Approaching the black hole horizon with mm-VLBI

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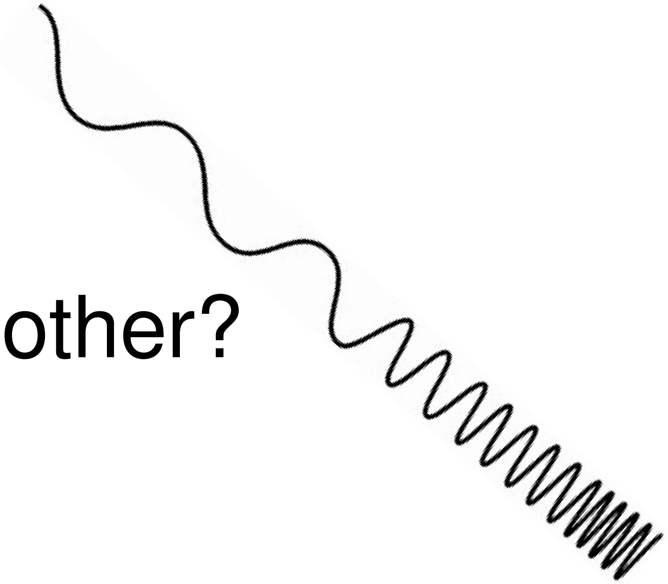
Lezioni di Dottorato, second internal course 2009: mm Astrophysics

Outline



1. mm-VLBI: what is it? why bother?
2. how do we do it?

3. science highlights
4. future expectations on 2) and 3)
    - to the black hole horizon!

ALMA MATER STUDIORUM A.D. 1088

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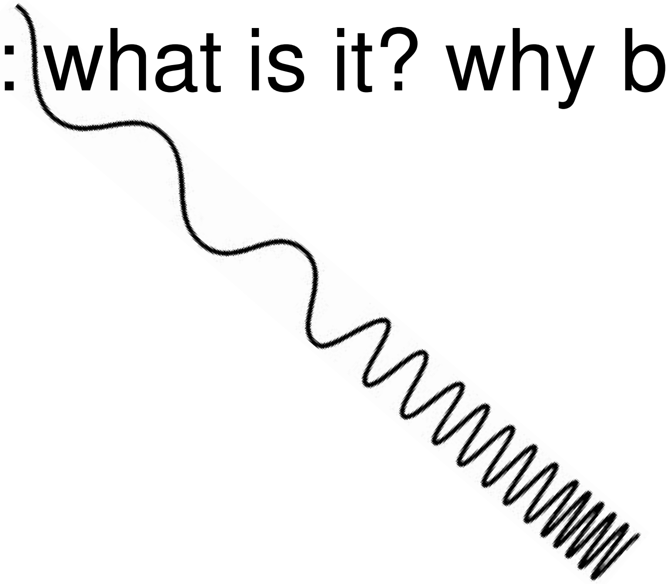
Part 1

mm-VLBI: what is it? why bother?



Angular resolution and the paradox of radio astronomy…

$$\theta = \frac{\lambda}{D}$$

$$\left.\begin{array}{l}\lambda \approx 10^{-6} m \\ D \approx 10^{-3} m\end{array}\right\} \Rightarrow \theta \approx 10^{-3}$$

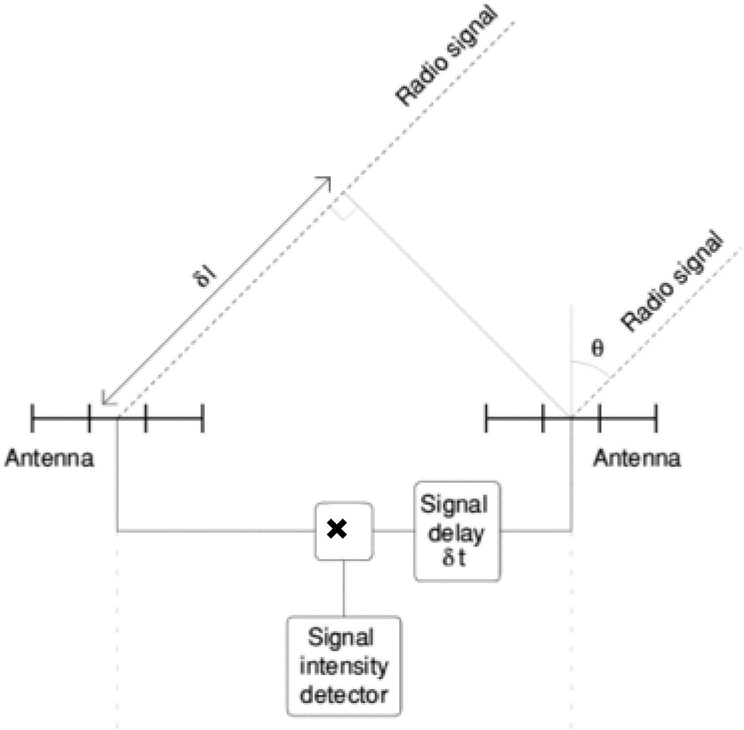
$$\left.\begin{array}{l}\lambda \approx 10^{-1} m \\ D \approx 10^{2} m\end{array}\right\} \Rightarrow \theta \approx 10^{-3}$$

- A 100m radio telescope is no better than your naked eye…
- …however, the best angular resolution of all astronomy is obtained through radio waves!

Interferometry is the key!

$$\theta = \frac{\lambda}{B}$$

$$\left.\begin{array}{l} \lambda \approx 10^{-1} m \\ B \approx 10^{4} m \end{array}\right\} \Rightarrow \theta \approx 10^{-5}$$



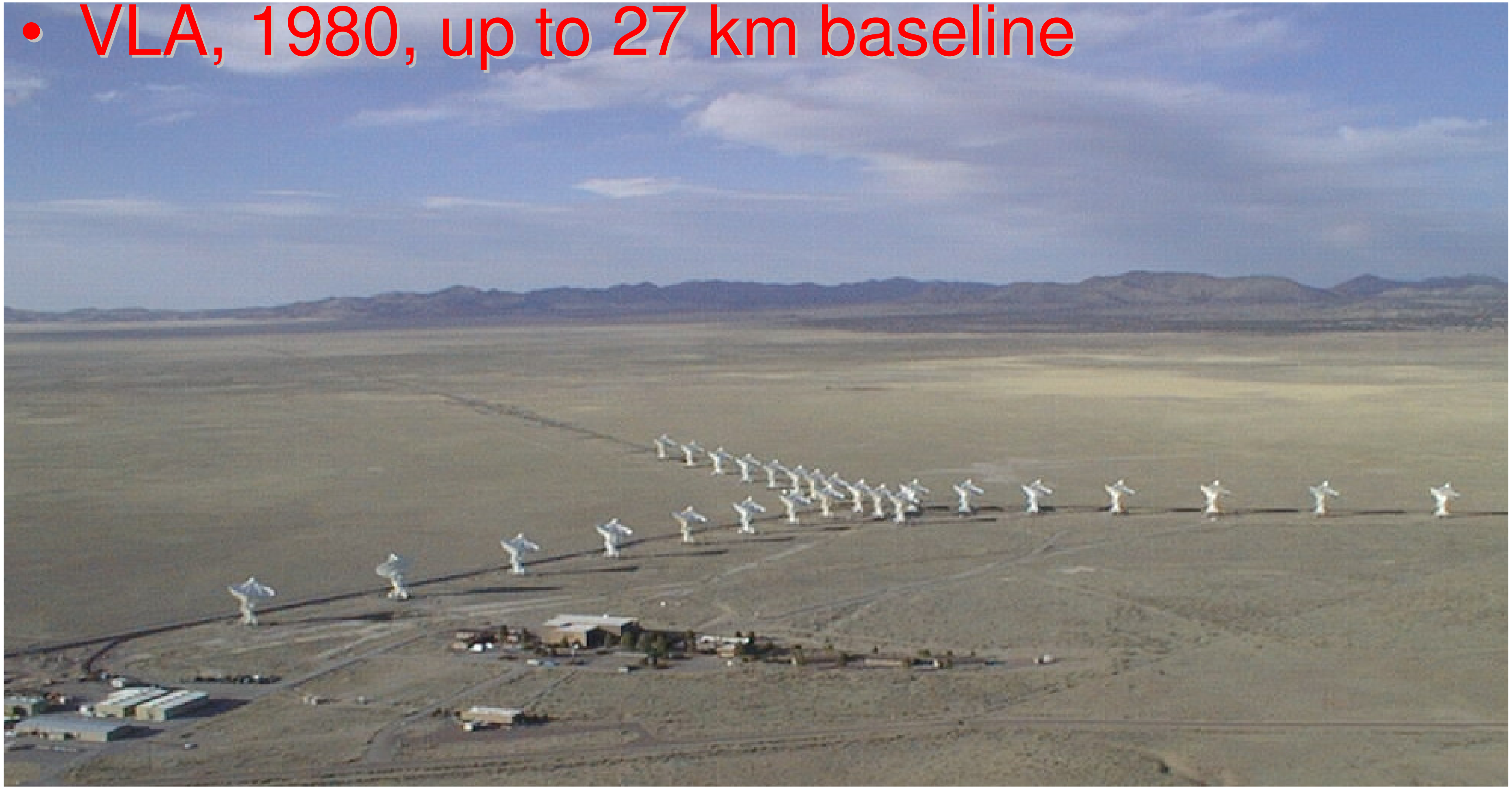
With a few kilometers baseline we can easily get to arcsecond resolution

How big can your interferometer be?

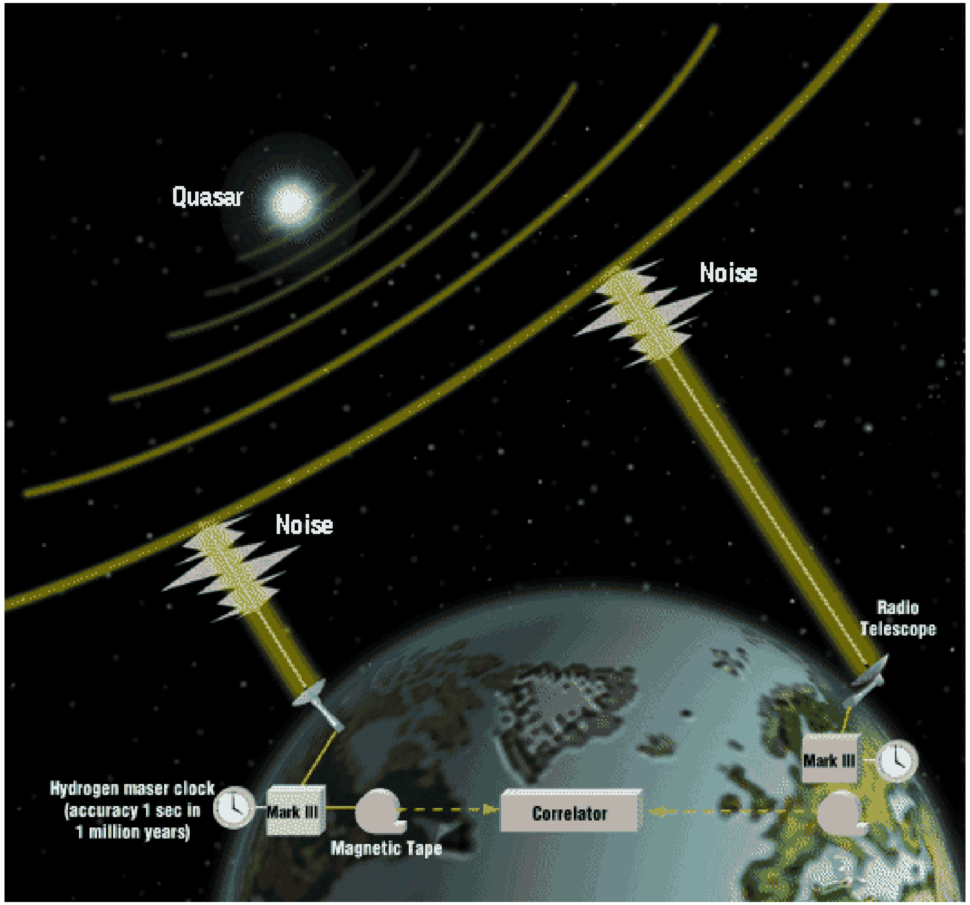
- Croce del Nord/Northern Cross
  - 1964, 564x512m

How big can your interferometer be?

- VLA, 1980, up to 27 km baseline



How big can your interferometer be?

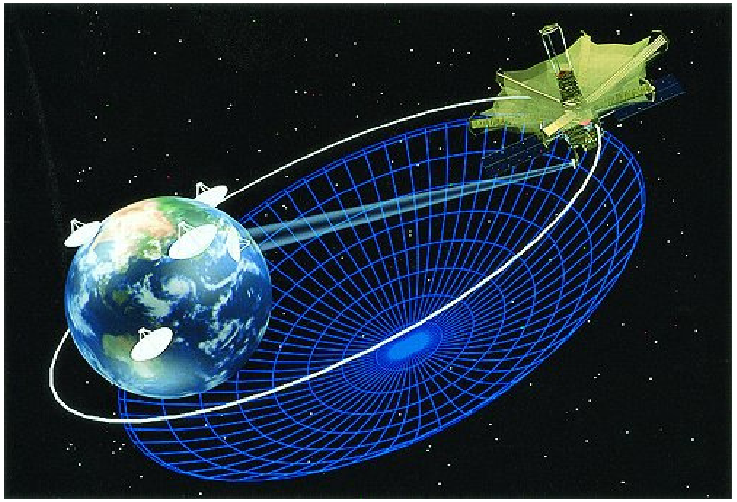


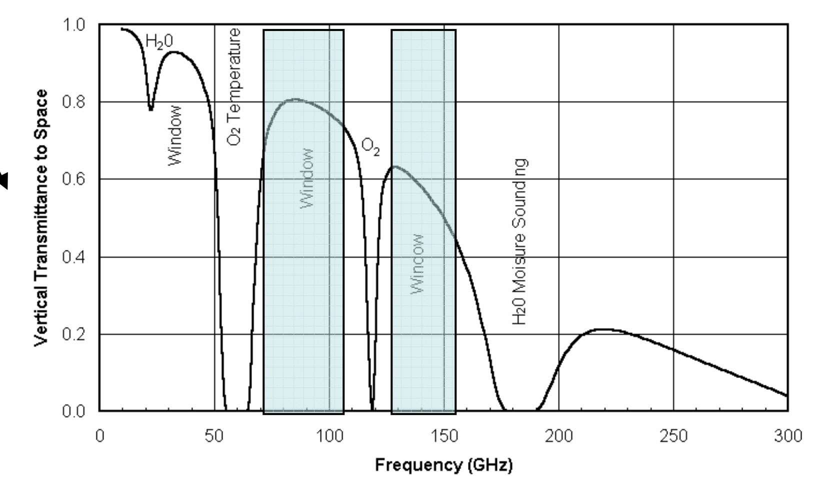
- Very Long Baseline Interferometry: as big as the earth!
- VLBI correlates radio signals recorded on tapes all over the world
  - real time correlation is also now possible
- With B=10000 km, resolution can be as good as milliarcseconds

How can we increase the resolution further?

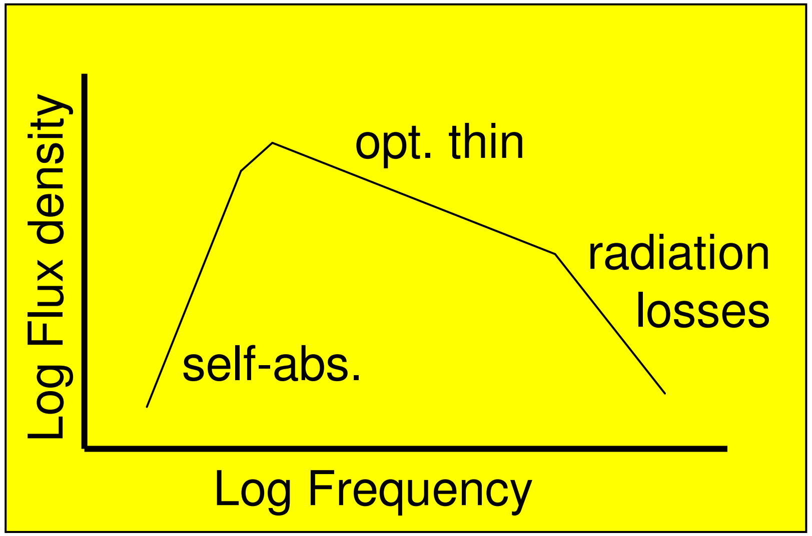
$$\theta = \frac{\lambda}{B}$$

- Longer baselines
  - Space VLBI,
  - good for sources brighter at low frequency
- Shorter wavelengths
  - Millimeter VLBI
  - good for regions brighter at high frequency
  - but challenging!!!





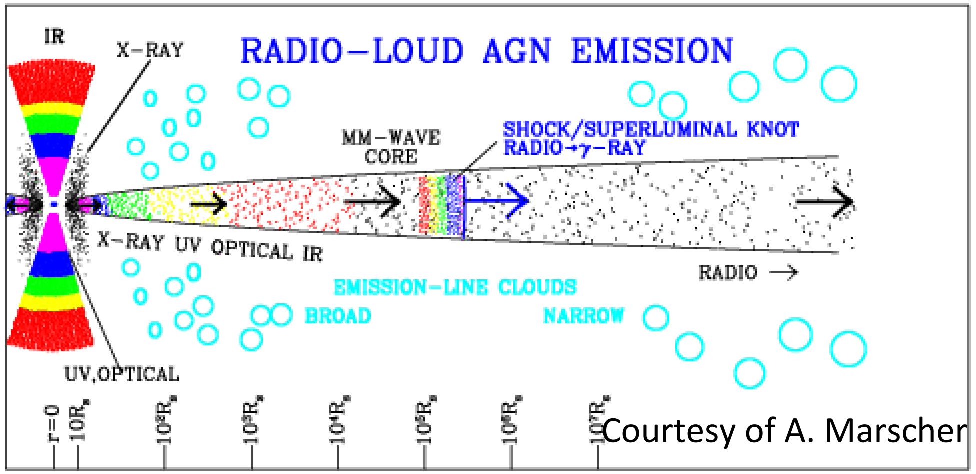
mm-VLBI, why bother?



- Challenges for mm-VLBI
  - low atmospheric transmittance
  - telescope surface accuracy needs to be smaller than wavelength
- Driving issue
  - synchrotron emission low frequency self-absorption
  - $\boxed{\nu_{\max} = e(\alpha)\, H^{1/5}\, \theta^{-4/5}\, S_{\max}^{2/5}\, (1+z)^{1/5}}$

mm-VLBI main motivation

What are the processes acting at the centers of Quasars (AGN)?
How are the powerful jets launched and accelerated?



Courtesy of A. Marscher

End of Part 1 (Introduction – why bother)

Part 2

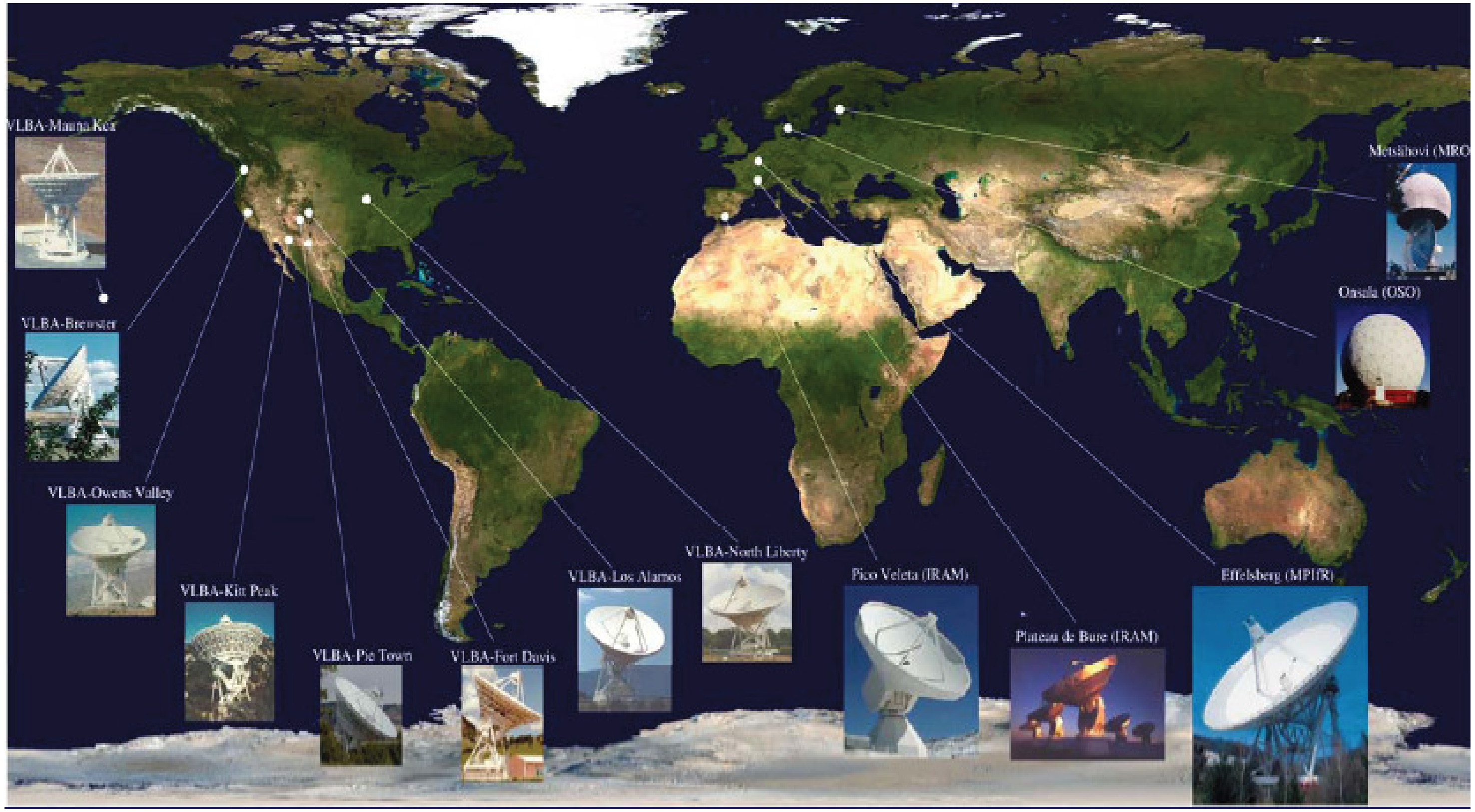
How do we do it?

History of mm-VLBI

- Challenges repeated
  - need good site
  - need accurate surface
- Hystorically, first experiments back in the 1980s, and mostly US based
  - Readhead et al. (1983), 3mm observations of 3C84 over 485 km baselines
  - Coordinated Millimeter VLBI Array (CMVA), with US telescopes and occasionally European ones. Lonsdale et al. (1998)
    - 116 selected sources, 79 observed, 14 detected, 6 with transatlantic fringes

Present of mm-VLBI: from CMVA to GMVA

- The Global Millimeter VLBI Array (GMVA):
  - http://www.mpifr-bonn.mpg.de/div/vlbi/globalmm/



The Global Millimeter VLBI Array

- Founded in 2003 by MPIfR, NRAO, IRAM, OSO, Metsähovi
- 13 participating telescopes
  - Europe: Effelsberg (100m), Pico Veleta (30m), Plateau de Bure (eq 35m), Onsala (20m), Metsähovi (14m)
  - USA: 8 x VLBA (25m)
- 2 sessions per year
- Baseline sensitivity 50-350 mJy
- Angular resolution 40 μas
  - What do these numbers mean?

Sensitivity of VLBI - Detection threshold

- Defining the System Equivalent Flux Density of i-th element [Jy]

$$SEFD_i = \frac{T_{sys,i}}{g_i}$$

  - Tsys [Kelvin]: telescope measured system temperature
  - G [Kelvin/Jy]: gain factor, elevation dependent quantity for each individual telescope
- 100 m telescope, typical values
  - Tsys= 100 K, g = 1.4 K/Jy
  - SEFD = 100/1.4 Jy = 71 Jy

Sensitivity of VLBI - Detection threshold

- The 1- σ detection threshold for baseline between i-th and j-th telescopes in array is

$$\boxed{\sigma_{ij} = \frac{1}{\eta_c} \times \sqrt{\frac{SEFD_i \cdot SEFD_j}{2 \cdot \Delta\upsilon \cdot \tau_{\mathrm{integ}}}}}$$

  - η correction for correlator losses due to sampling
  - Δv recorded bandwidth
  - τ integration time – limited by atmospheric coherence
- For a two 100m radio telescope baseline (η=0.5)
  - SEFD = 100/1.4 Jy = 71 Jy
  - Δv=256MHz, τ=100 sec
  - σ= 0.4 mJy – very ideal case!!!

Angular and spatial resolution of mm-VLBI

λ	ν	θ	z=1	z=0.01	d= 8 kpc
3 mm	86 GHz	45 μas	0.36 pc	9.1 mpc	1.75 μpc
2 mm	150 GHz	26 μas	0.21 pc	5.3 mpc	1.01 μpc
1.3 mm	230 GHz	17 μas	0.13 pc	3.4 mpc	0.66 μpc

- for nearby sources, these scales correspond to 1–100 Schwarzschild radii, depending on distance and black hole mass!
  - linear size: $10^3 R_s$ (log M_{BH}=9), 30-100 R_s (log M_{BH}=9), 1-5 R_s (log M_{BH}=6)
- mm-VLBI is able to ***directly image*** the vicinity of SMBHs!
  - best candidates: Sgr A*, M87

Present GMVA capabilities - summary

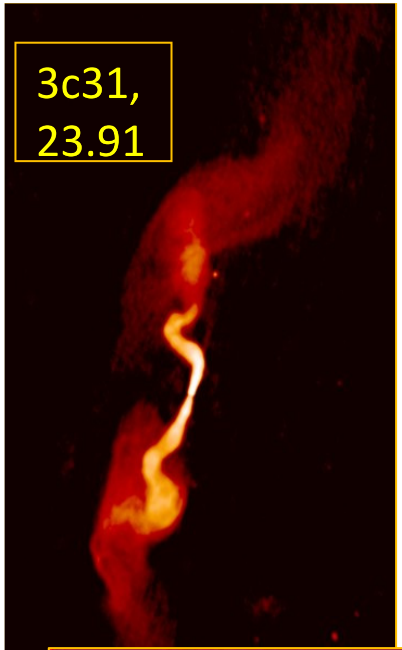
- Angular resolution 40 μas
- Baseline sensitivity 50-350 mJy
- Image sensitivity 1-5 mJy
- GMVA survey (Lee et al. 2008)
  - 127 observed, 121 detected, 109 imaged
  - remember Lonsdale et al. (1998): 14/79

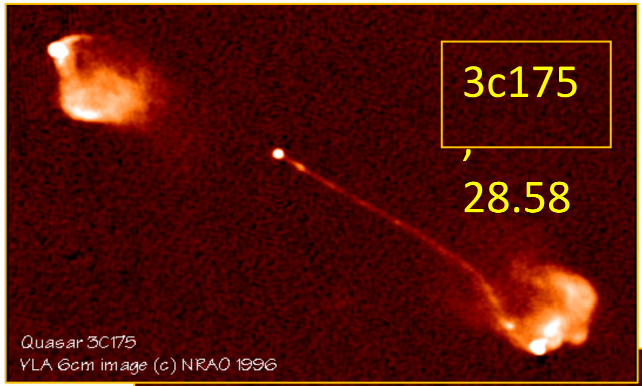
End of Part 2 (How do we do it)

Part 3

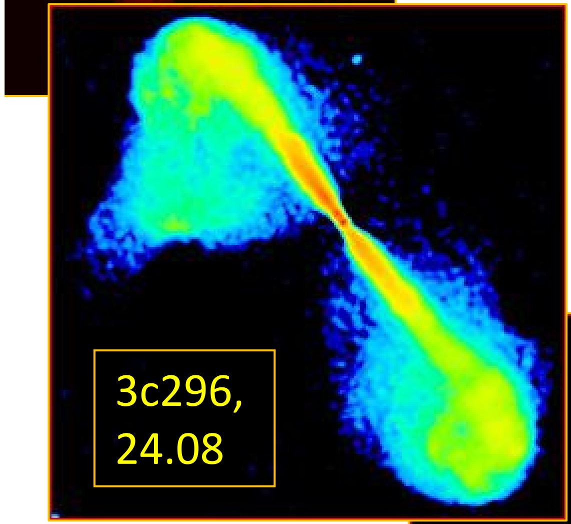
Science highlights

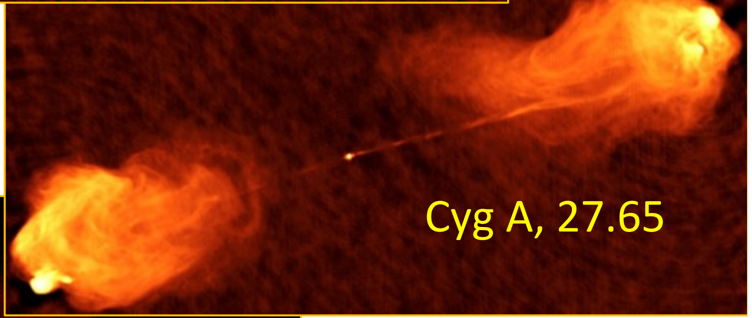
The radio loud zoo

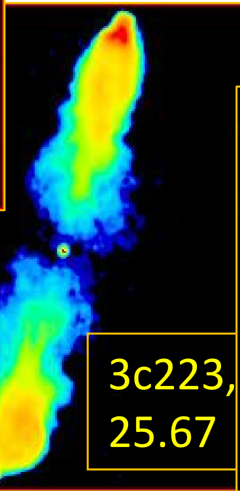

3c31,
23.91

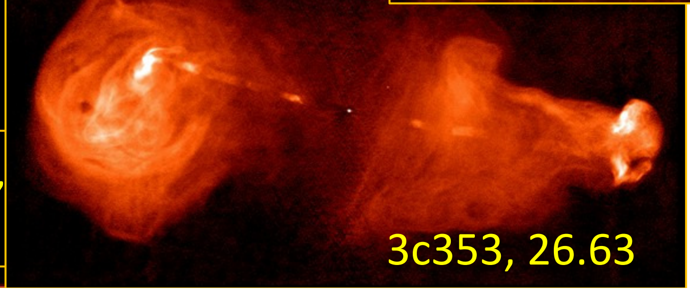

3c175
,
28.58

Quasar 3C175
VLA 6cm image (c) NRAO 1996


3c296,
24.08


Cyg A, 27.65

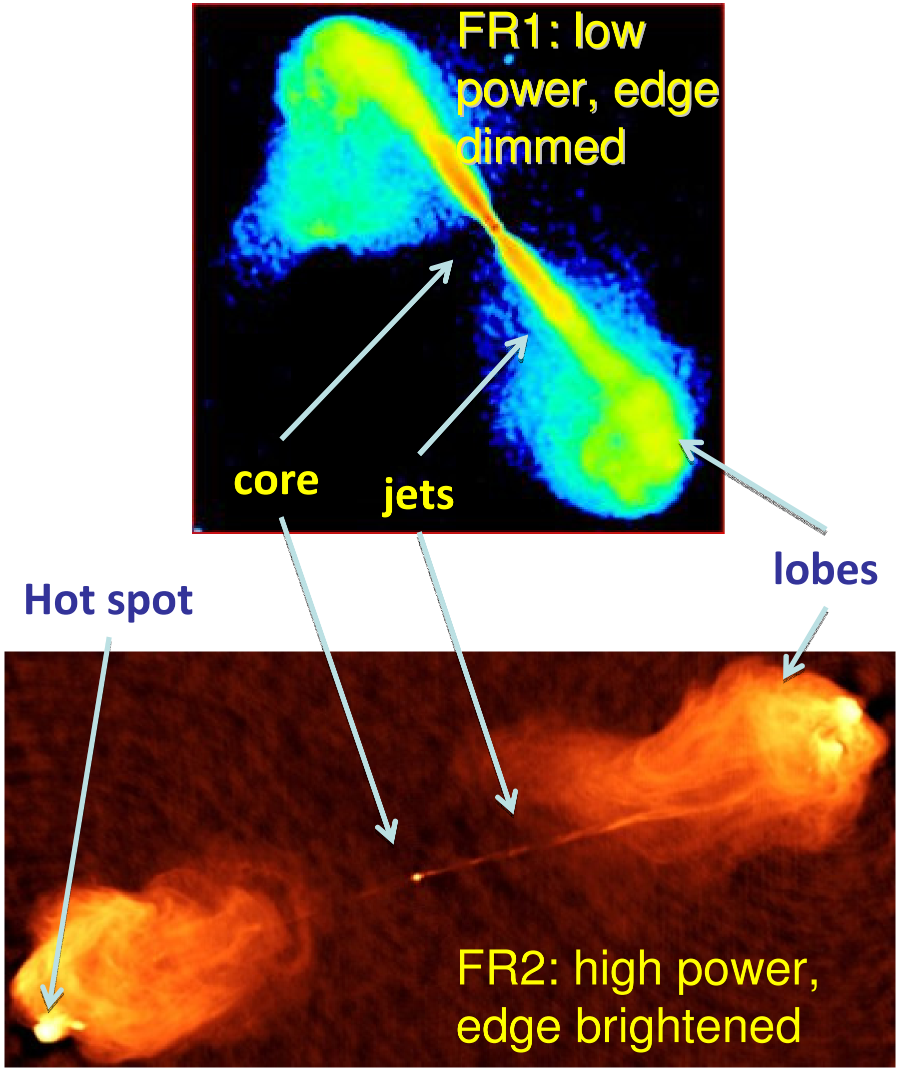

3c223,
25.67


3c353, 26.63

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

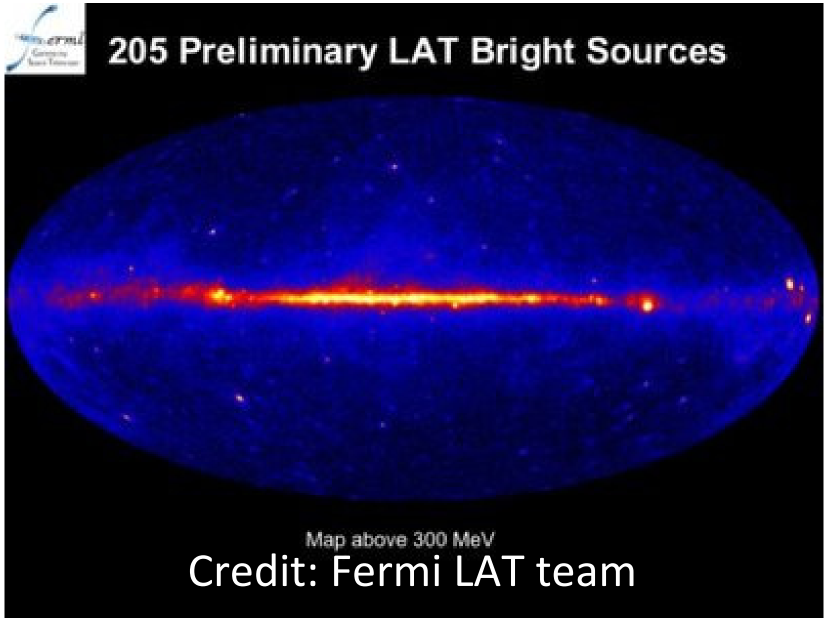
Radio galaxies

- 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



Beyond radio galaxies: blazars

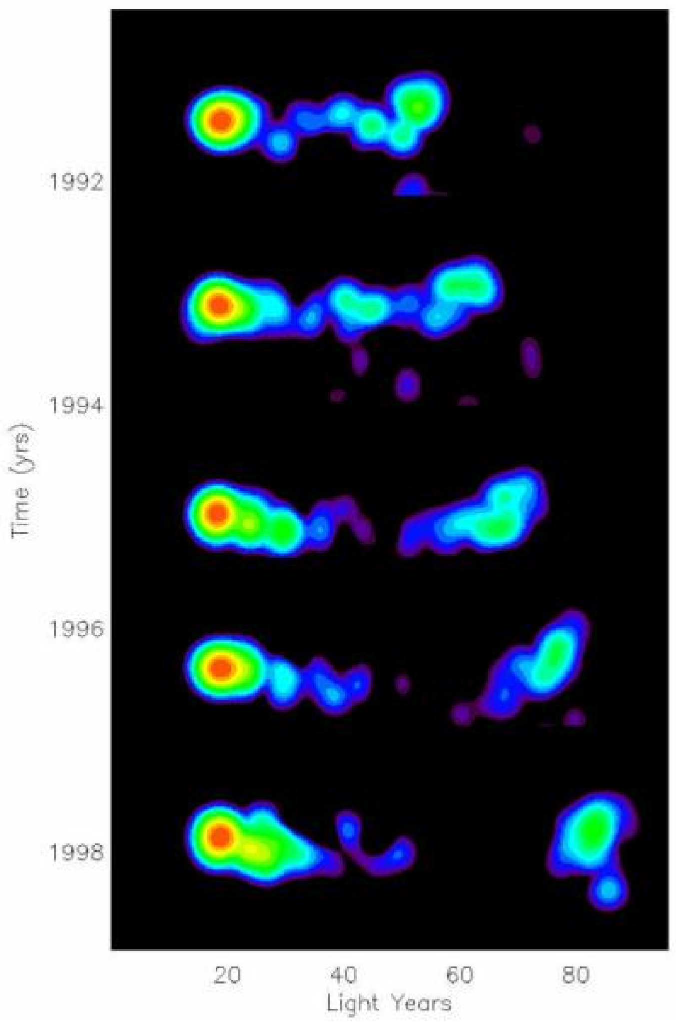
- Not all extragalactic radio sources are radio galaxies – powerful radio sources can also:
  - Be associated to **blazars** (QSOs or BL Lacs, ie strong non thermal sources, with or without emission lines)
  - Be dominated by compact components, lacking extended lobes
  - Display large variability in short timescales and high energy emission (eg gamma-rays)



Credit: Fermi LAT team

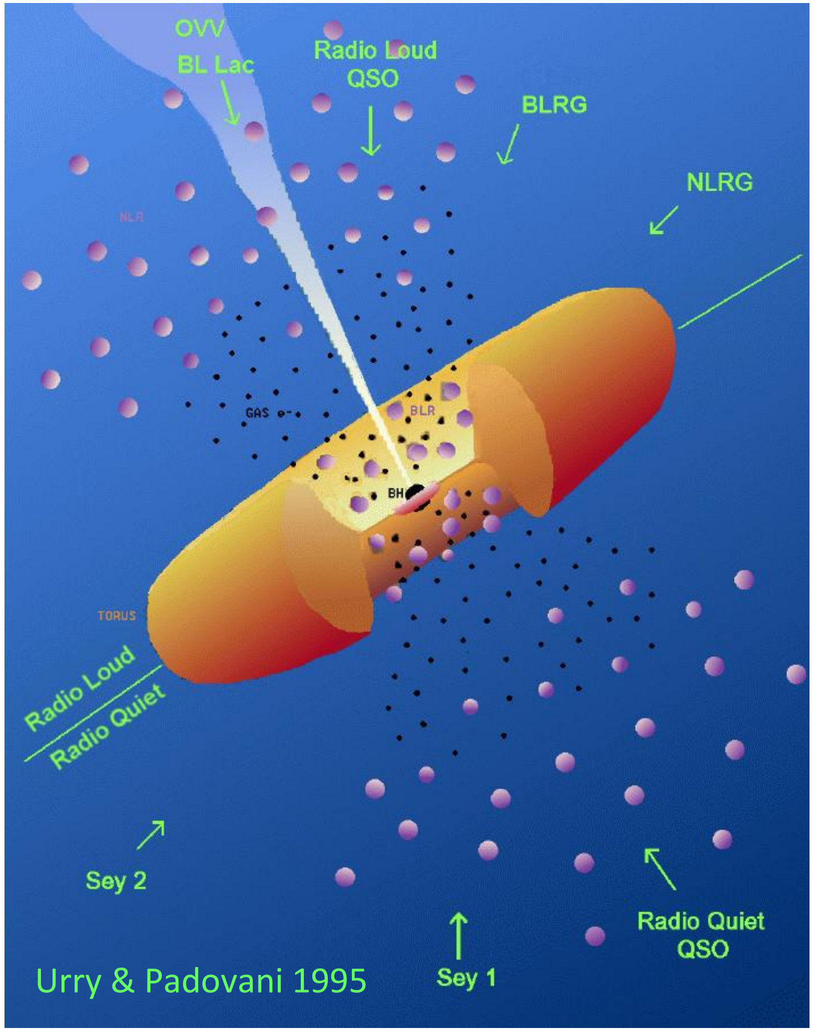
Properties of VLBI cores

- VLBI observations of cores in radio galaxies and blazars find:
  - Very compact components: brightness temperatures beyond inverse Compton catastrophe limit (10^{12} K)
  - Jets are more frequently one sided than two-sided
  - Jet components move faster than speed of light!!!



3C 279, Image courtesy of NRAO-AUI

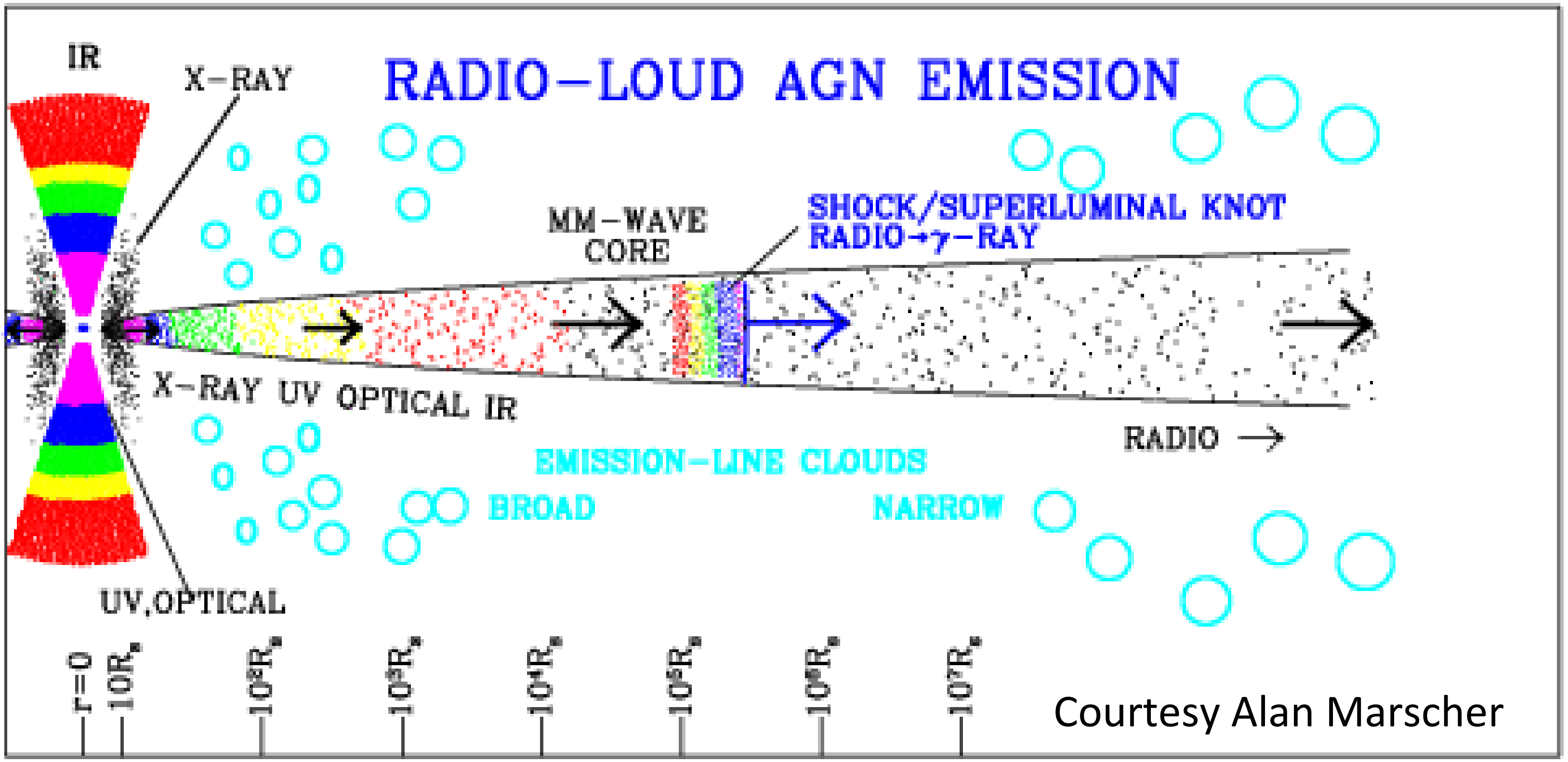
Unified scheme of radio loud AGN



Urry & Padovani 1995

- Huge powers from release of gravitational energy
  - super-massive black hole
  - hot accretion disk
  - absorbing torus
  - gas clouds (BLR/NLR)
  - relativistic jet of plasma
- Intrinsically similar sources appear differently under different viewing angles – effect of:
  - obscuration
  - relativistic beaming

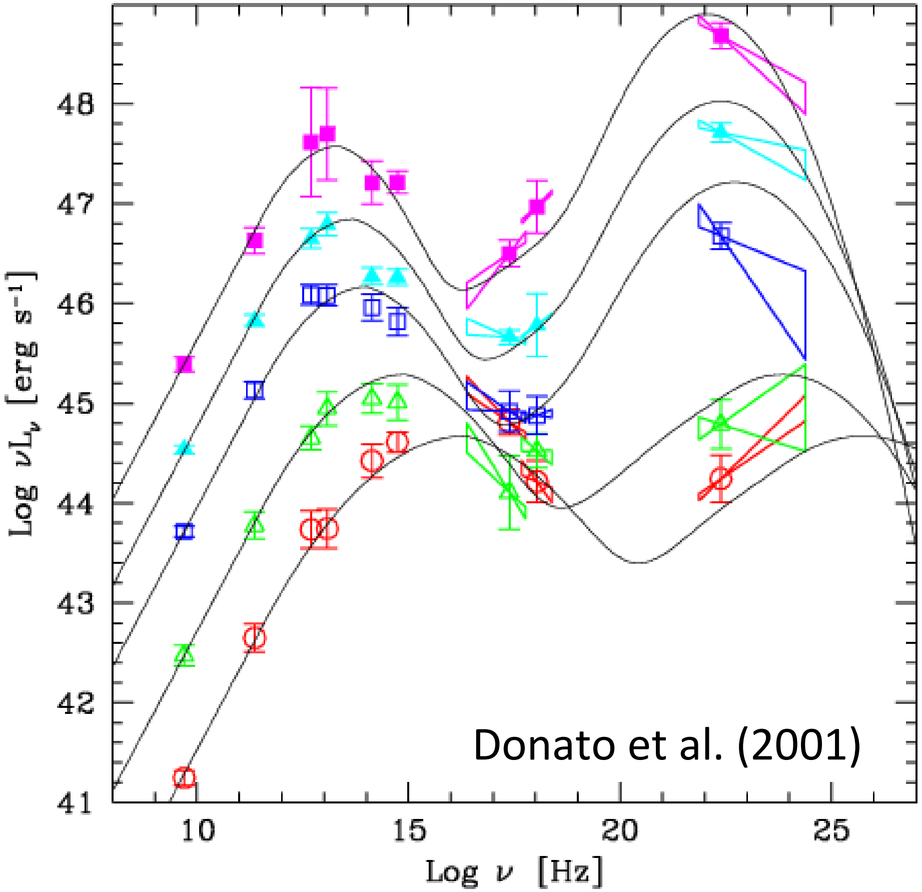
Key element: the jet



Courtesy Alan Marscher

Key element: the jet

- Jet emission spans >15 decades in energy
  - low energy emission: synchrotron process
  - high energy: Inverse Compton, either self or external
- Relativistic particles AND bulk motion required to explain their properties



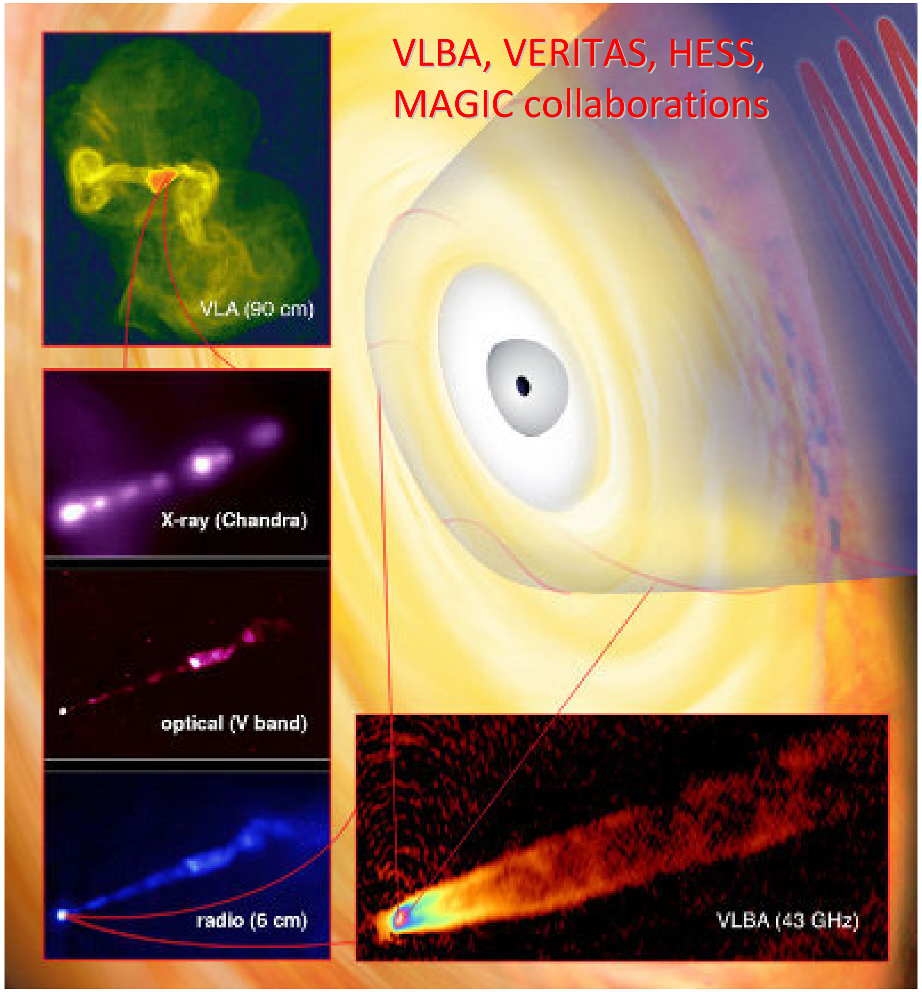
Donato et al. (2001)

Key element: the jet

- Ten challenges from R. Blandford (2008)
  1. Locate the sites of radio, γ emission
  2. Map jet velocity fields
  3. Identify the emission mechanism
  4. Understand the changing composition
  5. Measure jet pressures
  6. Deduce jet confinement mechanism
  7. Infer jet powers, thrusts
  8. Test and apply central hypothesis
  9. BHGRMHD capability
  10. Quantify role in clusters

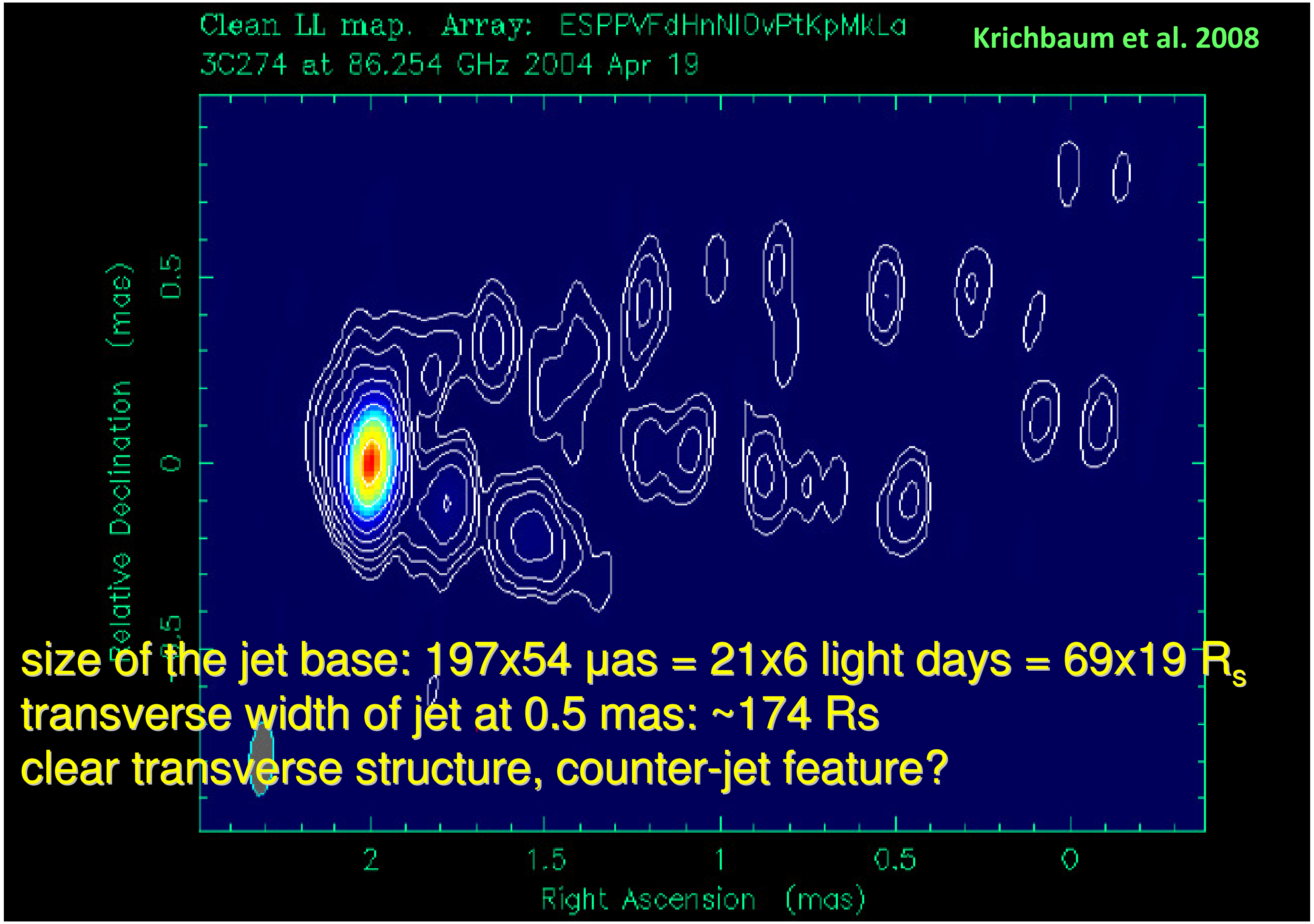
mm-VLBI lessons, case 1

- M87 (3C274, Virgo A)
  - d=16 Mpc
  - low power but bright FR1 radio galaxy
  - most massive black hole in nearby universe: $M_{BH}=10^9\ M_{sun}$
  - Schwarzschild radius RS=3.7 μas
  - optical and X-ray jet with superluminal motions
  - source detected at GeV/TeV energy



VLBA, VERITAS, HESS, MAGIC collaborations

M87: the 3mm image

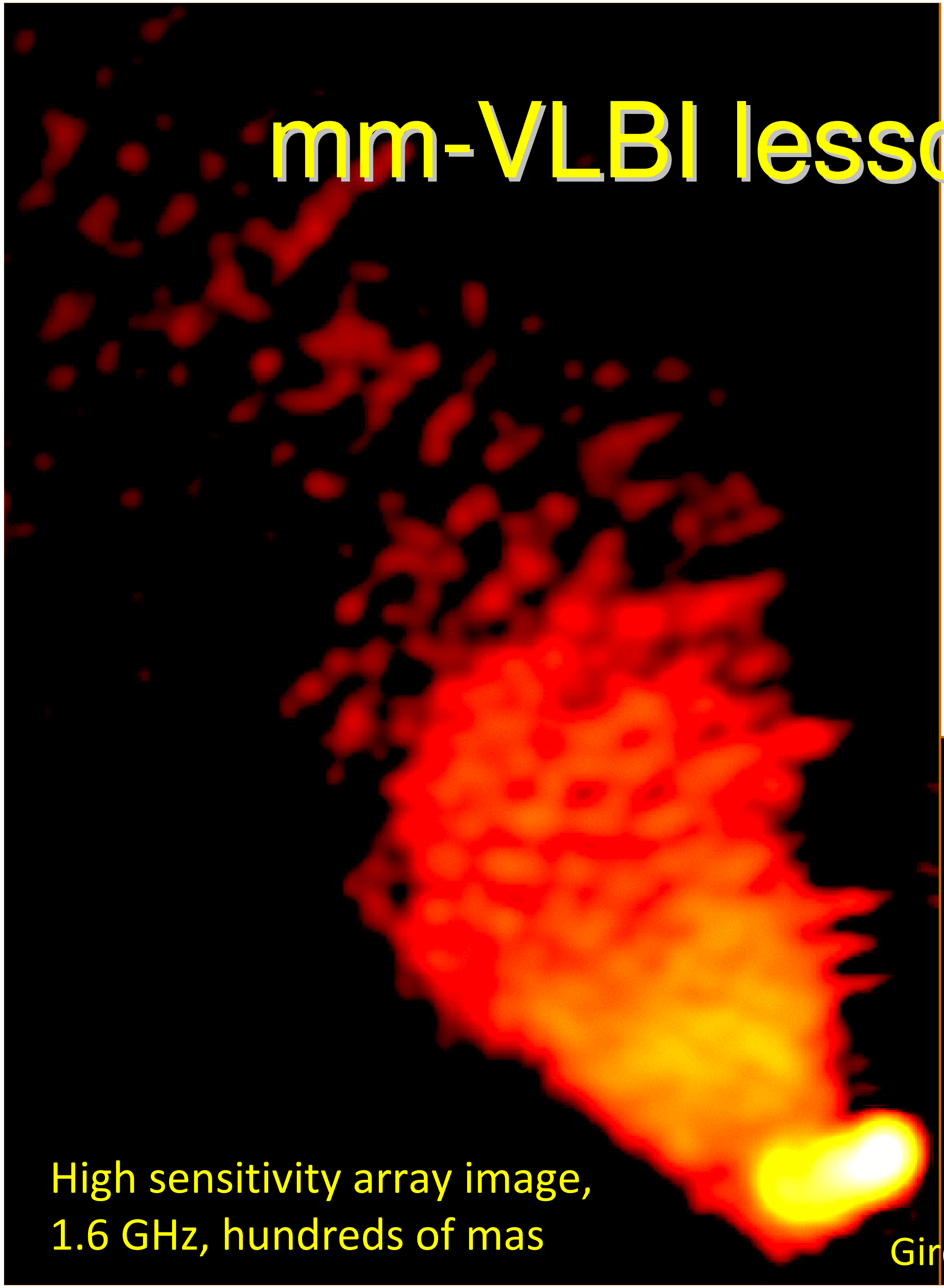


Krichbaum et al. 2008

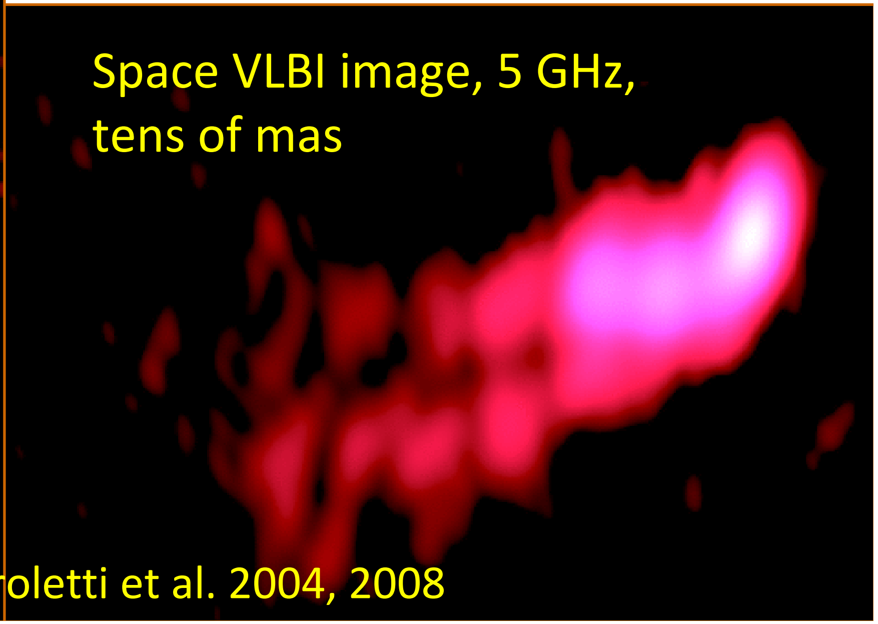
size of the jet base: 197x54 µas = 21x6 light days = 69x19 R_s
transverse width of jet at 0.5 mas: ~174 Rs
clear transverse structure, counter-jet feature?

mm-VLBI lessons, case 2

- Mrk501, more challenging target, since more distant
  - z=0.034
  - 1 $R_S=10^{-4}$ pc
  - and weaker!
- optically BL Lac, gamma-ray source
- promising target from cm-wavelength VLBI



High sensitivity array image, 1.6 GHz, hundreds of mas

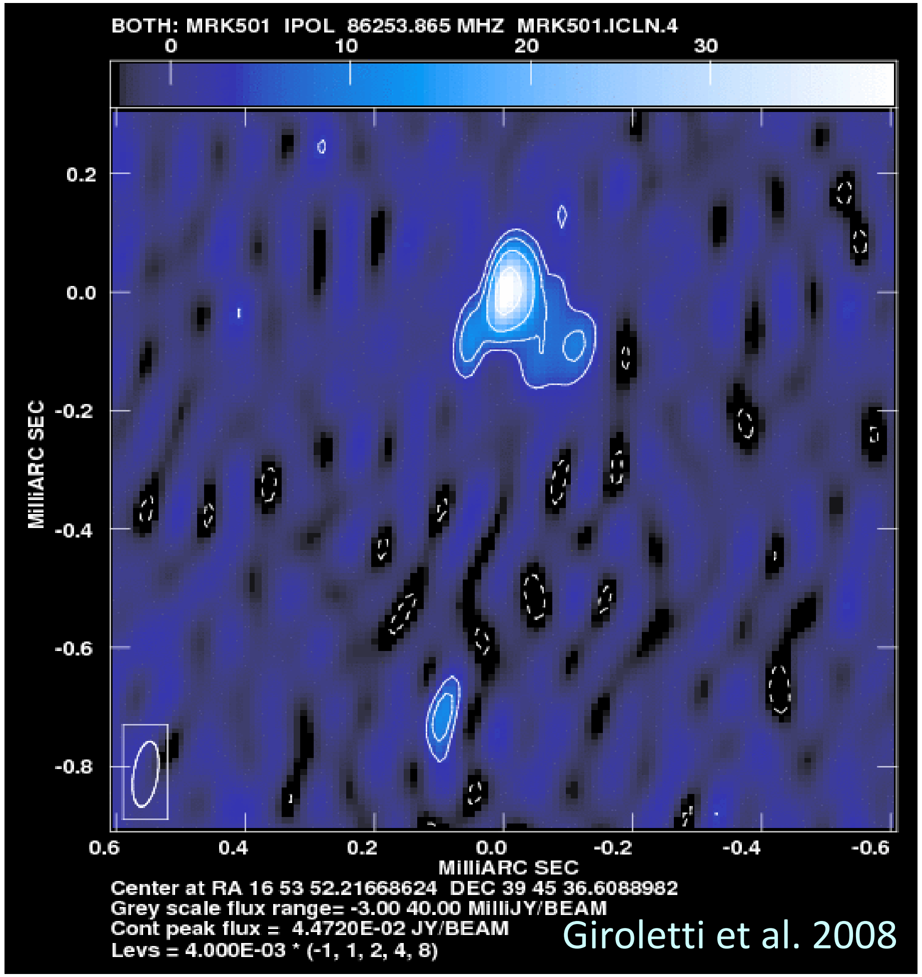


Space VLBI image, 5 GHz, tens of mas

Giroletti et al. 2004, 2008

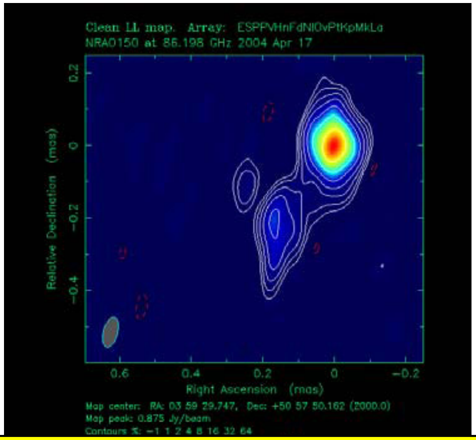
GMVA obs of Mrk 501: results

- resolution ~110 x 40 μas
- rms ~ 1.5 mJy/beam
- core unresolved at 86 GHz
  - size smaller than 0.03 pc (gaussian fit)
  - radius ~ 300 R_S
- S_t=150 mJy, S_c=45 mJy
  - limb brightening in core region?
  - 10 mJy component @0.73 mas, PA 172°

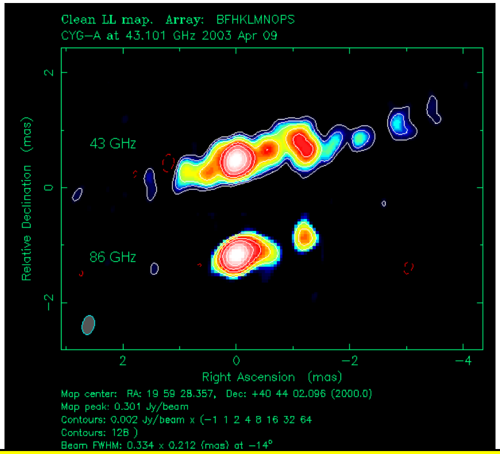


Giroletti et al. 2008

more mm-VLBI lessons…



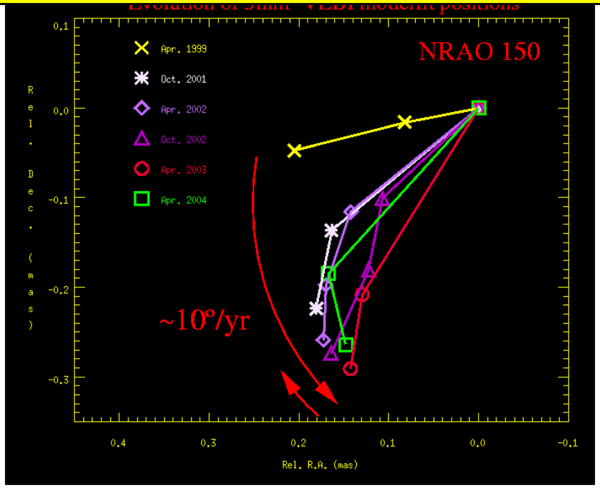
Agudo et al. 2007

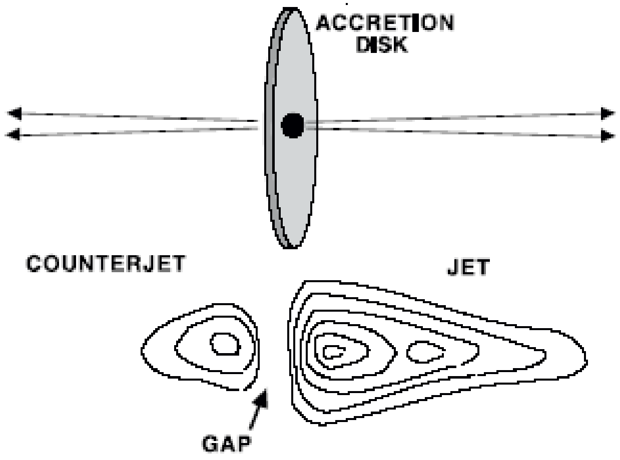


Bach et al. 2008

NRAO150, precessing jet

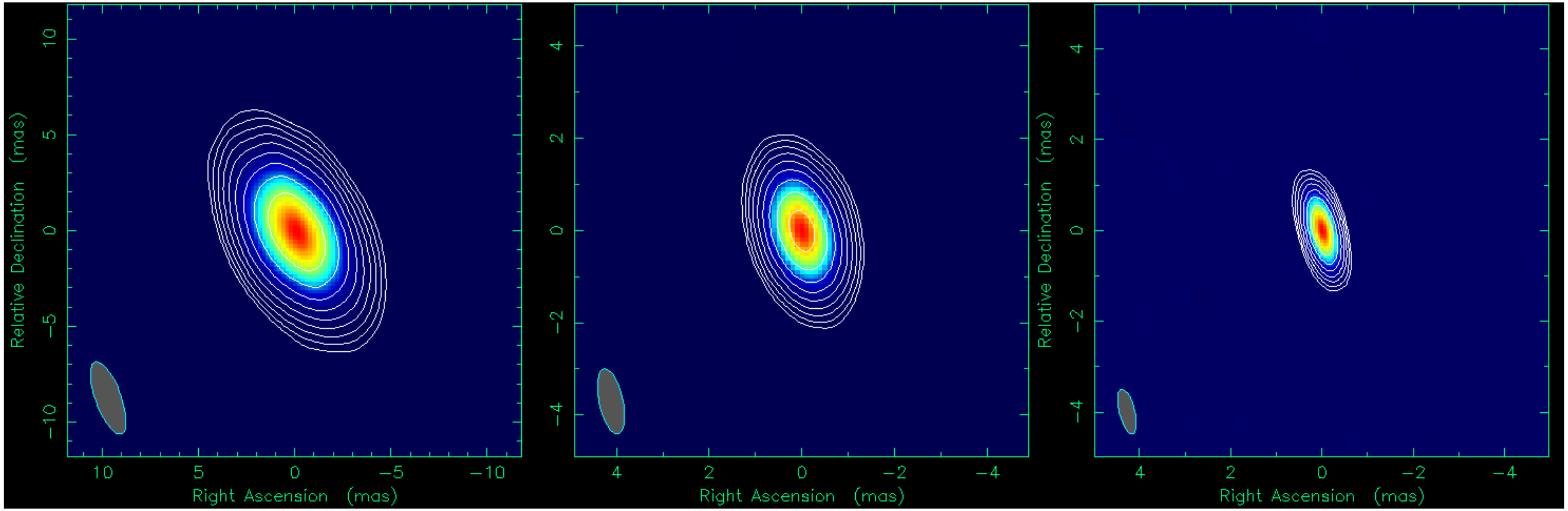
CygA, absorption and acceleration





and finally… SgrA*

d=8kpc, M=10^6 M_{sun}



22GHz
4.0×1.31mas, 20°

43GHz
1.44×0.51mas, 12°

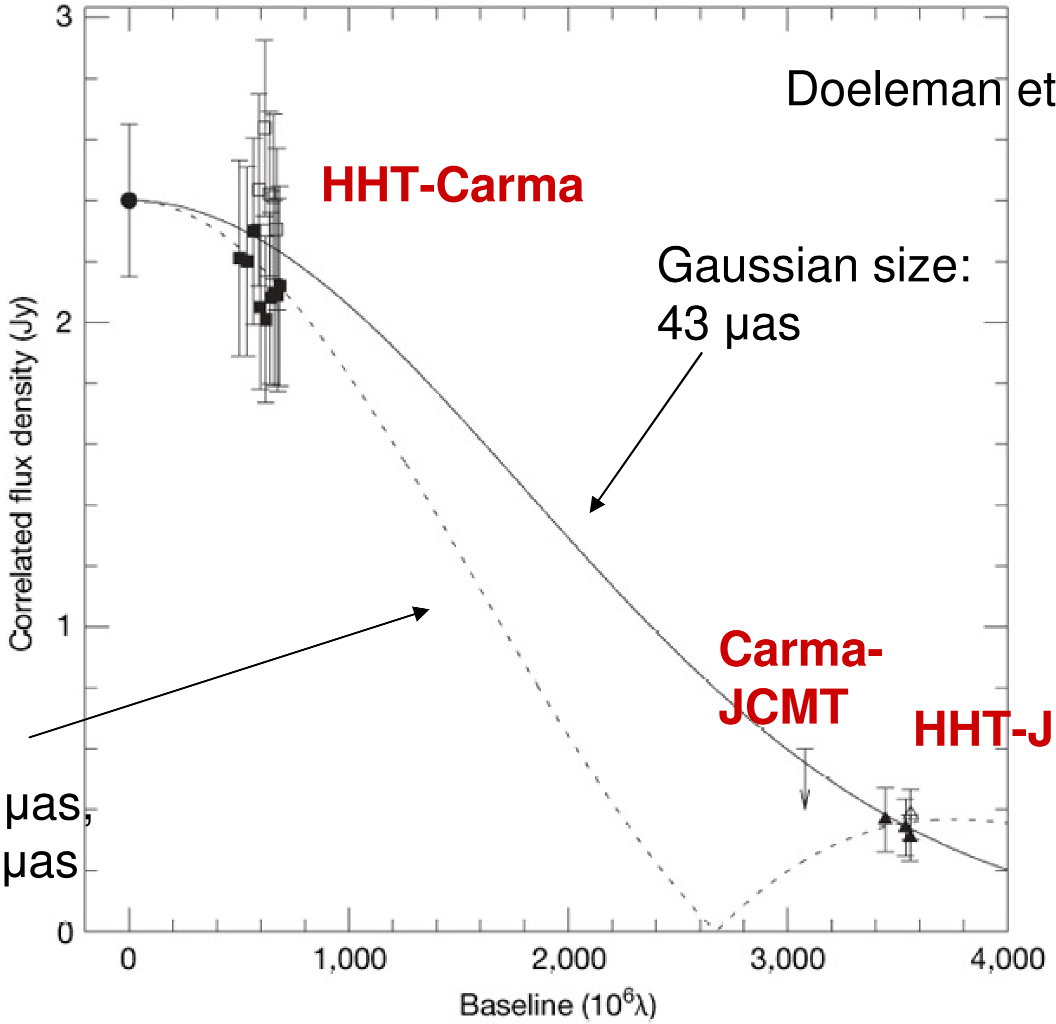
86GHz
1.01×0.34mas, 14°

230 GHz VLBI of Sgr A*

Doeleman et al. (2008)

10 & 11 April 2007 @3.84 Gbit/s

Fitting and resolving the size of Sgr A* with 1.3 mm VLBI



Doeleman et al. (2008)

HHT-Carma

Gaussian size:
43 µas

Carma-JCMT

HHT-JCMT

Ring ("doughnut")
outer diameter: 80 µas,
inner diameter: 35 µas

Summary of scientific results

- Main topic: radio loud extragalactic AGNs need to be studied at highest resolution to understand black hole environment
- Successful mm-VLBI survey, tens of AGN detectable
- M87, Mrk501, etc. – down to our own galaxy central region

End of Part 3 (Scientific highlights)

Part 4

Future expectations

Millimeter VLBI desiderata

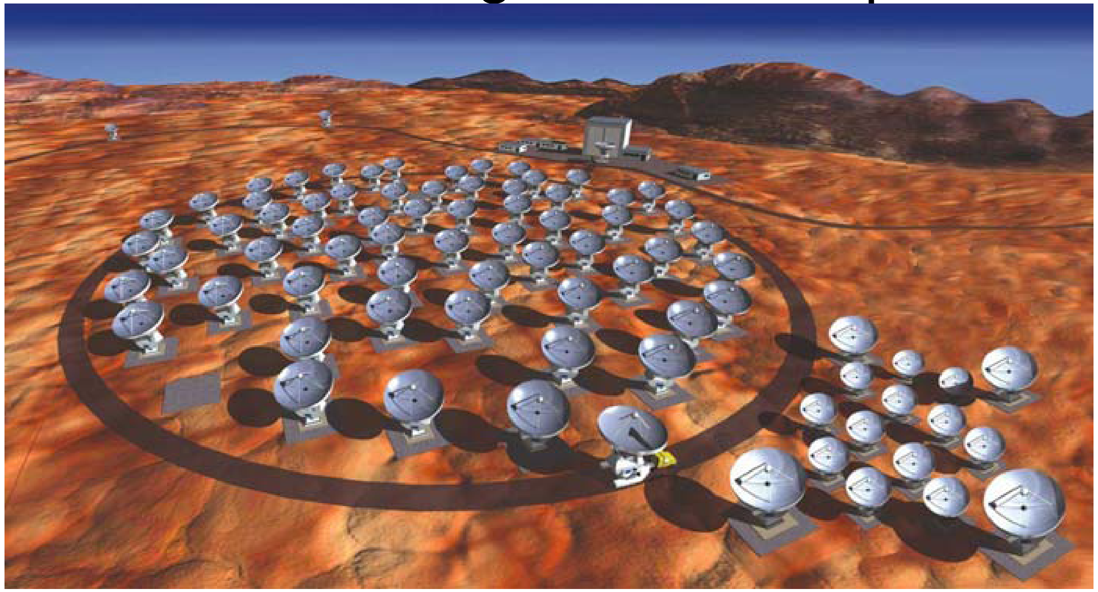
1. need more sensitivity
    - large millimeter wavelength telescopes
    - large bandwidth
2. need more stations to allow better self – calibration
3. need southern antennas for low declination sources
4. need even higher frequency

3mm

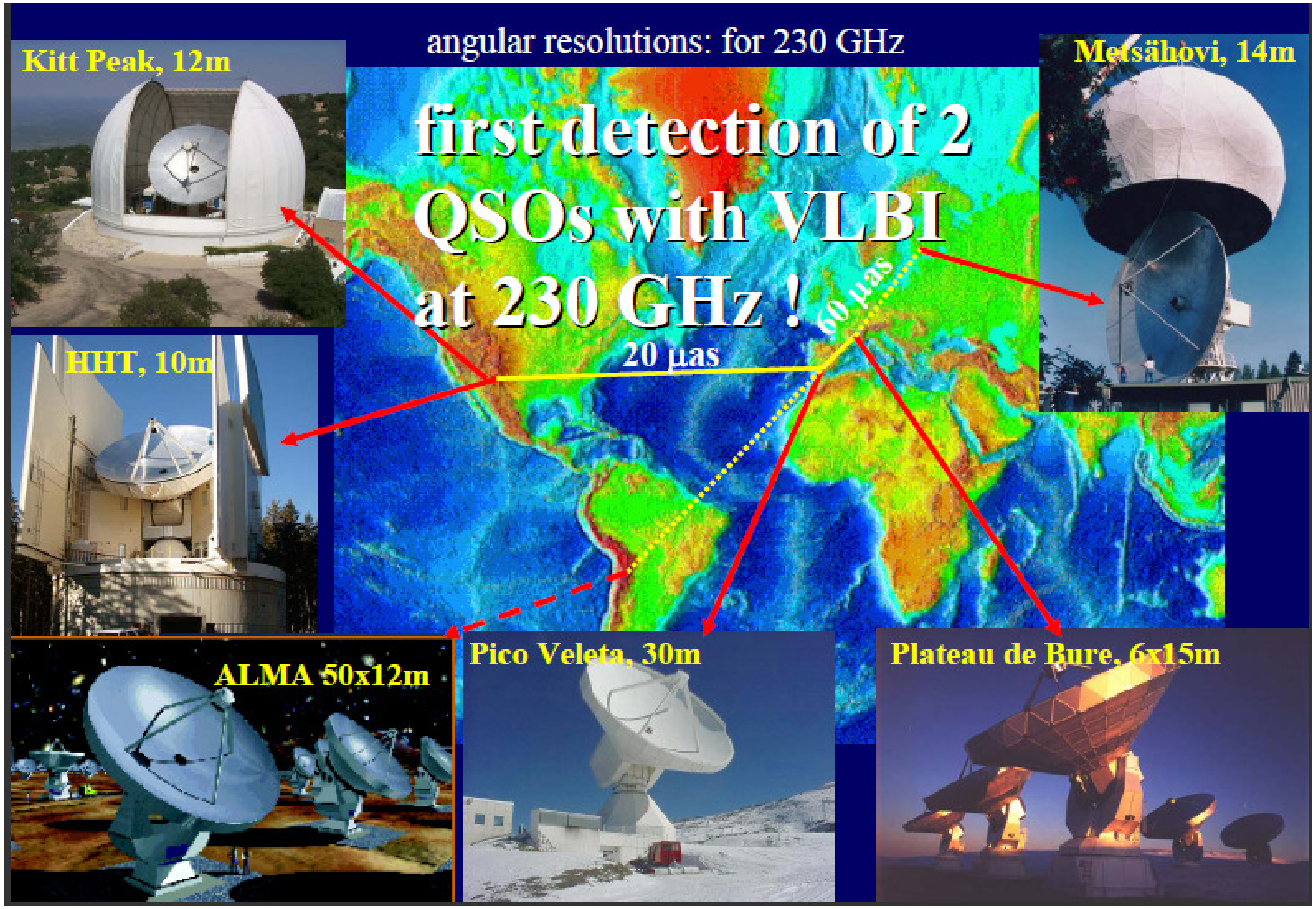
Station	Country	Diameter [m]	Zenith tsys [K]	Gain [K/Jy]	SEFD [Jy]
Effelsberg	Germany	80	130	0.14	930
Pl. de Bure	France	35	120	0.21	570
Pico Veleta	Spain	30	120	0.14	715
Onsala	Sweden	20	300	0.049	6100
Metsähovi	Finland	14	400	0.017	23500
VLBA(8)	USA	25	100	0.036	2800
Hopefully soon:					
GBT	USA	100	150	1.0	150
Noto	Italy	32	150	0.052	3000
Yebes	Spain	40	150	0.22	680
Nobeyama	Japan	45	150	0.17	880
Future					
CARMA	USA	35	150	0.14	1070
LMT	Mexico	50	150	0.43	350
SRT	Italy	64	170	0.46	370
ALMA	Chile	50x12	100	1.870	55

mm-VLBI above 100 GHz

- Very limited number of telescopes capable of doing VLBI at 150-230 GHz
  - CARMA, SMA, HHT (USA)
  - PdBI, Pico Veleta (IRAM), Metsahovi (Europe)
- Transatlantic fringes found for a few sources!
- ALMA will be a real blessing for these experiments!



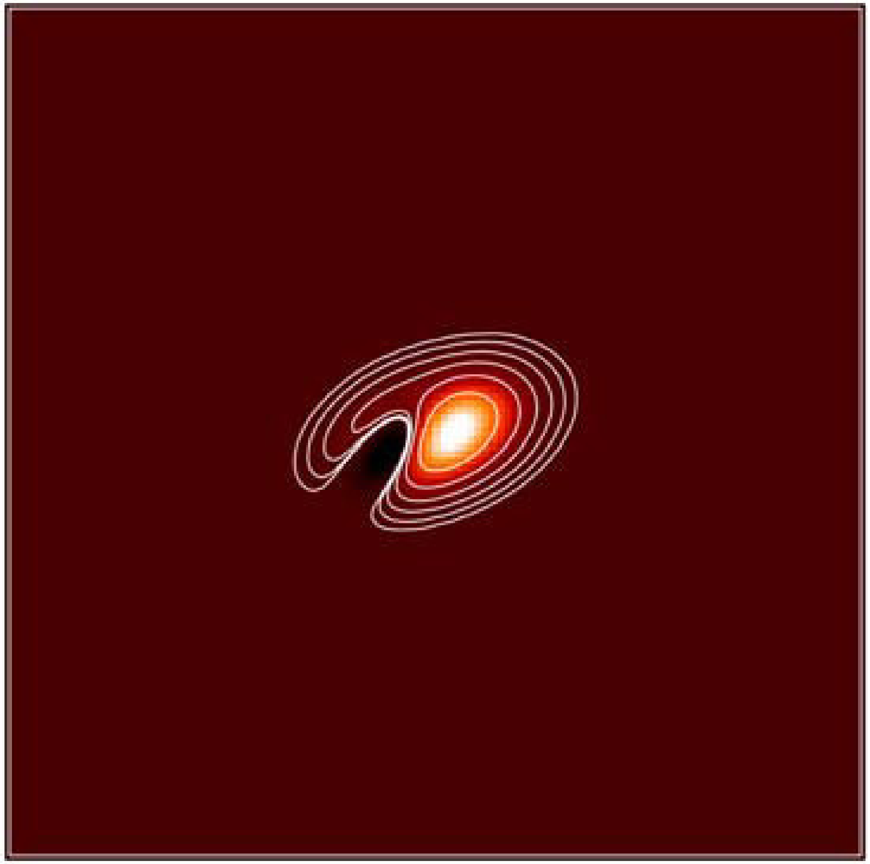
Towards 1mm VLBI

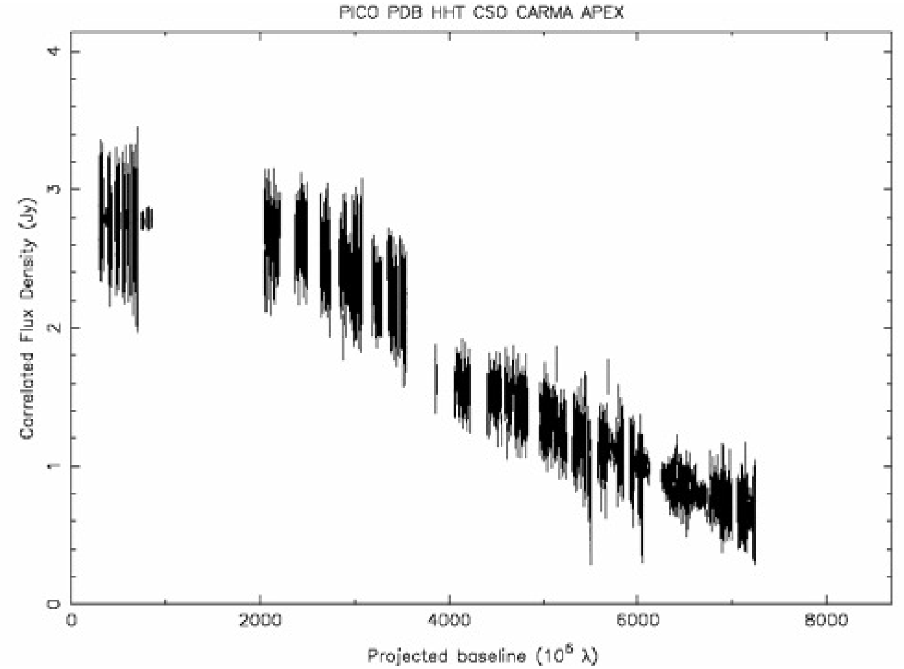


Doeleman et al. (2005), Krichbaum et al. (2008)

Imaging of SMBH vicinity

- Again, M87 and SgrA* will be our best prospects

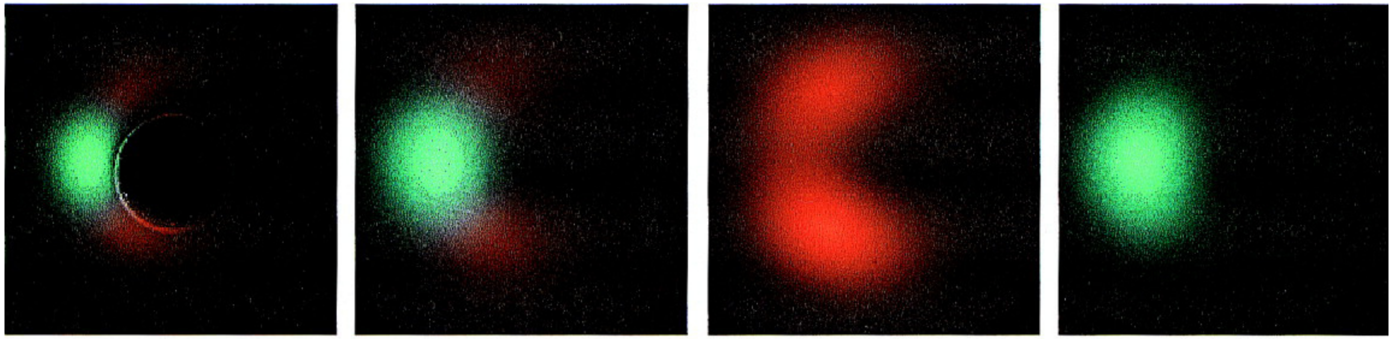




Simulated visibilities for SgrA* model shown to left, for Pico Veleta, PdB, HHT, CSO, CARMA, APEX at 1mm (Krichbaum et al. 2008)

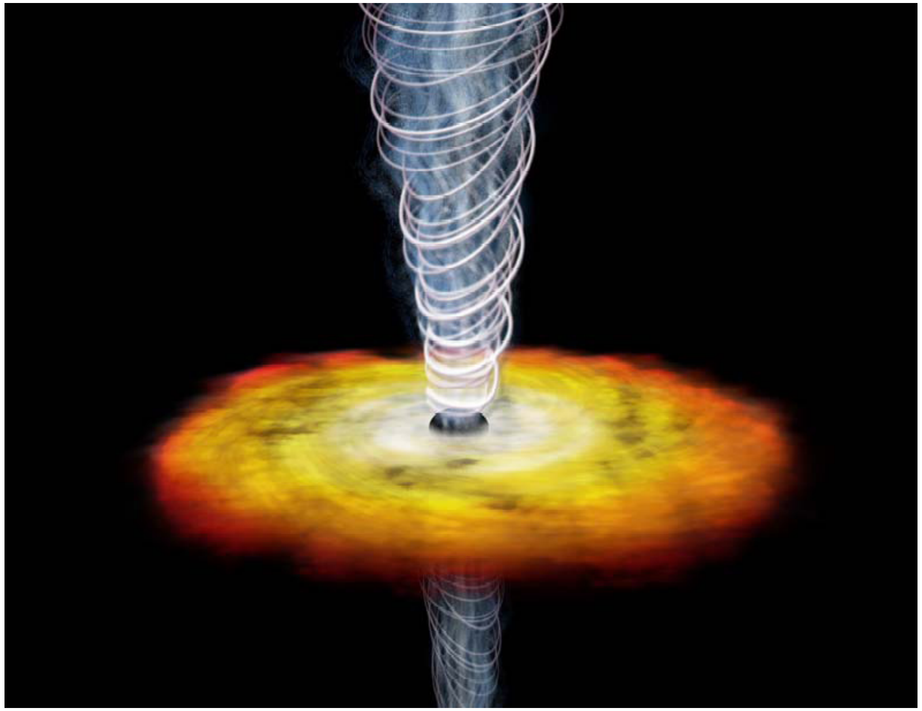
SgrA* @1mm, more expectations

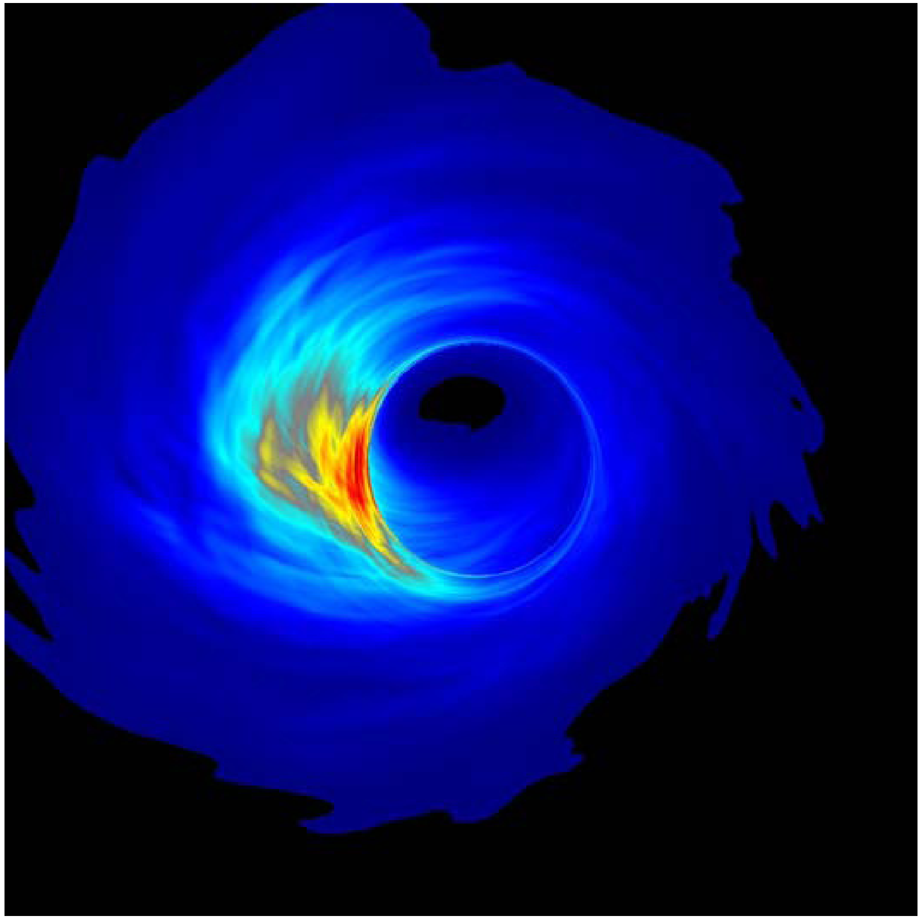
Model VLBI Pol. comp. 1 Pol. comp. 2



Bromley et al. 2001, ApJ

The future is bright at mm-VLBI!





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