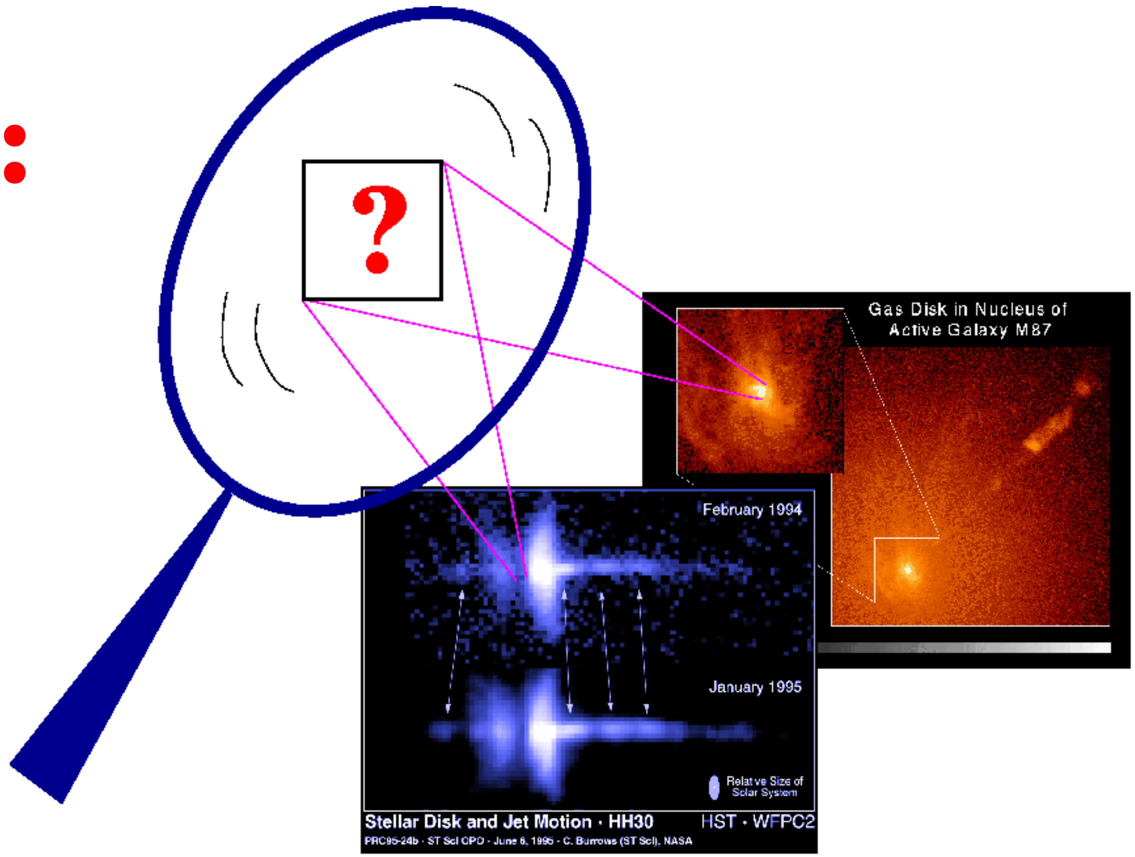
# Outflows & Jets: Theory & Observations




## Lecture - summer term 2011

**Henrik Beuther & Christian Fendt**

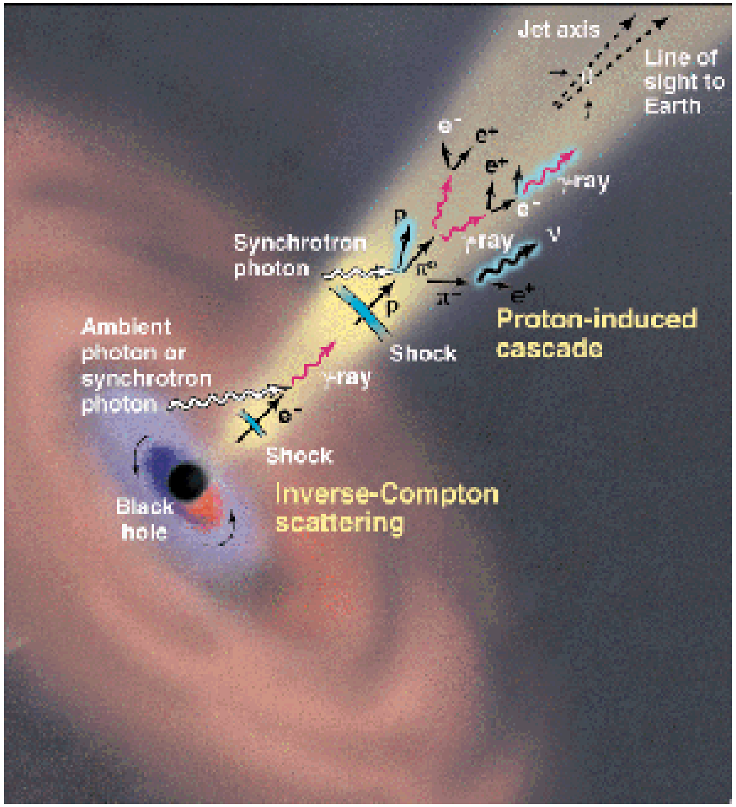
More Information and the current lecture files:

www.mpia.de/homes/beuther/lecture_ss11.html

www.mpia.de/homes/fendt/Lehre/

beuther@mpia.de fendt@mpia.de

# Lecture plan & schedule




## Summer term 2011
## Henrik Beuther & Christian Fendt

***15.04 Today: Introduction & Overview ("H.B." & C.F.)***

29.04 Definitions, parameters, basic observations (H.B.)

06.05 Basic theoretical concepts & models I (C.F.)

13.05 Radiation processes - 1 (H.B.)

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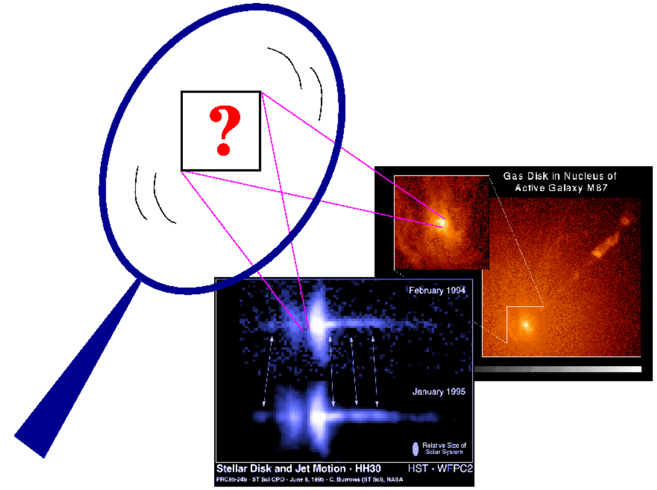
22.07 Some aspects of relativistic jet theory (C.F.)

## Outflows & Jets: Theory & Observations




# Henrik's part:

- Chemistry, tracers
- Radiation, molecular emission
- Massive young stars
- Evolutionary scenarios, entrainment
- Accretion disks, jet-disk interaction

# Christian's part:

- Basic jet physics: plasma - HD - MHD
- Concepts & models of MHD jets & outflows
- Accretion disk theory, disk winds, launching
- Theory of outflow interaction, instabilities
- Relativistic jets: beaming, superluminal motion, unified model

# Extragalactic jets – first data

**M87** (Vir A, NGC 4486)

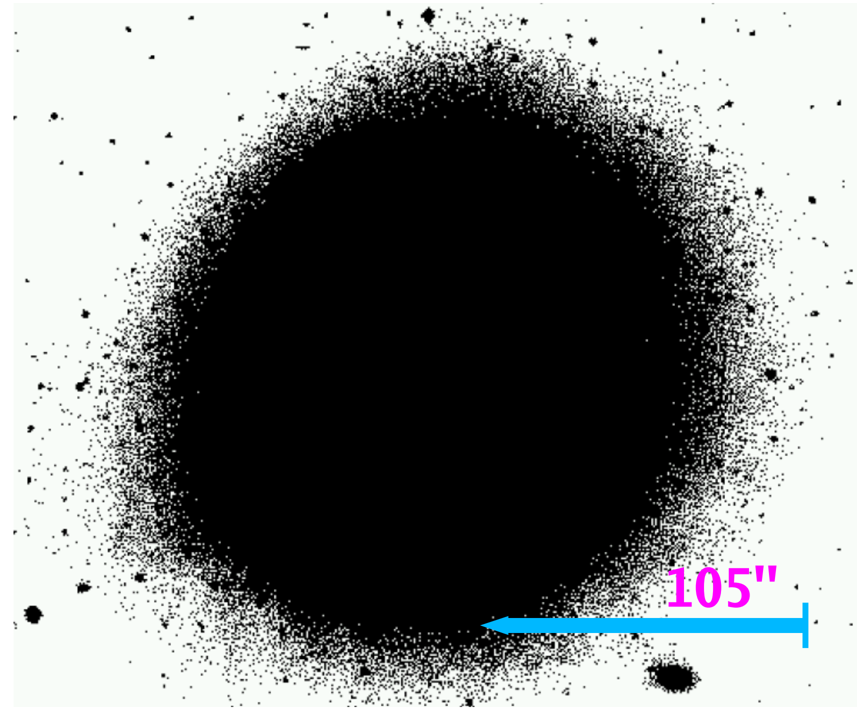
-> first jet source detected

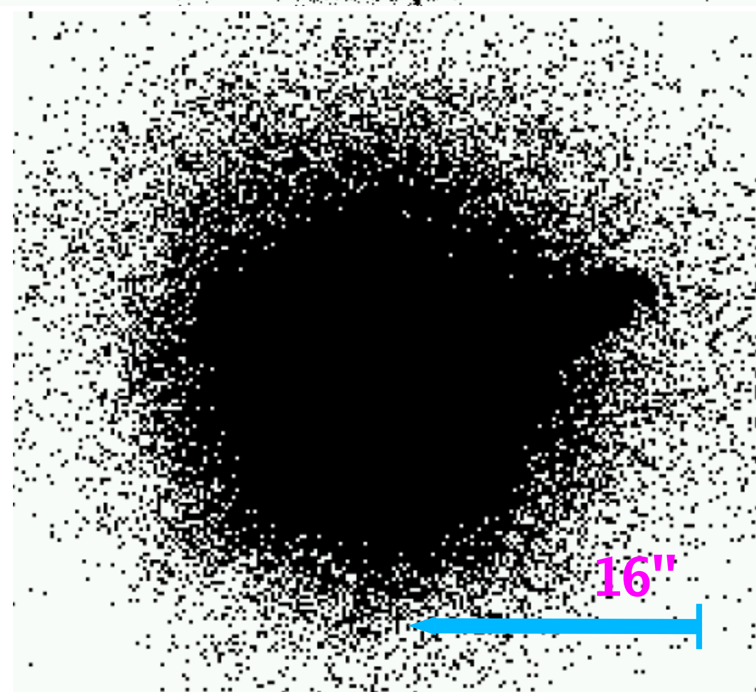
Discovered 1918 by Curtis: *"A curious straight **ray** lies in a gap in the nebulosity ... apparently connected with the nucleus by a thin line of matter. The ray is brightest at its inner end ..."*

Un-noticed until mid-1950s ...

Baade & Minkowski (1954): M87 is optical counterpart of strong radio source:

*"The interpretation ... is that the jet was formed by ejection from the nucleus and that the [OII] line is emitted by .... the material which forms the jet ...."*




M87: Baade 1954: λλ 3500-5000; λλ < 4500

# Extragalactic jets – first data

**M87** - First jet source detected

Baade (1956):

-> optical polarisation in M87

-> resolving the jet; 3 inner condensations

-> polarization degree ~30%

-> interpretation: synchrotron radiation

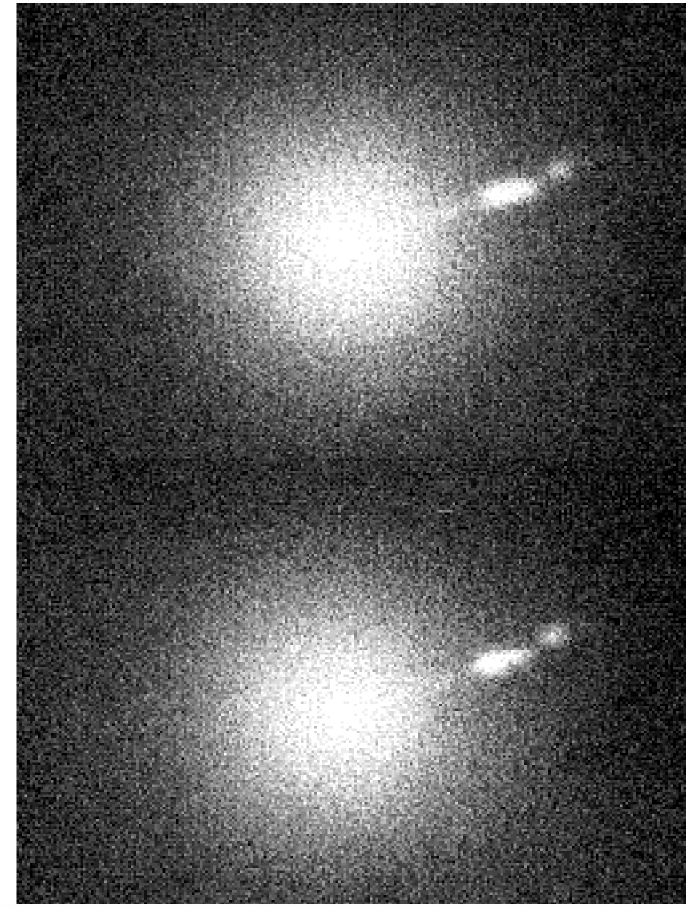
(note contemporary discovery of Crab pulsar & theory of radio emission (Shklovskii 1953))

-> very first hint on the magnetic character of astrophysical jet phenomenon

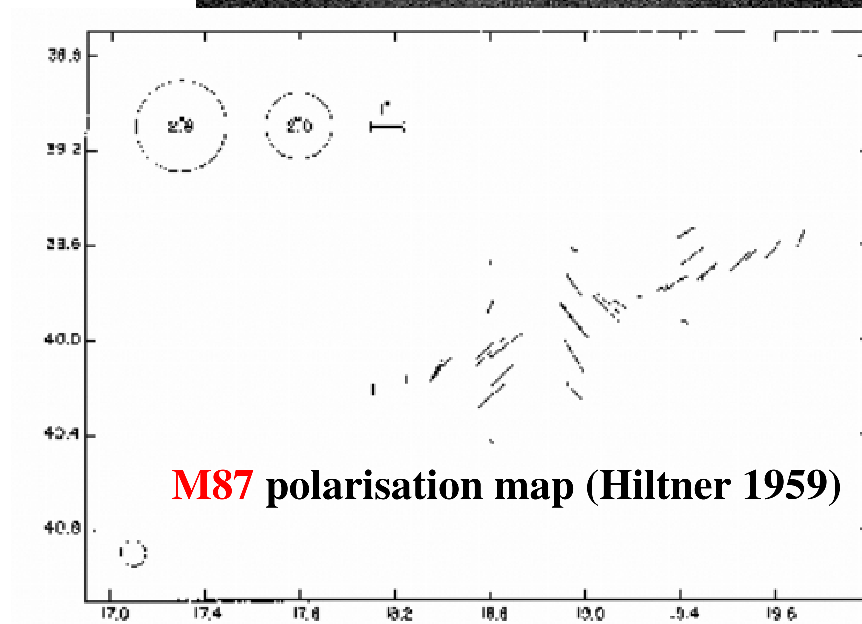
Hiltner (1959):

-> polarization vector maps of M87 jet:

*"no significant polarization was observed in M87 except in the jet"*



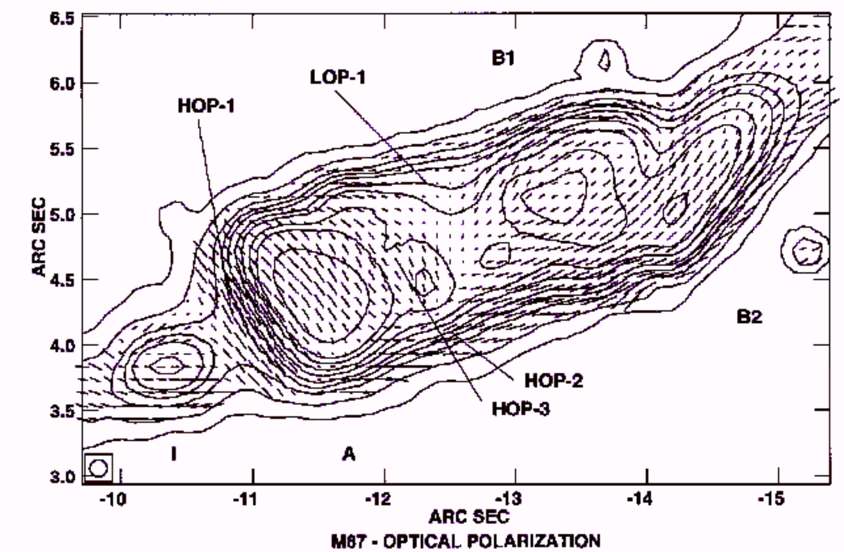
**M87 optical polarisation (Baade 1956)**

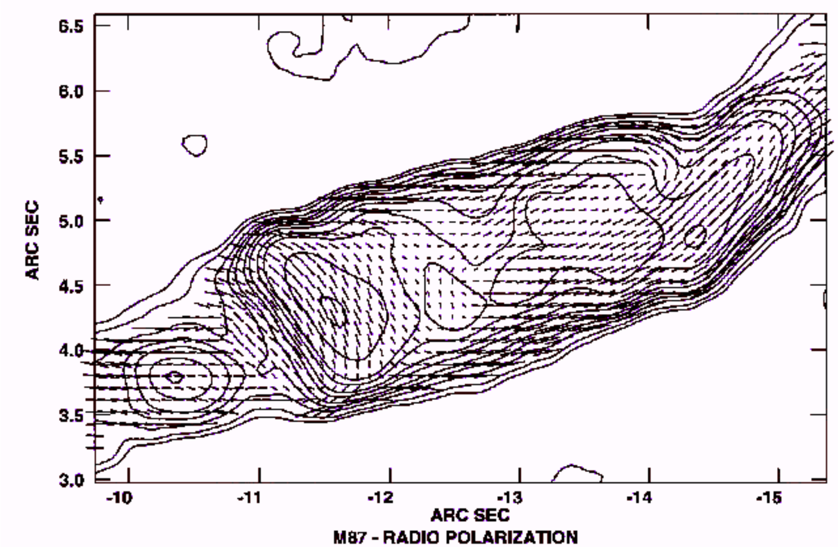


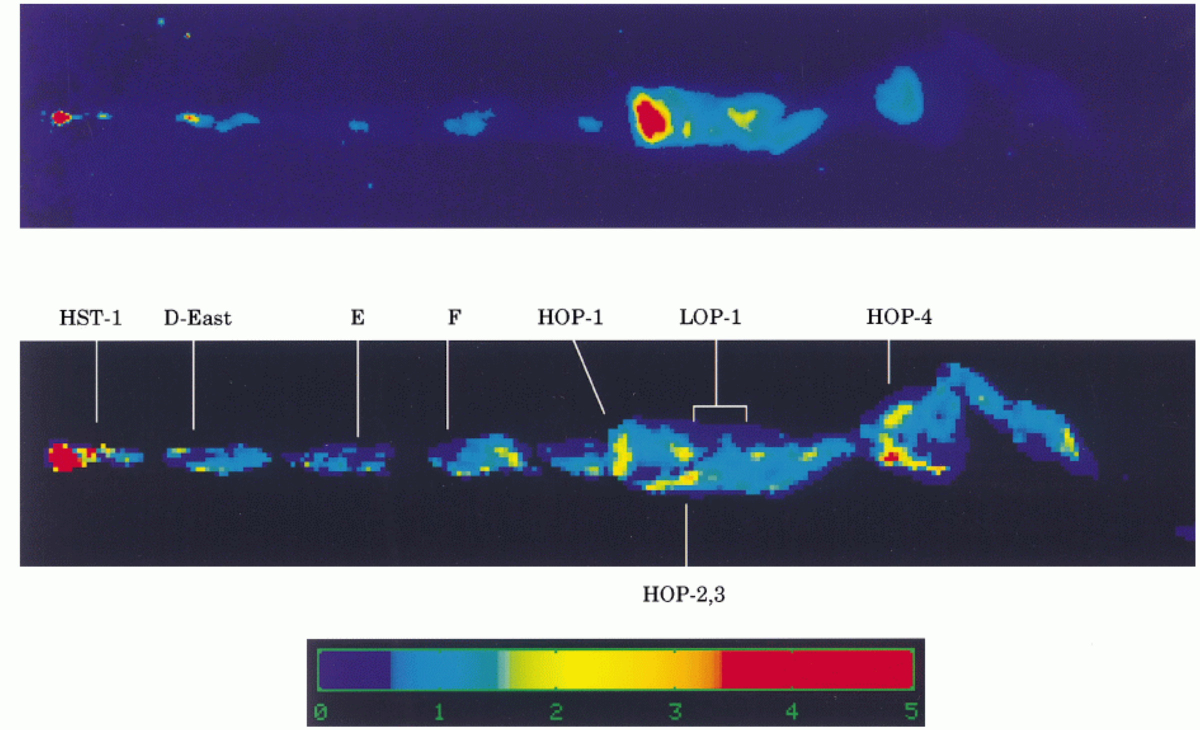
**M87 polarisation map (Hiltner 1959)**

# Extragalactic jets – recent data

Polarisation measurements today:




Example: M87 HST & VLA observations:

**(Perlman et al 1999)**

-> optical / radio polarisation

-> resolution 0."2 (15 pc)

-> P up to 40 – 50%

~ maximum for optically-thin synchrotron emission

-> **highly ordered magnetic field**

# Extragalactic jets – contemporary data

“Famous” jet sources: CenA

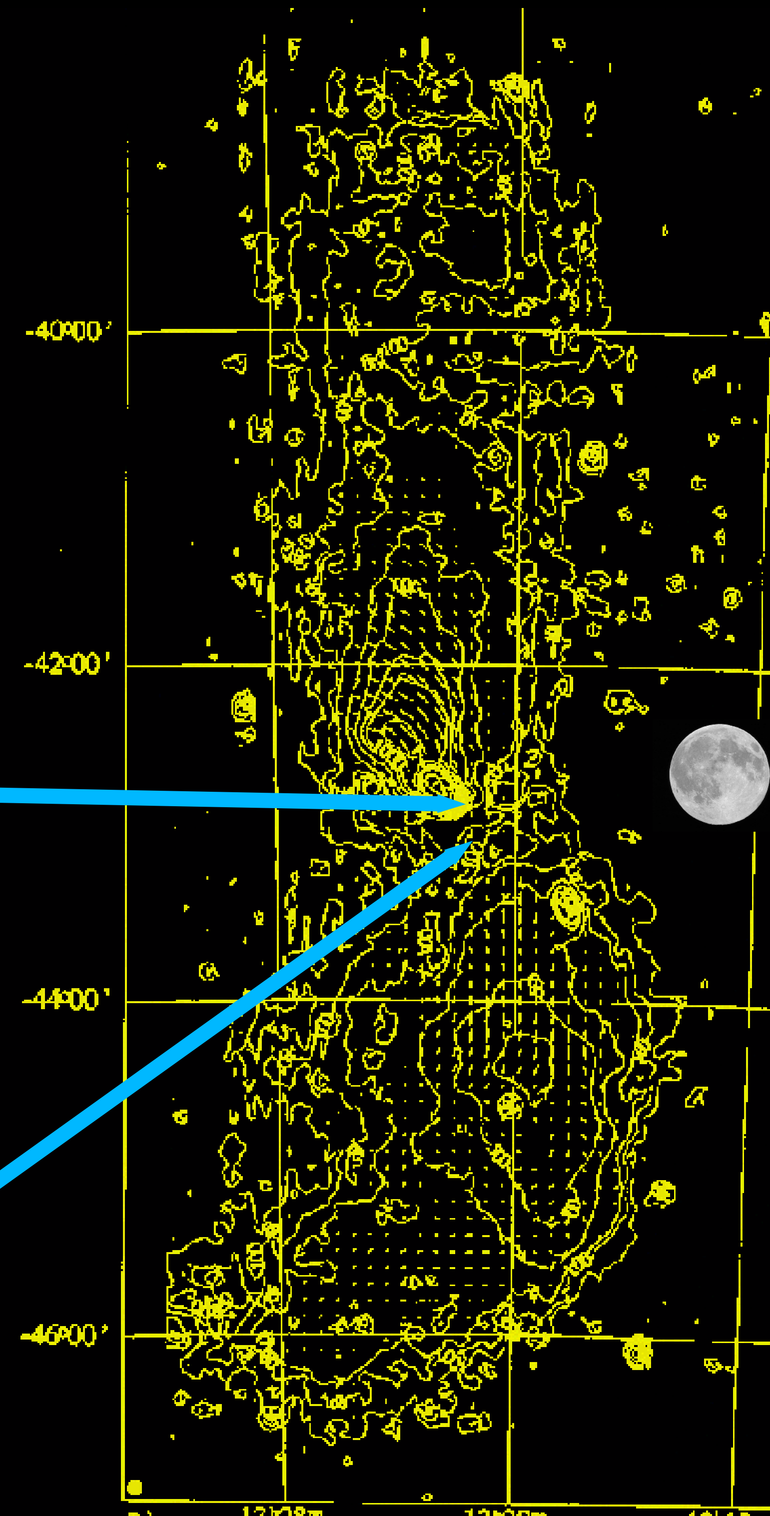
(size comparison to scale)

www.noao.edu/image_gallery/images/d3/FullMoon.jpg

# Extragalactic jets – contemporary data

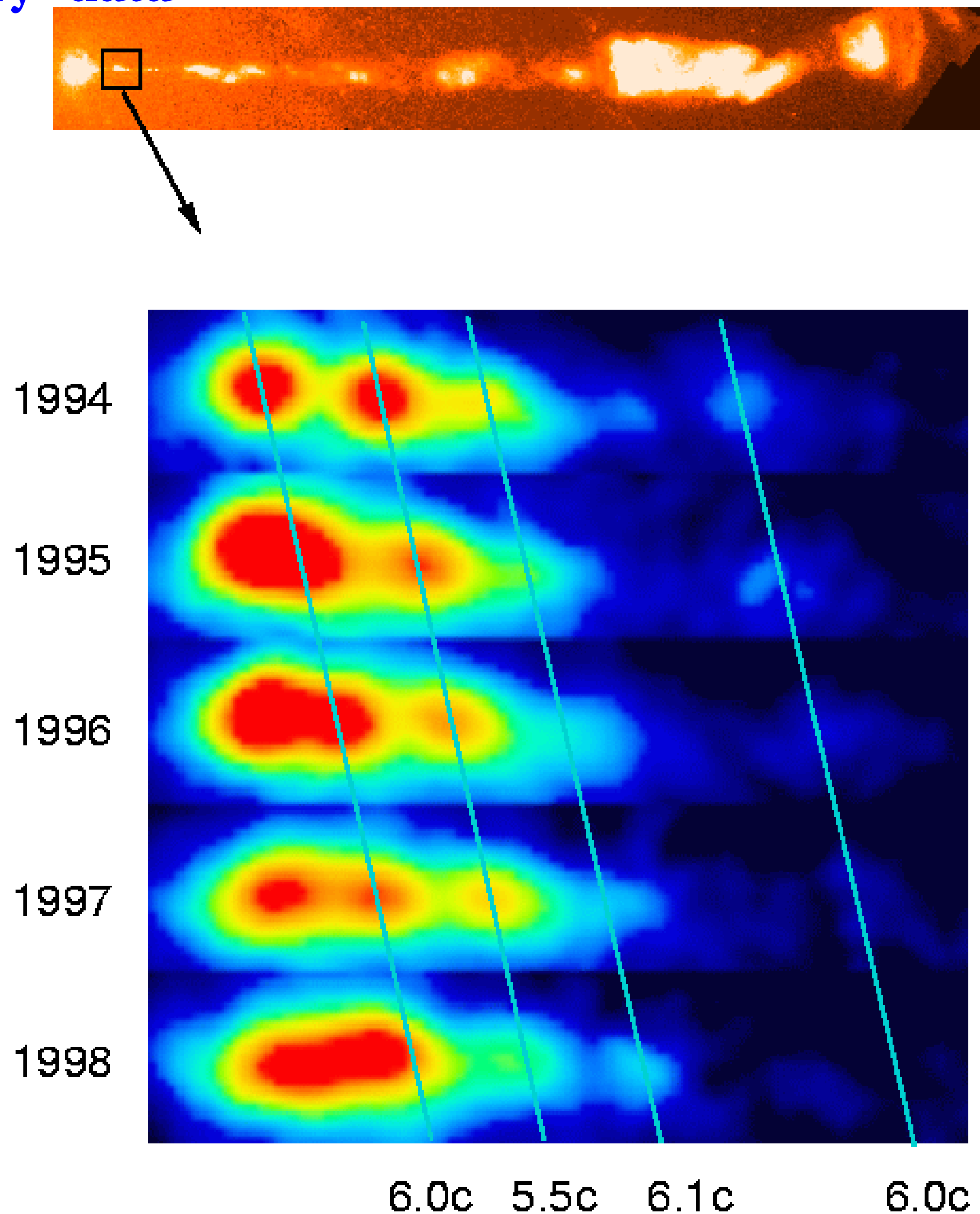
## Centaurus A:

- brightest and nearest of giant radio galaxies
- angular size ~ 10 degrees!!
- distance 3.5 Mpc
- inner lobes (Burns et al 1983)
- outer lobes (eg. Junkes et al 1990)




Cen A radio map (Junkes et al, 1990)

# Extragalactic jets – contemporary data




## Velocity of extragalactic jets

Proper motion of jet knots

Example 1:

M87 inner knots by HST:

**apparent superluminal motion**

(Biretta et al. 1999)

**-> v ~ 6c**

Note: optical resolution sufficient for nearest extragalactic jet source (16 Mpc), for other sources: radio interferometry

# Extragalactic jets – contemporary data

## Velocity of extragalactic jets

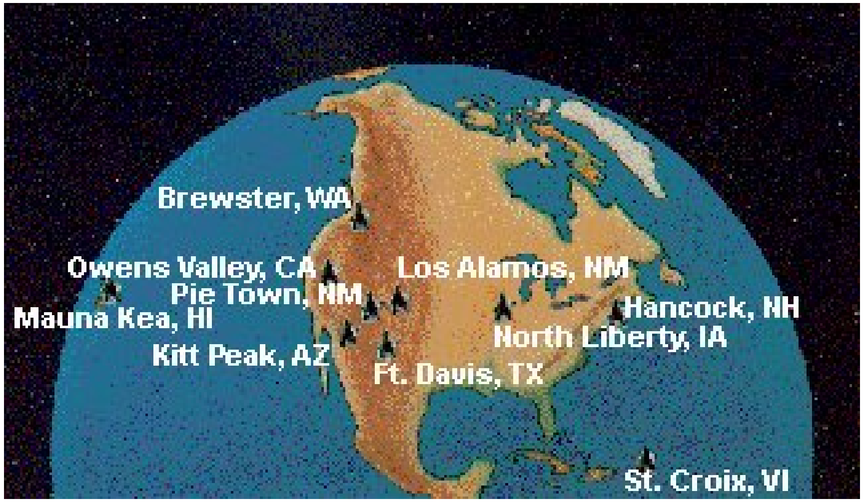
Proper motion of jet knots

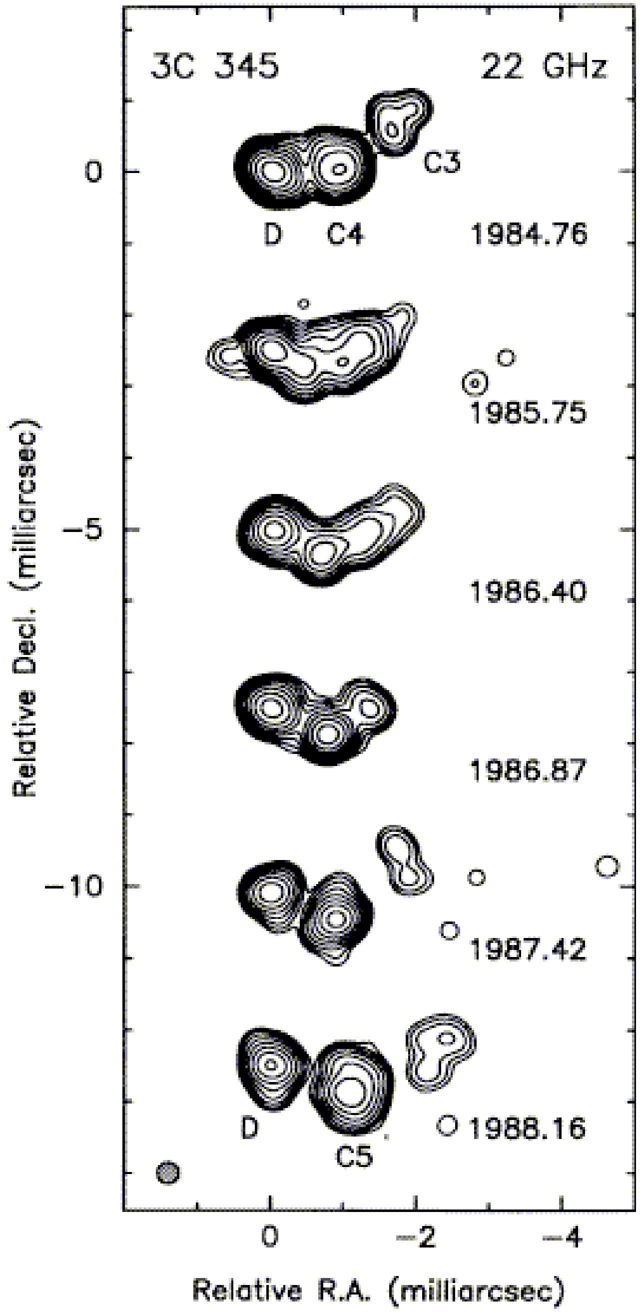
### Blazars & Quasars:

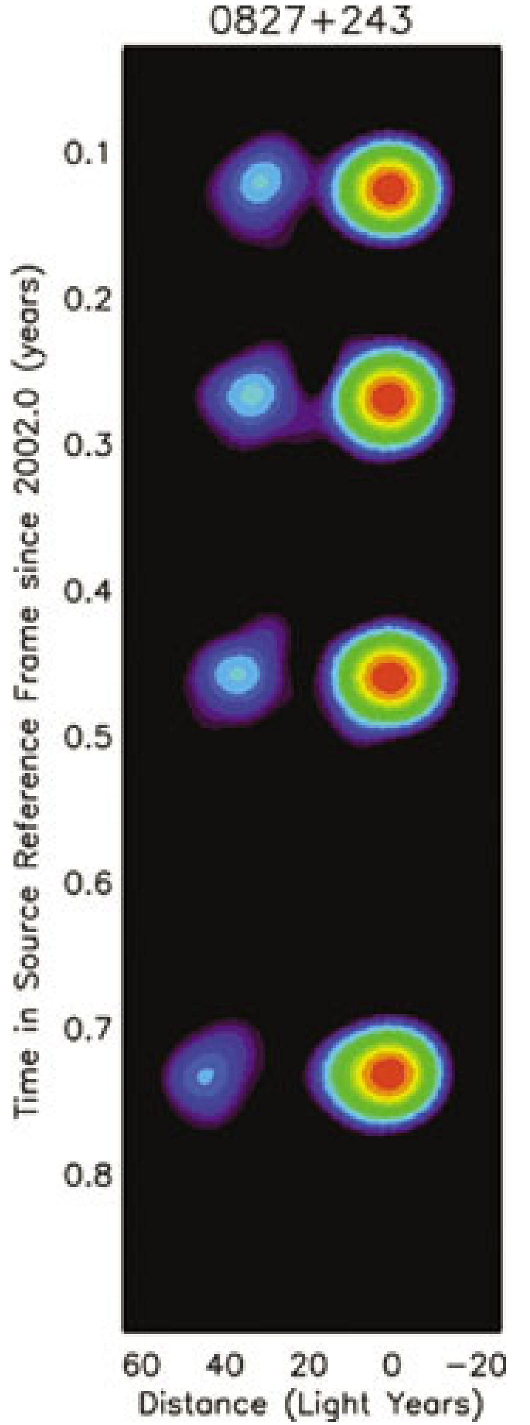
Jets directed towards observer;
-> variability due to beaming

3C 345: ~7c (period 5 yrs)
0827+243: Lorentz factor ~20

High resolution by VLBA radio interferometry needed



# Extragalactic jets – contemporary data

The central engine:

High (relativistic) jet speed

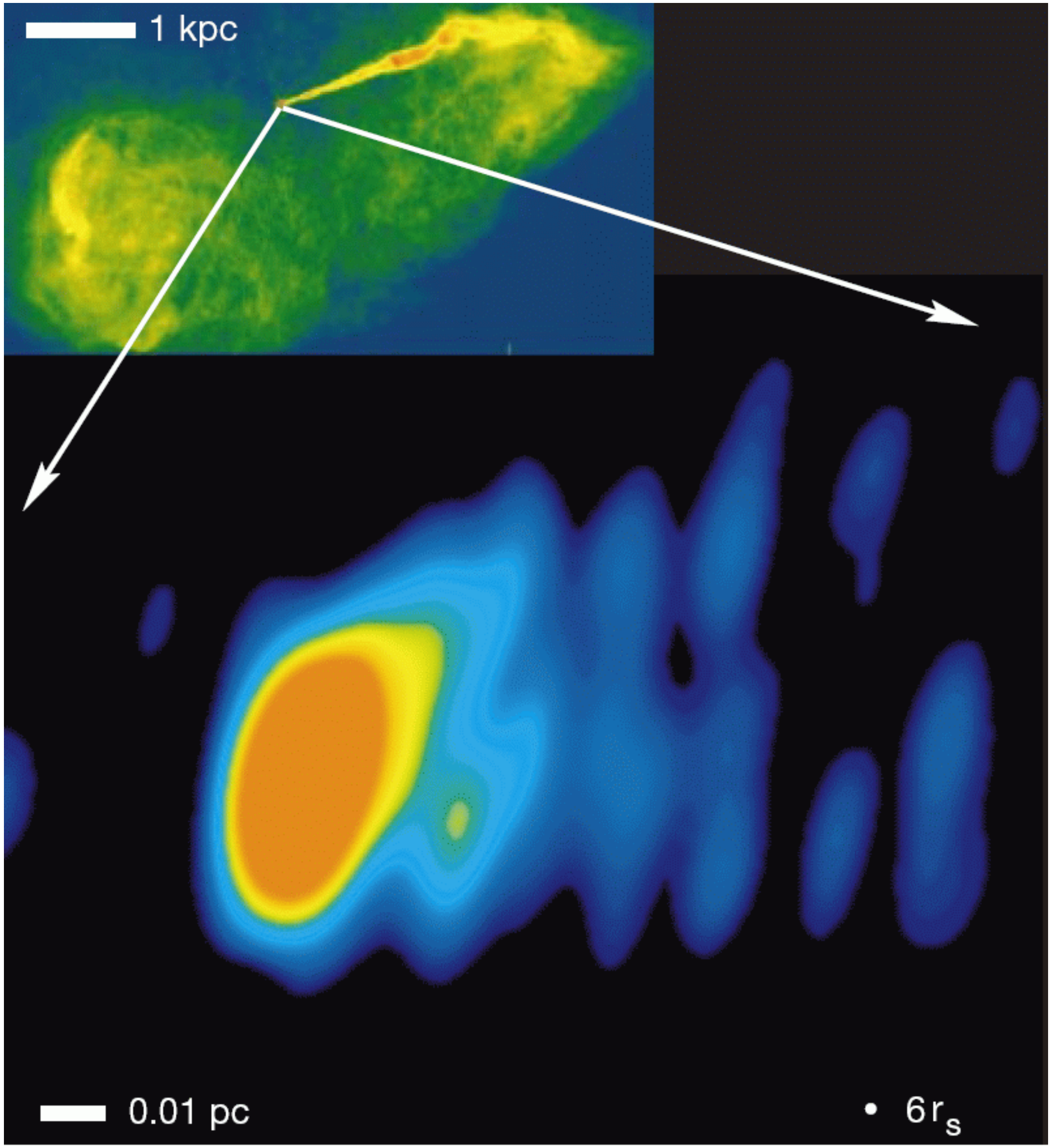
-> jet launched close to BH

M87 high resolution 43GHz observations (1000 AU resolution)

- initial opening angle ~ 60°
- strong collimation at ~30-100 $R_S$ (Schwarzschild radii) from BH
- collimation continues out to ~ 1000 $R_S$

## -> model of jet formation:

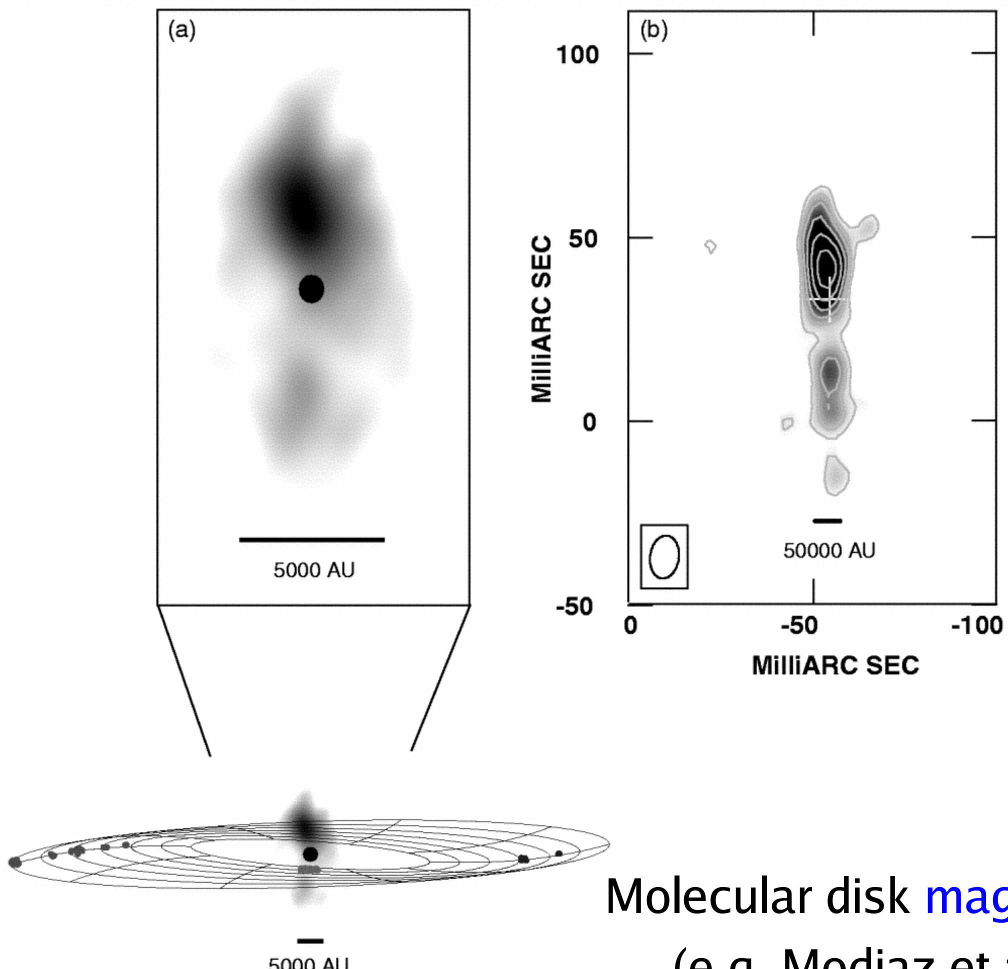
"*jets are formed by an accretion disk around the central black hole, threaded by a magnetic field*"

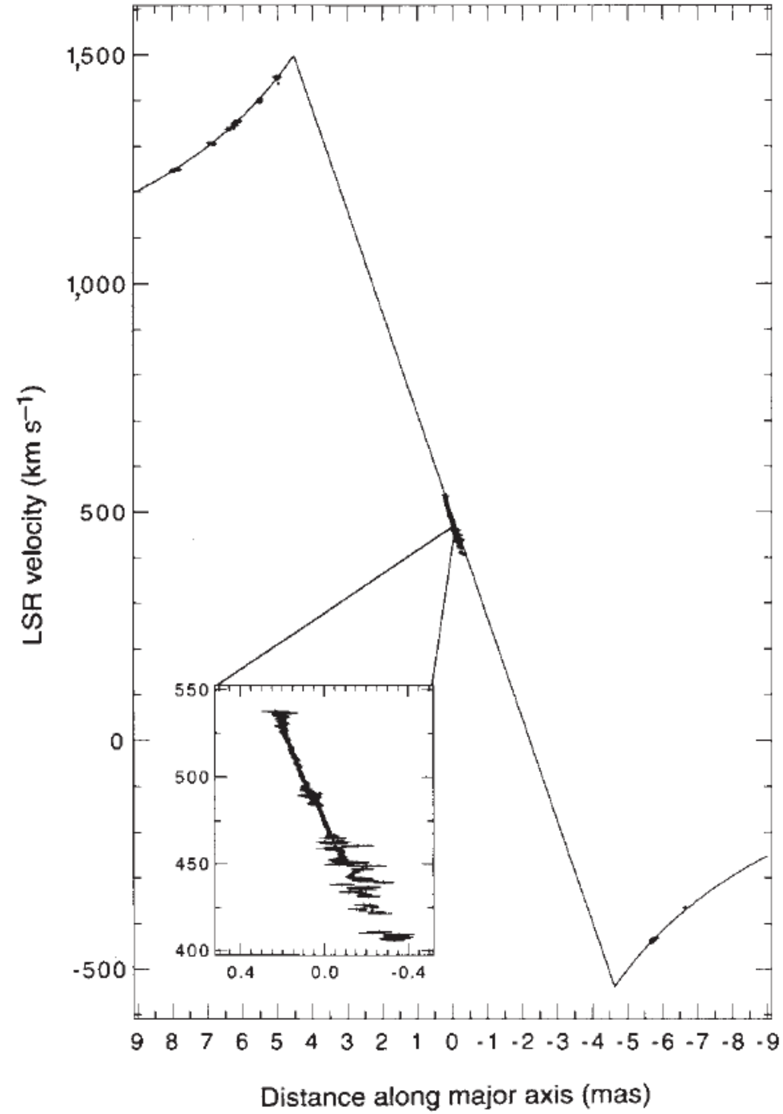



M87 central region (Biretta et al, 1999)

# Extragalactic jets – contemporary data

Central engine: example NGC 4258
Water maser spectroscopy, polarimetry




Central radio jet perp. to central molecular disk (Cecil et al. 2000)

Molecular disk magnetic field: (e.g. Modjaz et al. 2005)

-> B_tor ~ 90–300 mG at 0.2pc

-> B_rad ~30 mG at 0.15pc

-> dM/dt ~ $10^{-3.7}$ Mo/yr

**Evidence for a BH in jet source NGC 4258**

(Miyoshi et al 1995)

-> Keplerian disk rotation

-> central mass: $3.6 \times 10^7$ Mo

# Extragalactic jets – nomenclature

**Nomenclature** of radio double sources:

- core: central source, active nucleus (supermassive BH + disk)
- jets: relativ. hot, magnetized plasma
- hot spots: jet plasma is shocked
- cocoon: surrounding layer of backflow
- lobes: bow-like features beyond hot spots

## Historical classification:

comparison of radio surface brightness & source size (Fanaroff & Riley 1974)

-> ratio RFR ~ distance (bright) / size (faint)

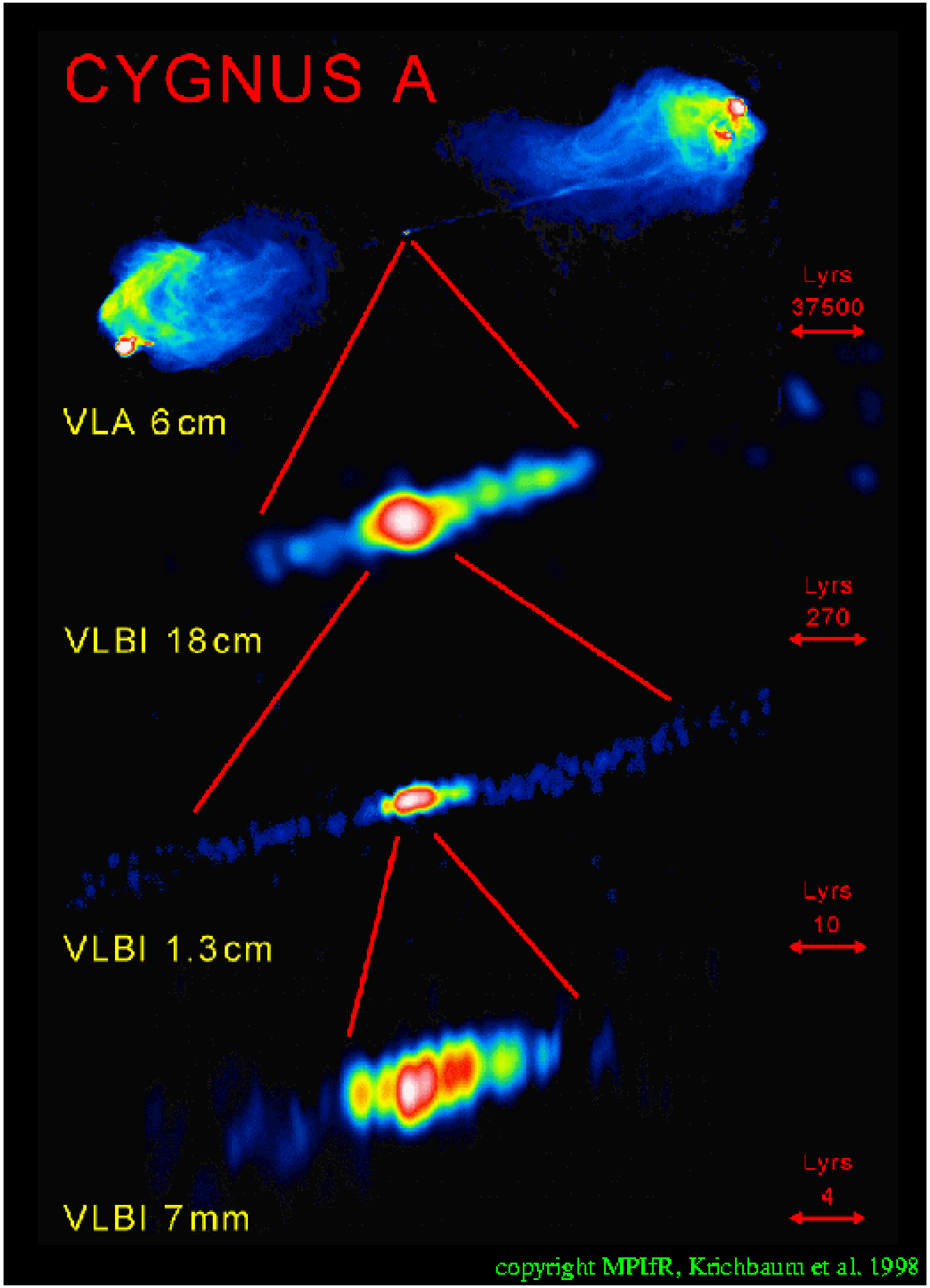
-> two classes: FR 1 : RFR < ½
FR 2 : RFR > ½

"lobe dominated" / "'core dominated"

see FR2 example Cyg A at 233 Mpc

-> FR correlation with
spectral radio luminosity,
spectral index $\alpha$ : $S(\nu) \sim \nu^\alpha$ :

**Unified model of AGN (~viewing angle)**




**max resolution: 0.00015 " ~0.1pc = 130 lightdays**

# Galactic relativistic jets

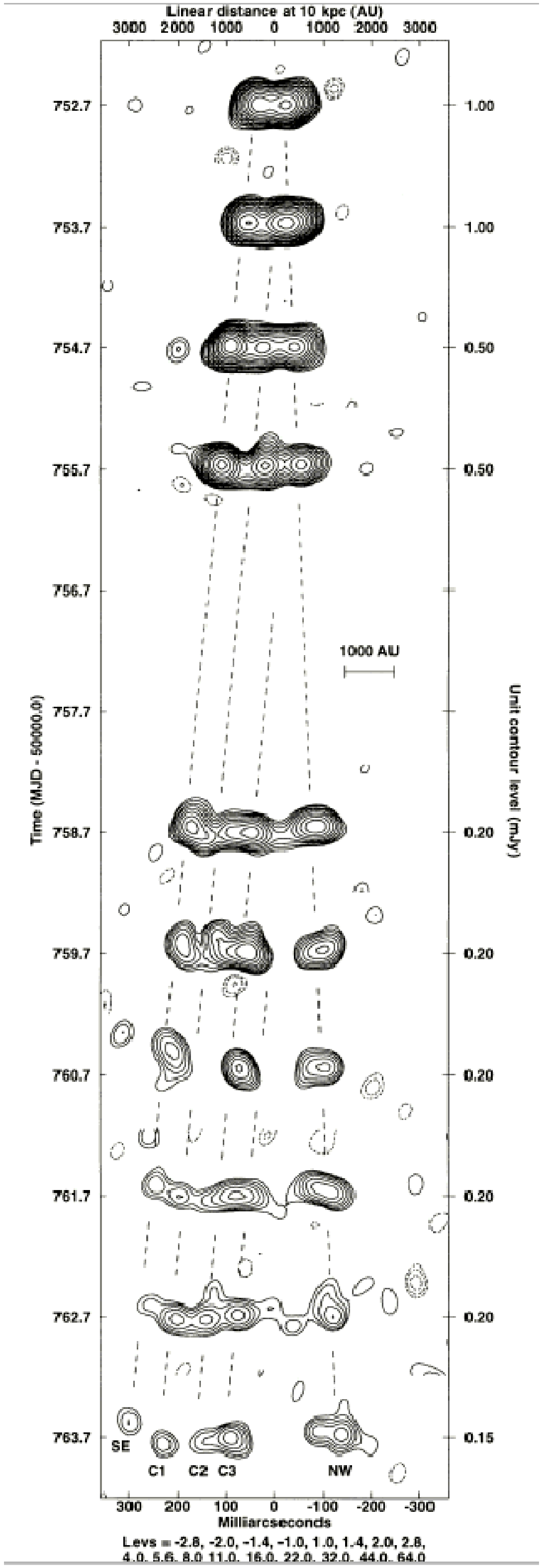
## "Micro quasars":

- detected in radio emission:
  ejection of knots with
  superluminal motion
  (Mirabel & Rodriguez 1994)

- jet sources: (# ~ 20)
  Galactic high energy sources :
  High Mass X-ray Binaries

- model : similar to AGN/quasars:
  black hole + accretion disk

- central mass ~ 10 $M_O$
  -> time scale reduced for physical processes (Kepler, free fall, instabilities)
  -> accessible for observations:
  4 weeks (MQ) = 10 years (AGN)




## GRS 1915+105

propagation:
jet 17.6 mas/d
c-jet 9.0 mas/d

distance: 12 kpc

velocities:
$v = 0.92$ c
$v_{j,app} = 1.25$ c
$v_{cj,app} = 0.65$ c

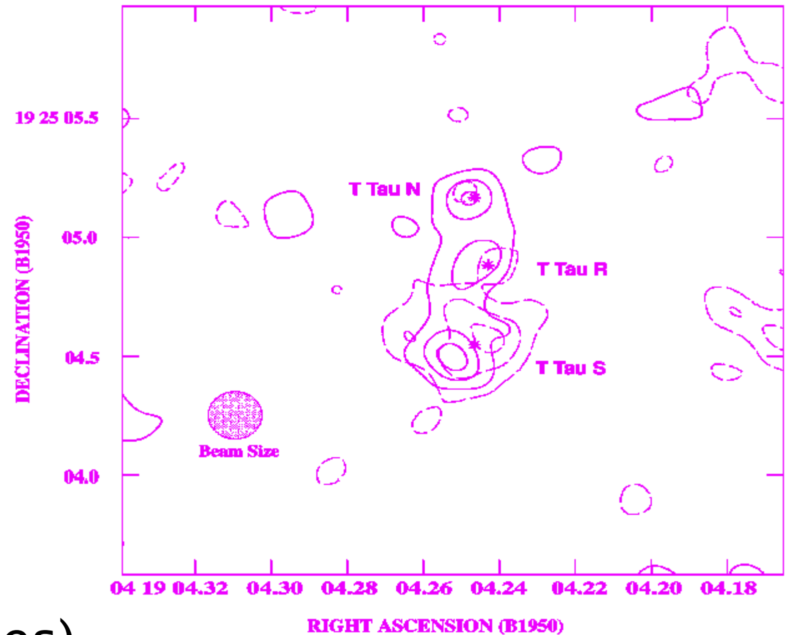
inclination: 70 °

source mass:
$M_{BH} = 14\ M_O$

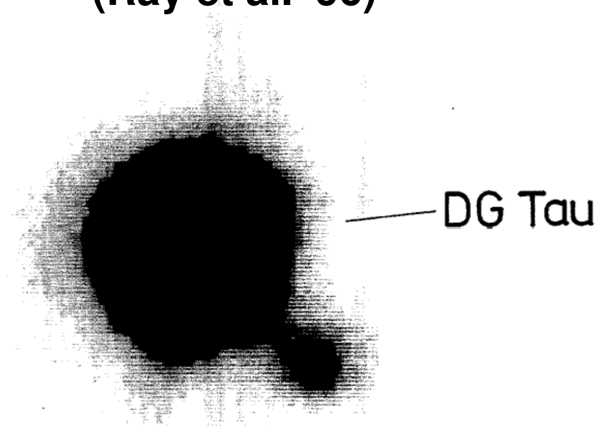
(Fender 1999,
Greiner et al. 2002)

# Protostellar jets

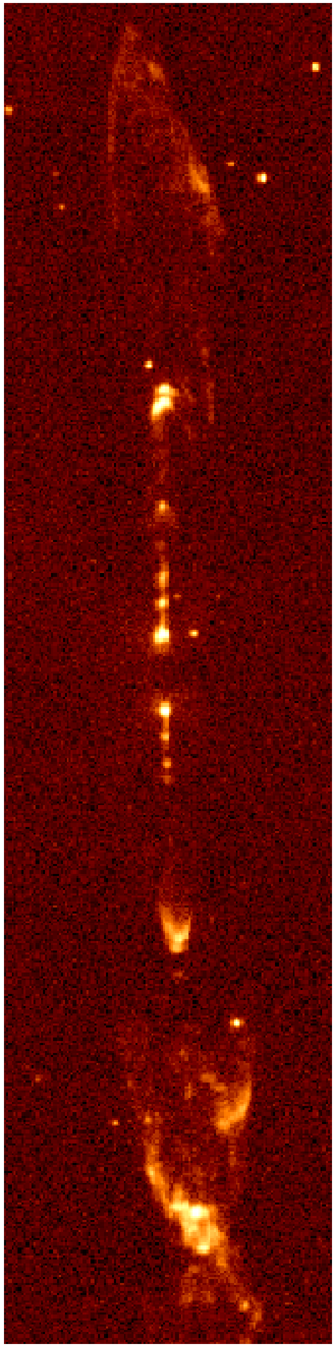
- Collimated to r ~ 50 – 100 AU, knotty morphology, bow shocks
- Line emission -> shocks
- Sources: Young Stellar Objects
  -> indication for accretion
  -> optically visible: “micro jets”
  (classical TT stars, class II sources)
  -> embedded sources, opt. obscured
- Jet / knot velocity ~ 300 km/s
- Magnetic field: strongly indicated:
  stellar activity ~1 kG;
  jet cyclotron emission ~1 G
- Asymmetry jet/counter jet is typical
- First detected in forbidden emission lines: DG Tau (Mundt & Fried '83)




T Tau, 6 cm, circ.pol.
(Ray et al. '96)

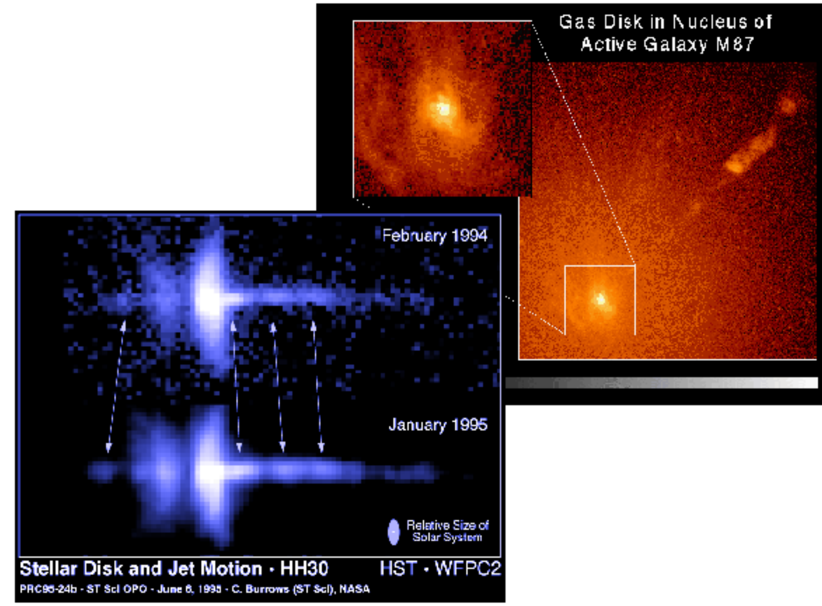



DG Tau SII (Mundt & Fried '83)



HH 212 H2, 2.12 μm
(McCaughrean et al. '98)

# Summary – astrophysical jets



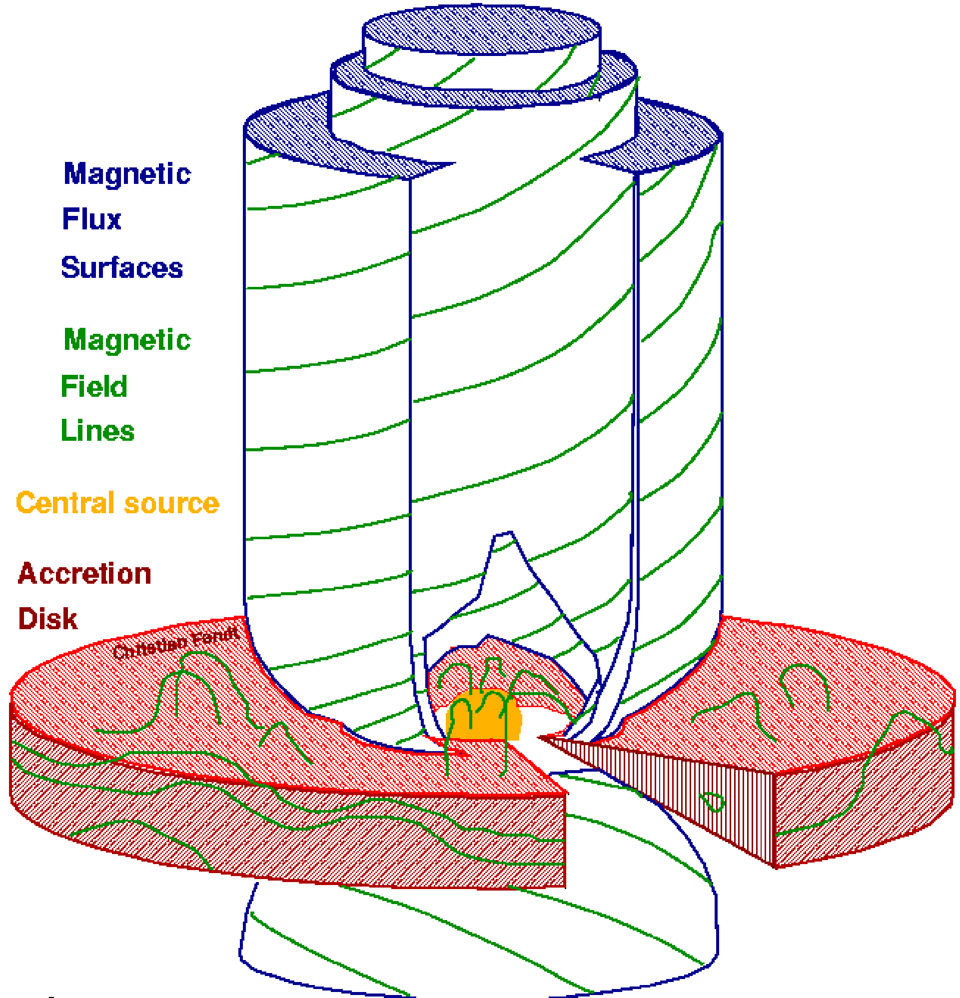

- Definition: collimated beam of matter of high velocity
- Sources: young stars, active galactic nuclei, m-quasars, gamma-ray bursts, planetary nebulae, pulsars
- Velocity > escape speed:
  -> jets launched close to central object
- Jet sources host accretion disks
- Indication for magnetic field:
  $B_{jet} \sim \mu G \ (YSO) \ ... \ mG \ (AGN)$
  $B_{source} \sim kG \ (YSO) \ ... \ 10^9 G \ (MQ)$
- Young stars: dipolar magnetosphere (?)
  BLack holes: disk magnetic field (?)
- Jets are huge: $R_{jet} \sim 10^3 - 10^4 \ R_{source}$

# Conclusion:

- jets seen over wide range of energy output & central mass :
  -> mass $M \sim 1 \ldots 10^{10} M_{\odot}$
  -> luminosity $L \sim 10^{33} \ldots 10^{43} erg \ s^{-1}$

- i) jets launched from accretion disks
  ii) not relativistic but magnetic phenomenon -> same launching mechanism for all jets ! (?)

# Standard model of jet formation




## MHD model of jet formation:

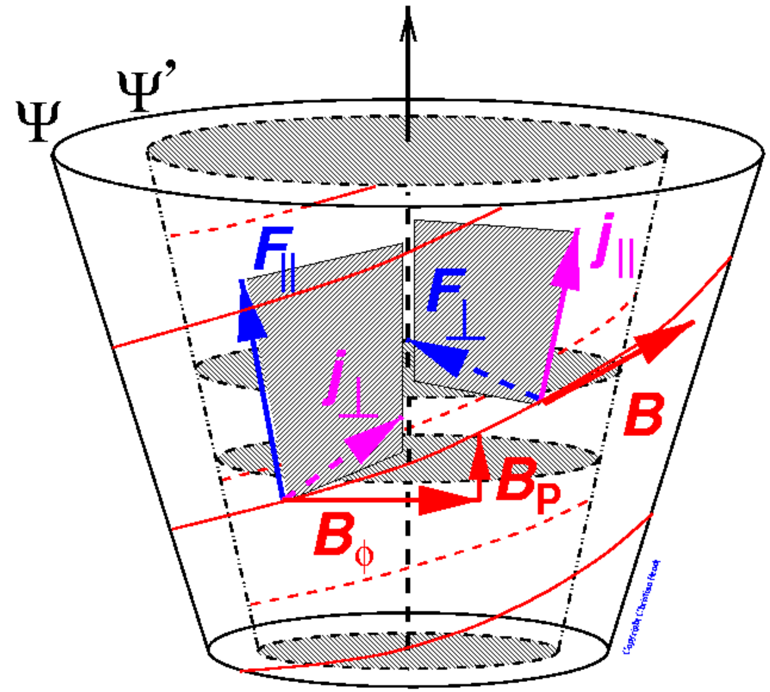
Jets are collimated disk/stellar winds,
launched,
accelerated,
collimated
by magnetic forces

Energy source: gravity, rotation

## -> 5 basic questions of jet theory:

- ejection of disk/stellar material into wind?
- collimation & acceleration of a disk/stellar wind into a jet
- jet propagation / interaction with ambient medium
- accretion disk structure?
- origin & structure of magnetic field?

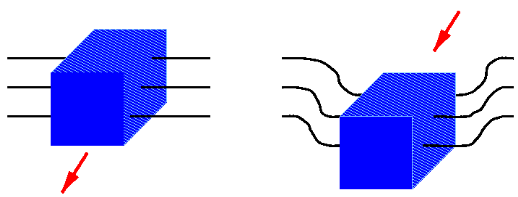
# Jet-Magnetohydrodaynamics




**MHD concept:** ionized, neutral fluid:
average quantities:

$$\vec{j} \equiv q_e \vec{v}_e n_e + q_i \vec{v}_i n_i$$

**Ideal MHD:** infinite conductivity,
"frozen-in" field lines:



**MHD Lorentz force:** $\vec{F}_L \sim \vec{j} \times \vec{B}$

**MHD equations,** solved numerically:

$$\partial_t \rho + \nabla \cdot (\rho \vec{v}) = 0$$
$$\rho(\partial_t \vec{v} + (\vec{v} \cdot \nabla)\vec{v}) = -\nabla P - \rho \nabla \Phi + \vec{j} \times \vec{B} + \rho \vec{F}_{rad}$$
$$\partial_t E + \nabla \cdot \left[\vec{v}(E + P + B^2/8\pi) - \vec{B}(\vec{v} \cdot \vec{B}) + (\eta \cdot \vec{j}) \times \vec{B}\right] = .$$
$$. = \vec{v} \cdot \left[-\nabla \Phi + \vec{F}_{rad}\right]$$
$$E = \rho\epsilon + \rho v^2/2 + B^2/8\pi \;, \quad P = \rho\epsilon(\gamma - 1)$$
$$\partial_t \vec{B} = \nabla \times (\vec{v} \times \vec{B} - \eta \vec{j})$$
$$\nabla \cdot \vec{B} = 0 \;, \quad \nabla \times \vec{B} = 4\pi \vec{j}$$

**Axisymmetric flows:**

-> poloidal, toroidal field: $B = B_p + B_\phi$

-> magnetic flux surfaces:

$$\Psi(r, z) \sim \int \vec{B}_p \cdot d\vec{A}$$

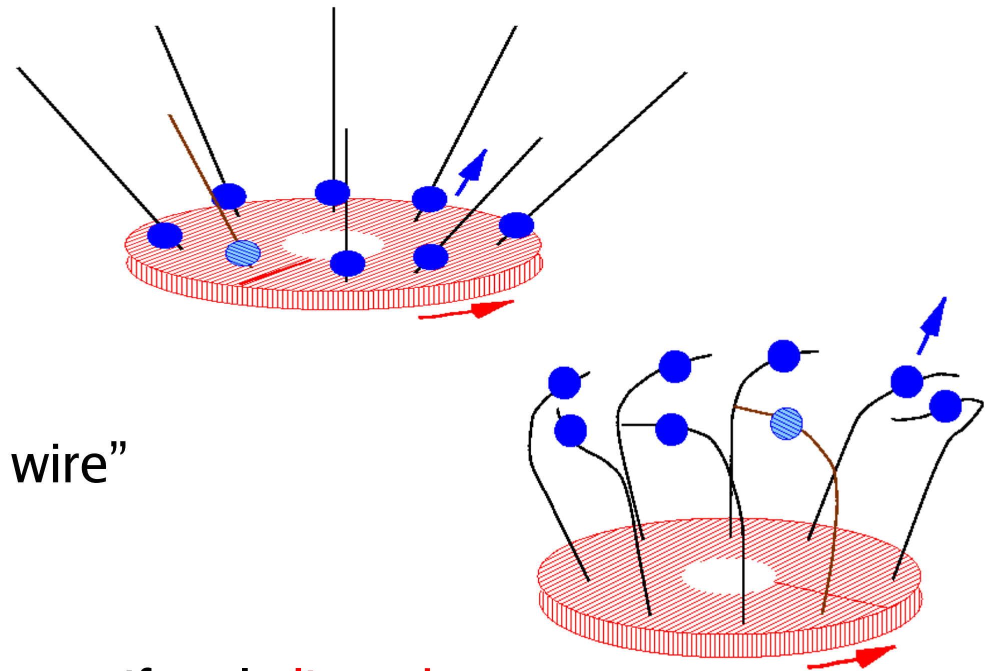
**Lorentz force components:**

projected on Ψ : $\vec{F}_L = \vec{F}_{L,par} + \vec{F}_{L,per}$

-> (de/)accelerating: $\vec{F}_{L,par} \sim \vec{j}_{per} \times \vec{B}_\phi$

-> (de-)collimating: $\vec{F}_{L,per} \sim \vec{j}_{par} \times \vec{B}$

# Jet-Magnetohydrodaynamics



## Magneto-centrifugal acceleration:

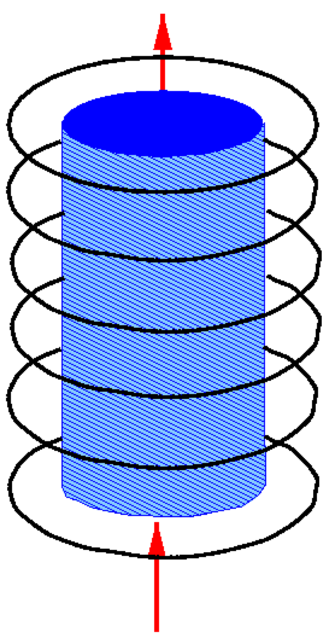
(Blandford & Payne 1982)

-> field lines corotate w/ disk, "beads on wire"

-> strong poloidal field: $B_P > B_\Phi$

-> field line inclination $< 60°$

-> unstable equilibrium, (magneto-) centrifugal sling-shot



## Self-collimation of MHD jets:

Alfven radius: kinetic ~ magnetic energy:

-> poloidal field inertially twisted -> toroidal field component

-> collimation: toroidal field tension: $\vec{F}_{L,per} = \frac{1}{4\pi}\left(\vec{B}_\phi \cdot \nabla\right)\vec{B}_\phi$

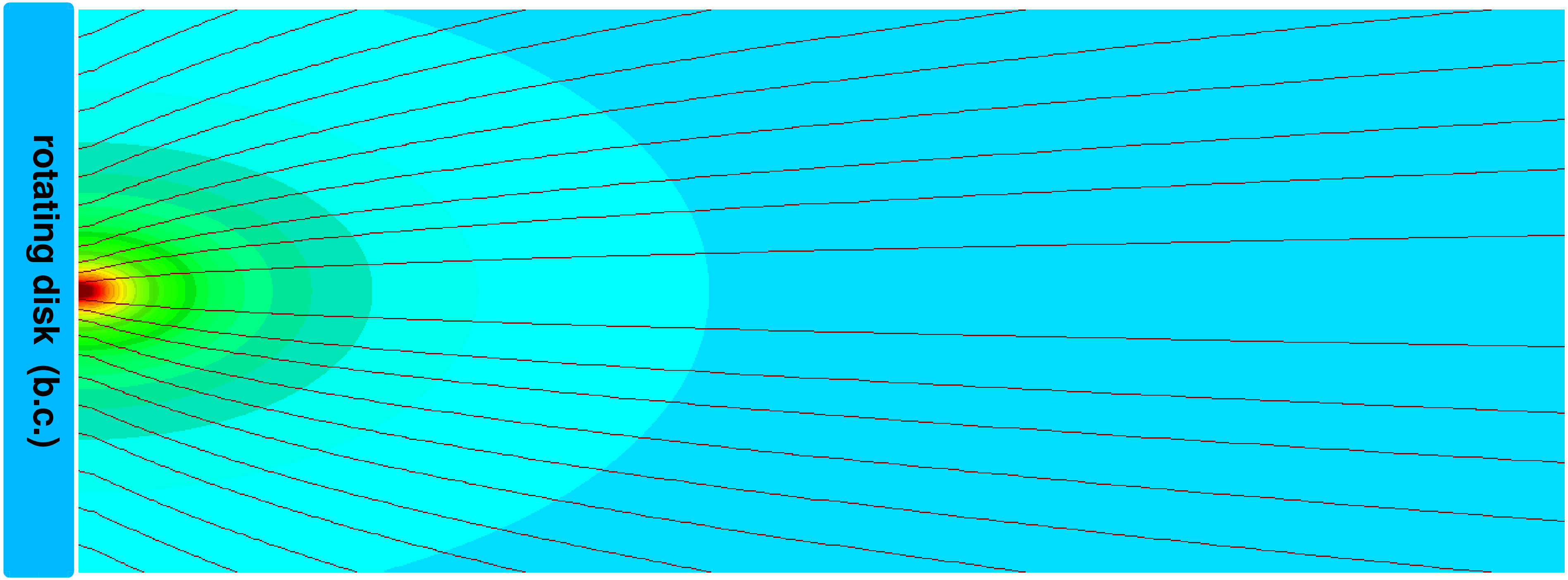
**MHD acceleration:** Lorentz force: $\vec{F}_{L,par} \sim \vec{j}_{per} \times \vec{B}_\phi$

# Jet MHD simulations

Proof of **MHD self-collimation** by simulations under various boundary conditions

**Model assumptions:** (Ouyed & Pudritz 1997; Ustyugova etal. 1996)

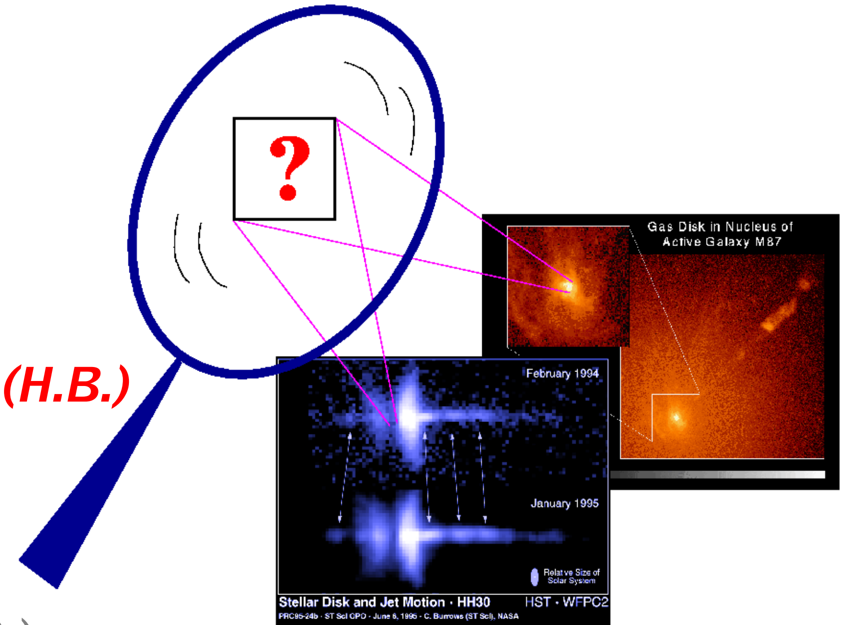
-> ideal / non-ideal MHD, axisymmetry, polytropic gas + turb. Alfvenic pressure
-> Keplerian disk as boundary condition, prescribed mass flux, inner disk radius
-> disk magnetosphere, various field profiles; grid size 150 x 300 R_in
-> collimation degree quantified by mass flux in axial versus radial direction




**colors: gas density, lines: poloidal magnetic field lines**

# Lecture plan & schedule

## Summer term 2011
## Henrik Beuther & Christian Fendt

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comparison of radio surface brightness & source size (Fanaroff & Riley 1974)

-> ratio RFR ~ distance (bright) / size (faint)

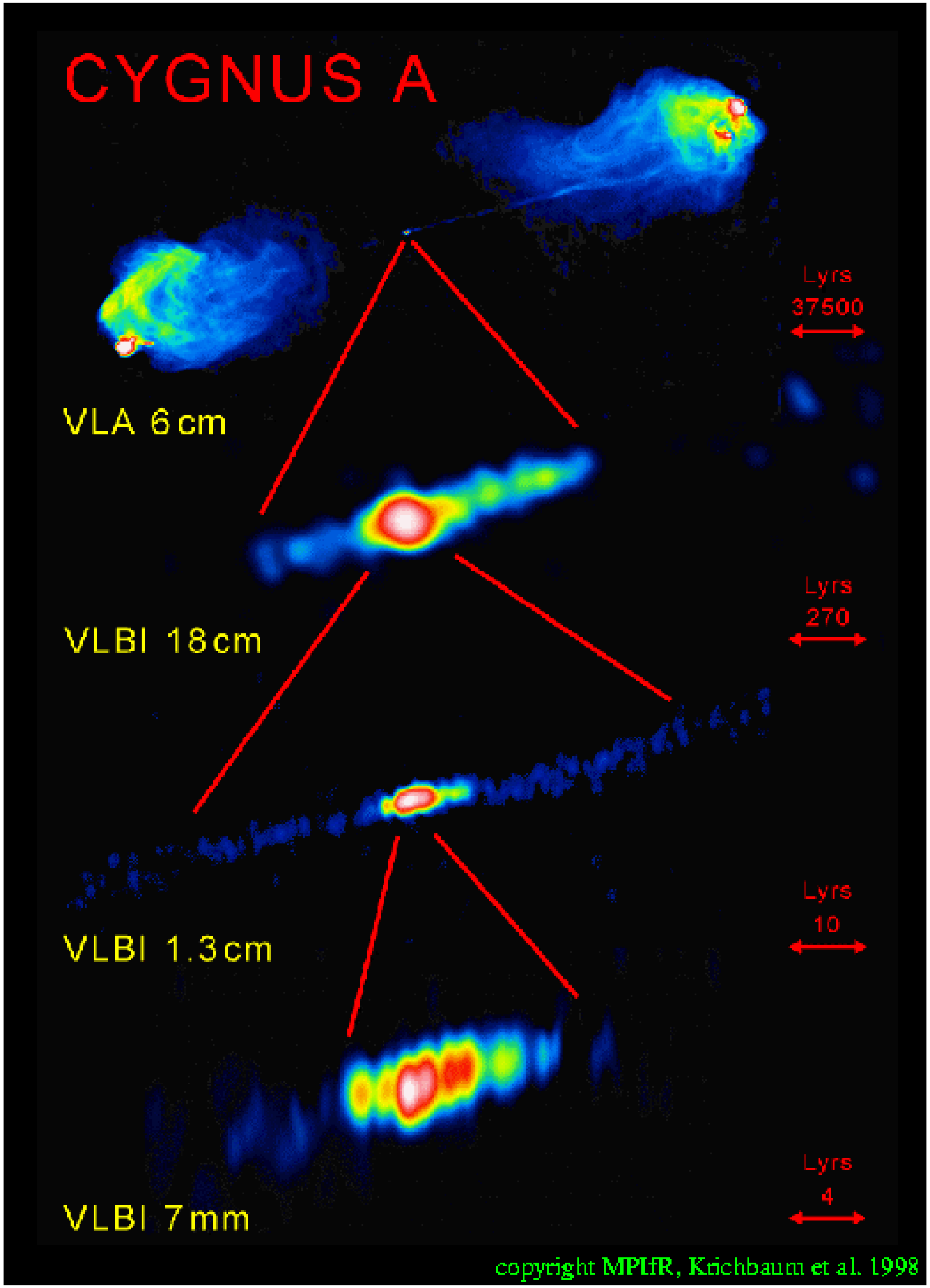
-> two classes: FR 1 : RFR < ½
FR 2 : RFR > ½

-> "lobe dominated" / "core dominated"
FR2 example Cyg A (233 Mpc)

-> FR correlation with spectral radio luminos

-> spectral index $\alpha$ : $S(\nu) \sim \nu^\alpha$ :
core: $\alpha \sim 0$ (flat), jets: $\alpha \sim 0.6$ (steep)
hot spots: $\alpha \sim 0.5...1.0$

**Unified model of all AGN (viewing angle)**

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