NUMERICAL SIMULATIONS OF RELATIVISTIC JETS FROM BLACK HOLES

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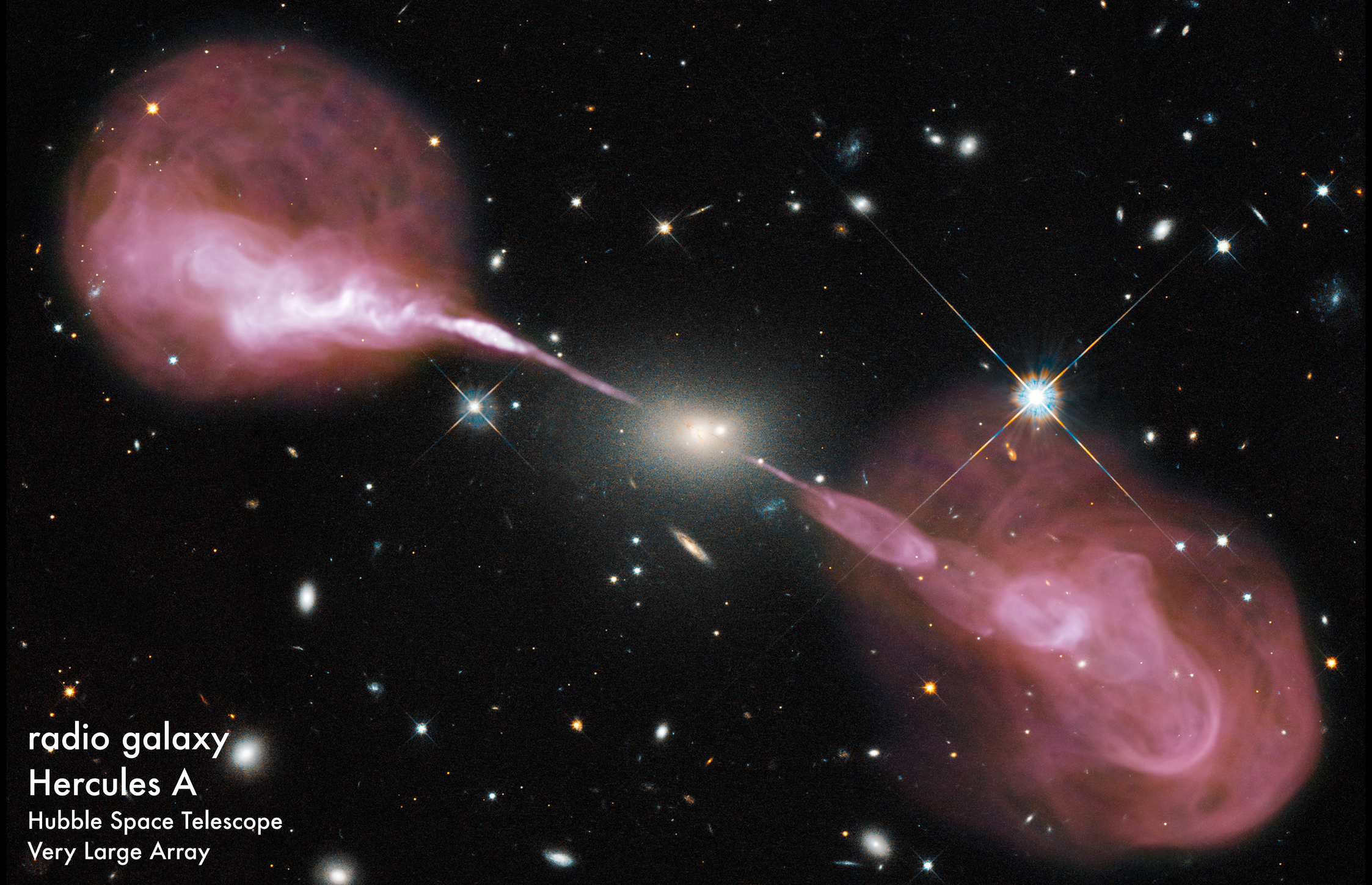
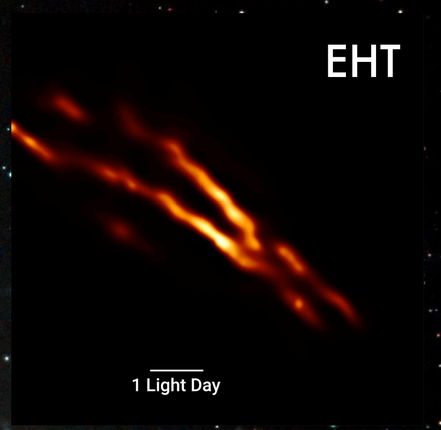
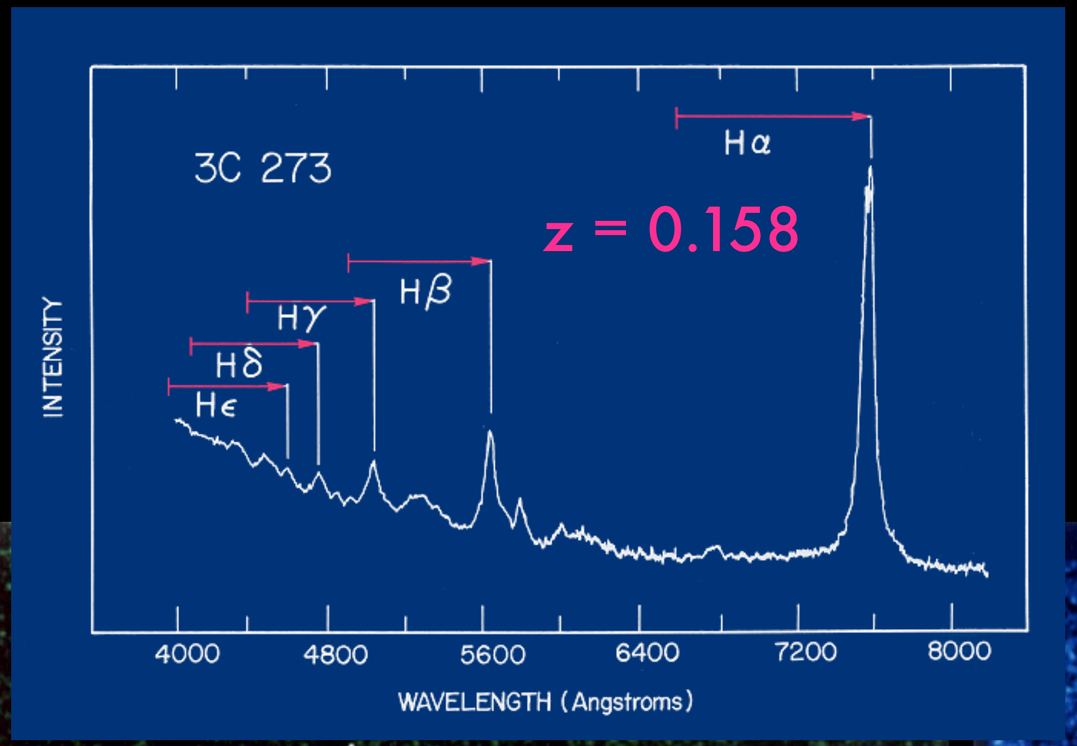
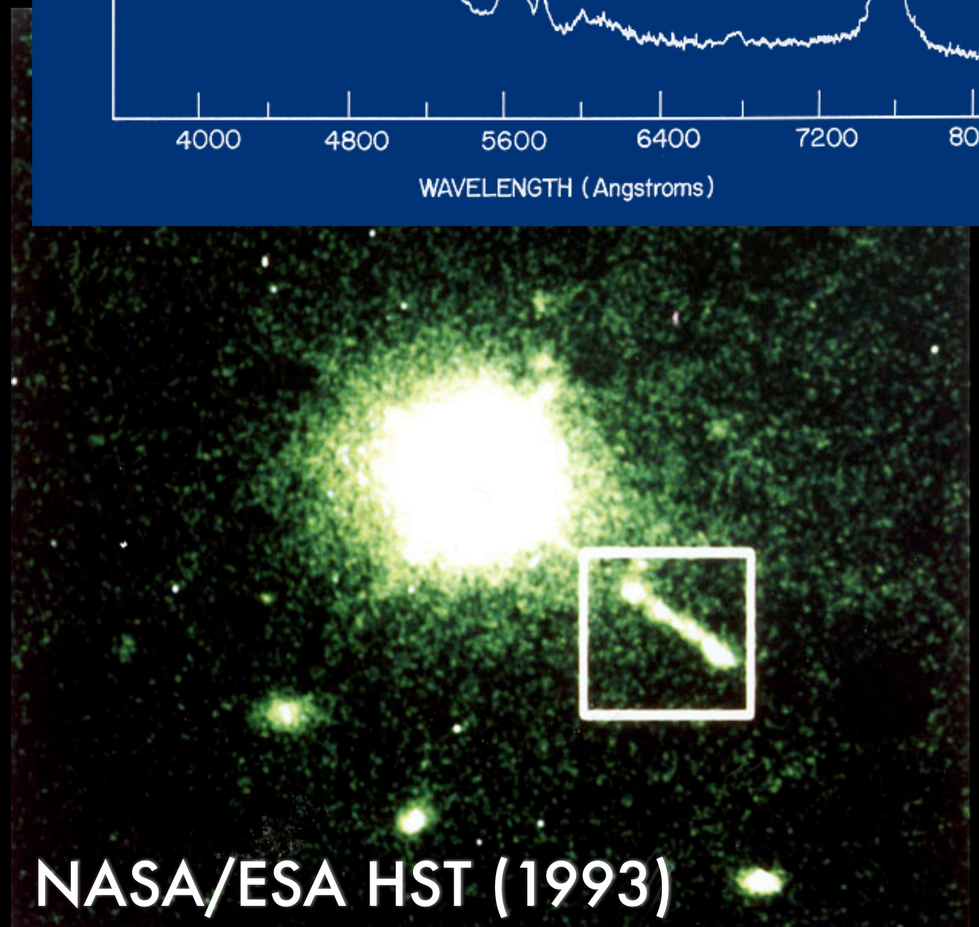

radio galaxy
Hercules A
Hubble Space Telescope
Very Large Array

radio galaxy
Centaurus A
ESO
Chandra
APEX

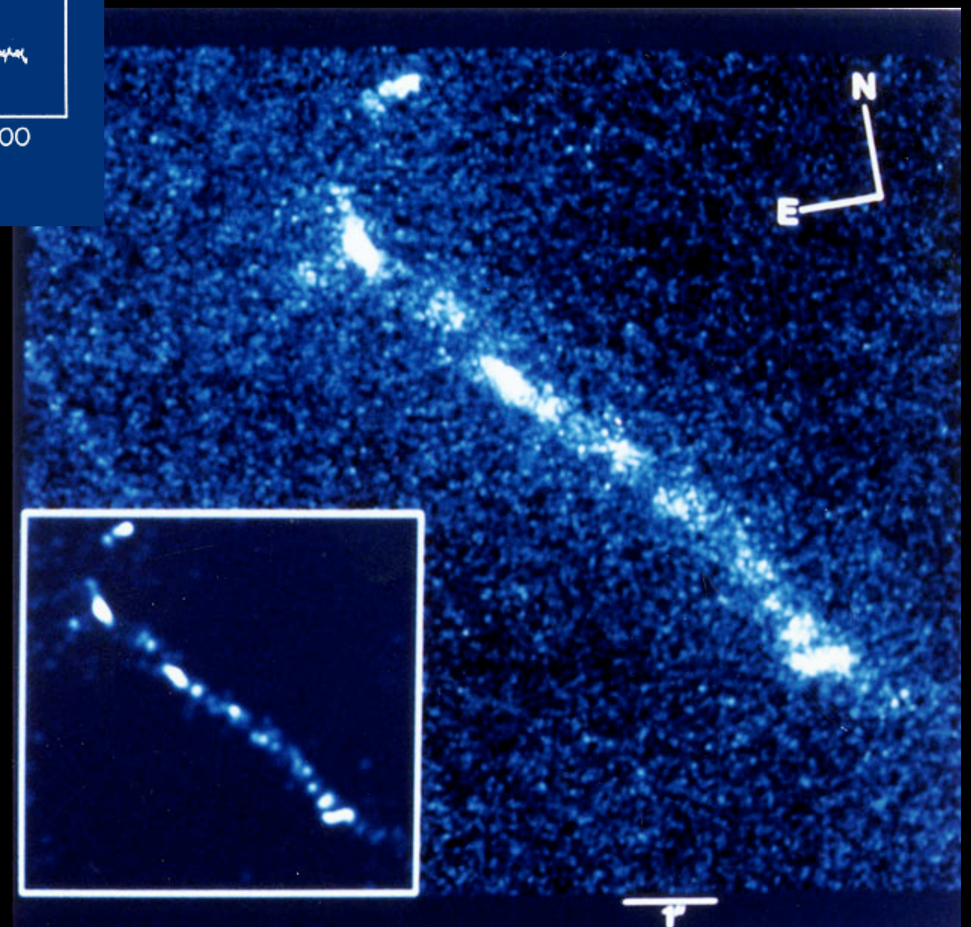


quasar 3C 273

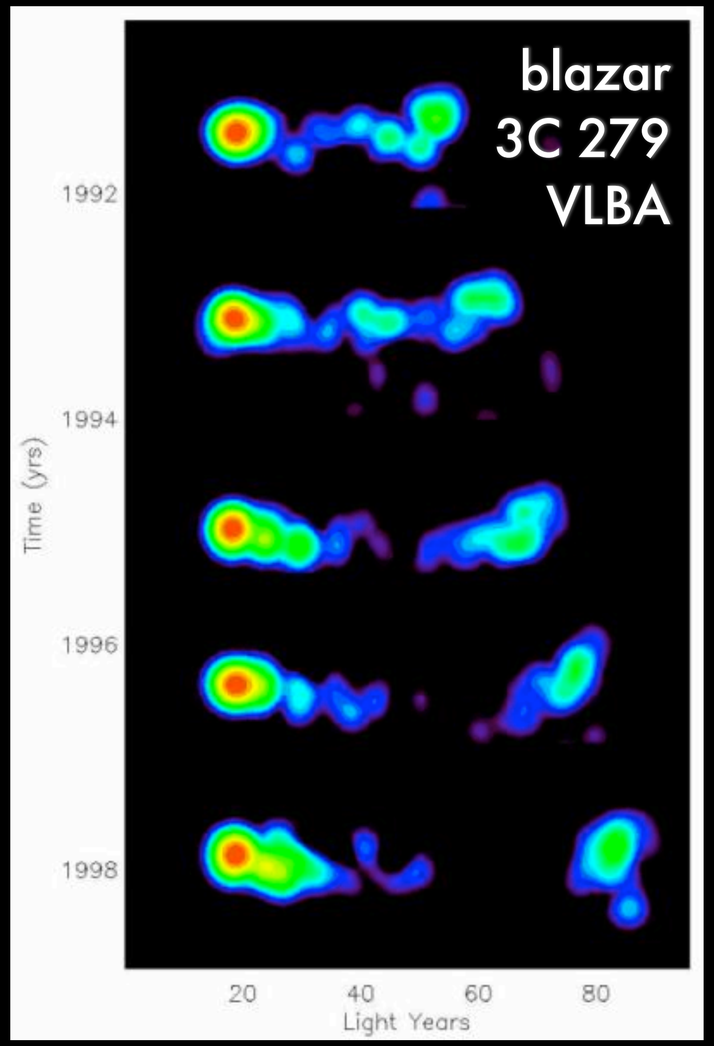


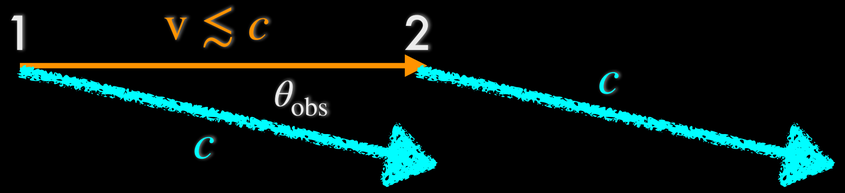


NASA/ESA HST (1993)

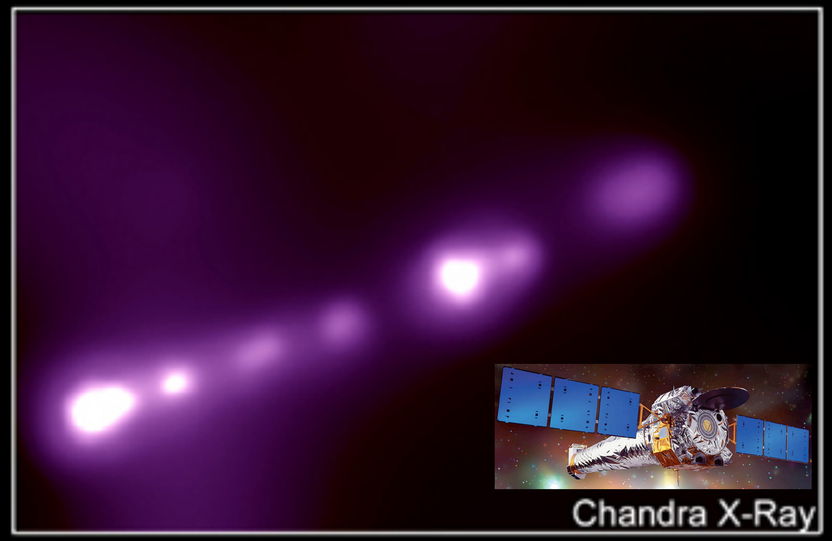


apparently superluminal motions

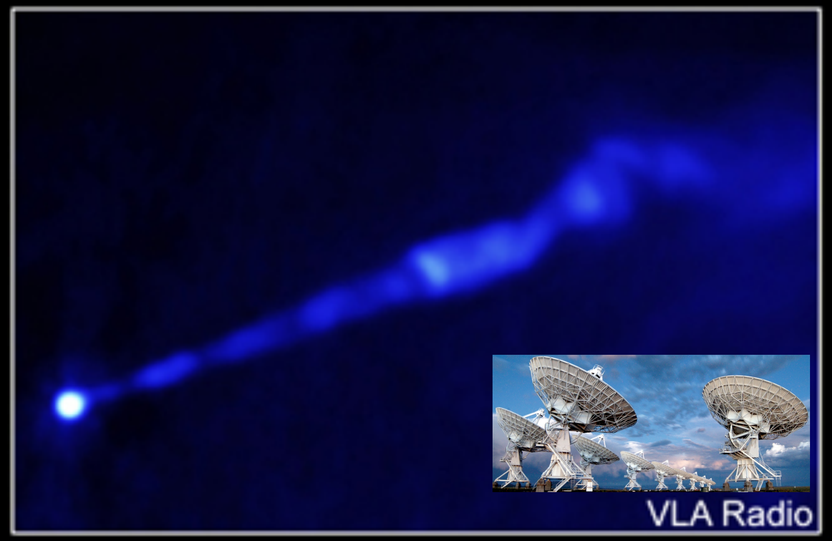


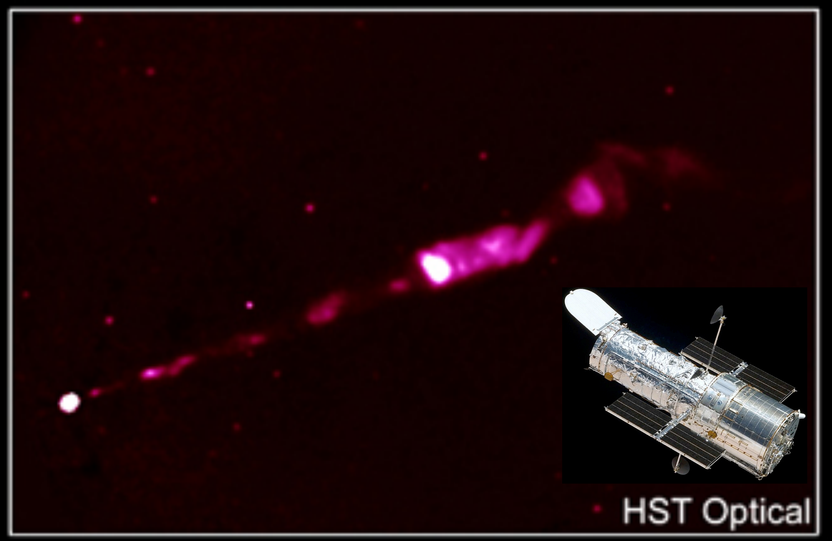


multiwavelength emission
energy dissipation, particle acceleration



radio galaxy
M87





radio galaxy M87

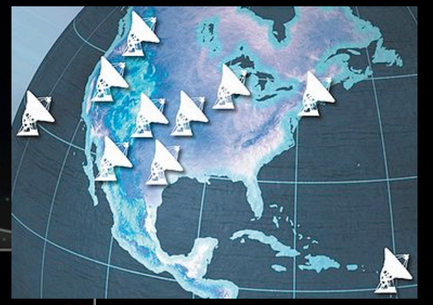
radio→microwaves

Very Large Array

VLA – 1.5 GHz

10 arcseconds

3000 light years



Very Large Baseline Array

VLBA – 43 GHz

0.01 arcseconds

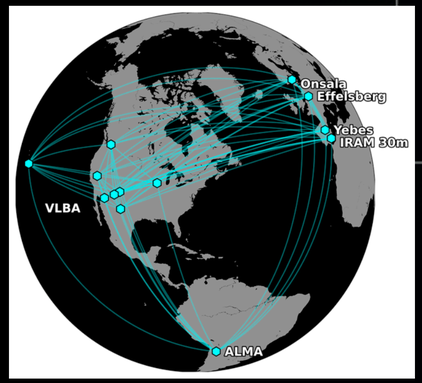
3 light years

GMVA – 86 GHz

0.001 arcseconds

0.3 light years

Global Millimeter VLBI Array

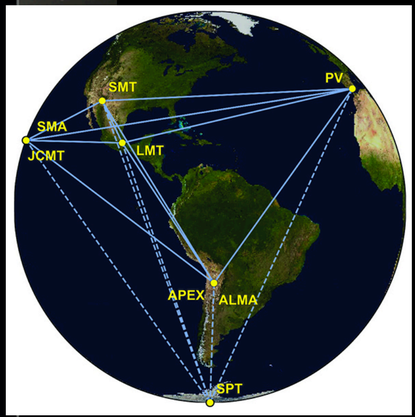


EHT – 230 GHz

0.00001 arcseconds

0.003 light years

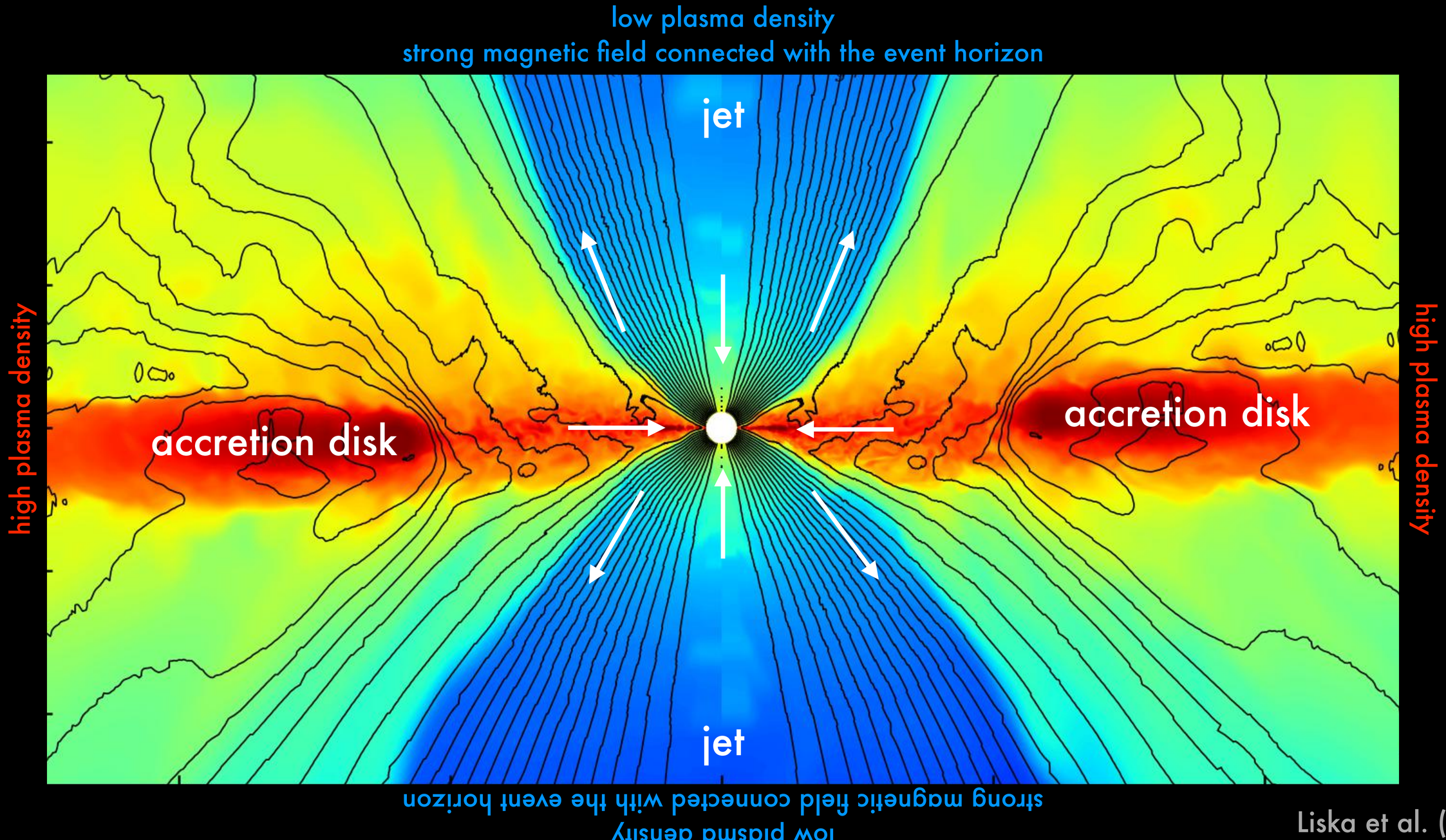
M87*



Event Horizon Telescope

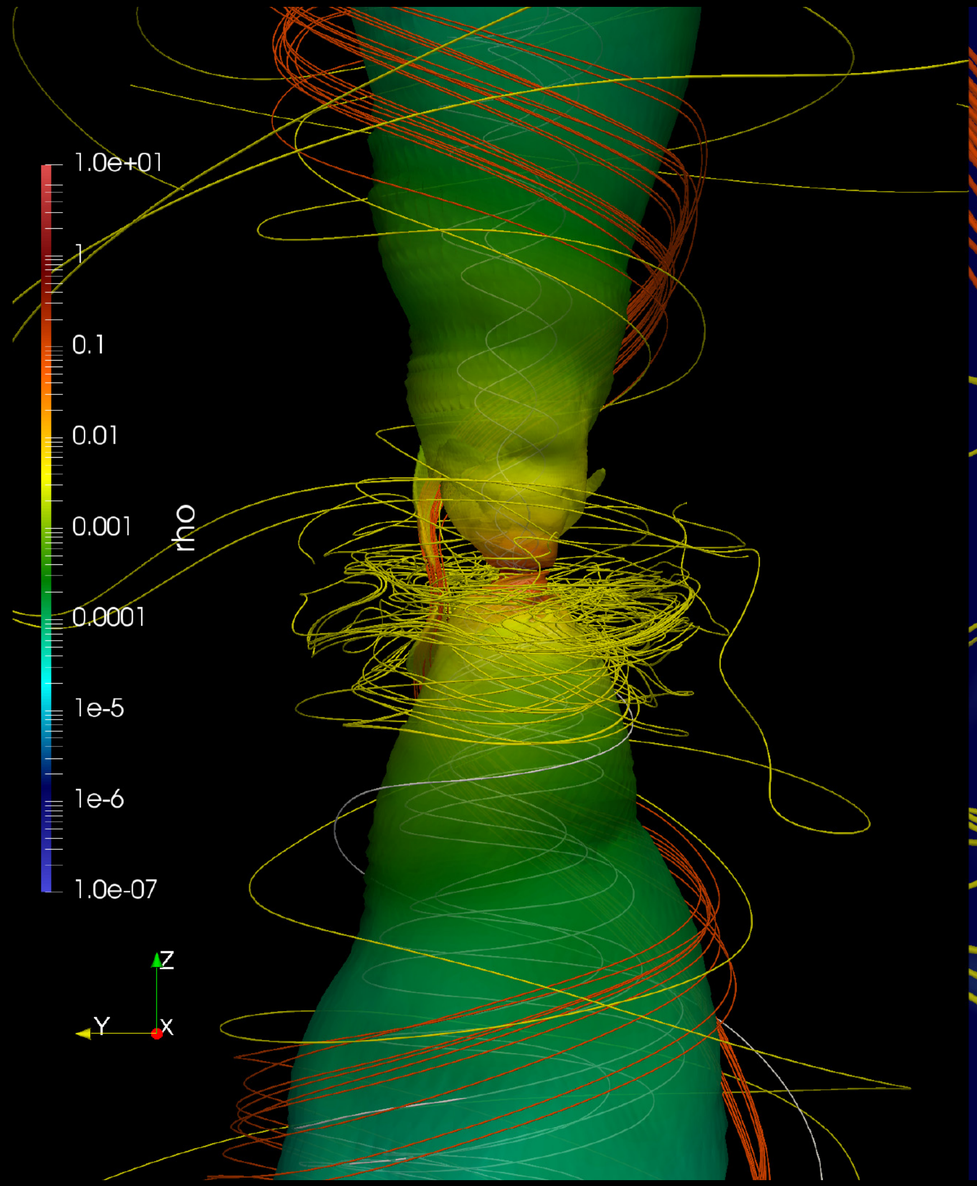
C. Goddi et al. 2019, The Messenger, 177, 25
EHT Collaboration/M. Kornmesser/ESO

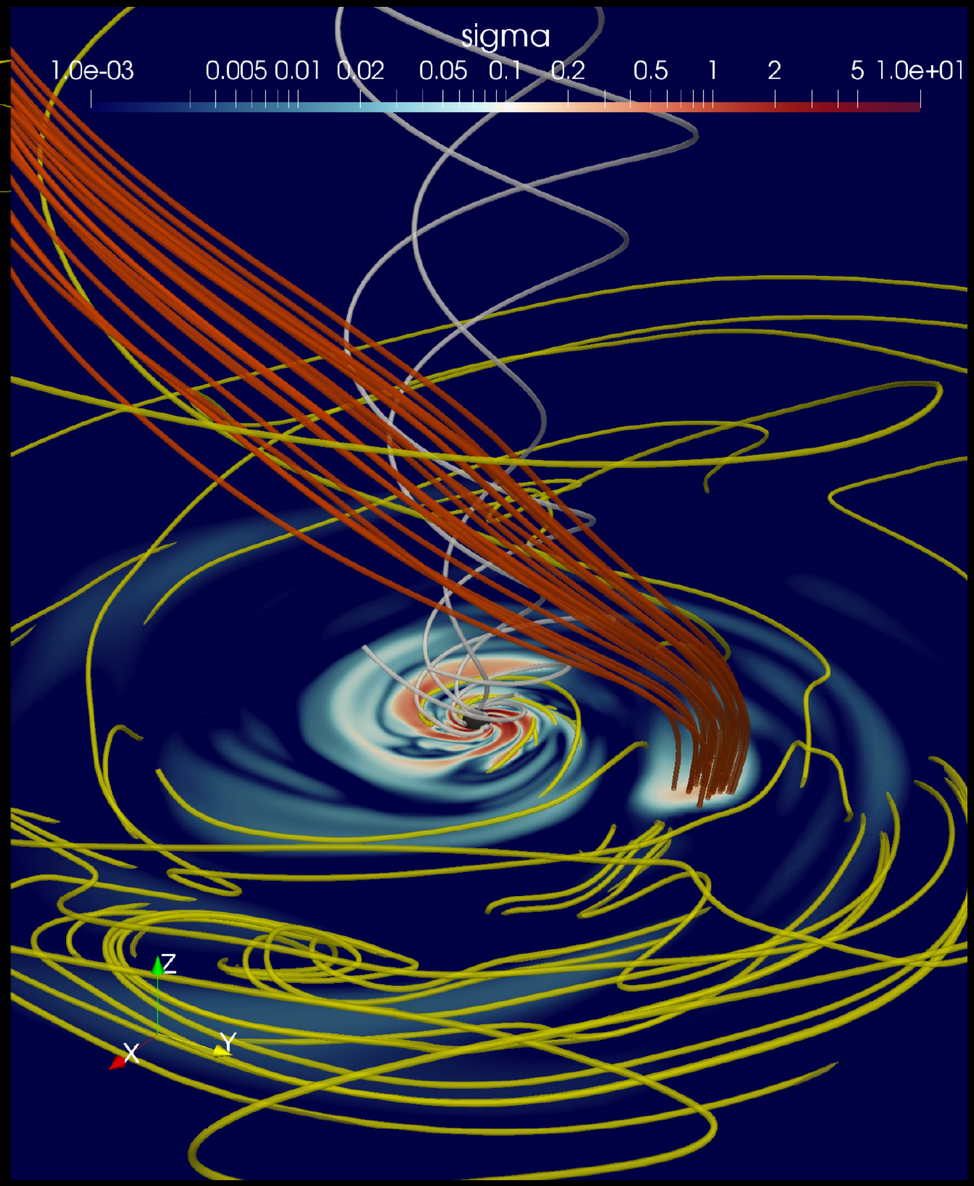
magnetized jets: general relativistic magnetohydrodynamics



Liska et al. (2018)

magnetic flux tubes ejected from the horizon by eruption as orbiting hotspots (Sgr A*)

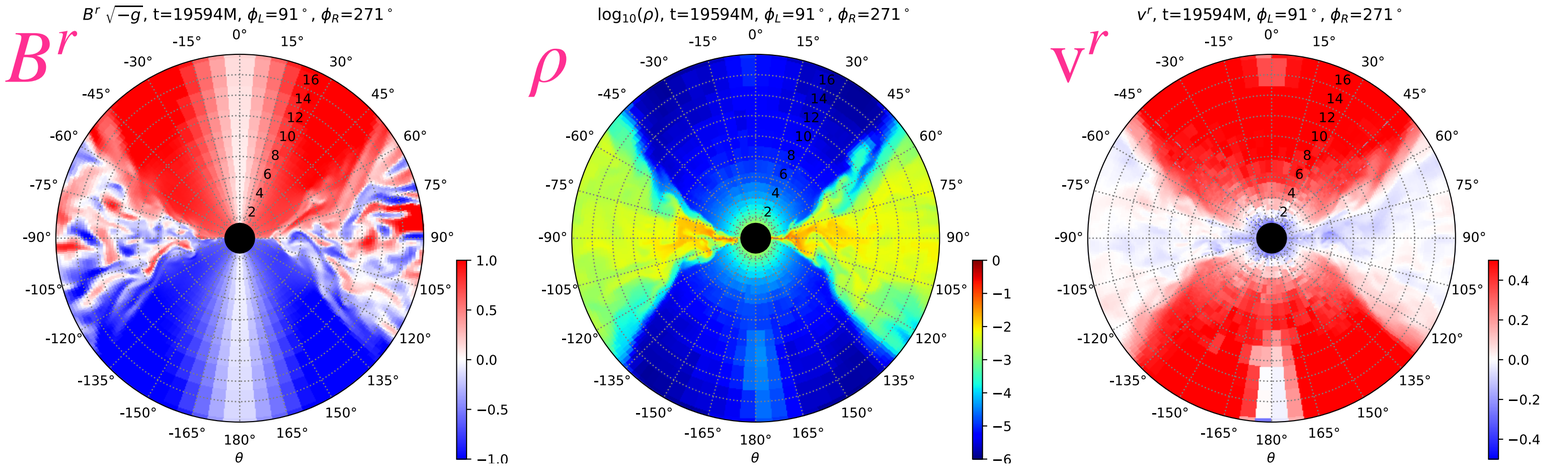


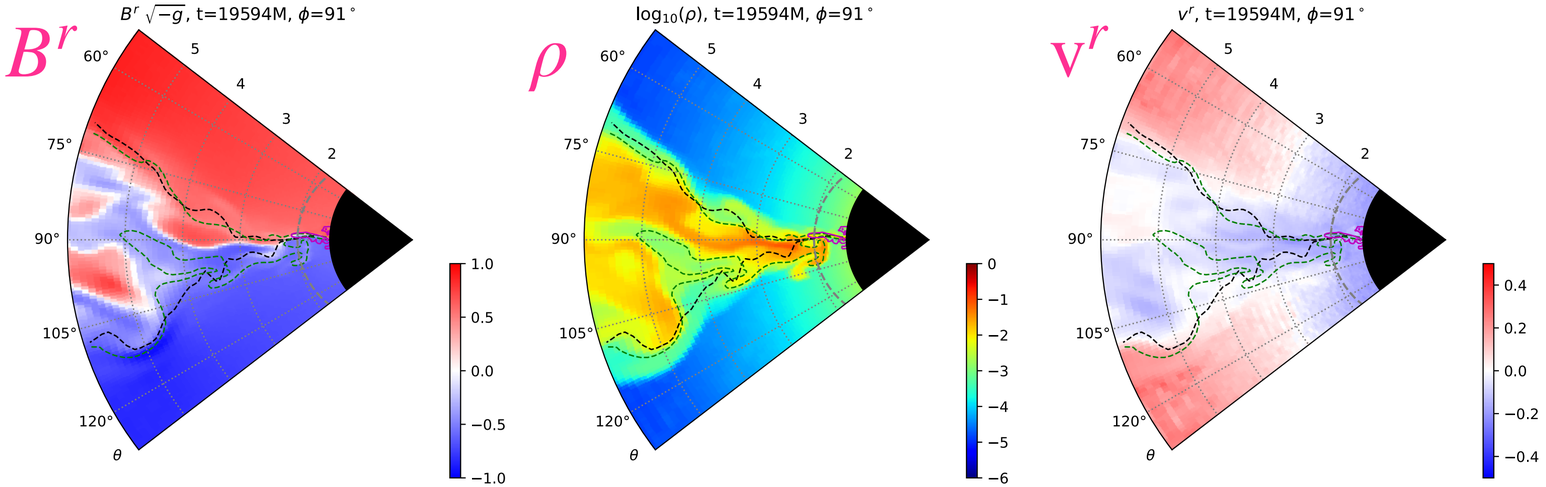


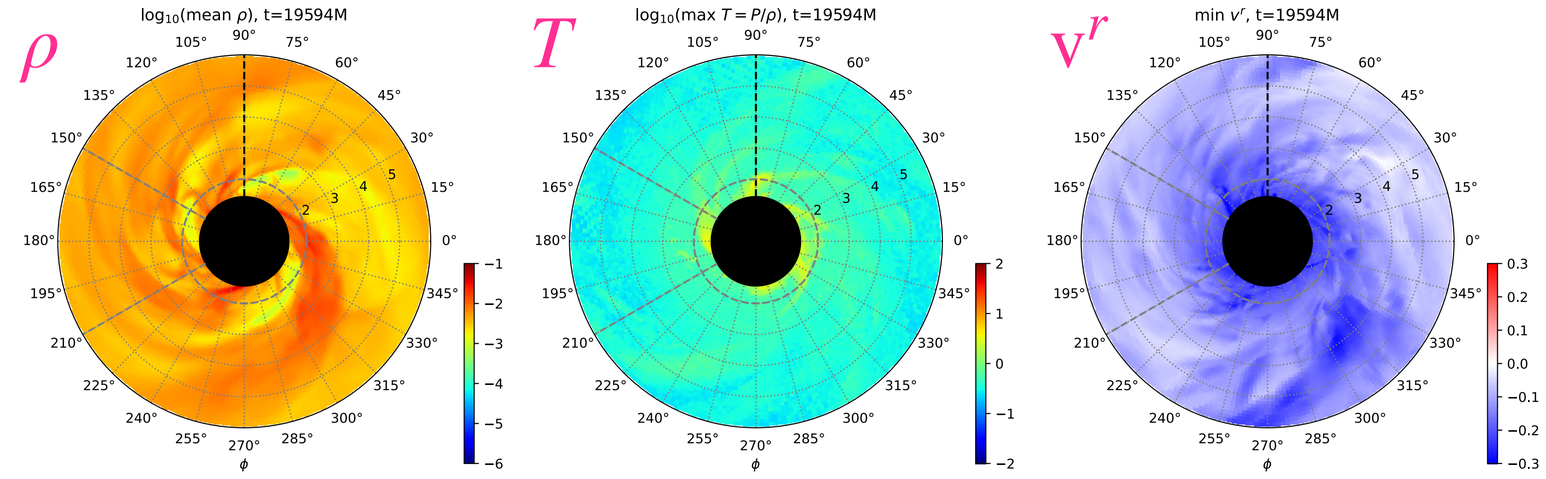
Porth, Mizuno, Younsi & Fromm (2021)

see also Dexter, Tchekhovskoy, Jiménez-Rosales, et al. (2020)

- ideal GRMHD
- Athena++
  (HLLE, PPM, vL2)
- Kerr metric ($a = 0.9$)
- Kerr-Schild coordinates
  $N_r = 288, N_\theta = N_\phi = 256$
- prograde MF76 torus
  $6M < r < 70M$
- single poloidal field loop







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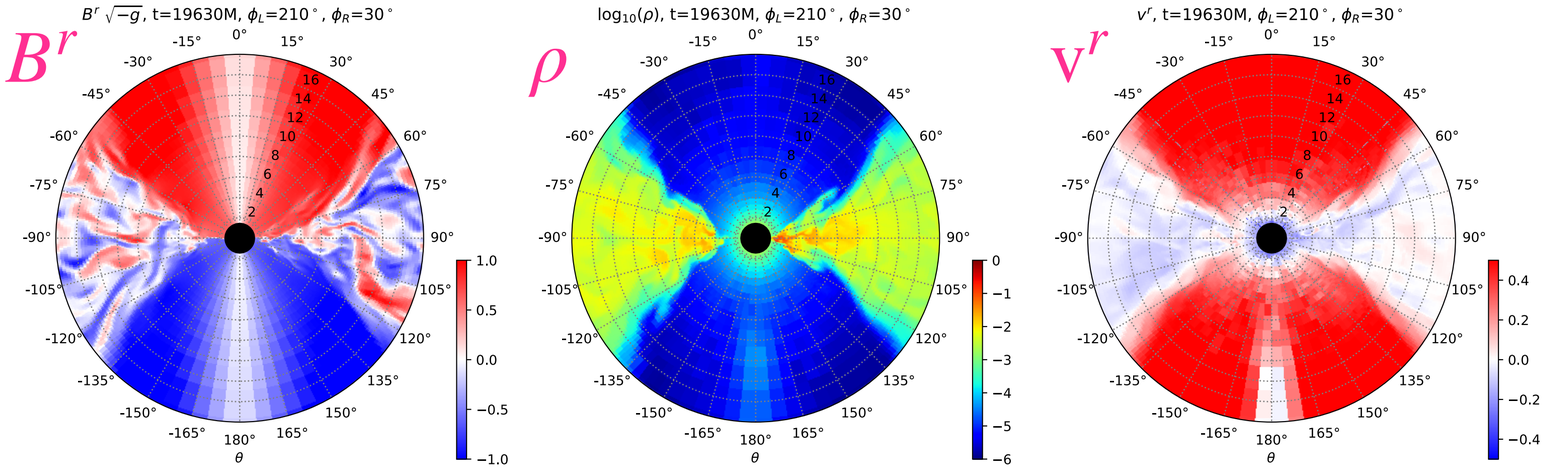
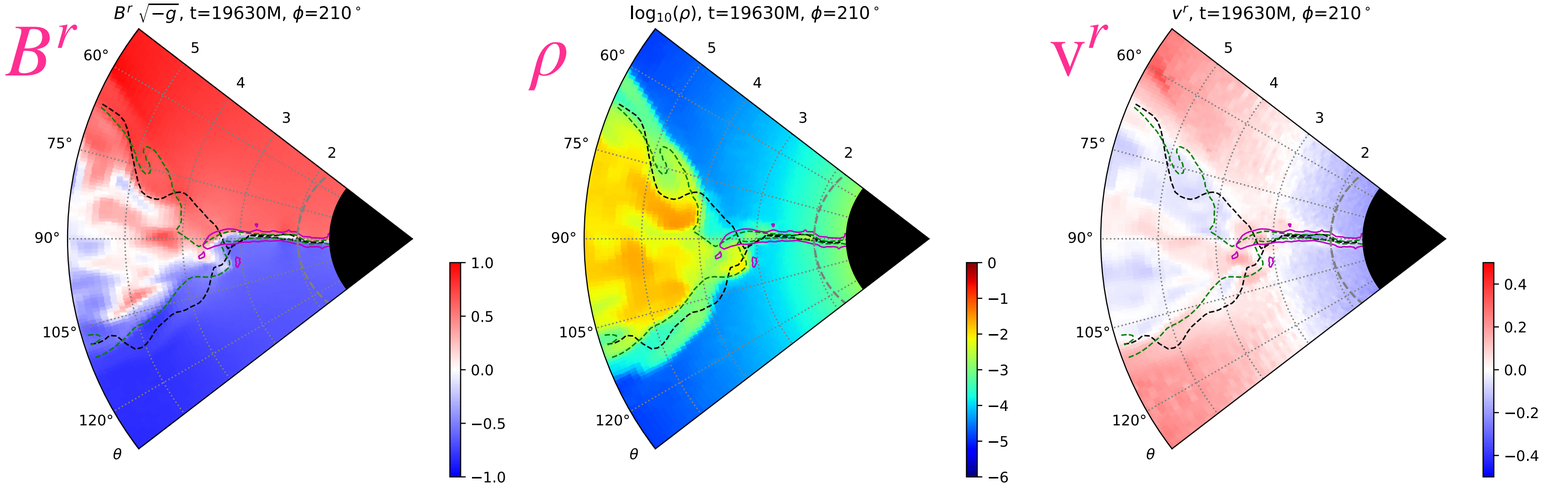
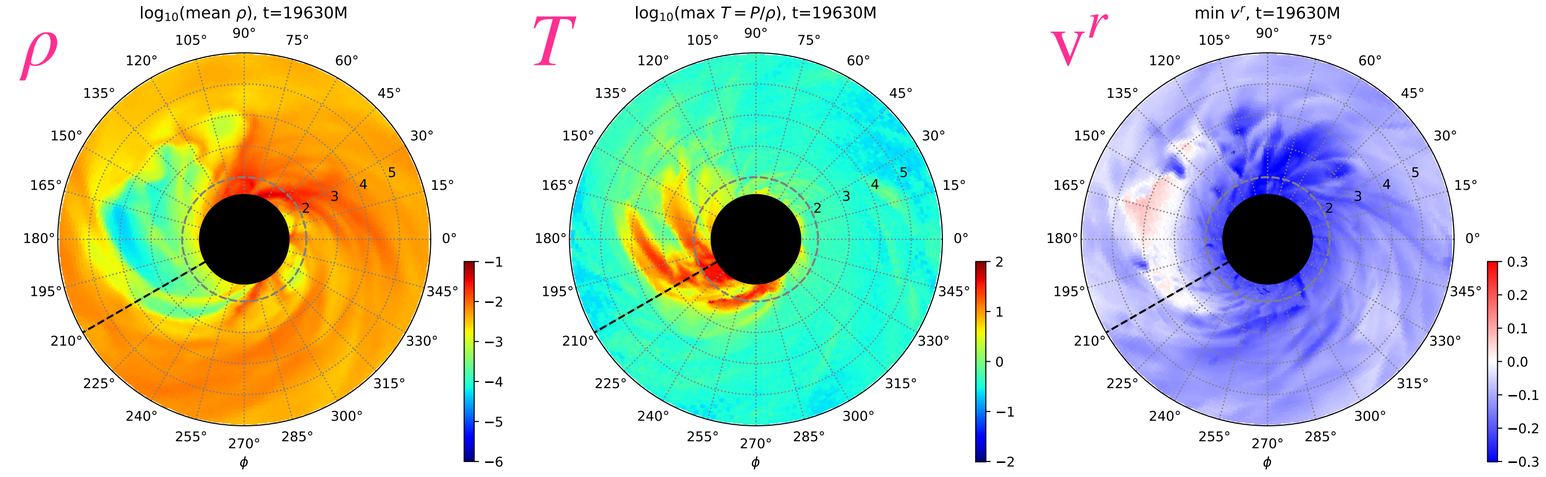
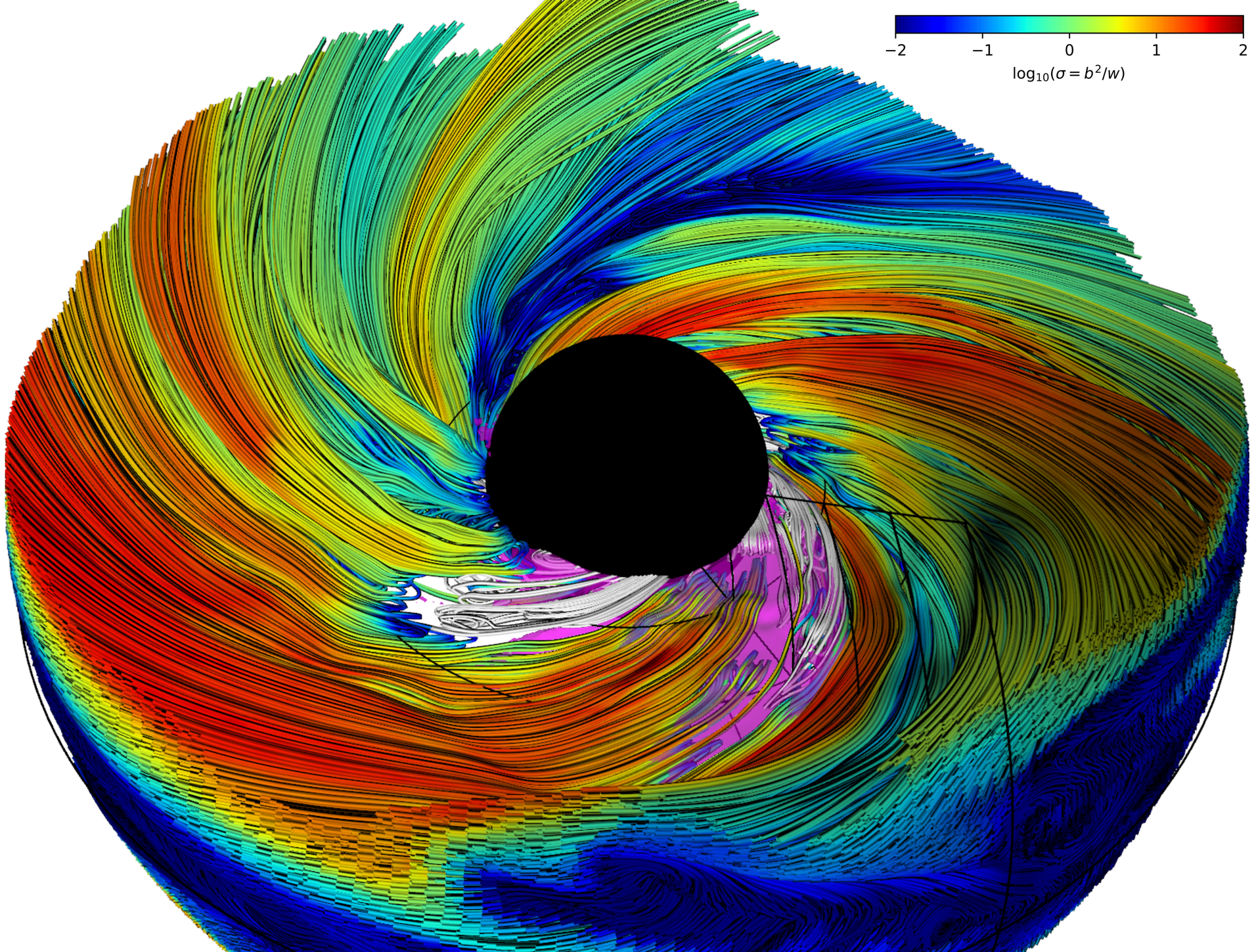
- black hole magnetic flux saturation
- magnetic flux eruption
- relativistic magnetic reconnection









- horizon-disconnected field lines seeded at fixed (θ, ϕ) lattice at $r \simeq 6M$, colored by magnetization $\sigma = b^2/w$
- doubly-connected field loops seeded at $r \lesssim r_{\rm H}$
- relativistic temperature $\log_{10} T > 0.5$

SUMMARY

- Relativistic jets are powerful outflows driven by strong magnetic fields in the vicinity of rotating black holes.
- Relativistic jets are observed in many active galaxies, appearing as radio galaxies or blazars (depending on jet orientation).
- The best studied jet of M87 has been resolved by radio/mm interferometry to the black hole ring image M87* (EHT).
- Global numerical simulations of relativistic jets can be performed by general relativistic magnetohydrodynamics public codes.
- Numerical resources: high performance computers (CPU, GPU) across Poland and Europe; international collaboration.
- Extensive analysis of 3D datasets, e.g., by integrating large samples of magnetic field lines.

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