Global mm-VLBI with Apex

Imaging nearby super-massive Black Holes and the study of jet formation in AGN

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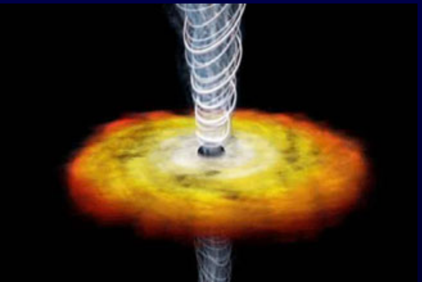


people involved in the European 1mm VLBI effort:

MPIfR: W. Alef, A. Bertarini, T. Krichbaum, H. Rottmann, A. Roy, J. Wagner, J.A. Zensus, et al.

IRAM: M. Bremer, P. Cox, C. Kramer, S. Sanchez, K. Schuster, M. Torres, et al.

OSO: M. Lindqvist, I. Marti-Vidal, H. Olofsson, et al. (+ GUARD team)

INAF: G. Tuccari

APEX: R. Güsten, K. Menten, D. Muders, G. Wieching, et al.

in collaboration with:

US-EHT: S. Doeleman et al. (Haystack + SMA/JCMT + Carma)

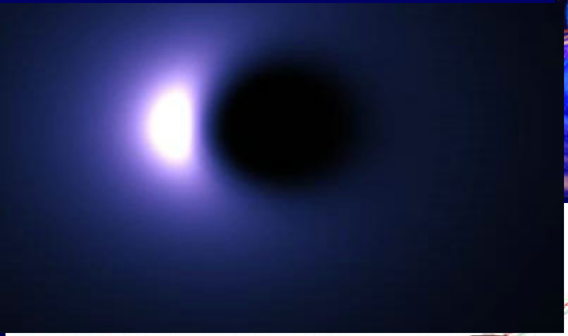
SMTO: L. Ziurys, P. Strittmatter, et al.

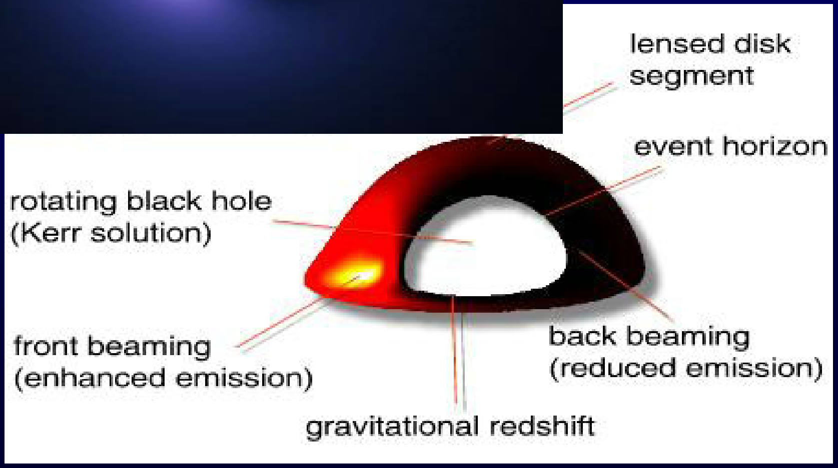
Motivation:

What are the physical processes acting at the center of SgrA* and in other galaxies ? Want to directly image the region around Black Holes, and in case of AGN jets study how they are made.

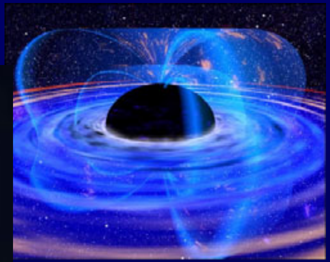
mm- and sub-mm VLBI provides micro-arcsecond scale resolution and will help to answer fundamental questions about BH-physics and jet formation, e.g.

Asymmetric emission around a rotating Black Hole ?

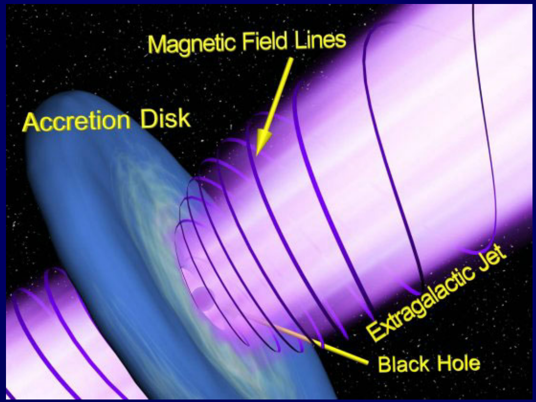




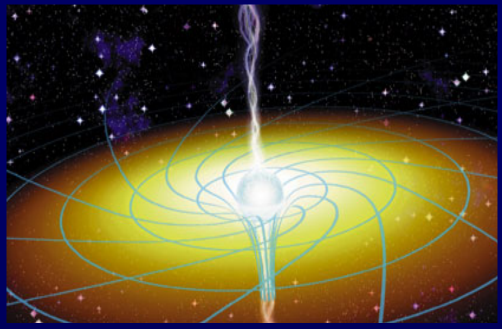
The Black Hole:
A GR-MHD dynamo ?



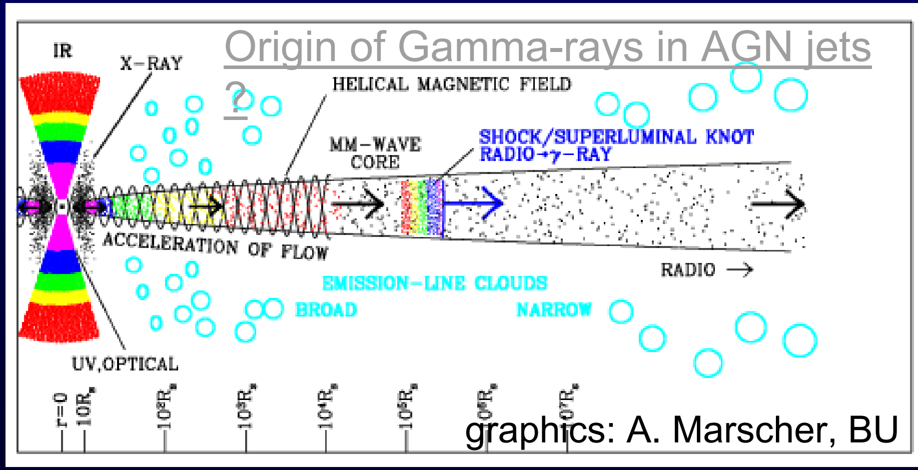
Magnetically driven jet launching ?



Jet rotation/precession due to frame dragging or binary BH?



Origin of Gamma-rays in AGN jets ?



graphics: A. Marscher, BU

The size of a synchrotron self-absorbed emission region

size:

$$\theta_{\min} \geq \sqrt{\frac{1.22 \cdot S}{\nu^2} \cdot \frac{1}{T_B^{\max}}}$$

T_B = brightness temperature

IC limit:

$$\text{for } T_B^{\max} \leq 10^{12}\,\mathrm{K} \cdot \delta$$

$$\rightarrow \theta_{\min} \geq 10 - 20\,\mu as \cdot \delta^{-0.5}$$

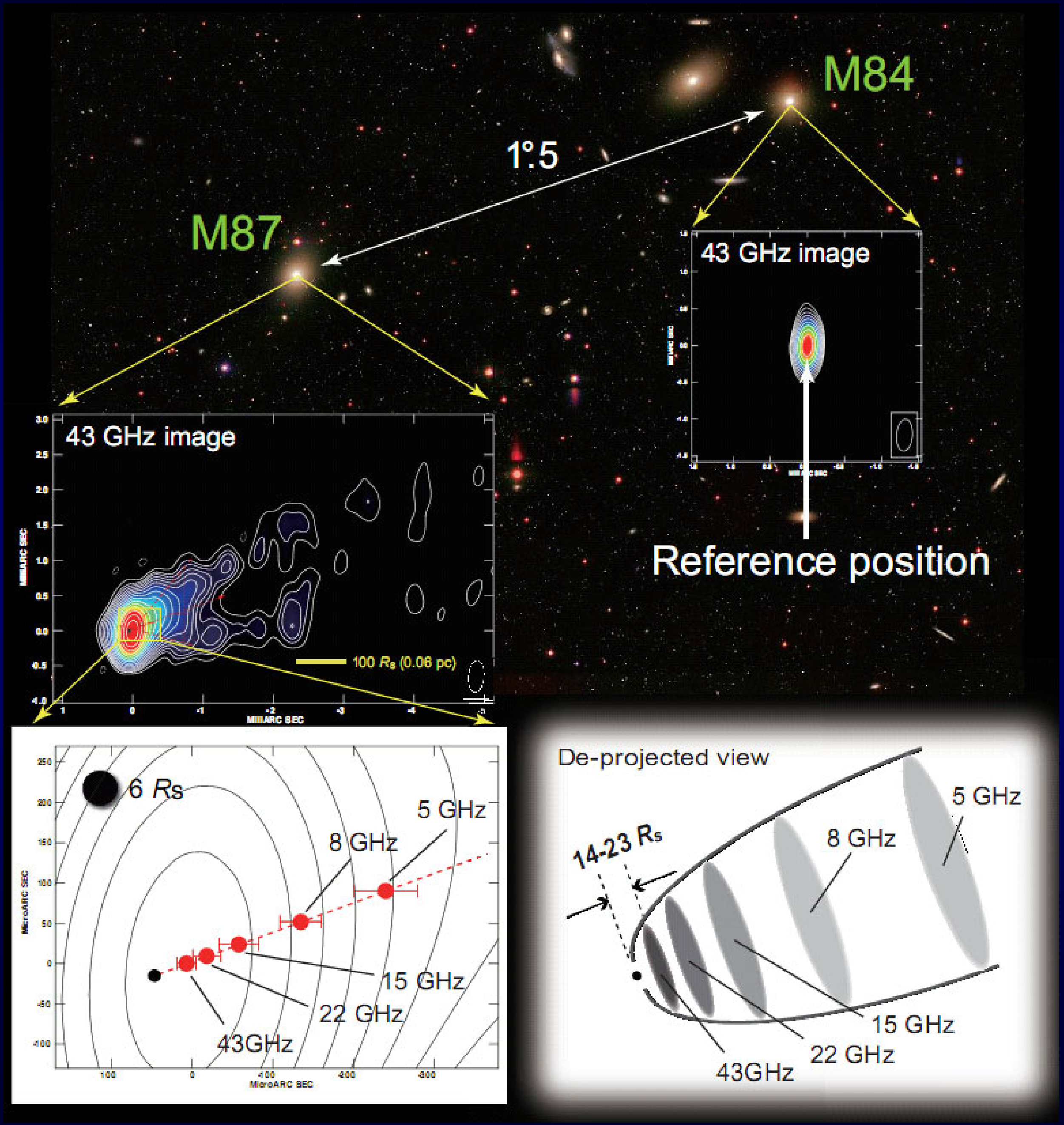
The size of the emission region is one of the primary physical paramameters in radiation transport. Accurate size measurements are important for the determination of energy budget (equipartition ?, role of B-field), particle composition, and in the relativistic jet model for jet speed, jet geometry, etc...

Astrometric phase-referencing VLBI on M87:

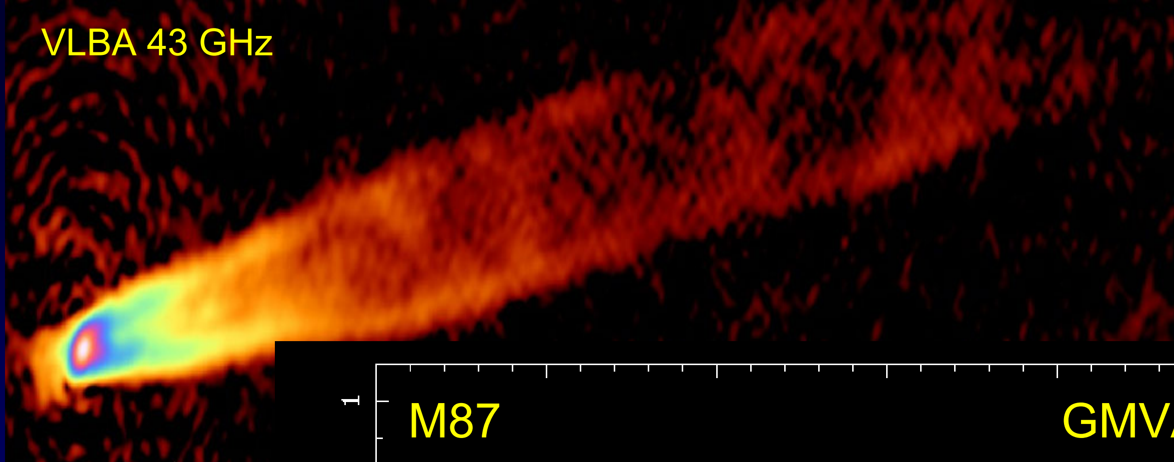
$D_{jetbase}$= 14-23 R_s

distance between jet base and black hole.

The higher the observing frequency the closer one approaches the 'central engine' – the SMBH

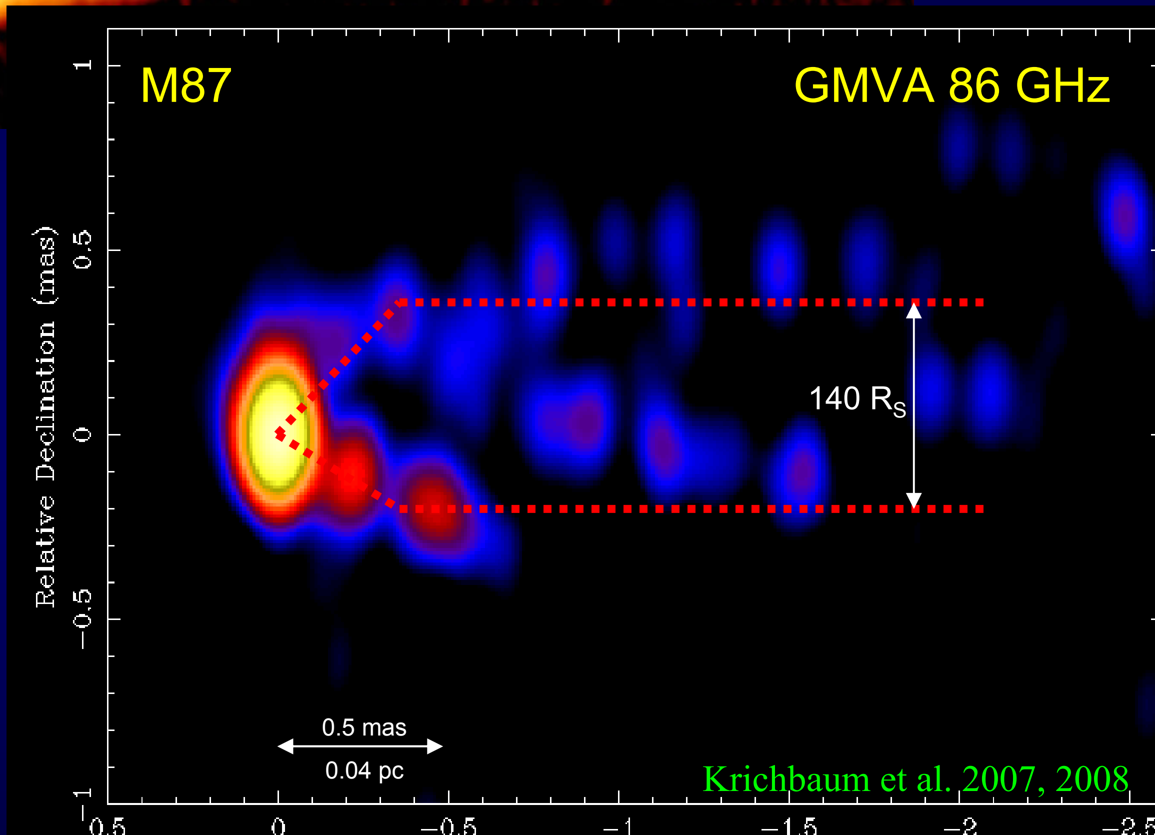


Hada et al. 2011



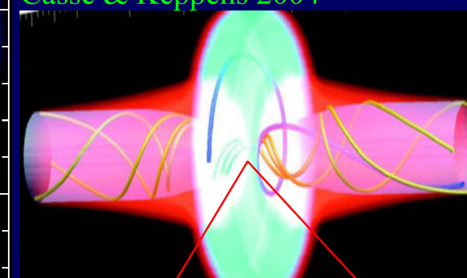
Walker et al. 2008

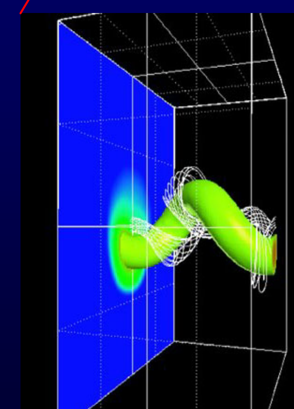
mm-VLBI provides the angular resolution for the study of the formation of jets and the BH-jet connection !



MHD Jet Simmulation:

Casse & Keppens 2004



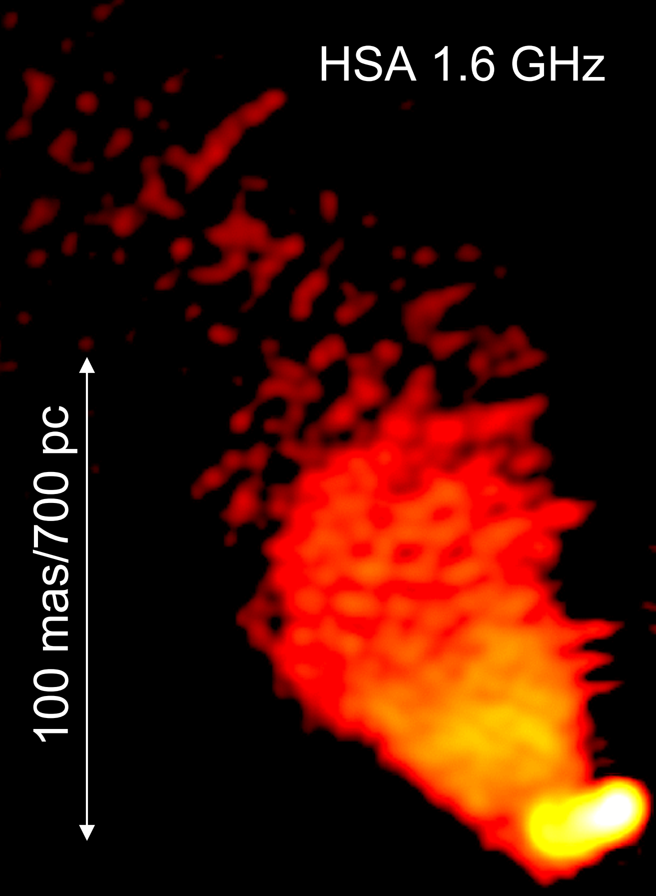


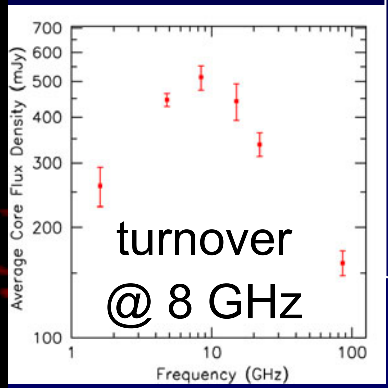
Mizuno et al. 2009

Limit of the size of the jet base (uniform weighting):

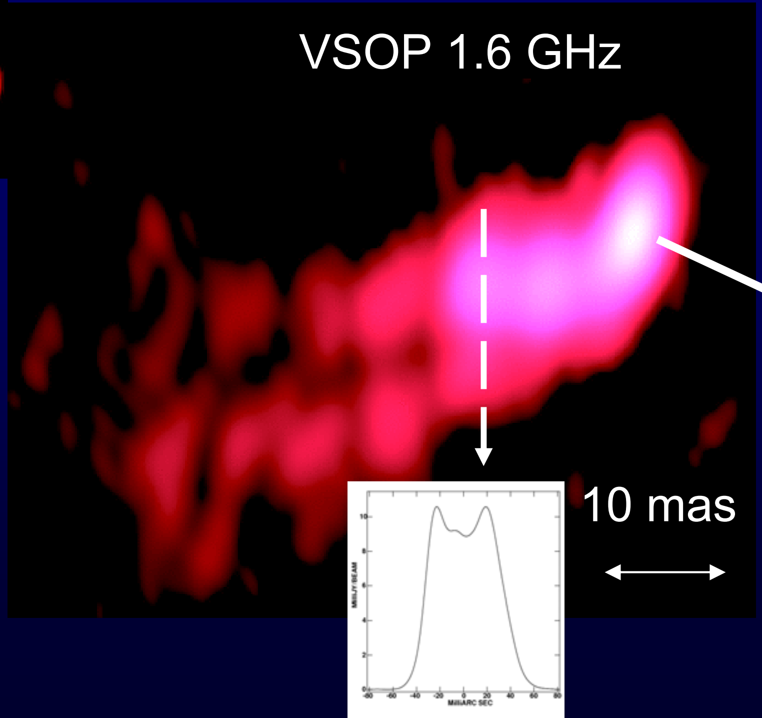
197 x 54 μas = 21 x 6 light days = <u>54 x 15</u> R_s^9

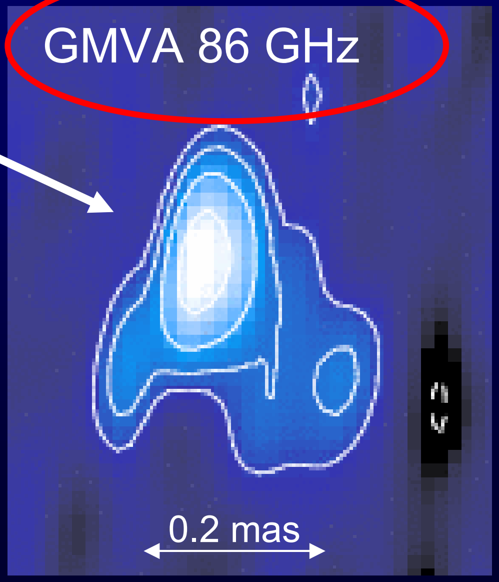
transverse width of jet at 0.5 mas: ~140 R_s^9





- resolution ~110 x 40 μas
- core unresolved at 86 GHz
  - size smaller than 0.03 pc (gaussian fit)
  - $M_{BH}=10^9\ M_{sun}$, $1\ R_S=10^{-4}$ pc
  - size ~ 320 x 210 R_S
  - $T_B > 4 \times 10^9$ K
- S_t=150 mJy, S_c=45 mJy





Mrk 501

z=0.0337

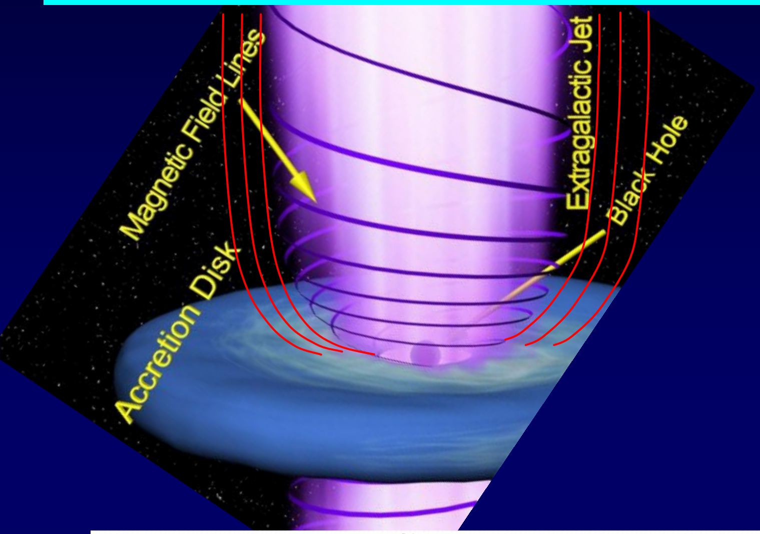
TeV & γ-ray source

Giroletti et al. 2004, 2008

BP versus BZ mechanism

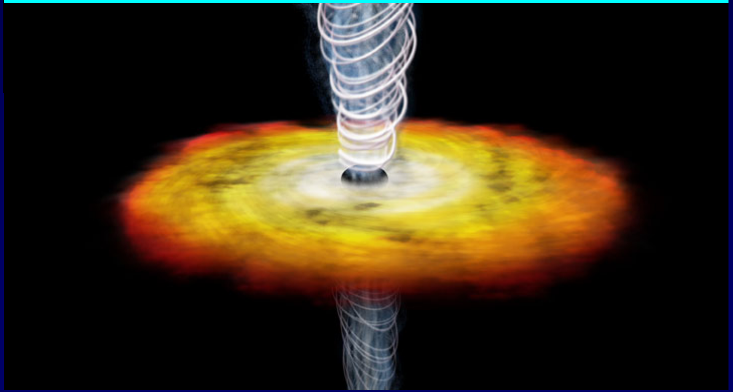
Blandford – Payne mechanism:

centrifugal acceleration in magnetized accretion disk wind



Blandford – Znajek mechanism:

electromagnetic extraction of rotational energy from Kerr BH



measure

Jet speed f(r,z)

Jet width f(z)

T_B f(z)

→

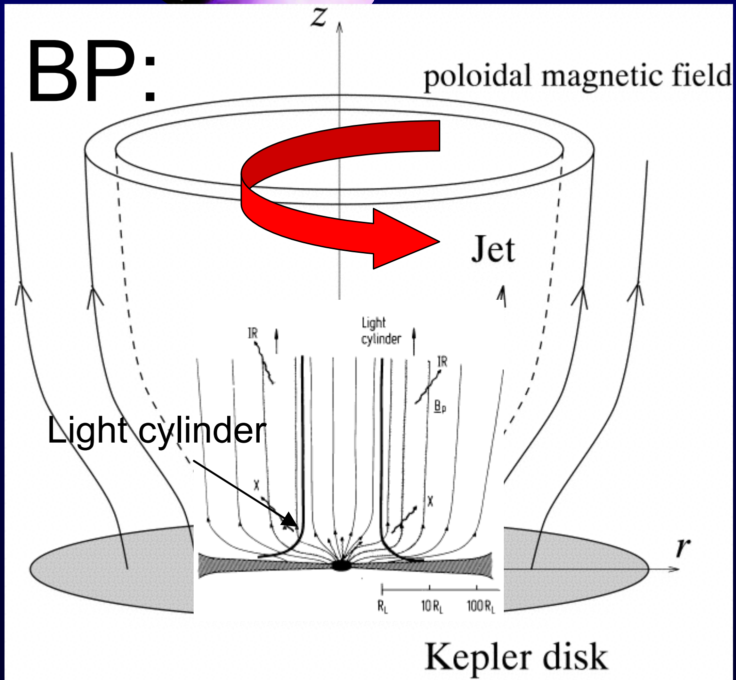
Shape of Nozzle

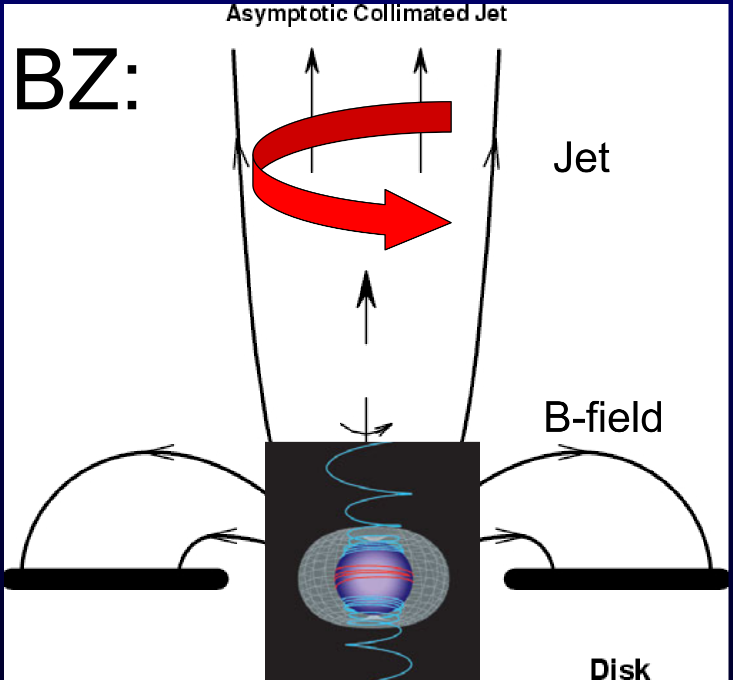
Magnetic Field

BH Spin

etc.

need to reach scale of a few R_G





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	0.14 pc	3.4 mpc	0.66 μpc
0.87mm	345 GHz	11 μas	0.09 pc	2.2 mpc	0.43 μpc

linear size: ~10^3 R_s^9 20-100 R_s^9 1-5 R_s^6

for nearby sources, these scales correspond to 1 – 100 Schwarzschild radii, depending on distance and black hole mass !

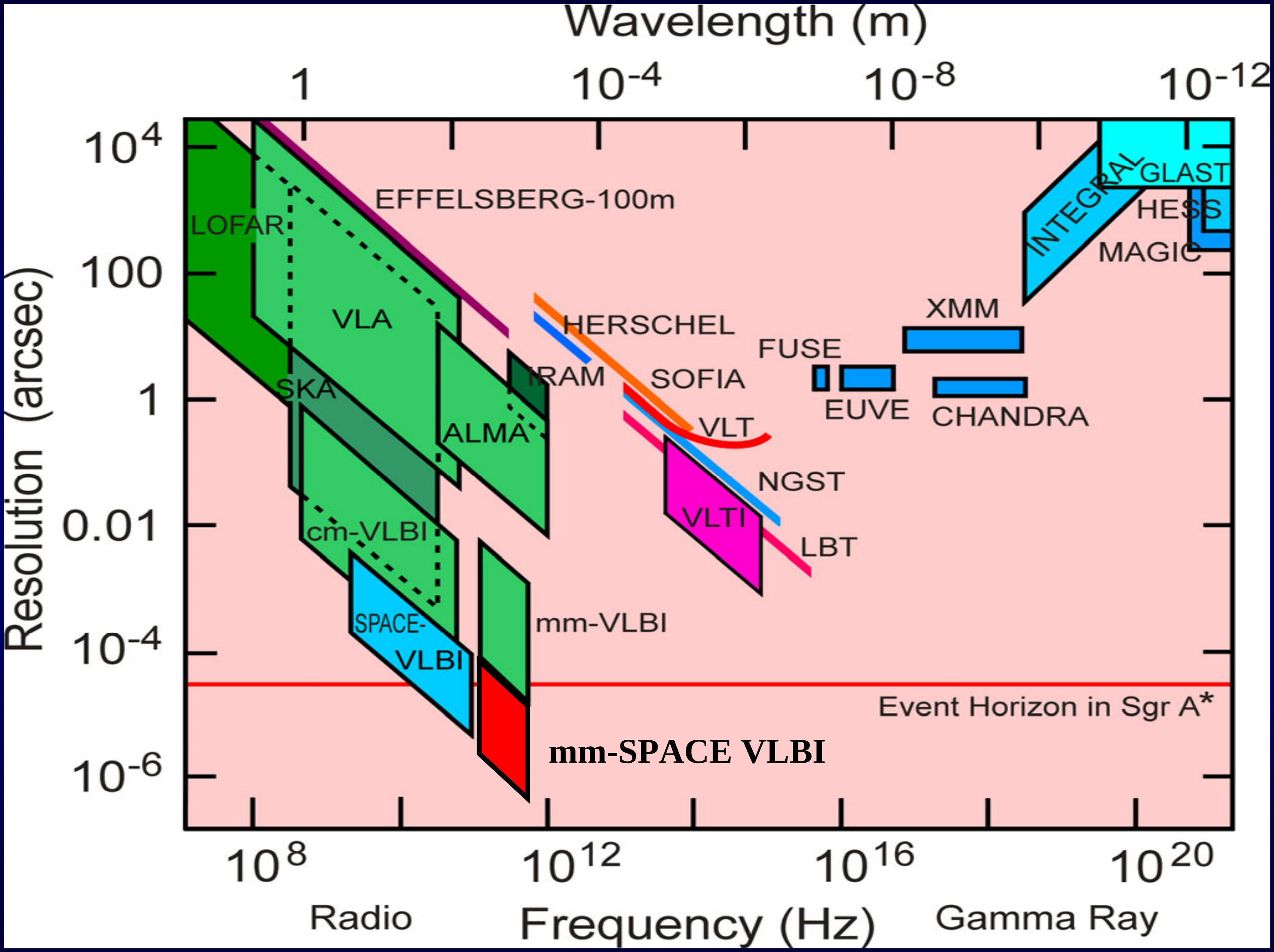
→ mm-VLBI can directly image (!) the vicinity of SMBHs (Event Horizon, BH-Shadow, GR-theory) !

→ best candidates: Sgr A* (10 μas = 1 R_s^6) and M 87 (Cen A is far south, M81 & NGC4258 are weak)

→ need sensitive mm-telescopes (i.e. ALMA) to image the emission around Black Holes in AGN

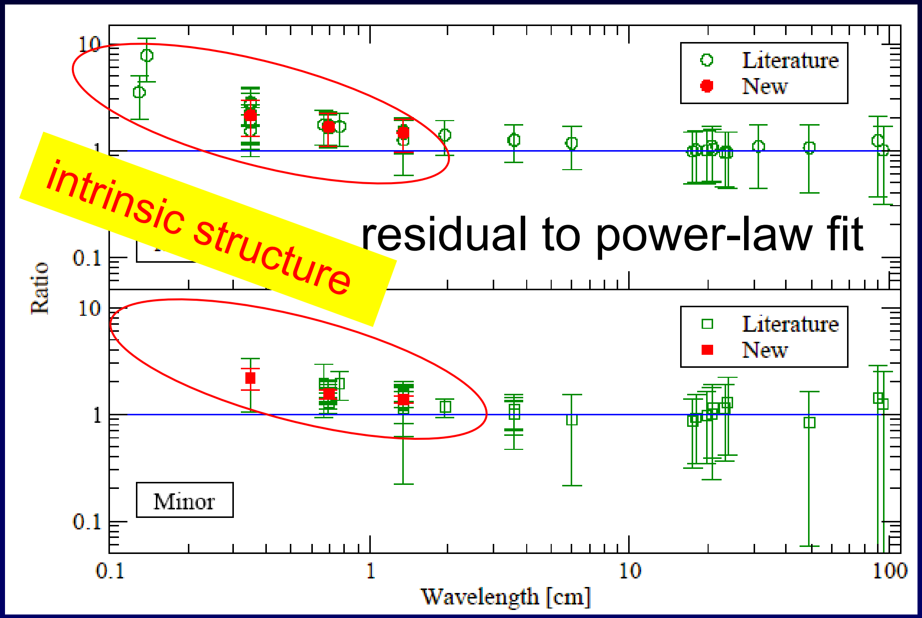
→ need a full global VLBI array for sensitivity and resolution .

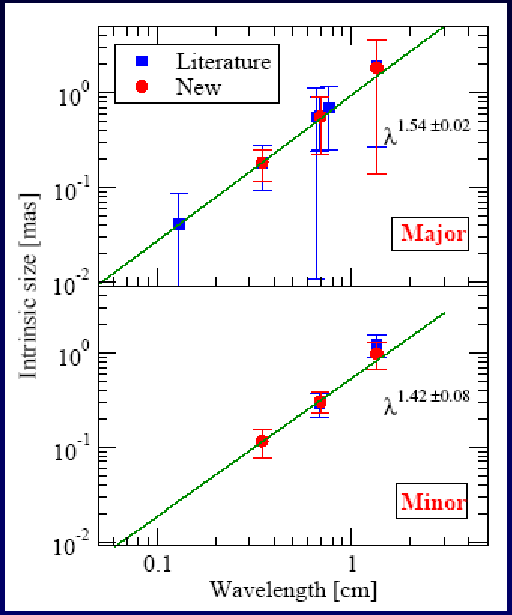
Angular Resolution



Millimetre VLBI provides the highest angular resolution in Astronomy !

SgrA*: Observed and intrinsic size as a function of wavelength





intrinsic size

Lu, Krichbaum et al. 2011 (A&A)

$\Theta^2_{obs} = \Theta^2_{scat} + \Theta^2_{int}$

fit for x:

$\Theta_{scat} = a \cdot \lambda^x$

$\Theta_{scat} \sim \lambda^{\beta/(\beta-2)}$

$\sim \lambda^2$ (with inner scale)

$\sim \lambda^{2.2}$ (Kolmogorov, $\beta=11/3$)

best fit:

$\Theta_{scat} \sim \lambda^{2.12 \pm 0.02}$

$\Theta_{int} \sim \lambda^{1.54 \pm 0.02}$

at 3mm:

$\Theta_{int} \sim (18.5 \times 11.5)\ R_S$

Correlated X-ray – IR – sub-mm variability in Sgr A*:

t_{var} ~ 5 – 10 min

$R \leq c\, t_{var}$

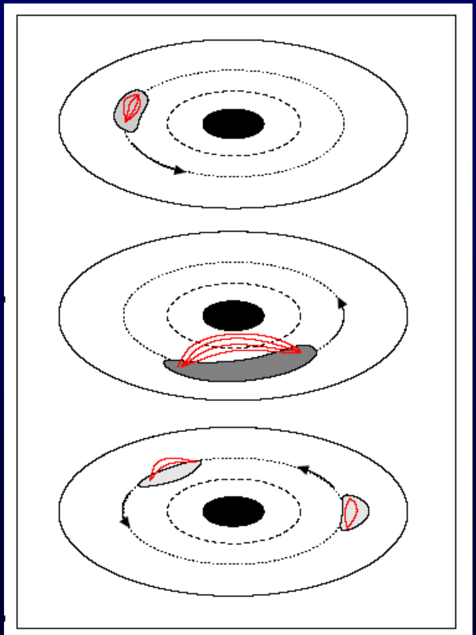
$R\, [R_G] \leq 90\, t\, [hrs]$

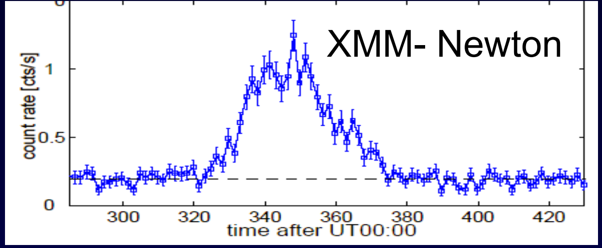
$\rightarrow R \leq 7.5 - 15\, R_G$

Orbiting hot spot model:

quasi-periodic variations faster & more pronounced towards shorter wavelength.

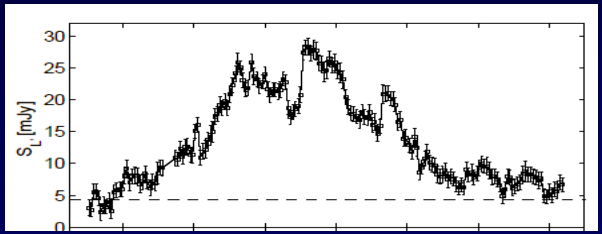
→ synchrotron radiation





April 4, 2007

X-ray

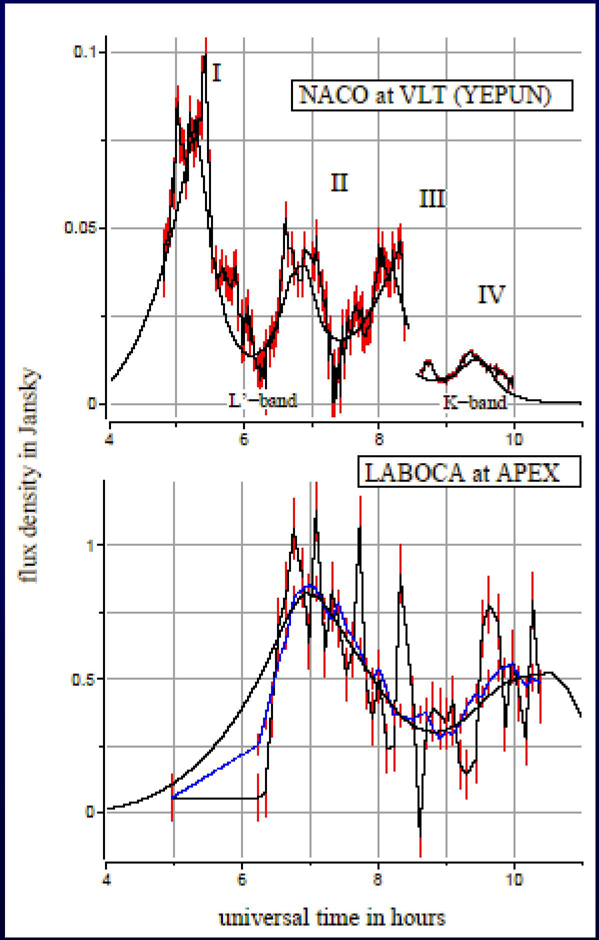


and

infrared (L')

Porquet et al. 2009

Dodds-Eden et al. 2009



June 3, 2008

infrared

(L' and K band)

sub-mm

(345 GHz)

Eckart et al. 2008a&b

Zamaninasab et al. 2008, 2010

SSC and synchrotron cooling in Sgr A* from X-rays to mm-wavelengths:

A broad band study of a flare on May 18, 2009

consistent discription of flare evolution through inverse Compton and synchrotron losses.

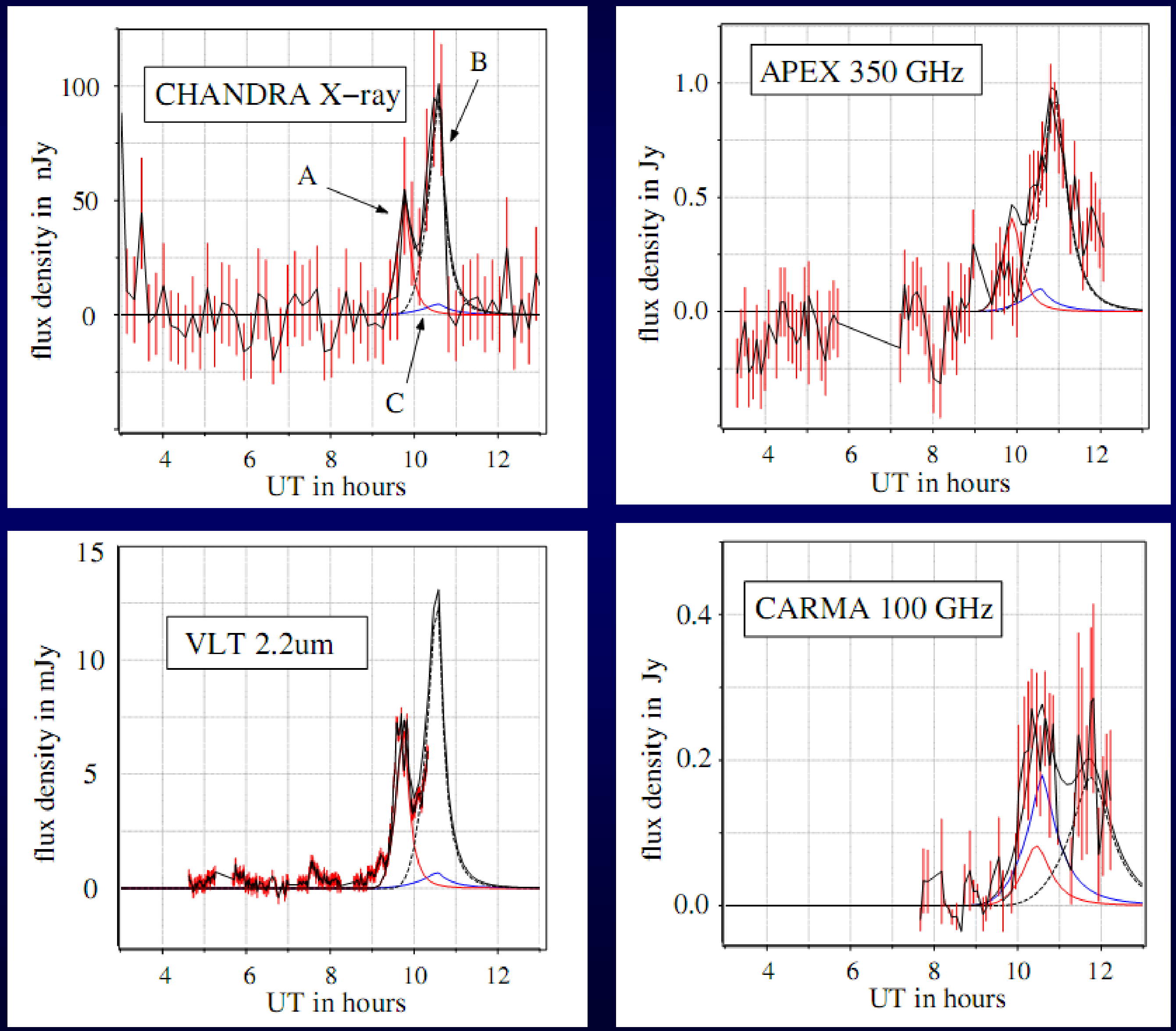
$\nu_m \sim 1$ THz

$\gamma_e \sim 10^3$

$v \sim 10^{-(3....2)}$ c

$n_e \sim 10^{(6...7)}$ cm^{-3}

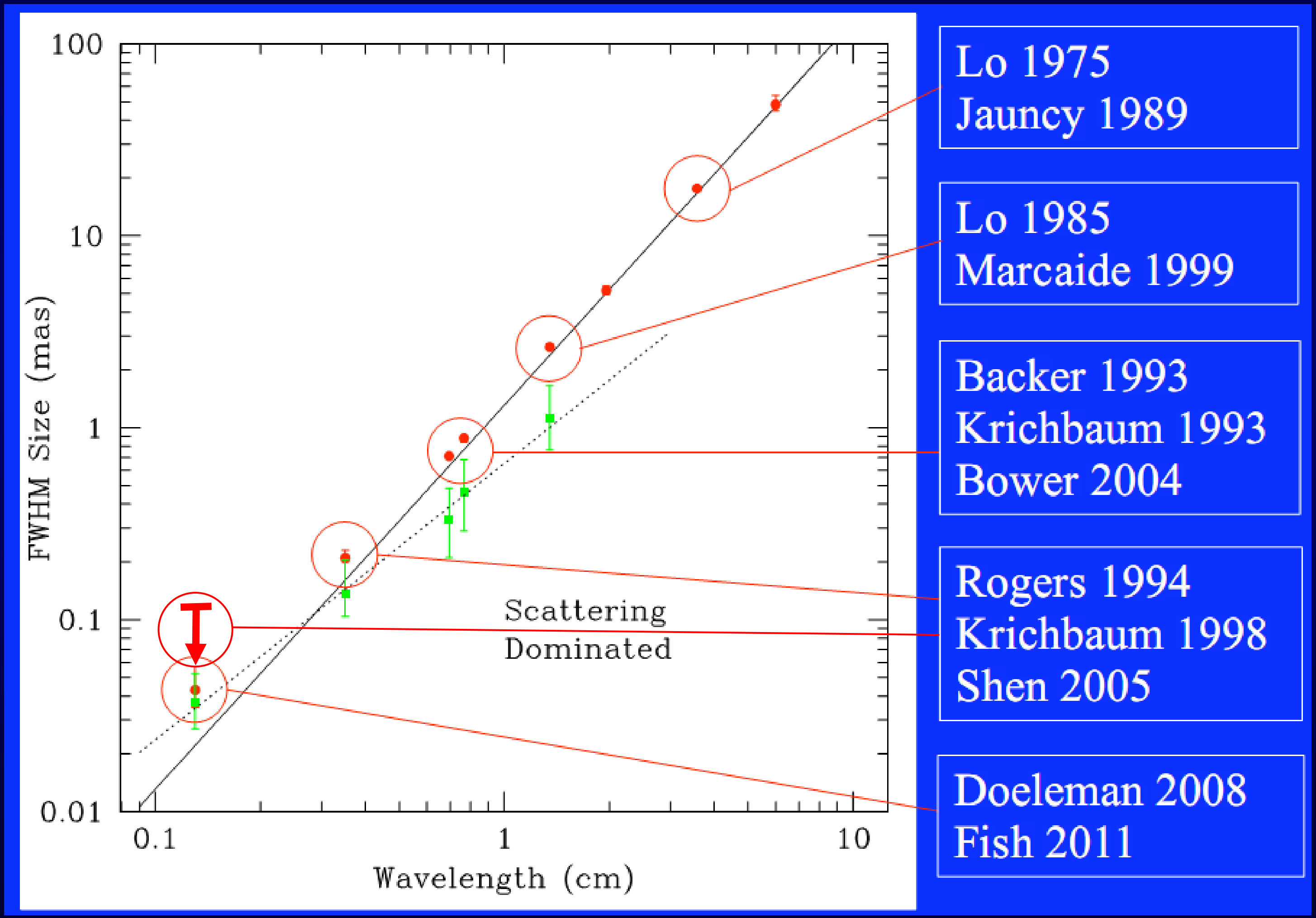
B ~ 90 ... 130 G



Eckart et al. 2012

Wavelength dependence of the size of Sgr A*

λ^2 dependence from interstellare scatter broadening



graphics: S. Doeleman EHT meeting 2012

New size measurement of SgrA* with VLBI at 1.3 mm wavelength

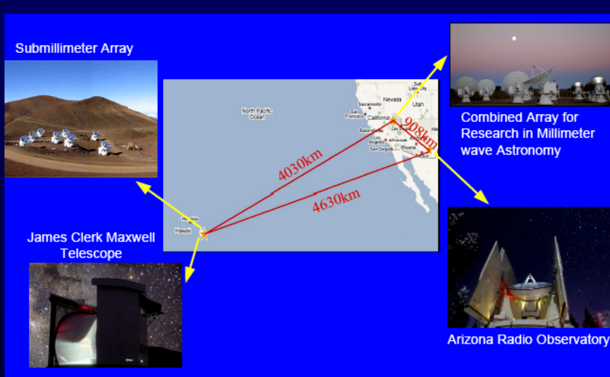
1.3 mm-VLBI at 230 GHz

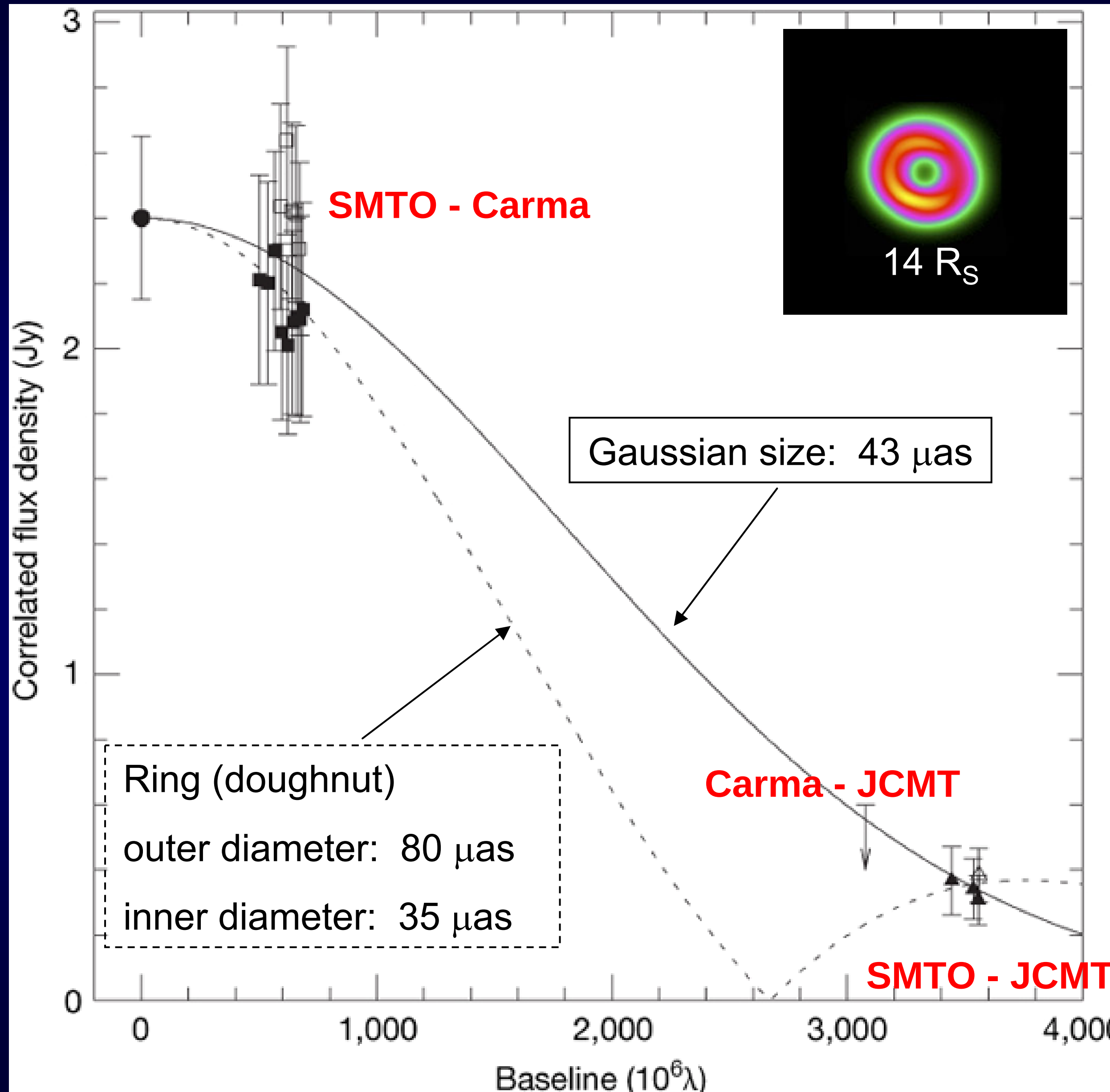
April 10-11, 2007

Mk5C, 3.84 Gbit/s, 480 MHz

Interpret sparse data with a circular Gaussian

JCMT/SMA-SMTO-CARMA$_{1}$:





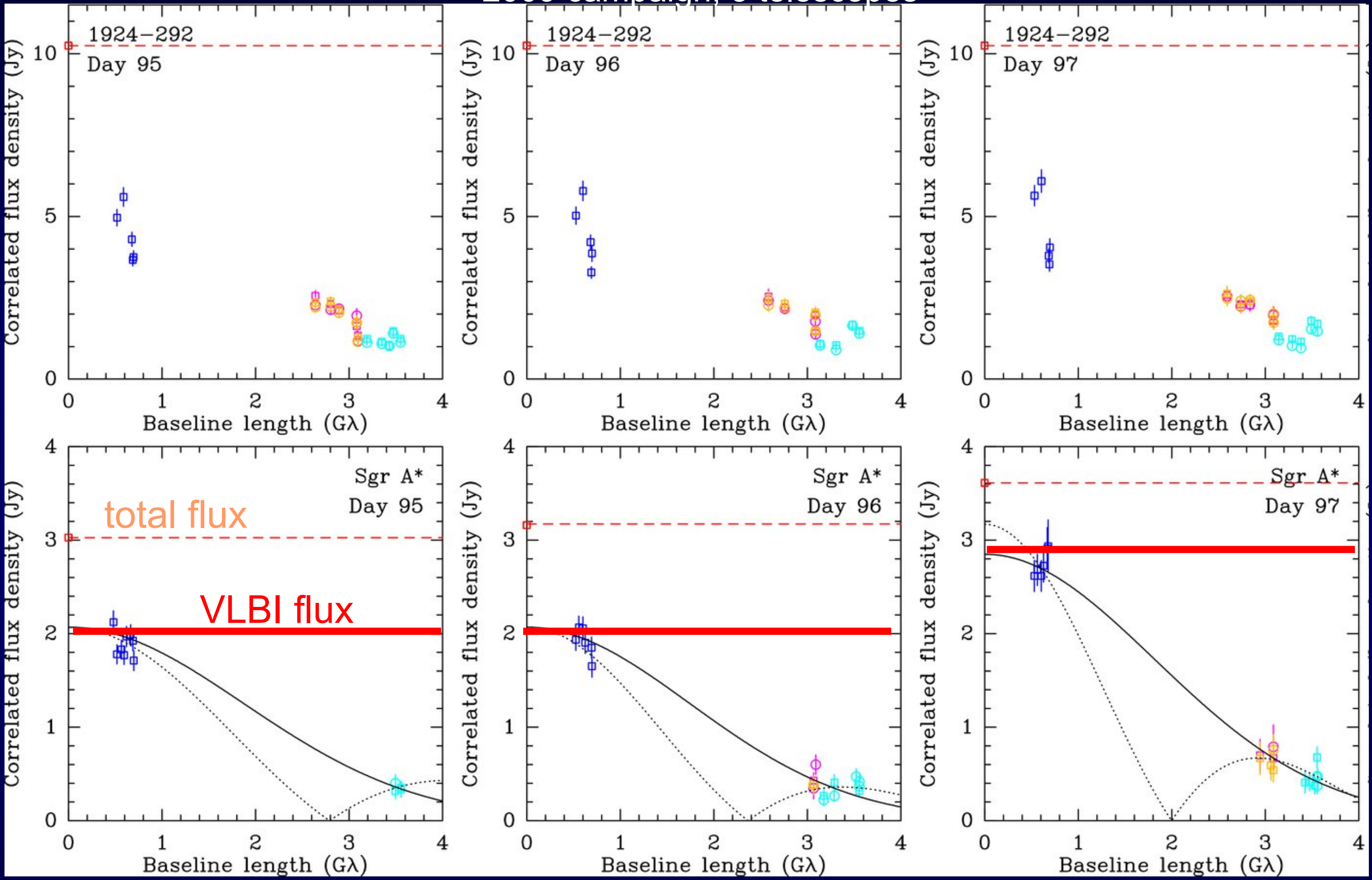
Doeleman *et al.* *Nature* **455**, 78-80 (2008)

Time variable emission on event horizon scales

2009 campaign, 3 telescopes

calibrator:

Sgr A*:



39 % flux increase in one day

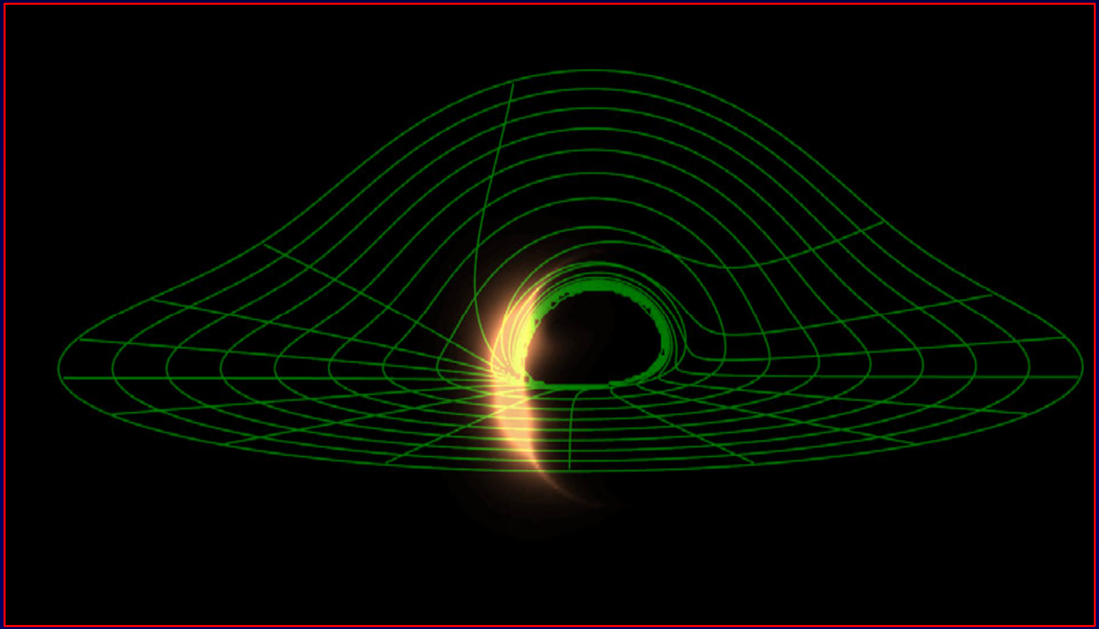
no significant change of source size (43 μas) – geometrical ?

→ variability appears on small ISCO scales

Fish et al. 2011

Interpretation of the 1mm VLBI size measurement

gravitationally lensed image of accretion disk



Broderick & Loeb 2008

orbiting hot spot / instability

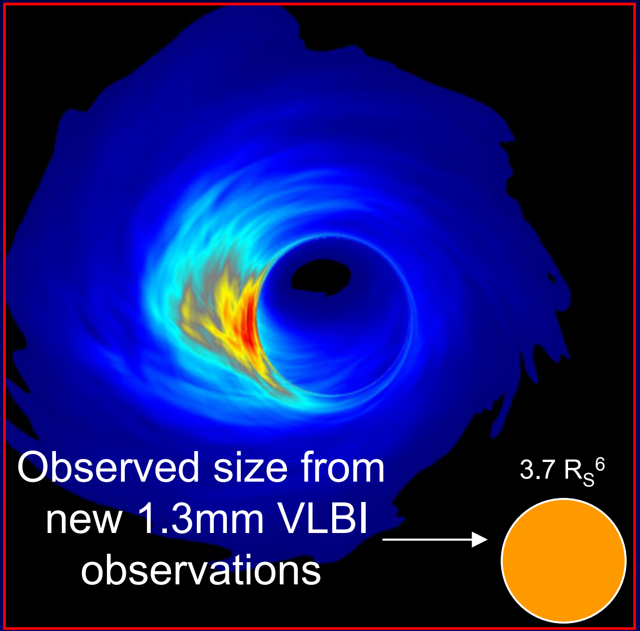


image credit: Noble & Gammie

Doeleman *et al. Nature* **455**, 78-80 (2008)

observed size: 43 (+14/-8) μas

deconvolved : 37 μas

intrinsic : 3.7 R_S

Observed size is smaller than expected size of accretion disk !

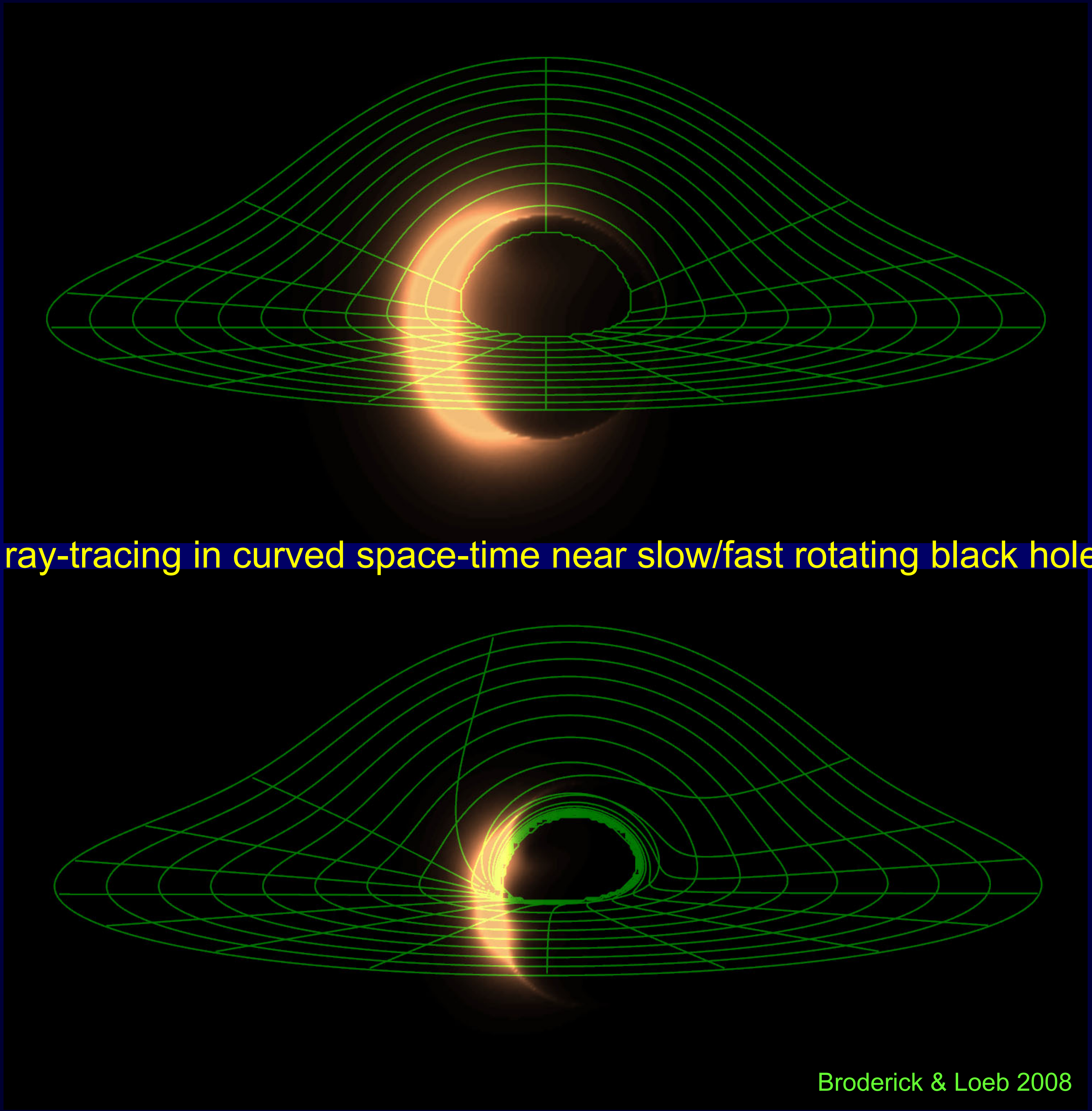
Determination of mass and spin of black hole from VLBI measurement of the shape of the silhouette

slow BH rotation

larger width of crescent

fast BH rotation

smaller width of crescent

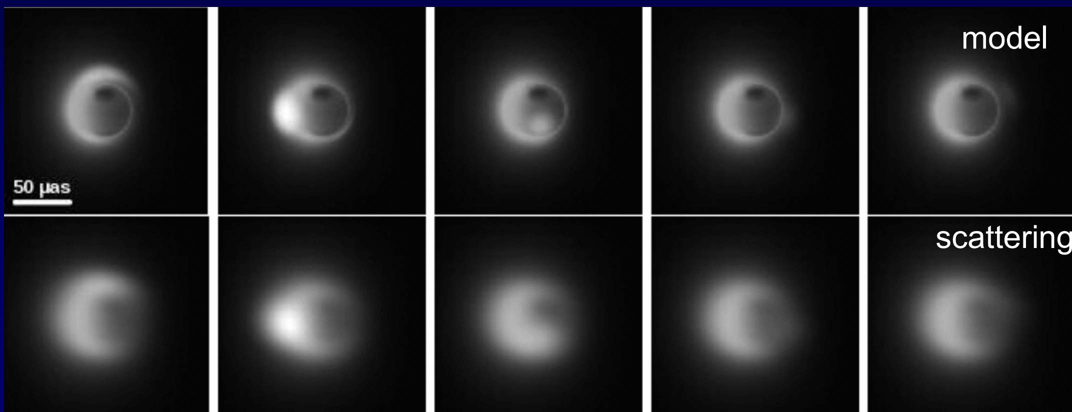


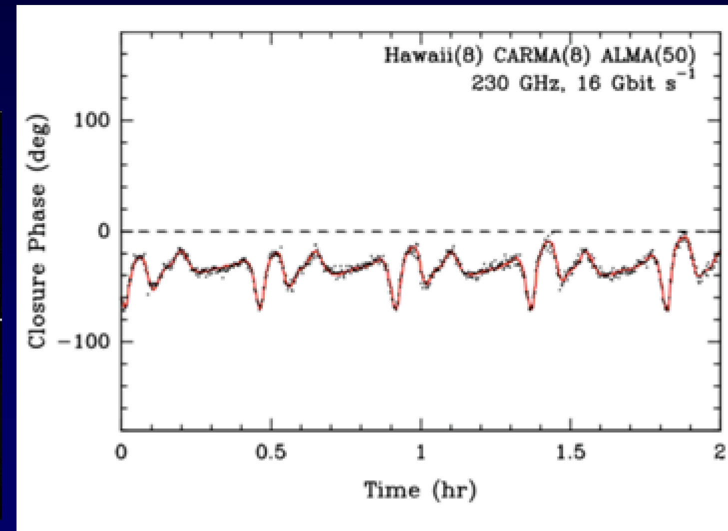
ray-tracing in curved space-time near slow/fast rotating black hole

Broderick & Loeb 2008

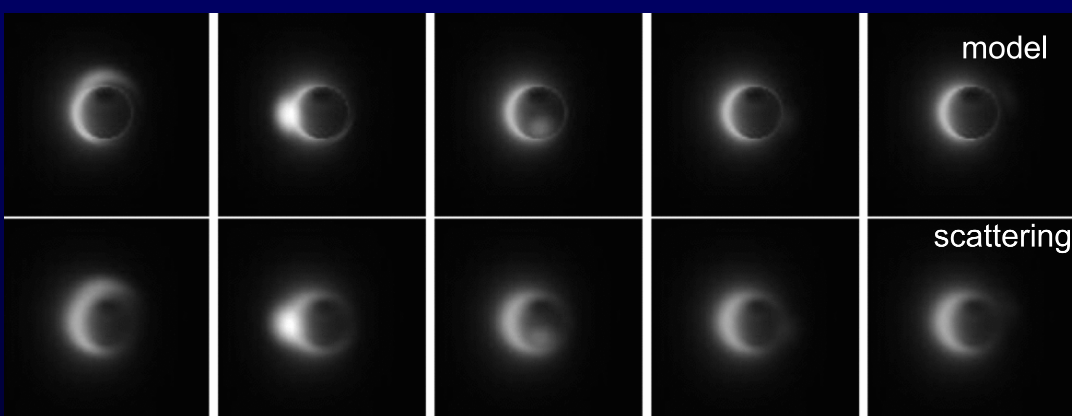
Modulation of the closure phase by orbiting hot spots around a rotating BH

230 GHz



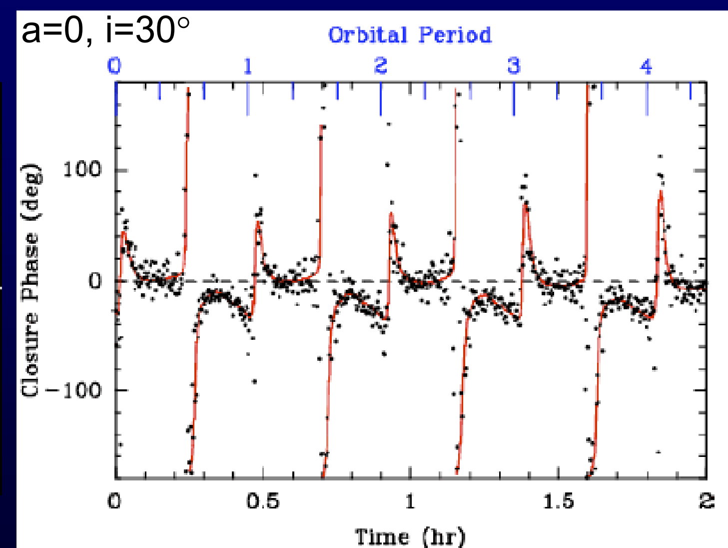


345 GHz



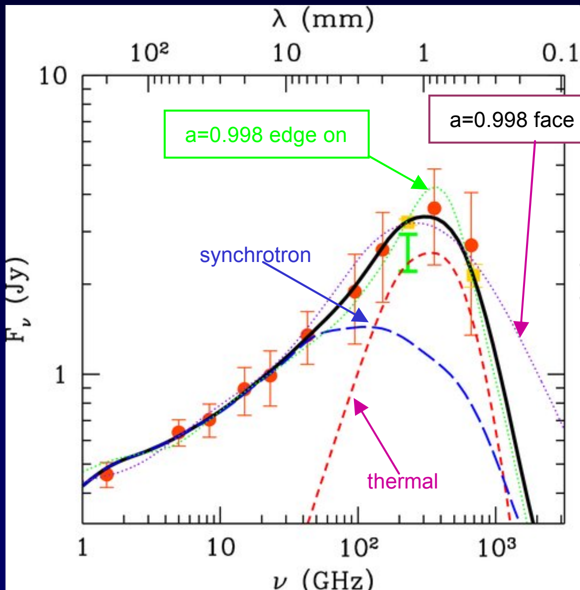
0.0 0.2 0.4 0.6 0.8

orbital phase



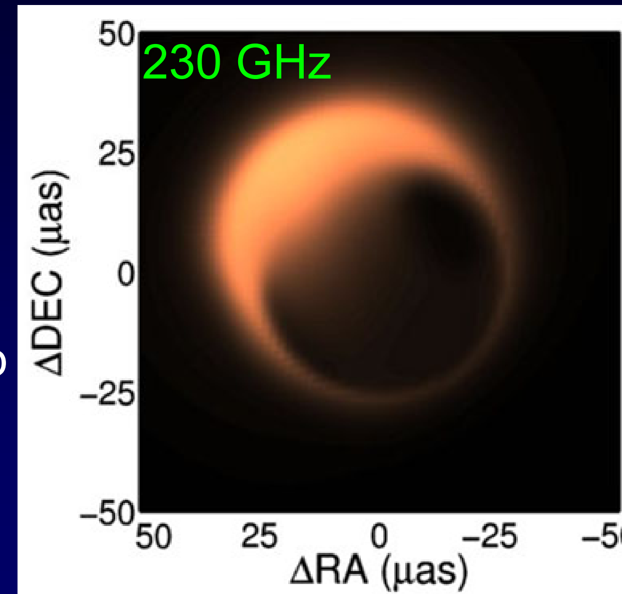
Fish et al. 2008, Doeleman et al. 2009

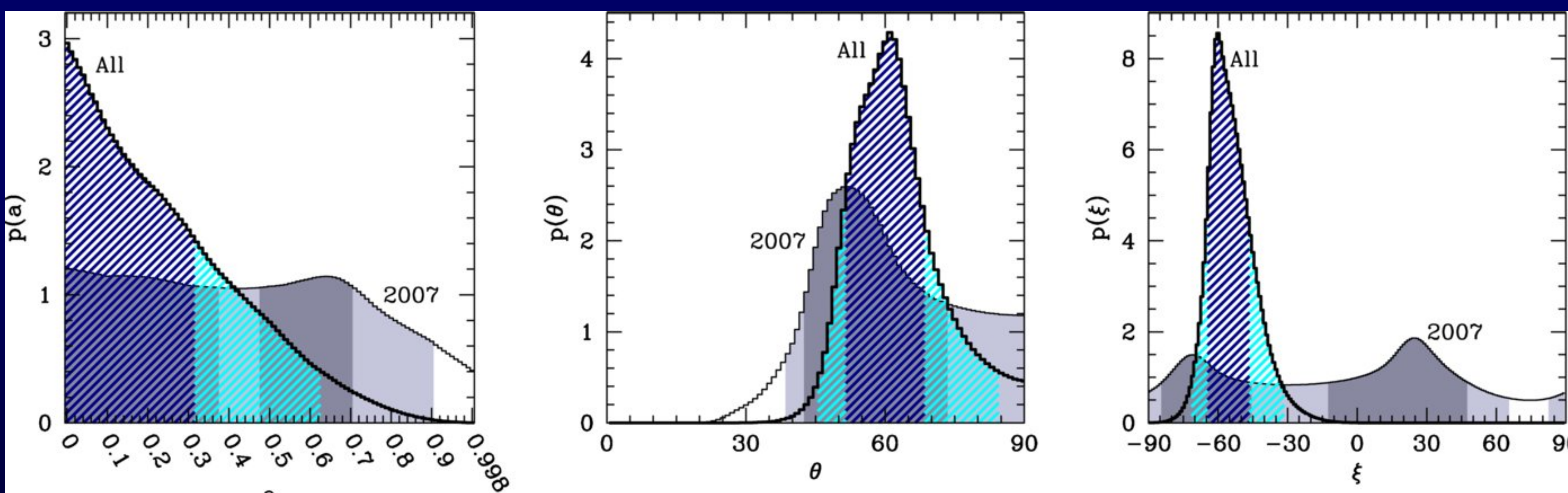
Combined Results from theoretical modeling



best fit image

using RIAF model of Broderick & Loeb 2006





spin

inclination

orientation

still uncertain

Borderick et al. 2011

The Photon Ring

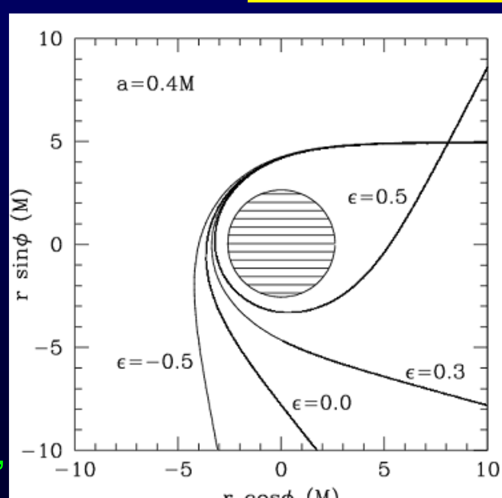
- diameter of photon ring: 10.4 R_G (Johannsen & Psaltis 2010)
- because of 'geometrical' origin its size is independent of details of accretion flow (eg. Falcke et al. 2000)
- solely determined by BH mass, spin, disk inclination

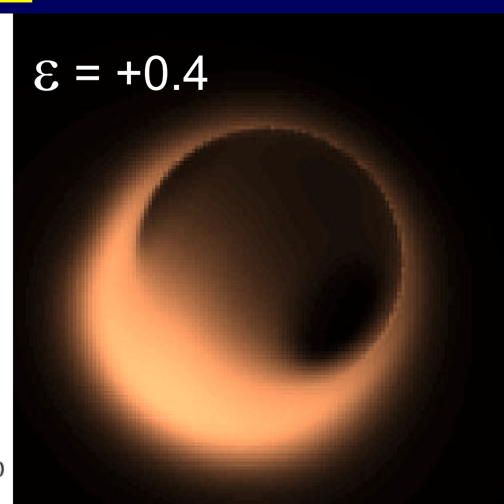
$$M\ [10^6 M_\odot] = 9.8\ 10^{-3} \cdot \theta_{\mu as}\, D_{kpc}$$

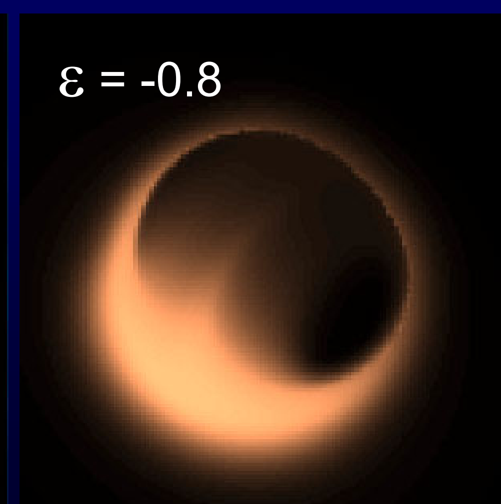
Sgr A* : angular size of photon ring $\theta_{\mu as}$: 53 μas

- and quadropole moment $q = -(a^2 + \varepsilon)$, for Einsteins GR $\varepsilon = 0$, GR violation $\varepsilon \neq 0$

Lightbending f(ε):







Johannsen et al. 2012

Broderick, Johannsen, Loeb, Psaltis, 2012

The appearance of the photon ring is independent from the details of the accretion flow modeling

Moscibrodzka et al. 2009 | Dexter et al. 2009 | Shcherbakov & Penna 2010

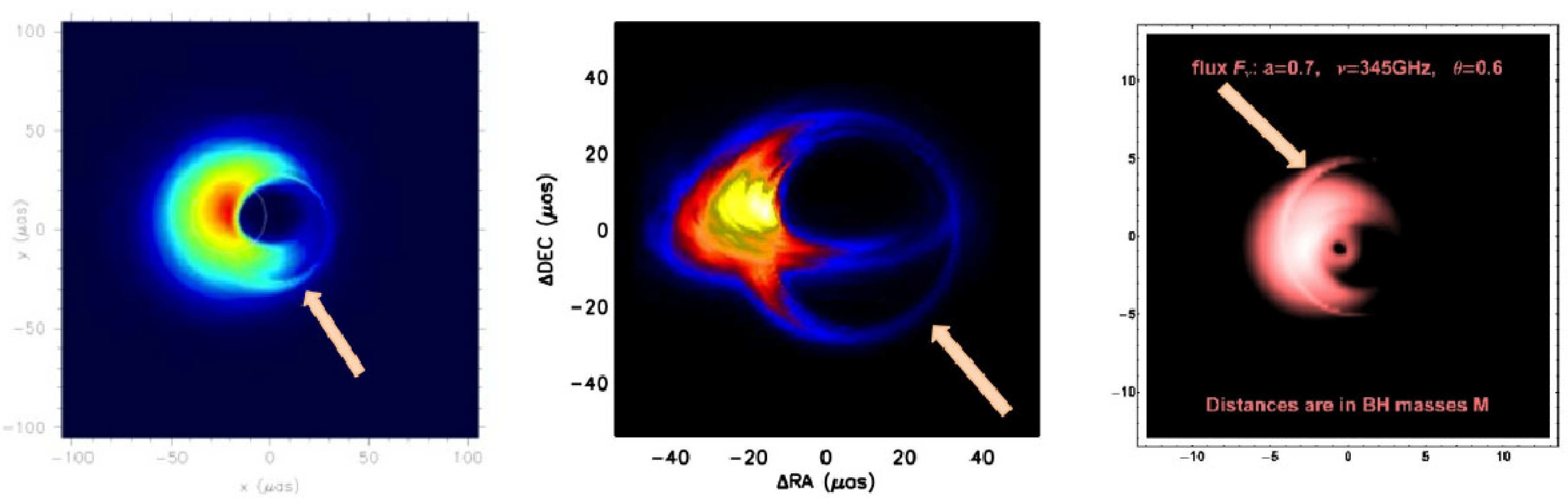


Figure 8. The presence of a bright photon ring surrounding the black-hole shadow is ubiquitous in all current simulations of images from radiatively inefficient accretion flows (from left: Moscibrodzka et al. 2009; Dexter et al. 2009; Shcherbakov & Penna 2010). The size, location, and shape of the photon ring is determined by the projected photon orbit at infinity and, as such, it depends only on the metric of the spacetime. The accretion flow is necessary only to provide the photons that will trace the photon ring for an observer at infinity.

figure compilation: Psaltis & Johannsen 2011 (JPhCS)

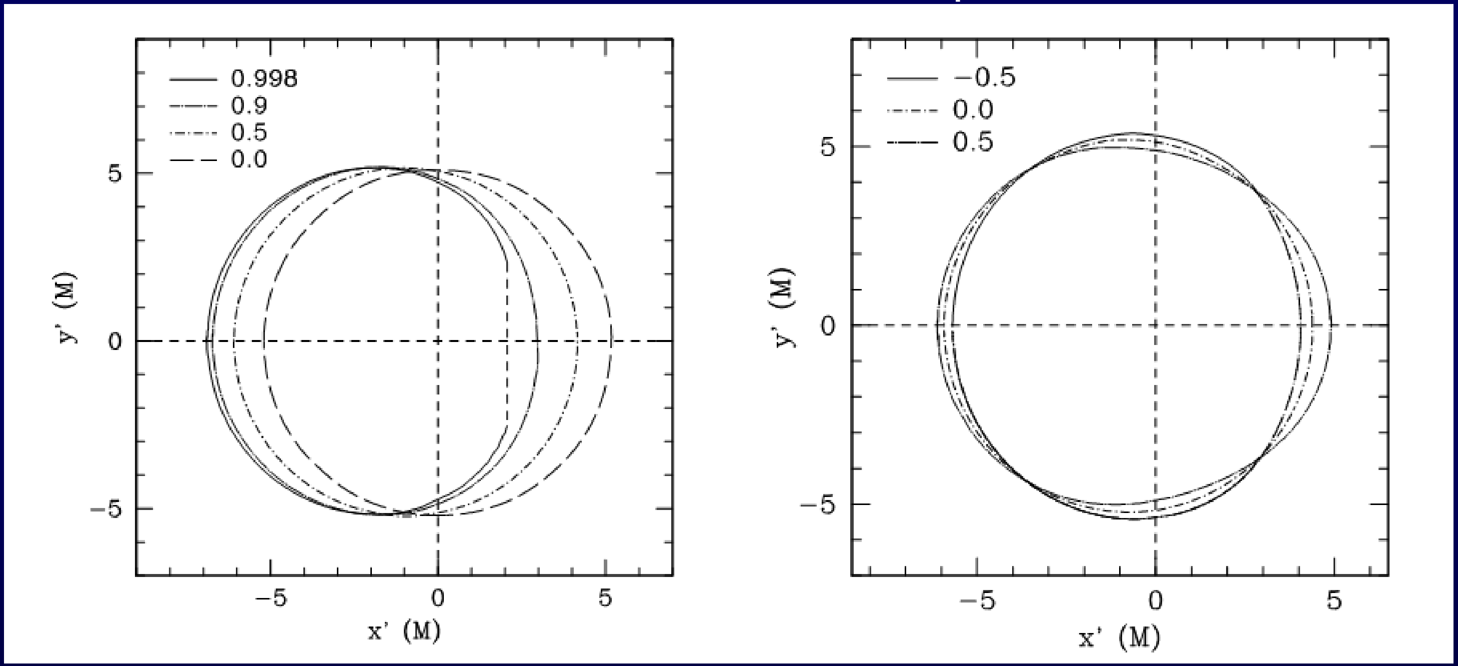
Testing the no-hair theorem

(Johannsen & Psaltis 2010, 2012)

quadrupole moment $q = -(a^2 + \varepsilon)$, for GR $\varepsilon = 0$ (Kerr metric)

Photon ring around BH

Kerr metric quasi-Kerr metric



increasing spin parameter a causes displacement to the left, circularity remains

for $\varepsilon \neq 0$ the ring becomes ellipsoidal, assymmetry increases for higher spin values

Testing the "no-hair theorem" using mm-VLBI with APEX/ALMA

"No-hair" theorem of General Relativity:

A Black Hole is uniquely defined by its mass (monopol moment) and spin (dipole moment).

Broderick et al. 2010   see also: Johannsen & Psaltis 2010   Doeleman et al. 2009, Astro2010

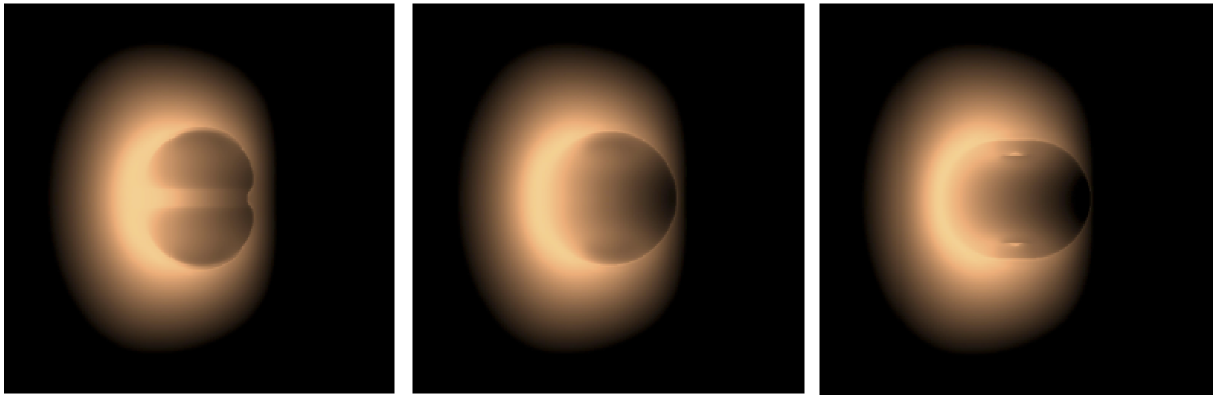
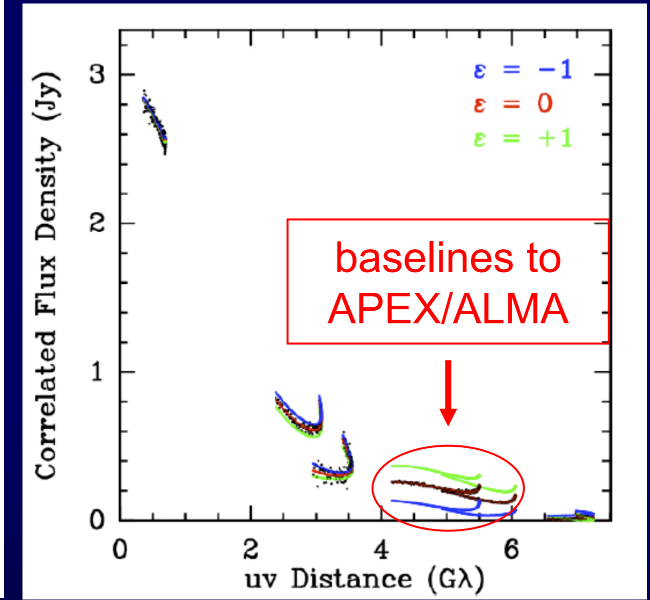


Figure 4: Testing GR. The left three images show the best fit RIAF model for SgrA* ray-traced through space times with $\varepsilon=-1$, $\varepsilon=0$, and $\varepsilon=+1$. If $\varepsilon\neq0$, then SgrA* is either not a GR black hole, or GR does not describe the space time of black holes.

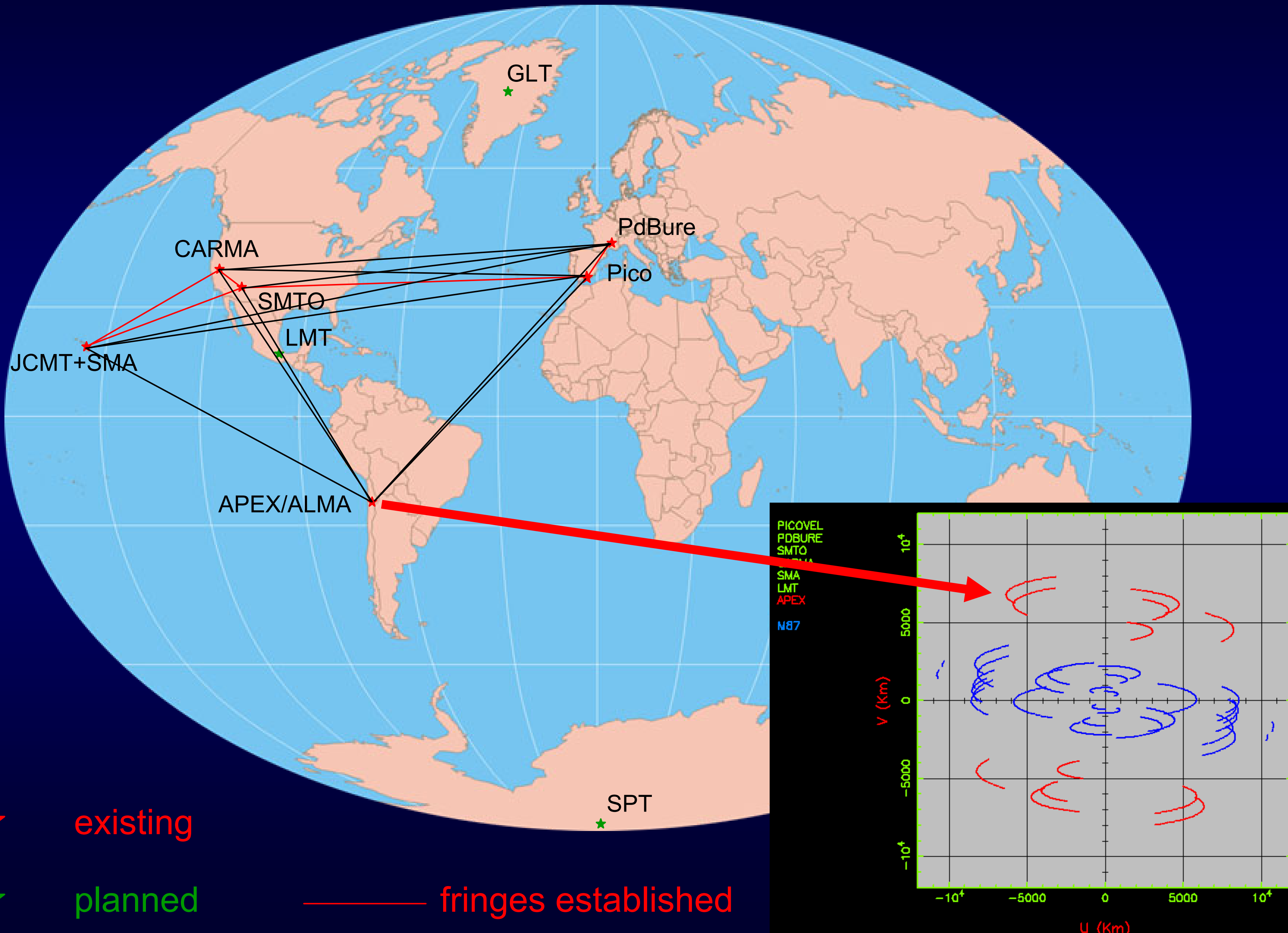


quadrupole moment: $Q = -M(a^2 + \varepsilon M^2)$

$\varepsilon \neq 0$, GR is violated

mm/ sub-mm VLBI can test the validity of General Relativity in the strong field regime (but: excellent image fidelity required) !

The Event Horizon Telescope – a global mm-/sub mm VLBI array

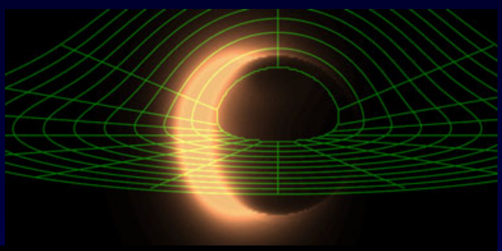


★ existing

★ planned

——— fringes established

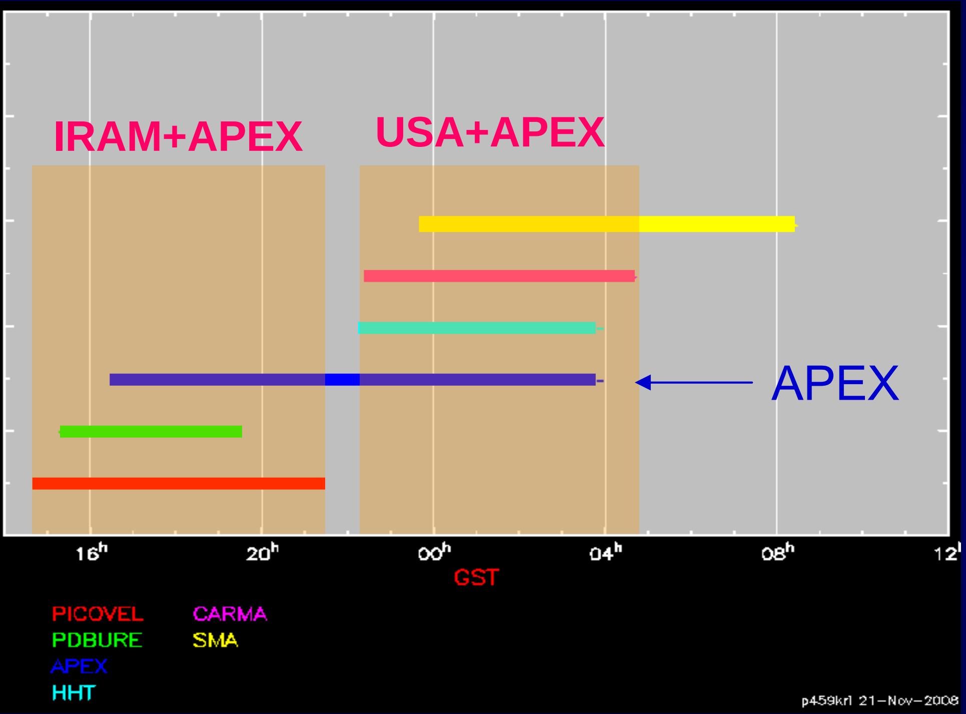
Global Millimeter VLBI with APEX



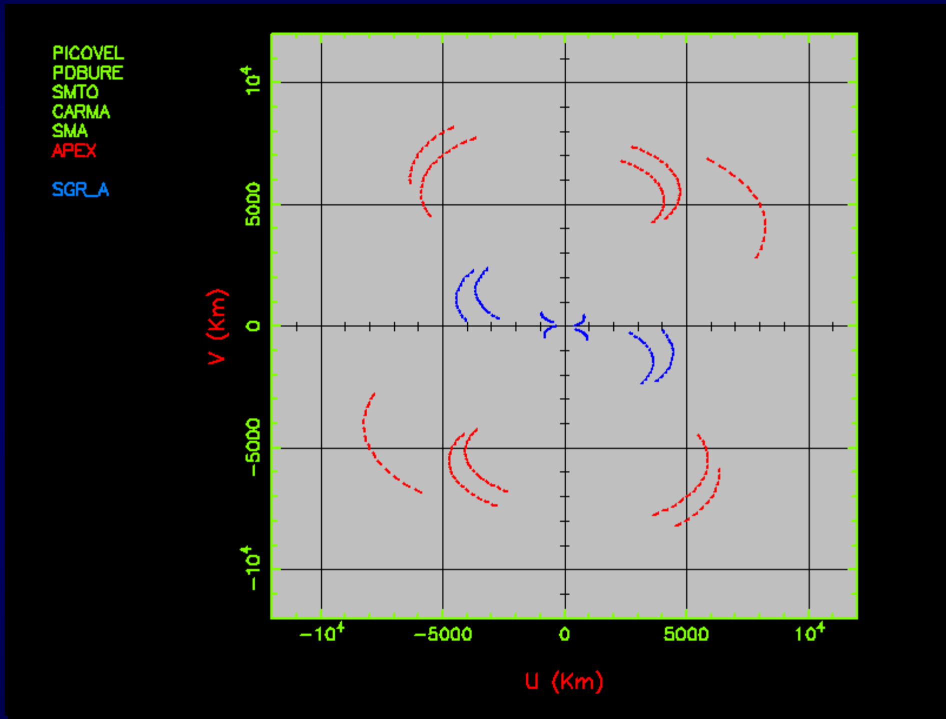
Determine the shape of the event horizon

Observations of Sgr A*

ν = 230, 345 GHz



Mutual Visibility



uv coverage (Apex high-lighted)

APEX connects 2 IRAM telescopes with 3 US stations

IRAM + APEX: ~5 hrs

USA + APEX: ~6 hrs

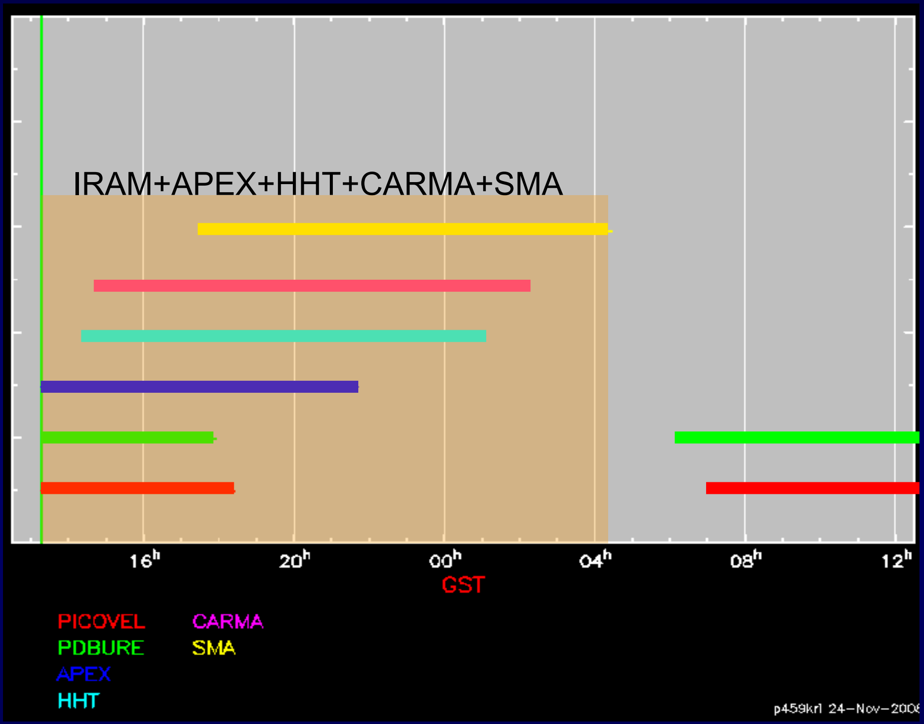
Angular Resolution: 20-30 μas @230 GHz

10-20 μas @345 GHz

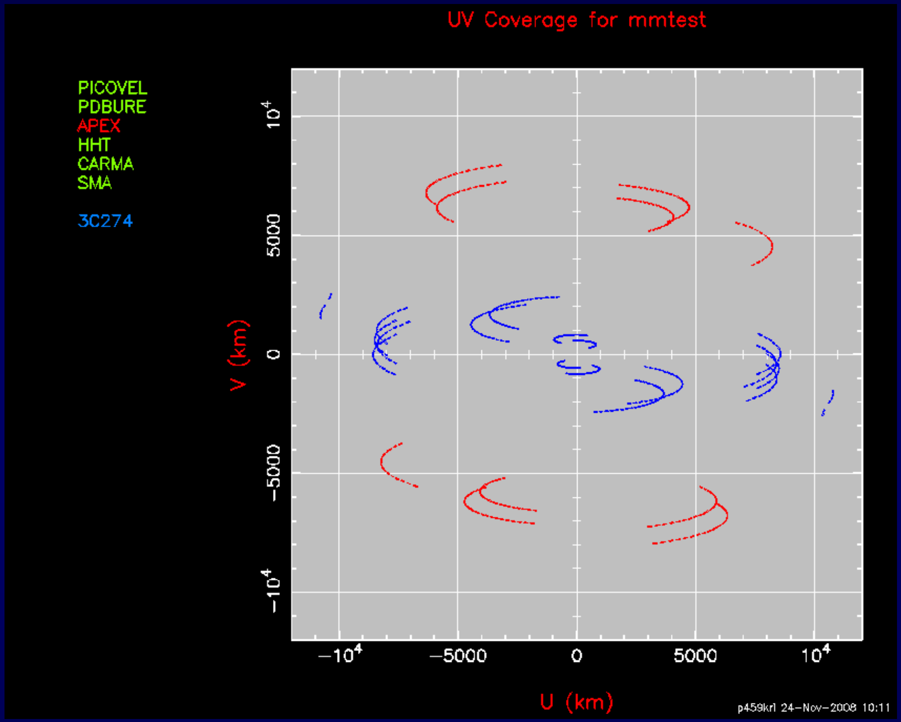
Global Millimeter VLBI Experiments with APEX

Observations of M87

ν = 230, 345 GHz



Mutual Visibility



uv-coverage (6 telescopes)

geograph. latitude of APEX: $\phi = -23°$

IRAM + APEX: ~6 hrs

height above horizon: elv = 67° - δ

USA + APEX: ~7 hrs

$\Rightarrow$ declination limit δ < (67° – horizon (15°)) ≈ 52°

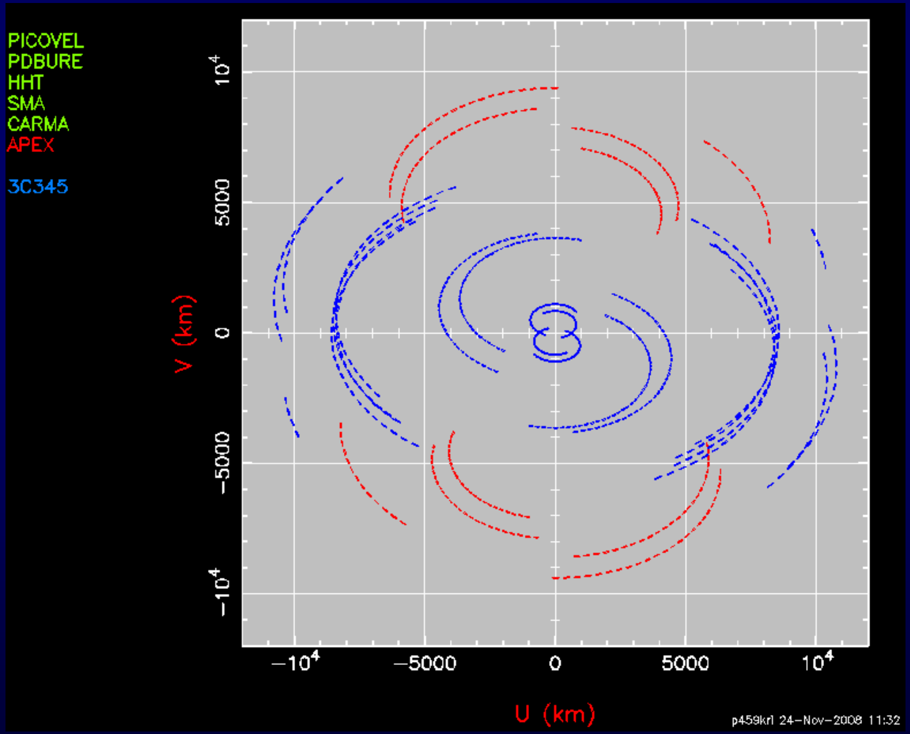
VLBI with APEX/ALMA: Mutual Visibility for "Northern" Sources

geograph. latitude of APEX: $\phi = -23°$

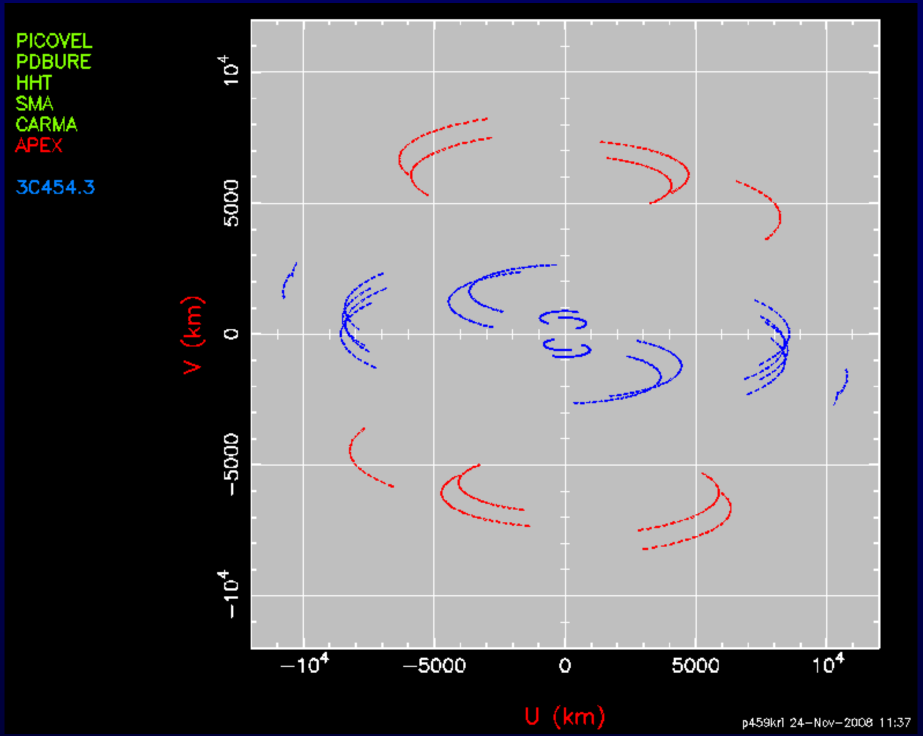
culmination height above horizon: $elv = 67° - \delta$

$\Rightarrow$ northern declination limit $\delta \leq (67° – \text{horizon } (15°)) \approx +52°$

3C345, δ = 39.8° (6 hrs with APEX)



3C454.3, δ= 16.1° (8.5 hrs with APEX)



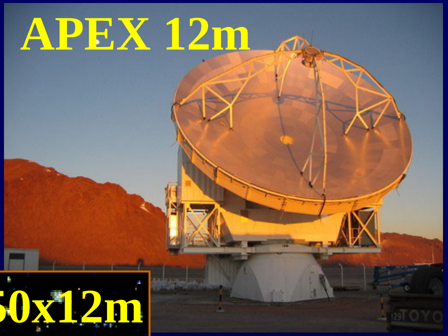
Global mm-VLBI with participation of APEX greatly improves the uv-coverage also for sources with moderate northern declinations $\rightarrow$ Great scientific potential !!

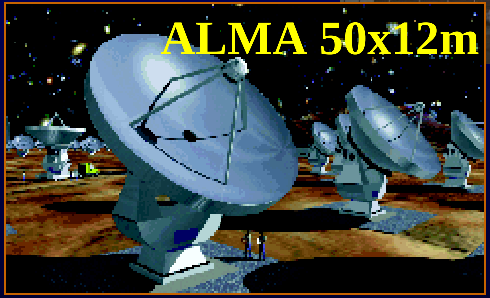
Future 1mm-VLBI – Sensitivities

(7σ in [mJy])

	PdBure	CARMA	Hawaii	SMTO	APEX	ALMA
Pico	40	50	56	124	100	14
PdBure		40	45	100	81	12
CARMA			56	124	100	15
Hawaii				139	113	17
SMTO					254	39
APEX						31

assume: 4 GHz (16 Gbit/s) bandwidth , 20 s integration time, 2 bit sampling





expected (7σ) detection limits:

Pico-SMTO/APEX : ~ 110 mJy

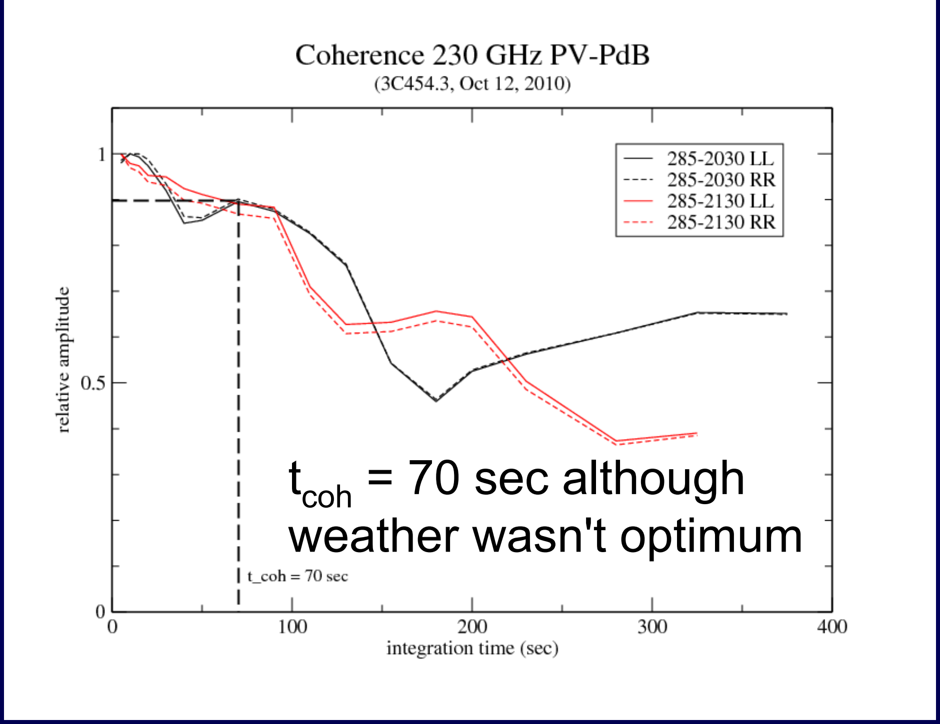
plus PdBure /CARMA : ≥ 40 mJy

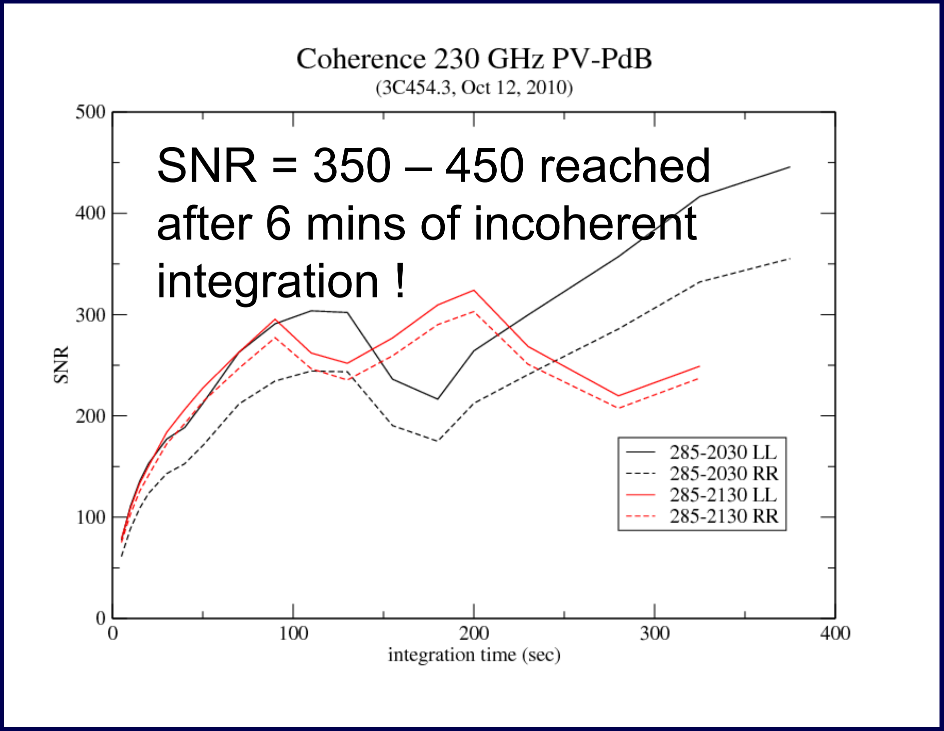
plus ALMA : ≥ 12 mJy

numbers will improve if phase corrections are used to prolongue coherence

Phase coherence at 230 GHz in October 2010

PV - PdB (phased)





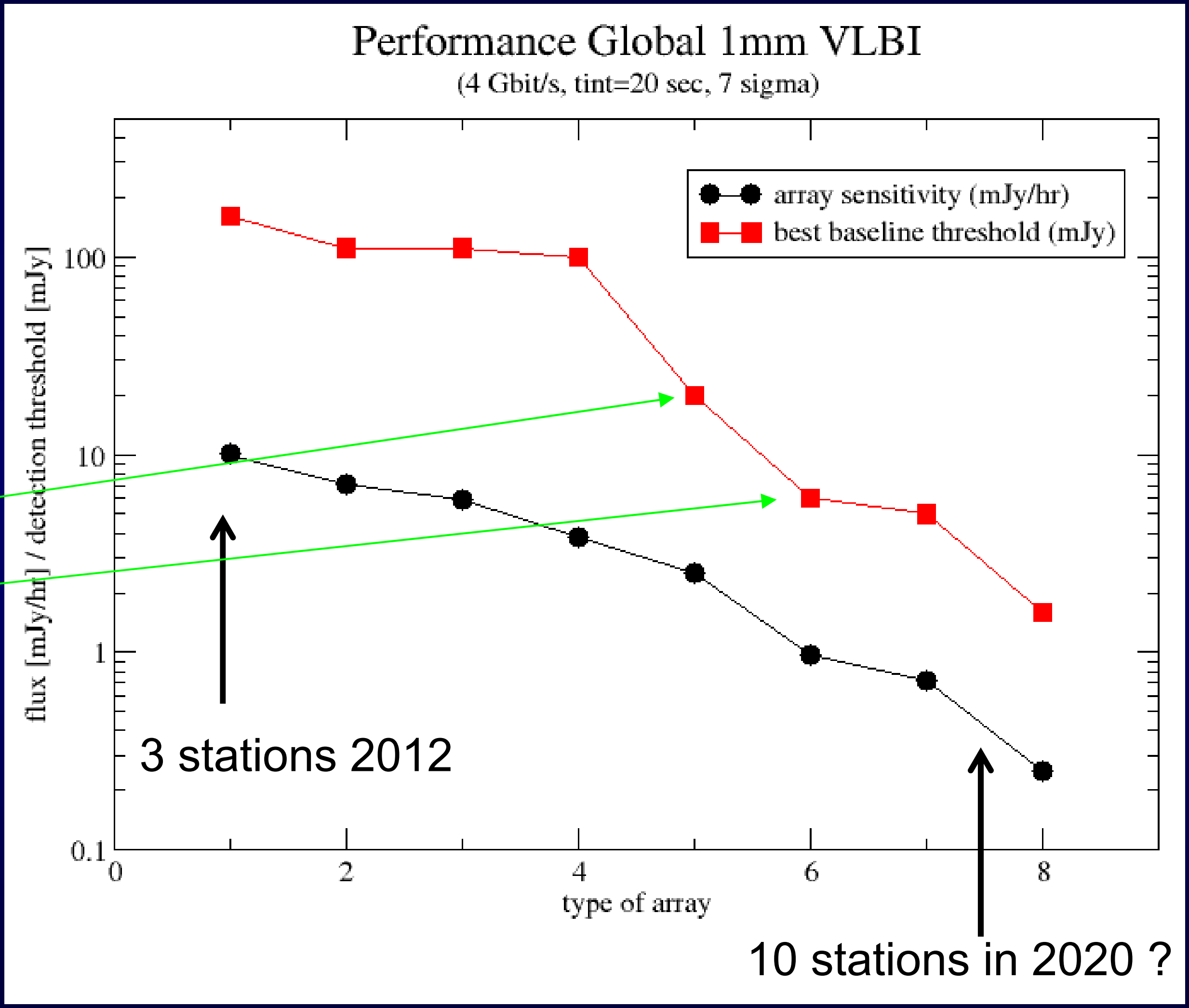
good VLBI-phasing efficiency of the 6 elements of the PdB interferometer

but: present correlator supports only ≤1 GBit/s (16 x 16 MHz, MK5A)

new correlator will support 32 MHz bands and VLBI array phasing

Performance of a global 1mm VLBI array

1. SMTO-CARMA-JCMT
2. SMTO-CARMA-Hawaii
3. + Apex
4. + Pico Veleta
5. + PdBure
6. + ALMA
7. +LMT+SPT+GL
8. +2x4GHz (32 Gb/s)

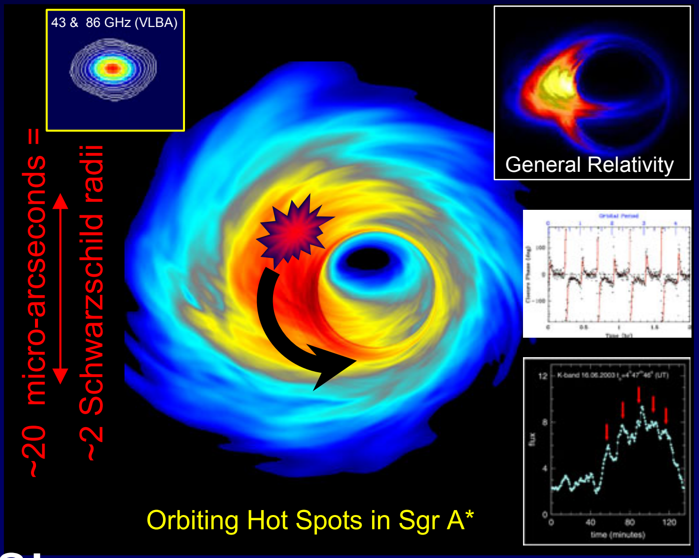


With the participation of ALMA the baseline sensitivity will be lowered to 1-5 mJy (depending a bit on BW). With 10 VLBI stations 1.5 mJy / hr can be reached.

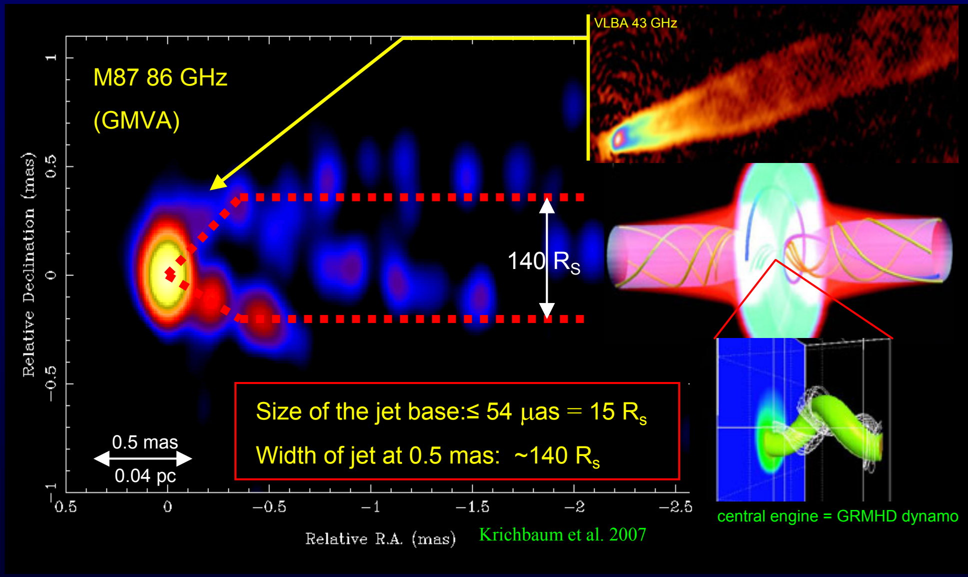
Image Black Holes and the region of jet formation with sub-millimeter VLBI

- achieve 10-25 micro-arcsecond resolution at sub-mm wavelengths
- build a global sub-mm VLBI array: PV, PdBI APEX, SMTO, Hawai, Carma, LMT, ... (Event Horizon Telescope).
- image Sgr A* and M87 with a few R_G resolution (BH imaging and GR-effects)
- study jet formation in nearby Radio-Galaxies (jet-disk connection)
- AGN studies at mm-λ, study SMBHs at high redshifts (cosmological evolution of SMBHs)
- establish global submm-VLBI with ALMA and milli-Jansky sensitivity

Sgr A*:



M87+Jets:



Do we need APEX when ALMA is there ?

- phasing capability of ALMA for VLBI is now beeing developed
- 1st VLBI test experiments with ALMA sub-array expected in 3-5 yrs from now
- sensitivity of phased ALMA array will be sqrt(N) better than APEX, but:

  - phased ALMA array may not be available right in the beginning and at all times (mm-VLBI needs pre-allocated time slots)
  - available VLBI time at ALMA will be limited due to heavy general oversubscription (VLBI: 1-2 times per year, per month?)
  - full sensitivty of ALMA may not be needed for bright sources
  - APEX could provide VLBI time more flexibly than ALMA, ALMA may not be so easily avaliable for pilot studies
  - a VLBI telescope in Chile always improves the uv-coverage
  - combination of APEX with ALMA and other telescopes in south america also provides interesting short baselines (e.g. for spectral line VLBI)