Title: Acceleration of highest energy cosmic rays

Date: Nov 01, 2005 10:00 AM

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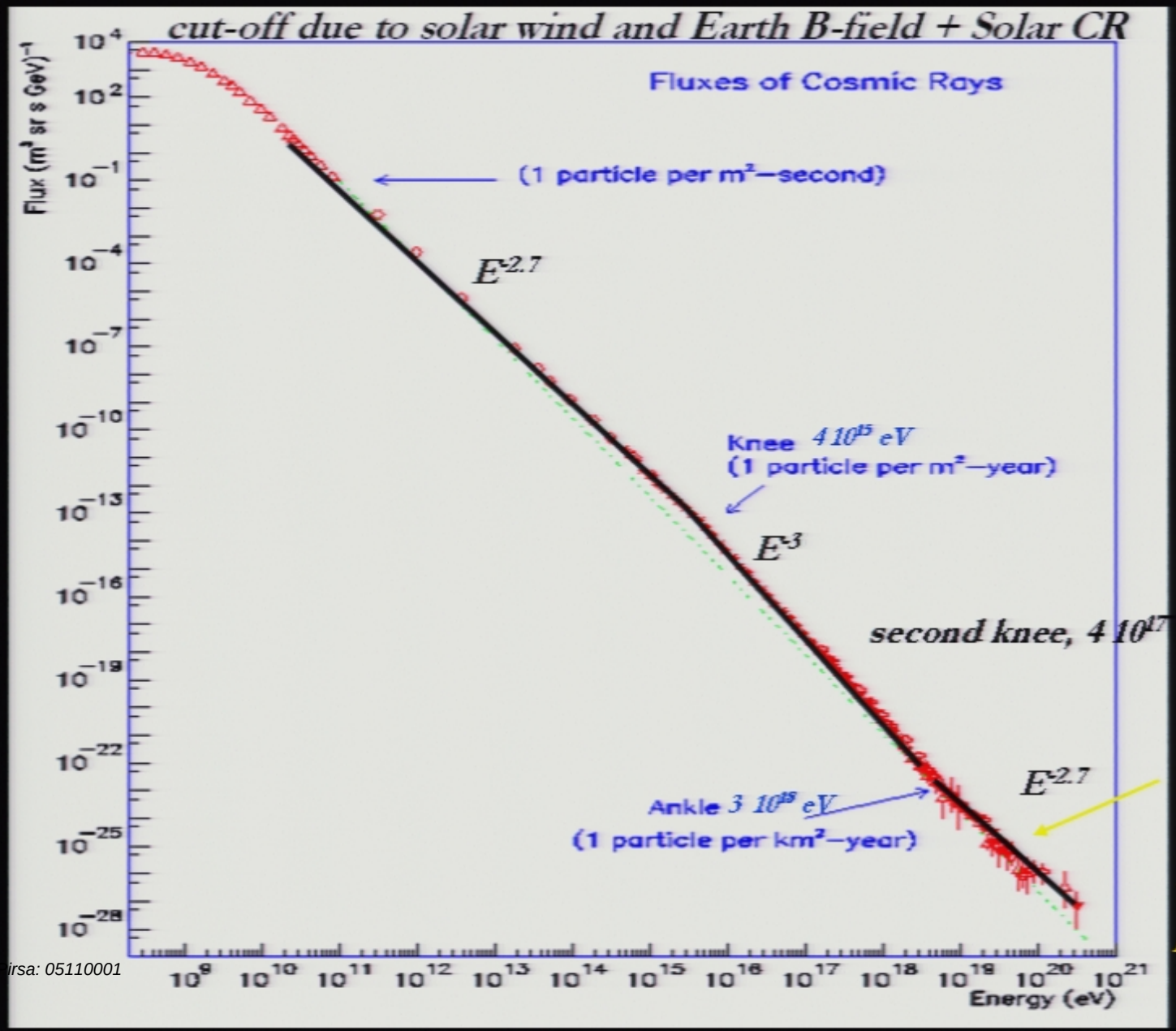
Abstract: Highest energy cosmic rays reach {\it macroscopic} energies $> 10^{20}$ eV (~ 10 joules; corresponding linear momentum in one proton is similar to a slapshot hockey puck's). Such protons can either be accelerated by nearby astrophysical sources or be by-products of decay of unknown superheavy fundamental particles. After reviewing phenomenology of cosmic rays, I will discuss a novel {\it non-stochastic} acceleration mechanism in jets of powerful active galactic nuclei. The mystery of ultra high energy cosmic rays is likely soon to be resolved by Pierre Auger observatory.

Cosmic Rays Spectrum



isotropic to highest energies

UHECRs

1 particle per km² per century

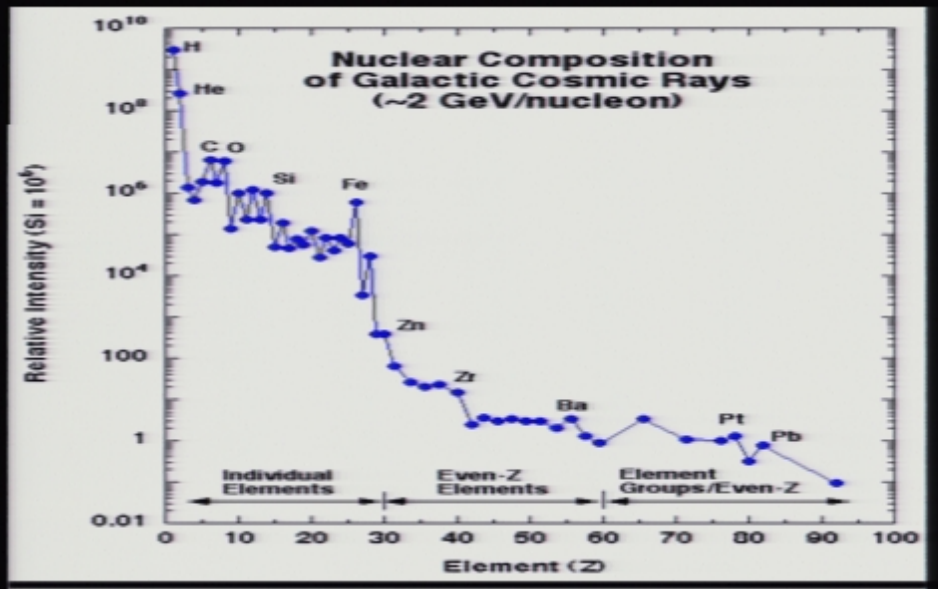
CR composition

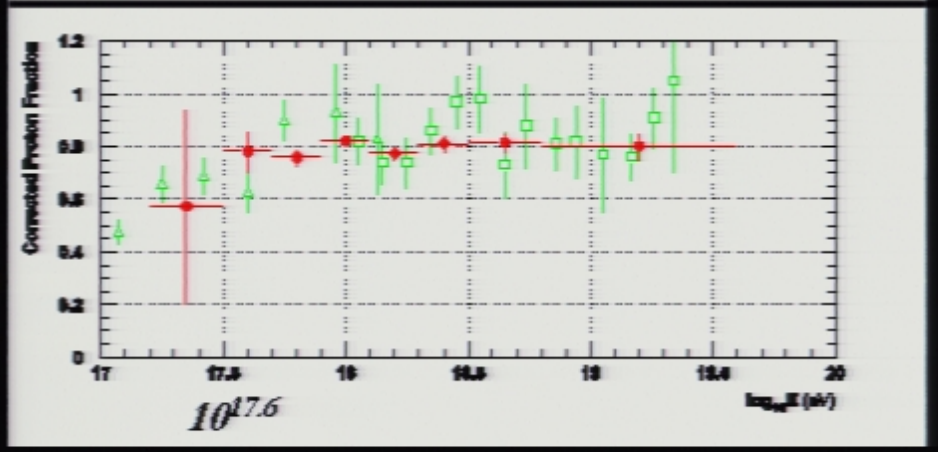
Low energy:

- Overabundance of the rare elements Li, Be, and B produced at spallation
- Depends on residence time, (10^7 years at GeV range)
- τ esc ~ $E^{-0.6}$, acceleration $E^{-2.1}$
- Things are messy (e.g. reacceletioan of secondaries

Highest energy: p-heavy-p

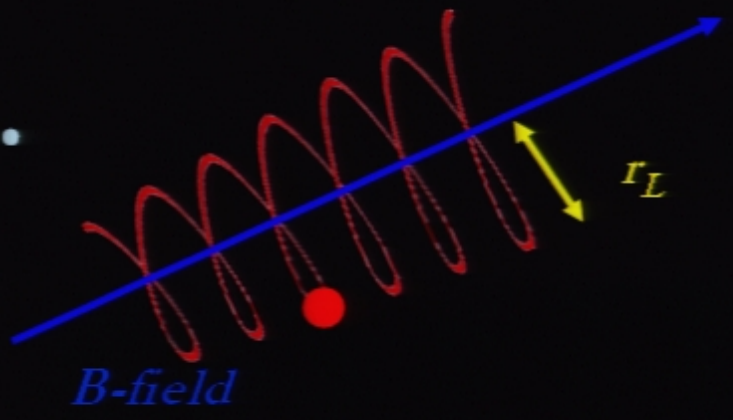
- below knee: protons, between knee & ankle: heavy (Fe), UHECRs are mostly protons, (measured by position of shower maximum); (both Fly's Eye and AGASA)

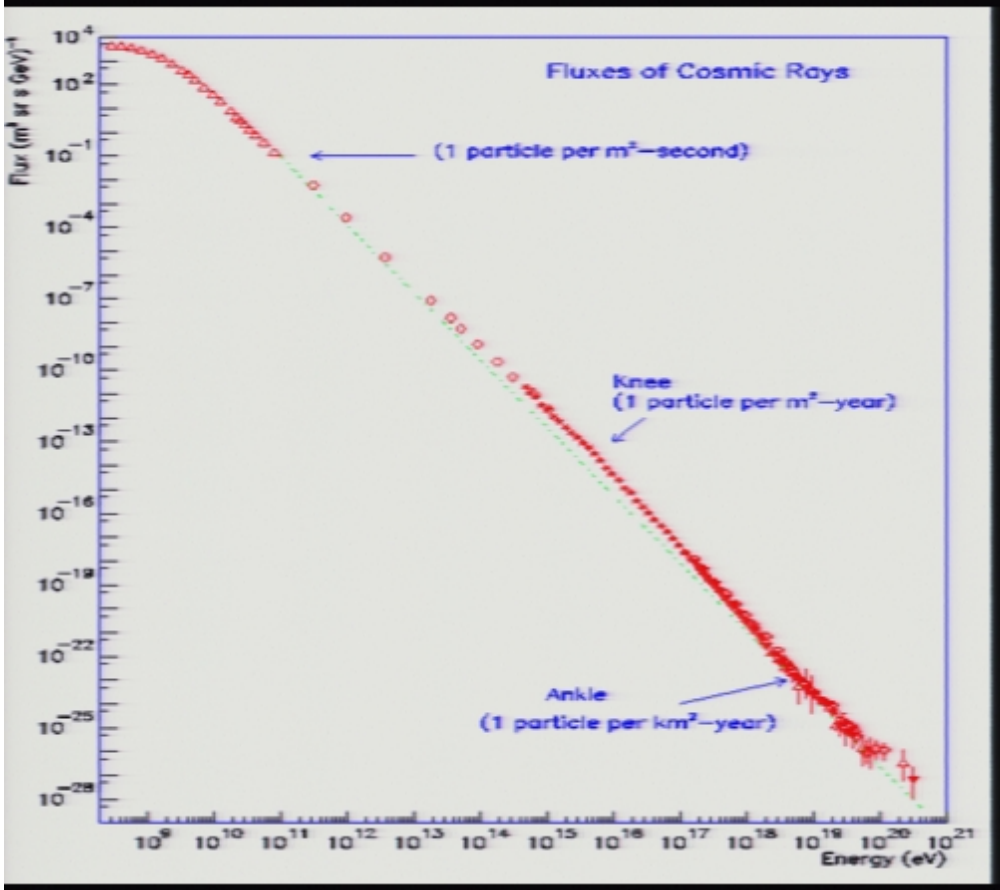




Proton fraction (green: HiRes stereo)

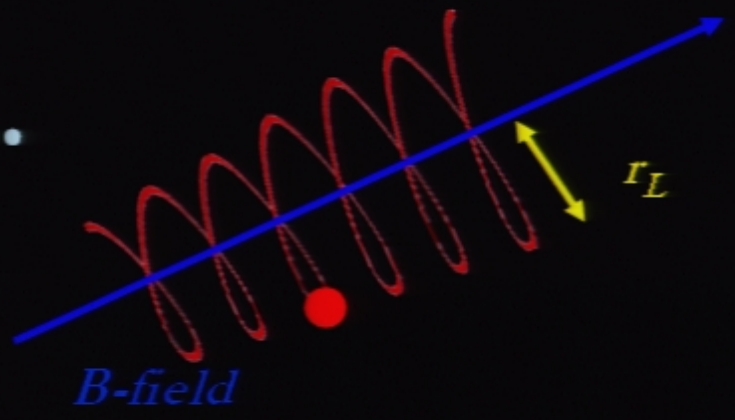
Propagation: B-field...

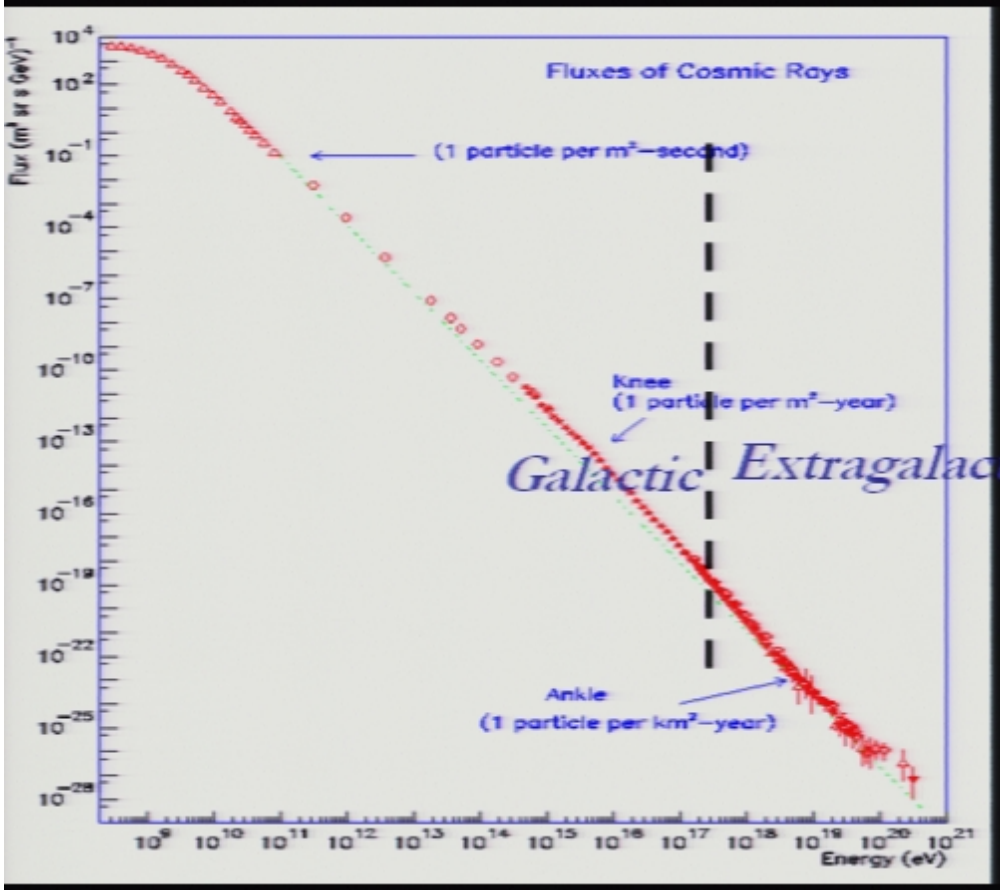




- *Charged particles move along spiral trajectories in B-field. For proton $r_L \sim E_{21}/B_G$ pc (1 pc = 3 10^{18} cm, nearest star is ~ 1pc away, Galaxy is ~ 10^4 pc, universe is ~ 10^{10} pc)*
- *B-field in the Galaxy ~ 10^{-6} G, only particles with $E < 10^{19}$ eV are confined*
- *CR excite Alfven waves and are scattered by Alfven waves: diffusive propagation for $E < 10^{19}$ eV*

Propagation: B-field...





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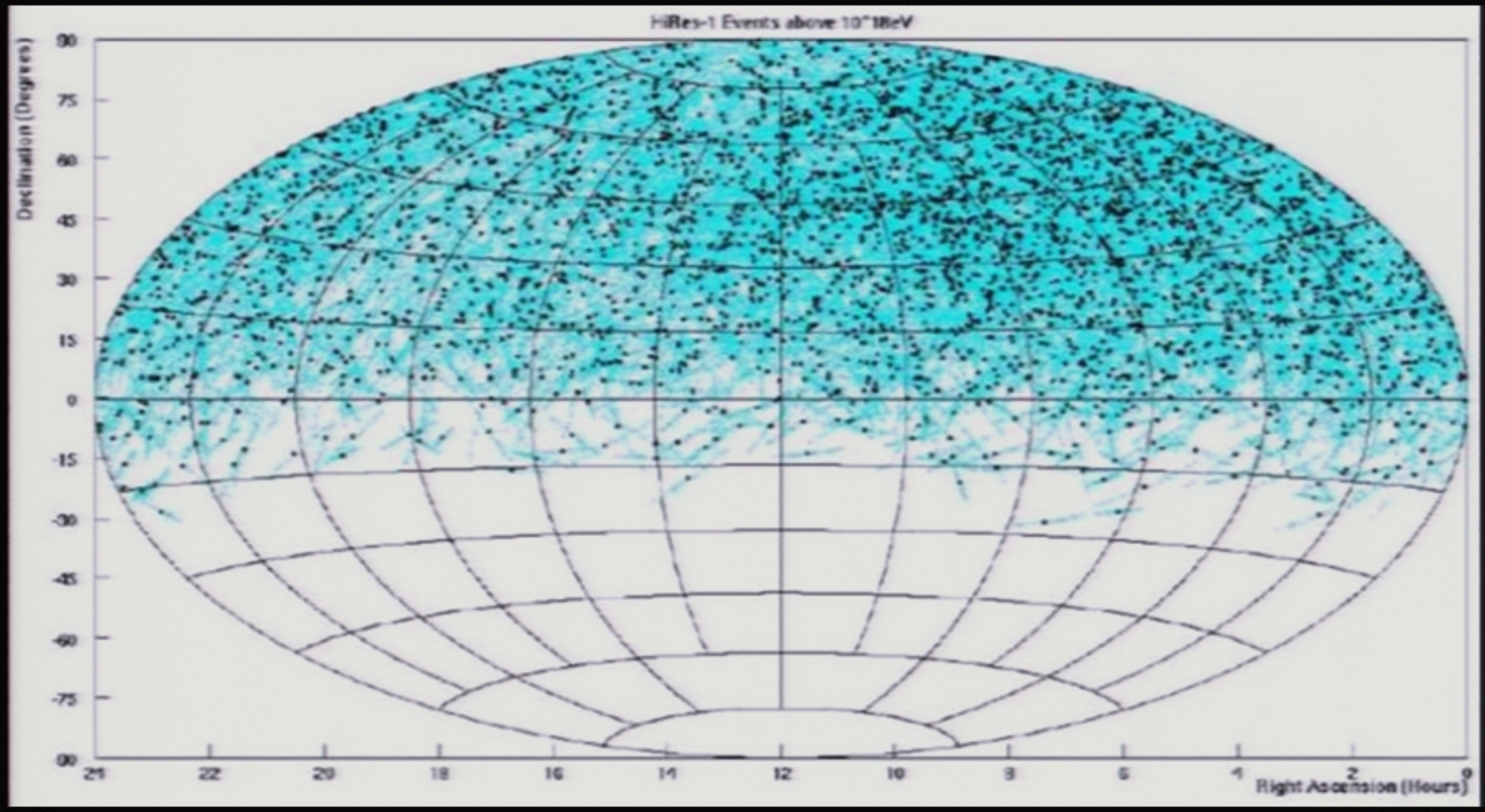
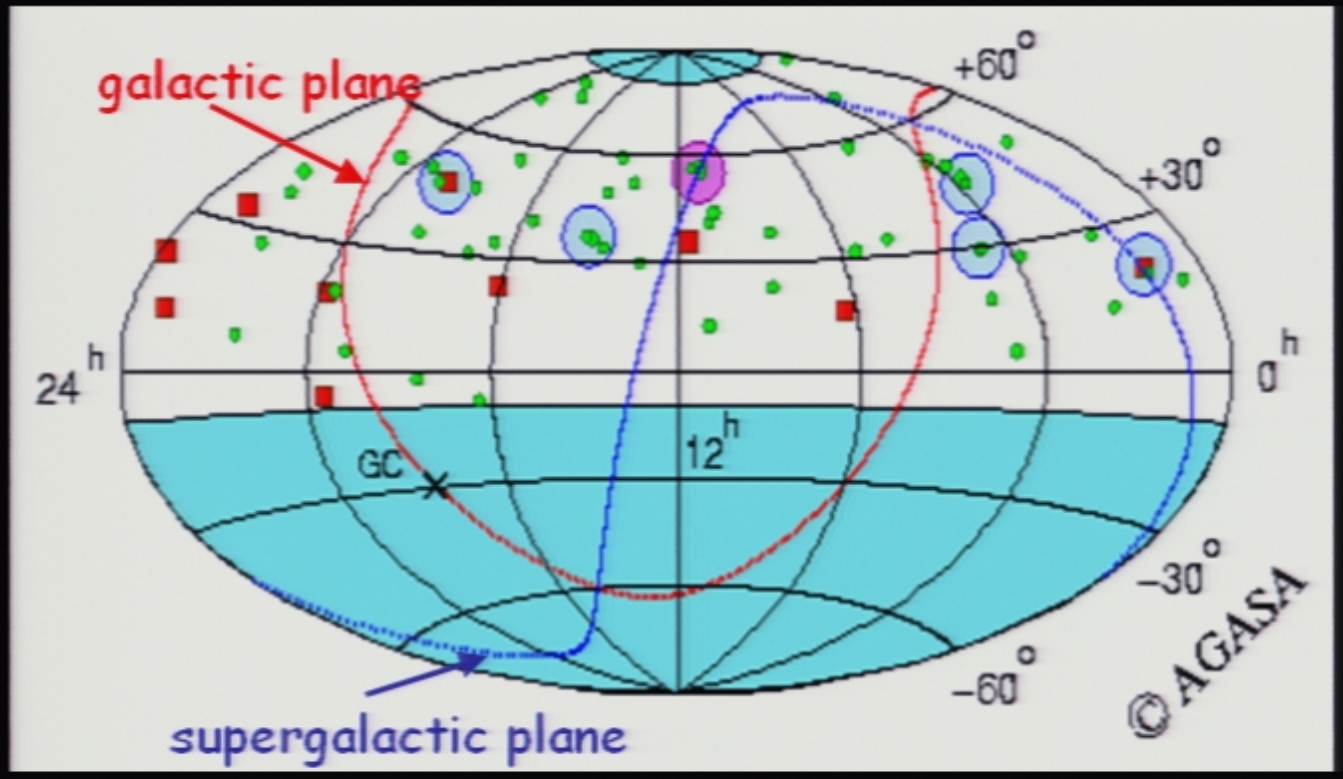
Consistent with change in composition at ankle

Large scale isotropy (HiRes)



Small scale clustering (AGASA)?



Arrival Directions of Cosmic Rays above 4×10^{19} eV

- *Several doublets and triplets*
- *Chance probability of clustering from isotropic distribution is < 1%*
- *Either we see sources and/or clumps or B-field lensing*

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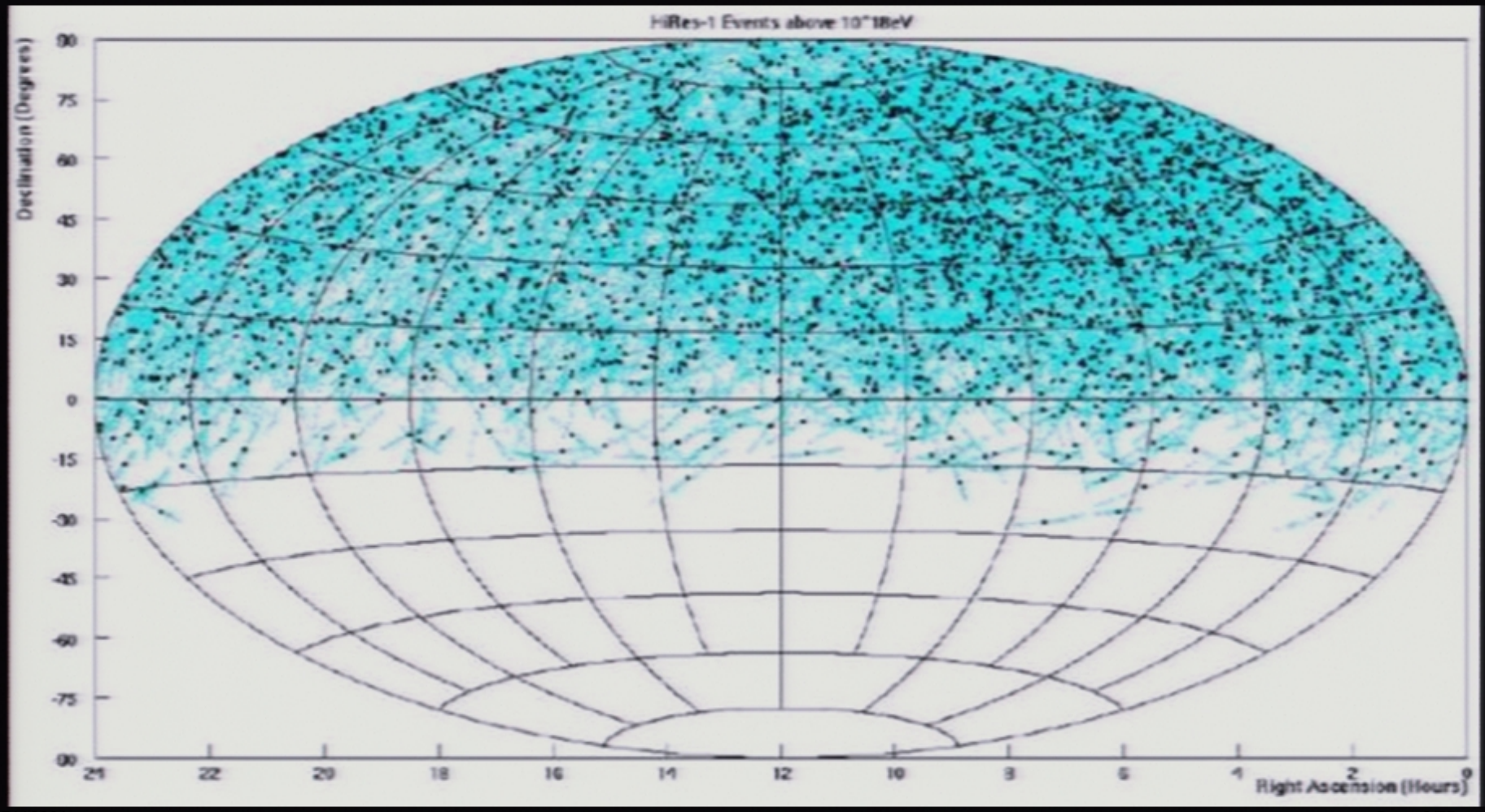

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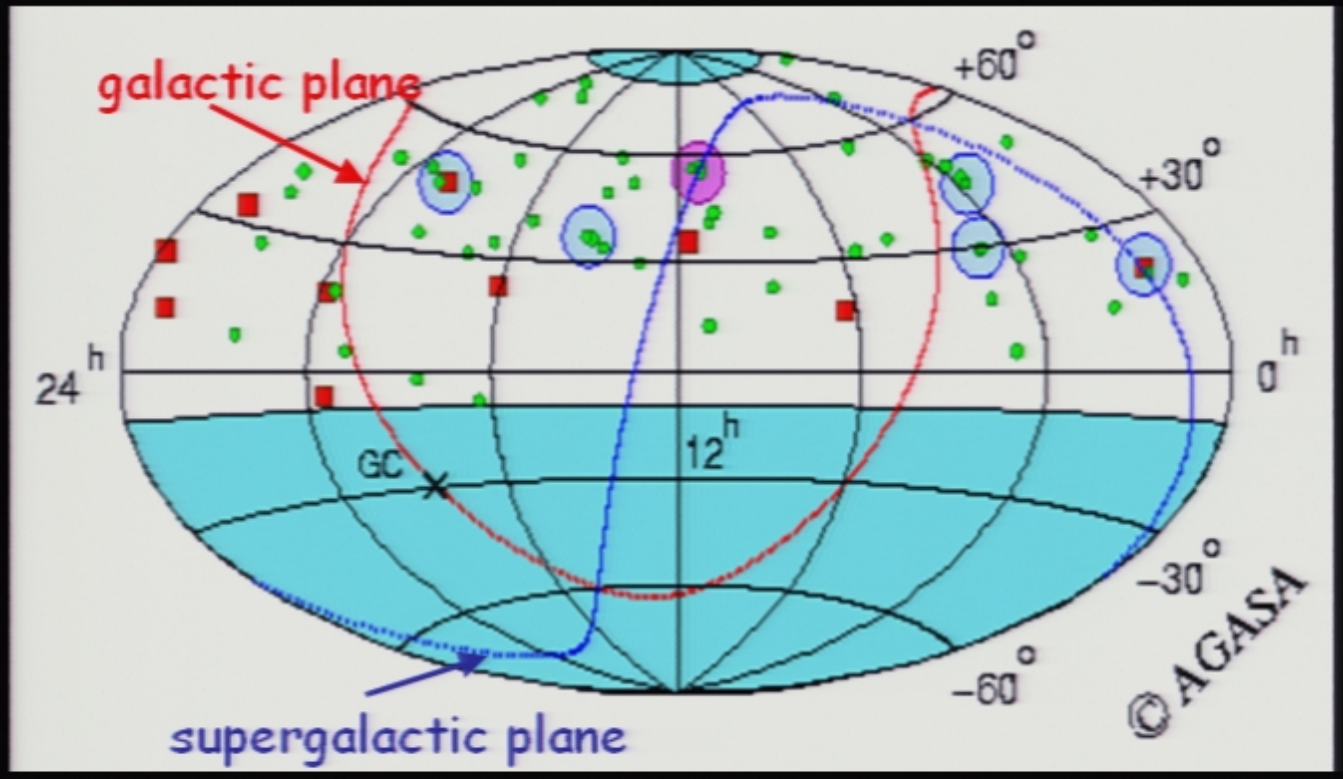

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Intergalactic propagation of UHECR

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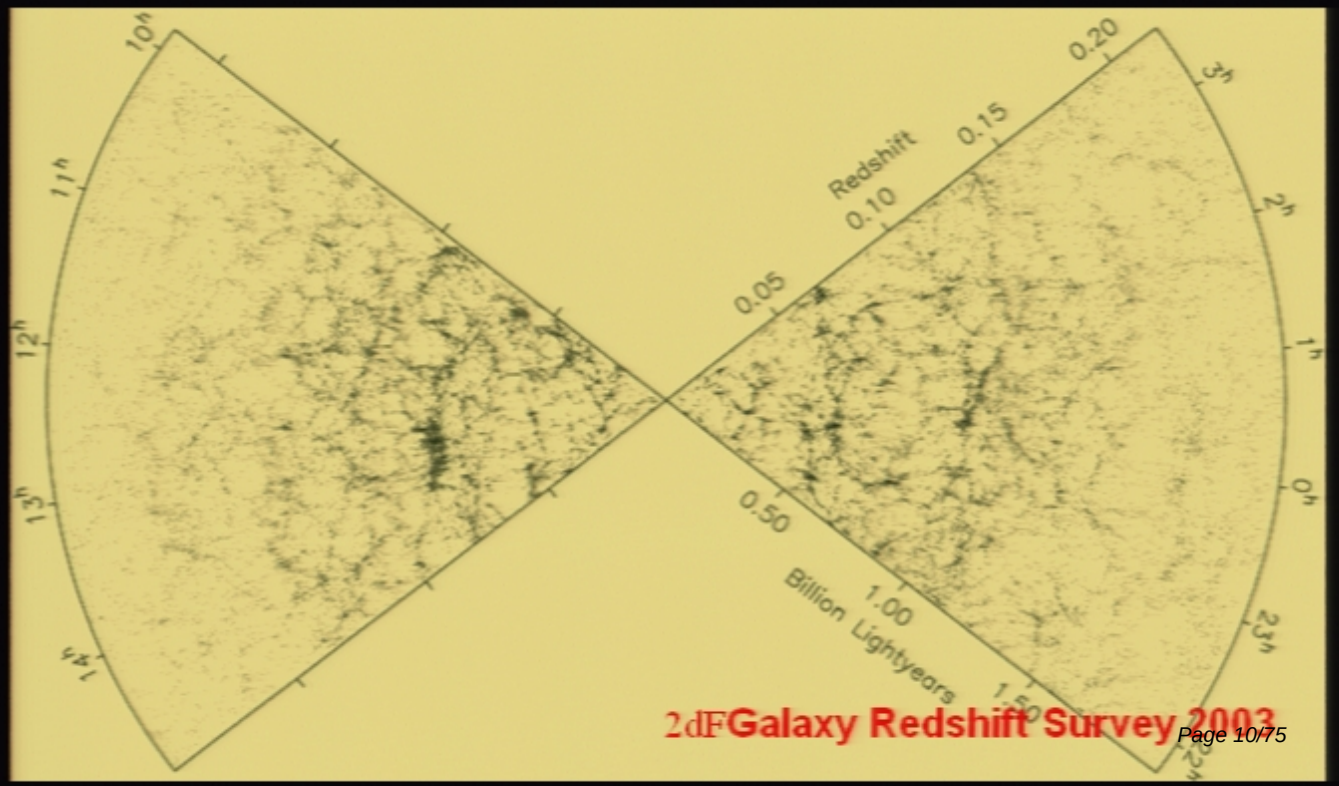
- *Average B-field < 10^{-9} G*
- *r_L ~ 100 Mpc for 10^{19} eV*



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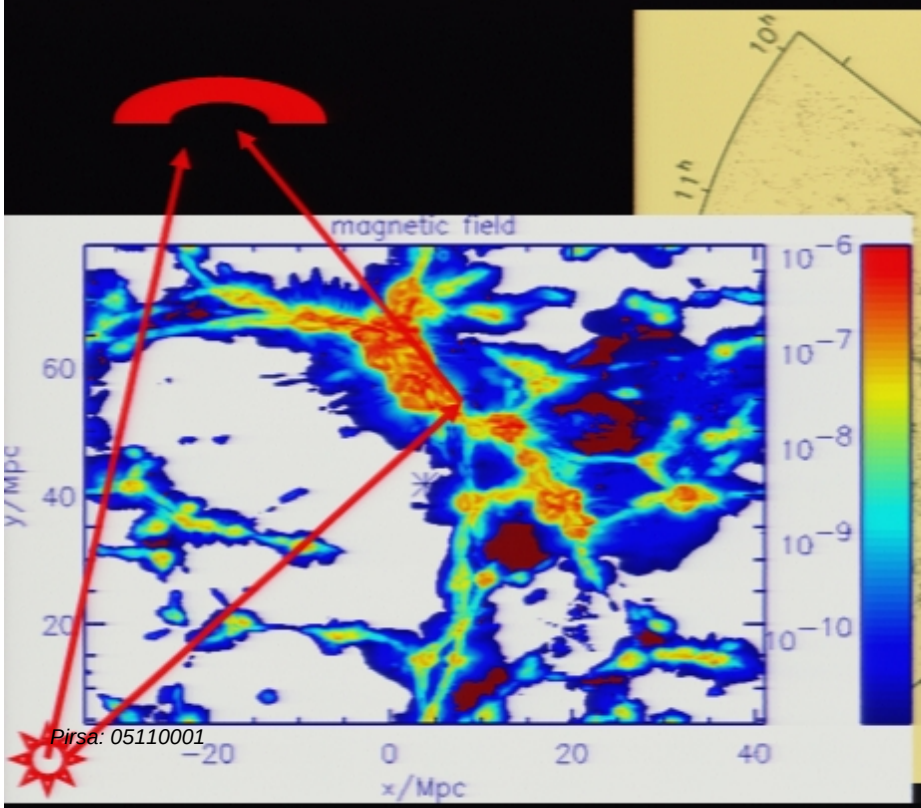

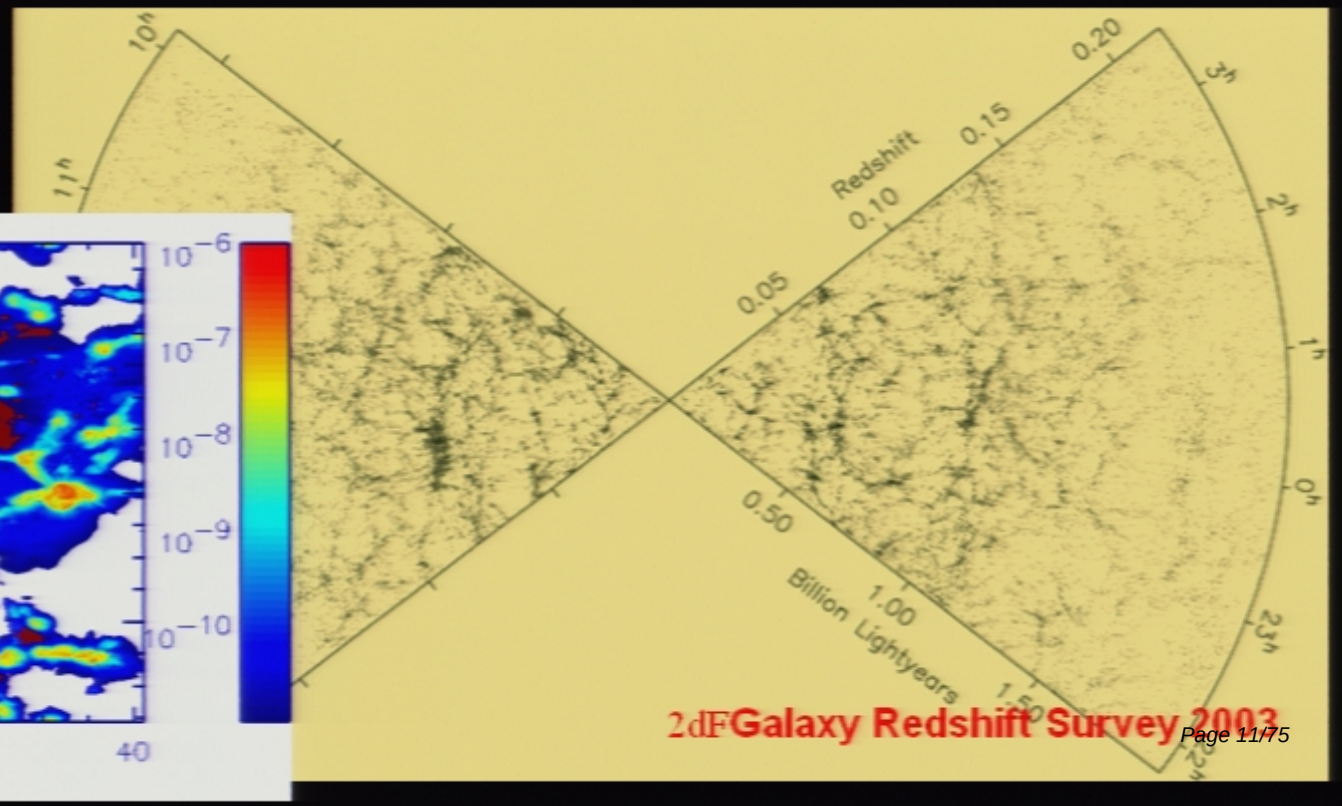

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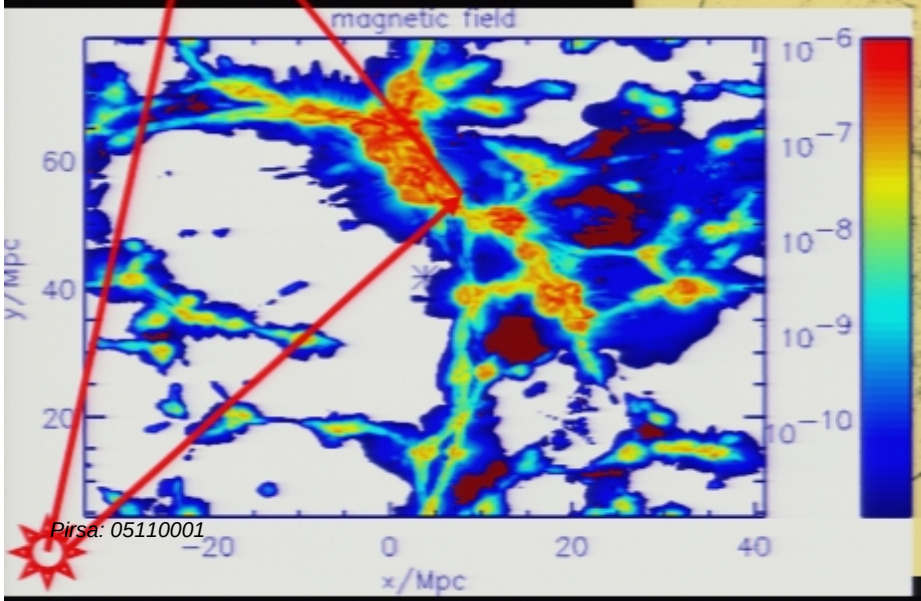

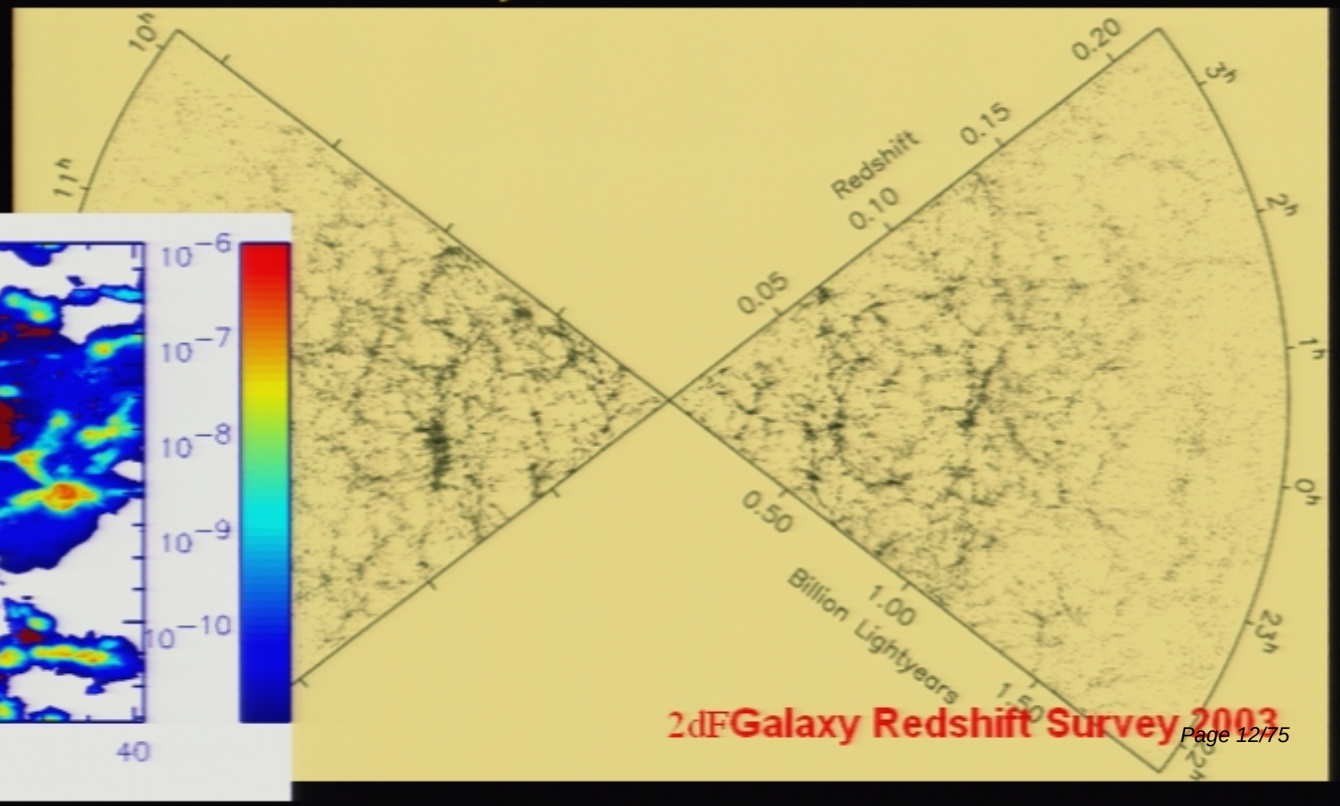

GZK cut-off

Greisen PRL; Zatsepin & Kuzmin JETP Lett (1966)

- *Cosmic Microwave Background radiation (CMB) T=2.7 K*
- *Photo-pion production*

$$p + \gamma_{2.7k} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

$$n + \pi^{+}$$

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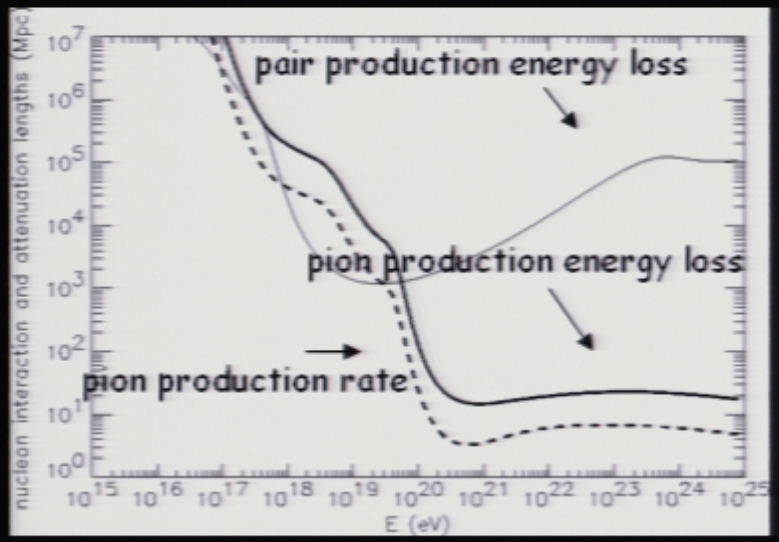
  - *tens of Mpc. Very solid estimate;*

  worse for Z> 1



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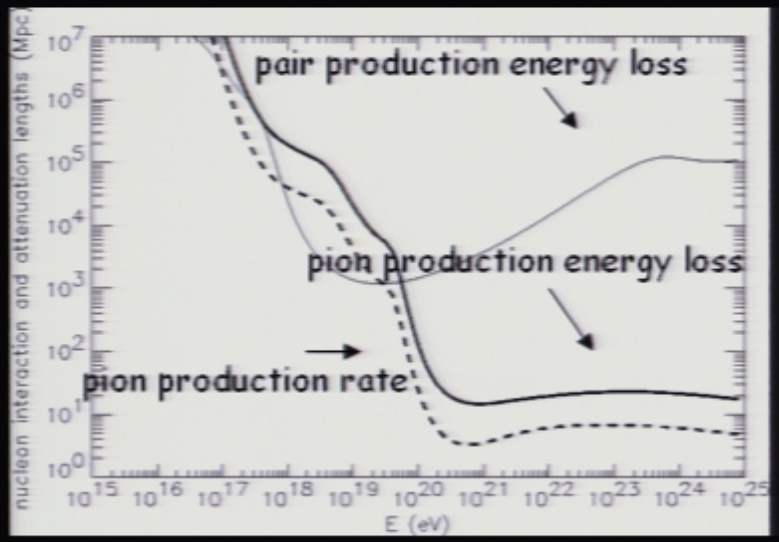

- *Attenuation length for ~ 10^{20} eV CR is*
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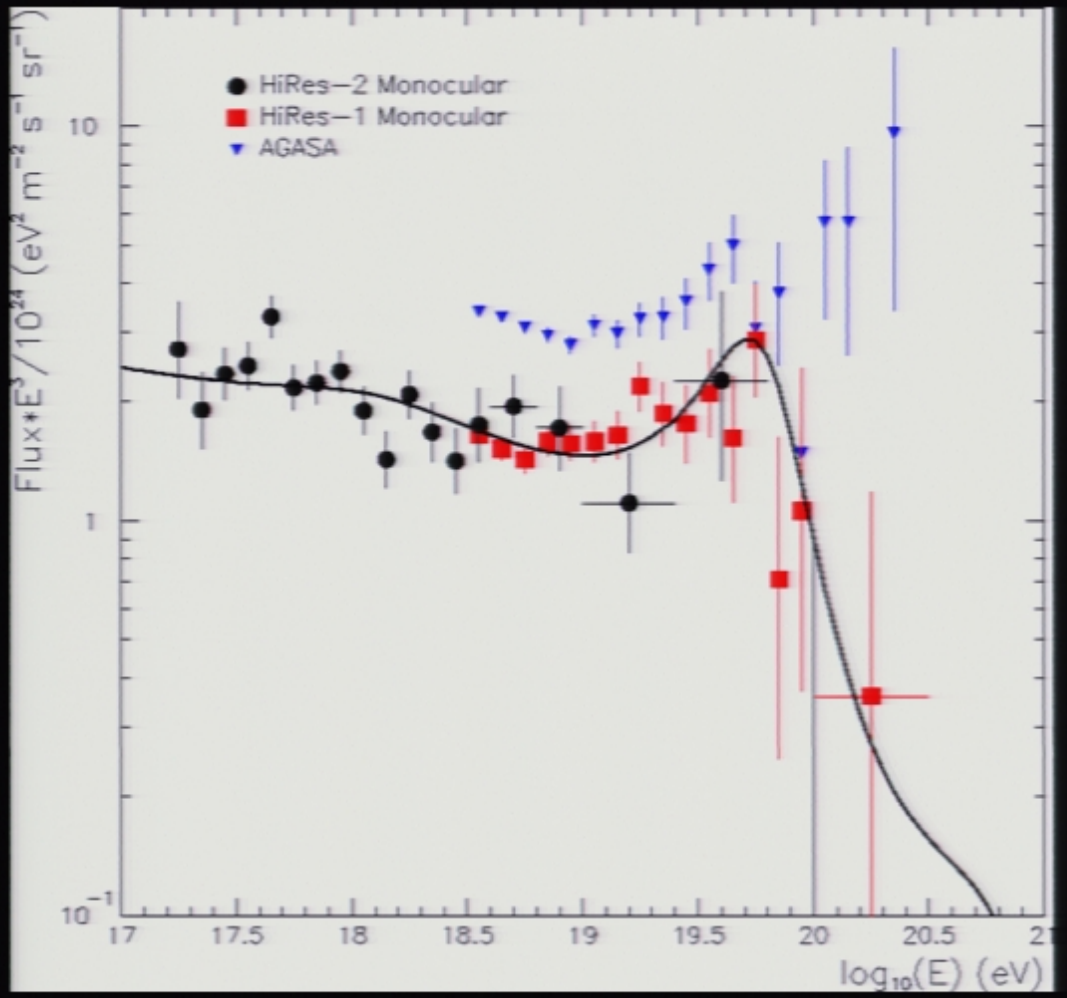
  worse for Z> 1
- *UHECRs must be produced locally ("cosmological backyard) < 100 Mpc (size of Universe is ~ 10^{4} Mpc)*
- *NB: this logic assumes invariance of Lorentz transformation up to $\gamma \sim 10^{10}$. Perhaps….*

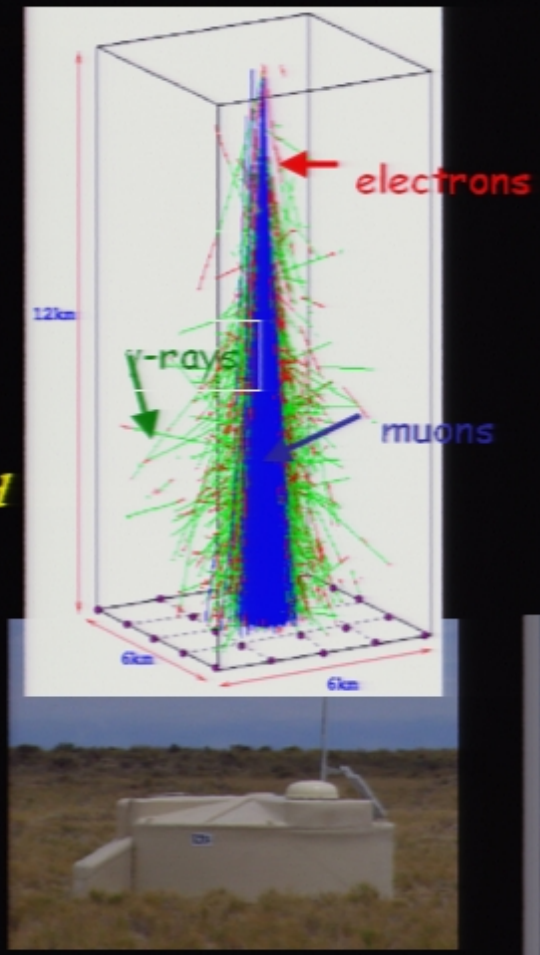
Is GZK cutoff seen?



- *HiRes (fluorencence) and AGASA (ground array) disagree*
- *Auger now has similar statistics to all of AGASA (no result announced)*

Detectors: two types

- *Earth atmosphere is a telescope*
- *Ground monitors of charged particles (e.g. AGASA)*
  - *Neutron Monitors and Supermonitors*
  - *Ionization Chambers*
  - *Muon Telescope*
- *Observation of fluorencence and Cherenkov light (Fly's eye & HiRes, Haverah Park)*



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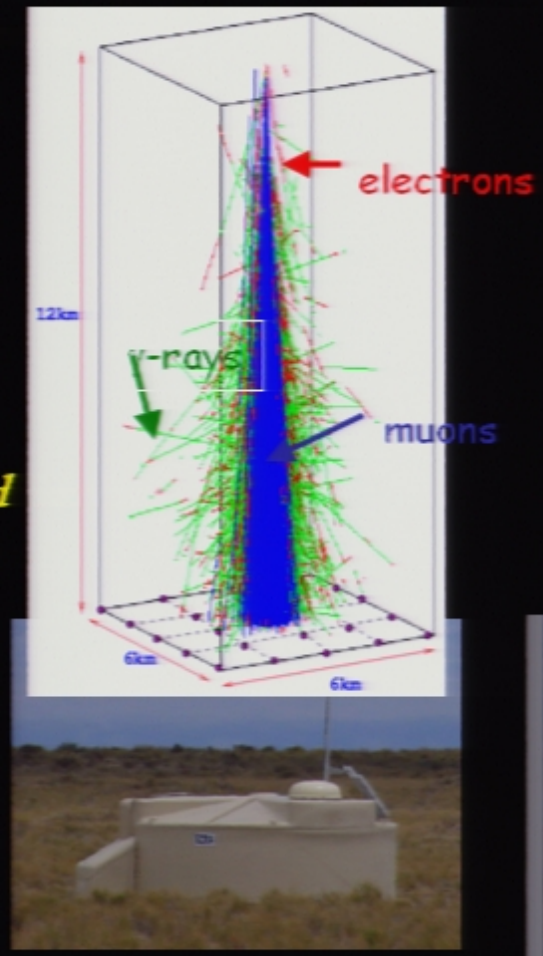


When statistics is low, calibration problems begin

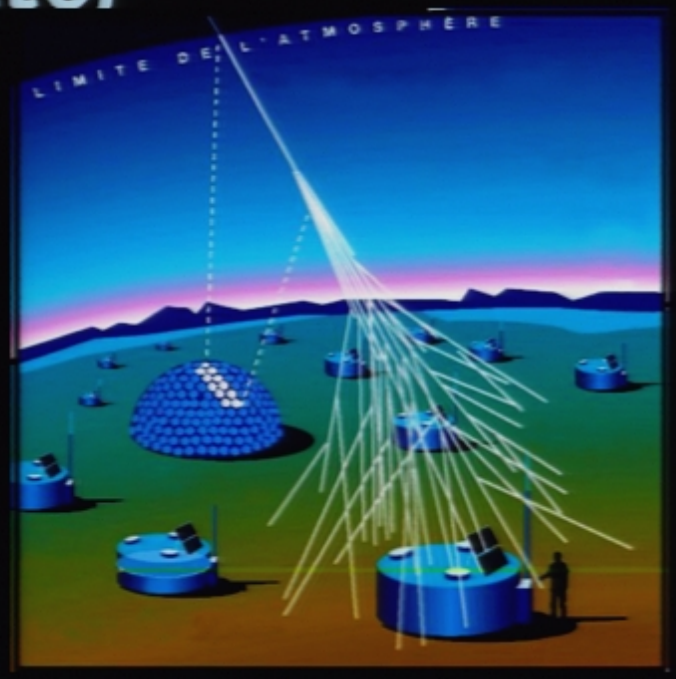
The Auger Observatory (Argentina): hybrid detector

The Auger Observatory combines

Surface Detector Array and Air Fluorescence Detectors

- *Advanced control of position, performance, weather (e.g. T, humidity)*
- *Independent measurement techniques allow control of systematics*
- *Energy: $\Delta E/E \sim .5$ @ 10^{20} eV*
- *Angle: 0.6°*
- *Primary mass measured in complementary ways*
- *First result:*
  - *no extra flux from Galactic center (contrary to AGASA and SUGER)*
  - *< 25% of photons @ > 10^{19} eV*

  (bad for top-down and Z-model)
- *Coverage ~ AGASA*



GZK cutoff will tell a lot

If GZK is seen

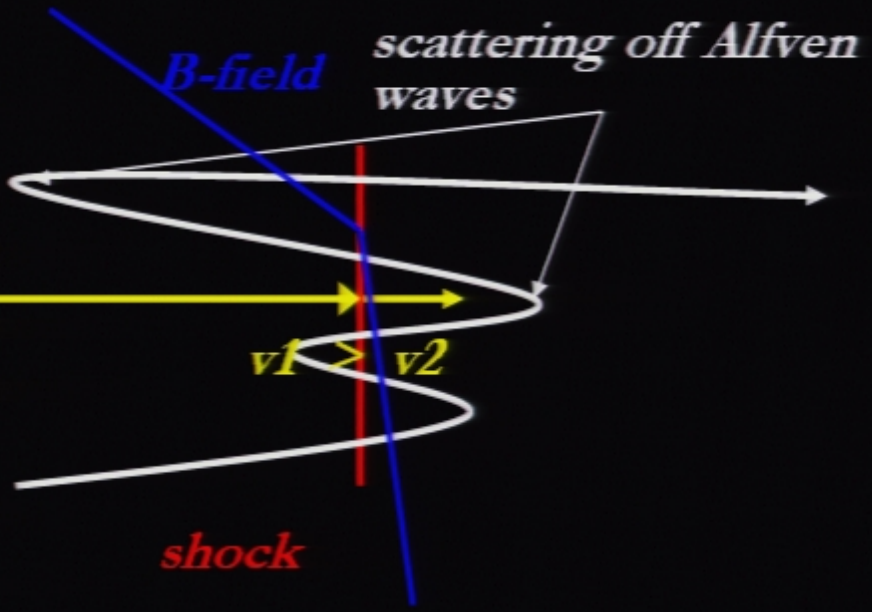
- *Distribution of sources of UHECRs and their cosmological evolution*
- *Identify point sources*
- *Injection spectrum*
- *Emax*
- *Extragalactic B-field*
- *Probe of hadronic interactions at larger energies than terrestrial accelerators*
- *cosmogenic neutrino flux*

If GZK is not seen

- *Super-Heavy Particle Relics*
- *Topological Defects*
- *New Neutrino Sources + Z bursts*
- *New primary*
- *Lorentz violation*
- *…*

Low energy CRs ($< 10^{15}$ eV): production in SNRs through Fermi shock acceleration

- observed in interplanetary space
- Predicted spectrum is "right" $dn/dE \sim E^{-2}$
- Total power in $< 10^{15}$ eV is $\sim 10^{41}$ erg/s, SN can give 10^{42} erg/s/Galaxy (barely enough)
- But: not yet confirmed by γ-ray observations of π^0 decay in SNR (confusion with electron emission)
- SNs cannot accelerate beyond $\sim Z\, 10^{14}$ eV (maybe a bit higher for non-linear shock accelerations). This is the knee.
- But one expects a cut-off, not just a change in power law



What are UHECRs (above the ankle ~ $3\,10^{18}$ eV)?

Have to be extragalactic, $r_L > L_G$

Top-down

- *By-products of decay of some heavy fundamental particle or topological defect, $m_X > 10^{21}$ eV*
- *exciting but, perhaps, unlikely*

Bottom-up

- *protons accelerated by some astrophysical source (pulsars, magnetars, AGN, GRB)*
- *banal but, perhaps, true*
- *So far all acceleration mechanism & sources proposed are not compelling*

Top-down

- *CRs are decay products of super heavy X-particle, $m_X > 10^{21}$ eV (e.g. CDM particles, coming from Galactic halo)*
- *Most energy is released in EM and υ channels (quarks combine more easily into mesons than baryons)*
- *EM energy cascades (γ - $e^{\pm}$) down to ~ GeV range*
  - *EGRET GeV energy ~ 100 x UHECR energy*
  - *but UHECRs are local while γ-rays are global*
  - *limits on abundance of X-particles: tight constraints on any type of X-particle*
- *Detection of very high energy υ: very promissing; can be done with Auger, but hard …*

Bottom-Up ($E > 10^{19}$ eV)

- *Need to be produced locally:*
  - electromagnetically or strongly interacting particles above 10^{20} eV loose energy within less than about 100 Mpc
- Tight constraints on acceleration:
  - Sources with large potential $\Delta\Phi \sim 10^{20}$ V (very powerful) with extremely efficient acceleration mechanism are neeed
- *Proton composition $E > 10^{19}$ eV*
- Isotropy :
  - The observed distribution seems to be very isotropic with possible small scale clustering, $N_{source} \sim 10$ /GZK sphere (Di Marco etal)
- Not to warry:
  - *Total luminosity, ~10^{44} erg/sec/* GZK sphere *is reasonably small*

Astrophysical sources of UHECRs: AGNs

ow power (FRI),

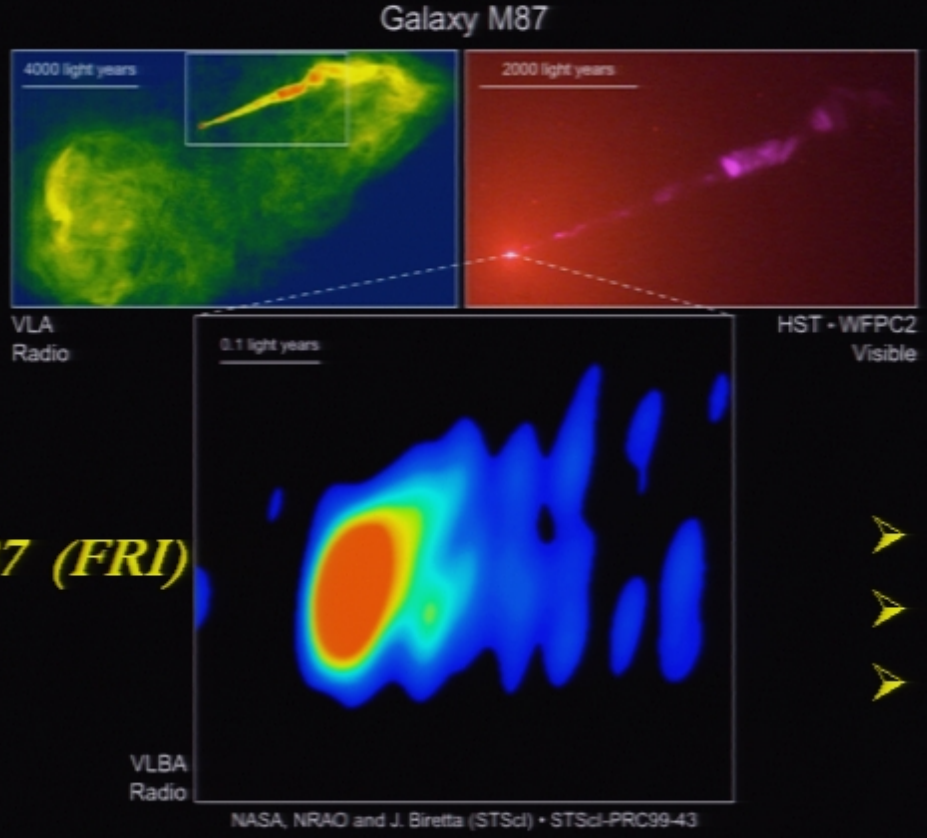
$_{obs}$ ~10^{42}-10^{44} erg/sec

$_{et}$ < 10 kpc

High power (FRII),

L_{obs} ~10^{45}-10^{46} erg/sec

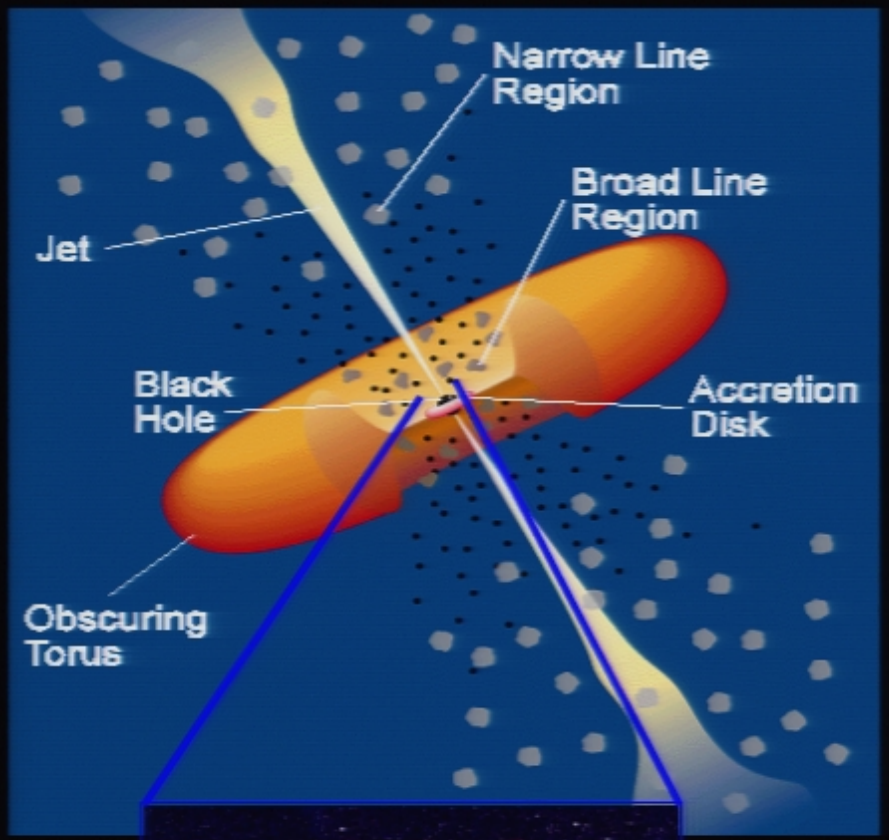
z_{jet} > 100 kpc

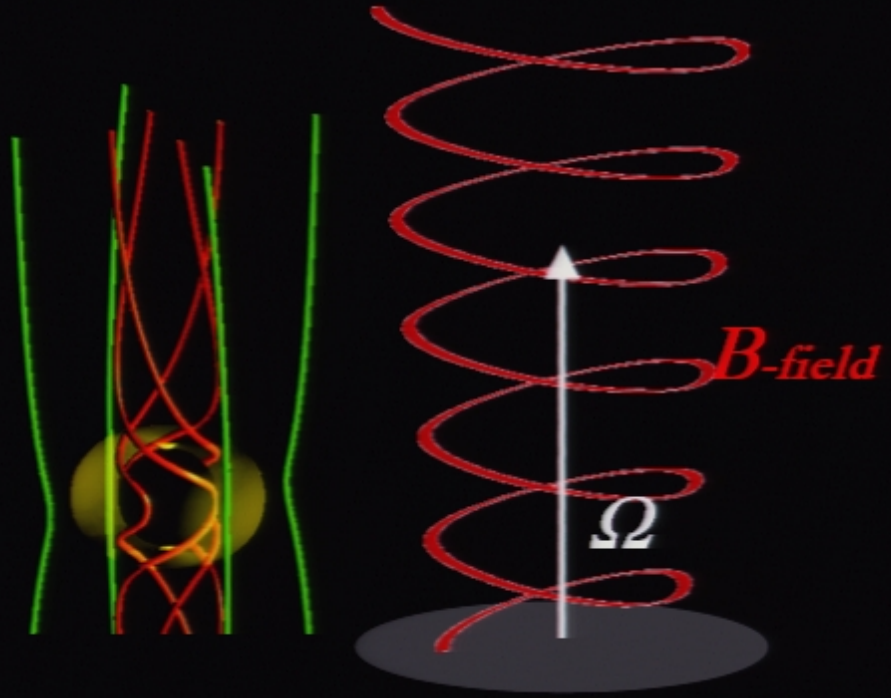


M87 (FRI)

- *Minimal jet power (in leptons) ~ 10^{45} erg/s*
- *Can be much larger in p, B-field*
- *Several galaxies ~ 10^{45} erg/s within 100 Mpc*

What are AGNs





- *Jets are launched by central black hole using B-field (~ Faraday disk). In a jet B-field may be energetically important* $B^2 \sim 8\ \pi \varrho\ c^2$ *(large fraction of energy is in Poynting flux)*
- *At large distances* B_φ *dominates*

Intergalactic propagation of UHECR

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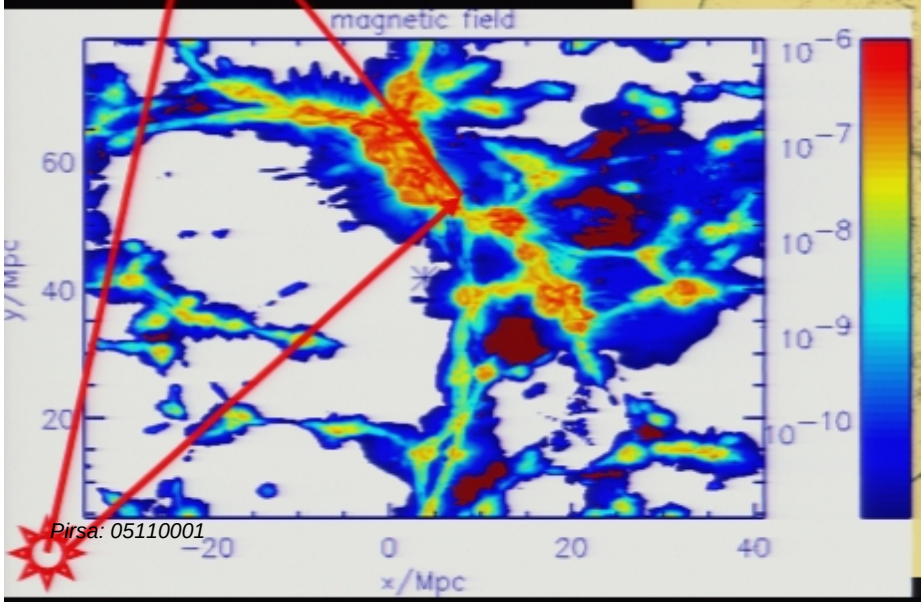

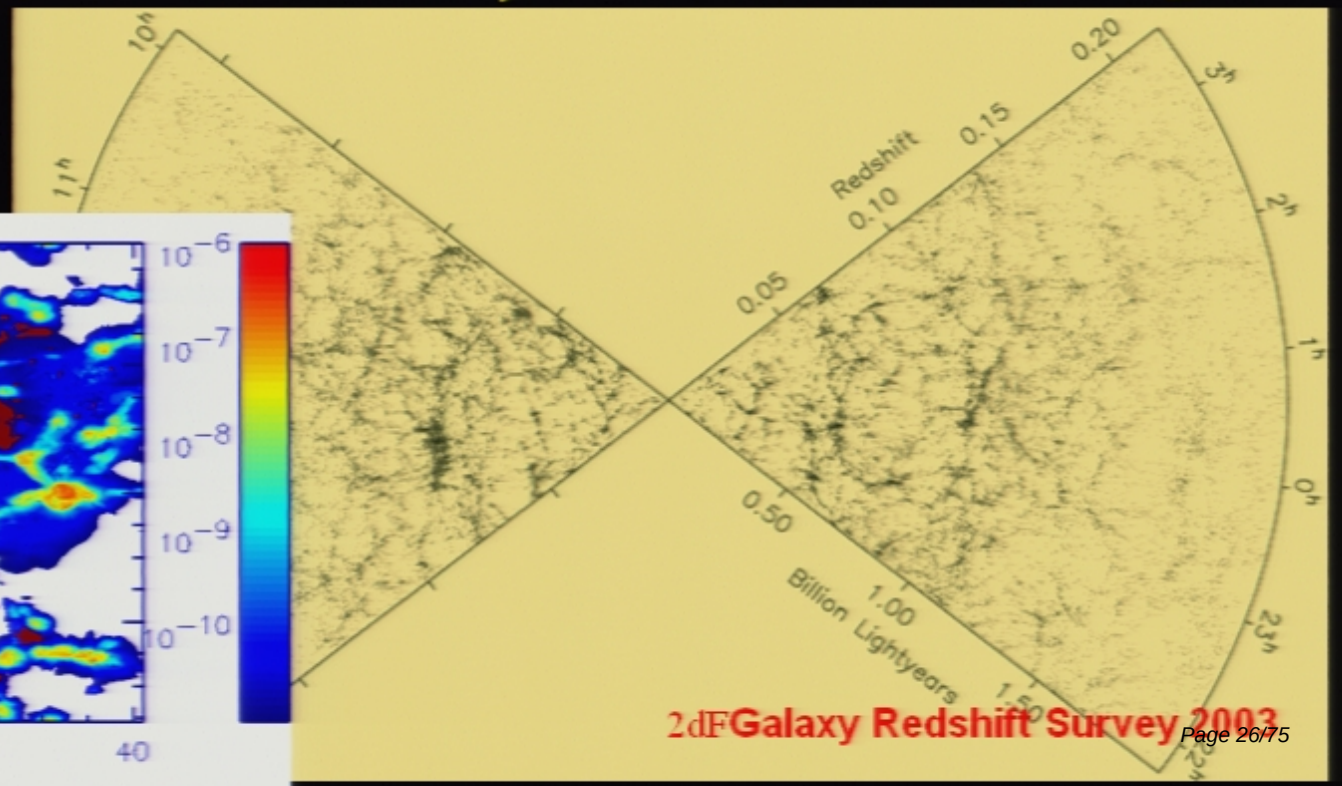

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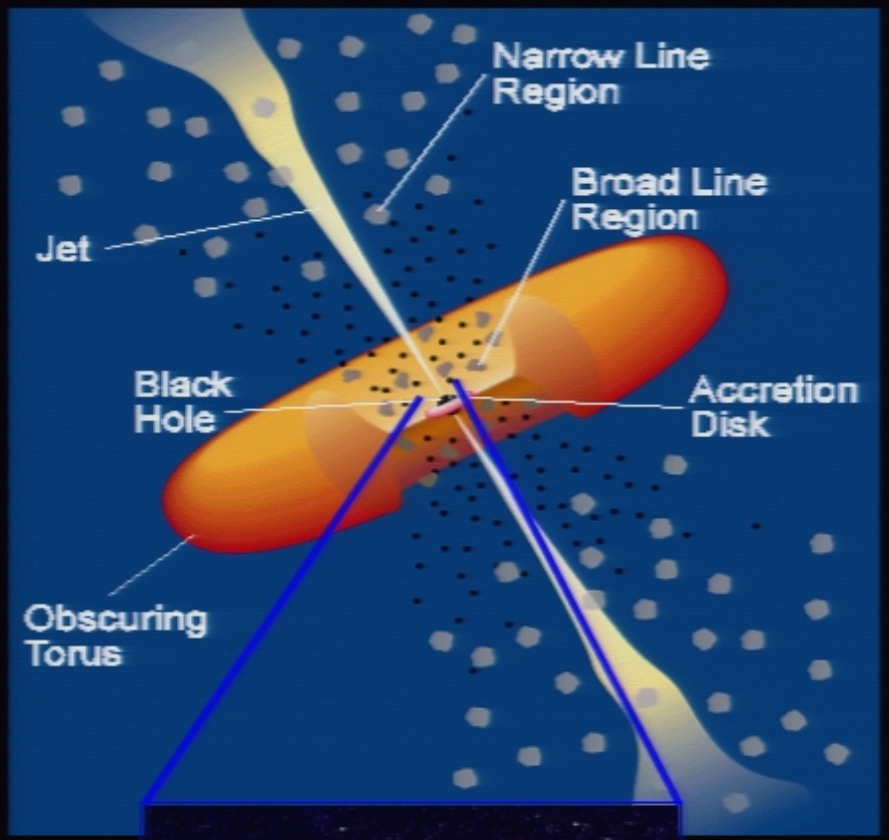

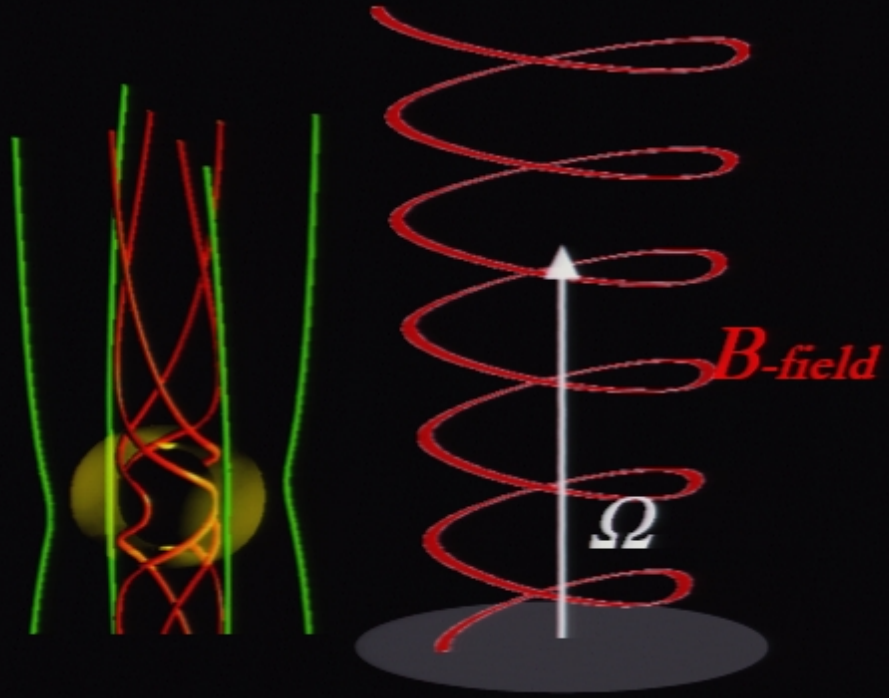

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Acceleration of UHECRs

- *Conventionally – Fermi I & II at relativistic shocks:*
  - *not clear if can be extended to UHECR regime*
  - *maximal efficiency ($\tau_{acc} \sim \gamma/\omega_B$) is usually either assumed or put "by hand" by using more than allowed (super-Bohm) cross-field diffusion*
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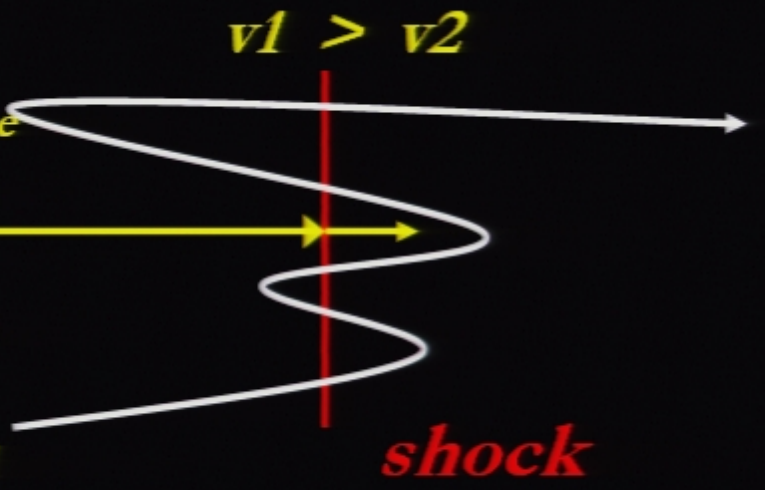
  - *Hardening above the "ankle" ~ 10^{18} eV may indicate new acceleration mechanism*



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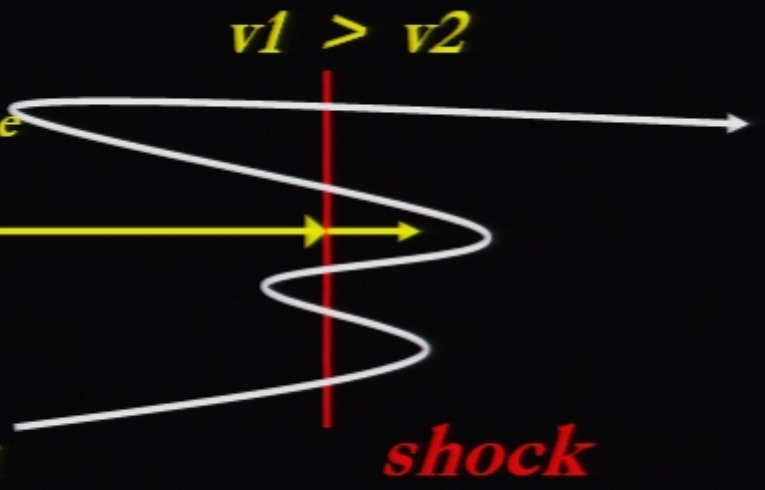


We propose new, non-stochastic acceleration mechanism that turns on above the ankle, E> 10^{18} eV

General constraints on acceleration cite:

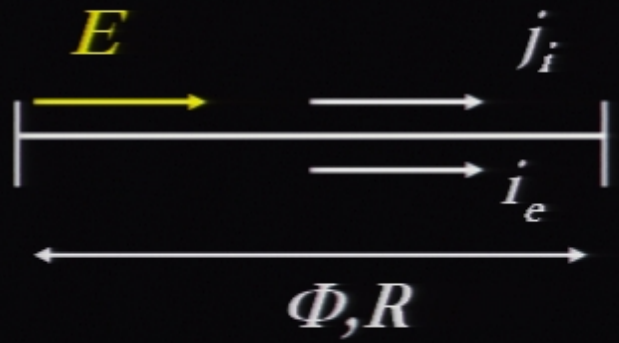
- Constraints on UHECRs are so severe, "~" estimates are useful
- Maximal acceleration E-field < B-field: $E=\beta_0 B, \quad \beta_0 \leq 1$
- Total potential $\Phi = E R = \beta_0 B R$
- Maximal energy $E \sim Z e \Phi = \beta_0 Z e B R$
- Maximal Larmor radius $r_L \sim \beta_0 R$ (Hillas condition)
- Two possibilities:
  - $E \,||\, B$ (or $E>B$) – DC field
  - $E \perp B$ – inductive E-field

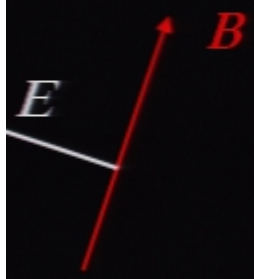
} Two paradigms for UHECR acceleration

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**

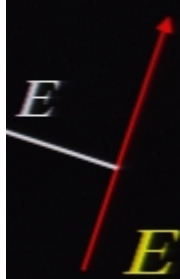
1. **leptons will shut off $E_{||}$ by making pairs (typically after $\Delta\Phi << 10^{20}$ eV)**
2. **Double layer is very inefficient way of accelerating UHECRs: E-field will generate current, current will create B-field, there will be large amount of energy associated with B-field. One can relate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





$E \perp B$: Inductive potential

Lovelace 76
Blandford 99



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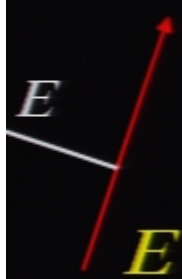

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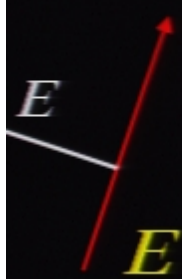

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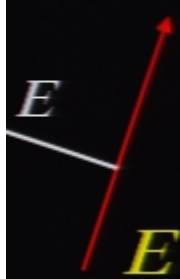

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Electric potential $\Phi \sim ER = \beta_0 BR \Rightarrow L \sim \frac{\Phi^2}{\beta_0} c$

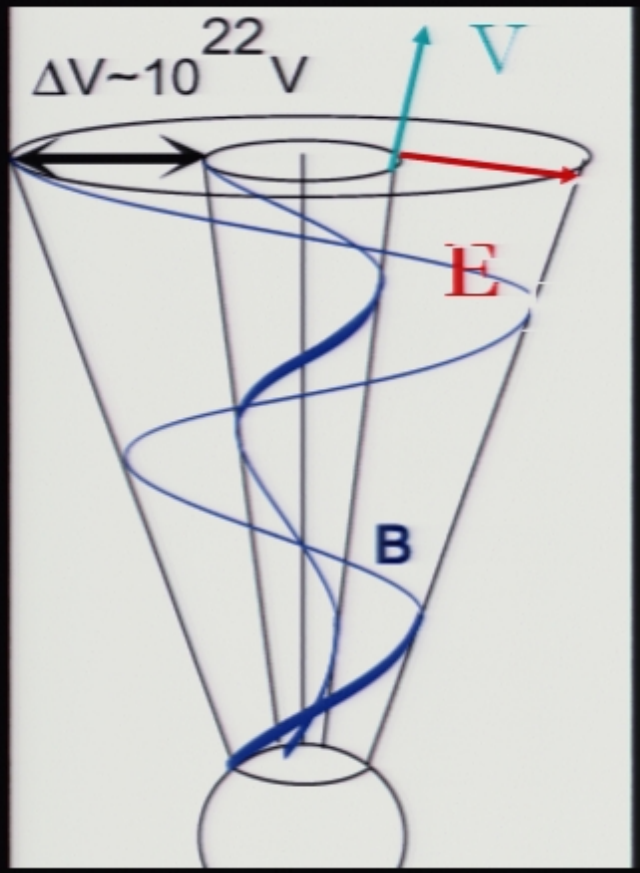
$$\Phi \leq \sqrt{\frac{4\pi \beta_0 L}{c}}, \quad BR \sim \frac{I}{2\pi c} \Rightarrow I \sim \sqrt{\frac{L c}{4\pi}}$$

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

- *To reach $\Phi = 3\ 10^{20}$ 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 may be few systems with enough potential within GZK sphere, 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*
- *Particle has to cross flux surfaces*
- *What is the mechanism of acceleration? Before, it was only noted that there is large potential (Lovelace, Blandford, Blasi), but no mechanism*
- *Kinetic motion across B-fields- particle drift*



Potential energy of a charge in a sheared flow

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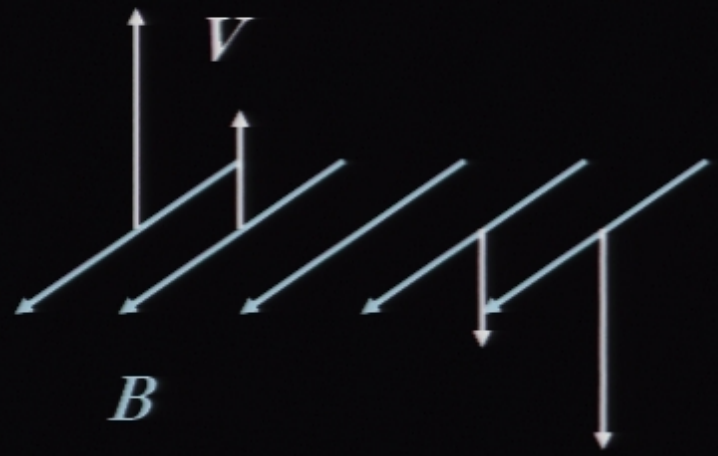

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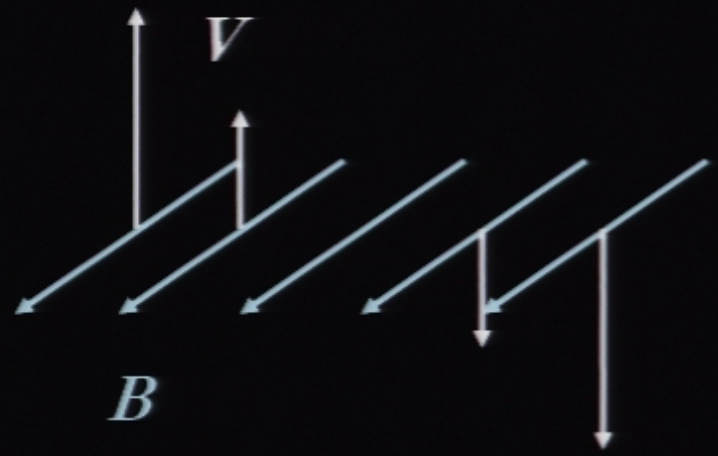

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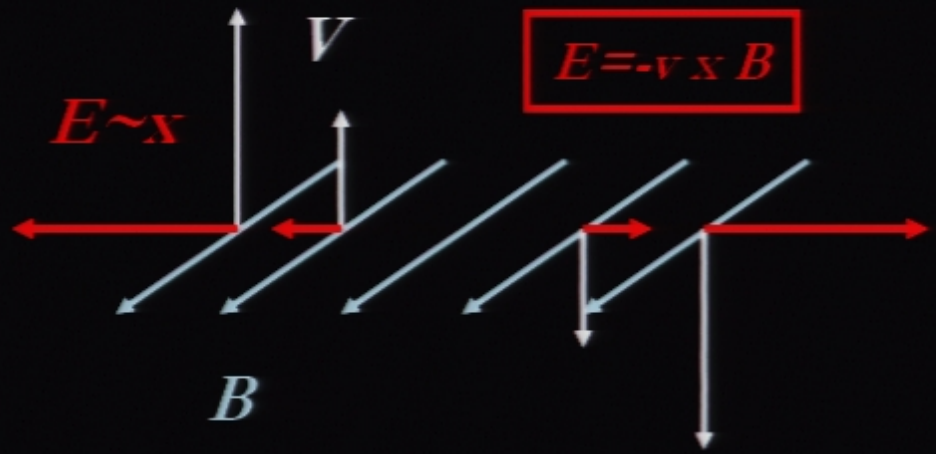

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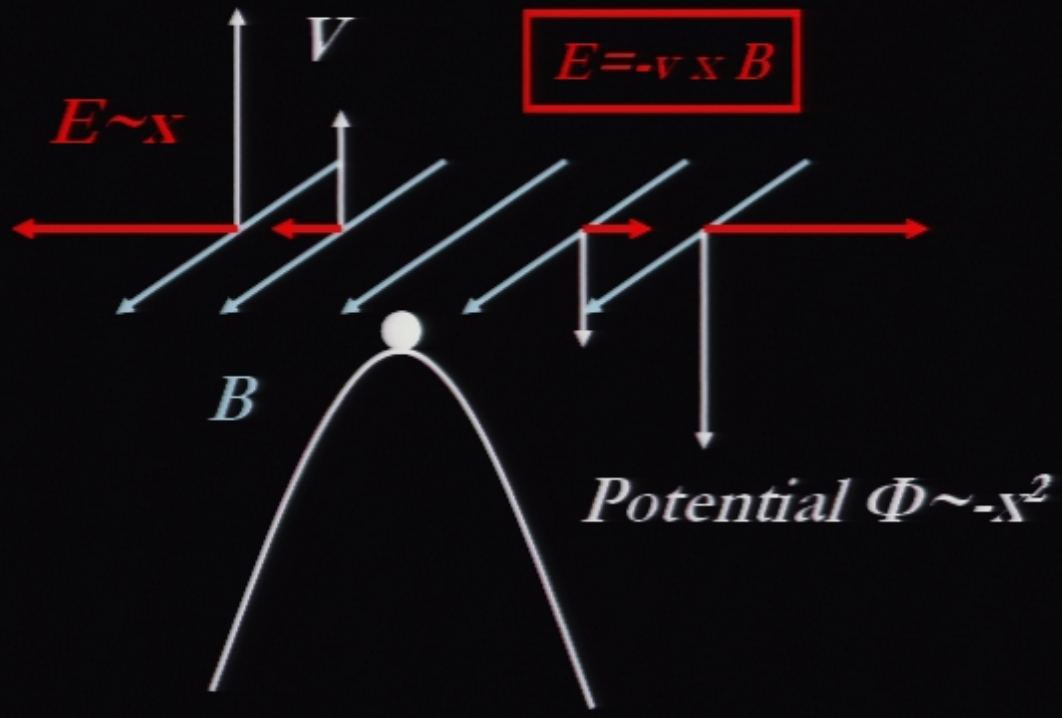

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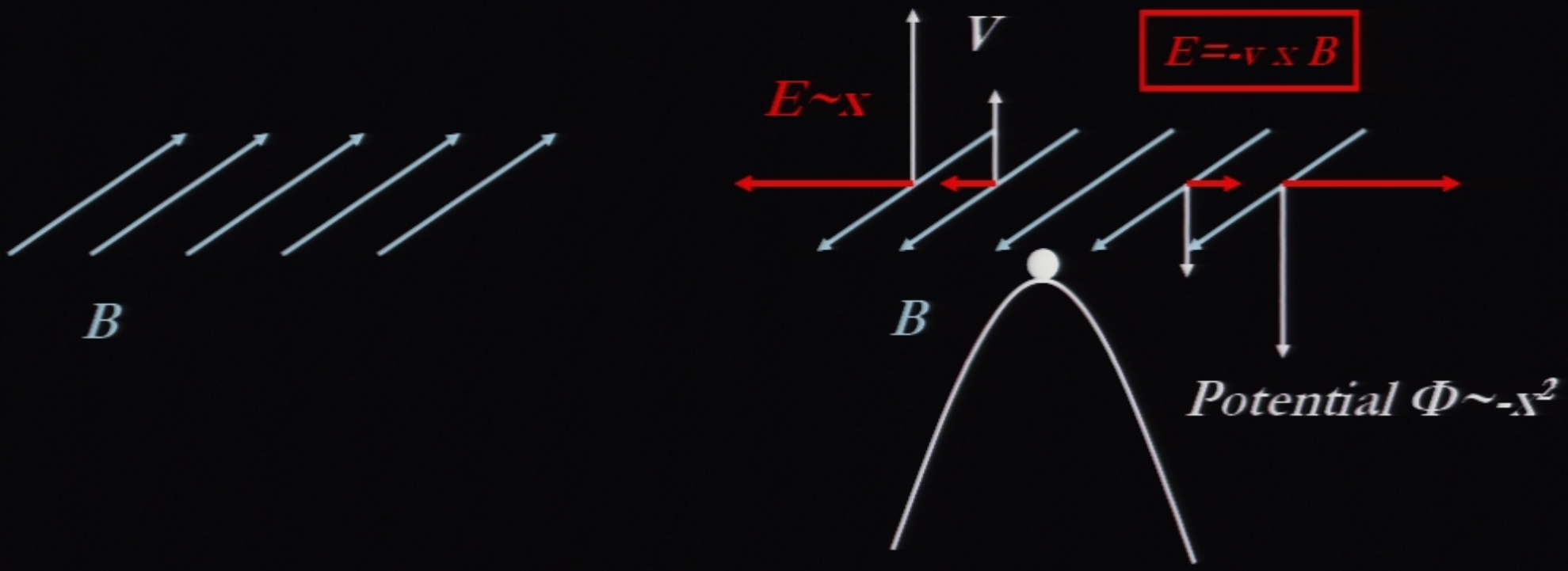

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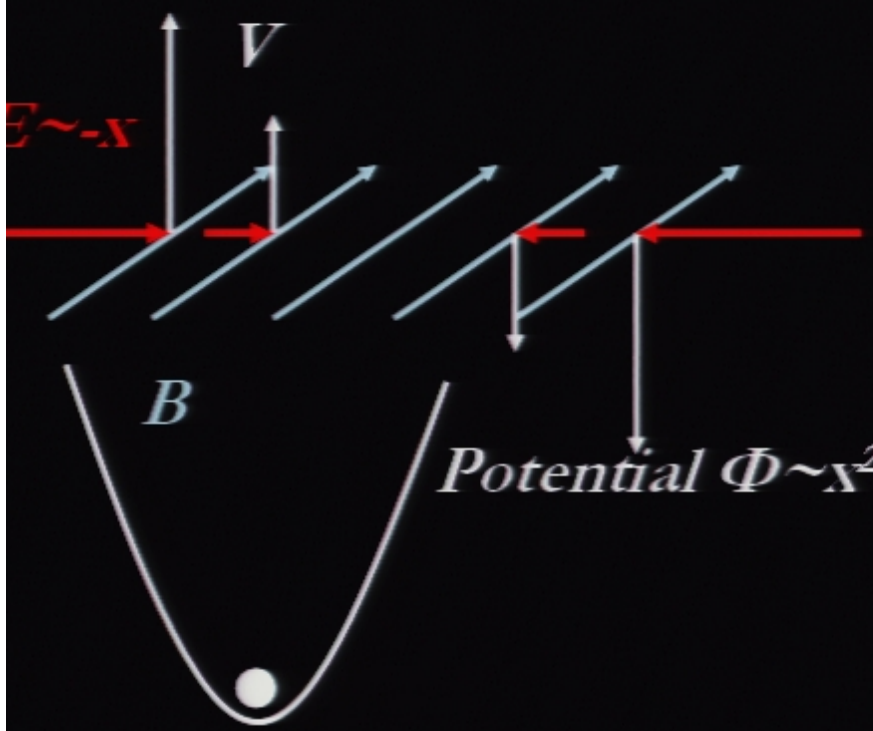

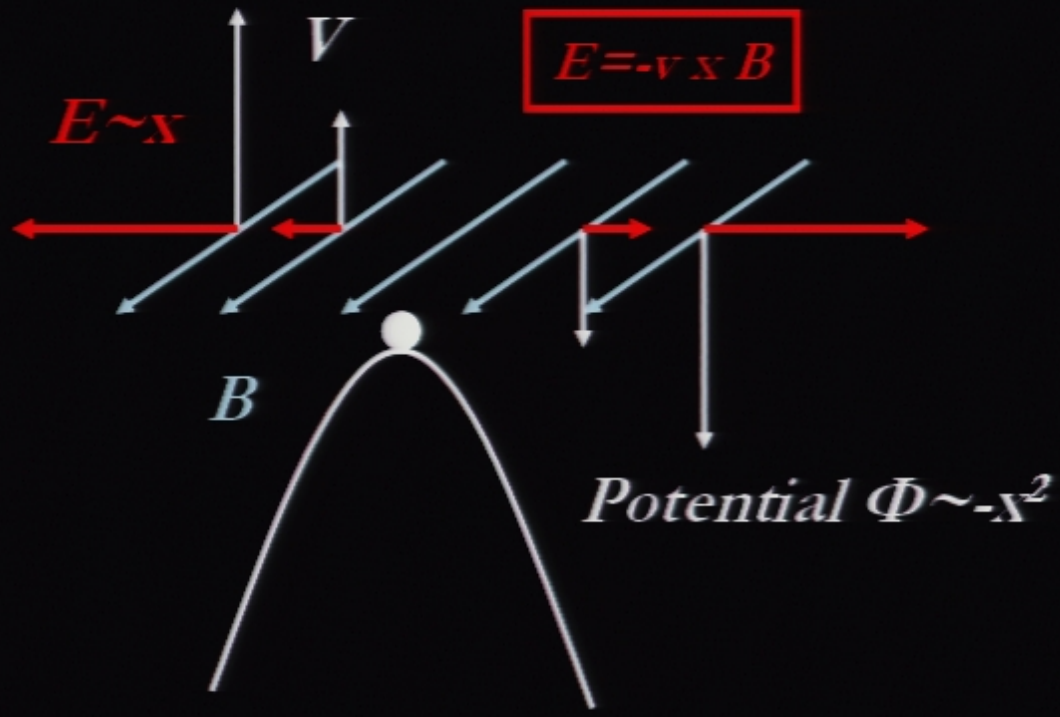

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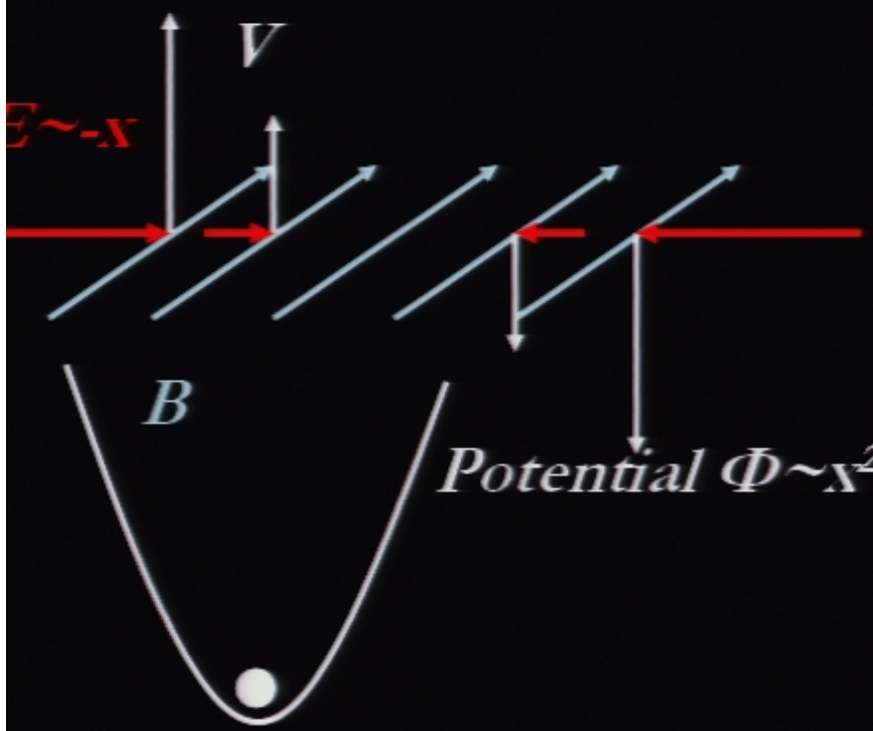

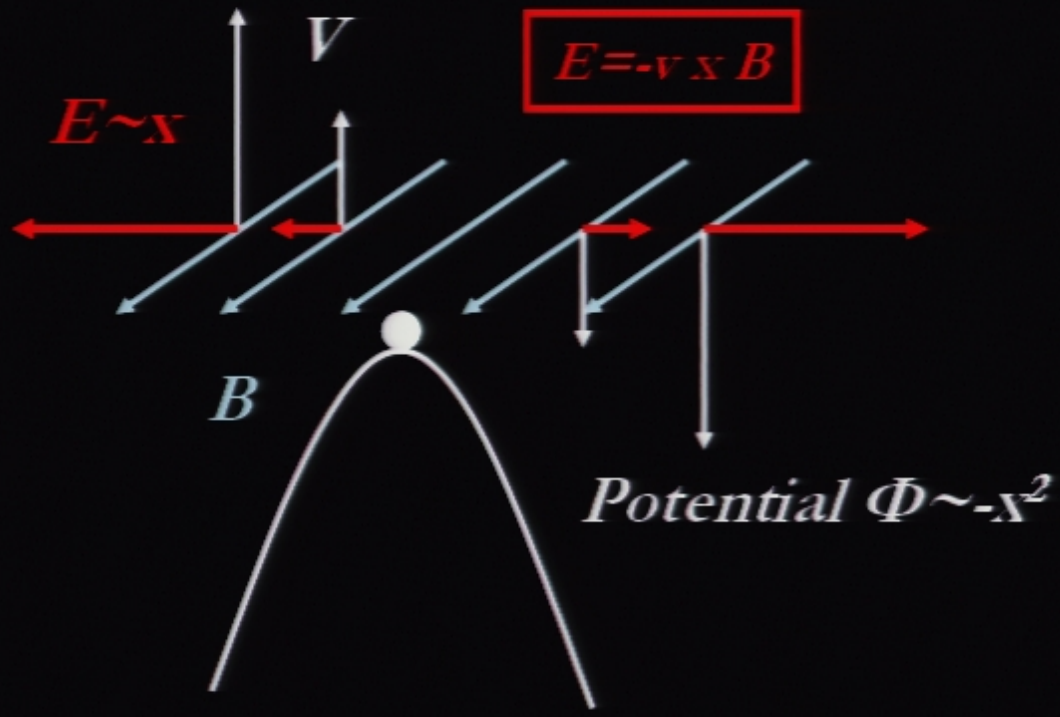

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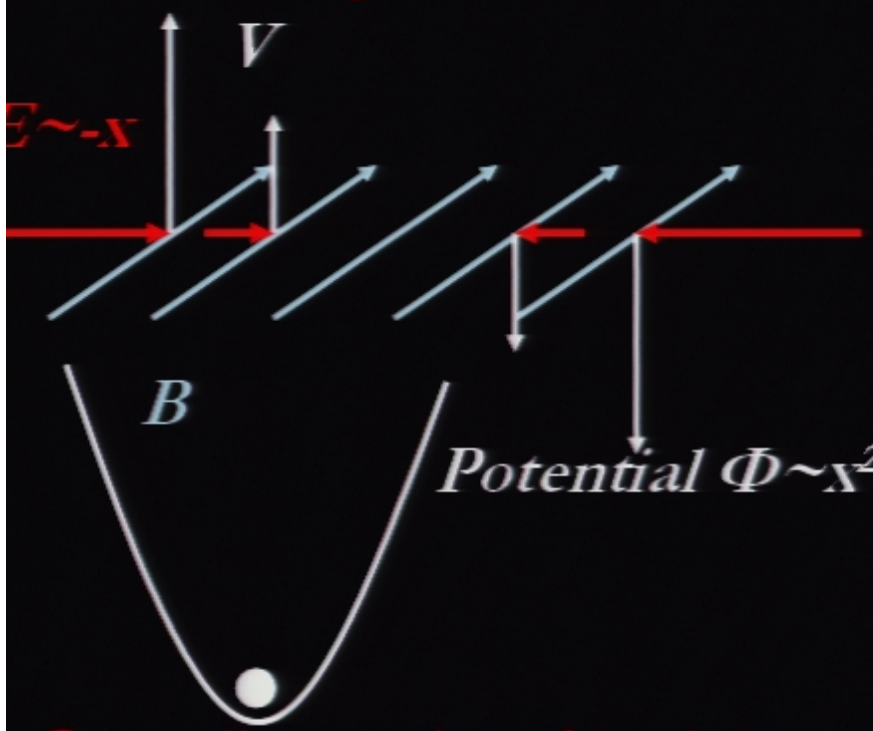

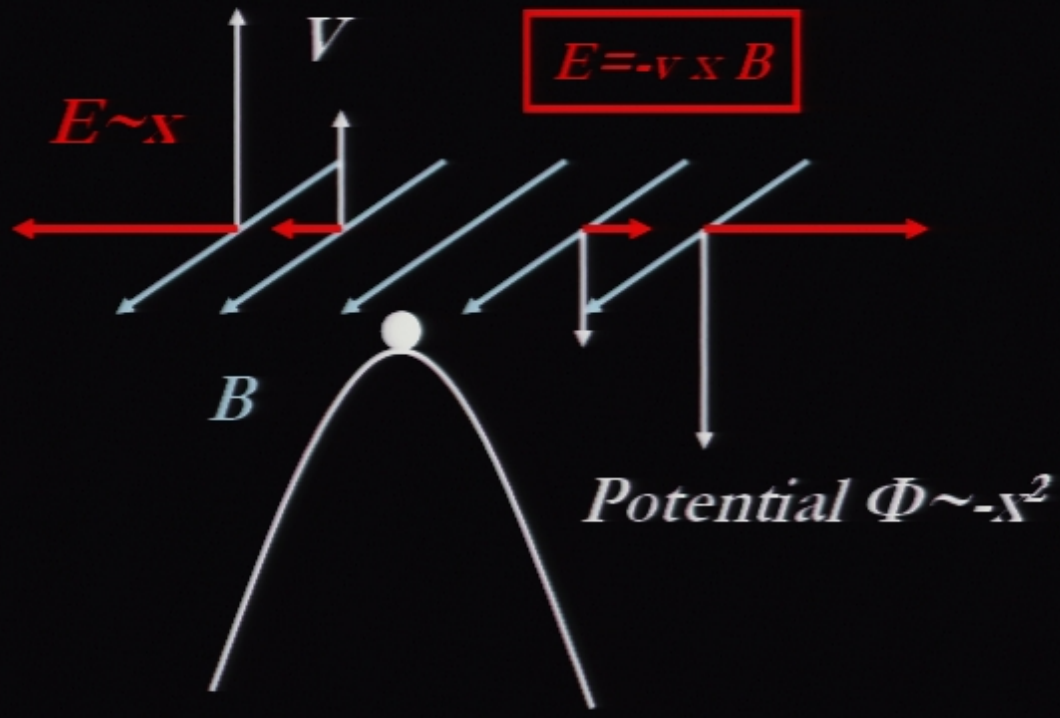

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Protons are at maximum for negative shear (B *curl v) < 0

This derivation is outside of applicability of non-relativisitc MHD

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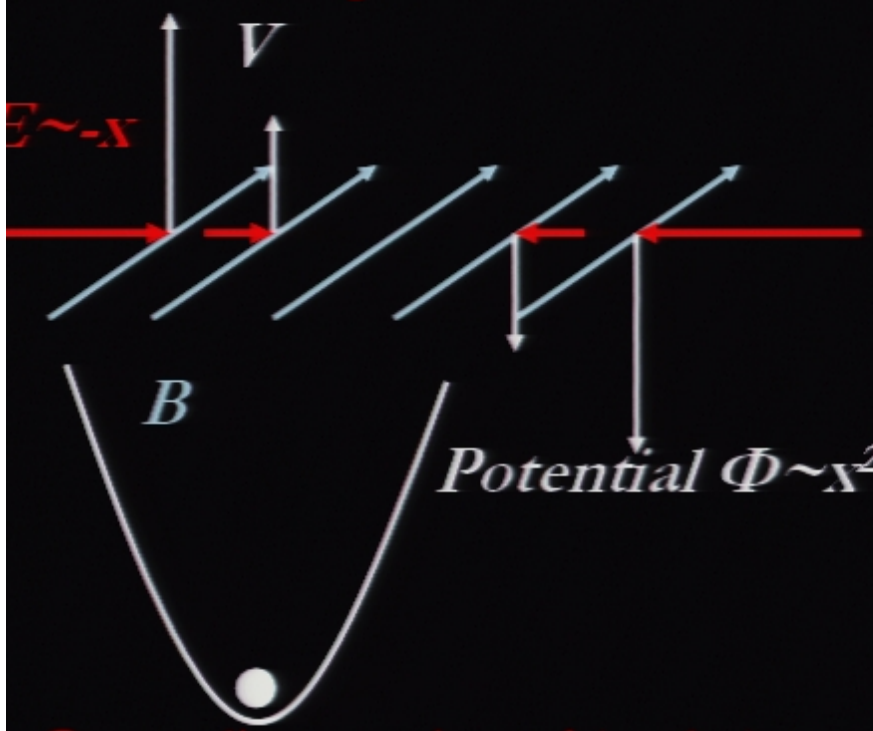

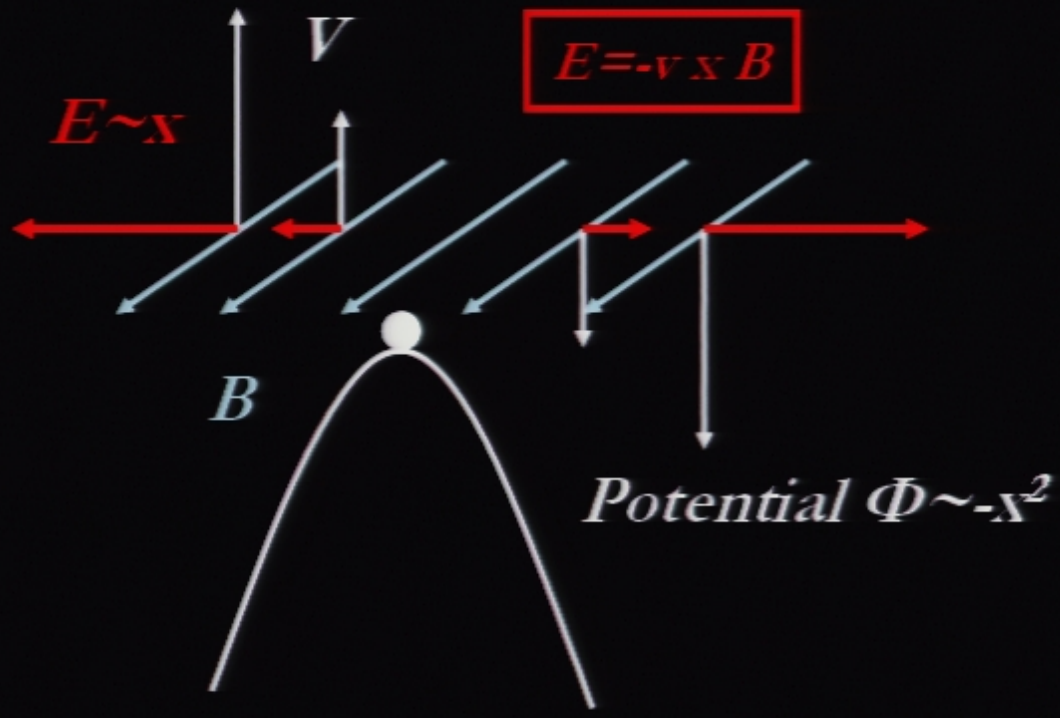

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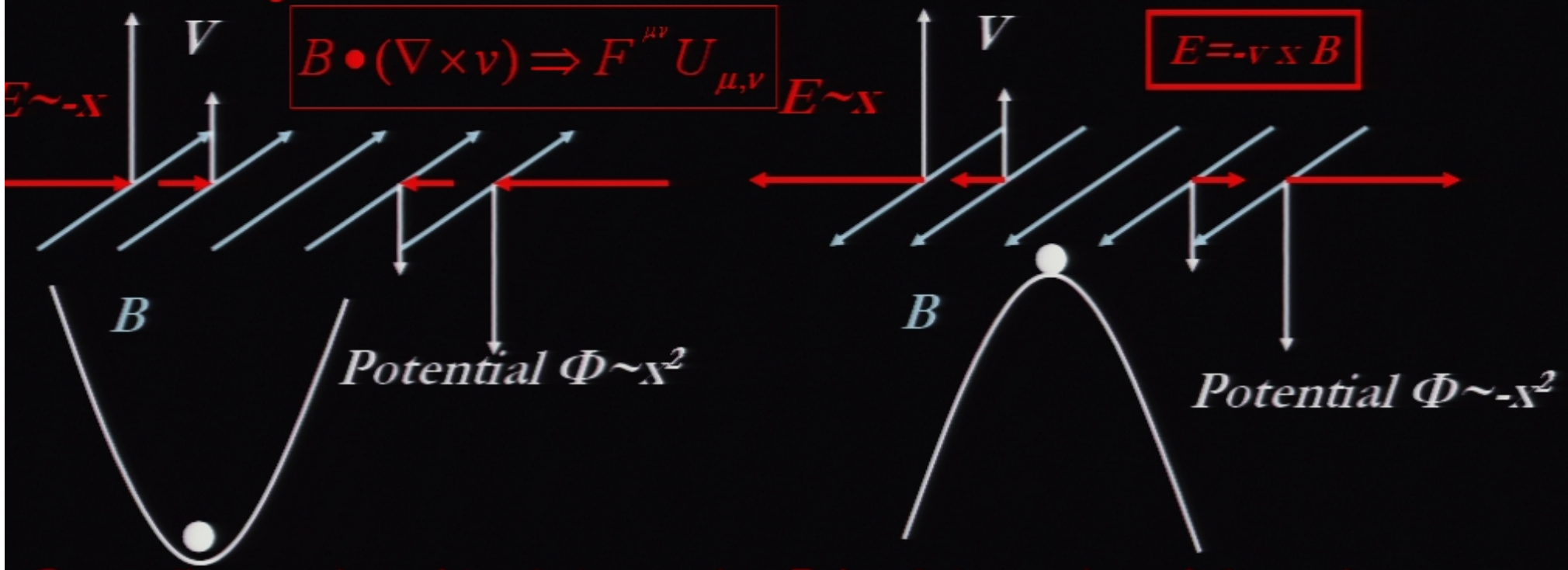
$$B \bullet (\nabla \times v) \Rightarrow F^{\mu\nu} U_{\mu,\nu}$$



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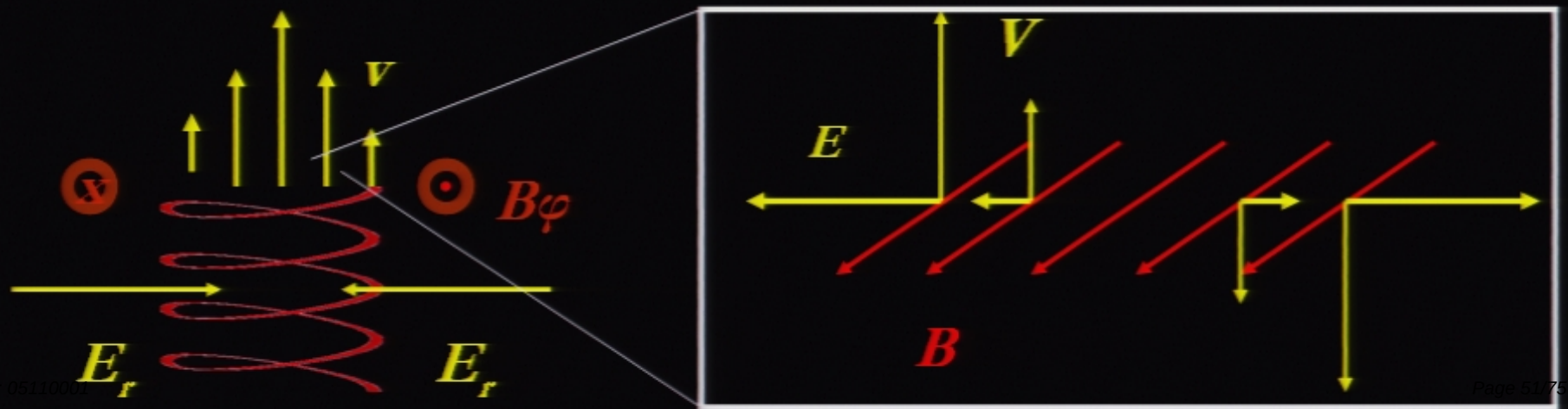
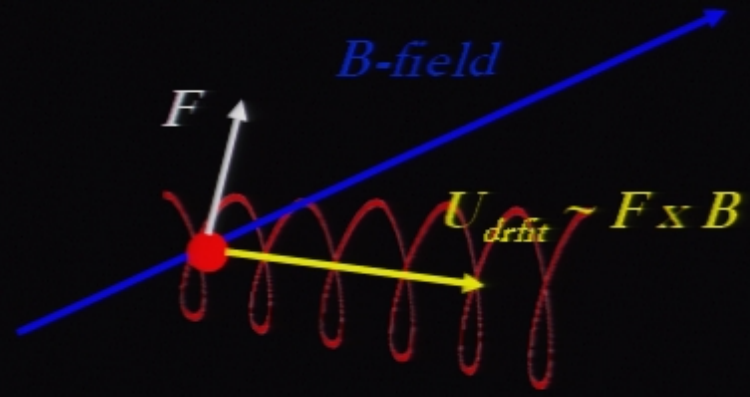
Astrophysical location: AGN jets

- *There are large scale B-fields in AGN jets*
- *Jet launching and collimation (Blandford-Znajek, Lovelace)*
- *Observational evidence of helical fields (Lyutikov et al 2004,)*
- *Jets may collimate to cylindrical surfaces (Heyvaerts & Norman)*
- *Jets are sheared (fast spine, slow edge)*



Drift due to sheared Alfven wave

- Electric field $E \sim vz \times B\varphi \sim er$: particle need to move in radially, but cannot do it freely ($B\varphi$).
- Kinetic drift



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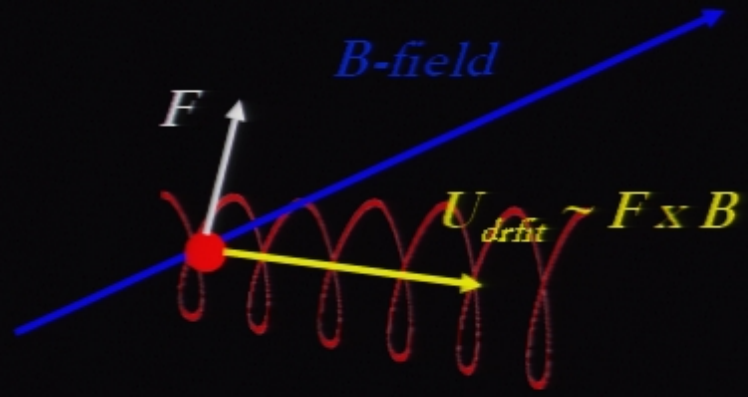

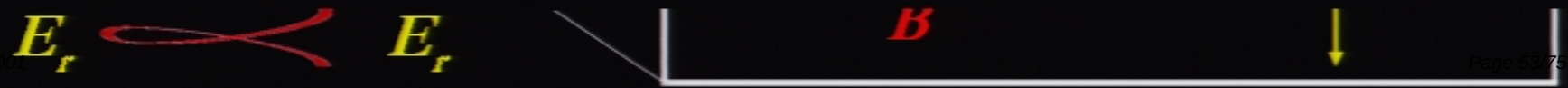

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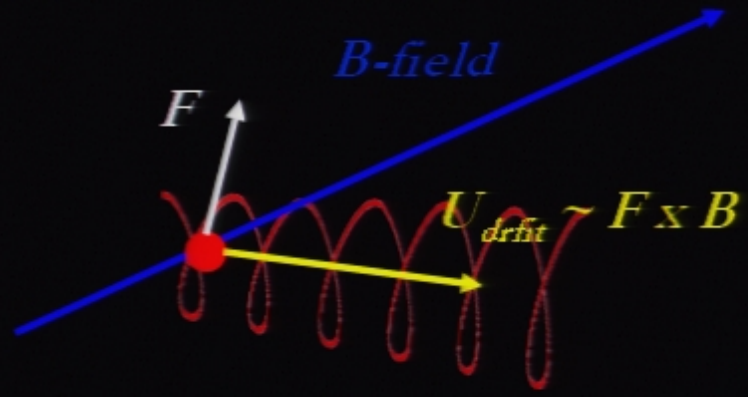

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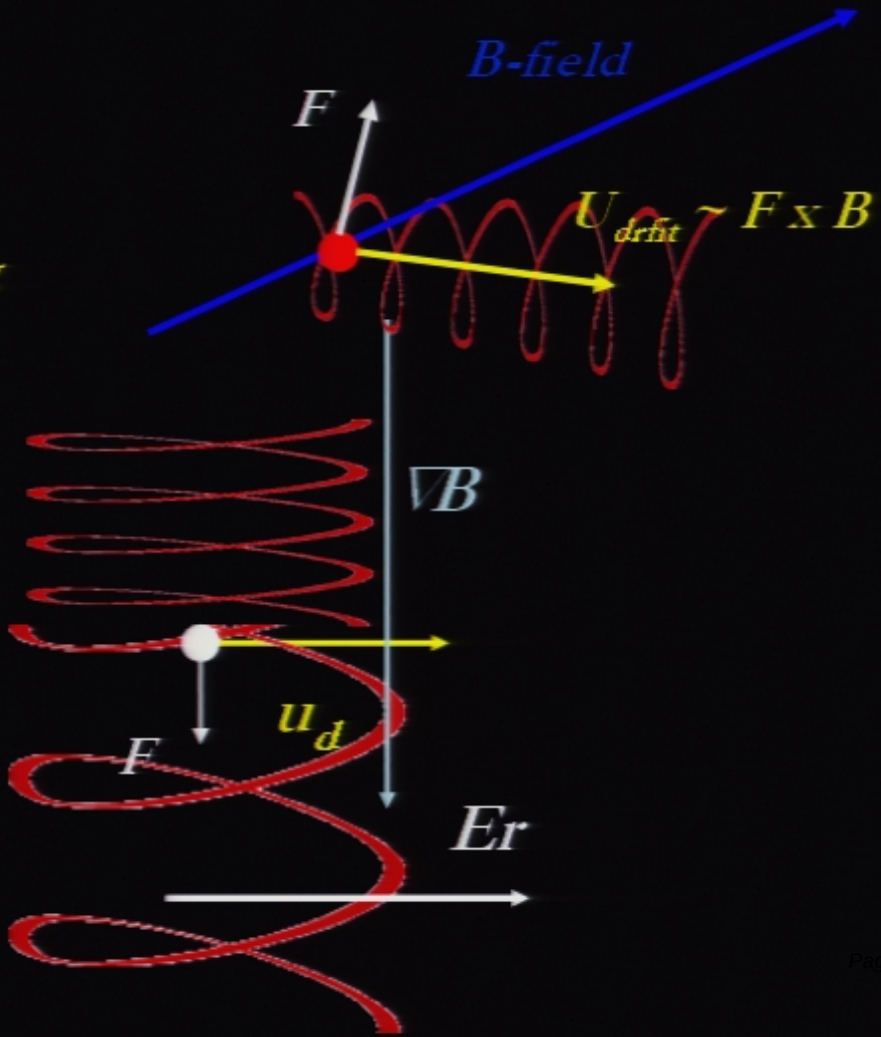

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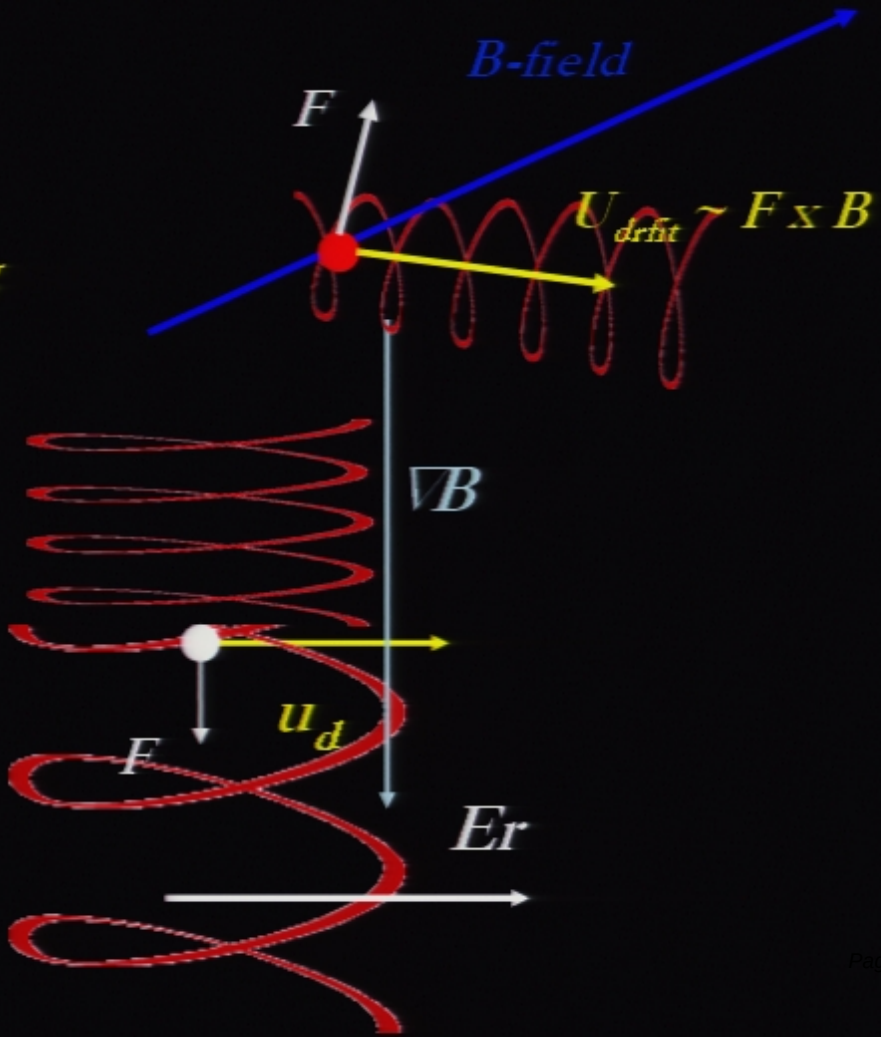

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$$\tau_{acc} \sim \frac{1}{|k_A| c} \sqrt{\frac{ZeBc}{\mathcal{E}\eta}}$$

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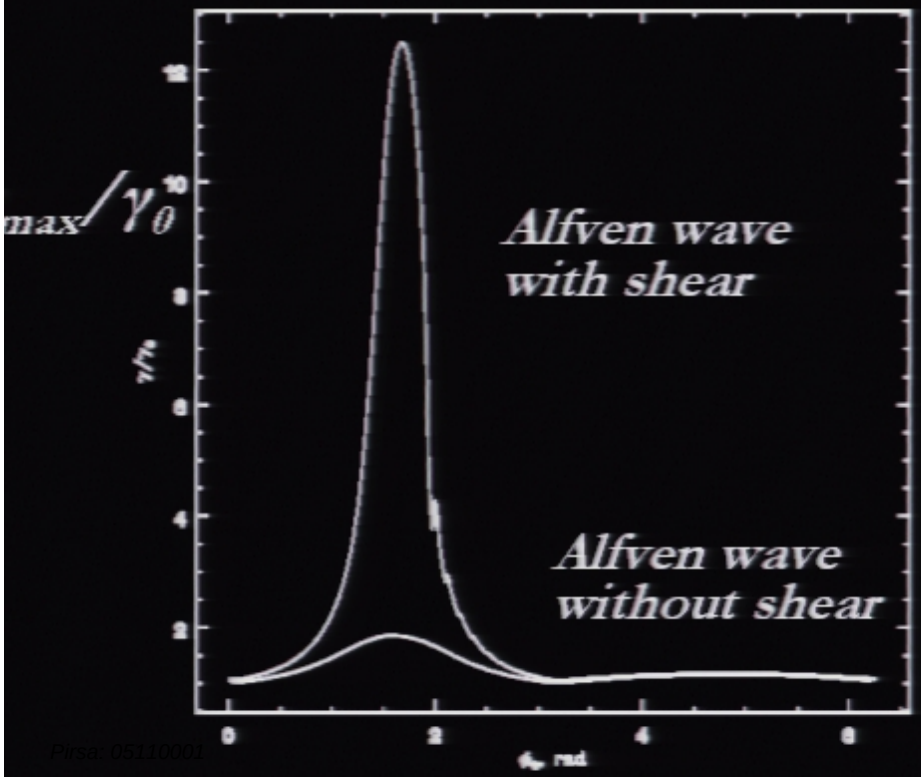

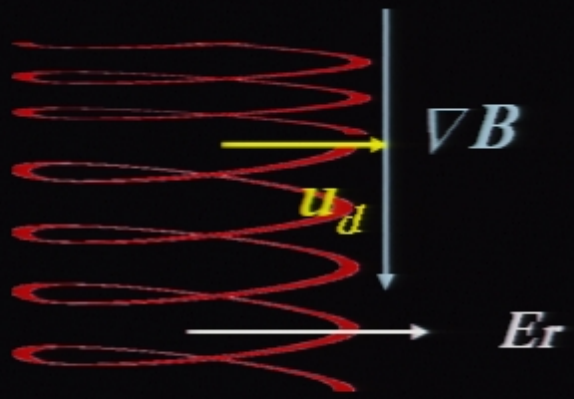

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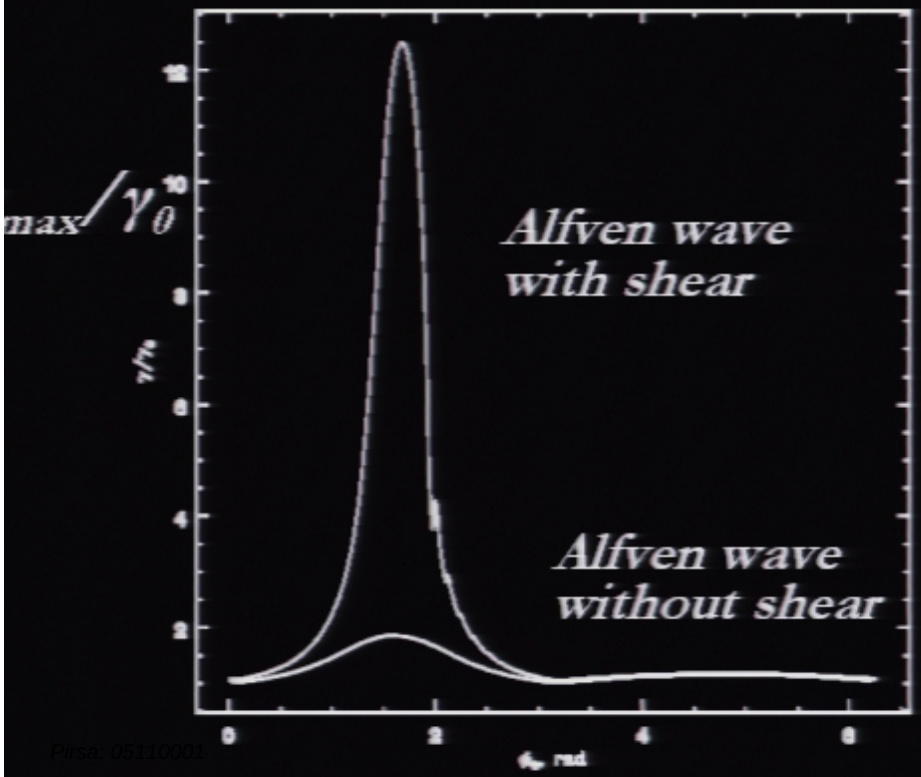

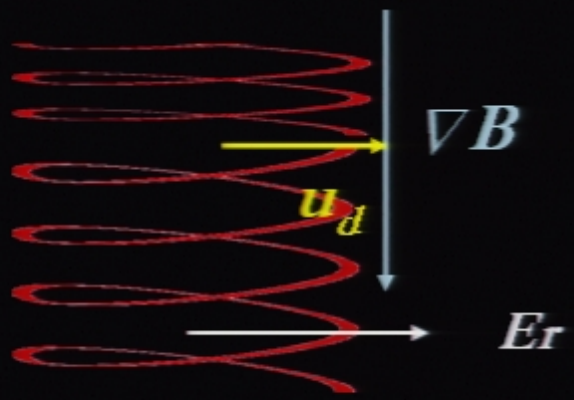

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- When r_L becomes ~ jet radius, drift approximation is no longer valid
- New acceleration mechanism
- Larmor radius of the order of the shear scale, $\eta = V' \sim \omega_B/\gamma$ (Ganguli 85)
- Non-relativistic, linear shear: $Vy = \eta x$

$$\eta = V'/\omega_B$$

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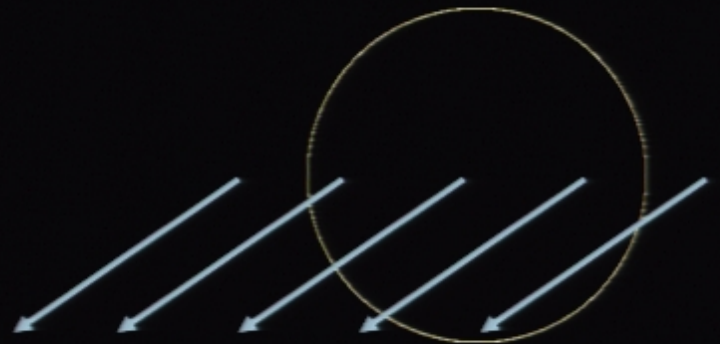

B

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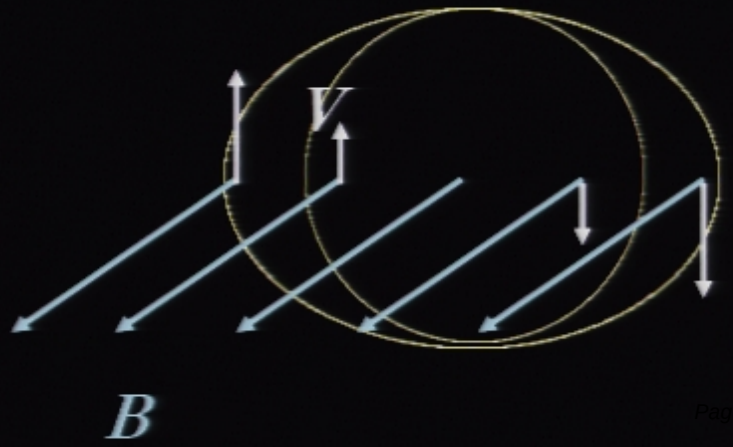

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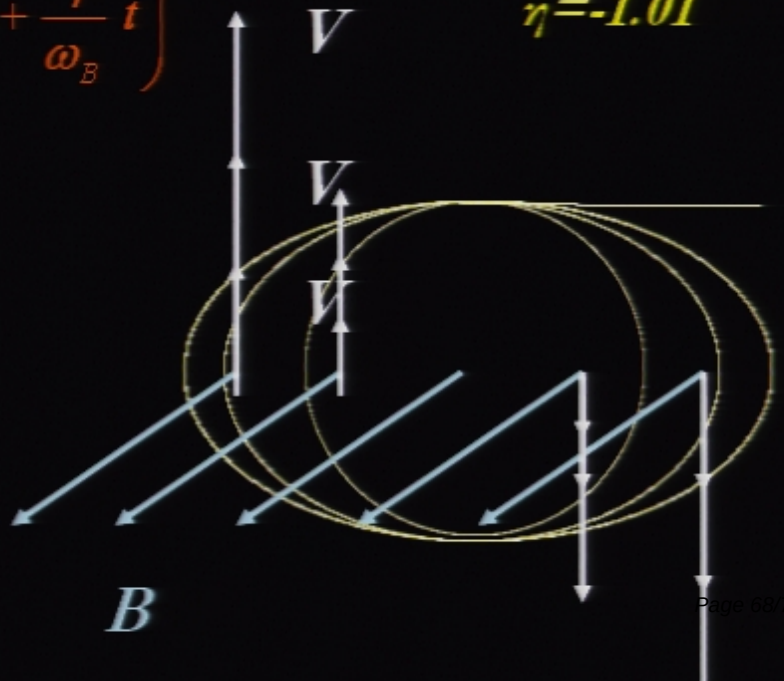
- When r_L becomes ~ jet radius, drift approximation is no longer valid
- New acceleration mechanism
- Larmor radius of the order of the shear scale, $\eta = V' \sim \omega_B/\gamma$ (Ganguli 85)
- Non-relativistic, linear shear: $Vy = \eta x$

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

unstable motion for $\eta < -\omega_B$

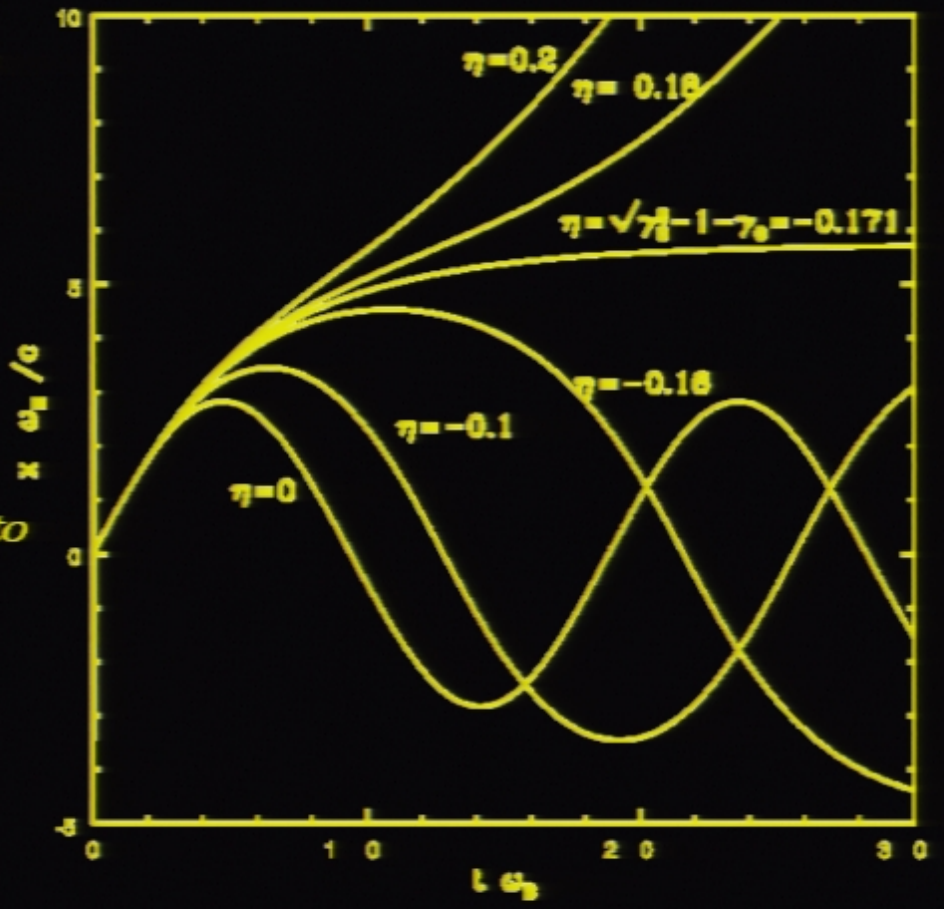
$\eta = V'/\omega_B$

$\eta = -1.01$



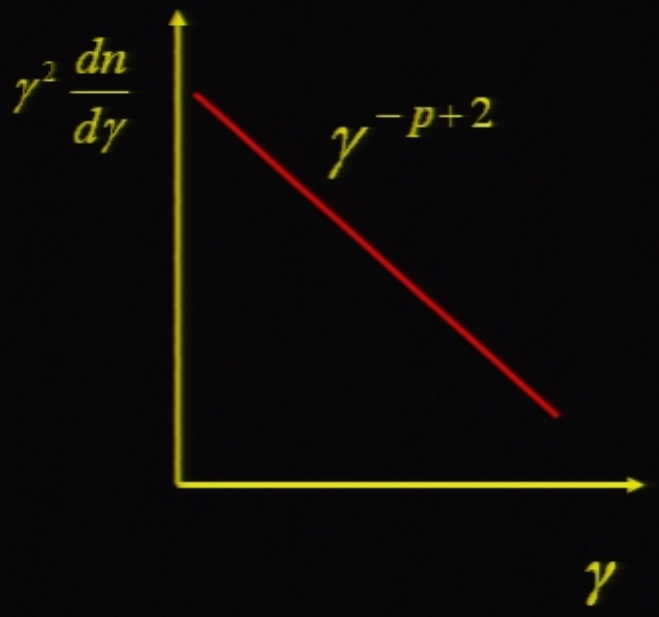
Final orbits: relativistic

- **Relativistic** $\dfrac{\eta_{crit}}{\omega_B / \gamma_0} = \gamma_0\left(-\gamma_0 + \sqrt{\gamma_0^{\,2} - 1}\right) \approx -\dfrac{1}{2}$ $\eta = V'$
- 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 (contrary to shock acceleration)



Spectrum

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



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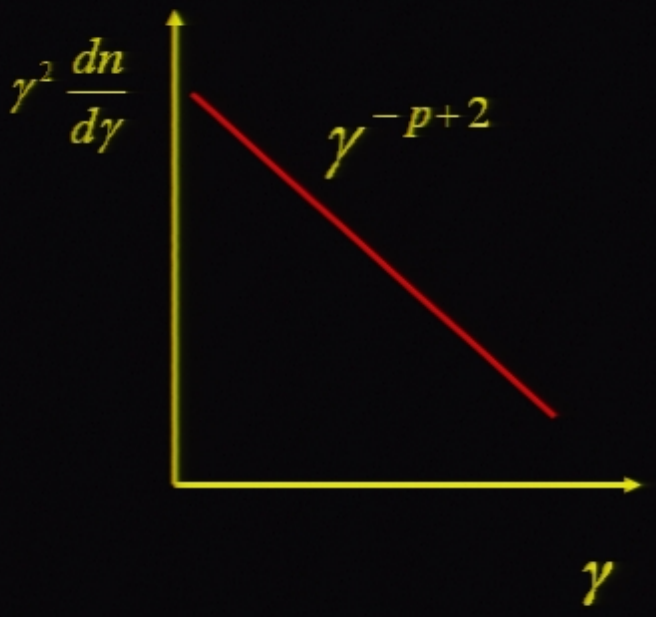

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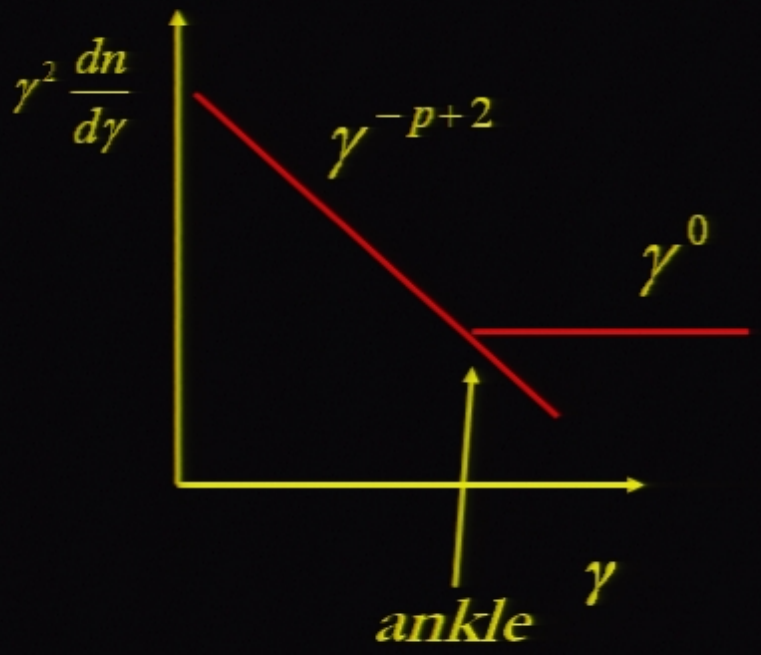
- From injection $dn/d\gamma \sim \gamma^{-p} \rightarrow dn/d\gamma \sim \gamma^{-2}$



Particles below the ankle do not gain enough energy to get $r_L \sim R_j$ and do not leave the jet

Radiative losses

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

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

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

- *As long as expansion is relativistic, total potential remains nearly constant,* $\Phi \leq \sqrt{\frac{4\pi\beta_0 L}{c}}$*, 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 our Galaxy, 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 $(B * \mathrm{curl}\ v) < 0$ (related to $(B*\Omega_{BH})$)
- Acceleration rate increases with energy and 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
- Acceleration @ 1 pc < r< Mpc: no radiative losses, lots of time
- Pierre Auger: powerful AGNs?
  - GZK cut-off
  - few sources
- May see ν & γ fluxes toward source (HESS, IceCube)