Poetry, Mountains and Radio Astronomy: A Tale of Two Supermassive Black Holes

by

James Moran

Harvard-Smithsonian Center for Astrophysics

The Kavli Science Journalism Workshop, June 23-25, 2010

The Two Black Holes

1. Sgr A* (aka the Galactic Center)

   D = 8.3 kpc

   M= 4.3 x 10^6 solar masses

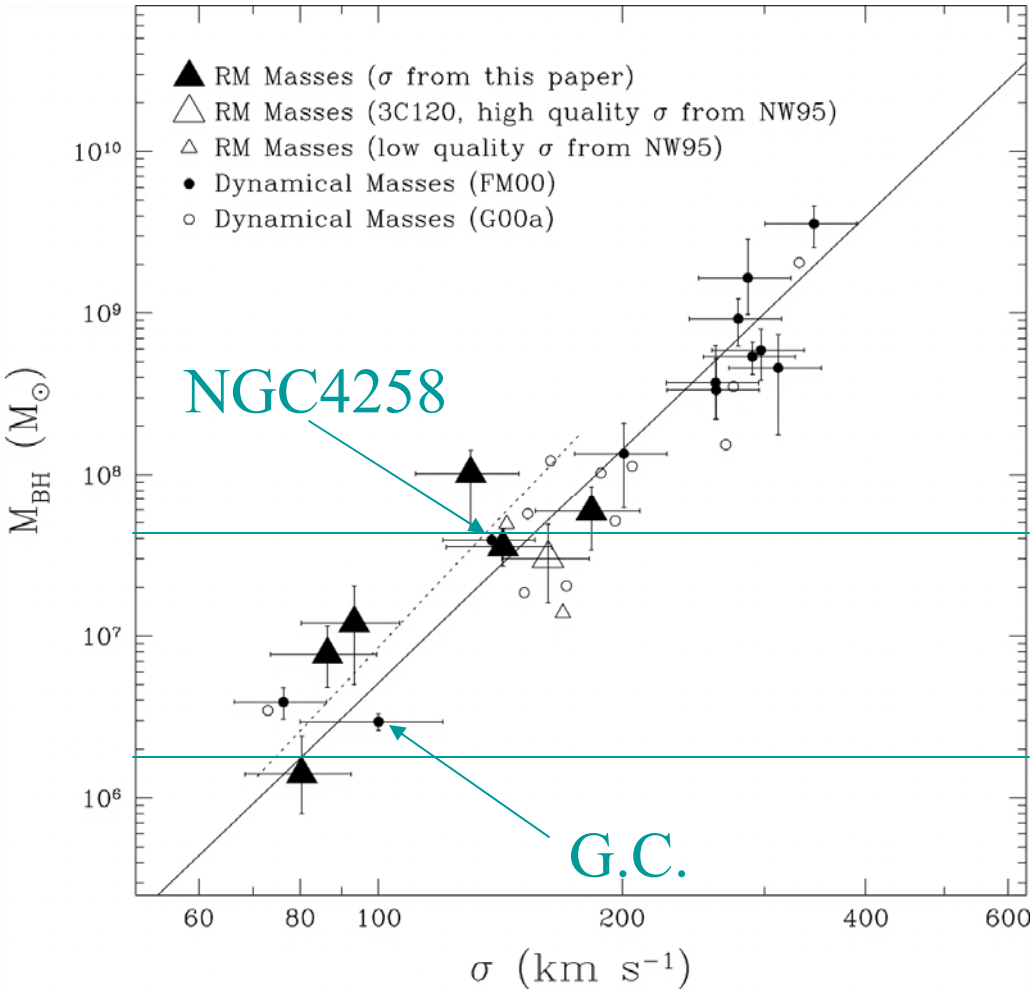
2. NGC4258 (aka M106)

   D = 7.2 Mpc

   M = 4.3 x 10^7 solar masses

Correlations: $M_\bullet$ vs σ_*

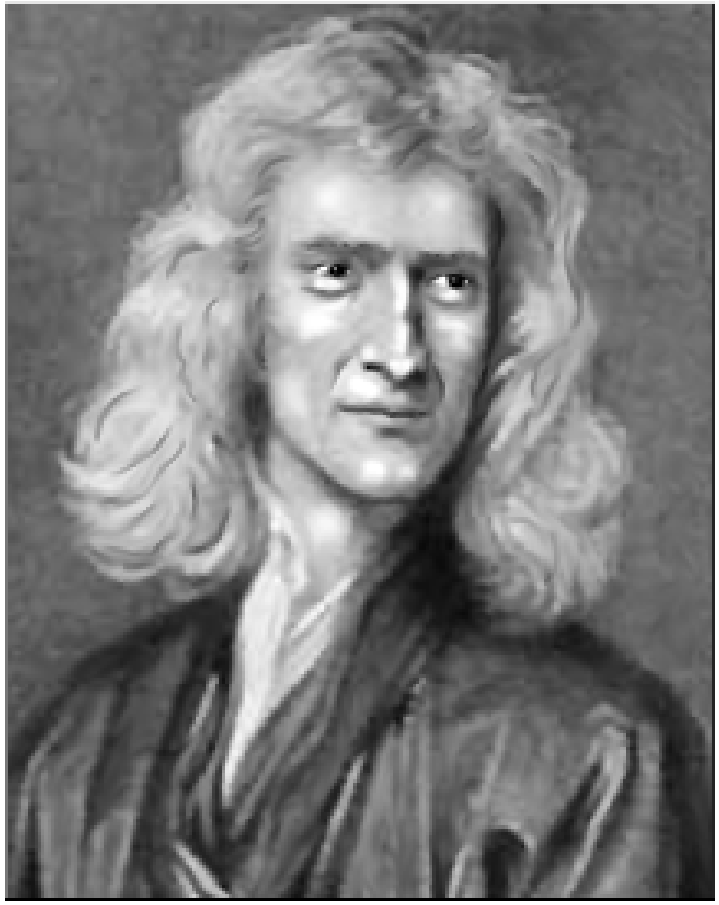
Galaxy	$10^6\ M_\odot$
NGC4258:	39
NGC1068:	~15
Circinus:	1.7
NGC1386:	~1
IC2560:	~3
TXS22265:	~1
MRK1419:	~10
NGC3079:	~2
NGC4945:	~1 (?)



Ferrarese et al. 2001

Two Great Physicists

1689

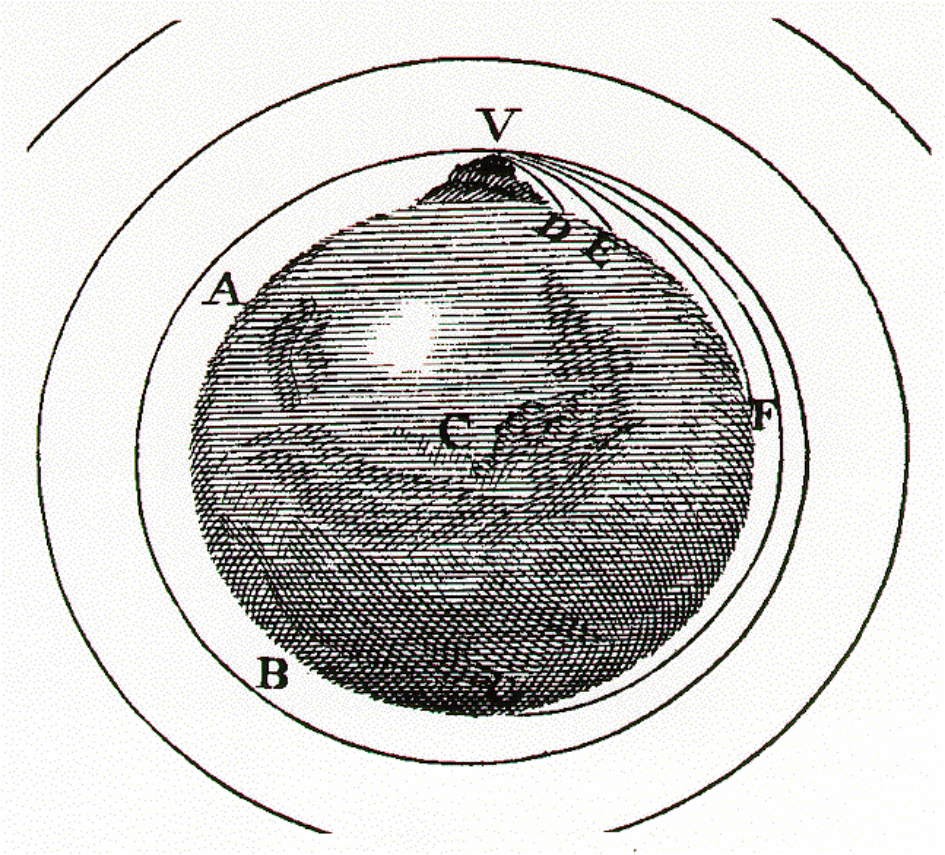


Isaac Newton (1642 - 1727)

1905

Albert Einstein (1879 - 1955)

Illustration in The System of the World,
A “popular” version of Principia Mathematica,
By Isaac Newton (1686)



ORBITING SATELLITES

1543 Copernicus Planets revolve around the sun

1604 Kepler $$T^2 \propto R^3$$

1686 Newton $$F = \frac{GMm}{R^2}$$

$$F = \frac{GMm}{R^2} = \frac{mV^2}{R}$$

hence $$V^2 = \frac{GM}{R}$$

but $$T = \frac{2\pi R}{V}$$

thus $$T^2 = (\frac{4\pi^2}{GM})R^3$$

WEIGHING THE EARTH AND THE SUN

Earth orbit satellite

T = 90 minutes R = 4000 miles

V = 17,600 mph or 5 mps

$M = 6 \times 10^{27}$ grams

Density = 5 grams/cm^3 (x five the density of water)

Earth orbiting the Sun

T = 1 year R = 93 million miles

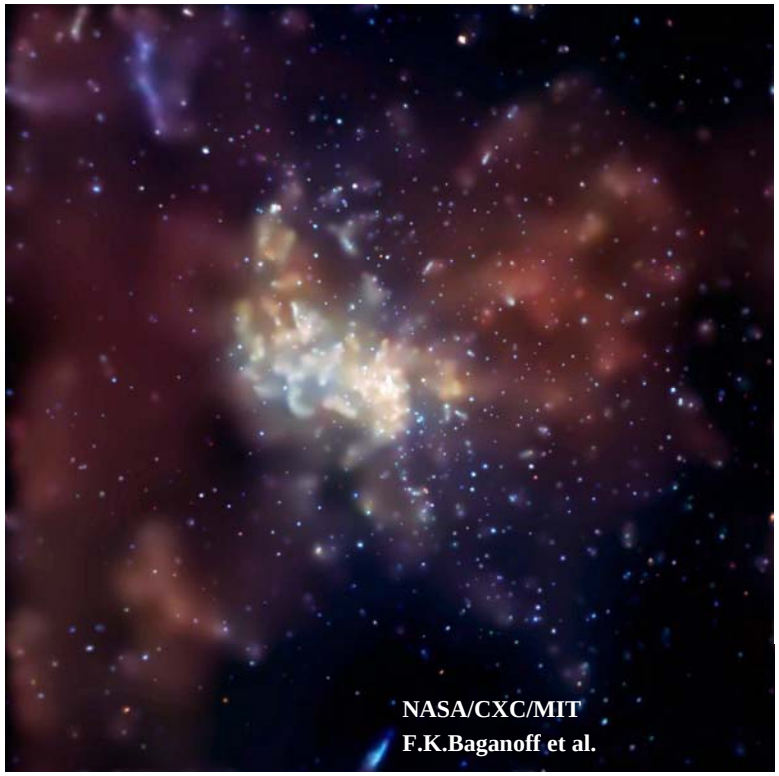
V = 20 mps

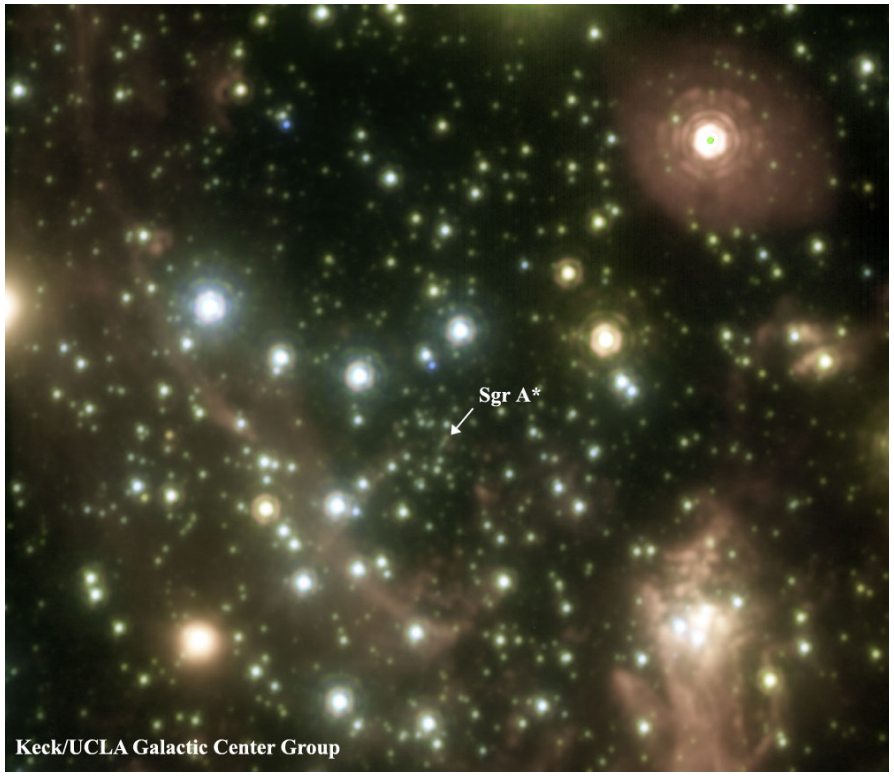
M = 2×10^{33} grams

Density = 1.4 grams/cm^3

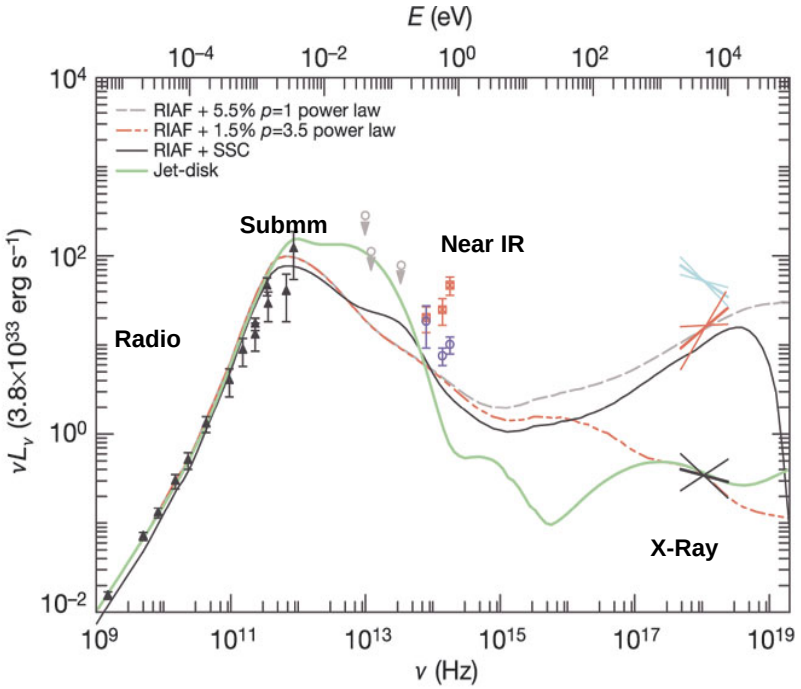
THE MILKY WAY ON A SUMMER'S NIGHT

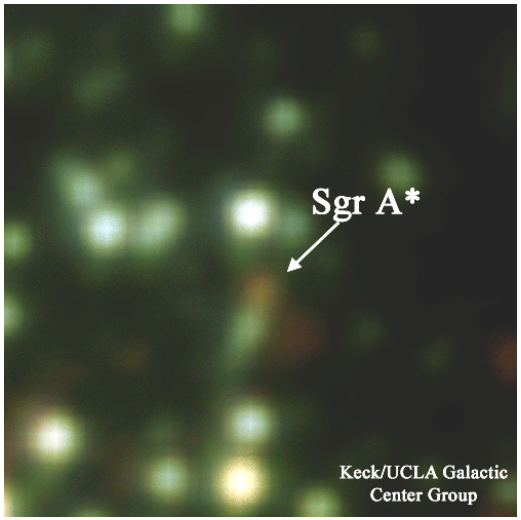
Sagittarius A* Region



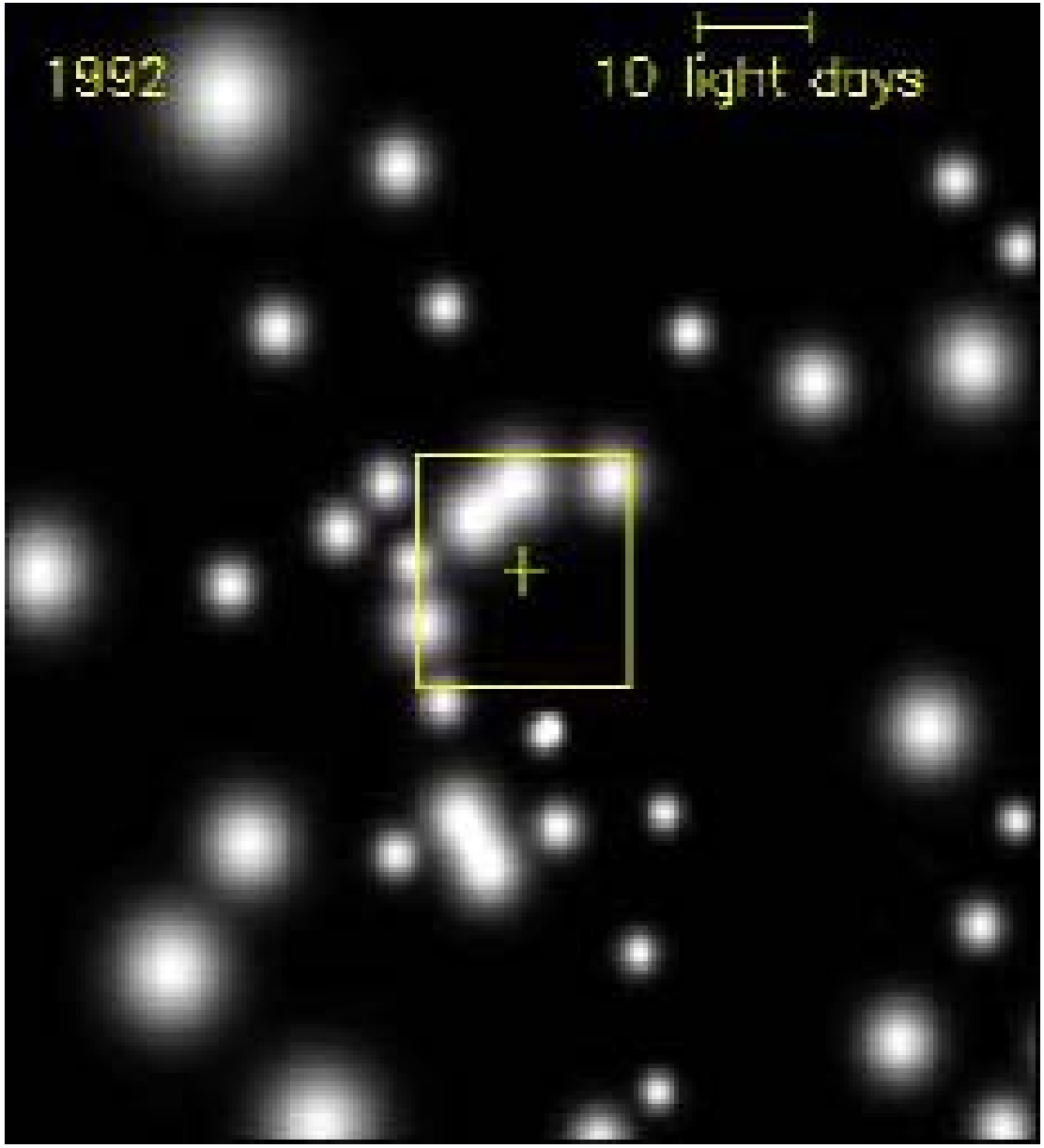


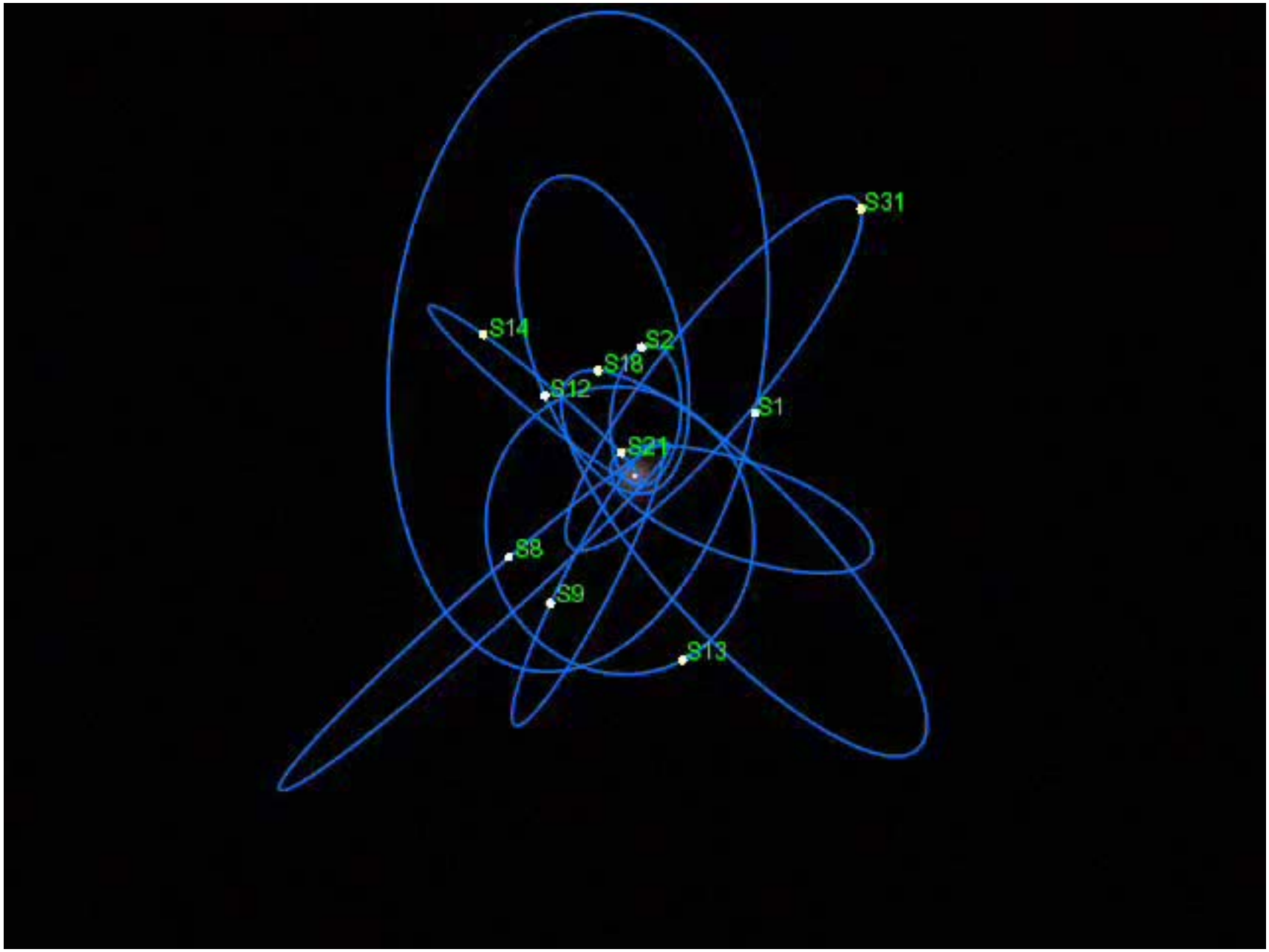
- Very faint source still detectible at most astronomical observing bands
  - SED measurements span 10 decades in frequency
- $L_{SgrA*} \sim 300\ L_{Sun} \sim 10^{-9}$ *Eddington limit*





Genzel et al. (2004)


1992
10 light days


S31
S14
S2
S18
S12
S1
S21
S8
S9
S13


lactic Center
ernung: 0,042280 Lj
zentrum des Sternsystems
1992 Aug 19 02:28:24 UTC
Zeit angehalten
chwindigkeit: 0,00000 m/s
FOV: 28° 34' 28,8" (1,0

WHAT IS THE CENTRAL MASS AROUND WHICH THESE STARS ARE ORBITING?

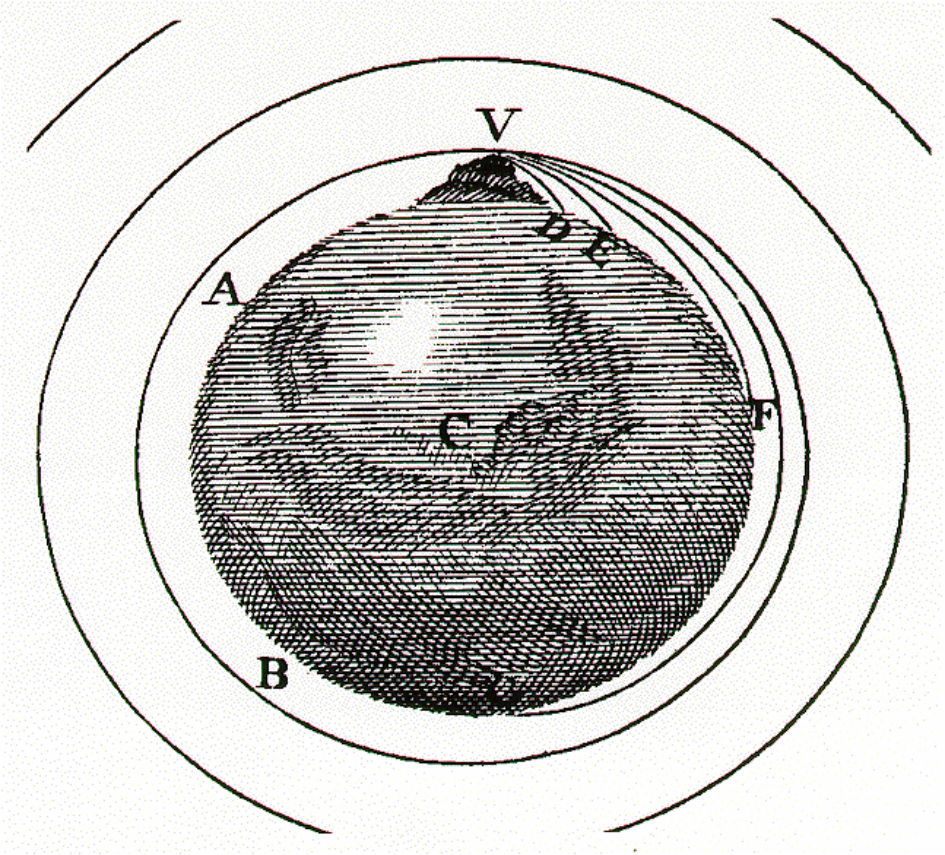
T = 15.2 years

R = 0.12 arcseconds = 17 light hours

M = 4.3 million x the mass of the sun

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

Illustration in The System of the World,
A “popular” version of Principia Mathematica,
By Isaac Newton (1686)



THE IDEA OF A BLACK HOLE

1783 John Michell (British clergyman and mathematician)

$$V_{escape}^2 = \frac{2GM}{R}$$

What if $V_{escape} = c$?

$$R_s = \frac{2GM}{c^2}$$

$$R_s(\text{Sun}) = 3 \text{ Kilometers}$$

$$R_s(\text{Jim}) = 200 \text{ to } 150 \times 10^{-25} \text{ cm}$$

$$R_s(SgrA*) = 0.1 \text{ AU}$$

See: Black Holes and Time Warps: Einstein's Outrageous Legacy by Kip Thorne

A HUNGRY BLACK HOLE

Submillimeter Valley, Mauna Kea, HI

CSO
10 m single dish
(79 m^2)

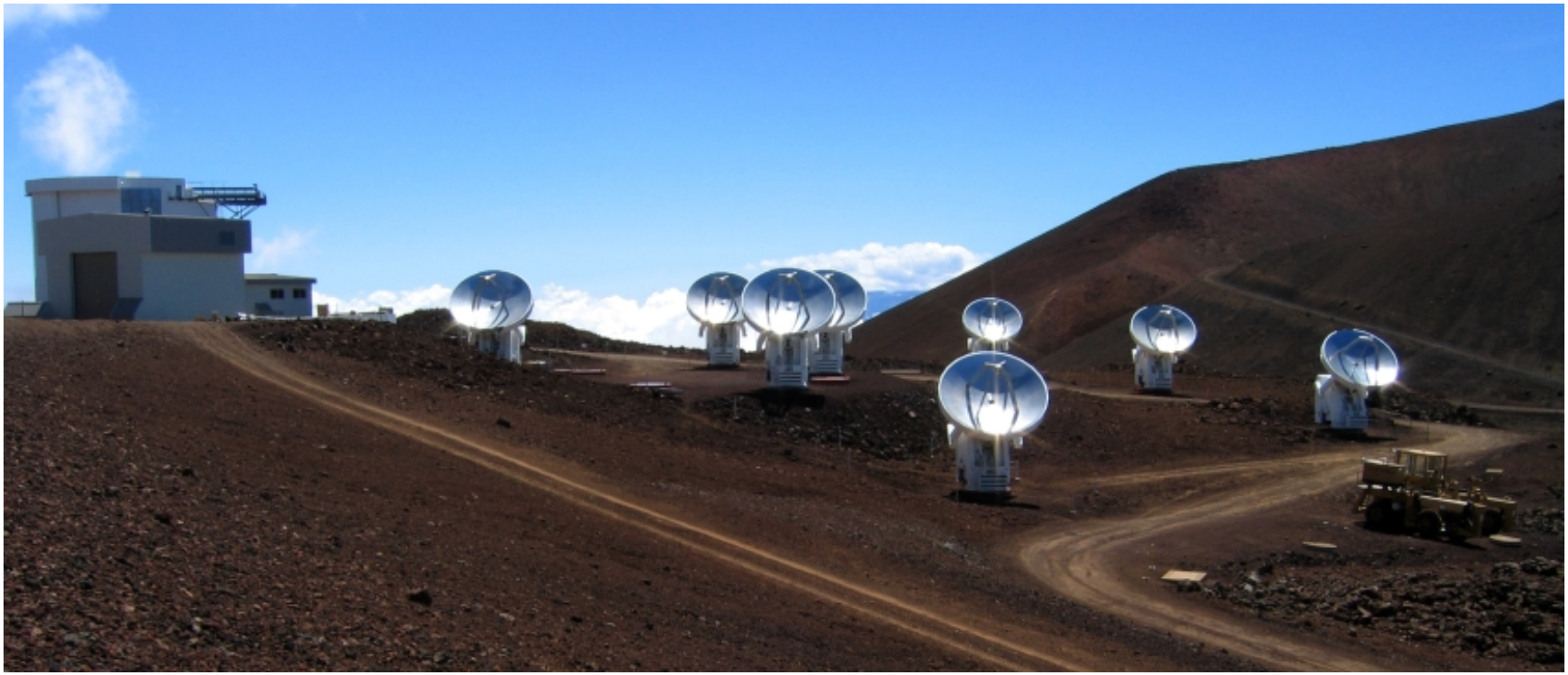
JCMT
15 m single dish
(177 m^2)

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

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


CAUTION

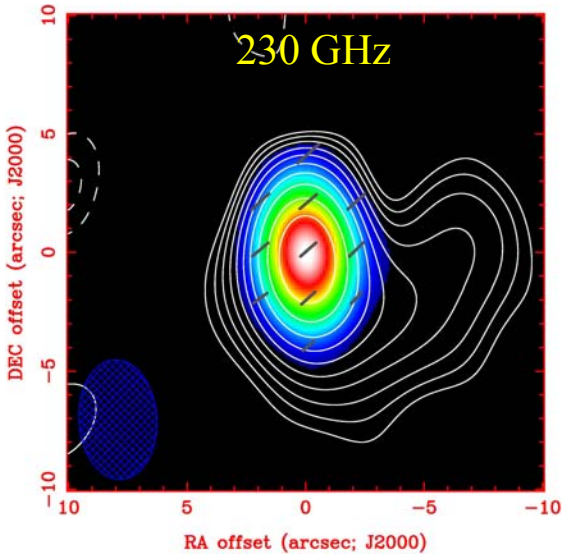

2
WERNER

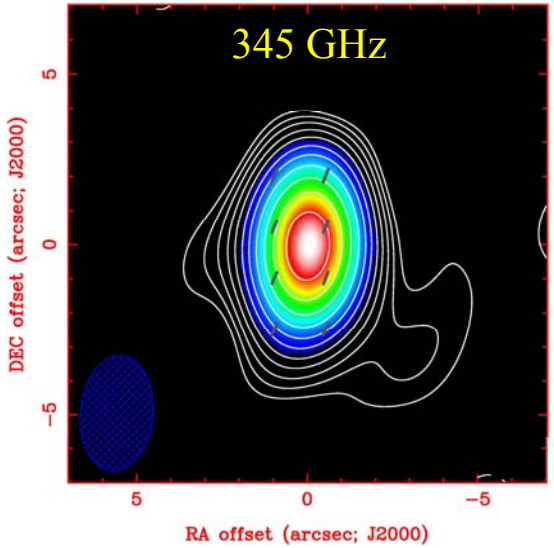


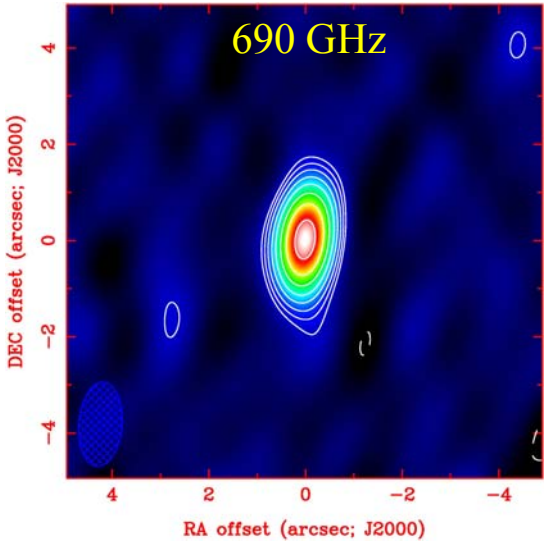

© Leigh Hilbert 2006


Left
Rear
Right
Rear

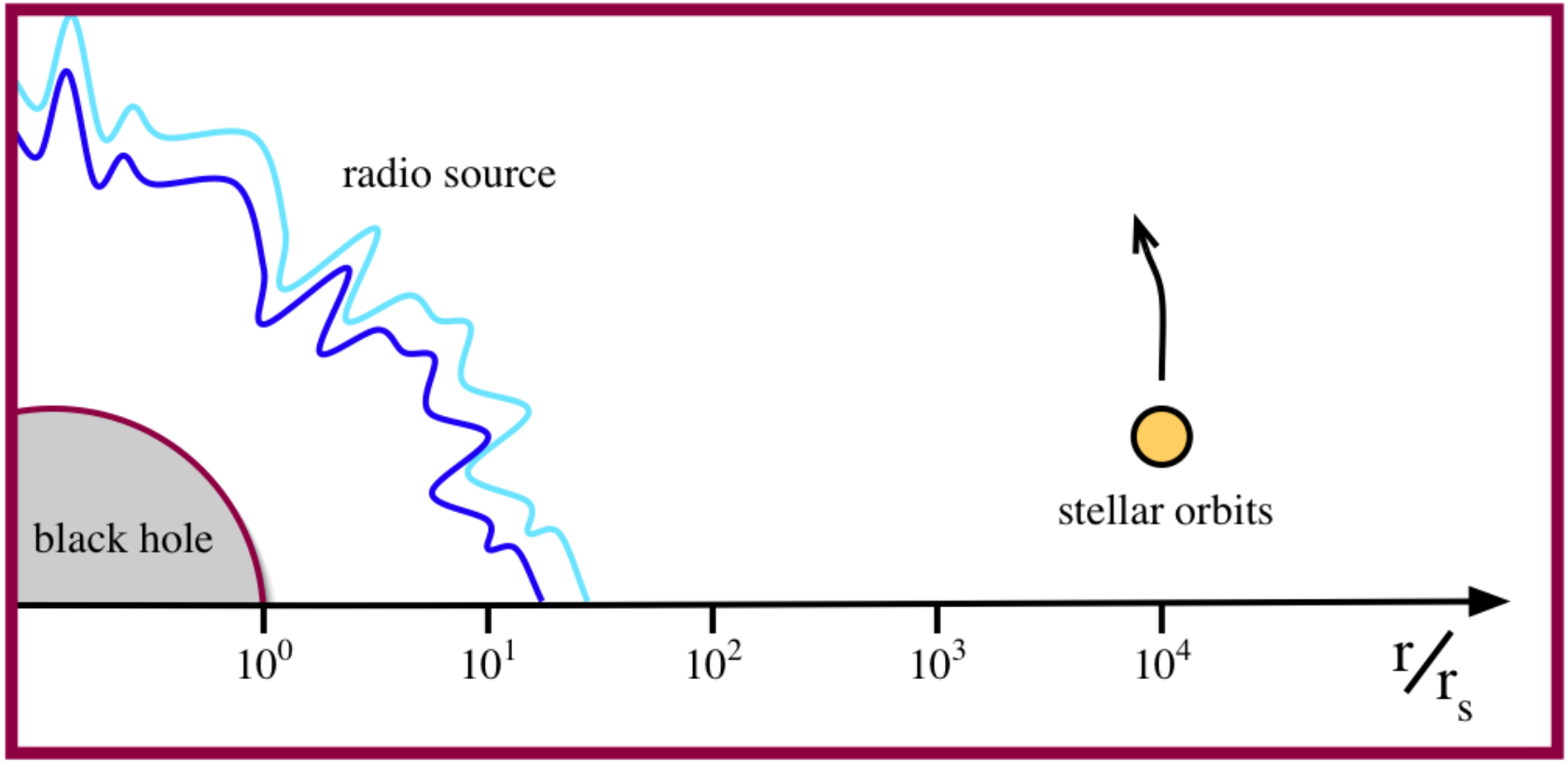
Submillimeter Polarization of Sgr A*





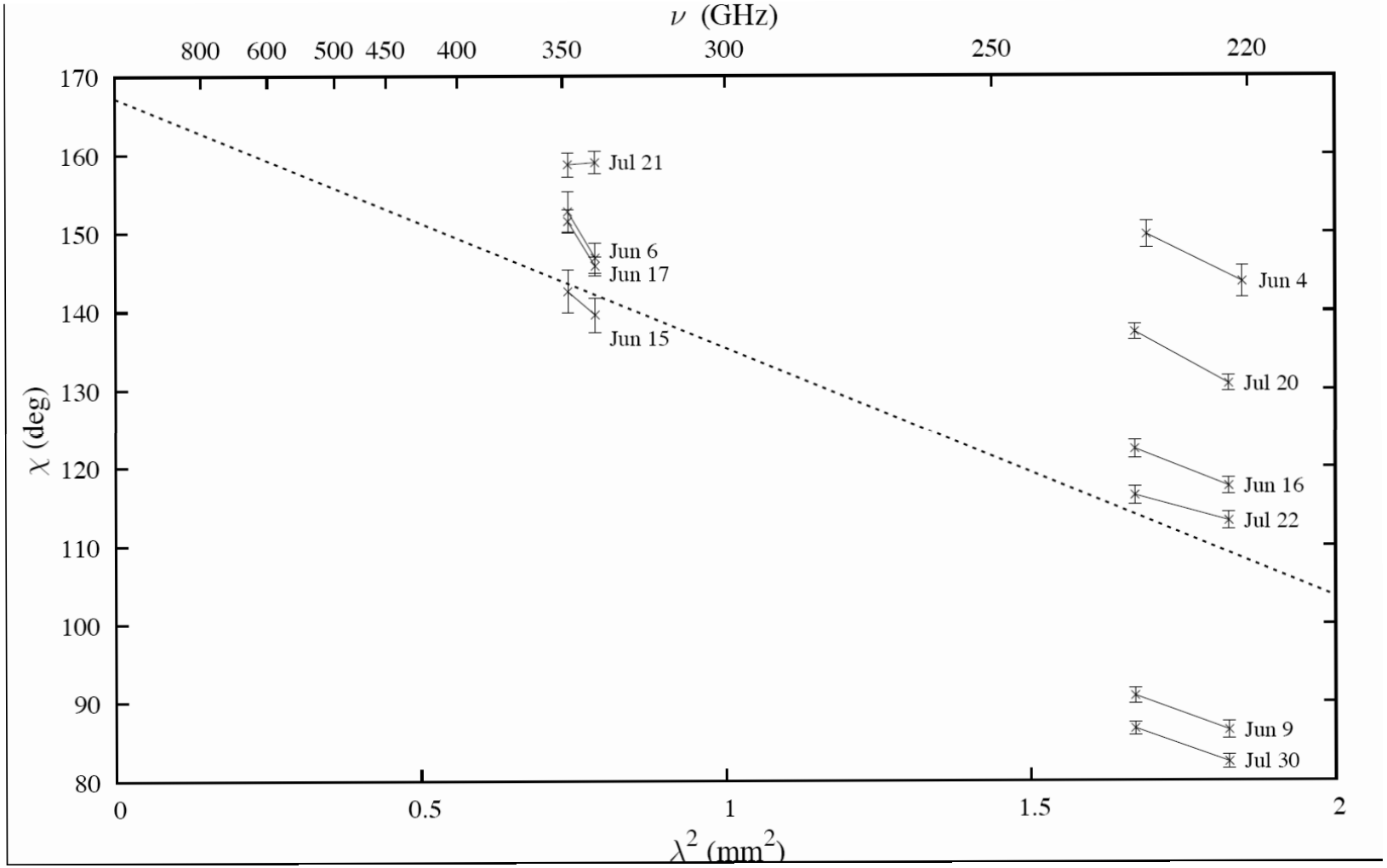


Some Scales in the Galactic Center



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

2005 SMA Measurements of Faraday Rotation in Sgr A*



WHAT IS THE CURRENT FEEDING RATE ?

About 1 solar mass per 100 million years

It must be in a “dormant” state

What we really want: the 'Shadow'

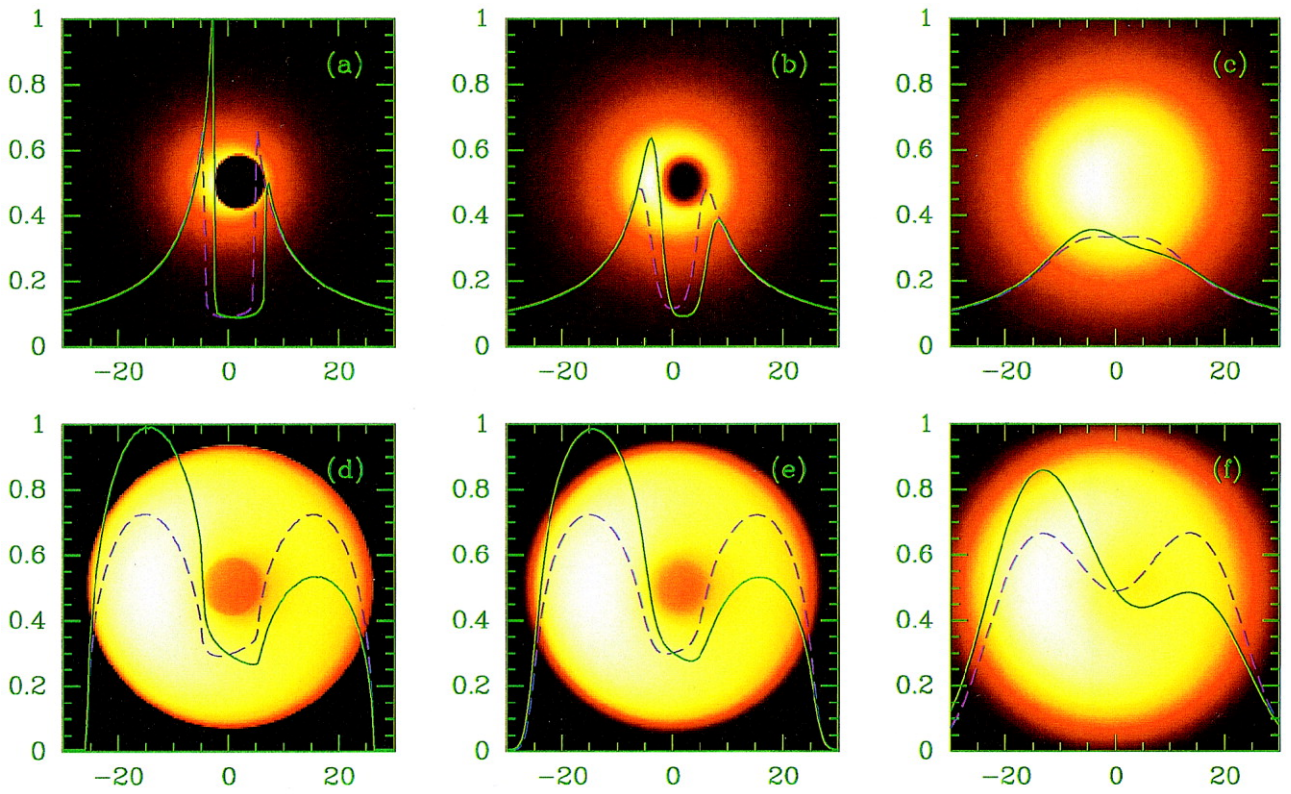
Falcke et al

free fall

rotating

orbiting

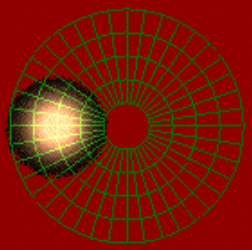
non-rotating

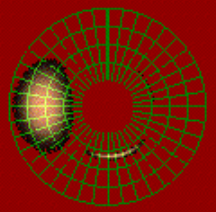


GR Code | 0.6mm VLBI | 1.3mm VLBI

SgrA* has the largest apparent Schwarzschild radius of any BH candidate. BUT… SgrA* scattered ~ λ^2

a=0, r=6M





F_{LP}

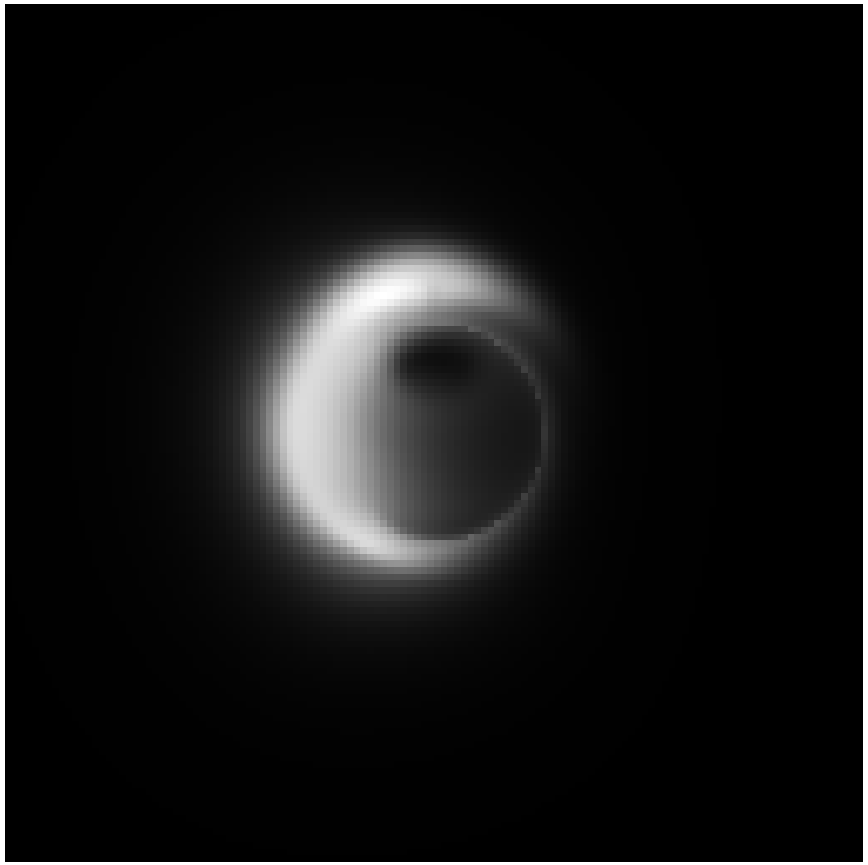
F_{tot}

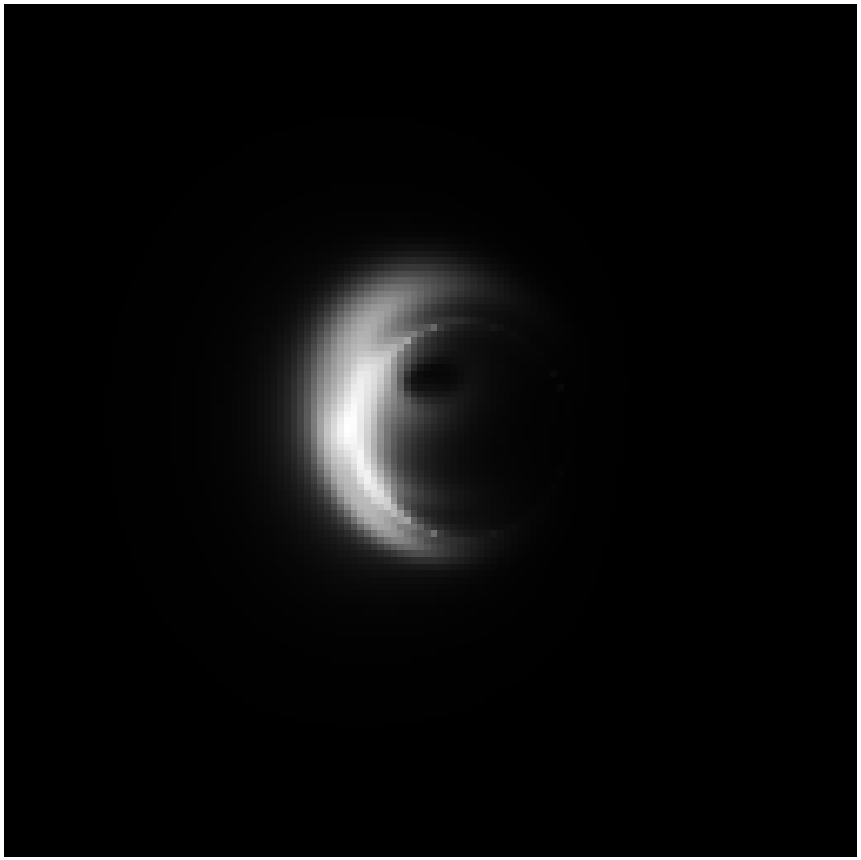
Broderick & Loeb, 2006, MNRAS, 367, 905

Hot Spot Models (P = 27 min)

230 GHz, ISM scattered

Models: Broderick & Loeb

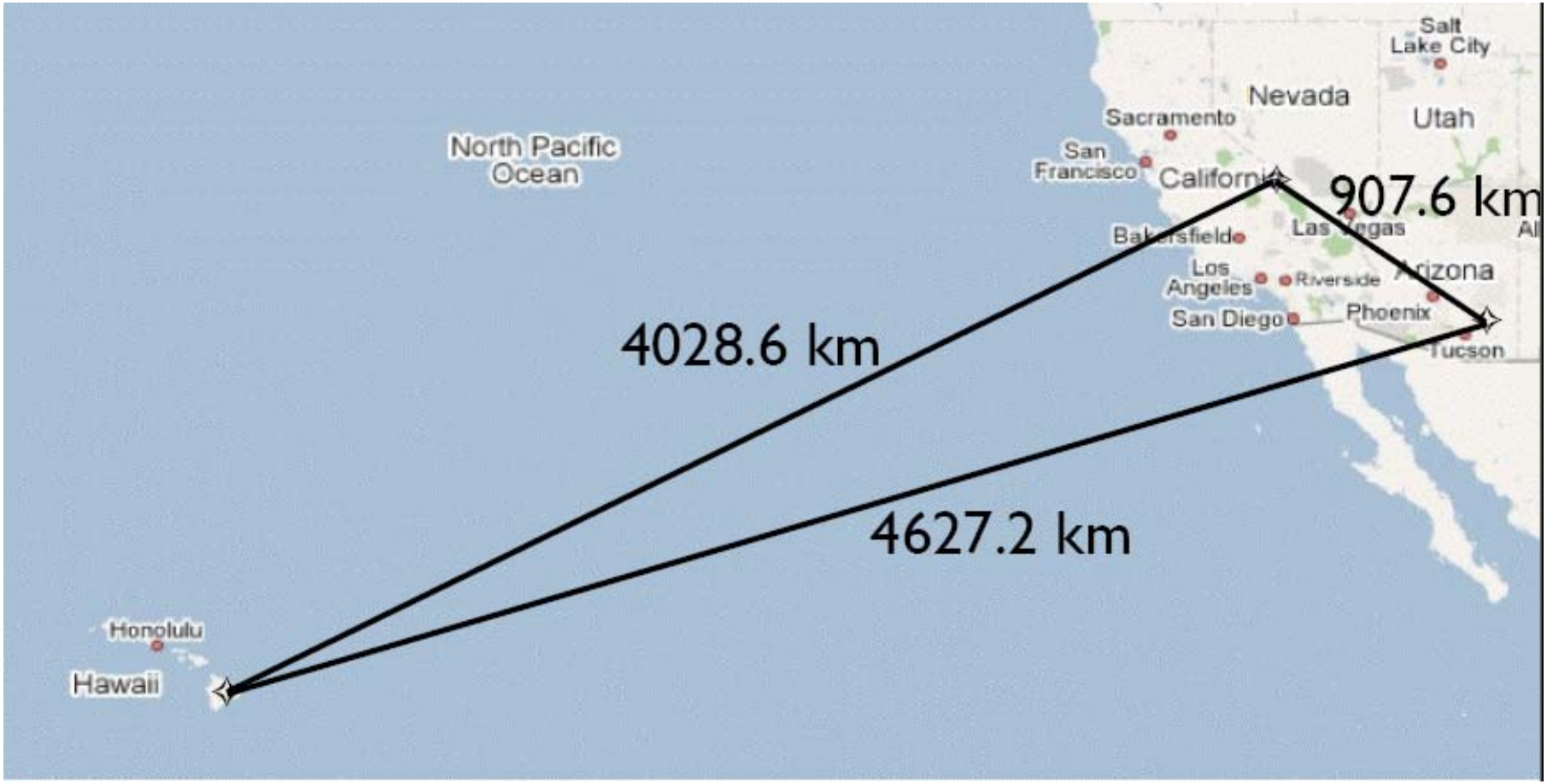




Spin = 0, orbit = ISCO

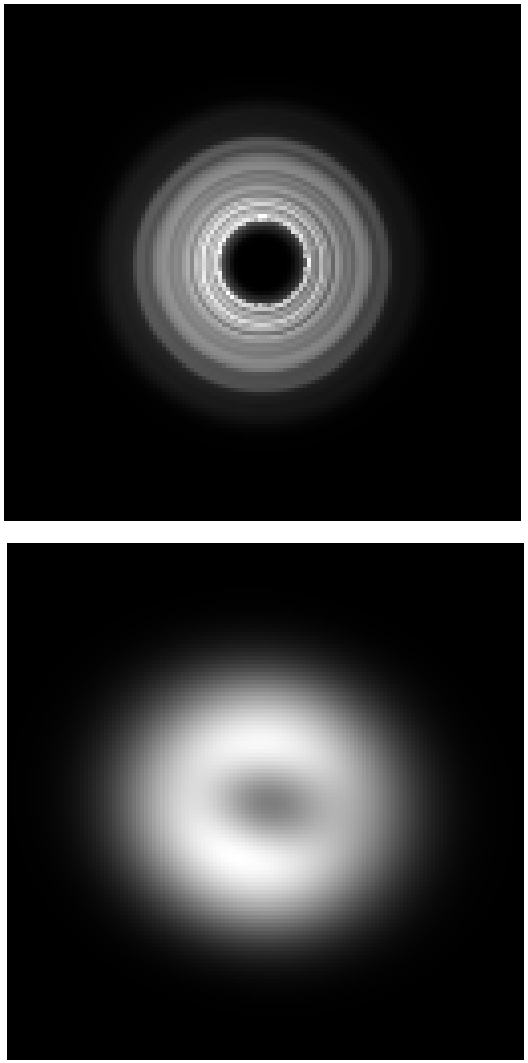
Spin = 0.9, orbit = 2.5 x ISCO

THE SIZE OF THE RADIO "IMAGE" OF THE BLACK HOLE IN THE CENTER OF OUR GALAXY HAS BEEN MEASURED TO BE 37 MICROARCSECONDS

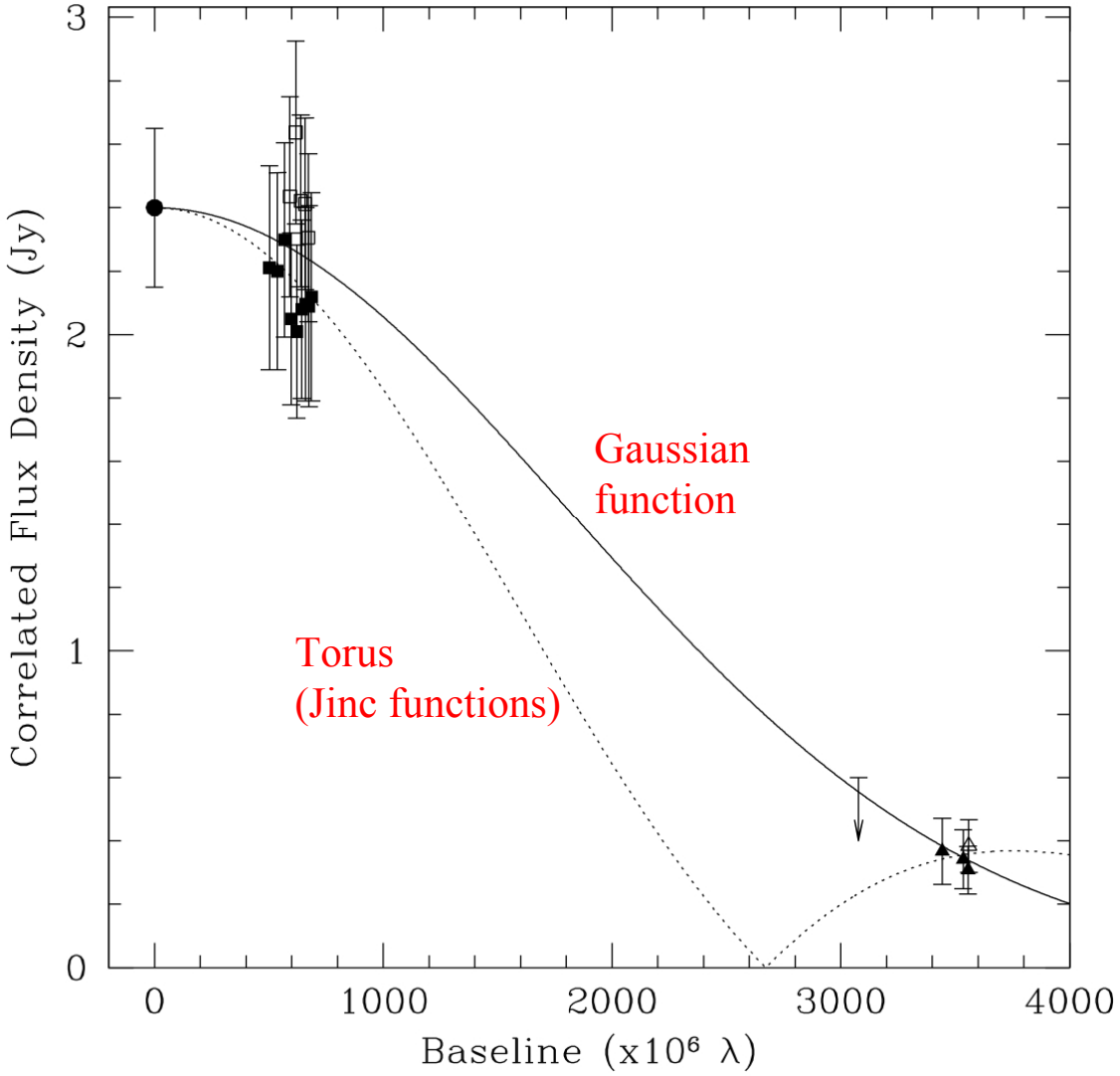


Fits to Visibility Data

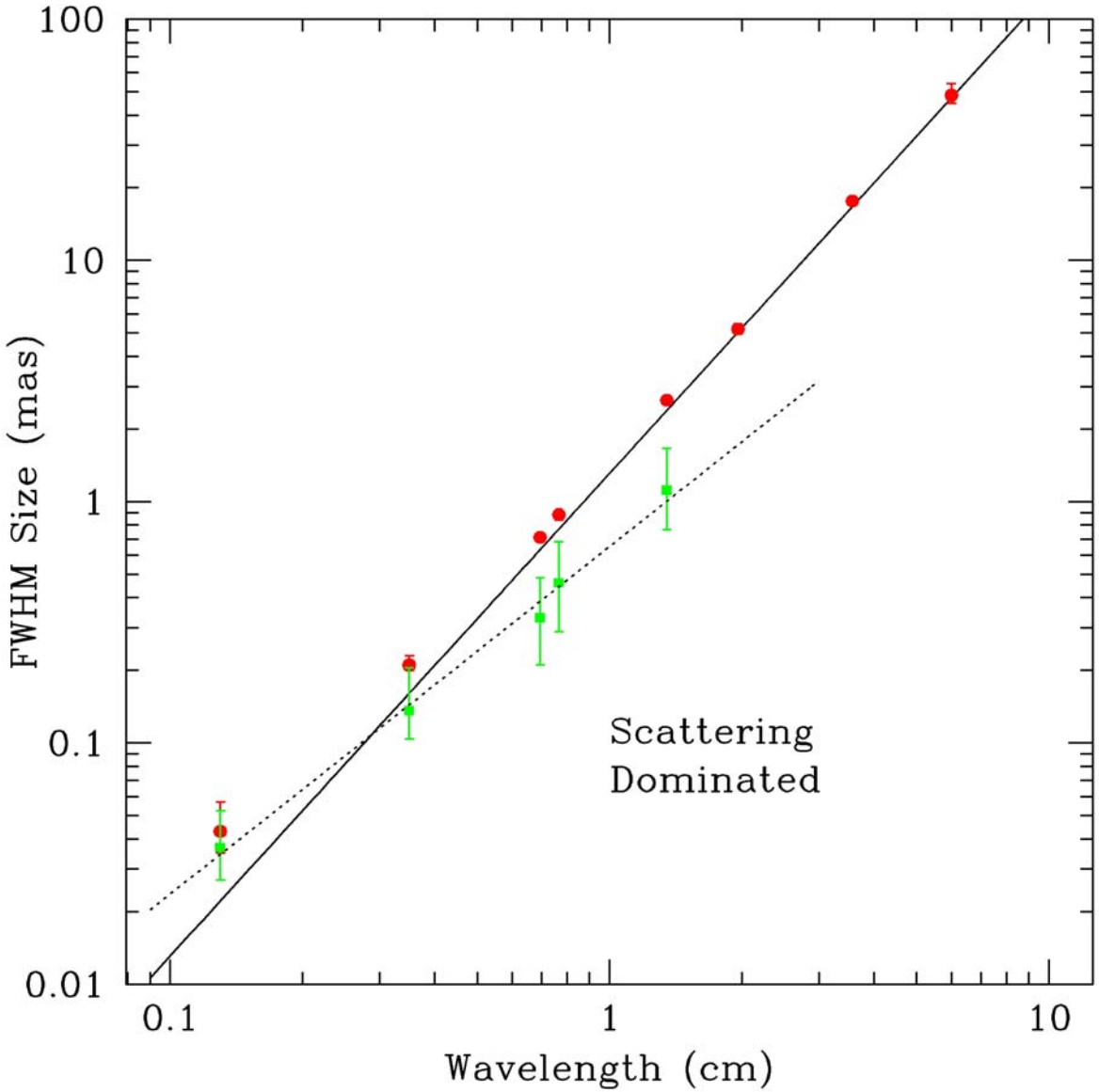
14 Rsch (140 μas)



Gammie et al



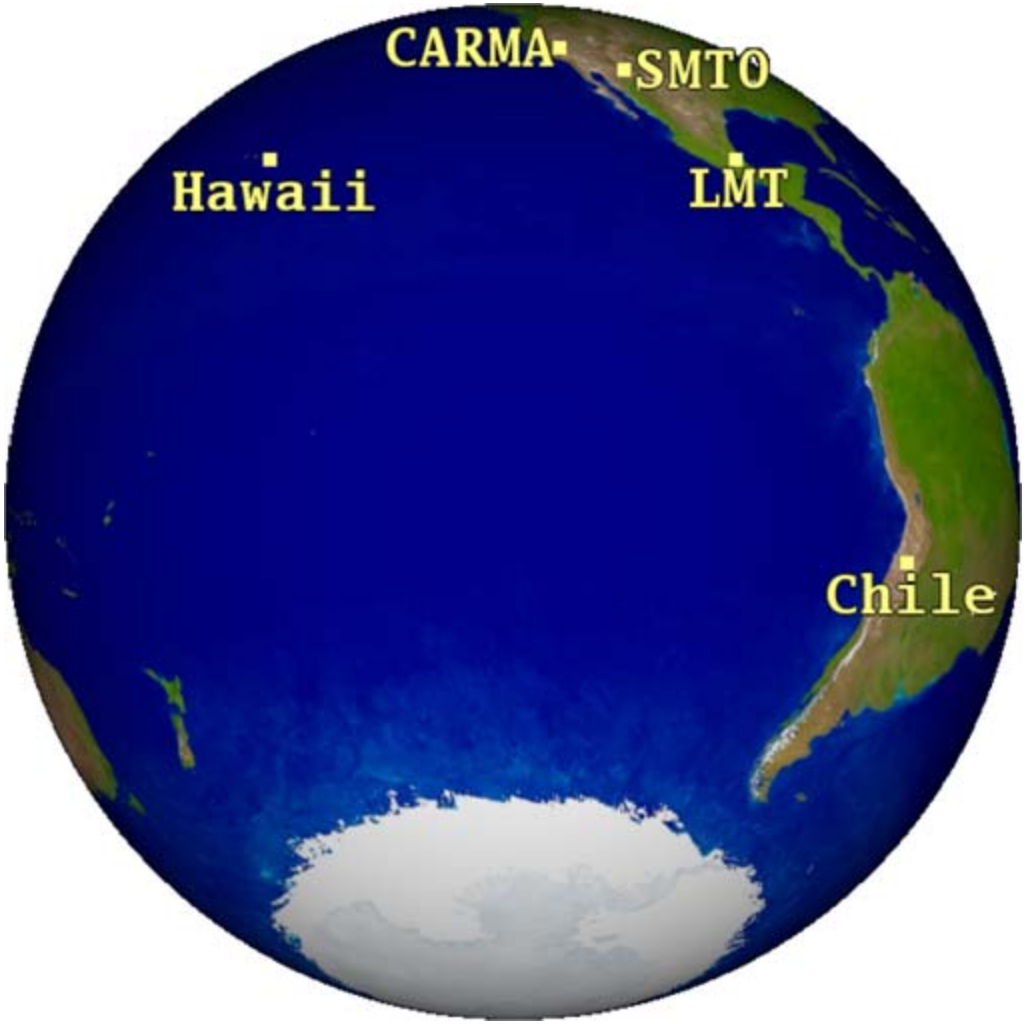
Seeing Through the Scattering



θ_{OBS} deviates from scattering for $\lambda \sim 1$ cm

$\theta_{INT} \ll \theta_{SCAT}$ for $\lambda \sim 1$ mm

$\theta_{INT} \propto \lambda^{1}$

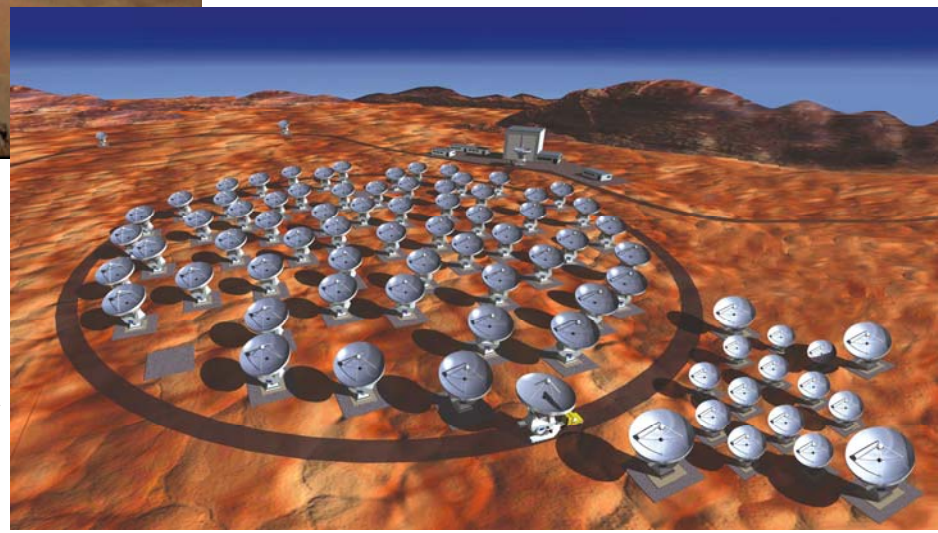

CARMA
SMTO
Hawaii
LMT
Chile

Atacama Large Millimeter/submillimeter Array

International astronomy facility,
partnership between Europe, North America and Japan, in cooperation with Chile (2003,2006)

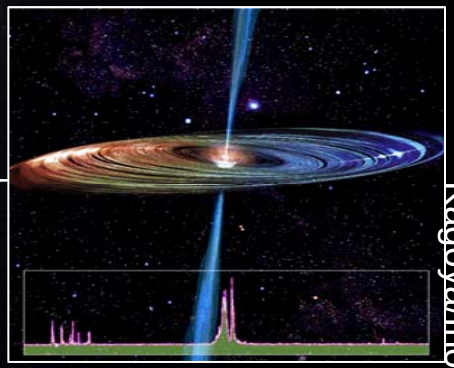
Plano Chajnantor
Northern Chile
at 5000m elevation

Operational 2013
(Early Science in 2010)



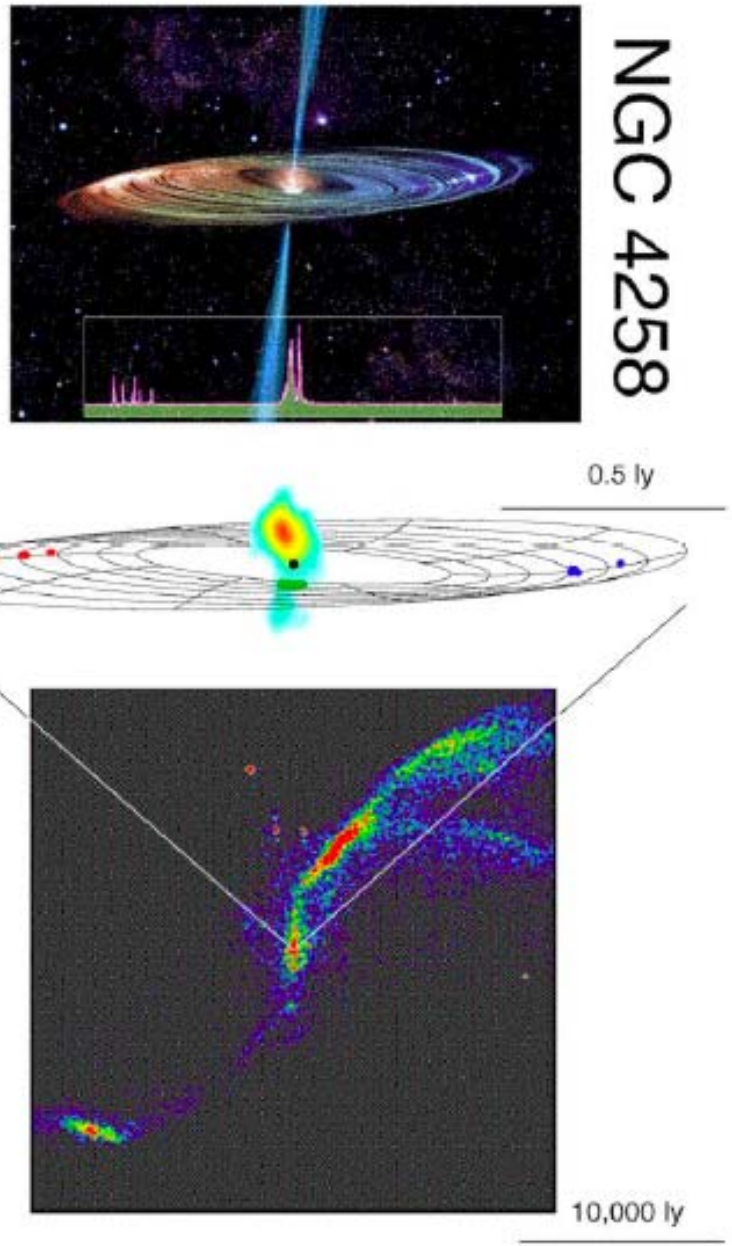
50 × 12-m telescopes
+
ACA: 12 × 7-m + 4 × 12-m

NGC 4258

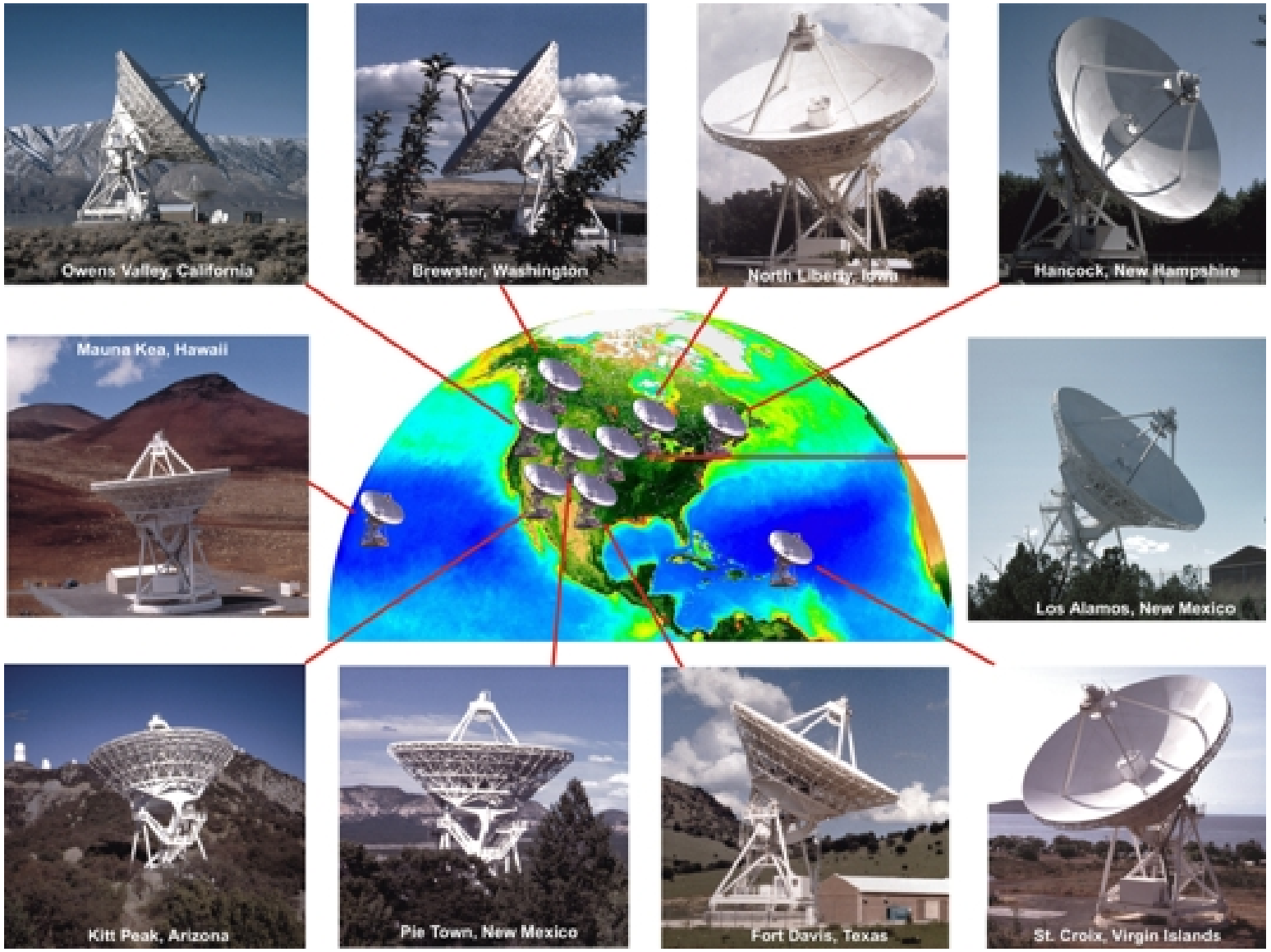


Optical: Slotnick, Slotnick & Block

Kagoya/Inoue

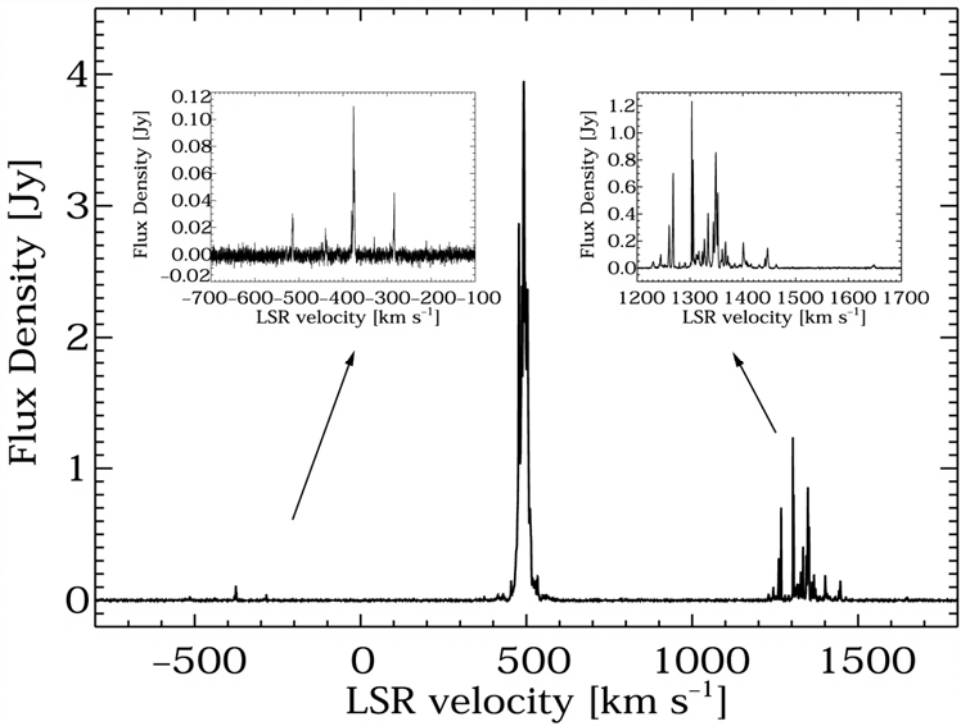

NGC 4258
0.5 ly
10,000 ly

VLBA

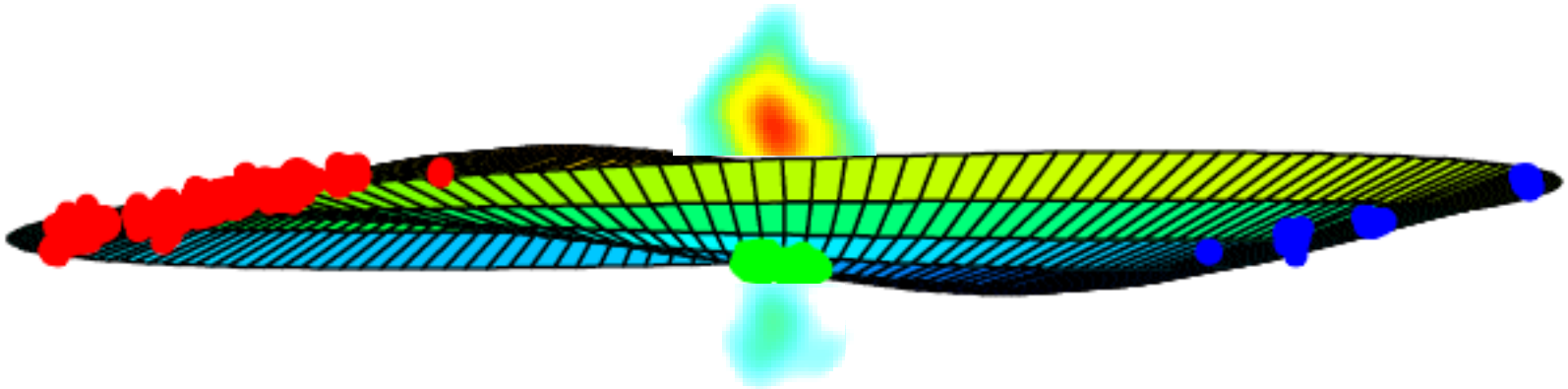


Angular resolution = 200 μas (0.006 pc at 7.2 Mpc)

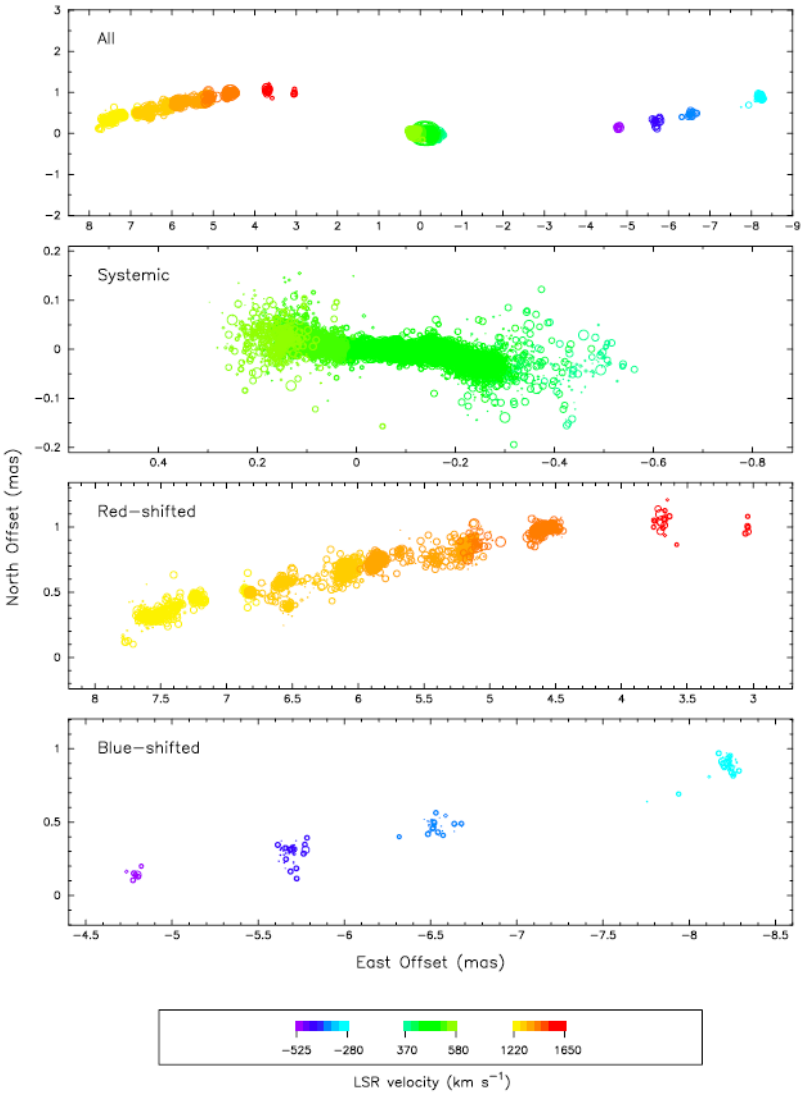
Spectral resolution < 1 kms^{-1}

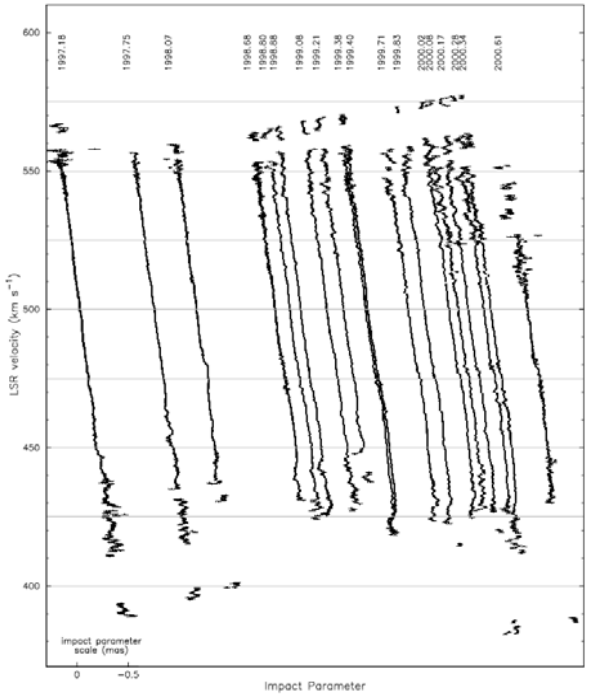


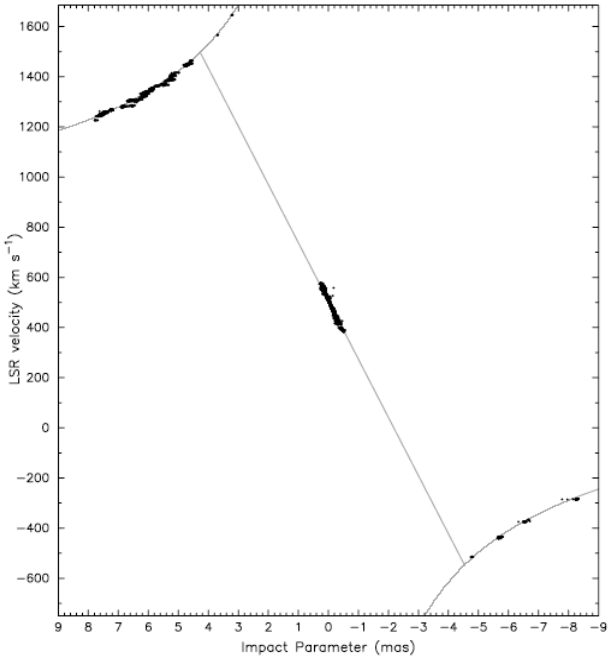
The Archetype: NGC 4258



NGC 4258: 18 VLBI Epochs 1997 - 2000





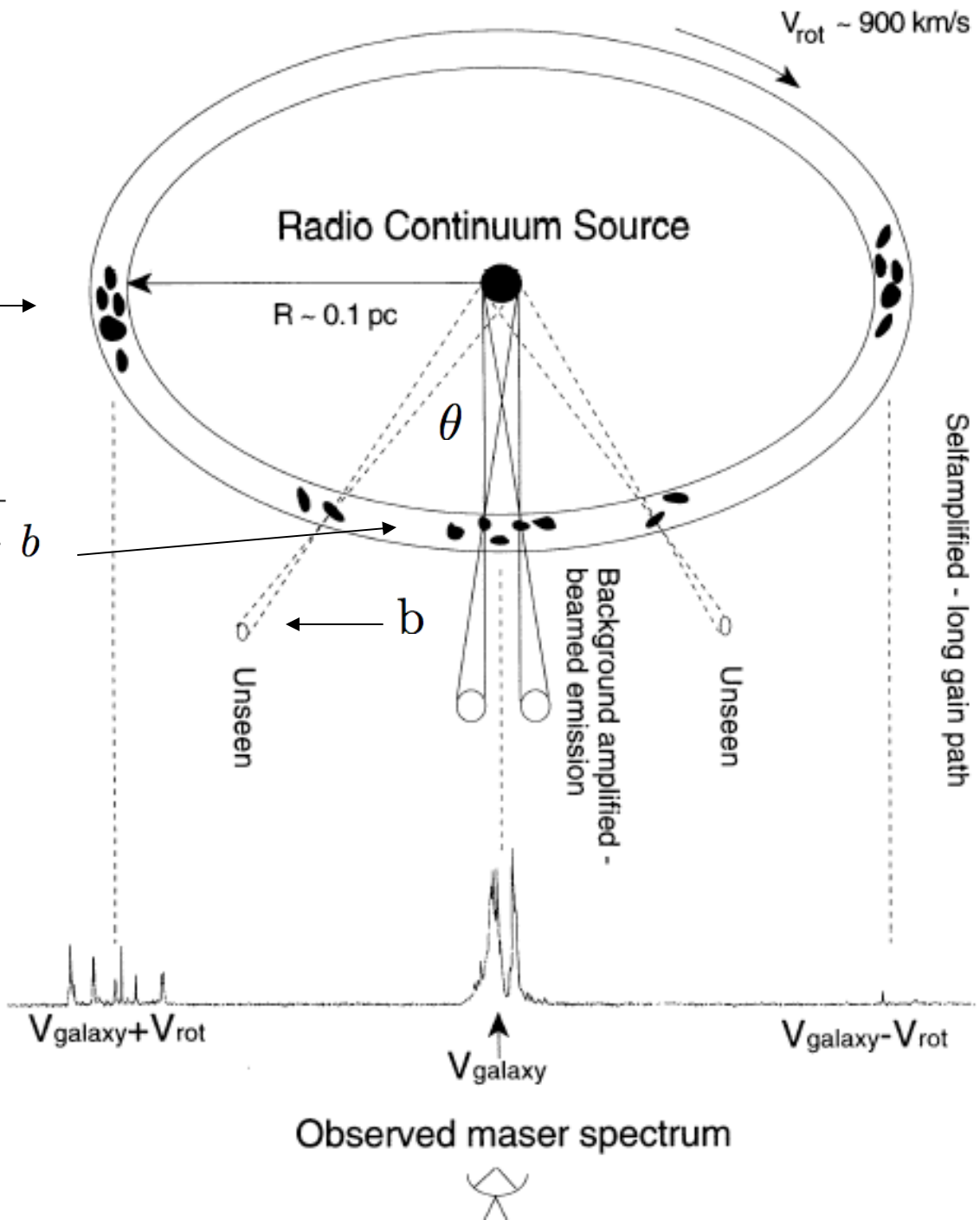


CfA Maser Group, Argon et al. 2007

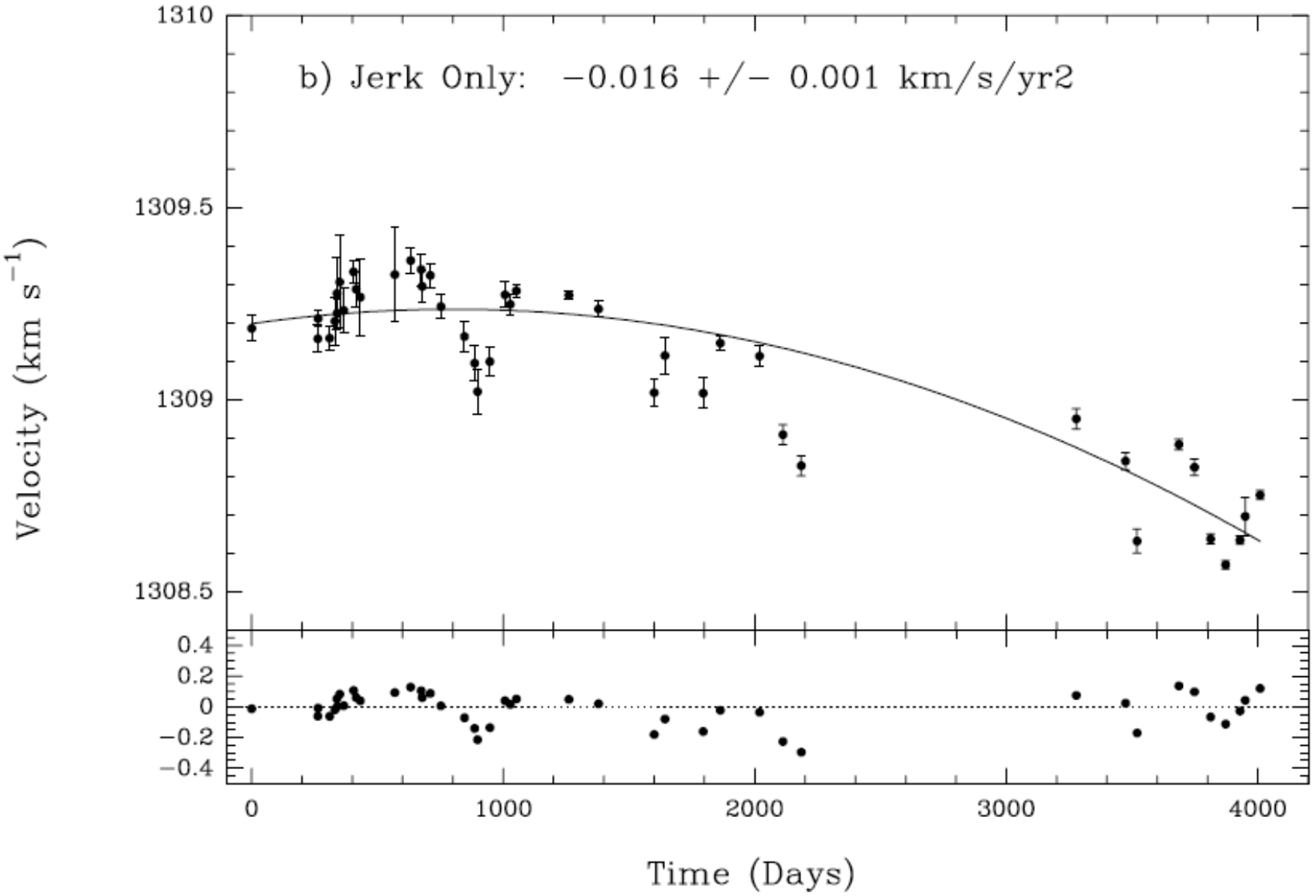
$$V_z = \sqrt{\frac{GM}{R}}\sin\theta$$

$$V_z = \sqrt{\frac{GM}{R}}$$

$$V_z = \sqrt{\frac{GM}{R}}\frac{b}{R} = \sqrt{\frac{GM}{R^3}}\,b$$



Acceleration of the “1306” kms^{-1} Feature



Humphreys et al. In preparation

Distance Measurements to NGC 4258

- Masers

7.2 +/- 0.3 +/-0.4 Mpc Herrnstein et al., Nature 1999

- Cepheid Variables

8.1 +/- 0.4 Mpc Maoz et al., 1999, Nature
(15 Cepheids)

7.8 +/- 0.3 +/- 0.5 Mpc Newman et al., 2001, Ap.J. (same 15 Cepheids)

7.5 +/- 0.3 Mpc Macri et al., 2006, Ap.J. 652,1133 (300 Cepheids)

H = 74.2 +/- 3.6 Riess et al, 2009, Ap.J. 699, 563