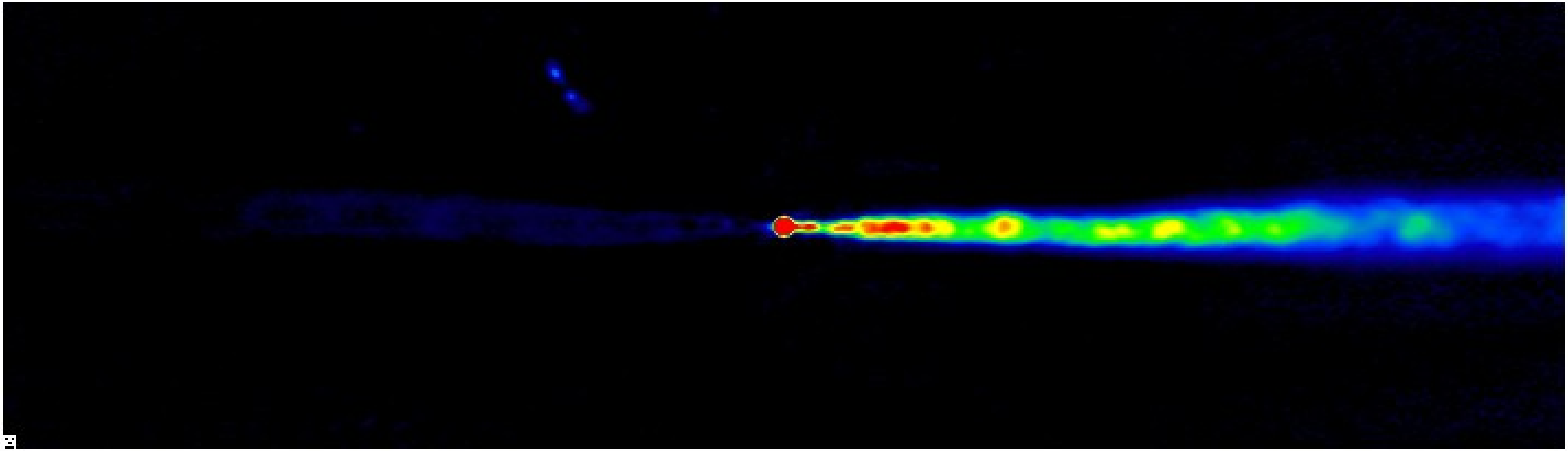
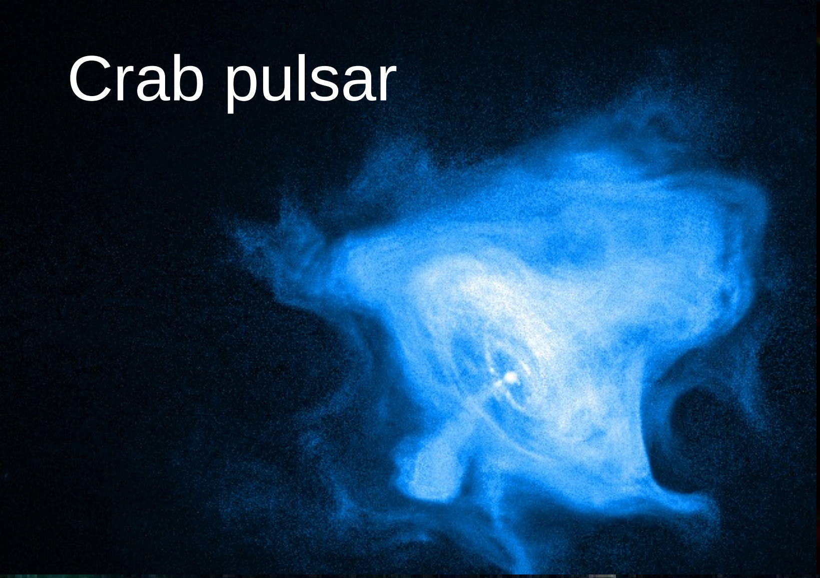
Extragalactic Relativistic Jets: Cause and Effect

Robert Laing (ESO)



Bangalore, October 2015

Jets


Crab pulsar


Radio Galaxy Centaurus A


Young stellar object
HH47

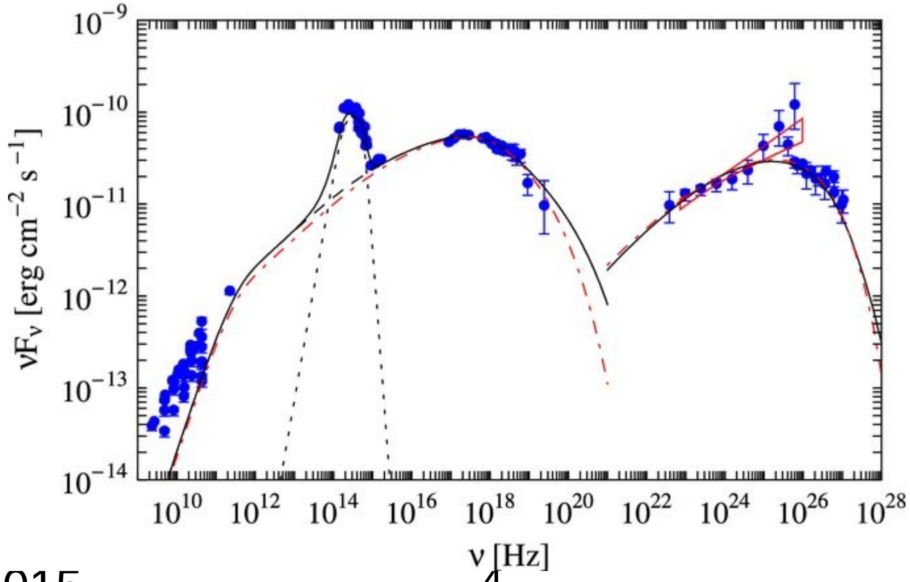

Gamma Ray Burst

Selected Topics

- Jet formation: numerical simulations
- Accretion modes
- Where do jets light up?
- Magnetic field strength and structure
- Velocity fields: acceleration, deceleration, spines and shear layers
- The Fanaroff-Riley division
- The impact of jets
- Future observations

Basic Numbers for Extragalactic Jets

- Jet power ~10^{41} – 10^{47} $\mathrm{erg\,s^{-1}}$
- Relativistic bulk flow: pc-scale Lorentz factor $\Gamma \sim 5 - 40$
- Supermassive black holes $M \sim 10^{6} - 2 \times 10^{10}\ M_{Sun}$
- Formation scale <50 r_g in M87
- Ages (with persistent directions) up to ~10^{8} yr
- Observed synchrotron and inverse Compton radiation
- Relativistic electrons and magnetic field; thermal particles
- Accelerate electrons to very high Lorentz factors



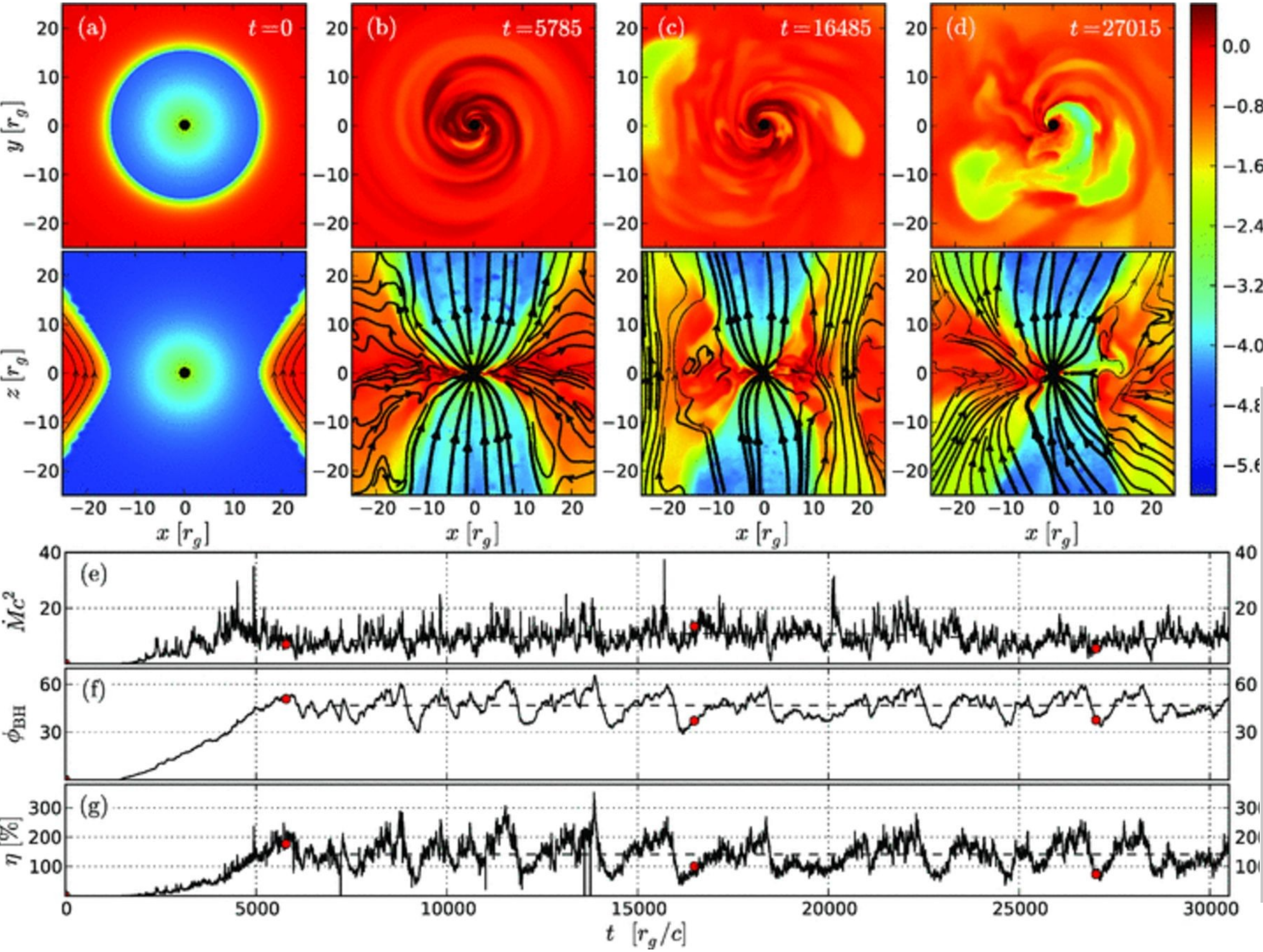
Mkn 501
average

Abdo et al. (2011)

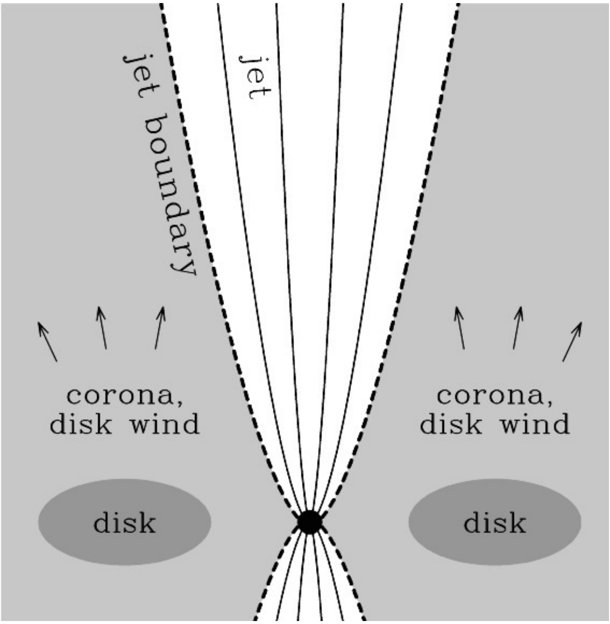
Simulations of Jet Formation

- 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
- Super-Eddington accretion flows also seem to be able to form jets – but they are driven by radiation, not magnetic field, and are slower than observed jets (Sadowski & Narayan 2015).

MAD simulations



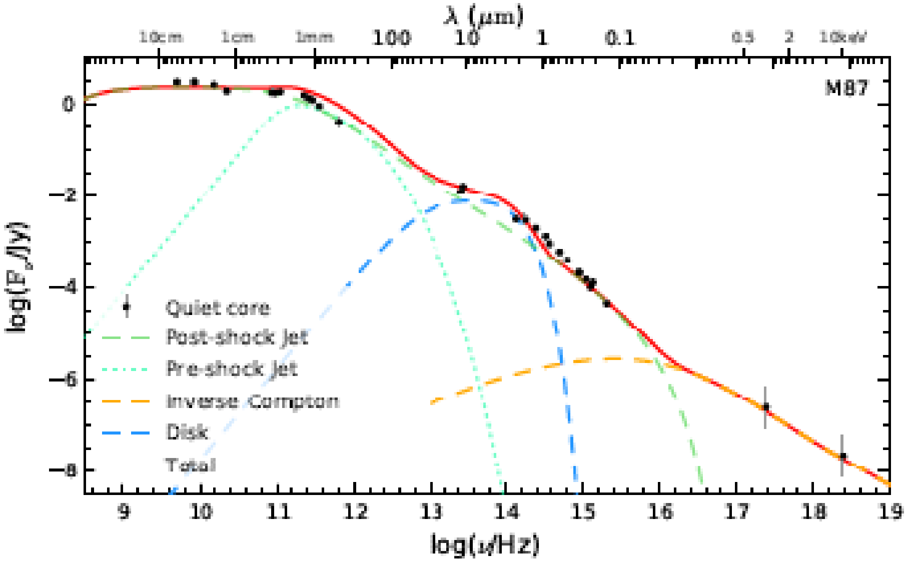
Tchekhovskoy et al. (2011)



Accretion Rate

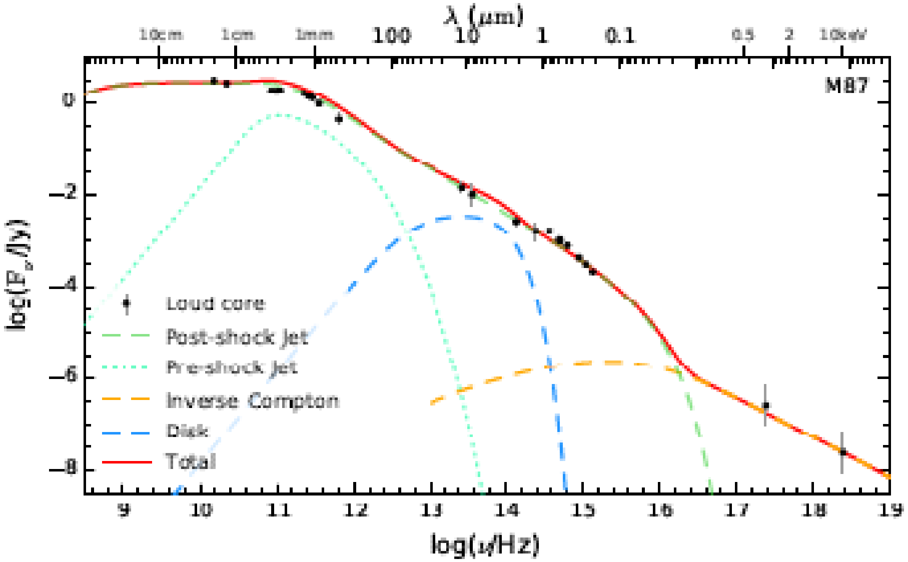
- High-excitation radio galaxies (HEG)
  - Radiatively efficient accretion
  - High-excitation narrow lines; broad permitted lines
  - Obscuring torus
  - X-ray emission and reflection; blue bump
  - Less massive galaxies and black holes; strong evolution
  - $L_{Acc} \sim 0.1 – 1 L_{Edd}$
  - Accretion of cold gas?
- Low-excitation radio galaxies (LEG)
  - Radiatively inefficient accretion (RIAF/ADAF/CDAF/ADIOS)
  - Very massive galaxies and black holes; weak evolution
  - Very hard to detect emission from the accretion disk at all
  - $L_{Acc} < 0.01L_{Edd}$; L_{jet} can be >> L_{Acc}
  - Accretion of hot gas? Maybe, but plenty of molecular gas available too.

M87 Nuclear Spectrum



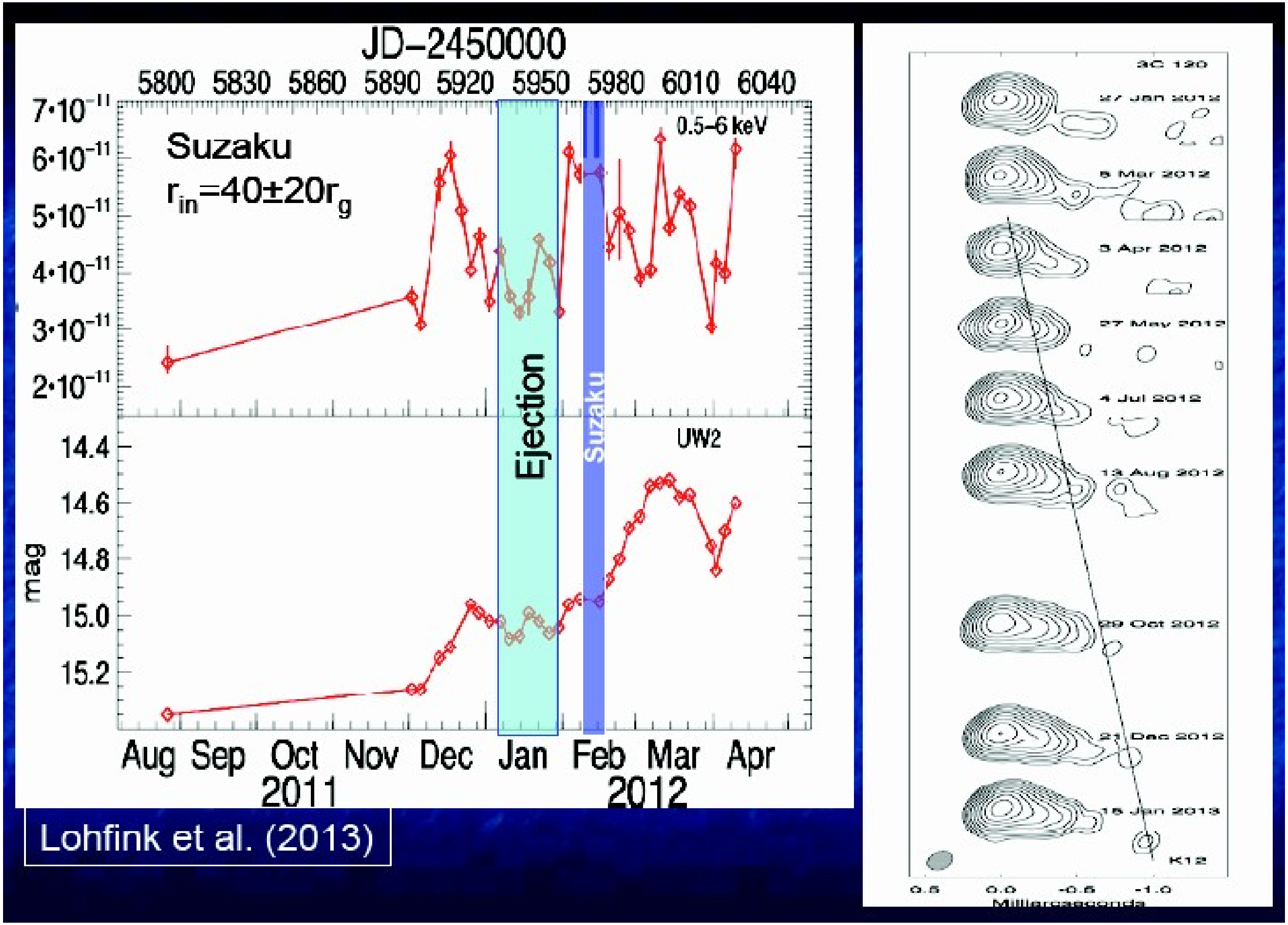
Active

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



Quiescent

3C120 jet ejection events

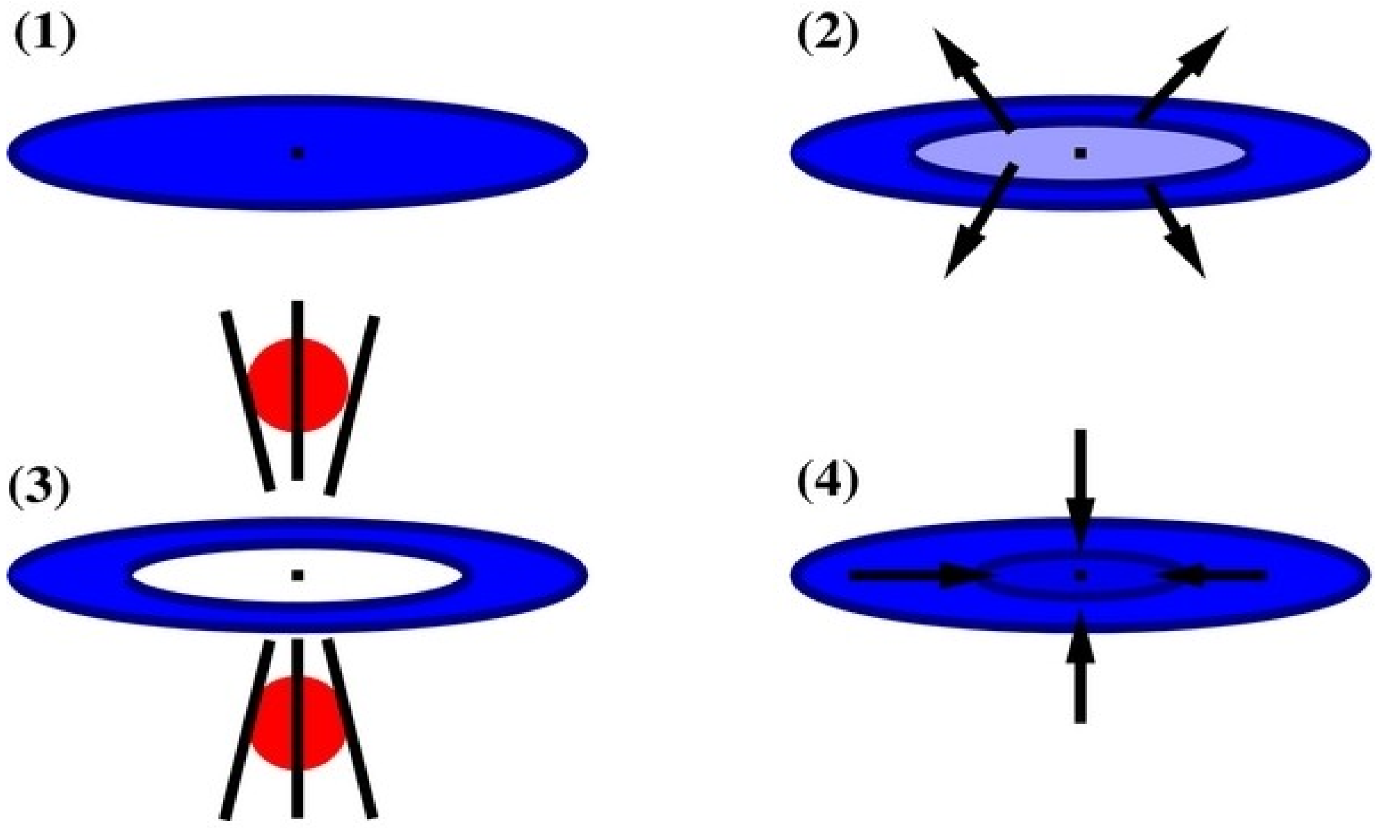


Lohfink et al. (2013)

Jet Ejection Cycle in BLRG

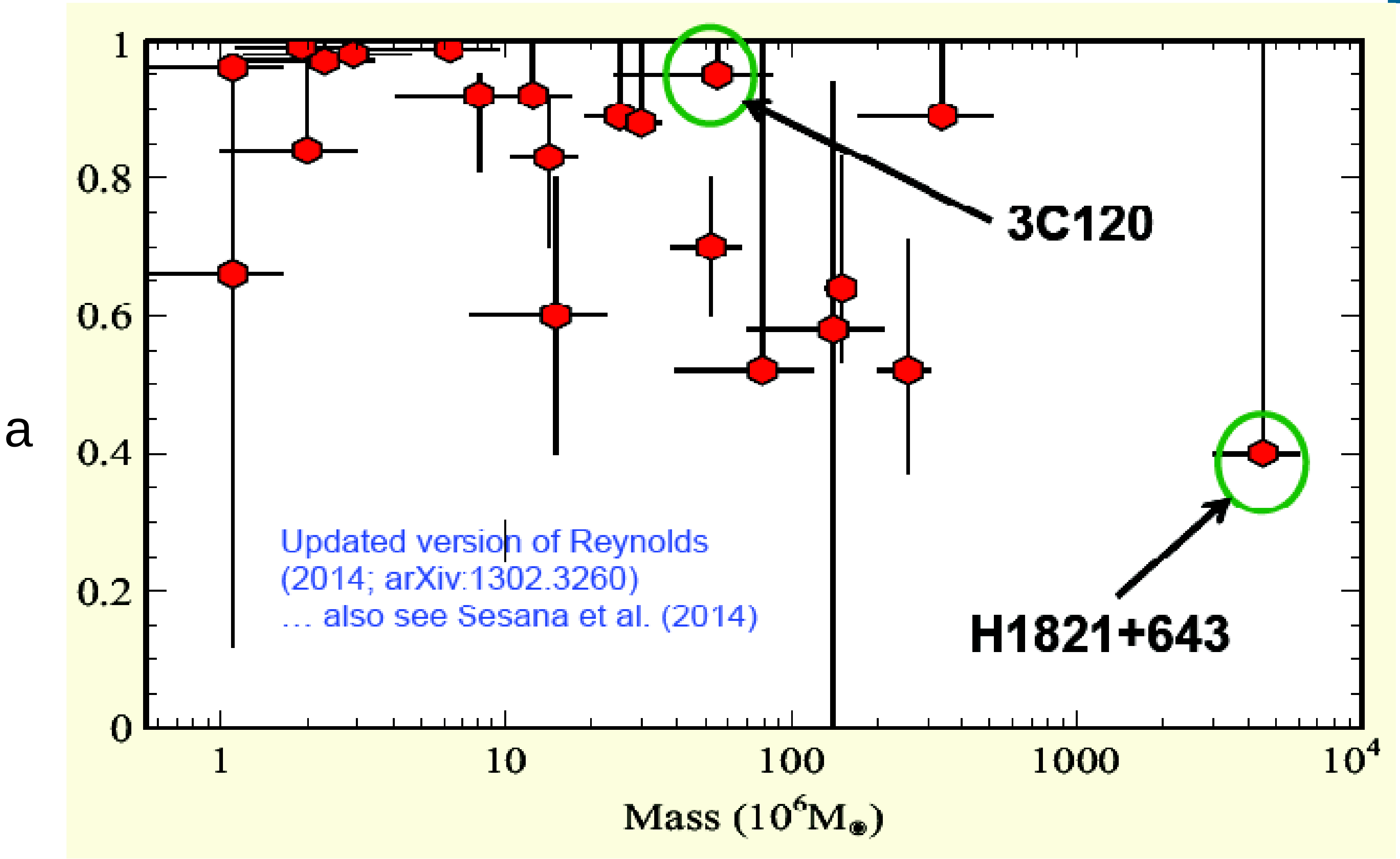
Lohfink et al. (2013)
Fe line fitting

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



Updated version of Reynolds (2014; arXiv:1302.3260)
… also see Sesana et al. (2014)

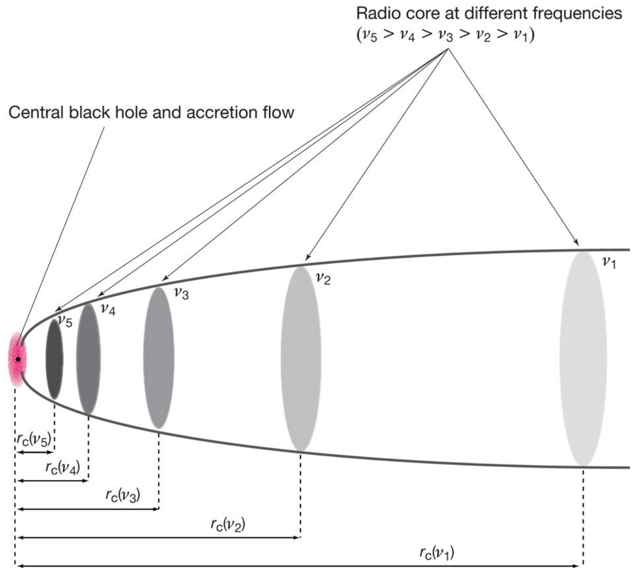
Why no obvious trend for radio-loud objects to have higher spin? (Reynolds 2015)

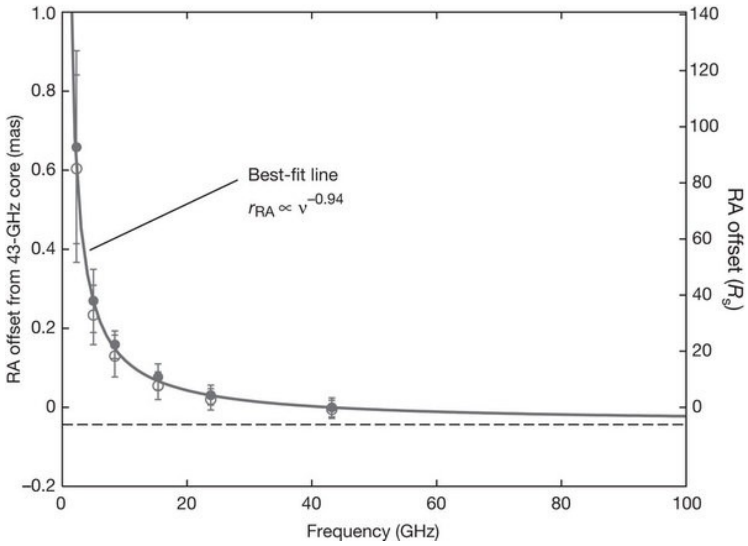
Accretion mode: questions

- Why are the jets in HEGs and LEGs so similar, despite the gross differences in accretion disk properties?
  - Although the much higher photon density for radiatively efficient accretion obviously affects inverse Compton emission from the jets
- Why is there a correlation between accretion disk luminosity and jet power in high-accretion-rate systems (e.g. Rawlings & Saunders)?
- Is the absence of a thin disk at small radii a necessary condition for jet formation? Why?
- Why is there no obvious relation between efficient jet production and measures of black-hole spin?

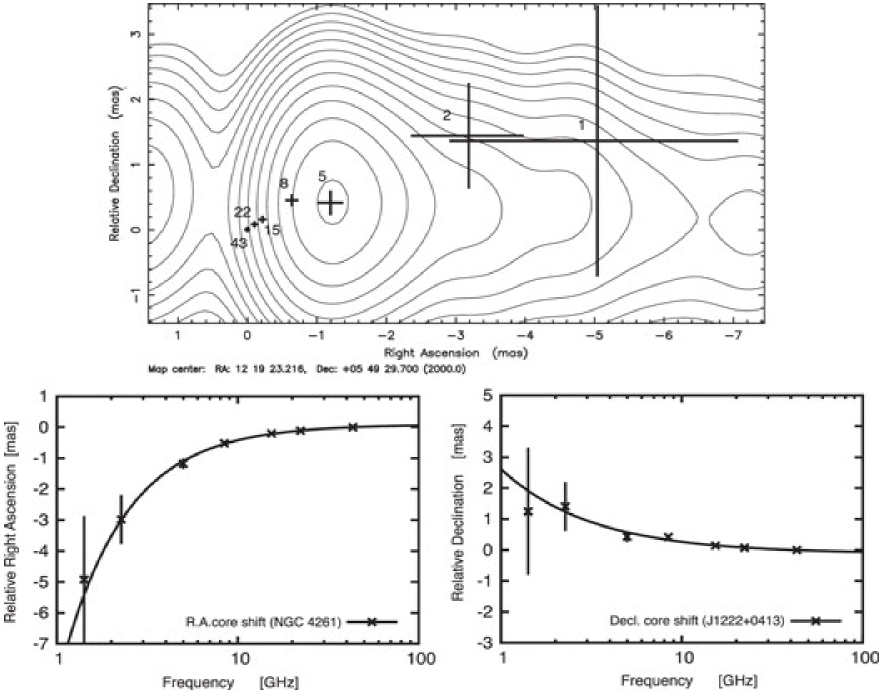
.. and please can we stop using the terms “radio-loud” and “radio-quiet” to refer to ill-defined ratios of radio core flux and some random mixture of accretion disk, stars and optical jet.

Where do jets light up?
Very close to the black hole





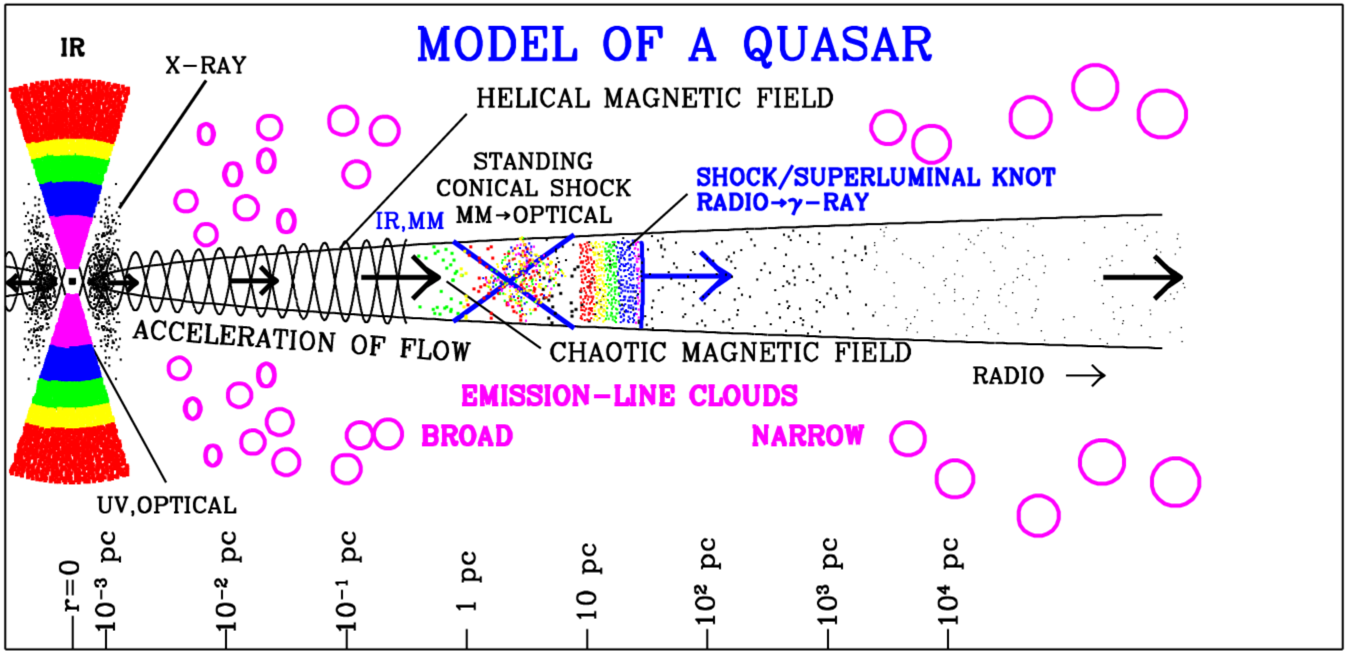
M87: Hada et al. (2011)



3C270: Haga et al. (2015)

Core shift: measuring the position of the τ = 1 surface as a function of frequency

..... or not



Marscher

But where do the gamma rays come from?

Radio core is a stationary feature (conical shock).

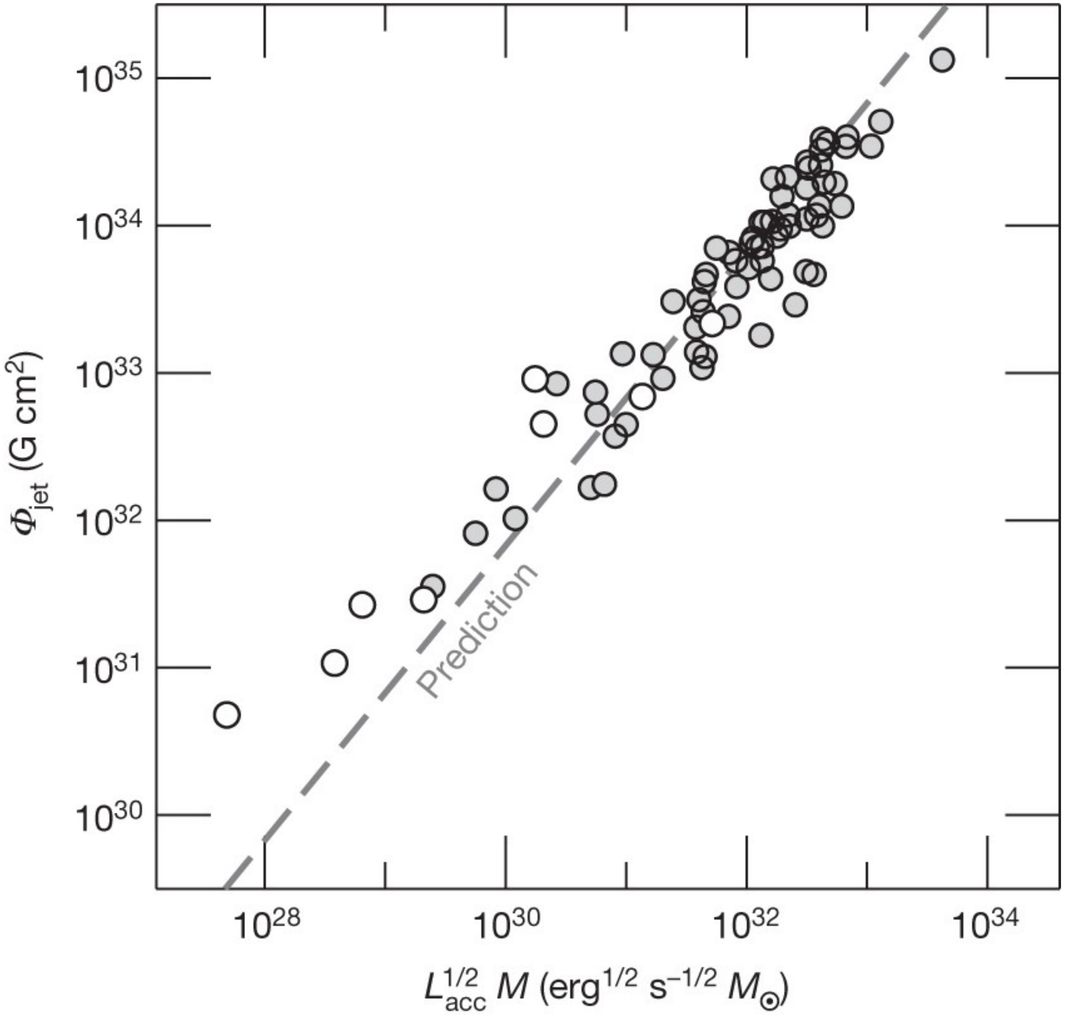
Dip in X-ray emission from accretion disk, followed after some time by the appearance of a new radio component [same observations as used to infer inner disk truncation.]

Delay interpreted as travel time from the black hole to the shock.

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.

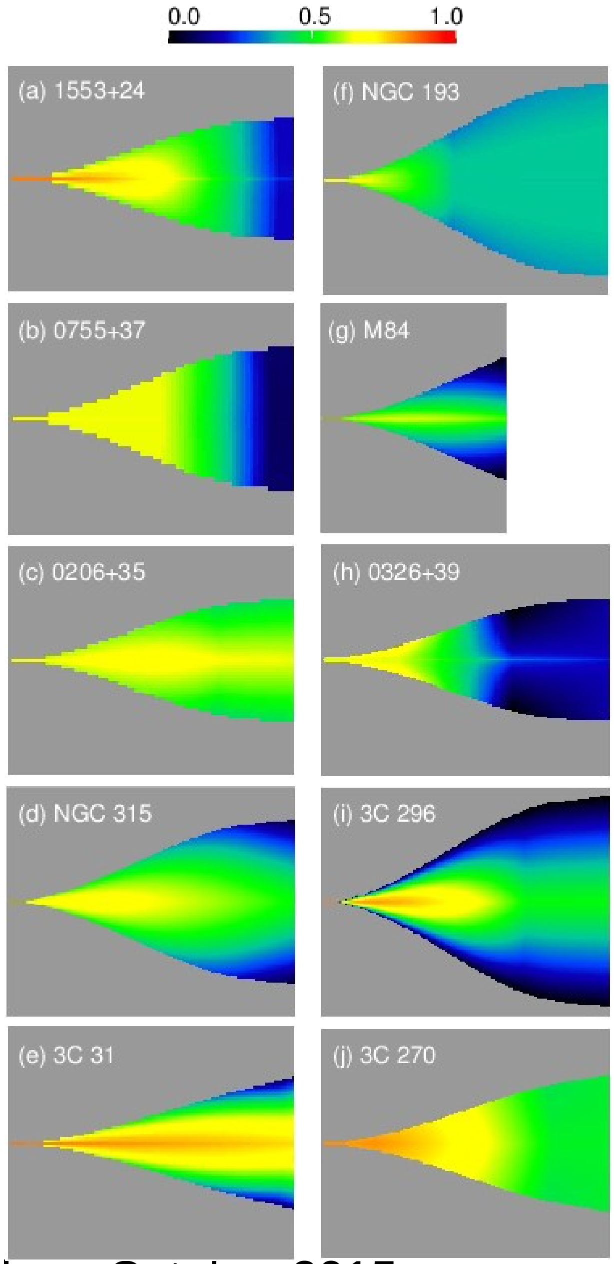
Magnetic Flux from core shift



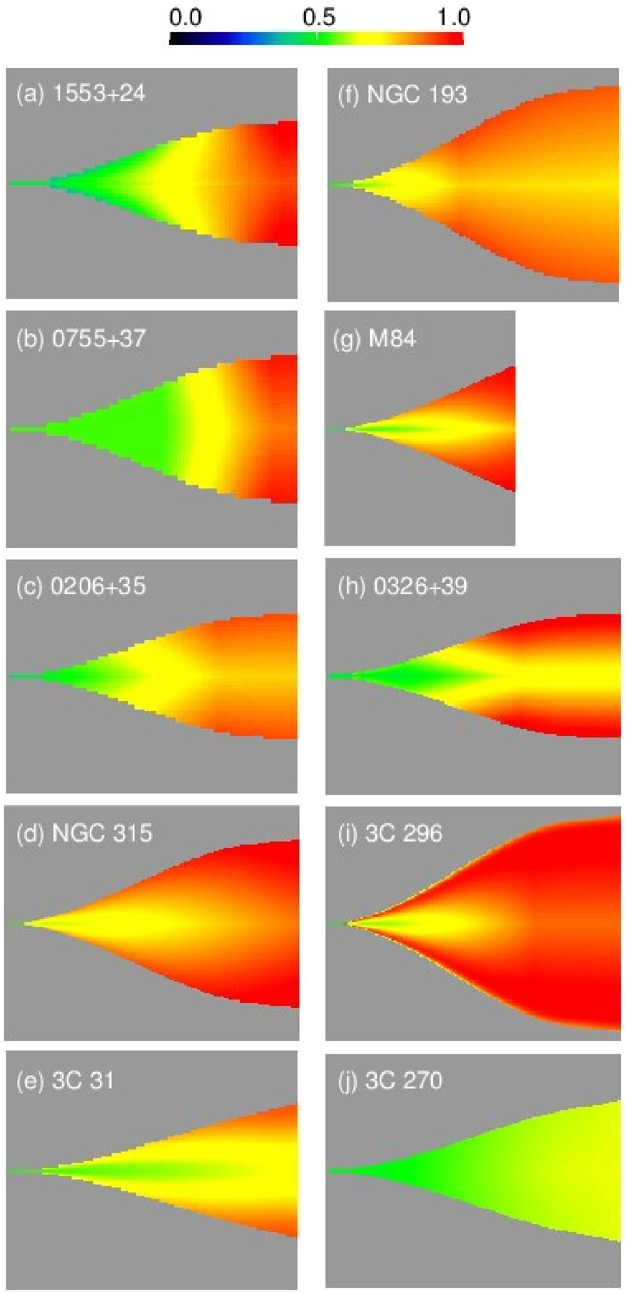
Zamaninasab et al. (2014) see also Zdziarski et al. (2015) for different assumptions.

B-field geometry in FRI jets

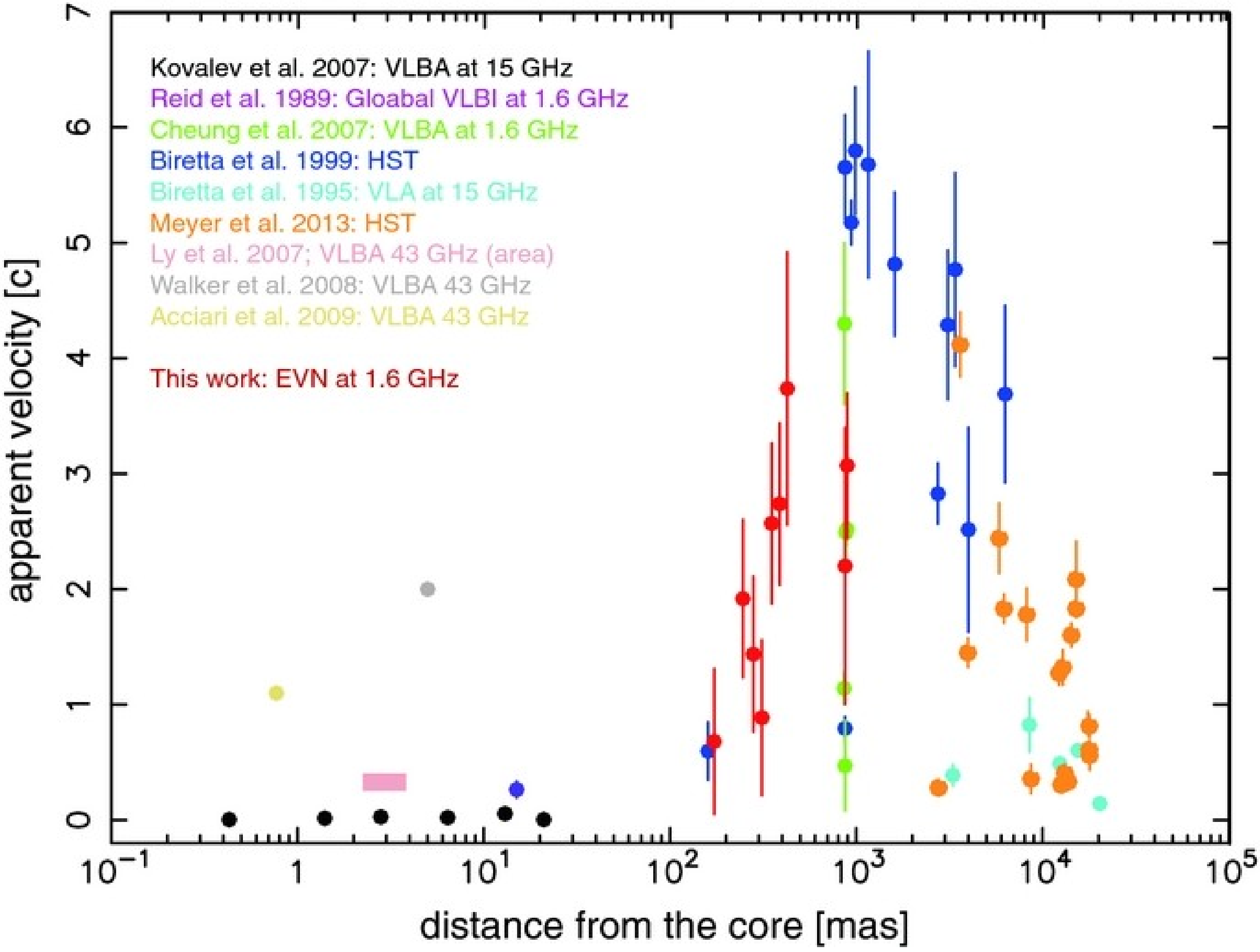
Longitudinal



Toroidal

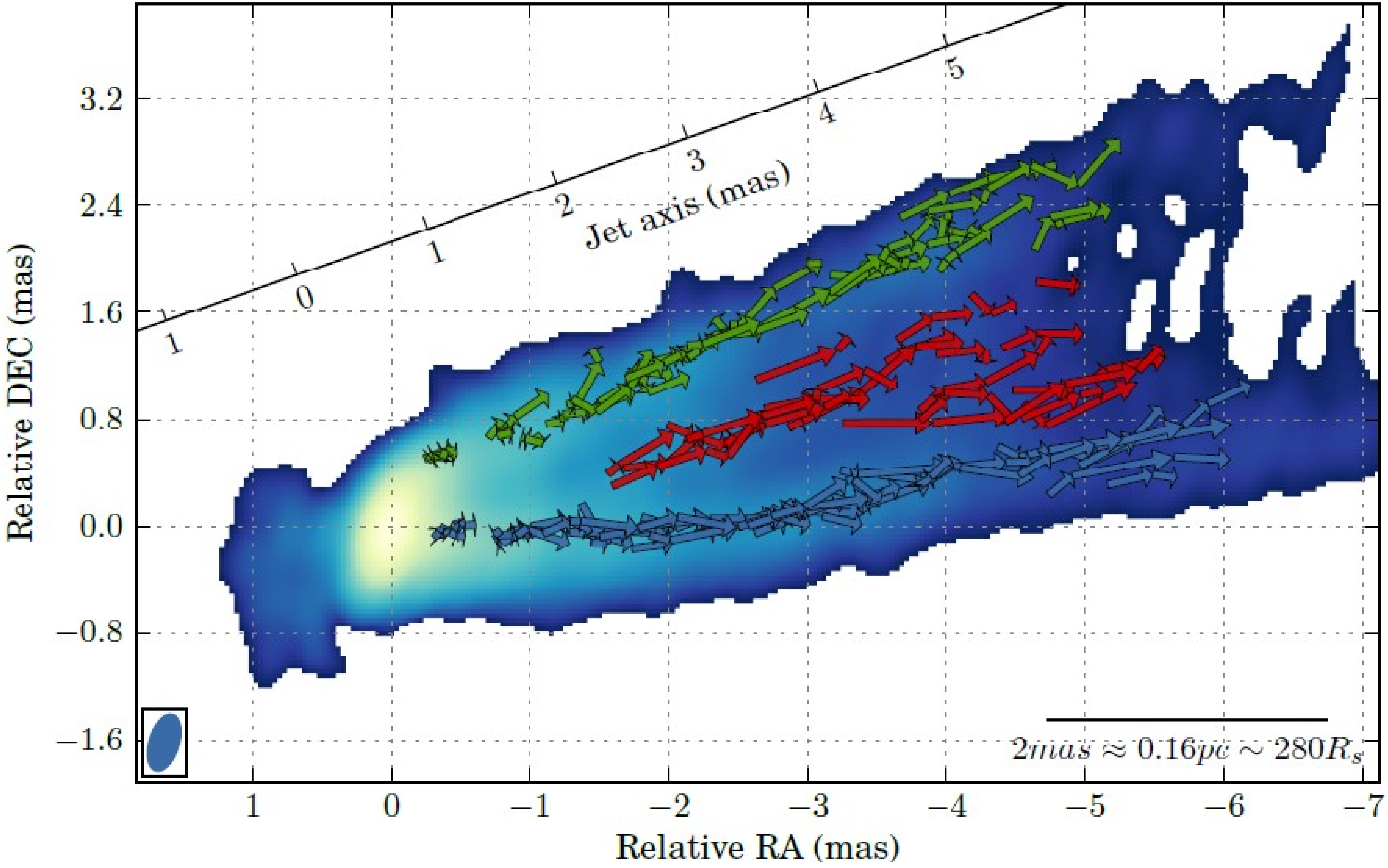


Accelerations and decelerations



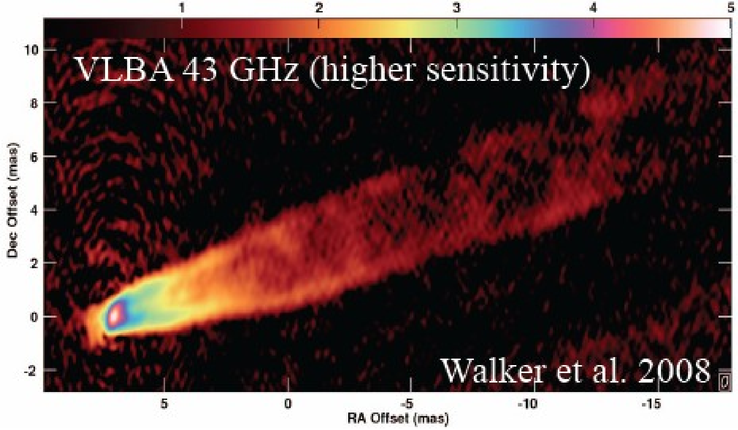
Apparent speeds in M87 (Asada et al. 2014)

But maybe not that simple



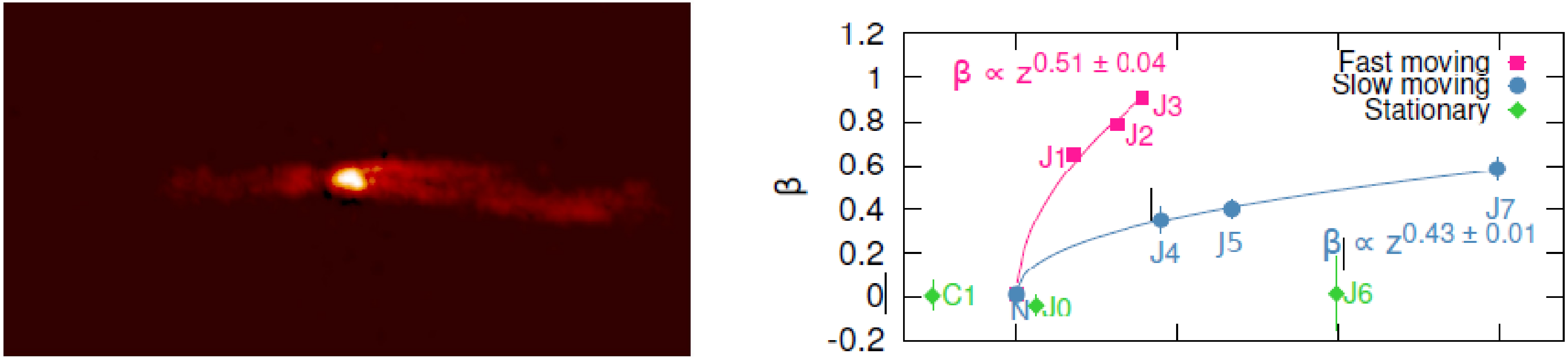
Apparent speeds 0.5 – 2.25c; Mertens & Lobanov (2015)

Transverse gradients: pc scales


VLBA 43 GHz (higher sensitivity)

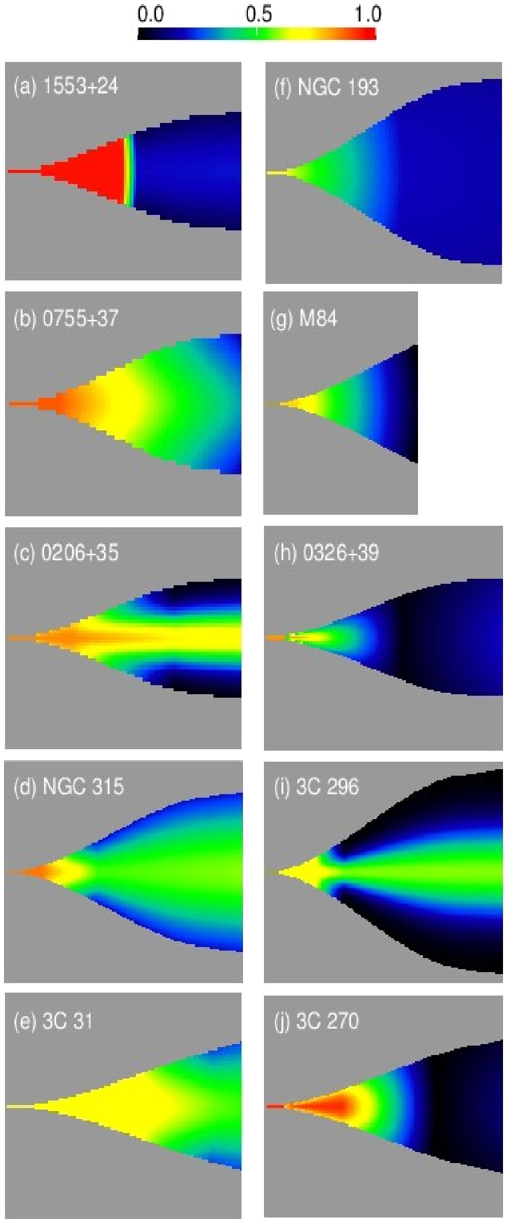
Walker et al. 2008

- 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

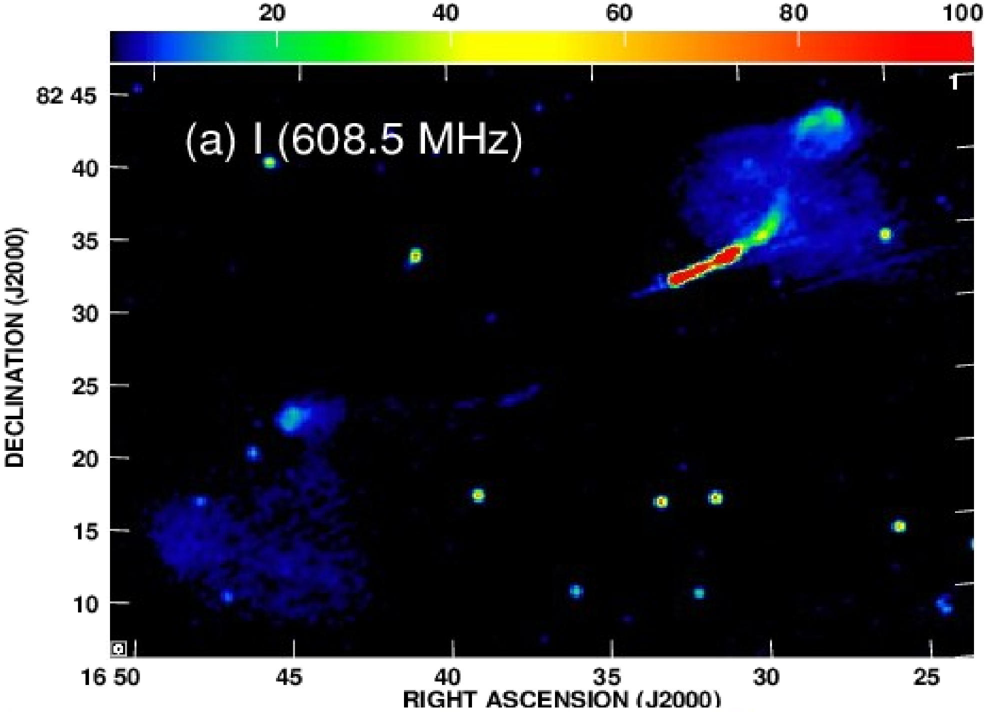
Development of smooth (quasi-Gaussian) transverse velocity profiles.

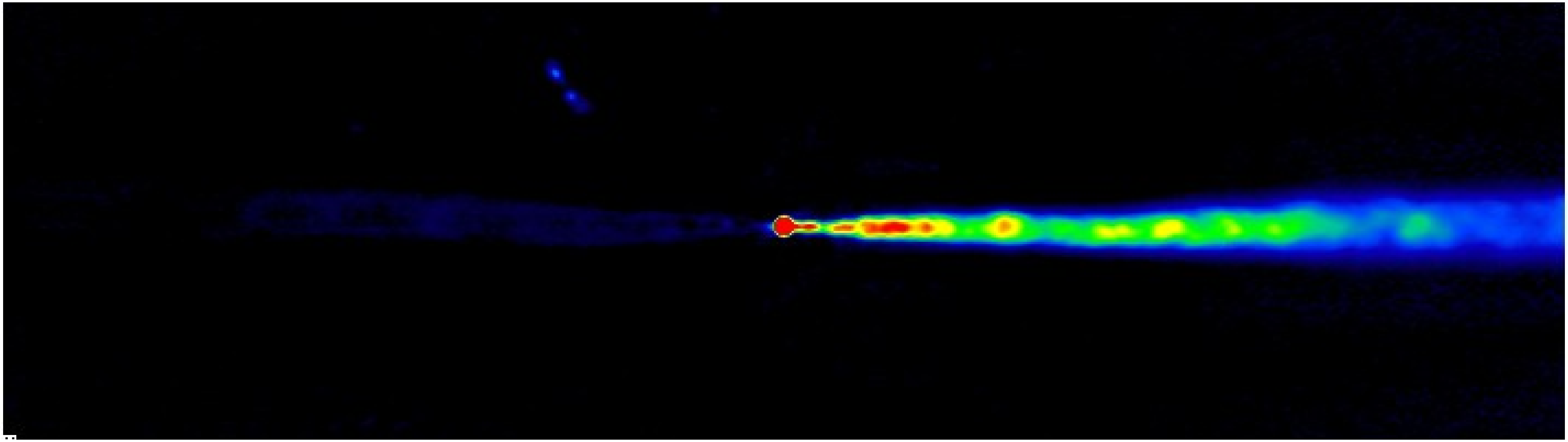
Boundary-layer entrainment

Velocities: questions

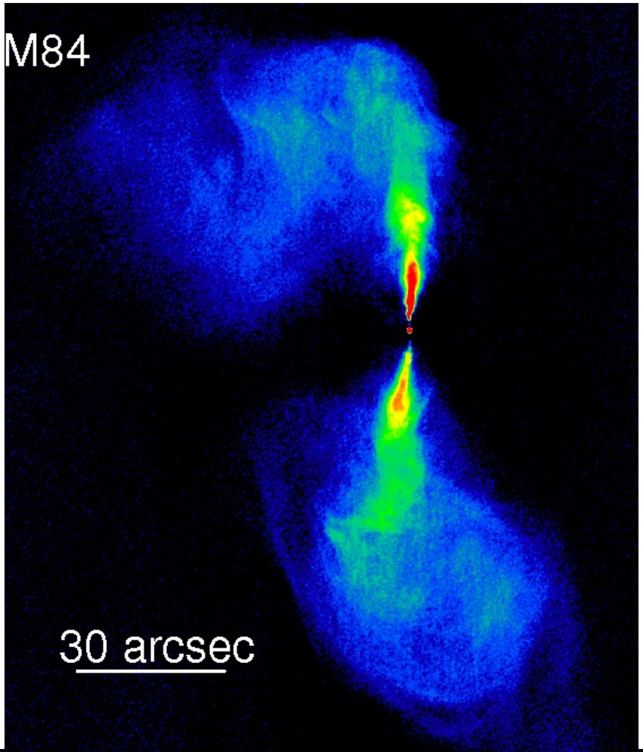
- What are we measuring with proper motions?
  - components moving with the flow?
  - or at some other speed?
  - stationary features (e.g. shocks)?
- Is there bulk acceleration on pc scales, or are we seeing material entrained into a faster flow?
- How fast are FRII jets on kpc scales?

A transition case

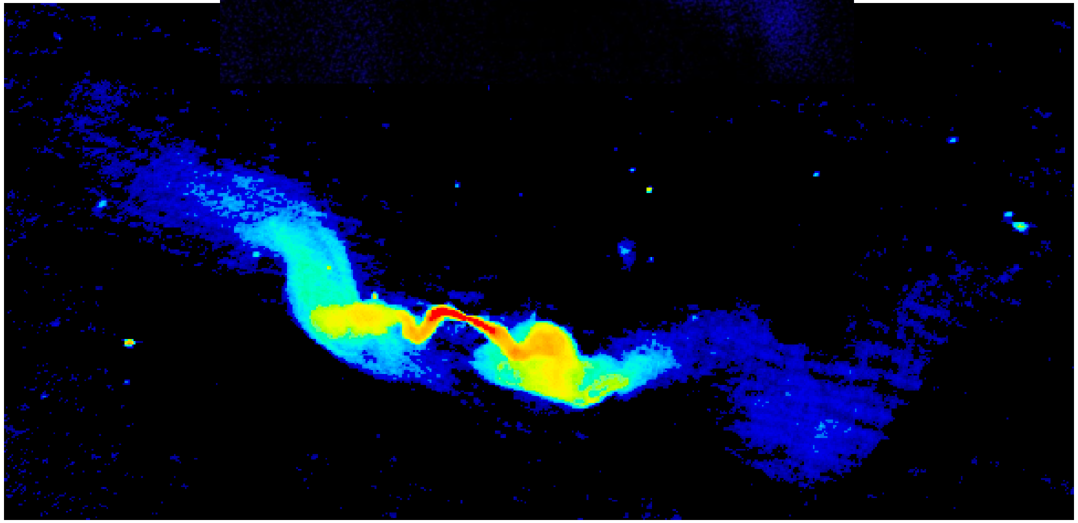


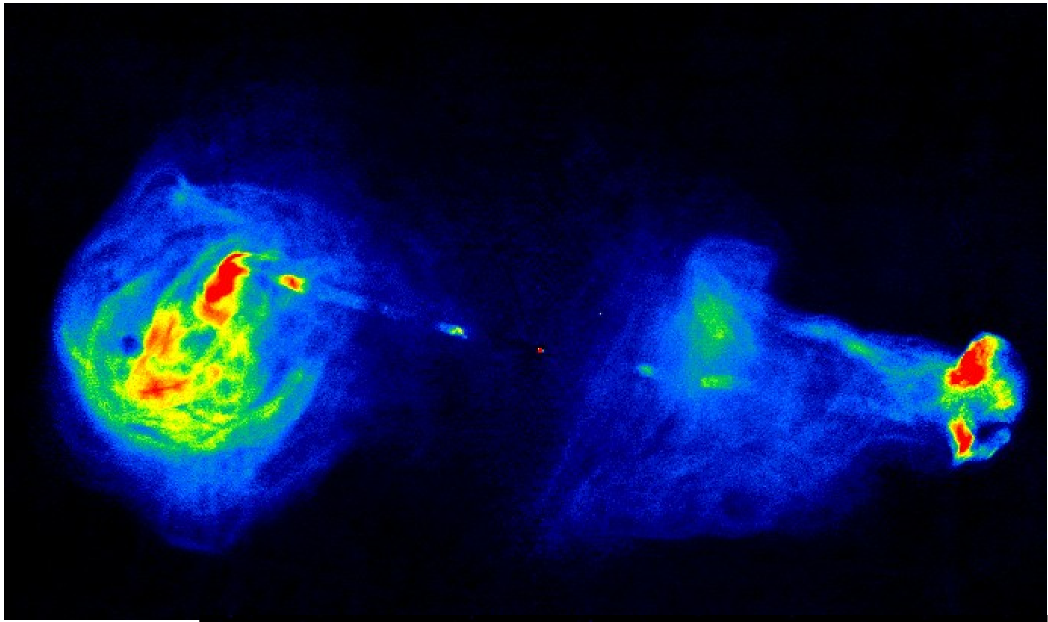


The Fanaroff-Riley Division

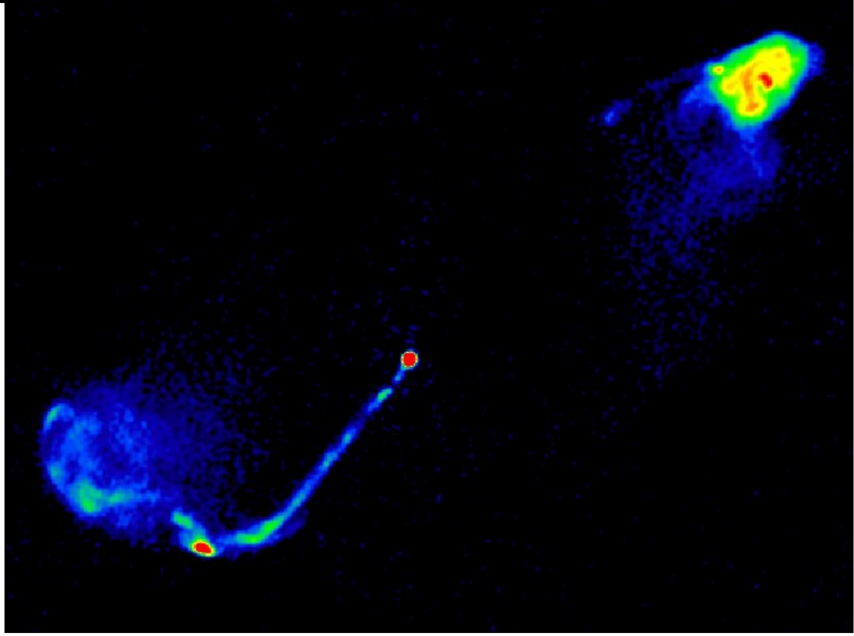


FRI

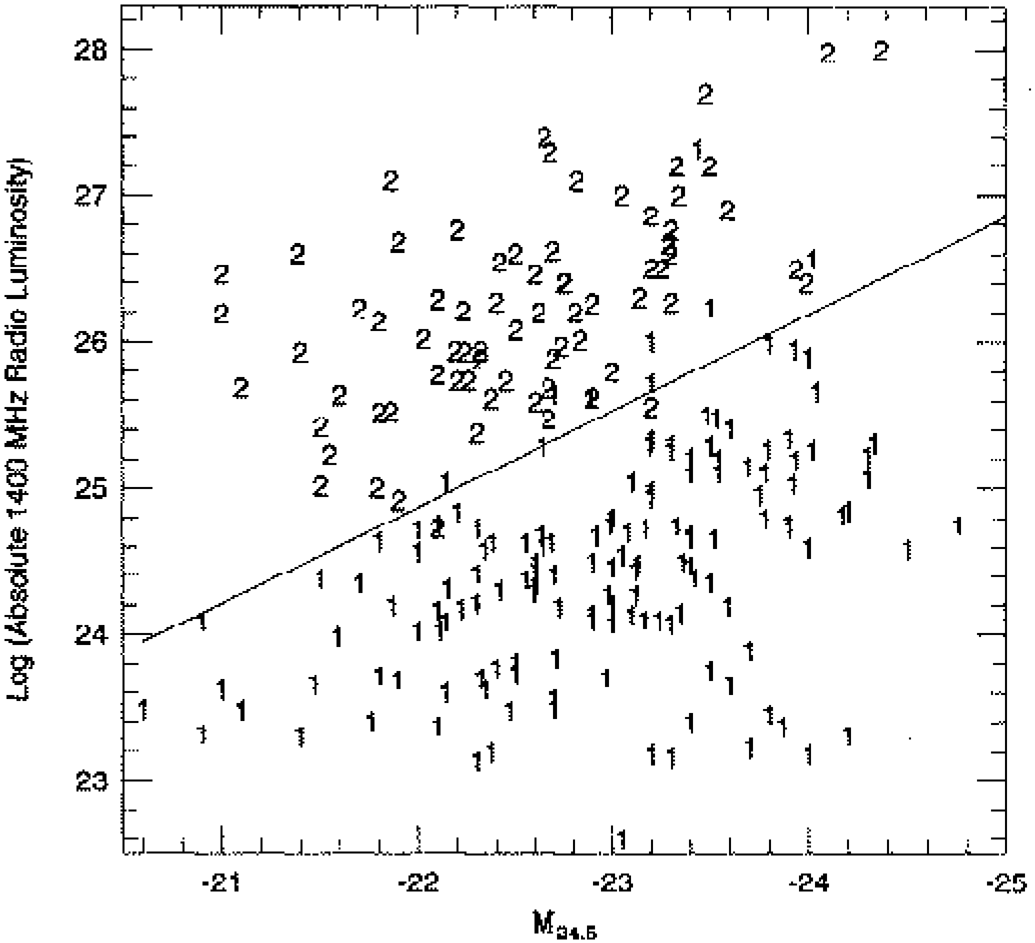


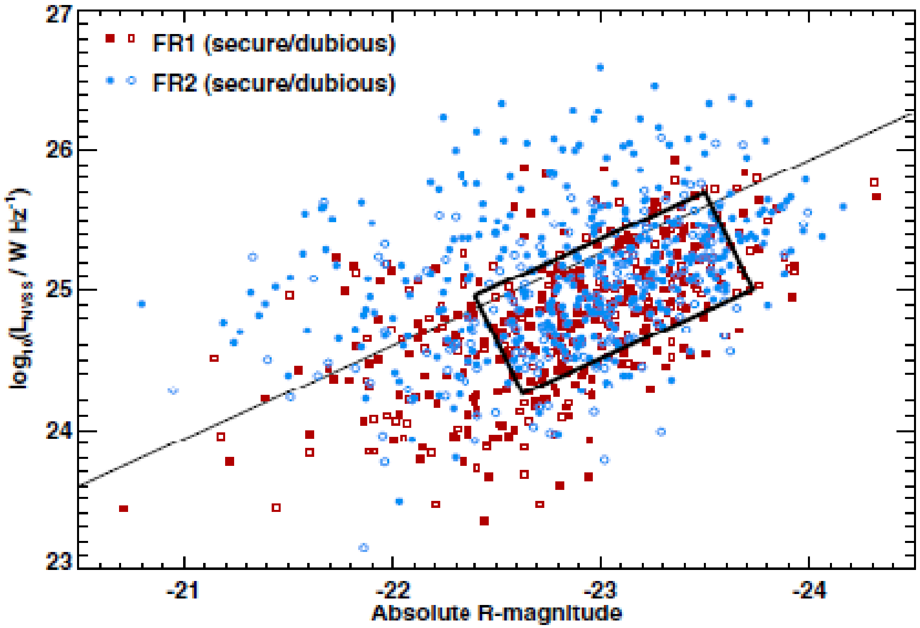


FRII



FR Division and Environment

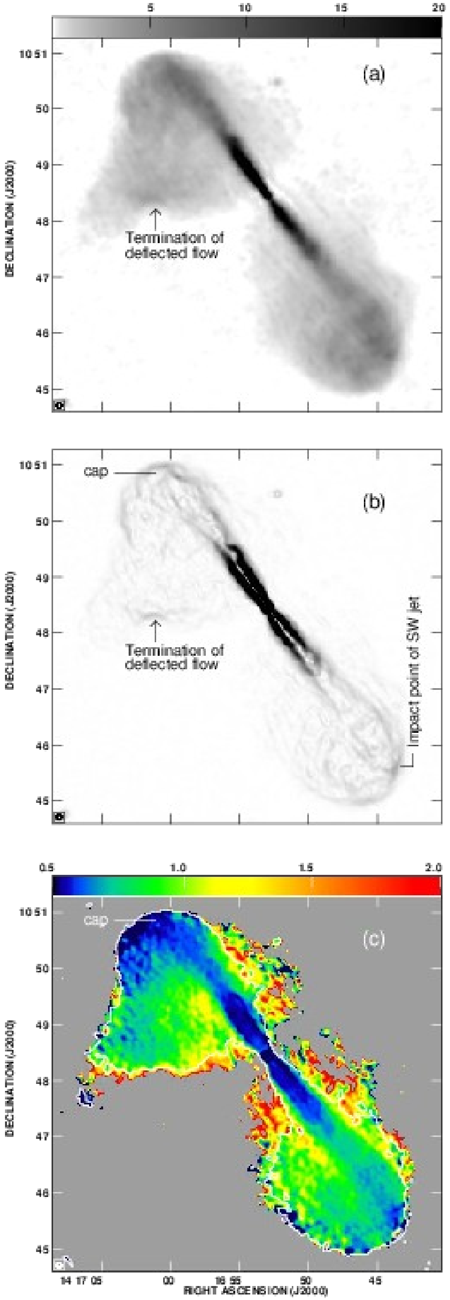




Ledlow & Owen (1996)
Heterogeneous

Best (2009)
SDSS/FIRST/NVSS

Lobes and Spectral Gradients



FRI radio galaxy 3C296

Lobes, not plumes (50% of complete sample)

Spectrum in the lobes steepens towards the nucleus

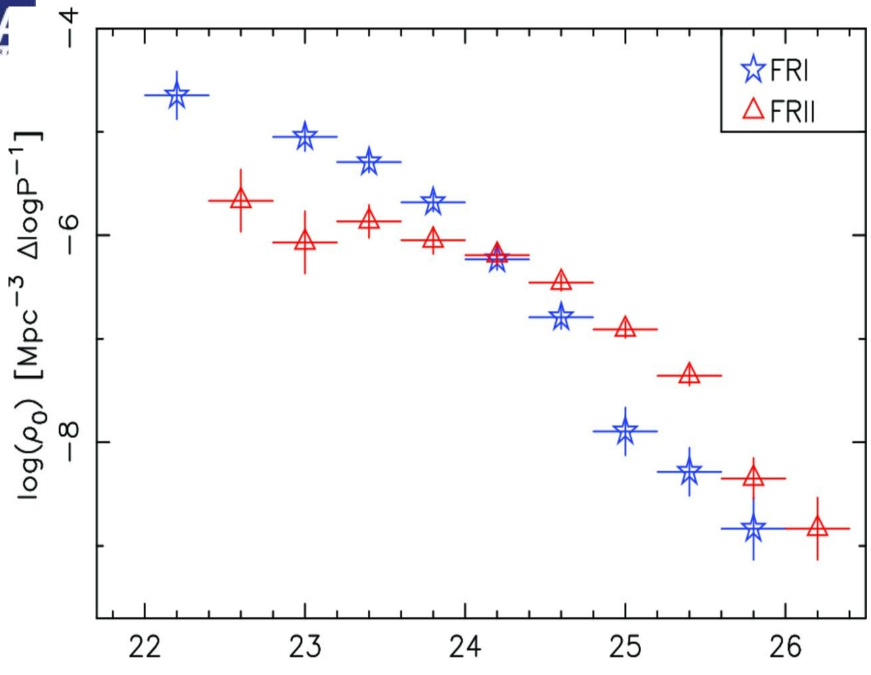
Dynamics of lobe propagation – and hence feedback - likely to be similar in lobed FRI's and FRII's

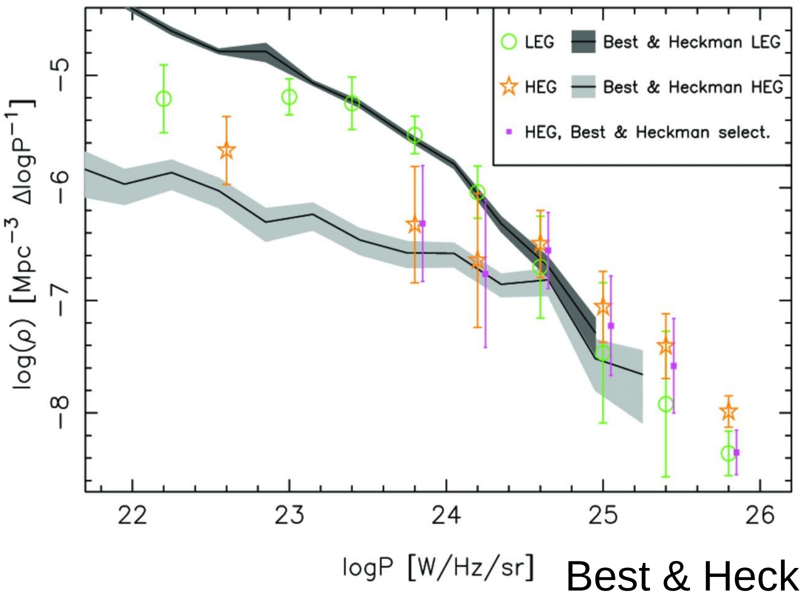
(RL et al. 2011)

What do we know that Bernie did not know in 1974?

- FRI jets are bright close to the nucleus
  - **Entrainment → deceleration → adiabatic compression** (Bicknell)
  - **Particle acceleration is required**
  - **Now have reasonable estimates of power, speed, density, ..**
- FRII jets are **relativistic** and do not decelerate on kpc scales
  - But how relativistic – spine/shear layer again?
- Does the transition just depend on power and external density/pressure?
  - Early attempts:
    - Bicknell (1995): If a jet entrains enough material to decelerate to ~0.1c, then it can only remain collimated if its power is lower than some (environment-dependent) threshold. But what sets the entrainment rate?
    - Gopal Krishna & Wiita (2001). Bow-shock velocity becomes transonic in FRI's. But what about lobed FRI's?

FR and accretion: demographics





Best & Heckman (2012); Gendre et al. (2013)

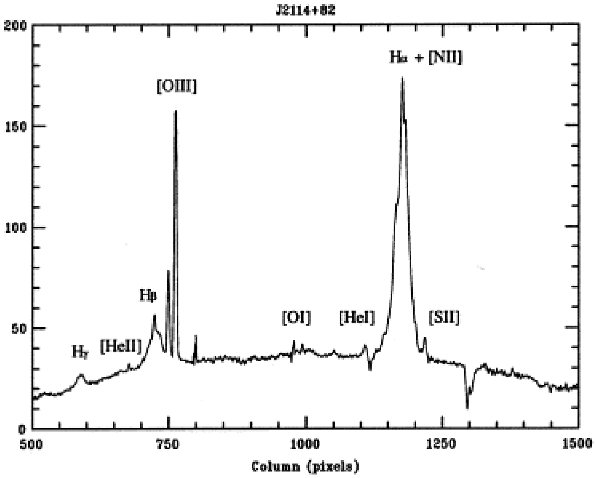
At low powers, the space density of radio galaxies is dominated by FRI LEG's.

Conversely, at very high powers, most sources are FRII HEG's.

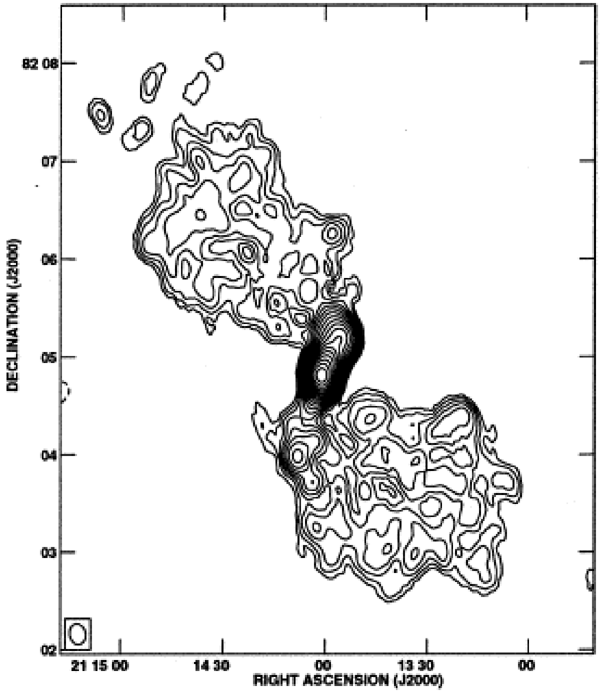
Power at which LEG/HEG and FRI/II have equal space densities locally: $P_{1.4} \approx 10^{26}$ WHz^{-1}

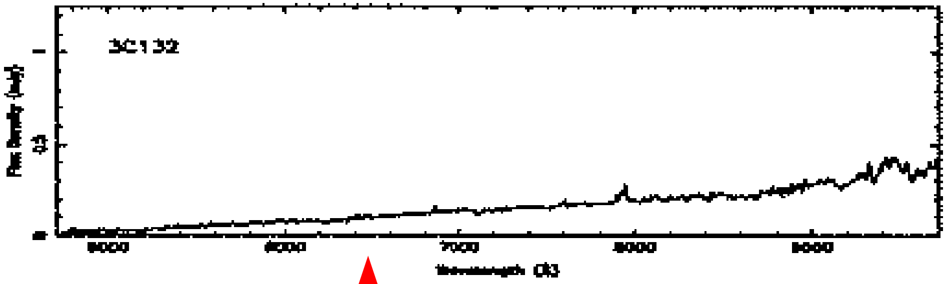
This does **not** mean that all FRI's are HEG's and all FRII's are HEGs.

Examples

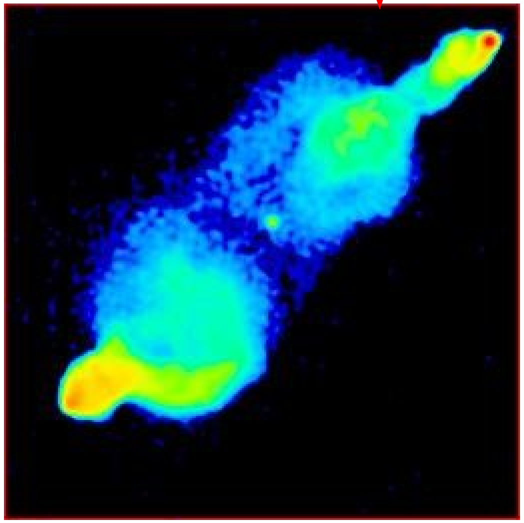


FRI HEG
Lara et al.
(1999)

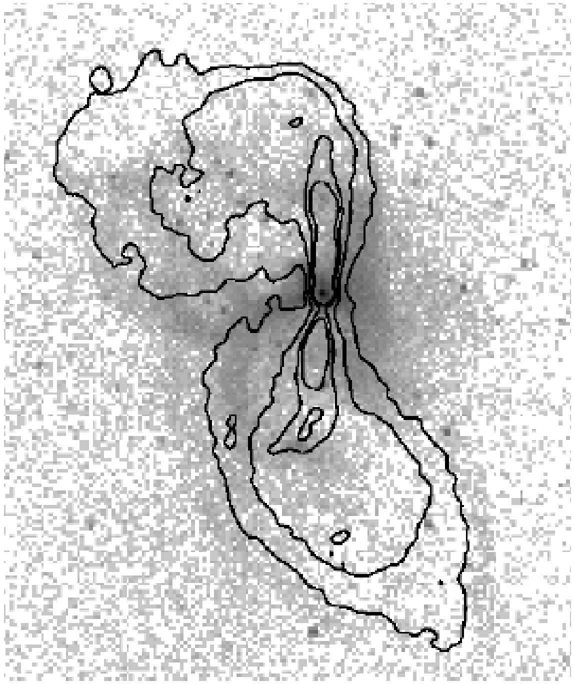


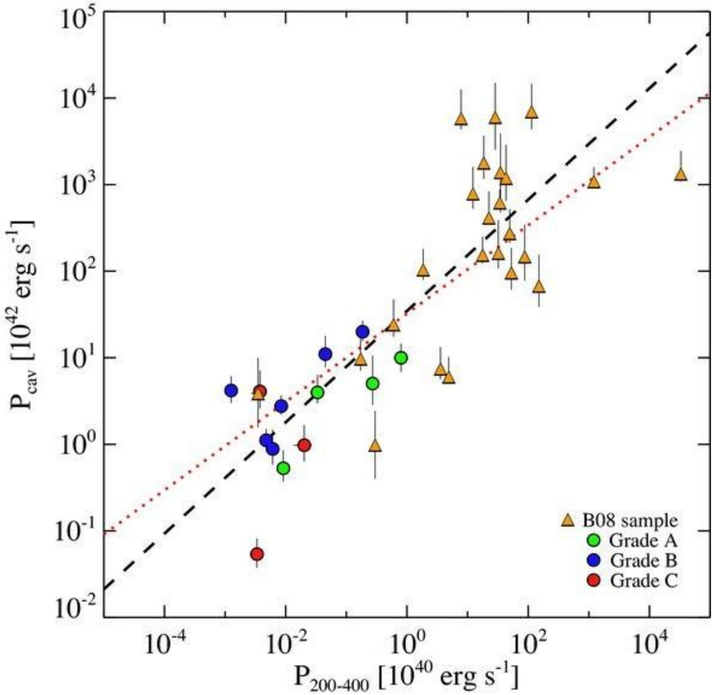


FRII LEG 3C132



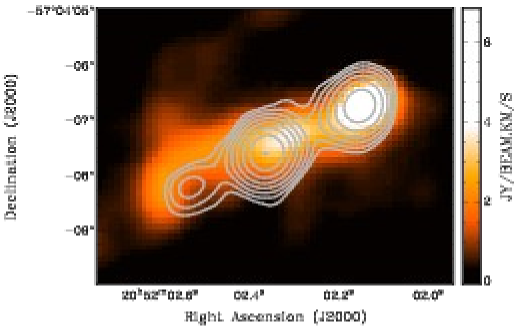
The impact of jets on hot and cold gas

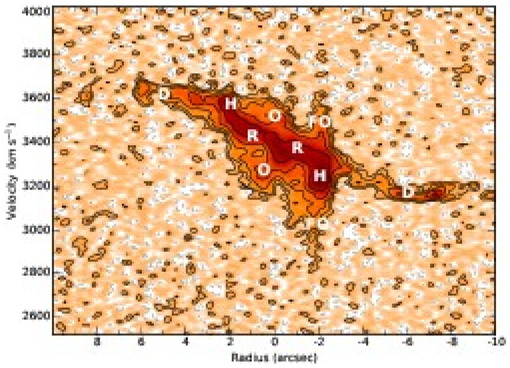




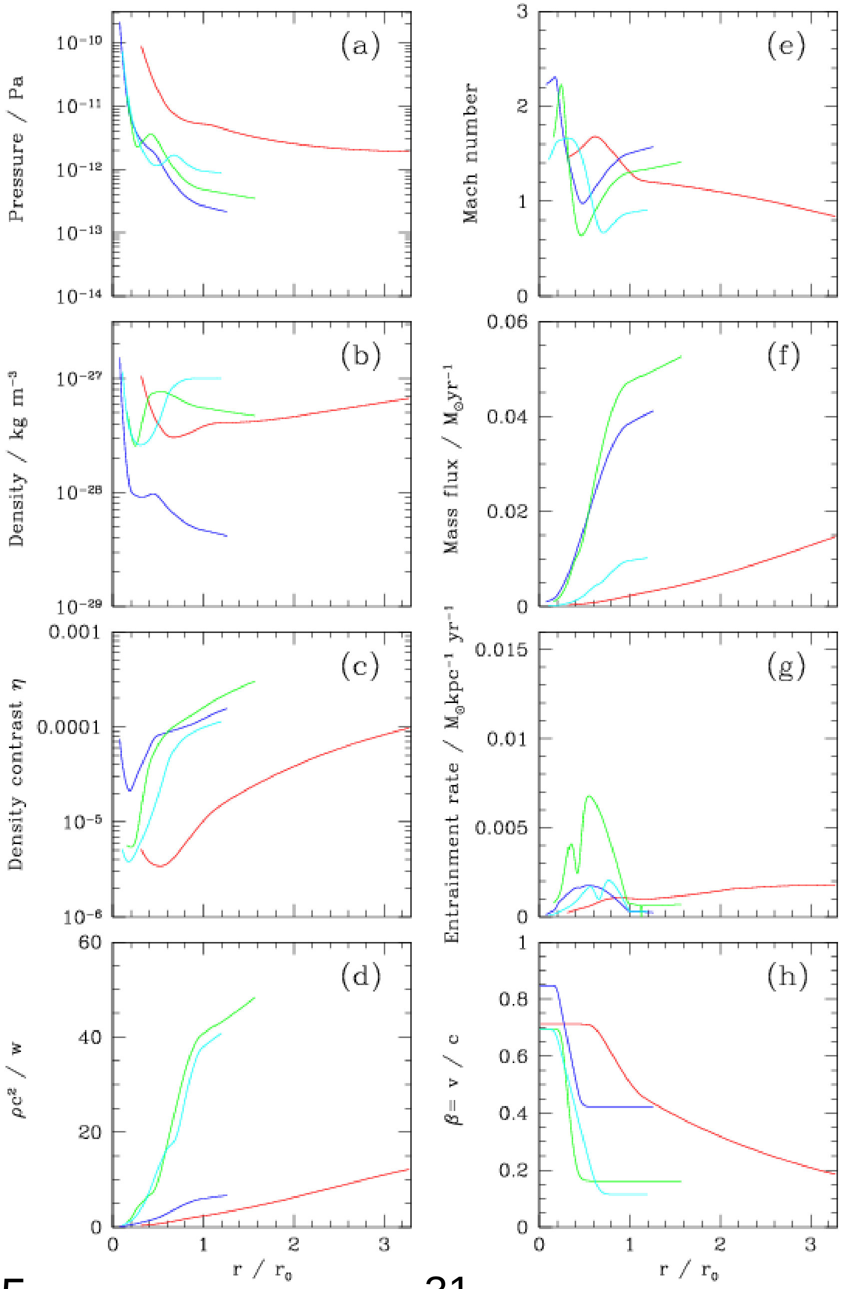
M84 (Finoguenov et al.; Hydra A (Mcnamara etal.); Cavagnolo et al.

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





Jet entrainment



3C31, NGC315,

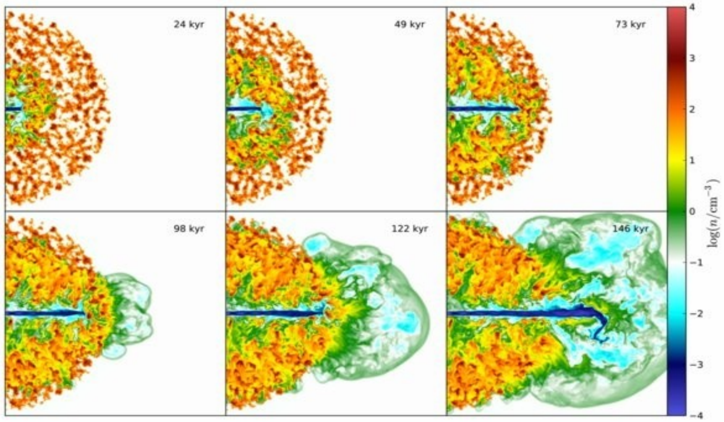
3C296, B2 0326+39

Velocity fits from Laing & Bridle (2014) Conservation-law analysis following Laing & Bridle (2002)

Jets in a multiphase medium

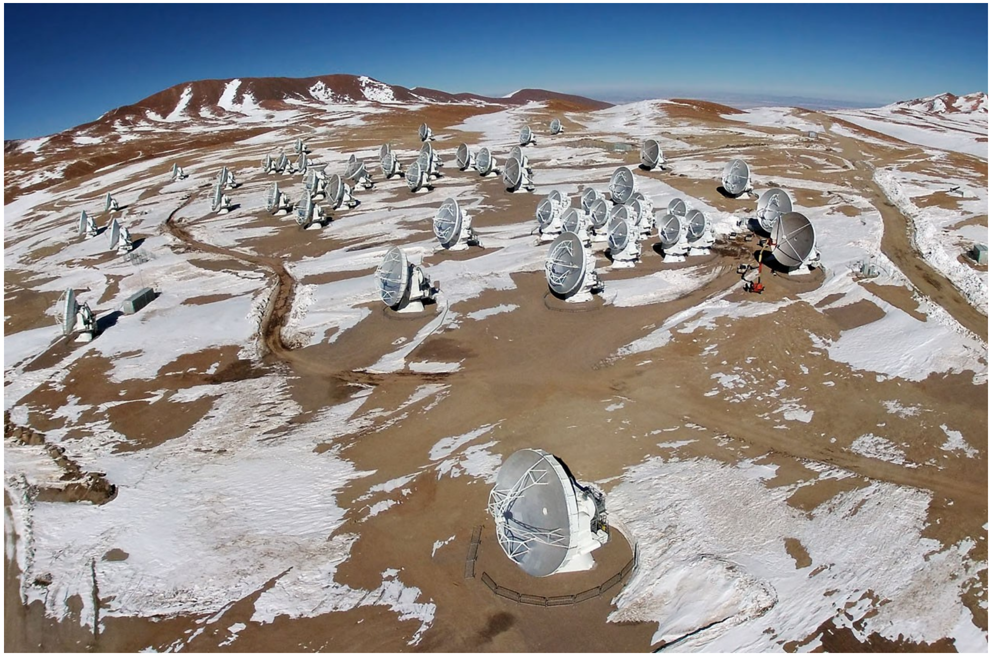
- Hot gas
  - Displace
  - Shock (usually low M, but cf. Cen A; Croston et al.)
  - Entrainment and heating? May be dominant pressure term.
- Cold molecular gas
  - Can dominate the mass outflow (10-30 M_{Sun}/yr in IC5063)
  - Probably cooling behind shock
  - Energy budget is 0.05 – 0.1 times the jet power: efficient
- Warm molecular gas
- Neutral hydrogen
- Warm ionized gas

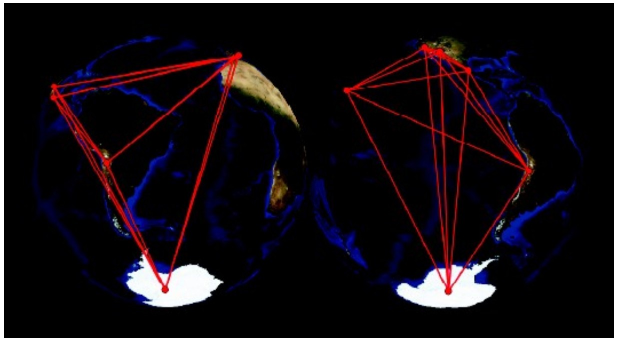
Wagner & Bicknell (2011)



Observations: what next

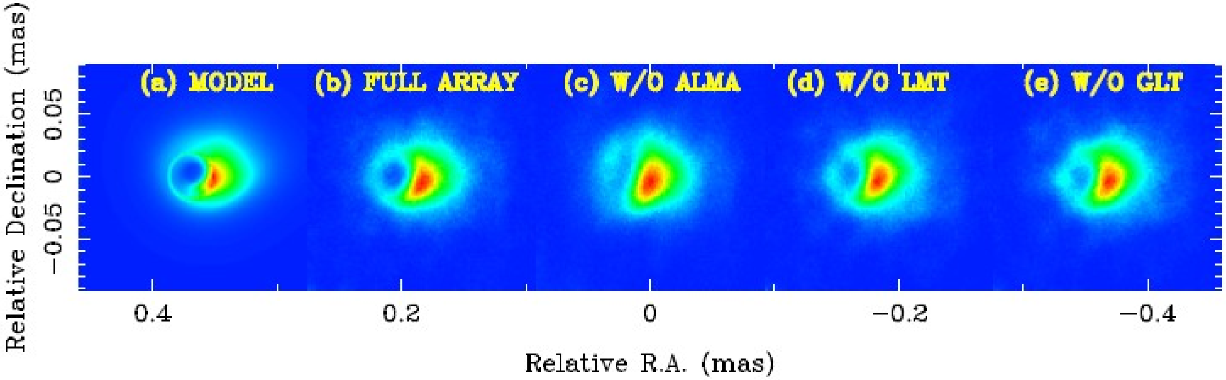
- CTA for TeV gamma rays
- ASTRO-H, JWST, ALMA for inflows and outflows
- SKA (NGVLA)
- X-ray polarimeters
- mmVLBI
  - Phased ALMA
  - If all goes well, offer from Cycle 4 (Oct 2016)





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

Resolution ≈ 20 μarcsec at 230 GHz



Lu et al.
(2014)