AGN research in Bologna

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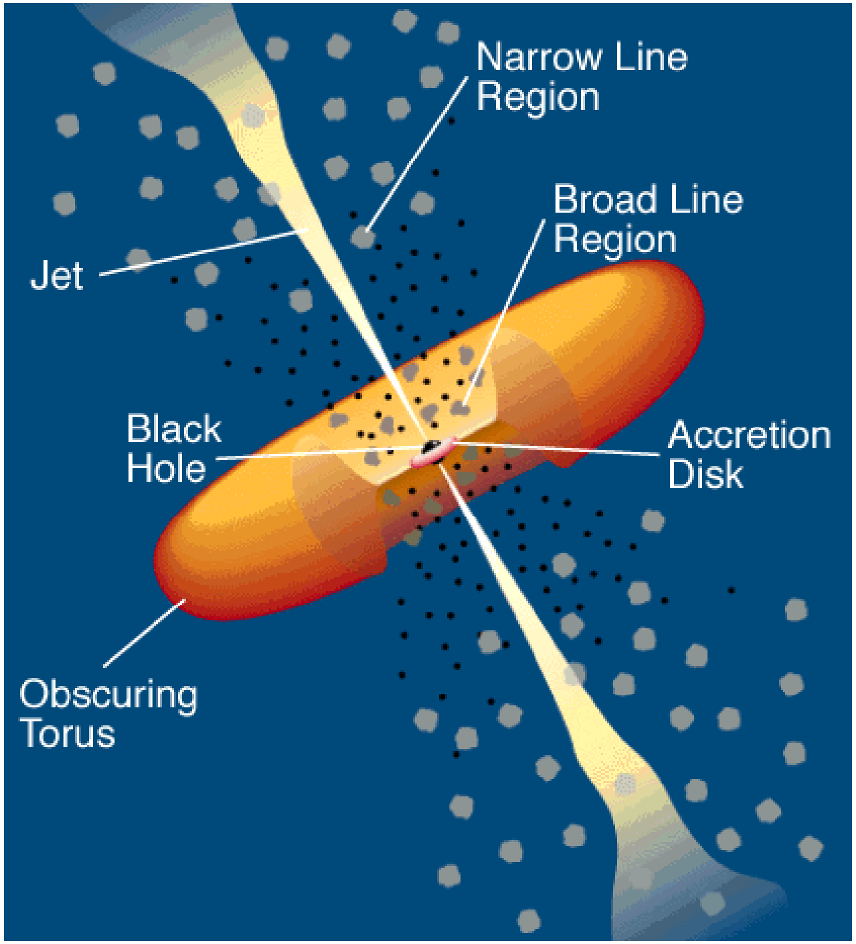
Outline

- Active Galactic Nuclei
  - Galaxy-> Nucleus -> AGN
  - Radio Loud/Radio Quiet dichotomy
- Radio Loud Zoo
  - Kiloparsec scale properties
  - Parsec scale properties, VLBI
  - Unified models

Galaxies and nuclei

- Most galaxies reveal some level of nuclear activity in their central regions. How do we know that?
  - Optical spectroscopy shows broad emission lines
  - X-ray observations from satellites reveal non-thermal continua
  - Radio interferometers image jets emerging from galaxy central regions
  - UV, IR, gamma-ray observations provide further evidence

Basic AGN picture

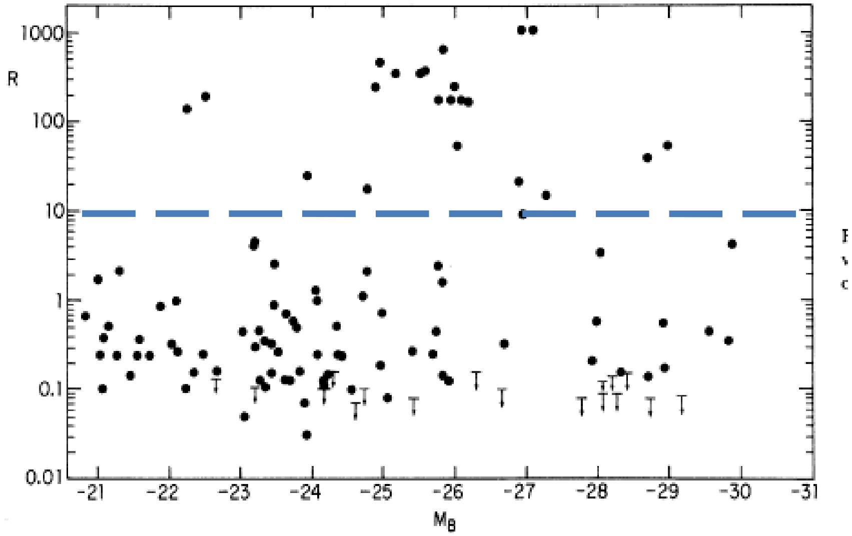


- Disk: optical, UV, X
- NRL, BLR: optical
- Jet: radio to gamma-ray
- Torus: IR
- BH: gravitational waves

- But not all AGNs are equal…

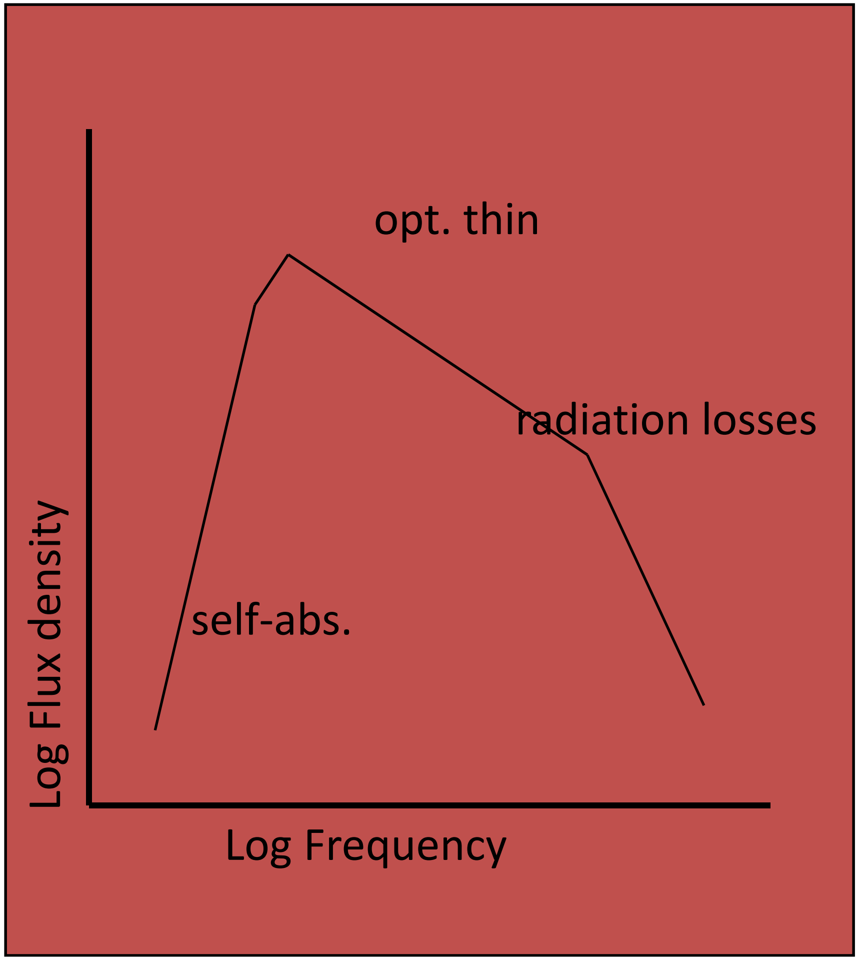
Radio quiet/radio loud dichotomy

- Radio luminosity vs optical magnitude plot reveals a dichotomy
- $R = f_R/f_O$
- R>10, radio loud
- R<10, radio quiet
  - (Kellermann et al. 1989 and many other)
- Radio loud are about 1-10% of all AGN, but their luminosity makes them important



Origin of the radio emission

- $N(E)=N_0E^{-\delta}$
- Electrons emit at a frequency $\nu=4.2\ 10^{-6}\,\gamma^2\,H$
- Electrons with $\gamma=1000$ –> emission at radio wavelengths
- $dE/dt = -bH^2E^2$, $Q(t)=NE^{-\delta}$
- $S(\nu)=$
  - $\nu^{-\alpha}$ if $\nu < \nu^*$
  - $\nu^{-(\alpha+0.5)}$ if $\nu > \nu^*$
- $\nu^*=10^9 \times t^{-2} \times H^{-3}$ (GHz, yr, mG)
  – multifrequency observations constrain ν^*, and allow us to derive t_{spec}



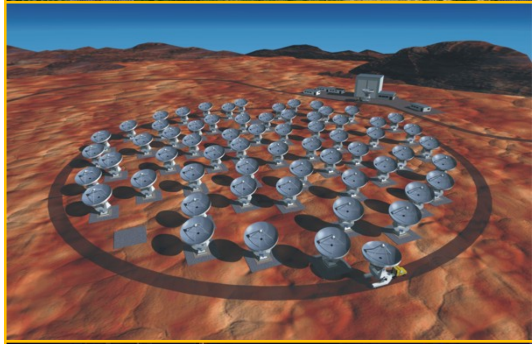
How do we study radio emission?

Today

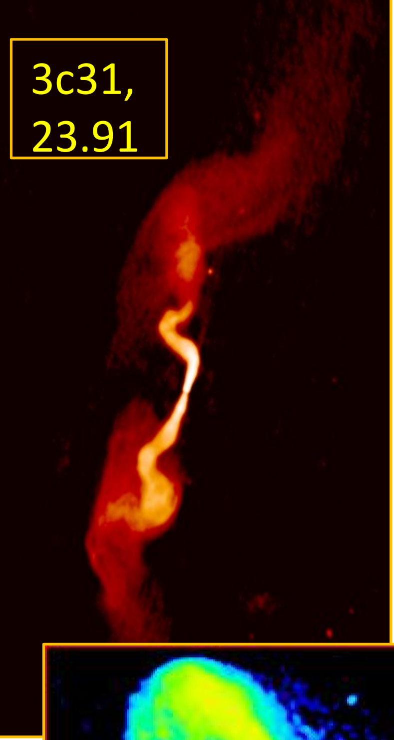
- Single dish at cm to mm wavelengths
  - Medicina, Noto, Effelsberg, Pico Veleta, …
- Linked interferometers
  - VLA, WSRT, PdBI, …
- Very Long Baseline Interferometry
  - EVN, VLBA, LBA, …

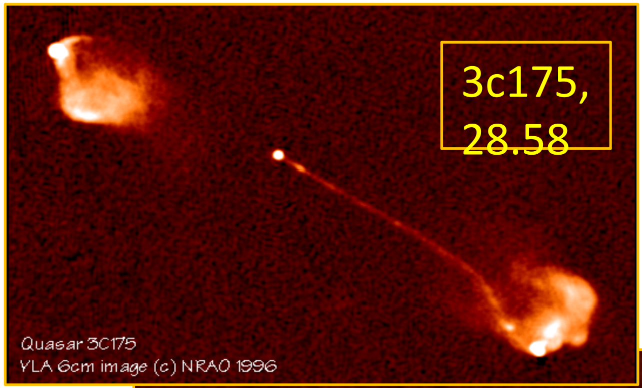
In the future

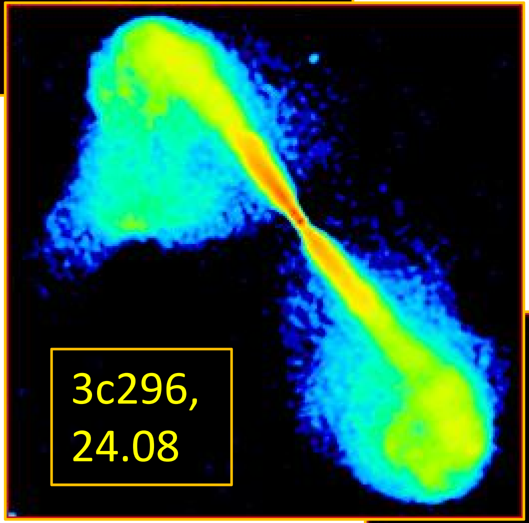
- Upgrade of current instruments
  - E-VLA, e-MERLIN, eVLBI
- New facilities from single dish to space VLBI
  - Sardinia Radio Telescope
  - LOFAR, ALMA
  - VSOP2, Radioastron
- And eventually the SKA…

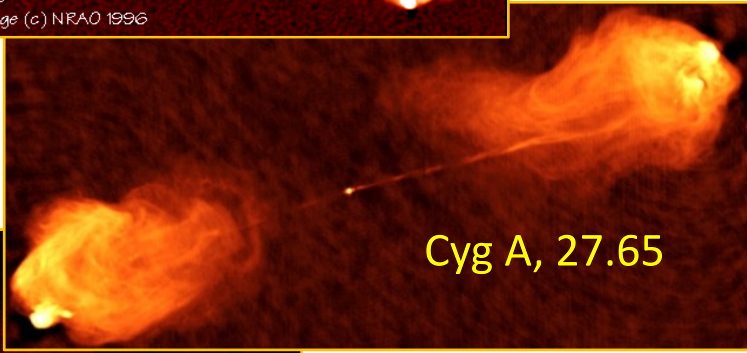


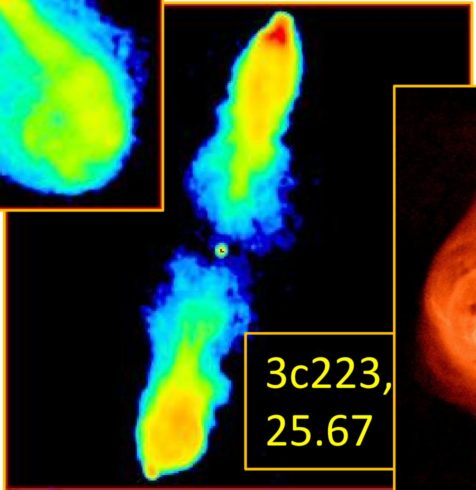
The radio loud zoo

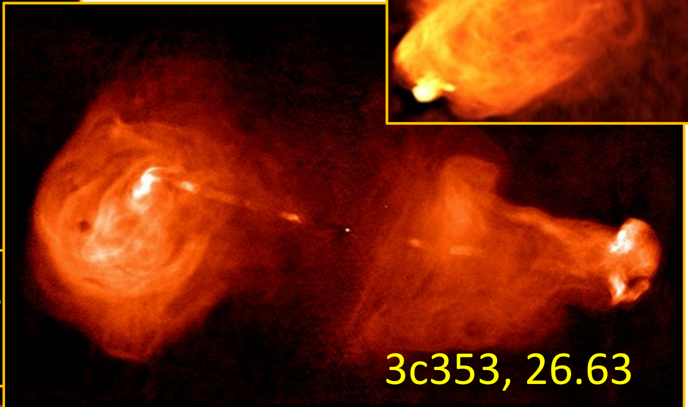








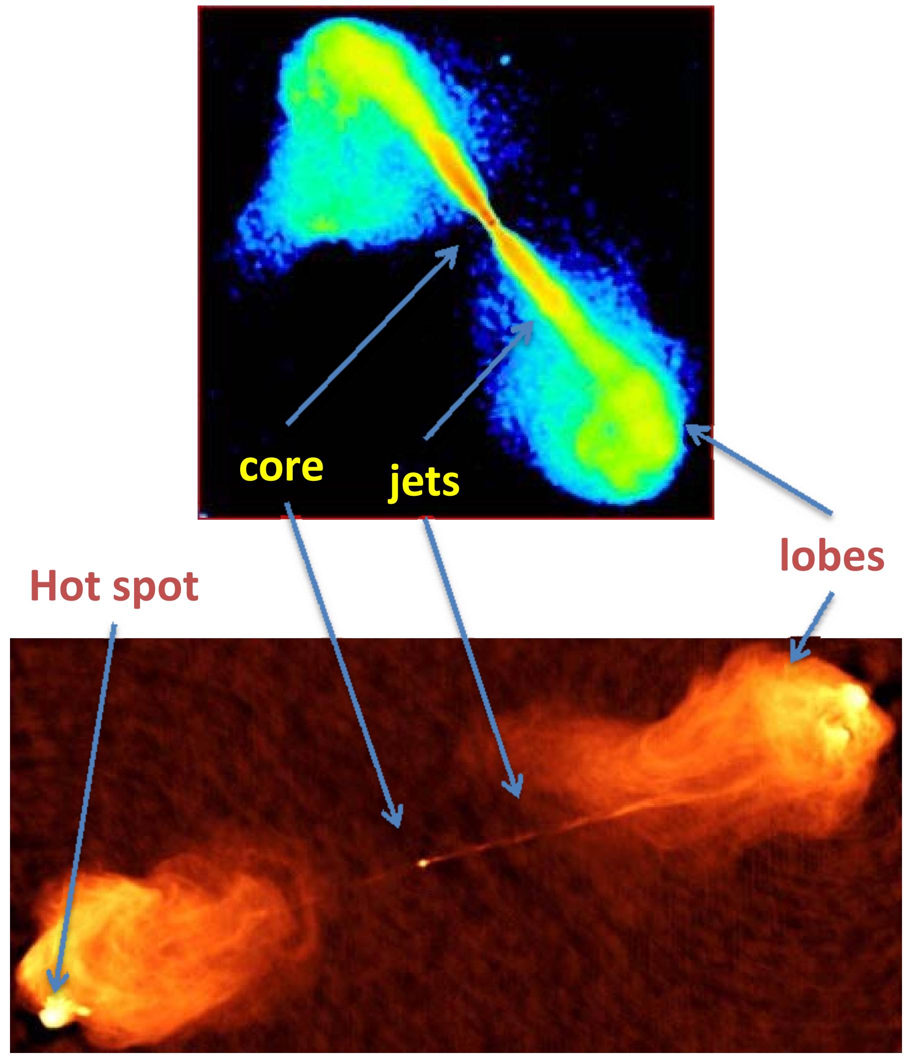




Images courtesy of NRAO/AUI, Atlas of DRAGN, and Dreamworks ®

Radio galaxies

- Morphology:
  – Core: flat spectrum, unresolved
  – Jets: up to several 100’s kpc, steeper spectrum, may contain “knots”
  – Lobes: big amorphous structure, contain “old” particles
  – Hot spots: present in more powerful sources, bright and compact, site of reacceleration



Radio galaxies cont'd

- Typical linear size is some 100's kpc: well beyond host galaxy
  - Giant radio galaxies up to >1 Mpc
  - Compact sources as small as <1 kpc but with same morphology/power
- Host galaxies are typically bright ellipticals
- Radio power is in the range 10^{22}-10^{27} W Hz^{-1}, with a significant threshold at $10^{24.5}$ W Hz^{-1}
  - $L<10^{24.5}$ W Hz^{-1}: edge dimmed, disrupted jets, no hot spots (FR1)
  - $L>10^{24.5}$ W Hz^{-1}: edge brightened, collimated jets, presence of hot spots (FR2)

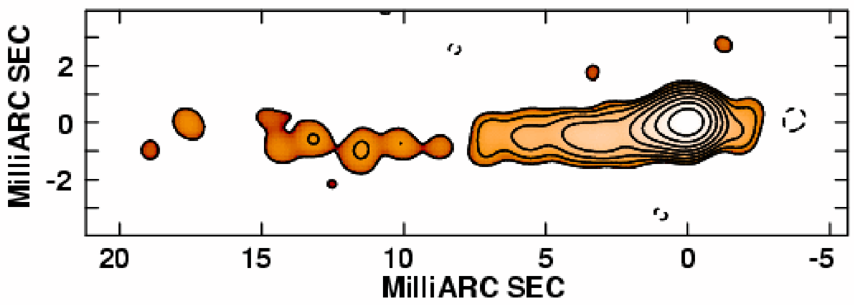
Beyond radio galaxies: blazars

- Not all extragalactic radio sources are radio galaxies – powerful radio sources can also:
  - Be associated to QSOs, BL Lacs **= blazars**
    - (strong non thermal sources, with or without emission lines)
  - Have flat spectral index, rather than typical steep spectrum
  - Be dominated by compact components, lacking extended lobes
  - Display large variability in short timescales and high energy emission

What's in the engine of RGs?

- RG cores are typically unresolved on arcsecond scale: we need VLBI!
- Bologna Complete Sample:
  - A sample of 95 radio galaxies with VLBI images, suitable for statistical studies (Giovannini et al. 2005)
  - Contains both FR1 and FR2 source (low and high power)
  - No remarkable differences are found on parsec scales!

3C 66B



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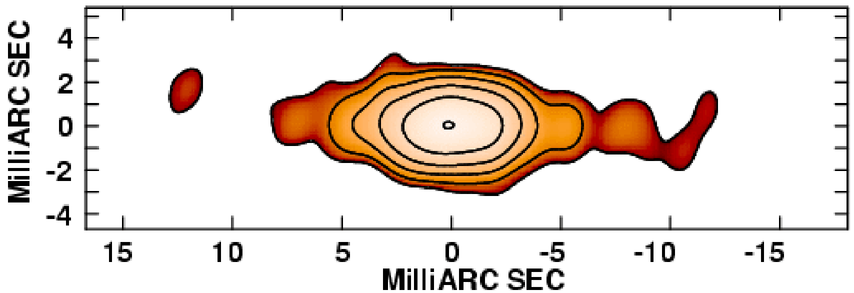
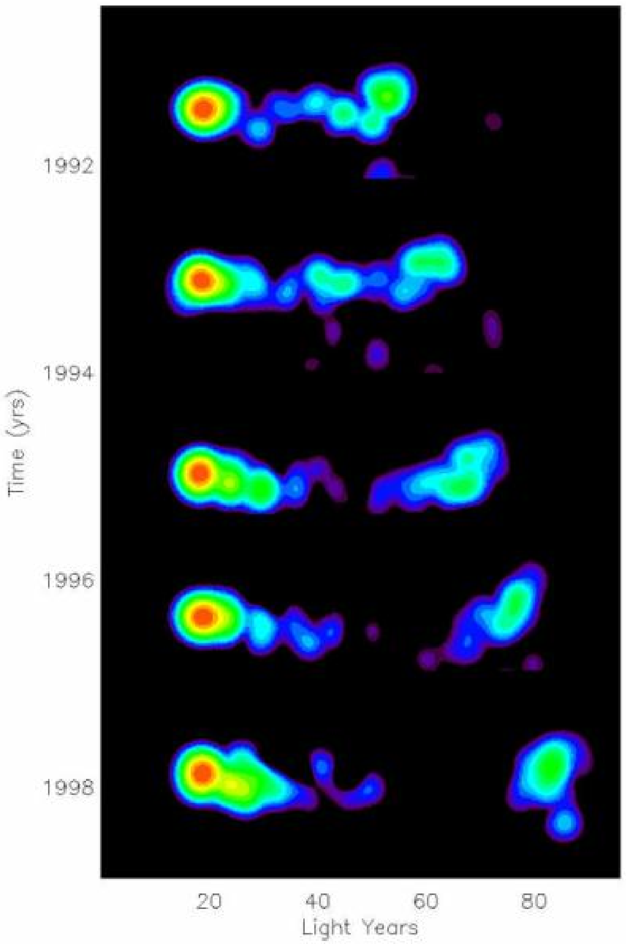


Properties of VLBI cores

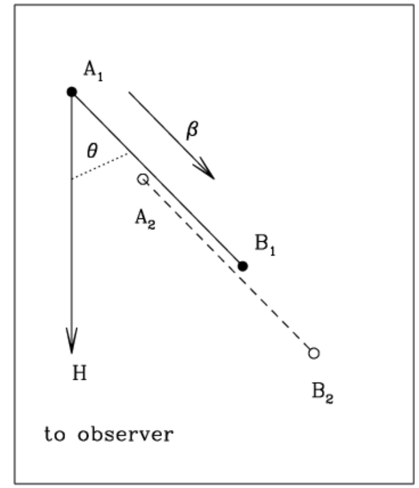
- VLBI observations of cores in radio galaxies and blazars find:
  - More compact components: brightness temperatures beyond inverse Compton catastrophe limit
  - Jets are more frequently one sided than two-sided
  - Jet components move faster than speed of light!!!

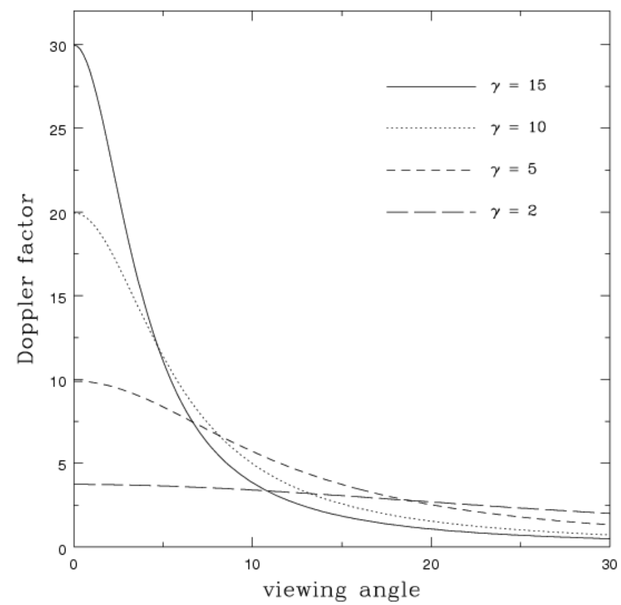


Relativistic effects

- Photons emitted by a fast moving component in a trajectory close to the line of sight "catch up" with ones emitted earlier
  - Radiation beamed towards us gets a boost
  - Radiation emitted in all other directions gets dimmer
  - Beware of the "Doppler factor":

$$\delta = \frac{1}{\gamma(1-\beta\cos\theta)}$$





Doppler factor

$$\delta = \frac{1}{\gamma(1-\beta\cos\theta)}$$

$$B = \delta^{2+\alpha} B'$$

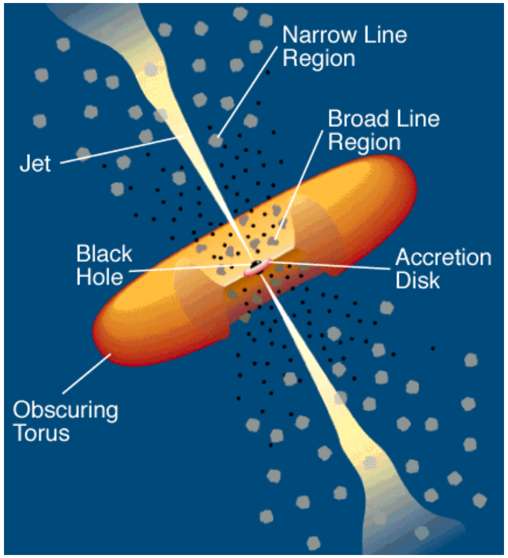
$$\beta_{app} = \frac{\beta\sin\theta}{1-\beta\cos\theta}$$

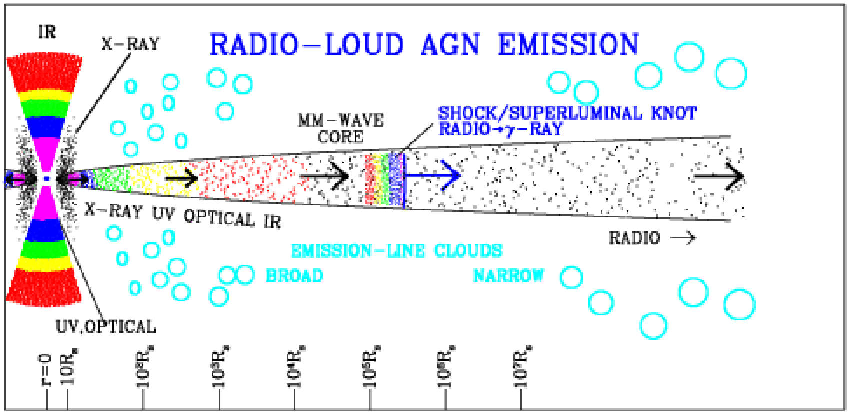
$$R_{jet/cjet} = \left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^{2+\alpha}$$

- Main effects of Doppler beaming:
  - Large jet/counterjet ratio, one-sided jets
  - Superluminal motions
  - Larger number of sources viewed on-axis
  - Short-term variability
  - High-energy Inverse Compton radiation

Unified models

- Doppler beaming can reconcile most differences between various radio beasts!
- If we are interested in how jets are formed – and we are! – we have to look to blazar (small viewing angle, large Doppler beaming)

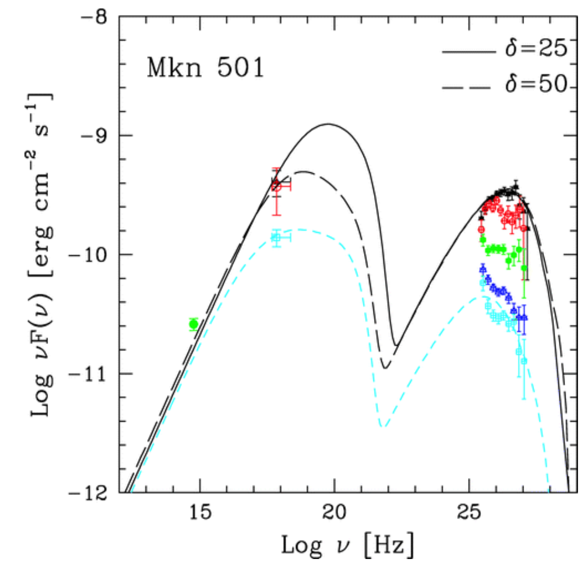




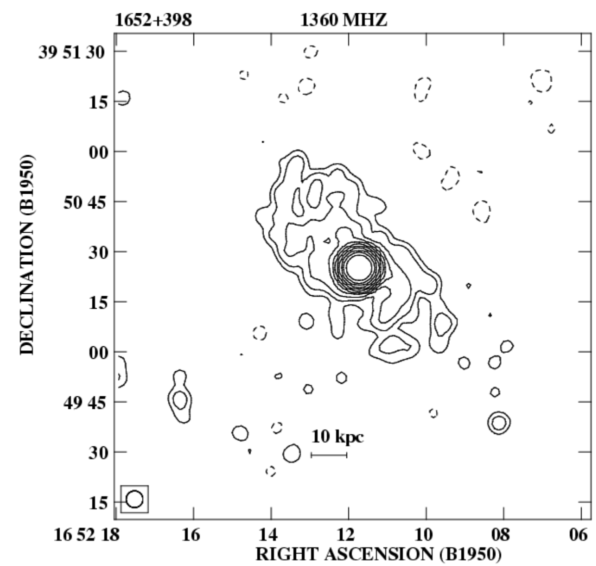
courtesy of A. Marscher

Markarian 501

- A radio source associated to a BL Lacs like object at z=0.034
  - detected across all the electromagnetic spectrum
  - A bright radio source ($S_{5\ \mathrm{GHz}}$ = 1 Jy)
  - Flat spectrum, compact, core dominated
  - two sided in VLA images, a nice one sided, twisting parsec scale jet



Albert et al. 2007



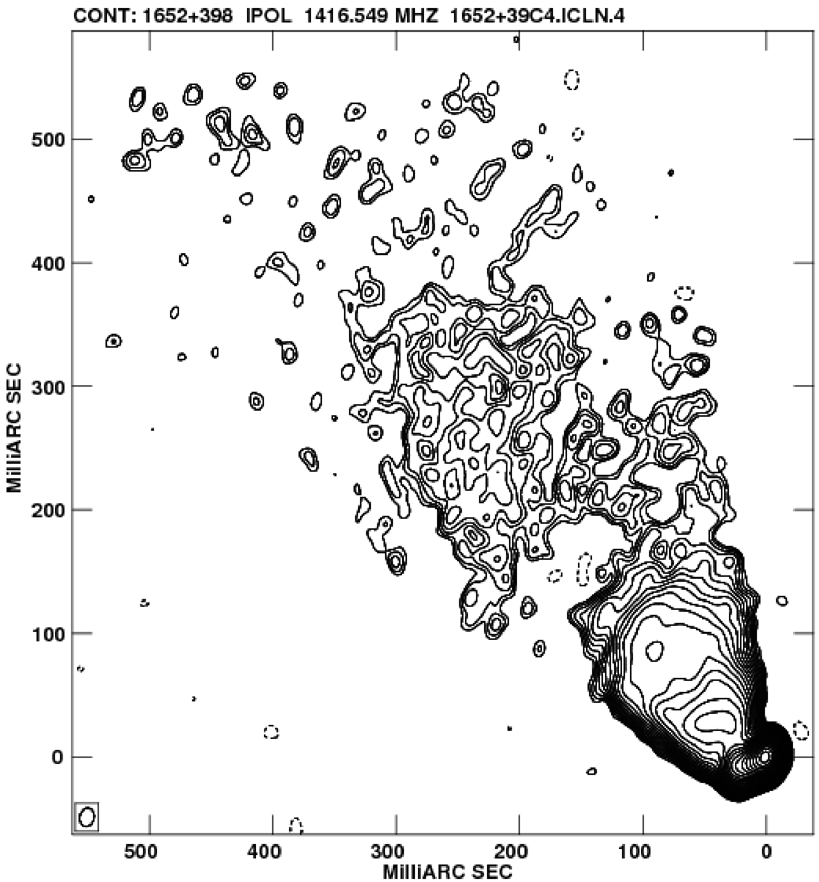
Cassaro et al. 1999

High Sensitivity Array observations

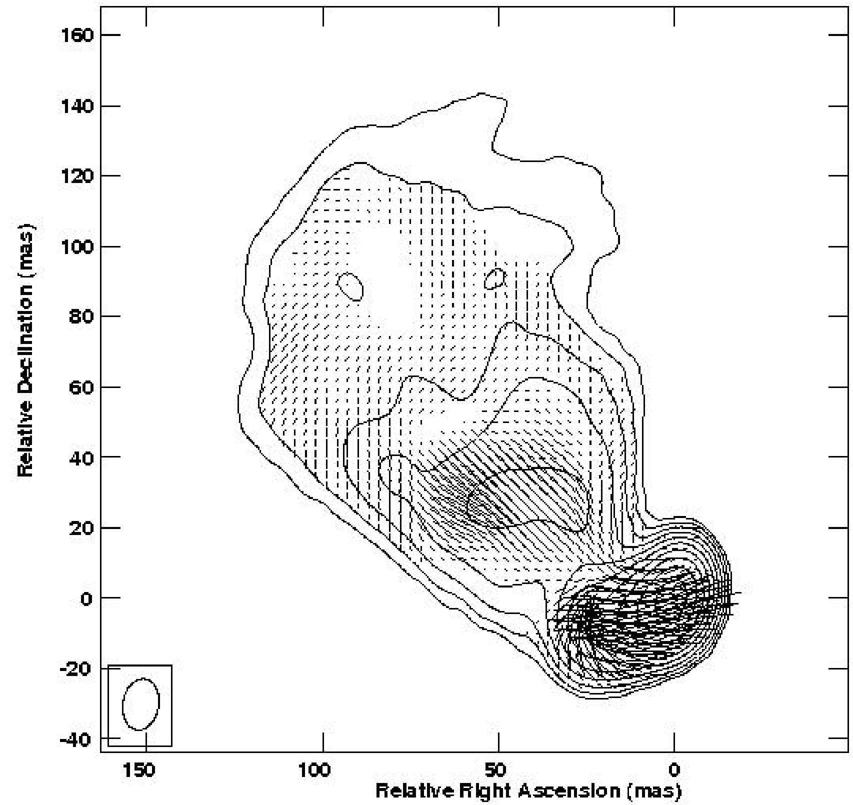
- The High Sensitivity Array:
  - VLBA (10x25m)
  - phased VLA (27x25m)
  - Arecibo (300m)
  - Green Bank (110m)
  - Effelsberg (100m)
  - 7x more sensitive than the VLBA alone!
- Final image parameters:
  - rms noise around 25 μJy beam^{-1}
  - Resolution around 10 mas (HPBW) at 1.6 GHz
  - polarization information available

High sensitivity images

Total intensity

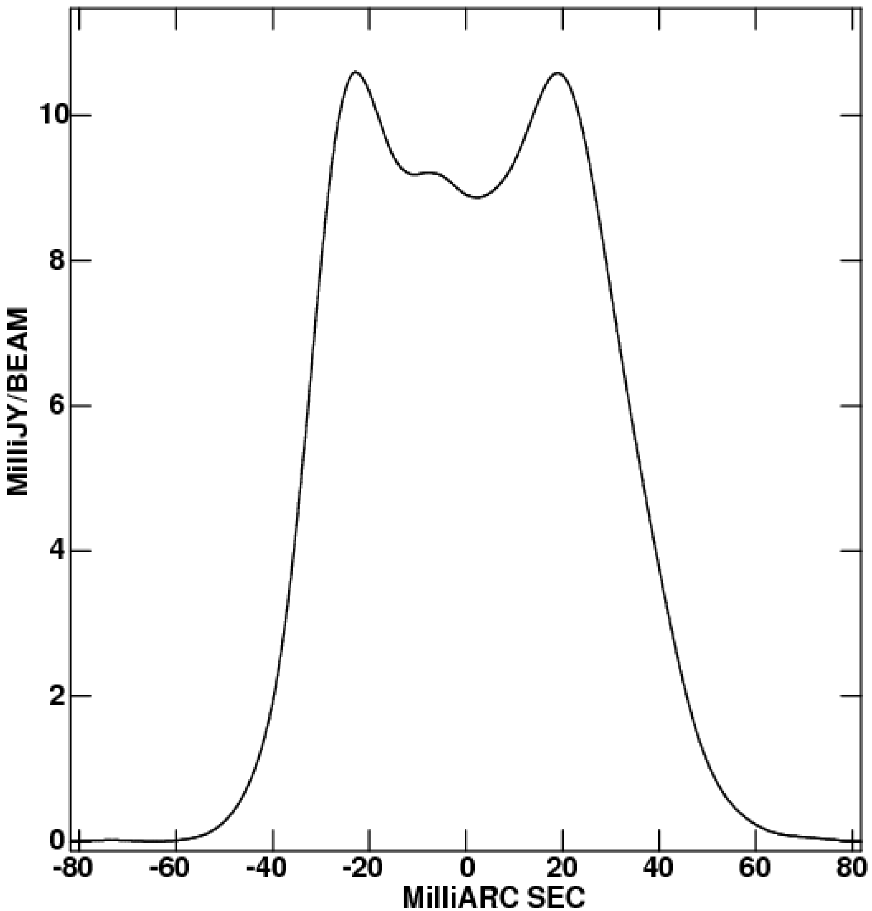


polarization



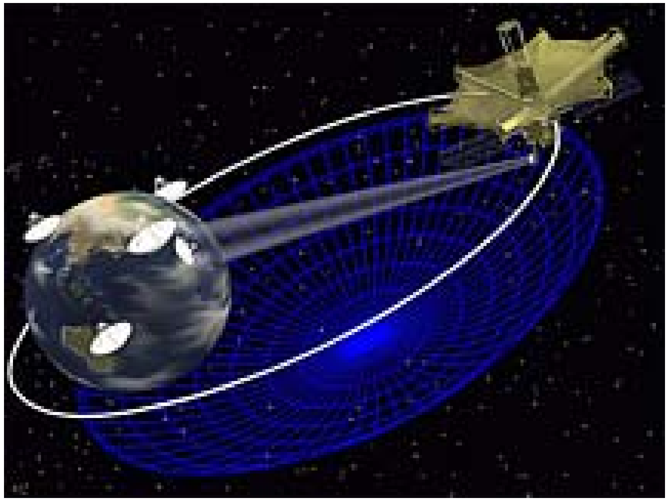
HSA: jet structure

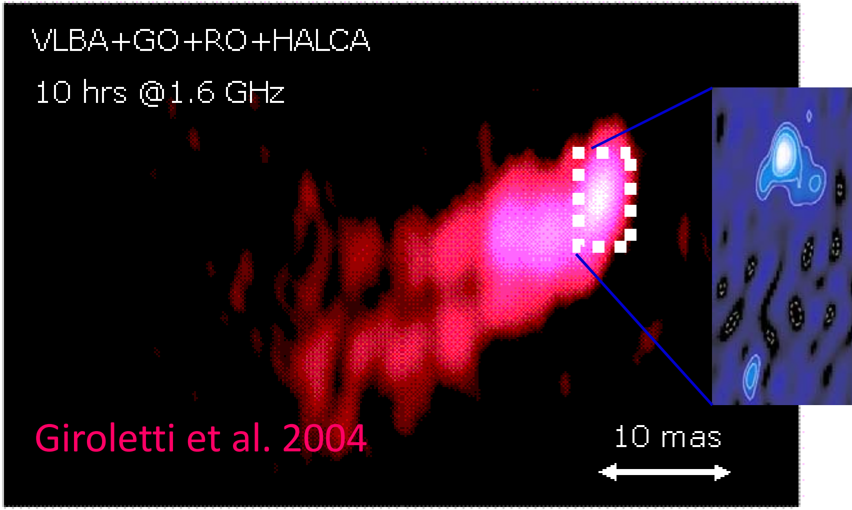
- Total intensity
  - one-sided jet confirms relativistic velocity out to 1” from the core
  - viewing angle θ=10°-15°, Lorentz factor Γ=10, $\delta\sim$2.6
  - slice at 100 mas from core is limb brightened
  - Remember different velocity = different Doppler = different brightness: two velocity regime?
- magnetic field structure
  - polarized intensity as high as 100 mJy/beam
  - organized magnetic field
  - **B** stratified in the inner jet, perpendicular to jet axis after the bend



Approaching the Black Hole

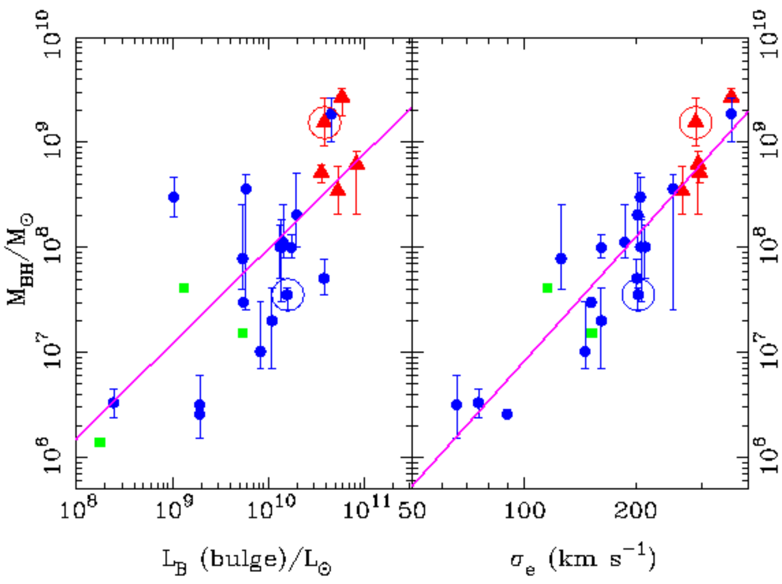
- Resolution is given by $\theta=\lambda/d$
  - Increase d: space baseline (VSOP)
  - Decrease λ: millimeter VLBI (GMVA)
- compact structures are resolved in higher resolution images
- limb brightening clearly revealed by VSOP on 10 mas scale
- GMVA probes 100's Schwarzschild radii scales ($M_{BH}=10^9\ M_{sun}$)
  - Another jet direction change
  - Suggestion of intrinsic of limb brightening





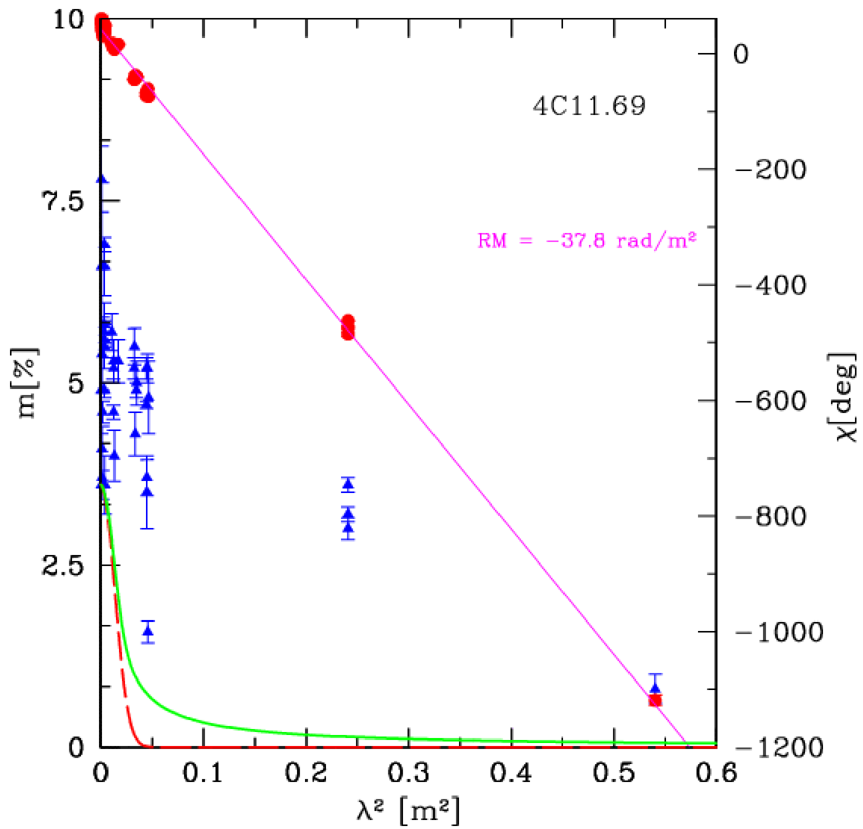
Jets and their environment

- Tight relations between BH and host galaxy properties – feedback
  - Jets are intimately related to their environment
- We can use polarization, spectral lines to study jet environments



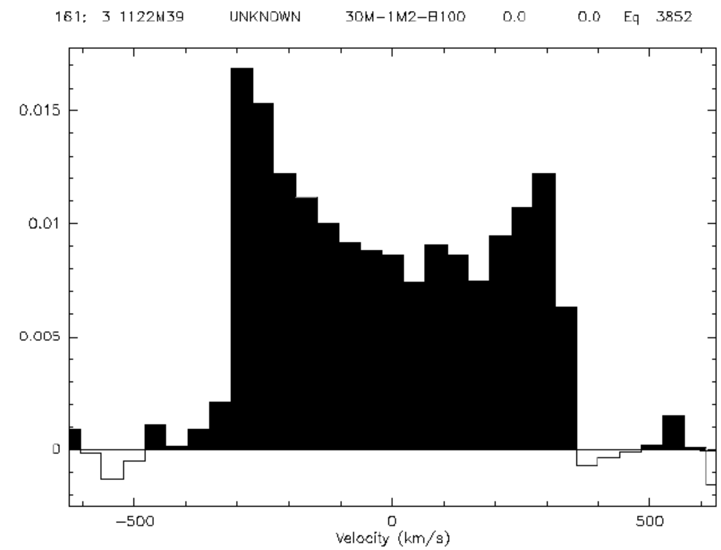
Polarization information

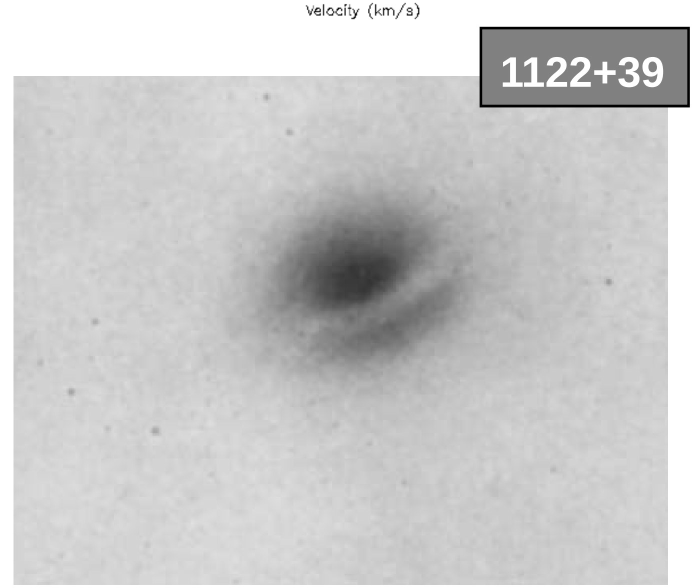
- From RM (change of polarization angle with square of observing wavelength) it is possible to derive properties of the intervening medium
- RM range in a sample of CSS sources from -20 rad m^{-2} and 3900 rad m^{-2}
  - Mantovani et al. (2009)



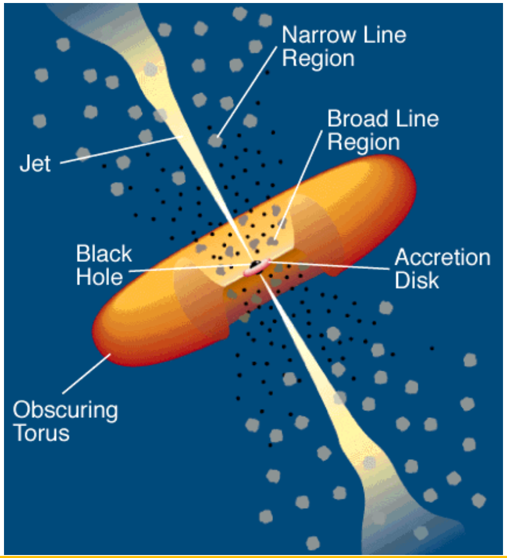
Spectral line observations

- Accretion of cool gas may power radio jets?
  - study of dynamics of cool gas through mm-interferometry
- Study of B2 sources with IRAM reveals evidence for a physical link between dust (HST) and molecular gas (CO).
  - Eg., CO line with double-horn profile indicating ordered rotation (Prandoni et al. 2007)
- Future Perspectives
  - ALMA will provide high-quality and high resolution imaging in the (sub)mm range
  - ALMA will resolve structure and dynamics of molecular gas around nearby AGN: direct information on accretion scenario

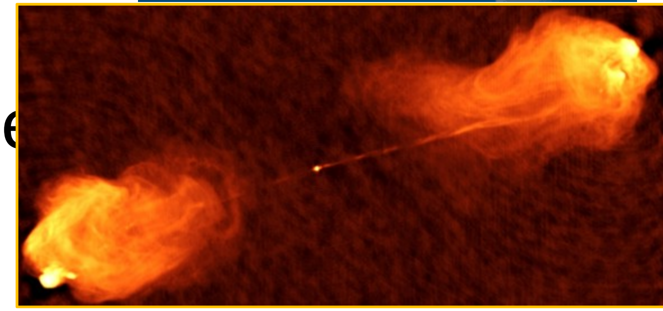




Summary



- AGN are exciting phenomena, useful for physics and cosmology
- Radio galaxies, blazars are particularly interesting owing to their emission across all the electromagnetic spectrum



- In the next years new radio facilities, as well as high energy missions (eg Fermi), will greatly enhance our current understandings.