# Acceleration in Active Galactic Nuclei II

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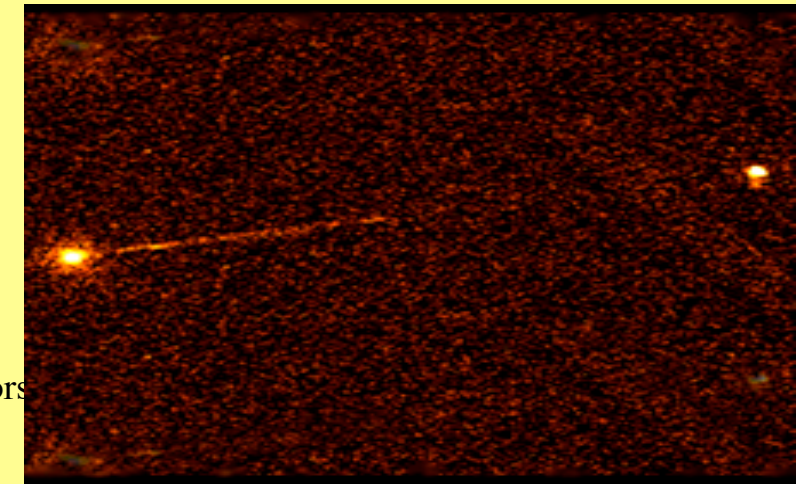
# Why study jets?

- Jets major component of galactic energy budget, impact cosmology
- Diagnostic of hole, history and environment
- GRBs you can image!
- UHECR acceleration sites?
- GeV/TeV + RXO observations should enable great advances

# Some Big Questions on Jets

- Location
  - TeV, GeV, Radio, X-ray…
- Emission Mechanisms
  - Leptonic vs Hadronic, Synchrotron vs Coherent
- Composition
  - EM, pairs, ionic plasma
- Velocity Field
  - Monolithic, vs laminar vs turbulent
- Collimation
  - Pinch vs inertial vs pressure
- Particle acceleration
  - Shocks vs reconnection vs stochastic…
- Transport
  - Power, thrust, discharge, current
- Origin
  - Black hole, relativistic accretion disk



# Location

- mm/submm VLBI resolve down to 10m (r~100m) in nearby low power sources
- $\gamma$-ray variability
  - $t_{var}$~mins reported in MKN501, PKS2155-304 at 1TeV
    - Nearby low power galaxies
  - <m! cf pulsars
  - $\Gamma$>50! cf GRBs
  - Pair production opacity to external infrared photons => r>100m
  - Breaking shockwave??
  - Cross correlate TeV-GeV variations
  - Cross correlate with radio observations
  - OVRO 40m – up to 1000 sources per day
  - VLBI observations
- Test hypotheses on whole sample

# Emission Mechanisms

- **Radio emission - synchrotron radiation?**
  - **However, intraday variability is very hard to explain**
    - $I_{\nu\Omega}=2kT_B\nu^2/c^2$, defines Brightness Temperature
    - $T_B<10^{12}$K; $S\sim\Gamma^3t^2$
    - =>r(5GHz) ~ $10^{18}$cm in high power sources
    - => $\Gamma>100$=>radiatively inefficient
  - **Or coherent emission eg cyclotron maser**
    - Nonlinear opacity constraints
  - **Or refractive interstellar scintillation**
    - Most likely now?
    - Check with frequency studies

# Emission Mechanisms

- γ-ray emission
  - **Inverse Compton scattering of synchrotron photons**
    - 10TeV => $\gamma > 10^7$ => soft photons are FIR photons
    - Soft photons also provide an opacity for escaping TeV photons
    - Test by determining location of emission
  - **Hadronic emission models**
    - Accelerate protons to >30 TeV
    - Pion produced γ-rays
    - Neutrinos!
    - Test with IceCube etc

# Composition

$$\frac{\partial B}{\partial t} = -\nabla \times E$$

$$\frac{\partial E}{\partial t} = \nabla \times B - j$$

$$\rho = \nabla \cdot E$$

$$\nabla \cdot B = 0$$

- **What carries the jet power?**
- **Electromagnetic field**
  - **DC models**
    - Force-free
    - Rel. MHD
    - Add inertia, pressure of plasma
    - Dissipation?
  - **Energy initially Poynting Flux?**
    - E x B
    - Plasma supplies currents and charge
    - Inertial effects expected to become more important with $r_7$

$$\rho E + j \times B = 0 \Rightarrow E \cdot B = E \cdot j = 0$$

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

# DC/AC Models

- Where do the currents close?
  - Near hole?
  - At end of jet?
- How do they close?
  - Dissipatively j.E => Heat
    - Hot spot?
  - Non-dissipatively j x B => Plasma Momentum
    - Fluid jet
- AC models
  - tangled field
  - Rapidly changing disk field polarity

# Pair plasma

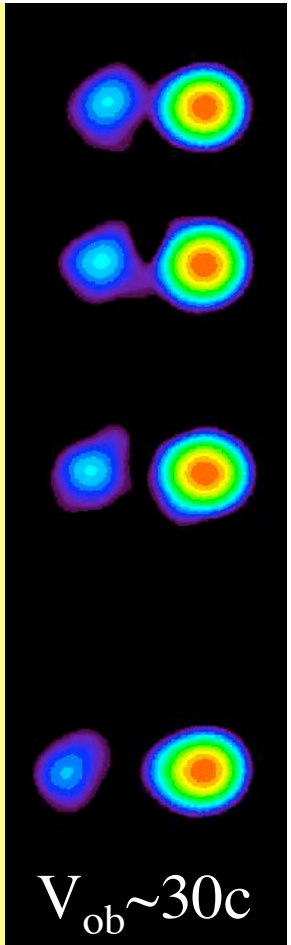
- Pairs easy to make
  - GV voltages out of EV-ZV
    - GeV gamma ray + keV X-ray -> pairs
  - Pair annihilation just as easy until energy density falls
- Pure pair jet cannot escape radiation field close to black hole
  - Something else must carry momentum

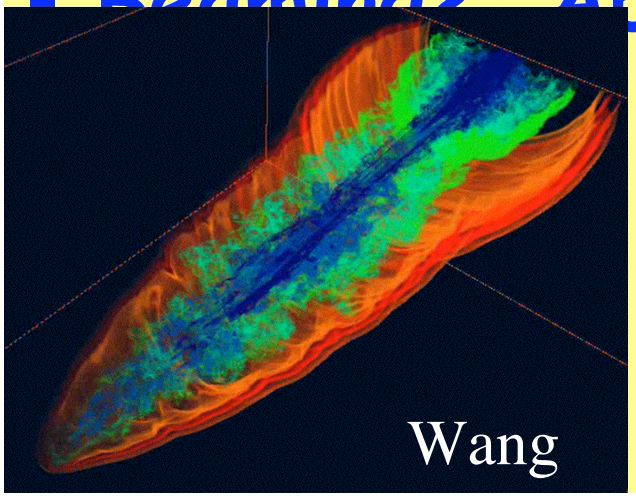
# Electron-ion plasma

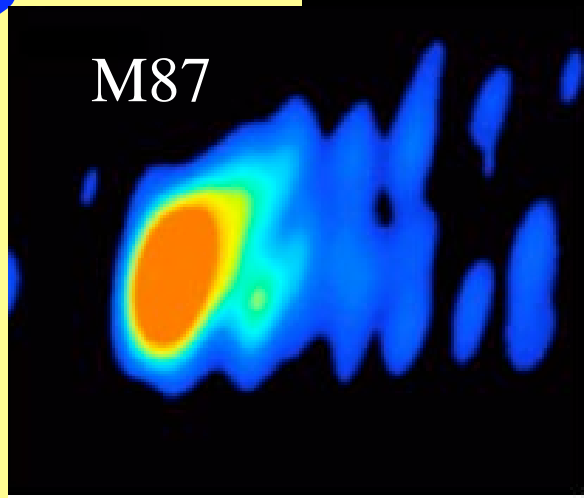
- Ions carry energy, momentum
  - Do not radiate
- Surely entrained into jet eventually
- If original jet ionic, probably originates from disk not hole
- Problems
  - Cold electrons moving with relativistic ion beam, with $\Gamma \sim 10$, create (unseen?) Compton-scattered X-rays
  - Depolarization of radio emission
- EM->pairs->ions? Where?

# Velocity Field

- Doppler blinding
  - Optically thin stationary flow, $j_\nu \propto \left(\frac{2\Gamma}{1+\Gamma^2\theta^2}\right)^{2+\alpha}$
- Jet shear is natural
  - Spine-sheath structure?
  - AMR gas-dynamical simulations exhibit turbulent sheaths
- Beaming?, Absorption?, MHD?



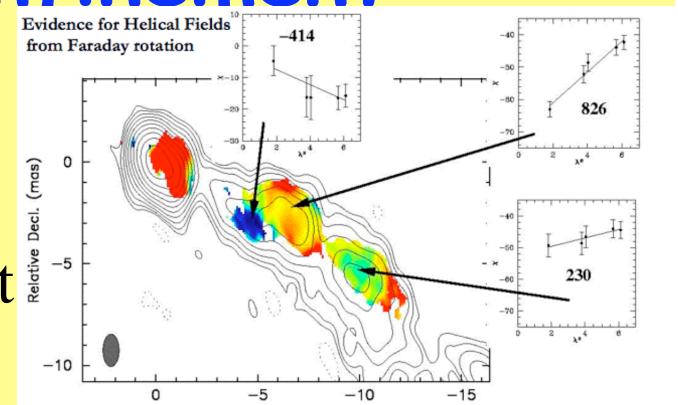



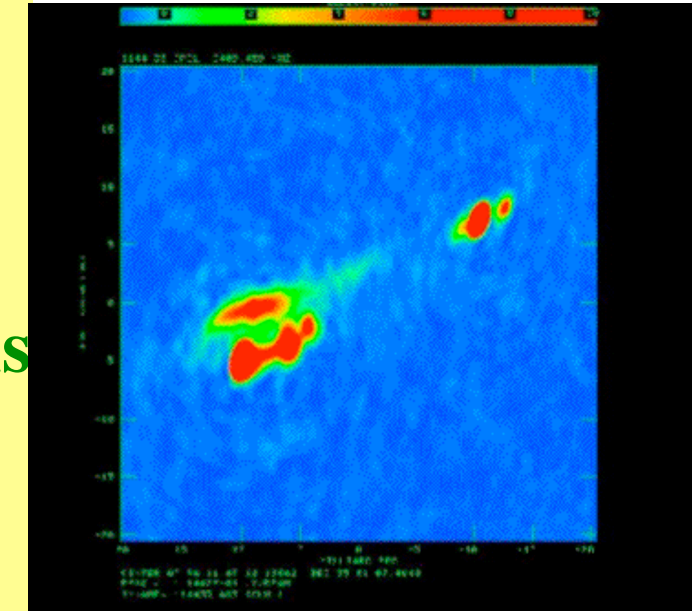
# Collimation

- **Jets overpressured with respect to external gas =>magnetic confinement**
  - **Toroidal field**
    - eg $B_\phi \sim R^{-1}$ => $(P_{ext}/P_{int}) \sim (R_{max}/R_{min})^{-2}$
    - =>Faraday rotation gradients across jet

$$\Delta\Phi = \int \frac{\omega_P^2 \omega_{G\parallel} dl}{\omega^2 c}$$

    - VLBI polarimetry
    - How far does current flow?
  - **Inertial confinement requires ions**



# Particle acceleration

- Need $\gamma \sim 10^8$ for X-rays, $\gamma$-rays
- Natural accelerator is shock
  - Internal due to disturbance at source
  - External due local instability
- Relativistic shocks
  - Gas dynamical: $P=e/3 \Rightarrow \beta_-\beta_+=1$; $\beta_s=3^{-1/2}$
  - RMHD; $\beta_s \to 1$, less dissipative
  - Force-free emission fronts
    - $B^2$-$E^2$ can change sign => catastrophic pair production emission

# UHECR

- EMF ~ $(LZ_0)^{1/2}$
  - ~ZV for quasars, Cyg A etc
- Are lower power AGN Auger sources?
- Is EMF sufficient?
- Can currents flow to region where protons can escape without photopion production?
- Must field be regenerated?

# Homogeneous acceleration

- Required by X-ray observations eg M87
  - Electrons cool between shocks
    - $t_{cool} \sim B_{mG}^{-3/2}$ yr
- Stochastic acceleration
  - Relativistic MHD wave modes/weak shocks
  - Second order process
- Relativistic reconnection
  - Poorly understood but likely to be efficient
  - Non-realtivistic reconnection better understood now

# Transport

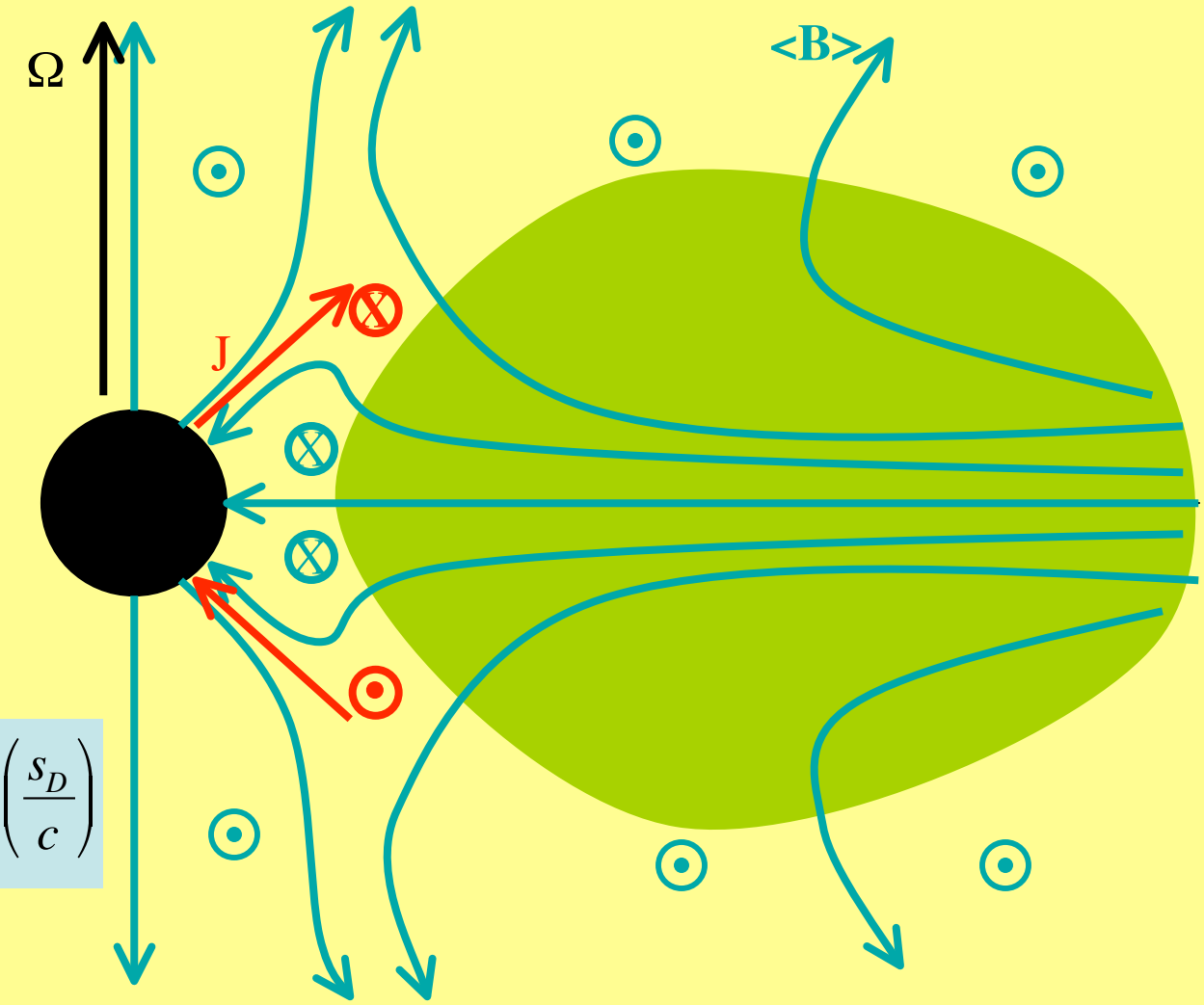
- What is energy, momentum, mass, current carried by jets
  - $F = w\Gamma^2 B + E \times B$
- Important for environmental impacts
- Measure jet properties
  - Sample average -> angle average
- Measure calorimetrically using radio lobes
  - Important correlations with proxies are emerging

# Origin

- What can we learn about the hole/disk?
- VLBI observations
  - mm/submm observations
  - VSOP2 (2012)
  - R~ few m in M87, Cen A Sgr A*
- Internal shocks?
  - Correlated features in both jets?
- Understand current flow
- Test Central Dogma

# On the Electrodynamics of Moving Bodies

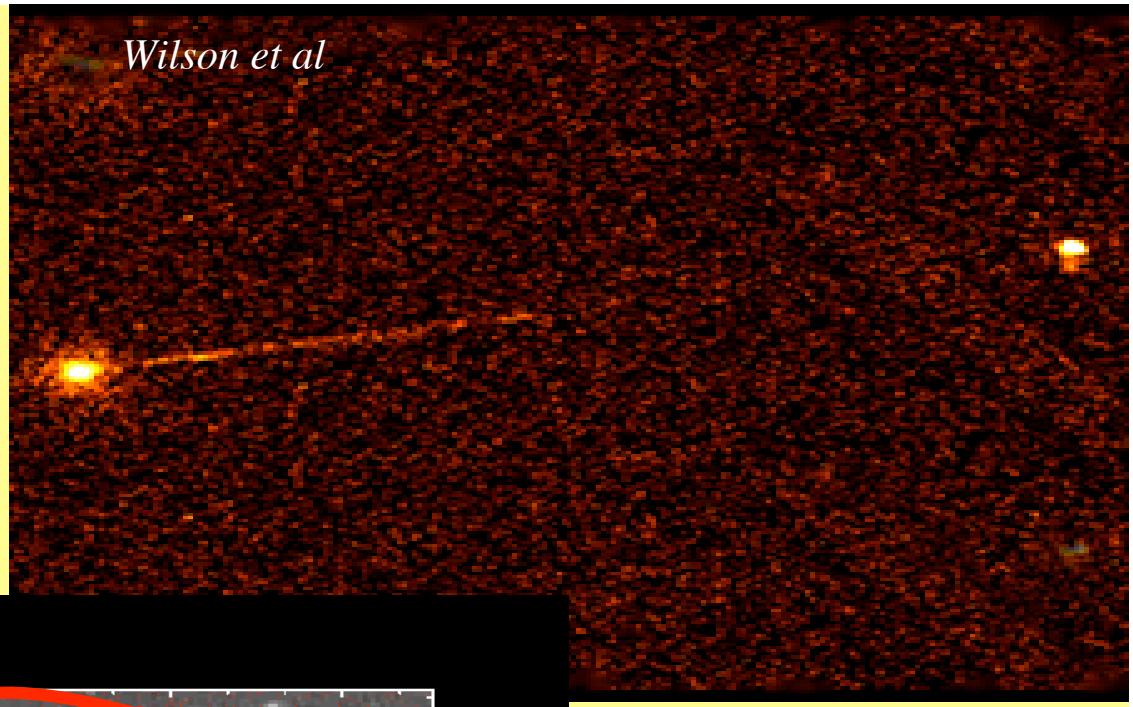
**Even field**
**Odd current**

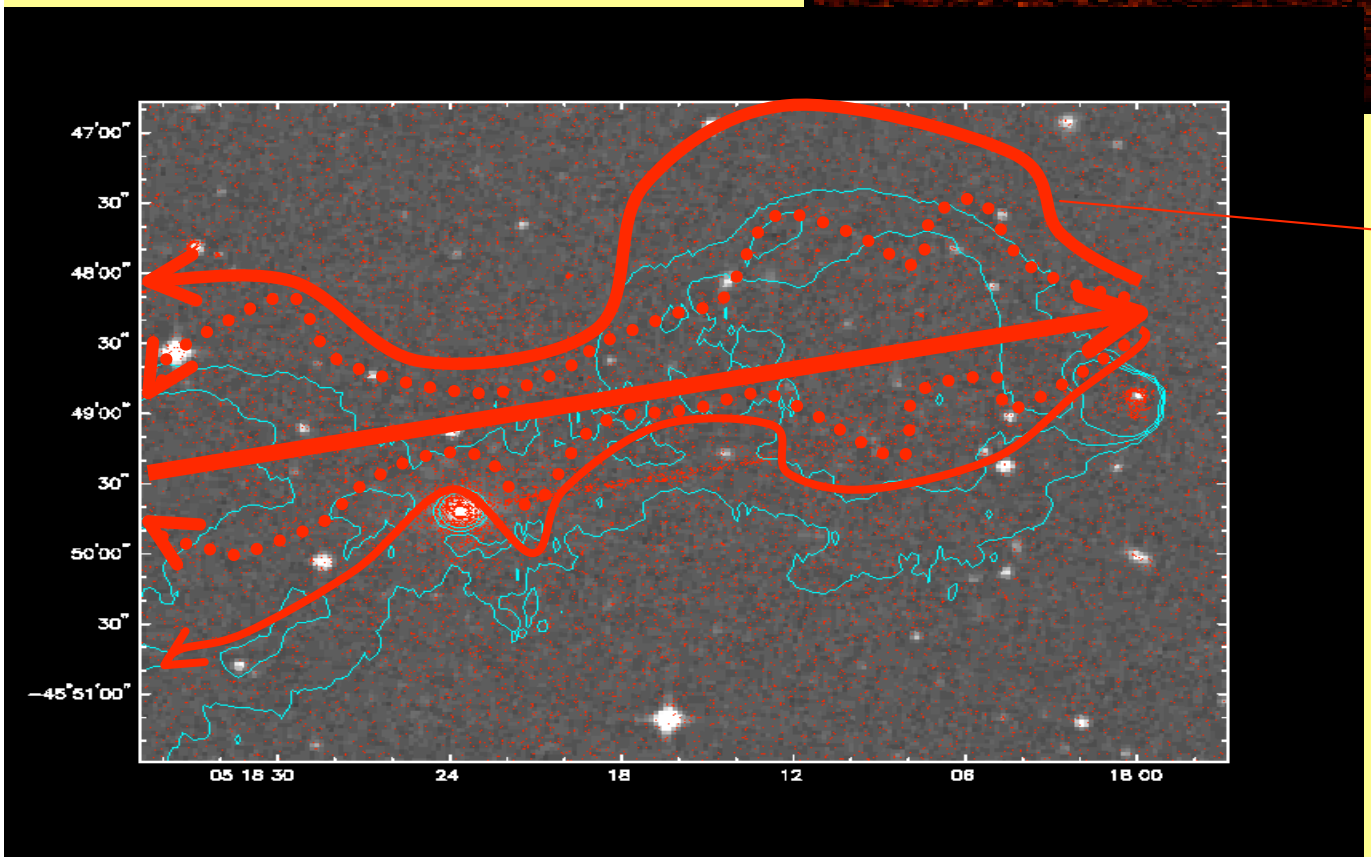



$$\frac{L_H}{L_D} \sim \left(\frac{1}{\alpha_D \beta_D}\right)\left(\frac{\Omega_H}{\Omega_D}\right)^2\left(\frac{s_D}{c}\right)$$

# Pictor A

Electromagnetic Transport
$10^{18}$ not $10^{17}$ A
DC not AC
No internal shocks
New acceleration mechanisms




## Current Flow

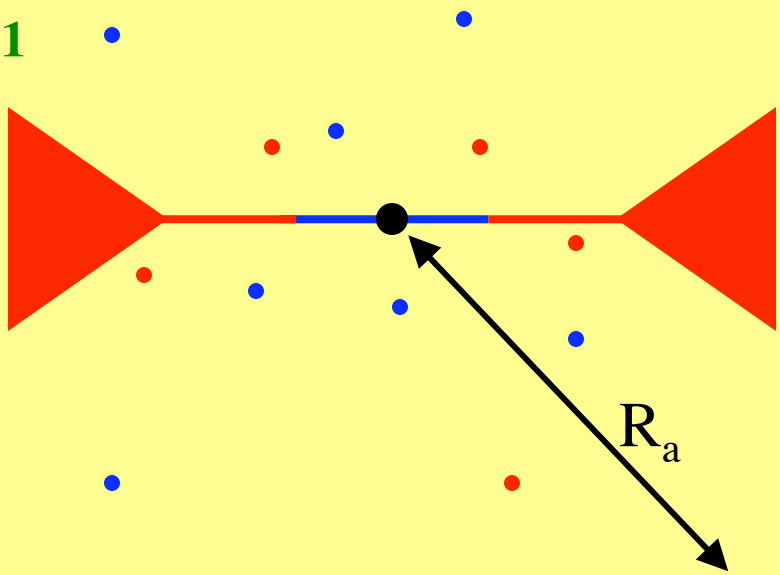
**Nonthermal emissio is ohmic dissipation of current flow?**

**Pinch stabilized by velocity gradient**

**Equipartition in core**

# Evolution of Mass Supply, Hole

- Disk begins at accretion radius
  - $R_a \sim GM/\sigma^2 \sim (c/\sigma)^2 m \sim 10^6 R_{in} \sigma_{300}^{-2}$
- Supply rate
  - $\sim(\sigma^3/G) f_{gas} \sim 4\times10^{29} \sigma_{300}^3 f_{gas}$ g s$^{-1}$
- Inflow time
  - $R_a/\sigma \sim 2\times10^{-3} M_6$ Myr
  - >Jet flow time
- Mass increment
  - $\Delta\mu \sim f_{gas}$
  - Spin evolves stochastically



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