What Polarization Tells Us About the Accretion Disk in SgrA*
or
"What I Want to Do with ALMA but They Wouldn't Let Me"

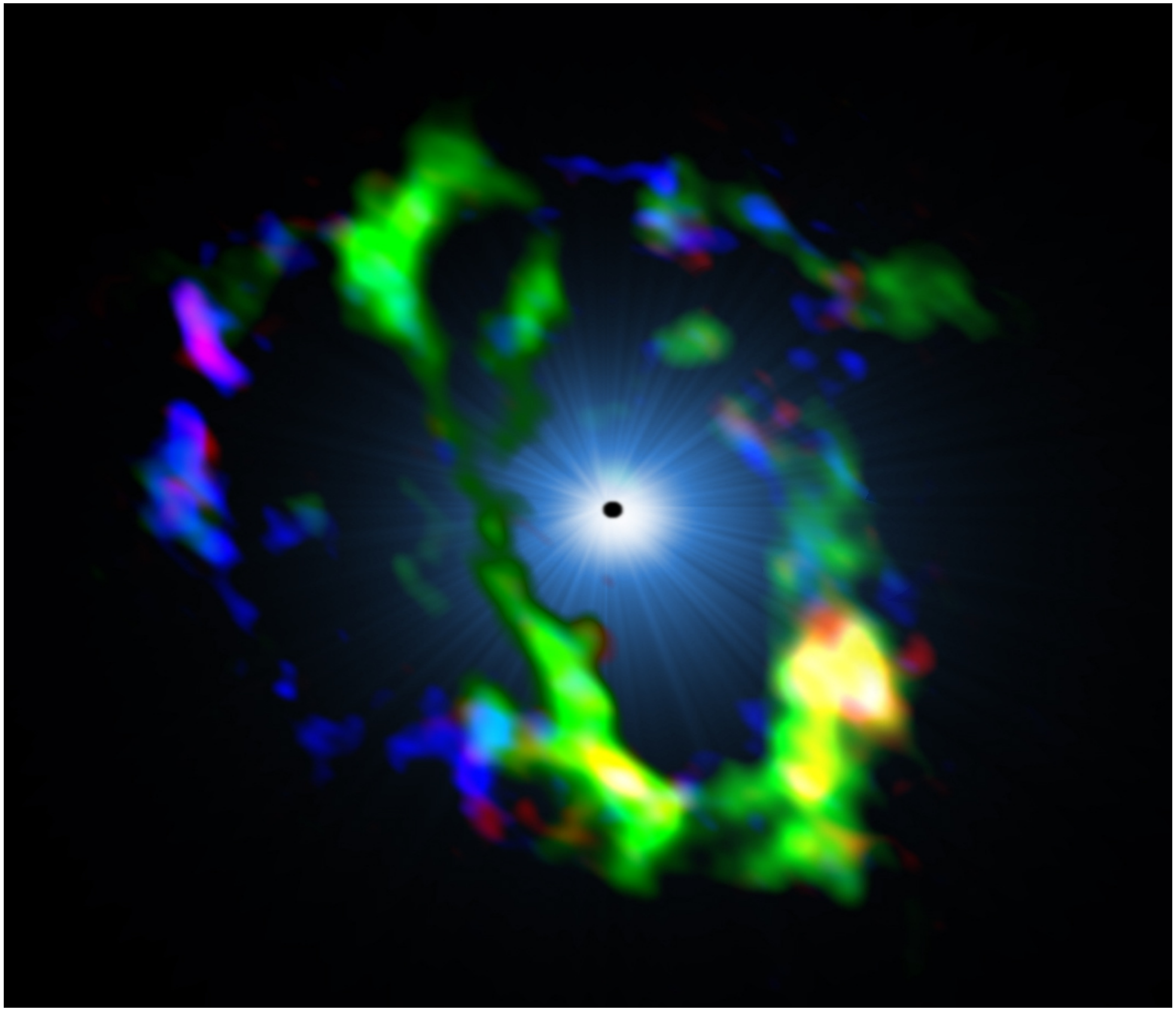
Jim Moran

Miller-Fest, Durango, CO May 18, 2011

The Galactic Center on Three Size scales

- 1. Circumnuclear (molecular) Disk (CND) and Mini-spiral (ionized streamers)
  120 arcs / 5 pc
  Zhao, Blundell, Downes, Schuster, Marrone
- 2. Black hole accretion envelope (100 R_S)
  1 mas / 0.03 milli pc
  Marrone, Munoz, Rao
- 3. SgrA* radio source
  37 microarcseconds / 1 micro pc
  Doeleman, et al., Fish et al., 2011

Nine Field Mosaic Image of Circumnuclear Disk in Galactic Center



CN

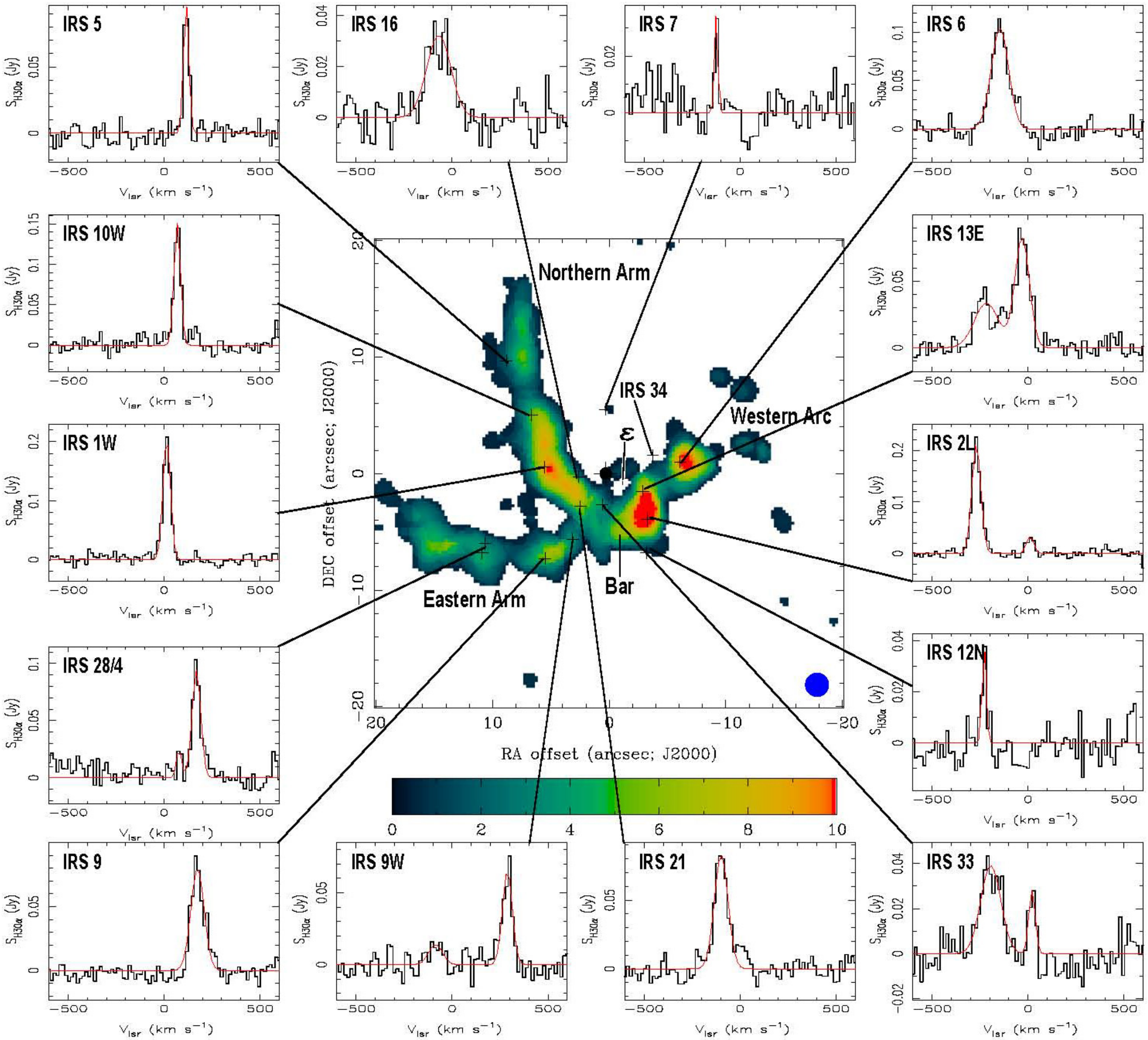
H2CO

SiO

SMA Data
Sergio Martin Ruiz

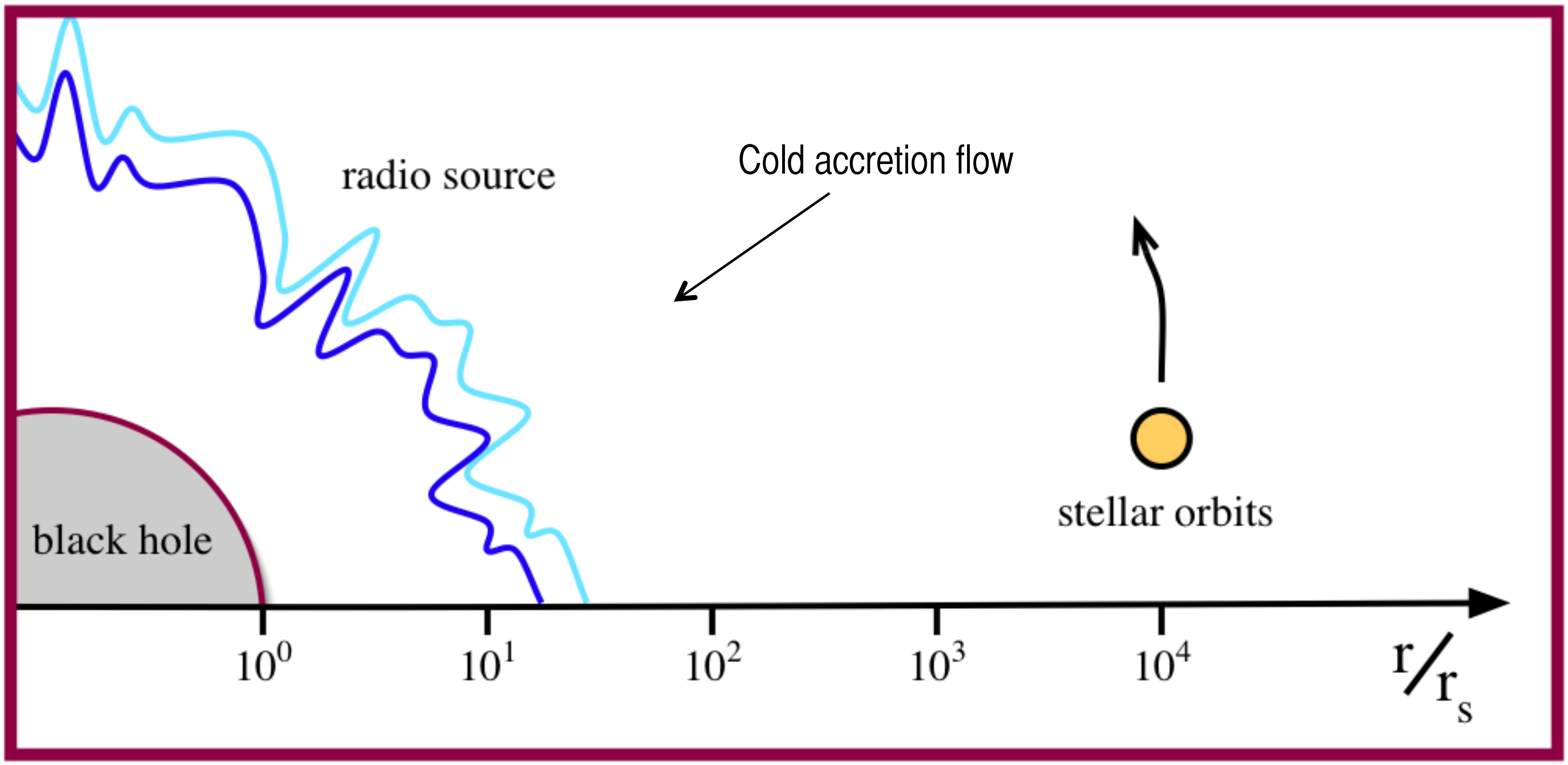
3 arcmin field
3 arcs resolution
1.3 mm wavelength

H 30 α RRL Zhao, et al, ApJ 2010



A HUNGRY BLACK HOLE

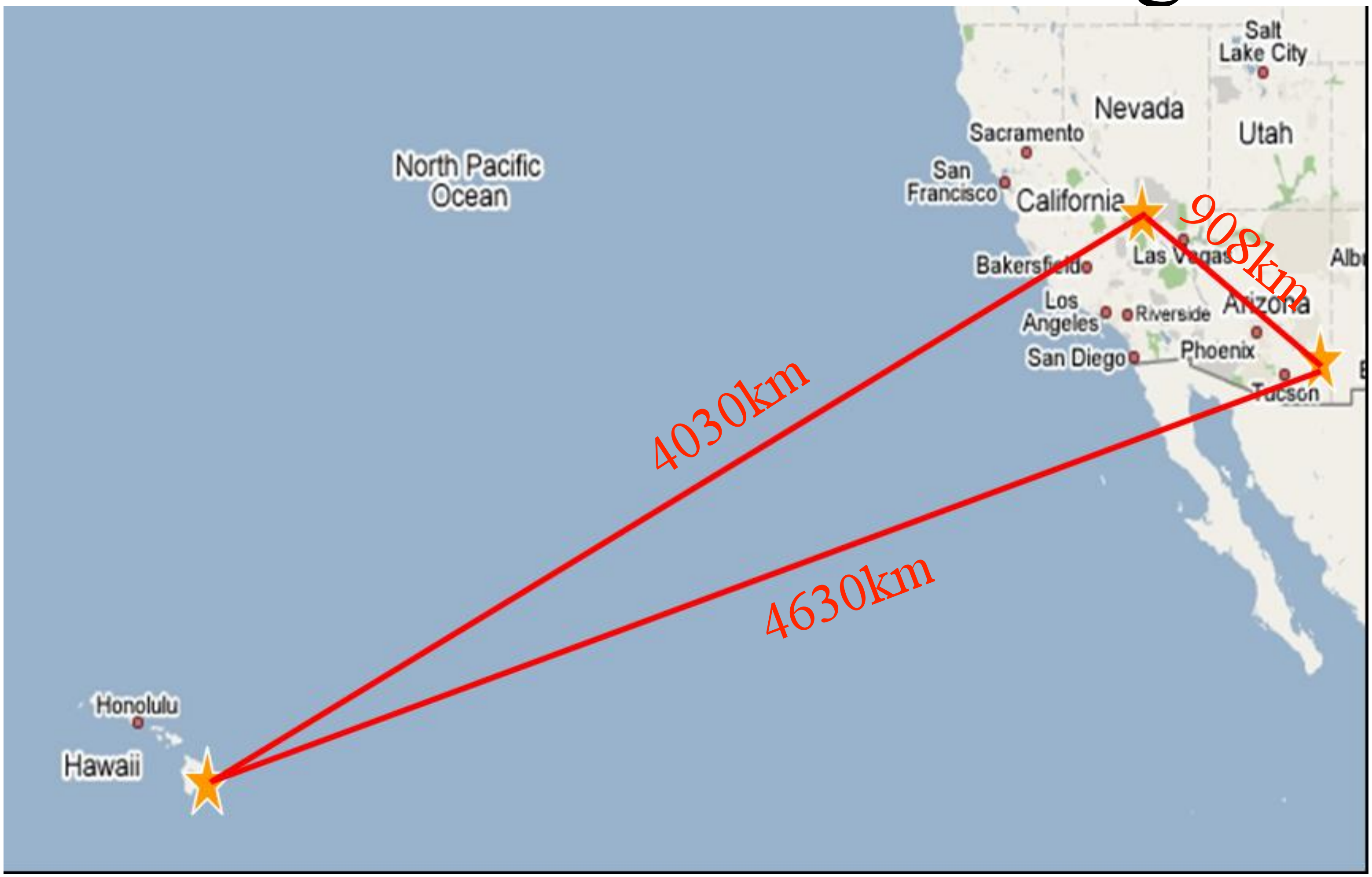
Some Scales in the Galactic Center



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

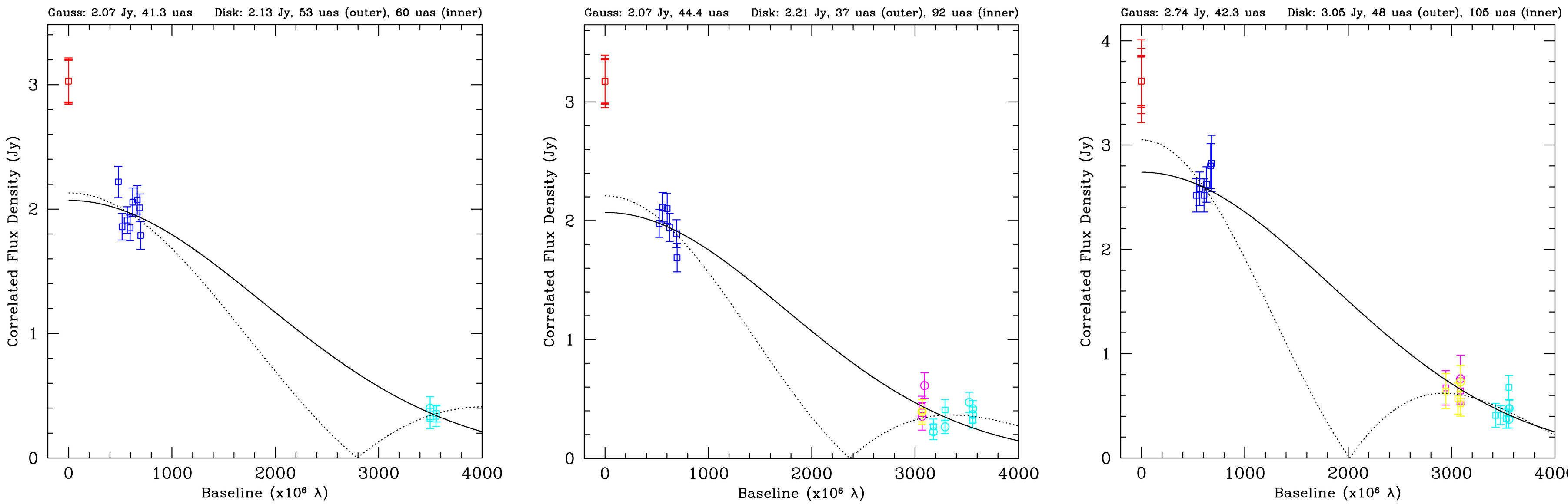
$$r_s = 1.3 \times 10^{12}\text{cm (for } 4.3 \times 10^6 \text{ solar masses)} \ = 10\mu\text{as at 8.3 kpc}$$

1.3mmλ Observations of SgrA*



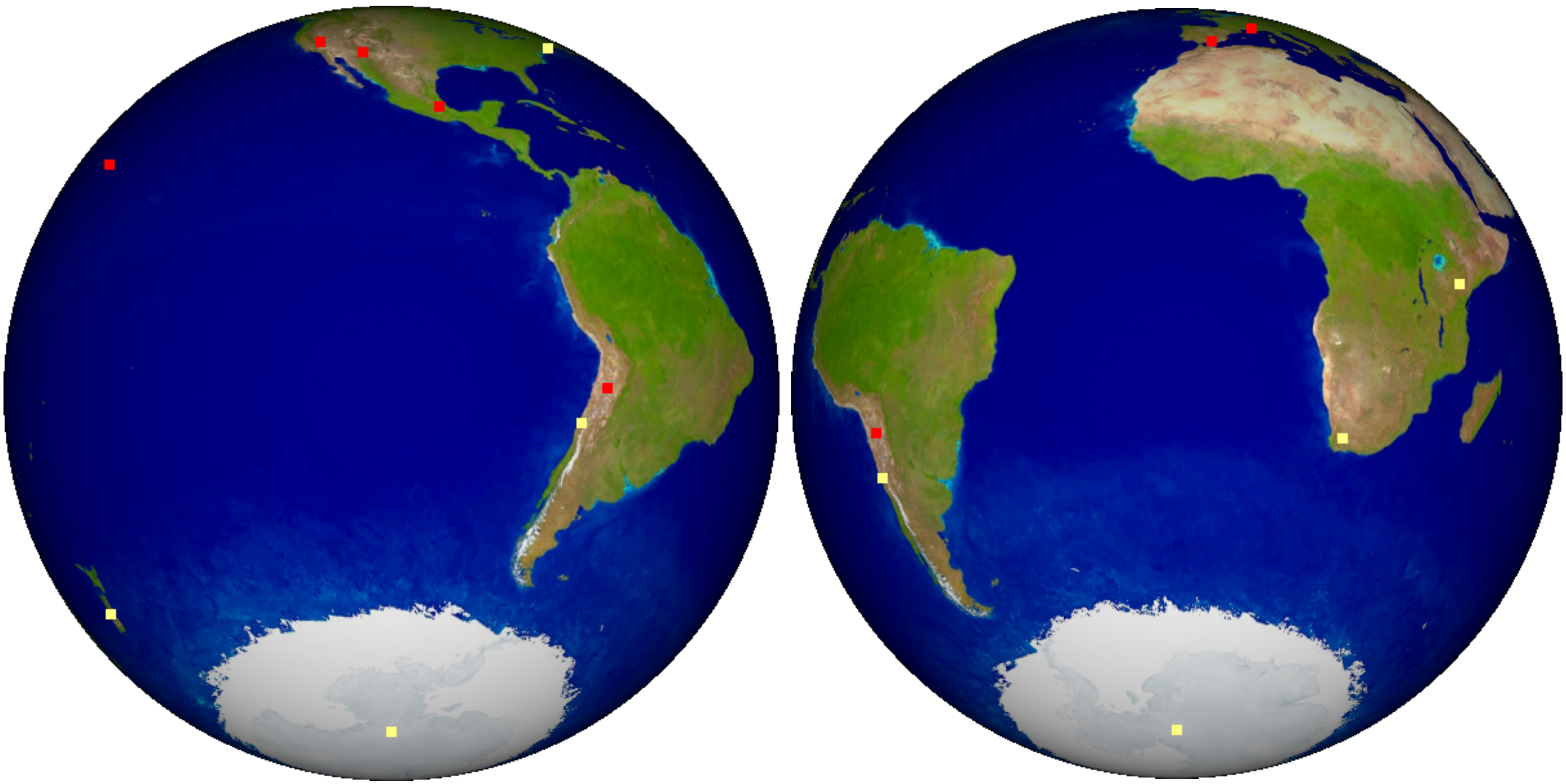
VLBI program led by large consortium led by Shep Doeleman, MIT/Haystack

VLBI Observations 2009



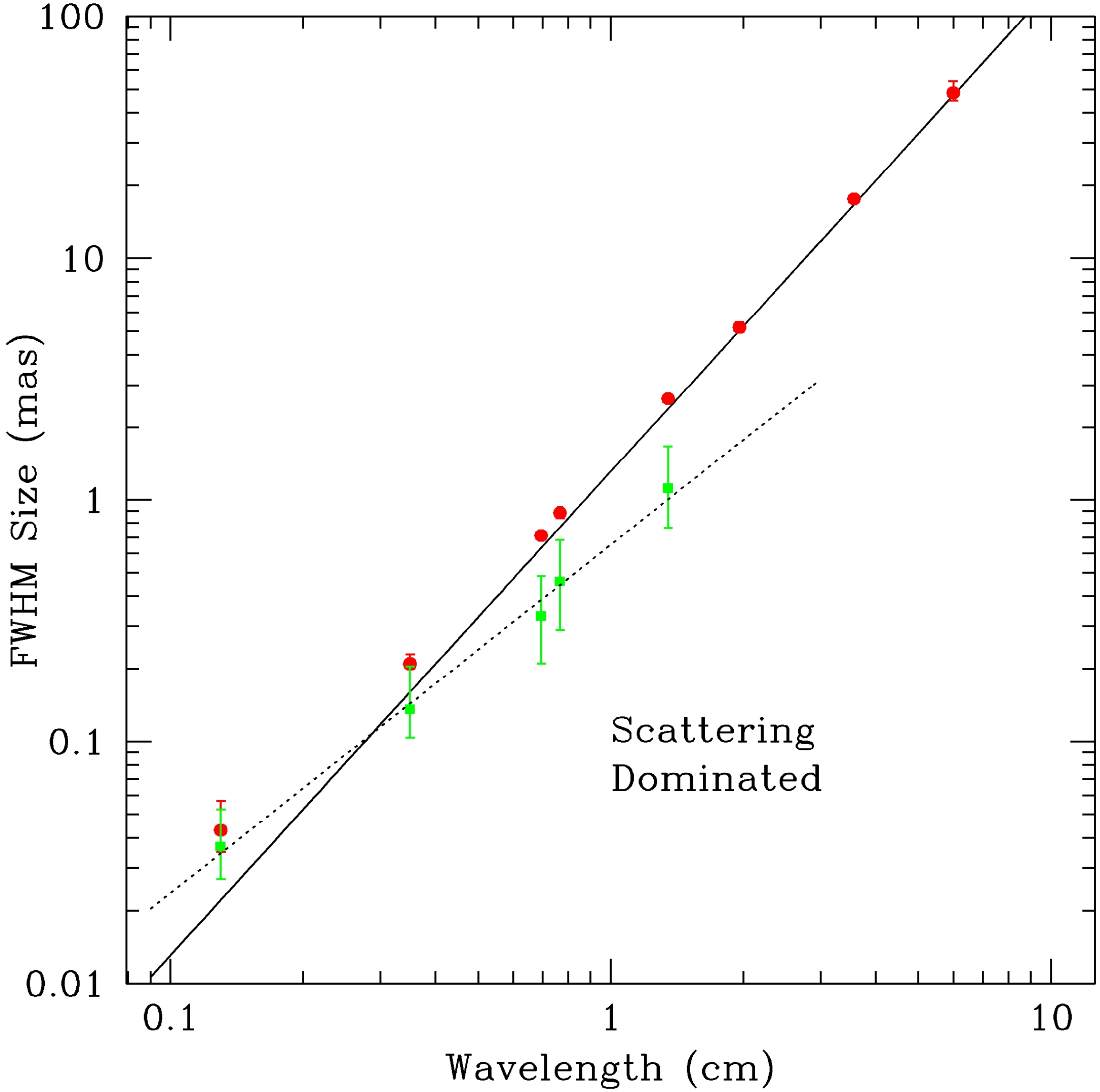
See Fish, et al., Ap.J. (Lett), 727, L36, Feb 1, 2011

New (sub)mm VLBI Sites for EHT



Phase 1: 7 Telescopes (+ IRAM, PdB, LMT, Chile)
Phase 2: 10 Telescopes (+ Spole, SEST, Haystack)
Phase 3: 13 Telescopes (+ NZ, Africa)

Seeing Through the Scattering

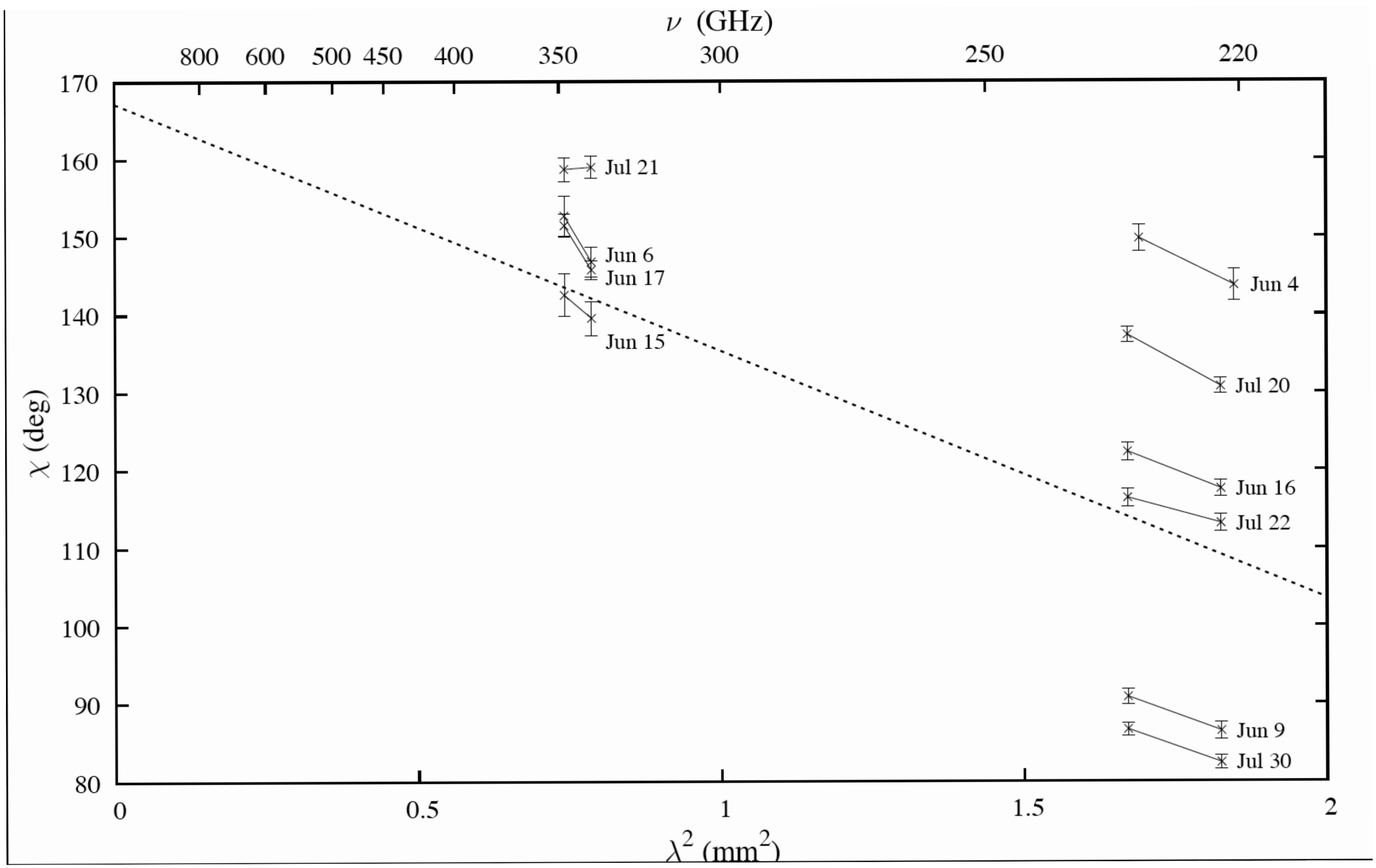


θ_{OBS} deviates from scattering for $\lambda < 1.35$ cm

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

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

2005 SMA Measurements of Faraday Rotation in Sgr A*



Accretion Rate and Faraday Rotation

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

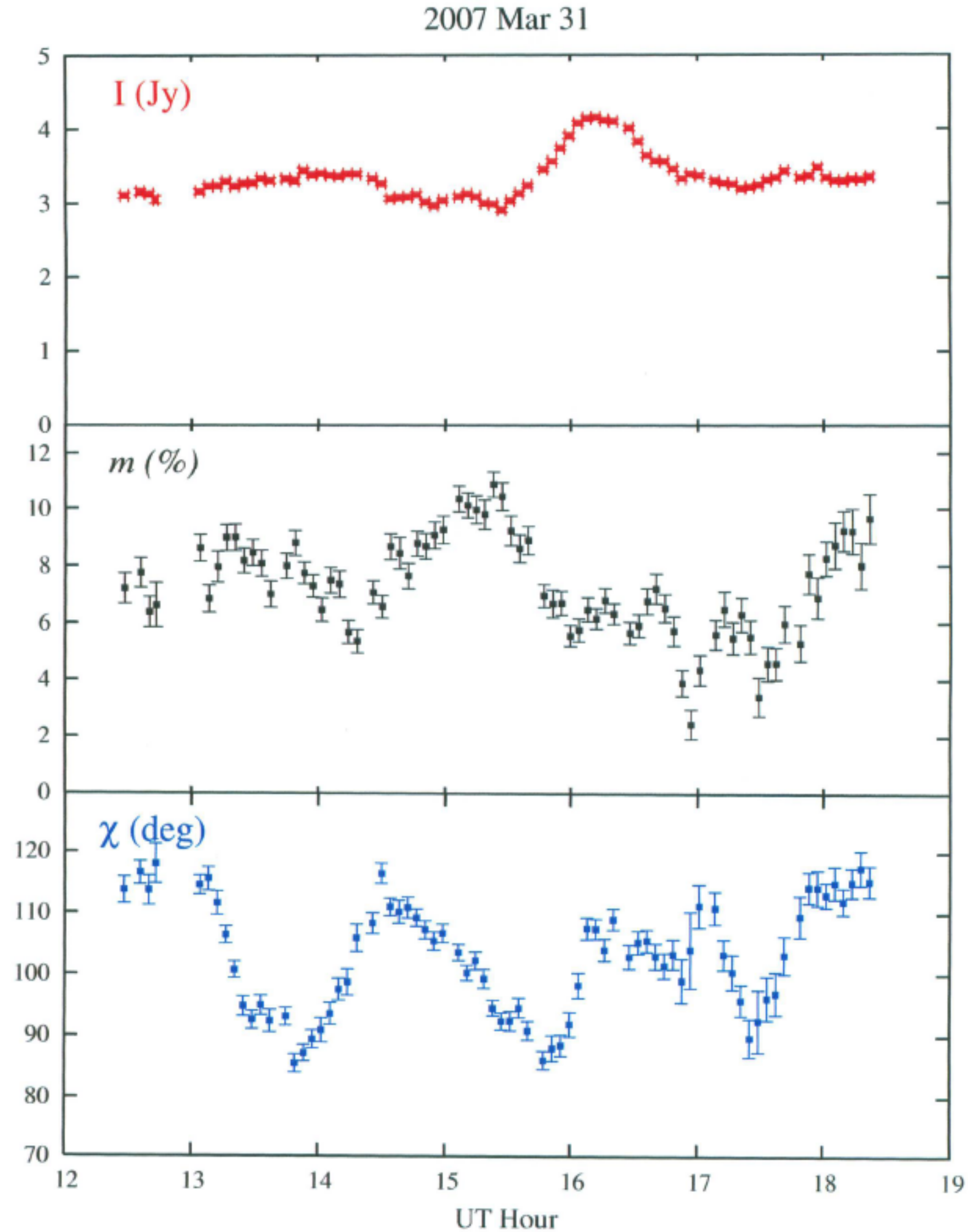
$$RM = 8.1 \times 10^5 \int n_e \vec{B} \cdot d\vec{l}$$

- RM = -5.1 x 10^5 rad/m^2

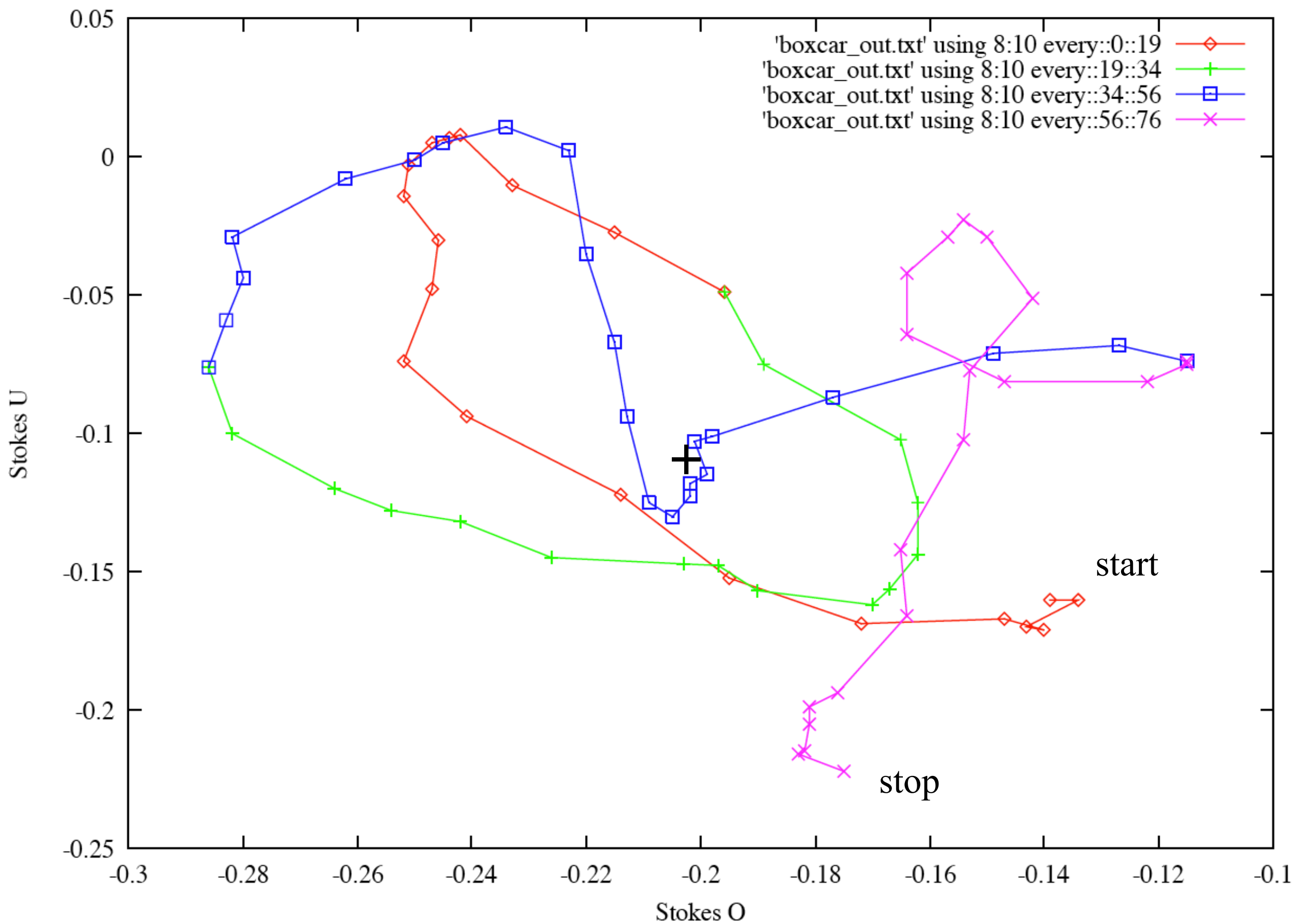
Assumptions:
equipartition
density power law
inner radius cutoff of Faraday screen

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

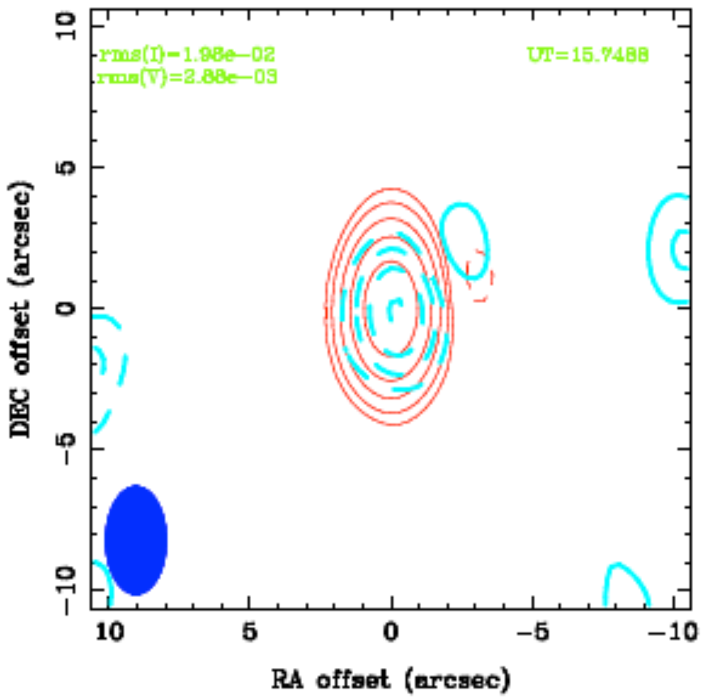
Polarization of Sgr A* at 230 GHz (1.3 mm) (SMA)

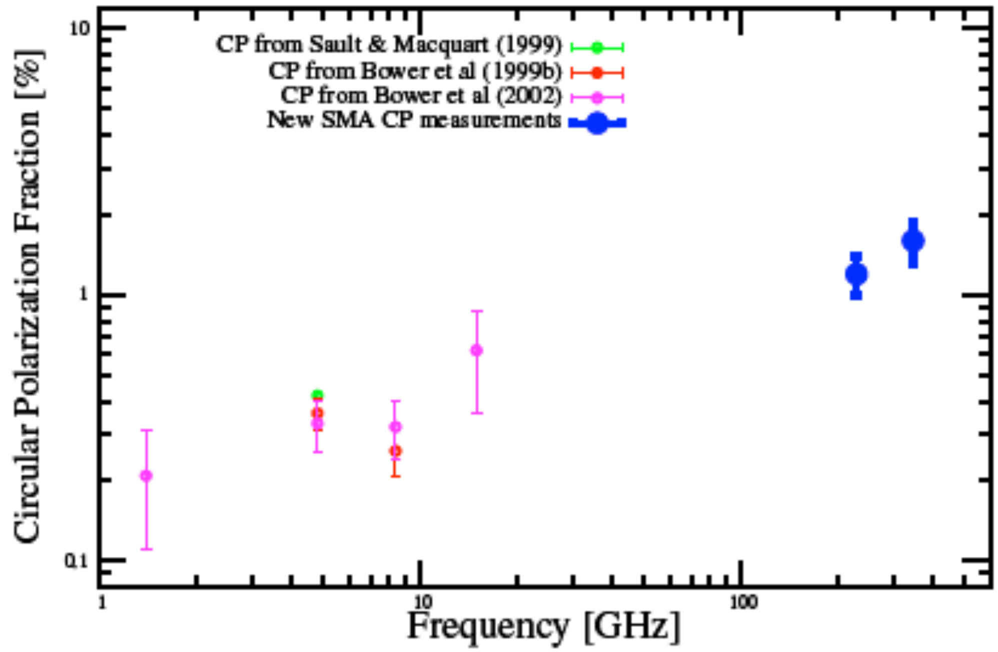


Polarization Track for 3/31/07 Observation of SgrA*



Circular Polarization of Sgr A*



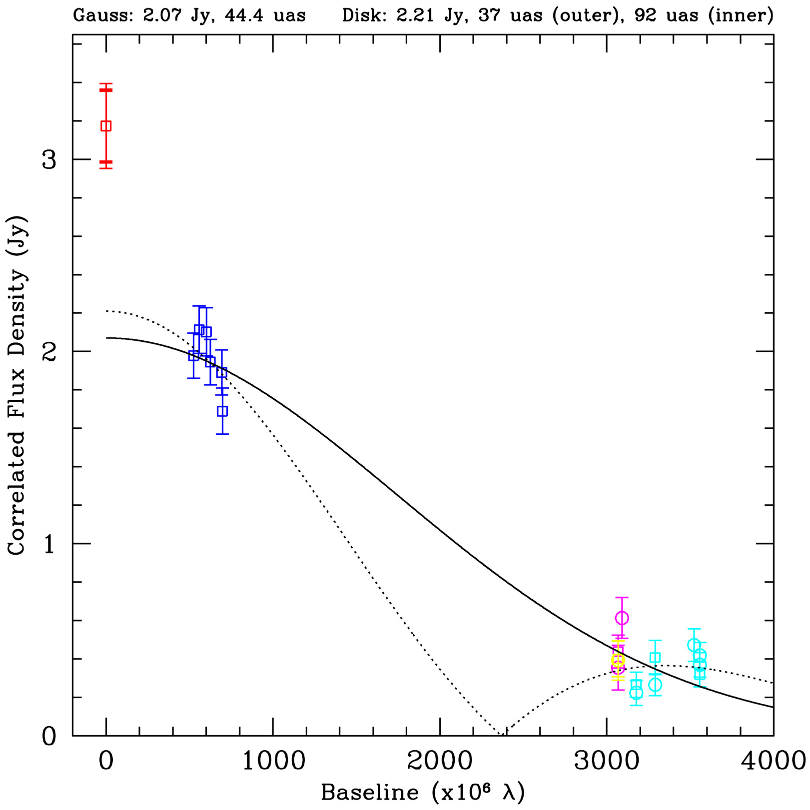


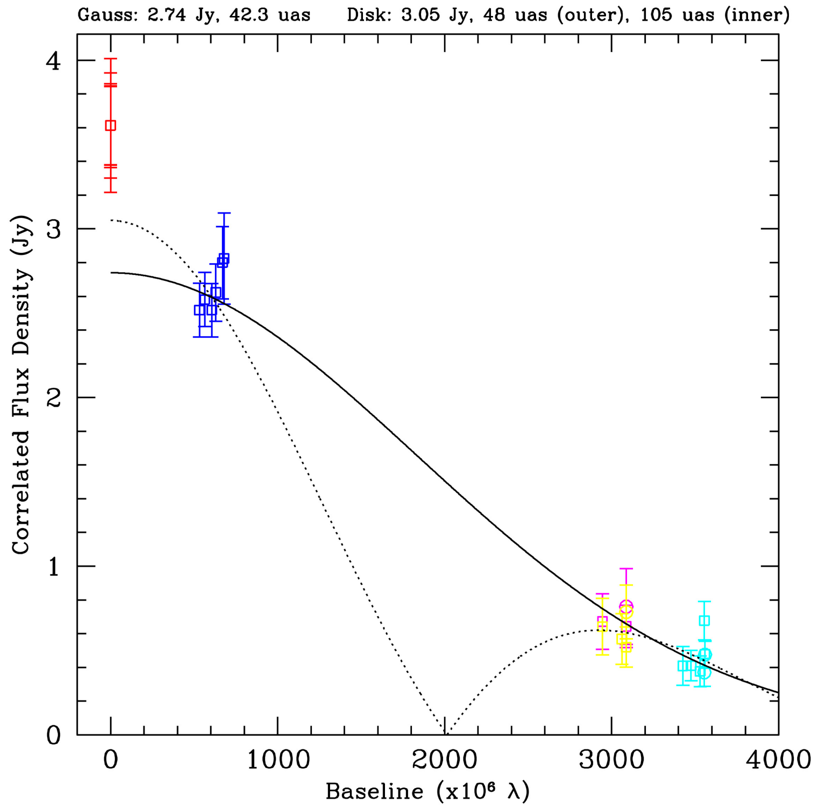
(red) Stokes I
(blue) Stokes V

Fractional Circular Polazization
vs Frequency

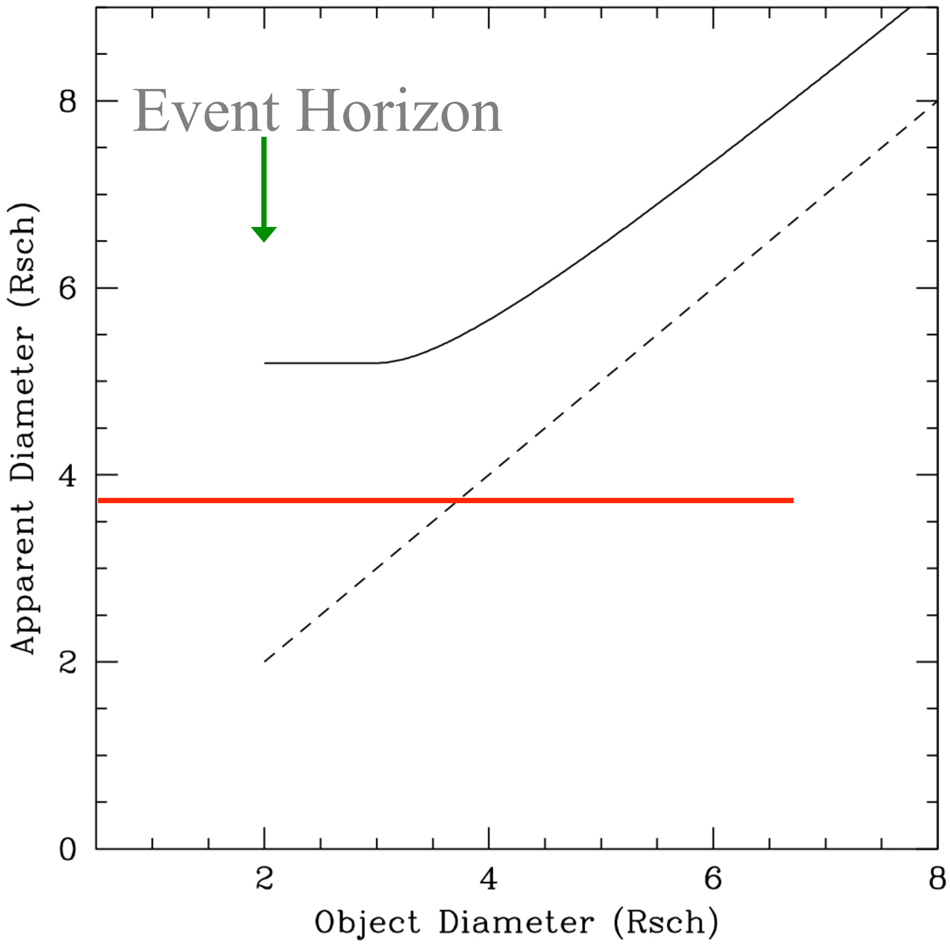
Diego Munoz, Harvard Research Exam Project, 2009

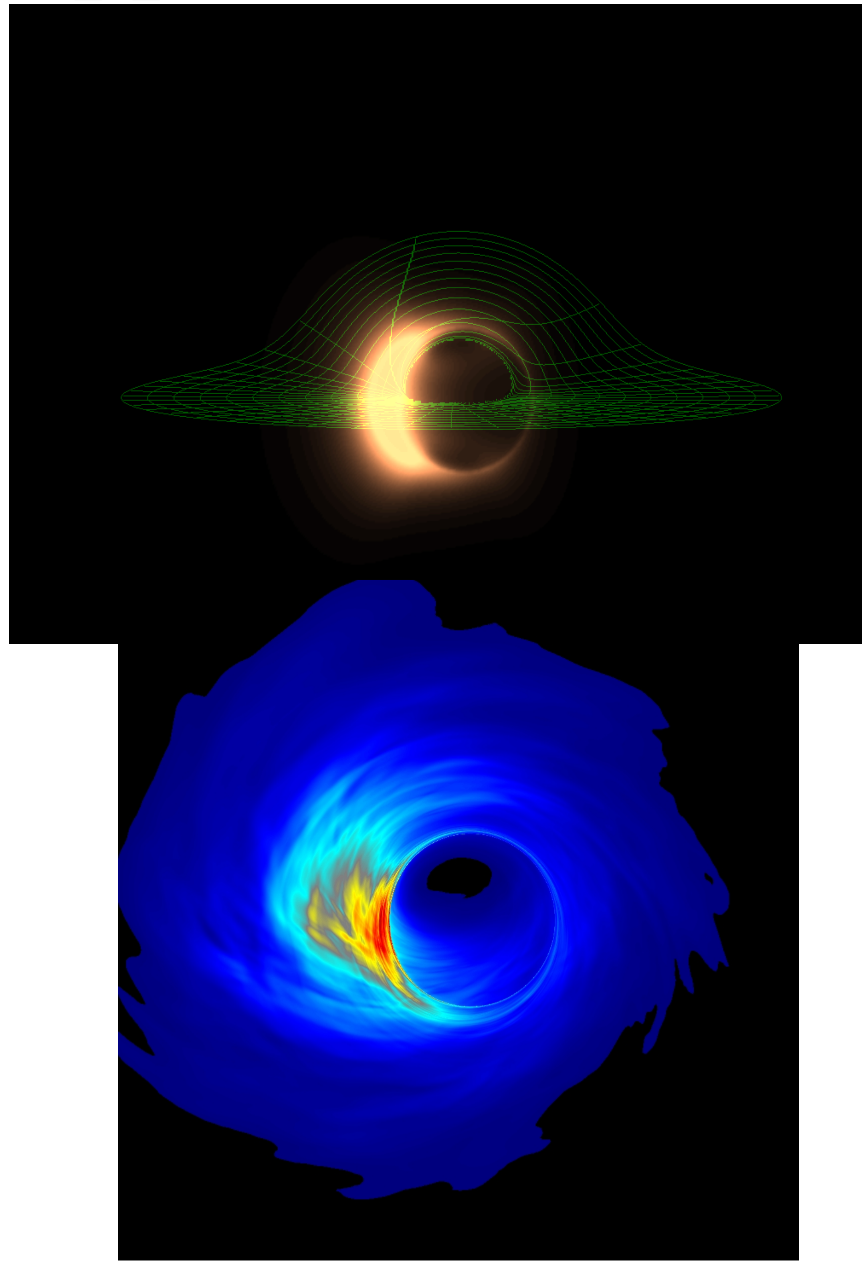
Days 96 and 97 (2010)





The Minimum Apparent Size





EHT Phases:

Phase I: 7 station 8Gb/s array

Phasing ALMA and CARMA

2010 -- 2014

Phase II: 10 station 32Gb/s dual-pol array

Activate SEST, equip S.Pole

move to 0.8mm observations

2015 -- 2018

Phase III: 12 station array up to 64Gb/s

New dishes for optimal baseline coverage

2019 -- 2024

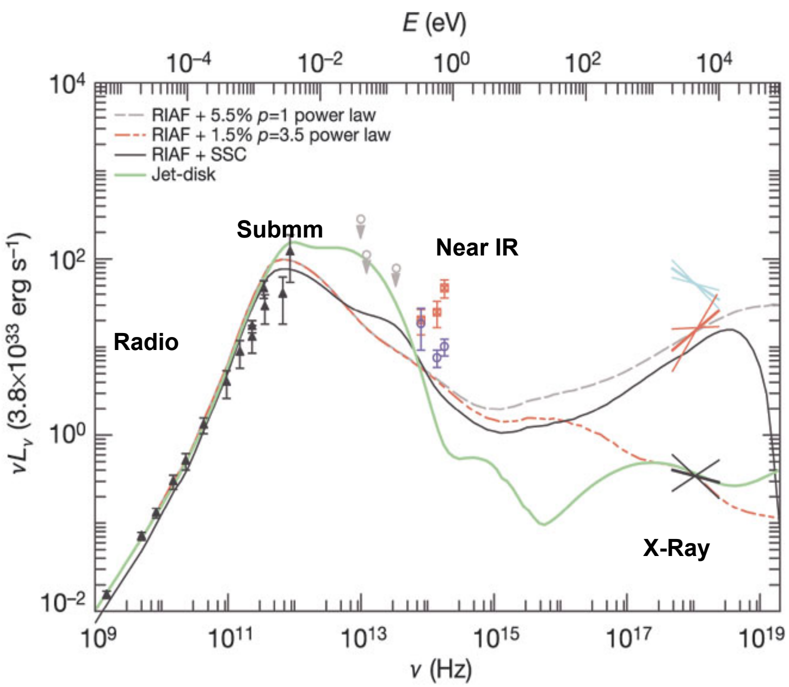
Circular Polarization: Null results for Quasars

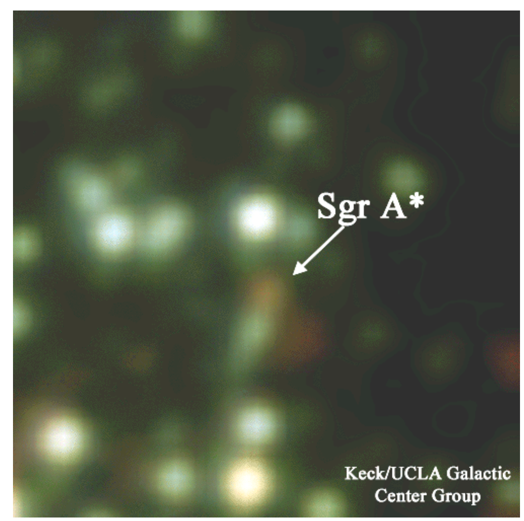
Table 2. Circular Polarization for Quasars (showing null results) on March 31st, 2007

	LSB		USB	
Source	I [Jy]	V/I	I [Jy]	V/I
3C273	15.40 ± 0.03	$(1.2 \pm 1.2) \times 10^{-3}$	15.05 ± 0.02	$(1.1 \pm 1.3) \times 10^{-3}$
3C279	12.92 ± 0.02	$(1.5 \pm 1.4) \times 10^{-3}$	12.88 ± 0.02	$(1.3 \pm 1.4) \times 10^{-3}$
3C286	0.49 ± 0.01	$(7.9 \pm 15.2) \times 10^{-3}$	0.46 ± 0.01	$(14.8 \pm 17.9) \times 10^{-3}$
1337-129	6.92 ± 0.03	$(2.1 \pm 3.0) \times 10^{-3}$	6.89 ± 0.03	$(2.5 \pm 3.4) \times 10^{-3}$
1924-292[a]	7.00 ± 0.01	$(-0.2 \pm 1.1) \times 10^{-3}$	6.95 ± 0.01	$(-0.1 \pm 1.2) \times 10^{-3}$

[a]Shown here for comparison, quasar 1924-292 was observed on the night of May 30th, 2008. This measurement was part of our extensive testing program. 1924-292 has nearly the same declination as Sgr A* so their tracks of parallactic angle are nearly identical.

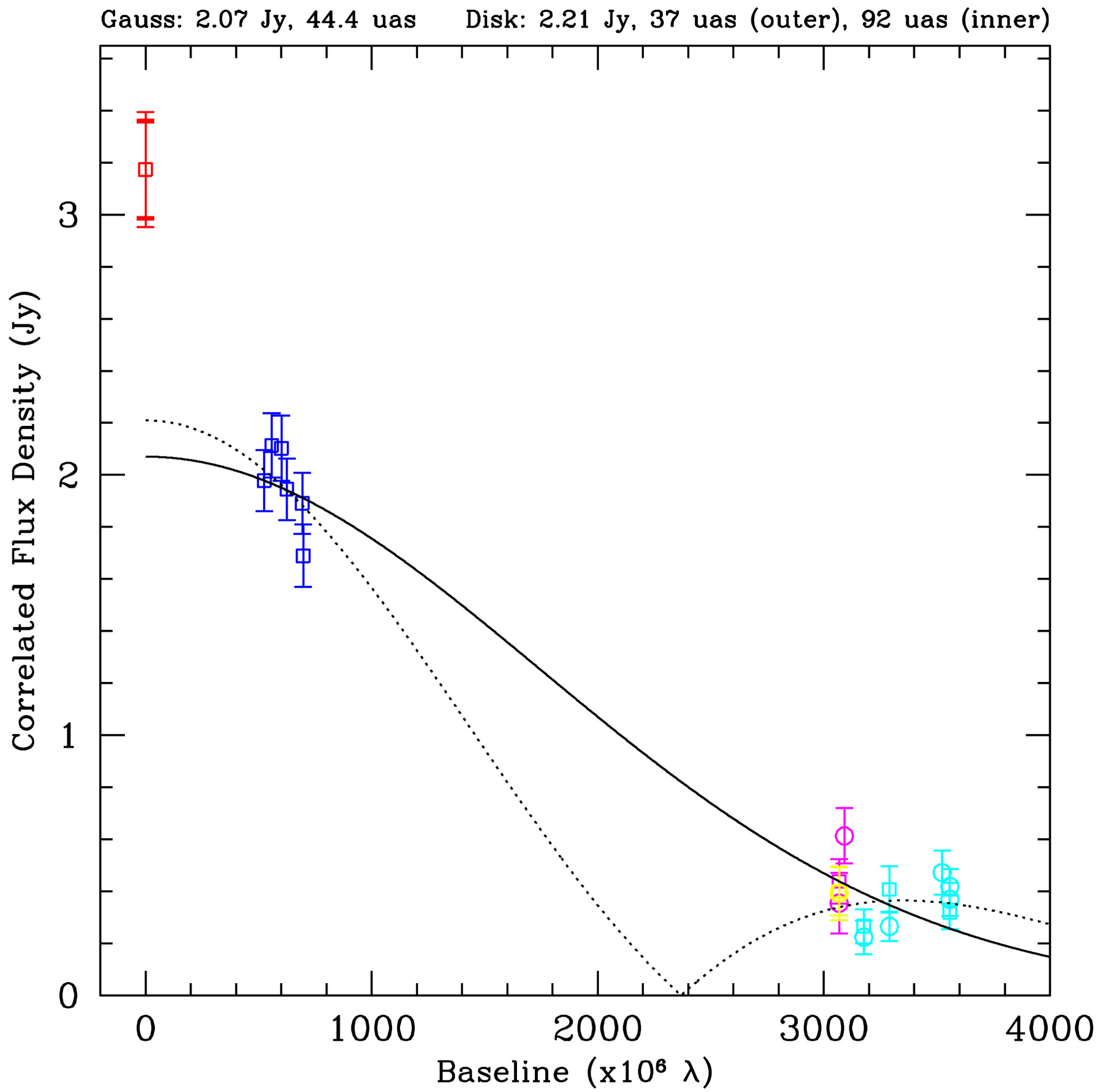
- Very faint source still detectible at most astronomical observing bands
  - SED measurements span 10 decades in frequency
- $L_{SgrA*} \sim 300\ L_{Sun} \sim 10^{-9}$ *Eddington limit*



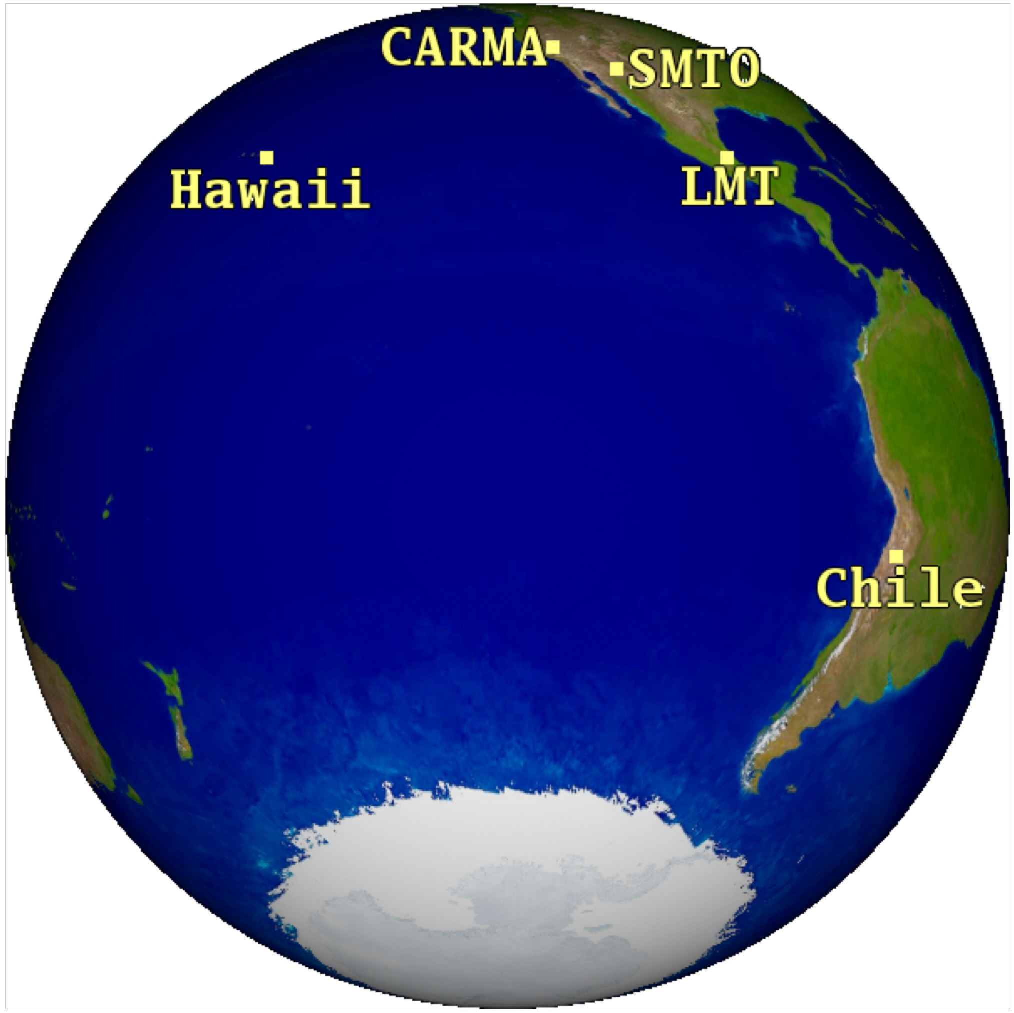


Genzel et al. (2004)

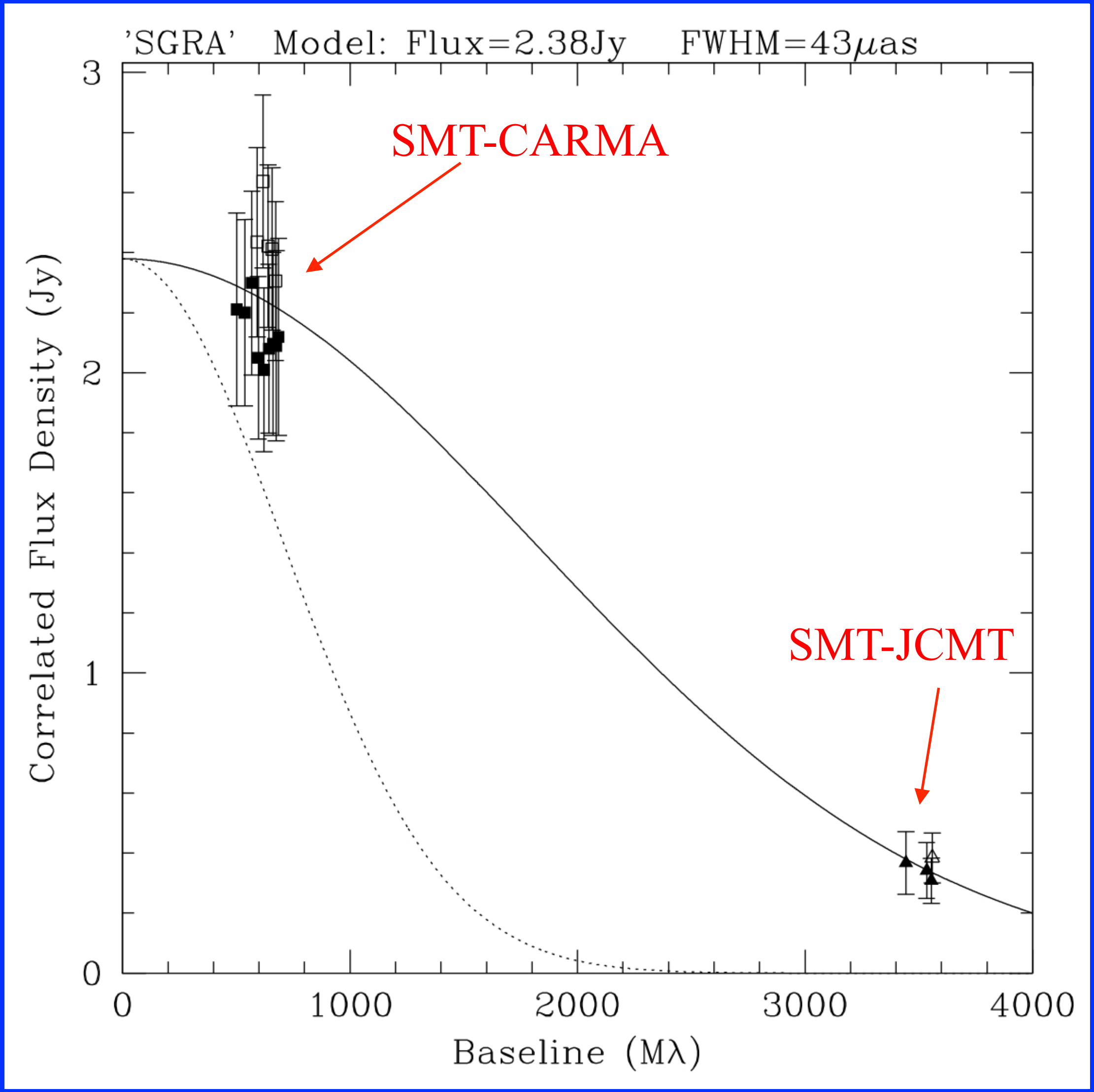
Δαψ 96



Gauss: 2.07 Jy, 44.4 uas
Disk: 2.21 Jy, 37 uas (outer), 92 uas (inner)
Correlated Flux Density (Jy)
0
1
2
3
0
1000
2000
3000
4000
Baseline (x10⁶ λ)


CARMA
SMTO
Hawaii
LMT
Chile

Determining the Size of SgrA*



$\theta_{OBS} = 43\mu as\ (+14, -8)$

$\theta_{INT} = 37\mu as\ (+16, -10)$

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

Doeleman et al 2008

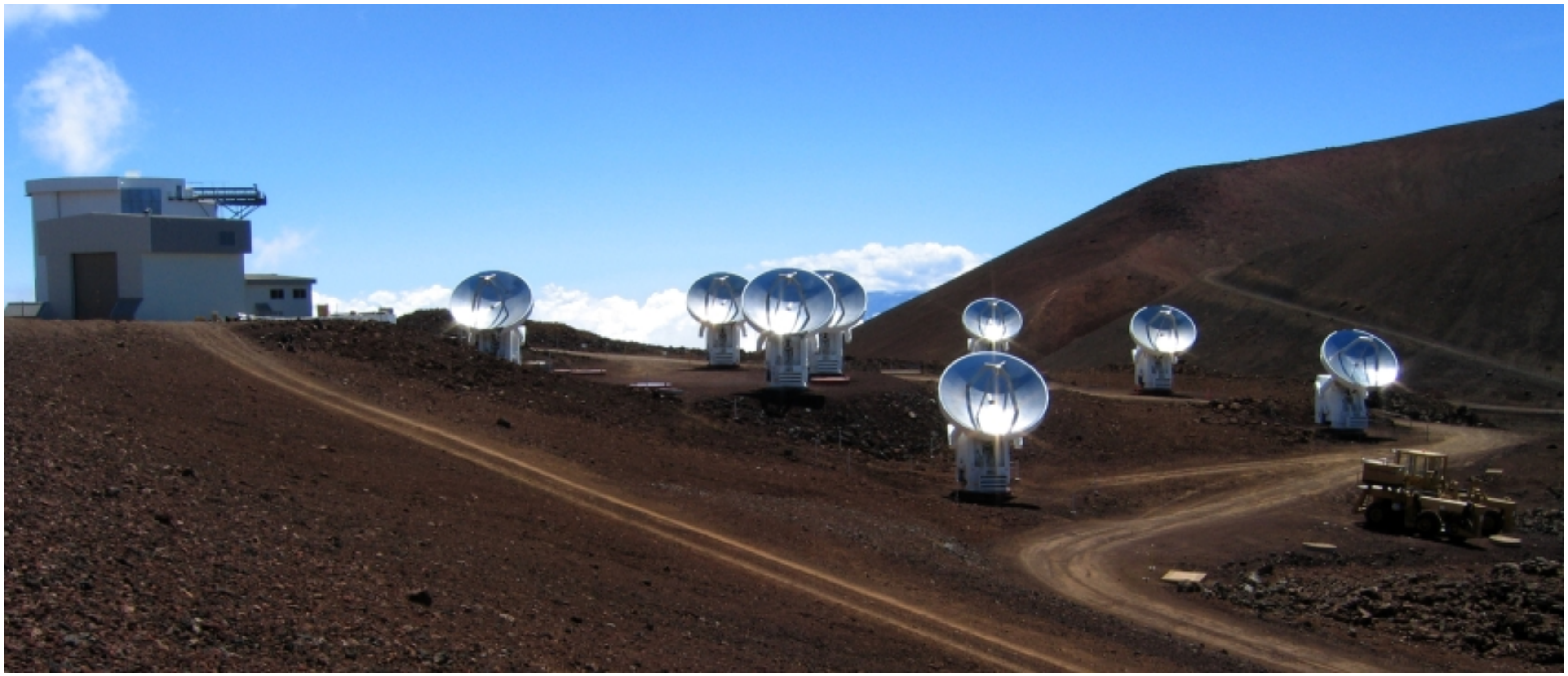
Submillimeter Valley, Mauna Kea, HI

CSO
10 m single dish
($79\ m^2$)

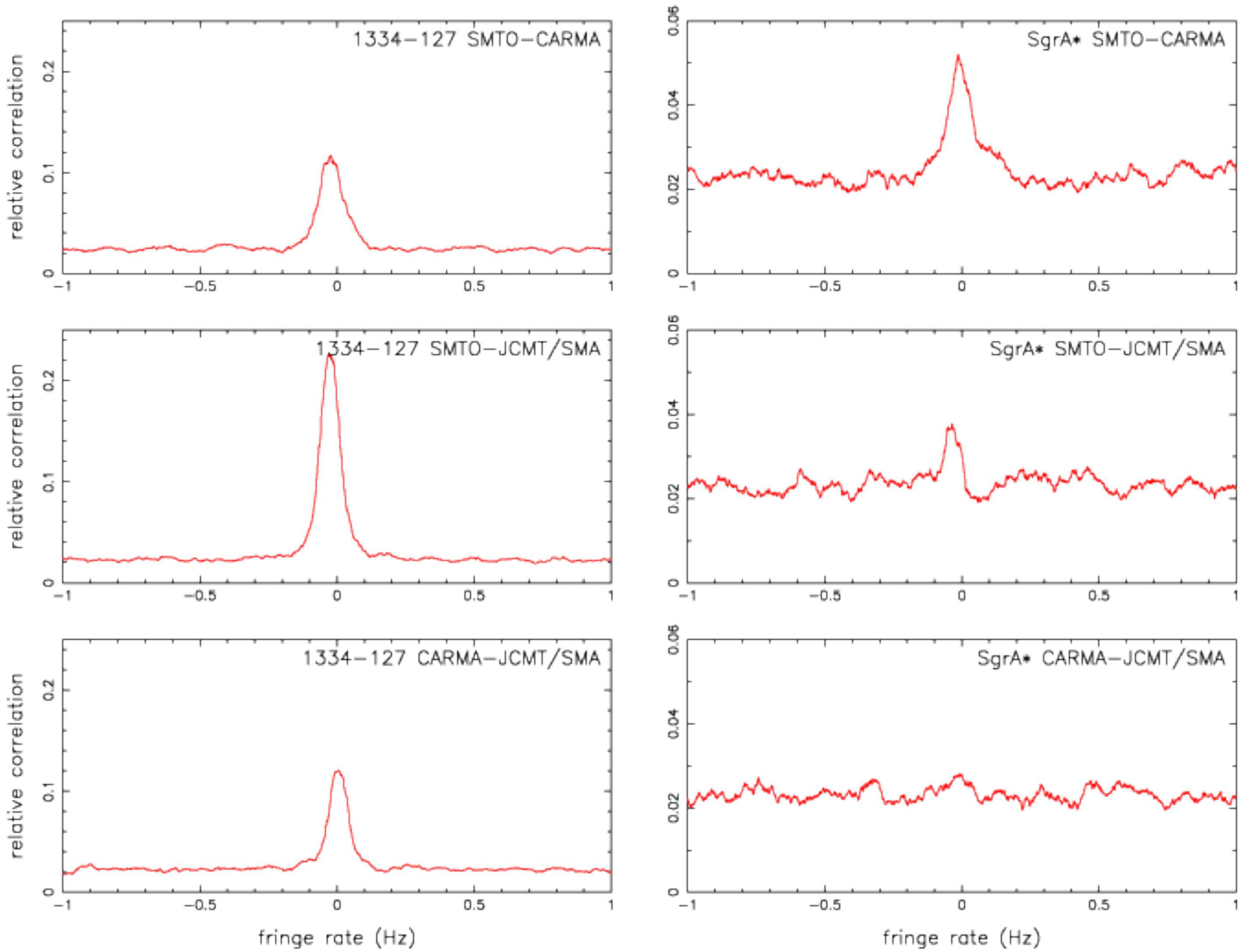
JCMT
15 m single dish
($177\ m^2$)

SMA
eight 6 m dishes
(compact configuration)
($226\ m^2$)

(aggregate area $482\ m^2$
equivalent of 25 m aperture)

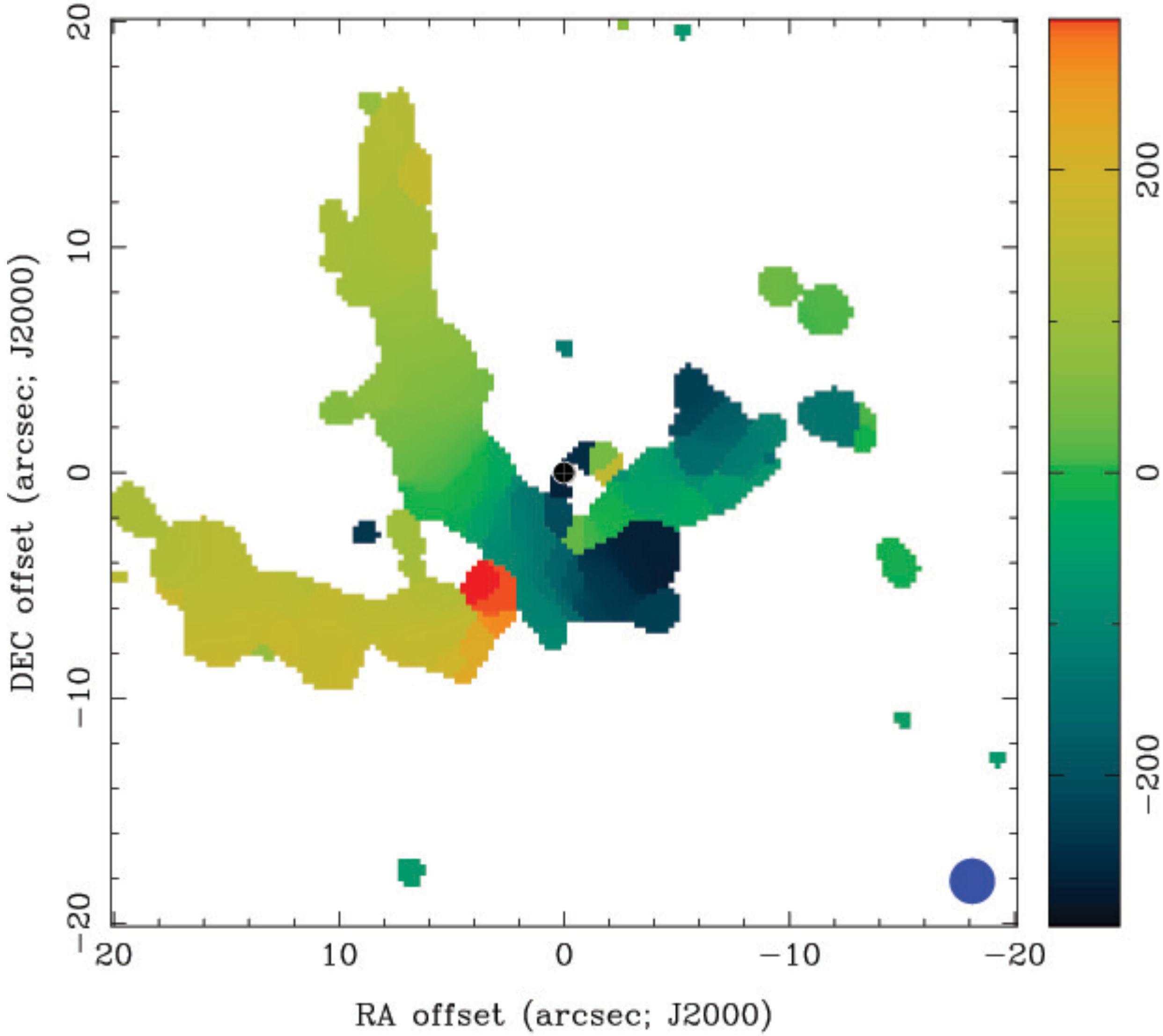


Fringe Amplitude vs Fringe Rate

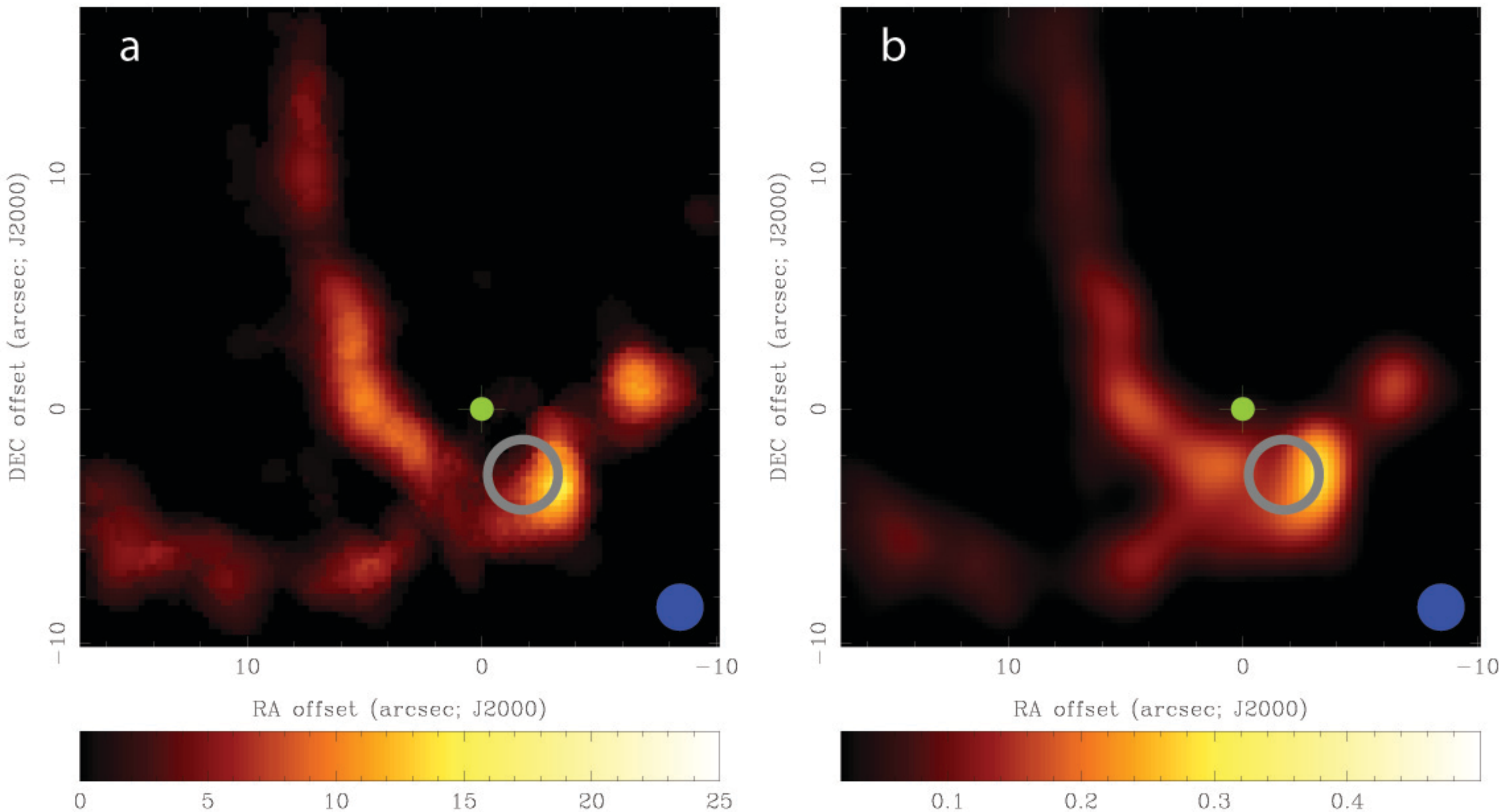


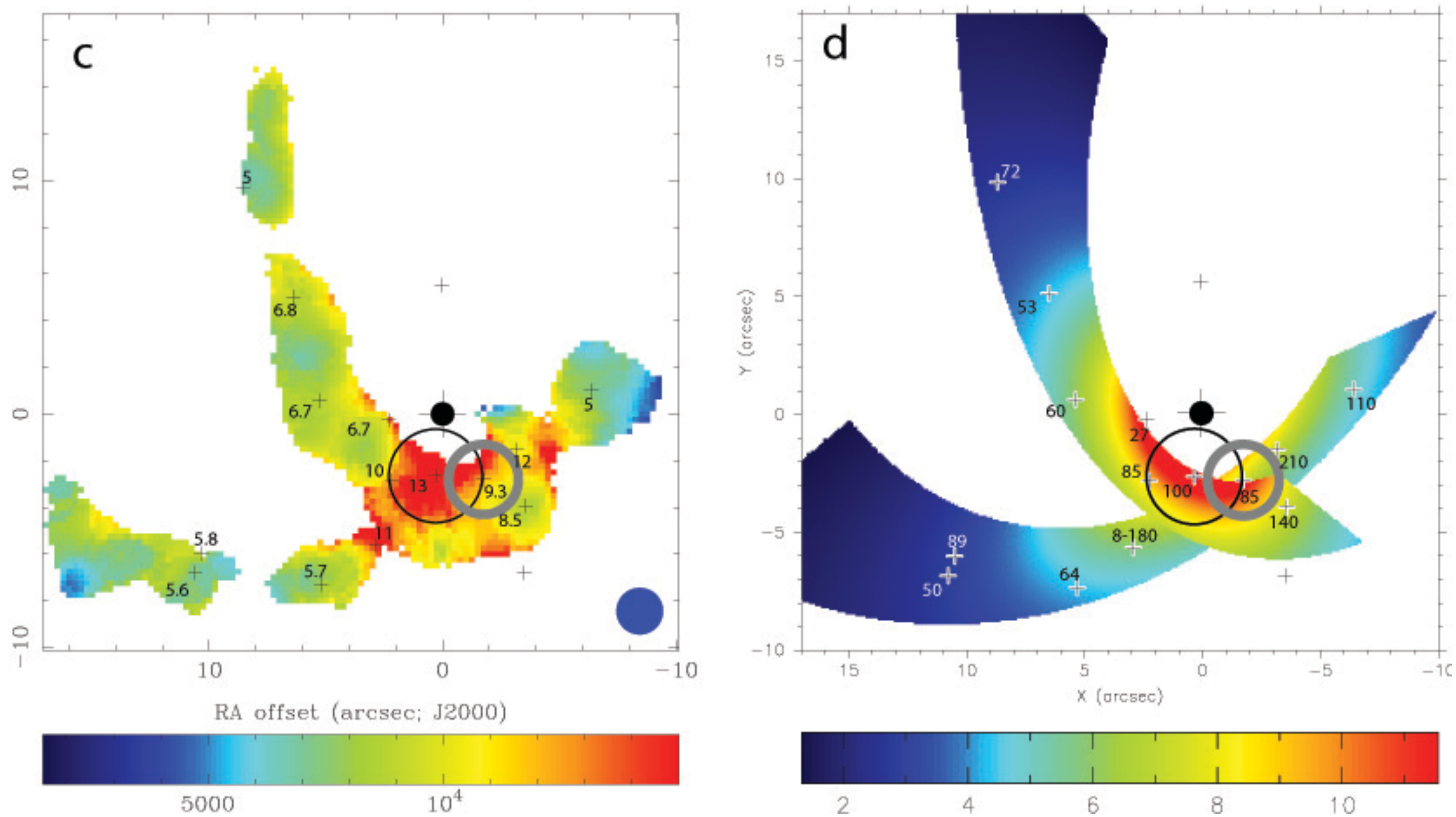
Building an Event Horizon Telescope
Required Technical Developments

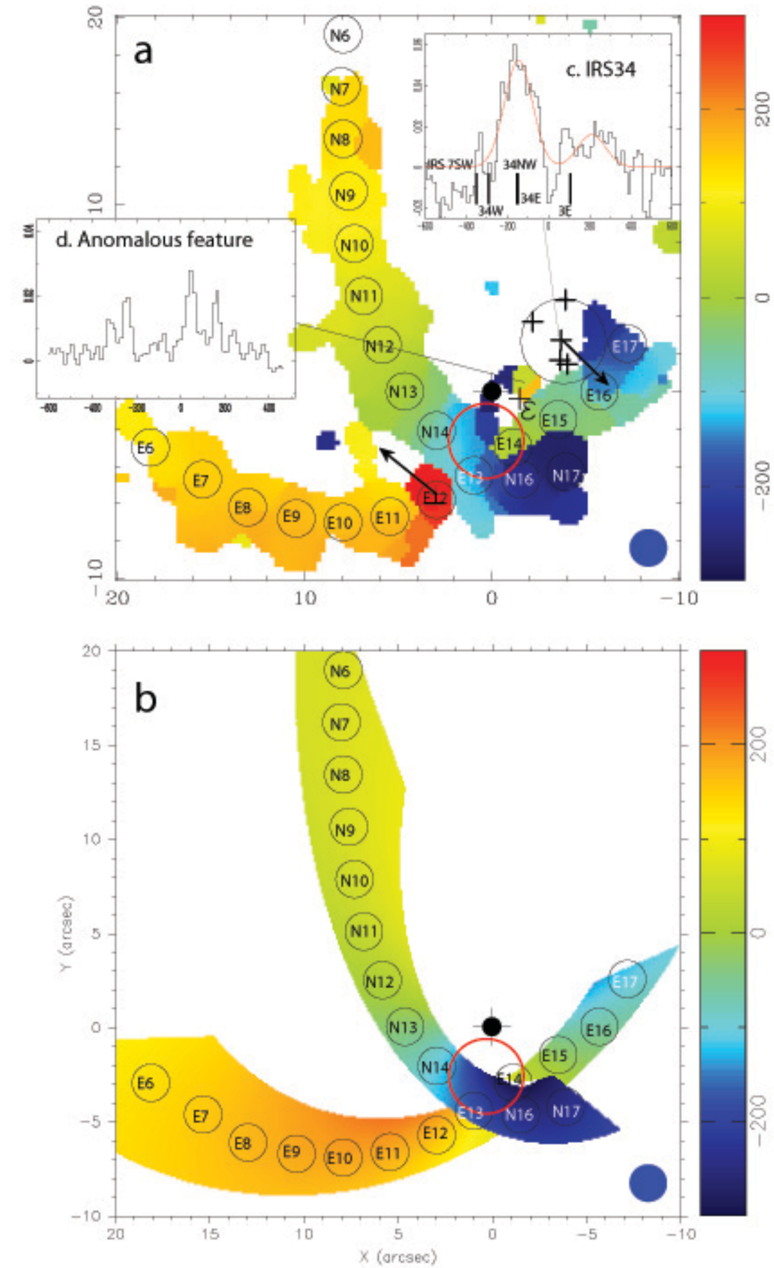
Adding Telescopes: uv coverage, flare coverage, closure quantities for real-time modeling.
Low noise, dual pol receivers for all sites.
Central wideband correlation facility.
VLBI backends/recorders that support > 4Gb/s.
Phased Array processors (ALMA, PdeBure, CARMA, Hawaii)
Low noise freq. references: H-Masers/CSO's

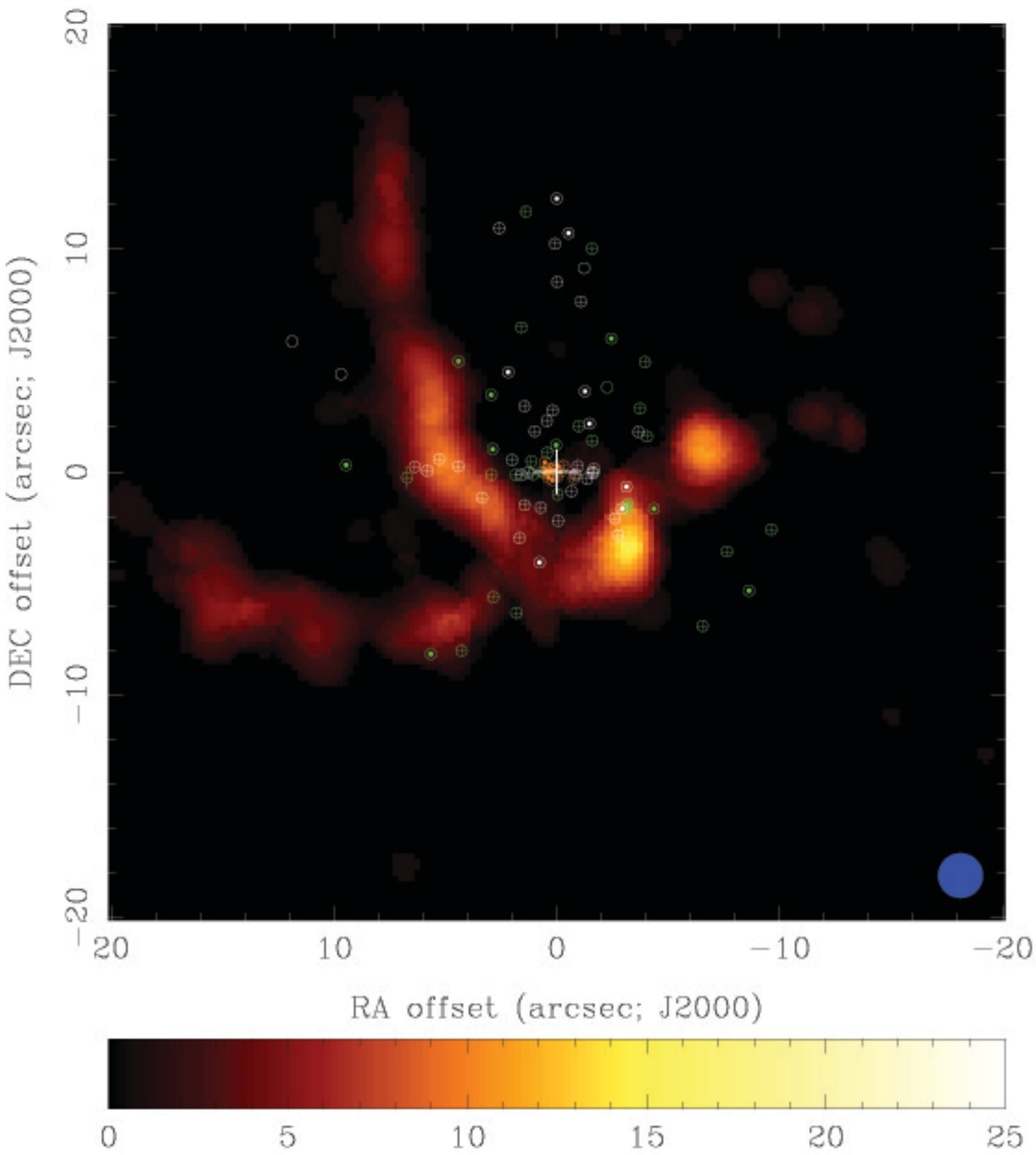


DEC offset (arcsec; J2000)
RA offset (arcsec; J2000)
20
10
0
−10
−20
200
0
−200

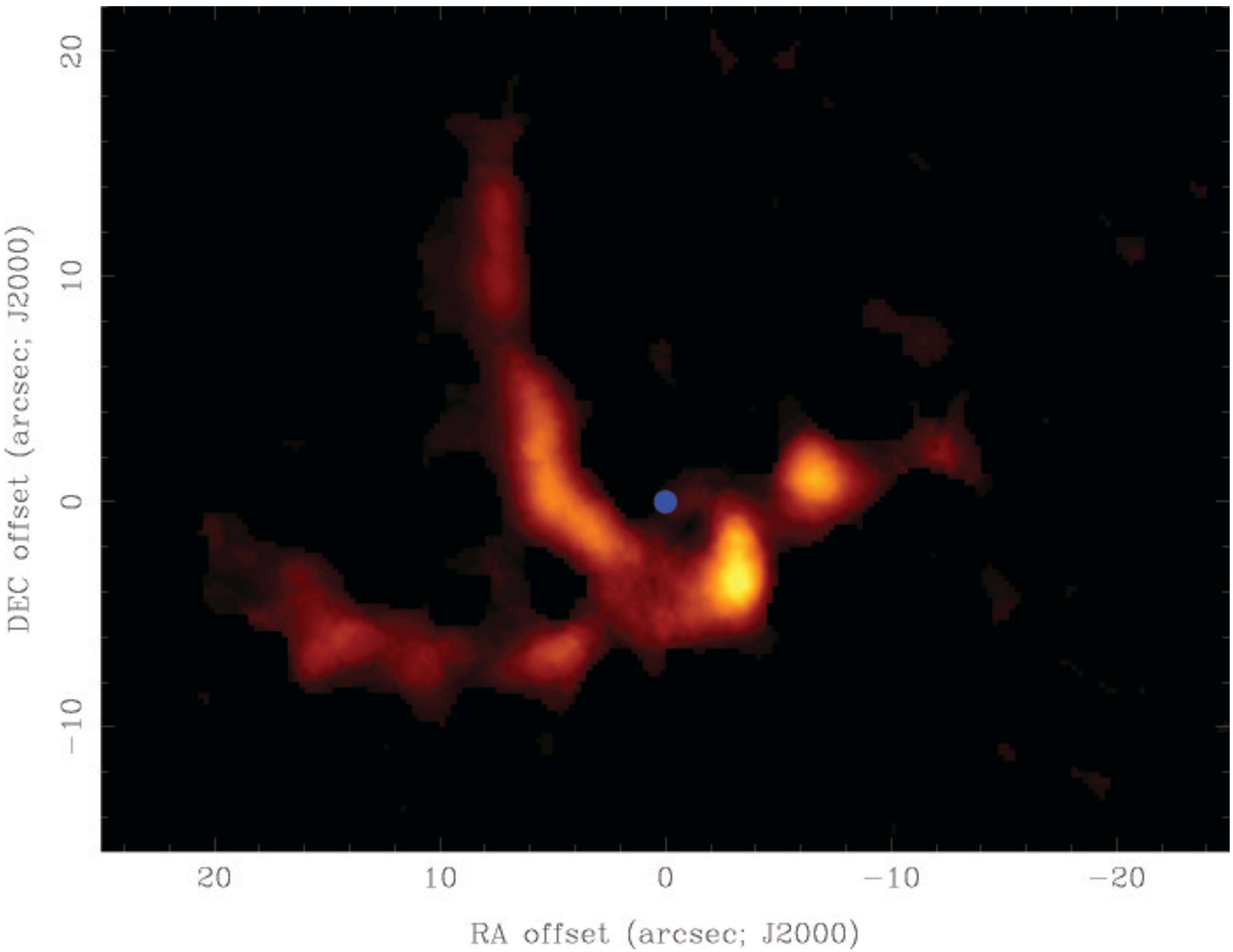

a
b
DEC offset (arcsec; J2000)
RA offset (arcsec; J2000)
10
0
−10
0
5
10
15
20
25
0.1
0.2
0.3
0.4


c
10
0
−10
10
0
−10
RA offset (arcsec; J2000)
5000
10^4
5
6.8
6.7
6.7
10
13
9.3
12
8.5
11
5.8
5.6
5.7
5
d
15
10
5
0
−5
−10
Y (arcsec)
X (arcsec)
72
53
60
27
85
100
85
210
140
110
8-180
89
50
64
2
4
6
8
10

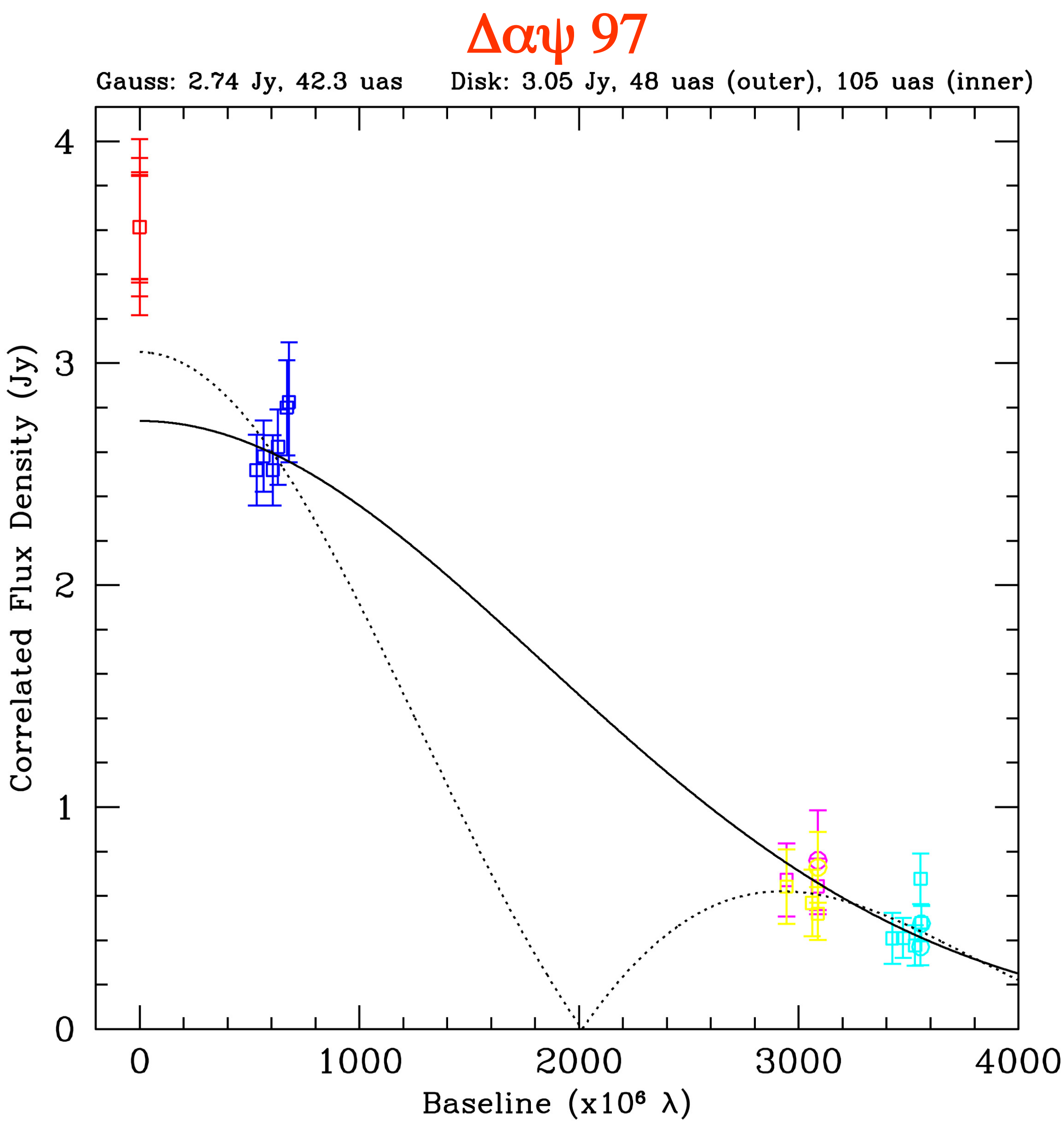

a
b
c. IRS34
d. Anomalous feature
N6
N7
N8
N9
N10
N11
N12
N13
N14
N16
N17
E6
E7
E8
E9
E10
E11
E12
E13
E14
E15
E16
E17
IRS 7SW
34NW
34W
34E
3E
Y (arcsec)
X (arcsec)



DEC offset (arcsec; J2000)
RA offset (arcsec; J2000)
20
10
0
−10
−20
0
5
10
15
20
25

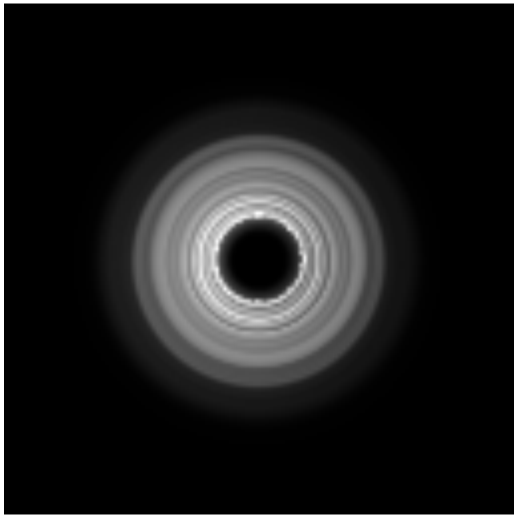


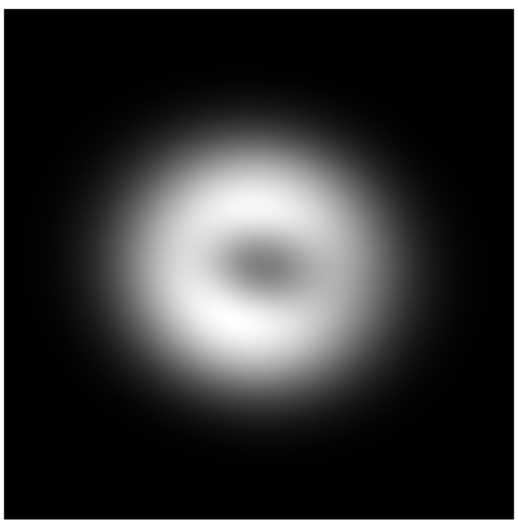
20
10
0
−10
DEC offset (arcsec; J2000)
20
10
0
−10
−20
RA offset (arcsec; J2000)


Δαψ 97
Gauss: 2.74 Jy, 42.3 uas
Disk: 3.05 Jy, 48 uas (outer), 105 uas (inner)
Correlated Flux Density (Jy)
0
1
2
3
4
0
1000
2000
3000
4000
Baseline (x10⁶ λ)

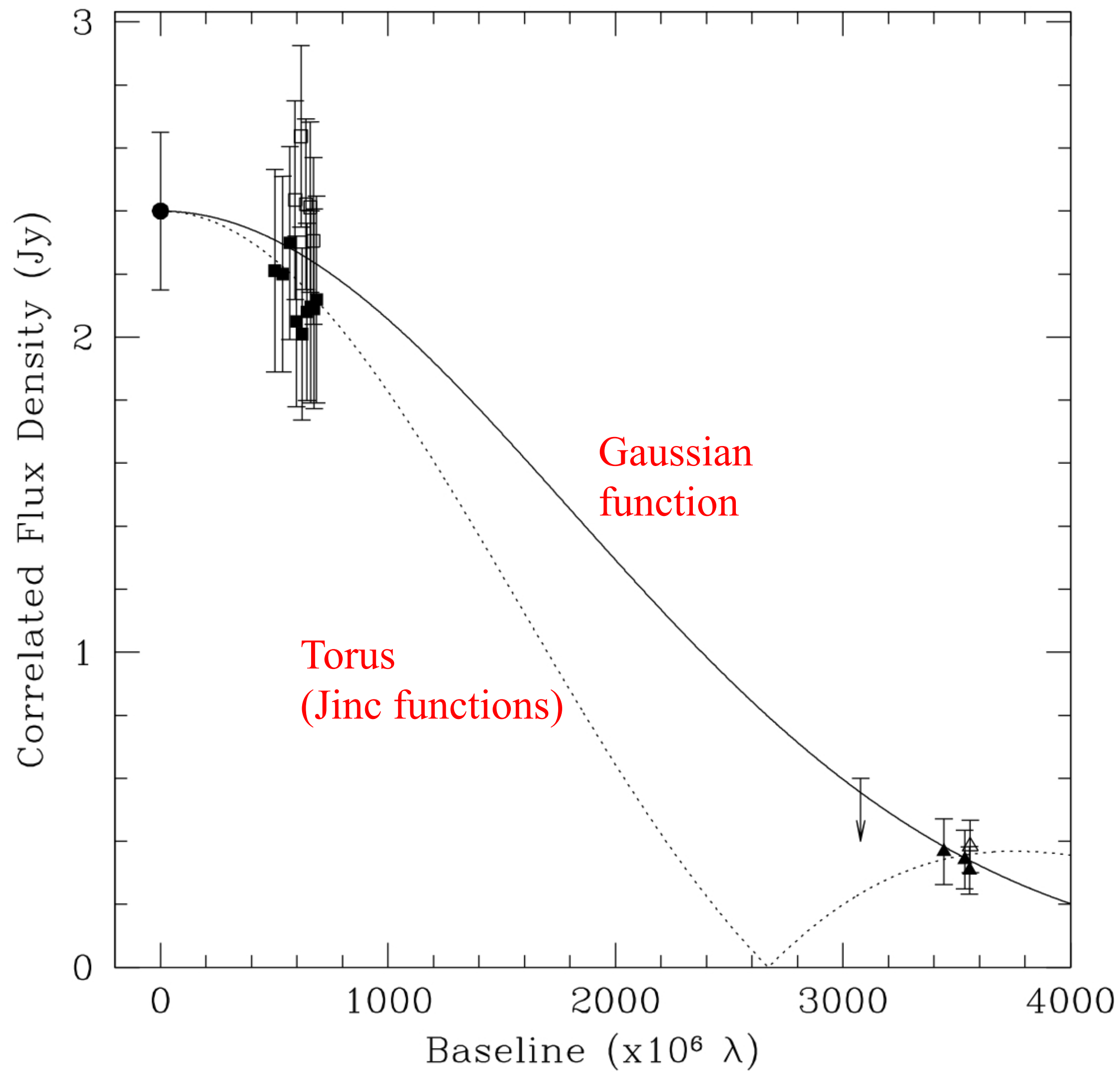
Fits to Visibility Data

14 Rsch (140µas)

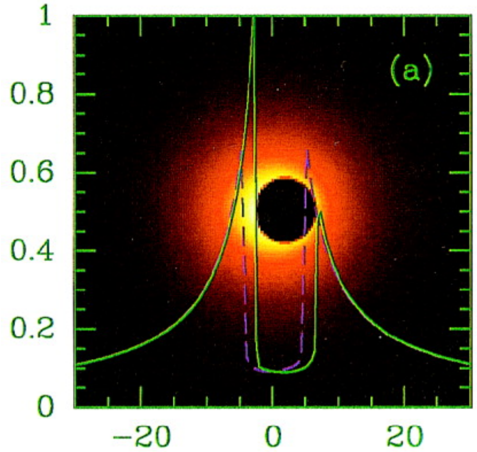




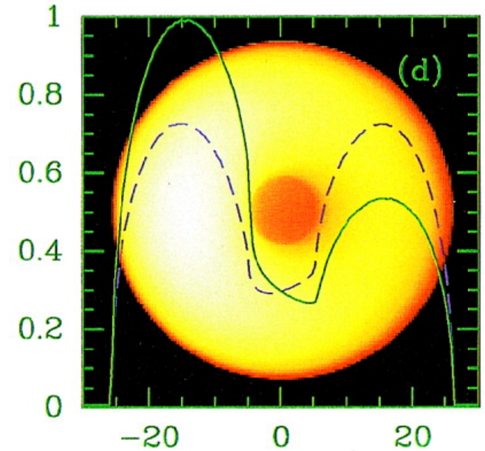
Gammie et al



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

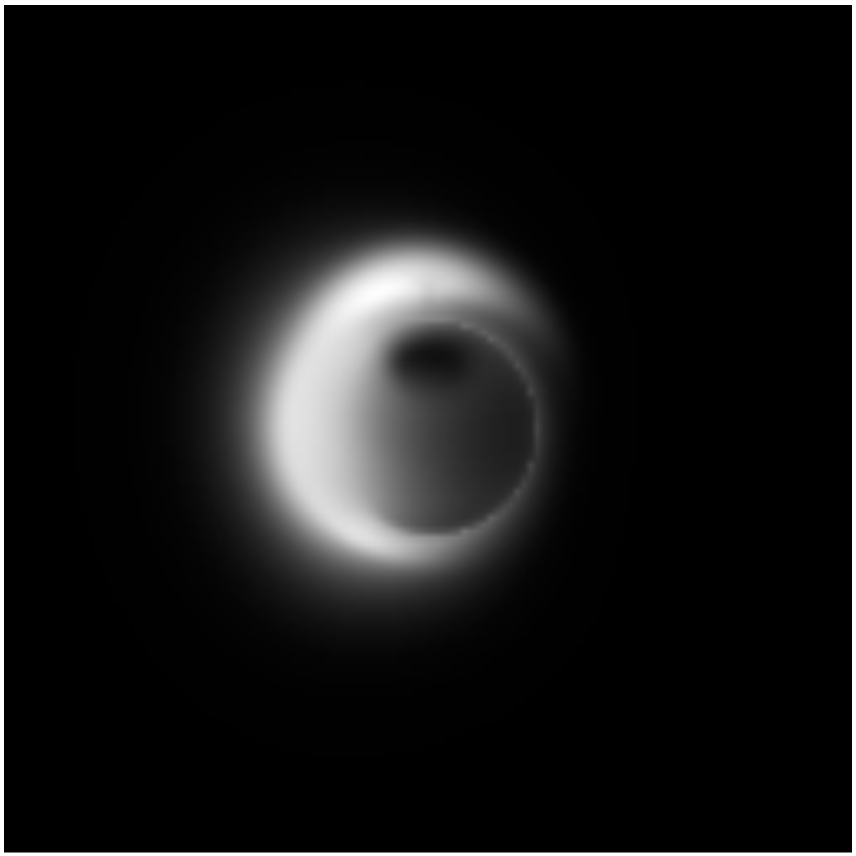
Shadow = 5.2 Rsch (non-spinning)

= 4.5 Rsch (maximally spinning)

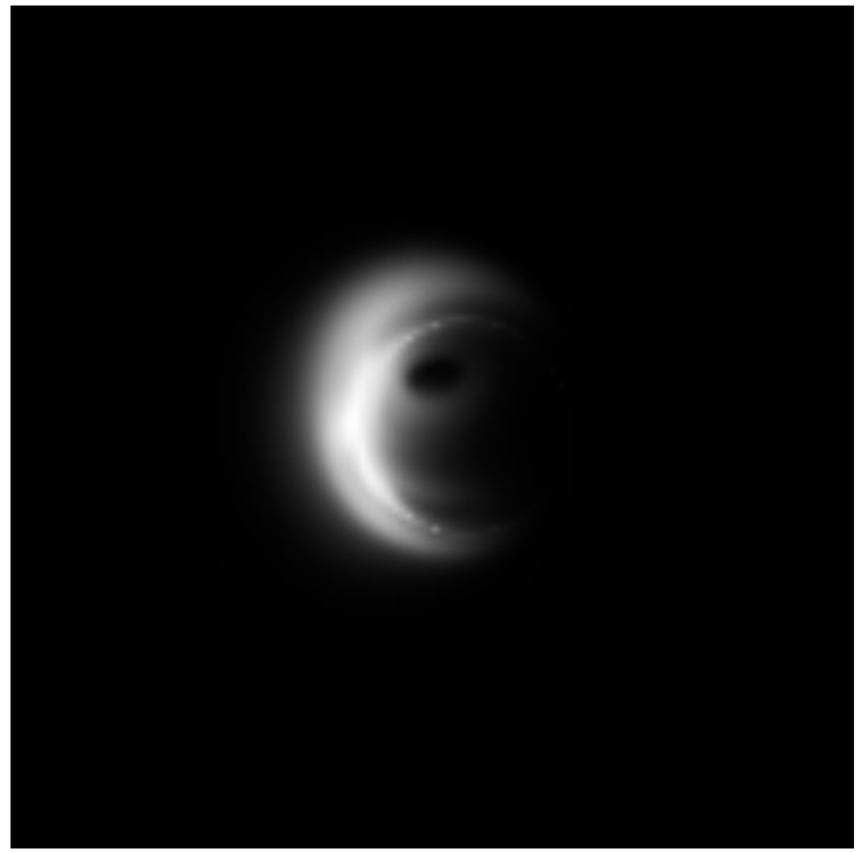
Hot Spot Models (P = 27 min)

230 GHz, ISM scattered

Models: Broderick & Loeb



Spin = 0, orbit = ISCO



Spin = 0.9, orbit = 2.5 x ISCO