Multimessenger Approach: Radio Emission from (some) transients

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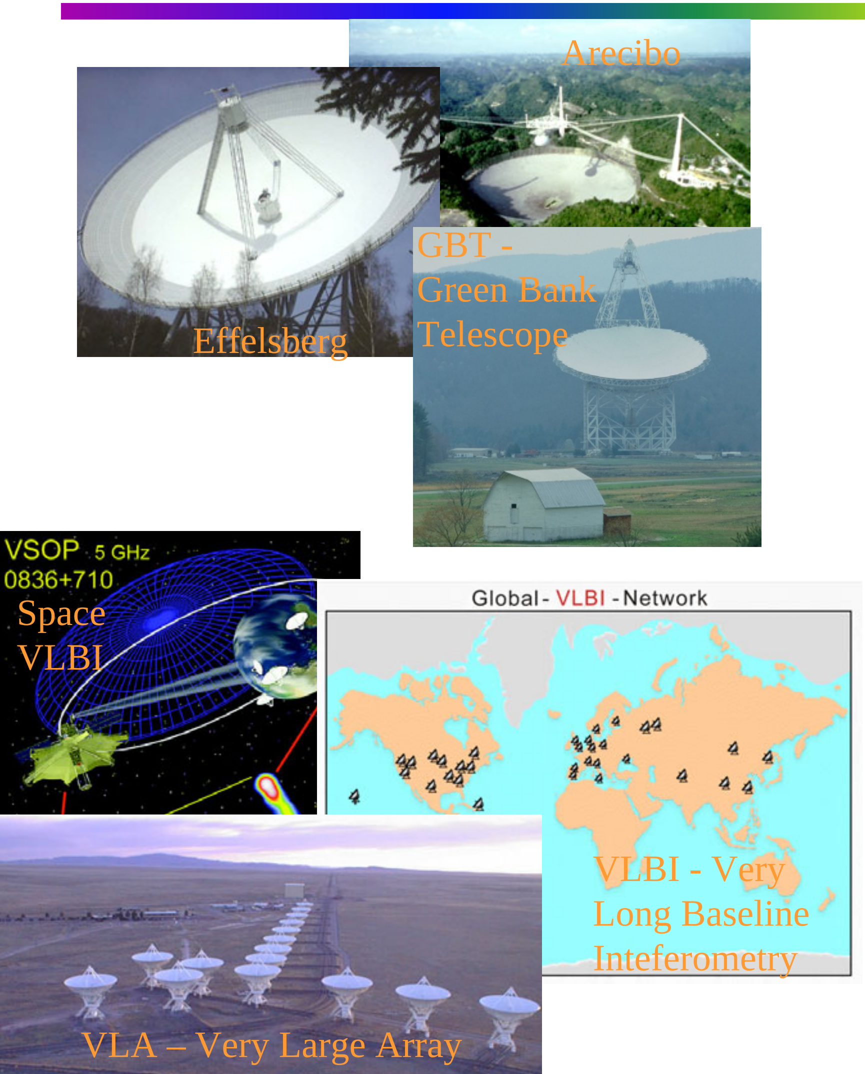
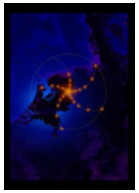
Great Radio Telescopes



Development Paths in Radio Astronomy

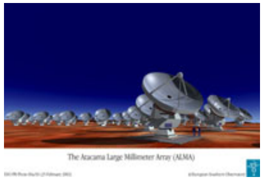
Improvements	Telescopes
1) Resolution. **2) Sensitivity.** **3) Frequency.** **4) Flexibility!**	see below

2006-2010: LOFAR



- "new" frequency windows
- 100 times more resolution
- 100 times more sensitivity
- very flexible digital beam forming

2007-2011: ALMA



- new frequency window
- 10-100 times more sensitivity
- 10-100 times more resolution

2012-2015: SKA

- 100 times more sensitive
- very flexible beam forming
- extreme frequency agility

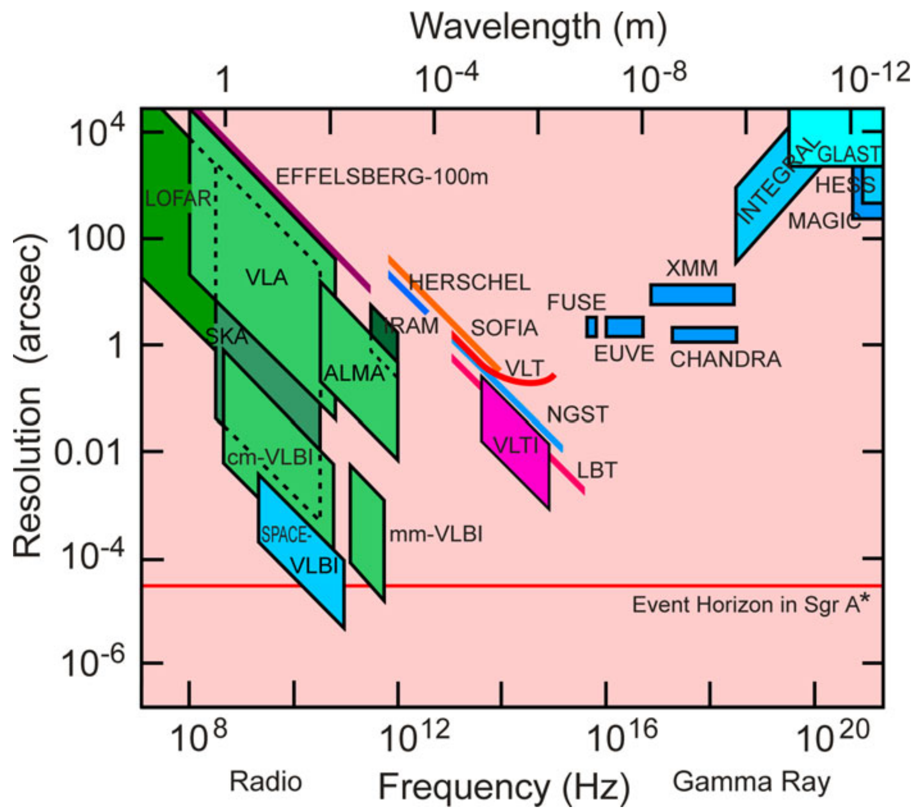
NOW: → eVLBI

promises rapid response

Factor 100 improvement in **all** areas within a decade over 5 decades of frequency!
This will be the largest step radio astronomy has ever made.

Resolution of Upcoming Telescopes

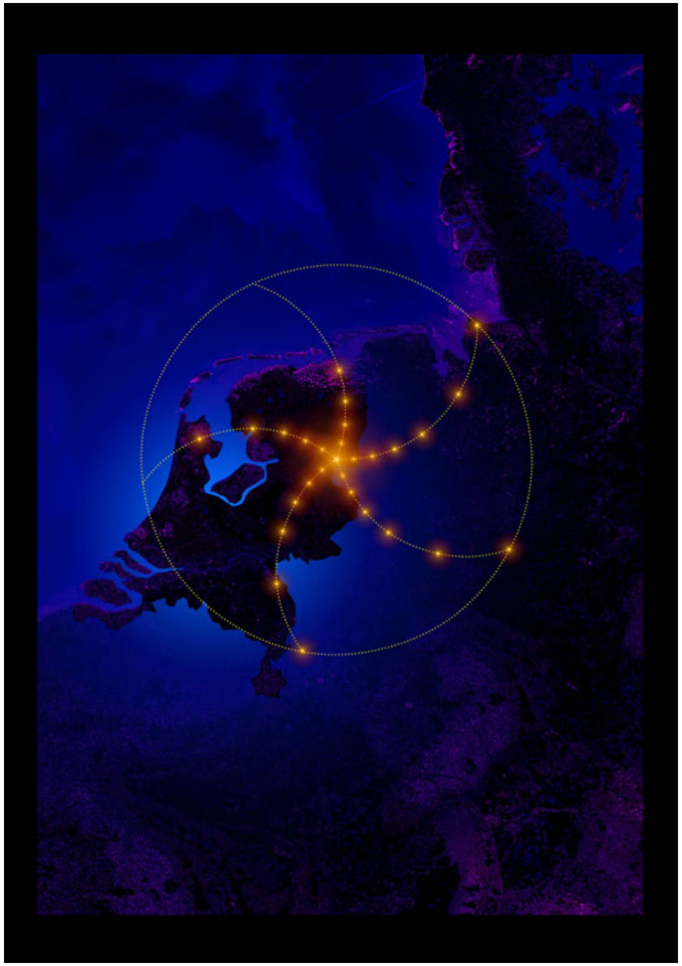
- The resolution of radio interferometers remains unchallenged.
- Even optical interferometers cannot probe the parameter range sensed by VLBI.
- Radio covers all possible scales with state-of-the-art instruments.



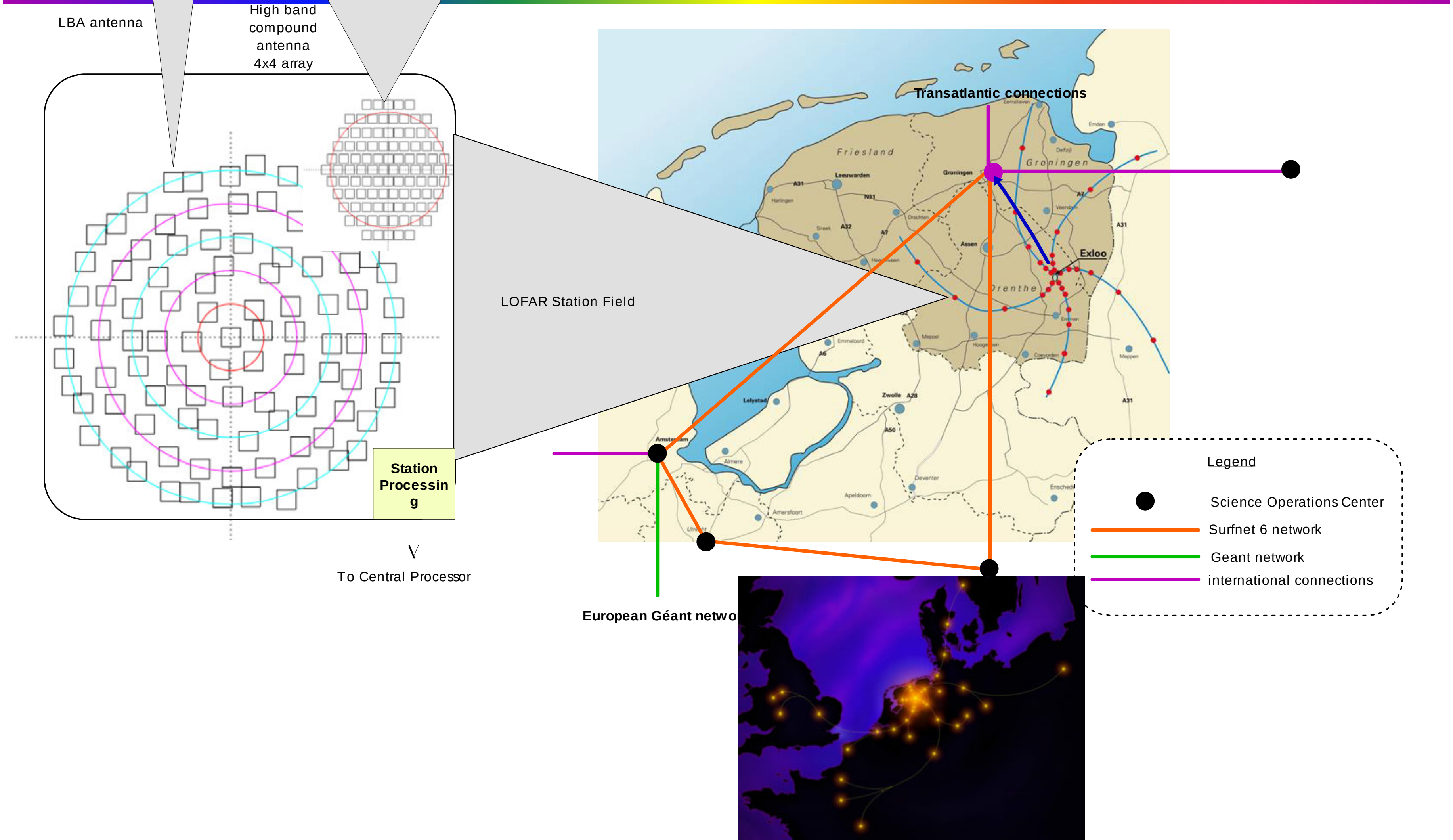
Denkschrift Astronomie (2000+)

LOFAR

- interferometer for the frequency range of 10 - 200 MHz
- array of 100 stations of 100 dipole antennas
- baselines of 10m to 400 km
- baselines up to 100 km are funded with 52 M€ by Dutch cabinet + 22 M€ from Northern Provinces
- core near Dwingeloo (Borger Odoorn/Exloo) and German boarder
- IBM Blue Gene/L supercomputer in Groningen: now
- Antenna roll-out: end 2006
- Ideal science applications:
  - Large surveys of the universe
  - Transients (cosmic and local)



LOFAR top-level architecture: Geometry view

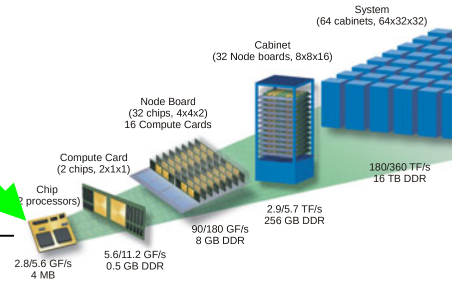


Extreme Flexibility: Electronic Beamforming

0.5 Tbit/s

25 Tflops

Blue Gene^{TM} (IBM)



Principles:

a) **E** is detected, interference can be performed (off-line) in computer

b) No quantum shot noise: extra copies of the signal are free!

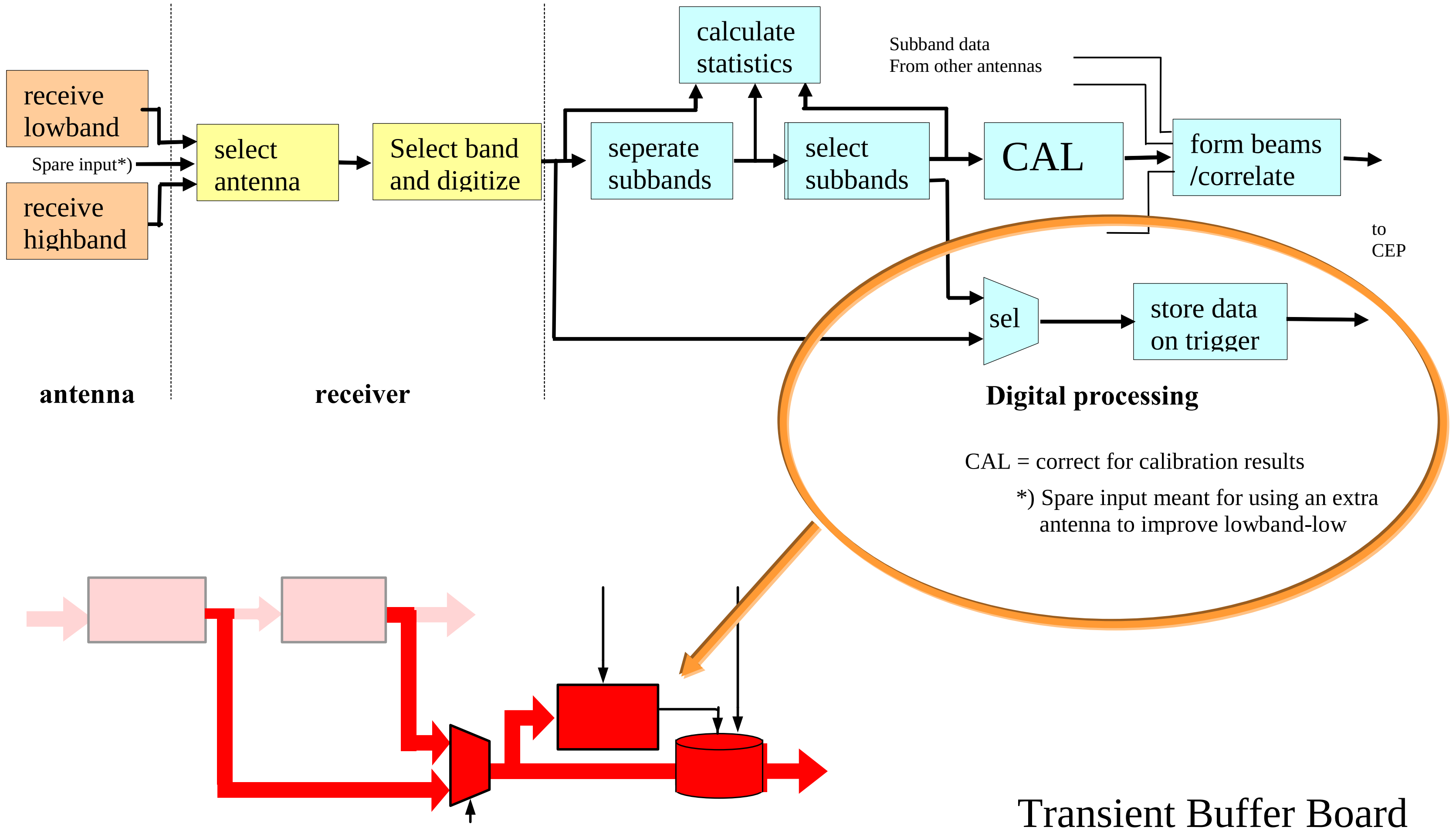
Consequences:

a) Can replace mechanical beam forming by electronic signal processing

b) Put the technology of radio telescopes on *favorable cost curve*

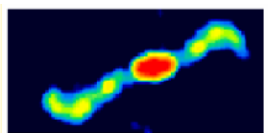
c) Also: multiple, independent beams become possible

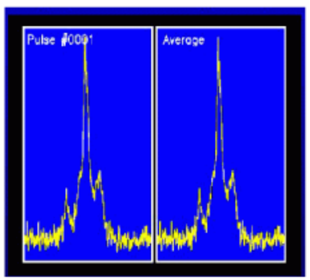
Remote Station Functionality

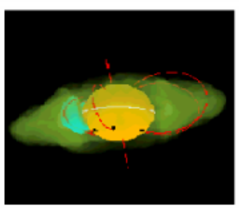


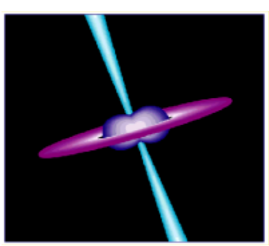
Transient Buffer Board

Transient Sources





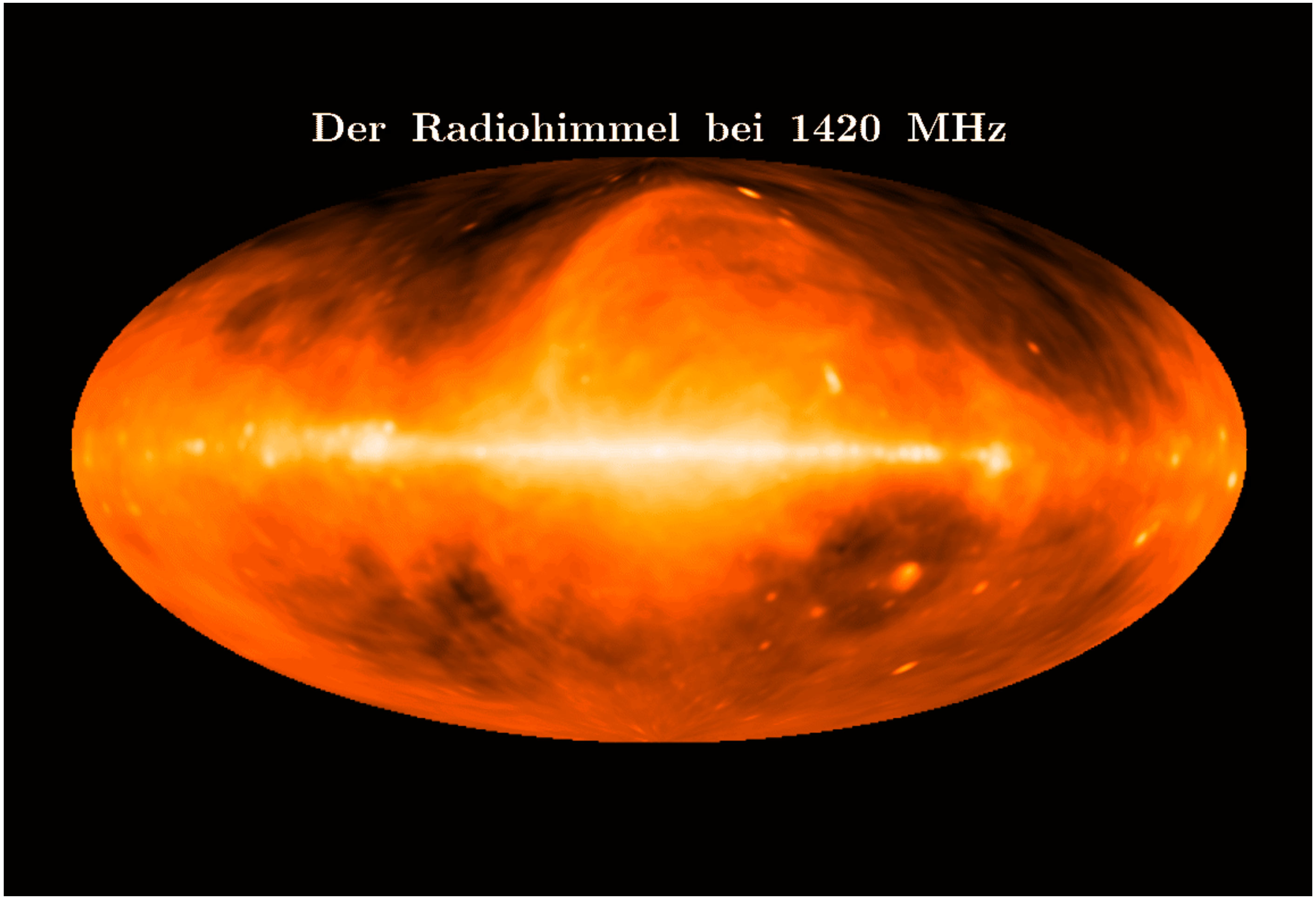




- X-ray Binaries (stellar mass black holes)
- AGN (supermassive black holes) – long-term var.
- Pulsars (neutron stars)
- CV's/Flare Stars
- LIGO Events (merging neutron stars)
- Supernovae
- Jupiter-like Planets
- Gamma-Ray Bursts (prompt emission and afterglows)
- Cosmic Rays & Neutrinos
- Meterorites
- … New sources …
  - Aliens, Airplanes, etc.

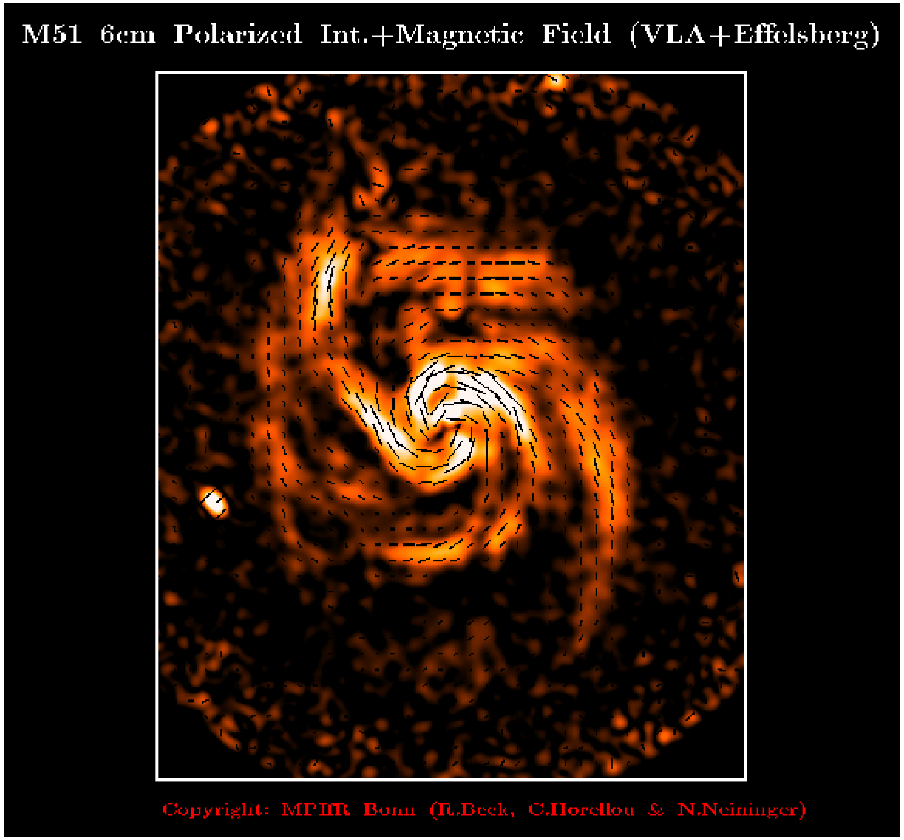
For the first time we will have an (almost) all-sky monitor of the radio sky!

Radio Survey of the Milky Way



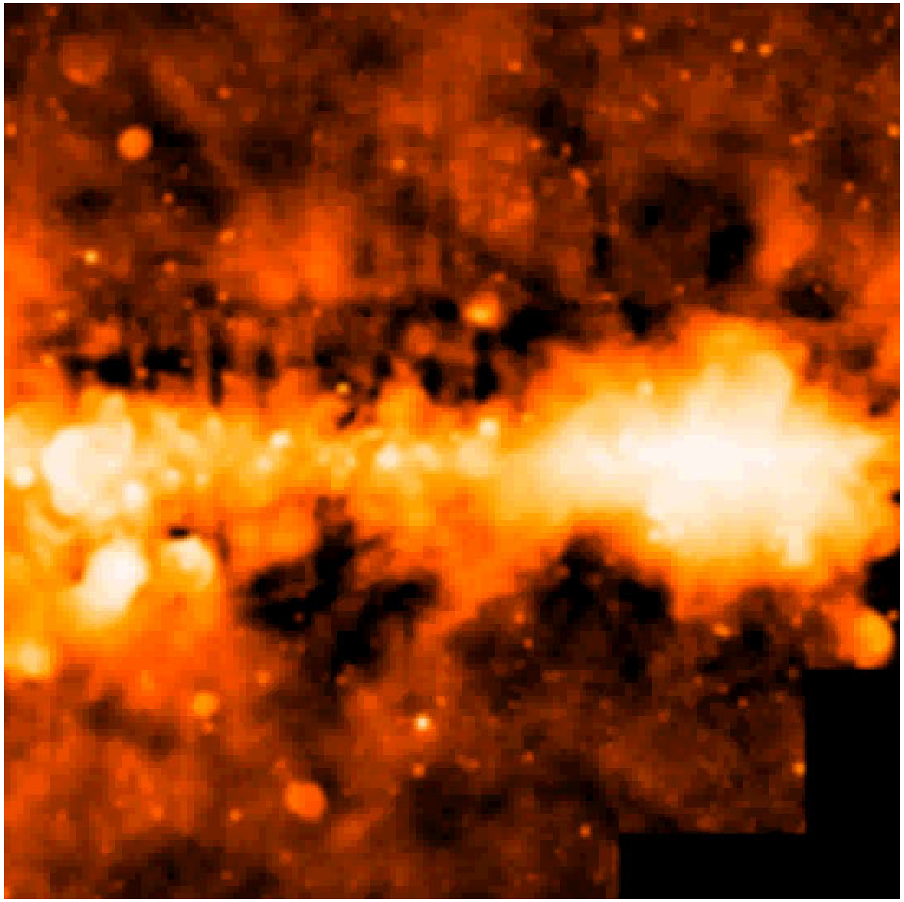
Polarization – Magnetic fields

- Magnetic fields can be determined from the observations of the linear polarization of the radio continuum emission.
- The non-thermal radio emission, that is dominant at cm-wavelength, originates in the synchrotron emission process.
- The emitted **E** polarization vector is perpendicular to the magnetic field.
- The magnetic field seems to trace the spiral structure in spirals.
- It can also be perpendicular to a galaxy due to strong galactic winds (from star formation activity).



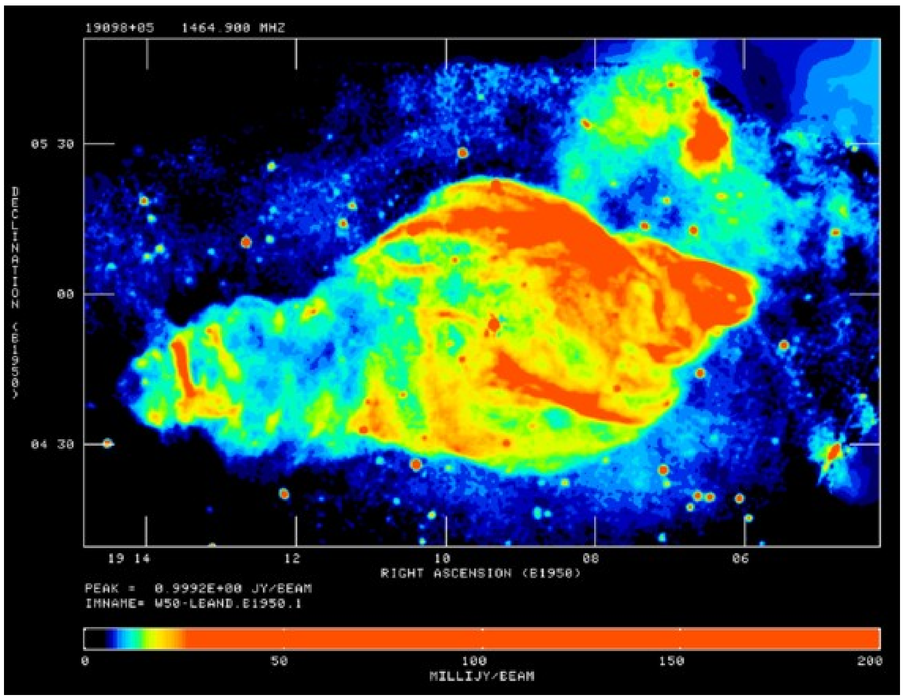
Along the Galactic Plane

- The dominant feature in the radio sky is the Galactic plane.
- The continuum emission mainly comes from:
  - synchrotron radiation of cosmic ray electrons.
  - Thermal emission (free-free, i.e. Bremsstrahlung) from HII regions (example here: Eagle nebula)



X-ray Binaries and Supernovae: high-resolution radio-observations are key

VLA



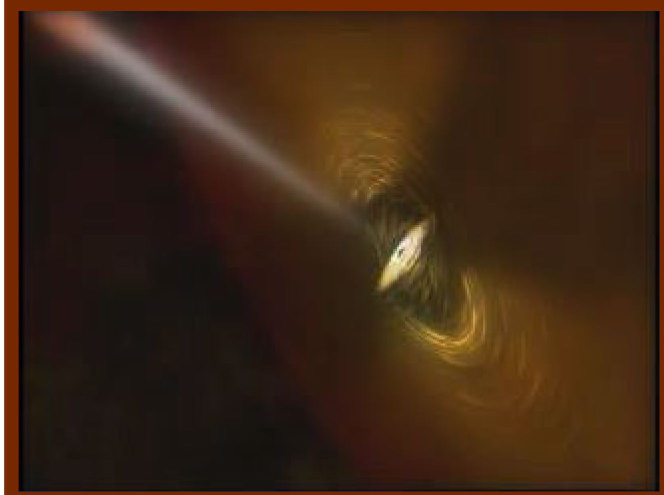
W50/SS433

VLBI

⇒ Opportunity for eVLBI

The Black Hole Paradigm

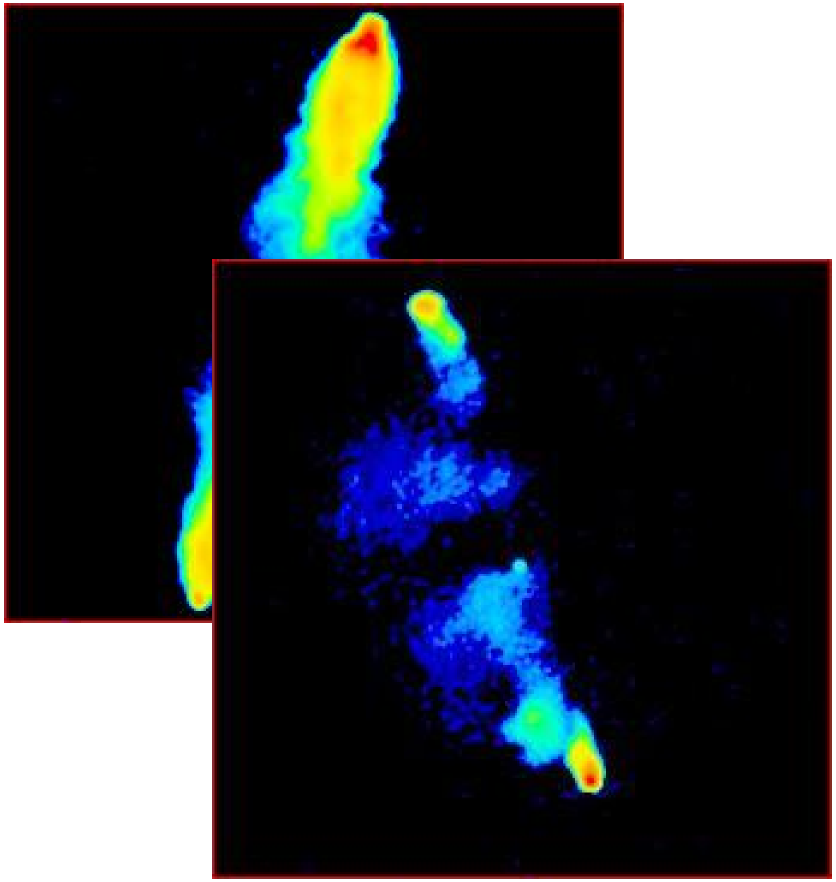
- The AGN engine consists of a
  - black hole (potential well)
  - accretion disk (fuel)
  - dust torus (mass reservoir, obscuration)
  - jet (why?)
- Emission:
  jet: high-energy processes
  disk: UV+IR emission



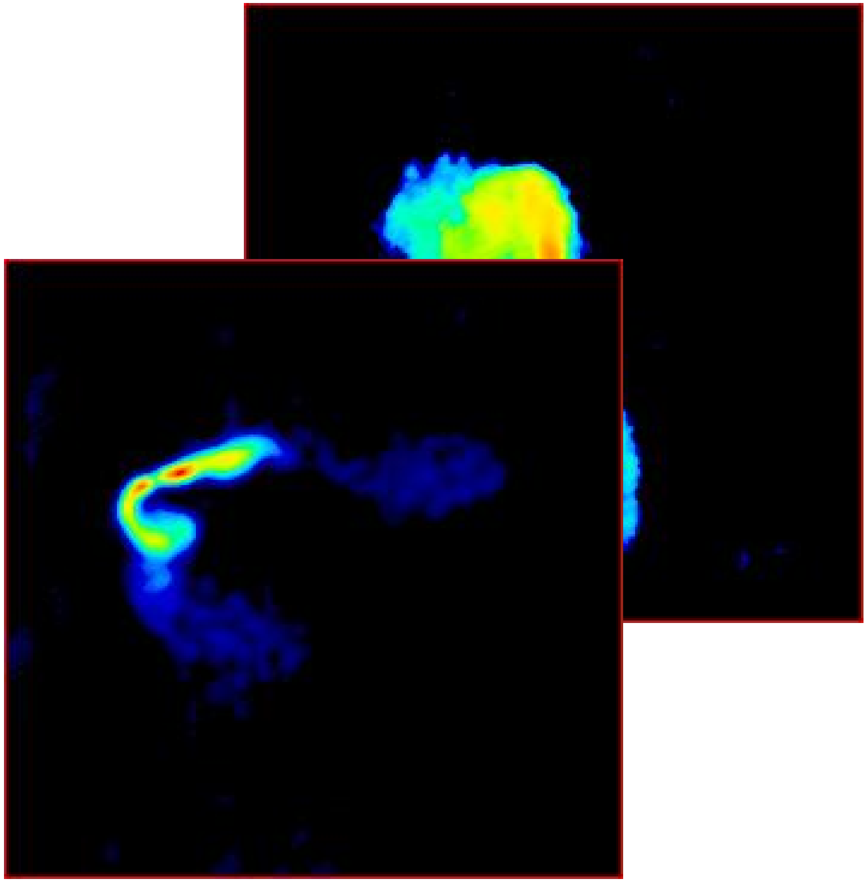
jet-disk symbiosis

Jets are the only component of an AGN that are actually seen!

High-Power (FR II)



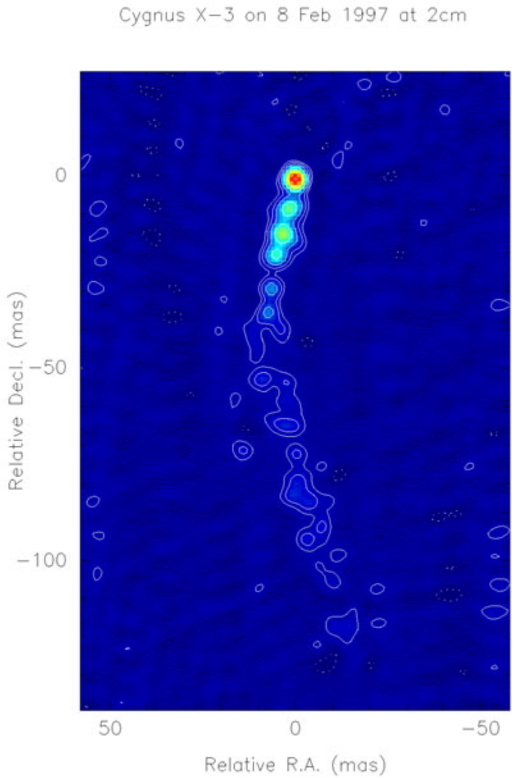
Low-Power (FR I)



DRAGN Atlas (Leahy)

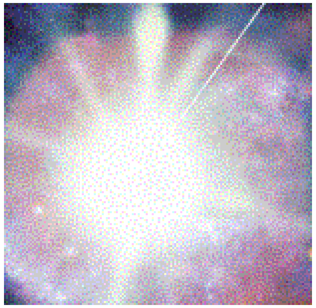
Jets exist on all scales: The faint radio sky is full of jets

X-ray binaries
(Cyg X-3)

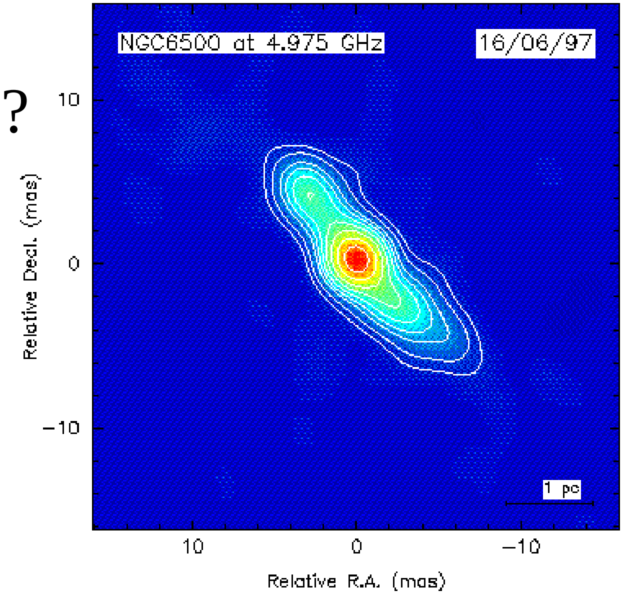


VLBI: Mioduszewski et al. (2003)

Gamma-Ray Bursts?

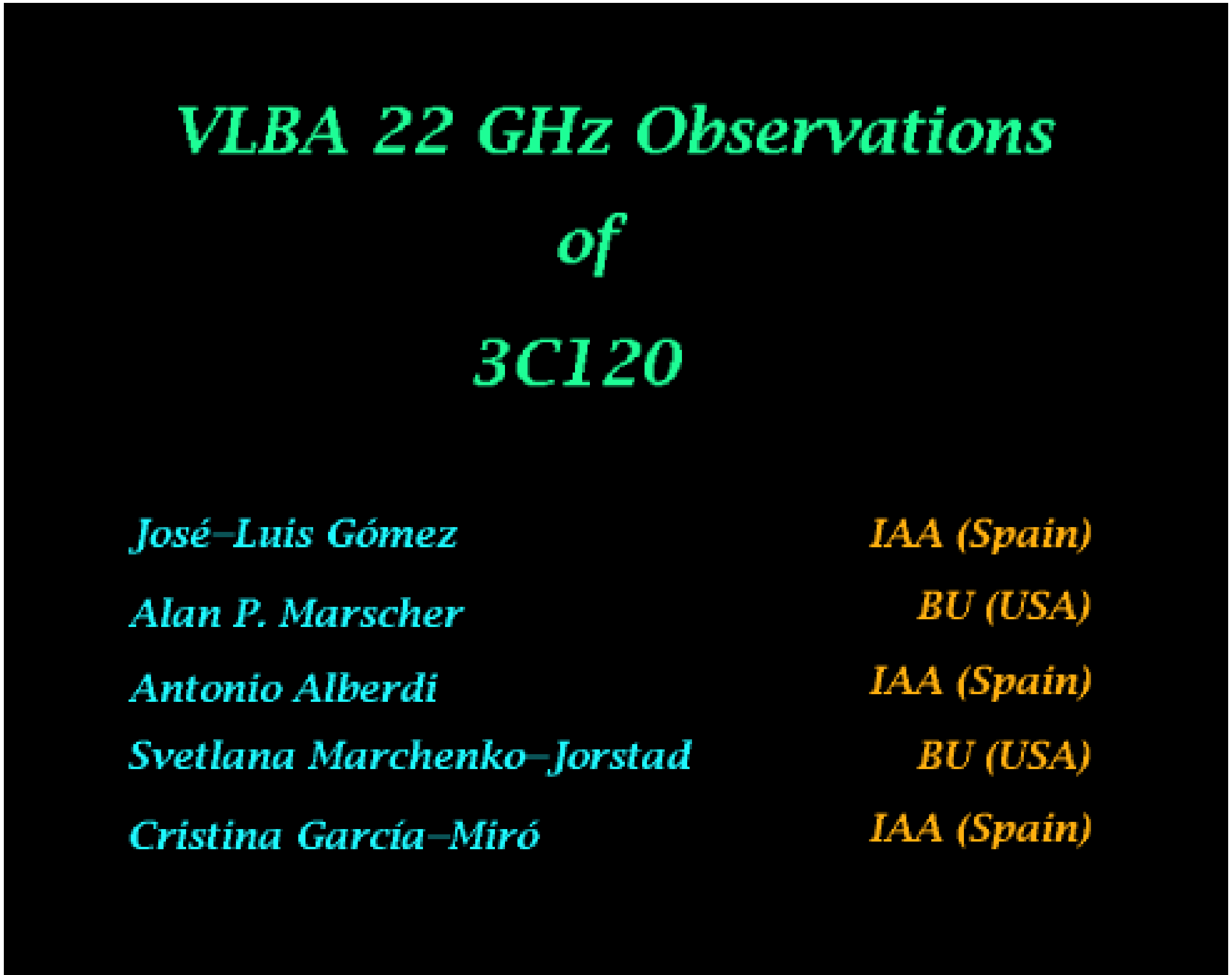


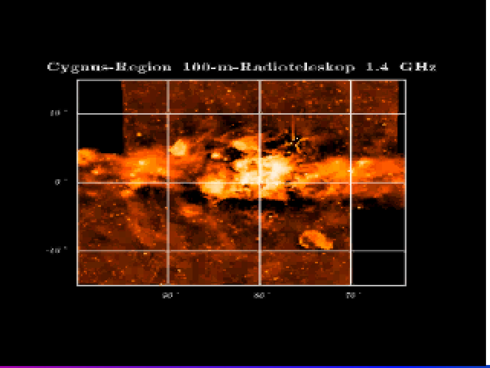
Low-Luminosity AGN



VLBI: Falcke, Nagar, Wilson, Ulvestad (2000)

Monitoring of the quasar 3C120 with VLBI





Jets remain self-similar over many orders of magnitude!

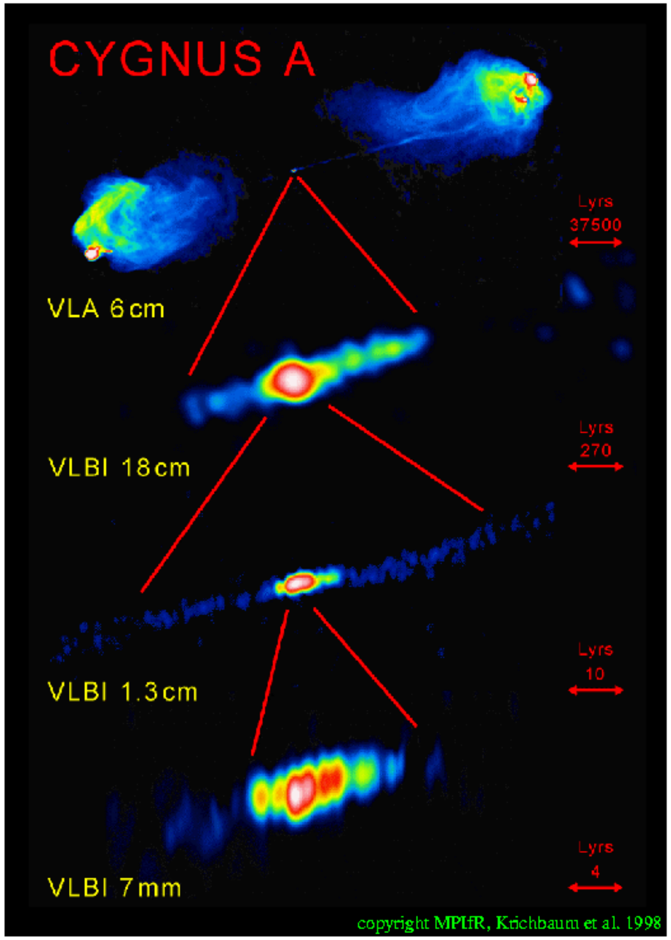
- Jets inflate steadily by a factor of 10^8.

$\Rightarrow$ Magnetic field varies by 10^8.

$\Rightarrow$ Particle density varies by a factor 10^{16}.

$$\nu_{sync} \propto B\gamma^2$$

$\Rightarrow$ $B \propto r^{-1}$ – Frequency will change over 8 orders of magnitude.



Krichbaum et al. 1999

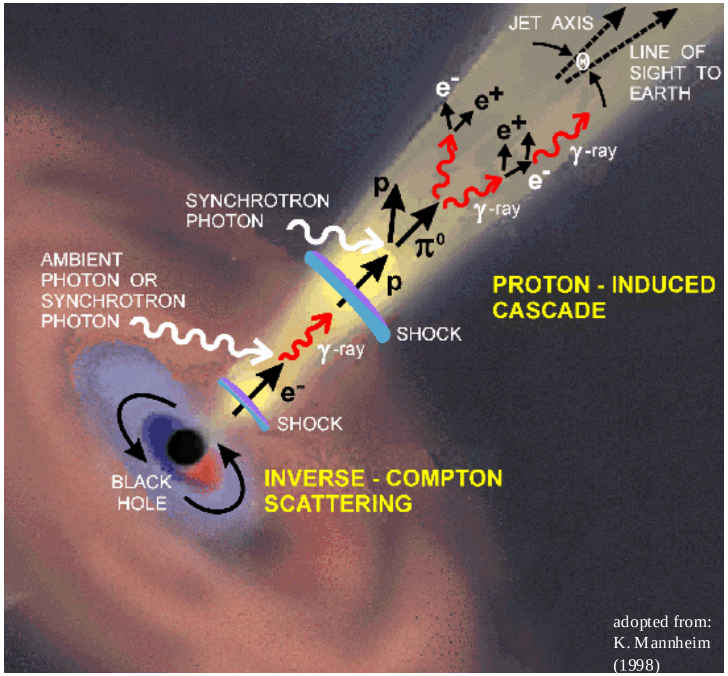
Jets are the most powerful particle accelerators

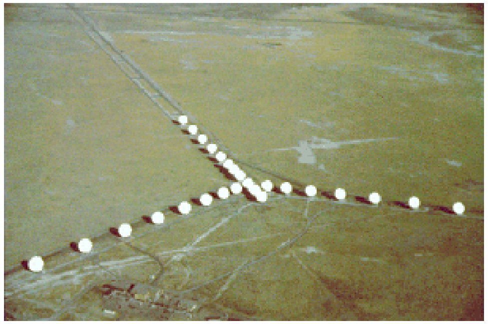
- Electrons are accelerated to TeV Energies ($\gamma \sim 10^6$).

$$\nu_{sync} \propto B\gamma^2$$

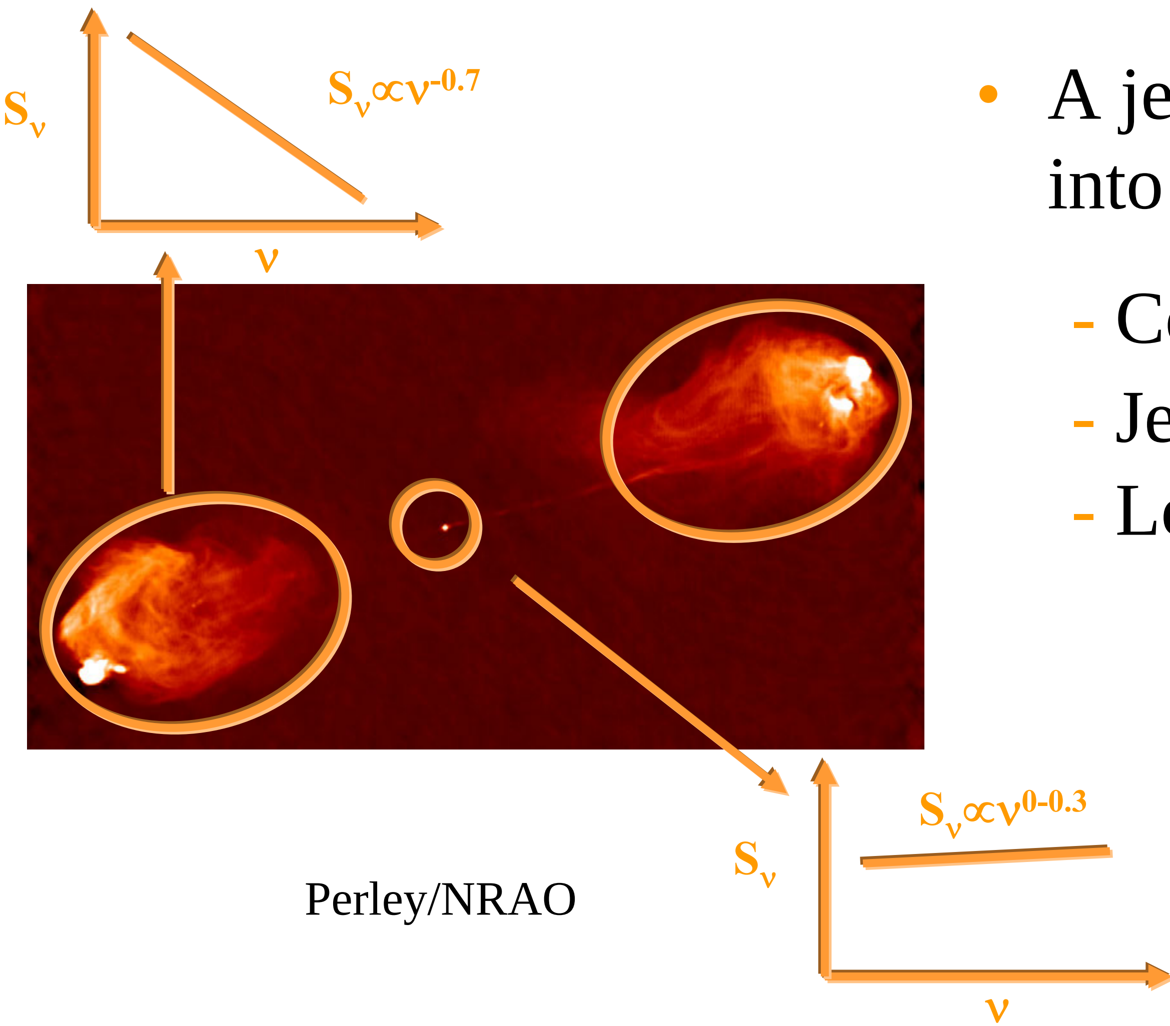
- Frequency spectrum at each spatial scale is already very broad, self-similarity increases this even further.
- Inverse Compton increases Frequency range even more.

$\Rightarrow$ As long as we have high-energy astrophysics jets will be of prime importance.





Jets in Quasars



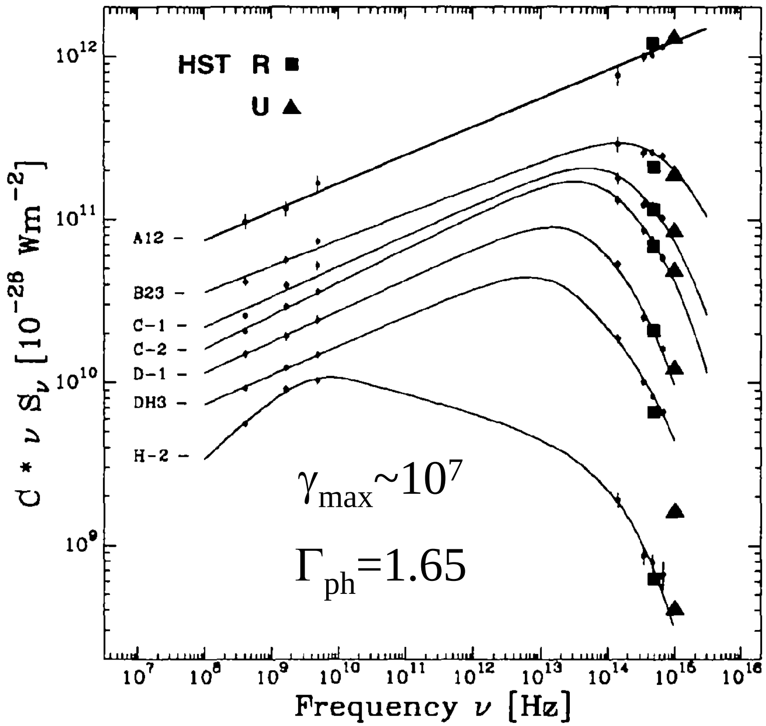
Perley/NRAO

- A jet can be separated into three regimes:
  - Core (flat spectrum)
  - Jet
  - Lobes (steep spectrum)

All Blazars (beamed jets) are flat-spectrum!

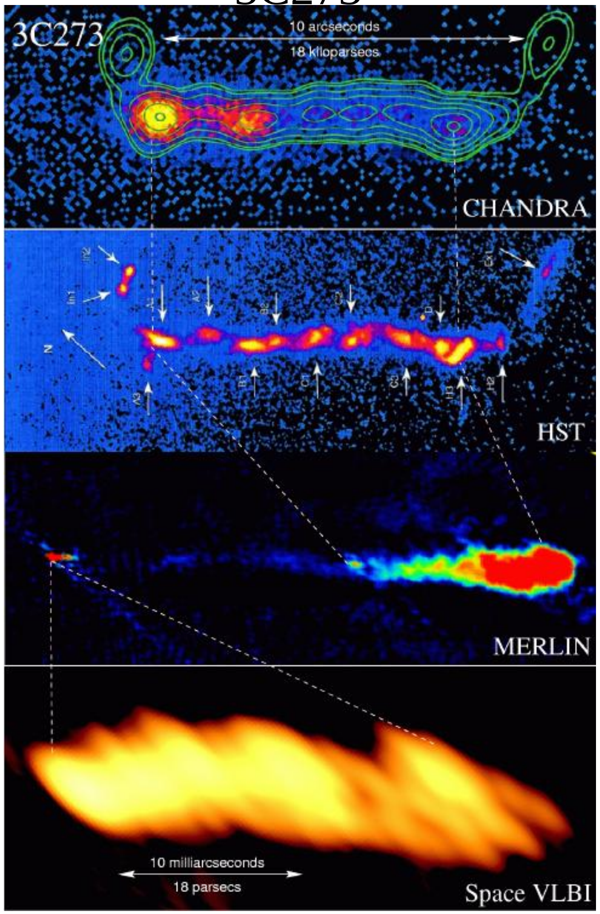
Radio & X-Rays from extended jets
A universal acceleration mechanism?

M87 jet spectra of bright knots



Meisenheimer et al. (1997)

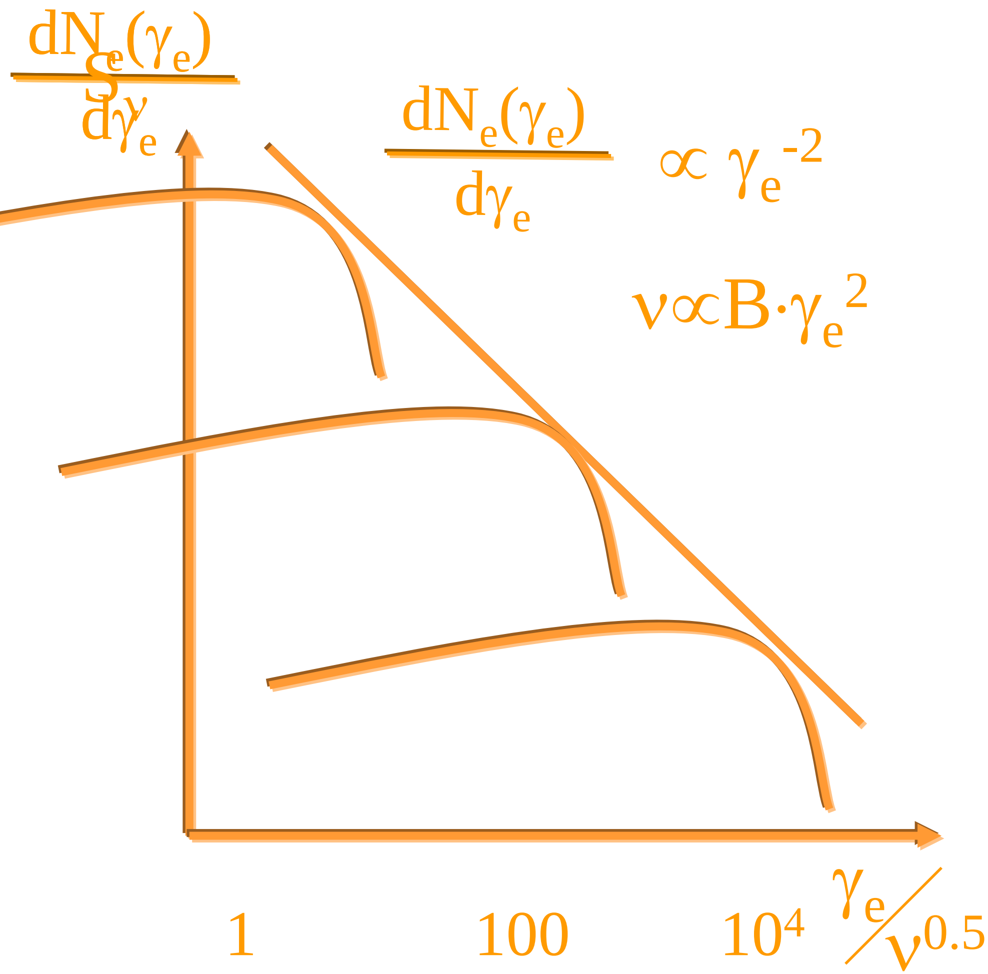
3C273



Chandra: Marshall et al. (2001)
Space-VLBI: Lobanov et al. (2001)

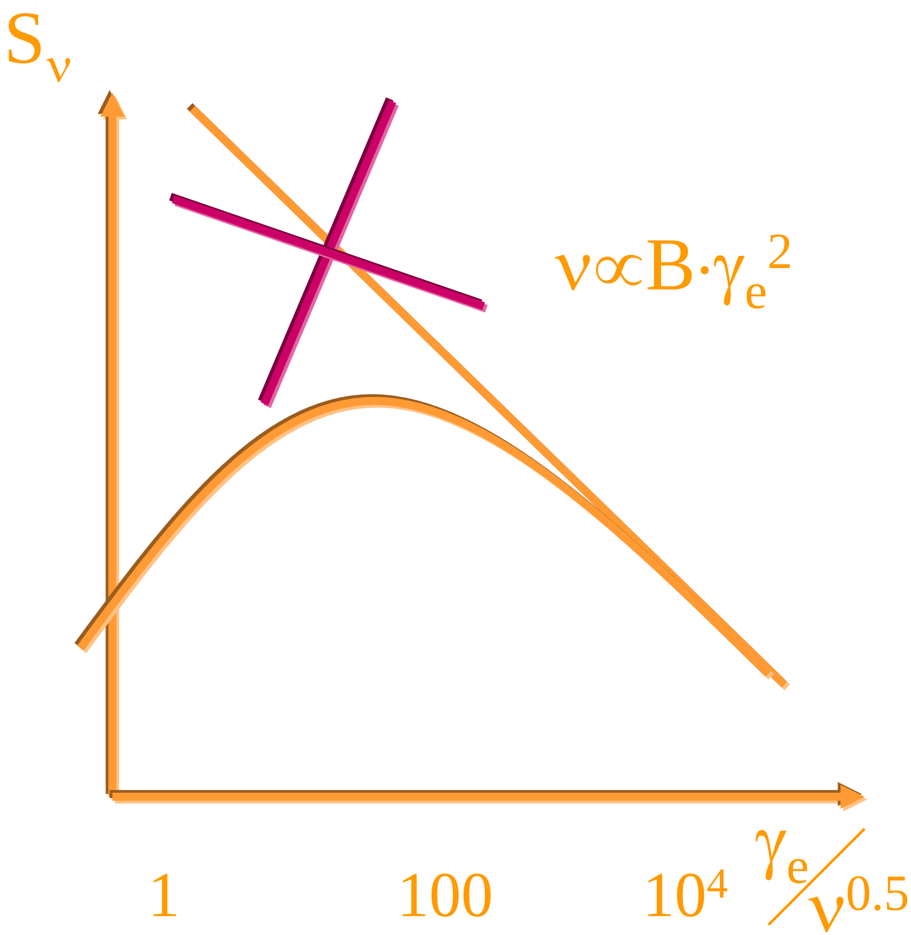
Optical and perhaps X-ray synchrotron require TeV electrons and continuous re-acceleration in the jet!

Electron Energy Distribution in Jets



- The typical energy distribution of relativistic electrons is a power-law in γ_e ($E=\gamma_e m_e c^2$).
- The energy of electrons is related to a characteristic frequency.
- A power-law in the energy distribution produces a powerlaw in the spectrum

Electron Energy Distribution in Jets

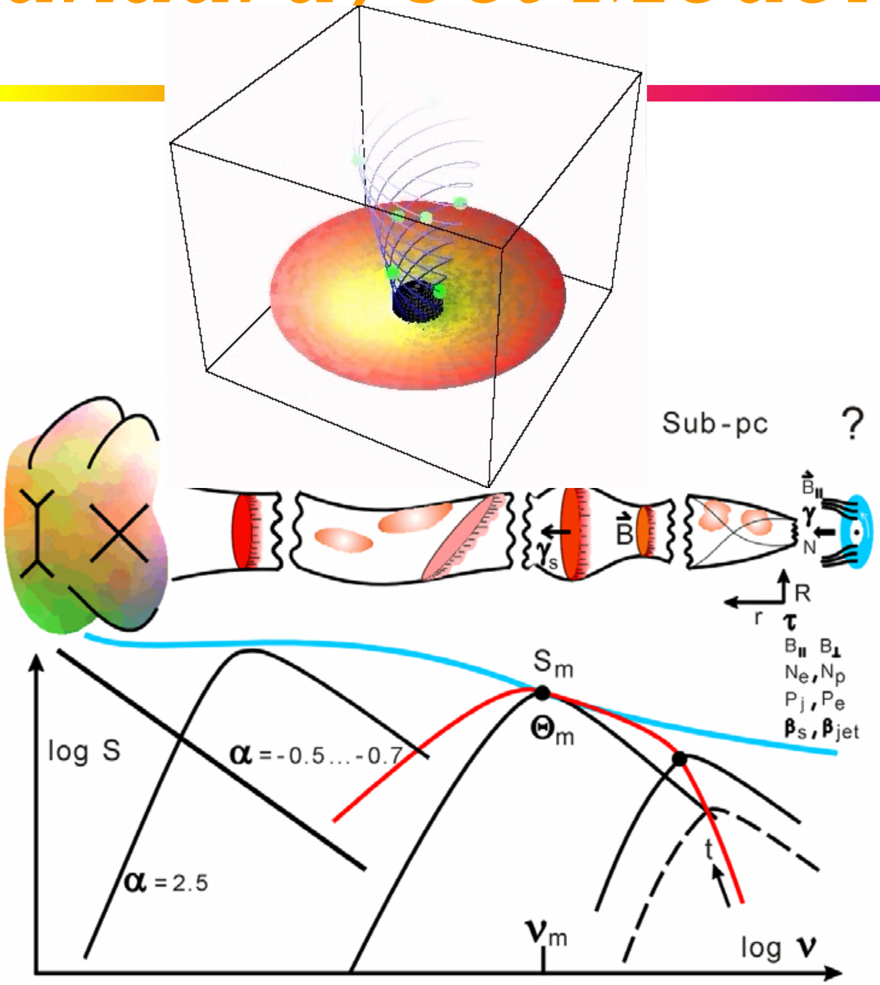


- Coincidentally in the inner jet region the low-frequency spectrum is self-absorbed.
- Hence, electrons with $1 \leq \gamma_e \leq 100$ remain invisble but they make up 99% of the total electron content!

$$\frac{dN_e(\gamma_e)}{d\gamma_e} \propto \gamma_e^{-2} \Rightarrow N_{tot} \propto \gamma_{min}^{-1}$$

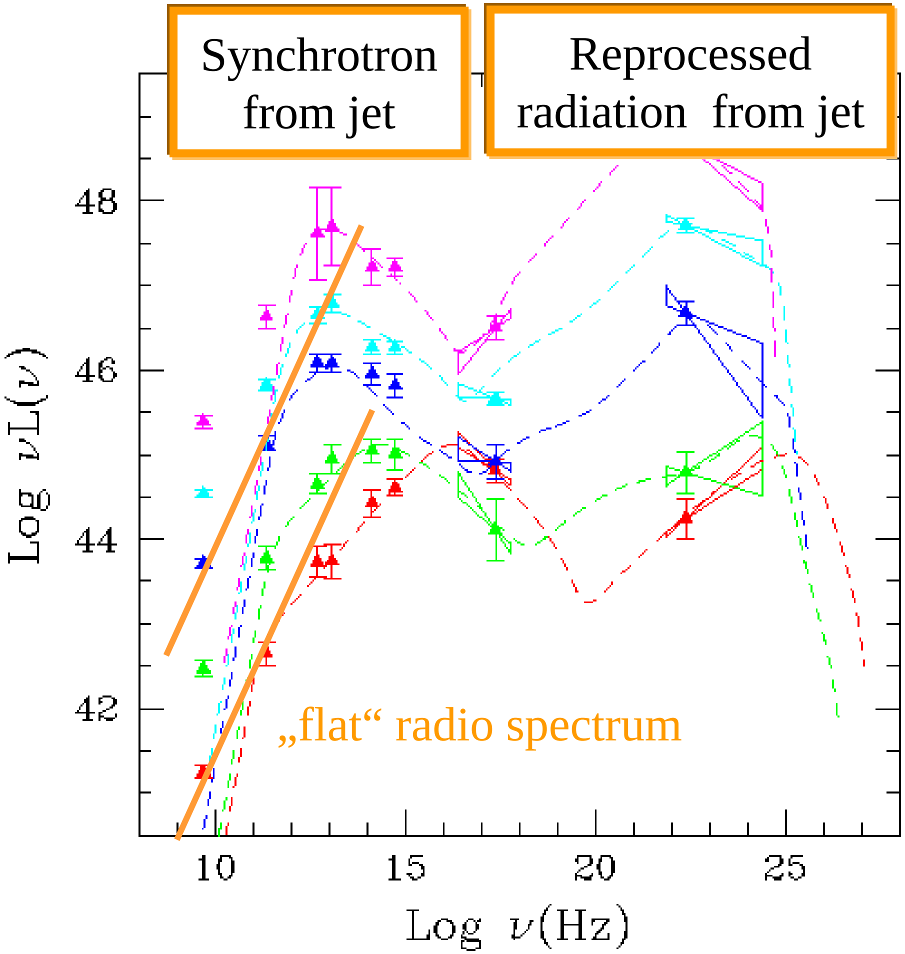
The (Standard) Jet Model

- Radio-Plasma freely expanding in a supersonic jet
- superposition of self-absorbed synchrotron spectra
- at each frequency one sees the $\tau = 1$ surface as the “core”

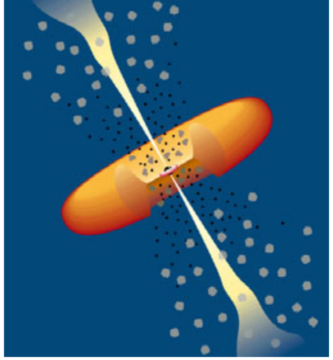


Blazars – looking down the jet

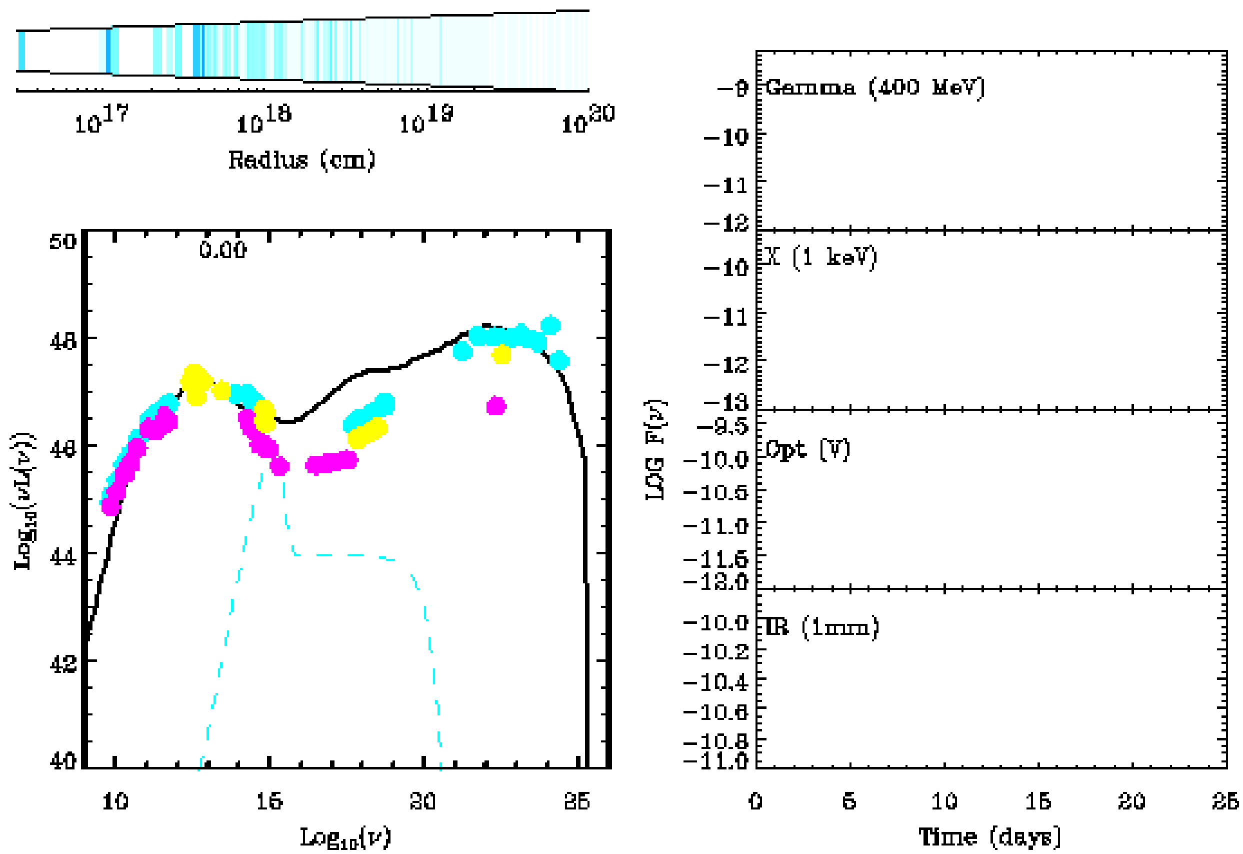
- In Blazars the emission is completely dominate by the jet because of relativistic beaming.
- The spectrum resembles a „camel's back"
- Radio - Optical: synchrotron emission from jet
- X-ray – TeV: inverse Compton/hadronic cascades (e-γ, p-γ)



Fossati et al. (1998)

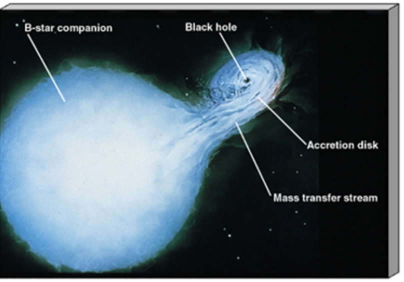


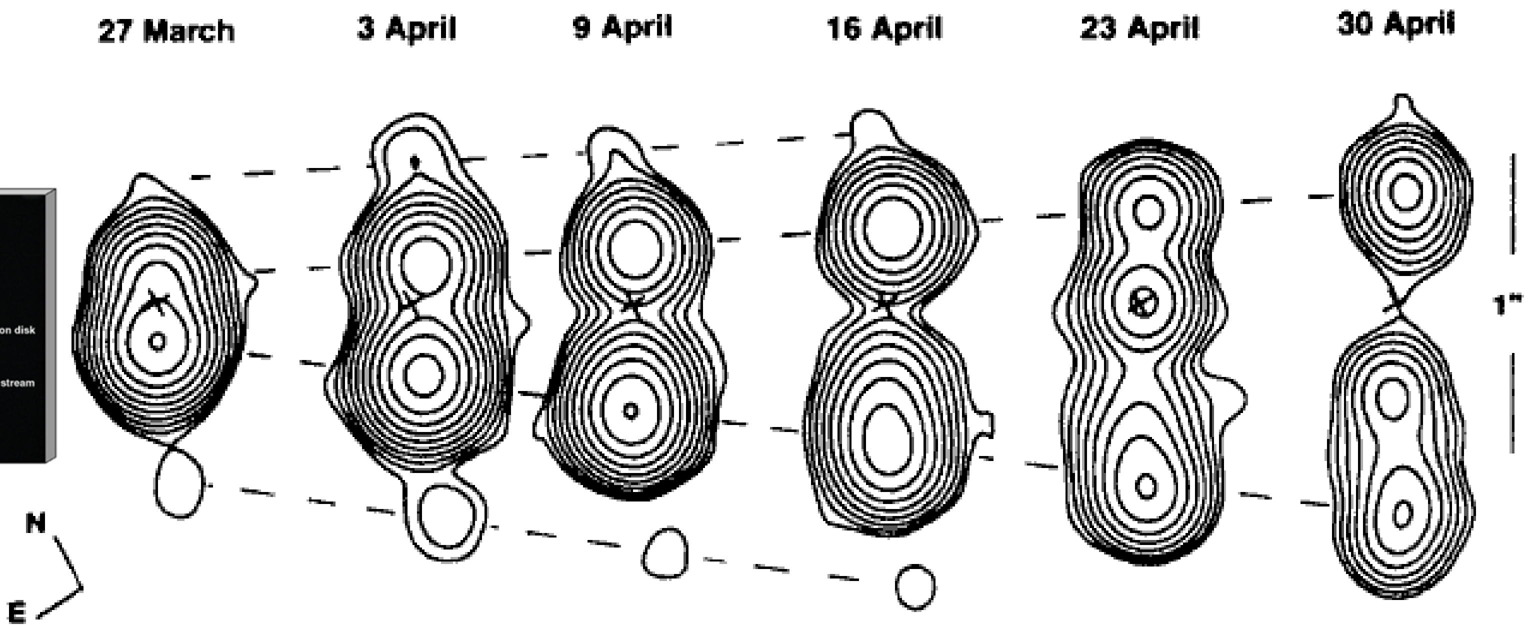
Blazars - Variability



Ghisellini et al. (2001)

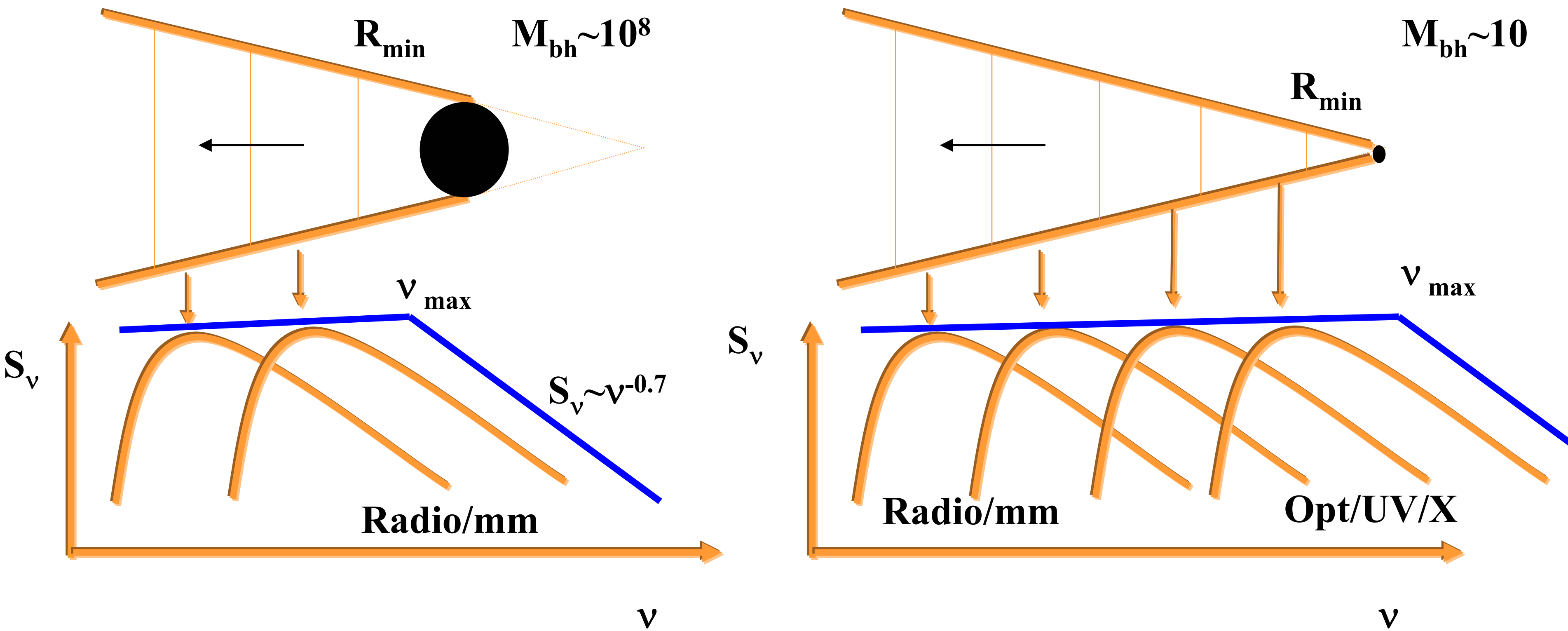
„Microquasar“ GRS 1915+105





Mirabel & Rodriguez (1994)

The Synchrotron Spectrum of Jets



In jets $\nu \propto r^{-1} \Rightarrow \nu_{max} \propto r_{min}^{-1} \propto M_{bh}^{-1}$

$\Rightarrow$Turnover Frequency in stellar black holes >> blazars!

Jet Model for the X-Ray Binary XTE J1118+480

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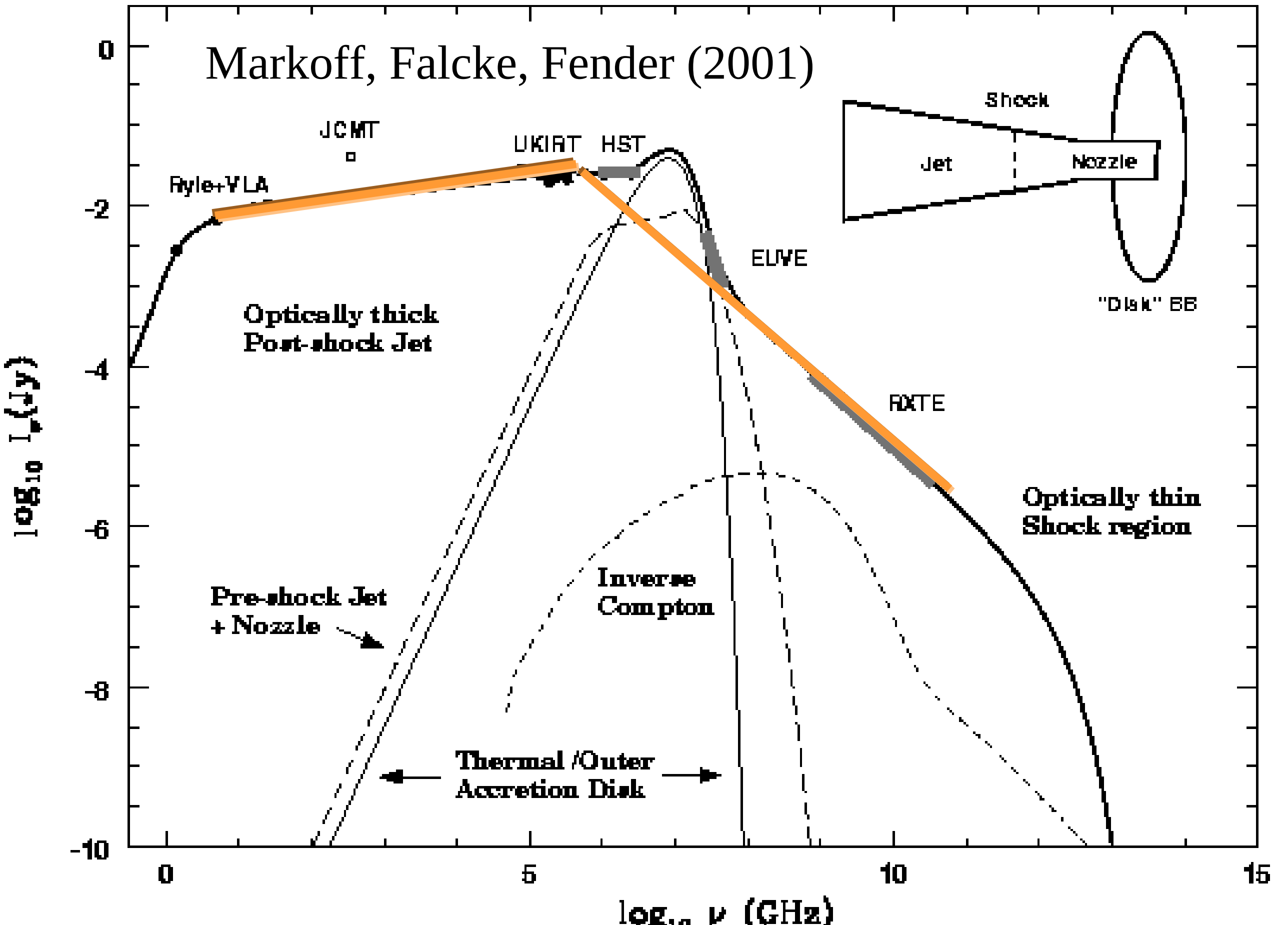
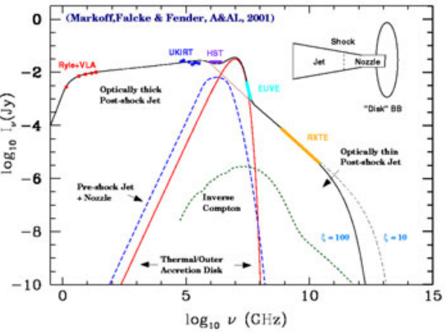


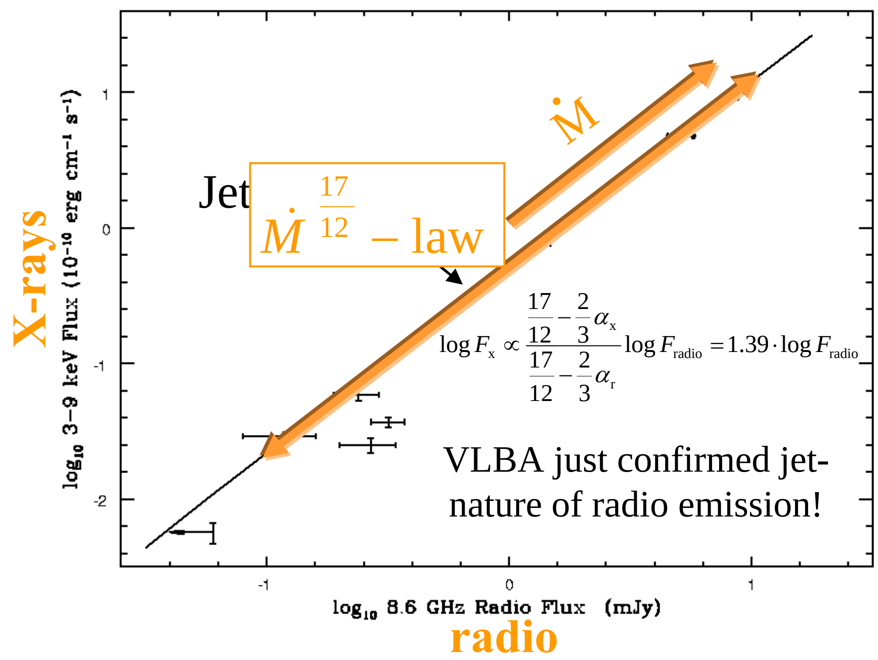
Are X-rays from the jet and not from the disk?



X-ray/Radio Correlation: Scaling with Accretion Rate

- The X-ray emission in a number of low-hard state X-ray binaries seems to tightly follow the radio emission.
- The slope seems universal and is non-linear.
- Obviously the mass does not change - only the accretion rate.
- Jet scaling laws reproduce radio-x-ray slope perfectly

X-ray vs. Radio correlation (GX339-4)



Markoff et al. (2003), Corbel et al. (2003)

X-ray/Radio Correlation: Scaling with Accretion Rate

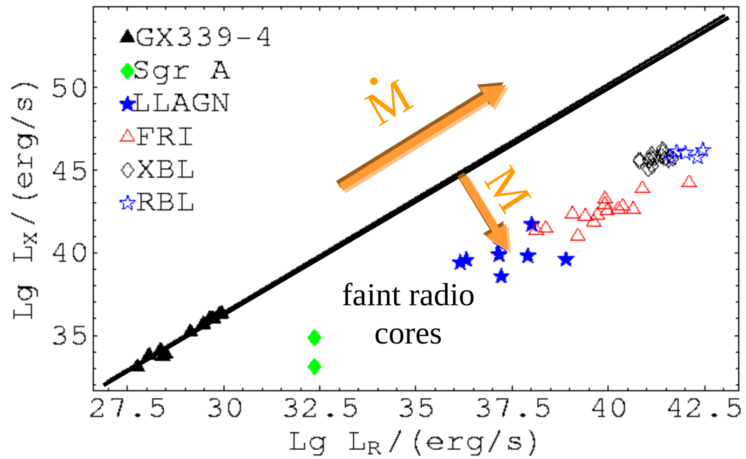
- Collect radio and X-ray/optical emission for VLA and VLBA **radio cores** from **sub-Eddington black holes**:
  - Liners (Nagar et al. 2003)
  - FR Is (3C sample, Chiaberge et al. 2000)
  - BL Lacs
  - Sgr A*
- „Correct“ X-ray/optical flux for black hole mass.

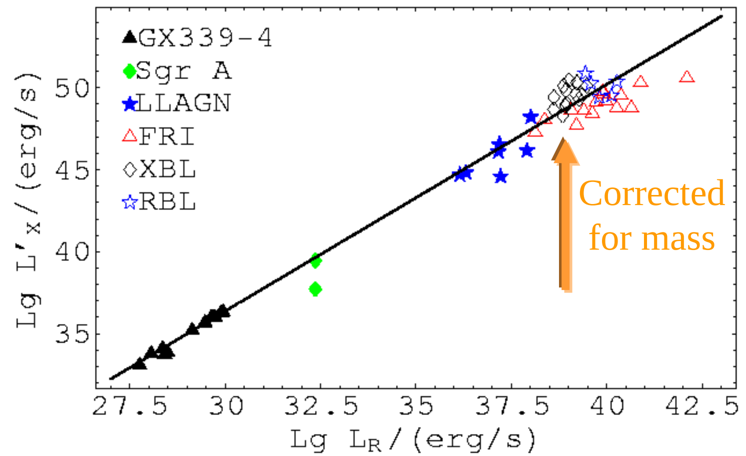
⇒ Sub-Eddington AGN magically fall on XRB extension + pure jet model

⇒ Jet domination works very well!

⇒ Mass and accretion rate form a „fundamental plane“.

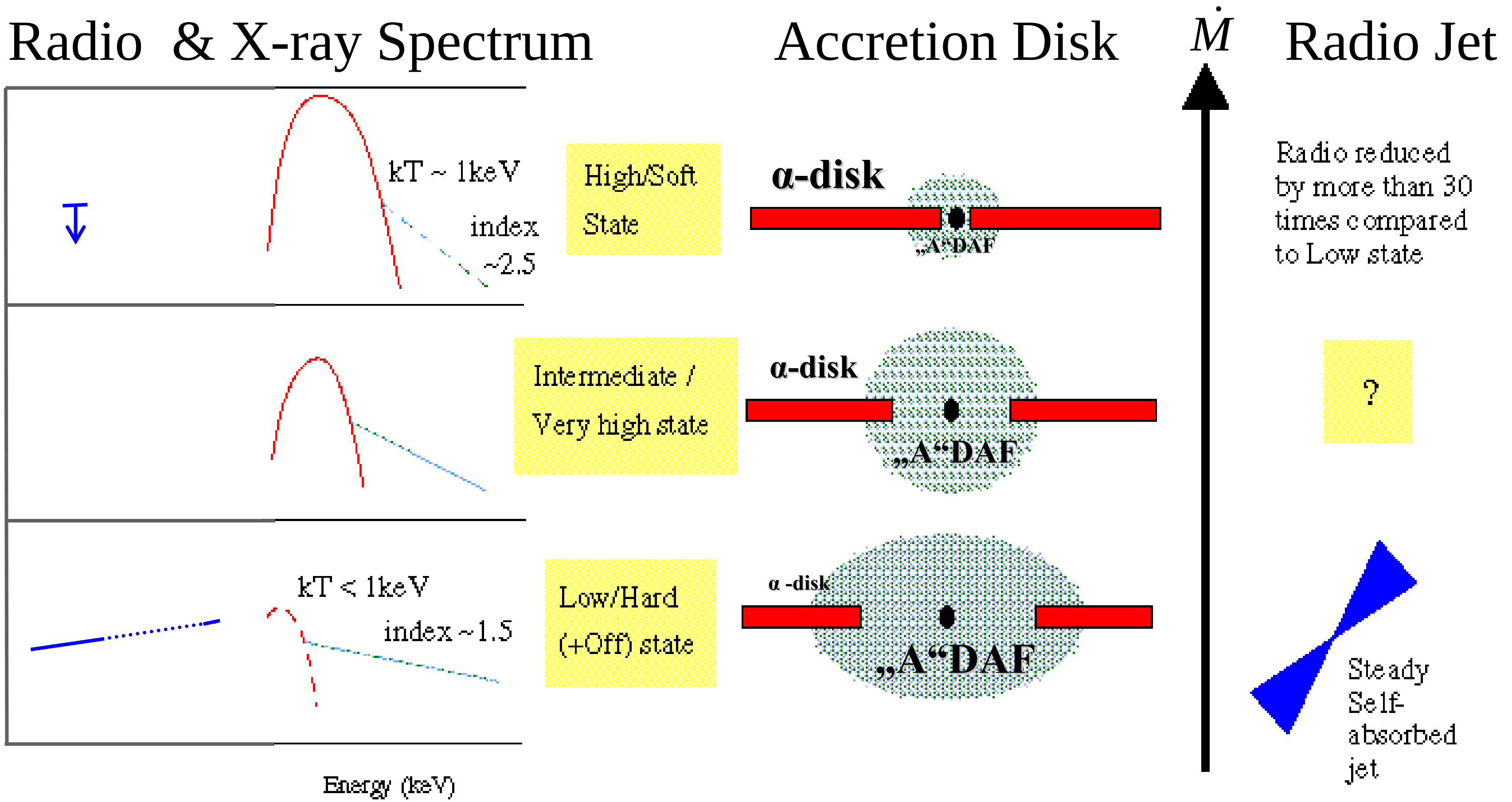
(see also Merloni et al. 2003)





Falcke, Körding, Markoff (2003, A&A)

Change of SED with Luminosity? Clues from the Evolution of XRBs



Summary

- Radio Emission is ubiquitous and in many – not all – cases related to high-energy processes.
- Radio telescopes will become more and more user-friendly and able to rapidly respond (eVLBI, LOFAR, eventually SKA)
- Radio traces magnetic fields
- Jets are the main suspects for extragalactic high-energy emission.
  - Flat radio cores are the **stratified** bases of jets and are found in basically every jet. Low-frequency emission comes from far out (time after outburst and frequency are related!).
  - High-energy emission is (some sort of) inverse-Compton from this jet core.
  - Sub-Eddington black holes may be completely jet-dominated
- Is there a possibility for prompt (coherent) radio emission?