Feeding Sgr A*, the Supermassive Black Hole at the Center of our Galaxy

Thanks to James M. Moran

Luis F. Rodríguez
Centro de Radioastronomía y Astrofísica, UNAM and
El Colegio Nacional

Summary

- Astronomical black holes
- Sgr A*: the supermassive black hole at the center of the Milky Way (our Galaxy)
- Images of the “shadow”
- Waiting for G2

Types of Astronomical Black Holes

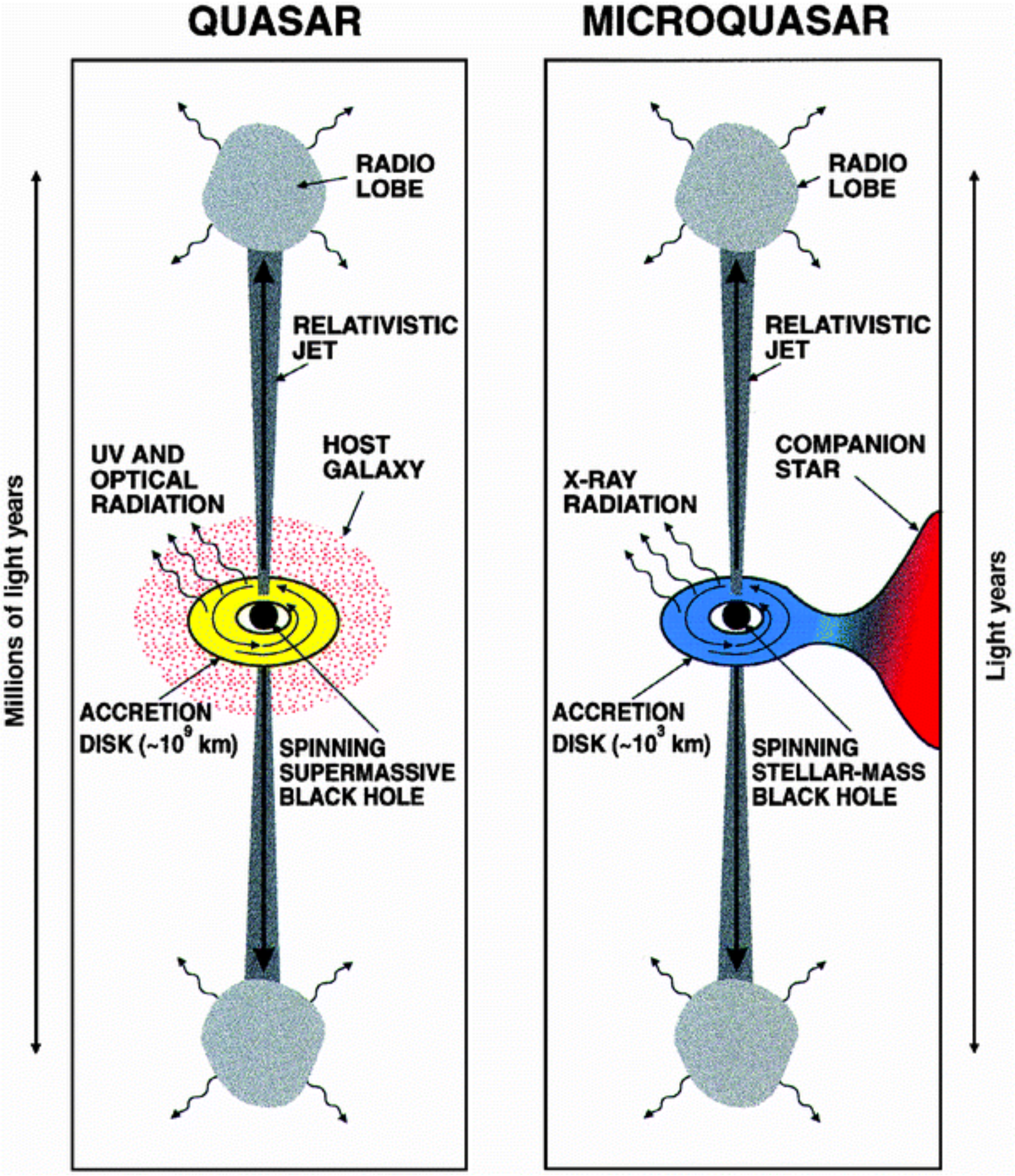
1. “stellar” sized black holes found through the galaxy in binary stellar systems,

   $M \sim 3\text{-}10 \quad M_{sun}$

2. “supermassive” black holes (SMBHs) found in the centers of most galaxies,

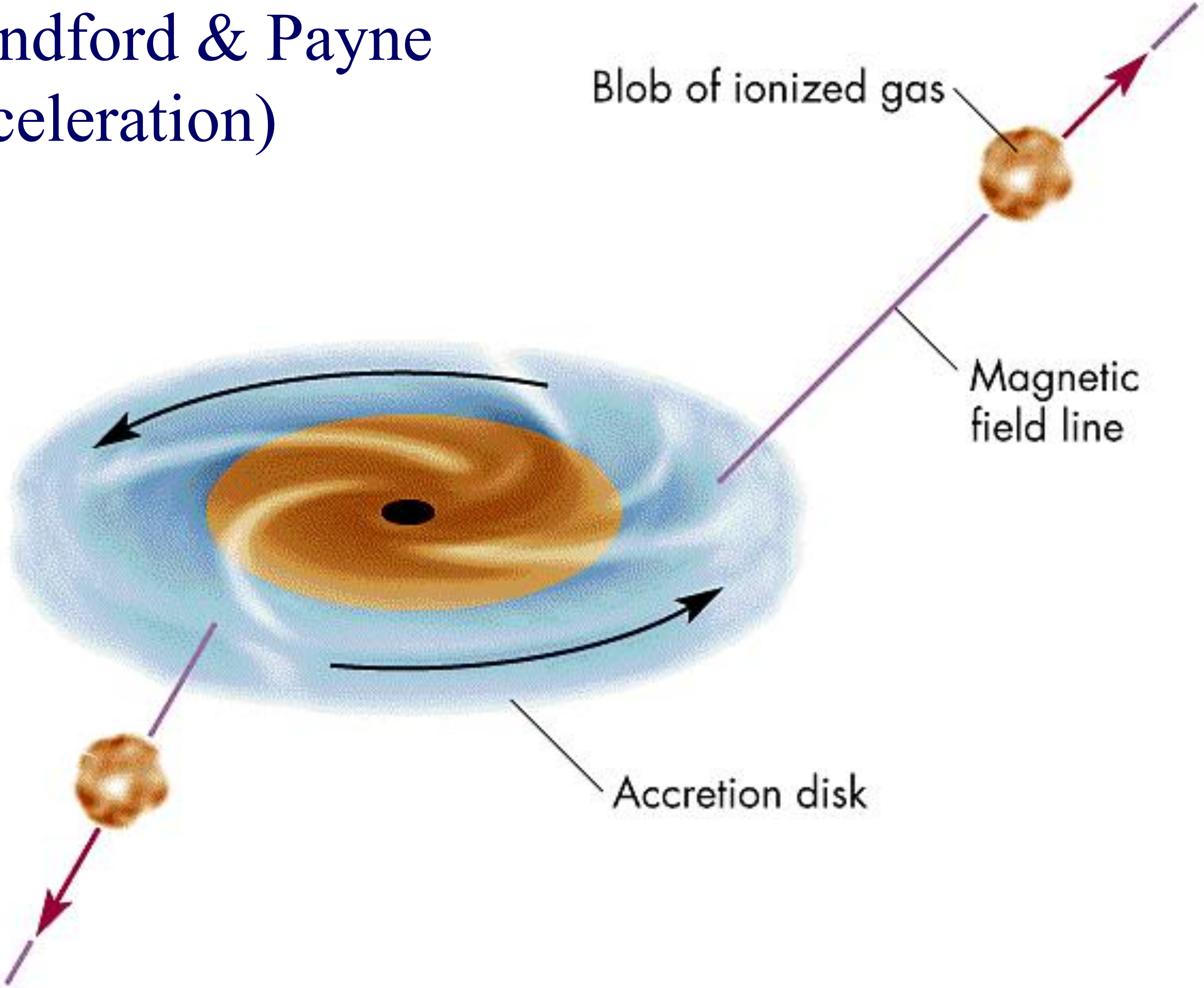
   $M \sim 10^{6\text{-}9}\ M_{sun}$

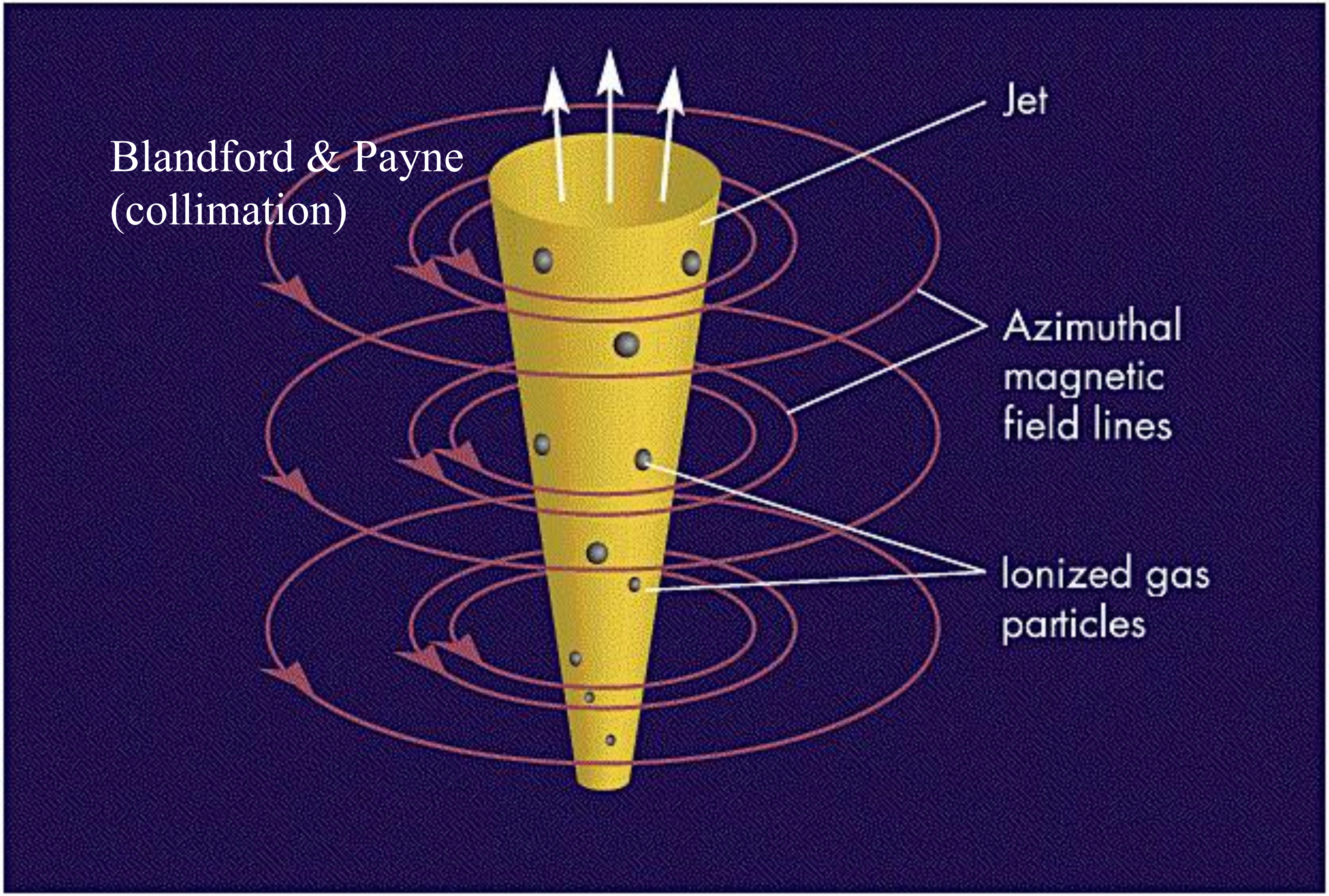
Some evidence for the existence of intermediate mass black holes



Black hole, accretion disk and relativistic jets common to both types of systems (Mirabel & Rodríguez 1998)

Blandford & Payne (acceleration)



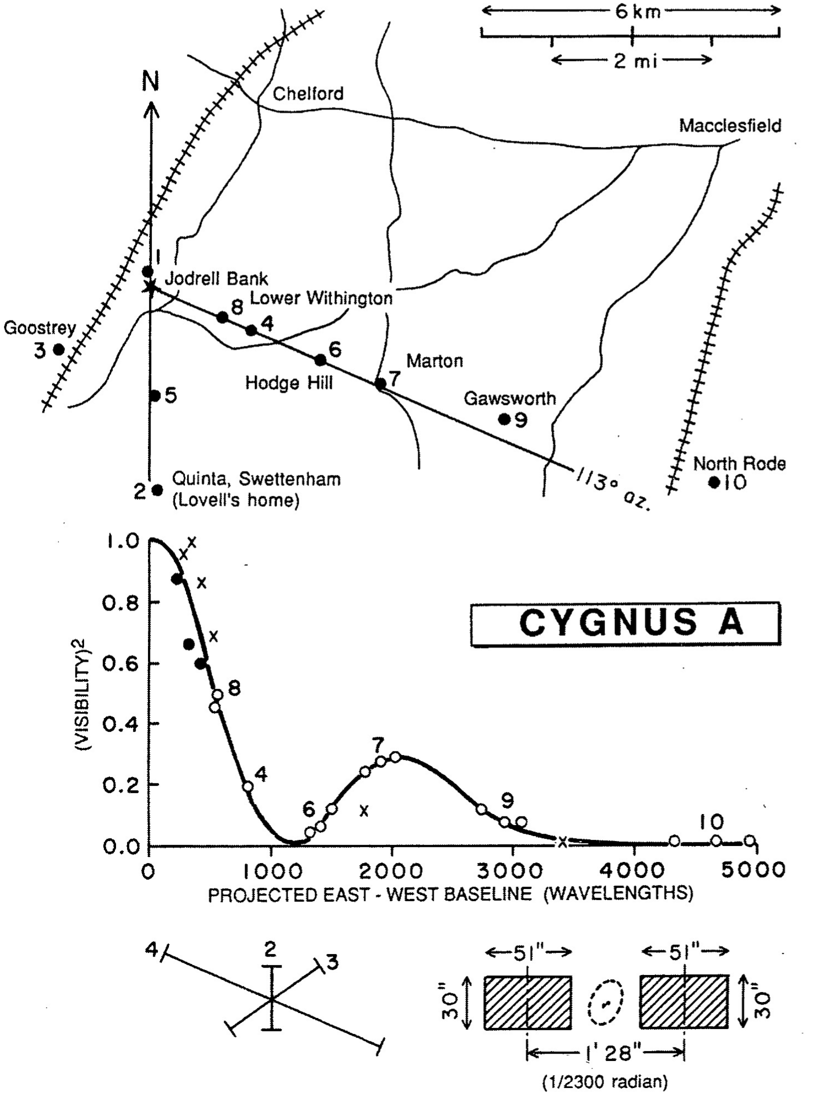


Blandford & Payne
(collimation)

Hercules A in optical and radio

Jets detectable in the radio (synchrotron emission)

Observations of Cygnus A with the Jodrell Bank Intensity Interferometer



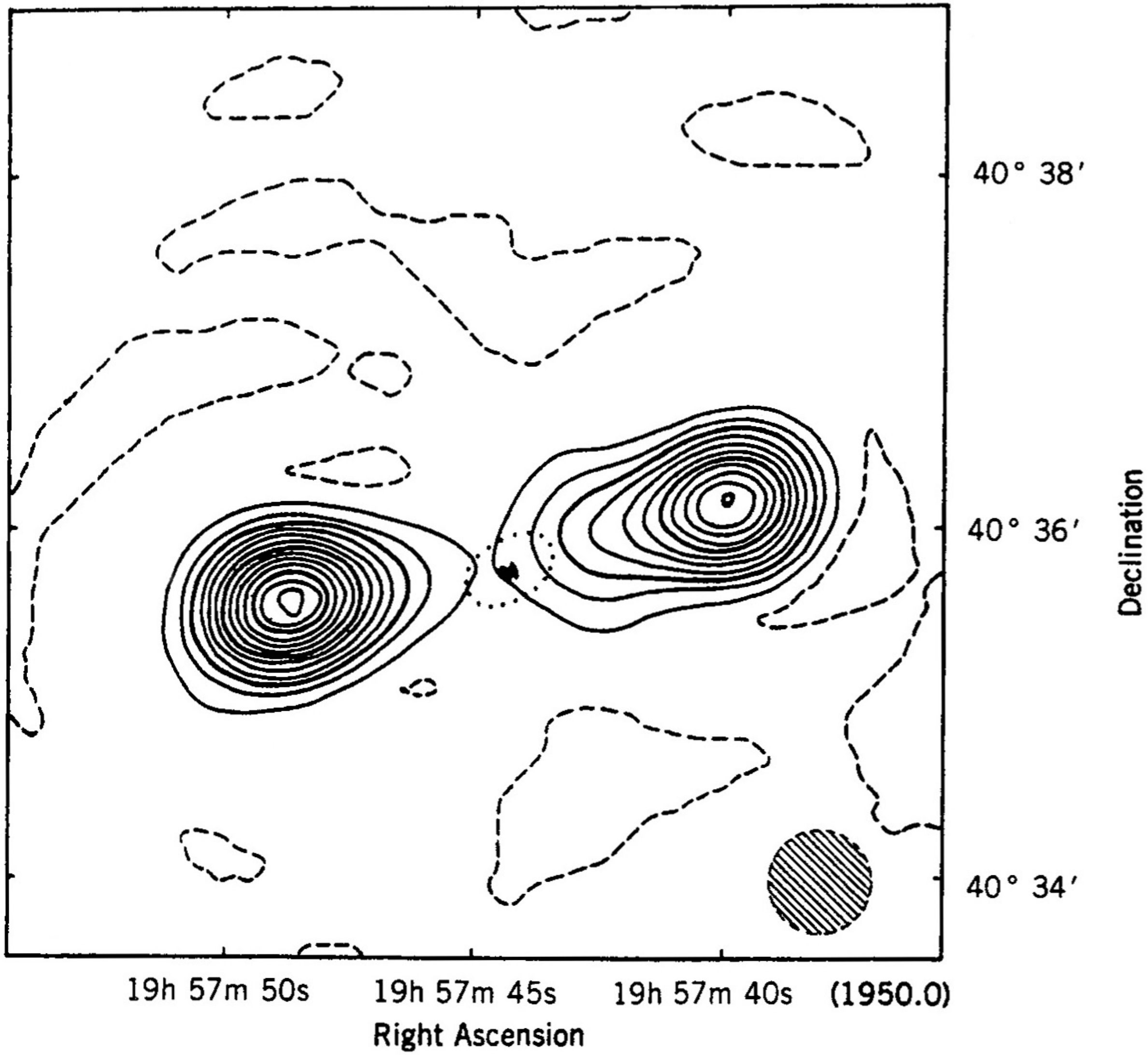
Square of visibility
125 MHz

Jennison and Das Gupta 1952; see also Sullivan 2010

Cygnus A with Cambridge 1-mile Telescope at 1.4 GHz

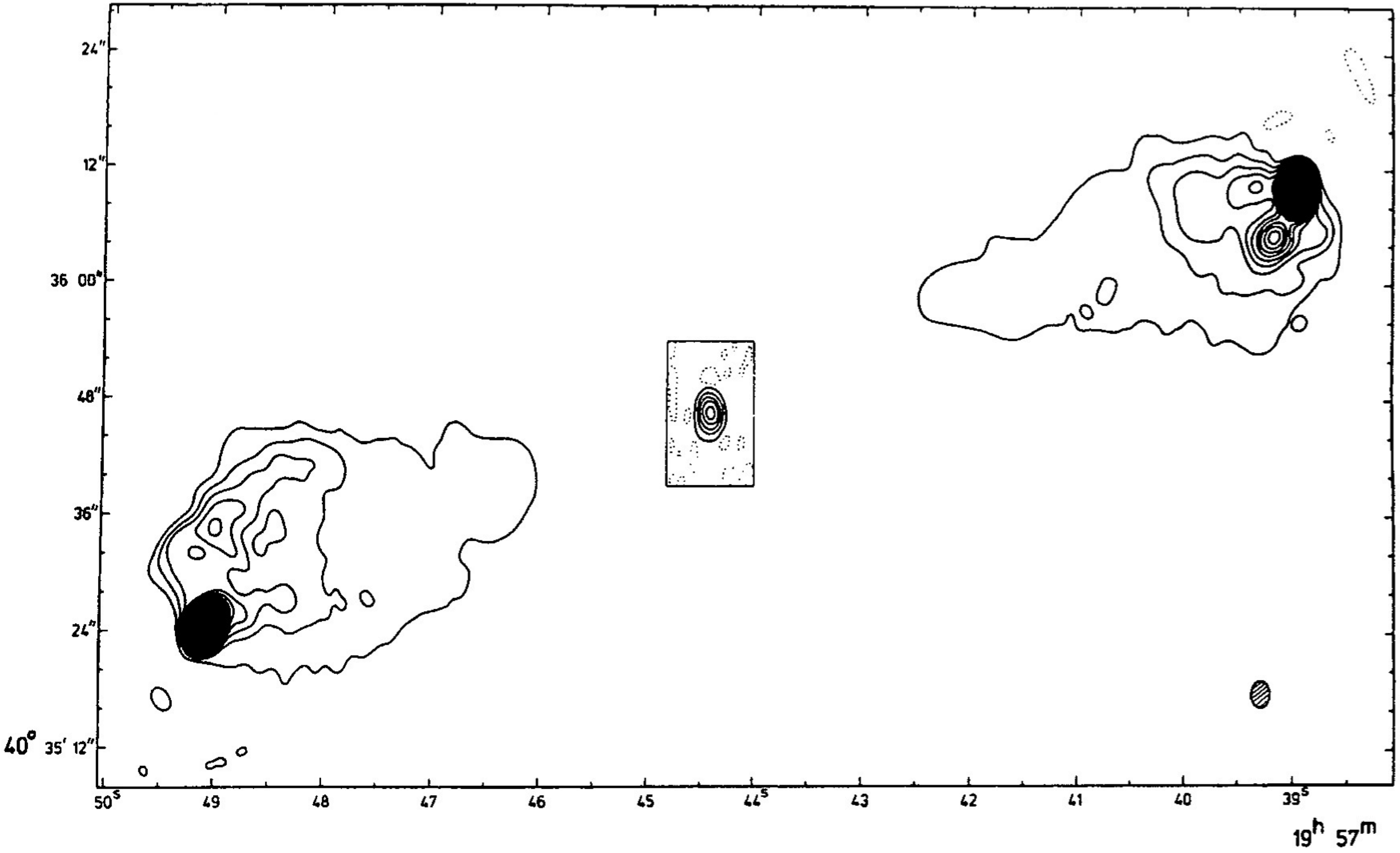
3 telescopes

20 arcsec
resolution



Ryle, Elsmore, and Neville, *Nature*, 205, 1259, 1965

Cygnus A with Cambridge 5 km Interferometer at 5 GHz

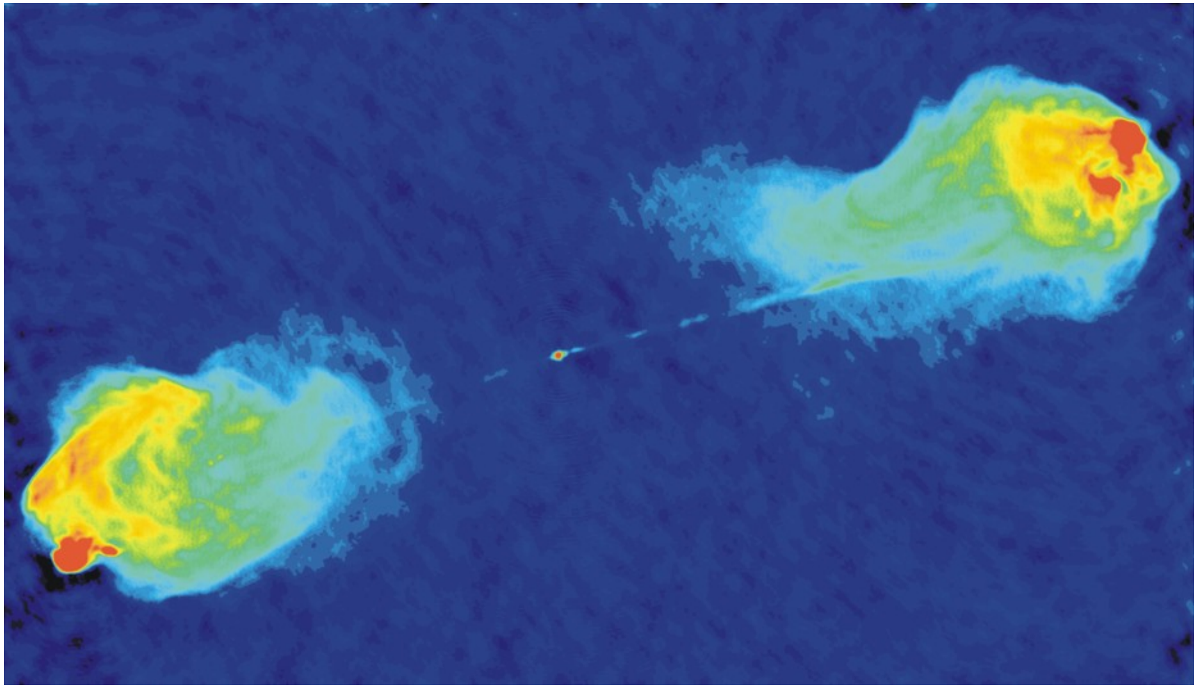


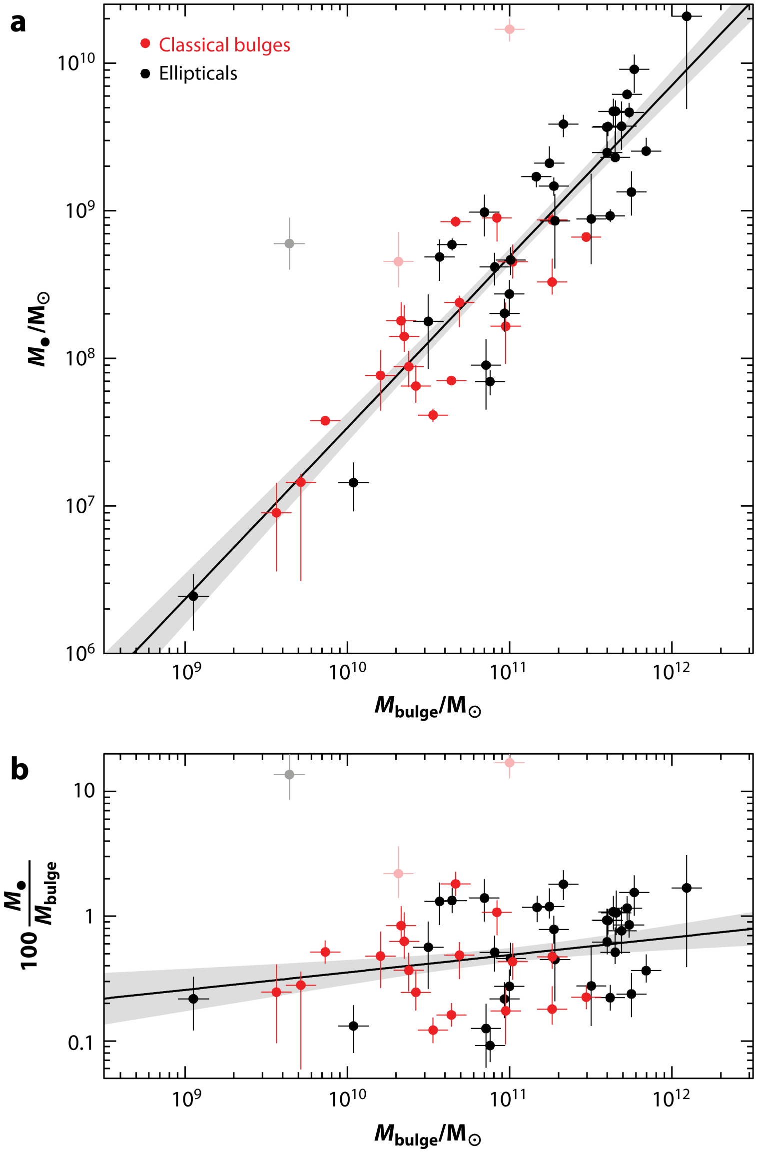
16 element E-W Array, 3 arcsec resolution

Hargrave and Ryle, *MNRAS*, 166, 305, 1974

The Very Large Array in D Configuration, Socorro, New Mexico

Synchrotron emission from Cygnus A (VLA at 6 cm)





Kormendy J, Ho LC. 2013.
Annu. Rev. Astron. Astrophys. 51:511–653

Do all galaxies have supermassive black holes at their centers?

Apparently yes, and furthermore there is a correlation between the mass of the black hole and that of the elliptical galaxy or bulge where it resides.

This suggests a poorly understood co-evolution between both objects.

Kormendy & Lo (2013)

Our galaxy, the Milky Way, also has a “starved” supermassive black hole at its center: Sgr A*

THE ASTROPHYSICAL JOURNAL, **194**:265–270, 1974 December 1

INTENSE SUB-ARCSECOND STRUCTURE IN THE GALACTIC CENTER

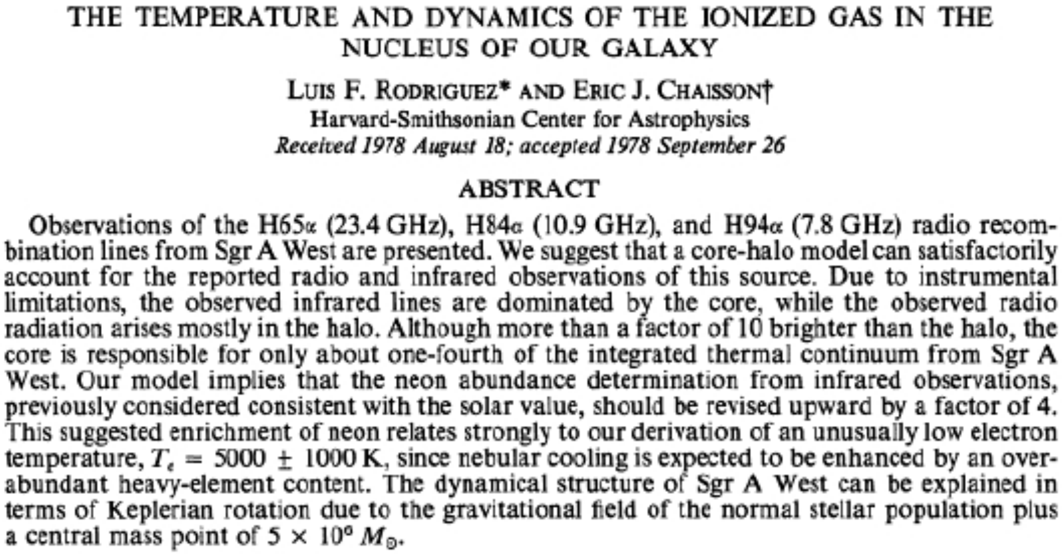
BRUCE BALICK
Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz
AND
ROBERT L. BROWN
National Radio Astronomy Observatory*

Received 1974 June 3

ABSTRACT

The detection of strong radio emission in the direction of the inner 1-pc core of the galactic nucleus is reported. The structure is bright (brightness temperature $\gtrsim 10^7$ ° K), unresolved ($\theta \lesssim 0\overset{''}{.}1$), and distributed within a few seconds of the brightest infrared and radio emission seen previously.

Subject headings: galactic nuclei — radio sources



THE TEMPERATURE AND DYNAMICS OF THE IONIZED GAS IN THE NUCLEUS OF OUR GALAXY

LUIS F. RODRIGUEZ* AND ERIC J. CHAISSON†
Harvard-Smithsonian Center for Astrophysics

Received 1978 August 18; accepted 1978 September 26

ABSTRACT

Observations of the H65α (23.4 GHz), H84α (10.9 GHz), and H94α (7.8 GHz) radio recombination lines from Sgr A West are presented. We suggest that a core-halo model can satisfactorily account for the reported radio and infrared observations of this source. Due to instrumental limitations, the observed infrared lines are dominated by the core, while the observed radio radiation arises mostly in the halo. Although more than a factor of 10 brighter than the halo, the core is responsible for only about one-fourth of the integrated thermal continuum from Sgr A West. Our model implies that the neon abundance determination from infrared observations, previously considered consistent with the solar value, should be revised upward by a factor of 4. This suggested enrichment of neon relates strongly to our derivation of an unusually low electron temperature, $T_e = 5000 \pm 1000$ K, since nebular cooling is expected to be enhanced by an overabundant heavy-element content. The dynamical structure of Sgr A West can be explained in terms of Keplerian rotation due to the gravitational field of the normal stellar population plus a central mass point of $5 \times 10^6\ M_\odot$.

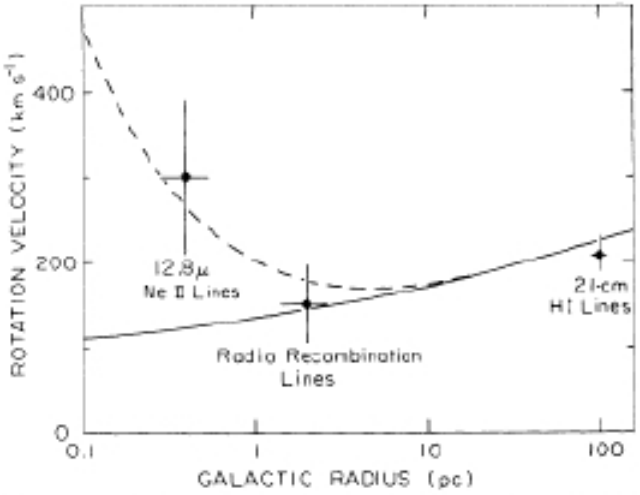


FIG. 4.—A tentative rotation curve for the galactic nucleus. *Solid curve*, model having normal stellar population; *dashed curve*, model having the same normal stellar population plus a mass point of $5 \times 10^6\ M_\odot$. Error bars are estimated to be twice the standard deviation.

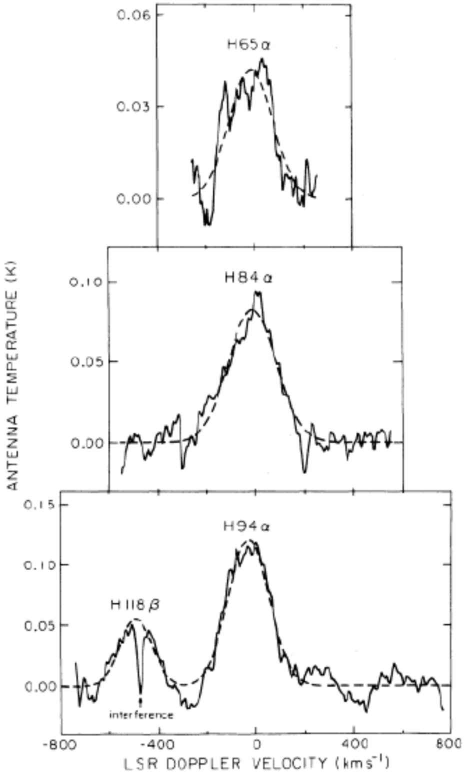
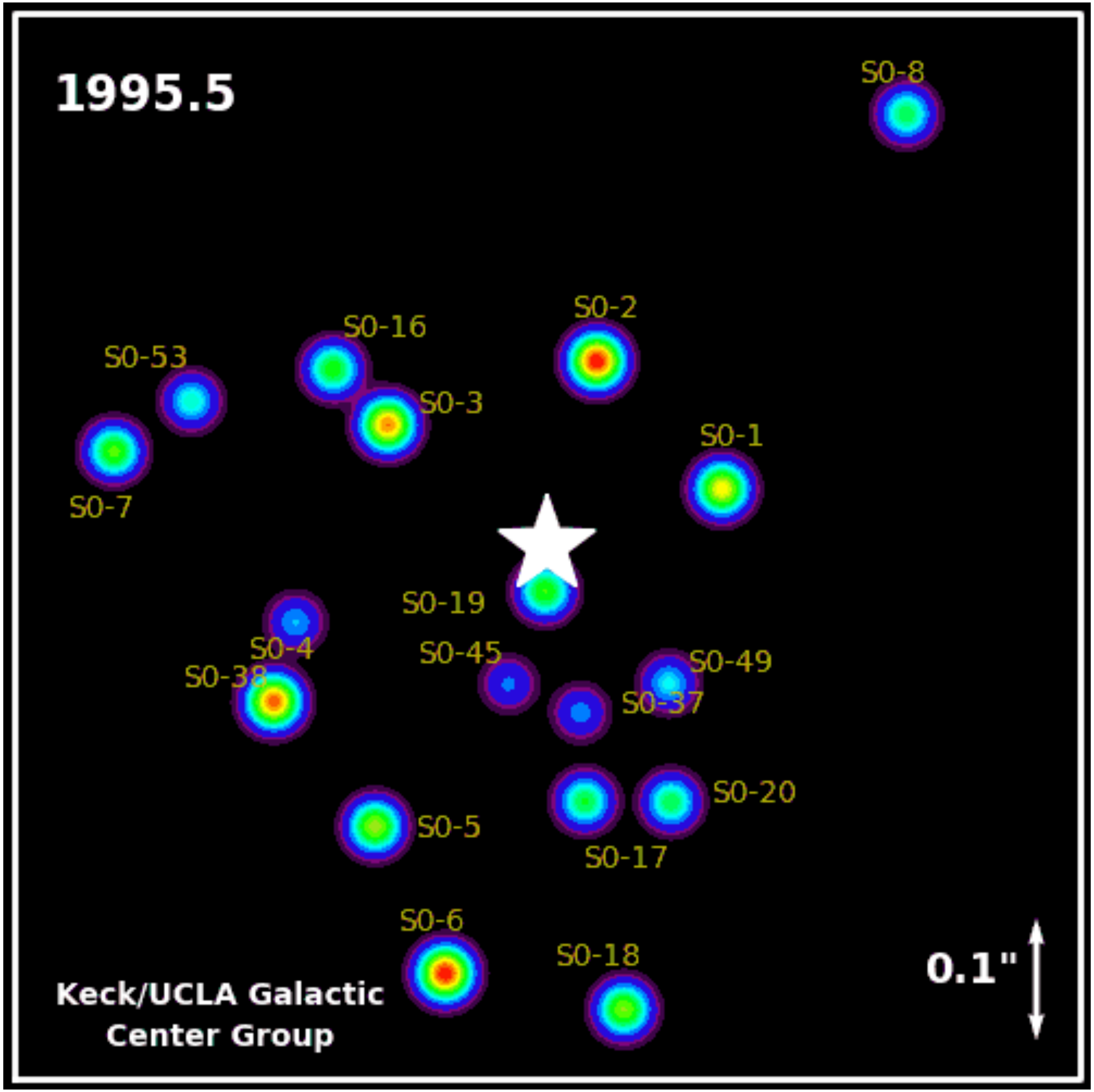


FIG. 1.—H65α, H84α, and H94α spectra observed in the direction of Sgr A West. *Solid curve*, data; *dashed curve*, suggested least-squares fit. The autocorrelator sampling rate for each spectrum was 100 MHz.

"…the gravitational field of the normal stellar population plus a central mass point of 5 million solar masses."

However, gas motions can be altered by several mechanisms, so this was not widely accepted.

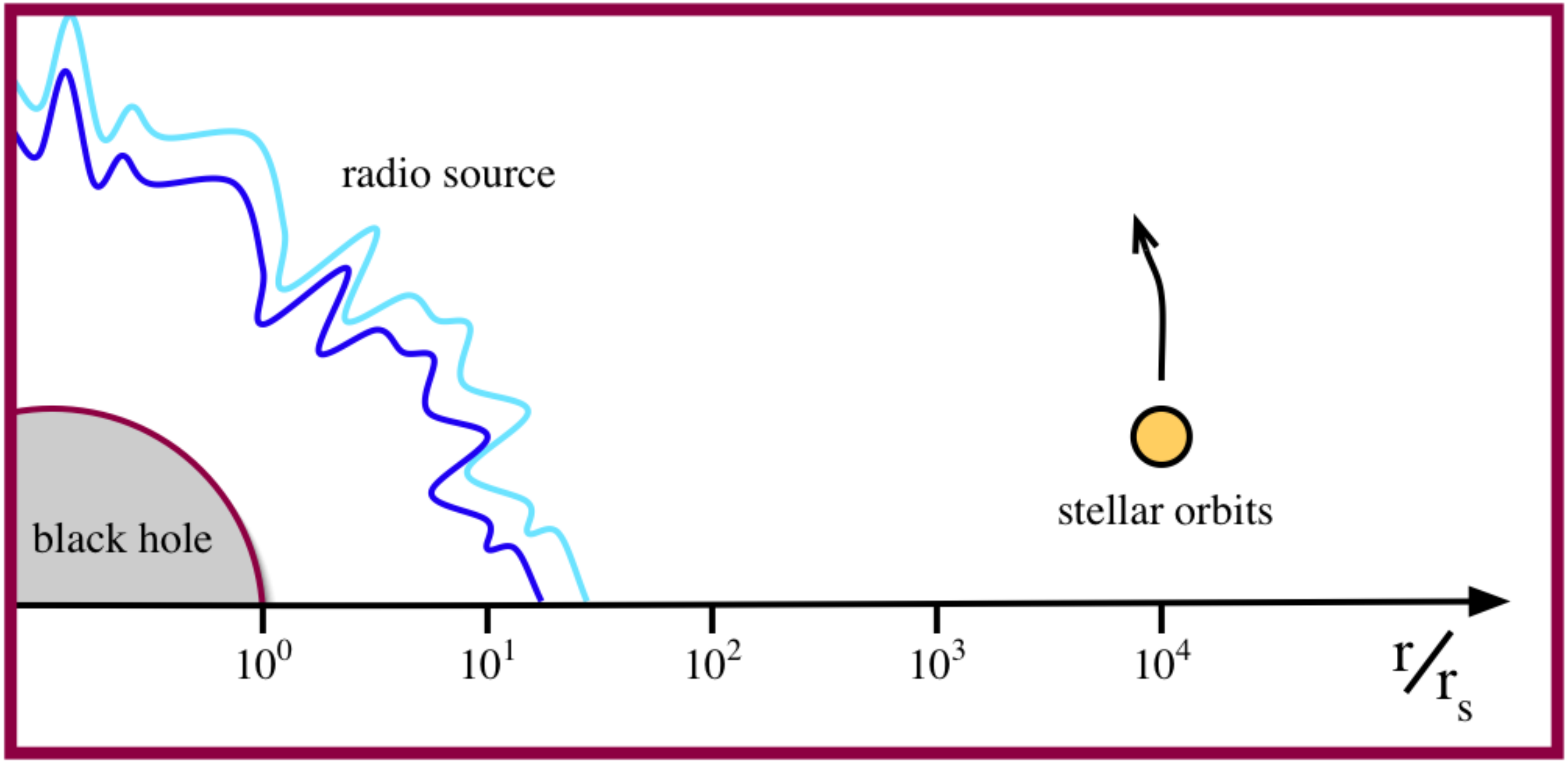


Infrared observations with high angular resolution (laser guide star adaptive optics).

Ghez et al.

Genzel et al.

Some Scales at the Galactic Center

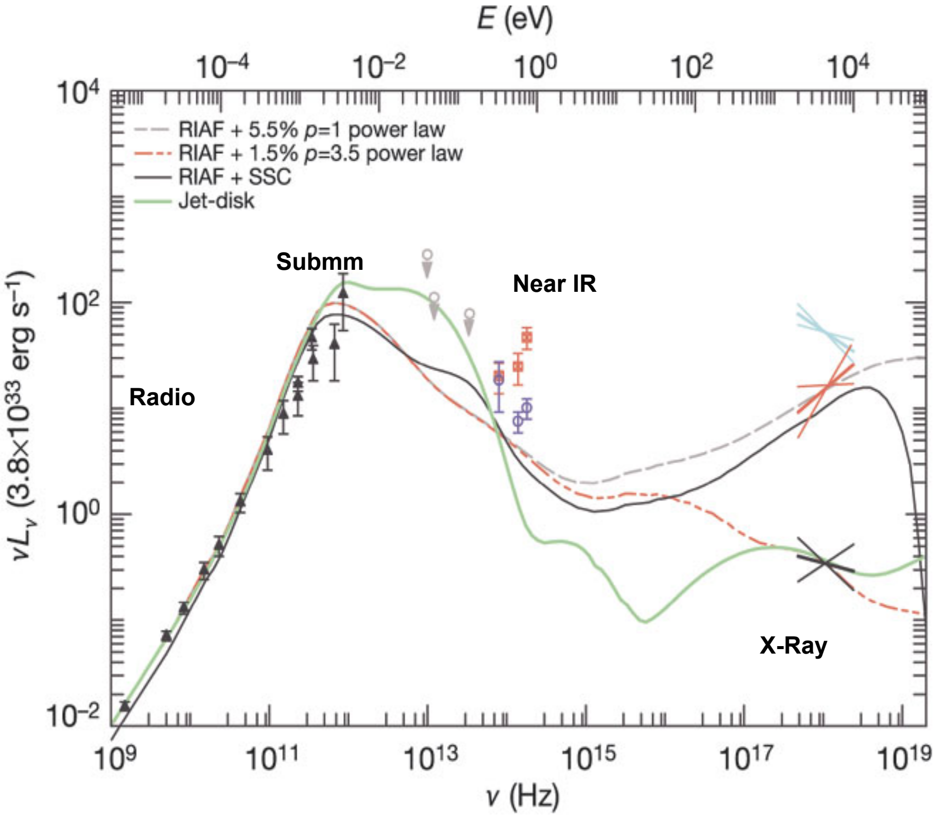


$r_s = 10^{12} cm = 8 \mu as$

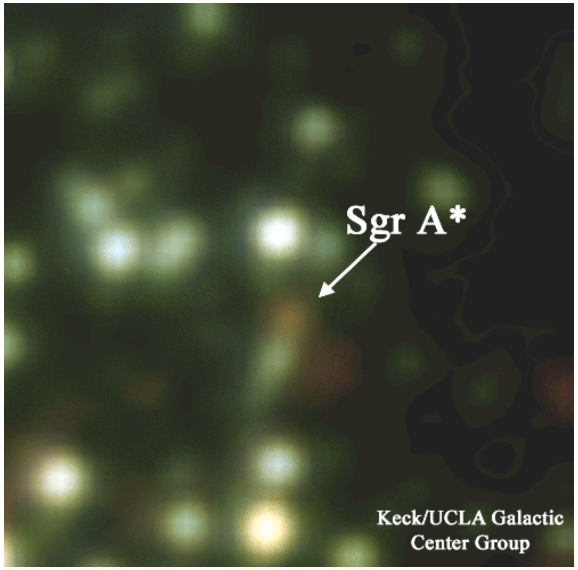
$$r_s = 1.3 \times 10^{12}\text{cm (for } 4.3 \times 10^6 \text{ solar masses)} \;\; = 10\mu\text{as at } 8.3 \text{ kpc}$$

Luminosity ~ 300 L_{Sun} or 10^{-9} Eddington ("starved" black hole)

- Sgr A* is a relatively weak source but can be detected at several astronomical bands
  - The measured spectrum covers 10 decades in frecuency
- $L_{SgrA*} \sim 300\ L_{Sun} \sim 10^{-9}$ *Eddington limit*



Genzel et al. 2004

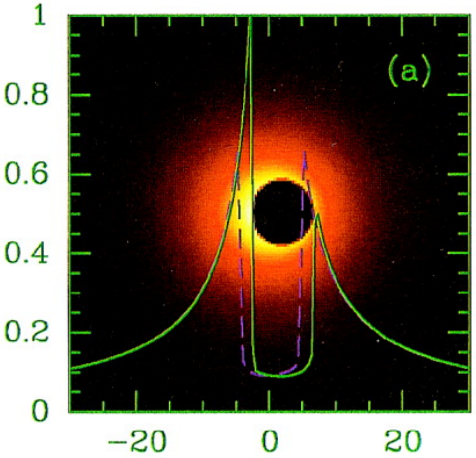


IR flare (Hornstein et al. 2007)

Black Hole “image” Dominated by GR

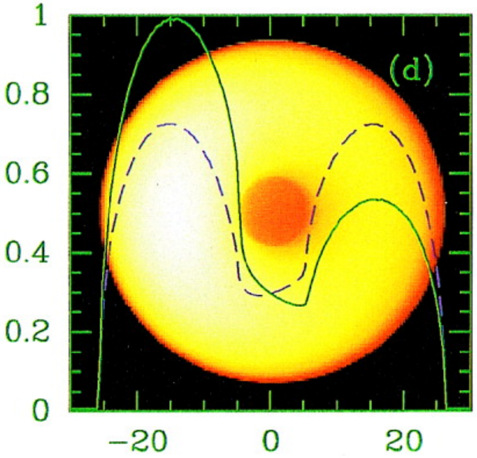
The black hole “shadow”

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



Maximally spinning BH
Free fall envelope

$D_{shadow} = 9/2 * R_{sch}$



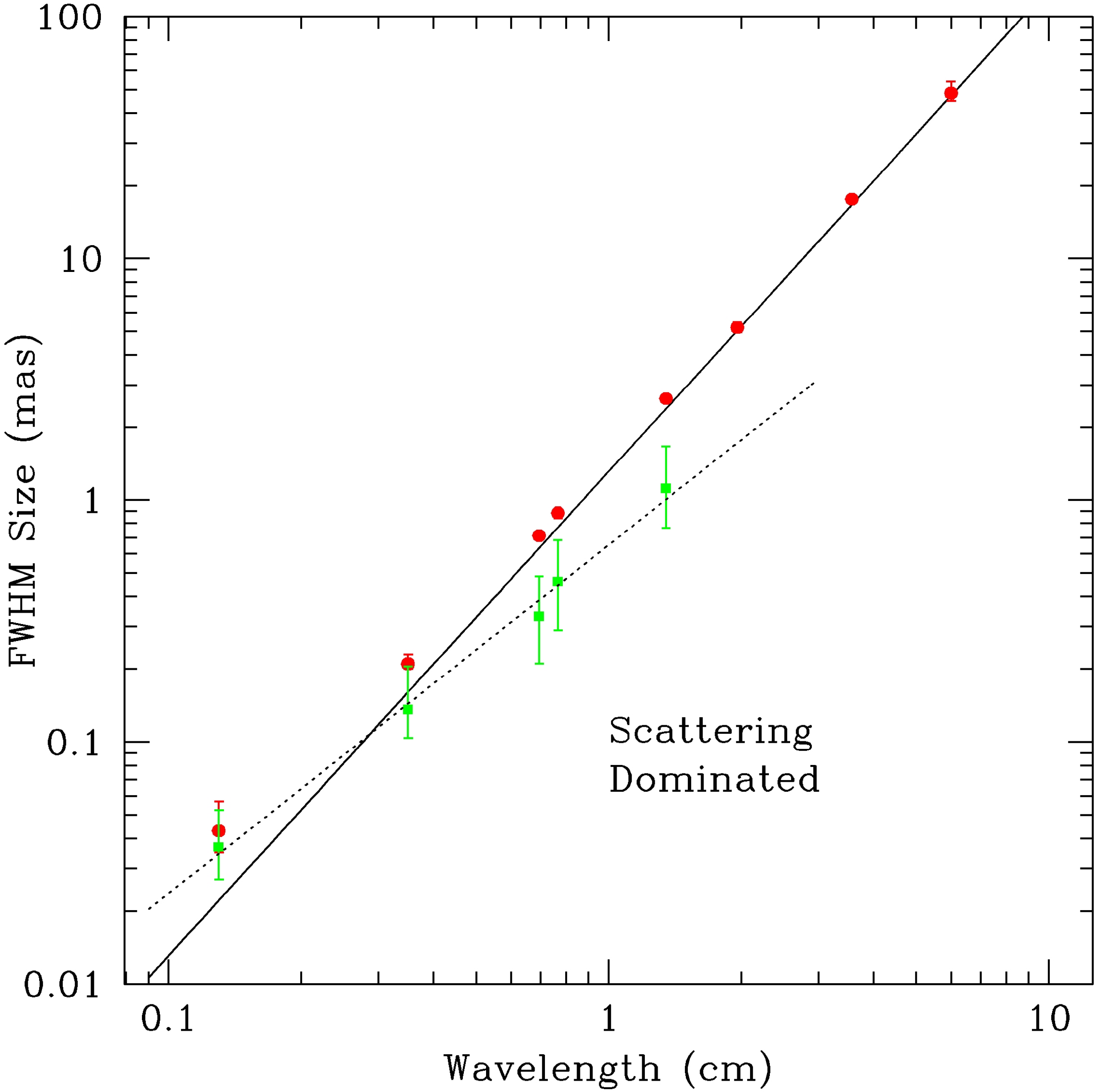
Non-spinning BH
Rotating accretion envelope

$D_{shadow} = \mathrm{sqrt}(27) * R_{sch}$

Measuring the shadow gives mass and spin.

(Johannsen, Psaltis et al. 2012)

Seeing Through the Scattering



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

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

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

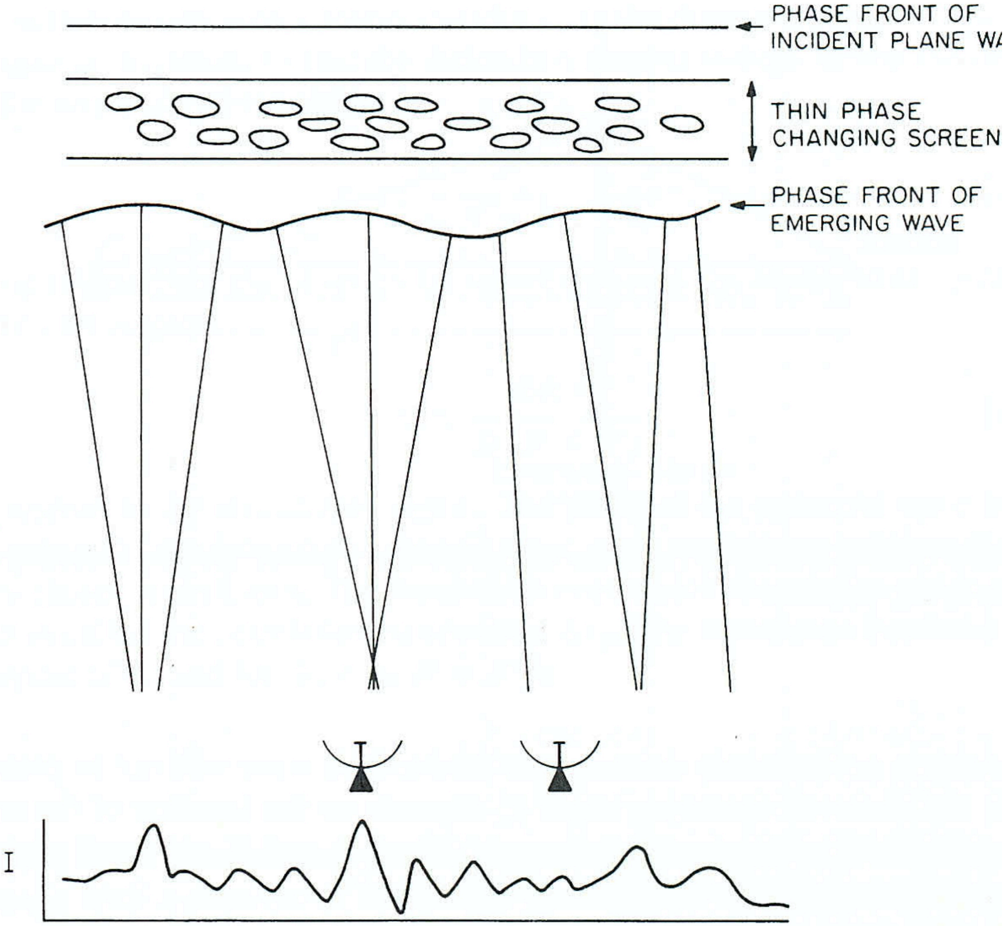
Plasma Scattering

- Index of refraction in plasma:

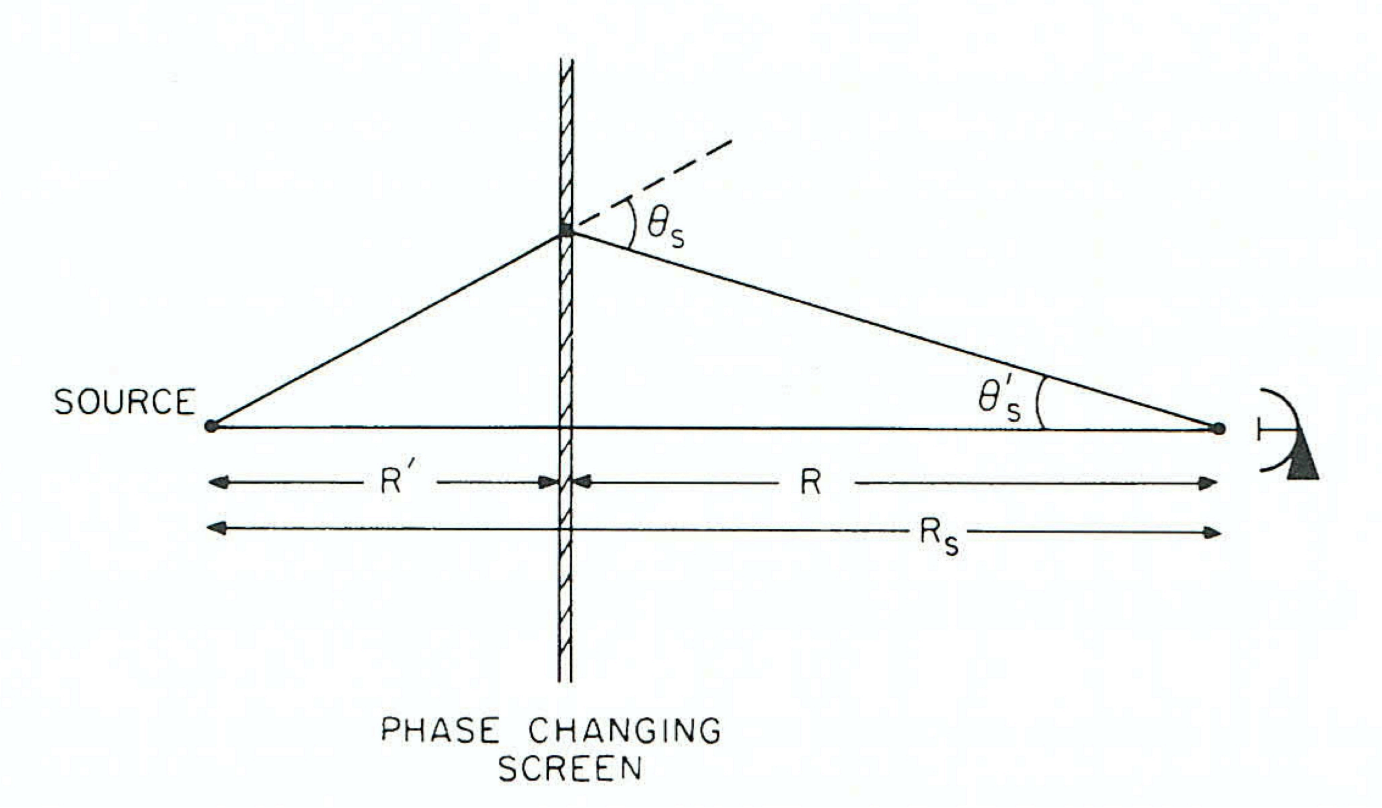
$$n \simeq 1 - \frac{r_e n_e \lambda^2}{2\pi}$$

- This means that radiation refracts (changes direction) as it goes through a region of different electron density (that is, index of refraction).

Radio effect, similar to optical “seeing”



From another angle of view…



Intrinsic deflection

$$\theta_s = \frac{1}{\pi} r_e \lambda^2 \, \Delta n_e \sqrt{\frac{L}{a}}$$

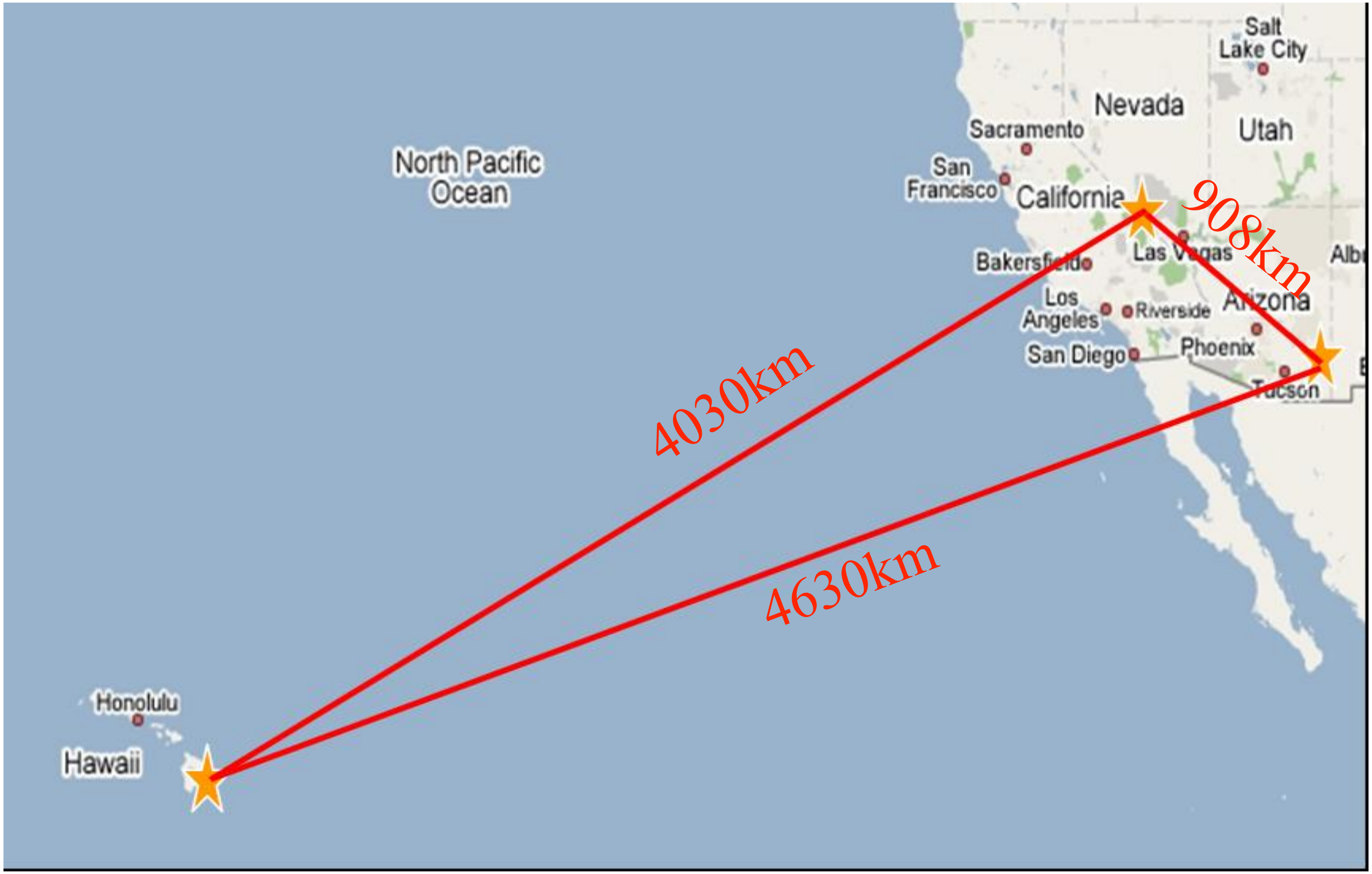
Geometry of problem

$$\theta'_s = \frac{R'}{R+R'} \theta_s$$

Apparent source size goes as λ^2

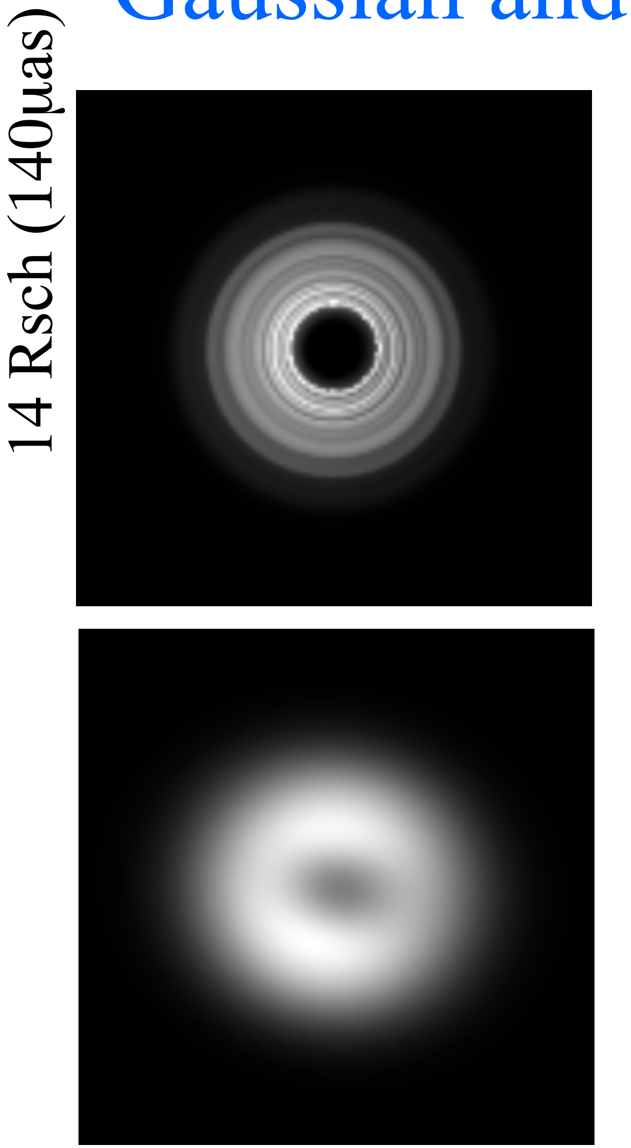
$$\theta'_S \propto \lambda^2$$

1.3 mmλ Observations of Sgr A*

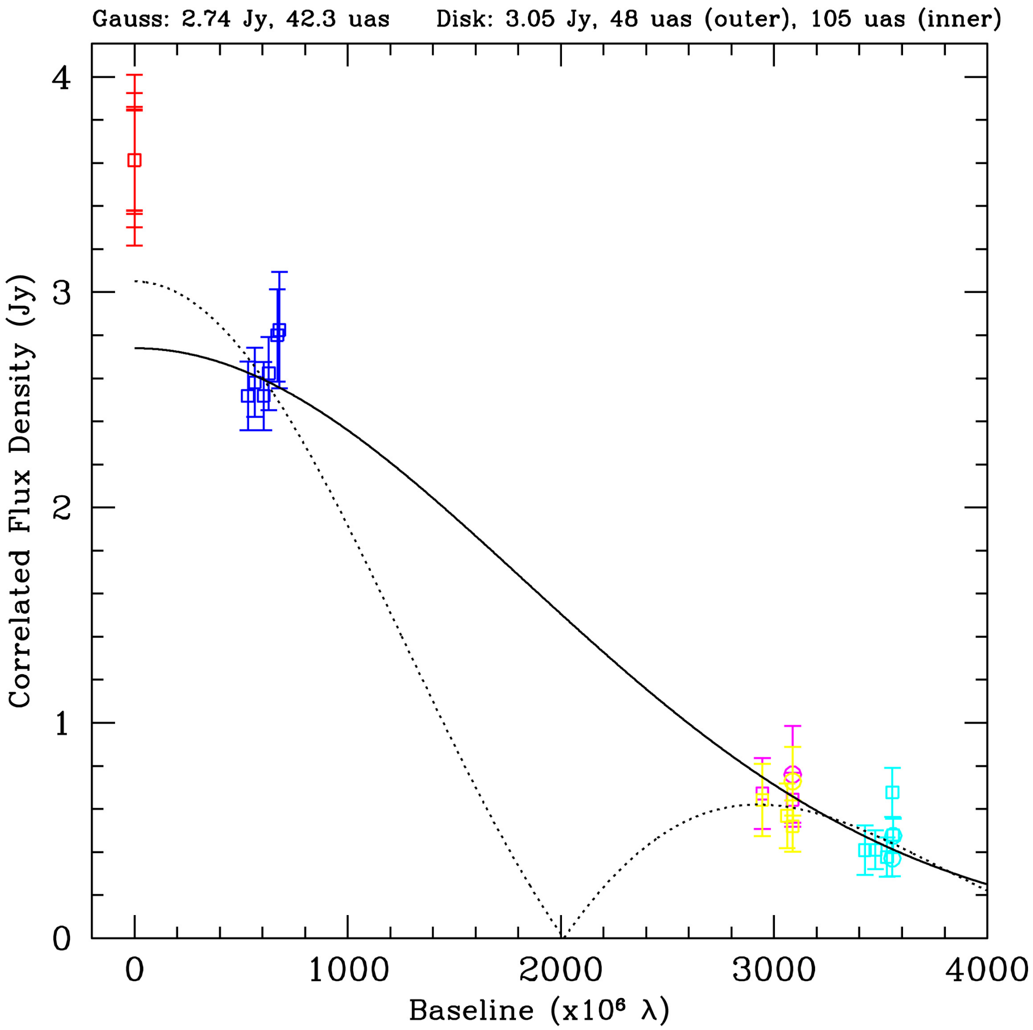


VLBI program led by a large consortium led by Shep Doeleman, MIT/Haystack/CfA

Gaussian and Torus Fit to Visibility Data

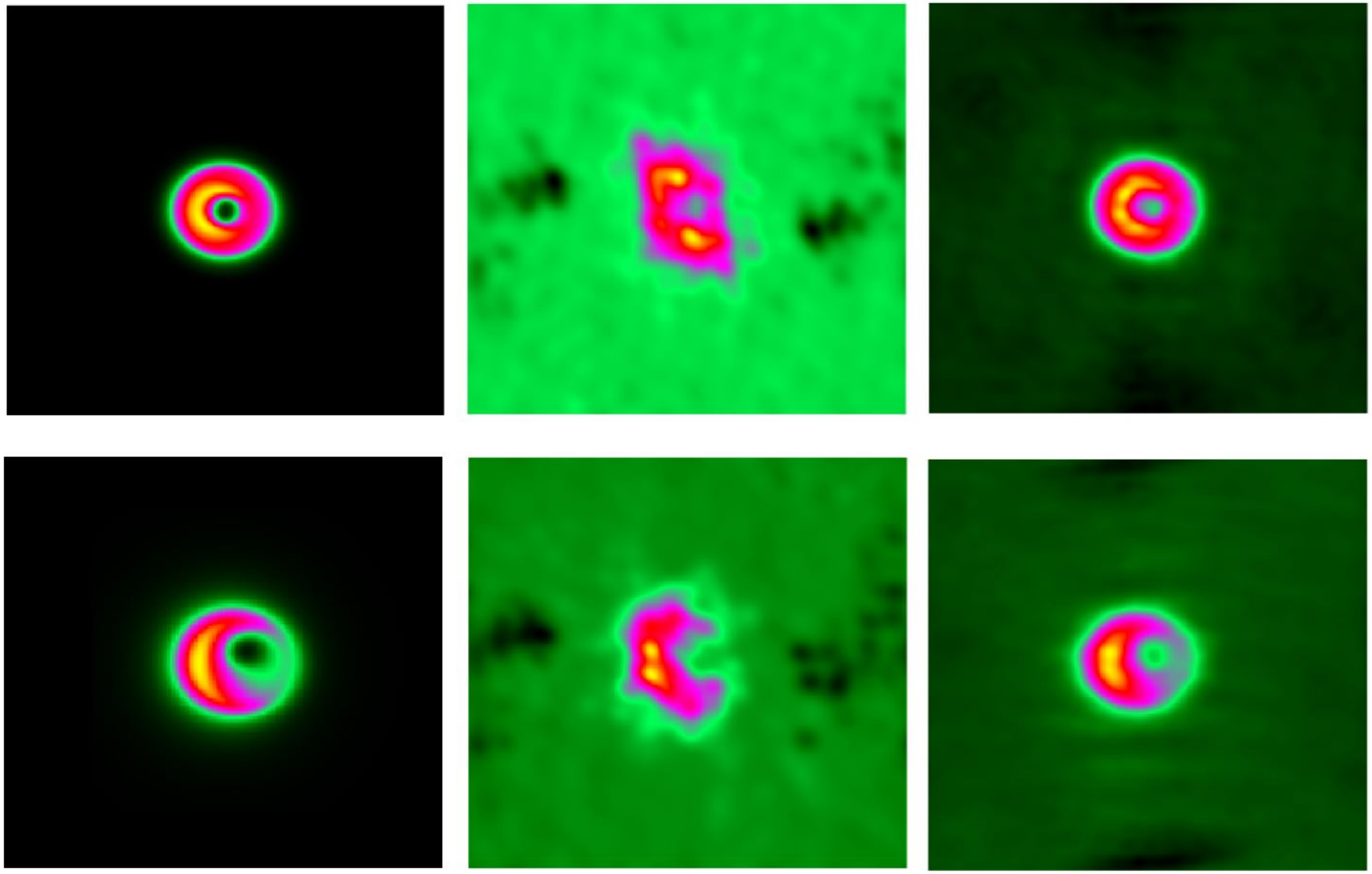


Gammie et al.



Doeleman et al. 2008; Fish et al. 2011

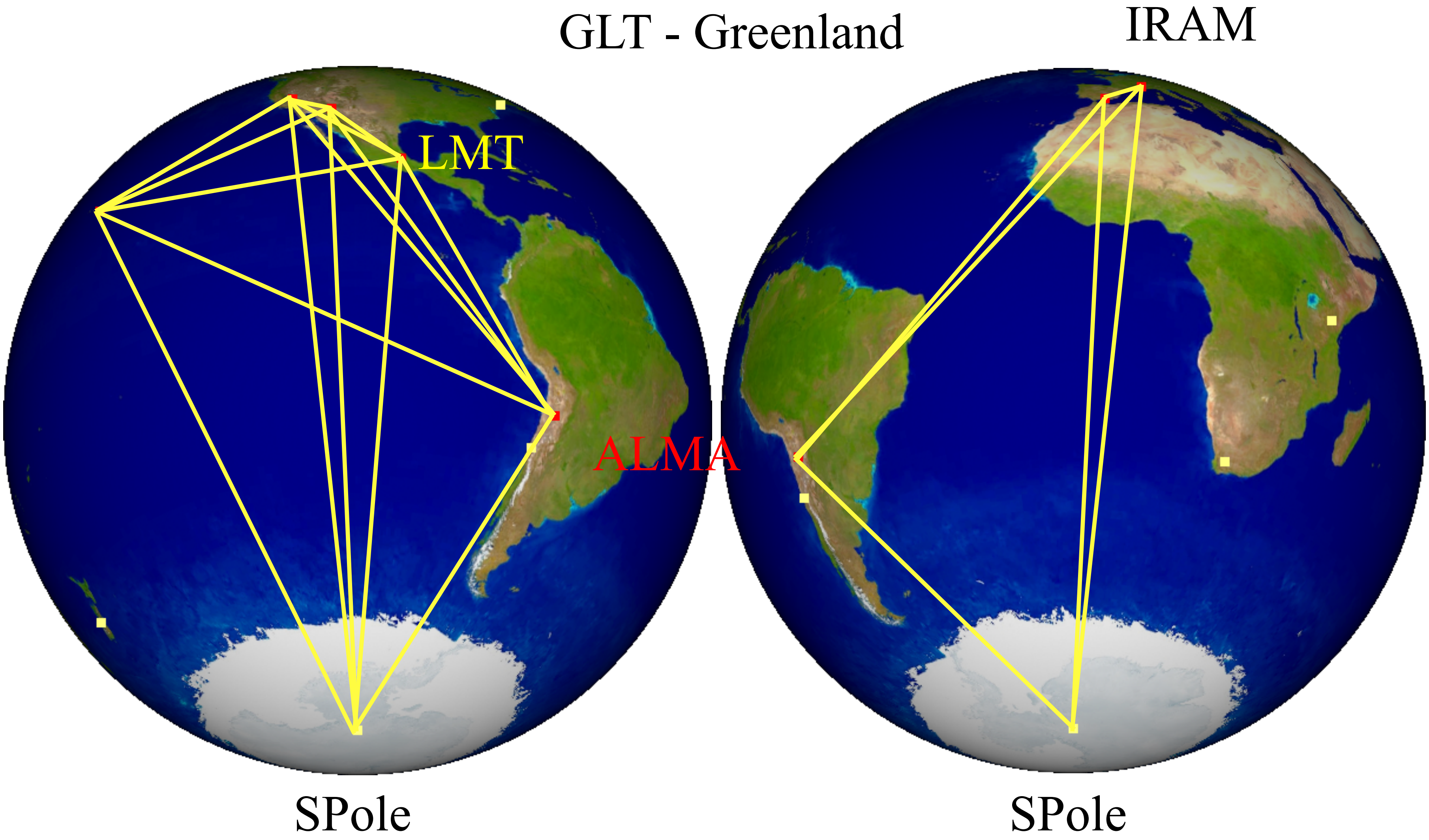
Progression to an Image



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

Sgr A*'s View of the EHT

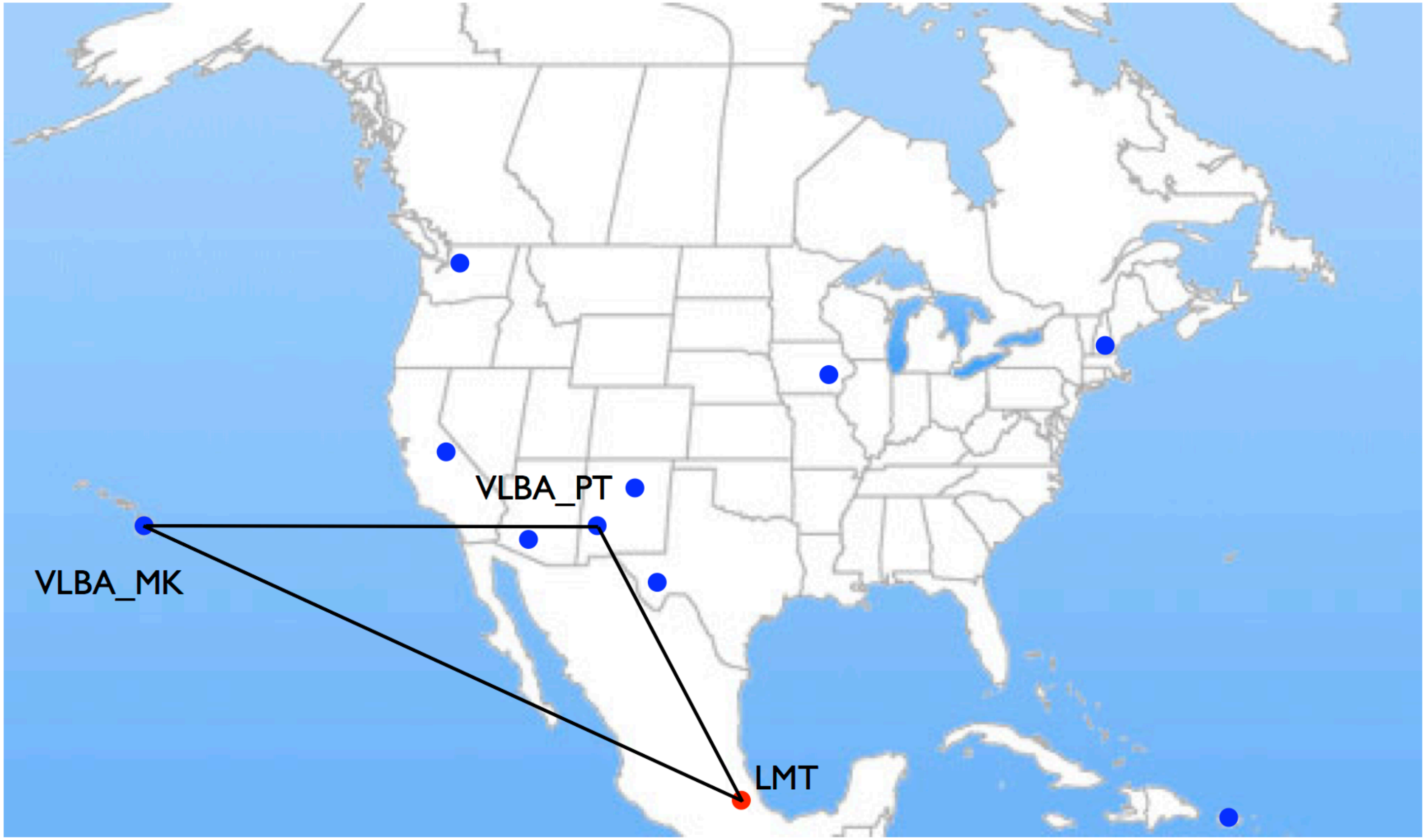


Large Millimeter Telescope

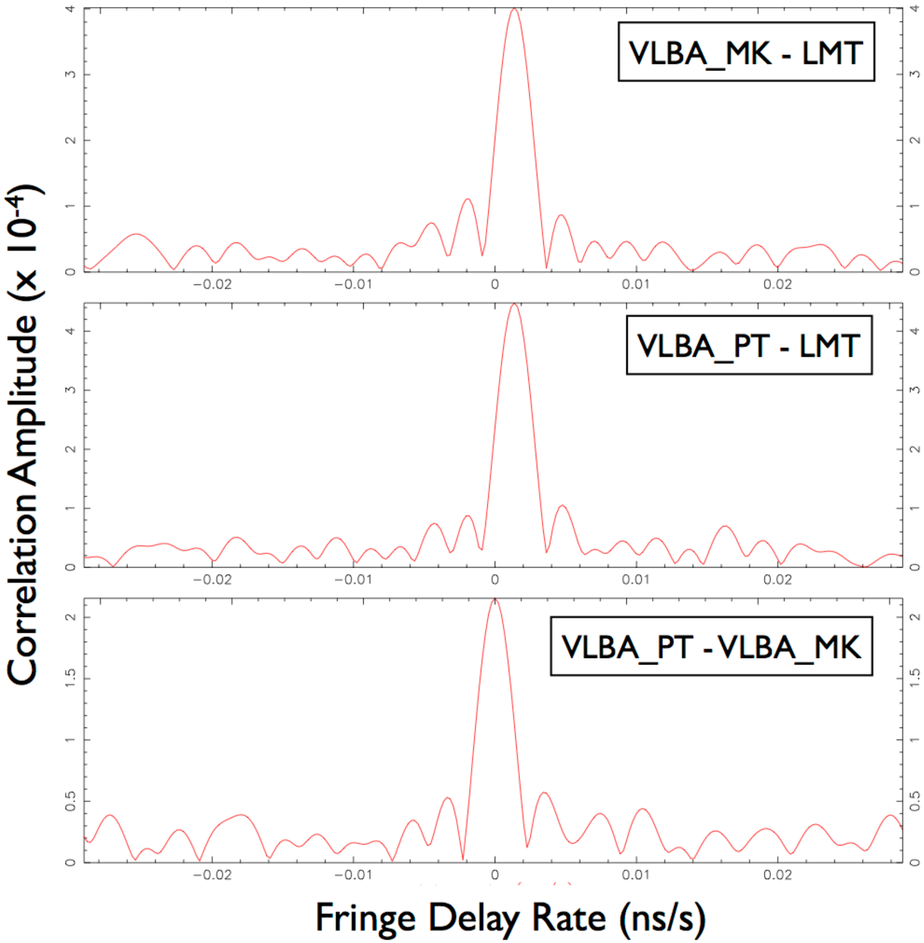
Cerro La Negra, Puebla

A collaboration INAOE-UMass

VLBA stations + LMT

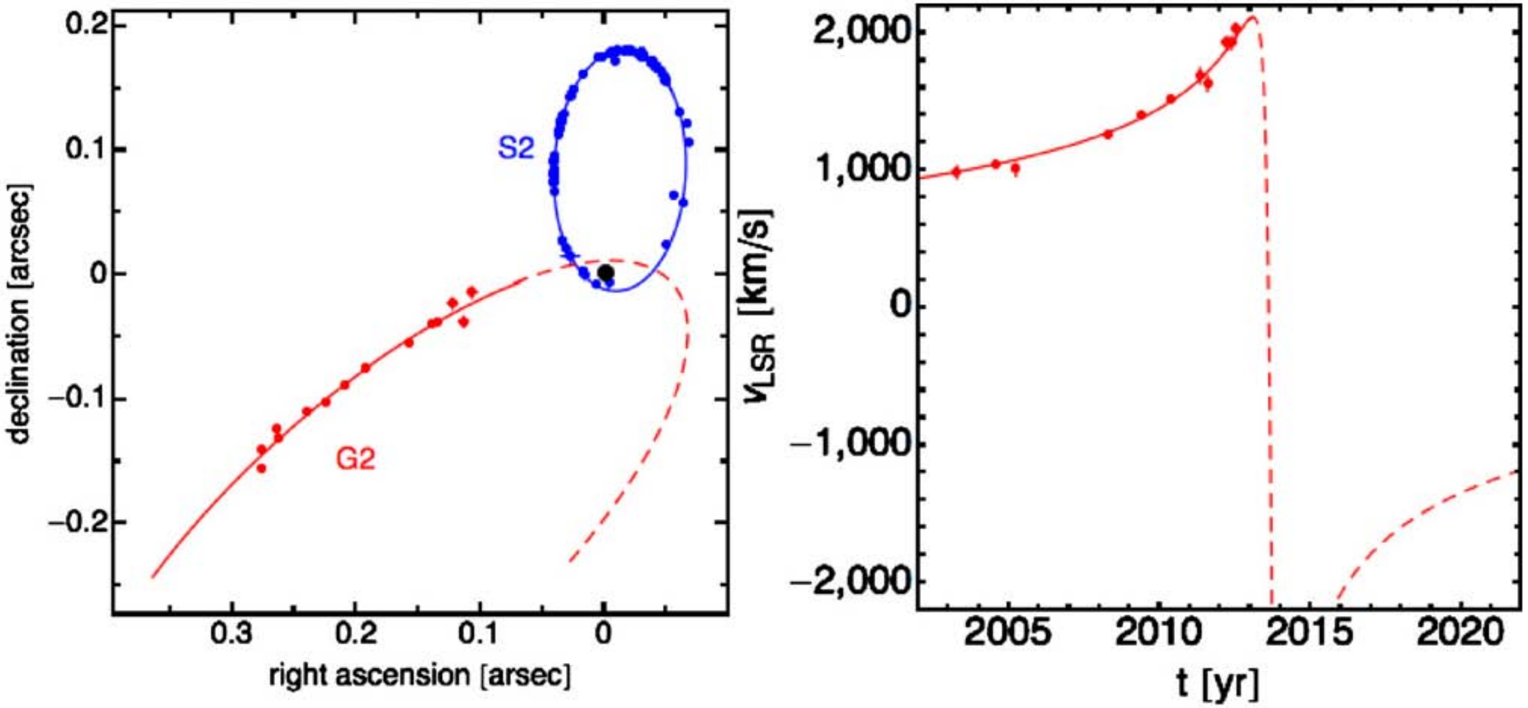


Fringes at 3mm



Animation of Cloud 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

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}

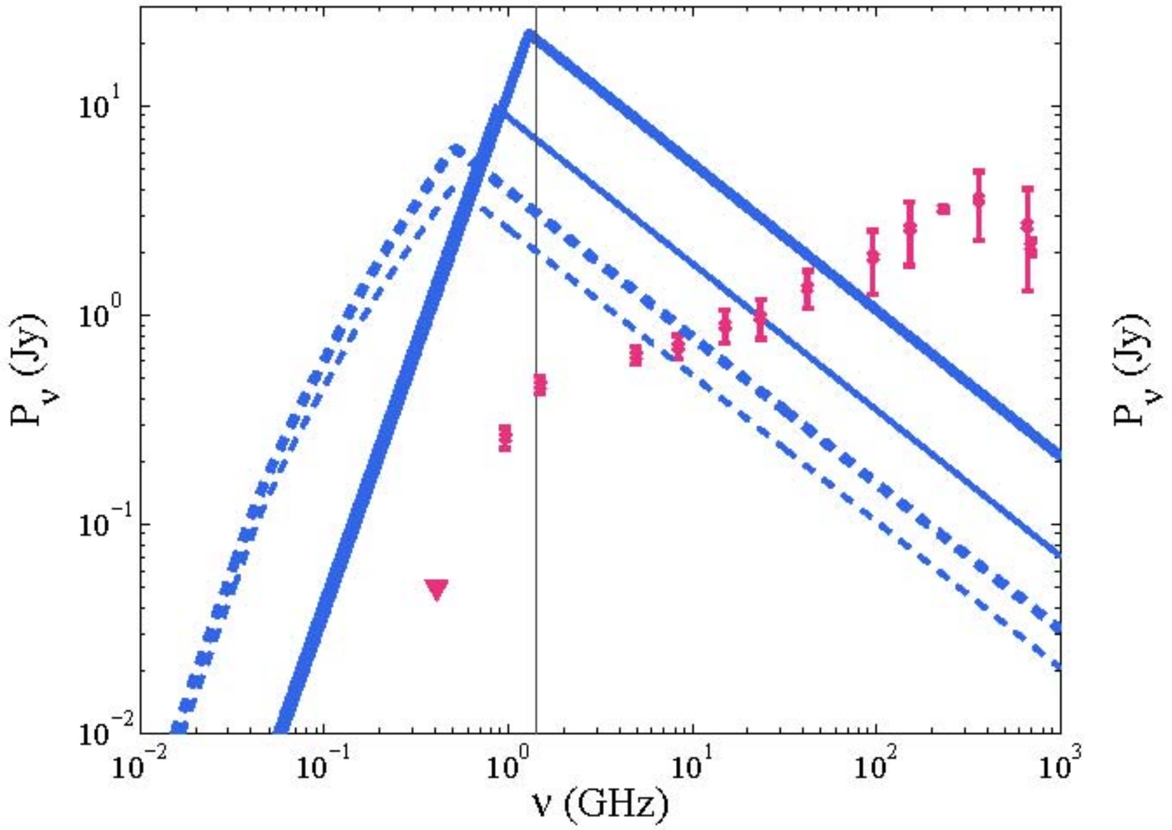
Accretion over 100 years means an increase of 10^{-7} M_{Sun} over ambient 10^{-8} M_{Sun}

Could brighten by factor of 10 !

Increase of emission predicted by two different episodes:

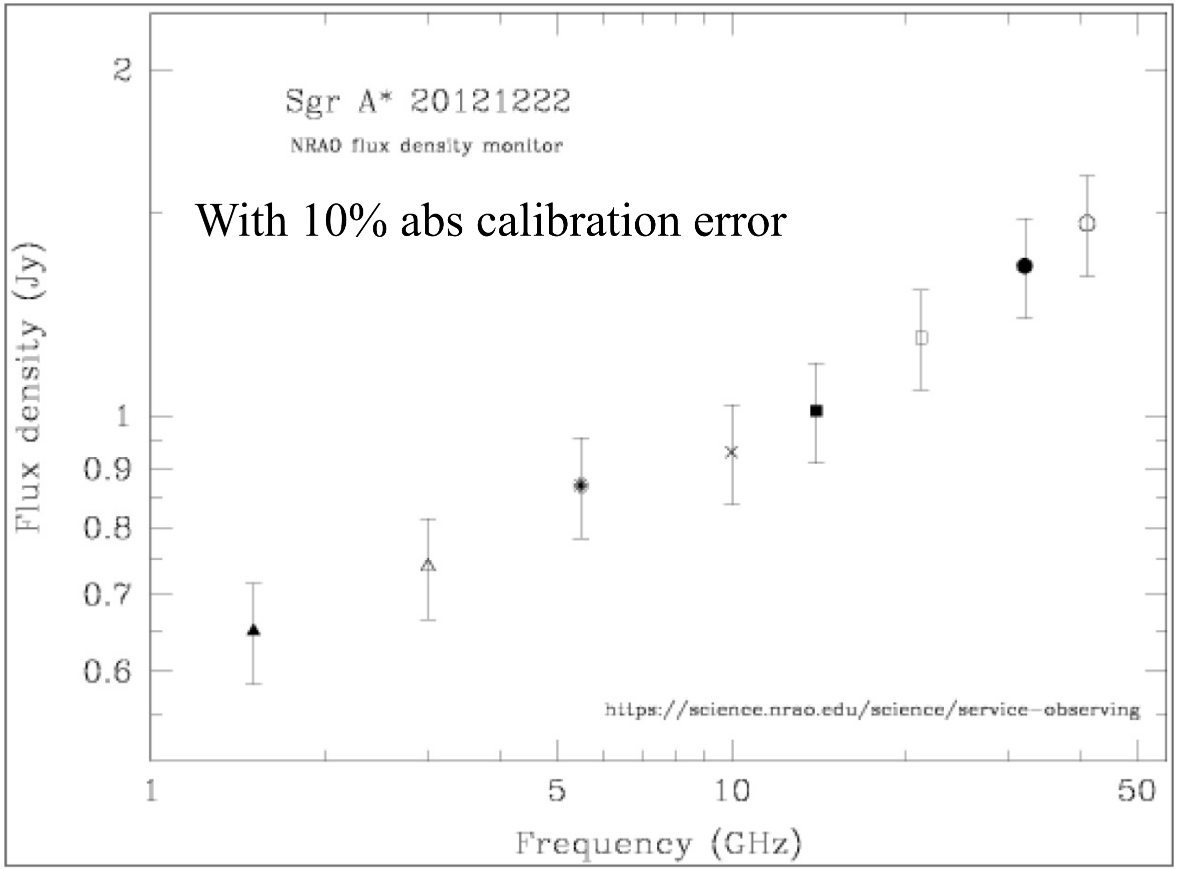
1. Near periastron (2013.7) strong shock should develop between G2 and ambient medium surrounding Sgr A*. This was expected to produce radio synchrotron emission: strong shock => Fermi acceleration of charged particles => synchrotron emission.
2. In the following years, part of the cloud is expected to be accreted by Sgr A* via a disk => X-ray emission (disk) + radio (jets).

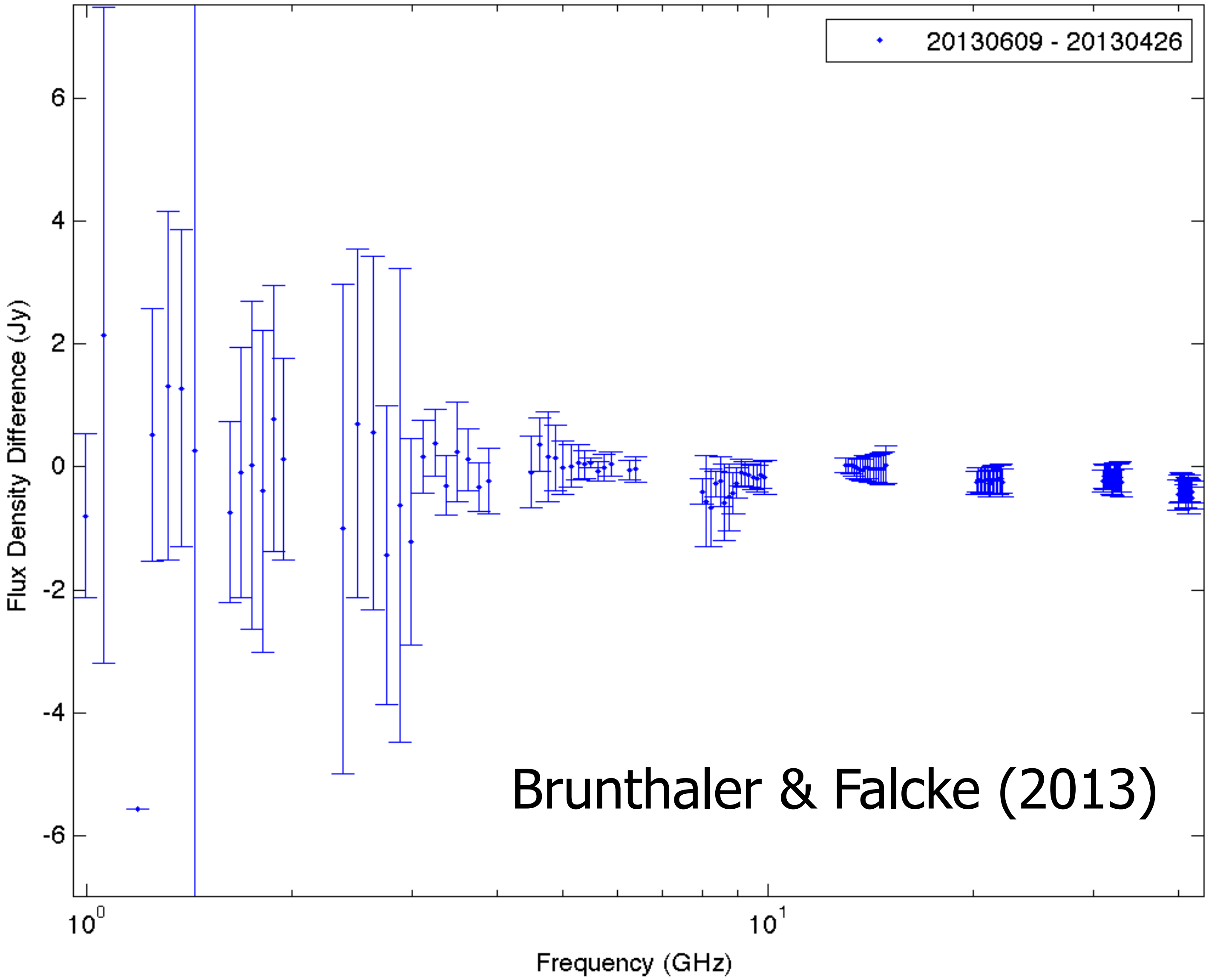
Bow Shock Emission Model for G2: August 2013



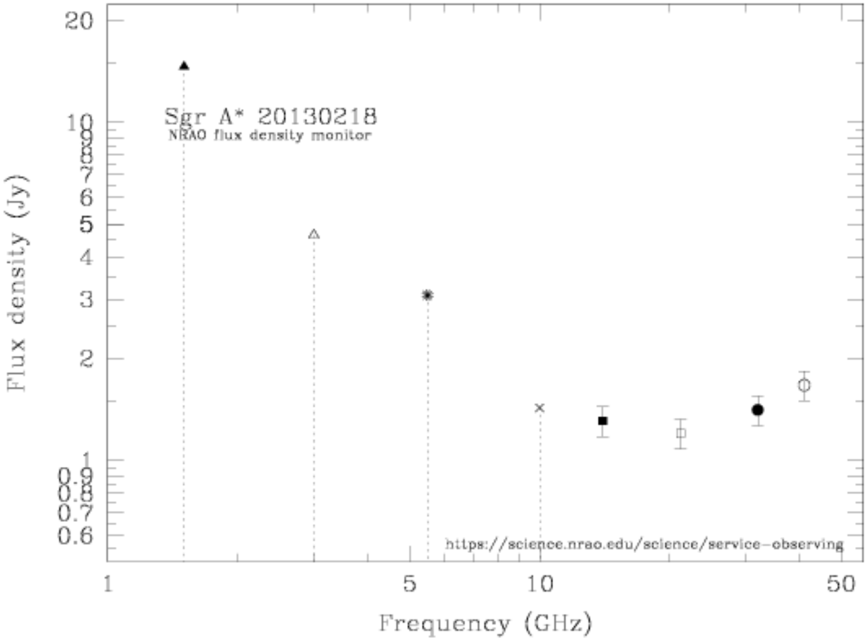
Sadowski, Sironi, Abarca, Guo, Ozel and Narayan, MNRAS, 2013, arXiv:1301.3906
Also: Narayan, Ozel and Sironi, ApJ(L) , 757, L20, 2012

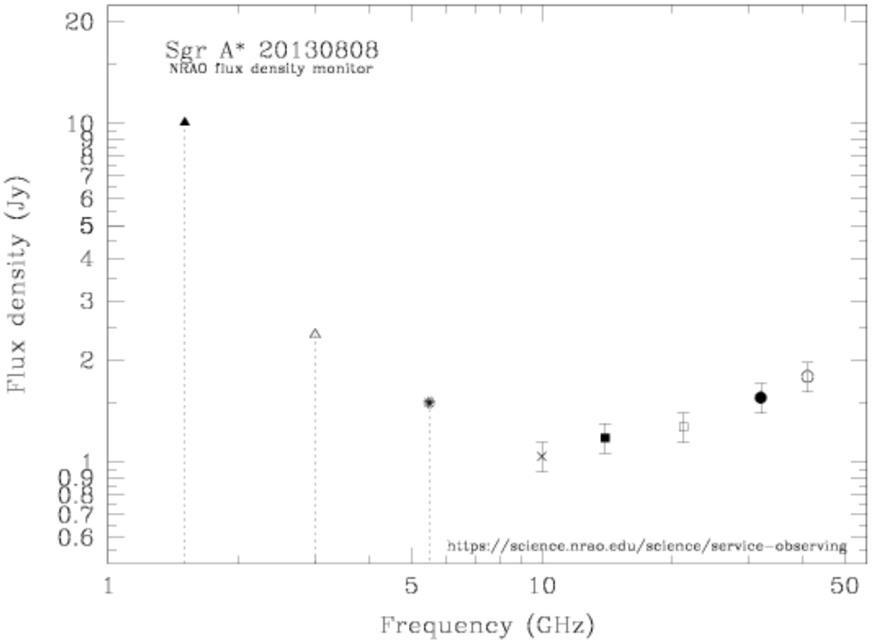
VLA SED Monitoring of Sgr A*





Brunthaler & Falcke (2013)


Sgr A* 20130218
NRAO flux density monitor
https://science.nrao.edu/science/service-observing
Flux density (Jy)
Frequency (GHz)
20
10
9
8
7
6
5
4
3
2
1
0.9
0.8
0.7
0.6
1
5
10
50


Sgr A* 20130808
NRAO flux density monitor
https://science.nrao.edu/science/service-observing
Flux density (Jy)
20
10
9
8
7
6
5
4
3
2
1
0.9
0.8
0.7
0.6
Frequency (GHz)
1
5
10
50

What´s going on?

- Narayan et al. (2013) argue that the excess emission will appear mostly at low frequencies and we have to wait for proper data (October 2013).
- Perhaps a shock was not formed (gas around Sgr A* has to be extremely hot > 10^9 K)

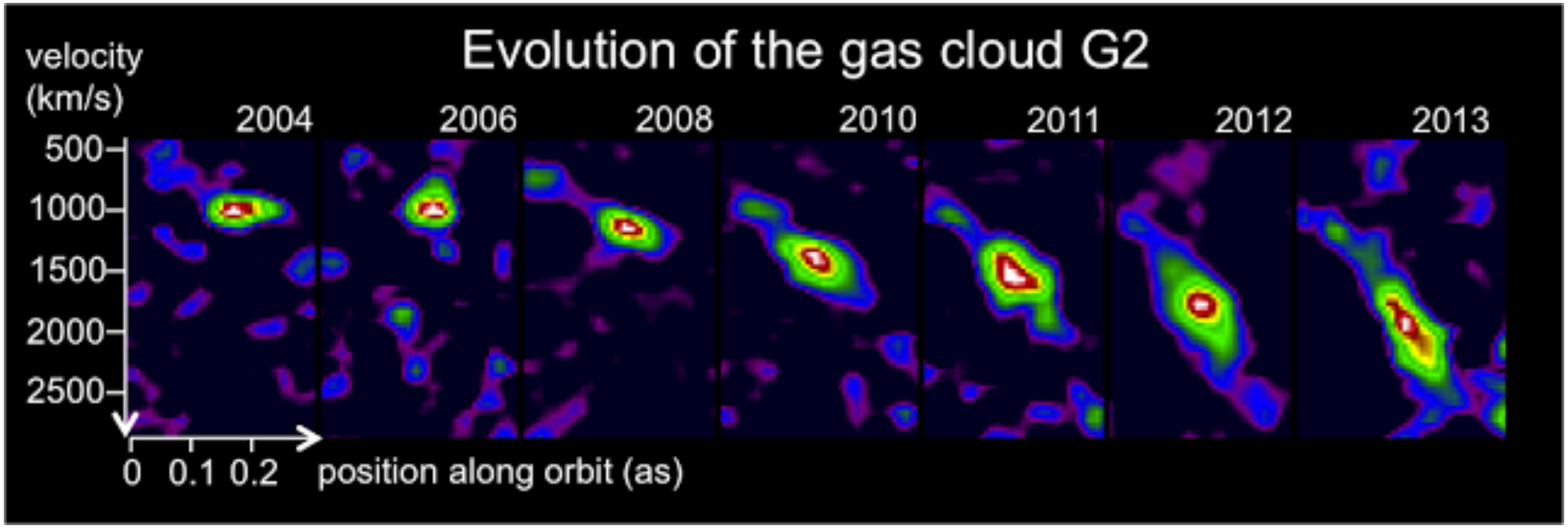
Gas accreted into Sgr A*

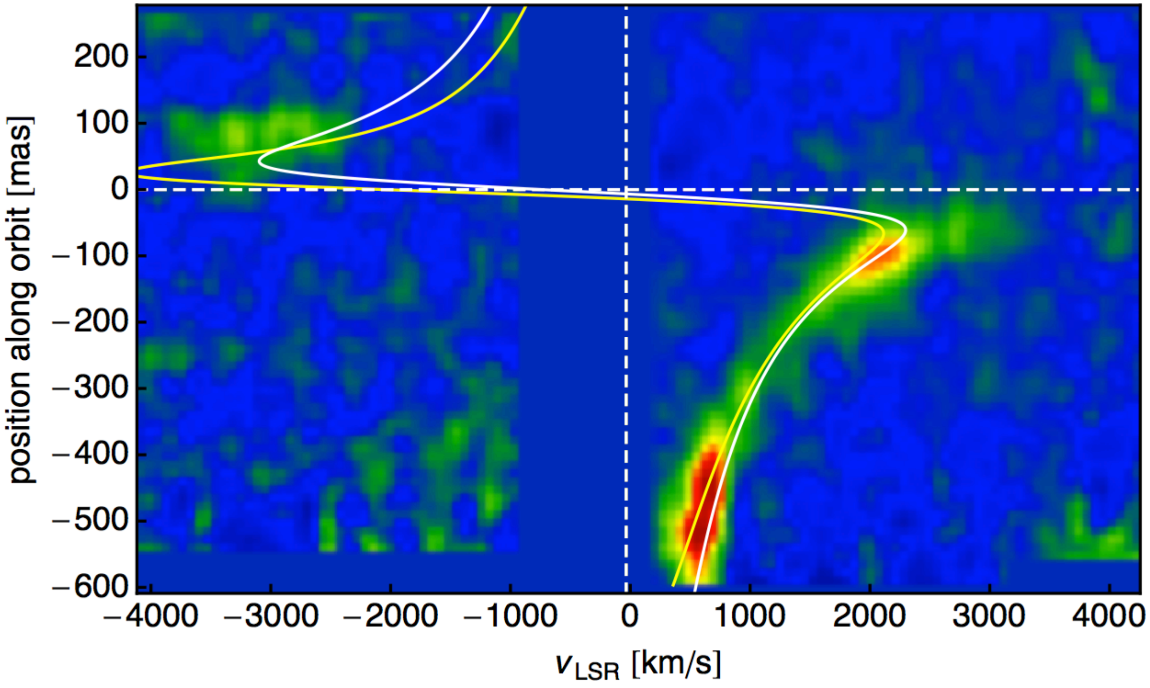
- This process should start within the next few years and may last for a decade or so.
- However, some groups believe that G2 is not a cloud (with little self-gravity) but a star with some kind of envelope. If the second possibility is correct, accretion may be rather weak.

Controversy

- The constant luminosity and the increasingly stretched appearance of the head of G2 in the position-velocity plane, without a central peak, is not consistent with several proposed models with continuous gas release from an initially bound zone around a faint star on the same orbit as G2 (Gillessen et al. 2003).
- While the observations altogether suggest that G2 has a gaseous component which is tidally interacting with the central black hole, there is likely a central star providing the self-gravity necessary to sustain the compact nature of this object (Phifer et al. 2003).
- While the observations altogether suggest that G2 has a gaseous component which is tidally interacting with the central black hole, there is likely a central star providing the self-gravity necessary to sustain the compact nature of this object (Ballone et al. 2013).

Gillessen et al. (2013)





April 2013

Saitoh et al. 2013

Hopefully, things will become clear during 2013-2014

- Need of more observations and fast theoreticians.

Thank you

Very Long Baseline Interferometry (VLBI) at Submillimeter Wavelengths

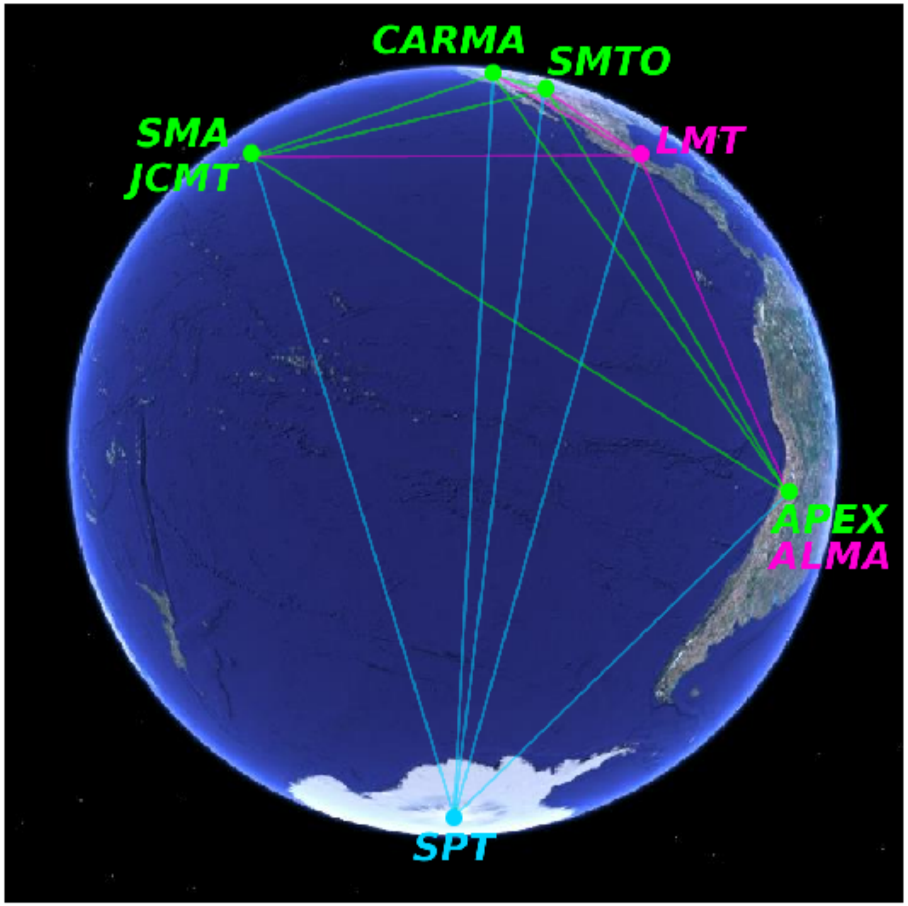


Figure 3: Existing and upcoming sub-millimeter radio telescopes in the Western hemisphere as seen from Sgr A*. Green telescopes already exist and are ready to be phased into a small array. The *Large Millimeter Telescope* (LMT) will begin operations at sub-millimeter wavelengths sometime next year. The *Atacama Large-Millimeter Array* (ALMA) is scheduled to be completed by 2012, though it will begin taking data in 2010. Already at the ALMA site, the *Atacama Pathfinder EXperiment* (APEX) is presently operating. Finally, the *South Pole Telescope* (SPT) needs only a millimeter receiver to be adapted for sub-mm VLBI. The projected baselines associated with these telescopes are shown in green for telescopes

What is the Central Mass Around Which These Stars Are Orbiting?

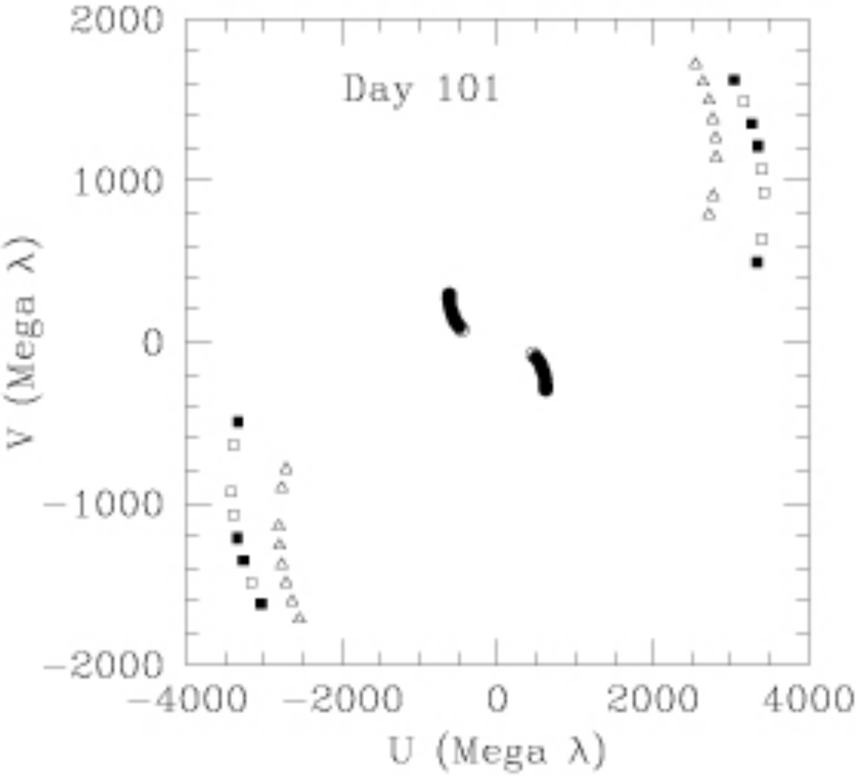
$T = 15.2$ years

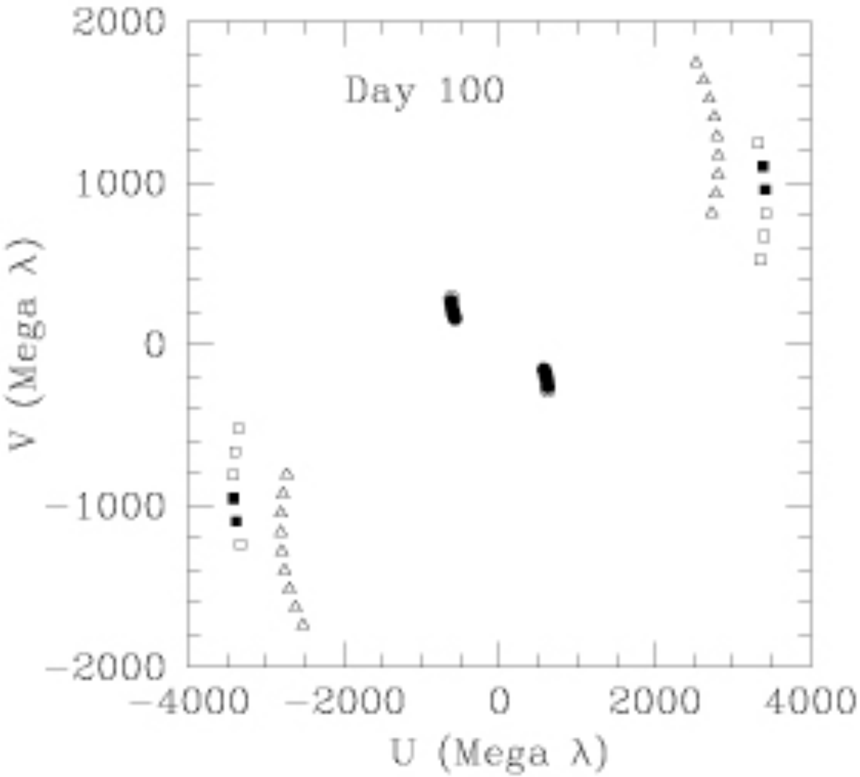
$R = 0.12$ arcseconds = 17 light hours

$M = 4$ million x the mass of the Sun

Density > 10^{17} solar masses/pc^3

U-V Tracks


Day 101
2000
1000
0
−1000
−2000
−4000
−2000
0
2000
4000
U (Mega λ)
V (Mega λ)


Day 100
2000
1000
0
−1000
−2000
−4000
−2000
0
2000
4000
U (Mega λ)
V (Mega λ)

The Galactic Center on Three Size Scales

1. Circumnuclear (molecular) Disk (CND) and Minispiral (ionized streamers)
   120 arcs / 5 pc

   Zhao, Blundell, Downes, Schuster, Marrone
2. Black hole accretion envelope (100 R_s)
   1 mas / 0.3 micro pc

   Marrone, Munoz, Zhao, Rao
3. SgrA* radio source
   37 microarcseconds / 0.01 microparsec

   Doeleman et al.

Types of Cosmic Black Holes

1. “stellar” sized black holes found through the galaxy in binary stellar systems,

   $M \sim 10 \quad M_{sun}$

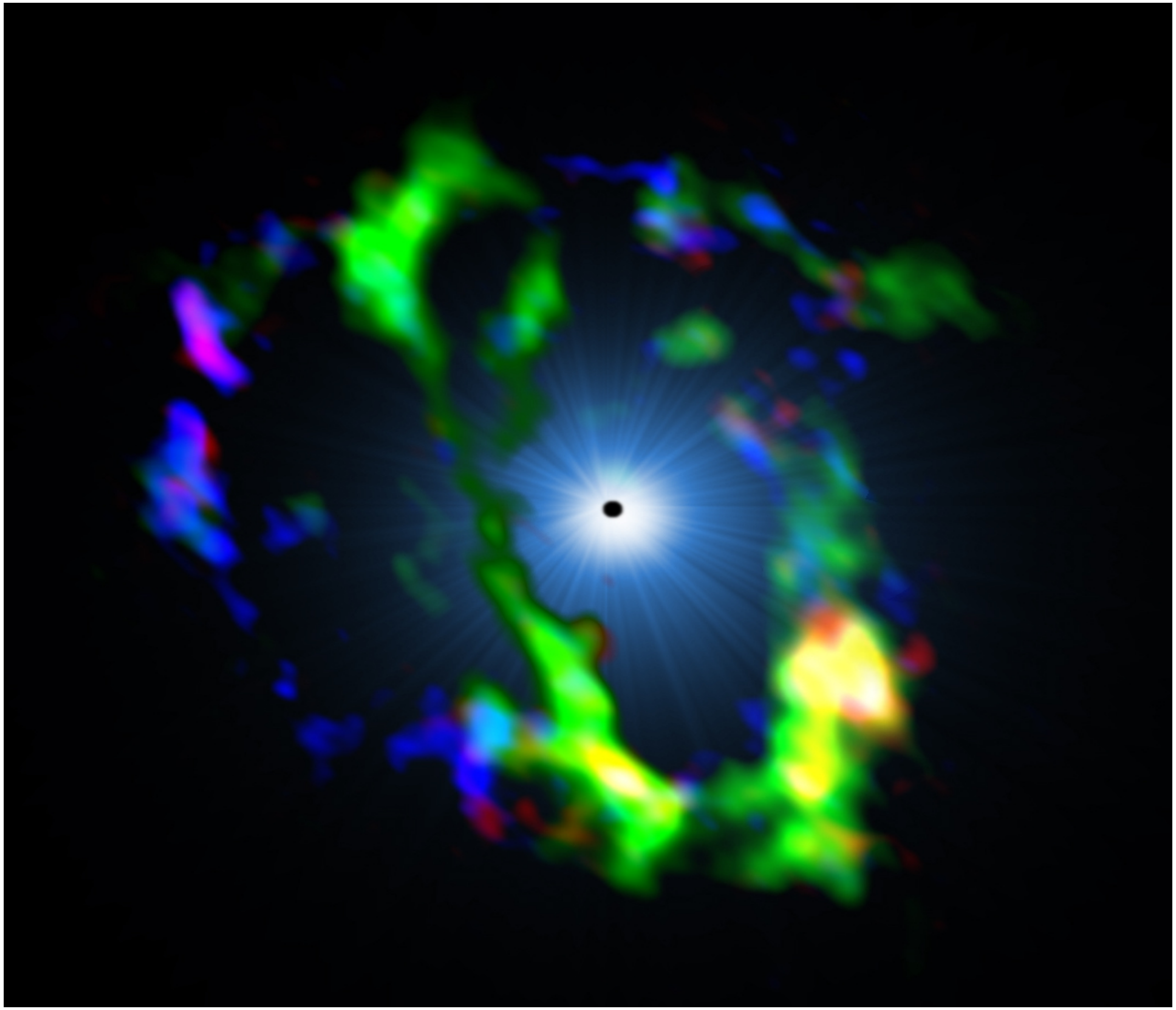
2. “supermassive” black holes (SMBHs) found in the centers of most galaxies,

   $M \sim 10^{6-9}\ M_{sun}$

Summary

- 1.3mm VLBI finds Rsch scale structure in and Sgr A*.
- International collaboration forming strong EHT organization.
- Key technical advances under way and roadmap to full EHT by 2015 clear.
- Most effort low risk: greatest risk is funding.
- EHT is opening a new window on BH study.
- GLT is key new element to the EHT.

Nine Field Mosaic Image of Circumnuclear Disk in Galactic Center



CN

H_2CO

SiO

SMA Data
Sergio Martin Ruiz

3 arcmin field
3 arcs resolution
1.3 mm wavelength

Summary of Talk

- 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 polarization is LCP at all wavelengths from 1 mm to 30 cm.
- The angular diameter of the radio emission from Sgr A* is about 37 microarcseconds at 1.3 mm wavelength.
- A object of earth mass is approaching the Galactic Center and could increase the accretion rate significantly starting in mid-2013.
- VLBI observations of 1924-293 have also been made at 1.3 mm.
- (EHT) under development

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)