Towards the Event Horizon

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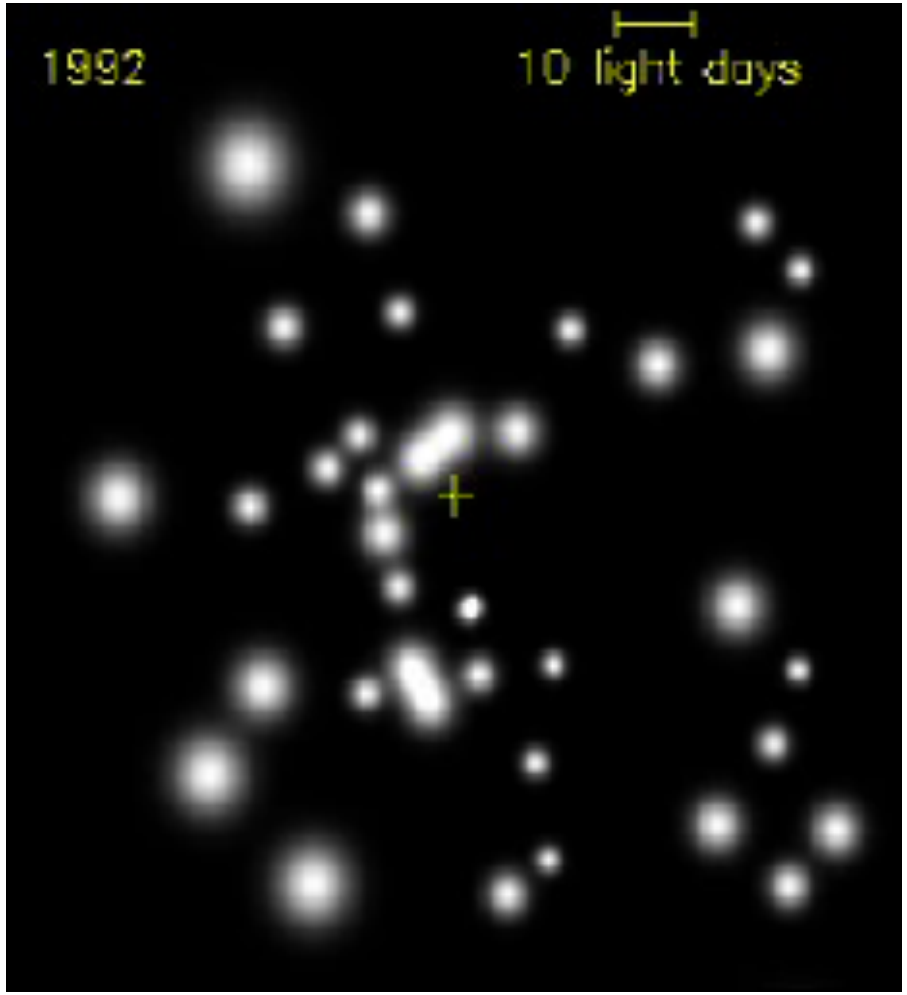
Dark Mass in the Galactic Center

- Stellar proper motions have revealed a dark mass in the Galactic Center of 4 Million solar masses within the size of the solar system.
- The center of gravity coincides with Sgr A* within 215 R_s (15 AU).

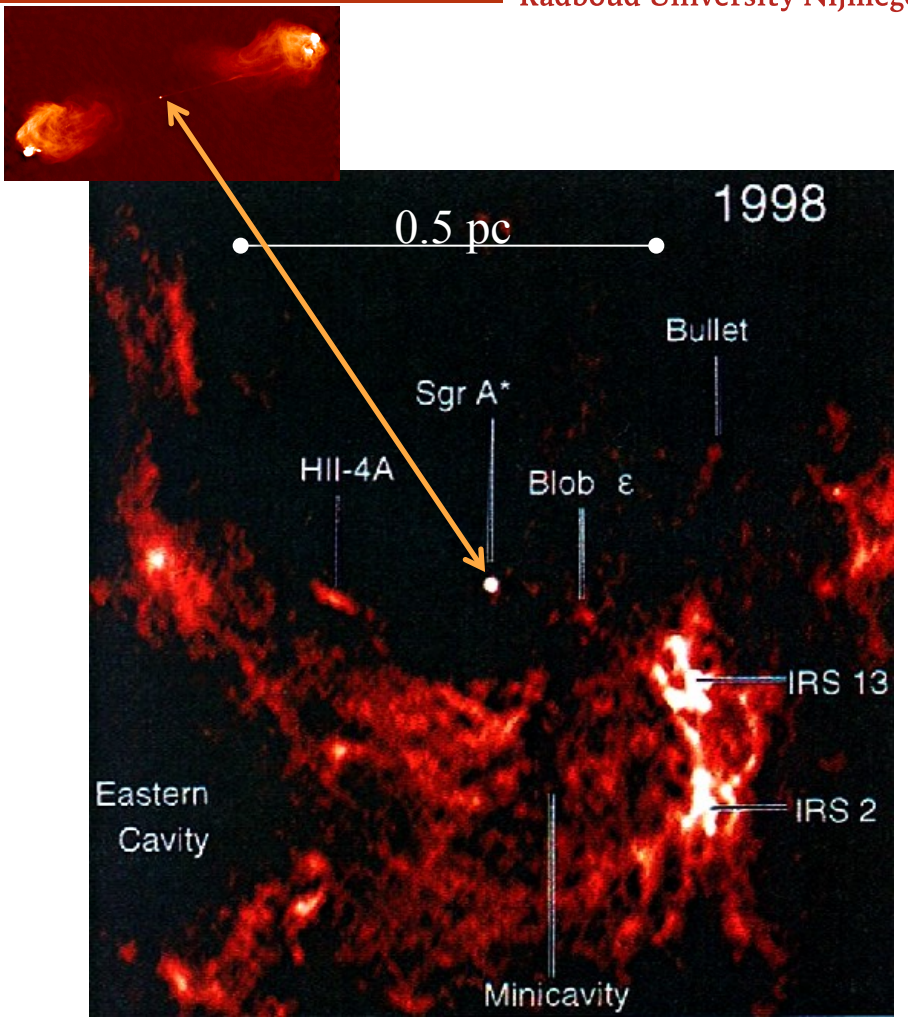


Genzel, Ghez, Eckart ….

Schoedel et al. (2002)

The Galactic Center in the radio: Sagittarius A (Sgr A*)*

- The very center of the Galaxy is a compact bright radio source (Balick & Brown 1974, Ekers et al. 1975).
- It has a flat-to inverted radio spectrum, similar to the nuclei of bright AGN, Quasars, and radio galaxies.
- It's luminosity is 10^{10} times lower then in quasars!



Zhao & Goss (1999)

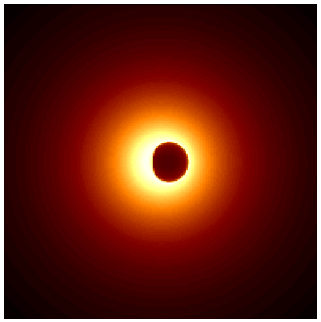
What is Sgr A (radio)*

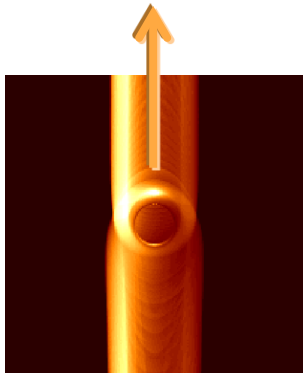
- Long standing question: is the radio emission of Sgr A* produced in
  - an accretion flow (ADAF/RIAF)?

    Melia (1994)
    Narayan et al. (1998), Yuan et al. (2004)
    Quataert & Gruzinov (2000)

  - or a moderately relativistic jet?

    Falcke, Mannheim, Biermann (1993),
    Falcke (1996)
    Falcke & Markoff (2000)





LLAGN Jetmodel: collimated within a few Rg, Γ~2, supersonic, pressure driven expanison into Mach cone of some tens of degrees.

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THE SIMULTANEOUS SPECTRUM OF SAGITTARIUS A* FROM 20 CENTIMETER TO 1 MILLIMETER AND THE NATURE OF THE MILLIMETER EXCESS

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ABSTRACT

We report results of a multiwavelength campaign to measure the simultaneous spectrum of the supermassive black hole candidate Sgr A* in the Galactic center from centimeter to millimeter wavelengths using the Very Large Array, the Berkeley-Illinois-Maryland Array (BIMA), the Nobeyama 45 m, and the Institut de Radioastronomie Millimetrique (IRAM) 30 m telescopes. The observations confirm that the previously detected millimeter excess is an intrinsic feature of the spectrum of Sgr A*. The excess can be interpreted as and effect of the presence of an ultracompact component of relativistic plasma with a size of a few Schwarzschild radii near the black hole. If so, Sgr A* might offer a unique possibility to image the putative black hole against the background of this component with future millimeter VLBI experiments.

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Falcke, Goss, Matsuo et al. (1998)

$$R \sim 1.5 \times 10^{12}\ \mathrm{cm}\ k^{-1/17} \left(\frac{S_{\nu_{max}}}{3.5\ \mathrm{Jy}}\right)^{8/17} \times \left(\frac{\nu_{max}}{10^{12}\ \mathrm{Hz}}\right)^{-16/51} \left(\frac{\nu_{ssa}}{100\ \mathrm{GHz}}\right)^{-35/51}$$

$\sim R_s$

S_ν [Jy]

10^{0} 10^{-1} 10^{-2}

10^{10} 10^{11} 10^{12} 10^{13} 10^{14}

ν [Hz]

Spectrum: Melia & Falcke (2001, ARA&A)

Sgr A: Size of radio source*

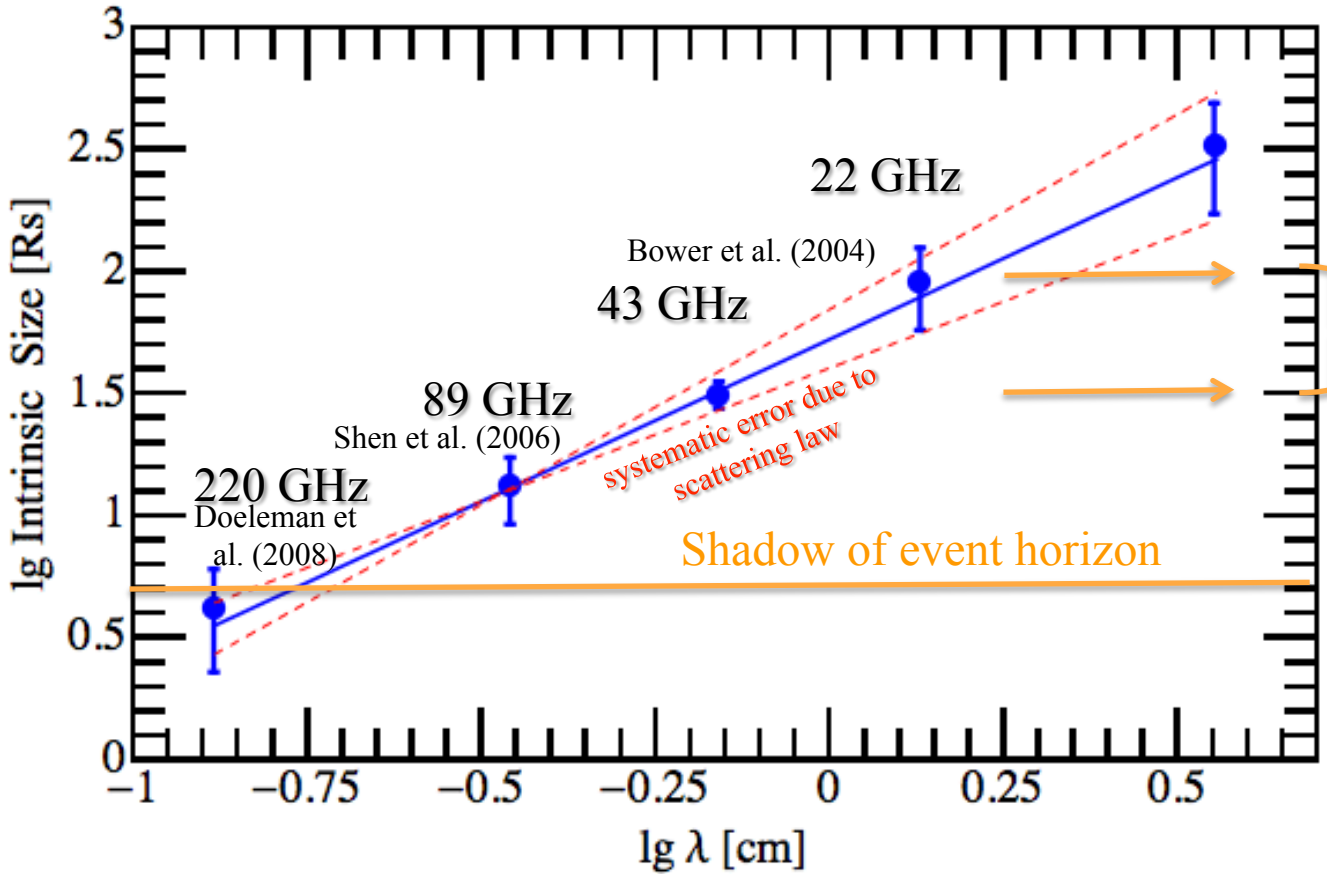
Size in Schwarzschild radii

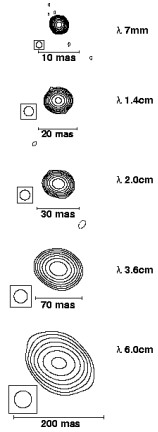
300 Rs

30 Rs

3 Rs

Size after subtracting λ^2 scattering-law





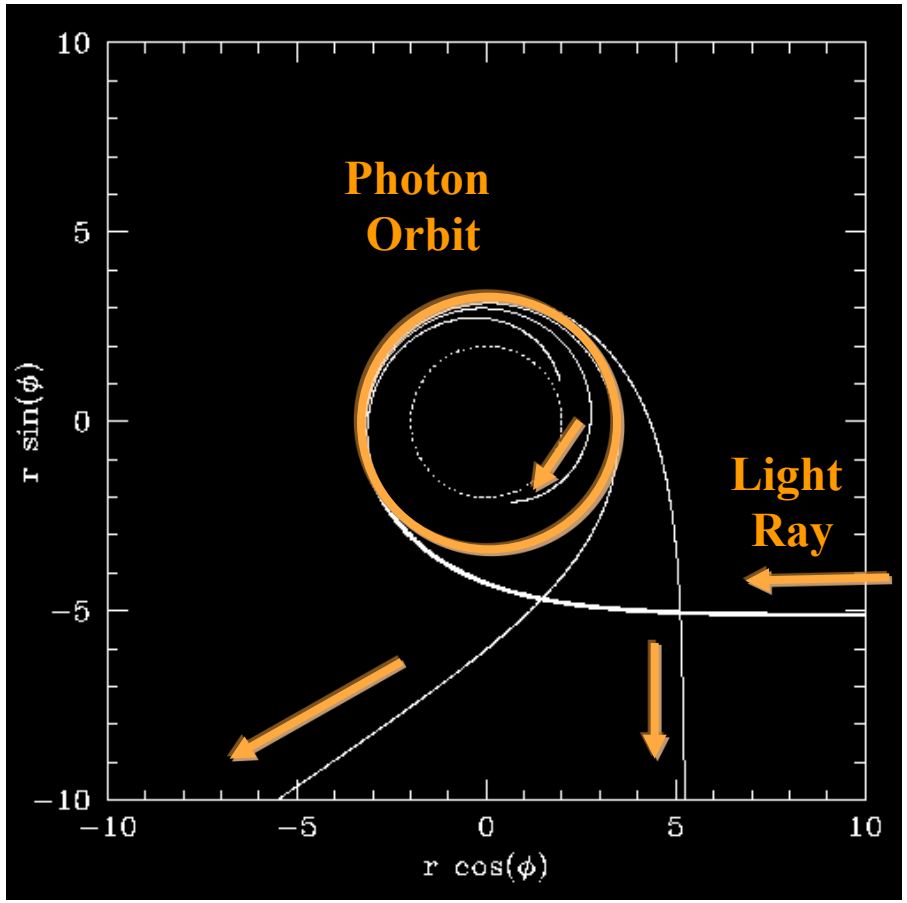
30 light minutes
lag = 20 minutes

⇒ Relativistic outflow

updated from Falcke, Markoff, Bower (2009)

Ray-Tracing in the Kerr Metric

- In Sgr A* there is optically thin emission on event horizon scales!
- Photon orbits are bent due to the black hole.
- At R~4-5R_g orbits can become circular – closed "photon orbit".
- Closer orbits end in event horizon.
- This produces a "shadow" in the emitting region around the black hole, surrounded by a circular photon-ring



(Bardeen 1973, Falcke et al. 2000, de Vries 2000)

The Shadow of a Black Hole

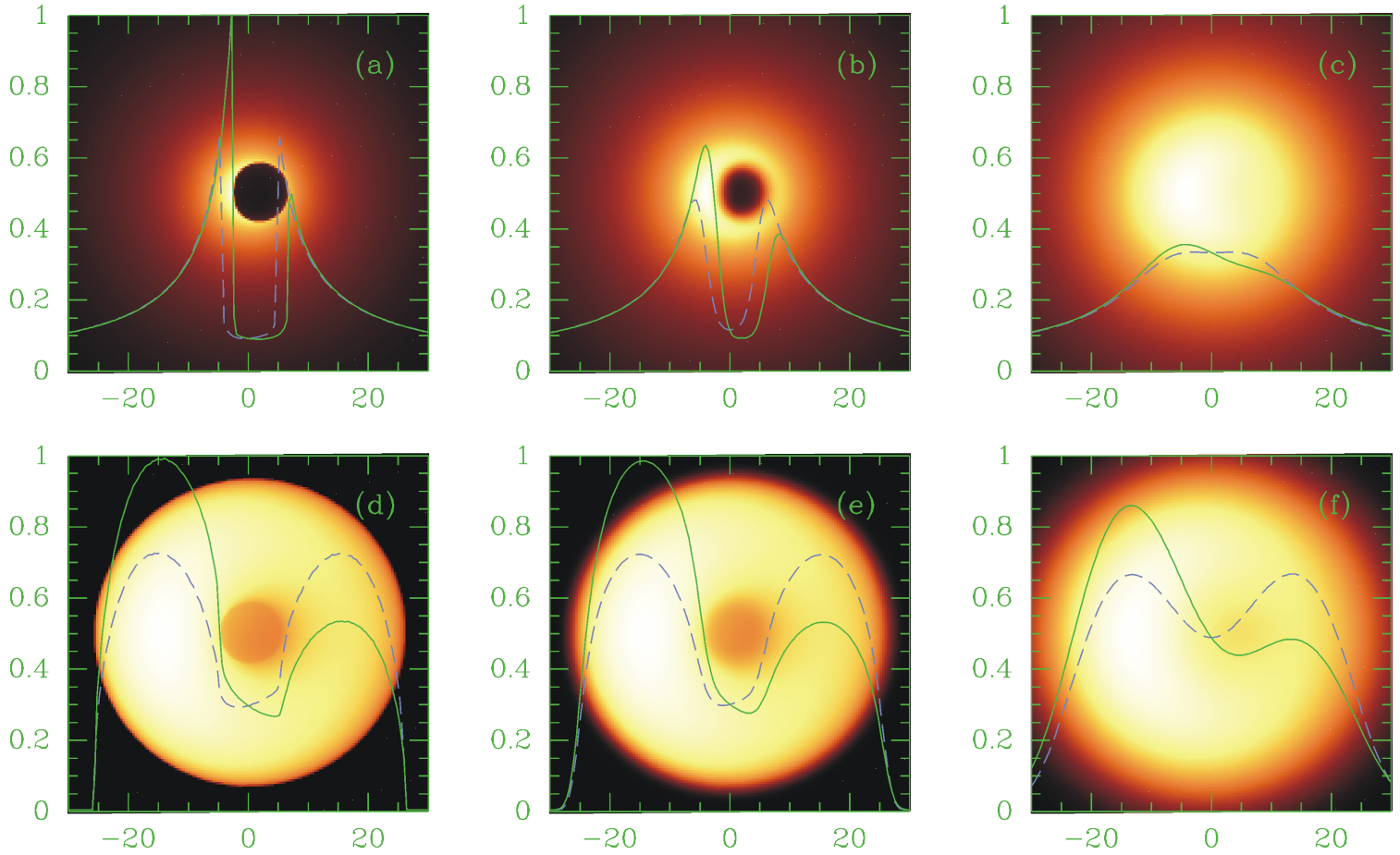
GR Model | λ0.6mm VLBI | λ1.3mm VLBI

a=0.998

$I=r^{-2}$

a=0

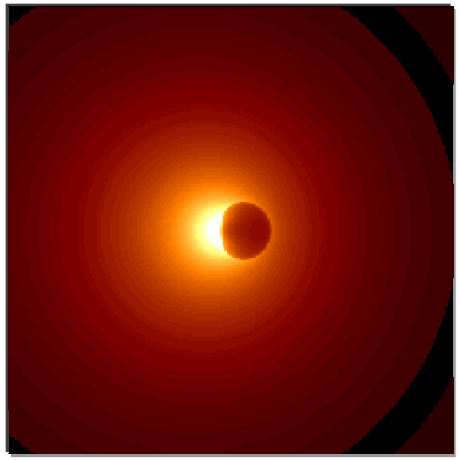
I=const

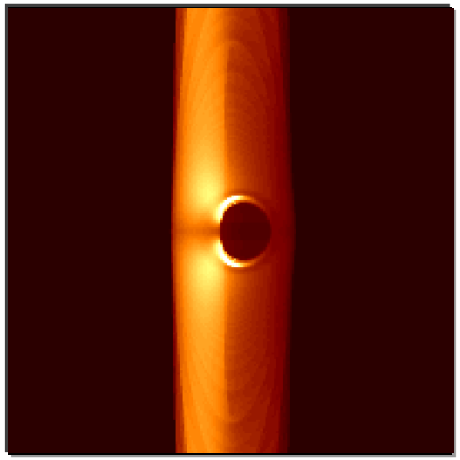


(Falcke, Melia, Agol 2000)

Varying the Models

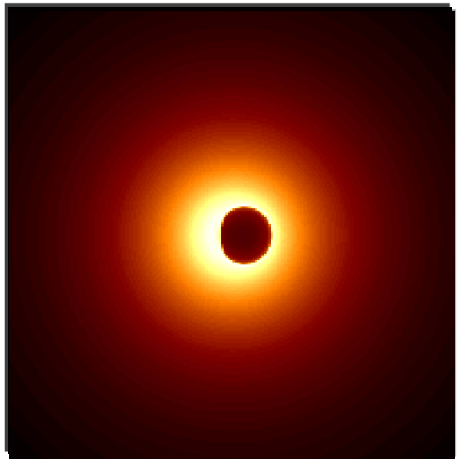
<u>Infall:</u>
a=0.998
i=90º
$I=r^{-2}$

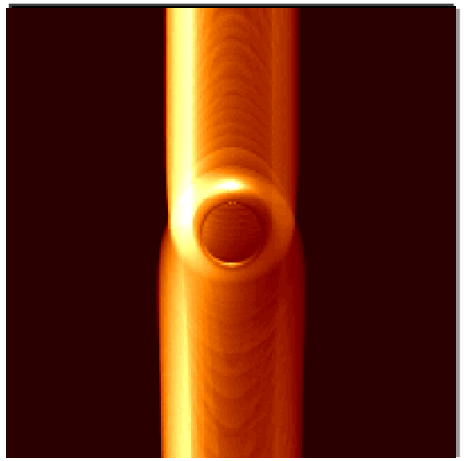




<u>Jet:</u>
a=0.998
i=90º
I=hollow

<u>Infall:</u>
a=0
i=90º
$I=r^{-2}$

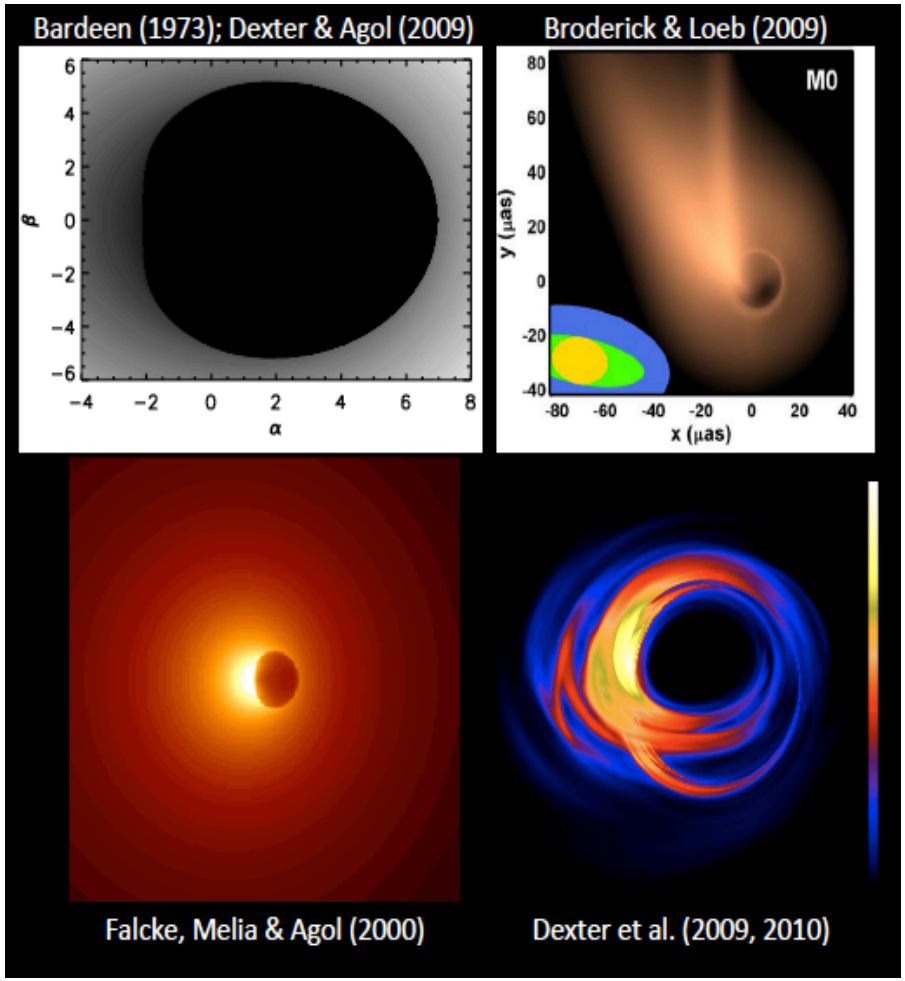


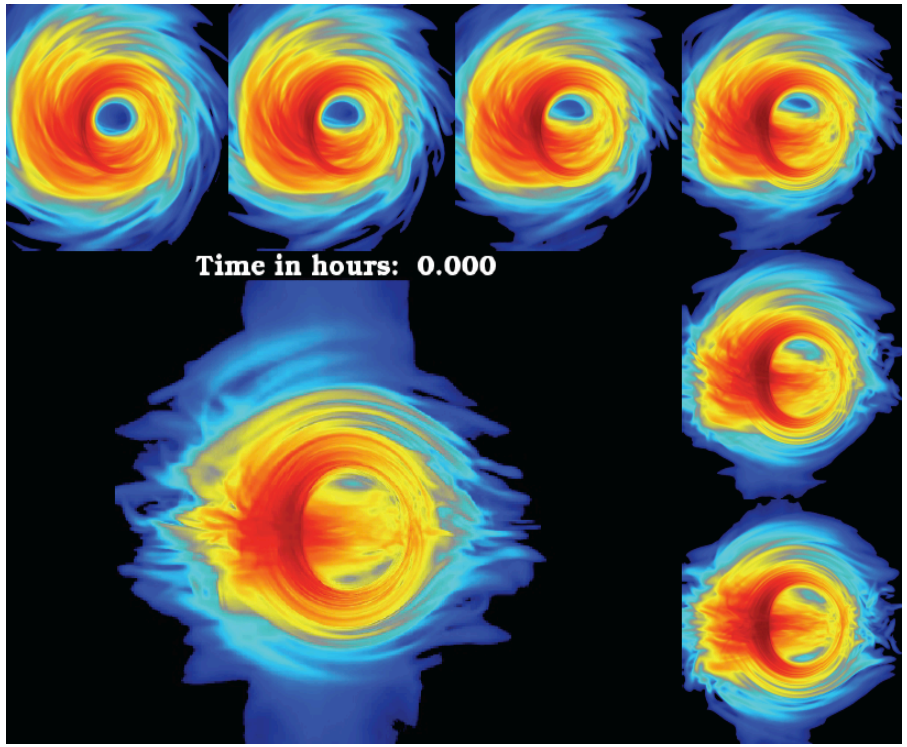


<u>Jet:</u>
a=0
i=45º
I=hollow

(Falcke, Melia, Agol)

Shadow Industry

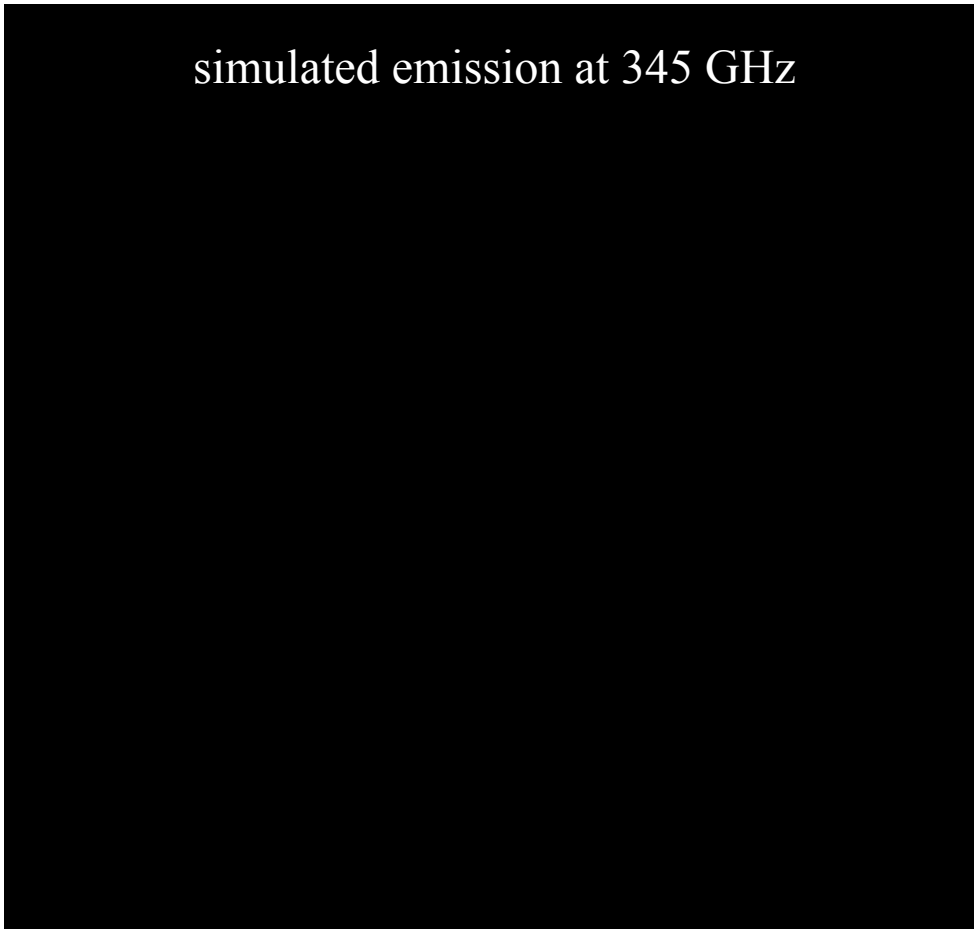




Dolence

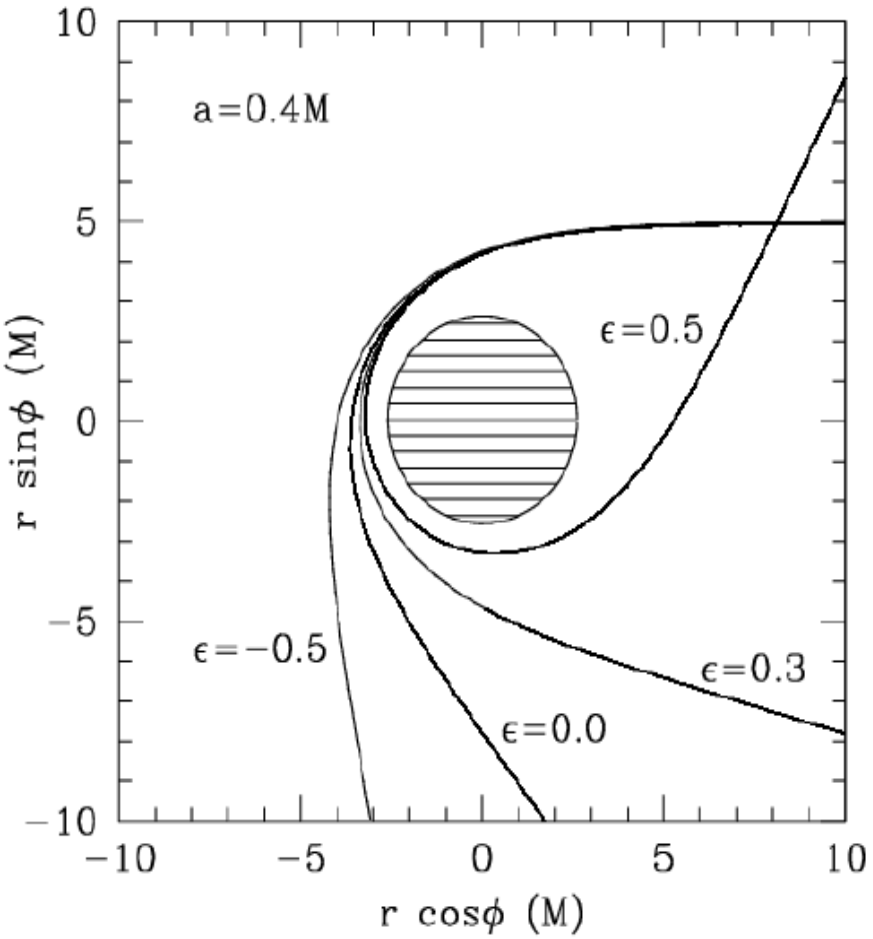
3DGRMHD

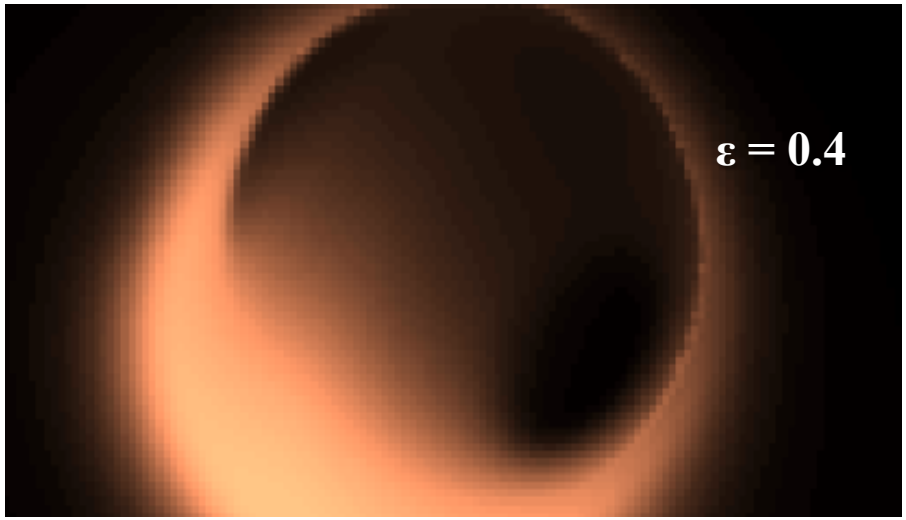
3D general relativistic magnetohydrodynamic simulations with radiation transfer and ray tracing in the Kerr metric.

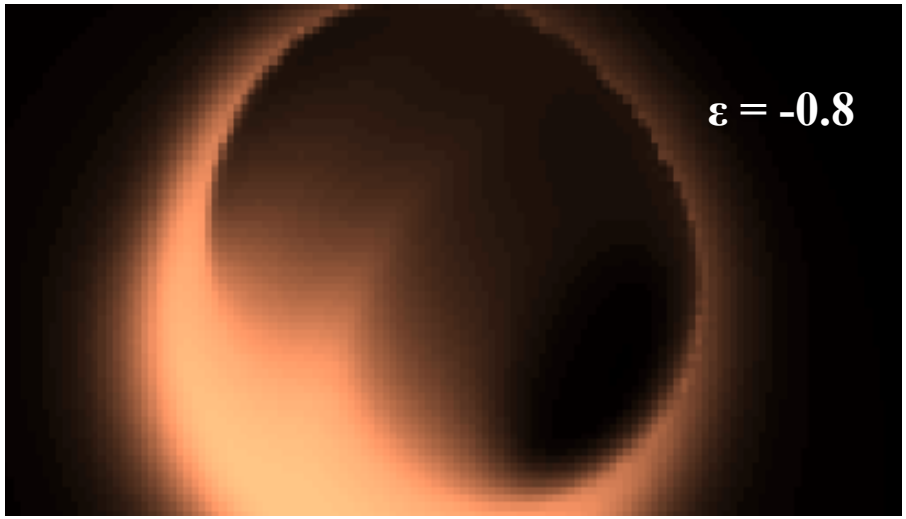


Gammie et al. (2009)

Testing the No-Hair Theorem - Quadropole Effects on Shadow



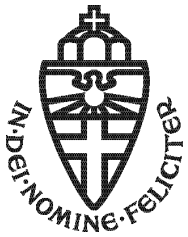




Johannsen & Psaltis 2010, 2011, ApJ

mm-VLBI with ALMA - a global super-resolution radio camera

350 GHz VLBI images from 2D MHD simulations



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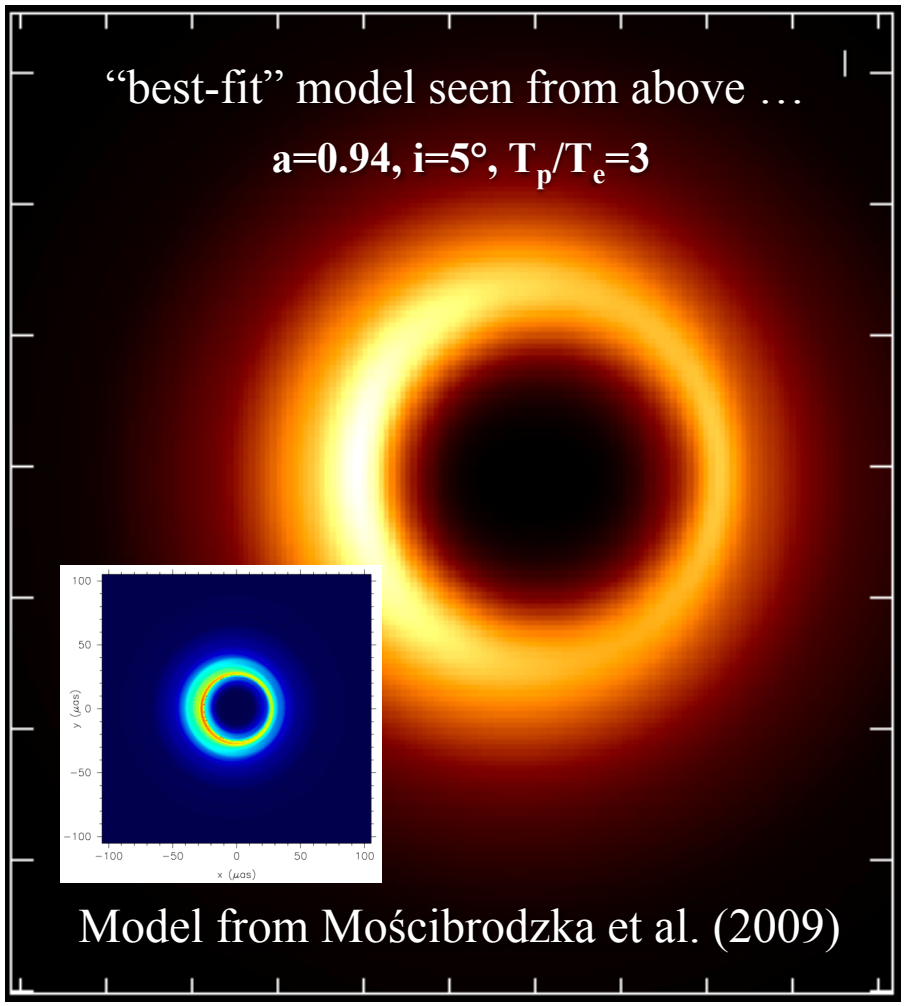
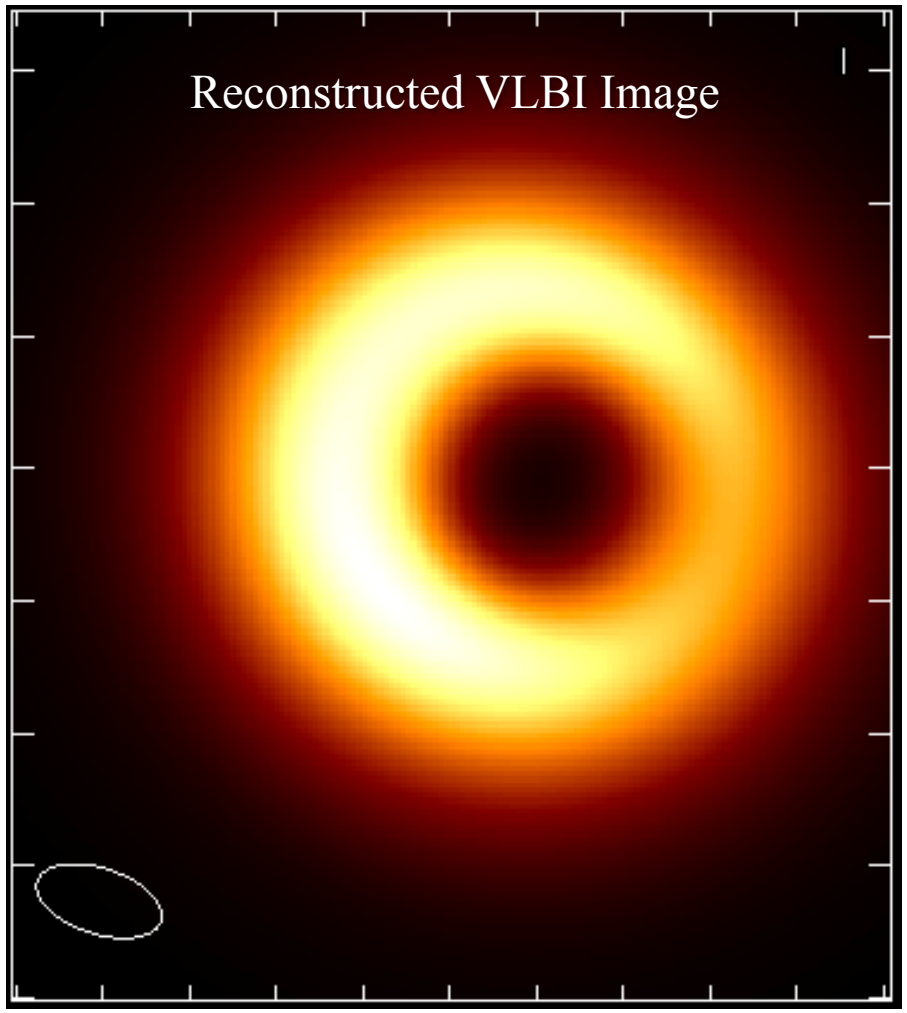
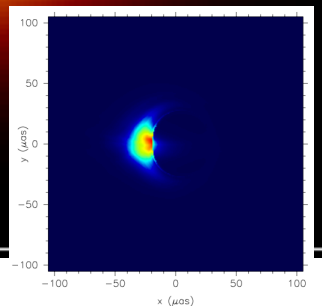




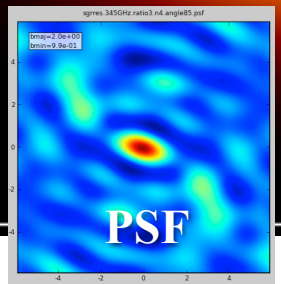
350 GHz VLBI images from 2D MHD simulations

Scatter-Broadened best-fit Model
powerlaw scale

a=0.94, i=85°, T_p/T_e=3



Reconstructed image



Dynamic range
of ring: 200:1

Tracing orbiting blobs around Sgr A with just three Antennas*

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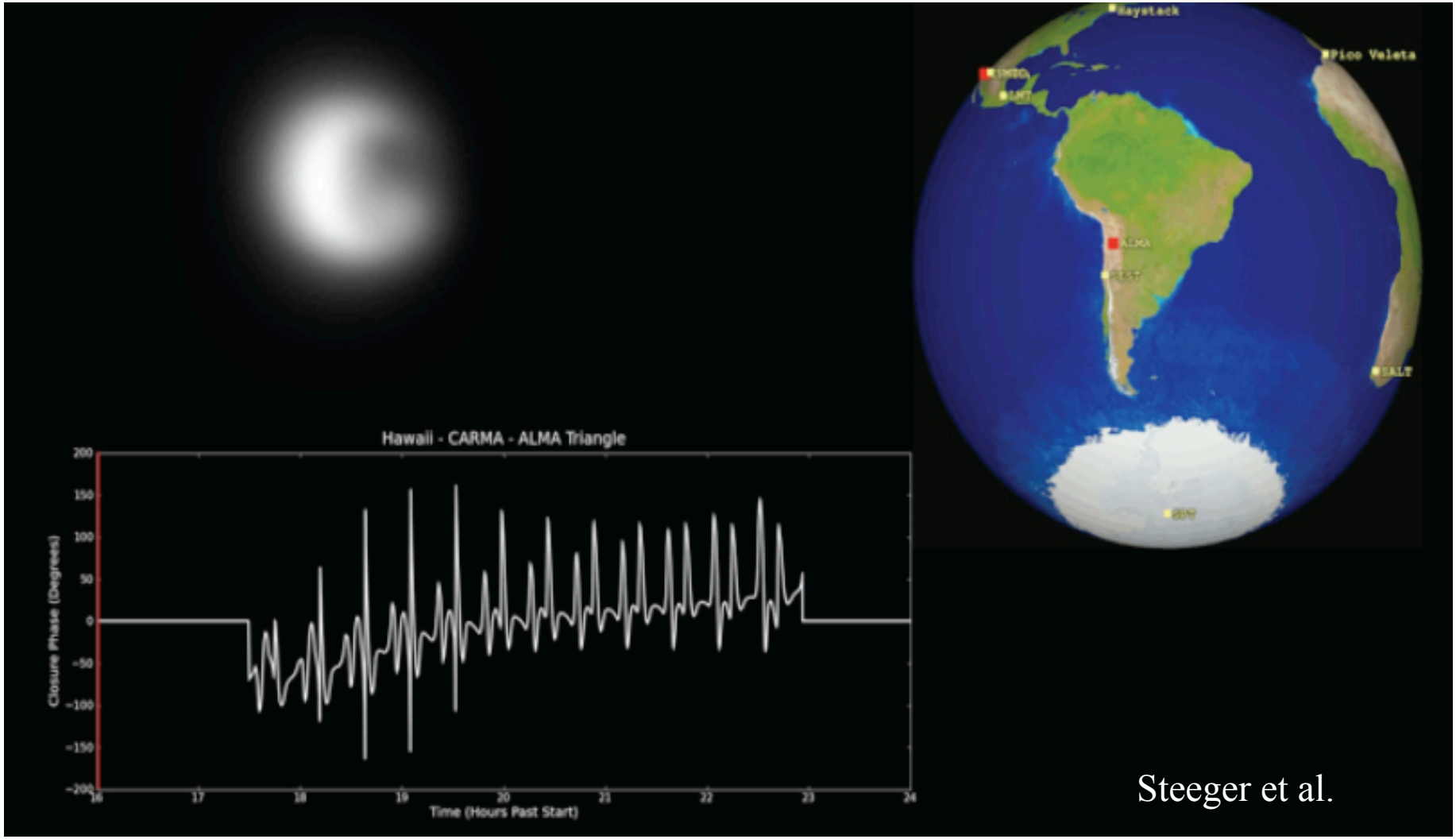
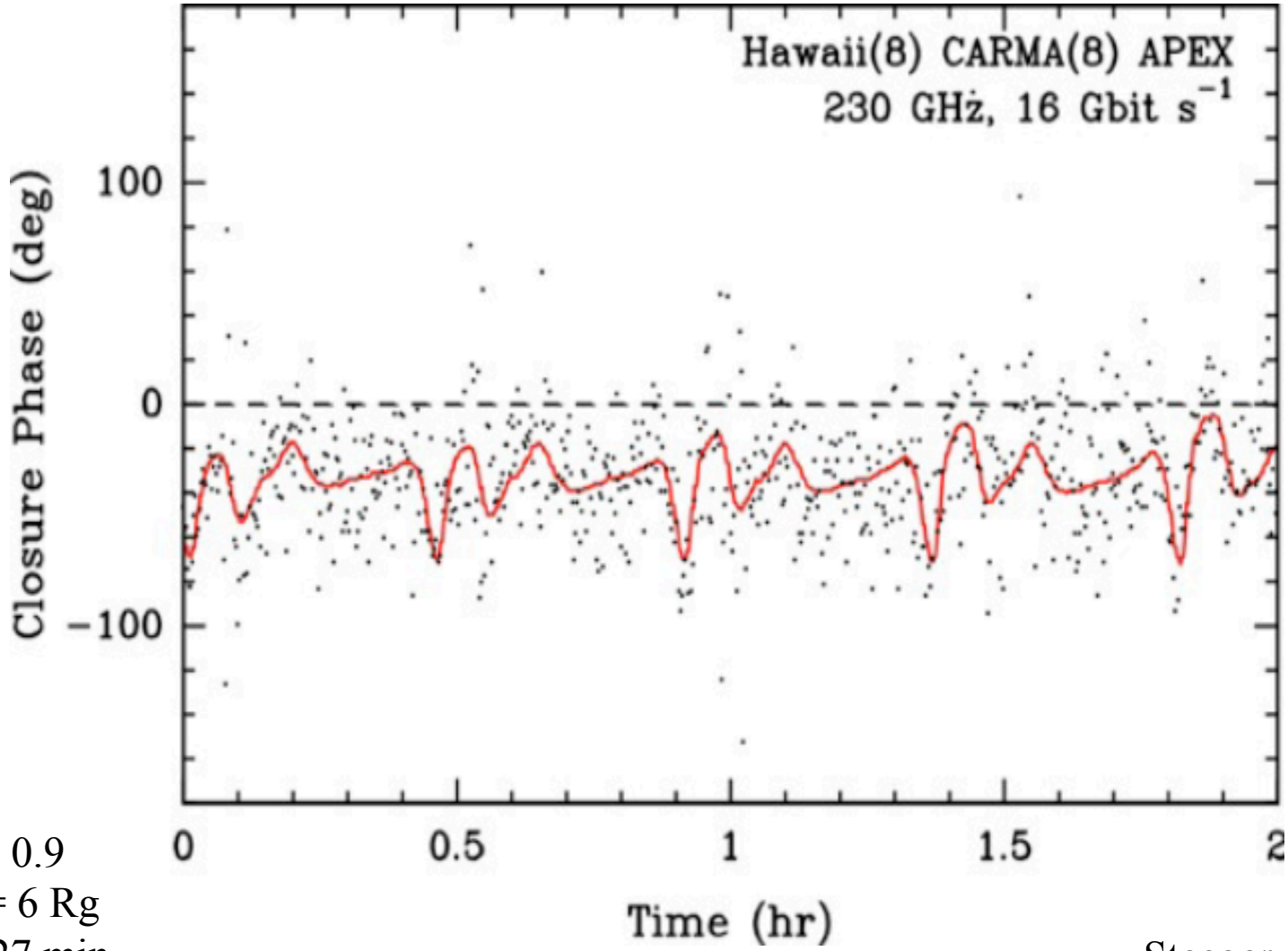


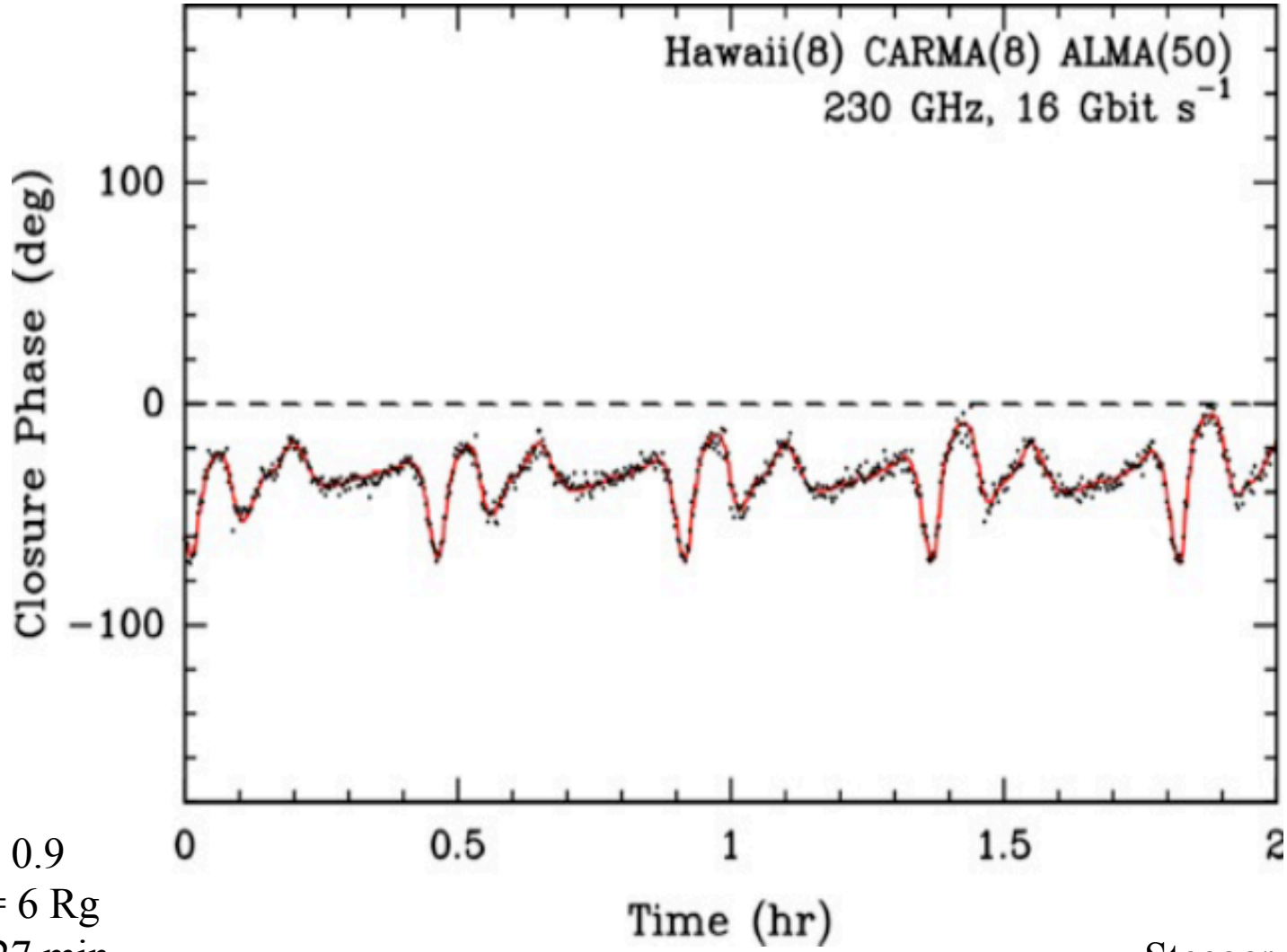
Tracing orbiting blobs around Sgr A with just three Antennas*



Spin = 0.9
Radius = 6 Rg
Period =27 min

Steeger et al.

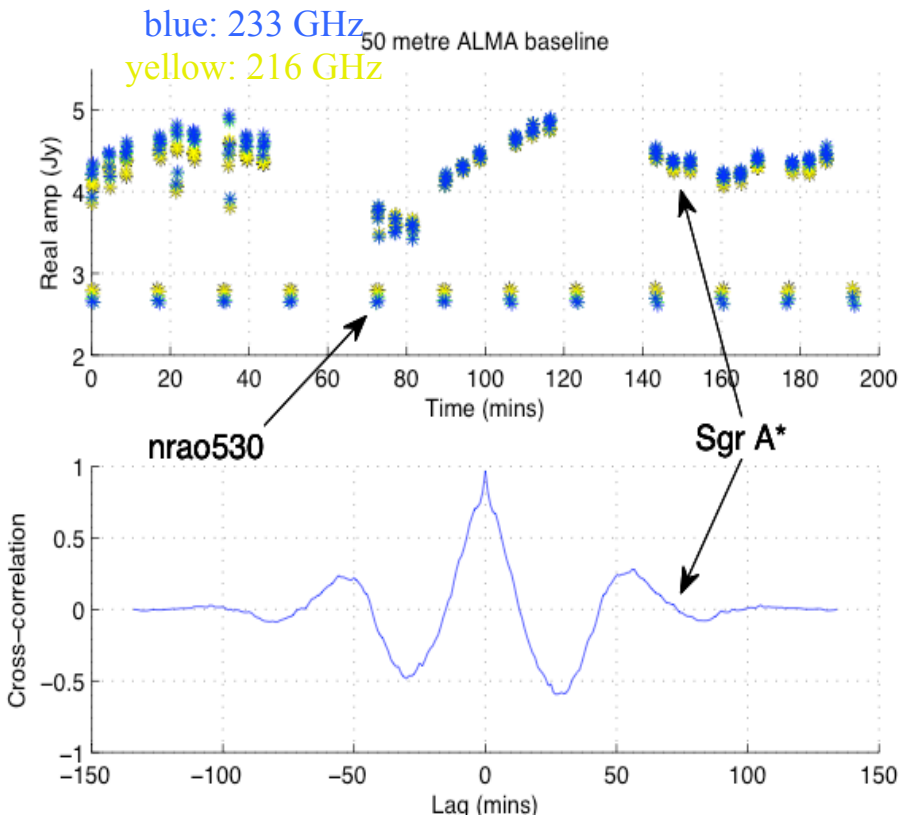
Tracing orbiting blobs around Sgr A with just three Antennas*

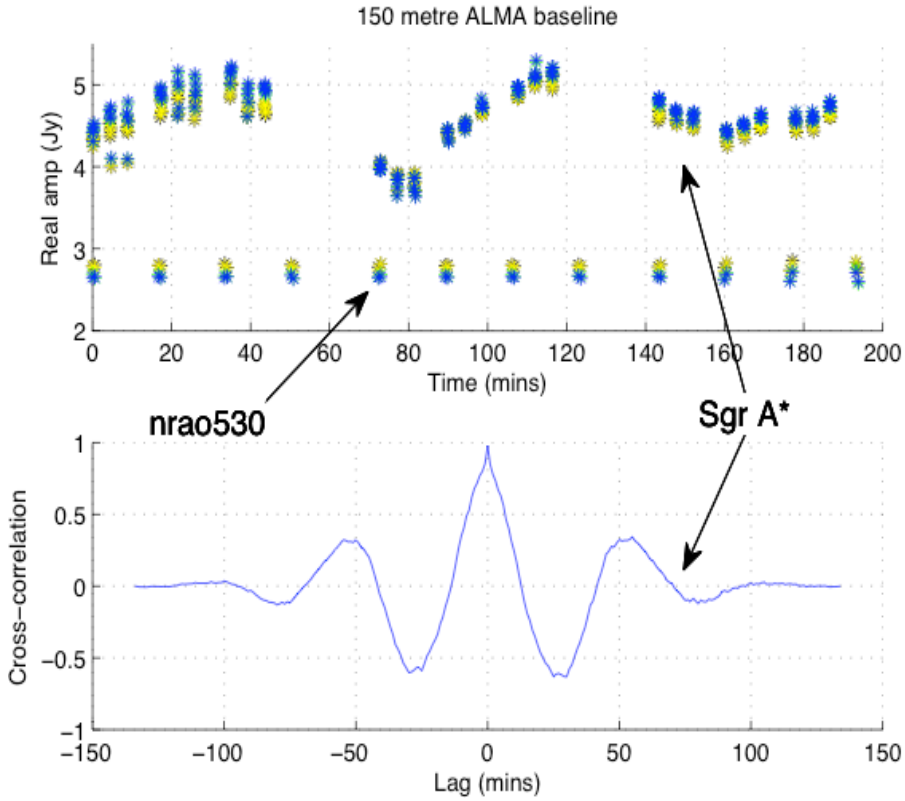


Spin = 0.9
Radius = 6 Rg
Period =27 min

Steeger et al.

Alma Science Verification Data

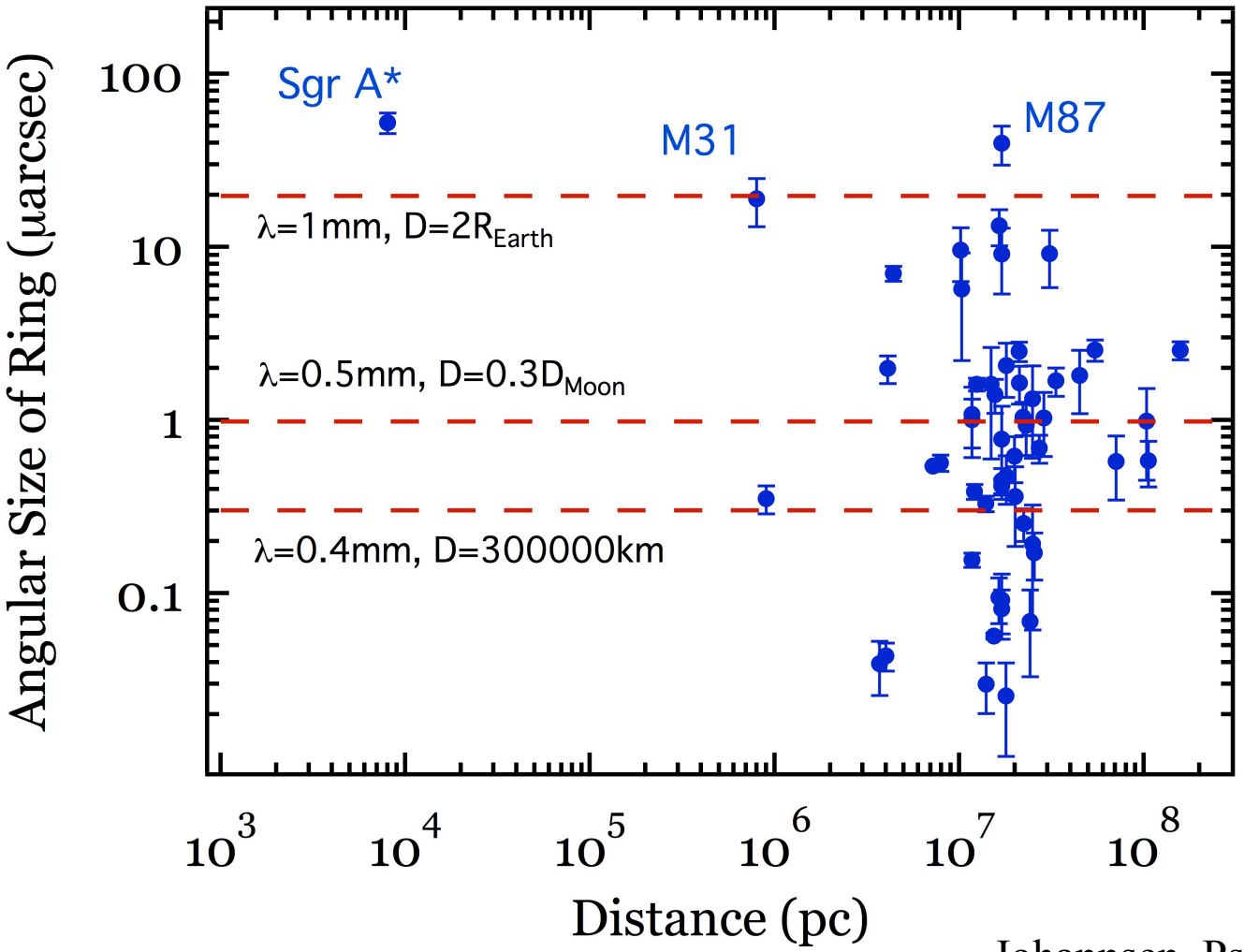




ALMA cycle 0 campaign underway …

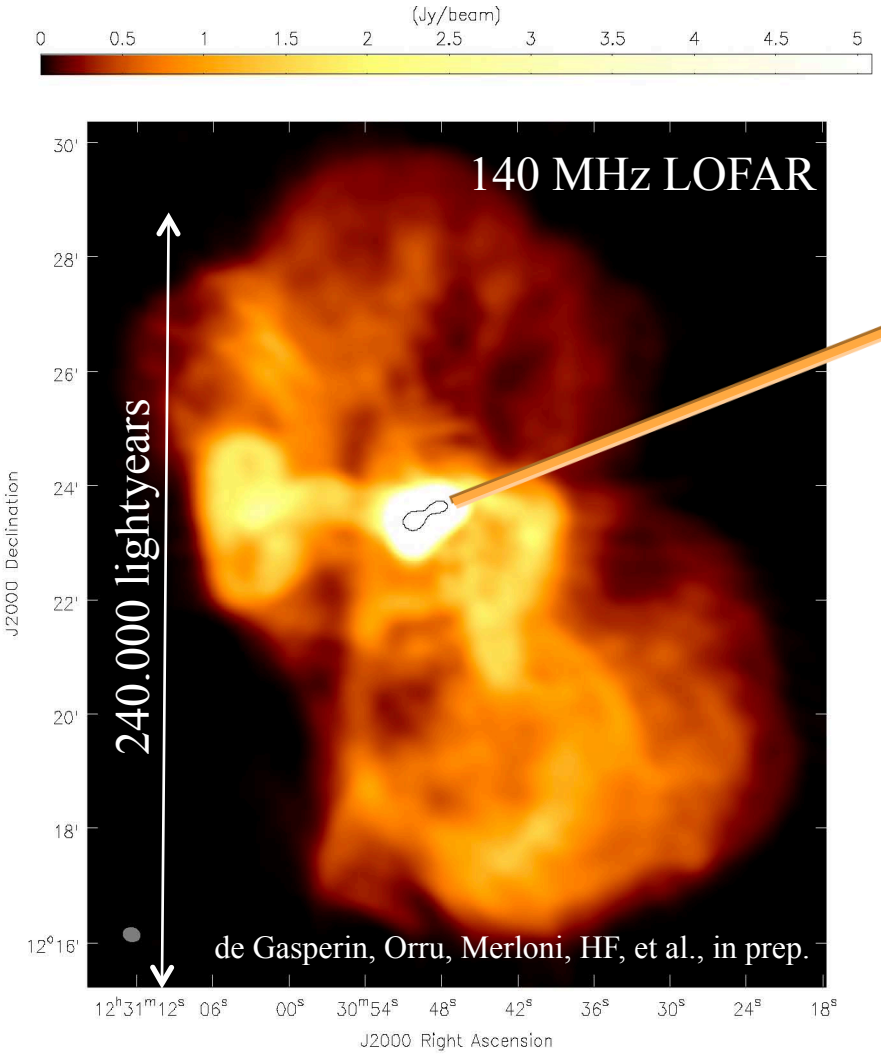
A. Rushton,….

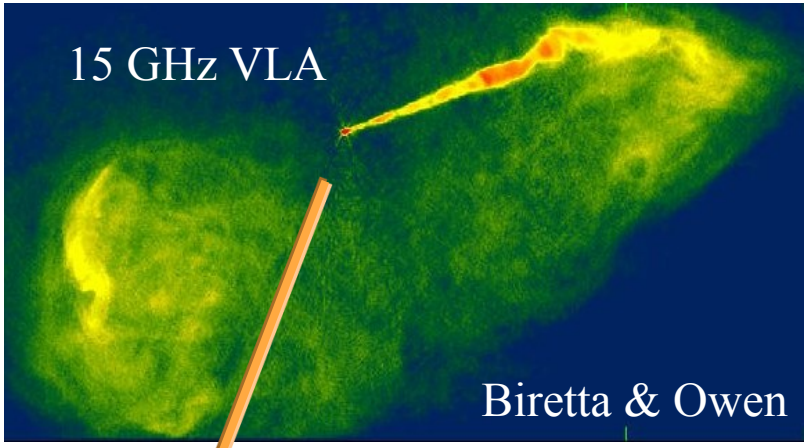
What else to look at …

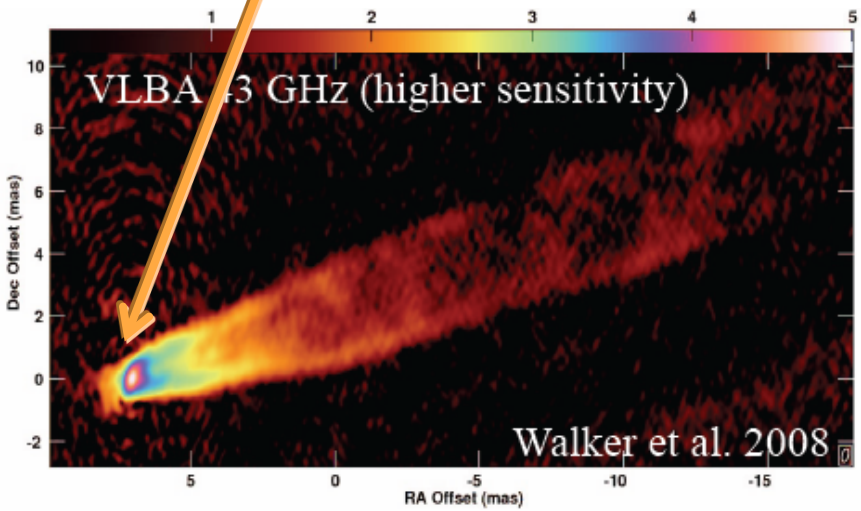


Johannsen, Psaltis et al. (2012)

The Supermassive Black Hole and Jet in M87

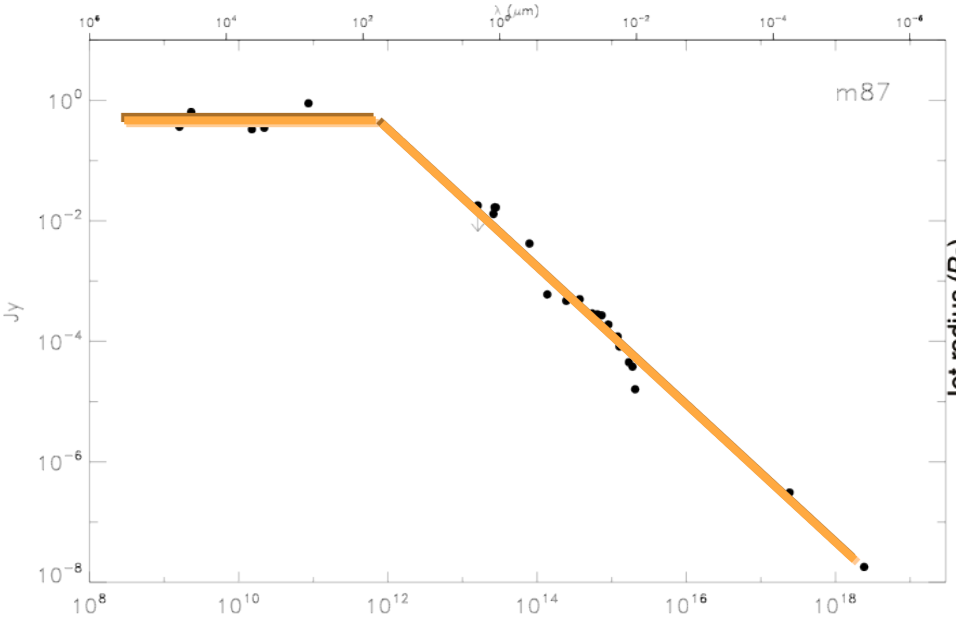


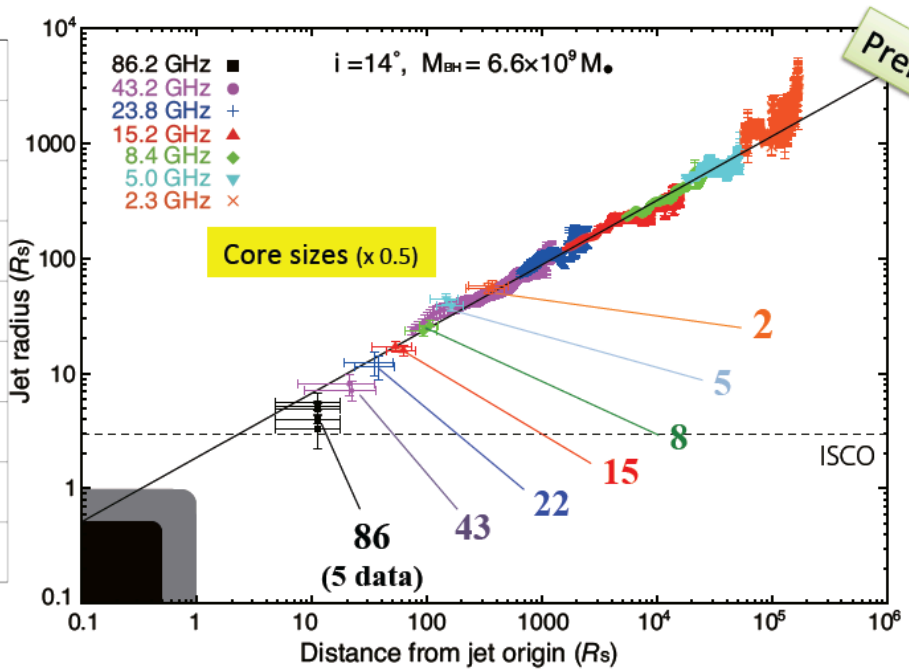




Size and Spectrum of M87

Spectrum of M87 core





Almudena Prieto

Hada et al. (2012)

Conclusions

- mmVLBI of Sgr A* (and M87) offers a unique and very realistic chance to image the black hole shadow for the very first time
  - Precise mass of BH known
  - optically thin radio emission on event horizon scales confirmed
  - VLBI technique works in principle
- This will be sufficient evidence for the existence of an event horizon and allow fundamental tests of GR and variants thereof.
- We will be able to study accretion disk and jet physics where it really matters – near the BH.
- There are risks:
  - Unknown source structure may complicate identification of shadow
  - Accretion rate increases due to cloud falling in by 2013 (Gillessen et al. 2012) - emission might become optically thick
  - Non-ALMA telescope go out of business in next few years
  - We don't get our act together …
- 10% << Chance of success < 100% - we should take that risk!