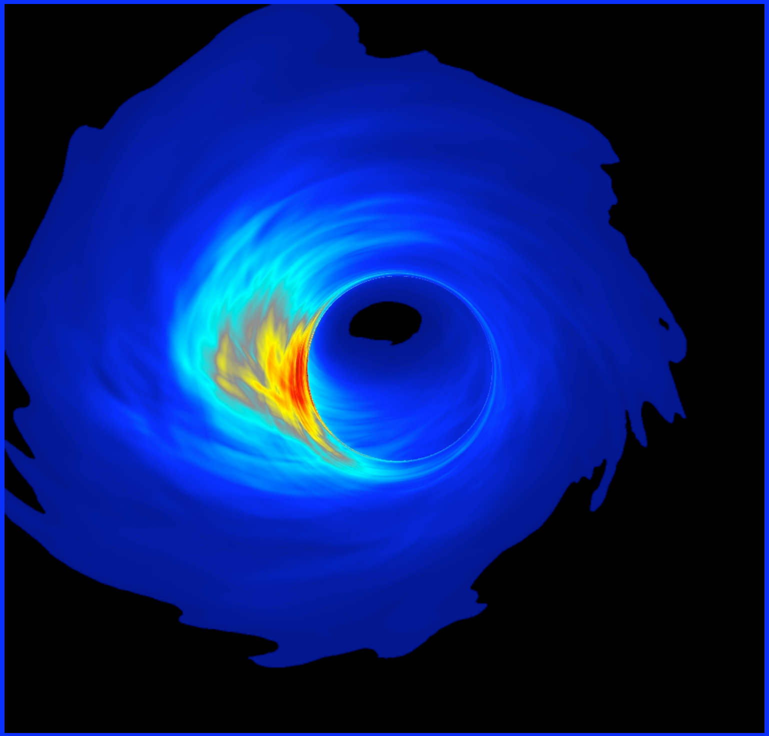
The Event Horizon Telescope: A (sub)mm-VLBI Network



Shep Doeleman
MIT Haystack Observatory
for the EHT Collaboration

Big Questions

- Is there an Event Horizon?
- Does GR hold near BH?
- How does matter accrete/outflow near a BH?
- Do Black Holes have spin?
- How do Black Holes launch jets?

- EHT addresses ASTRO 2010 questions and discovery areas:
- How do black holes work and influence their surroundings?
- What controls the mass-energy-chemical cycles within galaxies?
- What are the connections between dark and luminous matter?
- Time domain Astronomy.

SgrA*: Best Case for a SMBH

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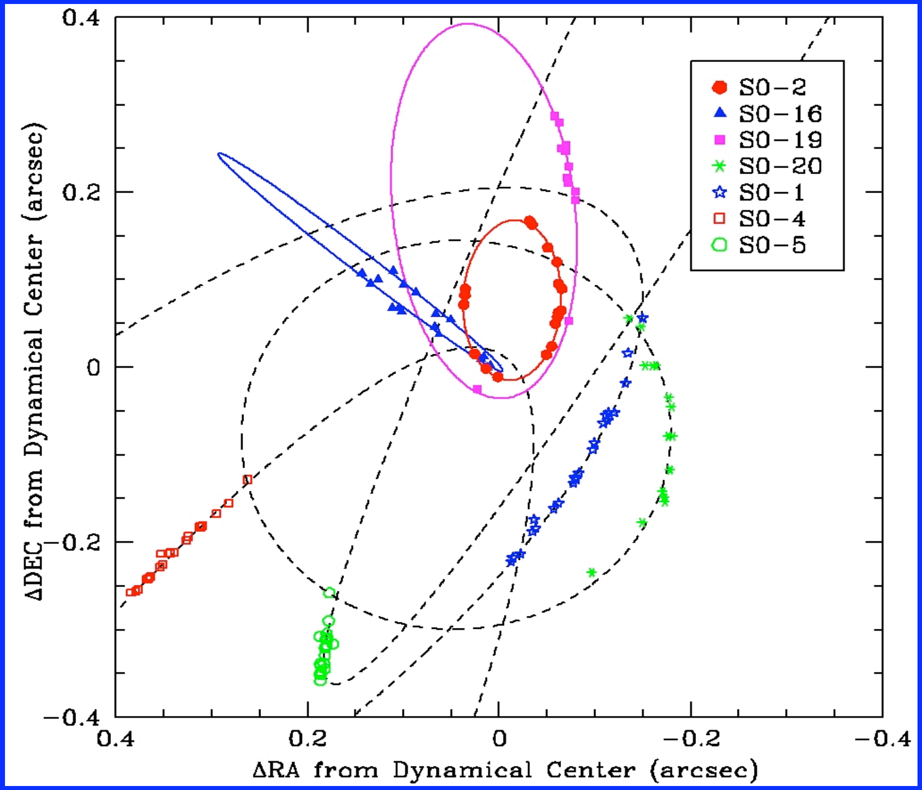
- Stellar orbits approaching within 45 AU.



Ghez et al 2005

SgrA*: Best Case for a SMBH

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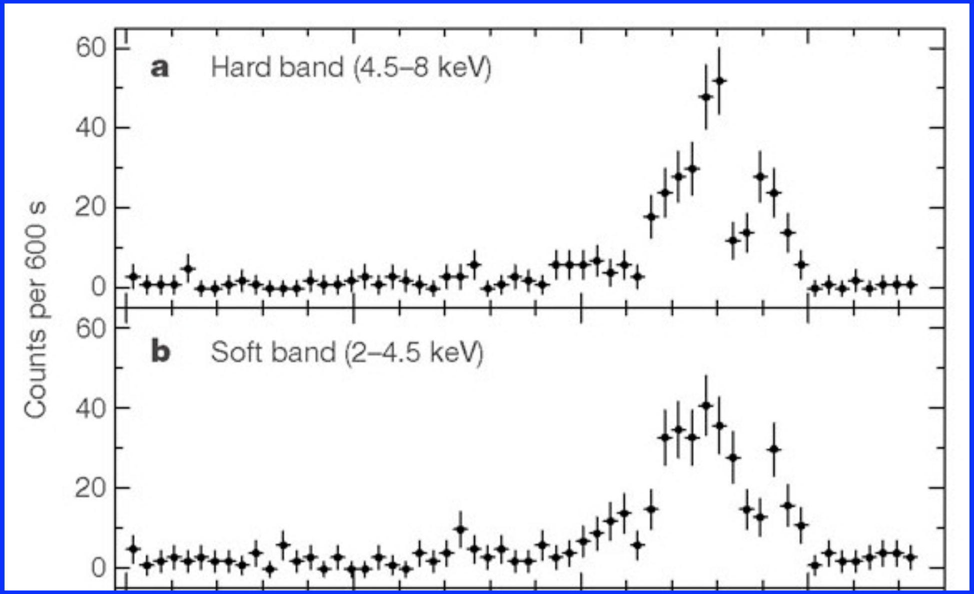

Baganoff et al 2001

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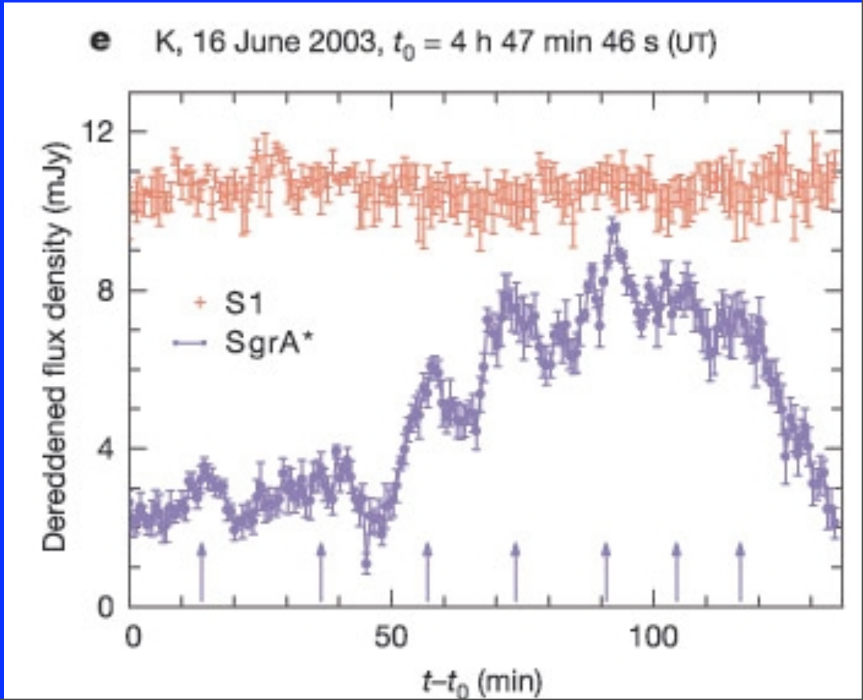
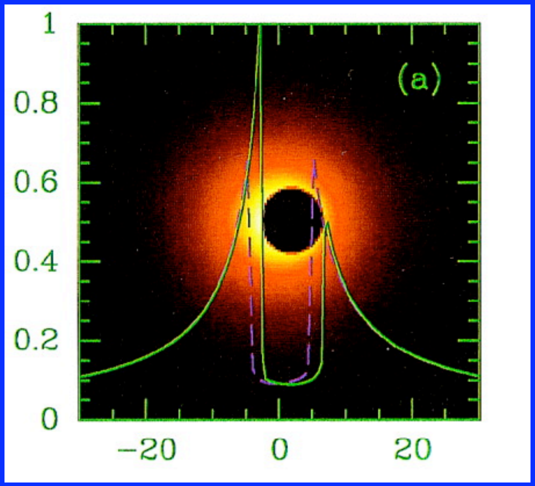
- Short time scale X-ray flares (300 sec rise).
- IF flares with modulation (a>0).

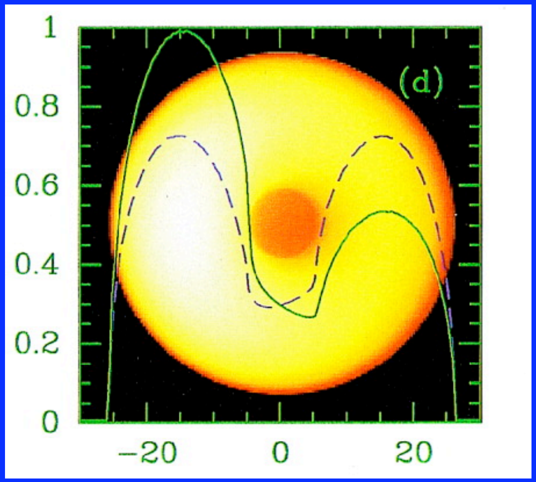


VLT: Genzel et al 2003

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)

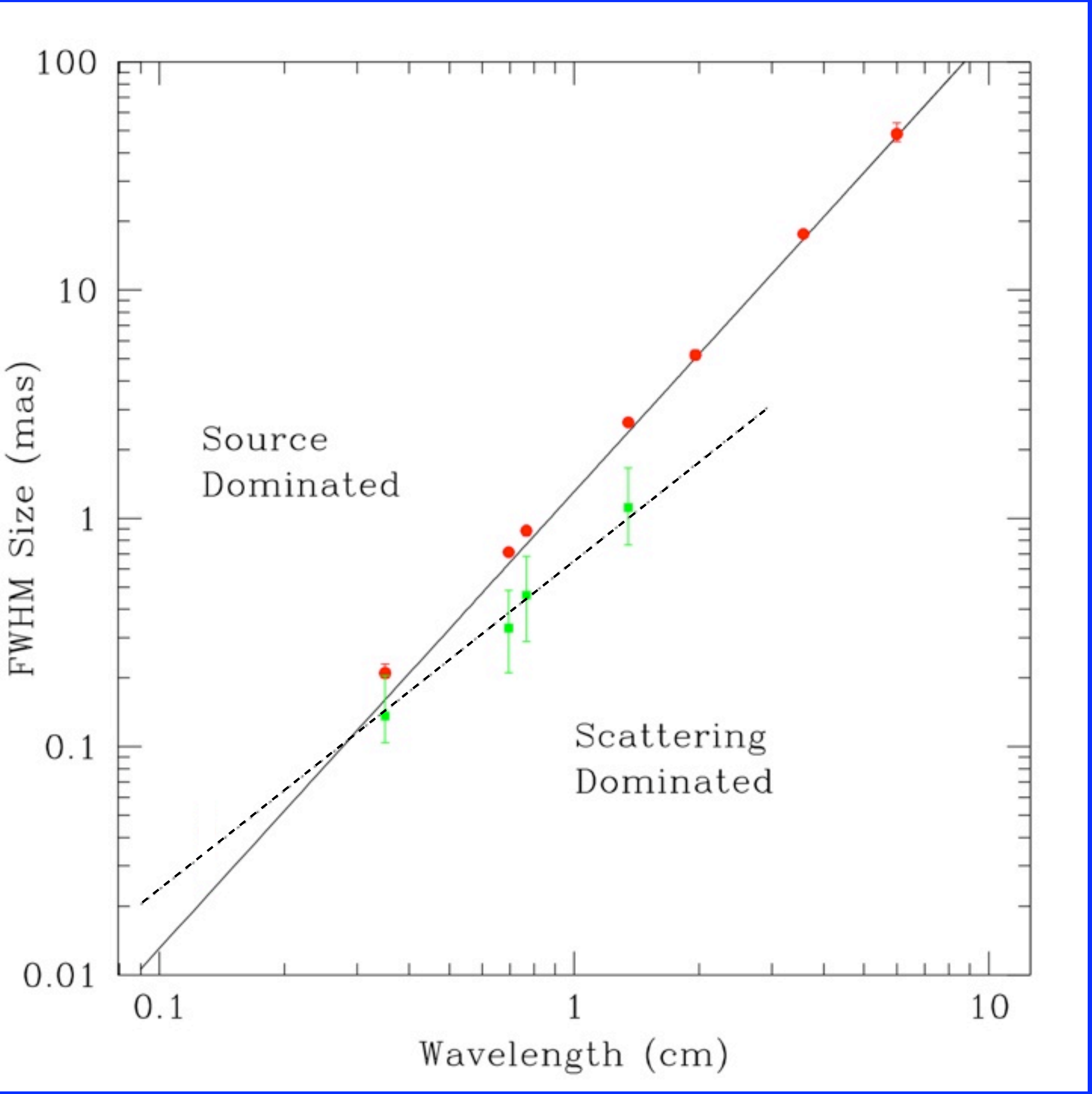
Scattering towards the GC

ISM Scattering:
$\Theta scat \sim \lambda^2$

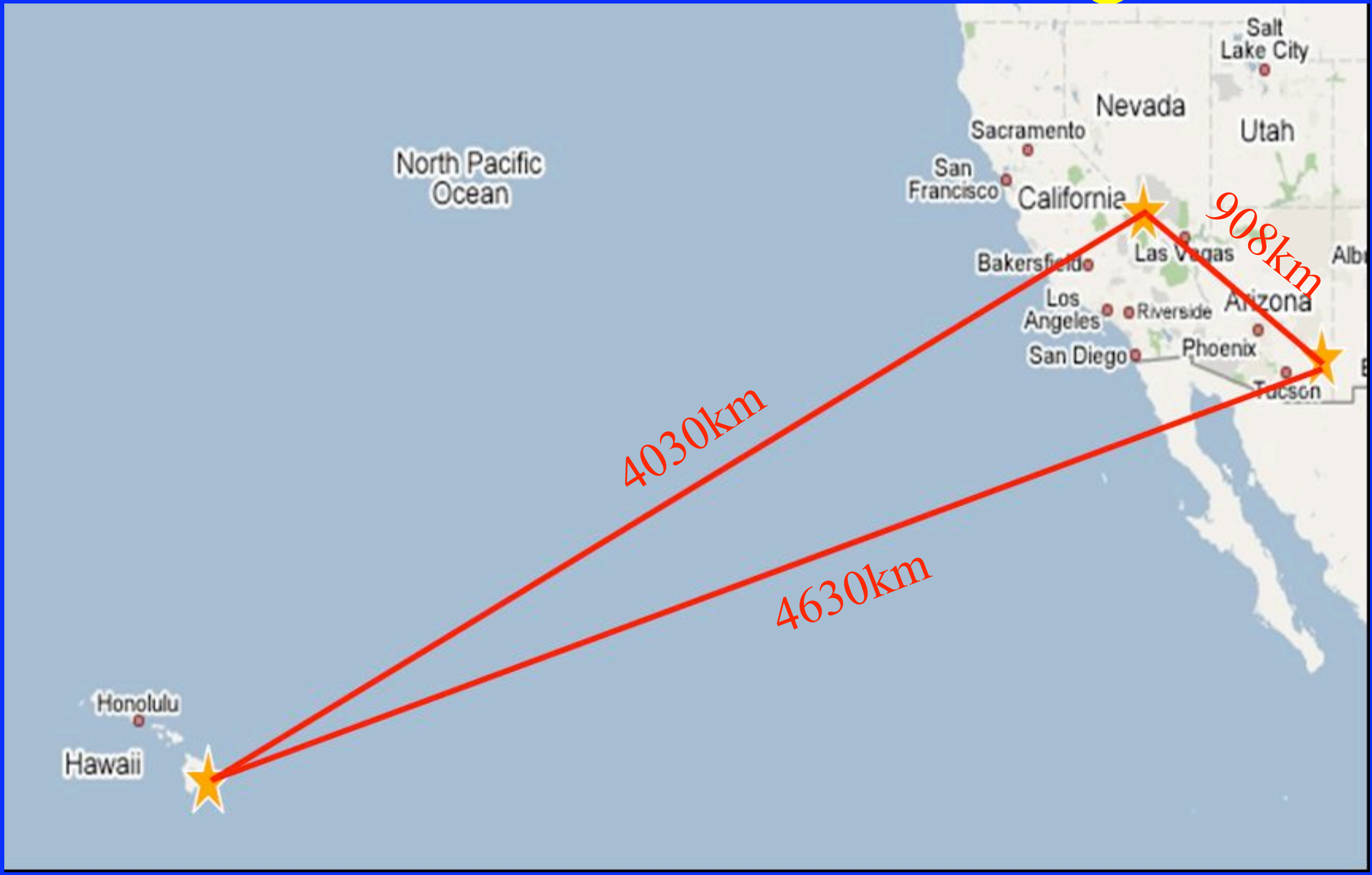
Need to observe with VLBI at short wavelengths.

Expected intrinsic size at 1.3mm is ~35 micro arcsec.

7mm: Bower et al
3mm: Shen et al

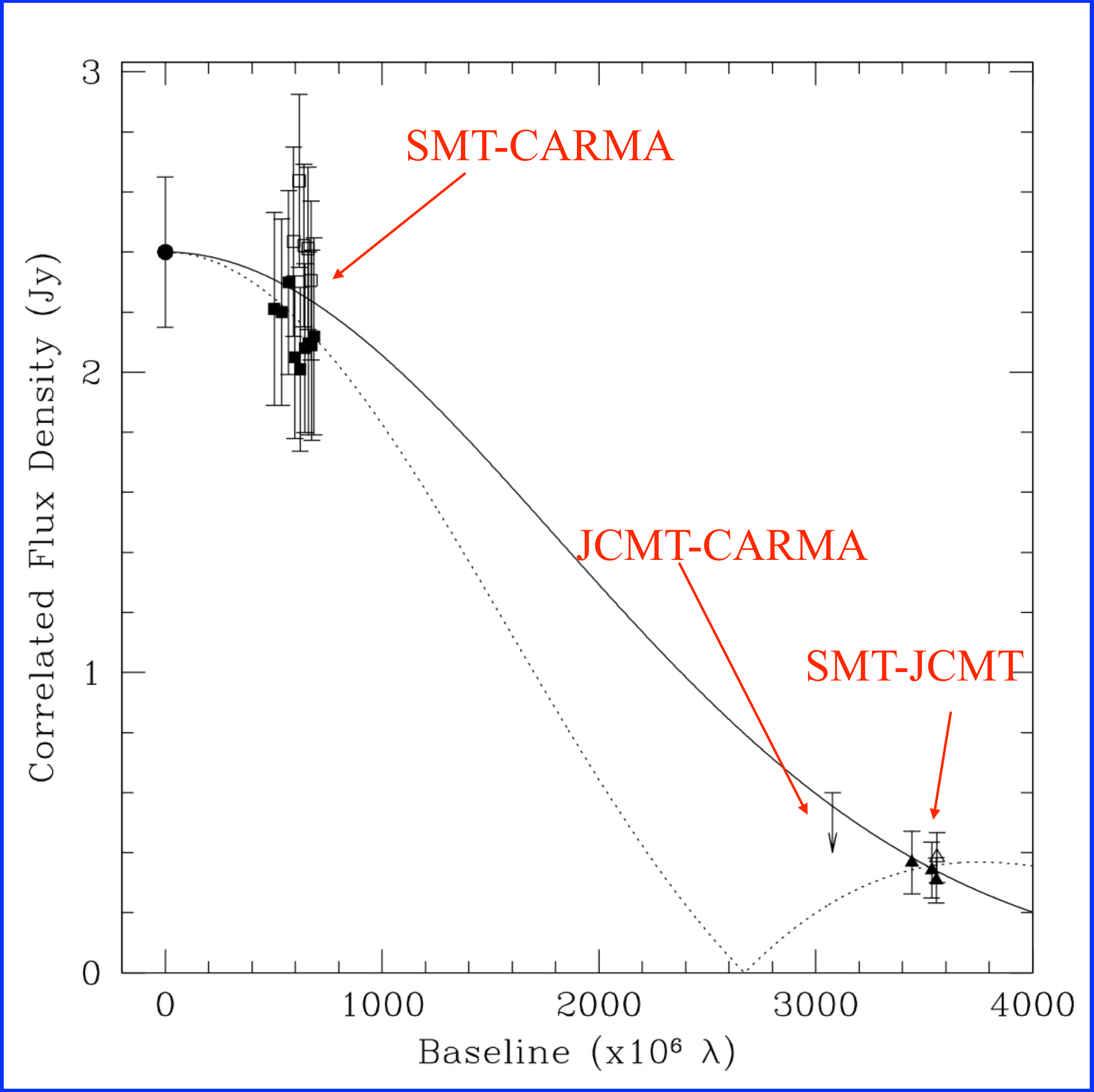


1.3mmλ Observations of SgrA*



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

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

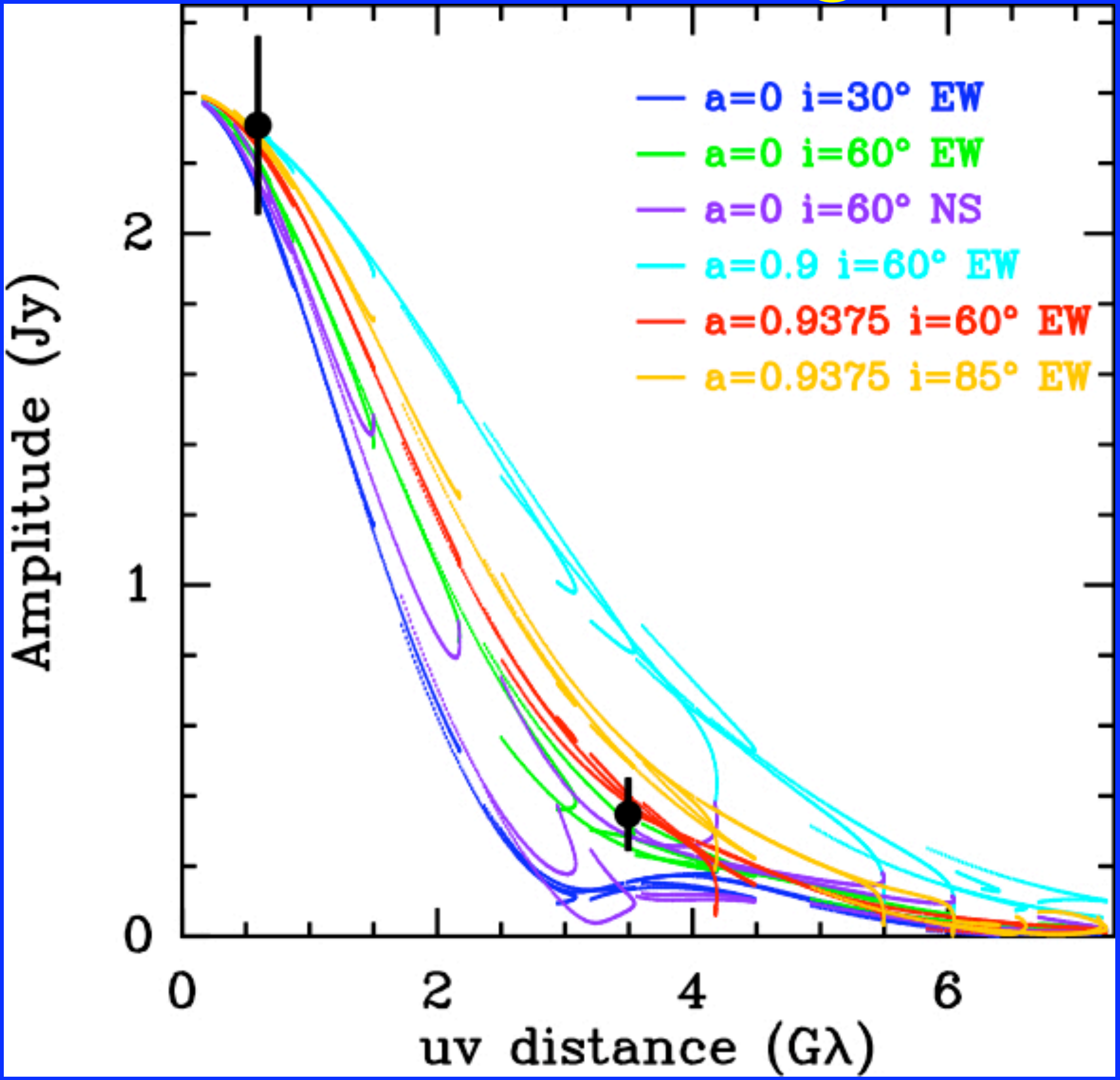
Alternatives to a MBH

- 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)

Constraining RIAF Models



SgrA* 10^{-8} Eddington

Inclination constrained to be >30 degrees: disk not 'face-on'.

Broderick, Fish, Doeleman & Loeb (2009)

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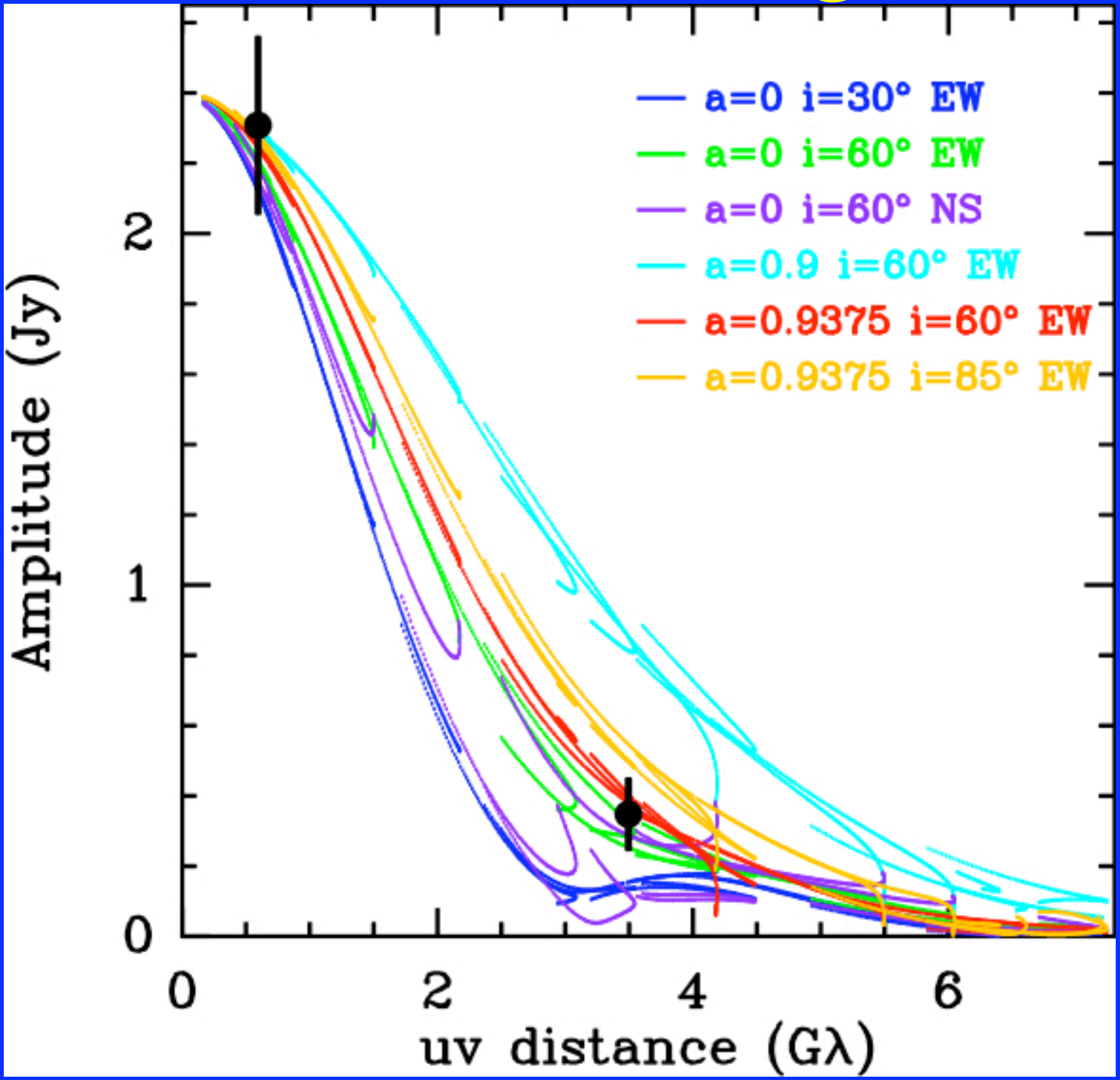

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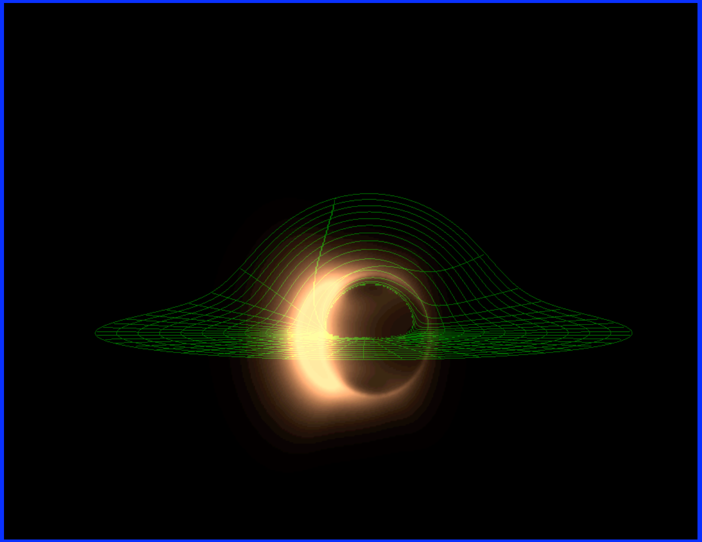
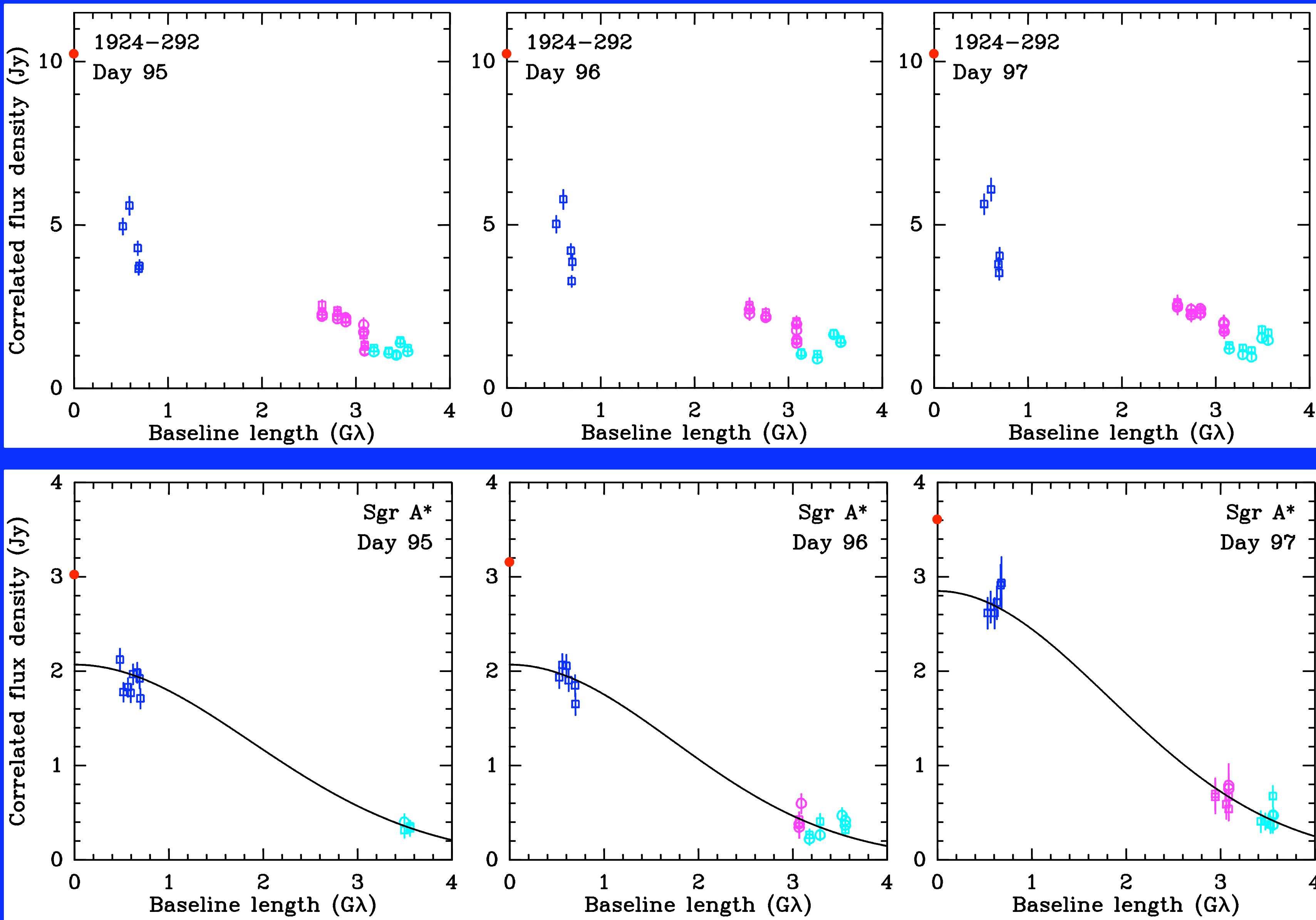


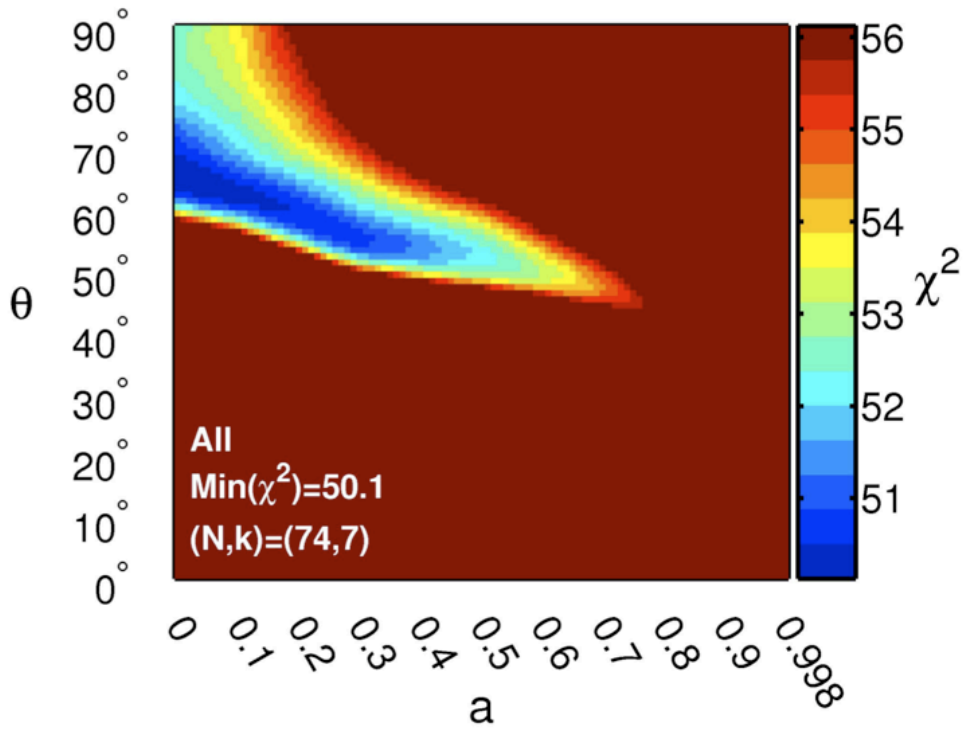
Broderick, Fish, Doeleman & Loeb (2009)

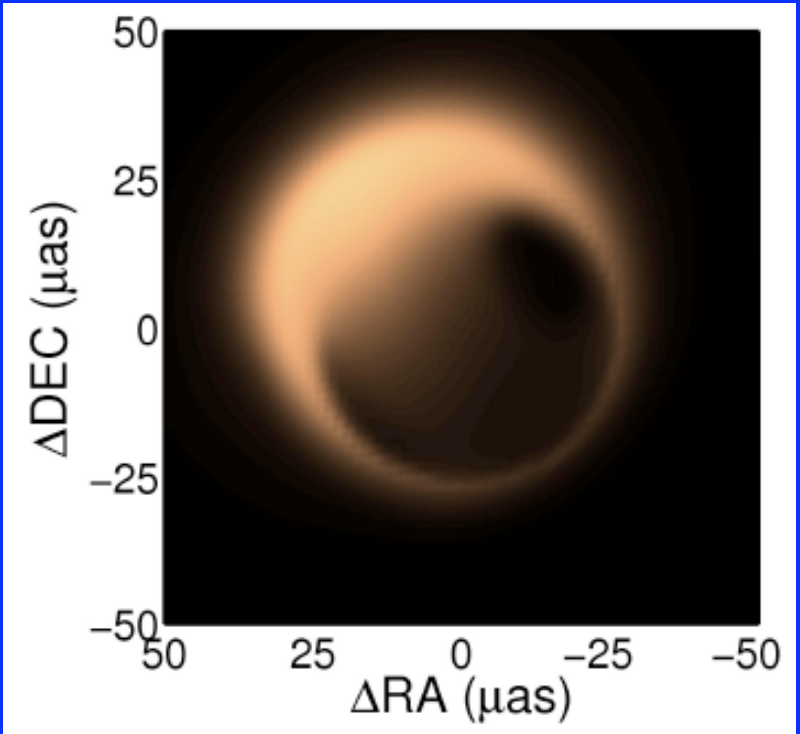
April 2009: SgrA* Flare on Rsch scales



Fish et al, ApJL, v727, L36, 2011

Tighter Constraints on BH spin.

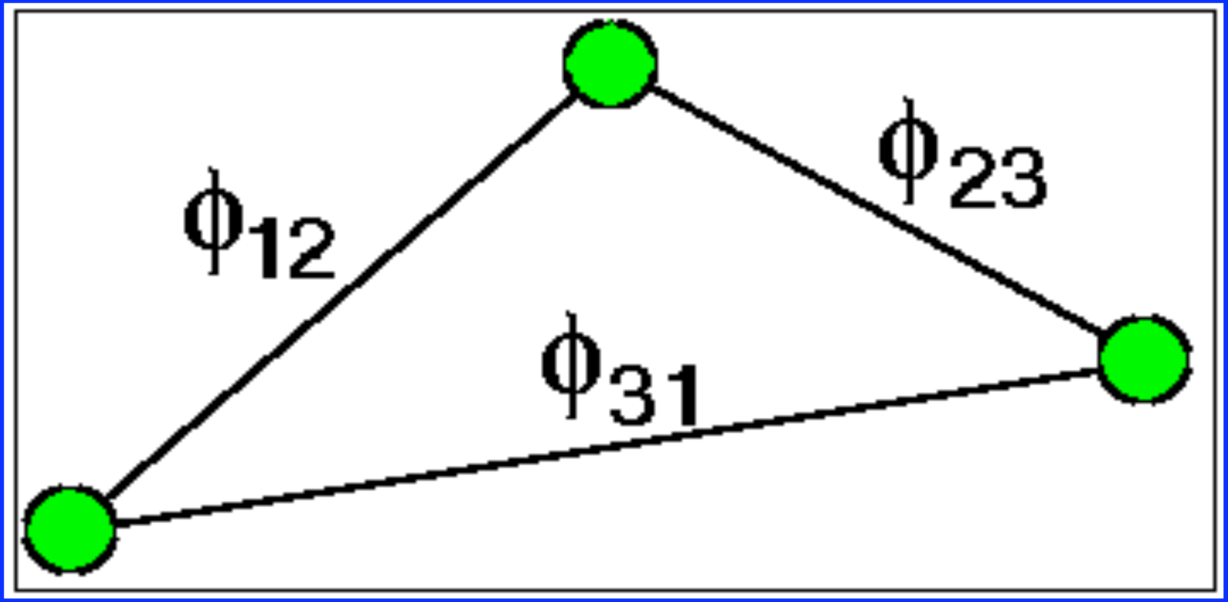




Broderick, Fish, Doeleman & Loeb, arXiv:1011.2770

Time Variable Structures

- Variabilty in NIR, x-ray, submm, radio.
- VLBI caught SgrA* ‘before’ and ‘after’ flare.
- Probe of metrics near BH, and of BH spin.
- Requires non-imaging analysis.
- Look for signatures of ‘hot spot’ flare models.



Hot Spot Model for SgrA* Flares

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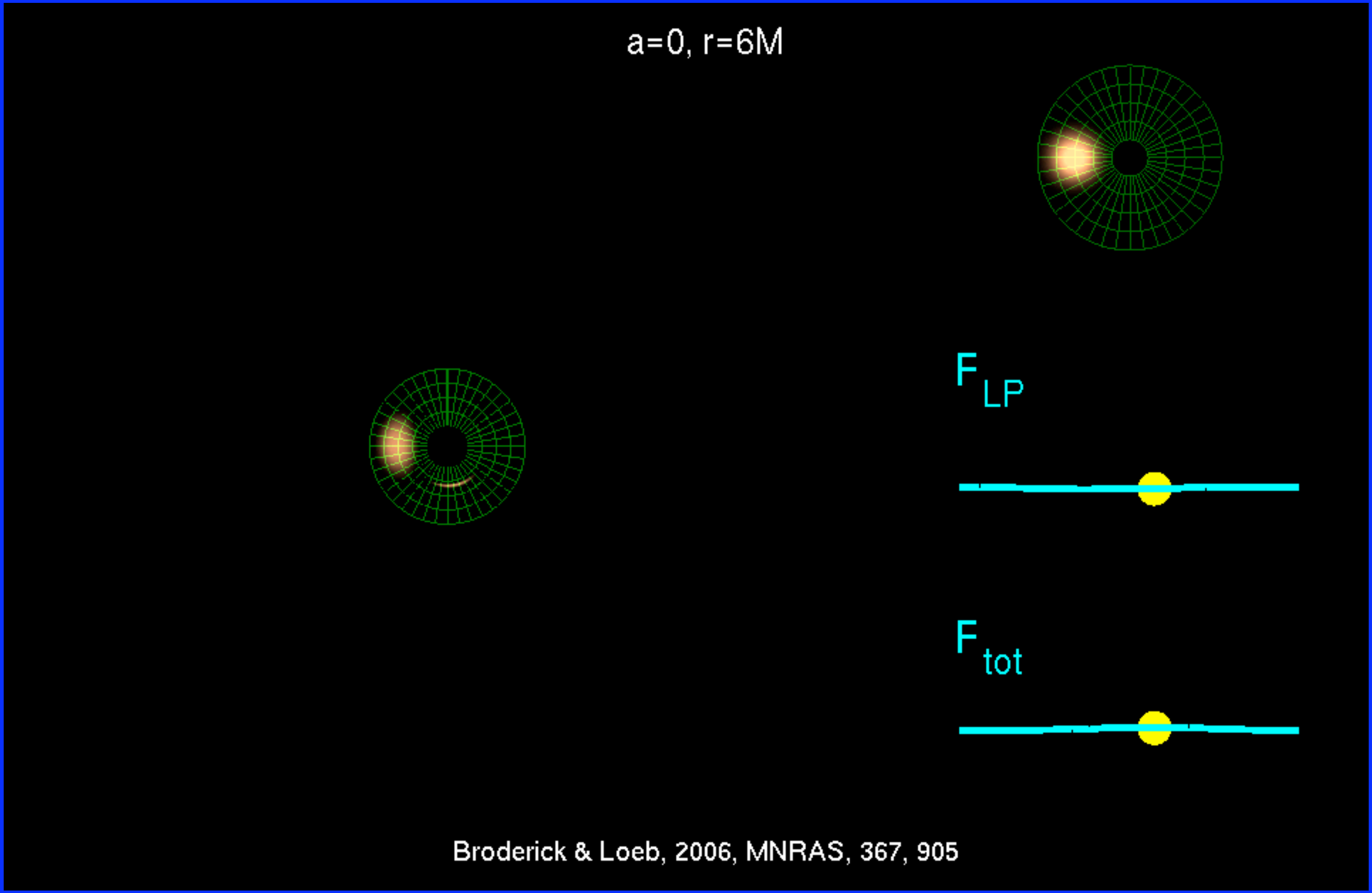
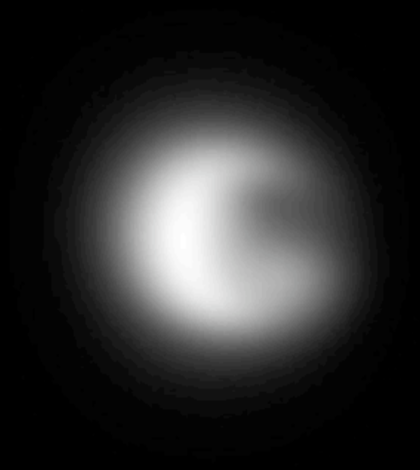
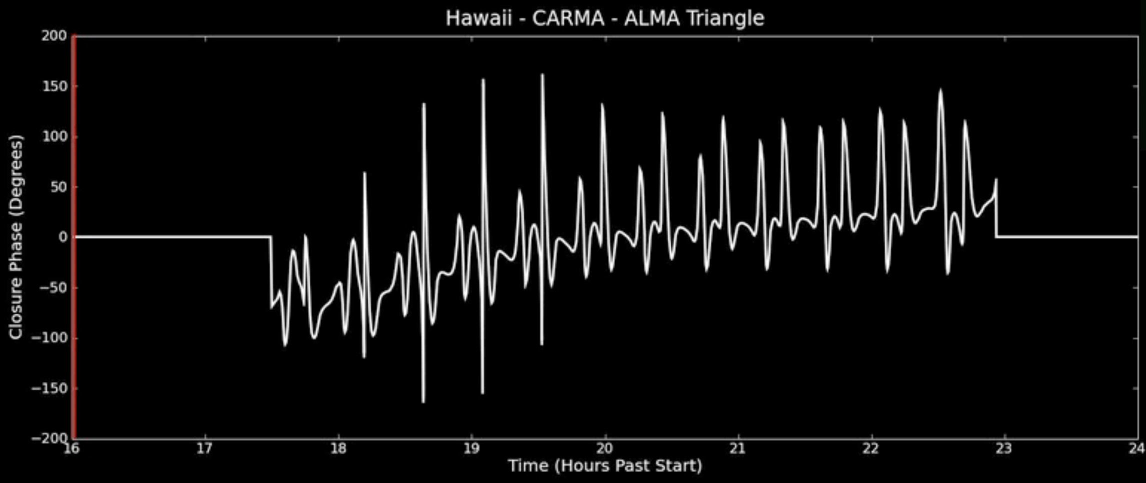


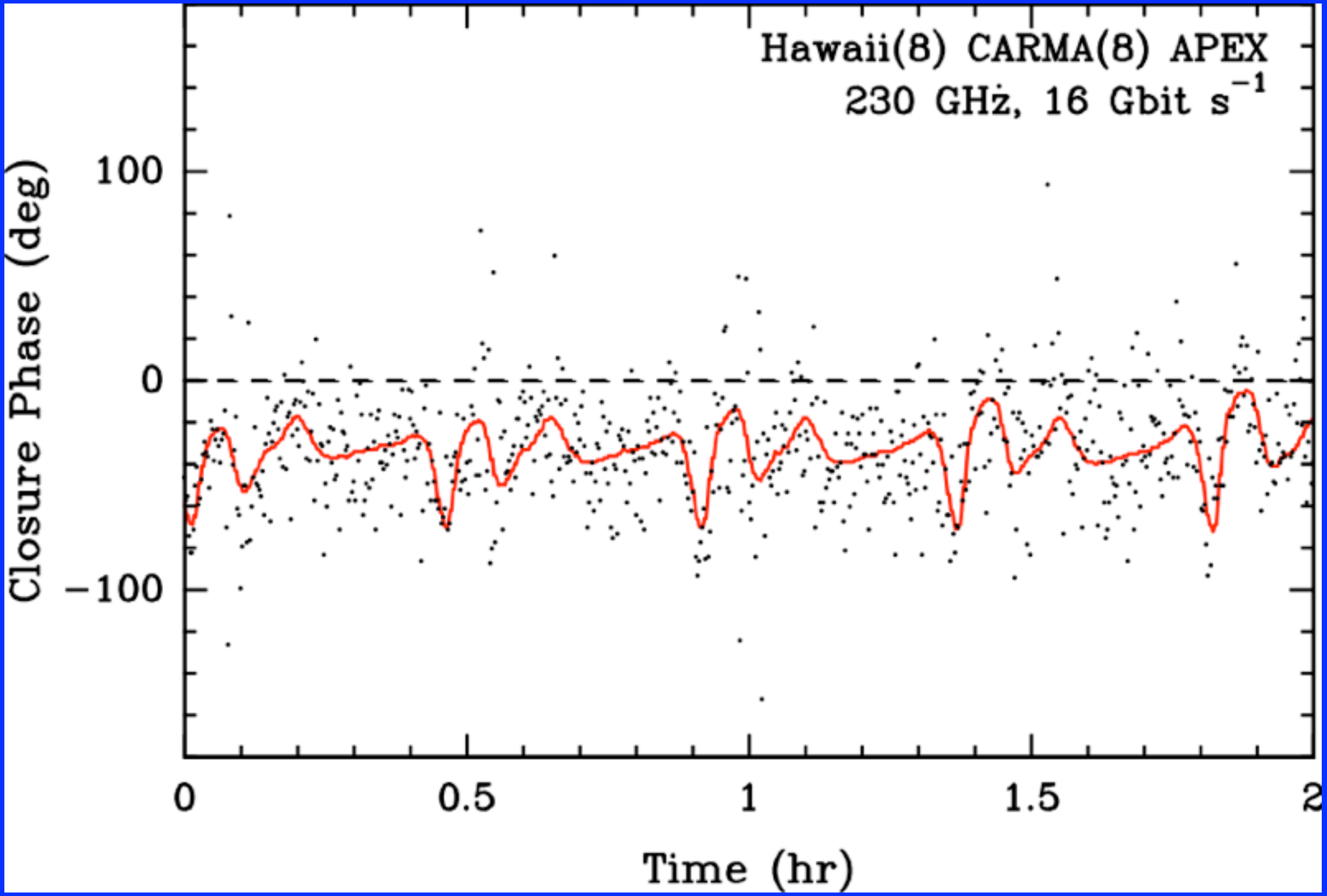
Tracing Black Hole Orbits with VLBI





Steeger et al

Measuring Black Hole Orbits with VLBI



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

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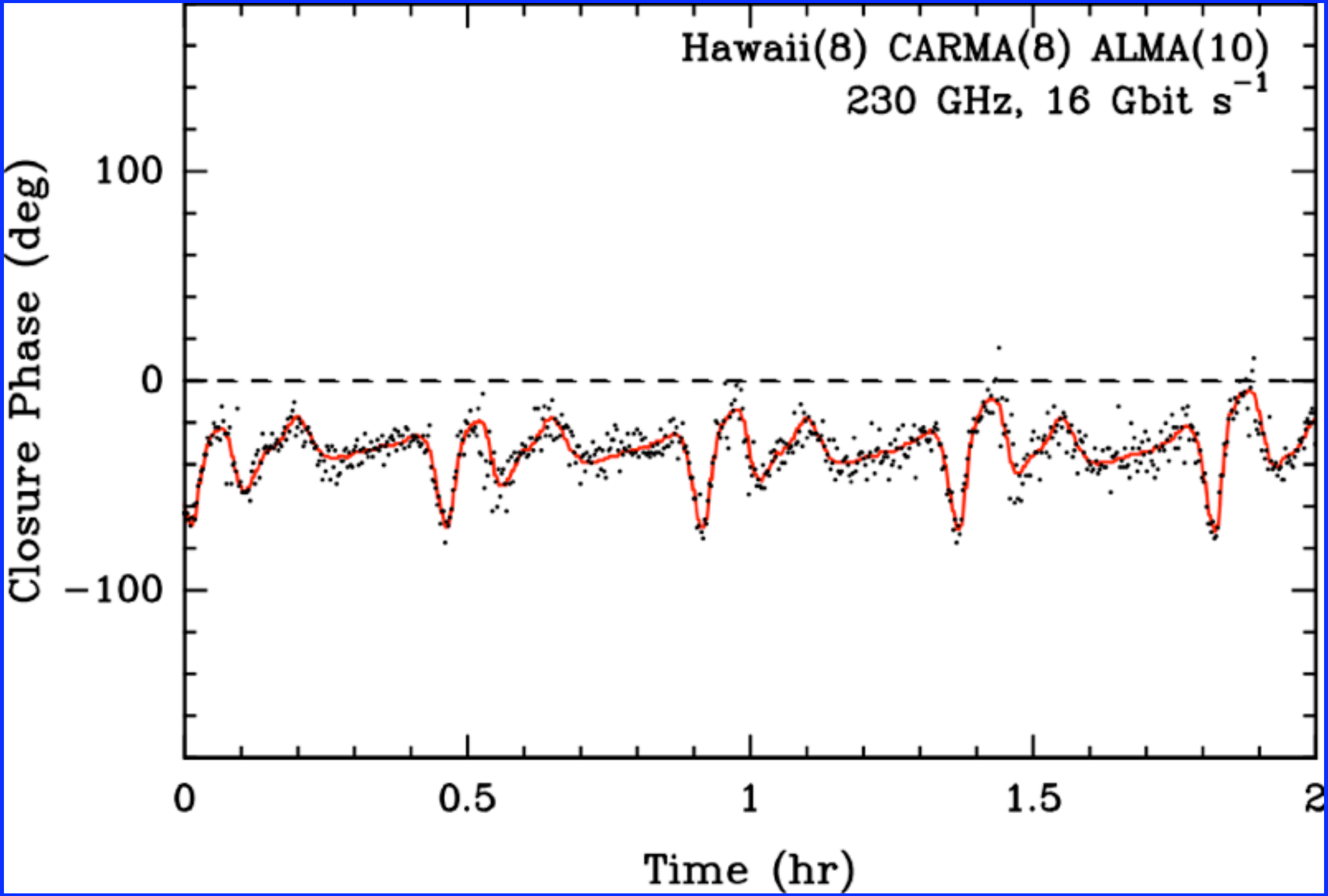

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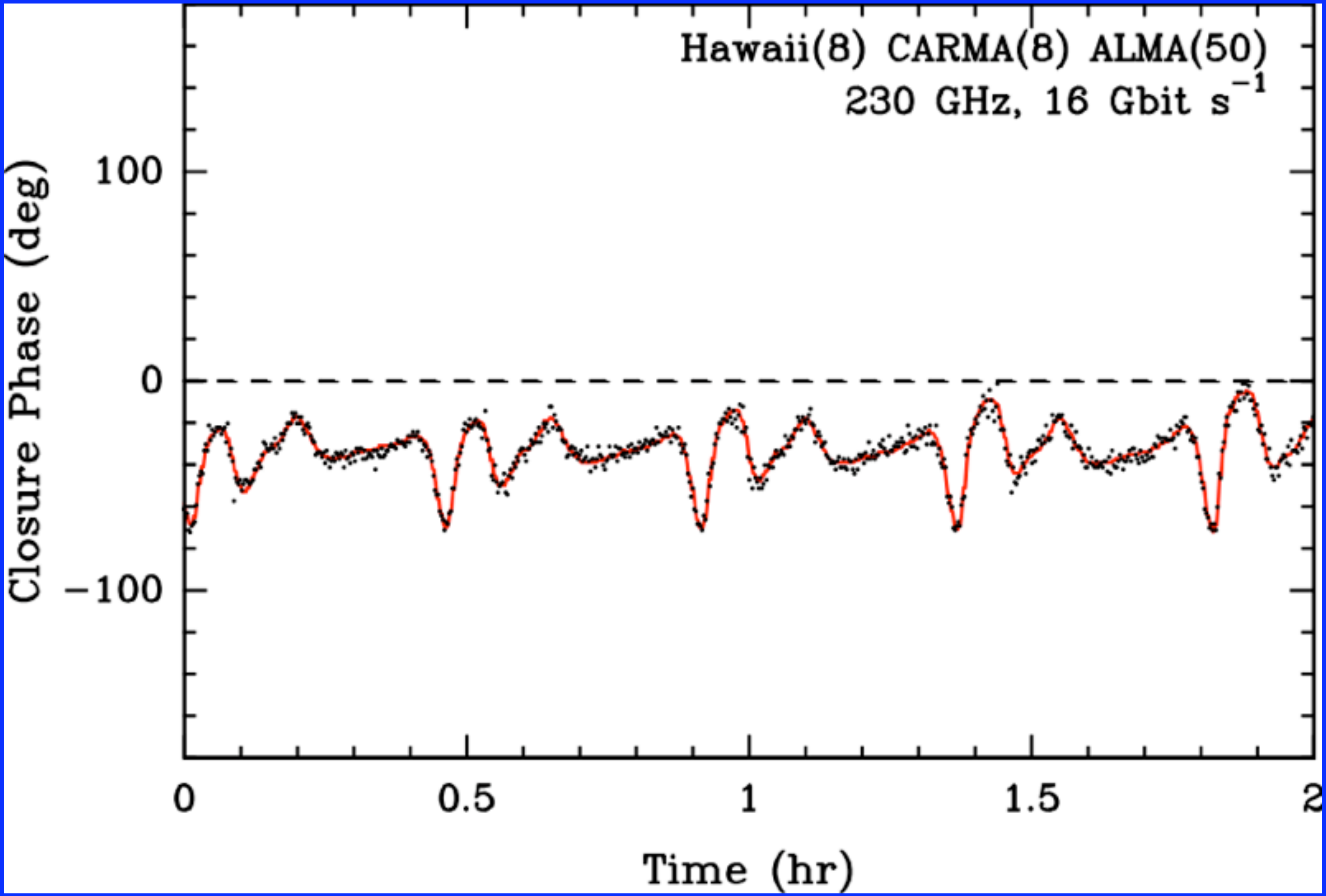

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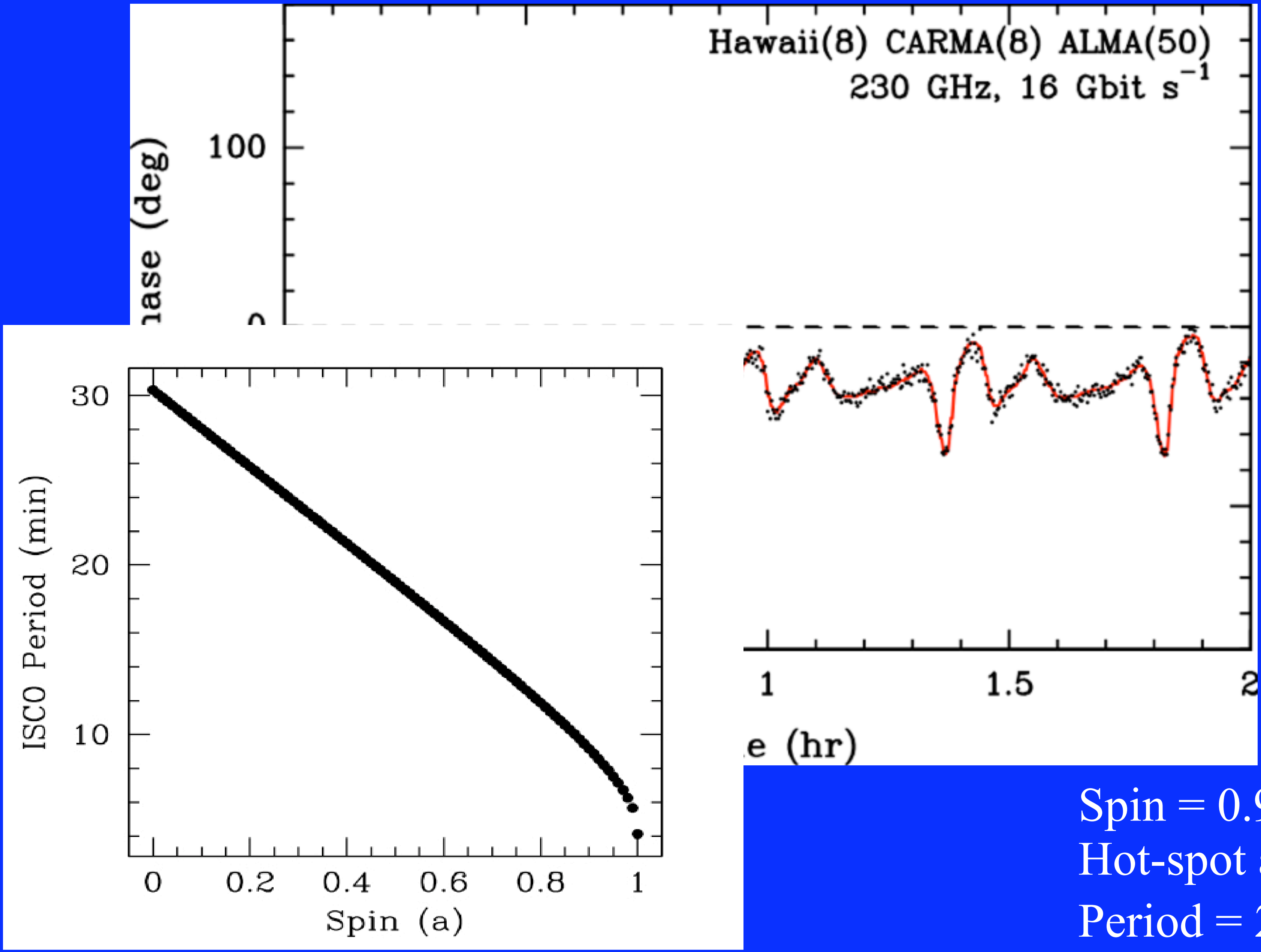

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VLBA Movie of M87 @ 43 GHz (7 mm)

Craig Walker et al. 2008

6.4 billion solar mass BH, FERMI & TeV source

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

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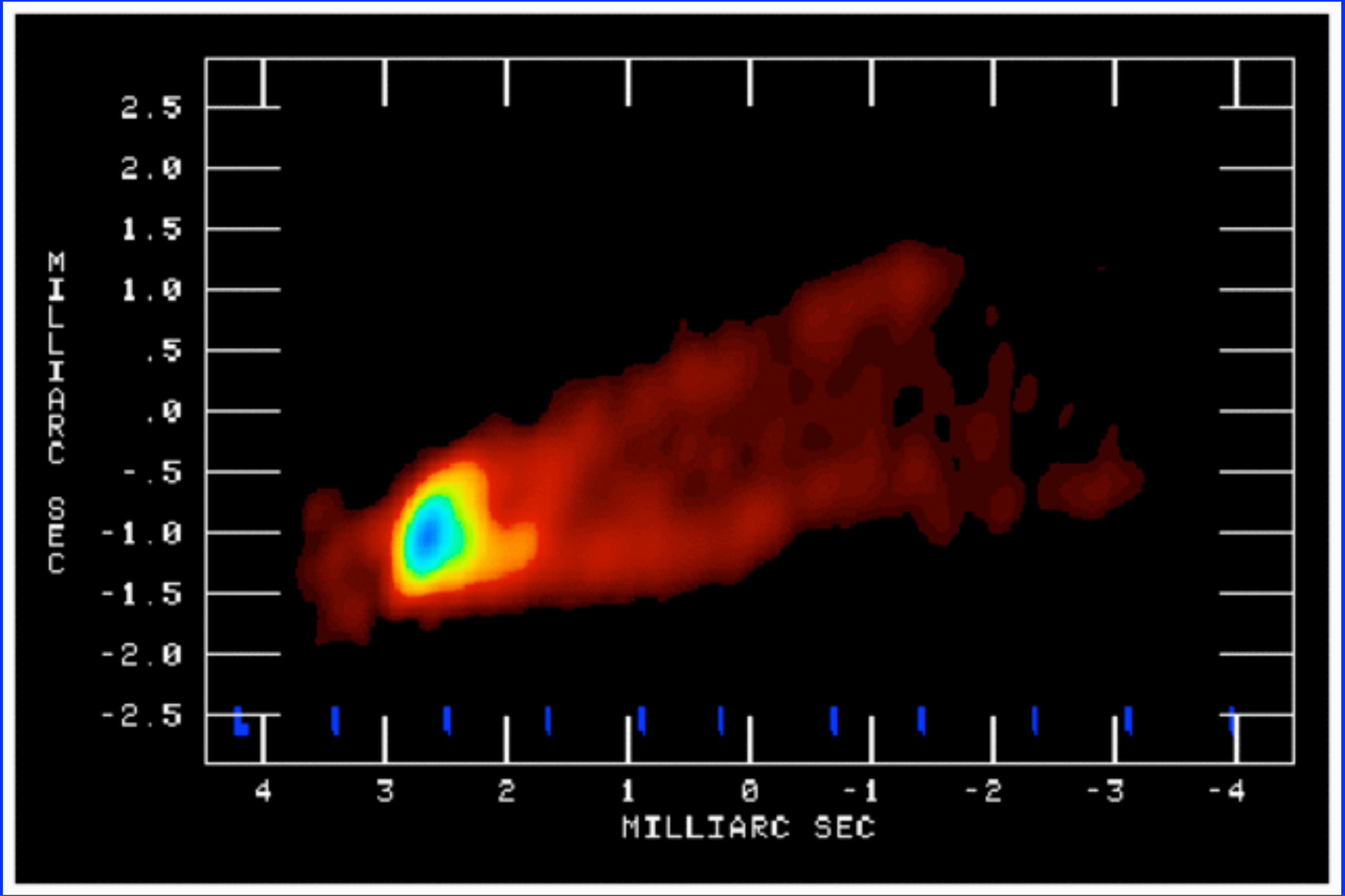
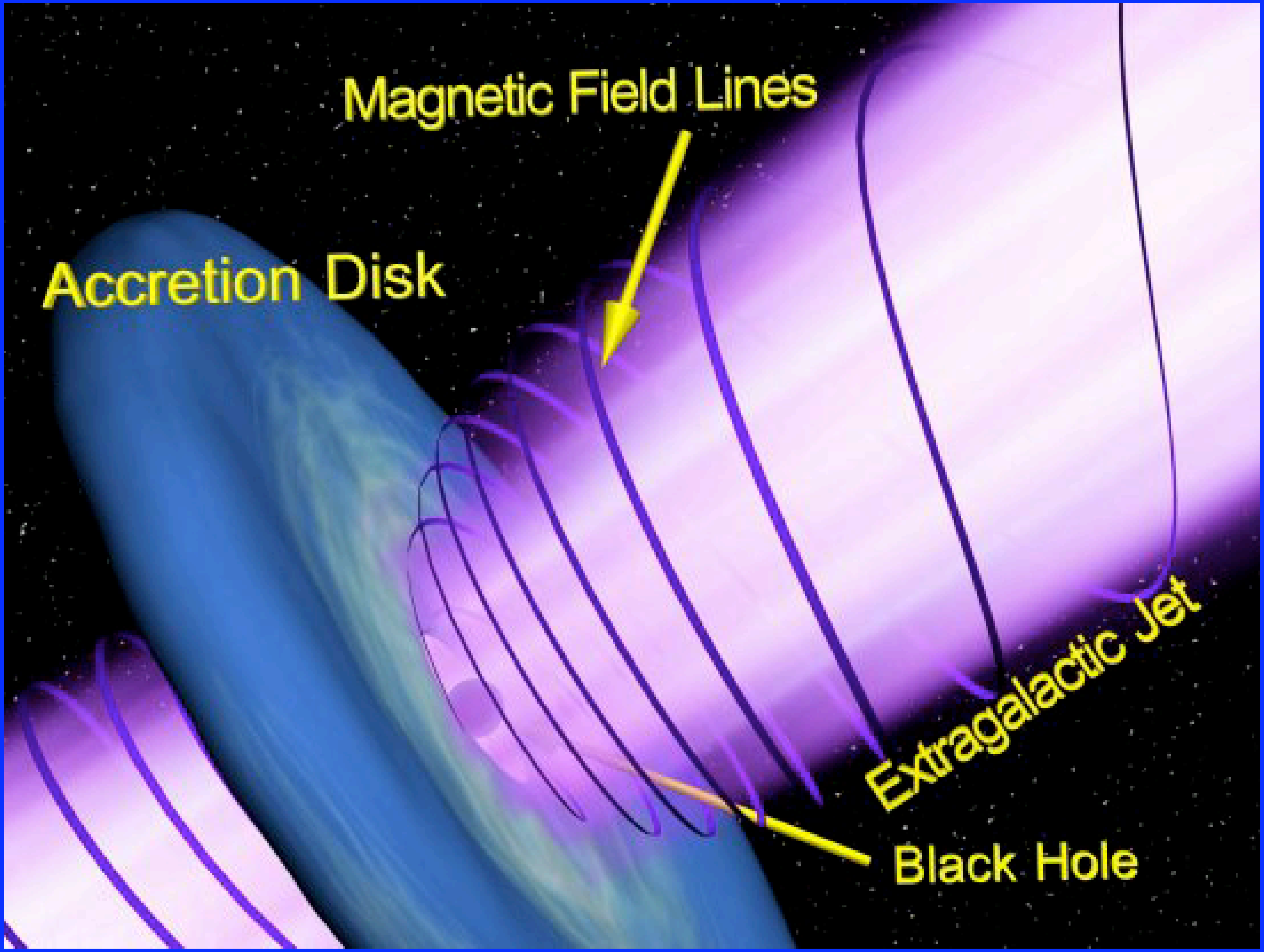


Magnetically Driven Jets



Building the Event Horizon Telescope
Astro2010 Roadmap Phase I

- Adding Telescopes: 7 station array.
- VLBI backends/recorders that support > 16Gb/s.
- Central wideband correlator (up to 64Gb/s) [ATI prop].
- Phased Array processors (SMA, ALMA, PdeBure, CARMA) [MRI prop]
- Leverage ALMA receivers for EHT [AAG prop].
- Procure Hydrogen Masers.
- 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

New (sub)mm VLBI Sites

Current: ARO/SMT + CARMA + SMA + JCMT + CSO
Phase 1: 7 Telescopes (+ IRAM, PdB, LMT, Chile/ALMA)
Phase 2: 9 Telescopes (+ Spole, Haystack)
Phase 3: 13 Telescopes (+ NZ, Africa,SEST)

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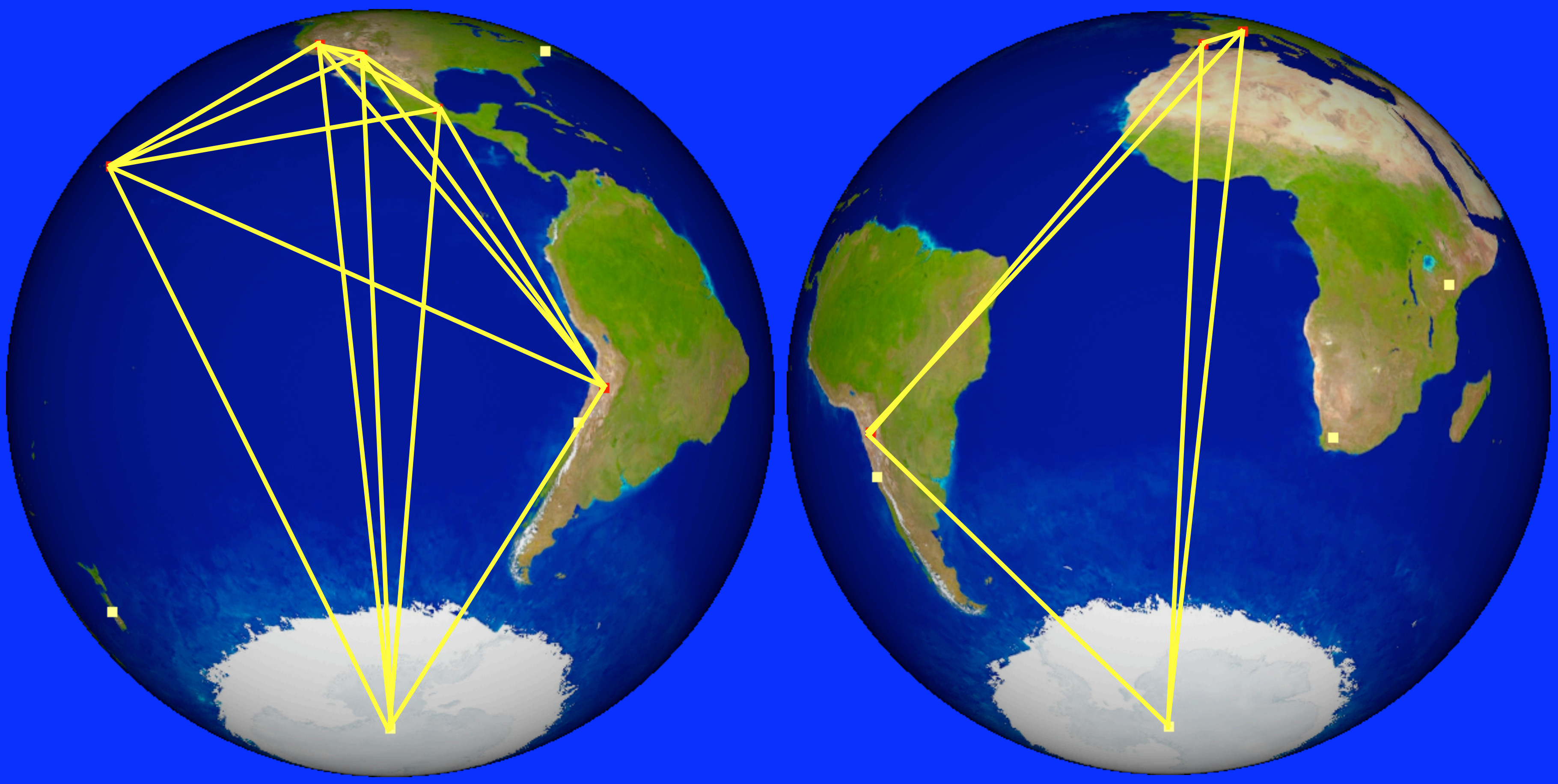

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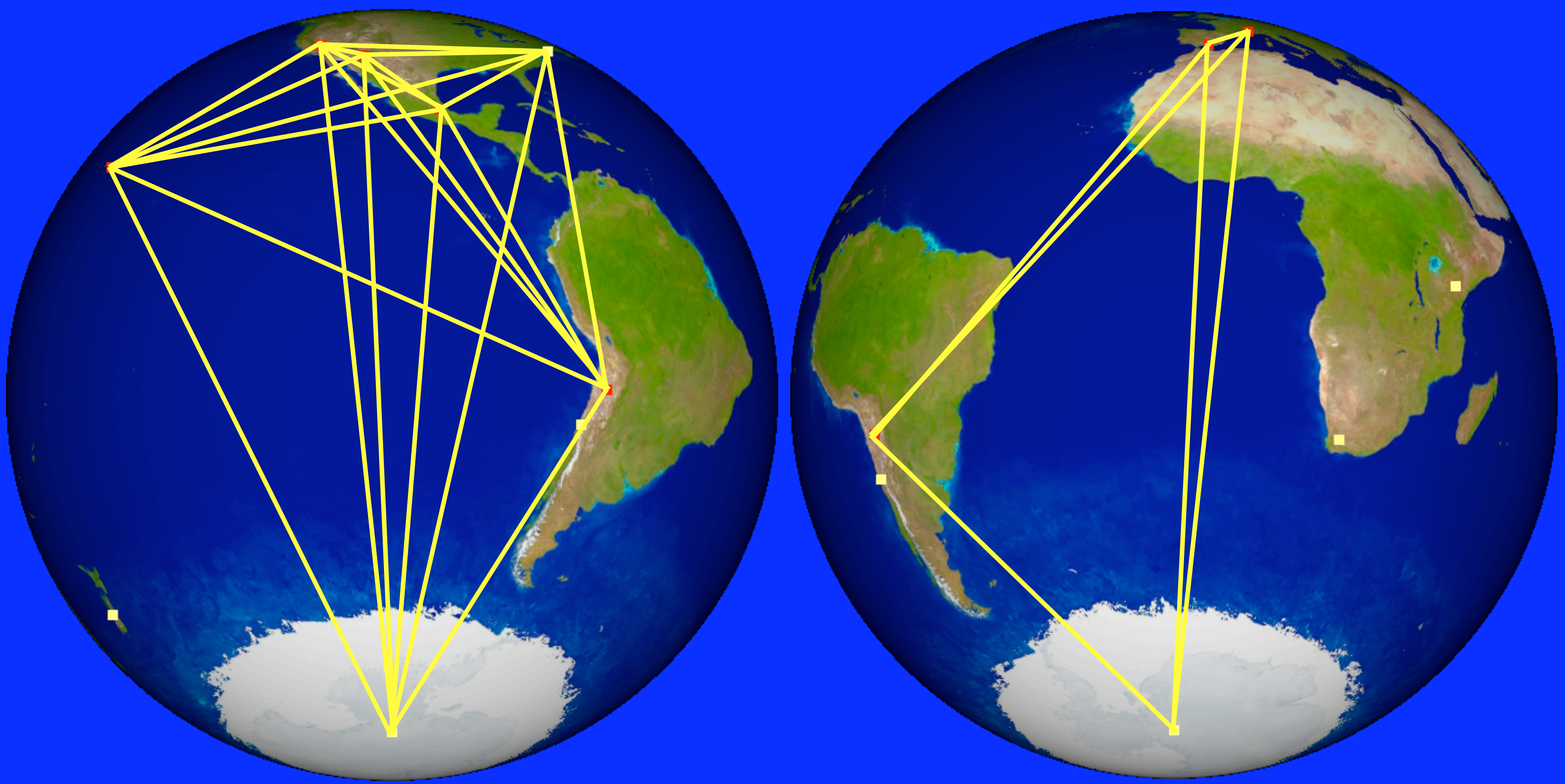

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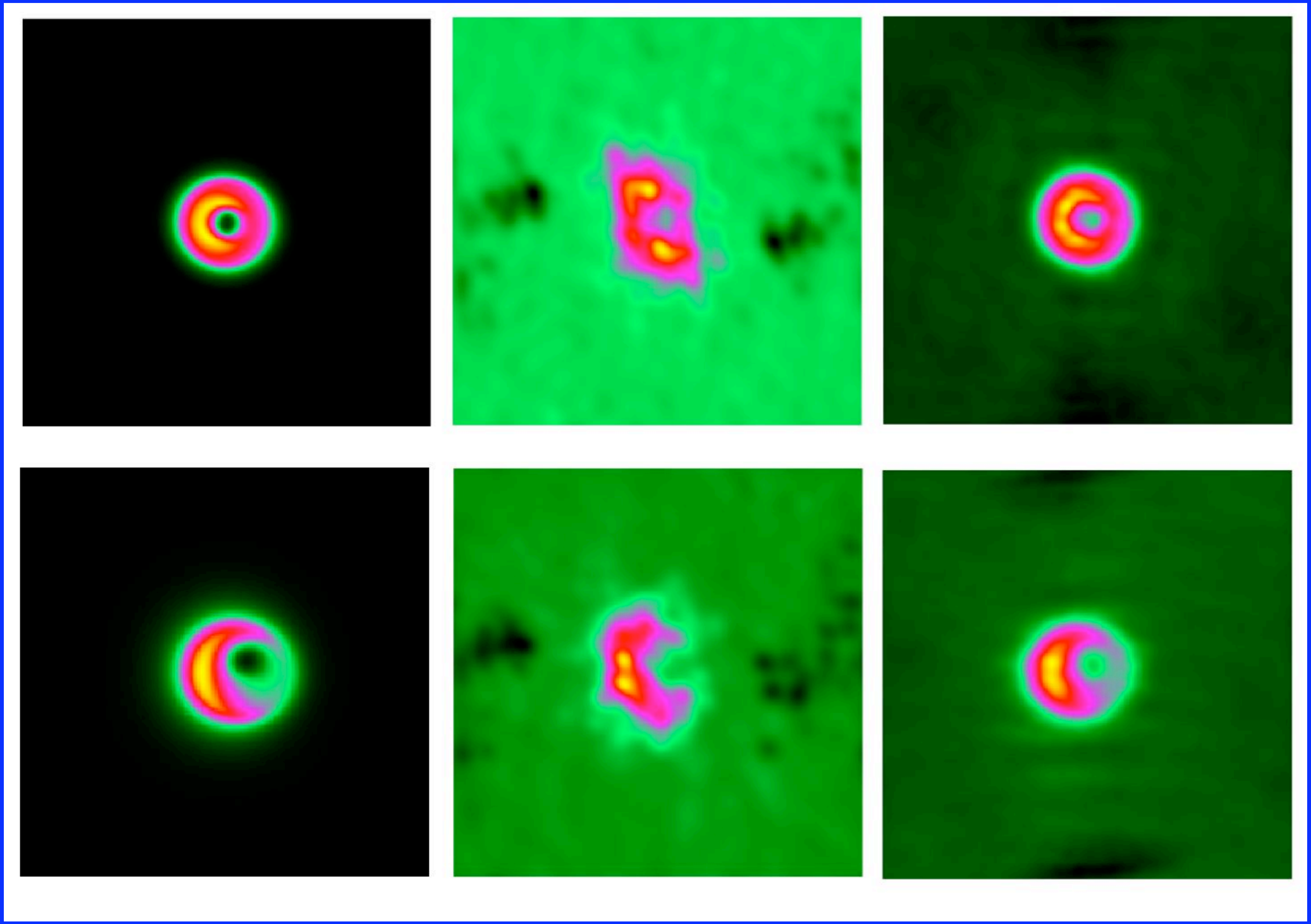
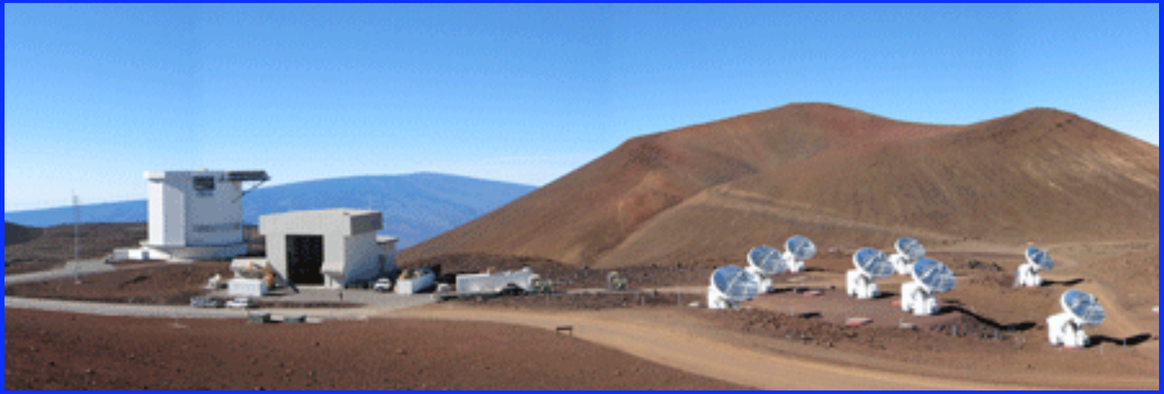
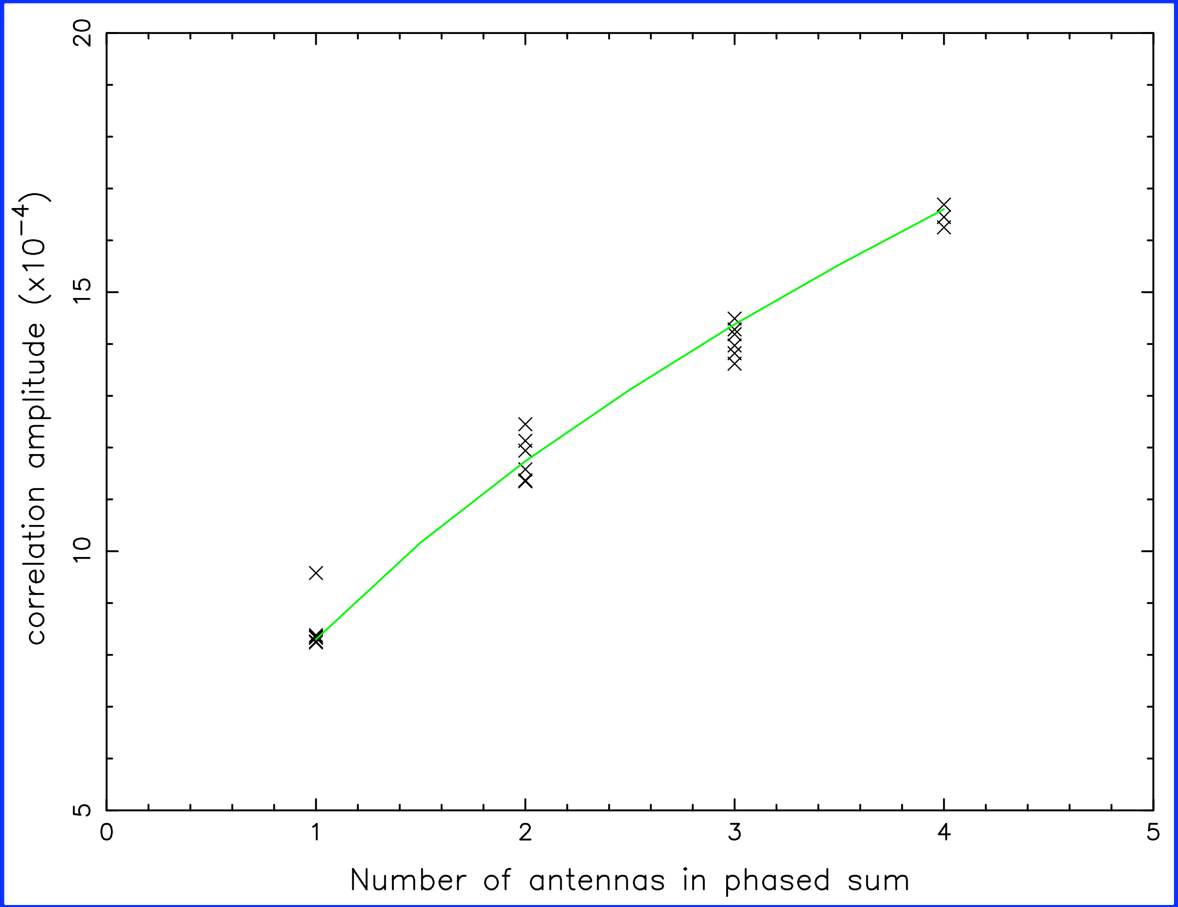
Progression to an Image



GR Model   7 Stations   13 Stations

Phasing Arrays: SMA, CARMA this month.



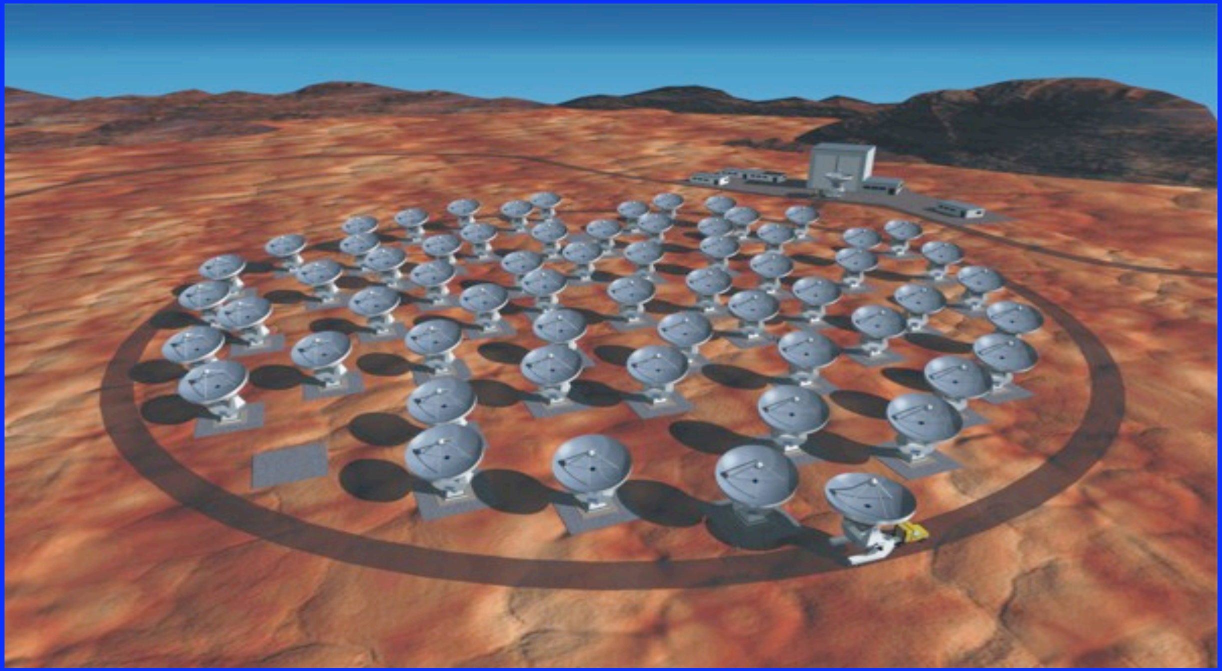


SMA:
Weintroub,
Primiani, et al

CARMA: Wright,
McMahon, Dexter,
et al

Phasing ALMA

- Single most important objective for EHT.
- Increases resolution by x2, sensitivity by x10.
- Allows detection in 10s to all other EHT sites.



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Event Horizon Telescope Collaboration

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

Summary

- EHT results confirm Rsch structures in SgrA* and M87.
- EHT has detected SgrA* closure phase and variability.
- Technical path for Phase I of EHT clear.
- New science results at each phase of the project: March/April ’11 - ARO/SMT, CARMA, Mauna Kea, APEX, IRAM30m.
- Transformative enhancements in EHT within 3/4 years.
- Imaging an Event Horizon and observing BH orbits are within reach in <5 years.
- Creates a fundamentally new telescope without building new dishes.
- Tailored for this decade (beginning of the ALMA era).