AGN at the Crossroads of Astrophysics

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Exploring the Cosmic Frontier
Astrophysical Instruments for the 21st Century

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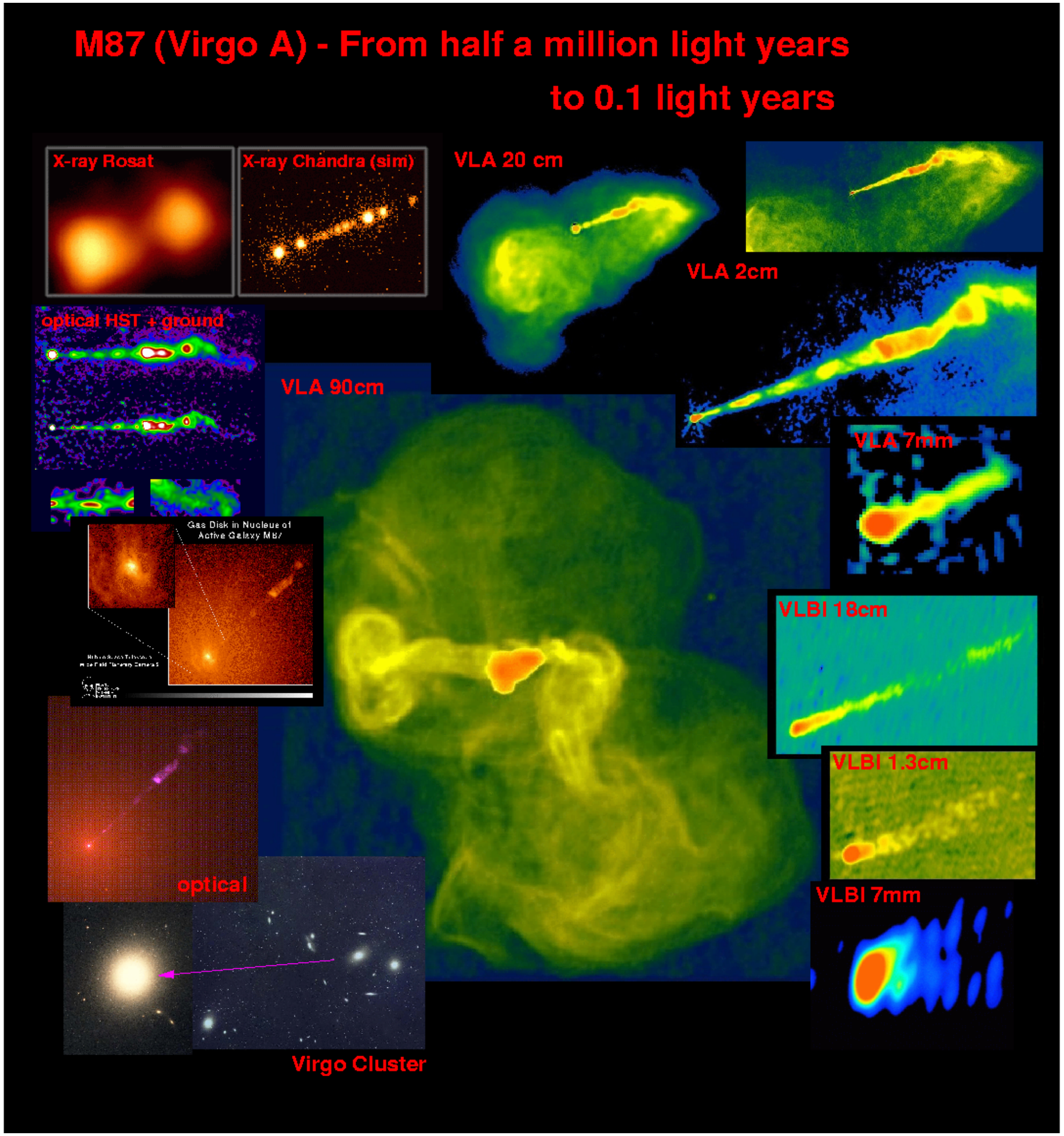
Active Galactic Nuclei

Nuclear activity

- is ubiquitous: almost every galaxy exhibits some level of activity
- comes in many faces: Quasars, BL Lac, BLRG, LINER, Sy1,2…
- covers the entire range of the electromagnetic spectrum
- spans over 12 orders of magnitude in spatial and temporal domain
- reflects processes and physical conditions in the immediate vicinity of a BH
- can be observed throughout much of the Universe: from the Galactic Center to z>6



Fundamental Questions

• Where does the emission come from and how is accretion energy converted to radiation? Energy extraction mechanism?

• Is there a unified model for all of the different types of AGN? Can we draw an evolutionary diagram for AGN?

• What is the relationship between the SMBH and the host galaxy? Which fo… s
ar…

Answering any of these questines can only be done by studying AGN in more than one spectral domain –

AGN science is synthetic by its virtue

• …

• …
limit.

• How are AGN jets produced and collimated?

• What is the physics of the relativistic outflows on pc to Mpc scales? How do they interact with, and affect, the host galaxy.

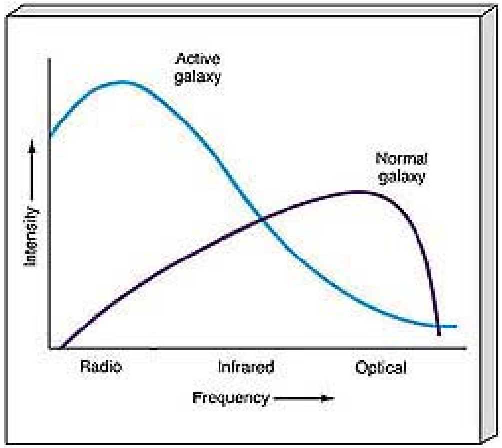
• Are multiple SMBH common in AGN, and how do they form and evolve?

AGN and their Studies

Properties	Popularity
Small angular size	Many
Galactic (or greater) luminosity	Many
Broad-band continuum	Most
Strong emission lines	Most
Variability	Most
Weakly polarized	Most
Radio emission	Many
Collimated outflows	Many
Supermassive black holes	Most

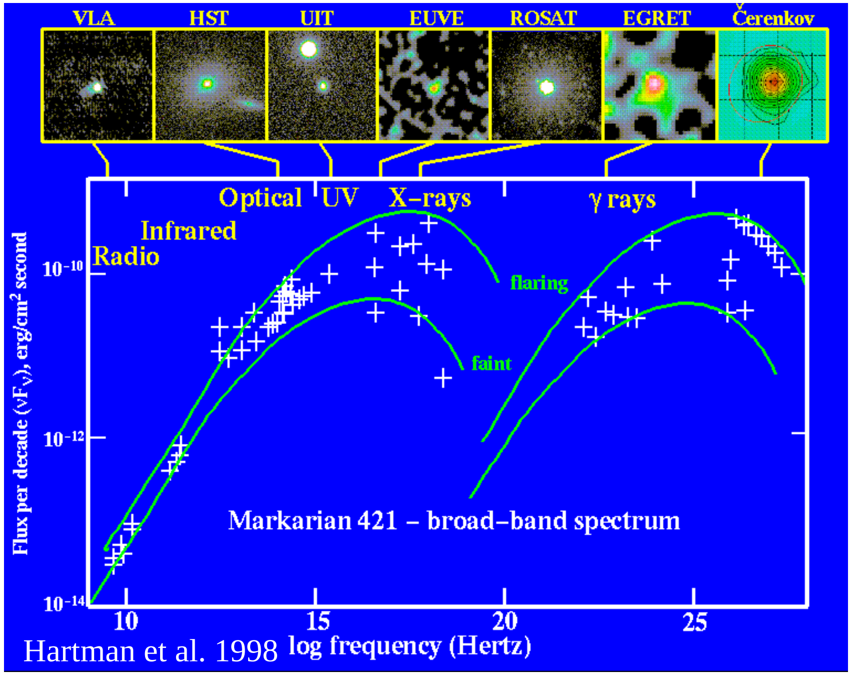
Source of energy in AGN

1. colliding galaxies
2. starburst
3. gravitational collapse
4. SN chain explosions
5. annihilation
6. quark interaction
7. compact stellar cluster
8. **accretion on a black hole**



AGN: basic studies

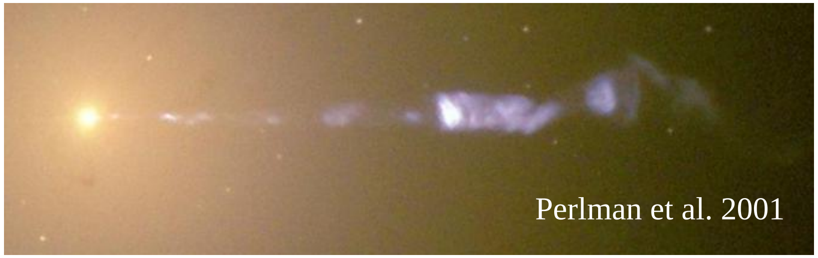
1. surveys: correlations between different types of AGN
2. multifrequency campaigns: broad-band spectra
3. spectroscopy: narrow-band spectra, X-ray spectra
4. variability: long and short term changes of emission
5. morphology: optical, X-ray and radio structures on scales of up to a few Mpc
6. radio interferometry: structure and evolution of parsec-scale emission



SMBH in a Larger Context

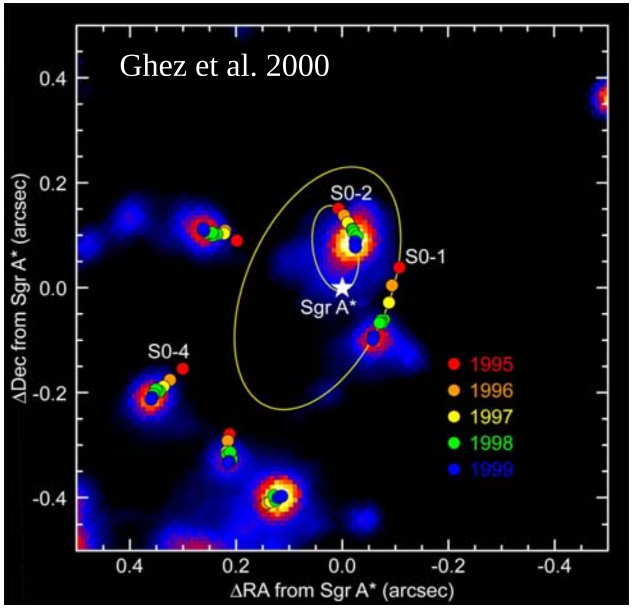
- SMBH are expected to form in the early Universe, in the course of multiple mergers of dark matter halos (hierarchical structure formation). Multiple SMBH may be common in galaxies.
- SMBH are seemingly present in all (*or almost all*) galaxies (Kormendy & Richstone 1995)
- BH masses correlated with velocity dispersion in galactic bulges (Merritt 2001)
- BH masses correlated with radio emission (Ho 2002)
- SMBH are closely related to (just about) every aspect of galactic activity, and may be one of the most significant energy sources in the Universe.
- Activity depends critically on the availability of accreting gas – may be connected to the presence of multiple SMBH in a host galaxy.
- Binary SMBH may be common in the most powerful AGN -- likely source of gravitational radiation on cosmologically significant scales.

Evidence for SMBH



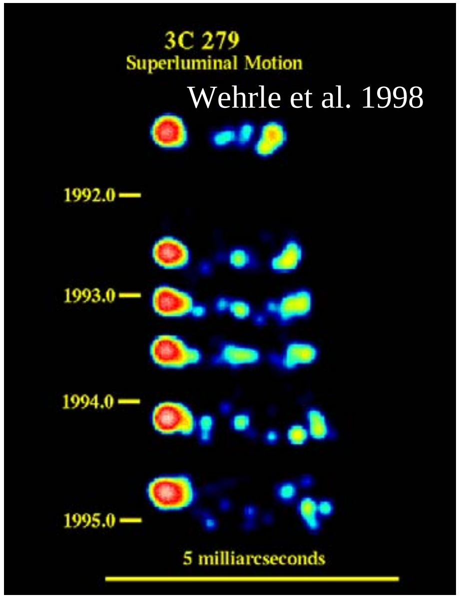
Exceptional stability of jet direction on timescales of ~10^6 years

Proper motions of stars around SgrA* imply a black hole of 10^5 solar masses

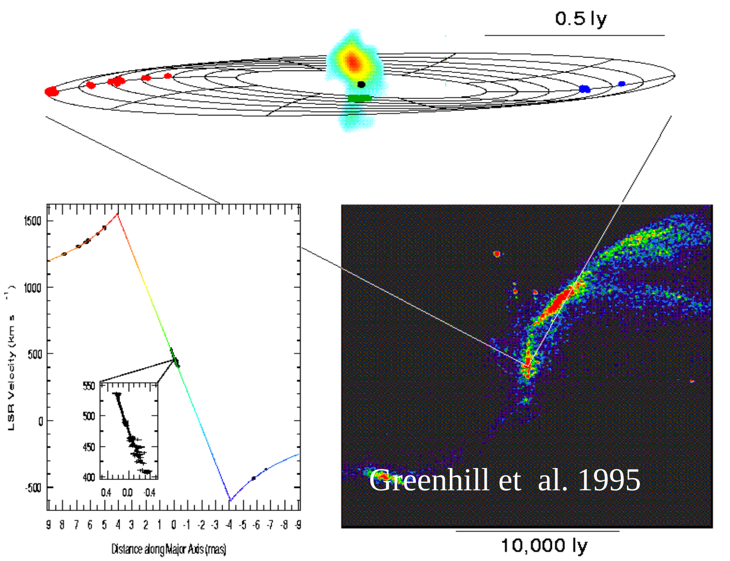


Superluminal motions: apparent speeds β_{app} ~20, which requires an effective mechanism for energy release

Observations of accretion disks: Keplerian motions imply densities of ~10^{12} M_{sol}/pc^3



Other evidence: rapid variability, emission line width, gravitational redshift of Fe K line, etc.

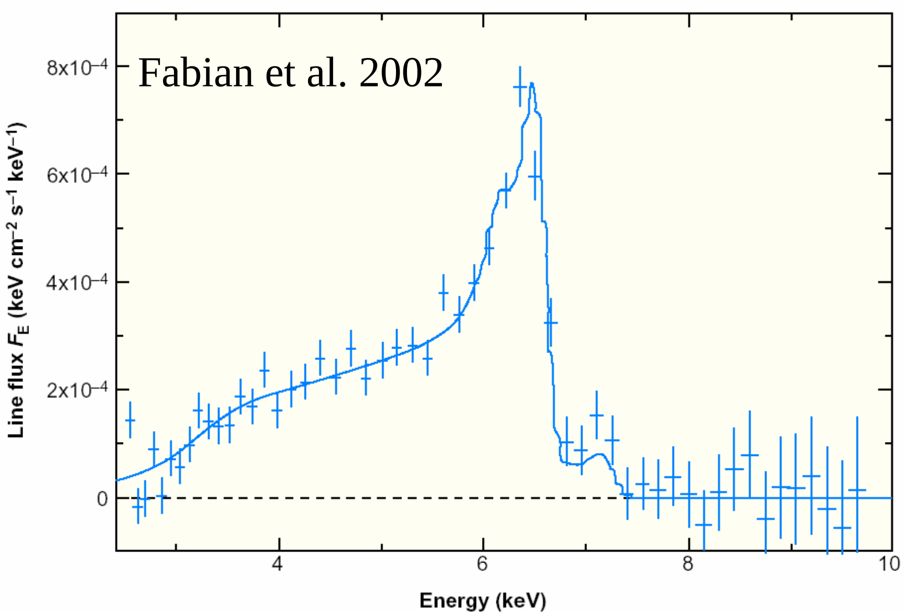


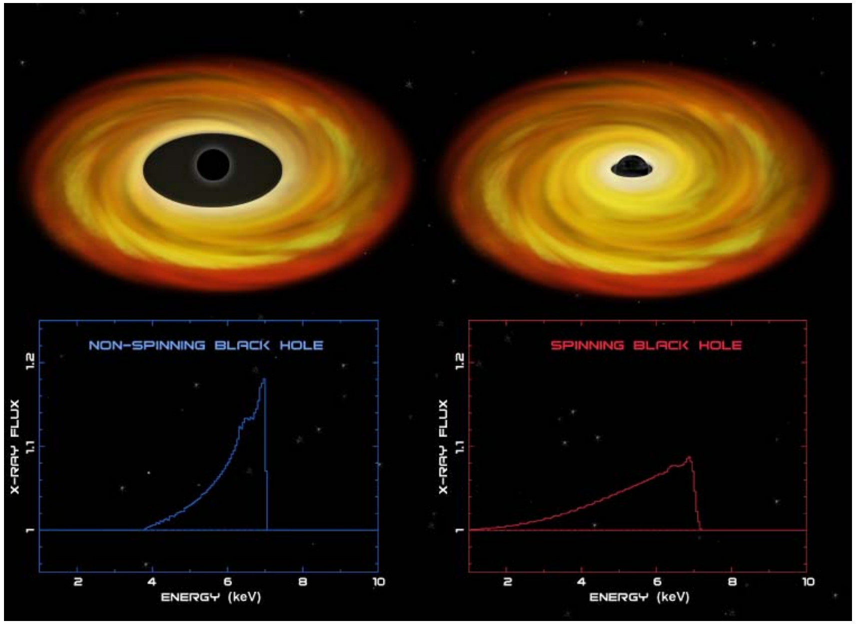
X-ray Evidence for SMBH

• **Line profile argument:** X-rays generated above the accretion disk interact with the disk material and produce Fe fluorescence line emission – observed by XMM

• Line profiles show relativistic velocities, Doppler shifts and gravitational redshift – modelling of the line profiles depends on the disk inclination and spin of the SMBH – can distinguish between rotating and non-rotating BH.

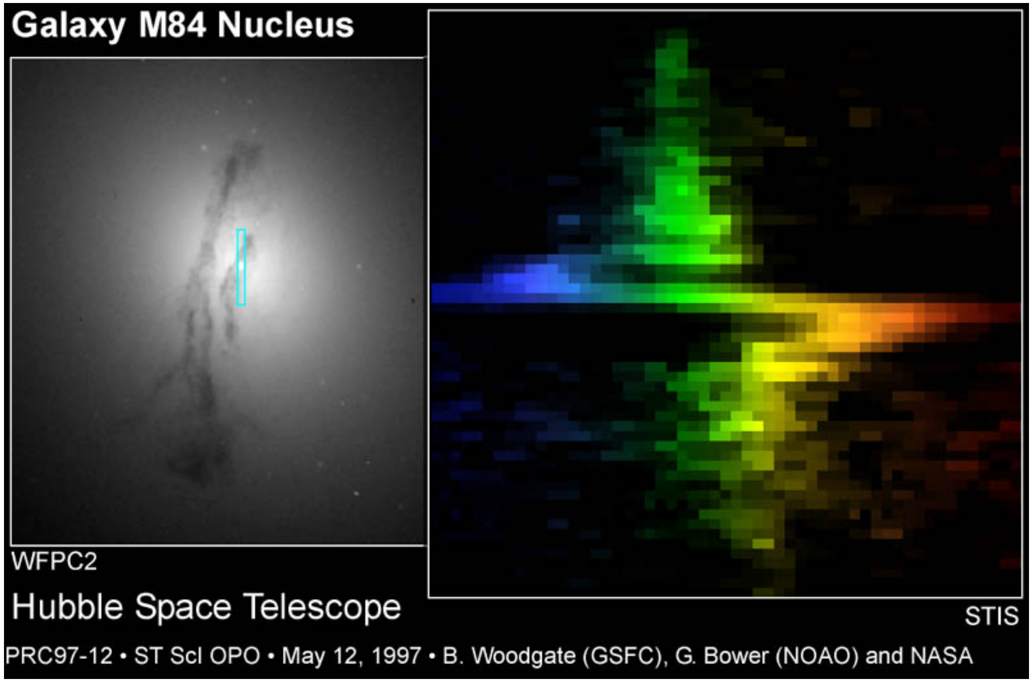
XMM on MSG 6-30-15

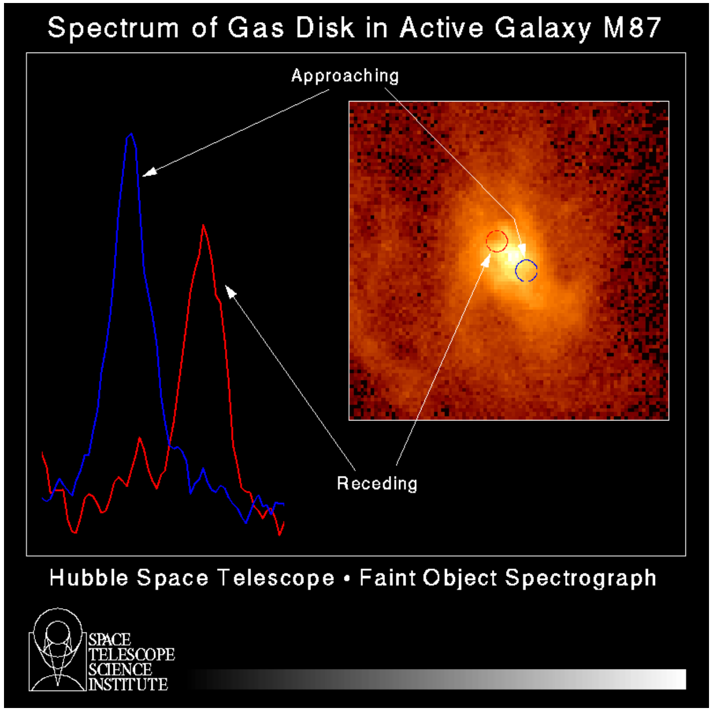




Optical Evidence for SMBH

• **Enclosed mass argument:** Optical spectroscopy reveals the Doppler shift caused by the fast rotation of material in the accretion disk – implying masses of $1{*}10^9$ M_{sol} in M84 and $2.5{*}10^9$ M_{sol} in M87.





Radio Studies of AGN

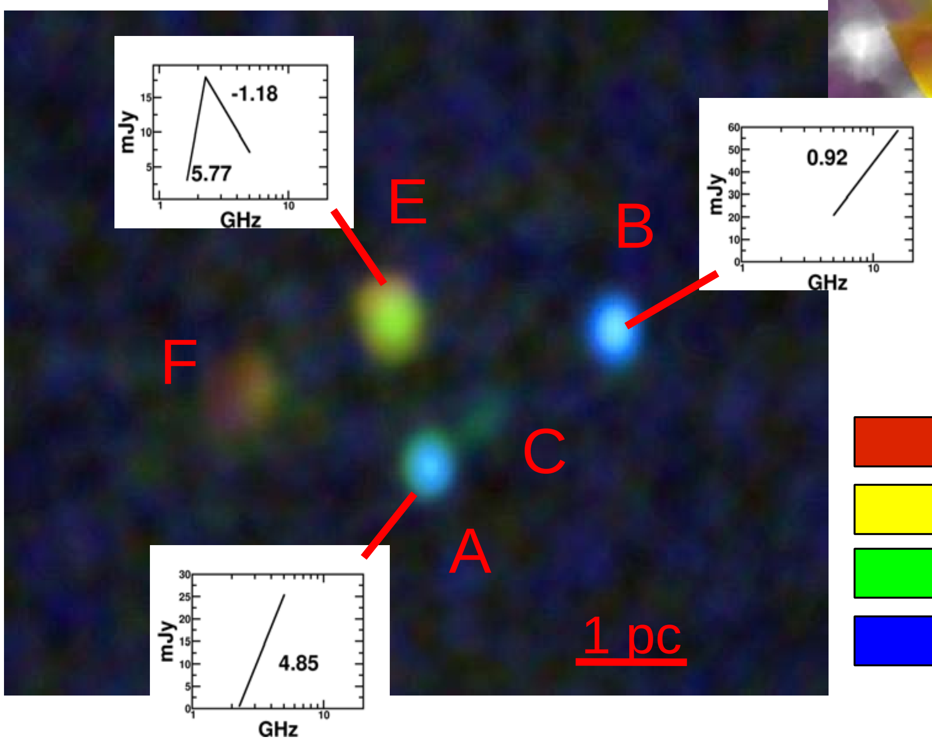
- **Monitoring programs:** jet kinematic and spectral evolution: 3C345, 3C273, etc.; detailed physical modelling of individual objects (3C345, 3C273, 0836+710, etc.).
- **Variability:** long-term: dynamics of nuclear regions; short-term & IDV:compact structures.
- **Surveys and statistics:** modelling the distributions of $\theta_{\mathbf{app}}$, $\beta_{\mathbf{app}}$, $\mathbf{T_b}$ $\Rightarrow$jet composition.
- **Polarization:** B-field distribution, circular polarization (jet composition).
- **Advanced imaging:** mapping the $\mathbf{S_m}$, $\nu_{\mathbf{m}}$ and **B** distributions; plasma diagnostics in jets.
- **Internal structure of jets:** diagnostics of jet plasma.
- **Physics of nuclear region:** opacity effects in the nucleus, synchrotron self-absroption and external absorption, magnetic field and rotation measures, H_2O and OH maser emission.

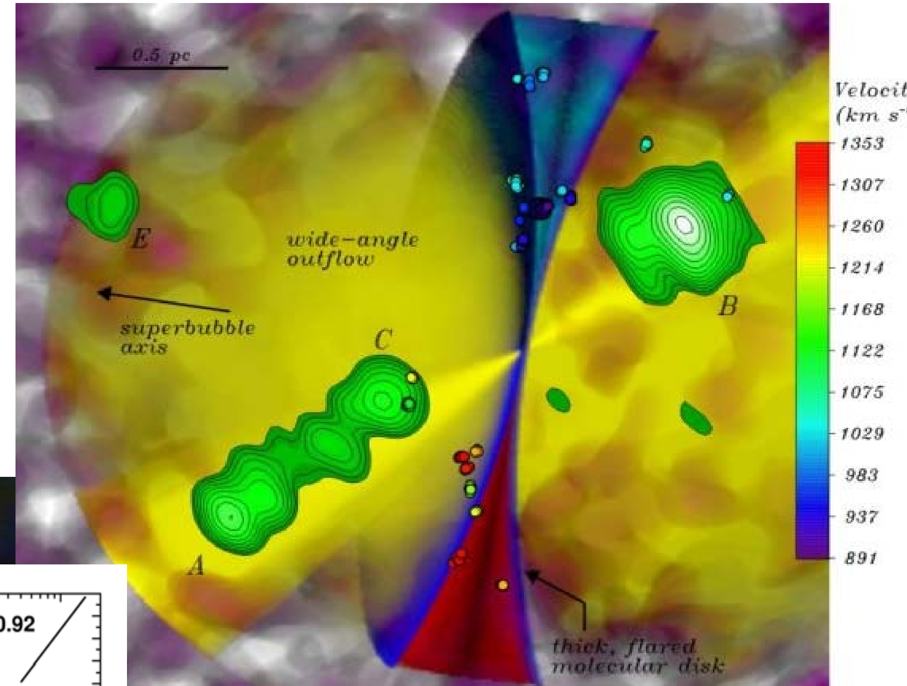
Activity in a Seyfert Galaxy

High resolution phase referencing VLBI Studies of Seyfert Galaxies –

NGC 3079 a different picture

Middelberg et al. (2003)

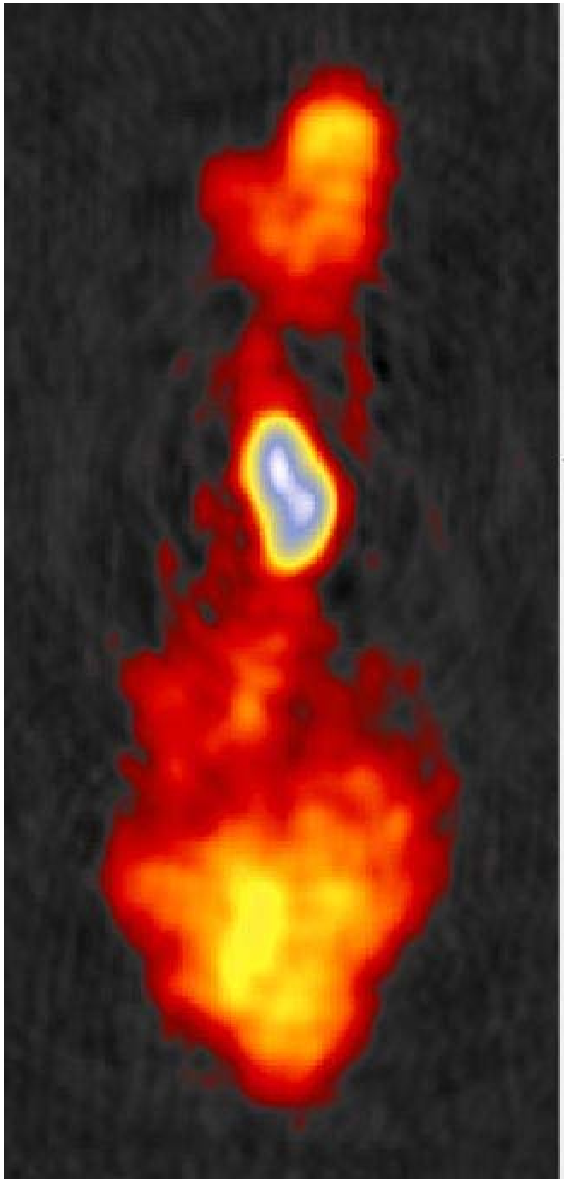




Kondratko et al. (2003)

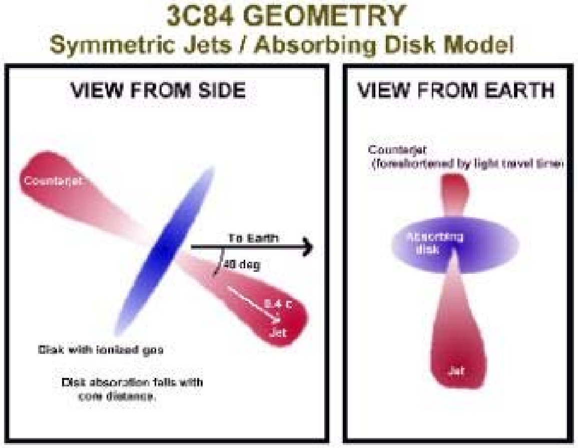
1.7 GHz
2.3 GHz
5.0 GHz
15 GHz

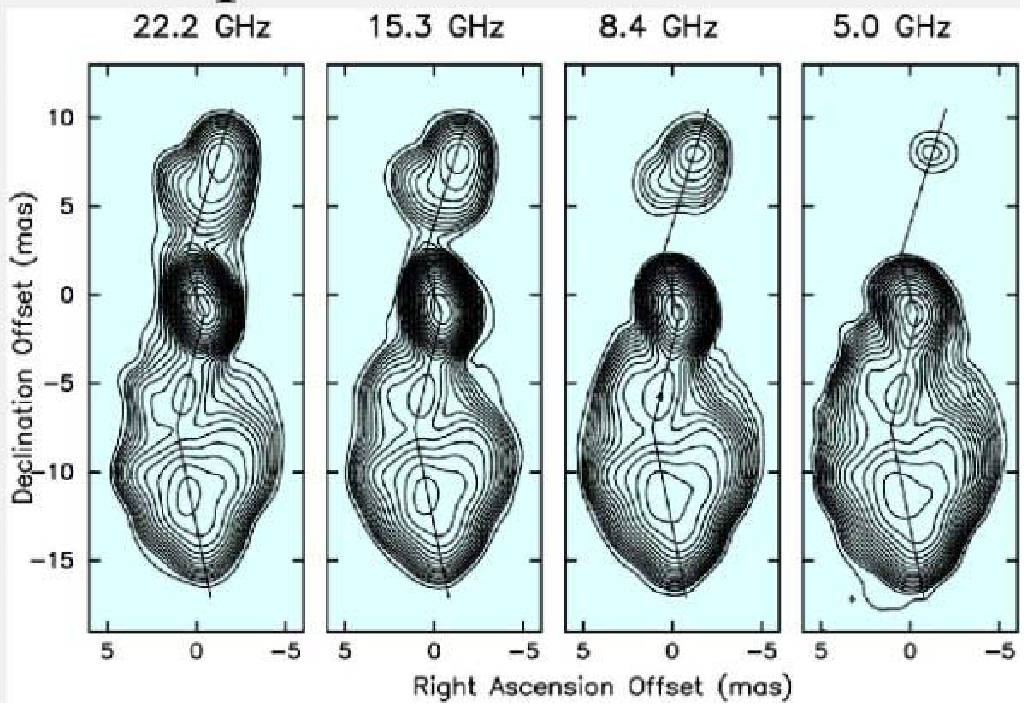
Free-free Absorption in 3C84



Walker et al. Ap.J. 530, 233

NGC1275 (3C84) Free-free Absorption





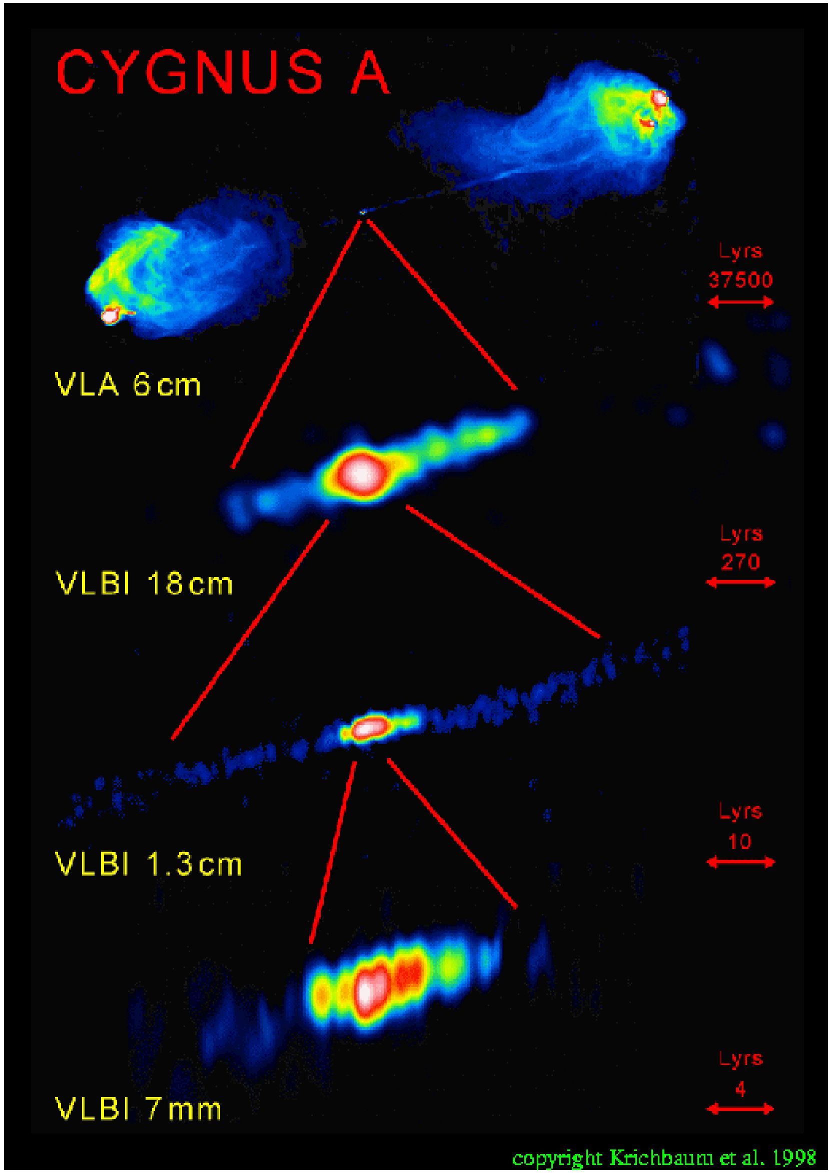
The Two-sided Jet in Cygnus A

Study of motion in two-sided jets allows one to determine the intrinsic jet speed and – in principle – the distance of the source (Hubble constant).

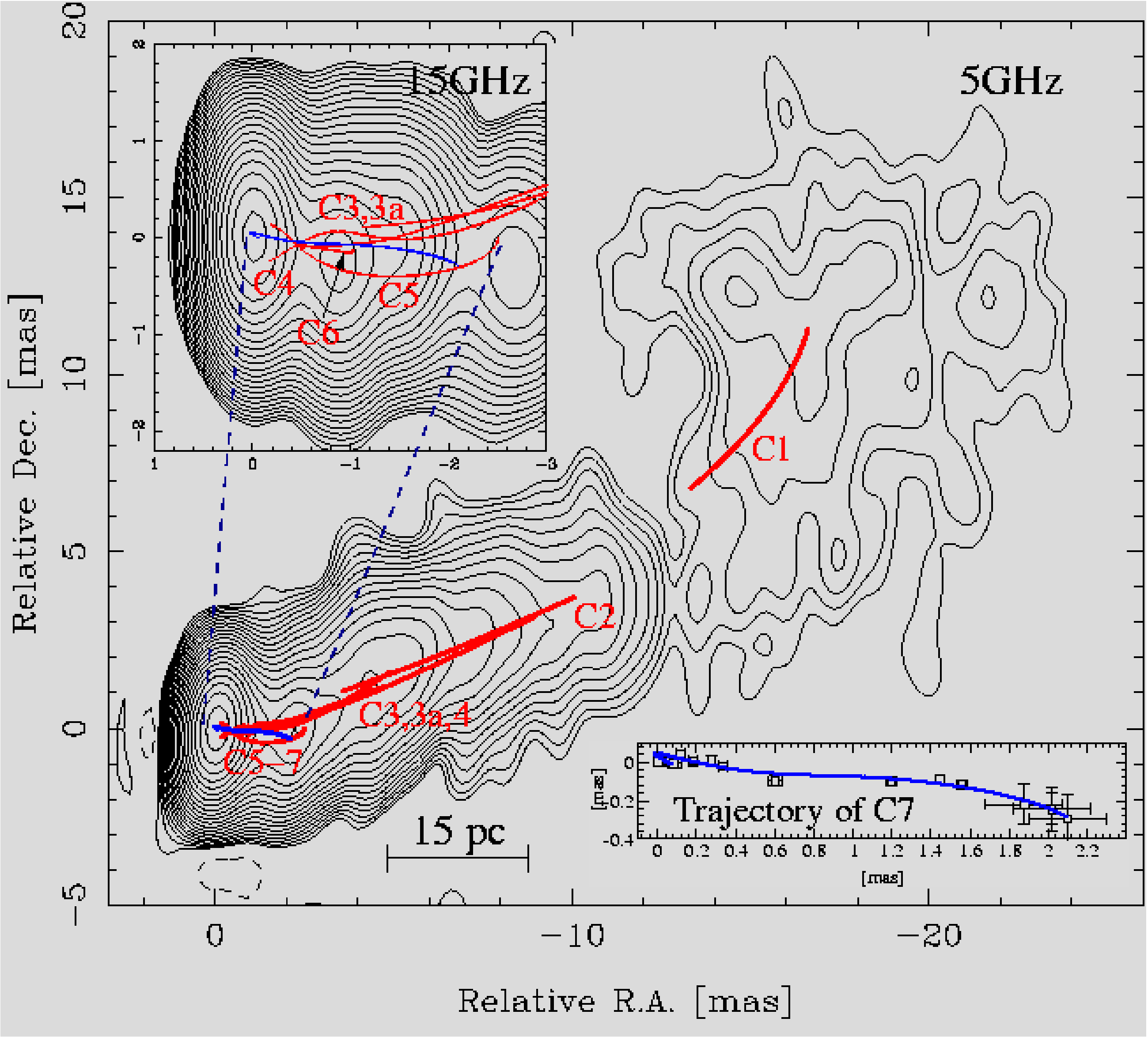
The determination of the (frequency dependent) jet-to-counter jet ratio gives insight on the absorbing accretion disk

The distance between base of jet and counter-jet yields important size limits of the region where the jet is made and accelerated.

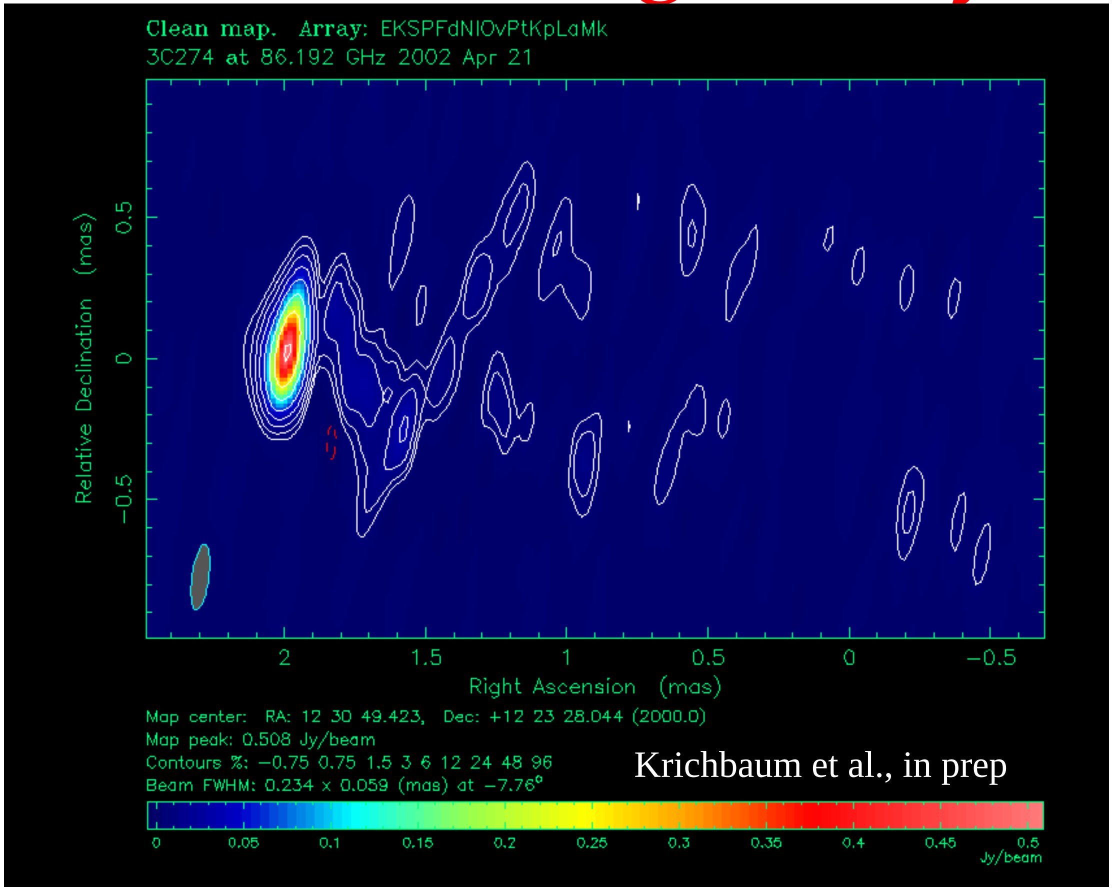
Towards millimeter wavelengths the foreground absorption becomes optically thin, facilitating a more direct view into the nucleus

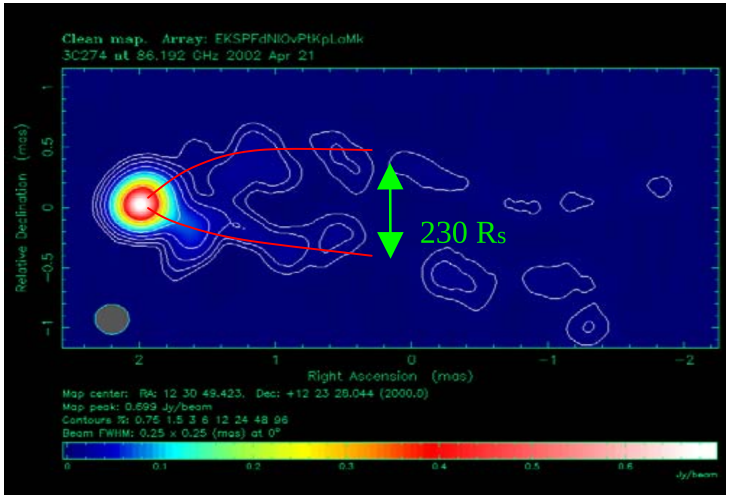


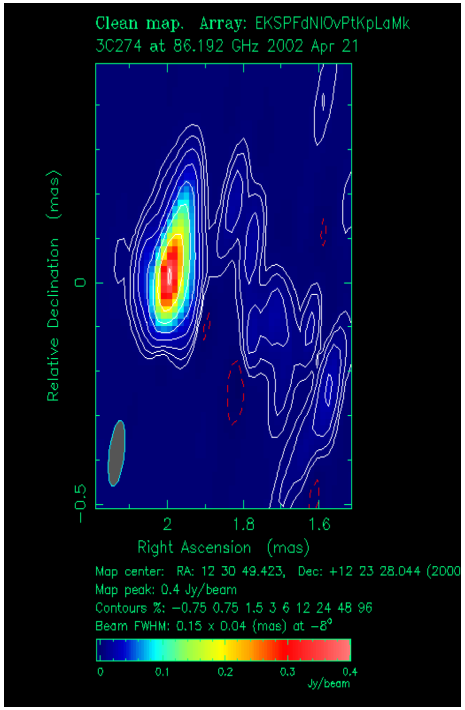
Outflow Physics: 3C345



The Light Day Scale: M87







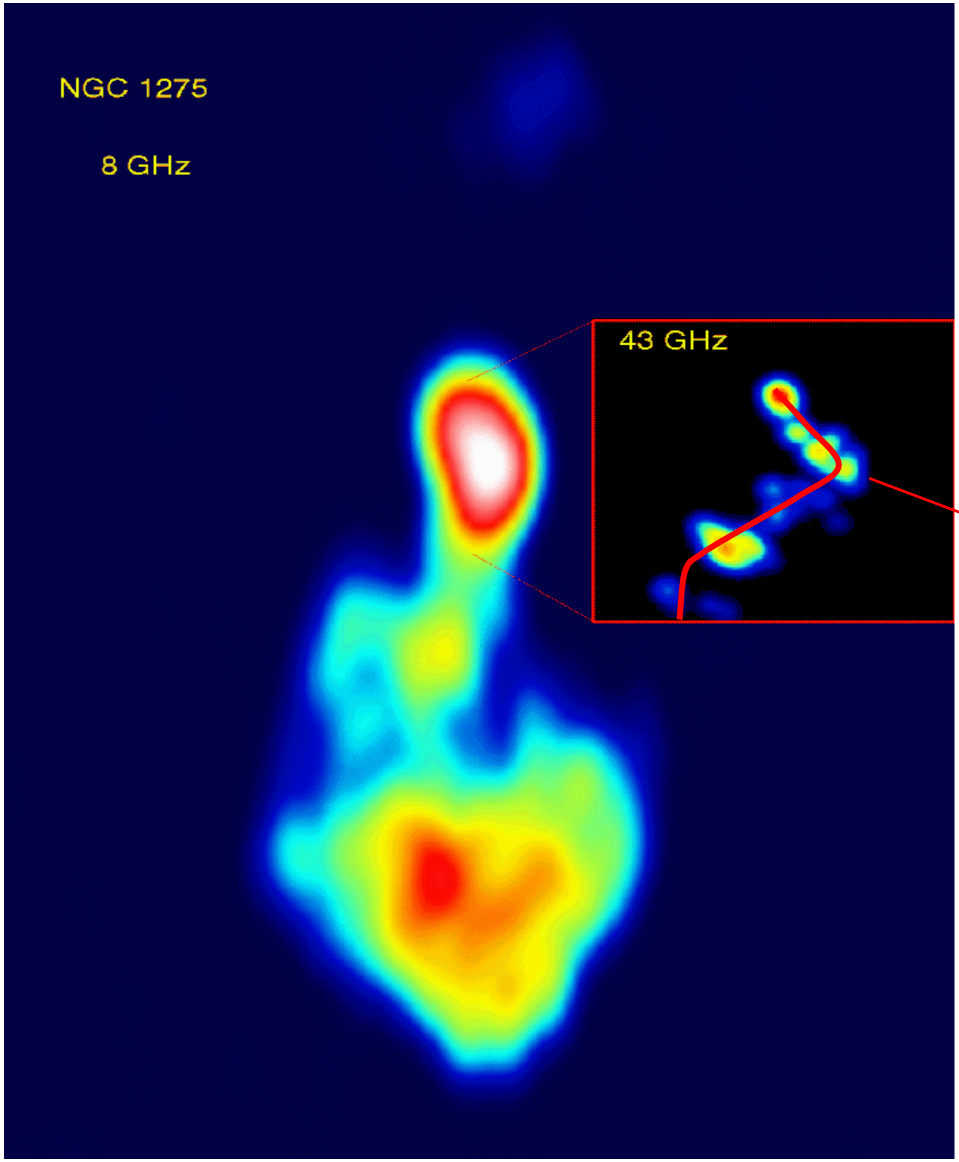
New upper limit for the size of the jet base in M87:

234 x 59 μas = 23 x 6 light days = <u>67 x 17</u> R_s

transverse width of jet at 1mas: ~230 R_s

→ see posters by Agudo, Krichbaum

The Light Day Scale: 3C84

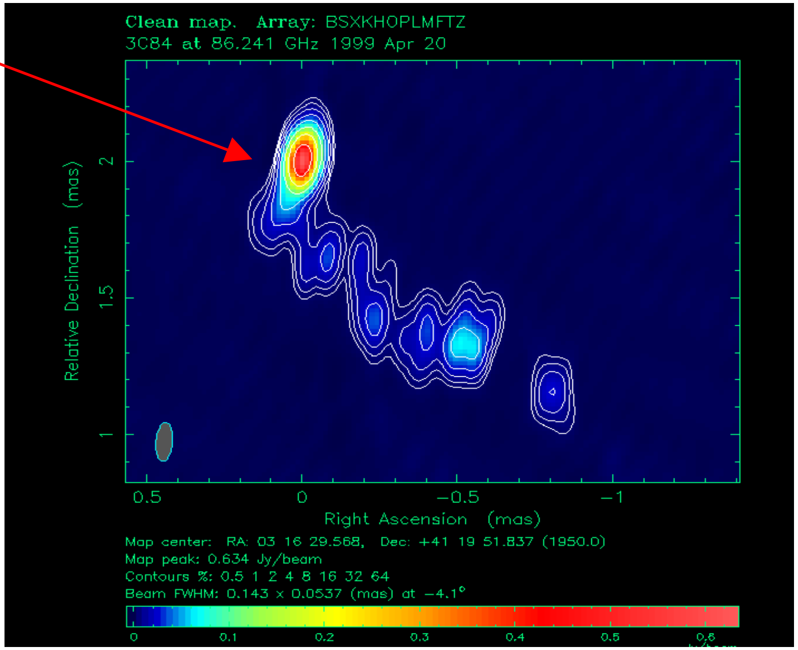


3C84 = NGC1275 = Per A

25 light days resolution

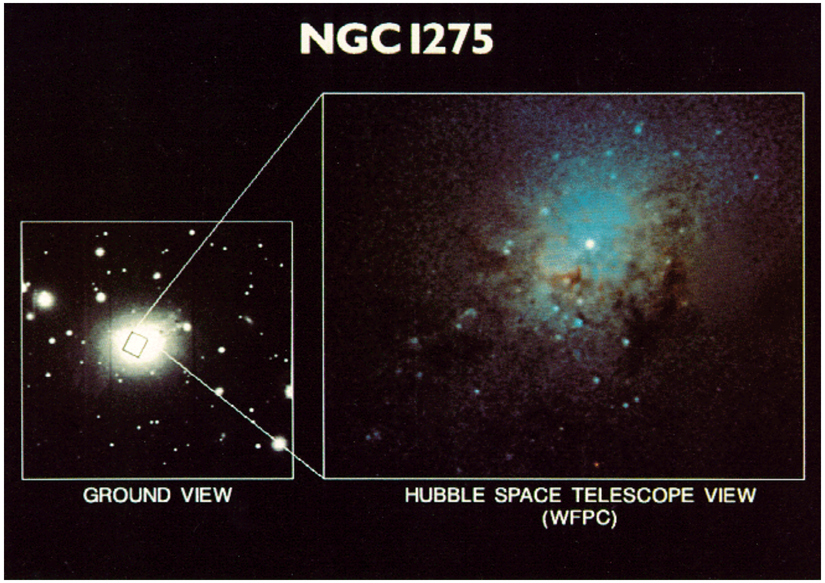
in the innermost jet at

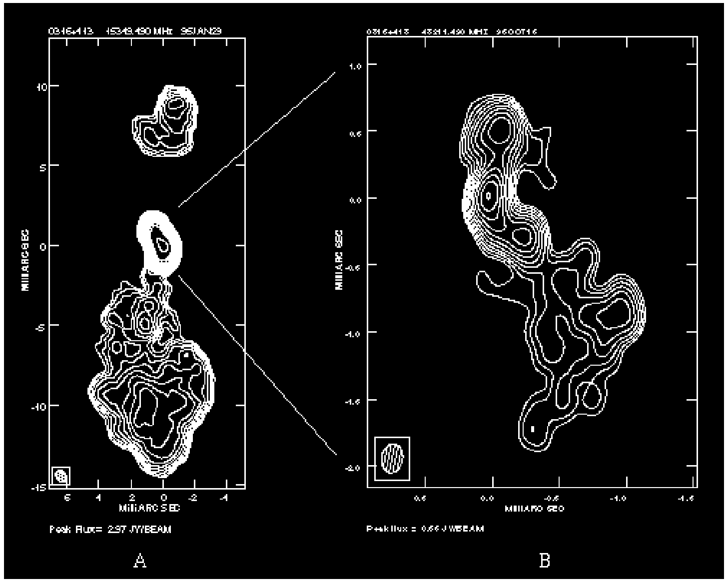
86 GHz

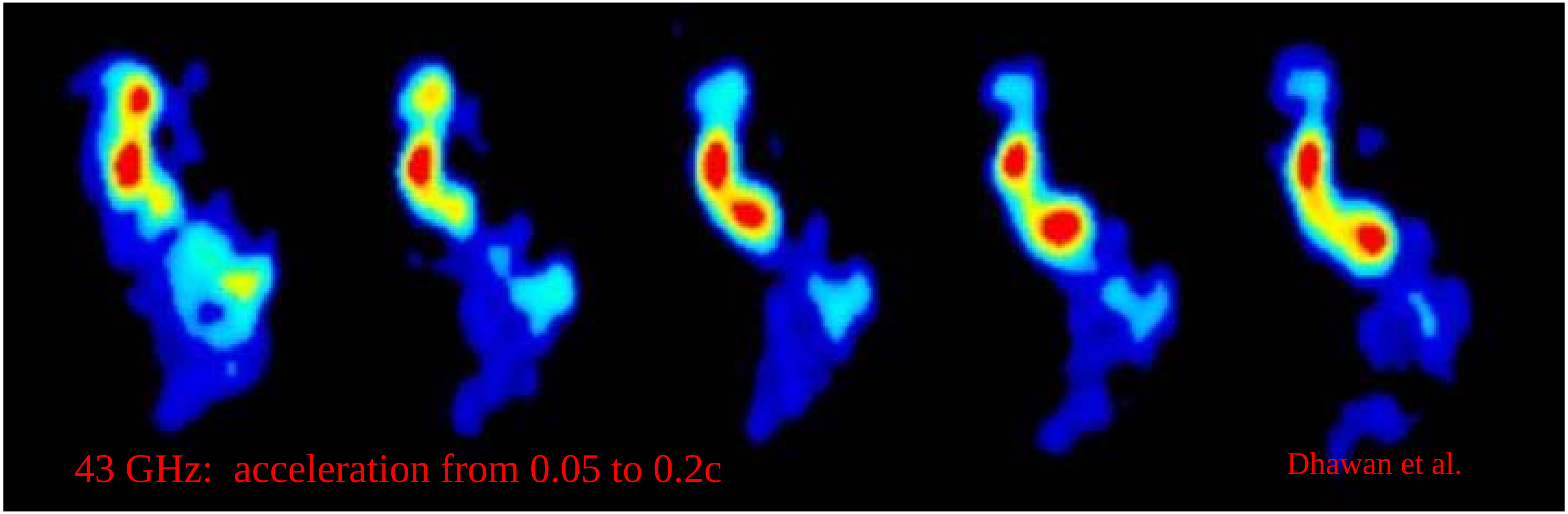


T. Krichbaum et al.

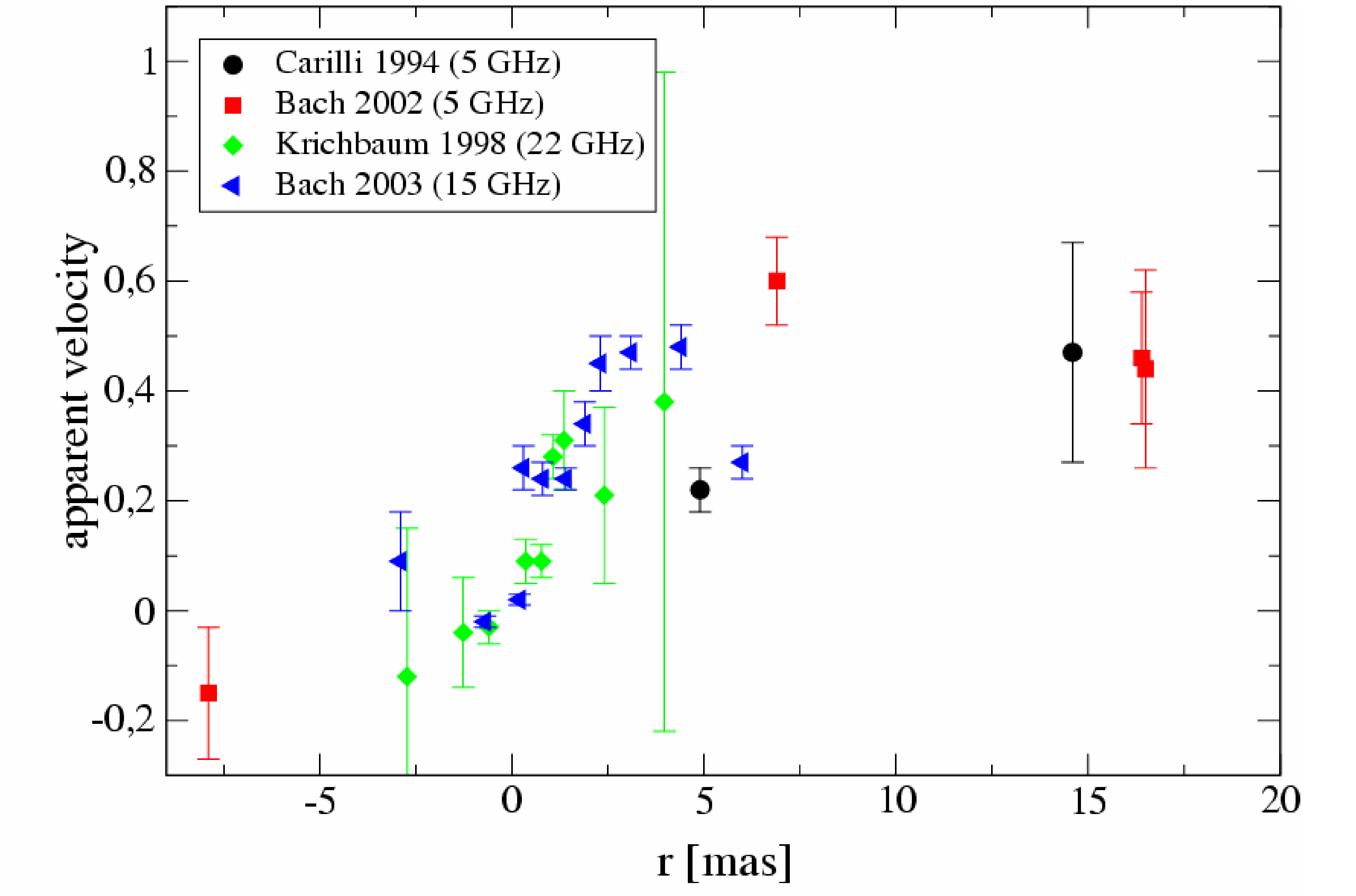
Accelerated motions: 3C84



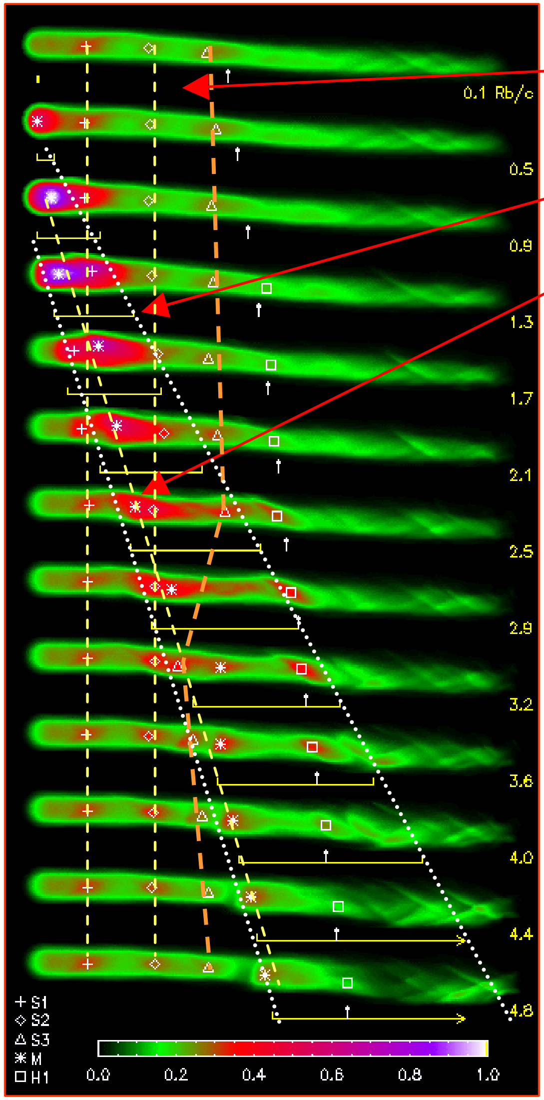




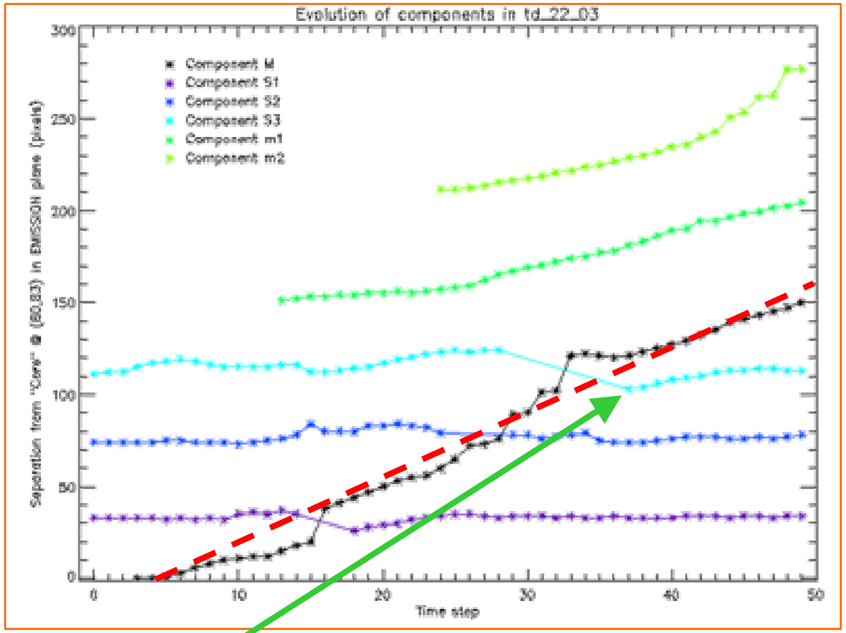
Accelerated motions: Cygnus A



Relativistic shocks: 3C120



- Standing components associated with the recollimation shocks
- New *stretched* region with increased emission
- Associated *peak brightness* motion reflects changes in the internal distribution

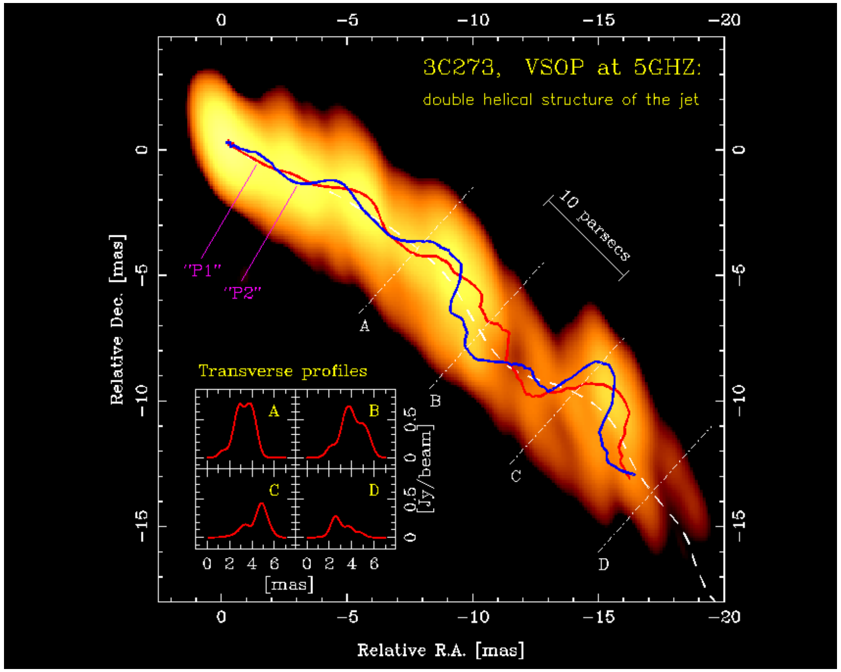


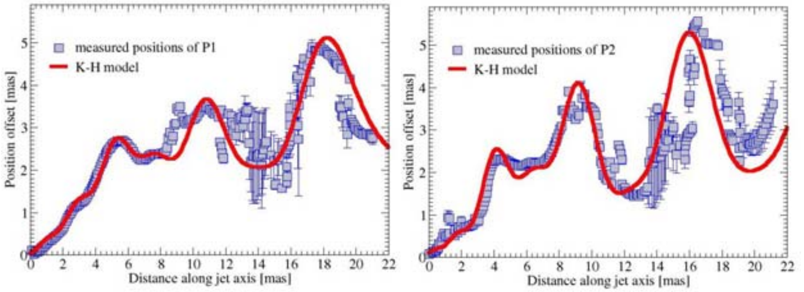
- *Upstream motions* during moving/standing components interaction

Relativistic, hydrodynamic simulations by Gomez et al. 2000, 2001

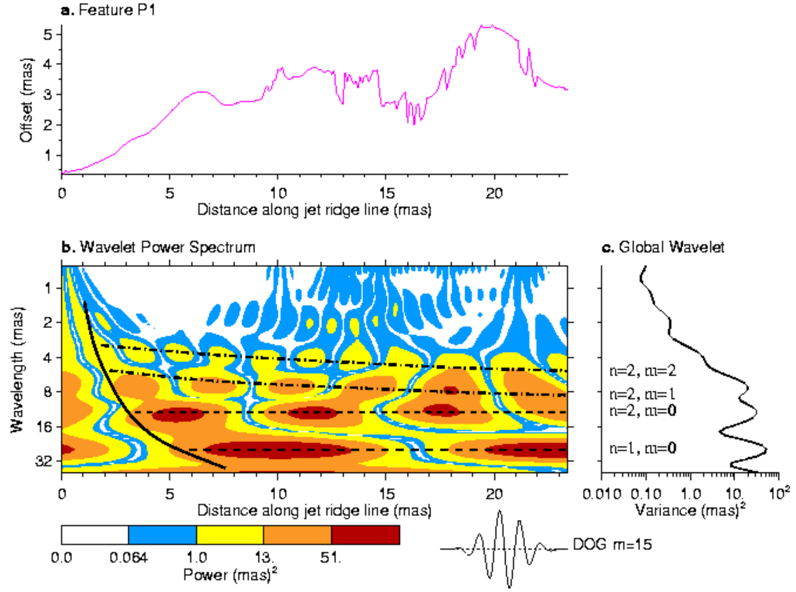
K-H Instability: 3C273

VSOP Space VLBI observations provided a resolution improvement sufficient for studying the interior of most prominent jets.





λ_{Hs}=18.0, λ_{Es}=12.0, λ_{Eb1}=4.0, λ_{Eb2}=1.9

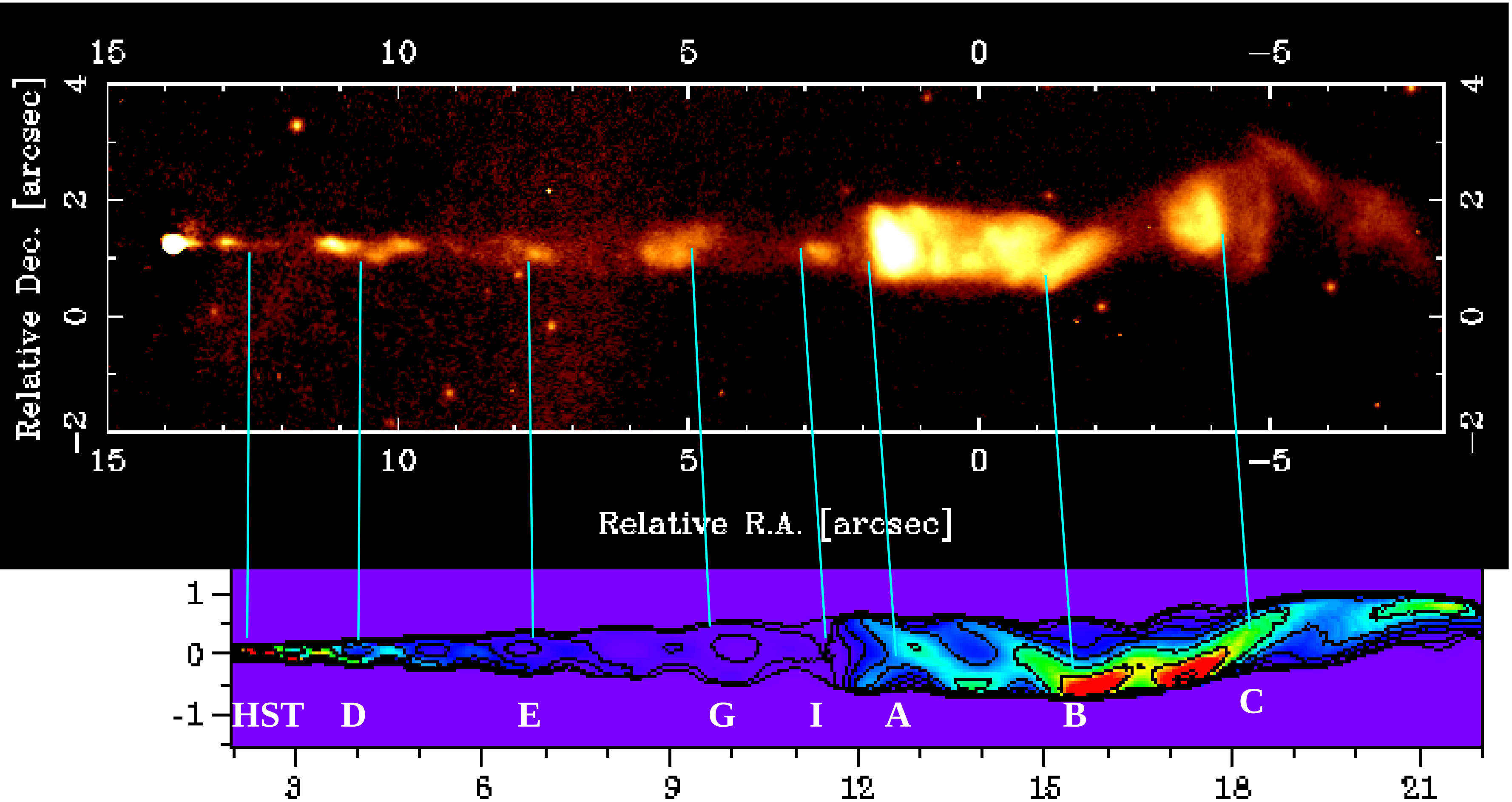


$\mathbf{G_j}$=2.1, $\mathbf{M_j}$=3.5, η=0.02, $\mathbf{a_j}$=0.53, $\mathbf{v_w}$=0.21

Lobanov & Zensus 2001

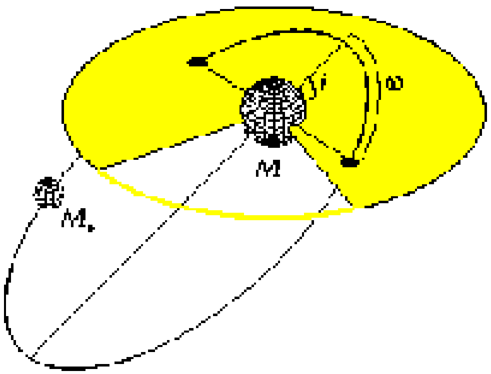
K-H Instability: M87

Compare the <u>analytical</u> K-H model image to the structure observed in M87



Lobanov, Hardee & Eilek 2003

Binary Black Hole: 3C345

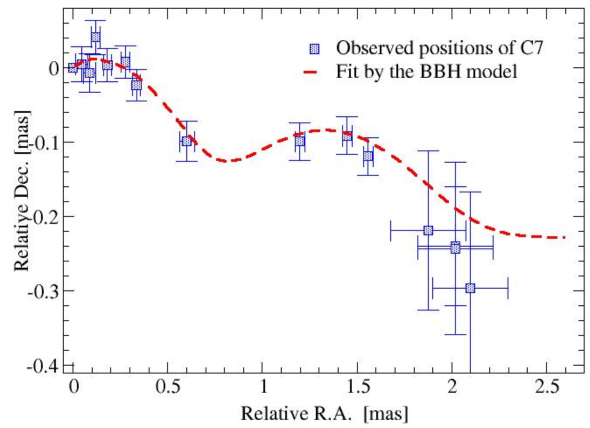


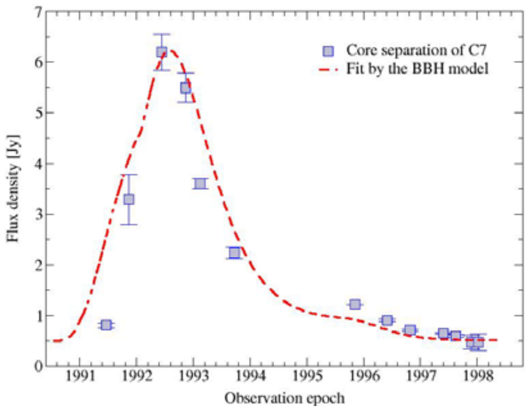
$$M_1 = 1\cdot10^9\,\mathrm{M_{sol}},\quad M_2 = 5\cdot10^8\,\mathrm{M_{sol}}$$

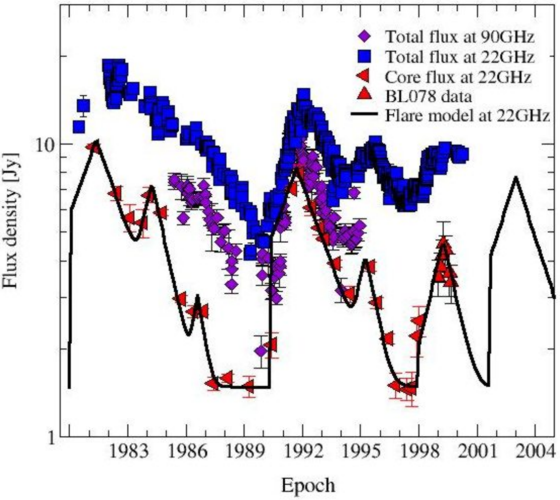
$$a_{\mathrm{maj}} = 0.63\mathrm{pc}\,(0.13\,\mathrm{mas}),\quad e = 0.1$$

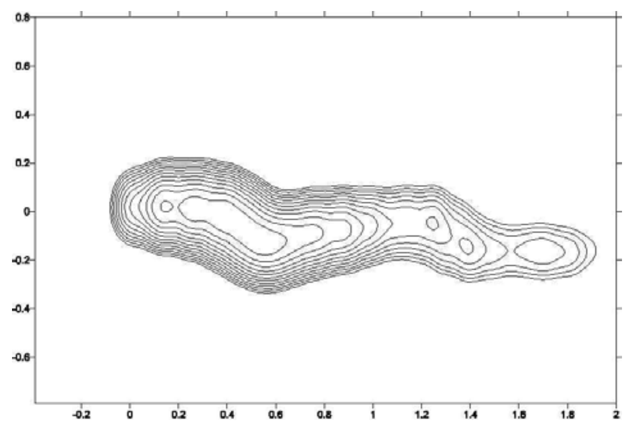
$$P_{\mathrm{orb}} \approx 170\,\mathrm{years},$$

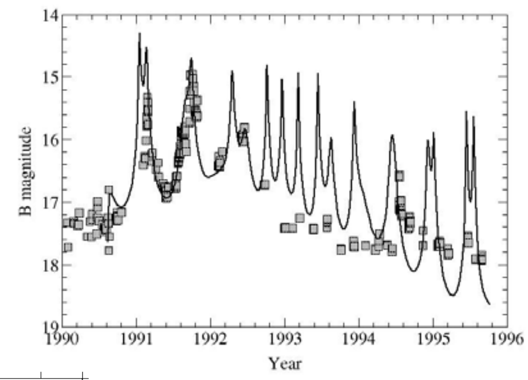
$$P_{\mathrm{prec}} \approx 2500\ \mathrm{years}$$

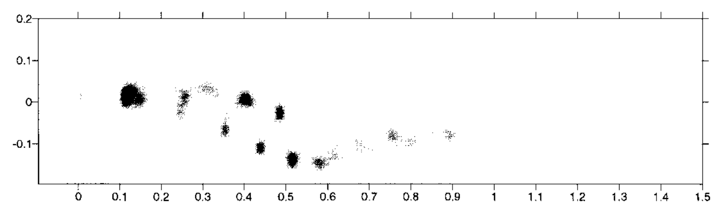












Lobanov & Roland 2002

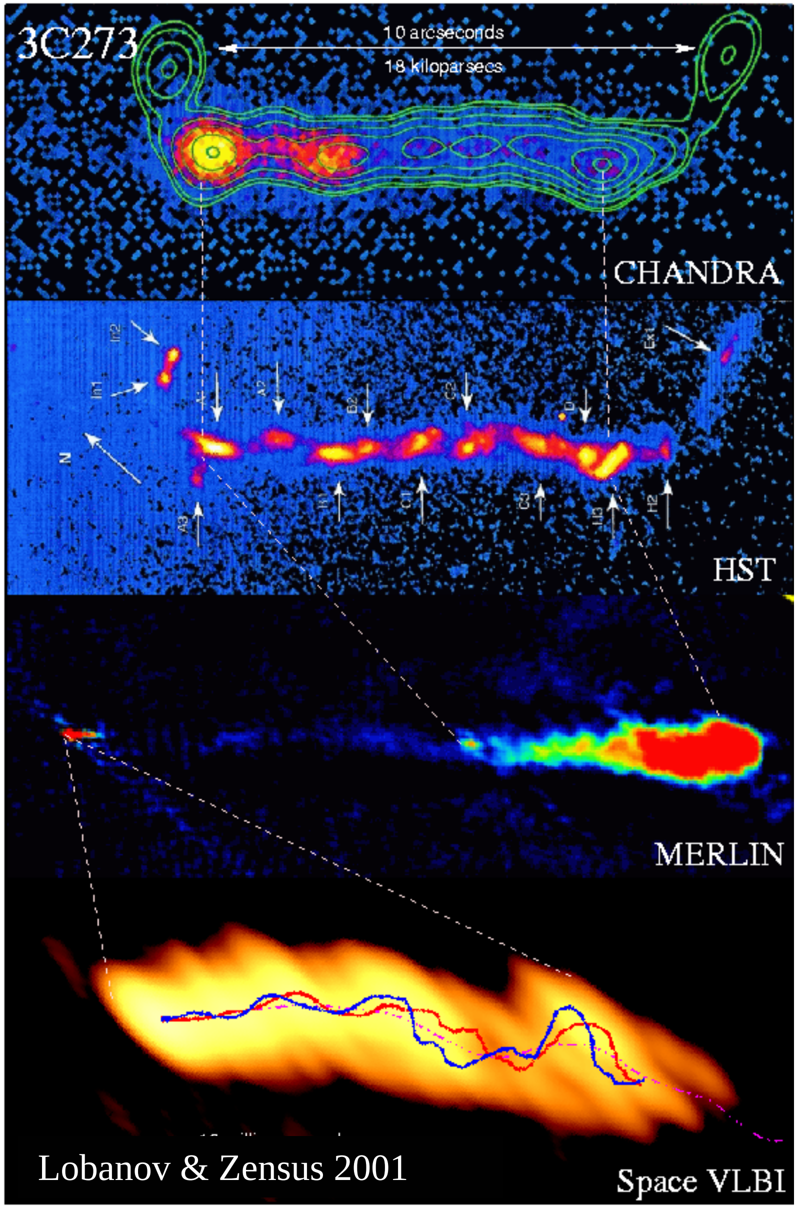
Jets across the Bands

Extragalactic jets are no longer the sovereign domain of radio astronomy

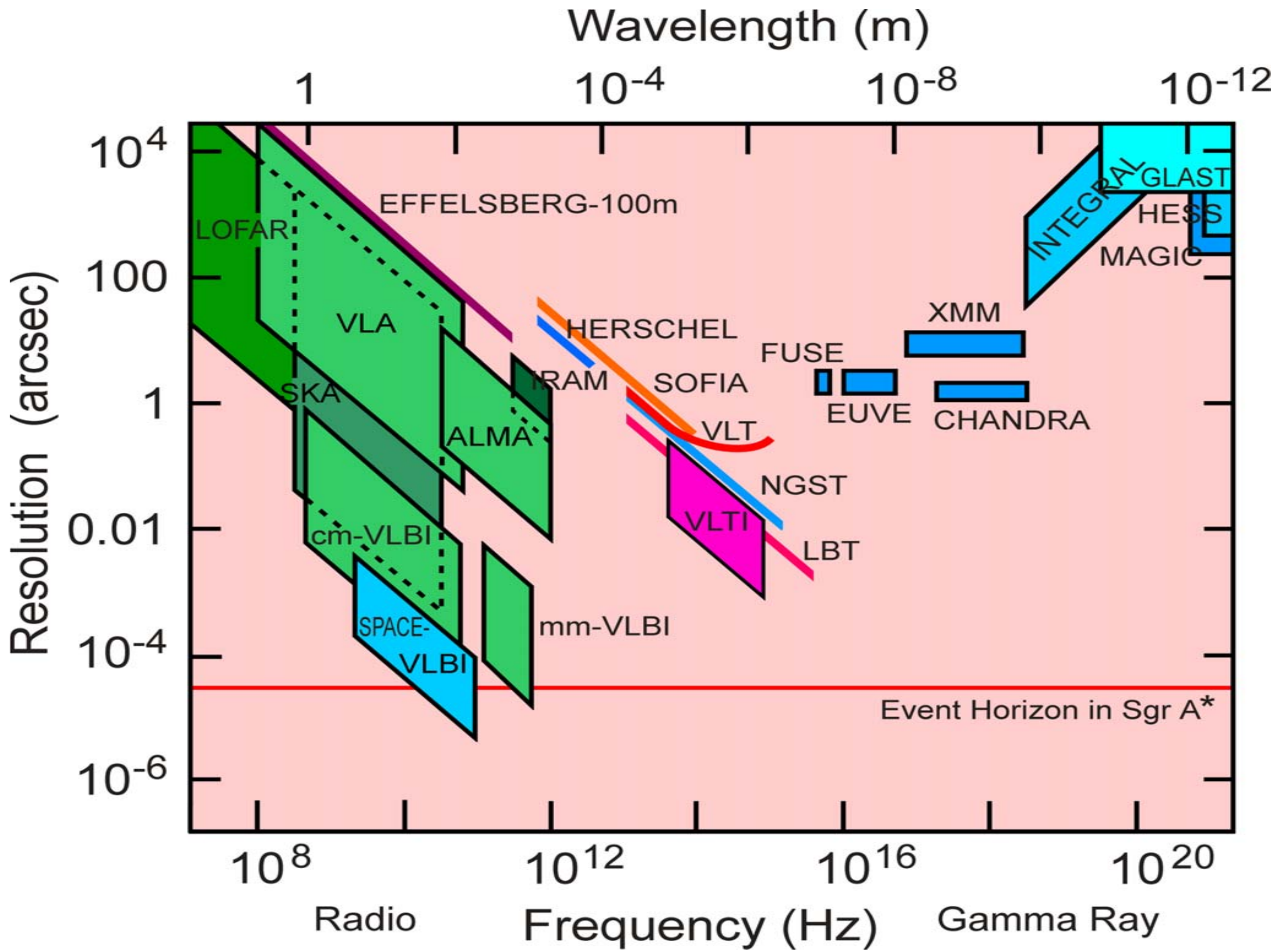
Relativistic outflows are prominent in the optical and in X-ray regimes (and possibly in others)

Nuclear X-ray activity and radio emision from jets are connected –

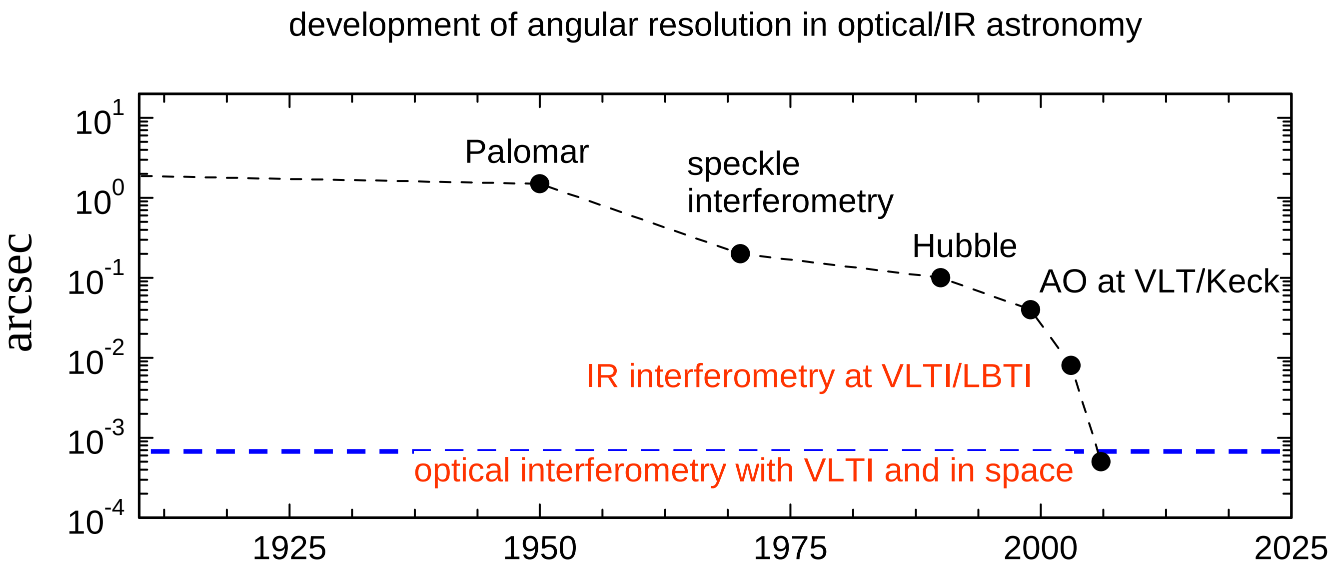
see poster by Kadler

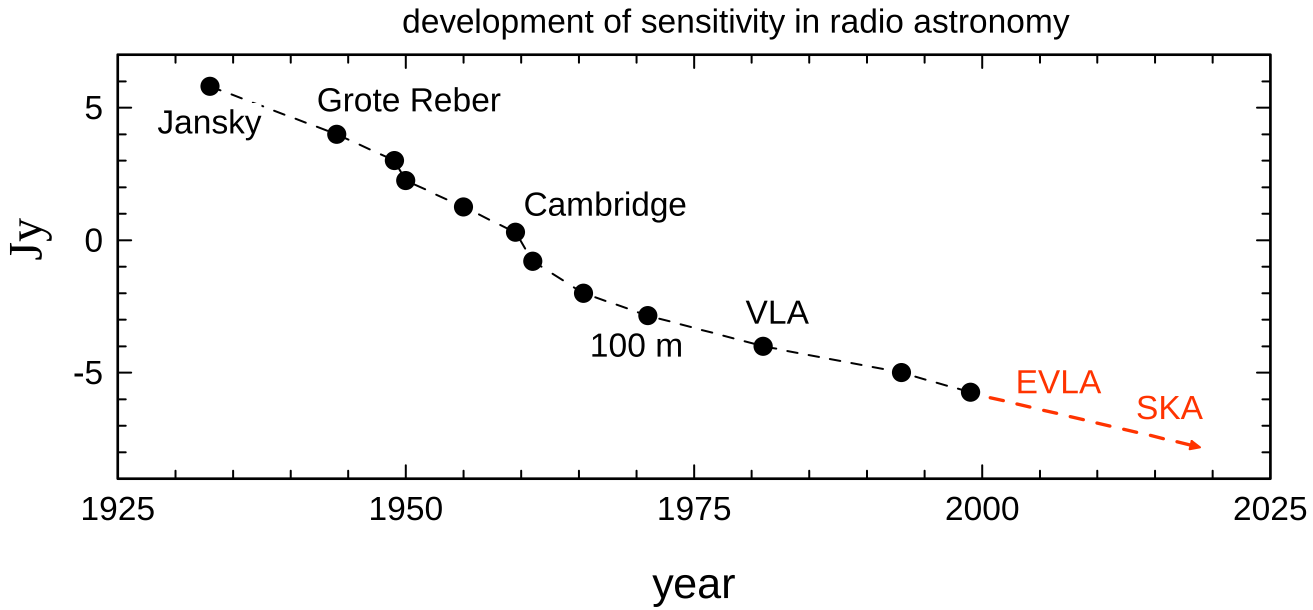


Radio vs. Other Domains



Radio vs. Other Domains



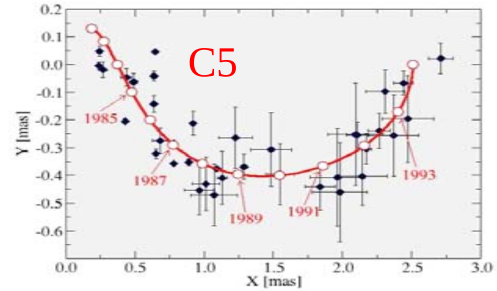


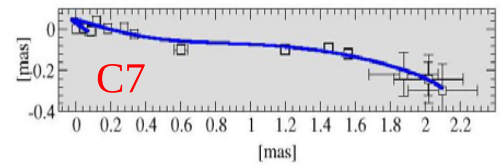
Outlook to the Future

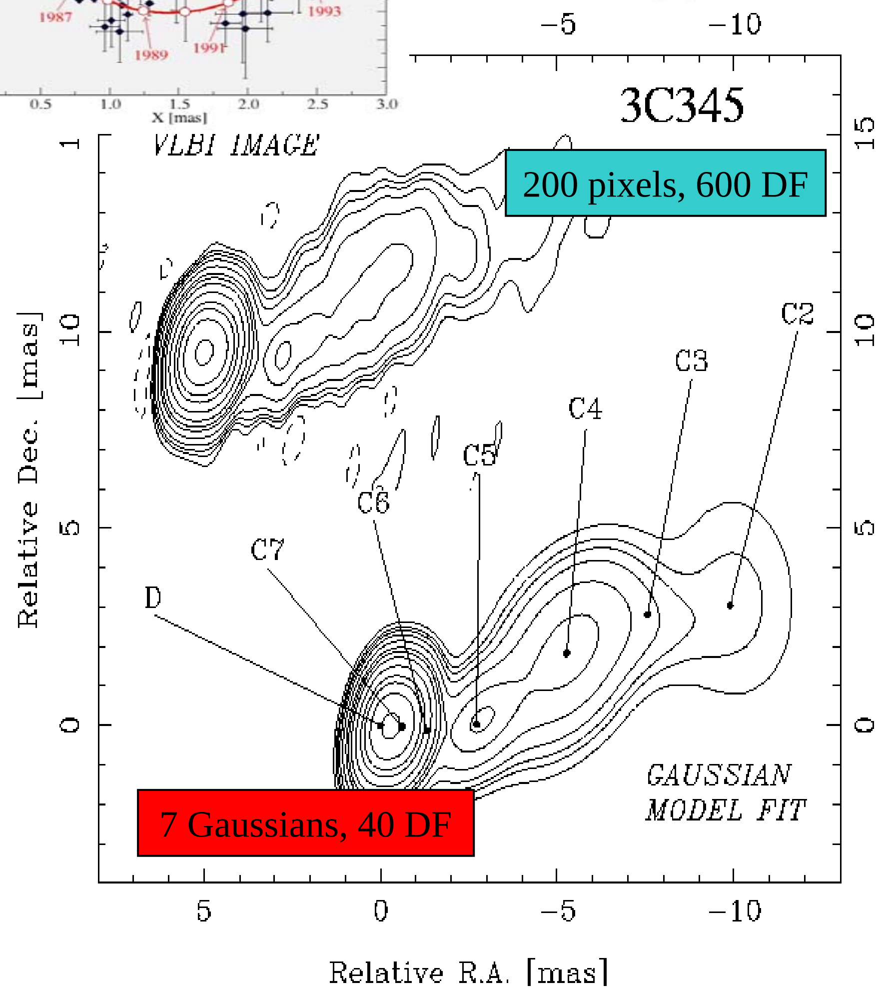
Major problem of the present high-resolution radio observations:
Most of information inferred from the data remains essentially one-dimensional (flux variations, spectra, trajectories, profiles of brightness, spectral index or degree of polarization, etc…) which limits severely the cross-section between data and theory. In the future, this will also limit the possibilities for comparison between radio observations and observations in other spectral domains.

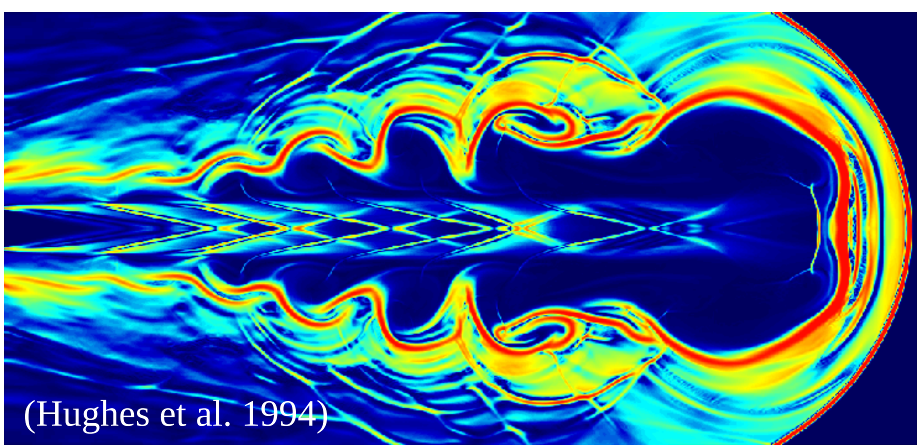
Information from images

- **Observations:** **1D** (routinely), **2D**(SoA)
- **Models (relativistic).**
  Analytical: **2D** (routinely), **3D(t)** (SoA)
  Numerical: **3D** (routinely), **3D(t)** (SoA)
- **Problems:** connecting predictions (**p**,**v**,ρ) to observables ($\mathbf{S}_\nu$, α, β_{app}). Elusive **B** , Γ_j and $\mathbf{M_j}$
- **Solution:** find a way to extract reliable 2D information from images! High-fidelity images and novel reduction and analysis techniques are much needed!





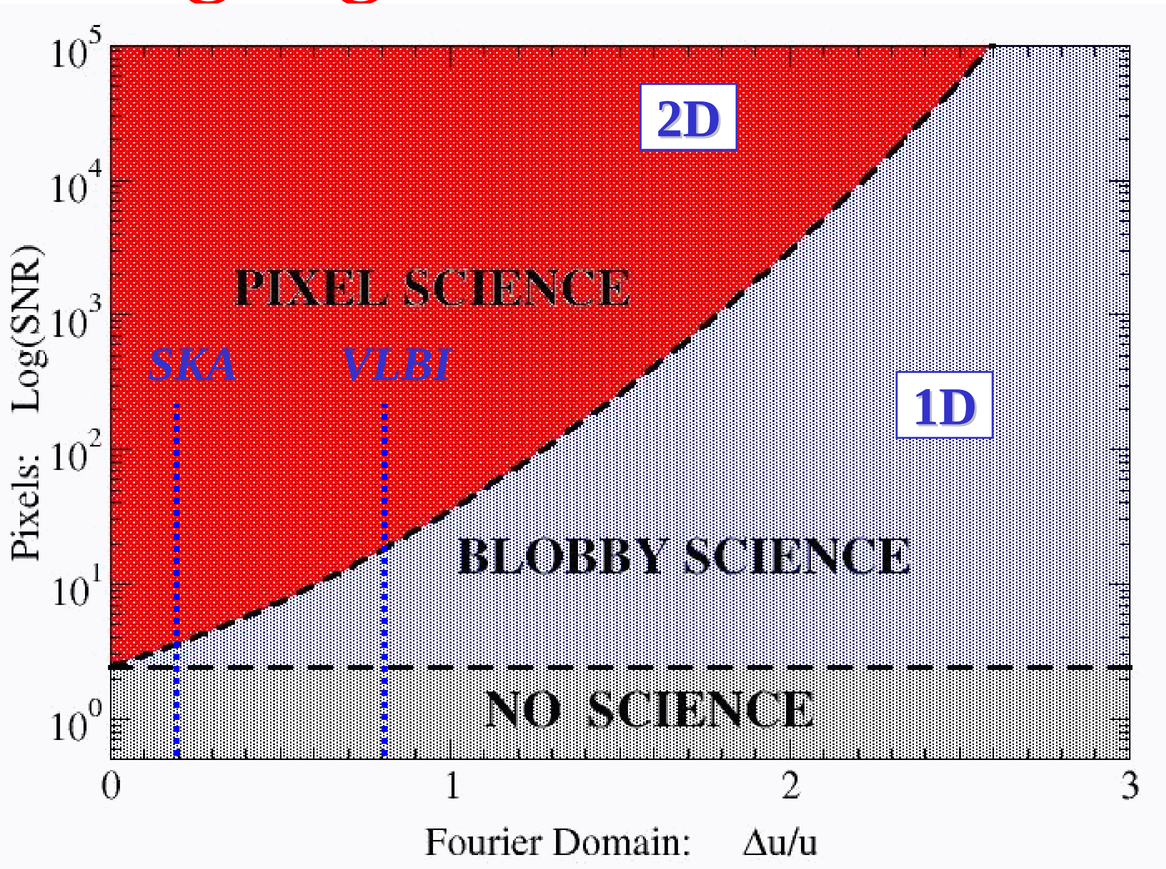



(Hughes et al. 1994)

Future Imaging Science

- Future advances in all aspects of high resolution studies will require “pixel-based” interpretation of data as opposed to the “blob-based” interpretation most commonly used at present.

- Need high-resolution interferometric imaging with <u>reliable pixels down to SNR~5</u> (in current VLBI images one can trust pixels with SNR>20).



see poster by Lobanov

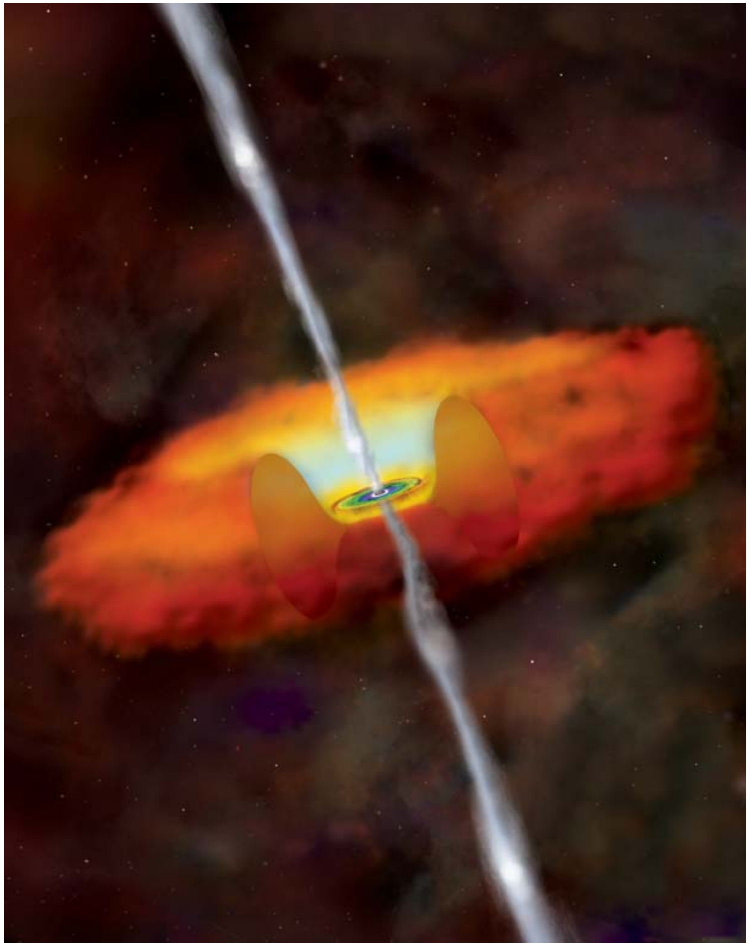
Synthetic view of AGN

SMBH: all bands, interferometry, spectroscopy

Accretion disk: optical, high-energy – structure and evolution of AD

BLR/NLR: optical, UV, high-energy – extent, morphology, matter composition

Torus: IR, optical, UV, radio – physics of molecular material



Outflow: radio, optical, X-ray – high fidelity imaging

Galaxy: all bands – galaxy – SMBH connection; formation and co-evolution og galaxies and SMBH

IGM: all bands – energy transport into IGM

Evolution: all bands – surveys, BH census and

Fundamental Questions

- Where does the emission come from and how is accretion energy converted to radiation? Energy extraction mechanism?
- Is there a unified model for all of the different types of AGN? Can we draw an evolutionary diagram for AGN?
- What is the relationship between the SMBH and the host galaxy? Which forms first and what causes the excellent correlation between black hole mass and bulge velocity dispersion.
- Do all galaxies have SMBH? What causes the activity phase in a galaxy?
- Is general relativity correct in the vicinity of a SMBH ? The strong gravity limit.
- How are AGN jets produced and collimated?
- What is the physics of the relativistic outflows on pc to Mpc scales? How do they interact with, and affect, the host galaxy.
- Are multiple SMBH common in AGN, and how do they form and evolve?

Summary

• Enormous progress in the field of AGN studies

• AGN and jets are far more common than it was expected even only a decade ago

• Jets can be used for a multitude of studies related to physics of relativistic flows and, as well, to more general questions about AGN

• There is a variety of processes governing the dynamics and emission from AGN, but the underlying physics may be simpler (and more fundamental!) than that which we are currently employing.

• Future advances in high-resolution studies of AGN (and many other objects) will depend on our ability to obtain a high-fidelity, two-dimensional information about structures observed on submilliarcesond scales.