Supernova remnants as cosmic ray laboratories

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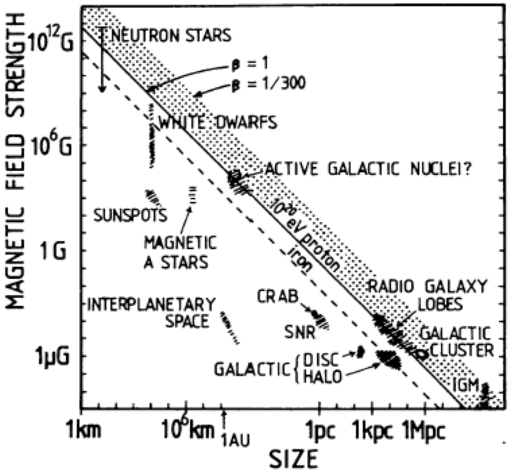
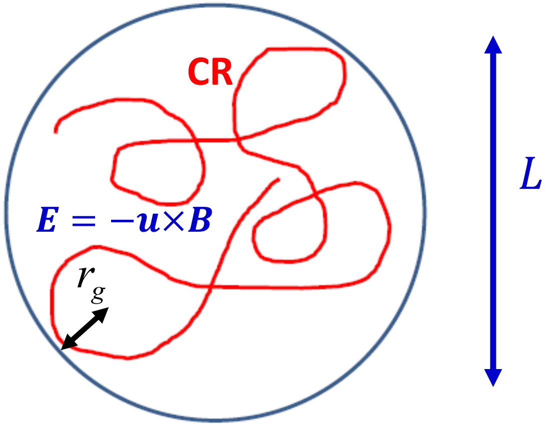
SN1006: A supernova remnant 7,000 light years from Earth
X-ray (blue): NASA/CXC/Rutgers/G.Cassam-Chenai, J.Hughes et al; Radio (red): NRAO/AUI/GBT/VLA/Dyer, Maddalena & Cornwell; Optical (yellow/orange): Middlebury College/F.Winkler. NOAO/AURA/NSF/CTIO Schmidt & DSS



Physics behind Hillas energy



Please note: I use T for CR energy (E is electric field)

1) Spatial confinement

Larmor radius less than size of accelerating plasma

$$r_g = \frac{T}{cB}$$

← CR energy in eV

$$T < cBL$$

2) All acceleration comes from electric field

$$E = -u \times B$$

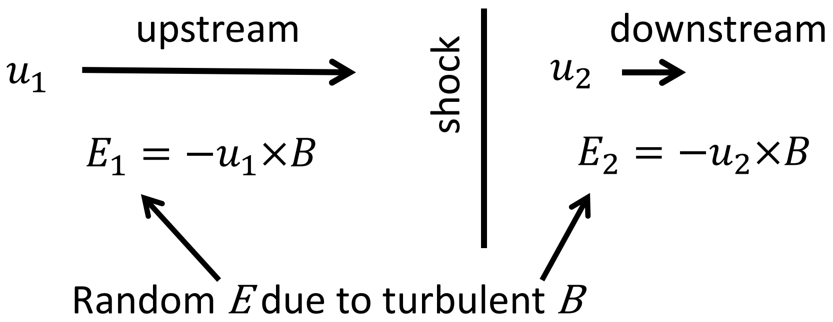
← velocity of thermal plasma

Maximum energy gain: $L \times$ maximum electric field

$$T < uBL$$

Where is the electric field in shock acceleration?

Scattering on random magnetic field



CR energy gain:

$$\frac{dT}{dt} = \boldsymbol{v}.\boldsymbol{E} \qquad \Rightarrow \qquad \frac{d\langle T\rangle}{dt} = \boldsymbol{u}.\langle \boldsymbol{v} \times \boldsymbol{B} \rangle$$

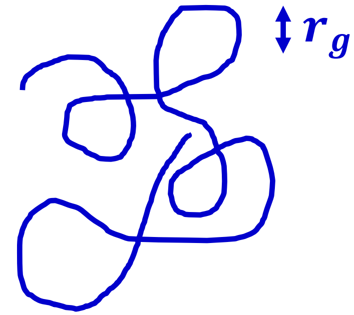
To get to maximum (Hillas) energy: $\boldsymbol{v}, \boldsymbol{B}$ optimally correlated

Hillas: necessary but not sufficient

The case of diffusive shock acceleration

upstream → u_1 | shock | downstream → u_2

D_1= diffusion coefficient | | D_2= diffusion coefficient



Bohm diffusion

Lagage & Cesarsky (1983): $$\tau_{accel} = 4\left(\frac{D_1}{{u_1}^2} + \frac{D_2}{{u_2}^2}\right)$$

Assuming that $\tau_{accel} = \frac{L}{u_1}$ $\quad D_{Bohm} = \frac{cr_g}{3}$ $\quad u_2 = \frac{u_1}{4}$ $\quad \frac{D_2}{{u_2}^2} \ll \frac{D_1}{{u_1}^2}$

(debatable)

Maximum CR energy is $$T = \frac{3}{4}\left(\frac{\boldsymbol{D_1}}{\boldsymbol{D_{Bohm}}}\right)^{-`1} u_1 BL$$ equivalent to $$T = \frac{1}{4}\left(\frac{\boldsymbol{\lambda}}{\boldsymbol{r_g}}\right)^{-`1} u_1 BL$$

To reach Hillas energy: need scattering length equal to Larmor radius $\lambda \sim r_g$

This is Bohm diffusion

Hillas: necessary but not sufficient

General considerations: getting to Hillas energy

$\boldsymbol{E} = -\boldsymbol{u}\times\boldsymbol{B}$ depends on frame

CR to need to move relative to $\boldsymbol{u} = 0$ frame

$T = uBL$

CR to need to move distance L parallel to $-\boldsymbol{u}\times\boldsymbol{B}$ electric field

$T = \int \boldsymbol{v}.\boldsymbol{E}\, \mathrm{dl}$

In disordered field need correlation between $\boldsymbol{v}$ and $\boldsymbol{E}$.
Makes Fermi1 better than Fermi2 (usually)

$T = \int \boldsymbol{v}.\boldsymbol{E}\, \mathrm{dl}$

A disordered field needs some structure on Larmor scale
of every particle being accelerated (GeV to PeV/EeV).

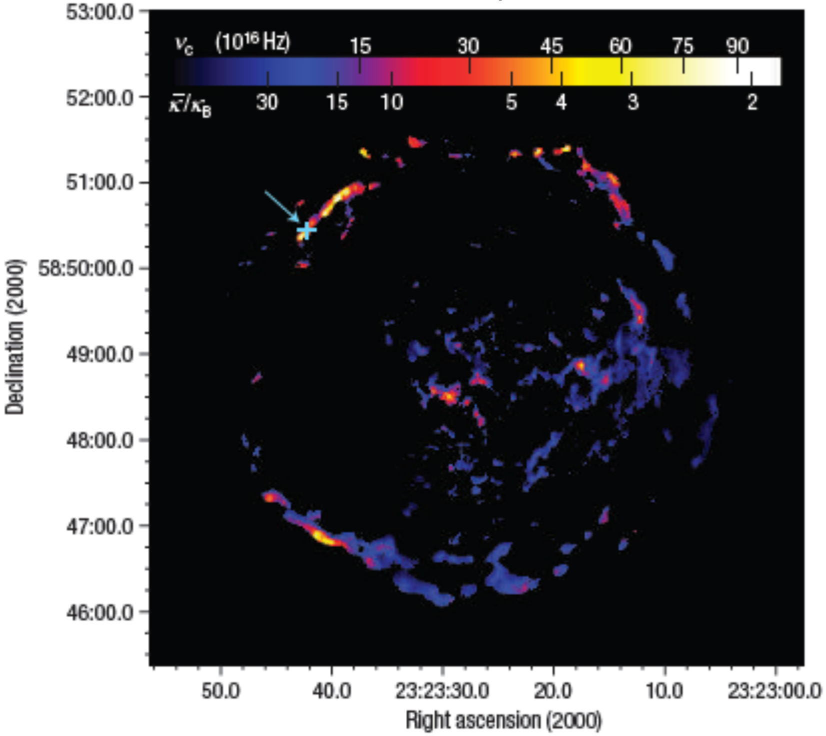
OK for shocks (Fourier components of delta function)
OK for broad spectrum turbulence
Problematic for magnetic reconnection, shear acceleration

Needs Plasma Physics!

Bohm diffusion indicated by synchrotron spectrum turnover

Cas A, Stage et al 2006

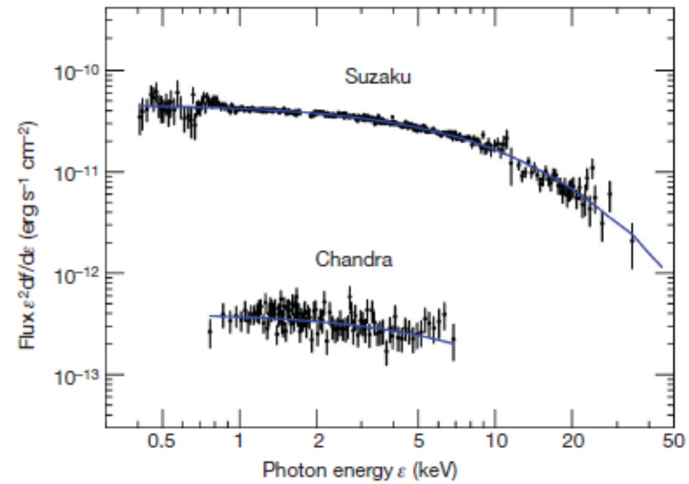
Cut-off frequencies

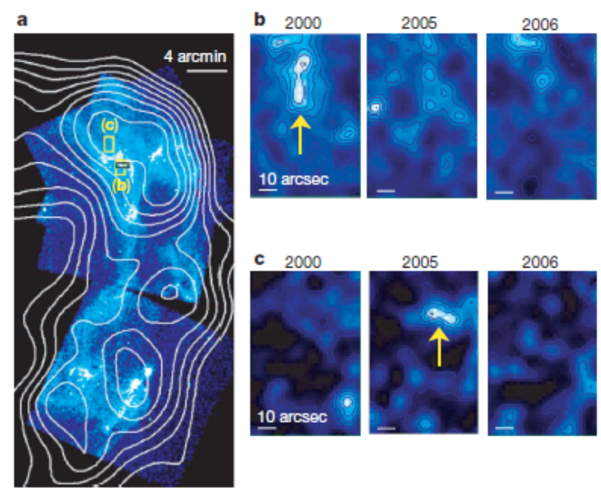


Turnover frequency is

$$(h\nu)_{eV} = 3\times10^{7}\left(\frac{u}{c}\right)^{2}\left(\frac{\lambda}{r_g}\right)^{-1}$$

RXJ1737-3946 Uchiyama et al 2007

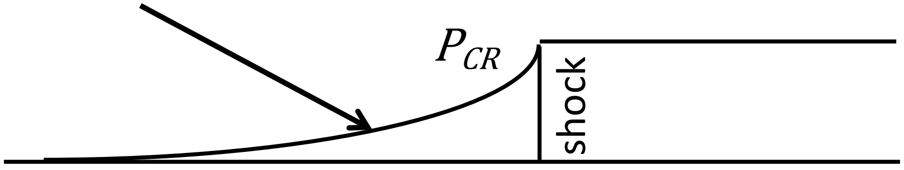




Observed cut-off requires close to Bohm diffusion

Need amplified magnetic field

CR current j_{CR} in rest frame of upstream (moving) plasma



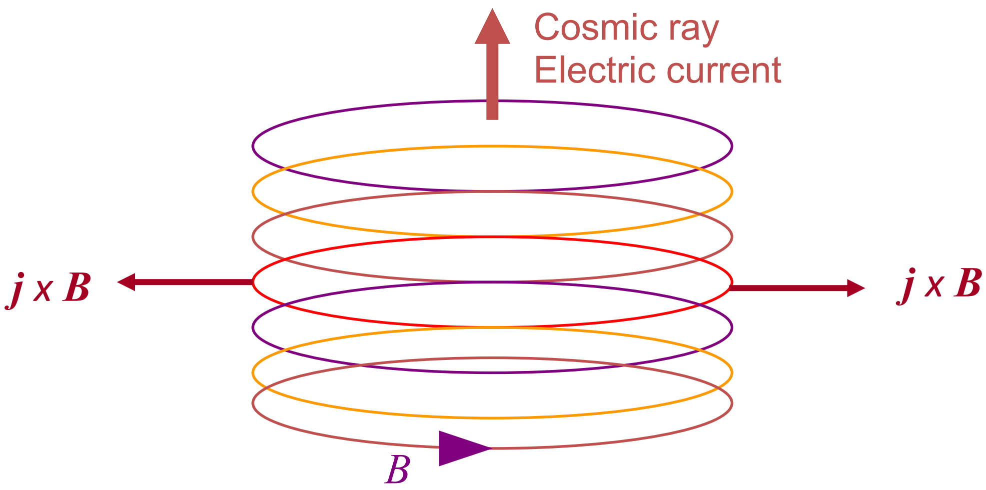
$j_{CR} \times B$ forces drive non-resonant instability (Bell 2004,2005)

produces turbulence

amplifies magnetic field

Magnetic field amplification increases B to near equipartition (100s μG in SNR)

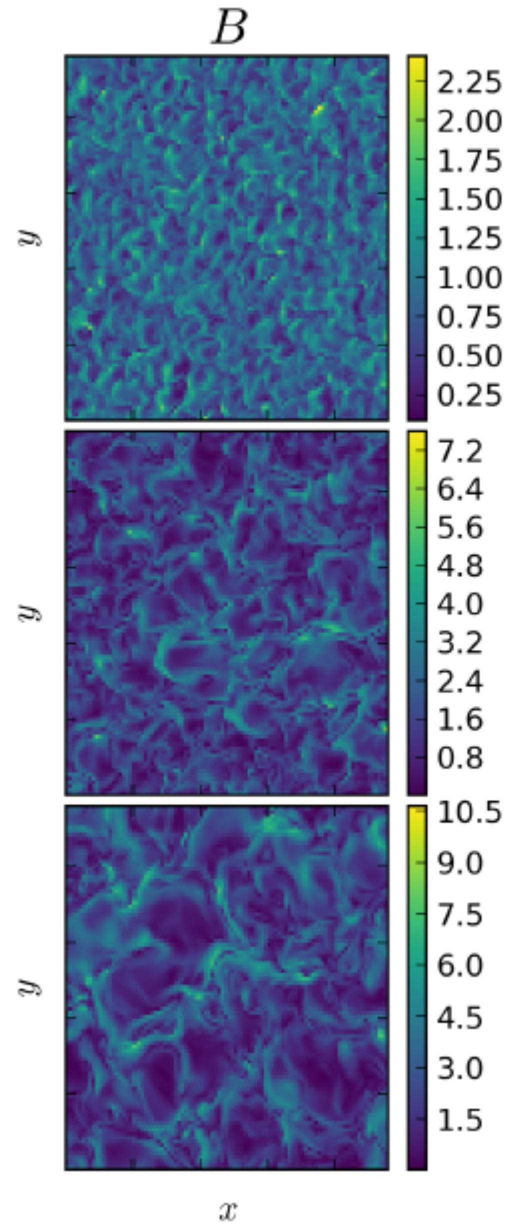
Magnetic field amplification



Instability grows until
1) Tension in field lines opposes $j \times B$
2) CR get tied to field lines: Loop size = r_g

Automatically saturates with $\lambda \sim r_g$

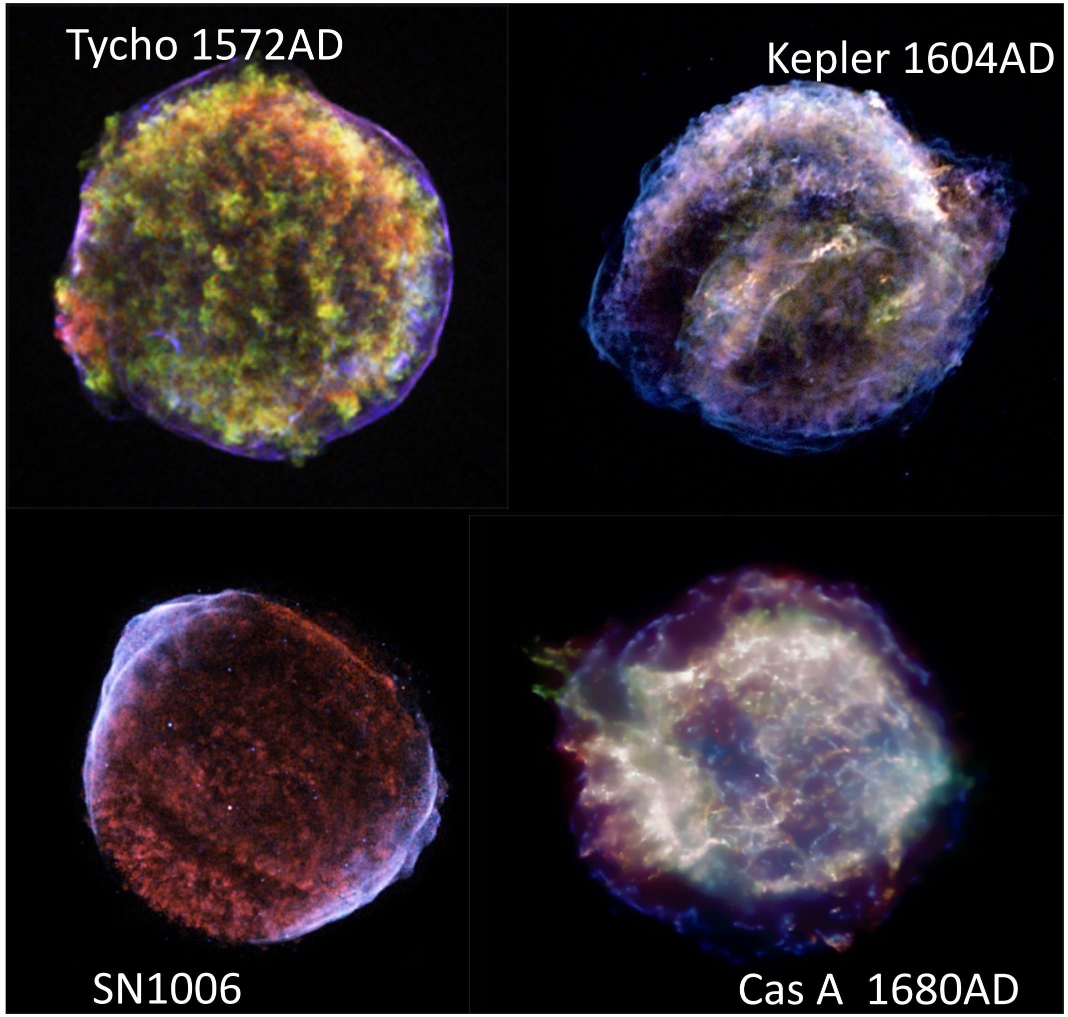
and $$\frac{B_{sat}^2}{\mu_0} \sim \frac{v_s}{c} U_{cr} \propto \rho v_s^3$$



Matthews et al (2017)

Historical shell supernova remnants

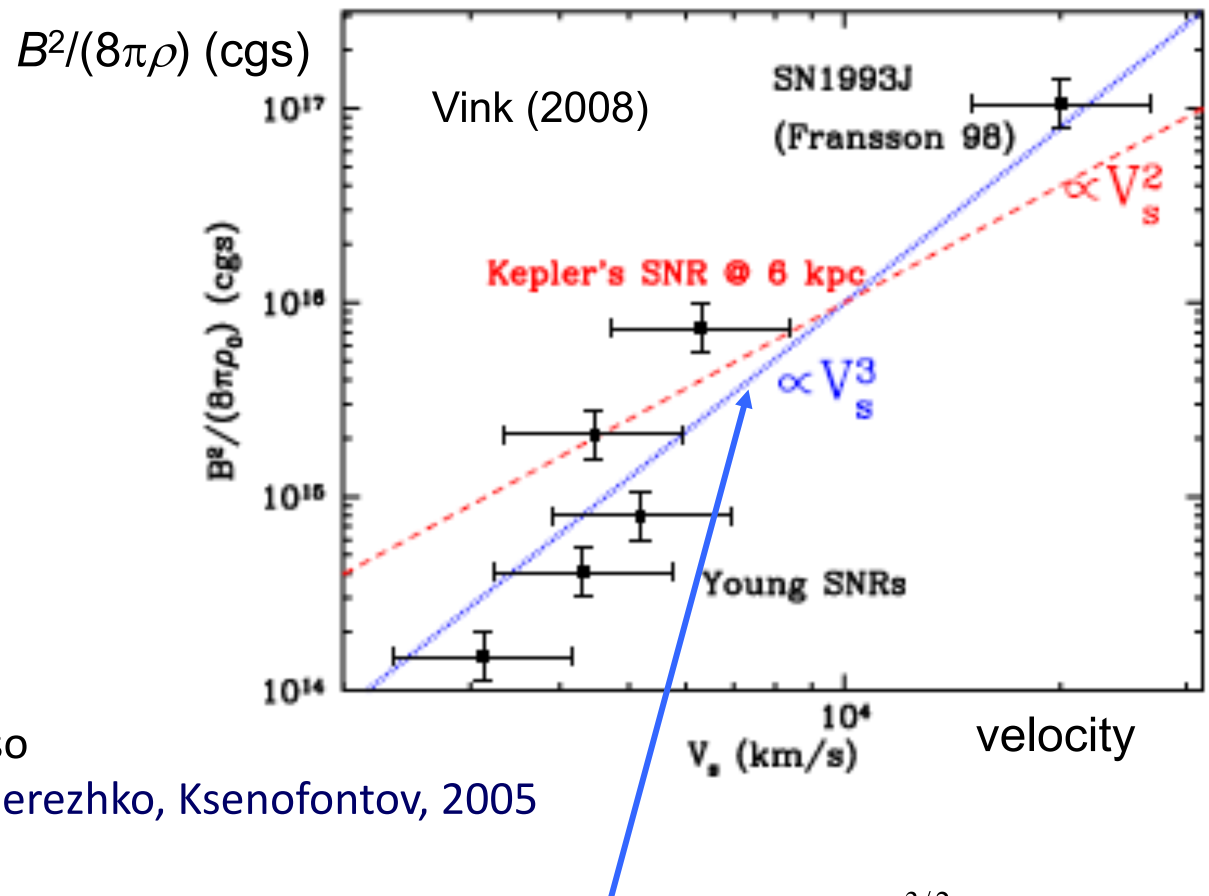
(interpretation: Vink & Laming, 2003; Völk, Berezhko, Ksenofontov, 2005)



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.

Magnetic field grows to near equipartition: limited by magnetic tension



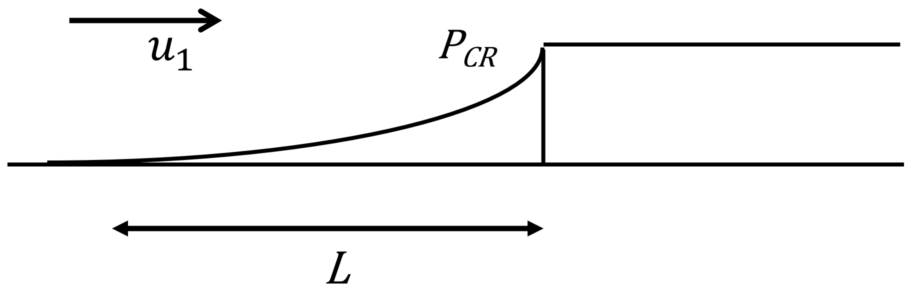
Data for
RCW86, SN1006, Tycho, Kepler, Cas A, SN1993J

See also
Völk, Berezhko, Ksenofontov, 2005

Fit to obs (Vink): $$B \approx 700 \left(\frac{u}{10^4 \,\mathrm{km\,s^{-1}}} \right)^{3/2} \left(\frac{n_e}{\mathrm{cm}^{-3}} \right)^{1/2} \mu\mathrm{G}$$

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

Difficulty: need time to amplify magnetic field



Need about 5 e-foldings in time L/u_1

For SNR parameters

Max CR energy $\approx 200\,\eta_{0.01}\, n_e^{1/2}\, u_7^2\, R_{\rm pc}$ TeV

acceleration efficiency ($\eta_{0.01}$); n_e in cm^{-3}; u_7 in 10,000 km s^{-1}; $R_{\rm pc}$: radius in parsec

$\approx$ **0.1×Hillas energy**

Zirakashvili & Ptuskin (2008), Bell et al (2013)

Non-resonant instability is best can do

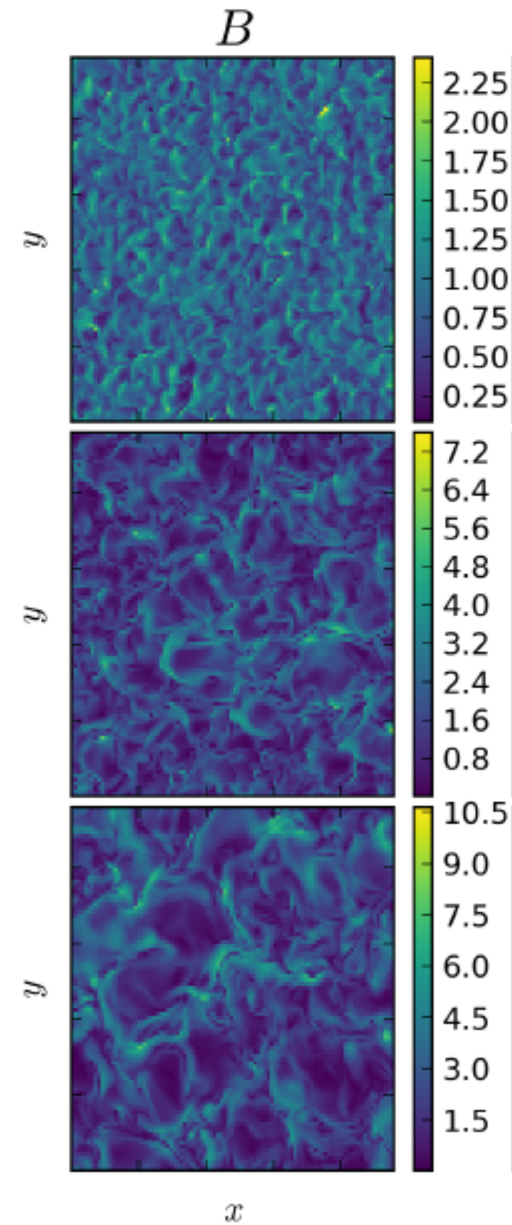
Instability growth rate $\gamma = \sqrt{\frac{kBj}{\rho}}$

1) Makes optimal use of jxB force

Invert $k^{-1} = \frac{jB}{\rho}\gamma^{-2}$

Compare with $z = \frac{j\times B}{\rho}t^2$

2) Grows rapidly on small scale in initially weak B



Matthews et al (2017)

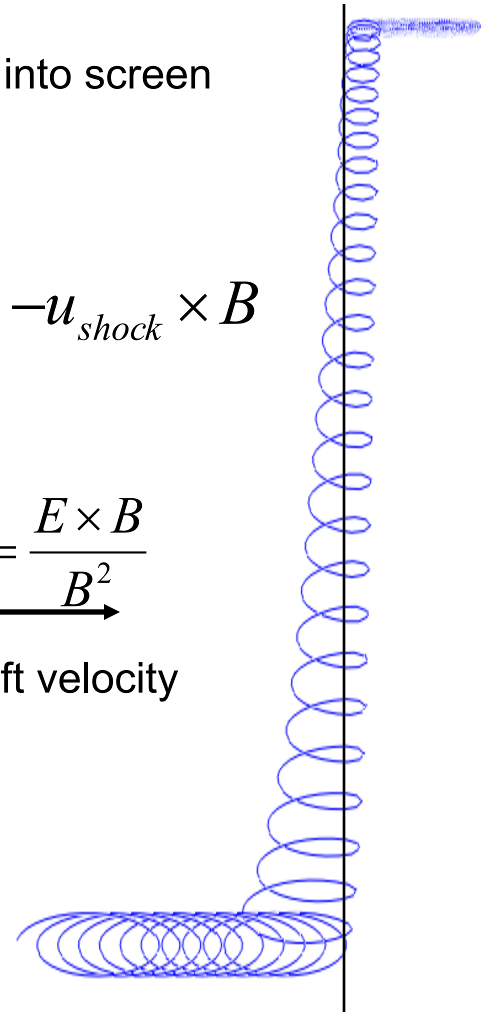
Difficulty with perpendicular shocks (applies to high velocity shocks)

B into screen

$$E = -u_{shock} \times B$$

$$\mathrm{v}_{drift} = \frac{E \times B}{B^2}$$

CR drift velocity



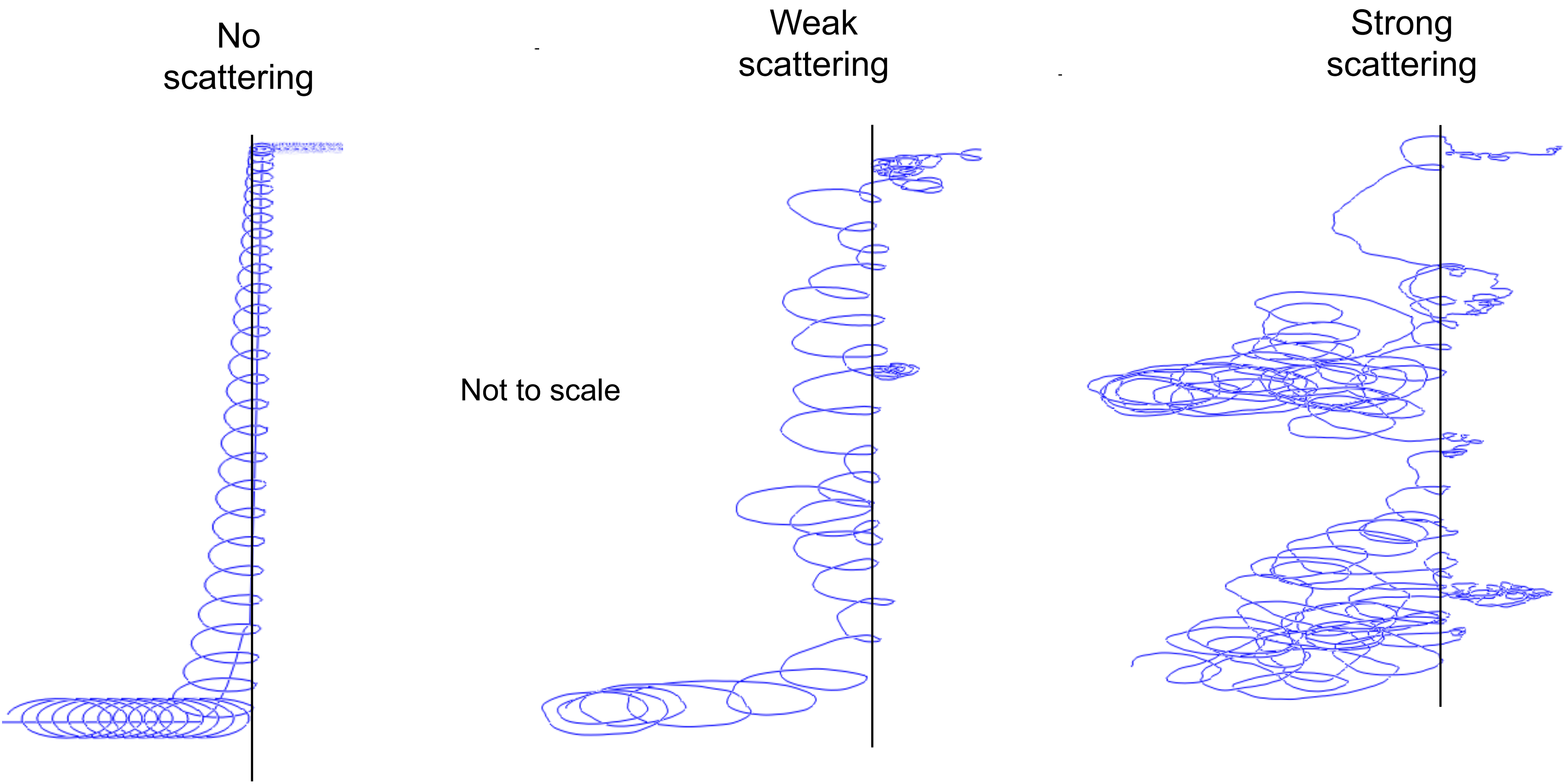
shock

CR gain energy by
drifting in E field

Without scattering,
All CR get same energy gain
No high energy tail

CR acceleration at perpendicular shock

Jokipii 1982,1987

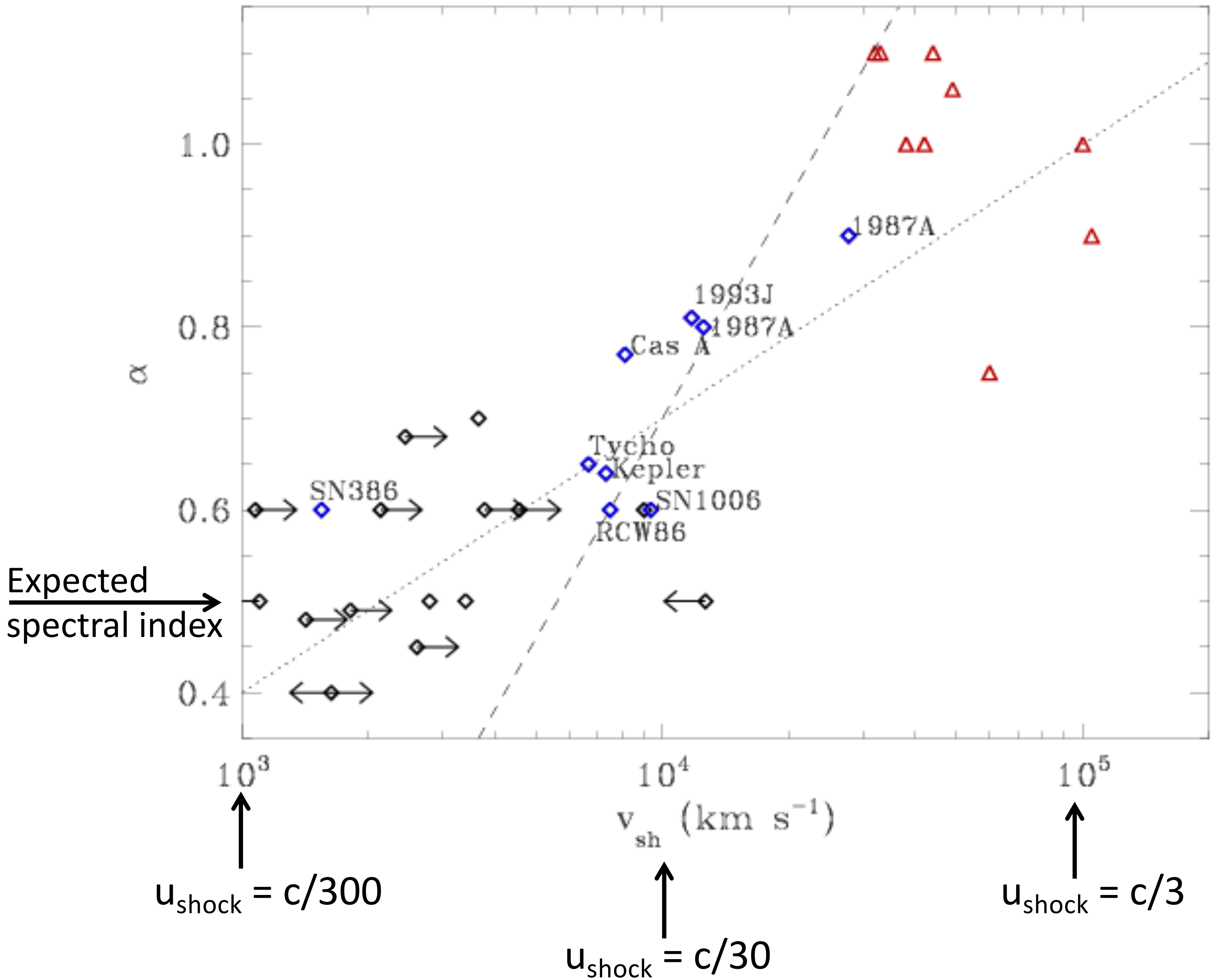


Currents located close to shock
Need very rapid magnetic field amplification

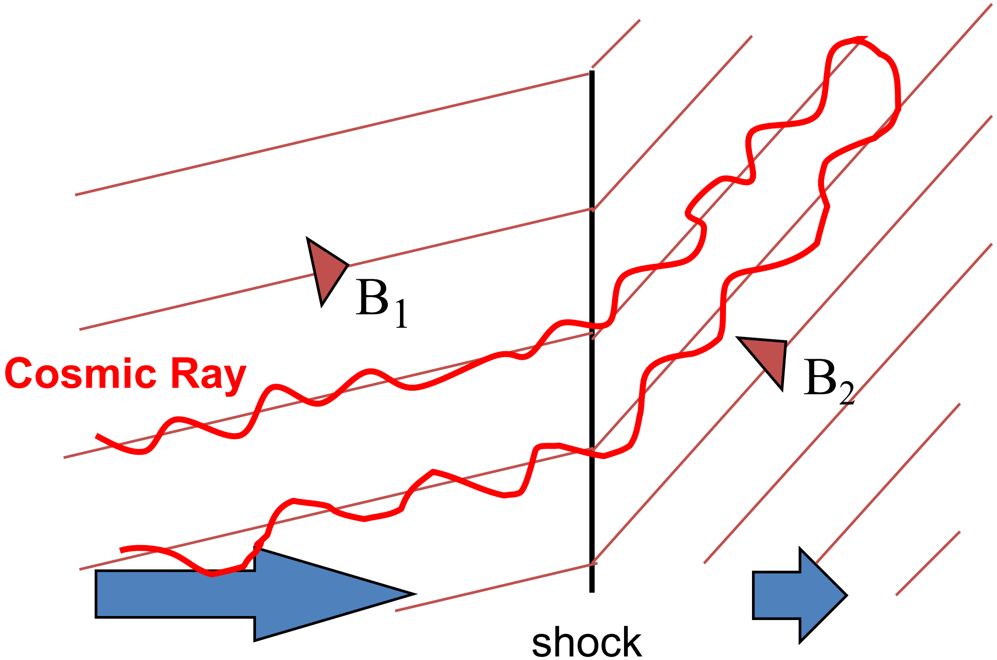
Previous discussions:
Lemoine & Pelettier (2010), Sironi, Spitkovsky & Arons (2013), Reville & Bell (2014)

Observed radio spectral index v. mean expansion velocity

(Klara Schure, following Glushak 1985)



How particles are accelerated: diffusive shock acceleration



Shock velocity: u_{shock}

Cosmic ray density at shock: n

At each shock crossing

Fractional CR energy gain $\frac{\Delta E}{E} = \frac{u_{shock}}{c}$

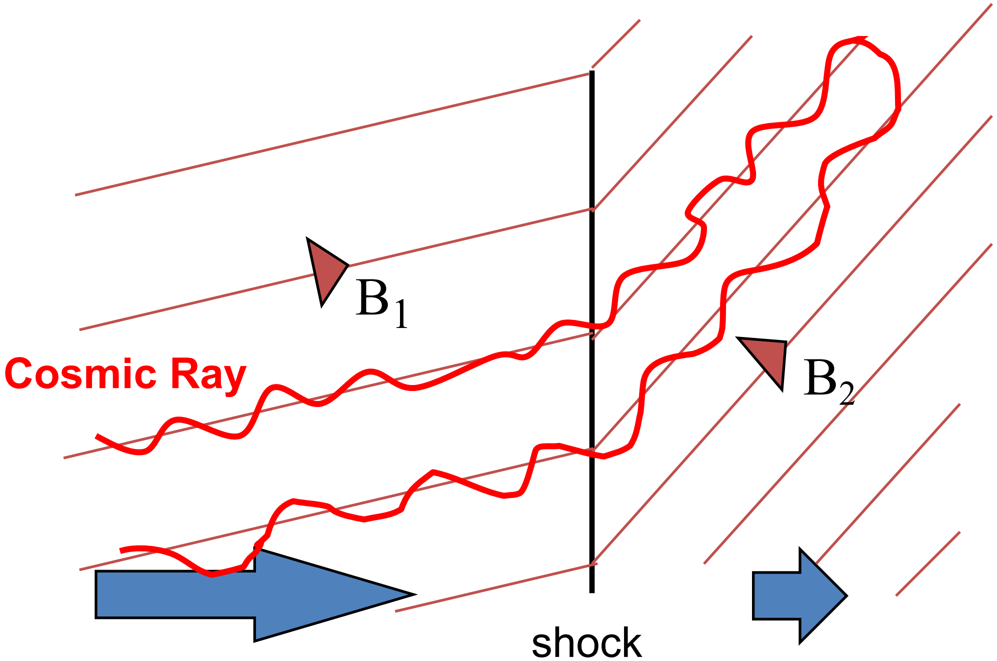
Fraction of cosmic rays lost $\frac{\Delta n}{n} = -\frac{u_{shock}}{c}$

Differential energy spectrum

$$N(E) \propto E^{-2}$$

Krimskii 1977, Axford et al 1977,
Bell 1978, Blandford & Ostriker 1978

How particles are accelerated: diffusive shock acceleration



Shock velocity: u_{shock}

Cosmic ray density at shock: n

Now add in energy loss to Magnetic field amplification

At each shock crossing

Fractional CR energy gain $$\frac{\Delta E}{E} = \frac{u_{shock}}{c}\left(1 - \frac{U_{mag}}{U_{CR}}\right)$$

Fraction of cosmic rays lost $$\frac{\Delta n}{n} = -\frac{u_{shock}}{c}$$

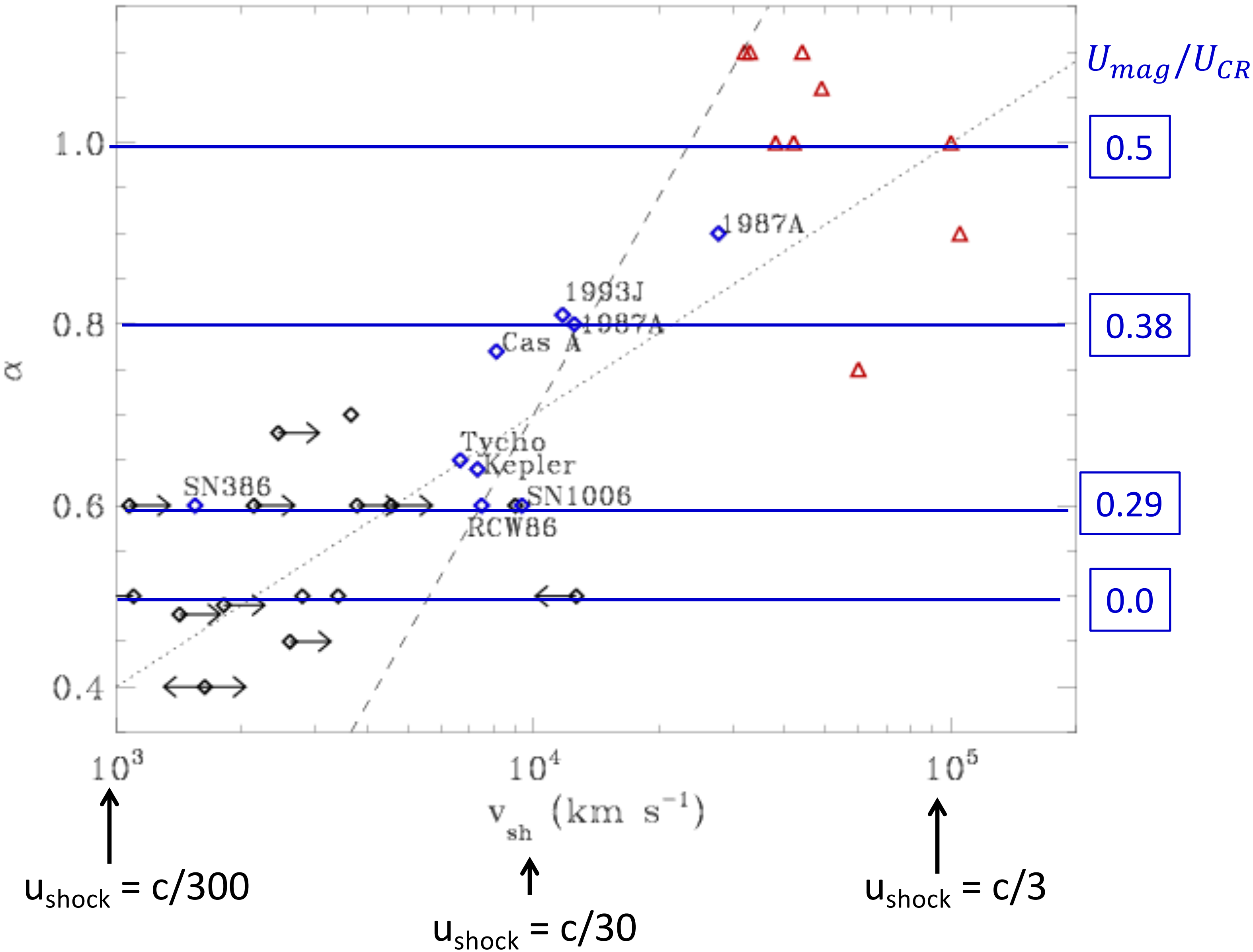
Differential energy spectrum

$$N(E) \propto E^{-(2-U_{mag}/U_{CR})/(1-U_{mag}/U_{CR})}$$

Krimskii 1977, Axford et al 1977, Bell 1978, Blandford & Ostriker 1978

Observed radio spectral index v. mean expansion velocity

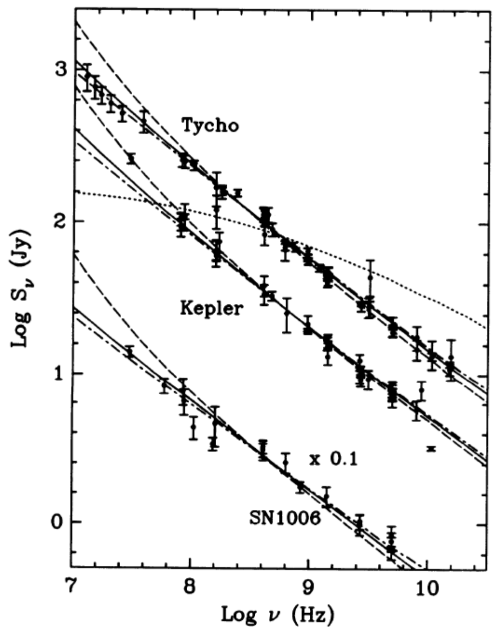
$$N(E) \propto E^{-(2-U_{mag}/U_{CR})/(1-U_{mag}/U_{CR})}$$



One thing I have not mentioned – non-linear feedback

(It has to be there, eg Drury & Völk 1981)

Reynolds & Ellison (1992)



From conclusions of Reynolds & Ellison

Third, the observed spectra show a *hint of curvature*, as was in fact noted in the data for Tycho some time ago (Braude et al. 1970; Roger, Bridle, & Costain 1973).

Comment:
If the spectrum is steepened by other factors,
non-linear curvature confined to low energies/frequencies

General class of interactions producing magnetic field

Three species

- Energetic particles: cosmic rays, fast/hot electrons in laser-plasmas
- Thermal electrons
- Slowly moving thermal ions

Interacting through

- Electric field (to maintain neutrality)
- Collisions (Coulomb, charge-exchange…)
- Large scale magnetic field ('frozen-in')
- (Sub-) Larmor-scale magnetic field (scattering, deflection)

Basic process

- Mutual motion (advection/diffusion/drift)
- Electric field secures neutrality
- Curl($\boldsymbol{E}$) generates $\boldsymbol{B}$

Magnetic field generated by Biermann battery

Favoured source of primordial field

$$\boldsymbol{E} = \frac{\nabla P}{ne} \quad \Rightarrow \quad \frac{\partial \boldsymbol{B}}{\partial t} = \frac{\nabla n \times \nabla T}{n}$$

Borghesi et al 1998

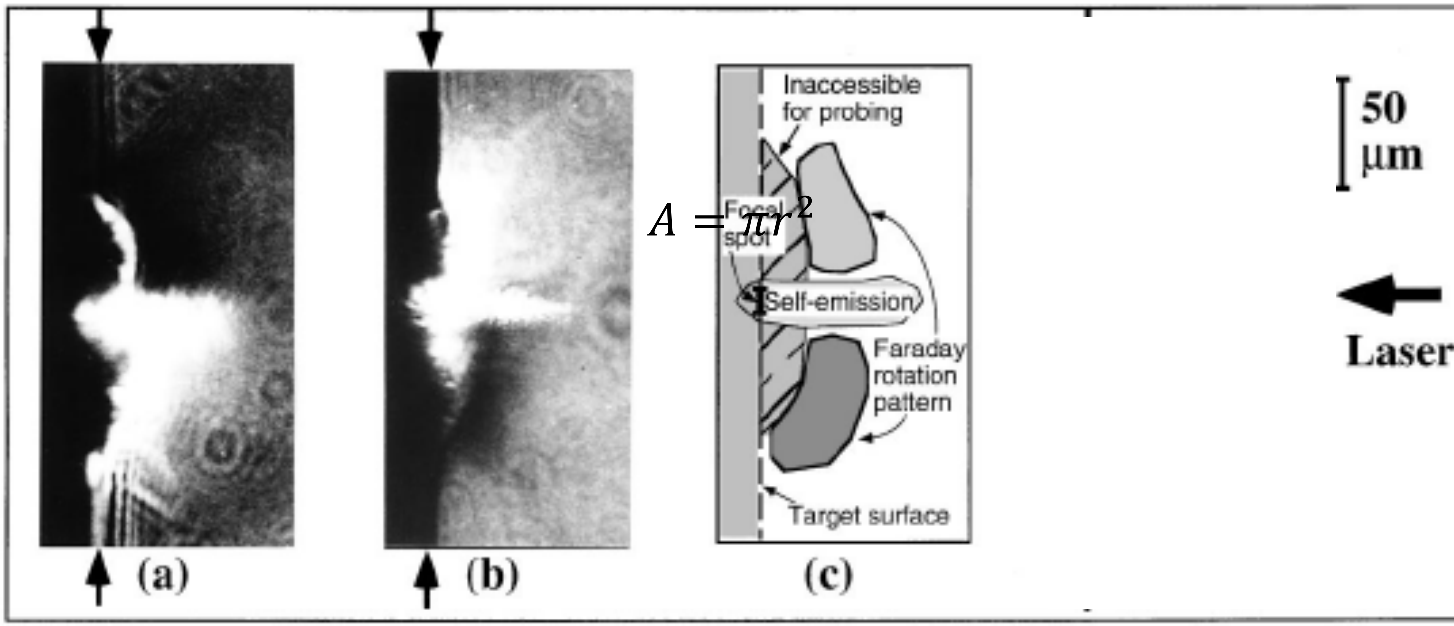
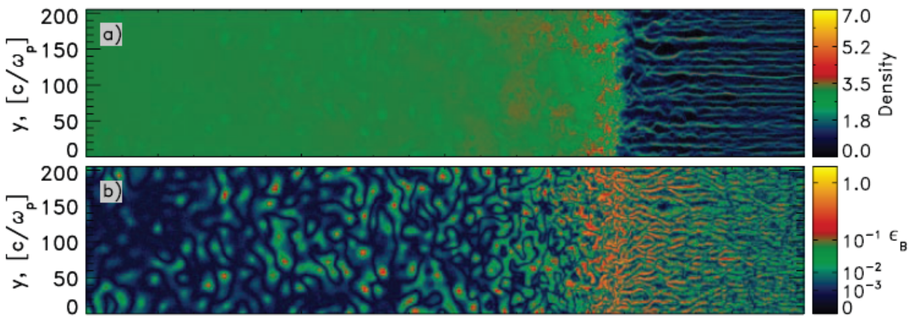


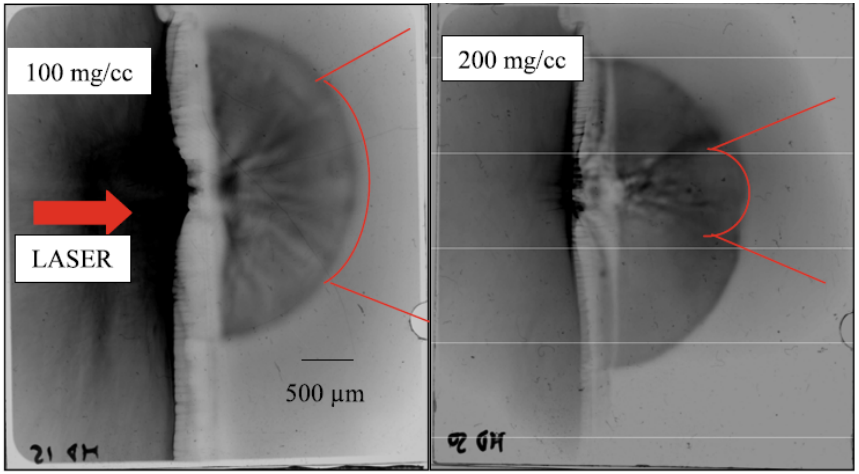
FIG. 1. (a), (b) Polarigrams taken 12 ps after the interaction of a 10 TW, 1.5 ps laser pulse with a solid Al target, with the two polarizers $-9°$ and $+12°$ off crossed. The position of the target surface is indicated by the arrows. (c) Schematic showing the main features of the polarigrams. (d) Interferogram recorded 15 ps after the interaction.

Weibel instability at shocks

Chang, Spitkovsky & Arons (2008)

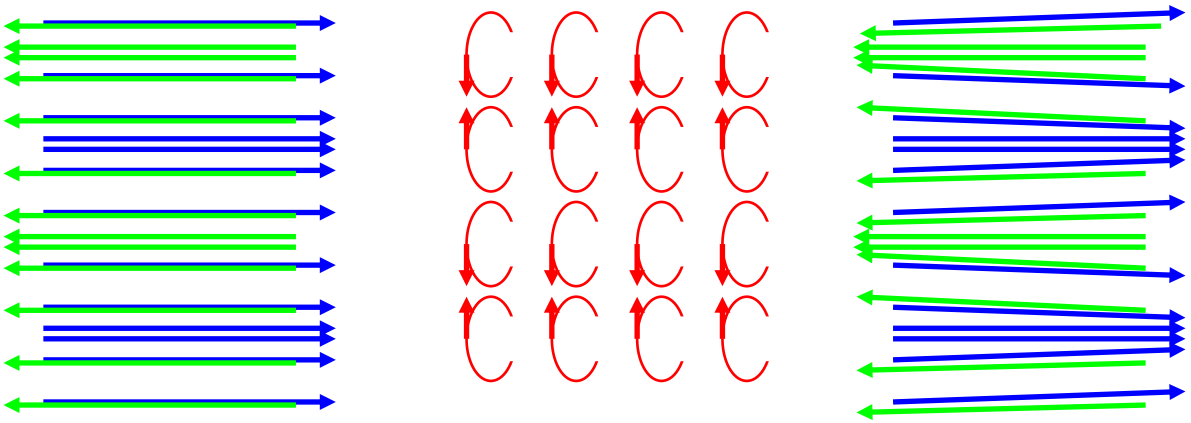


Ramakrishna et al (2009)



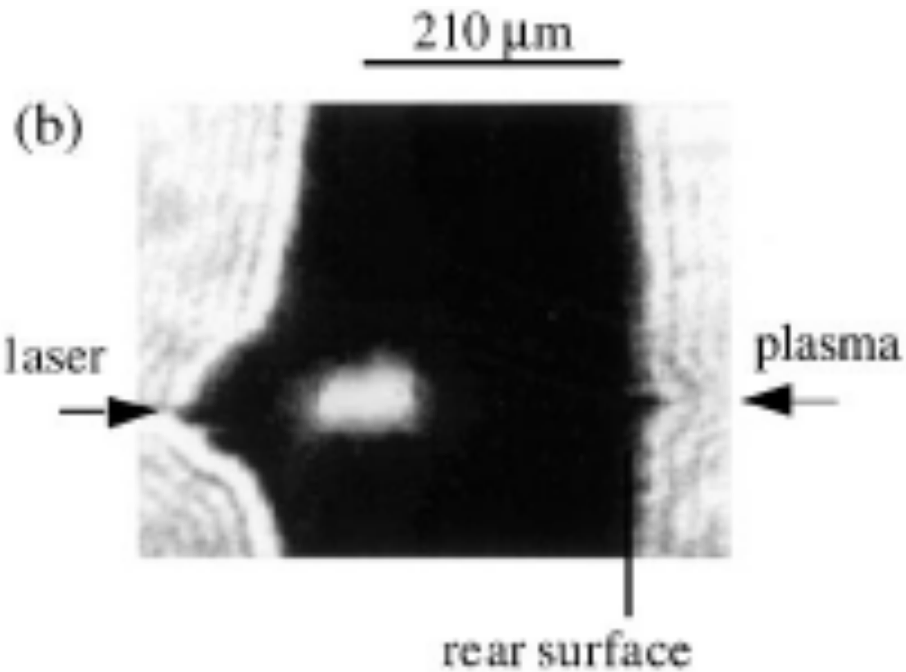
T= 2ps T=2ps

Opposing electron beams: 1) Perturbed beam density 2) Magnetic field 3) Focus currents



Kinetic instability on scale c/ω_p

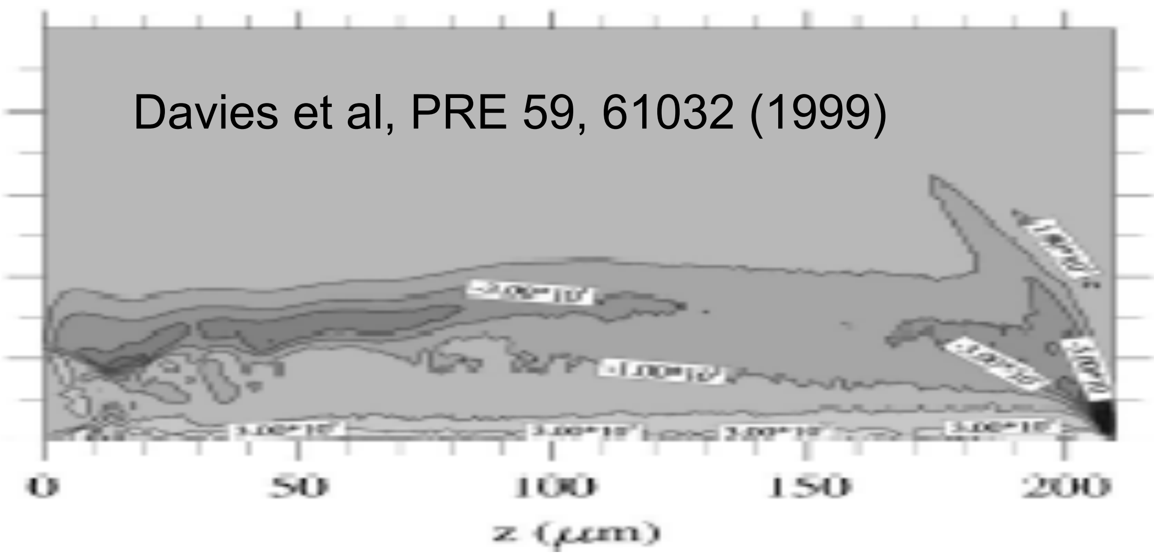
Energetic electron beam focussed by magnetic field



$$j_{return} = -j_{beam}$$

$$\frac{\partial B}{\partial t} = \nabla \times (\eta j_{beam})$$

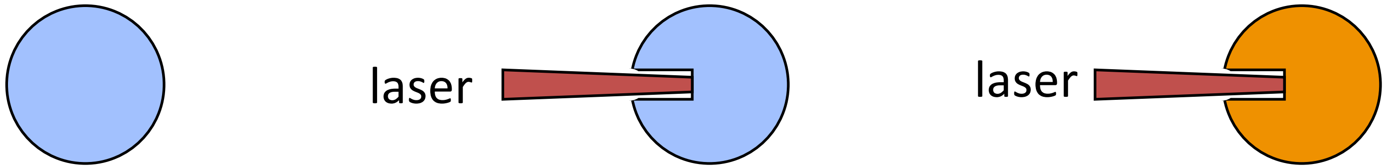
resistivity



Davies et al, PRE 59, 61032 (1999)

Fast Ignition

As first proposed by Tabak et al (1994)

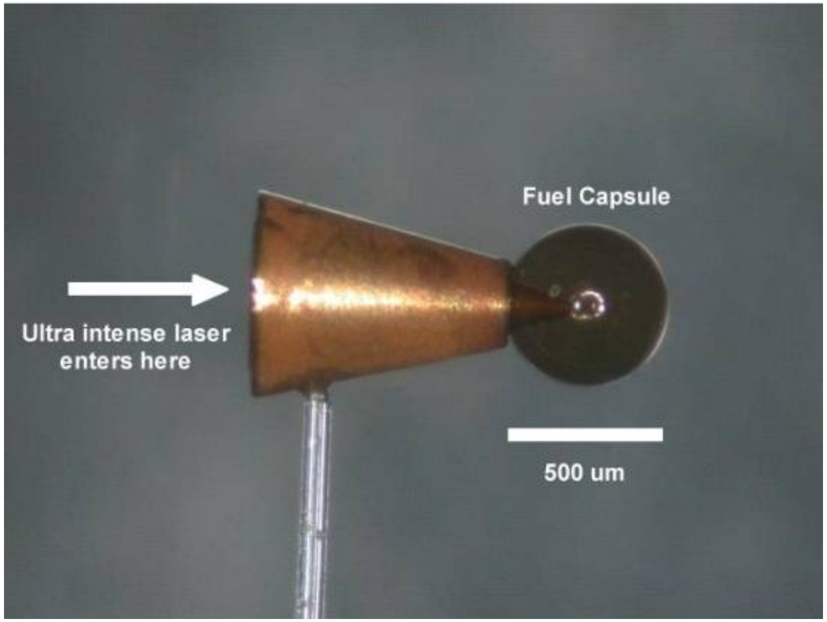


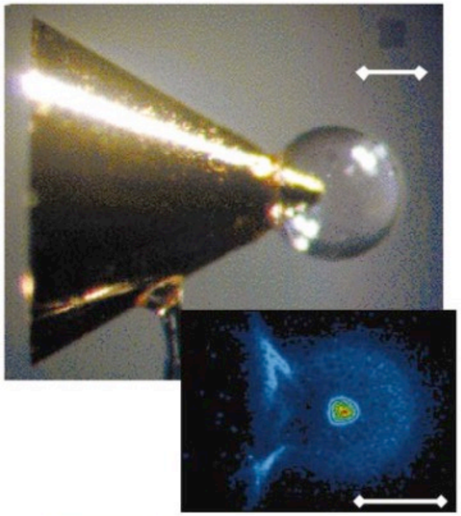
Cold compressed DT

Drill hole with laser

Heat with very high power laser

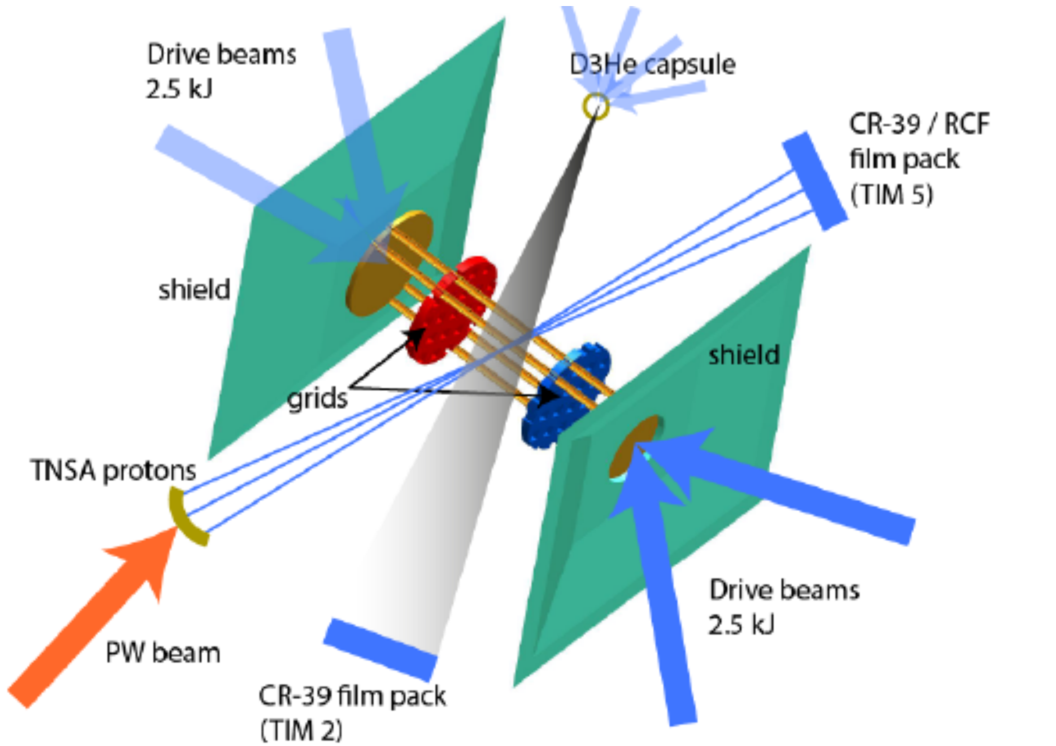
Cone target Kodama et al 2001





Experiment to test non-resonant instability (next summer)

Builds on series of experiments led by Gianluca Gregori



Experiment next summer on OMEGA laser
Experimental lead: Hui Chen (Livermore), Gianluca Gregori (Oxford)

LBS– Laboratory model of particle acceleration in supernova shocks **OMEGA FY19**

Scope and Overview: *snShocks-19A*
Revision Date: June 1, 2018

- Purpose:
  - *Determine the evolution of the Non-Resonant Hybrid instability driven by a proton beam into a turbulent magnetized plasma*
- Specific deliverable of this campaign (for this time period FY19) :
  - *Generate a turbulent plasma using the TDYNO platform.*
  - *Drive the non-resonant hybrid instability using a high-intensity proton beam using the EP beam*
- What would we do with results:
  - *Journal publications.*
- PIs: *H Chen, G Gregori, AR Bell, P Tzeferacos, D Lamb, S Sarkar, C Palmer, L Chen, J Meinecke, J Matthews, C-K Li, R Petrasso*
- Major issues: None