Diffusive shock acceleration of cosmic-rays in radio supernovae

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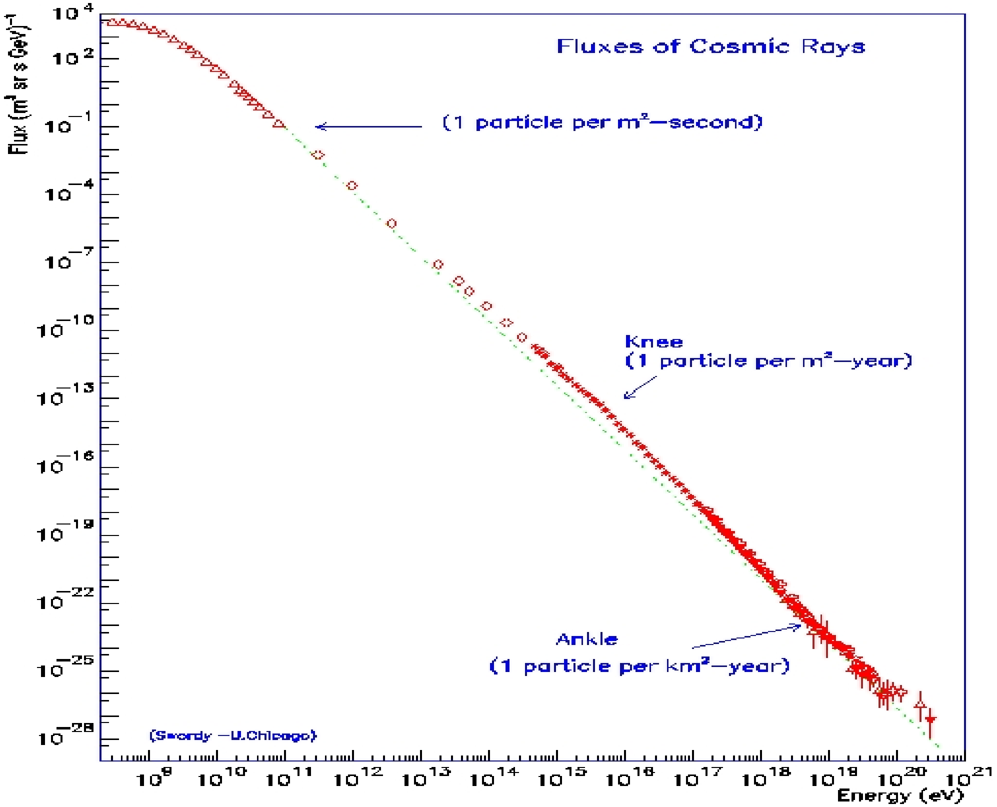
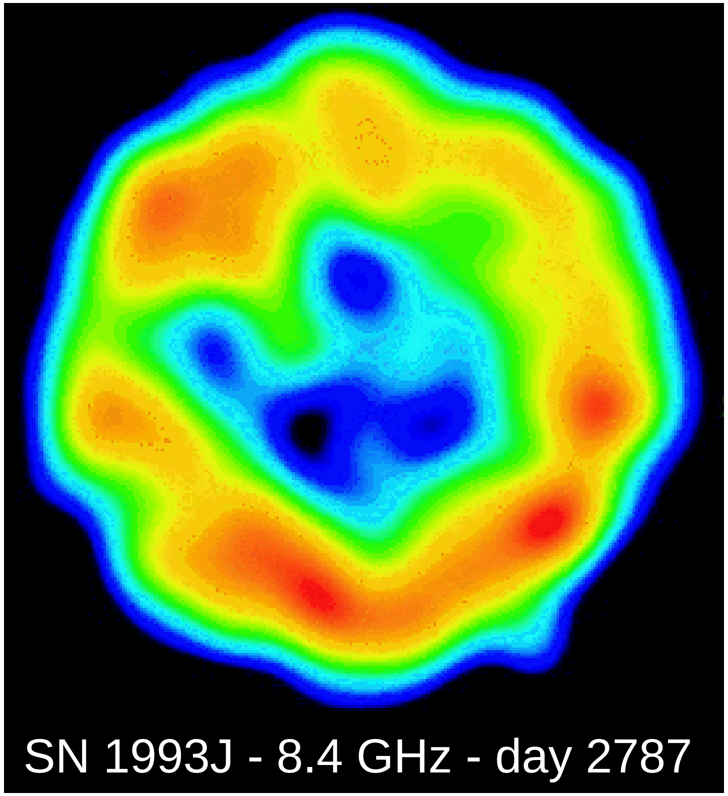
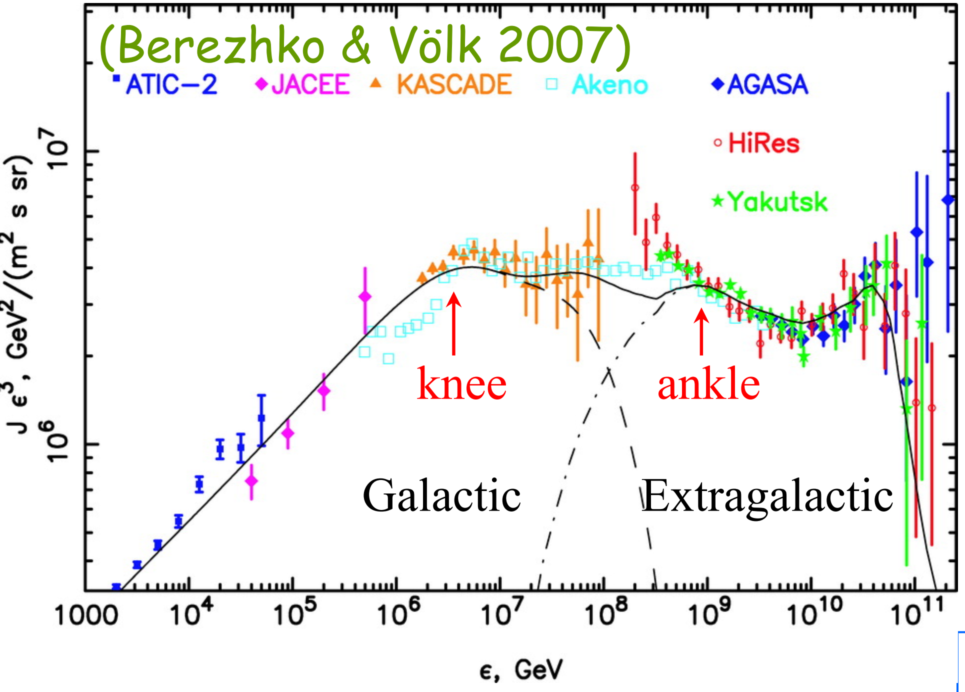
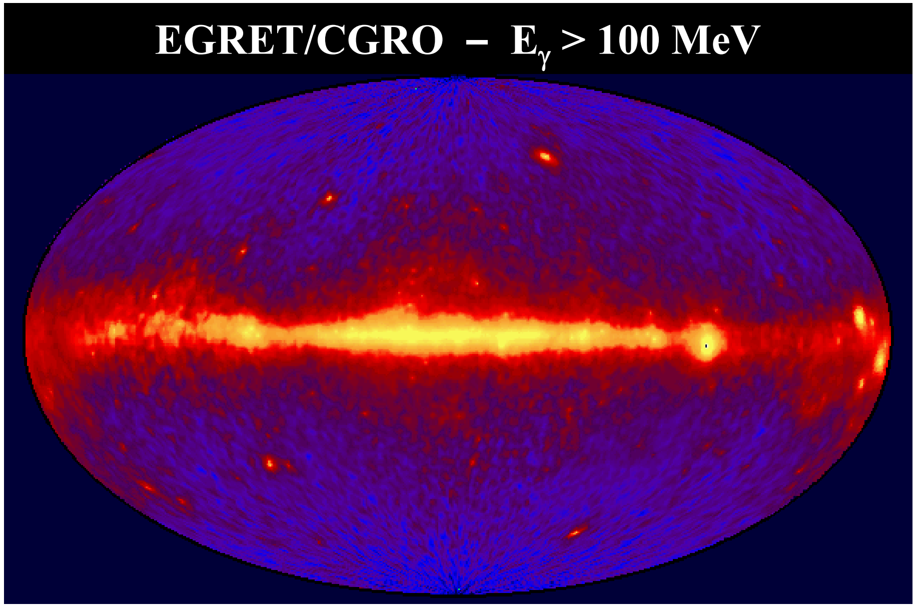



SN 1993J - 8.4 GHz - day 2787

KITP 2009

Galactic cosmic-ray and supernova energetics





- Galactic origin below ~10^{16}–10^{18} eV
- Extrag. from AGNs (Auger 2007)

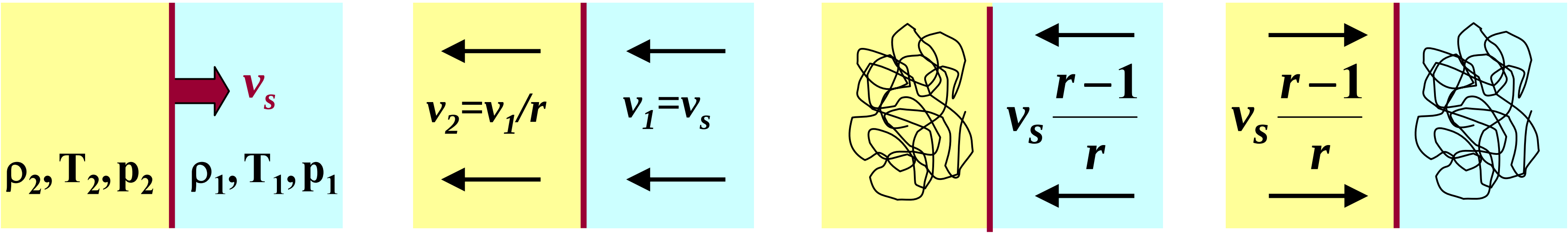
- Galactic diffuse γ-ray emission: CR + ISM → pion → γ
- CR source luminosity: $5\text{x}10^{40}$ erg/s

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

⇒ SN acceleration efficiency ~ 5%

Diffusive shock acceleration

- First-order Fermi (1949) acceleration process in SN shock waves (Krymskii 1977; Bell 1978; Axford et al. 1978; Blandford & Ostriker 1978)
- Particle diffusion on magnetic turbulences on both sides of the shock



ref. frame: observer — shock front — downstream gas — upstream gas

- Fractional momentum gain per cycle: $\frac{\Delta p}{p} = \frac{4}{3} \frac{r-1}{r} \frac{v_s}{c}$ (relativistic)
- Particle energy spectrum: $N(E) \propto E^{-q}$ with $q = 1 + 3 / (r - 1)$ (for a test-particle strong shock $r = 4 \Rightarrow q = 2$)
- Relatively slow process $\Rightarrow$ $E_{\mathrm{max}} = 23\,\mathrm{TeV} \frac{Z B_{\mu\mathrm{G}} E_{51}}{n_0^{1/3} M_{\mathrm{ej}}^{1/6}}$ (Lagage & Cesarky 1983)

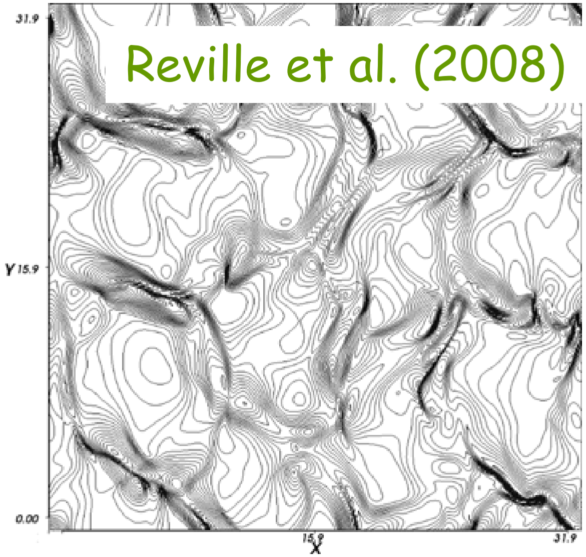
$\Rightarrow E_{p,\mathrm{max}} << 3 \times 10^{15}$ eV for $B \sim$ few μG !

Magnetic field amplification

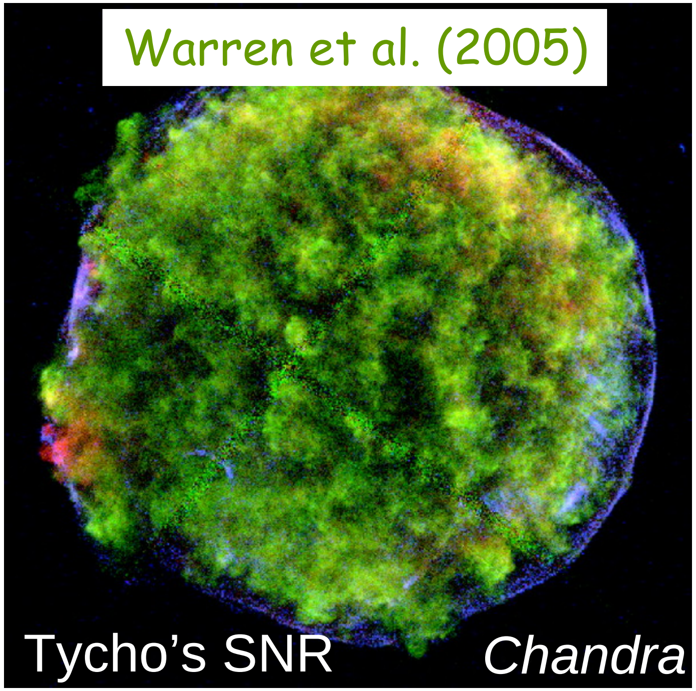
- CRs can excite magnetic fluctuations in the upstream plasma by both resonant (Bell and Lucek 2001) and nonresonant (Bell 2004) streaming instabilities: $\delta B/B \gg 1$

- Evidence for B-field amplification in SNRs ($\delta B/B \sim 100$) from
  (1) synchrotron X-ray filaments
  (but δB damping? Pohl et al. 2005) (2)
  variability of X-ray hot spots
  (Uchiyama et al. 2007) (3)
  broadband emission (4)
  spectral curvature in radio emission

$\Rightarrow$ Acceleration to $\approx 10^{15}$ eV. And beyond?



Reville et al. (2008)

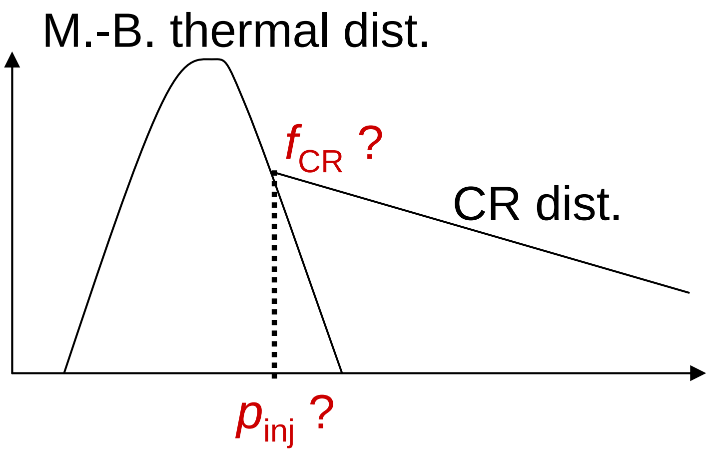


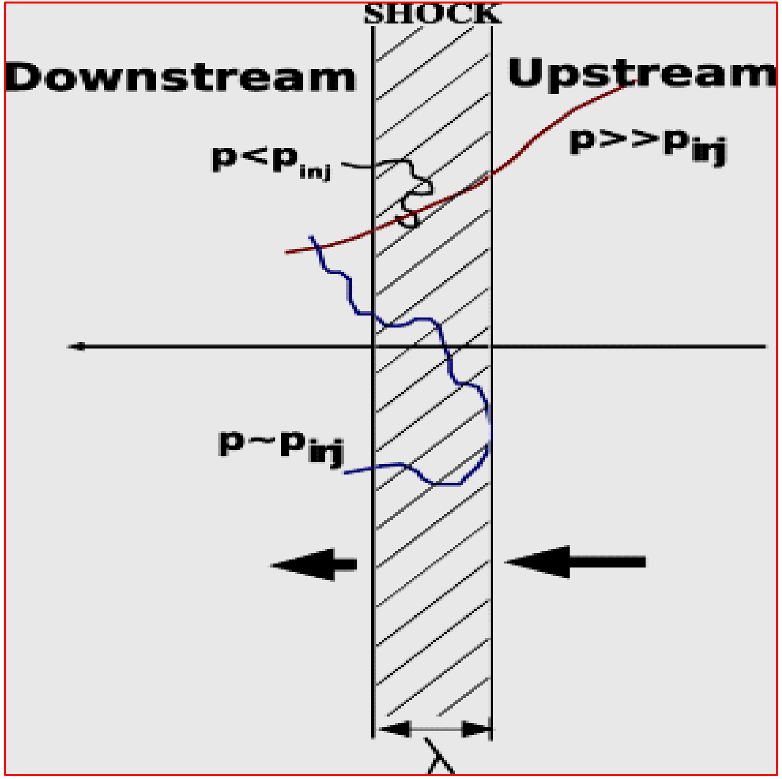
Warren et al. (2005)

Particle injection into the DSA process

- Particles injected into the DSA process: postshock thermal particles with $p > p_{\mathrm{inj}}$ (Ellison et al.; Monte-Carlo simulations)
- Condition for injection (Blasi et al. 2005): $r_L > \lambda = \alpha \, r_L^{th}$, with the shock thickness parameter $\alpha = 1 - 2$
- But depending on α (and the shock strength), the fraction of thermal particles converted into CRs $\eta_{\mathrm{inj}} \in [10^{-5}, 10^{-2}]$

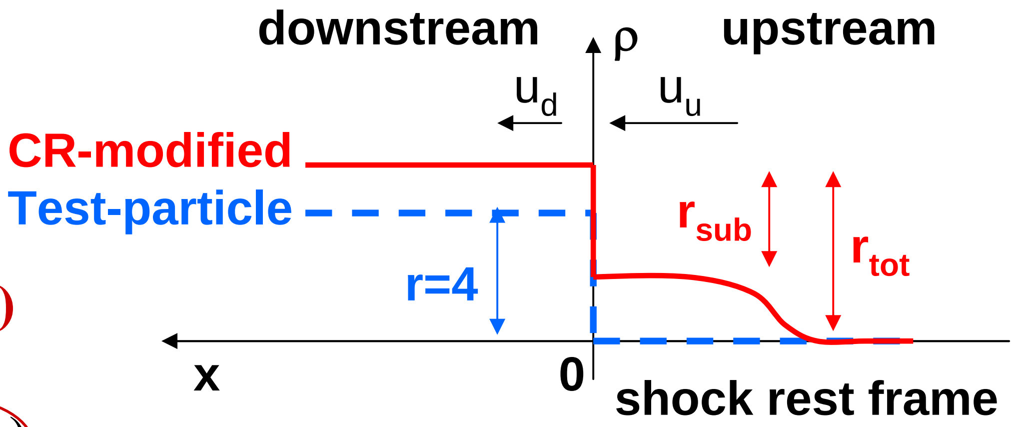
$\Rightarrow$ Acceleration efficiency ?





Cosmic-ray modified shock

See Berezhko & Ellison (1999);
Blasi et al. (2005)



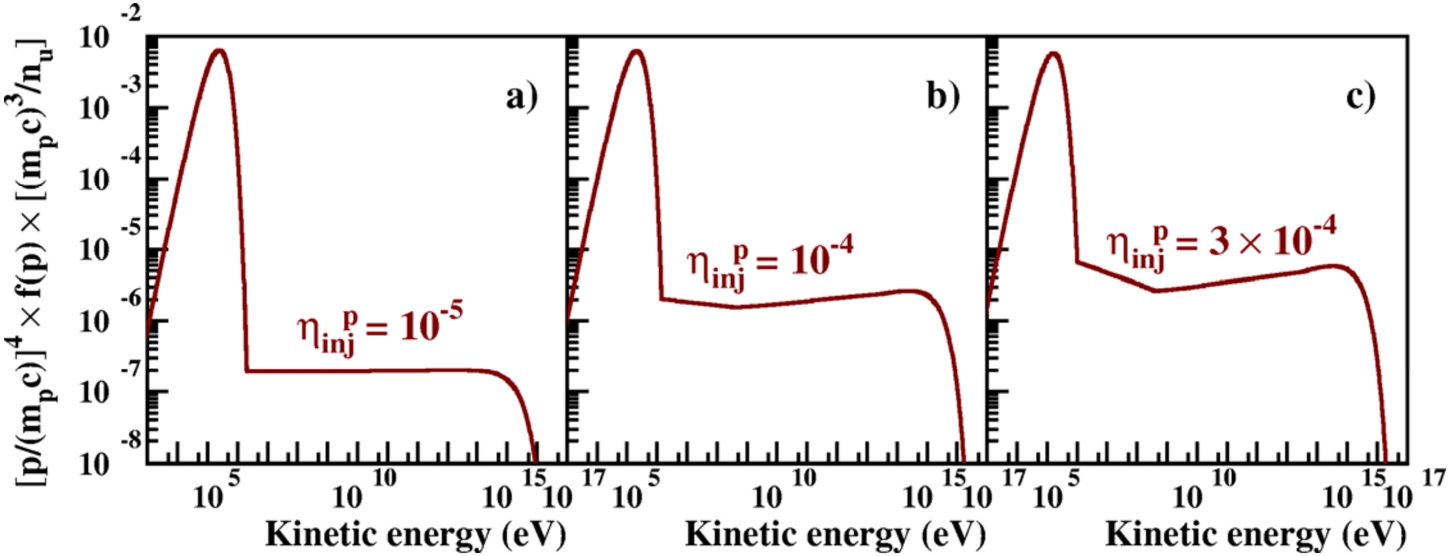
- Momentum flux conservation:

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

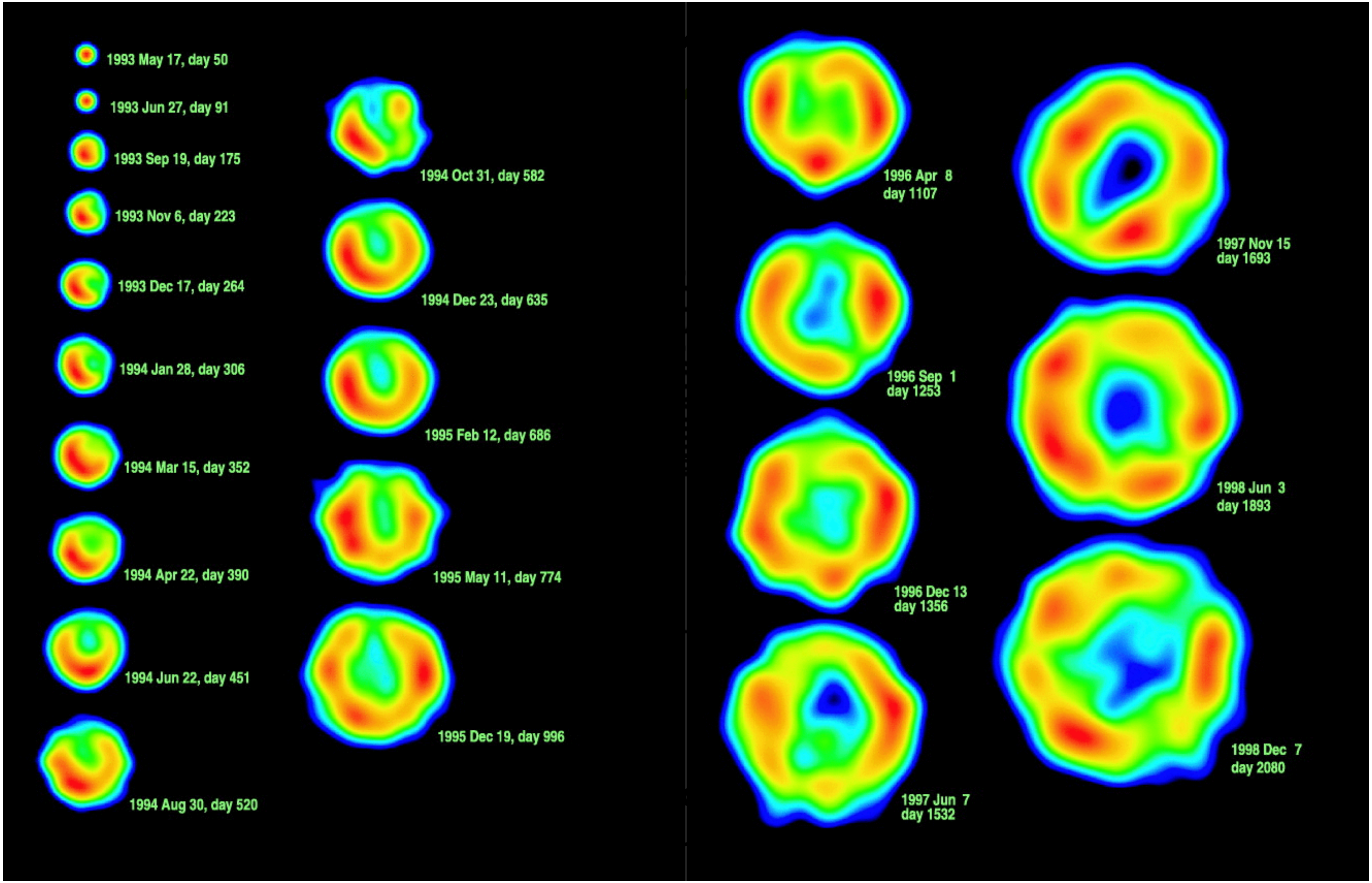
with $P_{CR}(x) = \frac{1}{3}\int_{p_{inj}}^{p_{max}} dp 4\pi p^3 v(p) f(x,p)$

particle dist. funct. (⇐ diffusive transport eq.)

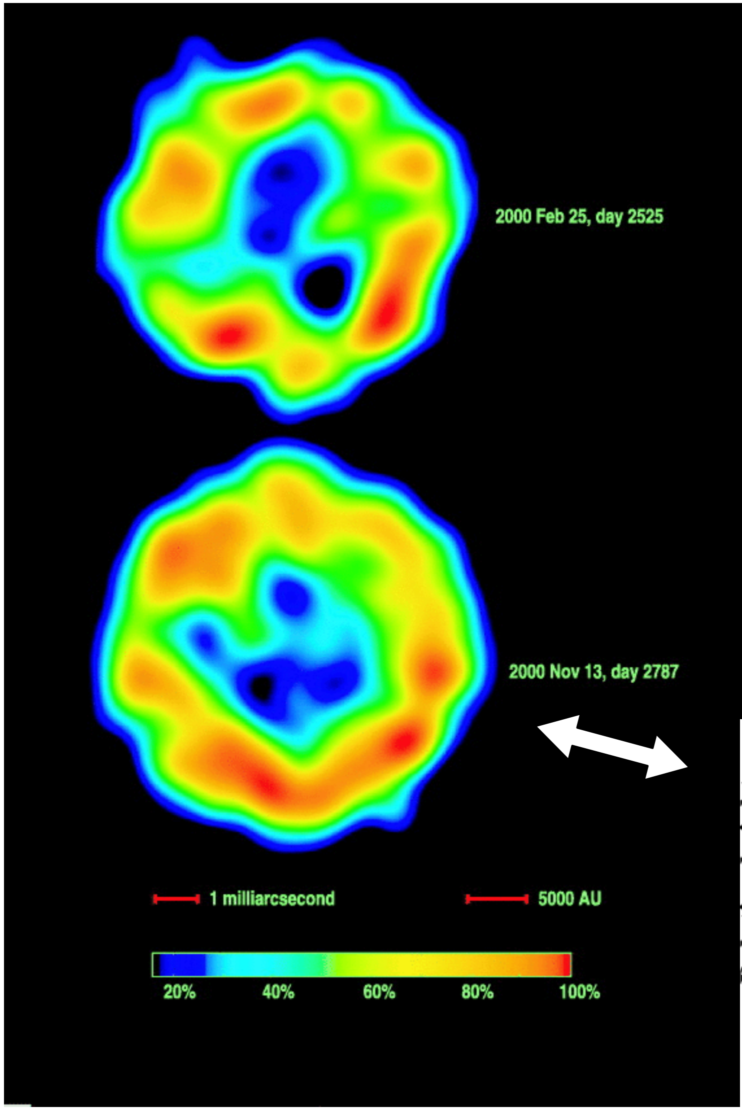
- Higher energy particles feel a higher compression ratio ⇒ concave spect.



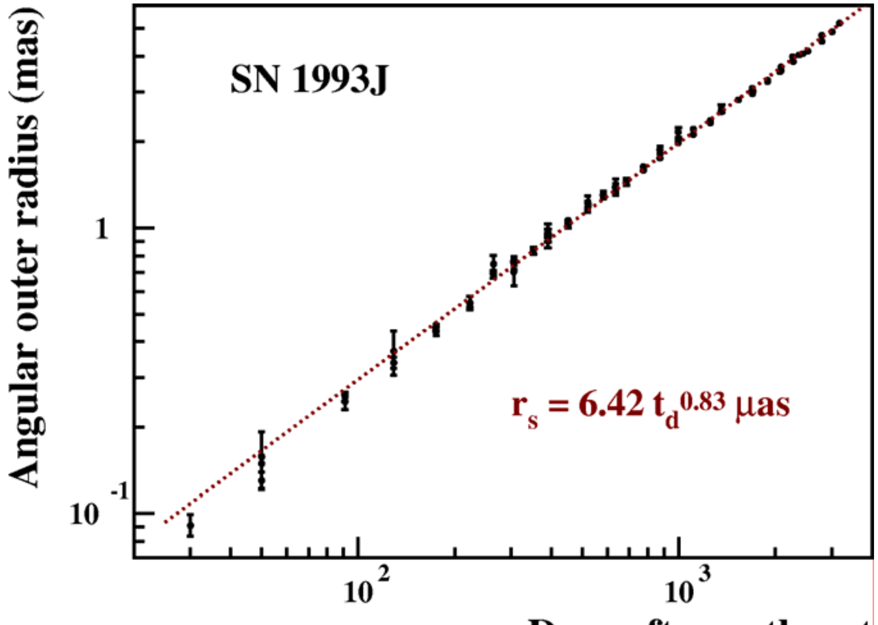
SN 1993J — One of the best observed radio SN

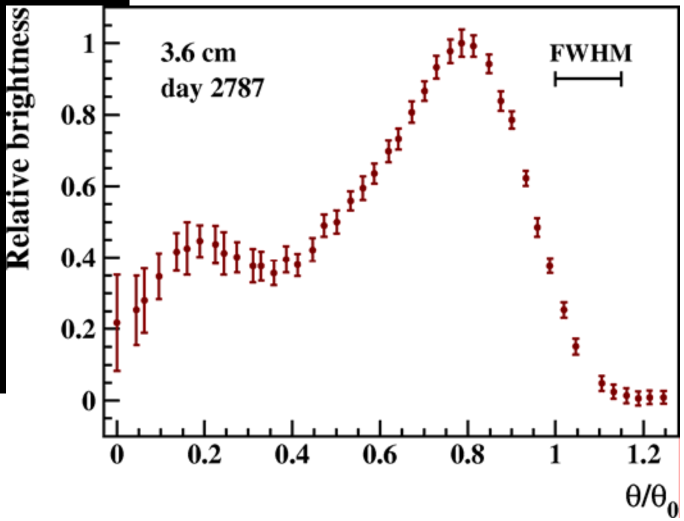


SN 1993J VLBI observations



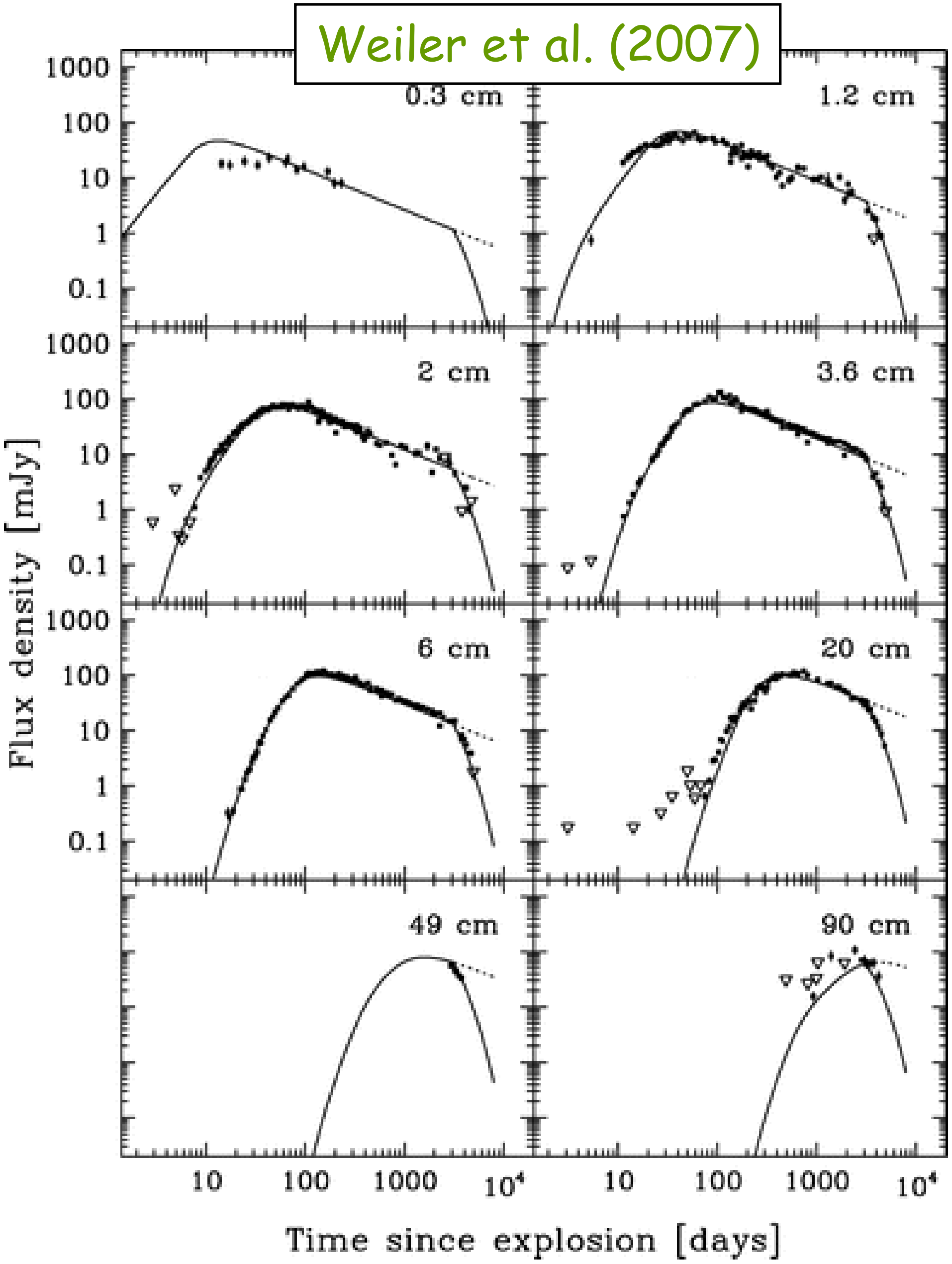
- The expansion is almost self similar

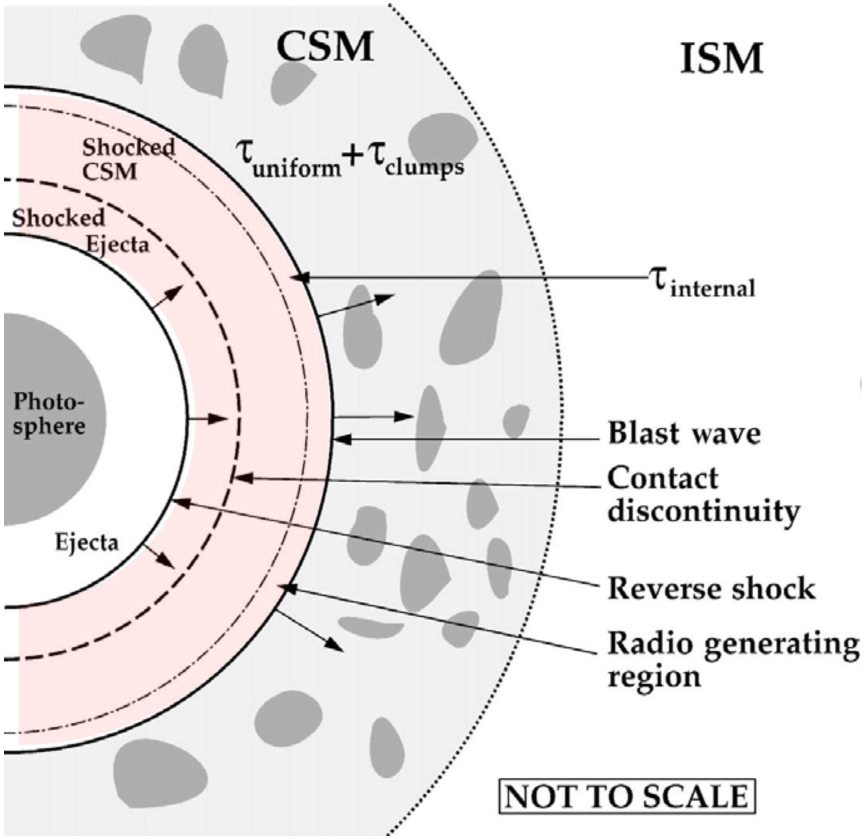




See, e.g.,
Marcaide et al.
(1995, 1997)
Bartel et al.
(2002, 2007)

Radio light curves


Weiler et al. (2007)



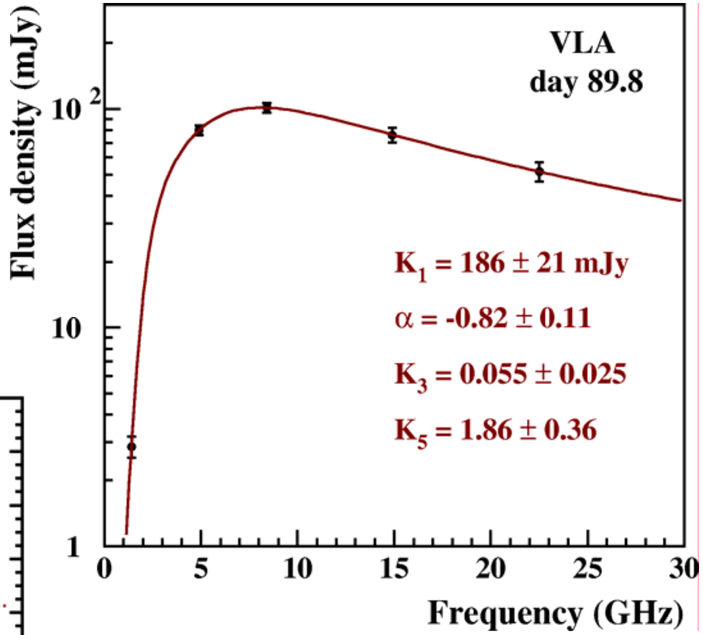
- Abrupt decline after day ~3100 as the shock has reached the outer limit of the dense CSM
- Weiler et al.: overall fit to all the data with 9 free parameters

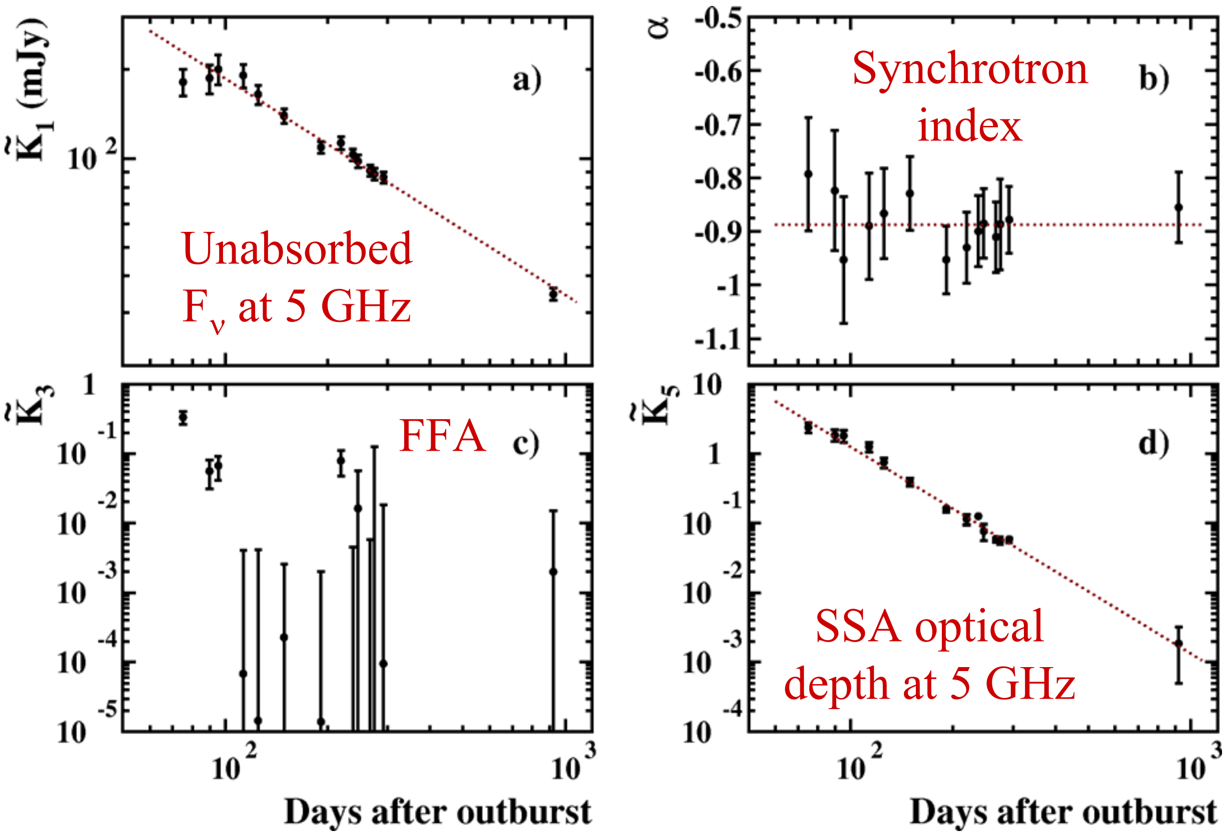
Synchrotron self-absorption (SSA)

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

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

- Fits to individual VLA spectra





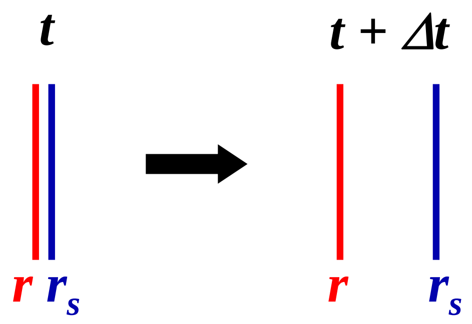
$$\langle B \rangle = (2.4 \pm 1.0)\left(\frac{t}{100\text{ days}}\right)^b \text{ G}$$

with $b = -1.16 \pm 0.20$

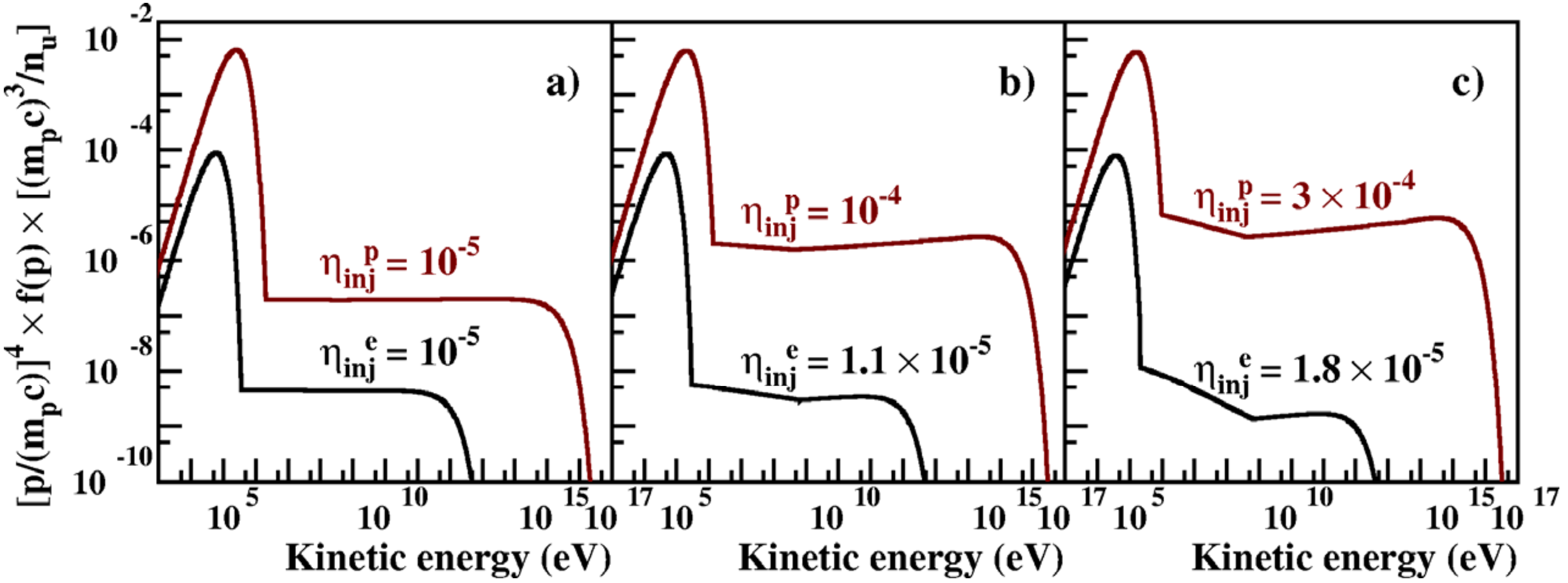
⇒ Strong amplification of the stellar B-field

Radio SN model (1)

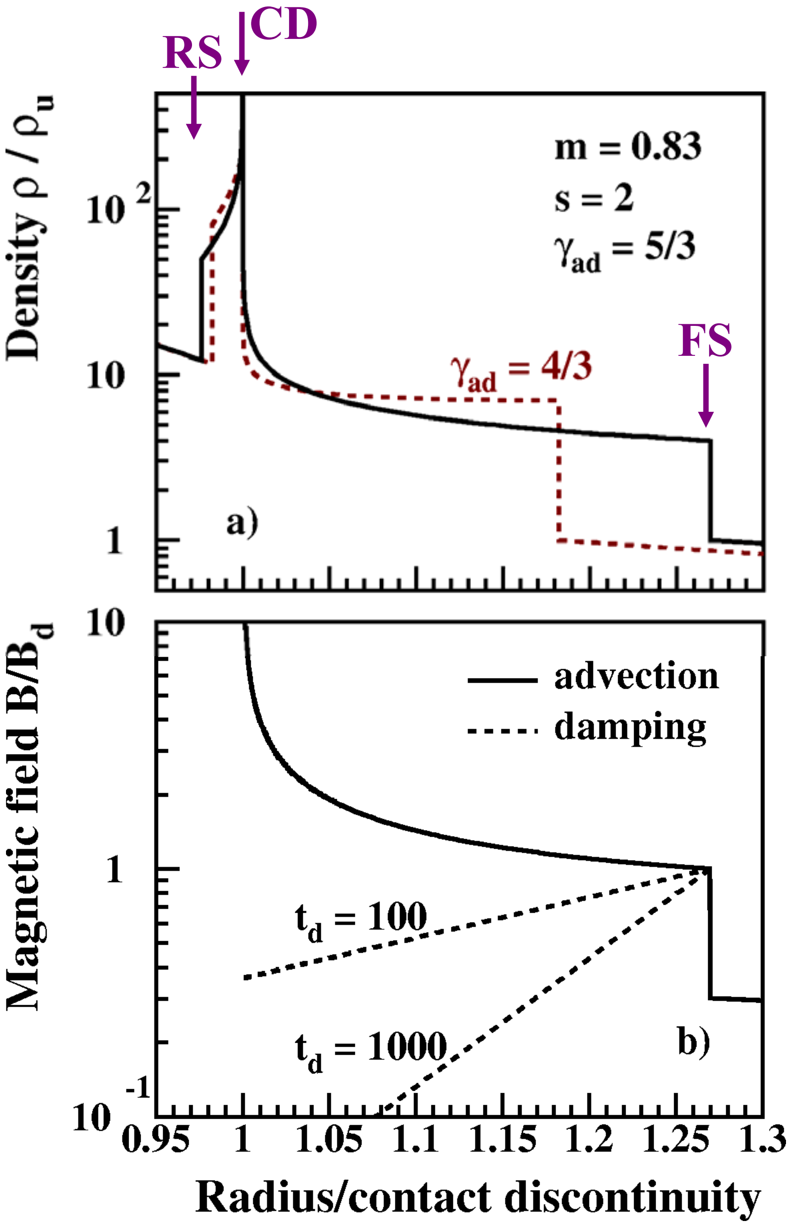
- Inspired by Cassam-Chenaï, Ellison et al. (2005) for Galactic SNRs
- Nonlinear diffusive shock acceleration model (Berezhko & Ellison 1999) $\Rightarrow f_p(p,r_s)$ and $f_e(p,r_s)$
  f_e depends on the proton injection parameter $\eta_{\rm inj}^{\rm p}$



- 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)

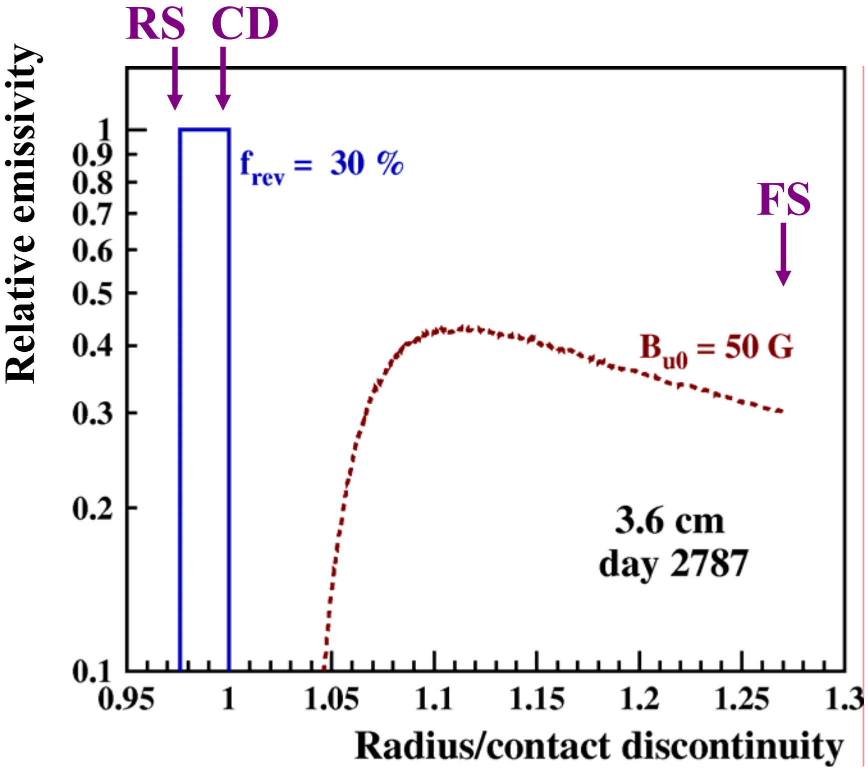


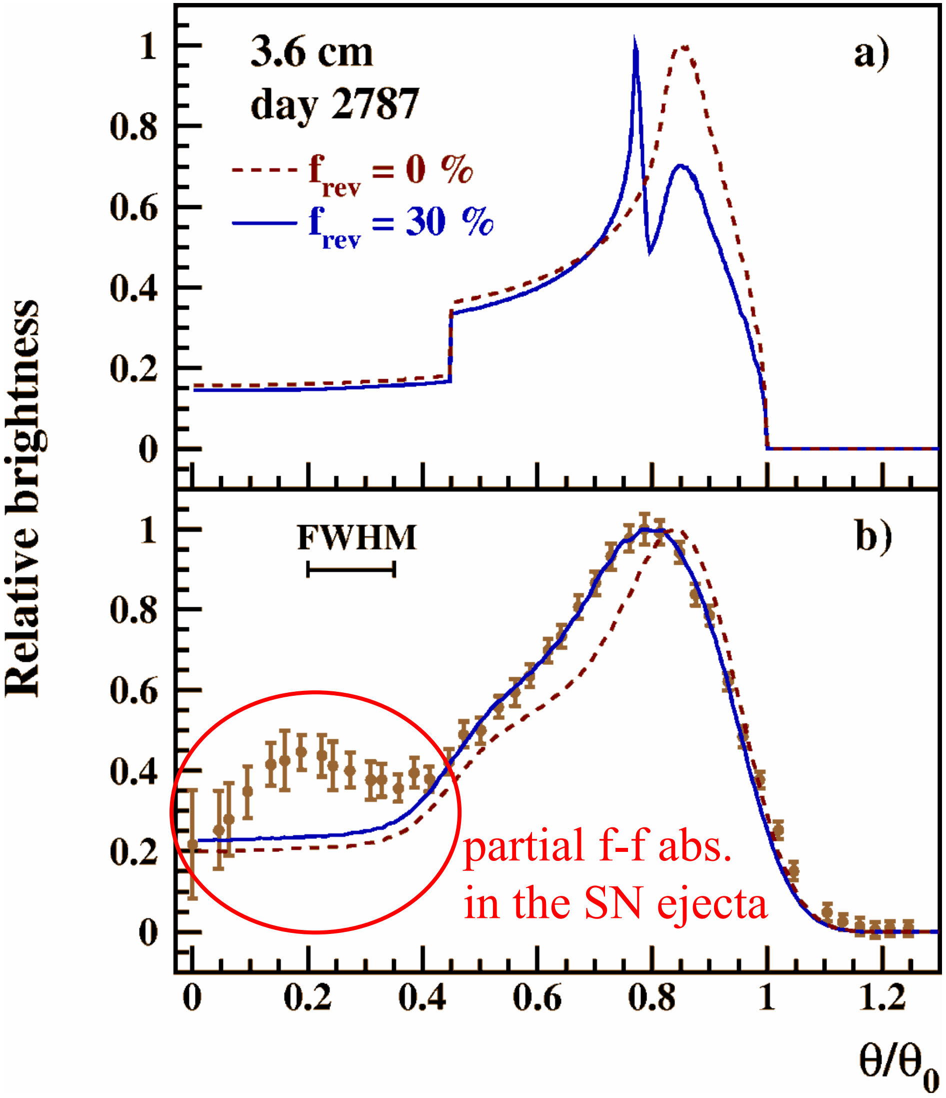
- Hydrodynamic of the postshock plasma: self-similar solutions (Chevalier 1983)
- Postshock magnetic field evolution:
  - advected in the plasma flow or
  - damped by cascading of MHD wave energy (Pohl et al. 2005)
- Synchrotron emission: radiative transfer calculations including synchrotron self-absorption
- 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 $\eta_{\mathrm{inj}}^{\mathrm{e}}$

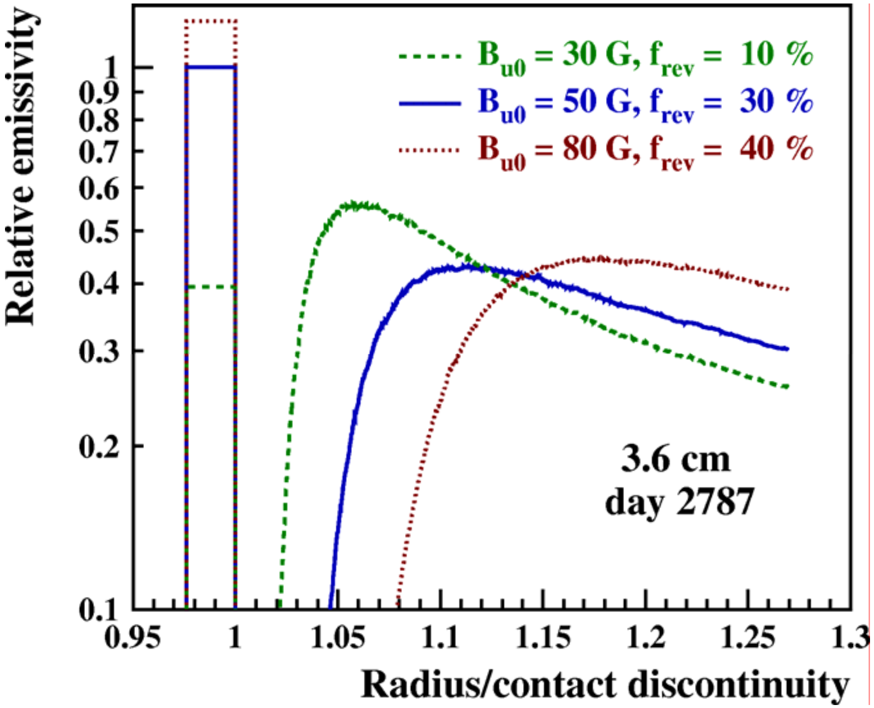
Acceleration at the reverse shock

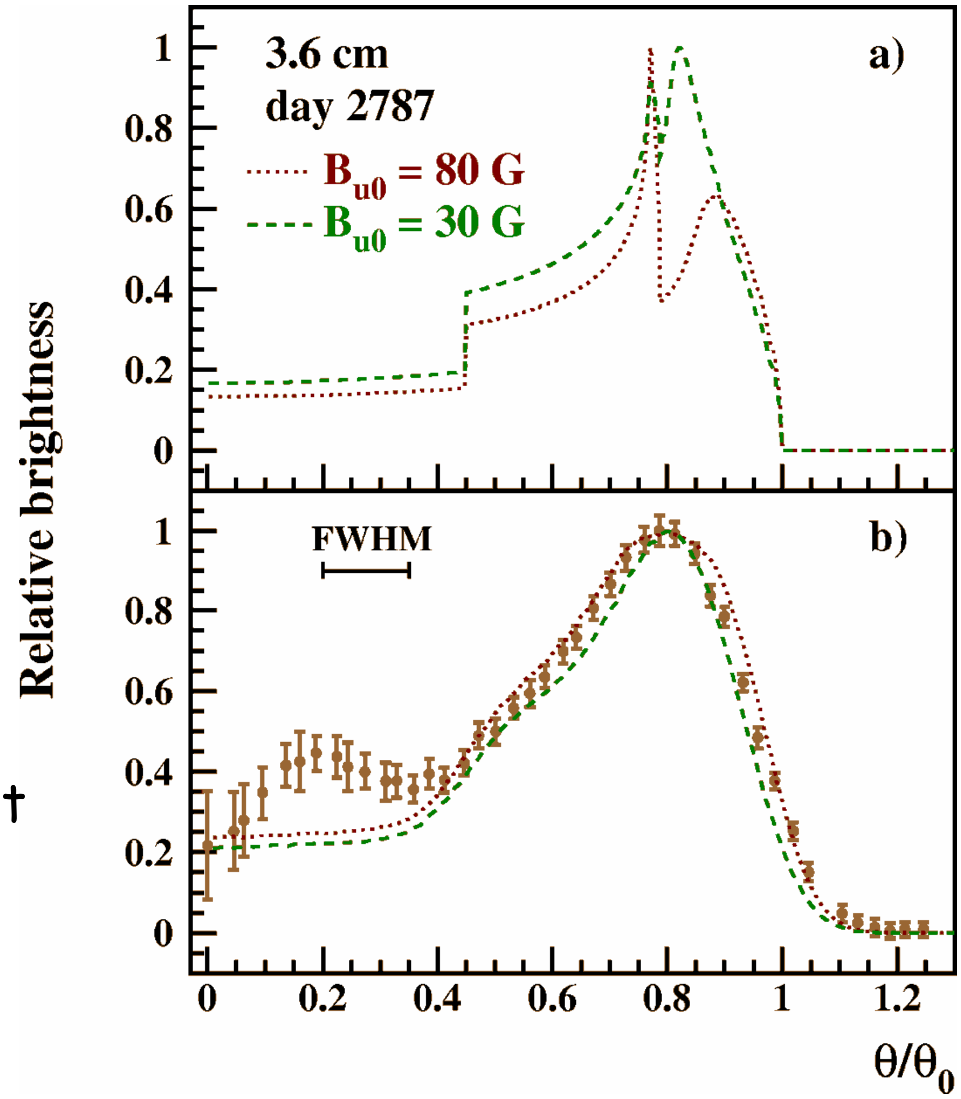




- Electrons accelerated at the reverse shock account for ≤17% of the total radio flux

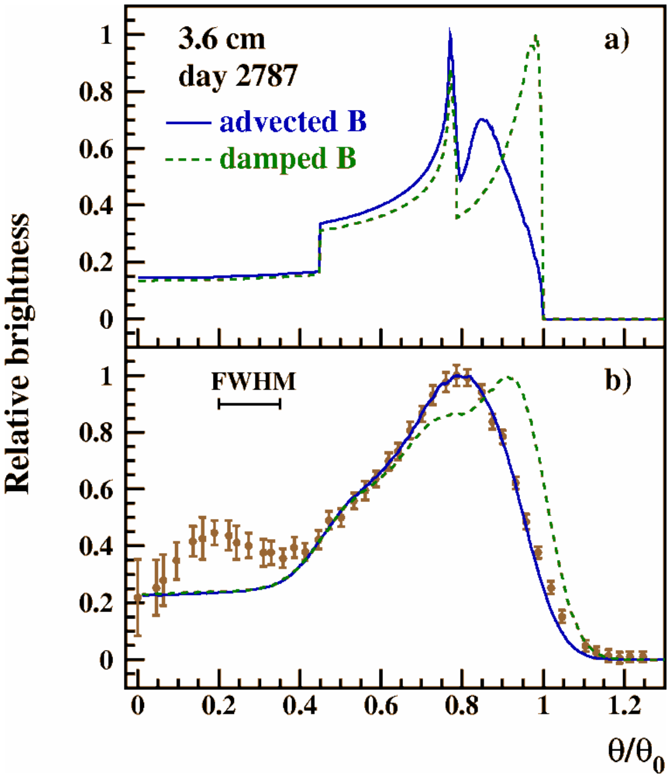
Radio profile — B-field estimate

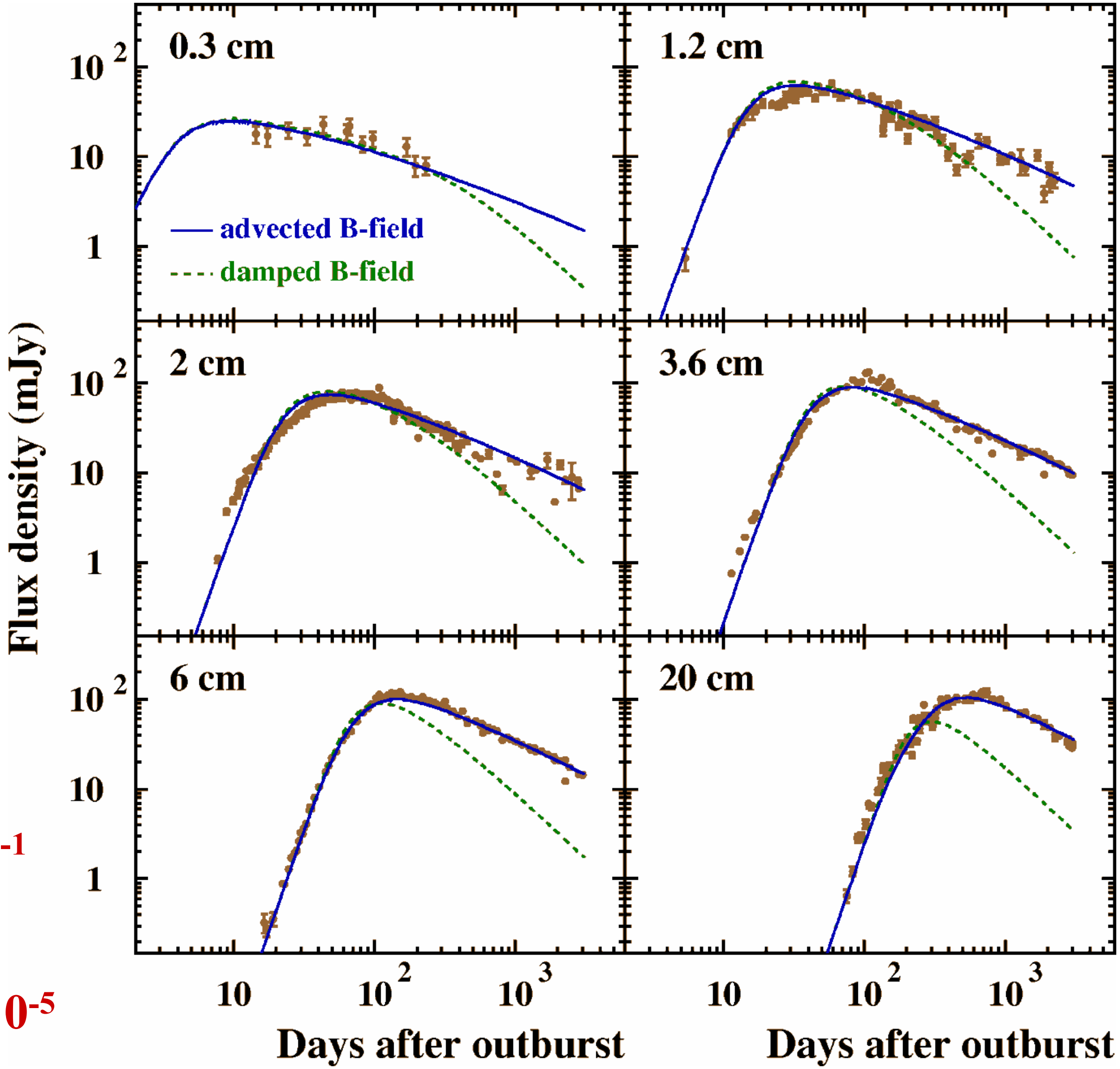




- Synchrotron losses are important to the radial emissivity
- From the width of the observed radial profile: 30 $< B_{u0} <$ 80 G

No damping of the postshock magnetic field





- Best parameter values:
  - $(\mathrm{d}M/\mathrm{d}t)_{\mathrm{RSG}} \approx 3.8\times10^{-5}\ M_\odot\,\mathrm{yr}^{-1}$
  - $B_{u0} = 50 \pm 20$ G
  - $\eta_{\mathrm{inj}}^{p} \approx 10^{-4}$ and $\eta_{\mathrm{inj}}^{e} \approx 1.1\times10^{-5}$

Magnetic field amplification

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

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

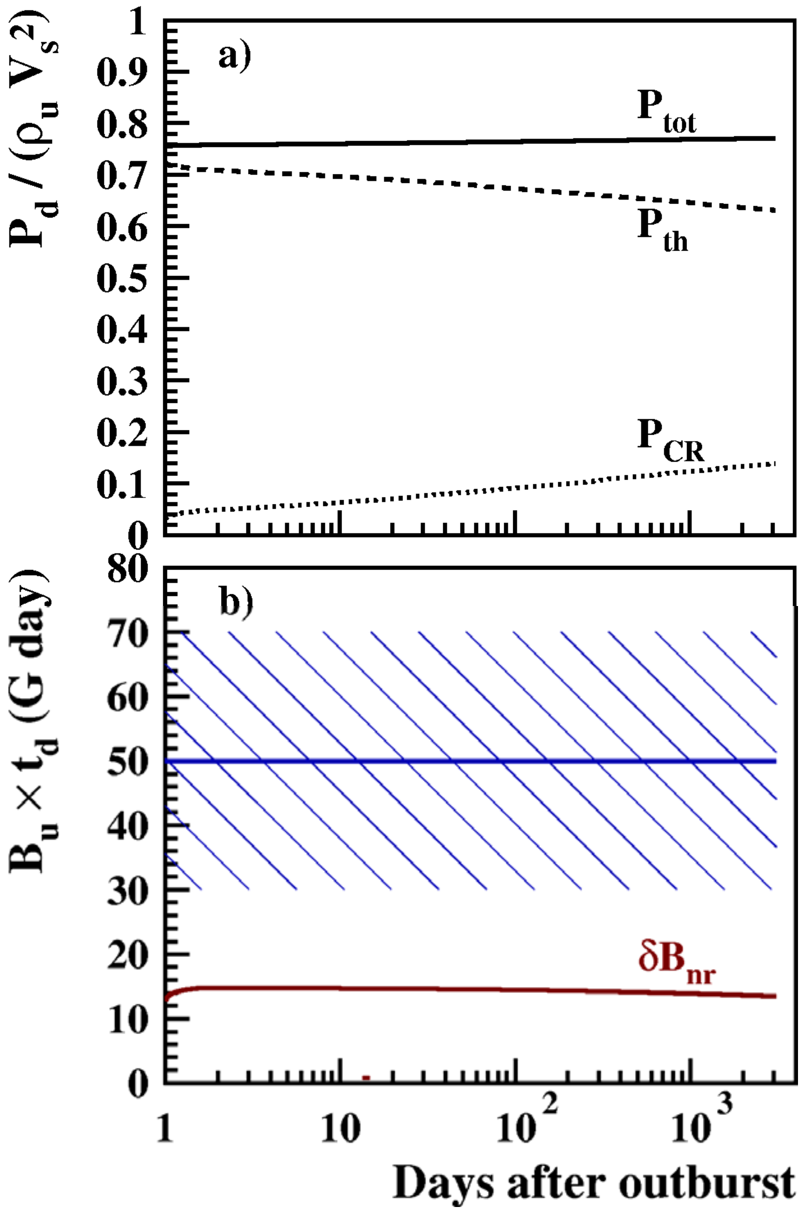
2-5 lower than the "measured" B-field

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

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

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

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

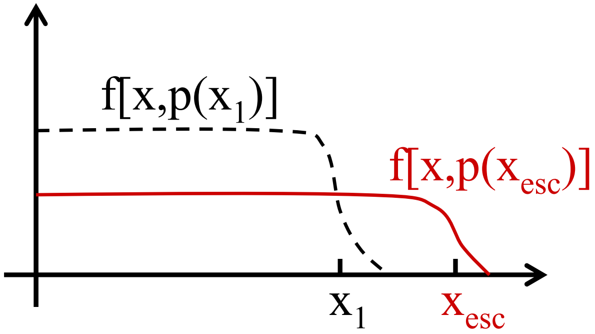


MFA and cosmic-ray escape

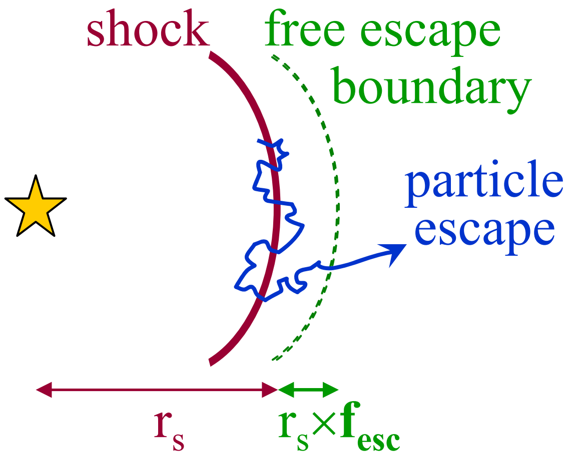
- Growth timescale for MHD waves driven by the nonresonant streaming instability (Bell 2004):

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

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

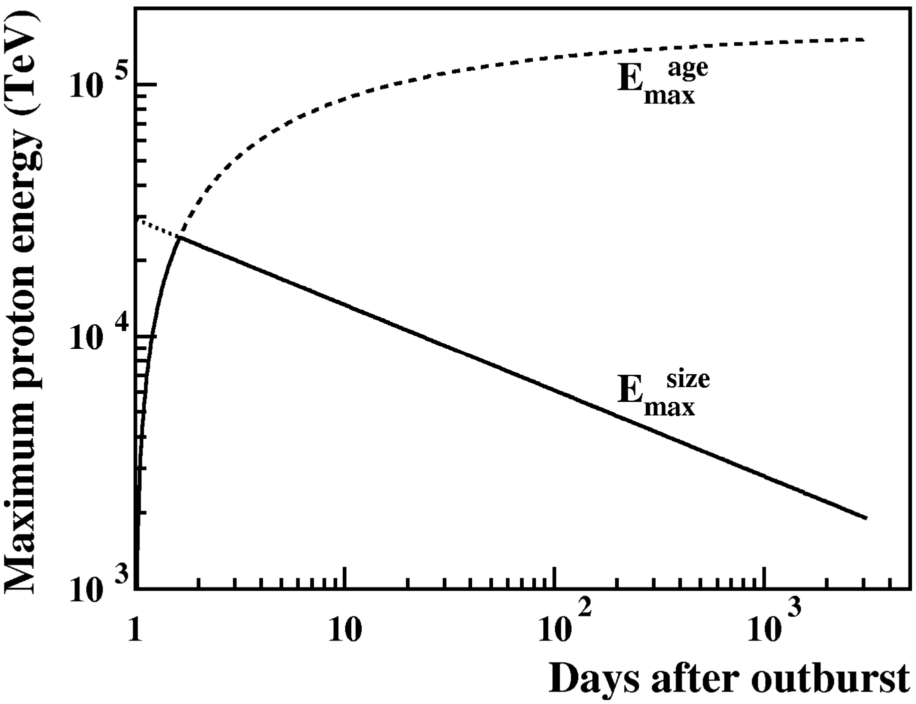


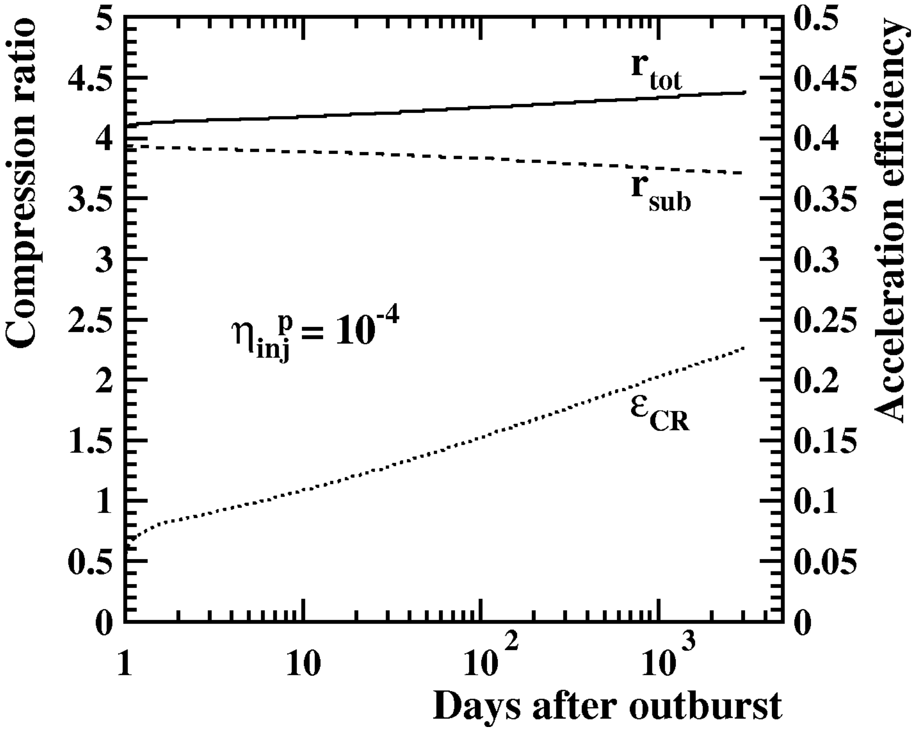
- The time constraint $\tau_{\rm nr}(x) \leq t$ defines a maximum distance $x_{\rm esc}$ for magnetic field amplification and particle confinement



- For SN 1993J, $f_{\rm esc} = x_{\rm esc} / r_s \approx 0.05$ independent of time

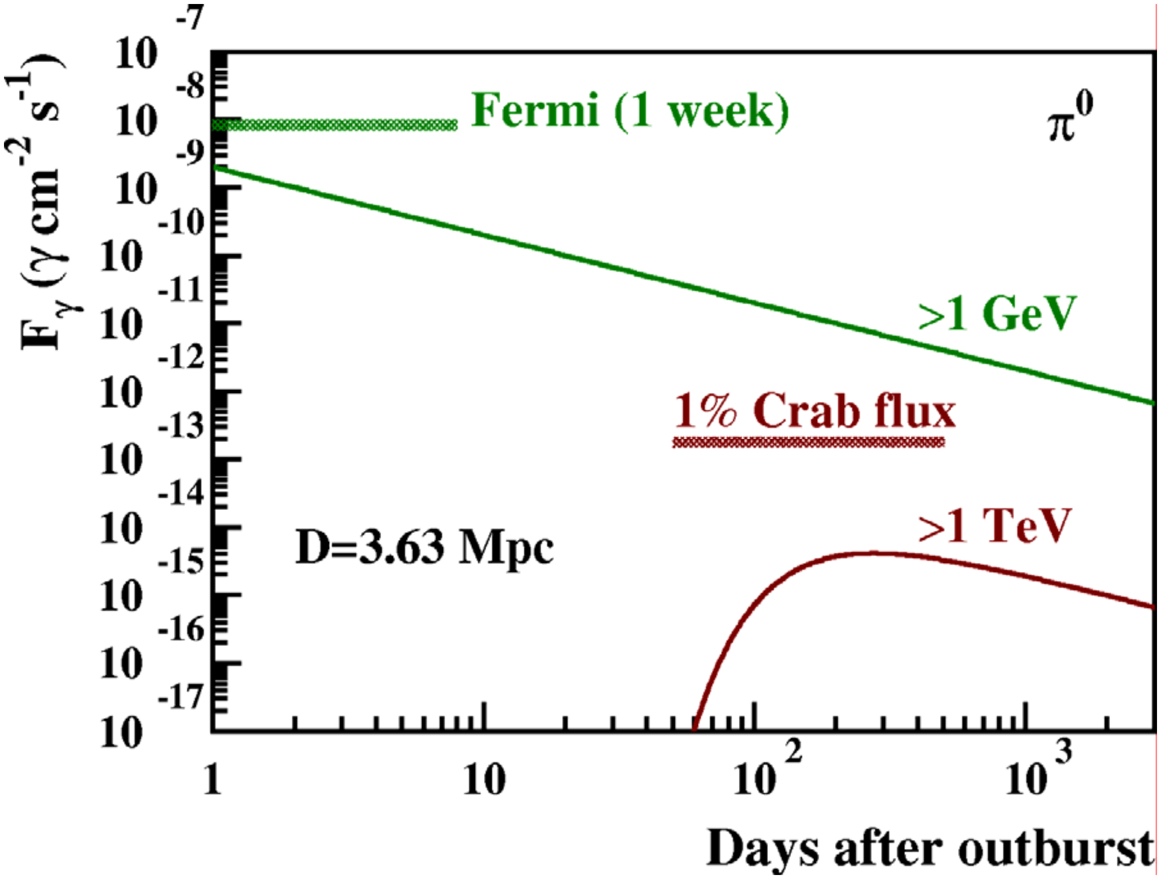
SN 1993J and the origin of cosmic rays





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

Gamma-ray emission from π^0 production

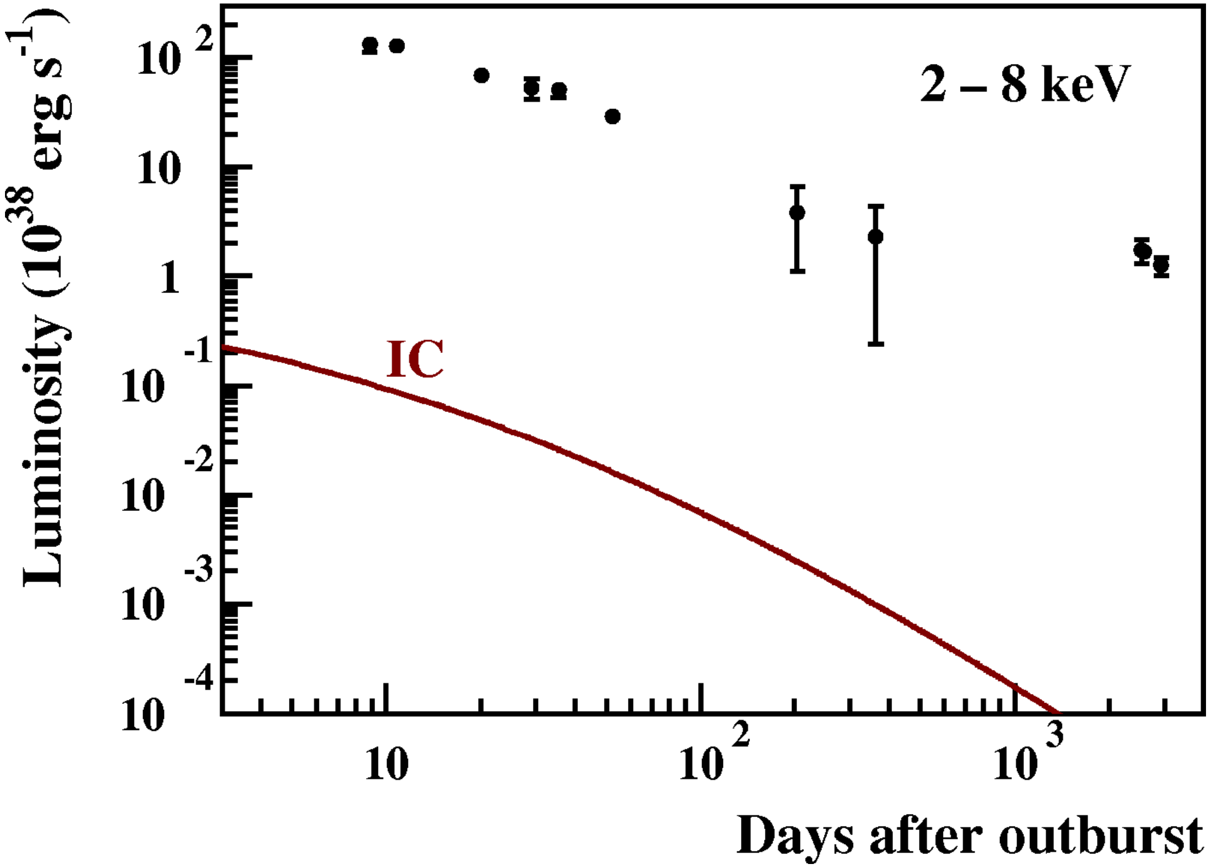


* *Fermi* LAT sensitivity for a 5σ detection in all-sky survey operation

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

⇒ Type II SNe could be detected in π^0-decay γ-rays out to a maximum distance of ≈1 Mpc

Inverse Compton contribution



Radiation field:

$$L_{\mathrm{bol}} \approx 4 \times 10^{42} \left(\frac{t}{10\ \mathrm{d}} \right)^{-0.9} \ \mathrm{erg\ s^{-1}}$$

$$T_{\mathrm{bb}} \approx 7000\ \mathrm{K\ for}\ > 120\ \mathrm{days}$$

Richmond et al. (1994);
Lewis et al. (1994);
Fransson & Björnsson (1998)

Not important in both the gamma-ray and X-ray energy domains

X-ray emission mostly from the reverse shock (Chandra et al. 2009)

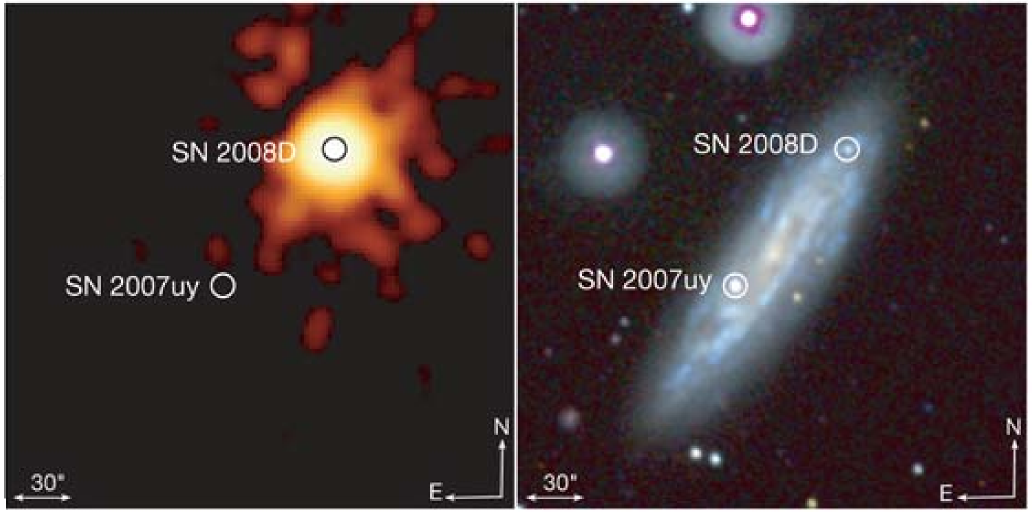
Conclusions

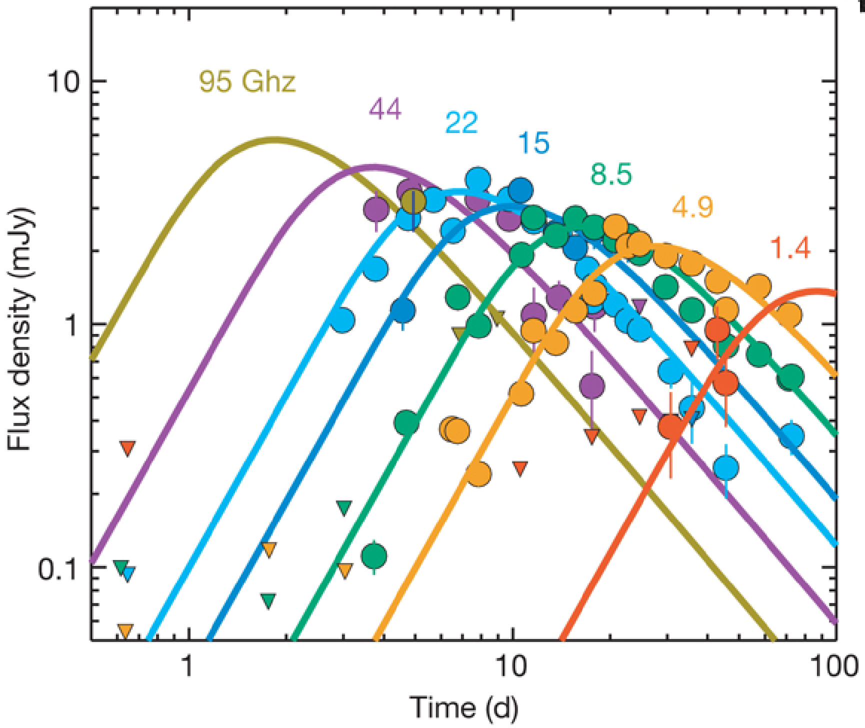
- Evidence from the morphology of the radio emission from SN 1993J that electrons are accelerated at the reverse shock
- The blast wave is a weakly cosmic-ray-modified shock, $\eta_{\mathrm{inj}}^{\mathrm{p}} \approx 10^{-4}$
- B-field amplification, possibly by the Bell's nonresonant streaming instability in the precursor region
- The magnetic turbulence is not damped behind the shock
- Massive stars exploding into their former stellar wind could be a major source of GCRs above ~10^{15} eV (Völk & Biermann 1988)
- Type II SNe could be detected at γ-ray energies out to only ≈1 Mpc
- A new model for radio SNe, e.g. SN 2008D…

Refs: Tatischeff (2008) PoS [arXiv:0804.1004]; *A&A* 499, 191 (2009)

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 ⇒ 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 ⇒ From the peak flux at each frequency (see, e.g., Chevalier 1998):

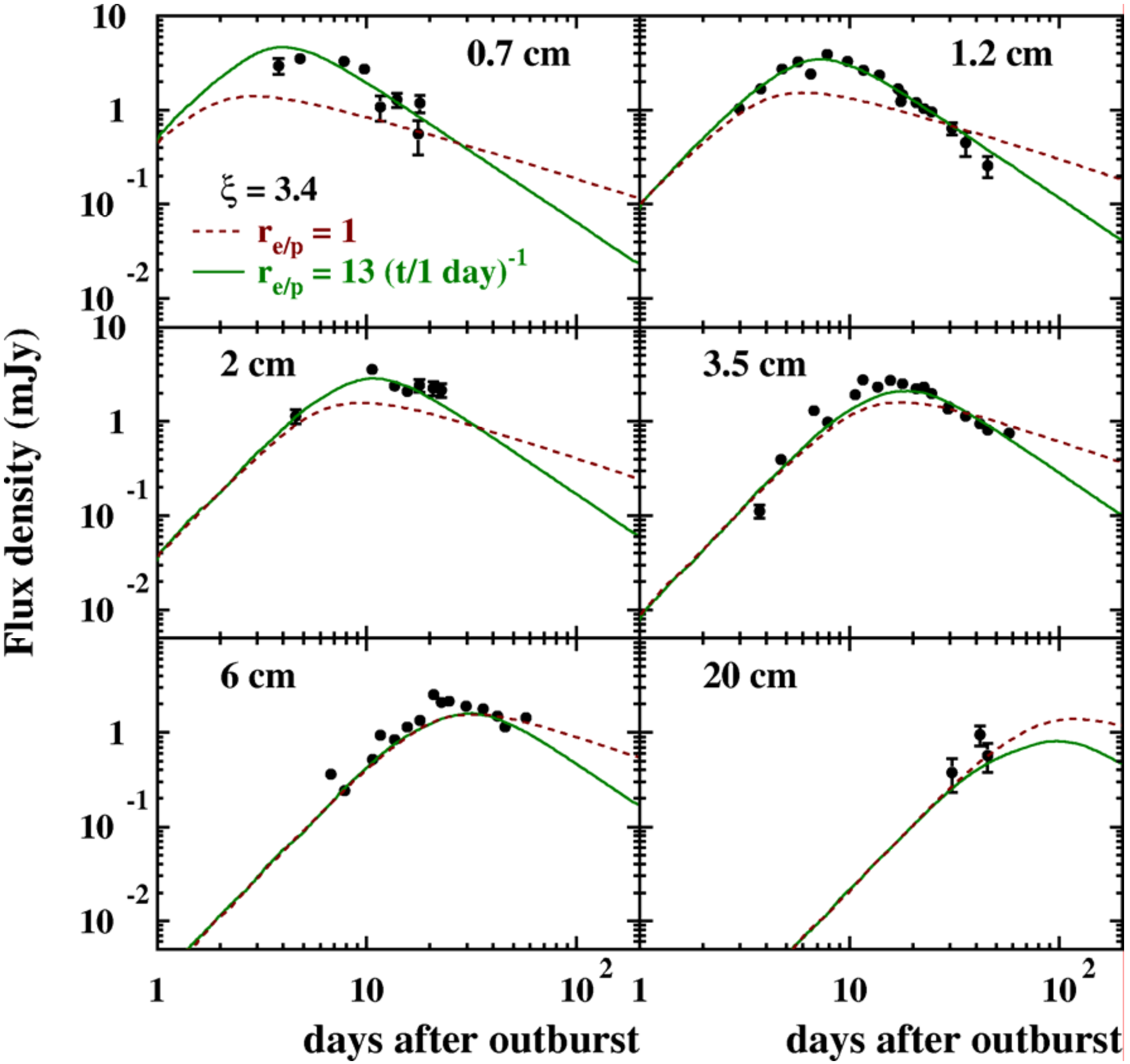
$$v_s \approx 7\times10^4\left(\frac{t}{1\text{ day}}\right)^{m-1}\ \text{km s}^{-1},\ \text{with } m = 0.91$$

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

SN 2008D — Preliminary results

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

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



SN 2008D — Preliminary questions

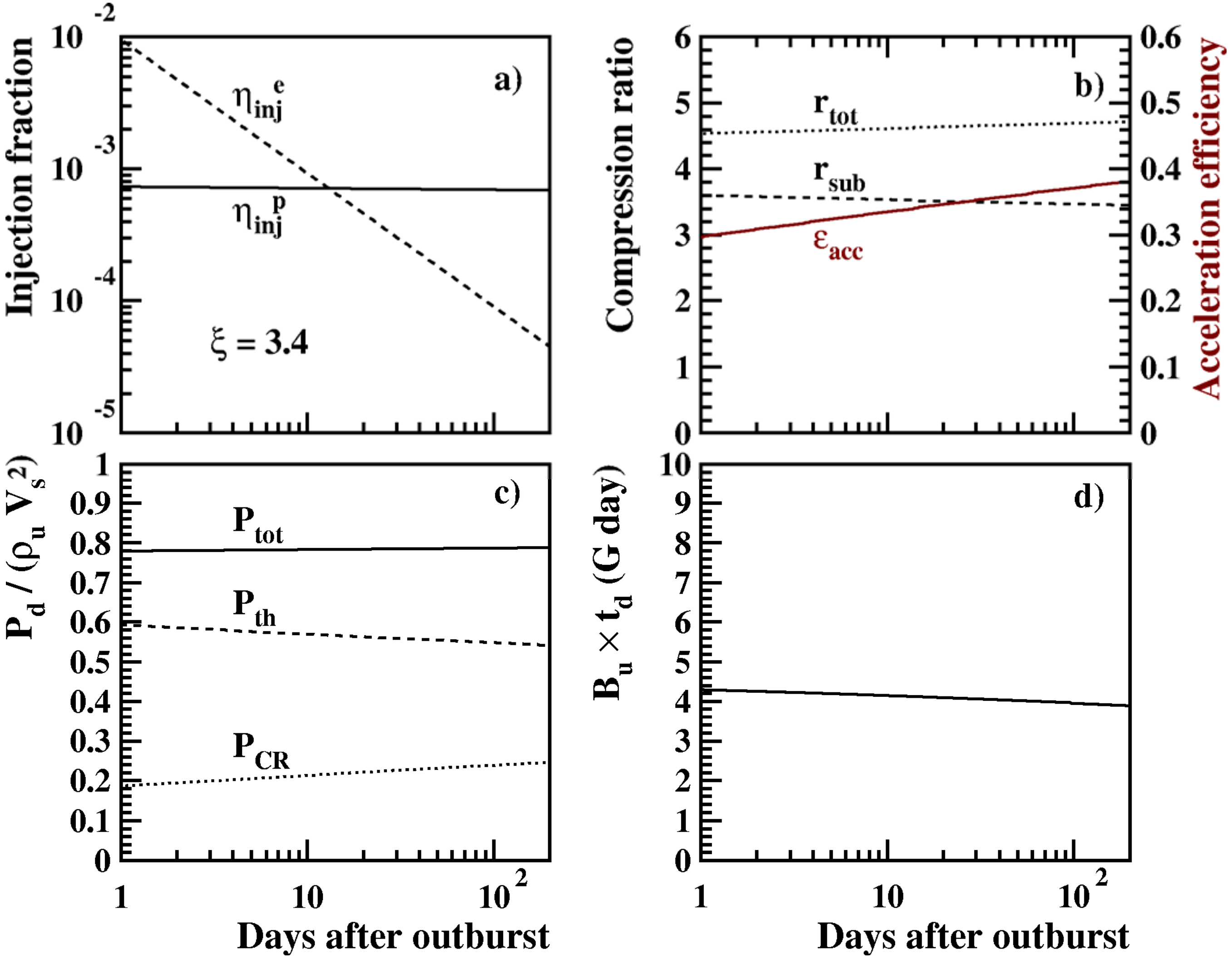
- The simplest model with constant ξ and $r_{e/p}$ + δB advection does not work

⇒ Decreasing $\eta_{inj}{}^{e}$ (e- injection)?

⇒ Increasing ξ (decreasing $\eta_{inj}{}^{p}$)?

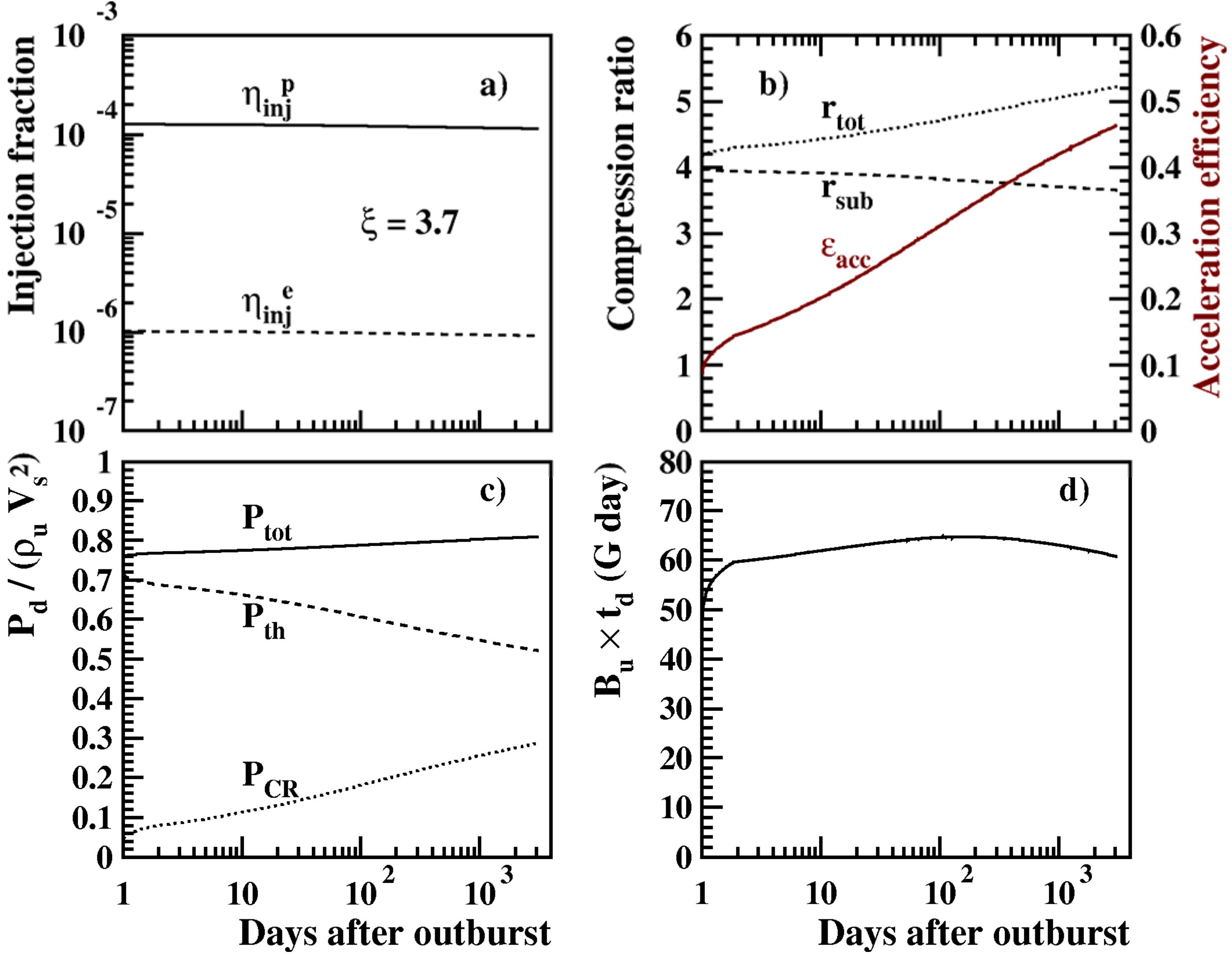
⇒ Postshock B-field damping?

⇒ …?

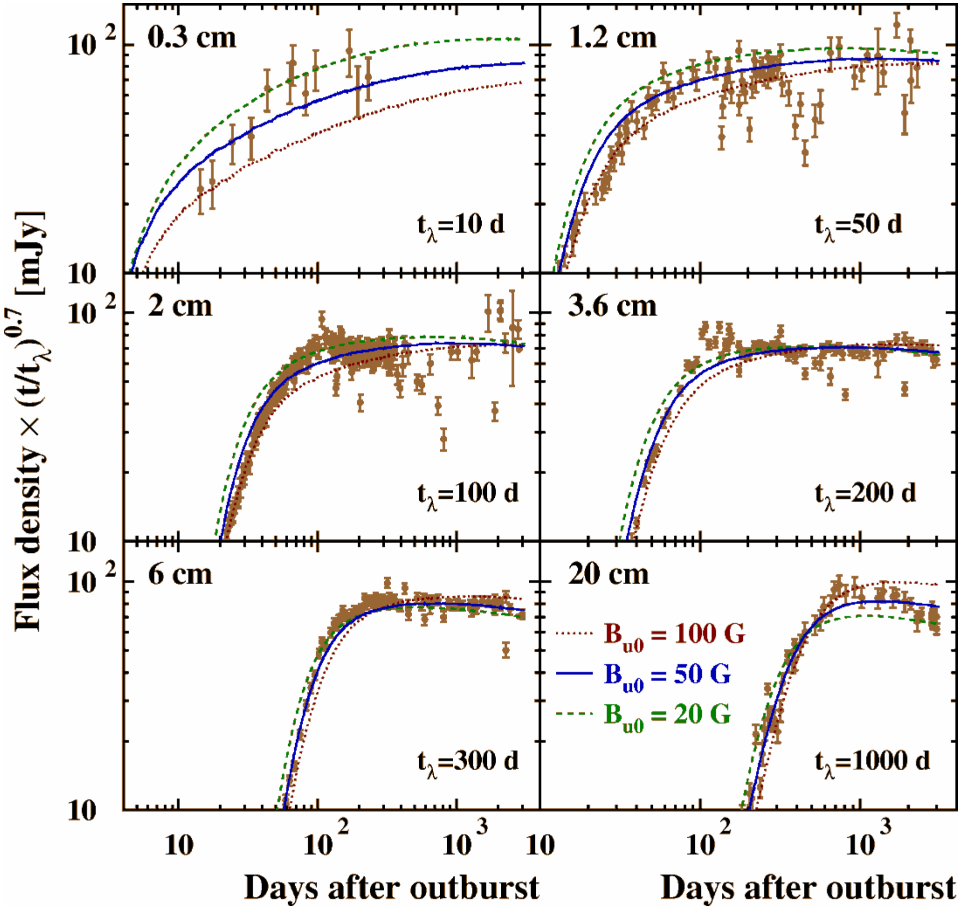


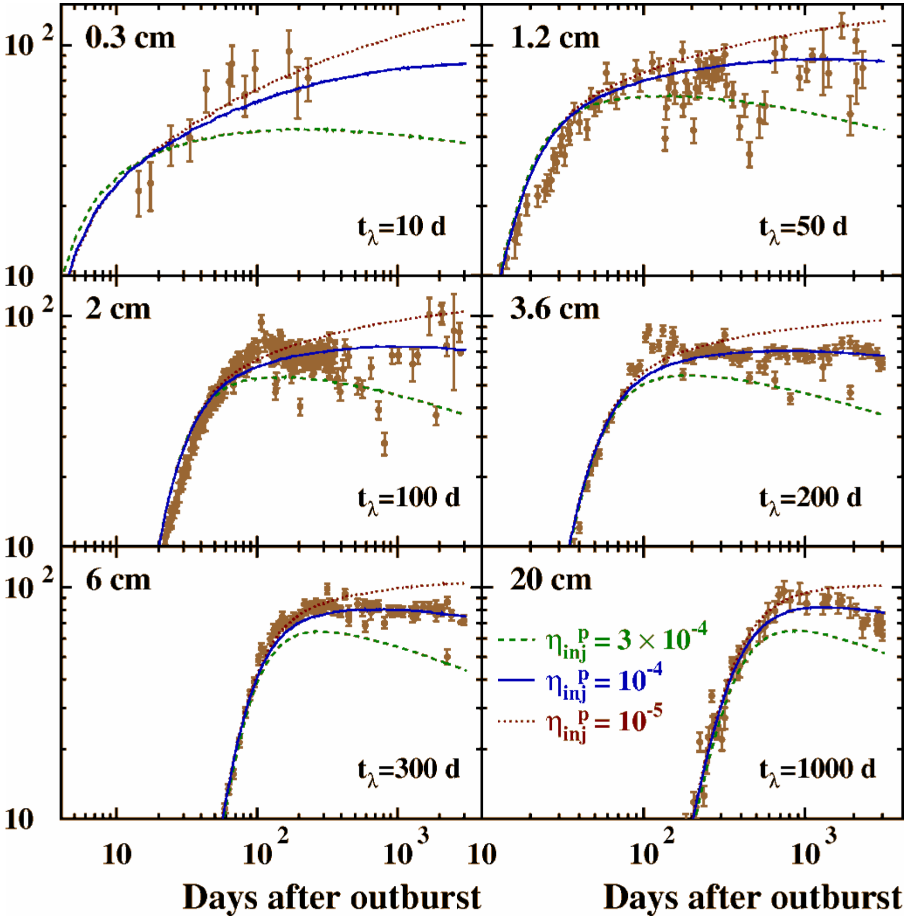
New modeling of SN 1993J

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



Parameter uncertainties





- The degeneracy between B and N_e is lifted by the synchrotron losses

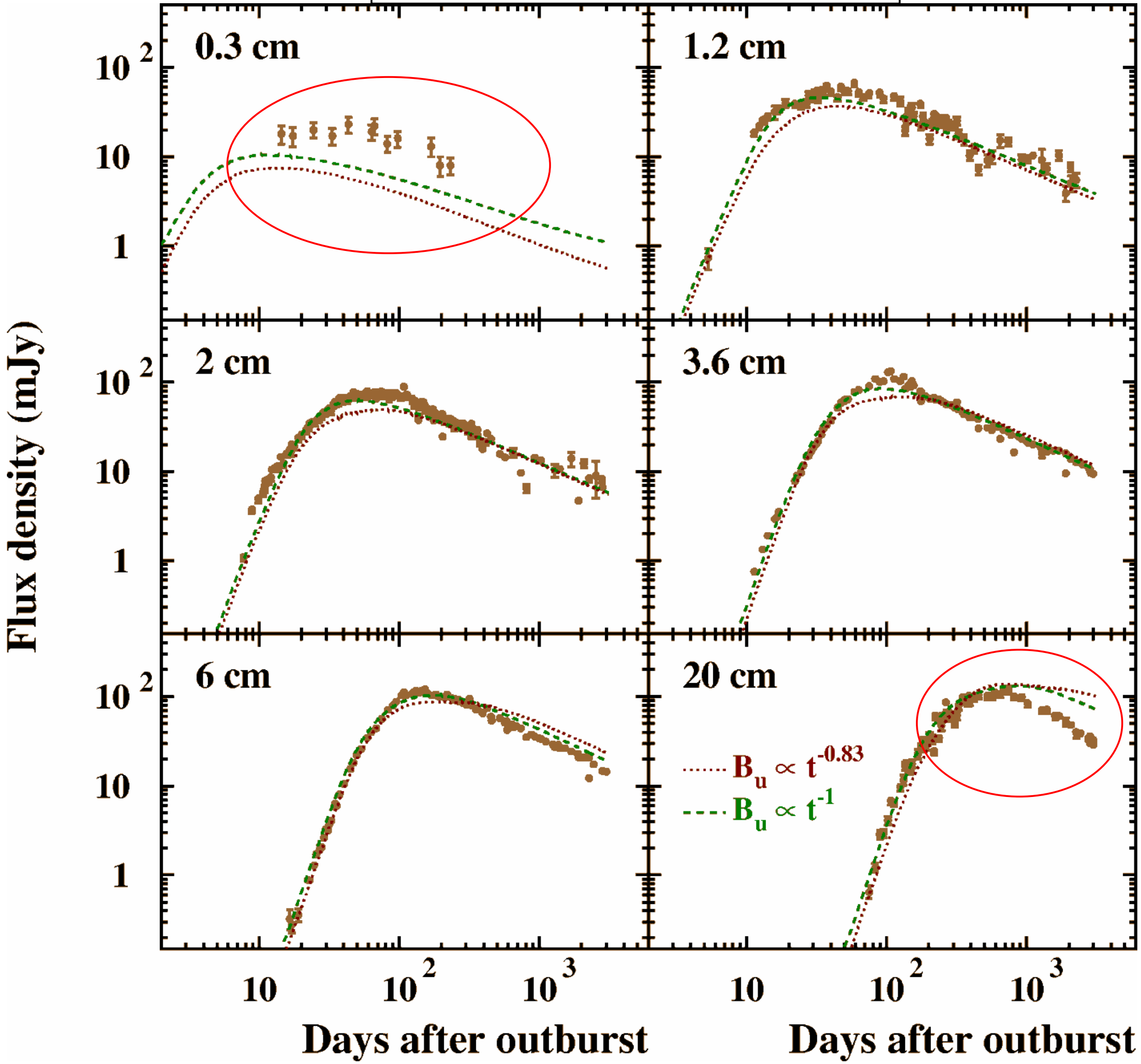
B_{u0} = 50 ± 20 G

- The shock is weakly modified:

$5\times10^{-5} < \eta_{inj}^p < 2\times10^{-4}$

Density profile of the CSM

$\rho_{\mathrm{CSM}} \propto r^{-s}$ with $s = 1.6$



- Van Dyk et al. (1994), Fransson et al. (1996), Immler et al. (2001), Weiler et al. (2007): the CSM density profile is flatter, s=1.5–1.7, than the standard s=2 case
- Fransson & Björnsson (1998,2005): s=2
- With the present model, the optically thin emission cannot be reproduced with s=1.6 ⇒ s=2