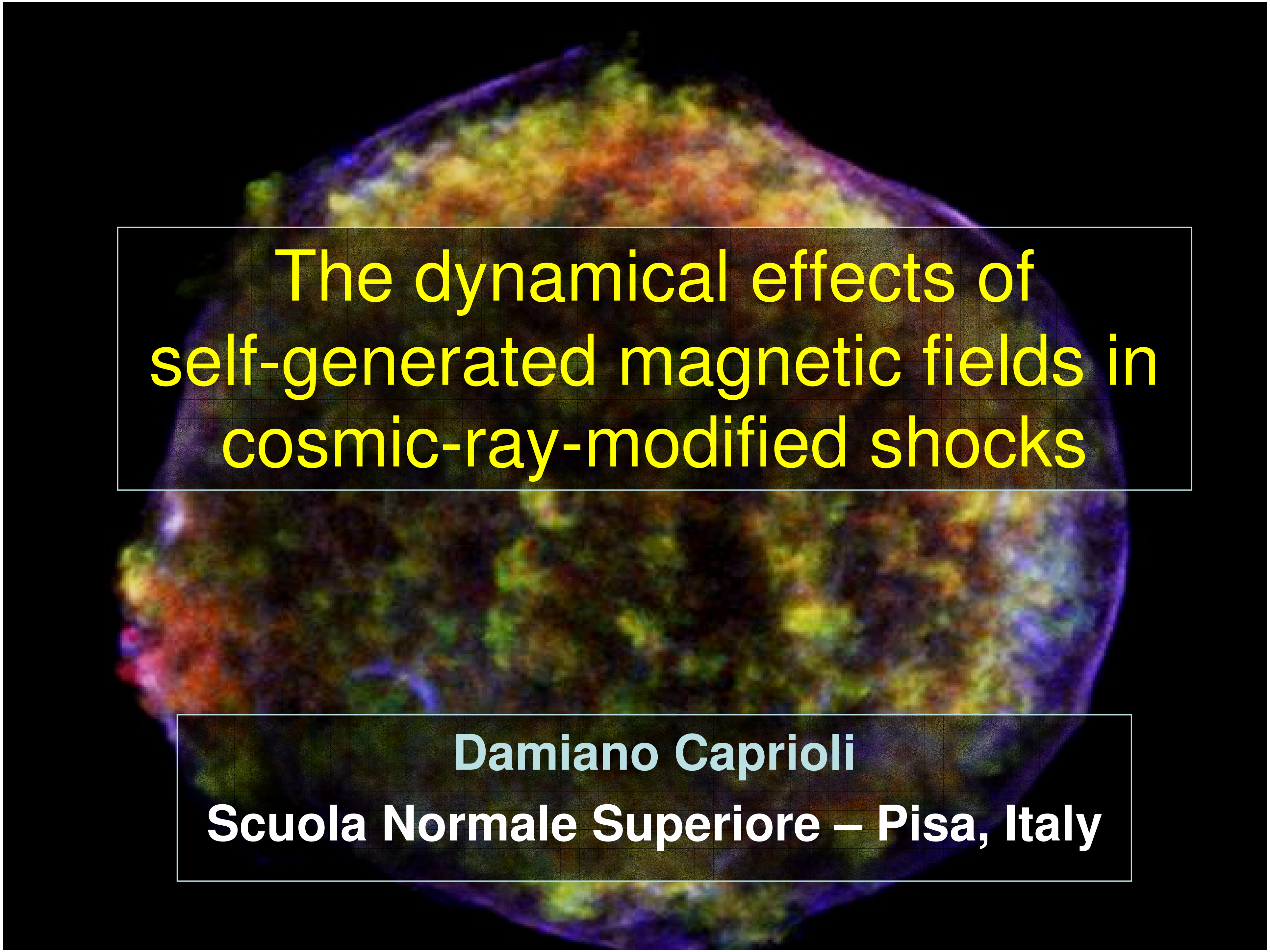


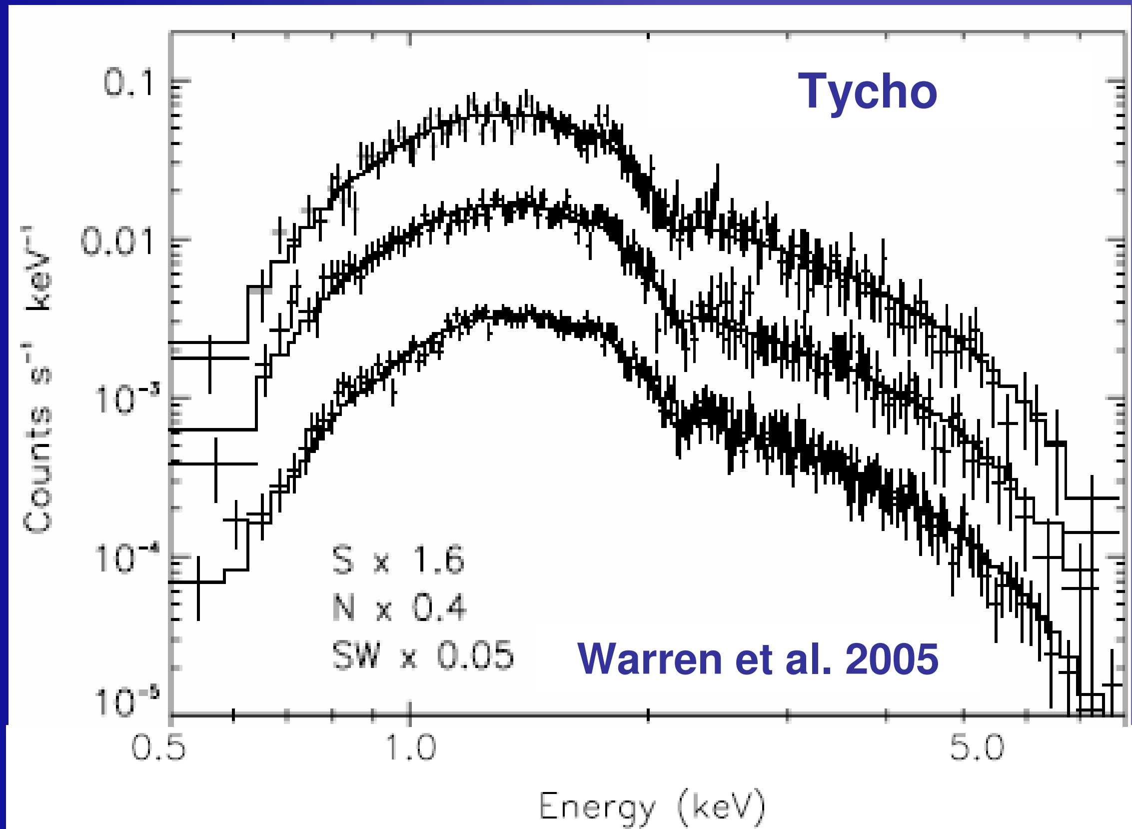
The dynamical effects of self-generated magnetic fields in cosmic-ray-modified shocks

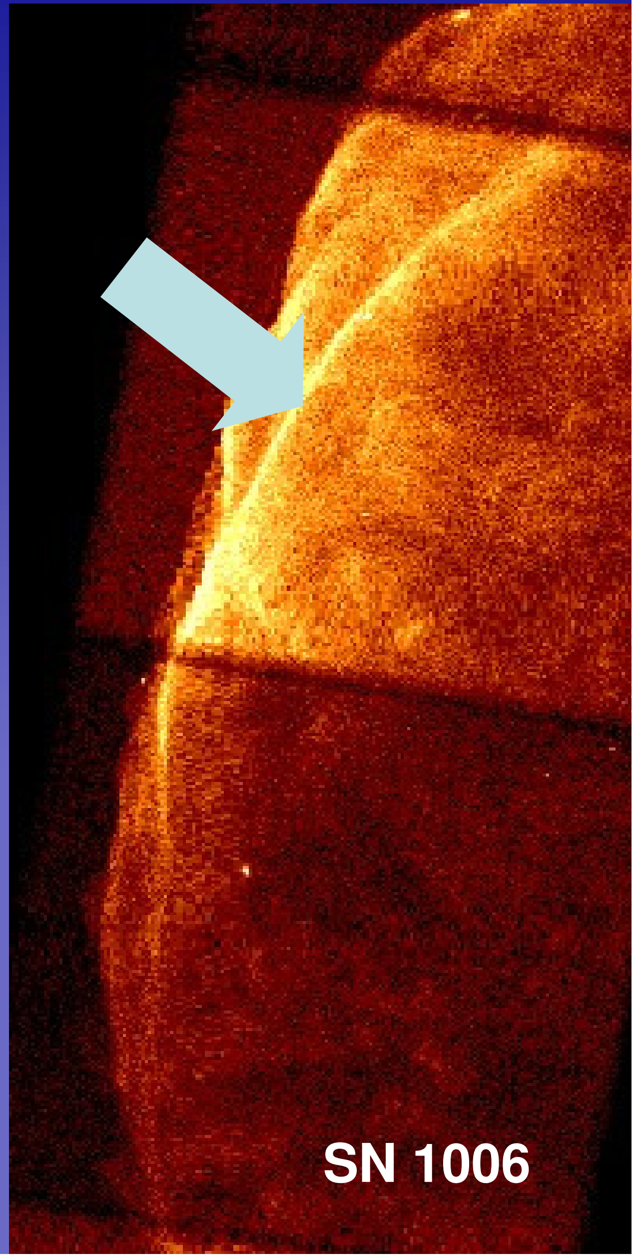
Damiano Caprioli

Scuola Normale Superiore – Pisa, Italy

X-ray observations of young SNRs

- Bright narrow rims at the blast wave
- Non-thermal spectra
- Synchrotron radiation by electrons up to 10-100 TeV





Magnetic field amplification (MFA)

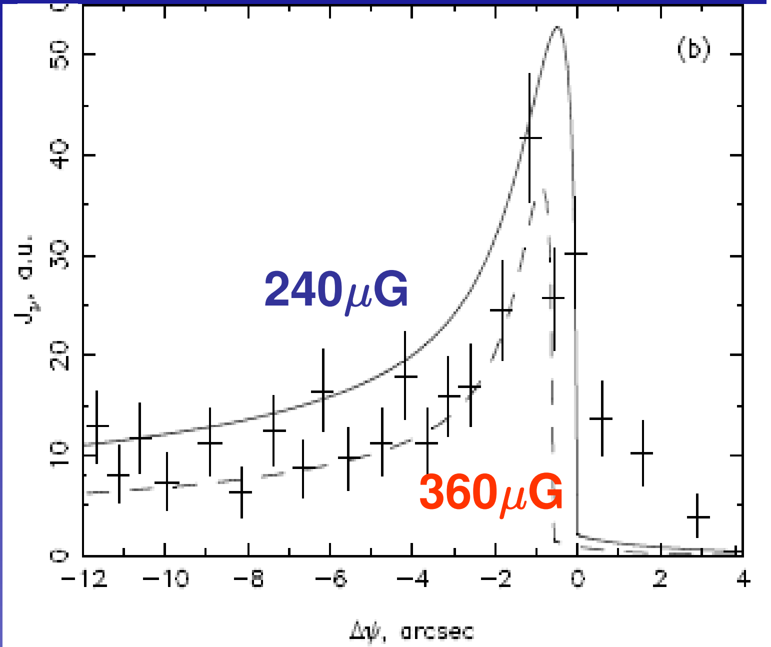
- The width of the rims requires

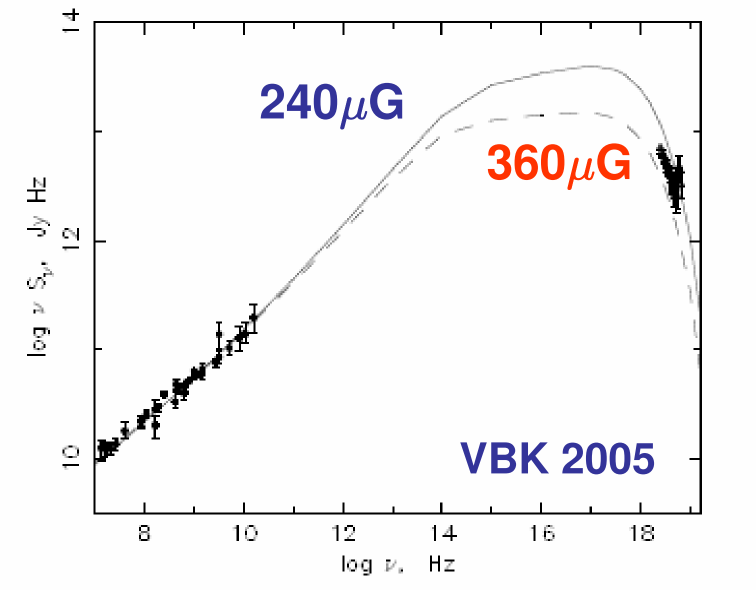
  $$B_{ds} \sim 90\text{-}500\mu G \gg B_0$$

  - **Völk, Berezhko & Ksenofontov 2005**
  - **Parizot et al. 2006**

SNR	B_{ds} (μG)	$P_{w,ds}$(%)
Cas A	250-390	3.2-3.6
Kepler	210-340	2.3-2.5
Tycho	240-530	1.8-3.1
SN1006	90-110	4.0-4.2

- Lower B_{ds} if the thickness of the rims were due to magnetic field damping
  - **Pohl et al. 2005**





MFA models

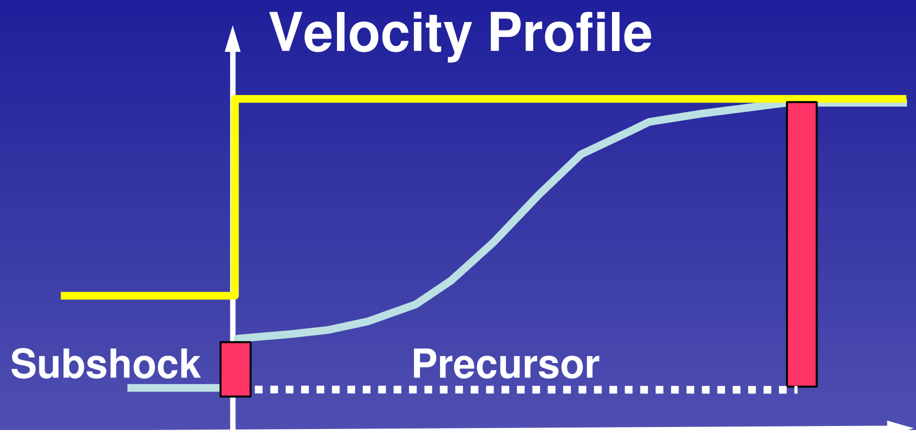
- Cosmic ray induced **Streaming Instability** (SI)
  - **Resonant** (standard) **Skilling 1975, Bell 1978**
  - **Non-resonant** **Bell 2004, Amato & Blasi 2008**

- **Phenomenological models**: isotropization of magnetic irregularities with opposite helicities
  - **Bell & Lucek 2001; Vladimirov, Ellison & Bykov 2007**

- Amplification of the magnetic field downstream due to **upstream clumpiness and shock corrugation**
  - **Giacalone & Jokipii 2007**

The SNR paradigm for galactic CR

- 10-20% of SN kinetic energy converted in CR
  - The upstream fluid is slowed down: **CR modified shock**

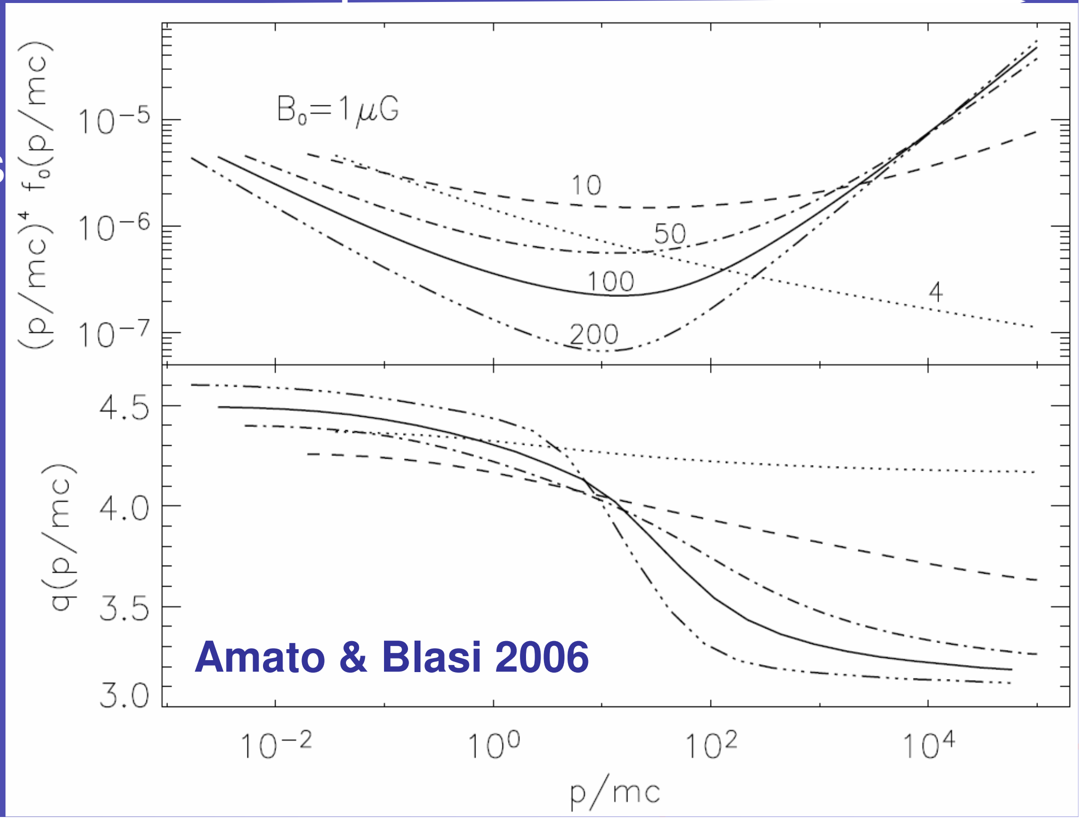


- Power law spectra
  - In modified shocks becomes rather **concave**

- Energies up to the *knee*

  $E_{knee} \sim 3 \times 10^6$ GeV

  achievable only with MFA
  - **Blasi, Amato, CD 2007**



SNR Hydrodynamics

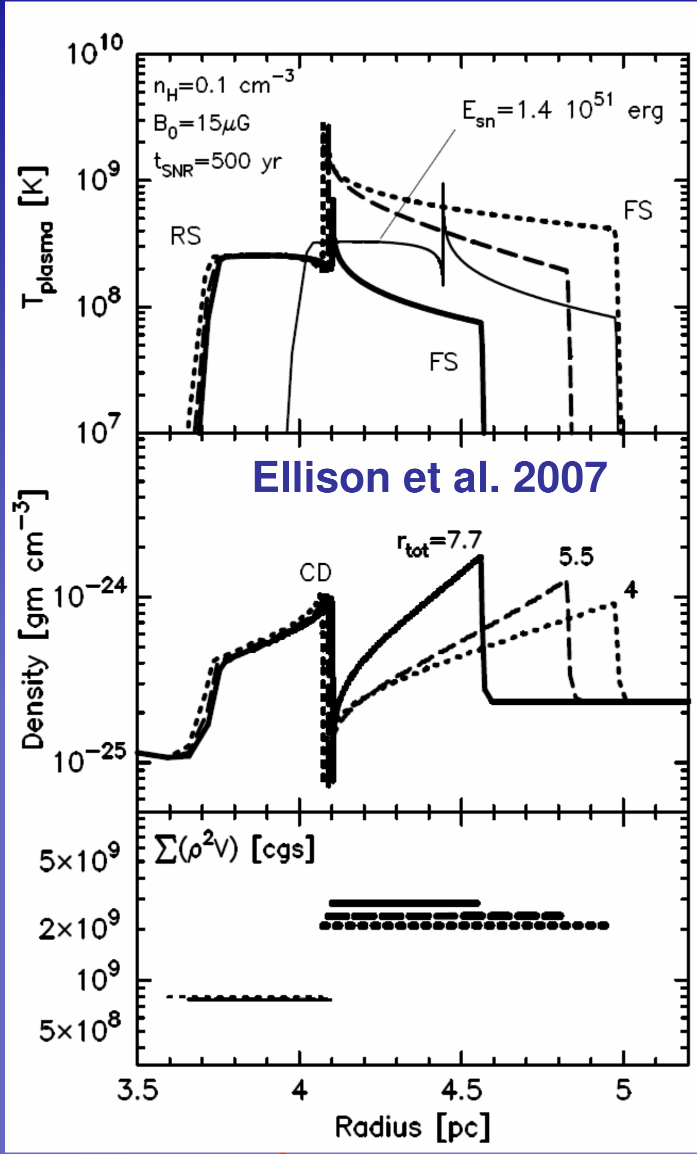
- Relative positions of forward shock and contact discontinuity
  - **Tycho**, Warren et al. 2005;
  - **SN 1006**, Cassam-Chenaï et al. 2007.
- Multiwavelength analysis
  - Berezhko & Voelk 2004 and following;

$\Rightarrow$ $R_{tot} \sim$ **6-10**

- Barely consistent with predictions of

$$R_{tot} \propto M_0^{3/4} \approx 10\text{-}100$$

  - Berezhko & Ellison 1999; Amato & Blasi 2006
- Non-adiabatic heating in the precursor?
  - **Alfvén heating**: McKenzie & Völk 1982
  - **Acoustic instability:** Wagner et al. 2007



The dynamical feedback of MFA

- *Three-fluid model* (plasma-cosmic rays-magnetic field)
  - Resonant Alfvén waves excited by standard SI
  - At the subshock:
    - Wave reflection and trasmission; **Scholer-Belcher 1971**
    - Magnetized jump conditions; **Vainio-Schlickeiser 1999**

- Conservation of mass, momentum and energy lead to

$$R_{tot}^{\gamma+1} = \frac{M_0^2 R_{sub}^{\gamma}}{2}\left[\frac{\gamma+1-R_{sub}(\gamma-1)}{1+\Lambda_B}\right]$$

which is the standard one a part from the factor Λ_B

$$\Lambda_B = W\left[1+R_{sub}\left(2/\gamma-1\right)\right]$$

$$W = P_{w1}/P_1$$

Ratio between magnetic and plasma pressure upstream

CD et al. 2008, ApJL

Magnetization of SNRs

- Normalized magnetic pressure downstream

  $P_{w,ds} \sim$ 2 - 4%

  imply *at least* **$W \geq 0.3$**

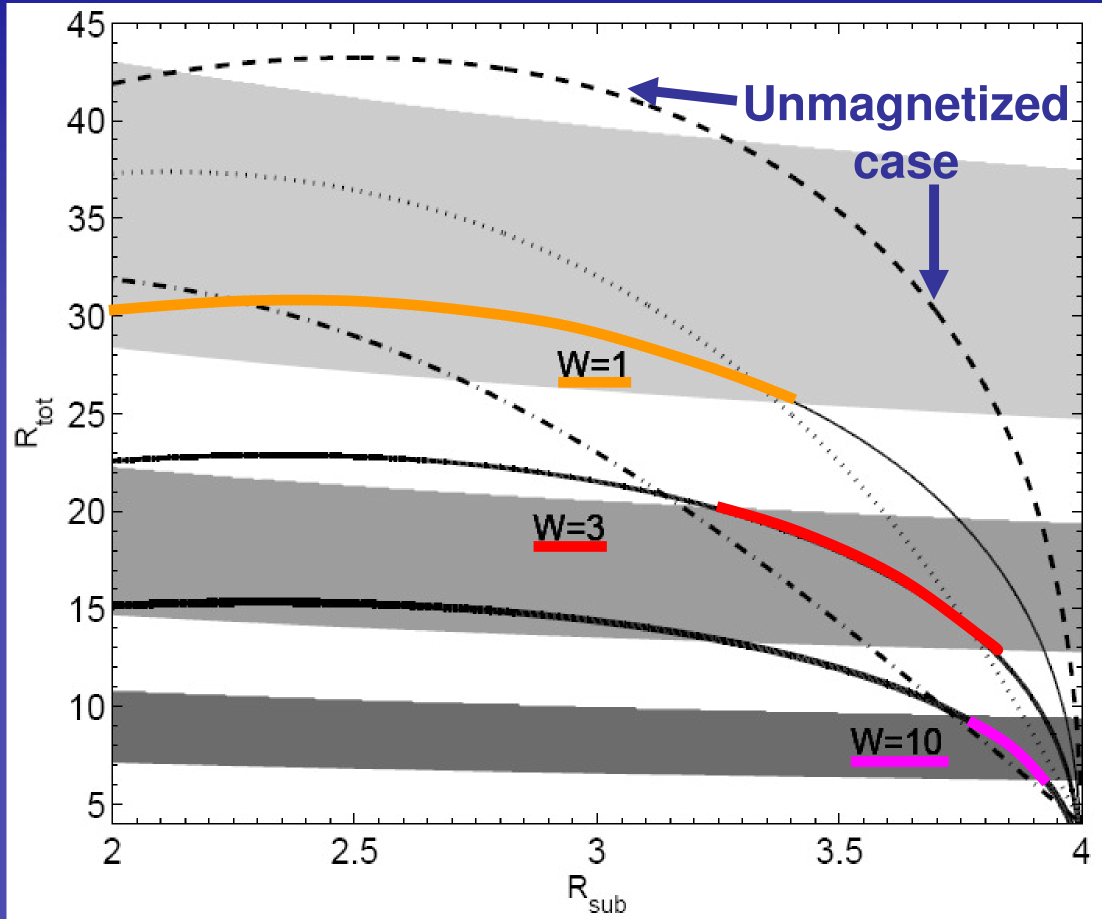
  - Typically $W \sim 1\text{-}100$

- The magnetic field can not be neglected!

- Relevant reduction of R_{tot}

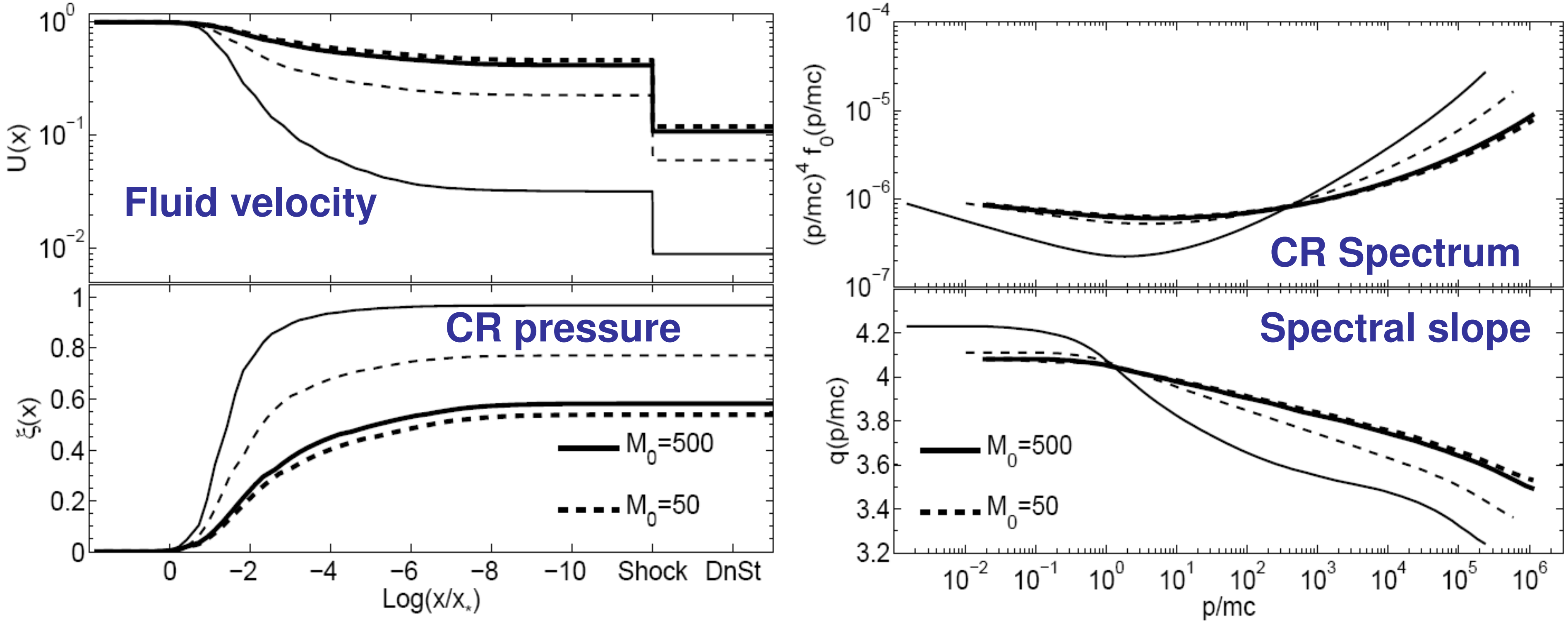
- The effect is driven by:

$$W = \frac{\alpha_1}{P_1} = \frac{\gamma}{4}\frac{M_0^2}{M_{A0}}\left(\frac{R_{sub}}{R_{tot}}\right)^{\gamma-3/2}\left[1-\left(\frac{R_{sub}}{R_{tot}}\right)^2\right] \propto \frac{u_0 B_0}{\sqrt{\rho_0 T_0}}$$



DC et al. 2008, ApJL

The kinetic calculation



B_0=10μG; Age of SNR=1000yr

DC et al., sbt. to MNRAS

T_0(K)	Λ_B	ξ_1	$p_{max}(10^6 GeV)$	R_{sub}	R_{tot}	$B_2(\mu G)$	$T_2(10^6$ K)
10^4	No	0.97	0.24	3.58	112.1	645.8	0.88
10^4	Yes	0.58	1.17	3.84	9.22	463.9	126.5
10^6	No	0.77	0.59	3.76	16.6	235.0	42.3
10^6	Yes	0.54	1.14	3.84	8.44	425.1	154.8

Bohm diffusion in the self-generated magentic field

Turbulent (Alfvén) Heating

- Often invoked in order to smooth the precursor, BUT it:
  - Is relevant only if $V_{sh} \ll 4000\, T_5^{1/2}$ km/s; **Völk & McKenzie 1981; Ptuskin & Zirakasvhili 2005**
  - Cannot be too efficient, otherwise no MFA $\zeta < 1$
  - Has no severe effects on the precursor; **DC et al. 2008; Vladimirov, Bykov & Ellison 2008**

$$R_{tot}^{\gamma+1} = \frac{M_0^2 R_{sub}^{\gamma}}{2}\left[\frac{\gamma + 1 - R_{sub}(\gamma - 1)}{(1+\Lambda_B)(1+\Lambda_{TH})}\right]$$

$$\Lambda_{TH} = \zeta(\gamma - 1)\frac{M_0^2}{M_A}\left[1 - \left(\frac{R_{sub}}{R_{tot}}\right)^{\gamma}\right]$$

DC et al. 2008, sbt. to MNRAS

ζ	ξ_1	$p_{max}(10^6 GeV)$	R_{sub}	R_{tot}	B_1/B_0	W	$B_2(\mu G)$	$T_2(10^6$ K)
0	0.60	1.17	3.76	9.52	25.3	1.941	475.6	114.6
0.5	0.66	0.84	3.65	10.96	20.8	0.390	379.6	132.6
0.8	0.65	0.53	3.68	10.76	12.8	0.115	232.5	128.3
0.99	0.55	0.12	3.85	8.69	2.26	0.005	43.5	162.2

$B_0=10\mu$G; Age=1000yr; $T_0=10^5$ K

Conclusions

- The magnetic feedback is always relevant for young SNRs
- The inclusion of the amplified magnetic field provides
  - A smoothening of the precursor ($R_{tot} \sim 6\text{-}10$)
  - Mildly-concave spectra ($\propto p^{-3.5}$ at highest momenta)
  - Higher p_{max}
  - No dependence on M_0
  - Higher temperature and pressure downstream
  - No need for turbulent heating
- The details can be *analytically* worked out only for resonant SI
  - Need for a theory of non-resonant turbulence
  - CR transport equation / pressure and energy densities