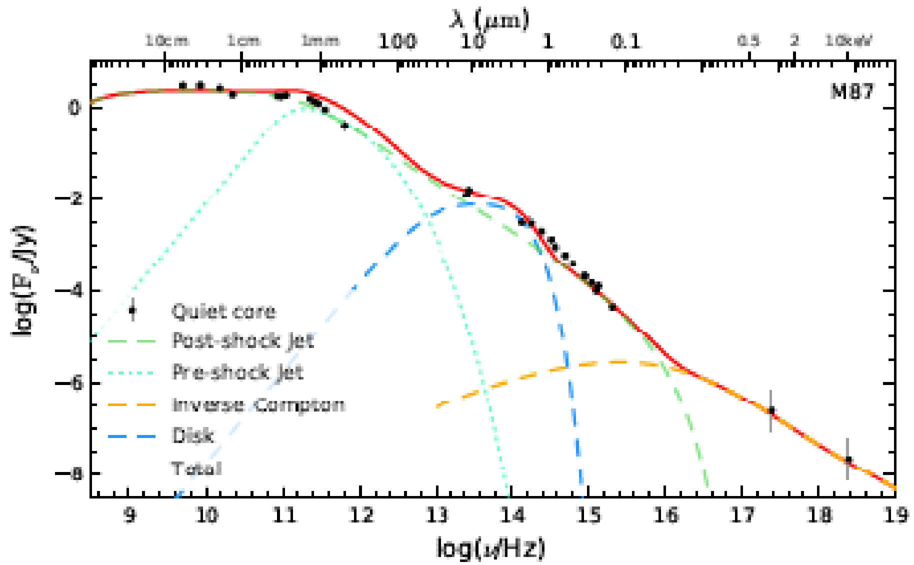
Radio Galaxies in the Local Universe: Perspective and Discussion

Robert Laing (ESO)

What did we learn (1)?

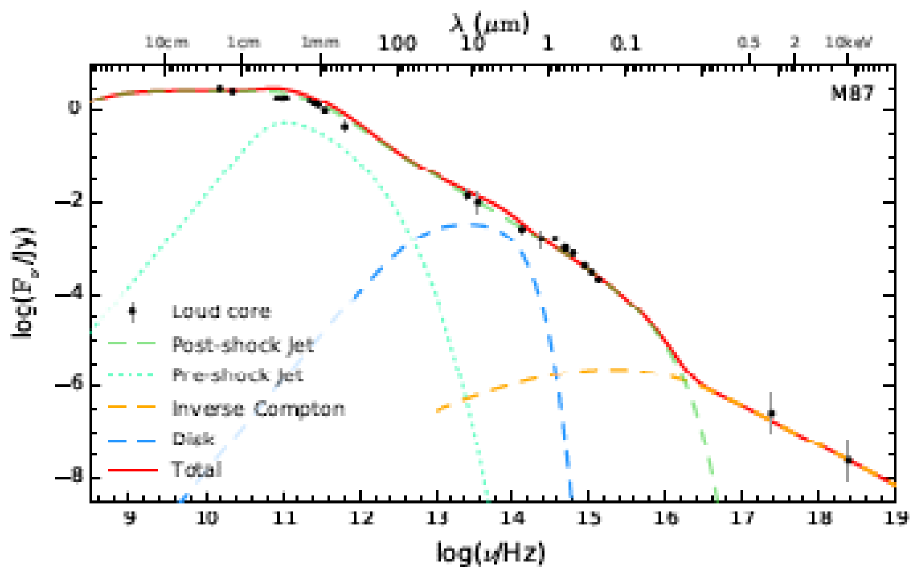
- Demographics [Sadler, Best]
  - Radio luminosity functions of HERG/LERG FRI/FRII, starbursts
  - Dependence on stellar mass
  - Clear differences in galaxy mass, stellar population, star formation rate between classes
  - Rapid space-density evolution associated with HERGs
  - HERG/LERG vs FRI/FRII: accretion, power, environment
- Very low-luminosity radio galaxy population [Baldi]
  - “FR0” radio galaxies: like FRIs, but smaller, weaker and much more numerous
  - Core/extended emission is larger at low powers
  - Deceleration closer to the AGN or slower initial speed?

Have we yet detected the emission from low-accretion-rate disks?



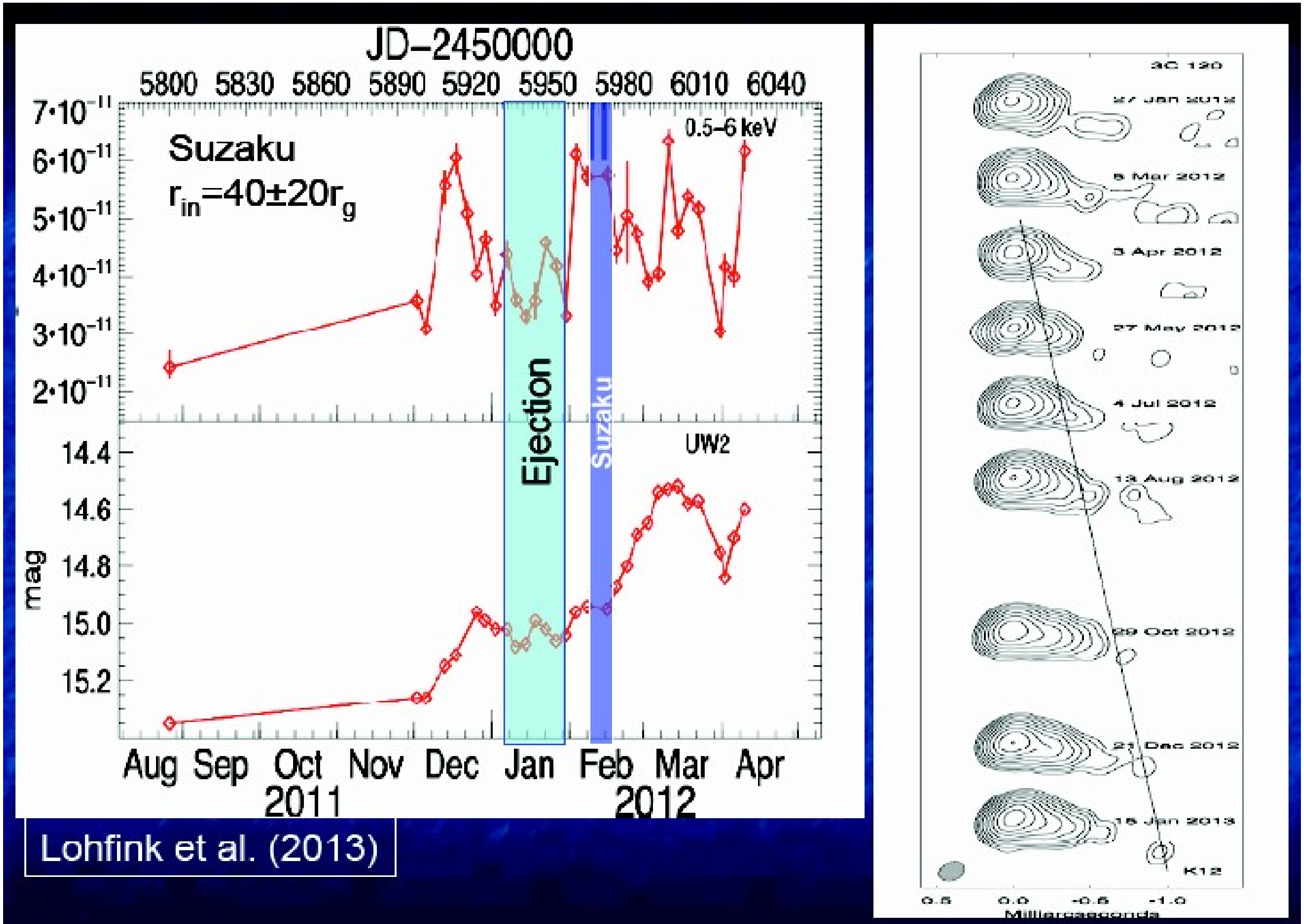
Active

M87 nuclear spectrum
Prieto et al. (2015)
Marginal evidence for **any** disk emission.



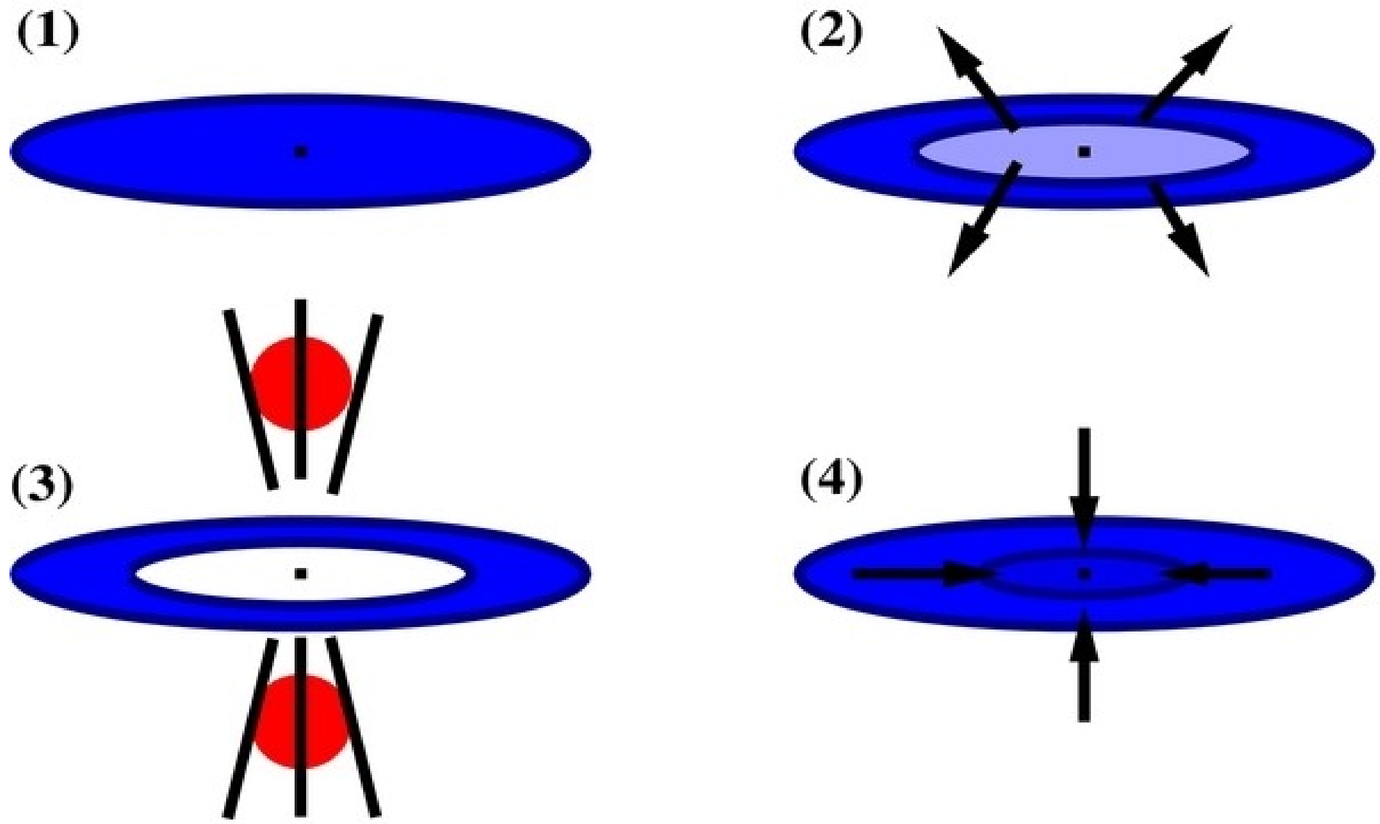
Quiescent

Jet launching in HERG: 3C120



Lohfink et al. (2013)

Jet Ejection Cycle in BLRG

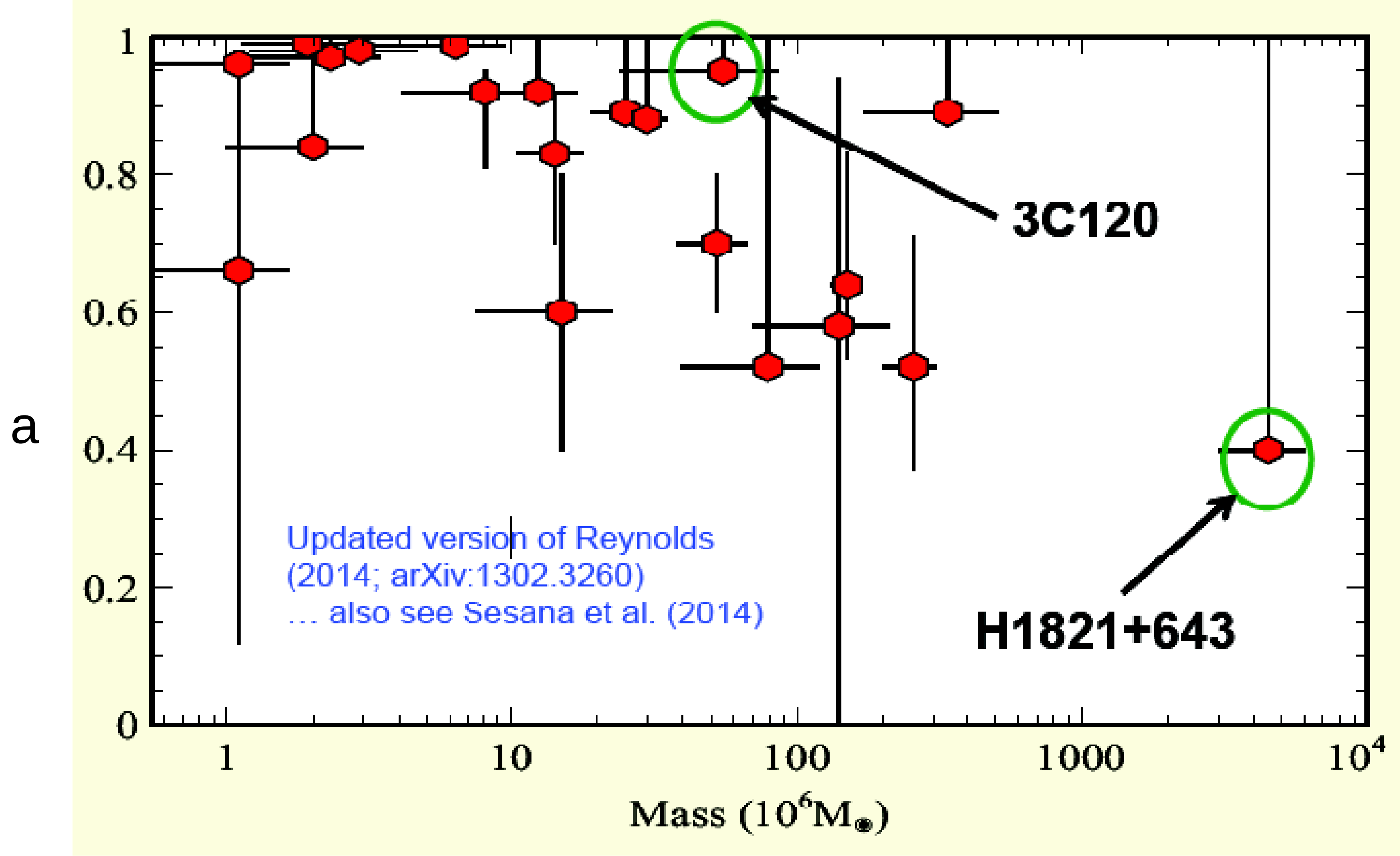


Lohfink et al. (2013)
Fe line fitting

Compare
microquasars

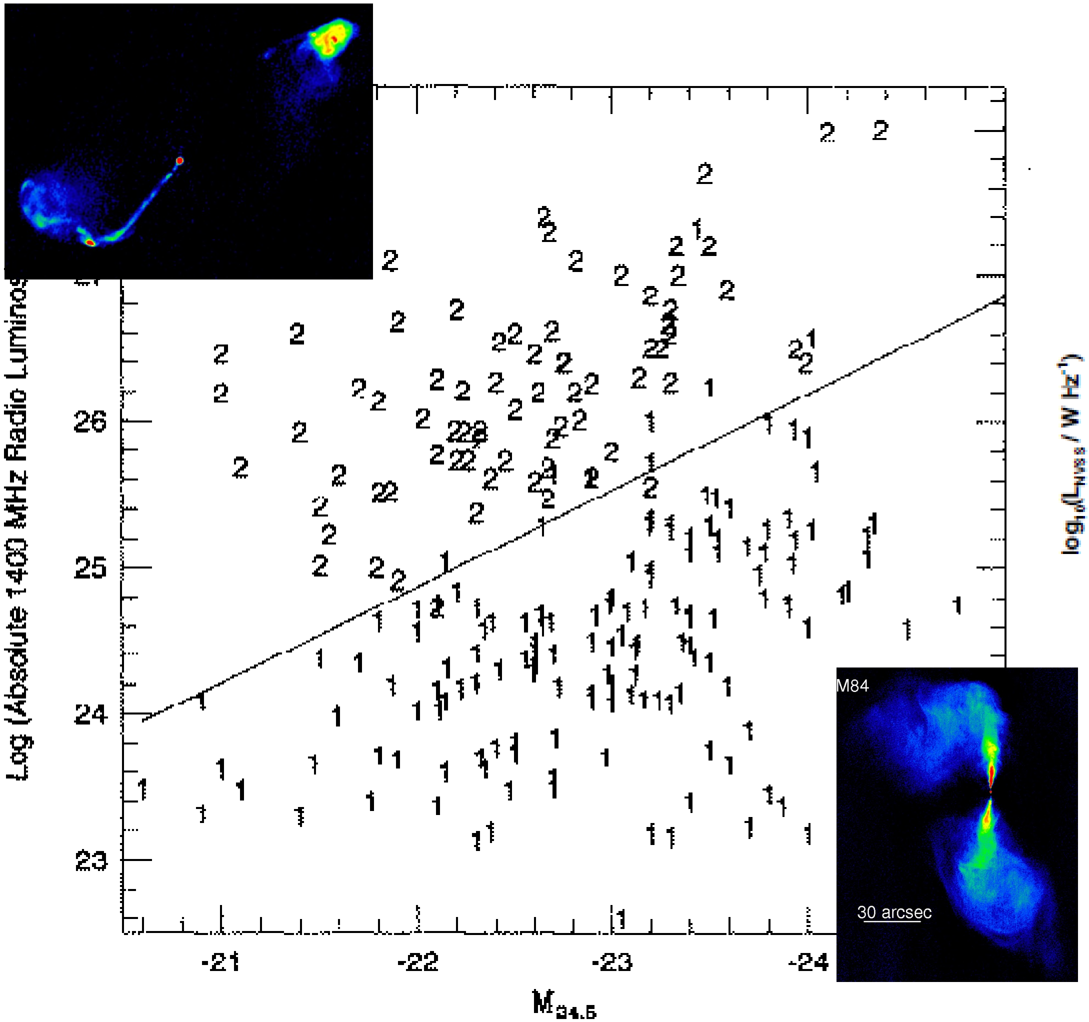
1. Geometrically thin accretion disk
2. Disk empties between ~10 and 40r_g
3. Ejection of new jet component
4. Disk refills

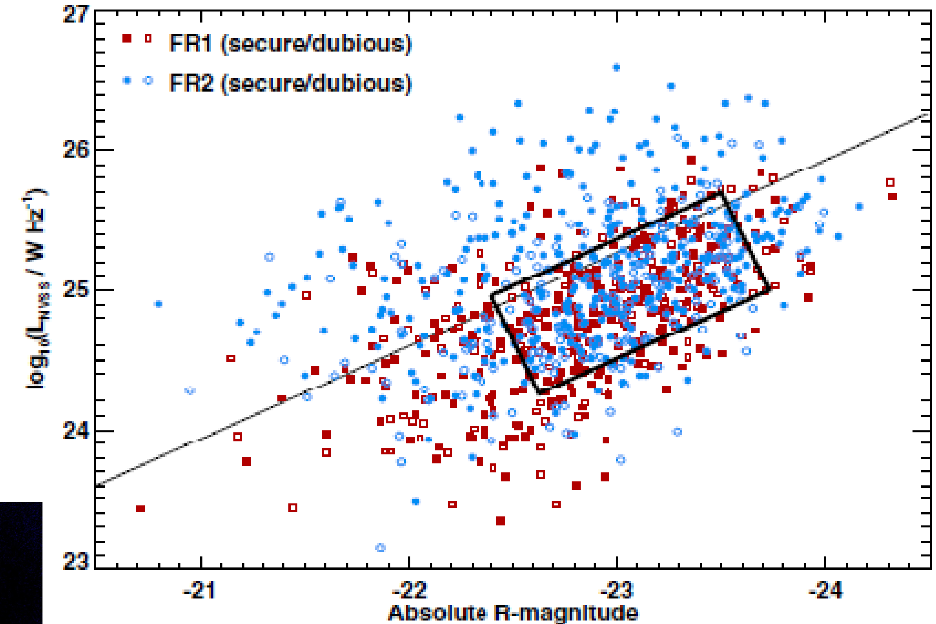
Black Hole Spin in HERG



Why no obvious trend for radio-loud objects to have higher spin? (Reynolds 2015)

FR Division and Environment





Current status?
Strict selection on morphology?

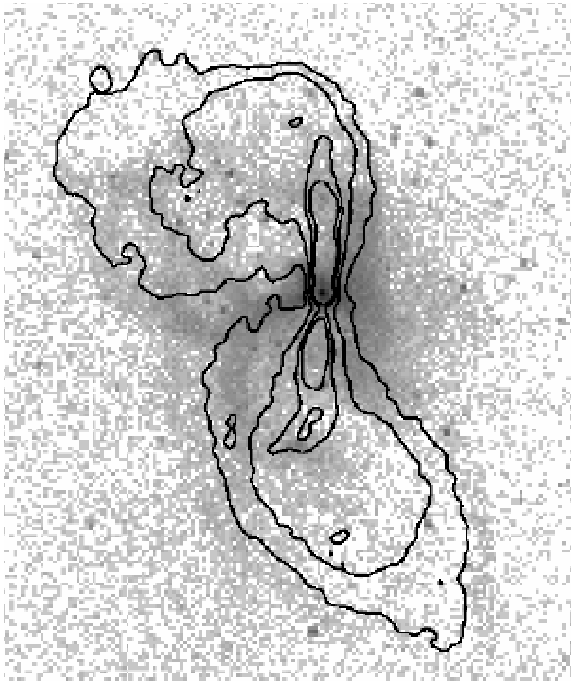
Ledlow & Owen (1996)
Heterogeneous

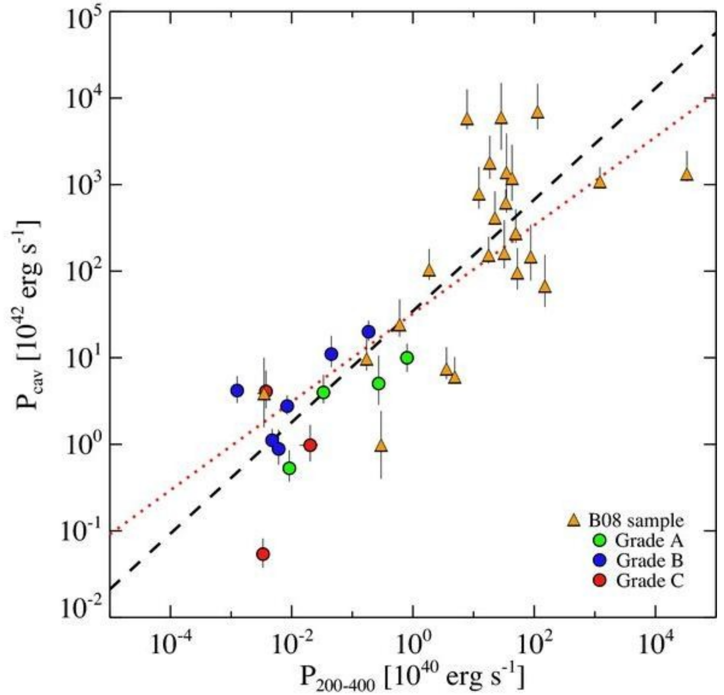
Best (2009)
SDSS/FIRST/NVSS

What did we learn (2)?

- Improving our knowledge of the electron energy distribution (at the low end)
  - Low-frequency absorption (free-free and synchrotron self-absorption; McKean et al. 2016)
  - Identify local GPS sources
  - Remnants [although only 10% in LOFAR survey]
  - Low-energy cut-offs
  - “Injection index”
  - Very broad band spectra – model the evolution of the electron energy distribution, acceleration and loss processes
- Unification models for HERG's are in good shape [Dicken, Morabito]

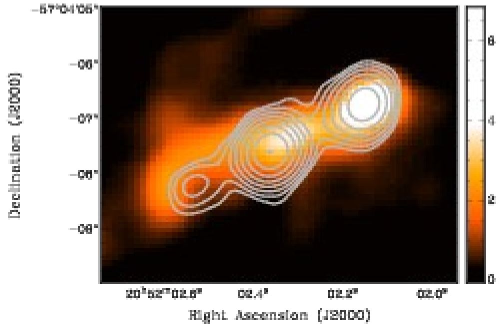
What did we learn (3): impact on hot and cold gas

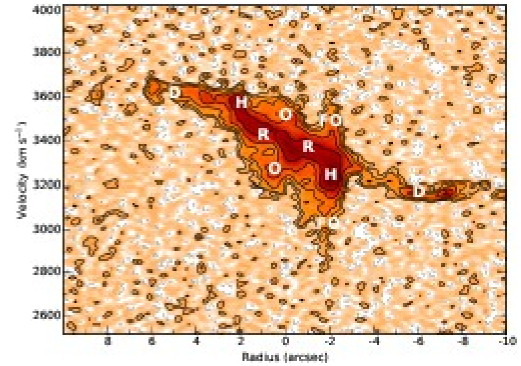




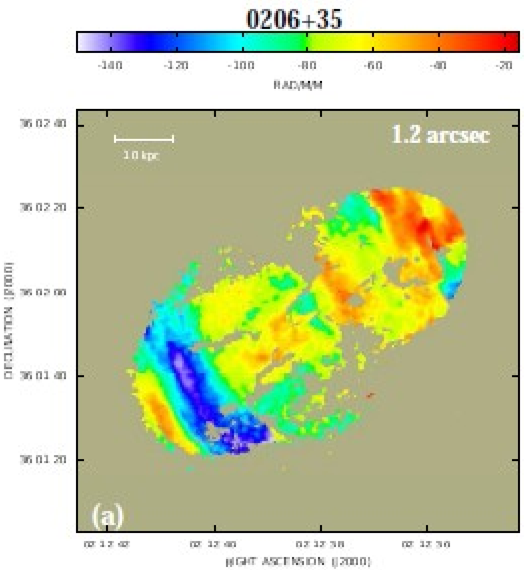
M84 (Finoguenov et al.; Hydra A (Mcnamara etal.); Cavagnolo et al.

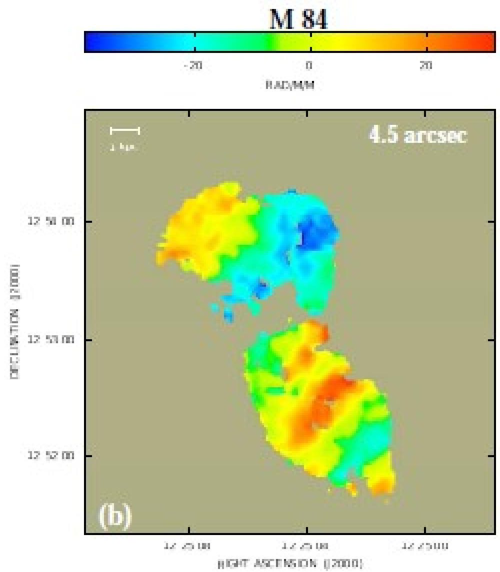
IC5063
ALMA CO2-1 and
230GHz continuun
Morganti et al. (2015)



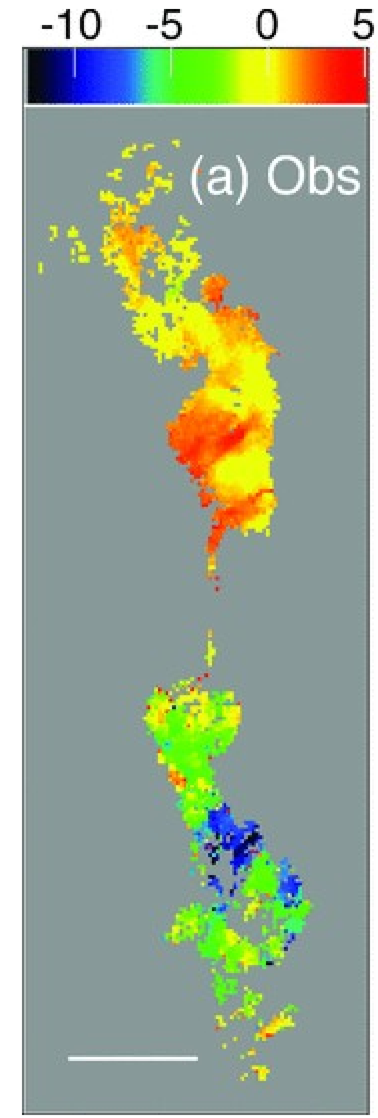


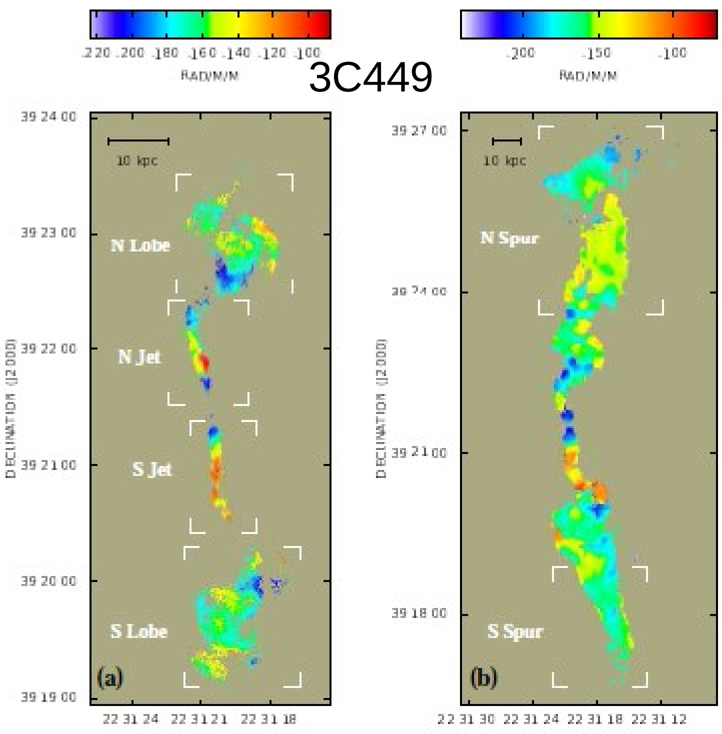
N.B.: interacting hot gas is magnetised

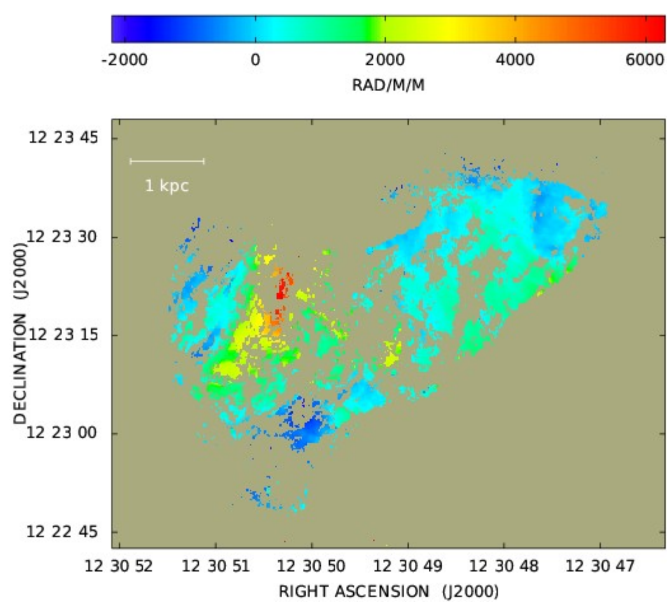




Guidetti et al. (2010,2011)
RL et al. (2008)
Data from F. Owen



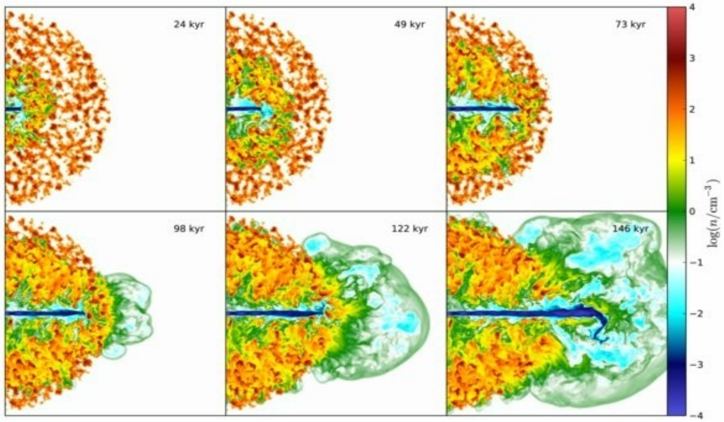




Outflows are complex and multi-phase

- Hot gas
  - Displace
  - Shock (usually low M, but cf. Cen A; Croston et al.)
  - Entrainment and heating: comparable thermal energy in shocked IGM and lobe
- Cold molecular gas [Morganti]
  - Can be driven by (young) jets or disk winds
  - Probably cooling behind shock
  - Need multiple transitions to understand physical state of the gas
- Warm molecular gas
- Neutral hydrogen
- Warm ionized gas

Wagner & Bicknell (2011)



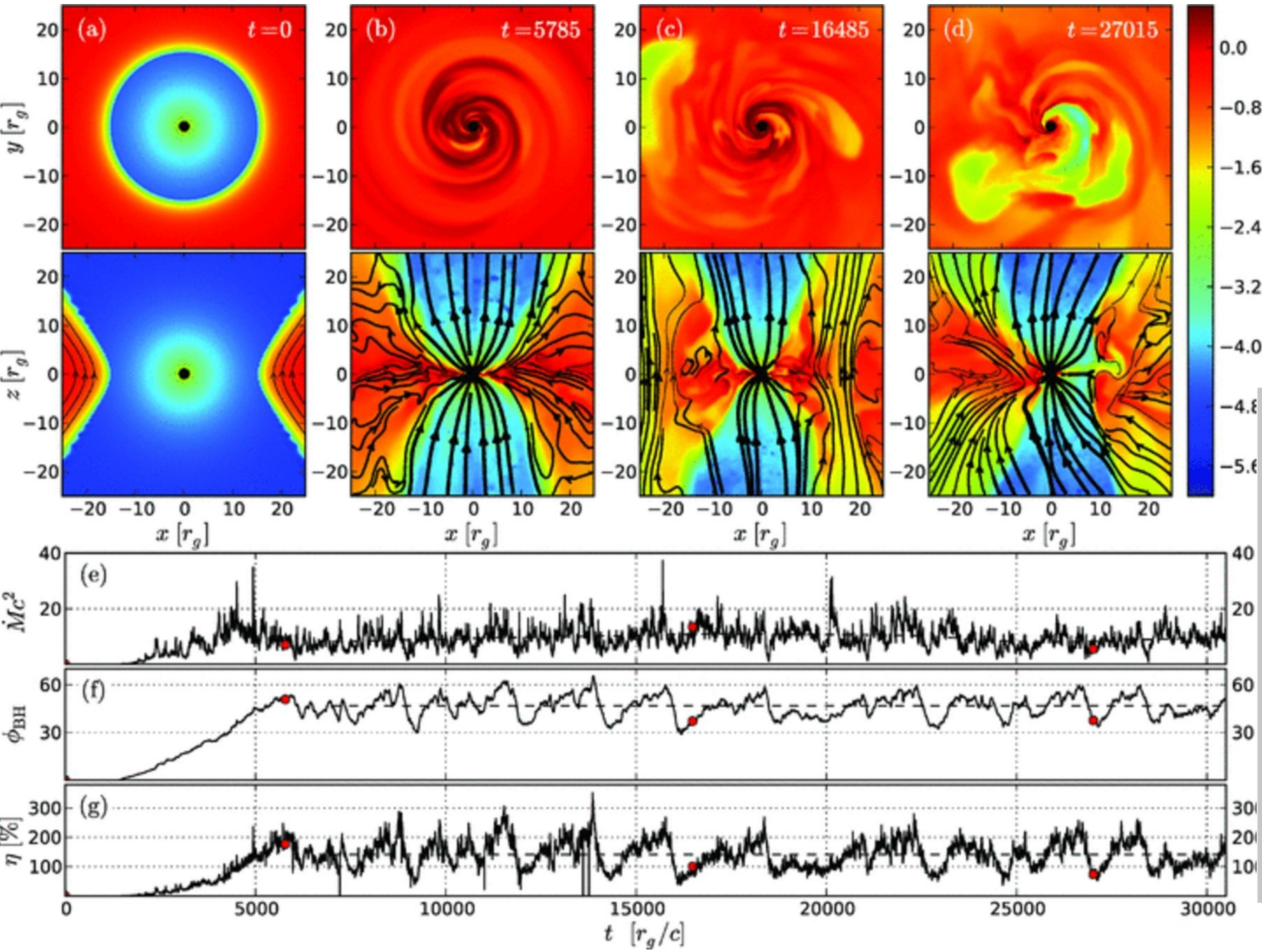
What did we miss?

- Jet formation: numerical simulations
- Jets at ultra-high resolution
- Magnetic field strength and structure
- Velocity fields: acceleration, deceleration, spines and shear layers
- Particle acceleration mechanisms

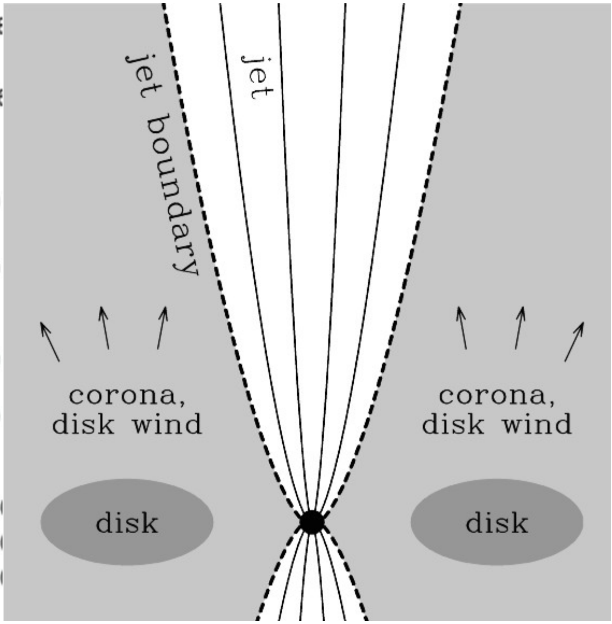
Simulations of Jet Formation

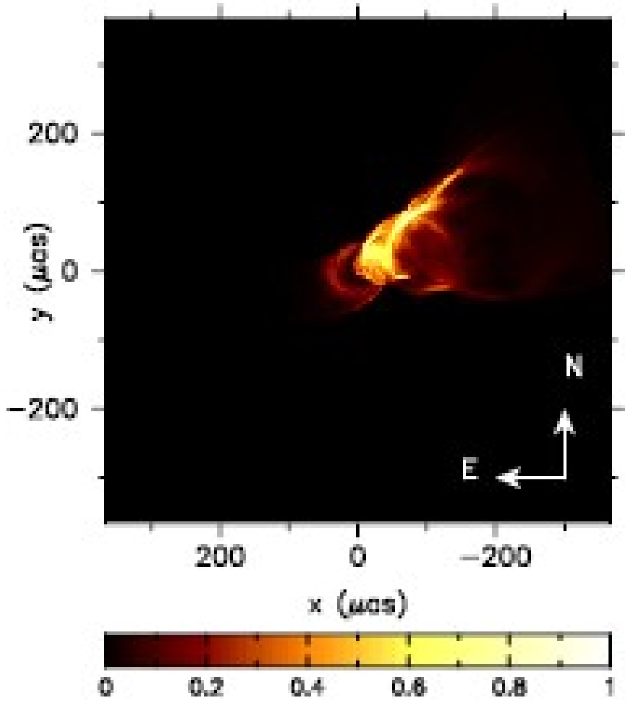
- Currently most successful simulations are of Magnetically Arrested Disks (MADs; Narayan 2003; Tchekovskoy et al. 2011)
  - Accreting gas drags in a strong poloidal magnetic field
  - Accumulated field disrupts the axisymmetric accretion flow
  - Inside the disruption radius, the gas accretes as discrete blobs or streams with a velocity much less than the free-fall velocity.
  - High spin: power dominated by Blandford-Znajek process; energy extracted from black hole spin
  - Low spin: disk dominates
  - Simulated disks are non-radiative and thick: LERG's

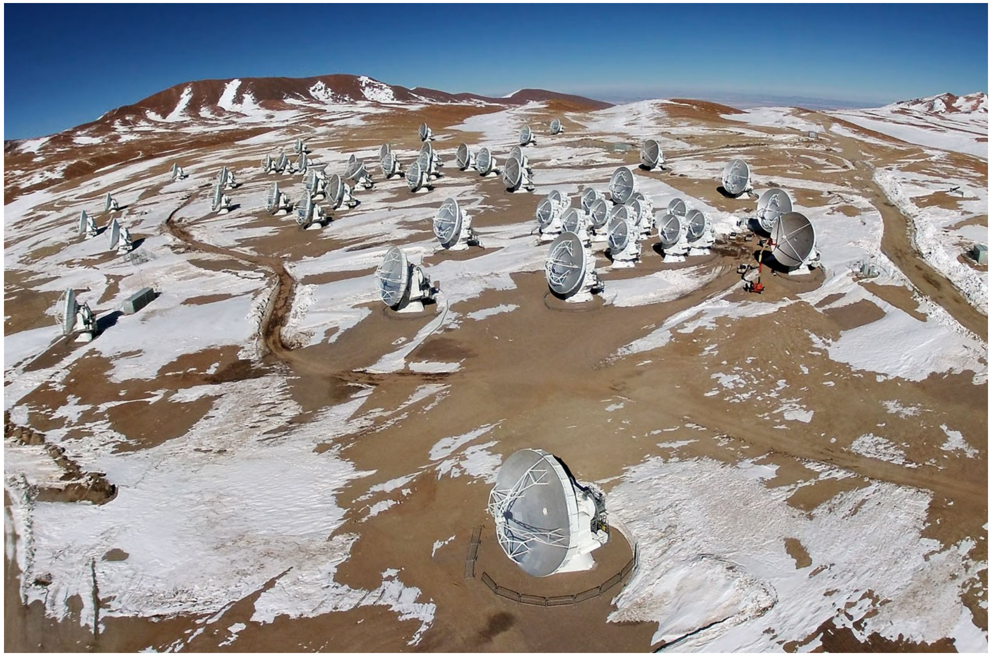
MAD simulations



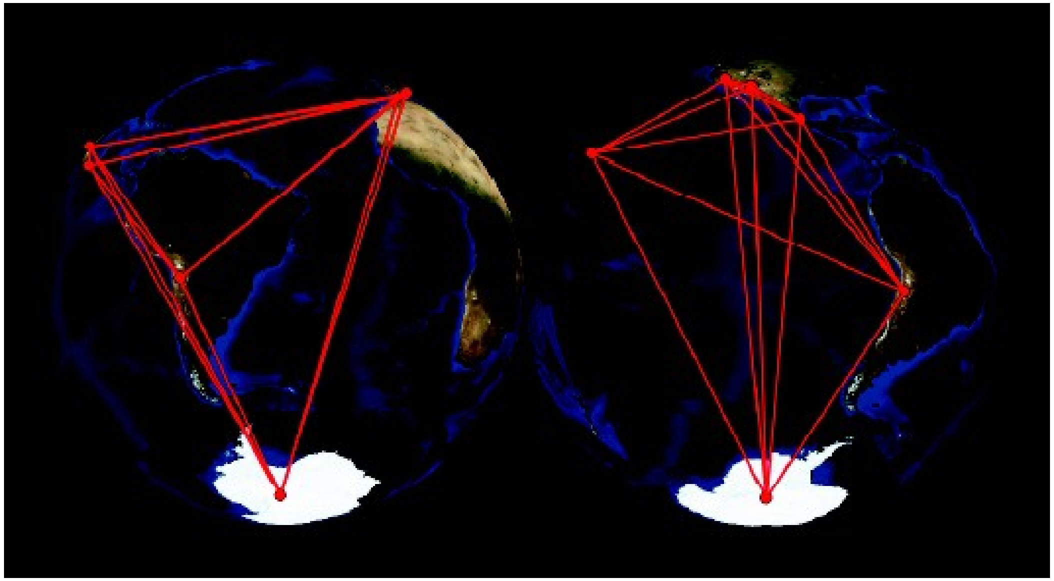
Tchekhovskoy et al. (2011)







GRMHD simulations of M87 (Moscibrodzka et al. 2016)



Phased ALMA with 50 antennas is the equivalent of an 85 m single dish on an excellent site

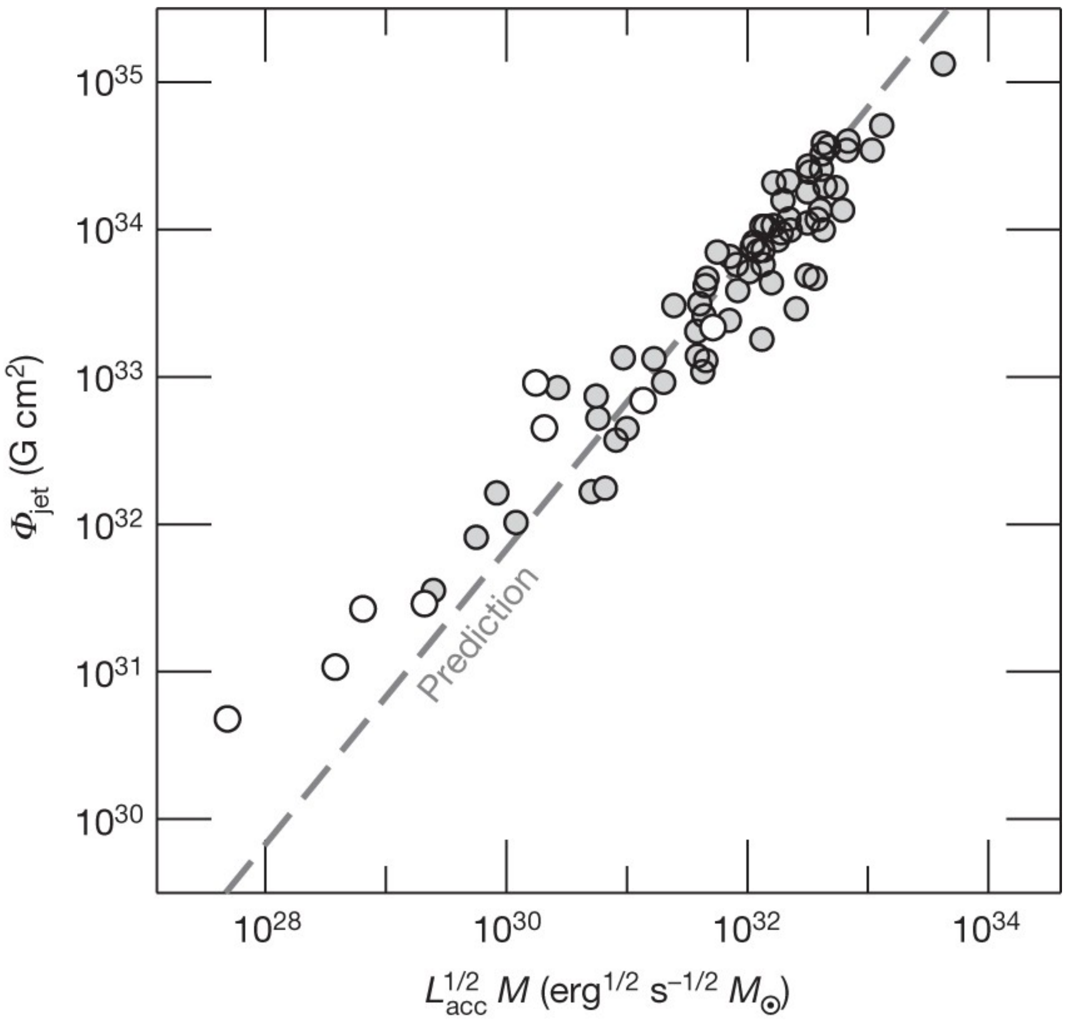
Resolution ≈ 20 μarcsec at 230 GHz

Observations April 2017

Magnetic Field Strength and Geometry

- kpc scales
  - FRI jets: evolution from longitudinally to toroidally dominated; not a globally ordered helix; e.g. ordered toroidal + longitudinal with many reversals (Laing & Bridle 2014)
  - Field strength estimates from equipartition ~1-30 μG) ; inverse Compton constraints not very useful
  - FRII jets: integrated apparent field usually longitudinal; one resolved case: longitudinal + toroidal in boundary layer
- pc scales
  - Core shift method gives magnetic field strength at ~1 pc (and, with additional assumptions, the magnetic flux)
  - Field geometry debated: helical/toroidal + rms longitudinal/disordered and anisotropic. Likely to evolve with distance.
  - Critical for jet launching models

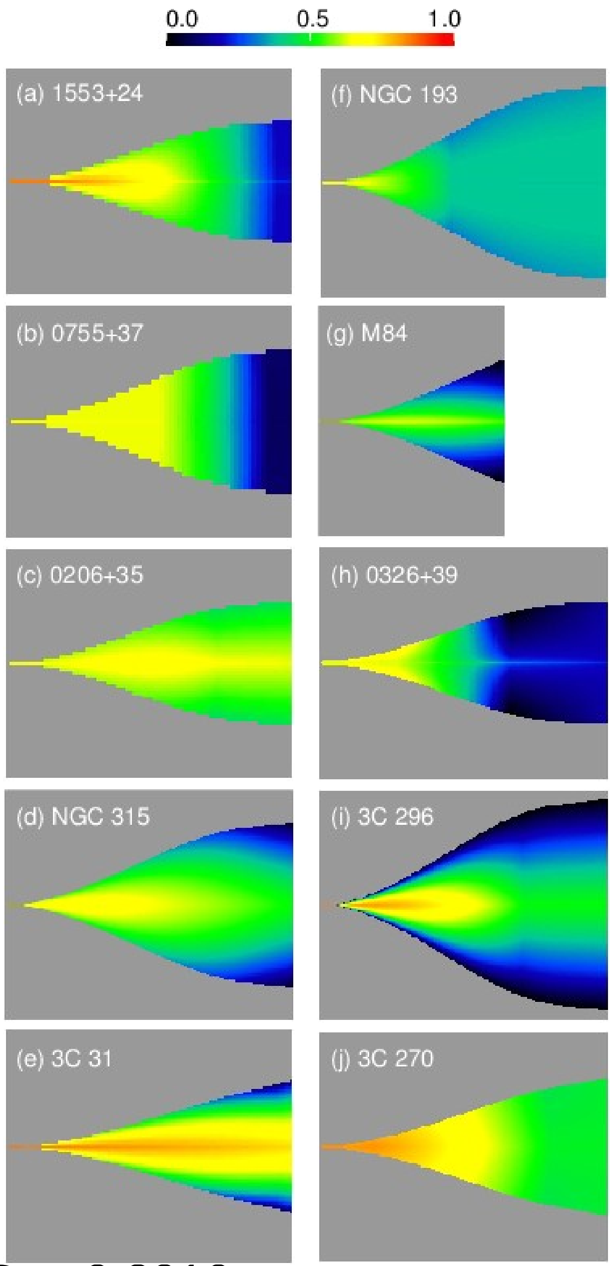
Magnetic Flux from core shift



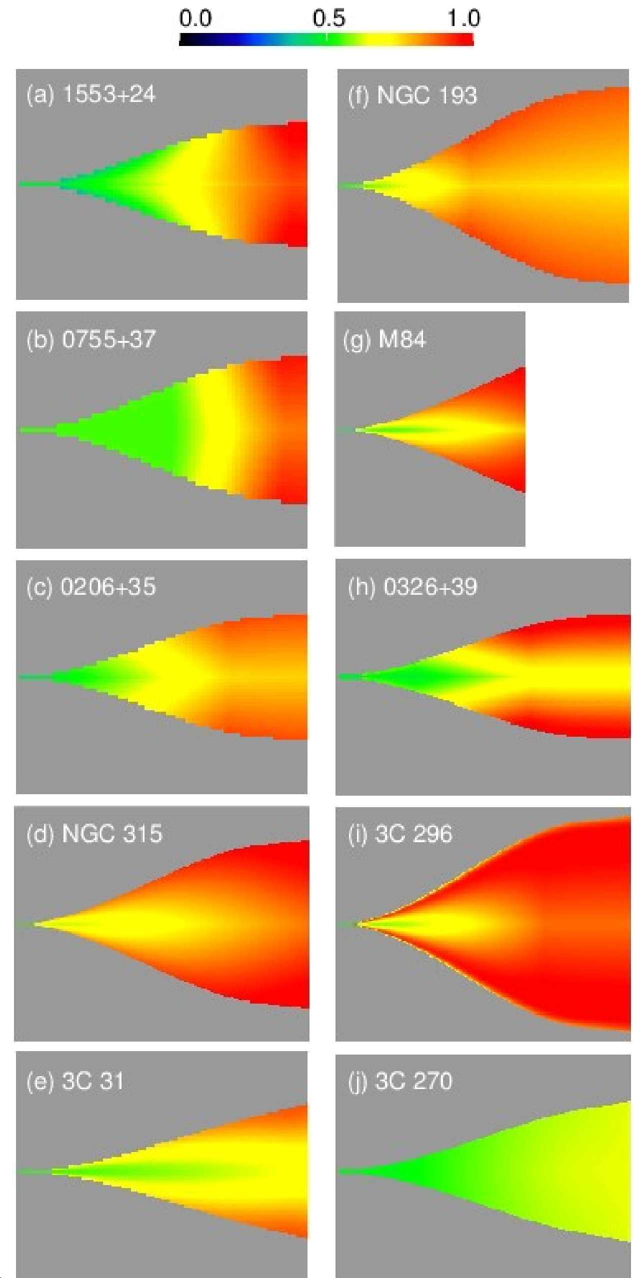
Zamaninasab et al. (2014) see also Zdziarski et al. (2015) for different assumptions.

B-field geometry in FRI jets

Longitudinal

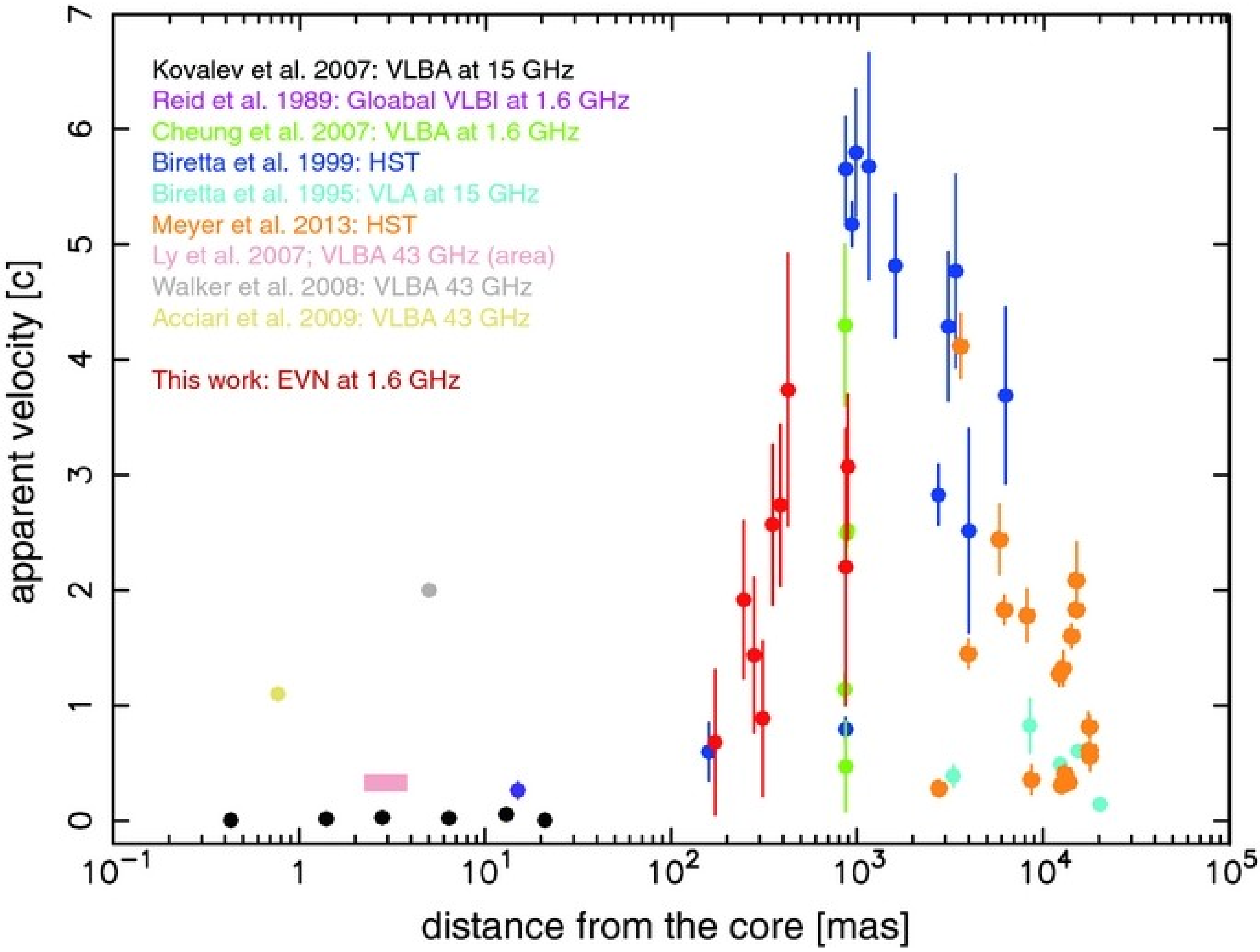


Toroidal



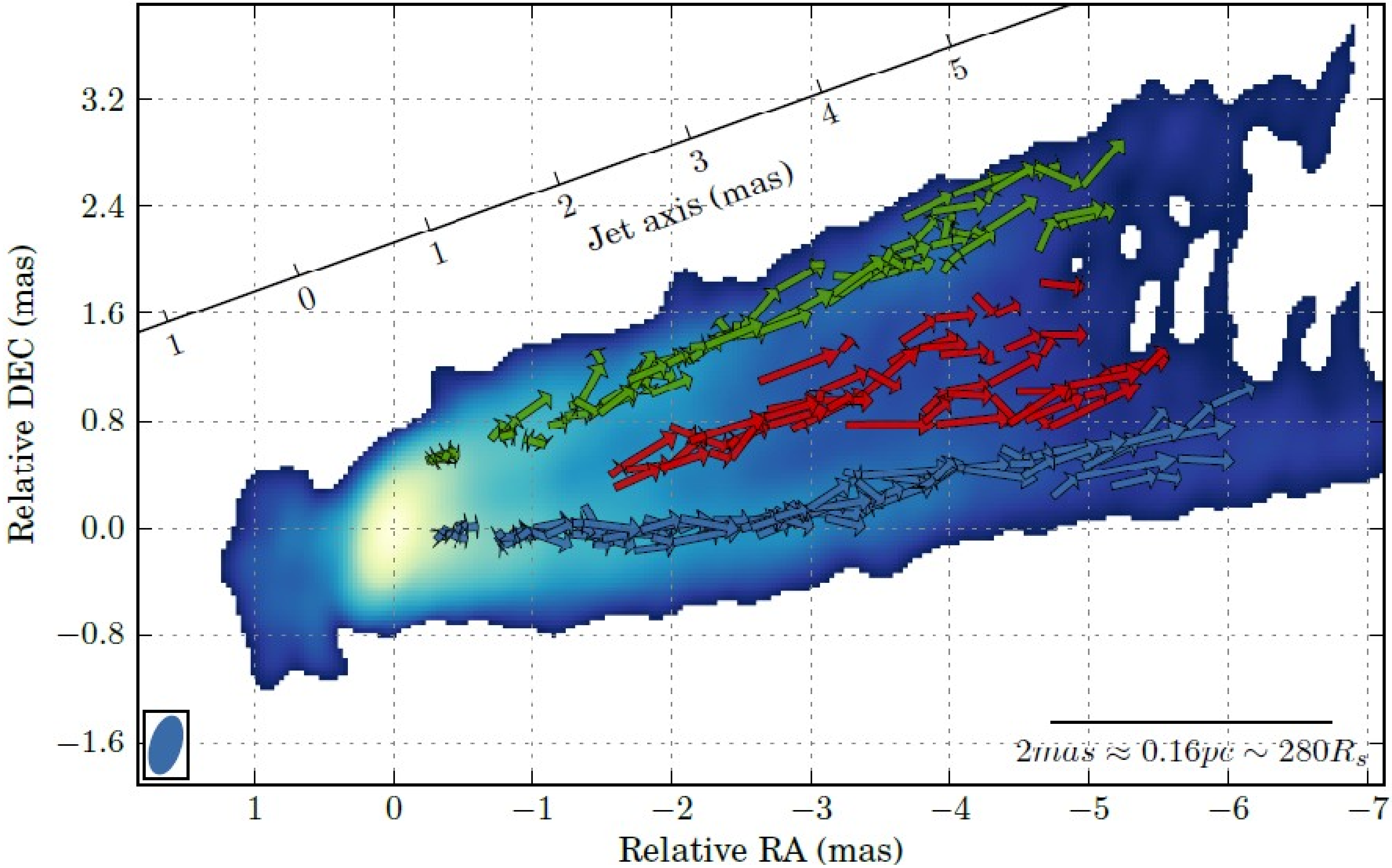
Laing & Bridle (2014)

Accelerations and decelerations



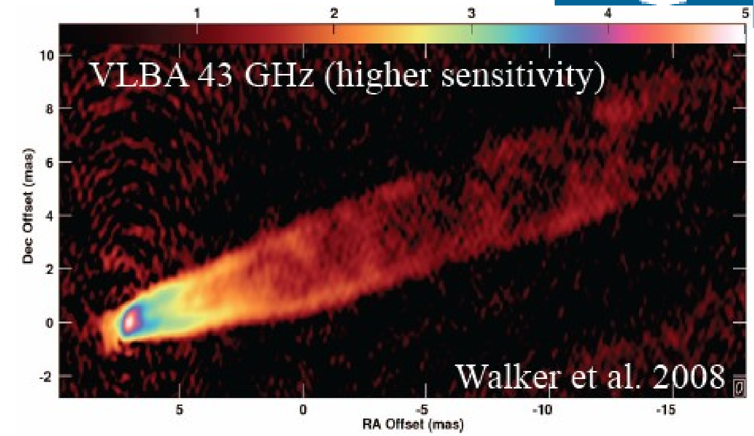
Apparent speeds in M87 (Asada et al. 2014)

... or maybe not

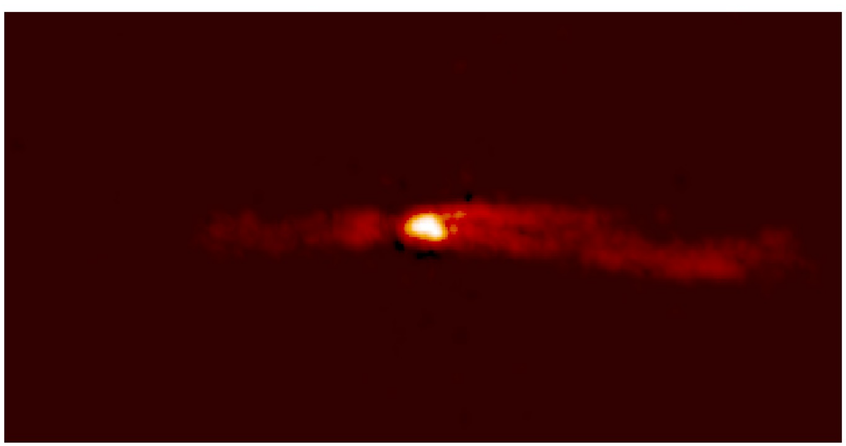


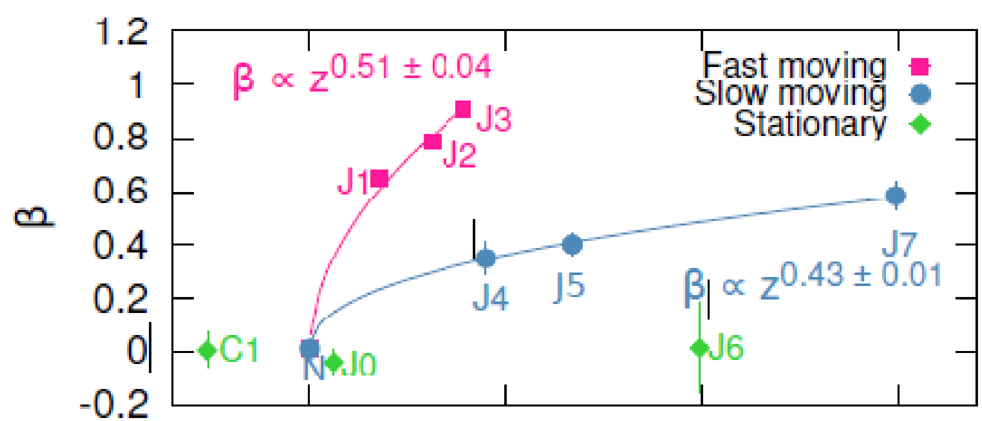
Apparent speeds 0.5 – 2.25c; Mertens et al. (2016)
On-axis β ≈ 0.92 (accelerating); edge β ≈ 0.5.

Transverse gradients: pc scales



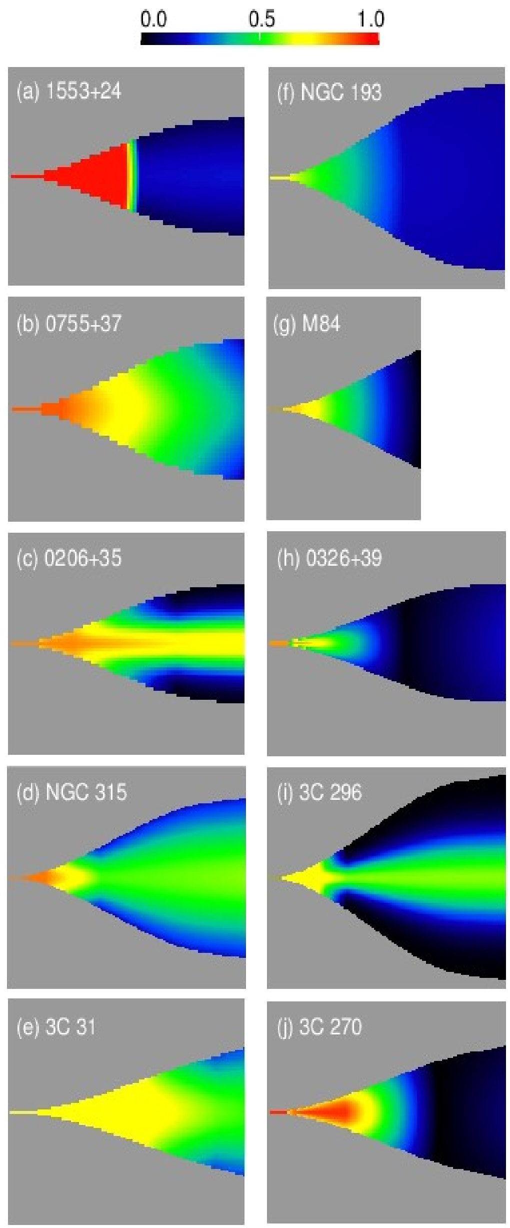
- Spine/shear layer models
  - Limb-brightened emission
  - Slow apparent speeds in TeV blazars
  - Consistency with FRI parent population
  - Inverse Compton emission (spine scatters photons from shear layer and vice versa; Ghisellini et al. 2005)
  - Consistency with B estimates from core shift (Tavecchio & Ghisellini 2015)





Cygnus A: Boccardi et al. (2015)

Deceleration and Transverse Velocity Gradients in FRI Jets



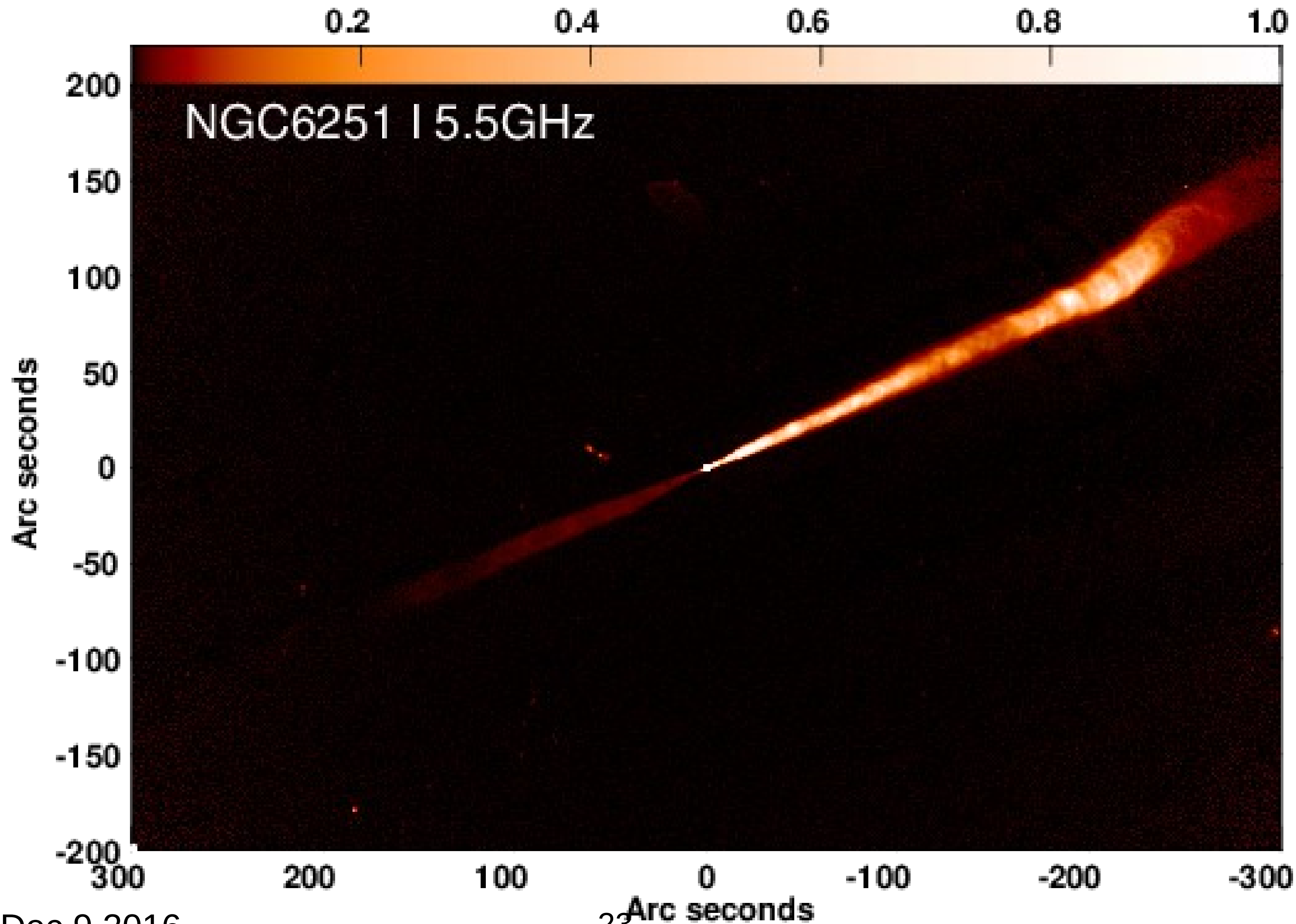
Laing & Bridle (2014)

Deceleration from ≈0.8c to <0.5c on scales of 1 – 20 kpc

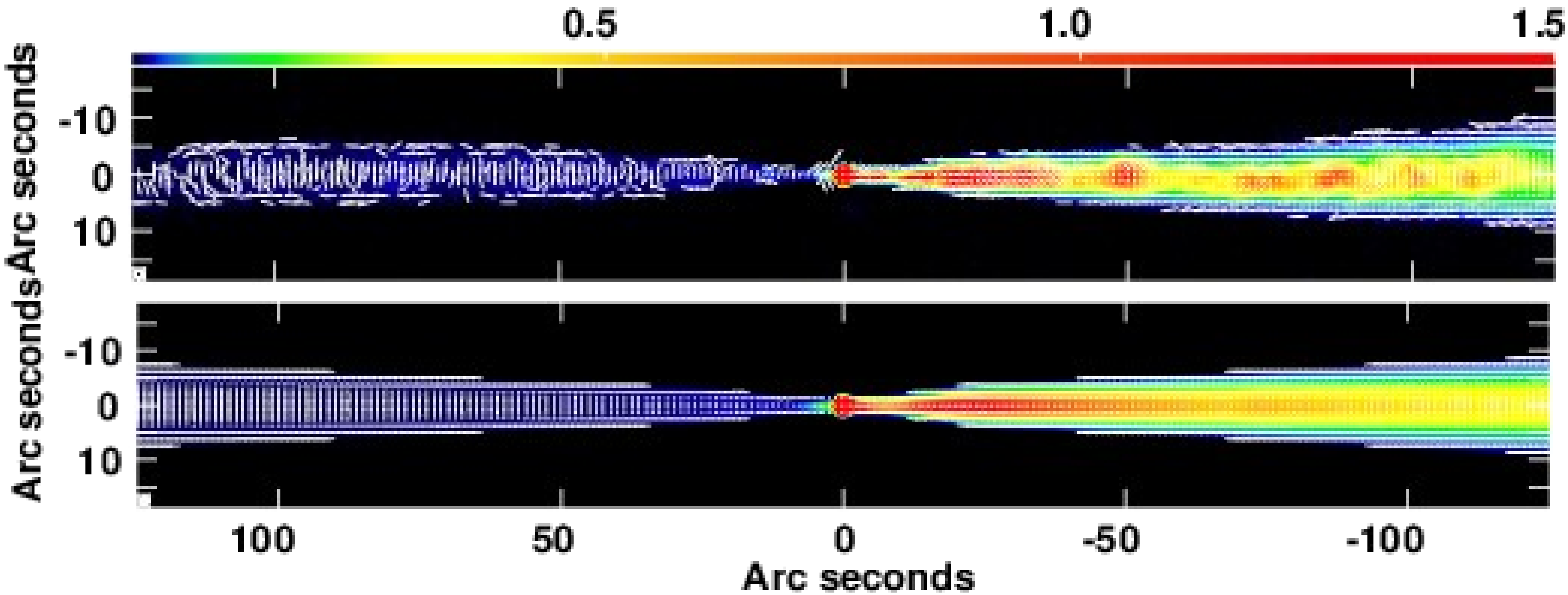
Development of smooth (quasi-Gaussian) transverse velocity profiles.

Boundary-layer entrainment

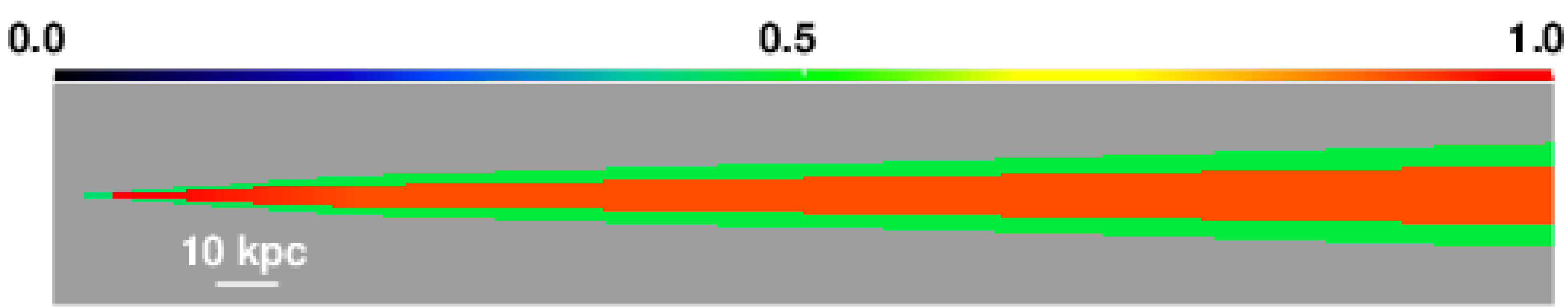
How fast are FRII jets on large scales?



Model fits: B vectors



v/c



Questions for Discussion

- How do jet properties depend on black hole mass, spin, accretion rate, environment?
  - Accretion disk physics is significantly different for radiatively efficient/inefficient.
  - Does the FRI/II division depend primarily on jet energy flux and environment and only indirectly on the jet formation process?
  - What are the lower-power LEG FRII's?
- Fueling: do LERGs and HERGS accrete from different gas phases?
  - Or is there just less cold gas available in LERGs?
- (How) is the feedback loop closed?