Physics of magnetically dominated plasma: dynamics, dissipation and particle acceleration

Maxim Lyutikov (UBC)

Cracow, June 2006

Dynamics and energy dissipation in electromagnetically-dominated plasmas

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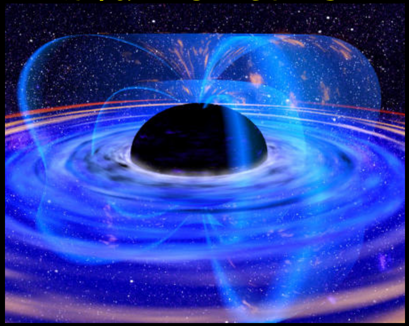
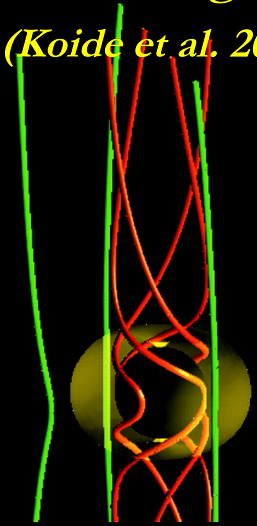
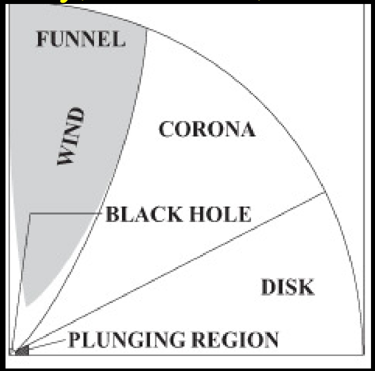
Relativistic outflows may be produced and collimated by large scale B-fields

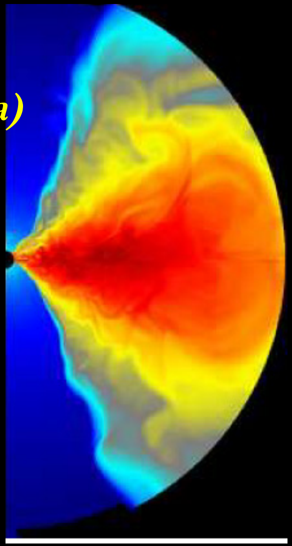
- ***AGN jets: ergosphere and Black hole itself can act as a Faradey disk (Blandford-Znajek, Lovelace), creating B-field dominated jets***
- ***Numerical simulations begin to show this dynamically***





(Koide et al. 2002), *(McKinney, Gammie, Krolik, Proga)*





Large scale, energetically dominant magnetic fields may be expected in the launching region of relativistic jets and may (should?) continue into emission regions

New plasma physics regime: magnetically dominated plasma

- *In plasma rest frame:*
  - *Magnetic energy $U'_B = B^2/8\pi$,*
  - *Plasma energy: rest-mass, ρc^2*
- *Magnetization parameter* $\sigma = \frac{U'_B}{U'_p} \Rightarrow \frac{B^2}{8\pi\rho c^2}$
  ($\sigma^{1/2} = \mu^{1/3}$)
- *Magnetically dominated: $\sigma > 1$*
- *Alfven 4-velocity* $\Gamma_{Alfven} = \sqrt{2\sigma}$, $\sigma_{crit} = \frac{\Gamma^2}{2}$

$\sigma > \Gamma^2/2$

(Subsonic relativistic flow)

$\sigma \sim 0$ — ***$\sigma \sim 1$*** — ***$\sigma = \infty$***

I. Hydrodynamics (all fluid) — ***II. MHD*** — ***III. Force-free (magnetodynamics)*** — ***Non-fluid***

Dissipation & acceleration

Fluid shocks (e.g. Fermi)

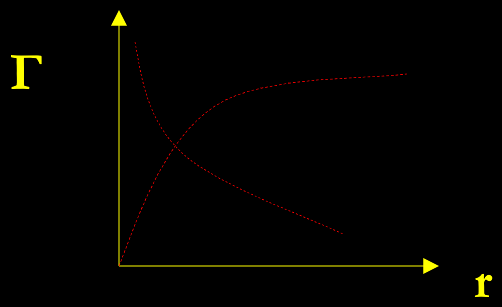
Magnetic dissipation

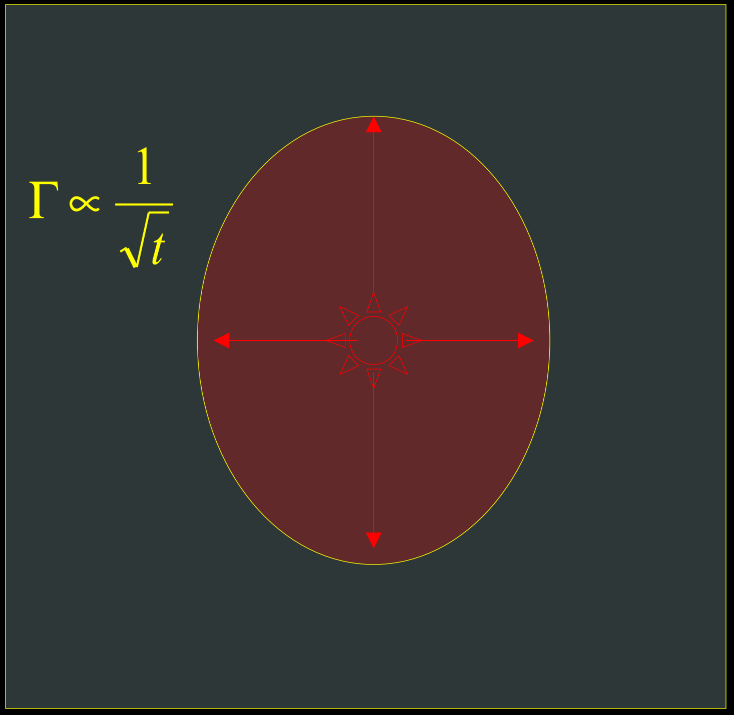
Dynamics

Expansion of σ >> 1 wind

- *supersonic (MHD), $\Gamma^2 > \sigma$, in vacuum: flow acceleration determined by internal flow dynamics: flow passes through fast sonic points (eg $\Gamma_F \sim \sqrt{\sigma}$), becomes causally disconnected (Michel)*
- *subsonic, $\Gamma^2 < \sigma$, : acceleration limited by external medium, causally connected flows*
  - *pressure balance at the contact*

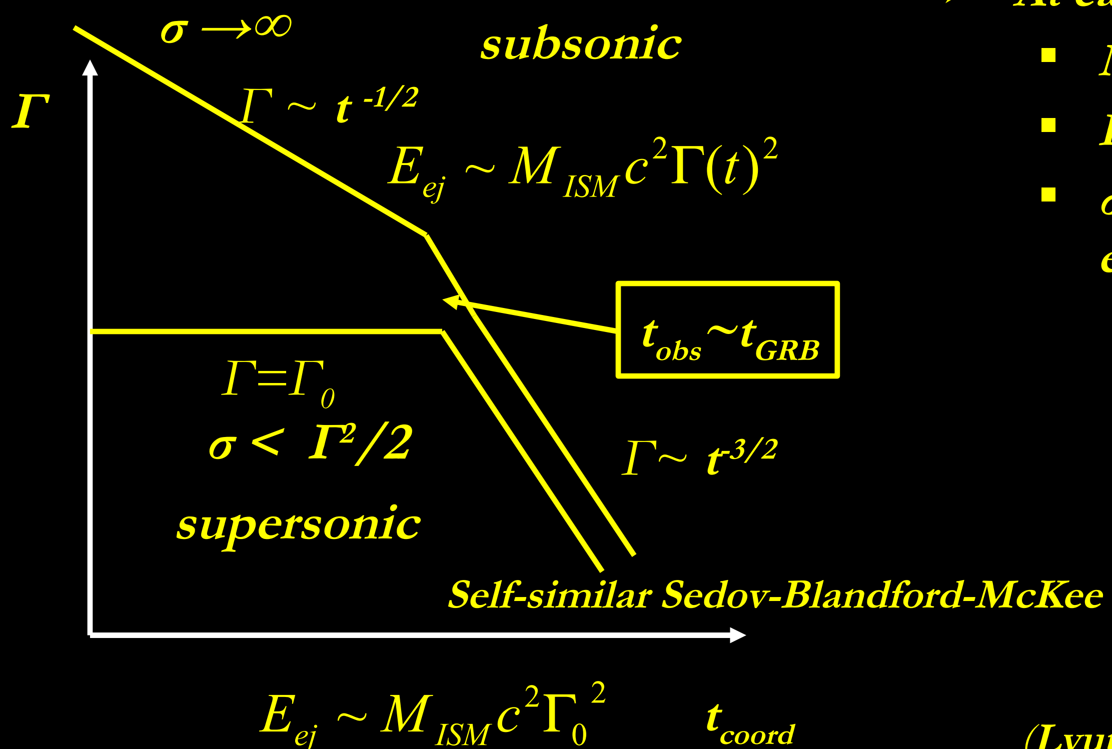
$$\frac{L}{4\pi R^2 \Gamma^2 c} \sim \frac{B^2}{8\pi \Gamma^2} \sim \Gamma^2 \rho_{ext} c^2$$





GRBs: σ < Γ²/2 and σ > Γ²/2 have different early dynamics

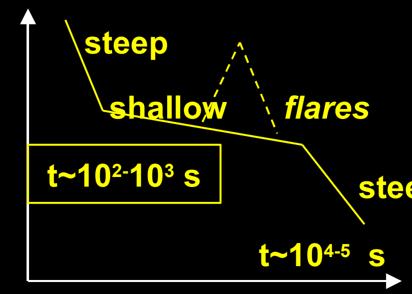
- *$\sigma > \Gamma^2/2$– subsonic flow*
- *$\sigma < \Gamma^2/2$– supersonic flow (reached terminal Γ_0)*



- *At late times, $t >> t_{GRB}$ (self-similar), composition of ejecta is not important*
- *At early times:*
  - *MHD, $\sigma < \Gamma^2/2$*
  - *Force-free $\sigma > \Gamma^2/2$*
  - *$\sigma > 1$: weak or no reverse shock emission*

(Lyutikov 2003,2006)

Observations?



- *Swift results are very puzzling:*

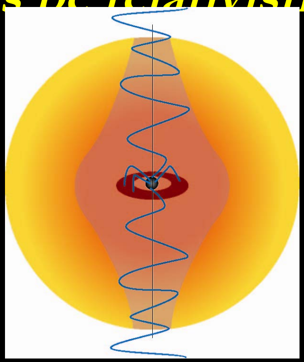
flares and lighcurve breaks at $t \sim 10$ -- 10^5 sec (Nousek; Zhang)

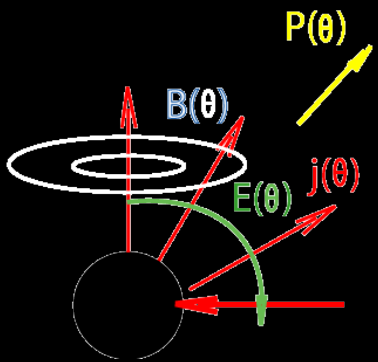
(two "breaks" were expected, t_{GRB}~100 sec and @ $\Gamma \sim 1/\theta$, 10^5 sec)

- *For $\sigma < 1$ strong reverse shock emission is expected*
    - *For $\sigma > 1$ no reverse shock is weak or non-existent*
- *Reverse shock in fireball: same type as internal shocks: microphysics is fixed by prompt emission*
    - *Expected optical flash m ~ 12-18.*
    - *Cooling: Flux ~ t^{-2} ; later: cooling to radio emission.*
- *In the Swift era absolute majority of GRBs do not show predicted RS behavior (despite UVOT and numerous robotic telescopes).*
- *This may indicate highly magnetized ejecta, $\sigma > 1$*
    - *Other possibilities to produce some optical emission (e.g. e± by γ)*

Long GRBs: expansion inside a star of a $\sigma > 1$ wind. As long as expansion is non-relativistic there must be dissipation

- *Energy and B_φ-flux is injected linearly with $v \sim c$*
- *for non-relativistic expansion volume is near constant , $B_\varphi \sim t$*
- *Energy $\sim B_\varphi^2 \sim t^2$??? (c.f. Gunn & Rees PWNs)*
- *Need to destroy B_φ – flux: inductance break down $\rightarrow$ dissipation*
- *Energy goes into $e^{\pm}$-γ (~ first 3 sec): lost after photosphere*
- *This is different from AGNs (c.f magnetic tower of Lynden-Bell), where expansion can always be relativistic, but not for GRBs*



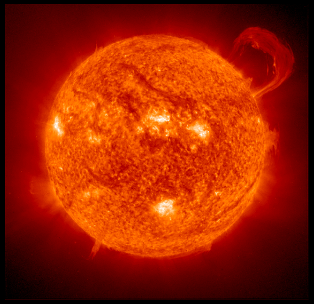


(Lyutikov & Blandford, 03)

Dissipation in magnetically-dominated plasma

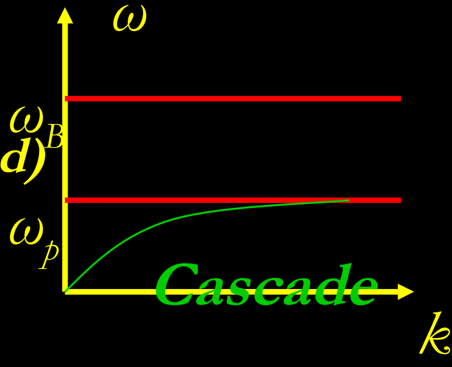
Dissipation: σ > 1 – energy in B-field

- *$\sigma > 1$: shock are weak; do not exist for $\sigma > \sigma_{crit}$*
- *B-field dissipation due to current instabilities ("reconnection")*
  - *B-fields are strongly non-linear systems: dissipation property of the emission region, NOT of the source activity (e.g. Solar B-field generated on ~22yr time scales, flares can rise in minutes)*



- *$\sigma > 1$ – new plasma regime*
  - *Adopt non-relativistic schemes:*
    - *Magnetodynamical tearing mode*
    - *Relativistic reconnection*
  - *new acceleration schemes (no hydro or non-relativistic analogues)*
    - *Charge-starved plasma, turbulent EM cascade*

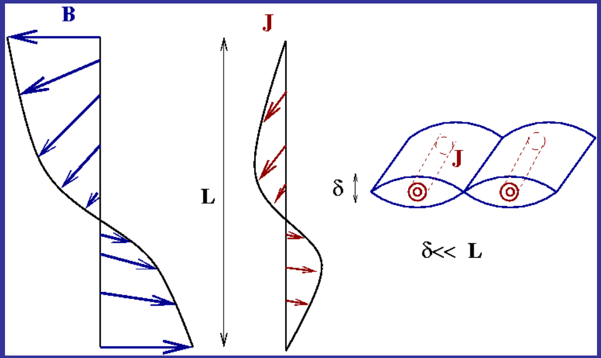
    3-wave processes are allowed: FFA, AAF! (in non-relativistic MHD 3-wave with $\omega \neq 0$ are prohibited)



Resistive instability of relativistic force-free current layer (unsteady reconnection)

- *Resistivity is usually very small ($\tau_R \sim L^2/\eta >> \tau$)*
- *Current sheets are unstable – formation of small scale sub-sheets*
- *Tearing mode $\tau \sim (\tau_A \tau_R)^{1/2}$*

$\tau_A \sim L/v_A \sim L/c, \quad \tau_R \sim L^2/\eta$



- *Similar to hydro (waves forms shocks) resistive RFF forms dissipative current layers*
- *Essential for RFF simulations, EM turbulent cascade*

(ML,03)

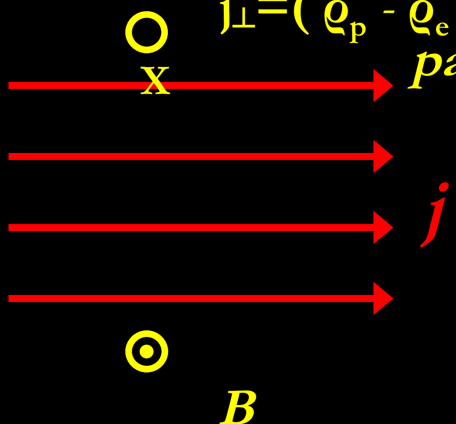
Tearing mode in σ=∞ plasma

- ***$\sigma = \infty$: matter inertia is not important, force-free currents ensure $J \times B + \varrho_e E = 0$ and decay resistively***

$$j = (\nabla E)\frac{(E \times B)}{B^2} + \frac{B \bullet (\nabla \times B) - E \bullet (\nabla \times E)}{B^2} B$$

$j_\perp = (\varrho_p - \varrho_e) v_\perp$ $\qquad$ $j_\parallel = \varrho_p v_{\parallel,p} - \varrho_e v_{\parallel,e} \sim E_{||} / \eta$

parallel currents attract



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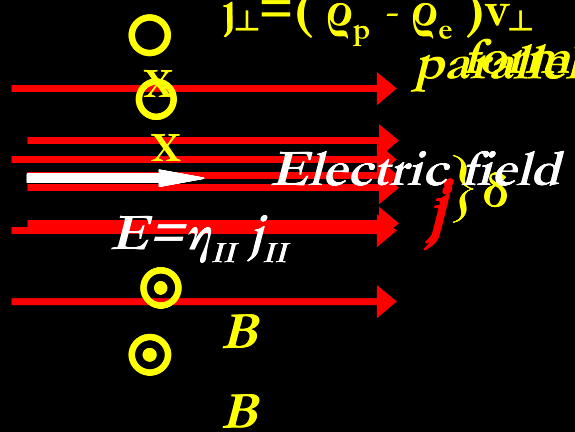
parallel currents attract

formation of current sheet



Dissipation rate ~ $\eta \Delta B \sim \eta B / \delta^2$

(Lyutikov 03)

- very fast

Resistive (tearing) EM instability

New plasma physics regime, same expression for growth rate?

(come from very different dynamical equations: Maxwell and MHD)

(Komissarov et al, 2006)

Tearing mode in σ=∞ plasma

- *slow motion in σ = ∞ plasma*

$$\nabla \mathrm{B} = 0$$

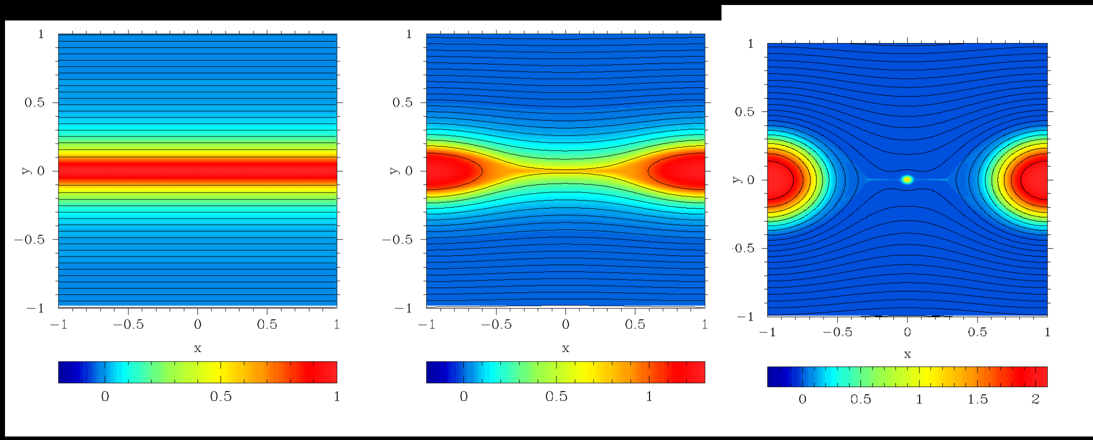
$$\partial_t \mathrm{B} - \nabla \times (\mathrm{V} \times \mathrm{B}) - \eta \Delta \mathrm{B} = 0$$

$$\partial_t \rho + \nabla (2\rho \mathrm{V}) = 0$$

$$\partial_t (\rho V) + \nabla \left(g \frac{\mathrm{B}^2}{4\pi} - \frac{\mathrm{B} \otimes \mathrm{B}}{8\pi} \right) = 0$$

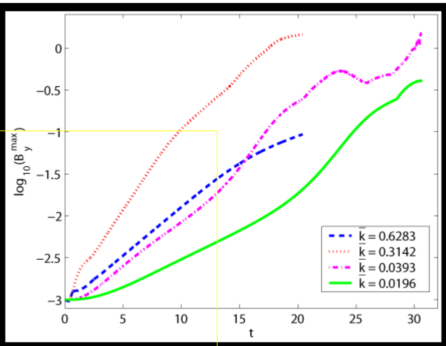
$$\rho = \frac{\mathrm{B}^2}{8\pi c^2}, \qquad \mathrm{V} = \frac{\mathrm{E} \times \mathrm{B}}{\mathrm{B}^2} c$$

- *Non-linear stage:* formation of magnetic islands



very similar to incompressible MHD!

This may be a step towards formation of reconnection layers.
Applications: magnetars (growth rate ~ msec, similar to flare rize time), AGN, GRB jets

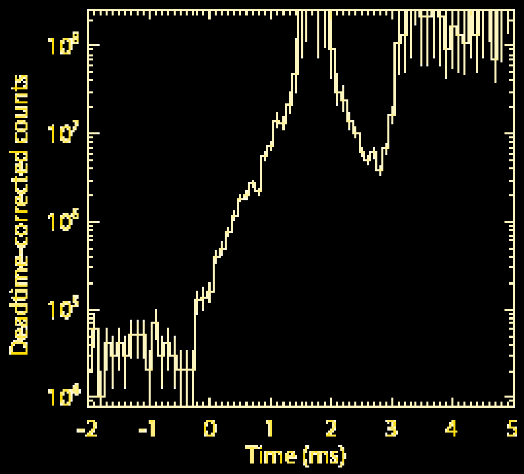


Growth rates in excellent agreement with analytics

Applications: magnetars, AGN, GRB jets.

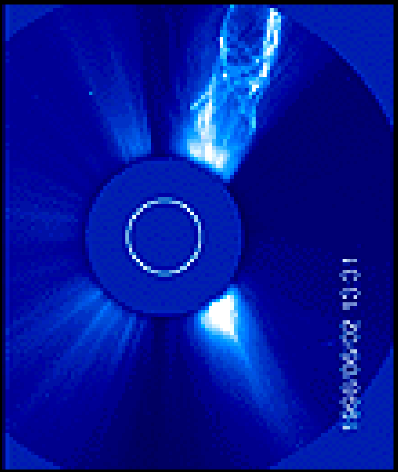
(Lyutikov 2006)

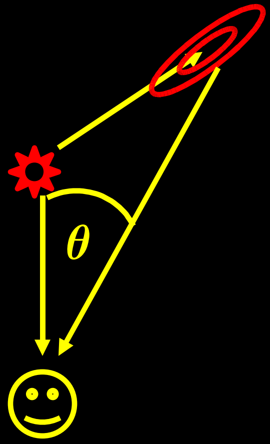
- ***Giant flare SGR 1806:***
- ***Time scales: observed rize time, < 250 μsec, implies reconnection in the magnetosphere (Alfven time , $t \sim R_{NS}/c \sim 30$ μsec)***



(Palmer et al. 2005)

- ***Similar to Solar Coronal Mass Ejection (CME). Magnetar jets (plumes)?***
- ***Late constant velocity, sub-relativistic outflow may be just a projection effect***





$\beta_{app} = \beta \, ctg \, \theta/2$

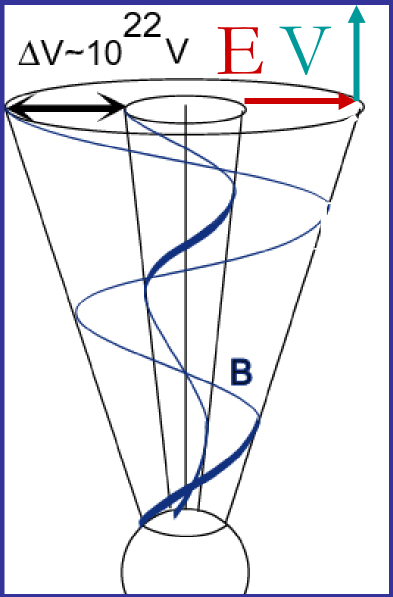
Acceleration of UHECRs

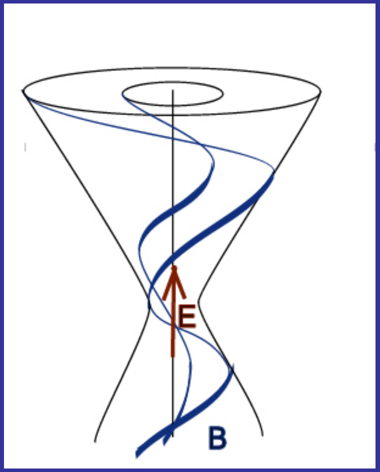
UHECRs:

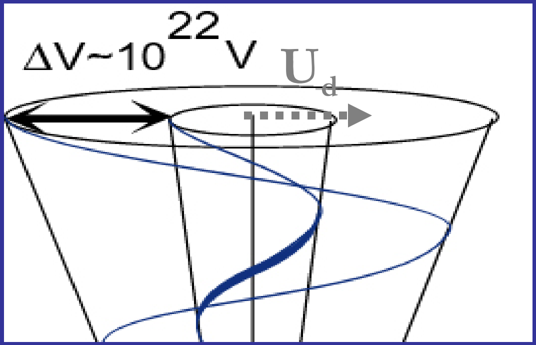
- *E_{max} ~ 3 10^{20} eV*
- *Isotropic, perhaps small scale clustering*
- *UHECRs must be produced locally , < 100 Mpc*
- *Perhaps dominated by protons above ~ 10^{18} eV*
- *Hard(ish) aceleration spectrum, p ~ 2-2.3*

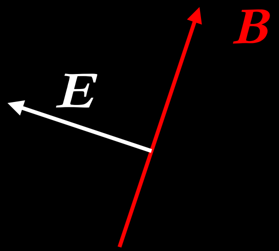
Acceleration by large scale inductive E-fields: $\mathcal{E} \sim \int v \cdot E \, ds$

- ***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***
- ***Bring flux surfaces together –Z-pinch collapse (Trubnikov etal95)***
- ***Kinetic motion across B-fields- particle drift - (Bell, Blasi, Arons)***







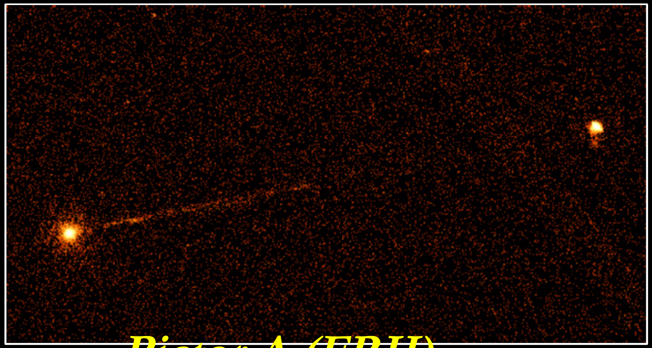


E ⊥ B : Inductive potential

Lovelace 76
Blandford 99

$$\Phi \leq \sqrt{\frac{4\pi L_{EM}}{c}}, \quad I \sim \sqrt{\frac{Lc}{4\pi}},$$

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



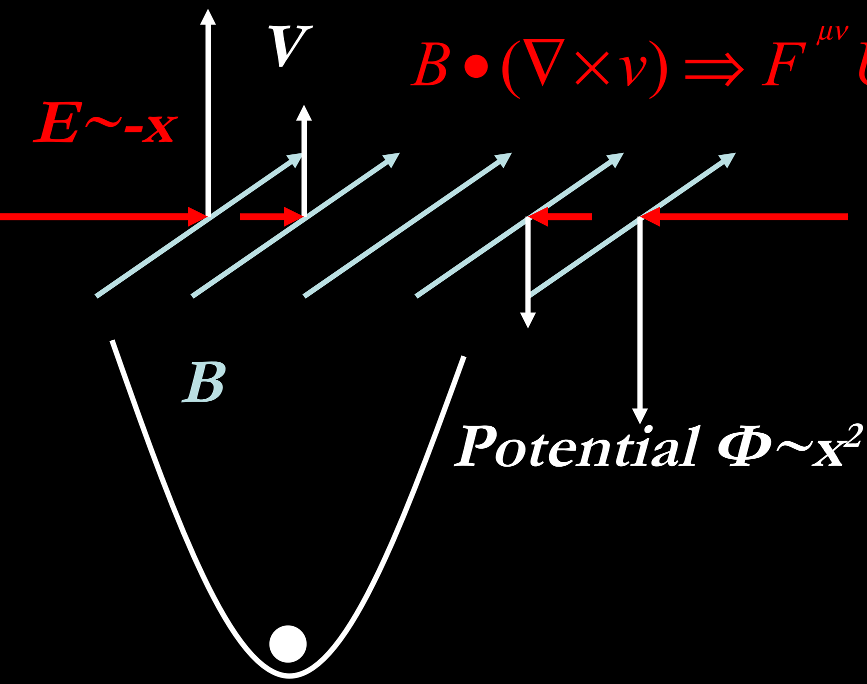
Pictor A (FRII)

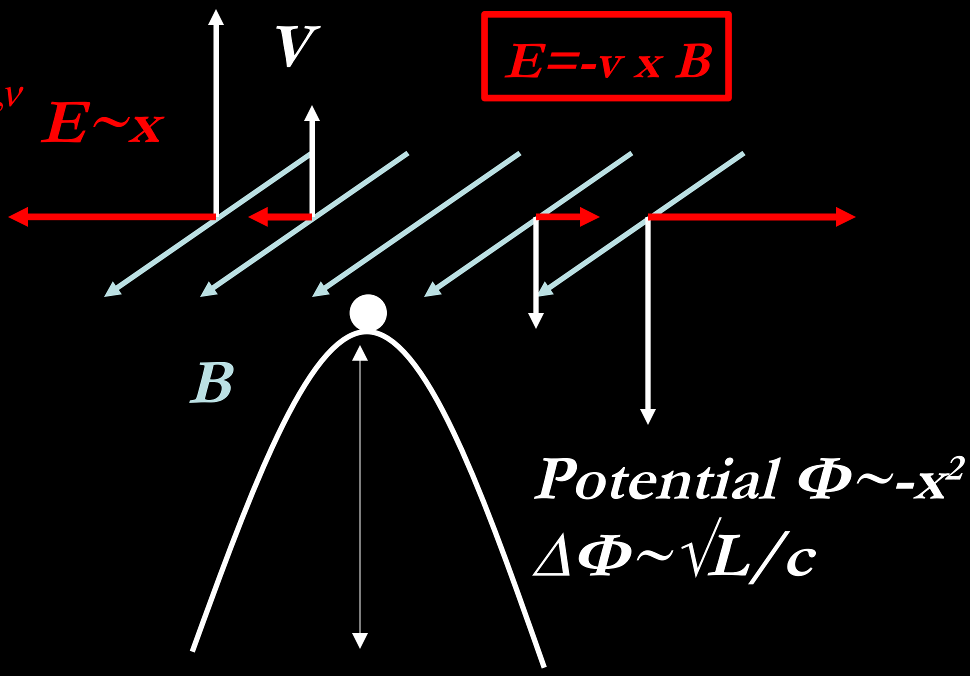
- ➢ *To reach $\Phi=3\ 10^{20}$ eV, $L_{EM} > 10^{46}$ erg/s (for protons)*
- ➢ *This limits acceleration cites to high power AGNs (FRII, FSRQ, high power BL Lac, and GRBs)*
- ➢ *There may be few systems with enough potential within GZK sphere (internal jet power higher than emitted), the problem is acceleration scheme*

Potential energy of a charge in a sheared flow

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

$$B \bullet (\nabla \times v) \Rightarrow F^{\mu\nu} U_{\mu,\nu}$$





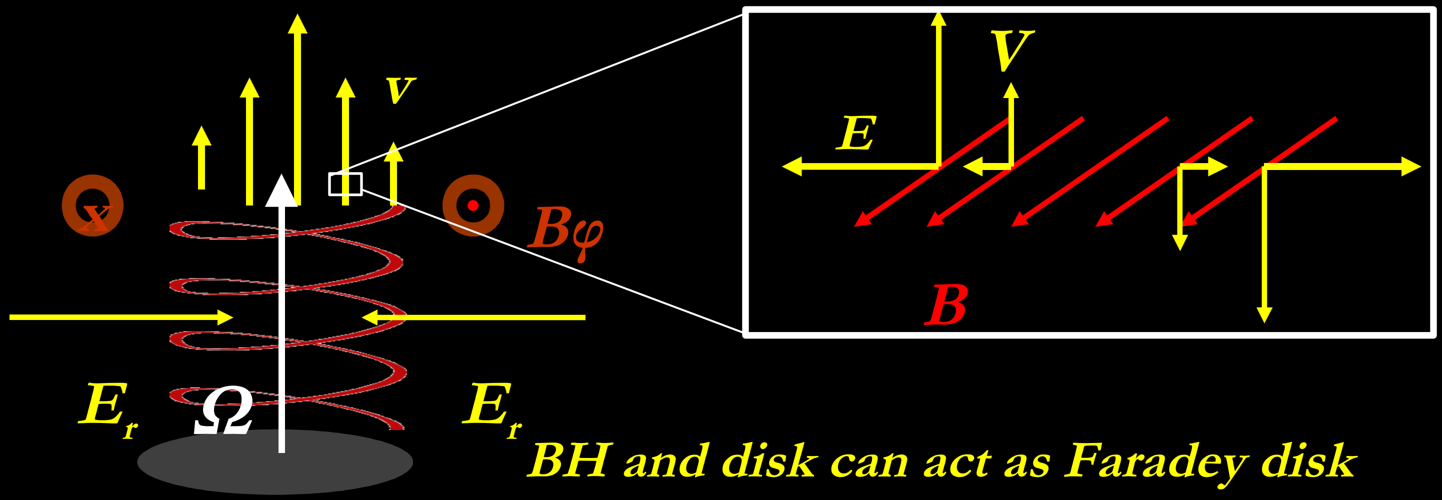
Depending on sign of (scalar) quantity (B *curl v) one sign of charge is at potential maximum

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

Astrophysical location: AGN jets

- *There are large scale B-fields in AGN jets*
- *Jet launching and collimation (Blandford-Znajek, Lovelace)*
- *Observational evidence of helical fields*
- *Jets may collimate to cylindrical surfaces (Heyvaerts & Norman)*
- *Jets are sheared (fast spine, slow edge)*

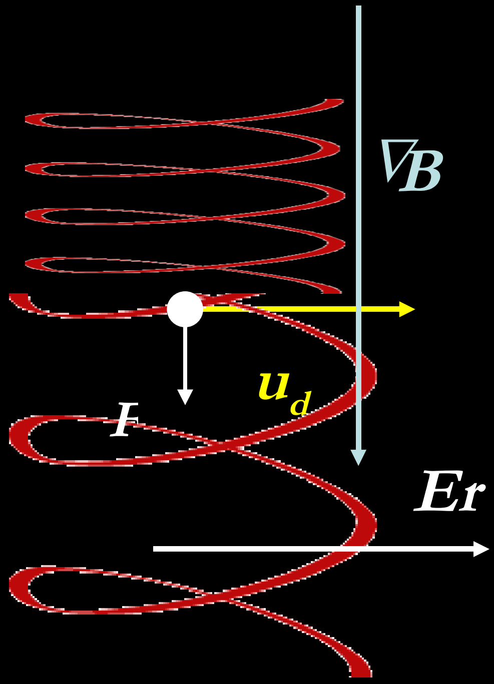
*Protons are at maximum for negative shear (B *curl v) < 0.*
*Related to (Ω*B) on black hole*

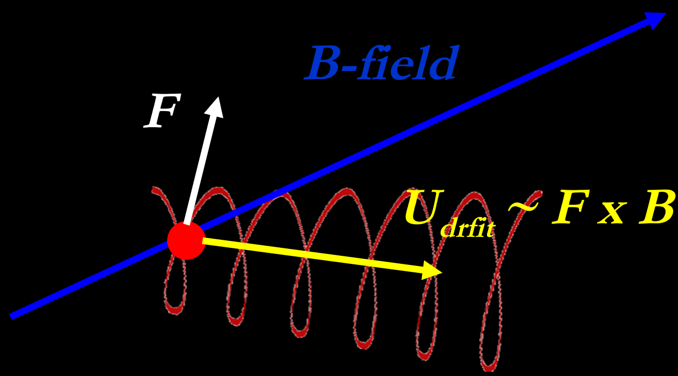


BH and disk can act as Faradey disk

Drift due to sheared Alfven wave

- *Electric field $E_r \sim - v_z \times B_\varphi$: particle need to move radially, but cannot do it freely ($B\varphi$).*
- *Kinetic drift due to waves propagating along jet axis $\omega = V_A k_z$*
- *$B\varphi(z) \rightarrow U_d \sim \nabla B\varphi x B\varphi \sim e_r$*





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

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

- *highest energy particles are accelerated most efficiently!!!*
- *low Z particles are accelerated most efficiently!!! (highest rigidity are accelerated most efficiently)*
- *Acceleration efficiency does reach absolute theoretical maximum $1/\omega_B$*
- *Jet needs to be ~ cylindrically collimated; for spherical expansion adiabatic losses dominate*

Acceleration rate DOES reach absolute theoretical maximum ~ γ/ω_B

- *Final orbits (strong shear), $r_L \sim R_j$, drift approximation is no longer valid*
- *New acceleration mechanism*
- *For $\eta < \eta_{crit} < 0$, $\eta_{crit} = -\frac{1}{2}\,\omega_B/\gamma$, particle motion is unstable*

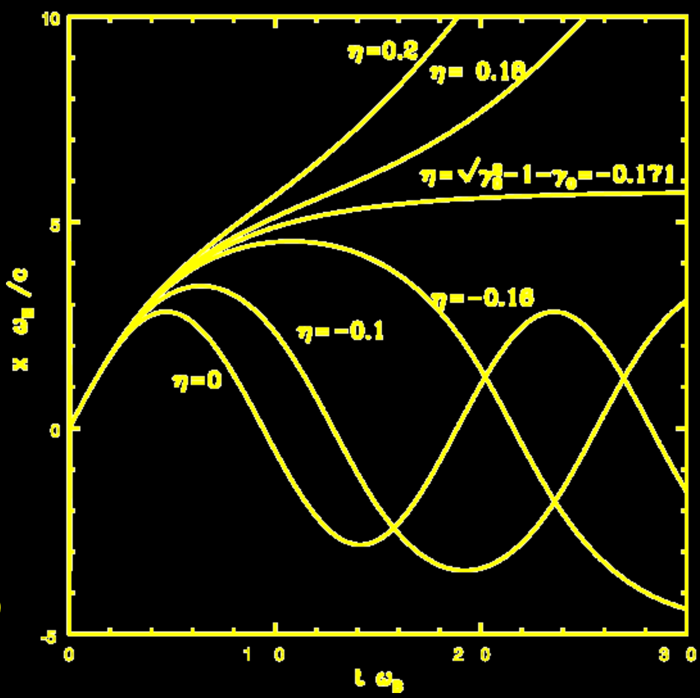
$$\frac{\eta_{crit}}{\omega_B/\gamma_0} = \gamma_0\left(-\gamma_0 + \sqrt{\gamma_0^{\;2}-1}\right) \approx -\frac{1}{2}$$

$\eta = V'$

- *non-relativistic:* $x = r_L \cos\left(\omega_B\sqrt{1+\frac{\eta}{\omega_B}}\,t\right),$

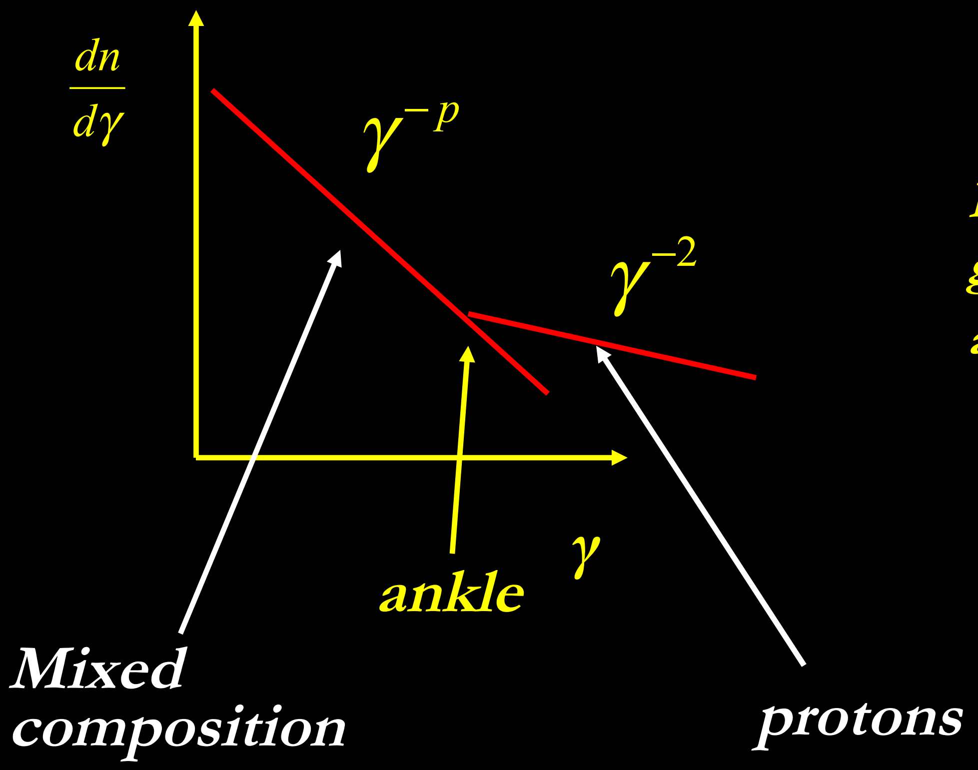
$$y = \frac{r_L}{\sqrt{1+\eta/\omega_B}}\sin\left(\omega_B\sqrt{1+\frac{\eta}{\omega_B}}\,t\right)$$

- *Acceleration DOES reach theoretical maximum ~ γ/ω_B*
- *Note: becoming unconfined is GOOD for acceleration (contrary to shock 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 $r_L \sim R_j$ and do not leave the jet

UHECRs are dominated by protons, below the ankle: Fe

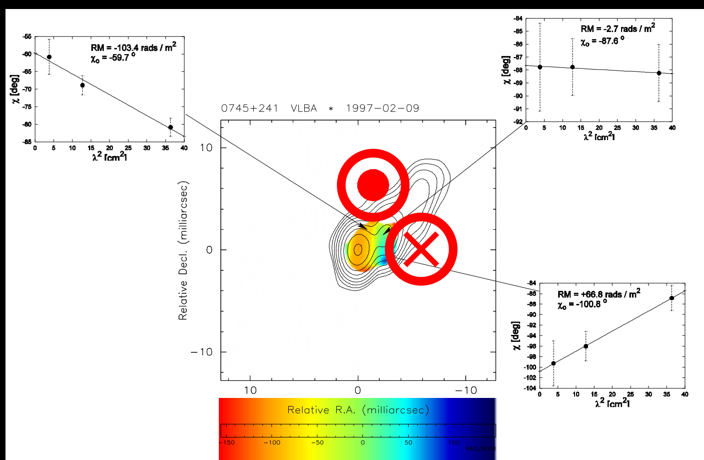
Astrophysical viability

- ***Need powerful AGN FR I/II (weak FR I , starbursts are excluded)***
  - ***UHECRs (if protons) are not accelerated by our Galaxy, Cen A or M87***
- ***Several powerful AGN within 100 Mpc, far way → clear GZK cut-off should be observed: Pierre Auger: powerful AGNs?***
  - ***GZK cut-off***
  - ***few sources***
  - ***IGM B-field is not well known***
- ***Fluxes: $L_{UHECR} \sim 10^{43}$ erg/sec/(100 Mpc)^3 –***

  1 AGN is enough

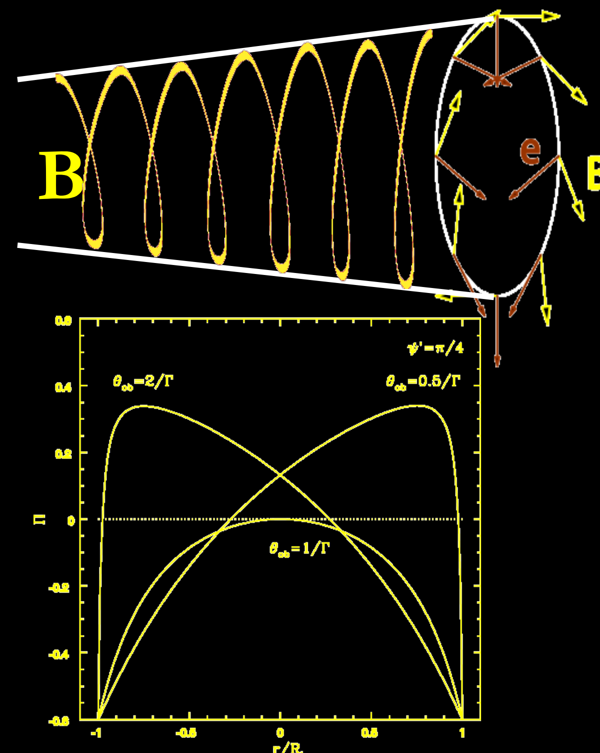
Faradey Rotation and gradient of linear polarization across the jet in 3C 273

- *Gradient of Rotation Measure across the jet*



(Gabuzda 03, confirmed by Taylor etal)

- *Gradient of liner polarization*



- *Possible interpretation: helical field*
- *Need lots of poloidal flux → may come from a disk, not BH*

Conclusion

- ***EM-dominated plasma: may be a viable model for a variety of astrophysical phenomena. Very little is done.***
- ***Macrophysical models (ideal dynamics)***
- ***Microphysics (resistivity is anomalous, $\eta \sim c^2/\omega_p$, $\eta \sim c^2/\omega_B$; particle acceleration)***
- ***Need for simulations (both dynamics and acceleration)***
  - ***EM codes with currents***
  - ***PIC codes (Nordlund)***
- ***Observations seem to be coming along***

- ***"Where have you seen plasma, especially in magnetic field?" Landau***
- ***"The magnetic field invoked is proportional to someone's ignorance" Woltijer***

Radiative losses

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

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

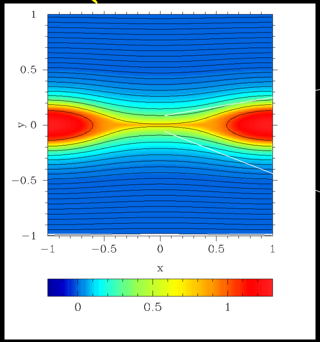
$$B < \frac{m^2 c^4}{Z^3 e^3}\left(\frac{E}{mc^2}\right)^{-2} \Gamma^3 \sim 6\,10^4\ \Gamma_{10}^{3}\left(\frac{E}{100\ \text{EeV}}\right)^{-2} \text{G}$$

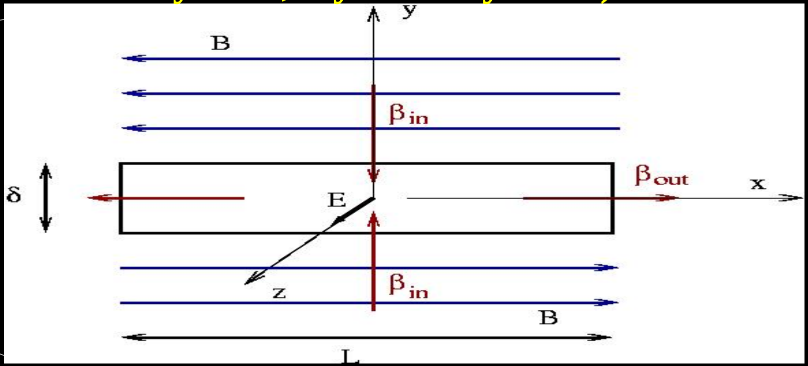
$$\Phi \leq \sqrt{\frac{4\pi\,\beta_0\,L}{c}},$$

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

Relativistic reconnection, $\sigma >> 1$ (Sweet-Parker)

(Blackman & Field 1994; Lyutikov&Uzdensky2003; Lyubarsky 2004)





- ***Two parameters: Lundquist $S=V_A L/\eta \gg 1$, $\sigma \gg 1$***
- $\gamma_{out} \approx (1+\sigma)\gamma_{in} >> 1$ ***outflow is always relativistic***
- ***Inflow:***
  - ***$\sigma \ll S$ – non-relativistic inflow*** $\beta_{in} \approx \sqrt{\frac{\sigma}{S}} = \sqrt{\frac{2}{S}}\gamma_A, \frac{\delta}{L} \approx \sqrt{\frac{S}{\sigma}} << 1$
  - ***$S \ll \sigma \ll S^2$ – relativistic inflow*** $\gamma_{in} \approx \frac{\sigma}{S}, \quad \gamma_{out} \approx \frac{\sigma^2}{S} >> 1, \quad \frac{\delta}{L} \approx \frac{1}{\sigma} << 1$
- ***Relativistic reconnection can be fast, ~ light crossing time***

Particle acceleration in relativistic reconnection

Leptons

- ***Numerical experiments are only starting (Hoshino02, Larrabee etal 02).***
- ***Spectra depend on kinetic properties and geometry***

∫(v•E)dl (McClements)

- ***If escape ~ r_L, then***

$$\frac{dn}{d\gamma} \propto \gamma^{-\beta_{in}}$$

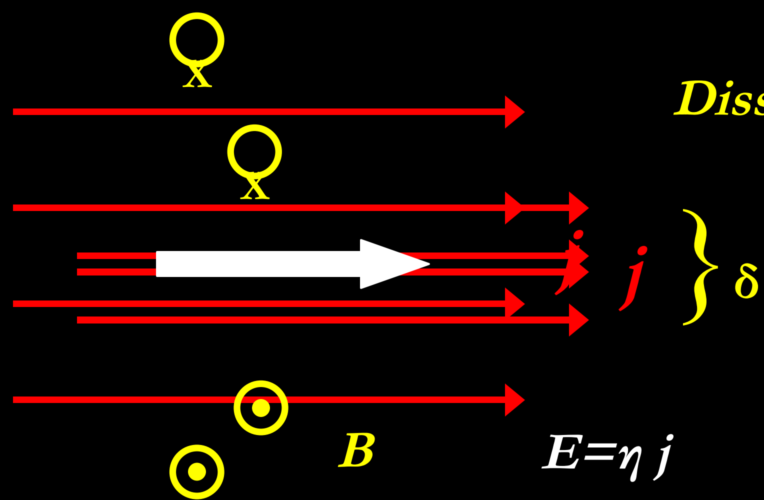
- ***For GRB we need γ^{-1} (Lazatti), also TeV AGNs (Aharonian)***
- ***No calculations of acceleration at relativistic tearing mode (should accelerate as well)***

Why magnetic energy wants to dissipate

What is needed for magnetic dissipation is presence of electrical current

formation of current sheet

parallel currents attract

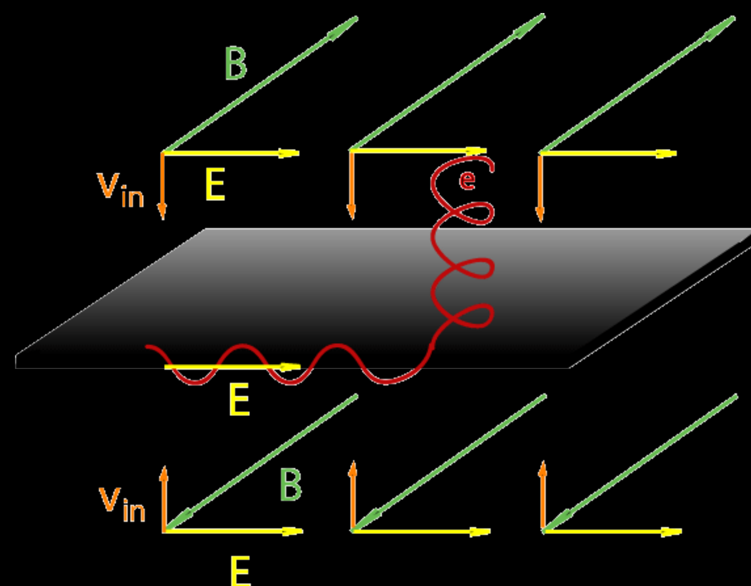


Dissipation rate ~ $\eta\Delta B \sim \eta B/\delta^2$

Anomalous resistivity $\eta(j)$

$E=\eta\, j$

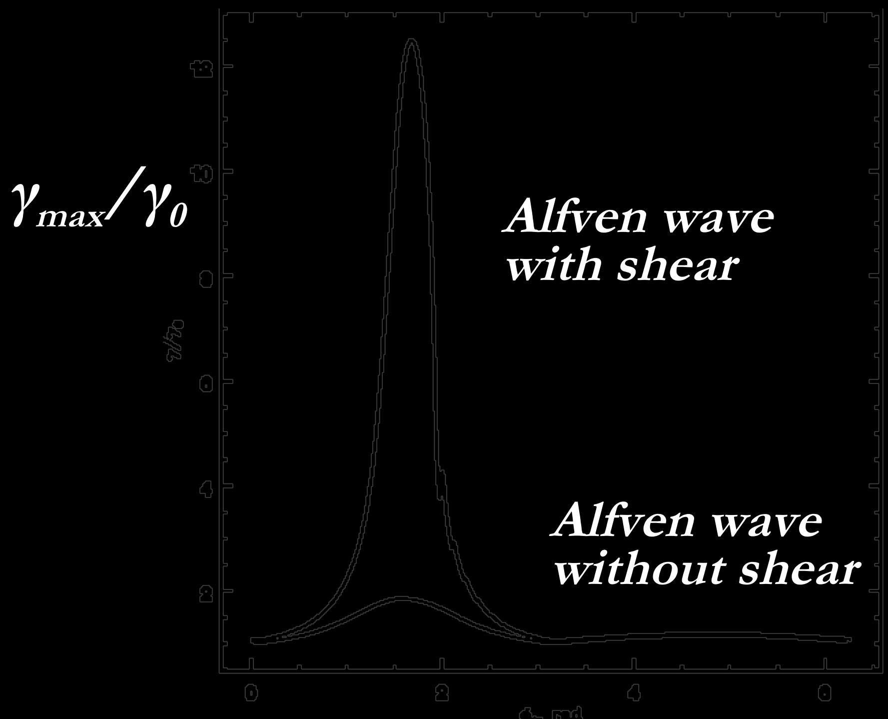
Electric field

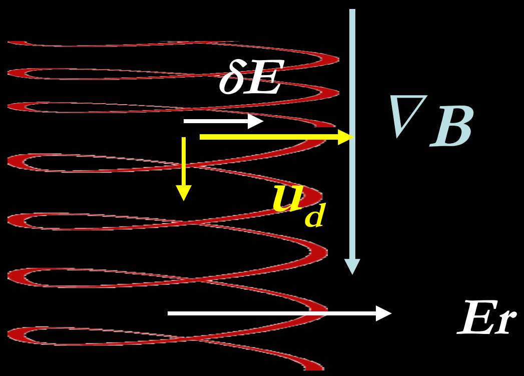


Next: generalize non-relativistic fluid models to new regime

Wave surfing can help

- ***Shear Alfven waves have $\delta E \sim (V_A/c)\ \delta B$,***
- ***Axial drift in δExB helps to keep particle in phase***
- ***Particle also gains energy in δE***





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

AGN jet

- ***In situ acceleration is required (t_{synch} < R/c, short time scale variability: 20 min at TeV!)***
- ***$e^{\pm}$ winds - strong losses at the source***
- ***Ion-dominated - hard to get variability, low radiation efficiency (Celotti,Ghisellini)***

EM- dominated! **(Lesch&Birk;Lovelace;ML)**

- ***Currents needed for collimation; Currents are unstable***
- ***Resistive modes may not destroy the jet, but re-arrange it (eg, sawtooth in TOKAMAKs, Appl)***
- ***Relativistic FF jets stabilized by rotation***
- ***Hard power law may be needed for TeV emission(Aharonian)***
- ***Polarization from helical B-field (Gabuzda; ML, in prep)***

Jets start as B-field-dominated, can σ changes on the way?

(Weber & Davis, Goldreich & Julian Vlahakis &Konigl)

- ***Ideal conversion: acceleration***
  - ***Acceleration to fast point $\Gamma_{fast} \sim \sqrt{\sigma_{fast}}$***
  - ***At this point $\sigma \sim \Gamma^2 >> 1$: flow remains B-field dominated***
  - ***Collimation $\sigma \rightarrow 1$, but it is slow ~ ln z and unlikely $\sigma << 1$***
    - ***There are some indication (Homan et al , Jorgstad et al.) moving features, (Sudou et al.) increased jet-counter jet brightness, but not conclusive (jet bending & aberration can give visible acceleration).***
- ***Dissipative: on scale > $R_{BH} \Gamma^2 \sim 10^{17}$ cm (e.g relativistic reconnection $\beta_{in} \sim 1$, Lyutikov & Uzdensky)***
    - ***blazar γ-ray emission zone (Lyutikov 2003). Variation in Γ produced locally (no large UV variations of disk are seen): (Sikora et al. 2005)***
- ***Jet can remain B-field dominated to pc scales***

How can the two paradigms ($\sigma>>1$ and $<< 1$) be distinguished?

1. Acceleration scheme with predictive power (γ_{min}, p)

Shocks

- ***Spectra of Fermi-accelerated particles (kinetic property) can be derived from shock jump conditions***
- ***Electrons need to be pre-accelerated to***

  $\gamma \sim m_p/m_e \sim 2000$

  (or $\sqrt{m_p/m_e} \sim 43$)

B-field

- ***"Reconnection" spectra are not "universal", depend on details of geometry (universal in relativistic case, p=1 ?)***
- ***No need for pre-acceleration: all particles may be accelerated***

How can the two paradigms be distinguished?: very hard spectra, p< 2

- ***Shock typically produce p>2, relativistic shocks have p ~ 2.2 (Ostrowki; Kirk)***
  - ***non-linear shocks & drift acceleration may give p<2, e.g. p=1.5 (Jokipi, Bell & Lucek)***

- ***B-field dissipation can give p=1 (Hoshino; Larrabee et al.); such hard spectra may be needed for TeV emitting electrons (γ-γ pair production on extragalactic light Aharonyan; Schroedter).***

p< 2 spectra should not be discarded as unphysical

2. Radiation modeling: not conclusive

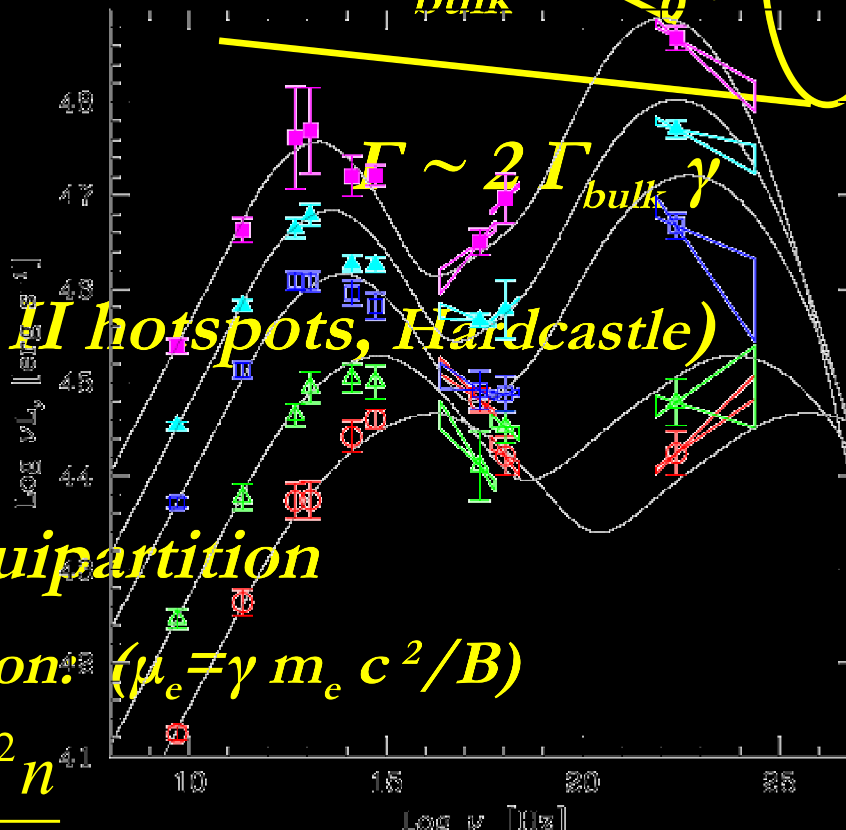
- ***Blazar dominance by IC: $U_{ph}'/U_B' \sim \Gamma^4$, $\Gamma > 10$;***

  TeV zoo, B-field strongly under equipartition @ 10^{17} cm → Γ~50-100 (Krawczynski 04). Outflows in bulk flow?

$U_{e\pm}' < U_B' < U_{ph}'$

$\Gamma_{bulk} < \gamma_0 \gamma$

$\Gamma \sim 2\,\Gamma_{bulk}\,\gamma$

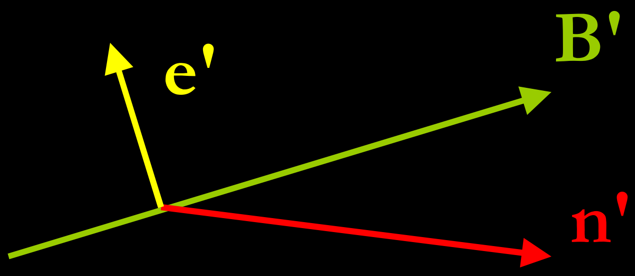


- ***Equipartition (e.g in FR II hotspots, Hardcastle)***
  - ***$U'_B \sim U'_{e\pm}$:***
  - ***Amplification: sub-equipartition***
  - ***Dissipation → equipartition: ($\mu_e = \gamma m_e c^2/B$)***

$$\frac{B_{ind}}{B} = \frac{\mu n}{B} = \frac{\gamma m_e c^2 n}{B^2}$$

Aberration of Π: B-field is NOT orthogonal to polarization

- *In plasma frame*



$$e' \perp B',\, n'$$

$$n \sim \gamma^{-p}, \Pi_{\max} = \frac{p+1}{p+7/3}$$

- *In laboratory frame*

$$\mathbf{e} = \frac{\mathbf{n}\times\mathbf{q}}{\sqrt{\mathbf{q}^2 - (\mathbf{n}\bullet\mathbf{q})^2}}$$

$$\mathbf{q} = \hat{\mathbf{B}} + \mathbf{n}\times(\mathbf{v}\times\hat{\mathbf{B}})$$

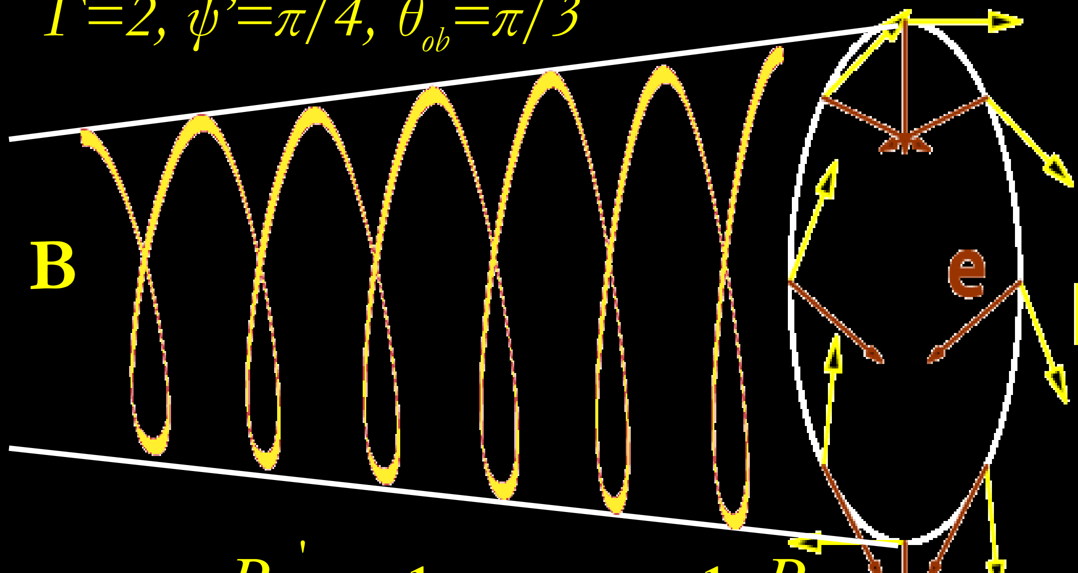
$$(\mathbf{e}\bullet\hat{\mathbf{B}}) = (\mathbf{e}\times\mathbf{n})(\hat{\mathbf{B}}\times\mathbf{v}) \neq 0$$

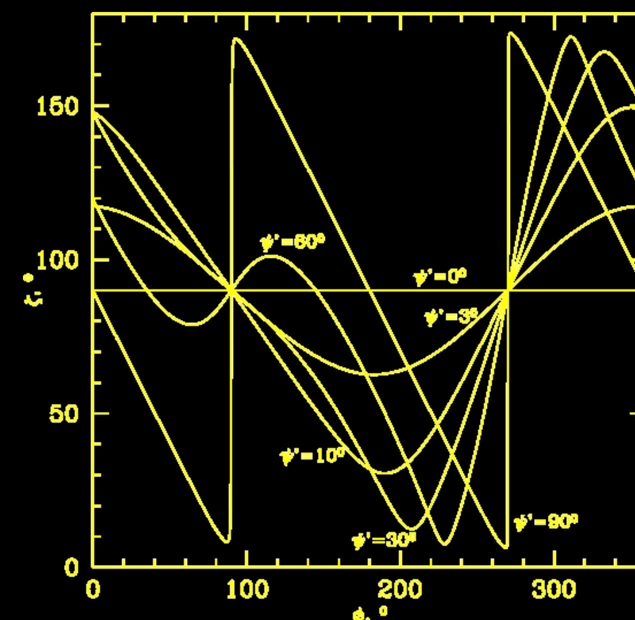
Both B-field and velocity field are important for Π

(Blandford & Konigl 79; Lyutikov,Pariev,Blandford 03)

Π from relativistically moving cylindrical shell with helical B-field

$\Gamma=2,\ \psi'=\pi/4,\ \theta_{ob}=\pi/3$

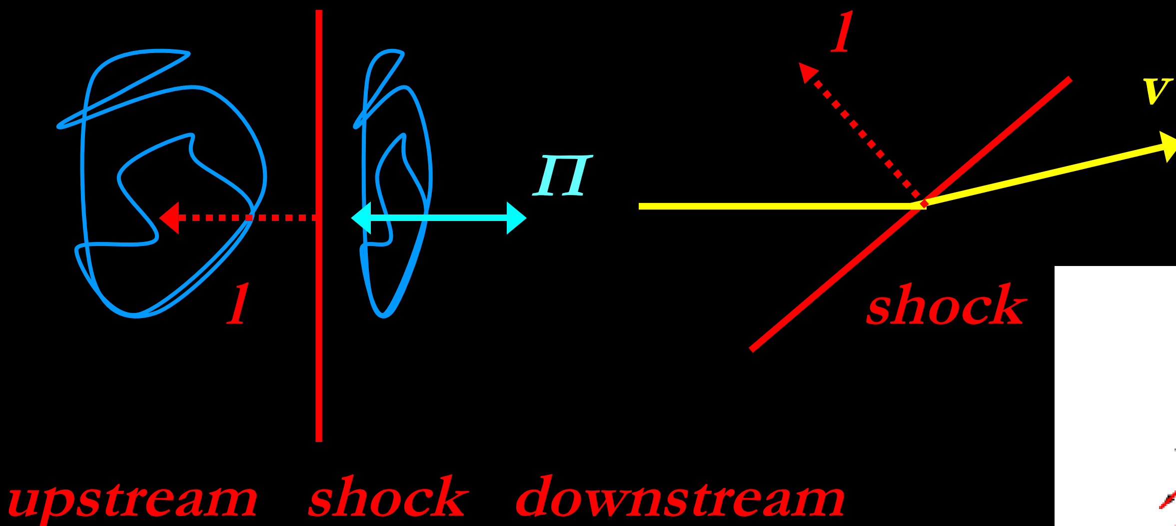


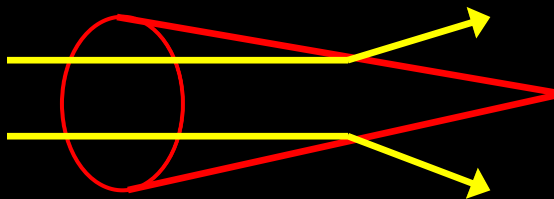


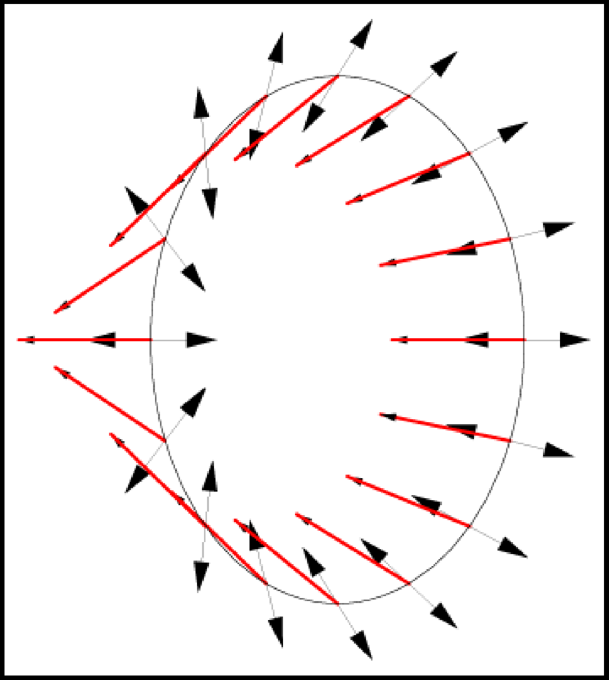
$$\tan\psi' = \frac{B_\varphi'}{B_z'} = \frac{1}{\Gamma}\tan\psi = \frac{1}{\Gamma}\frac{B_\varphi}{B_z}$$

- ***B <u>not</u> orthogonal to e***
- ***Jet can be B_φ dominated in observer frame and B_z-dominated in rest***

Π from random B-field compressed at an oblique shock







$$\mathbf{e} = \frac{\mathbf{n} \times \mathbf{q}}{\sqrt{\mathbf{q}^2 - (\mathbf{n} \bullet \mathbf{q})^2}}$$

$$\mathbf{q} = \mathbf{n} \times \left(\mathbf{l} - \mathbf{n} \times (\mathbf{l} \times \mathbf{v}) - \frac{\Gamma}{\Gamma + 1} (\mathbf{l} \bullet \mathbf{v}) \mathbf{v} \right)$$

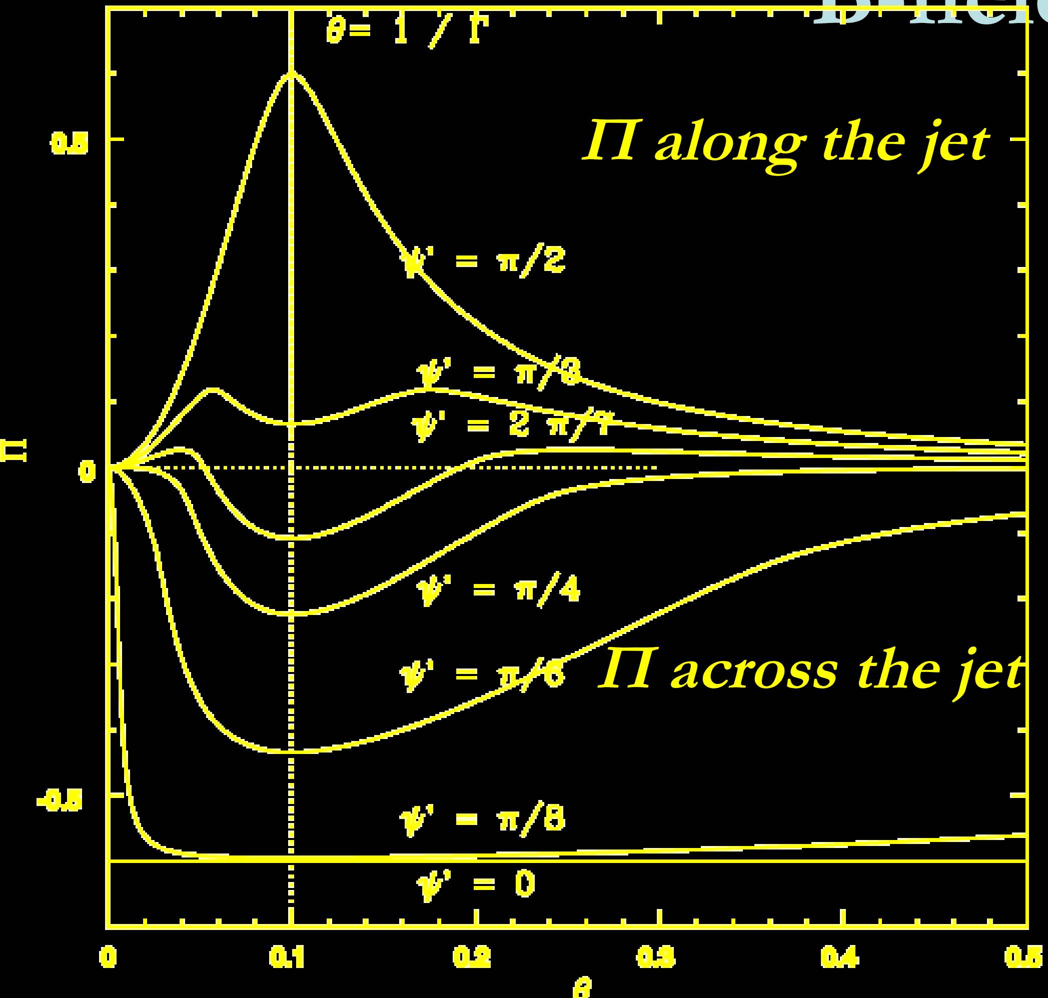
Lyutikov (in prep)

Π not aligned with projection of l,
also Cawthorn & Cobbs

Aberration of Π

- ***Direction of Π depends both on B-field and velocity field***
- ***Always plot "e", not "inferred" B-field***
- ***One needs to know velocity to infer internal B-field***
- ***Symmetries in the velocity field may help***
  - ***e.g. if shock is conical, on average polarization along or across jets (Cawthorn & Cobbs)***

Π from cylindrical shell with helical B-field



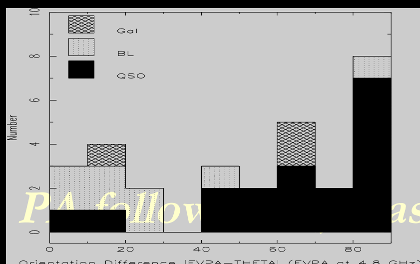
- ***Π depends on p***
- ***Even co-spatial populations with different p may give different Π (eg Radio & Optical)***

$$\tan\psi' = \frac{B_\varphi'}{B_z'}$$

Γ=10, p=1, different rest frame pitch angles

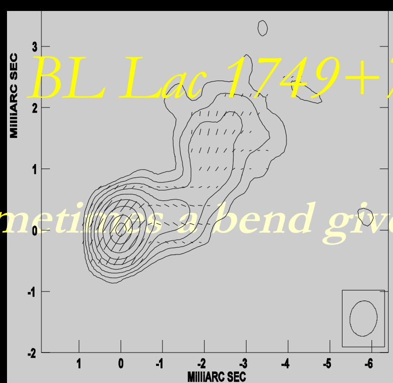
Large scale or small scale B-fields in pc-scale AGNs jets

- ***Bimodial distribution of PA***



(Aller et al)

- ***PA follow … as it bends***



BL Lac 1749+701

- ***Sometimes a bend gives 90 change of PA***

(Gabuzda 03)

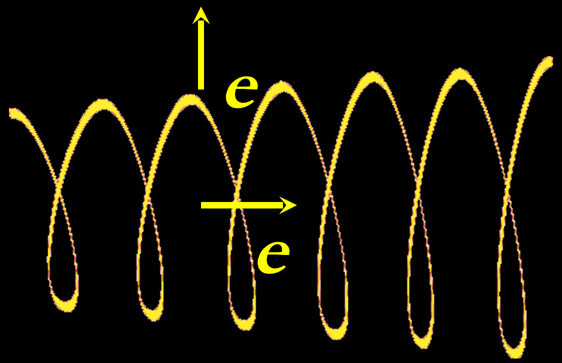
- ***For cylindrical jet U=0, average Π along or across the axis. Only conical shocks can give the same.***

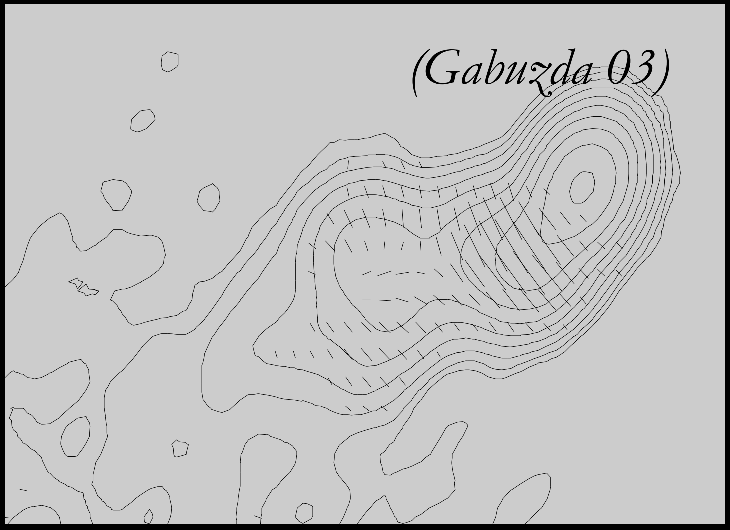
- ***For fixed ψ, Π mostly keeps its sign. Note: for plane shock there is no correlation between Π and bend direction.***

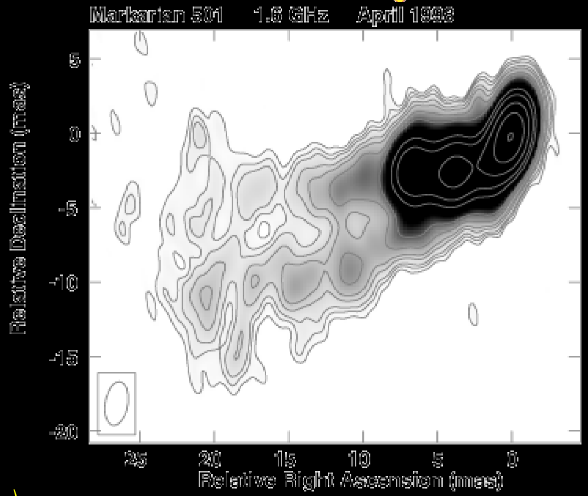
- ***Sometimes a change does occur***

Resolved jets

- *Resolved jets: center: PA ‖, edges: PA ⊥*
  - *Emission is generated in small range Δr < r (shear acceleration? Ostrowski)*
  - *Core is boosted away*

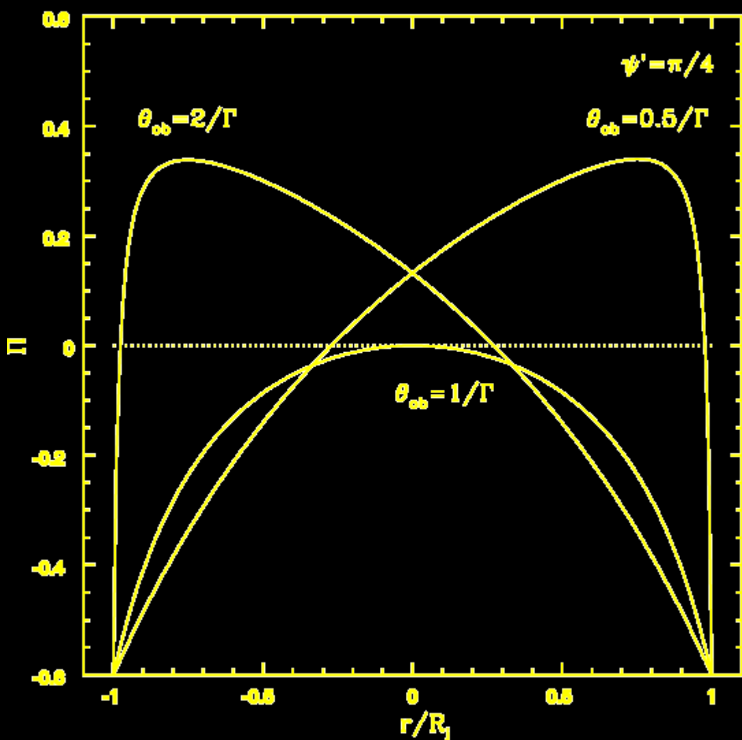


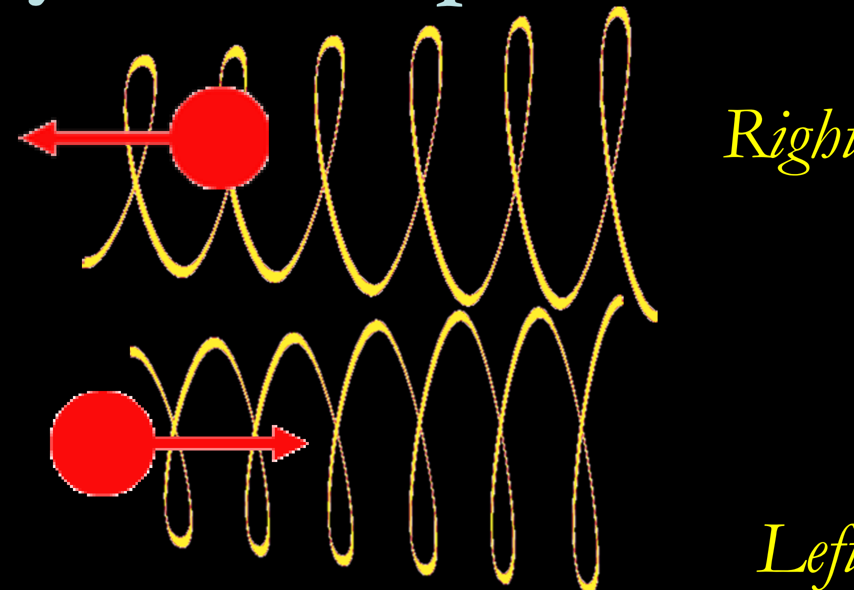


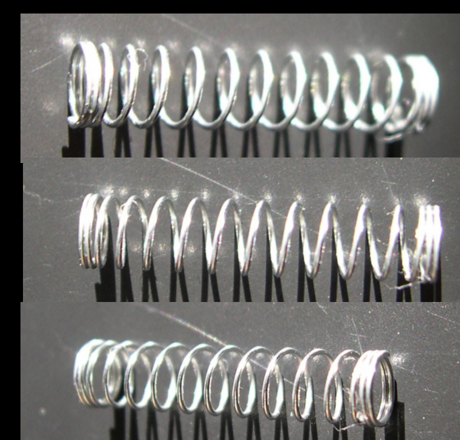


Limb-brightening Mkn 501, (Giroletti)

Jet polarization may tell the spin of BH







- ***Left & Right helixes look different***
- ***Different Π signature***
- ***Direction of BH or disk spin (if θΓ is known)***

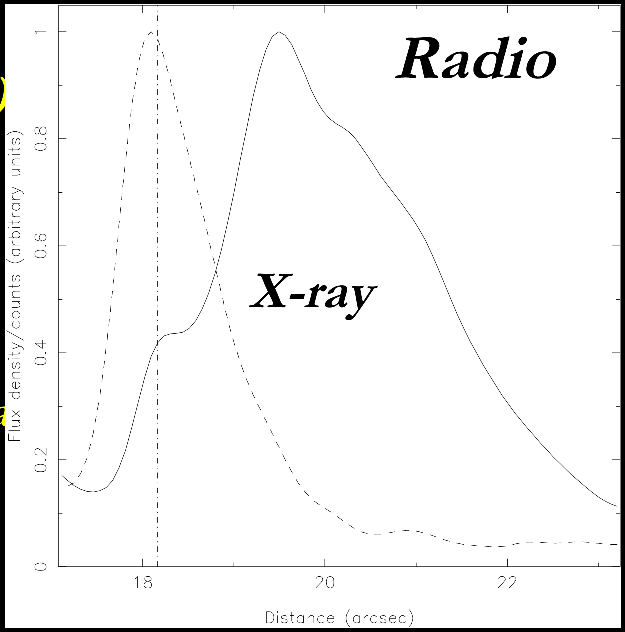
Tests/unresolved issues

- *Firmly established flow acceleration at (sub)-pc scales: evidence of B-field conversion*
- *More Π studies, especially CP (unidirectional B-field)*
  - *with MHD codes*
- *Spectra requiring p → 1*
- *Acceleration rates above*

$$\tau_{acc} \sim \frac{c^2}{v_s^2}\frac{\gamma}{\omega_B}$$

- *Very high Π > 50% in R*
  - *compressed B-fields isotropize on Aflven time sca dominated by small scale*
  - *turbulence will lead to isotropization*
- *Different e-acceleration mechanisms?*
  - *X-rays are displaces from O-R (e.g. Cen A)*
  - *Magnetic & shock accleration? (Kirk)*
  - *NB: similar in Crab pulsar*

Cen A (Hardcastle et al 20



Are all ultra-relativistic jet the same?

- ***E_{peak} – L correlations***
  - ***GRBs - positive, BL Lac – negative***
- ***Internal shocks in GRBs must be highly (unreasonably?) efficient, in BL Lac – inefficient***
- ***GRS 1915: jets appear after drop of the x-ray flux,***

blazars: no correlation between UV flux and flares

- ***jets without BH (Cirnicus X-1)***

Prospects

- ***Sept. 2002, Bolognia Conference: "Can one " prove" reconnection? – Not from first principles"***
  - ***By analogy to some Solar phenomena***
  - ***Nothing else can do***
- ***May be we can…***