Efficient turbulent amplification of magnetic field driven by dynamo effect at supernova remnant shocks

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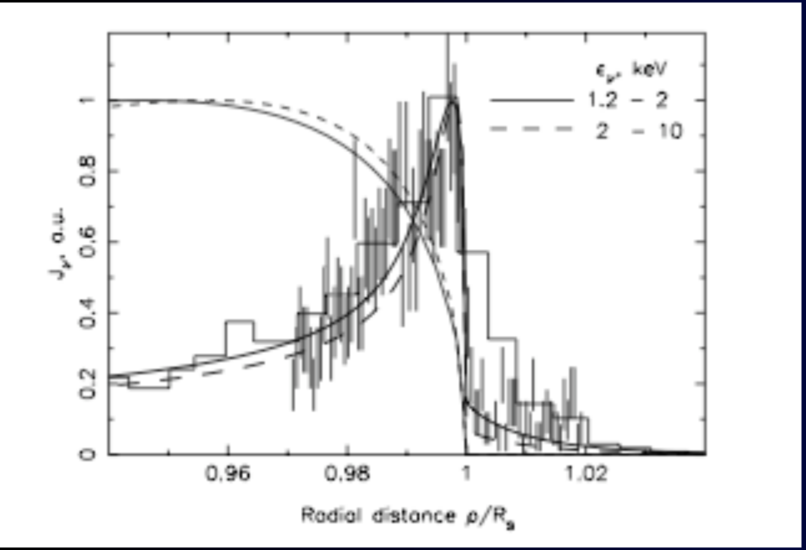
Outline

Multiwavelength evidence of amplified magnetic field

MHD approach to 2D rippled shocks

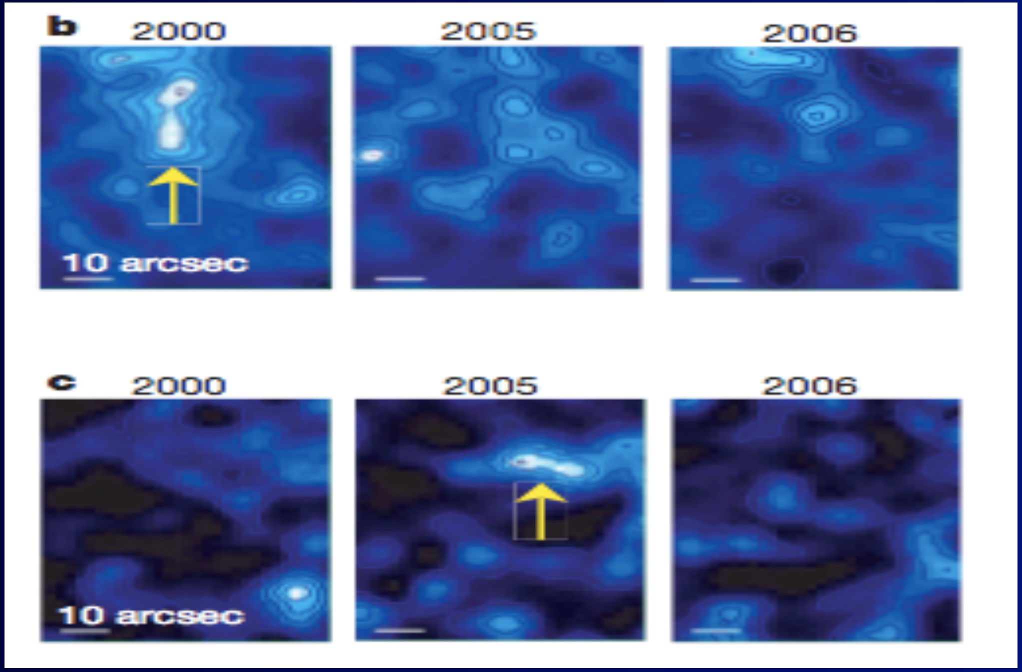
Secular evolution of magnetic energy at the shock

Evidence of large B in supernova remnant shocks

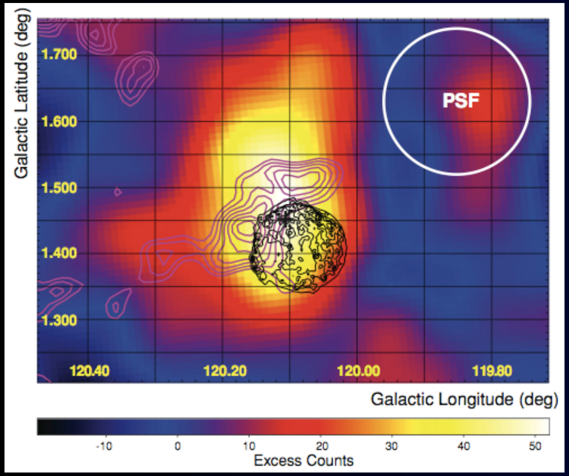


Sharp X-ray edges
(Berezhko et al. 2003)

Time variability of synchrotron emission from filaments
~0.03 pc
(Uchiyama 2007)



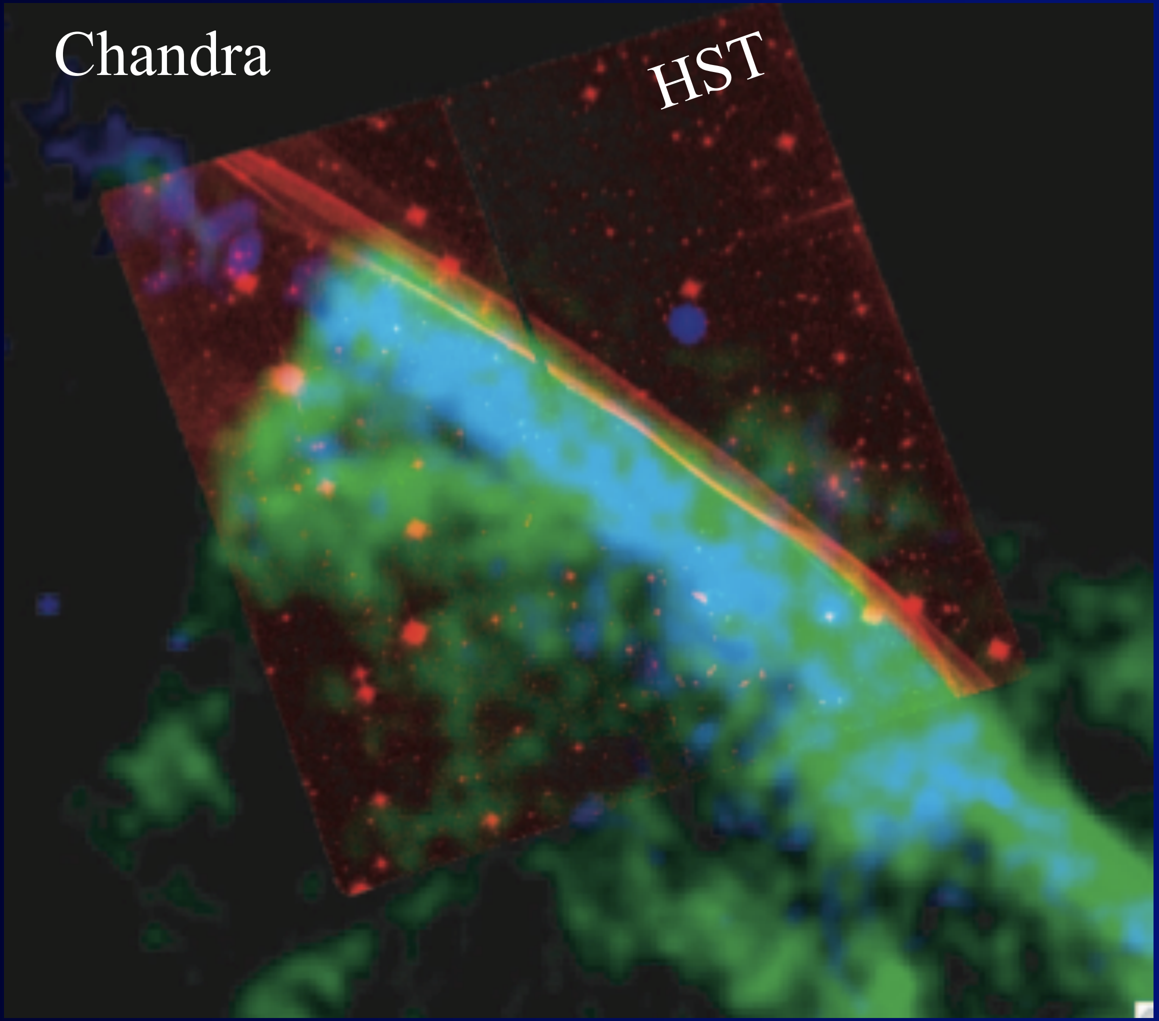
..and energetic particles?



Acciari et al. 2011

Real shocks are corrugated

SNR1006

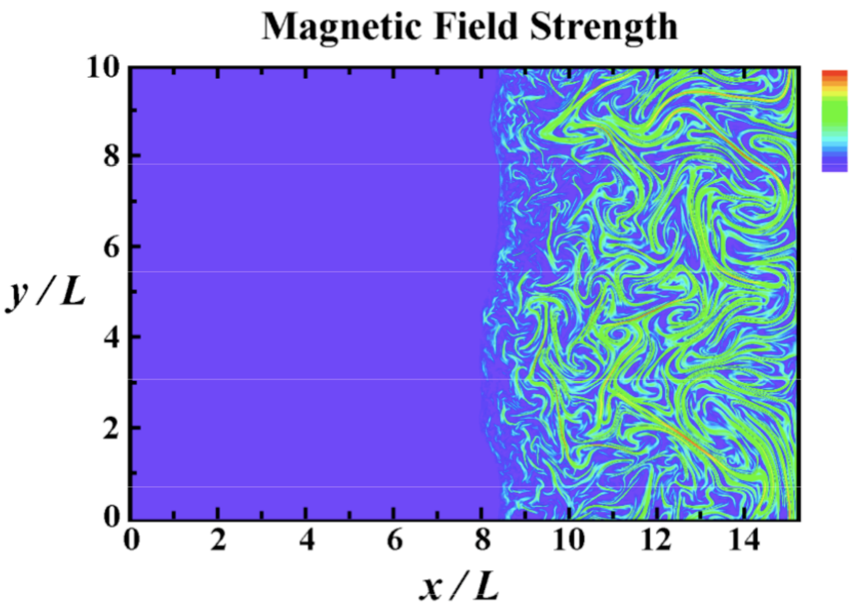


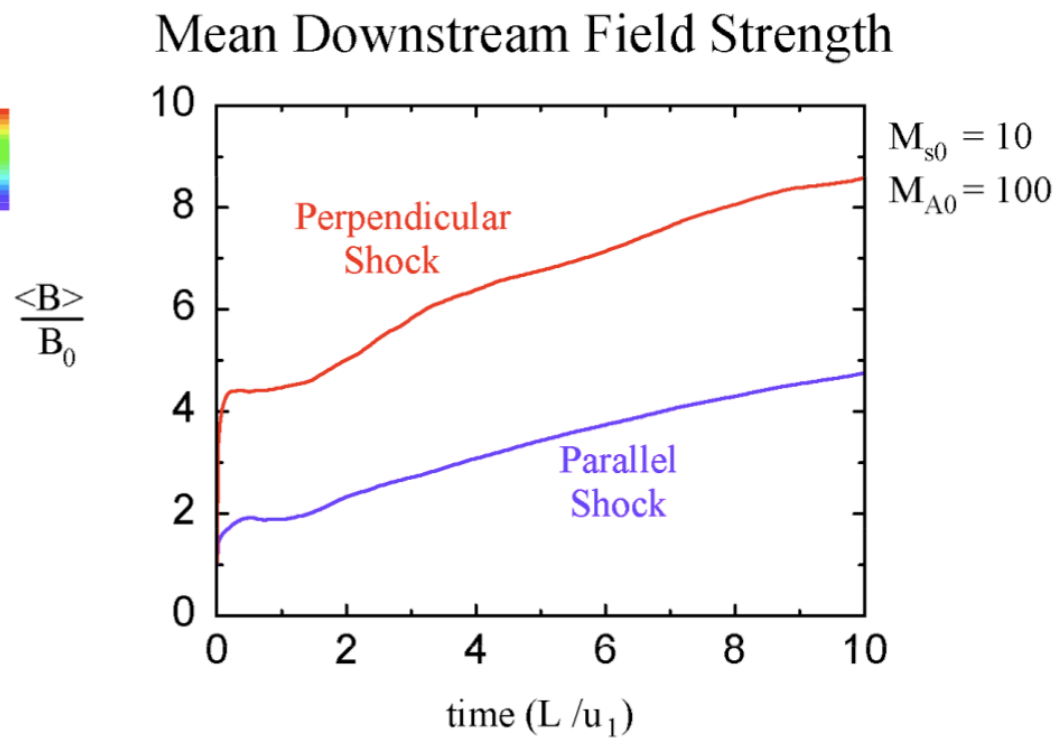
shock ripples ~10^{17} cm

Smaller for SNR
closer to galactic plane

Raymond et al. (2007)

Shocks: numerical simulations



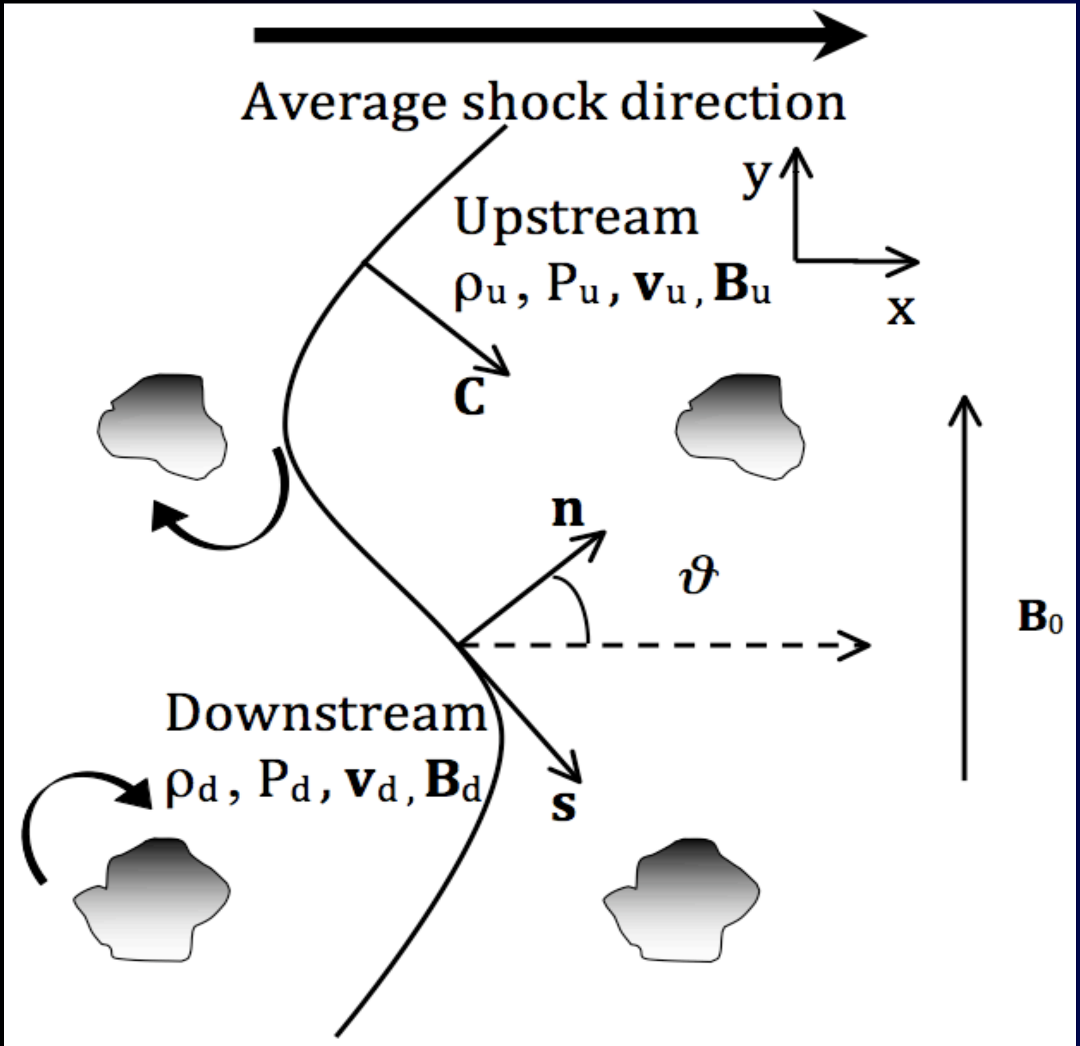


Significant amplification
of magnetic energy
(Giacalone Jokipii 2007)

Evidence of efficient magnetic field amplification downstream
of gamma-ray burst outflows (numerical simulations, Mizuno et al. 2011)

MHD analytical approach to rippled shock

2D shock, arbitrary Alfven Mach number



Fraschetti (2013)

Jump conditions can be applied locally at rippled shocks

ω downstream at distance smaller than local curvature radius

$$\mathbf{v} = (v_x, v_y, 0)$$

$$\boldsymbol{\omega} = \nabla \times \mathbf{v} = (0, 0, \omega_z)$$

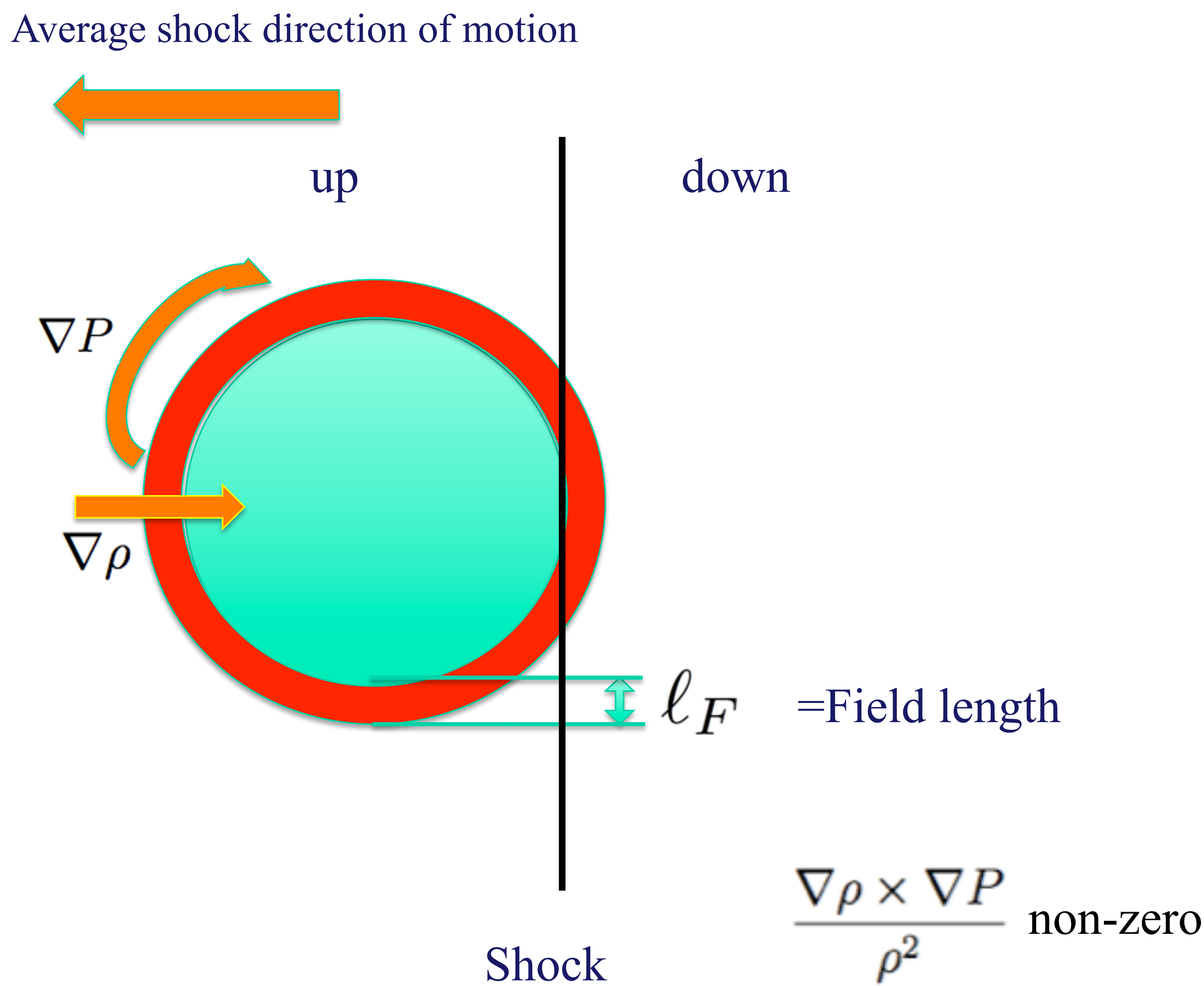
Local orthonormal frame:

(x,y) → (n,s)

Prasad (2001)

To first order in θ
(large curvature radius)

Perpendicular seed field upstream



Average shock direction of motion
up
down
∇P
$\nabla \rho$
ℓ_F
=Field length
Shock
$\frac{\nabla \rho \times \nabla P}{\rho^2}$ non-zero

Vorticity downstream

$$\delta\omega_z = \frac{r-1}{r}\left[\left(\frac{C_r}{\rho}\right)_u \partial_s\rho + \partial_s C_r\right] - \frac{B_n \delta B_s}{4\pi\rho C_r}\partial_s\vartheta$$

r: compression
C_r: shock speed

$$M_A = C_r\sqrt{4\pi\rho}/B_0$$

Fraschetti (2013)

Energy deposited in vortical motion grows with shock speed
Shear or power spectrum

Finite curvature radius (zero for planar shock)

growth rate

Turbulent field backreaction
Strongly rippled -> higher amplified field
Large B_0 makes resistance to filed lines tangling

backreaction

Small-scale dynamo

At each scale, the growth of magnetic field depends on vorticity
No assumption on the magnetic power spectrum

Exponential growth

$$\frac{d\varepsilon}{dt} = 2\beta\varepsilon$$

$$\varepsilon = B^2/8\pi\rho$$

Kulsrud, 2005

$$\frac{d\varepsilon}{dt} = 2(\tau^{-1} - \alpha\varepsilon)\varepsilon$$

Growth time-scale $\tau \sim \frac{r}{r-1}\frac{1}{C_r}\frac{R_c\ell_F}{R_c+\ell_F}$ $\tau \sim \ell_F/C_r$

Back-reaction $\alpha \sim \vartheta/(R_c C_r)$

Exact solution

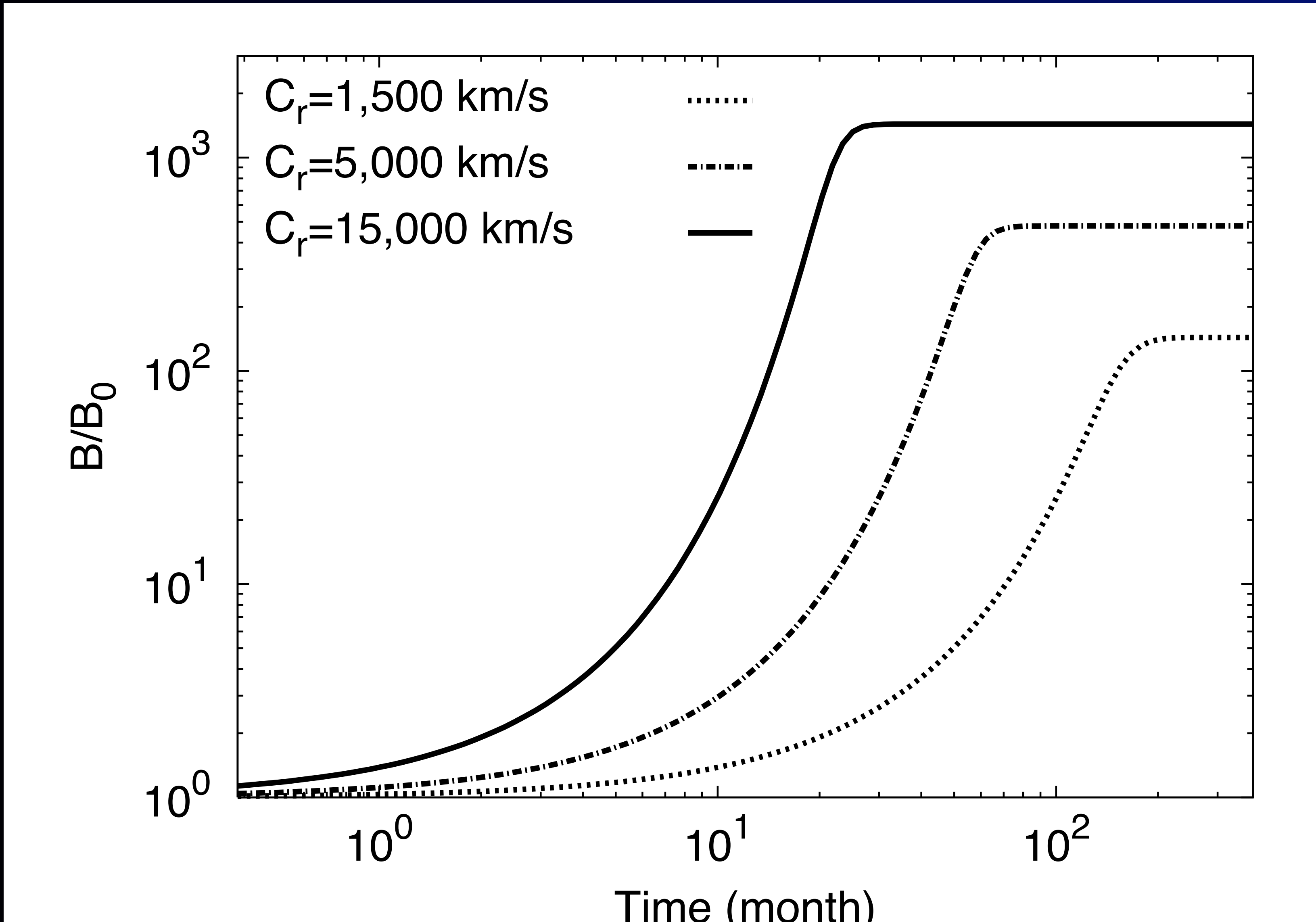
$$\left(\frac{B}{B_0}\right)^2(t) = \frac{e^{2t/\tau}}{1-\alpha\tau(1-e^{2t/\tau})v_A^2/2}$$

Fraschetti (2013)

Saturation

$t \gg \tau$

$$B/B_0 \sim M_A$$



Ripples scale $=10^{17}$ cm, rapid growth
(Raymond et al. 2007)

Bohm diffusion?

Energetic electrons

$$D_{\mathrm{B}}(E) \simeq (3.3 \times 10^{23}\,\mathrm{cm}^2\,\mathrm{s}^{-1}) \times E_{\mathrm{TeV}} \times B_{100}^{-1}$$

$$\tau_{\mathrm{acc}} \simeq D(E)/V_{\mathrm{sh}}^2$$ (energy losses)

Field growth

$$\tau \sim \ell_F / C_r$$

Summary

Turbulent vortical motions are an efficient tracker of strong magnetic field in astrophysical shocks

Real shocks in nature are rippled but MHD jump conditions can still be applied locally

Magnetic field amplification with saturation as short as a few months agrees with observations (X, optical)

Prediction of turbulence evolution on secular scale