Microarcsecond-size Black Holes

Kazu Akiyama

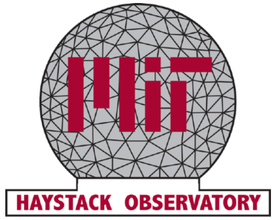
(NRAO Jansky Fellow / MIT Haystack Observatory)

Dom Pesce (SAO/CfA), Alexander Raymond (SAO/CfA)

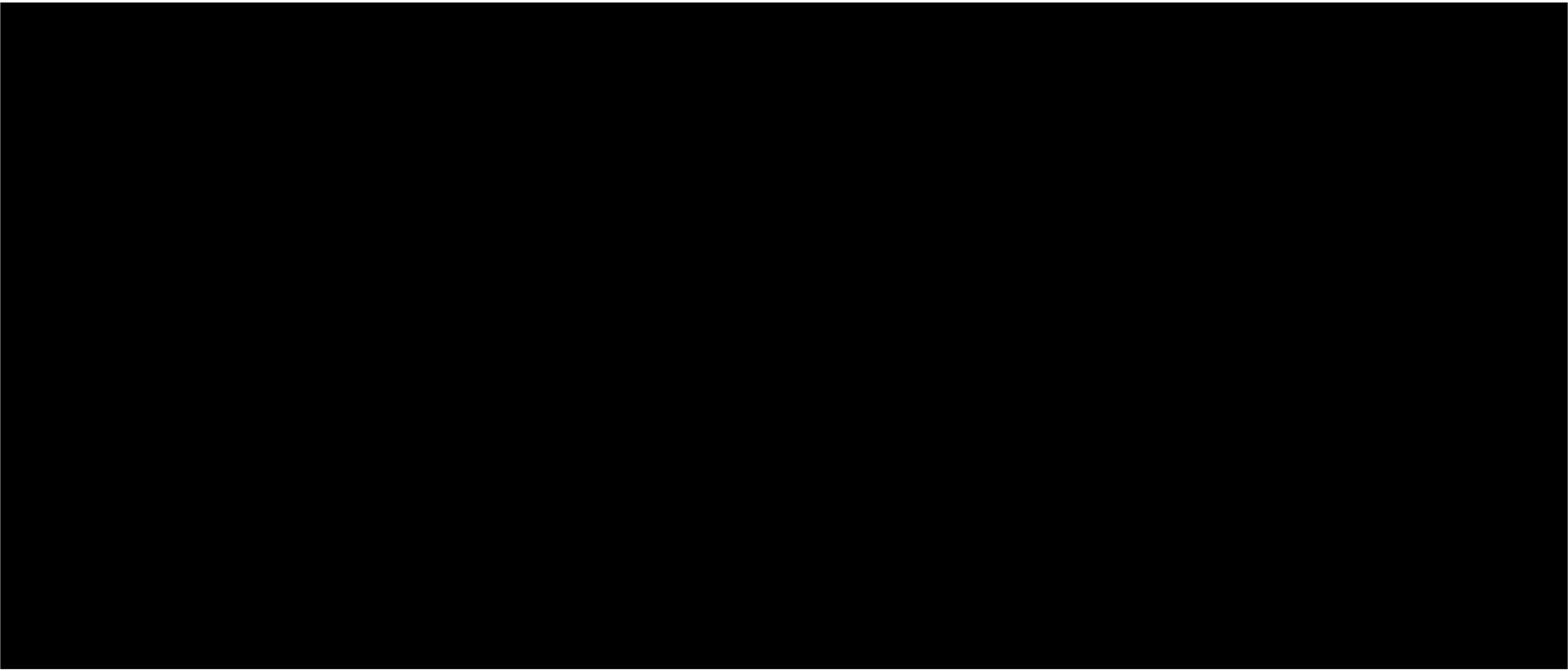
Venkatessh Ramakrishnan, Neil Nager (U. Concepción),

Vincent Fish (MIT Haystack), Michael Johnson and Many Others

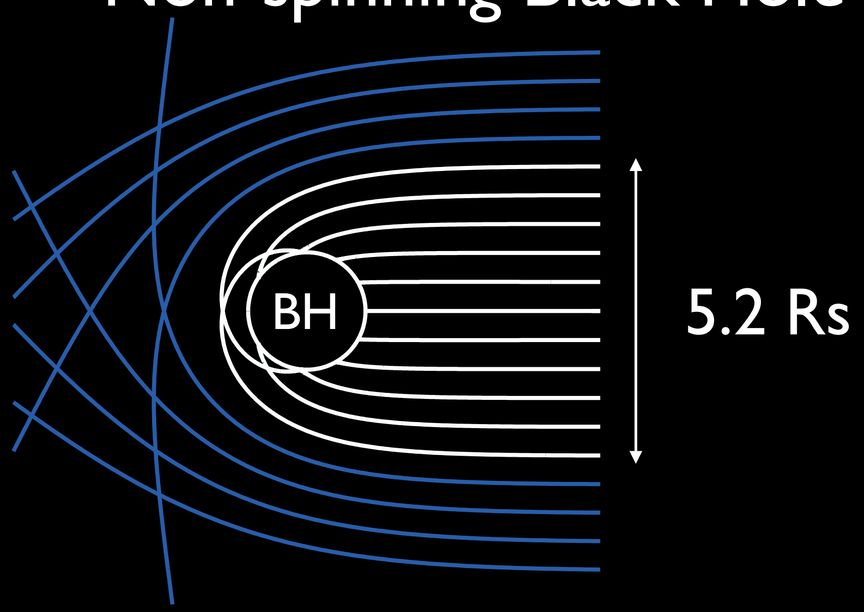
Event Horizon Telescope



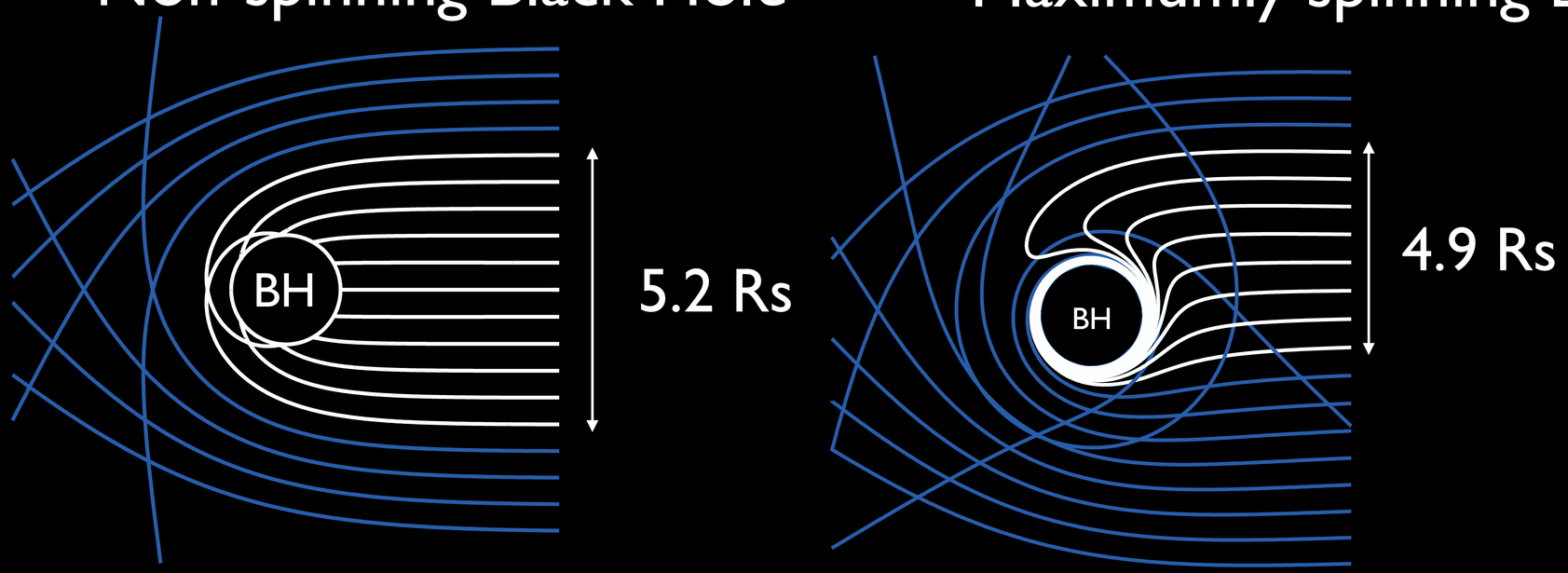
Diameter of the Black Hole Shadow



Diameter of the Black Hole Shadow



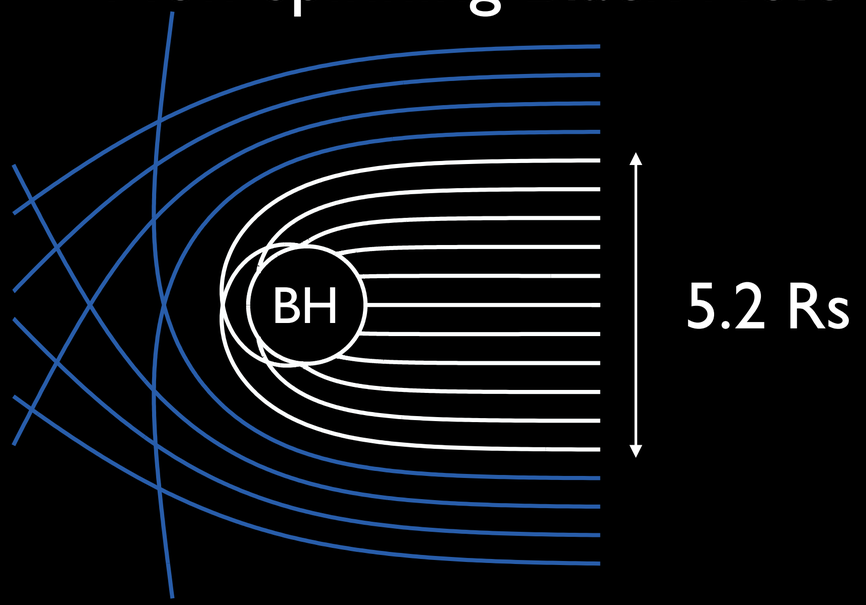
Diameter of the Black Hole Shadow



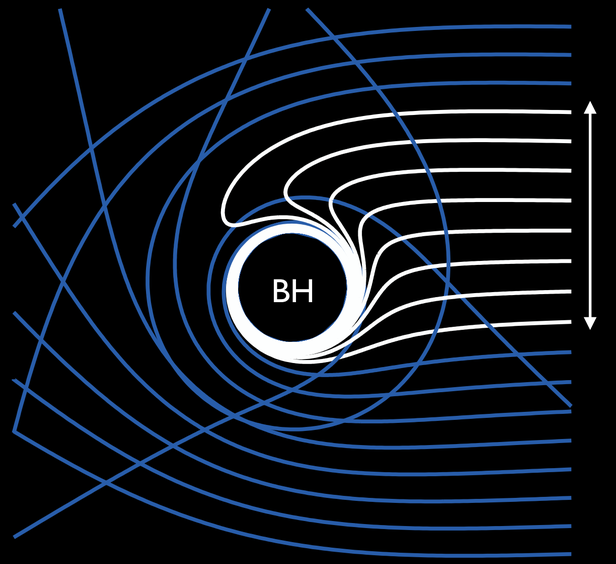
(Courtesy of Hung-Yi Pu)

Diameter of the Black Hole Shadow

Non-spinning Black Hole



Maximumly spinning BH



(Courtesy of Hung-Yi Pu)

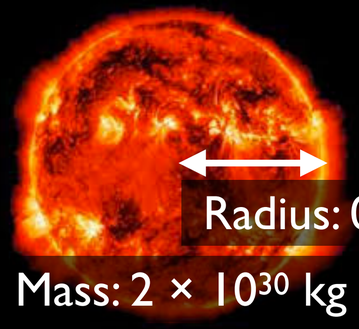
- Diameter of the "shadow" ~ 5 Rs
- It changes by only ~4% (4.84-5.2 Rs) (Bardeen 1973, Chan et al. 2013)

$$R_{\rm s} = \frac{2GM}{c^2} = 2.95\,{\rm km}\left(\frac{M}{1\,M_{\rm solar}}\right)$$

Angular Sizes of Various Black Holes

$$\theta_{\rm shadow} \approx \frac{10GM}{c^2 D} \sim 0.1\,\mu{\rm as} \left(\frac{M}{M_\odot}\right) \left(\frac{D}{1\,{\rm pc}}\right)^{-1}$$

Sun



Radius: 0.7×10^6 km

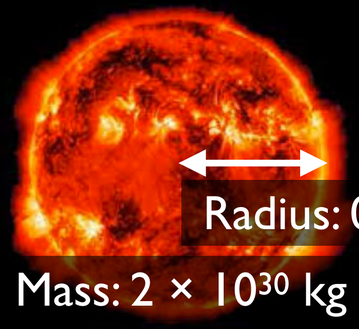
Mass: 2×10^{30} kg

Shadow Diameter
0.1 μas @ 1 pc

Angular Sizes of Various Black Holes

$$\theta_{\rm shadow} \approx \frac{10GM}{c^2 D} \sim 0.1\,\mu{\rm as} \left(\frac{M}{M_\odot}\right)\left(\frac{D}{1\,{\rm pc}}\right)^{-1}$$

Sun



Mass: 2 × 10^{30} kg

Shadow Diameter
0.1 μas @ 1 pc

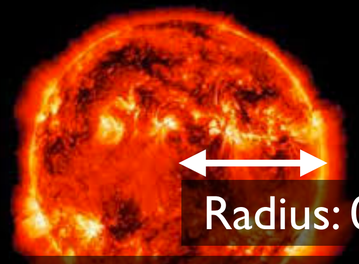
Stellar mass BH

$$\theta_{\rm shadow} \sim 0.001\,\mu{\rm as} \left(\frac{M}{10M_\odot}\right)\left(\frac{D}{1\,{\rm kpc}}\right)^{-1}$$

Angular Sizes of Various Black Holes

$$\theta_{\rm shadow} \approx \frac{10GM}{c^2 D} \sim 0.1\,\mu{\rm as} \left(\frac{M}{M_\odot}\right) \left(\frac{D}{1\,{\rm pc}}\right)^{-1}$$

Sun



Mass: 2 × 10^{30} kg

Shadow Diameter
0.1 μas @ 1 pc

Stellar mass BH

$$\theta_{\rm shadow} \sim 0.001\,\mu{\rm as} \left(\frac{M}{10M_\odot}\right) \left(\frac{D}{1\,{\rm kpc}}\right)^{-1}$$

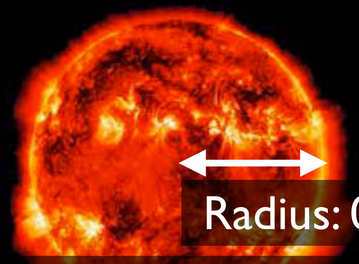
Intermed. mass BH
@ Galactic Center

$$\theta_{\rm shadow} \sim 0.01\,\mu{\rm as} \left(\frac{M}{10^4 M_\odot}\right) \left(\frac{D}{8\,{\rm kpc}}\right)^{-1}$$

Angular Sizes of Various Black Holes

$$\theta_{\rm shadow} \approx \frac{10GM}{c^2 D} \sim 0.1\,\mu{\rm as}\left(\frac{M}{M_\odot}\right)\left(\frac{D}{1\,{\rm pc}}\right)^{-1}$$

Sun



Mass: 2 × 10^{30} kg

Shadow Diameter
0.1 μas @ 1 pc

Stellar mass BH $\quad \theta_{\rm shadow} \sim 0.001\,\mu{\rm as}\left(\frac{M}{10M_\odot}\right)\left(\frac{D}{1\,{\rm kpc}}\right)^{-1}$

Intermed. mass BH
@ Galactic Center $\quad \theta_{\rm shadow} \sim 0.01\,\mu{\rm as}\left(\frac{M}{10^4 M_\odot}\right)\left(\frac{D}{8\,{\rm kpc}}\right)^{-1}$

Supermassive BH $\quad \theta_{\rm shadow} \sim 1\,\mu{\rm as}\left(\frac{M}{10^8 M_\odot}\right)\left(\frac{D}{10\,{\rm Mpc}}\right)^{-1}$

Sgr A*~ 52 uas (M=4x10⁶ M_{sun}, D=8 kpc)
M87 ~40 uas (M=6.5x10⁹ M_{sun}, D=16.7 Mpc)

Black Hole Mass Measurements

- Resolving the dynamics of gas or stars inside the sphere of the gravitational influence of the target black hole

Black Hole Mass Measurements

- Resolving the dynamics of gas or stars inside the sphere of the gravitational influence of the target black hole

  Sgr A*: spatially & timely resolved orbit of stars **(Talk by Shoko Sakai)**

Black Hole Mass Measurements

- Resolving the dynamics of gas or stars inside the sphere of the gravitational influence of the target black hole

  Sgr A*: spatially & timely resolved orbit of stars **(Talk by Shoko Sakai)**

Black Hole Mass Measurements

- Resolving the dynamics of gas or stars inside the sphere of the gravitational influence of the target black hole

  Sgr A*: spatially & timely resolved orbit of stars **(Talk by Shoko Sakai)**

  Stellar-dynamical measurements: spatially resolve orbits of stars

Black Hole Mass Measurements

- Resolving the dynamics of gas or stars inside the sphere of the gravitational influence of the target black hole

  Sgr A*: spatially & timely resolved orbit of stars **(Talk by Shoko Sakai)**

  Stellar-dynamical measurements: spatially resolve orbits of stars

  Gas-dynamical measurements: spatially resolve dynamics of gas
  - VLBI observations of H_2O mega masers
  - Optical spectroscopy of atomic lines
  - ALMA observations of cold molecular gas (CO, HCN+, etc)

Black Hole Mass Measurements

- Resolving the dynamics of gas or stars inside the sphere of the gravitational influence of the target black hole

  Sgr A*: spatially & timely resolved orbit of stars **(Talk by Shoko Sakai)**

  Stellar-dynamical measurements: spatially resolve orbits of stars

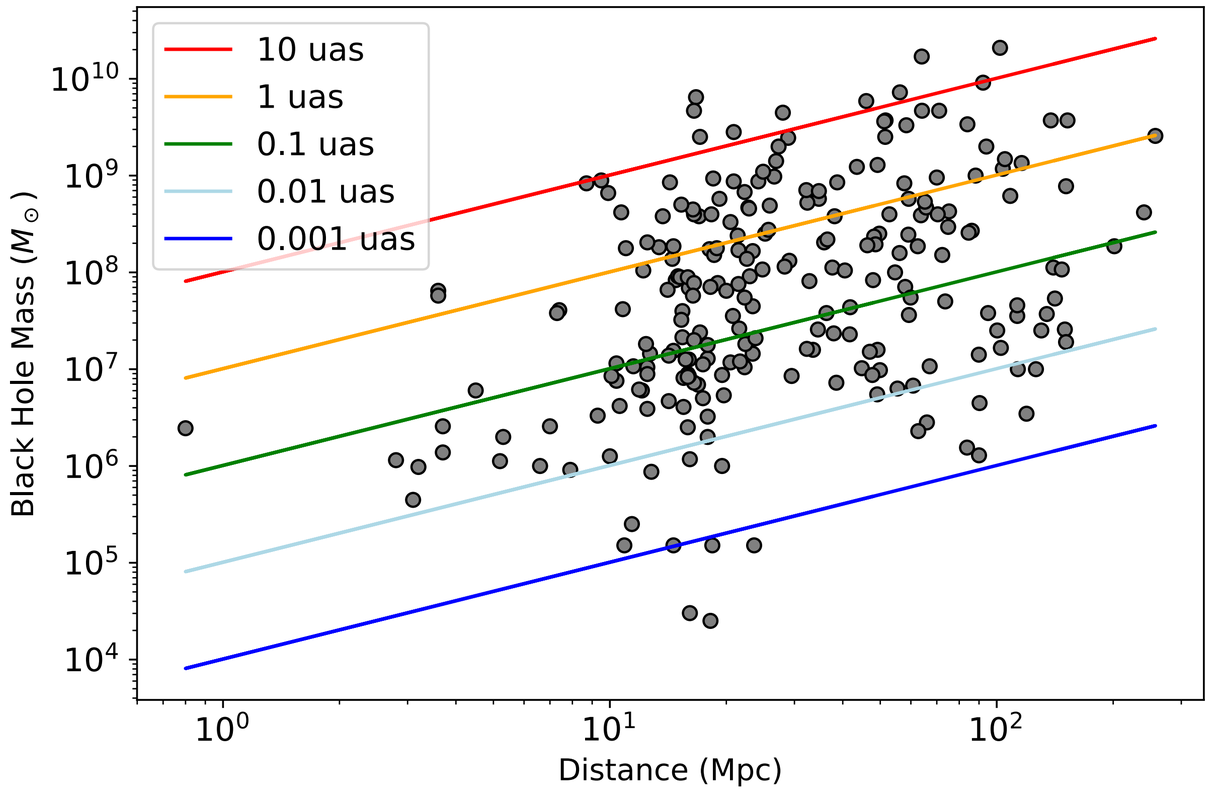
  Gas-dynamical measurements: spatially resolve dynamics of gas
  - VLBI observations of H_2O mega masers
  - Optical spectroscopy of atomic lines
  - ALMA observations of cold molecular gas (CO, HCN+, etc)

  Reverberation Mapping: spatially resolve orbits of BLRs using “echo”

Nearby Super Massive Black Holes

Known uas-size SMBHs

(stellar, gas, maser, reverberation mapping)

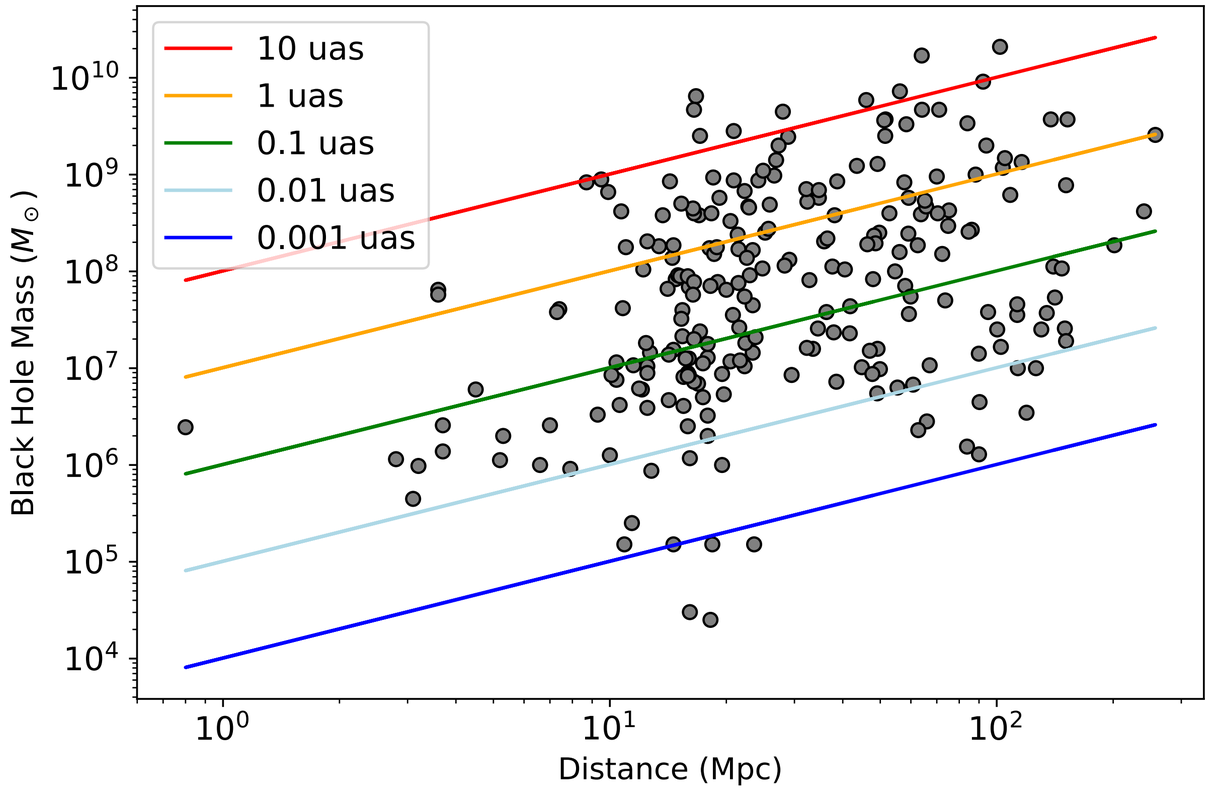


Data are from van den Vosch 2006

Event Horizon Telescope

Nearby Super Massive Black Holes

Known uas-size SMBHs
(stellar, gas, maser, reverberation mapping)



Extragalactic SMBHs with D_{shadow} > 5 uas (22 sources)

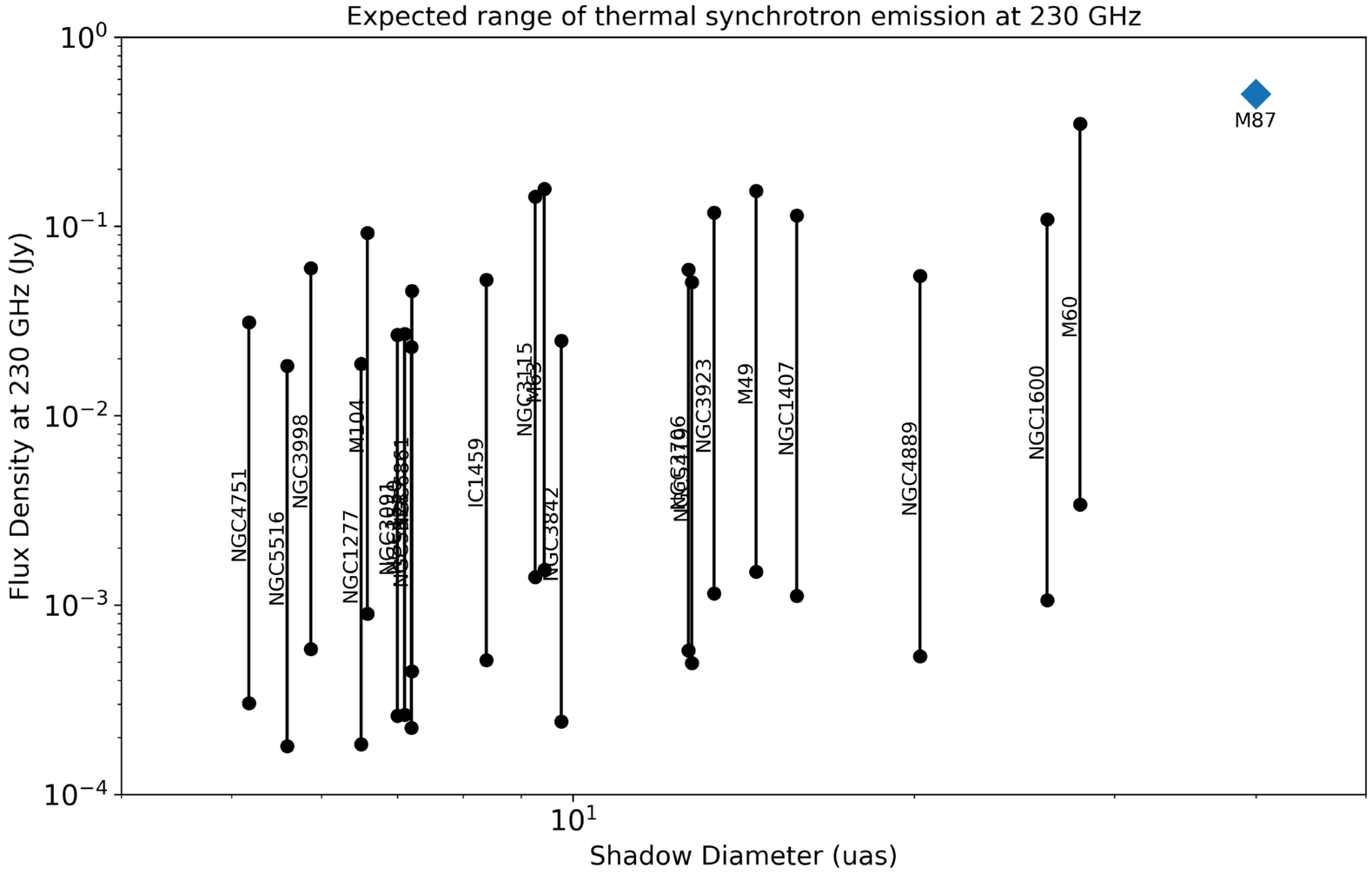
Name	D (Mpc)	M_{BH} ($10^9 M_\odot$)	θ_{shadow}† (μas)	Name	D (Mpc)	M_{BH} ($10^9 M_\odot$)	θ_{shadow}† (μas)
M87	16.7	6.5	38.2	NGC3115	9.5	0.9	9.3
M60	16.5	4.7	28.0	IC1459	28.9	2.5	8.4
NGC1600	64.0	17.0	26.2	NGC6861	27.3	2.0	7.2
NGC4889	102.0	20.9	20.2	NGC5328	64.1	4.7	7.2
NGC1407	28.0	4.5	15.7	NGC1550	51.6	3.7	7.1
M49	17.1	2.5	14.5	NGC3091	51.2	3.6	7.0
NGC3923	20.9	2.8	13.3	M104	9.9	0.7	6.6
NGC5419	56.2	7.2	12.7	NGC1277	71.0	4.7	6.5
NGC3706	46.0	5.9	12.6	NGC3998	14.3	0.9	5.9
NGC3842	92.2	9.1	9.8	NGC5516	58.4	3.3	5.6
M63	8.7	0.8	9.4	NGC4751	26.9	1.4	5.2

† The expected diameter of the black hole shadow given by $5R_s$.

D_{shadow} > 1 uas: ~ 66 sources

Data are from van den Vosch 2006

Expected Horizon-scale Flux Density



Data are from van den Vosch 2006

RIAF's thermal emission

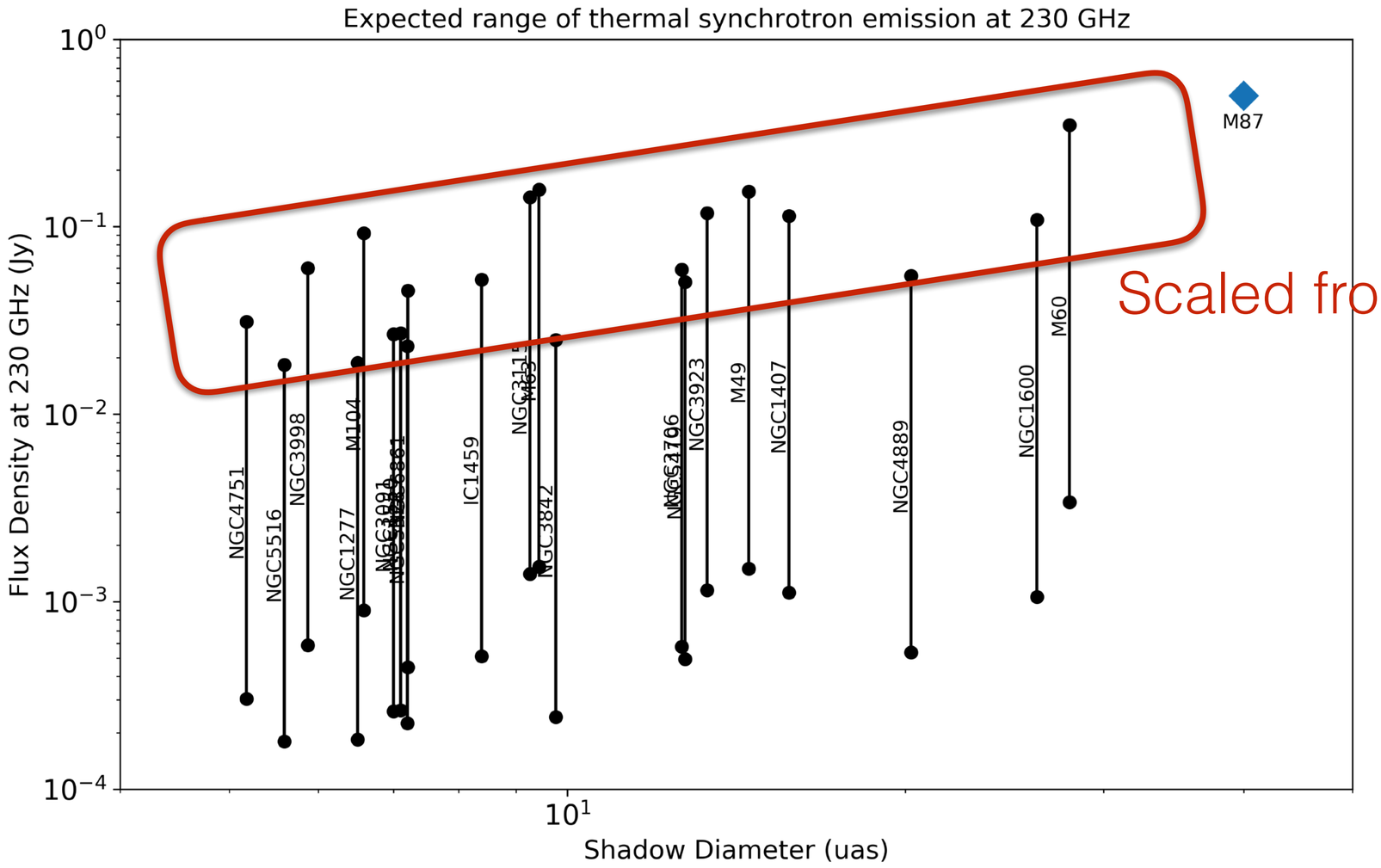
$$\propto M_{\rm BH}\dot{m}^{\frac{6}{5}}\nu^{\frac{2}{5}}D^{-2}$$

(Mahadevan 1997)

Accretion rate would be an important factor

Event Horizon Telescope

Expected Horizon-scale Flux Density



Scaled from M87

RIAF's thermal emission

$$\propto M_{\rm BH}\dot{m}^{\frac{6}{5}}\nu^{\frac{2}{5}}D^{-2}$$

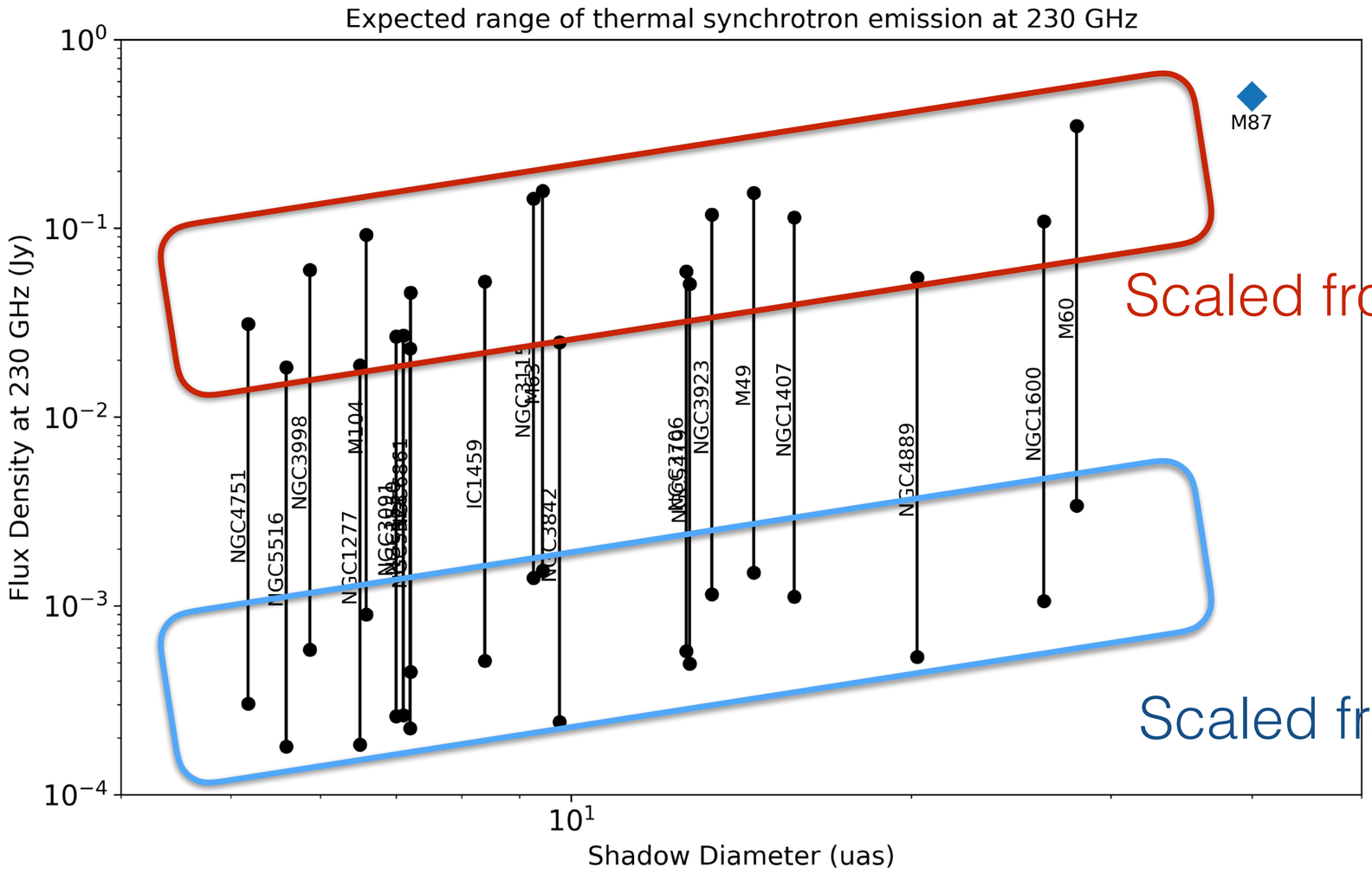
(Mahadevan 1997)

Accretion rate would be an important factor

Data are from van den Vosch 2006

Event Horizon Telescope

Expected Horizon-scale Flux Density



Scaled from M87

Scaled from Sgr A*

RIAF's thermal emission

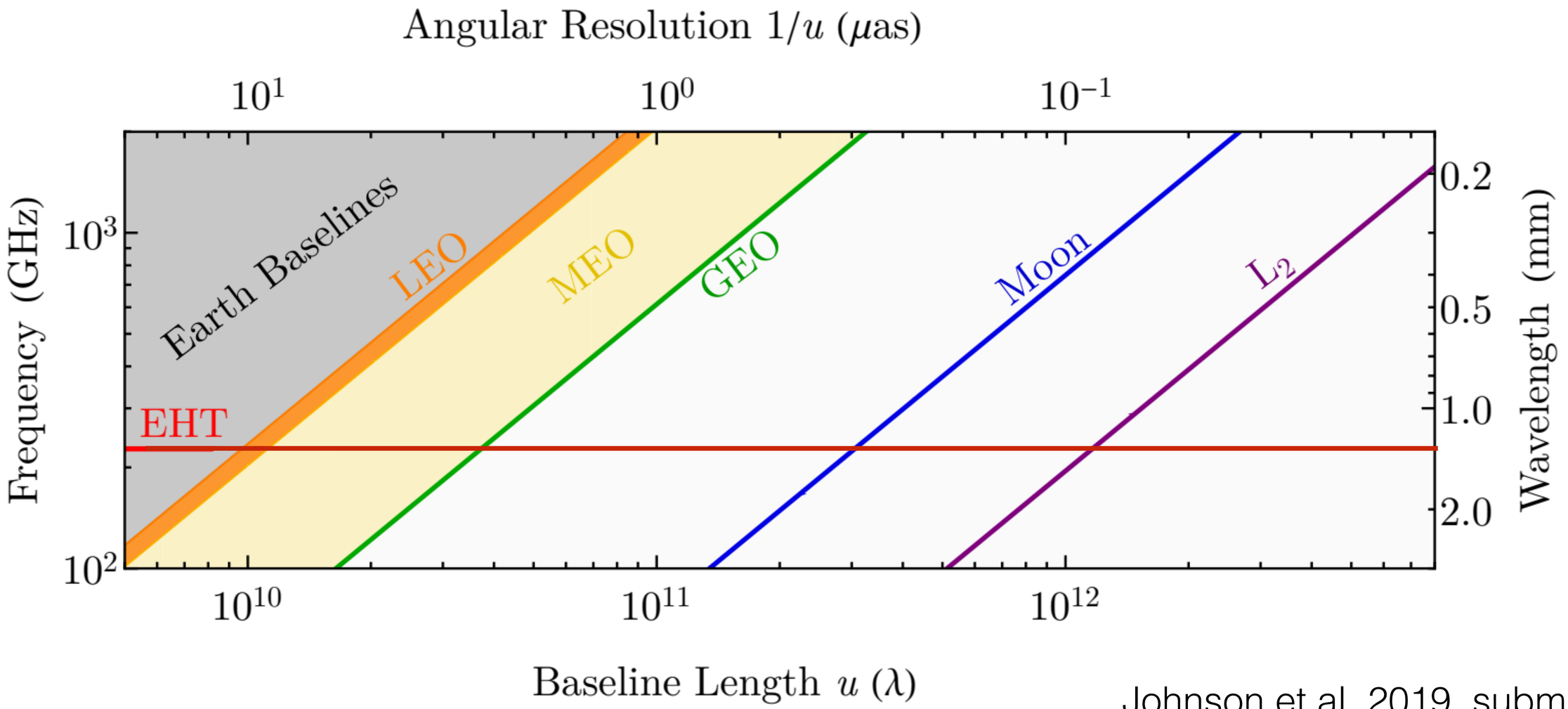
$$\propto M_{\rm BH}\dot{m}^{\frac{6}{5}}\nu^{\frac{2}{5}}D^{-2}$$

(Mahadevan 1997)

Accretion rate would be an important factor

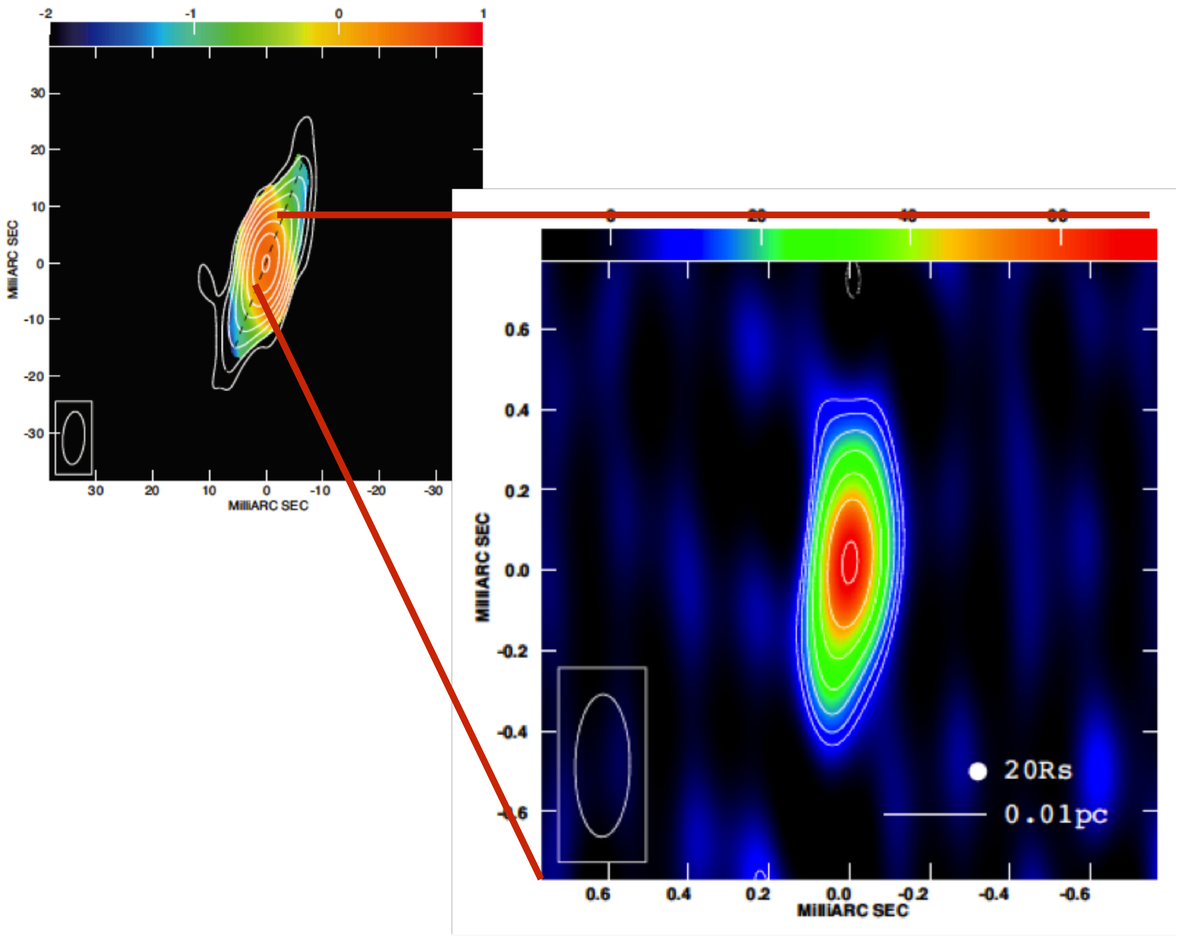
Data are from van den Vosch 2006

Angular size of ground/space VLBI



Johnson et al. 2019, subm.

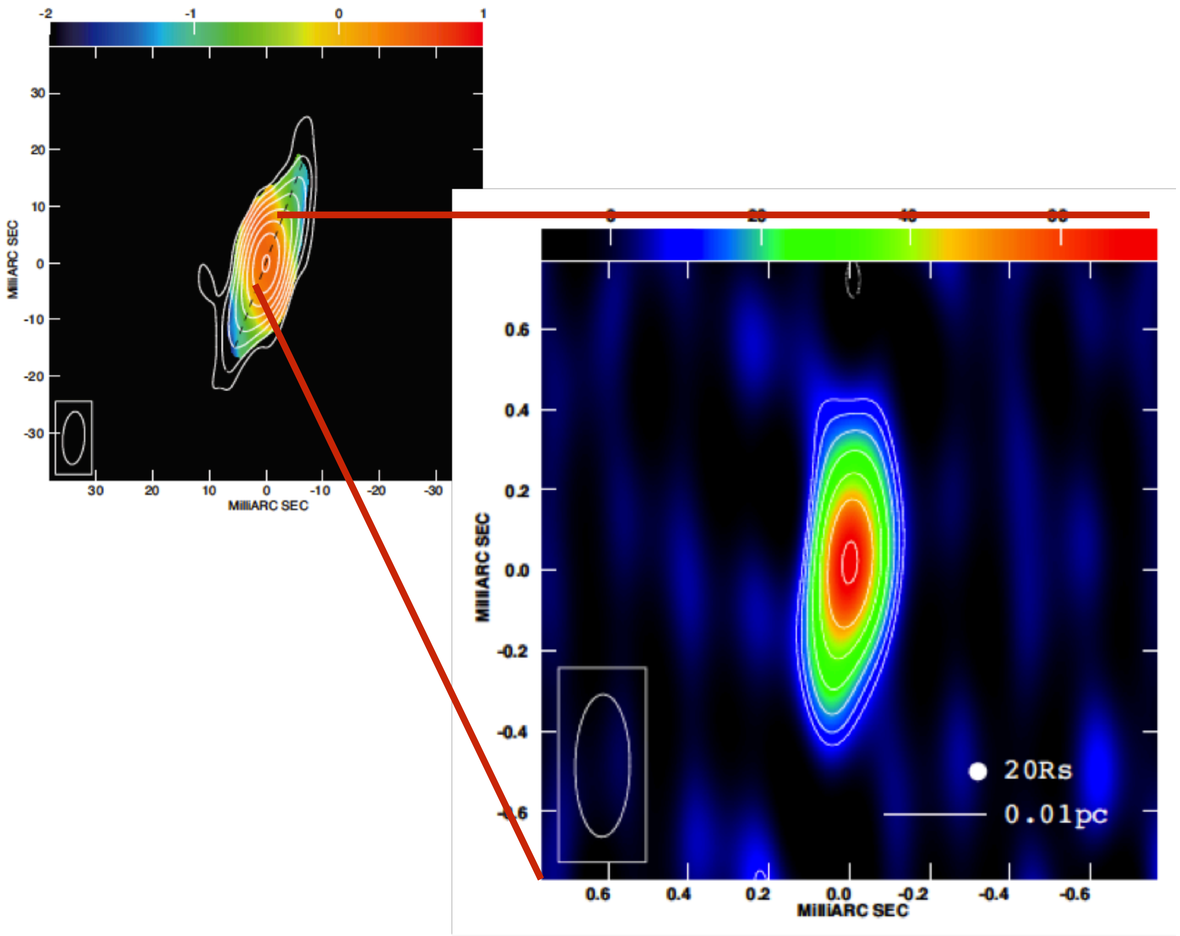
Example space VLBI simulations: Sombrero Galaxy



Hada, Doi et al. 2013, ApJ

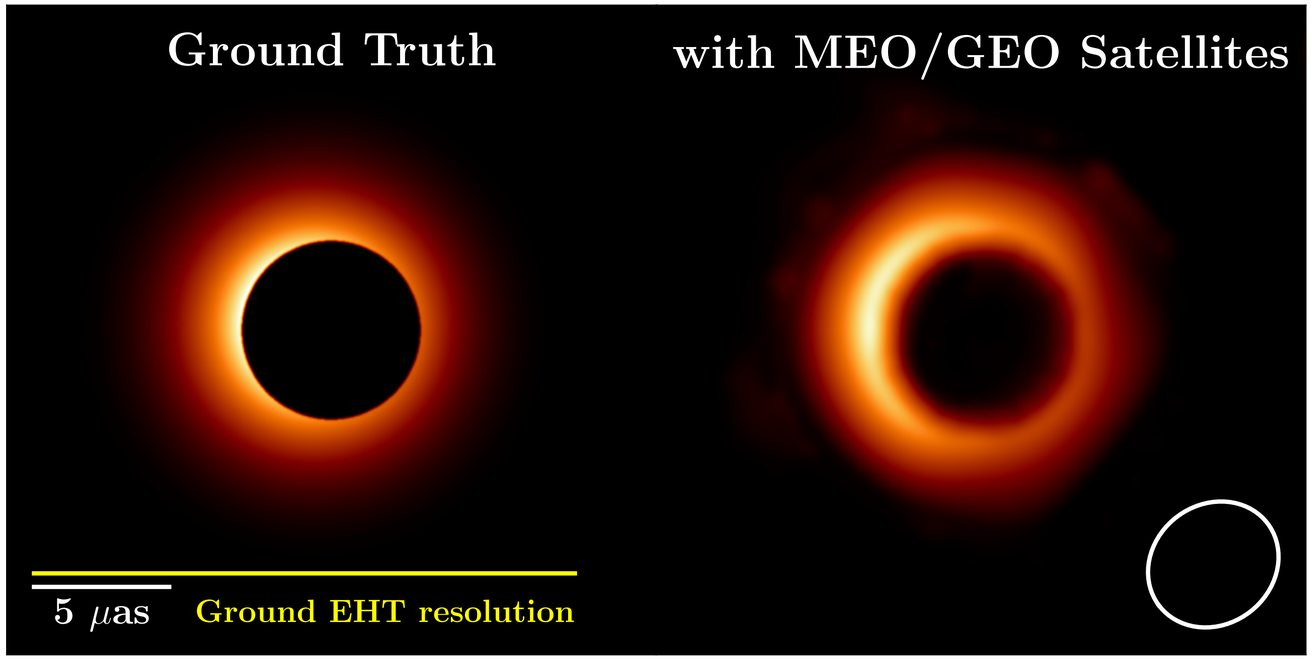
Event Horizon Telescope

Example space VLBI simulations: Sombrero Galaxy



Hada, Doi et al. 2013, ApJ

M104 (Sombrero Galaxy)



Fish, Shea & Akiyama 2019, ASR

Fish, Haggard & Akiyama+ in prep.

Shadow can be reconstructed at D > ~3 uas

Event Horizon Telescope