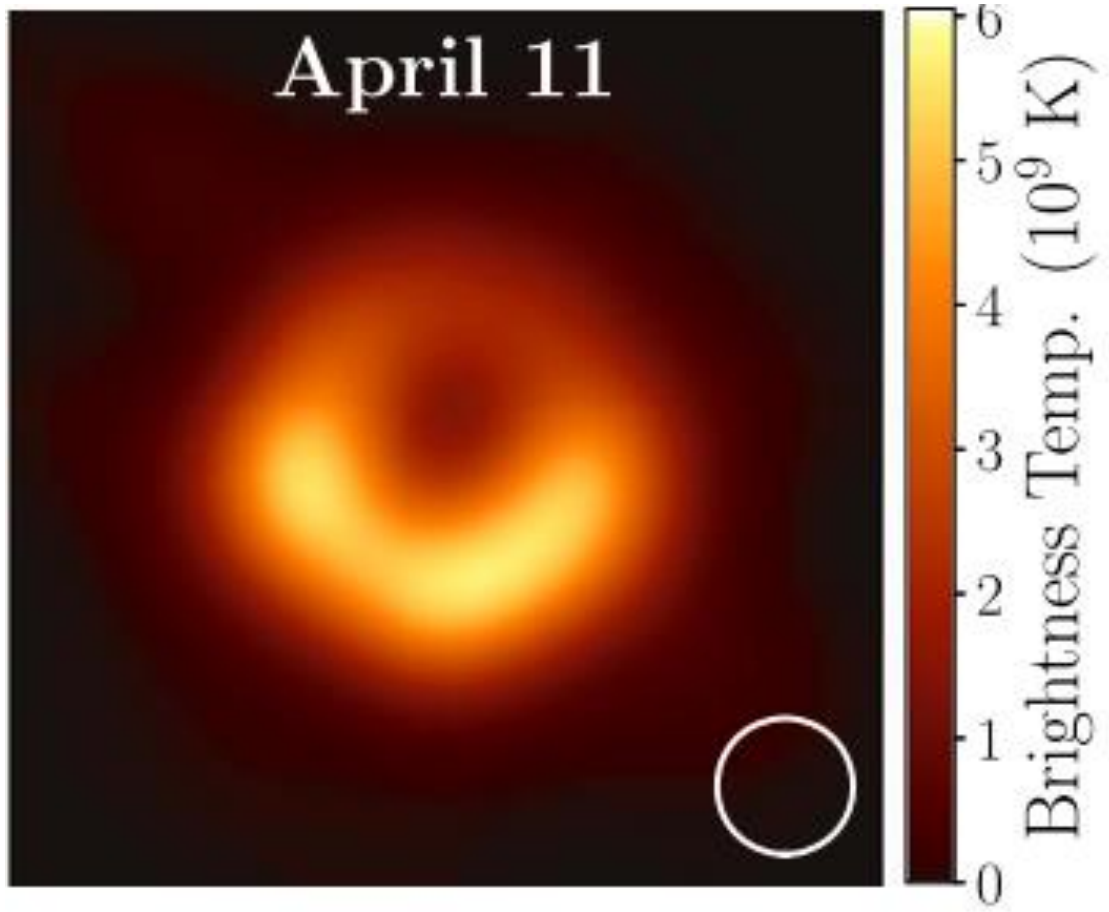
Deep Space Exploration Society
Science Meeting



First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole - IOPscience

May 24, 2021

Dr. Richard Russel, AC0UB

DrRichRussel@netscape.net

DSES.science

Information

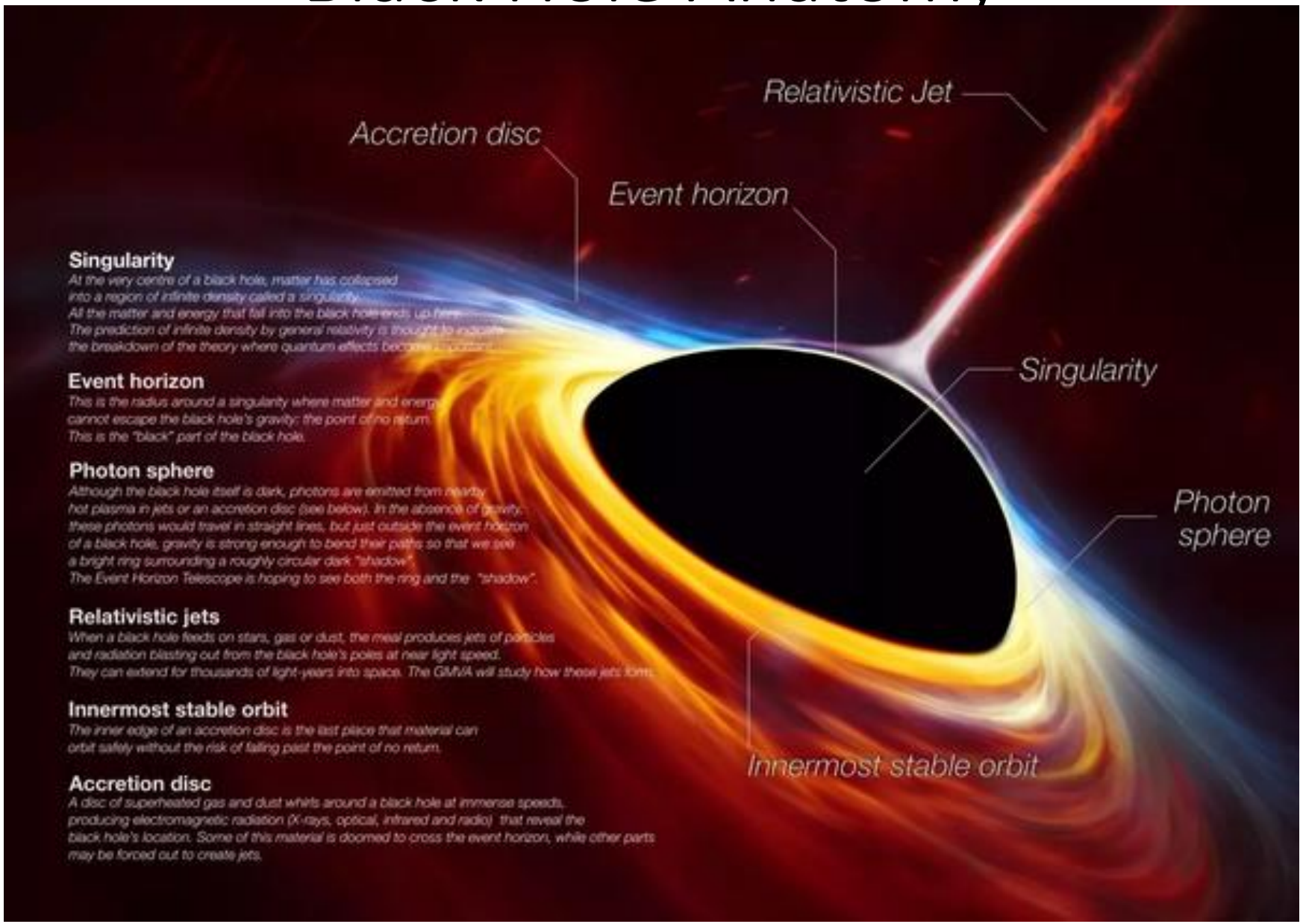
- 9 ft Dish – Spectracyber running
  - Plan to add RTL-SDR
  - Plan to view S7 and S8 to check calibration
- SuperSID – Working and porting data to Stanford
- Radio Jupiter – still need to get a new receiver and setup at site
- Pulsar:
  - Dan Layne fixed Ubuntu/ python 3.8 issue with gnu software
  - B210 capable of 50 MHz on 1 channel data acquisition without degradation
  - Significant issue with computer freezing and rebooting
    - System 76 thinks it is unstable ubuntu operating system
    - I think it is a heat issue with 32 cpus
    - Need to reload ubuntu and gnu software due to troubleshooting
- Tropospheric transmission – 1296 MHz feed available
- EME systems – 1296 MHz feed available
- Moon Orbit determination using EME equipment
- Don Latham contact with 2nd 60 ft dish

Black Hole Resolution with Radio Astronomy Interferometers

- Define the size of the observable black hole parts
  - Find the black hole Schwarzschild radius
  - Find the photon sphere radius
  - Find the radius of innermost closest stable orbit
- Determine the angular diameter of the black hole

- Based on antenna diameter – determine synthesized beamwidth
  - Compare different interferometers
- Show SGRA*, M87*, IC1101* (largest black hole) and Andromeda*(2nd closest supermassive black hole) results

Black Hole Anatomy



What are the parts of a black hole? - Quora

Black Hole Parts Distance Estimates

- Schwartzschild Radius (Rsch) $R_{Sch} = \frac{2GM}{c^2}$ km
- Photon Sphere: 1.5 Rsch
- Innermost Stable Orbit – non-rotating black hole: 3 Rsch
- Innermost Stable Orbit – rotating black hole: 4.5 Rsch

Innermost stable circular orbit - Wikipedia

Black Hole Angular Diameter

Angular Diameter $\boldsymbol{\delta = 206{,}265\left(\frac{d}{D}\right) arcseconds}$

d: object radius (km) – use Rsch

D: object distance (km)

Telescope Resolution

$$\theta_{HPBW} = \frac{\lambda}{D} \text{ radians}$$

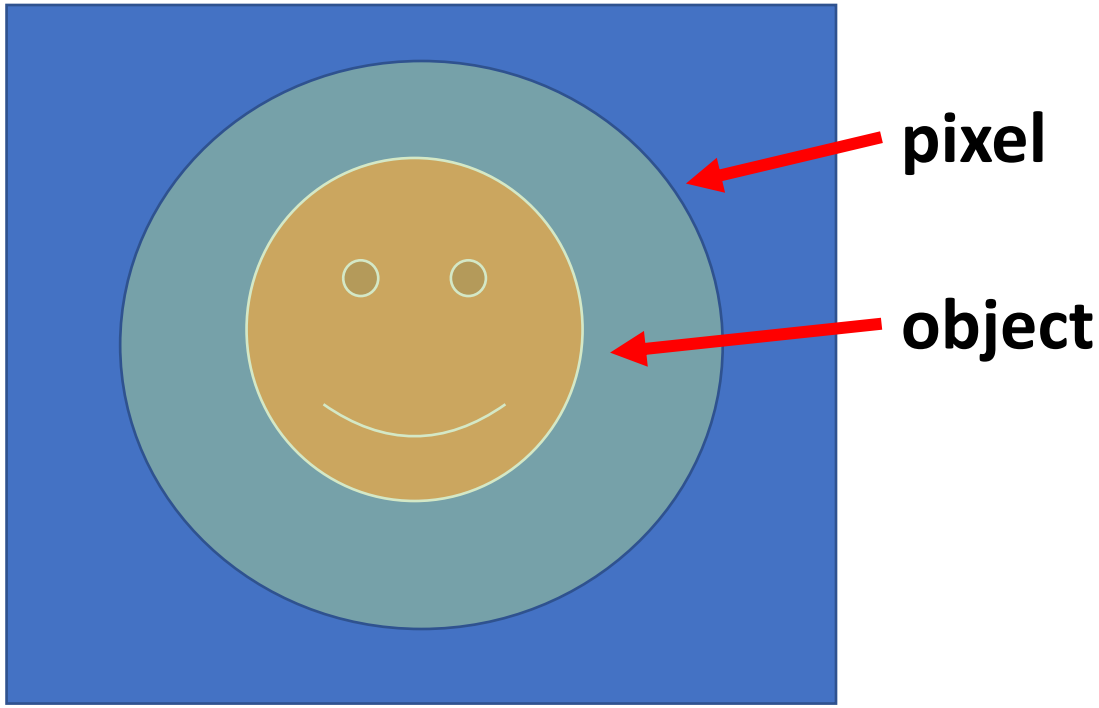
λ: $Telescope\ wavelength\ (meters)$

D: $Maximum\ antenna\ spacing\ (meters)$

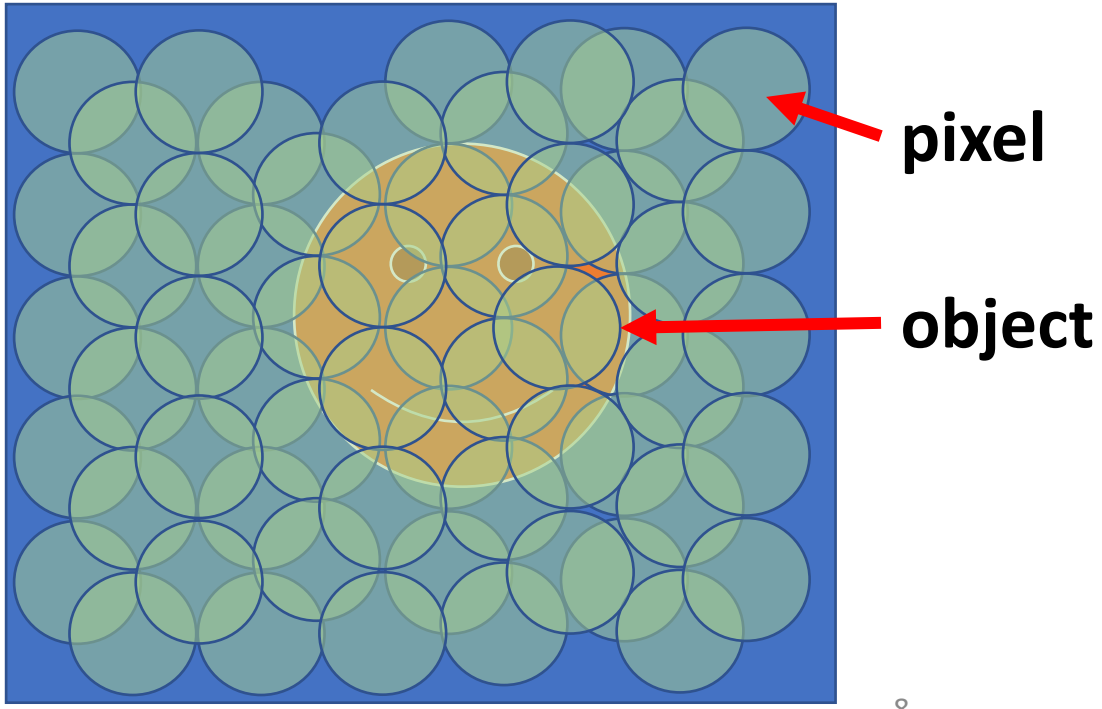
Visualizing Resolution

- Think of the resolution beamwidth as the pixel size.
- The best definition of the image uses as many pixels as possible, smaller than the image, to define the structures
- If the pixel is bigger than the image – then it is only one intensity describing the entire image and any overlap signal from the image background.

Poor definition of image



Better definition of image



Astrometric Data

- M87* mass 6.5×10^9 Msun
- M87* distance 1.67×10^4 kpc

- SGRA* mass 4.26×10^6 Msun
- SGRA* distance 8.32 kpc

- IC1101* mass $50\text{-}70 \times 10^9$ Msun
- IC1101* distance 3.204×10^5 kpc

- Andromeda* mass 1.08×10^8 Msun
- Andromeda* distance 765 kpc

Calculations

	Control Panel				
2	Parameter	Min	Max	Random	Units
3	Sun Velocity	220.00	220.00	220.0	km/s
4	Sun Distance from Galactic Center	8.32	8.50	8.4	kParsecs
5	Mass M87	6.50E+09	6.50E+09	6.50E+09	Msun
6	Mass SGR A*	4.26E+06	4.26E+06	4.26E+06	Msun
7	Mass IC1101	6.00E+10	6.00E+10	6.00E+10	Msun
8	Mass Andromeda	1.08E+08	1.08E+08	1.08E+08	Msun
9	G	6.67E-11	6.67E-11	6.67E-11	
10	Msun	1.99E+30	1.99E+30	1.99E+30	kg
11	c (km/s)	3.00E+08	3.00E+08	3.00E+08	
12	Rm87 (kpc)	1.67E+04	1.67E+04	1.67E+04	
13	Rsgra* (kpc)	8.32E+00	8.32E+00	8.32E+00	
14					
15	VLA Max sep (km)	3.60E+04	km		
16	VLA Freq (HZ)	4.50E+10	Hz		
17	EHT Max Sep (m)	1.28E+07	m	Earth Diam	
18	EHT Freq (HZ)	2.30E+11	Hz		
19	EHT freq (HZ) - new	3.45E+11	Hz		
20	Resolution EVN+VLBA (0.7 cm) (42.83 GHz)	4.23E+10	Hz		
21	Independent Equations				
22	Rsch M87	1.92E+13	km		
23	Rsch SGR A*	1.26E+10	km		
24	Rsch IC1101*	1.77E+14	km		
25	Rsch Andromeda*	3.19E+11	km		
26	D M87 kpc	1.67E+04	kpc		
27	D SGR A* kpc	8.32E+00	kpc		
28	D IC1101*	3.20E+06	kpc		
29	D Andromeda*	7.65E+02	kpc		

30	EVENT HORIZON				
31	Angular Diameter M87 Event Horizon	7.68E-06	arcseconds	7.685	uarcseconds
32	Angular Diameter SGRA* Event Horizon	1.01E-05	arcseconds	10.110	uarcseconds
33	Angular Diameter IC1101* Event Horizon	3.70E-07	arcseconds	0.370	uarcseconds
34	Angular Diameter Andromeda* Event Horizon	2.79E-06	arcseconds	2.788	uarcseconds
35	TELESCOPE RESOLUTION				
36	GBT 115 GHz			6.50E+09	uarcseconds
37	Resolution VLA (45 GHz)	1.85E-04	radians	38,170.80	uarcseconds
38	Resolution EHT (230 GHz)	1.02E-07	radians	21.08	uarcseconds
39	Resolution EHT (345 GHz)	6.81E-08	radians	14.05	uarcseconds
40	Resolution EVN+VLBA (0.7 cm) (42.83 GHz)			140.00	uarcseconds
41	PHOTON SPHERE				
42	R Photon sphere M87	2.88E+13	km		
43	R photon sphere SGRA*	1.89E+10	km		
44	R photon sphere IC1101*	2.66E+14	km		
45	R photon sphere Andromeda*	4.78E+11	km		
46	Angular Diameter photon sphere M87	1.15E-05	arcseconds	11.53	uarcseconds
47	Angular Diameter photon sphere SGRA*	1.52E-05	arcseconds	15.17	uarcseconds
48	Angular Diameter photon sphere IC1101*	5.55E-07	arcseconds	0.55	uarcseconds
49	Angular Diameter photon sphere Andromeda*	4.18E-06	arcseconds	4.18	uarcseconds
50	INNERMOST STABLE ORBIT				
51	R Innermost Stable Orbit rotating M87	8.64E+13	km		
52	R Innermost Stable Orbit rotating SGRA*	5.66E+10	km		
53	R Innermost stable orbit IC1101*	7.97E+14	km		
54	R Innermost stable orbit Andromeda*	1.44E+12	km		
55	Angular Diameter IMSO M87	3.46E-05	arcseconds	34.58	uarcseconds
56	Angular Diameter IMSO SGRA*	4.55E-05	arcseconds	45.50	uarcseconds
57	Angular Diameter IMSO IC1101*	1.66E-06	arcseconds	1.66	uarcseconds
58	Angular Diameter IMSO Andromeda*	1.25E-05	arcseconds	12.54	uarcseconds

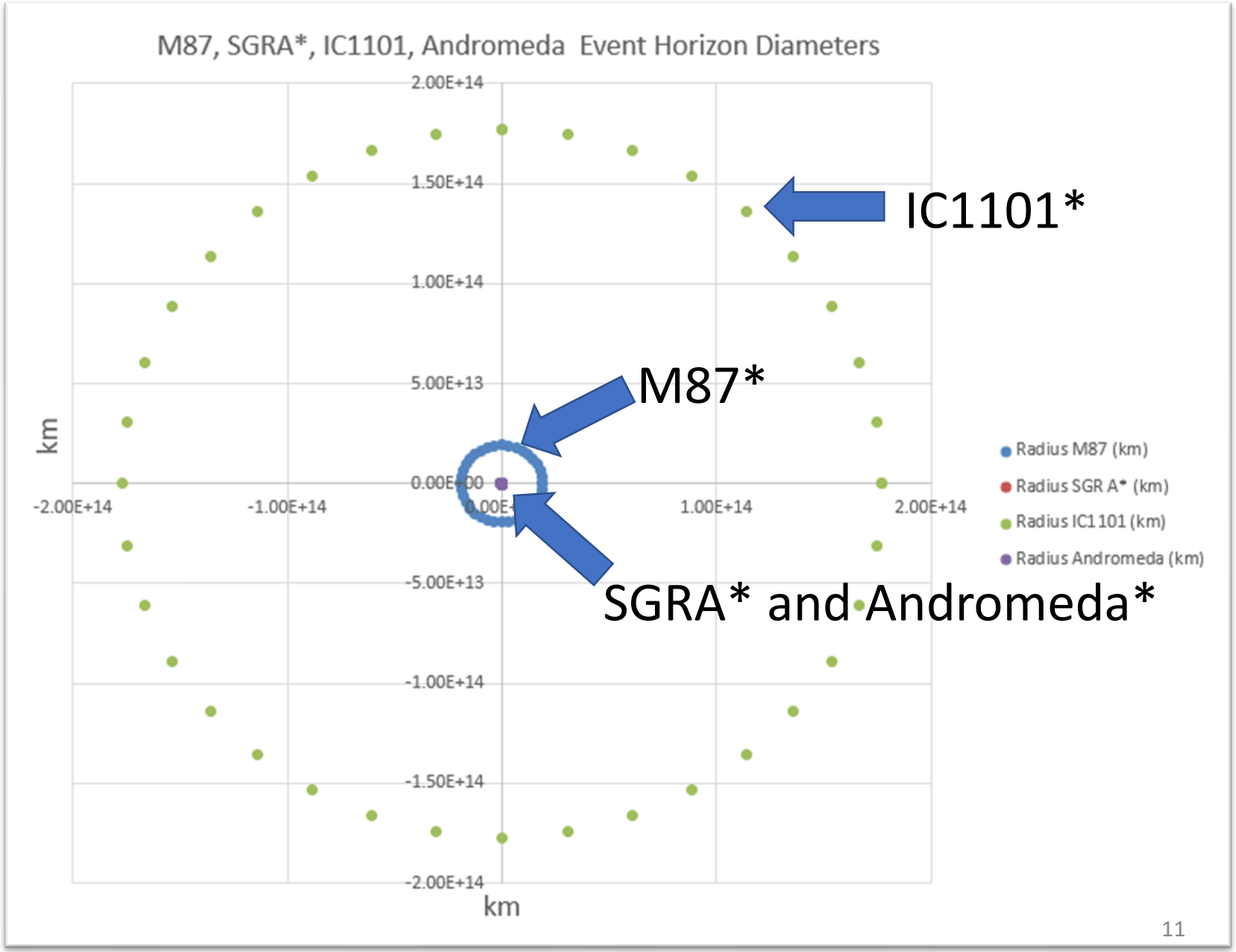
Schwarzschild radius of the black hole event horizon

$$R_{Sch} = \frac{2GM}{c^2} \text{ km}$$

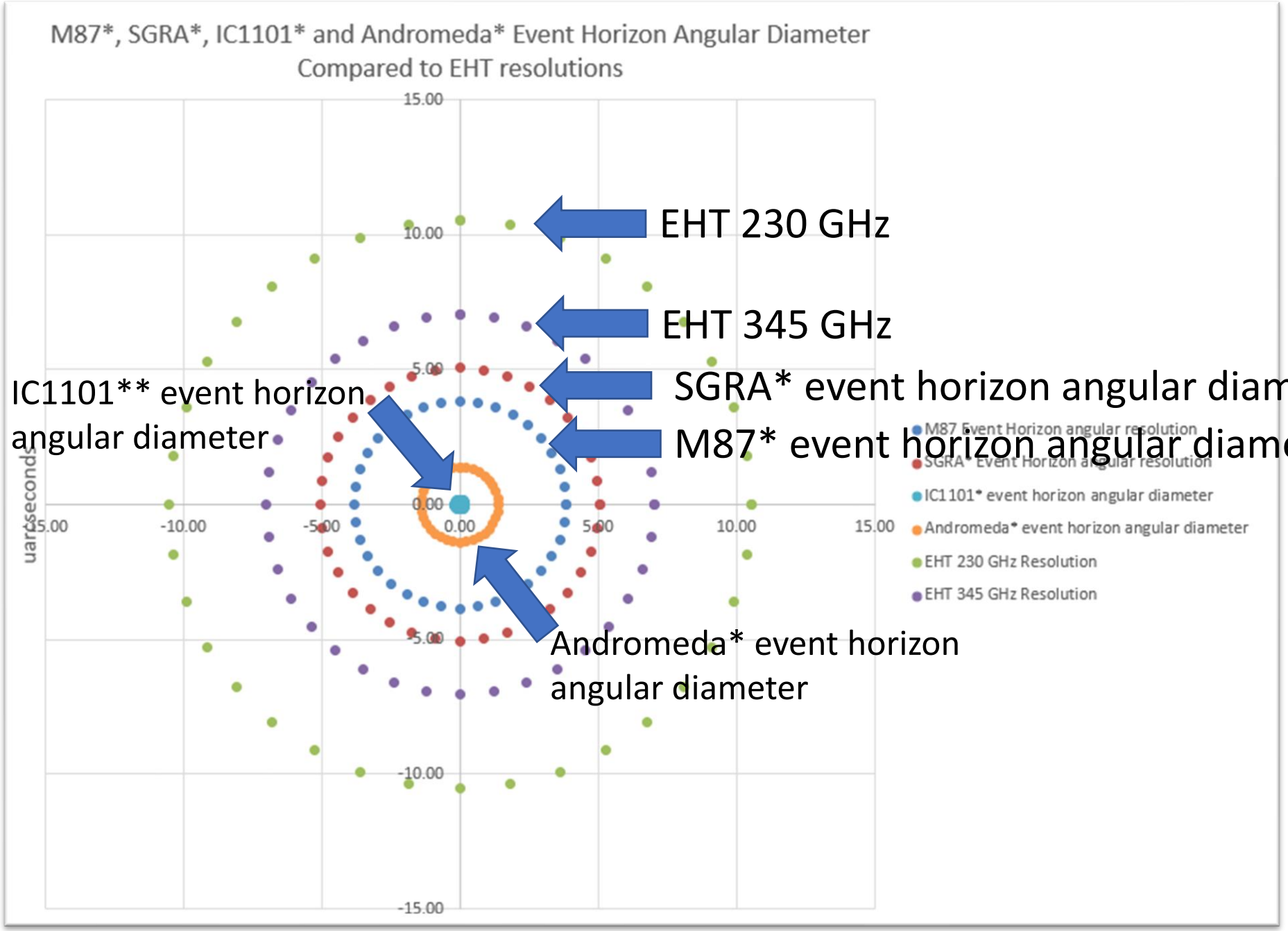
$G = 6.6743\ x\ 10^{-11} m^3 kg^{-1} s^{-2}$

c= 299,792,458 m/s

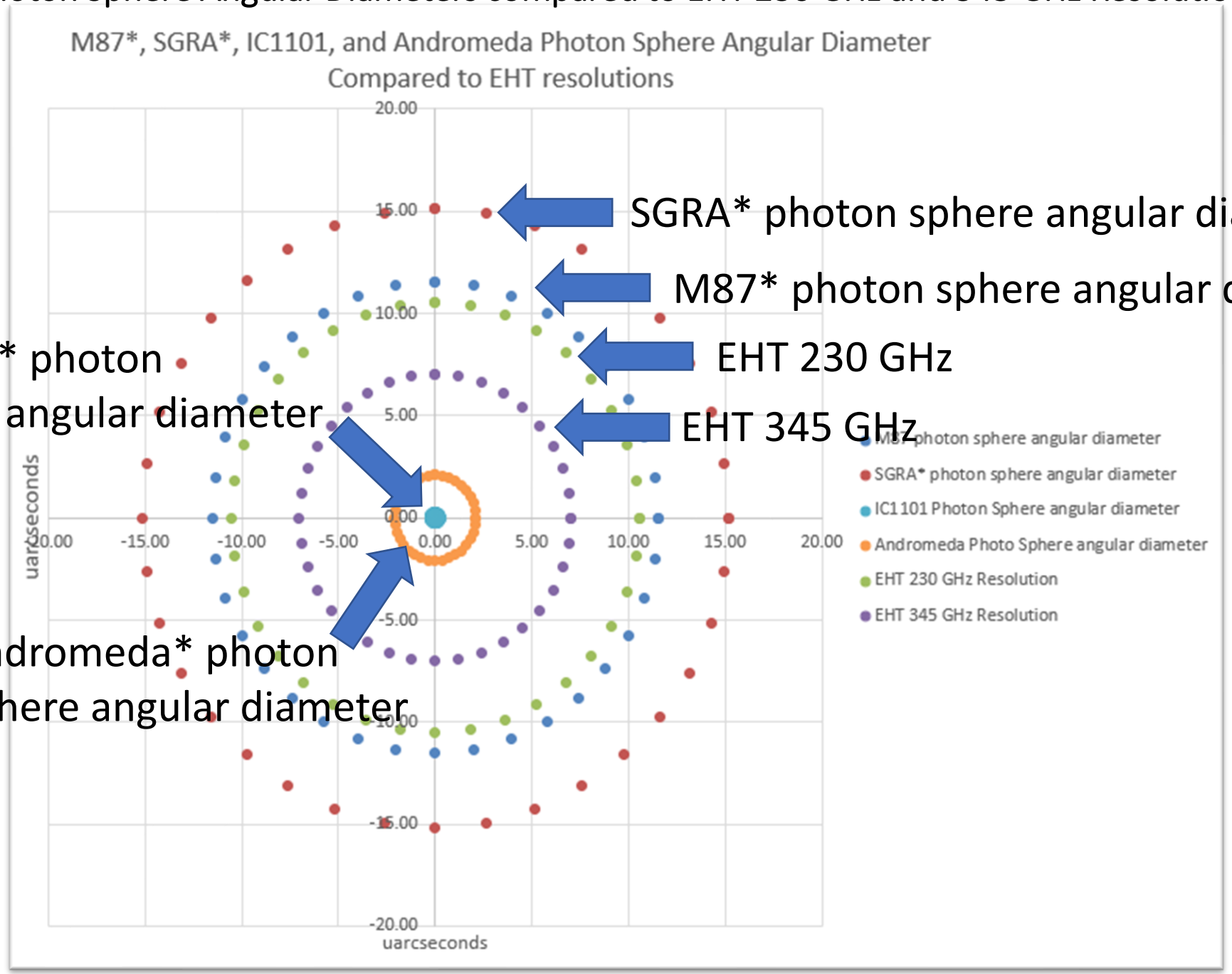
$m_{\odot} = 19.884\ x\ 10^{30} kg$



Event Horizon Angular Diameters compared to EHT 230 GHz and 345 GHz Resolutions



Photon Sphere Angular Diameters compared to EHT 230 GHz and 345 GHz Resolutions



SGRA* photon sphere angular diameter

M87* photon sphere angular diameter

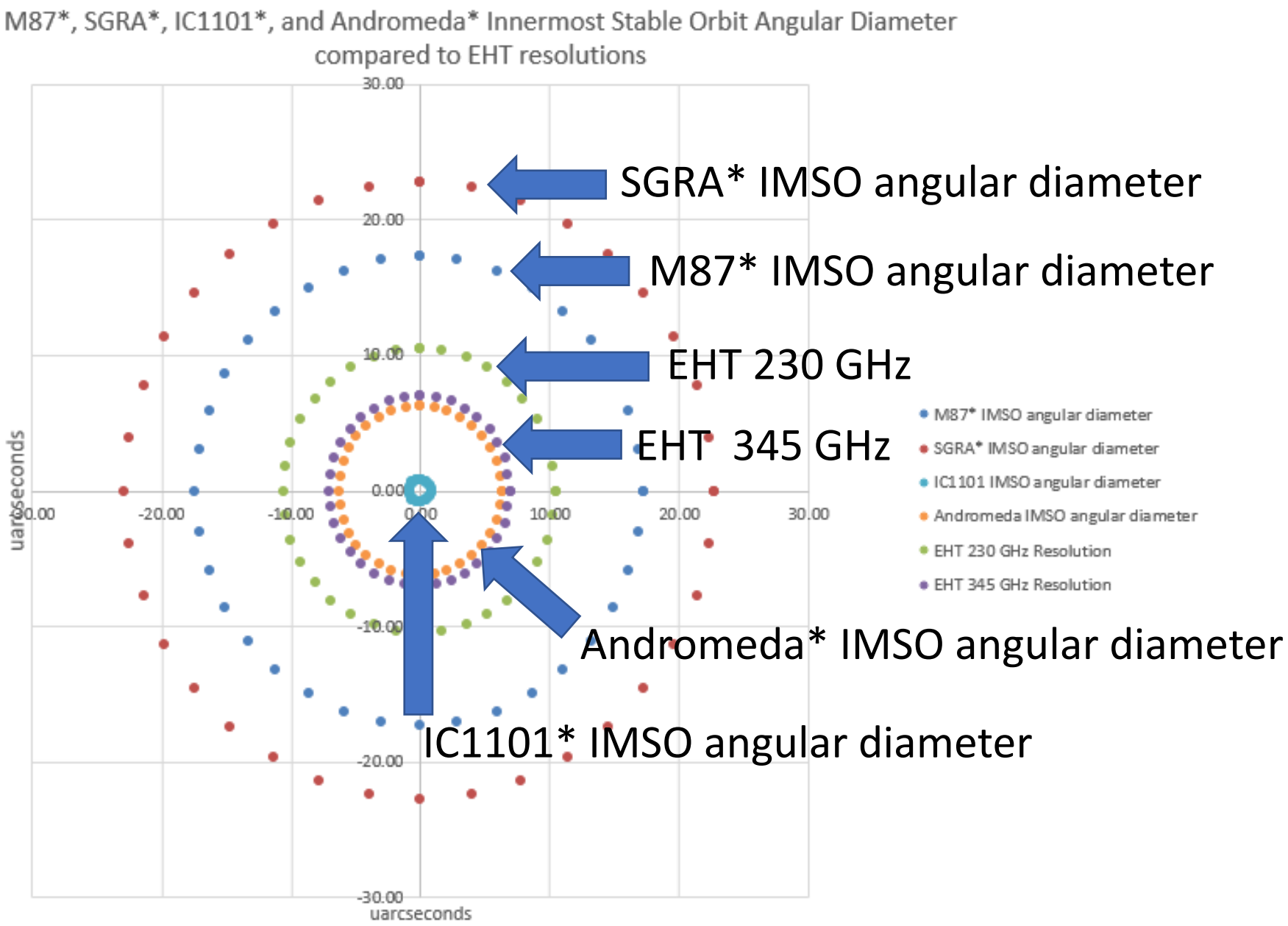
EHT 230 GHz

EHT 345 GHz

IC1101* photon sphere angular diameter

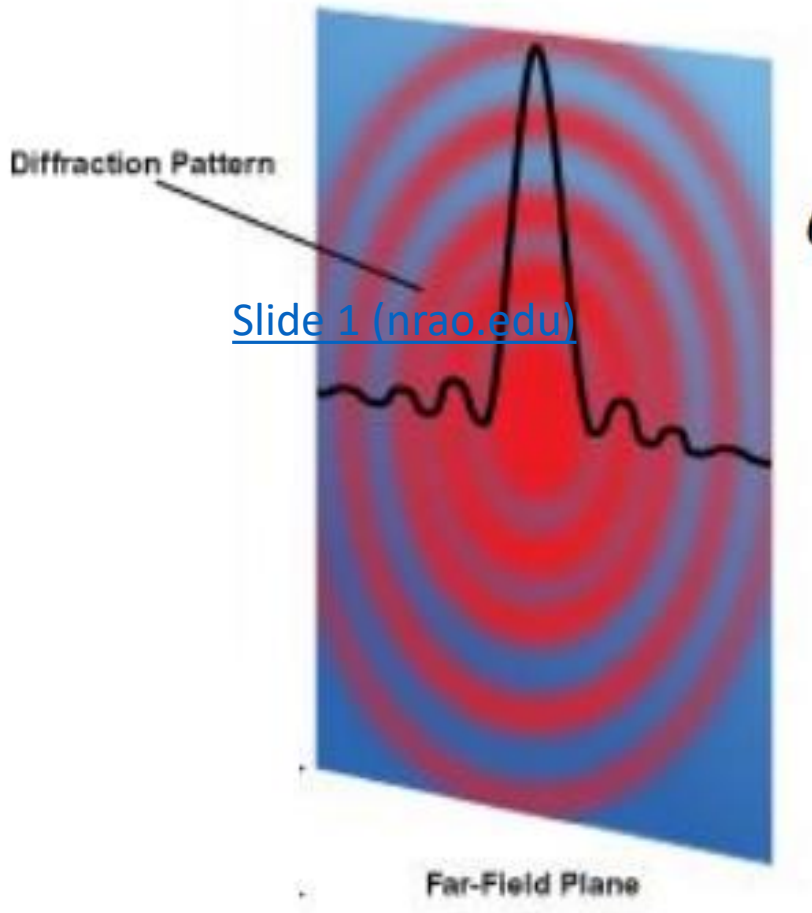
Andromeda* photon sphere angular diameter

Innermost Stable Orbit Angular Diameters compared to EHT 230 GHz and 345 GHz Resolutions



GBT Capability

Image quality, efficiency, resolution



Slide 1 (nrao.edu)

$$\theta_{HPBW} = 1.2\lambda/D$$
$$= 40' \text{ at } 300\,\text{MHz}(1\,\text{m})$$
$$= 9' \text{ at } 1420\,\text{MHz}(21\,\text{cm})$$
$$= 6.5'' \text{ at } 115\,\text{GHz}(3\,\text{mm})$$

https://www.gb.nrao.edu/~rmaddale/Education/GBTFundamentalsSingle-DishTelescopes.pdf

Very Long Baseline Array (VLBA)

Locations of VBA bases

Toponym	U.S. state	Geographic coordinate system	
St. Croix	U.S. Virgin Islands	17.75652°N 64.58376°W	SC
Hancock	New Hampshire	42.93362°N 71.98681°W	HN
North Liberty	Iowa	41.77165°N 91.574133°W	NL
Fort Davis	Texas	30.635214°N 103.944826°W	FD
Los Alamos	New Mexico	35.7752887°N 106.2455897°W	LA
Pie Town	New Mexico	34.30107°N 108.11912°W	PT
Kitt Peak	Arizona	31.956253°N 111.612361°W	KP
Owens Valley	California	37.23176°N 118.27714°W	OV
Brewster	Washington	48.13117°N 119.68325°W	BR
Mauna Kea	Hawaii	19.80159°N 155.45581°W	MK

High-Sensitivity Array [edit]

The use of the VLBA can be scheduled dynamically, and its sensitivity can be improve as the Arecibo radio telescope in Puerto Rico, the Green Bank Telescope in West Virg Effelsberg radio telescope in Germany. These four additional sites are brought online configuration, the entire array is known as the **High-Sensitivity Array** (**HSA**).[5]

High-Sensitive Array locations

Toponym	State	Geographic coordinate system	
Arecibo	Puerto Rico	18°20'36.60"N 66°45'11.10"W	AR
Green Bank	West Virginia	38°25'59.24"N 79°50'23.41"W	GB
Very Large Array	New Mexico	34°04'43.75"N 107°37'05.91"W	Y27
Effelsberg	Germany	50°31'30"N 6°53'00.3"E	EB

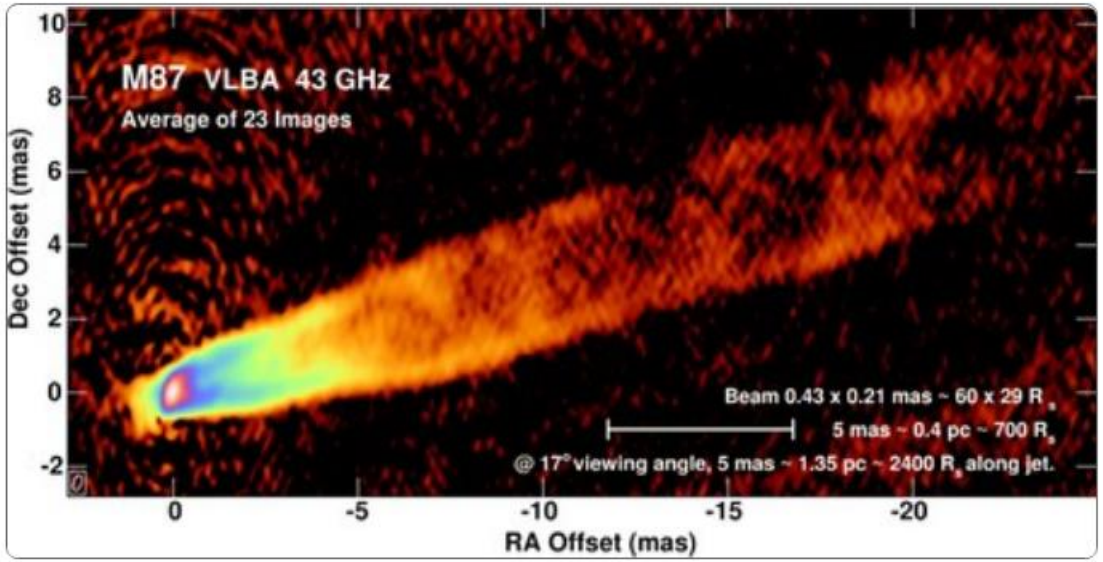


Figure: The averaged 23-epoch VLBA image of the relativistic jet and counterjet in M87 providing new insights on the formation and evolution of extragalactic jets. The image resolution is 0.43x0.21 milli-arsec (corresponding to linear scales of 0.017-0.034 parsecs at the M87 redshift), and the noise level is 62 μJy/beam. Credits: NRAO/Walker et al. (2018), The Structure and Dynamics of the Subparsec Jet in M87 Based on 50 VLBA Observations over 17 Years at 43 GHz.

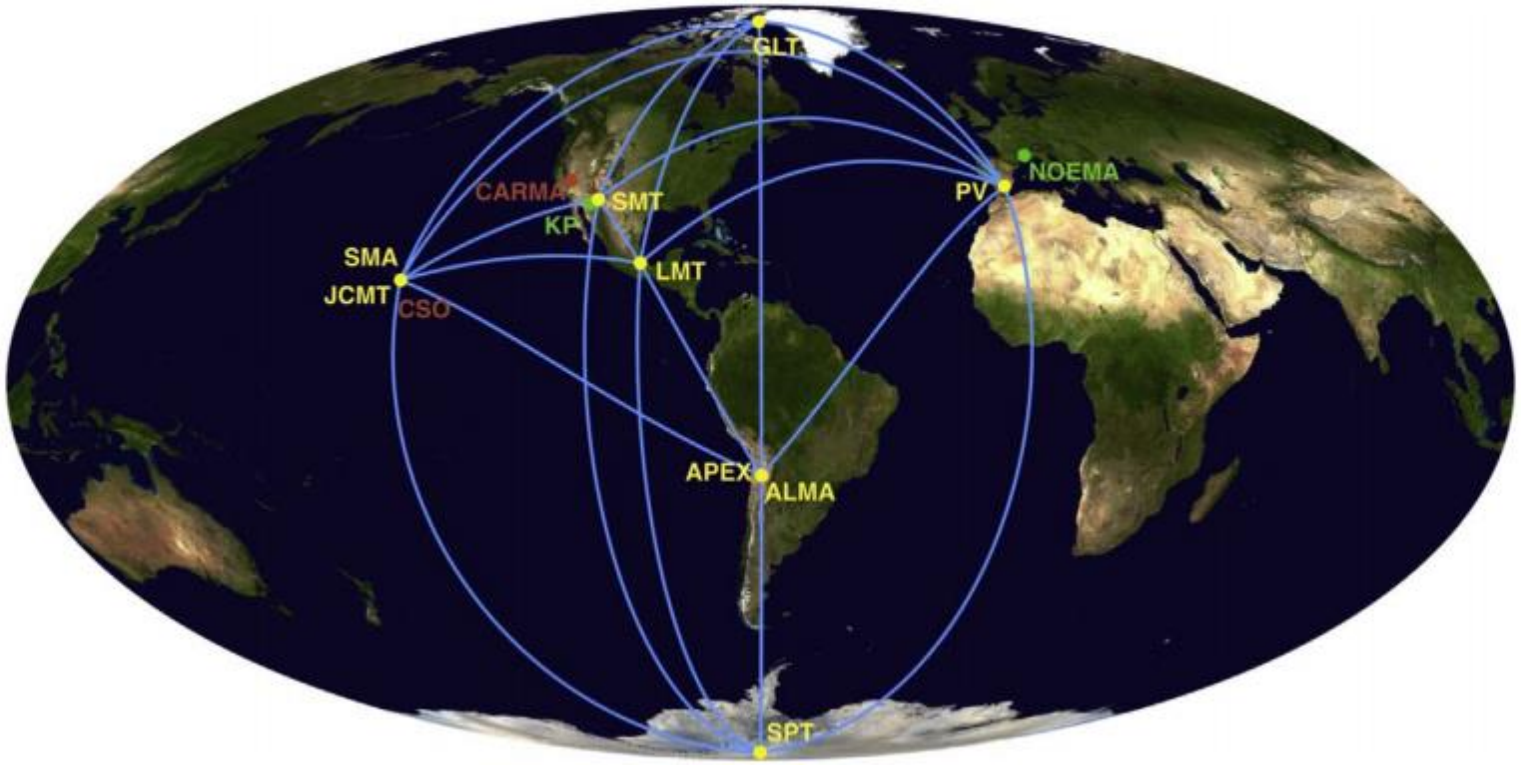
Introduction to the VLBA — Science Website (nrao.edu)

Very Long Baseline Array - Wikipedia

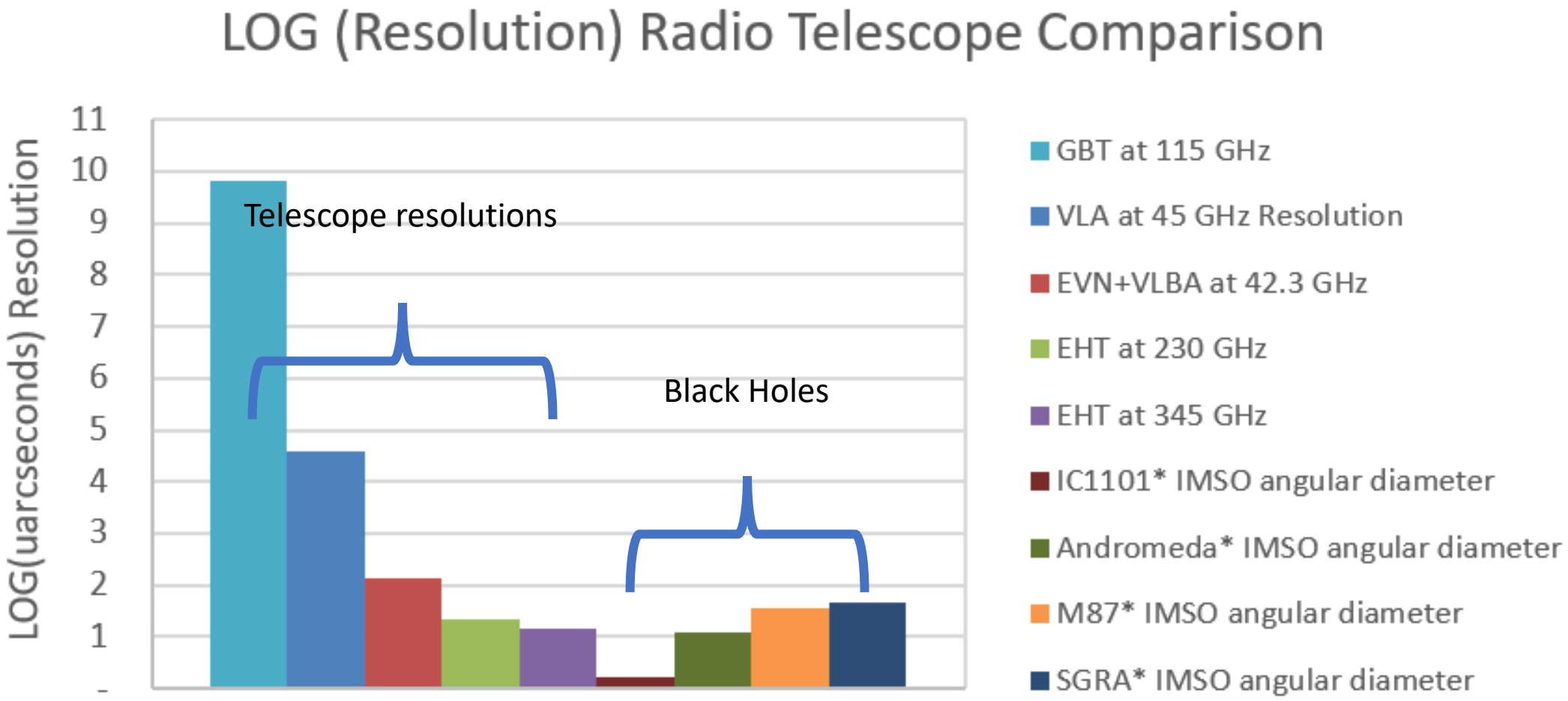
European VLBI Network (EVN)

[EVN-Newsletter-59.pdf (evlbi.org)]

EHT Antenna Locations



Radio telescope and astronomical object Comparison



Event Horizon telescope observation at 240 GHz

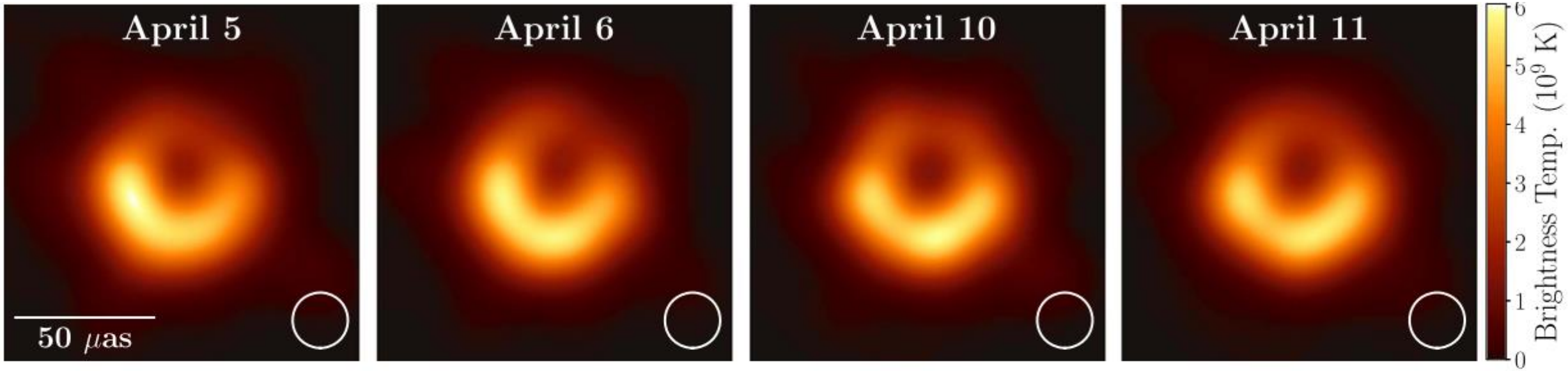


Figure 15. Averages of the three fiducial images of M87 for each of the four observed days after restoring each to an equivalent resolution, as in Figure 14. The indicated beam is 20 μas (i.e., that of DIFMAP, which is always the largest of the three individual beams).

The Astrophysical Journal Letters, 875:L4 (52pp), 2019 April 10

First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole - IOPscience

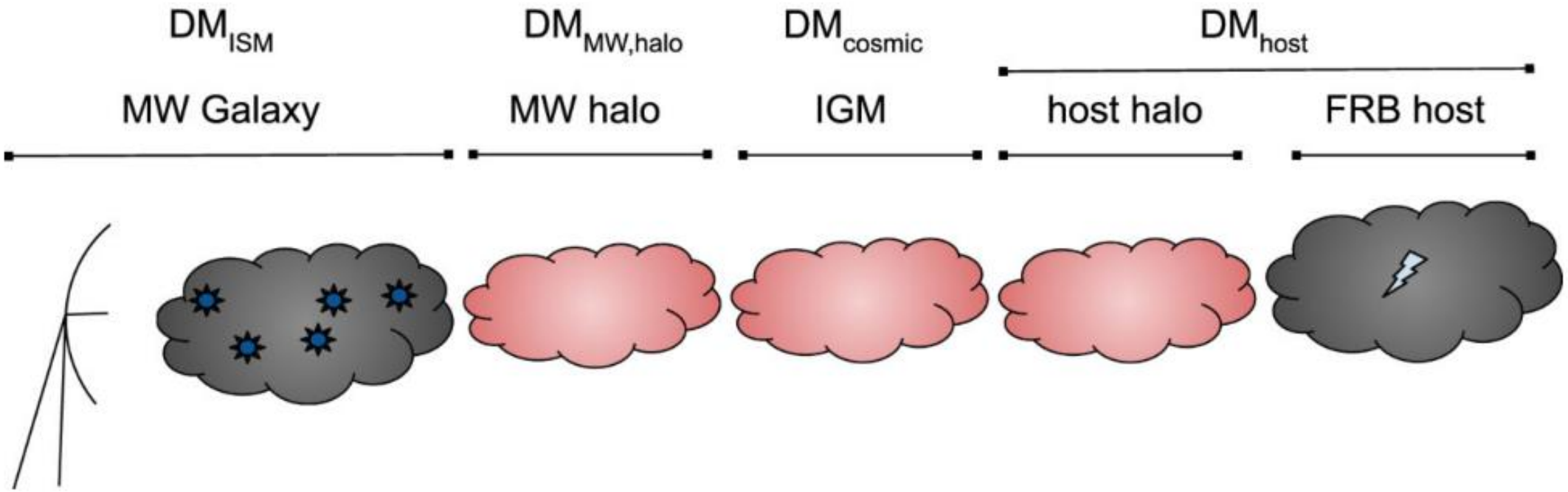
Summary

- Black holes observations are dependent on mass and distance
- Telescope observations are dependent on maximum antenna spacing and frequency

- SGRA* should be “easier” to observe with the EHT than M87*
  - Issue is probably dust blocking observation
- IC1101* and Andromeda* angular diameters are too low for the EHT to resolve the black hole parts
  - Andromeda* is almost the same angular diameter as the EHT at 345 GHz resolution – should be able to see a rough image

- This analysis does not go into the # of antennas and observation time to get proper UV coverage

More Science: FRB Path Analysis



Schematic illustrating how transient radio signals travel to us. Pulsars (marked by sun symbols) lie in the galaxy, interior to the halo; their signals are affected only by the Milky Way's interstellar matter. Fast radio bursts (marked by lightning symbol) lie in other galaxies; their signals travel through multiple different regions. [Platts et al. 2020]

https://aasnova.org/2021/05/21/what-fast-radio-bursts-tell-us-about-galaxy-halos/

2021 Observation/ Feed Schedule

- May – June 2021 Down to fix pointing system
- July 2021
  - 1420 MHZ Feed for pulsar, FRB, and HI observations
  - 1296 MHz if EME team wants it

Questions?