# First Direct Image of a Black Hole

Paul Ho, EAO/ASIAA

# BLACK HOLE SHADOW: APRIL 10, 2019



# Why is This Result Important ?
## because it's not theory !

- Black Hole: "INVISIBLE" or "UNSEEABLE"
- Black Hole: where "GRAVITY" is strongest
- Black Hole: no escape — not even light
- Black Hole: no information from inside
- Small Black Hole: "end state" of big stars (>5-10 times sun) — leftover after "supernova" explosion
- Big Black Hole: Billions times the sun's mass — in the nucleus of galaxies
- Black Hole Properties: high temperature? high density? — depends on mass of Black Hole
- Black Hole Physics: tests General Relativity

- <u>This Experiment is an "Optics" + "Information" Problem</u>

# Some Very Simple Physics

- Light: Energy ~ $\nu$ ~ 1/ $\lambda$

  Energy ~ Temperature

- Speed of Light constant: $c = 3 \times 10^{10}$ cm/s

- Apparent Size ~ 1 / Distance

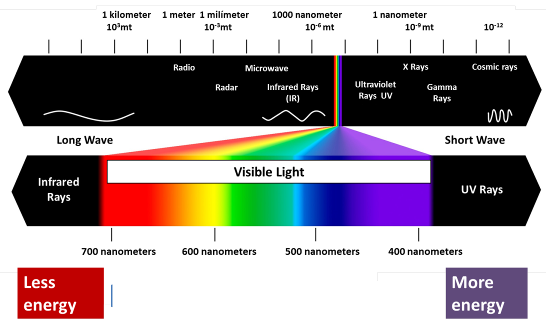
- Doppler Motion: Like Train Whistle:

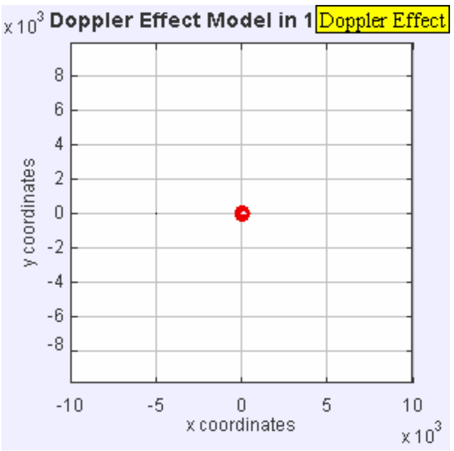
  $\Delta \nu = (\Delta \text{Velocity} / c)\ \nu_o$

- Total Energy Conserved

- Angular Momentum (MVR) Conserved : V ~ 1 / R

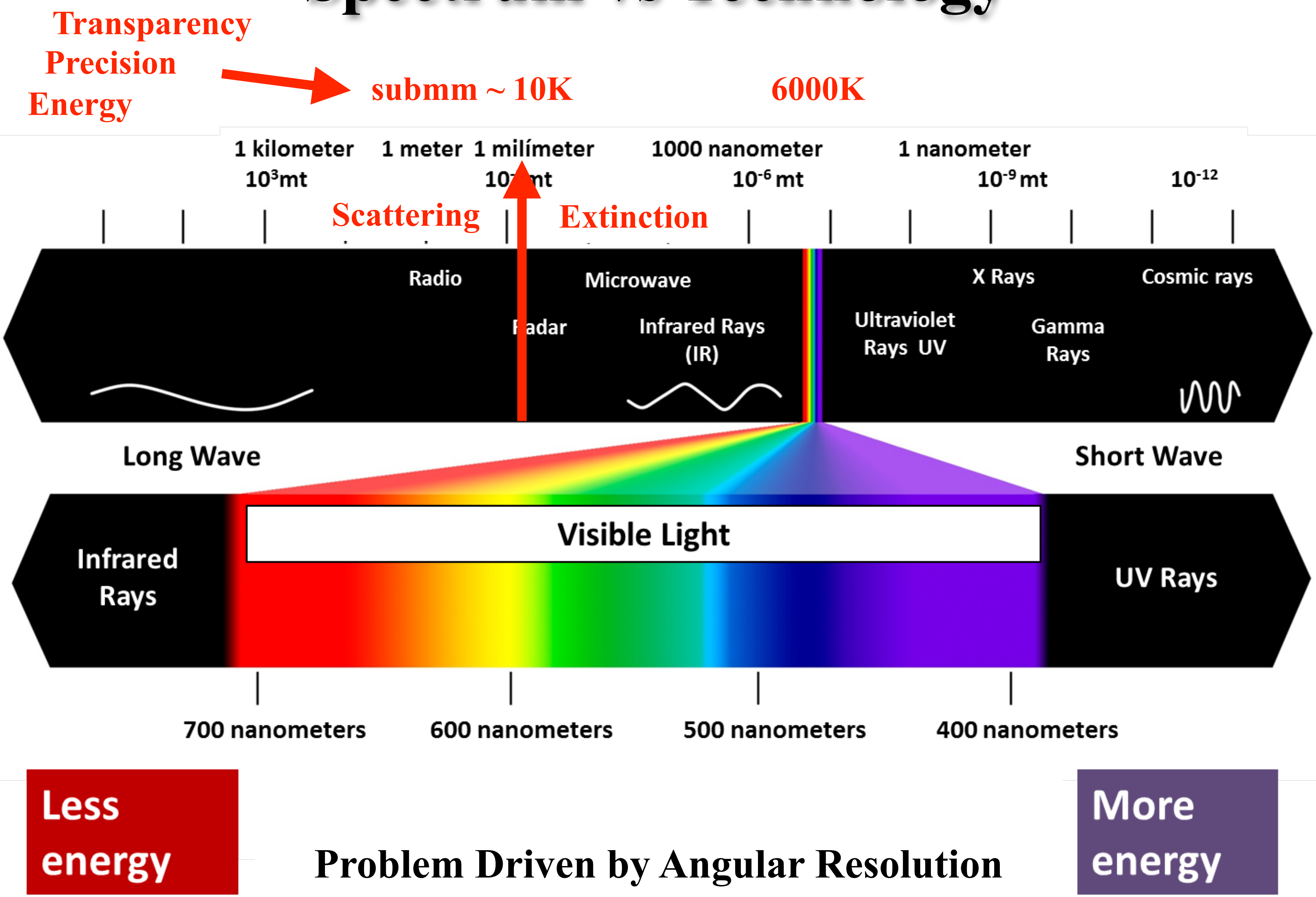
- Special Relativity; General Relativity



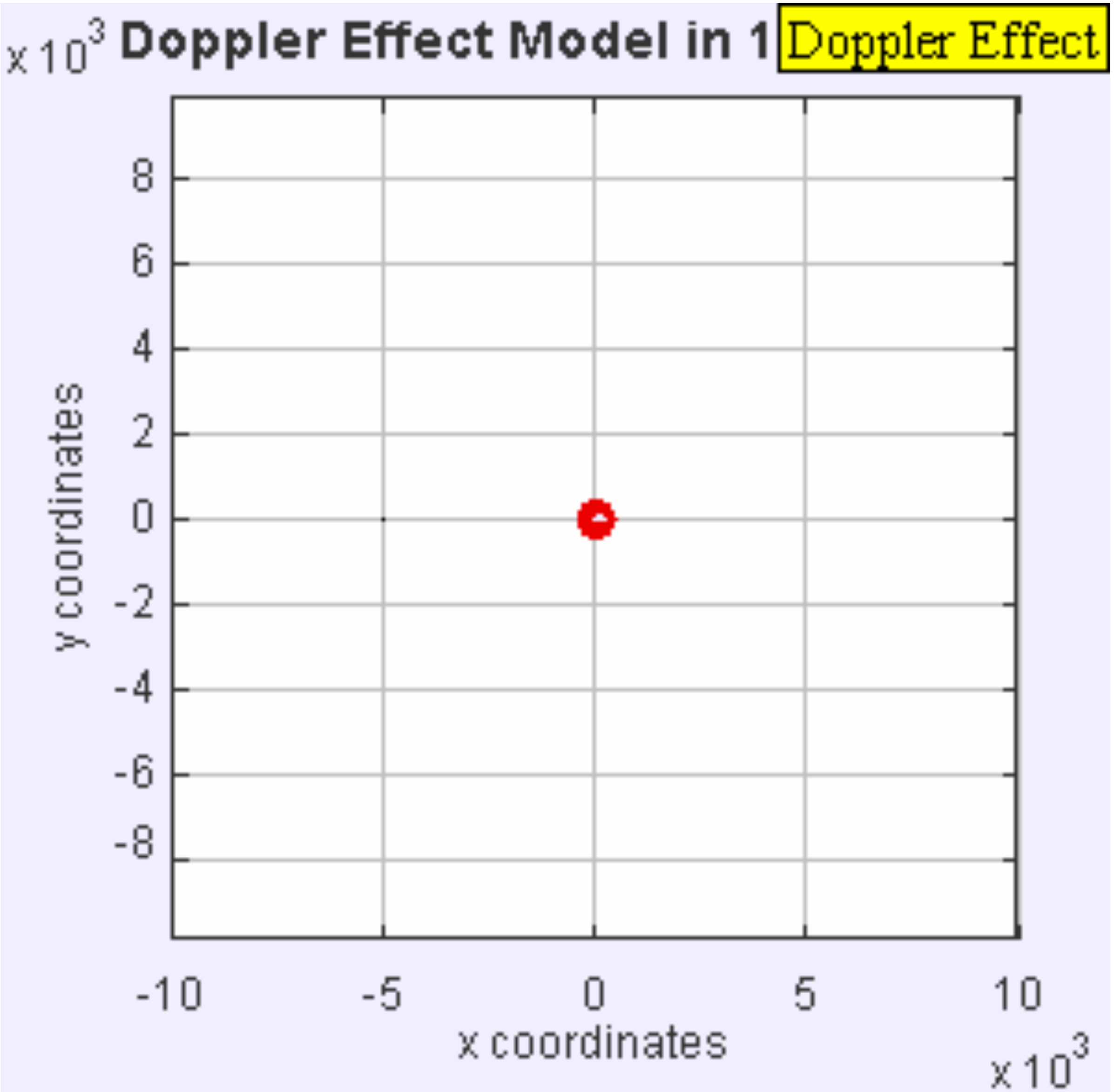

(wikipedia: F.K. Hwang)

# Spectrum vs Technology




**Problem Driven by Angular Resolution**

# Signature of Doppler Motions



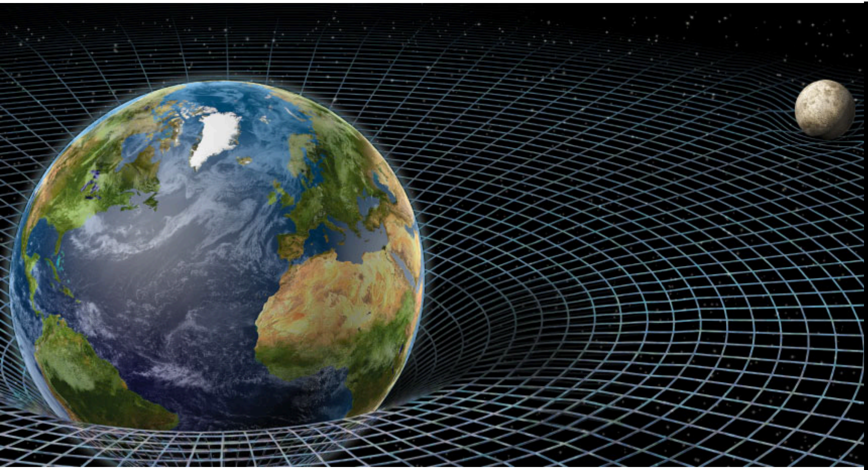

$$\Delta \nu = \left(\frac{\Delta \text{Velocity}}{c}\right) \nu_o$$

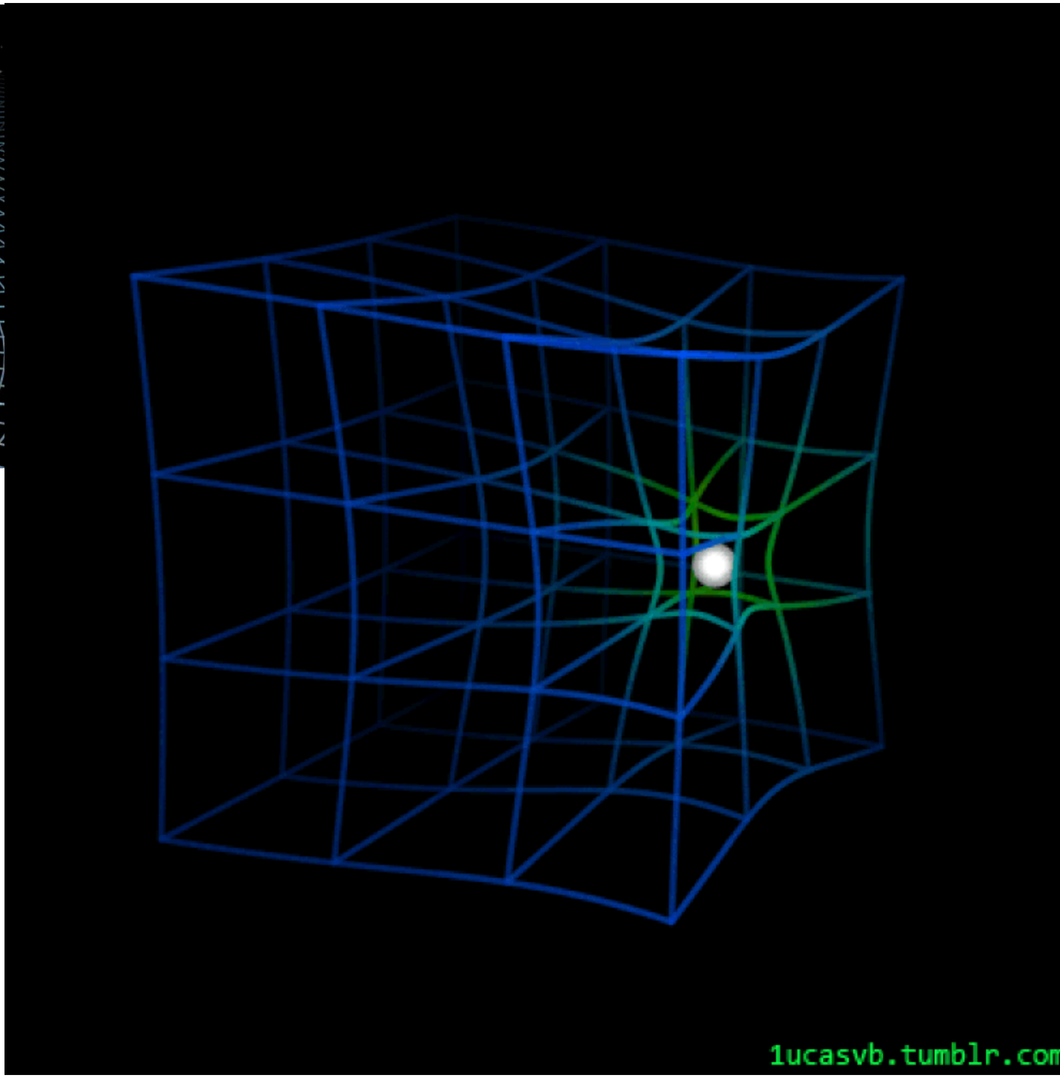
**approaching:**

— **higher ν**

— **higher energy**

# Gravity affects Geometry of Space

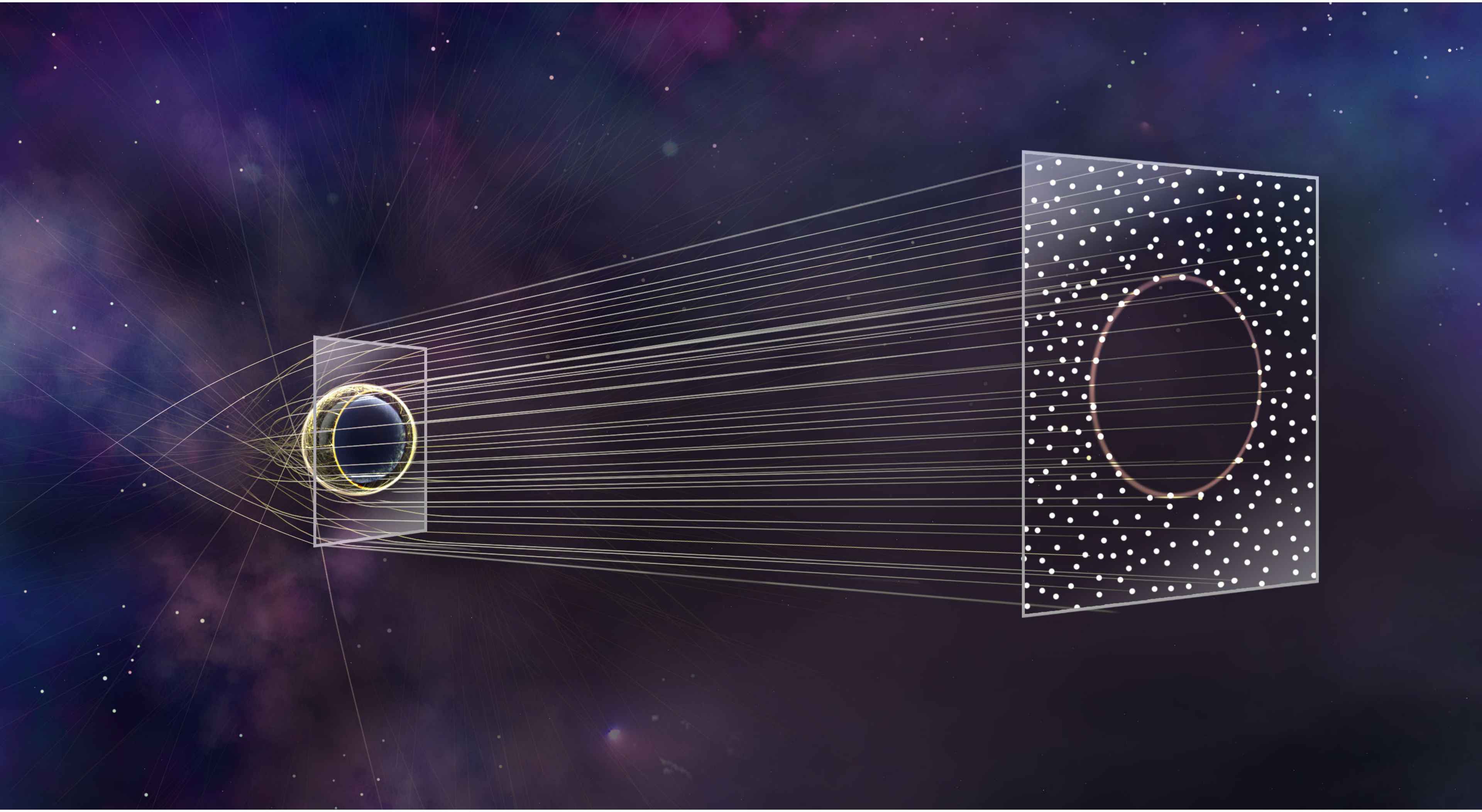





- Mass will distort space-time until even light cannot escape
- Einstein predicted the existence of black holes - though even he was not comfortable with the conclusions from his equations

**Gravity/Geometry instead of Material/Dielectric to bend Light**

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



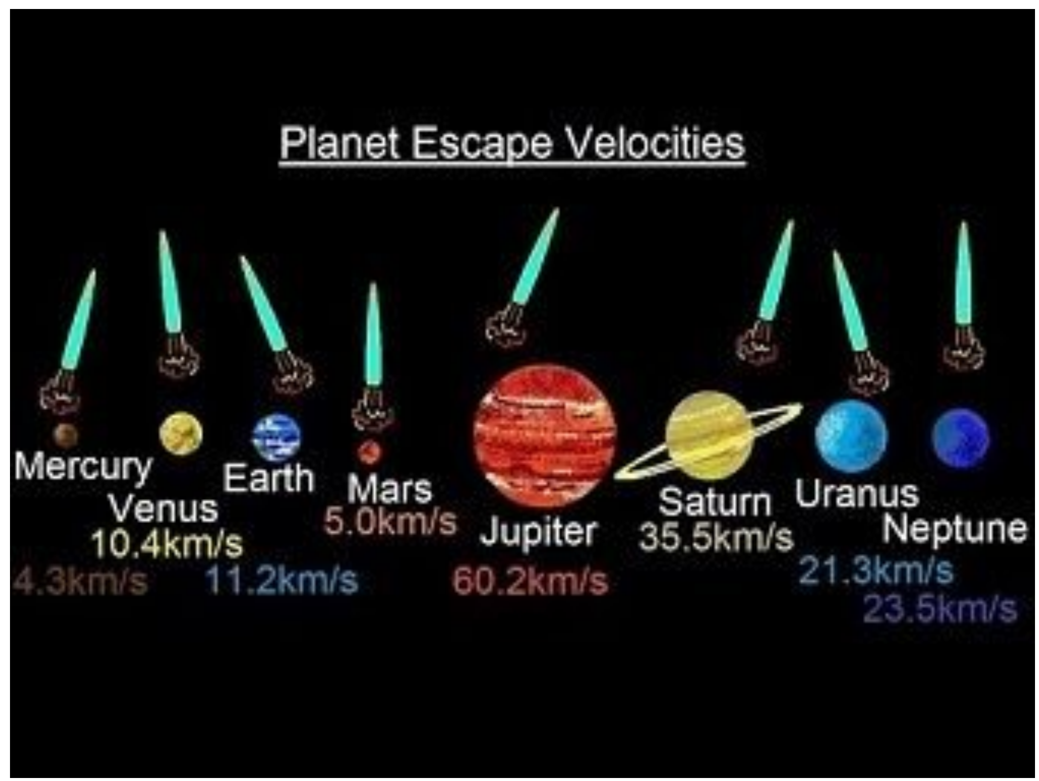
# Newtonian Escape Velocity

$$v_{escape} = 11.2\ km/s$$

$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

$$v_{escape} = \sqrt{\frac{2GM}{r}}$$

**Kinetic Energy > Gravity**



# No Escape From Black Hole ?

- $V_{escape} = (2GM/r)^{1/2}$

$V_{escape} < c$

- $r = 2GM / (V_{escape})^2$

- Schwarzchild Radius: $R_{sch} = 2GM / c^2$

$E = \gamma mc^2$

$ds^2 = (1 - 2GM/c^2 r)\, c^2 dt^2 - dr^2/(1 - 2GM/c^2 r) - r^2 d\theta^2 - r^2 \sin^2\theta \, d\phi^2$

- Special Relativity tells us Energy becomes Infinite as velocity approaches the speed of light — therefore no escape!
- General Relativity tells us even Light must follow the distorted geometry from Gravity — therefore "bent" light rays!

- Black Hole defined by $M / R = c^2 / 2G$ ← METRIC

# What is Physics like inside Black Hole?

- **Physics depends on density and temperature**
- **Black Hole defined by $M / R = c^2 / 2G \sim 6.7 \times 10^{27}$ g/cm**
- **Density ~ $M / R^3$ *not* $M / R$**
- **earth size black hole ~ $6 \times 10^{27}$ g ~ 1 cm ; $10^{27}$ times water density**
- **sun size black hole ~ $2 \times 10^{33}$ g ~ 300 km; $10^{11}$ times water density**
- **M87 black hole ~ $1 \times 10^{43}$ g ~ 130 AU; $10^{-3}$ water density**

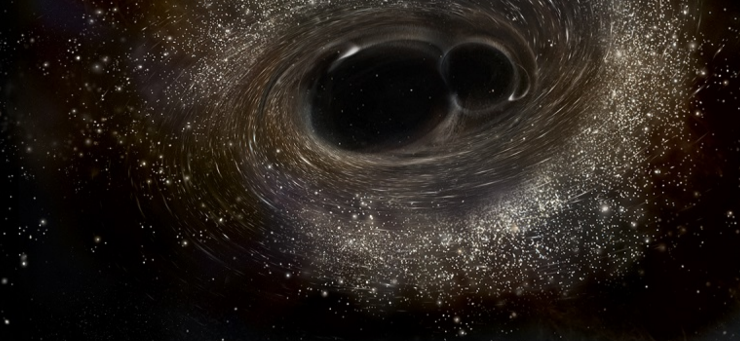
**Really Big Black Holes may be "Ordinary"**

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

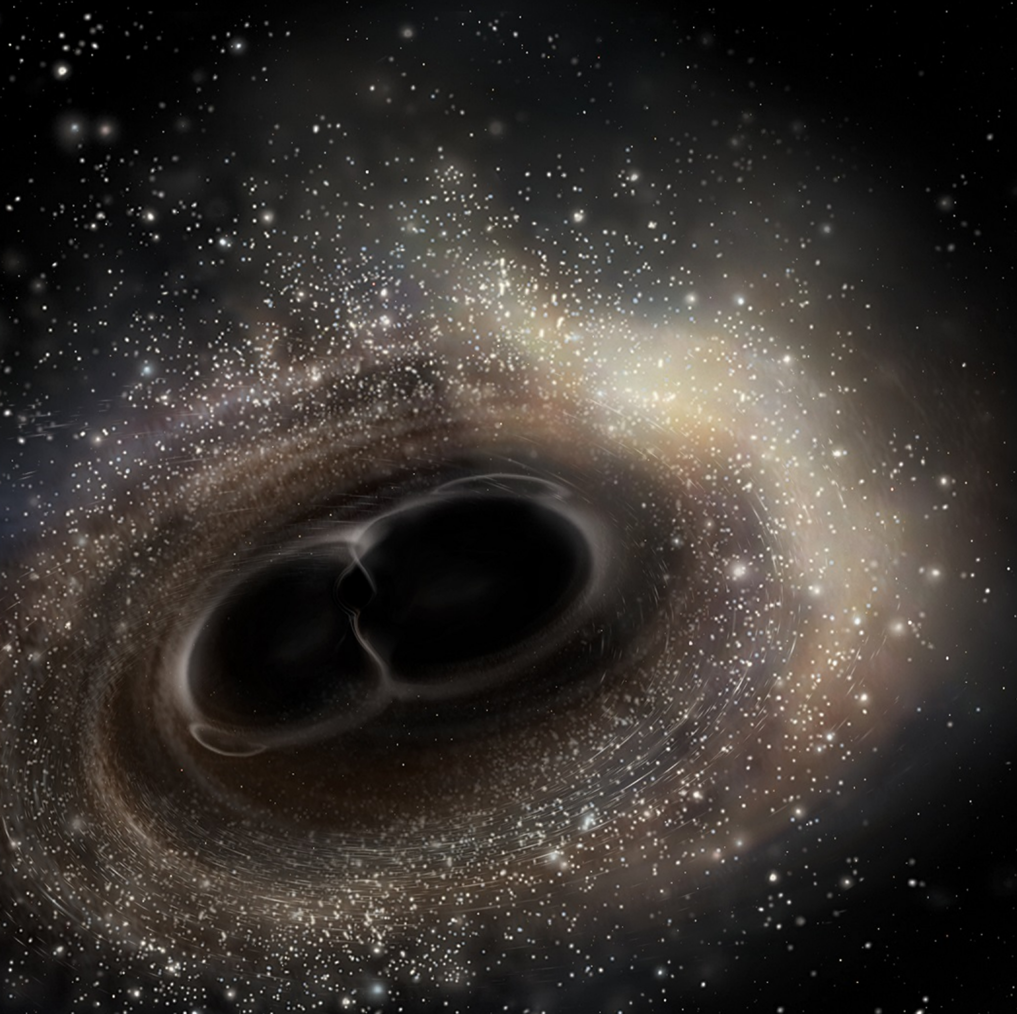
- Detection of Gravitational Waves (tens of cases)
- Progenitors of Gravitational Waves (one + )
- Orbital Motions at the Event Horizon (one)
- Imaging of the Event Horizon (two)
- GR Effects

- common technique: Interferometry
  (optics and missing information problem)

# LIGO 'HEARD' GW



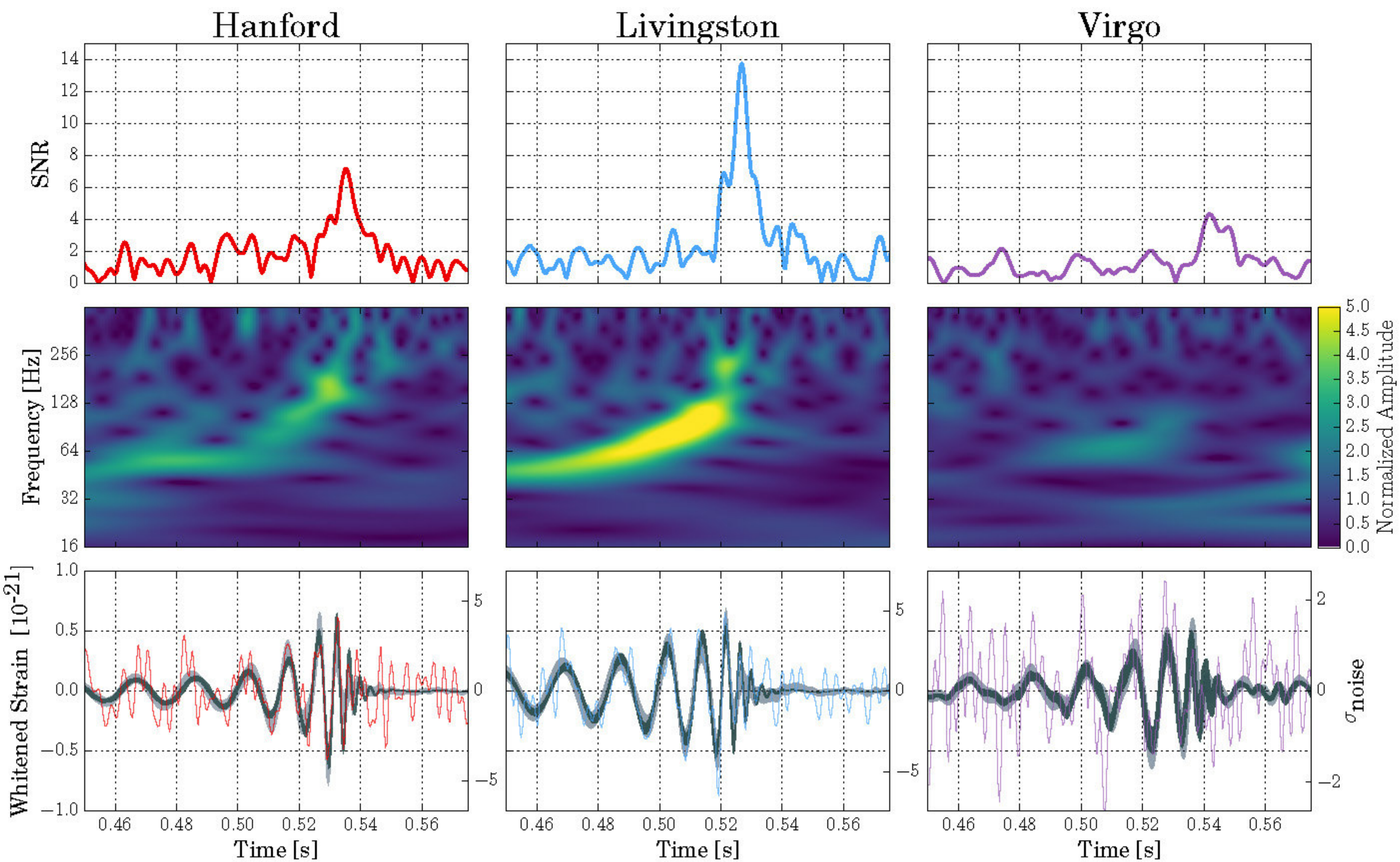
- **The LIGO experiment (another interferometer) was designed to be sensitive to the very ripples in space caused by gravitational disturbances**
- **Like two black holes colliding…**



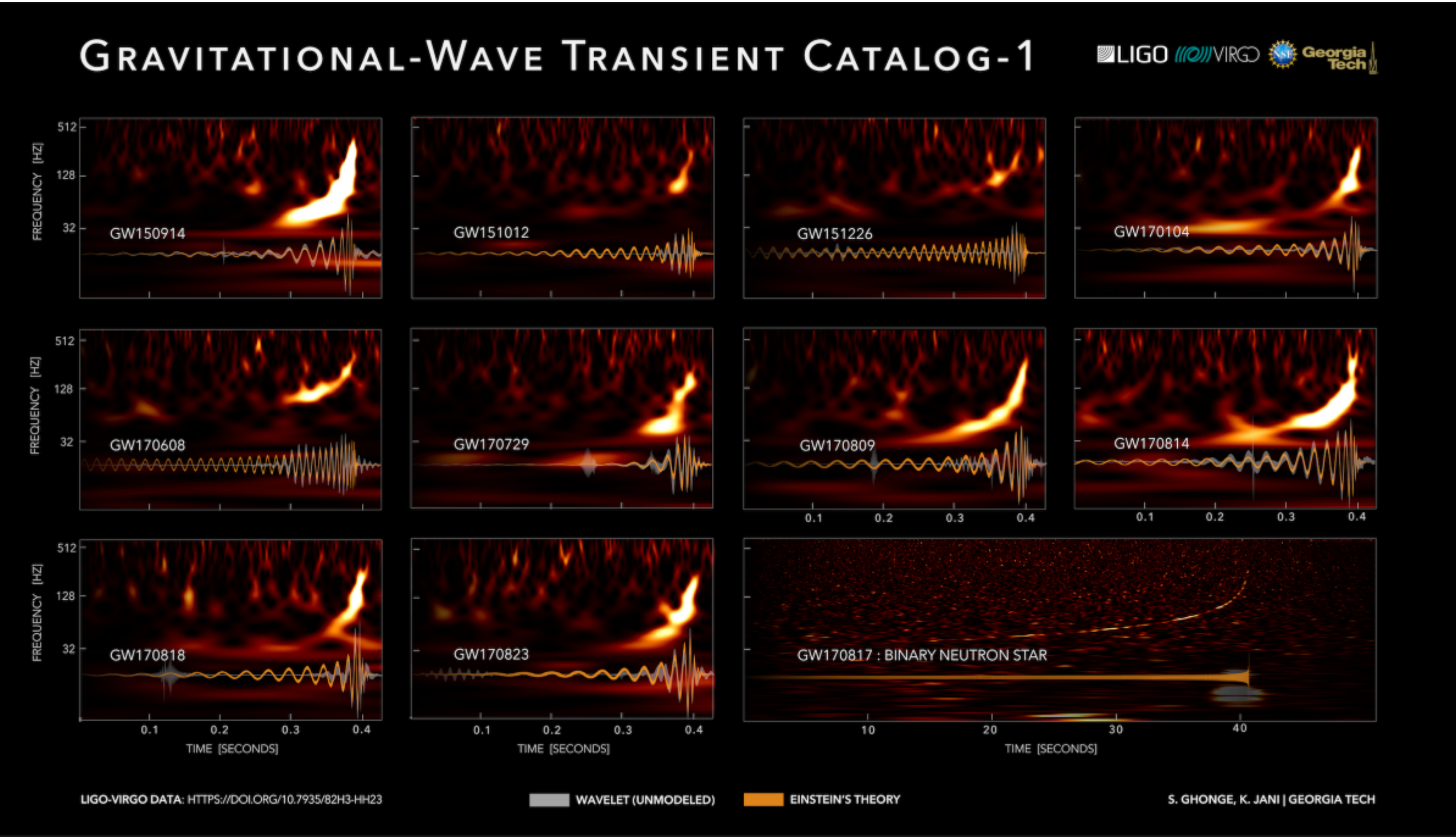
# GW Detectors:  LIGO, VIRGO, KAGRA



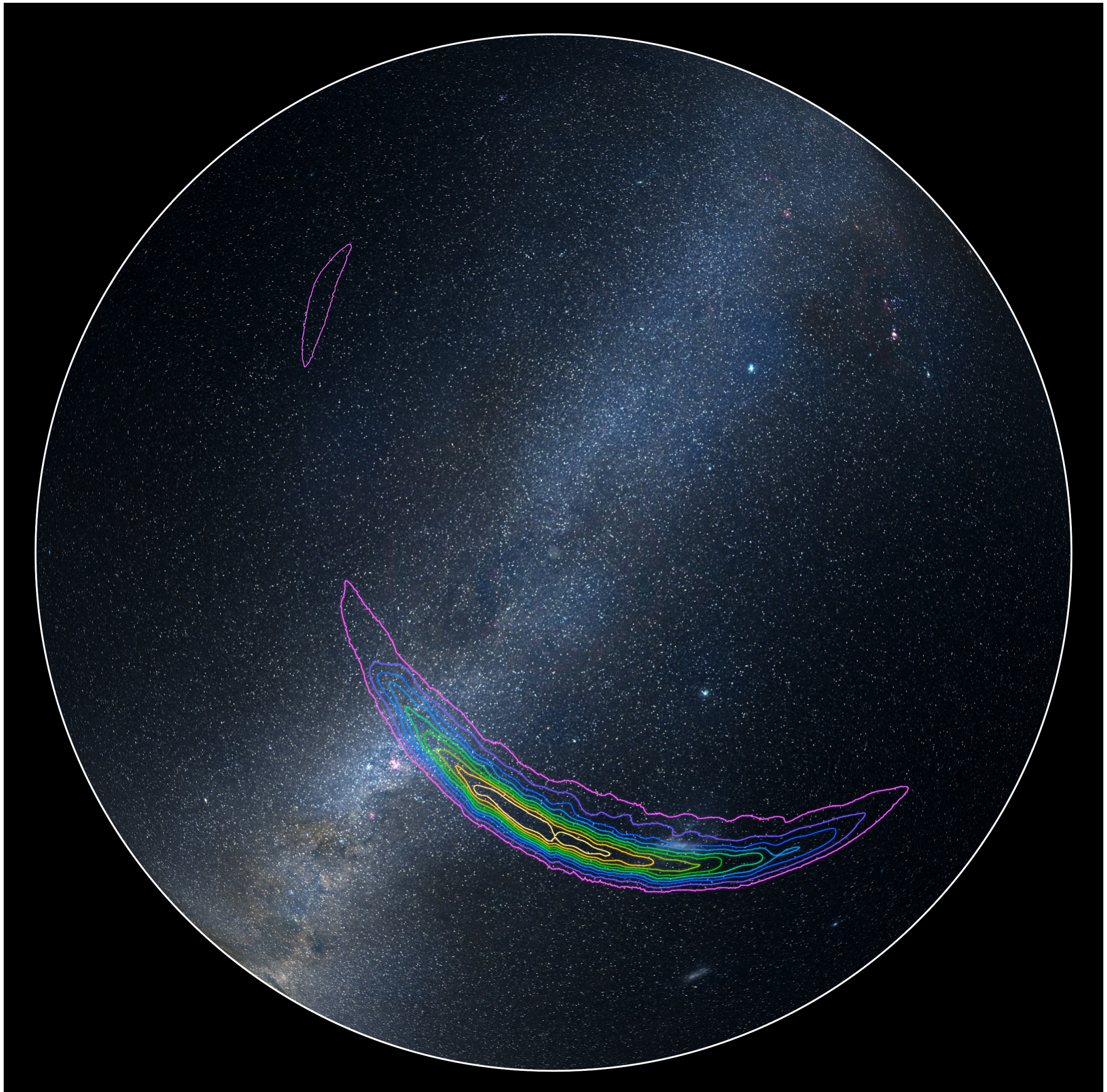

# Signatures of Gravitational Waves



# More Examples



# Where is GW091415: LMC ?



**TIME DELAYS**

**Detection at :**

**LIGO at Livingston**

**followed by 7 x $10^{-3}$ sec**

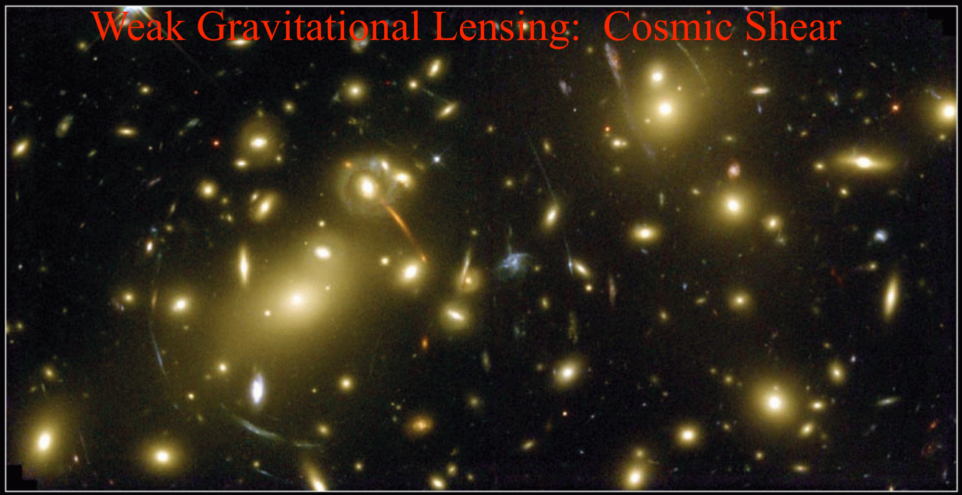
**LIGO at Hanford**

**positioning will improve**

**with VIRGO and KAGRA**

# Subaru Hyper Suprime Cam Project

## Target Dark Matter and Dark Energy




**Galaxy Cluster Abell 2218** **HST** • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

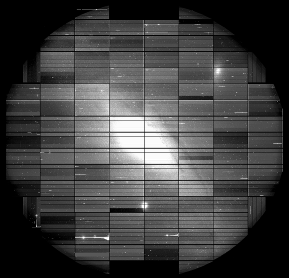
**1.5  degree FOV,   10 x  FOV (Surpime Camera)**

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

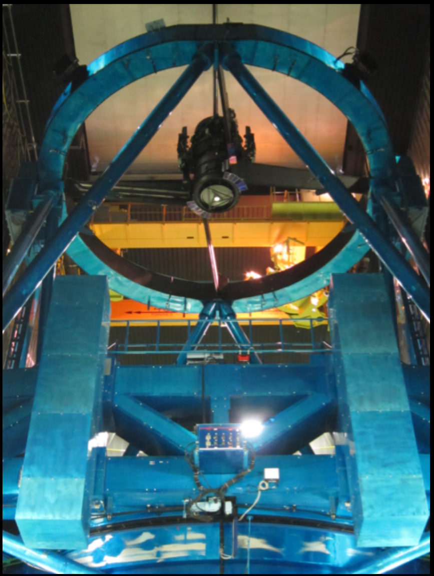
**ASIAA:  Filter Exchanger, CCD and Lens Testing**

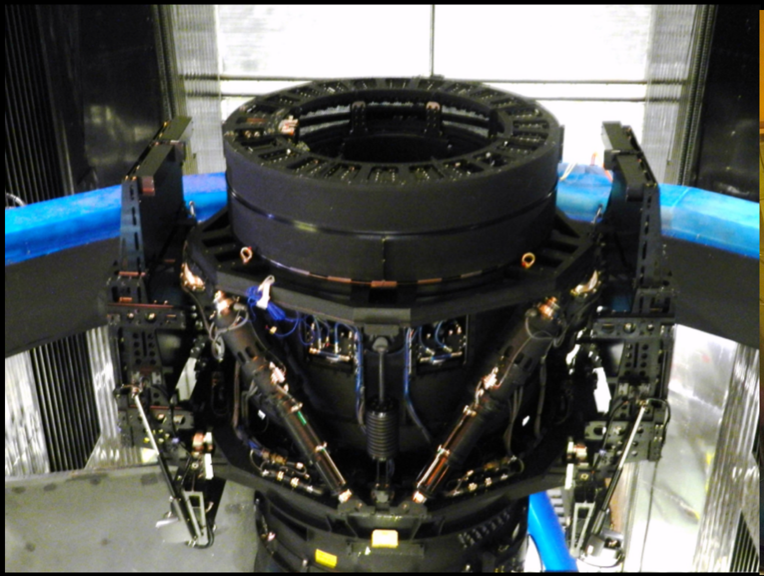
**Weak Lensing Tomography;  z>6**

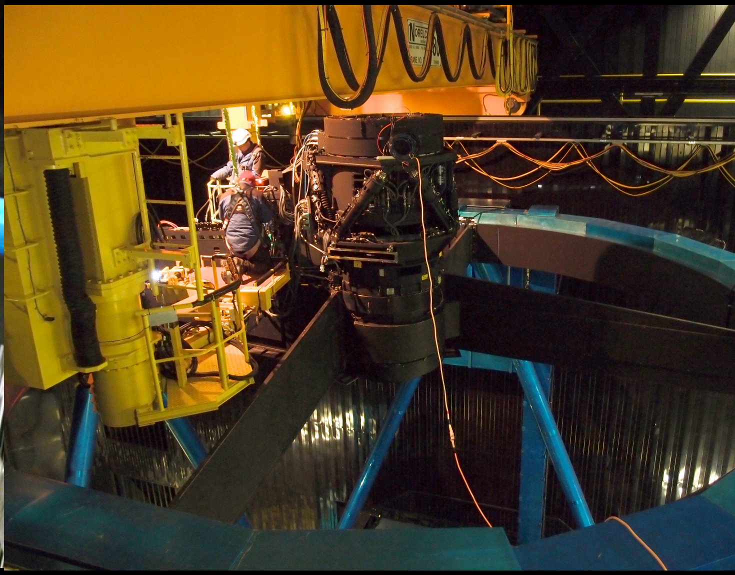
- **ASIAA delivered 2011**
- **HSC on Subaru 02.12**
- **HSC commission 08.12**
- **HSC survey papers 2018**



*raw image of M31*





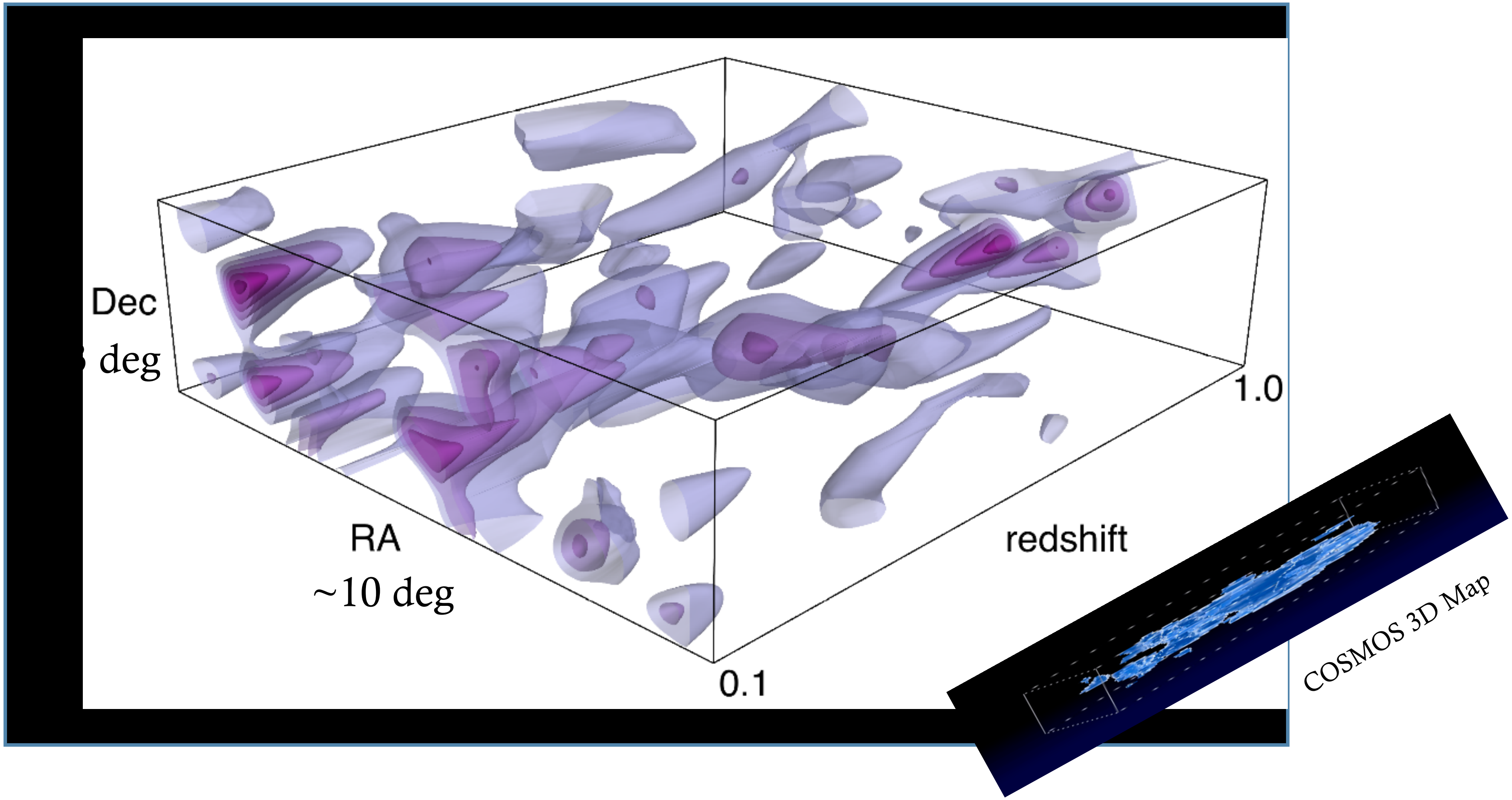


**HSC Integrated on Subaru**

# Widest 3D dark matter map ever

Miyazaki et al. 2018

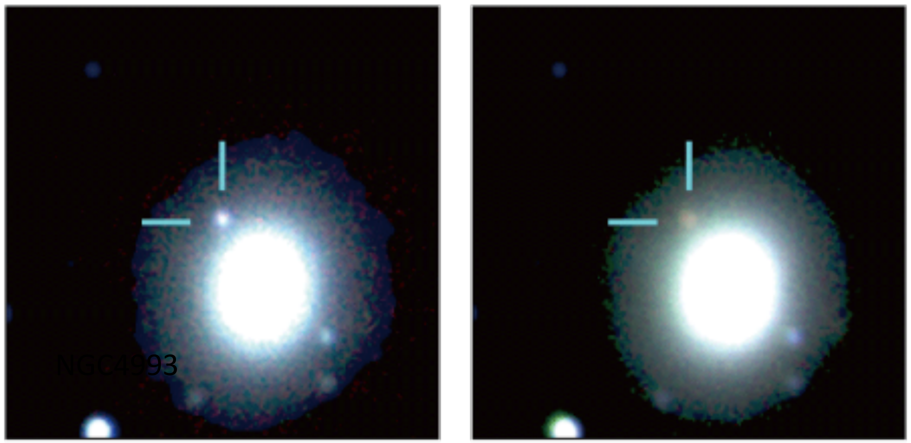
Growth of the structure clearly visible for the first time.



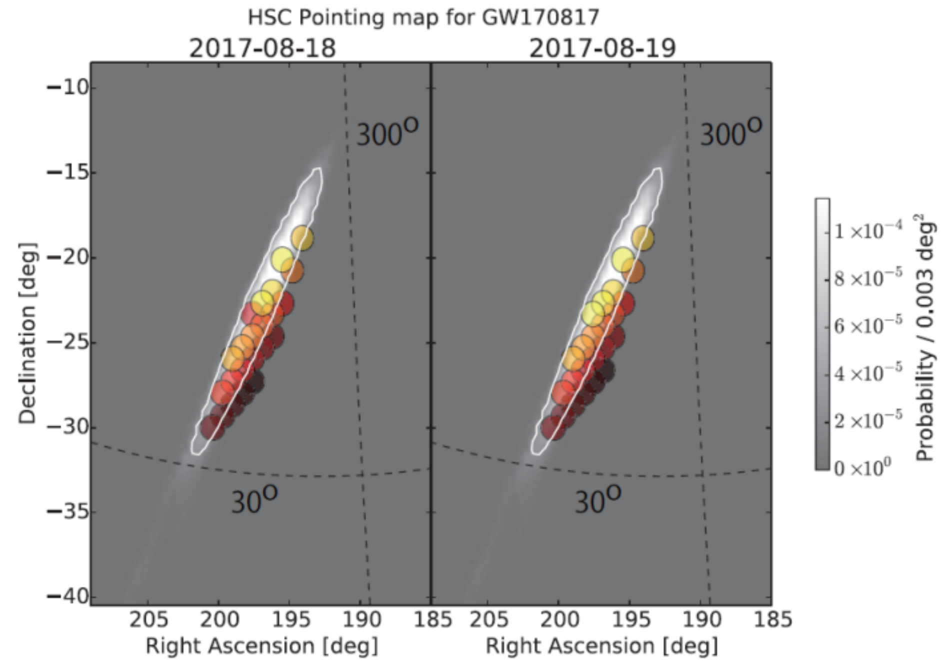

Only Subaru can create this, for now.

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

2017.08.18-19 2017.08.24-25




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



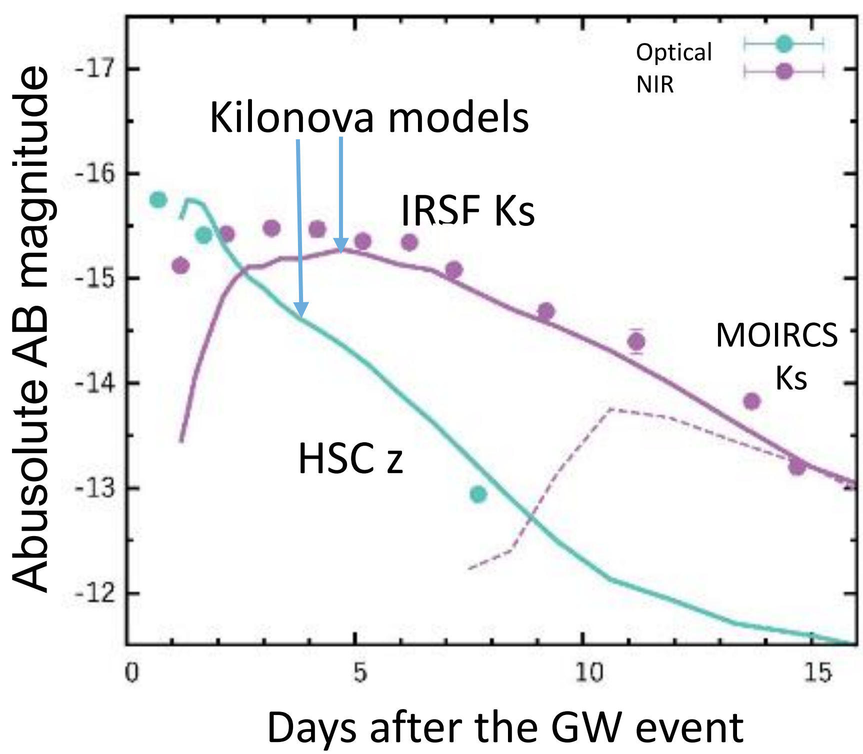

Subaru HSC & MOIRCS succeeded to get the optical – near-infrared light from a binary neutron star merger event GW170817.

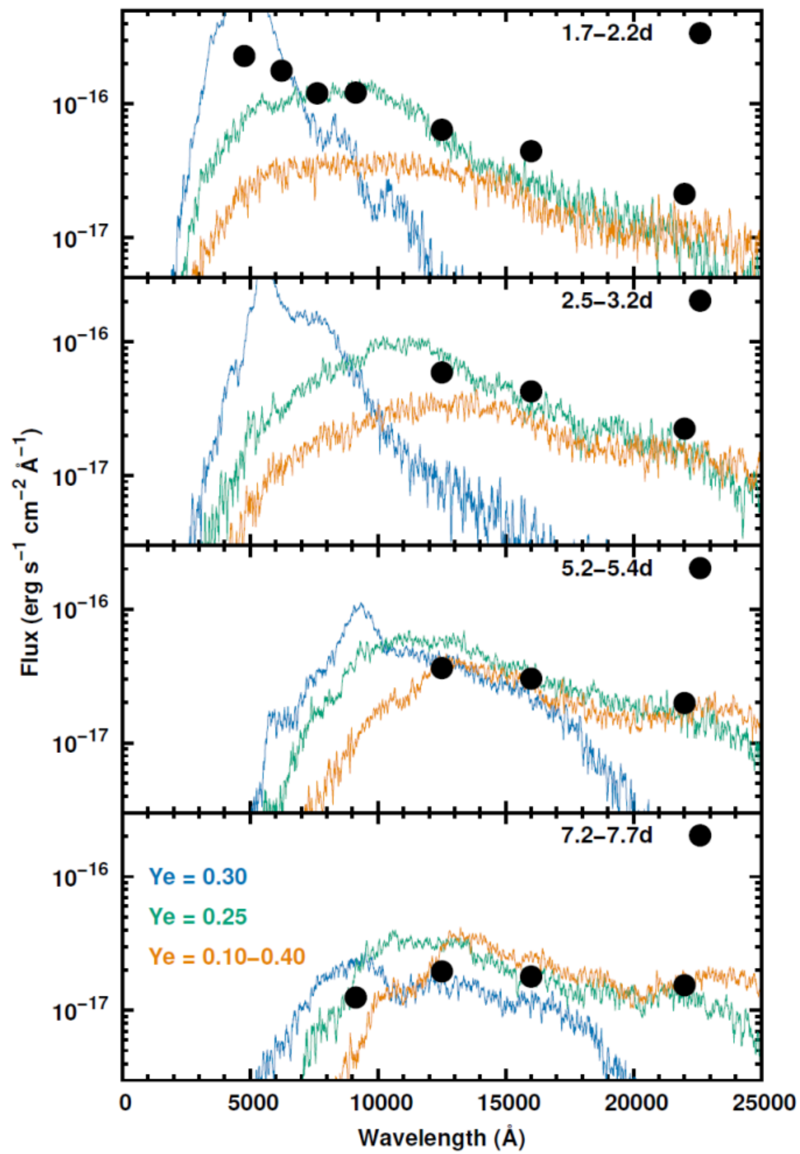
Ustumi et al. 2017

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

# Kilonova models and the OT of GW170817



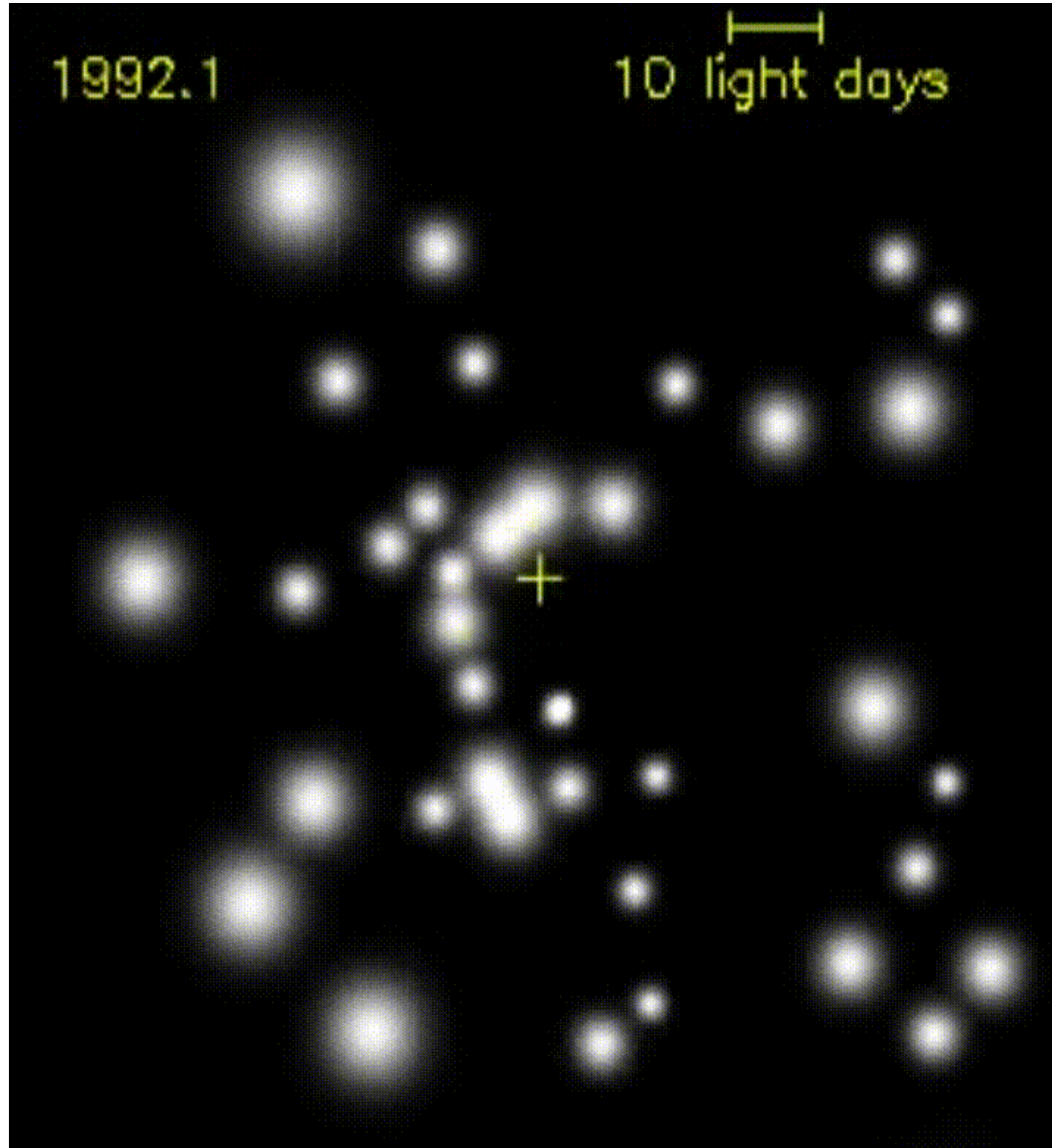

The optical – NIR light curves and SED variation are well reproduced by the kilonova models ➔ The site of the cosmic *r*-process was observationally identified!

# Future GW Research

- **Expanded Sensitivity and New Instruments (Einstein Telescope, Cosmic Explorer, LISA)**
- **Many more detections, plus SMBHBs?**
- **Inspiral phase and post merger phase**
- **Theoretical Tests for GR effects**

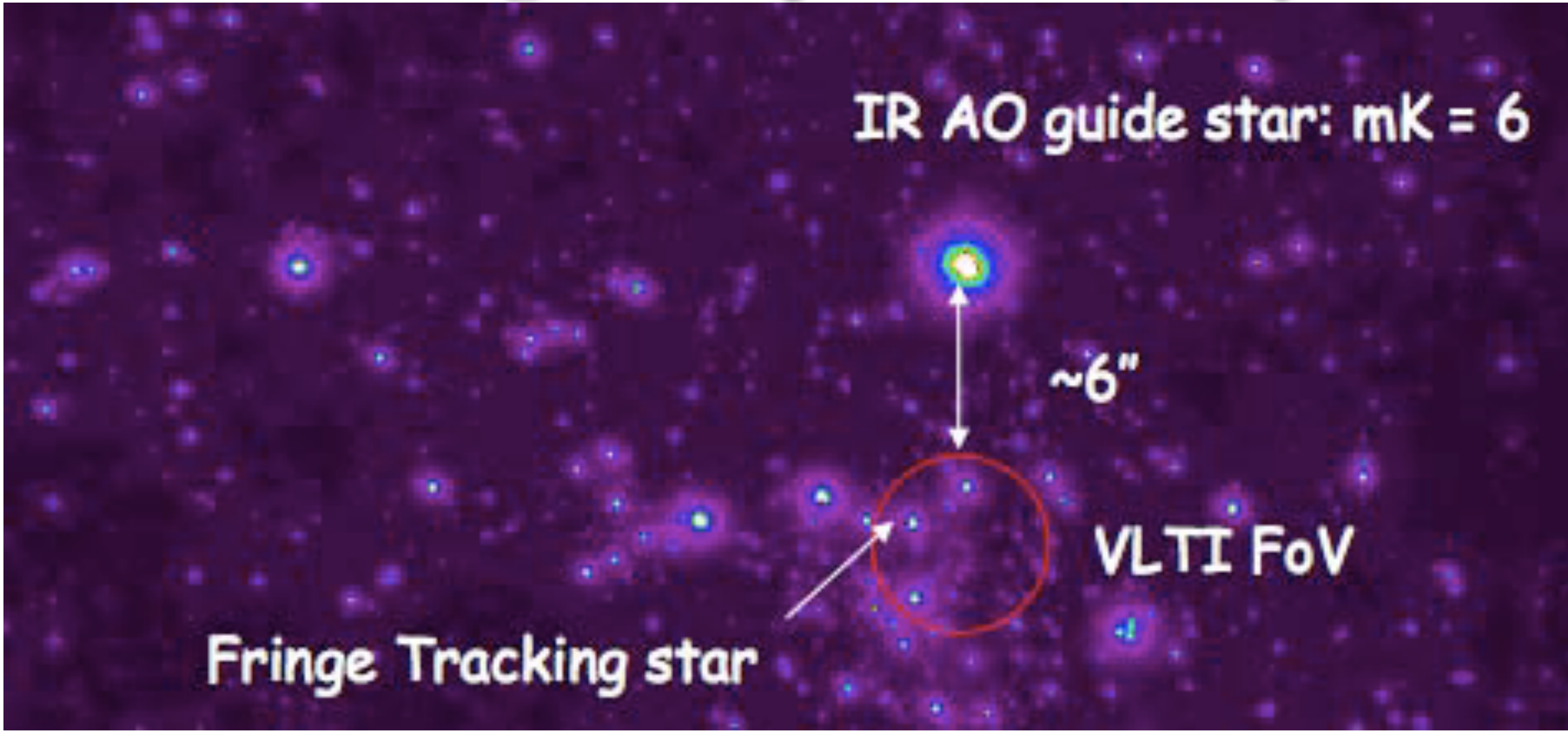
# GRAVITY can be "FELT"

- 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)

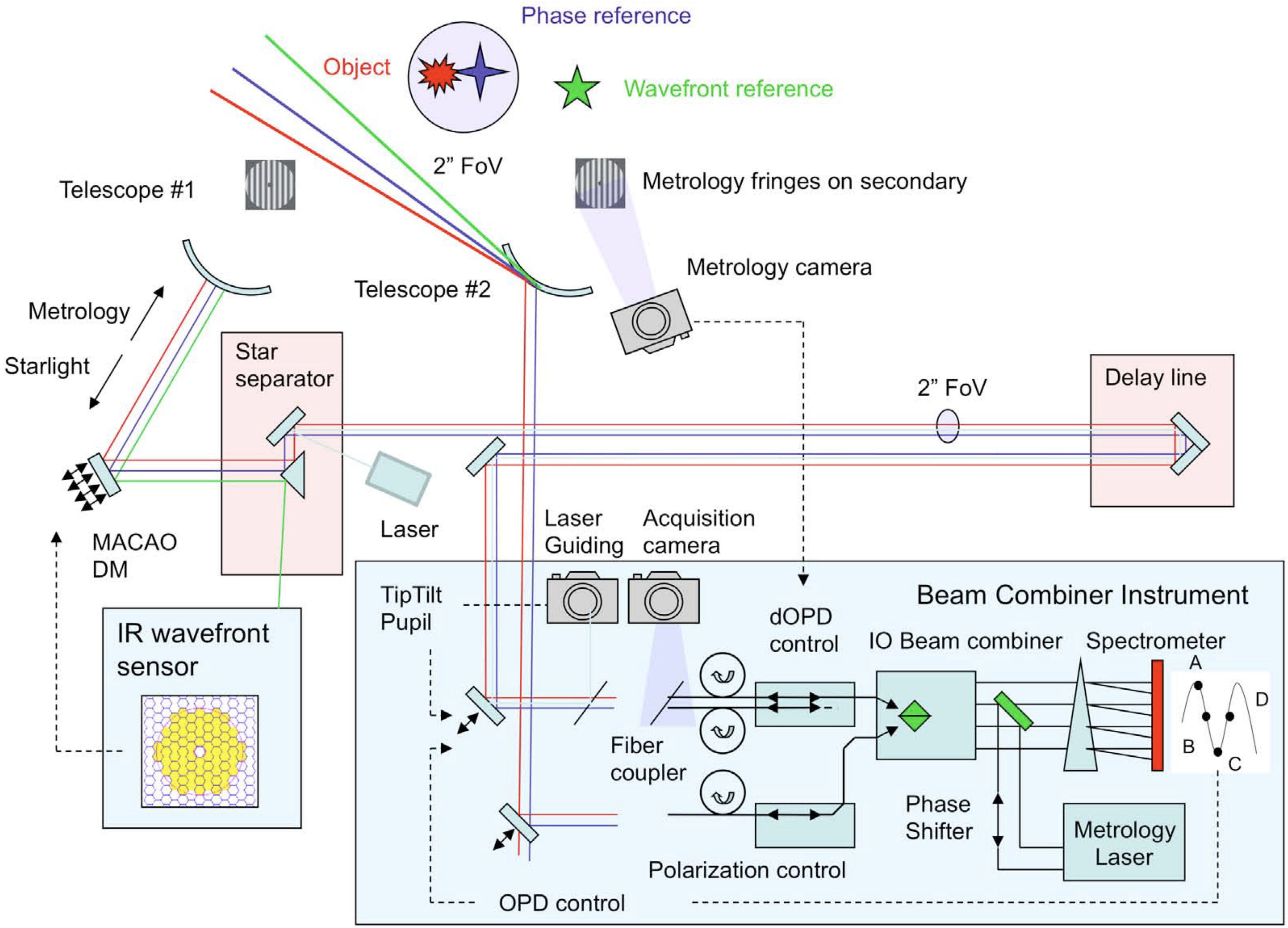



ESO VLTI

# Working Principle of "Gravity"



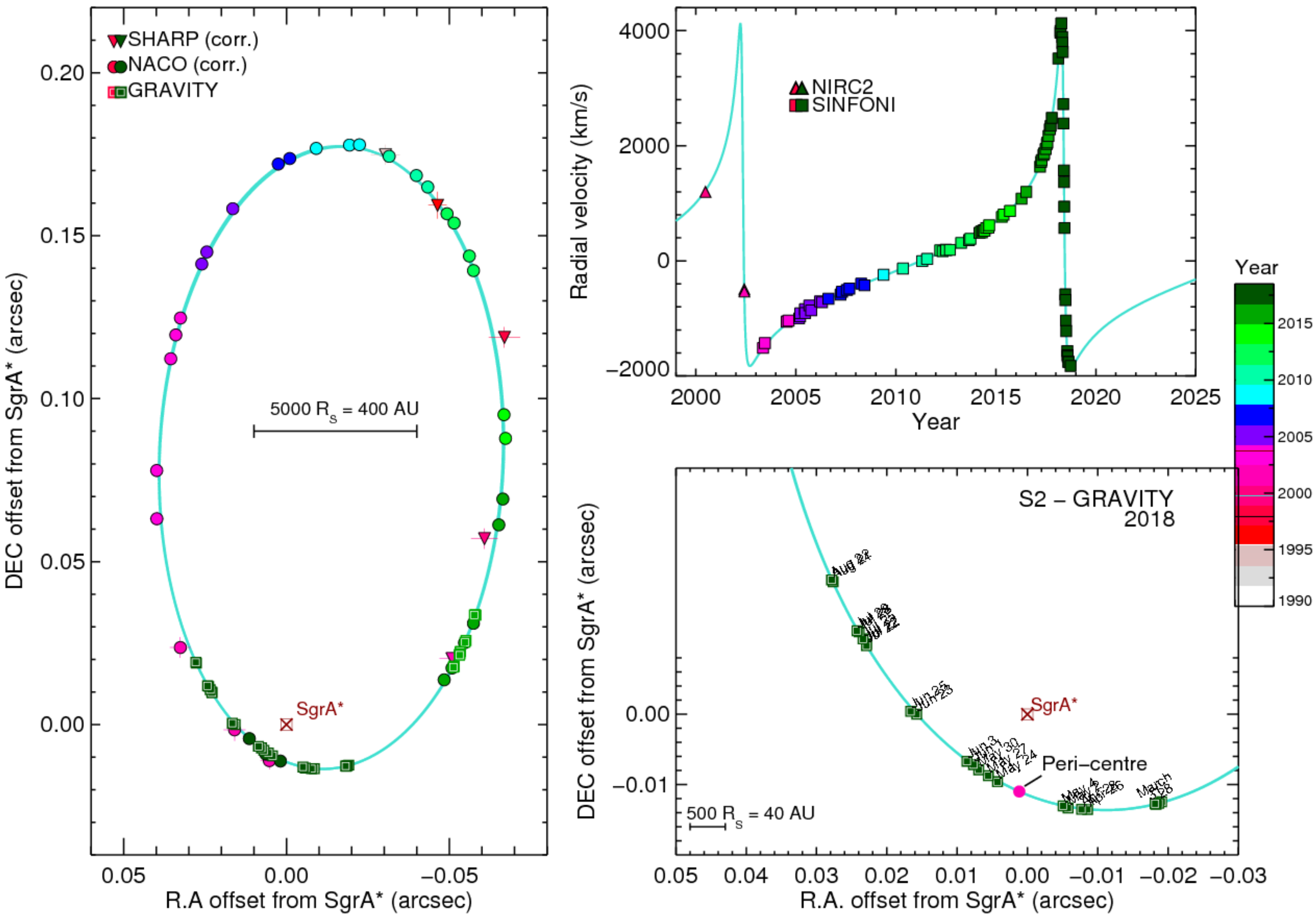

- **Guide Star for Adaptive Optics (atmospheric seeing)**
- **Fringe Tracking Star for Phase (interferometer baselines)**
- **VLTI for Interferometry (high angular resolution)**
- **6 baselines; 3 x $10^{-3}$ ″ resolution; ~40 x $10^{-6}$ ″ astrometry**



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

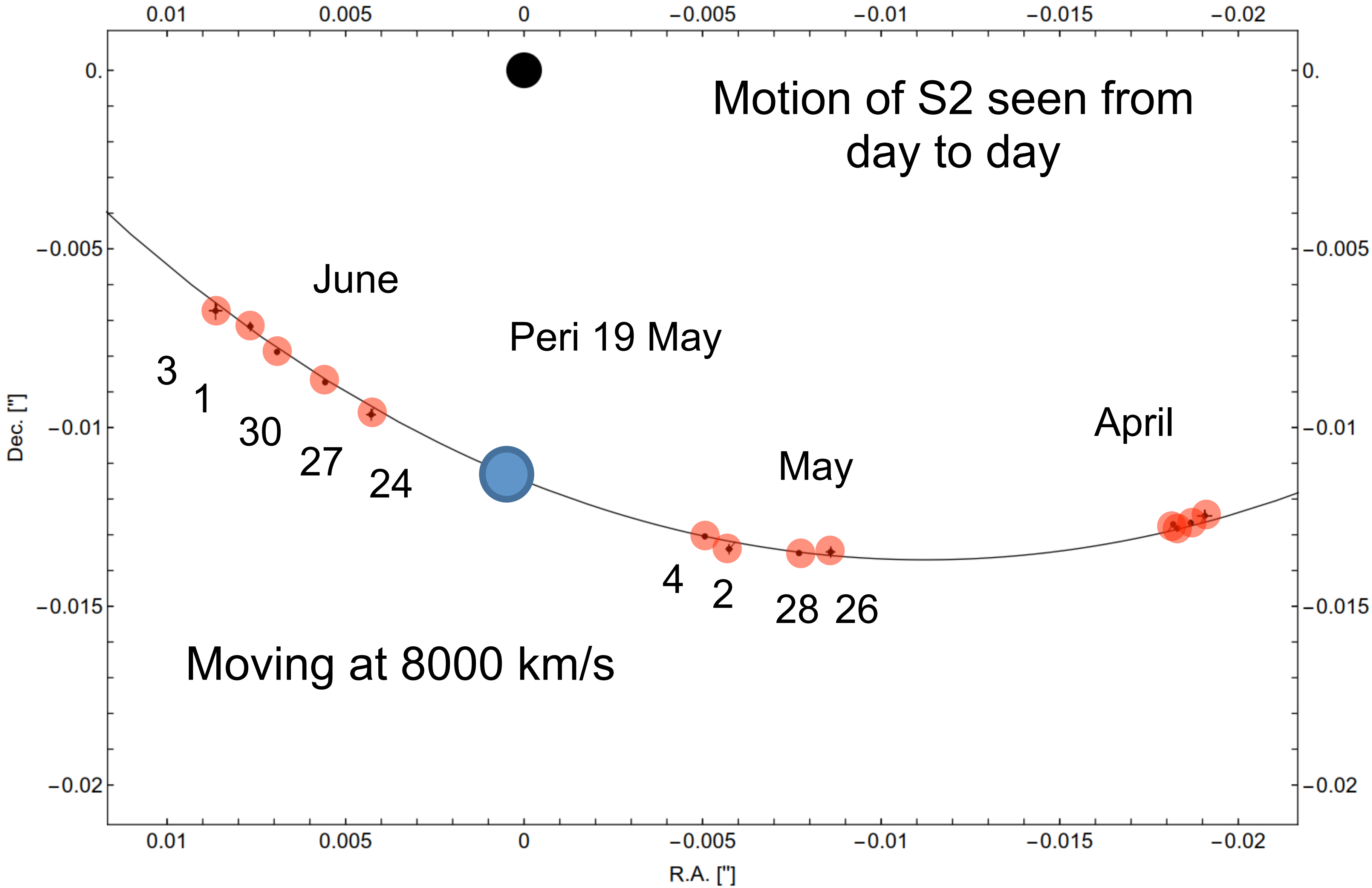
# Stars in Orbit around SgrA*

## 26 years of observations of S2

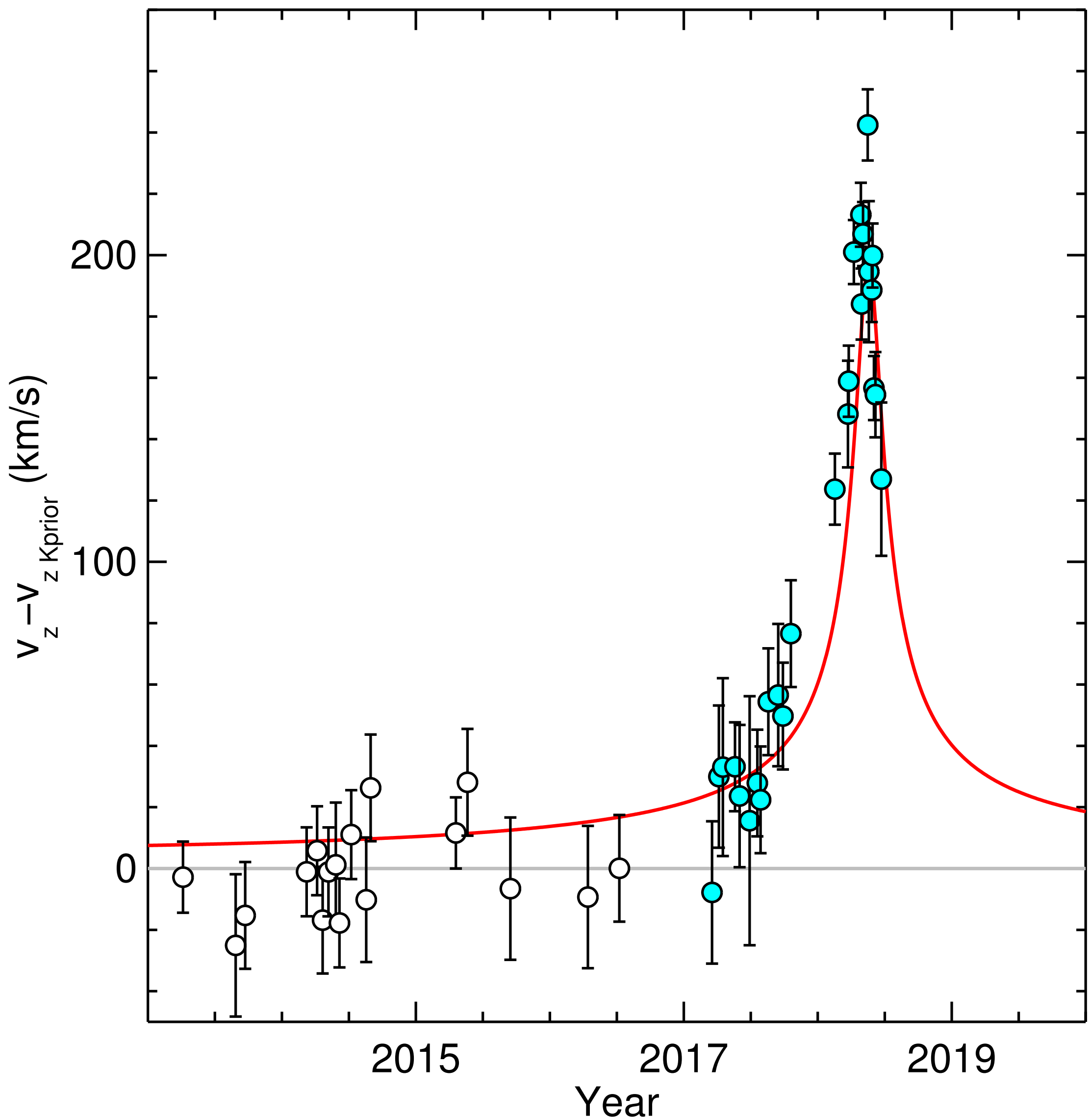


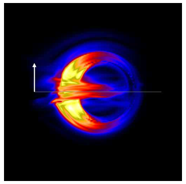

GRAVITY collaboration+18a, A&A 615, L10

# Orbit of S2 relative to SgrA*



# Motion of S2 shows GR Redshift

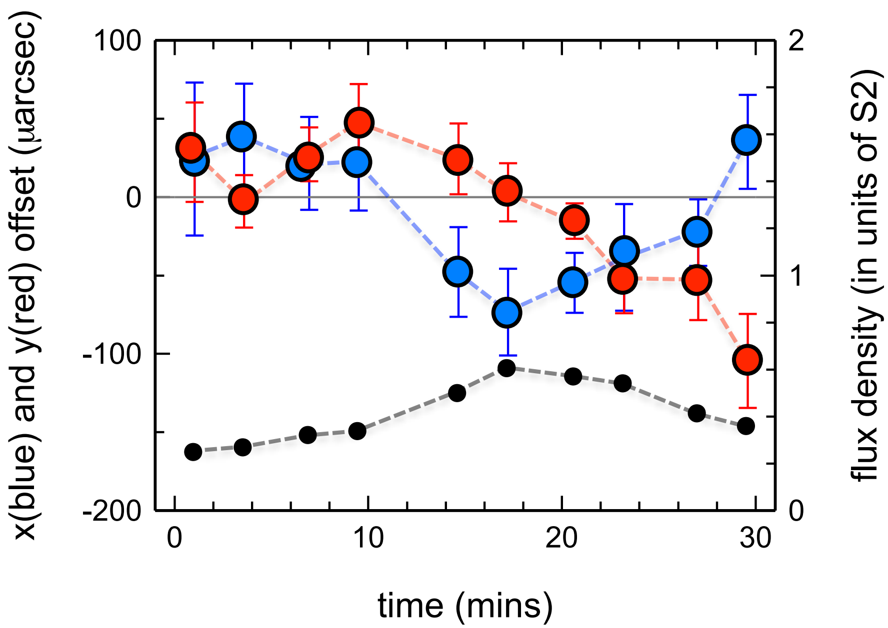


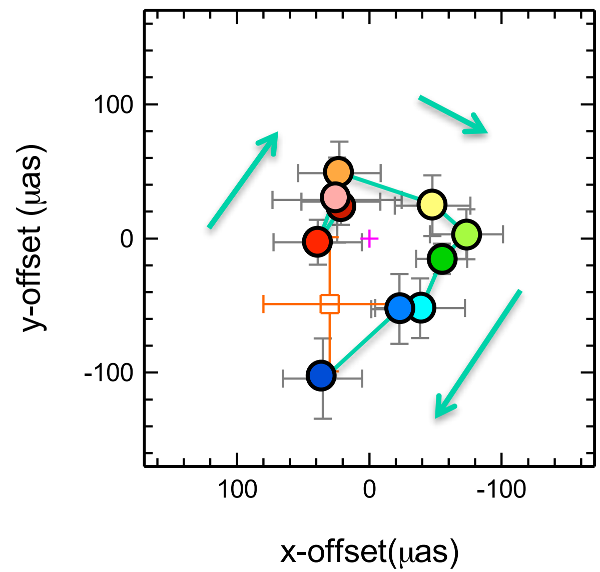


# Hot SPOT in ORBIT at ISCO

## Detection of orbital motions near SgrA*s ISCO

**July 22nd, 2018**




**$v_{orb}$~0.3 c**

Broderick & Loeb 2006,
Hamaus et al. 2009

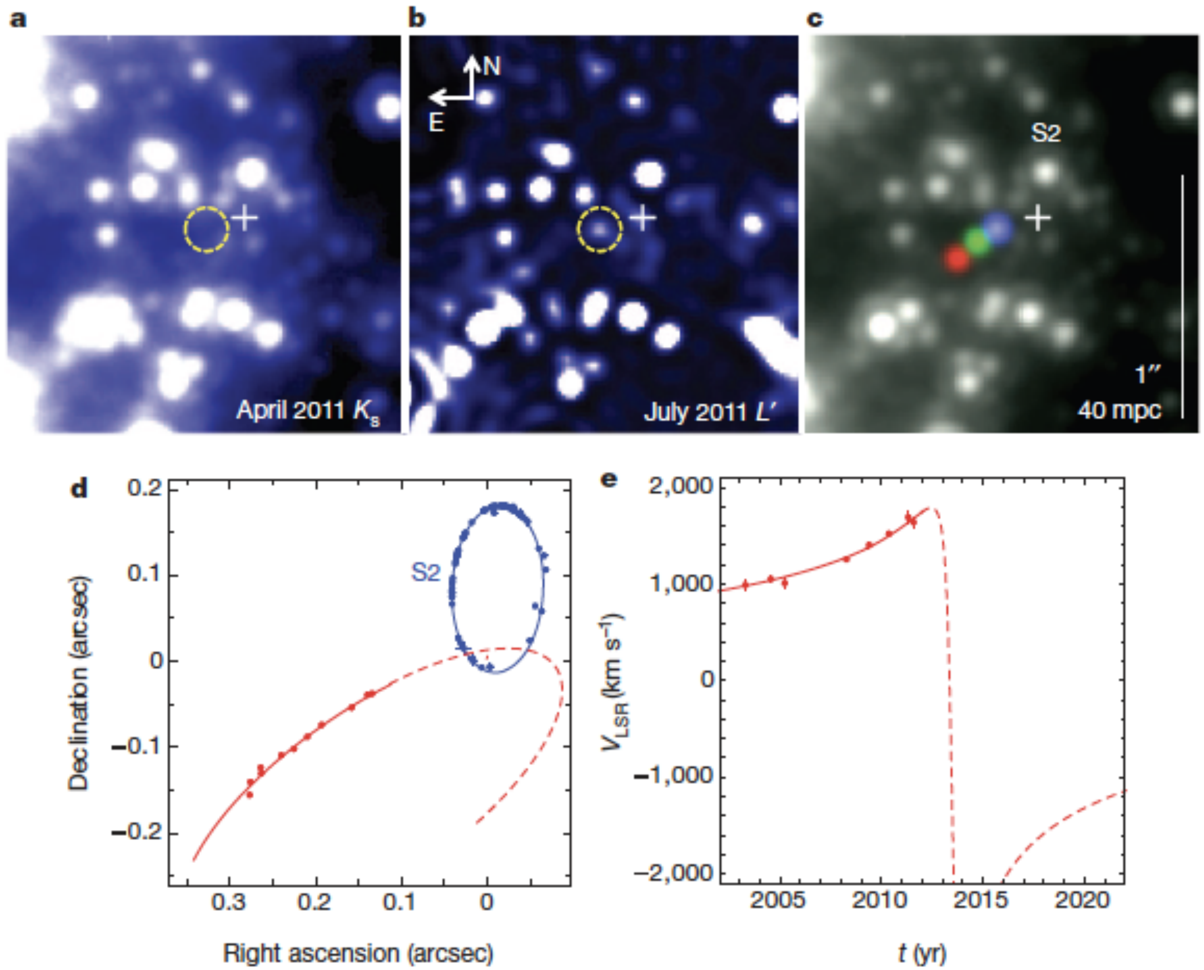
*GRAVITY collaboration 2018b, A&A 618, L10*

# Future Research of ISCO

- **Next Generation ISCO experiments**
- **extremely large telescope projects such as TMT, ELT, GMT, can provide better precision**
- **more accurate measurements of orbits**
- **fainter targets for orbital tests**
- **gas infall events detectable**

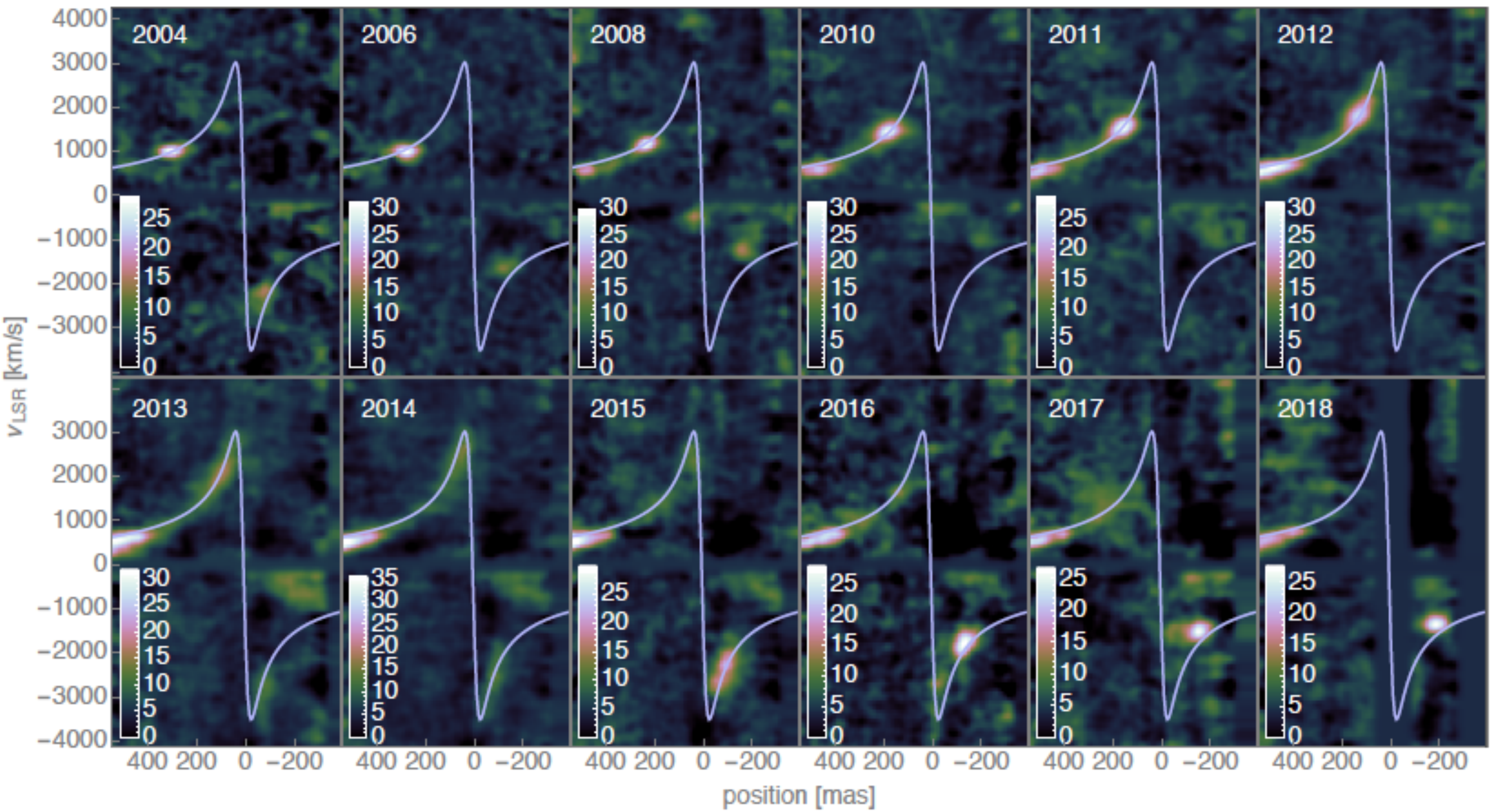
# Ionized Gas Gloud G2 near SgrA*

**2.2μm** **3.8μm** **3.8μm over 7 yrs**




**G2 orbit in Red approaching SgrA*** Gillenssen et al. 2012

# Ionized Gas Gloud G2 near SgrA* Position-Velocity Diagrams




Br-γ and He-I 2μm lines

Gillessen et al. 2019: SINFONI

# Gas Inflow to SgrA*

- G2 does not hit SgrA*
- G2 traverses some ISM which provides drag
- G2 is not a singular event,  has another clump following
- Where does G2 come from?

- We pull back to look at the surrounding ISM

# GRAVITY can be "SEEN" ?
# 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

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

- **Target Supermassive Black Hole**
- **Nearest Examples (SgrA*, M87)**

  **(Shadow: ~5$R_{sch}$ ~40 x $10^{-6}$ ″)**
- **Very Long Baseline Interferometry at Submm Wavelength**

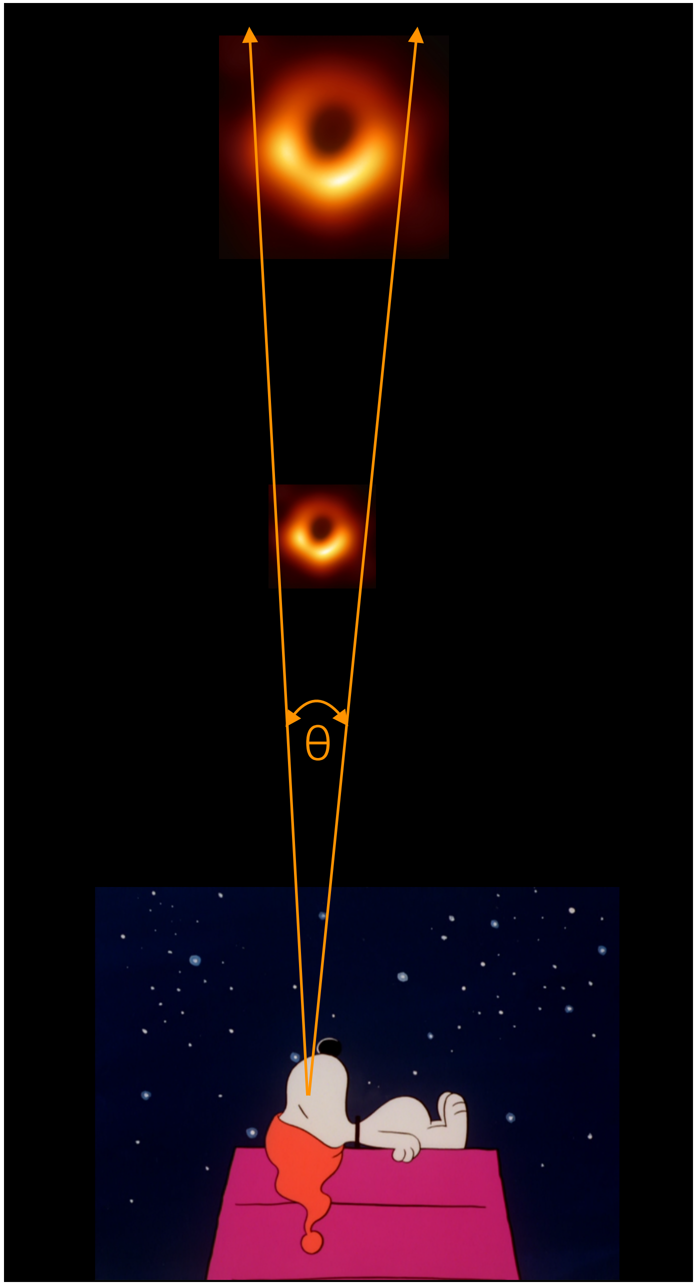
**Precision ~ $10^{-10}$**

# Problem is Size

- **The problem is nearby black holes are too small, and supermassive black holes are too far. Existing telescopes cannot resolve them.**
- **Two cases that look biggest to us would be at the center of our galaxy…** ***and one in M87 - 1000 times further away, but also 1000 times bigger.***
- **The expected shadow around the black hole is just 50 µas**
- **We Need a telescope the size of the earth:**

$$\theta_{array} = \lambda/D = 1.3\text{mm}/11000\text{ km} \sim 20\ \mu\text{as}$$

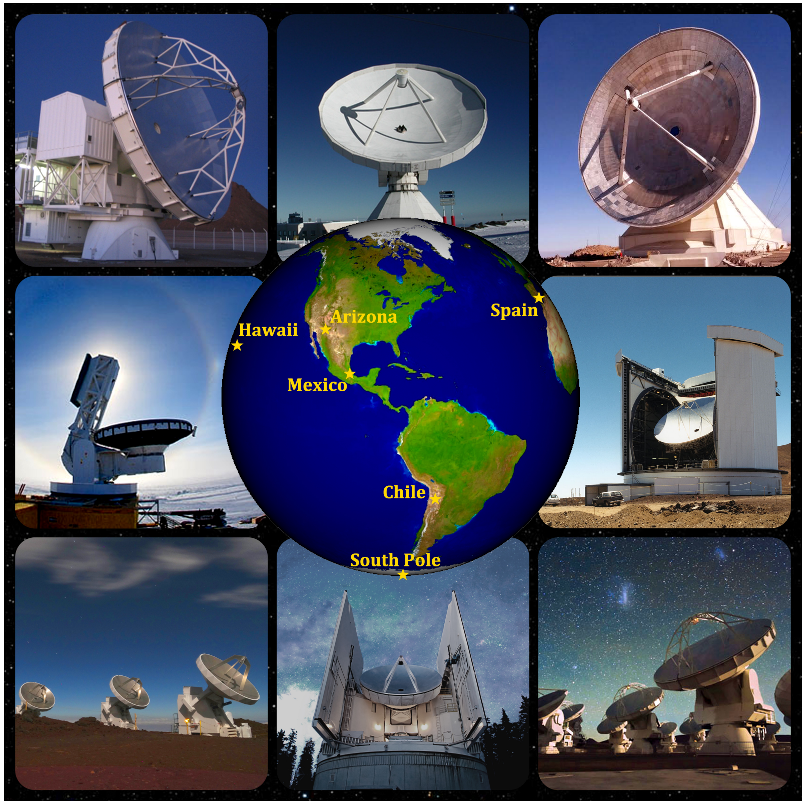
**DIFFRACTION PROBLEM**



Event Horizon Telescope

# JCMT is an EAO Initiative

- **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

# East Asian Observatory

- History of Development: Established 2014
- Model: Asian Counterpart to ESO
- EAO Members: NAOC, NAOJ, KASI, ASIAA
- Goals and Aspirations: Looking to the Future
- Current Status: Operating JCMT, Access SMA, Access UKIRT
- Current Plans: Access more Facilities (Subaru), Construct Next Generation Instruments
- Future Plans: Expand EAO Members

  (Observer: Vietnam, Thailand, Malaysia, Indonesia )

  other Southeast Asian regions and India ?

  Observer Status: Access EAO Facilities

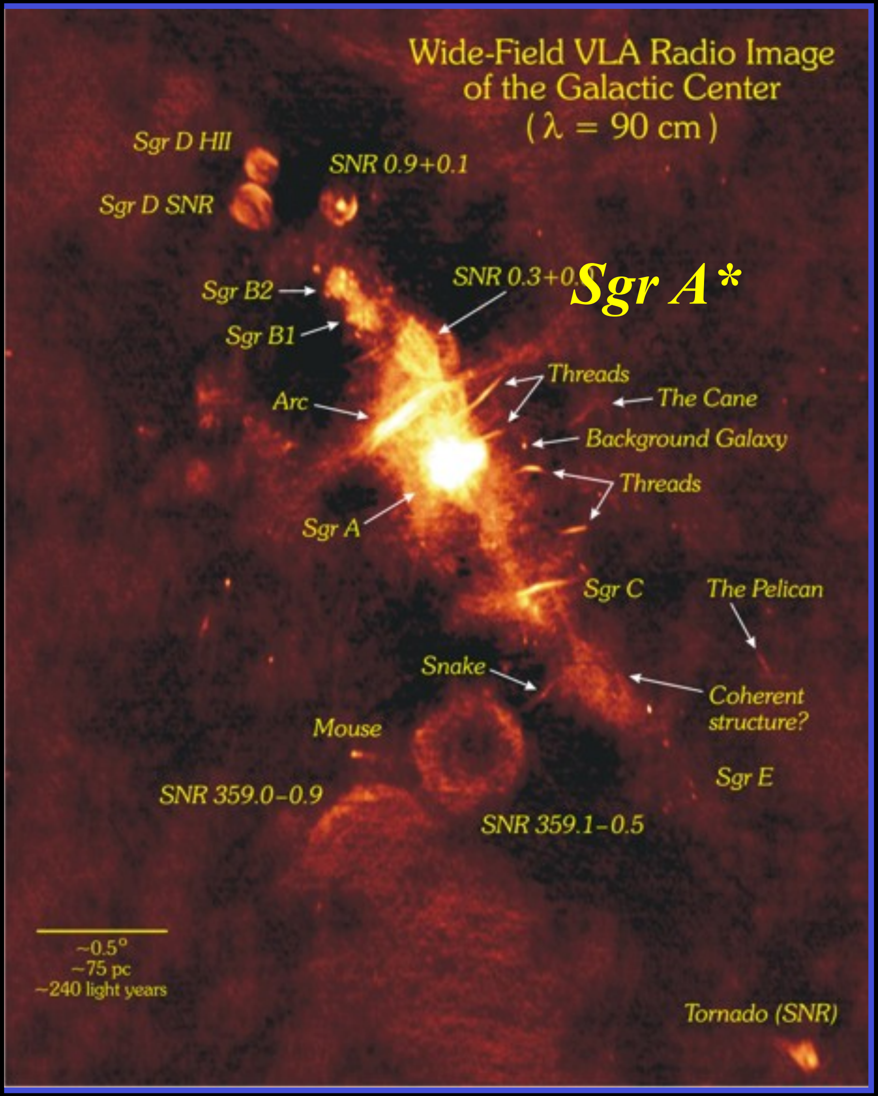
  Thailand will soon become Partner in EAO

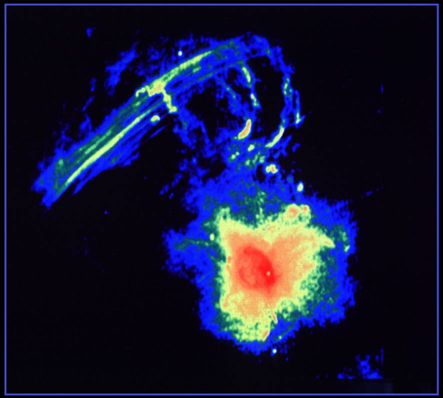
# Very Long Baseline Interferometer

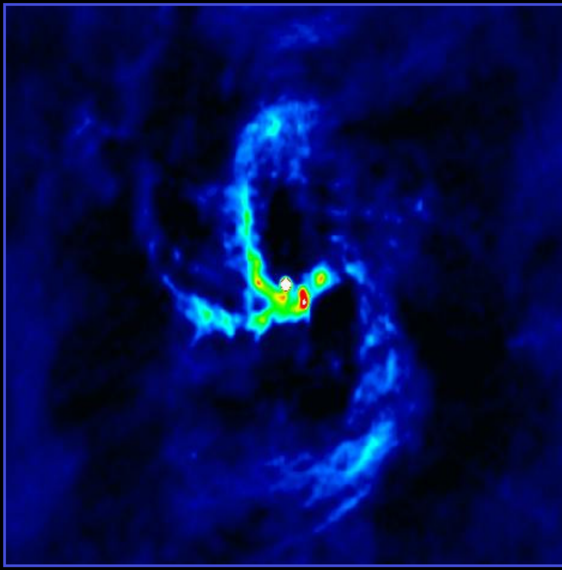
- Simulate a Very Large Telescope (Intercontinental Distance)
- Link Telescopes by synchronizing Wave Front
- Precision at 1/20 wavelength (40μm), over ~10,000 km
  - — distance between telescopes
  - — arrival of wavefront at each telescope
  - — compensate for differential atmospheric effects
  - —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

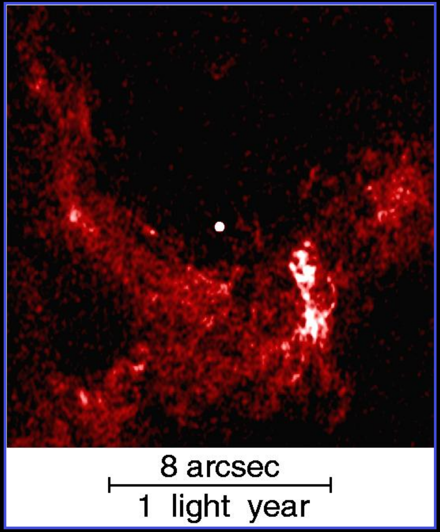
- VLBI is one of Nobel Prizes in Radio Astronomy
  (Ryle and Hewish 1974) — <u>IMAGE RECONSTRUCTION</u>

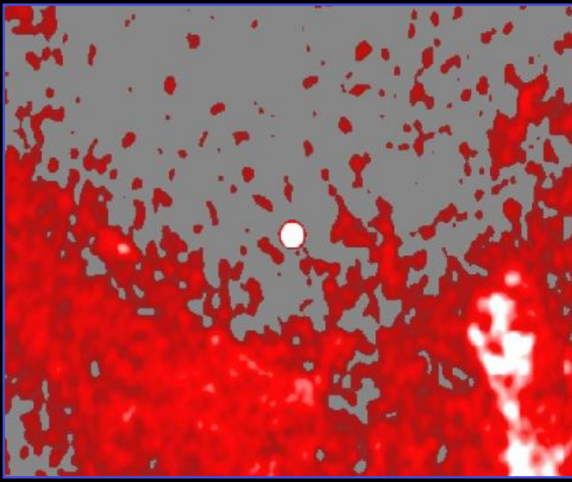
# Center of the Galaxy (radio)



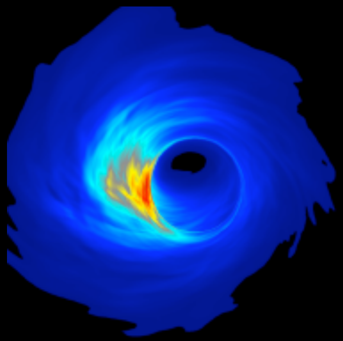



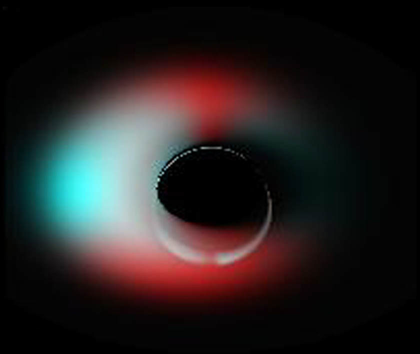


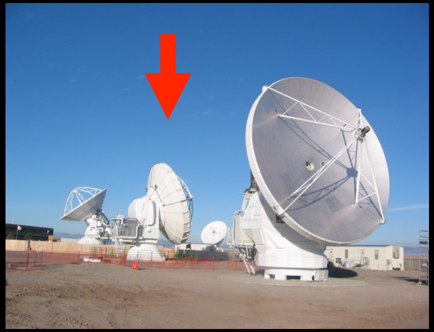


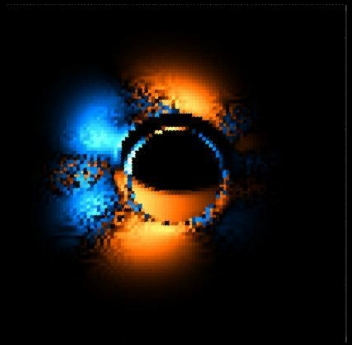



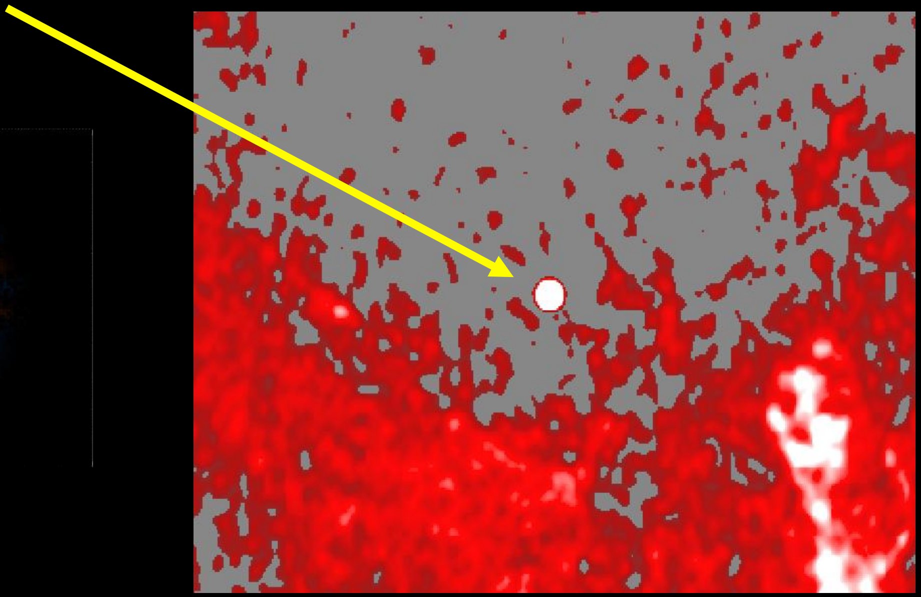
# VLBI (2014): Imaging SgrA*



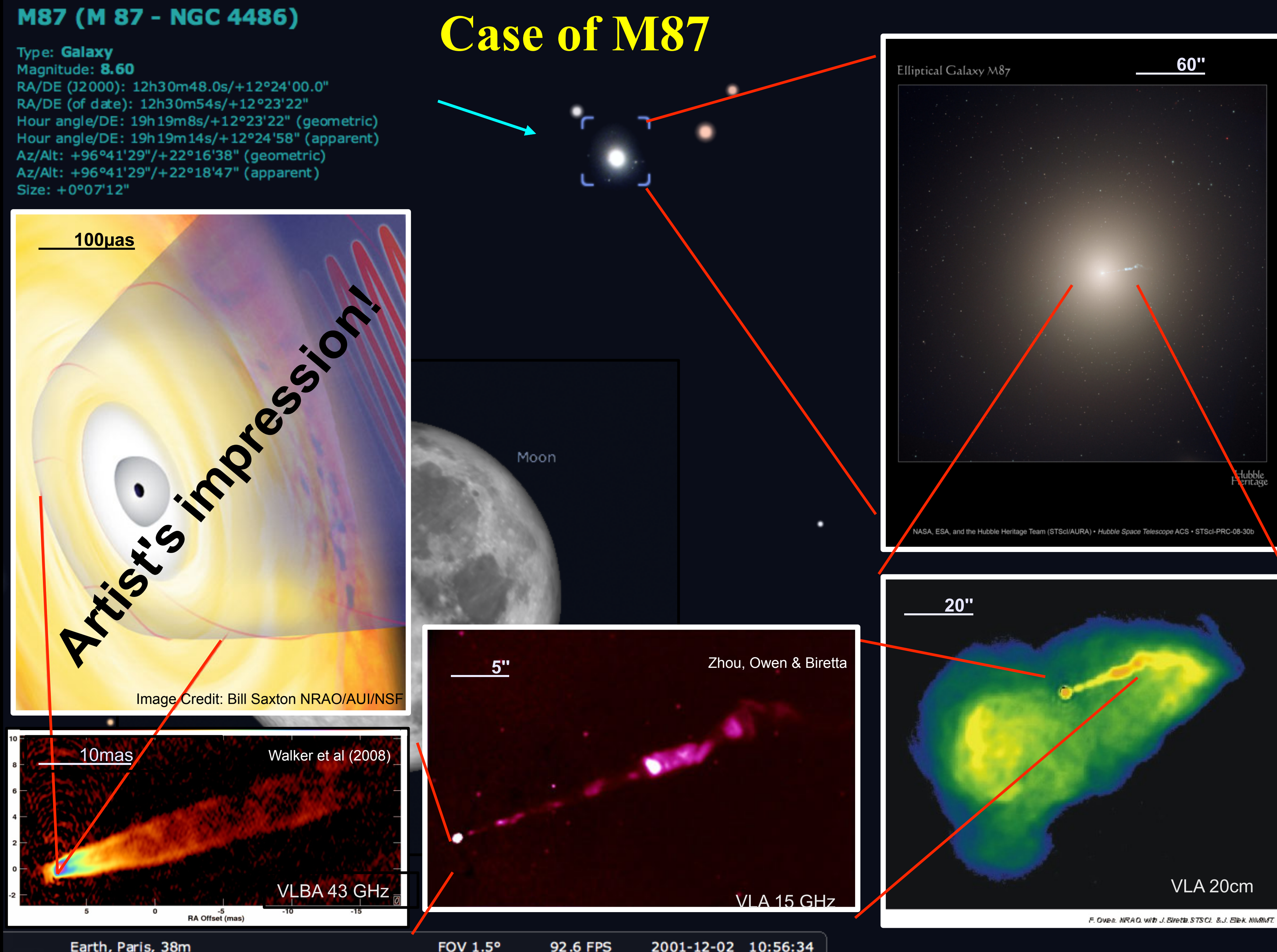




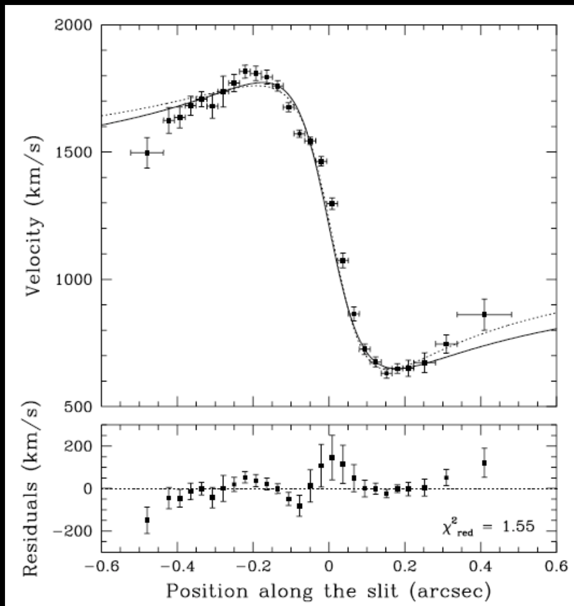


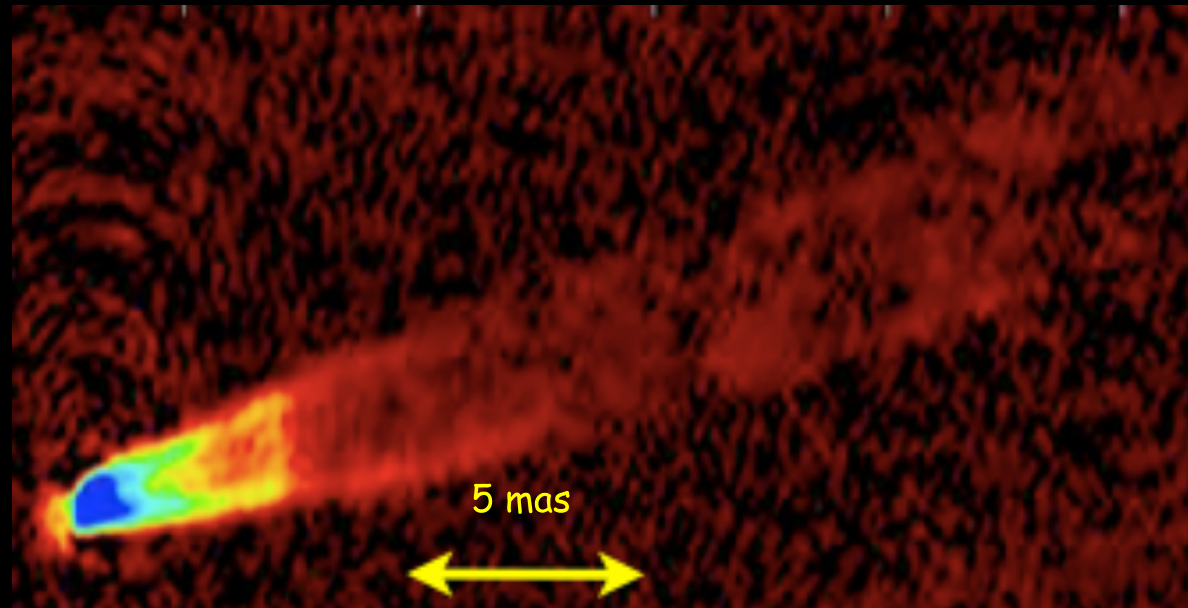


# Case of M87


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"
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
Moon
20"
VLA 20cm
F. Owen, NRAO, with J. Biretta, STScI, & J. Eilek, NMIMT
5"
Zhou, Owen & Biretta
VLA 15 GHz
10mas
Walker et al (2008)
VLBA 43 GHz
RA Offset (mas)
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**

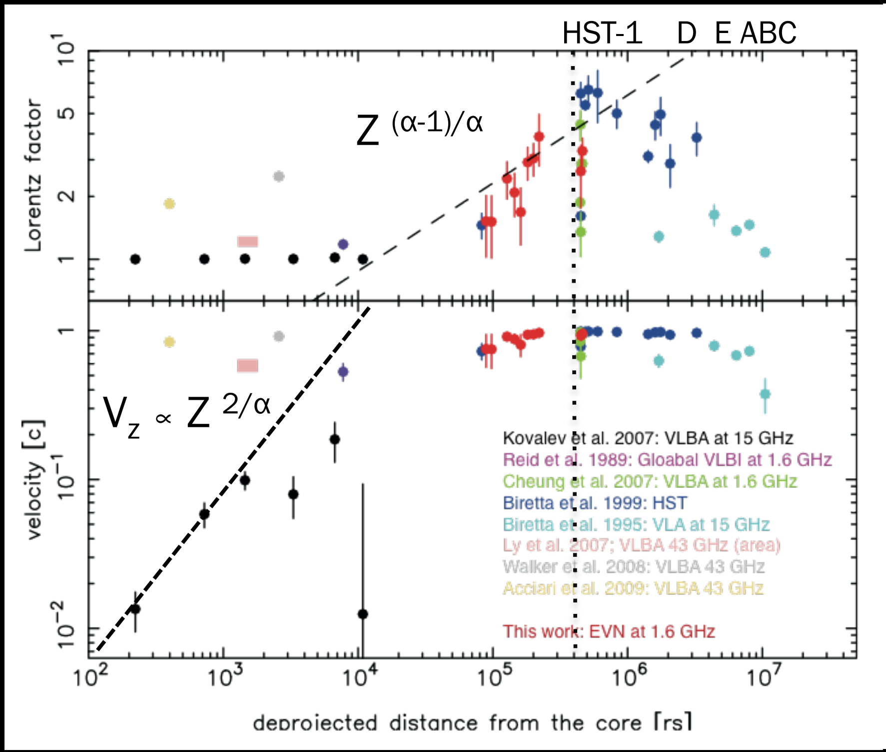
**Accretion Disk: Shadow**

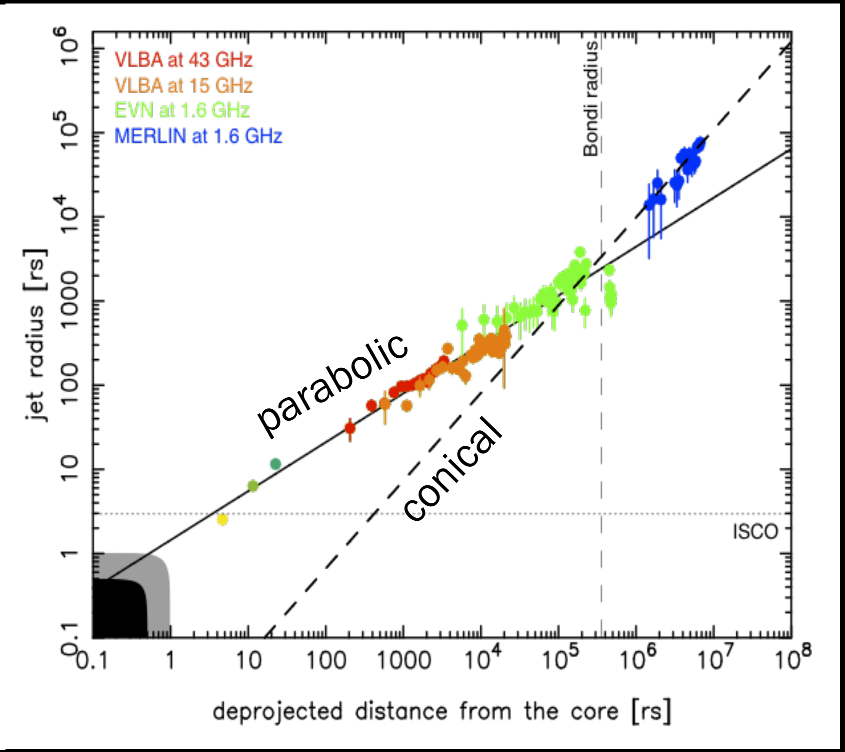
► **Shadow ~ 20 (40)μas**

# Collimation and Acceleration of M 87 Jet

Asada, K. et al. 2014, ApJL, 781, 2

Asada & Nakamura 2012, ApJ, 745, 28
Nakamura & Asada 2013, ApJ, 775, 118




**In relativistic regime,**

$$\Gamma \propto Z^{(\alpha-1)/\alpha}$$

**In non- relativistic**

$$V_z \propto Z^{2/\alpha}$$

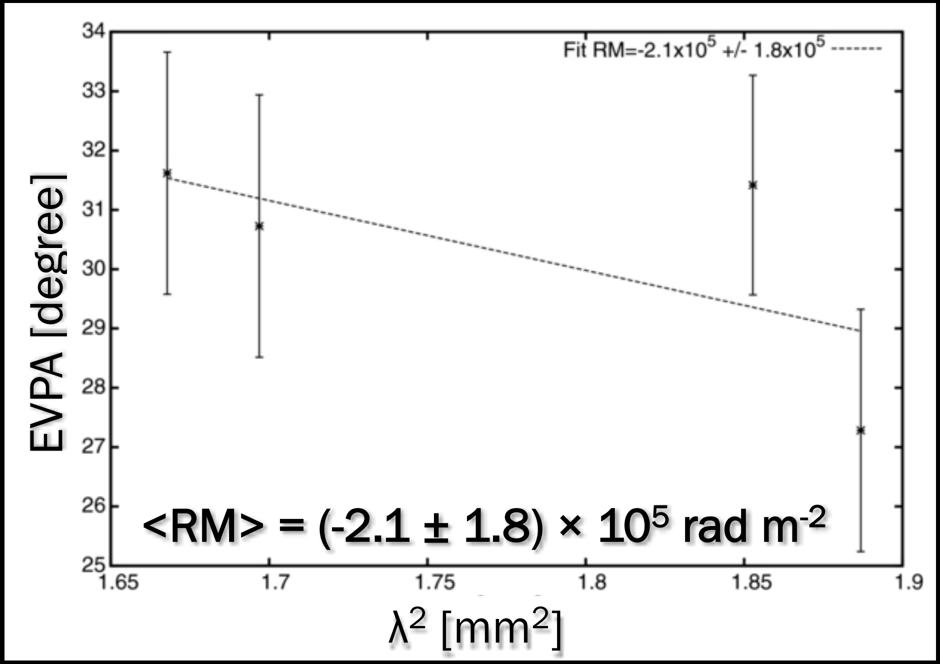
**α: power-law index of streamline (= 1.7)**

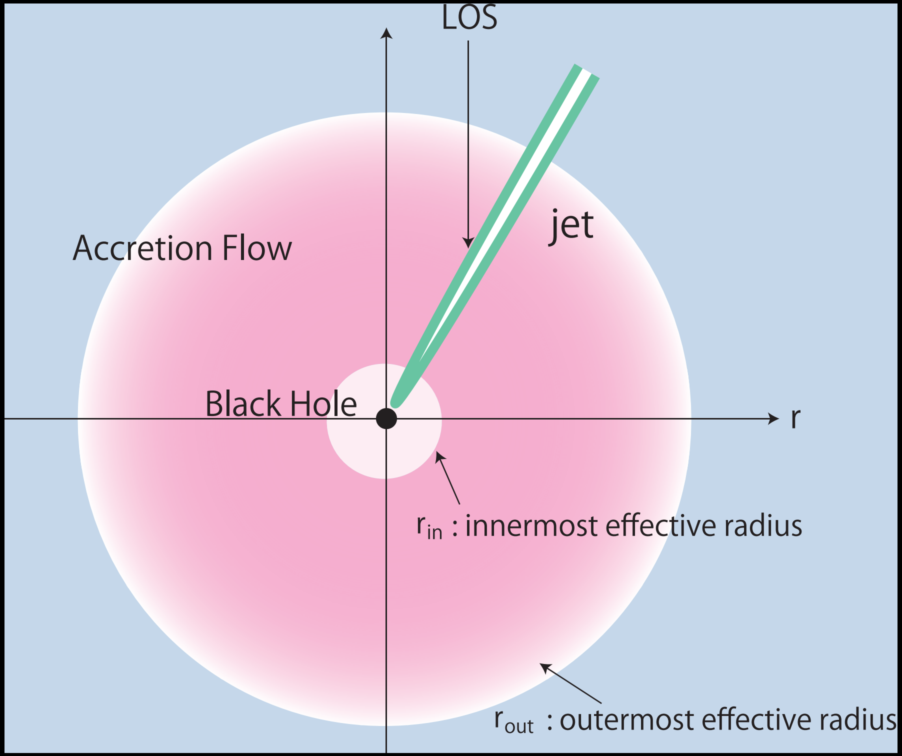
Komissarov et al. 2009 MNRAS, 394, 1182

Nakamura & Asada 2013, ApJ, 775, 118

# Mass Accretion onto M87 BH

**RM : Kuo et al. 2014, ApJL, 783, 33**




$$\dot{M} = 1.1 \times 10^{-8} \left[1 - (r_{\rm out}/r_{\rm in})^{-(3\beta-1)/2}\right]^{-2/3} \times \left(\frac{M_\bullet}{6.6 \times 10^9 M_\odot}\right)^{4/3} \left(\frac{2}{3\beta - 1}\right)^{-2/3} r_{\rm in}^{7/6} RM^{2/3}$$

$$\dot{M} = 9.2 \times 10^{-4}\, M_\odot\, {\rm yr}^{-1} = 7.4 \times 10^{-3}\, \dot{M}_{\rm Bondi}$$

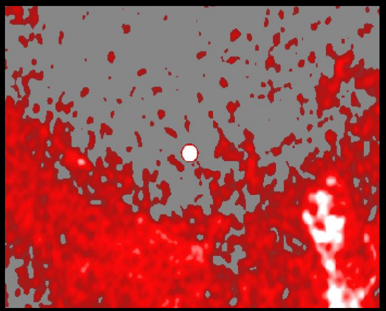
⇨ Mass accretion is significantly suppressed while material is accreted from Bondi radius to a few 10 $r_s$.

# Submmm VLBI Science Objectives

**1. Direct proof of the existence of the SMBH**

**2. Imaging the shadow = measuring the Metric !!**

- Test for General Relativity in the strong field
- Mass, Spin of the BH

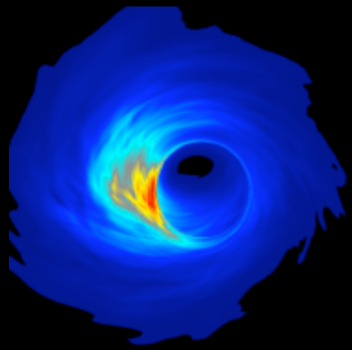


0.1 arc second resolution

**3. Astrophysics related to the SMBH**

-Accretion process onto the SMBH

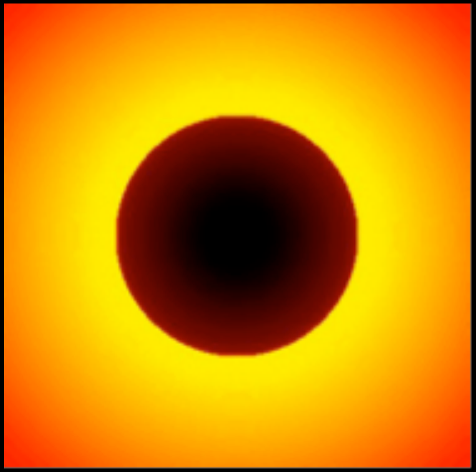
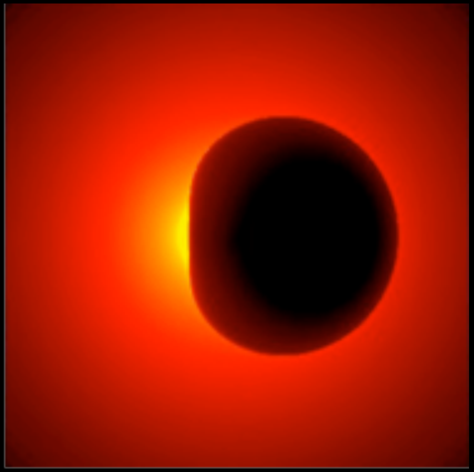
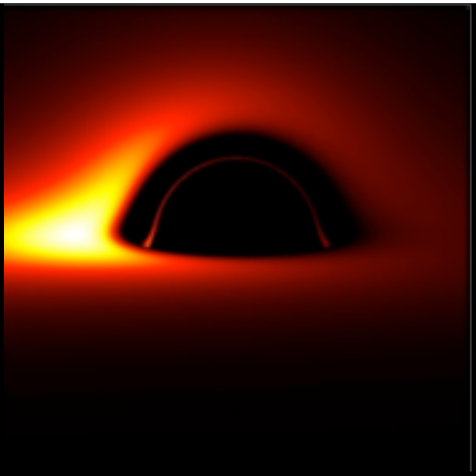
- Formation process of the jets



$10^5$ x improvement

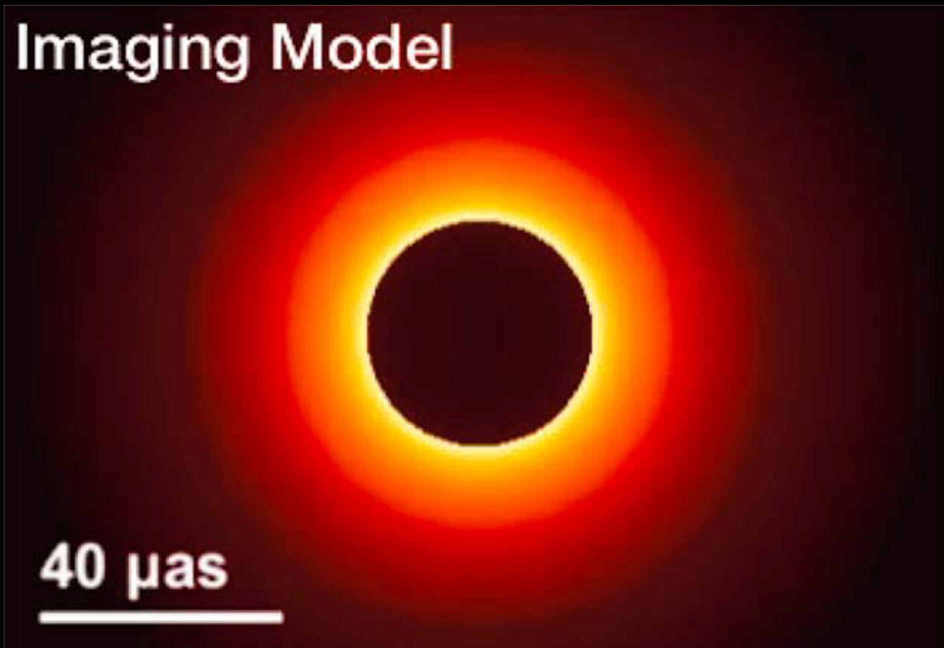
# Appearance of the shadow of the SMBH

**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

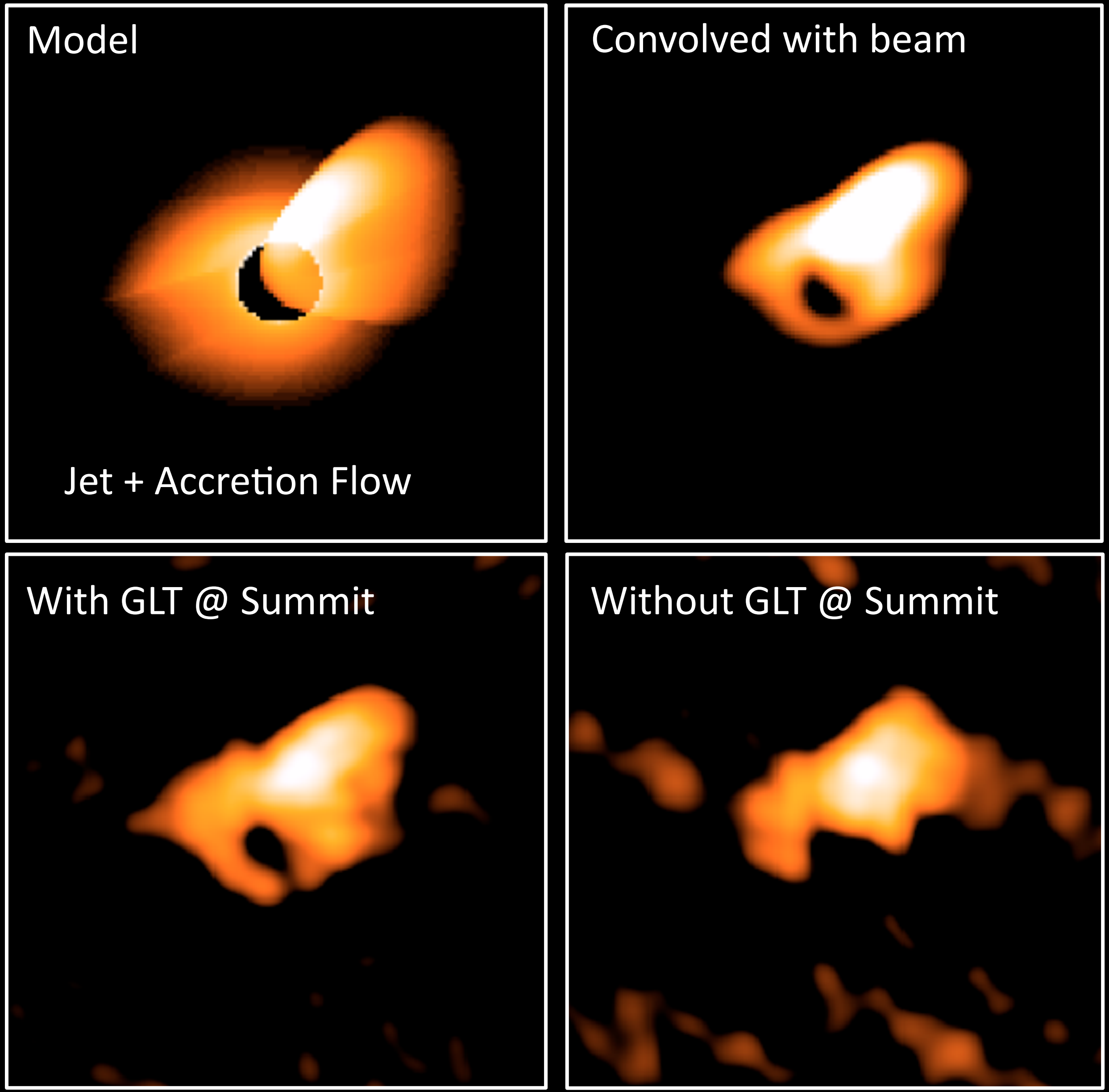
# Image simulation of M87



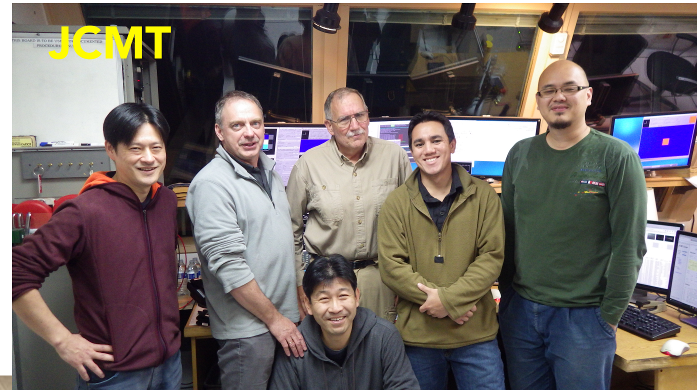

Model image with a $6 \times 10^9$ Mo SMBH and optically thin accreting matter, derived by the Ray Tracing method.

Observed image simulation with the submm VLBI at 345 GHz.

# Imaging Simulation of M87



Event Horizon Telescope



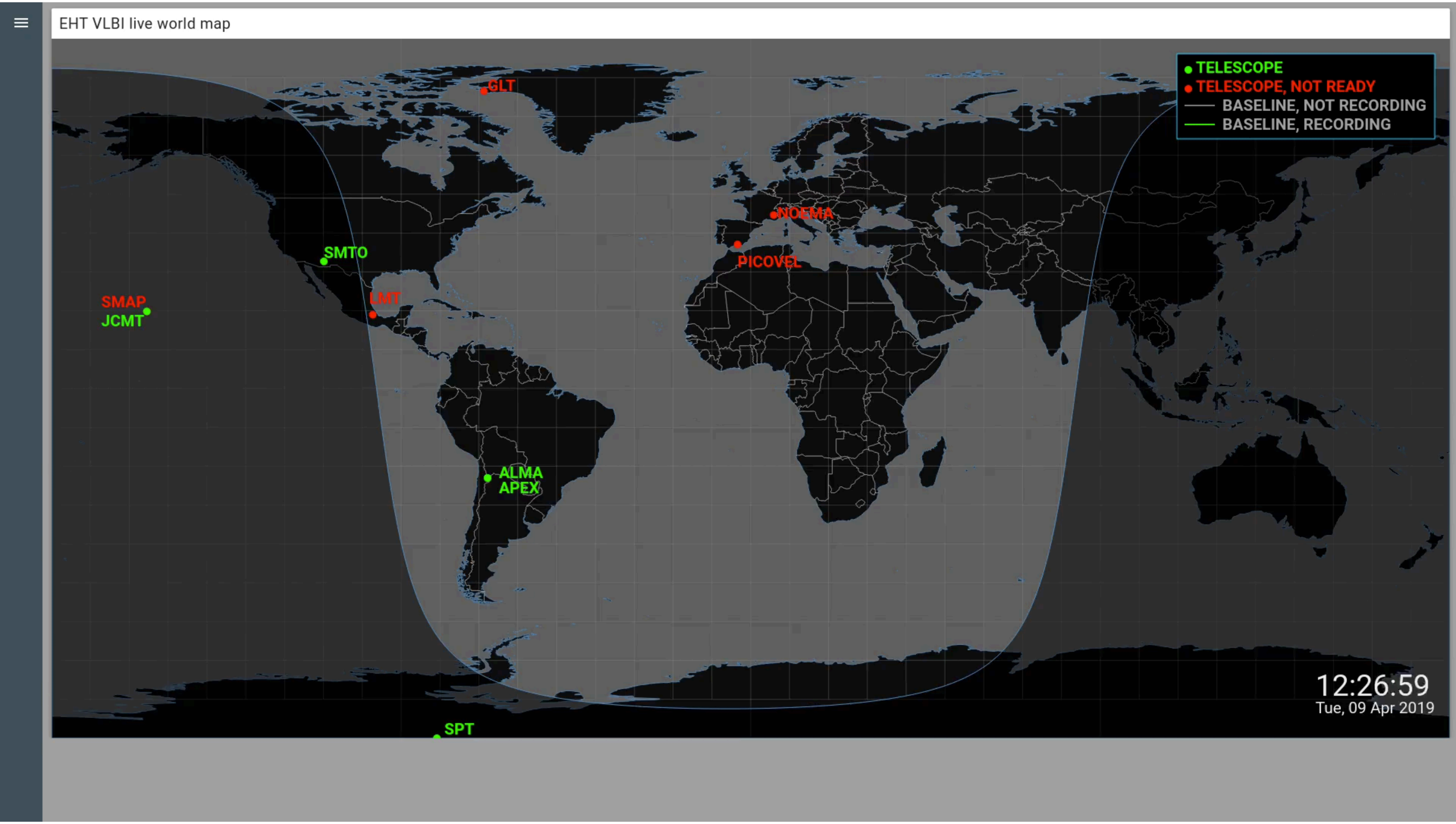




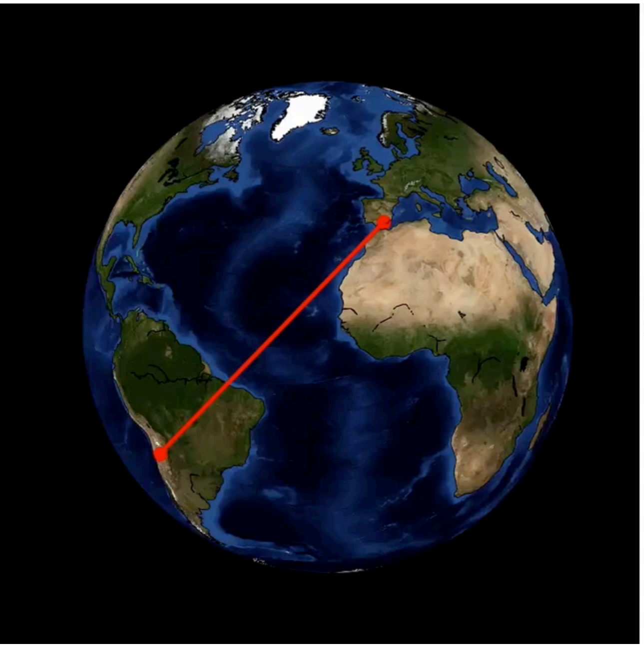


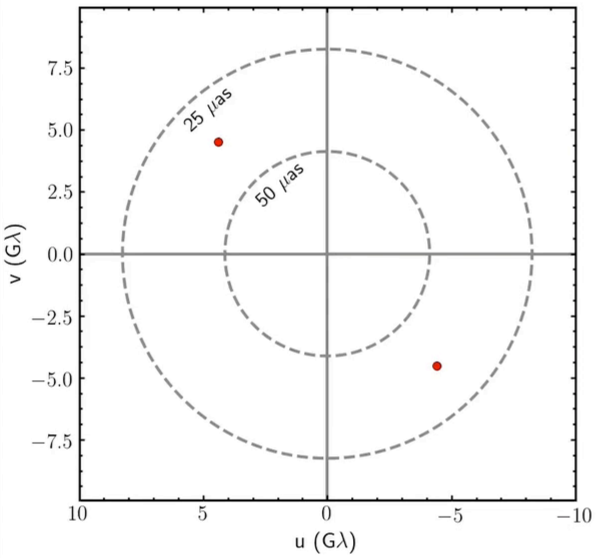
# April 2017

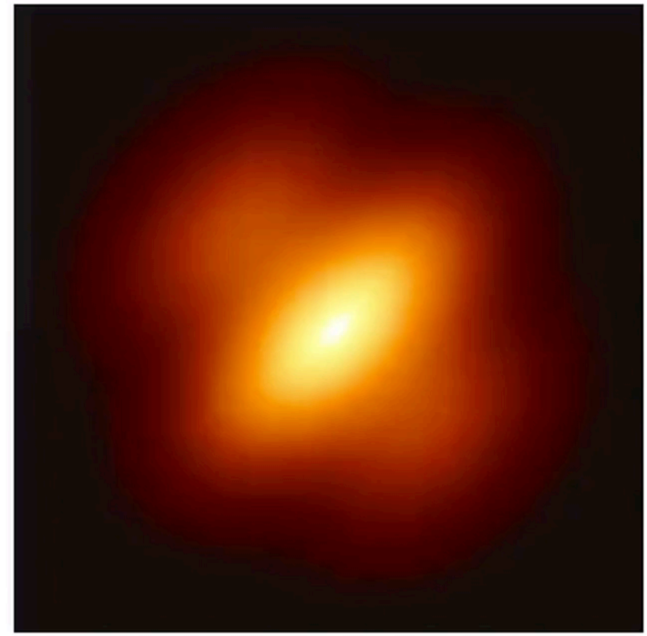
# VLBI Experiment April 6, 2017



Event Horizon Telescope





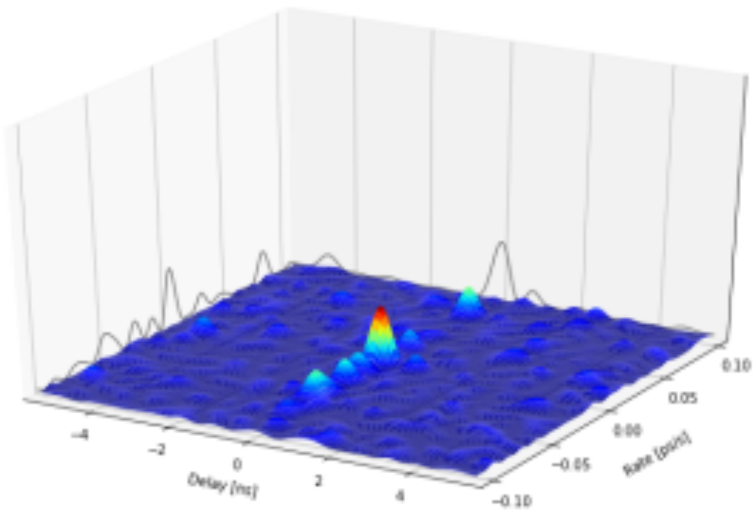
# Aperture Synthesis: Building up UV Coverage

## Visibility = Sampling · Source + Error

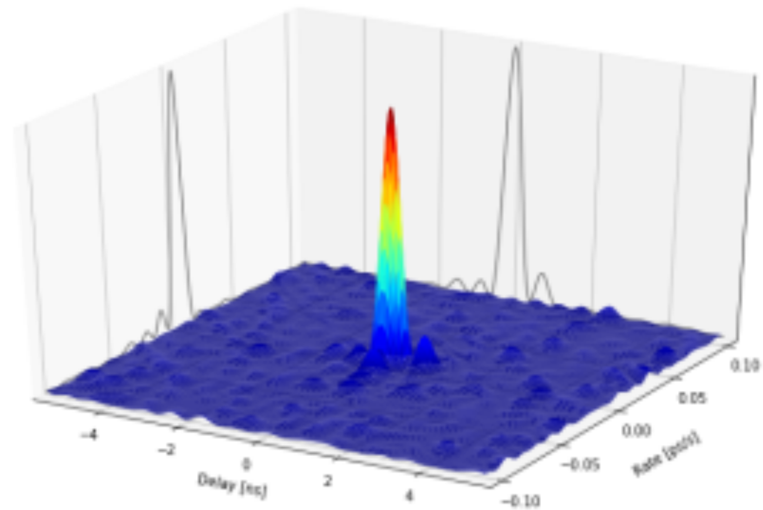
Event Horizon Telescope

# 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.**

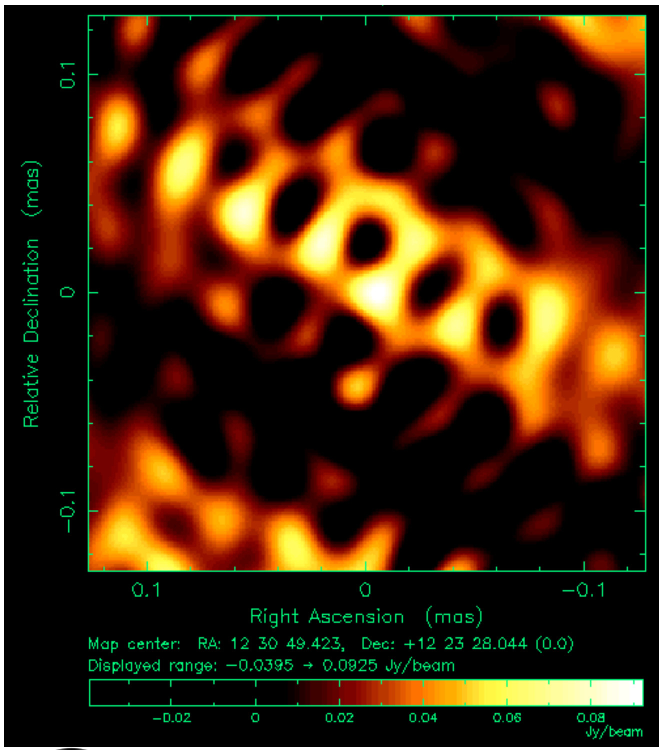
# Phase Referencing with ALMA

Event Horizon Telescope

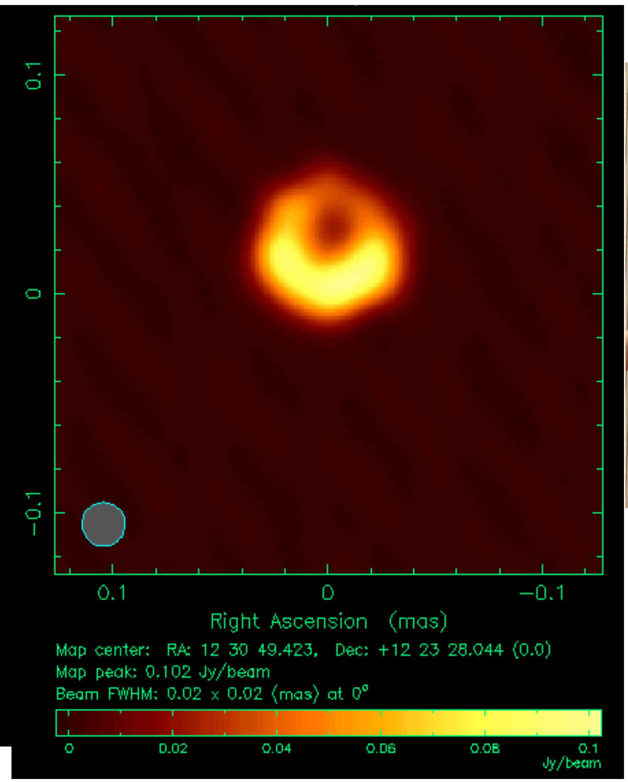
# Removing “Defects”

## Imaging of M87

Dirty Map




Final map after imaging process



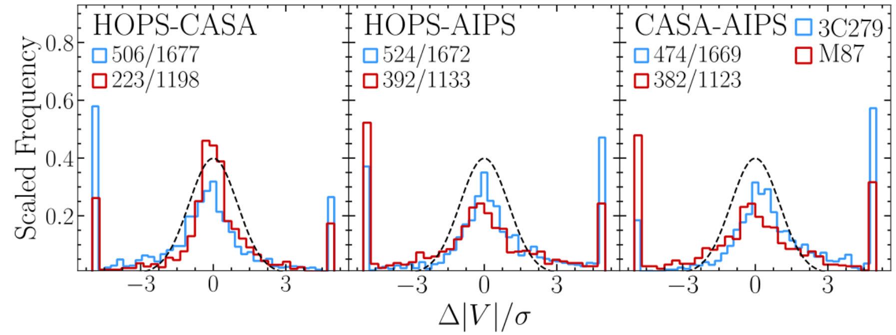




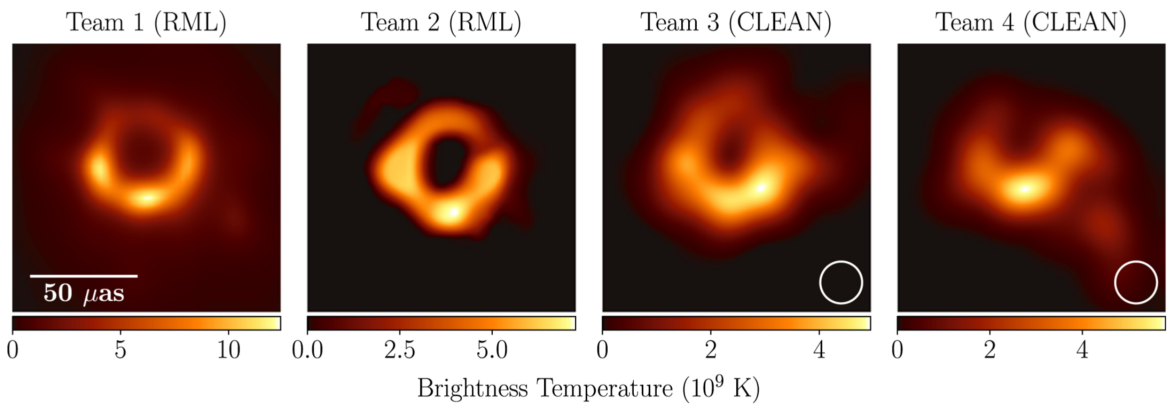
**UV-weighting, Clean, Phase Self-Calibrate, Amplitude Self-Calibrate**

# Calibration and Imaging

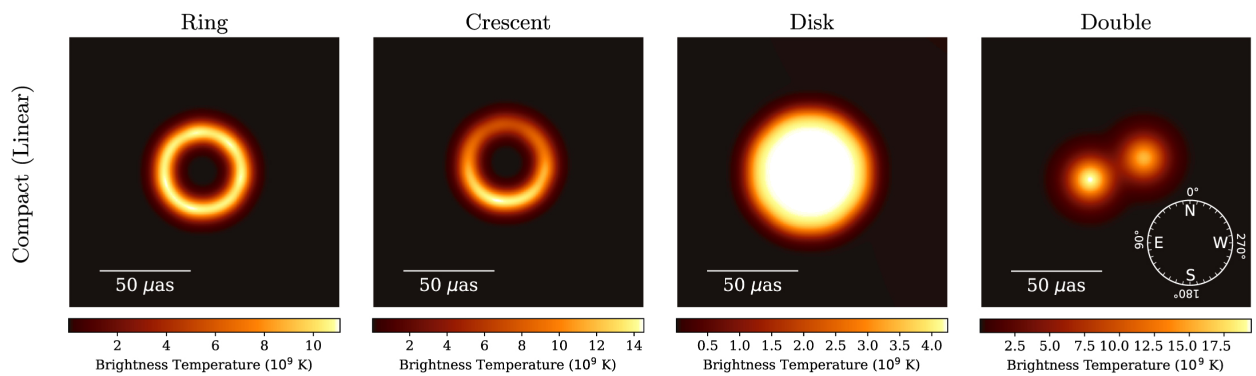
**Calibration**




**Imaging**

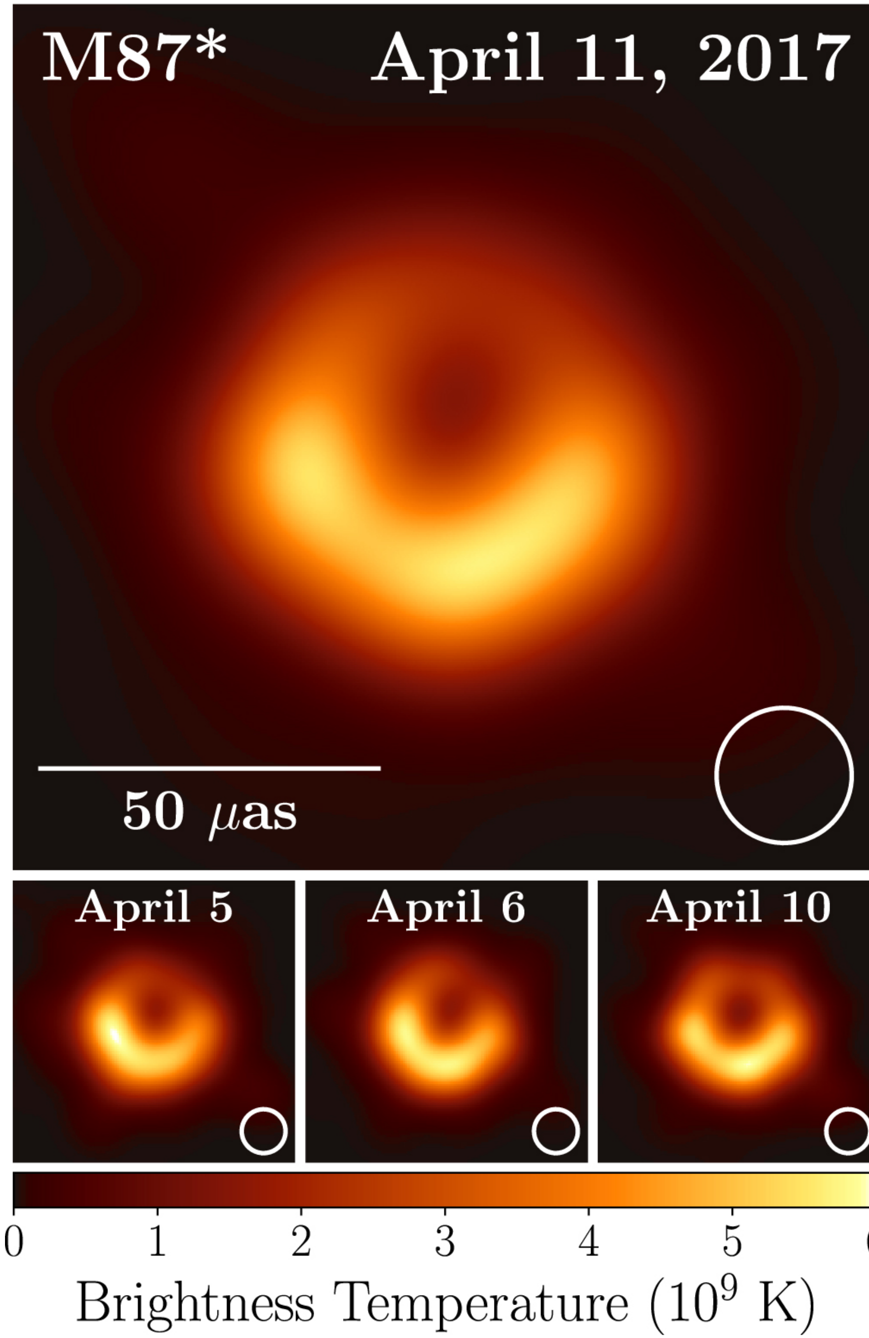



**Models**



# Variability?

- **Large Scale:**
  **—— slight difference**
- **Small Scale:**
  **—— STABLE**
- **Longest Baselines:**
  **—— Probe Horizon**



# EHT + ALMA proposal in 2016

**Imaging the Black Hole Shadow and Jet Launching Region of M87**

**PI: The EHT consortium**

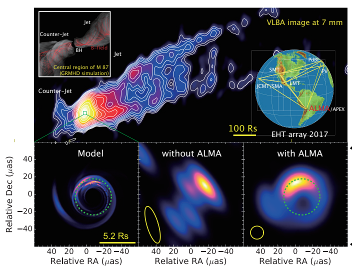
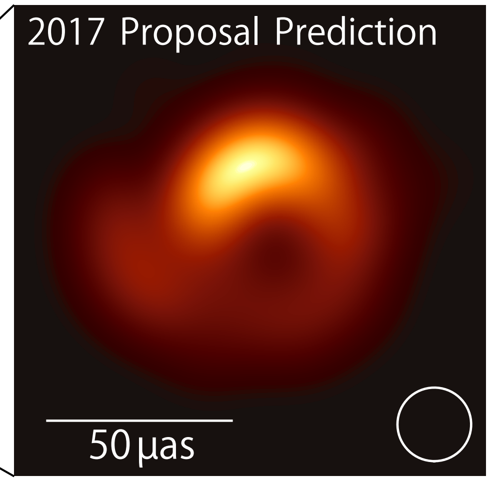
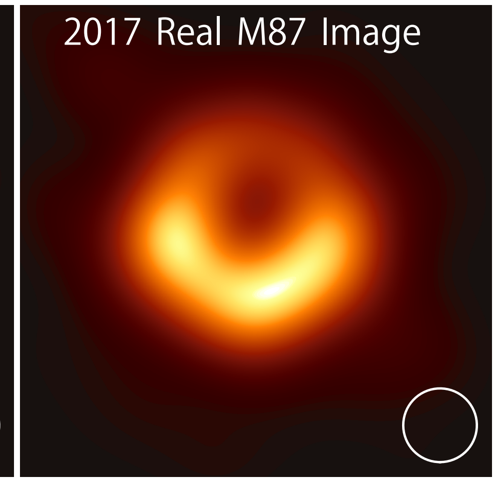



Figure 1. **Project Overview.** (top) Image of M87 at 7 mm with the VLBA. Upper Insets show particle density and magnetic field lines threading a simulated jet (Moscibrodzka+ 2016) and the 2017 EHT array as viewed from M87. (bottom) Model image of M87 at 230 GHz and simulated EHT reconstructions. The model image is based on Moscibrodzka+ (2016) with general relativistic radiative transfer (Dexter+ 2016). Images are reconstructed with sparse modeling (Honma+ 2015) showing expected EHT performance with and without ALMA (see Fig. 2). We have compared these results with four imaging techniques (Bouman+ 2016) and have confirmed that we can clearly detect the shadow with each method.

**A. Introduction and Background:** Among all AGN known to power jets, M87 presents us with the best opportunity to forge a link between the SMBH and relativistic outflow. At a distance of 16.7 Mpc, and with an estimated mass of $6.6\times10^9\,M_\odot$ (Gebhardt+ 2011), the Schwarzschild radius of this black hole subtends $\sim 8\,\mu$as on the sky. Because of strong gravitational lensing near the black hole, the apparent diameter of the shadow cast by the black against the local hot plasma will be $42\,\mu$as (Bardeen 1973), and the corresponding apparent diameter of the Innermost Stable Circular Orbit (ISCO) for accreting matter is $59\,\mu$as. Remarkably, the sizes of these strong-field GR features are well matched to the angular resolution of 1.3mm wavelength VLBI arrays that span the Earth. The EHT Consortium has used observations on a three-station 1.3mm VLBI array to report size measurements for the jet base of M87 of just $44\,\mu$as (5.5 times the Schwarzschild radius), confirming the existence of horizon-scale structure and bringing the possibility of imaging the jet launch region within reach (Doeleman+ 2012, Akiyama+ 2015). In parallel, members of our team have carried out the most detailed VLBI imaging of the M87 jet at longer wavelengths. At a wavelength of 3mm, the inner jet down to $\sim 20$ Schwarzschild radius scales exhibits a broad parabolic opening, indicating the start of an accelerating outflow, as well as a clear counter jet, constraining the location of the central black hole (Asada & Nakamura 2012, Hada+ 2016, Fig. 1). Phase-referenced VLBI results over multiple wavelengths show a clear frequency dependent shift of the jet base, as expected for a jet that becomes optically thin at higher frequencies close to the black hole (Hada+ 2011). Together, these prior results place the 1.3mm VLBI emission within a few Schwarzschild radii of the black hole.

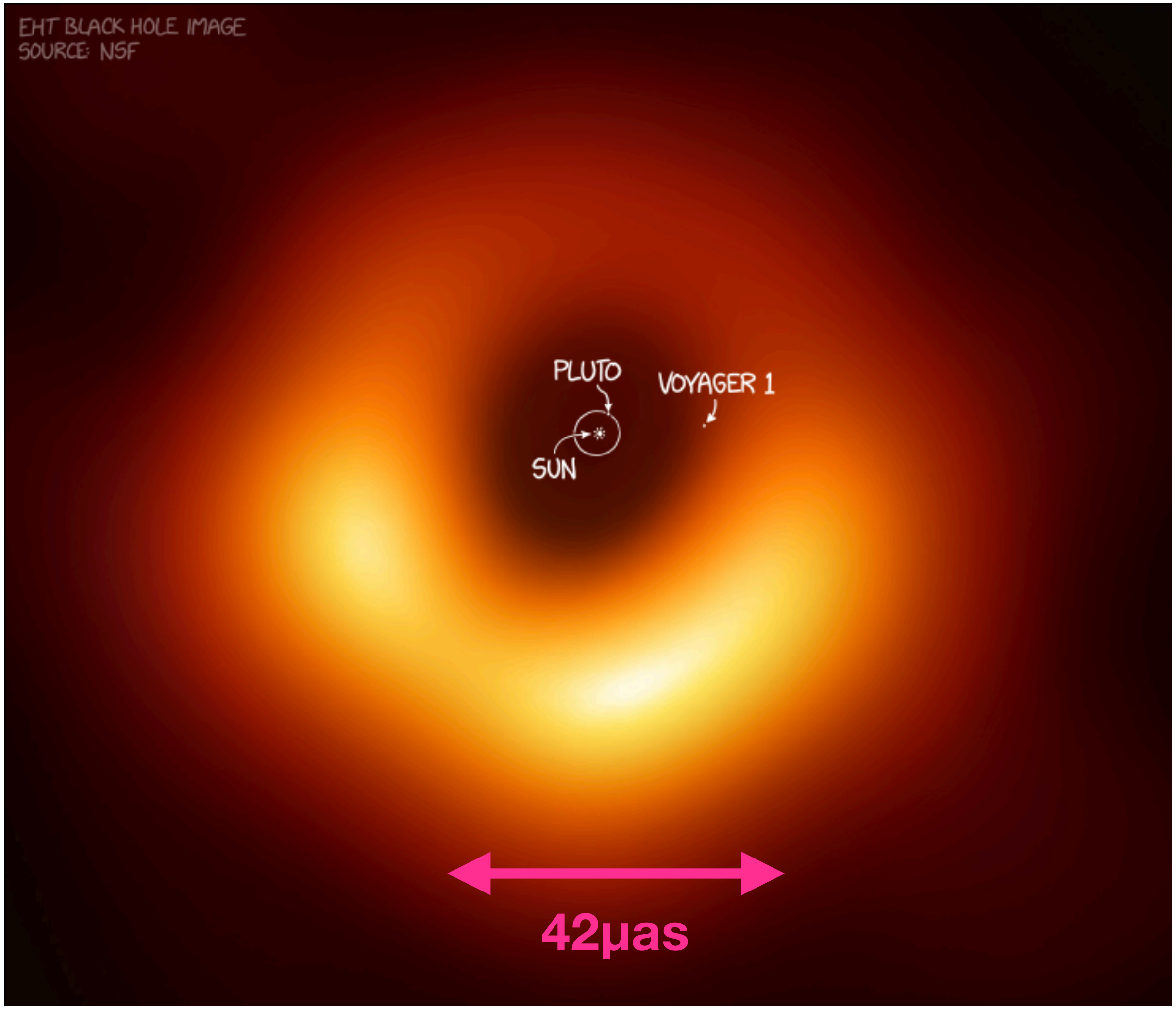
1




**Led by Asada (ASIAA)** together with Ros (MPIfR) and Akiyama, Fish, Hada, Nakamura et al.

# 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**

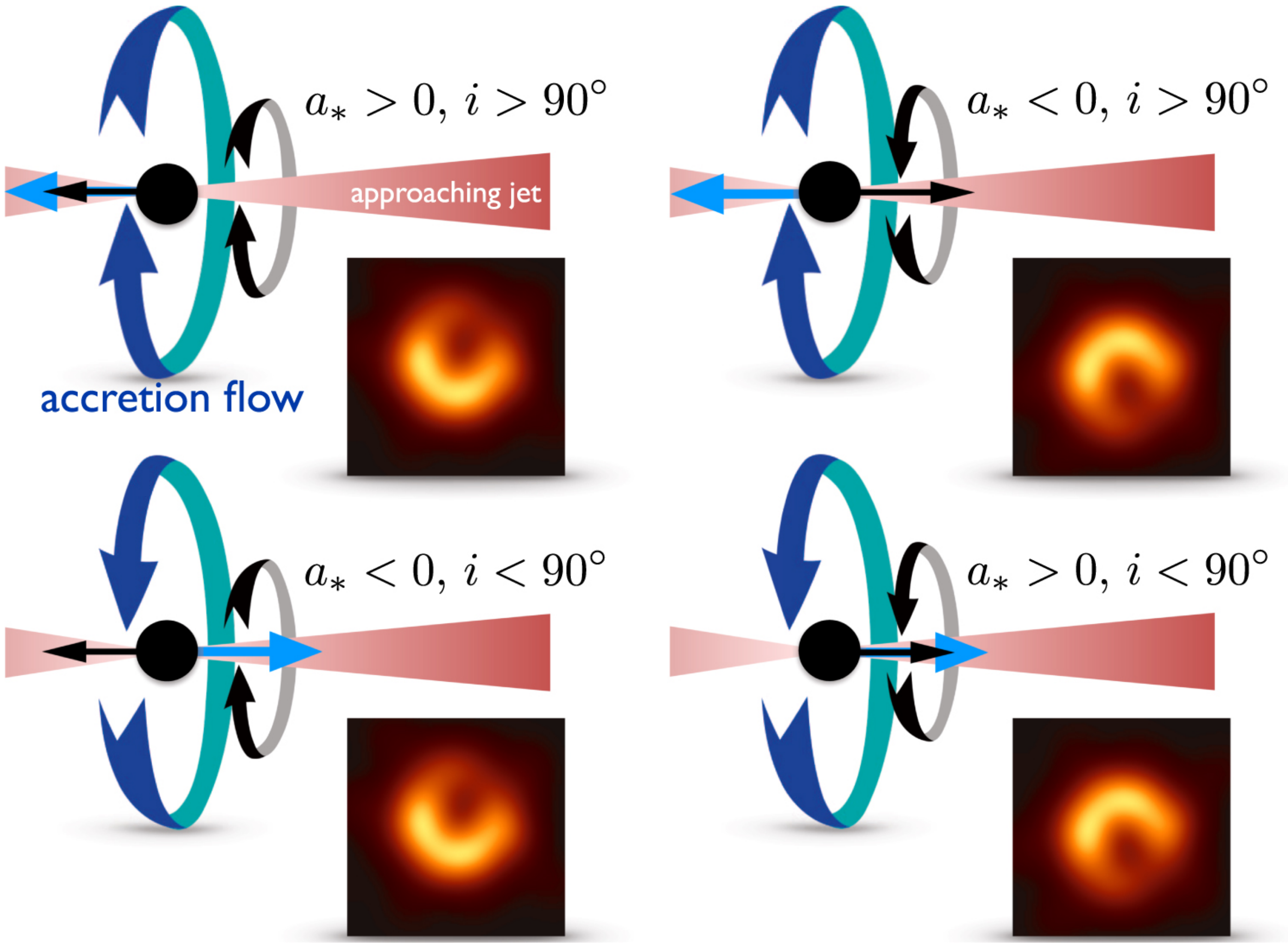
**—— deduced mass ~ 6.5 billion solar mass**

- **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**

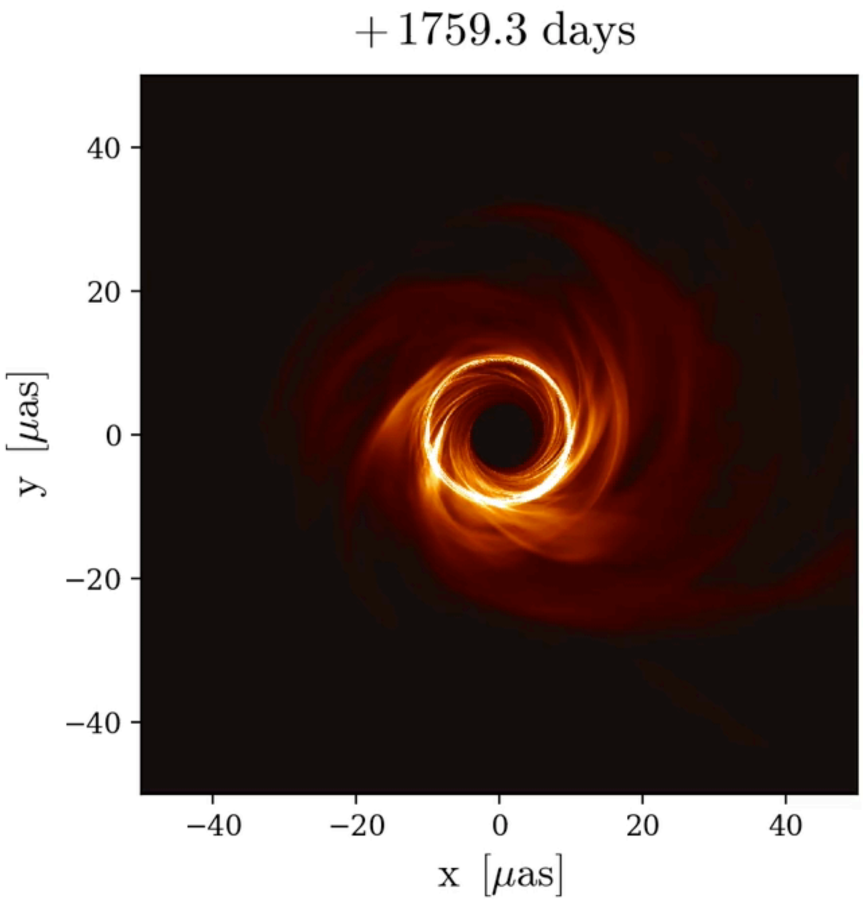
- **Tipped Disk: Perpendicular to Relativistic Jet**
- **Spin of Black Hole: Pointed away from Earth**

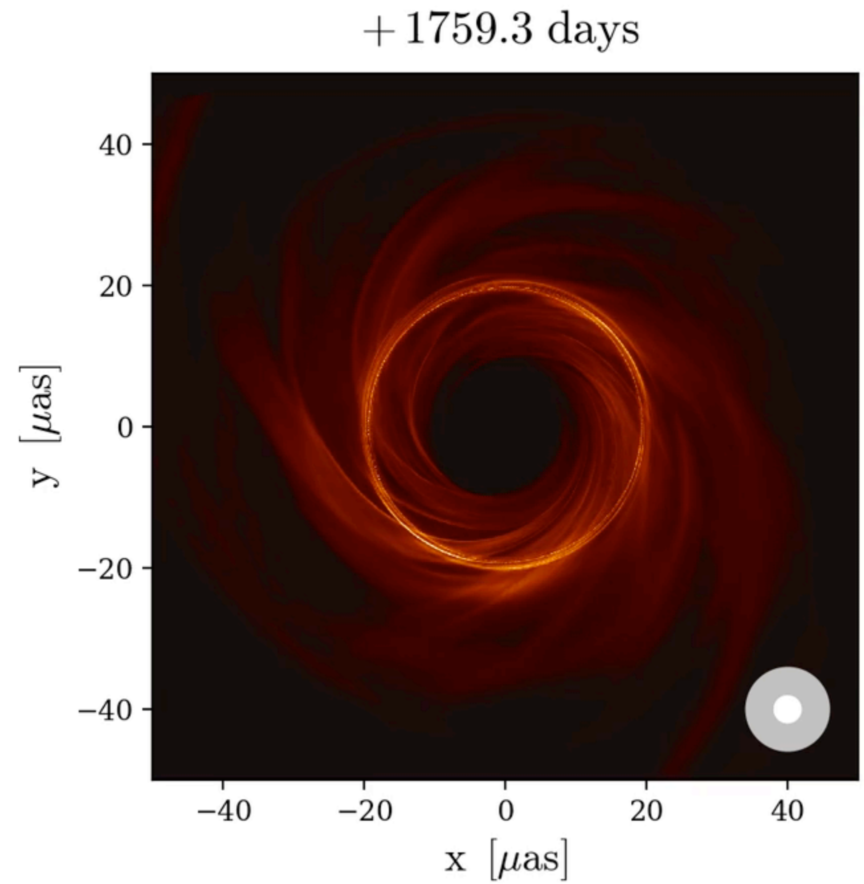
# Doppler Boosting of Approaching Part of Rotating Ring



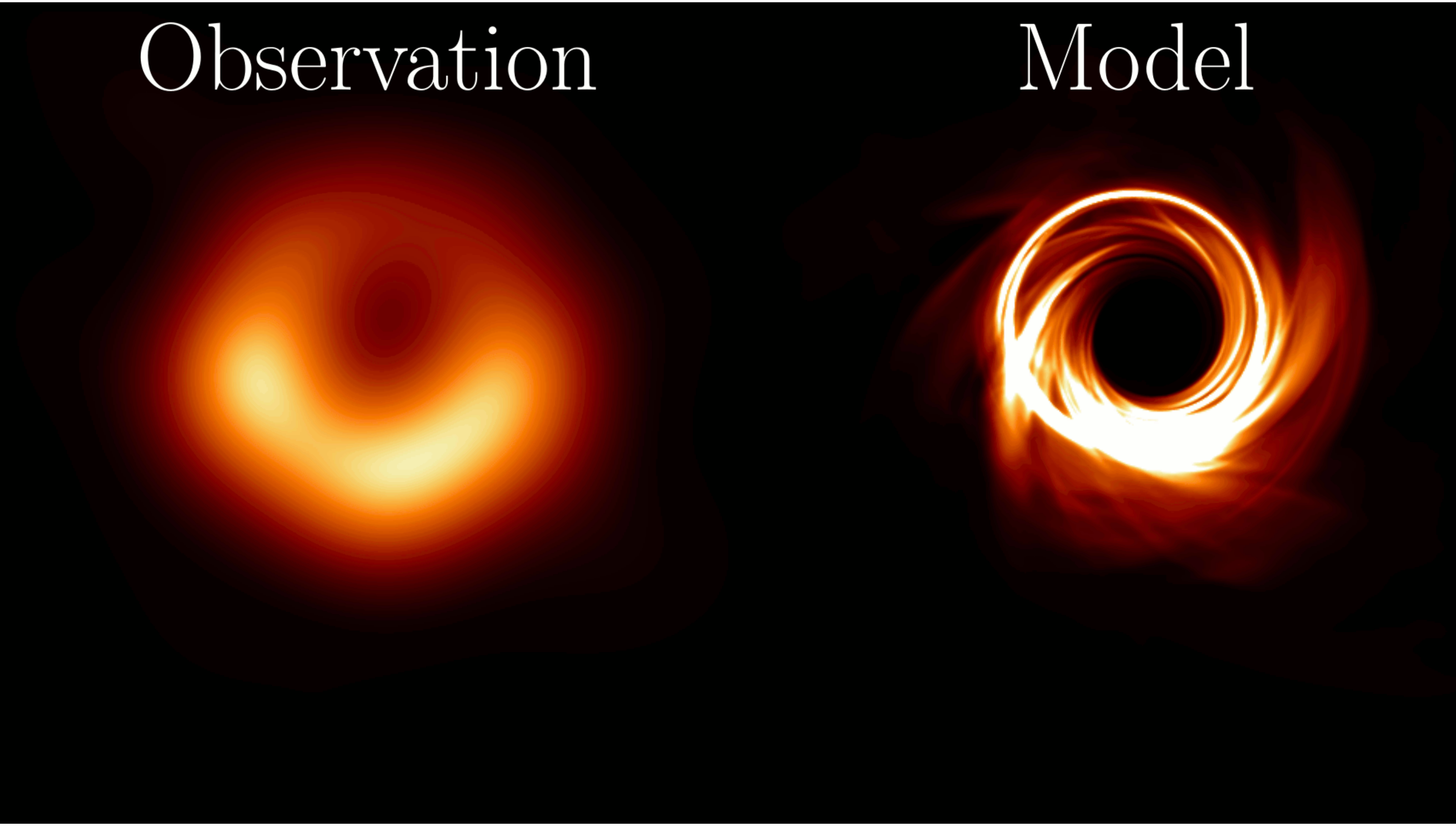

**Inner Rotation must lock to Black Hole Rotation**

# Simulation of Doppler Boosting




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


Observation
Model

# 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!**

# Where are the Problems?

- Resolution still limited (only 2 targets: M87, SgrA*)
- Resolution can be improved by factor of 10
- How to look at "milliparsec" problem
  (merging black hole binaries at what scale?)
- How to measure rotation/spin
- How to do the astrophysics (jet launching, accretion disk)
- How to use the black hole to probe other phenomena

- what should we do next?

# What is Next?

**Higher frequency = better resolution**

**More sensitive instruments - Namakanui!**

**More stations - Greenland telescope**

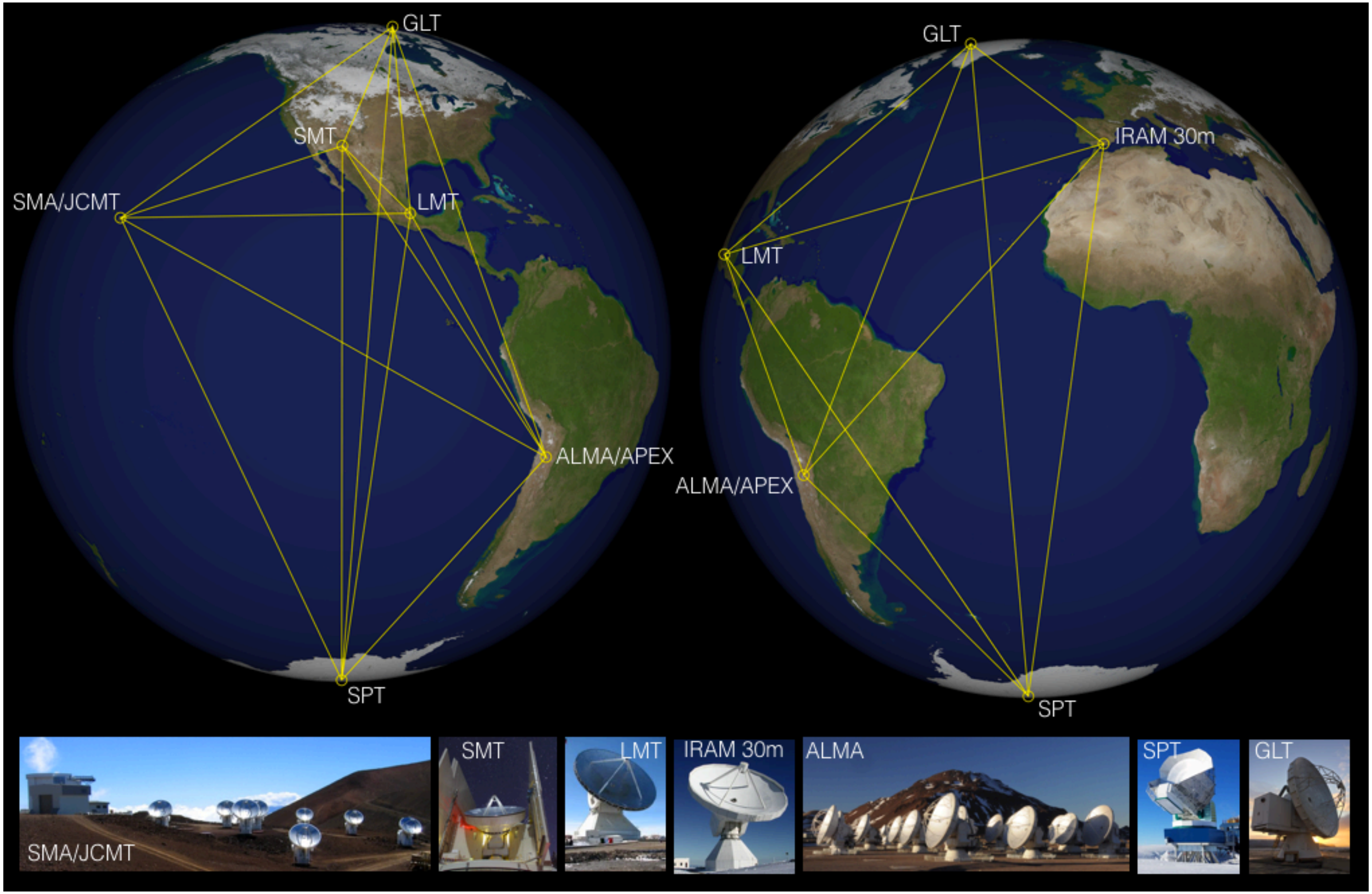
**Polarization measurements**

**Milky Way black hole…**

**Merging SMBHs?**

## ASIA will have Increasing Impacts

# The Event Horizon Telescope in 2018

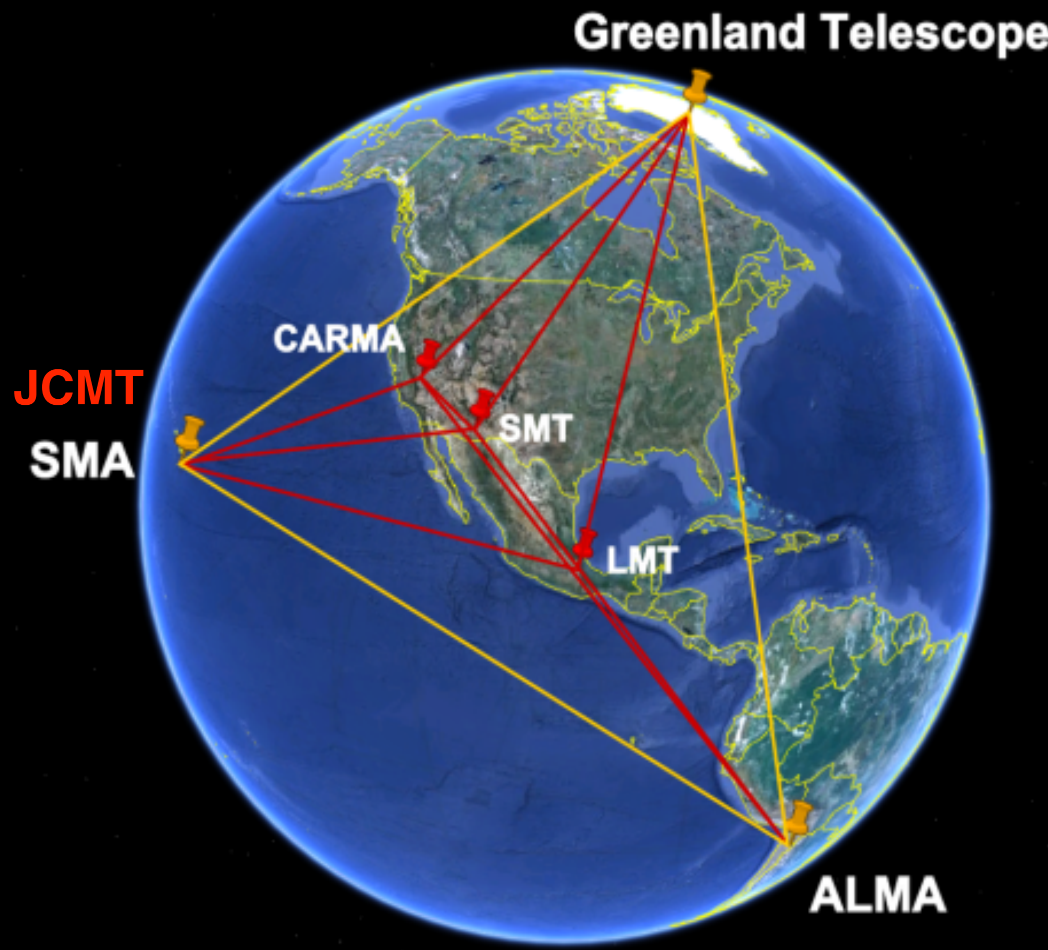


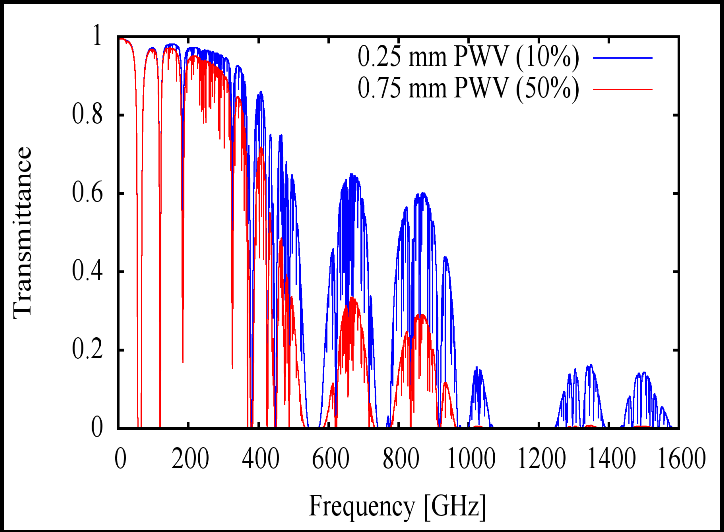

D. Marrone/UofA

Event Horizon Telescope

# The Largest Telescope Ever:

## Greenland Telescope leverages SMA and ALMA and JCMT




Aim: LOW PMV

Sensitivity: ALMA Surface Area

# The Greenland Telescope Project

# Starting The GLT Project

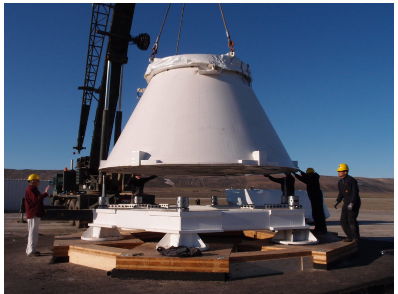
- Recover ALMA-Taiwan Investment
- Extend ALMA Capabilities
- Recover ALMA Proto-Type Antenna
- Leverage ALMA Collecting Area
- Attain Highest Angular Resolution
  — shortest $\lambda$, longest BL
- VLBI Imaging instead of Fringe Fitting

- ALMA-Taiwan approved in 2008
- GLT Project began in 2009

# Arrival in Greenland 07.16.16

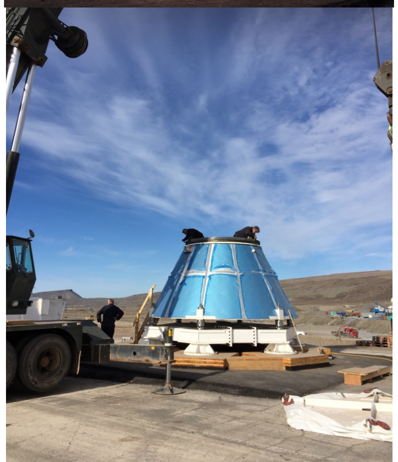


# Assembly of Antenna Mount 09.10.16

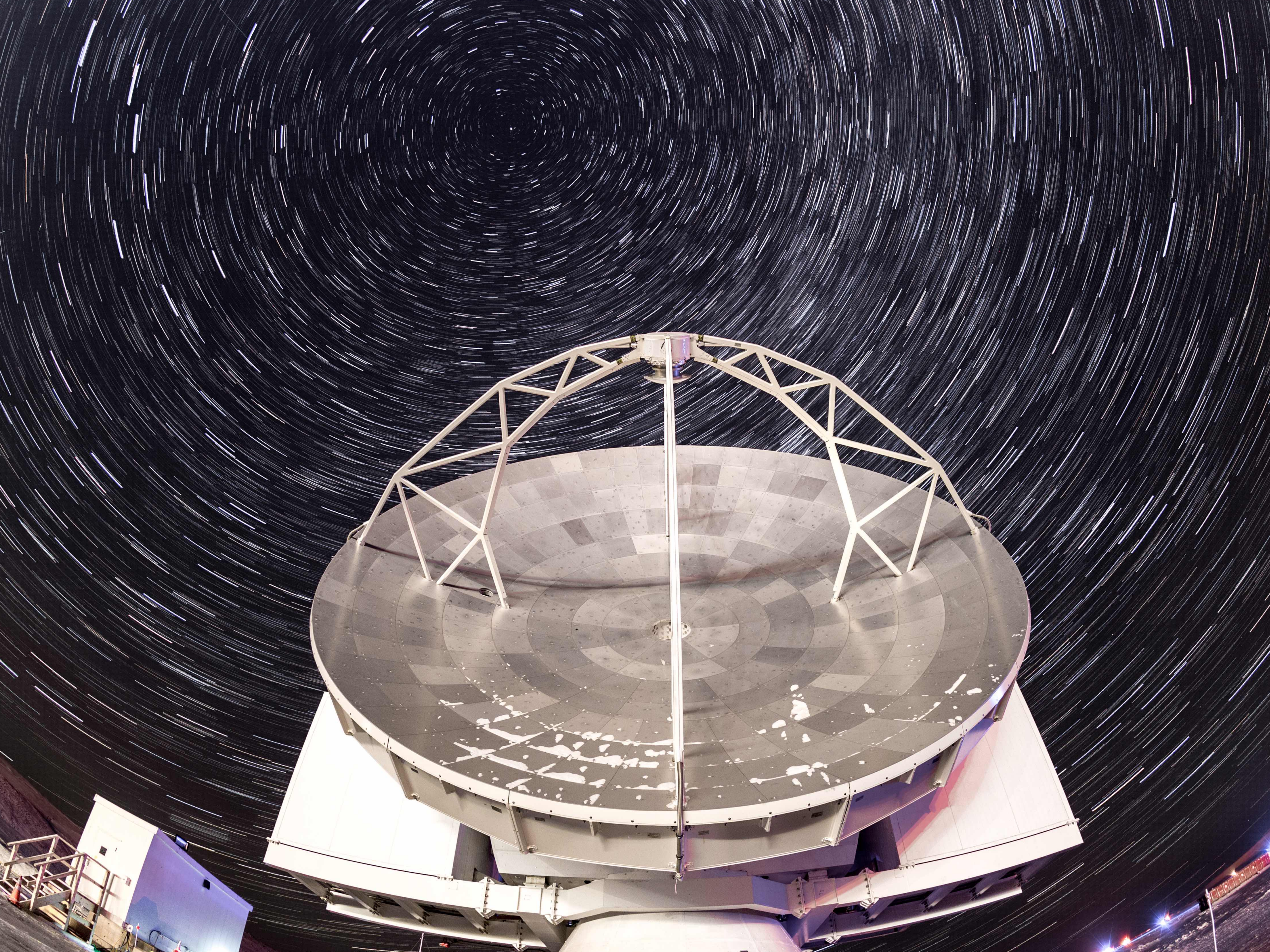






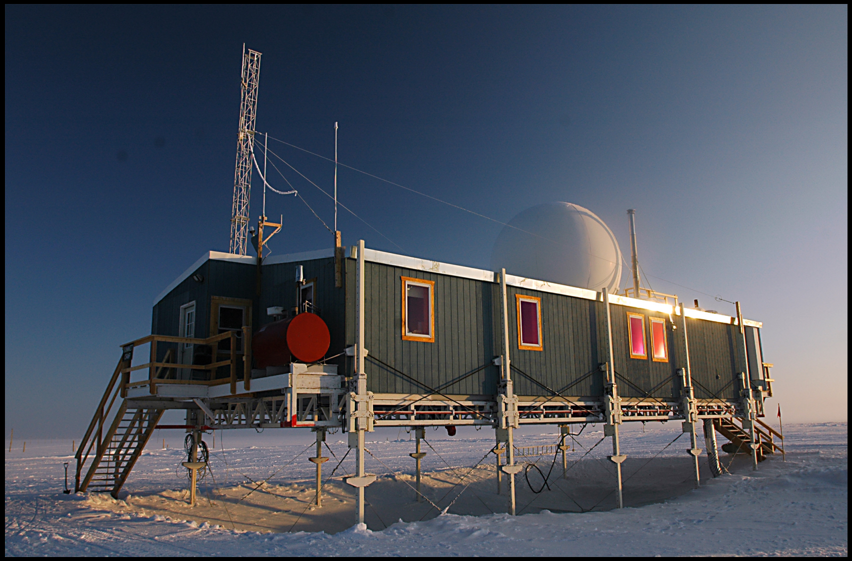


# Fully Assembled Telescope 08.2017



# TARGET: SUMMIT STATION GREENLAND

N 72.5, W 38.5, altitude: 3200 m

# Future in EHT Science

- Move GLT to Summit in 2021-2022

- Need: Establish Base at Summit
- Need: Housing, Power
- Need: Transport to Summit
- Need: Construction at Summit
- Need: Winter-over Operations


In 2021

# Final Remarks

- **BH Image made the "expectations" REAL**
- **Resonance with the Public: Seeing the "un-seeable"**
- **Resonance in Asia: We can work at the Forefront**

- **Importance: Measure BH Properties Directly**
- **Importance: Test General Relativity at Extreme Gravity**

- **Problem: Compete Internationally for Credit**
- **Problem: Generate Support within Asia**

- **Present: Asia is Partner on 4 of 9 EHT facilities**
- **Future: Asia to Lead at Highest Frequencies, Highest Resolution**

# Denmark in the EHT/GLT

*Visits to Denmark: 10.2014, 11.2015, 02.2019, 04.2019*

- **Integration and Cooperation with existing and future Danish projects at Greenland Summit; Collaboration with Greenlanders**

- **Joint Development of 1st Arctic Observatory**

1. **Site development and support infrastructures: energy generation**
2. **Platform for future experiments and projects: arctic investigation station**
3. **Development of future observatories: planning and studies**

- **Partner on the GLT Project**

1. **Science on the GLT: VLBI, THz science, theory**
2. **Deployment and Commissioning of GLT: construction and testing**
3. **Engineering Aspects of GLT: hardware, construction**
4. **Staffing: faculty, postdocs, graduate students, interns**
5. **Operations: site support, administration, engineering**
6. **Politics: interface with Denmark and Greenland government agencies**