Drift acceleration of UHECRs in sheared AGN jets

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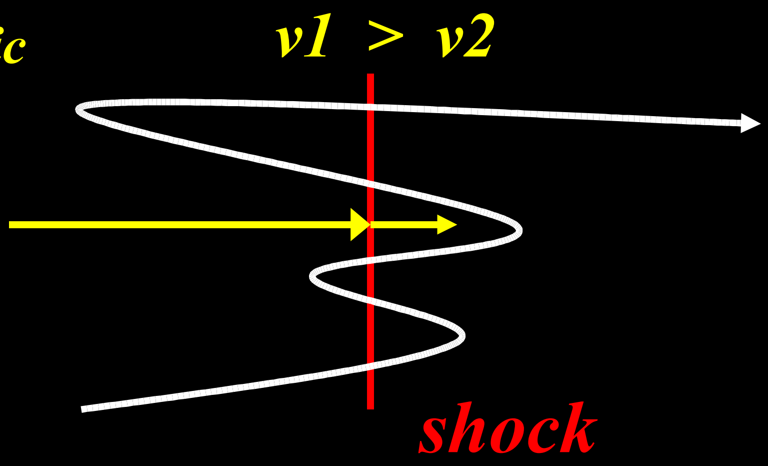
Acceleration of UHECRs: there is more than Fermi

Conventionally – Fermi I & II at relativistic shocks:

- *maximal efficiency ($\tau_{acc} \sim \gamma/\omega_B$) is usually either assumed or put "by hand" by using (super)-Bohm cross-field diffusion*
- *so far NO self-consistent simulations produced required level of turbulence*
- *Hardening above the "ankle" ~ 10^{18} eV may indicate new acceleration mechanism*

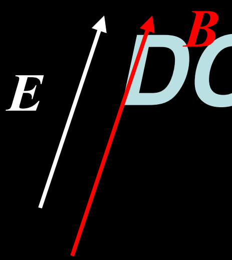


We propose new, non-stochastic acceleration mechanism that turns on above the ankle, E> 10^{18} eV

General constraints on acceleration cite:

- *Constraints on UHECRs are so severe, "~" estimates are useful*
- *Maximal acceleration E-field < B-field:* $E=\beta_0 B, \quad \beta_0 \leq 1$
- *Total potential* $\Phi = E R = \beta_0 B R$
- *Maximal energy* $E \sim Z e \Phi = \beta_0 Z e B R$
- *Maximal Larmor radius* $r_L \sim \beta_0 R$
  - *For* $\beta_0 < 1$ *system can confines particles with energy large than is can accelerate to (NB: Hillas condition* $r_L \sim R$ *is condition on confinement, not acceleration)*
- *Two possibilities:*
  - $E \parallel B$ *(or E>B) – DC field*
  - $E \perp B$ *– inductive E-field*

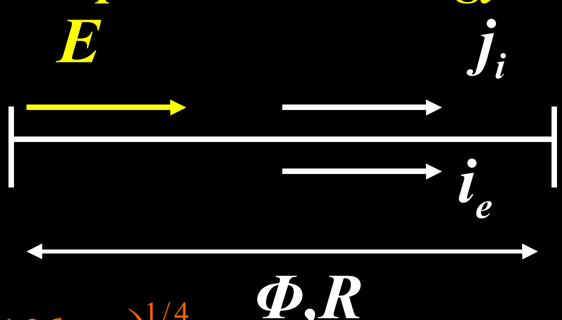
} *Two paradimes for UHECR acceleration*



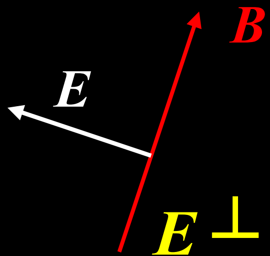
DC (linear) acceleration for UHECR do not work

Full DC accelerations schemes (with E-field || to B-field or E>B) cannot work in principle for UHECRs

2. *leptons will shut off $E_{||}$ by making pairs (typically after $\Delta\Phi \ll 10^{20}$ eV)*
3. *Double layer is very inefficient way of accelerating: E-field will generate current, current will create B-field, there will be large amount of energy associated with B-field. One can relate potential drop with total energy:*
   - *Relativistic double layer:* $R \sim \Phi^{1/4}$
   - *Maximal energy* $E_{\max} = \sqrt{I\, m_p c Z e}$
   - *Total energy:* $E \sim B^2 R^3 \sim I^2 R c^2$



$$E_{\max} = \sqrt{m_p c^2 Z e \left(\frac{E_{tot}}{R}\right)^{1/4}} \leq 10^{15}\,\mathrm{eV}\left(\frac{E_{tot}}{10^{60}\,erg}\right)^{1/4}\left(\frac{10\,kpc}{R}\right)^{1/4}$$



Lovelace 76
Blandford 99

E B : Inductive potential

E ⊥ B: Poynting flux in the system: relate Φ to luminocity

$$L_{EM} = 4\pi\ R^2 \frac{E\times B}{4\pi} c = \frac{\sigma}{\sigma+1} L_{tot} \sim L_{tot},\ \text{for}\ \sigma \sim 1$$

$$\mathrm{E} \sim \beta_0 B,\quad L_{EM} \sim \beta_0 (BR)^2 c$$

Electric potential $\Phi = \mathrm{ER} = \beta_0 BR \quad \Rightarrow L \sim \frac{\Phi^2}{\beta_0} c$

$$\Phi \le \sqrt{\frac{4\pi\ \beta_0\ \mathrm{L}}{c}},\quad BR \sim \frac{I}{2\pi c} \quad \Rightarrow \quad \mathrm{I} \sim \sqrt{\frac{\mathrm{L\ c}}{4\pi}}$$

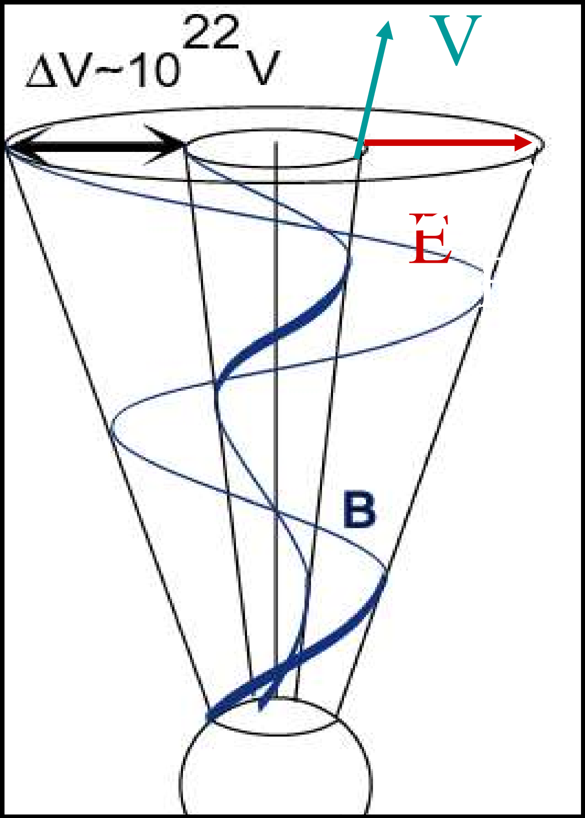
$$\mathrm{R} \sim \frac{4\pi}{c} \sim 377\Omega,\quad \mathrm{L_{EM}} \sim \mathcal{E}\ \mathrm{I}$$

To reach Φ=3 10^{20} eV, L > 10^{46} erg/s (for protons)

This limits acceleration cites to high power AGNs (FRII, FSRQ, high power BL Lac, and GRBs)

There are a few systems with enough potential, the problem is acceleration scheme

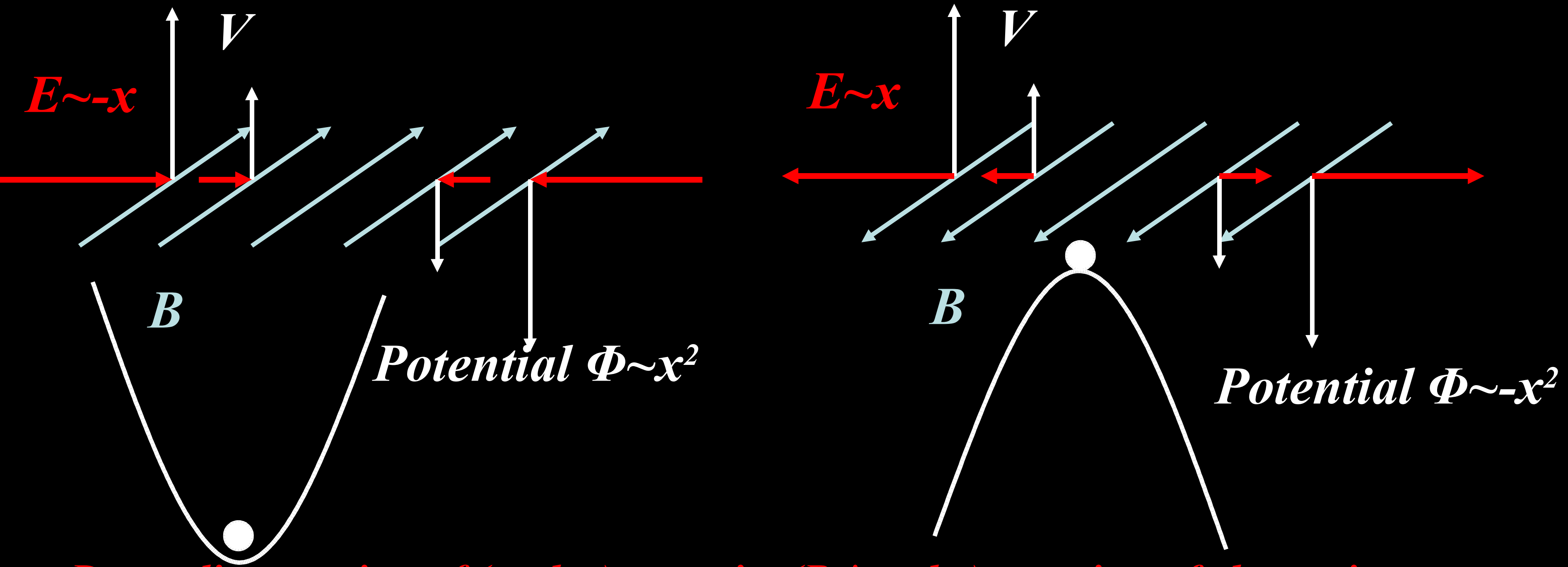
Acceleration by large scale inductive E-fields: $\mathcal{E} \sim \int v \cdot E \, ds$



- ***Potential difference is between different flux surface (pole-equator)***
- ***In MHD plasma is moving along $V = E \times B / B^2$ – cannot cross field lines***
- ***What is the mechanism of acceleration? Before, it was only noted that there is large potential (Lovelace, Blandford, Blasi), but no mechanism (Bell)***
- ***Kinetic motion across B-fields- particle drift***

Potential energy of a charge in a sheared flow

$$\Delta = \frac{4\pi}{c} B \bullet (\nabla \times v)$$ ***For linear velocity profile*** $v = \eta x: \ \Phi = \frac{4\pi}{c} B \eta \frac{x^2}{2}$



Depending on sign of (scalar) quantity (B *curl v) one sign of charge is at potential maximum

Protons are at maximum for negative shear (B *curl v) < 0

This derivation is outside of applicability of non-relativisitc MHD

Astrophysical location: AGN jets

There are large scale B-fields in AGN jets

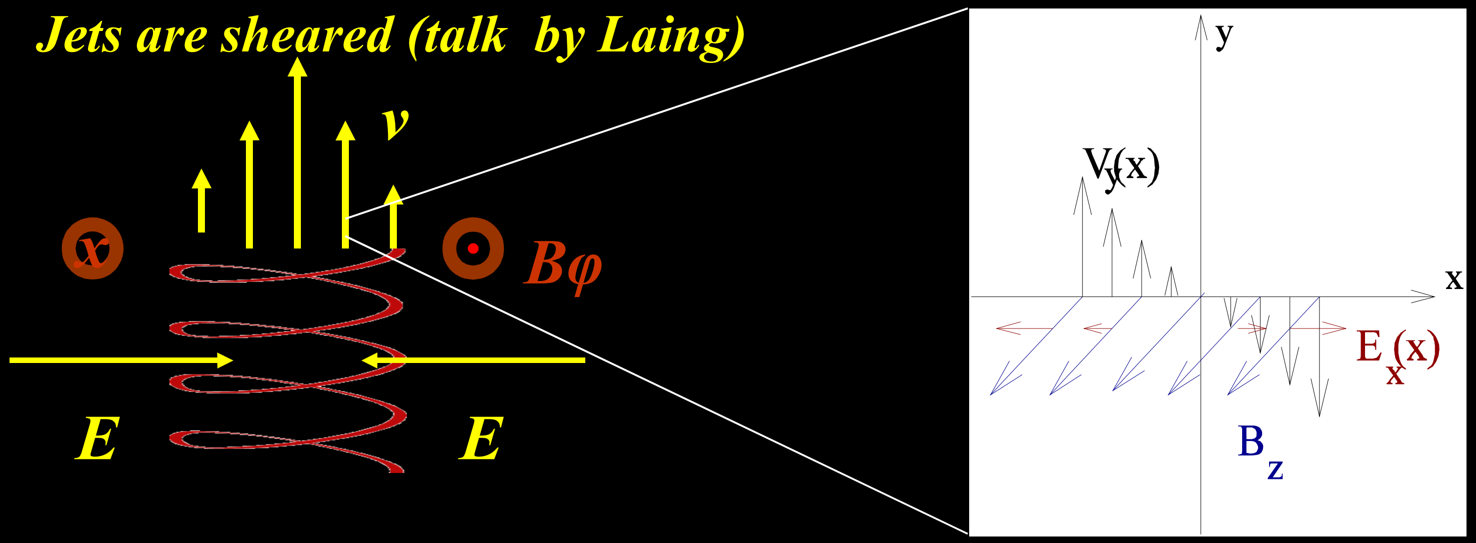
Jet launching and collimation (Blandford-Znajek, Lovelace, Blandford-Payne; Hawley)

Observational evidence in favor of helical fields in pc-scale jets (talk by Gabuzda ,posters, Lyutikov et al 2004,)

Jets may collimate to cylindrical surfaces (Heyvaerts & Norman)

At largest scales Bφ is dominant

Jets are sheared (talk by Laing)



Drift due to sheared Alfven wave

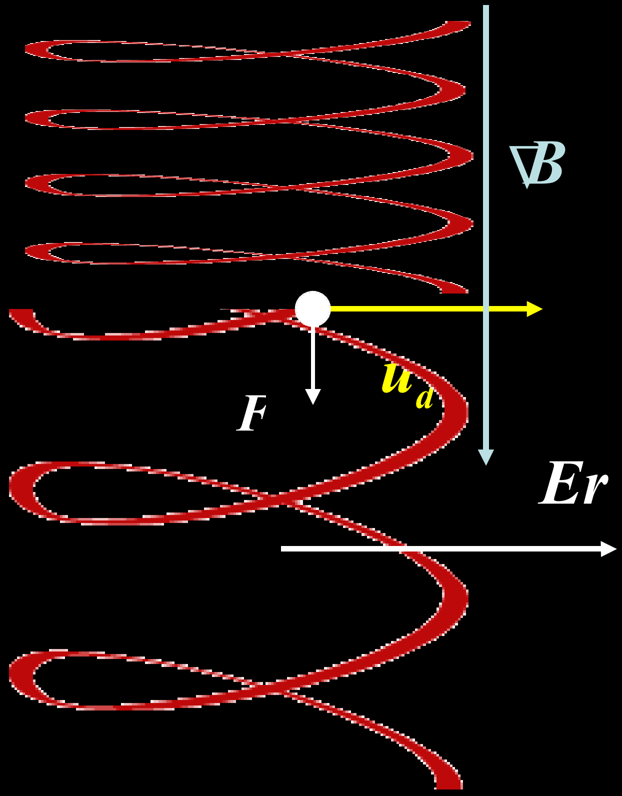
Electric field $E \sim vz \times B\varphi \sim er$

*For negative shear, (B *curl v) < 0, proton is at potential maximum, but it cannot move freely along it: need kinetic drift along radial direction*

Inertial Alfven wave propagating

along jet axis $\omega = V_A k_z$

$B\varphi(z) \rightarrow U_d \sim \nabla B\varphi x B\varphi \sim er$



Why this is all can be relevant? Very fast energy gain :

Energy gain: $< \partial_t \mathcal{E} > \quad eZ < (\mathbf{E} \bullet \mathbf{v}) > \quad eZEu_d$

For linear velocity profile, *$V = \eta\, x$, $E = \eta\, x\, B/c$, $x = ud\, t$,*

$$u_d = \frac{k_A \mathcal{E}}{2ZeB} c \qquad \rightarrow \qquad \partial_t \mathcal{E} = \frac{\eta \mathcal{E}^2 k_A{}^2 t}{4ZeB}$$

$$\tau_{acc} \sim \frac{1}{\sqrt{\gamma}} \frac{1}{|k_A| c} \sqrt{\frac{\omega_B}{\eta}} = \frac{1}{|k_A| c} \sqrt{\frac{ZeBc}{\mathcal{E}\eta}}$$

highest energy particles are accelerated most efficiently!!!

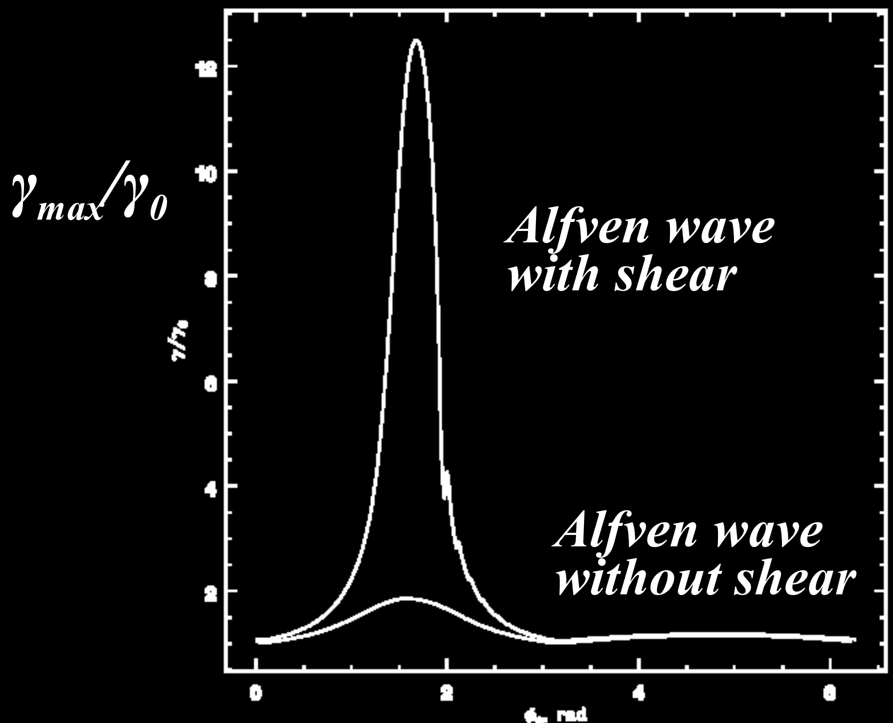
low Z particles are accelerated most efficiently!!! (highest rigidity are accelerated most efficiently)

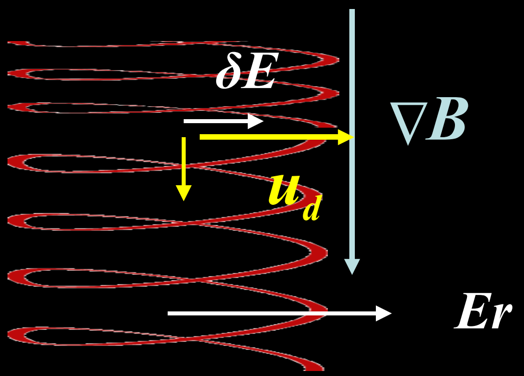
Jet needs to be ~ cylindrically collimated; for spherical expansion adiabatic losses dominate

Wave surfing can help

Shear Alfven waves have $\delta E \sim (V_A/c)\,\delta B$, particle also gains energy in δE

Axial drift in $\delta E x B$ helps to keep particle in phase





Most of the energy gain is in sheared E-field (not E-field of the wave, c.f. wave surfing)

Final orbits (strong shear), $r_L \sim R_j$

When r_L becomes ~ jet radius, drift approximation is no longer valid

New acceleration mechanism

Larmor radius of the order of the shear scale, $\eta = V' \sim \omega_B/\gamma$ (Ganguli 85)

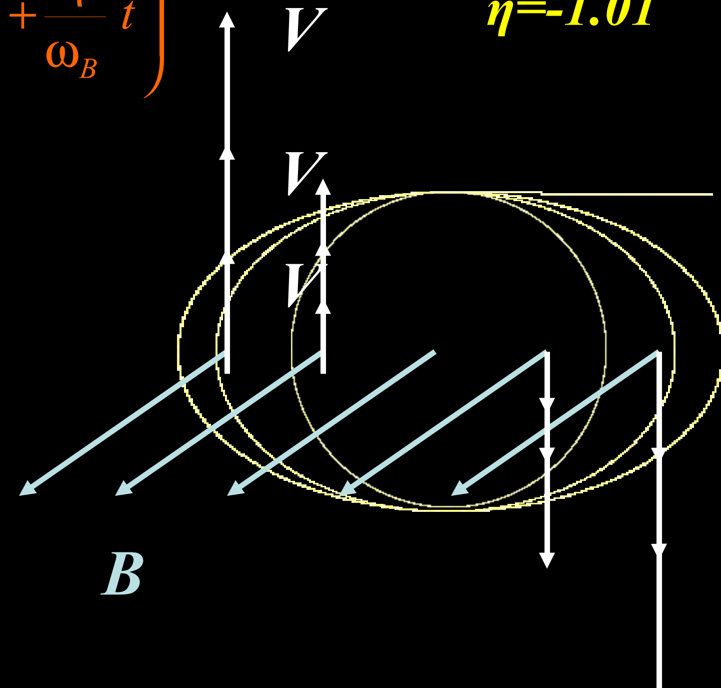
Non-relativistic, linear shear: $V_y = \eta x$

$\eta = V'/\omega_B$

$\eta = -1.01$

$$x = r_L \cos\left(\omega_B \sqrt{1+\frac{\eta}{\omega_B}}\, t\right), \quad y = \frac{r_L}{\sqrt{1+\eta/\omega_B}} \sin\left(\omega_B \sqrt{1+\frac{\eta}{\omega_B}}\, t\right)$$

unstable motion for $\eta < -\omega_B$



Final orbits: relativistic

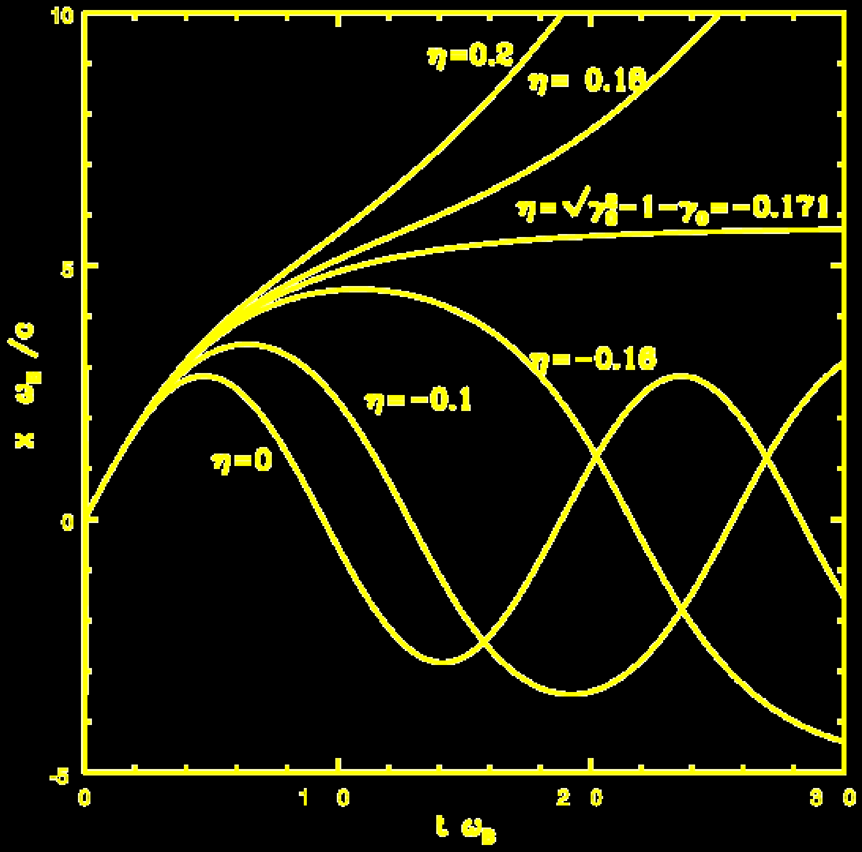
Relativistic $$\frac{\eta_{crit}}{\omega_B/\gamma_0} = \gamma_0\left(-\gamma_0 + \sqrt{\gamma_0^{\;2} - 1}\right) \approx -\frac{1}{2}$$ *η=V'*

For $\eta < \eta_{crit} < 0$ particle motion is unstable

When shear scale is ½ of Larmor radius motion is unstable

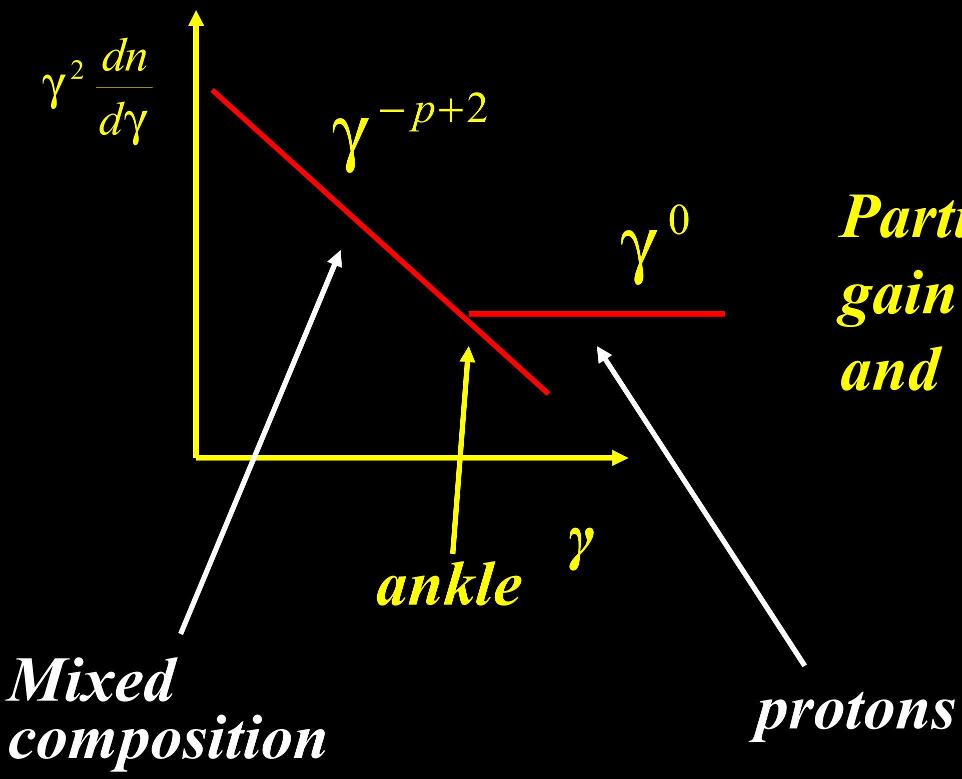
Acceleration DOES reach theoretical maximum

Note: becoming unconfined is GOOD for acceleration



Spectrum

From injection $dn/d\gamma \sim \gamma^{-p} \rightarrow dn/d\gamma \sim \gamma^{-2}$



Particles below the ankle do not gain enough energy to get rL ~Rj and do not leave the jet

This is what is seen

Radiative losses

Equate energy gain in E =B to radiative loss ~ $U_B \gamma^2$

$$r > \frac{Z^2 e^2}{mc^2}\left(\frac{E}{mc^2}\right)^3 \Gamma^{-2} \sim 10^{16}\ \Gamma_{10}^{-2}\left(\frac{E}{100\ \mathrm{EeV}}\right)^3 \mathrm{cm}$$

$$B < \frac{m^2 c^4}{Z^3 e^3}\left(\frac{E}{mc^2}\right)^{-2} \Gamma^3 \sim 6\ 10^4\ \Gamma_{10}^{3}\left(\frac{E}{100\ \mathrm{EeV}}\right)^{-2} \mathrm{G}$$

$$\Phi \le \sqrt{\frac{4\pi\ \beta_0\ L}{c}},$$

As long as expansion is relativistic, total potential remains nearly constant,   one can wait yrs – Myrs to accelerate

Astrophysical viability

- *Need powerful AGN FR I/II (weak FR I , starbursts are excluded)*
  - *UHECRs (if protons) are not accelerated by Cen A or M87*
- *Several powerful AGN within 100 Mpc, far way → clear GZK cut-off should be observed*
- *For far-away sources hard acceleration spectrum, p~ 2 , is needed*
- *Only every other AGN accelerates UHECRs*
- *Clustering is expected but IGM B-field is not well known*
  - *μGauss field of 1Mpc creates extra image of a source (Sigl)*
  - *Isotropy & clustering: need ~ 10 sources (Blasi & Di Marco)*
- *Fluxes:* $L_{UHECR} \sim 10^{43}$ *erg/sec/(100 Mpc)*^{3} *– 1 AGN is enough*
- *Pre-acceleration can be done outside of the jet and pulled-in*
- *Shock acceleration in galaxy cluster shock stops @* 10^{18} *eV*
- *Matching fluxes of GCR and EGCR….*

Main properties of the mechanism:

*Protons are at maximum for negative shear (B *curl v) < 0*

*Acceleration rate **increases** with energy*

*At highest energies acceleration rate **does** reach absolute theoretical maximum* $\tau_{acc} \sim \gamma/\omega_B$

*At a given energy, particles with **smallest Z** (smallest rigidity) are accelerated most efficiently (UHECRs above the ankle are protons)*

produces flat spectrum

Pierre Auger: powerful AGNs?

- *GZK cut-off*
- *few sources*

May see ν & γ fluxes toward source (HESS, IceCube)

GRBs: L ~ 10^{50} erg/s

GRBs: I~ 10^{20} A, E_{max}=*3 10^{22} eV*

Max. acceleration E~B (on τ~ γ/ω_B), shorter than expansion time scale c Γ/R

Radiative losses (e.g. synchrotron). **For E_{CR}~ 3 10^{20} eV**

$$r > \frac{Z^2 e^2}{mc^2}\left(\frac{E}{mc^2}\right)^3 \Gamma^{-2} \sim 3\,10^{14}\ \Gamma_{100}^{-2}\ \mathrm{cm}$$

$$B < \frac{m^2 c^4}{Z^3 e^3}\left(\frac{E}{mc^2}\right)^{-2} \Gamma^3 \sim 3\,10^5\,\Gamma_{100}^{3}\mathrm{G}$$

Always fighting adiabatic losses: need to get all the available potential on less than expansion time scale

If there is GZK cut-off, and L_{GRB}~L_{CR} then GRBs are viable source

E B : Inductive potential

$$L \sim E\,B\,R^2 c \sim (BR)^2\,\beta c \sim \mathcal{E}^2\,c$$

$$\mathcal{E} \leq \sqrt{\frac{4\pi\,L}{c}}, \text{ or } \sqrt{\frac{4\pi\,E}{R}}\,\beta$$

$$I \leq \sqrt{\frac{L\,c}{4\pi}}$$

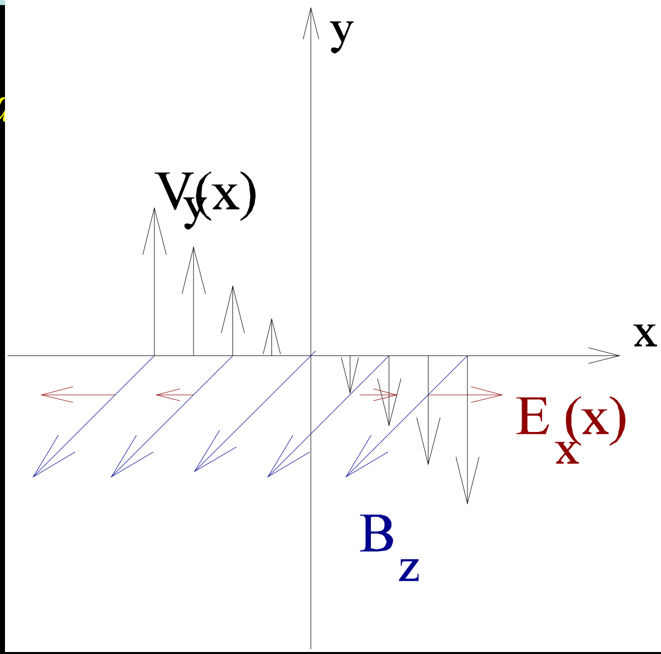
$$R \sim \frac{4\pi}{c} \sim 377\Omega$$

$$L_{EM} \sim \mathcal{E}\ I$$

	Voltage	Current
Sun	10^{8} V	10^{9} A
Pulsar	10^{16} V	$3\ 10^{12}$ A
SGR	$3\ 10^{14}$ V	10^{12} A
AGN	$3\ 10^{20}$ V	10^{18} A
GRB	$3\ 10^{22}$ V	10^{20} A
SLAC	10^{10} V	1 A

Potential energy of a charge in a sheared flow

Consider sheared fluid motion of plasma in ma



$$E = -\frac{v}{c} \times B \Rightarrow \Delta \quad = \frac{4\pi}{c} \nabla (v \times B) =$$

$$\frac{4\pi}{c} \left(B \bullet (\nabla \times v) - v \bullet (\nabla \times B) \right)$$

in stationary, current-free case

$$\Delta \quad = \frac{4\pi}{c} B \bullet (\nabla \times v)$$

,v

Depending on sign of (scalar) quantity (B *curl v) one sign of charge is at potential maximum

Protons are at maximum for negative shear (B *curl v) < 0

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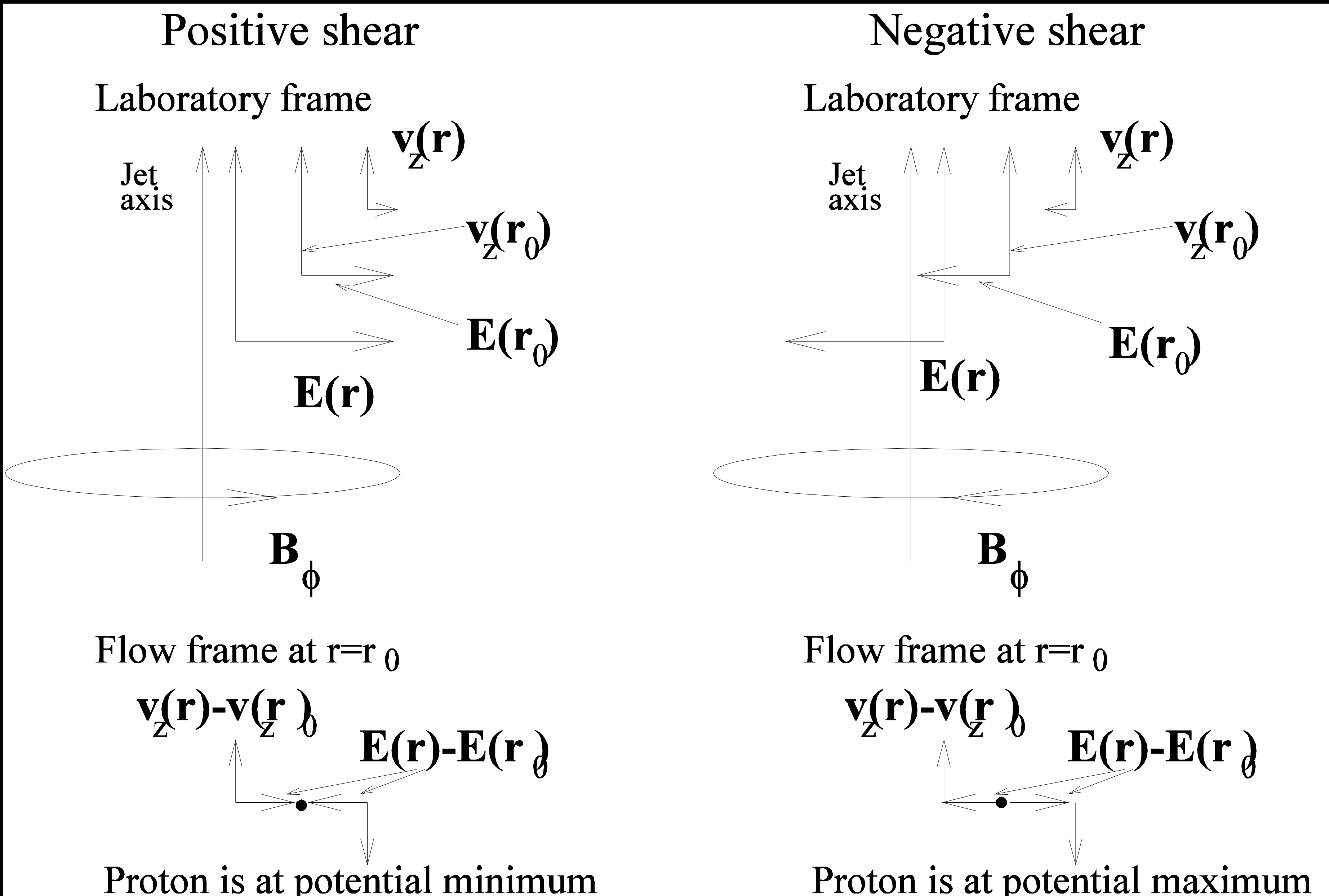
Positive shear
Negative shear
Laboratory frame
Jet axis
vz(r)
vz(r0)
E(r0)
E(r)
Bϕ
Flow frame at r=r 0
vz(r)-vz(r 0)
E(r)-E(r 0)
Proton is at potential minimum
Laboratory frame
Jet axis
vz(r)
vz(r0)
E(r0)
E(r)
Bϕ
Flow frame at r=r 0
vz(r)-vz(r 0)
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Proton is at potential maximum