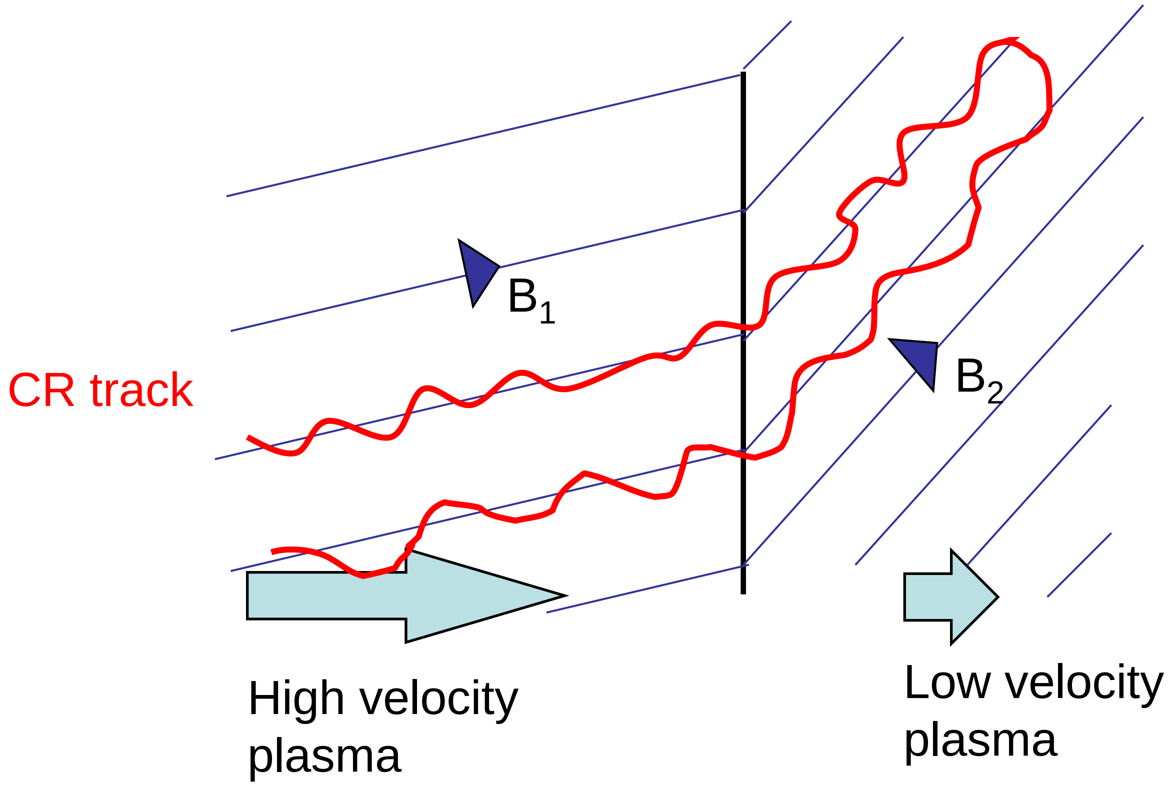
Shocks, instabilities & particle acceleration

Tony Bell

University of Oxford

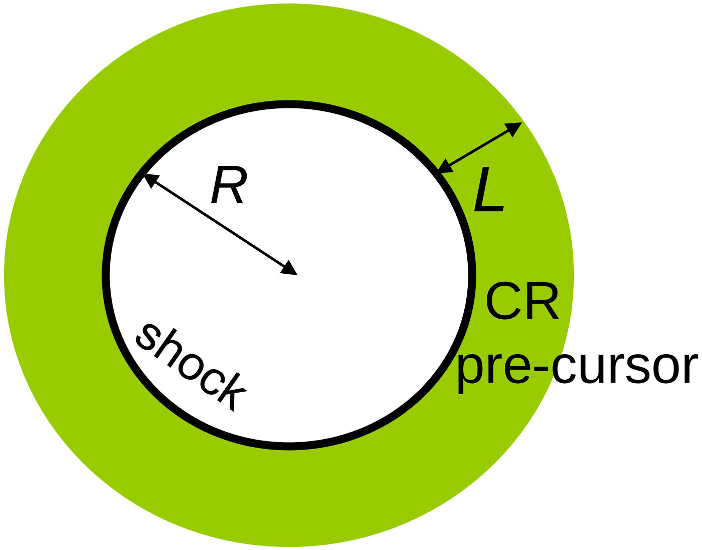
SN1006: A supernova remnant 7,000 light years from Earth
X-ray (blue): NASA/CXC/Rutgers/G.Cassam-Chenai, J.Hughes et al; Radio (red): NRAO/AUI/GBT/VLA/Dyer, Maddalena & Cornwell;
Optical (yellow/orange): Middlebury College/F.Winkler. NOAO/AURA/NSF/CTIO Schmidt & DSS

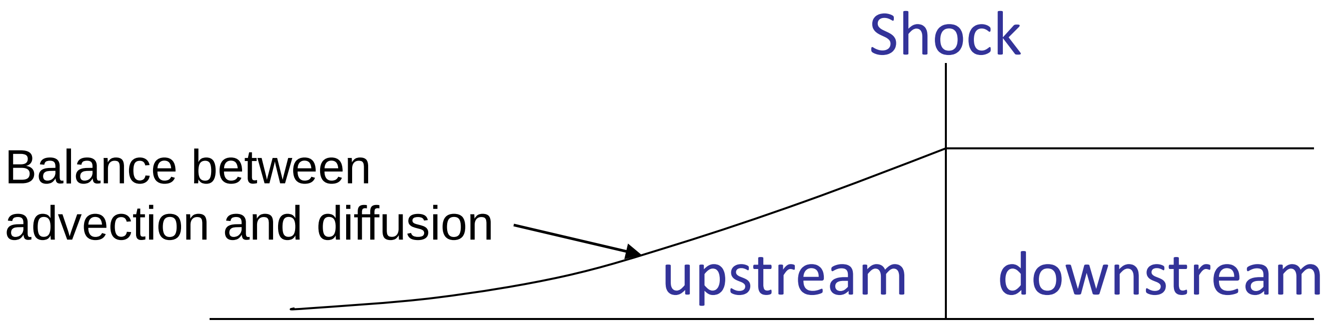
DIFFUSIVE SHOCK ACCELERATION



Due to scattering, CR recrosses shock many times
Gains energy on each crossing

Maximum CR energy





Typical interstellar magnetic field (3-5μG)

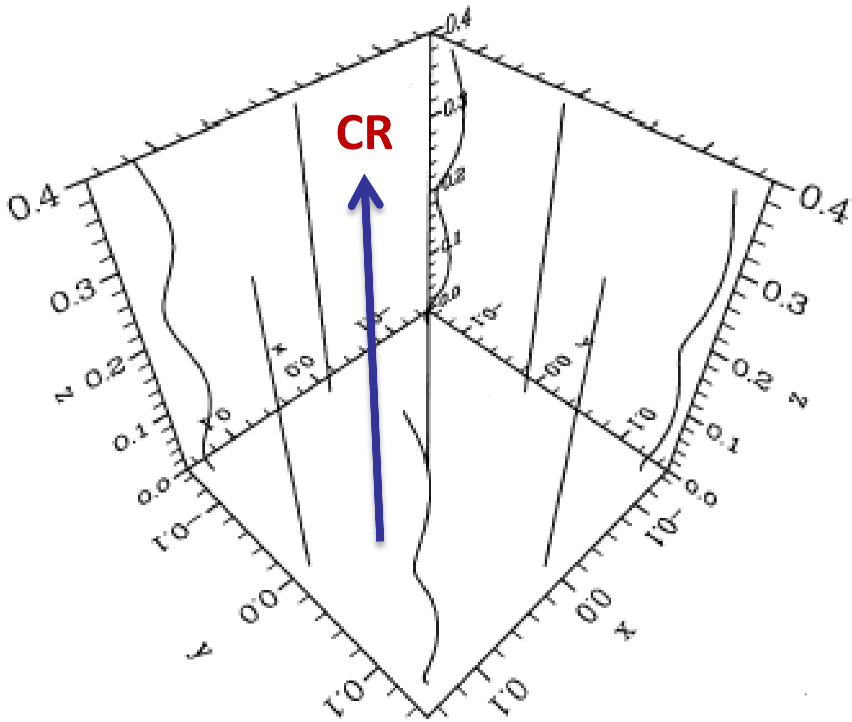
Optimistically: CR mean free path = Larmor radius

⟹ $E_{\max} < 8\text{x}10^{13}$ eV Too small!, need 10^{15}eV

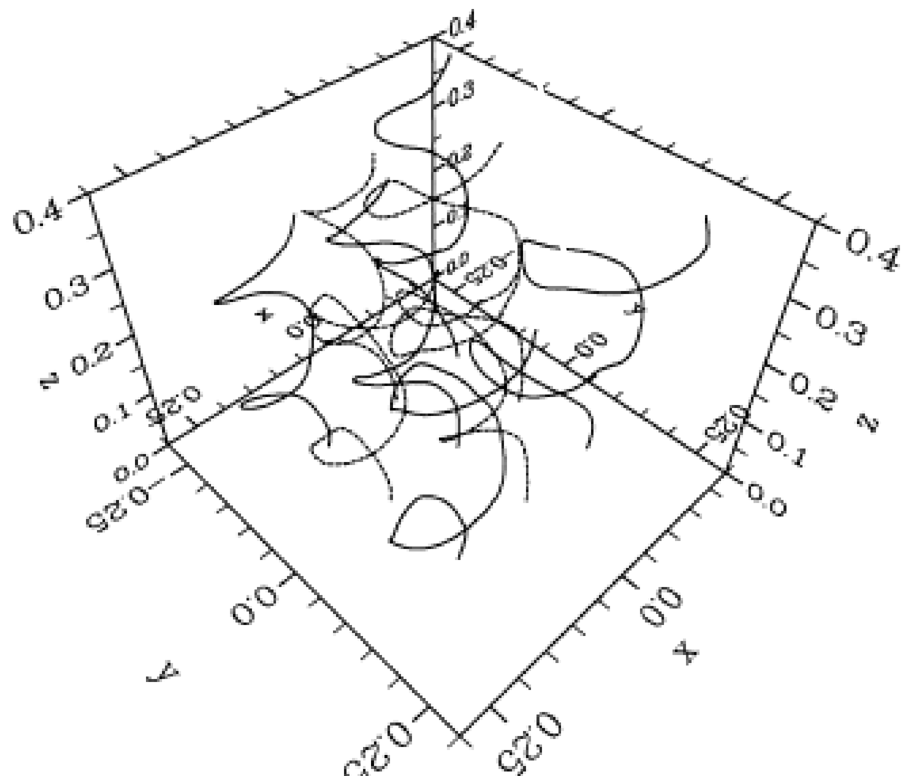
Streaming instability driven by cosmic rays

Lucek & Bell 2000

B field lines, t = 0

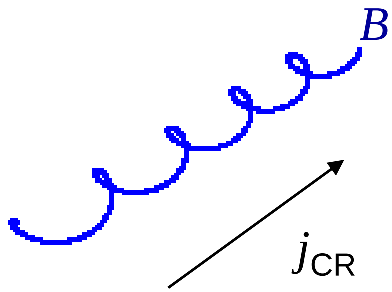


B field lines, t = 2



$\delta B/B$>>1 scatters energetic particles

Linear instability



Model

Thermal plasma as MHD fluid

CR as fixed uniform current $\mathbf{j}_{CR}$

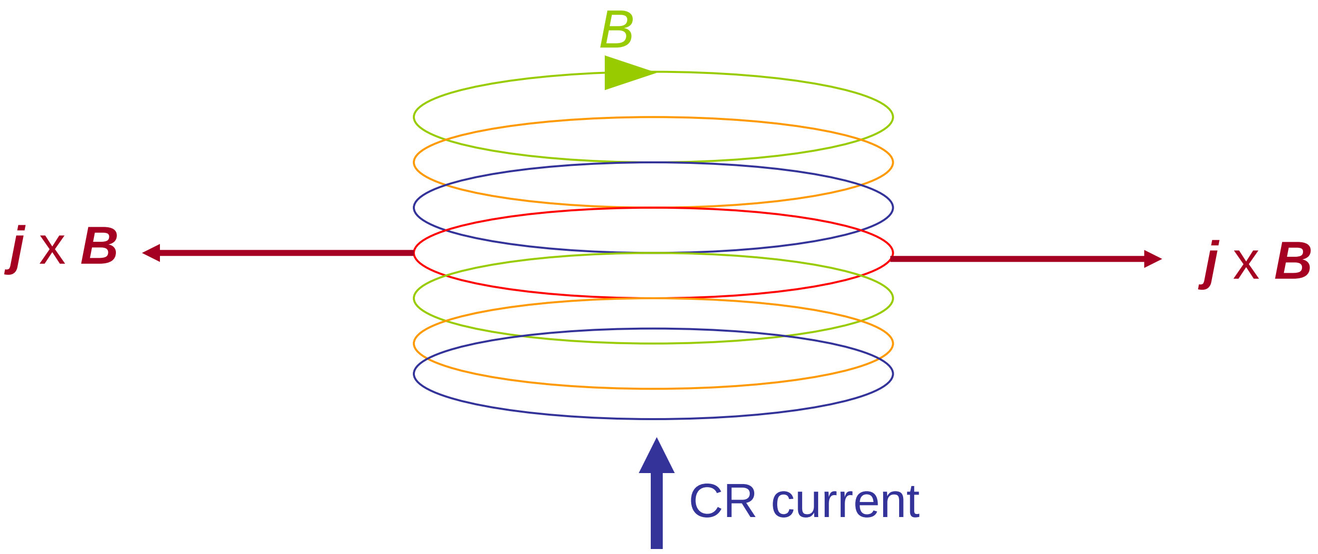
MHD equation of motion $$\rho \frac{d\mathbf{v}}{dt} = -\mathbf{j}_{CR} \times \mathbf{B}$$

1st order perturbation

Flux freezing $$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{v} \times \mathbf{B} \right)$$

Purely growing, circularly polarised transverse mode: $$\gamma = \left(\frac{k B_0 j_{CR}}{\rho} \right)^{1/2}$$

Essence of instability: expanding loops of B



jxB expands loops

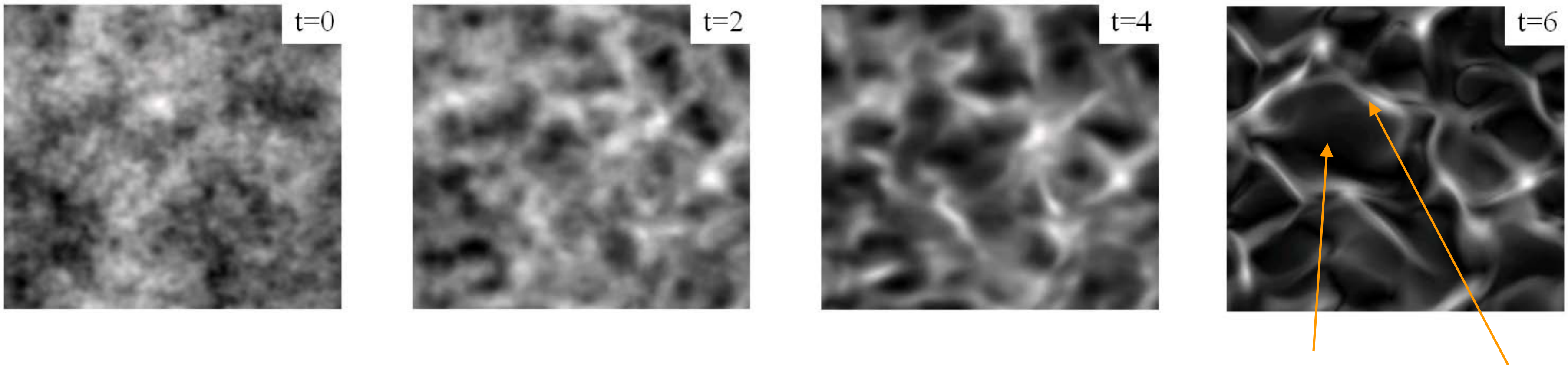
→ decreases mass attached to field line element

→ increases jxB/ρ acceleration

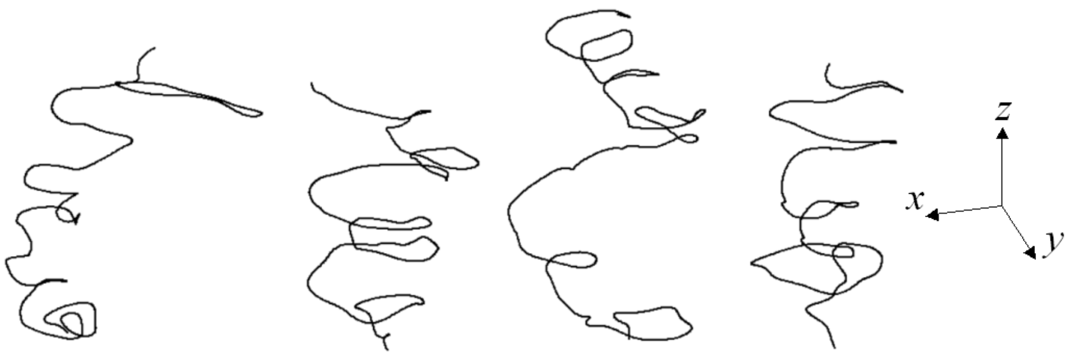
→ Loops expand more rapidly

Non-linear growth – expanding loops

Slices through |*B*| - time sequence (fixed CR current)



Field lines: wandering spirals



Non-linear growth – expanding loops

jxB force must exceed magnetic tension: curl(B) < $\mu_0 j_{CR}$ ⟶ $L > B/\mu_0 j_{CR}$

⟶

Scalelength must be less than CR Larmor radius $L < p/eB$

If saturation reached

$$B_{downstream} \approx 400 \left(\frac{u}{10^4 \,\mathrm{kms}^{-1}} \right)^{3/2} \left(\frac{n_e}{\mathrm{cm}^{-3}} \right)^{1/2} \left(\frac{\eta}{0.1} \right)^{1/2} \mu\mathrm{G}$$

Observations

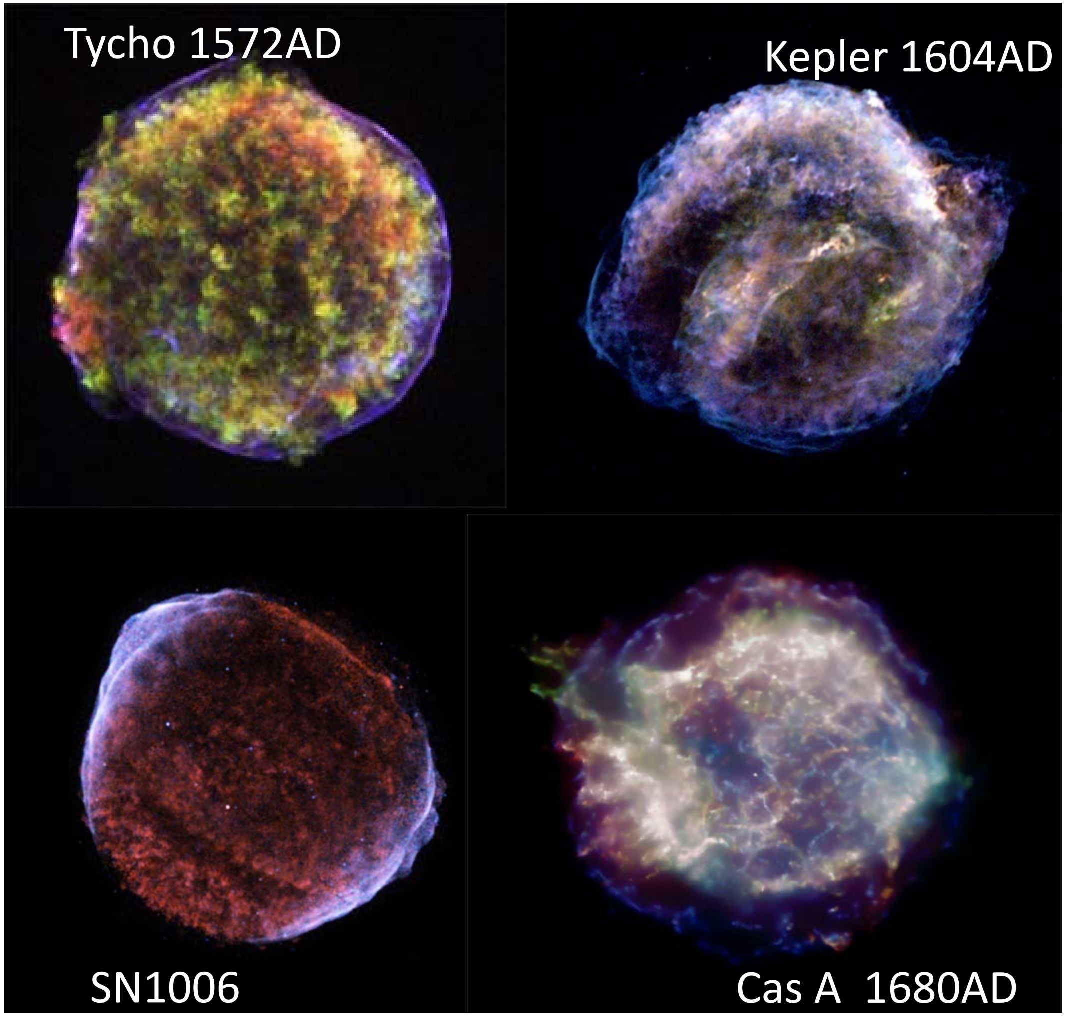
Shock thickness & synchrotron losses

Good evidence for field amplification

(Vink & Laming, Völk et al)

Evidence for magnetic field amplification at shock

(Vink & Laming, 2003; Völk, Berezhko, Ksenofontov, 2005)



Chandra observations

NASA/CXC/Rutgers/
J.Hughes et al.

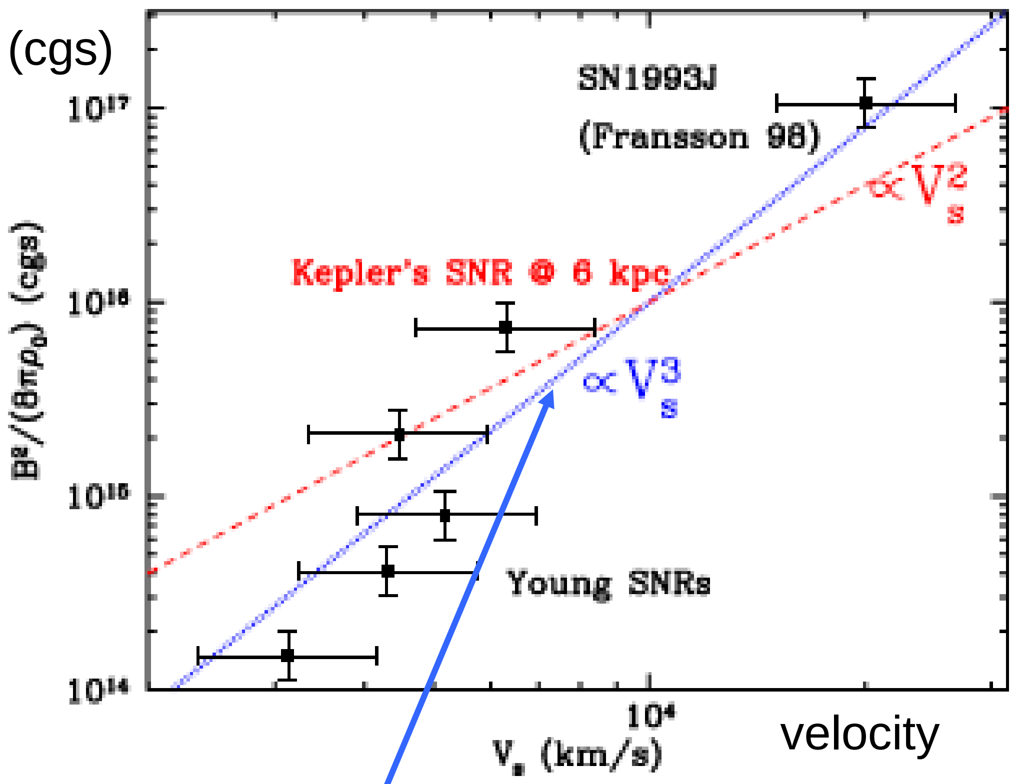
NASA/CXC/Rutgers/
J.Warren & J.Hughes et al.

NASA/CXC/NCSU/
S.Reynolds et al.

NASA/CXC/MIT/UMass Amherst/
M.D.Stage et al.

Inferred downstream magnetic field (Vink 2008)

$B^2/(8\pi\rho)$ (cgs)



velocity

Data for RCW86, SN1006, Tycho, Kepler, Cas A, SN1993J

Fit to obs (Vink):

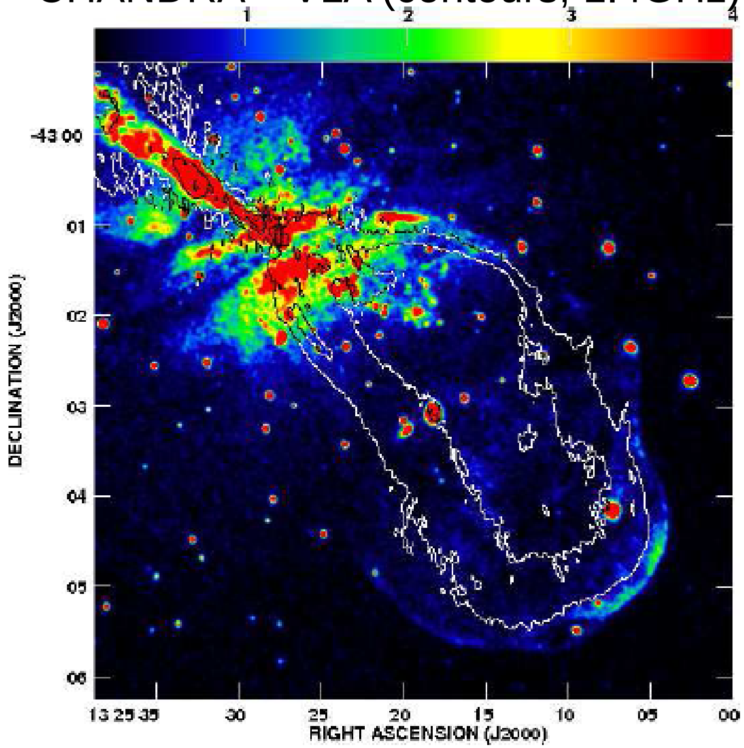
$$B \approx 700\left(\frac{u}{10^4\,\mathrm{kms}^{-1}}\right)^{3/2}\left(\frac{n_e}{\mathrm{cm}^{-3}}\right)^{1/2}\mu\mathrm{G}$$

Theory:

$$B \approx 400\left(\frac{u}{10^4\,\mathrm{kms}^{-1}}\right)^{3/2}\left(\frac{n_e}{\mathrm{cm}^{-3}}\right)^{1/2}\left(\frac{\eta}{0.1}\right)^{1/2}\mu\mathrm{G}$$

Shocks in radio jets
Centaurus A (Croston et al 2008)

CHANDRA + VLA (contours, 1.4GHz)



Values taken by Croston et al:
$n_e = 10^{-3}$ cm^{-3}
u = 2600 kms^{-1}

Shell thickness ΔR = 300pc
Shell radius R = 2000pc

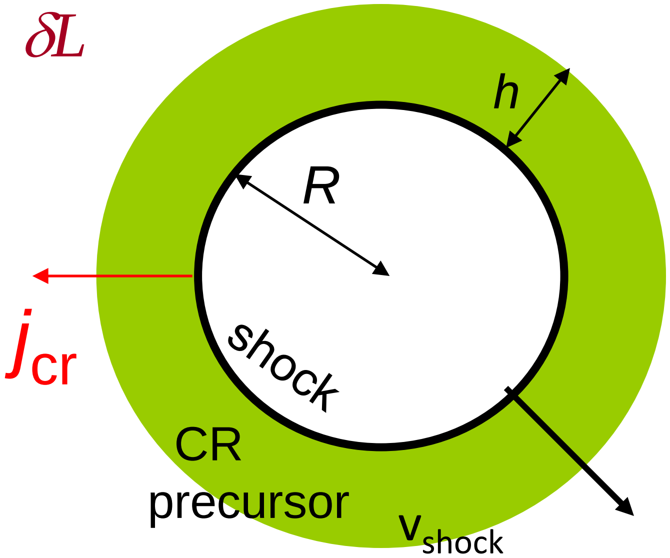
Estimates of B:
- Equipartition: 8 μG
- Shock thickness: ~ 1 μG

$$B \approx 400 \left(\frac{u}{10^4 \, \mathrm{kms}^{-1}} \right) \left(\frac{n_e}{\mathrm{cm}^{-3}} \right) \left(\frac{\eta}{0.1} \right) \mu\mathrm{G} \quad \Longrightarrow \quad B \sim 1.7 \, \mu\mathrm{G}$$

Observations

Can we observe structure of magnetic field?

Estimate shock structure scale δL



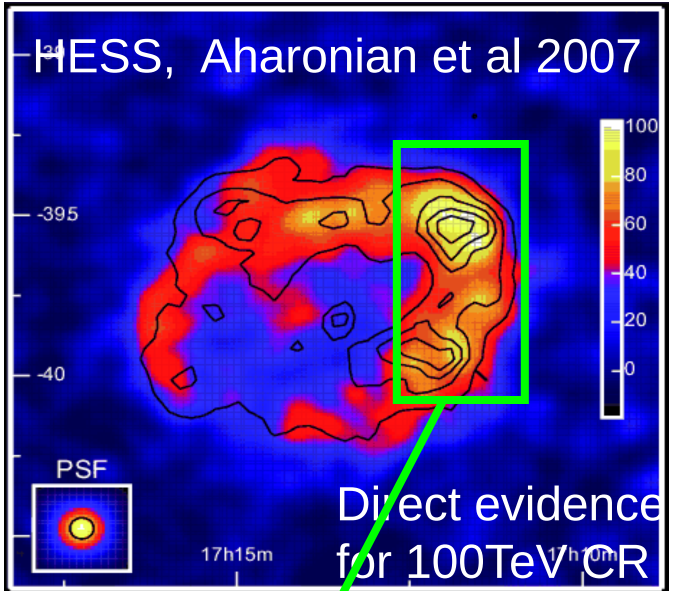
j_{cr}xB moves upstream plasma a distance

$$\delta L \approx \frac{1}{2}\frac{j_{CR}B}{\rho}t^2$$

Using scaling arguments for j_{CR}, B, ρ & t

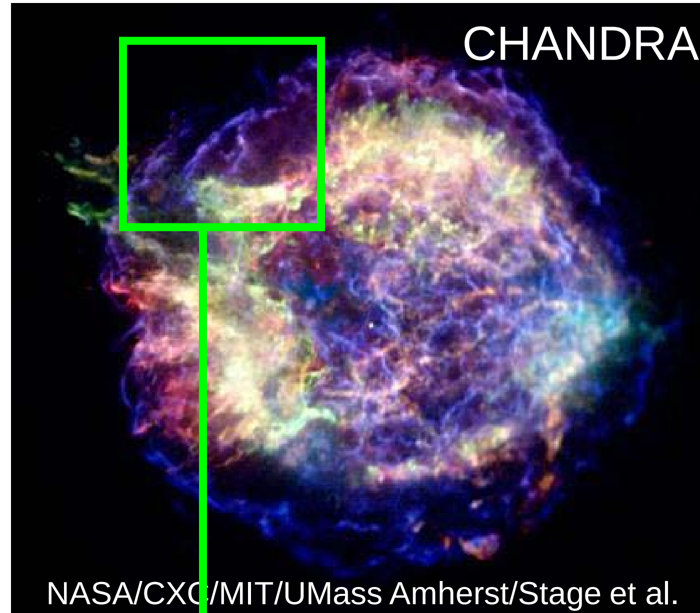
$$\frac{\delta L}{R} \approx \frac{\eta}{2}\frac{D}{D_{Bohm}}\frac{h}{R} \approx 0.01$$

~0.01 1 1

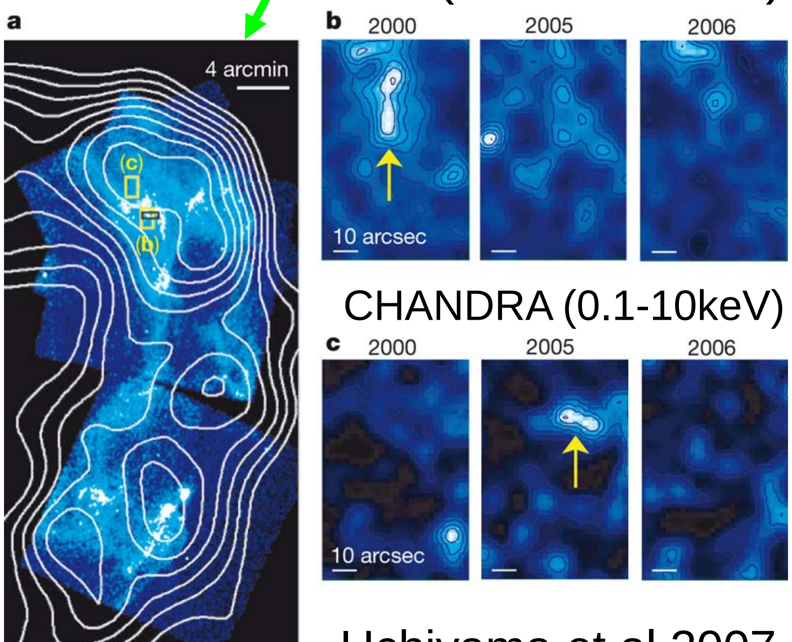


Two SN remnants with varying shock structure

Shock sweeps out pre-shock medium



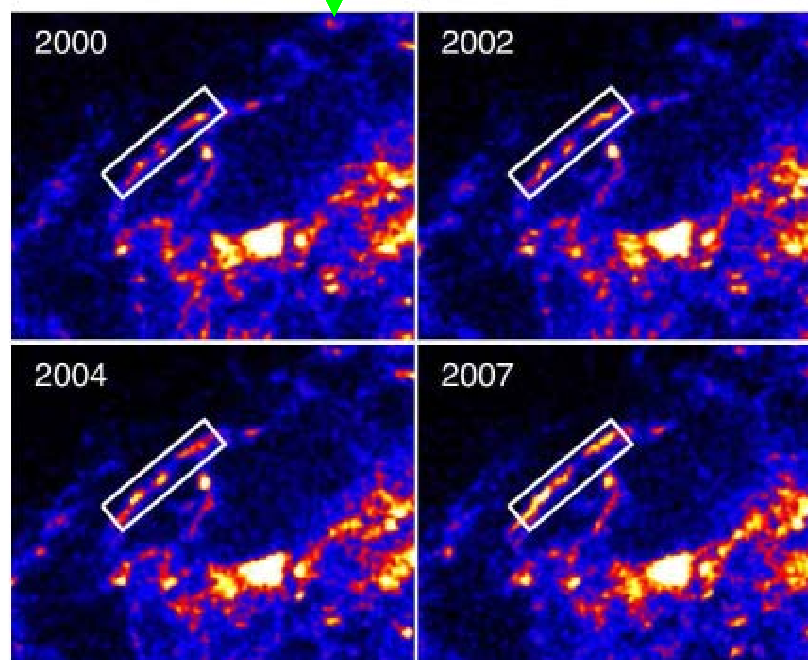
RX J1713.7-3946 (SN of 393AD)



Uchiyama et al 2007

Cas A (1680AD)

CHANDRA (Patnaude et al 2008)



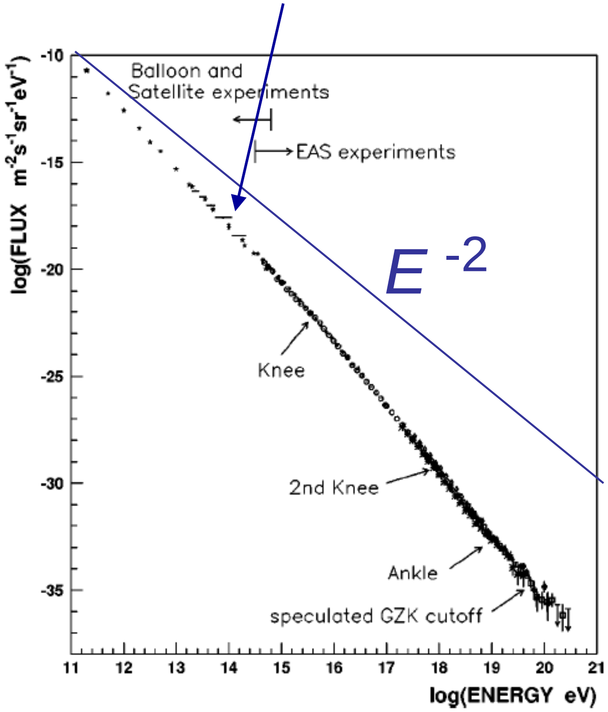
Observations

Spectral Index

Cosmic Ray spectrum arriving at earth

Nagano & Watson 2000

$n(E) \sim E^{-2.7}$



Leakage from galaxy accounts for some of difference (Hillas 2005)

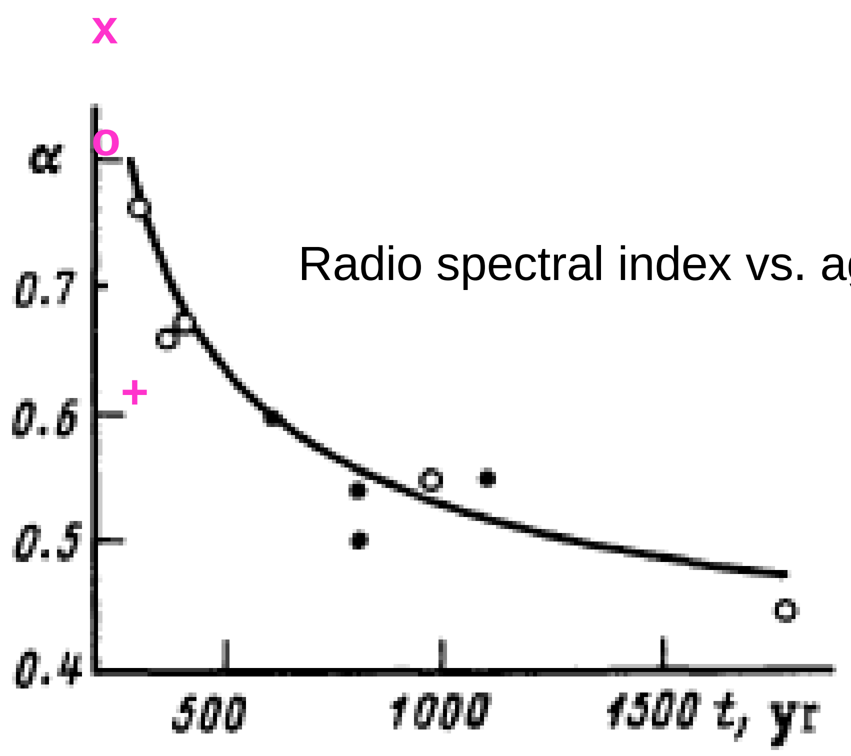
Historical SNR (Glushak 1985)

Cas A, Kepler, Tycho, SN1006, RCW86, RCW103, G319.7, 3C391, 0519-69.0

o SN1993J: α = 0.81 (Weiler et al 2007)

x SN1987A: α = 0.9 , flattening to 0.8 (Manchester et al 2005)

\+ G1.9+0.3: α = 0.62 (Green et al 2008)



Radio spectral index vs. age

'Diffusive' shock acceleration →

CR-dominated shocks

Non-linear effects: curved spectrum
steepen at low energy, flatten at high energy

Drury & Völk 1981

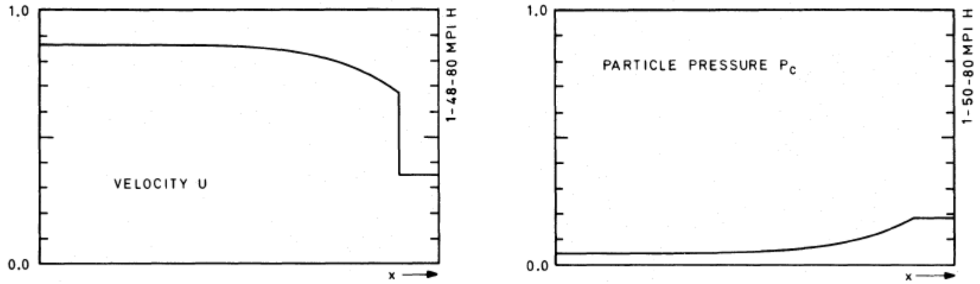
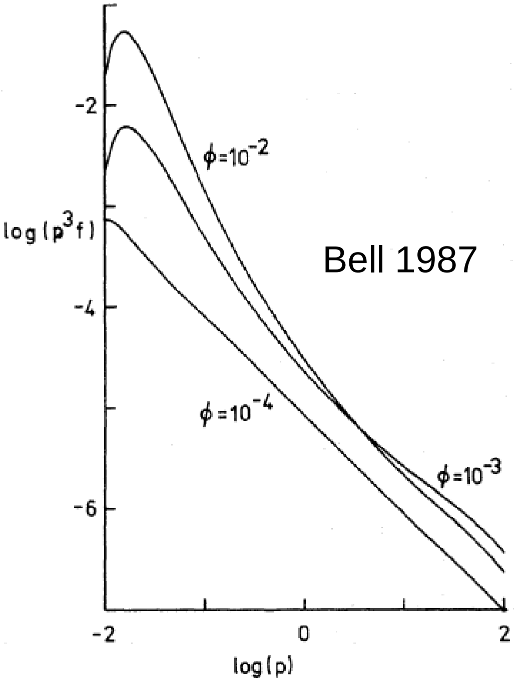


FIG. 2.—The shock structure for adiabatic exponents 5/3 for the gas and 4/3 for the cosmic rays, shock Mach number $M=2.0$, and fractional contribution of the cosmic rays to the upstream pressure $N=0.3$. The flow variables have been normalized to unit total momentum and mass fluxes. As the fluid passes through the shock, its state follows the heavy line in the (u, p_G)-diagram.

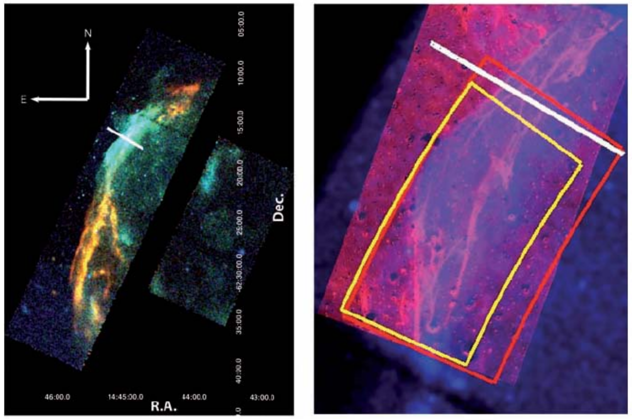


Bell 1987

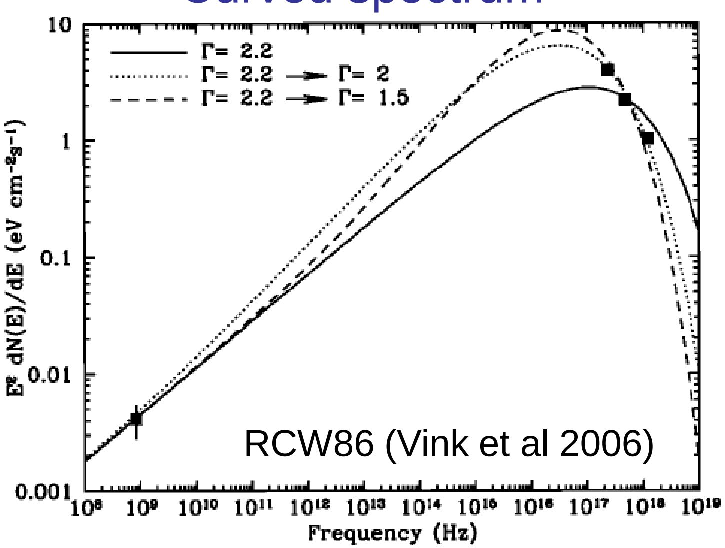
Evidence for CR-dominated shocks

Low post-shock temperature

RCW86 (CHANDRA/VLT Helder et al 2009)



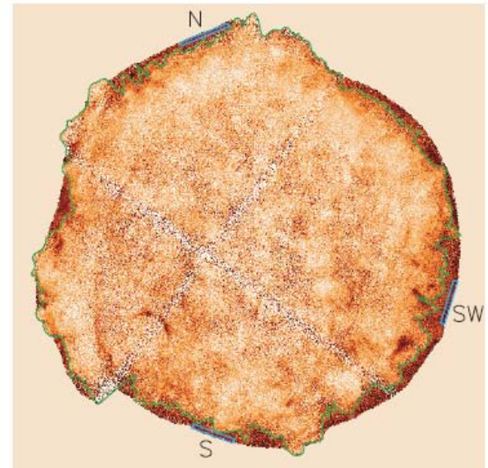
Curved spectrum



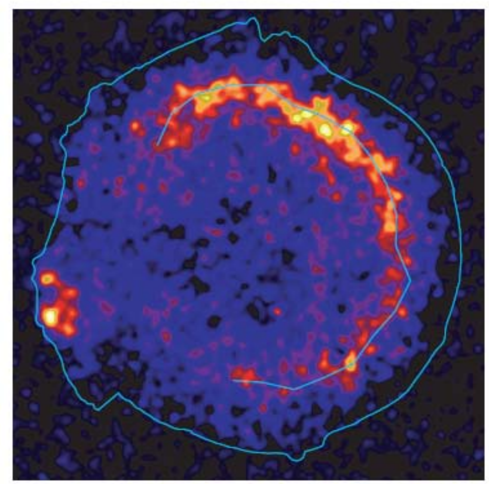
RCW86 (Vink et al 2006)

Strong compression at shock

SN1006 (CHANDRA, Warren et al 2005)

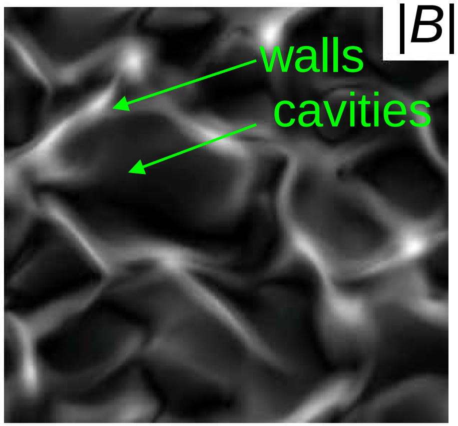


Contact discontinuity

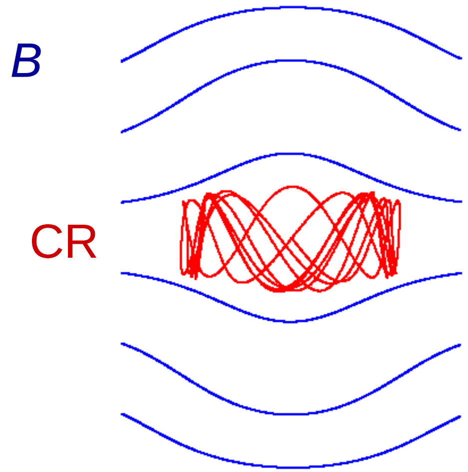


Reverse shock

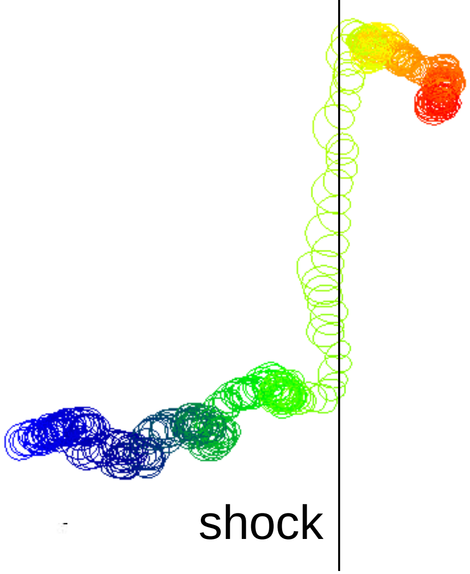
Varieties of non-diffusive behaviour



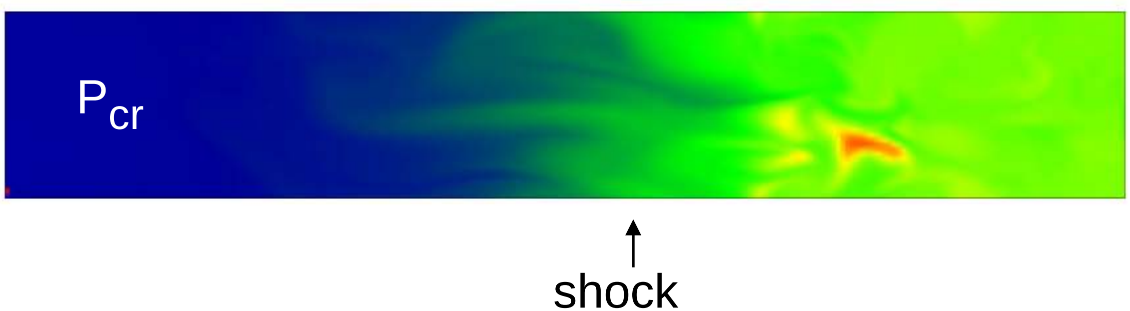
Magnetic barriers



Perpendicular shocks
B into screen



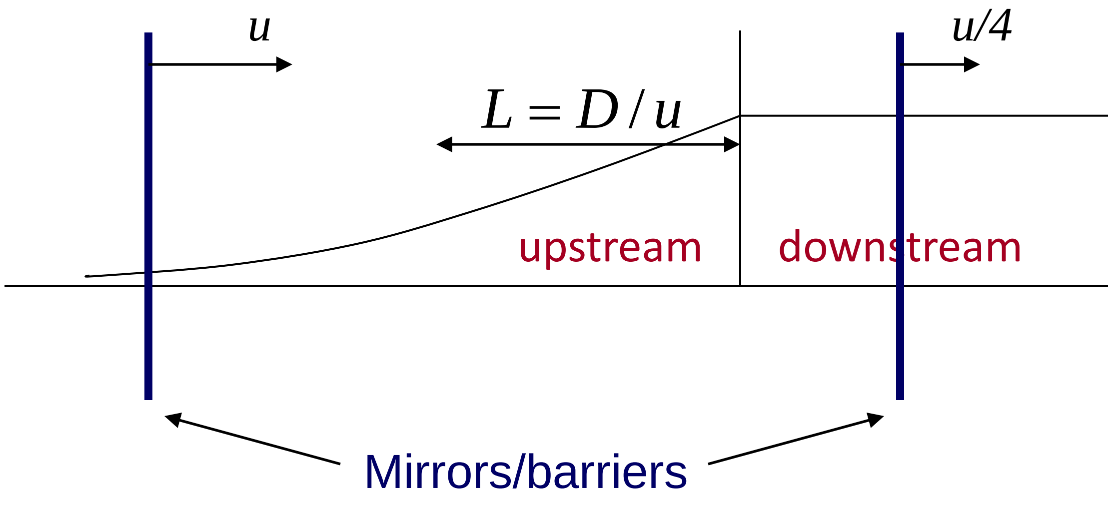
CR escape through cavities



Super-diffusion & sub-diffusion due to wandering field lines
(Duffy, Kirk, Gallant, Dendy 1995)

Postulate 'sweep-out' events

(mirrors, perpendicular field)



$$\frac{\partial f}{\partial t} + \frac{\partial (uf)}{\partial z} - \frac{\partial}{\partial z}\left(D \frac{\partial f}{\partial z} \right) - \frac{1}{3}\frac{\partial u}{\partial z}\frac{1}{p^2}\frac{\partial (p^3 f)}{\partial p} = S_{sweep-out}$$

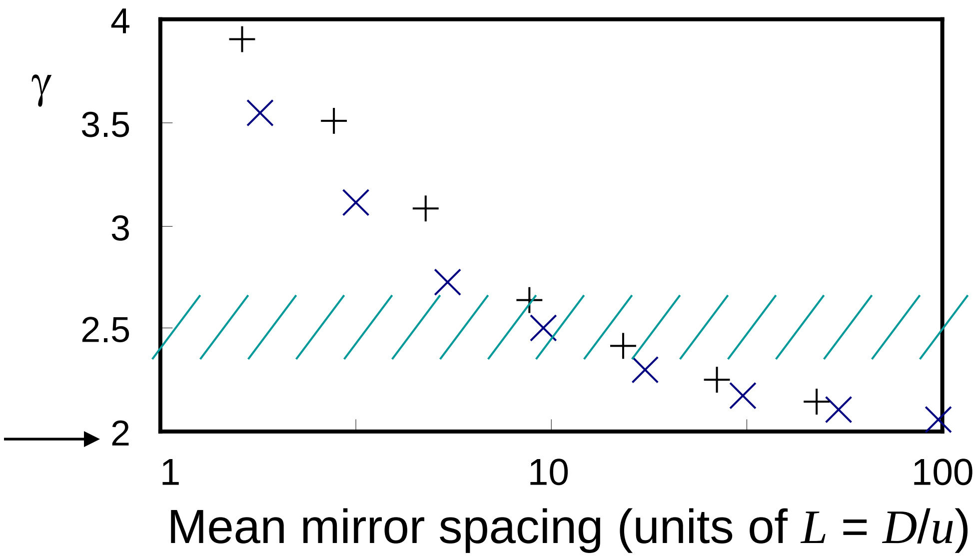
advection diffusion acceleration at shock

Randomly placed mirrors

Downstream CR: no return to shock

Mirrors/barriers steepen spectrum

Energy spectrum
$n(E) \sim E^{-\gamma}$

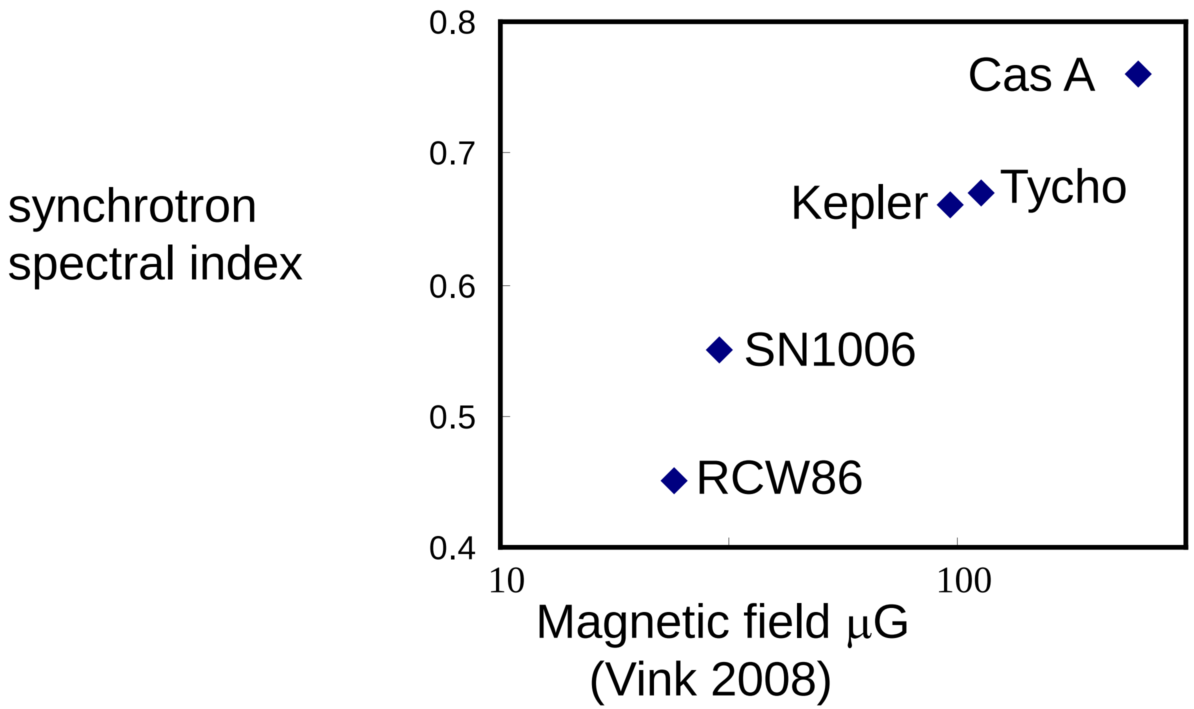


'diffusive' accel
γ=2, α=0.5

Synchroton spectrum
$S(\nu) \propto \nu^{-\alpha}$

α=0.5+(γ-2)/2

Young SNR: spectral index vs magnetic field



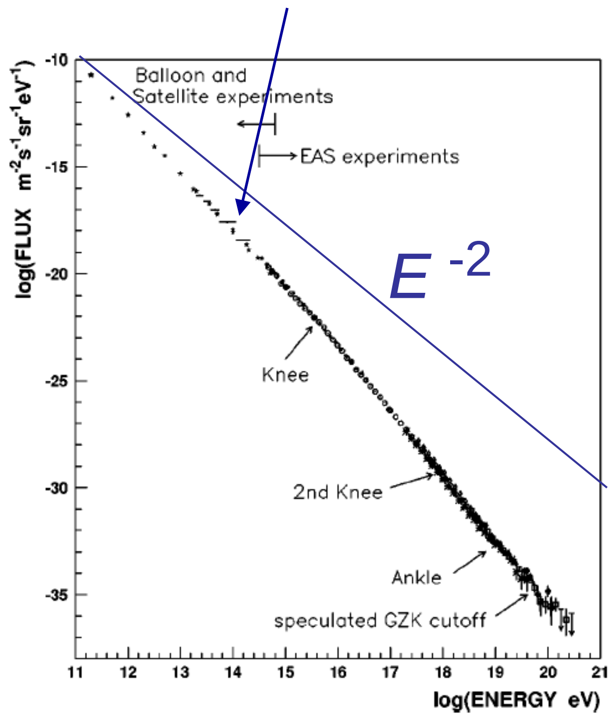
Connected phenomena:

- CR dominated shocks
- Steepened spectrum
- non-diffusive transport
- magnetic field amplification

Cosmic Ray spectrum arriving at earth

Nagano & Watson 2000

$n(E) \sim E^{-2.7}$



Why spectrum so straight 10^{11}-10^{15}eV?
Universal self-similarity?

CR origin above 10^{15}eV?

Expansion into stellar wind

Parameters, based on SN1993J (Fransson & Bjornsson, 1998)

- Mass loss rate ($\dot{M}$): $5 \times 10^{-5}\ M_o yr^{-1}$
- Wind velocity (v_w): $10^4\ ms^{-1}$
- SN shock velocity (v_s): $2 \times 10^7\ ms^{-1}$
- Shock radius (R): 10^{13} m
- Total CR efficiency (η): 0.3

Amplified magnetic field

$$\frac{B_{sat}^2}{\mu_0} \sim \eta \frac{v_s}{c} \rho v_s^2 \Rightarrow B_{sat} \sim 50\text{G}$$

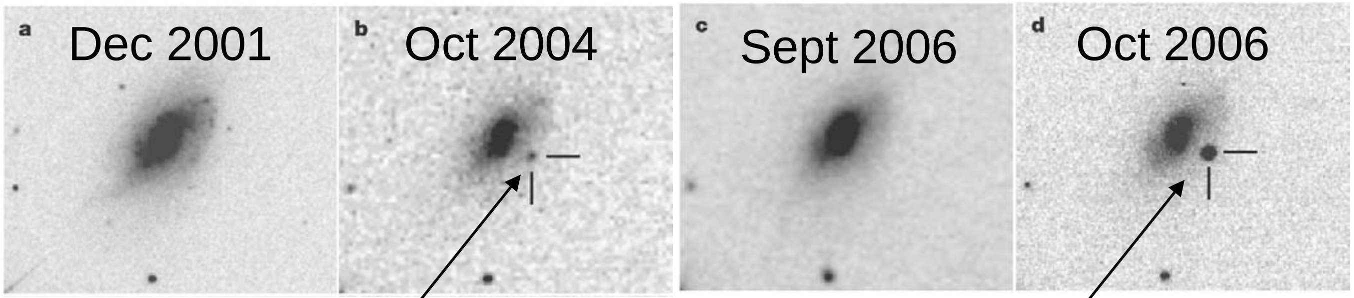
F&B deduce 64G from SN1993J observations

Maximum CR energy

Bohm diffusion $\Rightarrow$ $E_{\max} \approx 3 \times 10^{17}\,\text{eV}$

SN interaction with dense circumstellar plasma

Supernova 2006jc Pastorello et al 2007, Immler et al 2008



Pre-ejection $>0.01M_o$

Supernova inside pre-ejected shell

Shells $>1M_o$

Extreme luminosity requires large dense photosphere

SN2005ap (Quimby et al 2007)

SN2006gy (Smith & McCray 2007)

Theory, eg pulsational instability (Woosley et al 2007)

Connection with gamma-ray bursts (GRB/XRF)

eg GRB060218/SN2006aj

Continuum from XRF to GRB?

Summary

Magnetic field amplification an important part of shock acceleration

Potential diagnostics of physical environment & CR origin

- Magnetic field from shock thickness
- Spectral index/shape, CR dominated shocks, field amplification
- Time-dependent shock structure maps out ambient medium

Shocks in: very young SNR, GRB, galaxy clusters, early universe…