Massive Black Holes: Open Questions

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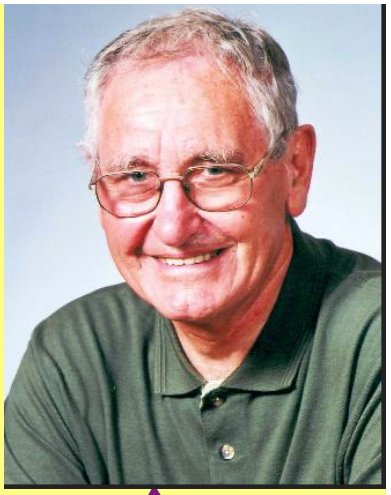
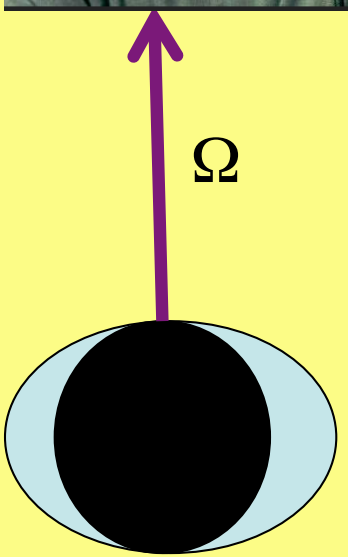
Topics

- Spin
- Jets
- Acceleration
- Timing
- Radiation
- Evolution

Astrophysical Black Holes





- Kerr Metric
  - Mass $m=M_8 AU=500 M_8 s=2 \times 10^{62} M_8$ erg
  - Angular momentum $a < m$
  - Event Horizon $r_+=m+(m^2+a^2)^{1/2}$
    - Area $A=8\pi m r_+=16\pi m_0^2$, increases
  - Irreducible mass $m_0=m[\{1+(1+a^2/m^2)^{1/2}\}/2]^{1/2}$
  - Reducible mass $m-m_0<0.29m$
  - Spin $\Omega = a / 4m_0^2$
  - Ergosphere $r_{ergo}=m+(m^2+a^2\cos^2\theta)^{1/2}$

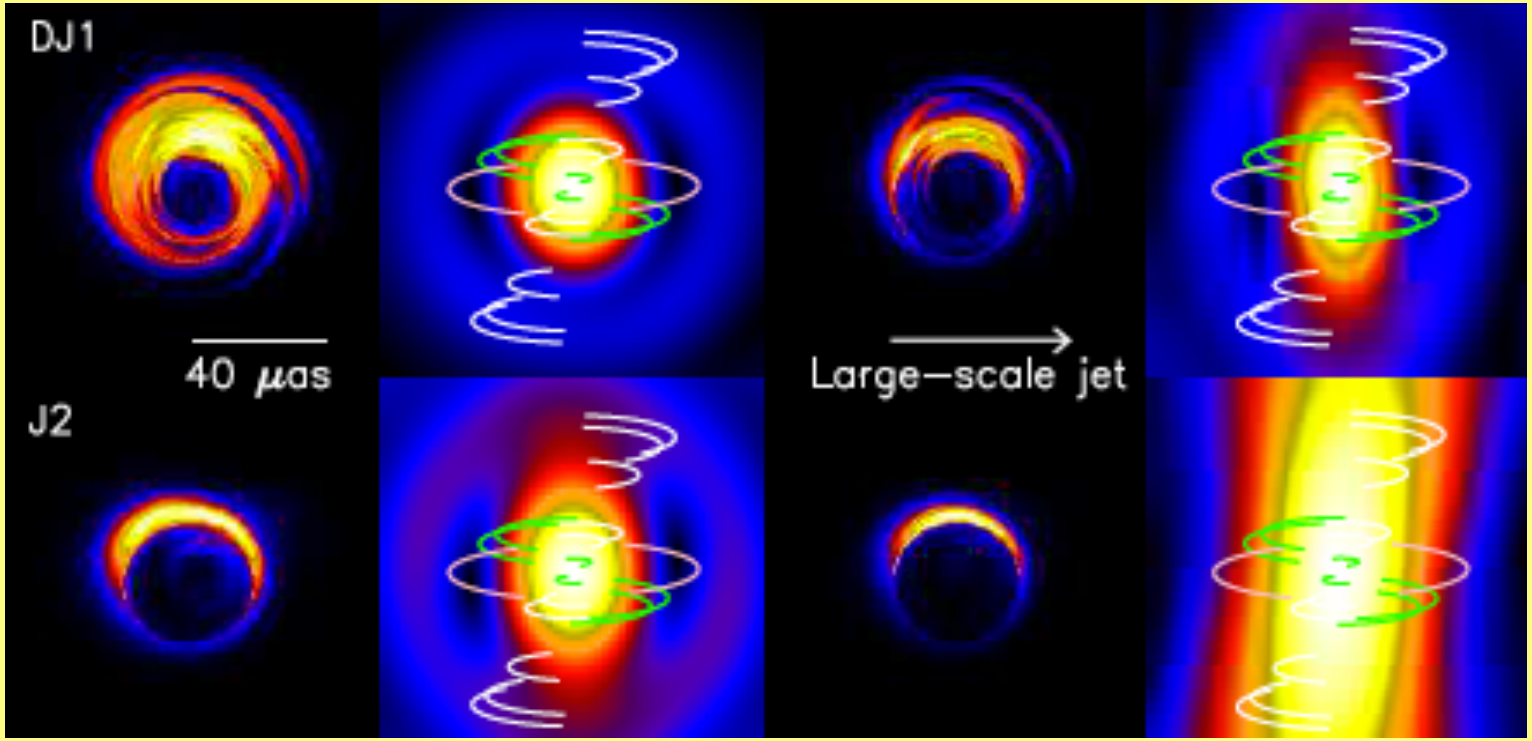
On the dragging of inertial frames

- **Newtonian:**
  - **Consider a "Uranus" with S.L=0, r=const.**
  - **Let $S=(S_r,0,S_\phi)$**
  - **$d^2S/dt^2=-(GM/r^3)S$**
- **Kerr metric:**
  - **Circular, equatorial orbit**
  - **$S=(-\Omega S_\phi, S_r,0,S_\phi)$**
  - **Parallel-propagate along geodesic**
  - **$d^2S/d\tau^2=-(GM/r^3)S$**
    - Independent of a including sign!
    - $\omega_{BL}=\Omega-r^{-3/2}u^{t-1}=3r^{-5/2}/2-ar^{-3}+\ldots$

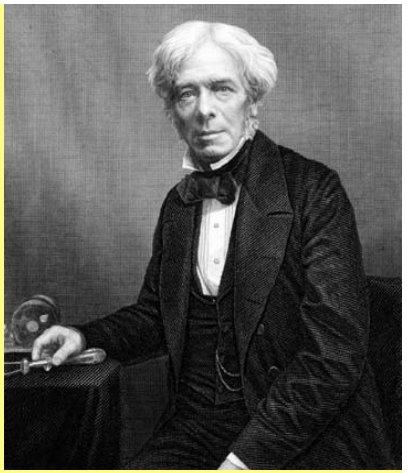
Imaging a Black Hole?

- For M87 and Galactic Center,
  - 2m ~10μas ~ 0.3 mm/R_E
  - Fringes at ~10m
- Event Horizon Telescope (Doeleman et al)
  - ALMA VLBI

Dexter, McKinney, Agol

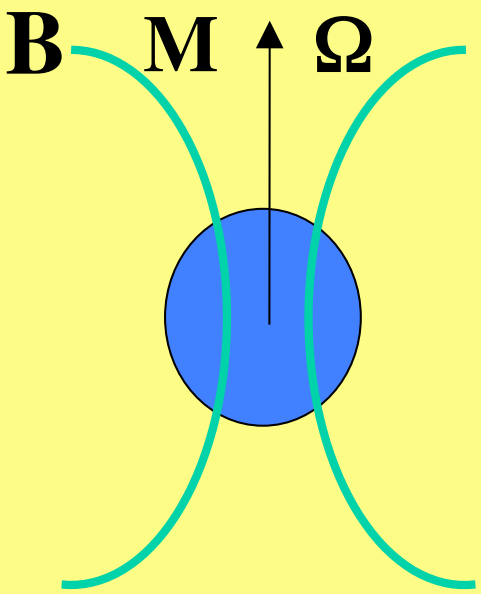


How to get Blood from a Stone



- Rules of thumb:
  - $\Phi \sim B R^2$; $V \sim \Omega \Phi$;
  - $I \sim V / Z_0$; $P \sim V I$

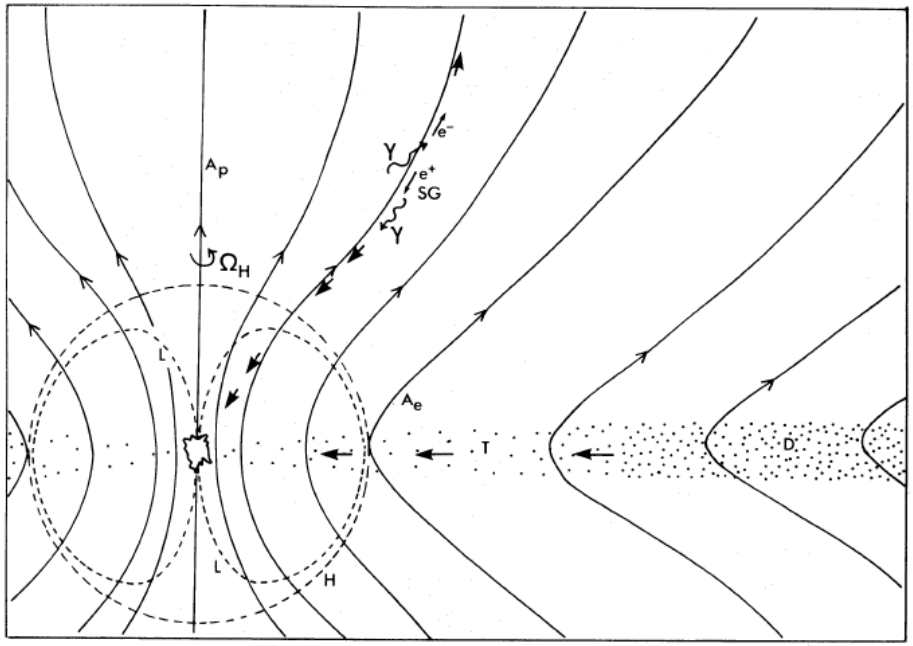
	PWN	AGN	GRB
B	100 MT	1 T	1 TT
Ω	10 Hz	10 μHz	1 kHz
R	10 km	10 Tm	10 km
V	3 PV	300 EV	30 ZV
I	300 TA	3 EA	300 EA
P	100 XW	1 TXW	10 PXW



Unipolar Induction

Force-Free Electrodynamics in Kerr Spacetime

- $F.J=0 \Leftrightarrow \text{div } T^{EM}=0$
  - Pair production necessary
- $\xi_{\phi,t}$
  - Conserved F, G
  - $I(\Phi)$, $V(\Phi)$, $\Omega(\Phi)$



MHD generalization

- **Boundary conditions**
  - **EM finite for infalling observer**
    - Kerr-Schild or numerical kludge
    - Energy flows out at horizon in non-rotating frame
    - Energy flows in at horizon in rotating frame

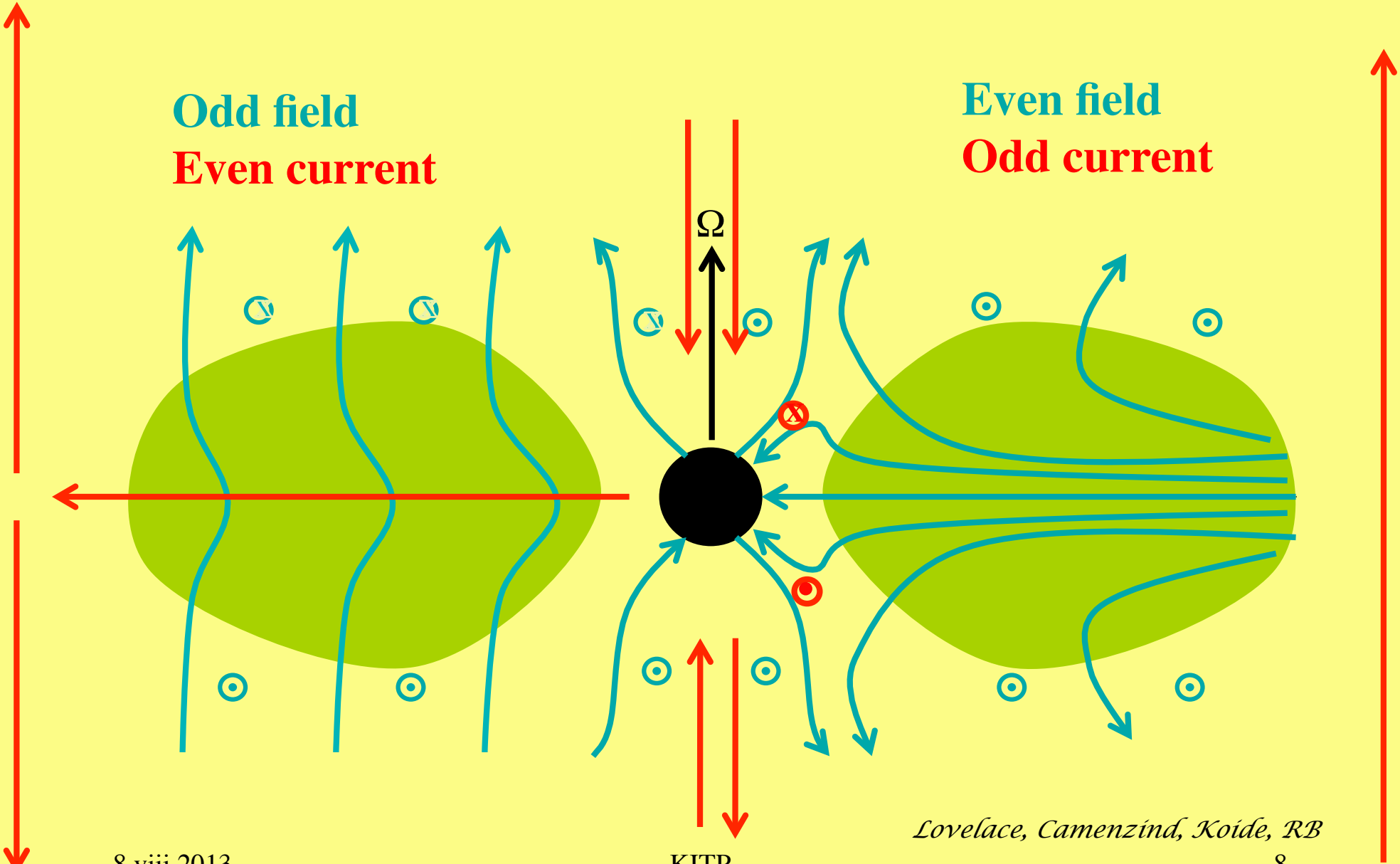
Hole vs Disk

- **Circuit analysis**

$$\Delta G\Omega_H=\Delta G\Omega_L + I^2\ \Delta R_H + I^2\ \Delta R_L$$

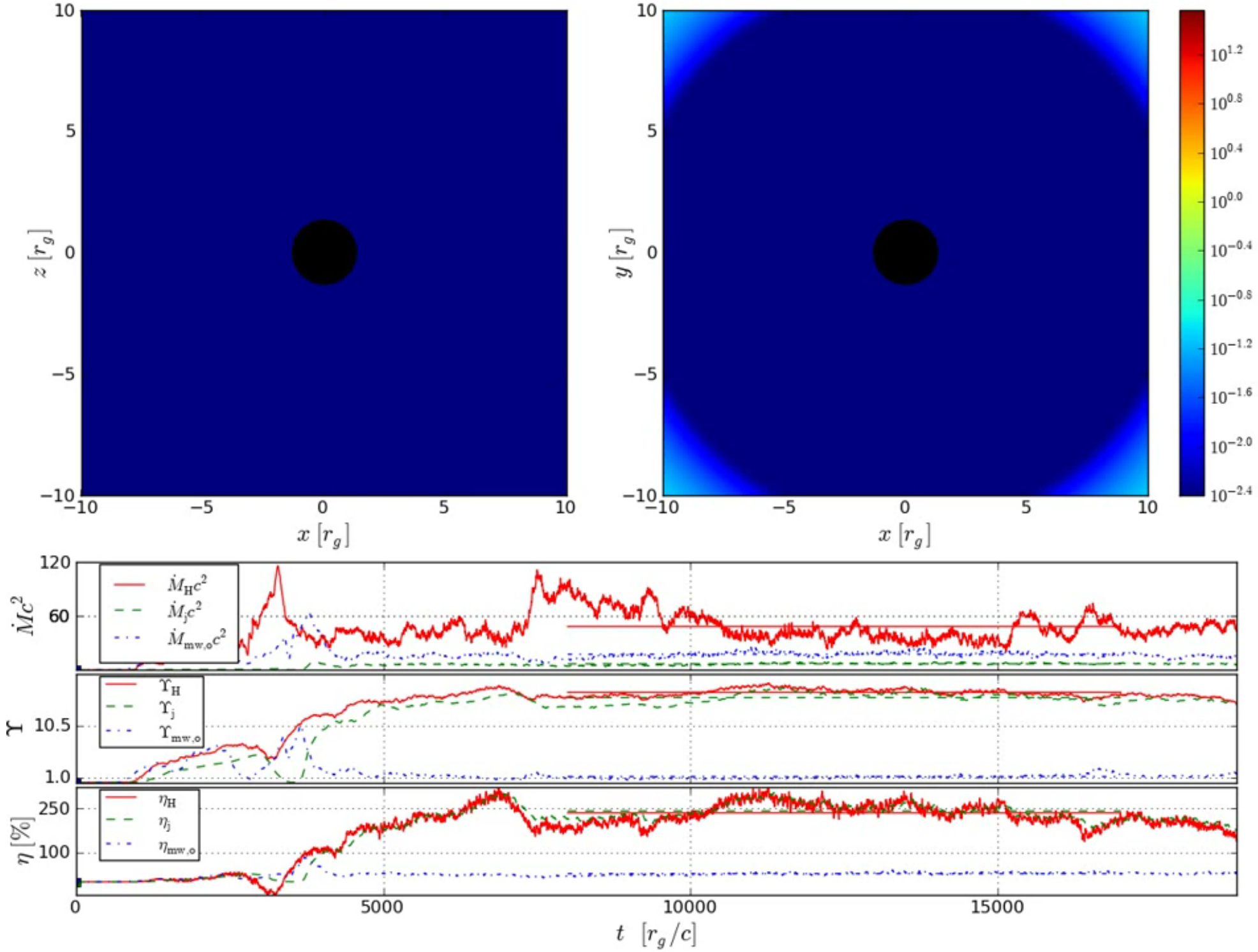
$$\Omega=\frac{\Omega_H\,\Delta R_L+\Omega_L\,\Delta R_H}{\Delta R_L+\Delta R_H}$$

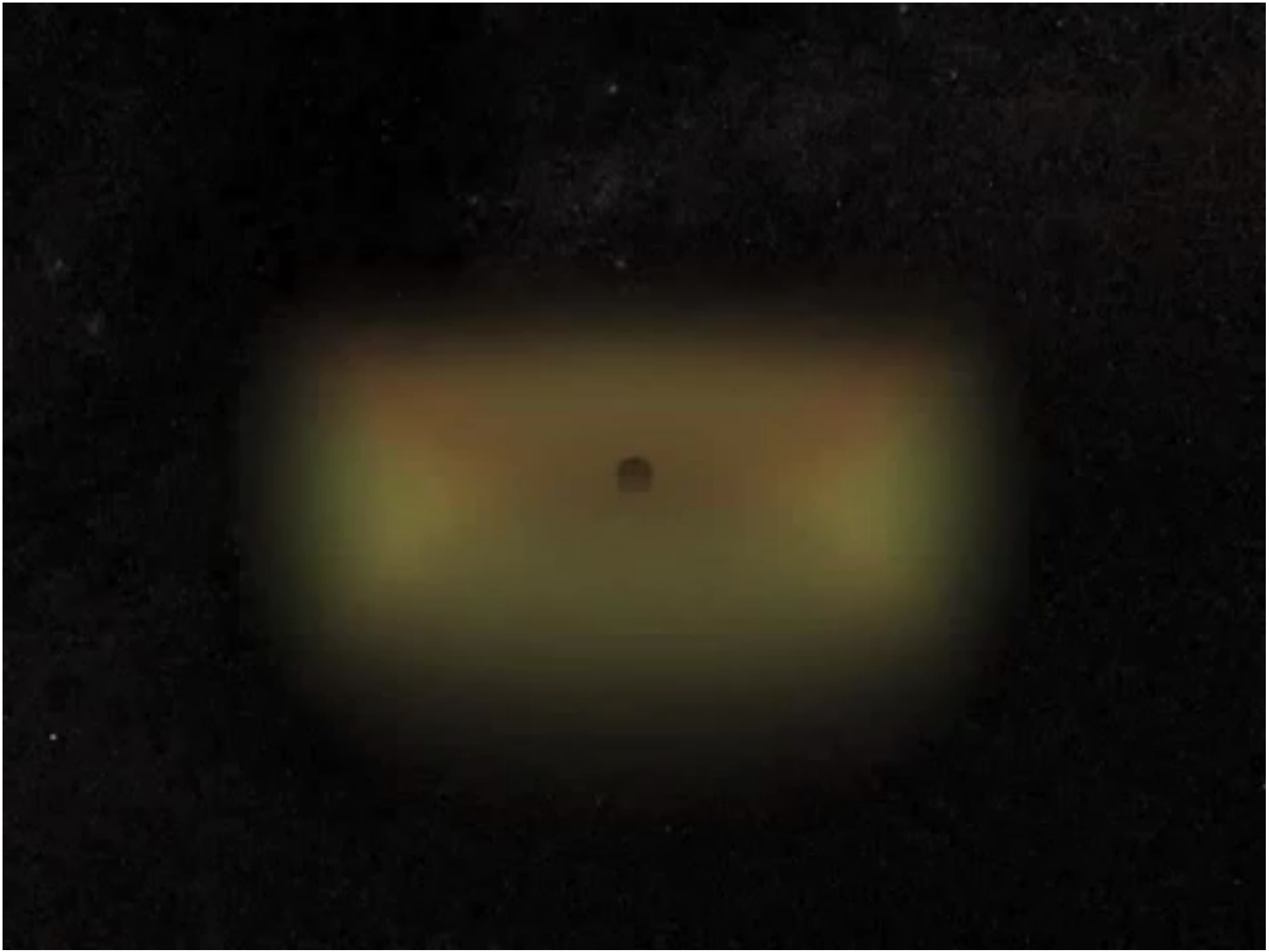
Dipolar or Quadrupolar?



Lovelace, Camenzind, Koide, RB

Also prograde vs retrograde?

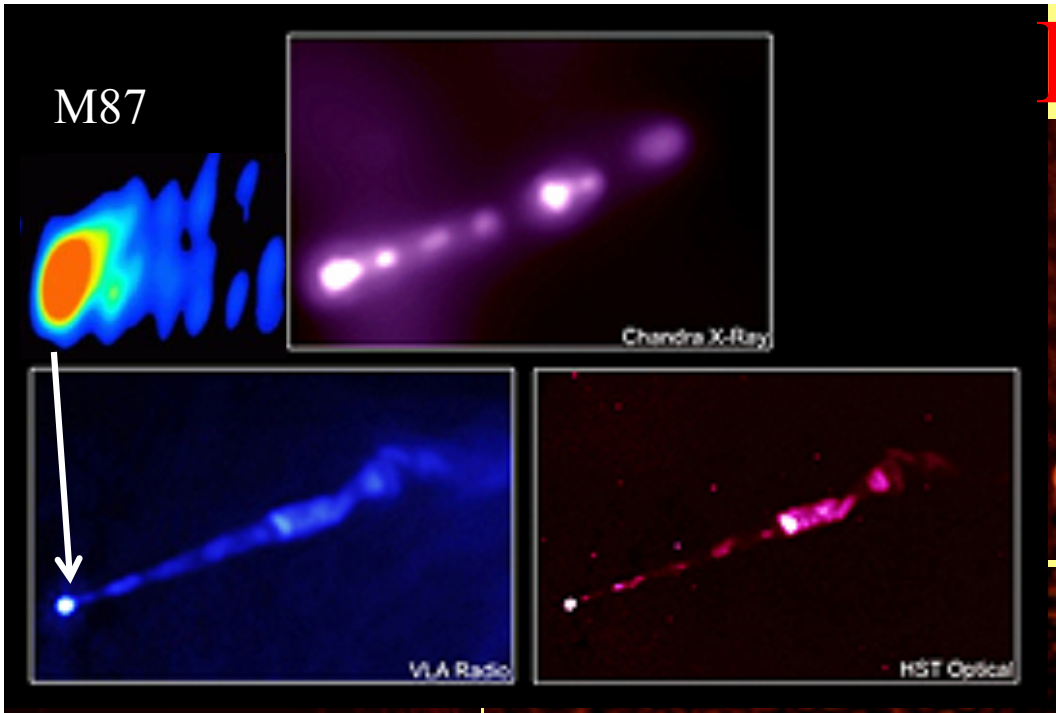

10
5
0
−5
−10
$z\ [r_g]$
$x\ [r_g]$
$y\ [r_g]$
$10^{1.2}$
$10^{0.8}$
$10^{0.4}$
$10^{0.0}$
$10^{-0.4}$
$10^{-0.8}$
$10^{-1.2}$
$10^{-1.6}$
$10^{-2.0}$
$10^{-2.4}$
120
60
$\dot{M}c^2$
$\dot{M}_{\rm H}c^2$
$\dot{M}_{\rm j}c^2$
$\dot{M}_{\rm mw,o}c^2$
Υ
10.5
1.0
$\Upsilon_{\rm H}$
$\Upsilon_{\rm j}$
$\Upsilon_{\rm mw,o}$
250
100
$\eta\ [\%]$
$\eta_{\rm H}$
$\eta_{\rm j}$
$\eta_{\rm mw,o}$
0
5000
10000
15000
$t\ \ [r_g/c]$

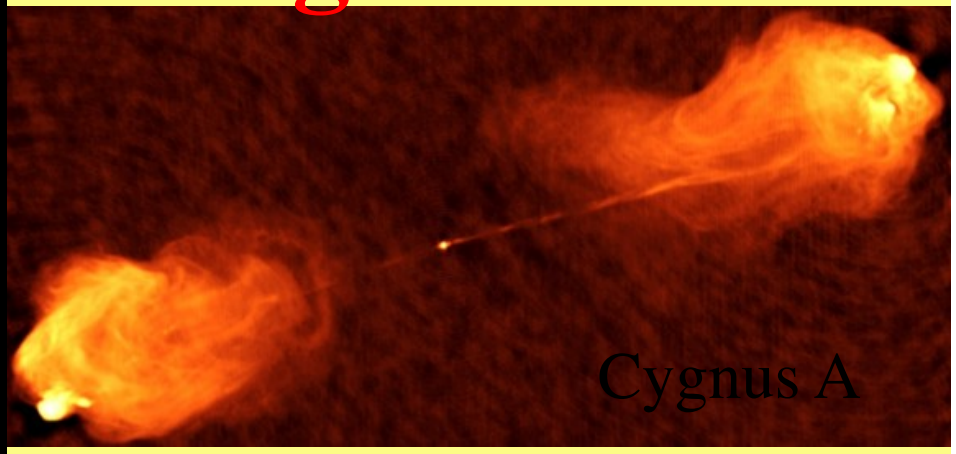


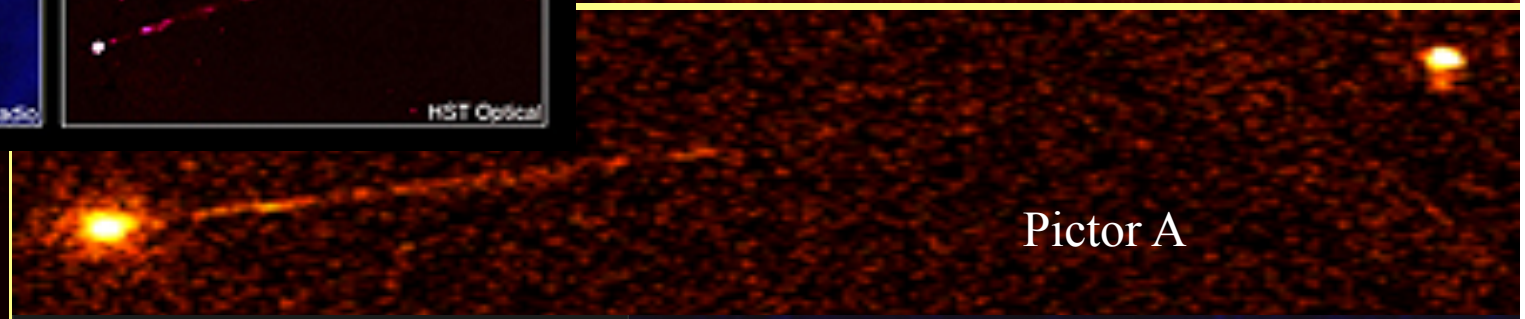
Magnetically-choked Accretion Flows

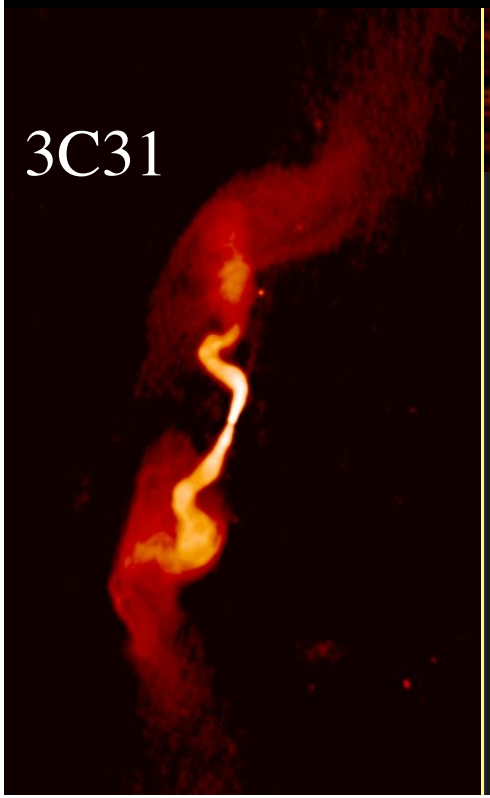
- Robust, collimated jets
  - $>10^5$ m
- Build up strong dipolar field
  - Thick spinning disks, suppress MRI
  - Not quadrupolar
- Efficient extraction of spin energy-> jets
  - Prograde (not retrograde) more efficient
- Magnetic collimation
  - Poorly collimated, slower winds
- QPOs,
  - Helical instability (m=1) ~Ω/4, Q~100 (jet) ~3 (disk)
- Strong intermittency
  - Acceleration
- Observe Simulated Jets

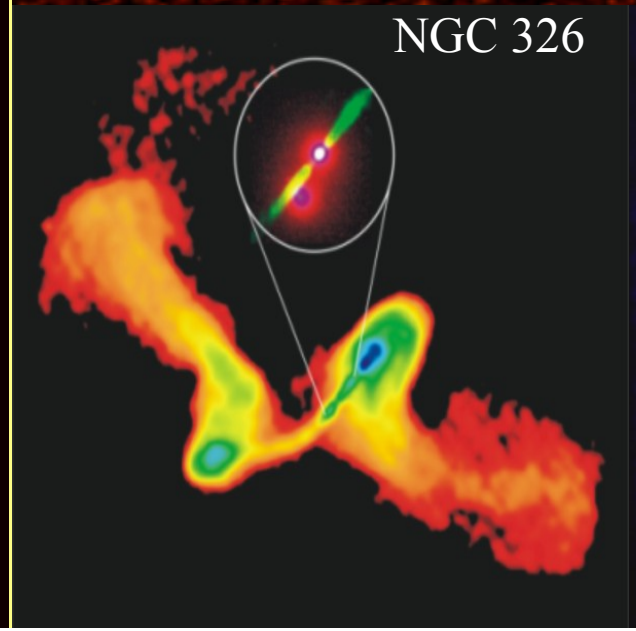
Extragalactic Jets

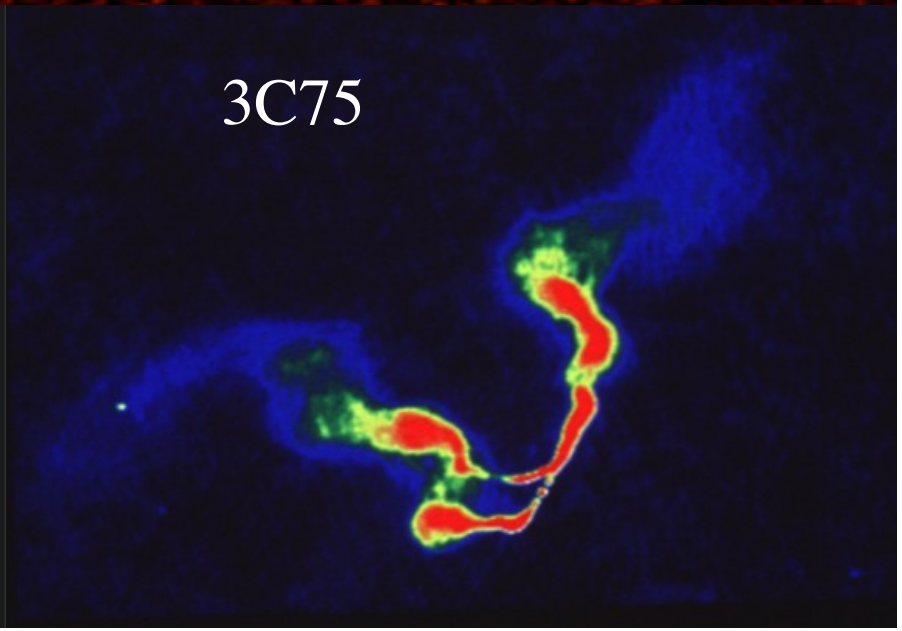










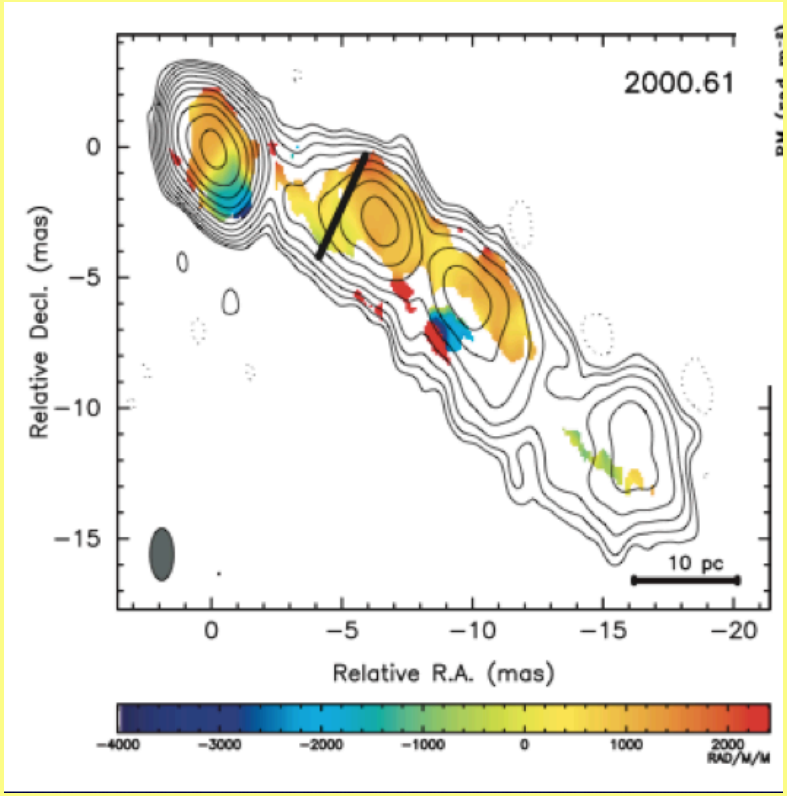


Magnetized Jets?

- Observed Jets are:
  - Fluid dynamical?
  - Continuous currents?
  - Poynting->Pairs->Plasma?
- Where do current, flux, helicity go?
  - $H = \int dVA \cdot B \sim \Phi_1 \Phi_2 (linked) \sim L_{EM}$
  - More durable than energy in laboratory.
  - Acceleration is resistance
    - Current carried by relativistic electrons?

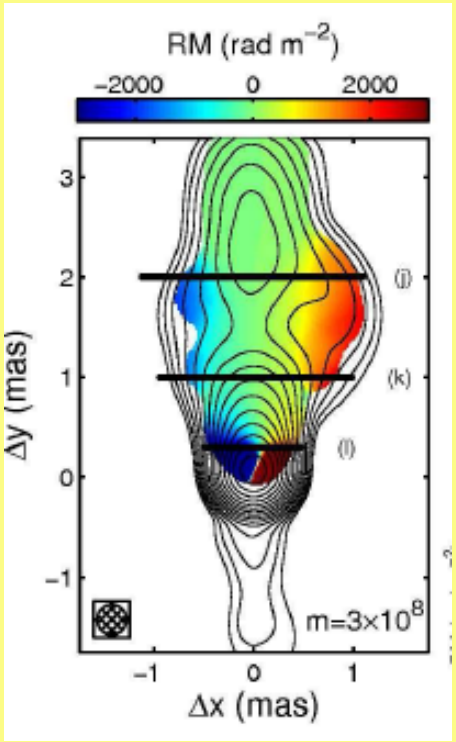
Faraday Rotation

Observation



Zavala& Taylor 2005

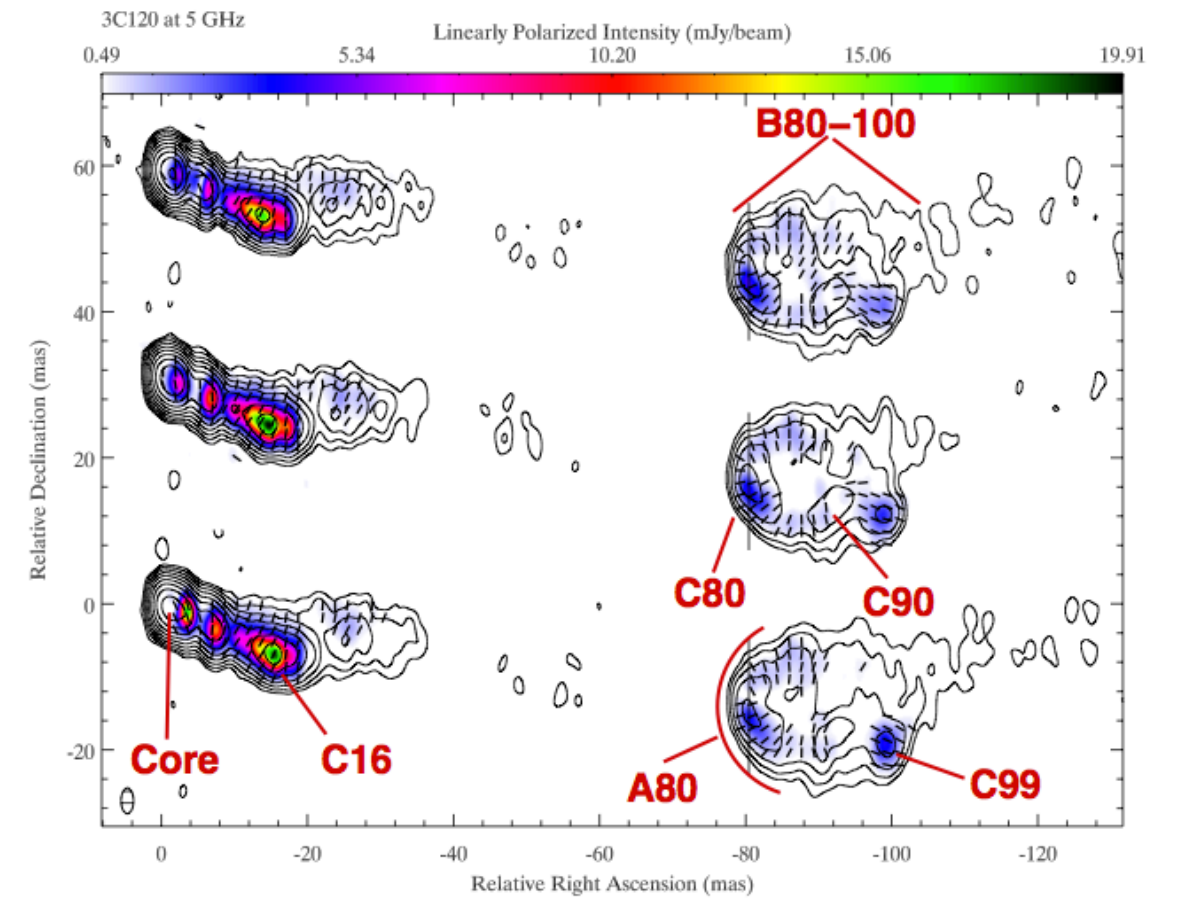
Simulation



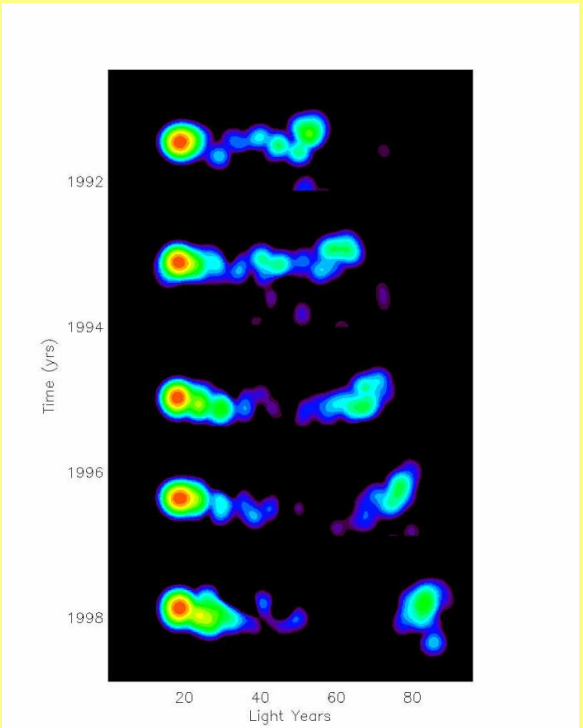
Broderick & McKinney

Signature of toroidal field/axial current

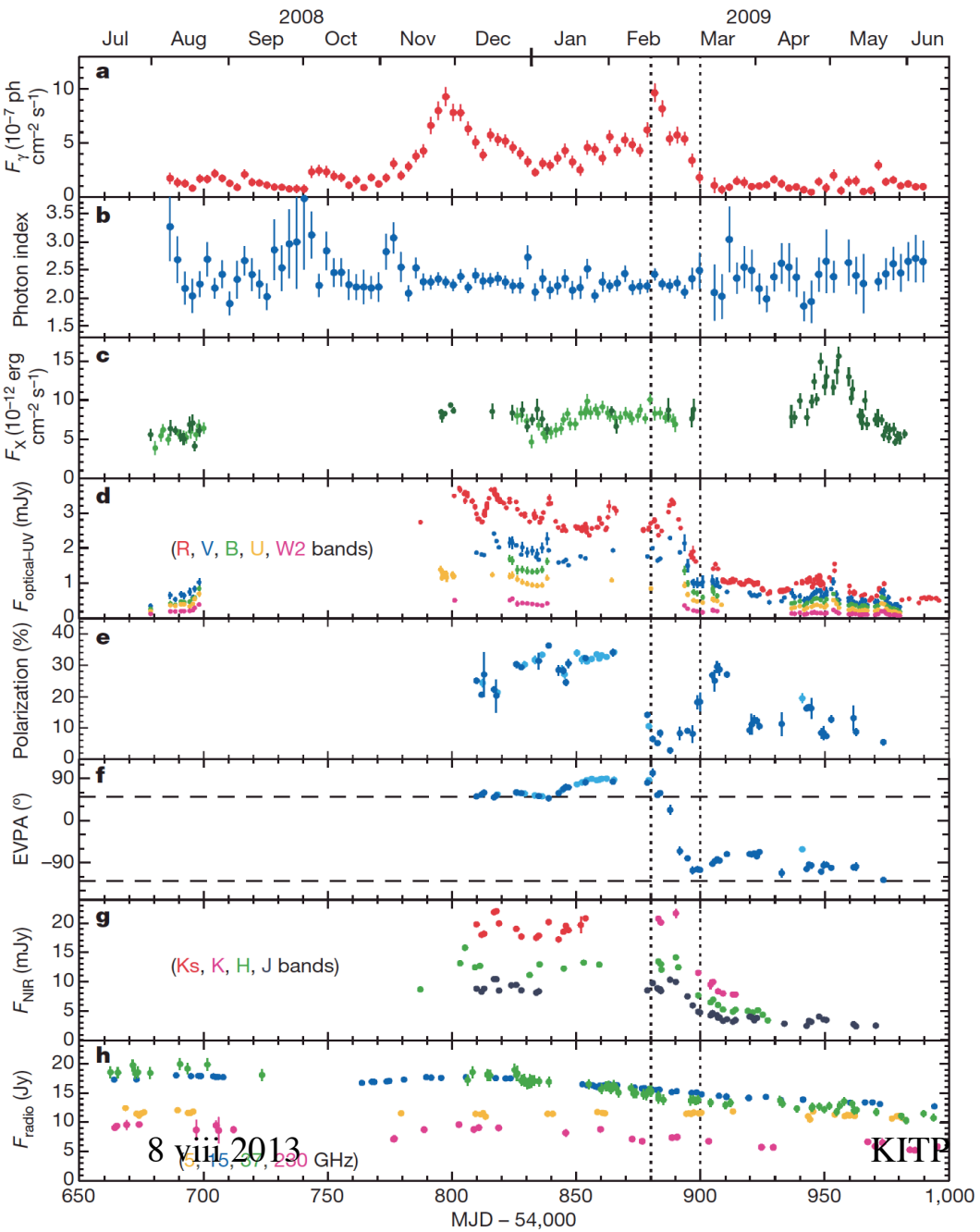
3C120



Do variable γ-rays come from recollimation shocks?



3C 279: multi-λ observation of γ-ray flare



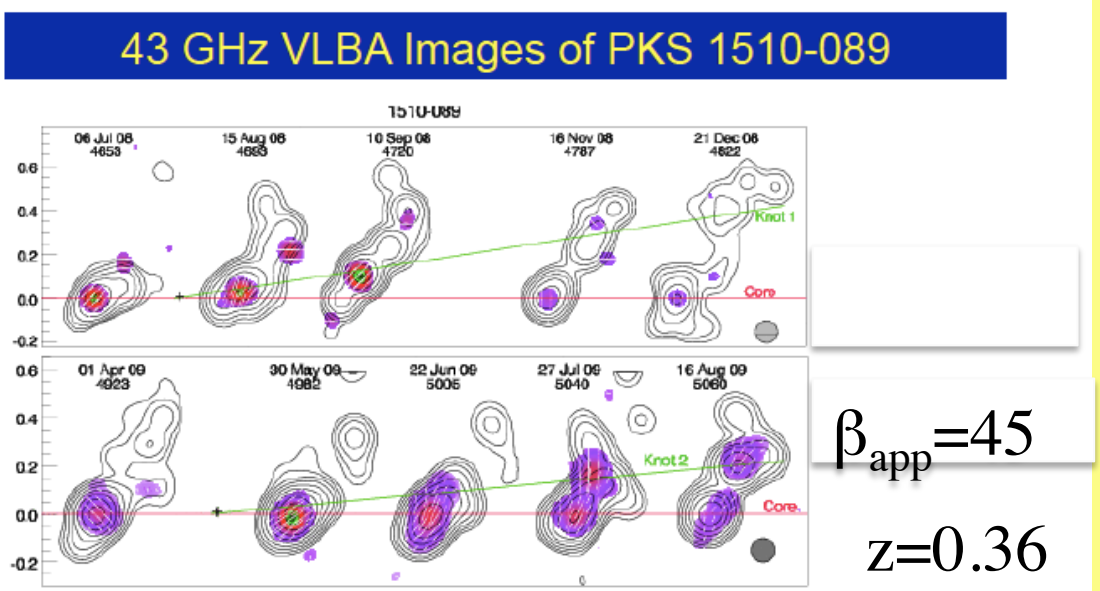
- ~30percent optical polarization
  => well-ordered magnetic field
- τ~ 20d γ-ray variation
  => $r \sim \gamma^2 c\tau$ ~ pc or τ_{disk}?
- Correlated optical variation?
- Ten day lag!
- X-ray, radio uncorrelated
  => different sites
- Rapid polarization swings ~200°
  => rotating magnetic field
  in dominant part of source
- PKS 1510+089 -720°!

r ~ 100 or 10^5 m?

Abdo, et al, Hayashida et al

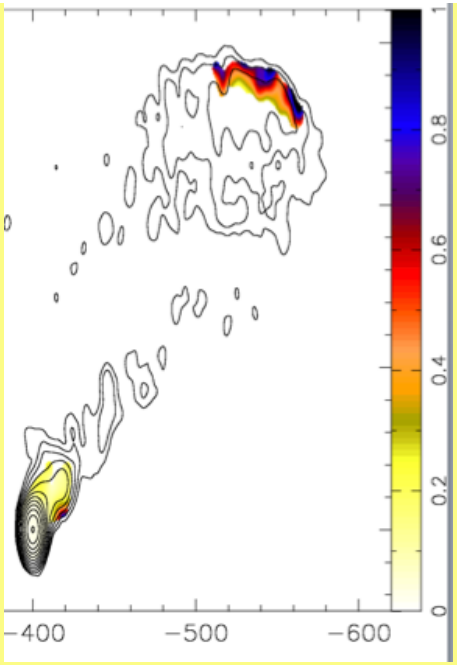
PKS1510+089

(Wardle, Homan et al)

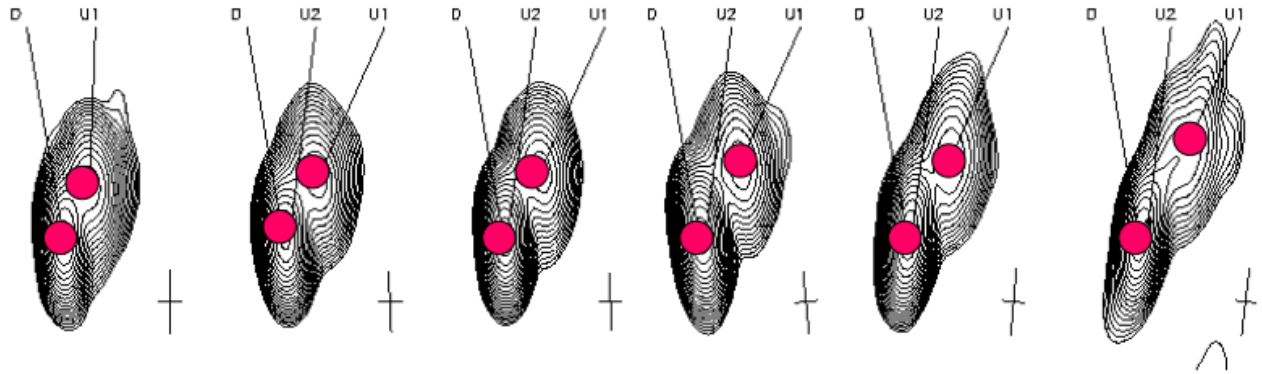


β_{app}=45

z=0.36

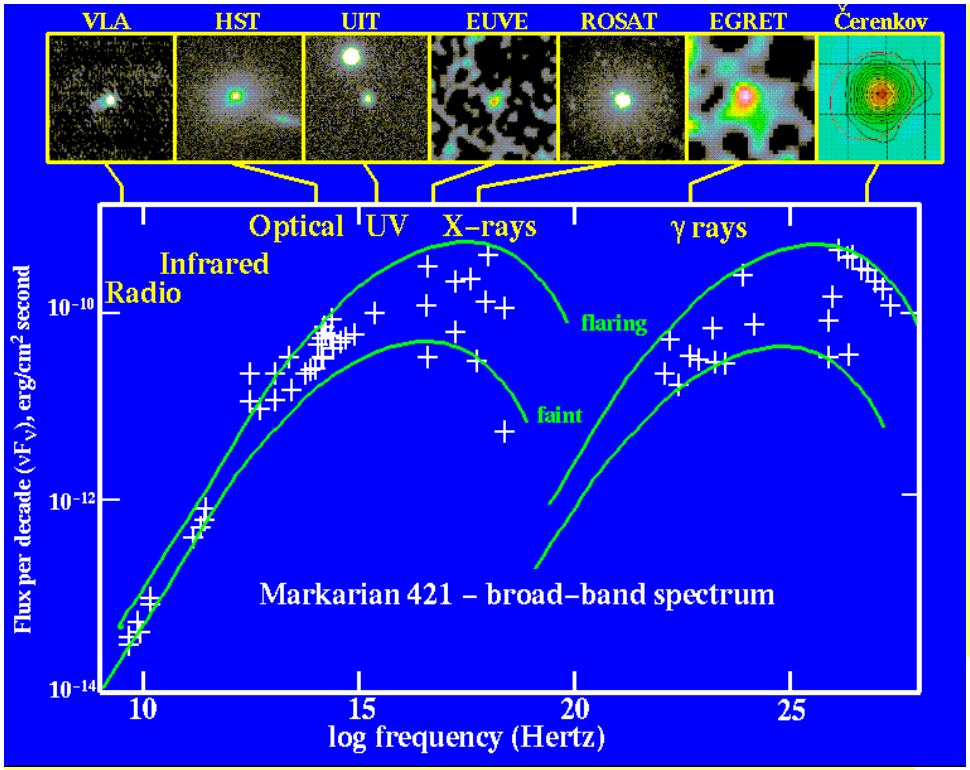


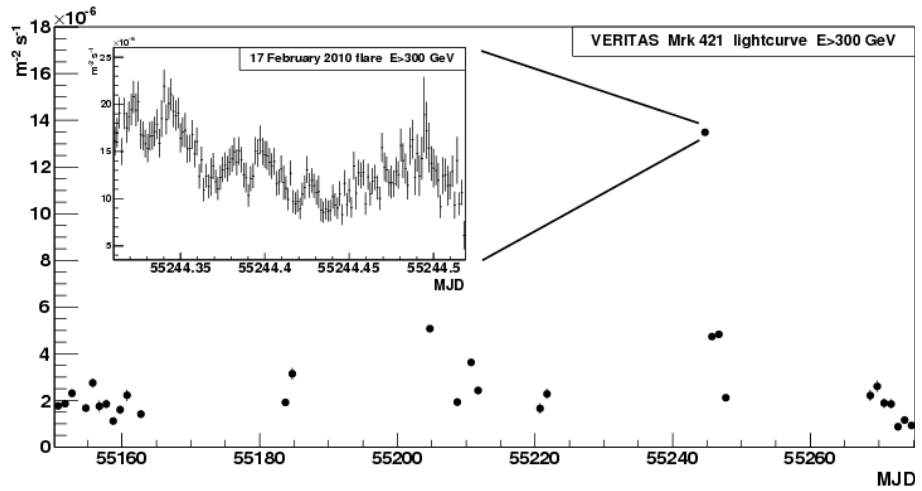
Two bright superluminal blobs emerged during the outbursts in brightness during the 2nd half of 2008 & the 1st half of 2009

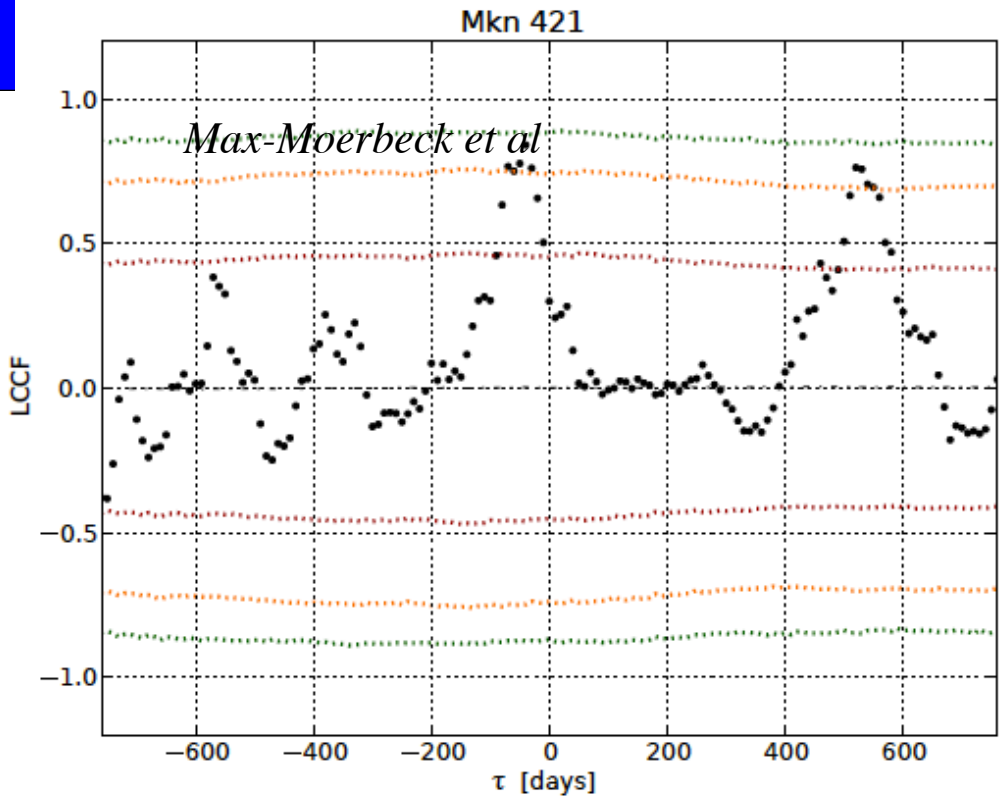


- Rapid swings of jet, radio position angle
- High polarization ~720° *(Marscher)*
- Channel vs Source
- TeV variation *(Wagner / HESS)*
- EBL limit
- r_{min} ; $r_{TeV} > r_{GeV}$ *(B+Levinson)*

MKN 421







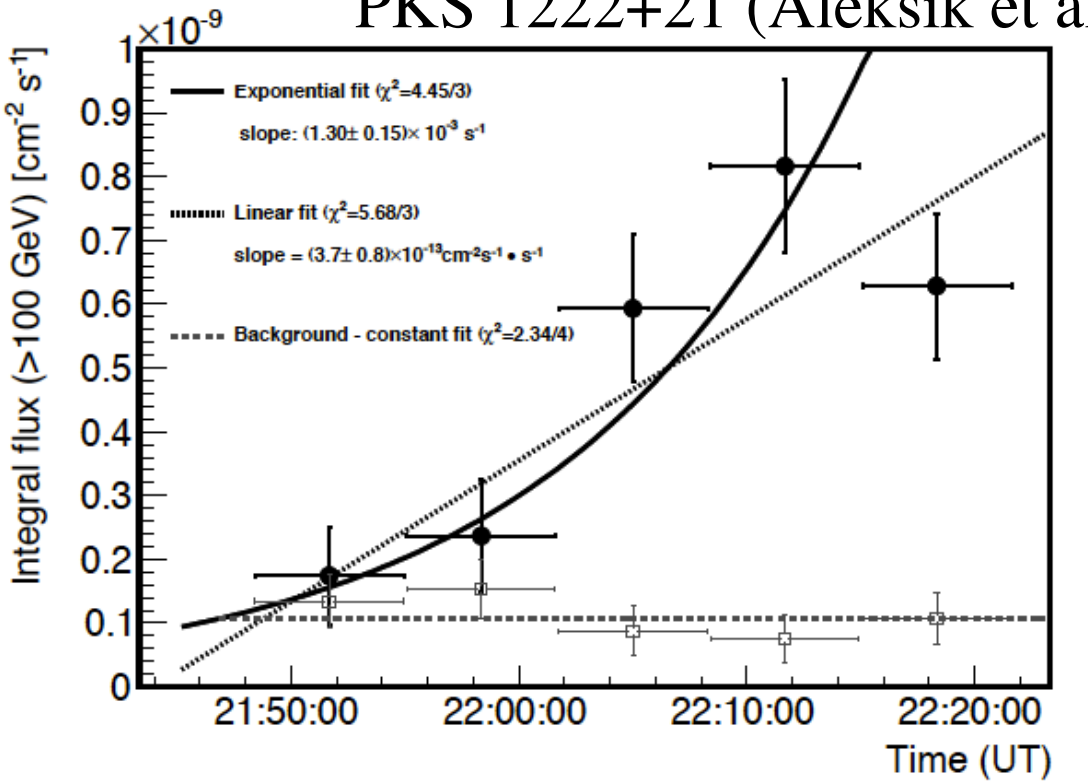
8 viii 2013

TeV Gamma-ray variation

- M87
  - 1 day
- PKS 1222+21
  - 10 min
- MKN 501
  - 5 min?
- PKS 2155-304
  - 2 min?

Crab Nebula?

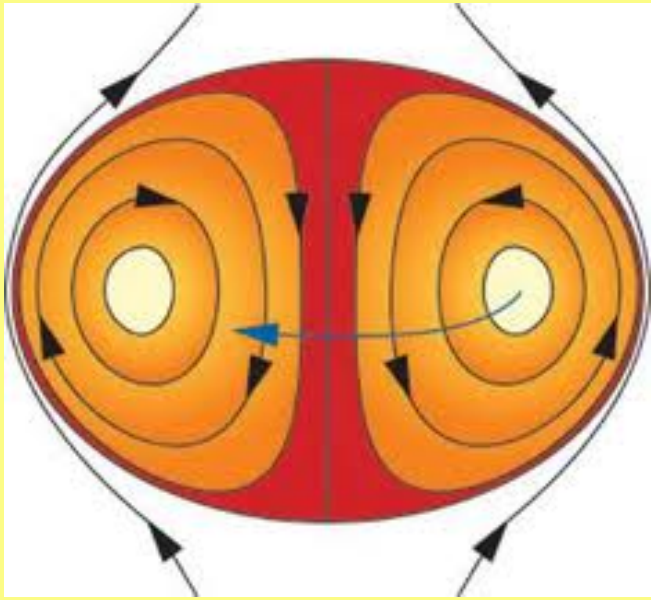
PKS 1222+21 (Aleksik et al)

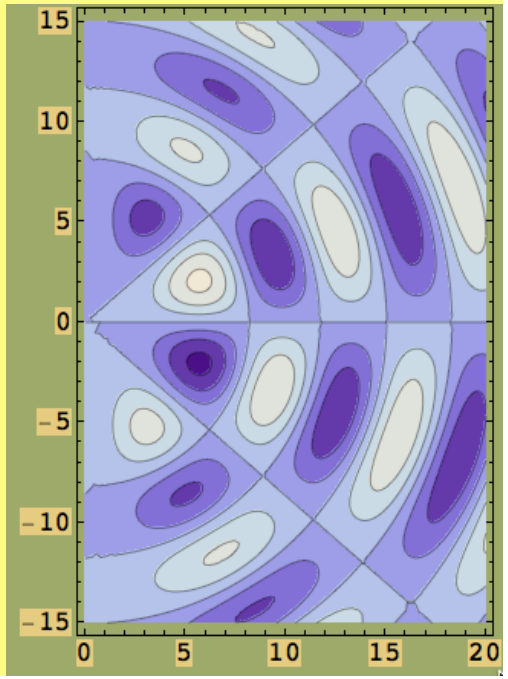


$E_{rad} >> P(ct_{var})^3$

Magnetoid Acceleration

- **Spheromak**
  - **Simplest example of helicity**
  - **Force-free configuration B ~ j ~ A**
  - **Magnetically isolated structures**
  - **$U_{mag} = 4\pi \langle P \rangle_{ext} R^3$; $u_{max} >> \langle P \rangle_{ext}$**
- **"Magnetoid"**
  - **Generic properties**
  - **Evolves in response to:**
    - Boundary conditions
    - Reconnection
    - Cooling
  - **Violent transition to lower energy state**
    - Inductive EMF => particle acceleration





Timing

- Timed X, γ-ray photons
- Search for:
  - QPOs
  - NuSTAR observations of Sgr A* flare
  - Temporal asymmetry in rapidly cooling environments
  - eg impulsive acceleration, radiative decay
    - Correlations in E_γ – t diagram
- More generally should devise automated, parasitic searches for specific signals in general observations
  - cf SETI !

Pulsars and Gravitational Waves

- Best bet is BMBH stochastic background
- Sensitivity ~30 ns ~ $h \sim 10^{-15}$ at $\nu \sim 1 yr^{-1}$
  - $\rho_{detect} \sim 10^{-20}$ erg cm^{-3}
- Principle of Least Pessimism
  - t ~10 Gyr, for $m_1 \sim m_2 \sim 10^7 M_{sun}$.
  - $\rho_{bckgd} < \rho_{bh} (\omega M)^{2/3} a \sim 30 \rho_{detect}$
- Requires relatively efficient release of binding energy as GW
- Cosmological background??
  - First order quark-hadron phase transition???

Spin Evolution

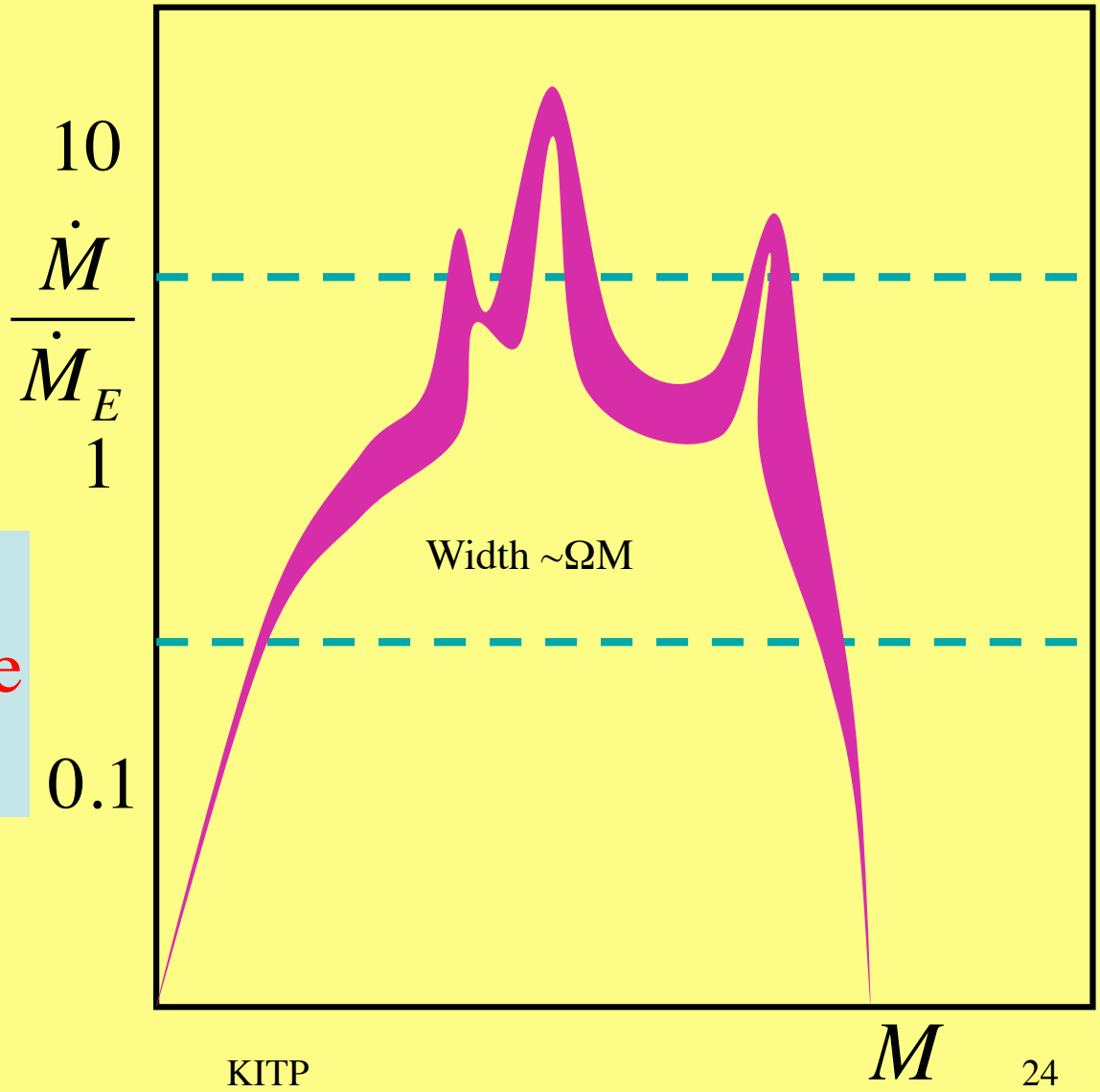
- Spin may evolve stochastically while mass evolves (almost) secularly
- $\mu = \ln M$; $\tau = t/t_{Sal}$; $\alpha = \Omega m$

$$\frac{\partial N}{\partial \tau} = -\frac{\partial}{\partial M_6}(M_6 \dot{\mu} N) - \frac{\partial}{\partial \alpha}(\dot{\alpha} N) + \frac{1}{2}\frac{\partial^2}{\partial \alpha^2}(DN) + S(M_6, \alpha, \tau)$$

Jet Fuel

- Relativistic Jets Powered by Black Hole Spin
- Thick disks spin down hole electromagnetically
- Thin disks spin up hole through accretion

Jet properties depend upon mass supply rate and history.



Summary

- Black hole spin as interesting as mass
  - Astrophysics and evolution
- Jets probes of intrinsic properties of holes
  - Current closure?
- New approaches to particle acceleration
  - Magnetoid? collapse
- New opportunities for AGN timing may yield discoveries
  - X,γ-ray QPO; impulsive acceleration
- Pulsar timing array
  - Detection requires gravitational evolution of orbits