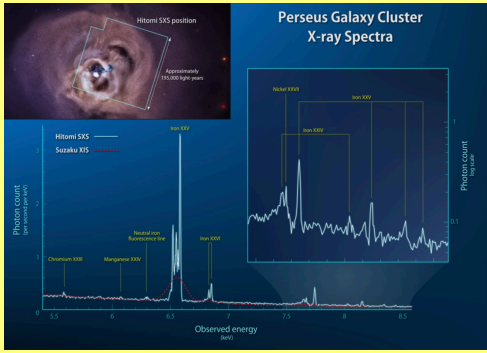
Electromagnetic Jets and the Black Hole Shadow



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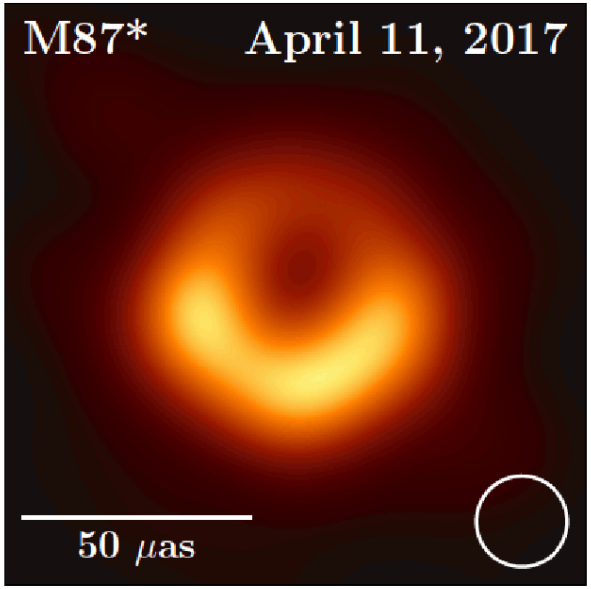
Summary

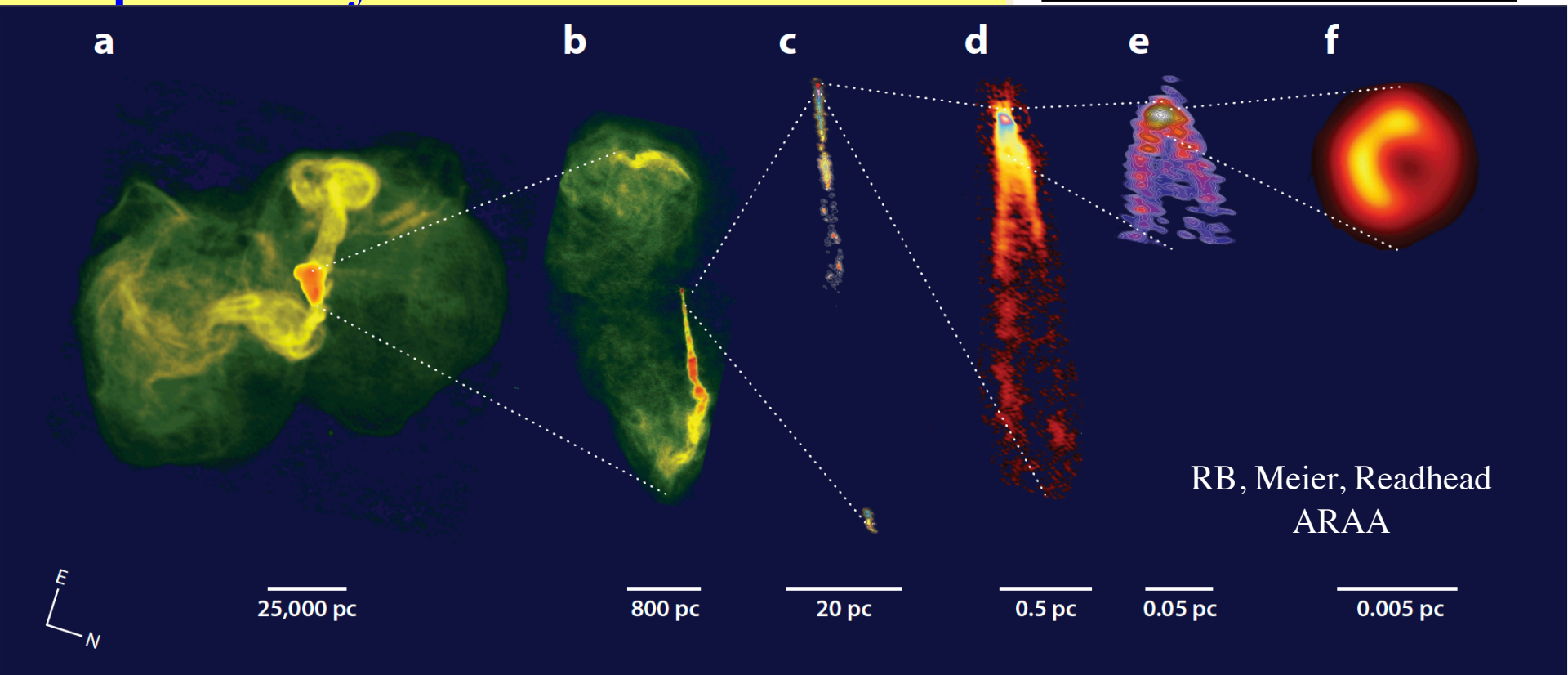
- 1. Holes Power Jets
- 2. Jets Confined Electromagnetically
- 3. EHT Observes Ergomagnetosphere
- 4. Radiative Transfer can Test GR
- 5. VLBI Observes Jet Boundary Layers
- 6. MHD Winds Shield Jets and Form BEL
- 7. γ–ray Hump is Synchrotron Radiation
- 8. FR I/II Imposed at Bondi Radius
- 9. RL/RQ due to Magnetic Concentration

1. Holes Power Jets

M87-EHT

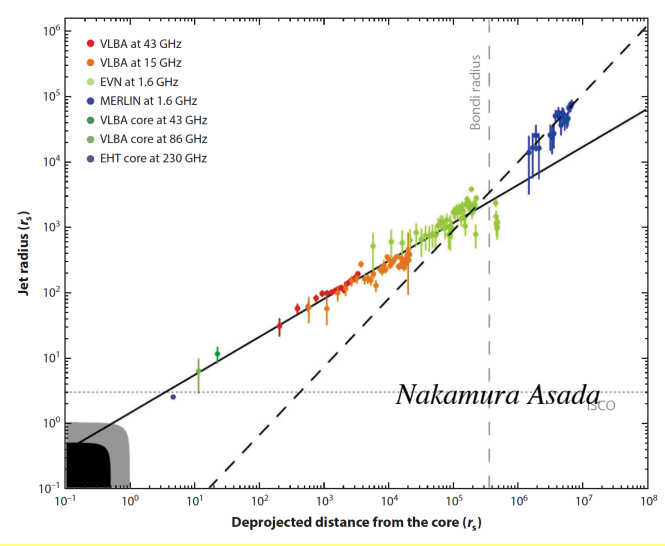
- D~17 Mpc
  - Rich Cluster of Galaxies
- M ~ 6.5 x 10^9 M_{sun}
  - ~ 10 Tm ~ 4 μas ~ 10 hr
  - Use as units
- Spin into sky at 163°

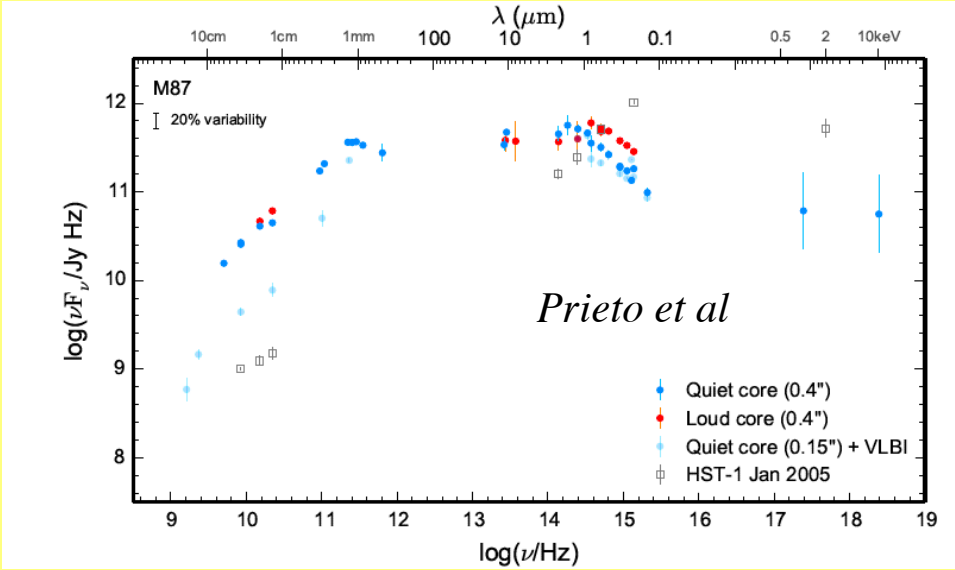




Disk vs Black Hole Jets

- Jet power > 10^{36} W ~$10^{-5}L_{Edd}$
  - Roughly paraboloidal, then linear
- L_{mm}~ 4 x 10^{33} W
  - $L_{iso,bol} < 10^{34}$ W ~ 10^{-7} L_{edd}
  - Once as bright as Vega!
- Disks naturally dissipative
  - MRI instability
  - Why are they invisible?
- Hole spin energy
  - Invisible dissipation!
  - Sufficient for 10^{14}yr
  - B > 0.1T at hole



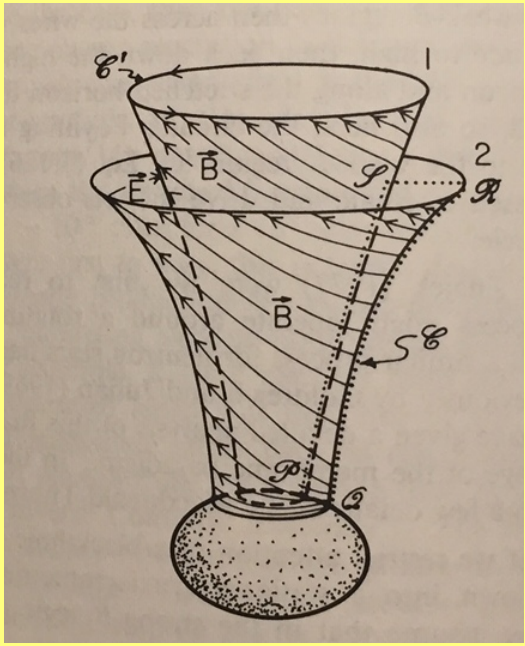


18 x 2

Jet is Powered by Spinning Black Hole not a Disk

Stationary, Axisymmetric, Force-Free, Magnetosophere

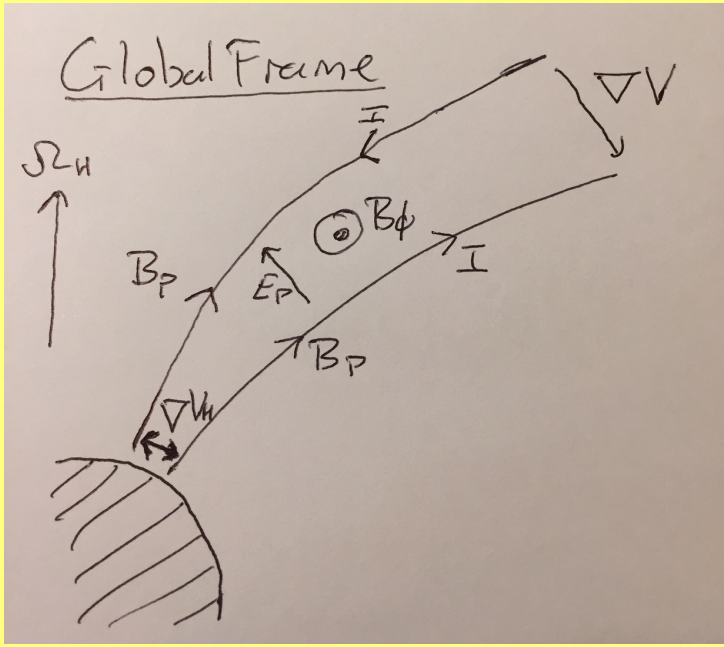
- **Kerr metric**
  - BL frame: symmetry -> conservation
  - ZAMO orthonormal basis; $\omega \rightarrow \Omega_h$
- **Force-free => $\rho E + j \times B = 0$**
  - Not RMHD!
  - Equipotential, Flux Surfaces: $V(\Phi)$
  - Rotation: $\Omega(\Phi) = 2\pi dV/d\Phi$
    - $0 < \Omega < \Omega_h$; two light cylinders
  - Poloidal Current $I=I(\Phi)$ => Toroidal Field
  - Torque: $dG_B = I\, d\Phi / 2\pi$; Power: $dL_B = I\, dV = \Omega\, dG_B$
  - $dL_Z = (\Omega - \Omega_h) dG_B < 0$



MacDonald, Thorne, Komessarov, Uchida, Gralla, Jacobso

Electromagnetic Penrose Process operating in entire spacetime

Boundary Conditions



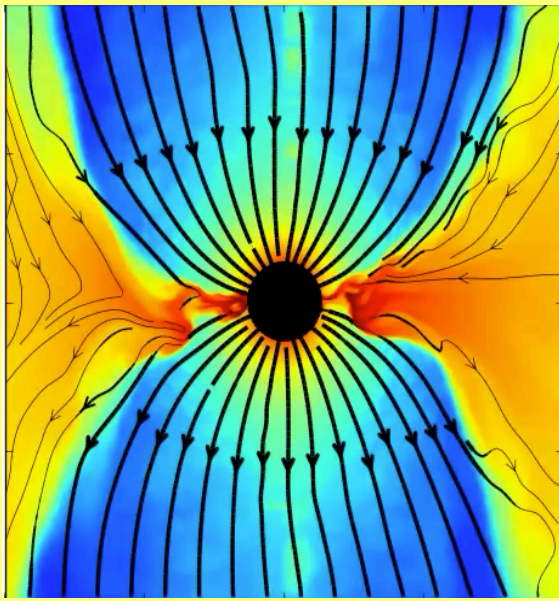
- Fix shape of Φ_{max}
  - Trial $s(\theta,\Phi)$, where $ds=dr/\Delta^{1/2}$
- Jet outflow:
  - $E_p \sim c\, B_\phi \Rightarrow \nabla V_B \sim Z_0 I/2\pi\varpi$
- Hole inflow:
  - $E_p \sim c\, B_\phi \Rightarrow \nabla V_Z \sim Z_0 I/2\pi\varpi$
- Compromise angular frequency
  - $\Rightarrow \Omega=\Omega_h(1+dR_J/dR_H)^{-1}$
- Relax to force-free solution
  - Transverse stress balance (Grad-Shafranov equation)
  - Variational principle *Scharlemann, Wagoner*
- Total EM power $L \sim \Omega_h^2 \Phi^2$

Efficiency of spin energy extraction ~ 0.5

2. Jets Confined Electromagnetically

Ion vs Magnetic Confinement

- **Ion Torus**
  - $n_i \sim 3 \times 10^{14}\ m^{-3}$; $T_i \sim 100MeV >> T_e$
  - Hard to avoid equilibration
  - $L_X \sim 100$ measured value
  - Faraday rotation $\sim 10^9$ rad.
- **Magnetic Confinement**
  - $t_{cool} < 30s \Rightarrow \gamma \sim 15 > 3\ kT_b/m_e c^2$ at 1.3 mm
  - $\langle P_e \rangle \sim L_{mm} t_{cool}/3V_{ring} < 10^{-11}\ P_{mag}$!
  - Add ions, cooler electrons, filling factor?

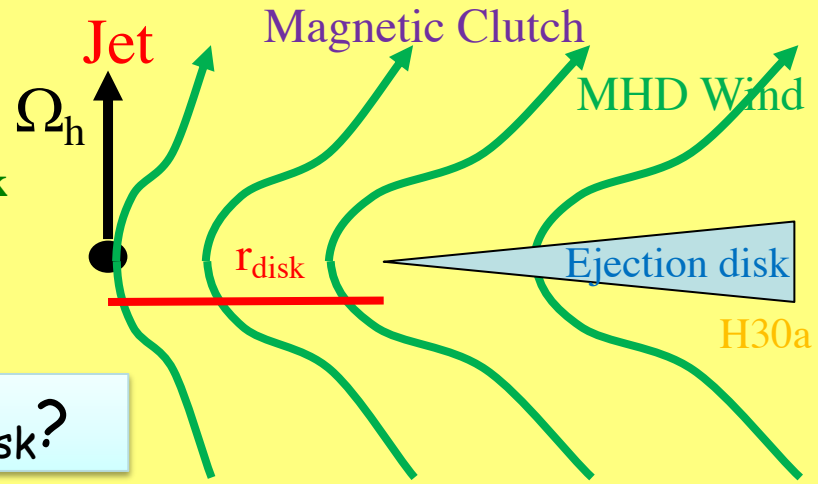


McKinney et al

Jet is confined and collimated by Electromagnetic Field

Ejection Disks

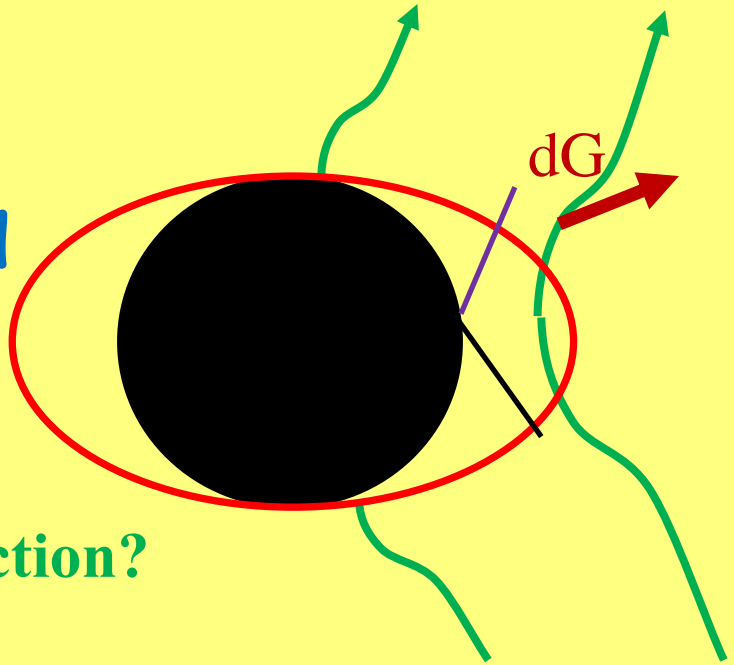
- Ultimately, field must be confined by gas
  - Inertia more than pressure
  - $r_{disk} \gg 1$, when $M'_{supply} \ll M'_{crit}$
- Large magnetic "clutch" between hole and disk?
  - $B_\phi \sim \varpi^{-1}$?
- Most disk mass supplied flung out by MHD torque
  - MHD wind ultimately confines jet
- Adiabatic disks
  - Torque does work $G_{disk}\Omega_{disk}$
  - Drives outflow



What determines R_{disk}?

3. EHT Observes Ergomagnetosphere

Ergomagnetosphere?

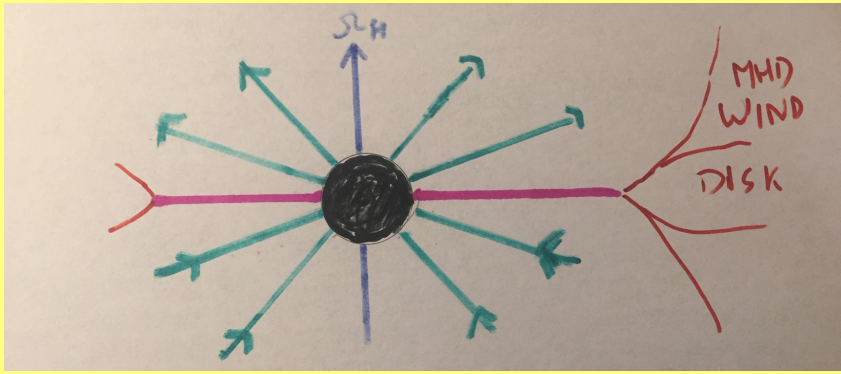


- **Strict force free hole field**
  - **Paraboloidal jet**
    - Ω falls from ~0.5 to ~0.25 Ω_h
- **Ω in ergosphere?**
  - **$\Omega=\Omega_{min}$, backward radiation reaction?**
    - Large emissivity?
  - **Cross flux stress?**
    - Local instabilities as with accretion disk?
    - dG, dL across as well as along field?
    - Low emissivity – polarized synchrotron radiation?
    - $\Omega(\varpi)$, $B(\varpi)$ vary smoothly from horizon to disk?
    - Current cones?
    - Power ejection disk?

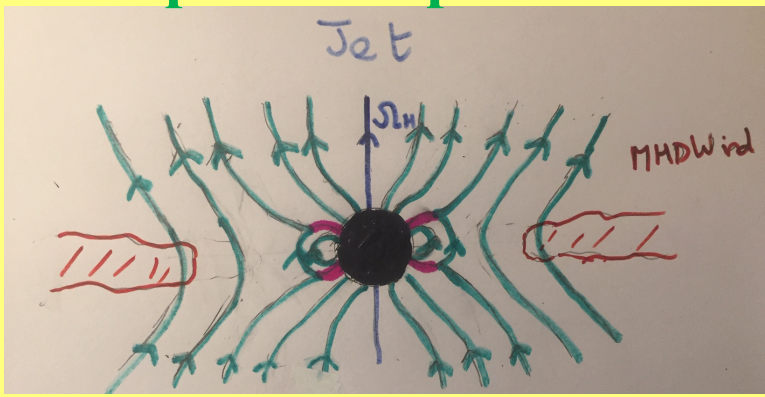
Magnetic clutch may behave mechanically like adiabatic disk

Other Configurations

- **Split Monopole**
  - **Equatorial current sheet**
    - cf EHT observation
    - Extend to $\varpi > 2$; disk?
    - Hole, not disk Doppler Factor
    - Jet collimation when $\varpi > 2$?



- **Closed Magnetosphere**
  - **Impossible with strict force-free solution (Gralla, Jacobson)**
    - Stabilize by non-axisymmetric entangling?
  - **Possible evolution of magnetic clutch or split monopole**
    - Conical current sheet
  - **Ephemeral?**
    - Quasi-Periodic Oscillation?
    - M87 ~ 9d
    - Sgr A* 20-40 min; observed??



Polarization, monitoring, simulation should sort out

4. Radiative Transfer can Test GR

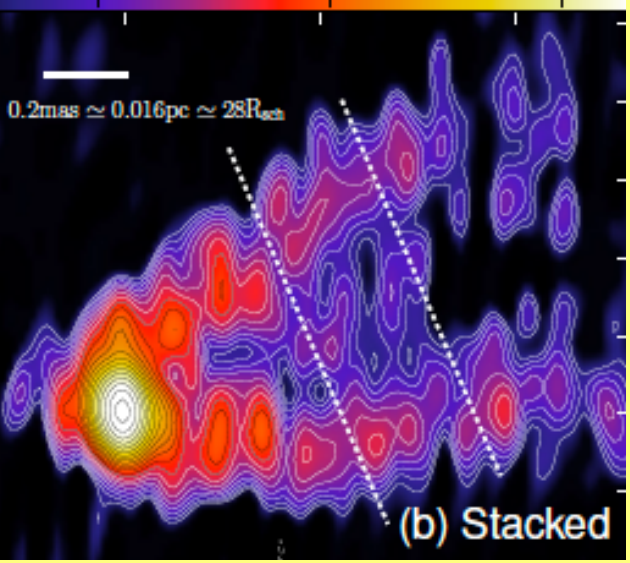
Observing the Ring of Power

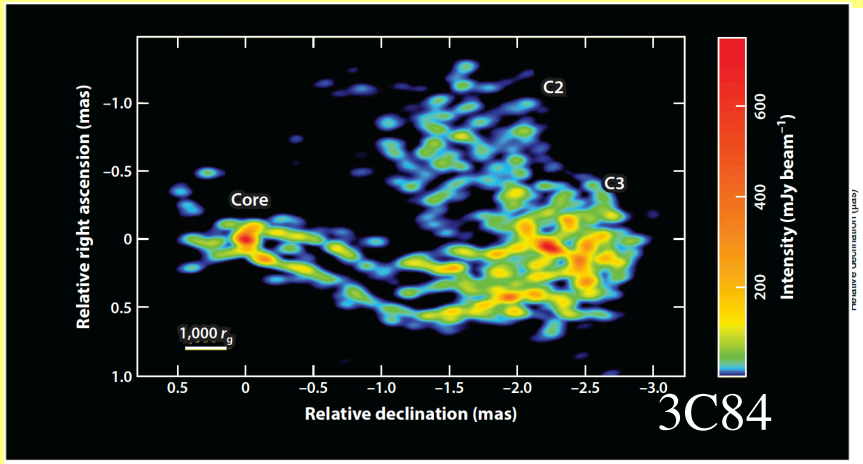
- BL coordinates: $dx/d\zeta=k$; $k^t=1$ when $r>>1$
- Conserved E, L, Q given by X, Y on sky
- Rays: $\mu'=M(\mu)$; $u'=U(u)$;$\phi'=F(\mu,u)$
- In a given EM field define $u_{em}.k=D$
- Synchrotron: $j=D^2 j_{em}$; $\kappa=D^{-1}\kappa_{em}$
- Polarization: LP $\nabla_k e=0$; CP preserved

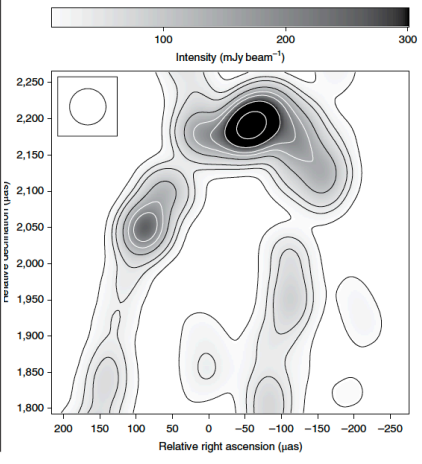
Simple sources can test strong GR

5. VLBI Observes Jet Boundary Layers

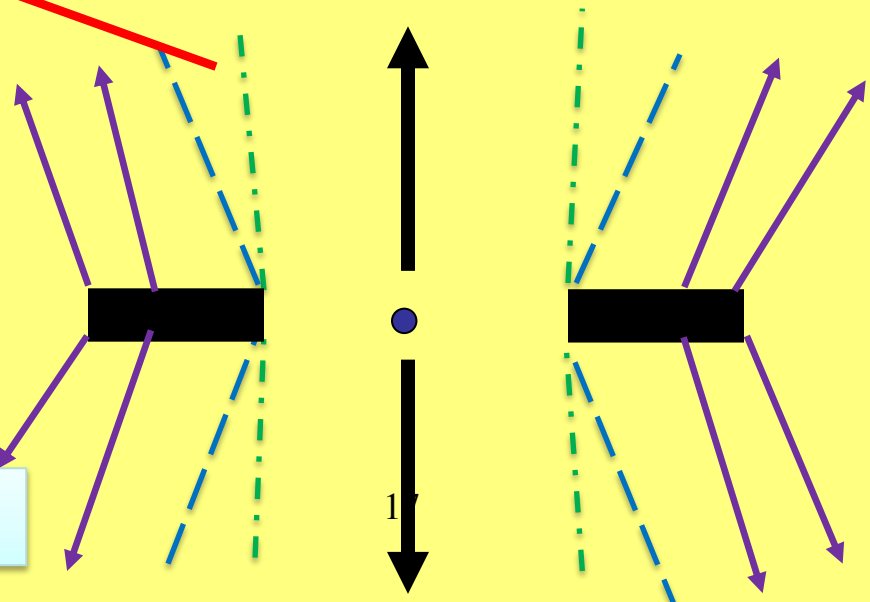
Low Power Jets







- Jet expands transversely and collimates
  - Magnetic hoop stress in disk wind
- Boundary layer/sheath
  - Gas entrained,
  - Magnetic field stretched
  - Particles accelerated
  - Faraday rotation

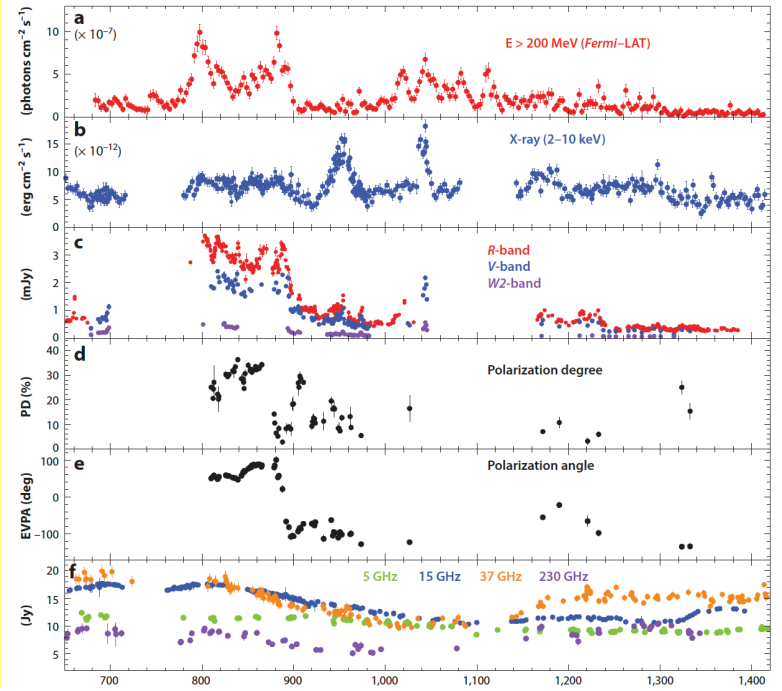


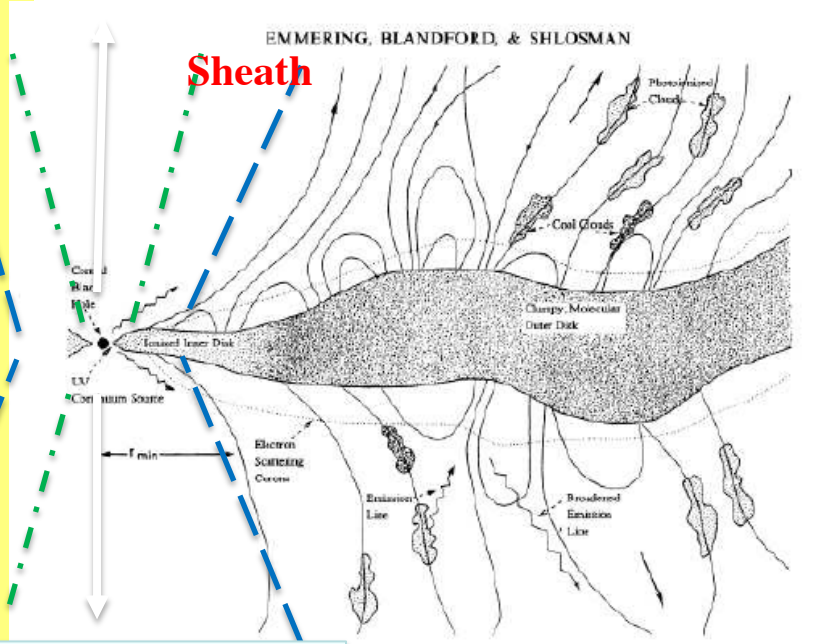
Polarization observations critical

6. MHD Winds Shield Jets and Form BEL

FSRQ-3C279

- **Bright quasar**
  - Known density of UV photons
- **Intense beamed γ-ray source**
  - Opaque to pair production
    - to BELR > light months
- **γ-rays can vary in 3 minutes**
  - Extreme relativistic kinematics??
  - Outflow provides absorbing sheath ?
  - Absorb ~0.1-10 GeV

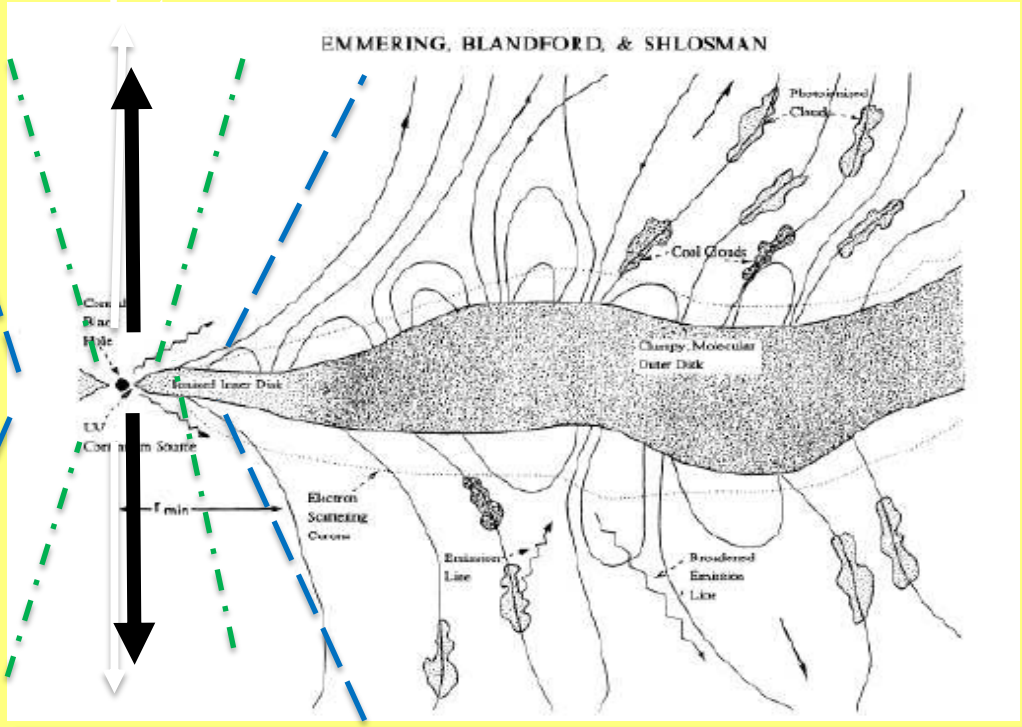


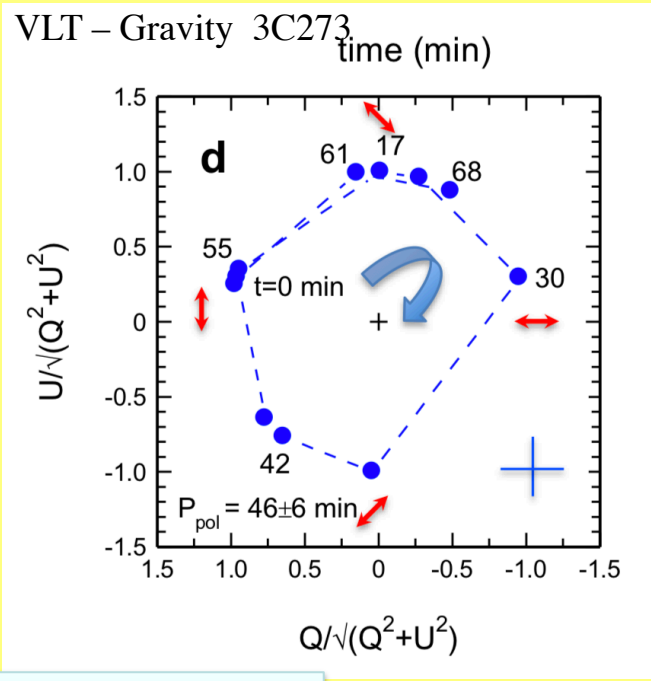


Where do γ-rays originate?

FSRQ-3C273

- Quasars must accrete to grow and spin
  - During high mass supply rate
  - Gaseous disks extend to horizon
- BEL observed at ~ 1 lt yr
  - Rotates
  - Magnetically-confined clouds?



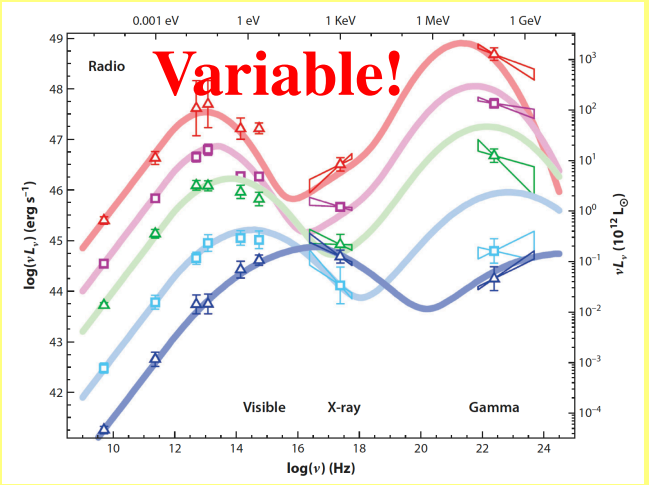


Are broad line clouds part of MHD Disk Wind?

7. γ–ray Hump is Synchrotron Radiation

γ-ray synchrotron radiation

- EM jet=> S, not C^{-1}?
  - E<B => E_γ<70 MeVß
- Accelerate protons
  - 0.1-1 EeV from 10 EV-1 ZV!
  - Reconnection/magnetoluminescence
    - Untangling of flux ropes
    - Accelerate protons preferentially by electric shear stress?



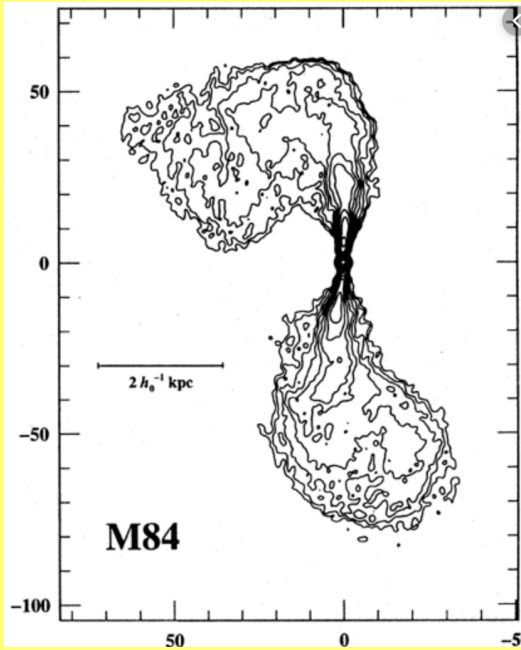
- Photo-pair on UV (Bethe-Heitler)
  - $\sigma \sim \alpha\, r_e^2$
  - Radiation reaction limits ion energy before pion threshold
  - Synchrotron-dominated showers till γ-rays escape
- Highly efficient!
  - cf neutrino models

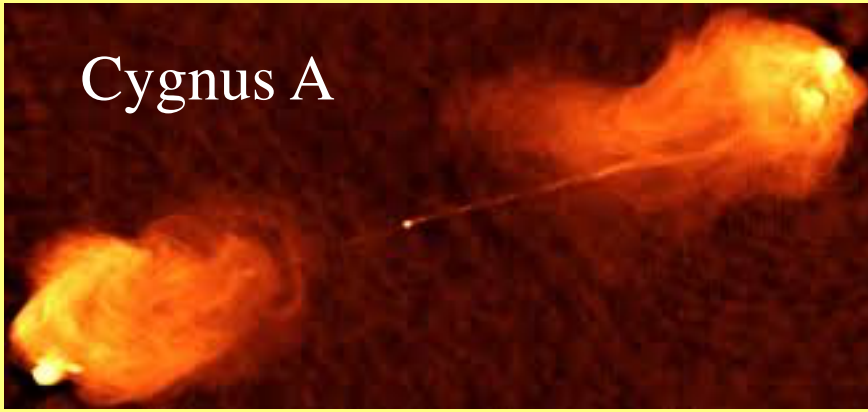
Test with multi-wavelength observations, PIC simulations

8. FR I/II at Bondi Radius

Extent of BH Influence

- FRI: center brightened, low power
  - Subsonic plumes?
- FRII: edge brightened, high power
  - Supersonic, mildly relativistic jets?
- All jets are made relativistically?
  - Seyferts?
- $R_{inf} \sim R_{bondi} \sim GM/\sigma^2 \sim 10^5 GM/c^2$
  - Hole->stars, recollimation shock



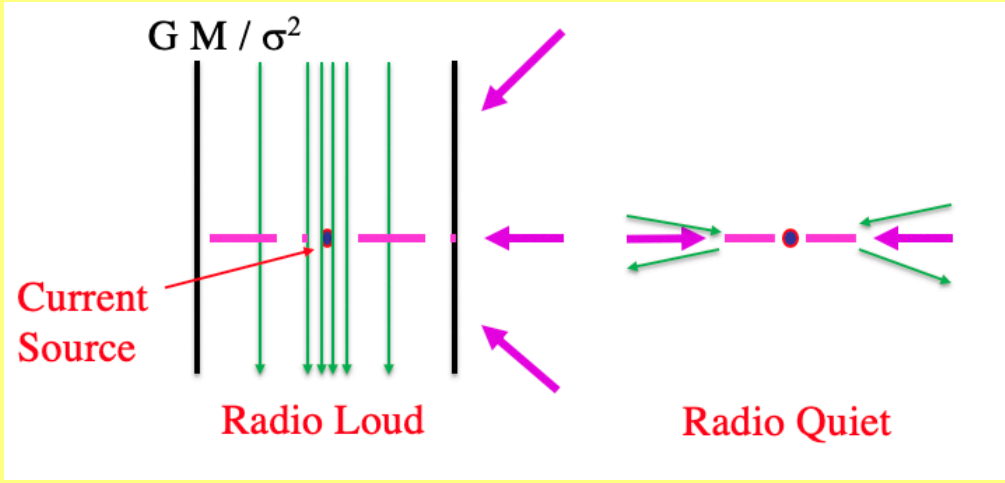


Need detailed observations of jet structure at R_{inf}

9. RL/RQ due to Magnetic Concentration

Radio Loud vs Radio Quiet AGN

- RL in E; RQ in S?
  - NLS1?
- Spin necessary for jet
  - Insufficient
- Long term feature
  - >10Myr?
- Strong hole field needed
  - $B \sim \omega^{-1} \Rightarrow L_{jet} \sim M' \sigma c$??
  - Steady high latitude accretion traps flux?
  - Randomly oriented disk accretion does not??



JWST/ALMA should explore mass supply at R_{inf}

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