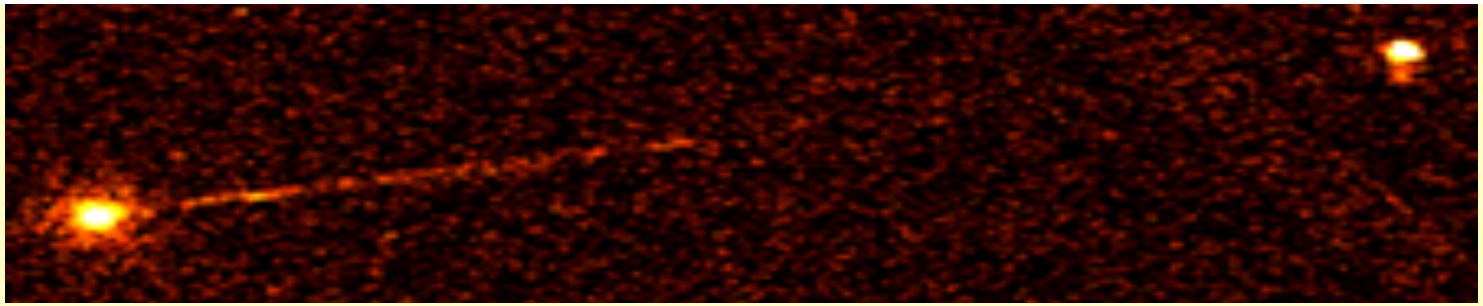
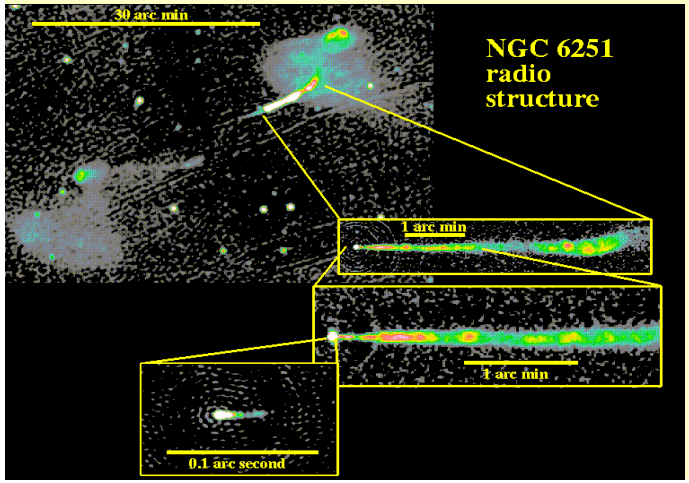
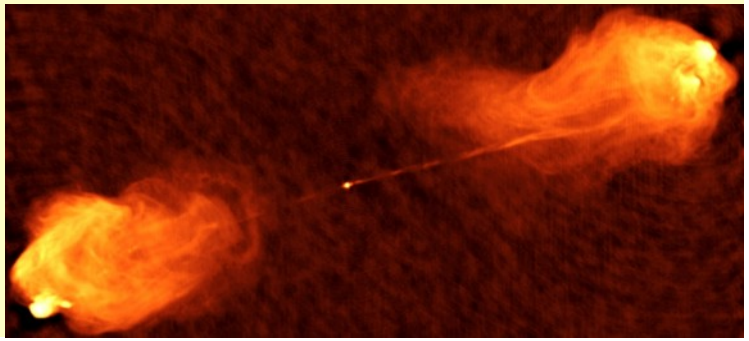


Relativistic Jets: Recent Progress and Open Questions

Roger Blandford
KIPAC
Stanford

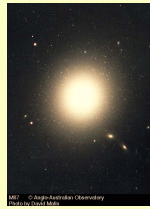


Krakow

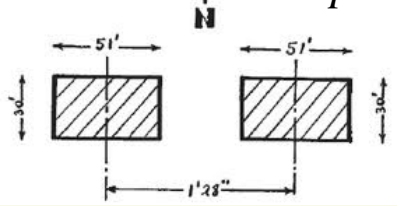


Introduction and Early History

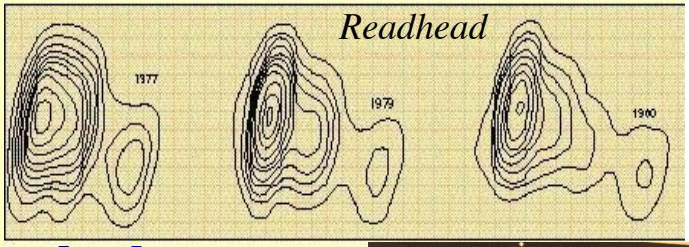
- 1918 M87 curious straight ray
- 1953 Double Radio Sources
- 1963 Quasars, Kerr black holes
- 1969-72 Superluminal motion; GRBs
- 1971-78 Jet models
- 1978 "Blazars"
- 1997 Relativistic Jets in AGNs zjwk

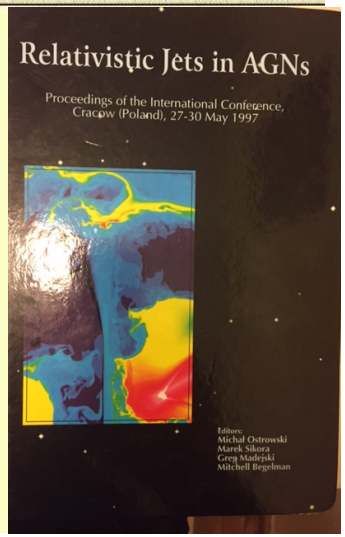


Jennison&DasGupta



Readhead





Paolo Coppi's (1997)Summary

- Unification
- VLBI jet structure and kinematics
- Interaction with environment
- GeV, TeV emission
- Microquasars
- Rapid variability
- Anatomy and physiology

Issues

- Prime Movers
- Electromagnetic Jets
- Particle Acceleration
- Observations
- Jet Models

Issues

- Prime Movers
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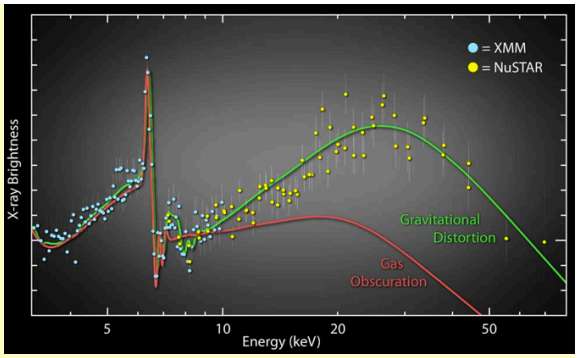
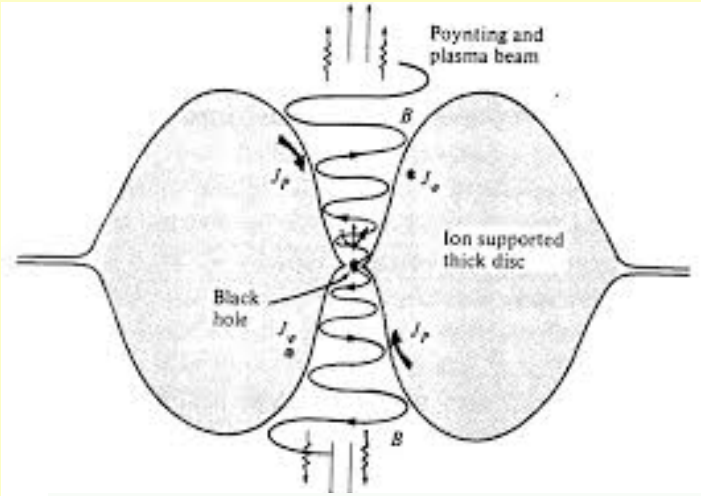
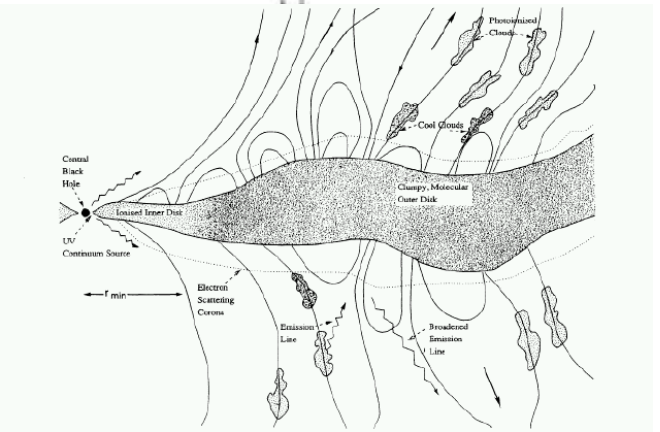
Prime Movers

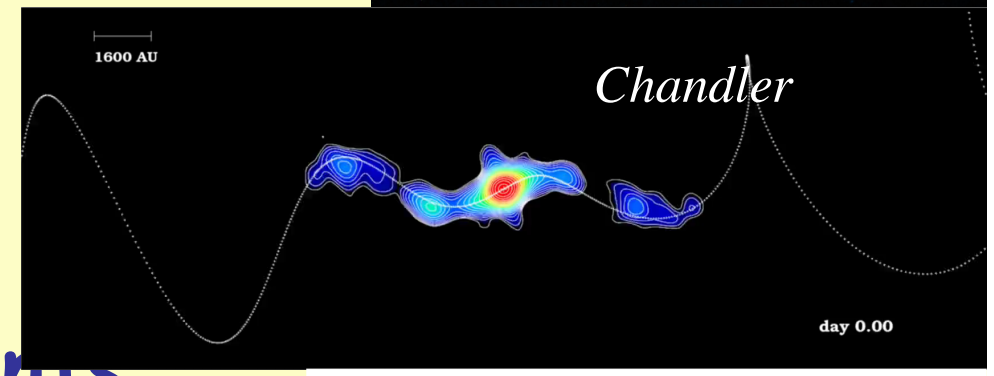
- **AGN – massive black holes**
  - **"million to billion solar masses"**
    - $<10^5$ - $2x10^{10}M_{sun}$, M87?
    - High radiative efficiency
  - **Spin**
    - Measured best in RQ Seyferts
  - **Unification**
    - Beaming
  - **Grand Unified Theory**
    - Adiabatic/thick vs Radiative/thin disks
    - Adiabatic supply->accretion or wind?

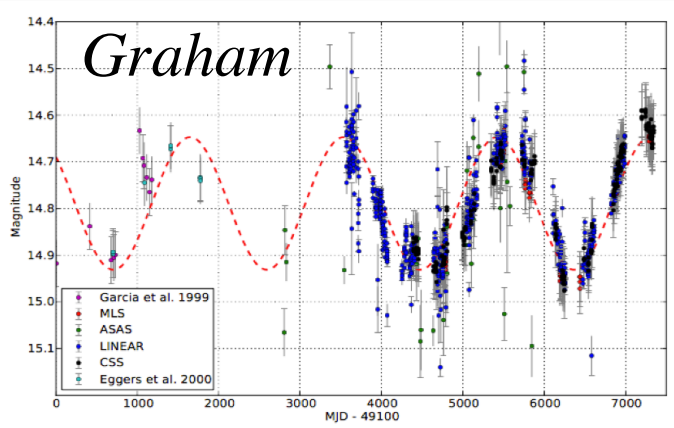




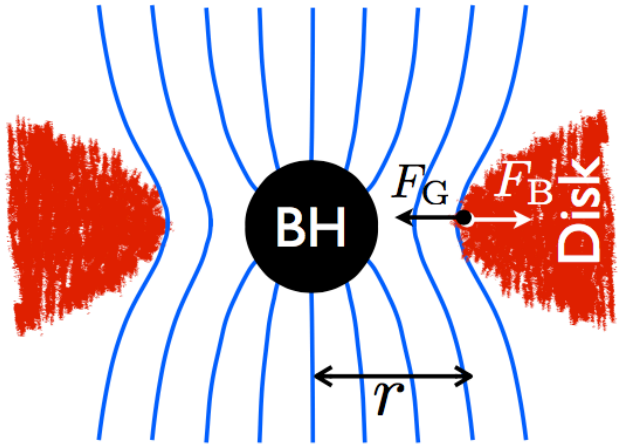


- **Intermediate Mass Black Holes**
  - **~100-10^5 M_{sun}**
    - NGC2276
    - But see M82 X-2!
- **Stellar Black Holes**
  - **Galactic superluminals**
    - SS433
  - **GRBs**
    - or millisecond magnetars
- **Tidal Disruption Events**
- **Binary Black Holes**
  - **Harbingers, IPTA**
    - OJ287, PG1302-102?

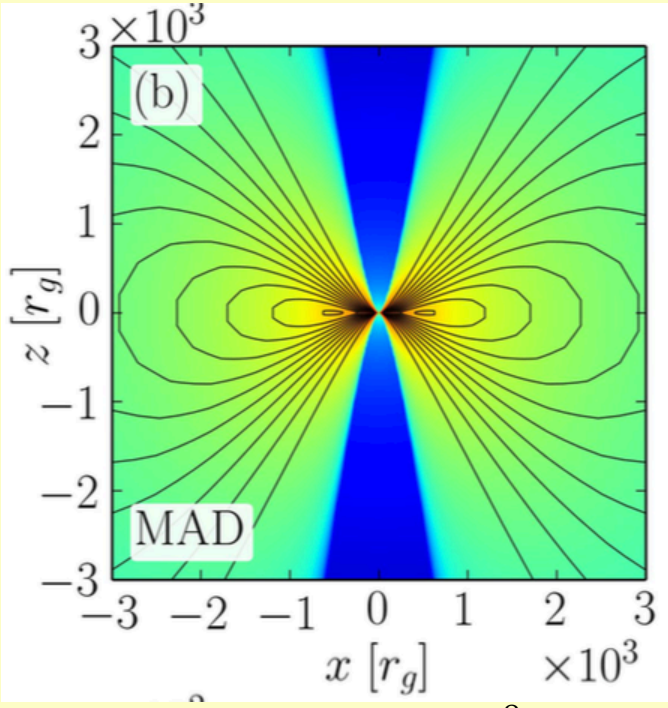




- **Jet Launching**
  - **EM vs hadronic vs radiation jets**
    - AGN, GRBs, SS433?
  - **Hole vs disk, Jet vs Wind**
  - **Magnetic extraction**
    - Dipolar not quadrupolar
    - Magnetically Arrested Disks
      - *cf Znajek (1976)*
    - $P_{EM} \sim V^2/Z_0 \sim \Omega_H^2 \Phi_H^2 / Z_0$
    - Diamagnetism (Bicak)
    - Ergosphere?
    - Relationship to Penrose P?
  - **3D simulations ->η>1, instability**



Tchechkovskoy

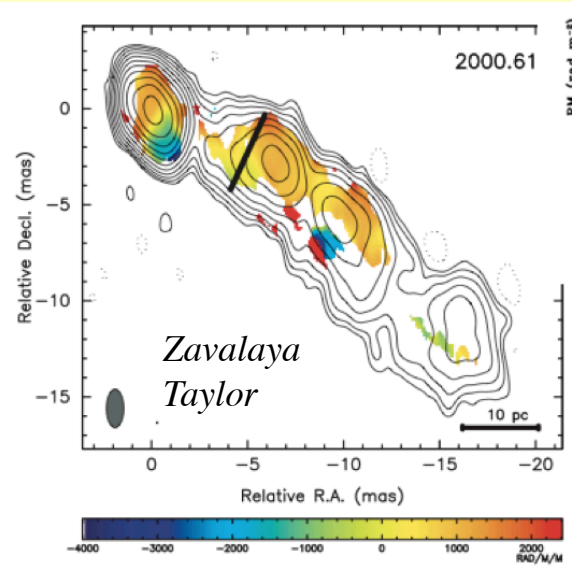


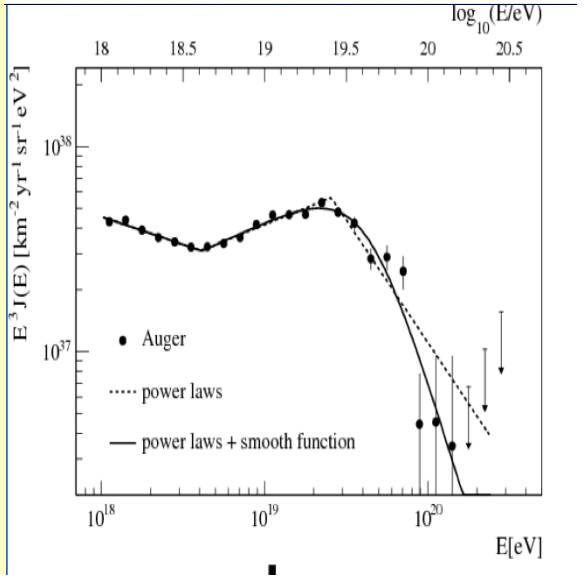
Issues

- Prime Movers
- **Electromagnetic Jets**
- Particle Acceleration
- Observations
- Jet Models

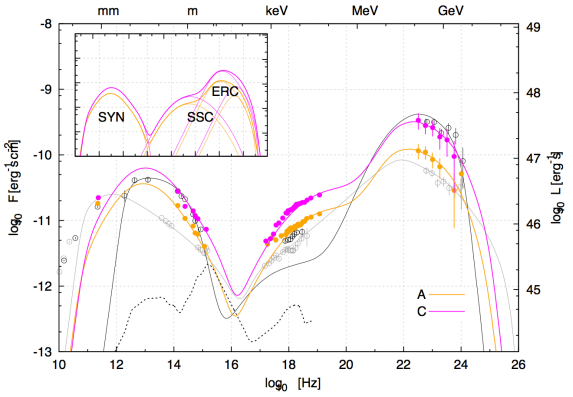
Electromagnetic Jets

- Collimation and acceleration
  - Currents vs fields
    - Boundary conditions
- $B_\phi \sim A^{-1/2}$, $\langle B_z \rangle \sim A^{-1}$, $B_{zrms} \sim ?$
  - Faraday rotation
    - Dipolar?
    - Large scale order in disk?
  - Core-shift
    - Does this measure Φ_H?
- UHECR
  - $V \sim L_{47}^{1/2}\, ZV$

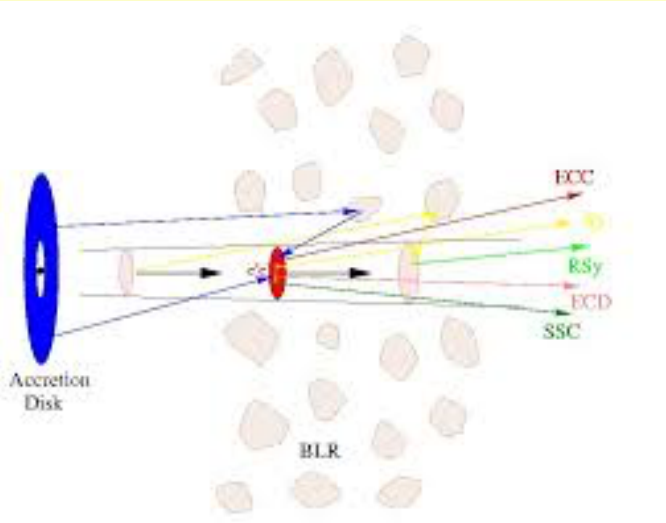




- **EM-> pair transformation**
  - **How is this effected?**
    - Too soon -> radiative drag, annihilation
    - Sikora bump?
    - Too late -> no rapid variation?



- **One zone vs inhomogenous models**
  - **Radio core shift**
    - R follows γ
  - **Gammasphere**
    - Pair production opacity
    - $\sigma_T \sim \sigma_{PP}$
    - Need angular distribution of soft photons



Issues

- Prime Movers
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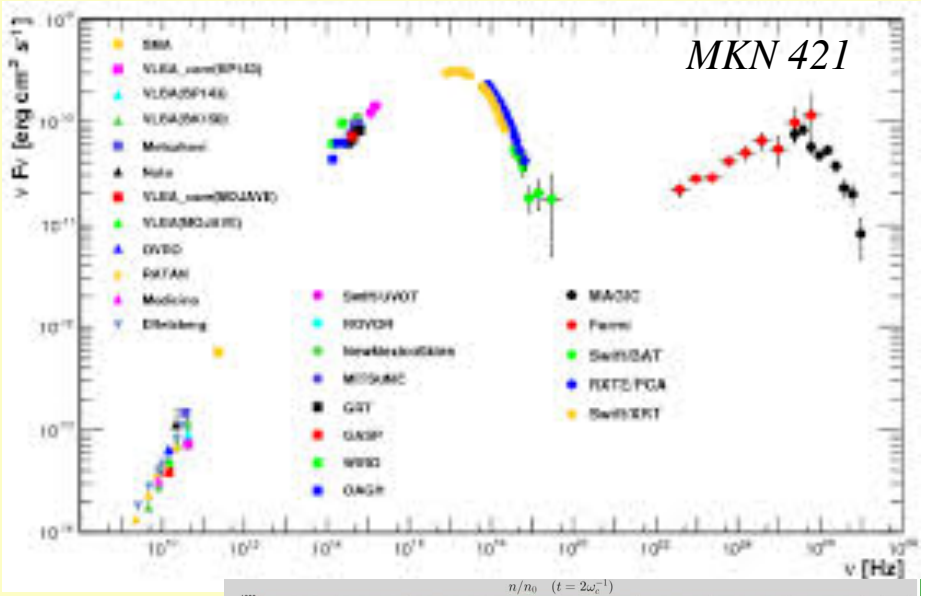
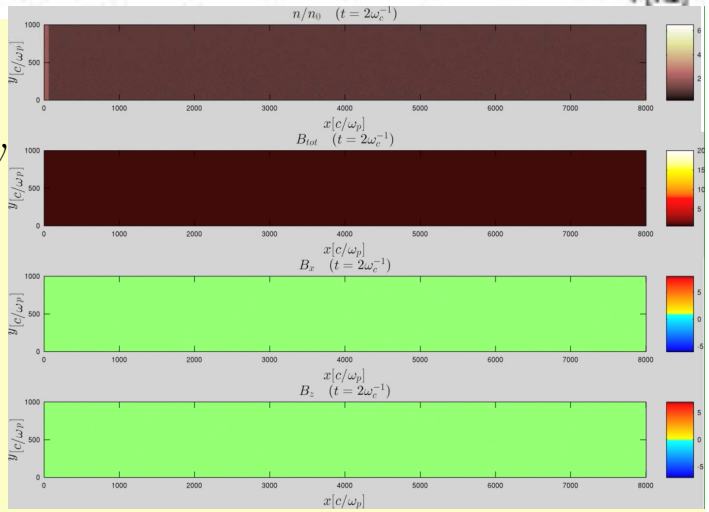
Particle Acceleration

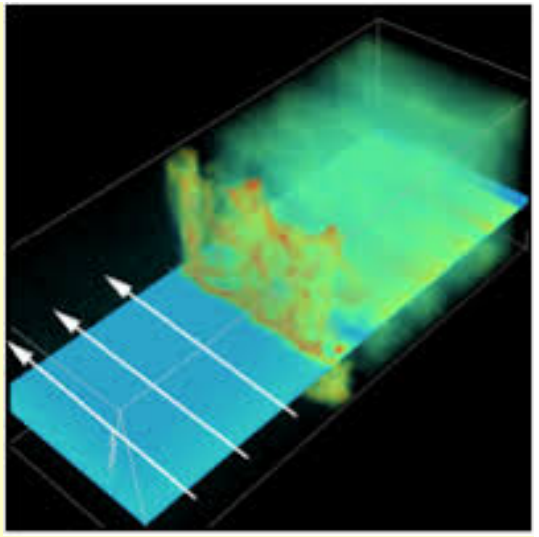
- **Dissipation of electrical circuit**
  - **Efficient**
    - I - accelerating particles
    - R may be radiation reaction
  - **Very rapid variation**
    - $r_\gamma >> ct_{var}$ in GeV/TeV
  - **RMHD vs MHD**
    - v, a ~c
- **Kinetic simulations**
  - **PIC codes**
  - **HED physics coming**





Cerruti
Spitkovsky

- Direct acceleration
  - $E_e \sim 100$TV γ, X
- Relativistic shocks
  - Intershock-region
- Recollimation
  - Observations-> multi-zo
- Reconnection
  - Steady acceleration?
- Turbulence
  - Cascade down to gyro radius
    - Inverse cascade?



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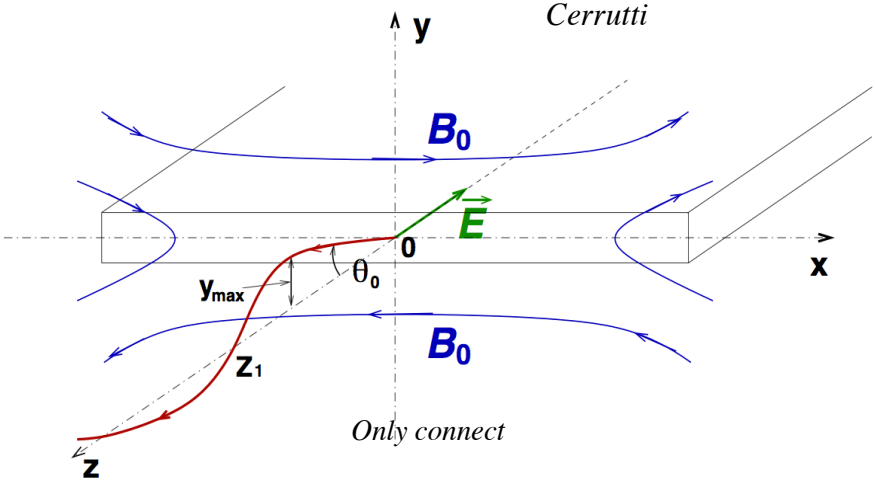
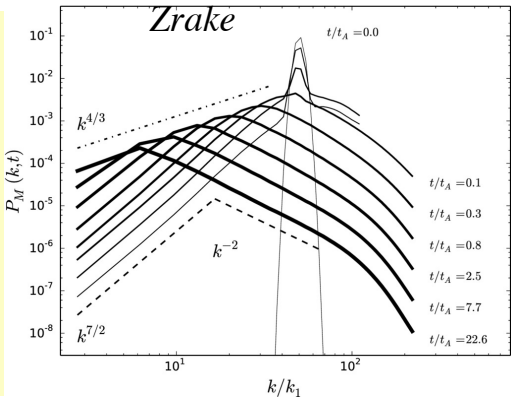
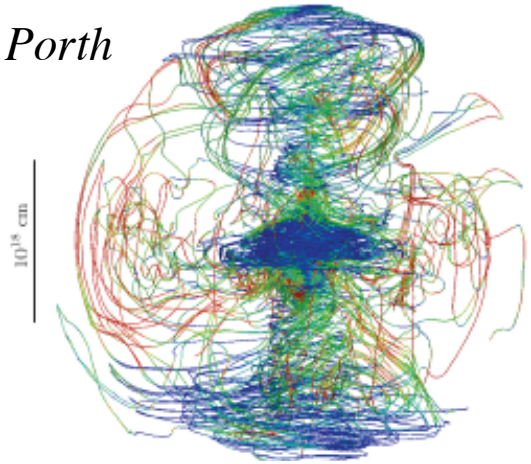


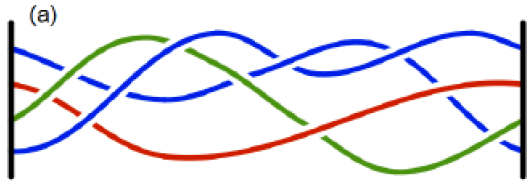
Only connect

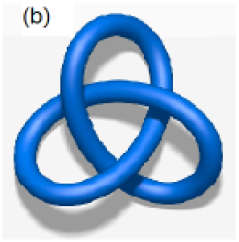


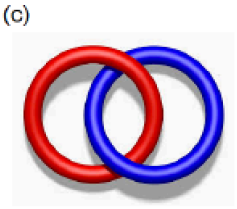
- **Magnetoluminescence**
  - **Magnetic field -> flux ropes**
  - **Helicity (K)<-> linkage**
  - **Reconnect with change of K**
    - Slow
  - **Untangle without change of K**
    - Fast
    - Transition to lower energy state
    - Terminates when E~B
    - Volumetric acceleration
    - S: $\gamma \sim< 137 \times 0.5$ MeV
    - C: $\gamma \sim< eV_H$

Porth









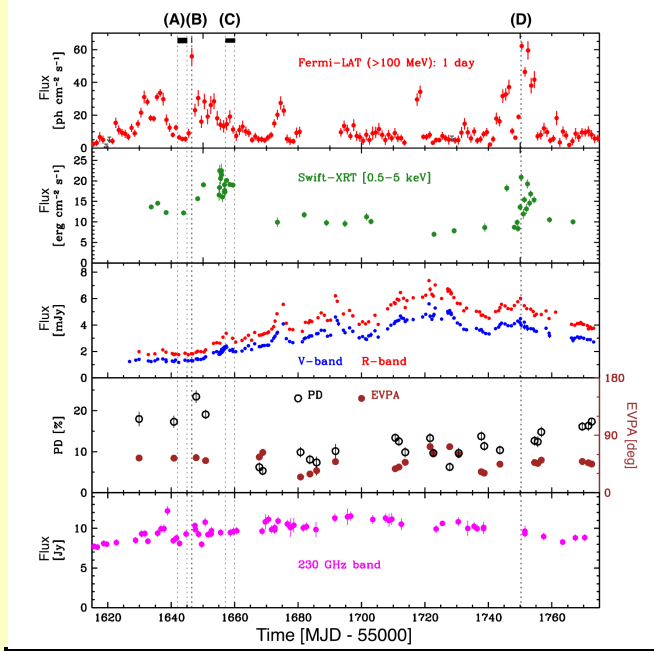
Issues

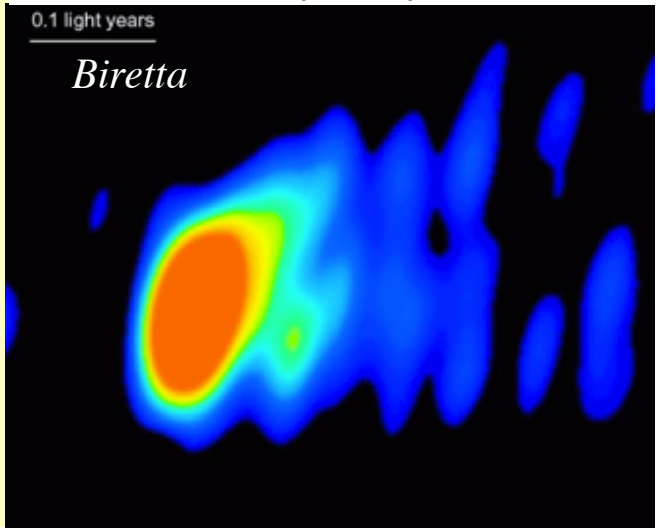
- Prime Movers
- Electromagnetic Jets
- Particle Acceleration
- **Observations**
- Jet Models

Observations

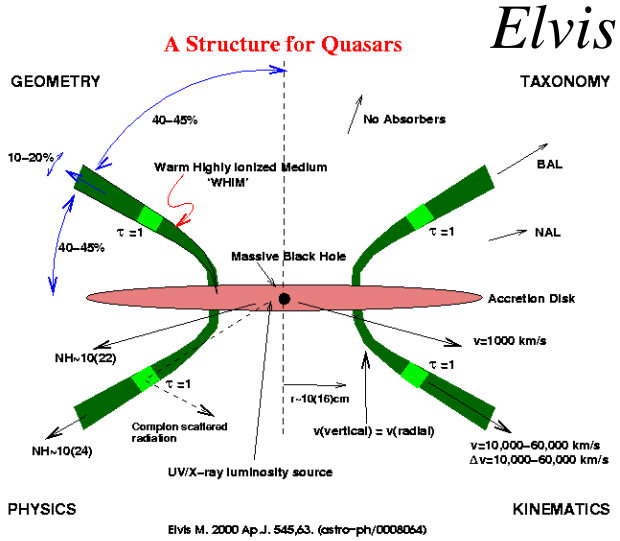
- **Fermi blazars plus multi-λ**
  - **Weak, occasional correlations**
    - Radio follows γ-ray
    - Coherent rotation of optical pa
  - **Huge range in models**
  - **Doppler factor discrepancy**
  - **Very low magnetic field?**
- **mm/submm VLBI**
  - **EHT- M87 Sgr A***
    - Fringes at 10m already
    - Observe ion tori?

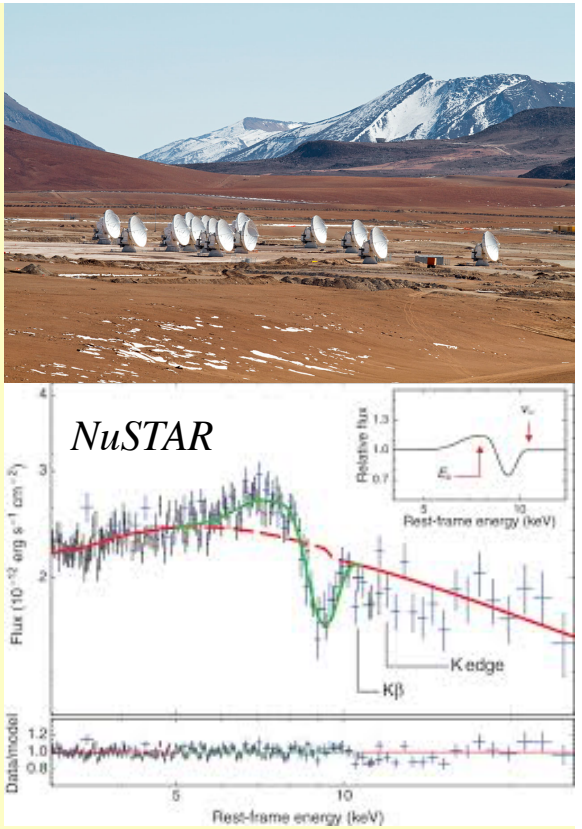
Hayashida





- **Disk Winds**
  - **Jet collimation**
  - **Magnetic confinement**
  - **Plasma entrainment**
  - **Momentum sharing**
    - Jet<Wind->FRI
    - Jet>Wind->FRII
  - **PDS 456**
- **ALMA**
  - **Reveal molecular inflow?**
    - Gravitational lensing
    - Spectroscopy
    - Source as well as lens!





Issues

- Prime Movers
- Electromagnetic Jets
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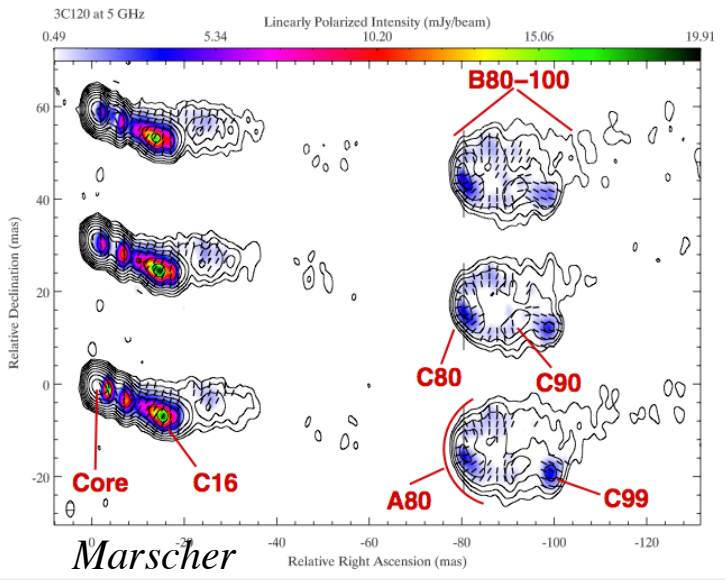
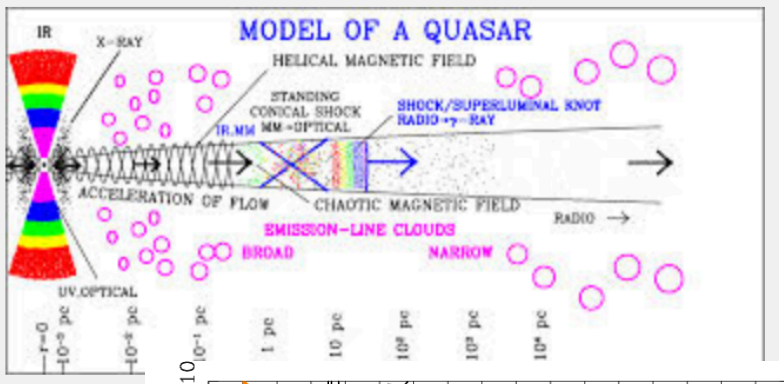
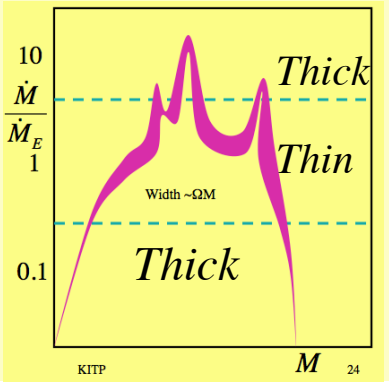
- **Jet Models**

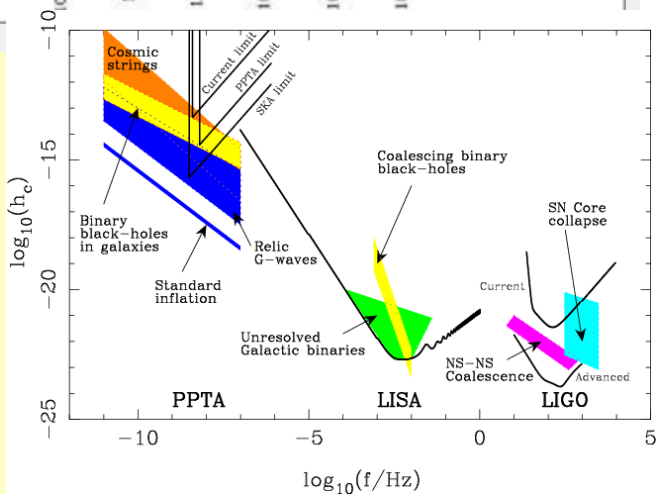
Jet Models

- Find r(ν), r(Eγ)
  - One zone models
  - structured models
    - Longitudinal and transverse
- Cosmology
  - Black hole assembly
    - IPTA background?
  - SDSSJ010013.02 (z=6.3 quasar),
    - M_{BH}~1.2 x$10^{10}M_{sun}$
    - Super-Salpeter growth









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Future

- EHT and for blazars
- Astro-H JWST for outflows…
- ALMA for molecular inflows, obstacles
- Polarimetry (including X-ray)
- LIGO, IceCube, Fermi, Swift for GRBs
- CTA for γ-rays
- SKA (NGVLA?)
- OVLBI – can we do this in mm/submm?
- Fluid, kinetic simulations