Radio sources

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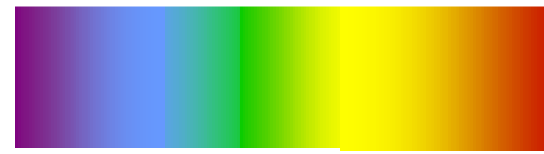
Outline

- Introduction
  - Continuum and spectral line emission processes
  - The radio sky: galactic and extragalactic
- Active Galactic Nuclei (AGN)
  - A brief history of their discovery
  - Observational properties
  - Standard unified model
  - Astrometric implications
- Imaging AGN
  - The quest for resolution
  - From connected arrays to VLBI

Radio emission processes

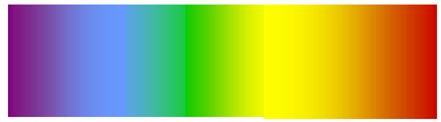
Electromagnetic emission can be divided into two types:

- Continuum emission
  - → emission over a very broad frequency range
  - → usually due to the acceleration of charged particles moving with a wide-range of energy

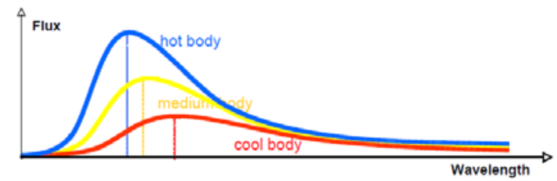


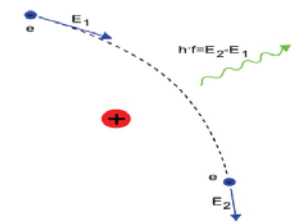
- Spectral line emission
  - → emission over a very narrow frequency range
  - → usually due to the discrete transitions in the internal energy states of atoms or molecules

Continuum emission

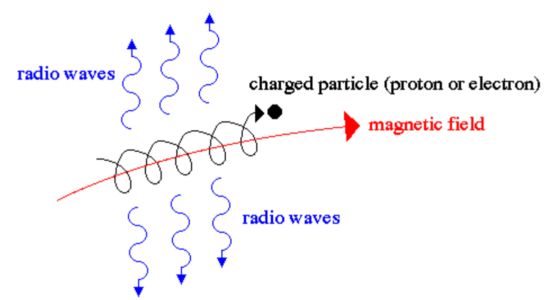


- Thermal emission
  - Black body radiation for objects with temperature T ~3-30 K
  - Bremsstrahlung (free-free) emission: deflection of a charged particle (electron) in the electric field of another charged particle (ion)



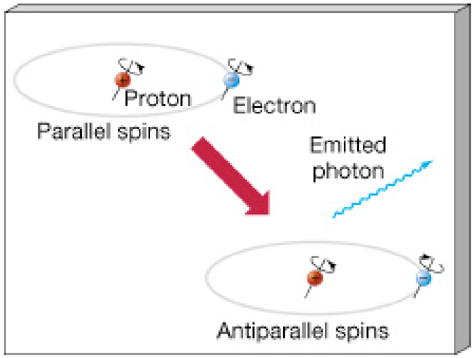


- Non-thermal emission
  - Synchrotron radiation: relativistic electrons spiraling around weak magnetic field lines

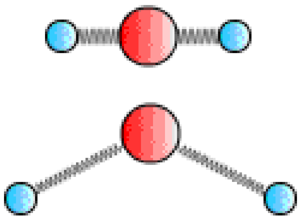


Spectral line emission

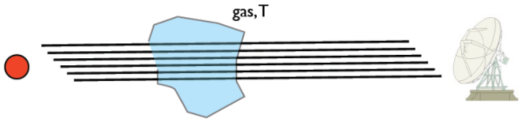
- Neutral hydrogen (21 cm)
  - spin-flip transition between high-energy state and low-energy state of the H atom (aligned vs opposed spins for p+ and e-)



- Molecular lines (CO, CS, CN,…)
  - produced by changes in the vibrational or rotational states of their electrons (due to collisions or interactions)

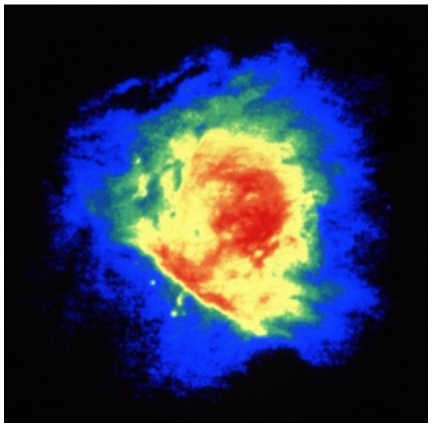


- Maser emission
  - Amplification of incident radiation passing through clouds of gas

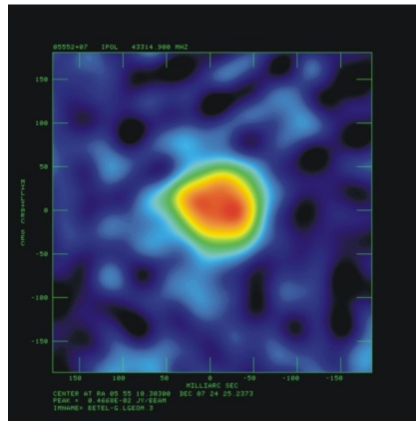


The radio sky: galactic objects

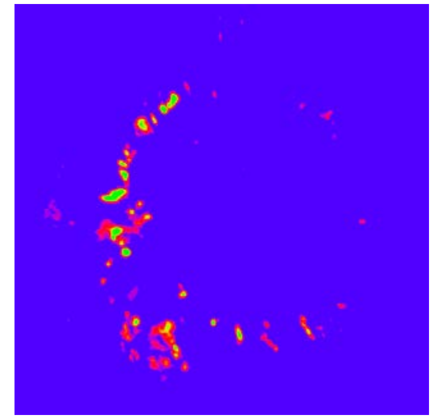
Ionized gas in the Orion nebula



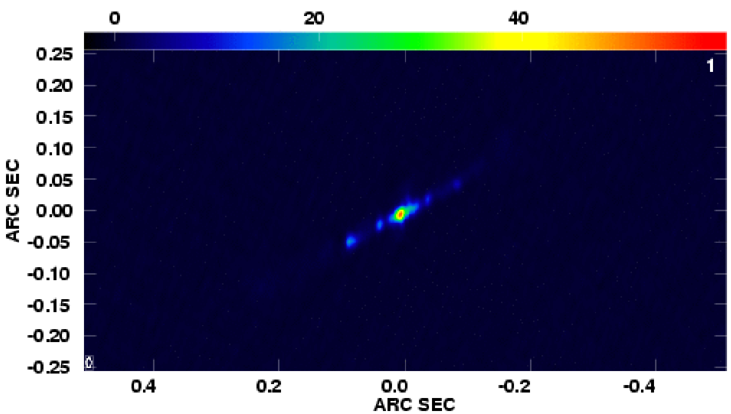
Betelgeuse



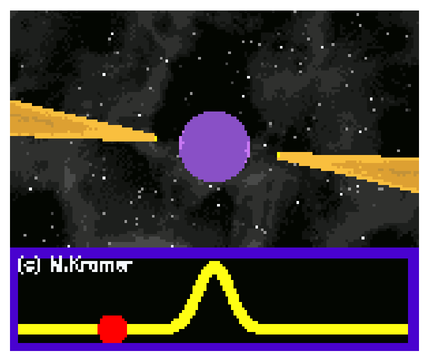
Masers around the star TX Cam



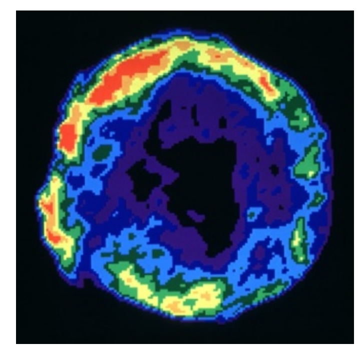
SS 433 (X-ray binary)



Pulsars



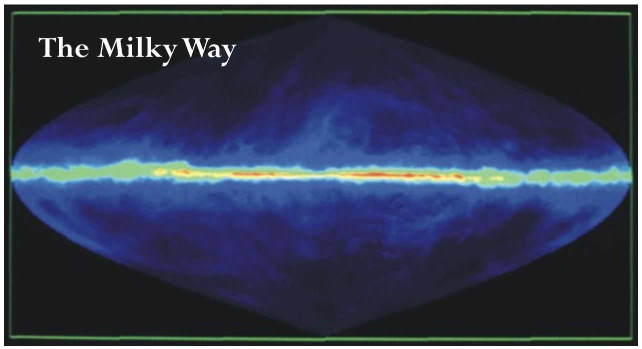
Supernova remnant

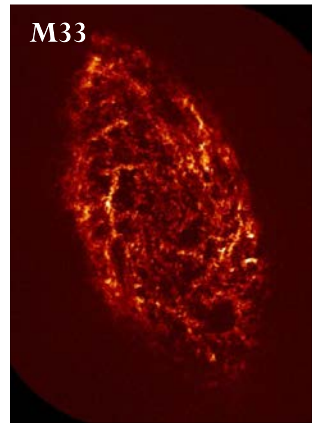


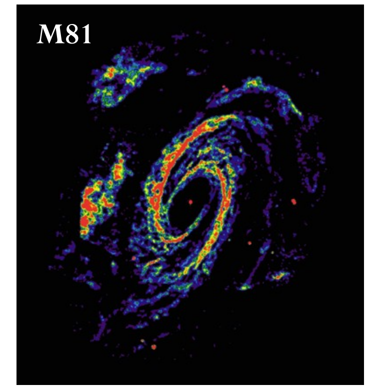
Credits: M. Kramer (pulsar animation) – all other images courtesy of NRAO/AUI

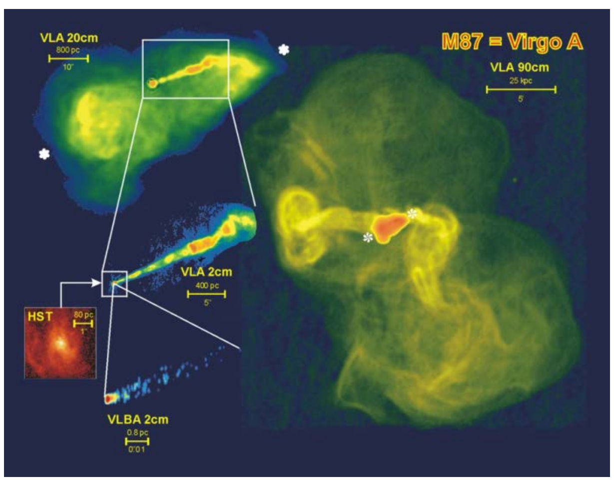
The radio sky: galaxies & AGN

Atomic hydrogen emission

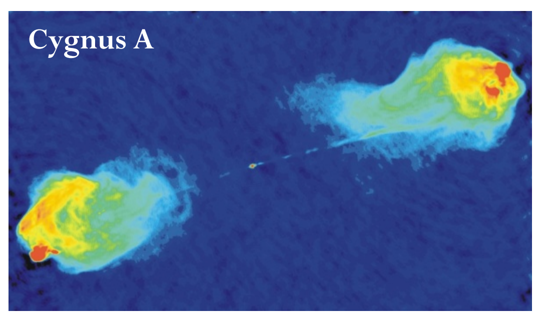


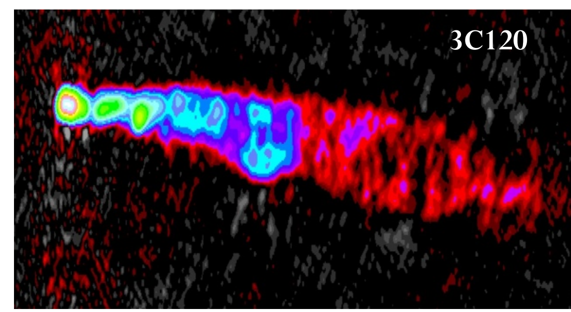






Continuum emission





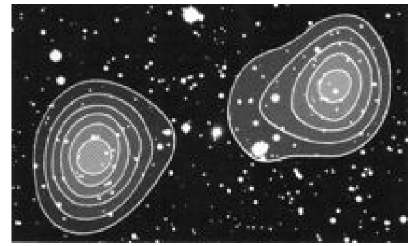
Images courtesy of NRAO/AUI

Active Galactic Nuclei (AGN)

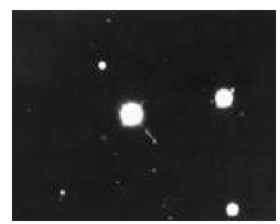
AGN: brief history

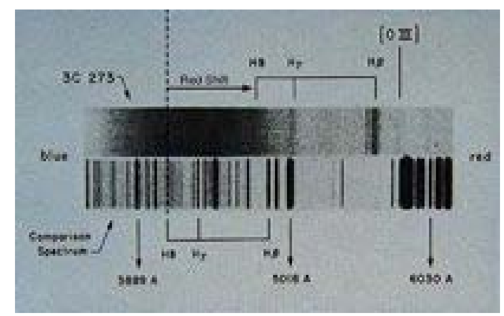
- 1949: identification of two strong radio sources (Cen-A, Virgo A) with nearby galaxies (Bolton et al.)

- 1954: identification of the radio source Cyg-A with a distant galaxy (Baade & Minkowski)



- 1963: discovery of quasars (quasi-stellar radio source)
  - ➢ Identification of 3C273 with a faint 13th magnitude star-like source… but with emission lines shifted longer wavelengths by 16%





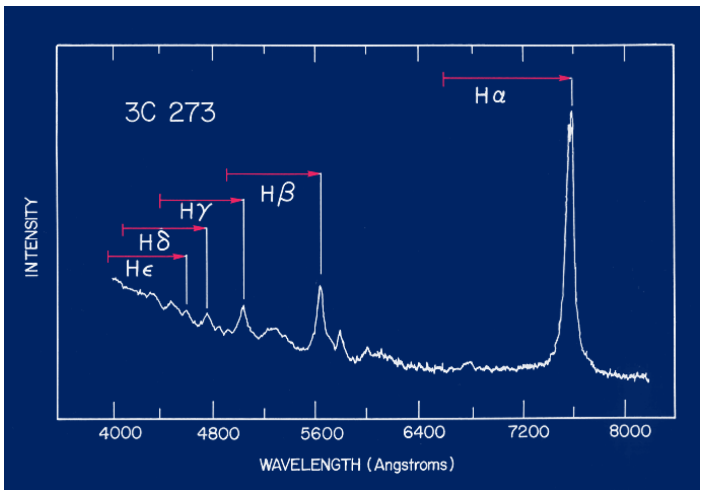
Schmidt (1963)

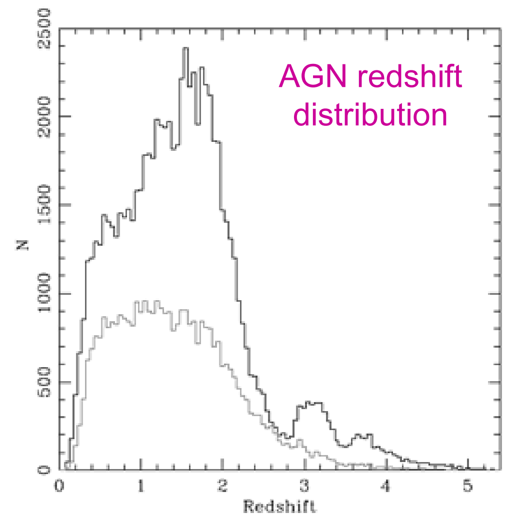
→ most distant known object in the Universe at the time but also intrinsically the most luminous one

→ first member of a new class of objects now referred to as « Active Galactic Nuclei » (AGN)

AGN distances

- AGN are located at cosmological distances
- Distance is measured by redshift: $z = \lambda - \lambda_0 / \lambda_0$

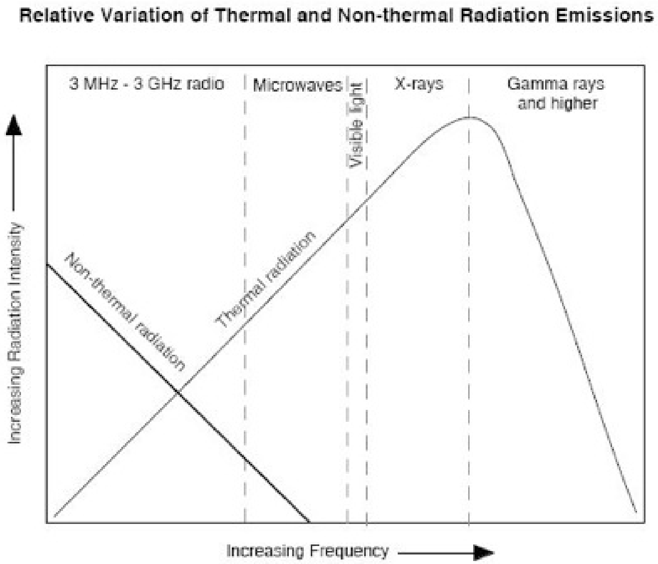


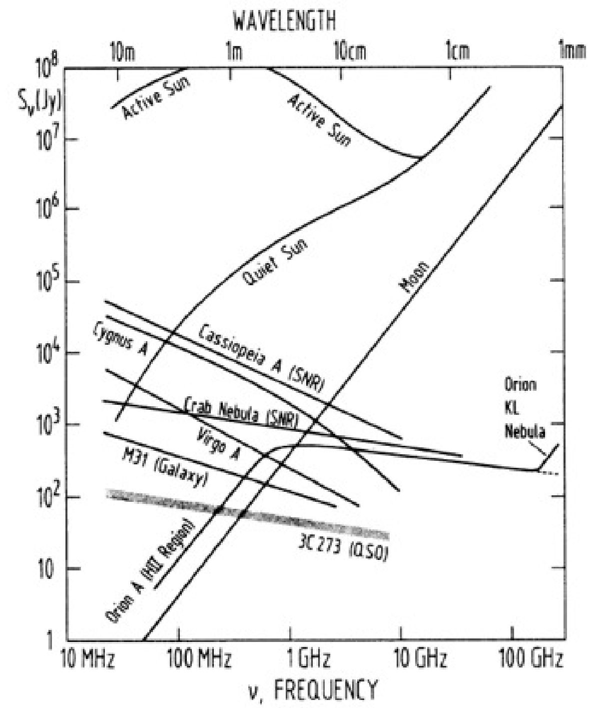


Schneider et al. (2007)

- highest-redshift quasar known at present is at z=7.54 while the highest-redshift radio source is at z=6.21
- AGN have no detected proper motions

AGN spectra



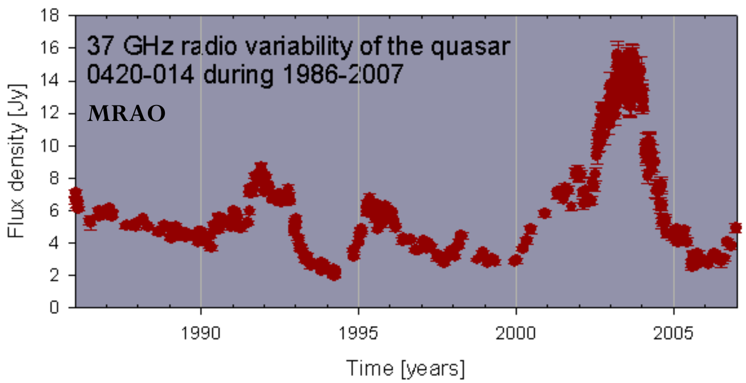


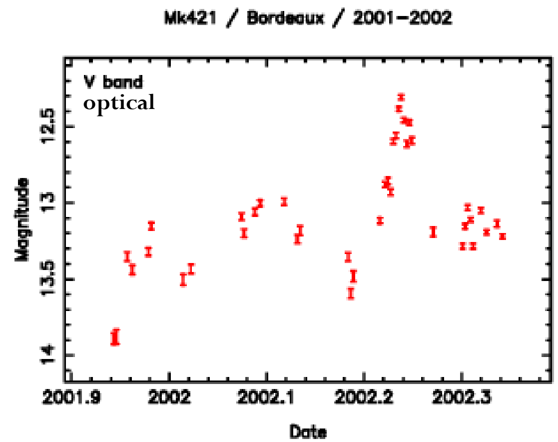
- Non-thermal emission
- About 15-20% of AGNs are « radio-loud » while the rest are « radio-quiet »

AGN variability

AGN may vary at any wavelength (from radio to gamma-rays) on timescales of minutes to years

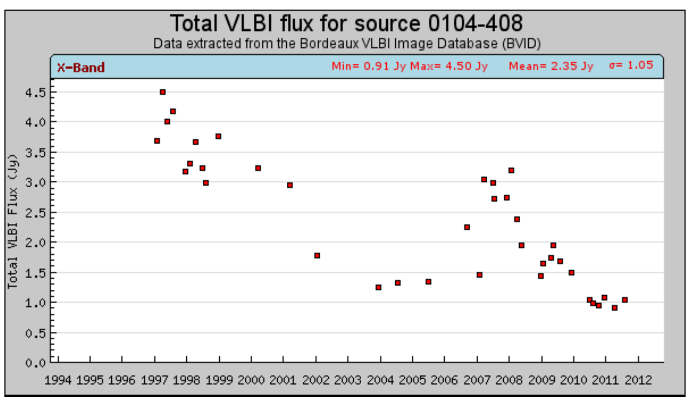
Years

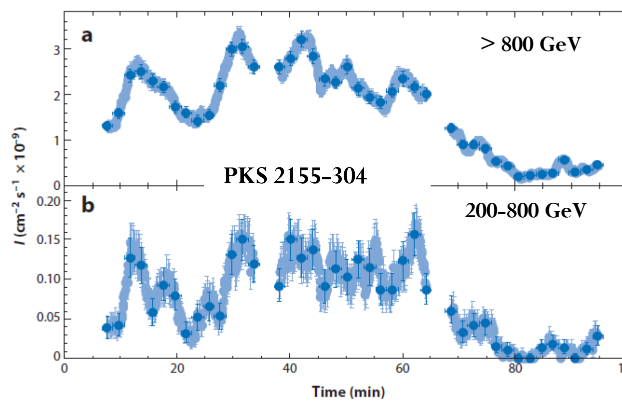




Months

Years





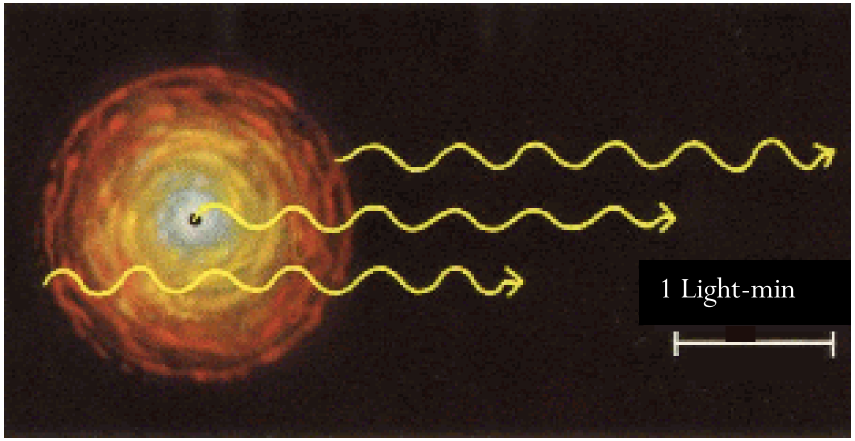
Hours

Aharonian et al. (2008)

AGN size

Intrinsic fast variations imply very small physical size for the variable region

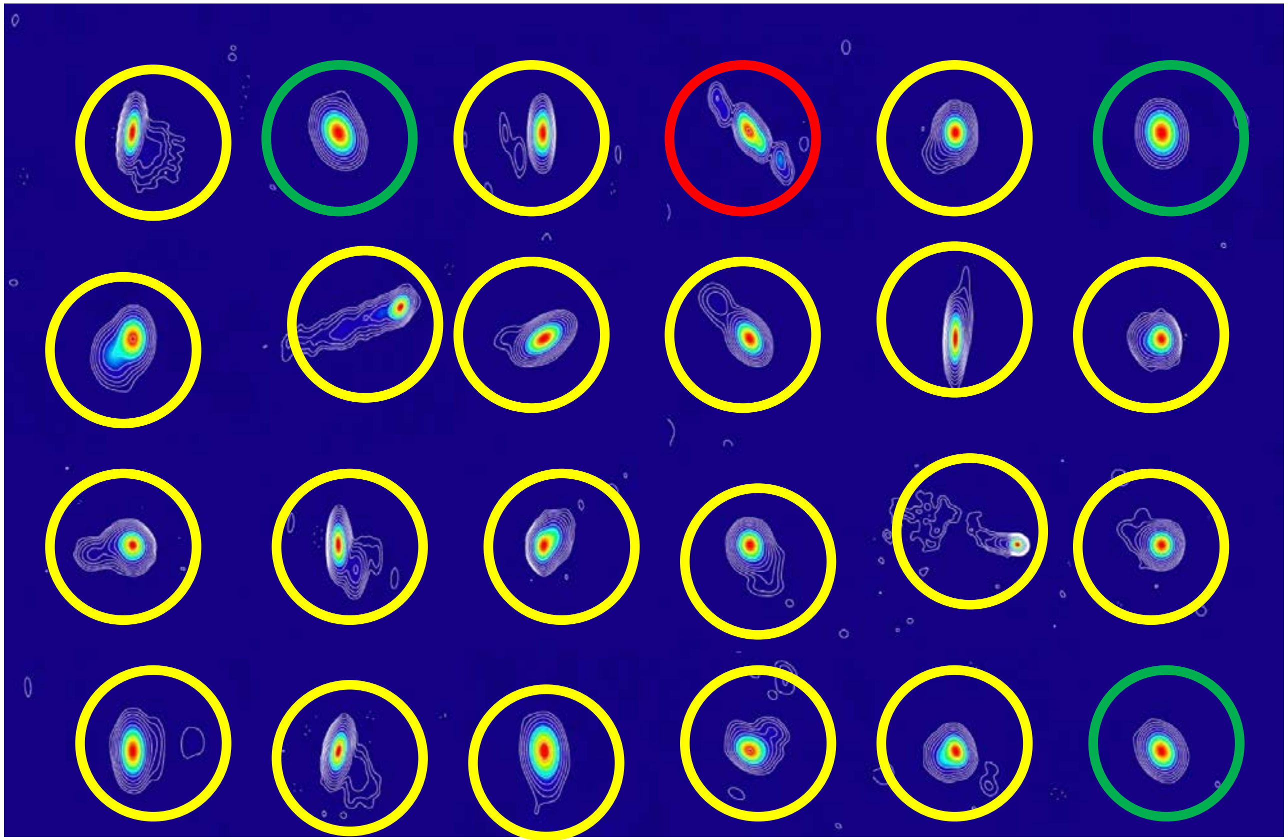
- An object that shows variability on a timescale Δt cannot be larger than c Δt.

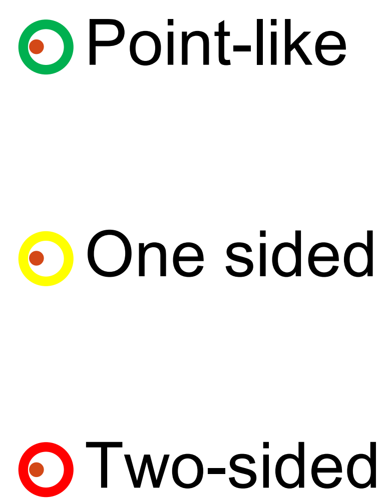


Credit: Gene Smith

- Variability on a scale of a few minutes means that the AGN size cannot be larger than a few light-minutes.

VLBI morphology



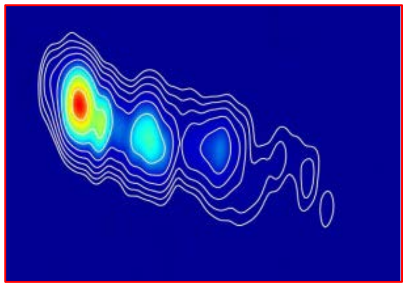


A sample of X band (8 GHz) VLBI maps with milliarcsecond resolution picked up randomly from the *Bordeaux VLBI Image Database (BVID)*

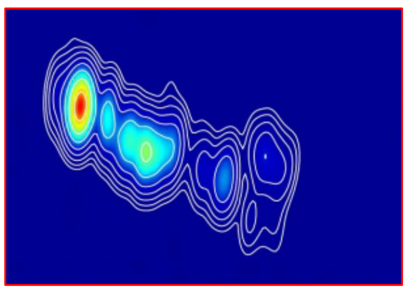
Time evolution

3C120

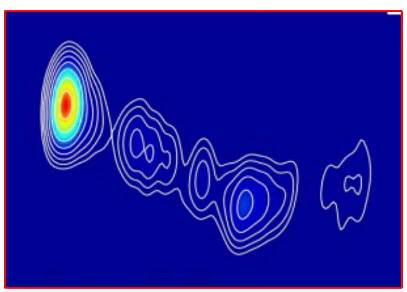
2000



2001



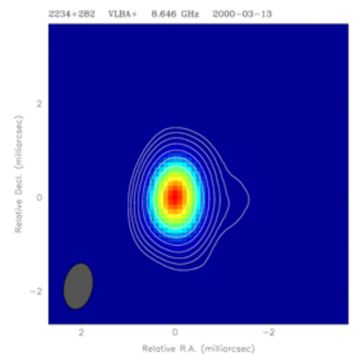
2003



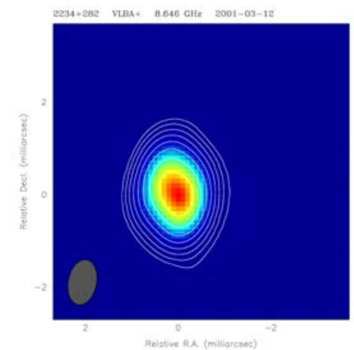
Credit:
Bordeaux VLBI
Image Database

2234+282

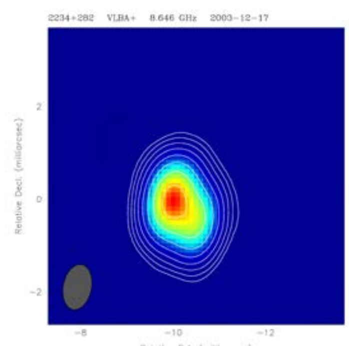
2000



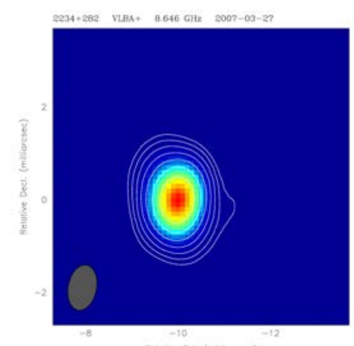
2001



2003

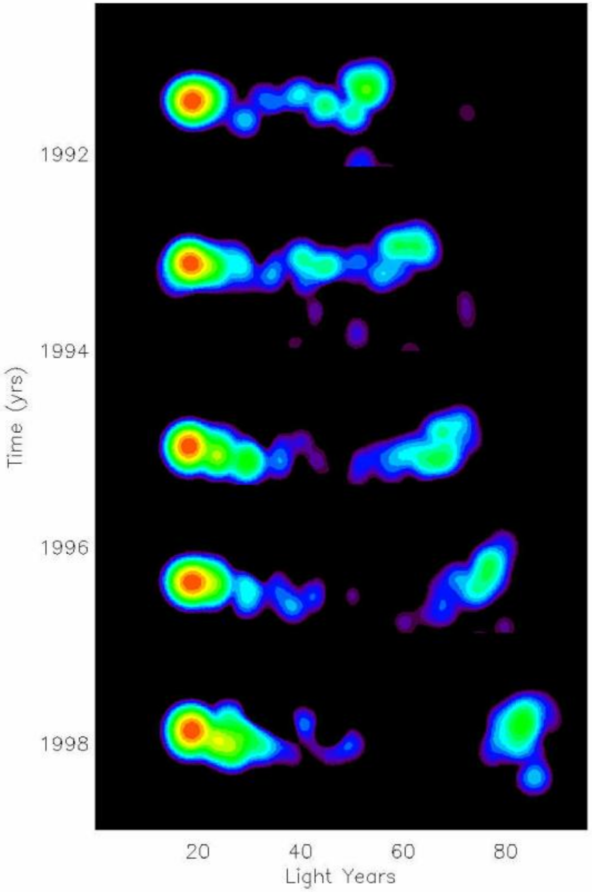


2007



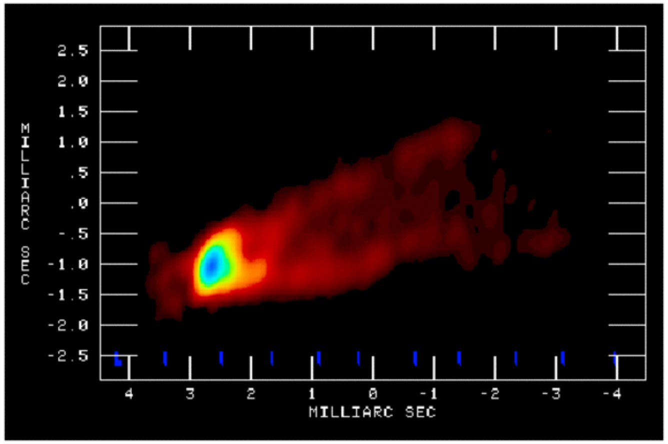
Superluminal motion: a VLBI discovery

- Apparent faster-than-light motions in AGN (known as superluminal motions)
  - 1971: through visibility curves (Whitney et al.)
  - 1981: through VLBI imaging (Pearson et al.)
- Interpreted as a geometrical effect in a relativistically-expanding source

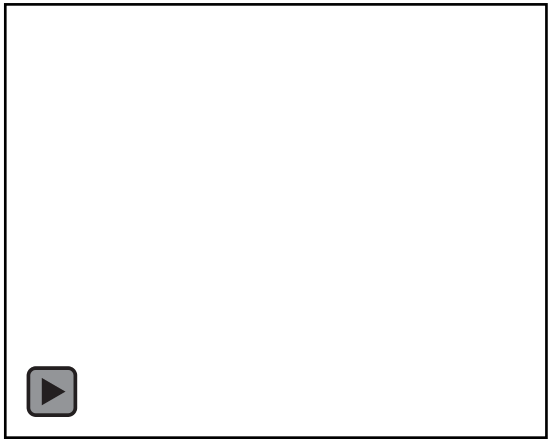


Images courtesy of NRAO/AUI

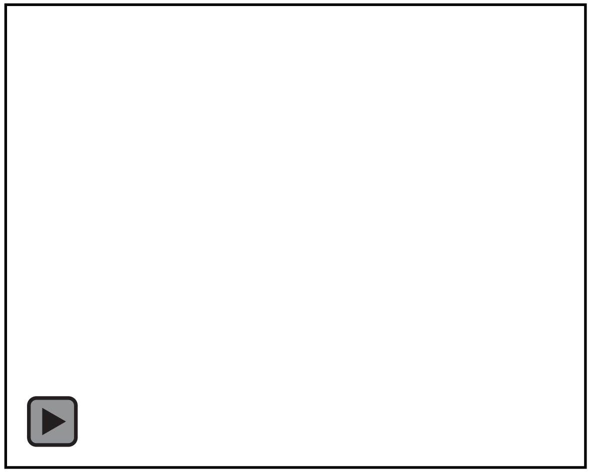
VLBI movies



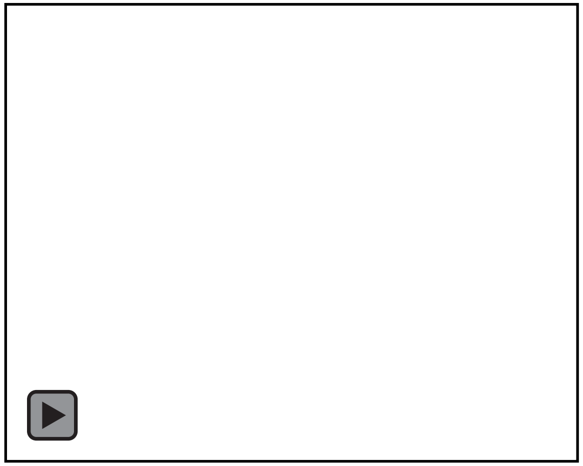
Credit: Craig Walker



Credit: MOJAVE database



Credit: MOJAVE database

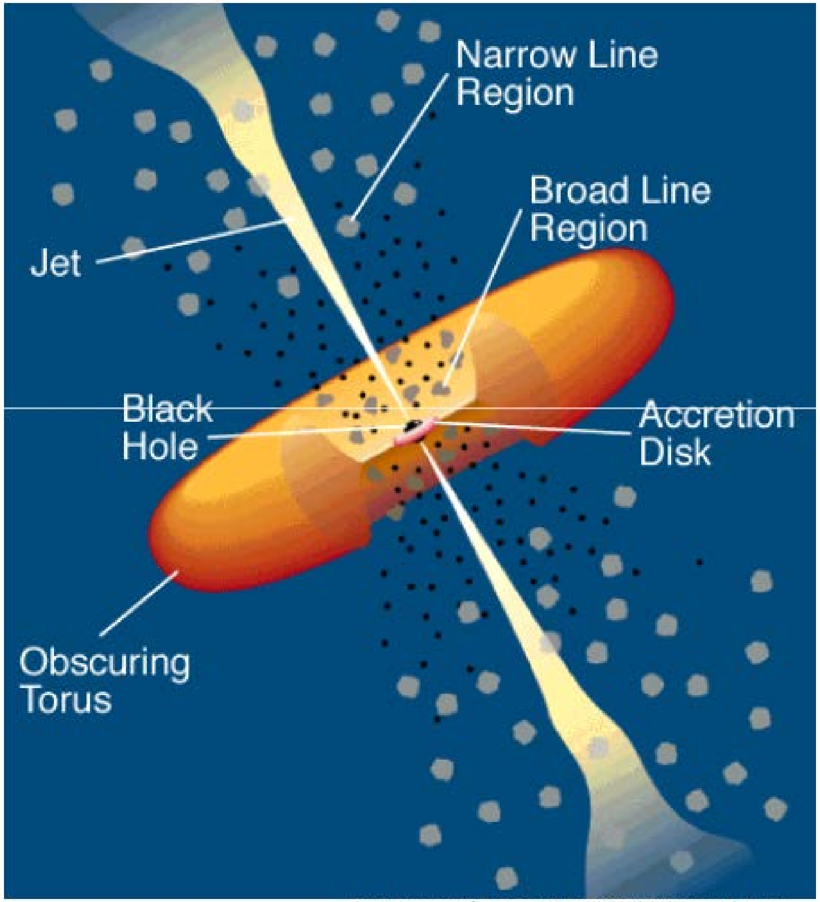


Credit: MOJAVE database

AGN standard unified model

<u>Major components</u>

- Black hole
- Accretion disk
- Torus
- Pair of relativistic jets



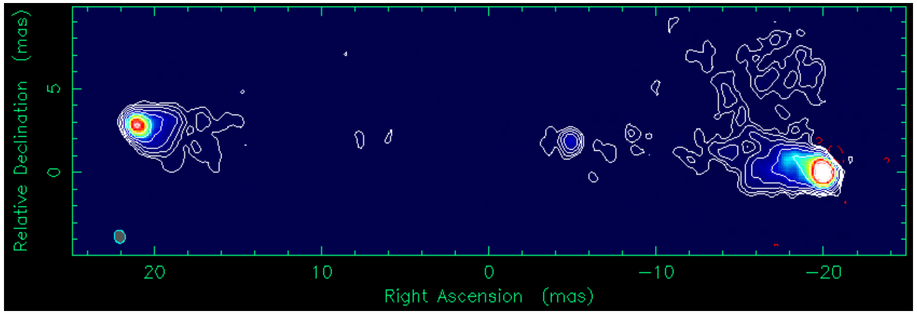
http://heasarc.gsfc.nasa.gov/docs/objects/agn/agn_model.html

Credit: C.M. Urry & P. Padovani

Impact of viewing angle

Object with jet close to the plane of the sky

- weak core
- two-sided jet



Polatidis et al. (1999)

Object with jet pointing towards the observer

- strong core
- one-sided jet

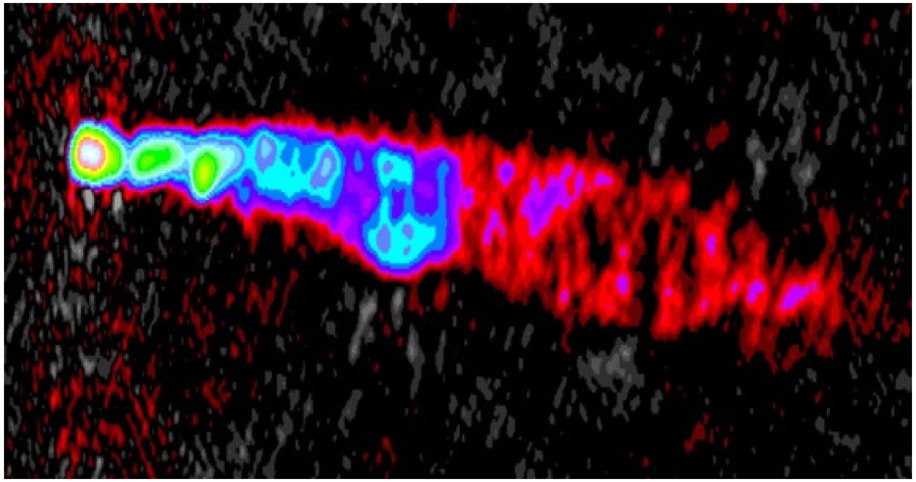
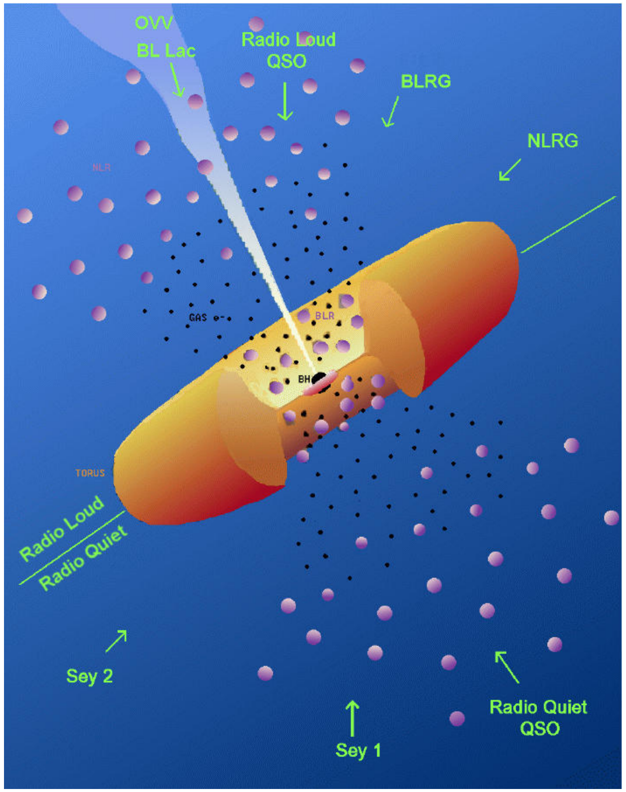


Image courtesy of NRAO/AUI and R. C. Walker

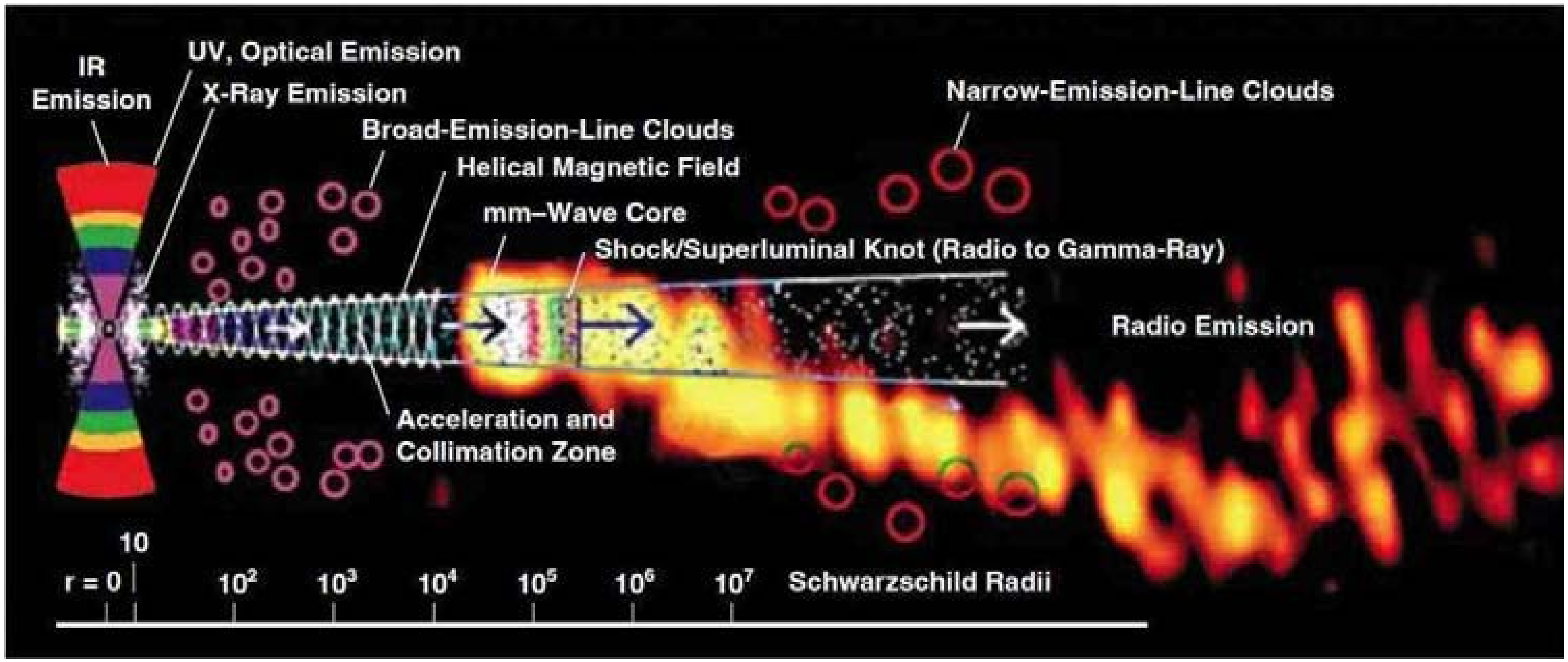
The AGN zoo

- Dichotomy radio-loud/ radio quiet
- Classification according to viewing angle
  - Radio loud: BL Lac, quasars, radio galaxies
  - Radio-quiet: QSO, Seyfert 1, Seyfert 2



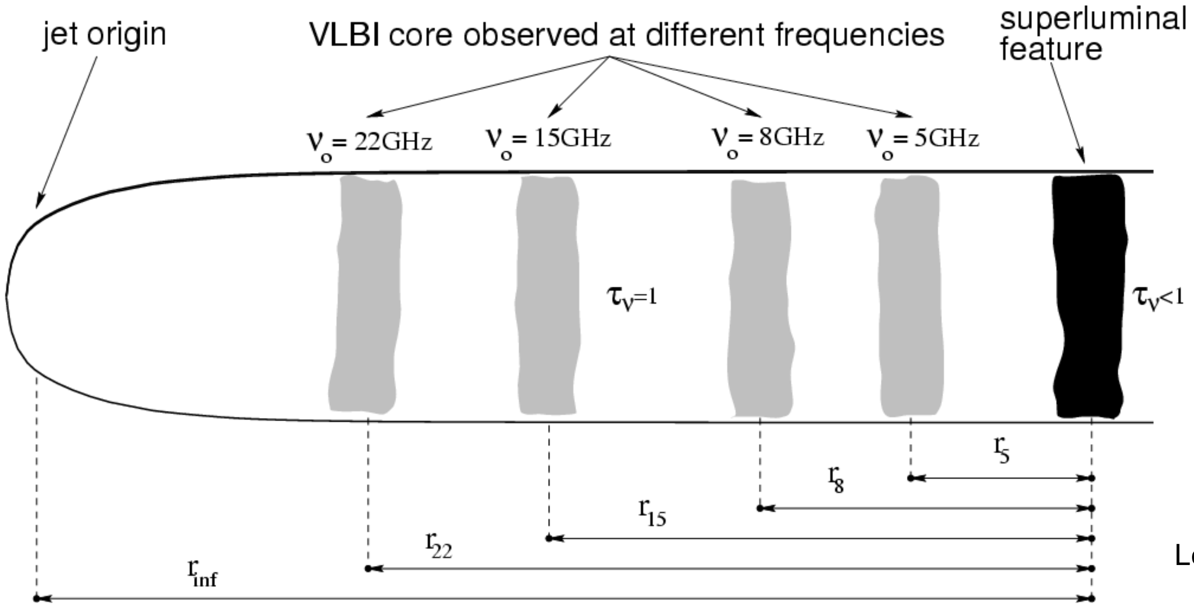
Credit: C.M. Urry & P. Padovani

Emission mechanisms in AGN



Credit: Alan Marscher

Jet properties

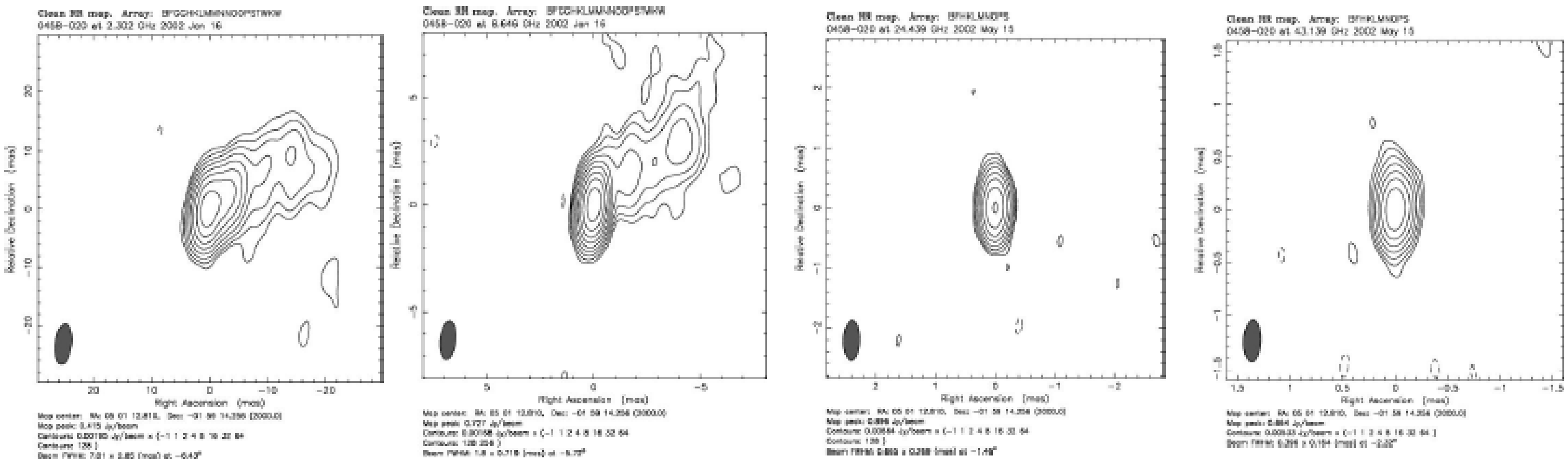


Lobanov (1996)

- Core emission not superimposed at different frequencies.
- Jet emission less prominent as frequency increases

Source structure vs frequency

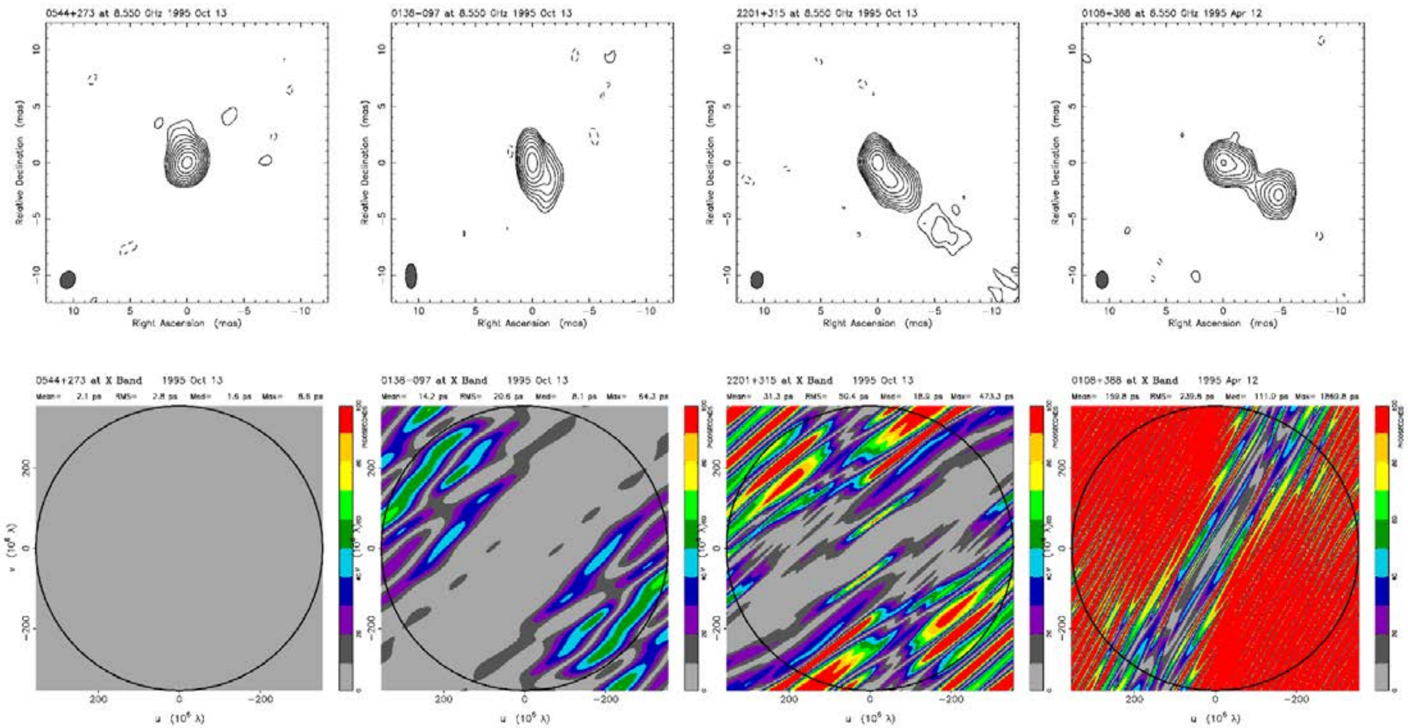
2 GHz | 8 GHz | 24 GHz | 43 GHz



Credit: Radio Reference Frame Image Database

➔Source structure gets more compact at higher frequencies

Astrometric implications



Source structure effect in VLBI delay

SI = 1
Excellent

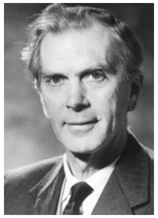
SI = 4
Very bad

The structure index (SI) – defined as the median « source structure effect » over the u-v plane – indicates the astrometric suitability of the sources.

Imaging AGN

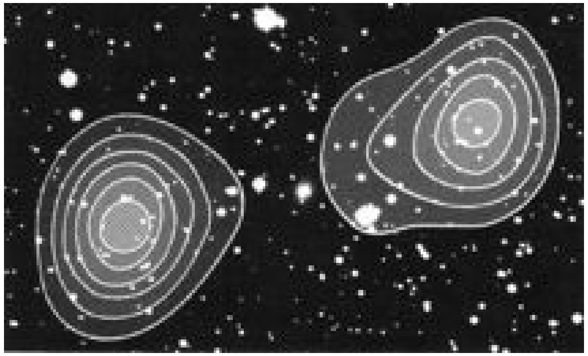
Radio interferometers

- Concept of aperture synthesis developed by Martin Ryle (receiving Nobel Prize in 1974)



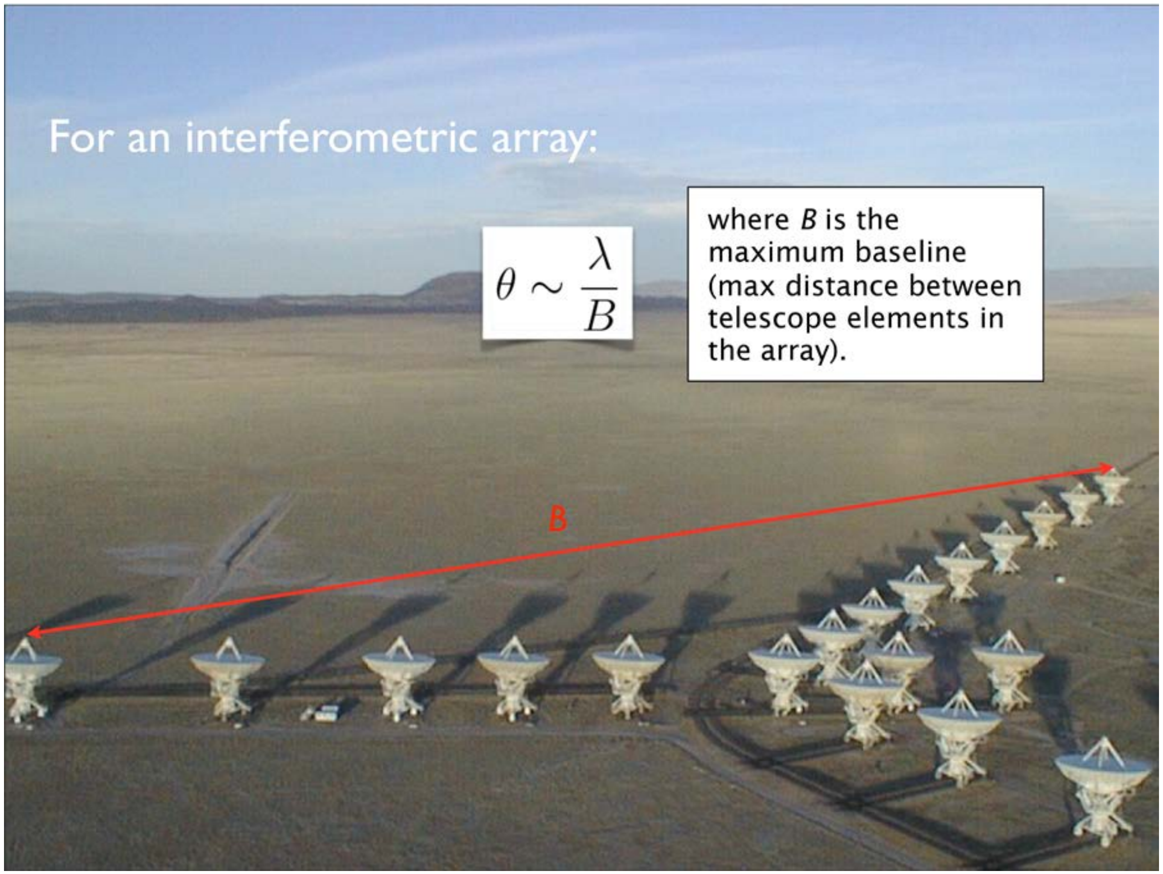
- First radio arrays with baselines of a few km built in the 1950s

In 1954, measurements of the radio emission from Cyg A revealed that it originates from a double structure



Resolution

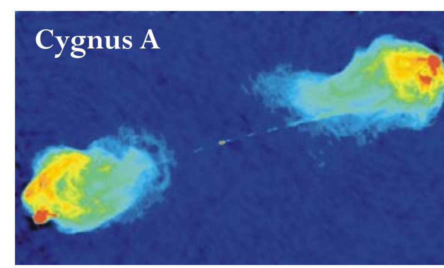
Very Large Array (27 antennas), 1980



Credit: Huib van Langevelde

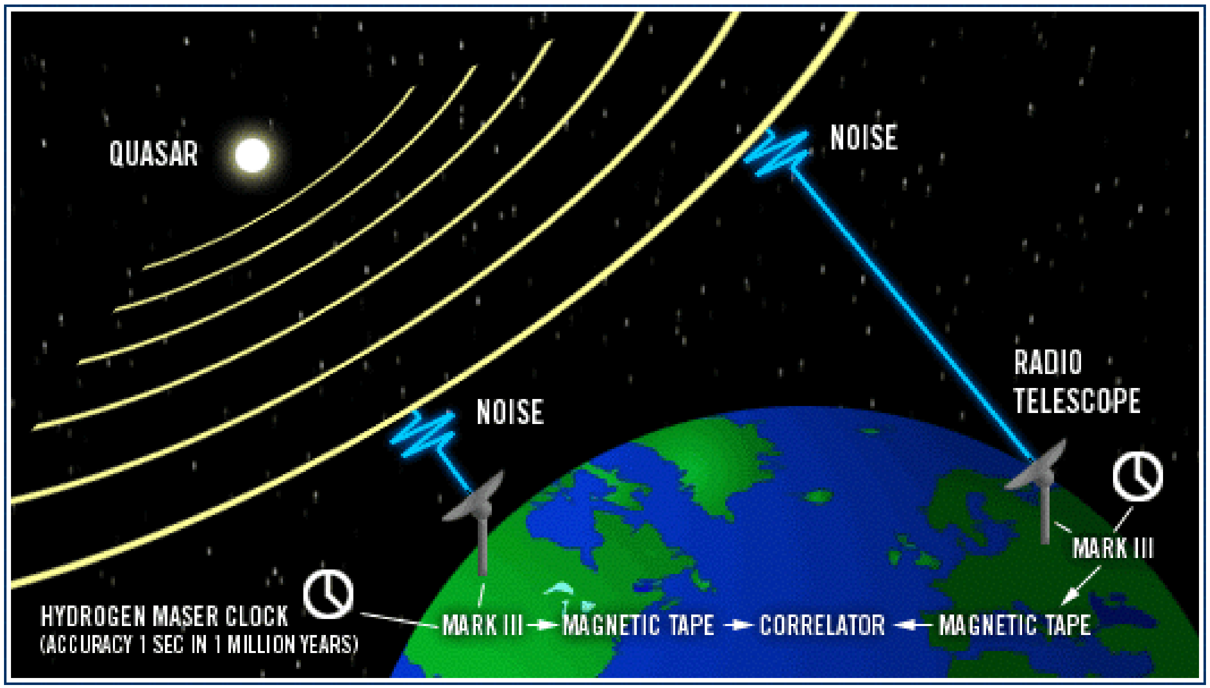
λ = 5 cm

D or B	Θ (″)
25 m	400
2.5 km	4
25 km	0.4



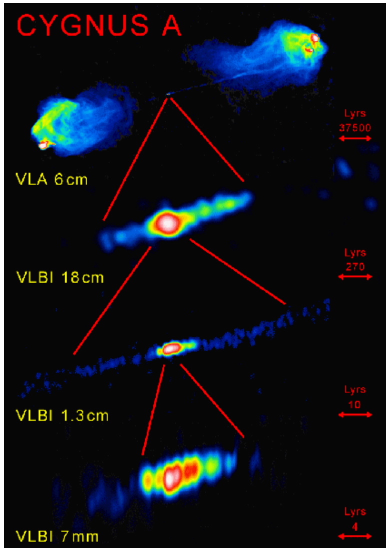
Very Long Baseline Interferometry (VLBI)

1967: First transatlantic baselines (USA-Sweden) detected compact radio sources

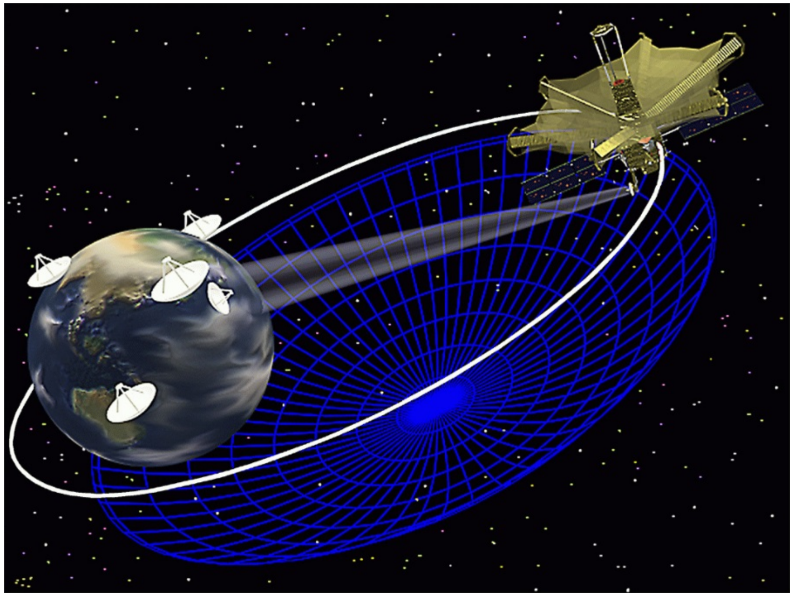


λ = 5 cm

B (km)	Θ (″)
10000	0.001 (1 mas)



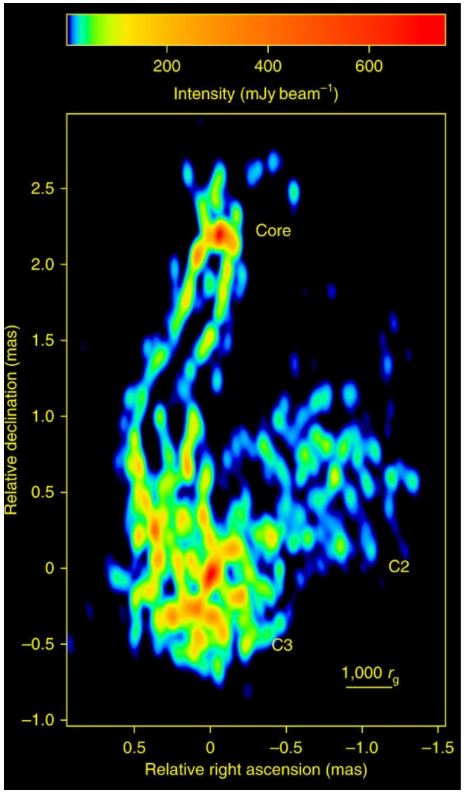
Space VLBI



λ = 5 cm

B (km)	Θ (mas)
10 000	1
20 000	0.5
200 000	0.05

Radioastron image of 3C84

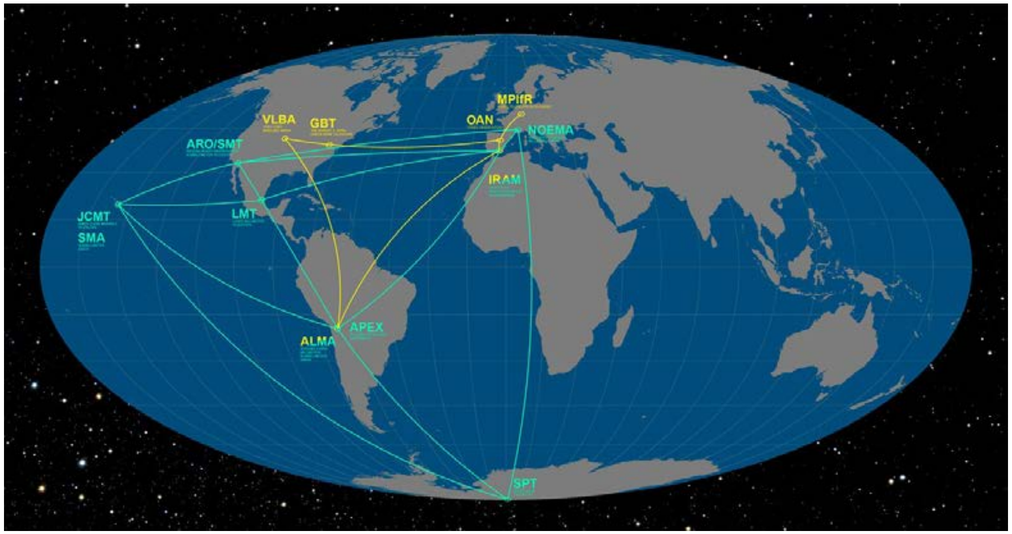


Giovannini et al. (2018)

- VSOP/Halca (launched 1997,operated until 2005), elliptical orbit with apogee 20 000 km
- Radioastron (launched 2011, operated until 2019): highly elliptical orbit (apogee 350 000 km)

VLBI at mm wavelengths

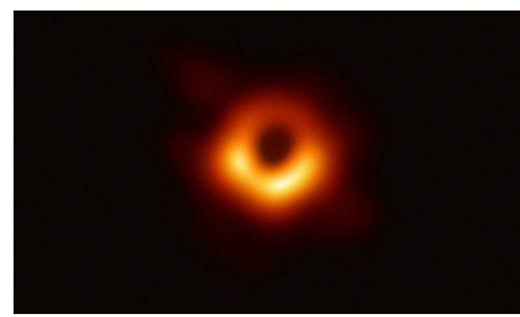
Event Horizon Telescope and Global mm VLBI array



B = 10 000 km

λ (mm)	Θ (mas)
10	0.2
3	0.06
1	0.02

- Shadow of the supermassive black hole at the center of M87 just imaged.
- Consistent with predictions from General Relativity



Event Horizon Telescope Collaboration (2019)

VLBI imaging surveys

- Bordeaux VLBI Image Database (2 & 8 GHz)
  http://bvid.astrophy.u-bordeaux.fr/
- Radio Reference Frame Image Database (2 & 8 GHz)
  http://www.usno.navy.mil/USNO/astrometry/vlbi-products/rrfid
- VLBA Calibrator Survey (2 & 8 GHz)
  http://www.vlba.nrao.edu/astro/calib/index.shtml
- MOJAVE data base (15 GHz)
  http://www.physics.purdue.edu/~mlister/MOJAVE/
- VLBI Imaging and Polarimetry Survey (5 & 15 GHz)
  http://www.phys.unm.edu/~gbtaylor/VIPS/vipscat/vipsncapindx.shtml

Acknowledgements

Information and figures presented in this lecture have been taken from the following sources:

- Mike Garrett's radioastronomy course
  https://www.astron.nl/~mag/dokuwiki/doku.php?id=radio_astronomy_course_description
- Huib van Langevelde's radioastronomy course
  https://www.strw.leidenuniv.nl/radioastronomy/doku.php?id=ra_2017
- NRAO Synthesis Imaging Workshops (2002-2012)
  http://www.aoc.nrao.edu/events/synthesis/2012
- NRAO image gallery
  http://images/nrao.edu/
- Bordeaux VLBI Image Database (2 & 8 GHz)
  http://bvid.astrophy.u-bordeaux.fr/
- Radio Reference Frame Image Database (2 & 8 GHz)
  http://www.usno.navy.mil/USNO/astrometry/vlbi-products/rrfid
- MOJAVE data base (15 GHz)
  http://www.physics.purdue.edu/~mlister/MOJAVE/