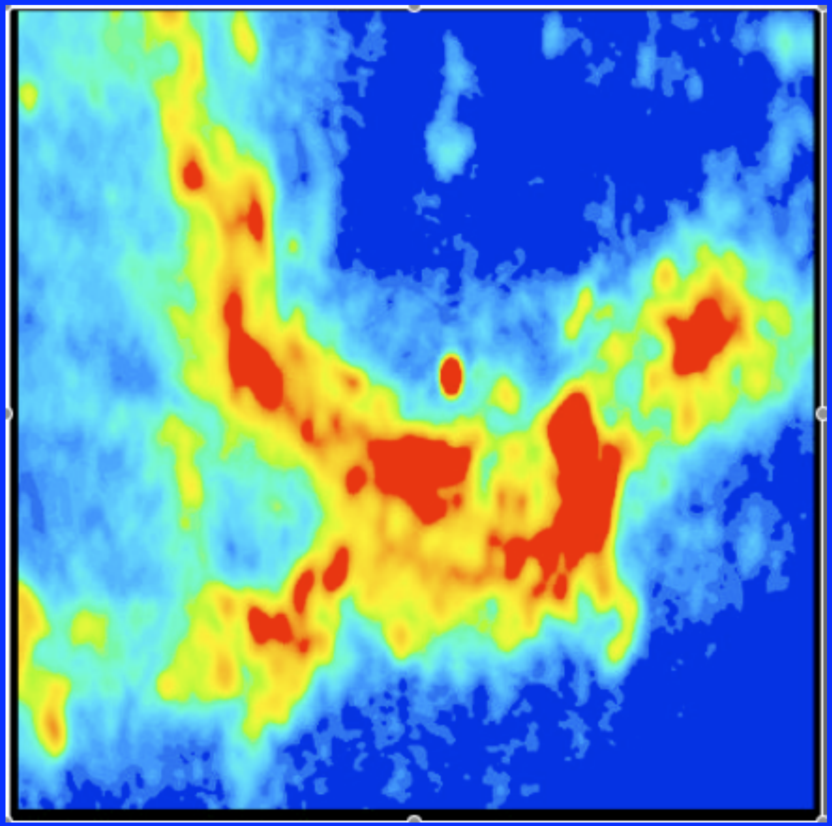
VLBI with the SMA: Observing an Event Horizon



Sheperd Doeleman
MIT Haystack Observatory

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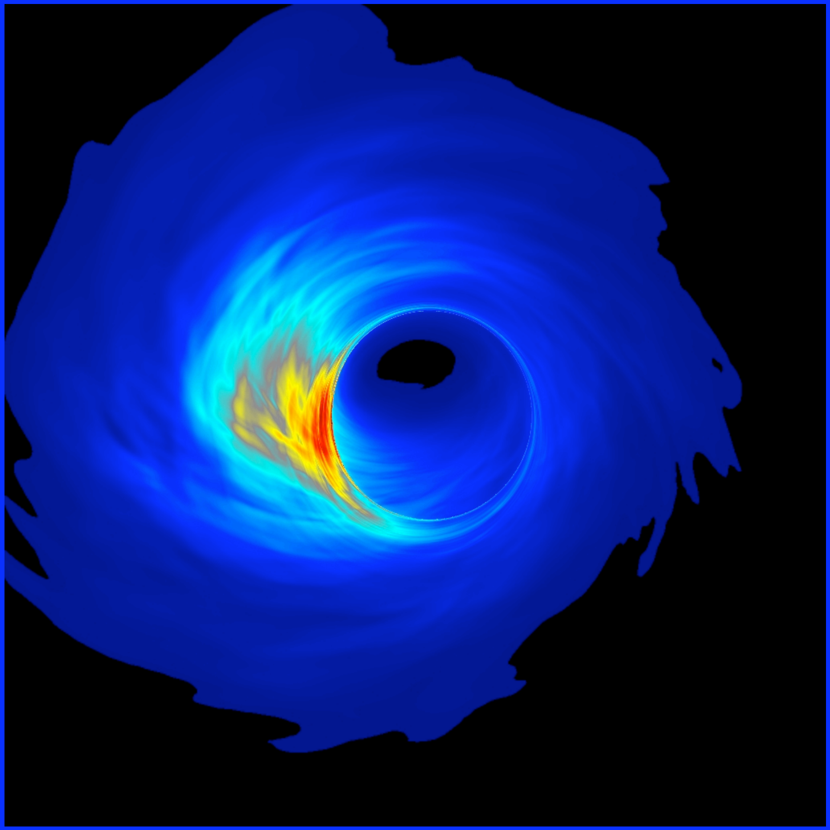

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SgrA*: Best Case for a SMBH

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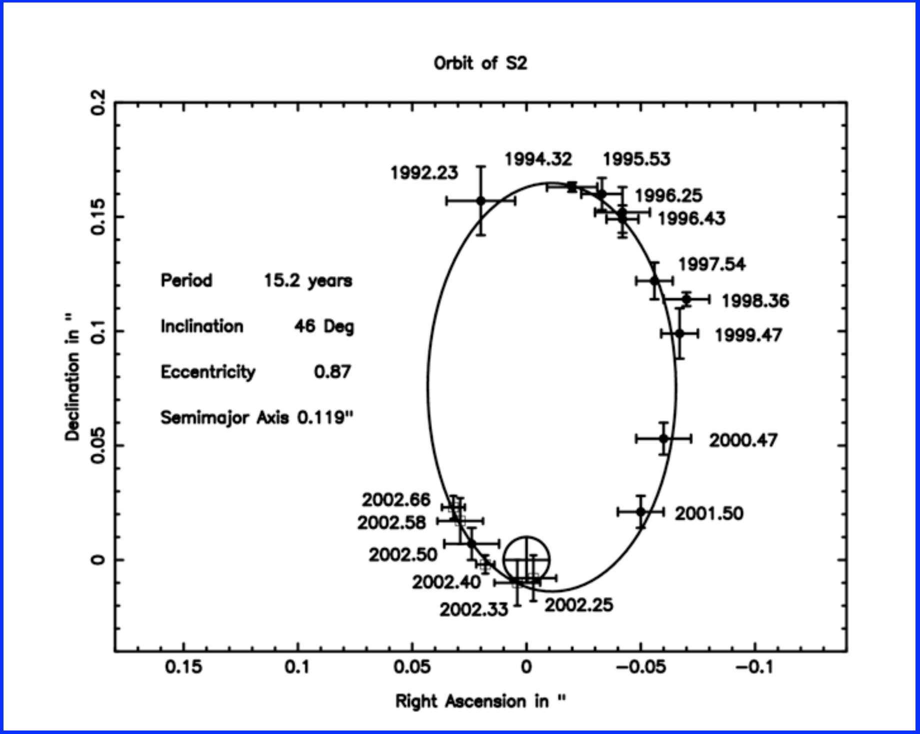
- Stellar orbits approaching within 45 AU.



Schoedel et al 2002

SgrA*: Best Case for a SMBH

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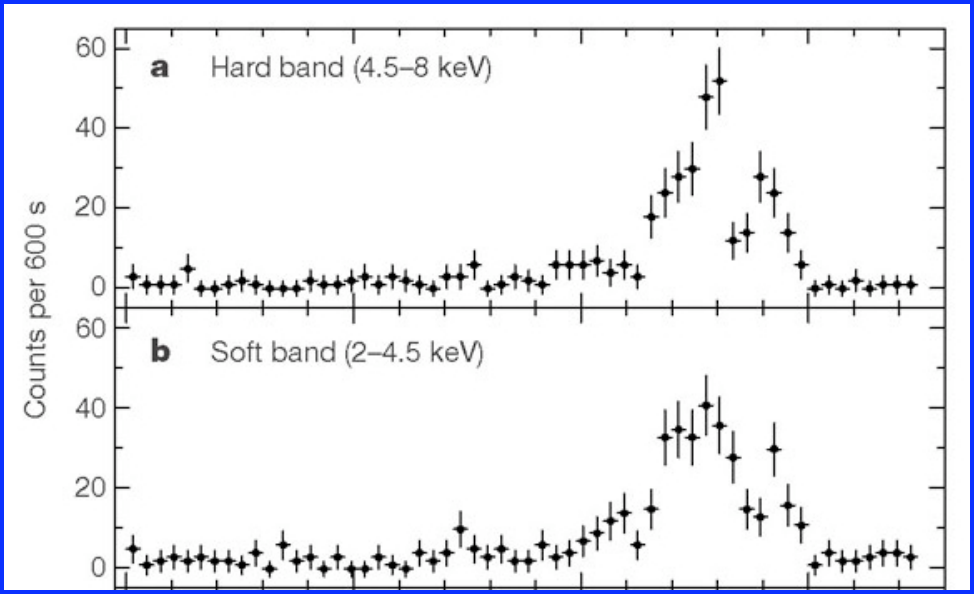

Baganoff et al 2001

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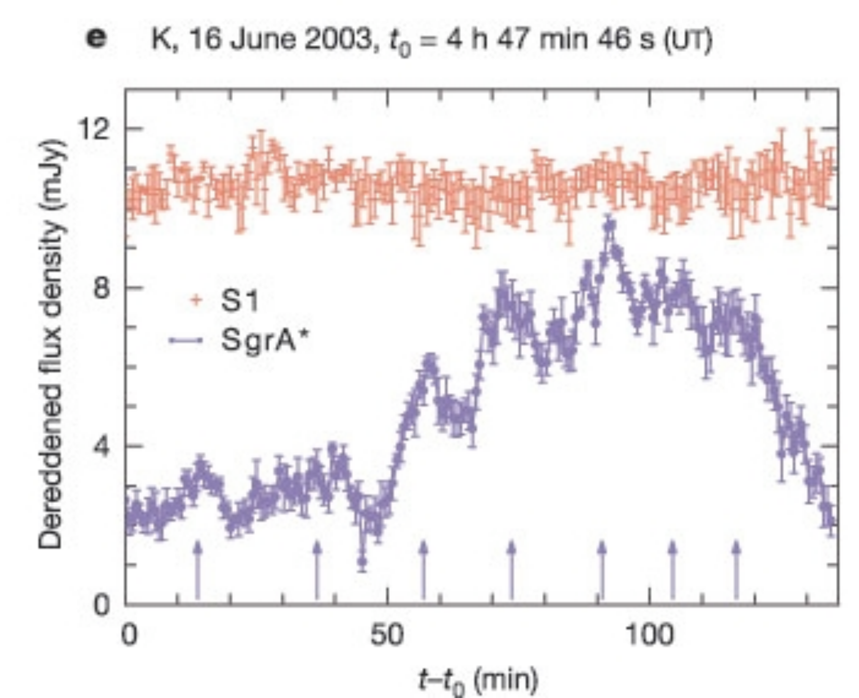
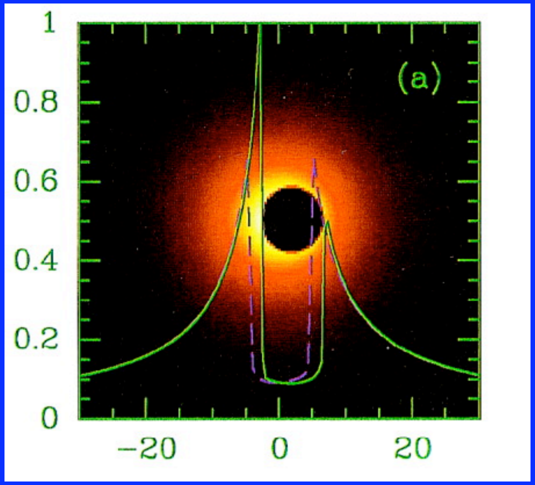
- Proper motions < 1km/s: M>10^5 Msol (Backer & Sramek 1999, Reid & Brunthaler 2004)
- Short time scale X-ray flares (300 sec rise).
- IF flares with modulation (a>0).

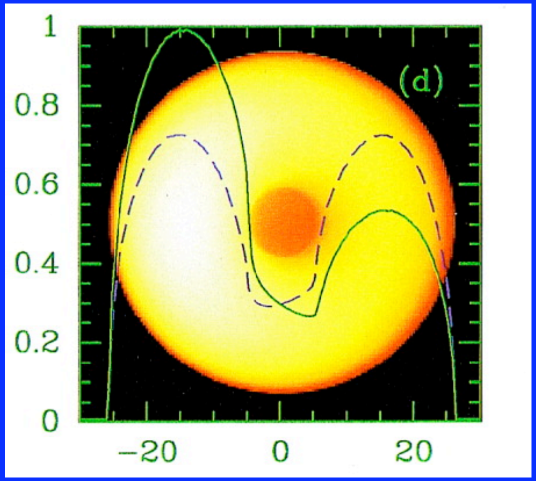


VLT: Genzel et al 2003

Resolving Rsch-scale structures



Spinning (a=1)

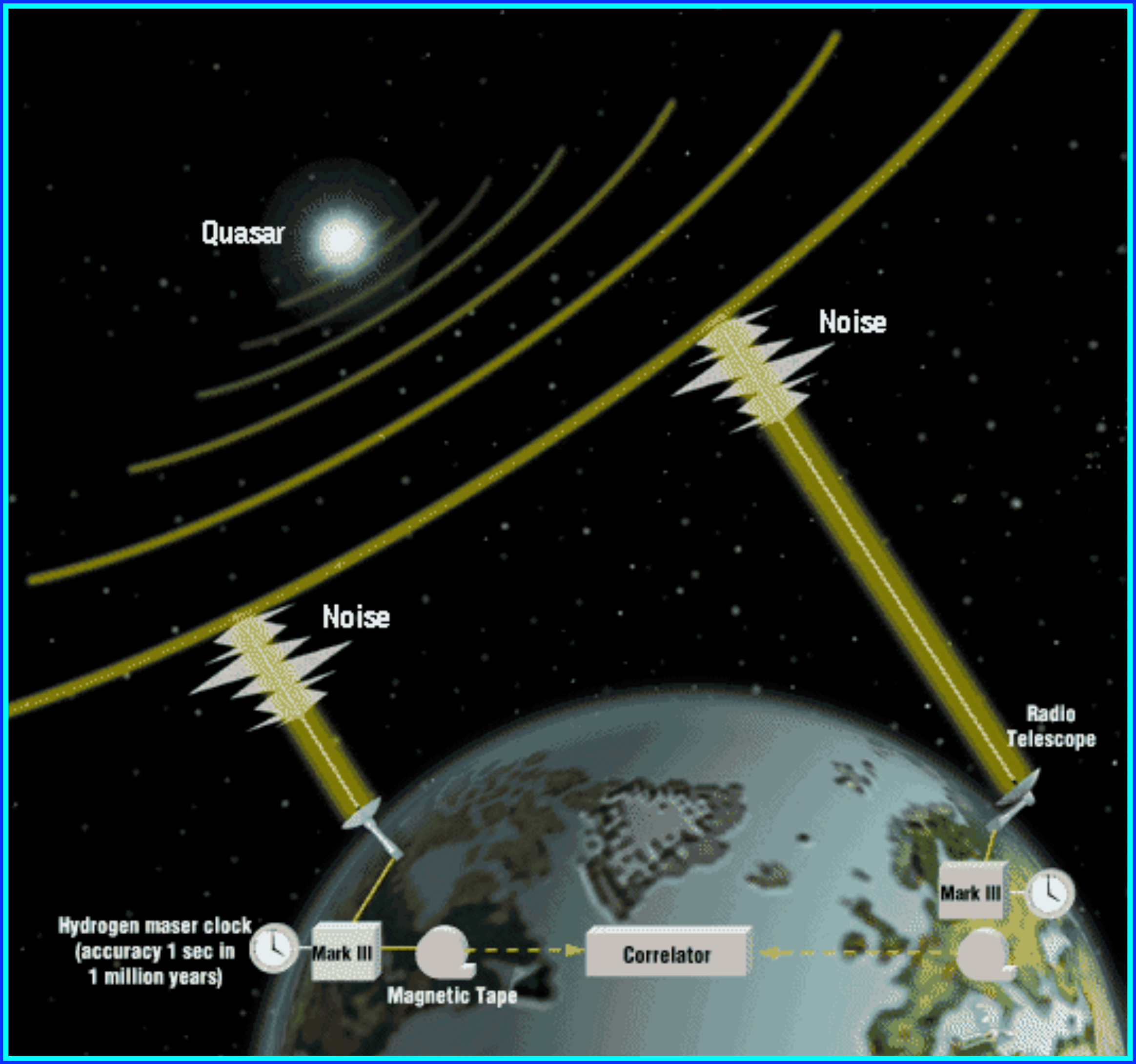


Non-spinning (a=0)

Falcke
Melia
Agol

- SgrA* has the largest apparent Schwarzschild radius of any BH candidate.
- Rsch = 10μas
- Shadow = 5.2 Rsch (non-spinning)
  = 4.5 Rsch (maximally spinning)

Short Wavelength VLBI



Resolution:

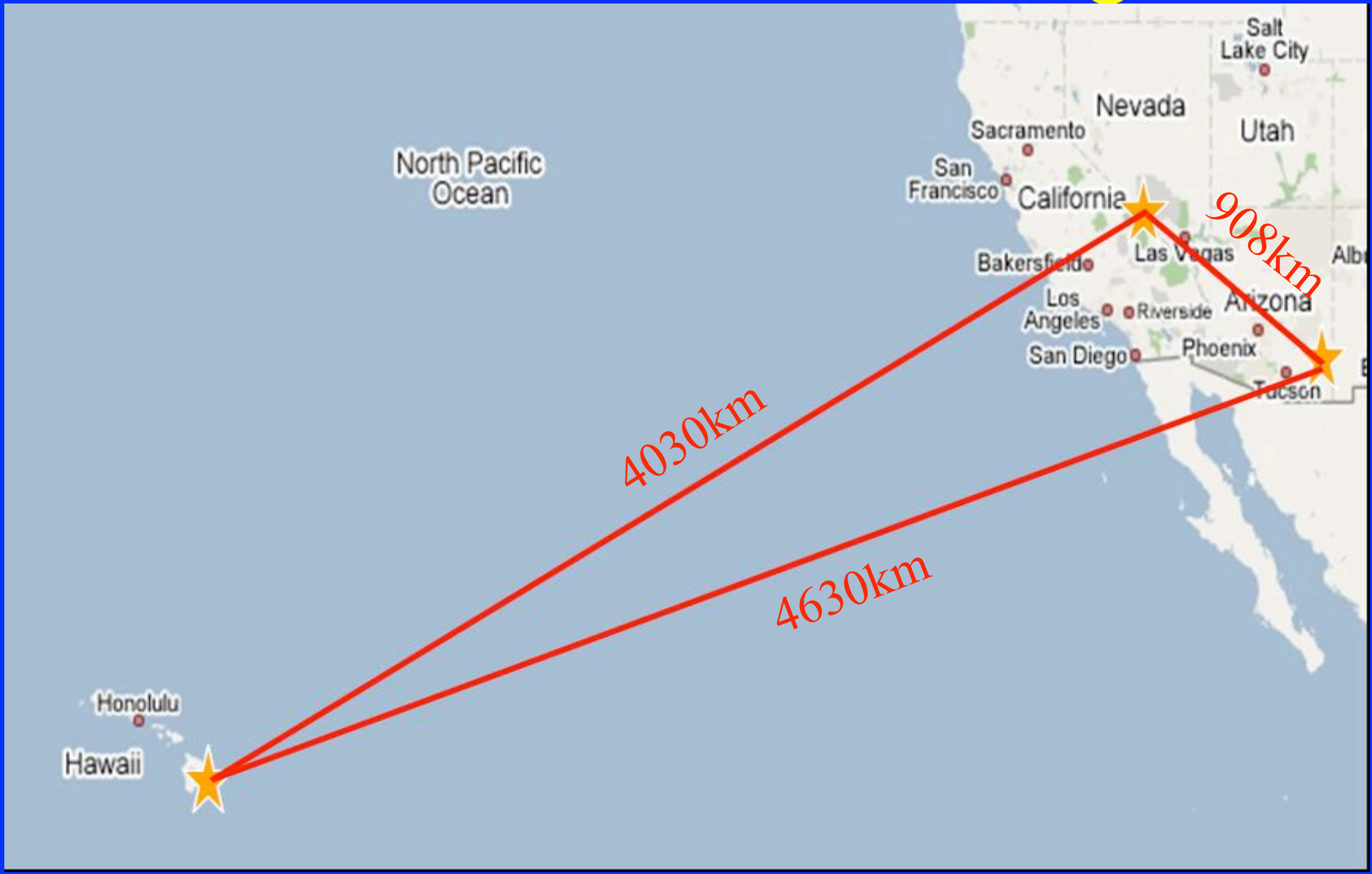
λ/D (cm) ~ 0.5 mas
λ/D (1.3mm) ~ 30 μas
λ/D (0.8mm) ~ 20 μas

ISM Scattering:

Θscat ~ λ^2

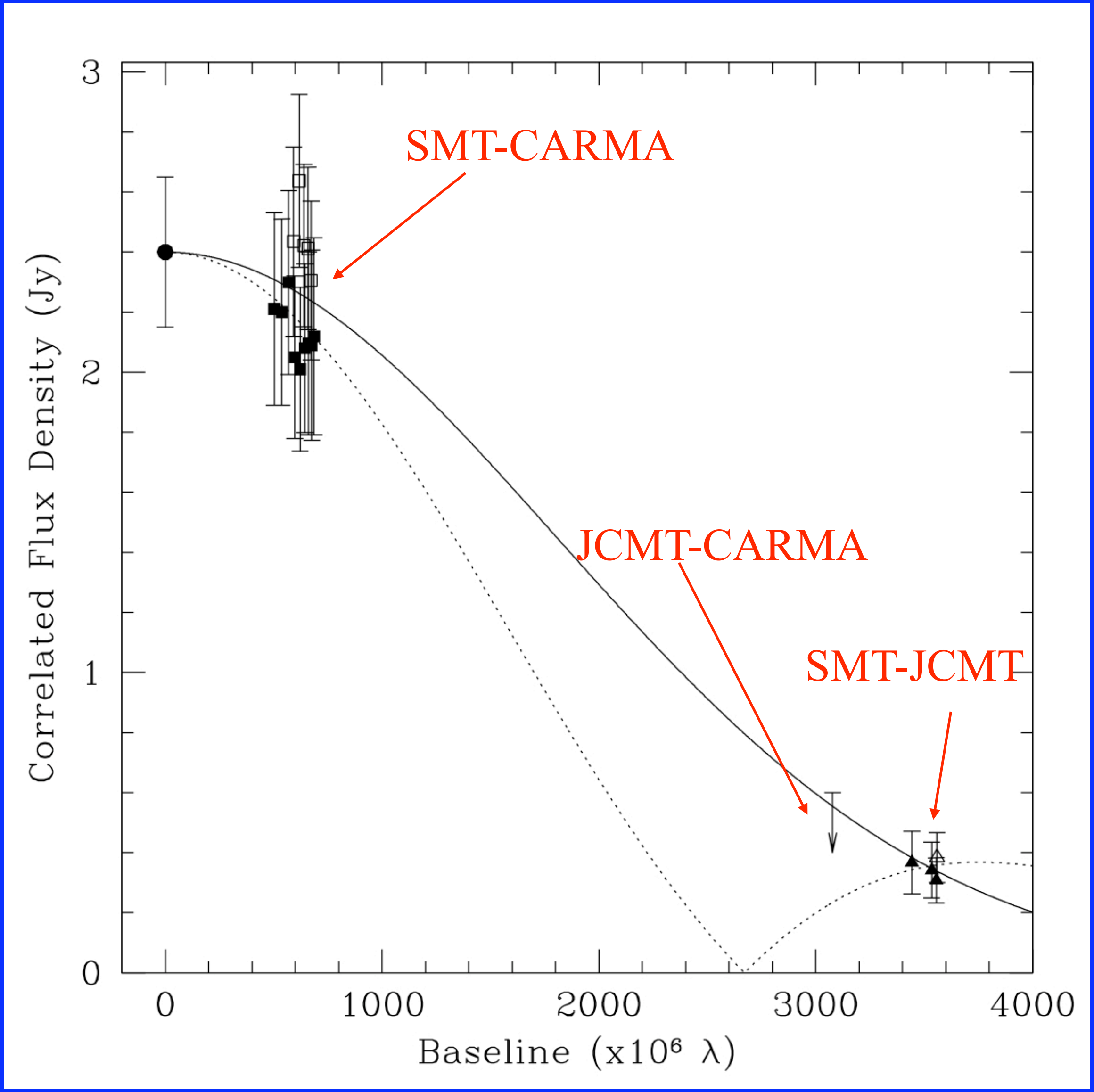
Sensitivity is critical.

1.3mmλ Observations of SgrA*



Builds on long history of SgrA* VLBI and mmVLBI.

Determining the size of SgrA*



θ_{OBS} = 43μas (+14, -8)

θ_{INT} = 37μas (+16, -10)

$$\theta_{OBS} = \sqrt{\theta_{INT}^2 + \theta_{SCAT}^2}$$

1 Rsch = 10μas

$$\rho = 10^{23} M_{\odot} pc^{-3}$$

Alternatives to a MBH

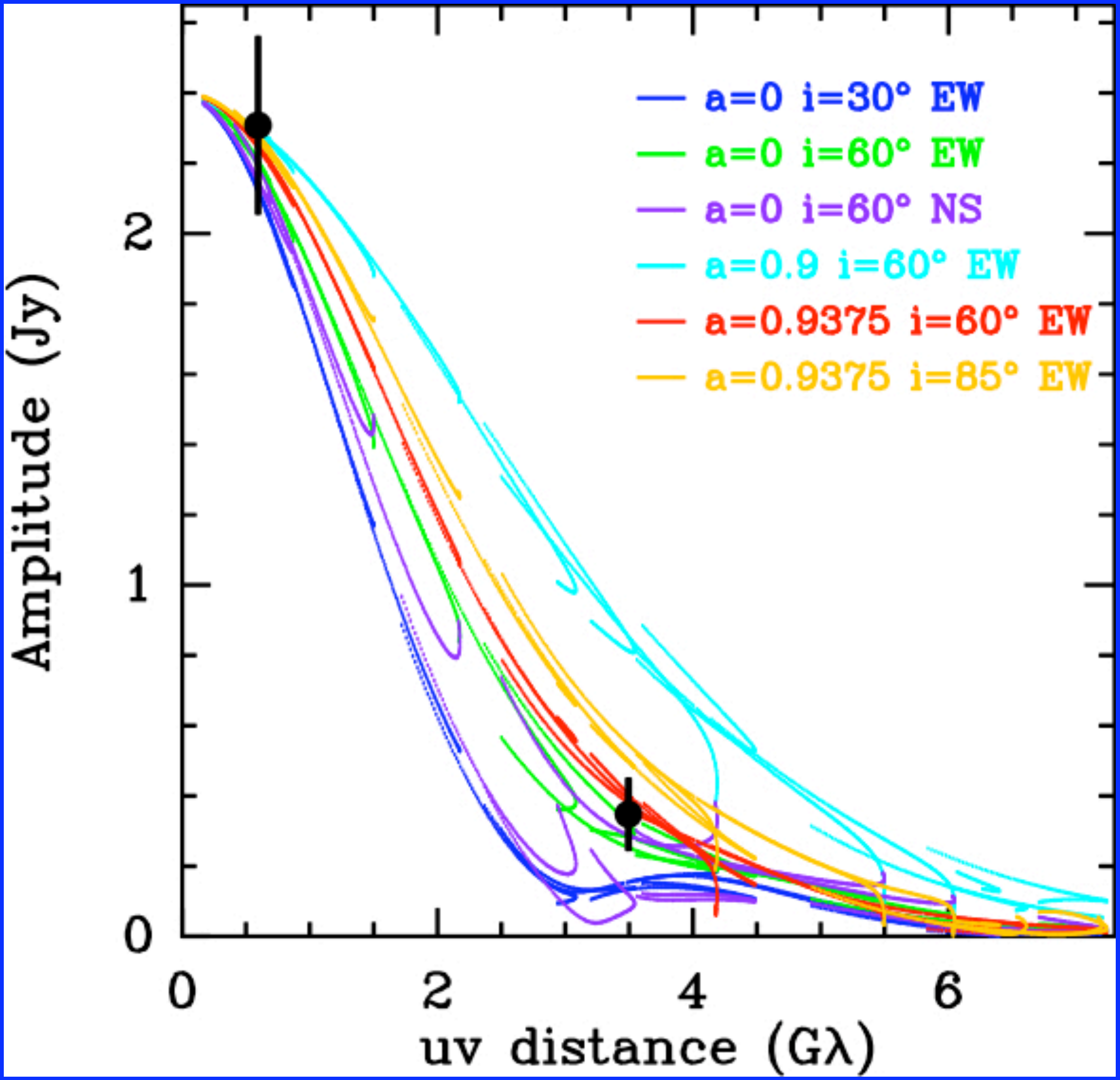
• Most condensations of smaller mass objects evaporate on short timescales. Current obs imply Tevap<500 yrs.

• Boson Star is a remaining ‘exotic’ possibility where R=Rsch + epsilon. Depends on Boson mass.

Proof of an Event Horizon?

•If no EH, then the ‘surface’ will radiate in the NIR, but none seen. (Broderick, Loeb, Narayan 2009)

Model Correlated Flux Density



Broderick, Fish, Doeleman & Loeb (2009)

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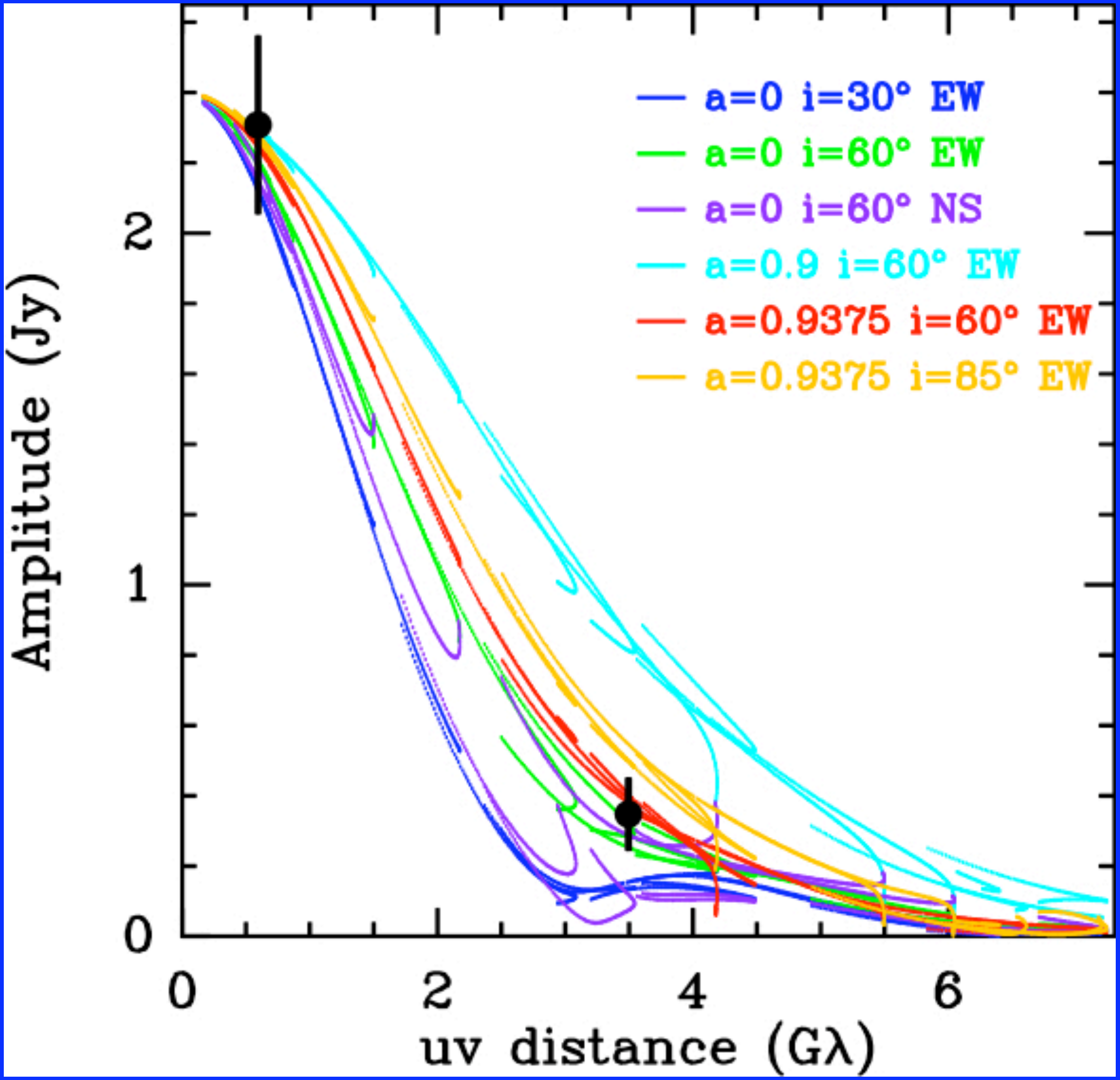
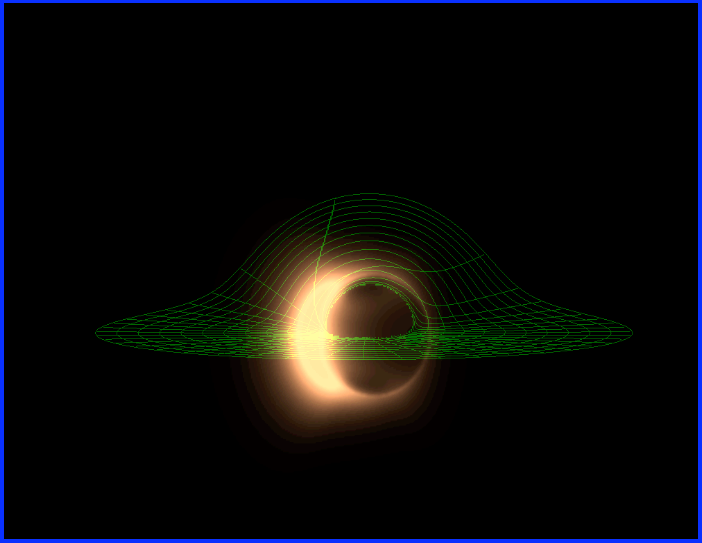
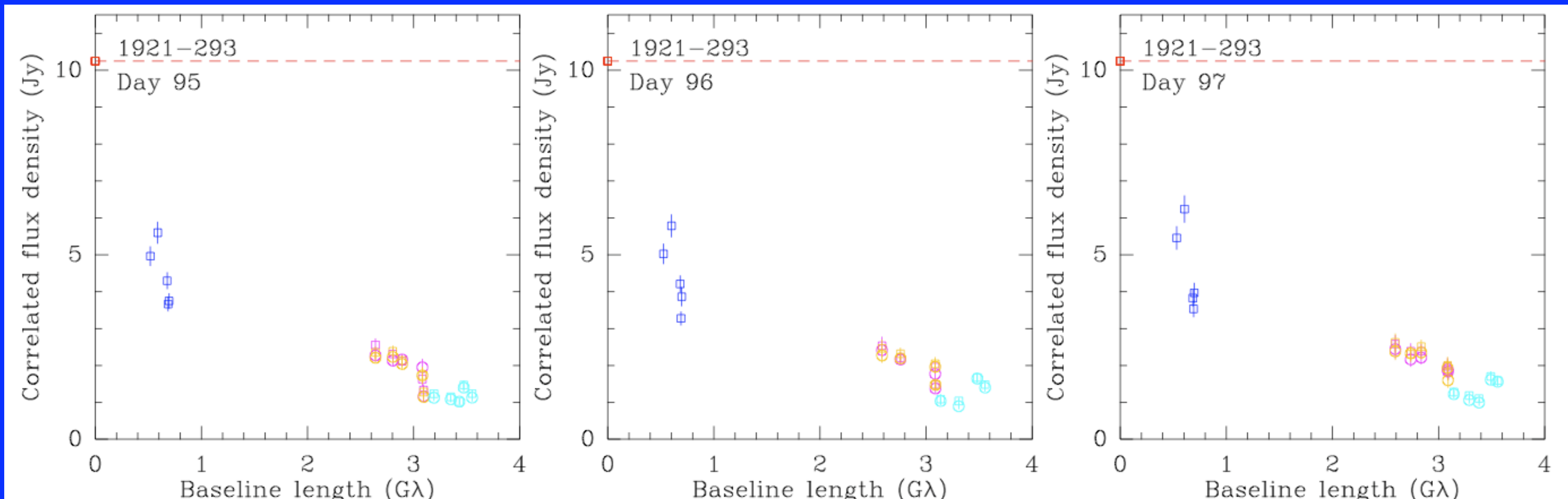
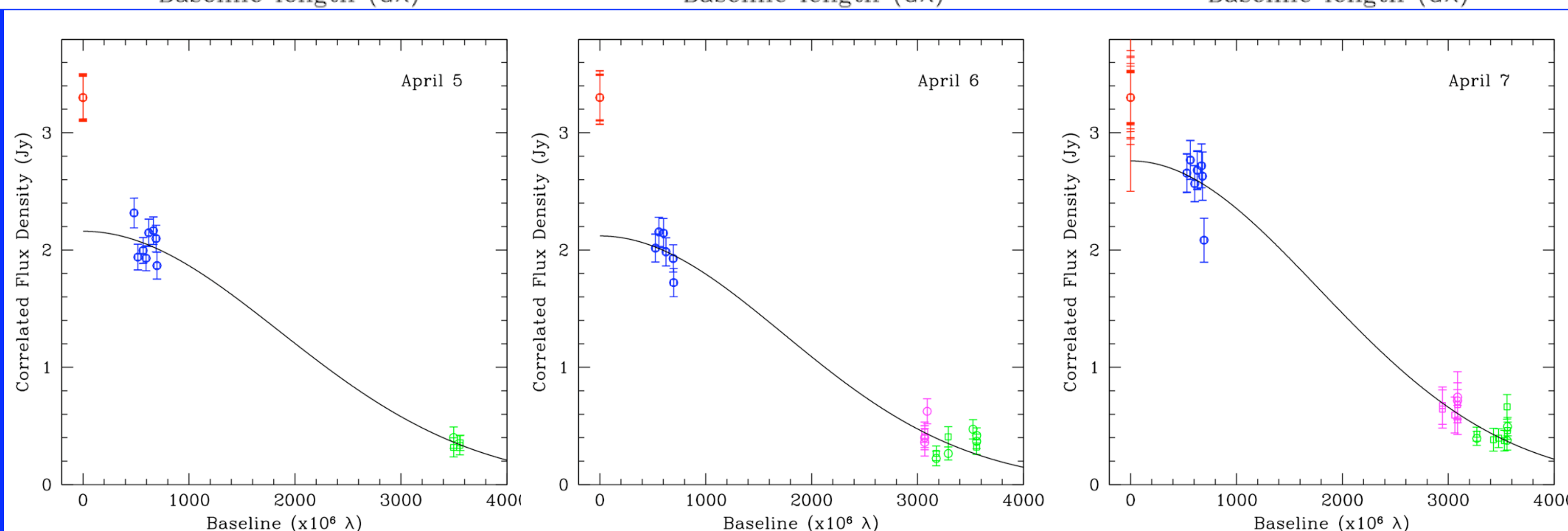




Broderick, Fish, Doeleman & Loeb (2009)

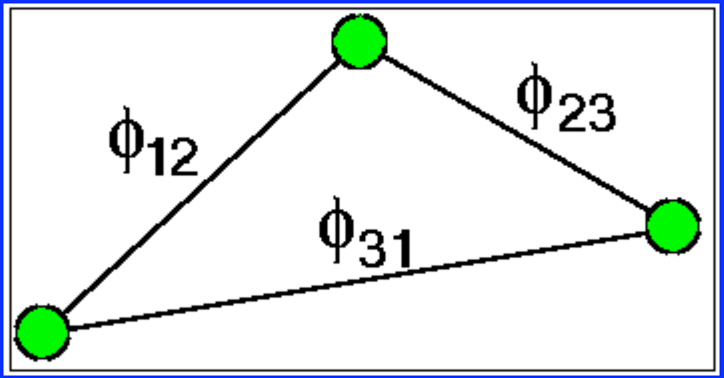
April 2009: SgrA* Flare on Rsch scales

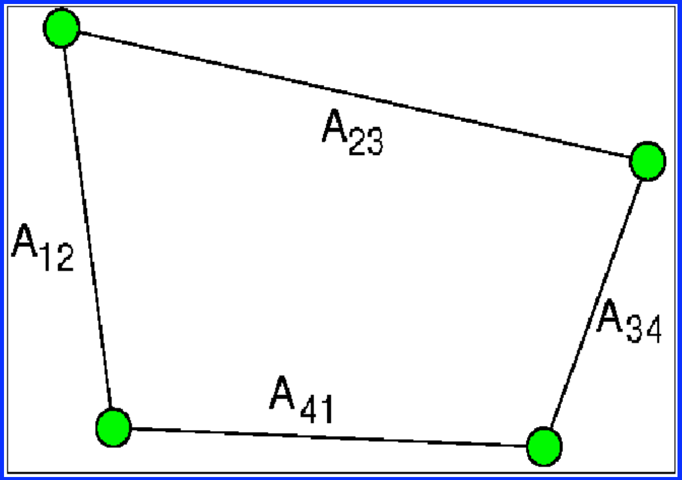




Time Variable Structures

- Variabilty in NIR, x-ray, submm, radio.
- Probe of metrics near BH, and of BH spin.
- Violates Earth Rotation aperture synthesis.
- Use 'good' closure observables to probe structure as function of time.
- Work with Avery Broderick and Avi Loeb.





Hot Spot Model for SgrA* Flares

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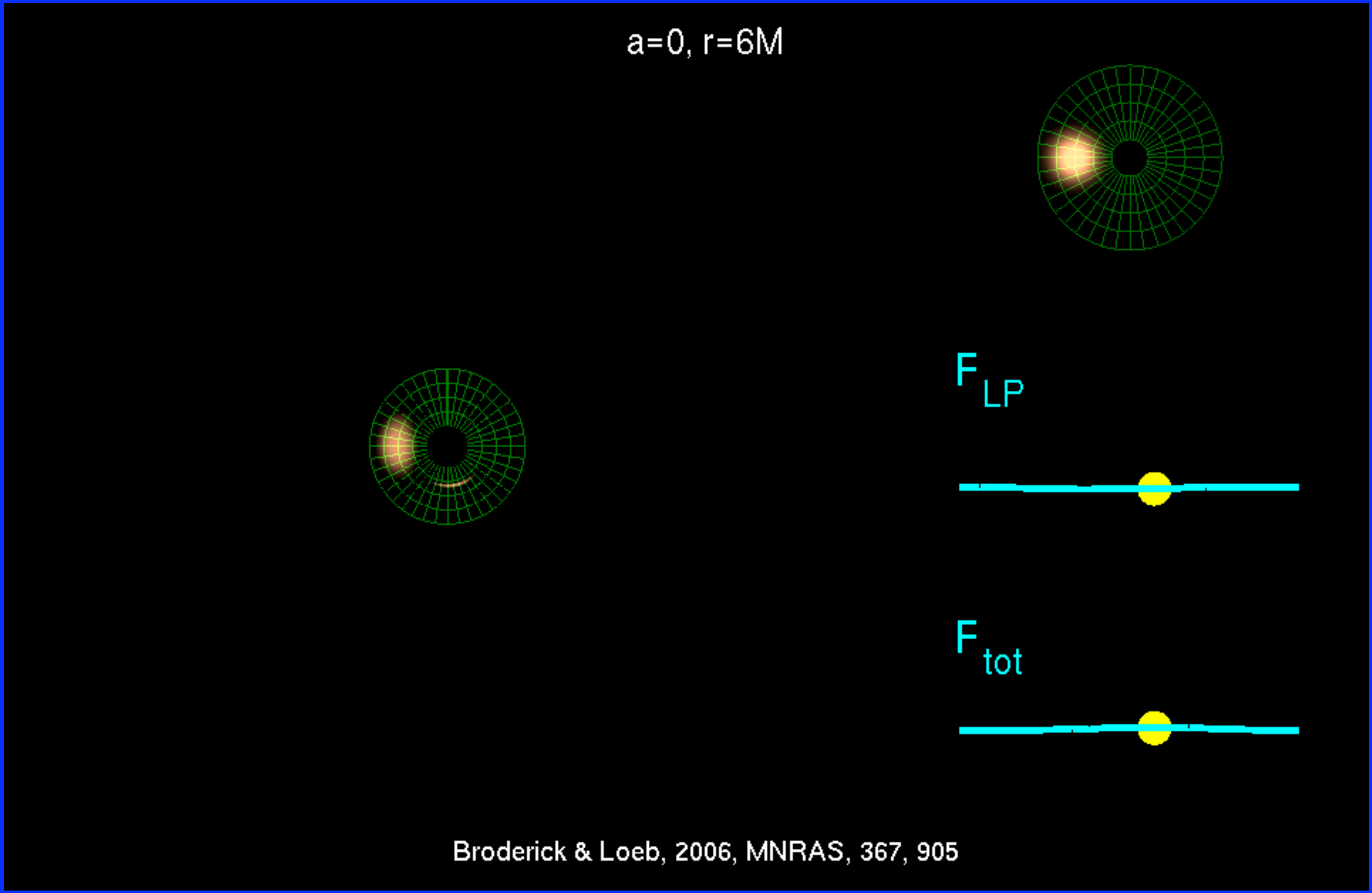
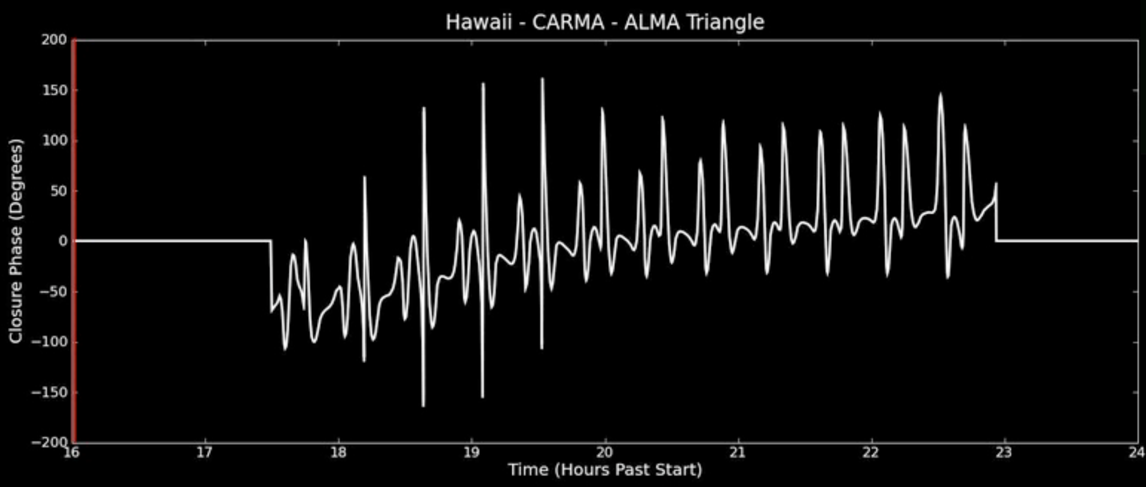
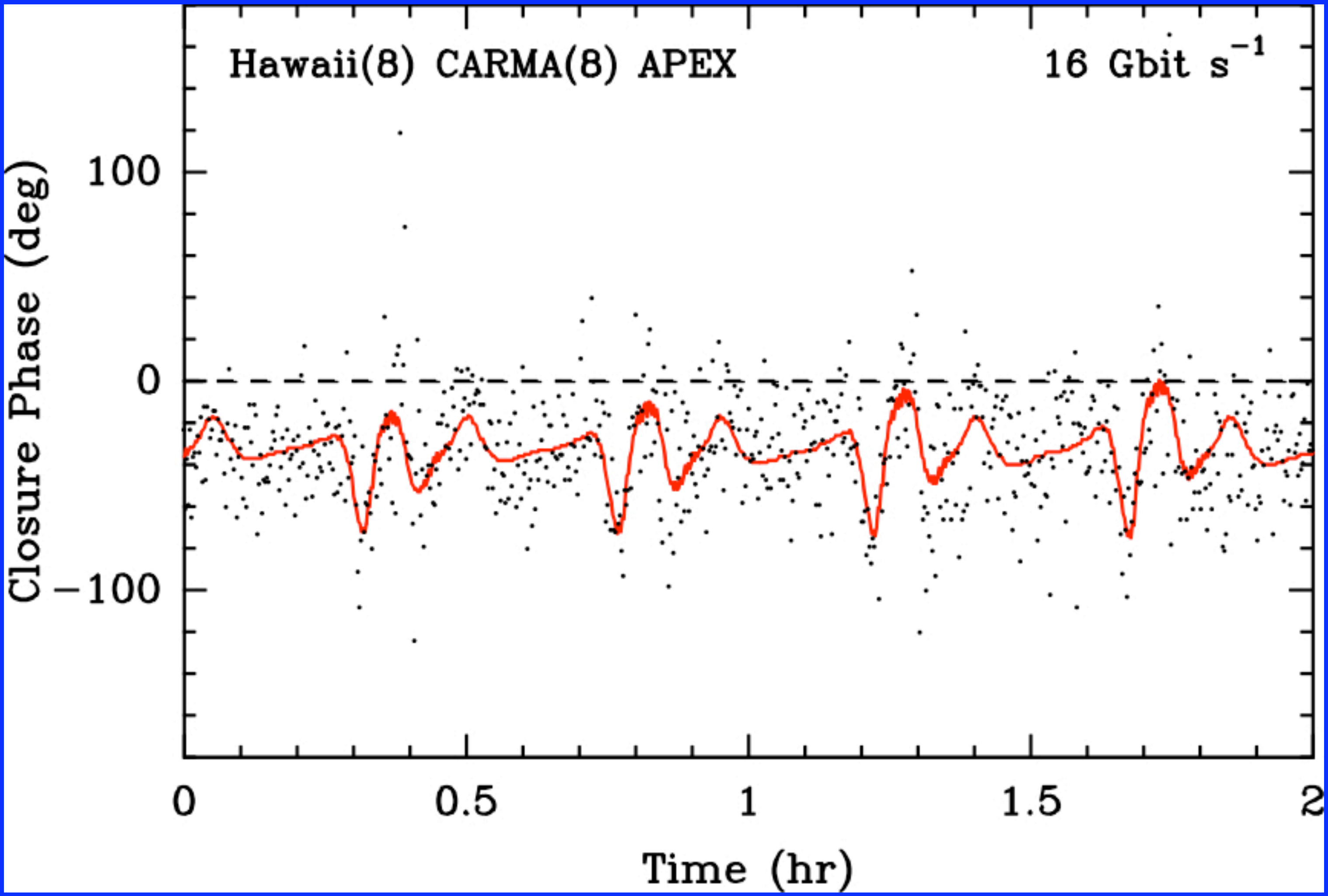


Tracing Black Hole Orbits with VLBI



Measuring Black Hole Orbits with VLBI



Spin = 0.9
Hot-spot at ~ $6R_g$
Period = 27 min.

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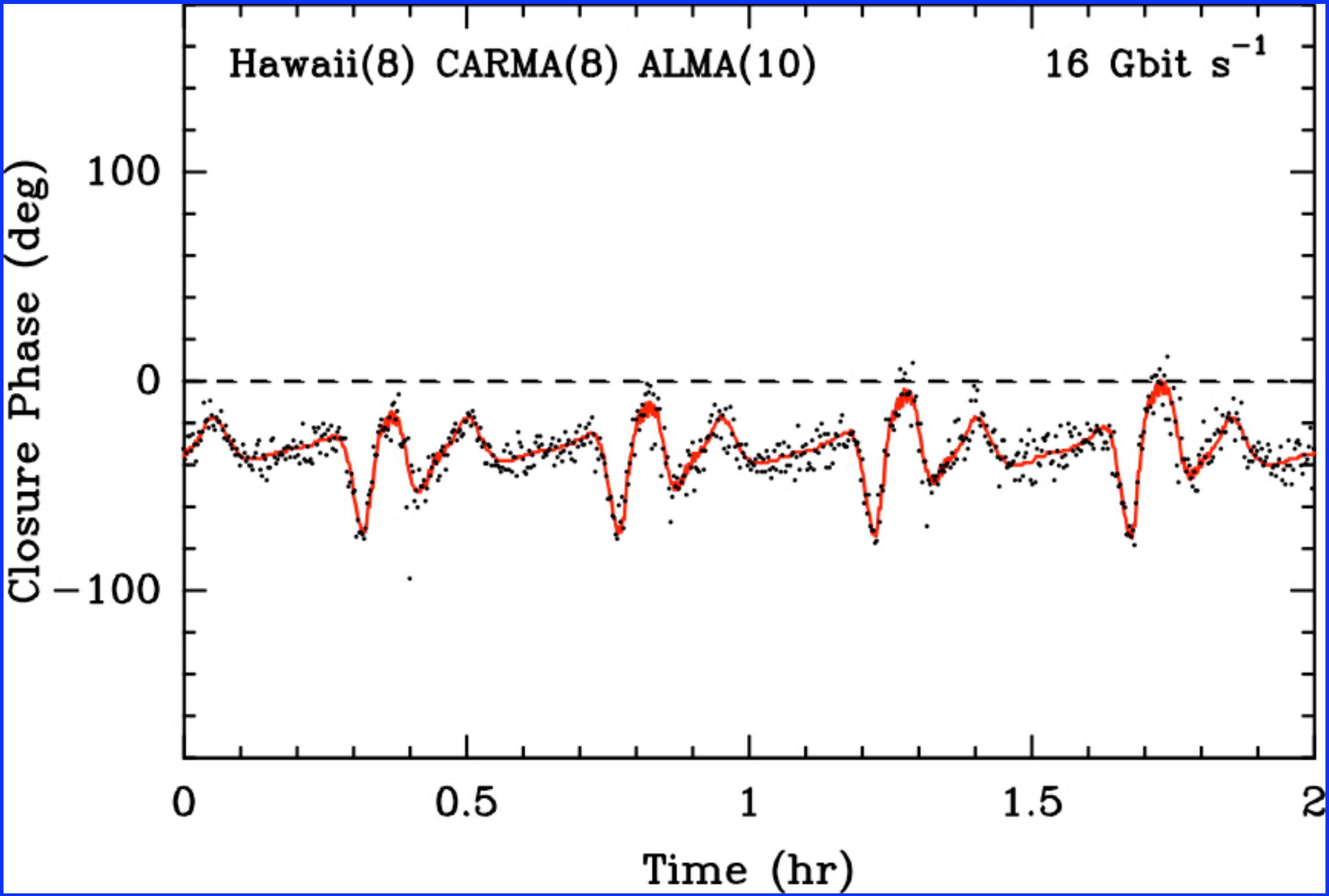

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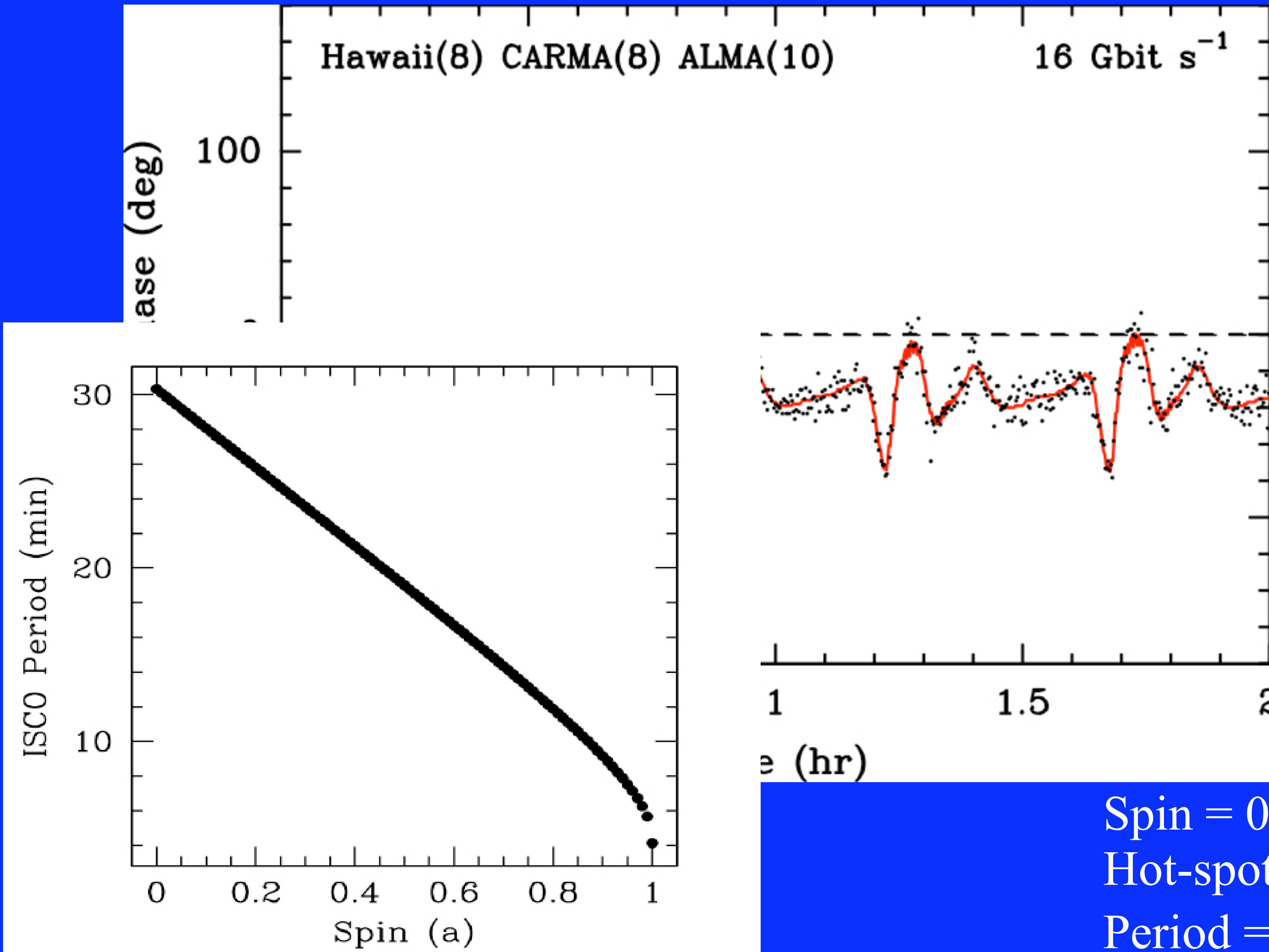

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VLBA Movie of M87 @ 43 GHz (7 mm)

Craig Walker et al. 2008

More luminous class of AGN with more massive central BH
Eg M87, half the apparent size of SgrA* (1000 x more massive)

Beam: 0.43x0.21 mas 0.2mas = 0.016pc = 60R_s 1mas/yr = 0.25c

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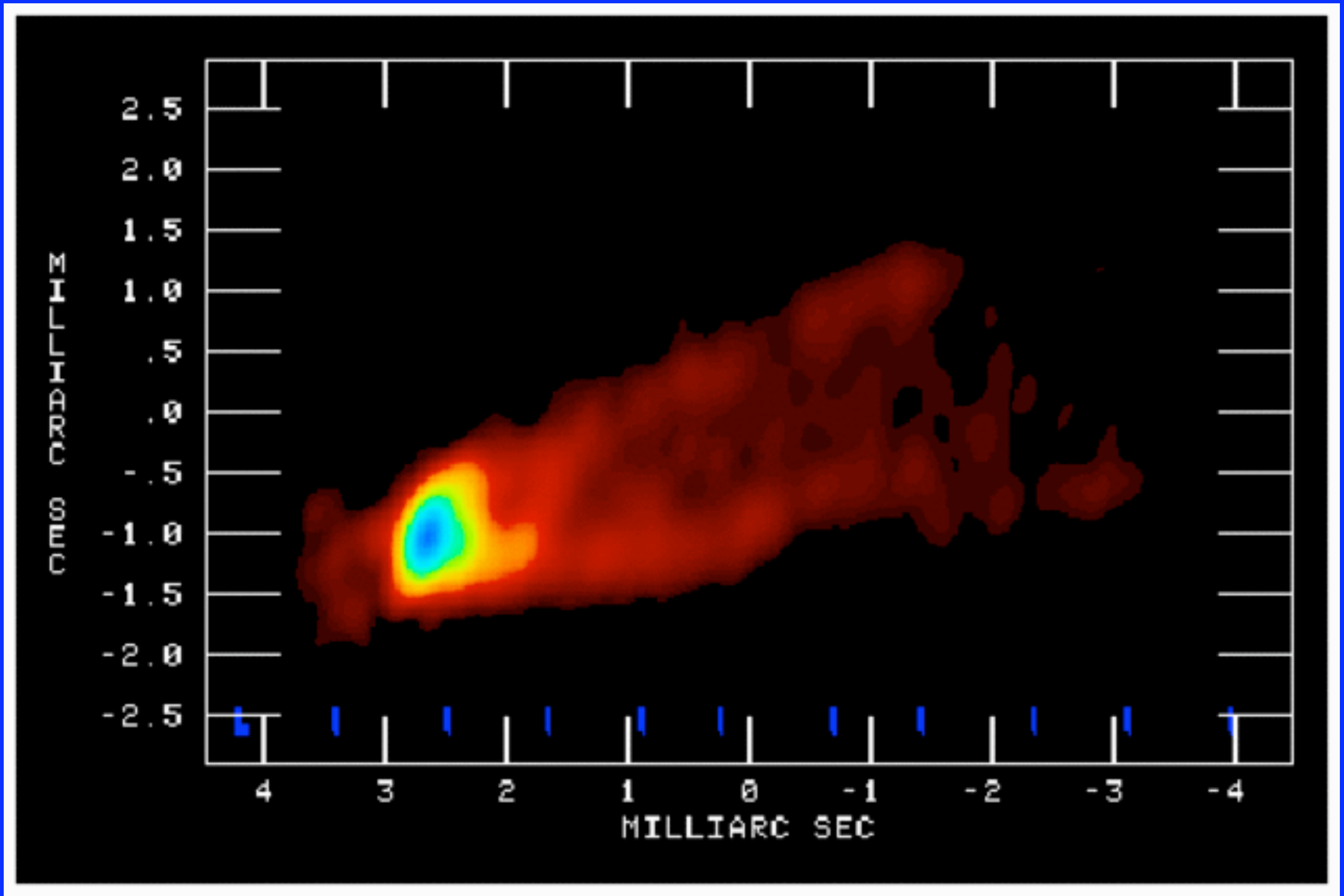
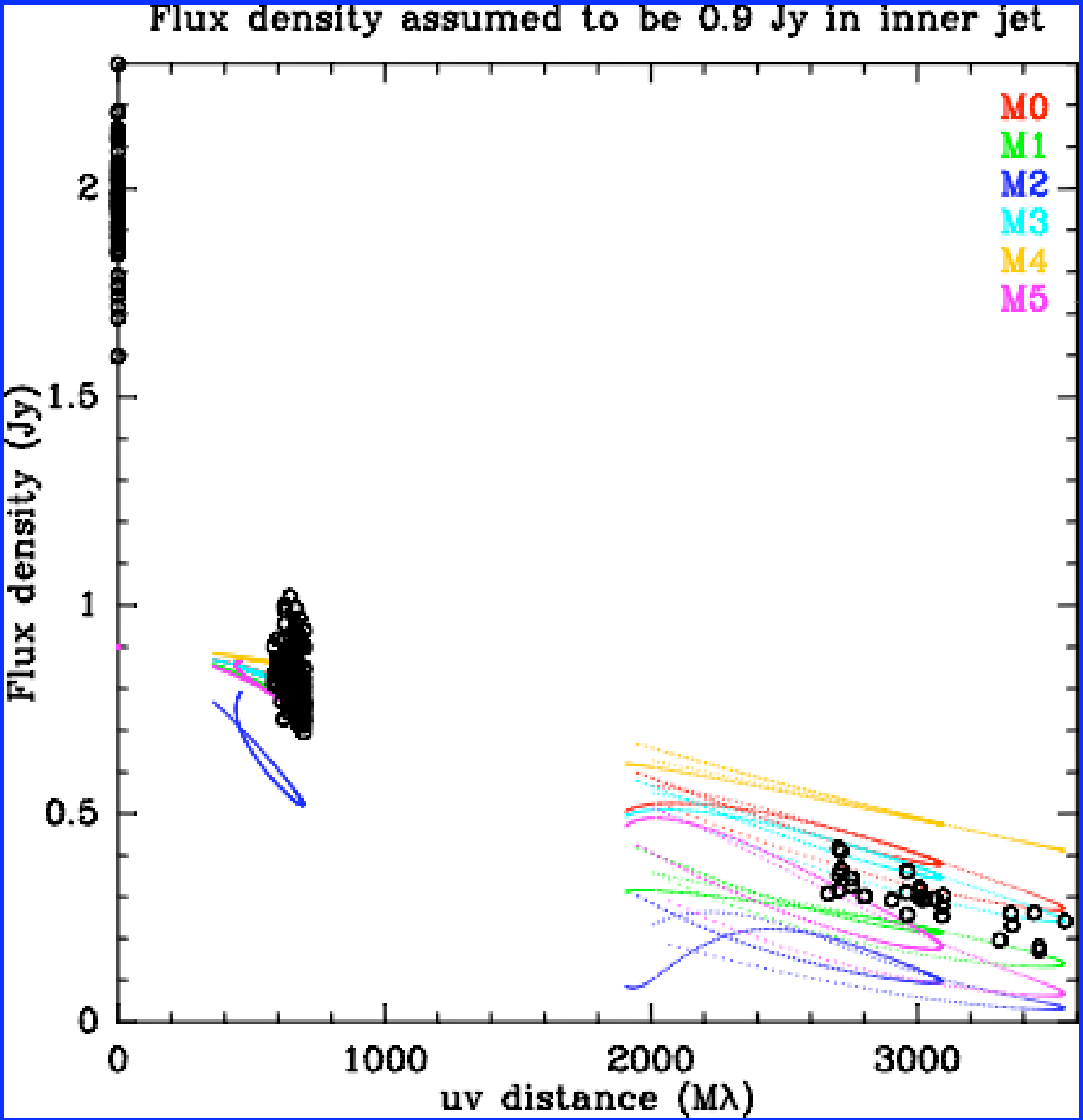
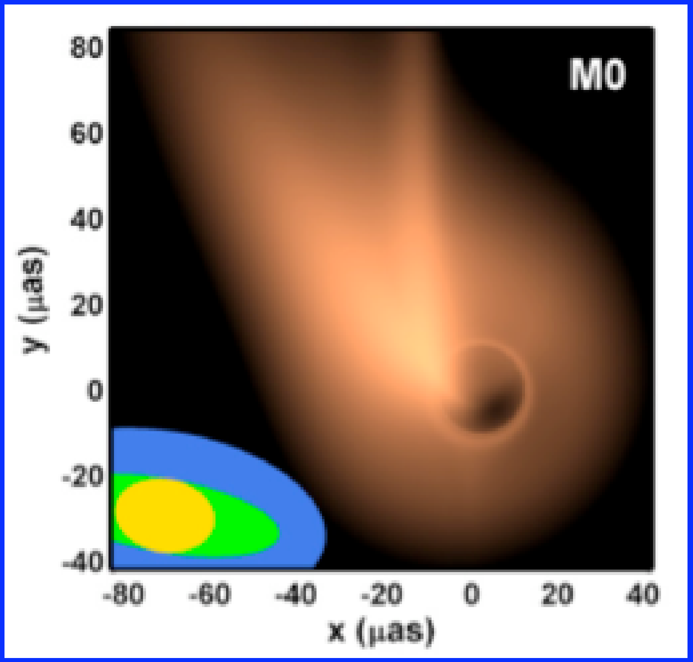


Comparison with Jet Models





a=0.998, =25deg

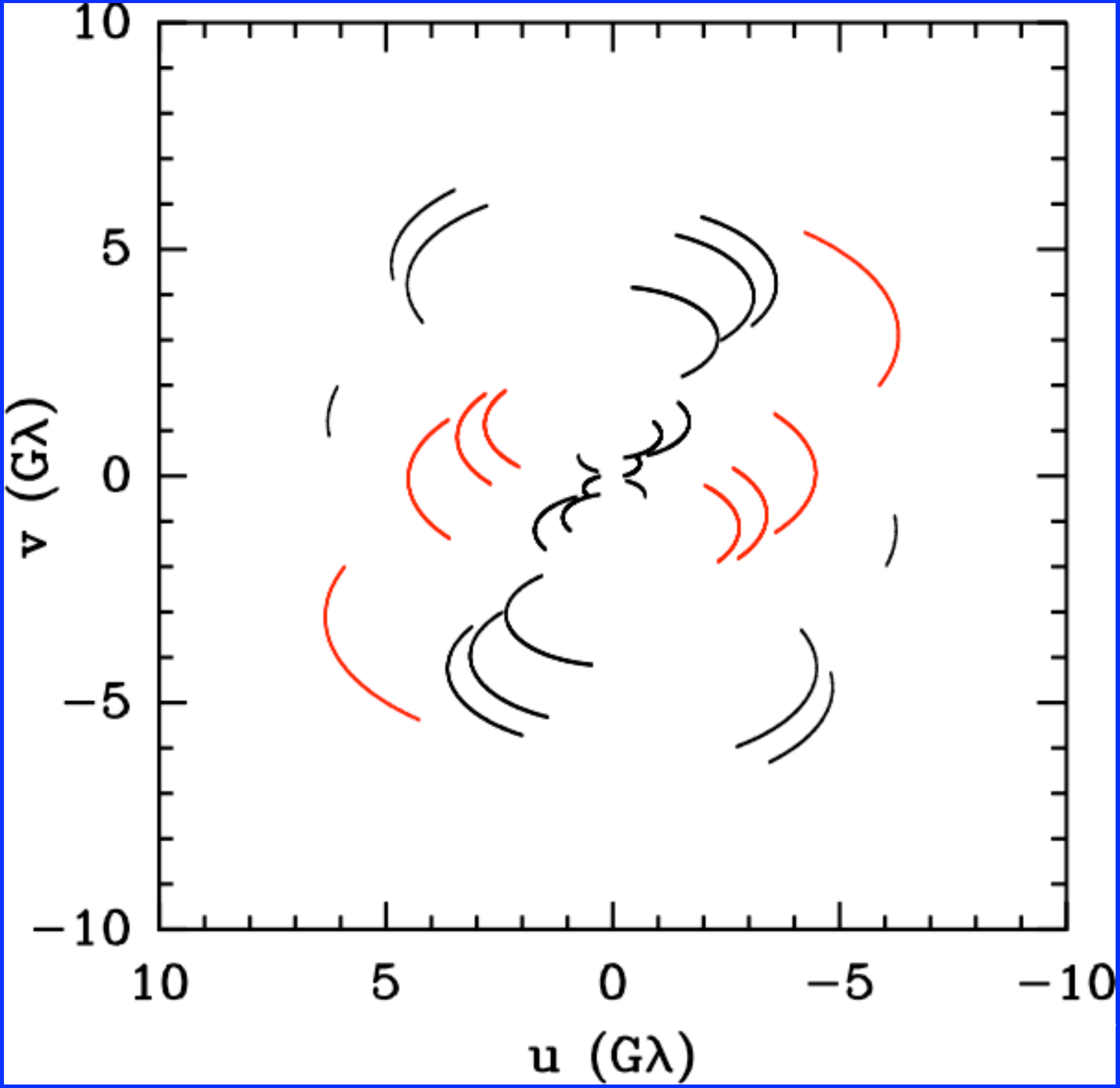
Broderick & Loeb (2009)

Building the Event Horizon Telescope
Astro2010 Roadmap Phase I

- Adding Telescopes: 7 station array.
- VLBI backends/recorders that support > 8Gb/s.
- Central wideband correlator (up to 64Gb/s).
- Phased Array processors (SMA, ALMA, PdeBure, CARMA)
- Begin work on low noise, dual pol receivers.
- Low noise freq. references: H-Masers/CSO's
- Recording media for 7-station 8Gb/s array
- New site studies
- Turn-key operations: remote operations
- Project management, operations.

- Endorsed by RMS Panel of US Decadal Review

Adding Stations



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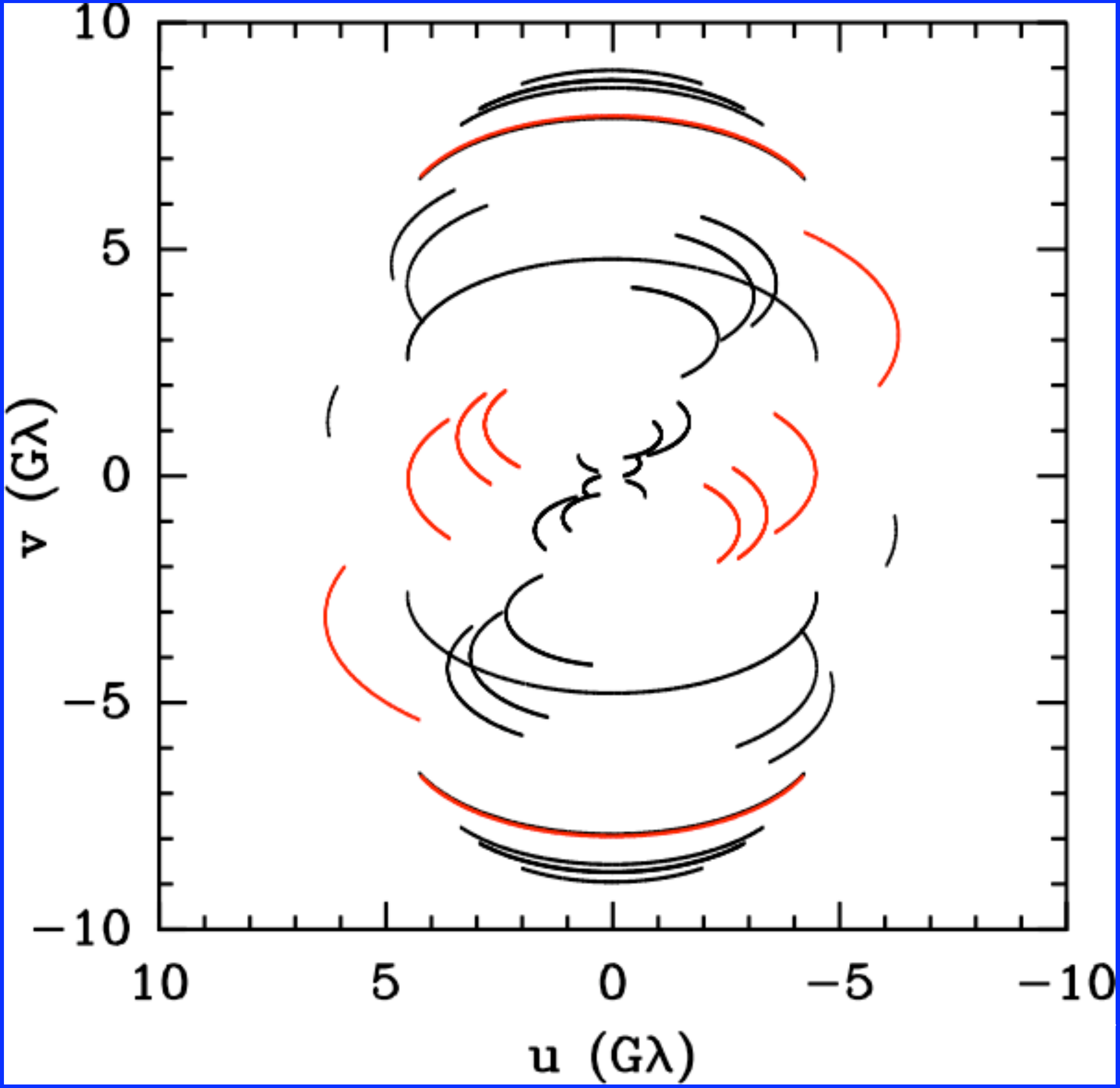
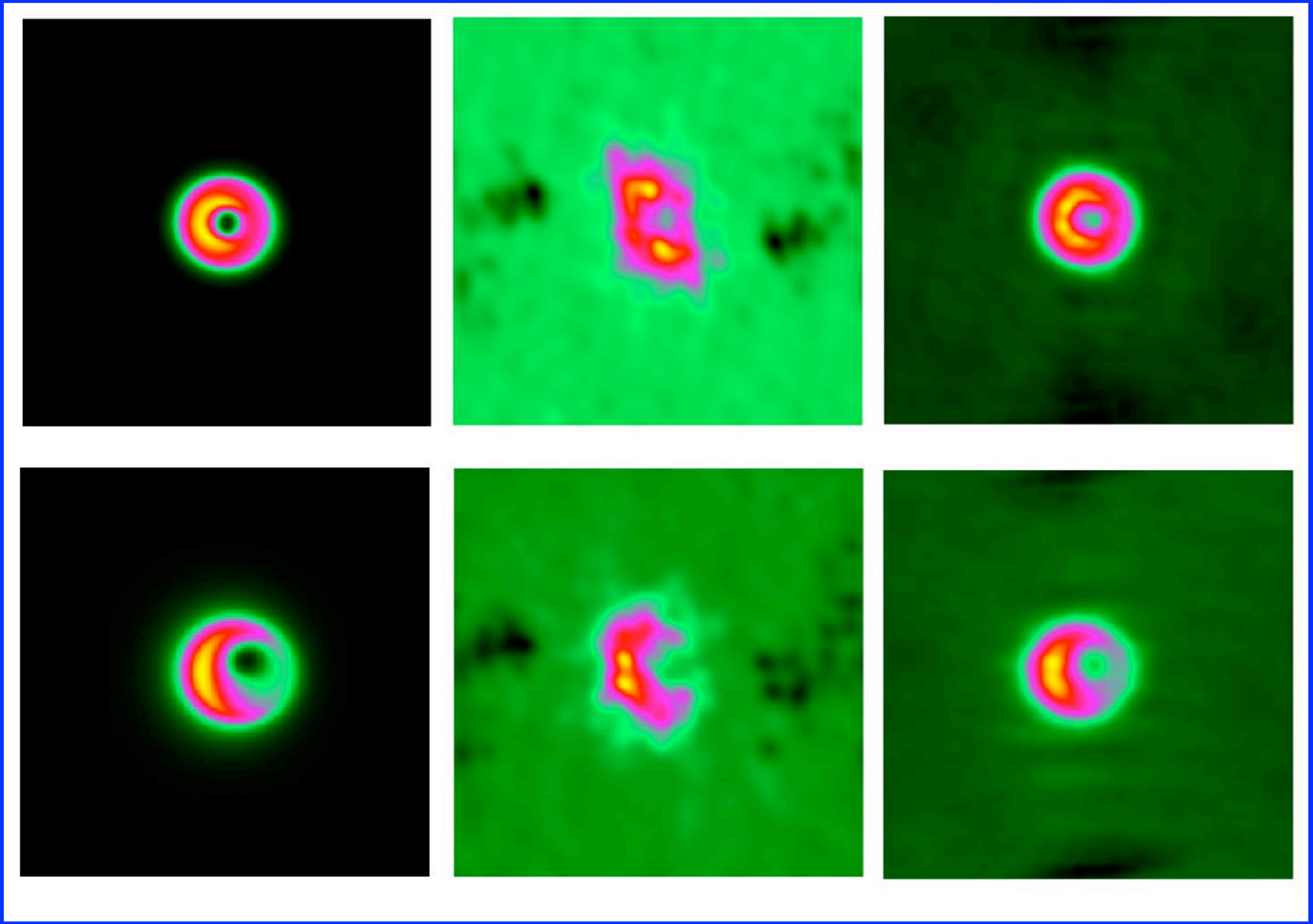


Progression to an Image



GR Model 7 Stations 13 Stations

Testing the No Hair Theorem

- BH defined solely by spin and mass.
- Test by perturbing quadrupole: $Q' = -a^2/M^2 + e$
- 'Shadow' size, ISCO, orbital period, all now depend on M, a, e.

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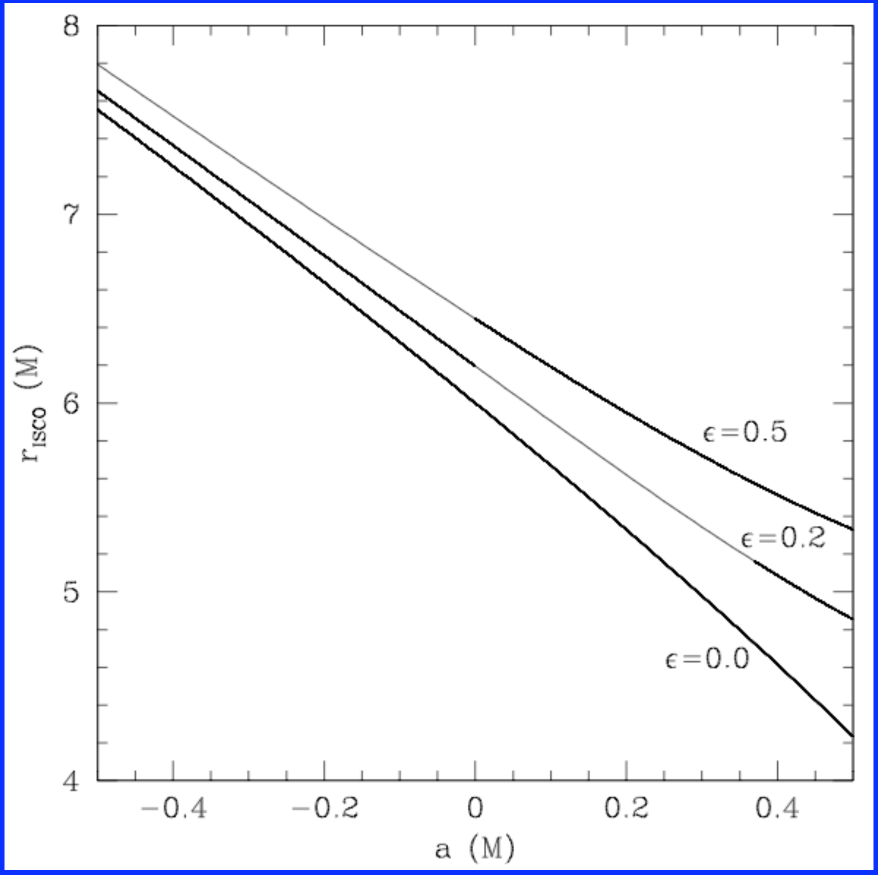
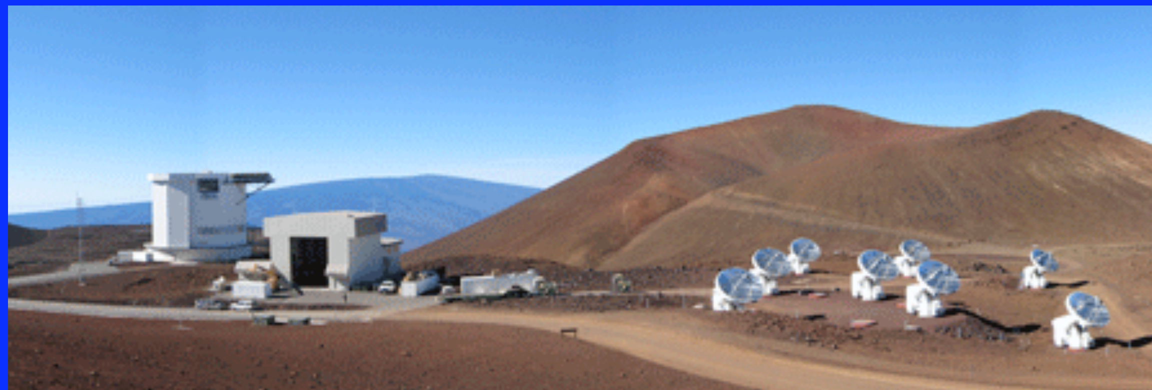
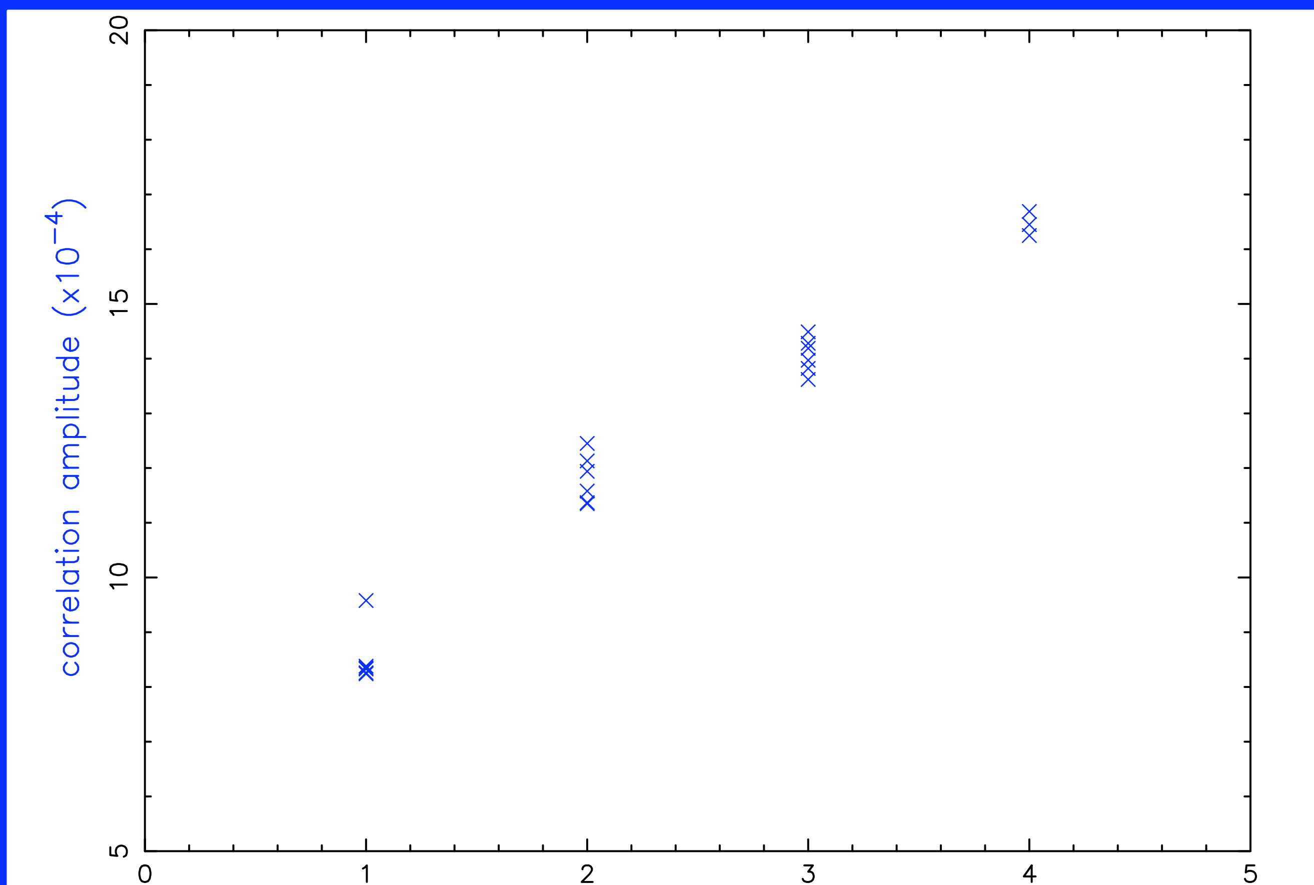


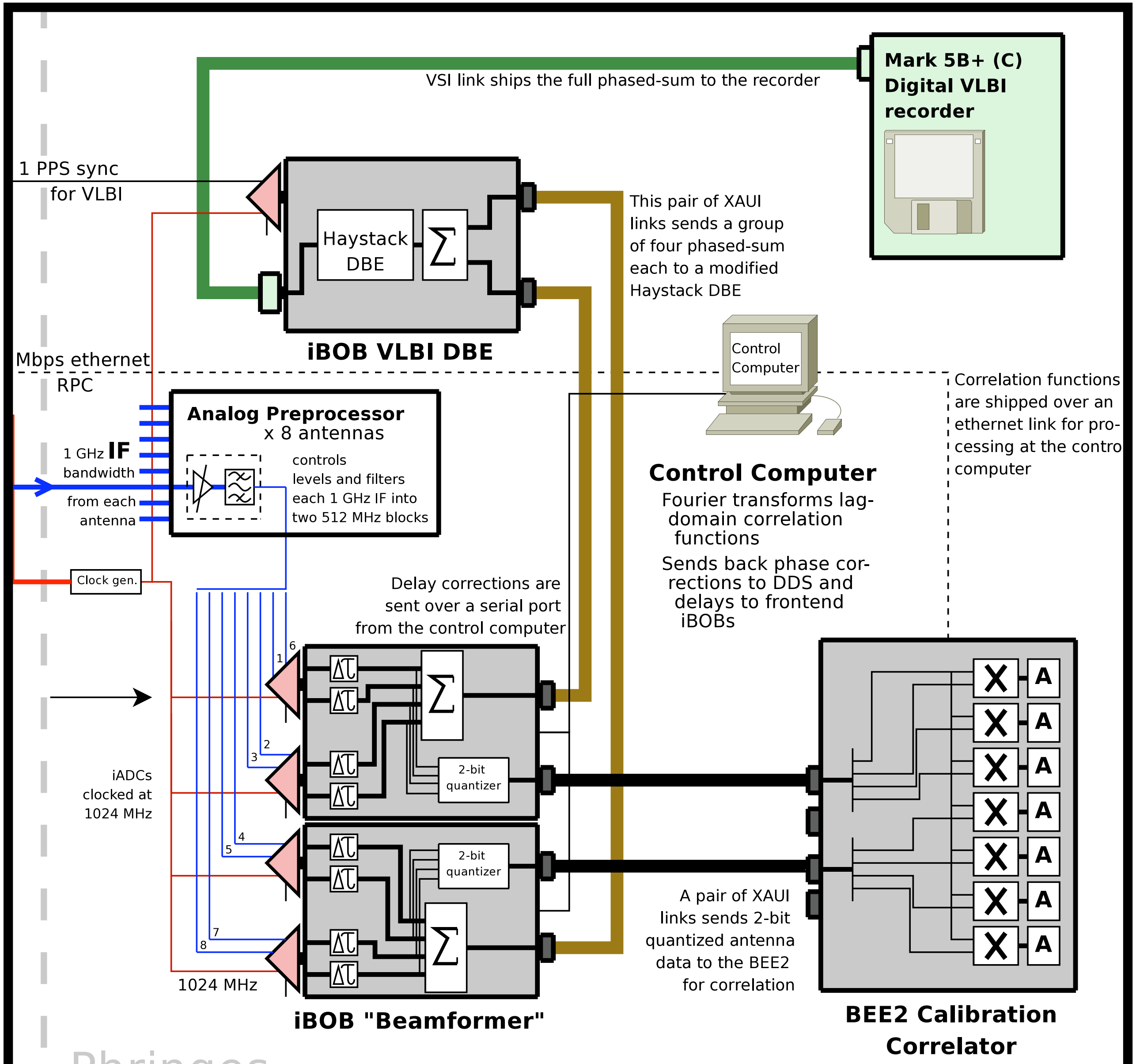
Johannson & Psaltis 2009

Phasing up the SMA





CASPER Phased Array (Weintroub et al)



mm/submm VLBI Collaboration

MIT Haystack: Alan Rogers, Vincent Fish, et al
Harvard CfA: Jonathan Weintroub, Jim Moran, Rurik Primiani, Ken Young, Ray Blundell, Mark Gurwell, et al
MPIfR: Thomas Krichbaum, Anton Zensus, Alan Roy
U. Arizona Steward Obs: Lucy Ziurys, Robert Freund, Dan Marrone
CARMA: Dick Plambeck, Mel Wright, David Woody, Geoff Bower
James Clerk Maxwell Telescope: Remo Tilanus, Per Friberg
UC Berkeley SSL: Dan Werthimer
Caltech Submillimeter Observatory: Richard Chamberlin
ASIAA: Paul Ho, Makoto Inoue
NAOJ: Mareki Honma
IRAM: Michael Bremer
NRAO: John Webber, Ray Escoffier, Rich Lacasse

VLBI and the SMA

- 2006/2007: H-Maser and LO ref for JCMT
- 2009: Tests of phased array (SMA+CSO+JCMT)
- 2010: Astronomical obs. with phased SMA, including polarimetry.
- 2011: Phased Mauna Kea, CARMA, SMT, APEX, IRAM + XMM and Chandra
- Next generation phased array (more bandwidth, new hardware)
- Application of SMA phasing techniques to CARMA, ALMA.

Summary

- SMA is pivotal contributor to 1.3mm VLBI array.
- Results confirm ~4Rsch diameter for SgrA*
- Similar compact structure observed in M87 Jet.

- Imaging an Event Horizon and observing BH orbits are within reach in <5 years.
- Pioneering work at SMA (Weintroub et al) on FPGA approach to array phasing.

- EHT highlighted in RMS Panel Report.
- SMA's role will be enhanced with broadband upgrades and emergence of ALMA.