Imaging of Black Hole Shadow from the Arctic Region

TCHoU Tsukuba 50th Anniversary

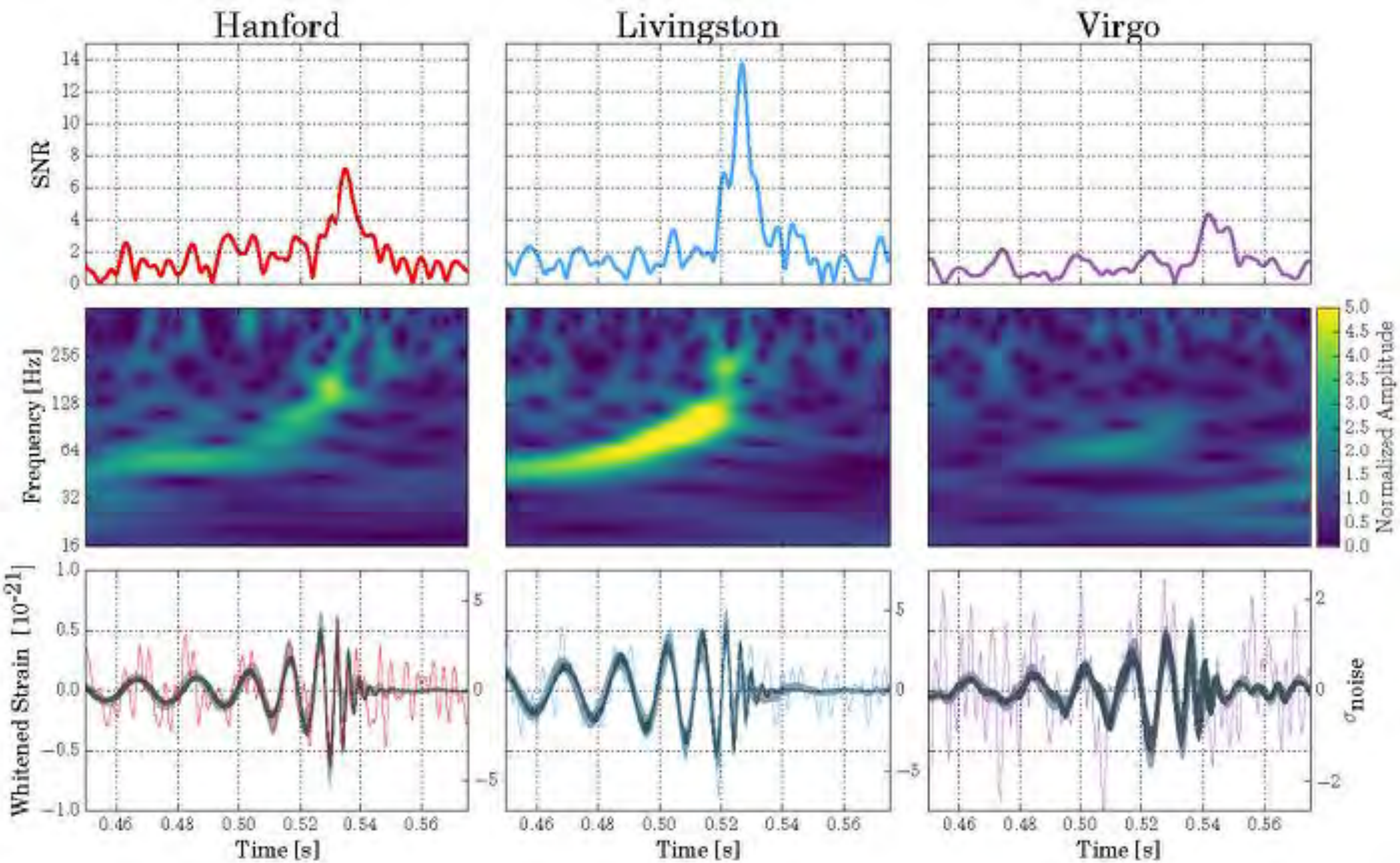
Paul Ho, ASIAA/EAO

Recent BLACK HOLE Research
— Hear it, Feel it, (Not) See it

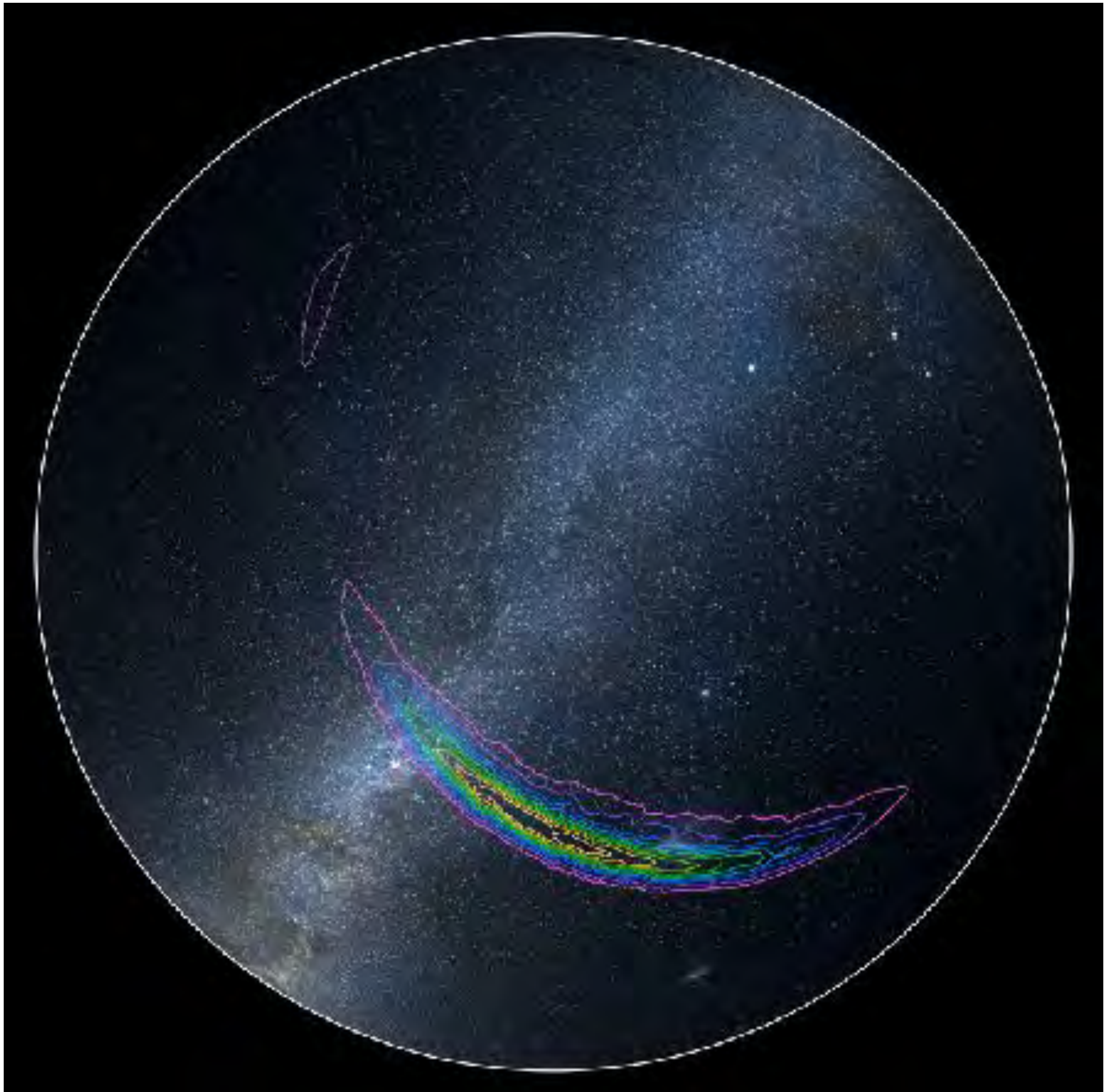
- Detection of Gravitational Waves (tens of cases)
- Orbital Motions at the Event Horizon (one)
- Imaging of the Event Horizon (two)
- GR Effects

- common technique: Lasers and Interferometry
  (optics and missing information problem)
- are these Nobel Prize winning work? 2017, 2020

"Hearing" Gravitational Waves



Where is GW091415: LMC ?



TIME DELAYS

Detection at :

LIGO at Livingston

followed by 7 x 10^{-3} sec

LIGO at Hanford

positioning will improve

with VIRGO and KAGRA

Subaru Hyper Suprime Cam Project

Target Dark Matter and Dark Energy

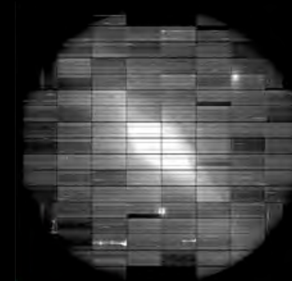
★1.5 degree FOV, 10 x FOV (Surpime Camera)

★40 M USD Budget (Taiwan 5M) , 5 year timescale

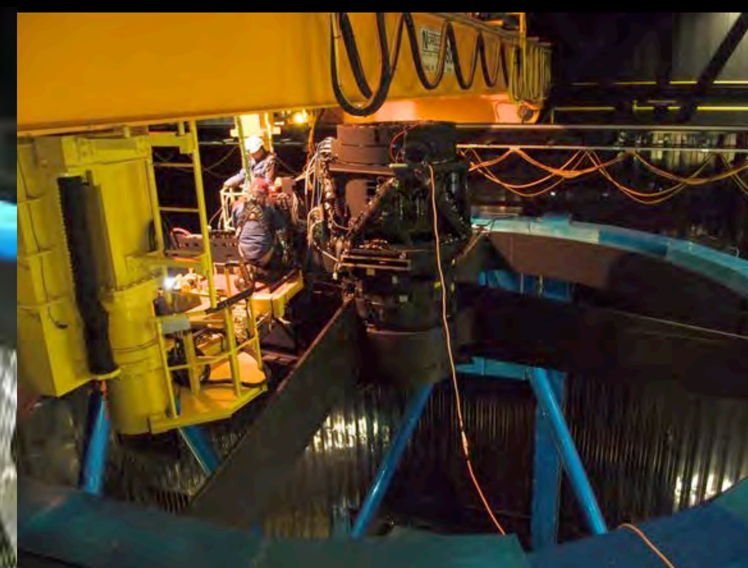
★ASIAA: Filter Exchanger, CCD and Lens Testing

★Weak Lensing Tomography; z>6

- **ASIAA delivered 2011**
- **HSC on Subaru 02.12**
- **HSC commission 08.12**
- **HSC survey papers 2018**



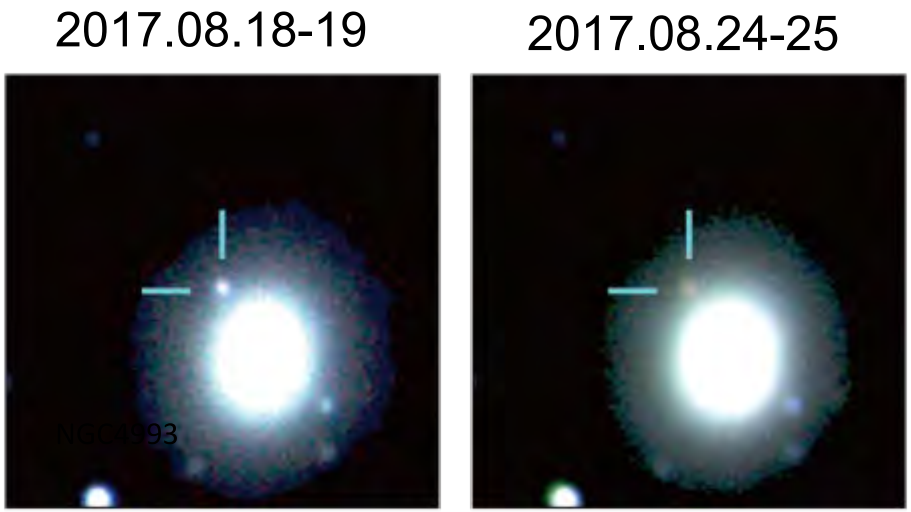
raw image of M31



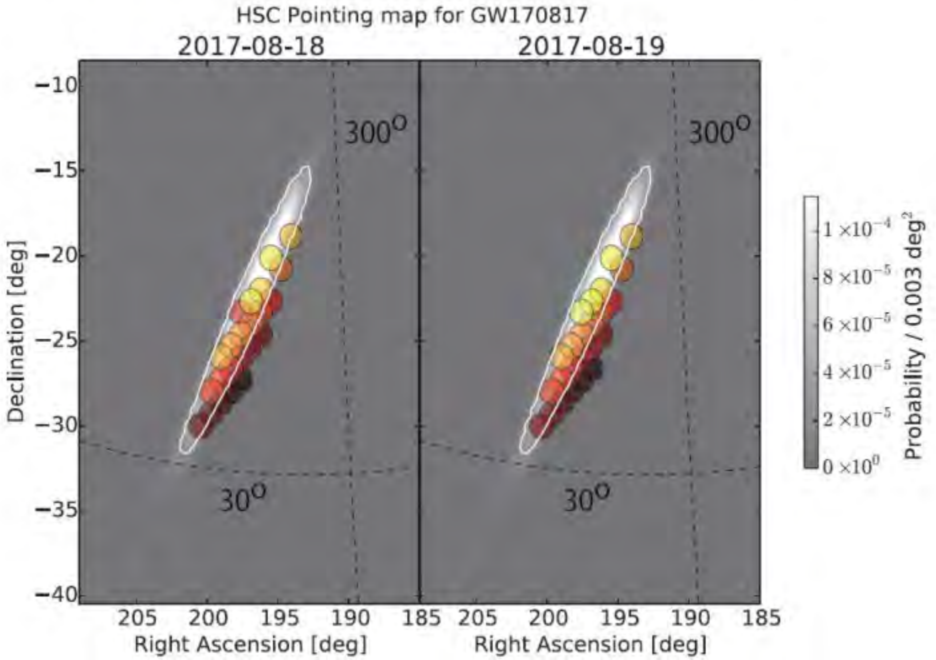
HSC Integrated on Subaru ★

Taiwan Industry: CSIST played Key Role

Subaru optical-infrared follow-up of the binary neutron star merger GW170817



HSC: z-band, IRSF: H, Ks-bands



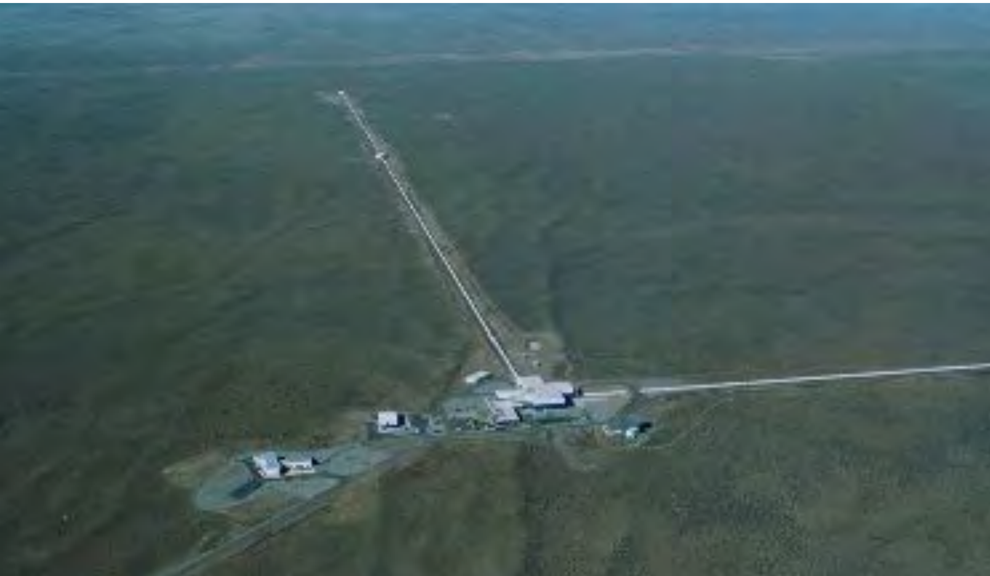
Subaru HSC & MOIRCS succeeded to get the optical – near-infrared light from a binary neutron star merger event GW170817.

Ustumi et al. 2017

We surveyed ~70% of the 90% credible area of the localization skymap of GW170817 with HSC. ➔ The OT at NGC4993 is the most promising candidate for the optical counterpart of GW170817

Tominaga et al. 2017

GW Detectors: LIGO, VIRGO, KAGRA



Nobel Prizes for Gravity Wave Detection

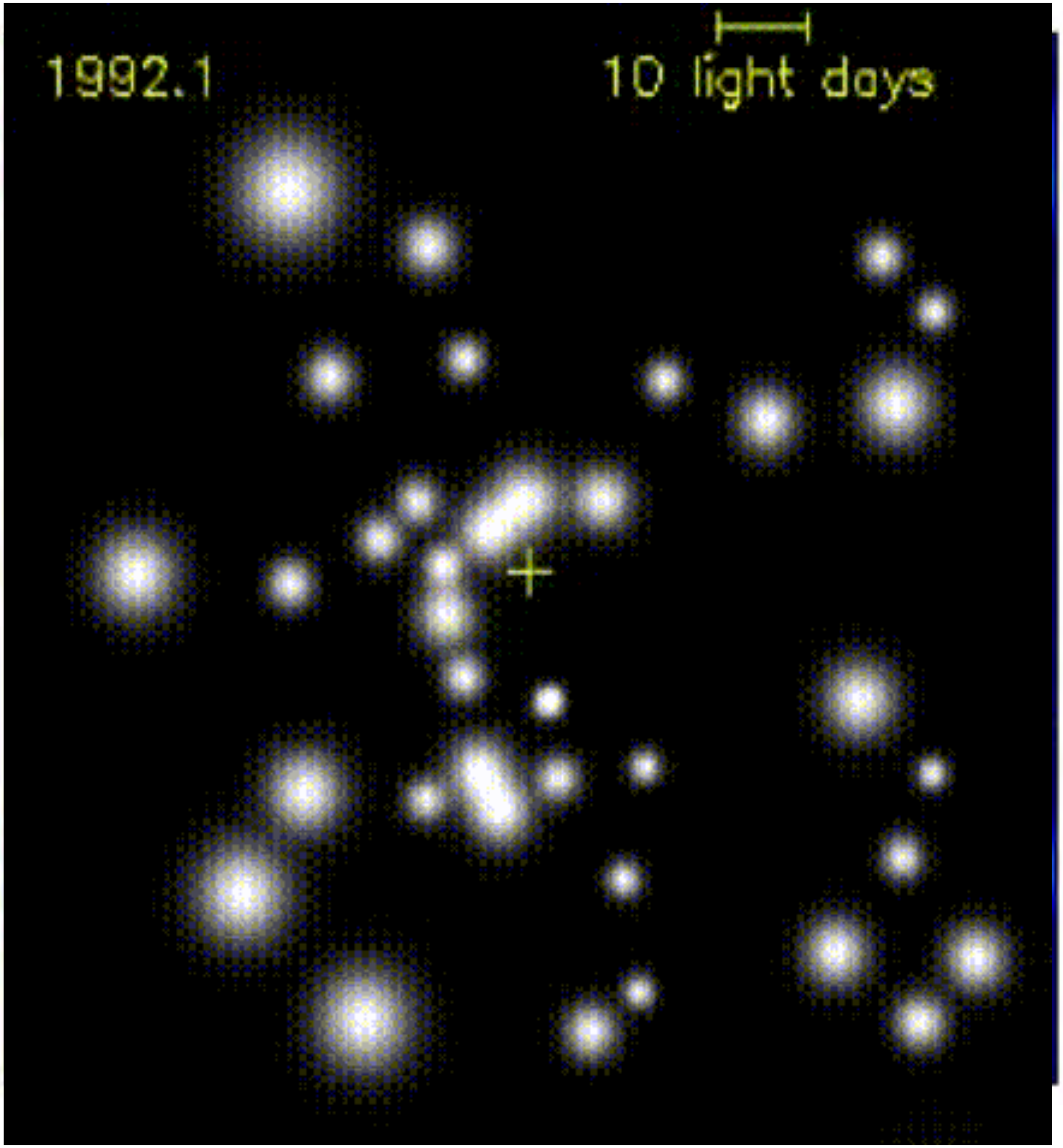
Taylor and Hulse (1993)

Weiss, Thorne, and Barish (2017)

Ray Weiss working on Detectors in 70's

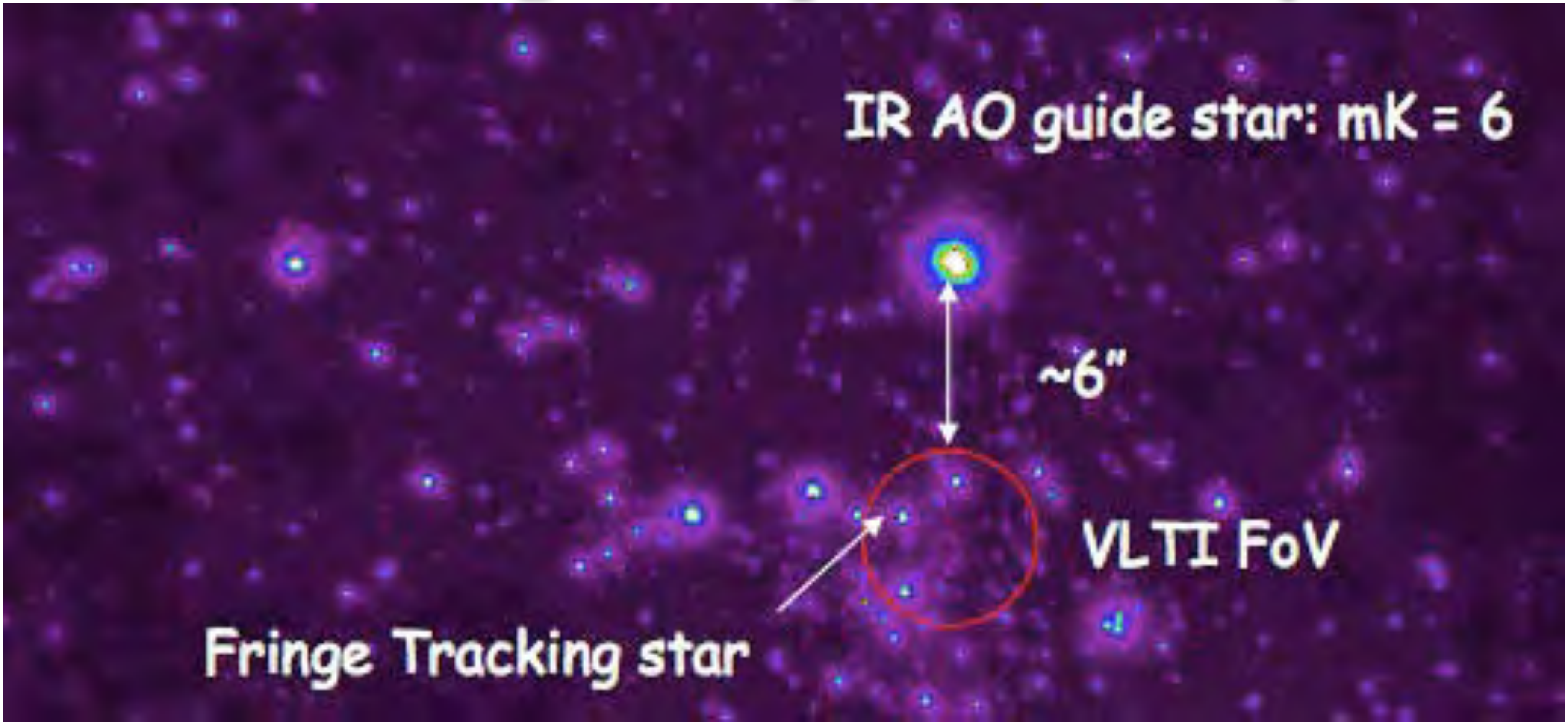
"Feeling" Gravity Pull

- ⋆The movement of stars - accelerated to a fraction of the speed of light around an invisible object - showed SgrA* is likely a supermassive black hole at the center of our galaxy
- ⋆Keck telescopes and GRAVITY (VLT) have tracked them over 20 years (Andrea Ghez, Reinhard Genzel)




ESO VLTI

Working Principle of "Gravity"

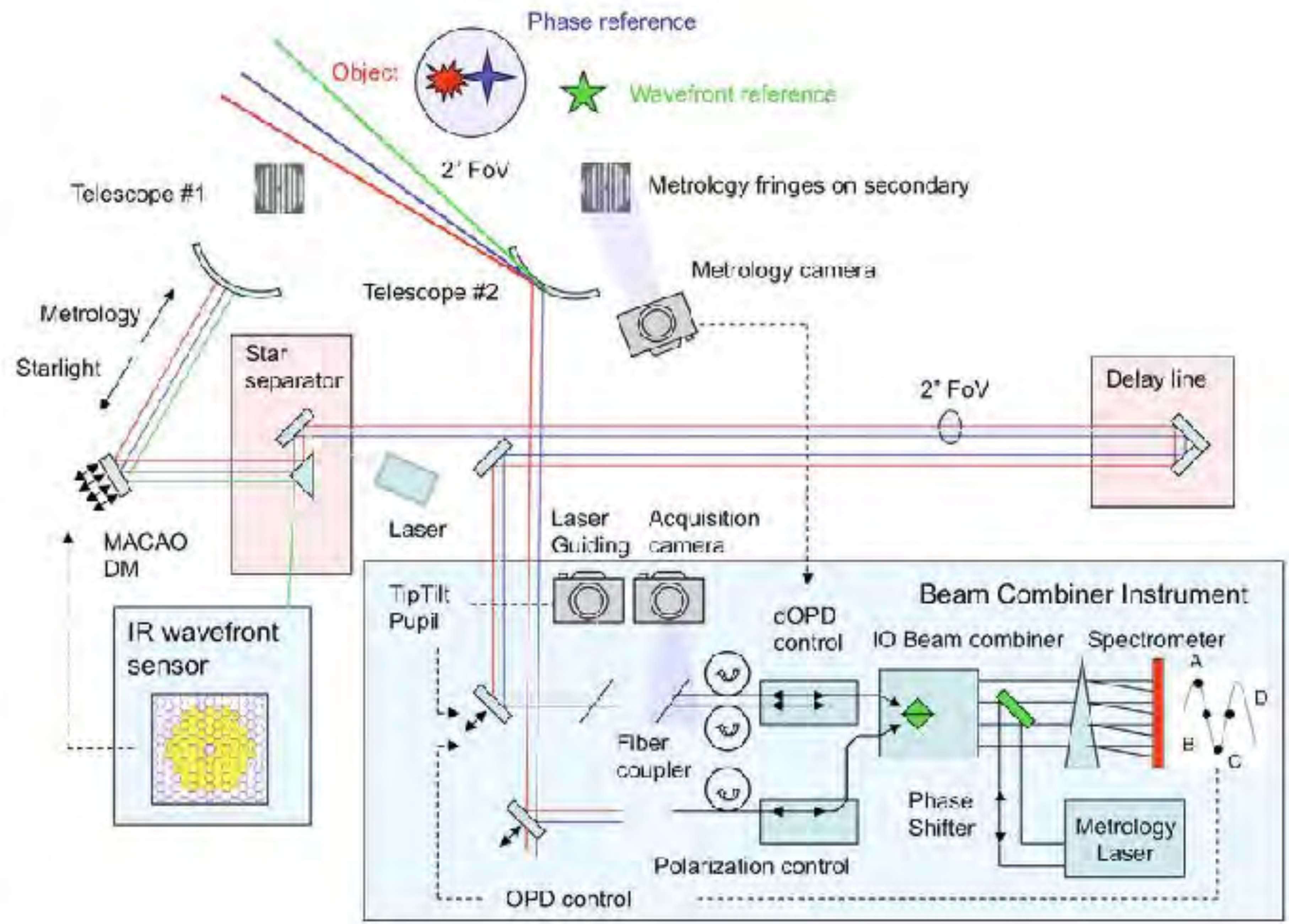


Guide Star for Adaptive Optics (atmospheric seeing)

Fringe Tracking Star for Phase (interferometer baselines)

VLTI for Interferometry (high angular resolution)

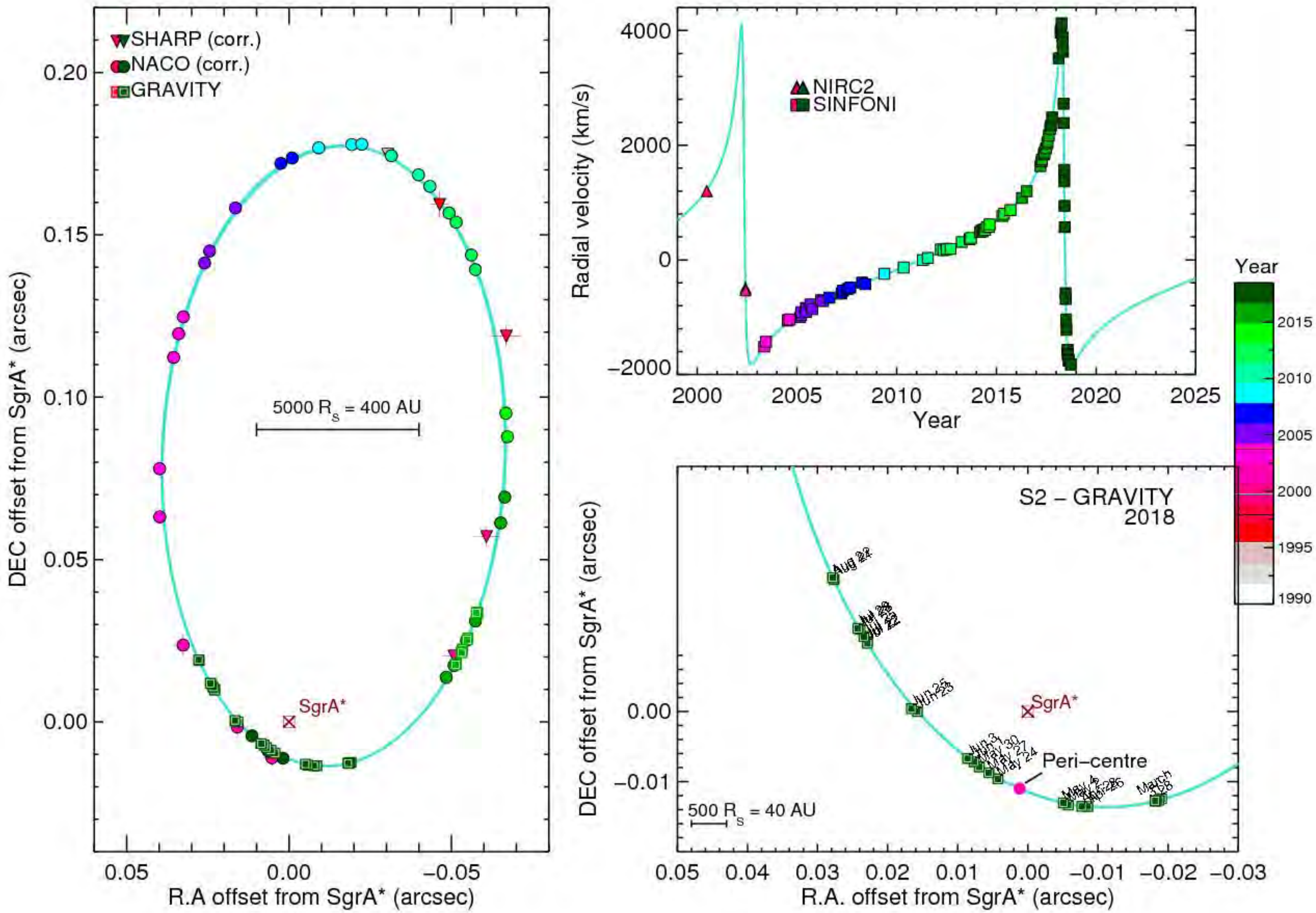
6 baselines; 3 x 10^{-3}″ resolution; ~40 x 10^{-6}″ astrometry



Phase reference
Object
Wavefront reference
2" FoV
Telescope #1
Metrology fringes on secondary
Telescope #2
Metrology camera
Metrology
Starlight
Star separator
Delay line
2" FoV
Laser
MACAO DM
Laser Guiding
Acquisition camera
Beam Combiner Instrument
TipTilt Pupil
IR wavefront sensor
cOPD control
IO Beam combiner
Spectrometer
A
D
B
C
Fiber coupler
Phase Shifter
Metrology Laser
Polarization control
OPD control

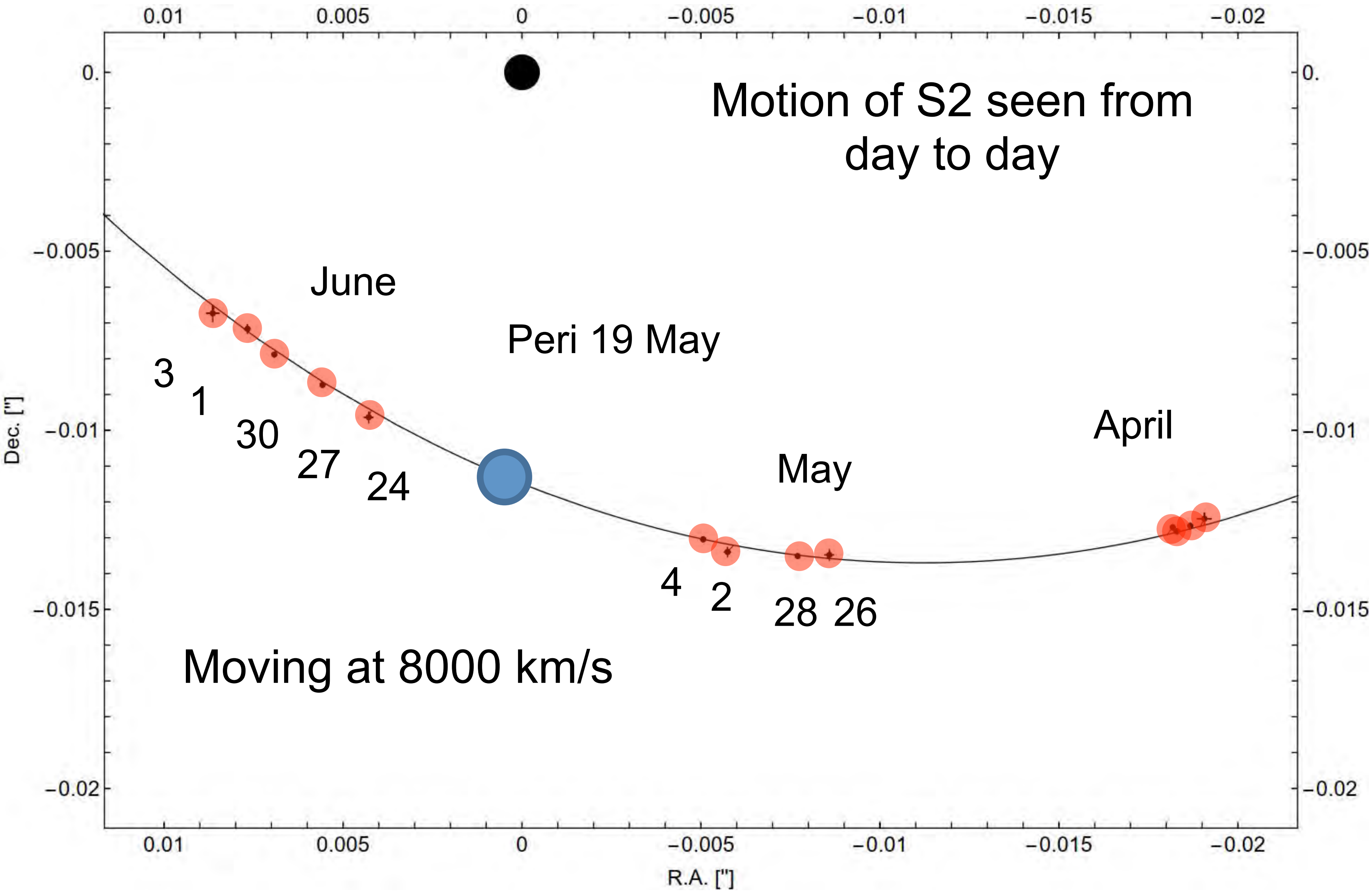
Stars in Orbit around SgrA*

26 years of observations of S2

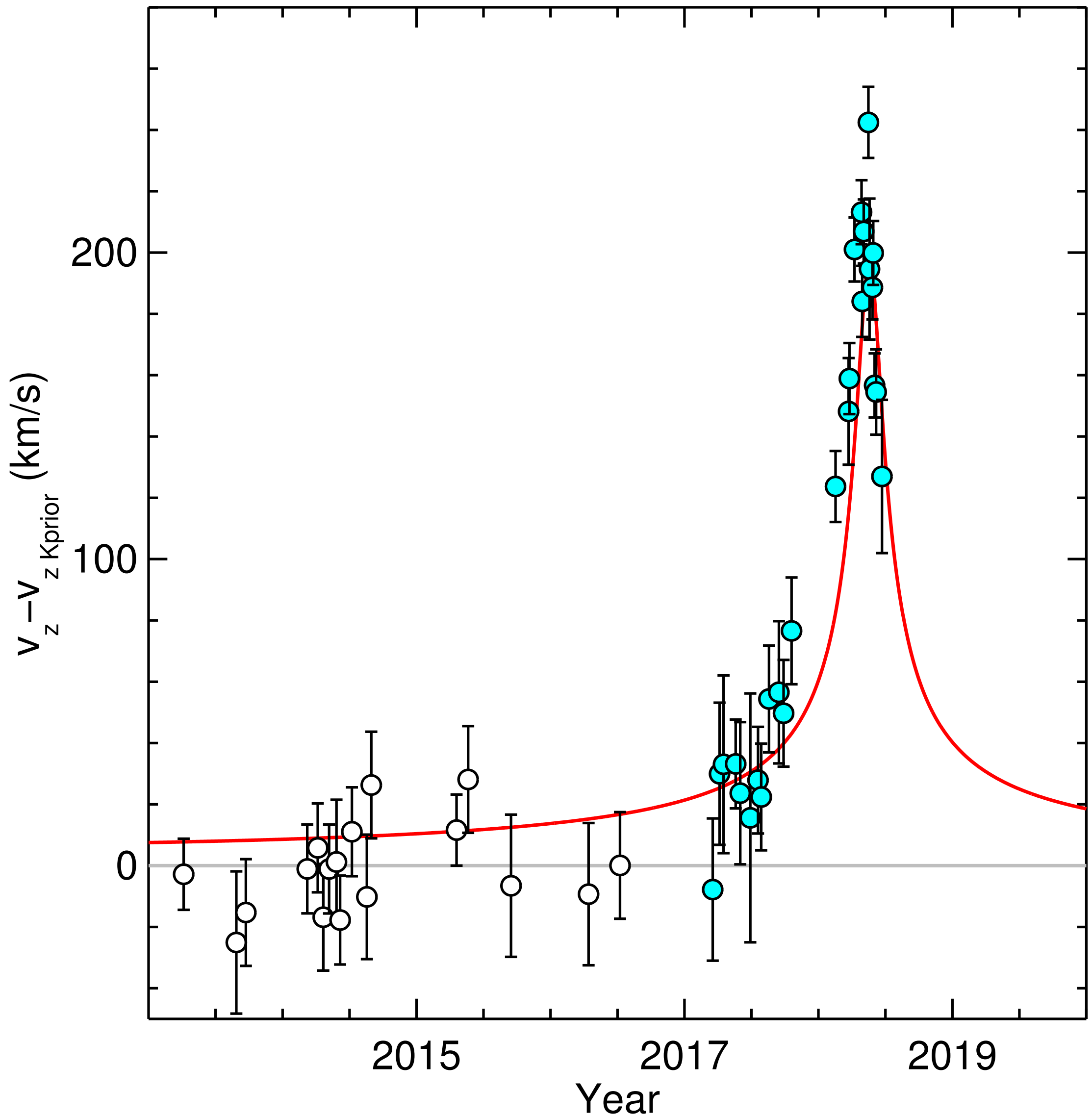


GRAVITY collaboration+18a, A&A 615, L10

Orbit of S2 relative to SgrA*



Motion of S2 shows GR Redshift



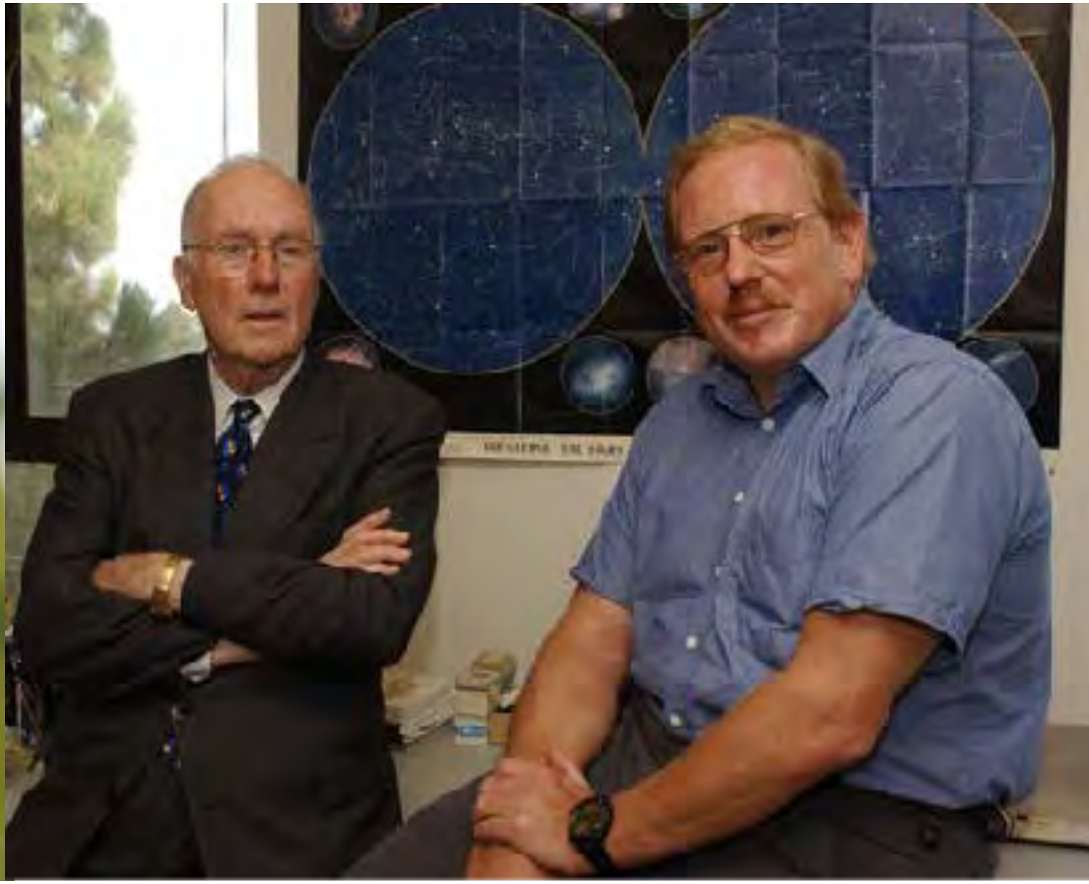
PPN1$_{RS}$(λ)

Nobel Prize Physics 2020: Black Hole

Roger Penrose (Oxford)

Reinhard Genzel Group (MPI)

Andrea Ghez Group (UCLA)



“Seeing” GRAVITY ?

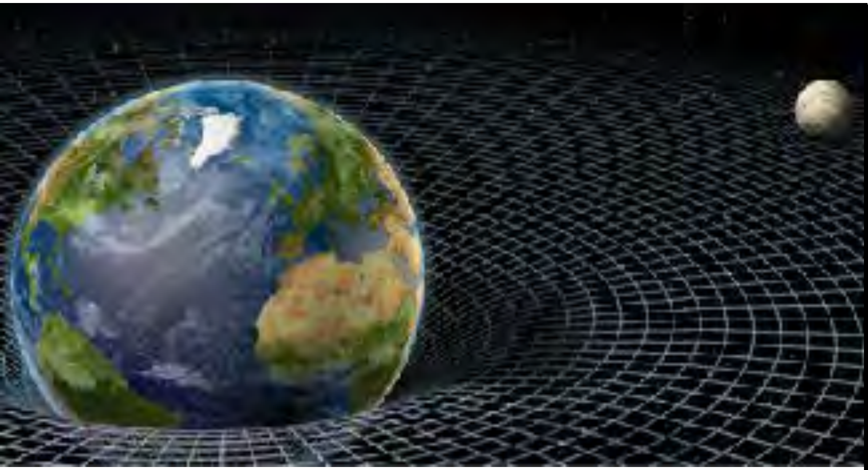
Take a Picture of Black Hole ?

- M87 black hole ~ 1 x 10^{43} g ~ 130 AU
- But M87 is very far! 53 Million Light Years — 5 x 10^{20} km from us
- Schwarzschild Radius ~ 10 micro arcsecond

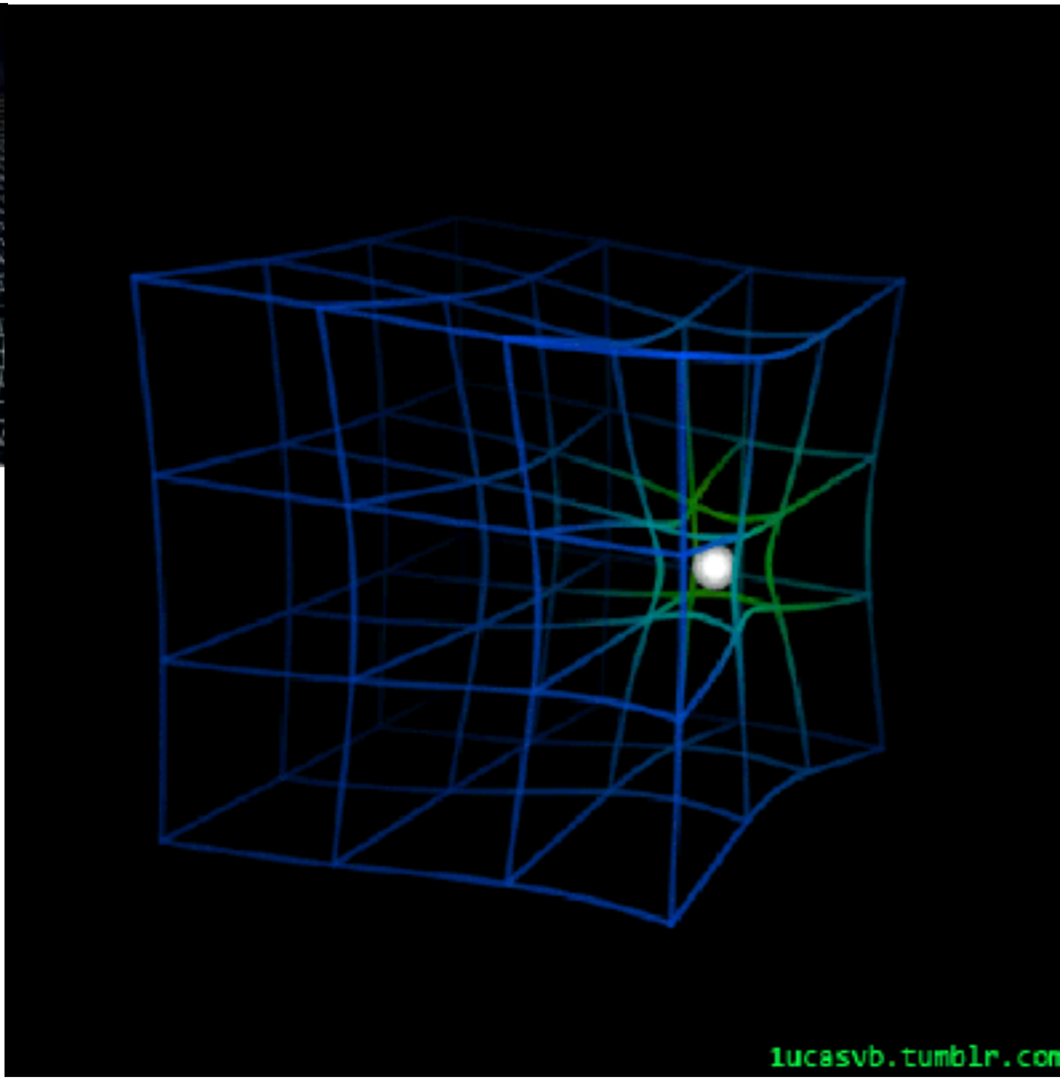
  Sun or Moon ~ 30 arc minutes

M87 black hole ~ 5 x 10^{-9} size of moon

Gravity affects Geometry of Space

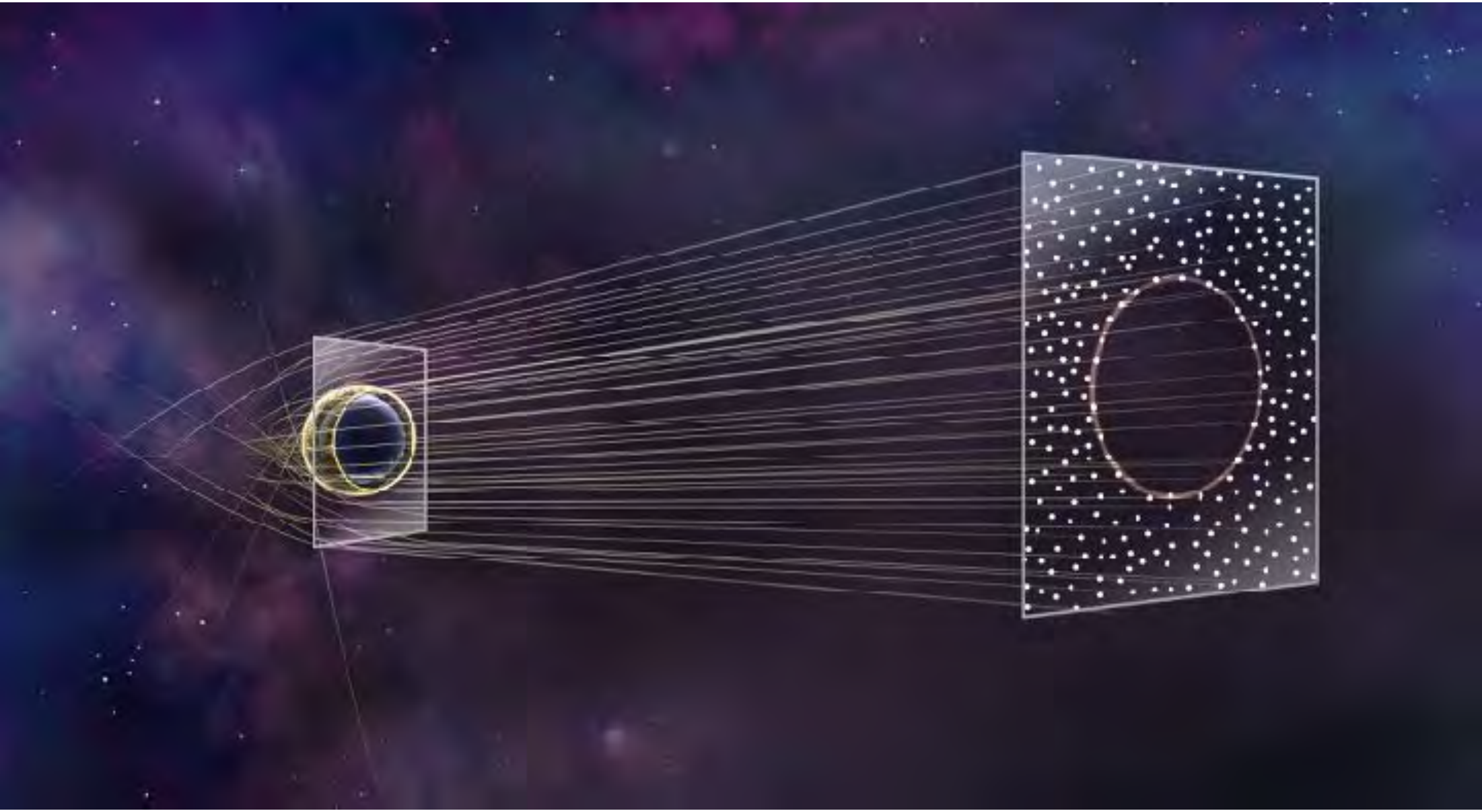


- Mass will distort space-time until even light cannot escape
- Einstein predicted the existence of black holes - though even he was not comfortable with the conclusions from his equations



Gravity/Geometry instead of Material/Dielectric to bend Light

Shadow comes from General Relativity
Shadow Diameter ~ 5.2 R_{sch}



Directly Resolving the Black Hole
"*because* Seeing is Believing"

Target Supermassive Black Hole

Nearest Examples (SgrA*, M87)

(Shadow: $\sim 5R_{sch} \sim 40 \times 10^{-6}\,''$)

Very Long Baseline Interferometry

at Submm Wavelength

<u>Precision $\sim 10^{-10}$</u>

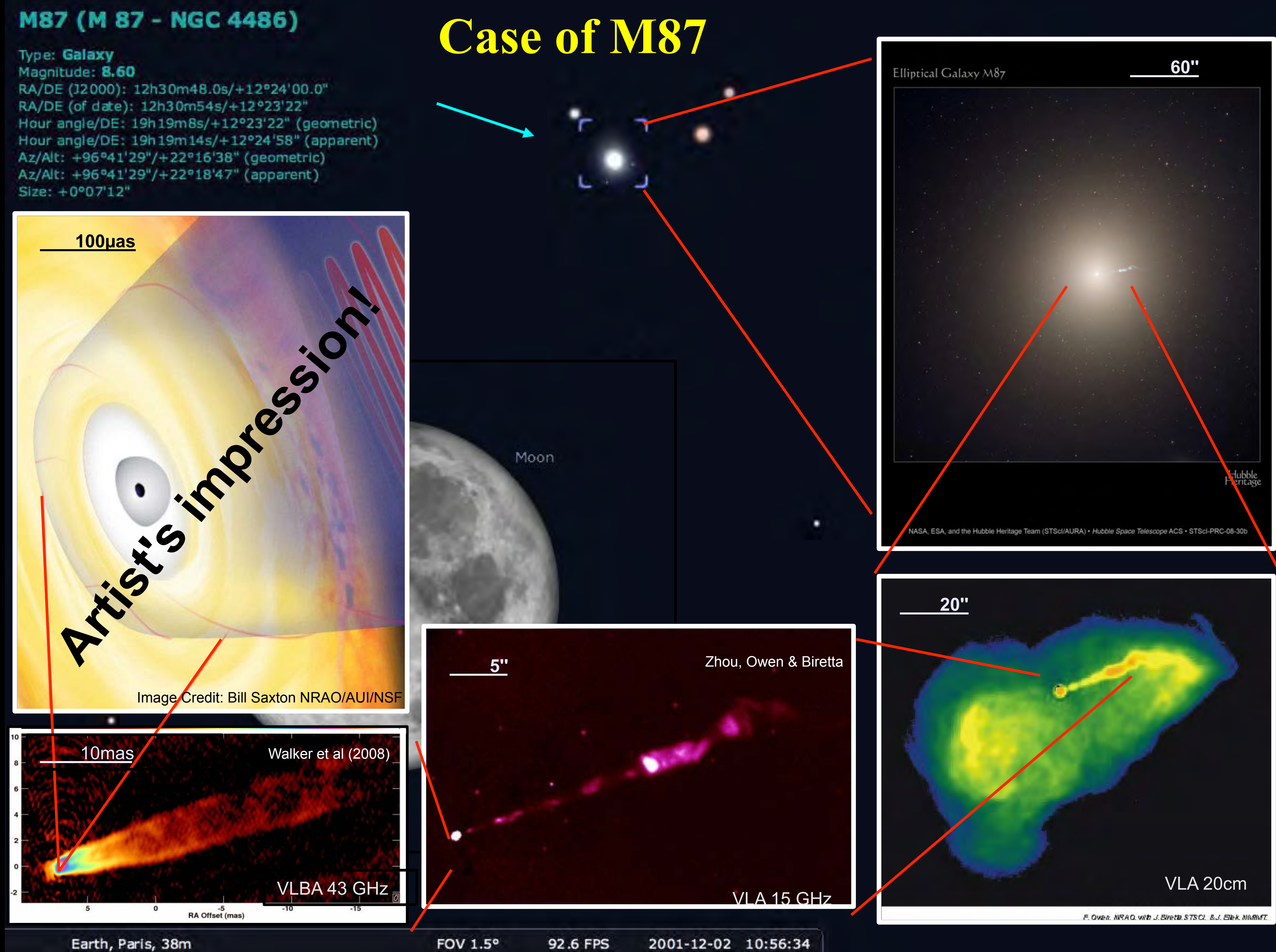
Very Long Baseline Interferometer

- Simulate a Very Large Telescope (Intercontinental Distance)
- Link Telescopes by synchronizing Wave Front
- Precision at 1/20 wavelength (40µm), over ~10,000 km
  - — distance between telescopes
  - — arrival of wavefront at each telescope
  - — compensate for differential atmospheric effects
  - — compensate for differential electronics effects
  - — compensate for individual telescope response
  - — correct for sparsely sampled telescope surface

- VLBI is one of Nobel Prizes in Radio Astronomy

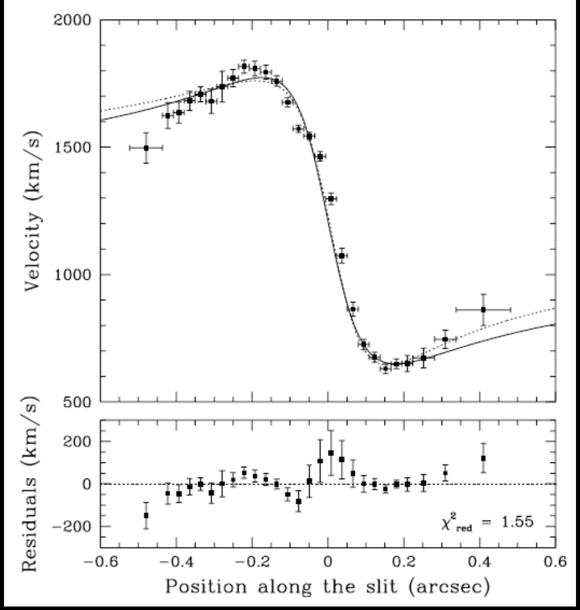
  (Ryle and Hewish 1974) — IMAGE RECONSTRUCTION

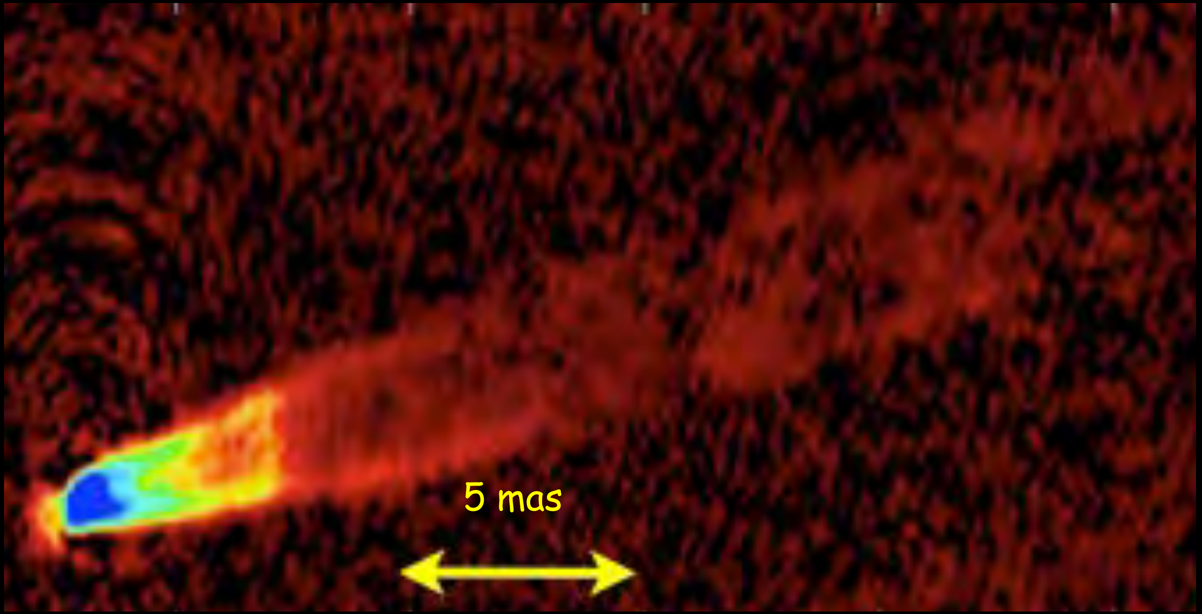
Case of M87



M87 (M 87 - NGC 4486)
Type: Galaxy
Magnitude: 8.60
RA/DE (J2000): 12h30m48.0s/+12°24'00.0"
RA/DE (of date): 12h30m54s/+12°23'22"
Hour angle/DE: 19h19m8s/+12°23'22" (geometric)
Hour angle/DE: 19h19m14s/+12°24'58" (apparent)
Az/Alt: +96°41'29"/+22°16'38" (geometric)
Az/Alt: +96°41'29"/+22°18'47" (apparent)
Size: +0°07'12"
Moon
Elliptical Galaxy M87
60"
Hubble Heritage
NASA, ESA, and the Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope ACS • STScI-PRC-08-30b
100μas
Artist's impression!
Image Credit: Bill Saxton NRAO/AUI/NSF
10mas
Walker et al (2008)
VLBA 43 GHz
RA Offset (mas)
5"
Zhou, Owen & Biretta
VLA 15 GHz
20"
VLA 20cm
F. Owen, NRAO with J. Biretta STScI & J. Eilek NMIMT
Earth, Paris, 38m
FOV 1.5°
92.6 FPS
2001-12-02 10:56:34

Case of M87: HST and VLBA data





HST Spectroscopy Yields Mass

Macchetto+ 1997

Gebhardt & Thomas 2009

Distance: 16 Mpc

Mass: 3.2 (6.4) × 10^9 M_o

► r_g = 2 (4) µas

VLBA Imaging Yields Jet

Walker et al 2008

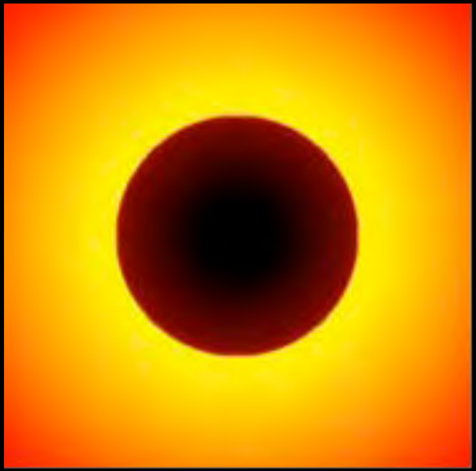
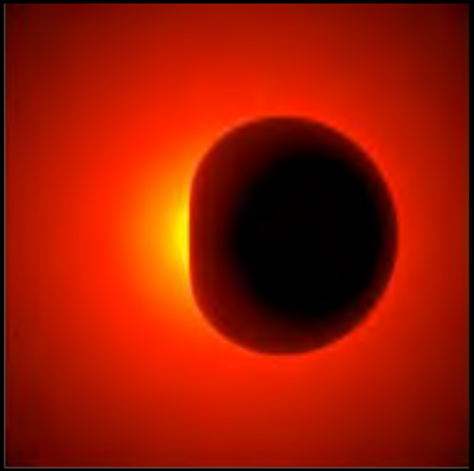
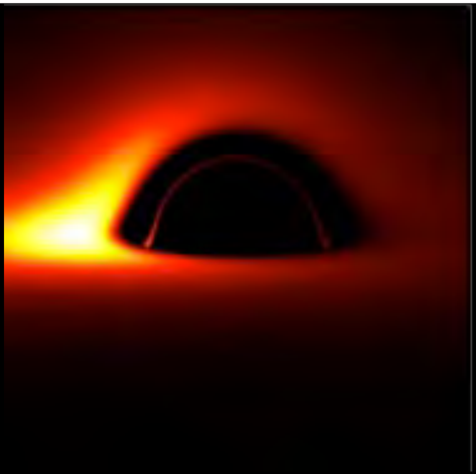
SMBH: Source of Jet

Accretion Disk: Shadow

► **Shadow ~ 20 (40)µas**

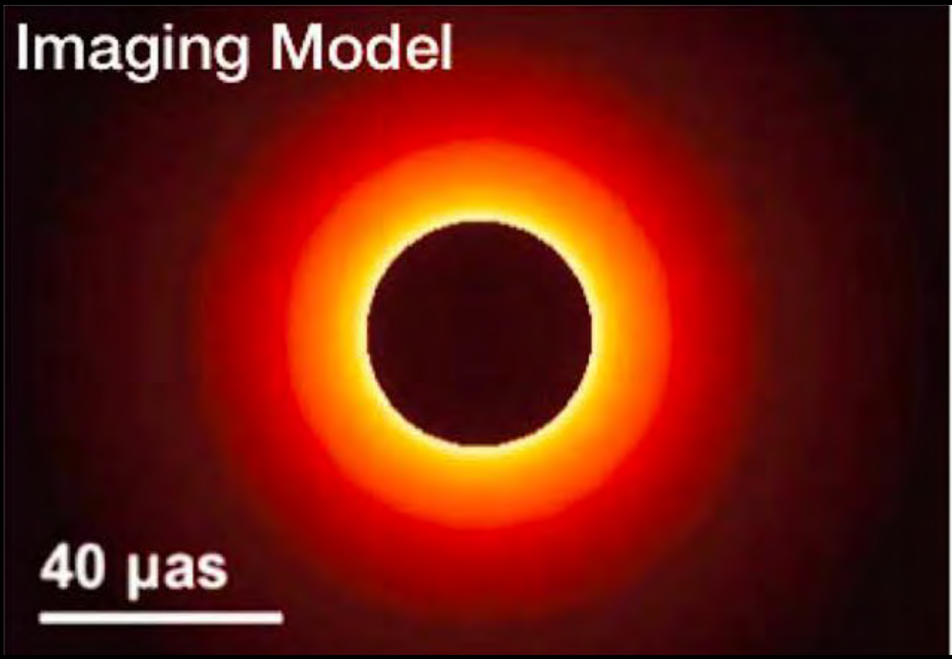
Appearance of the shadow of the SMBH

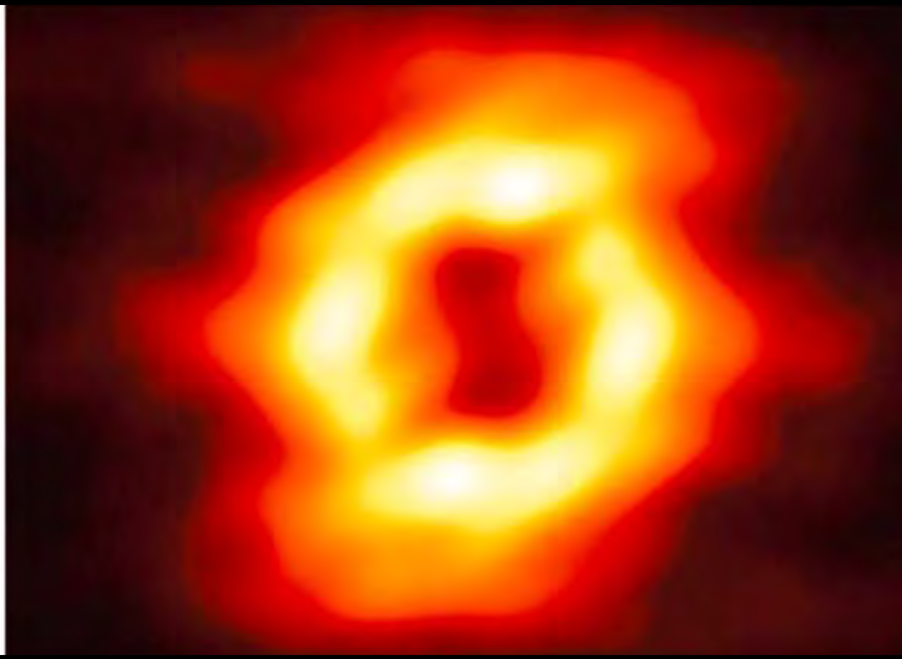
Size = Msss   Shape = Spin + Geometry

Geometry / Spin	No rotating BH	Maximum rotating BH
In optically thin flow and spherical geometry		
In optically thick flow and geometrically thin disk		

Takahashi 2004

Image simulation of M87



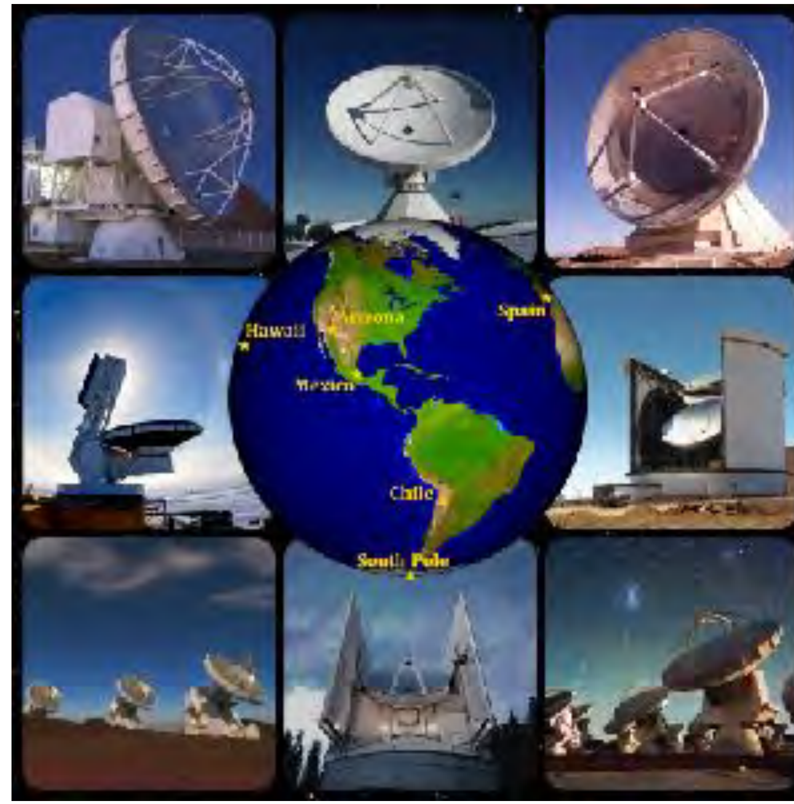


Model image with a 6×10^9 Mo SMBH and optically thin accreting matter, derived by the Ray Tracing method.

Observed image simulation with the submm VLBI at 345 GHz.

Taiwan is partner on ALMA, SMA, and JCMT

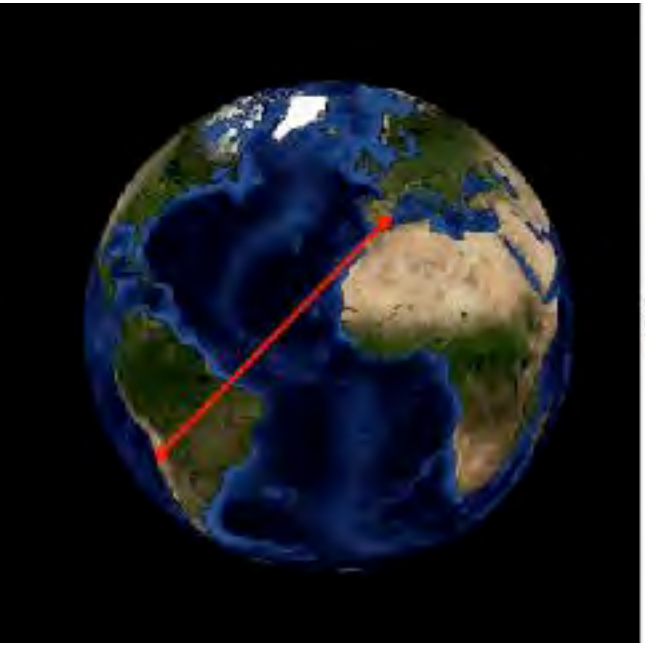
- Atacama Large Millimeter Array (ALMA), Chile
- ALMA Pathfinder Experiment (APEX), Chile
- James Clerk Maxwell Telescope (JCMT), Hawaii
- Large Millimeter Telescope (LMT), Mexico
- IRAM 30-meter Telescope, Spain
- South Pole Telescope (SPT), South Pole
- Submillimeter Array (SMA), Hawaii
- Submillimeter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

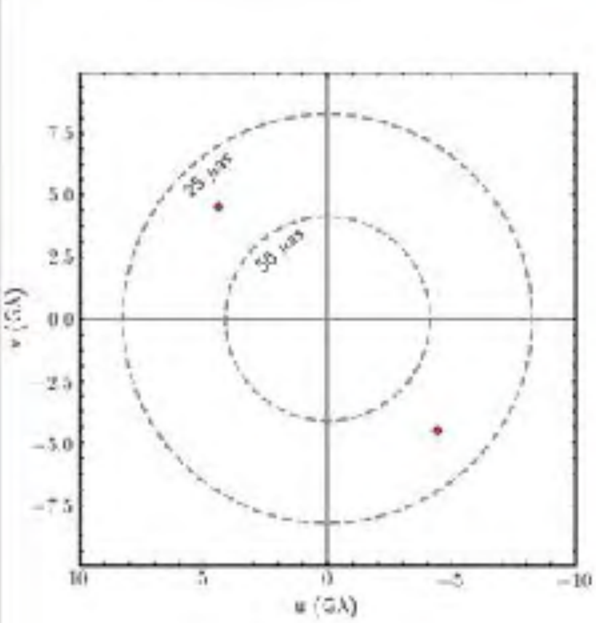


M. Johnson/SAO

Event Horizon Telescope in 2017

Event Horizon Telescope



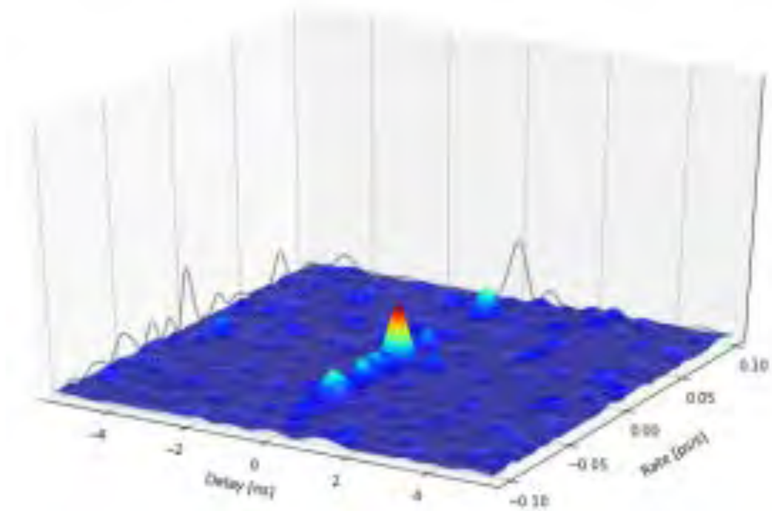


Aperture Synthesis: Building up UV Coverage

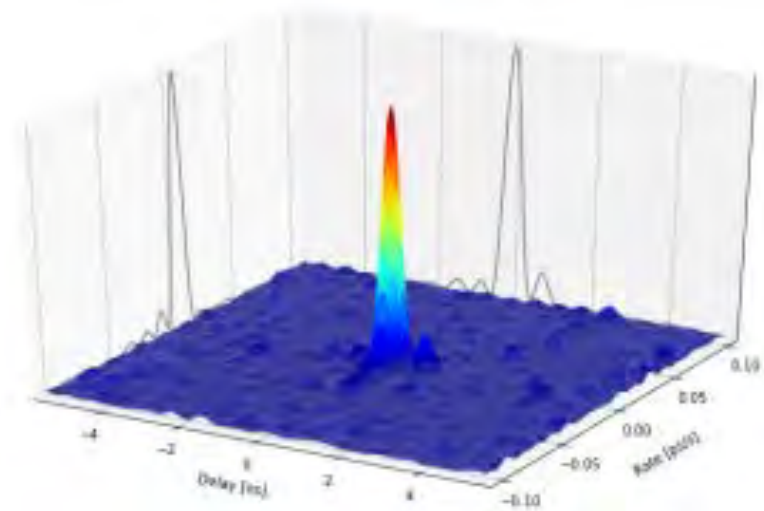
Visibility = Sampling · Source + Error

Removing “Errors”

before ad-hoc phasing



after ad-hoc phasing



Blazar OJ 287; Hawaii-Spain (SMA-IRAM) baseline 420-second integration

Ad-hoc phasing with ALMA corrects for atmospheric fluctuations and allows for strong detections in short time intervals on very long baselines.

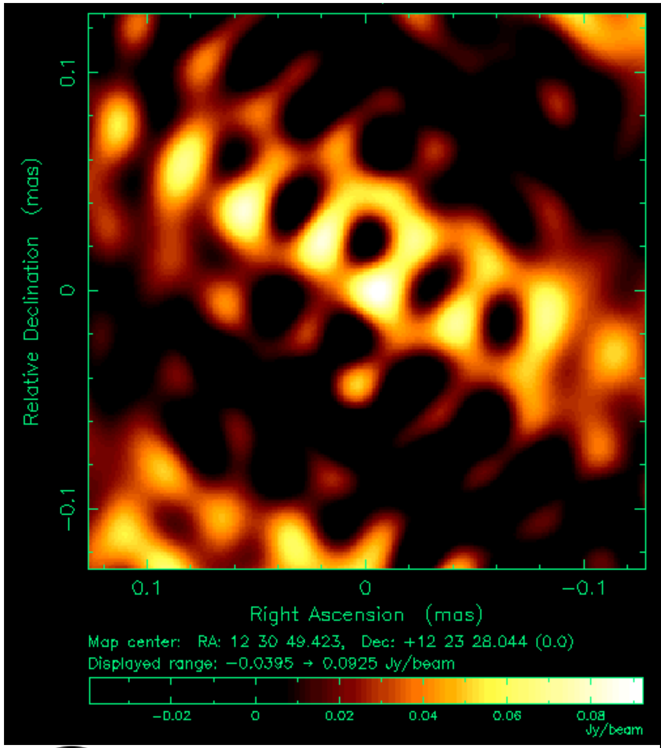
Phase Referencing with ALMA

Event Horizon Telescope

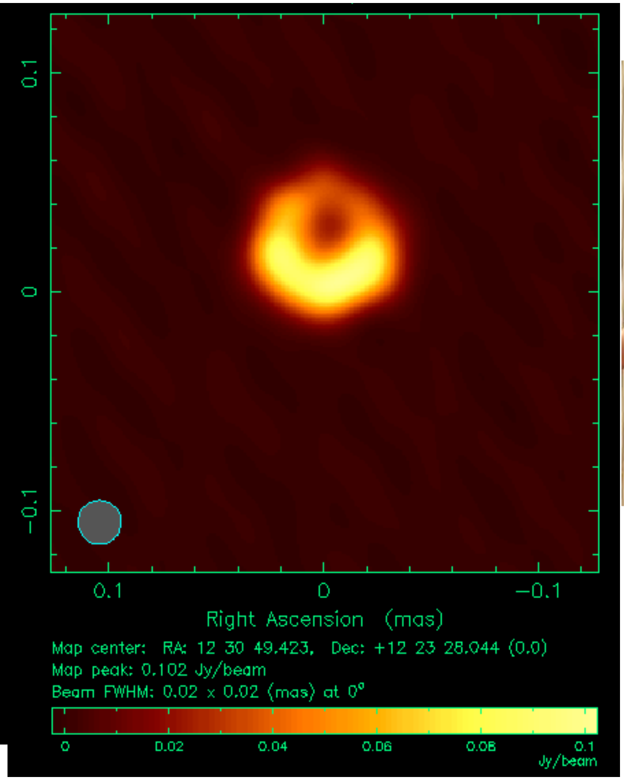
Removing "Defects"

Imaging of M87

Dirty Map

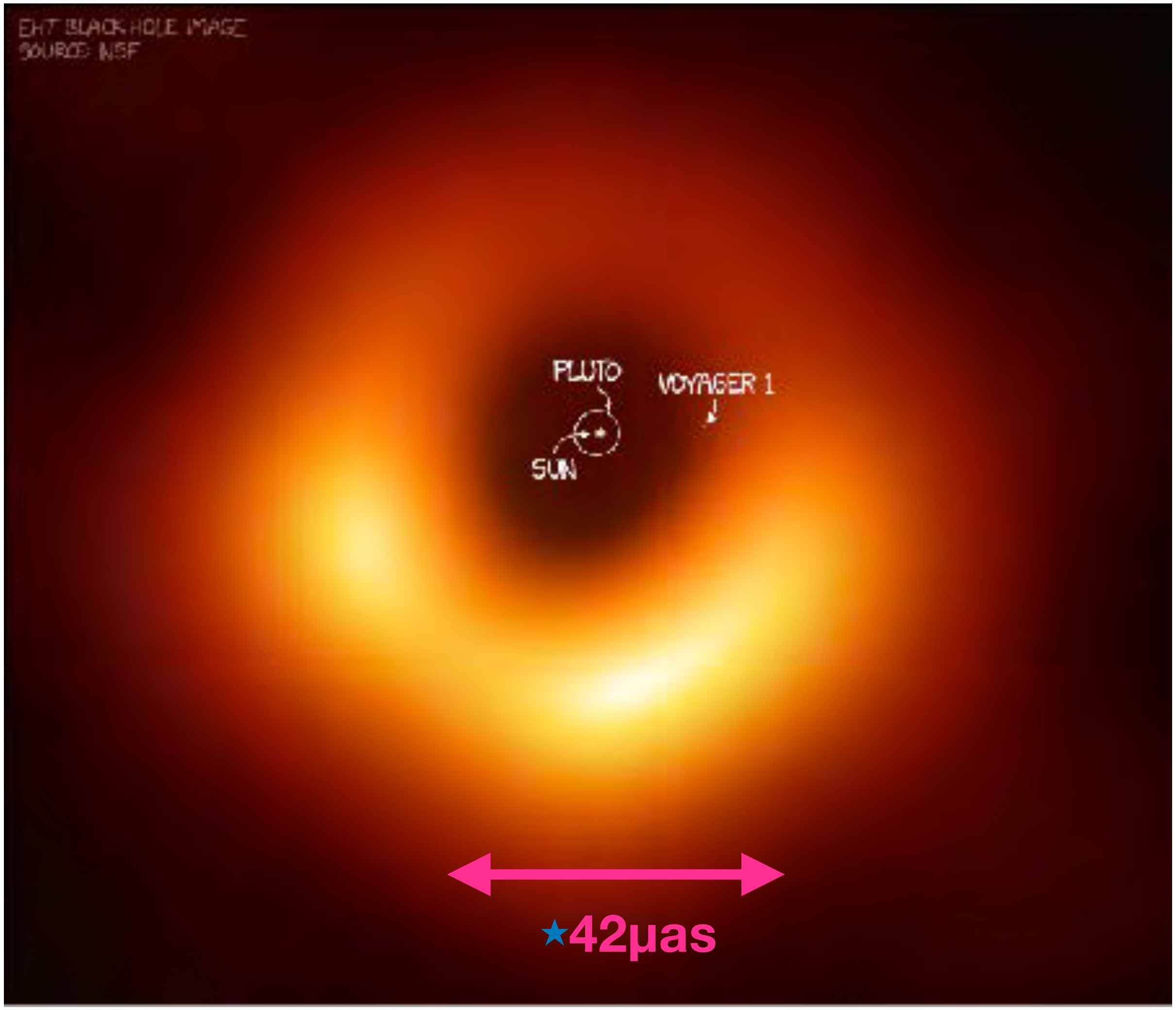


Final map after imaging process



UV-weighting, Clean, Phase Self-Calibrate, Amplitude Self-Calibrate

What does the Image Say?



It’s Black, and Looks like a Hole

Physical Parameters?

- **Photon Ring: ~42μas or ~400au, round**
- **Schwarzschild radius: $r_s = 2\ GM/c^2$**
- **Shadow Size ~5 times r_s (Event Horizon radius)**

—— **as expected by General Relativity**

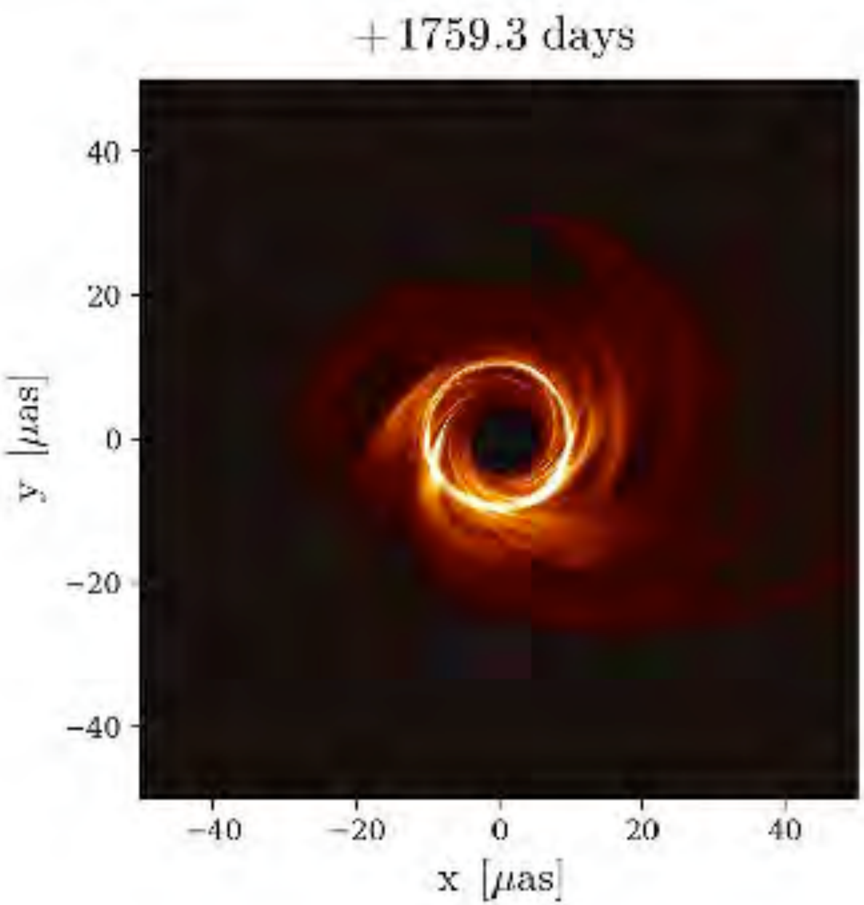
—— **deduced mass ~ 6.5 billion solar mass**

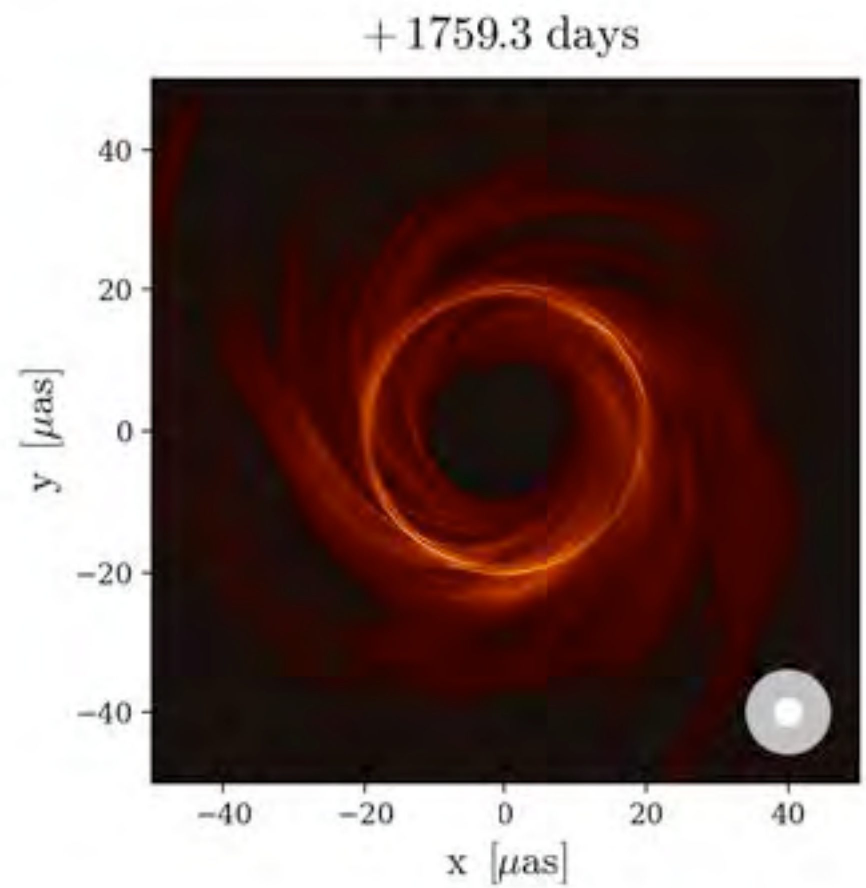
- **Ring Brightness: $n_e \sim 10^4\ cm^{-3}$, $B \sim 3G$, $M_{accr} \sim 10^{-3}\ M_{sun}\ yr^{-1}$**
- **Ring Asymmetry: Brighter on Bottom Side**

—— **consistent with rotation with doppler boosting**

- **Tipped Disk: Perpendicular to Relativistic Jet**
- **Spin of Black Hole: Pointed away from Earth**

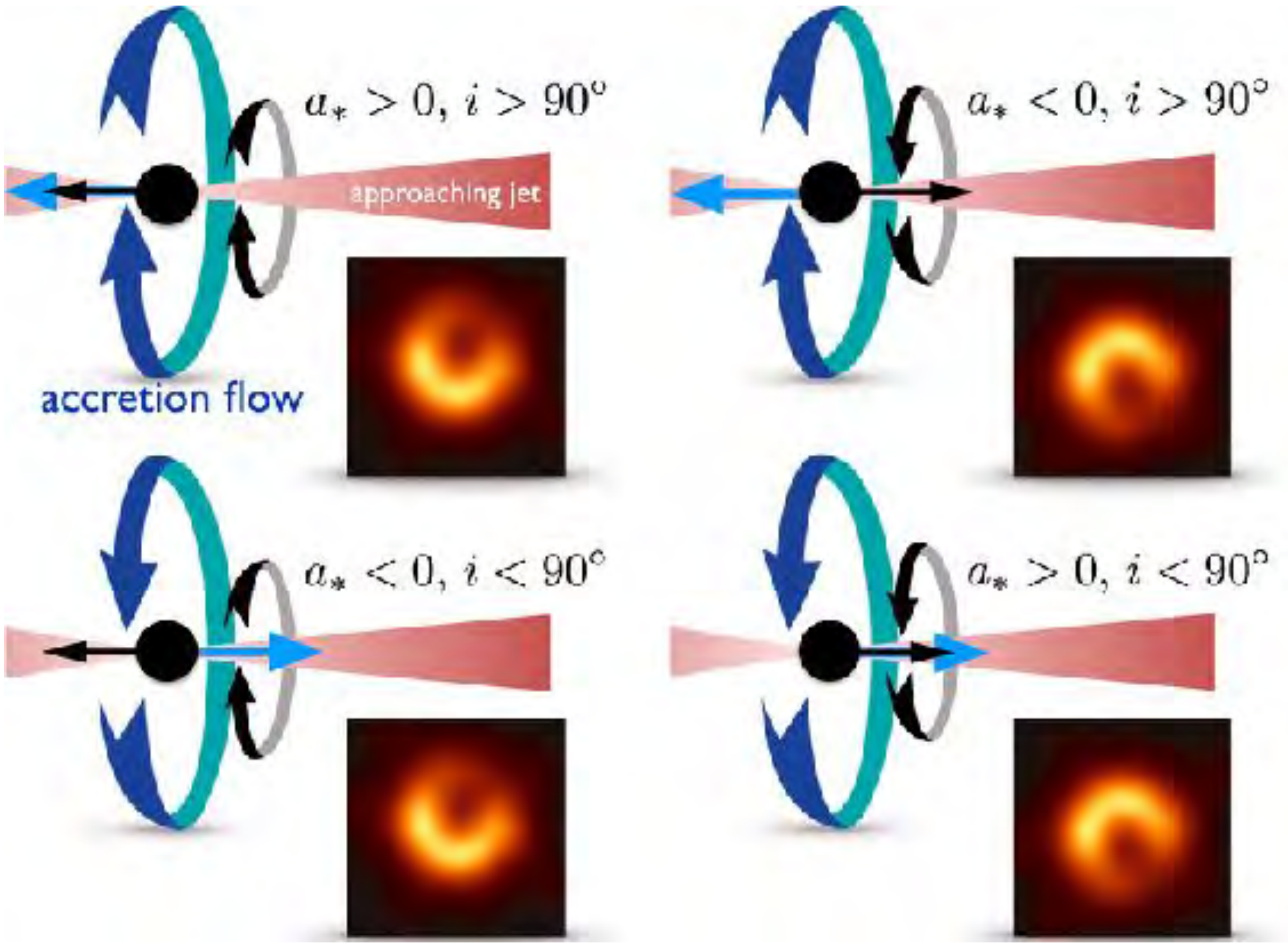
Simulation of Doppler Boosting





G. Wong, B. Prather, C. Gammie (Illinois)

Doppler Boosting of Approaching Part of Rotating Ring



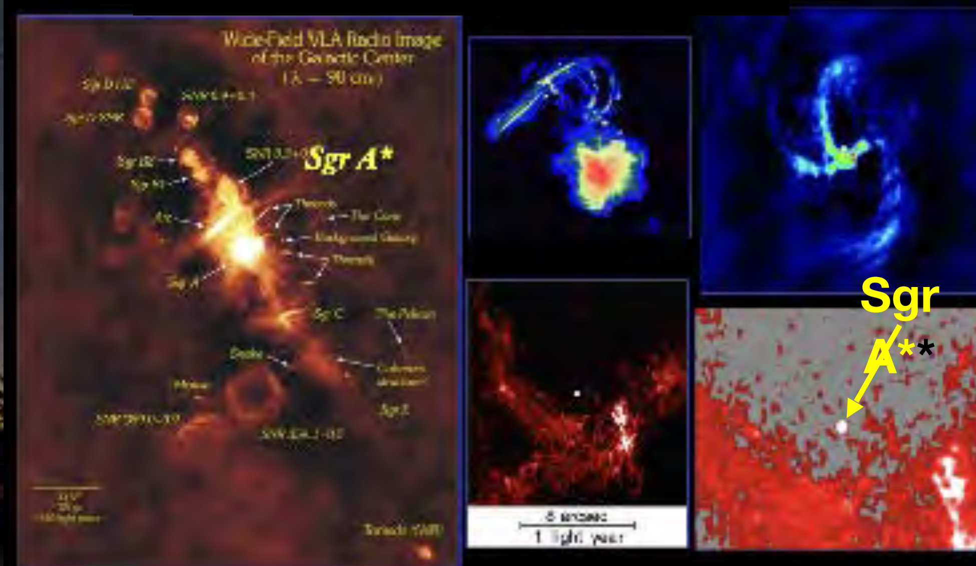
Inner Rotation must lock to Black Hole Rotation

The Galactic Center is Invisible in Optical Light

Milky Way Center Seen from Hehuanshan, Taiwan (optical light blocked by dust)

Photo Credit: Wang Wei-Hao, ASIAA

Milky Way Center in radio waves




Optical light

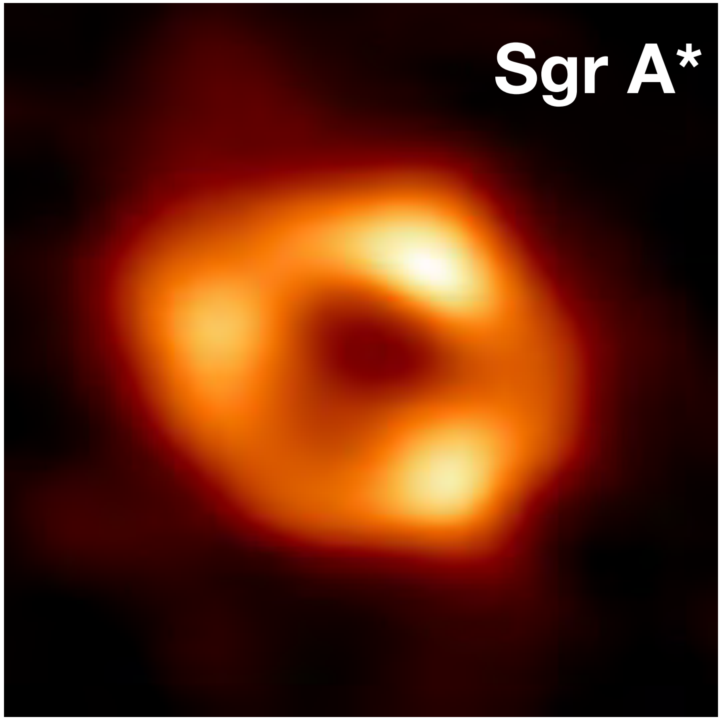
★Sgr A*: Seeing is Believing?

The Nobel Prize in Physics 2020

- discovery of "a supermassive compact object at the center of our Galaxy"

We now constrain this compact object into a region that is 1000 times smaller!

Our SgrA* images provide the first visual evidence that this compact object indeed looks like a black hole!

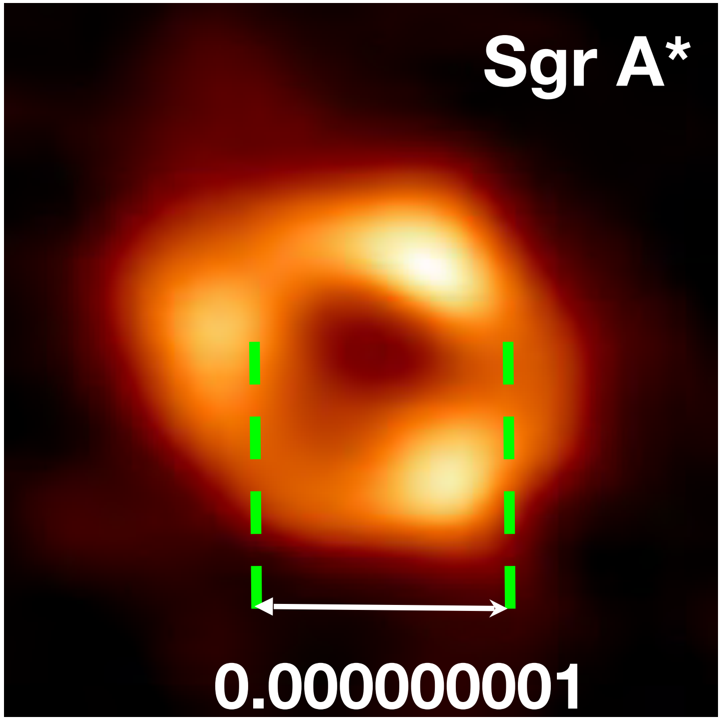


Event Horizon Telescope

Sgr A*: Einstein is right again!

Measured ring size is about **50 μarcsec**

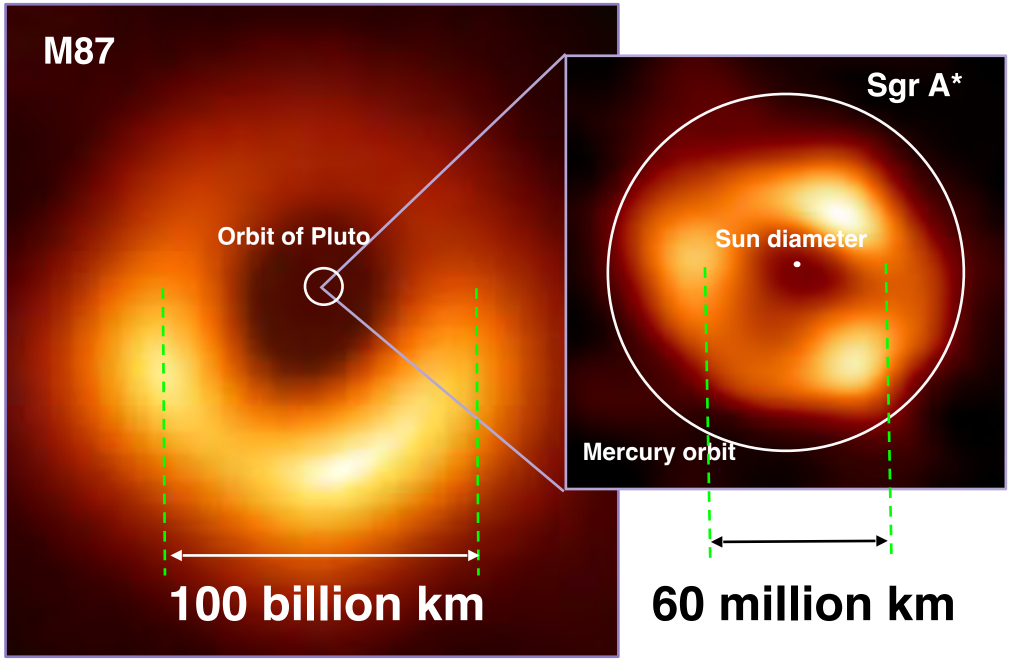
- 100 millionth of a degree (0.000000001°) on the sky
- similar to the **size of a donut on the Moon** as seen from Earth.
- this is the same size predicted based on the known mass and distance of the black hole!



Sgr A*: A Tiny Monster?

Comparison: Physical shadow size of M87* (first black hole we saw) is ~ 100 billion km in diameter because M87*:

- ~ 2000 times larger than SgrA*
- ~ 2000 times more mass



credit: based on xkcd illustration

Event Horizon Telescope

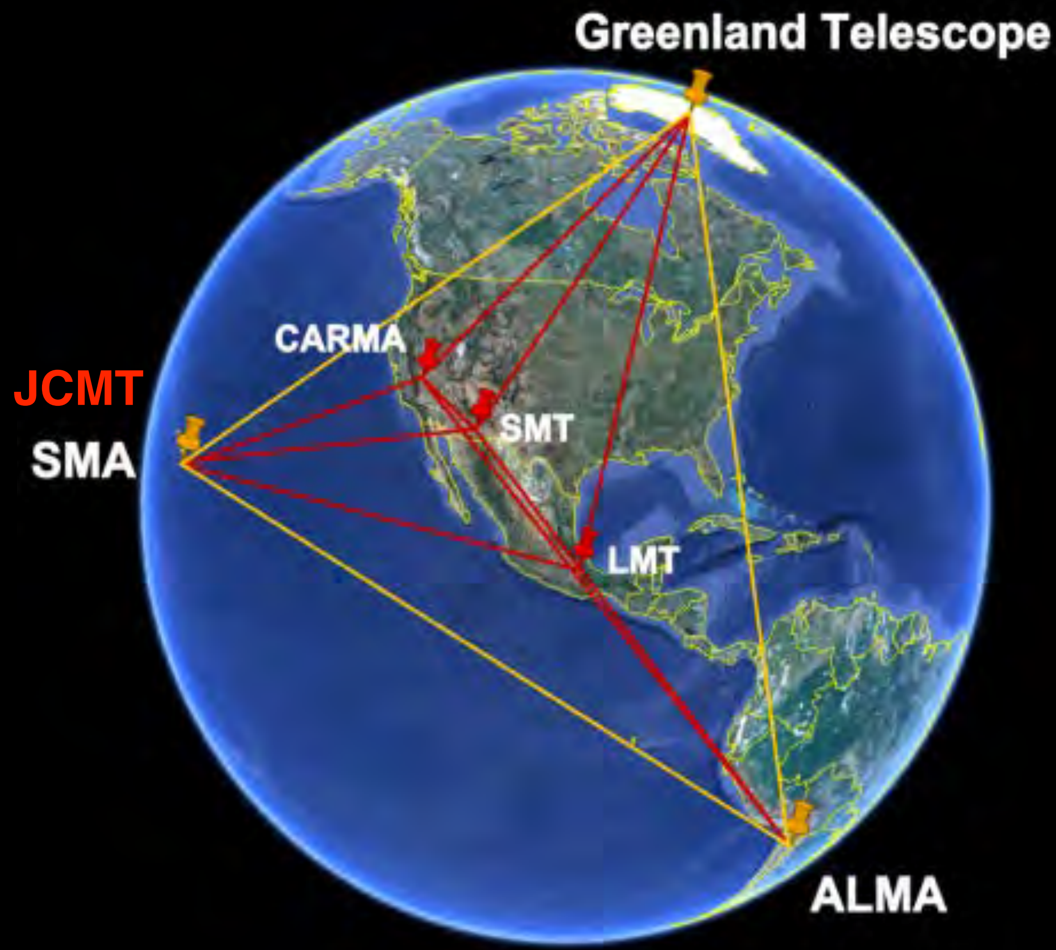
Summary

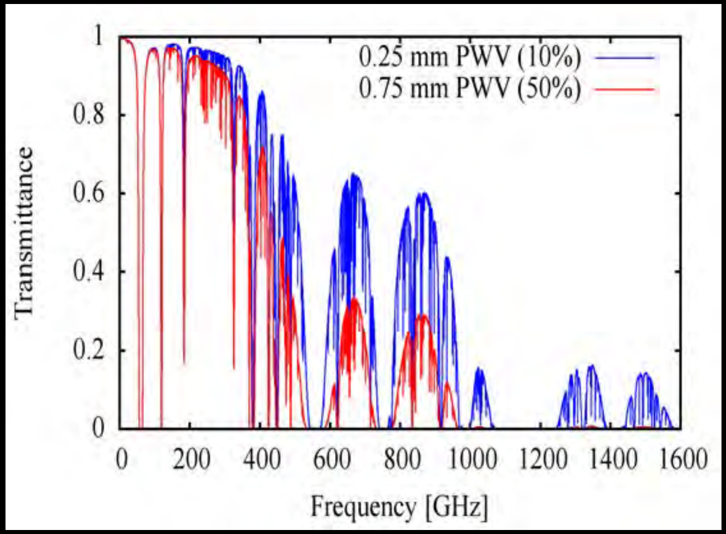
- **Current Research depends on Angular Resolution**
- **Gravity Wave Research probes Coalescence Process in building larger Black Holes**
- **Optical/IR Interferometry probes dynamics at Event Horizon and test GR effects**
- **Submm Very Long Baseline Interferometry probes structures of Event Horizon and physical processes and test GR effects**

- **Next Generation Instruments will have more resolution and more sensitivity (time domain, energy domain, dynamics domain)**
- **Asia will play a leading role in this Frontier in Optics/Physics!**

Building The Largest Telescope Ever:

Greenland Telescope leverages SMA and ALMA and JCMT





Aim: LOW PMV

Sensitivity: ALMA Surface Area

Arrival in Greenland 07.16.16

Assembly of Antenna Mount   09.10.16

Telescope Assembled July 28, 2017

Operations from Thule and Taipei

GLT operational very quickly
— Working Season very Short

- 2017 Nov. 30: Antenna construction finished.
- 2017 Dec. 1 : Commissioning started.
- 2017 Dec. 17: First Light with artificial light !!!
- 2017 Dec. 25: Astronomical First Light with Moon !!!
- 2017 Jan. 12: First Detection of Line source !!!
- 2018 Jan. 28 : Joined the EHT Dress Rehearsal !!!
- 2018 Mar. 20: First Fringe detected at 230 GHz!!
- 2018 Apr. 12-17: Joined the GMVA observations !!!
- 2018 Apr. 20-27: Joined the EHT Observations!!!

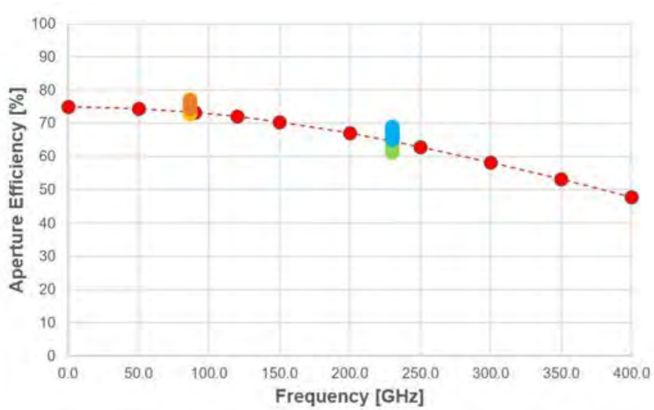
GLT operating since 2018

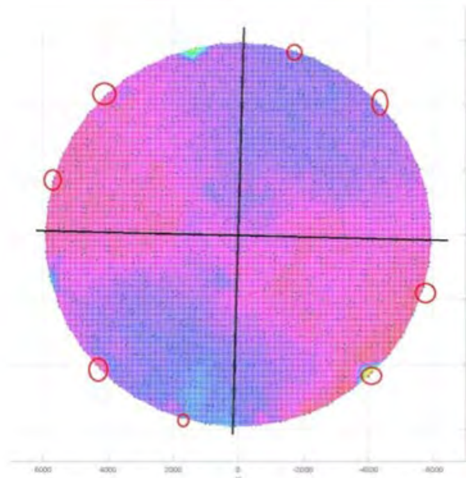
Date	Array	Freq.	Note	results
2018 Jan.	EHT	230	Fringe test	Fringe!!!, low sensitivity (η~25%?)
2018 Feb.	EB, Yb, PV	86/(230)	Fringe test	Missing one module
2018 Mar.	GMVA	86	**Science run**	Fringe!!!, dual linear polarization, **Published !!**
2018 Apr.	EHT	230	**Science run**	Fringe, low sensitivity (η~25%?), **to be submitted !!**
2018 Sep.	GMVA	86	**Science run**	Fringe, dual linear polarization, **Published !!**
2018 Oct.	EHT	345/230	Fringe test	No Fringe
2019 Jan.	EHT	230	Fringe test	Fringe
2019 Mar.	EAVN	230	Fringe test	No Fringe
2019 Mar.	EHT	230	**Science run**	Canceled
2019 Apr.	GMVA	86	**Science run**	Fringe
2019 Sep.	GMVA	86	**Science run**	Fringe
2019 Dec.	EHT	230	Fringe test	Data arrived at HO
2020 Jan.	EHT	230	Fringe test	Fringe
2020 Feb.	EAVN	230	Fringe test	Fringe!!!
2020 Apr.	EHT	230	**Science run**	Canceled
2021 Mar.	EHT	230	Fringe test	Fringe
2021 Apr.	EHT	230	**Science run**	Fringe
2021 Apr.	EHT	345	Fringe test	Fringe!!!
2021 Apr.	GMVA	86	**Science run**	Fringe
2022 Jan.	EHT	230	Fringe test	Fringe
2022 Mar.	EHT	230	**Science run**	Fringe
2022 Apr.	GMVA/G-VLBI	86	**Science run**	Fringe

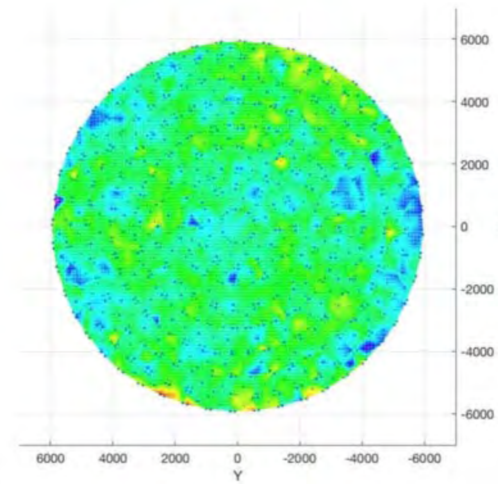
after 2019, Surface Accuracy Improved

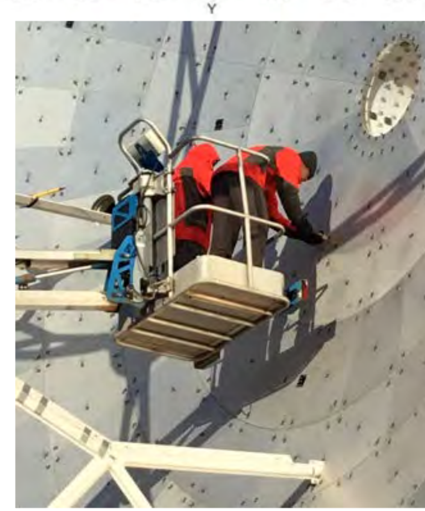
- Aperture Efficiency
  - Photogrammetry Before & After:
    - Surface accuracy improved from 180 µm to 21 µm.
  - Aperture efficiency Improved:

    [Freq.: 2018 □ 2019 □ 2020]
    - 86 GHz : 48% □ ------ □ 75%
    - 230 GHz: 22% □ 60% □ 65%



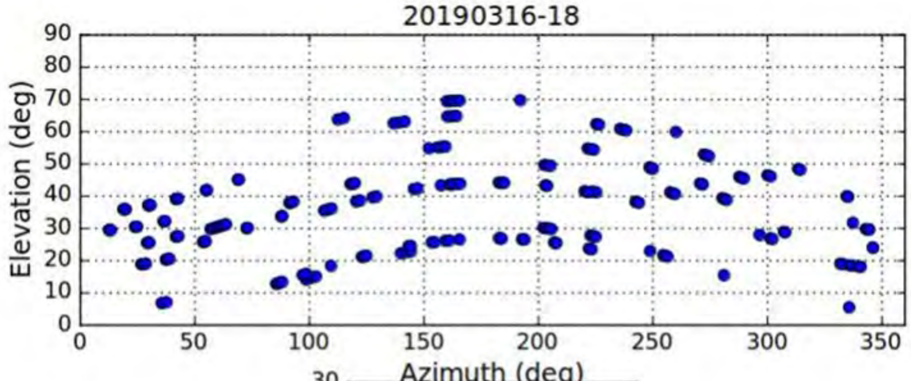


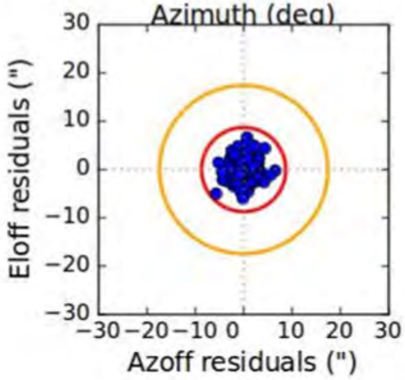




after 2019, Pointing Accuracy Improved

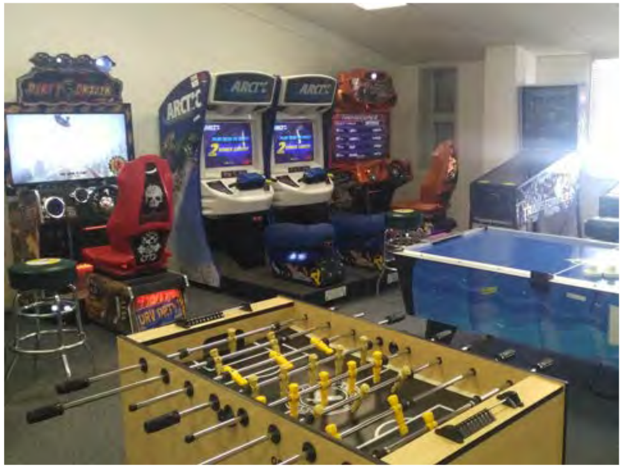
- **Pointing**
  - **There was an issue on pointing, especially at low elevation, in 2018**
  - **Pointing model was not good enough**
  - **We have improved it since 2019**



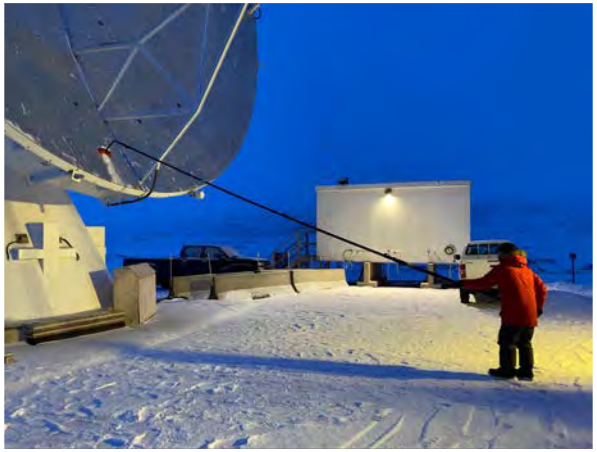


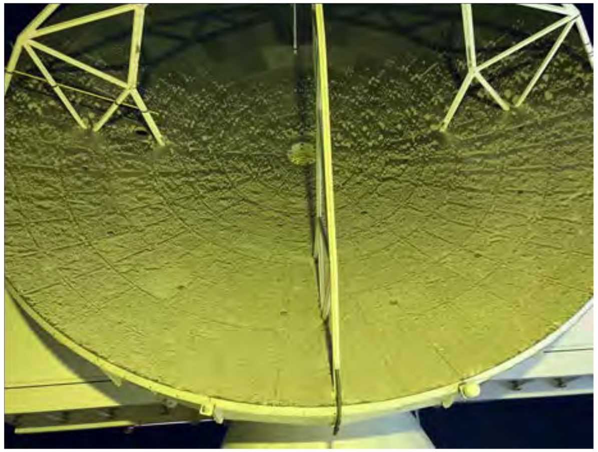
Receiver	RMS Pointing error (arcsec)	
	AZ	EL
86 GHz	2.9	2.8
230 GHz	1.9	1.9
345 GHz	1.8	1.9

Astronomers living in Thule



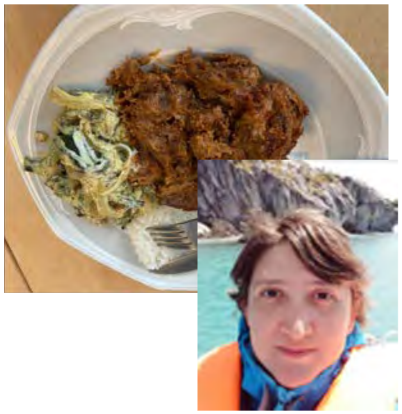
Astronomers must be able to Clean



Astronomers must be able to Cook!

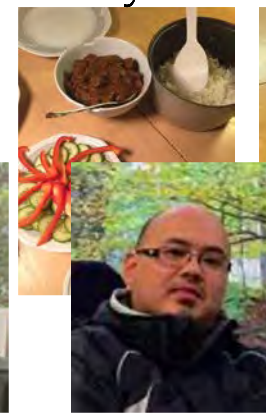
Mexican



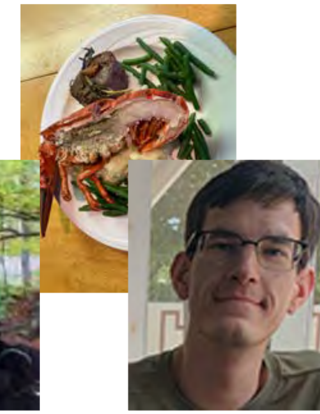
激悪めし

Italian

Malaysian

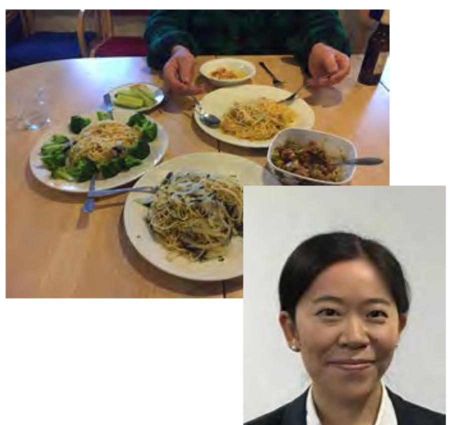


American

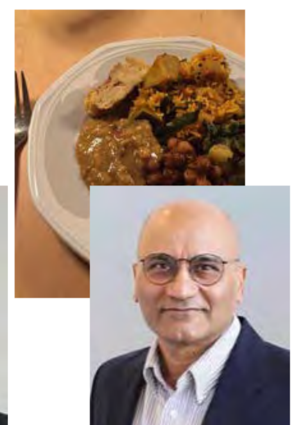


French

Pasta



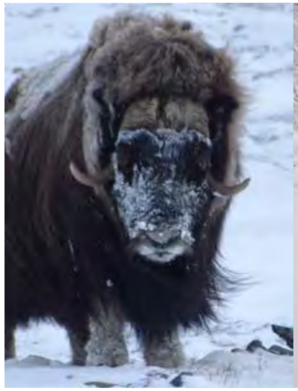
Indian

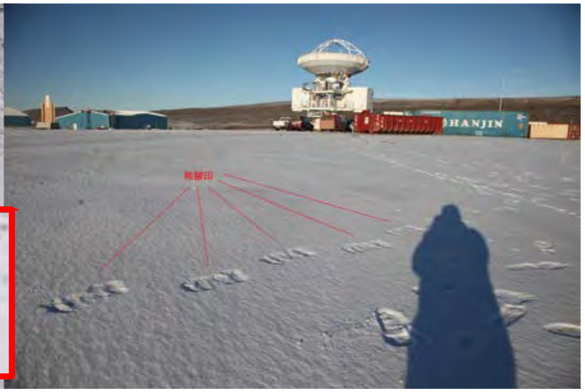


Korean

Chinese

Astronomers also need to Play





Some enjoys other things in Thule

VIP Visits to the GLT

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

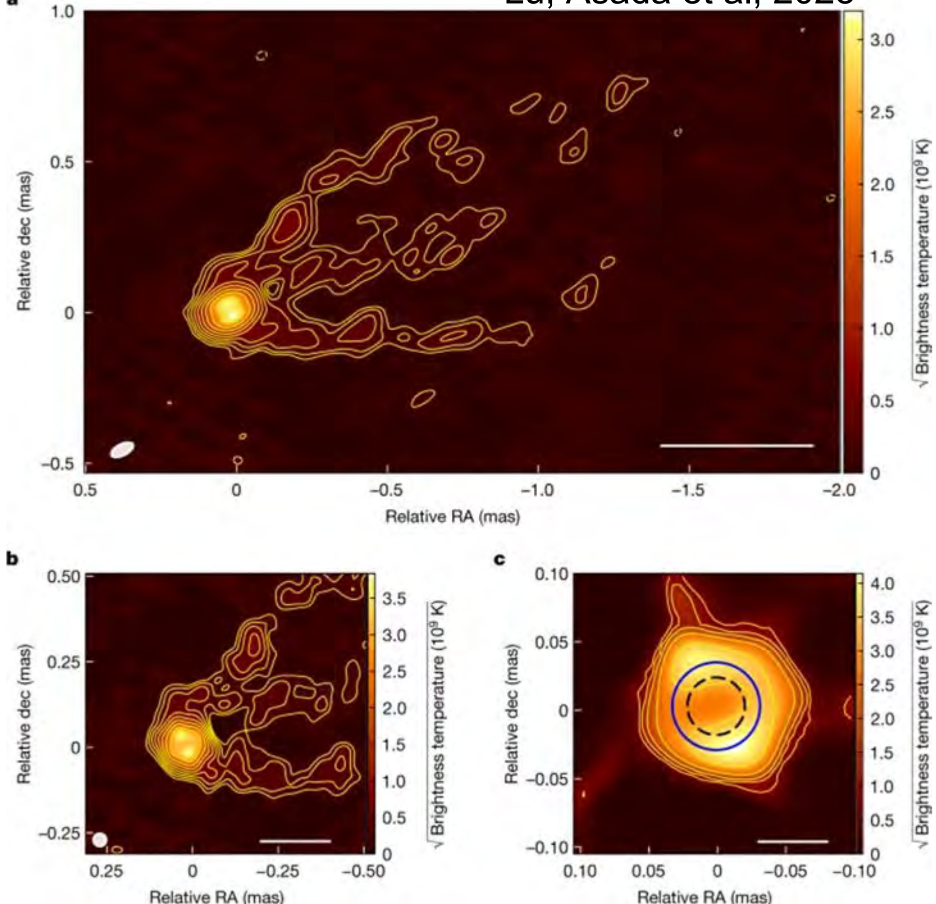
The Prime Minister of Denmark 2018/10/29

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

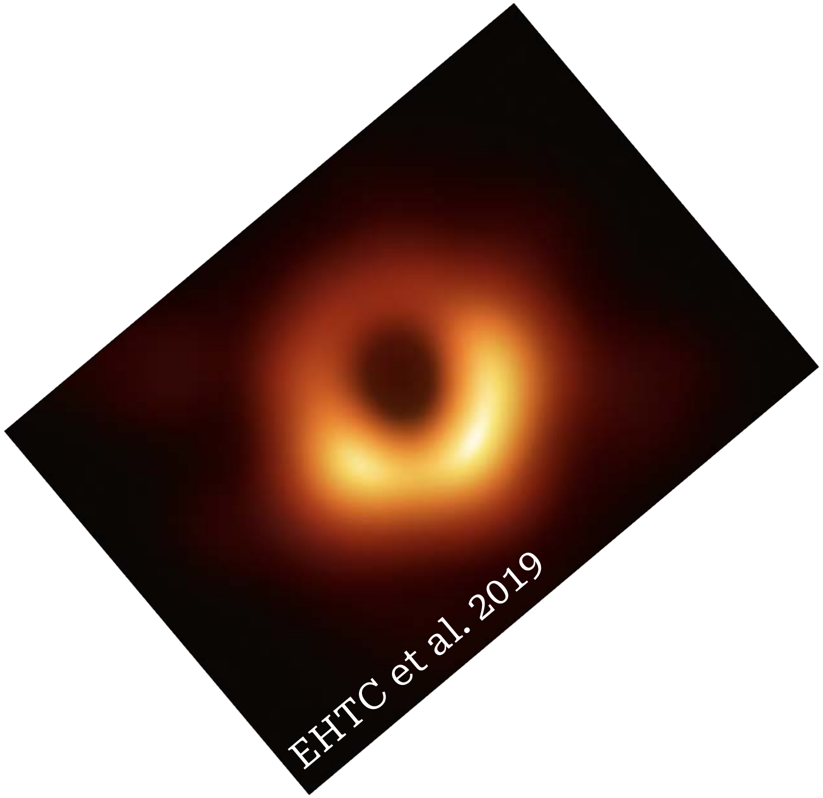
Barbara Barret 2019/11/29
(Secretary of US Air Force &
Smithsonian Institution Board Member)

First GLT Result: Connect BH to Jet see Accretion onto BH “Donut”

Lu, Asada et al, 2023

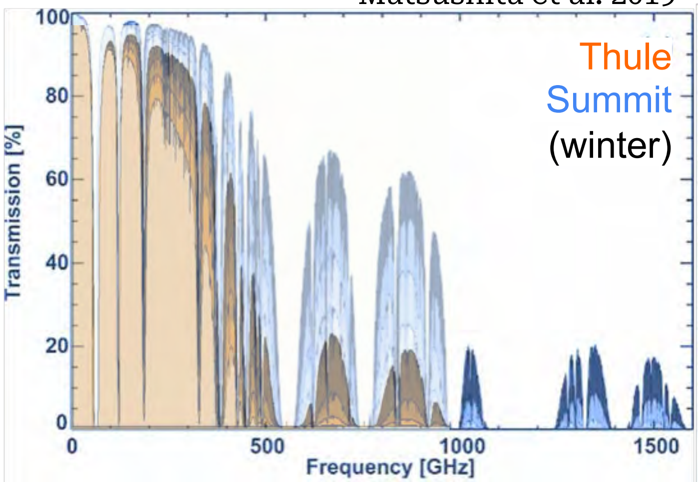


EHTC et al. 2023 to be submitted



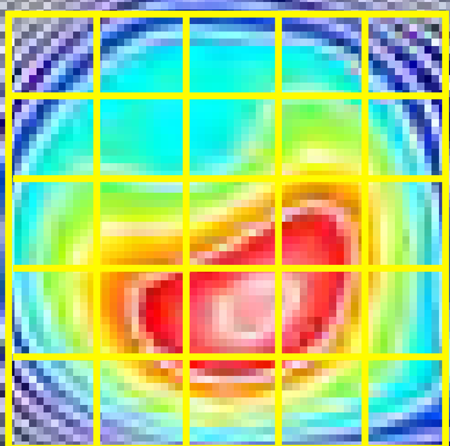
Goal is to get to the Summit

Matsushita et al. 2019



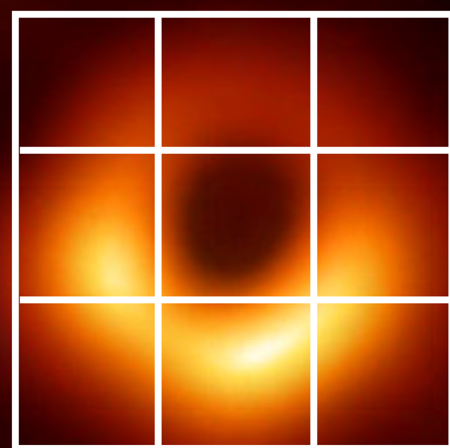
Current and Future Resolution of EHT

EHT with GLT
220 GHz
5 x 5 pix (25 pix)

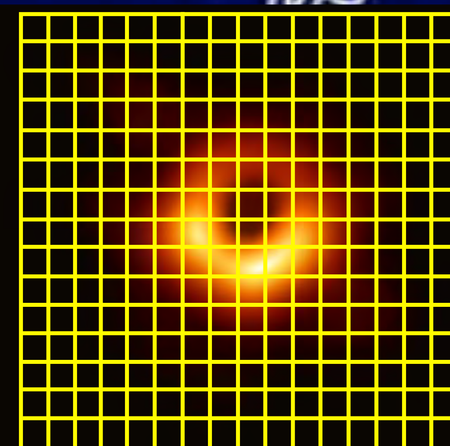


We will have better resolution & sensitivity on M87 black hole shadow & jet.

EHT 2017
220 GHz
3 x 3 pix (9 pix)



GLT @ Summit
660 GHz
15 x 15 pix (225 pix)



M31 (Andromeda)
Black Hole

We will have much better resolution for black hole shadows in various galaxies.

Summary of Talk

- **Black Hole Imaging is one of 3 key Gravity Experiments**
- **Asia played a key role in the BH Experiment**

- **Lasers and Interferometry are the key Techniques**
- **Black Hole Shadow Image verifies General Relativity, with deep implications for astrophysics and fundamental physics**

- **Asia is working on next steps in this field**
- **Excellence requires strong support from Government, Research Organization, Industry, Universities**

and, Science is the Product of Teamwork

Students from Tsukuba?