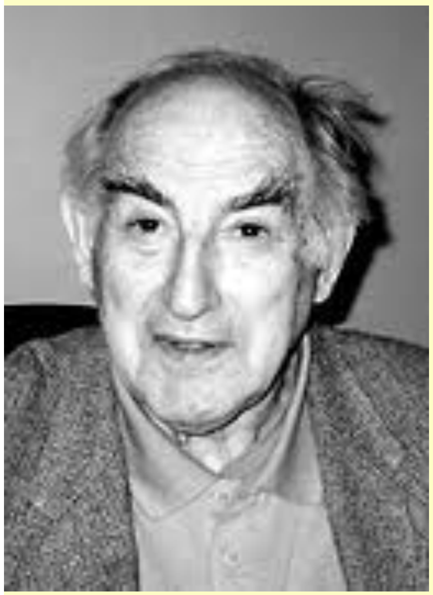
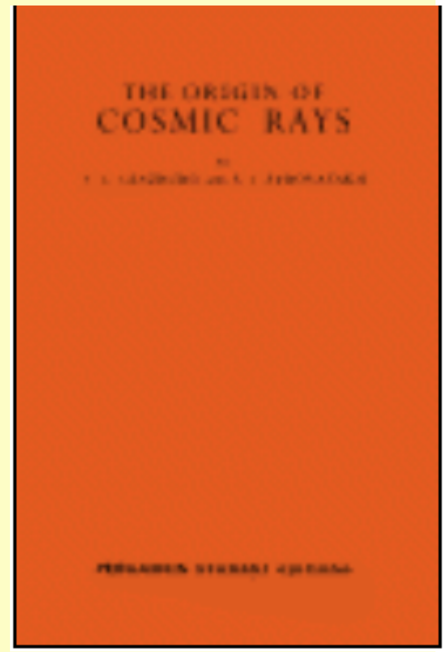
On the Formation of Relativistic Jets: Observation, Simulation and Theory

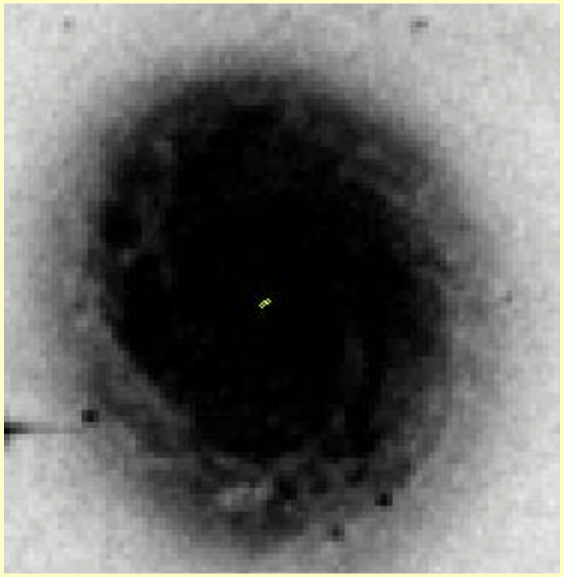


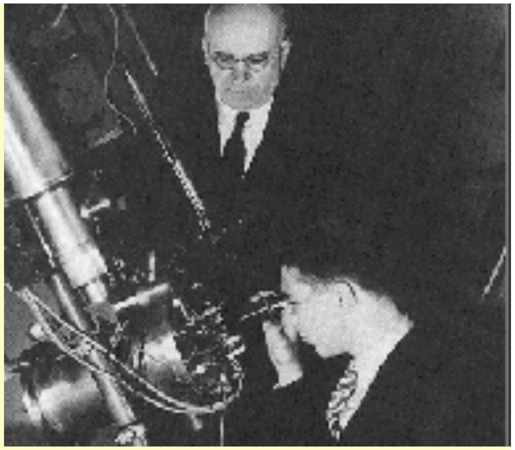
Roger Blandford
KIPAC
Stanford



Active Galactic Nucleus

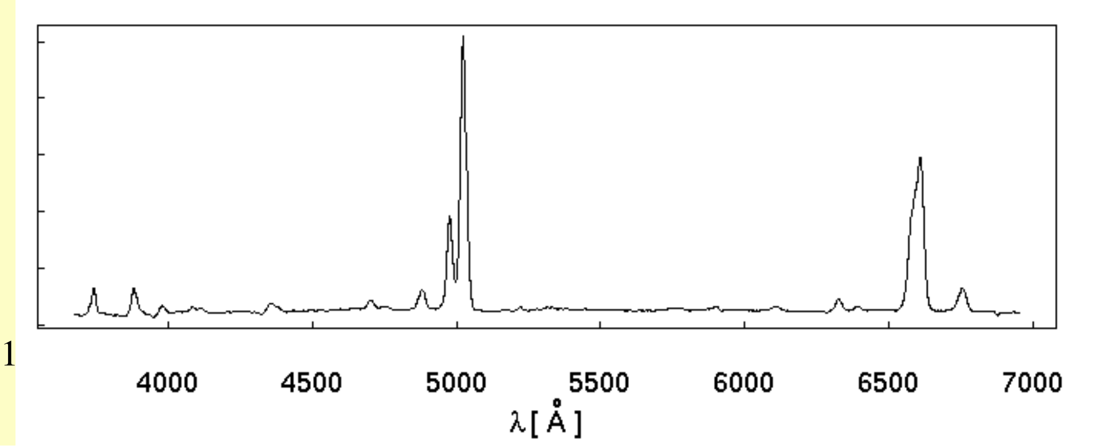
NGC 1068

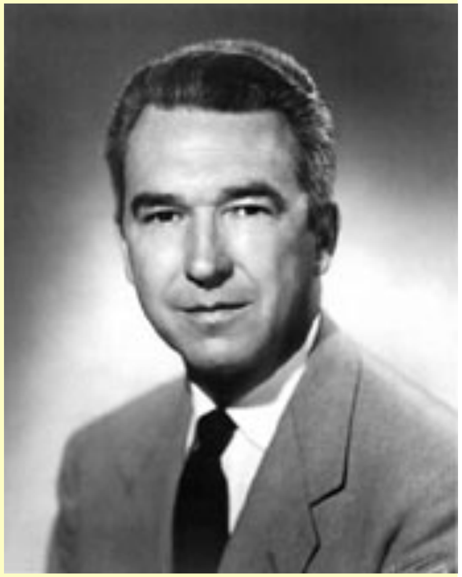




Edward Fath
1908

Seyfert Galaxy





Carl Seyfert
1943

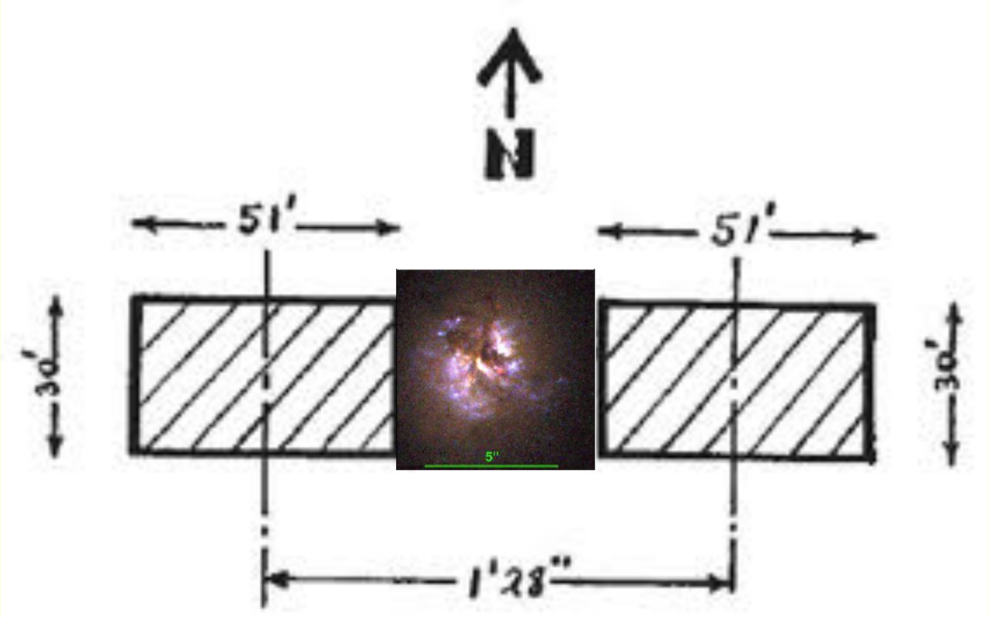
Elliptical Galaxy – M87

Heber Curtis
1918

Jet

Double Radio Source

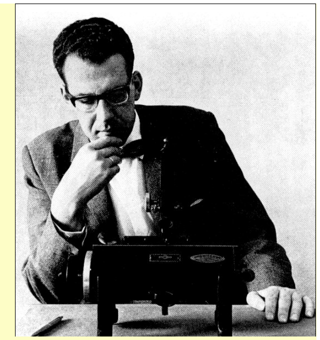
Cygnus A



Jennison
and
Das Gupta

1953

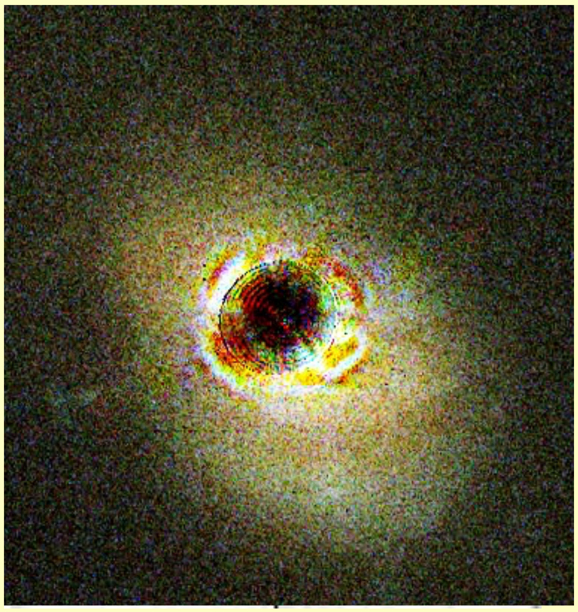
Quasar-3C273

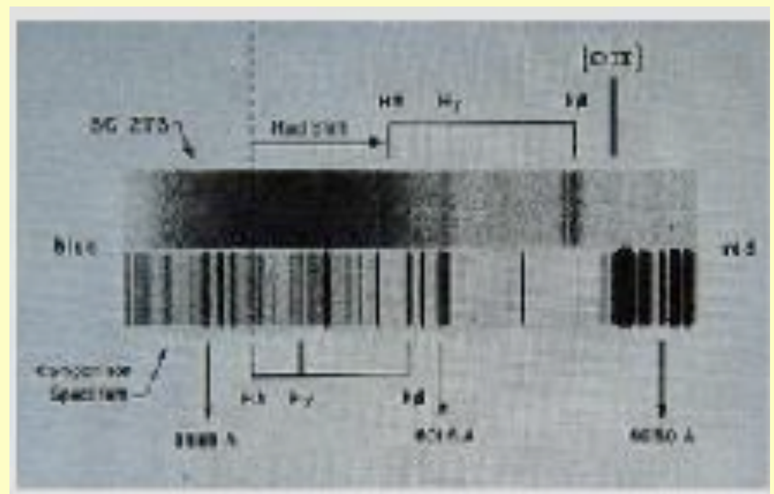


Cyril Hazard

1963

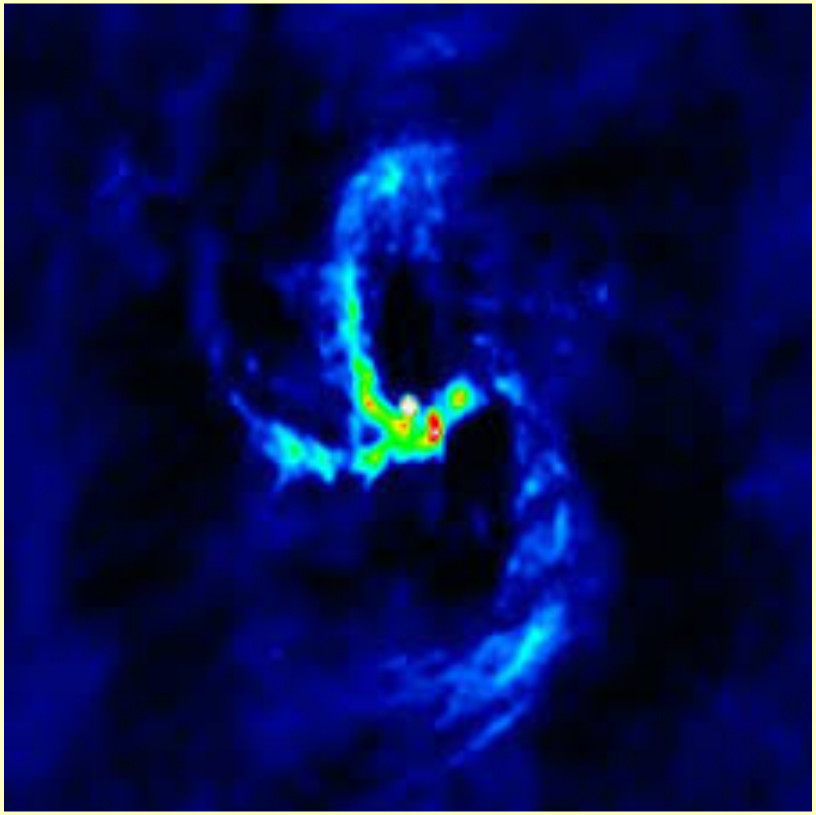
Maarten Schmidt





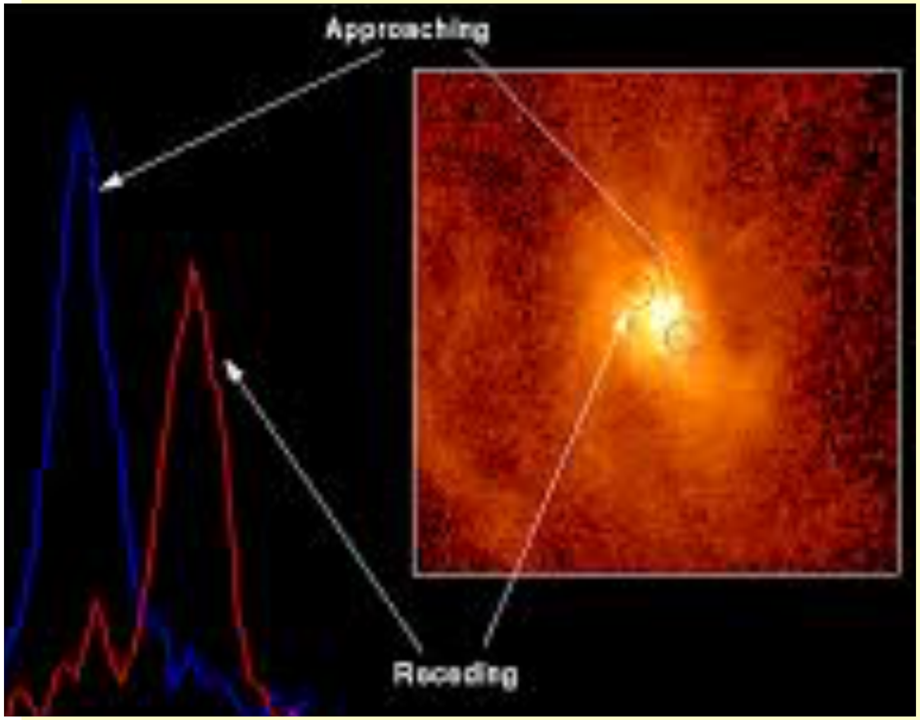
Quasars are Active Galaxies

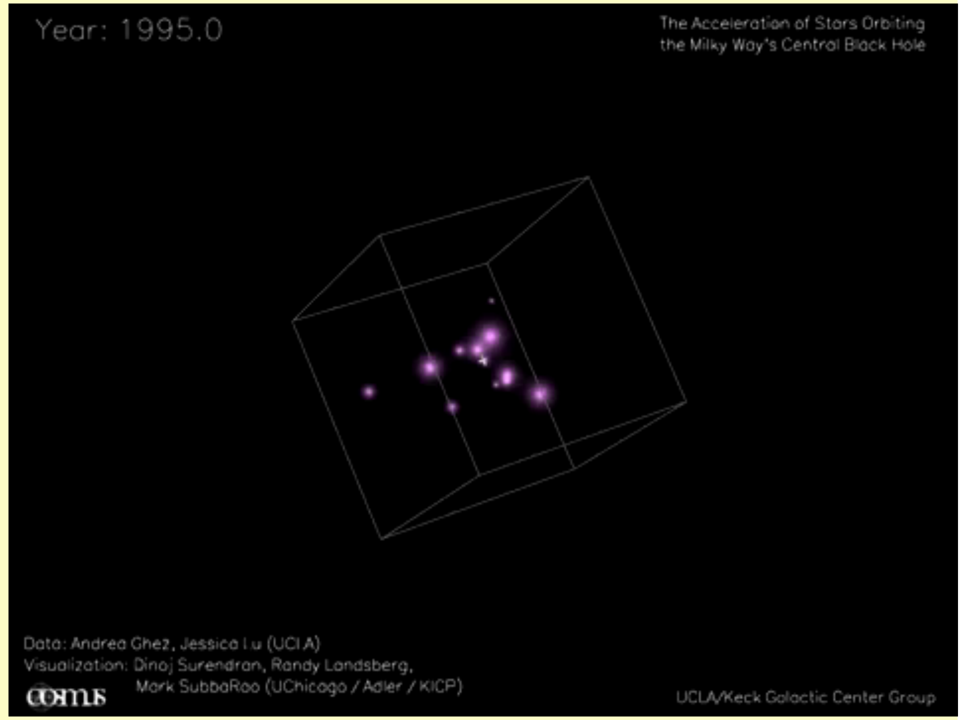
Galactic Nuclei



Milky Way Galaxy

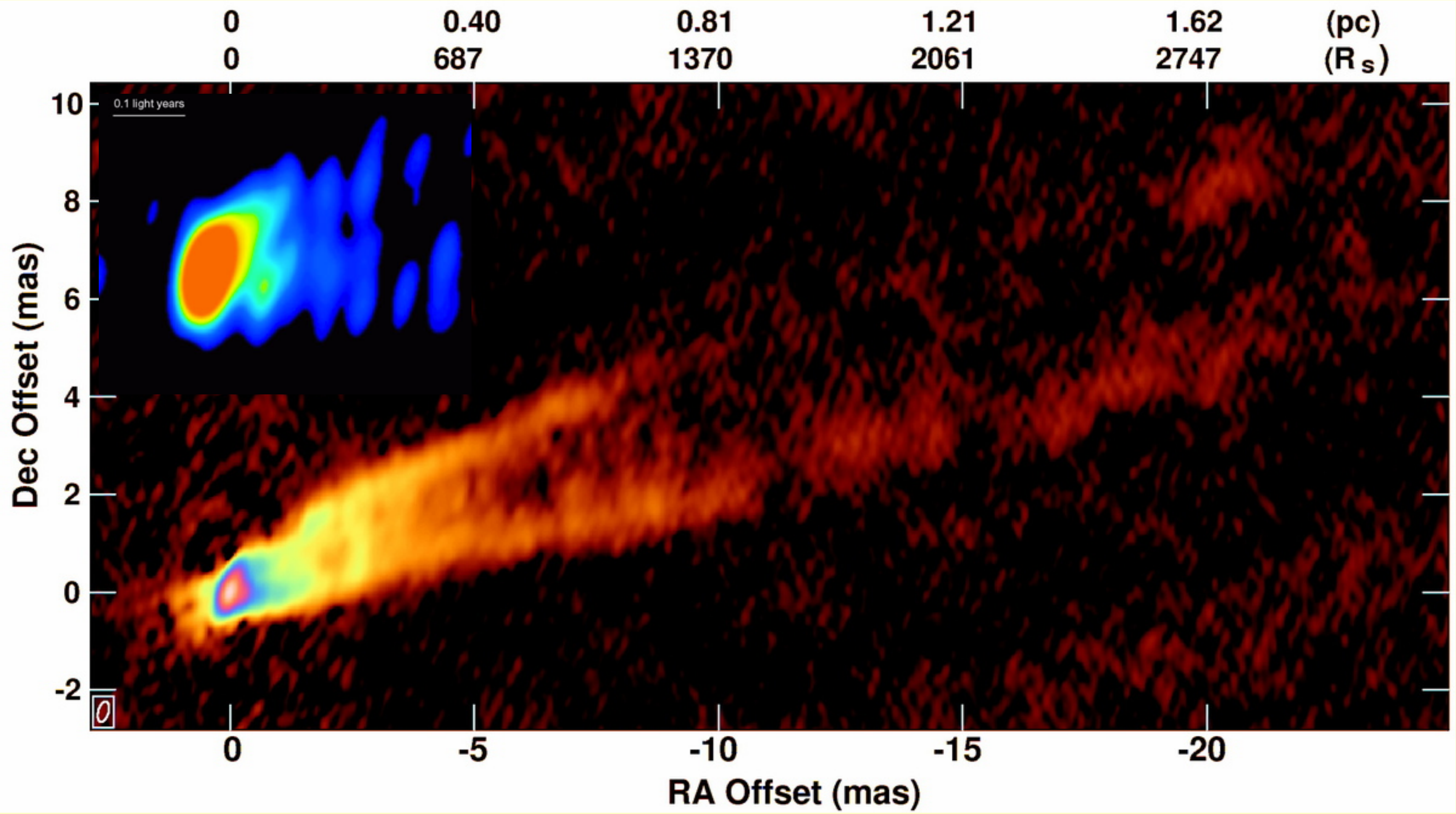
Nuclear Masses



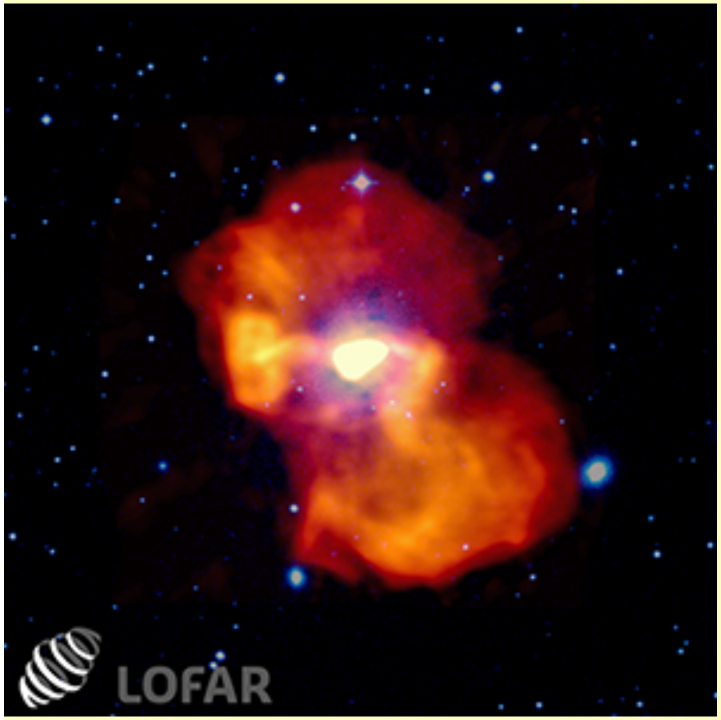


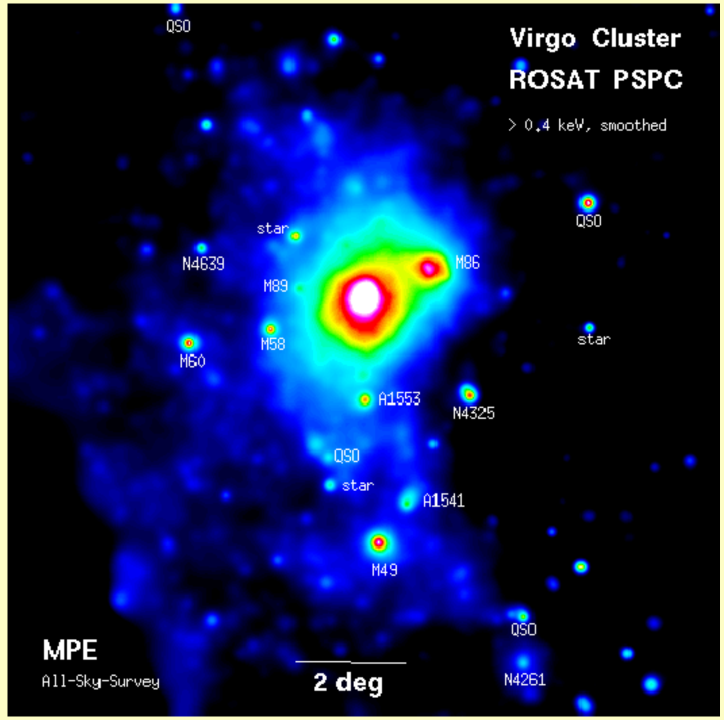
M87: six billion suns **Milky Way: four million suns**

Jets – M87

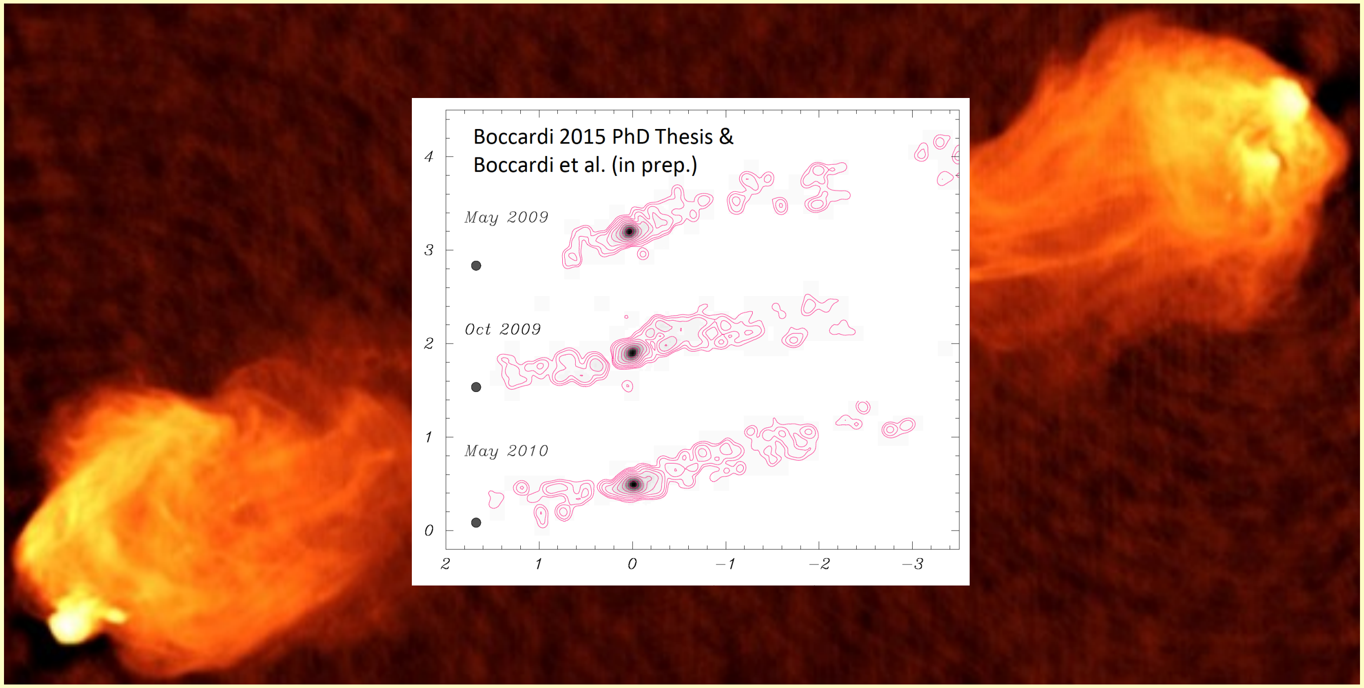

0 0.40 0.81 1.21 1.62 (pc)
0 687 1370 2061 2747 (R s)
0.1 light years
10
8
6
4
2
0
-2
Dec Offset (mas)
0 -5 -10 -15 -20
RA Offset (mas)

Environmental Impact



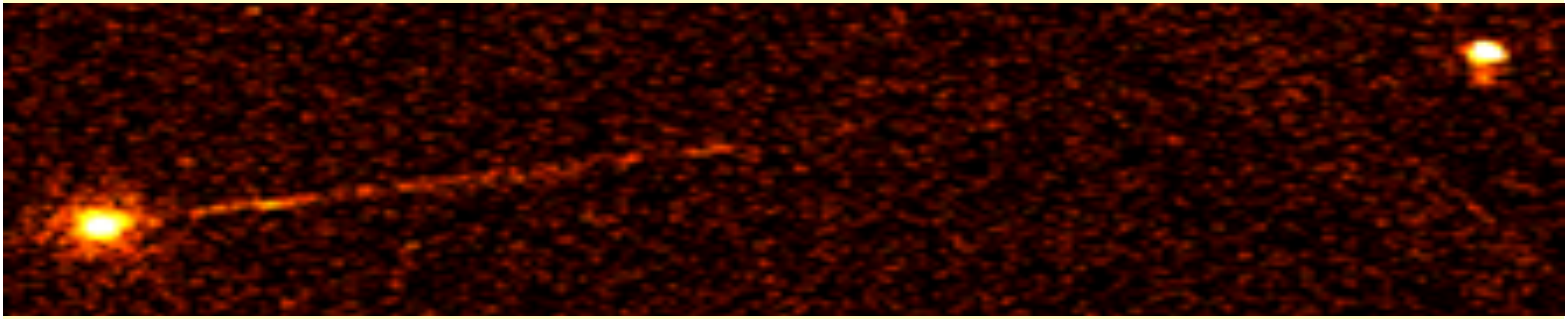


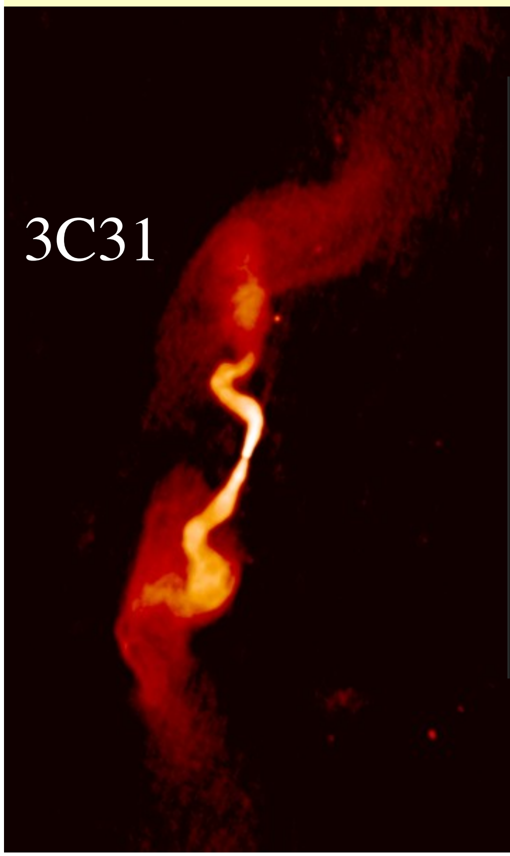
Jets - Cygnus A

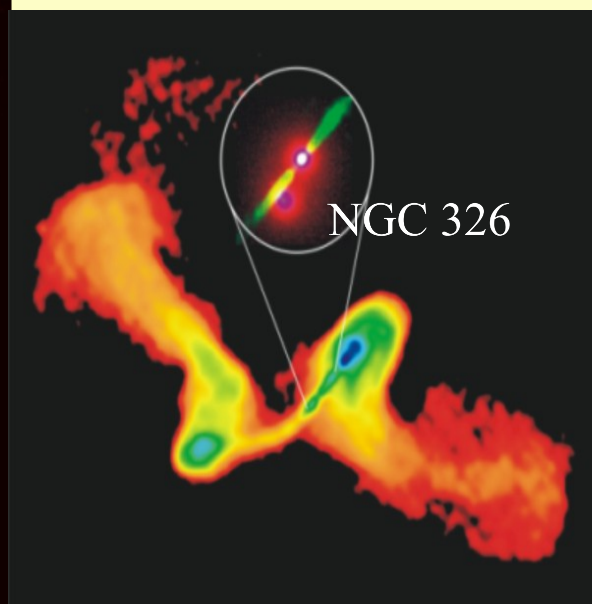


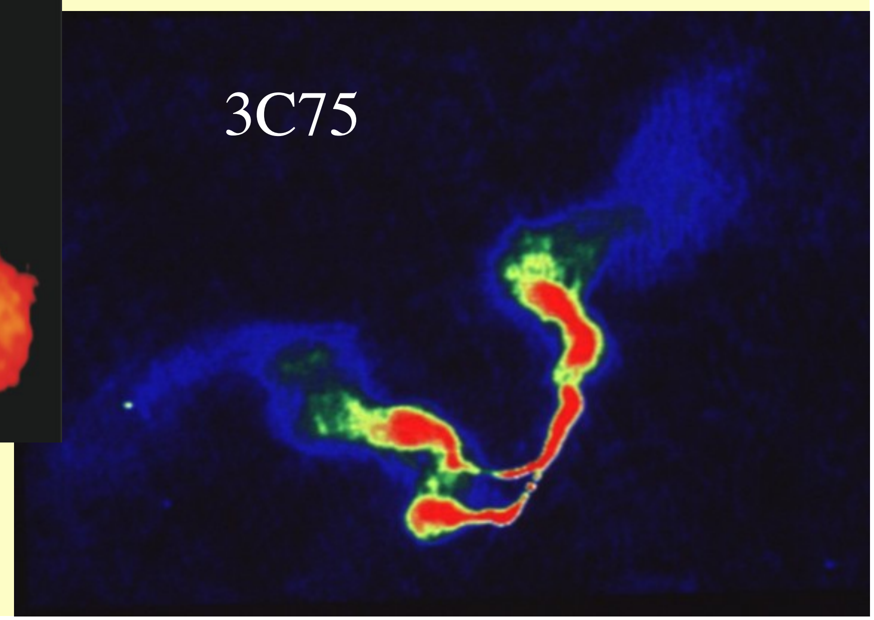
Extragalactic Jets

M87

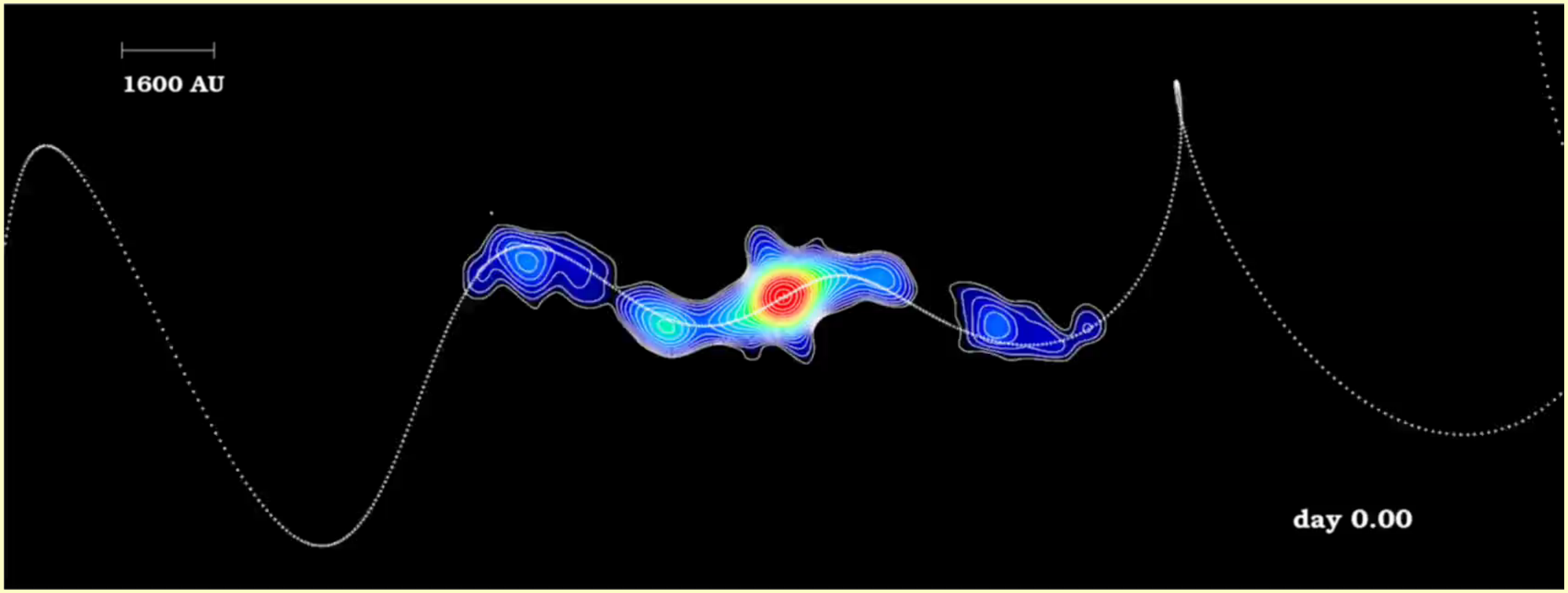






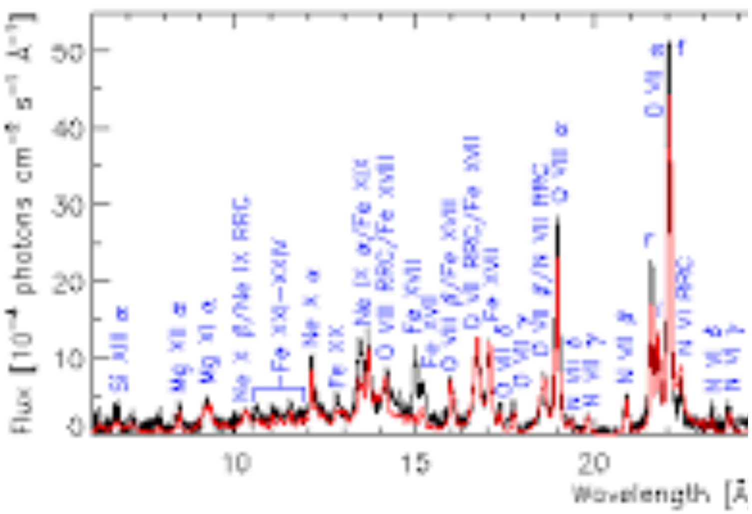


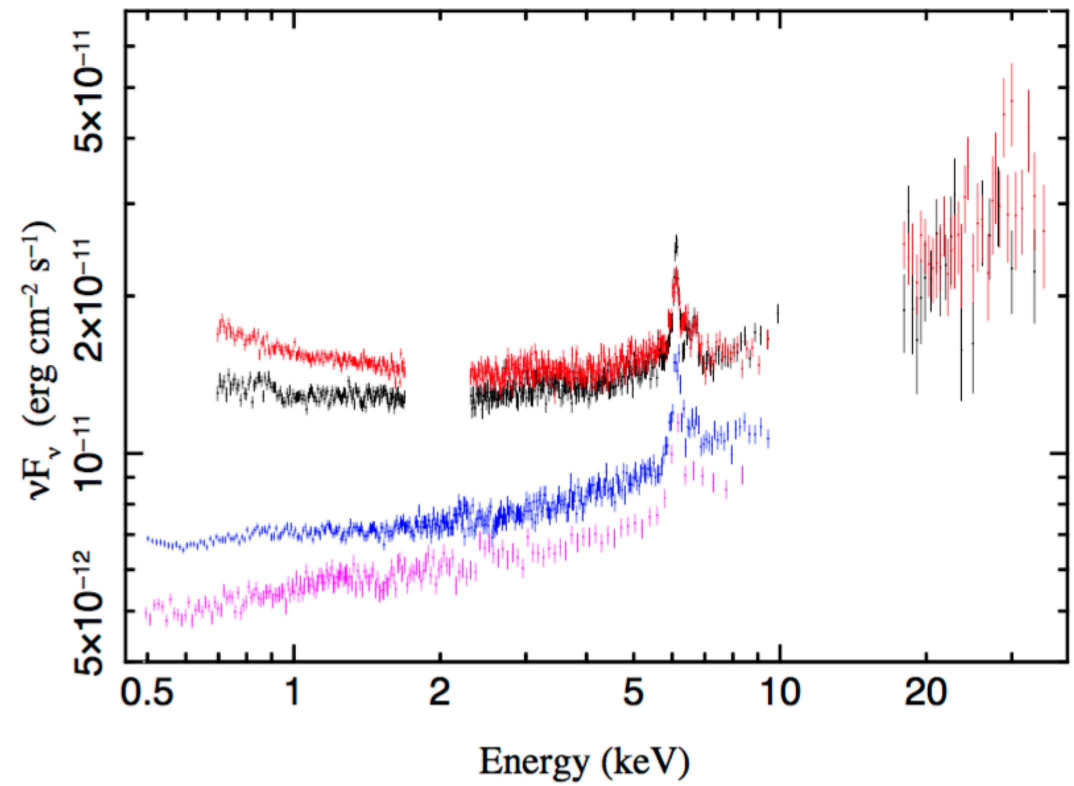
Galactic Jets



SS433

Spectrum



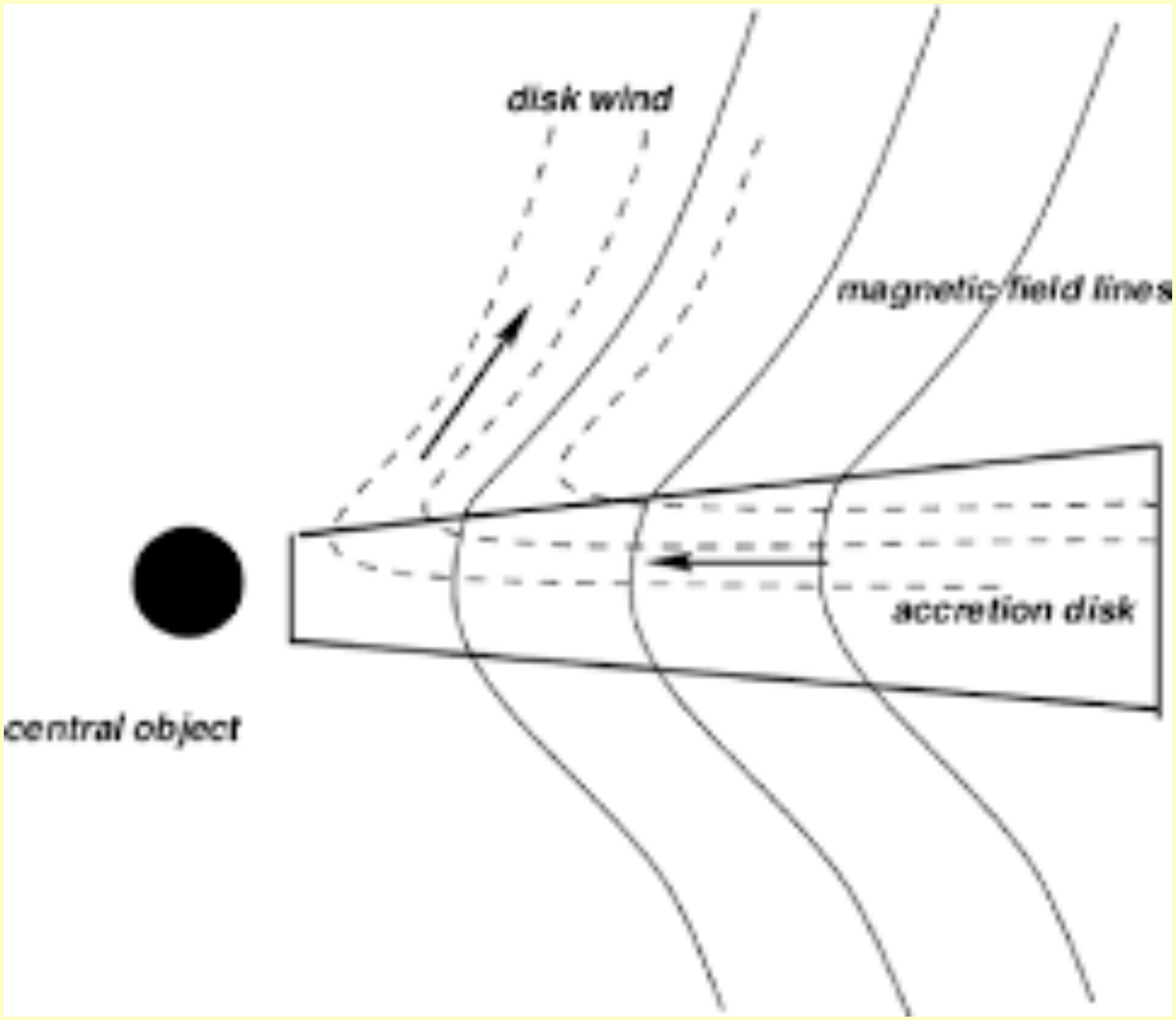


Black holes are orbited by accretion disks and can spin rapidly

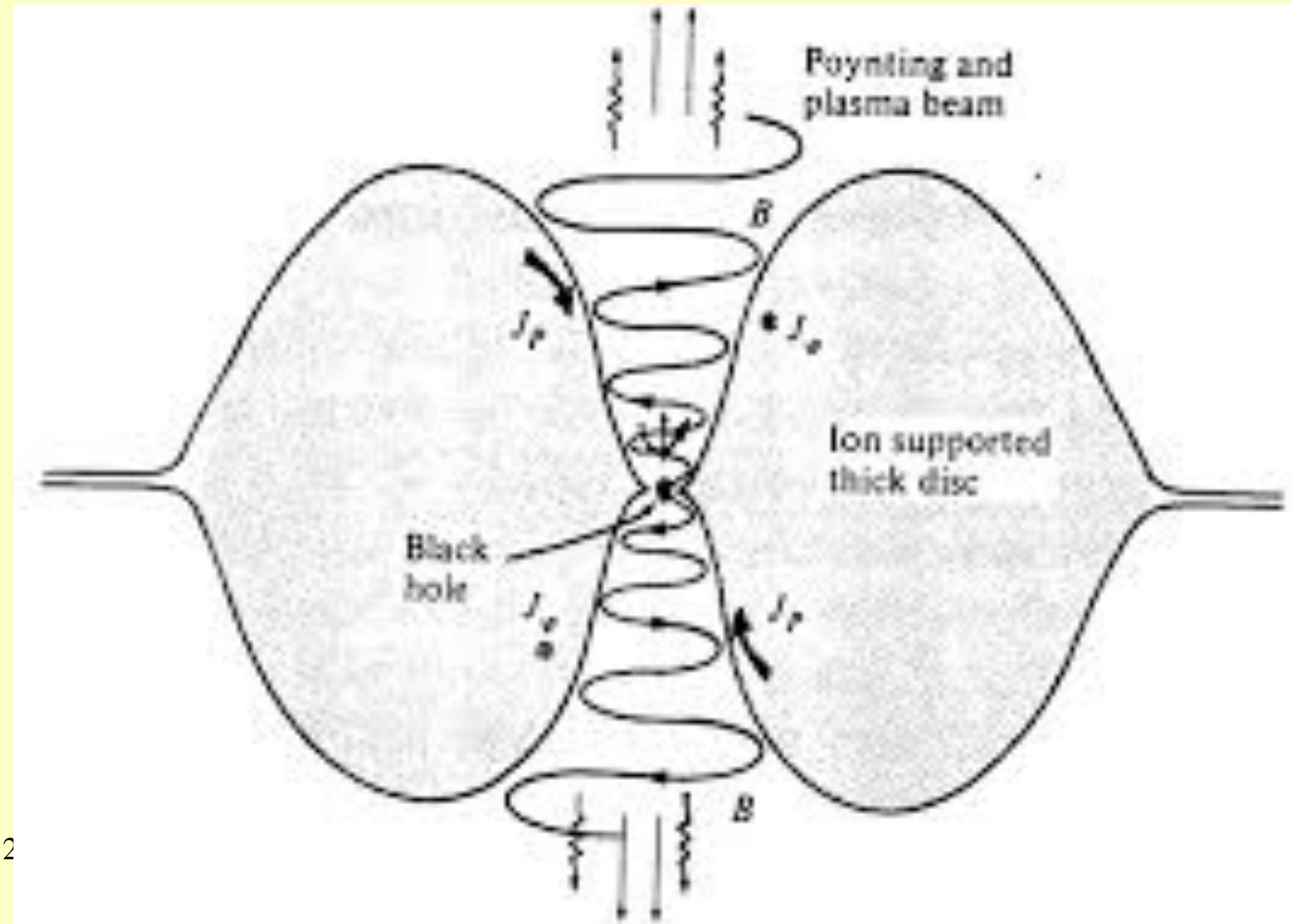
Astrophysical Black Holes

- Kerr Metric
  - $a<m$; $Q,\ldots=0$, classical event horizons
- Observed Black Holes
  - BH binaries ~4-~60 M_{sun} X-ray, LIGO
  - AGN ~ 10^5-~10^{10} M_{sun}

Winds from Accretion Disks



Extraction of Energy from a Spinning Black Hole



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- Modes of Accretion
  - Intermediate -> thin, radiative disk (corona) [Quasar]
  - Low (+cool electrons) -> thick disk + wind [Radio Source]
  - High -> thick radiation-dominated disk +wind [BALQ]

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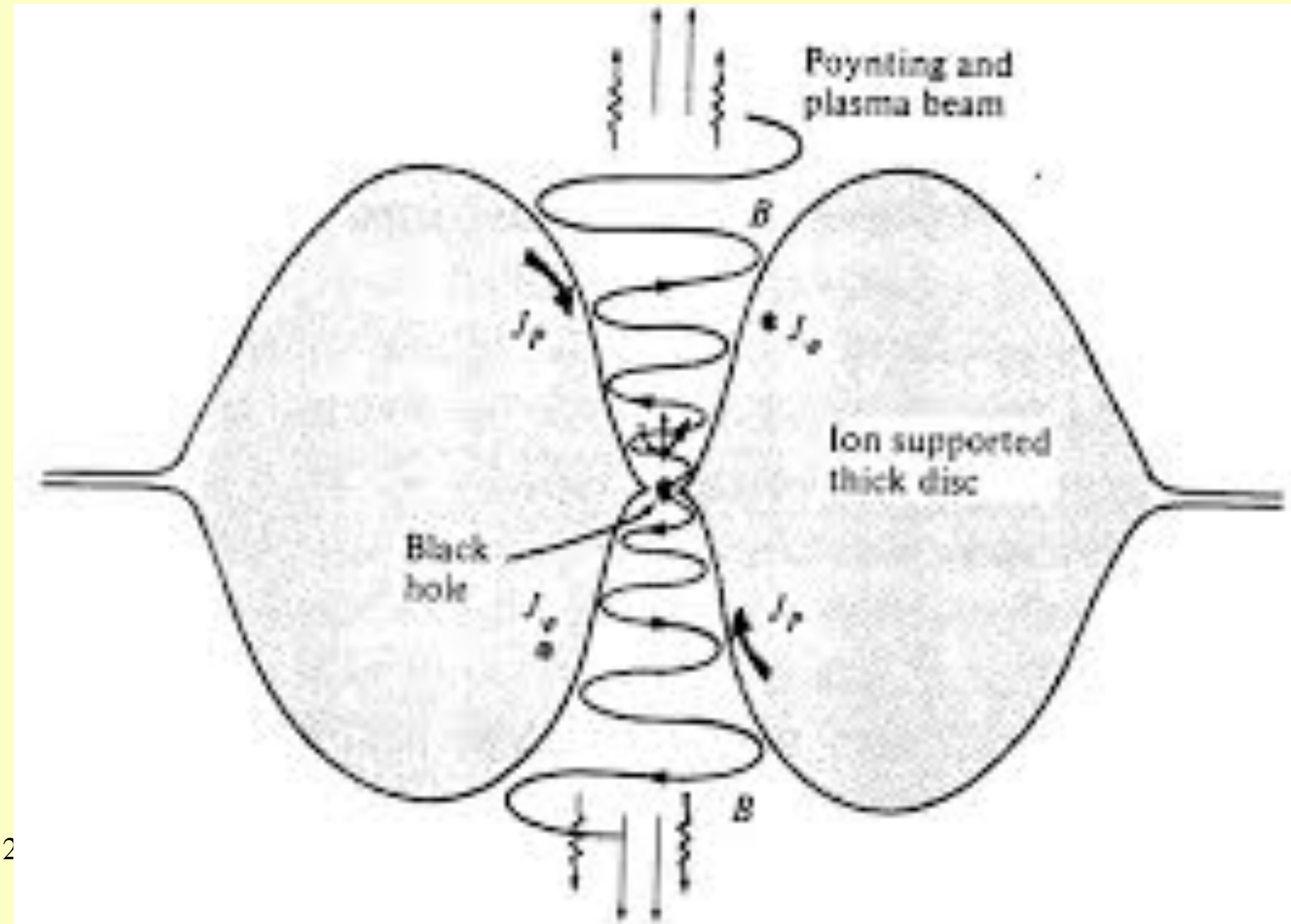

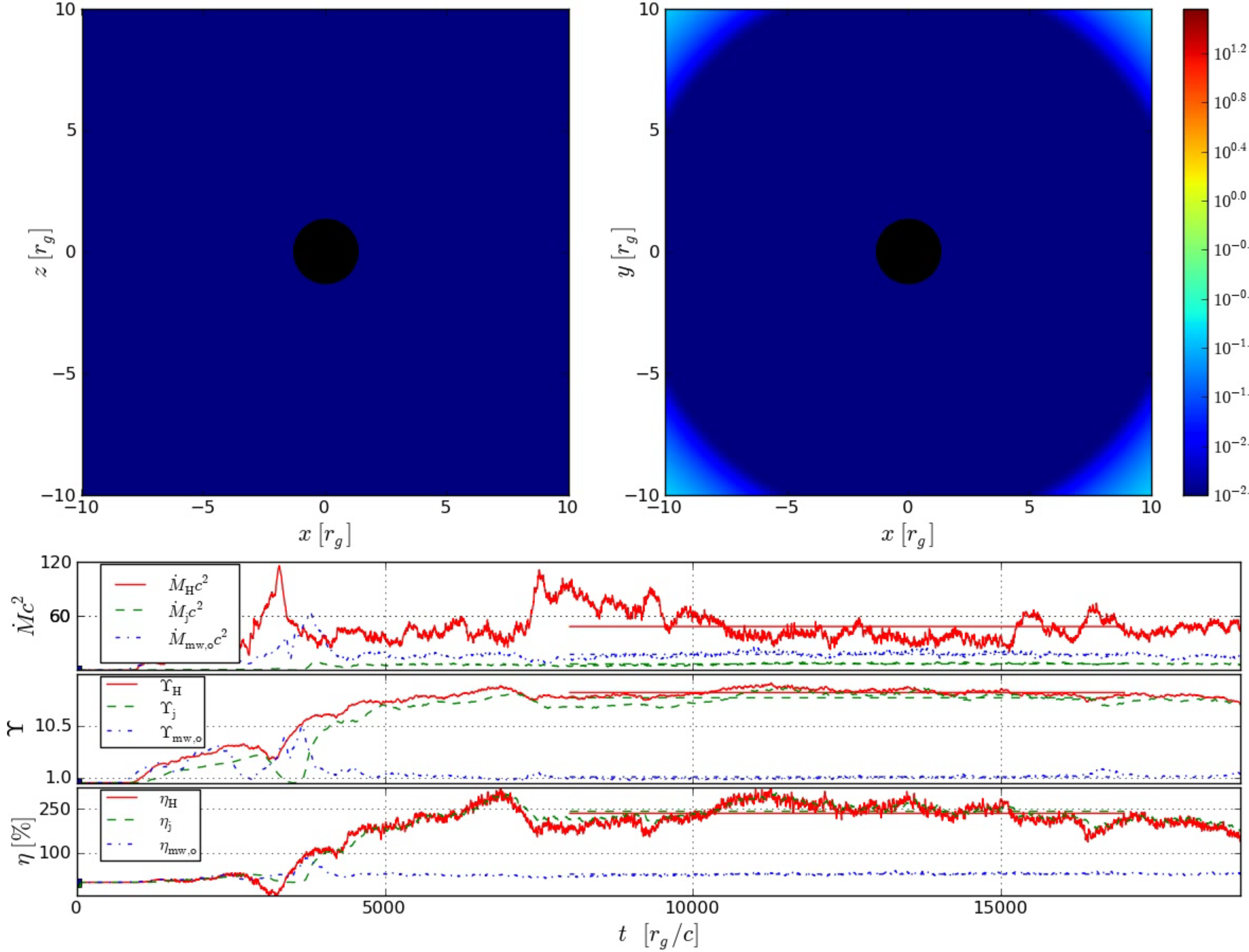

$z\ [r_g]$
$y\ [r_g]$
$x\ [r_g]$
$x\ [r_g]$
$10^{1.2}$
$10^{0.8}$
$10^{0.4}$
$10^{0.0}$
$10^{-0.4}$
$10^{-0.8}$
$10^{-1.2}$
$10^{-1.6}$
$10^{-2.0}$
$10^{-2.4}$
$\dot{M}c^2$
$\dot{M}_{\rm H}c^2$
$\dot{M}_{\rm j}c^2$
$\dot{M}_{\rm mw,o}c^2$
Υ
$\Upsilon_{\rm H}$
$\Upsilon_{\rm j}$
$\Upsilon_{\rm mw,o}$
$\eta\ [\%]$
$\eta_{\rm H}$
$\eta_{\rm j}$
$\eta_{\rm mw,o}$
$t\ \ [r_g/c]$

Astrophysical Black Holes

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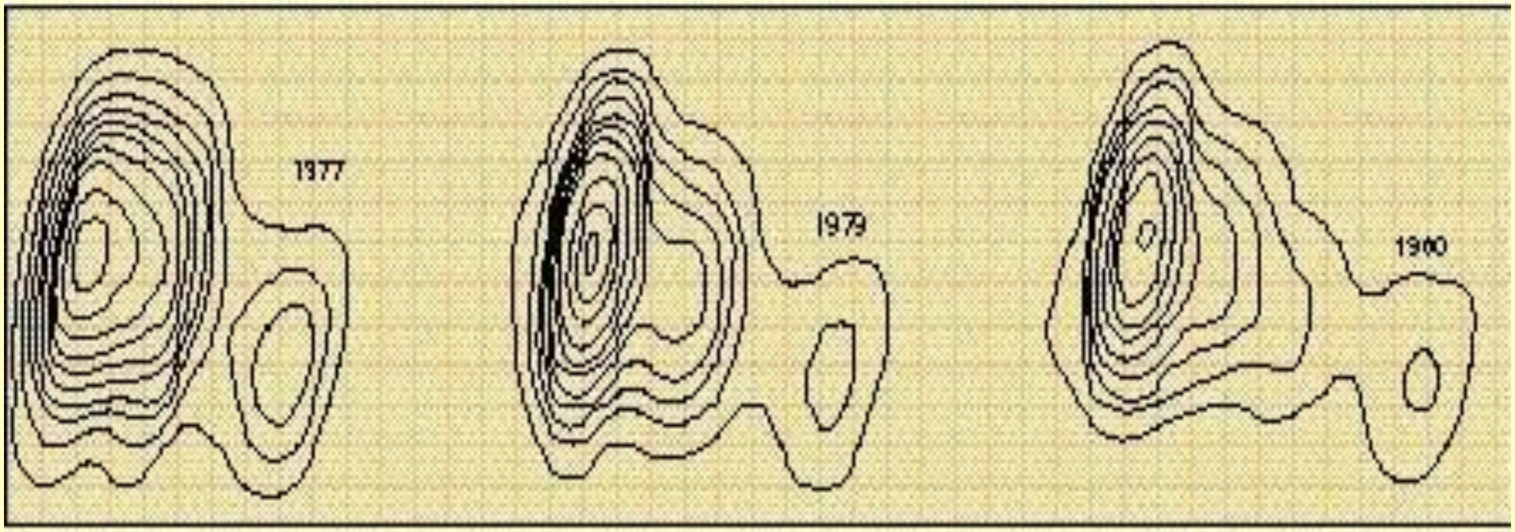
  - High -> thick radiation-dominated disk +wind [BALQ]
- Magnetic Field
  - MRI=>strongly magnetized flows
  - Disk and Hole – internal/external, thin/thick
  - Wind (from hole) and Jet (from torus?)
  - Power and torque- prodigal and industrious

Superluminal Expansion

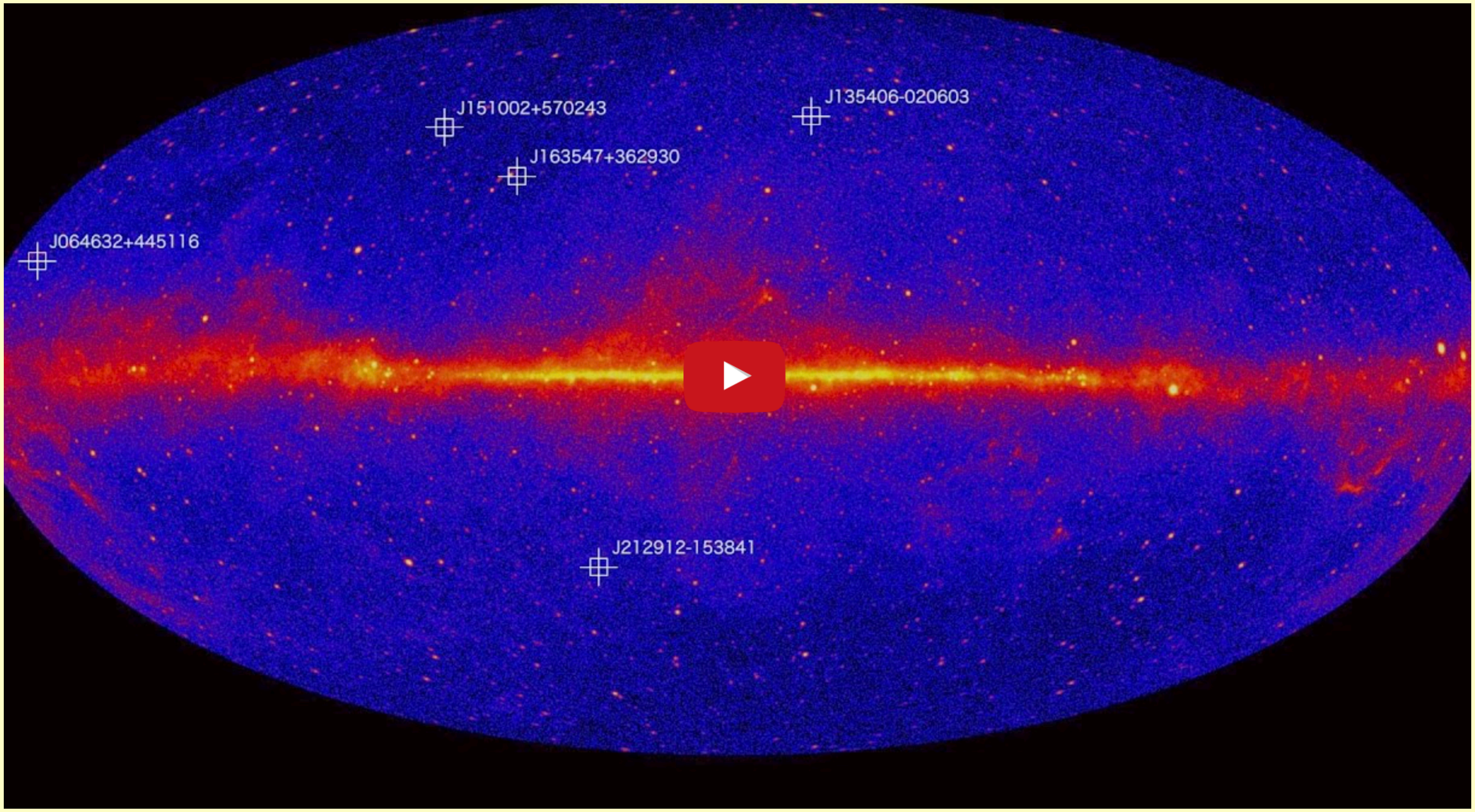


3C273

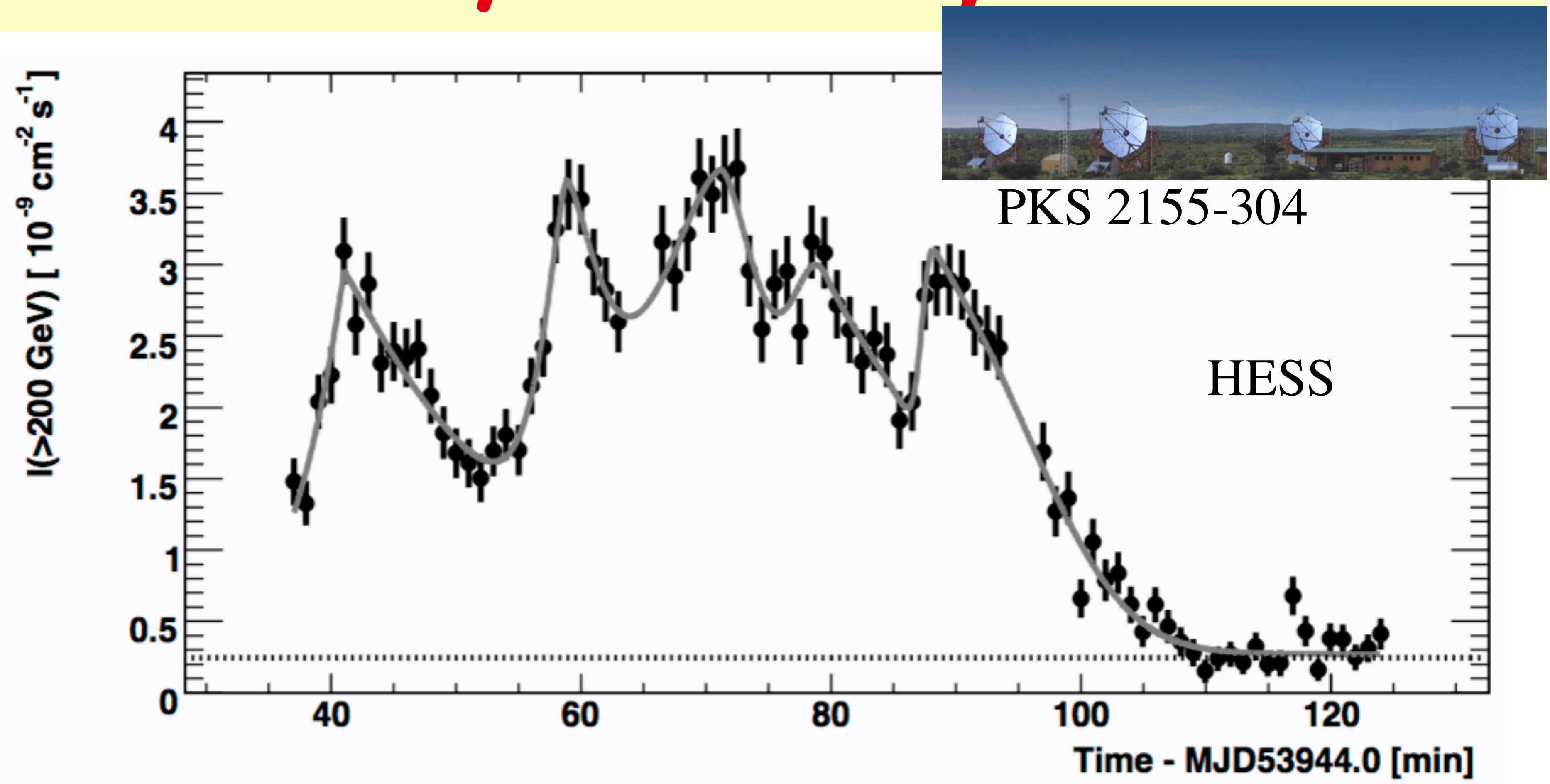
Readhead et al

Apparent speed ~ 8c
Actual speed ~ 0.99c

Fermi GeV Blazars



Gamma rays can vary in minutes

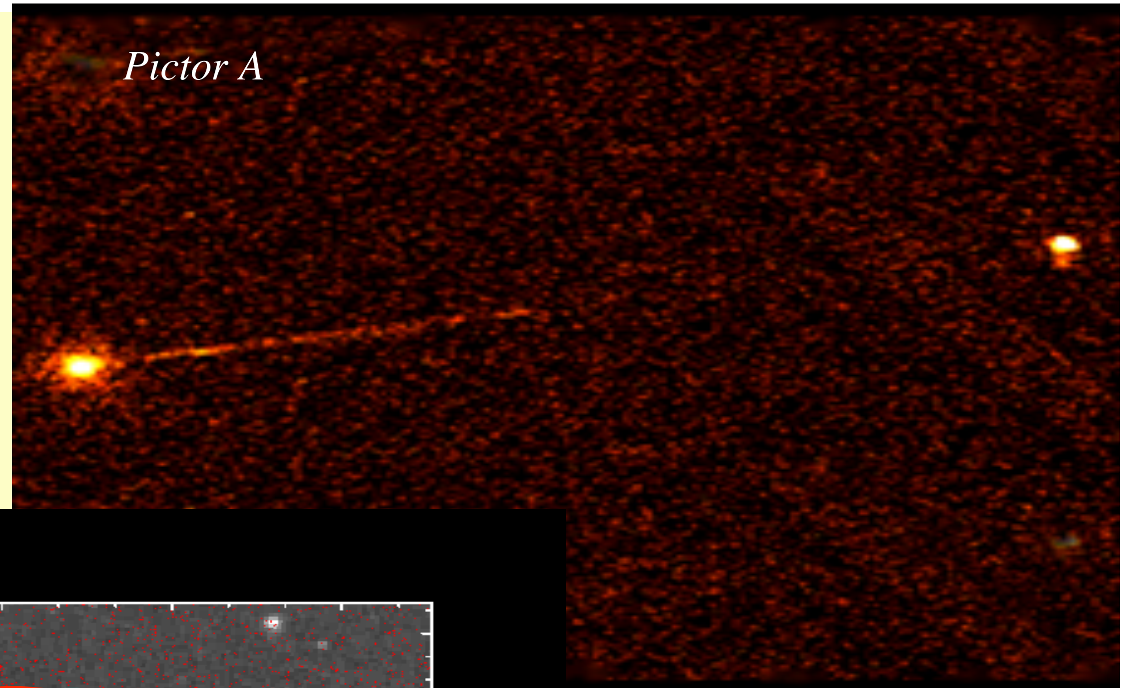


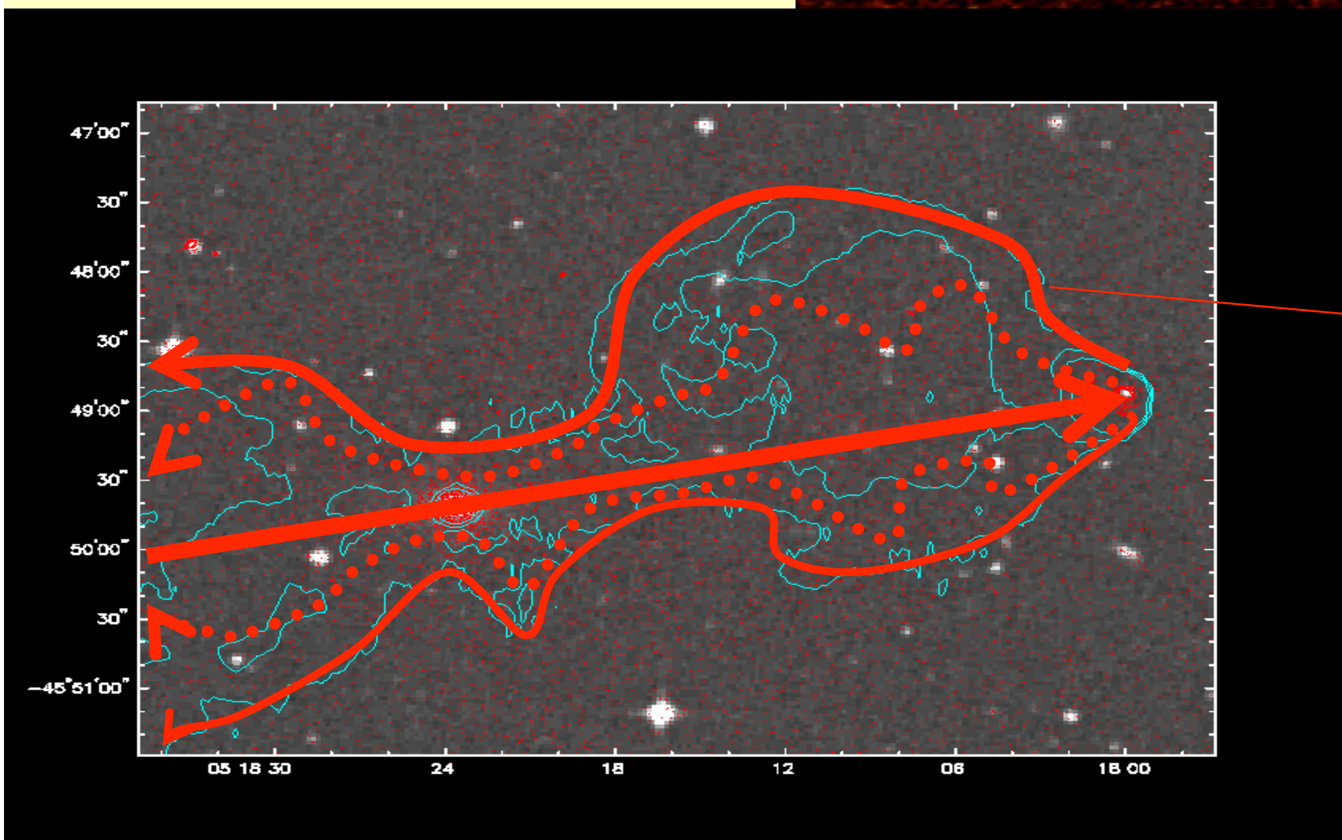
Electrons accelerated at small radii

Voltages, Currents, Discharges

- **Unipolar Induction:**
  - $V \sim \Omega\,\Phi \sim 100\ I$
- **Crab:**
  - $V \sim 50$ PV; $N'_{min} \sim 3 \times 10^{33}\ s^{-1} \sim 10^{-7}\ N'_{radio}$
- **3C 279:**
  - $V \sim 300$ EV; $N'_{min} \sim 2 \times 10^{37}\ s^{-1} \sim 10^{-5}\ N'_{radio}$
- **GRB080916C**
  - $V \sim 100$ ZV; $N'_{min} \sim 10^{40}\ s^{-1}$ $N'_{pair}(0) \sim 10^{56}\ s^{-1}$

Flow vs Pinch
Fluid vs EM





Current Flow?

Nonthermal emission is ohmic dissipation of current flow?

Pinch stabilized by velocity gradient

Emission Mechanism

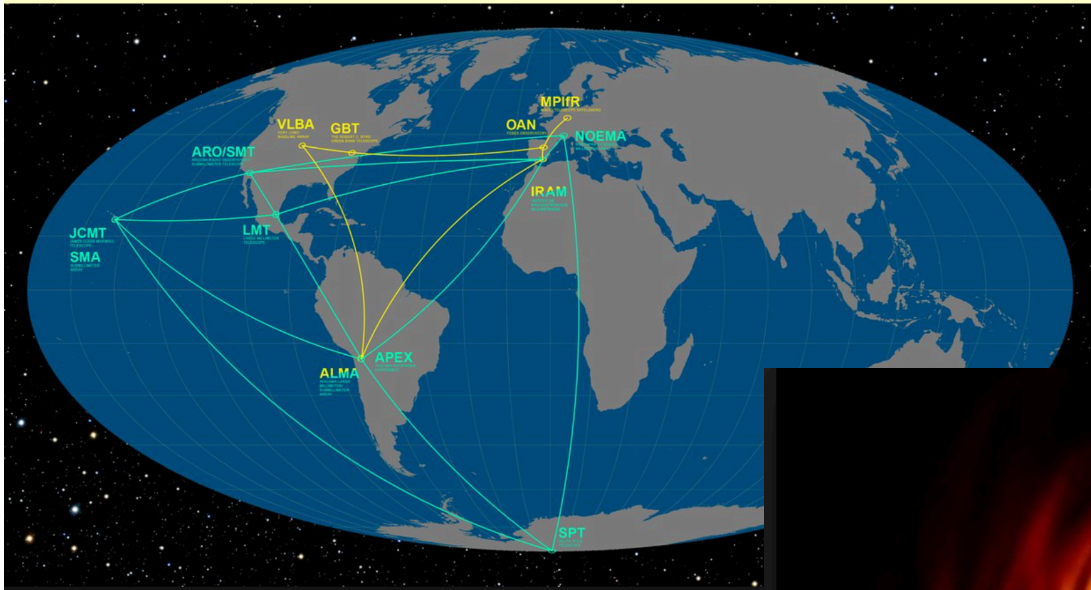
- **Synchrotron**
  - $E < B$ (any frame) => $\lambda > r_{e,}$ $E_\gamma < 70\text{MeV}$
    - GeV flares could be synchrotron if Doppler-boosted
- **Compton**
  - $E_e > E_\gamma, m_e^2/E_s$
    - TeV is Compton
    - External vs Internal
  - $L_c/L_s \sim U_l/U_B$ in inhomogeneous source
    - => inhomogeneous sources?

Emission along jet

Pairs vs Ions

- Pairs necessary in magnetospheres for j, ρ
  - Easy to create through $\gamma-\gamma$ or $\gamma-B$
- Ions will be entrained/transported
  - Disk, Wind, Interstellar Medium?
  - EM->Flow
- Ions radiate much less than positrons and can be accelerated to higher energy
  - UHECR??
  - Bethe-Heitler Pair Production?

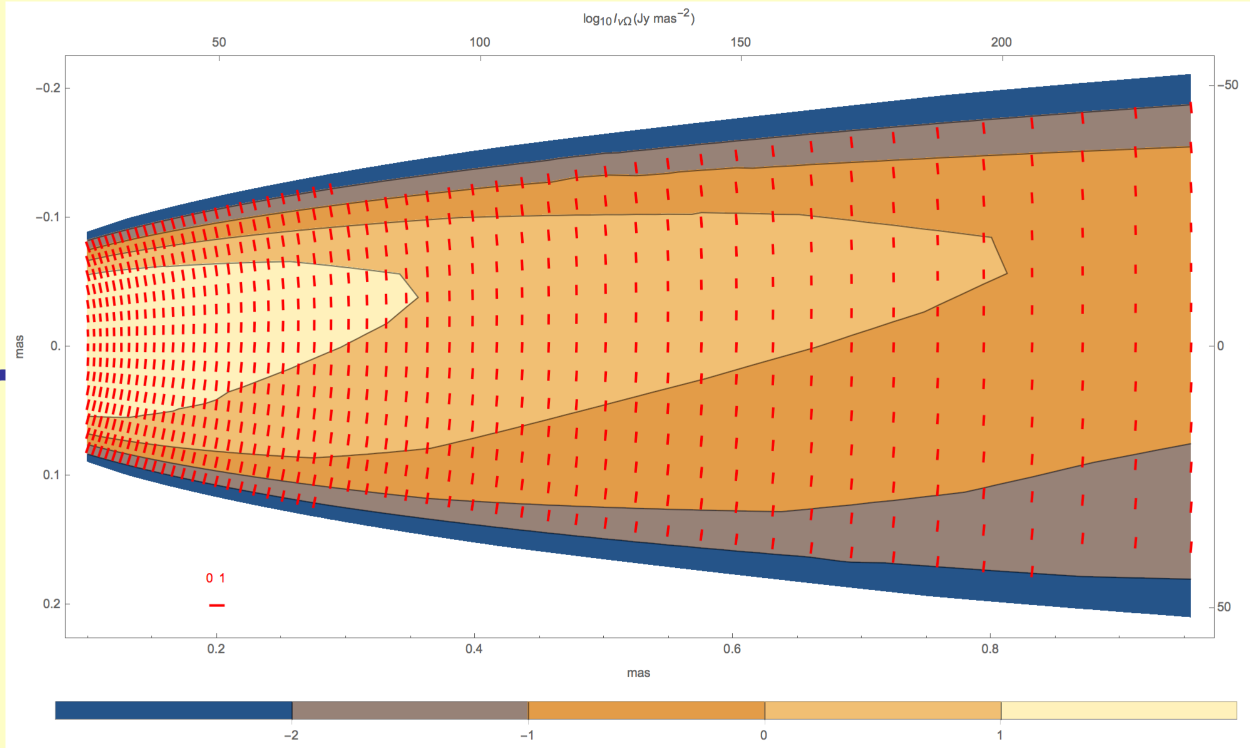
Event Horizon Telescope



M87 and Galactic Center

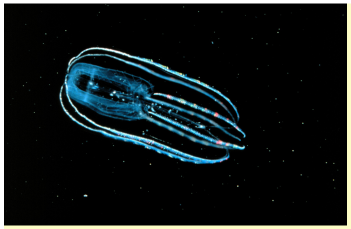
Future M87/EHT Observations

- Toroidal field, transverse shifts -> Ω_H
- Inclination, velocity, V_{obs}
- Pair vs ion plasmas - circular polarization
- Parity
- Acceleration
- Entrainment
- Lateral Shift



Anantua, Lyutikov

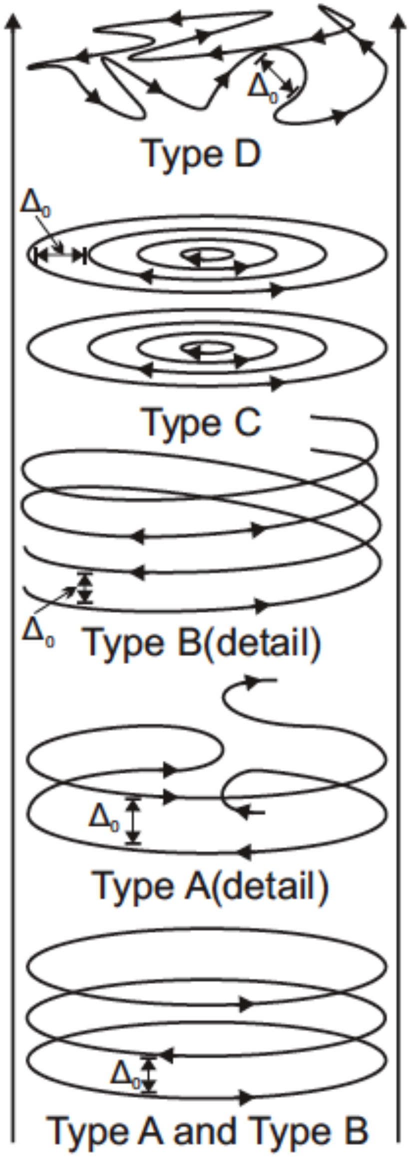
29v2017

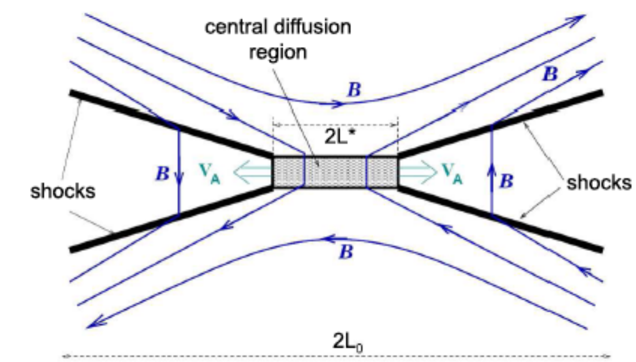


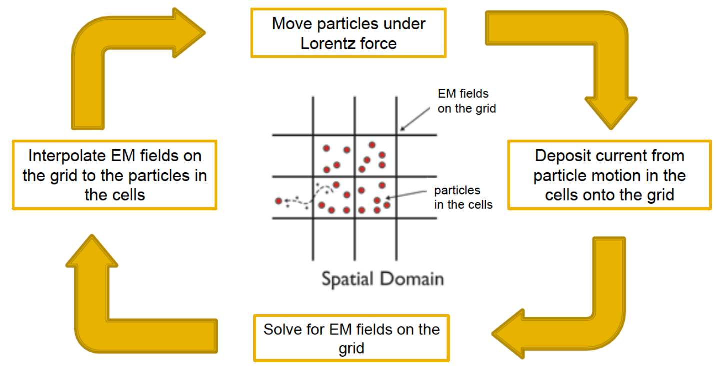
Magnetoluminescence

- **Efficient conversion of electromagnetic energy into γ-rays**
  - Gevatrons to Zevatrons
  - PWN, AGN, (QftI), GRBs…
- **Shocks too slow and not strong when EM dominant**
  - New Mechanisms

Relativistic Reconnection

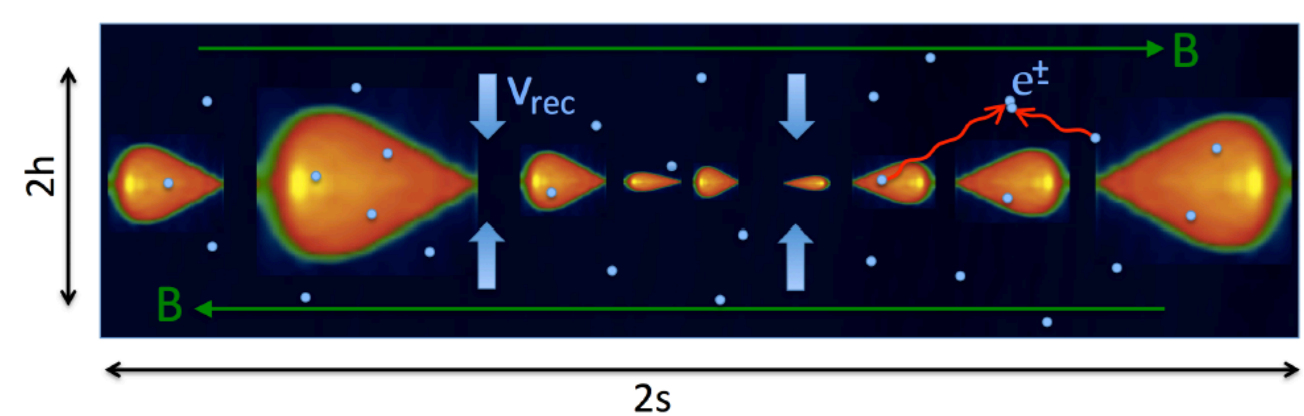






Syrovatskii

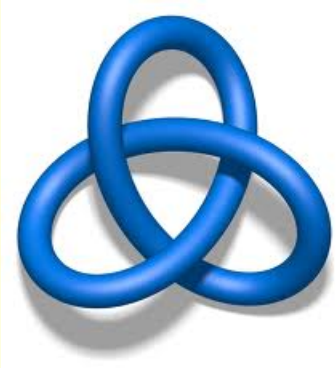
Particle In Cell (PIC) Codes



Beloborodov

McKinney & Uzdensky

Knots and Tangles



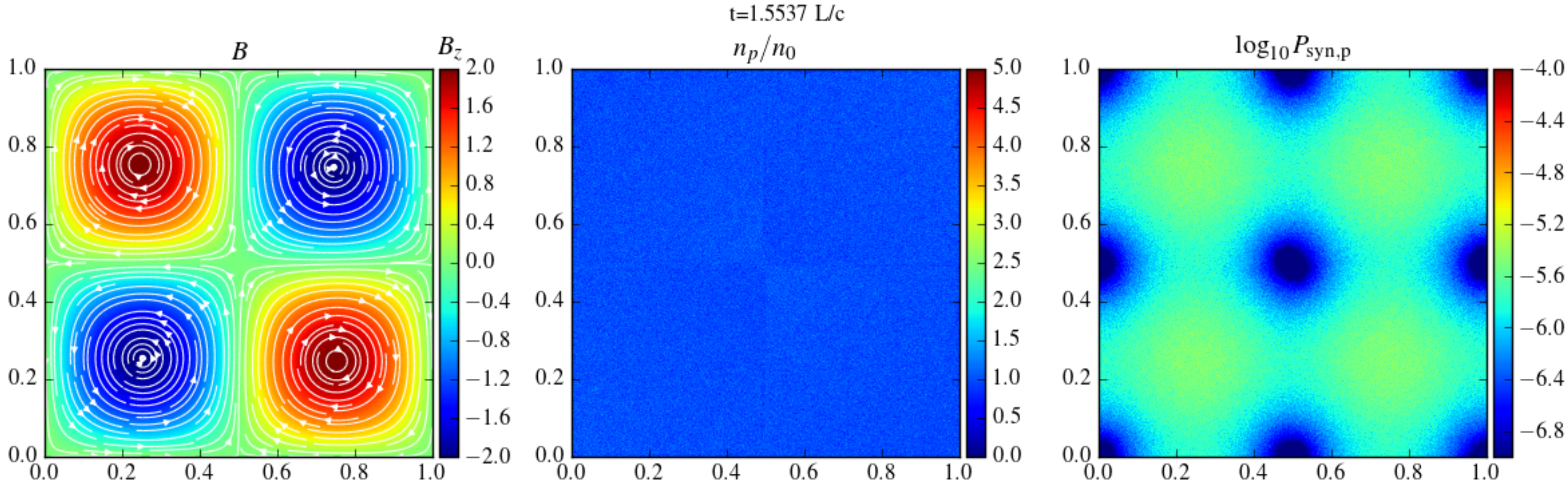
- **Knot (eg trefoil)**
  - **Describable by polynomials**
    - Tait, Alexander, Jones…: $t+t^3-t^4$
  - **Require reconnection to create and destroy**
    - Slow

- **Tangle (eg slip knot)**
  - **Can become unstable and transition to lower energy configuration at speed of light**
  - **Create E > B? and extensive runaway electron acceleration**
  - **Magnetic energy -> γ-rays**
  - **Followed by implosion, chain reaction?**

Unstable EM Configurations

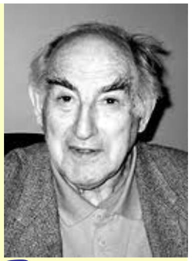
E/B

B



Yuan,Nalewajko, Zrake, East, RB

Summary



- Galactic nuclei - $\sim 10^{6-10}$sun, black holes
- Observe disks/tori, winds and jets
- Jets formed by spinning hole + torus?
- Jets propagate from ~m to $\sim < 10^{11}$m
- Jets radiate from m radio to TeV γ-rays
- Jets: EM/relativistic -> entraining flow
- 3D RMHD simulations are instructive
- EHT observing relativistic region
- Need to understand gas flow, acceleration