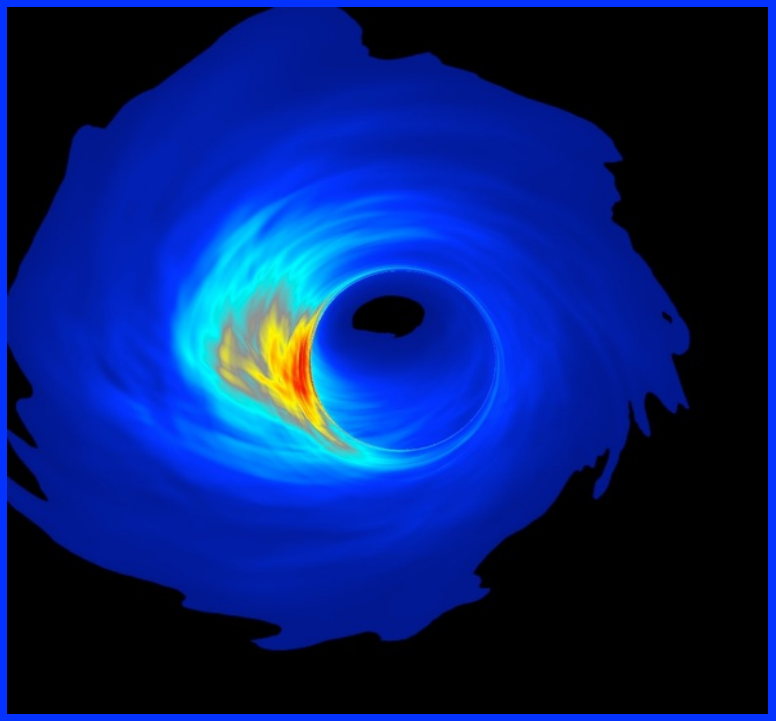
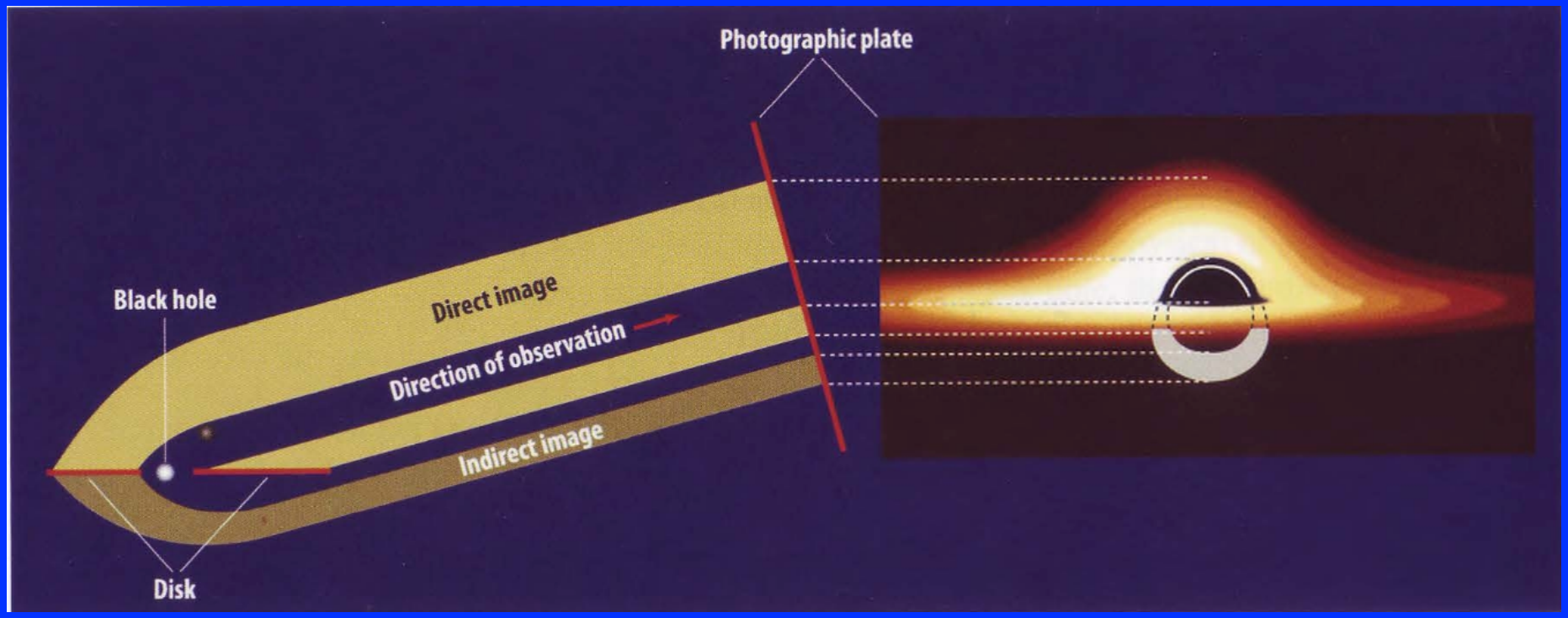
Building an Event Horizon Telescope: Imaging and Time Resolving Black Holes



Sheperd Doeleman
MIT Haystack Observatory & SAO

Strong GR: The Black Hole Shadow



Bardeen 1973
Luminet 1979

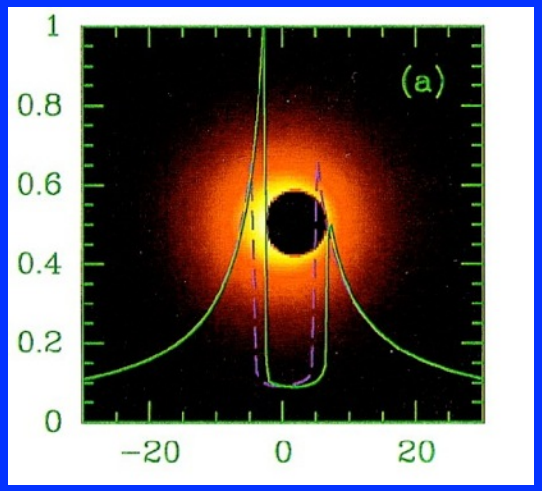
Shadow Diameter:

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

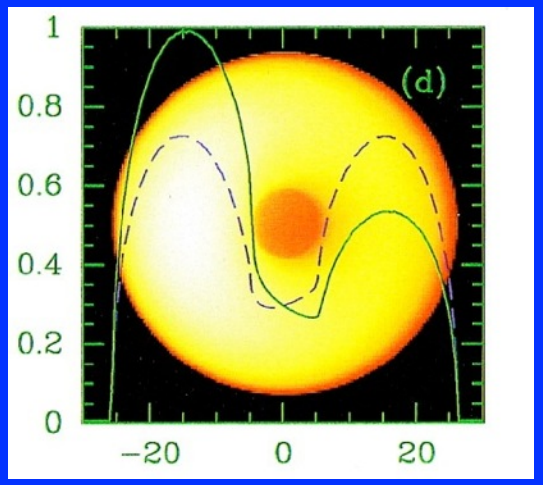
Spinning (a=1)
Dsh = 9/2 * Rsch

Shadow size and shape encodes GR (e.g., Johannsen & Psaltis 2010).

Theoretical Views of SgrA*



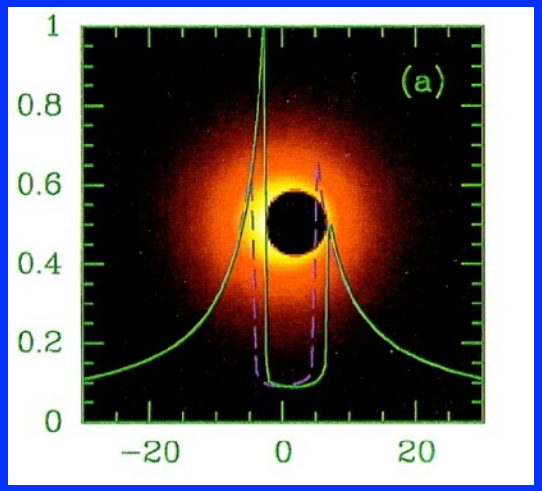
Spinning (a=1)

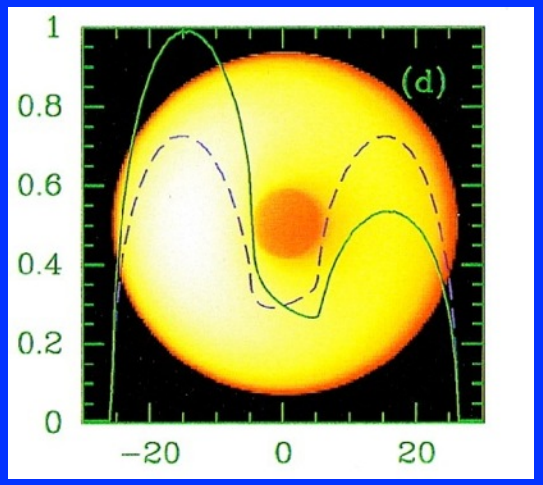


Non-spinning (a=0)

Falcke
Melia
Agol
2000

Theoretical Views of SgrA*

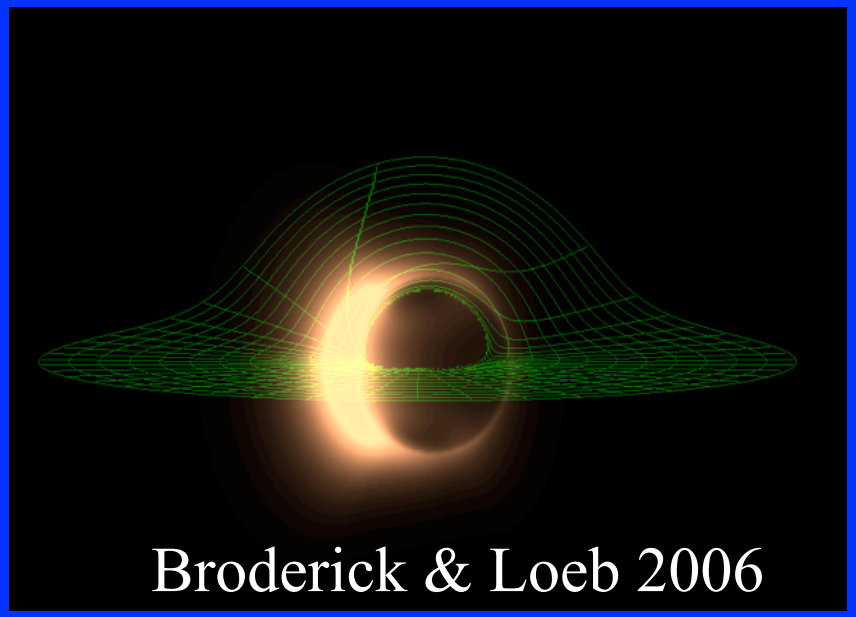




Falcke
Melia
Agol
2000

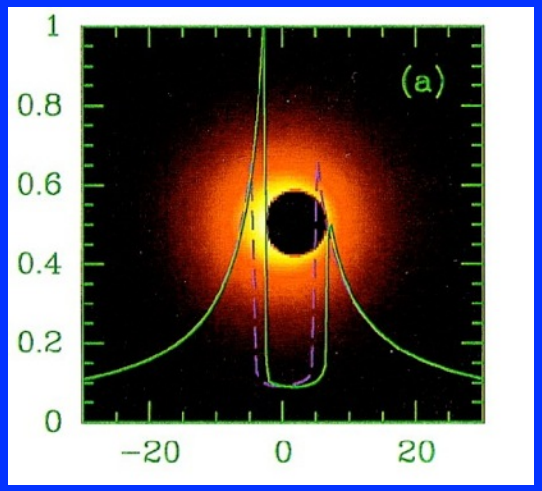
Spinning (a=1)

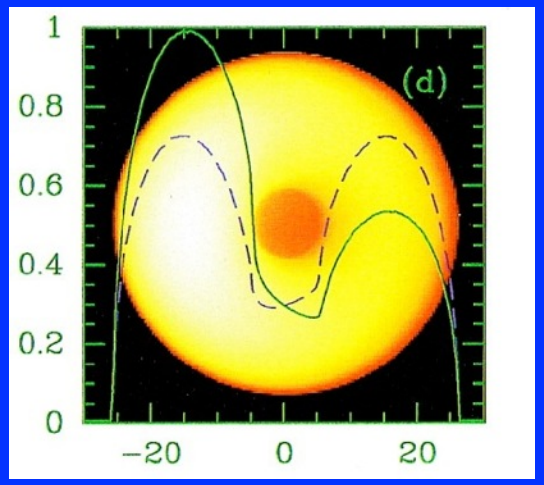
Non-spinning (a=0)



Broderick & Loeb 2006

Theoretical Views of SgrA*

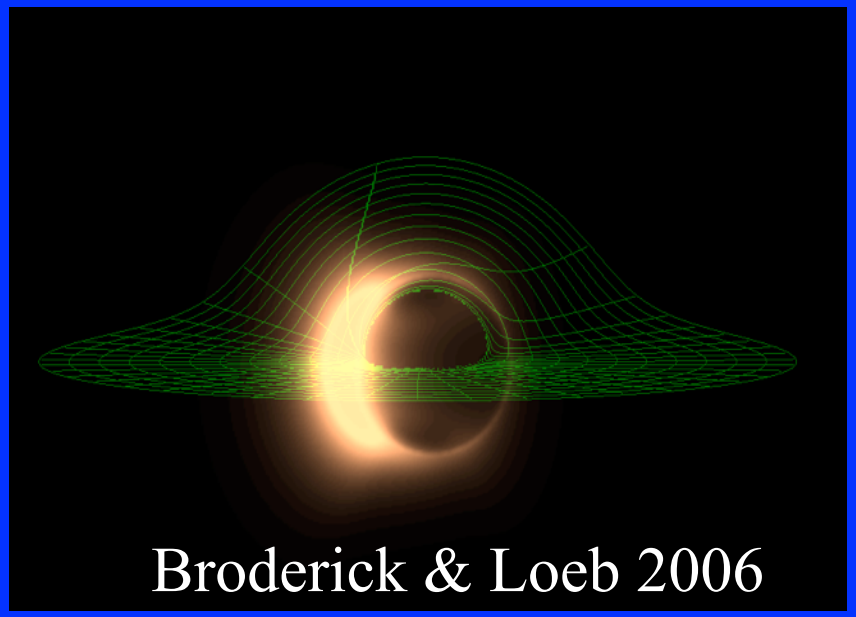




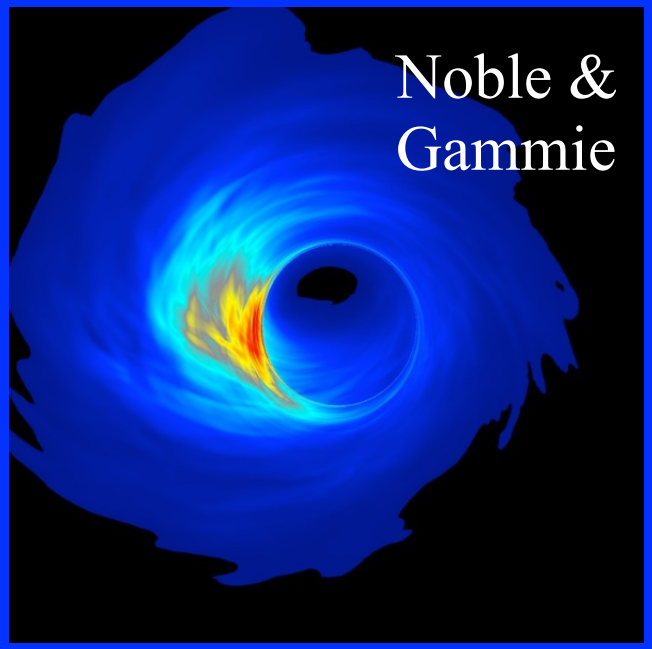
Falcke
Melia
Agol
2000

Spinning (a=1)

Non-spinning (a=0)



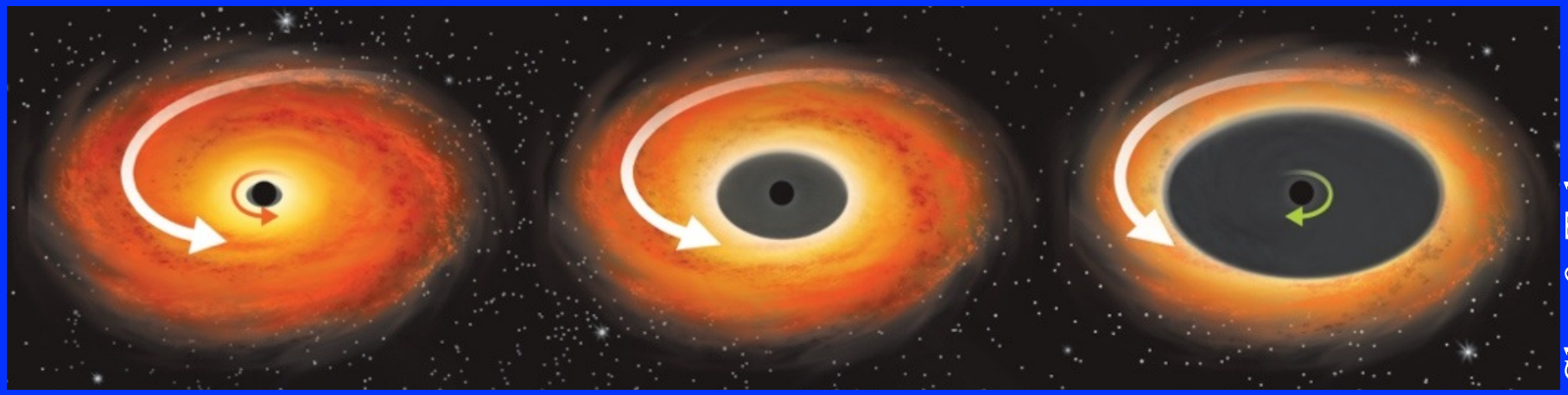
Broderick & Loeb 2006



Noble &
Gammie

Strong GR Effects:

- Innermost Stable Circular Orbit Size.



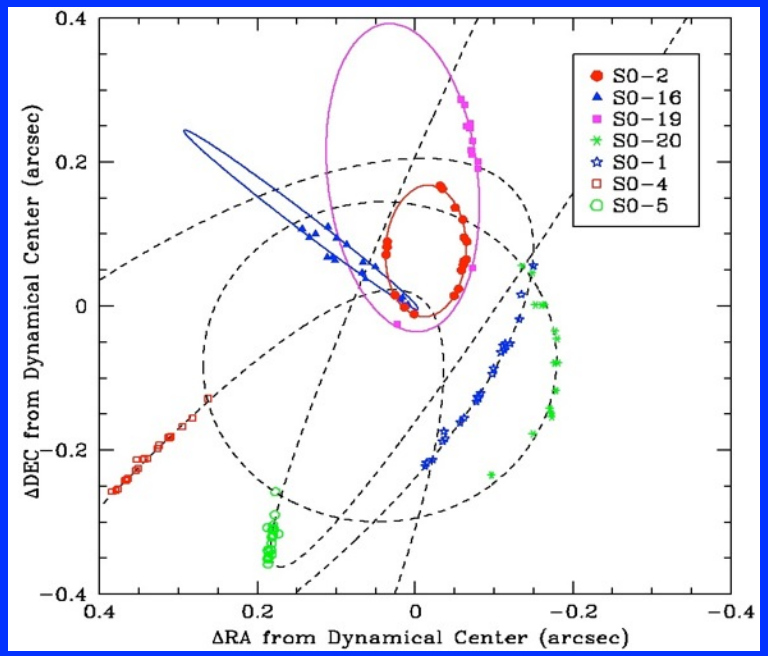
Sky & Telescope

Max. Prograde
ISCO_d = 1 Rsch

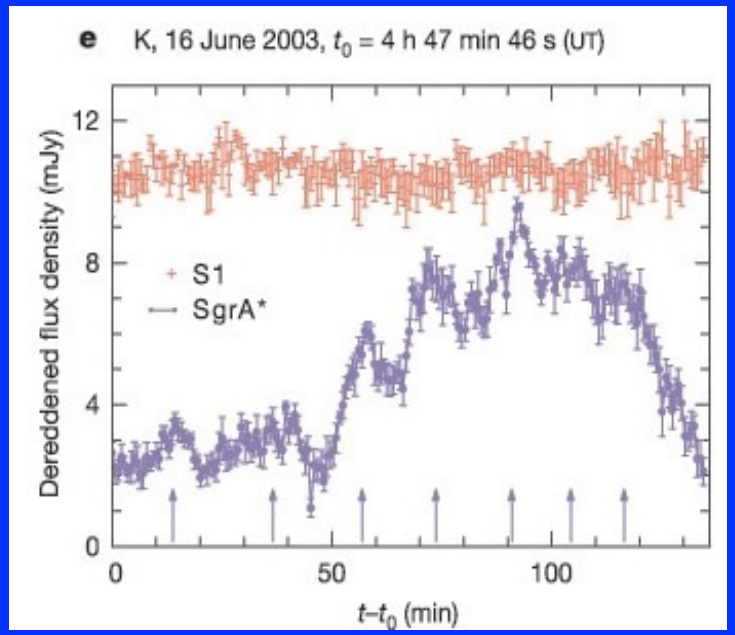
No Spin
ISCO_d = 6 Rsch

Max Retrograde
ISCO_d = 9 Rsch

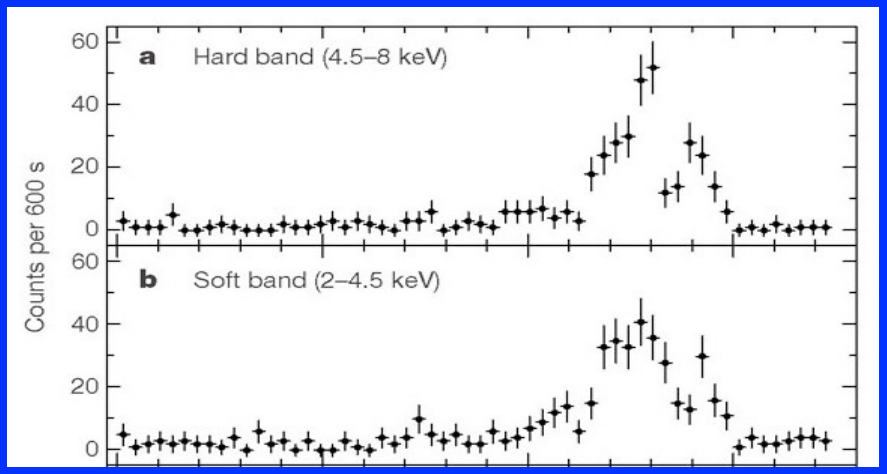
SgrA*: Best Case for a SMBH



Ghez et al 2005

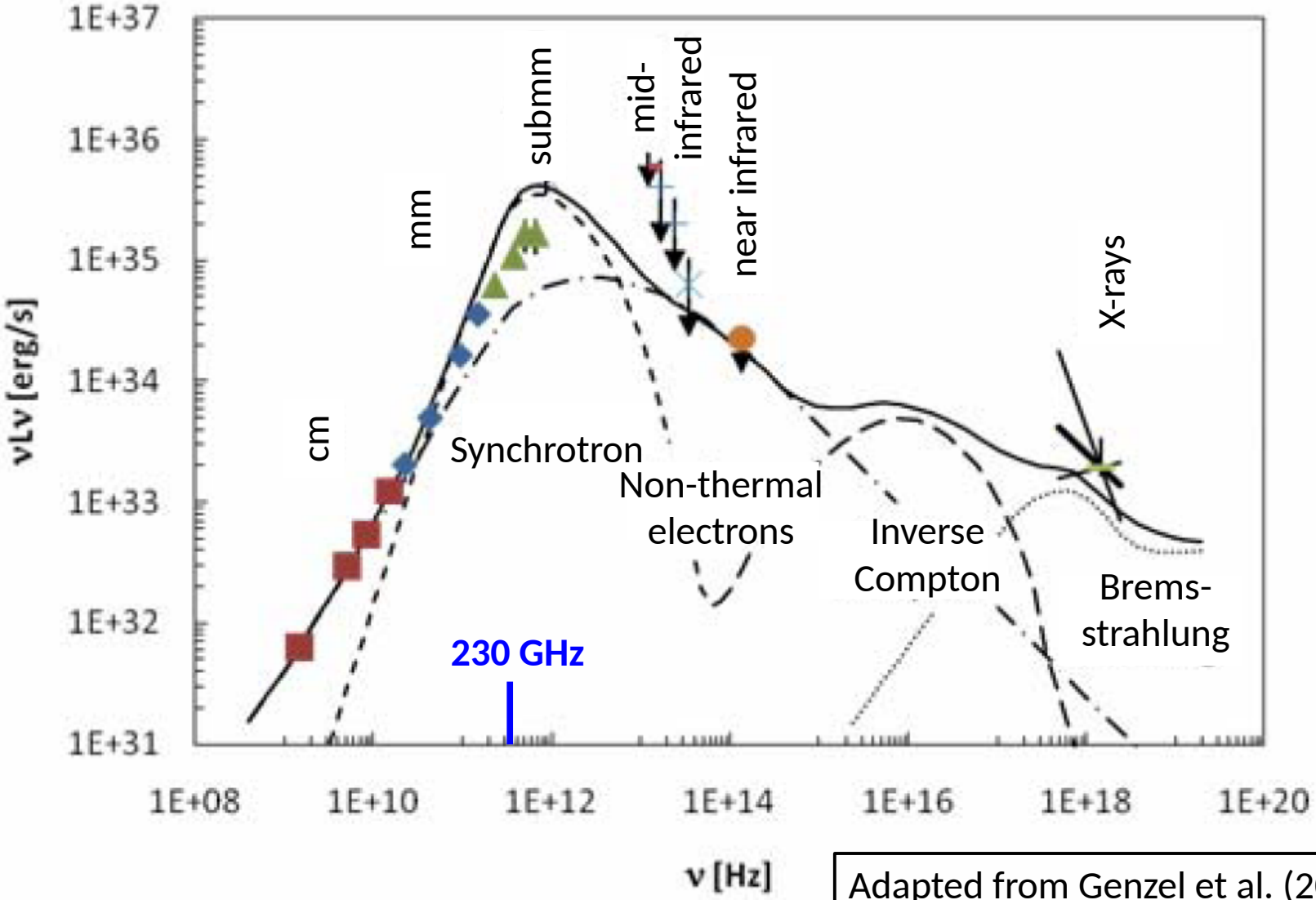


VLT: Genzel et al 2003



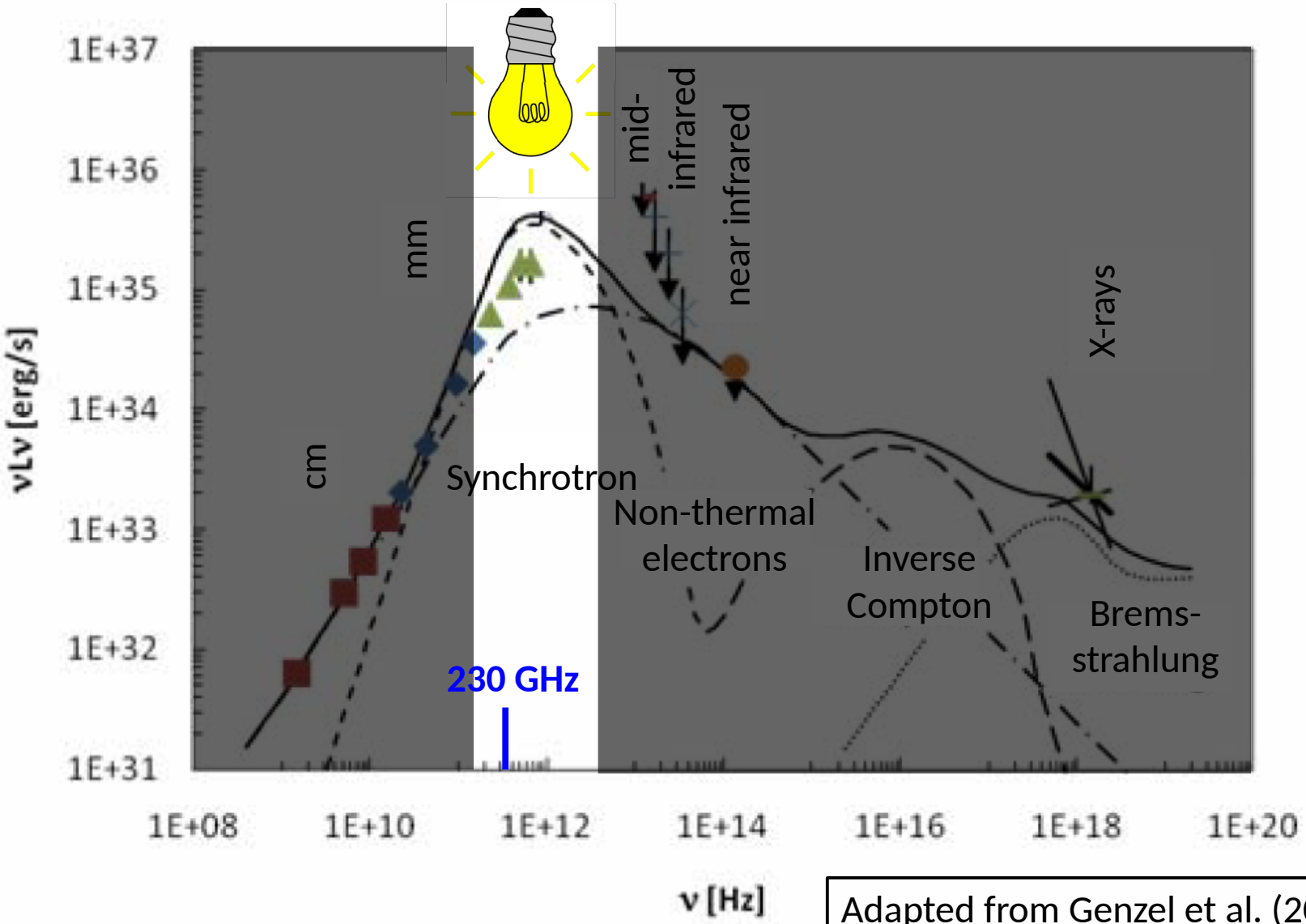
Baganoff et al 2001

Sgr A* Spectrum



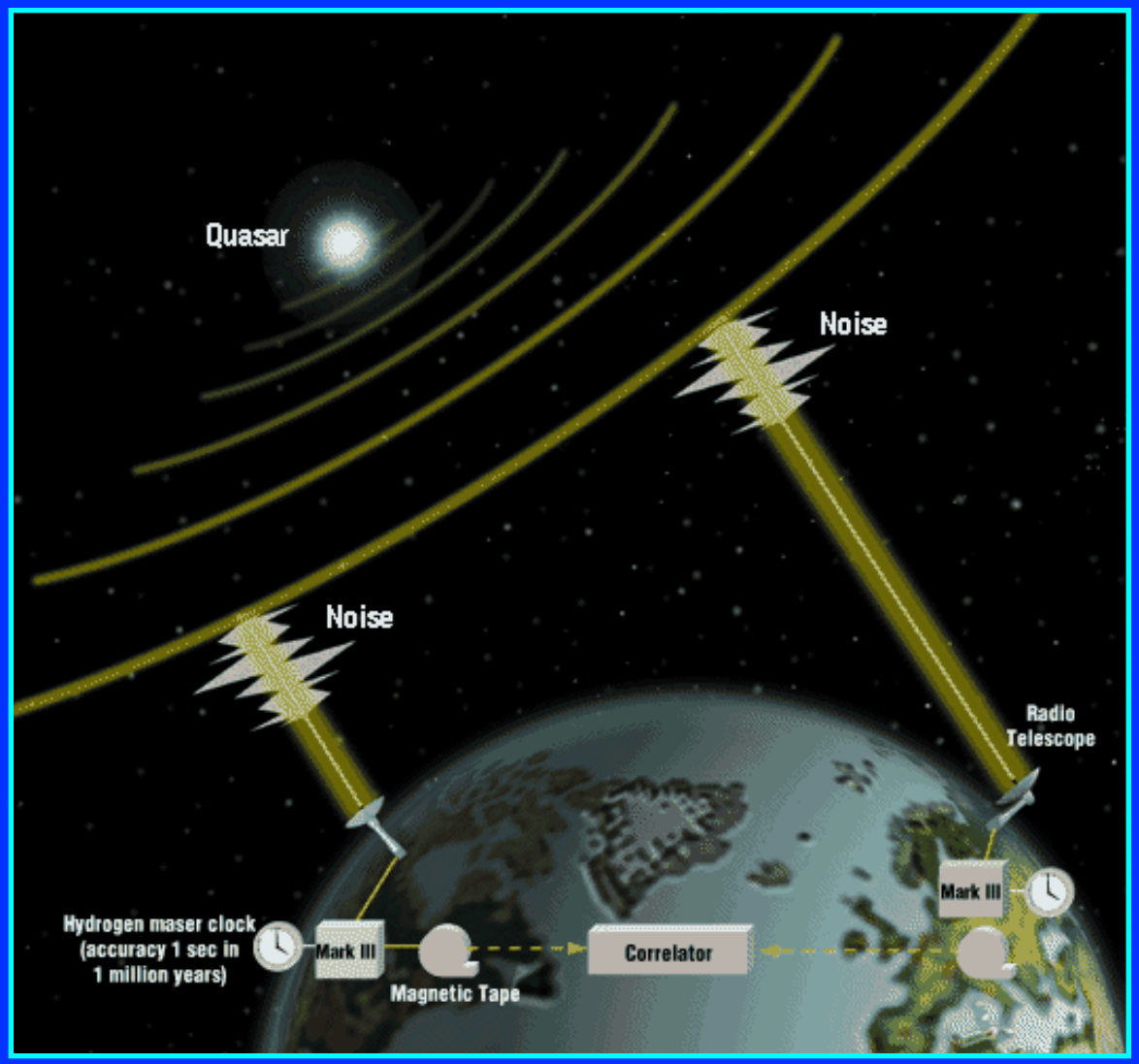
Adapted from Genzel et al. (2010)

Sgr A* Spectrum



Adapted from Genzel et al. (2010)

Short Wavelength VLBI



Resolution:

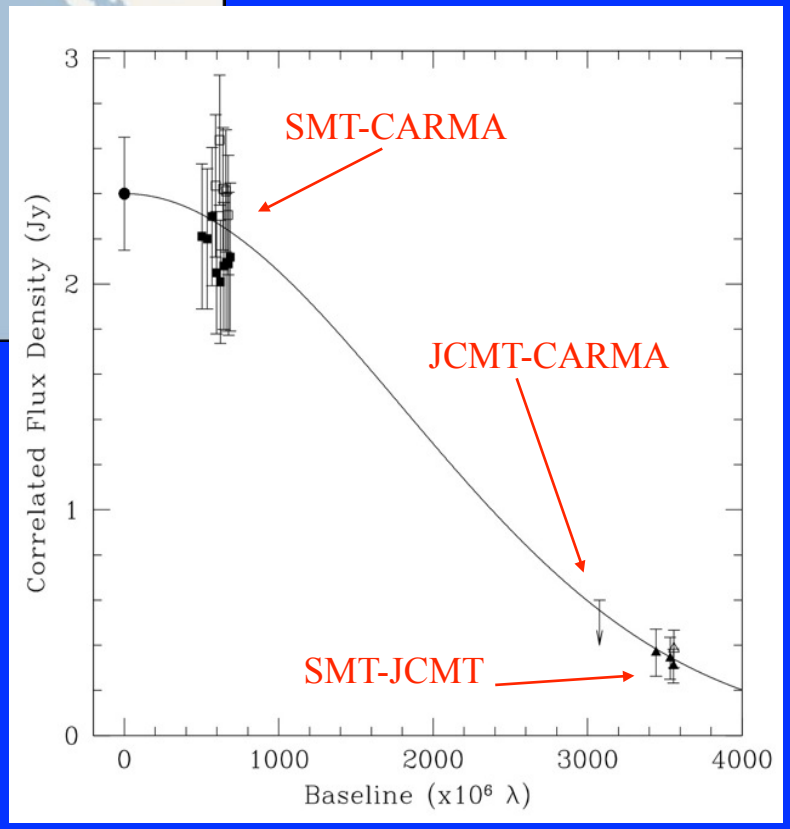
λ/D (cm) ~ 0.5 mas
λ/D (1.3mm) ~ 30 μas
λ/D (0.8mm) ~ 20 μas

ISM Scattering:

$\Theta scat \sim \lambda^2$

SgrA*: Event Horizon Structure Confirmed

Doeleman et al 2008

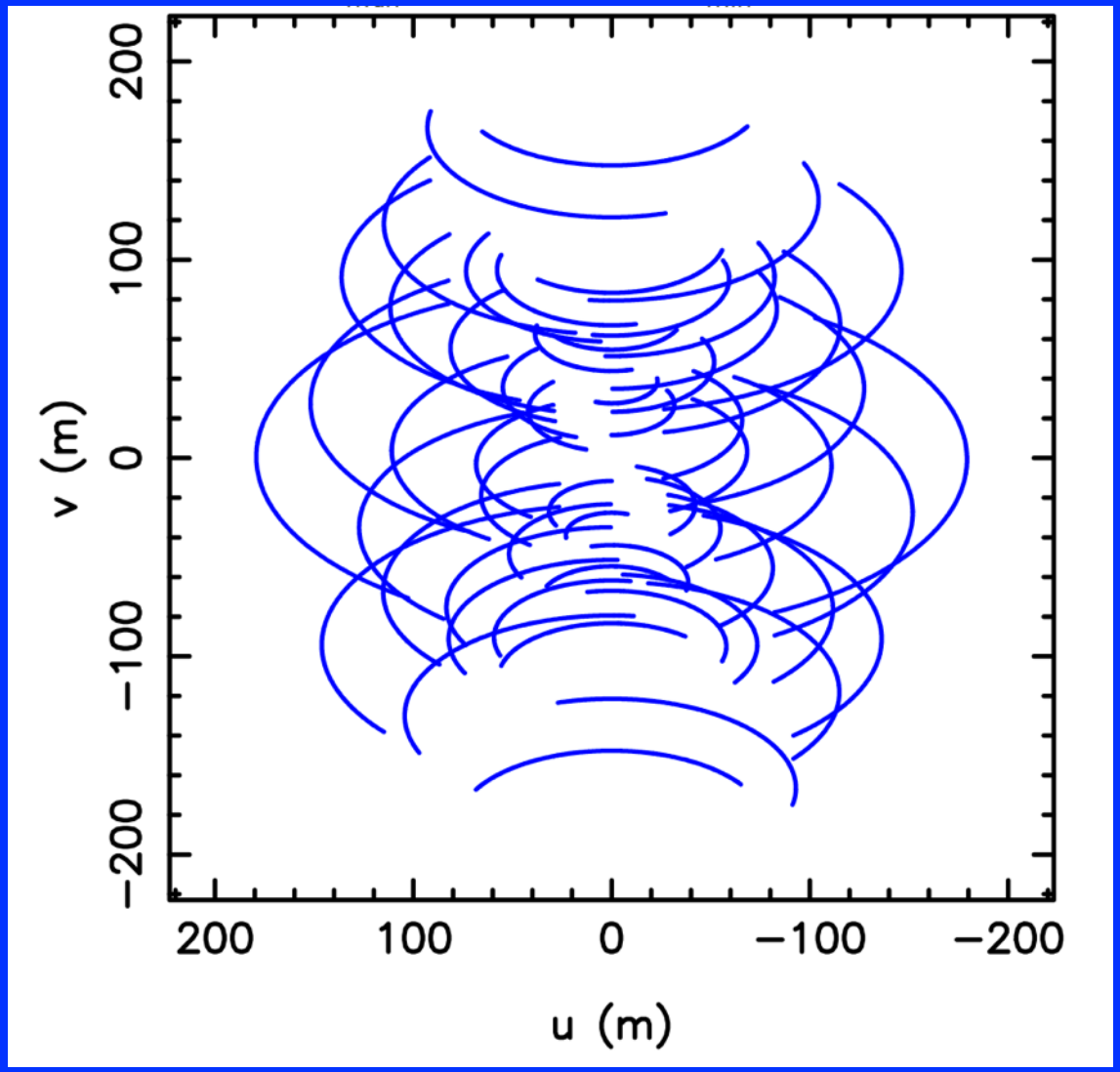


About 4 Schwarzschild radii across.

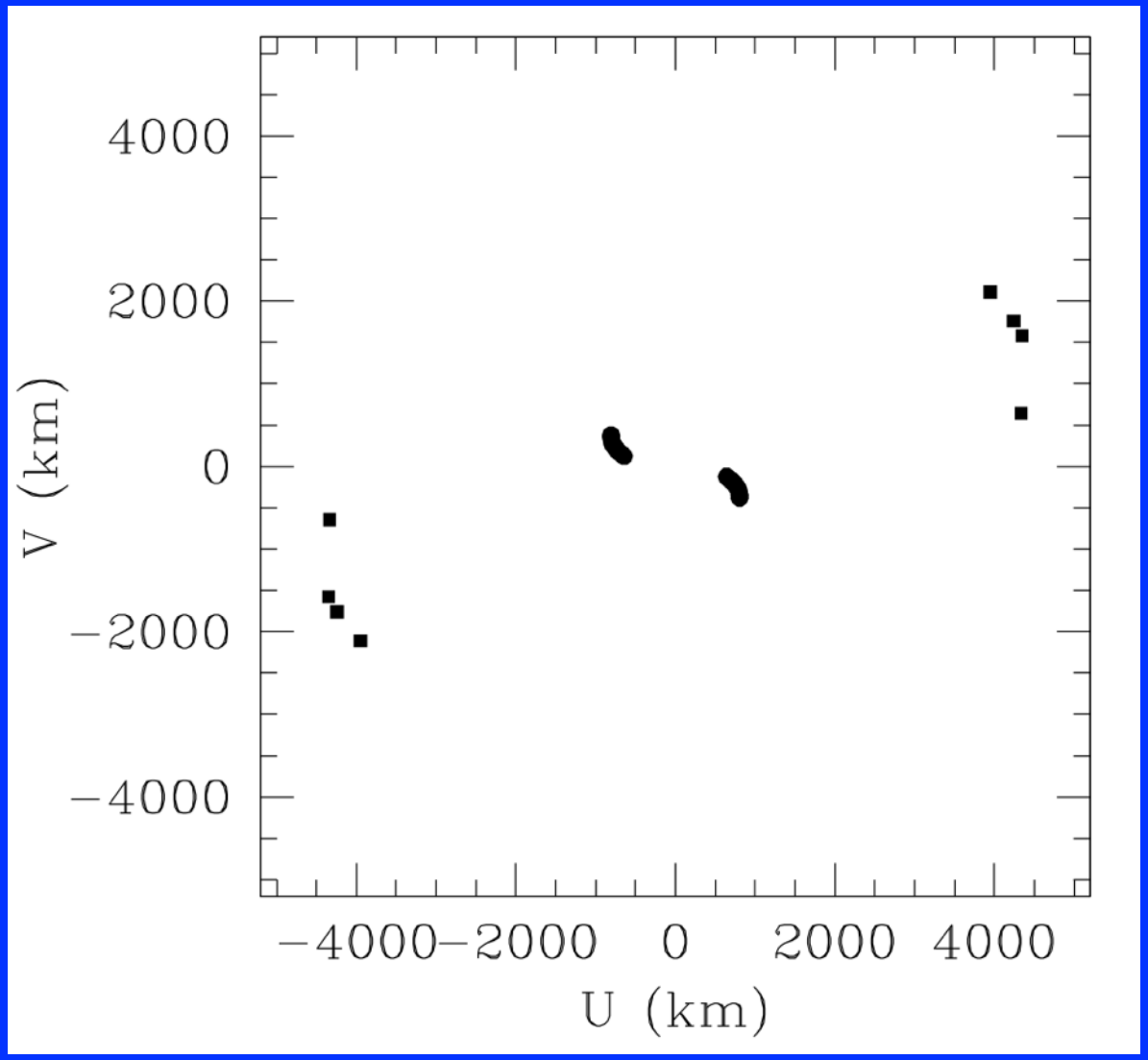
$$\rho = 10^{23} M_{\odot} pc^{-3}$$

4 million suns within the orbit of Mercury.

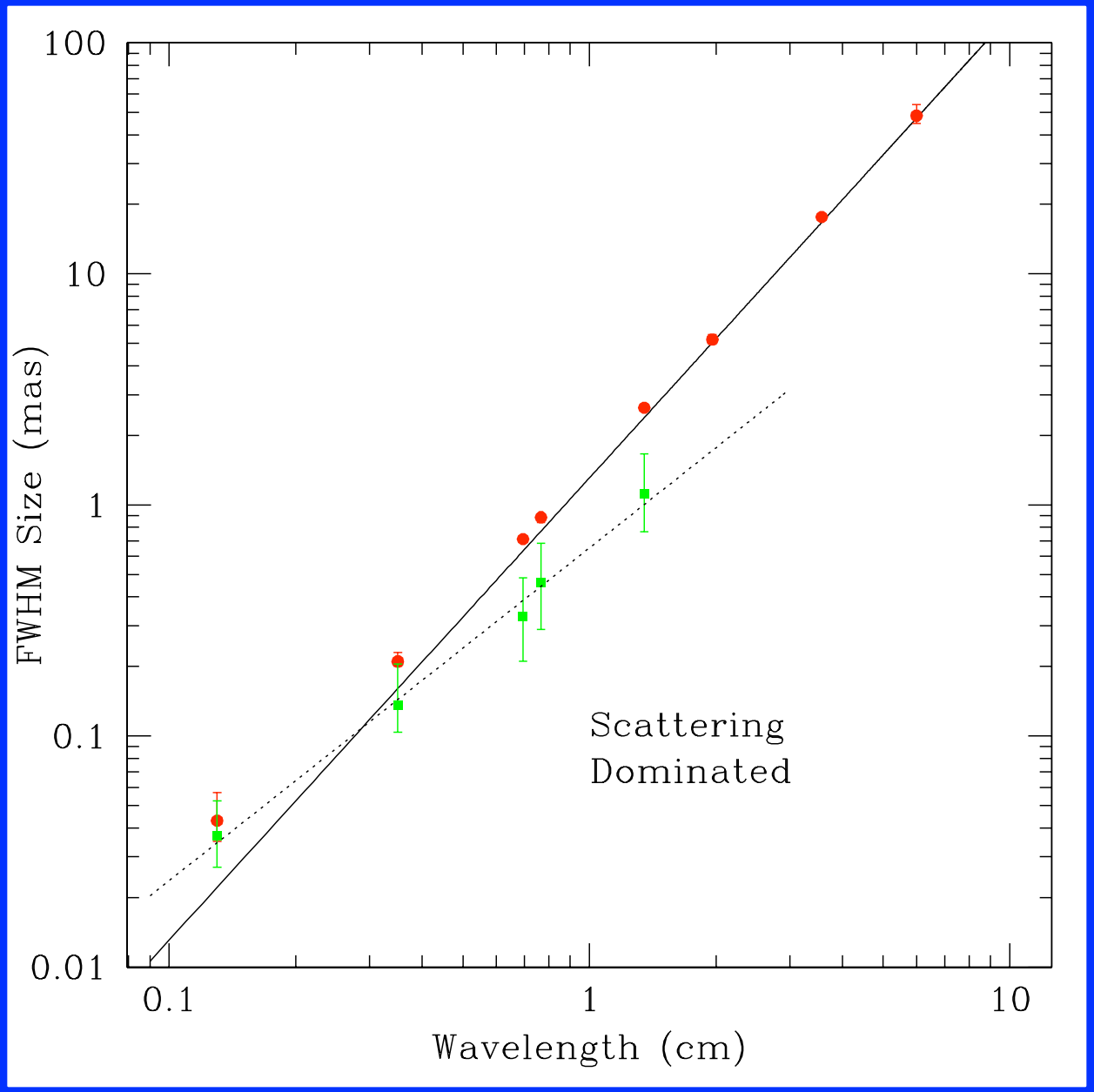
UV Coverage



UV Coverage



SgrA*: Piercing the Scattering Screen



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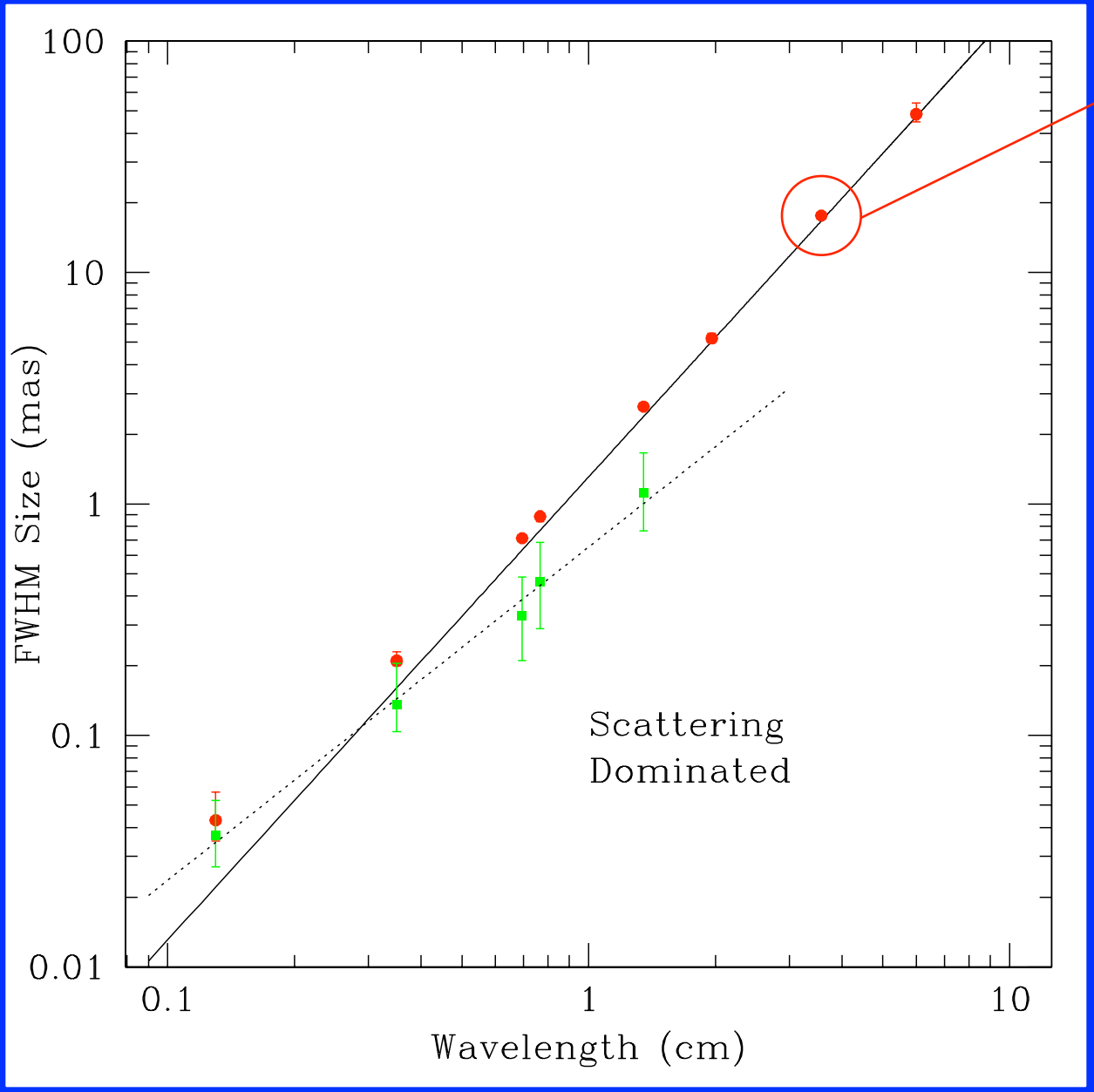
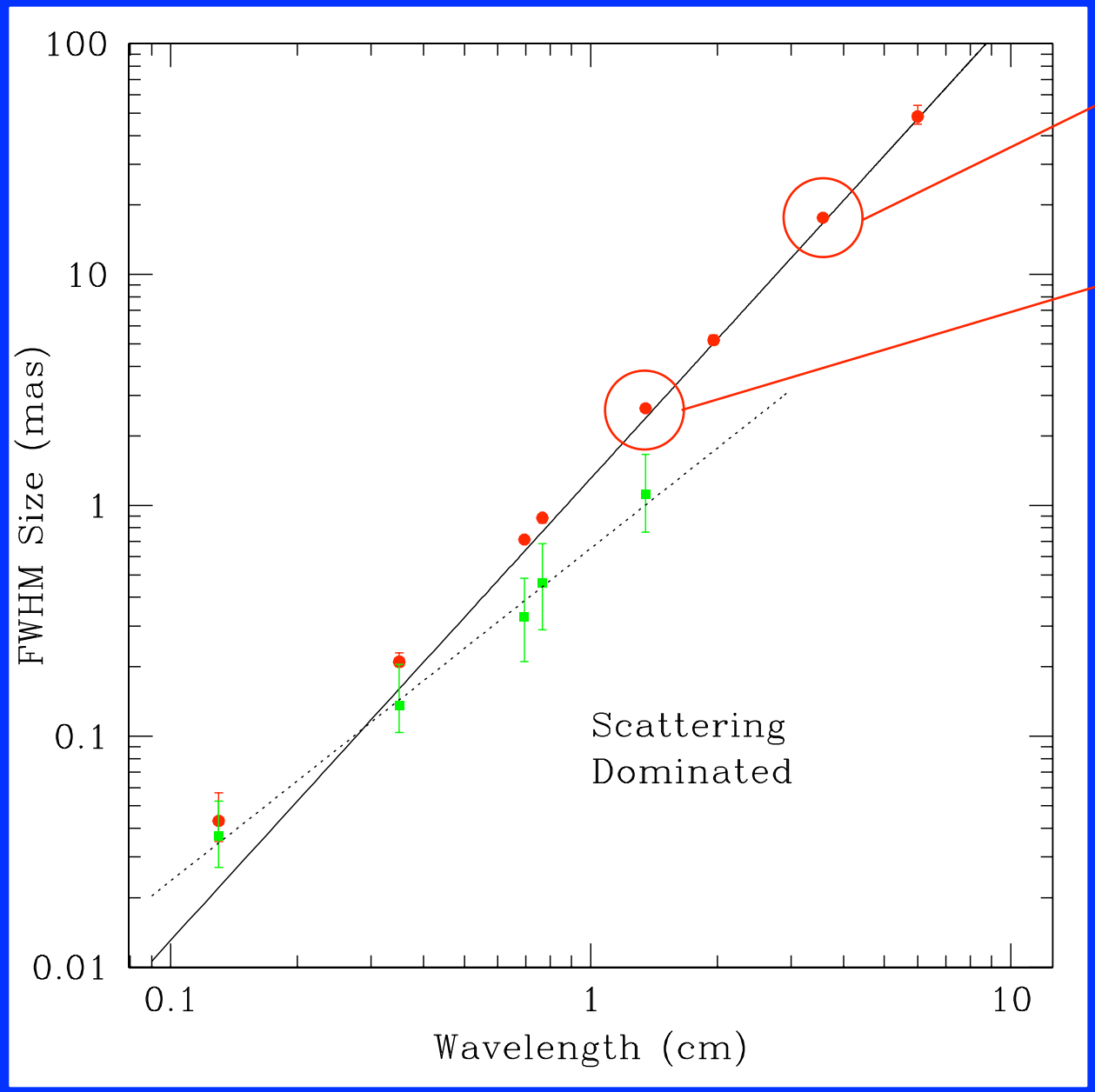


Lo 1975
Jauncy 1989

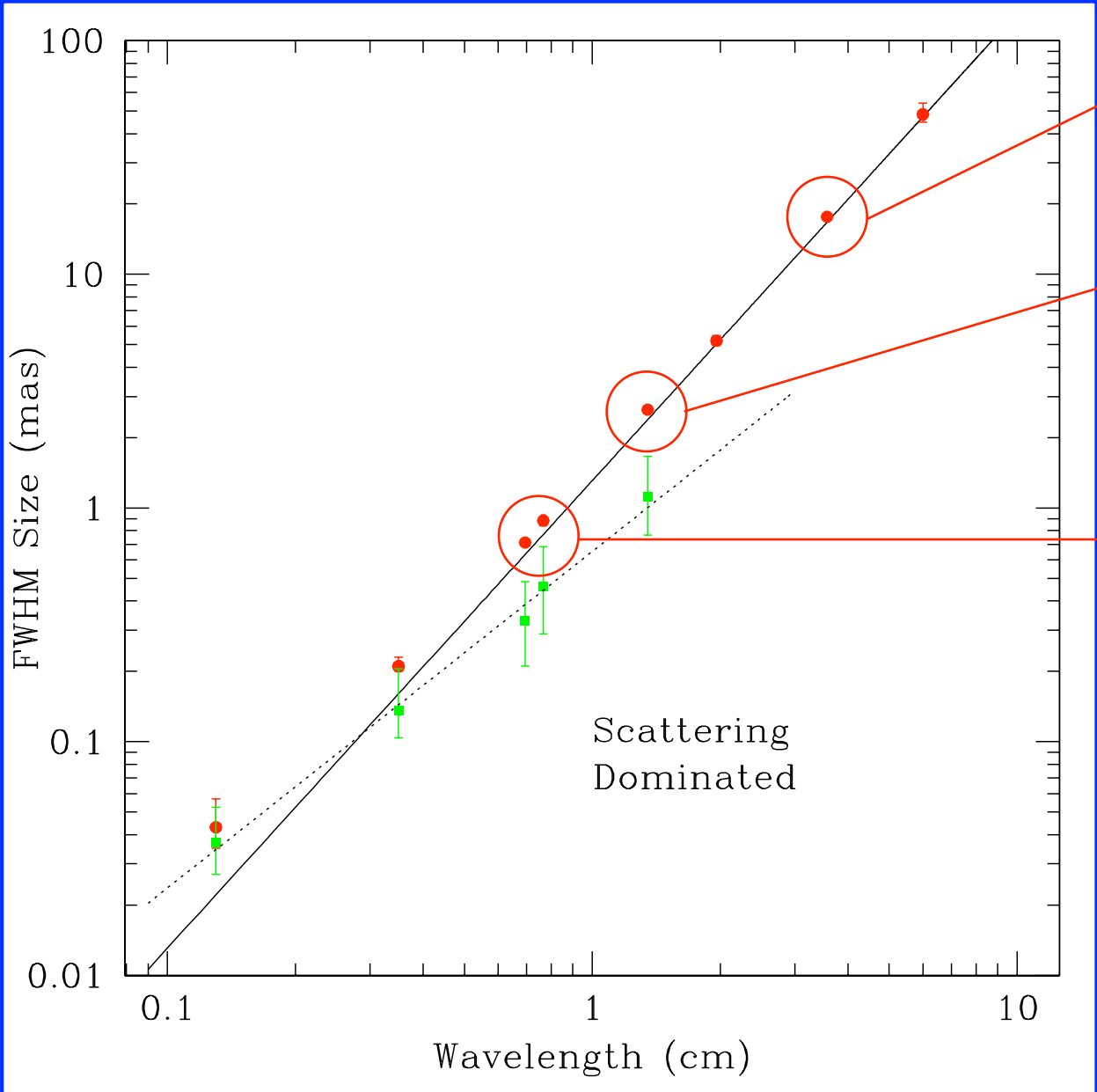
SgrA*: Piercing the Scattering Screen



Lo 1975
Jauncy 1989

Lo 1985
Marcaide 1999

SgrA*: Piercing the Scattering Screen



Lo 1975
Jauncy 1989

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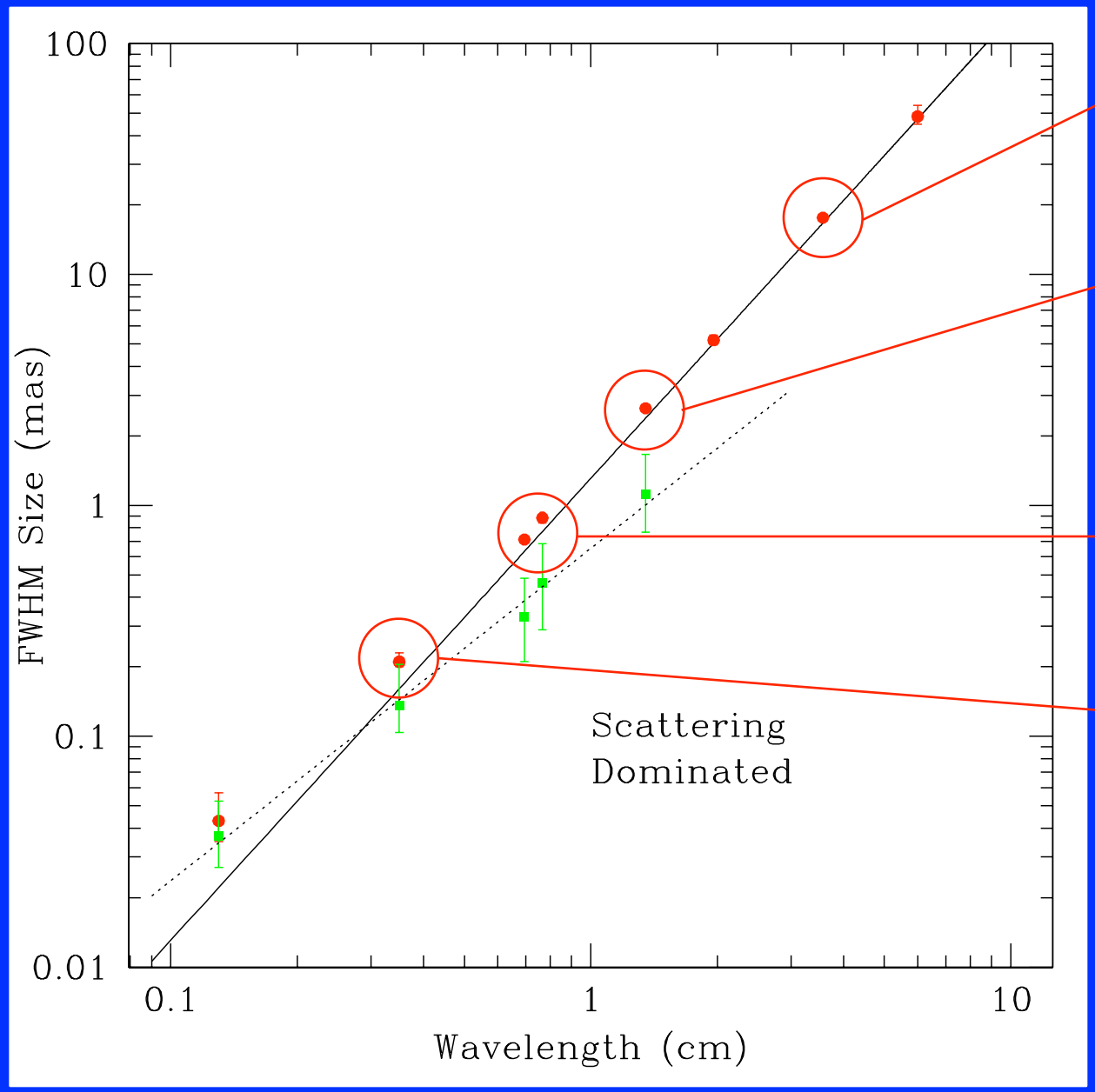
Marcaide 1999

Backer 1993
Krichbaum 1993
Bower 2004

SgrA*: Piercing the Scattering Screen



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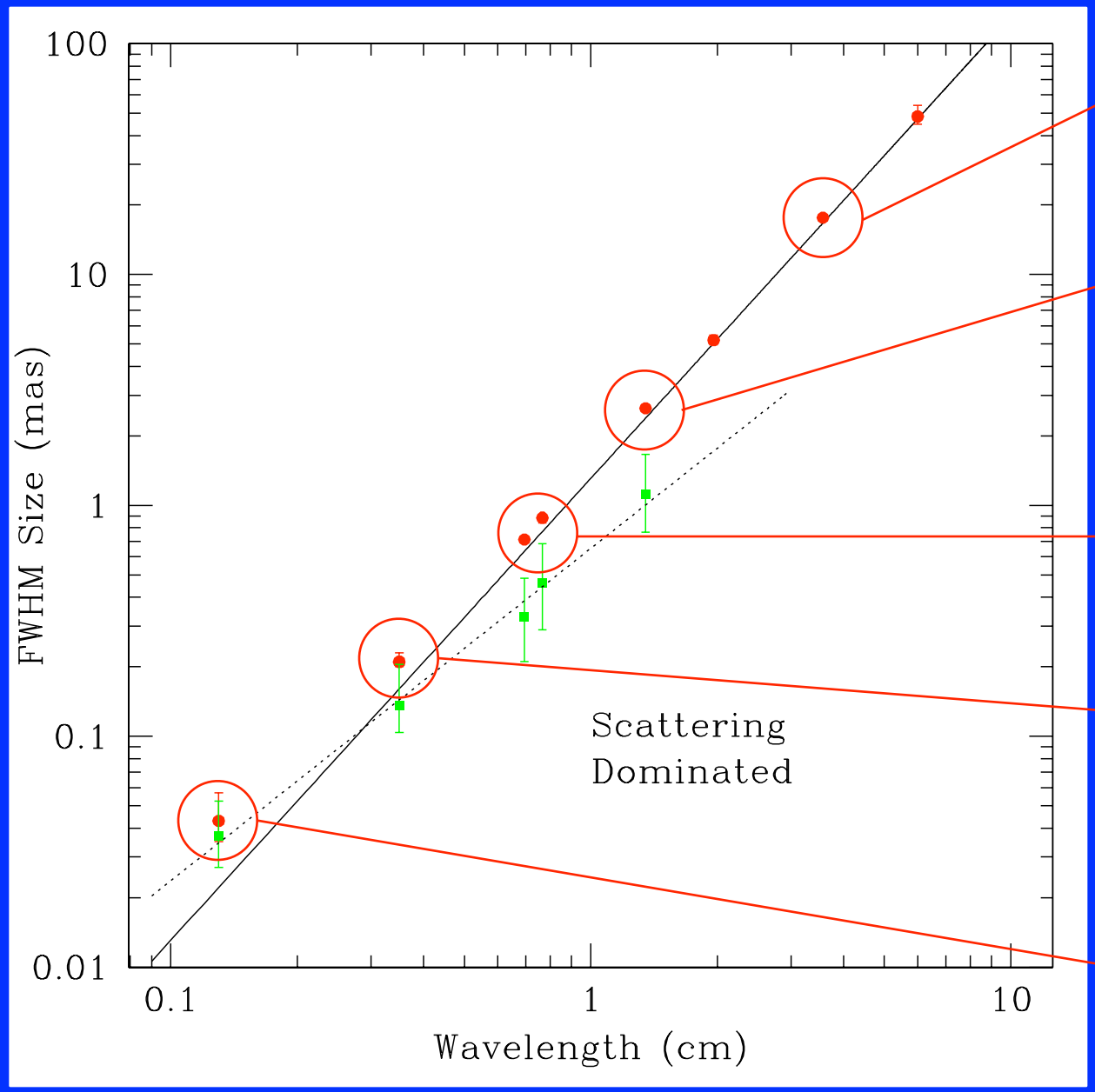

Lo 1975
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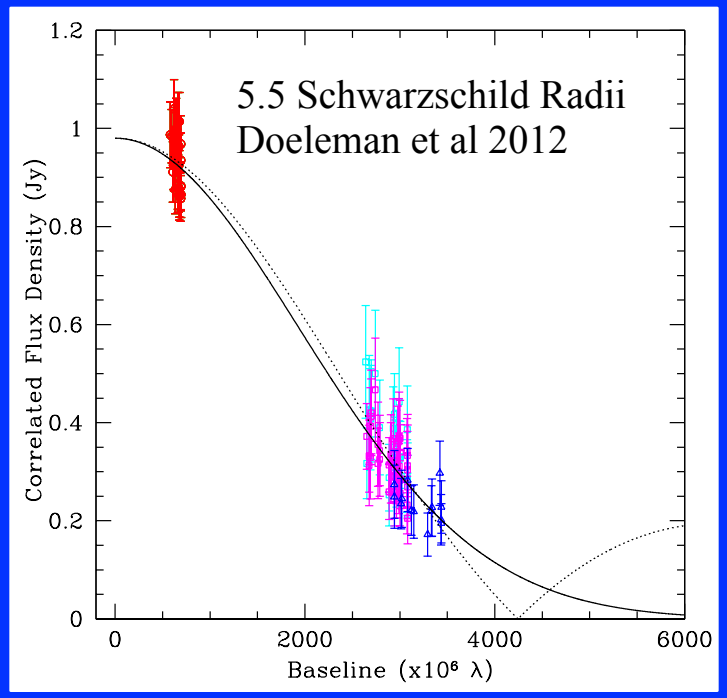
Backer 1993
Krichbaum 1993
Bower 2004

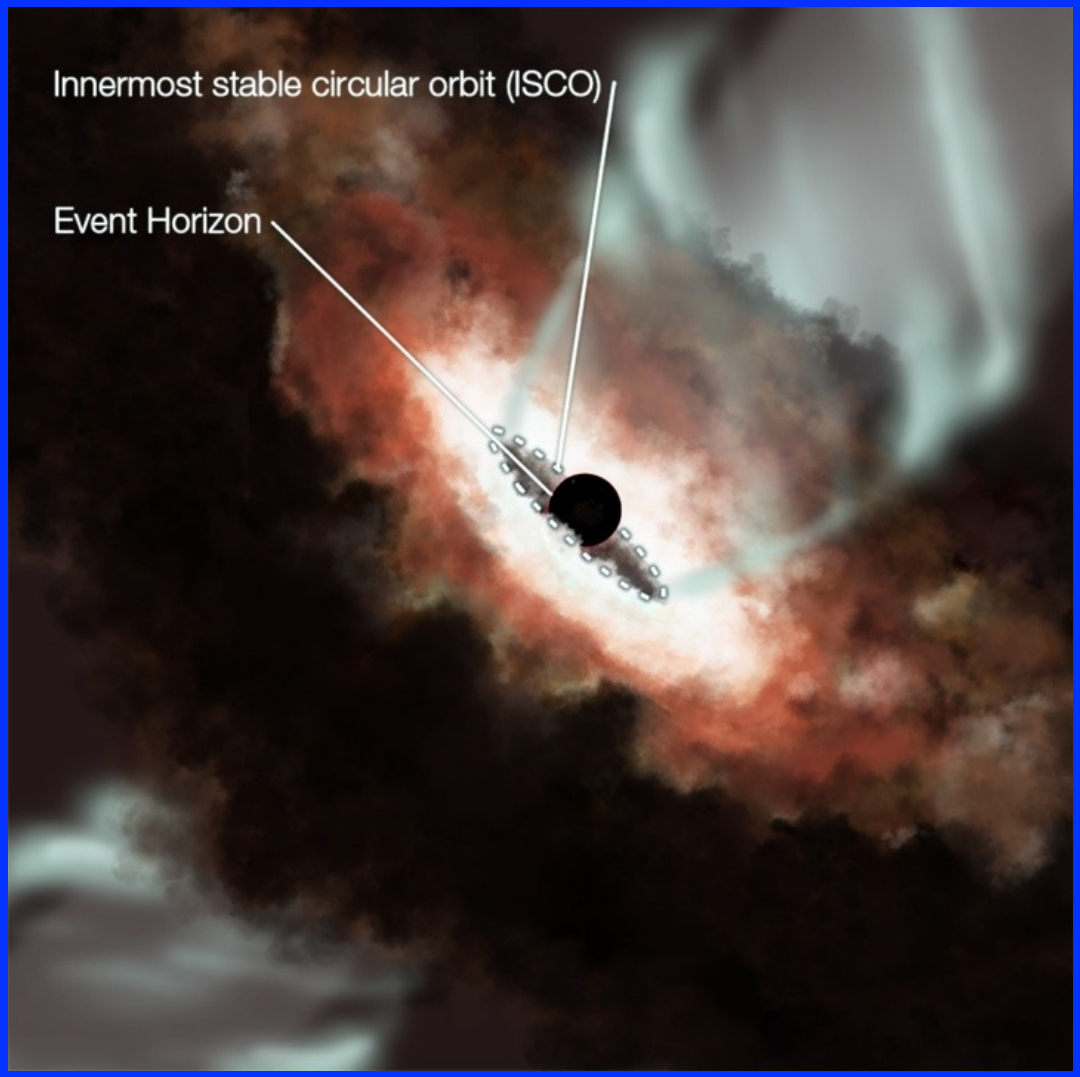
Rogers 1994
Krichbaum 1998
Shen 2005

Doeleman 2008
Fish 2011

M87: BH Origins of a Relativistic Jet

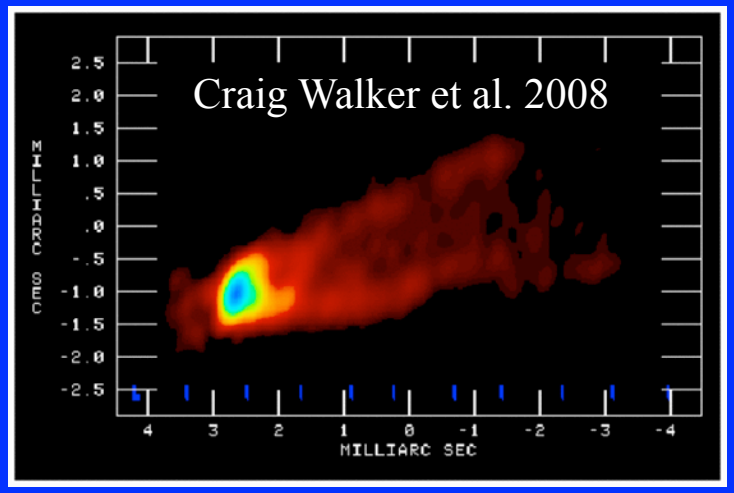
Craig Walker et al. 2008

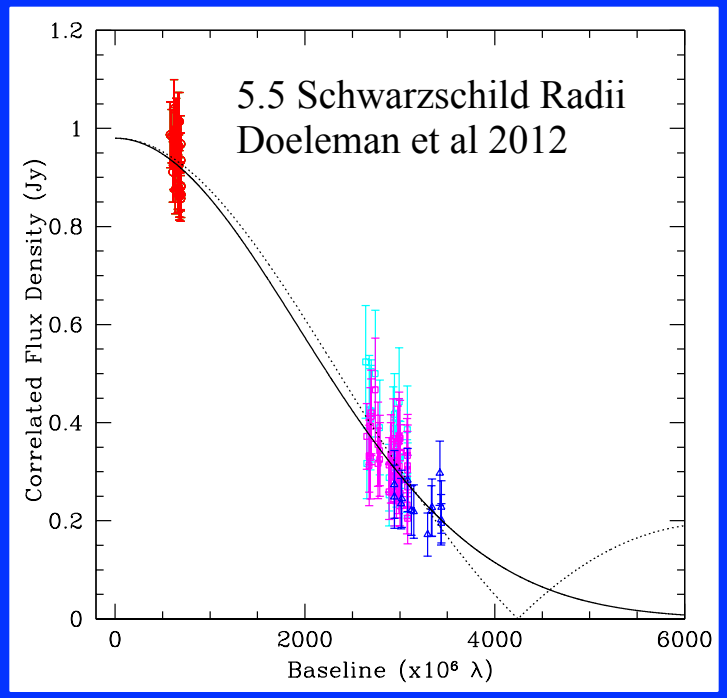


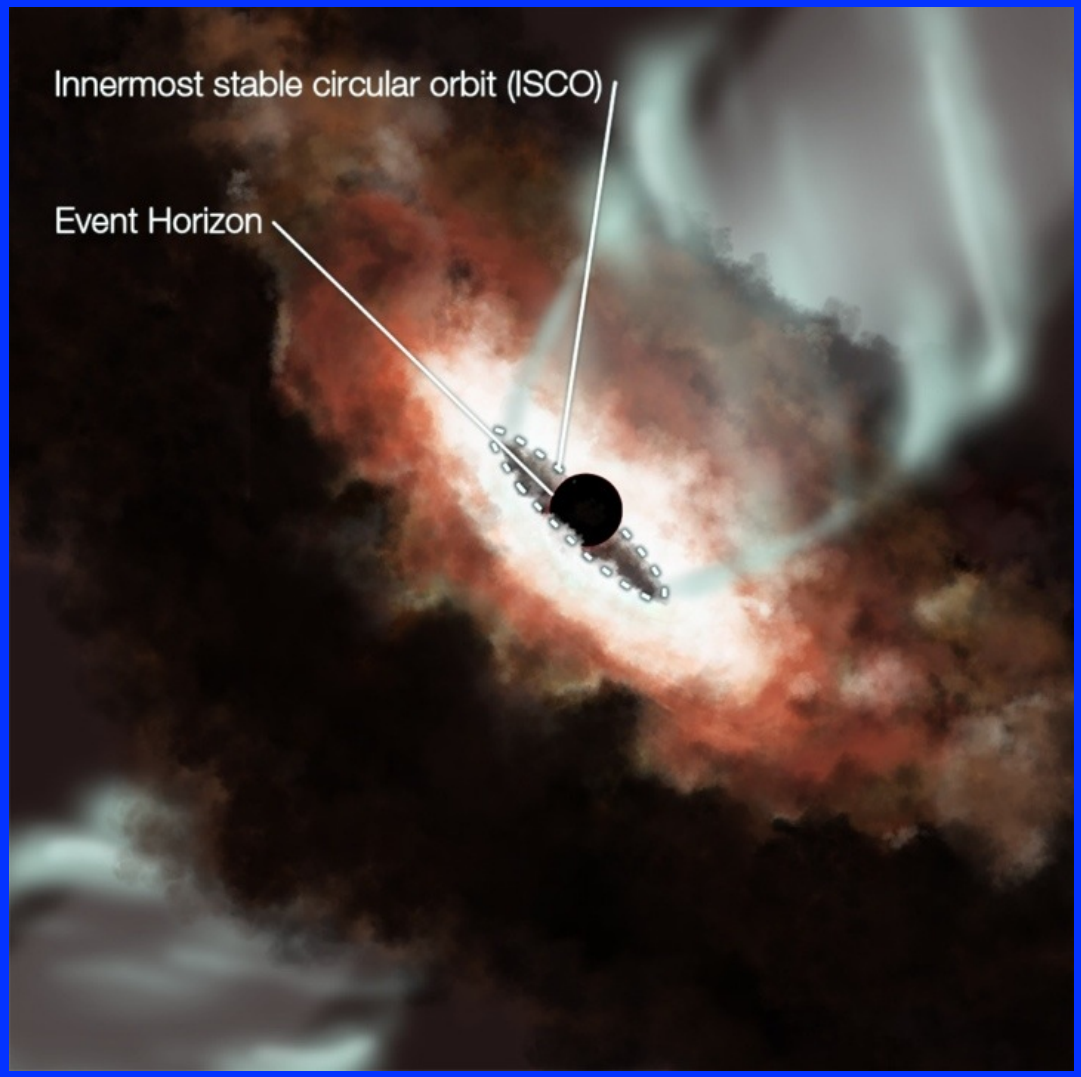


Graphic: Broderick

M87: BH Origins of a Relativistic Jet



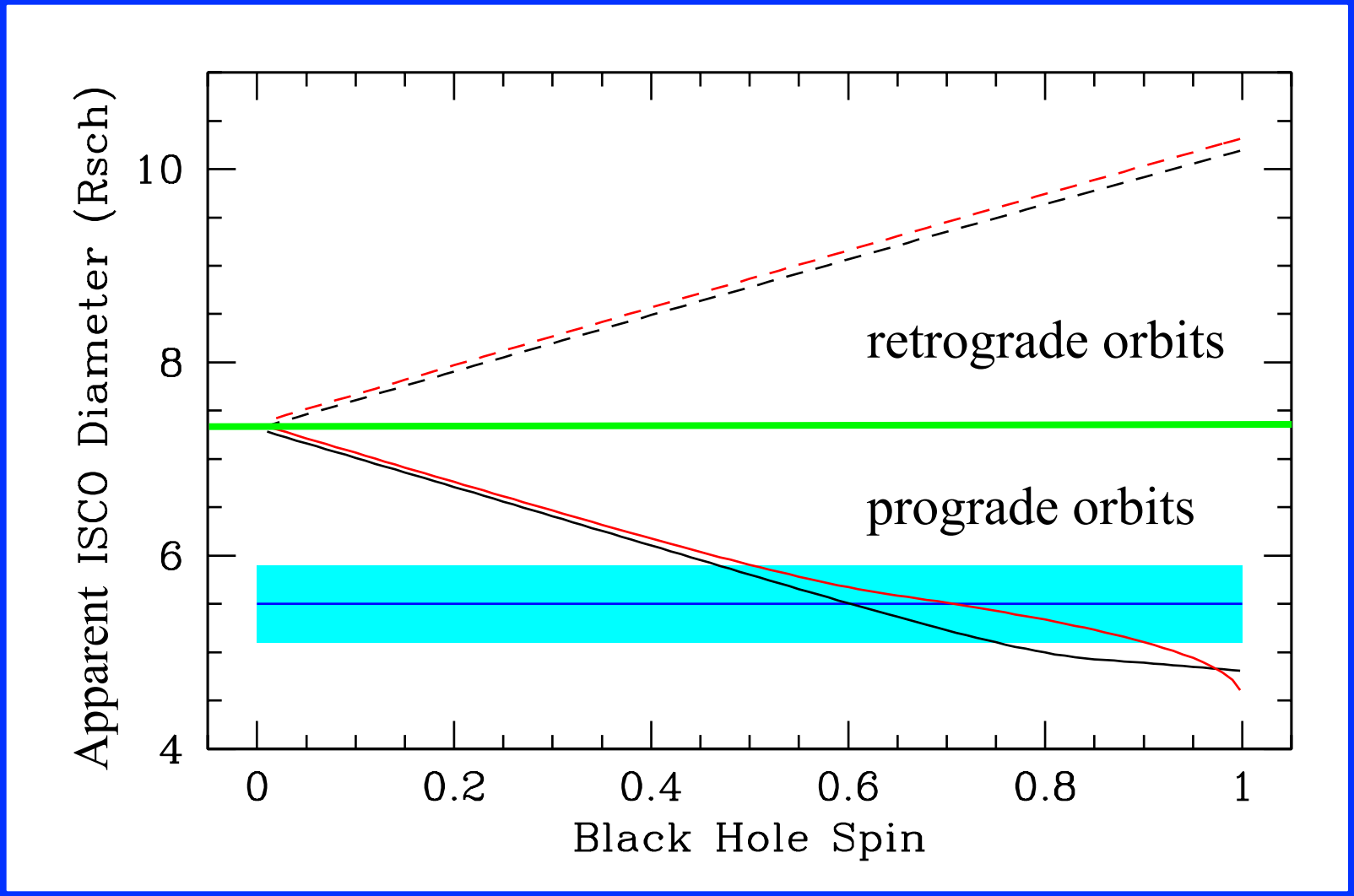




Graphic: Broderick

Strong GR Effects:

- Smaller than the expected ISCO: prograde disk.



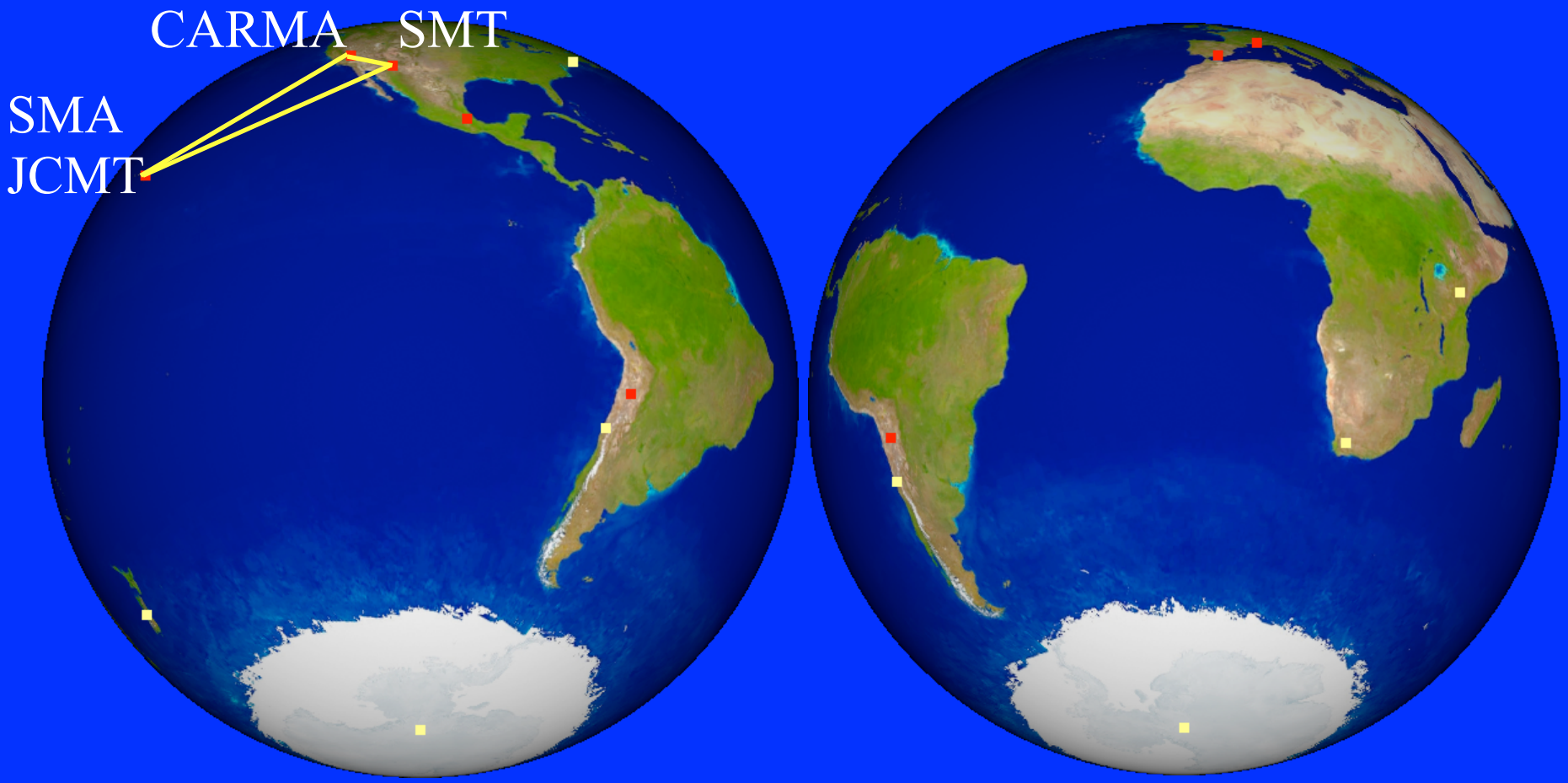
Doeleman et al 2012

EHT Specifications: The Next 2-3 Years

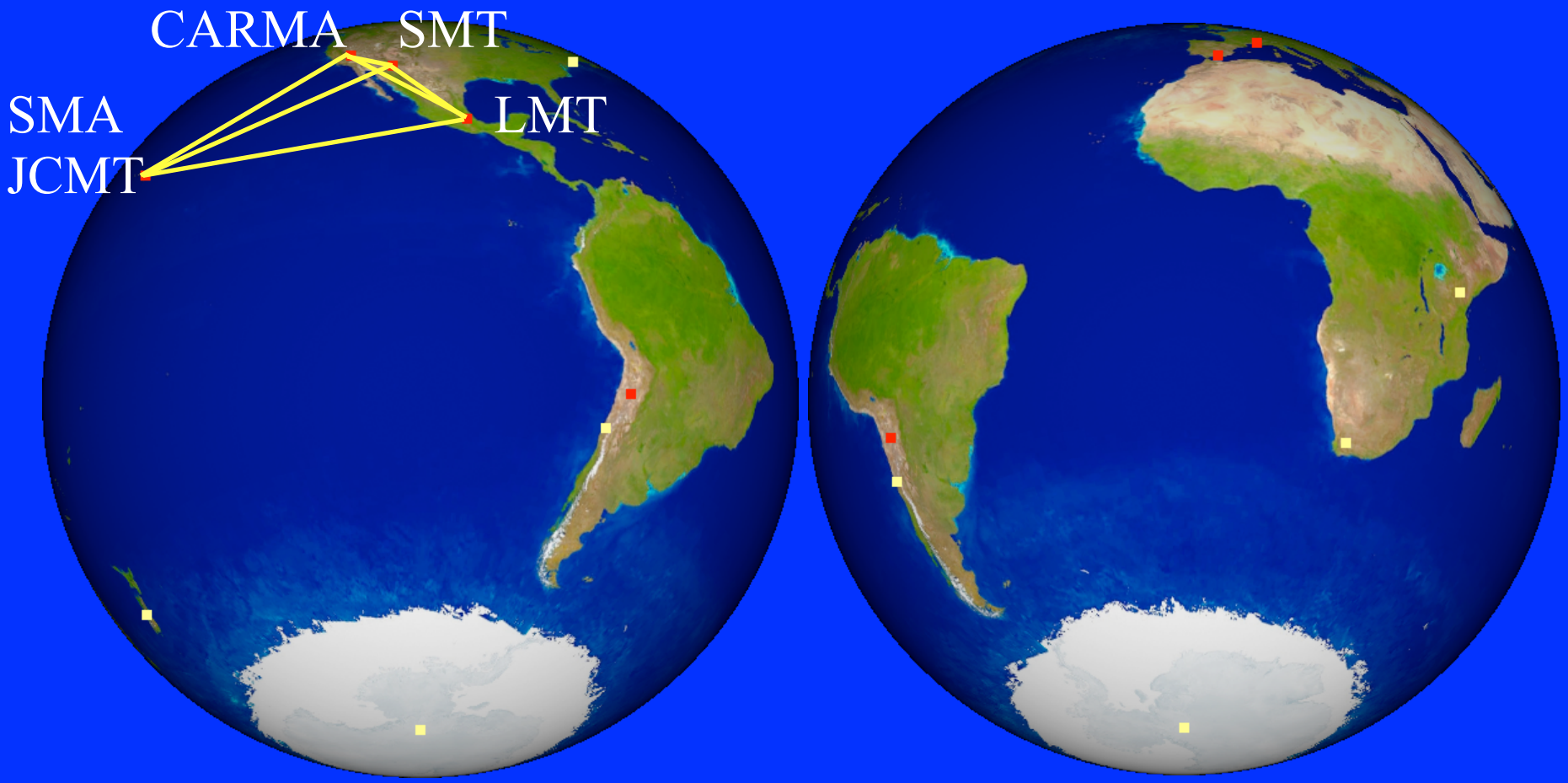
- Increase stations from 3 to 8: baseline number grows from 3 to 28 (n*(n-1)/2).
- Bandwidth increase from 1 GHz to 16 GHz.
- Collecting area increase by x10.
- Impact:
  - Sensitivity increase by x40: Long baselines.
  - Full closure phase information: modeling/imaging.
  - Full polarization information: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

SgrA*'s view of the EHT

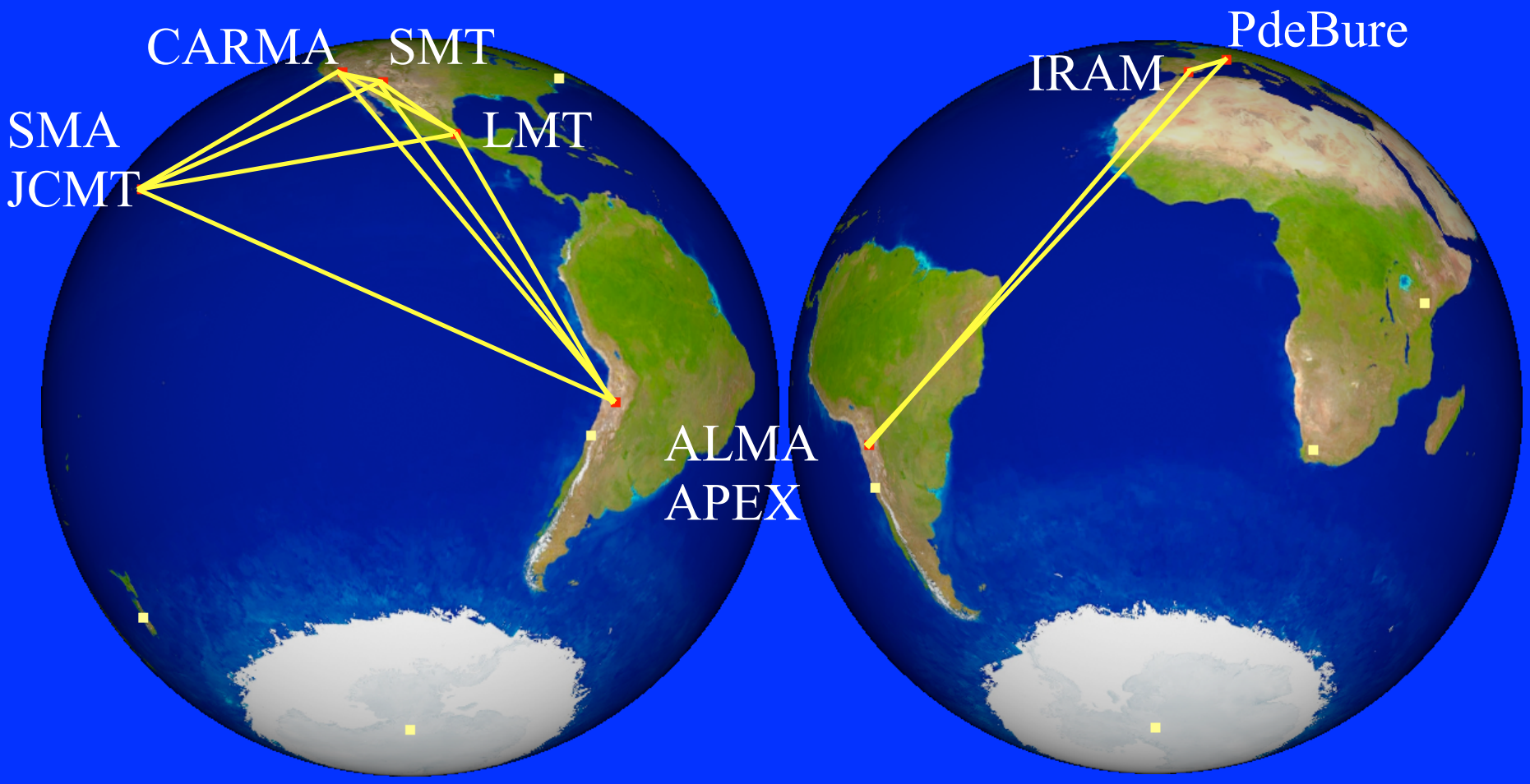
SgrA*'s view of the EHT



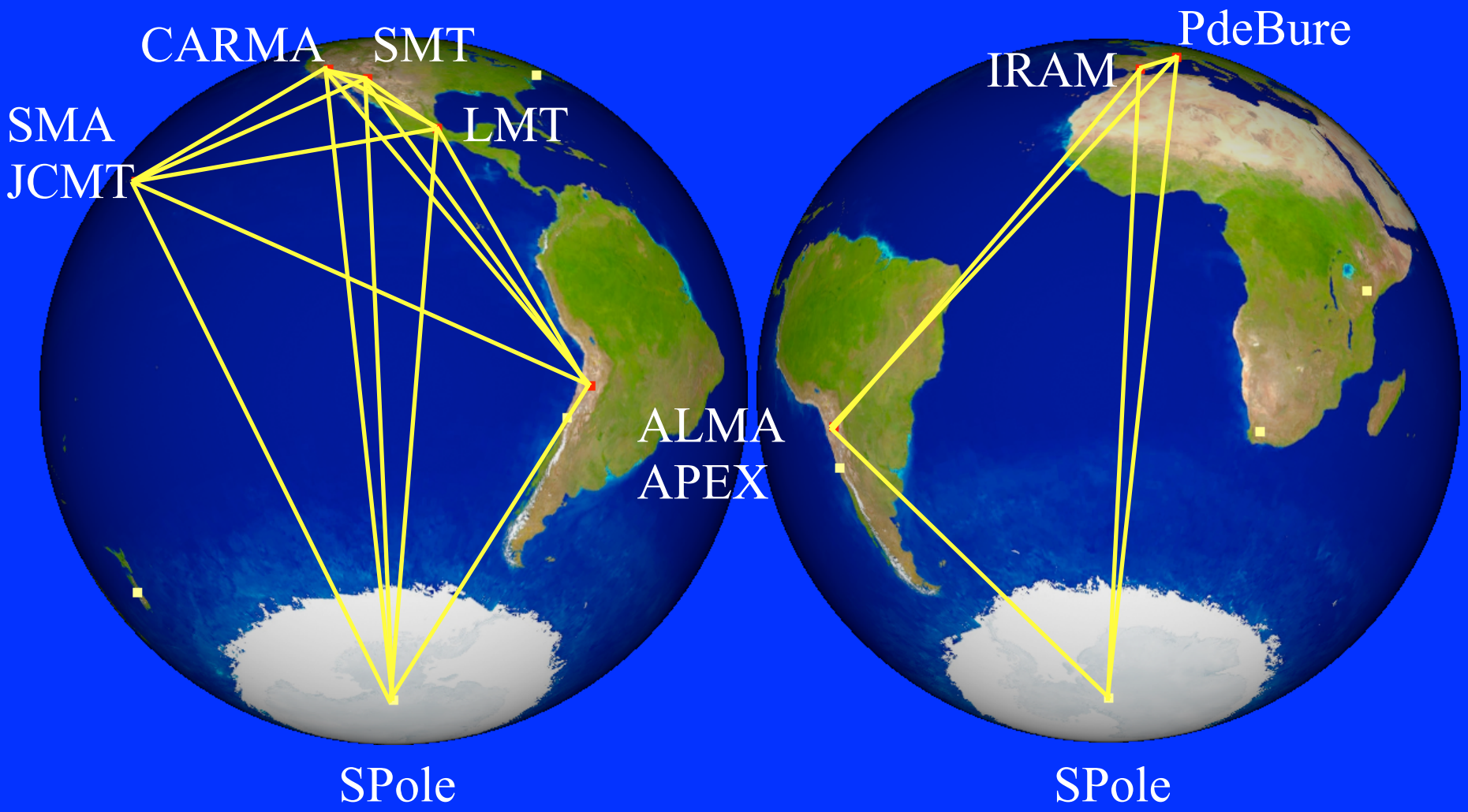
SgrA*'s view of the EHT



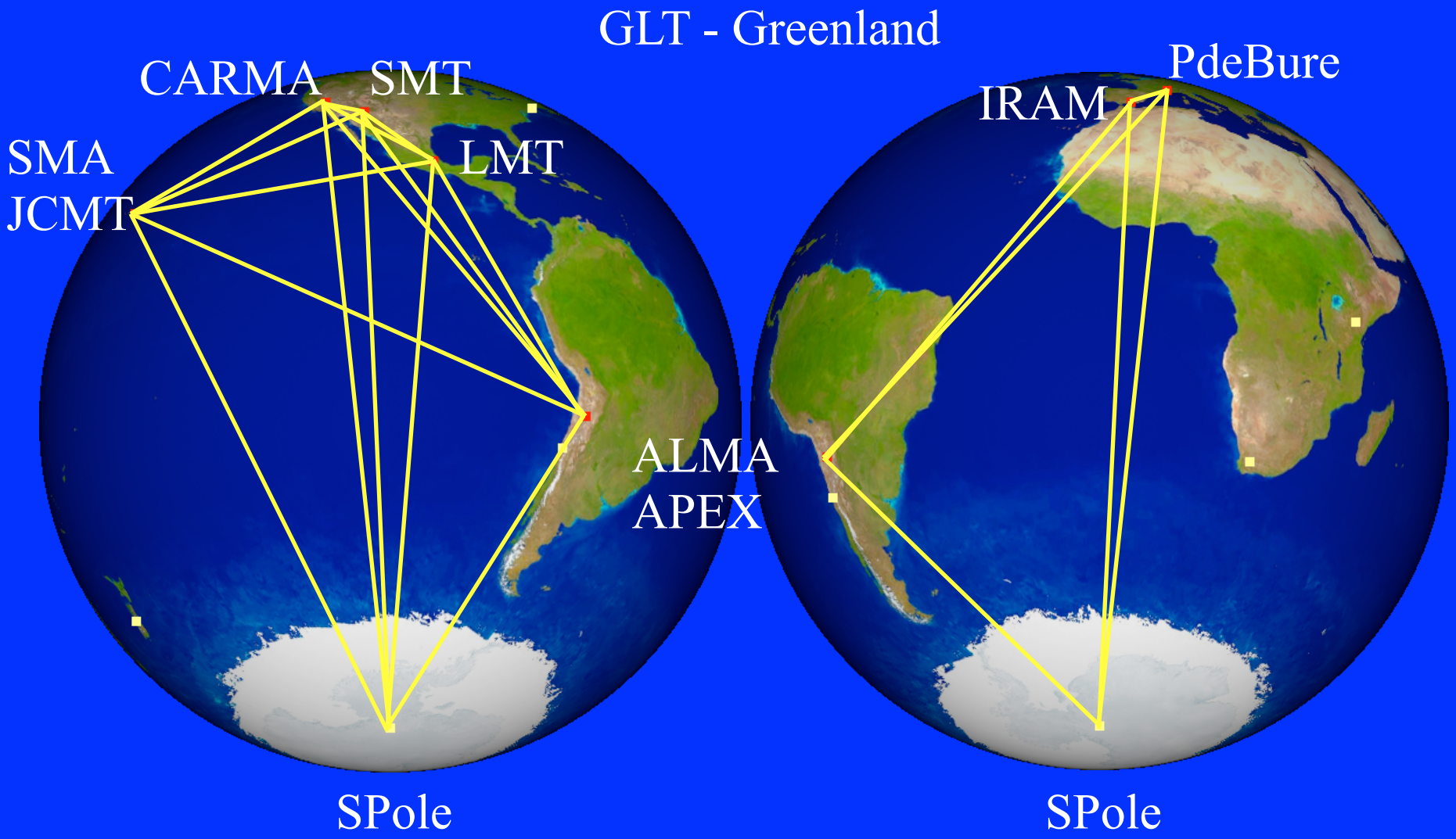
SgrA*'s view of the EHT



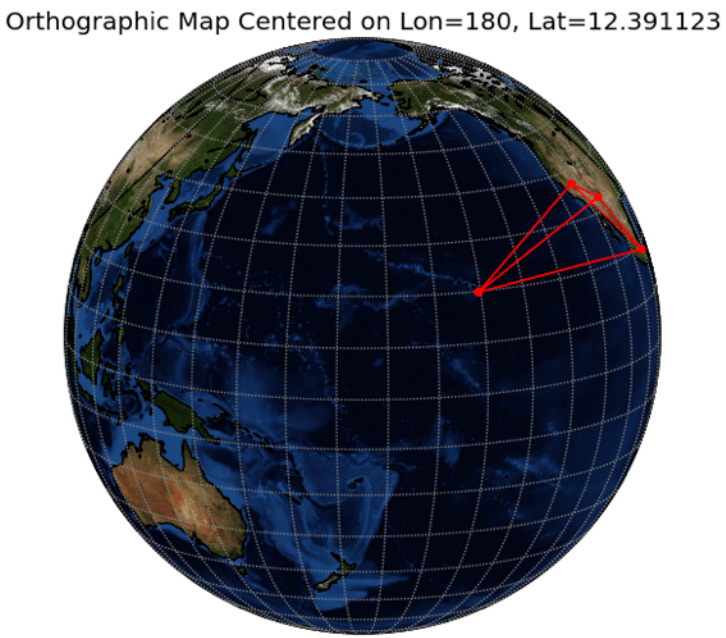
SgrA*'s view of the EHT

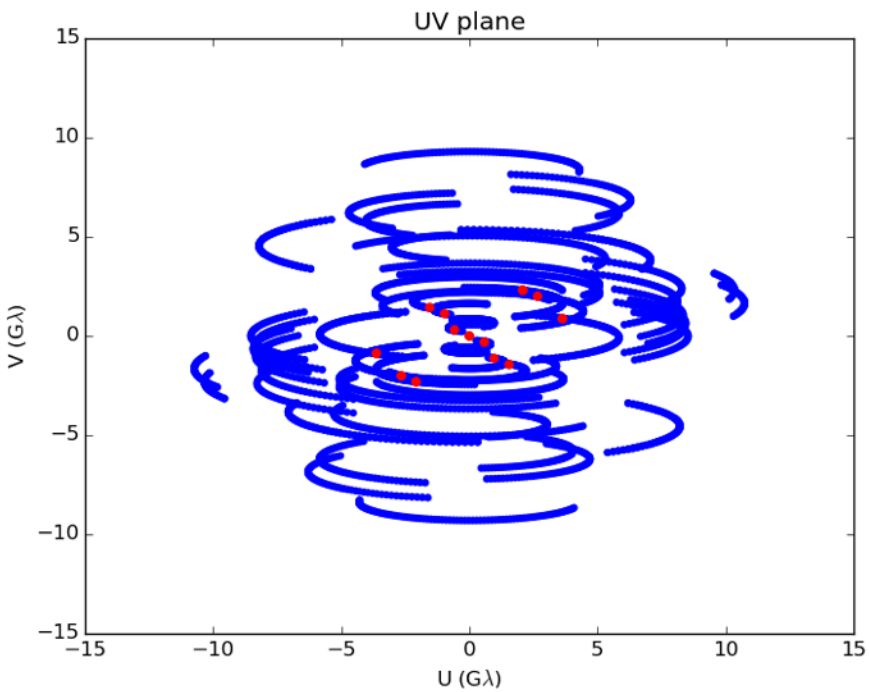


SgrA*'s view of the EHT



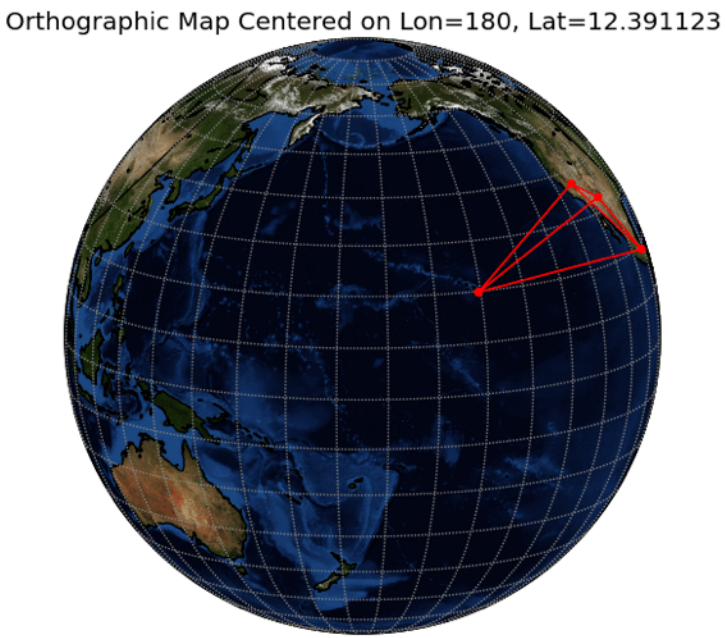
Future EHT Coverage

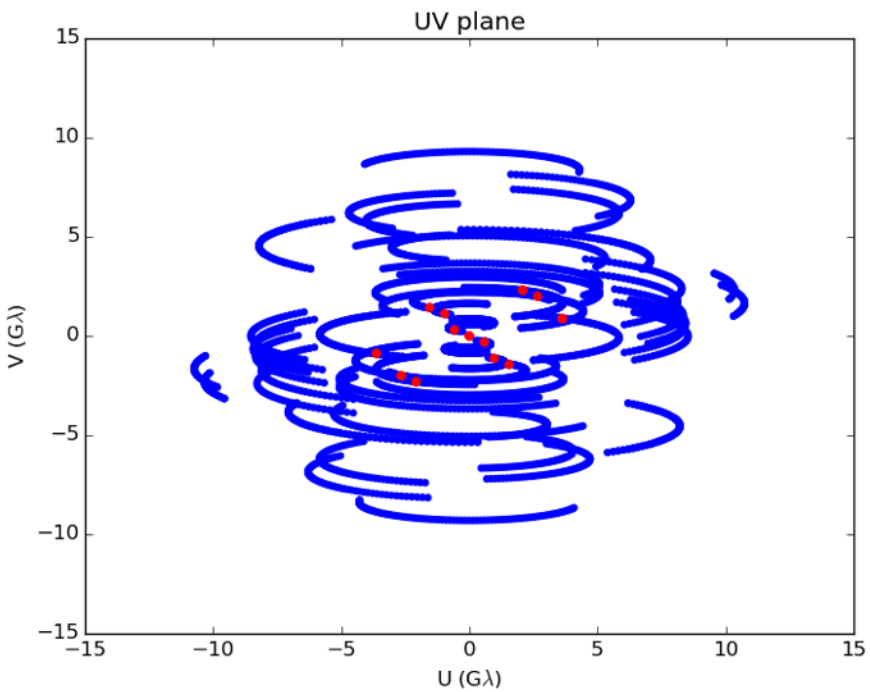




Animation: Laura Vertatschitsch (SAO)

Future EHT Coverage

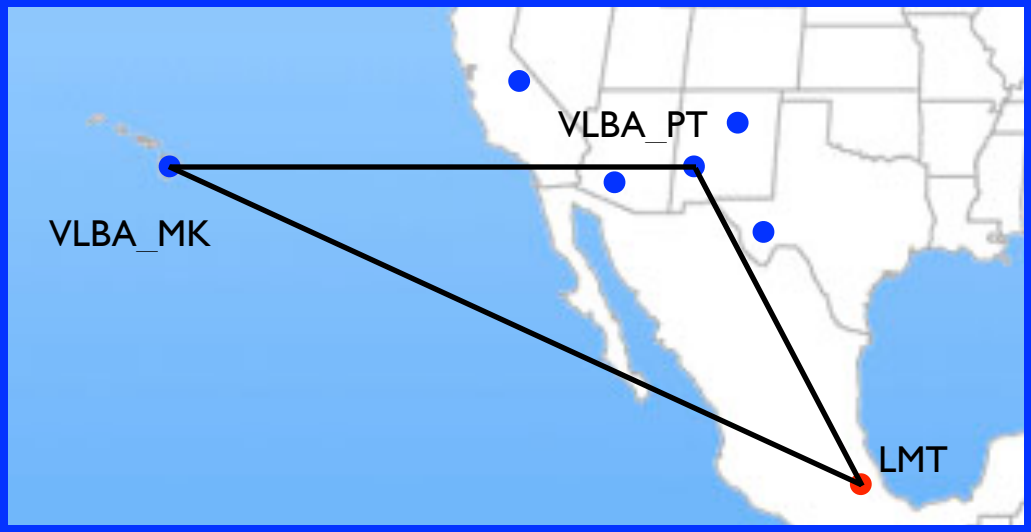




Animation: Laura Vertatschitsch (SAO)

3mm VLBI with the LMT

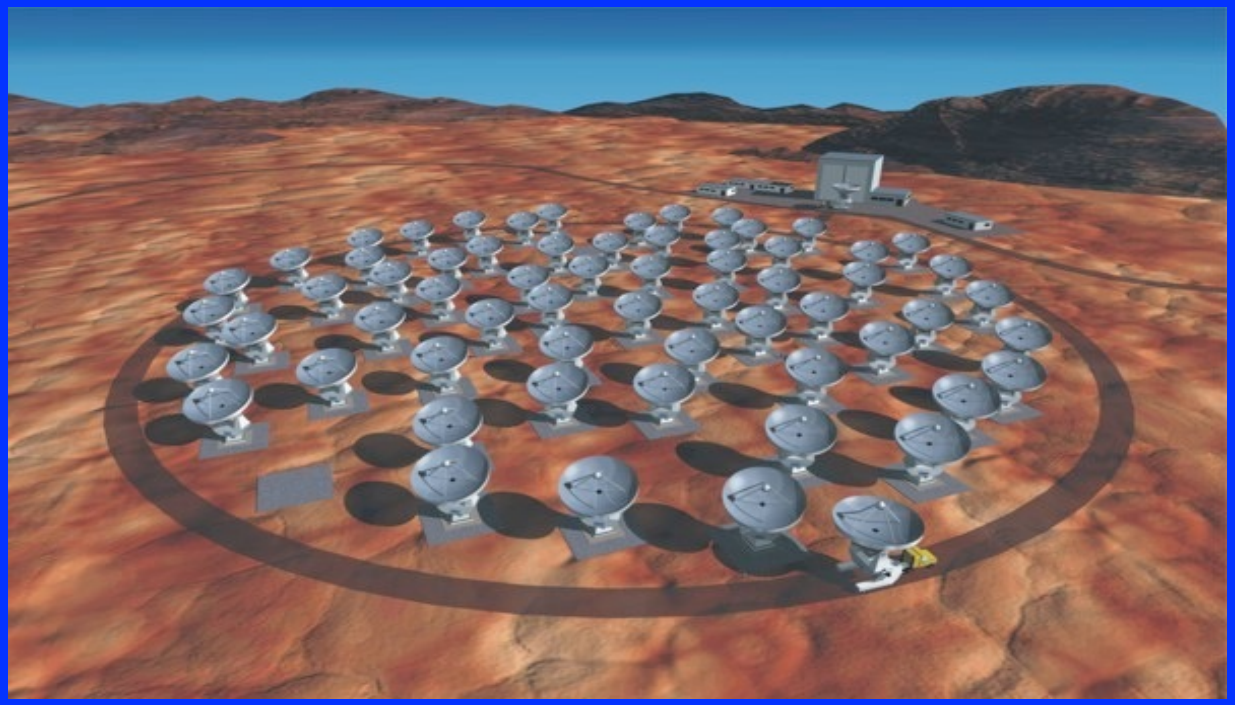
50m diameter.
First light at 3mm & 1.3mm.



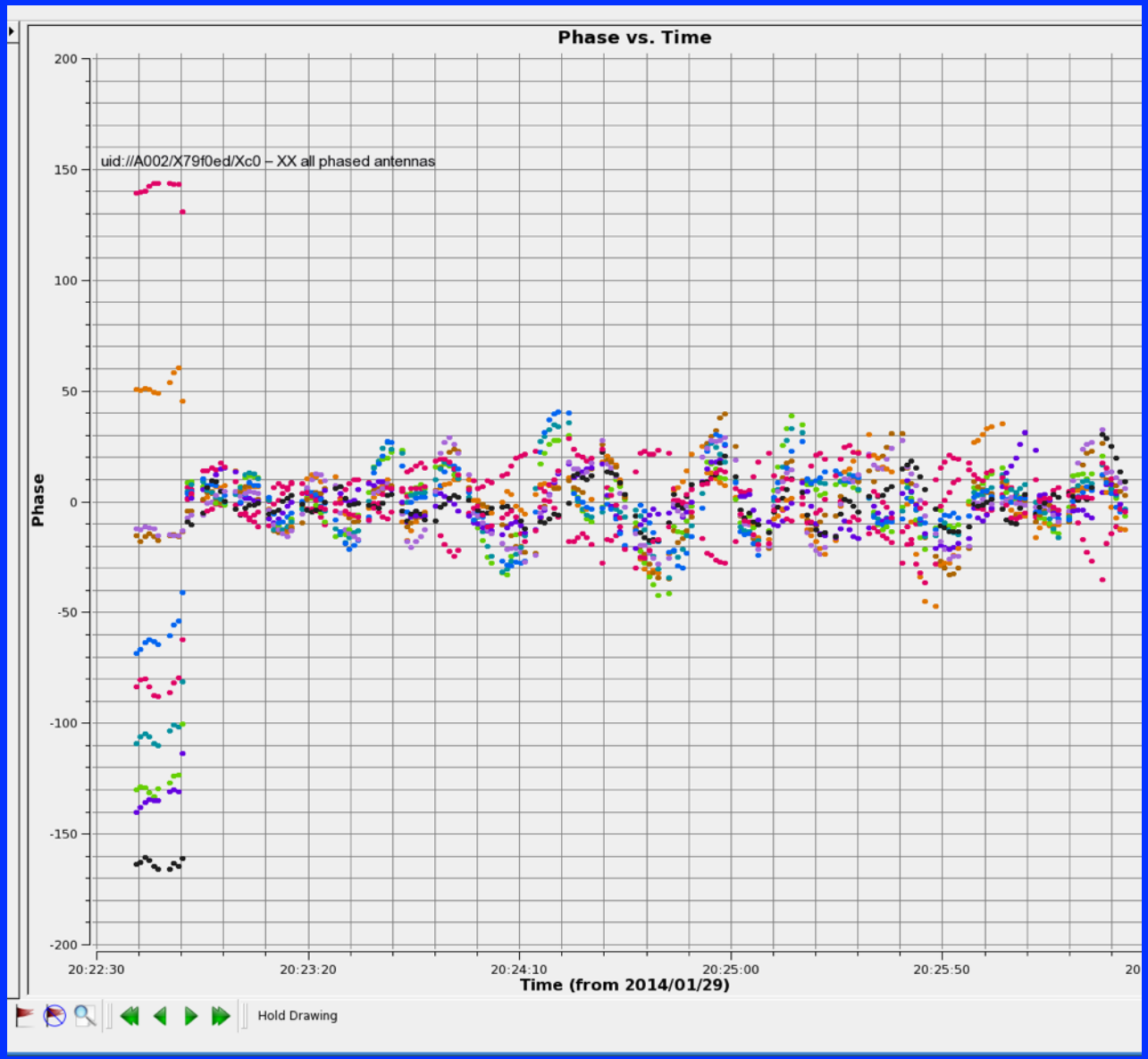
Requires new 1.3mm Receiver for EHT work.

Phasing ALMA

- Single most important objective for EHT.
- Increases resolution by x2, sensitivity by x10.
- First ALMA VLBI scheduled 2014/2015.



Phased ALMA


Phase vs. Time
uid://A002/X79f0ed/Xc0 – XX all phased antennas
Phase
200
150
100
50
0
-50
-100
-150
-200
20:22:30
20:23:20
20:24:10
20:25:00
20:25:50
Time (from 2014/01/29)
Hold Drawing

SMA Pivotal

- Hydrogen Maser
- VLBI instrumentation: recorders, D/C, DBE
- Provides LO and IF path for JCMT (dual pol).
- E-W baseline coverage for both SgrA* & M87.
- SWARM: expansion to ALMA specs (64Gb/s).

512Mb/s VLBI System

Analog Filter Backend

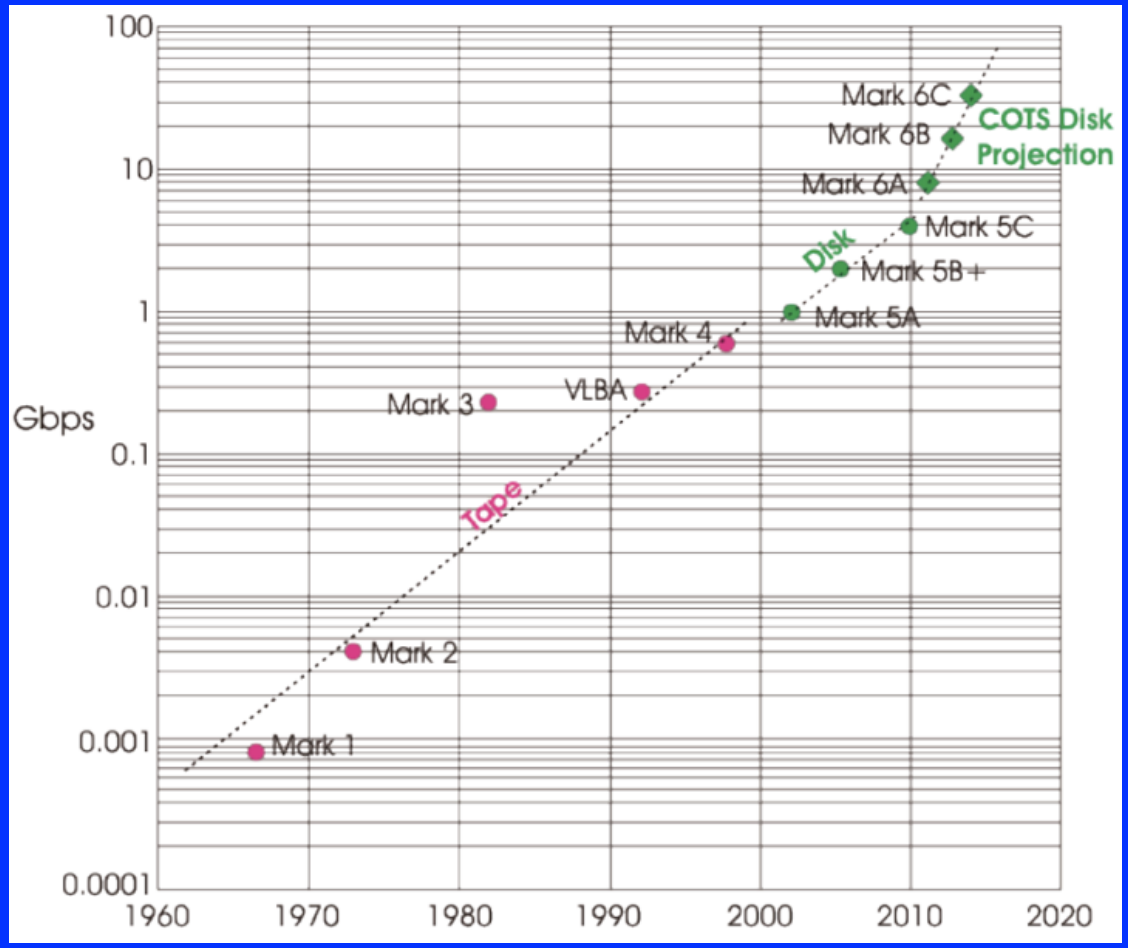
Tape Recorder

- Total cost $1 Million to equip a VLBI station
- 1990's: 128Mb/s

Next Gen VLBI Technology: Keeping up with Moore

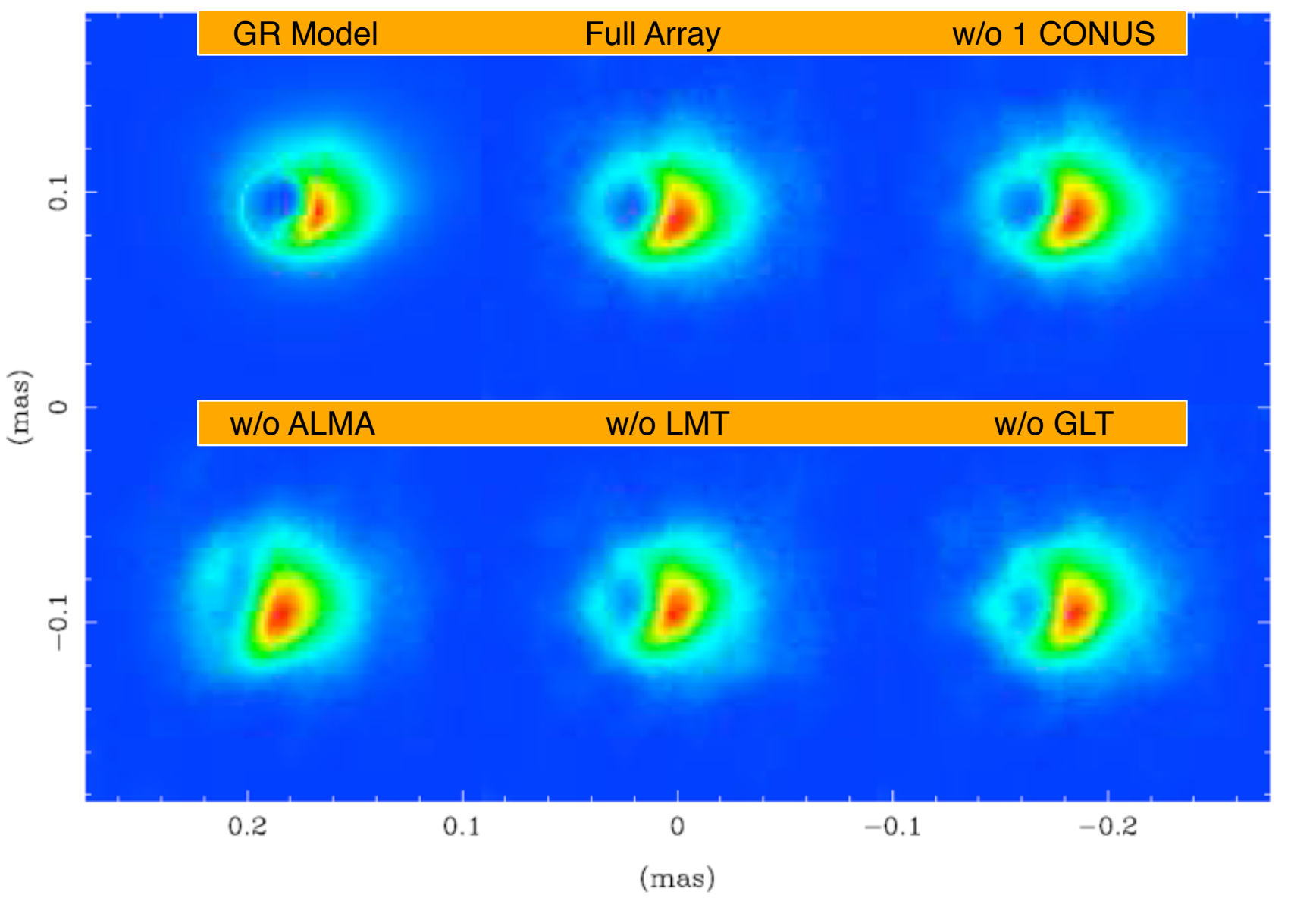
Digital Backend (DBE)

Digital Recorder (Mark6)



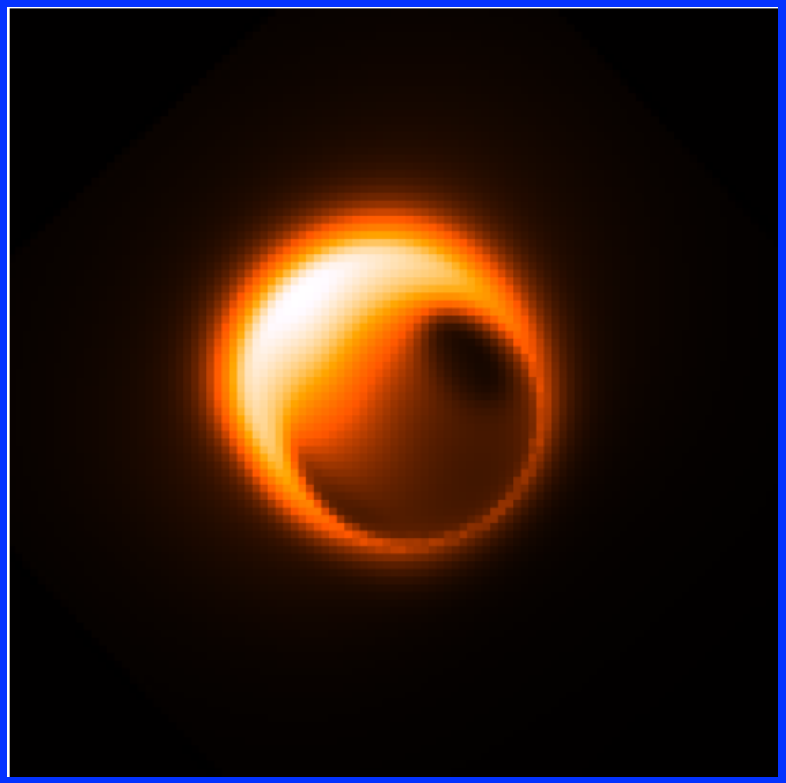
Current capability: 4 GHz real time.
Target: 16 GHz
Data per session: ~7 PetaBytes.

EHT Imaging: Optical Algorithms



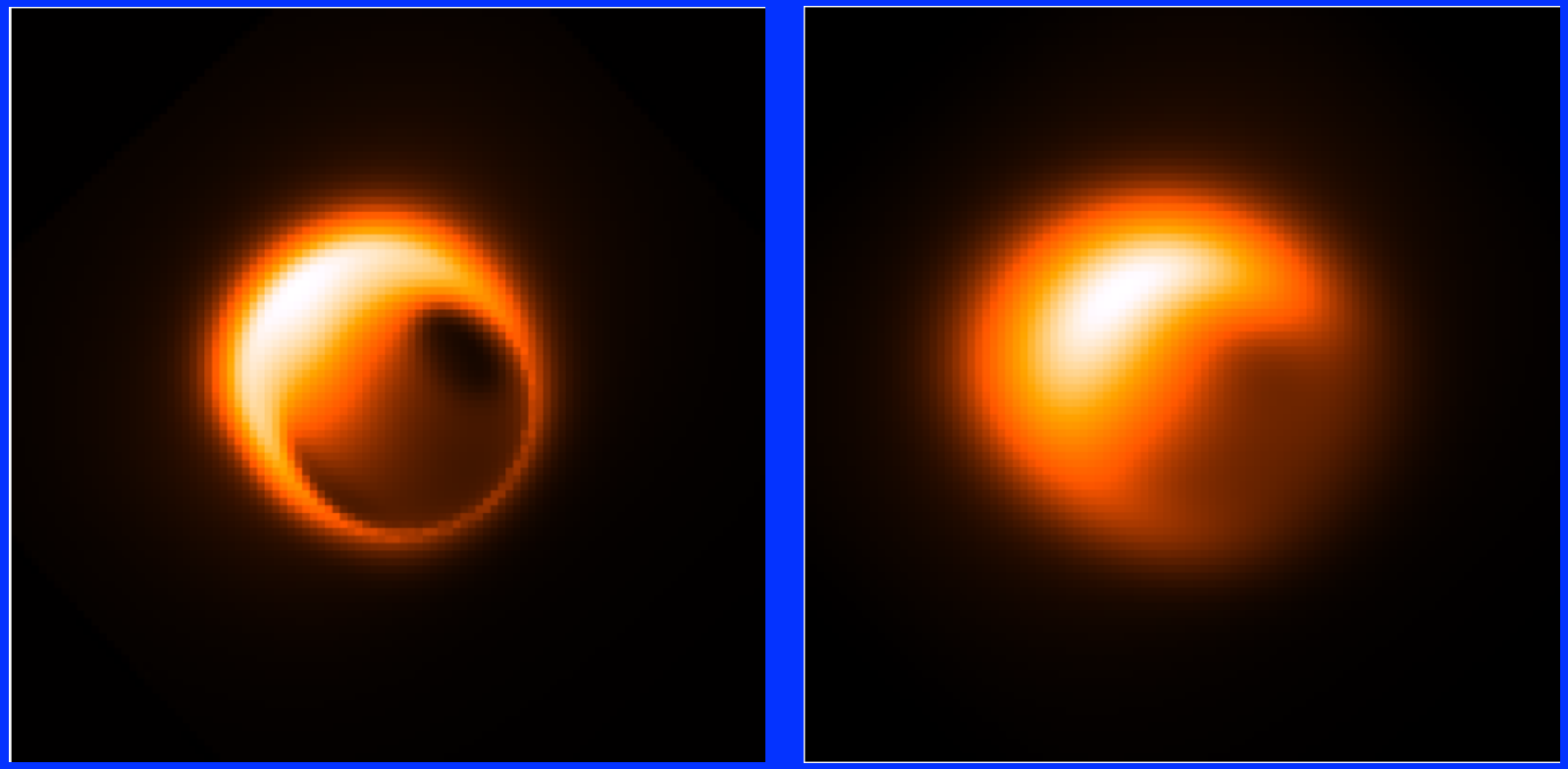
Lu, Broderick, Baron, Monnier, et al, ApJ, v788, 120L, 2014

De-blurring SgrA*



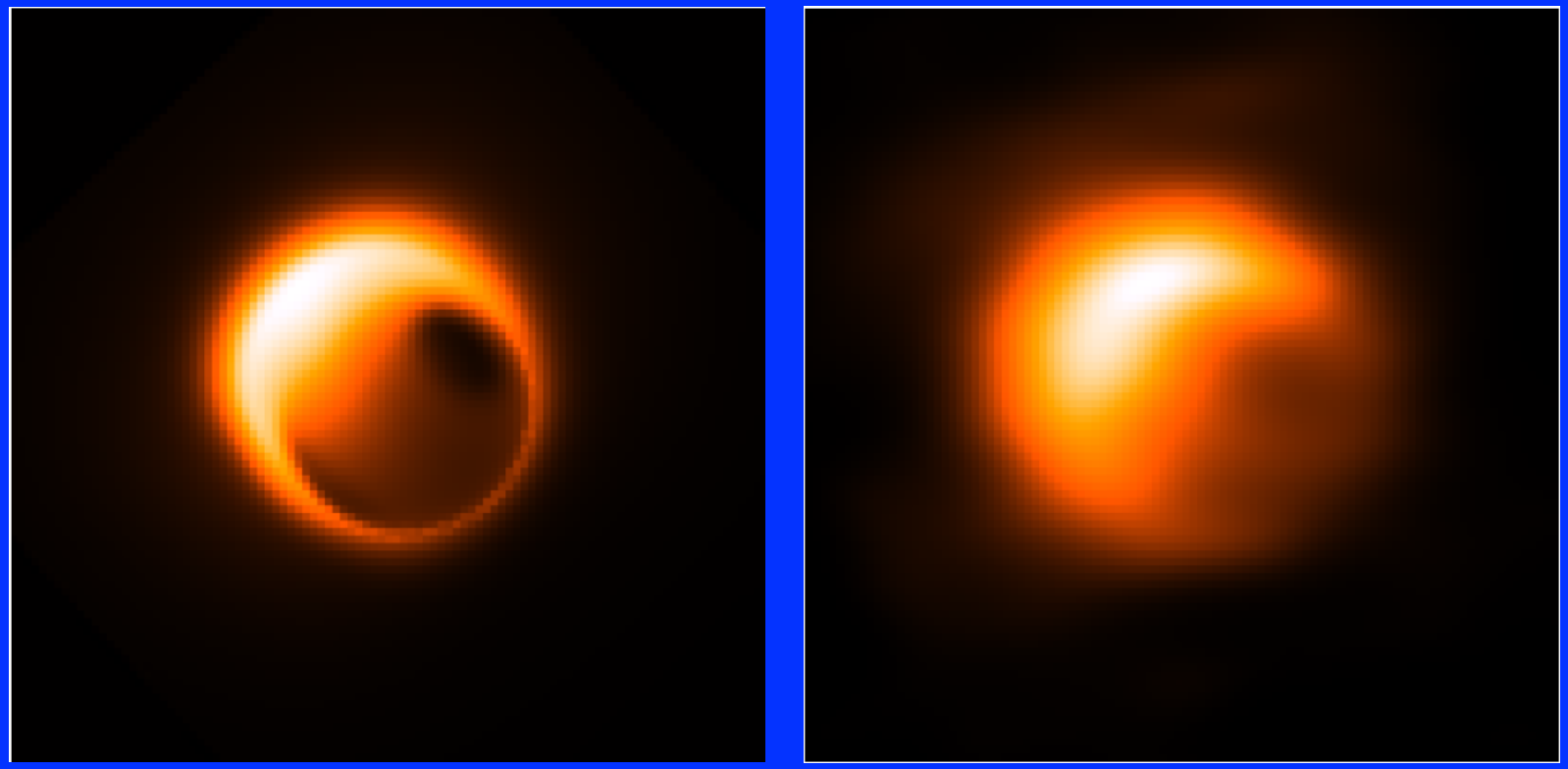
Fish et al, in prep.

De-blurring SgrA*



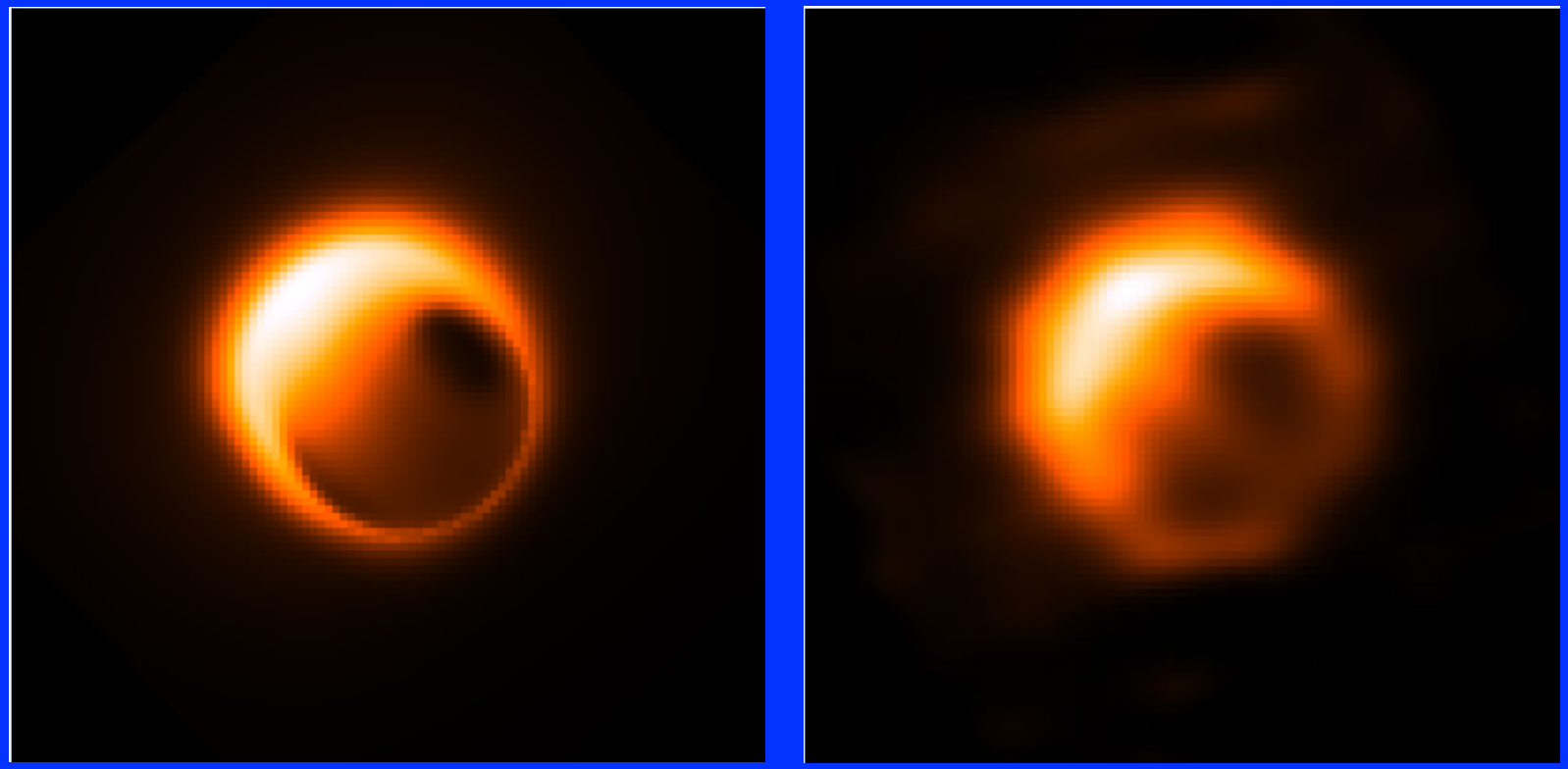
Fish et al, in prep.

De-blurring SgrA*



Fish et al, in prep.

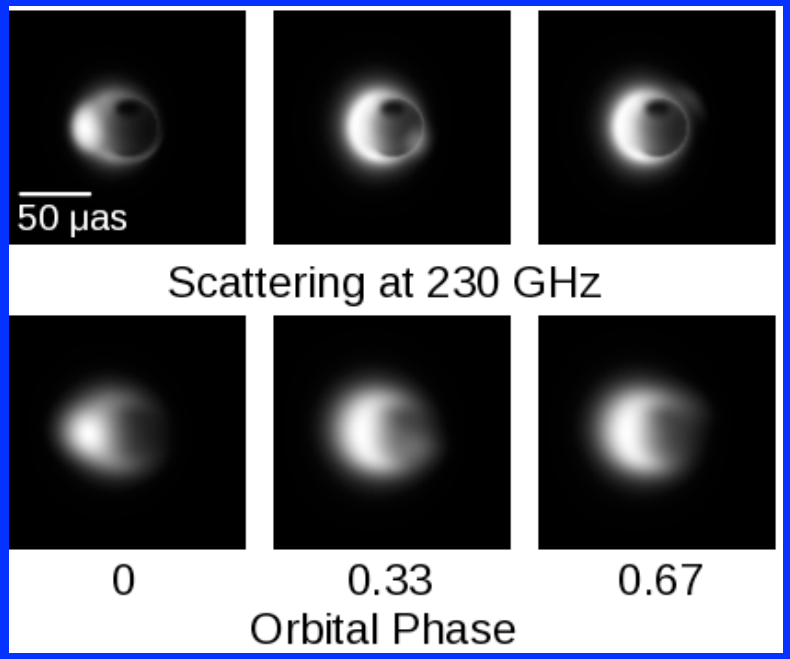
De-blurring SgrA*

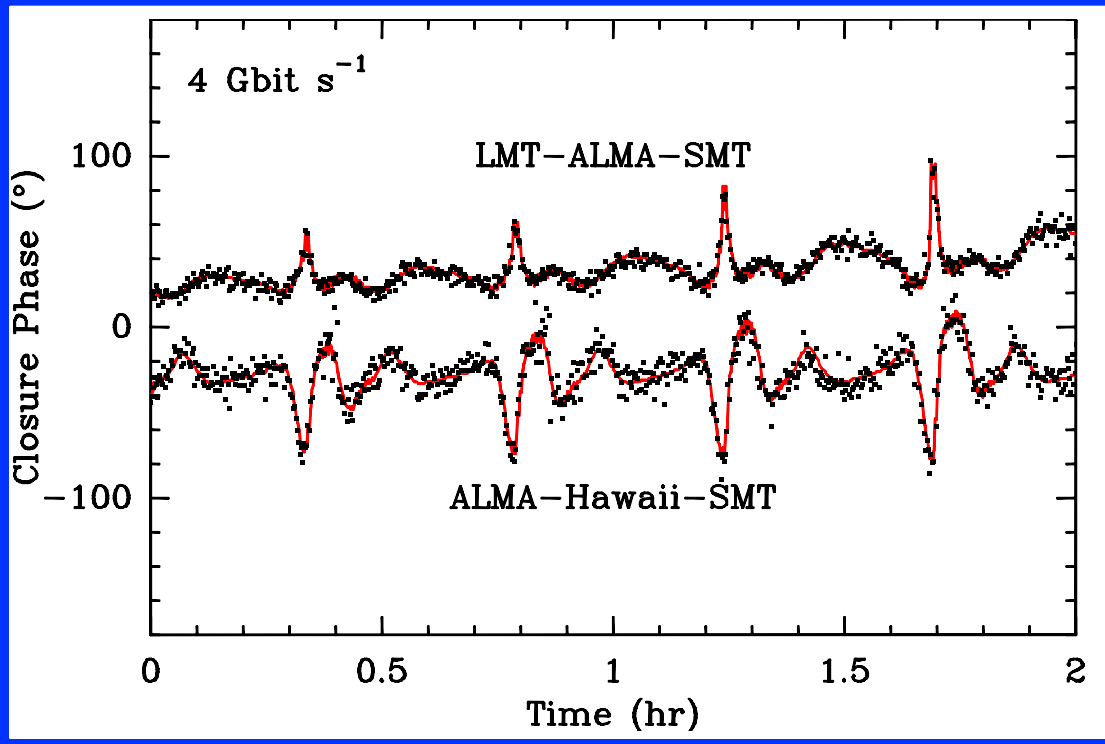


Fish et al, in prep.

Time Resolving BH Orbits

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





Time Resolving BH Orbits

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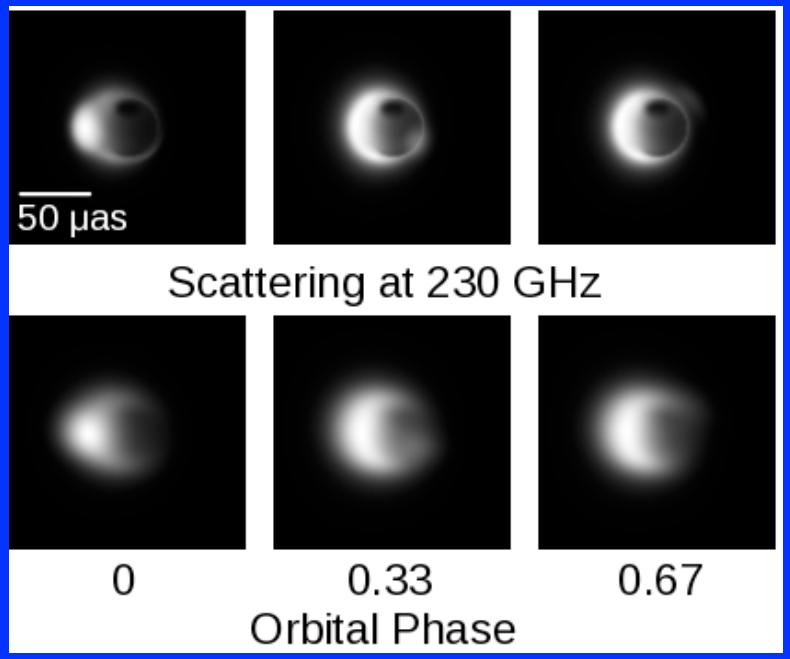
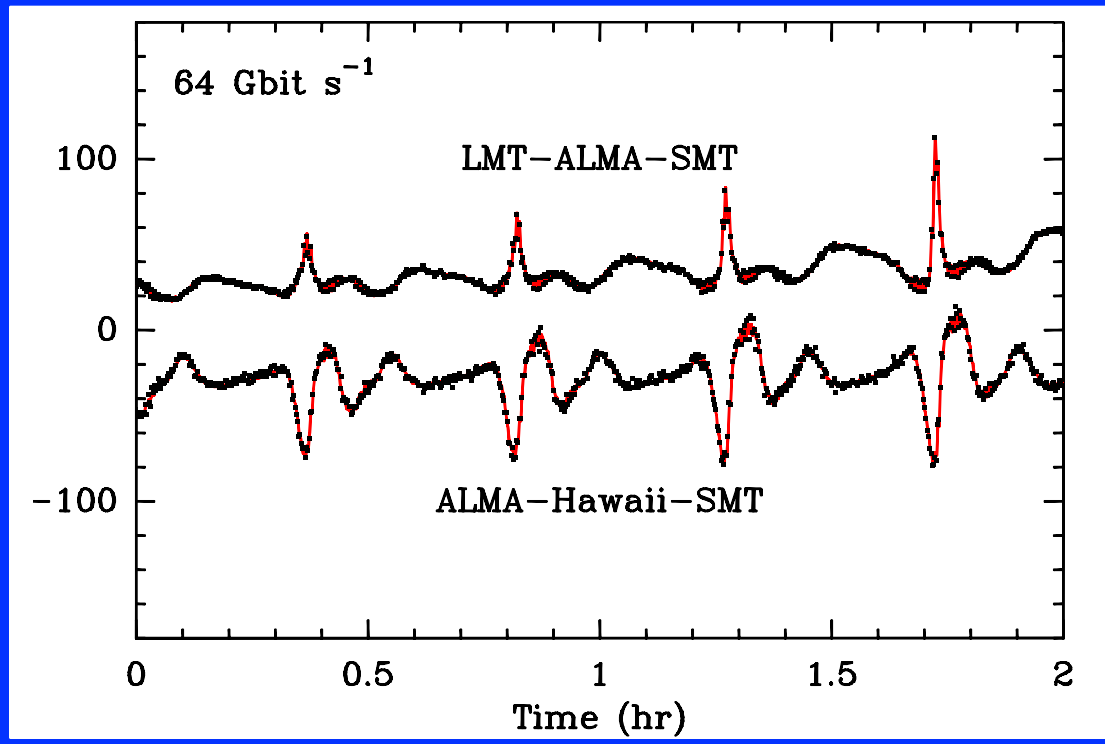
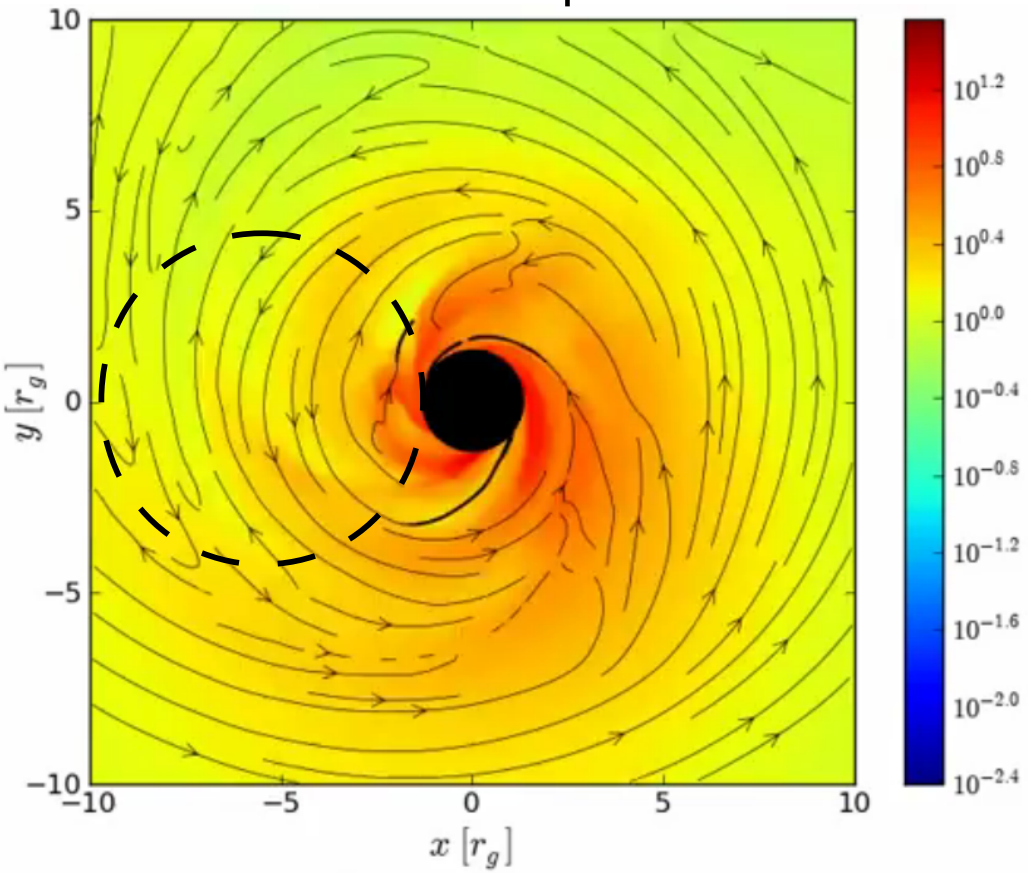




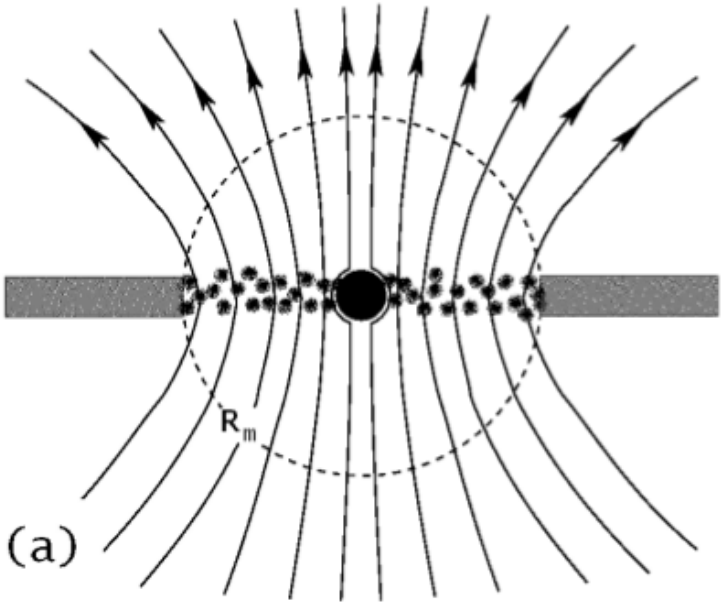
Ordered Fields?

Sheared Fields in Keplerian Flow



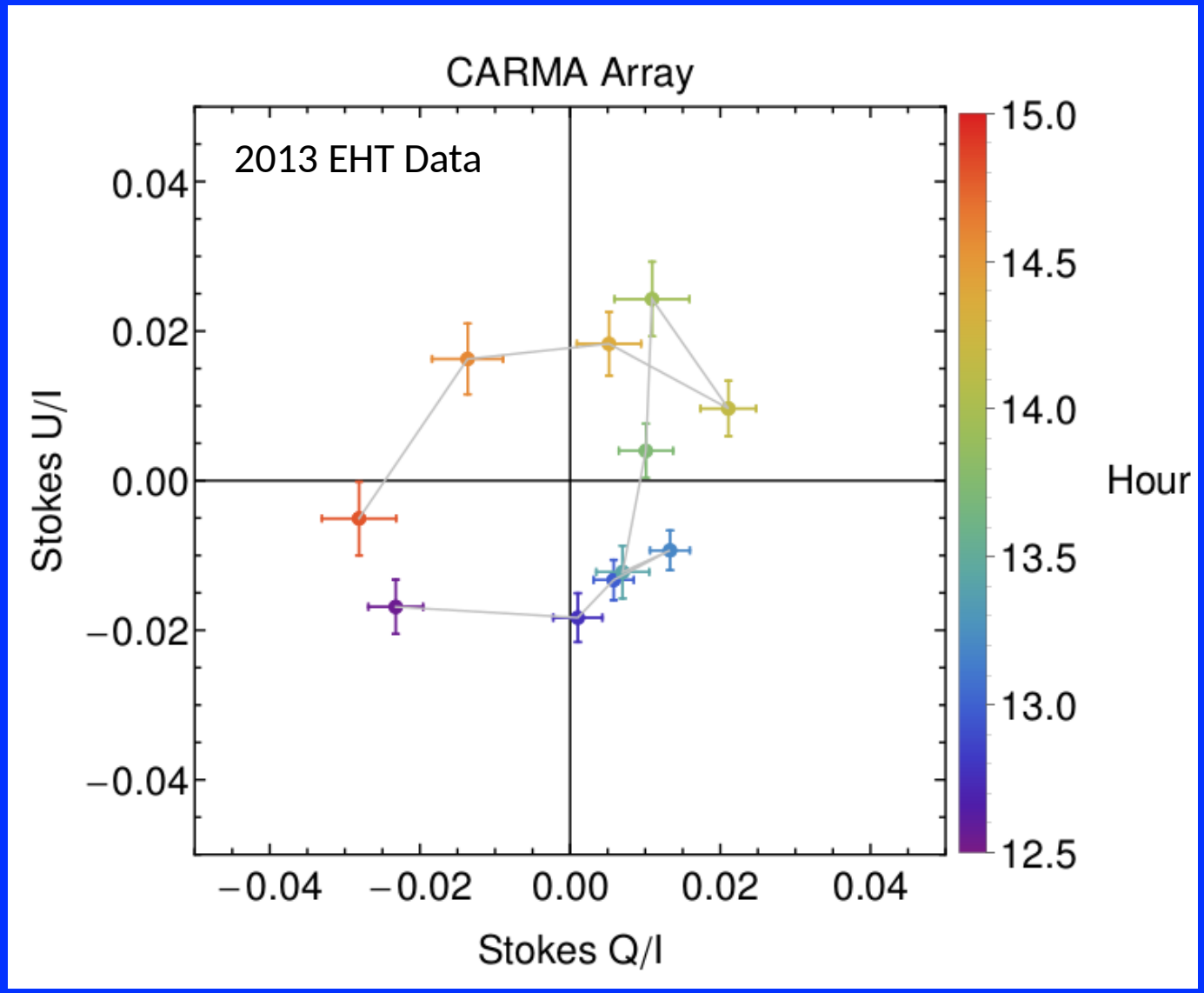
McKinney et al. (2012)

Magnetically-Arrested Disk

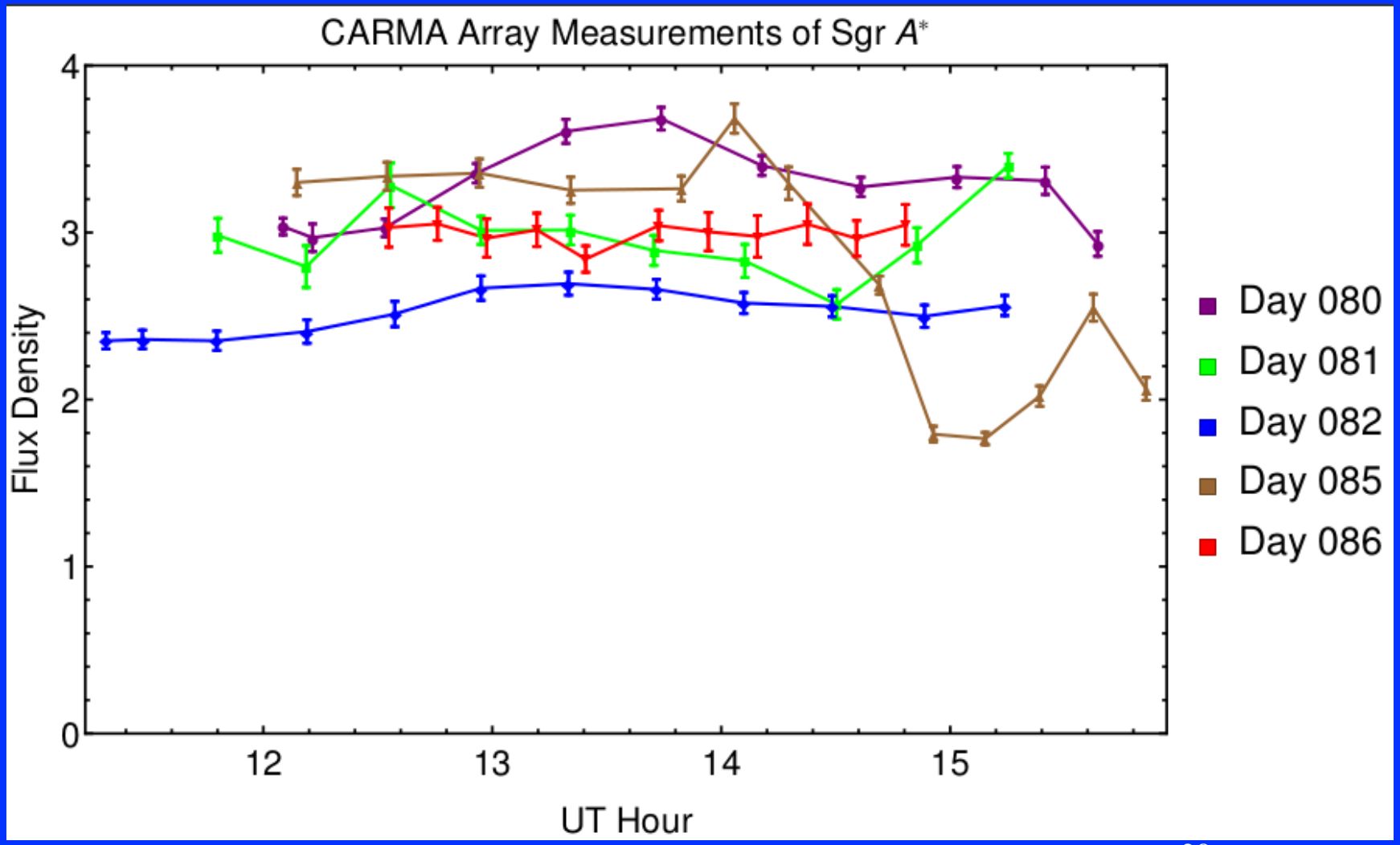


Narayan et al. (2003)

Connected Element Polarization

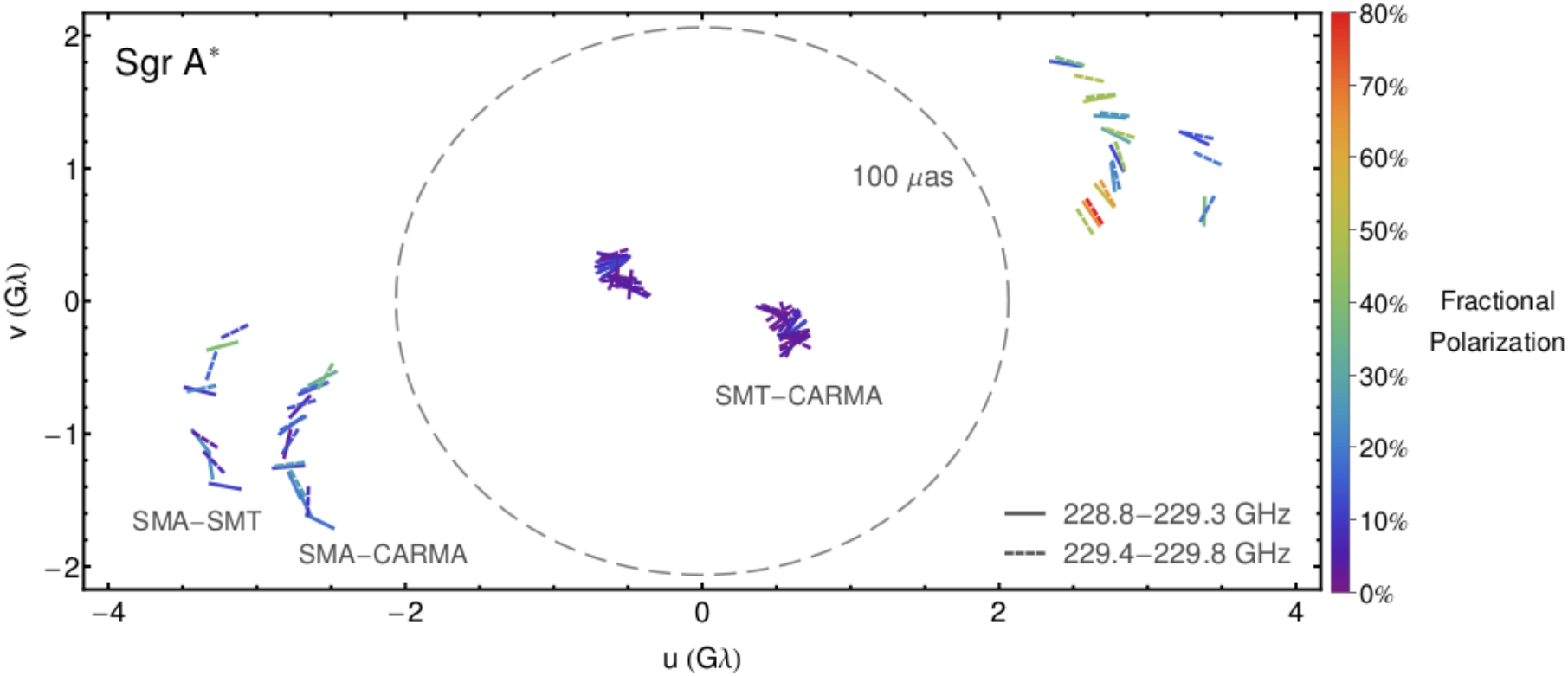


SgrA* Total Flux Density



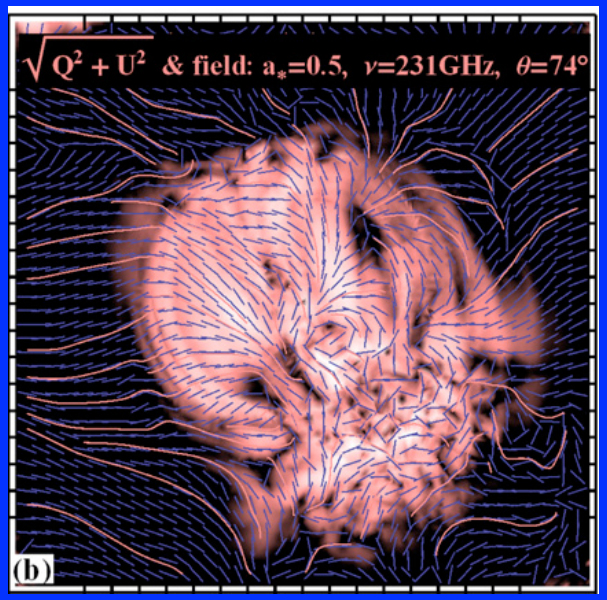
Sgr A*

2013 EHT Data (Preliminary)

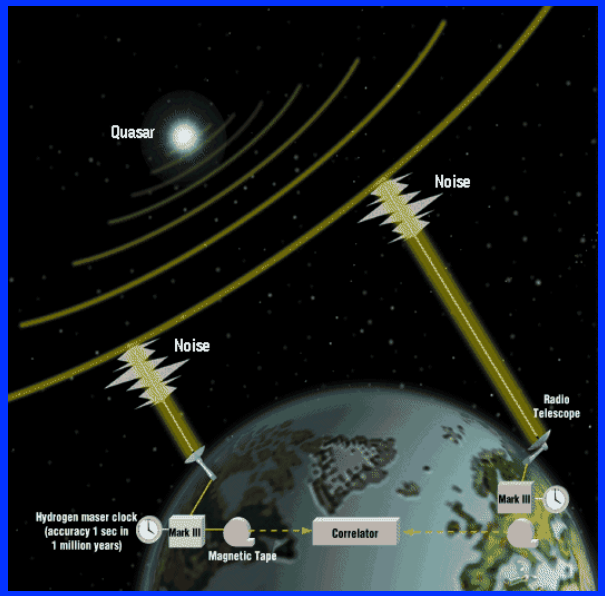


M. Johnson et al (in prep)

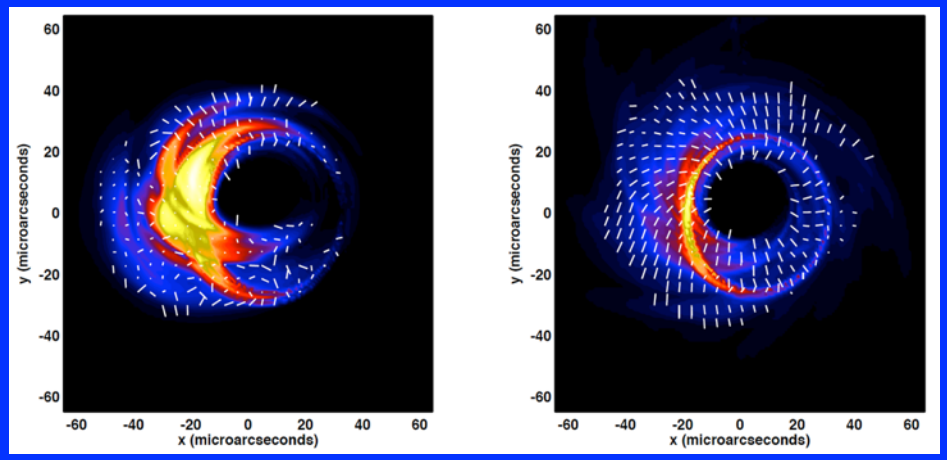
Mapping a BH Magnetic Field



Shcherbakov, Penna & McKinney 2012



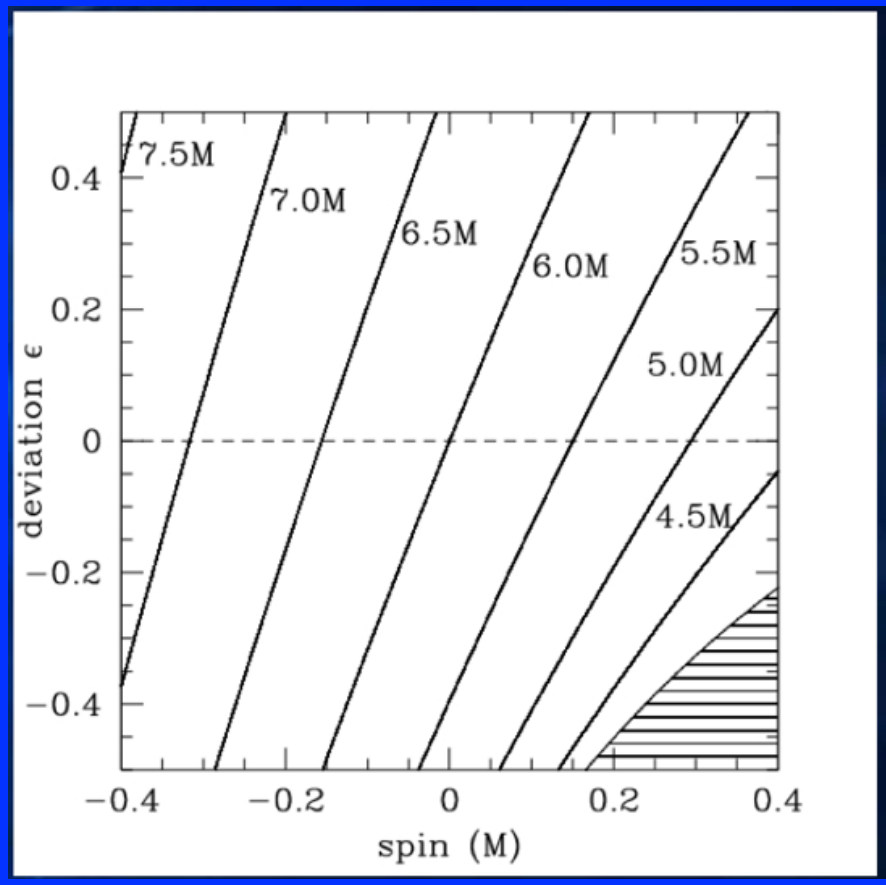
Fish, Broderick, et al 2009

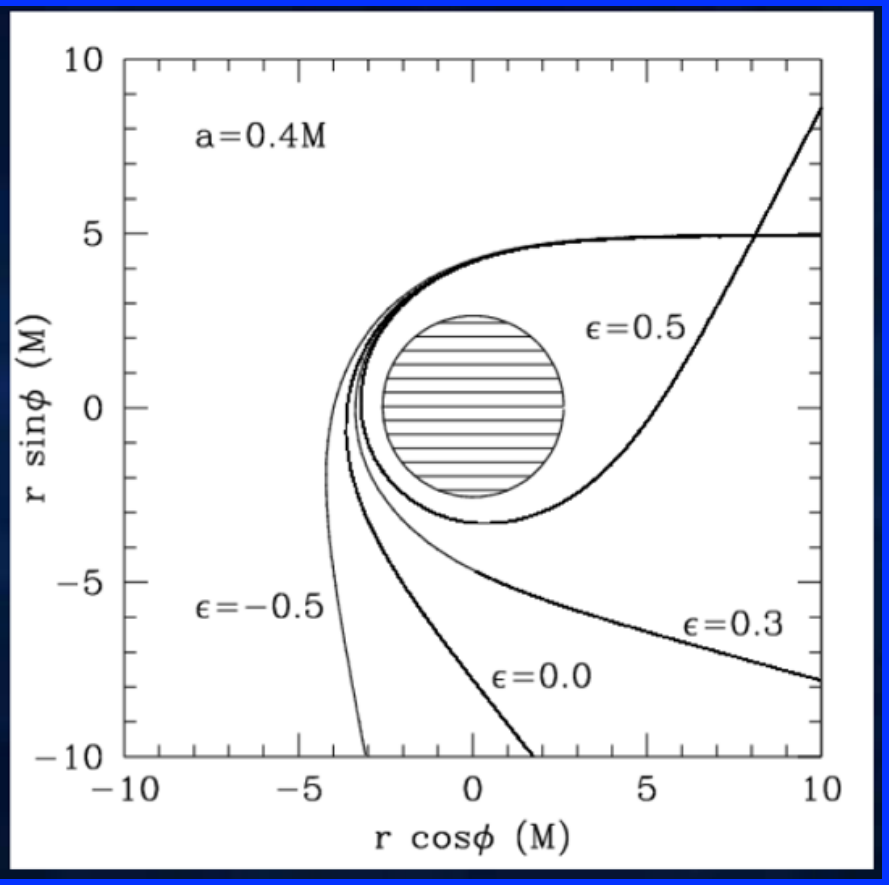


Dexter & McKinney (in prep).

Perturbing the Kerr Metric: Quasi-Kerr

$Q' = -a^2/M^2 + \varepsilon$



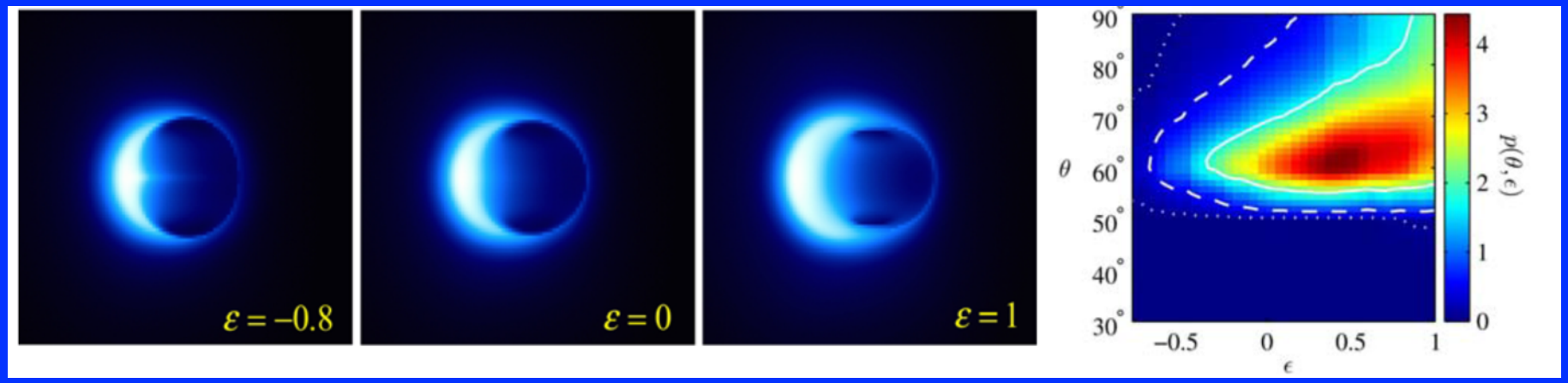


Location of the ISCO

Lightbending

Johannsen & Psaltis: (2010), (2011)

Tests of GR



Broderick, Johannsen, Loeb & Psaltis, ApJ, v784, 7B, 2014

EHT Roadmap

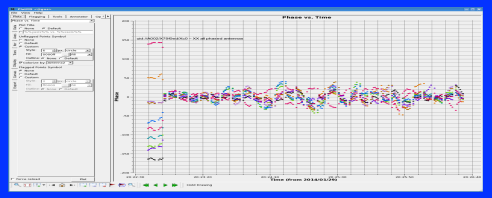
- Fringe test with APEX carried out in May 2012.
- 3mm VLBI test @ LMT completed: 1.3mm Rx.
- Greenland Tel. plans underway (dish retrofit).
- South Pole VLBI by 2015:funded through NSF.
- ALMA ready by early 2015.
- NSF Proposal pending for EHT operations and final build-out: correlator, data pipeline.
- New beam former for CARMA: NSF funded.
- IRAM 30m, PdeBure upgrades: MPIfR +ERC
- Organizing consortium.

EHT Roadmap

EHT

ASIAA
SAO/CfA
MIT Haystack
CARMA
NAOJ
U. Arizona Steward Obs
NRAO
UC Berkeley
MPIfR
IRAM
APEX
JCMT
U. Concepcion
(ERC)

Perimeter Institute
U. Illinois UC
UMD
Onsala Space Observatory
U. Mass Amherst
LMT
INAOE
UNAM



Summary

- 1.3mm VLBI confirms ~few Rsch sizes for SgrA* & M87. Definitive small scale polarized structures: ordered fields.
- Imaging an Event Horizon and observing BH orbits are within reach in <3 years.
- Required technical work is low-risk: early results validate all systems.
- Considerable work to do: requires support of community.
- Event Horizon Telescope fully on-line by 2015: G2?
- www.eventhorizontelescope.org

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?