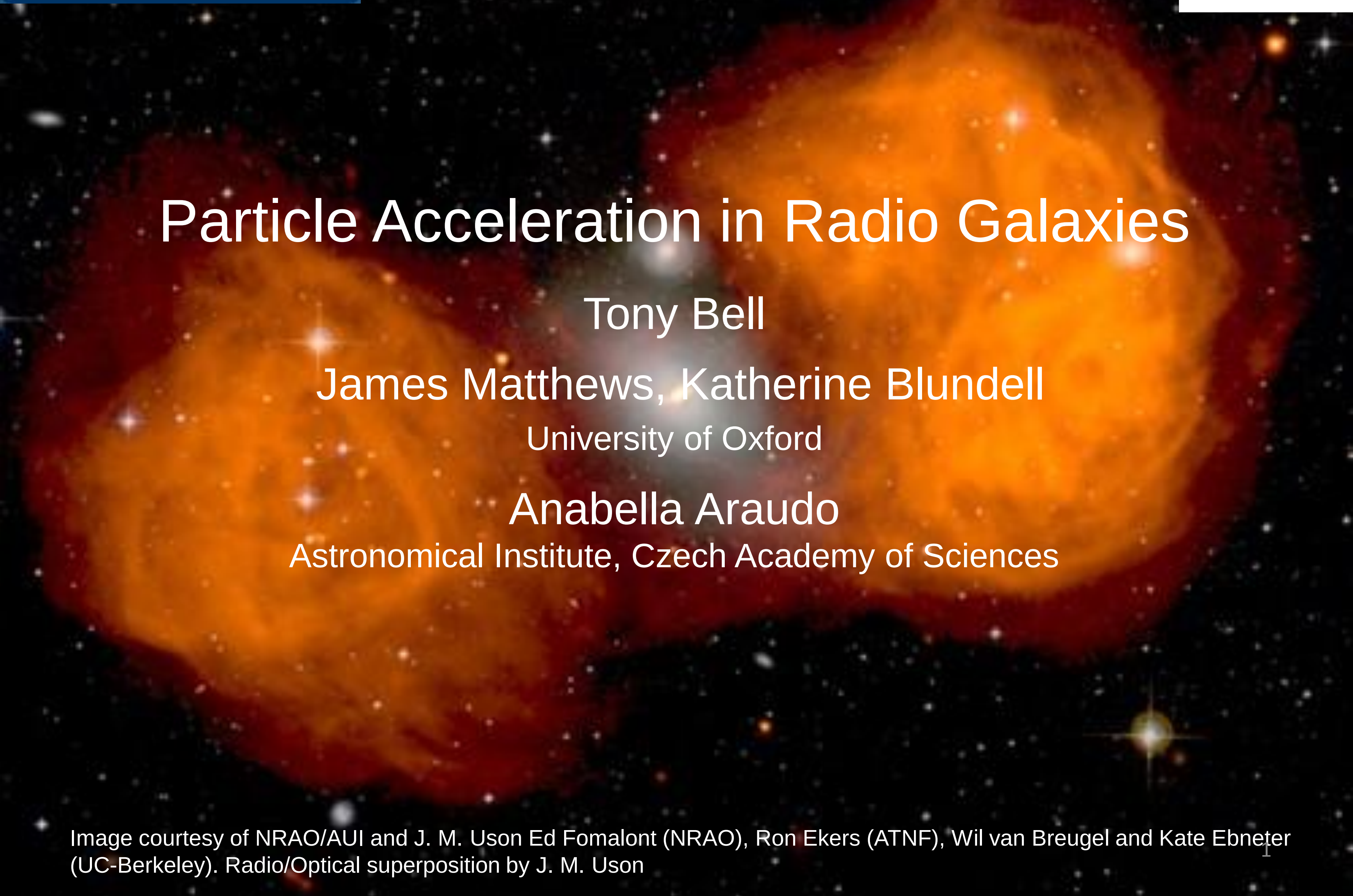

Fornax A (radio galaxy)

Particle Acceleration in Radio Galaxies

Tony Bell

James Matthews, Katherine Blundell

University of Oxford

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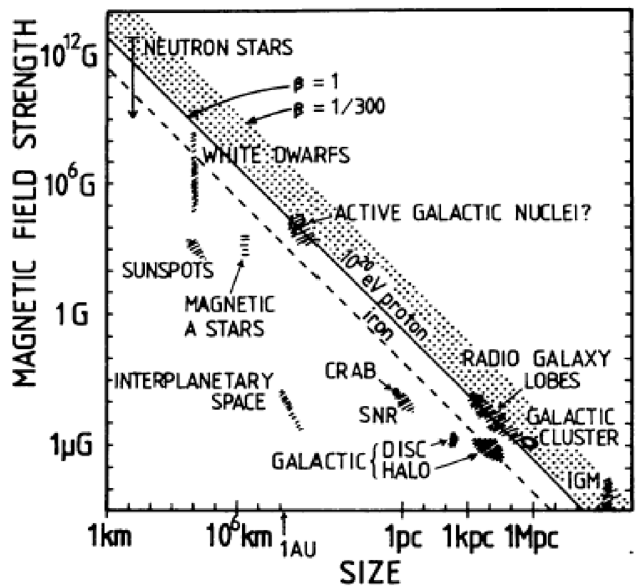
Image courtesy of NRAO/AUI and J. M. Uson Ed Fomalont (NRAO), Ron Ekers (ATNF), Wil van Breugel and Kate Ebneter (UC-Berkeley). Radio/Optical superposition by J. M. Uson

Hillas energy: Maximum CR energy $T = uBL\ (\mathrm{eV})$

Maximum CR energy: $T = \left(\frac{u}{c/3}\right)\left(\frac{B}{10\ \mu\mathrm{G}}\right)\left(\frac{L}{3\mathrm{kpc}}\right)\ 10\ \mathrm{EeV}$

Hillas 1984



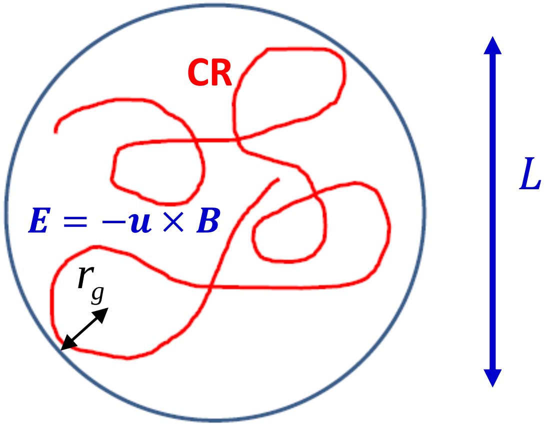
I’ll speak as though all cosmic rays are protons

T is CR energy in eV (avoids confusion with electric field)

SI units

Except where I say otherwise

Physics behind Hillas energy



1) Spatial confinement

Larmor radius less than size of accelerating plasma

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

CR energy in eV

$$\boldsymbol{T < cBL}$$

2) All acceleration comes from electric field $\boldsymbol{E} = -\boldsymbol{u} \times \boldsymbol{B}$

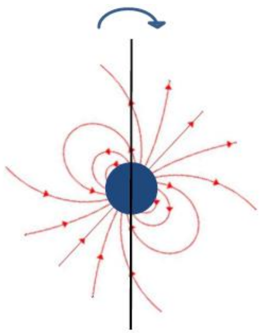
velocity of thermal plasma

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

$$\boldsymbol{T < uBL}$$

Some generic sites with large uBL

Rotating magnet

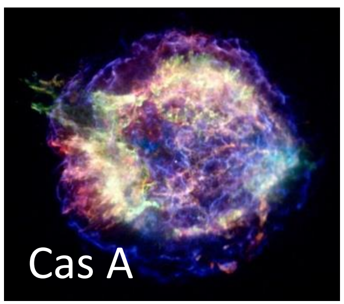


$u = \Omega R$

$T = B\Omega R^2$ =10^{19} eV for B=10^{15}G R=10km Ω=1 s^{-1} (magnetar)

Challenges: radiation loss, injecting protons, transfer pole to/from equator

Blast wave: $uBR \propto (\text{density})^{\frac{1}{6}} \times (\text{velocity})^{\frac{4}{3}} \times (\text{energy})^{\frac{1}{3}}$

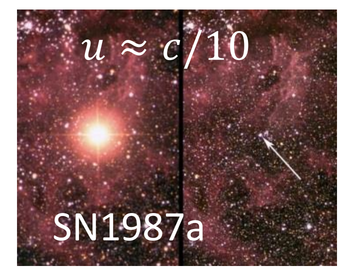


x-ray (CHANDRA)

u = 5000kms^{-1}
B = 300 μG
R = 1.7 pc

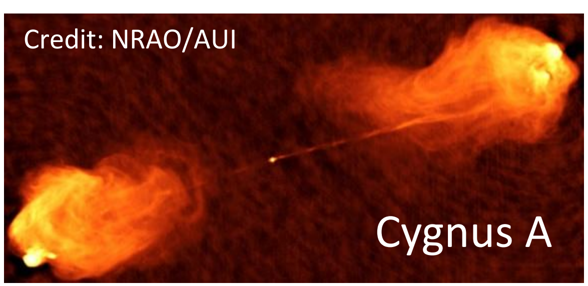
$T \approx 10^{16}$ eV

Recent SN for high CR energy



David Malin: Anglo-Australian telescope

Jets



u approaching c
B = 300 μG
R = 10 kpc

T =10^{21} eV

Hillas condition: necessary but not sufficient

The case of diffusive shock acceleration

upstream u_1 — D_1 = diffusion coefficient

shock

downstream u_2 — D_2 = diffusion coefficient

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

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

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

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

This is Bohm diffusion

Where is the electric field in shock acceleration?

Scattering on random magnetic field

upstream

u_1 $\longrightarrow$

shock

downstream

u_2 $\rightarrow$

$E_1 = -u_1 \times B$

$E_2 = -u_2 \times B$

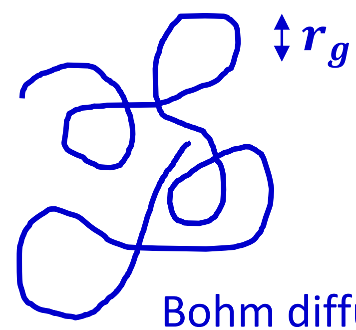
Random E due to turbulent B

CR energy gain:

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

For Hillas energy: $\boldsymbol{v}, \boldsymbol{B}$ optimally correlated

Need $\boldsymbol{B}$ structured on Larmor radius: $\boldsymbol{\lambda \sim r_g}$

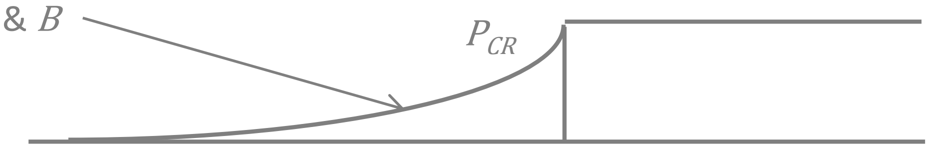


Bohm diffusion

Aside on why v, B are correlated

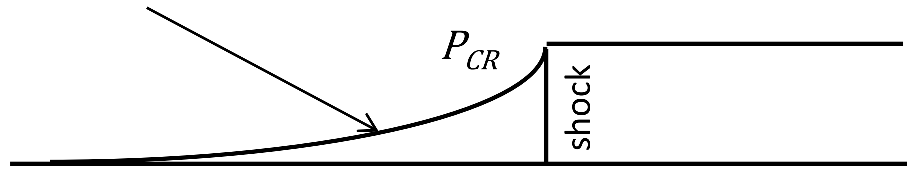
$$j_{CR} \times B \text{ balances } \nabla P_{CR} \Rightarrow \langle j_{CR} \times B\rangle = ne\,\langle v \times B\rangle = \nabla P_{CR}$$

CR accelerated by correlated v & B



Magnetic field in shock precursor

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



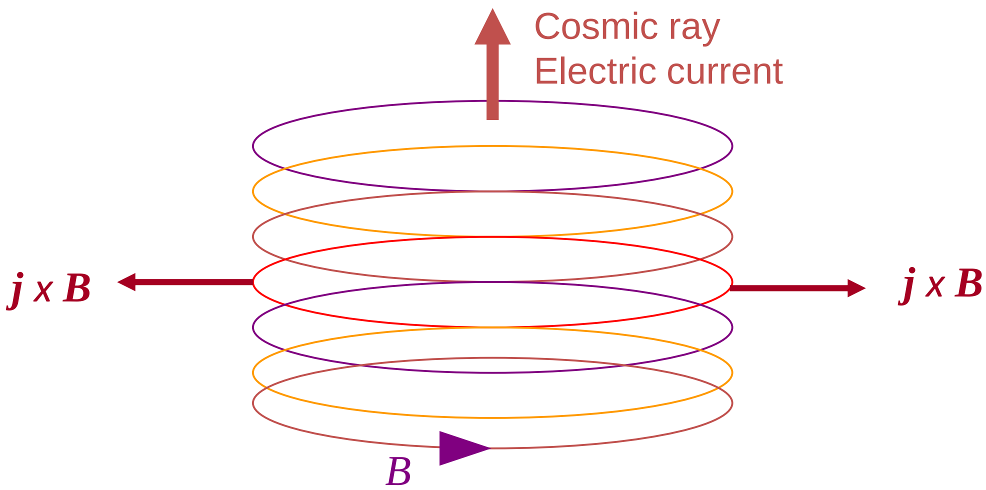
$j_{CR} \times B$ forces drive non-resonant instability (Bell 2004,2005)

produces turbulence

amplifies magnetic field

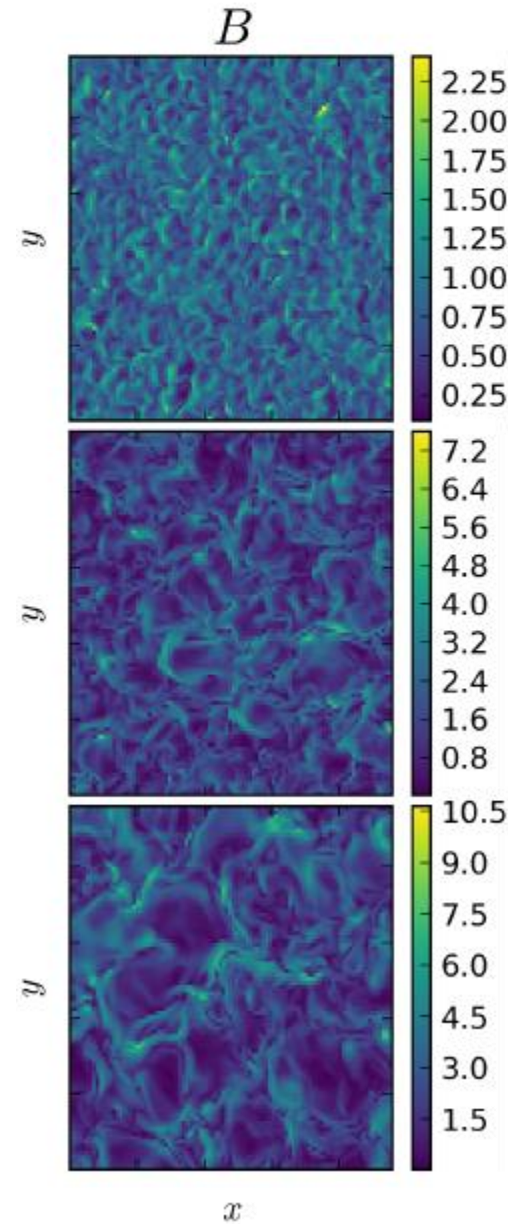
Magnetic field amplification increases B to near equipartion (100s μG in SNR)

Magnetic field amplification



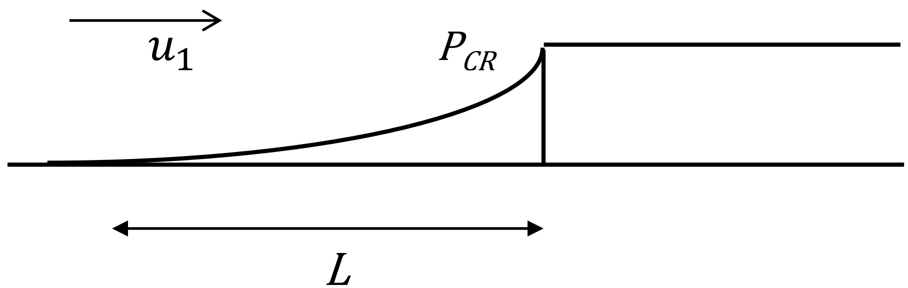
Instability grows until
1) Tension in field lines opposes $j\mathrm{x}B$
2) CR get tied to field lines: Loop size = r_g

Automatically saturates with $\lambda \sim r_g$



Matthews et al (2017)

Need time to amplify magnetic field



Need about 5 e-foldings in time L/u_1

For SNR parameters

acceleration efficiency

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

radius in parsec

in cm^{-3} in 10,000 km s^{-1}

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

$\approx \mathbf{0.1 \times Hillas\ energy}$

Challenges for CR acceleration

A) Magnetic field amplification (approaching equipartition)

$$B^2/\mu_0 \sim \rho u^2$$

B) Since $E = -u \times B$, no acceleration if CR tied to field lines

Ways for CR to cross field lines

1) Diffusion as above

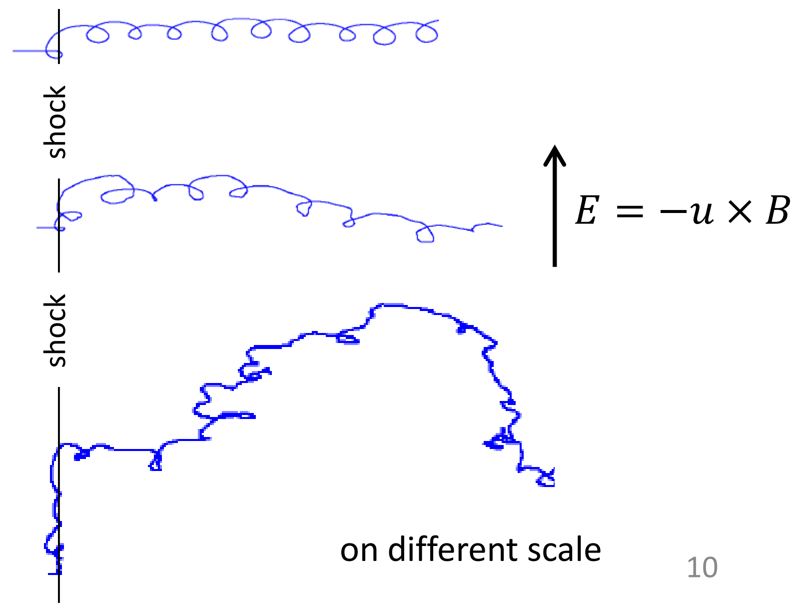
Need Bohm diffusion $\lambda \sim r_g$

Need time for turbulence to grow $\int \gamma_{\max} dt \approx 5$

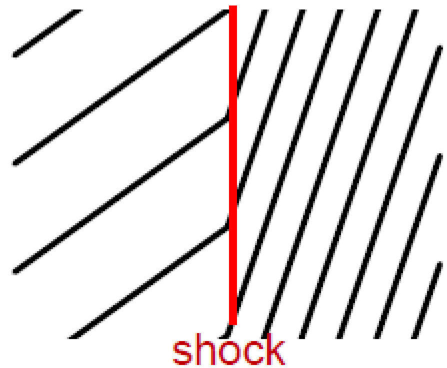
2) Cross-field drifts eg perpendicular shocks

Average B_0 perpendicular to page

Needs finely tuned scattering by turbulent field B_1

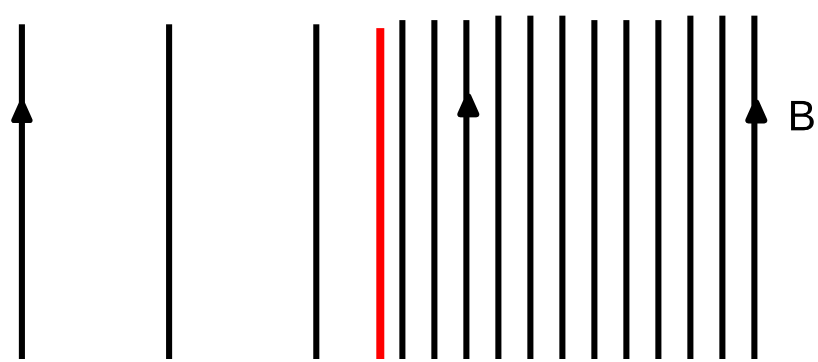


Relativistic shocks have extra problems

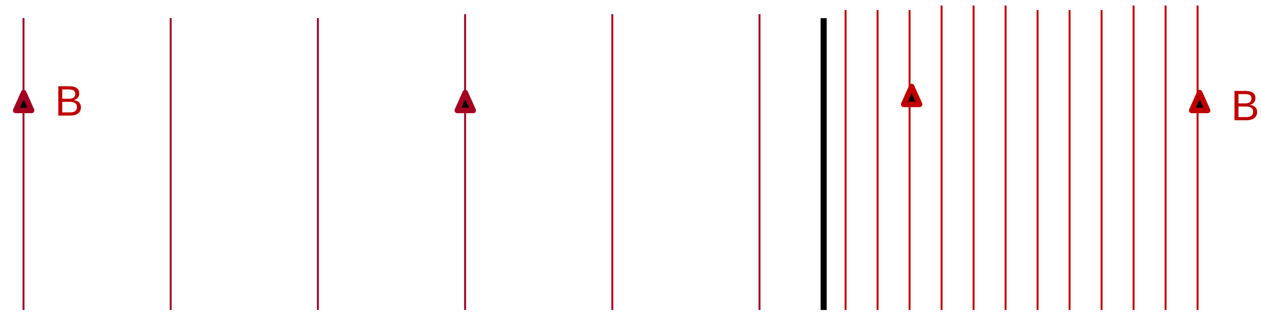


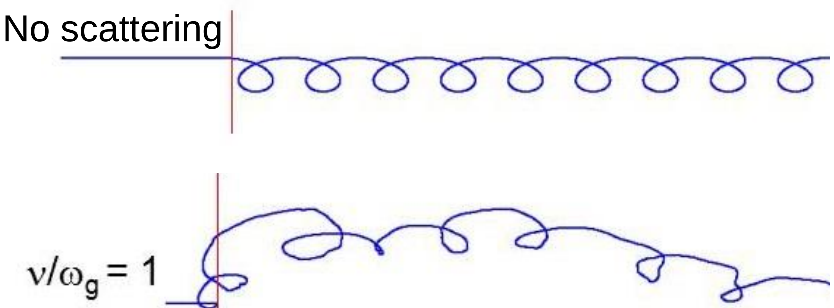
Behaves like perpendicular shock, because

1) Transformation into shock rest frame increases $B_\perp$ but not $B_\parallel$
2) CR cannot escape upstream



Perpendicular relativistic shock – poor UHECR accelerator

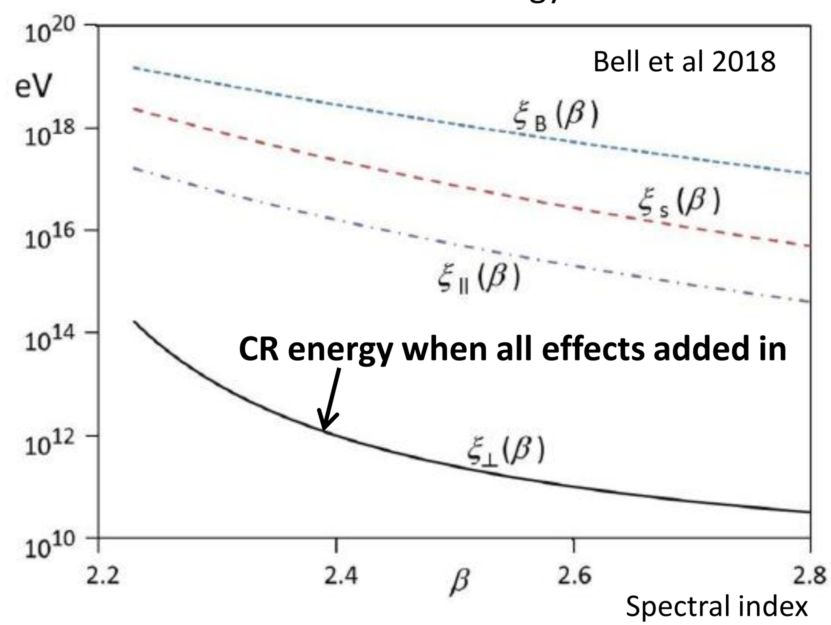




Need to generate turbulent field within one Larmor radius of shock

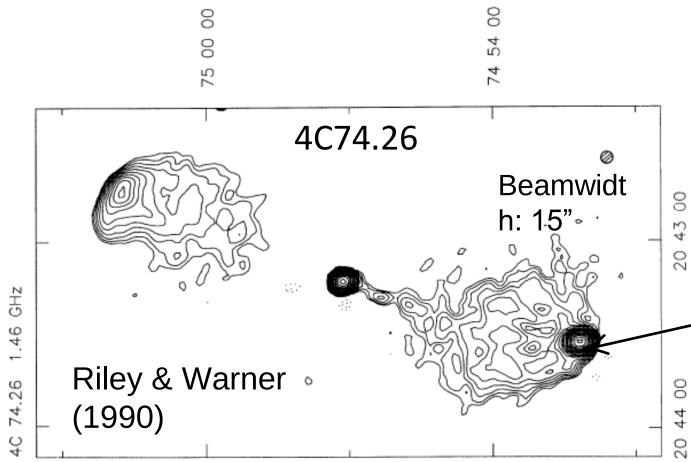
Not enough time to drive instability

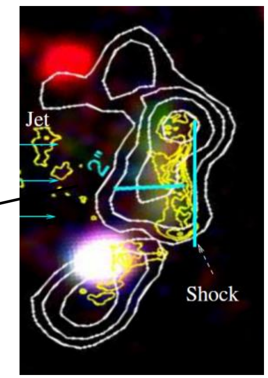
Reduction in max CR energy at rel. shock



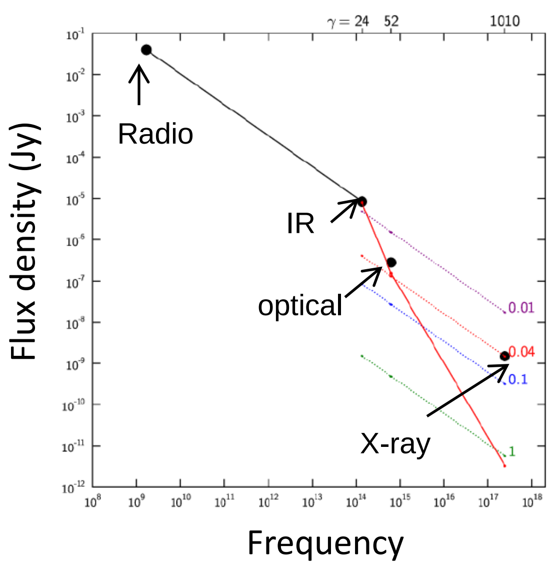
Observations: relativistic shocks are poor accelerators

Quasar jet 4C74.26 and other radio galaxy hotspot (Araudo et al 2015, 2016, 2018)





Erlund et al 2010
Merlin telescope

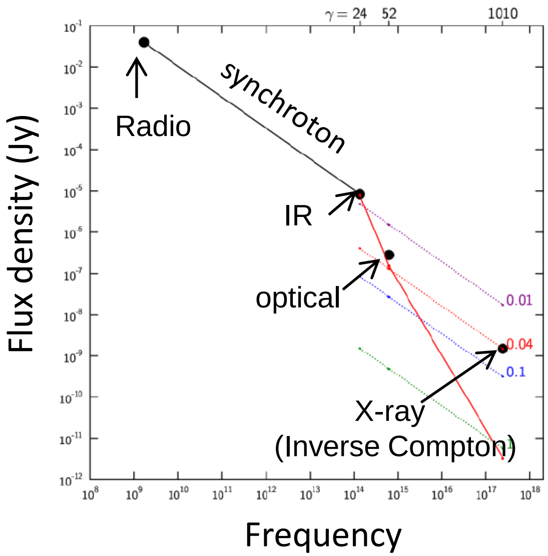


Hillas energy uBR ~ 3×10^{19} eV

However: spectral turnover in IR/optical:
Max electron energy ~ TeV

Common feature of jet termination hotspots

Spectral turnover at termination shock - I



Usual interpretation:
Turnover due to synchrotron losses
$\tau_{acceleration} = \tau_{cooling}$

If radiation losses limit electron acceleration

Acceleration time = synchrotron loss time $= \left(\frac{\mathrm{energy}}{\mathrm{TeV}}\right)^{-1} \left(\frac{B}{10\mu\mathrm{G}}\right)^{-2} 10^5\mathrm{yr}$

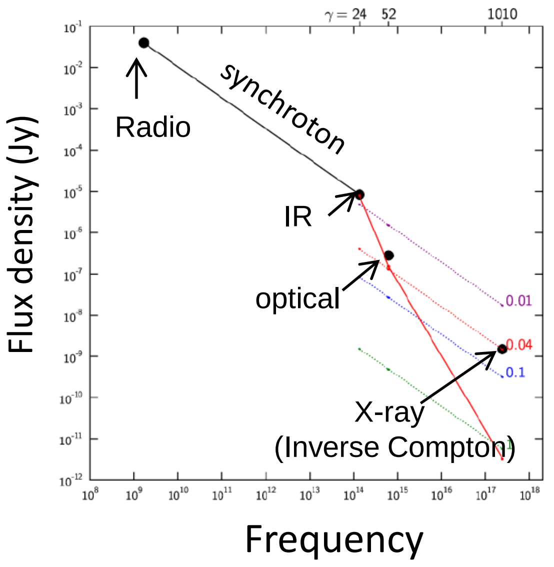
Expect acceleration time $\propto$ energy

$\Rightarrow$ acceleration time to 10 EeV is 1000 Gyr

proton acceleration rate = electron acceleration rate

Termination shocks too slow for UHECR acceleration

Spectral turnover at termination shock - II



Usual interpretation:
Turnover due to synchrotron losses

$$\tau_{acceleration} = \tau_{cooling}$$

Turnover frequency is $(h\nu)_{eV} = 3 \times 10^{7} \left(\frac{u}{c}\right)^{2} \left(\frac{\lambda}{r_g}\right)^{-1}$

$\Rightarrow$ CR scattering mean free path ~ 10^7 x Larmor radius

Defies plasma physics

Turnover not due to synchrotron losses

If turnover not due to synchrotron losses

Applies to protons as well as electrons

CR not accelerated beyond TeV

Araudo et al 2015, 2016, 2018 {poster on Thursday)

A further limitation: source power
(Blandford/Waxman/Lovelace)

Hillas energy: $T = ZuBL$

Magnetic energy passing through CR source: $P_{mag} = uL^2 \left(\frac{B^2}{2\mu_0}\right)$

Combine with Hillas energy: $T = Z\,(2u\mu_0)^{1/2} {P_{mag}}^{1/2}$

Rearrange: power needed to accelerate CR to energy T

$$P_{source} > P_{mag} = \left(\frac{Z}{6}\right)^{-2} \left(\frac{T}{100\mathrm{EeV}}\right)^{2} \left(\frac{u}{c}\right)^{-1} 4 \times 10^{42}\ \mathrm{erg\ s^{-1}}$$

Starburst and/or radio galaxies

$$P_{source} > P_{mag} = \left(\frac{Z}{6}\right)^{-2} \left(\frac{T}{100EeV}\right)^{2} \left(\frac{u}{c}\right)^{-1} 4 \times 10^{42}\ \mathrm{erg\ s^{-1}}$$

Starburst galaxies

u ~ c/1000 – c/300

Power up to ~ 10^{43} erg s^{-1}

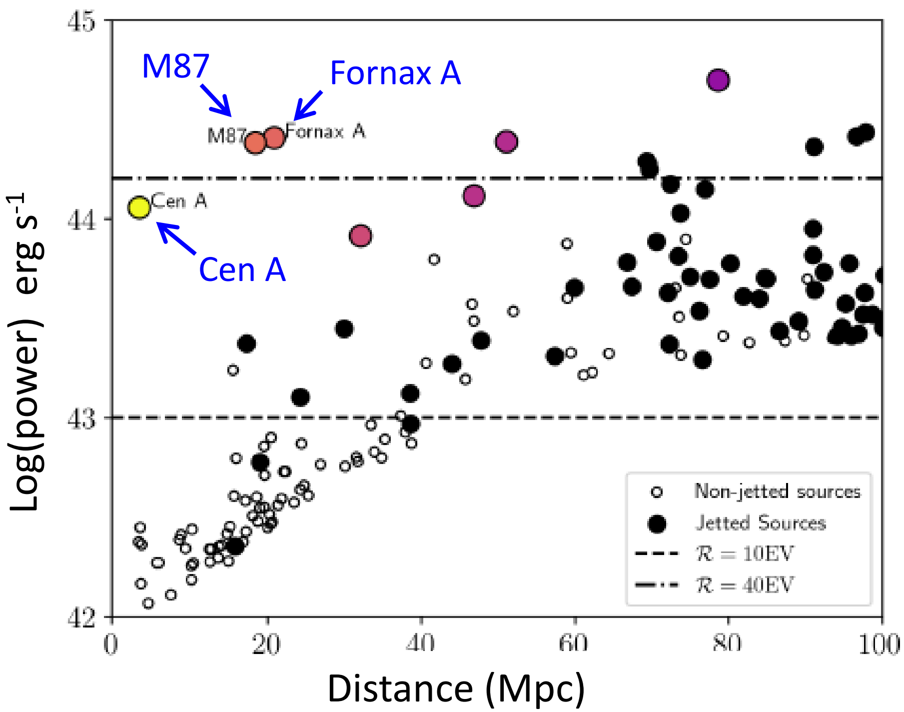
Anchordoqui 2017, Heckman et al 1990, Aab et al (Auger) 2018

Radio galaxies

u ~ c/3 – c

Power up to ~ 10^{46} erg s^{-1}

Radio galaxies within 100 Mpc



Total power (Cavagnolo 2010):

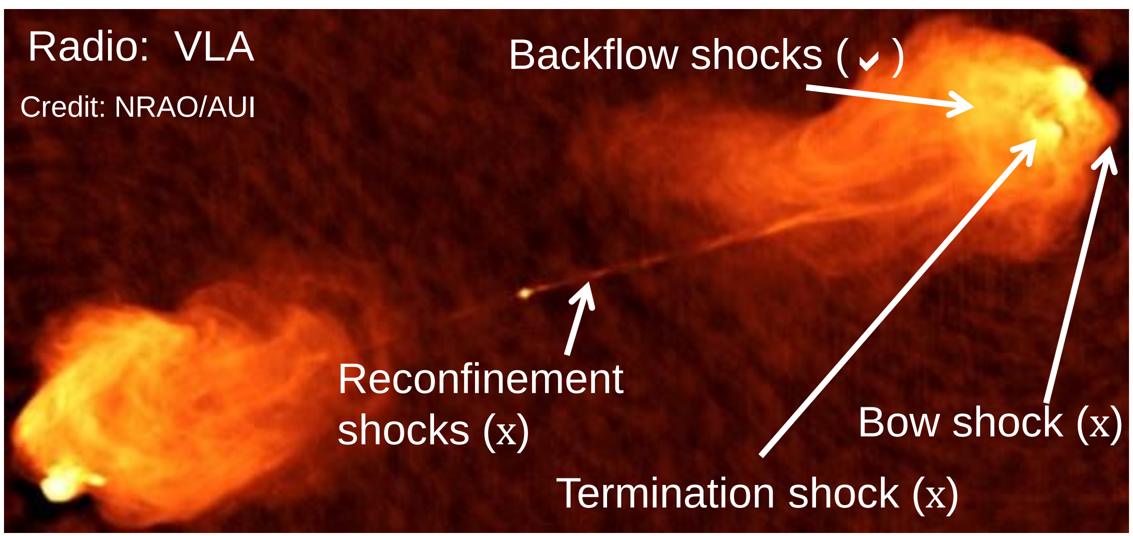
$$\bar{P}_{\mathrm{cav}} \approx 5.8 \times 10^{43} \left(\frac{P_{\mathrm{radio}}}{10^{40}\ \mathrm{erg\ s^{-1}}}\right)^{0.7}\ \mathrm{erg\ s^{-1}}$$

Shocks in radio galaxies

Cygnus A is the archetypal radio galaxy

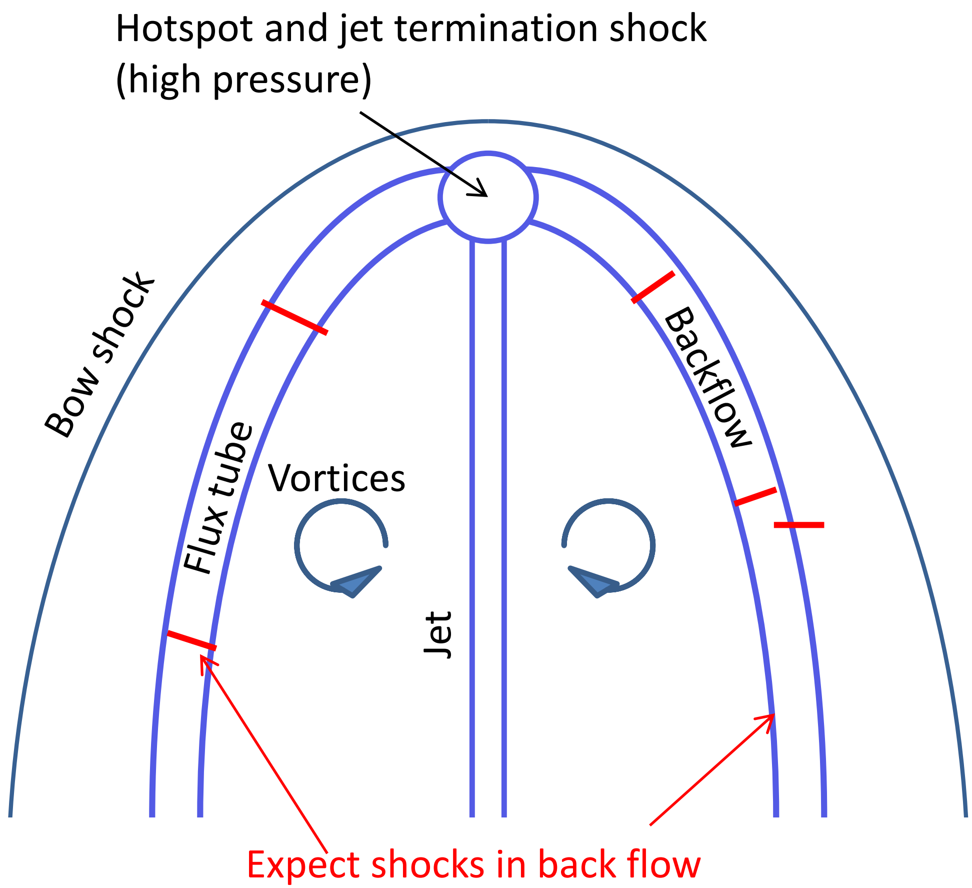
Power ~ 10^{46} erg s^{-1}
Jet velocity ~ c/3 - c

B ~ 300 μG
L ~ 3 kpc
ZuBL ~ Z x 300 -1000 EeV



Need shocks that are:
High velocity but not relativistic
Large & long-lived

Schematic diagram: flux tube/sheet



Backflow as Bernoulli flux tube/sheet

Flow out of hotspot:
pressure drops
sound speed drops
velocity increases
Mach number increases
$\longrightarrow$ **shocks**

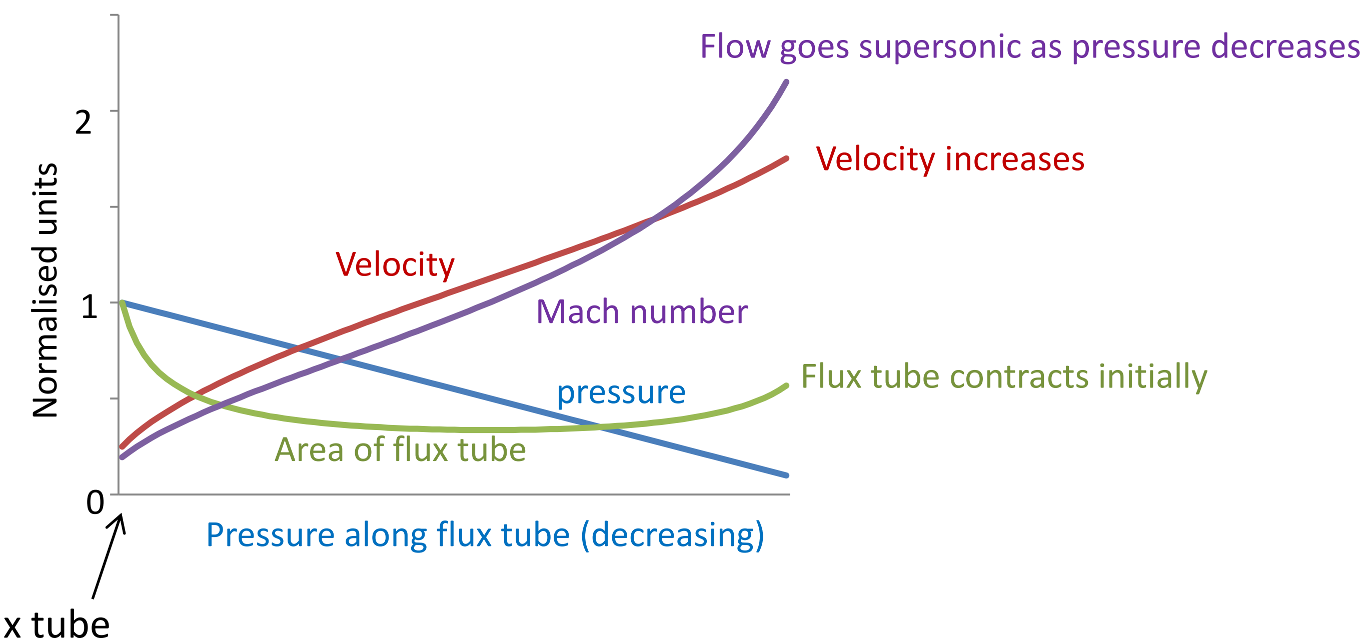
Backflow in adiabatic flux tube

Pressure drops as plasma exits hotspot

Adiabatic between shocks: $$\frac{P}{\rho^\gamma} = constant$$

Bernoulli equation: $$\frac{u^2}{2} + \frac{\gamma}{\gamma - 1}\frac{P}{\rho} = constant$$

Mass conservation: $$\rho u A = constant$$

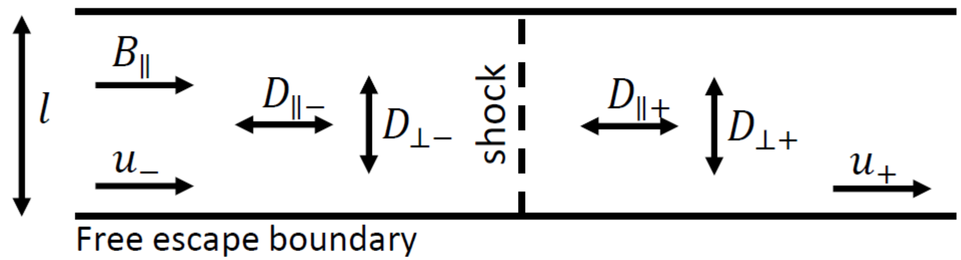


assume $u = 0.25\sqrt{(P/\rho)}$

Expect supersonic flow to end in a shock

Fermi1 (diffusive shock acceleration) in flux tube

Assume magnetic field $B_\parallel$ aligned along flux tube



$$\left.\begin{aligned} &\text{Acceleration time:} \quad \tau_{accel} = \frac{D_\parallel}{u^2} \\ &\text{Lateral escape time:} \quad \tau_{loss} = \frac{l^2}{D_\perp} \end{aligned}\right\} \quad \tau_{accel} = \tau_{loss} \quad \text{when} \quad \sqrt{(D_\parallel D_\perp)} = ul$$

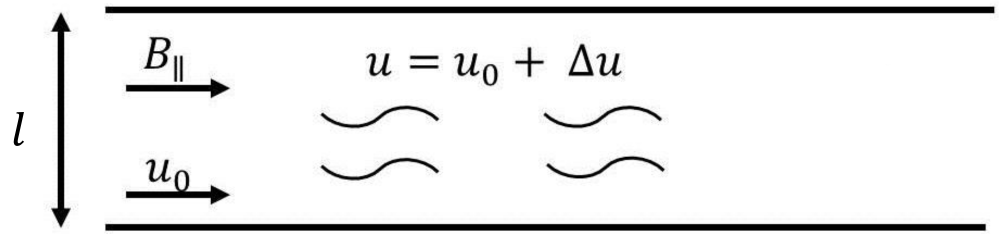
$$D_\perp = \frac{D_{Bohm}}{(\omega_g \tau_{scatt})} \qquad D_\parallel = (\omega_g \tau_{scatt}) D_{Bohm}$$

$$D_{Bohm} = \frac{c r_g}{3} \quad \Rightarrow \quad \text{Max CR energy} \quad T = \frac{1}{3} u_- B_\parallel l$$

CR reaches Hillas energy independent of $\boldsymbol{\omega_g \tau_{scatt}}$

Fermi2 acceleration in flux tube

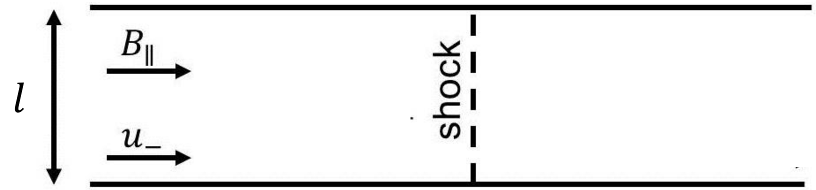
2[nd] order Fermi: flow velocity u varies along flux tube



Max CR energy $T \simeq u_0 B_\parallel l \left(\frac{\Delta u}{u_0}\right)^2$

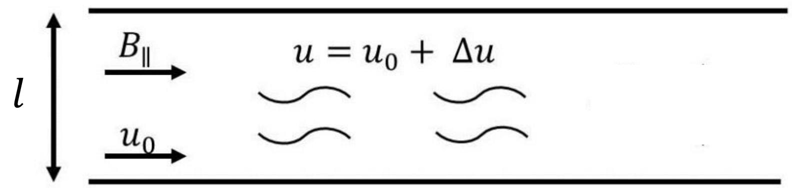
CR acceleration in flux tube

1st order Fermi: diffusive shock acceleration



Max CR energy $T \simeq Z u_{\parallel} B_{\parallel} l$

2nd order Fermi: flow velocity u varies along flux tube



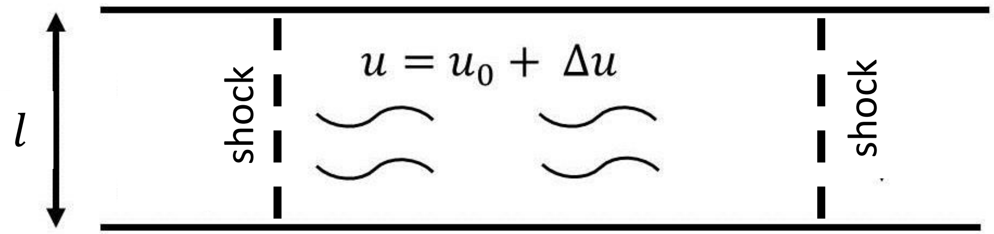
Max CR energy $T \simeq Z u_0 B_{\parallel} l \left(\frac{\Delta u}{u_0}\right)^2$

Flux tube on border between 1st & 2nd order Fermi (Fermi1.5)

Multiple shocks at low Mach number
Flow velocity varies with $\Delta u / u_0 \sim 1$

$$T = \left(\frac{Z}{6}\right)\left(\frac{u}{c/3}\right)\left(\frac{B}{10\ \mu\mathrm{G}}\right)\left(\frac{l}{3\mathrm{kpc}}\right)\ 60\ \mathrm{EeV}$$

Advantages of CR acceleration in flux tube



Gives Hillas energy $\sim uBl$ even if $D \neq D_{Bohm}$

Magnetic field pre-amplified in hotspot or previous shocks

Shocks velocities are non-relativistic but close to c

$$T = \left(\frac{Z}{6}\right)\left(\frac{u}{c/3}\right)\left(\frac{B}{10\ \mu\mathrm{G}}\right)\left(\frac{l}{3\mathrm{kpc}}\right)\ 60\ \mathrm{EeV}$$

Main points

Hillas energy is an upper limit – insufficient by itself

Need to get CR across field lines

Diffusion needs magnetic field on Larmor scale

Relativistic shocks are poor UHECR accelerators

Power requirement points to radio galaxies

Backflows in radio lobes well suited to accelerate UHECR

Talk by James Matthews this afternoon:
UHECR from radio galaxy backflows

Poster by Anabella Araudo on Thursday
Acceleration at termination shocks