Greenland Telescope (GLT): Imaging the Black Hole Shadow & the Photon Ring

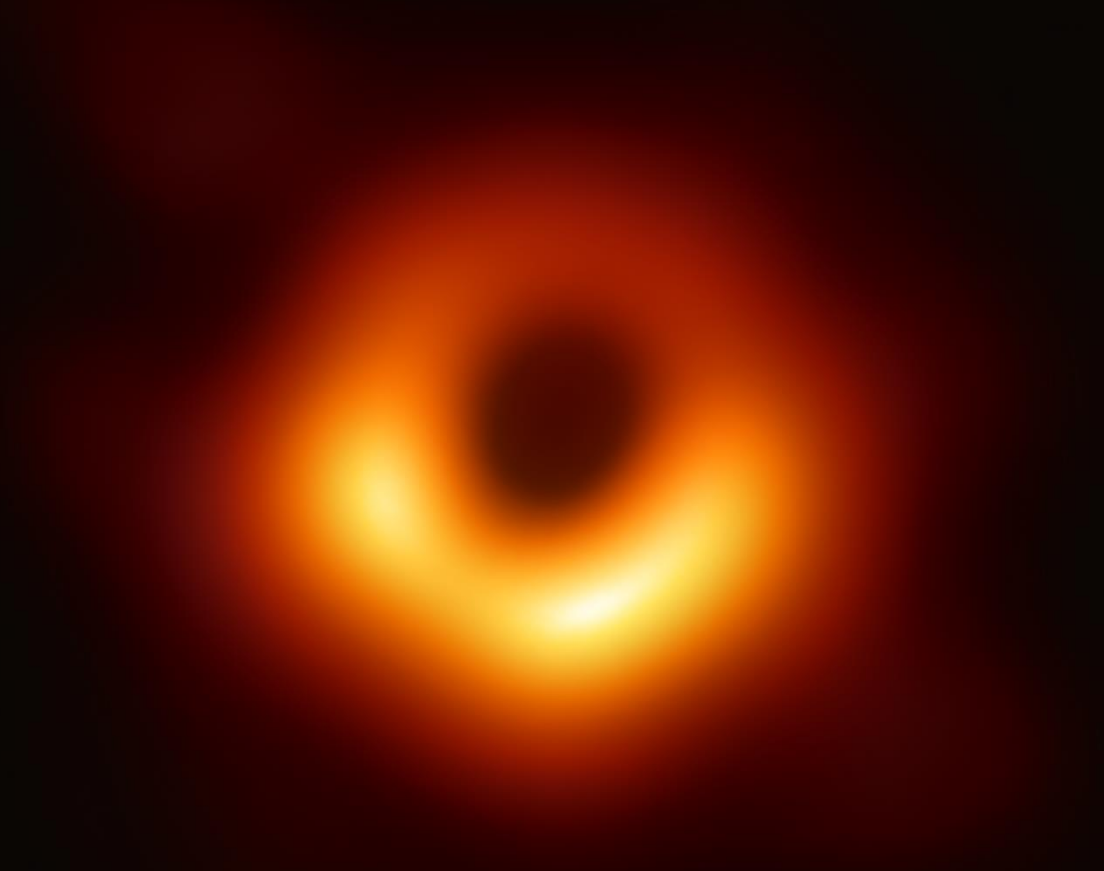
Satoki Matsushita (ASIAA)

P.I. of the GLT Project

EHT Taiwan Representative

How Black Holes Look Like???

M87

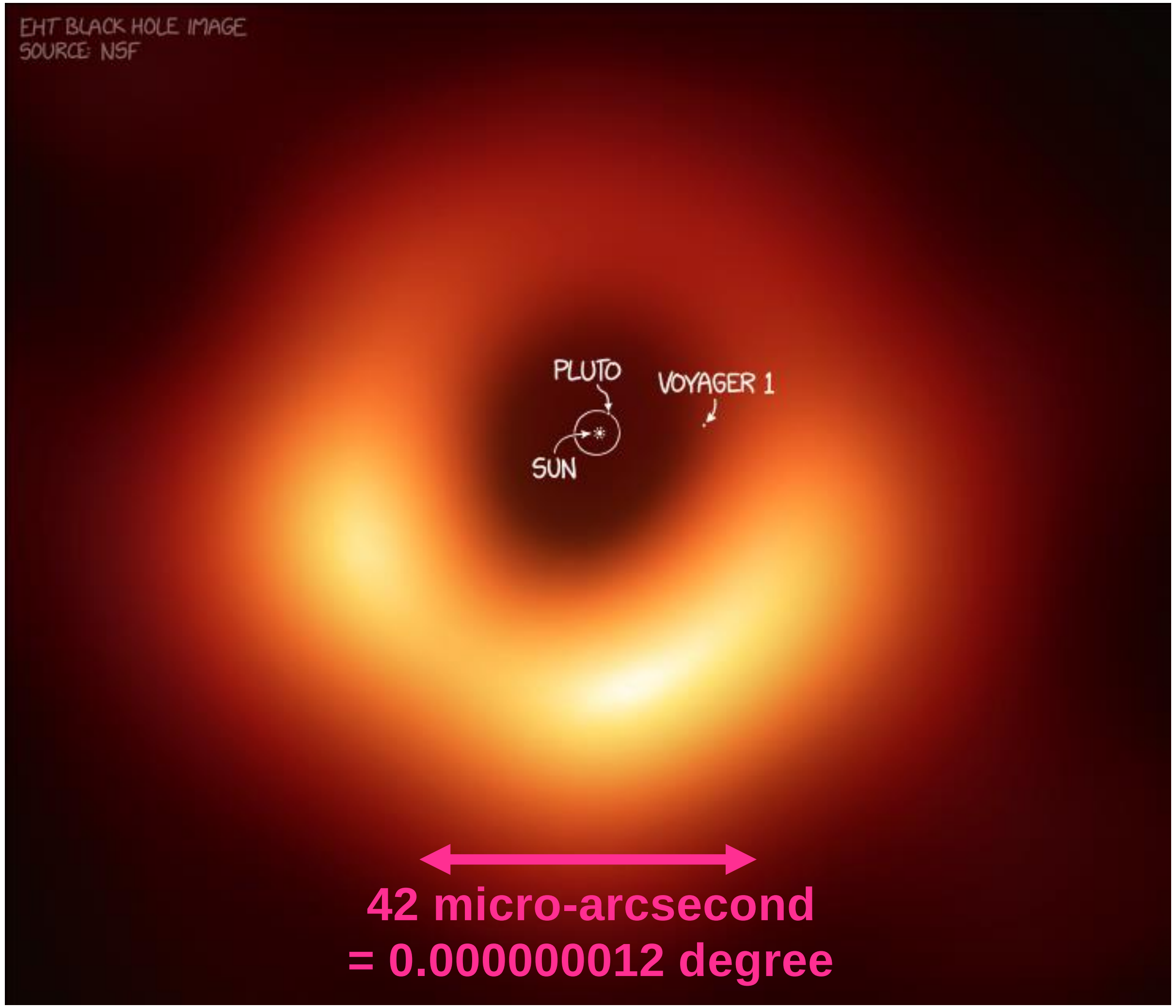


After April 10, 2019.

EHT Collaboration 2019, ApJL, 875, L1

Size of the Black Hole

- Distance to the Black Hole = 55 Million Light Years
- Angular size = 42 μarcsec



https://xkcd.com/2135/

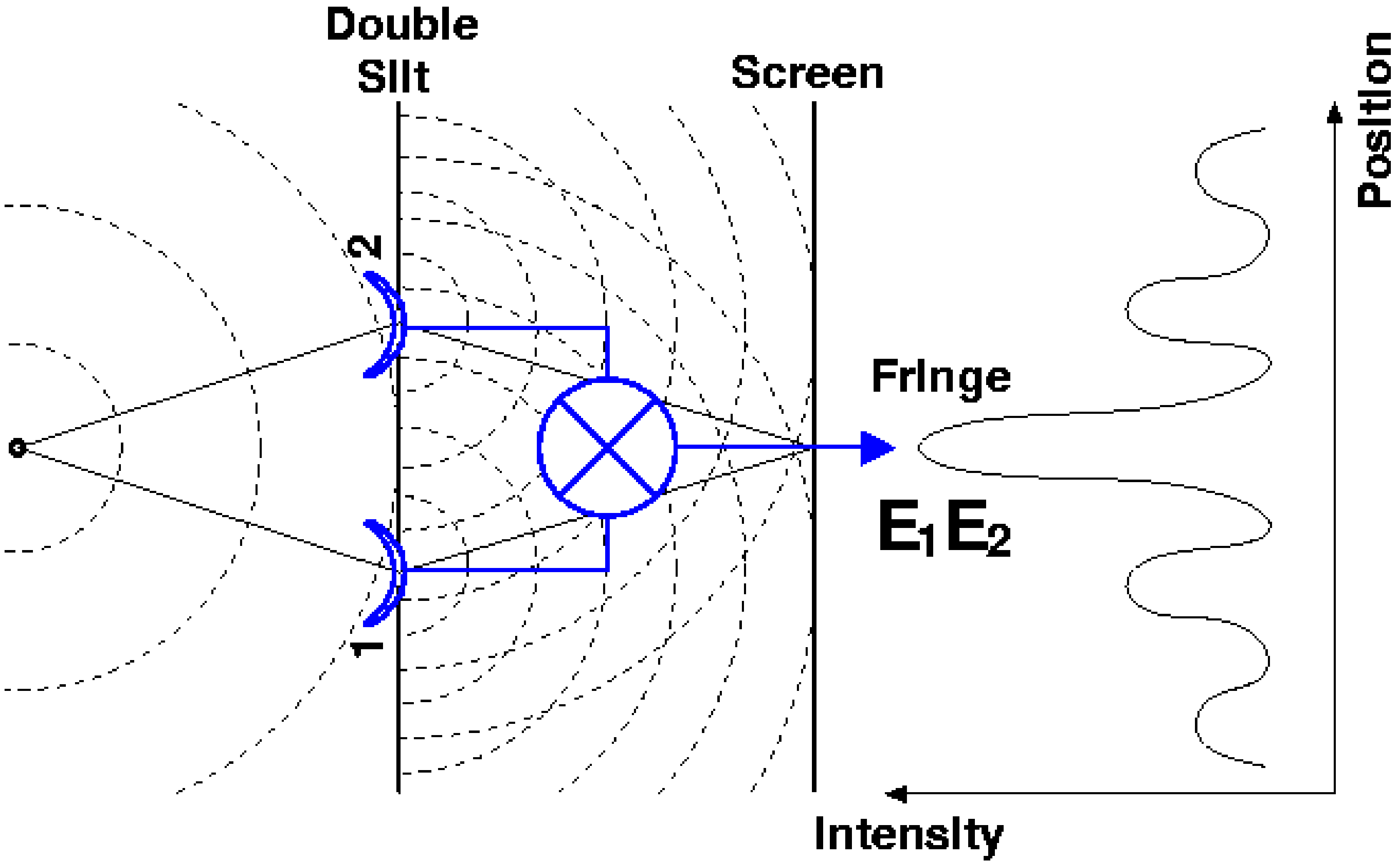
Spatial Resolution

- Spatial resolution goes high with shorter wavelength (or higher frequency) and bigger telescope (or longer baseline):
  - Resolution ~ λ/D
    - λ: Wavelength
    - D: Diameter of telescope (or baseline length)
- Spatial resolutions of the optical/infrared telescopes:
  - Hubble Space Telescope (HST): 0.04" (40 milliarcsec)
  - James Webb Space Telescope (JWST): 0.03" (30 milliarcsec)
  - VLT Interferometer (VLTI): 0.002" (2 milliarcsec) ⇦ GRAVITY is here!
  - Atacama Large Millimeter/submillimeter Array (ALMA): 0.01" (10 milliarcsec)

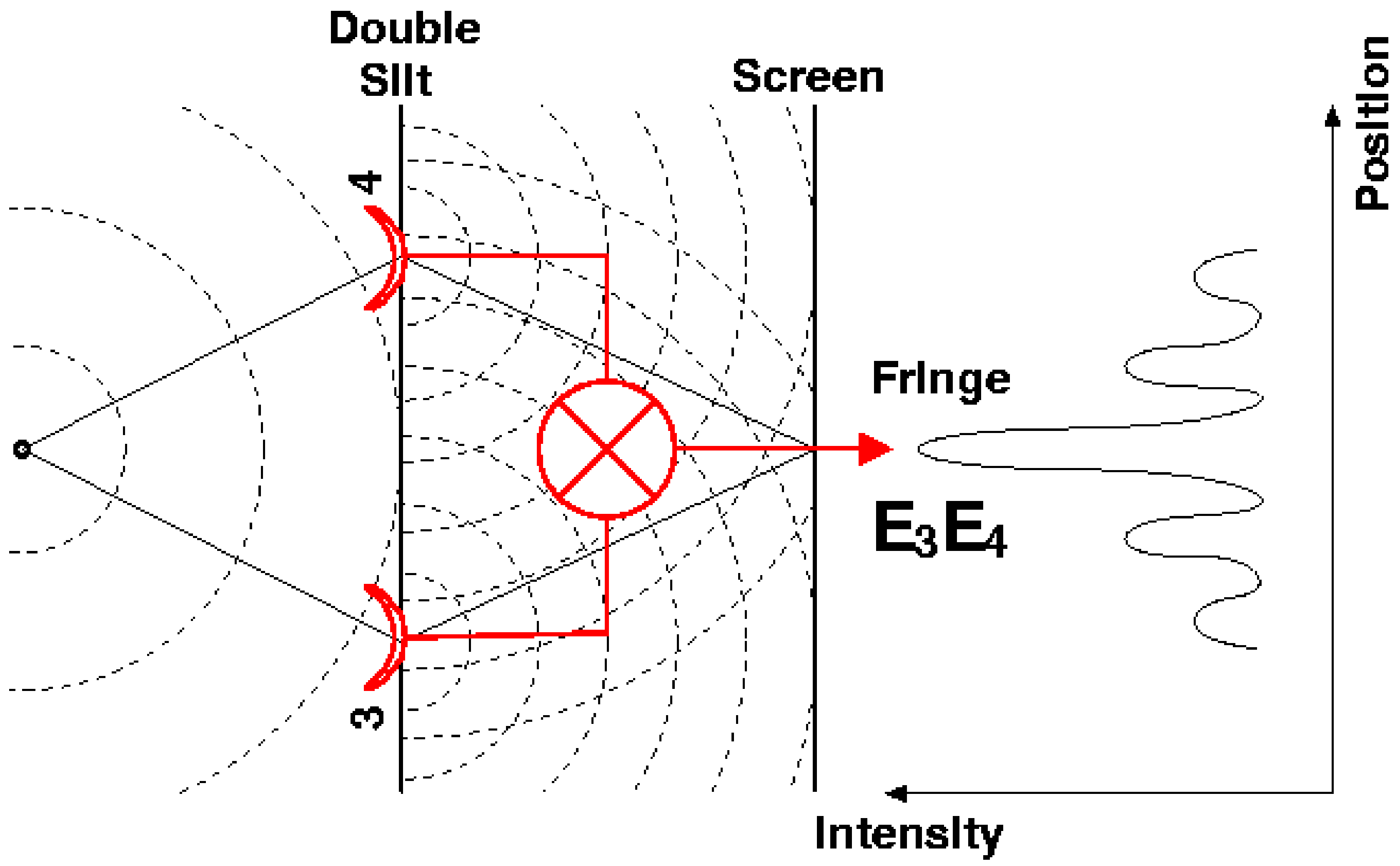
⇨ Too large to image black holes, whose sizes are μarcsec scale.

⇨ **Submillimeter Very Long Baseline Interferometry (Submm-VLBI) !!!**

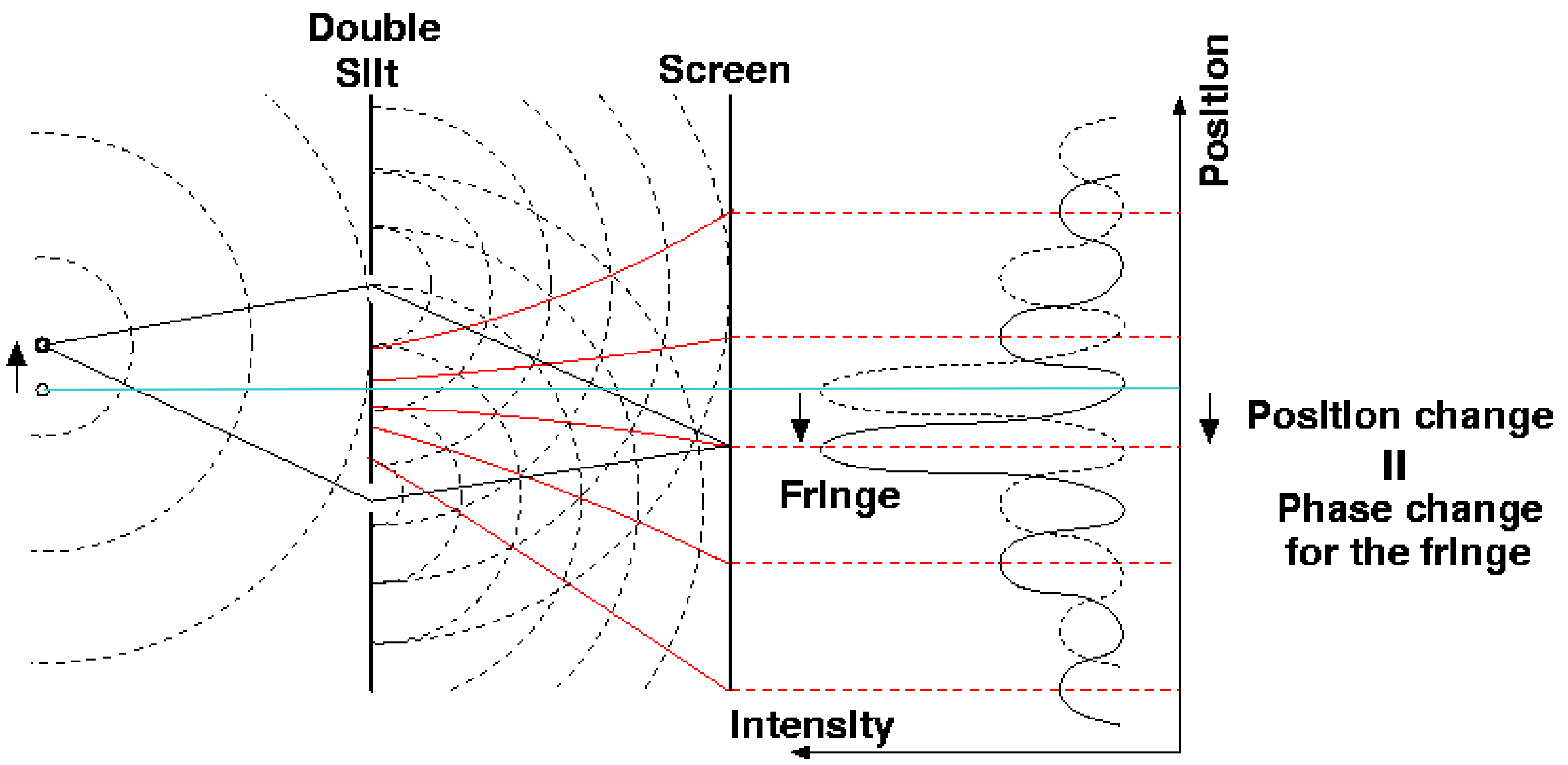
Basics of Interferometry: Young's Experiment



Basics of Interferometry: Young's Experiment



Basics of Interferometry: Young's Experiment

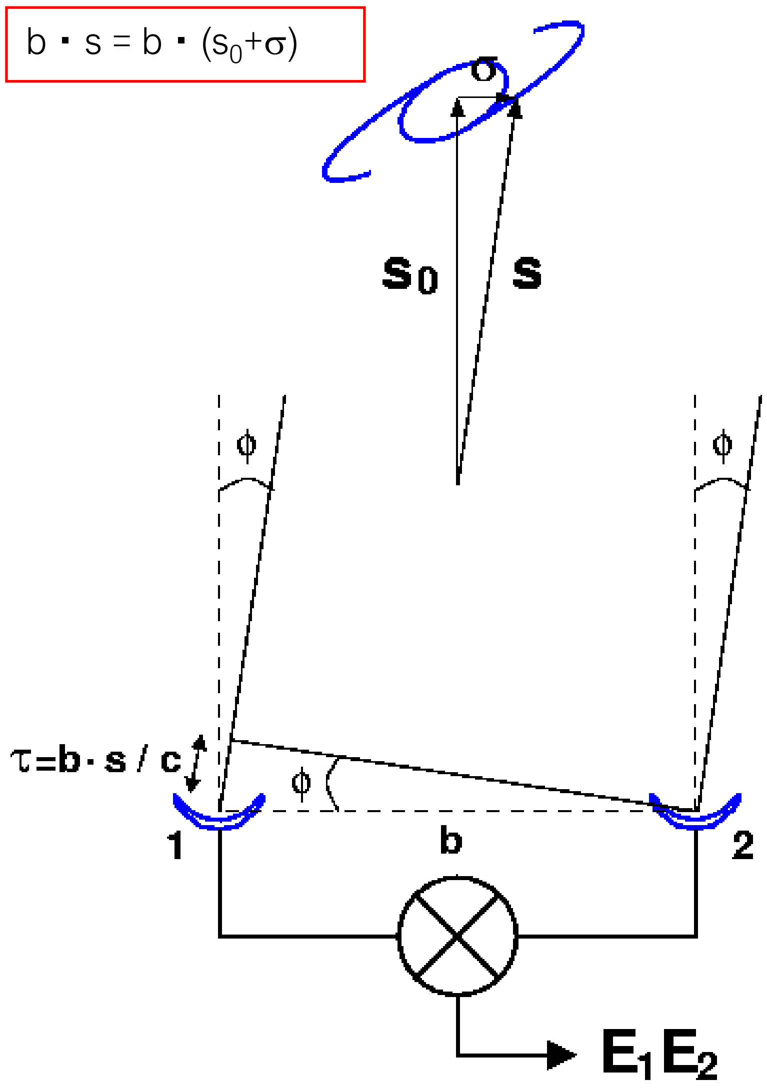


Basics of Interferometry

- $E_1 = E\exp\{2\pi i\nu(t-\tau)\}$
  $E_2 = E\exp\{2\pi i\nu(t)\}$
  - Phase information tells us position information.

- Visibility (You can obtain this information from interferometer):

$$V = \langle E_1 E_2{}^{*} \rangle$$
$$= \int E^2 \exp(-2\pi i\nu\tau)dS \text{ (integrate over the source)}$$
$$= \int E^2 \exp\{(-2\pi i\nu b \bullet s)/c\}dS$$
$$= \int E^2 \exp\{(-2\pi i\nu b \bullet s_0)/c\}\exp\{(-2\pi i\nu b \bullet \sigma)/c\}dS$$
$$= \int E^2 \exp\{(-2\pi i\nu b \bullet \sigma)/c\}dS$$



Basics of Interferometry

- Define coordinates:
  - For the observing source: $\sigma = (x,y)$
    - $E^2 = E(x,y)^2 = I(x,y)$

      : Intensity distribution of observing source. We want to obtain this information.
  - For the antenna baselines: $b = (u,v)$
- $$V(u,v) = \int E^2 \exp\{(-2\pi i v b \bullet \sigma)/c\} dS$$
  $$= \int I(x,y) \exp\{-2\pi i v (ux + vy)/c\} dx dy$$

: Fourier transformation relation between V(u,v) and I(x,y) !!

Basics of Interferometry

- So, the intensity distribution of the observing source is :

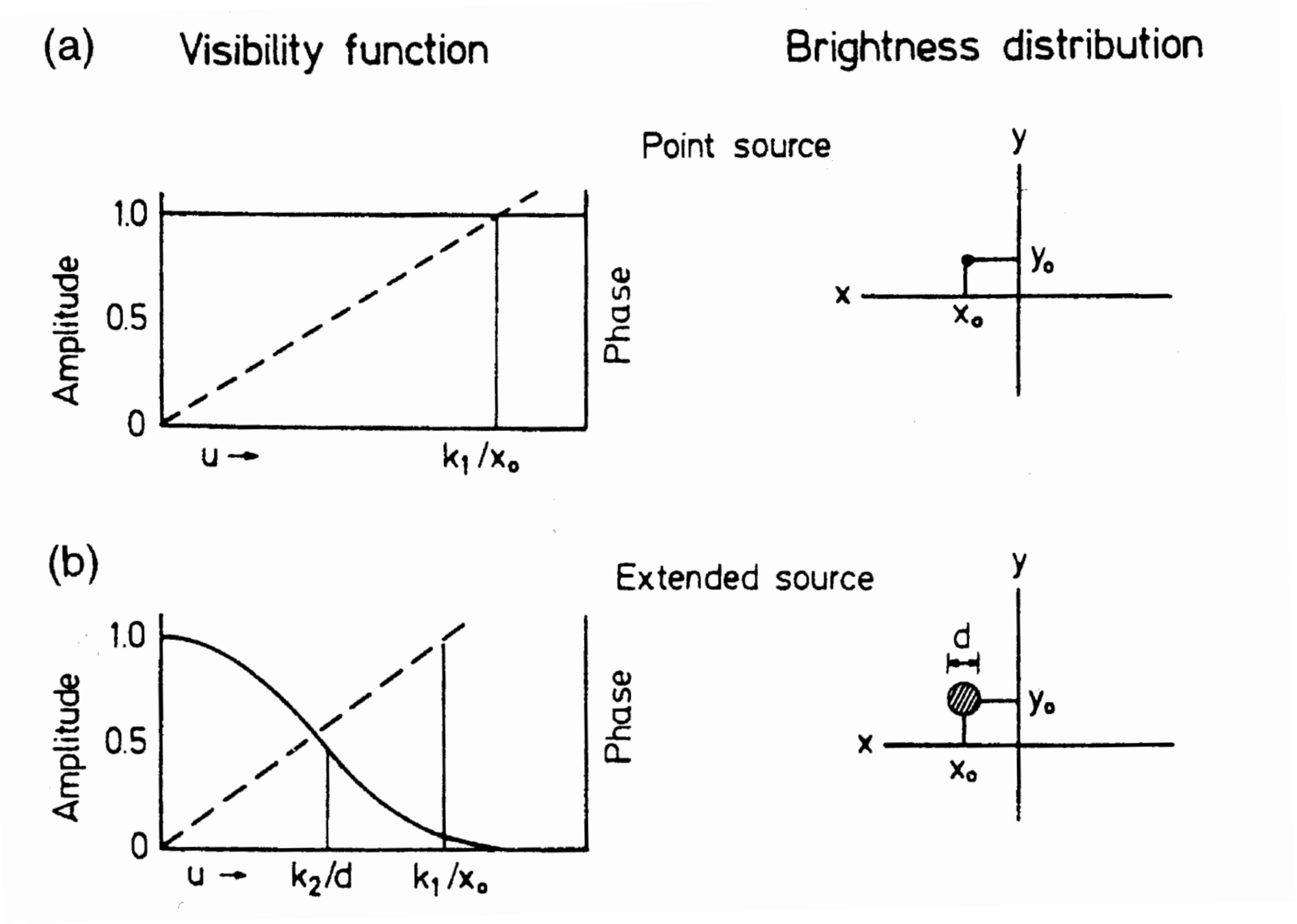
$$\mathrm{I(x,}y) = \int \mathrm{V(u,v)}\exp\{2\pi i v(ux+vy)/c\}dudv$$

- This equation tells us that if you obtain as many *uv* data points as possible toward the source, namely,
  - observe the source with many baselines,
  - observe the source for long time,

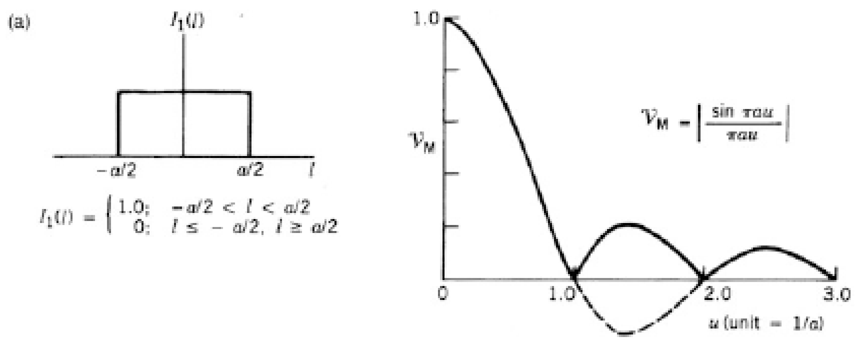
  you can obtain the source intensity distribution.

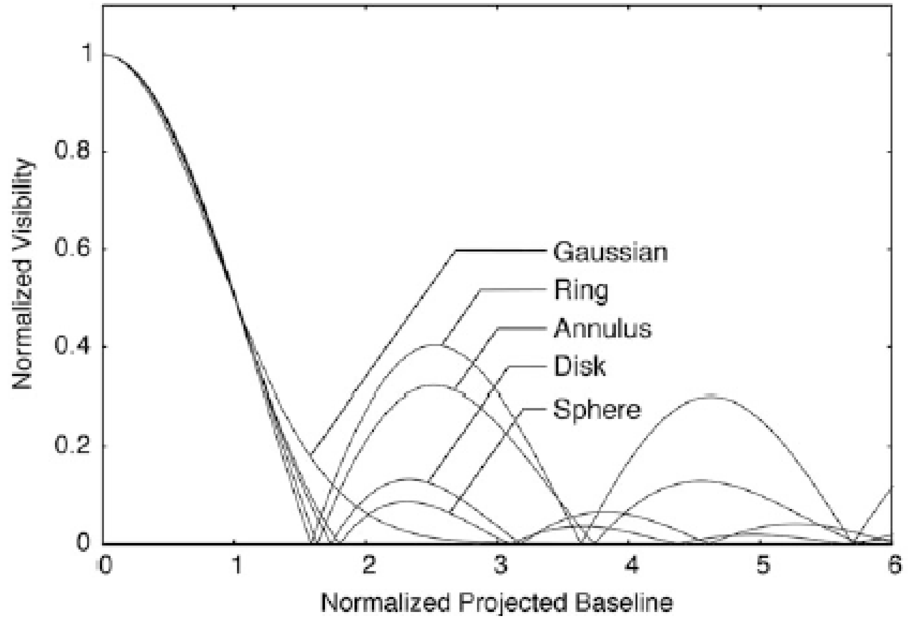
⇨ Nobel Prize in Physics 1974: Sir Martin Ryle for his observations and inventions, in particular of the aperture synthesis technique.

Basics of Interferometry: Visibility – Source Structure Relation



“Tools of Radio Astronomy”
T.L. Wilson, K. Rohlfs, S. Hüttemeister





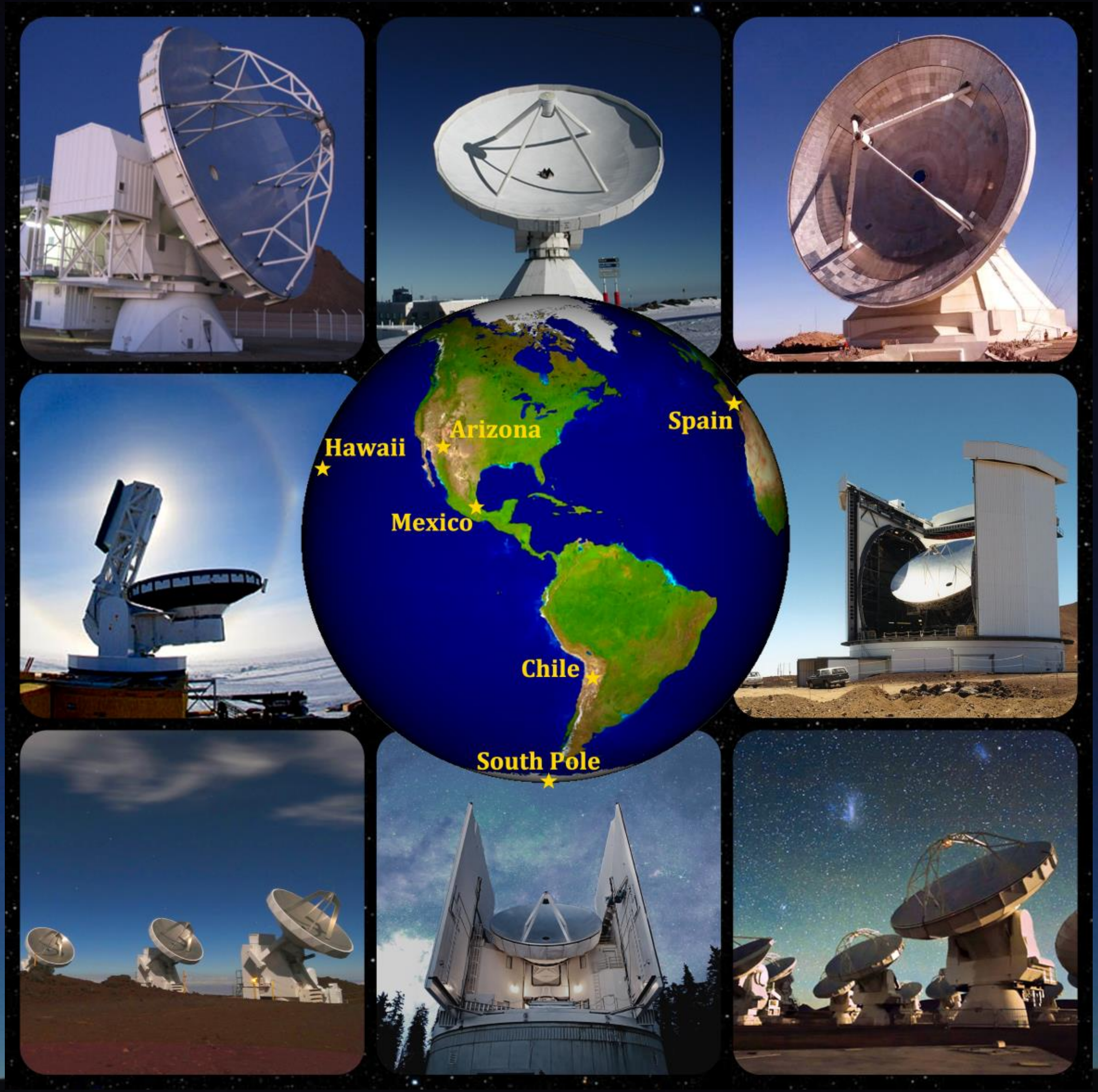
“Interferometry and Synthesis in Radio Astronomy”
A.R. Thompson, J.M. Moran, G.W. Swenson, Jr.

Event Horizon Telescope (EHT)

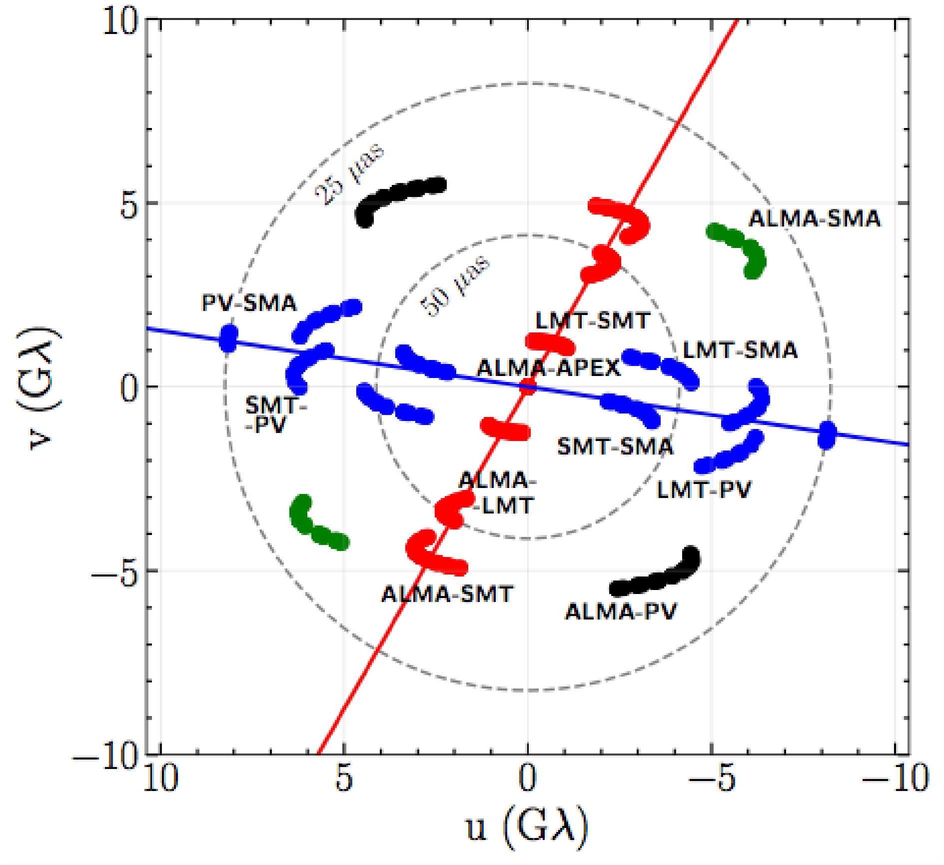
- Academia Sinica Institute of Astronomy and Astrophysics
- University of Arizona
- University of Chicago
- East Asian Observatory
- Goethe-Universität Frankfurt
- Institut de Radioastronomie Millimétrique
- Large Millimeter Telescope Alfonso Serrano
- Max-Planck-Institute für Radioastronomie
- MIT Haystack Observatory
- National Astronomy Observatory of Japan
- Perimeter Institute for Theoretical Physics
- Radboud Universiteit Nijmegen
- Smithsonian Astrophysical Observatory

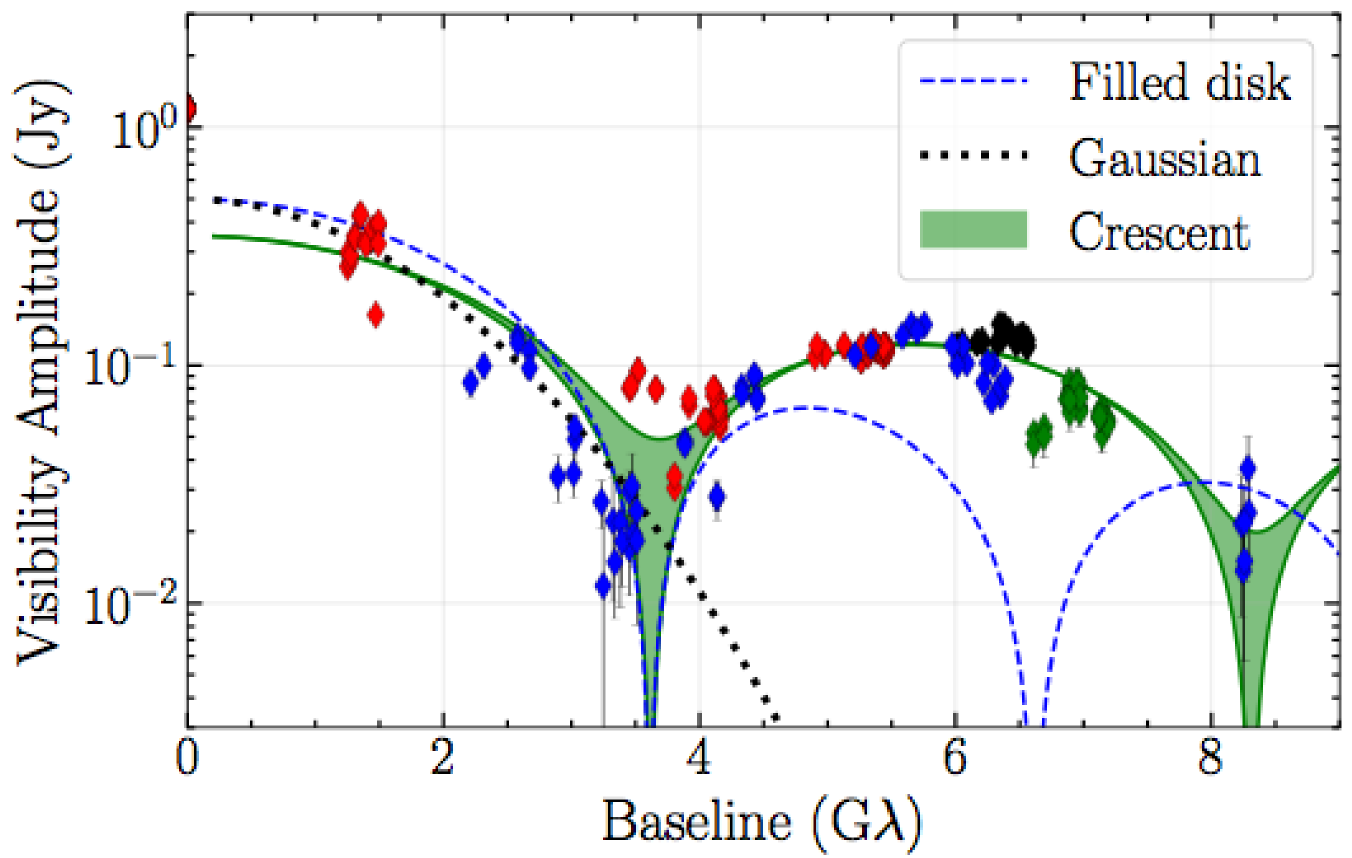
Millimeter/Submillimeter Telescopes in the World (2017)

- Observable at 230 GHz.
  - Atacama Large Millimeter Array (ALMA), Chile
  - ALMA Pathfinder Experiment (APEX), Chile
  - James Clerk Maxwell Telescope (JCMT), Hawaii
  - Large Millimeter Telescope (LMT), Mexico
  - IRAM 30-meter Telescope, Spain
  - South Pole Telescope (SPT), South Pole
  - Submillimeter Array (SMA), Hawaii
  - Submillimeter Telescope (SMT), Arizona



Visibility Domain Feature Extraction





- M87 visibilities consistent with ring ("crescent") geometry.
- Asymmetry between North-South and East-West baselines.

How to take the pictures of the Black Holes?

Black Hole Physics #1

- Heavier, the bigger.
  - If 2 times heavier, 2 times larger.
  - If 10 times heavier, 10 times larger.

(Schwarzschild Radius: $r_s = 2GM_{BH} / c^2$)

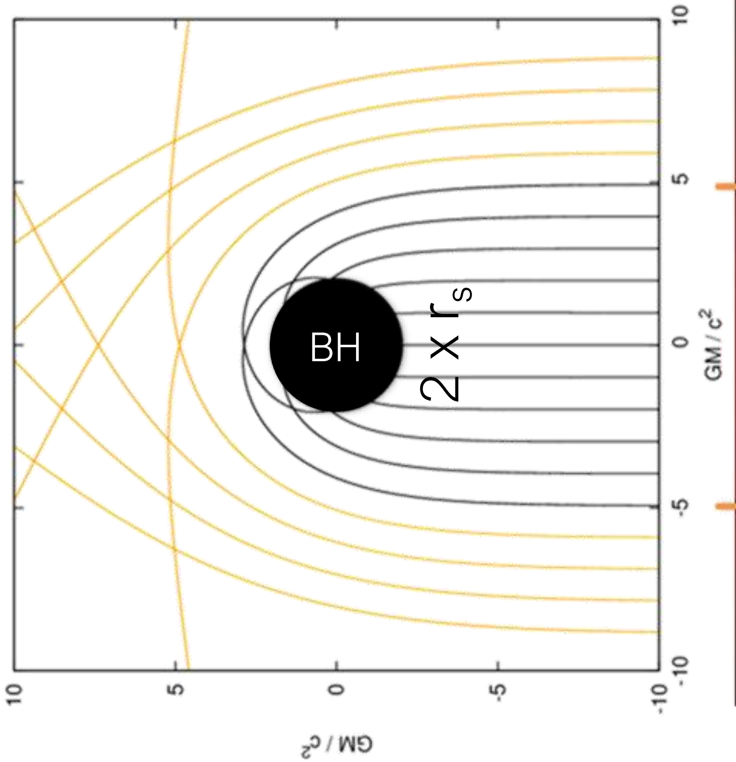
Black Hole and its Size

- As no emission can escape from the Black Hole, we are not able to observe the Black Hole itself.
- Instead, we are seeing the Black Hole as the shadow surrounded by emitting material (e.g., plasma in the accretion flow and/or jet).

Due to the light bending around the Black Hole, the size of the Black Hole Shadow is bigger than the Black Hole itself.

Schwarzschild radius:

$r_s = 2\ GM/c^2$



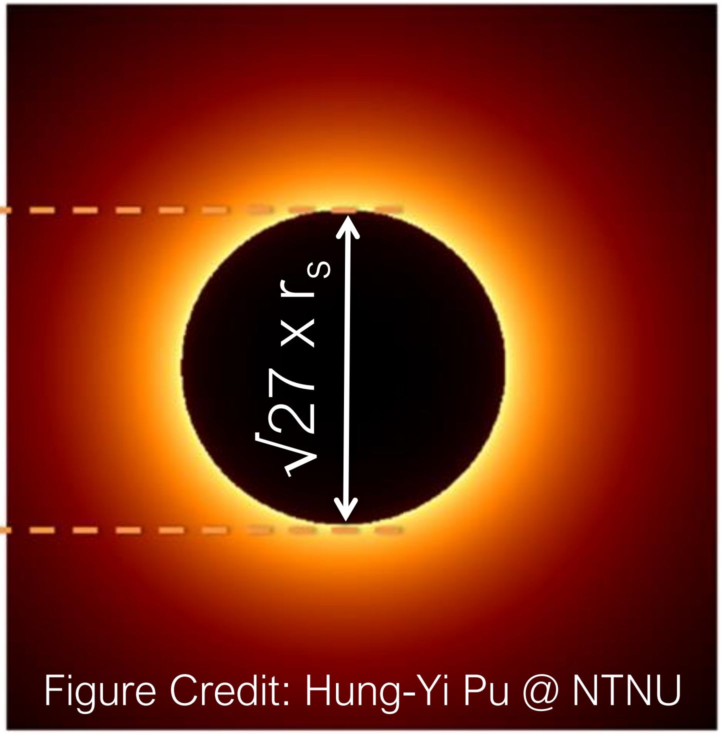
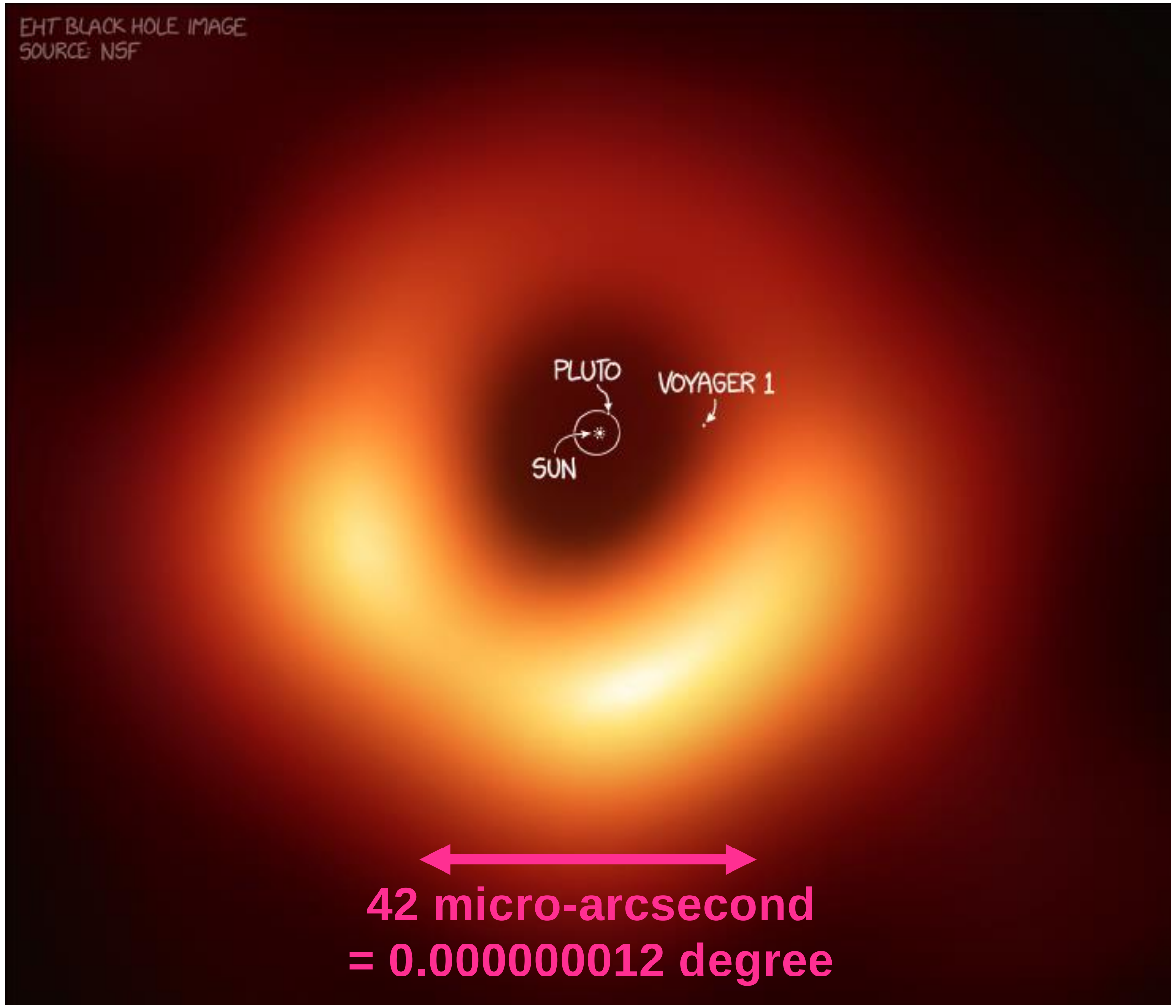


Figure Credit: Hung-Yi Pu @ NTNU

Mass of the Black Hole

- Distance to the Black Hole
  = 55 Million Light Years
- Angular size = 42 μarcsec

⇨ Black Hole Mass
  = 6.5 Billion Solar Mass



https://xkcd.com/2135/

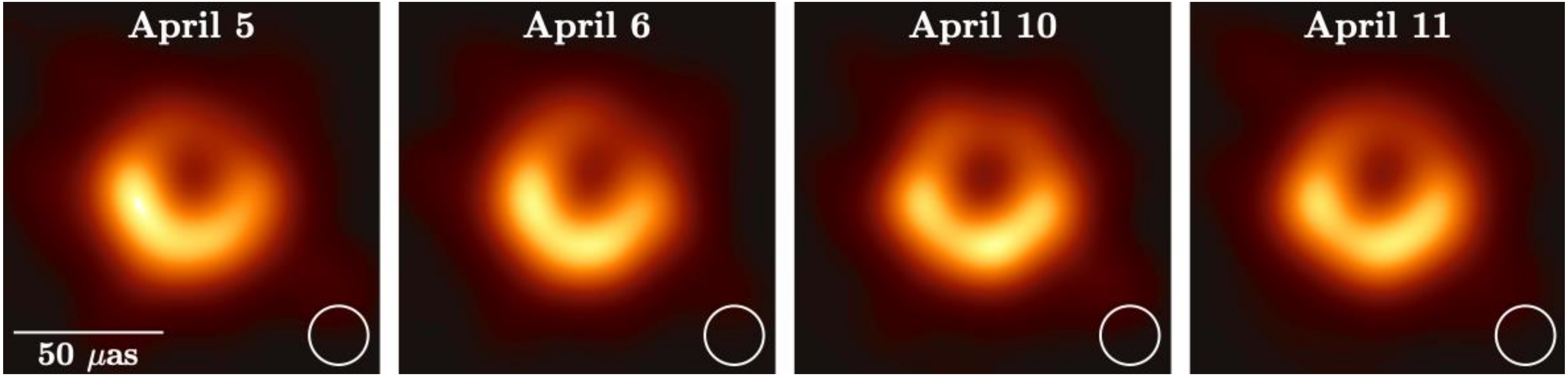
Black Hole Physics #2

- Heavier, Black Hole size bigger, so things moving around Black Hole slower.
  - If 2 times heavier, 2 times slower.
  - If 10 times heavier, 10 times slower.

(Light Crossing Time: $t_{lct} = r_s / c = 2GM_{BH} / c^3$)

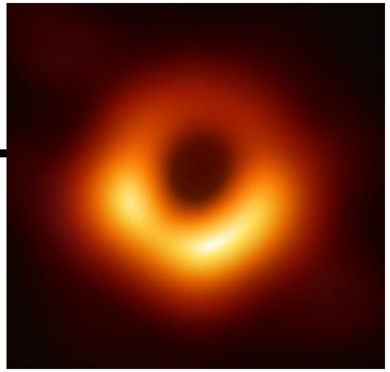
Mass of the Black Hole

- Structures almost stable for a week.
  ⇨ Black Hole must be heavy.



- Black Hole Mass = 6.5 Billion Solar Mass
- Takes days ~ months to rotate around the Black Hole.

Asymmetry of the Black Hole Ring



- If Black Hole is spinning, the frame dragging effect shows up, and one side will be darker, and one side will be brighter (Doppler boosting).

⇨ Black Hole is spinning.

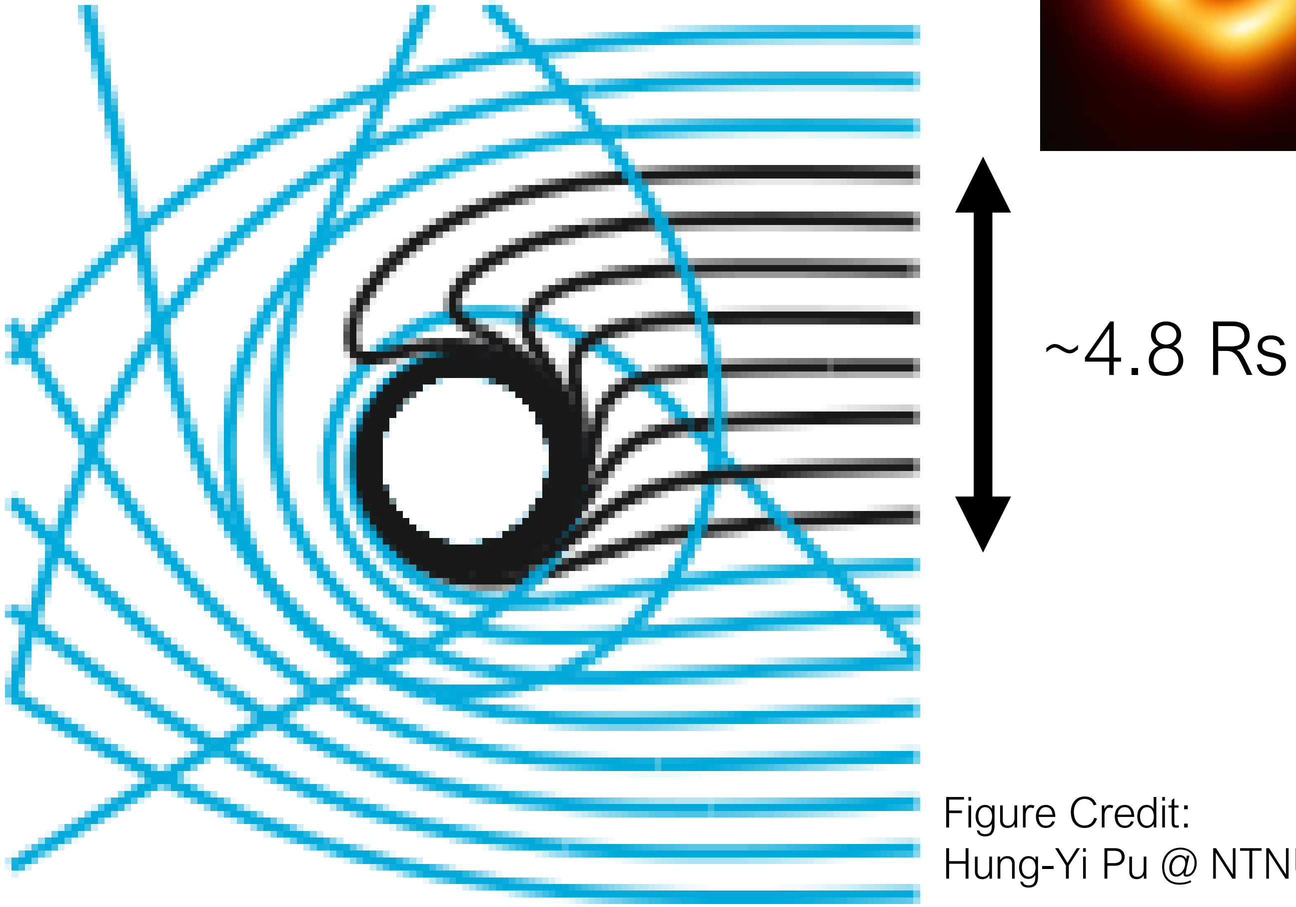


Figure Credit:
Hung-Yi Pu @ NTNU

Maximumly Rotating Black Hole

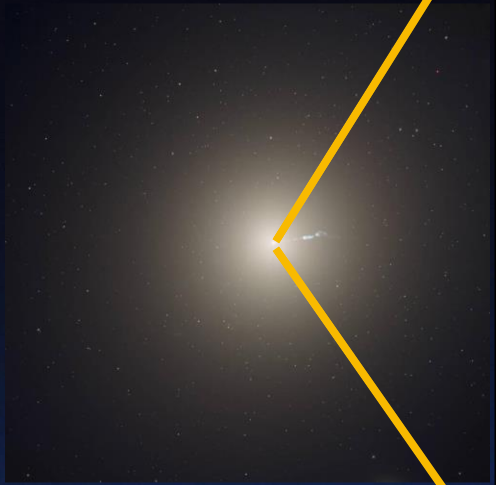
In 2022,

EHT Collaboration 2022, ApJL, 930, L12

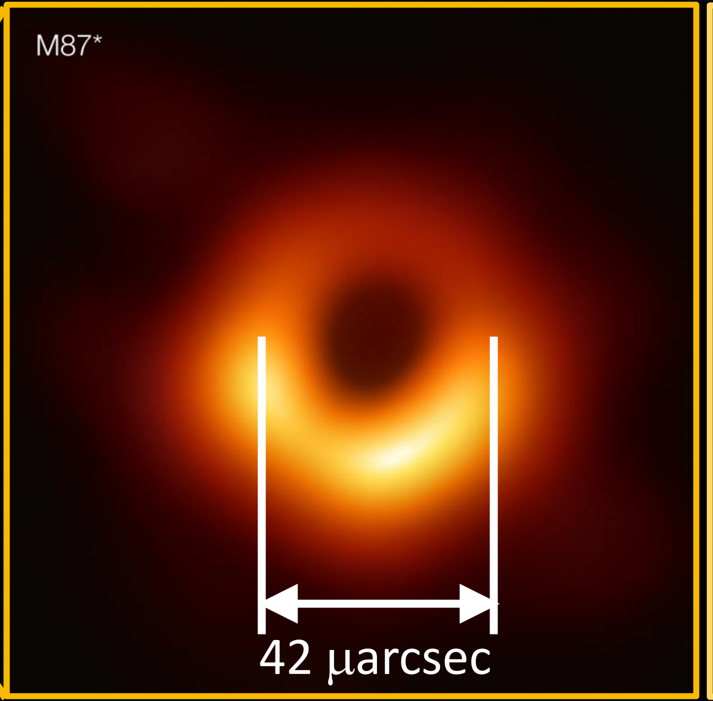
Image of the Black Hole at the Center of Our Galaxy

Two black holes have similar sizes

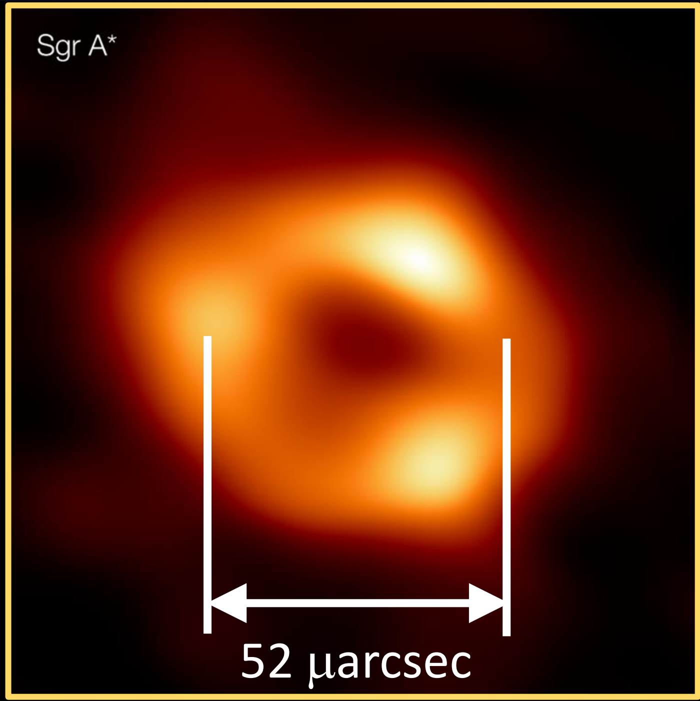
M87



Credit: NASA, ESA and the Hubble Heritage Team (STScI/AURA)

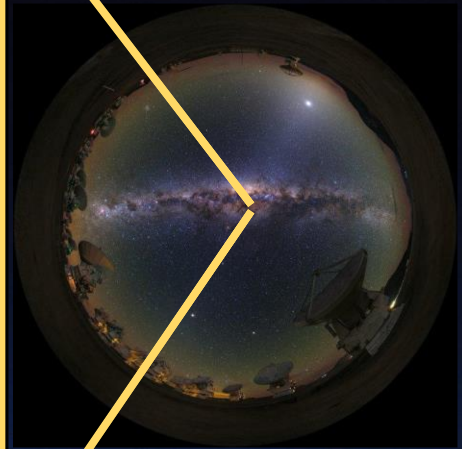


= 0.000000012 deg



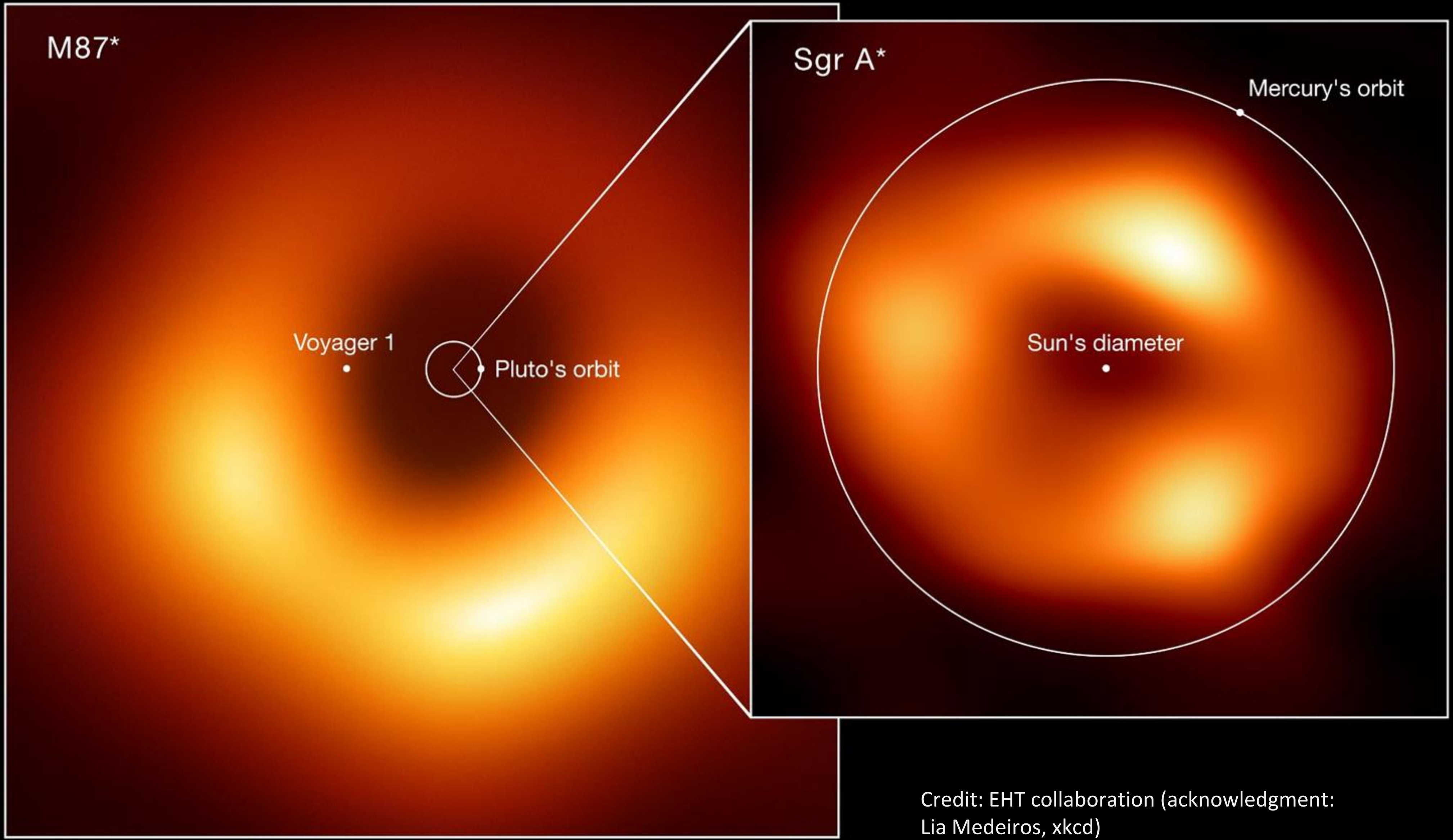
= 0.000000015 deg

Our Galaxy



Credit: ESO / B. Trafeshi (twanight.org)

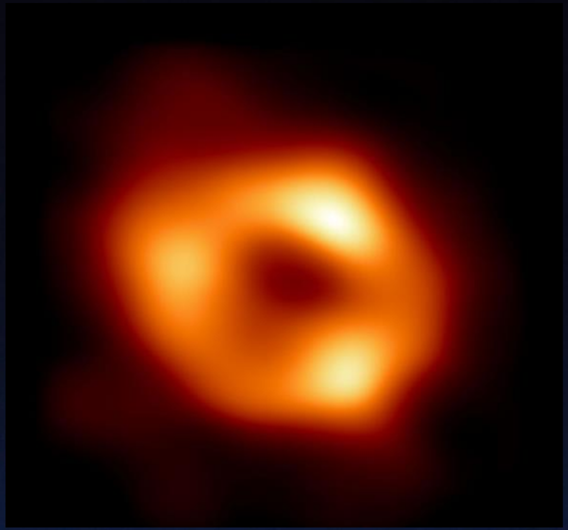
- M87 is 55 million light years away.
- The center of our Galaxy is 27 thousand light years away.



Credit: EHT collaboration (acknowledgment:
Lia Medeiros, xkcd)

Sgr A and M87* comparison*

Black Hole at the Center of Our Galaxy

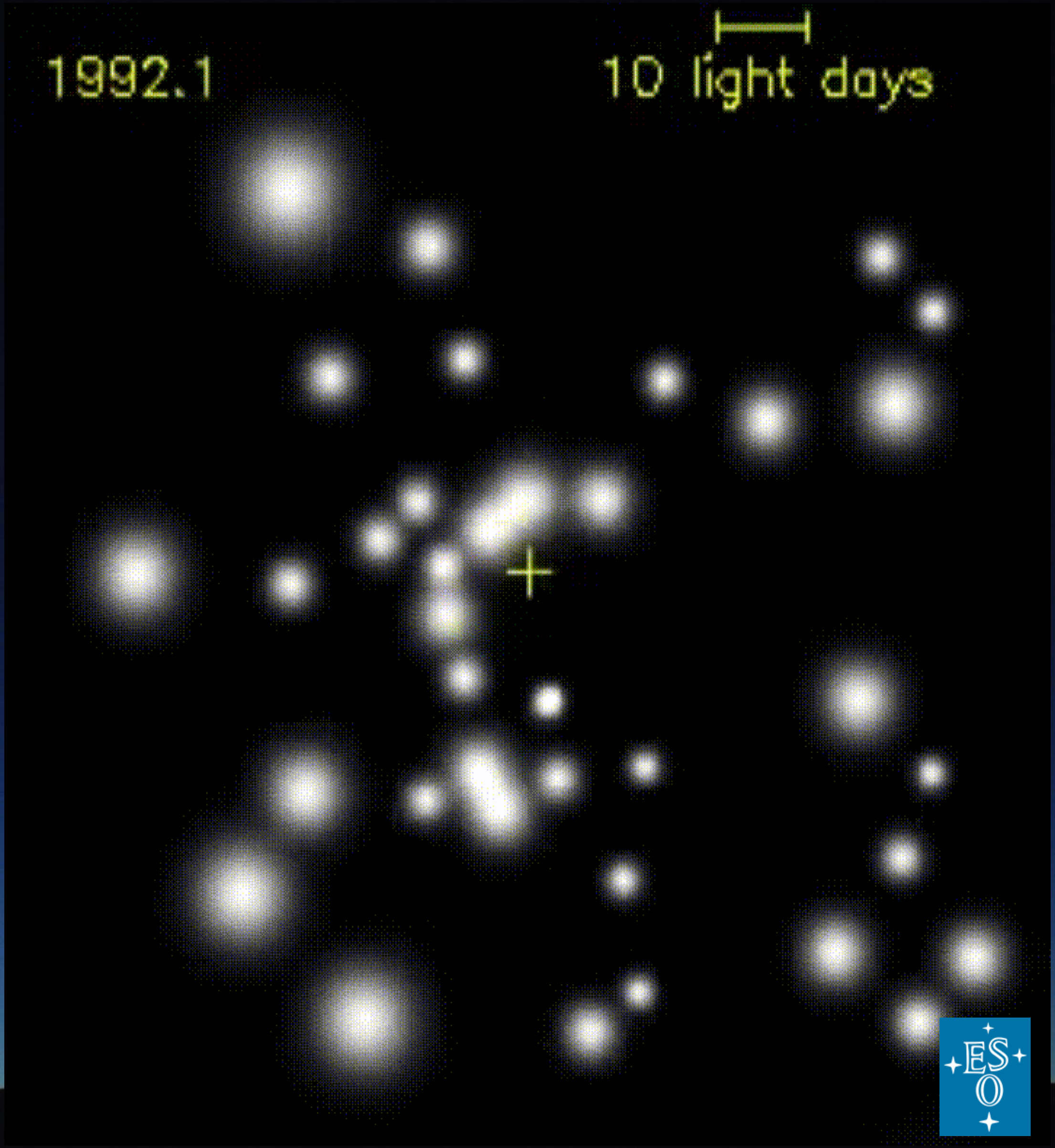


- Black Hole Mass:
  About 2000 times lighter than M87.

⇨ Timescale:
About 2000 times faster than M87.
⇨ Takes only minutes ~ hours to rotate around the Black Hole.
⇨ Just too fast to take an image!
⇨ The image of the black hole at the center of our Galaxy is showing only the stable component.

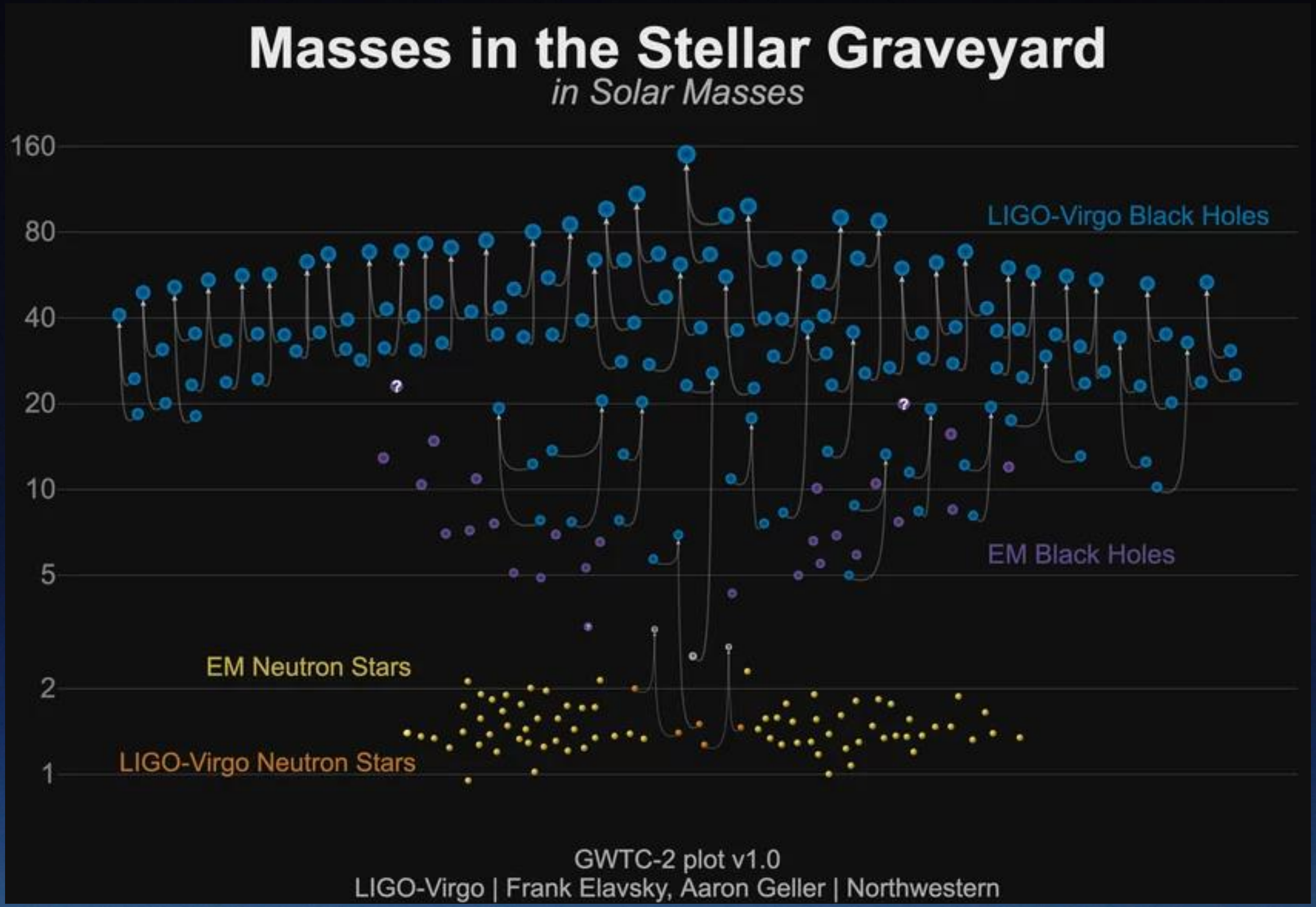
Nobel Prize in Physics 2020

- Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the centre of our galaxy".
  - The closest approach to Sagittarius A* is about 1.88 billion km, almost as close as Saturn gets to the Sun.
- What EHT showed is actual size of the black hole shadow (~5 Rs), which is a diameter of 51.8 million km, almost as close as Mercury gets to the Sun.
  - Solid evidence of the existence of a black hole.



Nobel Prize in Physics 2017

- Rainer Weiss, Barry C. Barish, and Kip S. Thorne "for decisive contributions to the LIGO detector and the observation of gravitational waves".
  - Solid evidence of the existence of stellar mass black holes.
- What EHT showed is the solid evidences of the existence of supermassive black holes with 4 million and 6.5 billion solar masses.



- **So far, Einstein's Theory of Relativity works fine for 9 orders of magnitude** (a few solar masses to 6.5 billion solar masses).


Why Greenland???

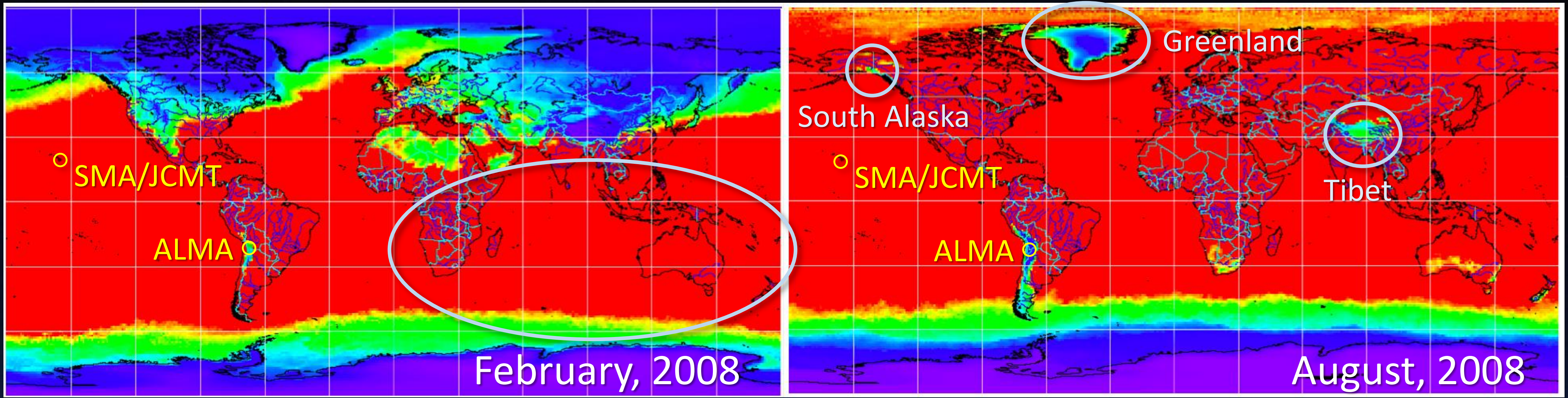
Telescope Site Selection

- Site selection criteria:
  - Precipitable water vapor (PWV) is low.
  - Longest possible baselines with existing submm telescopes. (i.e., site with no existing submm telescopes)
  - Overlapping sky coverage with ALMA.
    - ALMA has the largest aperture size. (corresponds to 85 m single-dish telescope)
    - Interferometric baseline sensitivity $\propto \sqrt{A_1 A_2}$
  - Accessible.

Telescope Site Selection

Winter in the North, Summer in the South

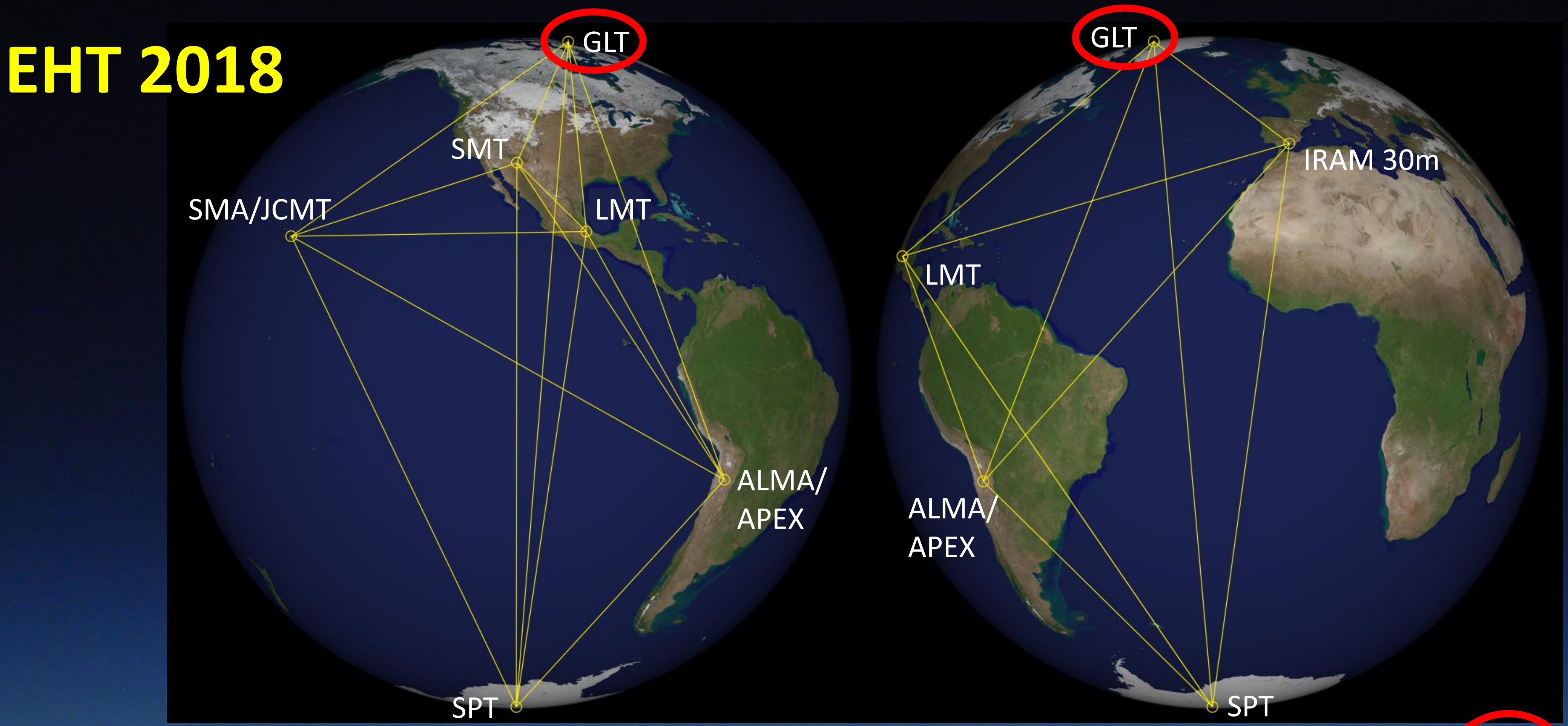
Winter in the South, Summer in the North



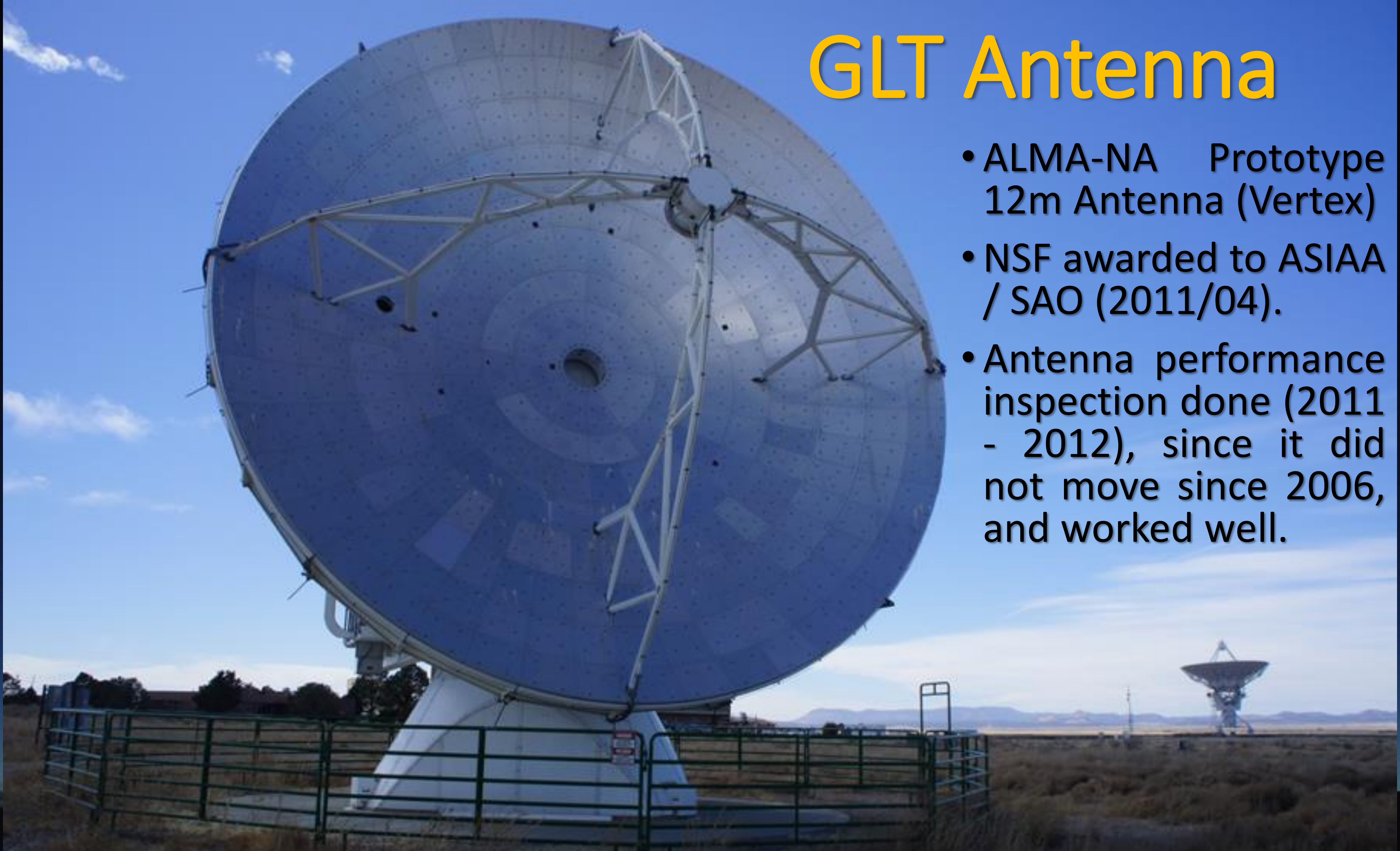
NASA Aqua & Terra/MODIS Satellite Data. PWV > 3 mm is displayed as red color.

- No obvious site in Southern Hemisphere, except Northern Chile & Antarctica.
- South Alaska (Mt. McKinley or Mt. Denali): Difficult to access.
- Tibet: opposite side of ALMA, so impossible to have baseline with it.
- Greenland: Similar condition as South Pole. It is also possible to have baselines with ALMA/SMA/JCMT.

Extend the Baseline Length to Whole Earth



GLT Antenna



- ALMA-NA Prototype 12m Antenna (Vertex)
- NSF awarded to ASIAA / SAO (2011/04).
- Antenna performance inspection done (2011 - 2012), since it did not move since 2006, and worked well.

GLT Antenna Disassembly

- Totally disassembled at VLA site (2012/12)

GLT Antenna Shipping & Reassembly

Norfolk Partial Reassembly after Upgrade for Extreme Weather

Pituffik Reassembly

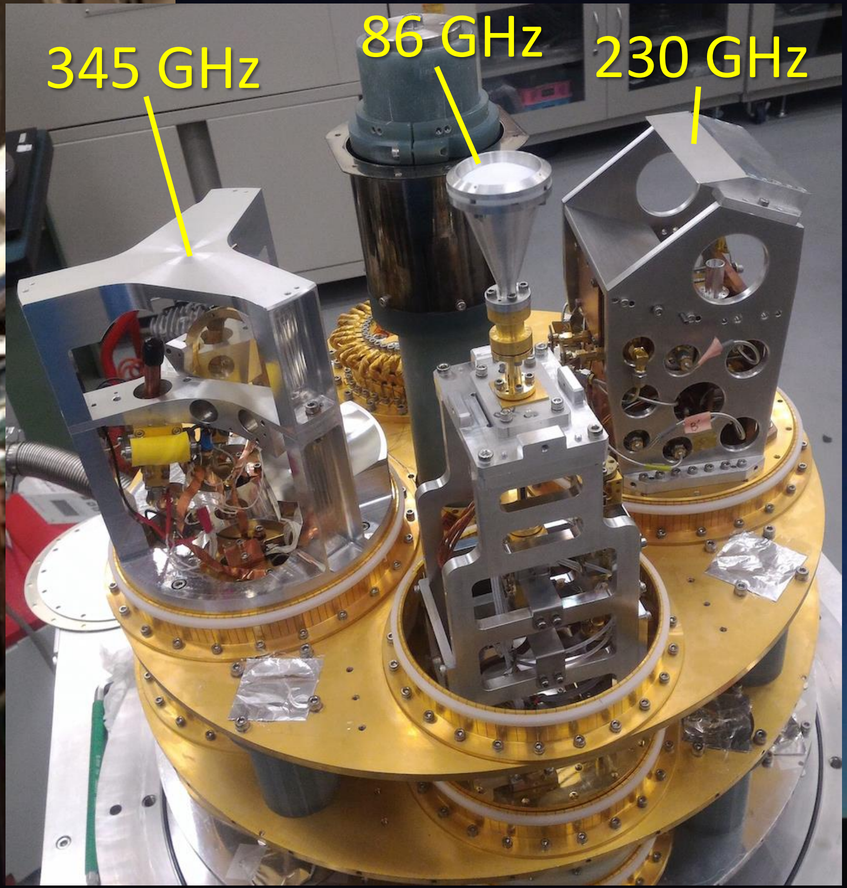
Feb. 18, 2017

Finishing Antenna Re-Assembly

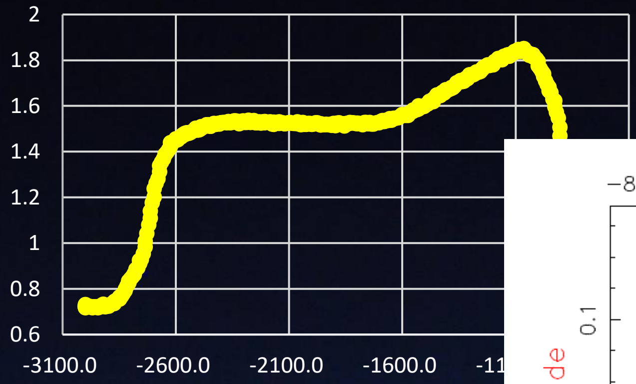
US Pituffik Space Base in Greenland

Greenland Telescope (GLT)

The only Asian telescope operating at the polar region.



Greenland Telescope (GLT)
Astronomical First Light & First Fringe!!!

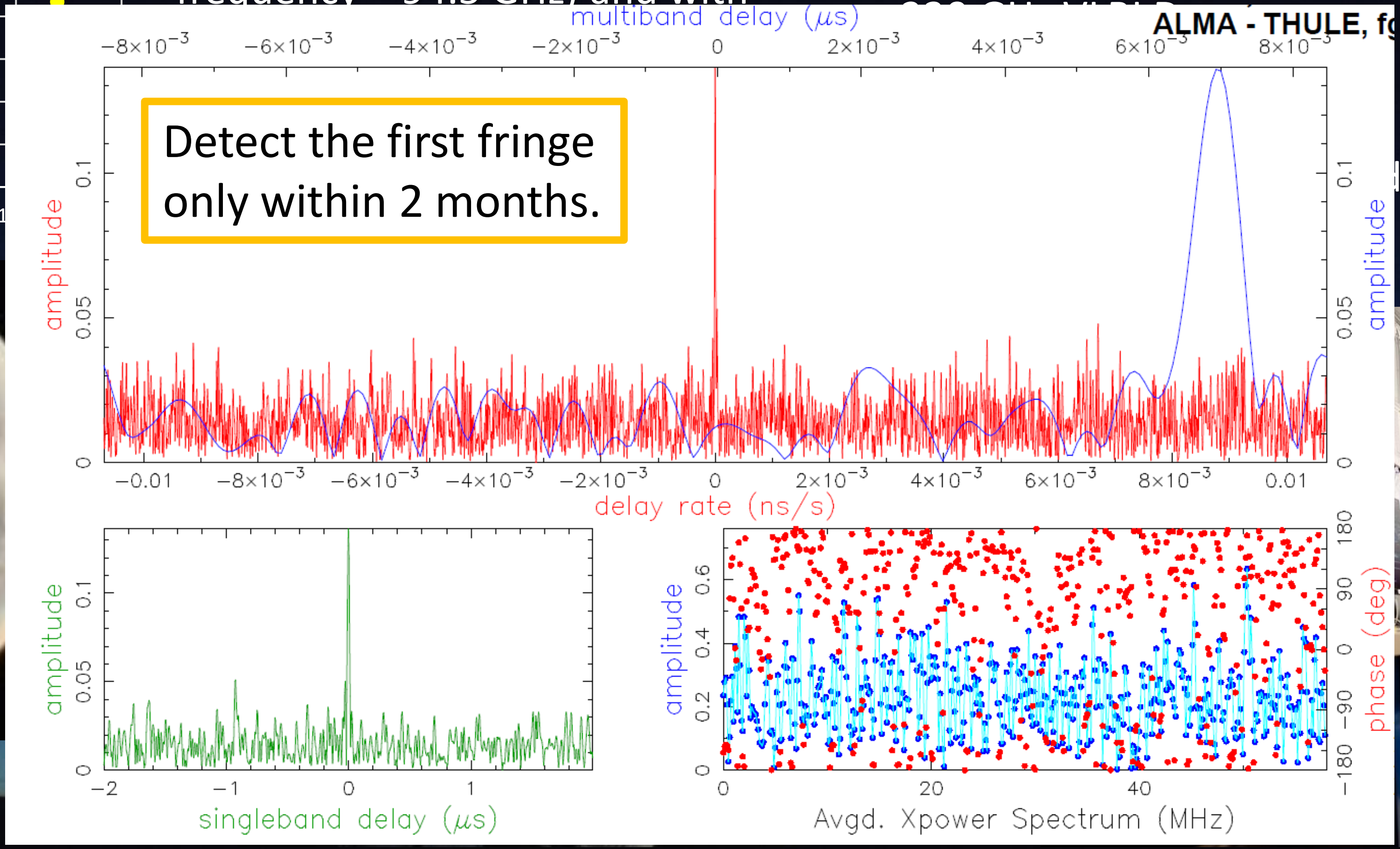


Azimuth scan of Moon with the GLT 86 GHz Receiver (observed frequency = 94.5 GHz) and with

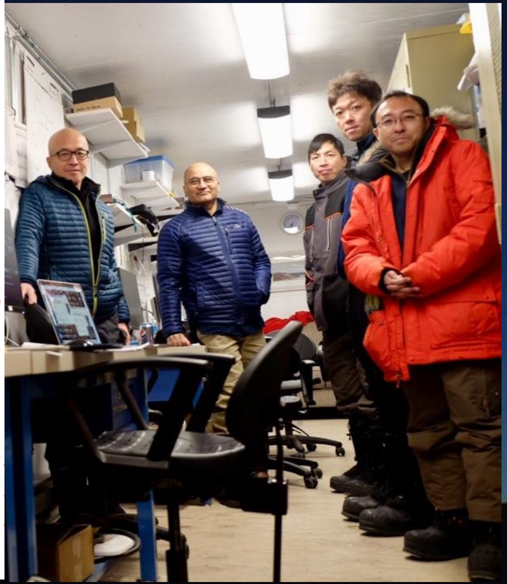
- We joined the Event Horizon Telescope (EHT)

Performed on
2018/1/28
11:30 - 14:30
Local Thule Time

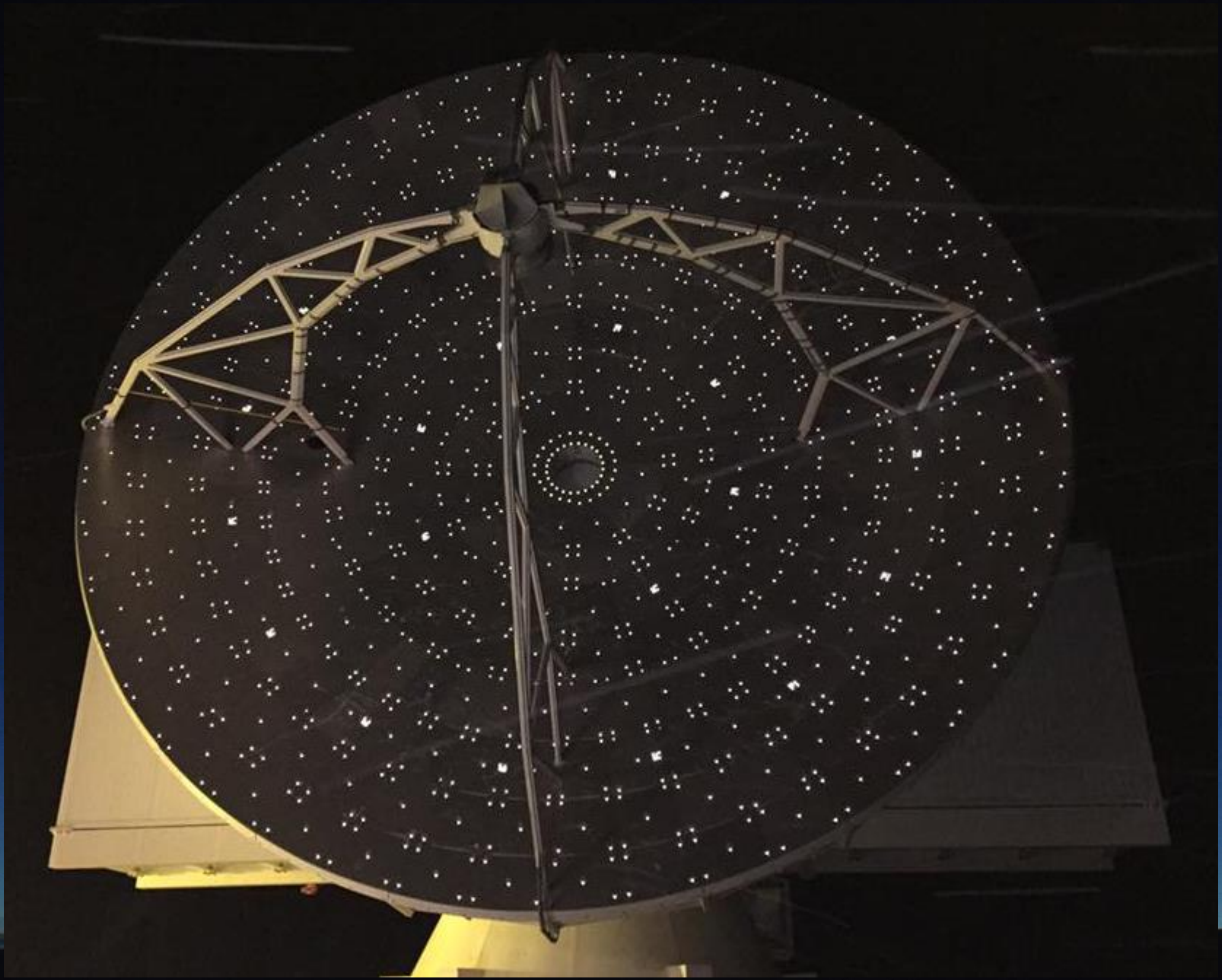
Moon at Christmas
(Size matched with
the above scan)



Ming-Tang Chen, Nimesh Patel, Kuan-Yu Liu, Keiichi Asada, & Hiroaki Nishioka at the GLT Control Room



Photogrammetry Surface Improvement

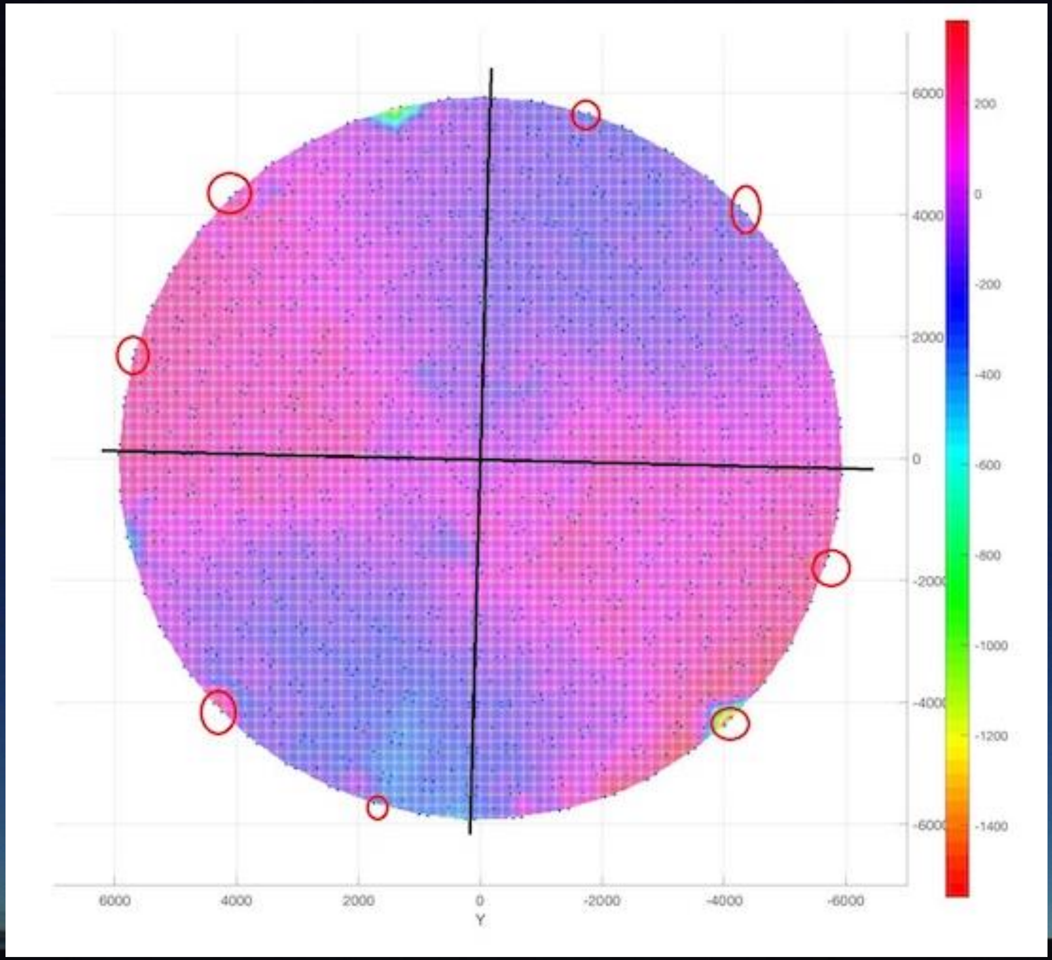


- We installed the photogrammetry targets on the telescope surface in 2018 summer.

Photogrammetry Surface Improvement

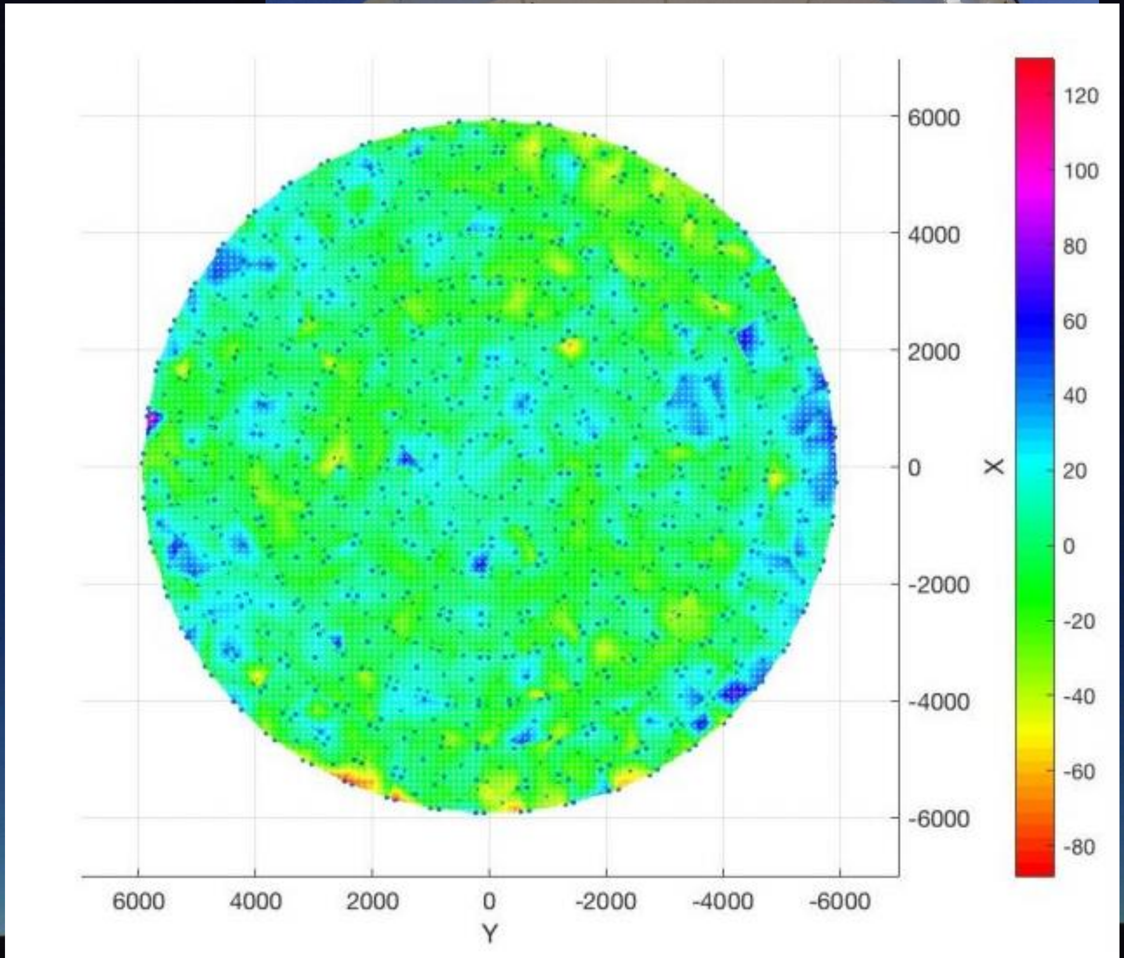
Before: 180 μm

Saddle-like Systematic Structure.



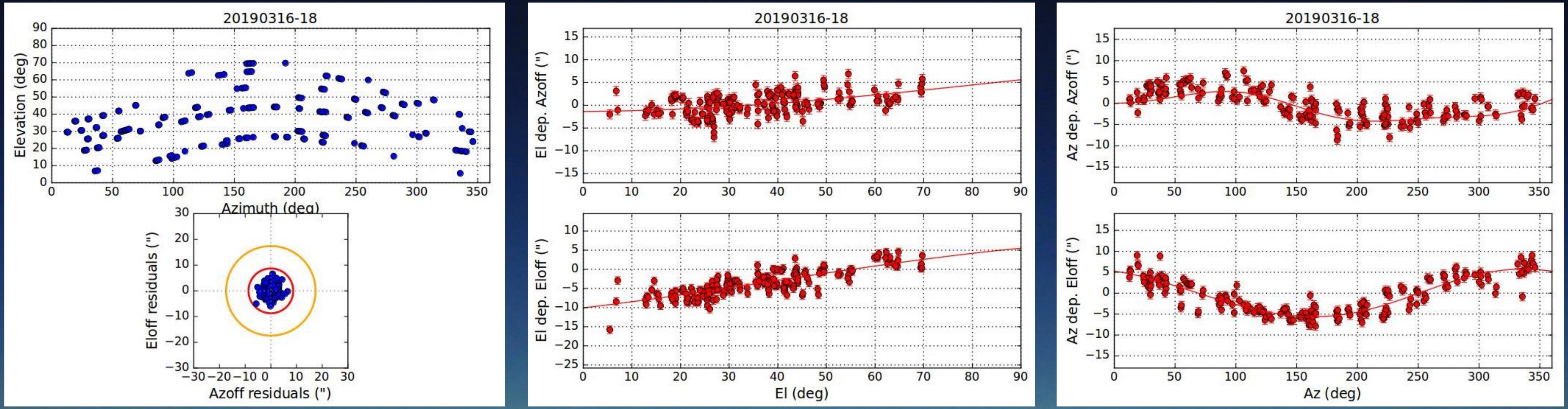
After: 21 μm

Random Structure.



Full-Sky Regular Line Pointing

- After the surface improvement, the antenna sensitivity significantly improved.
  ⇨ Weaker sources are now easily detected.
  ⇨ Full-sky molecular line pointing is now possible.
- Pointing accuracies for all 3 receivers constantly reach ~< 2”.

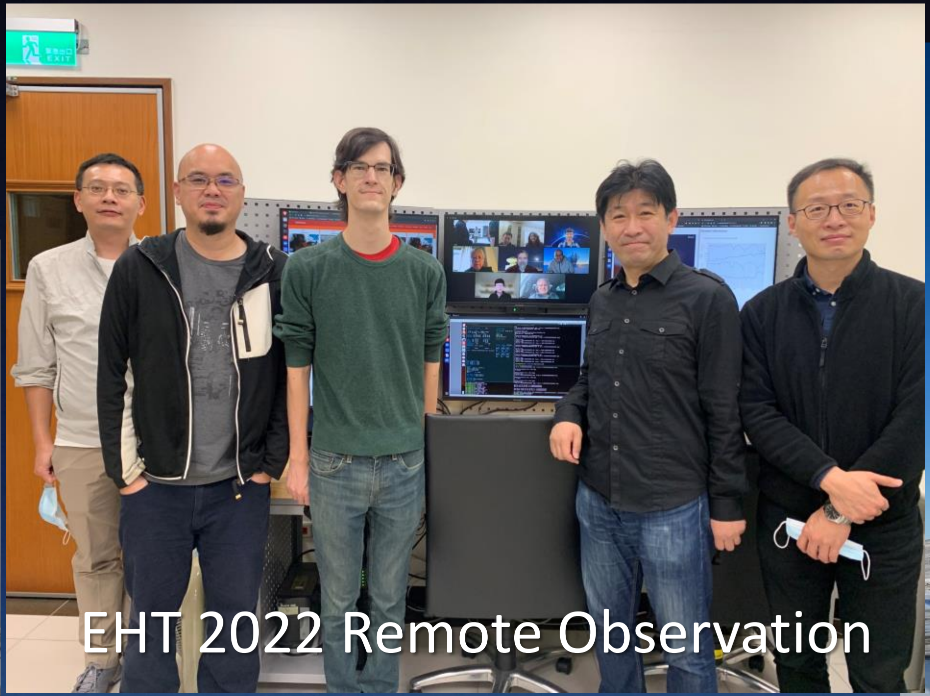


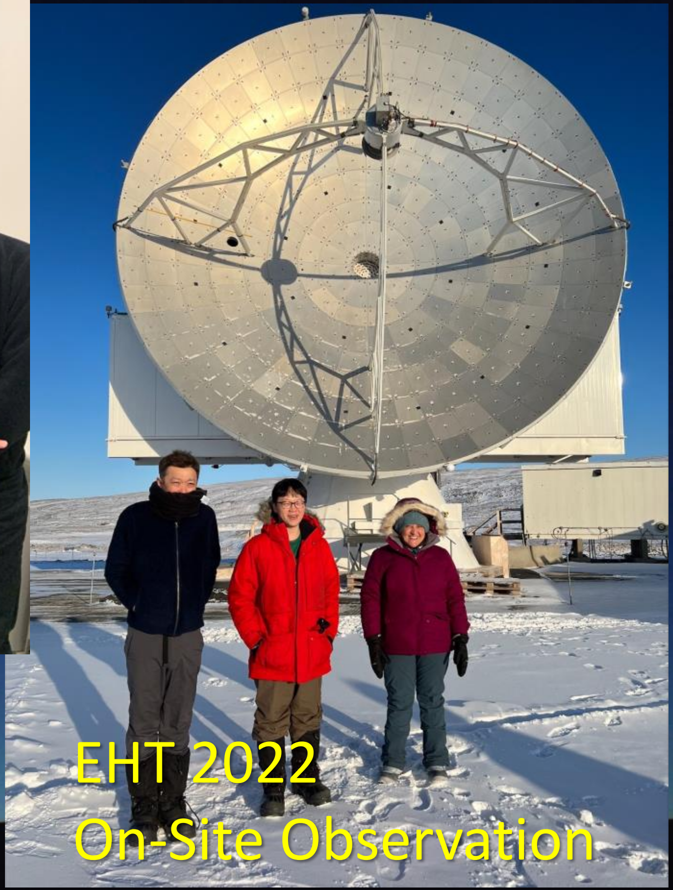
Rx230 Molecular Line Full-Sky Pointing Results

Remote Observations from Taiwan

- Due to the pandemic, we could not go to Pituffik for a while.
- We therefore made the remote observation system together with the local Pituffik engineers.


EHT 2021 Remote Observation


EHT 2022 Remote Observation


EHT 2022
On-Site Observation

Article

A ring-like accretion structure in M87 connecting its black hole and jet

Lu, Asada, et al., 2023, Nature, 616, 686

https://doi.org/10.1038/s41586-023-05843-w

Received: 21 October 2022

Accepted: 14 February 2023

Published online: 26 April 2023

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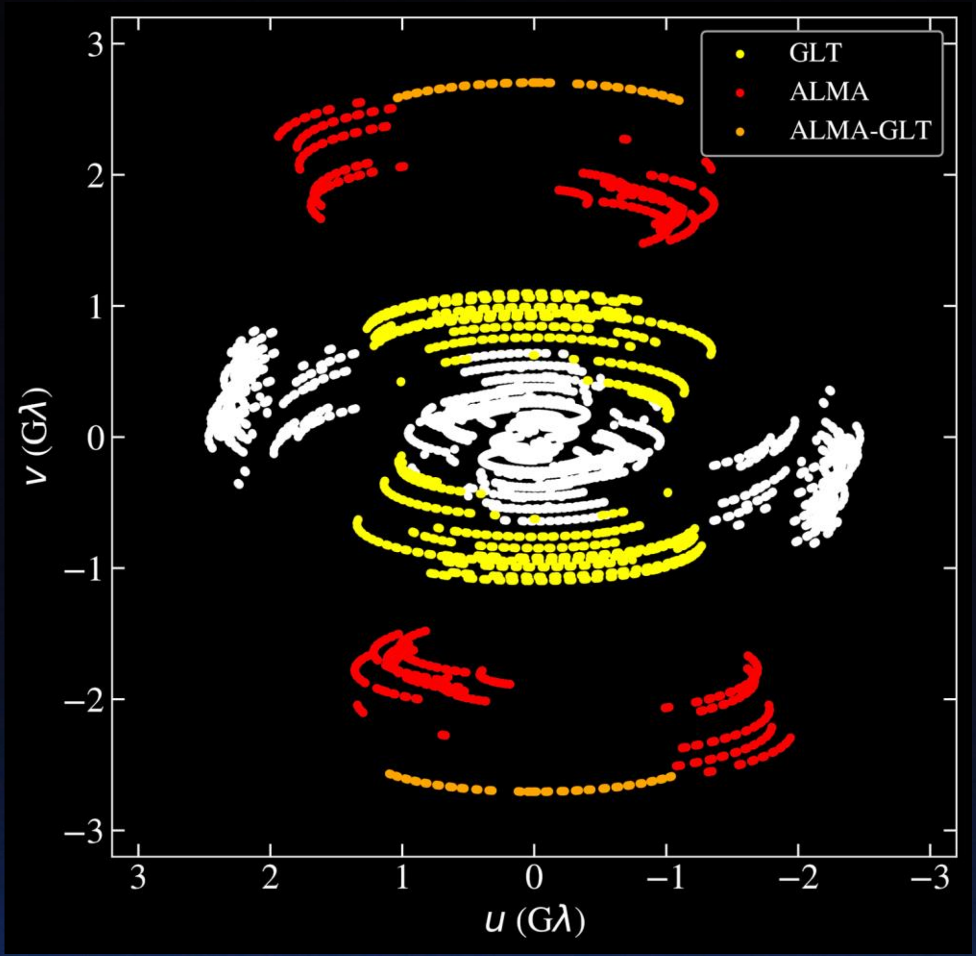
Ru-Sen Lu[1,2,3]✉, Keiichi Asada[4]✉, Thomas P. Krichbaum[3]✉, Jongho Park[4,5], Fumie Tazaki[6,7], Hung-Yi Pu[4,8,9], Masanori Nakamura[4,10], Andrei Lobanov[3], Kazuhiro Hada[7,11]✉, Kazunori Akiyama[12,13,14], Jae-Young Kim[3,5,15], Ivan Marti-Vidal[16,17], José L. Gómez[18], Tomohisa Kawashima[19], Feng Yuan[1,20,21], Eduardo Ros[3], Walter Alef[3], Silke Britzen[3], Michael Bremer[22], Avery E. Broderick[23,24,25], Akihiro Doi[26,27], Gabriele Giovannini[28,29], Marcello Giroletti[29], Paul T. P. Ho[4], Mareki Honma[7,11,30], David H. Hughes[31], Makoto Inoue[4], Wu Jiang[1], Motoki Kino[14,32], Shoko Koyama[4,33], Michael Lindqvist[34], Jun Liu[3], Alan P. Marscher[35], Satoki Matsushita[4], Hiroshi Nagai[11,14], Helge Rottmann[3], Tuomas Savolainen[3,36,37], Karl-Friedrich Schuster[22], Zhi-Qiang Shen[1,2], Pablo de Vicente[38], R. Craig Walker[39], Hai Yang[1,21], J. Anton Zensus[3], Juan Carlos Algaba[40], Alexander Allardi[41], Uwe Bach[3], Ryan Berthold[42], Dan Bintley[42], Do-Young Byun[5,43], Carolina Casadio[44,45], Shu-Hao Chang[4], Chih-Cheng Chang[46], Song-Chu Chang[46], Chung-Chen Chen[4], Ming-Tang Chen[47], Ryan Chilson[47], Tim C. Chuter[42], John Conway[34], Geoffrey B. Crew[13], Jessica T. Dempsey[42,48], Sven Dornbusch[3], Aaron Faber[49], Per Friberg[42], Javier González García[38], Miguel Gómez Garrido[38], Chih-Chiang Han[4], Kuo-Chang Han[46], Yutaka Hasegawa[50], Ruben Herrero-Illana[51], Yau-De Huang[4], Chih-Wei L. Huang[4], Violette Impellizzeri[52,53], Homin Jiang[4], Hao Jinchi[54], Taehyun Jung[5], Juha Kallunki[37], Petri Kirves[37], Kimihiro Kimura[55], Jun Yi Koay[4], Patrick M. Koch[4], Carsten Kramer[22], Alex Kraus[3], Derek Kubo[47], Cheng-Yu Kuo[56], Chao-Te Li[4], Lupin Chun-Che Lin[57], Ching-Tang Liu[4], Kuan-Yu Liu[4], Wen-Ping Lo[4,58], Li-Ming Lu[46], Nicholas MacDonald[3], Pierre Martin-Cocher[4], Hugo Messias[51,59], Zheng Meyer-Zhao[4,48], Anthony Minter[60], Dhanya G. Nair[61], Hiroaki Nishioka[4], Timothy J. Norton[62], George Nystrom[47], Hideo Ogawa[50], Peter Oshiro[47], Nimesh A. Patel[62], Ue-Li Pen[4], Yurii Pidopryhora[3,63], Nicolas Pradel[4], Philippe A. Raffin[47], Ramprasad Rao[62], Ignacio Ruiz[64], Salvador Sanchez[64], Paul Shaw[4], William Snow[47], T. K. Sridharan[53,62], Ranjani Srinivasan[4,62], Belén Tercero[38], Pablo Torne[64], Efthalia Traianou[3,18], Jan Wagner[3], Craig Walther[42], Ta-Shun Wei[4], Jun Yang[34] & Chen-Yu Yu[4]

The nearby radio galaxy M87 is a prime target for studying black hole accretion and jet formation[1,2]. Event Horizon Telescope observations of M87 in 2017, at a wavelength of 1.3 mm, revealed a ring-like structure, which was interpreted as gravitationally lensed emission around a central black hole[3]. Here we report images of M87 obtained in 2018, at a wavelength of 3.5 mm, showing that the compact radio core is spatially resolved. High-resolution imaging shows a ring-like structure of $8.4^{+0.5}_{-1.1}$ Schwarzschild radii in diameter, approximately 50% larger than that seen at 1.3 mm. The outer edge at 3.5 mm is also larger than that at 1.3 mm. This larger and thicker ring indicates a substantial contribution from the accretion flow with absorption effects, in addition to the gravitationally lensed ring-like emission. The images show that the edge-brightened jet connects to the accretion flow of the black hole. Close to the black hole, the emission profile of the jet-launching region is wider than the expected profile of a black-hole-driven jet, suggesting the possible presence of a wind associated with the accretion flow.



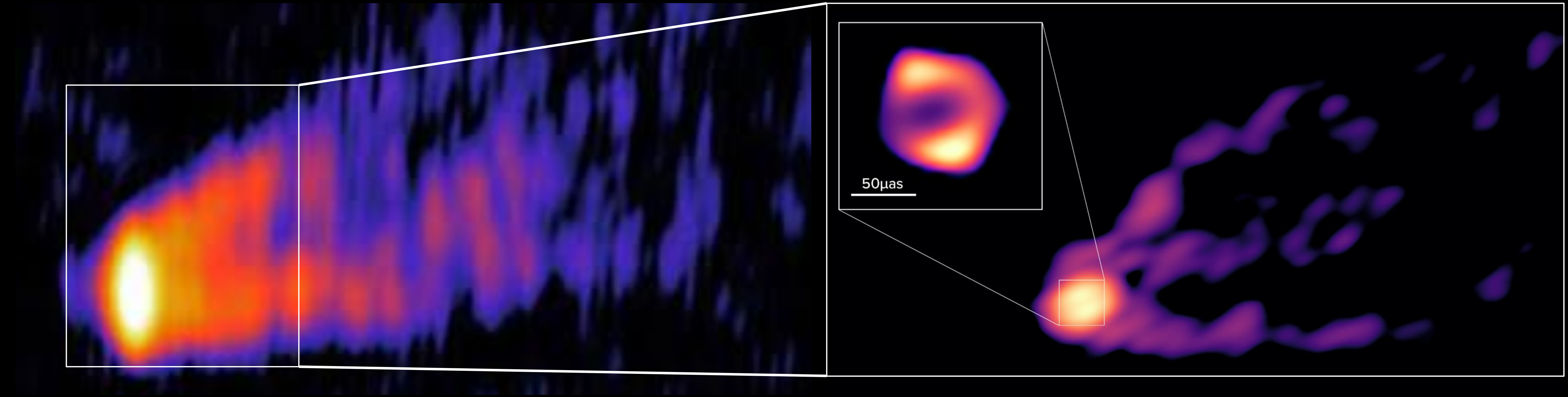
- GMVA+ALMA+GLT: April 14-15, 2018
- 86 GHz VLBI
- 3 Sources: M87, 3C273, & 3C279
- 16 Stations: Eb, On, Mh, Ys, Pv, GLT, GBT, 8 x VLBA, phased ALMA

Improvement by the GLT

M87 @ 86 GHz

Kim et al. 2018

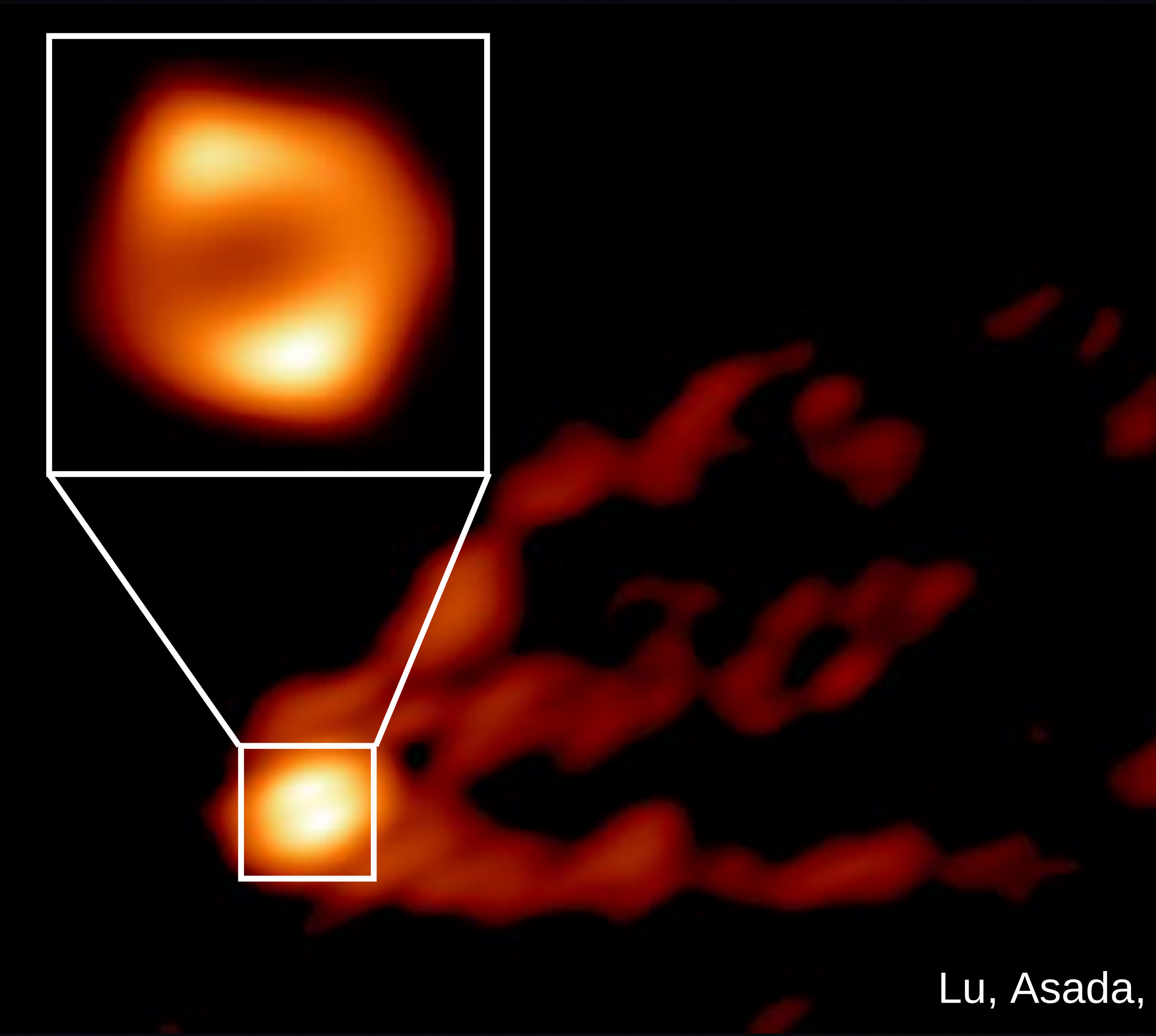
Lu, Asada, et al. 2023



GMVA

GMVA + ALMA + GLT

The First GLT Results on the M87 Black Hole

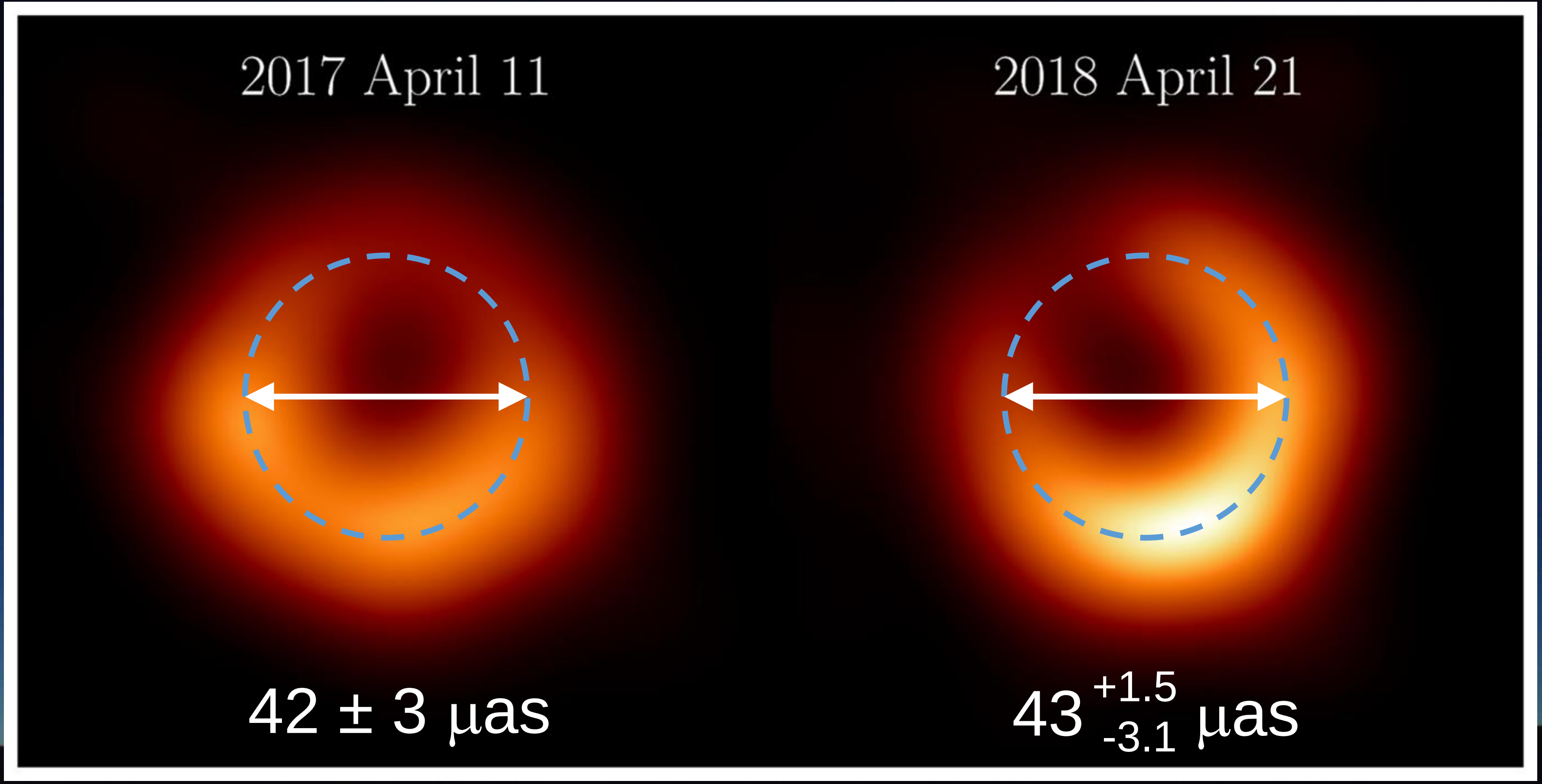


- The first-ever image of the spatially resolved accretion flow around a black hole.
- The first-ever simultaneous image of the central engine of Active Galactic Nucleus (black hole, accretion flow, and jet).

Lu, Asada, et al. 2023, Nature, 616, 686

The First GLT Results on the M87 Black Hole

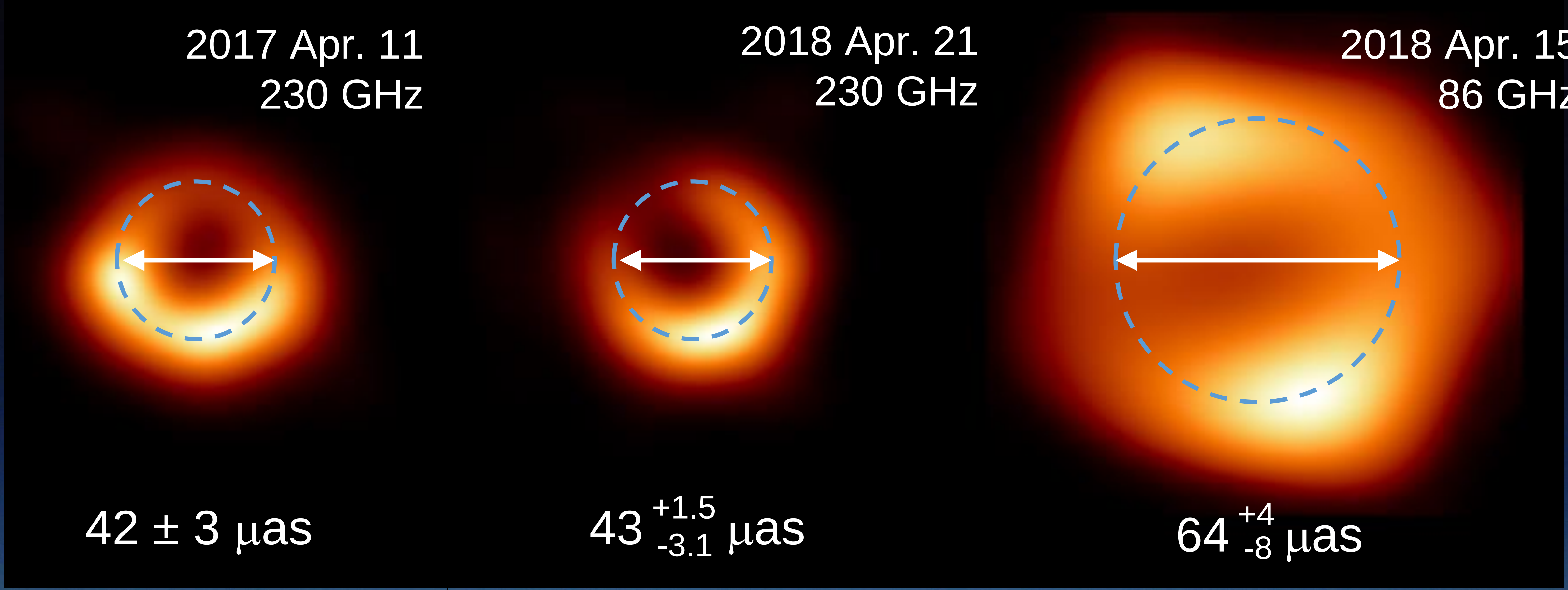
- M87 observed by the EHT again on 2018 April (GLT's first EHT obs).
- Persistent ring diameter between 1 yr
  ⇨ Strong evidence for the Black Hole shadow.



EHT Collaboration et al., 2024, A&A, 681, A79

The First GLT Results on the M87 Black Hole

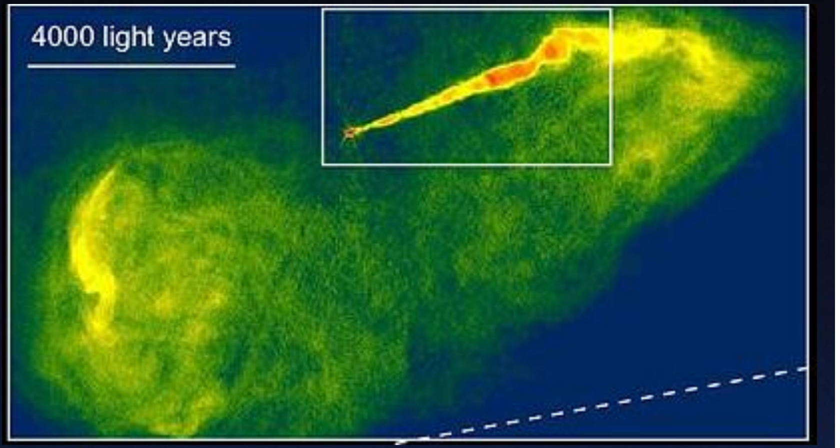
EHT Collaboration et al., 2024, A&A, 681, A79
Lu, Asada, et al., 2023, Nature, 616, 686

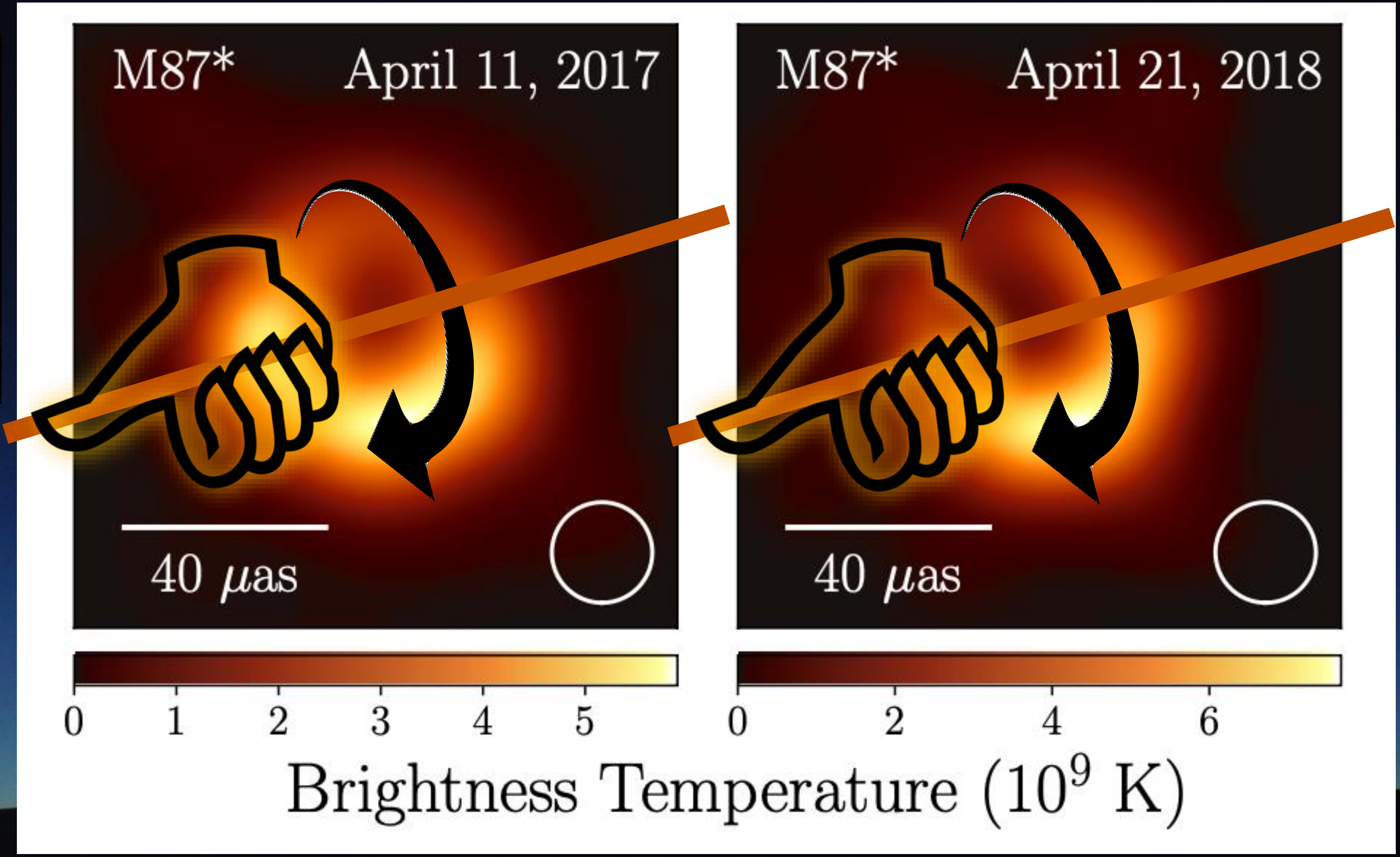


- M87 Black Hole shadow at different frequencies.

The First GLT Results on the M87 Black Hole

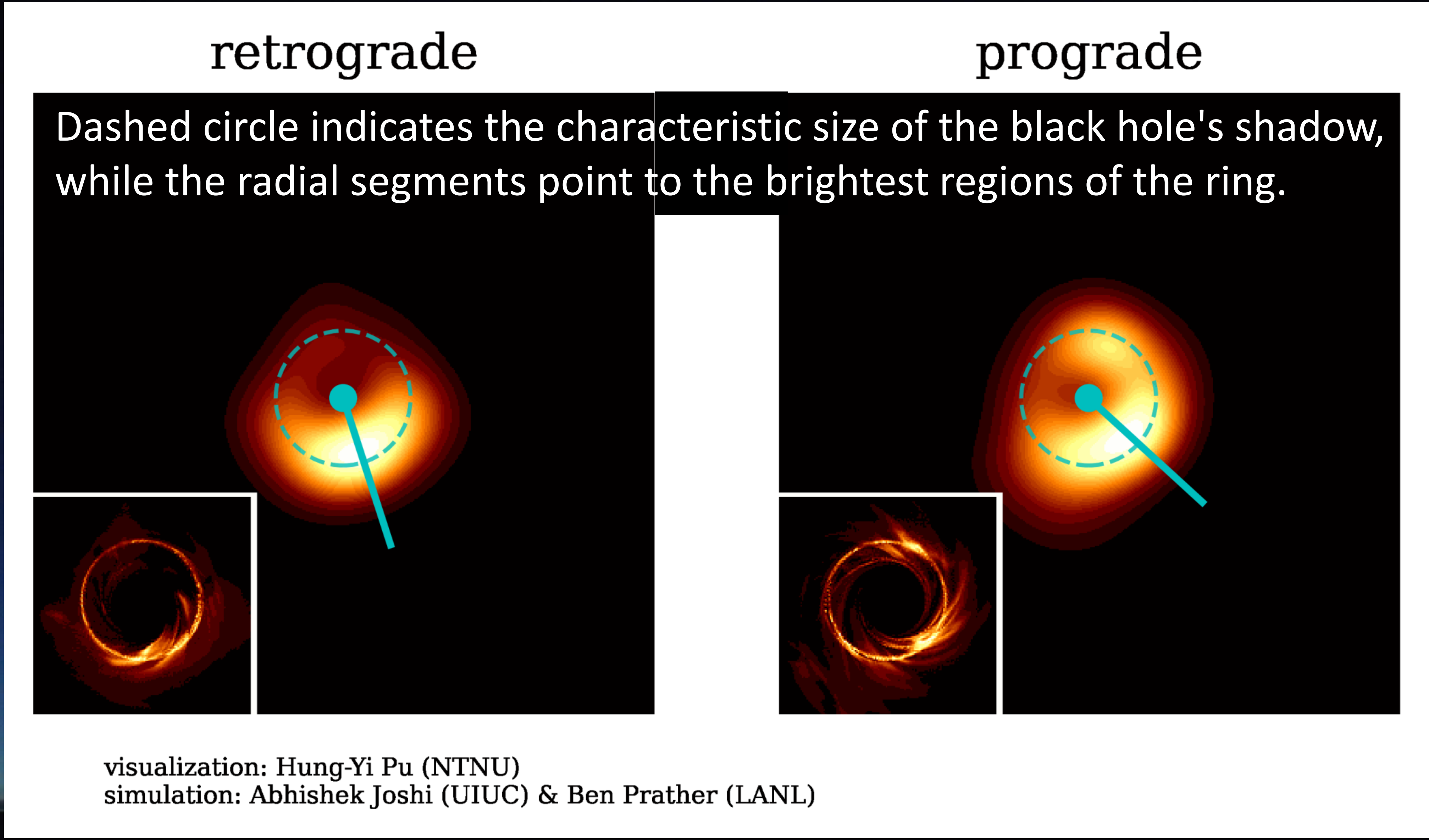
- Observational results show that the spin axis of the M87 black hole is toward away from the Earth.





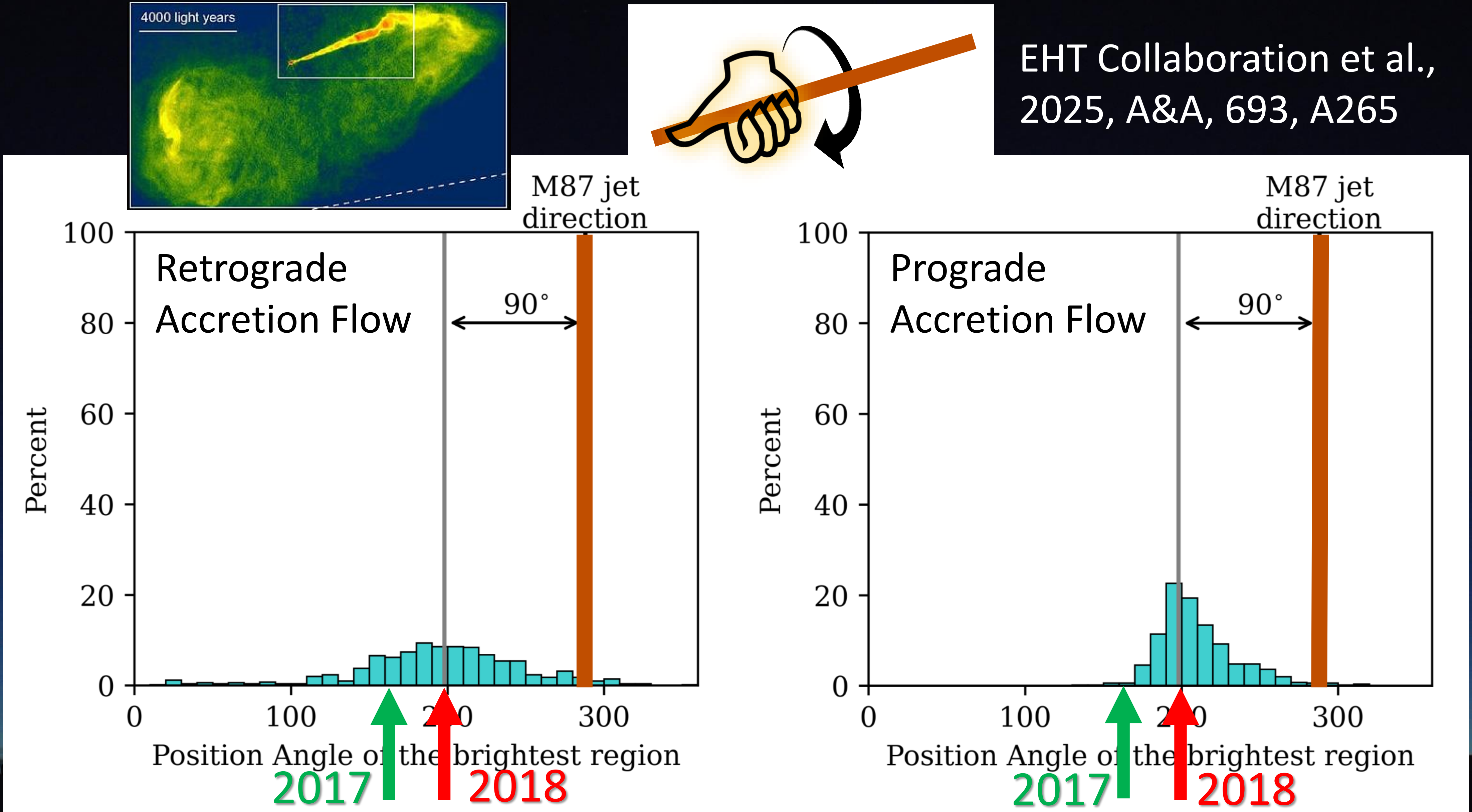
EHT Collaboration et al., 2025, A&A, 693, A265

The First GLT Results on the M87 Black Hole



The First GLT Results on the M87 Black Hole

EHT Collaboration et al., 2025, A&A, 693, A265



Life in Pituffik

Work

Daily Life

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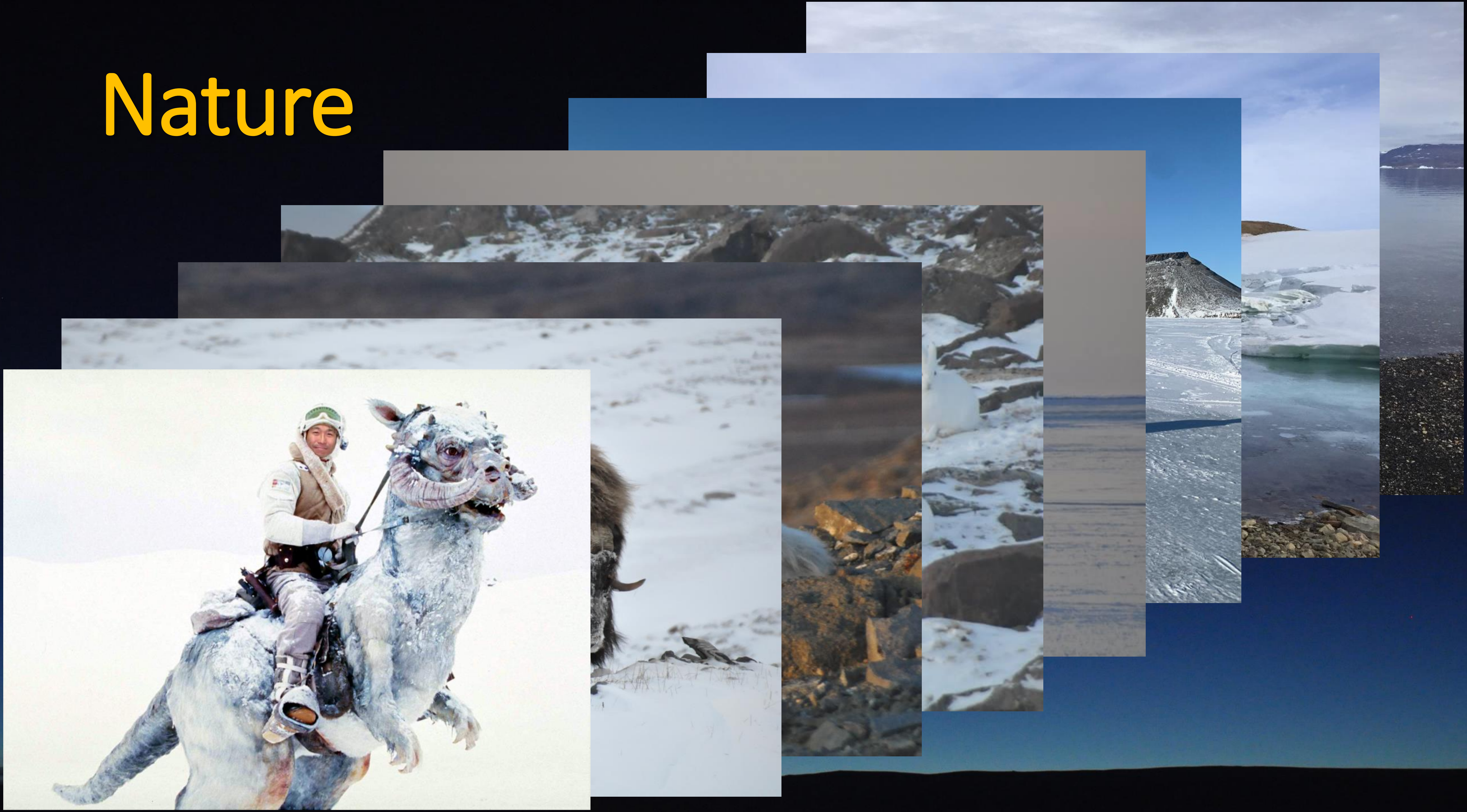
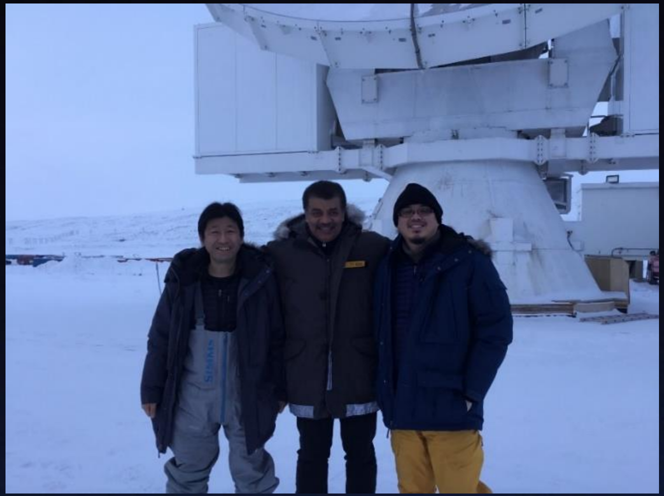
Dogfish Head
Indian Brown

Nature



VIP Visits to the GLT

Niel deGrasse Tyson 2018/03/15
(Carl Sagan in 21th Century)



The Prime Minister of Denmark

2018/10/29

2022/6/15

Jan Thomsen (Niels Bohr Institute Director), Andrew Crowdery (First Secretary of US Embassy in Denmark), & Ivalu B. Christensen (First Greenlandic astrophysicist, who did 2 summer internships with Nimesh Patel. Now at MPI)

Nikolaj Coster-Waldau 2018/08/09
(Jaime Lannister of Game of Thrones)

楊弘敦 (Yang Hung-Duen; former MoST Minister) visit was cancelled due to COVID-19.

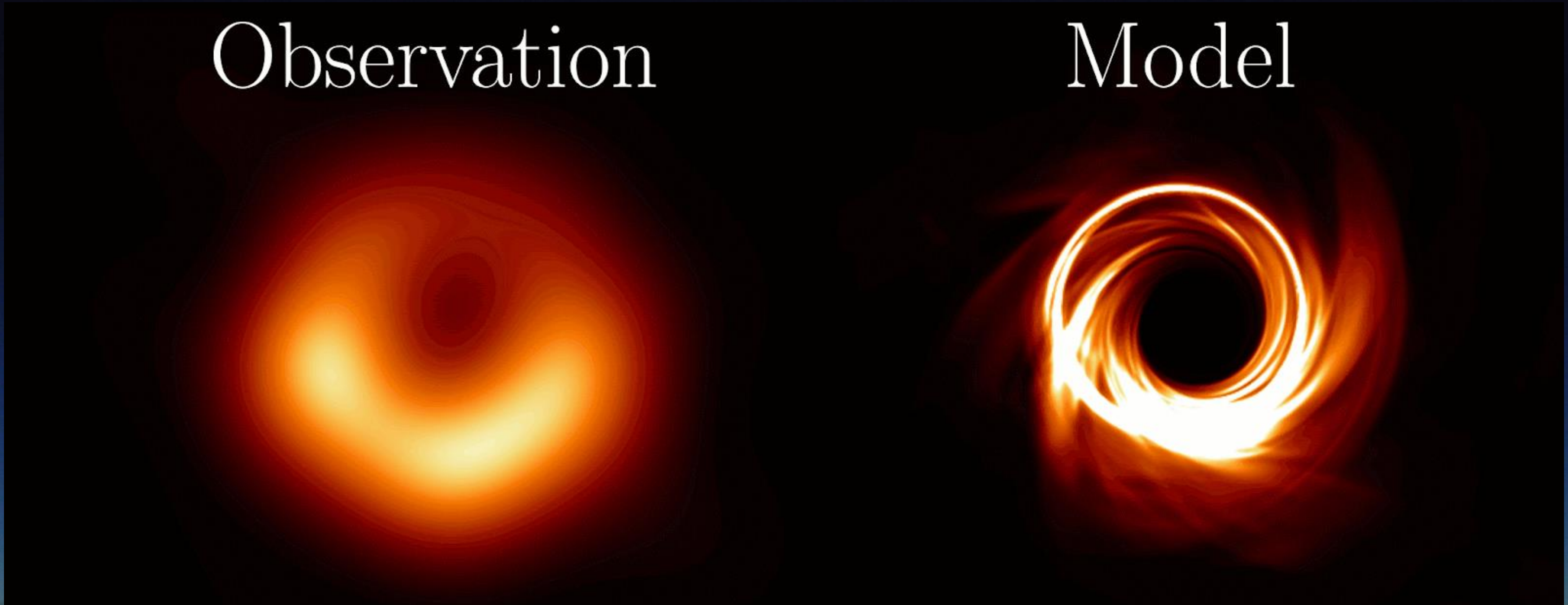
2019/11/29

Barbara Barret (Secretary of US Air Force & Smithsonian Institution Board Member)

690 GHz VLBI:
Toward Higher Resolution

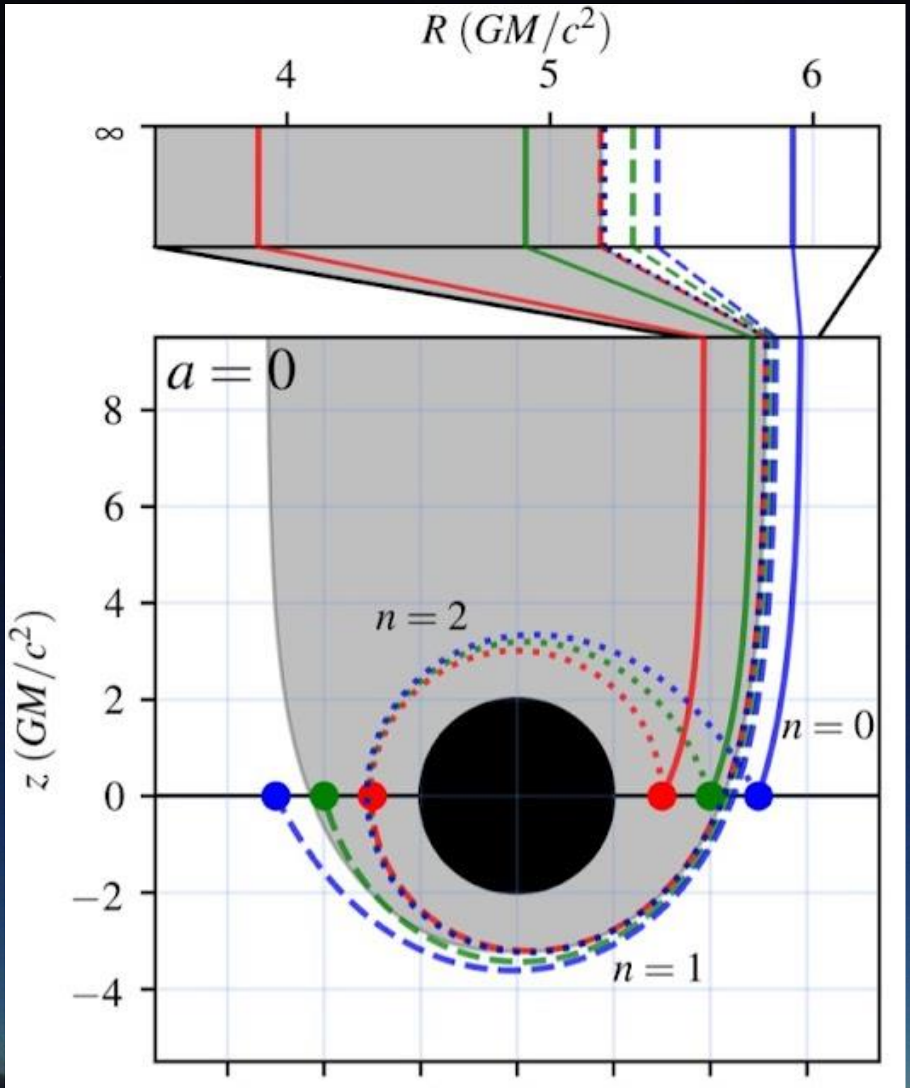
690 GHz VLBI: Toward Higher Resolution

- Next Step for the Black Hole Shadow Imaging:
  - Higher spatial resolution to see the “real” event horizon.

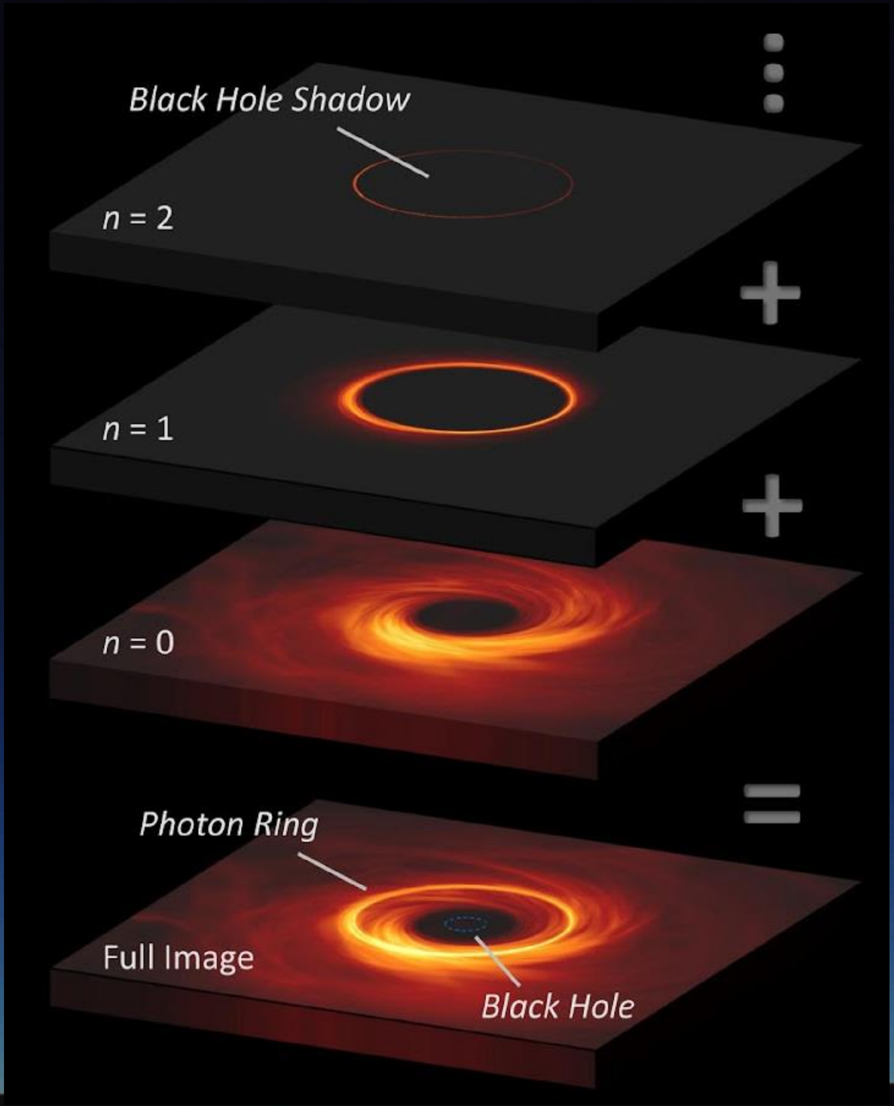


Credit: EHT Collaboration, Moscibrodzka et al.

Sub-Rings in the Photon Ring



Broderick et al. 2022

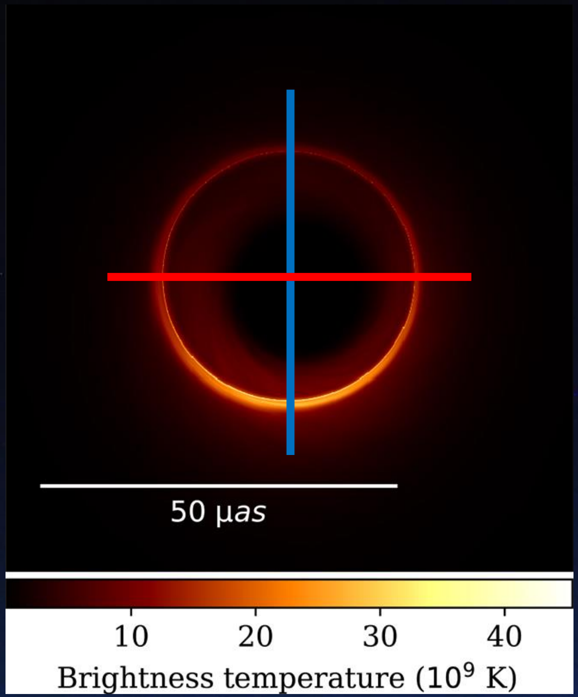


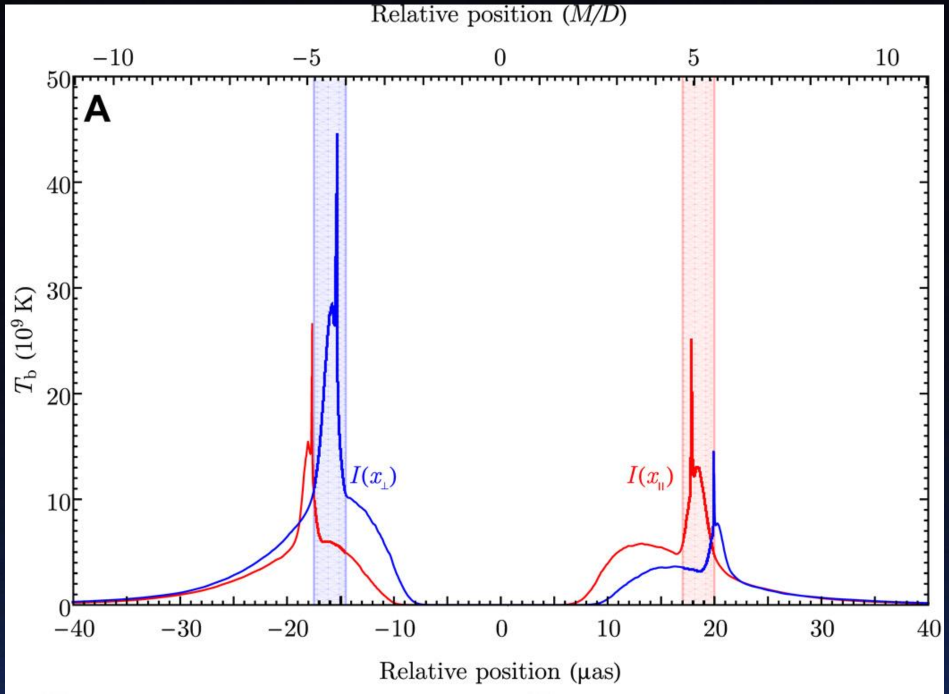
Johnson et al. 2020

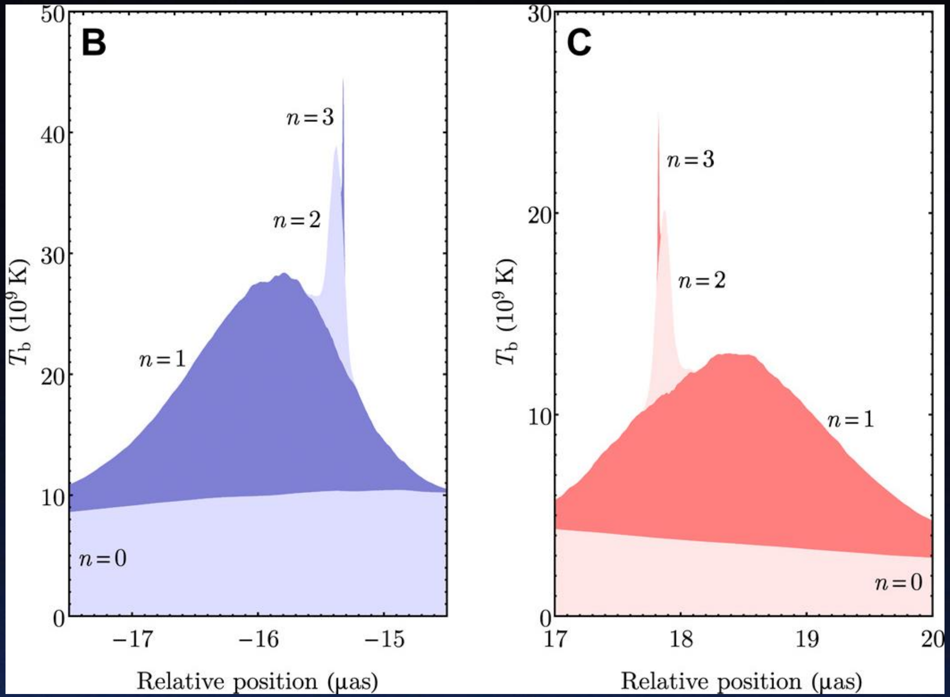
- BH shadow should be composed by multiple rings:
  - Depends on how many half rotations around black hole:
    - n = 0: Directly arrived observer.
    - n = 1: Experienced half rotation.
    - n = 2: Experienced one full rotation.
- Higher order rings become sharper rings.

Sub-Rings in the Photon Ring

Johnson et al. 2020

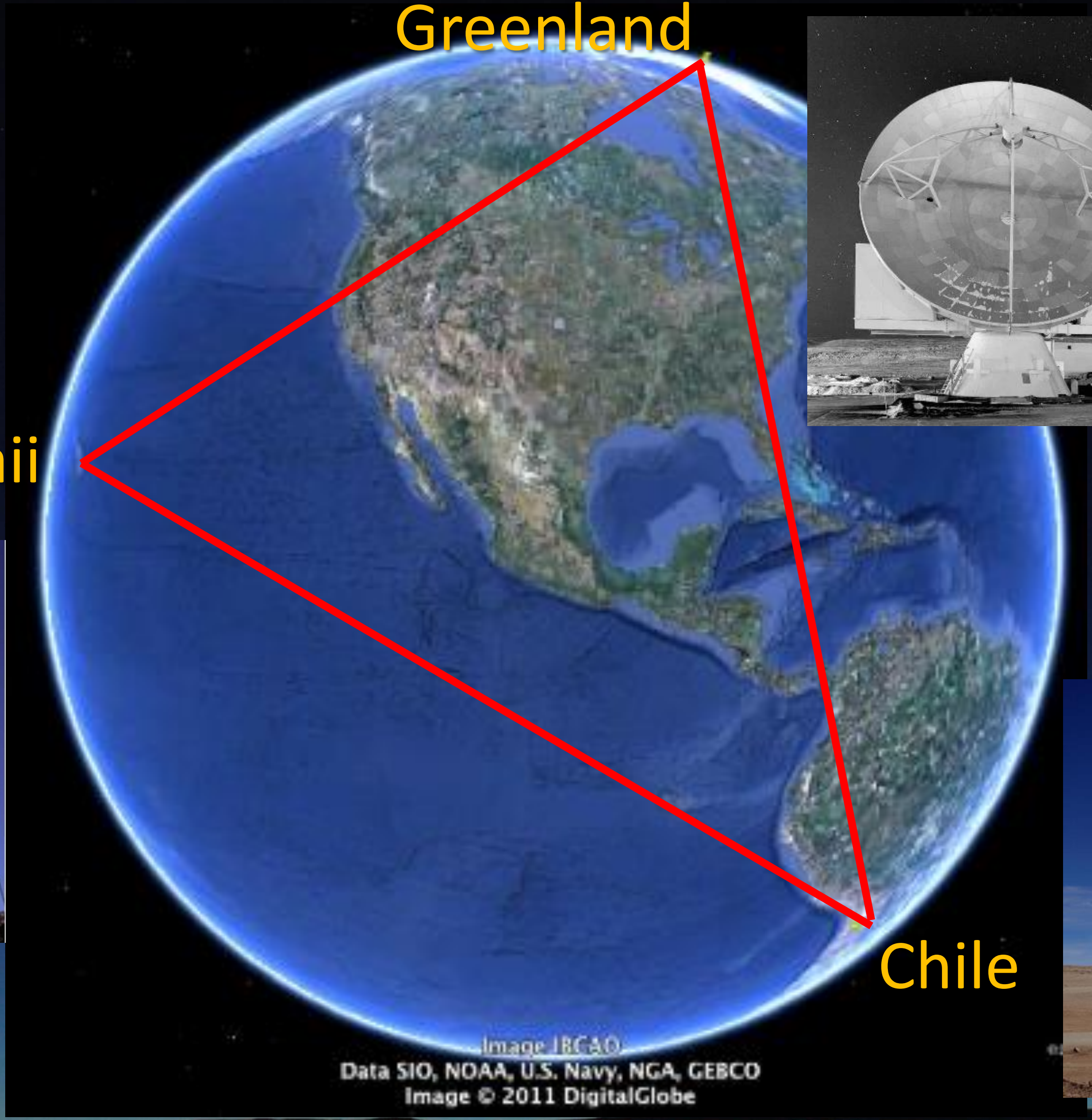


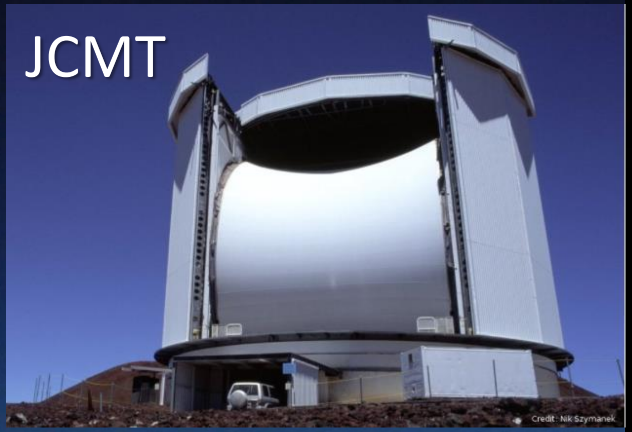




- To separate n = 0 and 1 rings, we need 3 μas resolution.
  - Current EHT at 230 GHz ~ 10 μas.
- VLBI observations at 690 GHz (or 3 times longer baseline length) enable us to achieve 3 μas resolution.

VLBI at 690 GHz

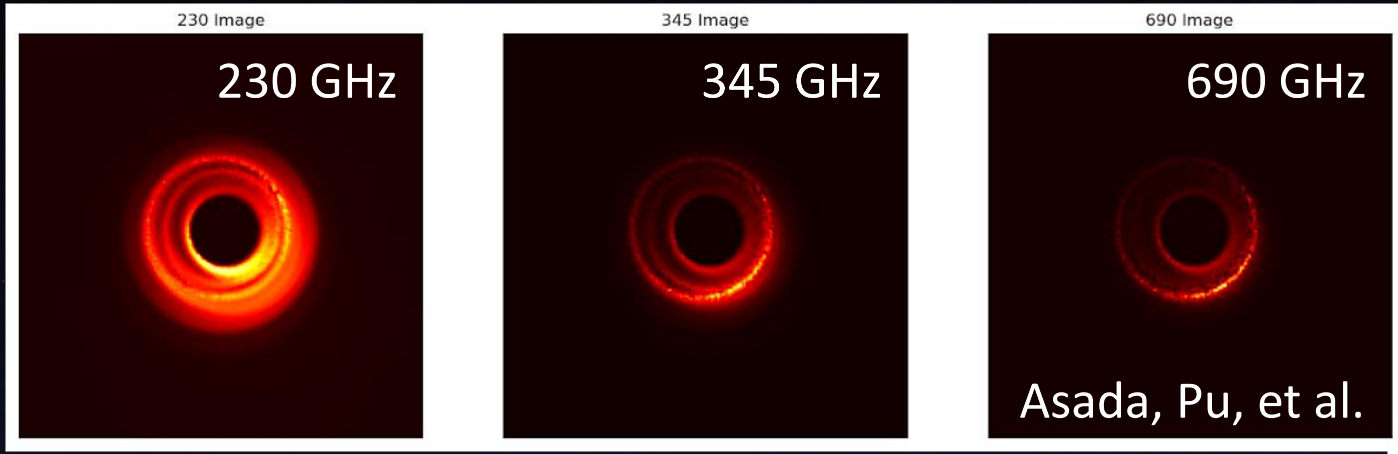


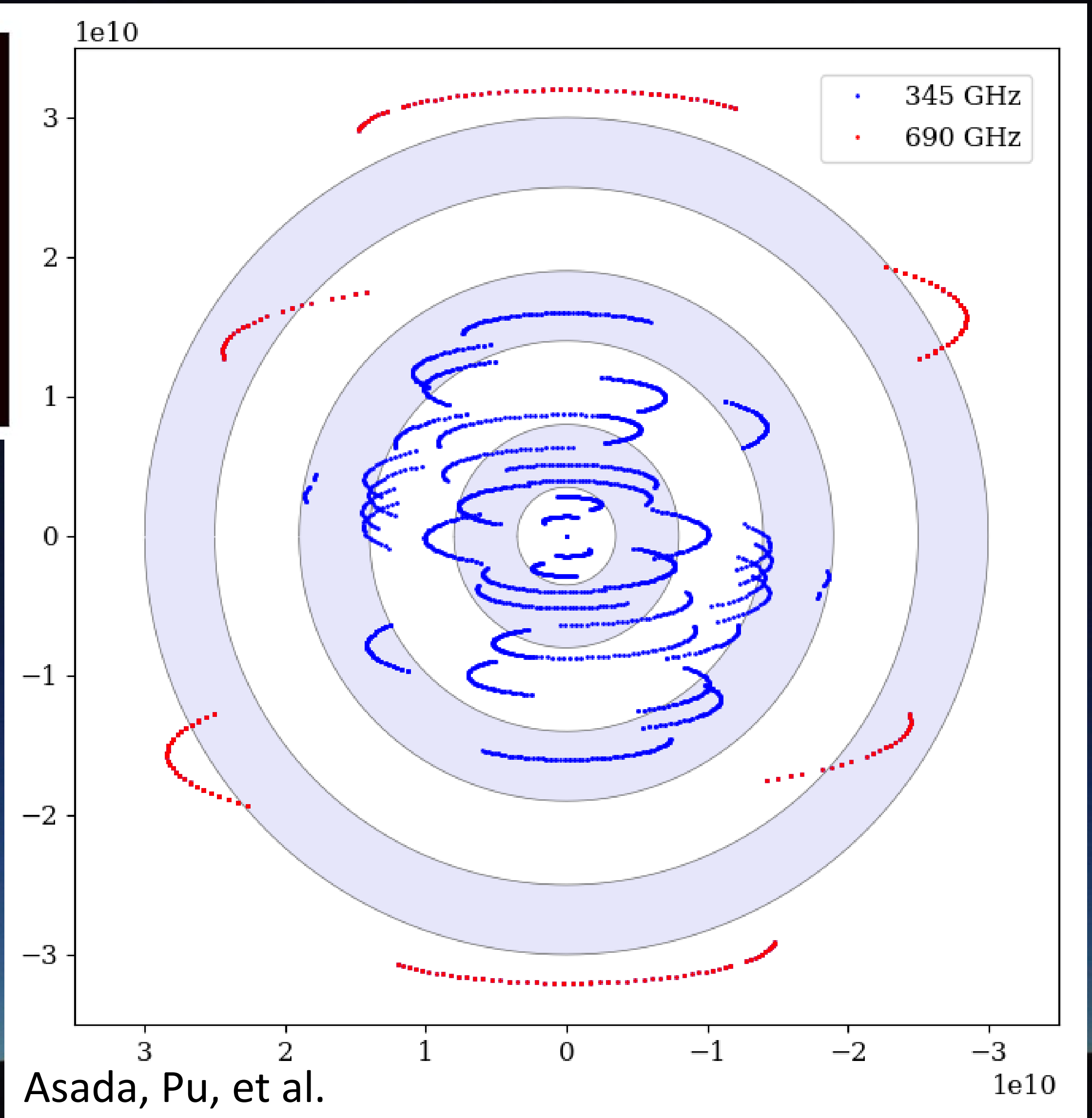


EAO

Baselines are 9,000 km long, and the resolution reaches 3 μas at 690 GHz.

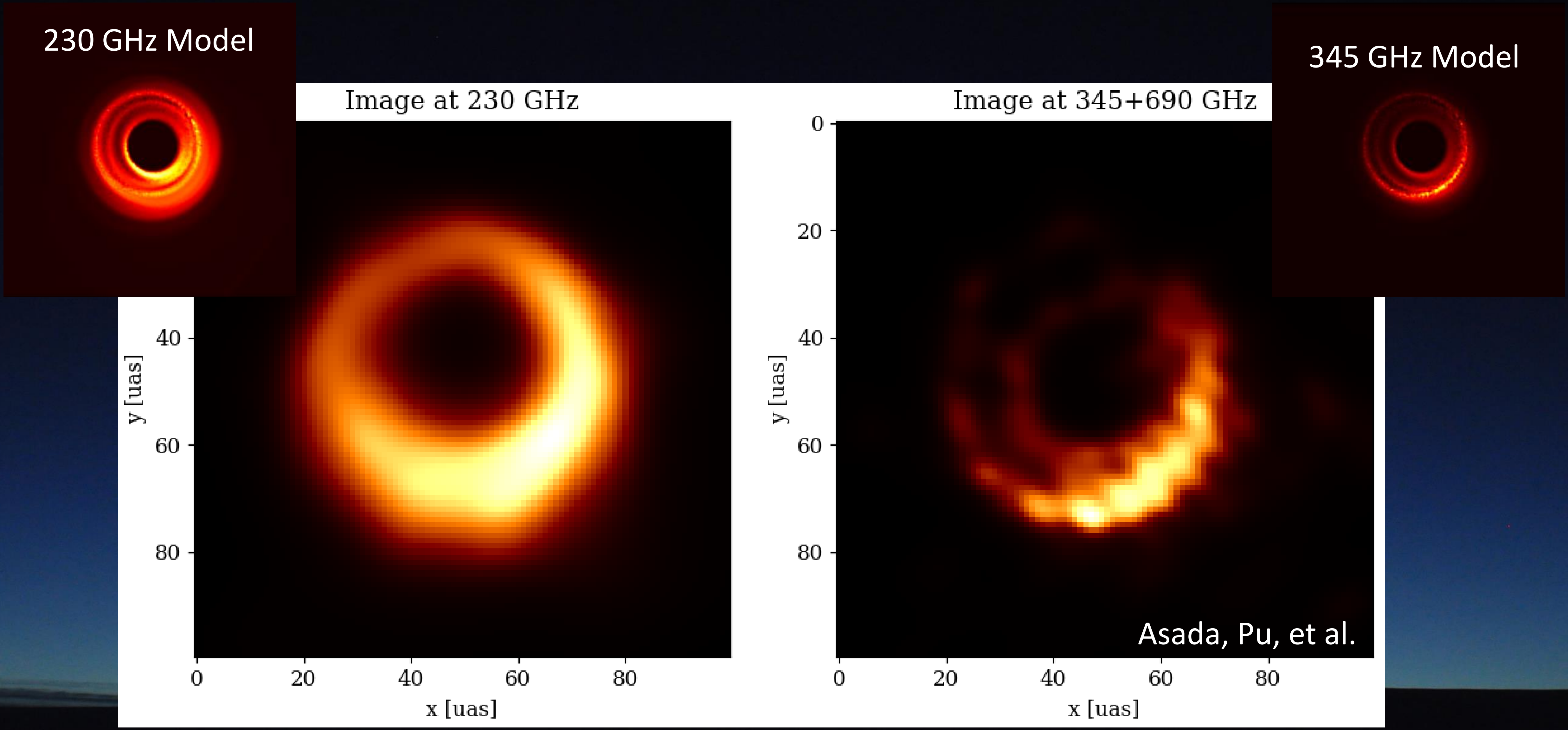
690 GHz VLBI to See Event Horizon





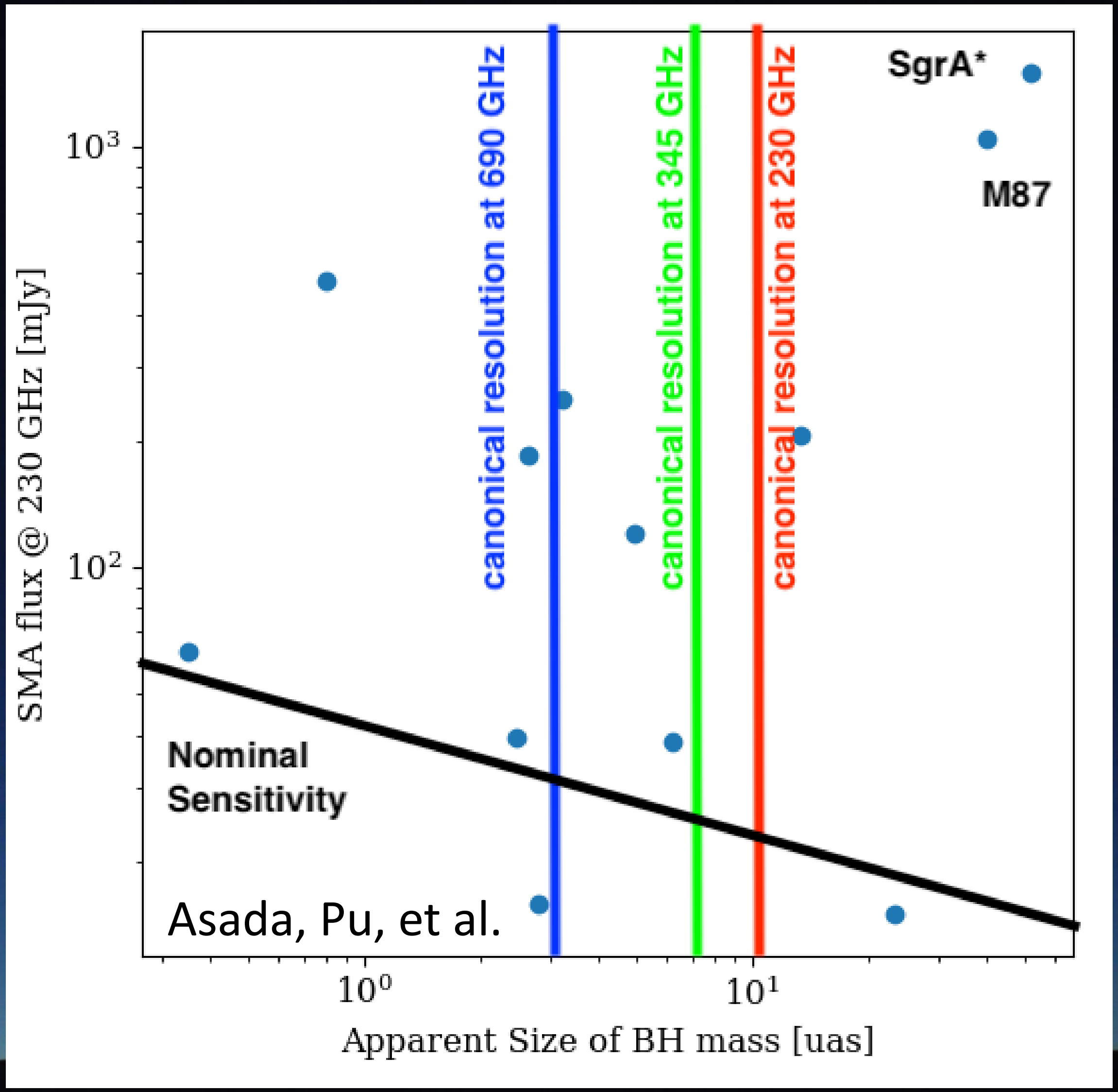
- 690 GHz VLBI telescopes:
  - GLT Summit, JCMT/SMA, & ALMA (LLAMA in the future).
- Multi-Frequency Synthesis.

690 GHz VLBI to See Event Horizon



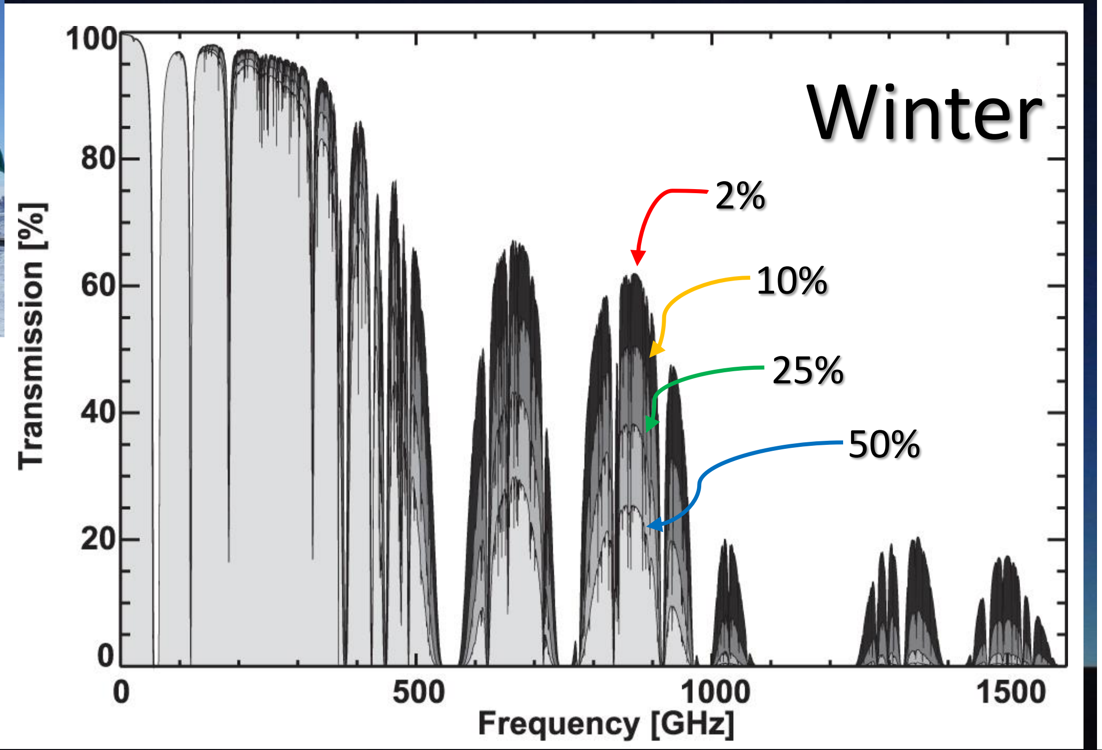
690 GHz VLBI to See More Black Holes

- Higher resolution will provide us to see more black hole shadows.
  - We may have 5 more sources with ~5 Rs resolution.
- Further more sources to see inflow (accretion) and outflow (jets) mechanisms.
  - Very important for the black hole physics.
  - ~10 Rs resolution is enough.

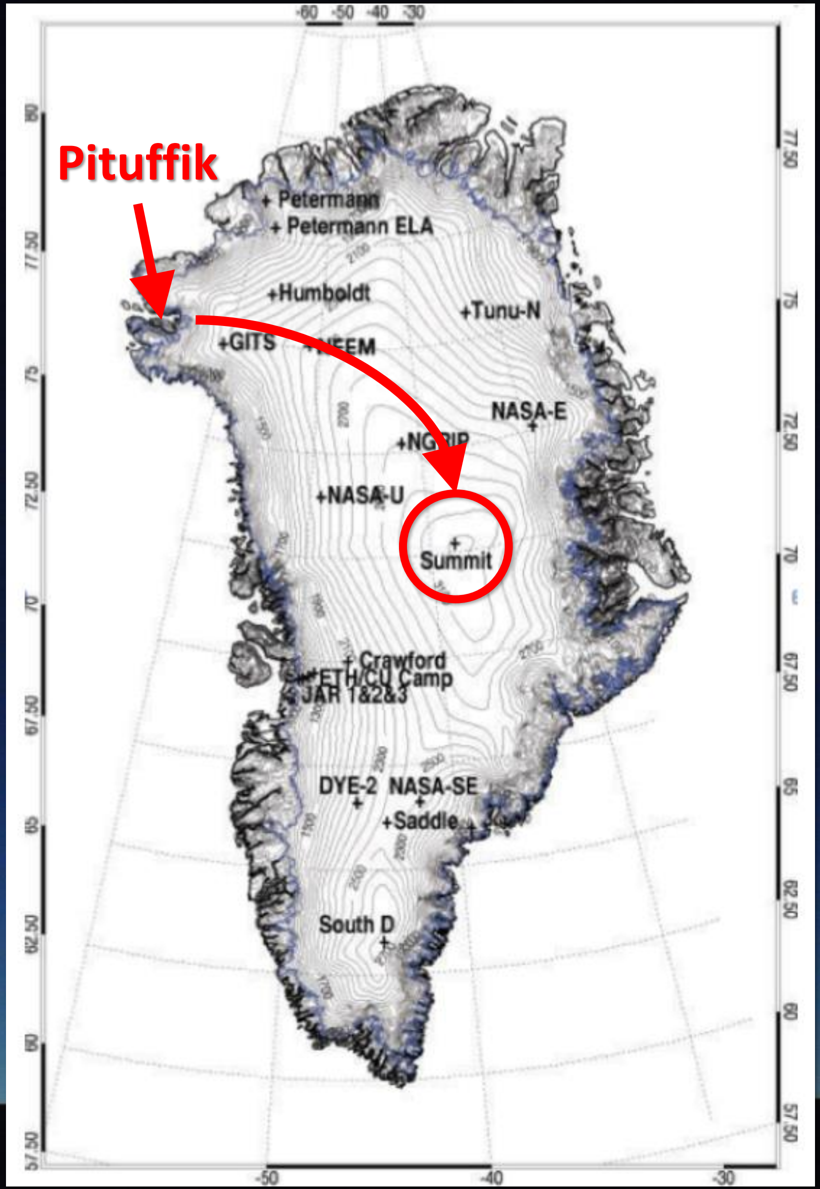


GLT Summit: Toward Higher Resolution

- Established/operated by US NSF & Greenland Government.
  - Atmospheric and weather researches are mainly ongoing.
  - Altitude: 3210m.



Matsushita et al. 2017, PASP, 129, 025001



Life at the Summit Station

Summary

- EHT imaged the shadows of black holes for the first time.
- So far, no violation of the Einstein's Theory of Relativity.
- Greenland Telescope (GLT) is the only Asian telescope operating at the polar region.
- GLT provides much longer and unique baselines, and therefore sharper and better quality (high fidelity) images.
- GLT at the Greenland Summit will be able to image the true Event Horizon (the photon ring) around the Black Hole.