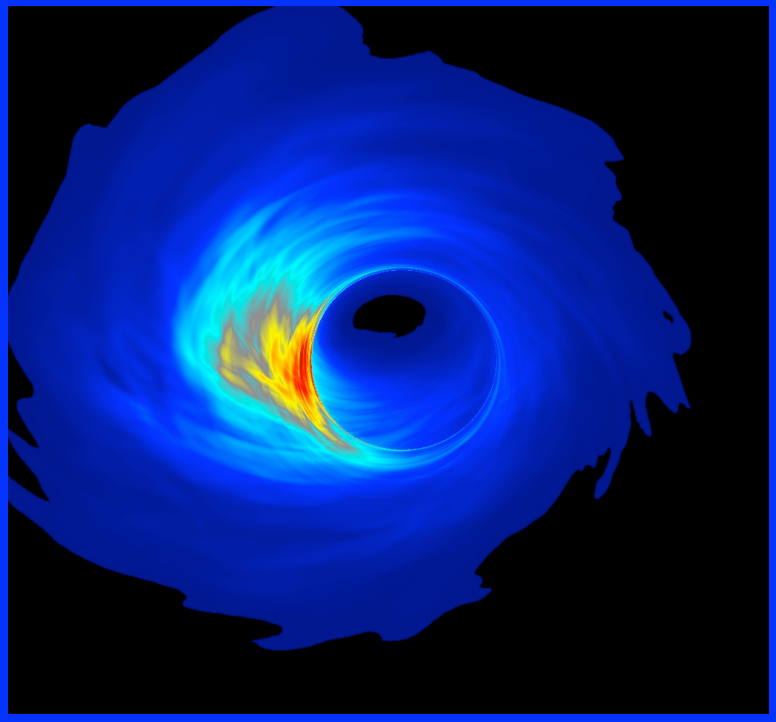
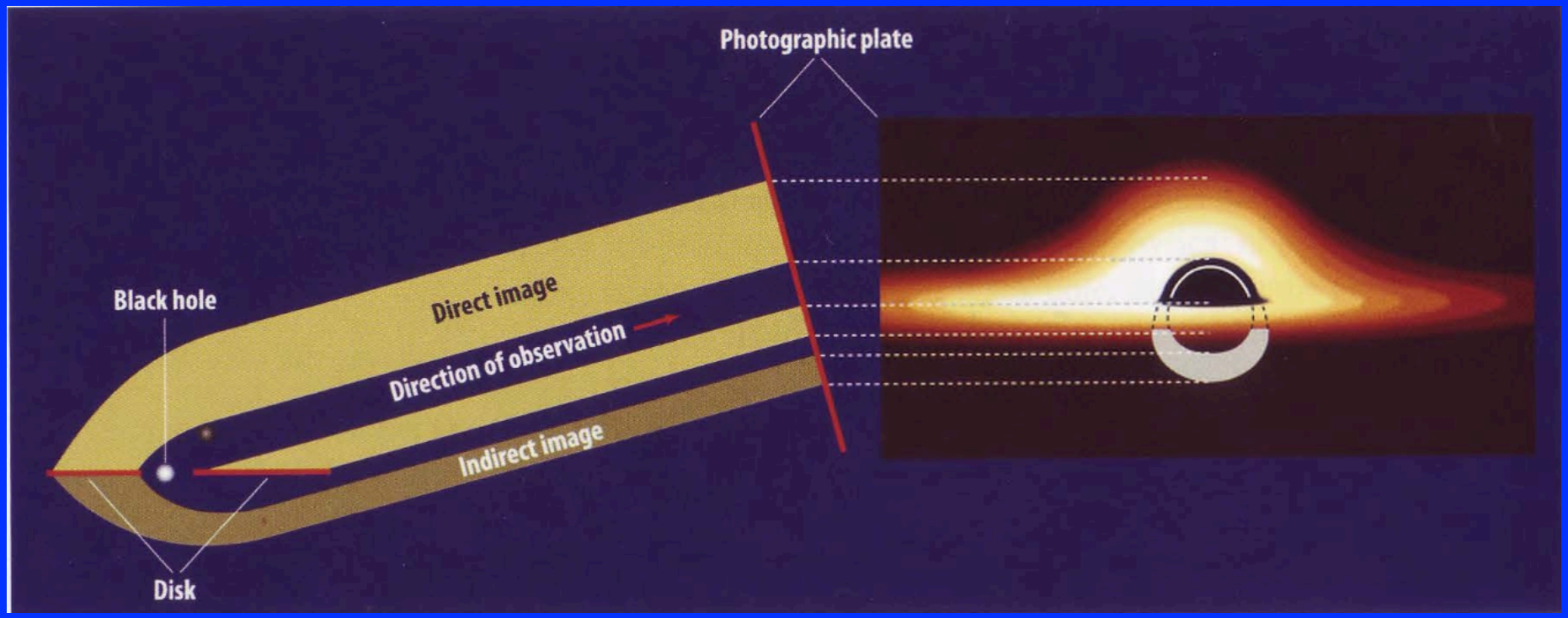
Accessing Schwarzschild Radius Scales with the Event Horizon Telescope



Sheperd Doeleman
MIT Haystack Observatory & SAO

Strong GR: The Black Hole Shadow



Bardeen 1973
Luminet 1979

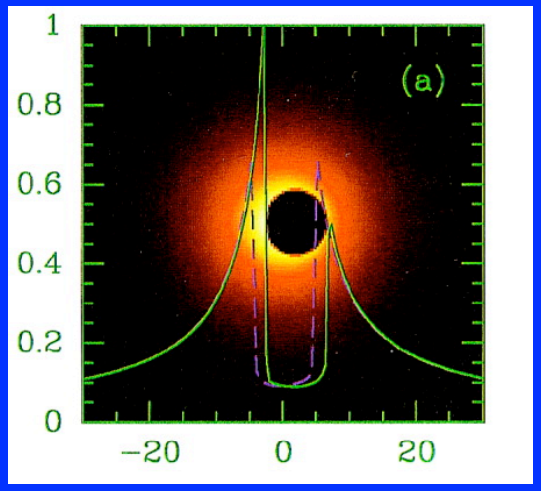
Shadow Diameter:

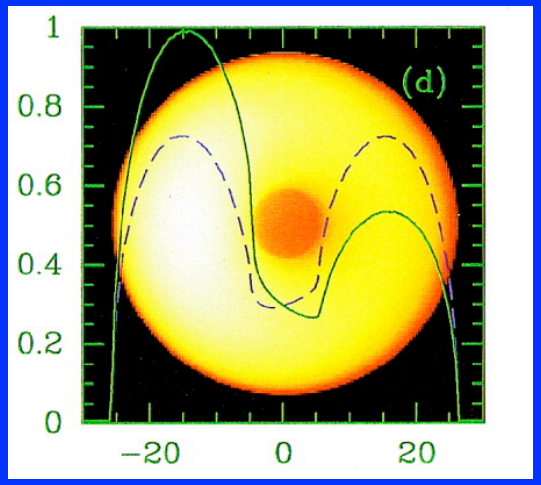
Non-spinning (a=0)
Dsh = sqrt(27) * Rsch

Spinning (a=1)
Dsh = 9/2 * Rsch

Shadow size and shape encodes GR.

Models/Simulations of SgrA*

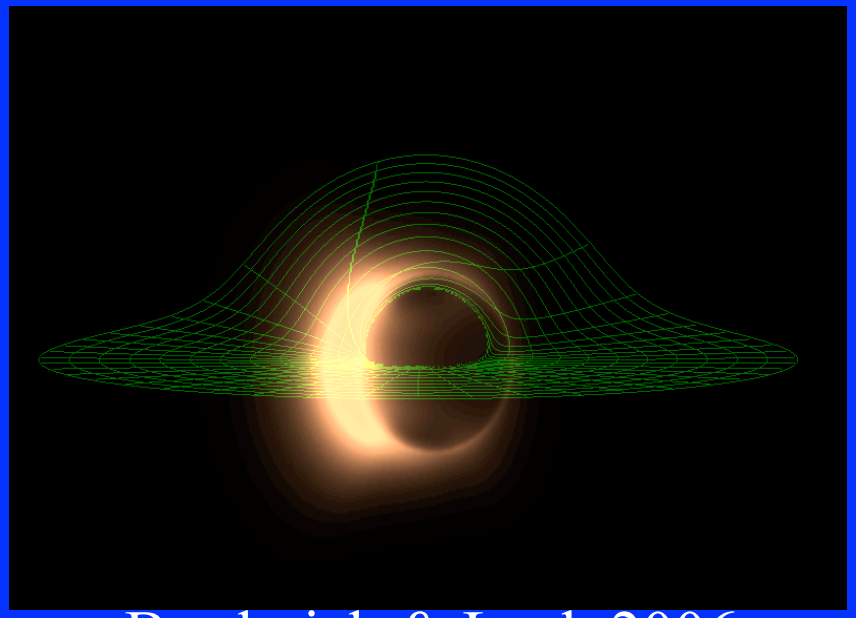




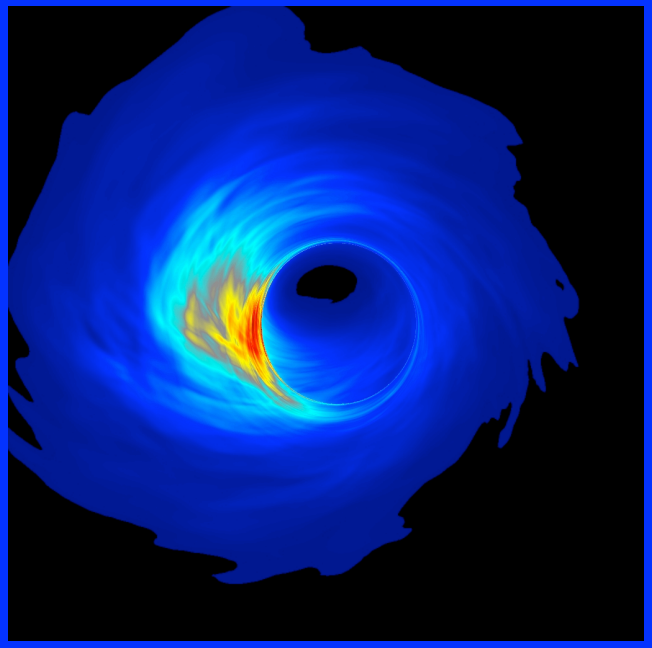
Falcke
Melia
Agol
2000

Spinning (a=1)

Non-spinning (a=0)



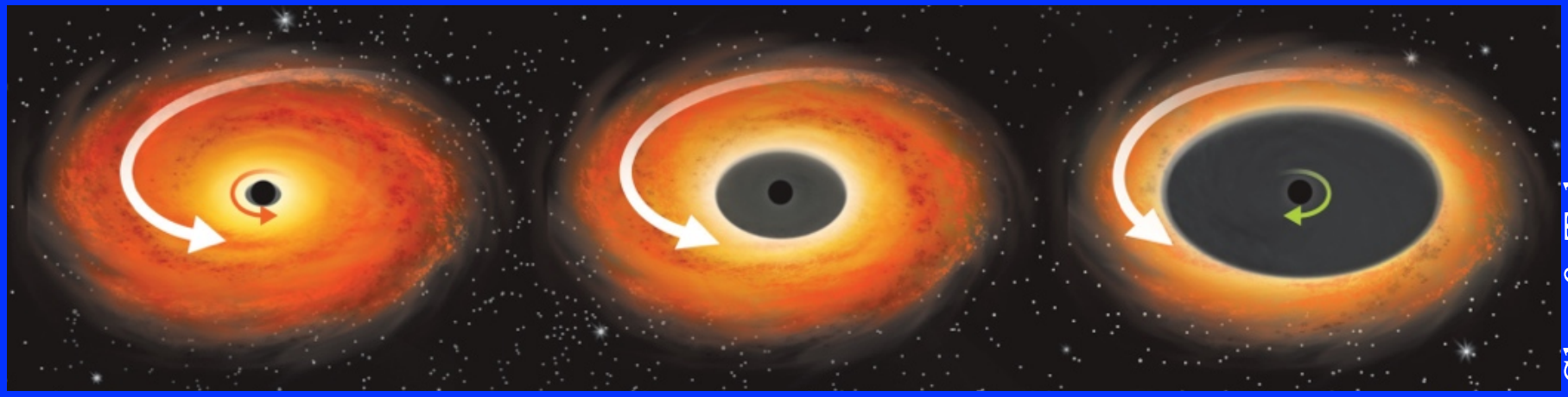
Broderick & Loeb 2006



Noble &
Gammie

Strong GR Effects: Matter

- Innermost Stable Circular Orbit Size.



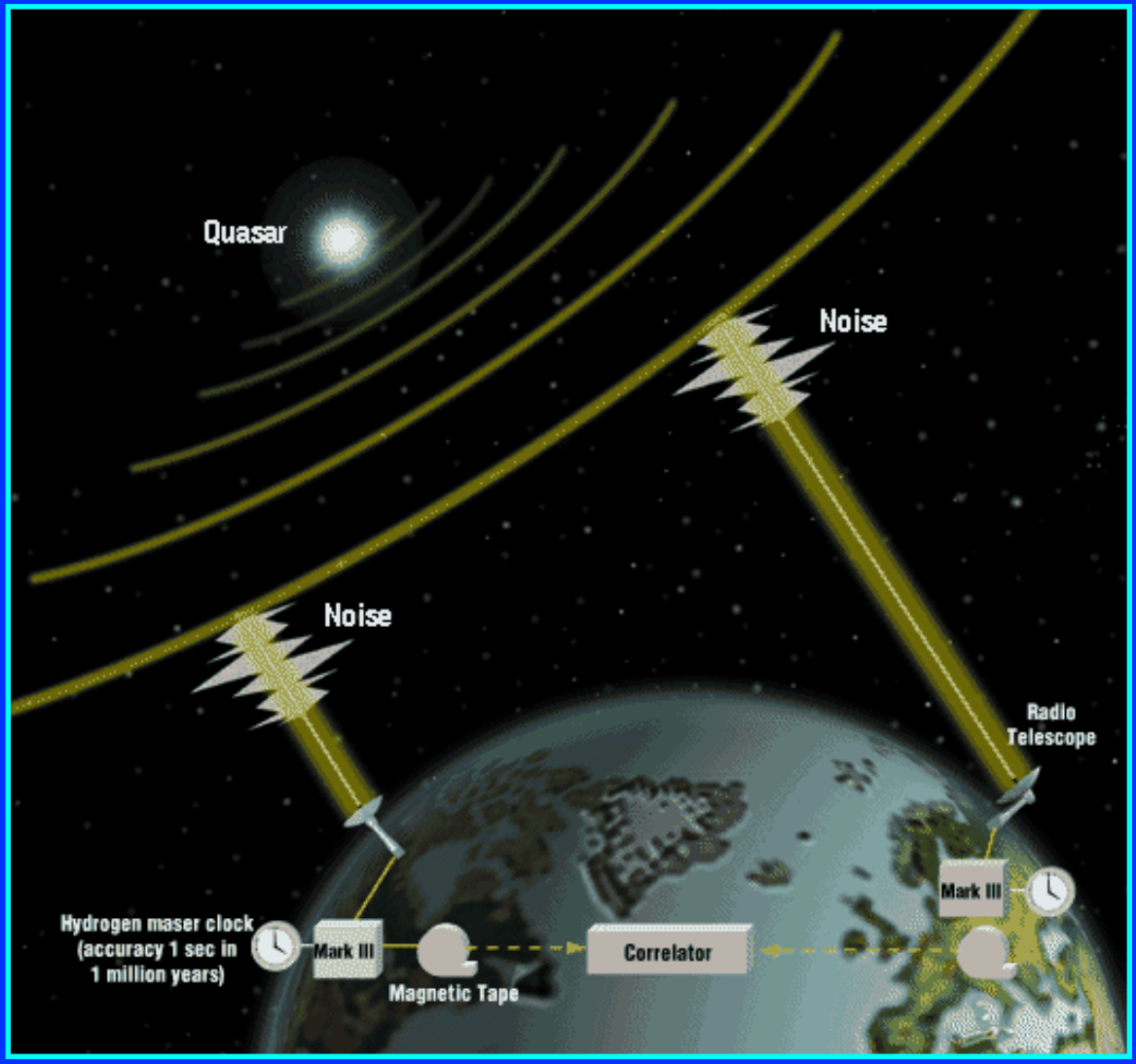
Sky & Telescope

Max. Prograde
ISCO_d = 1 Rsch

No Spin
ISCO_d = 6 Rsch

Max Retrograde
ISCO_d = 9 Rsch

Short Wavelength VLBI



Resolution:

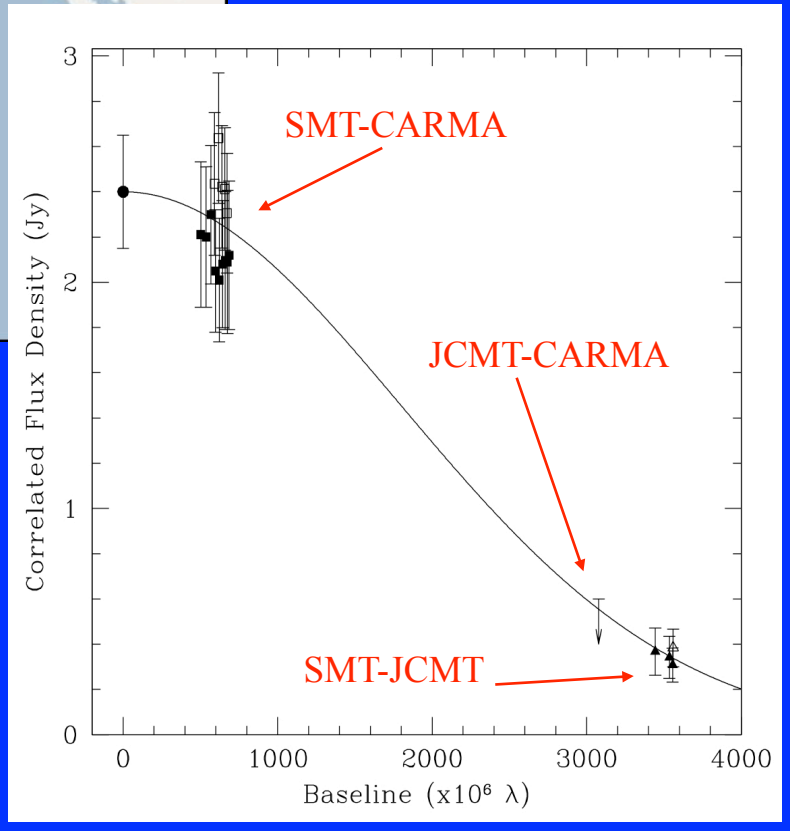
λ/D (cm) ~ 0.5 mas
λ/D (1.3mm) ~ 30 μas
λ/D (0.8mm) ~ 20 μas

ISM Scattering:

$\Theta scat \sim \lambda^2$

SgrA*: Event Horizon Structure Confirmed

Doeleman et al 2008

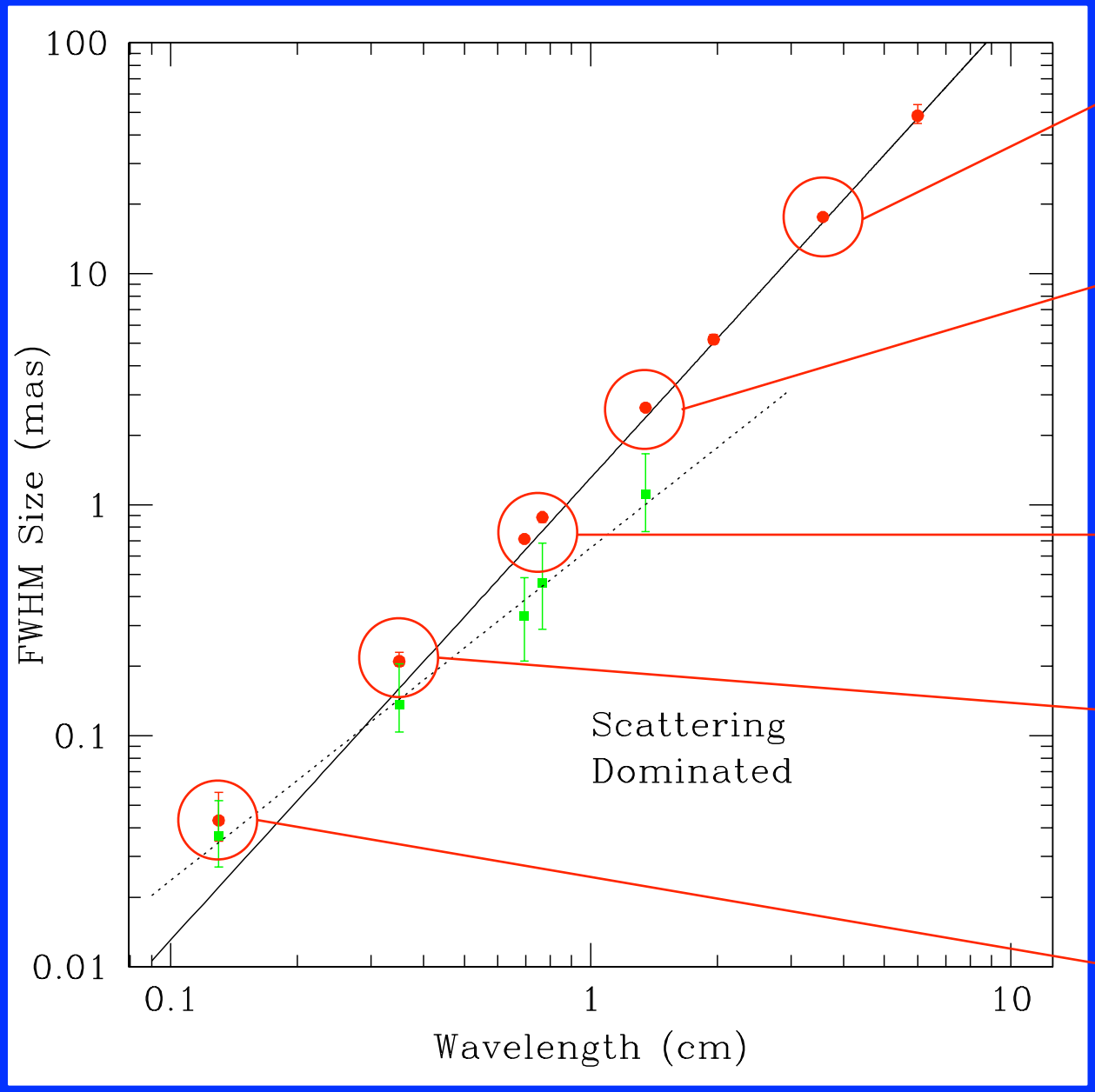


About 4 Schwarzschild radii across.

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

4 million suns within the orbit of Mercury.

SgrA*: Piercing the Scattering Screen



Lo 1975
Jauncy 1989

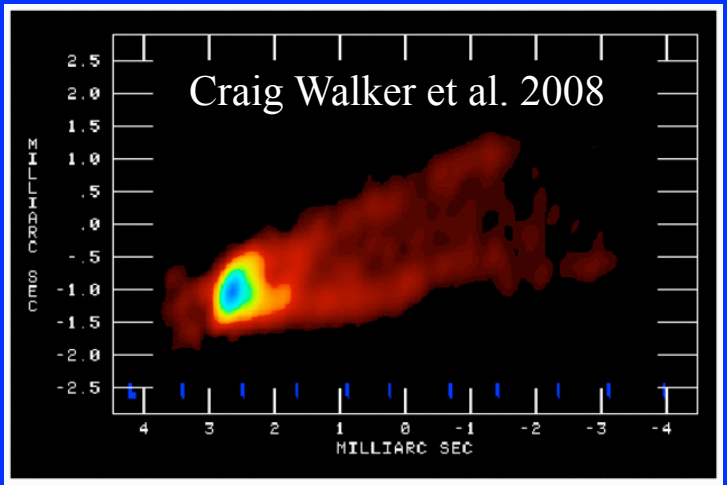
Lo 1985
Marcaide 1999

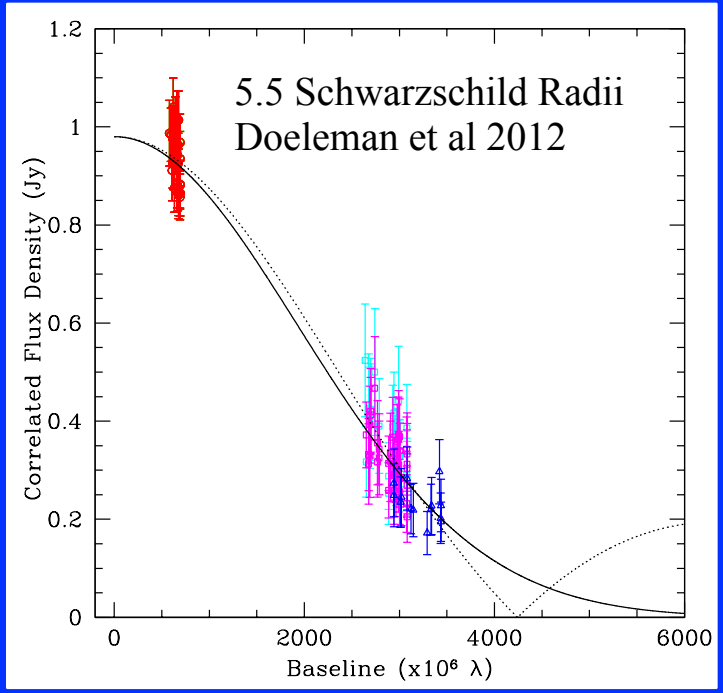
Backer 1993
Krichbaum 1993
Bower 2004

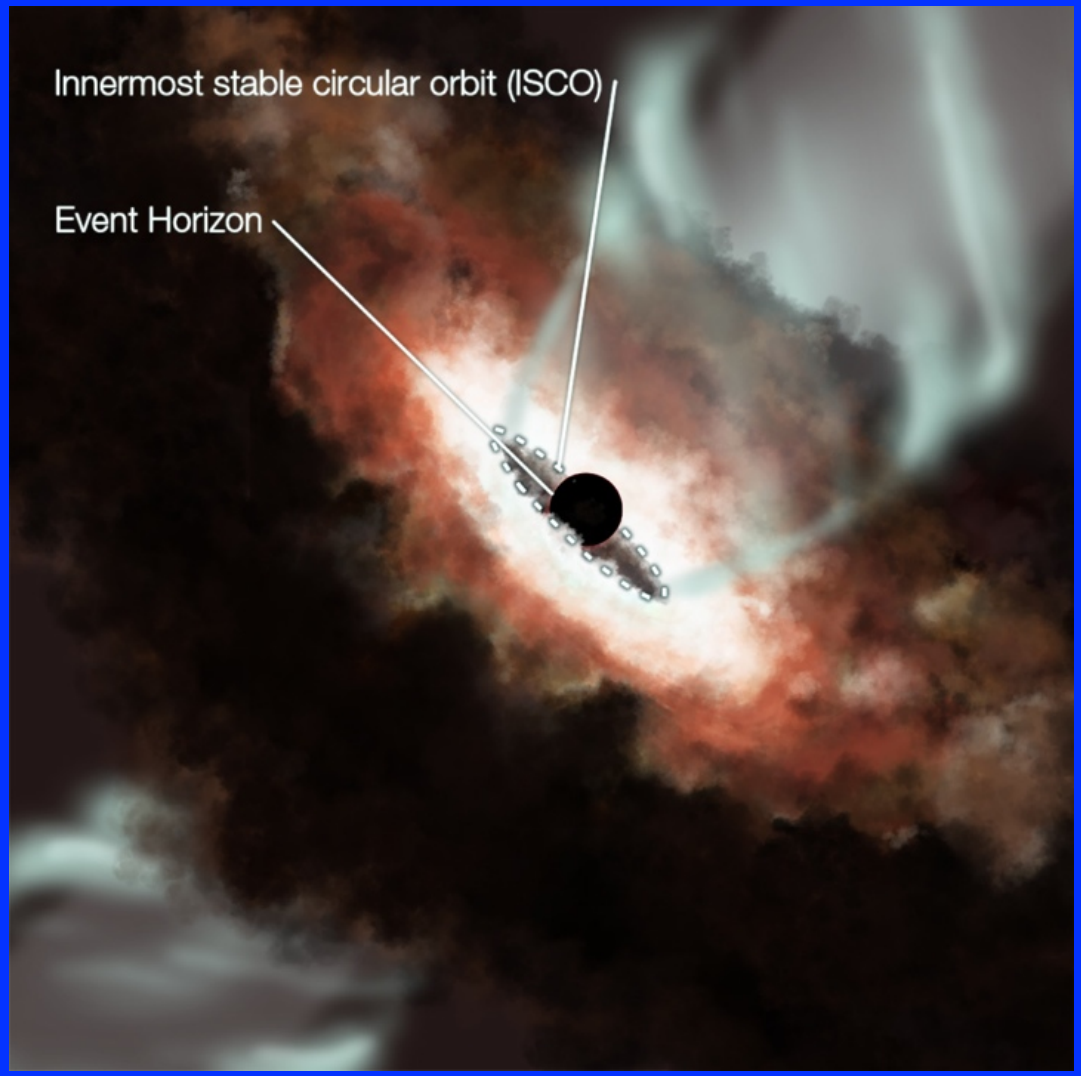
Rogers 1994
Krichbaum 1998
Shen 2005

Doeleman 2008
Fish 2011

M87: BH Origins of a Relativistic Jet



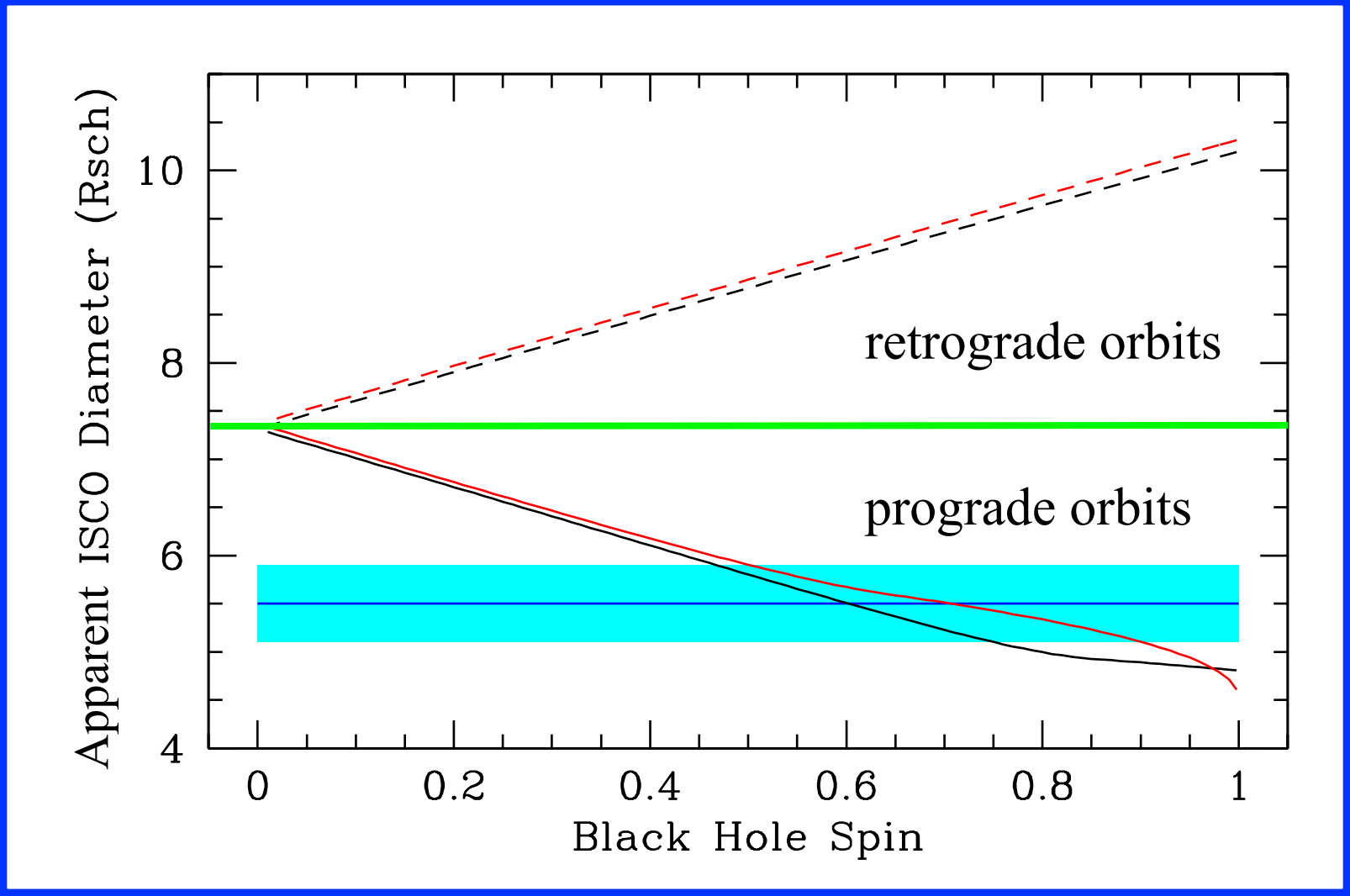




Graphic: Broderick

Strong GR Effects:

- Smaller than the expected ISCO: prograde disk.

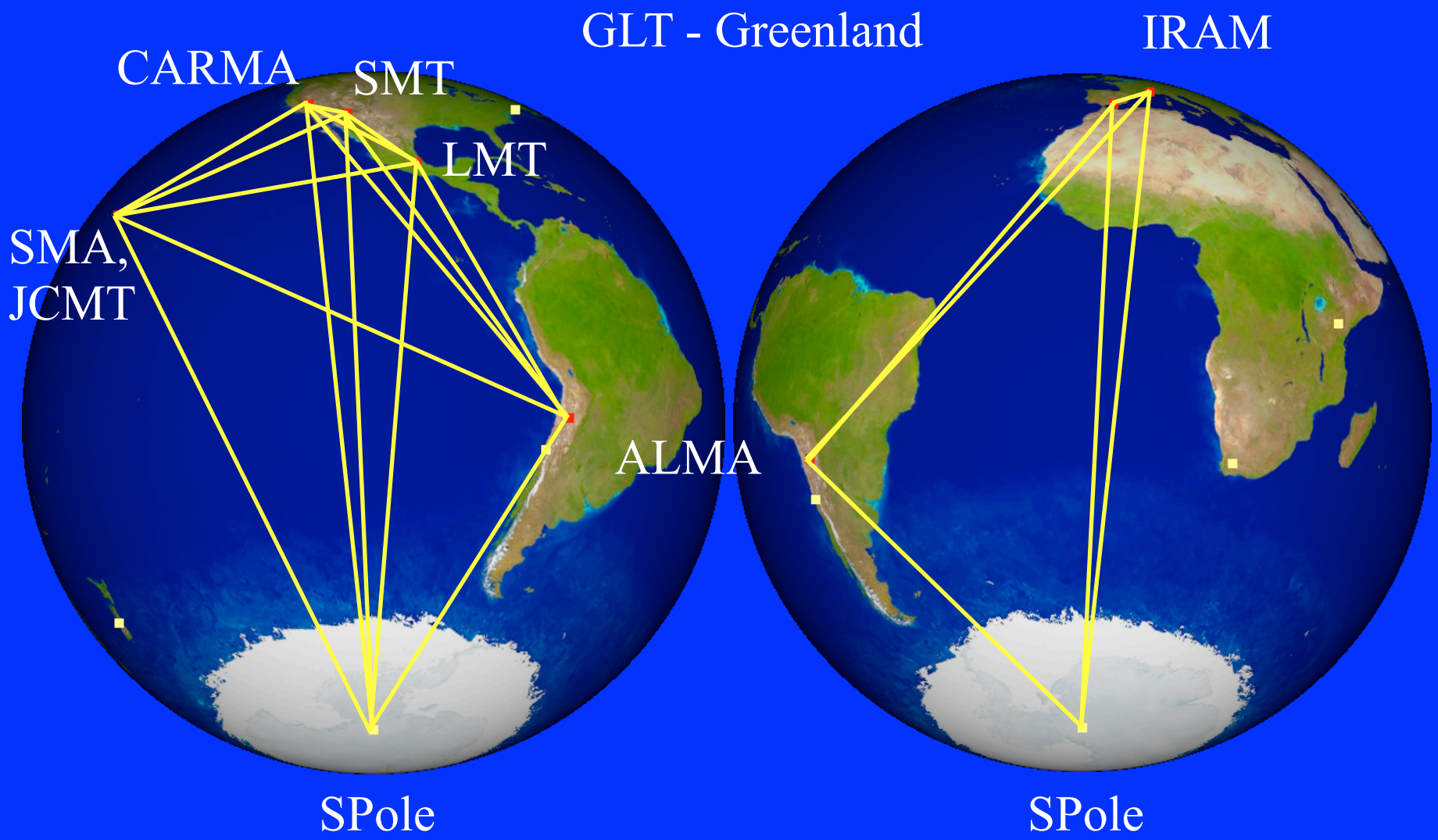


Doeleman et al 2012

EHT Specifications: The Next 2-3 Years

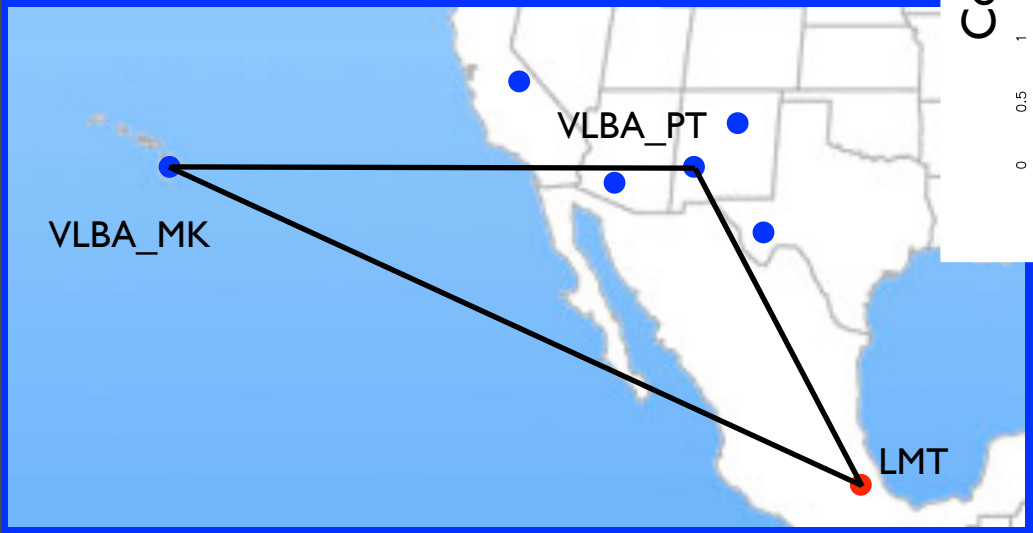
- Increase stations from 3 to 8: baseline number grows from 3 to 28 (n*(n-1)/2).
- Bandwidth increase from 1 GHz to 16 GHz.
- Collecting area increase by x10.
- Impact:
  - Sensitivity increase by x40: Long baselines.
  - Full closure phase information: modeling/imaging.
  - Full polarization information: magnetic fields.
  - Time domain: time resolving BH/jet dynamics.

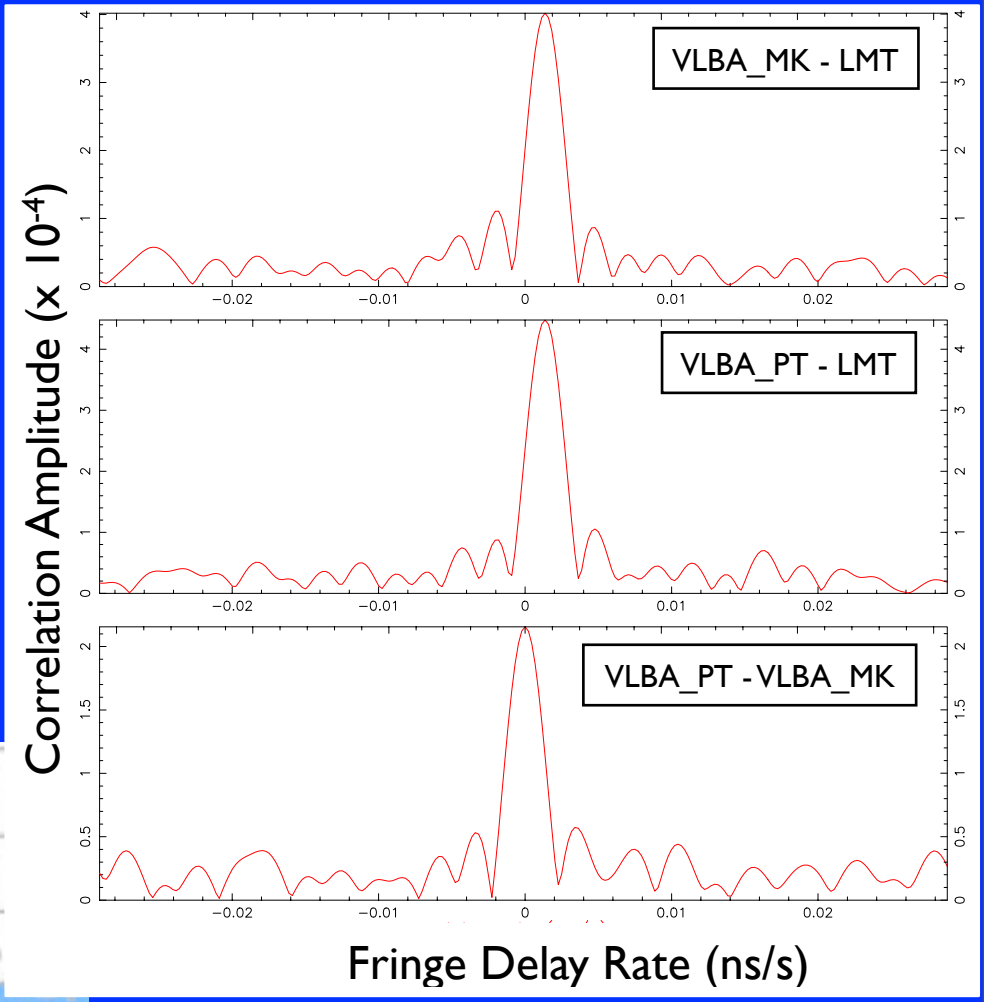
Assembling the Event Horizon Telescope



3mm VLBI with the LMT

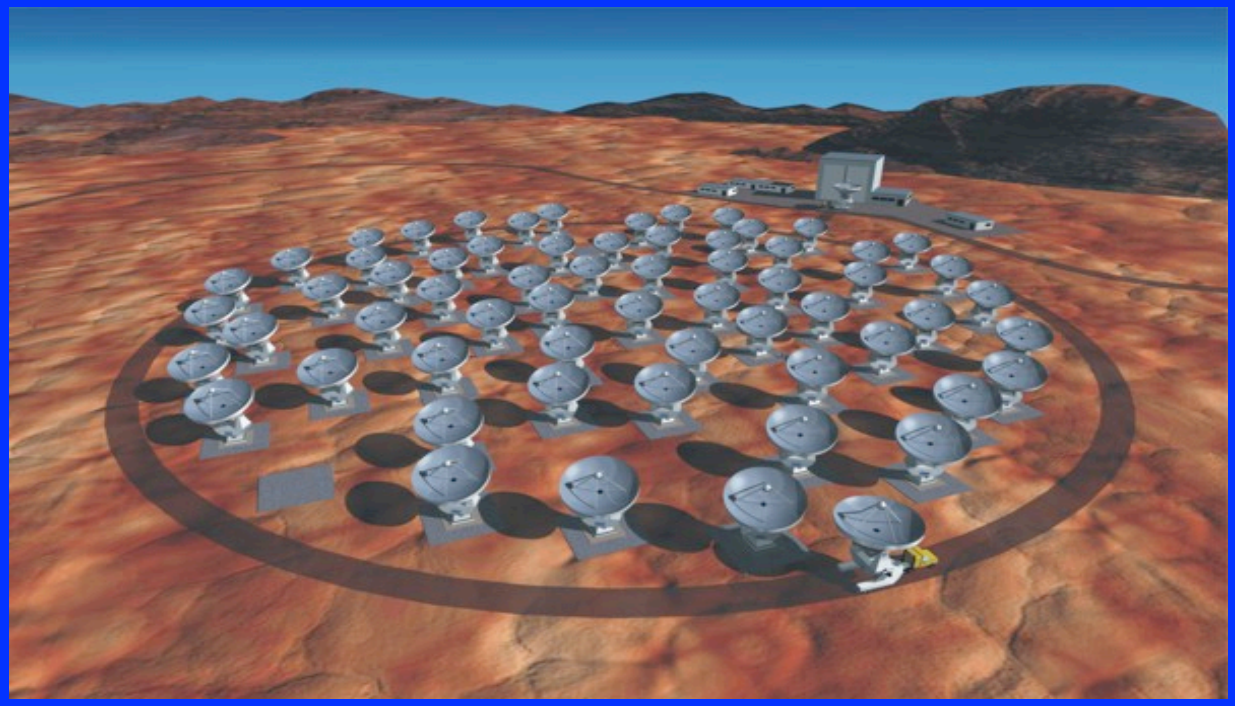
50m diameter.
First light at 3mm & 1.3mm.





Phasing ALMA

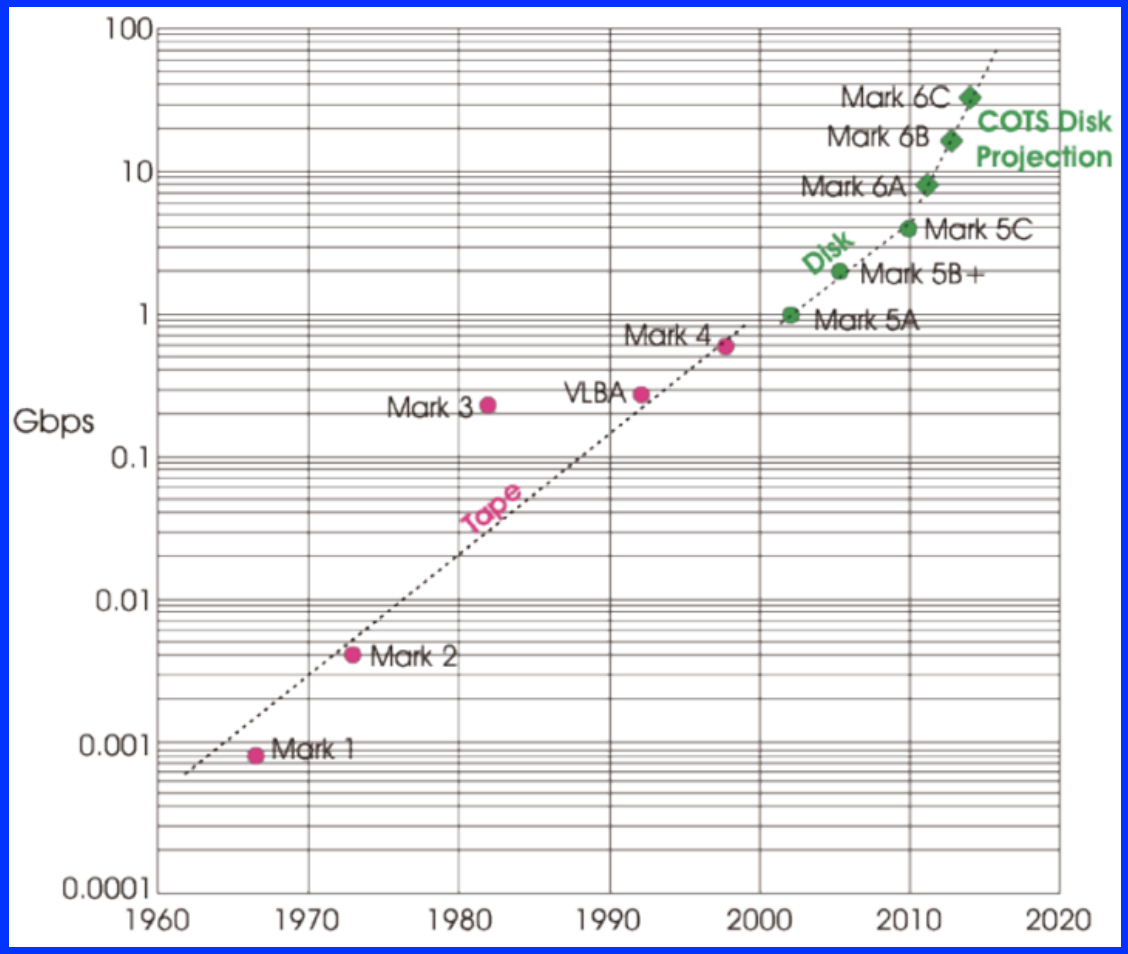
- An effective 85m aperture.
- Passed PDR (Nov 2012) and CDR (May 2013)
- First ALMA VLBI scheduled 2014/2015.



Next Gen VLBI Technology: Keeping up with Moore

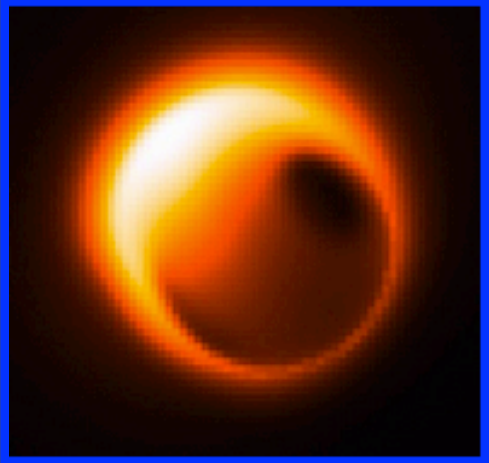
Digital Backend (DBE)

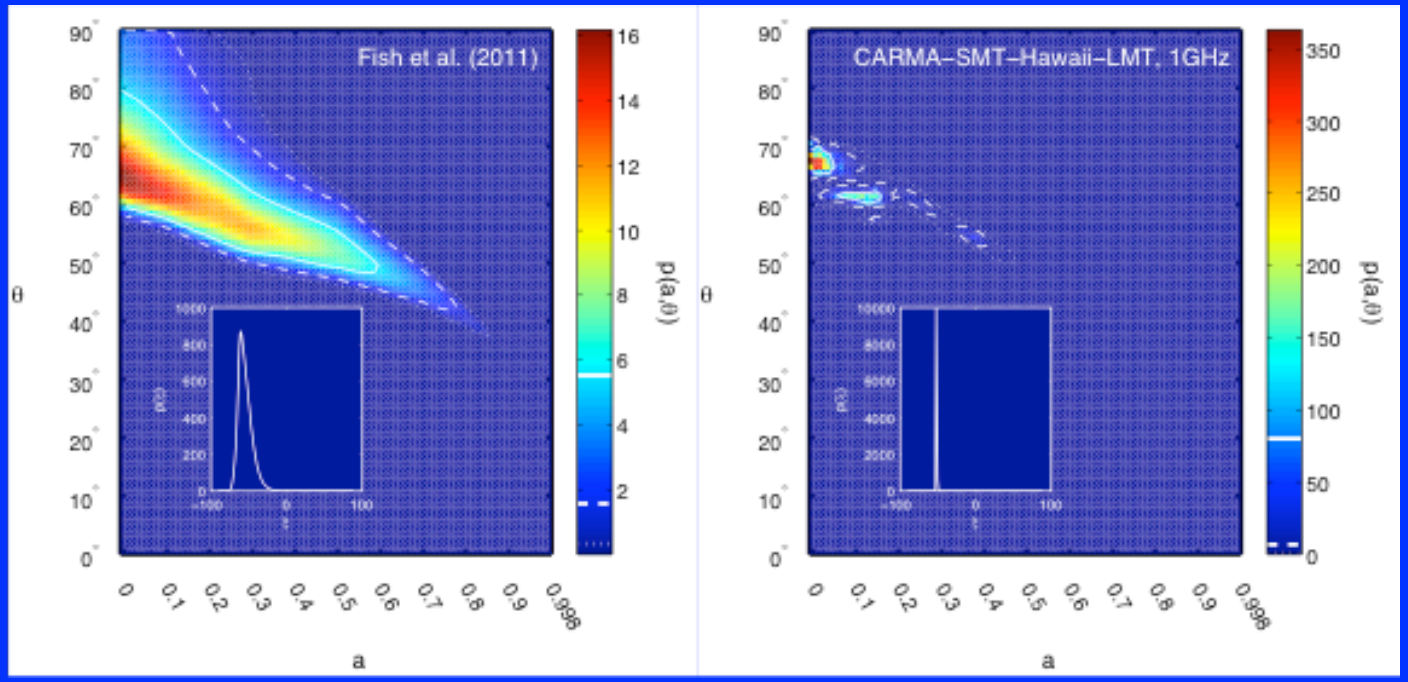
Digital Recorder (Mark6)



Current capability: 4 GHz real time.

Improved physical modeling through closure phases.



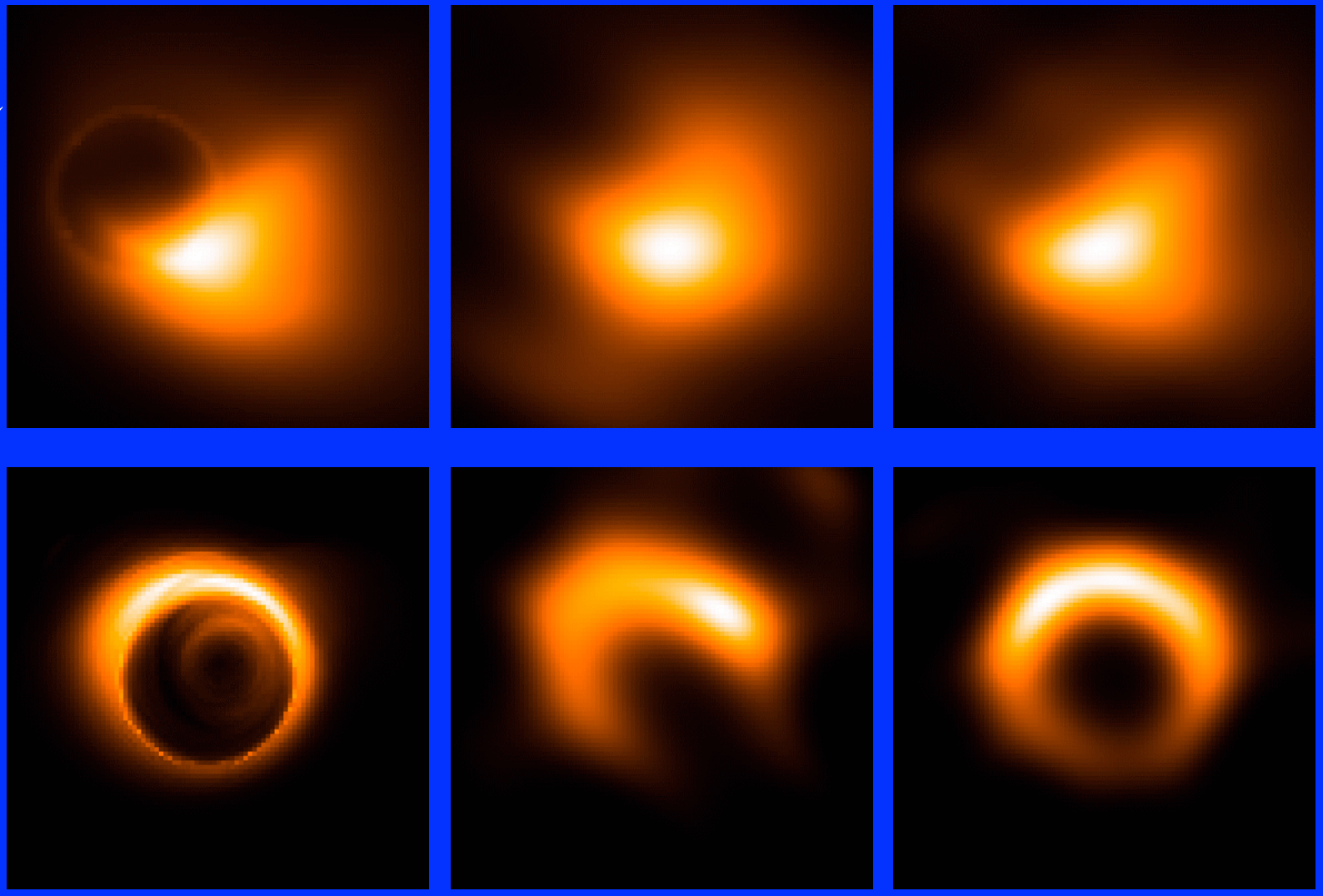


Broderick et al 2011

Progression to an Image: M87
Baron & Monnier (U. Michigan)

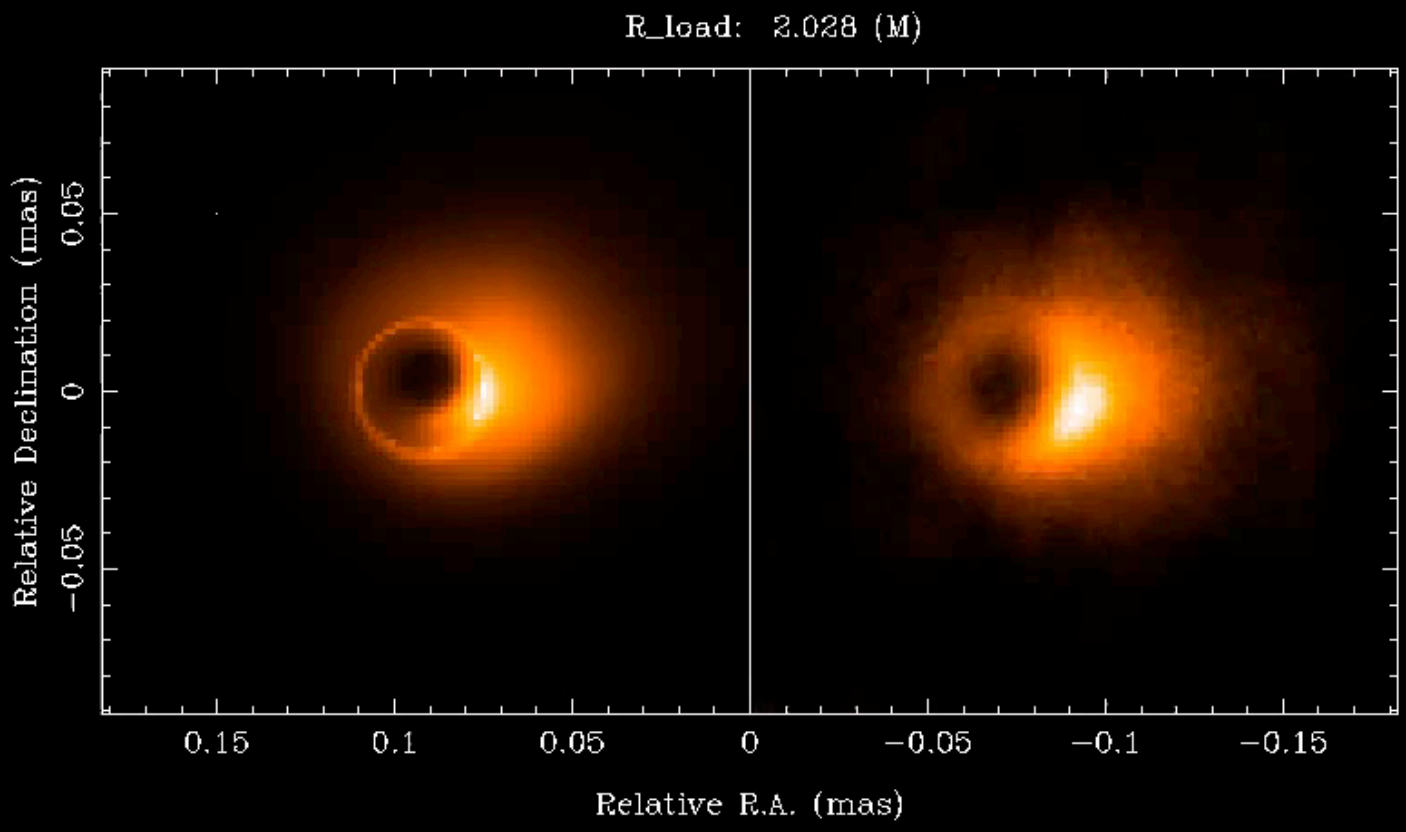
Broderick et al

Dexter et al



GR Model | 4 Stations | 7 Stations

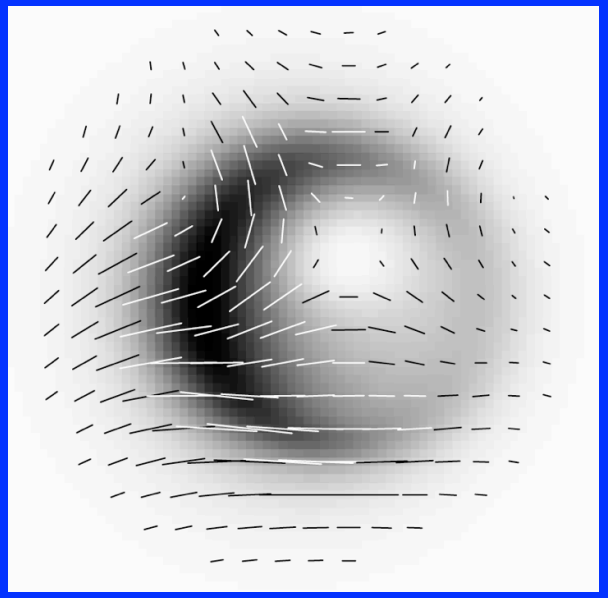
M87: Time Evolution of a Jet



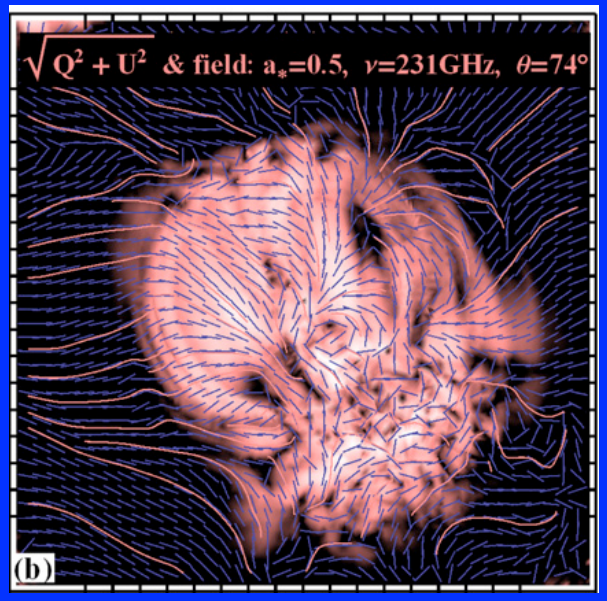
Lu, Broderick et al

Event Horizon Scale Polarization

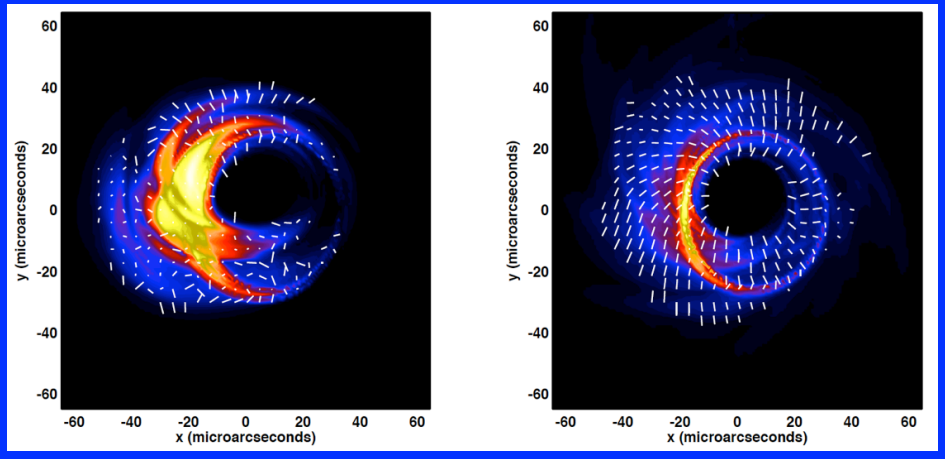
- CARMA, SMA: D. Marrone et al.
- Magneto Rotational Instability (MRI)
- Circularization in accretion flow
- Blandford-Payne: disk jet launch
- Blandford-Znajek: BH jet launch



Fish, Broderick, et al 2009



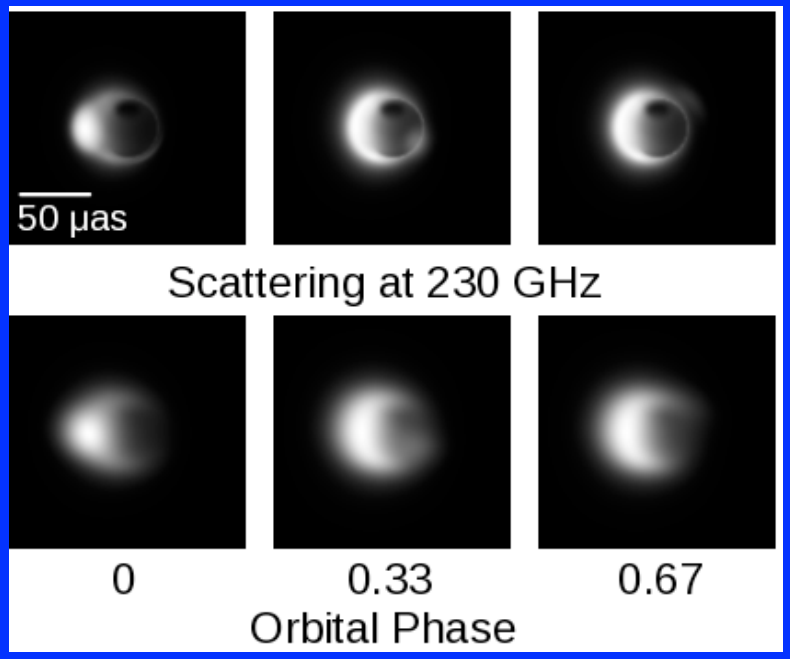
Shcherbakov, Penna & McKinney 2012

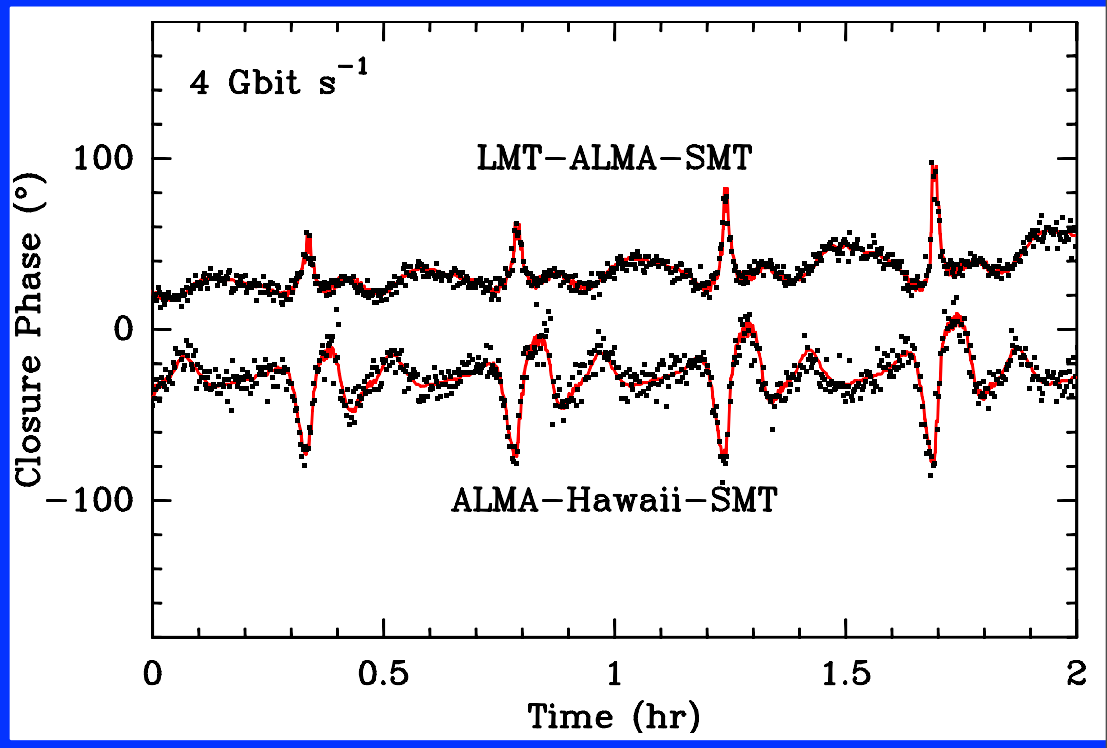


Dexter & McKinney (in prep).

Time Resolving BH Orbits

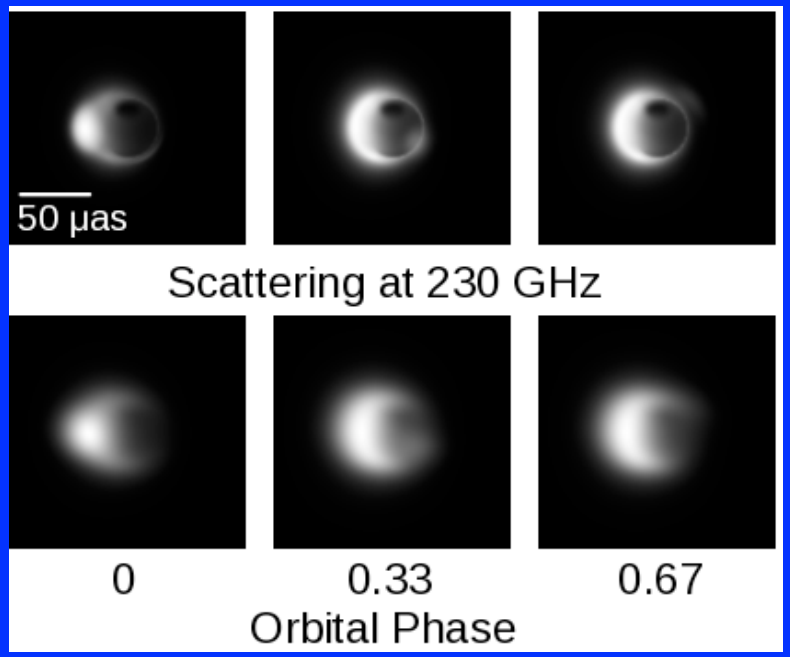
- Full EHT can measure closure phase on 10s intervals (25 times faster than smallest ISCO Period).

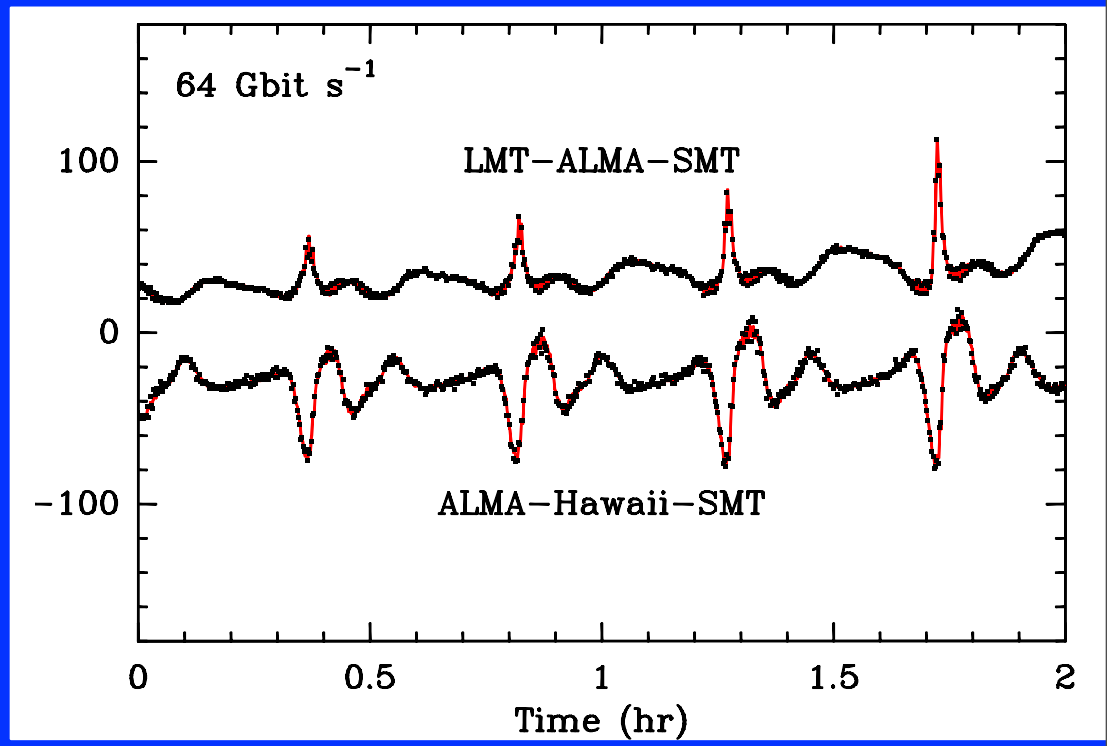




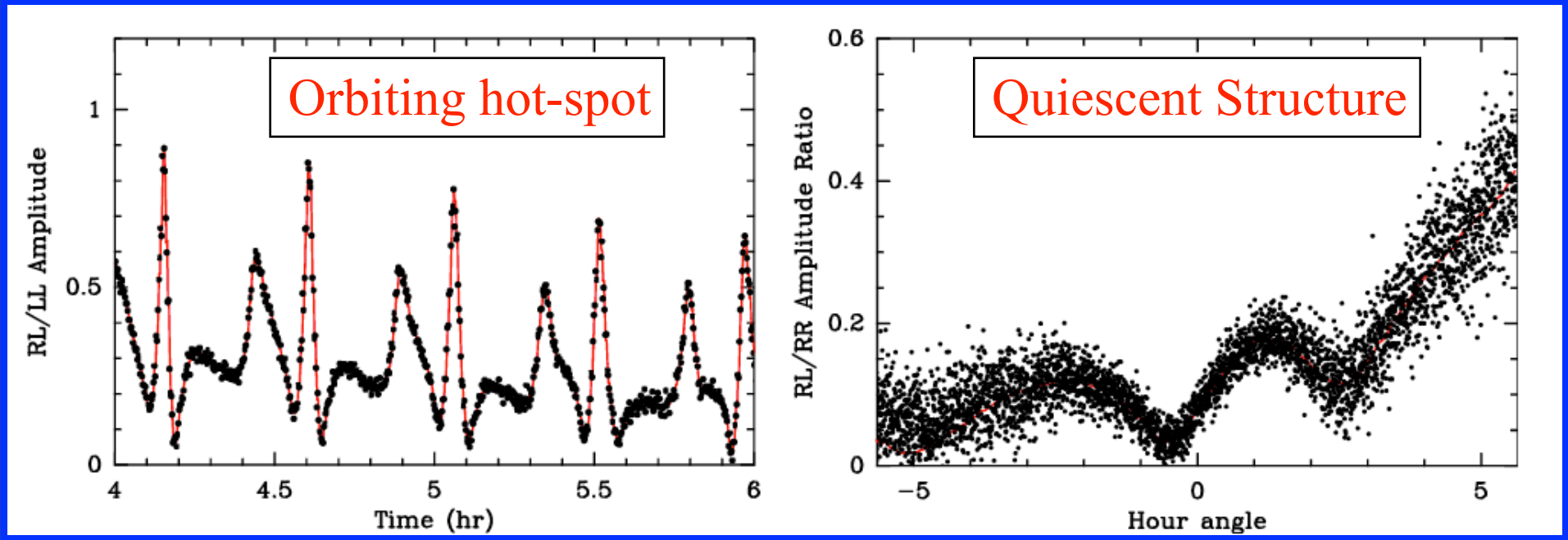
Time Resolving BH Orbits

- Full EHT can measure closure phase on 10s intervals (25 times faster than smallest ISCO Period).

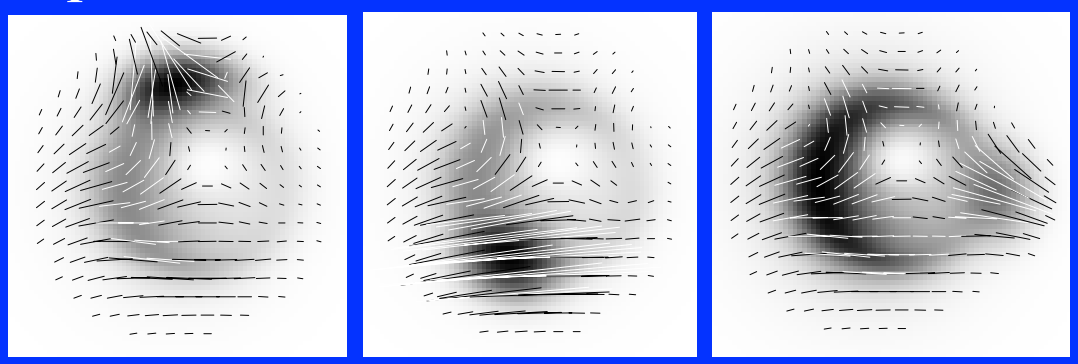


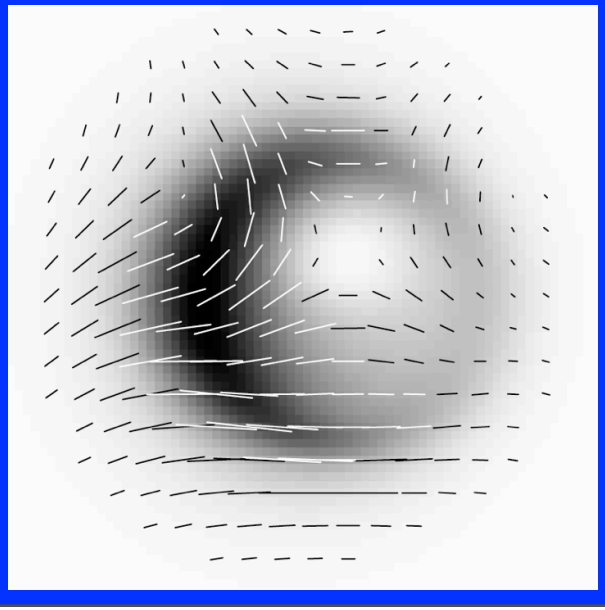


South Pole: Polarization at the Event Horizon:



phase= 0 0.33 0.67



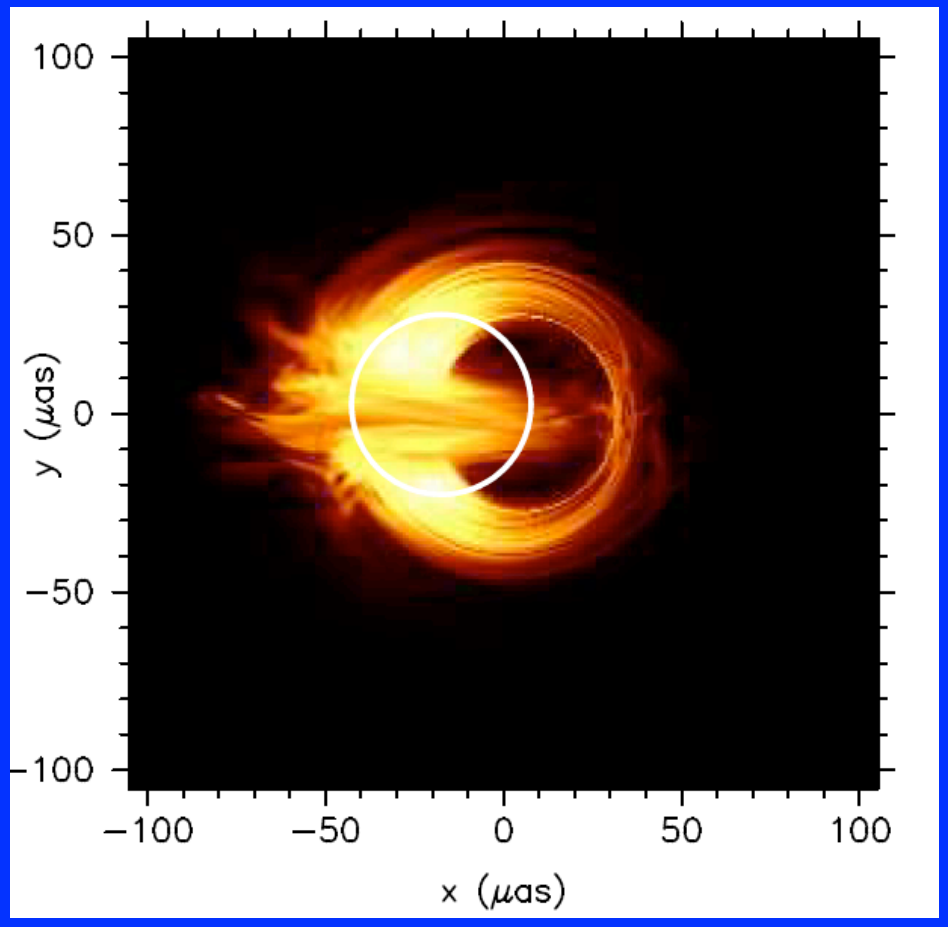


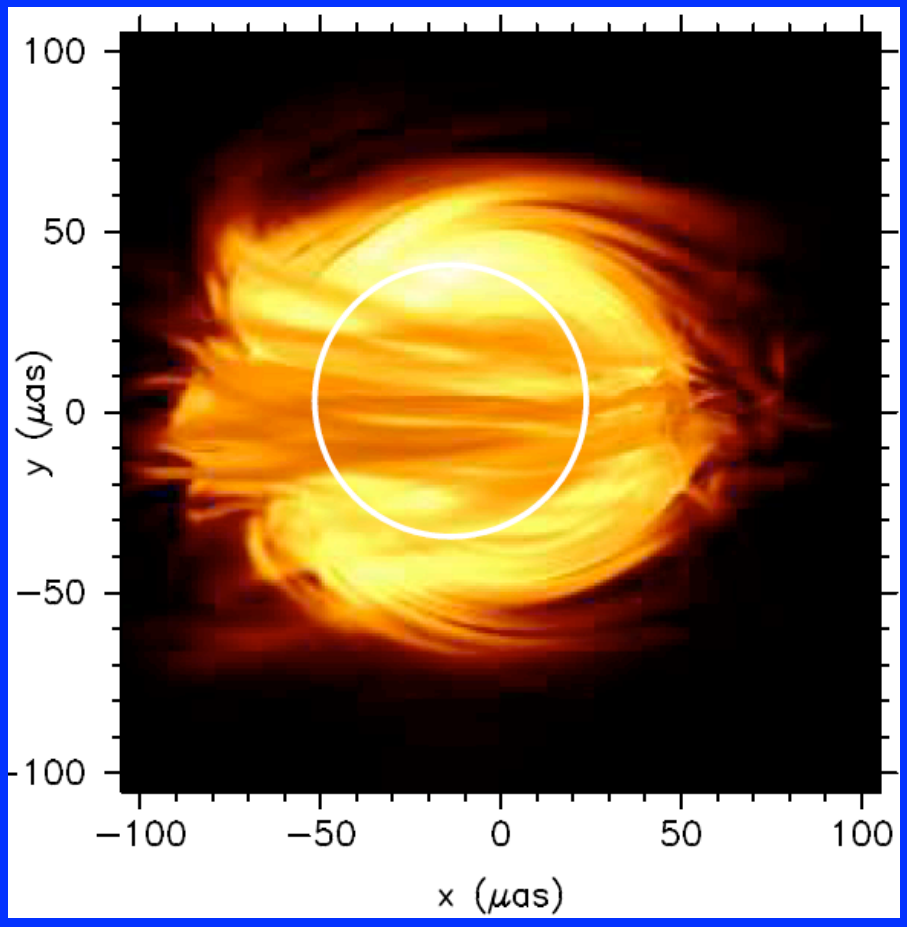
Fish et al 2009

Critical New Work

- VLBI Correlator: from 4 Gb/s to 64 Gb/s.
  - Data Challenge: ~10 Petabytes recorded per session.
- Instrumentation for the LMT.
- Data/Modeling/Imaging Pipeline
  - Polarization, more baselines.
- Operations (~3 years post-ALMA phasing).
- Time concerns
  - Some pressure on existing sites.
  - EHT can resolve G2 impact effects.

Increased accretion may hide shadow!





Moscibrodzka + (2012)

Event Horizon Telescope Collaboration

MIT Haystack: Shep Doeleman, Alan Rogers, Vincent Fish, R. Lu et al
NAOJ: Mareki Honma, Tomoaki Oyama, Kazunori Akiyama
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, Keiichi Asada
U. Concepcion: Neil Nagar

Summary

- EHT has confirmed targets (SgrA*/M87) with Horizon scale structure.
- Required technical work is low-risk: early results validate all systems.
- Considerable work to do: requires support of community.
- First imaging, modeling and time-resolving BH/Jet emission are within reach in <3 years.
- Event Horizon Telescope fully on-line by 2015.
- www.eventhorizontelescope.org