Probing the Black Hole in the Center of Our Galaxy at Radio through Submillimeter Wavelengths

by

James Moran

Harvard-Smithsonian Center for Astrophysics

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Types of Cosmic Black Holes

1. "stellar" sized black holes found through the galaxy in binary stellar systems,
   $M \sim 10\ M_{Sun}$

2. "supermassive" black holes (SMBHs) found in the centers of most galaxies,
   $M \sim 10^{6\text{–}9}\ M_{Sun}$

How to Detect Supermassive Black Holes?

1. Explanation of massive radio jets emanating from galaxies

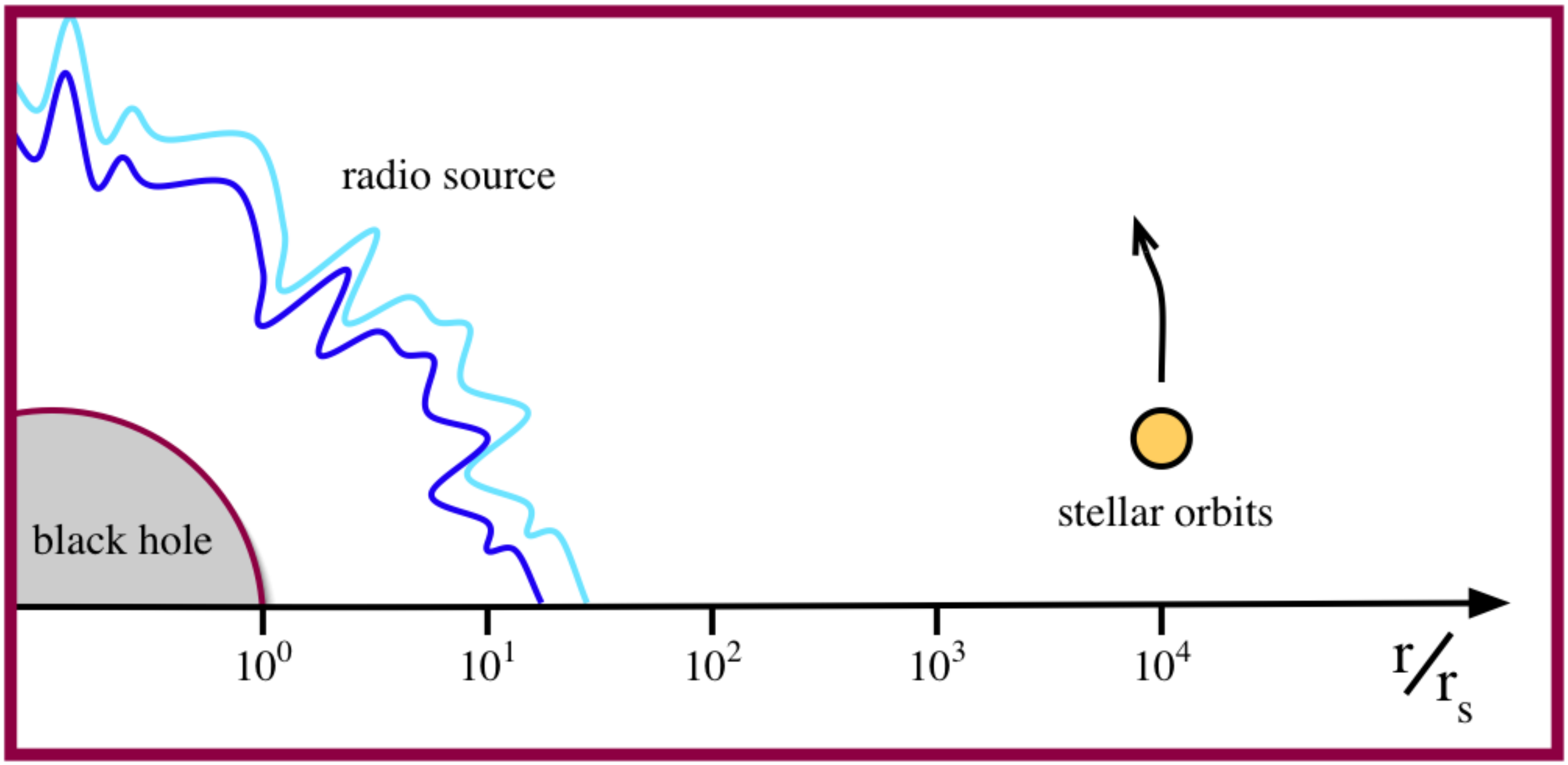
2. Track stars in orbit about unseen SMBH

3. Observe radio or X-ray emission from superheated gas in the inner accretion disk

Summary

- The mass of the black hole in the Center of the Galaxy (Sgr A*) is about 4 x 10^6 solar masses.
- The accretion rate is about 10^{-8} solar masses per year.
- The angular diameter of the radio emission from Sgr A* is about 37 microarcseconds at 1.3 mm wavelength.
- The circular polarization is LCP at all wavelengths from 1 mm to 30 cm.
- Linear polarization of compact structure is up to 80%, implying coherent structures.
- The earth-mass object in orbit about the Galactic Center that has just passed perihelion has shown no effects at radio wavelengths (either increased accretion rate or bow shock).
- EHT under development.

Some Scales in the Galactic Center



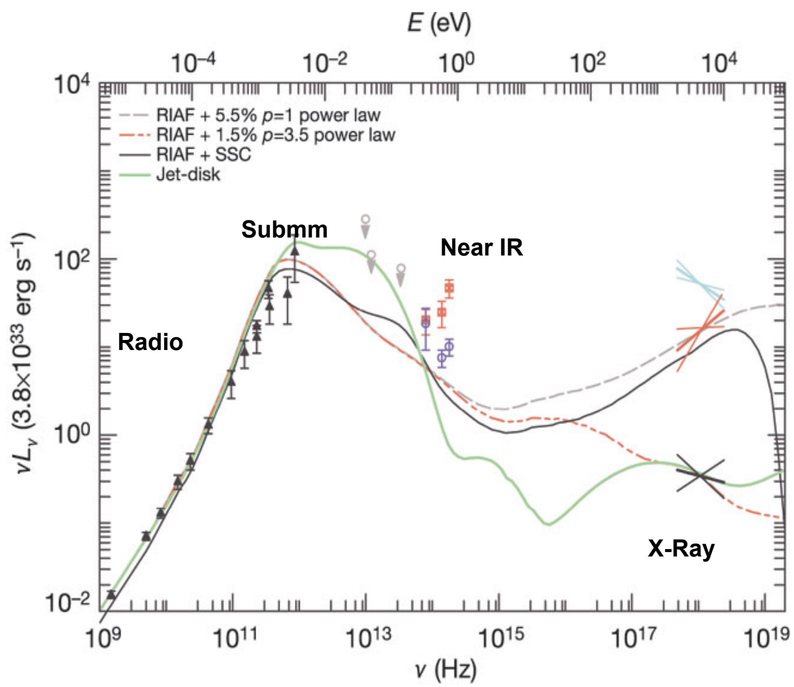
$r_s = 10^{12} cm = 8 \mu as$

$$r_s = 1.3 \times 10^{12}\text{cm (for } 4.3 \times 10^6 \text{ solar masses)} \;= 10\mu\text{as at 8.3 kpc}$$

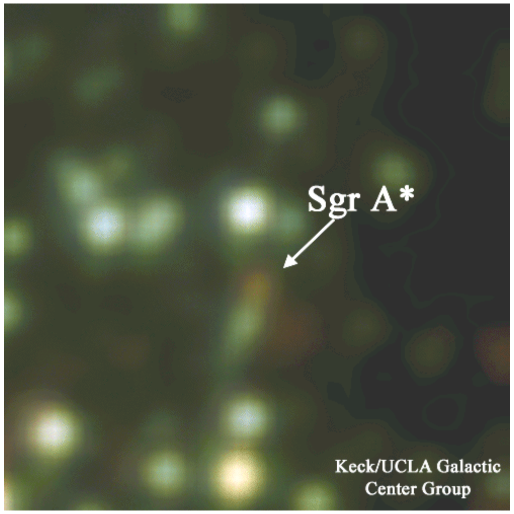
Luminosity ~ 300 L_{sun} or 10^{-9} Eddington

SgrA*: Spectral Energy Distribution

- Very faint source still detectible at most astronomical observing bands
- L_{SgrA*} ~ 300 L_{Sun} ~ 10^{-9} *Eddington limit*

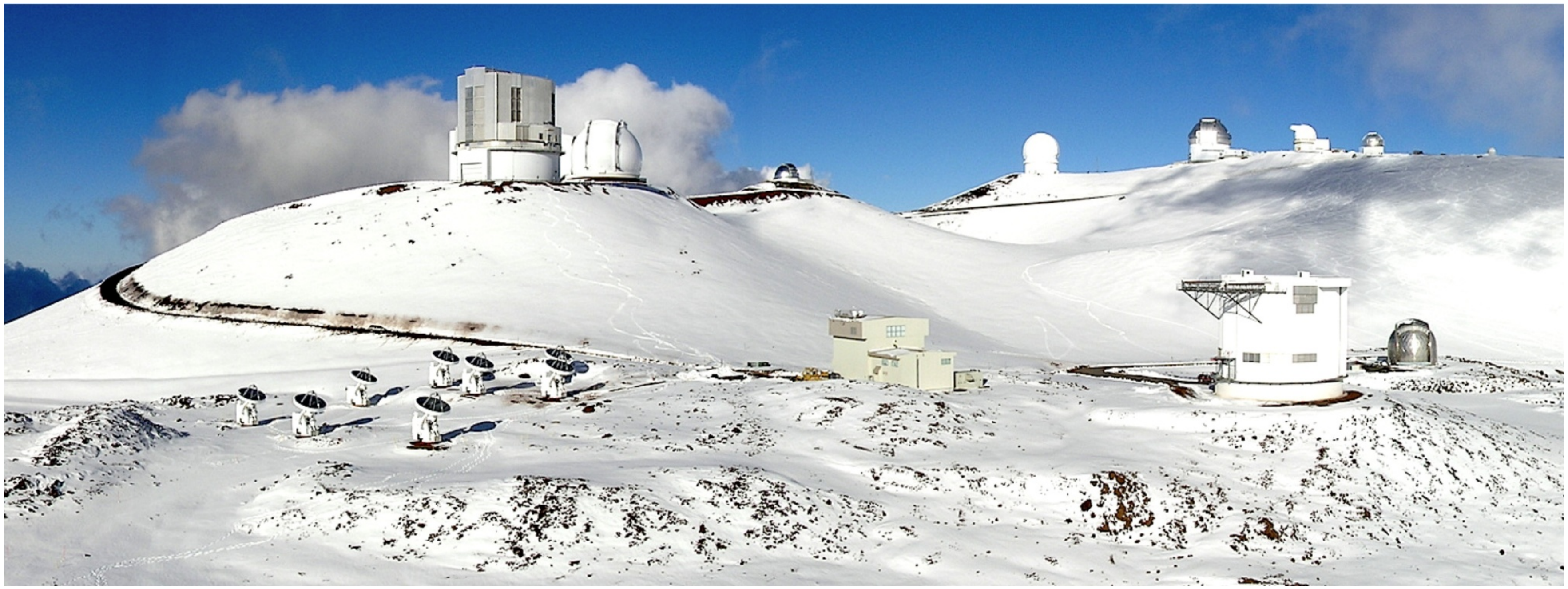


Genzel et al. 2004



IR flare (Hornstein et al. 2007)

Mauna Kea Summit

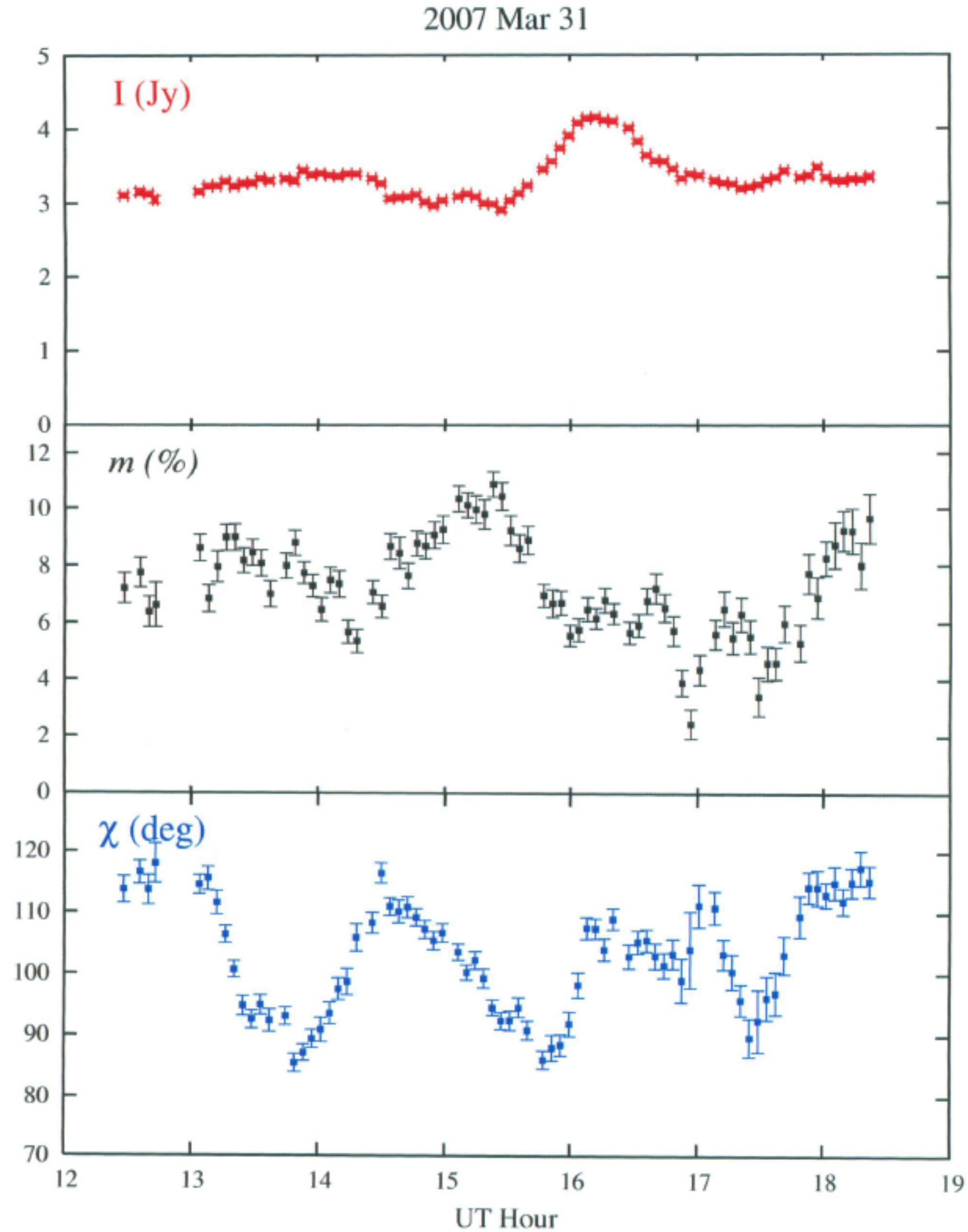


Paul Yamaguchi, 2007

SMA **SMA control building**

Frequency range: 200 – 900 GHz

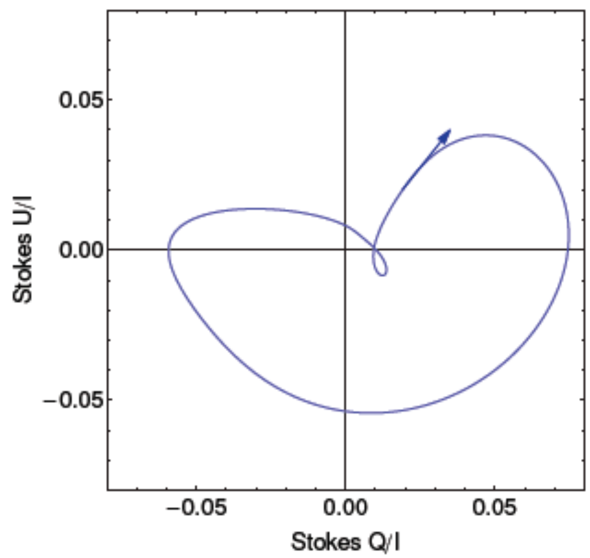
Polarization of Sgr A* at 230 GHz (1.3 mm) (SMA)

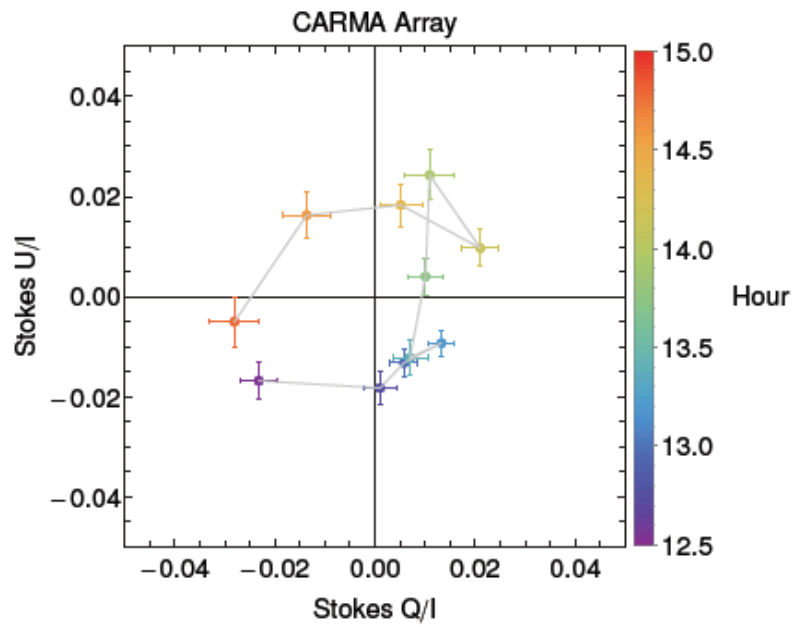


Marrone et al. 2007

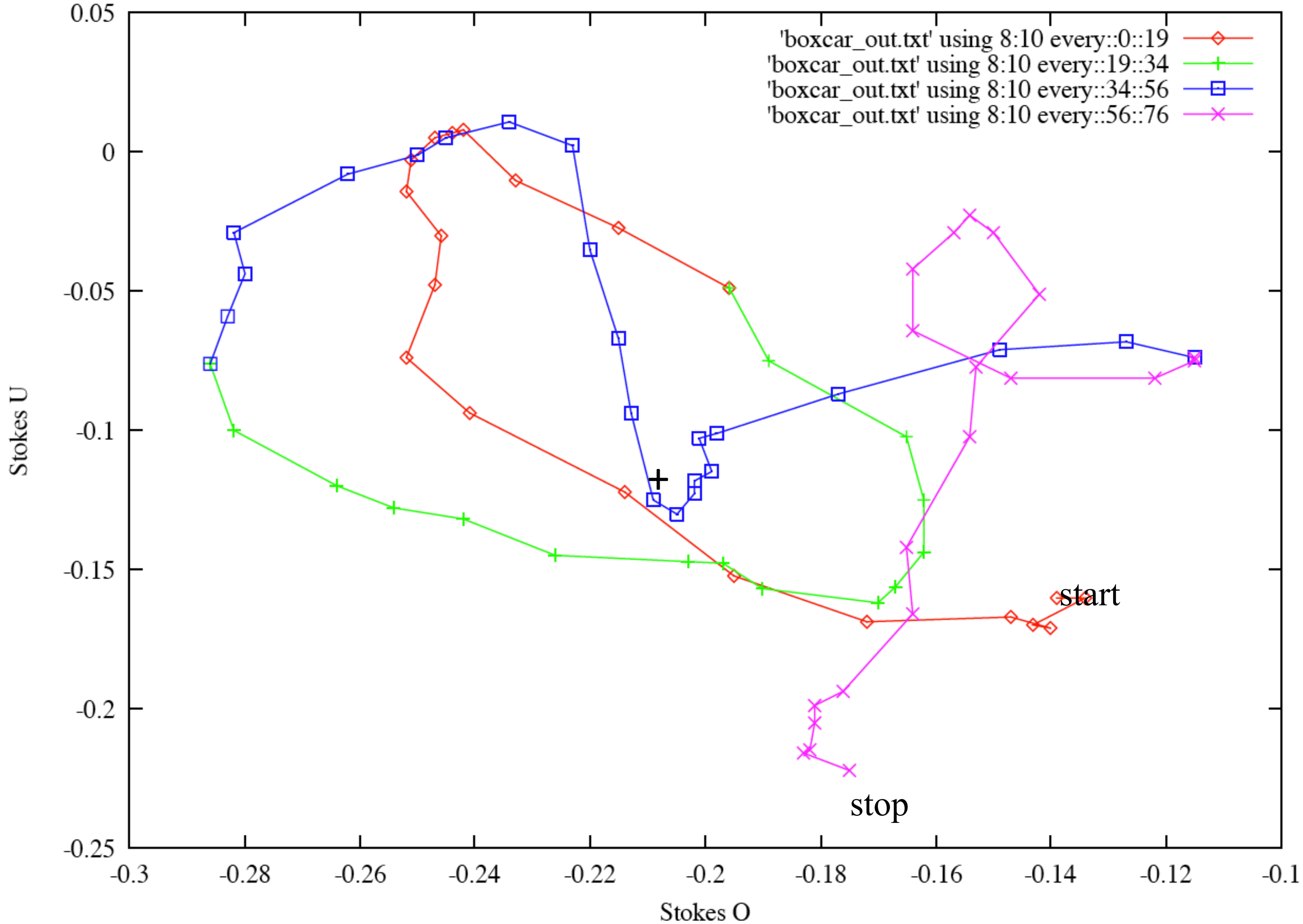
Sgr A* Polarization Orientation at 230 GHz

Orbiting blob Model

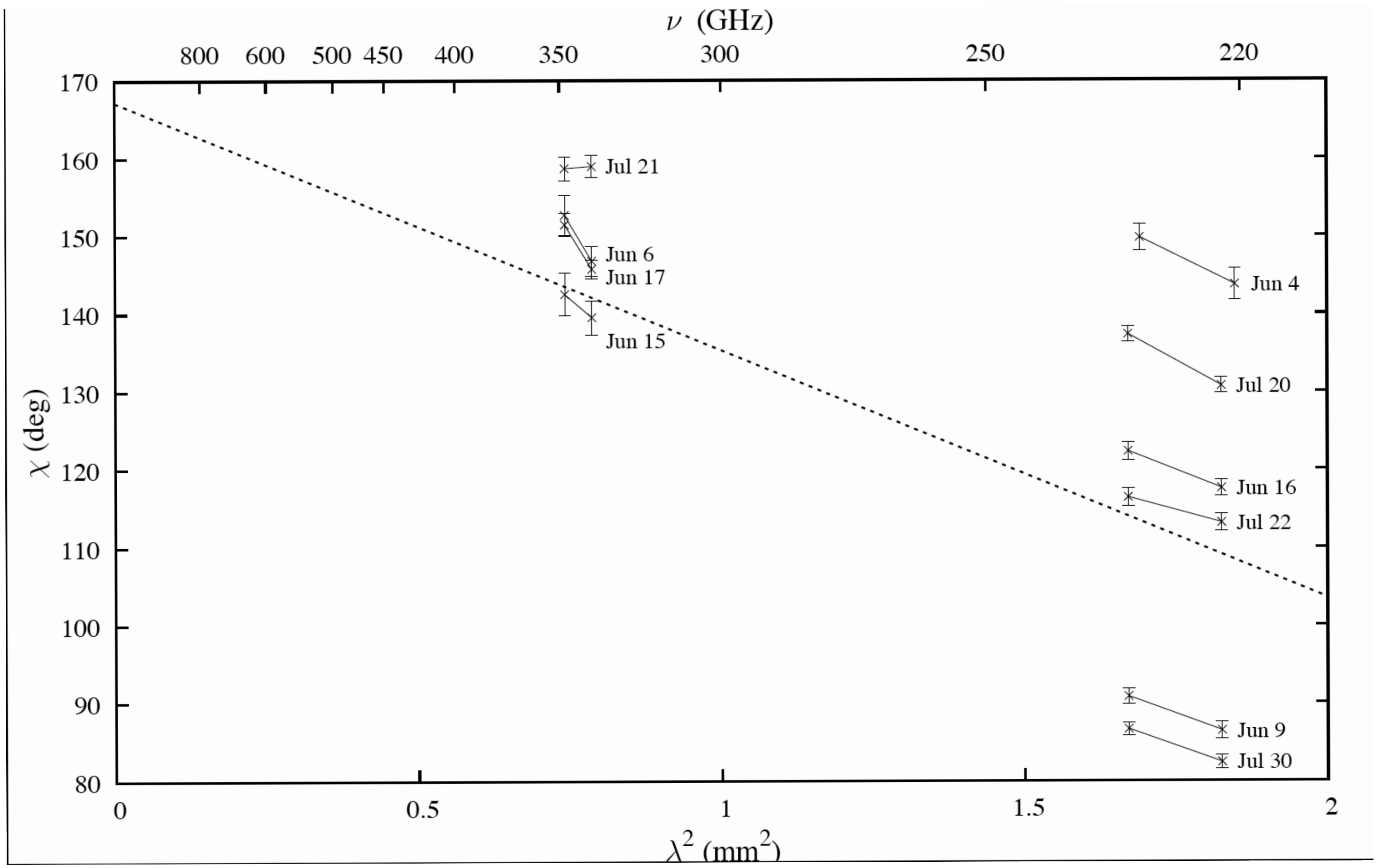




Polarization Track for 3/31/07 Observation of SgrA*



2005 SMA Measurements of Faraday Rotation in Sgr A*



Important: SLOPE of polarization angle ~ constant in time at 230 GHz

Marrone et al. 2007

Accretion Rate and Faraday Rotation

$$\chi(\lambda,t) = \chi_0(t) + \lambda^2 RM(t)$$

$$RM = 8.1 \text{ x } 10^5 \int n_e \overline{B} \times \overline{dl}$$

$$RM = -5.1 \text{ x } 10^5 \text{ rad/m}^2$$

Assumptions

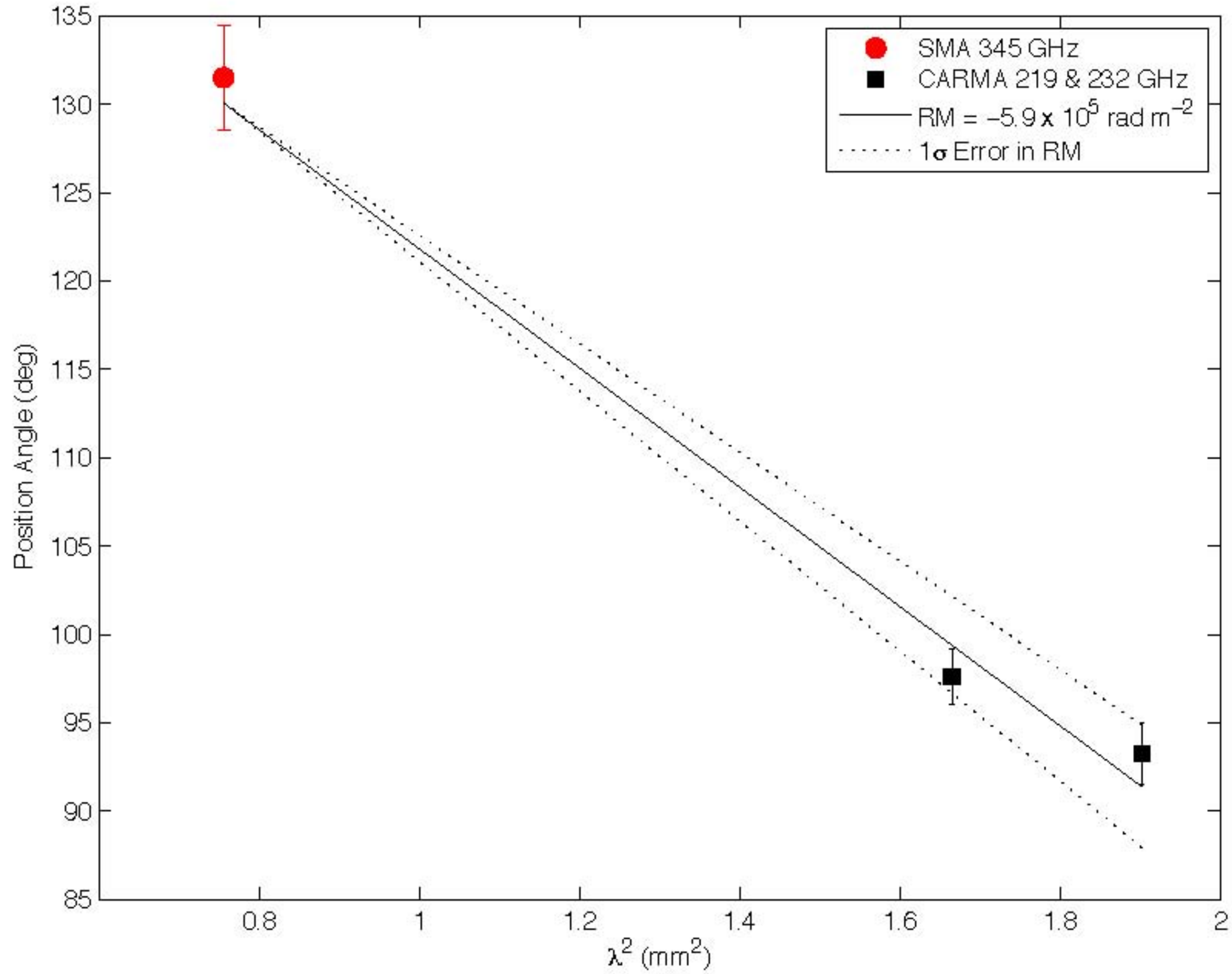
equipartition

density power law

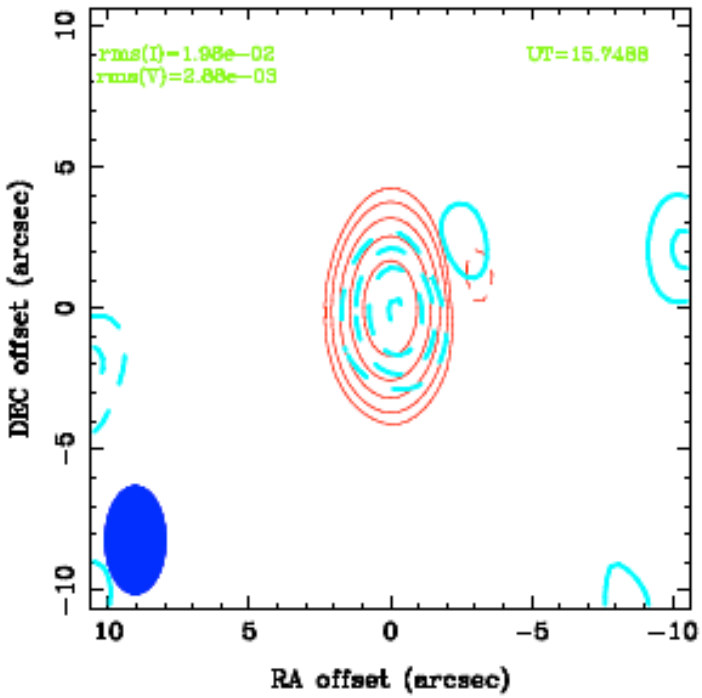
inner radius cutoff of Faraday screen

Accretion rate = 10^{-9}–10^{-7} M_{Sun}/yr

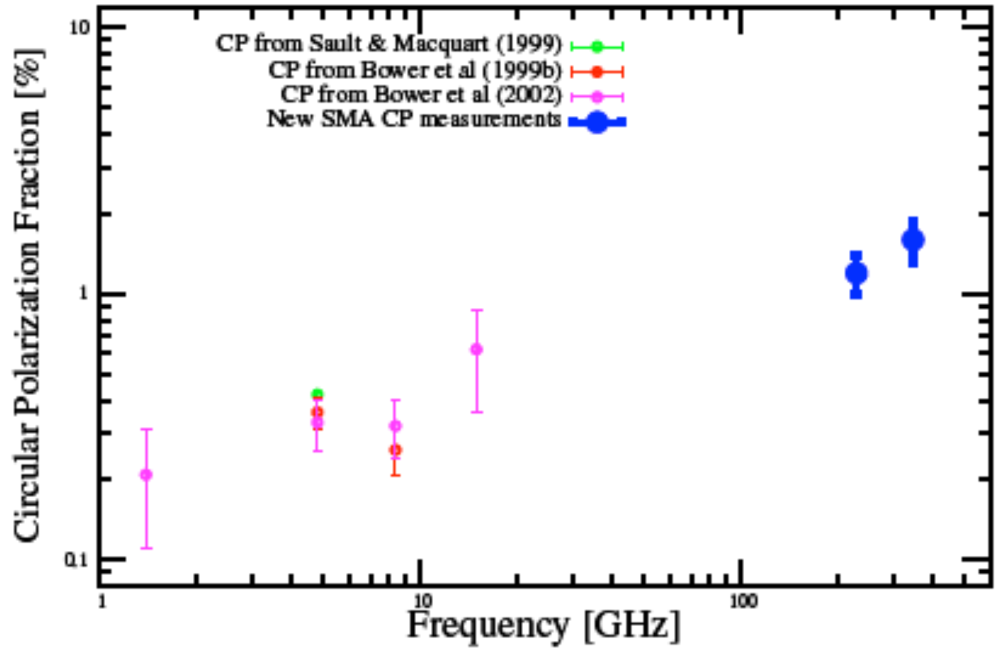
Polarization at Three Frequencies Simultaneously



Circular Polarization of Sgr A*



Left handed CP at all frequencies measured!!

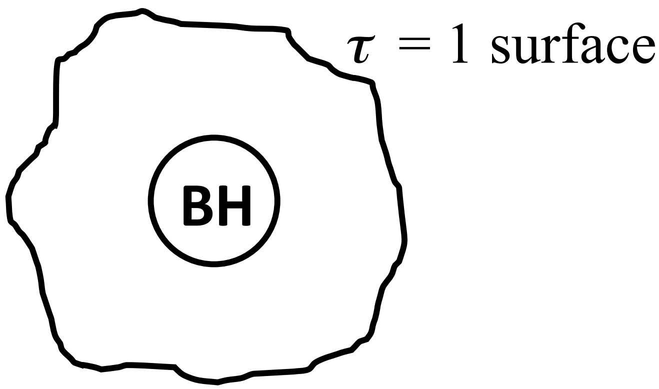


(red) Stokes I
(blue) Stokes V

Fractional Circular Polarization
vs. Frequency

Munoz, Marrone, Moran, and Rao 2012

Faraday Conversion in Sgr A*



ν	$\theta_{\tau=1}$	$\theta_{\tau=1}$ (diameter)
GHz	R_s	mas
230	6	0.06
22	80	0.8
1.4	1600	16

Range of $\tau = 1$ surface between 1.4 and 230 GHz: ~350 (based on $R_{\tau=1} \sim \nu^{-1.1}$)

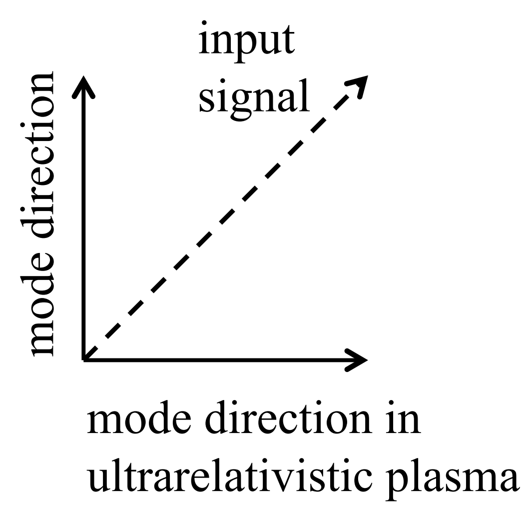
Faraday conversion phase shift

$\phi = 10^9 \, L \, B^4 \lambda^3 = \pi/2$ (optimum)

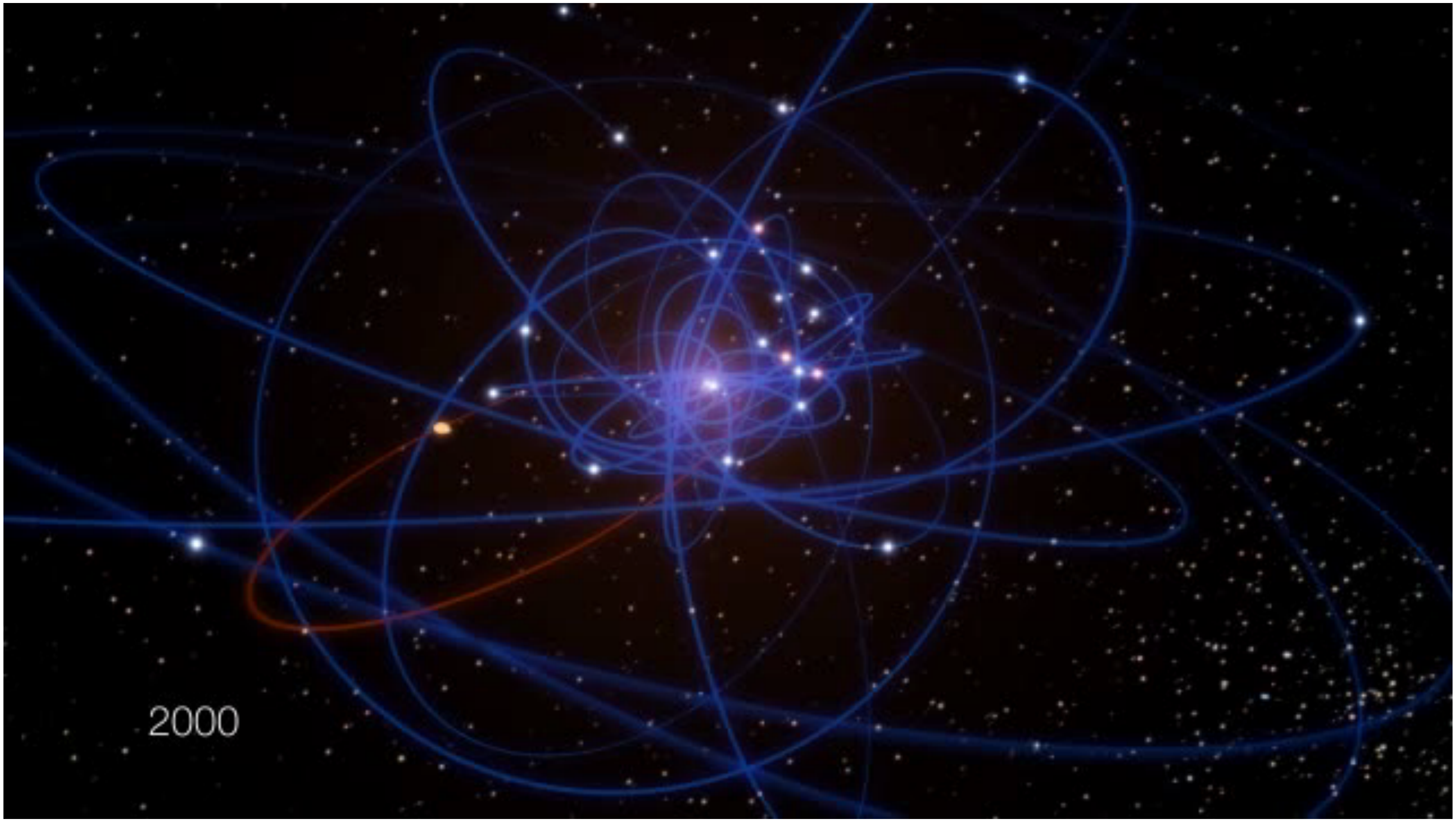
B = magnetic field in Gauss

L = length in pc

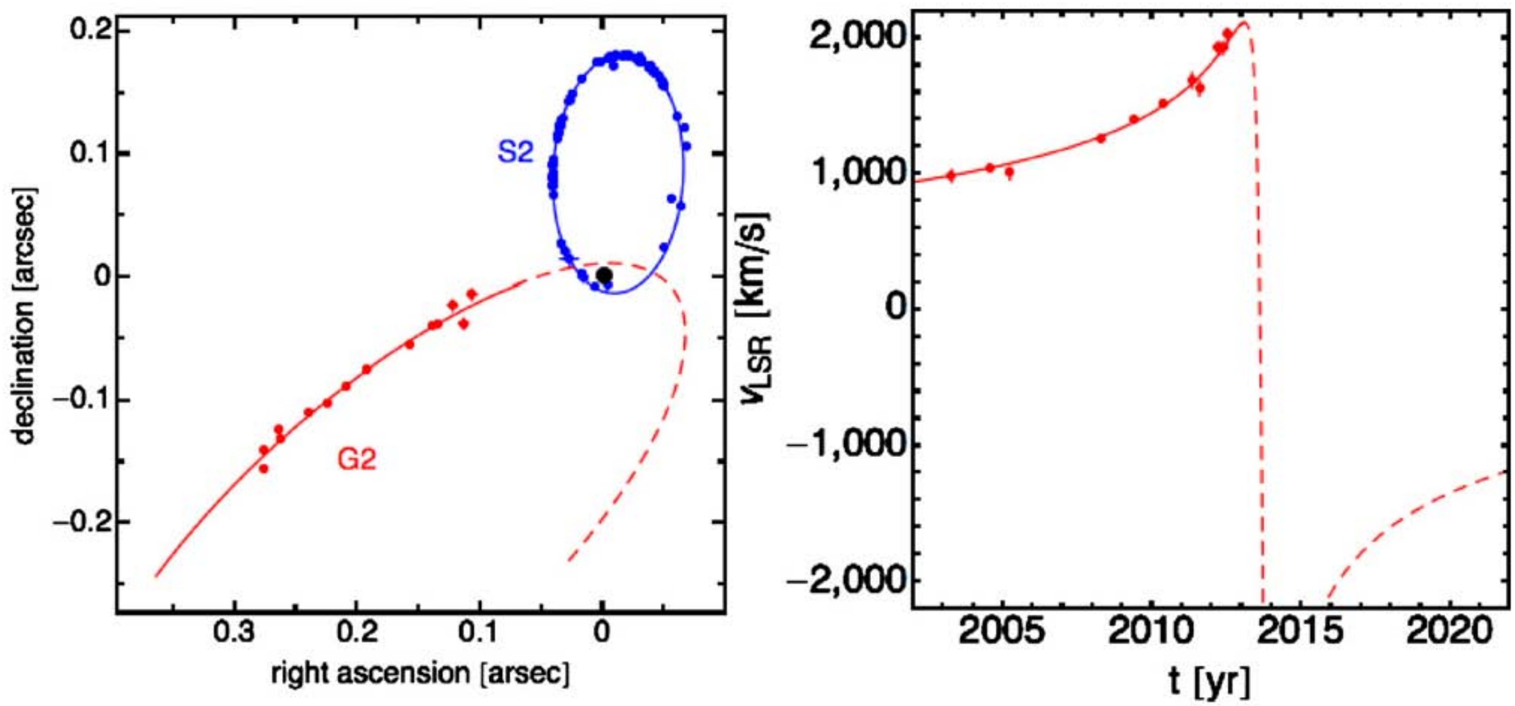
λ = wavelength in m



Animation of Accretion Object Discovered by Genzel Group, 2012



Predicted Orbit of G2 – earth mass cloud approaching Sgr A*



Gillessen et al., Ap.J. 767, 1, February 1, 2013

G2

Latest orbit information (Gillessen et al., *ApJ.*, **763**, 78, Feb. 1, 2013)

Closest approach 2013.7 at 3 x 10^{15} cm (2200 R_s)

Velocity ~ 3,000 km/s (c/1,000)

Orbital period ~ 198 years

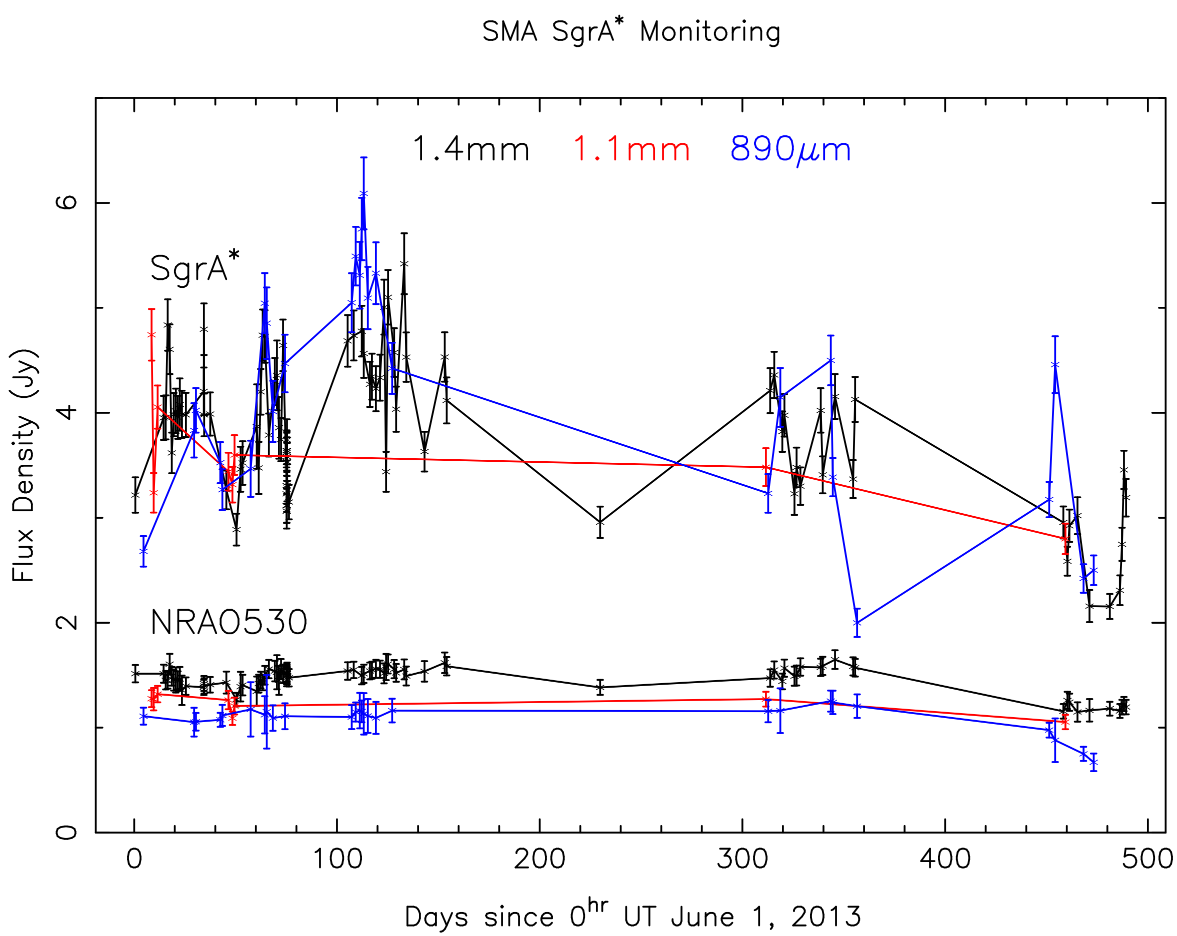
Mass ~ 1.7 x 10^{28} grams = 10^{-5} M_{sun}

Could brighten by 100!

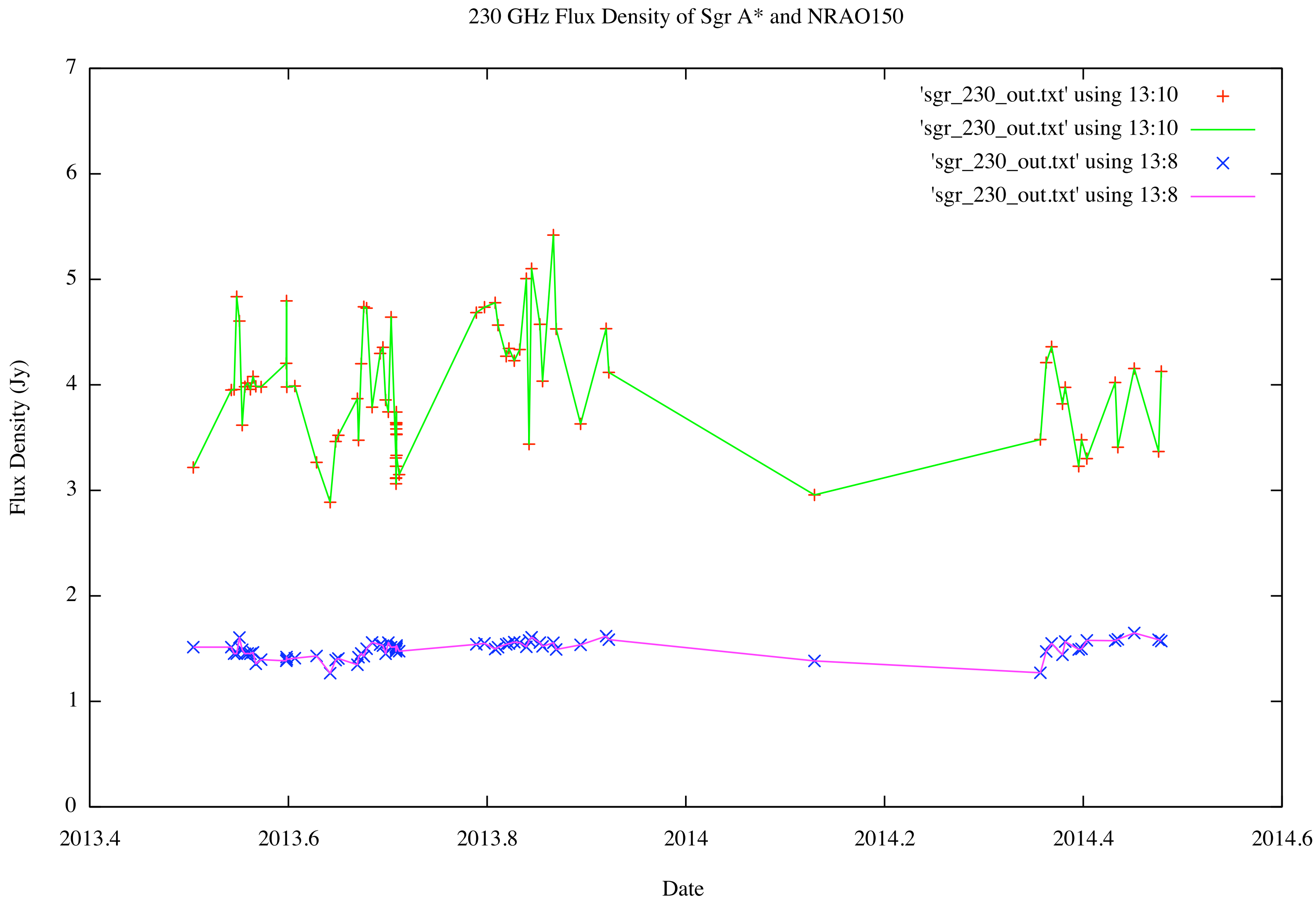
$$f = 100 \left(\frac{T}{10 \text{ yrs}} \right) \left(\frac{\dot{M}}{10^{-8}\, M_{sun}/\text{yr}} \right)$$

f = flux density change

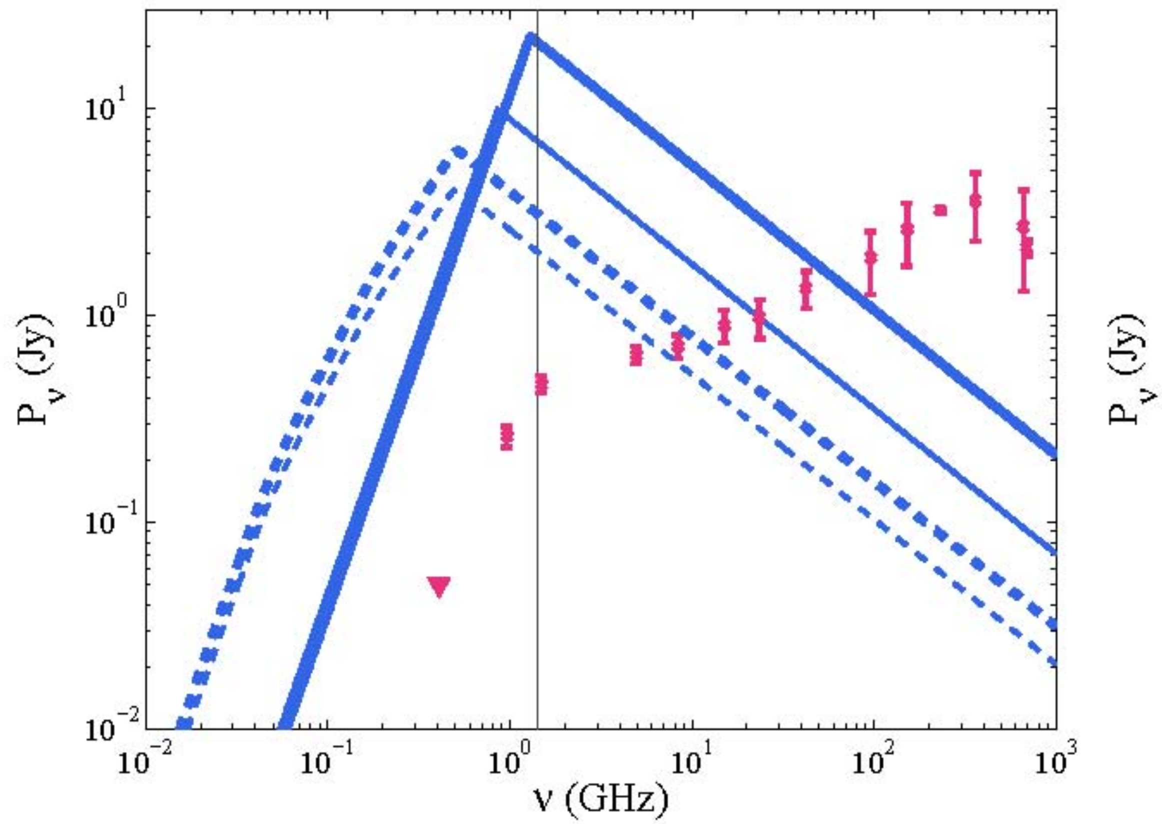
SMA Flux Monitoring
June 1, 2013 – September 15, 2014



Flux Density at 230 GHz

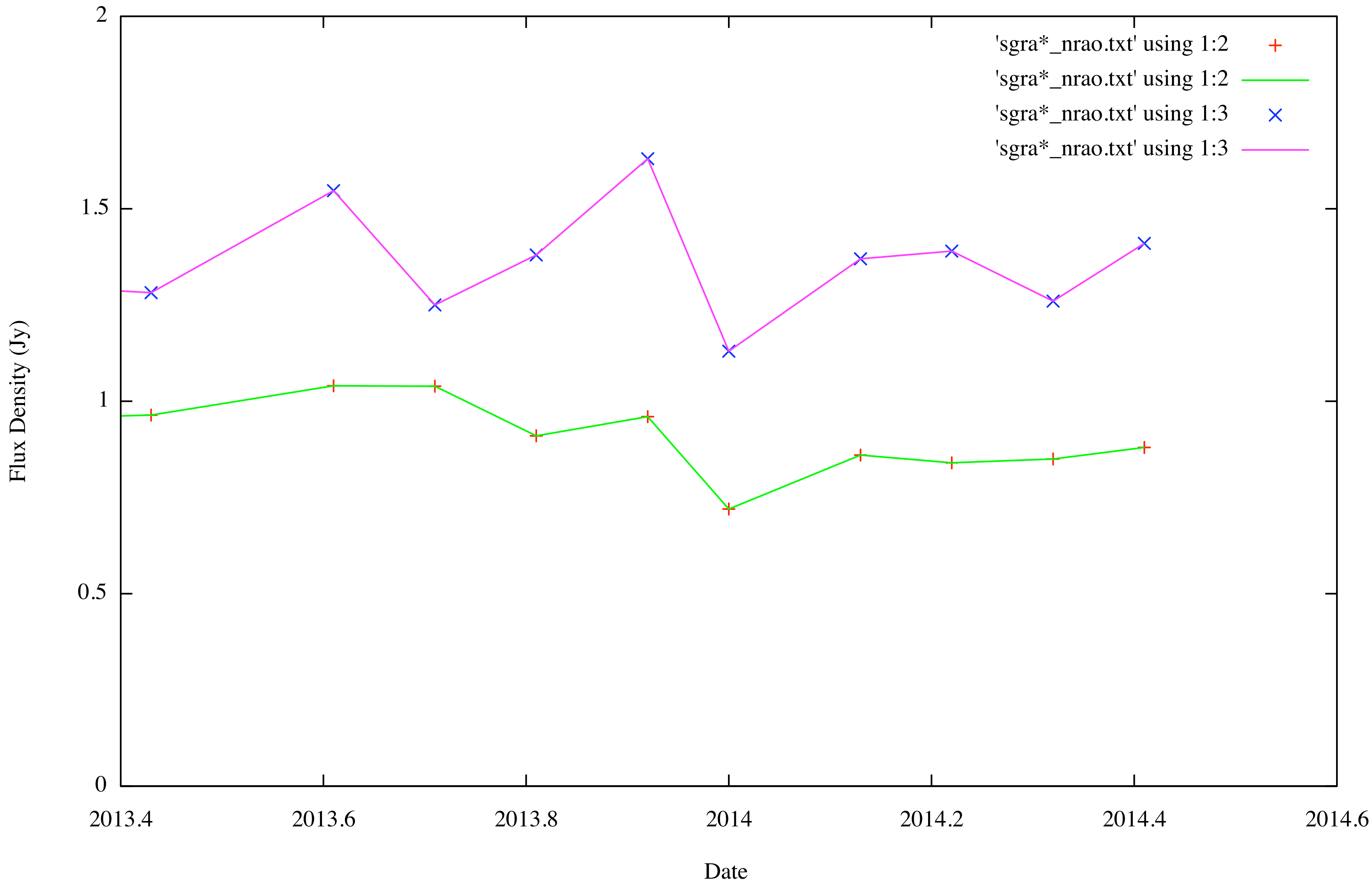


Bow Shock Emission Model for G2: August 2013



Sadowski, Sironi, Abarca, Guo, Ozel and Narayan, MNRAS, 432, 478, 2013
Also: Narayan, Ozel and Sironi, ApJ(L) , 757, L20, 2012

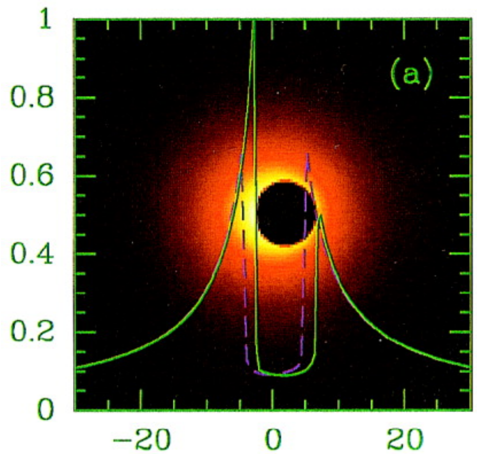
Flux Density of Sgr A* at 10.0 and 32.0 GHz



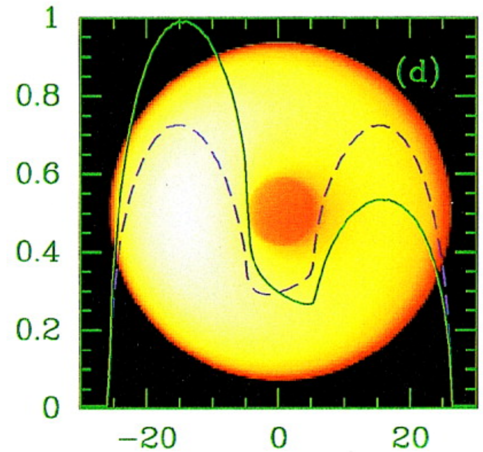
Black Hole "image" Dominated by GR

The black hole "shadow"

(Bardeen 1973; Falcke, Agol, Melia 2000; Johannsen and Psaltis 2010)



Maximally spinning BH
Free fall envelope
$D_{shadow} = 9/2 * R_s$



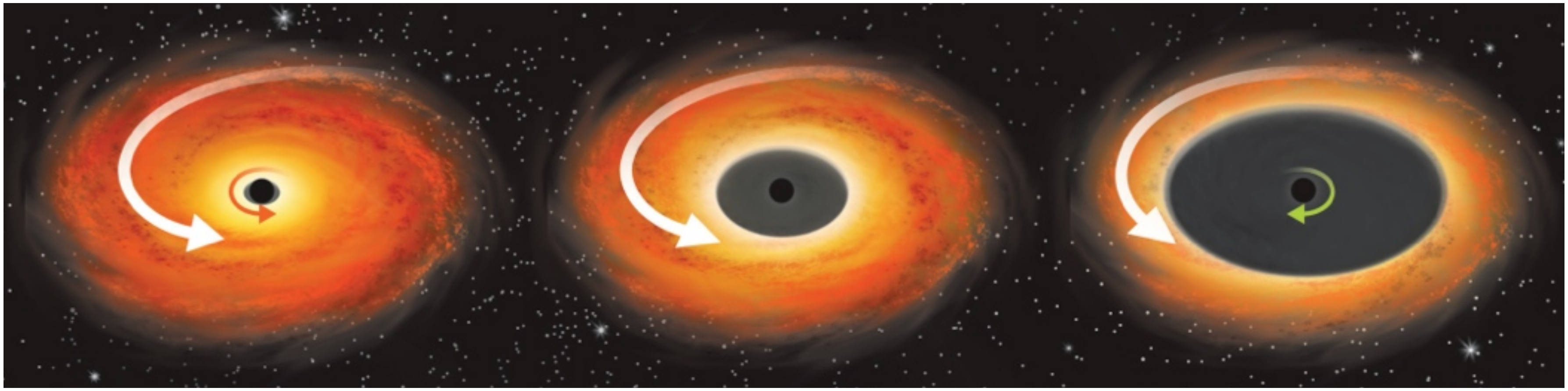
Non-spinning BH
Rotating accretion envelope
$D_{shadow} = sqrt(27) * R_s$

Measuring the shadow gives Mass.

(Johannsen, Psaltis et al. 2012)

Observing Strong GR Signatures

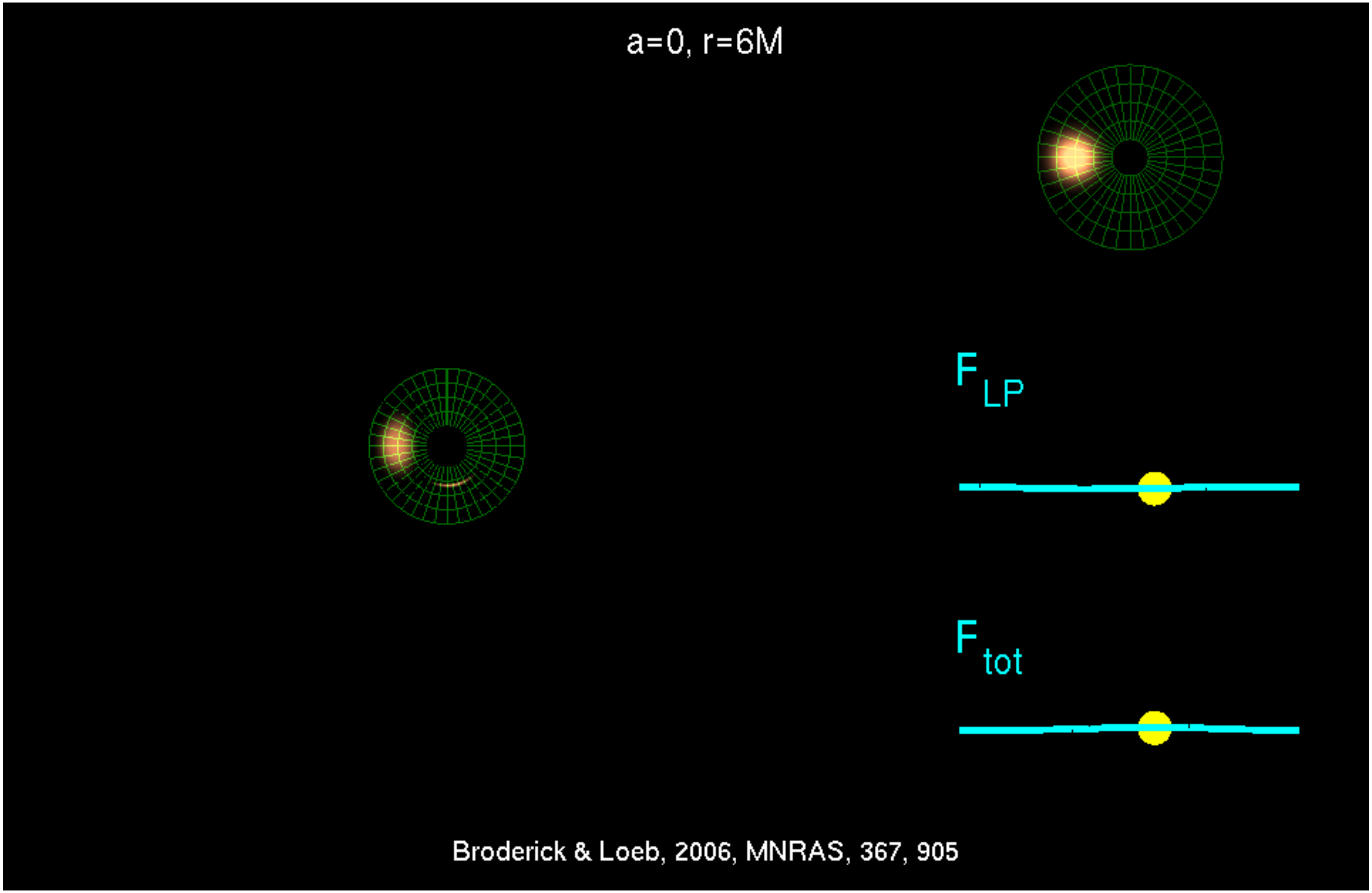
Innermost Stable Circular Orbit (ISCO) Size



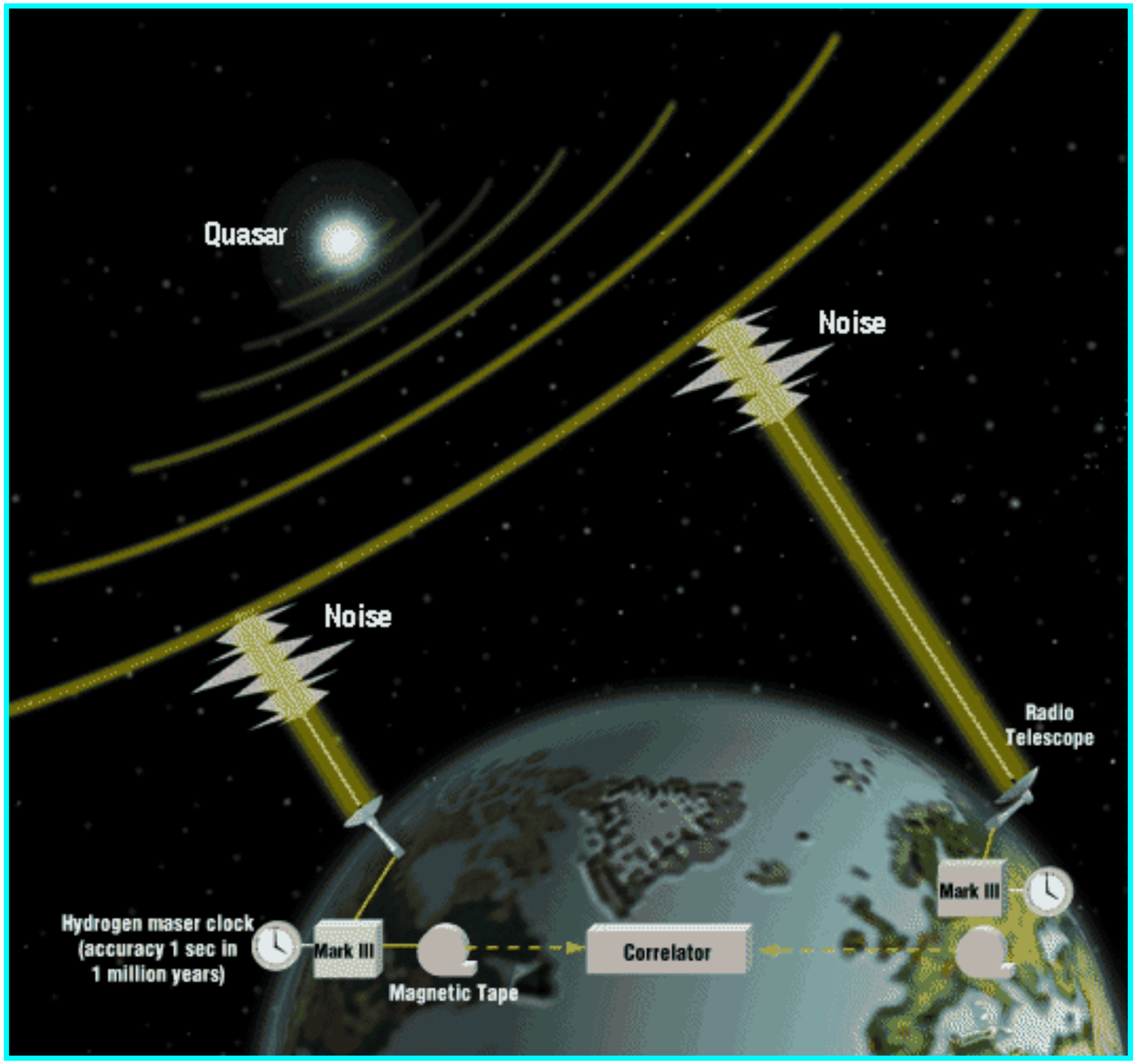
Max. Prograde
ISCO_D = 1 R_s

No Spin
ISCO_D = 6 R_s

Max Retrograde
ISCO_D = 9 R_s


a=0, r=6M
F LP
F tot
Broderick & Loeb, 2006, MNRAS, 367, 905

VLBI: An Earth Sized Telescope



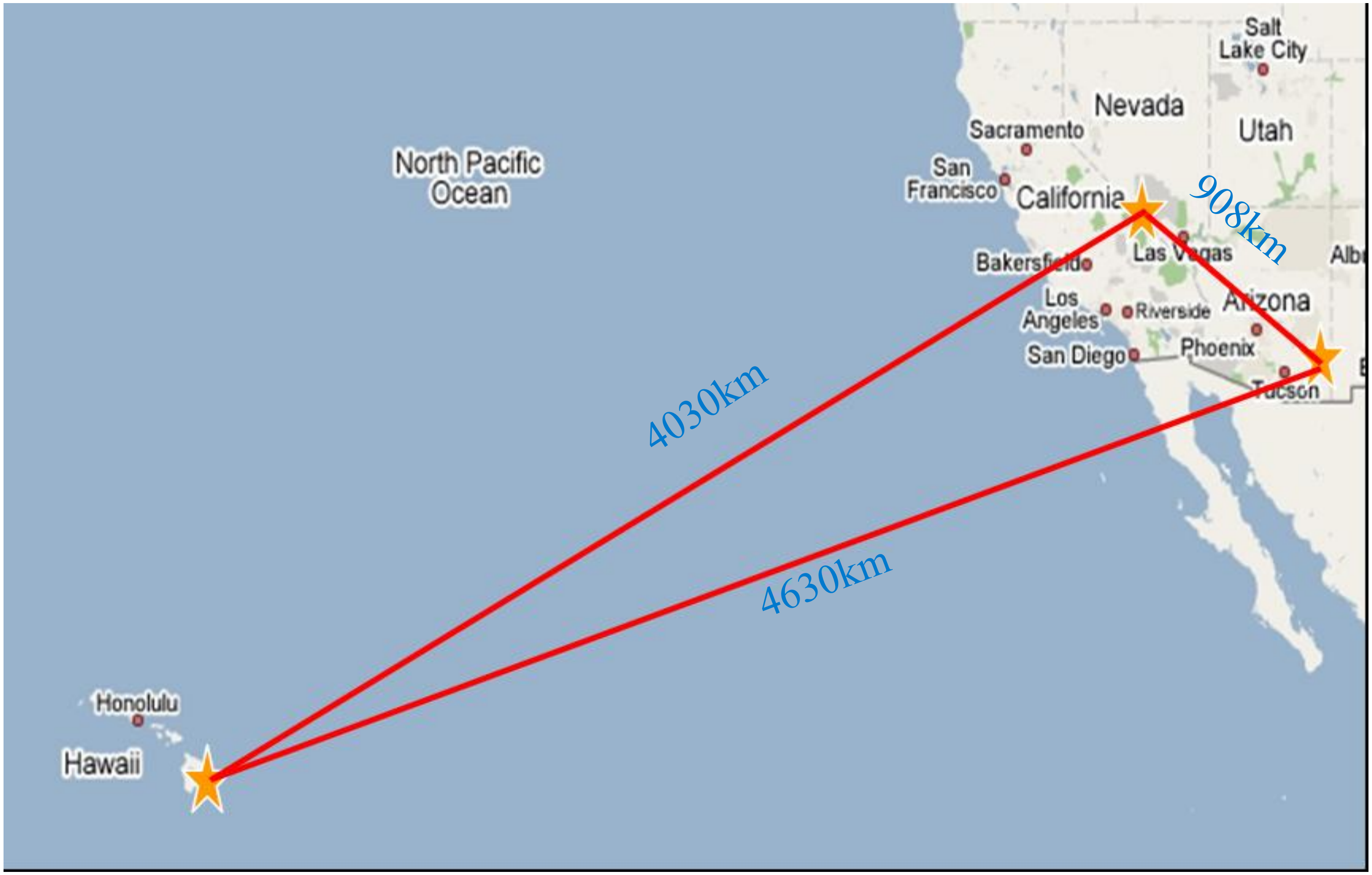
Resolution:

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

ISM Scattering:

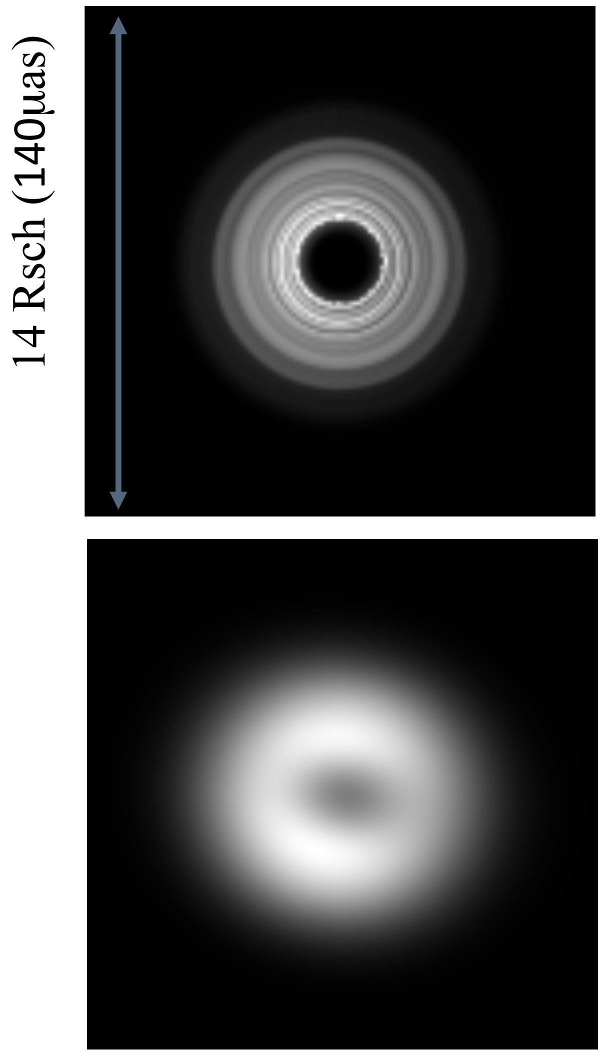
$\Theta scat \sim \lambda^2$

1.3 mmλ (230 GHz) Observations of Sgr A*

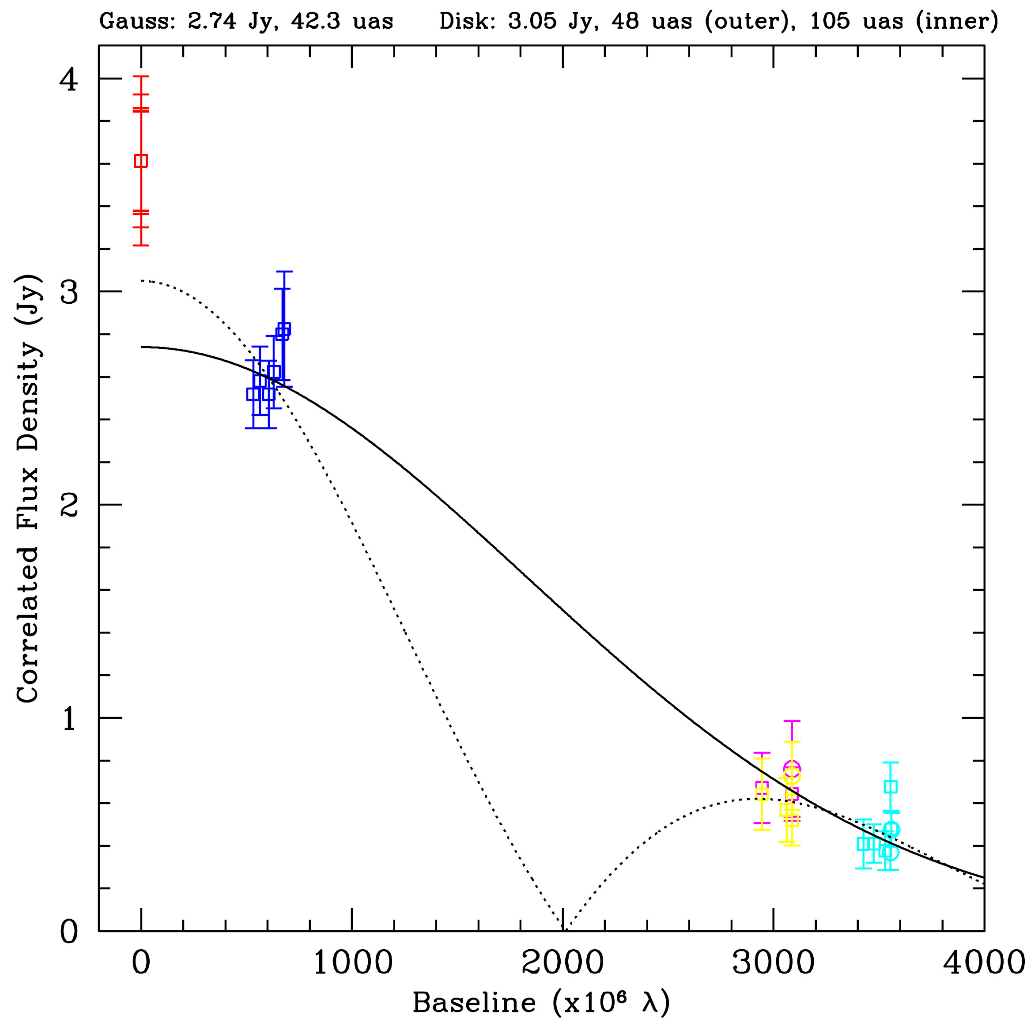


VLBI program led by a large consortium led by Shep Doeleman, MIT/Haystack/CfA

Gaussian and Torus Fit to Visibility Data

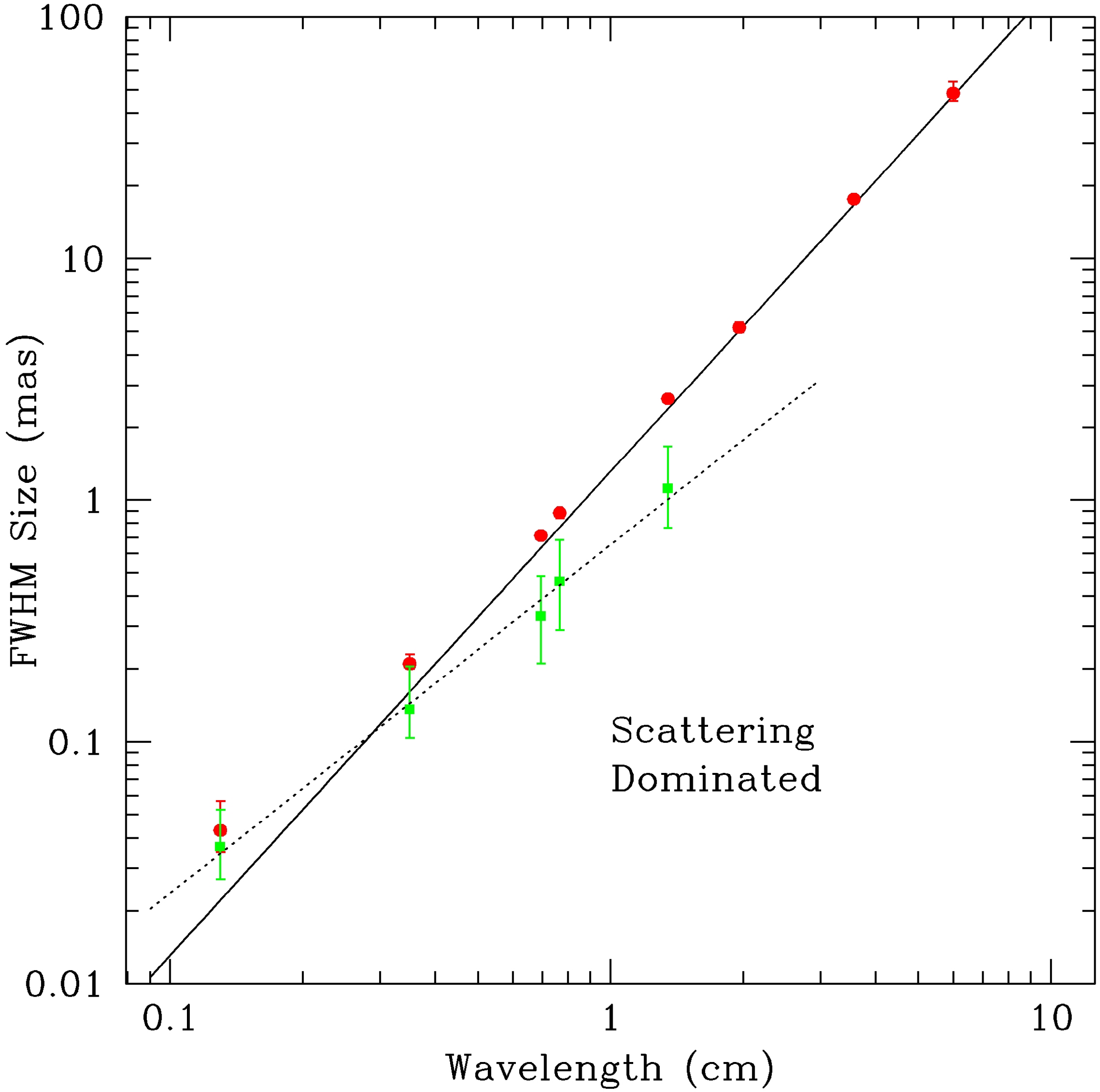


Gammie et al.



Doeleman et al. 2008; Fish et al. 2011

Seeing Through the Scattering



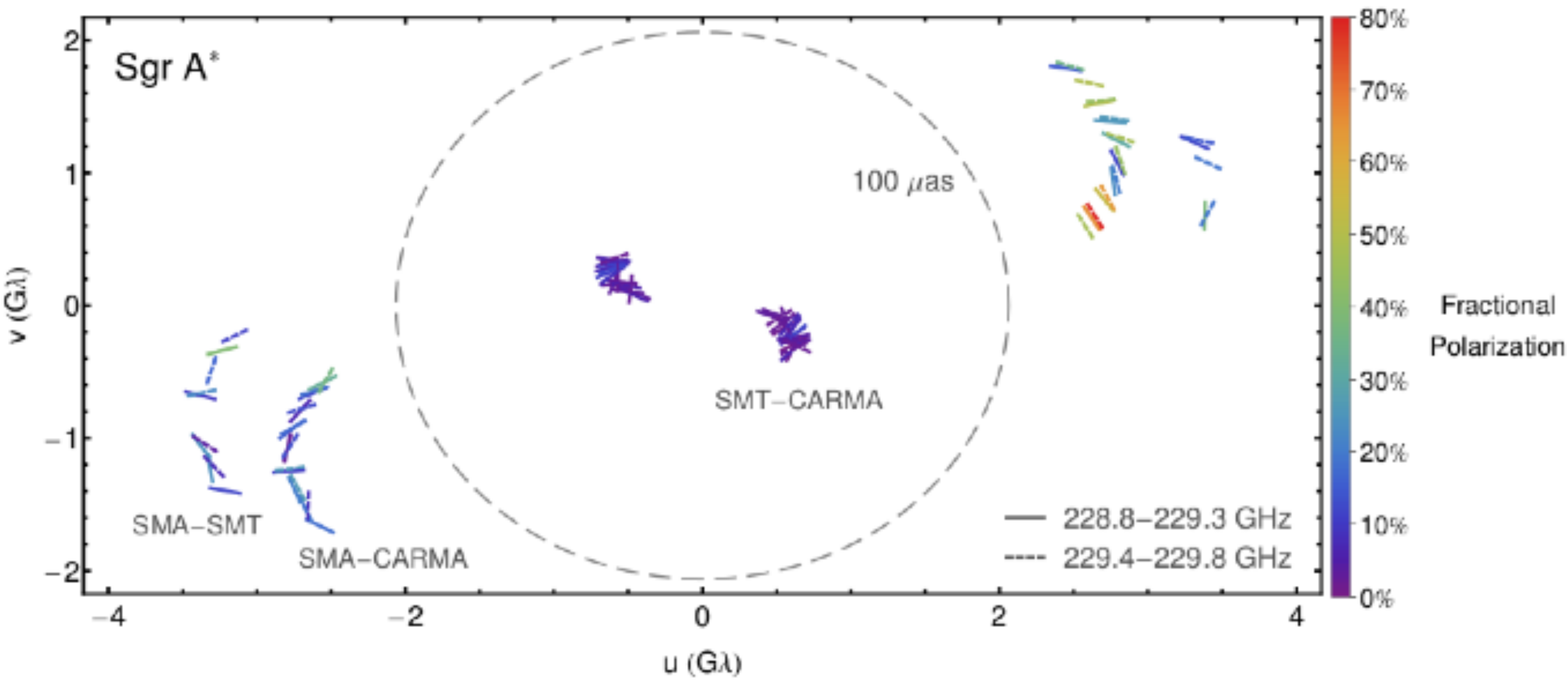
θ_{OBS} deviates from scattering for λ < 1.35 cm

$\theta_{INT} << \theta_{SCAT}$ for λ > 1.3 mm

$\theta_{INT} \alpha \lambda^{1.4}$

Sgr A*

2013 EHT Data (Preliminary)



M. Johnson et al. (in prep)

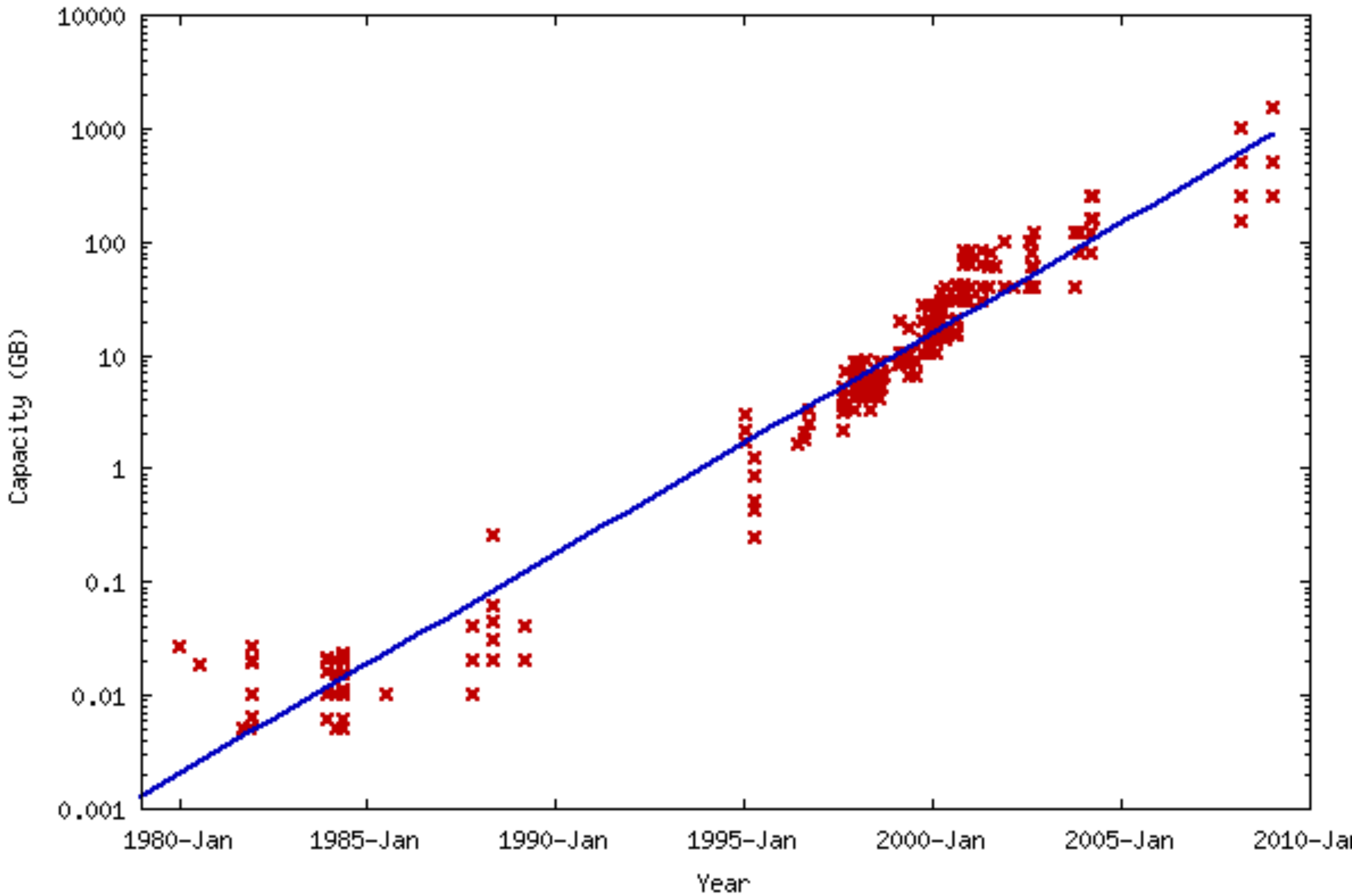
Event Horizon Telescope Collaboration

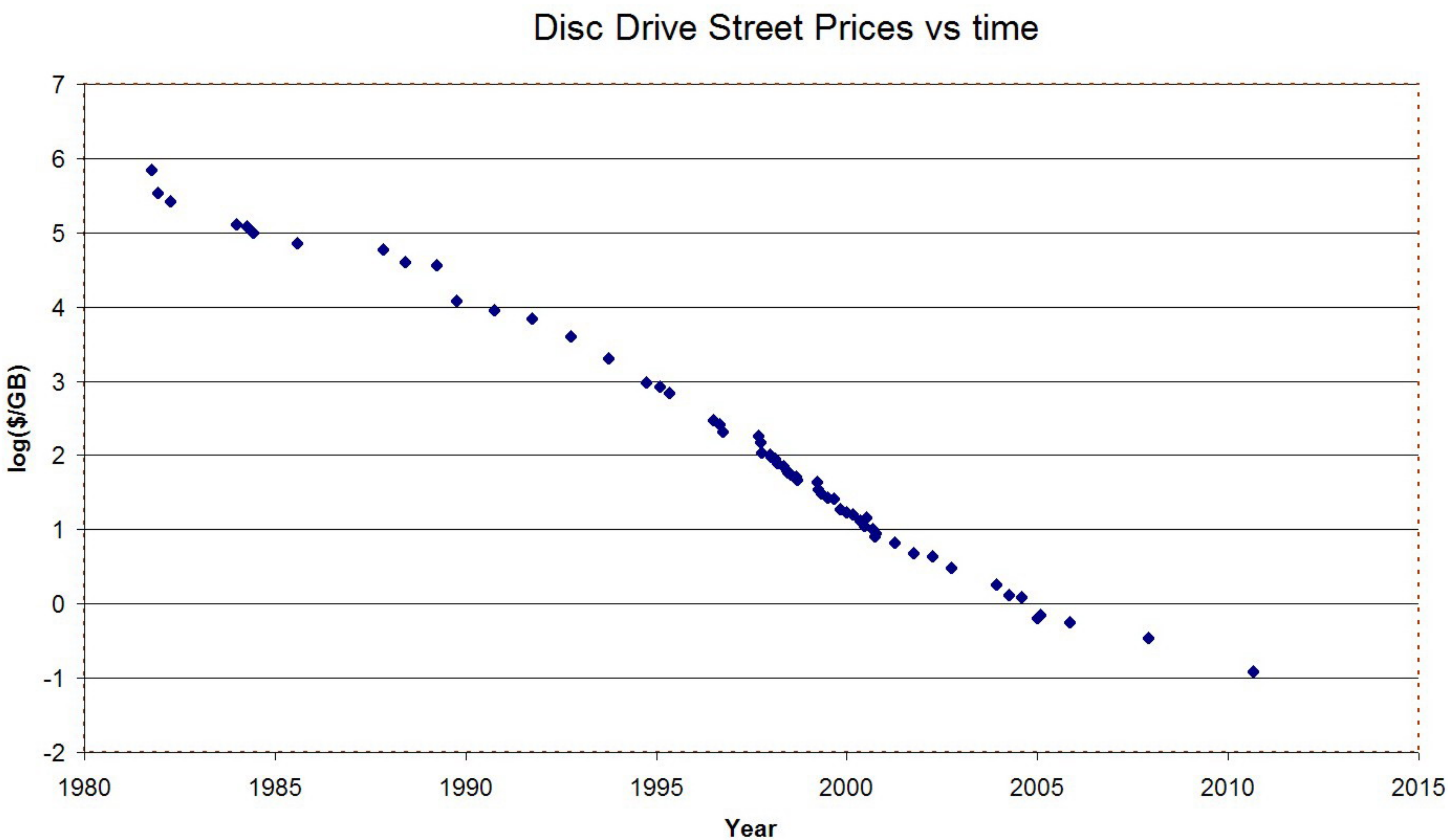
MIT Haystack: Shep Doeleman, Alan Rogers, Vincent Fish, et al.
NAOJ: Mareki Honma, Tomoaki Oyama, Kazunori Akiyama
U. Arizona Steward Obs: Lucy Ziurys, Robert Freund, Dan Marrone
Harvard CfA: Jonathan Weintroub, Jim Moran, Ray Blundell, et al.
CARMA: Dick Plambeck, Mel Wright, David Woody, Geoff Bower
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

Short-Term Goals of EHT

1. 2014 LMT Checkout
2. 2015 ALMA Phased Array Ready
3. 2015 SPT Ready
4. 2015 2 GHz Bandwidth

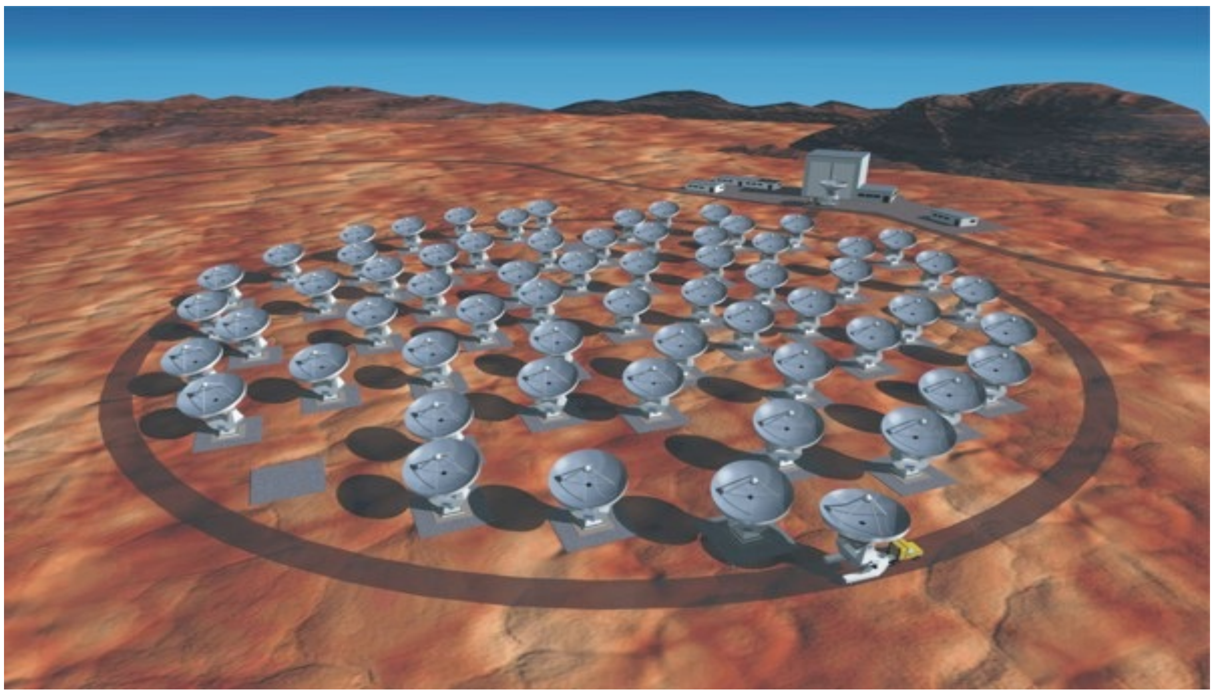
Disk Capacity vs. Year



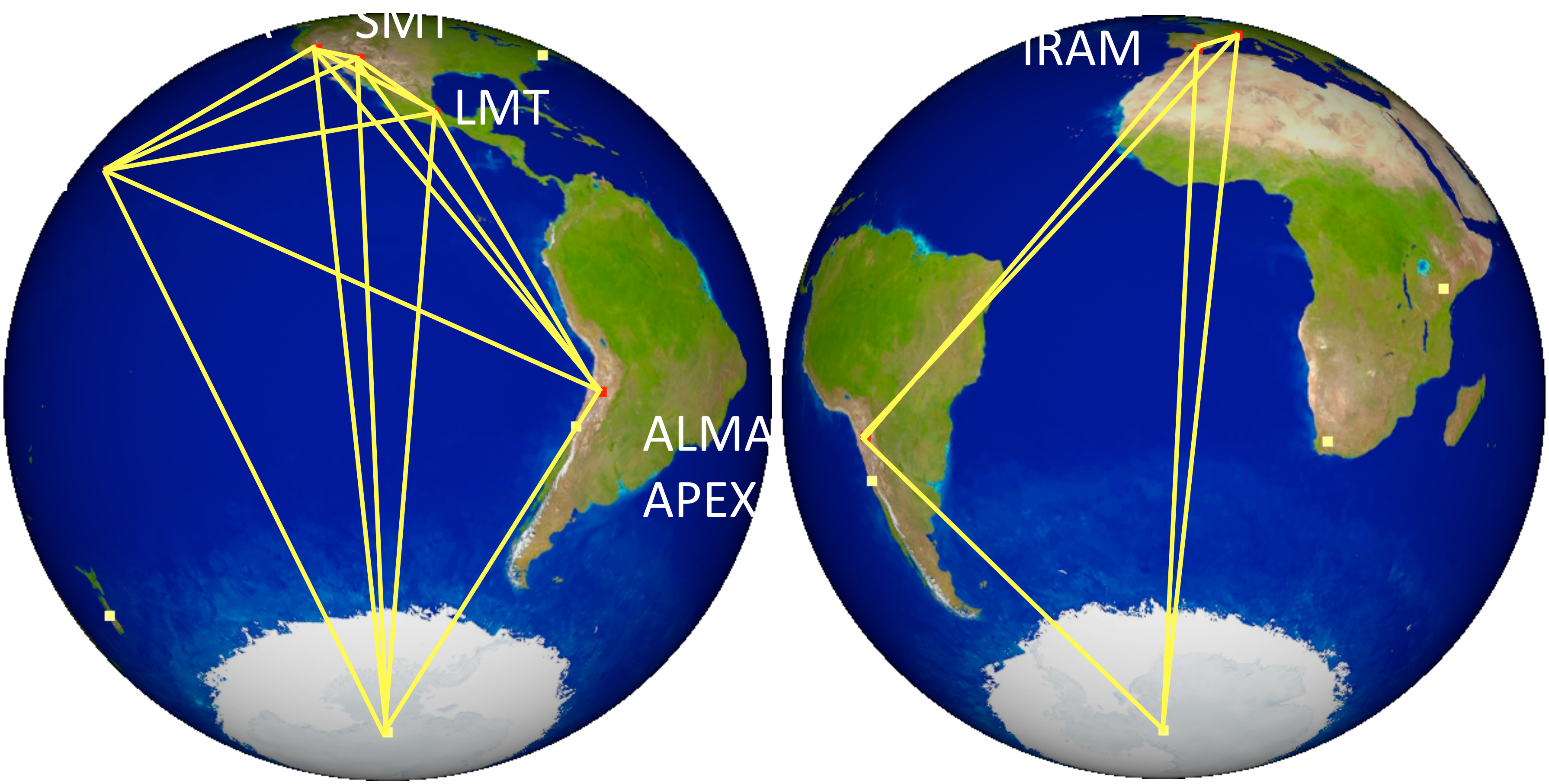


Disc Drive Street Prices vs time
7
6
5
4
3
2
1
0
-1
-2
log($/GB)
1980
1985
1990
1995
2000
2005
2010
2015
Year

Phasing ALMA

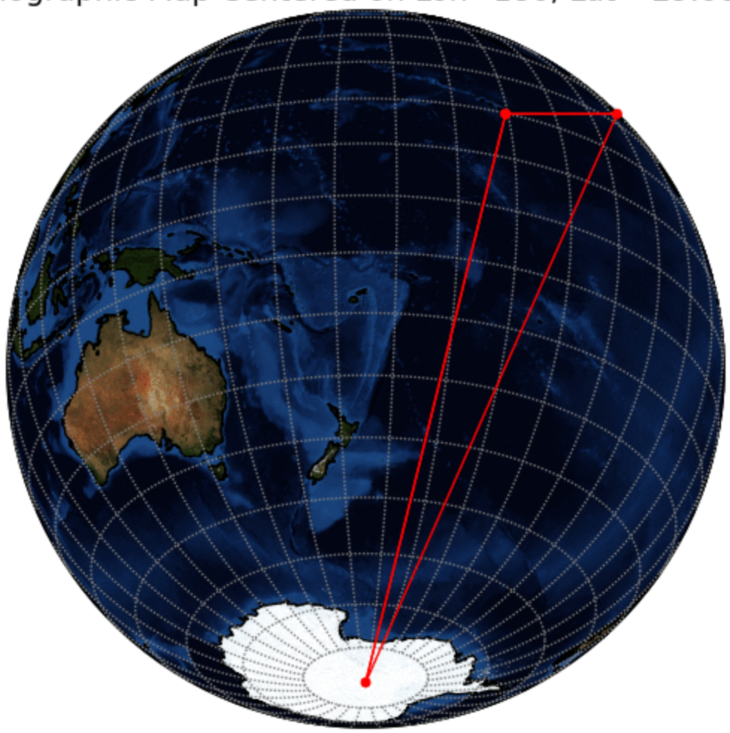


SgrA*'s view of the EHT

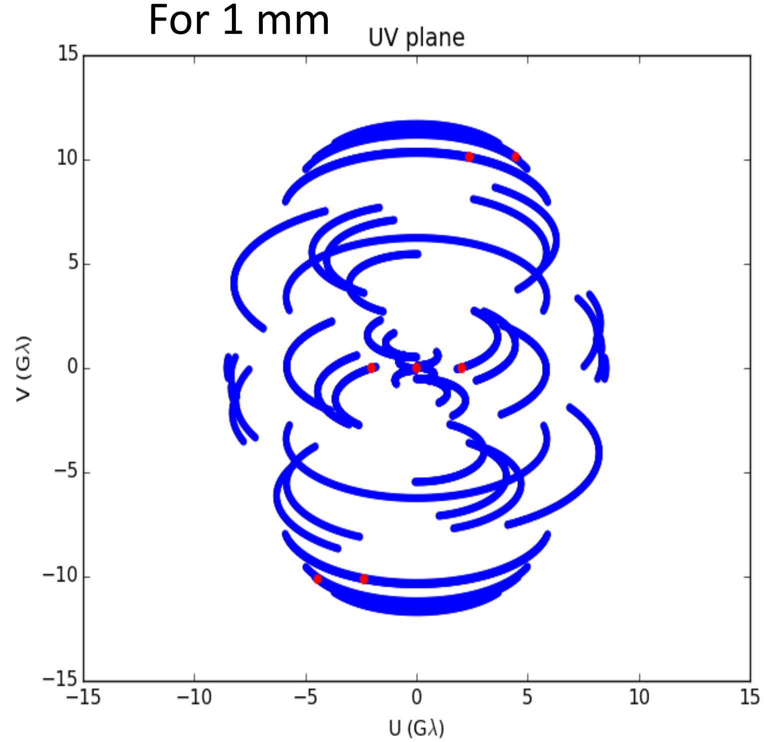


EHT, seen by Sgr A* near future

Hawaii
Chile
California
Arizona
Spain
France
South Pole
Mexico

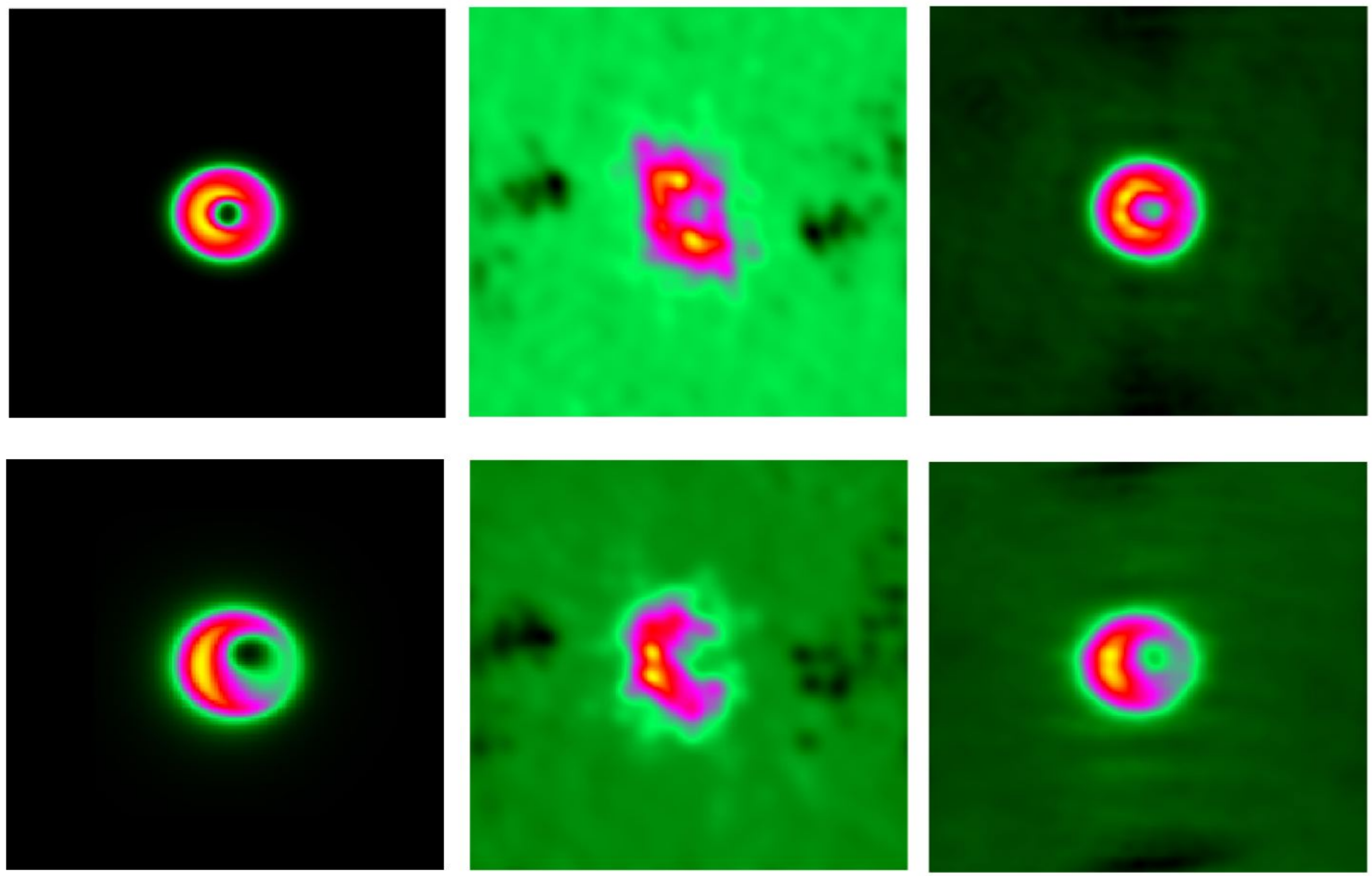


For 1 mm



Courtesy of L. Vertatschitsch

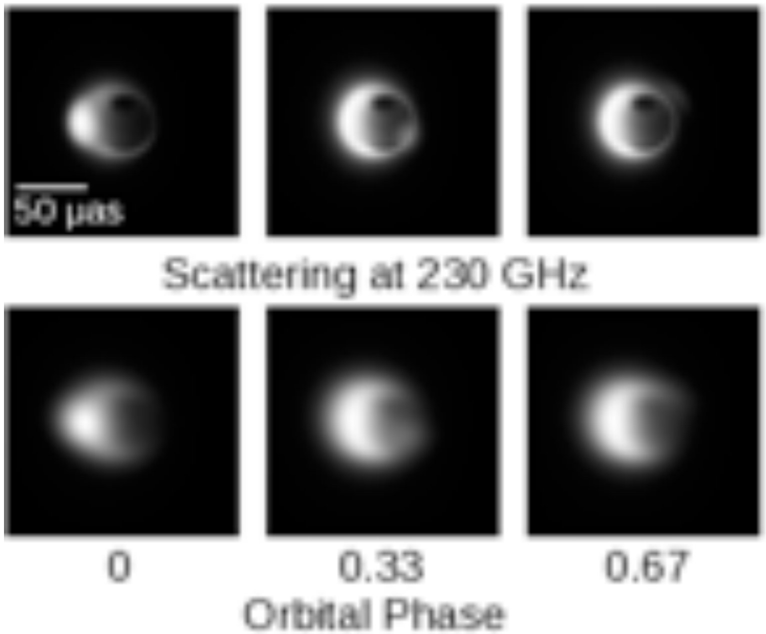
Progression to an Image

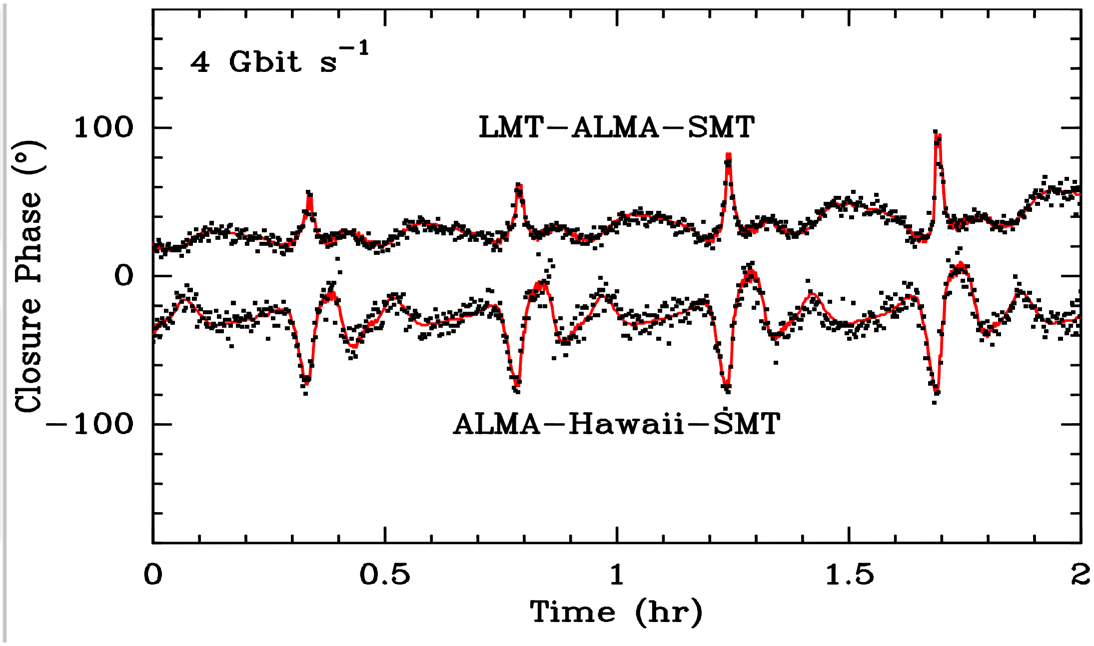


GR Model **7 station** **13 station**

Doeleman et al., "The Event Horizon Telescope," Astro2010: The Astronomy and Astrophysics Decadal Survey, Science White Papers, no. 68

Time Resolving BH Orbits





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