Cosmic-ray acceleration in radio supernovae

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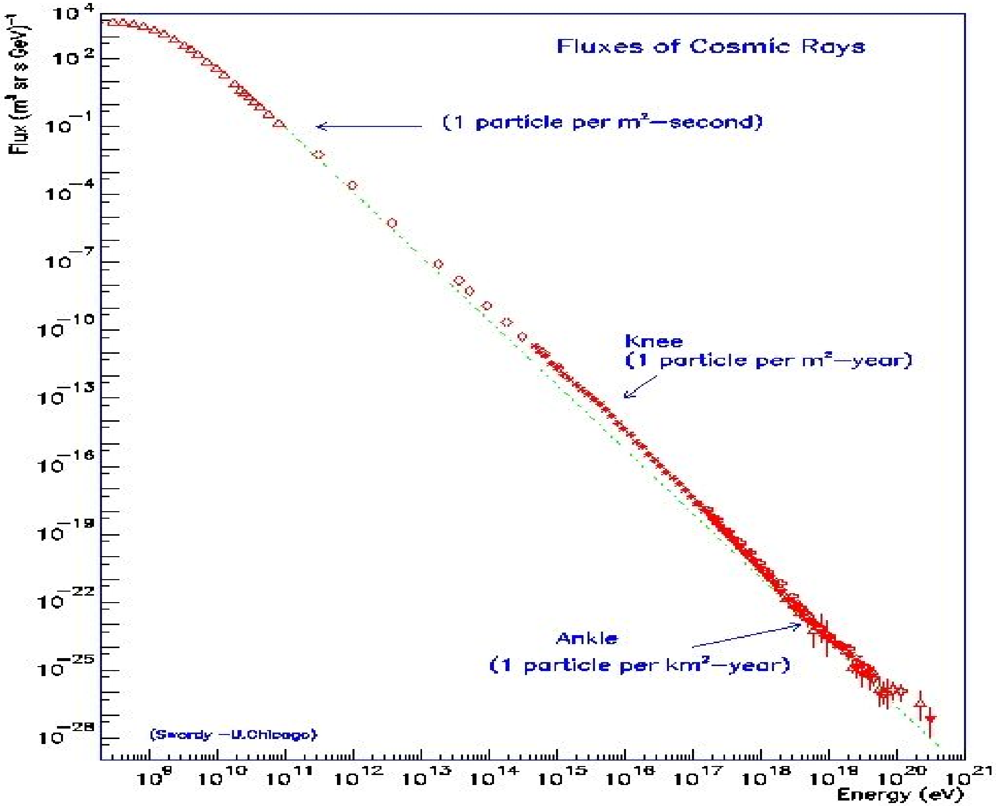

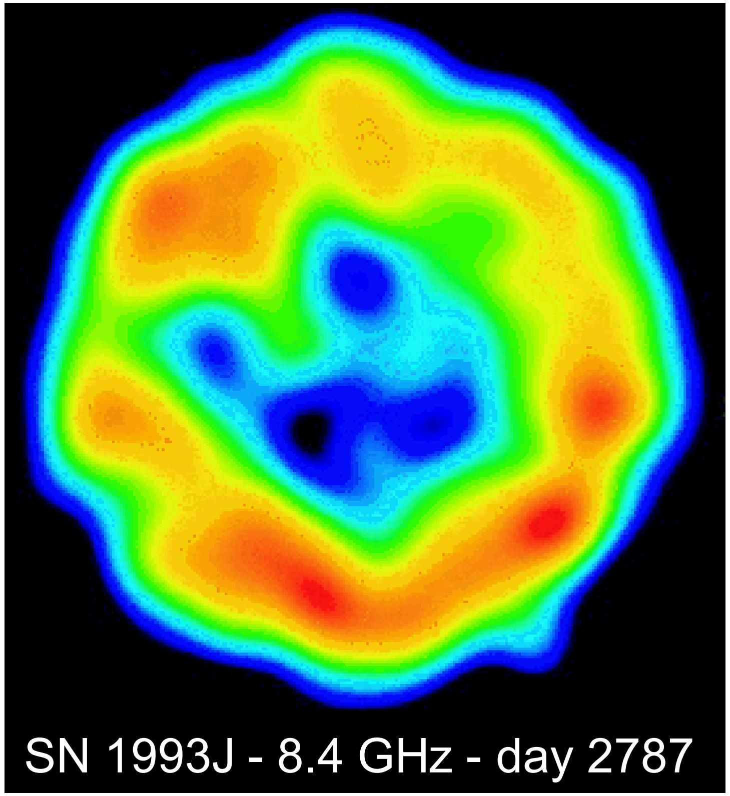

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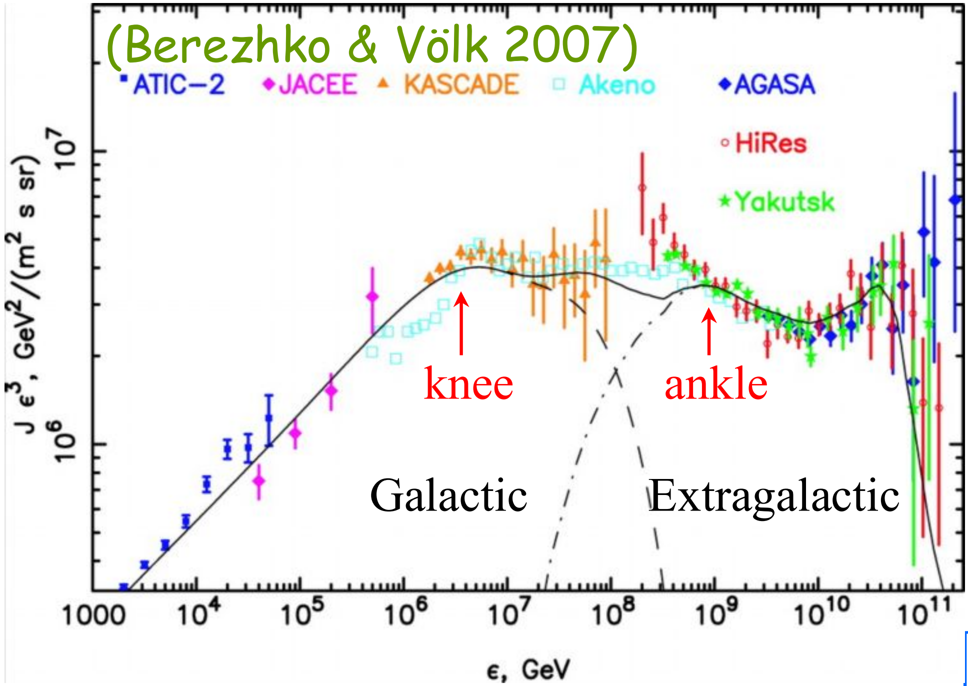
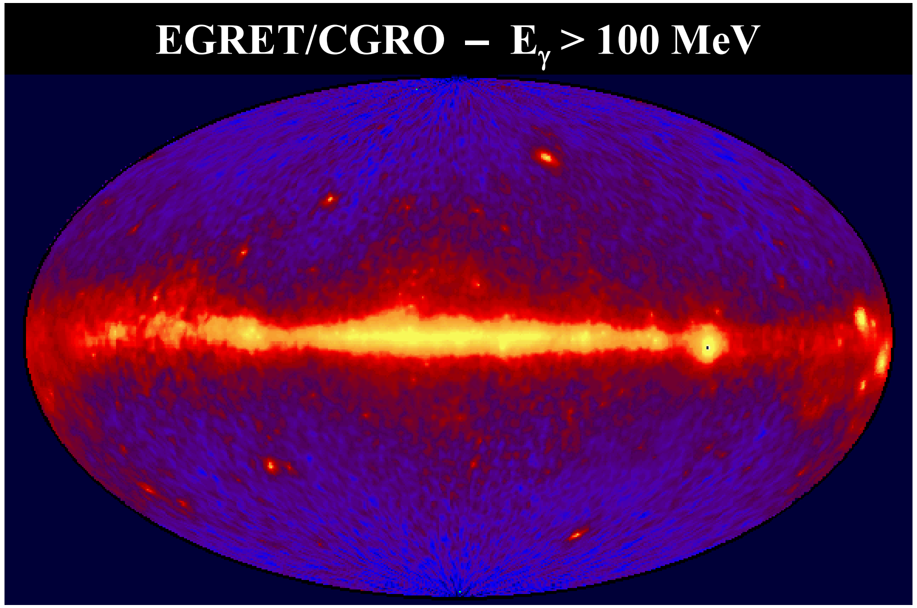
Galactic cosmic-ray and supernova energetics





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

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

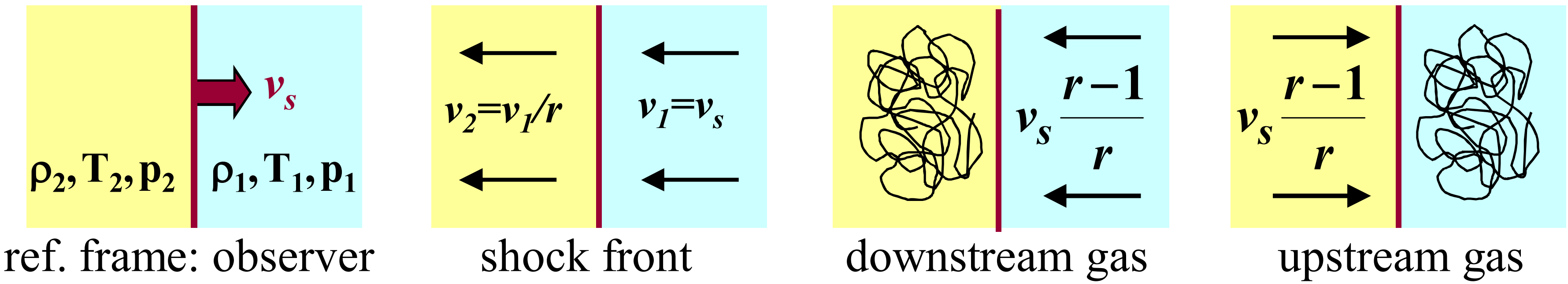
- Total power supplied by SNe: L_{SN} ~ $1.5\mathrm{x}10^{51}$ erg x 50 yr^{-1} ~ 10^{42} erg/s

$\Rightarrow$ 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



- Fractional momentum gain per cycle: $\frac{\Delta p}{p} = \frac{4}{3}\frac{r-1}{r}\frac{v_s}{c}$ (relativistic)

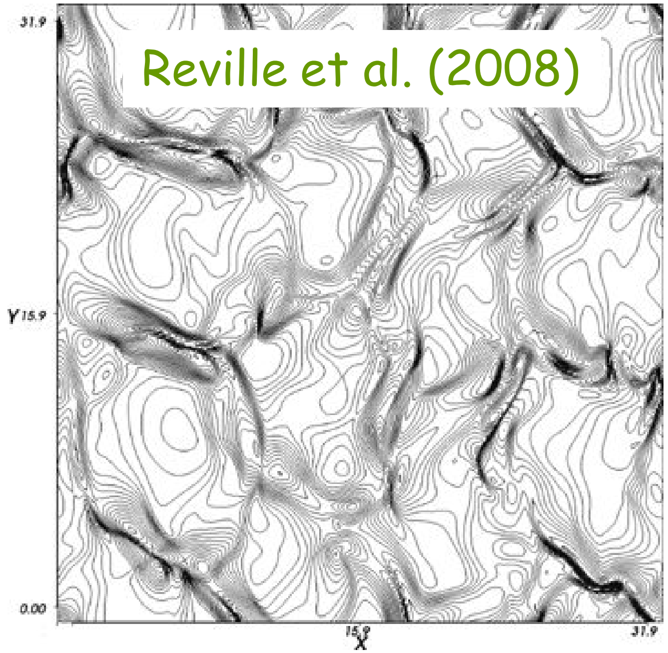
- Particle energy spectrum: $N(E) \propto E^{-q}$ with $q = 1+3/(r-1)$
  (for a test-particle strong shock $r = 4 \Rightarrow q = 2$)

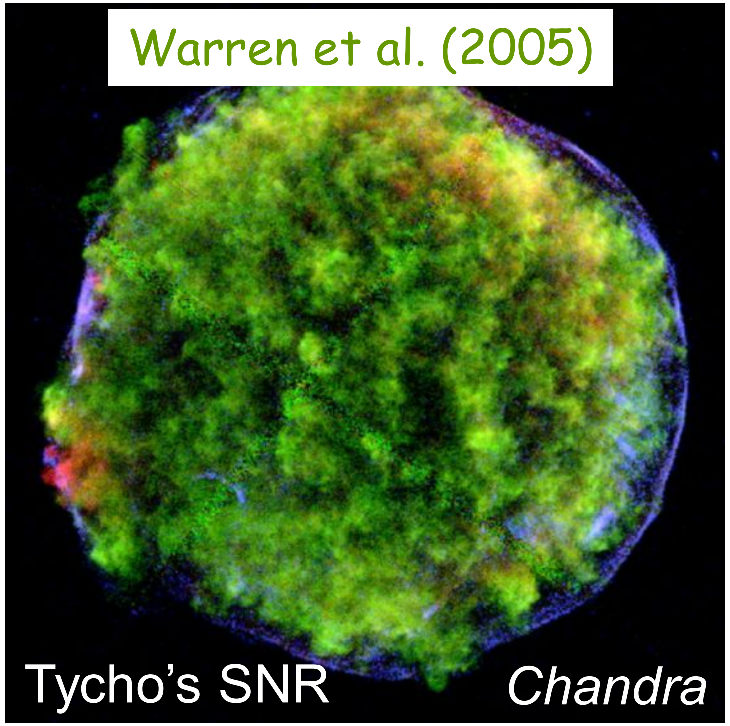
- Relatively slow process $\Rightarrow$ $E_{\rm max} = 23\,{\rm TeV}\,\frac{Z B_{\mu{\rm G}} E_{51}}{n_0^{1/3} M_{\rm ej}^{1/6}}$ (Lagage & Cesarky 1983)

$\Rightarrow E_{p,\rm max} << 3\times10^{15}$ 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: $\delta B/B >> 1$
- MHD simulations: yes (e.g. Zirakashvili et al. 2008) or no (Niemiec et al. 2008; $\delta B/B \sim 1$)





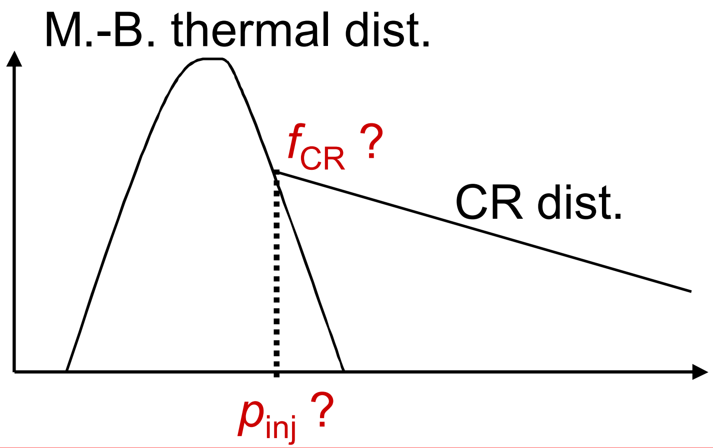
- Evidence for B-field amplification in SNRs ($\delta B/B > 20$) from synchrotron X-ray filaments (e.g. Parizot et al. 2006) (but δB damping? Pohl et al. 2005)

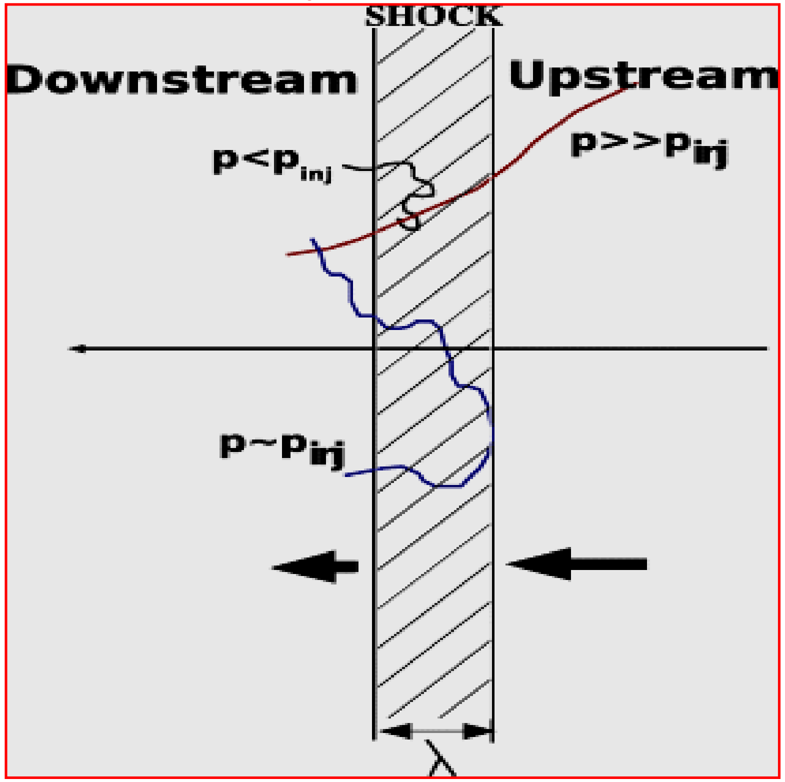
⇒ Acceleration to ≈10^{15} eV. And beyond?

The injection problem

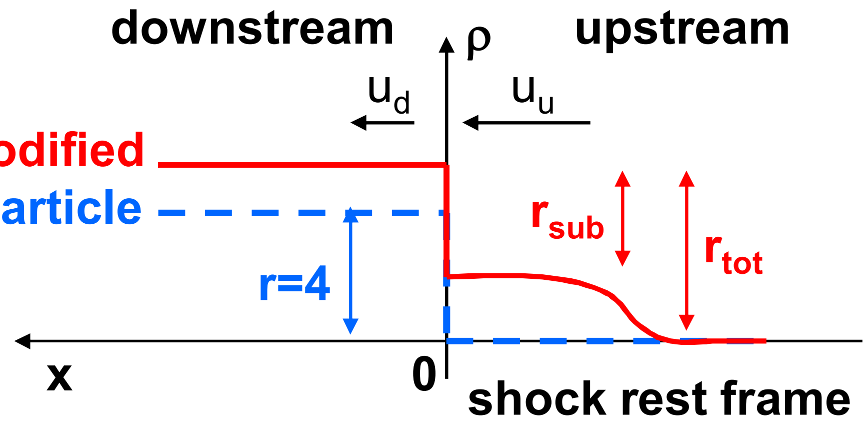
- Particles injected into the DSA process: postshock thermal particles with $p > p_{\mathrm{inj}}$ (Ellison et al.; Monte-Carlo simulations)
- Condition for injection (Blasi et al. 2005): $r_L > \lambda = \alpha\, r_L^{th}$, with the shock thickness parameter $\alpha = 1 - 2$
- But depending on the shock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

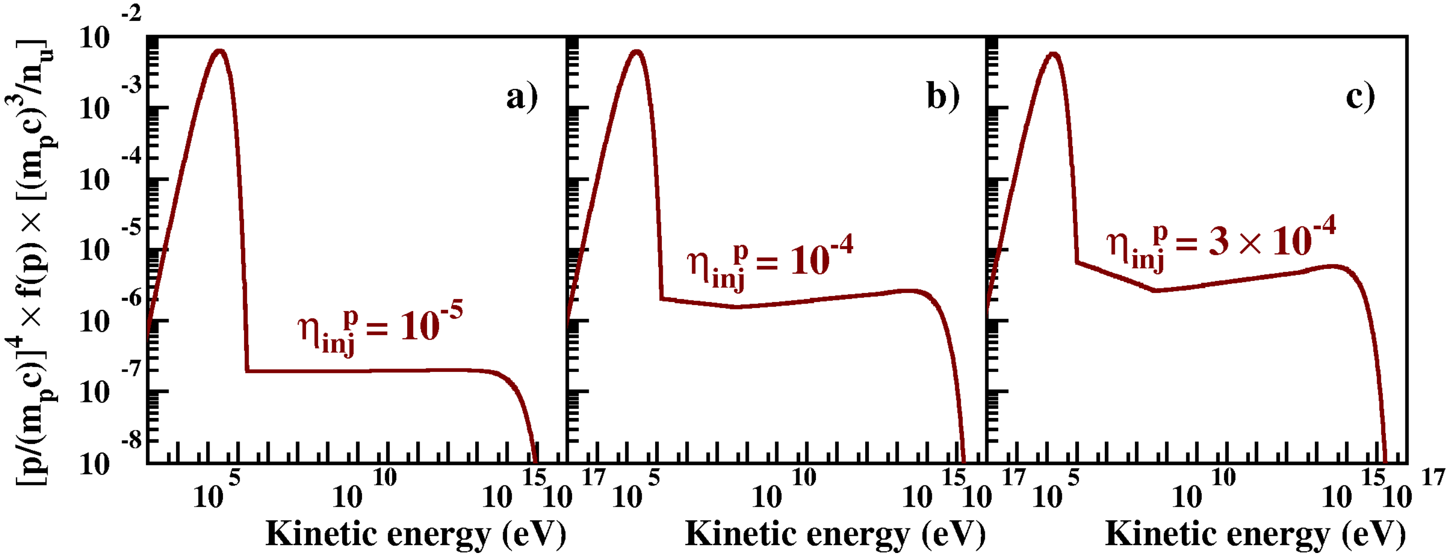
- Momentum flux conservation:

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

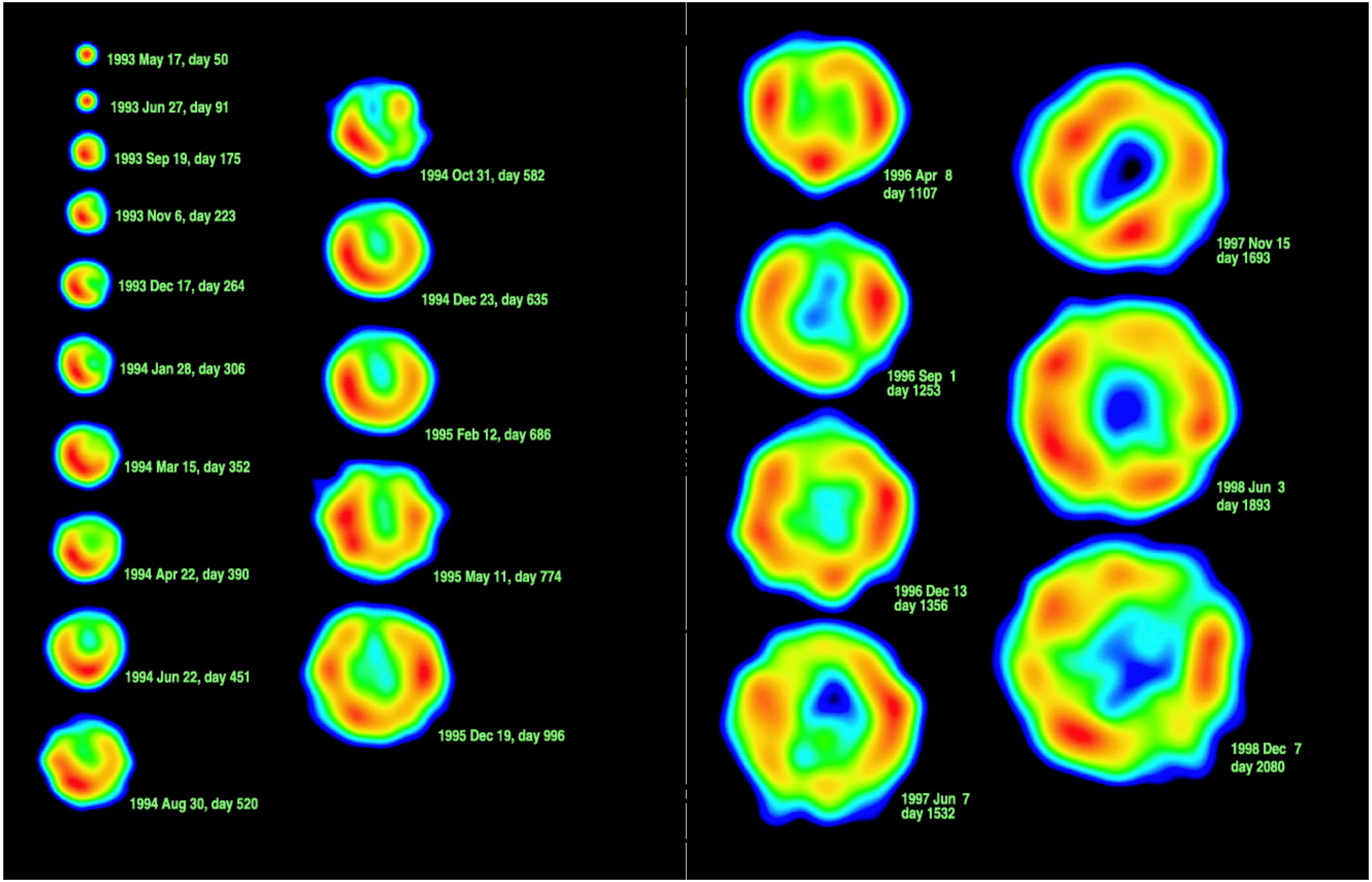
with $P_{CR}(x) = \frac{1}{3}\int_{p_{\rm inj}}^{p_{\rm max}} dp\, 4\pi p^3 v(p) f(x,p)$

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

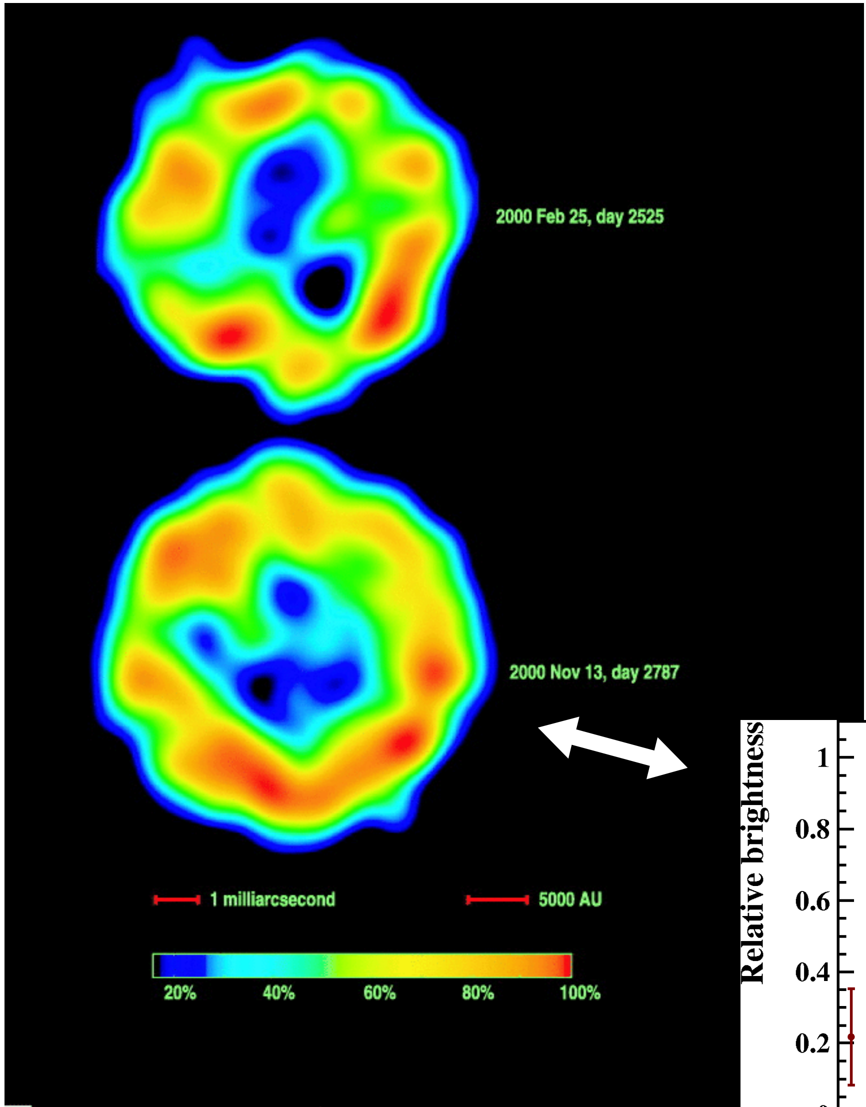
- Higher energy particles feel a higher compression ratio ⇒ concave spect.



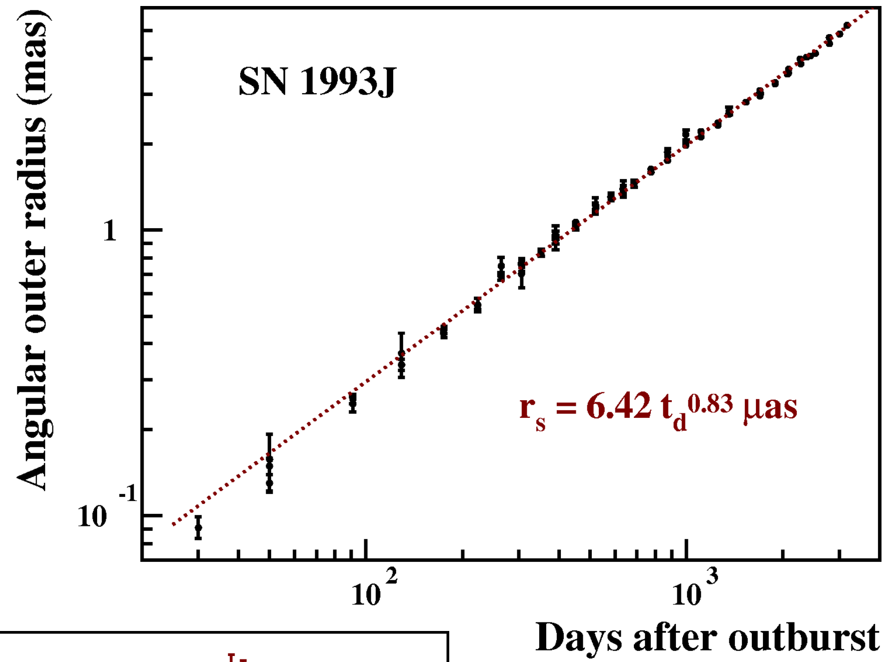
SN 1993J — One of the best observed radio SN

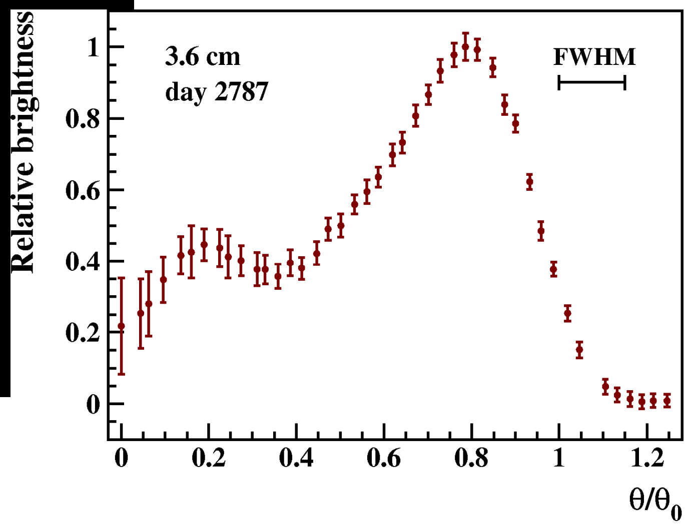


SN 1993J VLBI observations



- The expansion is almost self similar

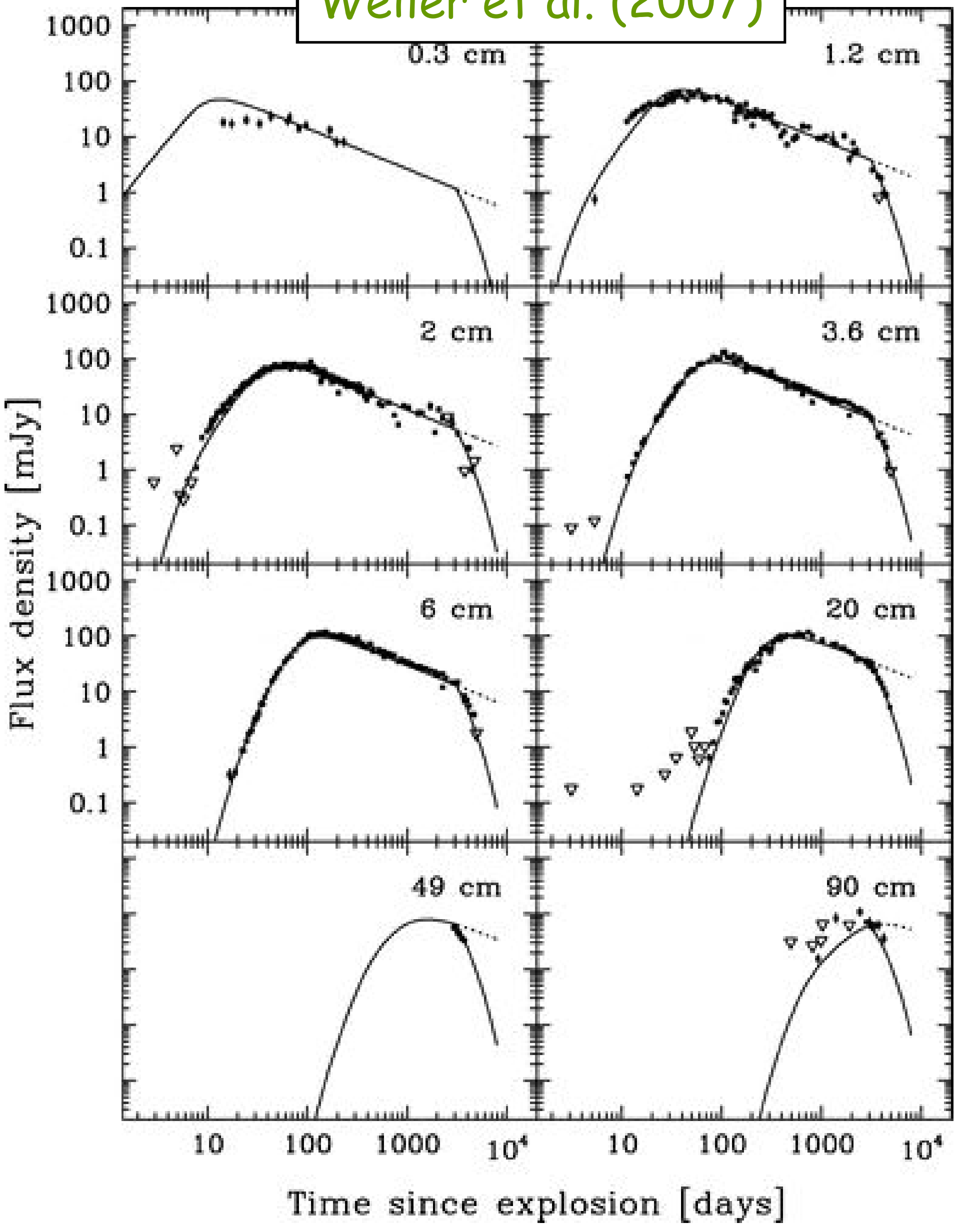


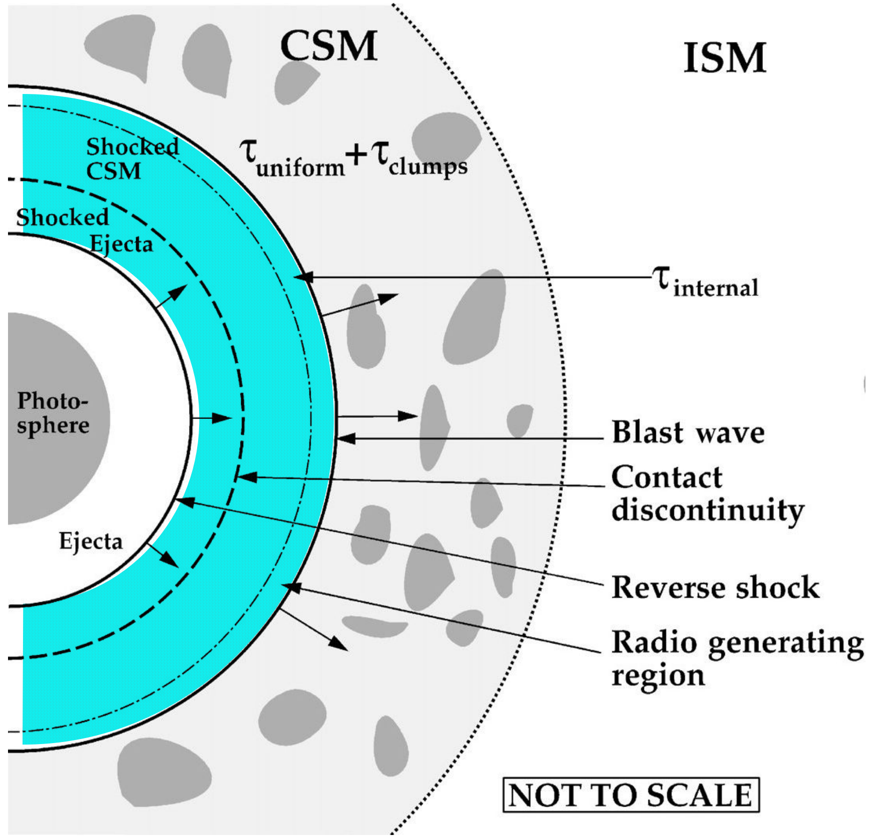


See, e.g.,
Marcaide et al. (1995, 1997)
Bartel et al. (2002, 2007)

Radio light curves

Weiler et al. (2007)





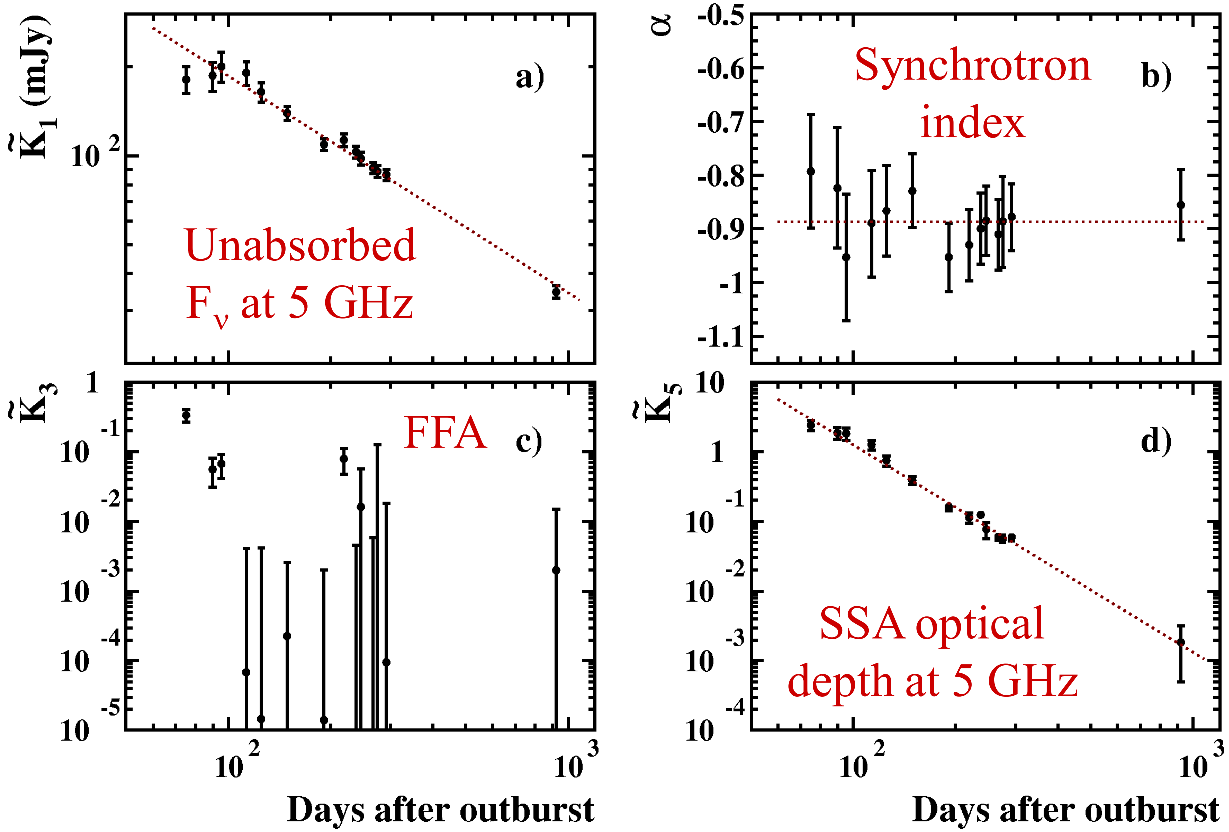
- Abrupt decline after day ~3100 as the shock has reached the outer limit of the dense CSM
- Weiler et al.: overall fit to all the data with 9 free parameters

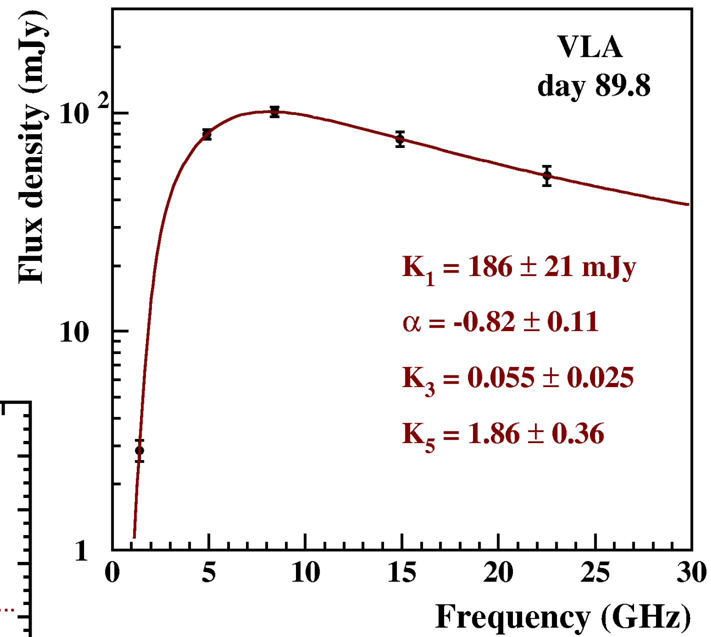
Synchrotron self-absorption (SSA)

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

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

- Fits to individual VLA spectra





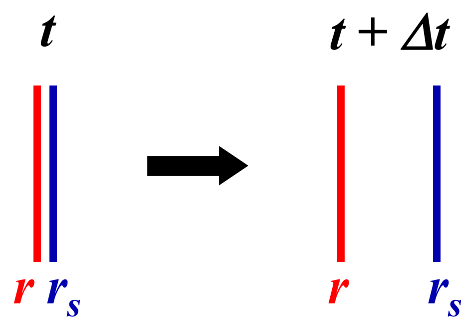
$$\langle B \rangle = (2.4 \pm 1.0)\left(\frac{t}{100\ \text{days}}\right)^{b}\ \text{G}$$

with $b = -1.16 \pm 0.20$

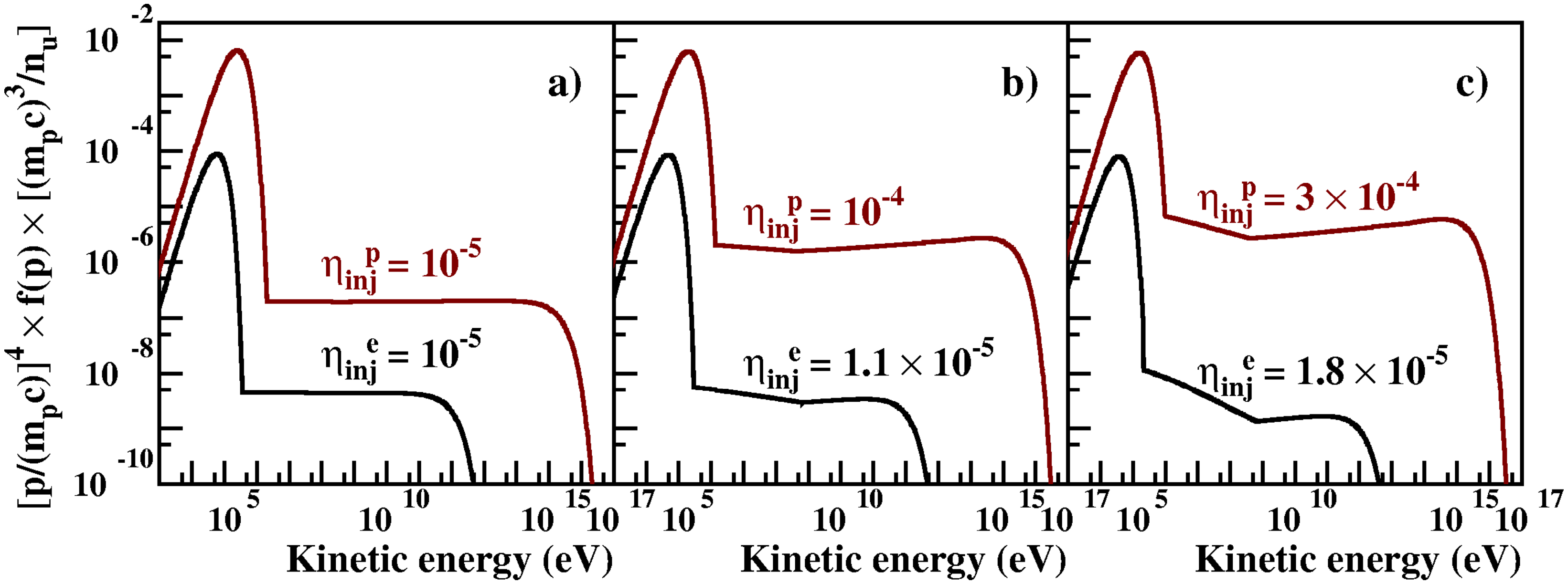
⇒ Strong amplification of the stellar B-field

Radio SN model (1)

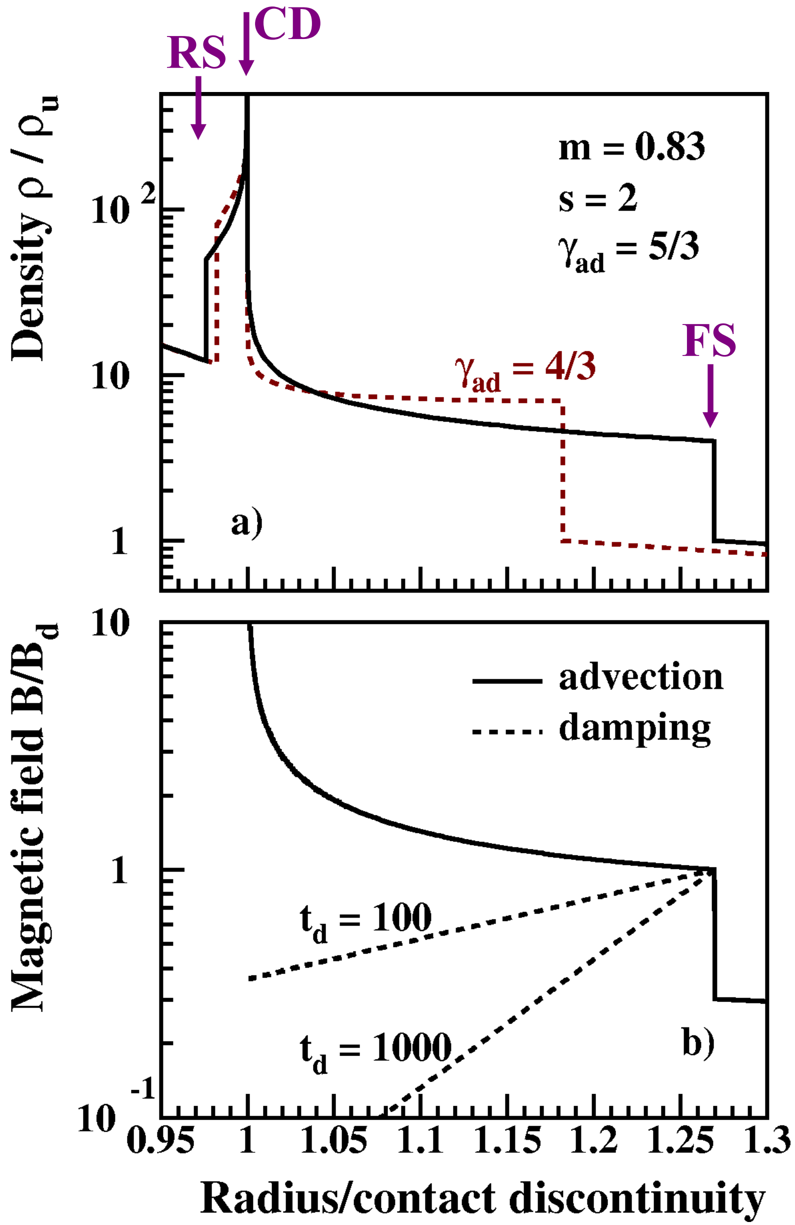
- Inspired by Cassam-Chenaï et al. (2005) for Galactic SNRs
- Nonlinear diffusive shock acceleration model (Berezhko & Ellison 1999) $\Rightarrow f_p(p,r_s)$ and $f_e(p,r_s)$
  f_e depends on the proton injection parameter η_{inj}^{p}



- 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)

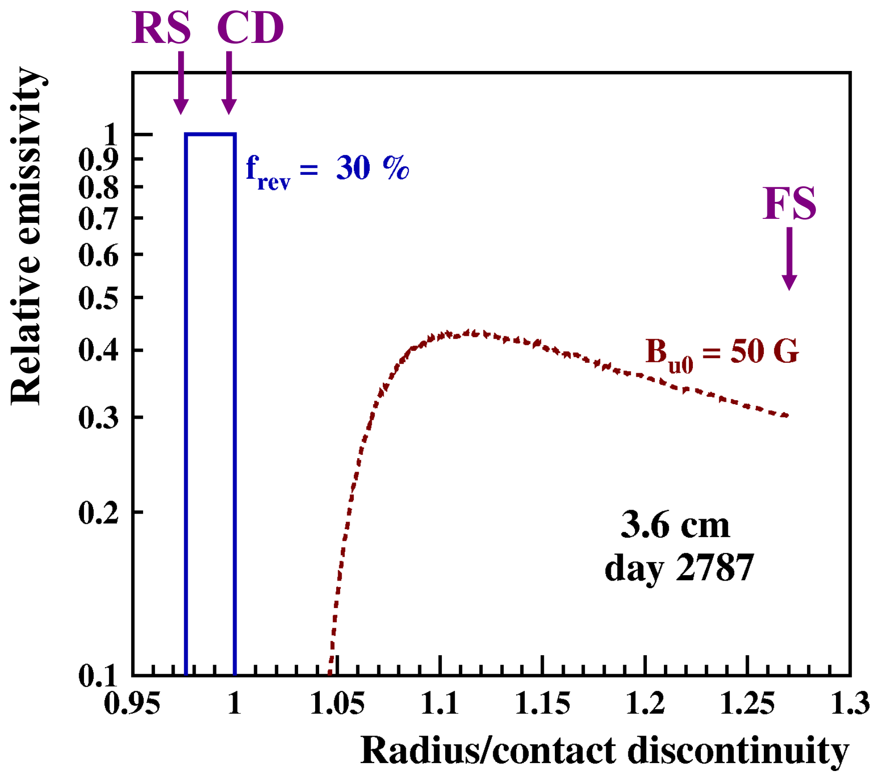


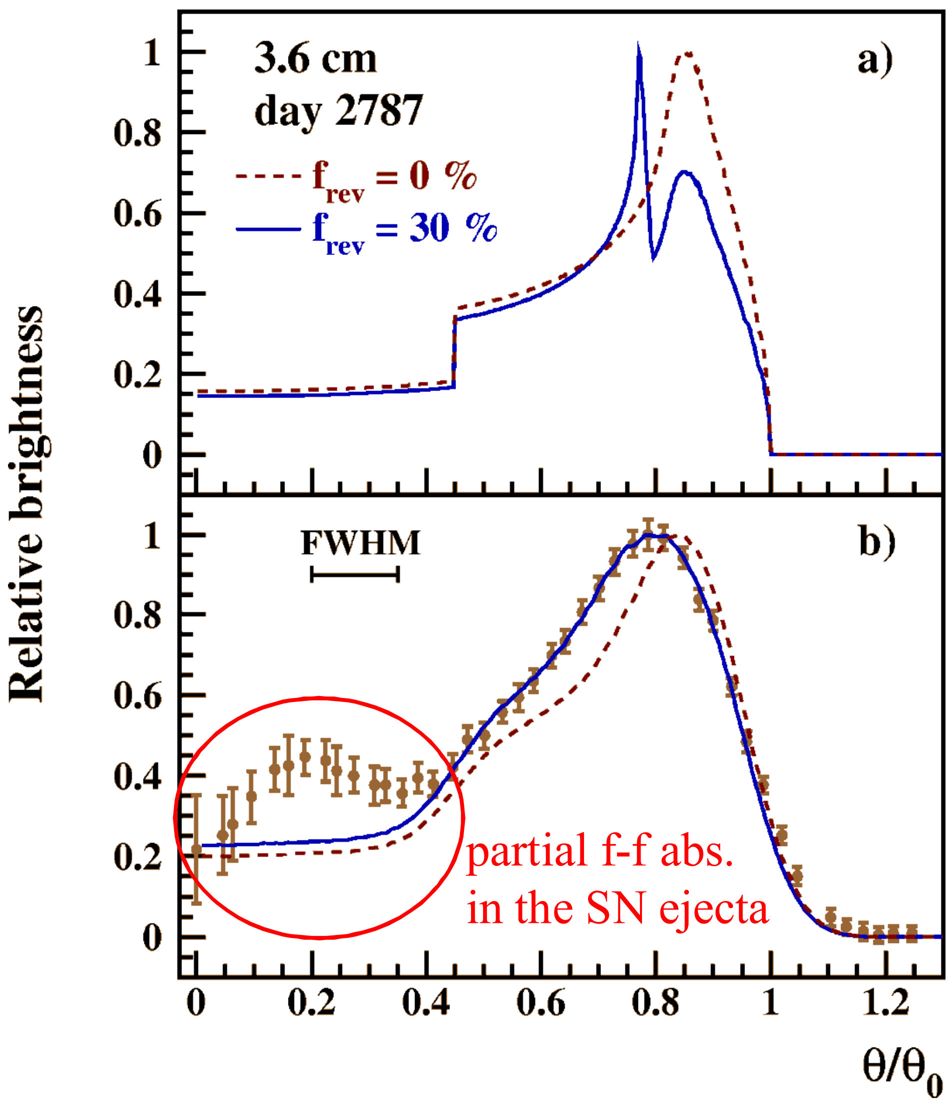
- Hydrodynamic of the postshock plasma: self-similar solutions (Chevalier 1983)
- Postshock magnetic field evolution:
  - advected in the plasma flow or
  - damped by cascading of MHD wave energy (Pohl et al. 2005)
- Synchrotron emission: radiative transfer calculations including synchrotron self-absorption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

$\Rightarrow$ 4 free parameters:

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

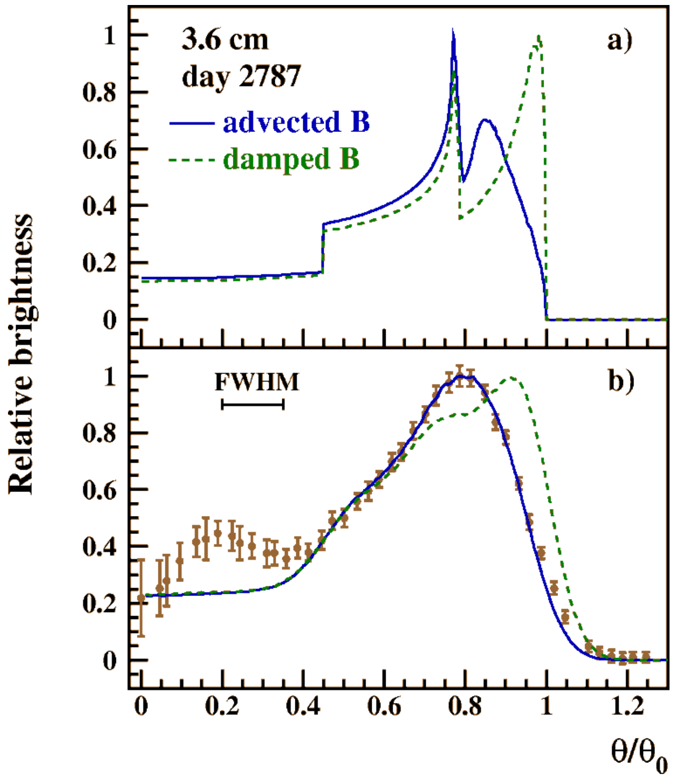
Acceleration at the reverse shock

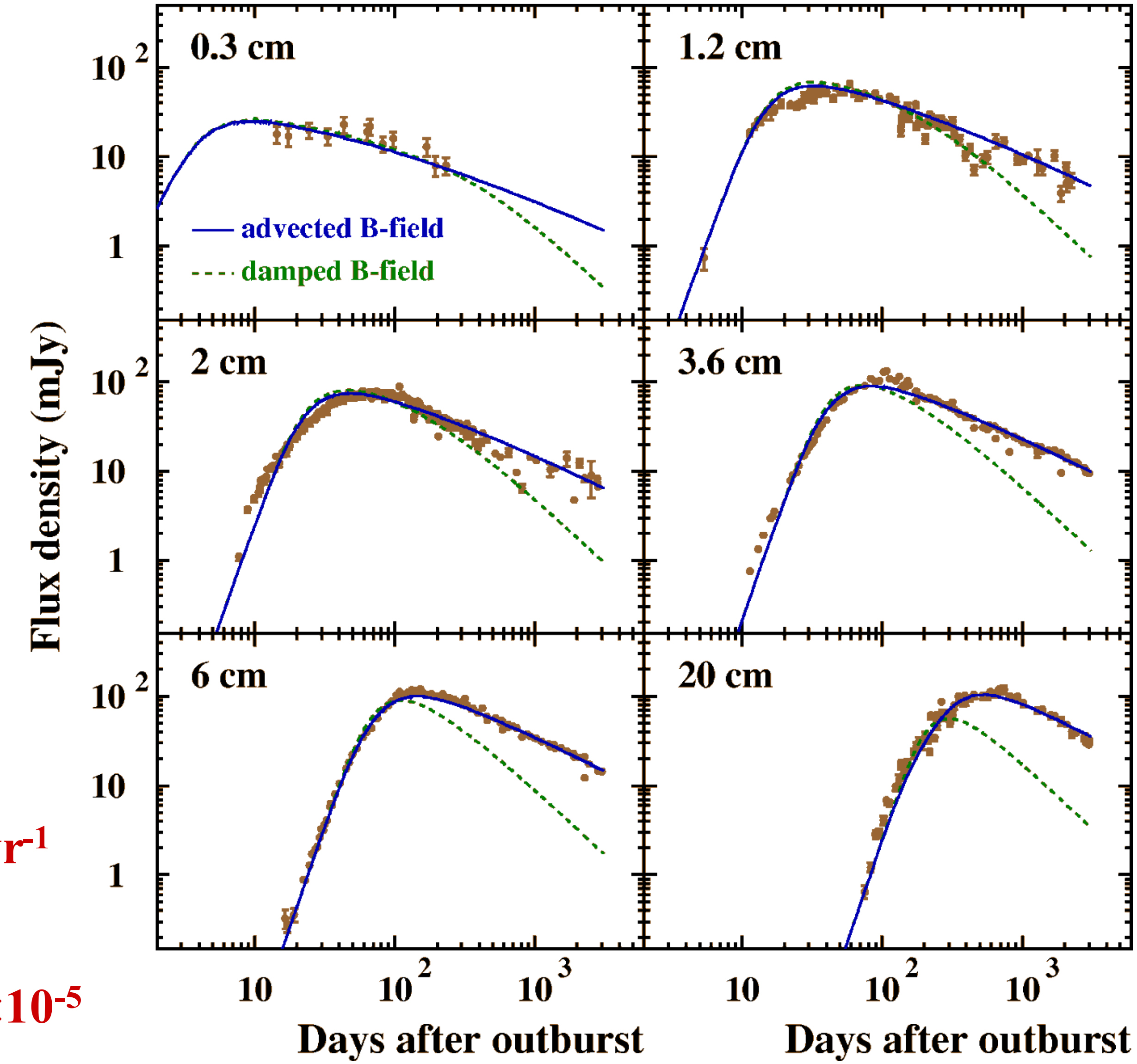




- Electrons accelerated at the reverse shock account for ≤17% of the total radio flux

No damping of the postshock magnetic field





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

Magnetic field amplification

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

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

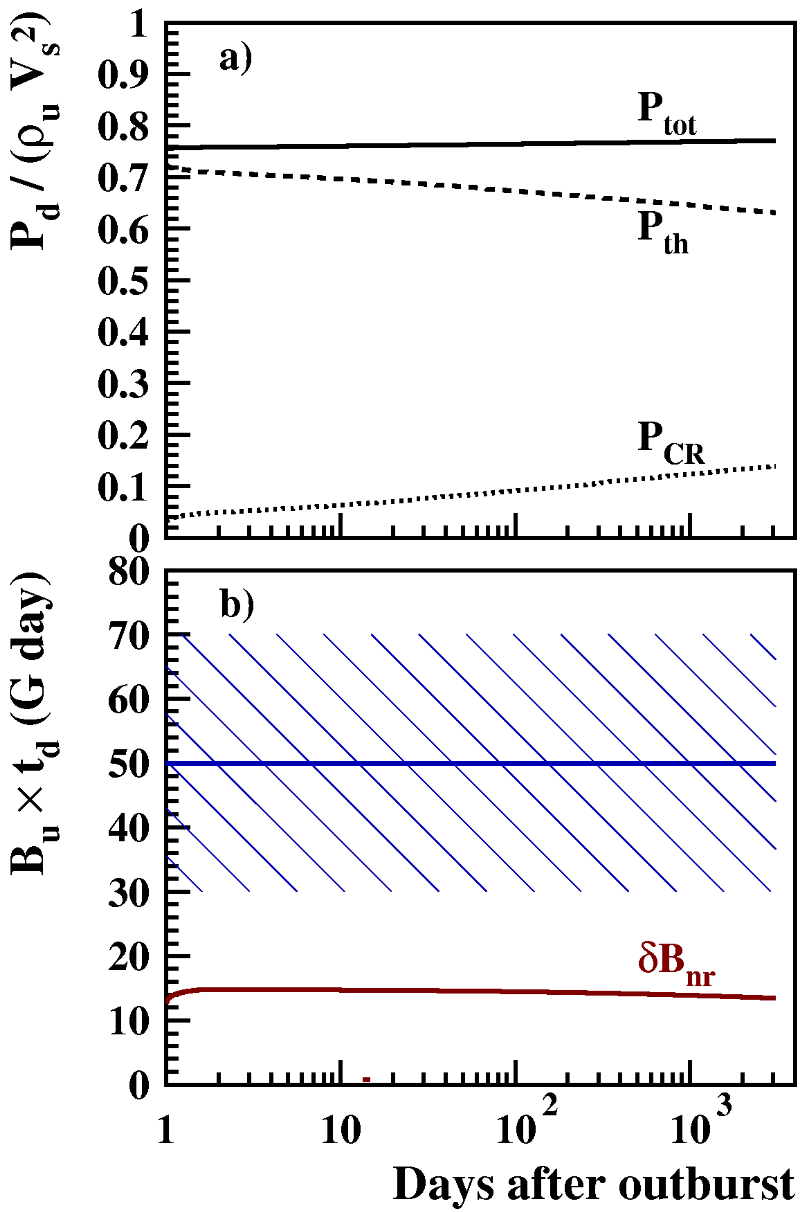
2-5 lower than the "measured" B-field

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

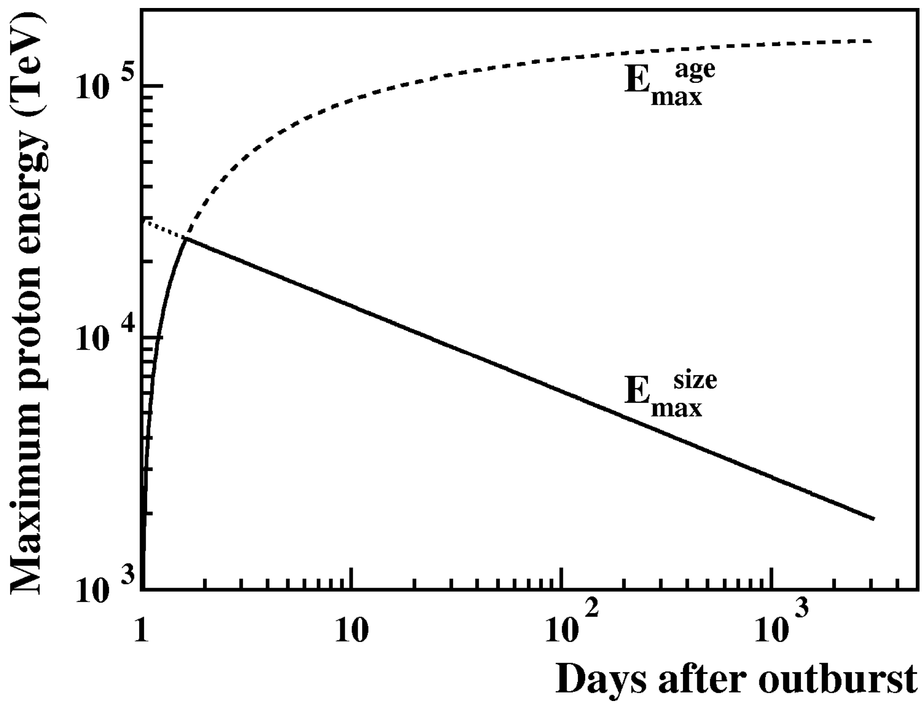
$$\frac{\delta B_{\rm res}^2}{\delta B_{\rm nr}^2} \sim \sqrt{\frac{P_{\rm CR}}{\rho_u v_s^2} \frac{c}{v_s}} \Rightarrow \text{No}$$

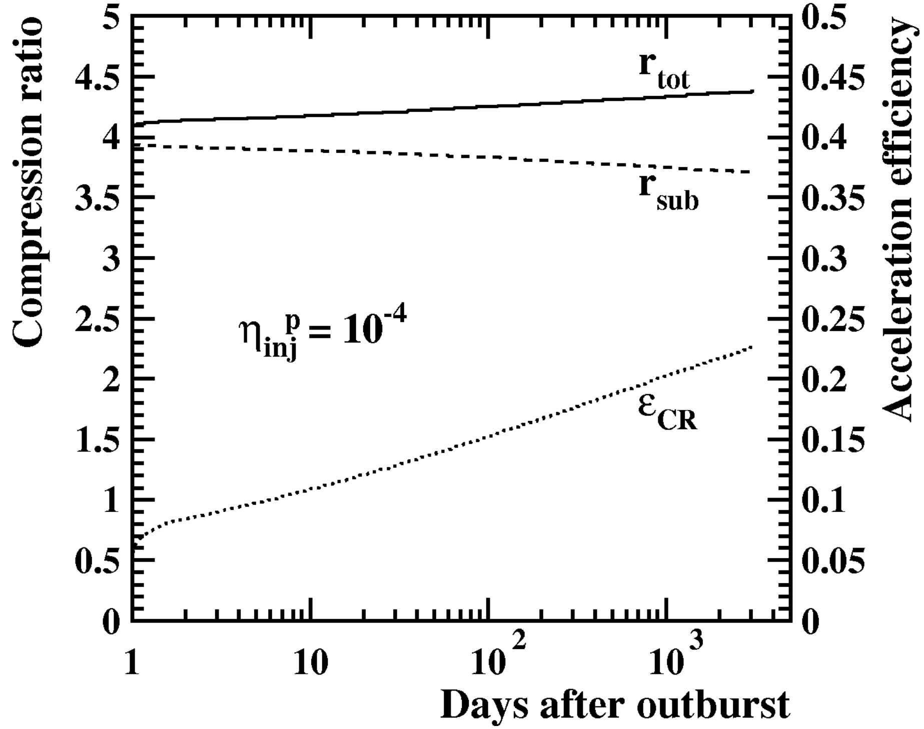
- Empirical formula for both Galactic SNRs (Berezhko 2008) and SN 1993J:

$$\frac{\delta B^2}{8\pi} \approx 10^{-1} P_{\rm CR} \left(\frac{v_s}{3\times10^4 \ {\rm km\ s^{-1}}} \right)$$



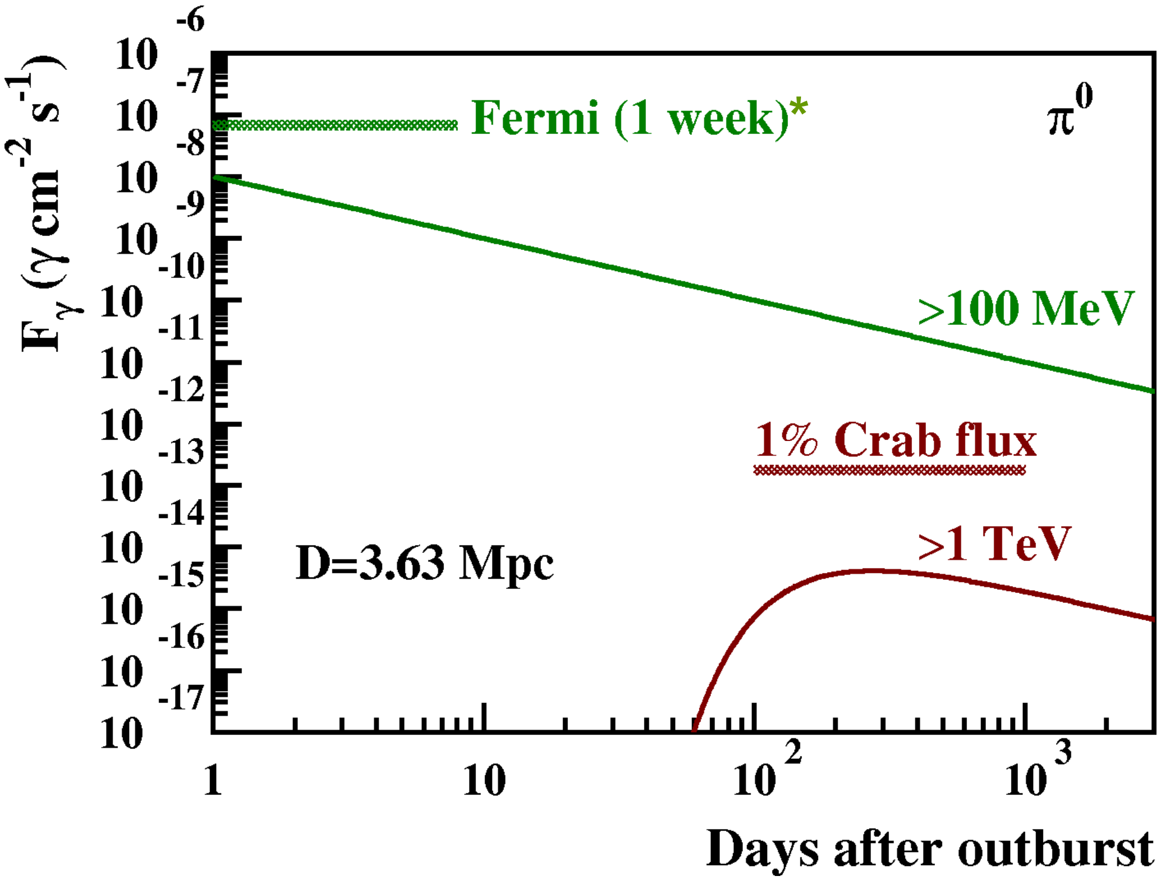
SN 1993J and the origin of cosmic rays





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

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

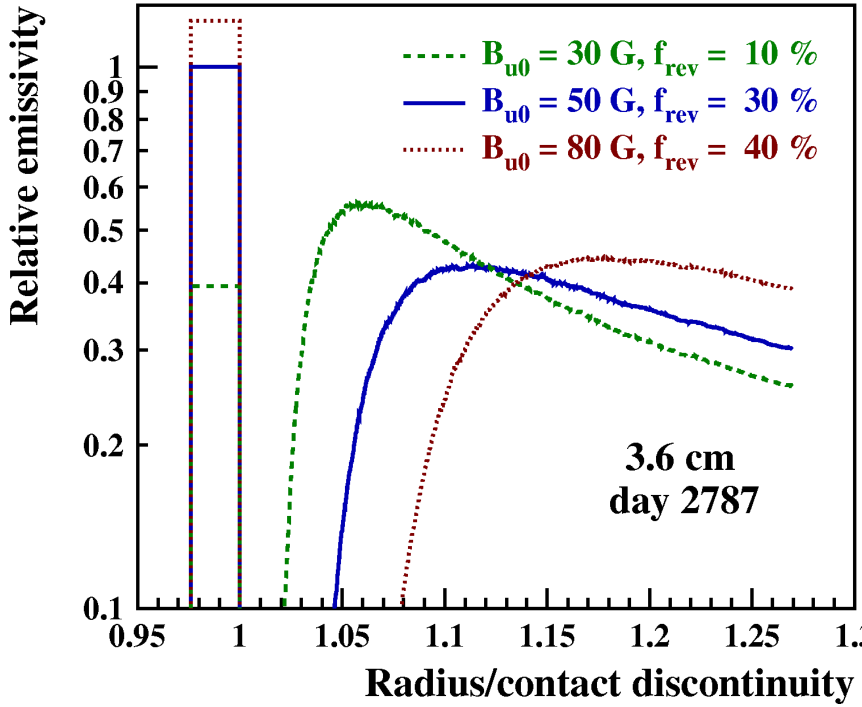
$\Rightarrow$ Type II SNe could be detected in π^0-decay γ-rays out to a maximum distance of $\approx$1 Mpc

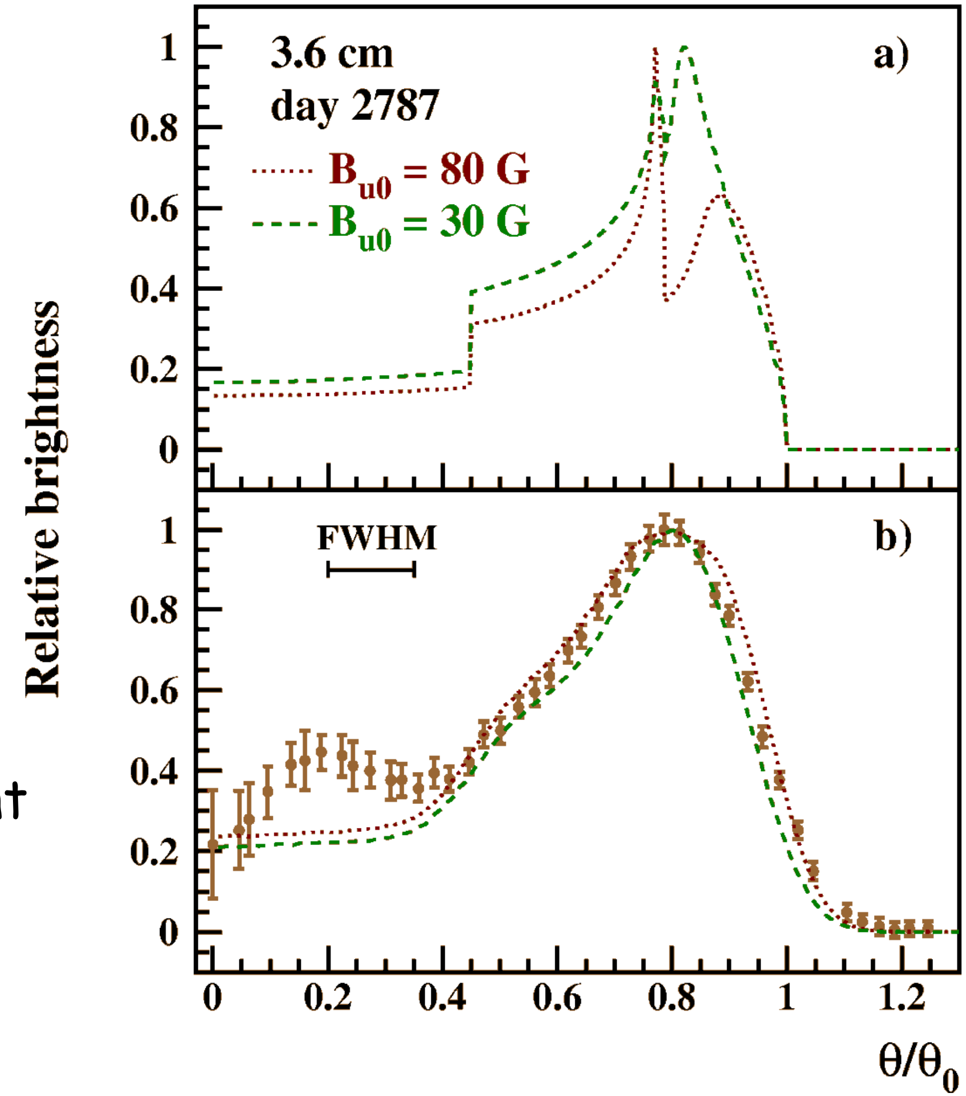
Conclusions

- 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, $\eta_{inj}^{p} \approx 10^{-4}$
- B-field amplification, possibly by the Bell's nonresonant streaming instability in the precursor region. Consistent with SNR results
- 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)
- A new model for radio SNe (e. g. SN 2008D…)
- Type II SNe could be detected at γ-ray energies out to only ≈1 Mpc

Refs: Tatischeff (2008) PoS [arXiv:0804.1004]; A&A (2009) in press [arXiv:0903.2944]

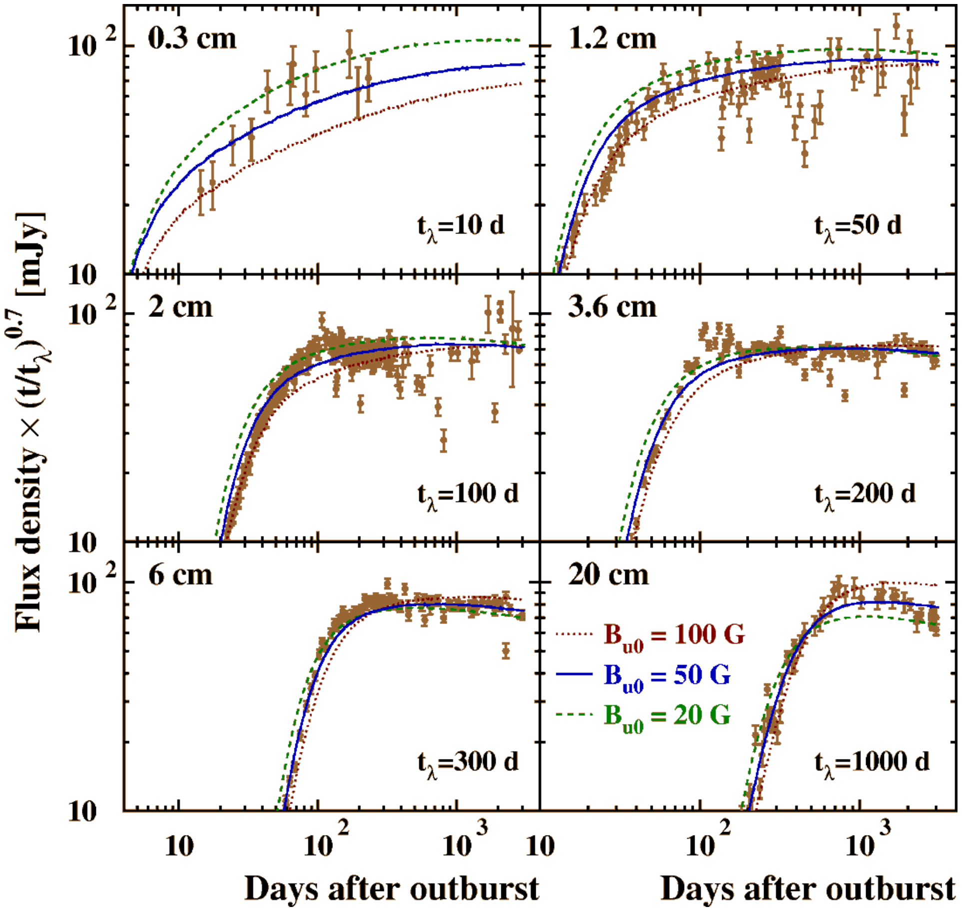
Radio profile — B-field estimate

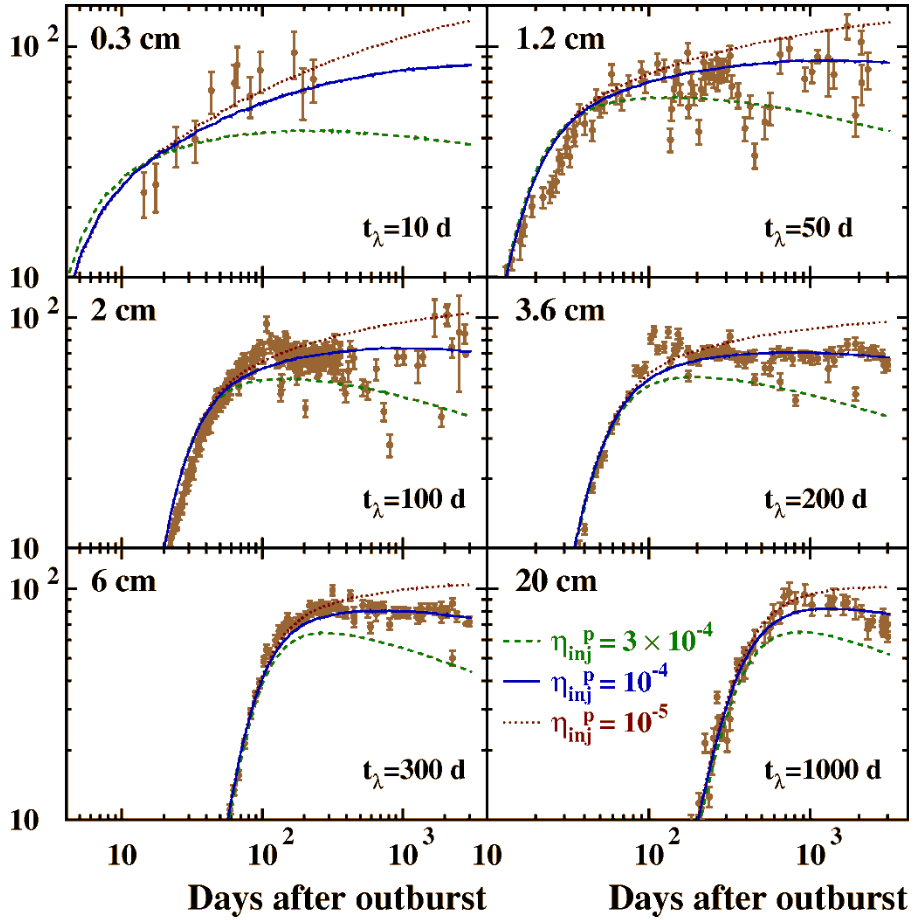




- Synchrotron losses are important to the radial emissivity
- From the width of the observed radial profile: $30 < B_{u0} < 80$ G

Parameter uncertainties





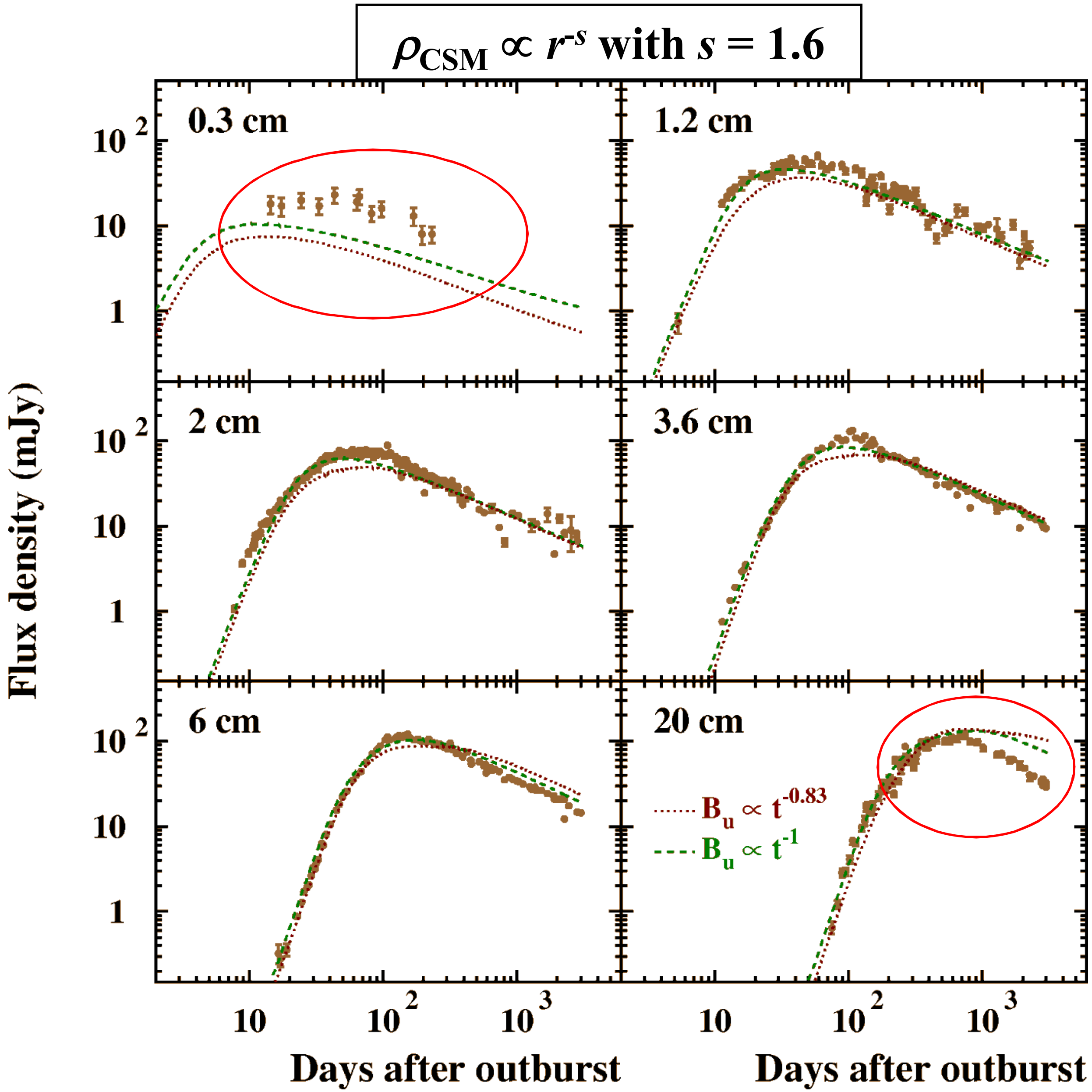
- The degeneracy between B and N_e is lifted by the synchrotron losses

$$B_{u0} = 50 \pm 20\ \mathrm{G}$$

- The shock is weakly modified:

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

Density profile of the CSM



- 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