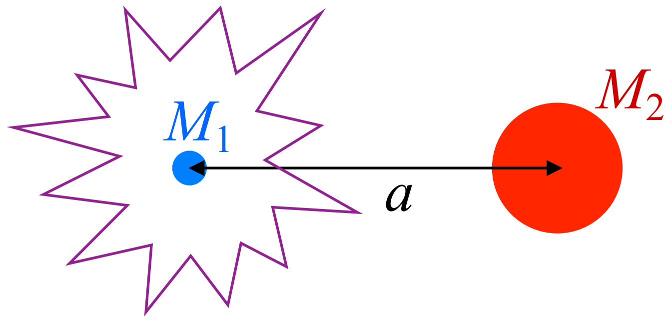
[1] Harrison et al. (1992); [2] Weight et al. (1994); [3] Hoard et al. (2002)

- ~340 CN outbursts detected since 1850 ⇒ ~5% in red giant sec.
- Galactic nova rate: 20−40 yr^{-1} (~10% detected) ⇒ ~1−2 yr^{-1} with RG
- *Fermi* would detect a burst like RS Oph (2006) at D_{max} = 10.5 kpc

⇒ *Fermi* may detect a few RS Oph-like novae during its all-sky survey

The 2010 outburst of V407 Cygni

- Symbiotic Mira binary system (WD + AGB star of Mira type)
- Detected with Fermi-LAT on 13-14 March 2010, ~2 days after the optical outburst (ATEL #2487), $F_\gamma(>100\text{ MeV}) \sim 10^{-6}\text{ cm}^{-2}\text{ s}^{-1}$
- From the Mira's pulsation ($P_{\rm AGB} = 763$ days)
  $\Rightarrow D = 1.8$ kpc, $(dM/dt)_{\rm AGB} \sim 3\times10^{-5}\, M_\odot\,\text{yr}^{-1}$
- From the orbital period ($P_{\rm orb} \sim 43$ years)
  $\Rightarrow$ Binary separation $a \sim 15.5$ AU



- From the width of optical and IR lines $\Rightarrow V_s \sim 3600\text{ km s}^{-1}$

$\Rightarrow$ Estimated γ-ray flux from π^0 production:

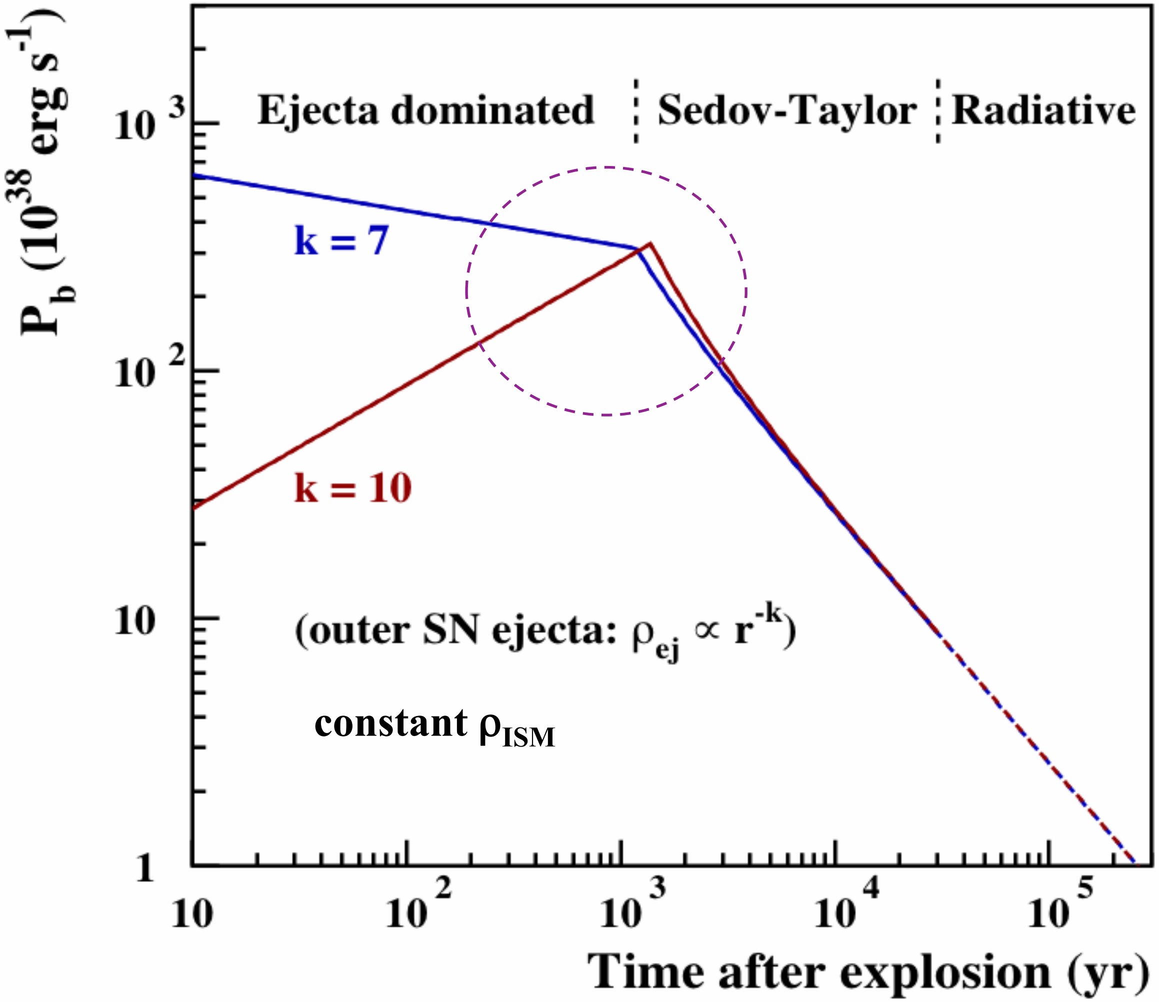
$$F_\gamma(>100\text{ MeV}) \approx 3\times10^{-6}\left(\frac{\langle n_{ps}\rangle}{2.4\times10^9\text{ cm}^{-3}}\right)\left(\frac{\theta_{\rm CR}E_{\rm nova}}{10^{43}\text{ erg}}\right)\left(\frac{D}{1.8\text{ kpc}}\right)^{-2}\ \text{cm}^{-2}\text{ s}^{-1}$$

$\Rightarrow$ CR injection, evolution of a CR modified shock…?

Extra

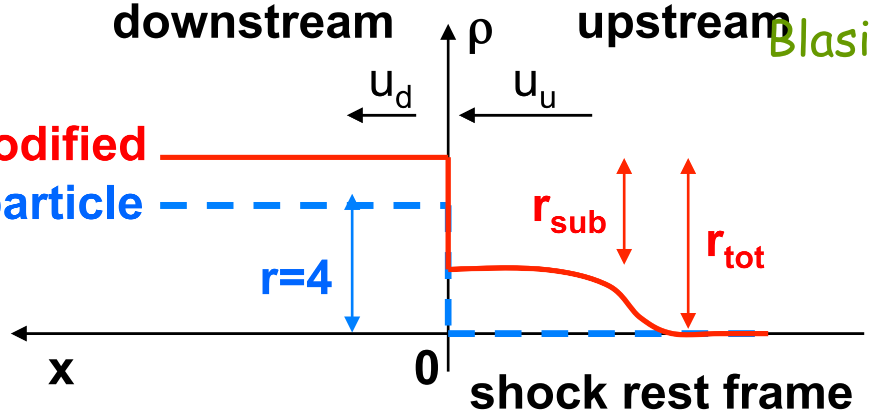
Cosmic-ray production and SNR evolution

- Mechanical power processed in a NR blast wave: $P_b = 0.5\rho_{\mathrm{ISM}} V_s^3 \times 4\pi R_s^2$



Cosmic-ray modified shock

See Berezhko & Ellison (1999); Blasi et al. (2...



- Momentum flux conservation:

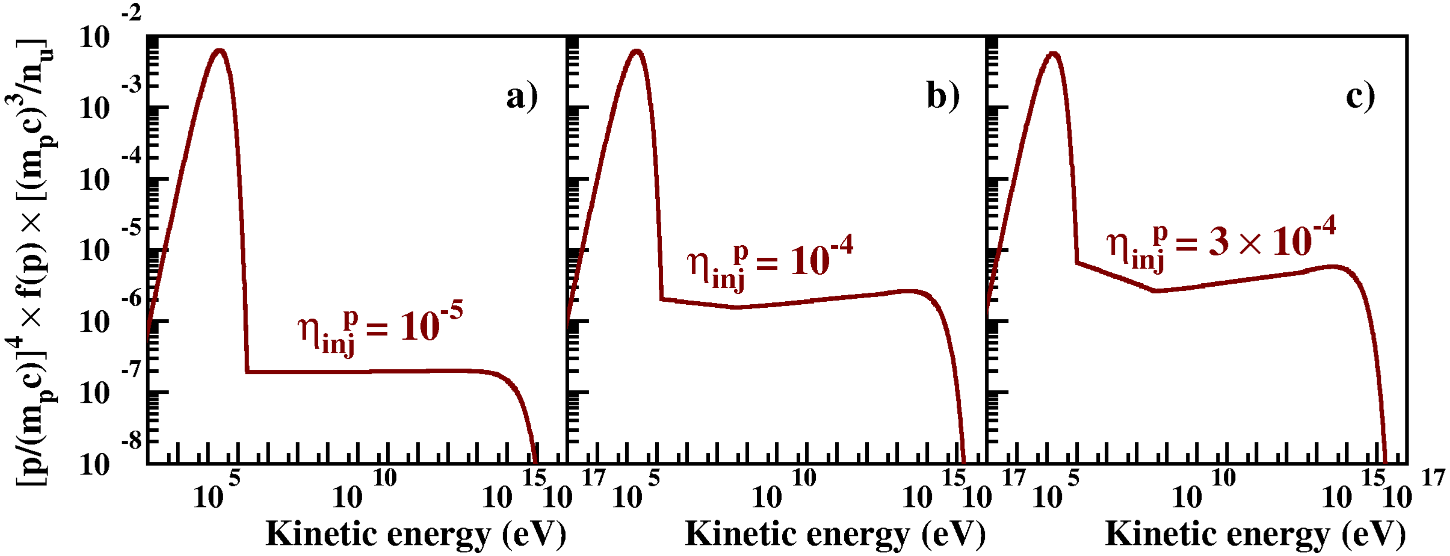
$$\rho_0 u_0{}^2 + P_{g,0} = \rho(x)u(x)^2 + P_g(x) + \boldsymbol{P_{CR}(x)}$$

with

$$P_{CR}(x) = \frac{1}{3}\int_{p_{inj}}^{p_{max}} dp\, 4\pi p^3 v(p) f(x,p)$$

particle dist. funct. ($\Leftarrow$ diffusive transport eq.)

- Higher energy particles feel a higher compression ratio $\Rightarrow$ concave spect.

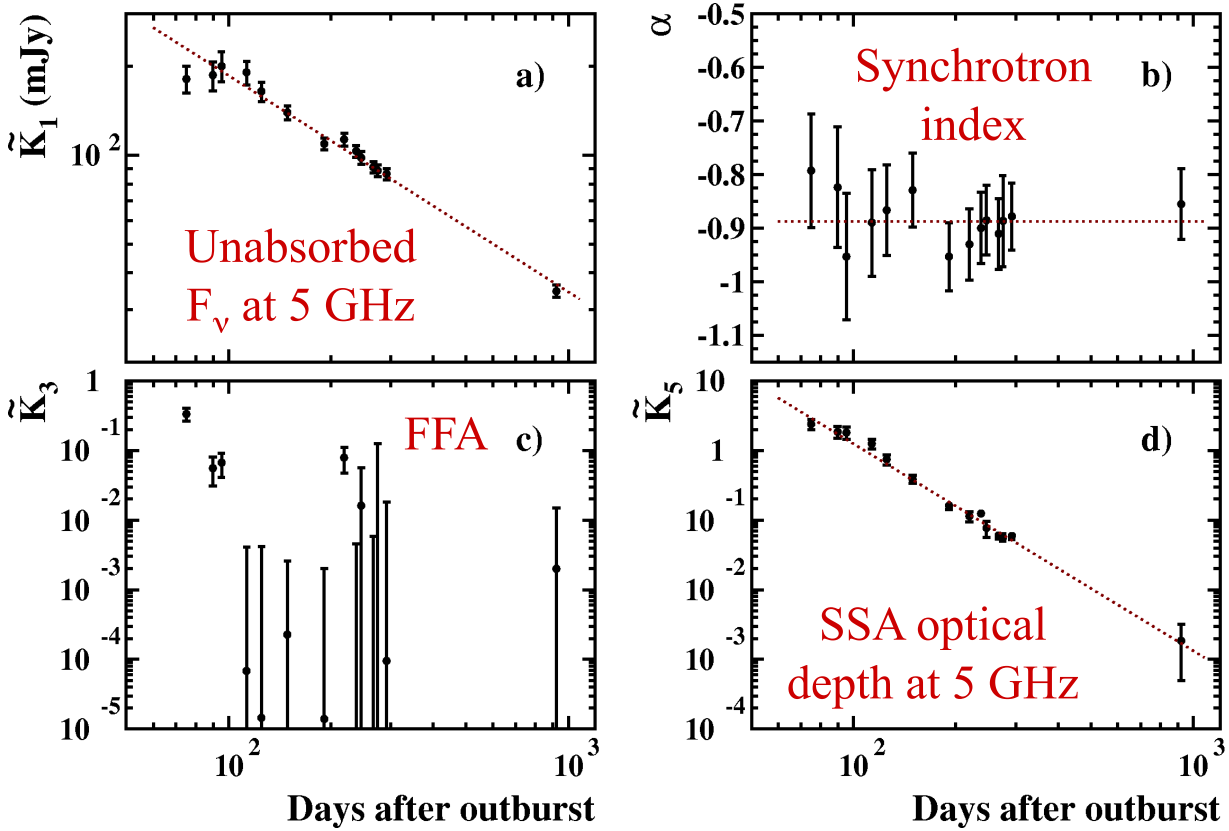


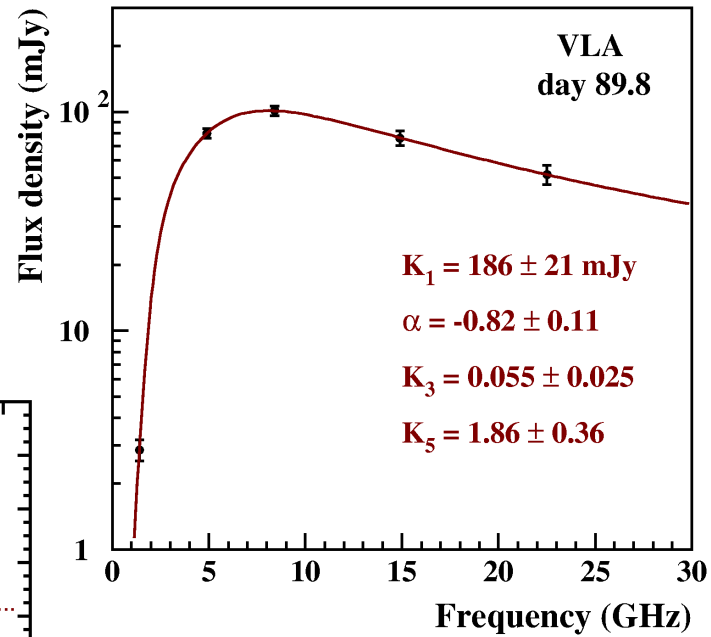
Synchrotron self-absorption (SSA)

- Assuming a power-law distribution of electrons radiating in a uniform shell:

$$\langle B \rangle \propto c(\alpha)\left(K_5 / K_1\right)^2$$

- Fits to individual VLA spectra





$$\langle B \rangle = (2.4 \pm 1.0)\left(\frac{t}{100 \text{ days}}\right)^b \text{ G}$$

with $b = -1.16 \pm 0.20$

⇒ Strong amplification of the stellar B-field

Magnetic field amplification

- Saturated δB from the Bell's nonresonant streaming instability (Pelletier et al. 2006):

$$\frac{\delta B_{\rm nr}^2}{8\pi} \approx 0.1 \left(\frac{P_{\rm CR}}{\rho_{\rm u} v_s^2} \right) \frac{\rho_{\rm u} v_s^3}{c}$$

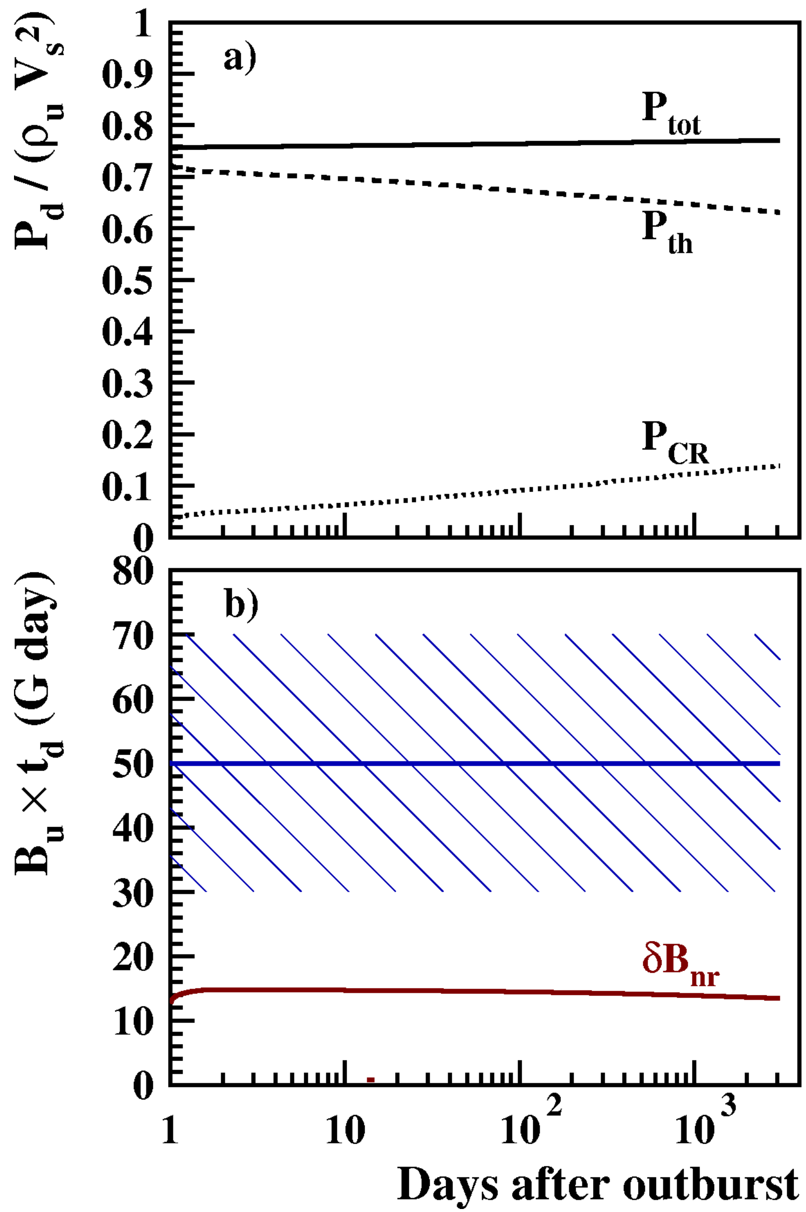
2-5 lower than the "measured" B-field

- Further amplification by the resonant instability (Pelletier et al. 2006)?

$$\frac{\delta B_{\rm res}^2}{\delta B_{\rm nr}^2} \sim \sqrt{\frac{P_{\rm CR}}{\rho_u v_s^2} \frac{c}{v_s}} \Rightarrow \quad \text{No}$$

- Empirical formula for both Galactic SNRs (Berezhko 2008) and SN 1993J:

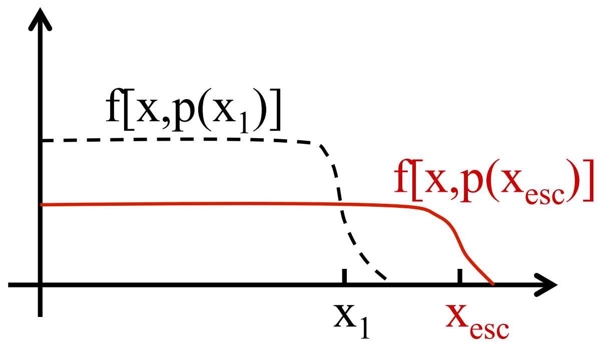
$$\frac{\delta B^2}{8\pi} \approx 10^{-1} P_{\rm CR} \left(\frac{v_s}{3 \times 10^4 \ \text{km s}^{-1}} \right)$$



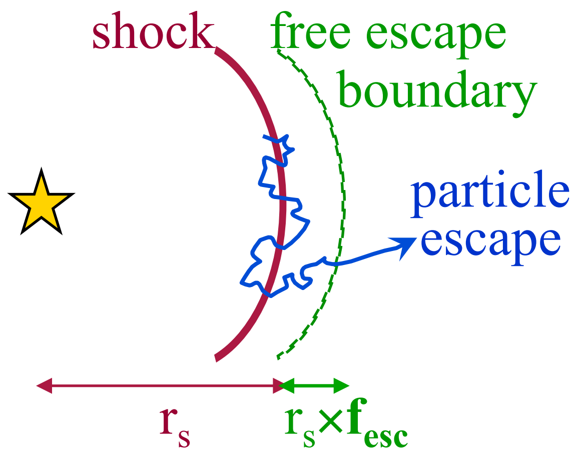
MFA and cosmic-ray escape

- Growth timescale for MHD waves driven by the nonresonant streaming instability (Bell 2004):

$$\tau_{\rm nr}(x) \propto \frac{E_{p,\min}(x)}{\varepsilon_{\rm CR}}$$

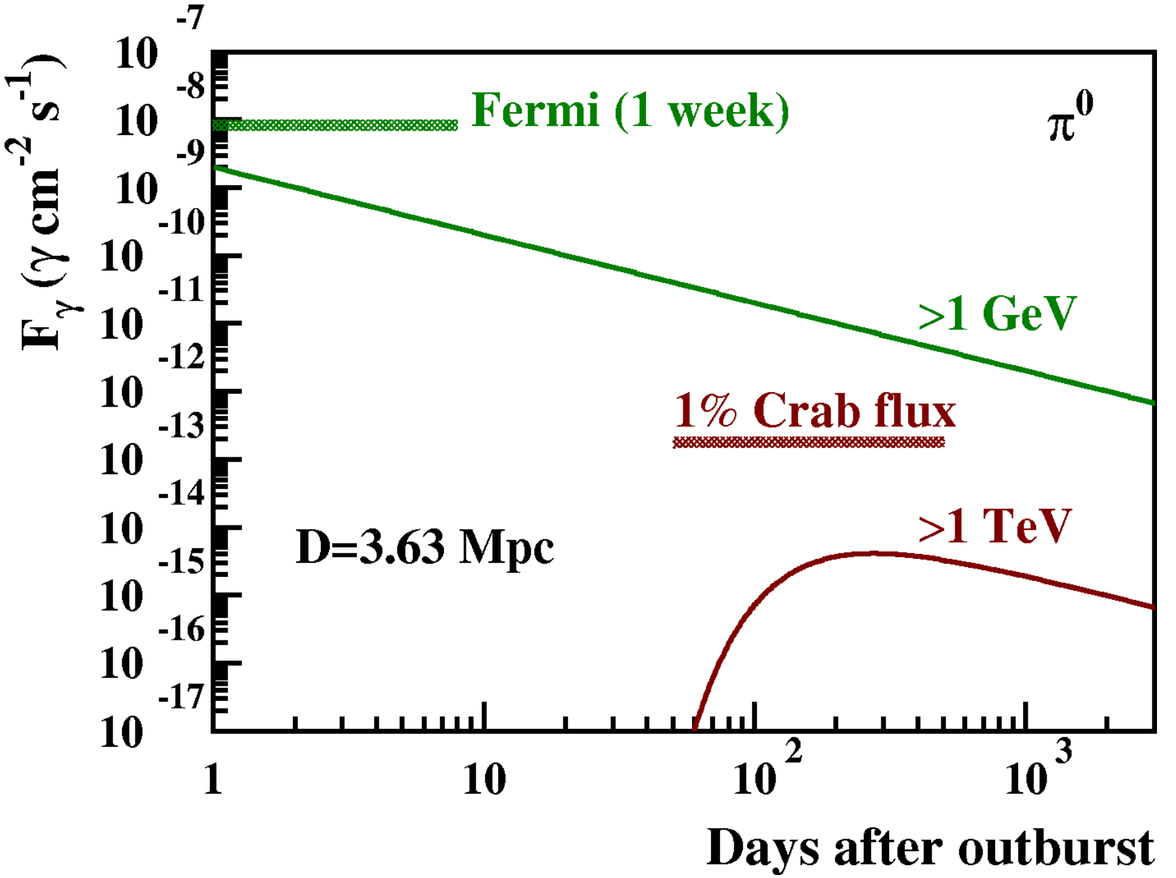


where $E_{p,\min}(x)$ is the minimum CR energy at the upstream distance x ($\tau_{\rm nr}(x)$ is increasing with x)



- The time constraint $\tau_{\rm nr}(x) \le t$ defines a maximum distance $x_{\rm esc}$ for magnetic field amplification and particle confinement
- For SN 1993J, $f_{\rm esc} = x_{\rm esc} / r_{\rm s} \approx 0.05$ independent of time

Gamma-ray emission from π^0 production



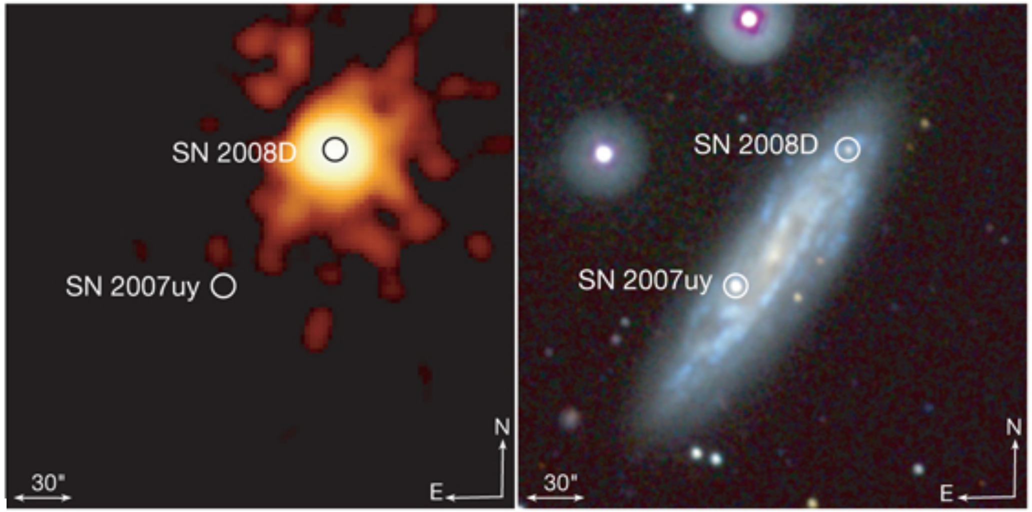
* *Fermi* LAT sensitivity for a 5σ detection in all-sky survey operation

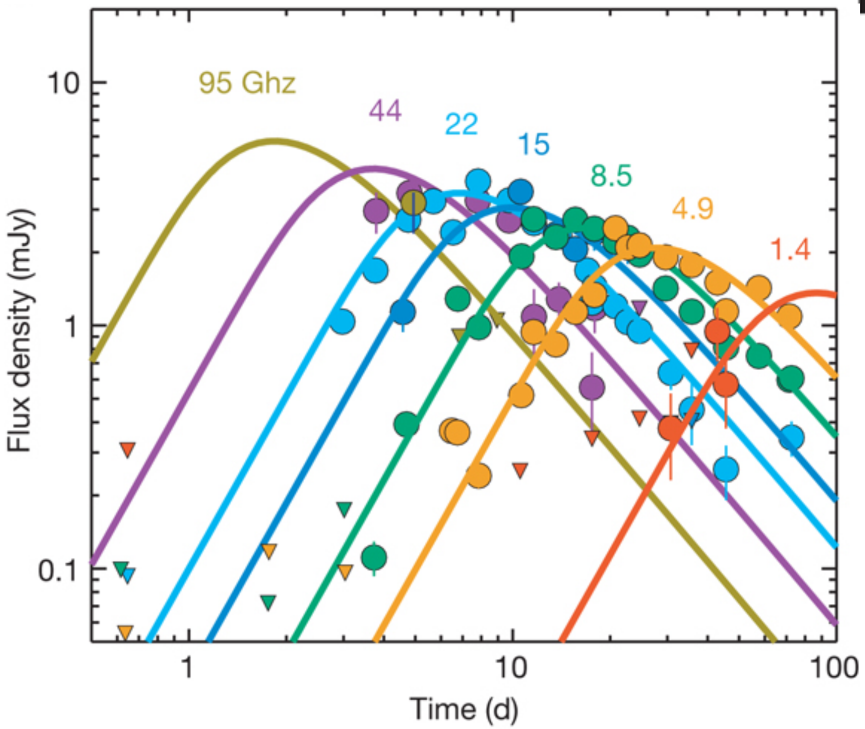
The early TeV emission was strongly attenuated by $\gamma + \gamma \rightarrow e^+ + e^-$ in the dense radiation field from the SN ejecta

$\Rightarrow$ Type II SNe could be detected in π^0-decay γ-rays out to a maximum distance of $\approx$1 Mpc

SN 2008D/XRT 080109

- X-ray transient: SN shock breakout (e.g. Soderberg et al. 2008; Chevalier & Fransson 2008)
- In NGC 2770 ($D = 28$ Mpc)
- Type Ib $\Rightarrow$ explosion of a WR star ($u_{WR} \sim 1000$ km s$^{-1} \sim 100\, u_{RSG}$)





- Radio light curves can be well fitted with a pure SSA model $\Rightarrow$ From the peak flux at each frequency (see, e.g., Chevalier 1998):

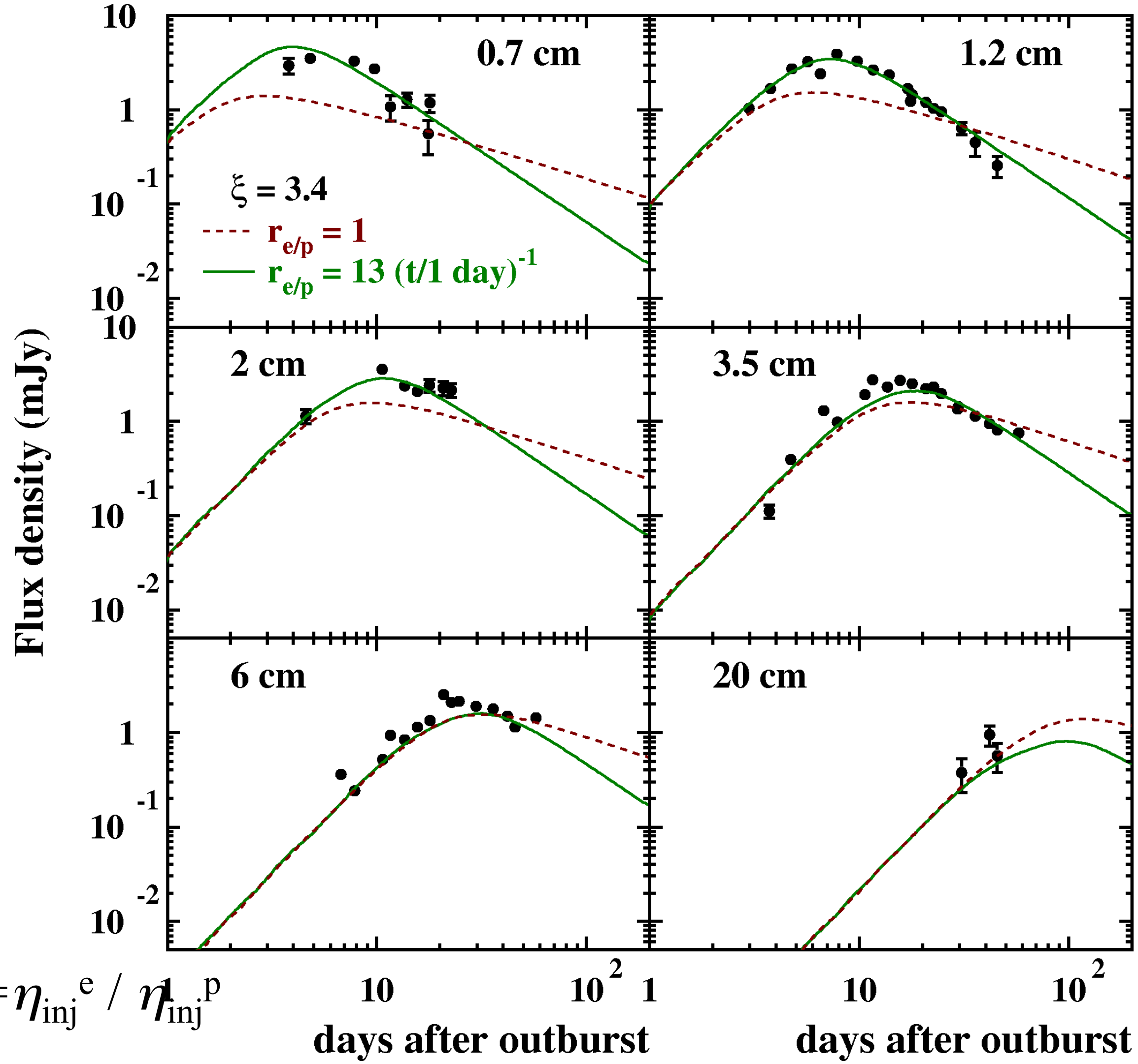
$$v_s \approx 7 \times 10^4 \left(\frac{t}{1 \text{ day}} \right)^{m-1} \text{ km s}^{-1}, \text{ with } m = 0.91$$

$$\langle B \rangle \approx 24.0 \left(\frac{t}{1 \text{ day}} \right)^{-b} \text{ G, with } b = \text{-}1.3$$

SN 2008D — Preliminary results

- MFA by the nonresonant streaming instability: $B_u \equiv \delta B_{nr}$ in the NDSA code
- Particle injection: $p_{inj} = \xi\, p_{th}$ with $\xi \sim 3.5\text{-}4 \Rightarrow \eta_{inj}^{p}$ (Blasi et al. 2005)
- No constraints on $(dM/dt)_{WR}$ (FFA is negligible). In Galactic WR stars: $(dM/dt)_{WR} \approx 3\times10^{-5}\, M_{\odot}\ \mathrm{yr}^{-1}$ (Cappa et al. 2004)

$\Rightarrow$ 2 free parameters:
- ξ
- $r_{e/p} = \eta_{inj}^{e} / \eta_{inj}^{p}$



SN 2008D — Preliminary questions

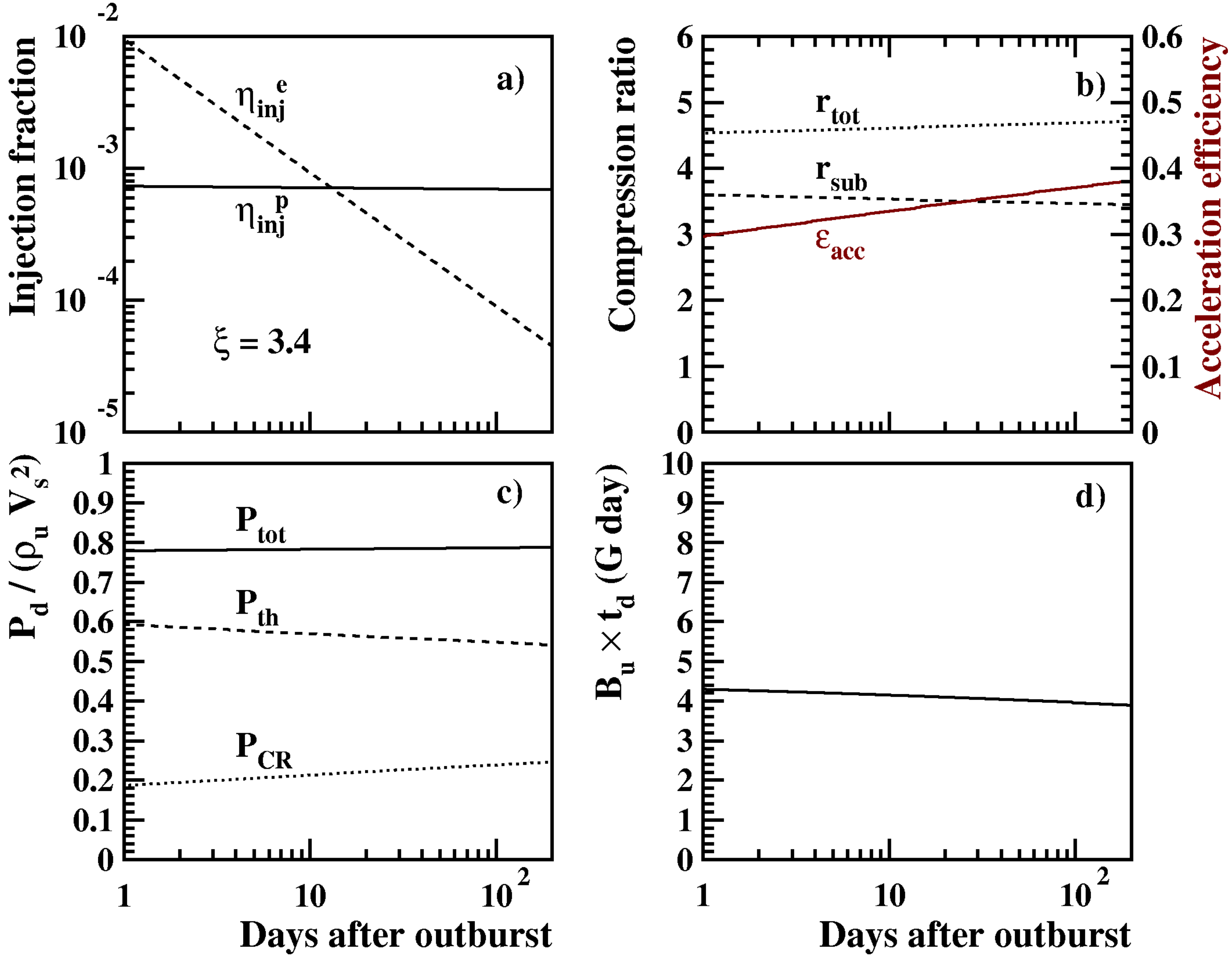
- The simplest model with constant ξ and $r_{e/p}$ + δB advection does not work

⇒ Decreasing η_{inj}^{e} (e- injection)?

⇒ Increasing ξ (decreasing η_{inj}^{p})?

⇒ Postshock B-field damping?

⇒ …?



New modeling of SN 1993J

- FFA being uncertain (T_{CSM}, gas clumps?), ρ_u and thus δB_{nr} might be higher. Assuming $(\mathrm{d}M/\mathrm{d}t)_{RSG} = 3.8\times10^{-4}\ M_{\odot}\mathrm{yr}^{-1}$: