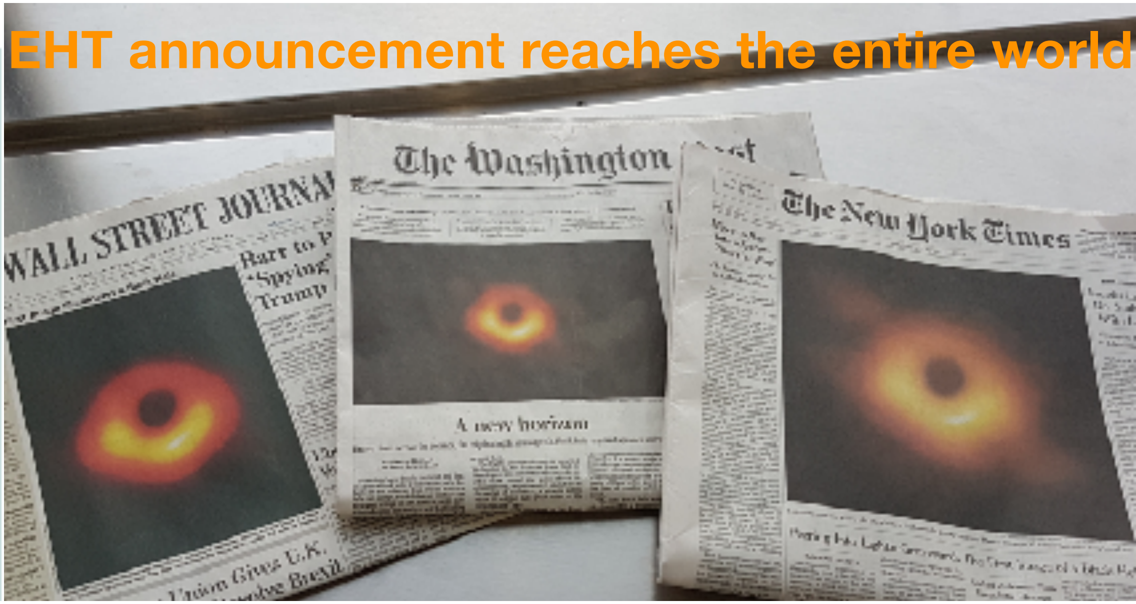
# Black Hole: 2020 Physics Nobel Prize

Paul Ho, ASIAA

# 2019.4.10： First Image of SMBH Shadow

# — “Not Seeing” the Black Hole



**Breakthrough Prize in Fundamental Physics, Einstein Medal, Bruno Rossi Prize…..**

# Why are Black Holes Important ?
## "key" to Fundamental Physics

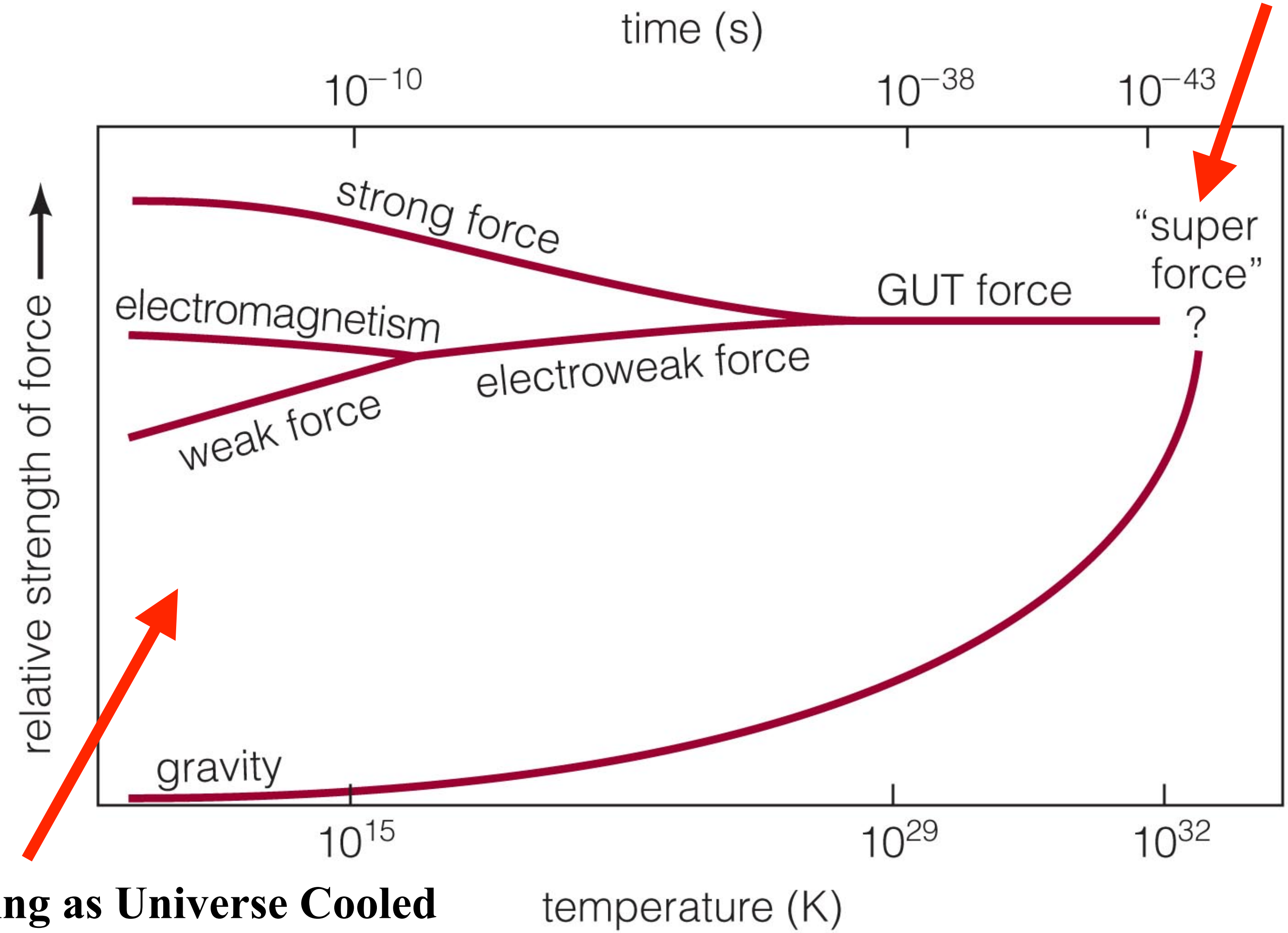
- **Black Hole: "INVISIBLE" or "UNSEEABLE"**
- **Black Hole: where "GRAVITY" is strongest**
- **Black Hole: no escape — not even light**
- **Black Hole: no information from inside**
- **Small Black Hole: "end state" of big stars (>5-10 times sun) — leftover after "supernova" explosion**
- **Big Black 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>These Experiments are on "Optics" + "Missing Information"</u>**

# Four Forces of Nature

**What will Black Holes Probe?**

**Unified at Beginning of Universe?**




**Decoupling as Universe Cooled**

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

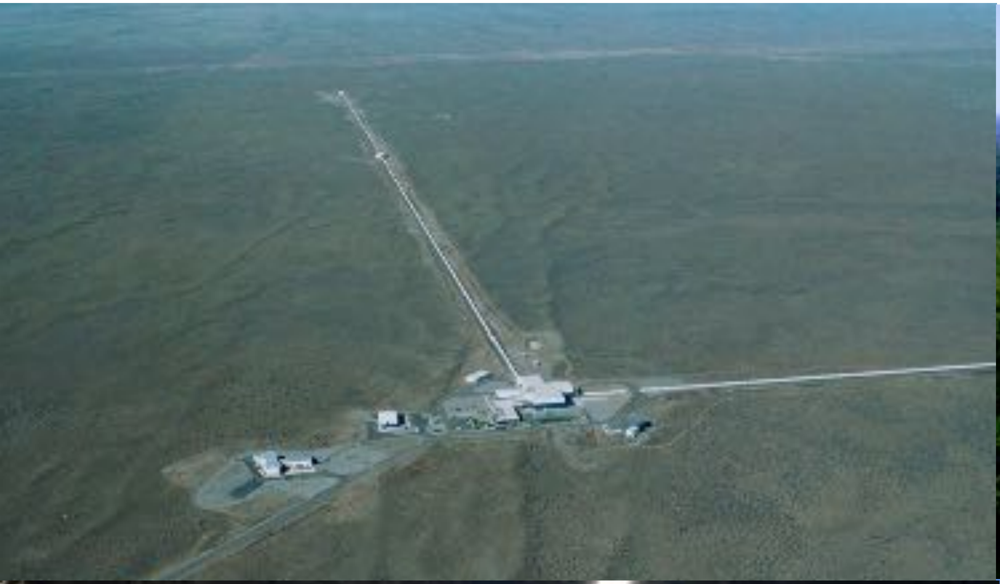
- Detection of Gravitational Waves  (tens of cases)
- Orbital Motions at the Event Horizon  (one)
- Imaging of the Event Horizon  (two)
- GR Effects

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

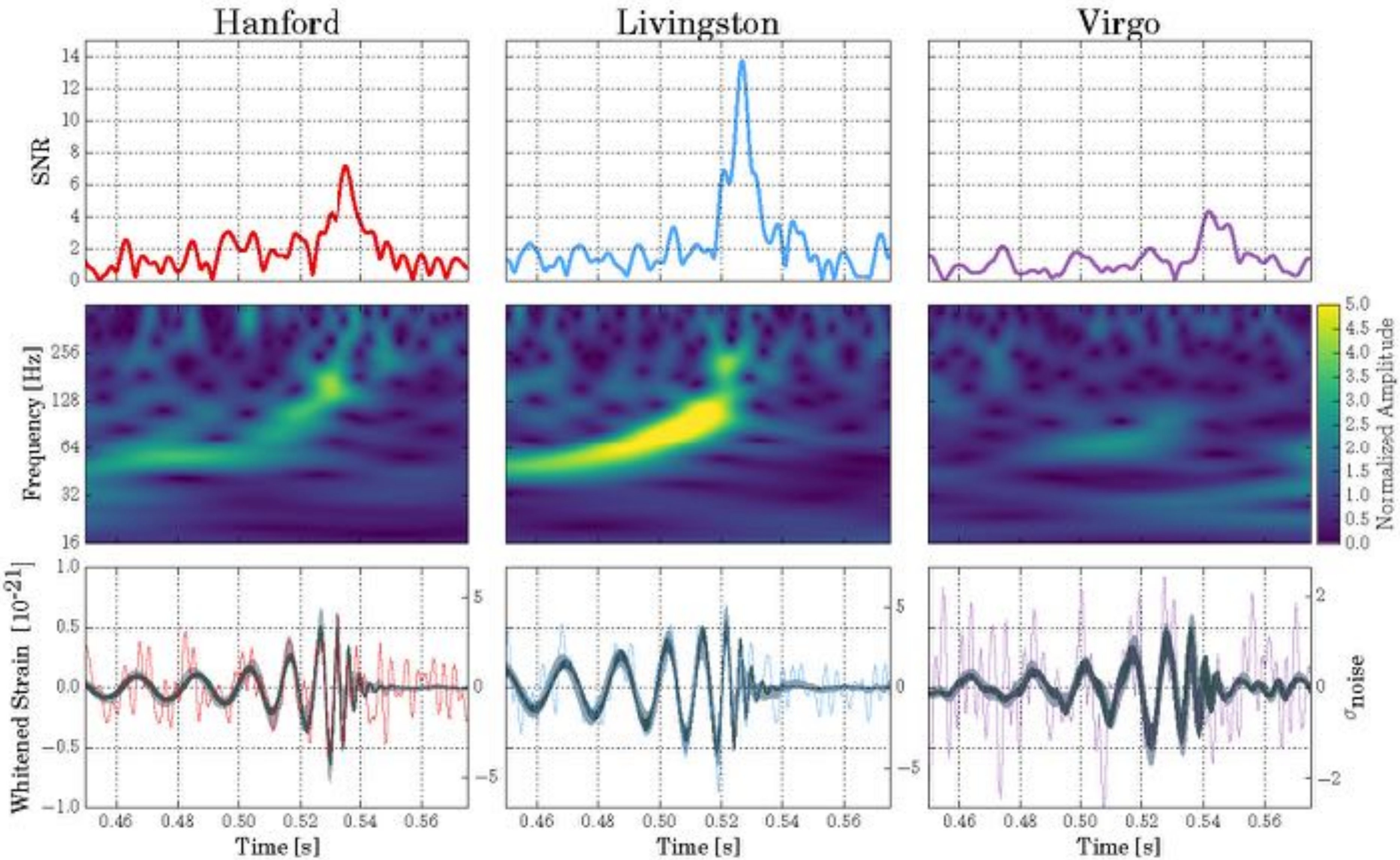
# LIGO ‘**HEARD**’ GW

- **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…**

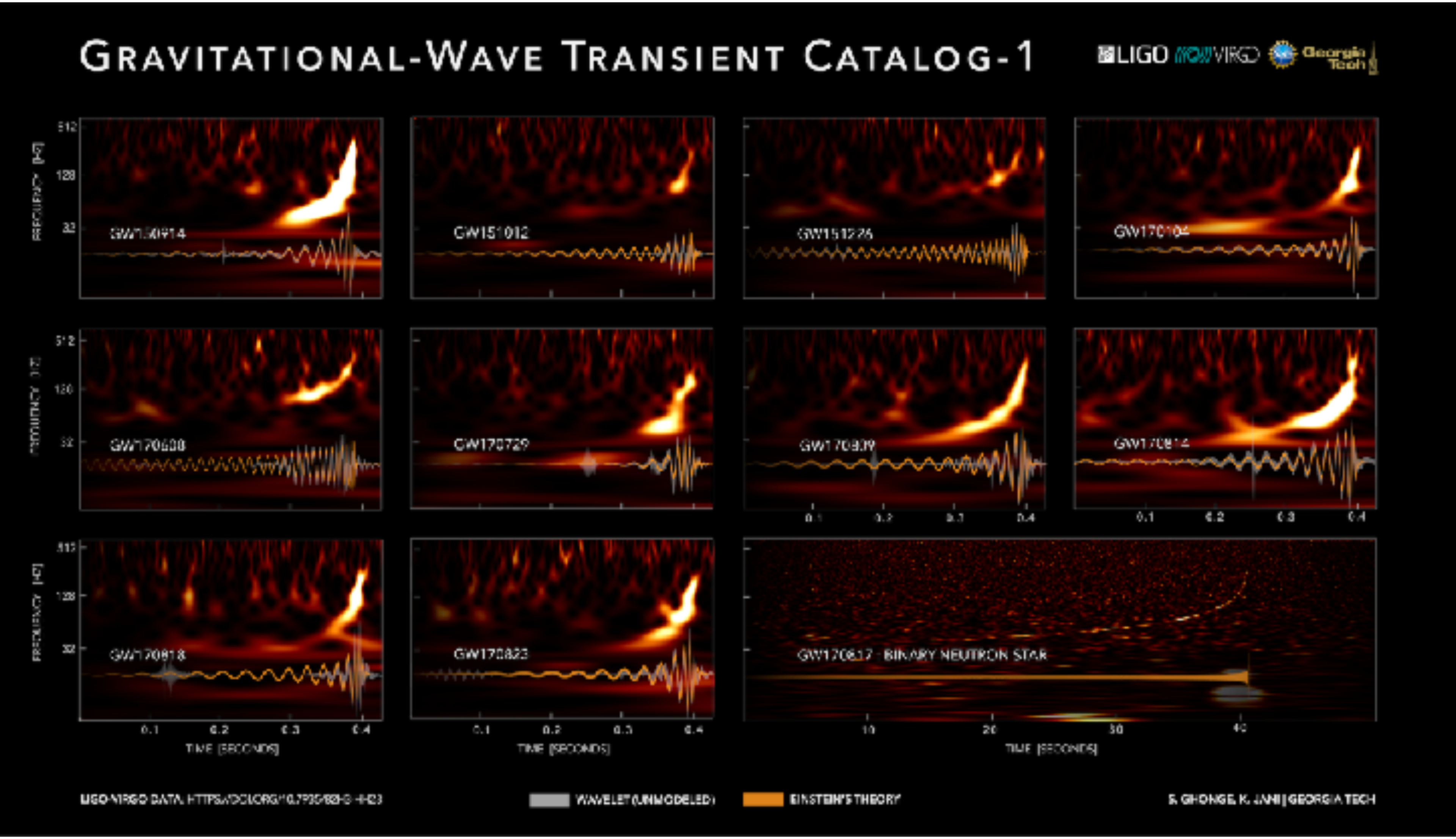
# GW Detectors:  LIGO, VIRGO, KAGRA




# Signatures of Gravitational Waves



# More Examples



# Future GW Research

- Identify sources of GW and precursors
- 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

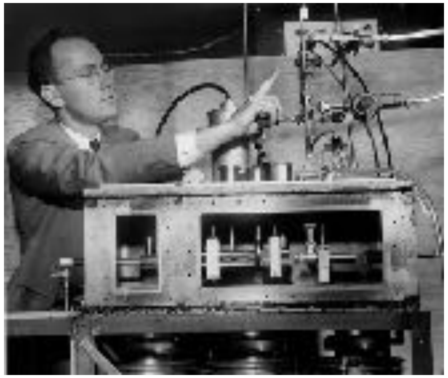
# Nobel Prizes for Gravity Wave Detection

- Taylor and Hulse (1993)
- Weiss, Thorne, and Barish (2017)

Ray Weiss working on Detectors in 70's

# Back Story on "Hearing Gravity"

- 1917: **Einstein** publishes "On the Quantum Theory of Radiation"
- 1953: Charles Townes discovered "maser"
- 1957: Charles Townes and others discovered "laser"
- 1964: **Townes**, Badov, Prokhorov awarded Nobel Prize for Quantum Electronics, Maser, and Laser
- 1968: MIT laboratories beginning to use lasers



  — as freshman at MIT, I joined evening "donut" seminars

  — central topic of seminar: what is the best experiment in physics

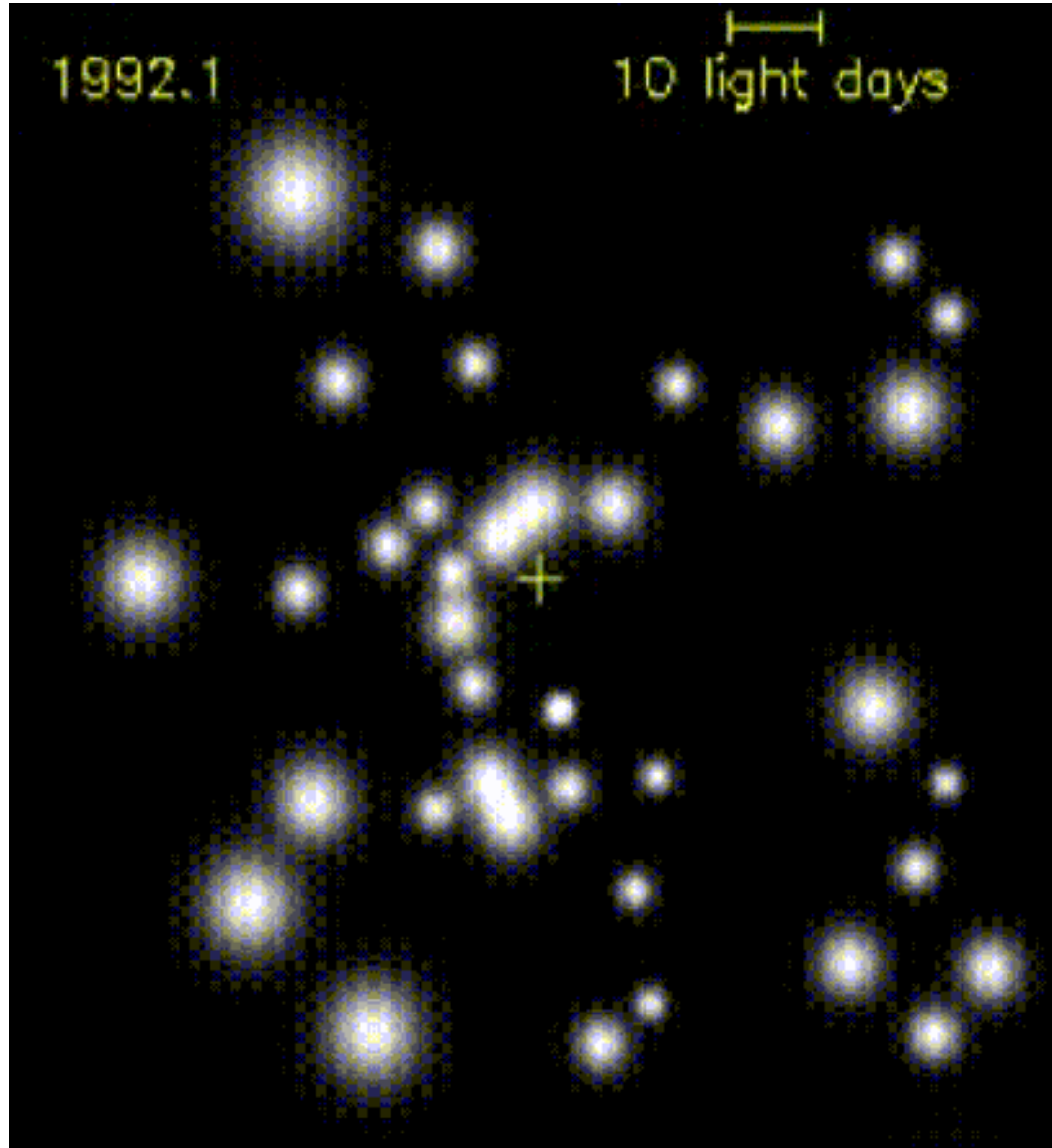
  — I worked on liquid dye lasers

  — Assistant Professor **Ray Weiss** worked on CMB and lasers

- 2017: Weiss, Thorne, Barish awarded Nobel Prize for Gravitational Wave detection: **~50 years** of laser + interferometry research

(— I gave up laboratory physics for astronomy)

# GRAVITY can be "FELT"



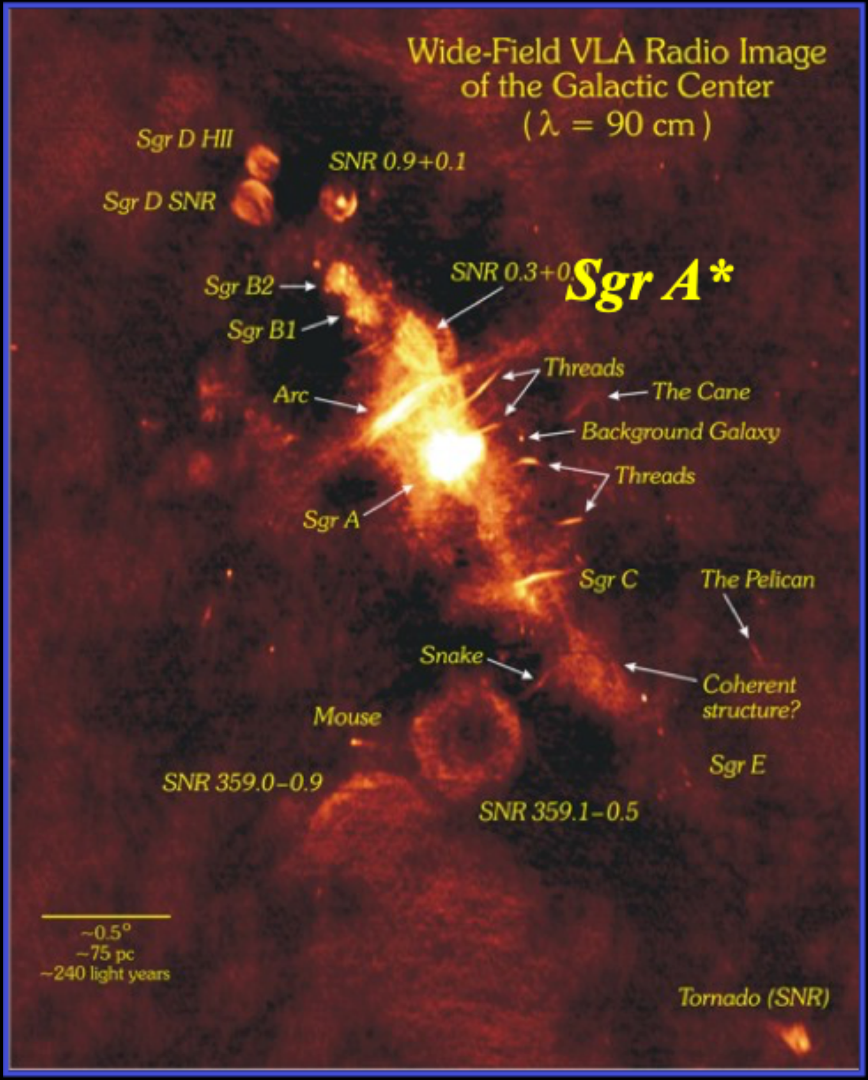

- The movement of stars - accelerated to a fraction of the speed of light around an invisible object - showed SgrA* is likely a supermassive black hole at the center of our galaxy
- Keck telescopes and GRAVITY (VLT) have tracked them over 20 years (Andrea Ghez, Reinhard Genzel)

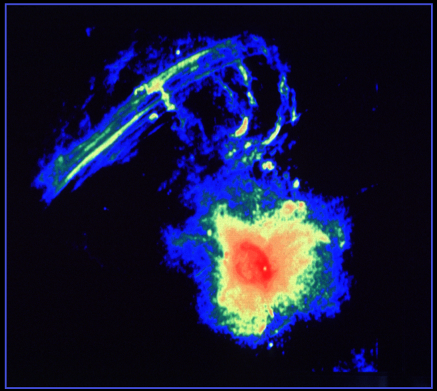
**MPIfR Movie**

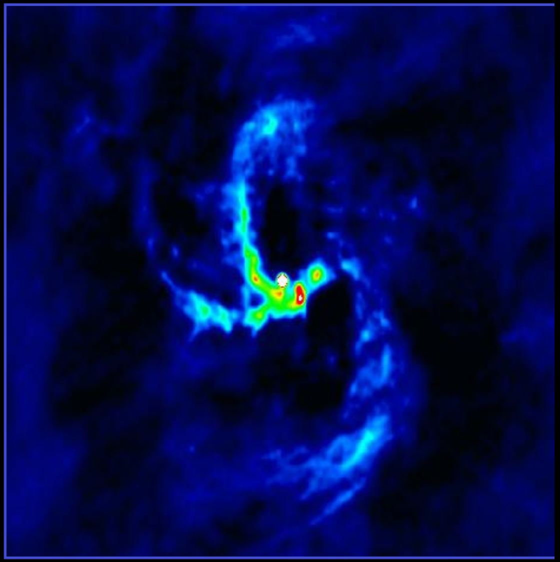
# Nobel Prize Physics 2020: Black Hole

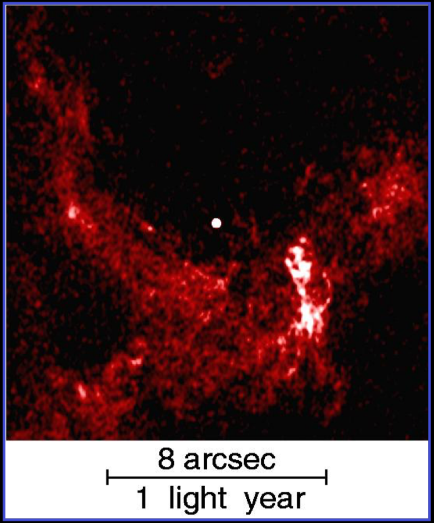
- **Roger Penrose (Oxford)**
- **Reinhard Genzel Group (MPI)**
- **Andrea Ghez Group (UCLA)**

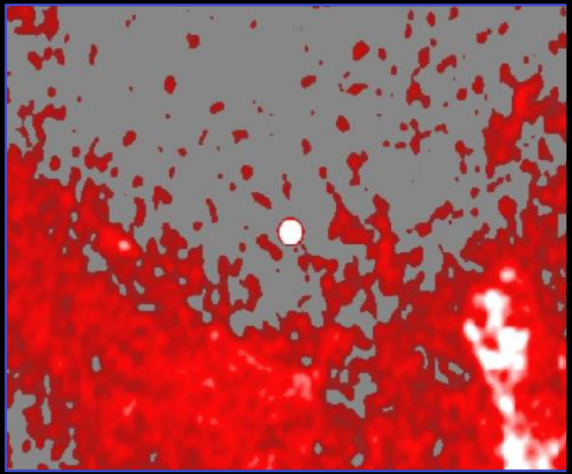
# Center of the Galaxy (radio)



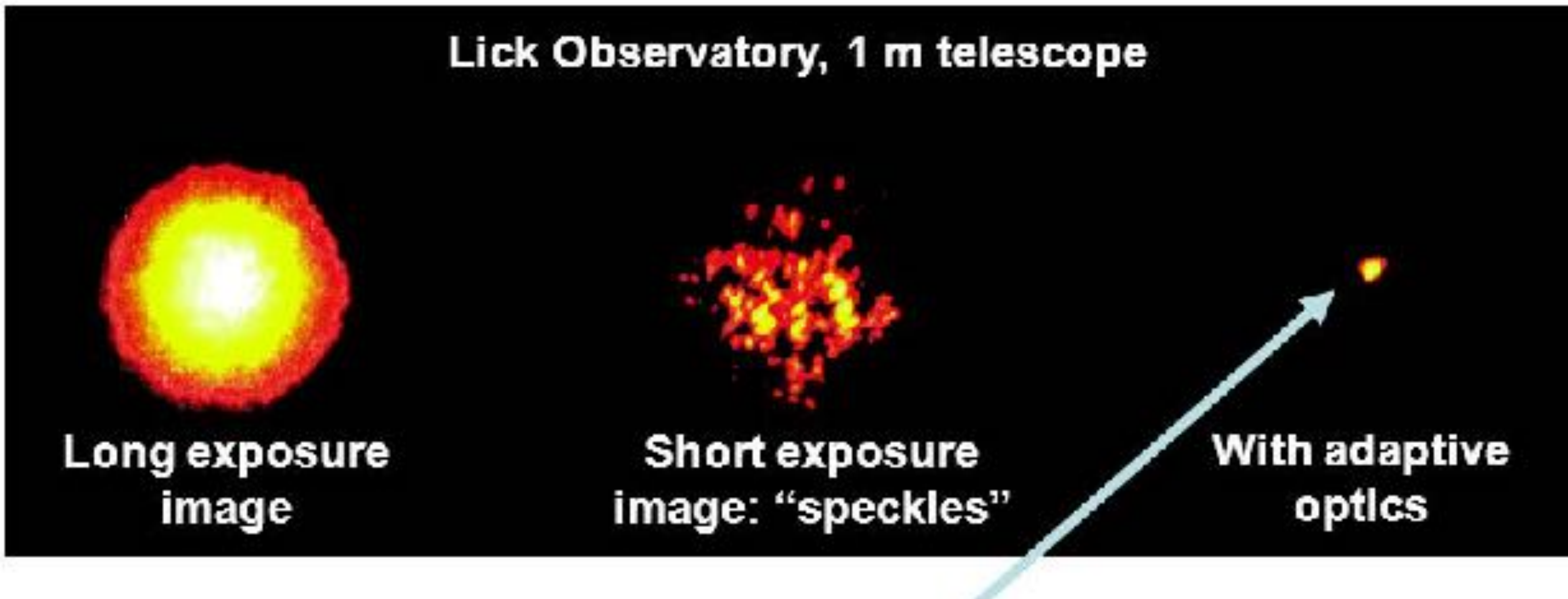




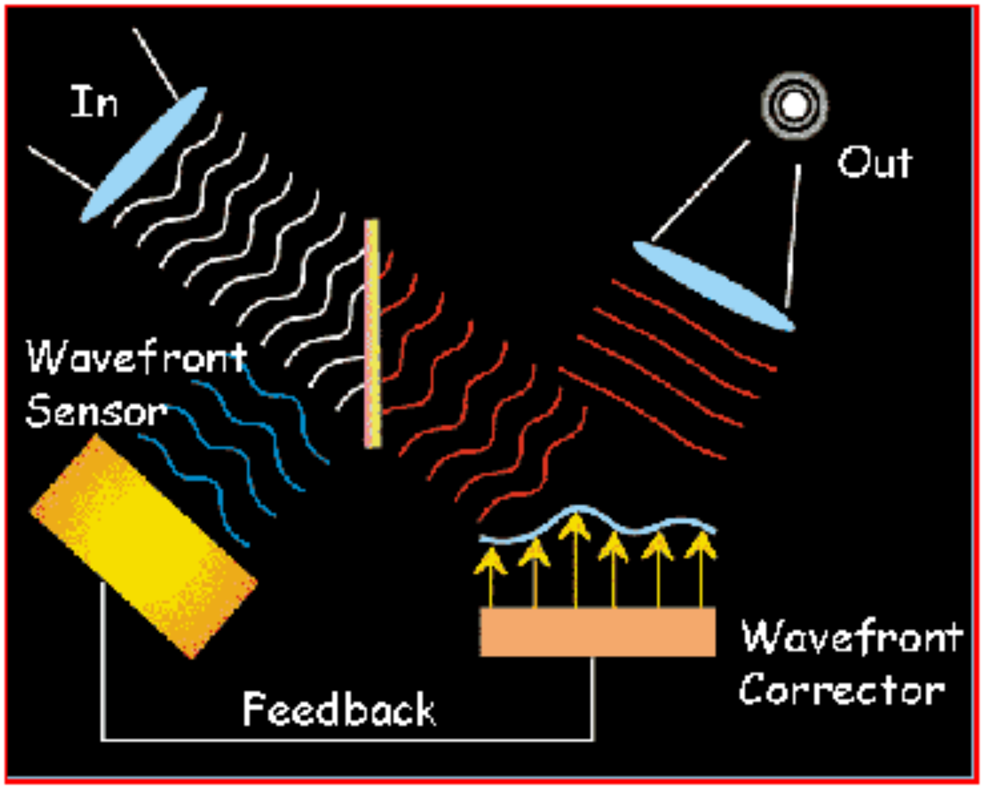
# Why do astronomers need AO?

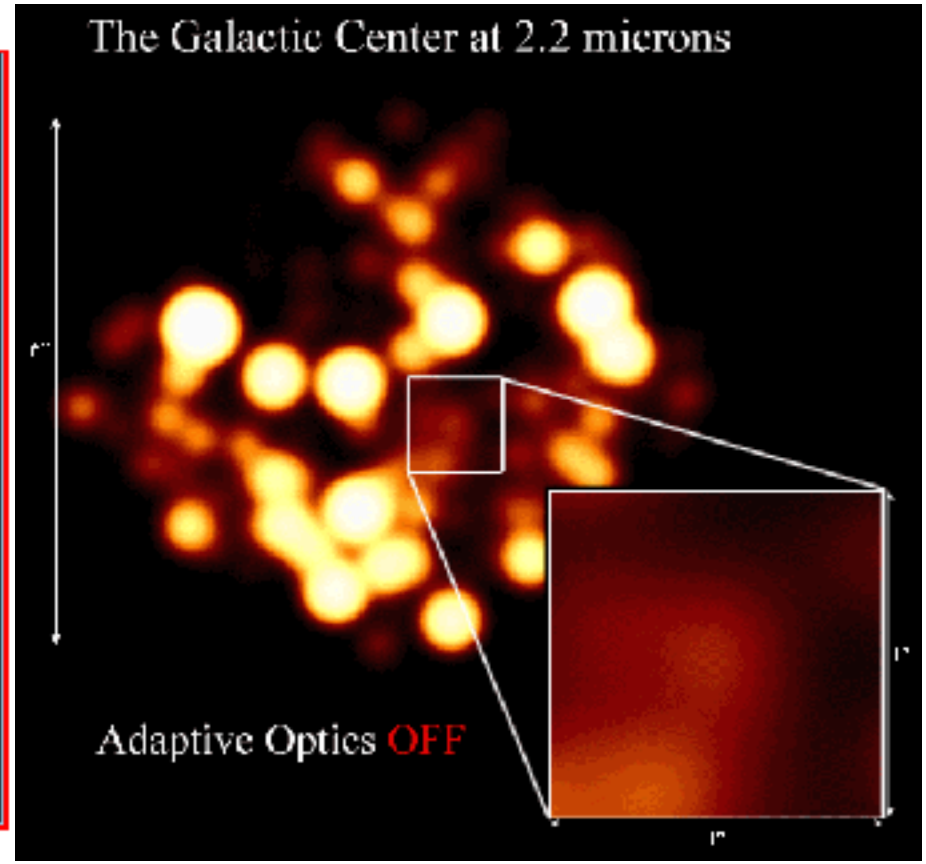
## Three images of a bright star:




If image of a star is very small, your telescope will also be able to see fine details of galaxies, star clusters, ...

# Adaptive Optics: New Technology

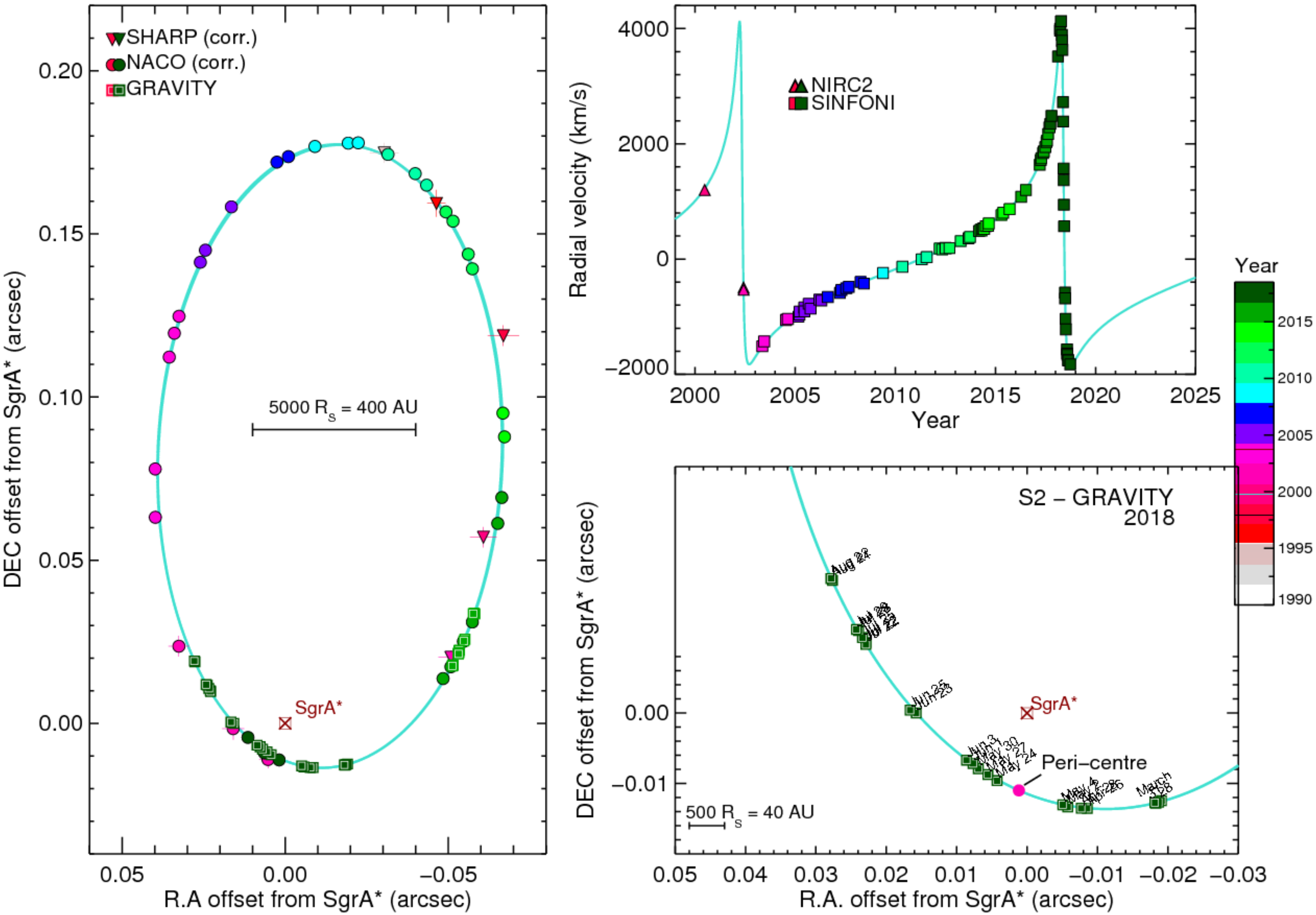



**Galactic Center results from UCLA**

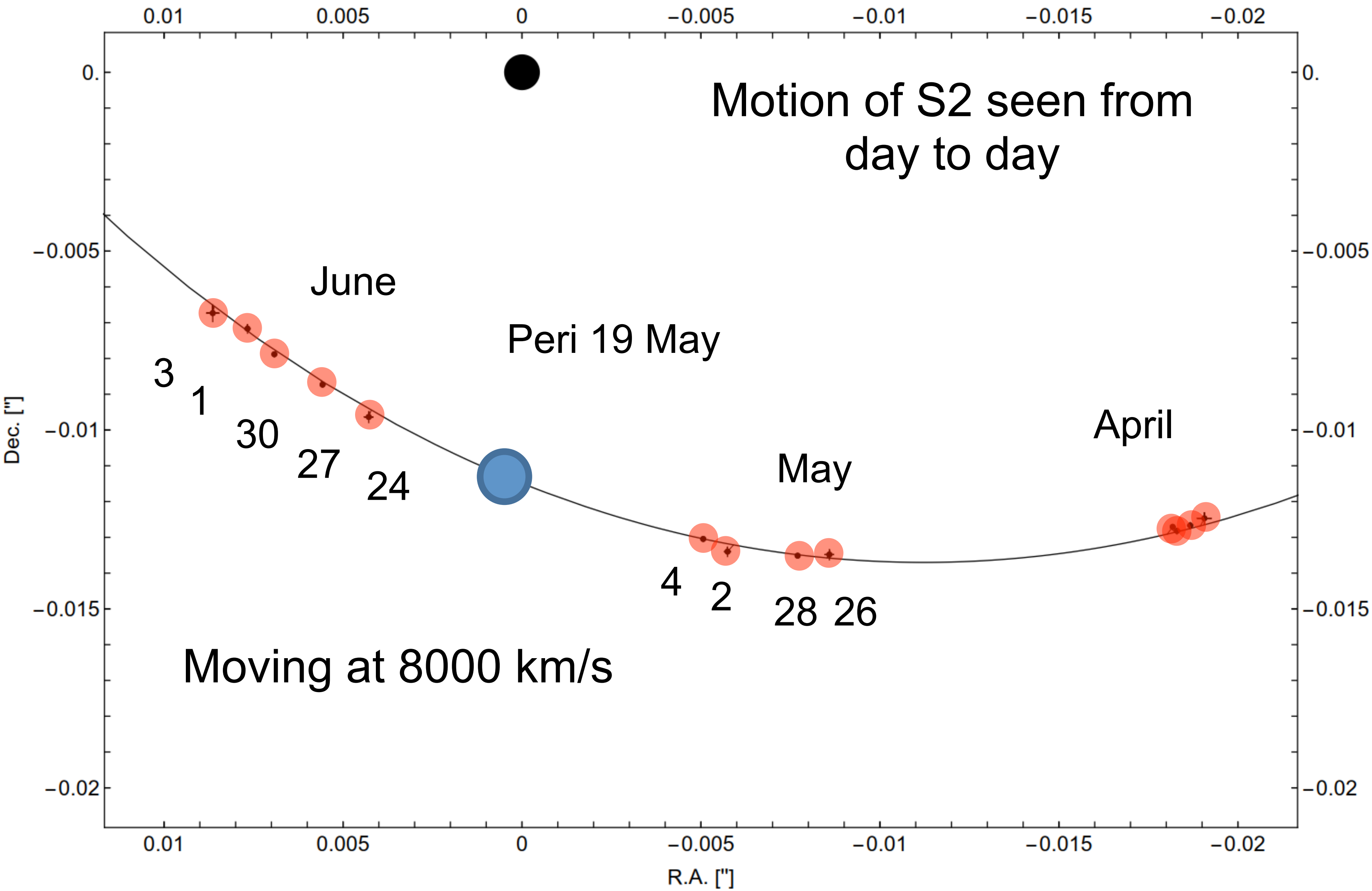
# Stars in Orbit around SgrA*

## 26 years of observations of S2



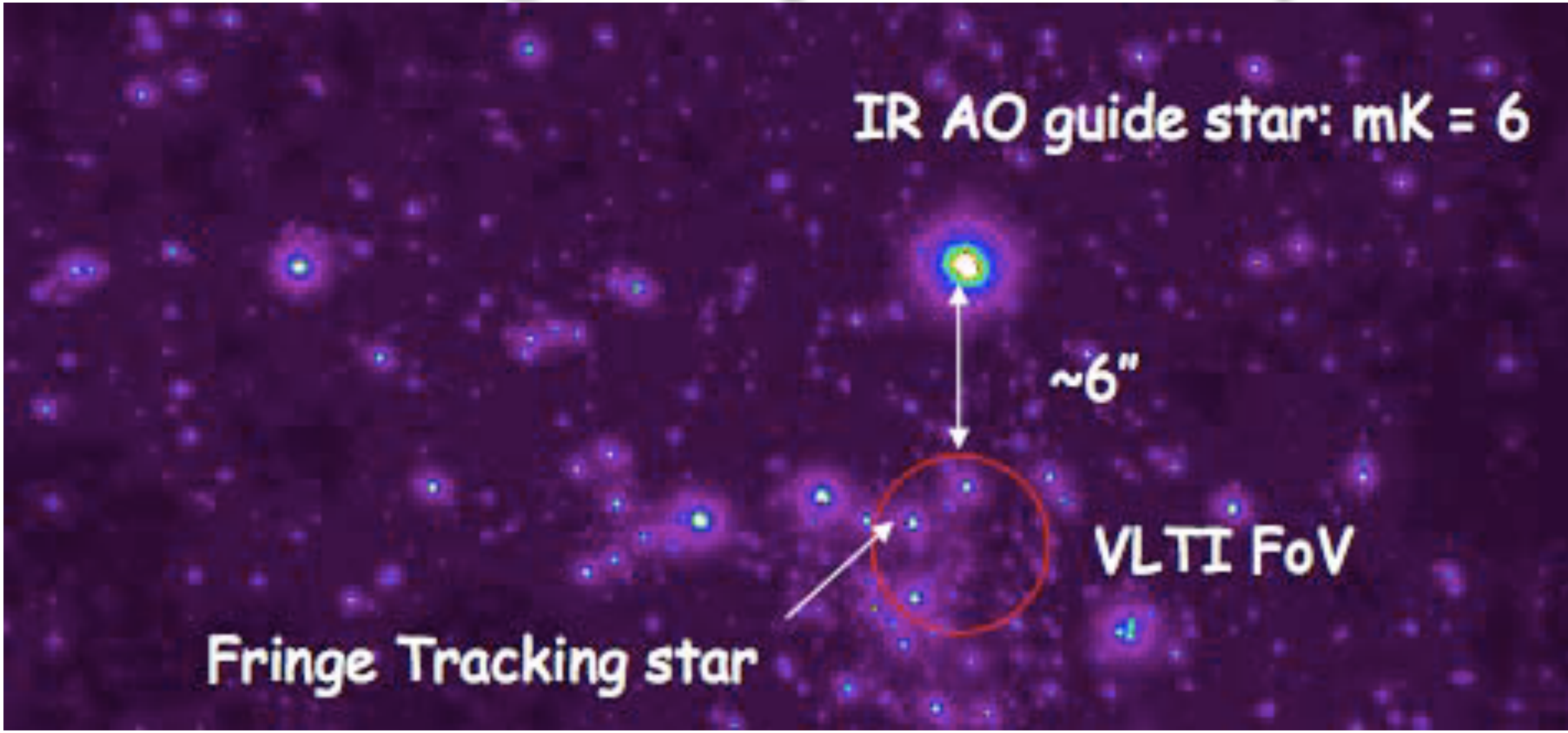

GRAVITY collaboration+18a, A&A 615, L10

# Orbit of S2 relative to SgrA*

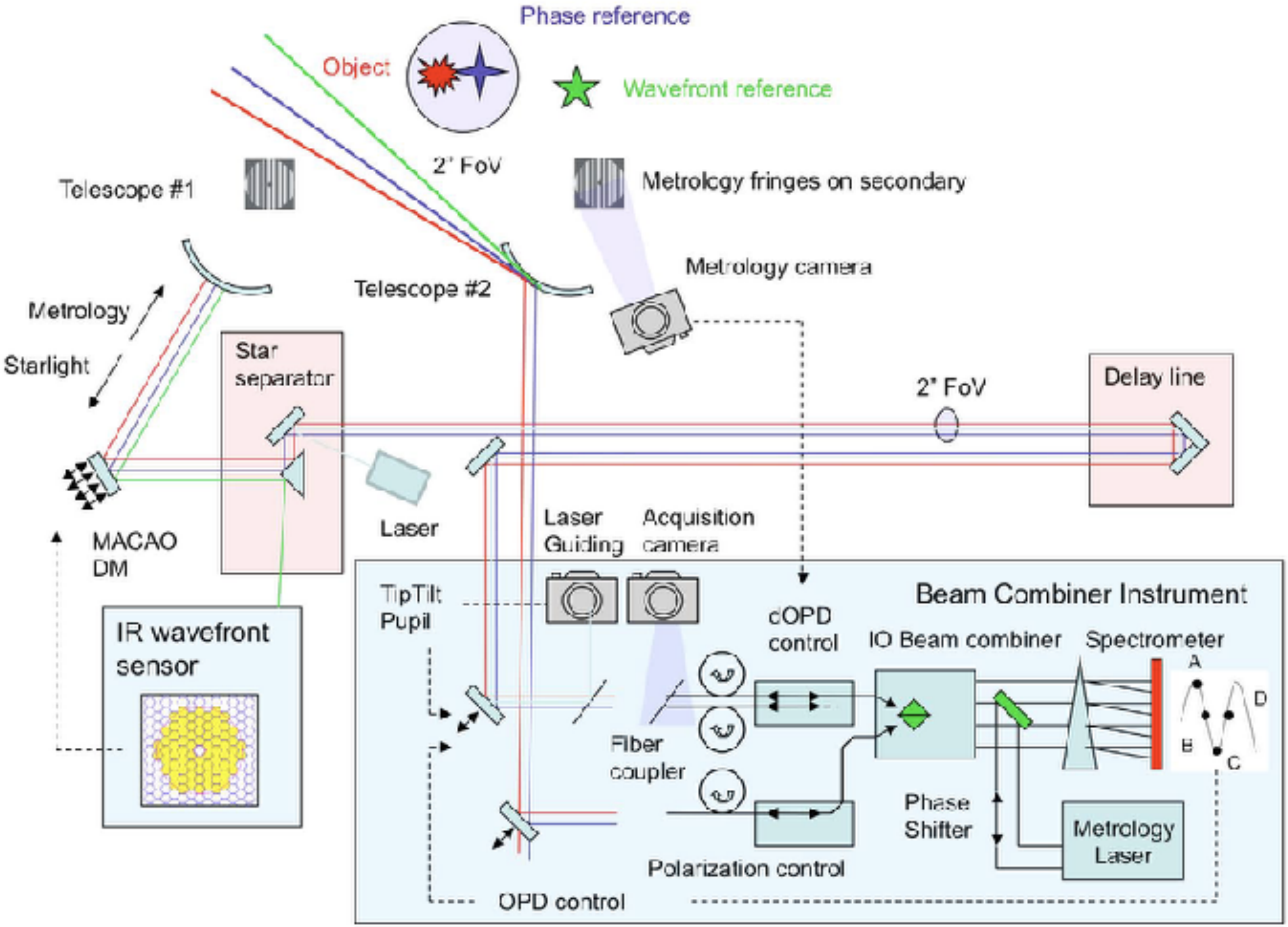



ESO VLTI

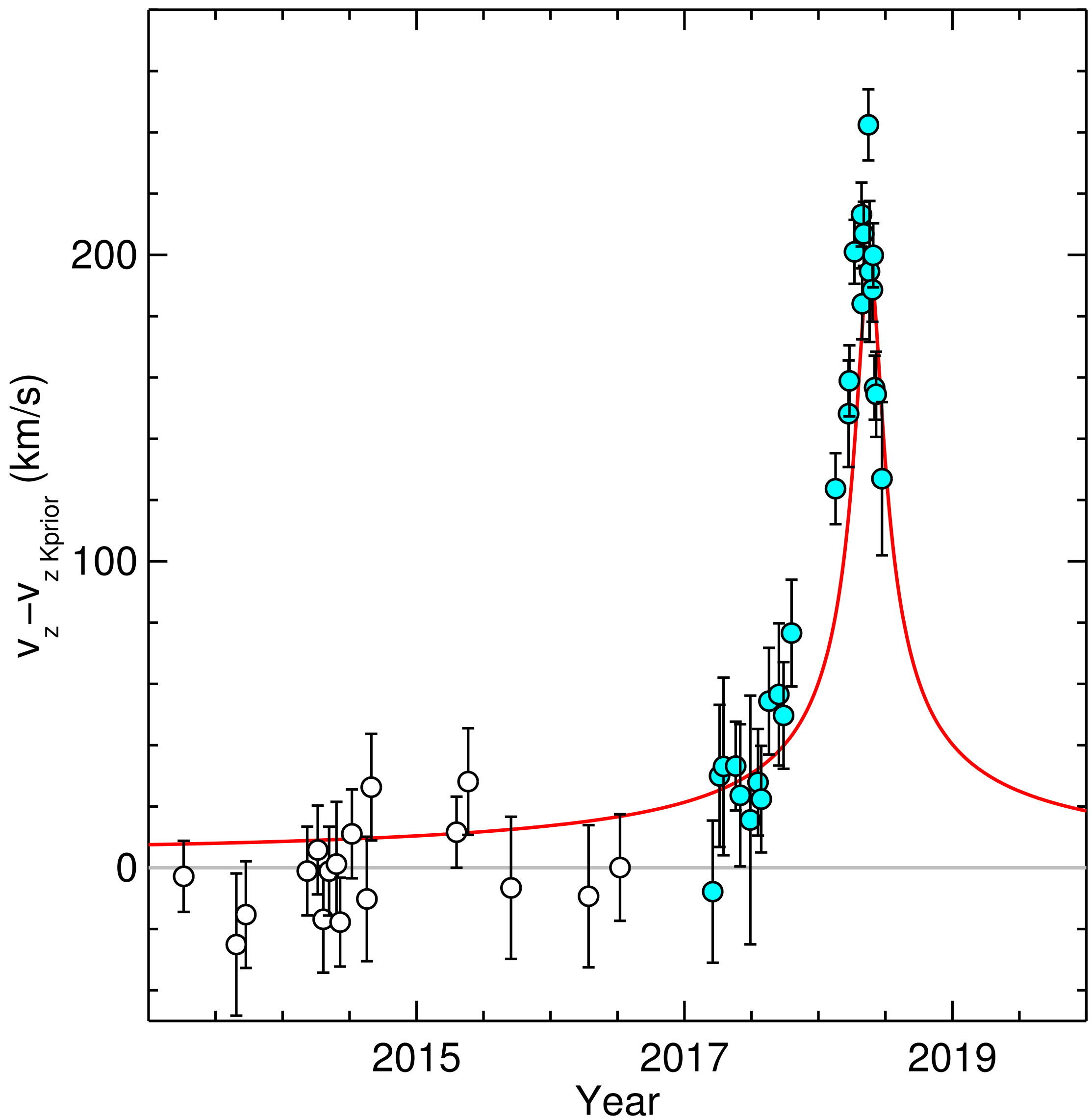
# Working Principle of "Gravity"



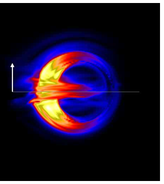

- Guide Star for Adaptive Optics (atmospheric seeing)
- Fringe Tracking Star for Phase (interferometer baselines)
- VLTI for Interferometry (high angular resolution)
- 6 baselines; 3 x $10^{-3}$ ″ resolution; ~40 x $10^{-6}$ ″ astrometry


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
Laser Guiding
Acquisition camera
MACAO DM
Beam Combiner Instrument
TipTilt Pupil
cOPD control
IO Beam combiner
Spectrometer
IR wavefront sensor
A
D
B
C
Fiber coupler
Phase Shifter
Metrology Laser
Polarization control
OPD control

# Motion of S2 shows GR Redshift



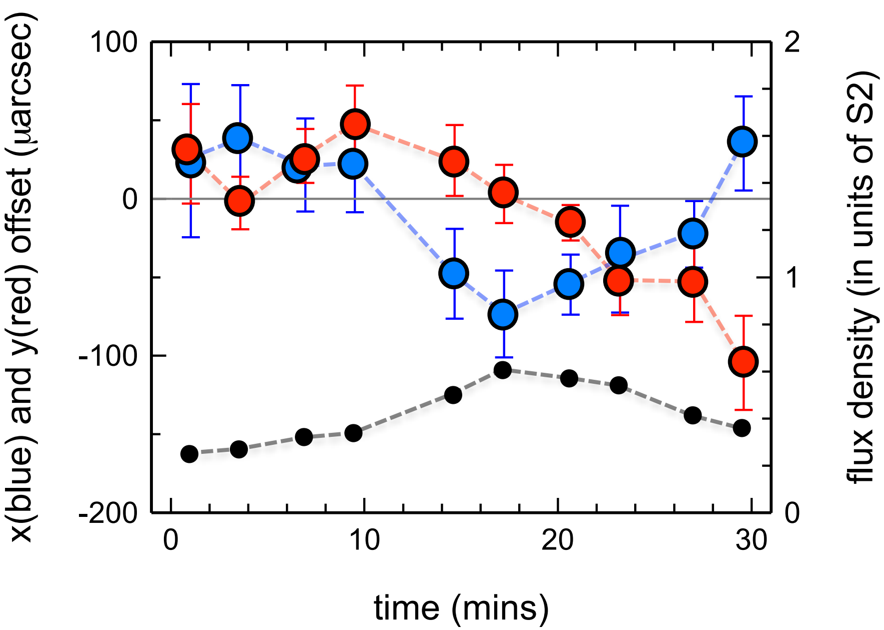

**PPN1$_{RS}$(λ)**

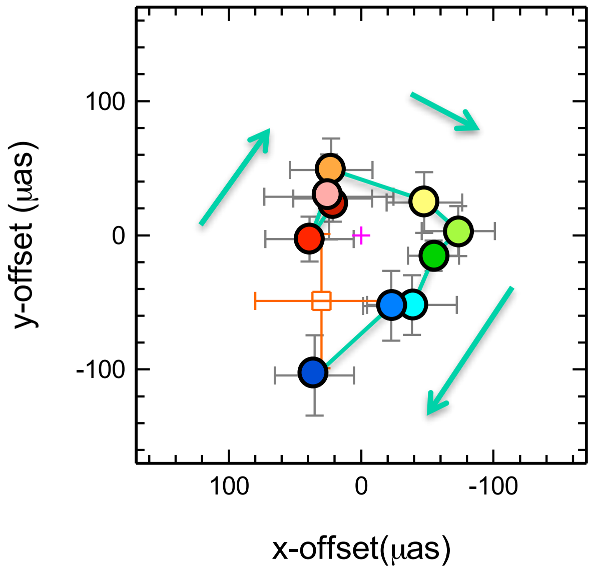


# Hot SPOT in ORBIT at ISCO

## Detection of orbital motions near SgrA*s ISCO

**July 22nd, 2018**



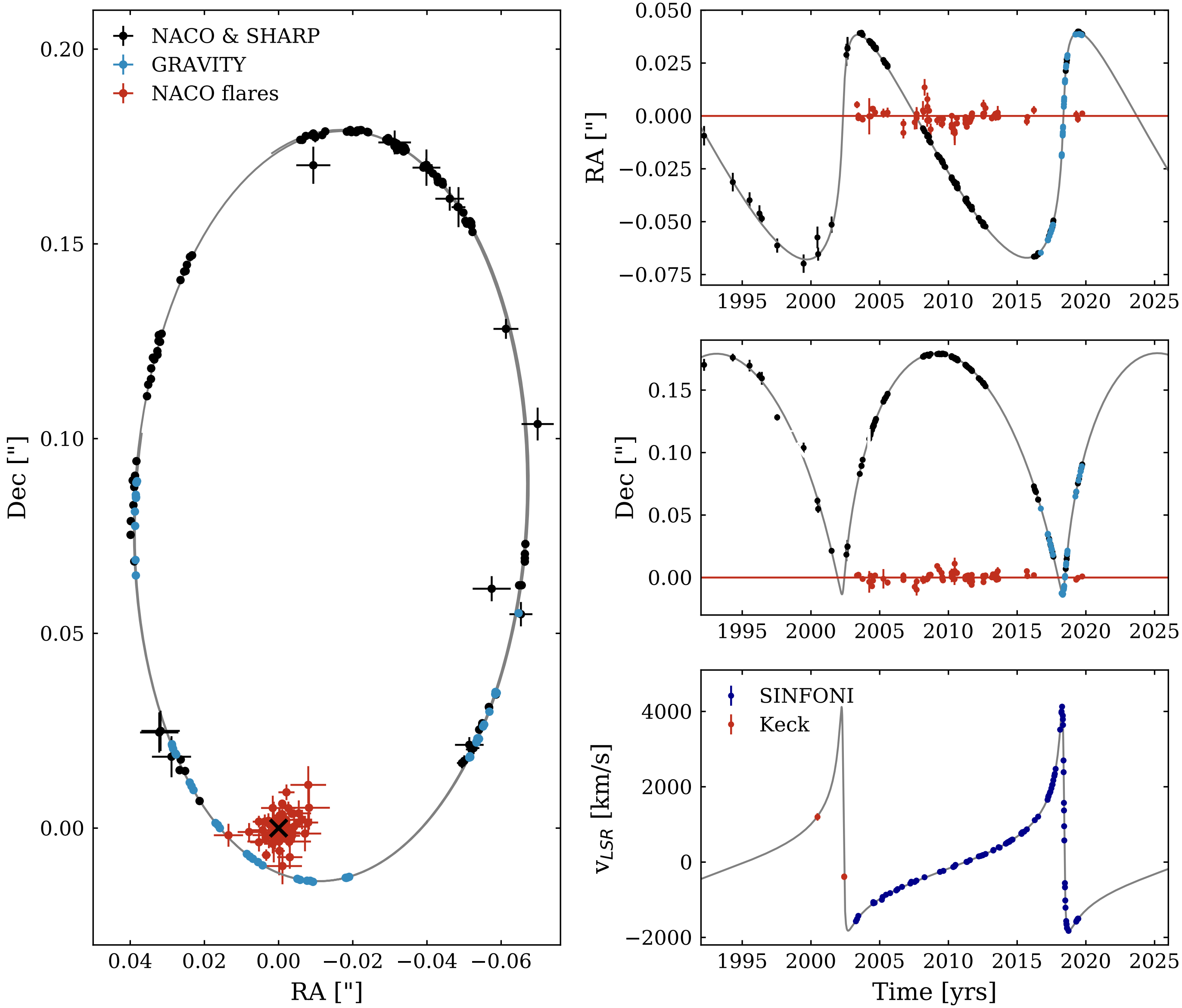




$v_{orb}$~0.3 c

Broderick & Loeb 2006,
Hamaus et al. 2009

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

# Schwarzschild Precession of Orbit



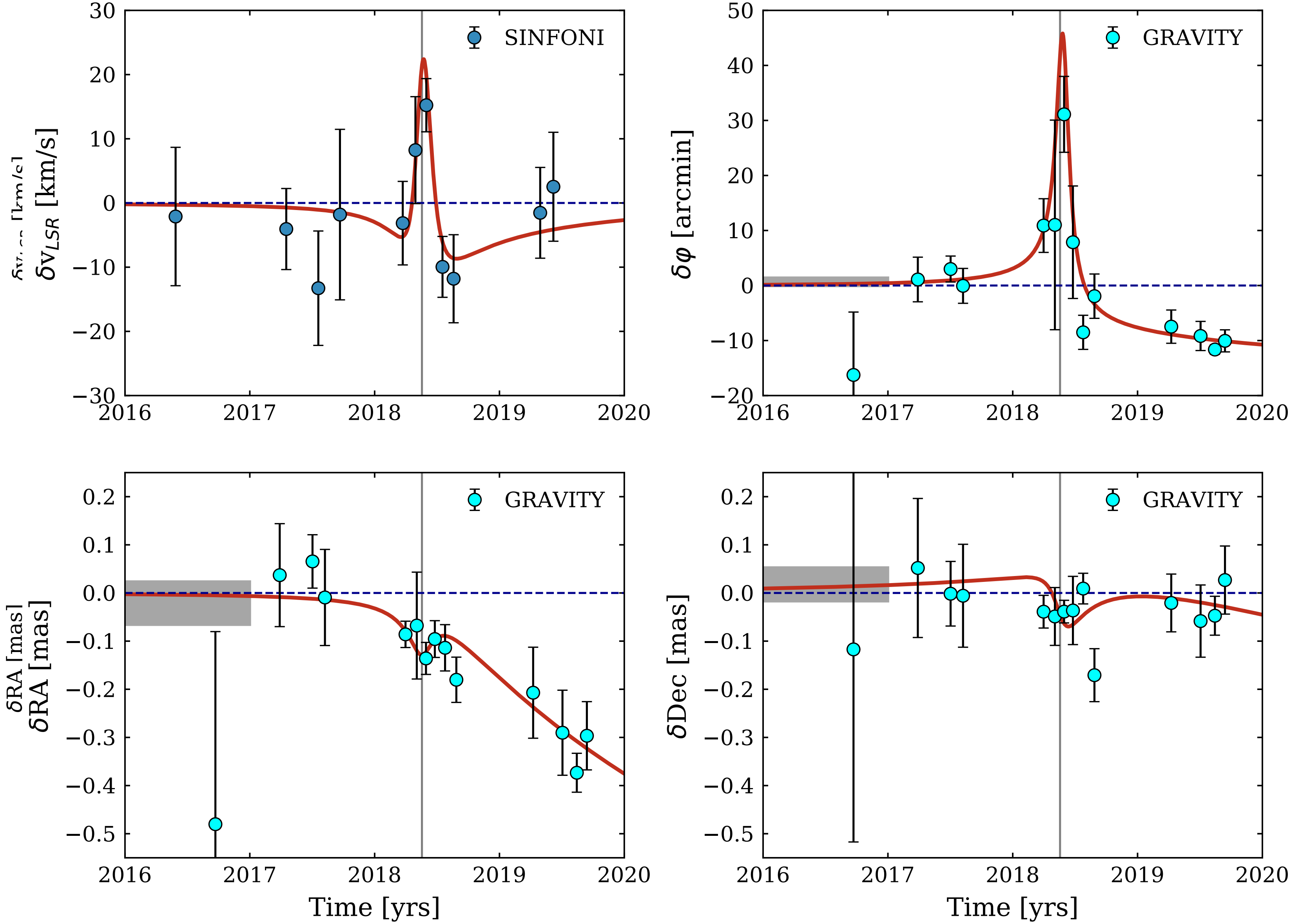

**GR Orbit:**

**PPN1$_{SP}$(x,y)**

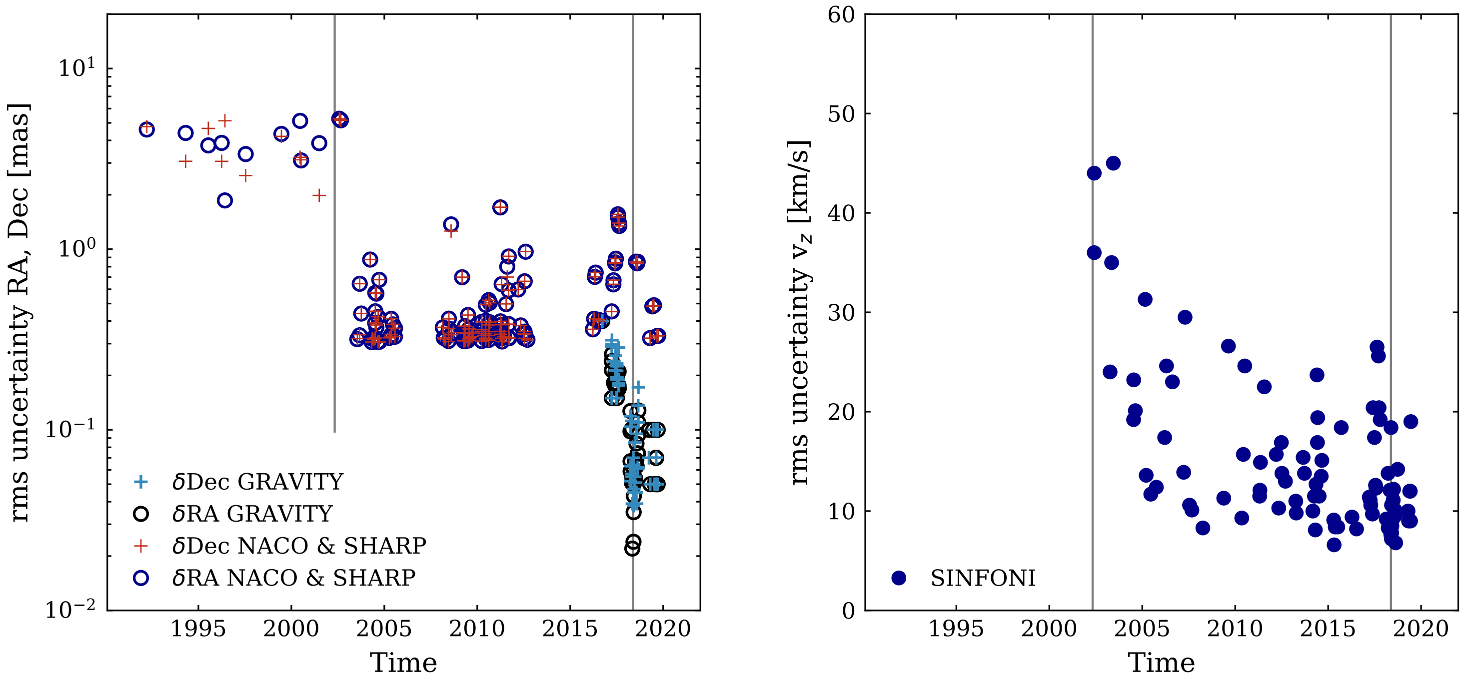
**Prograde Precession of 12.1' upon Kepler Orbit**

**Red Points are data of SgrA* wrt S2**

# GR Orbital Fits



# Increase in Precision



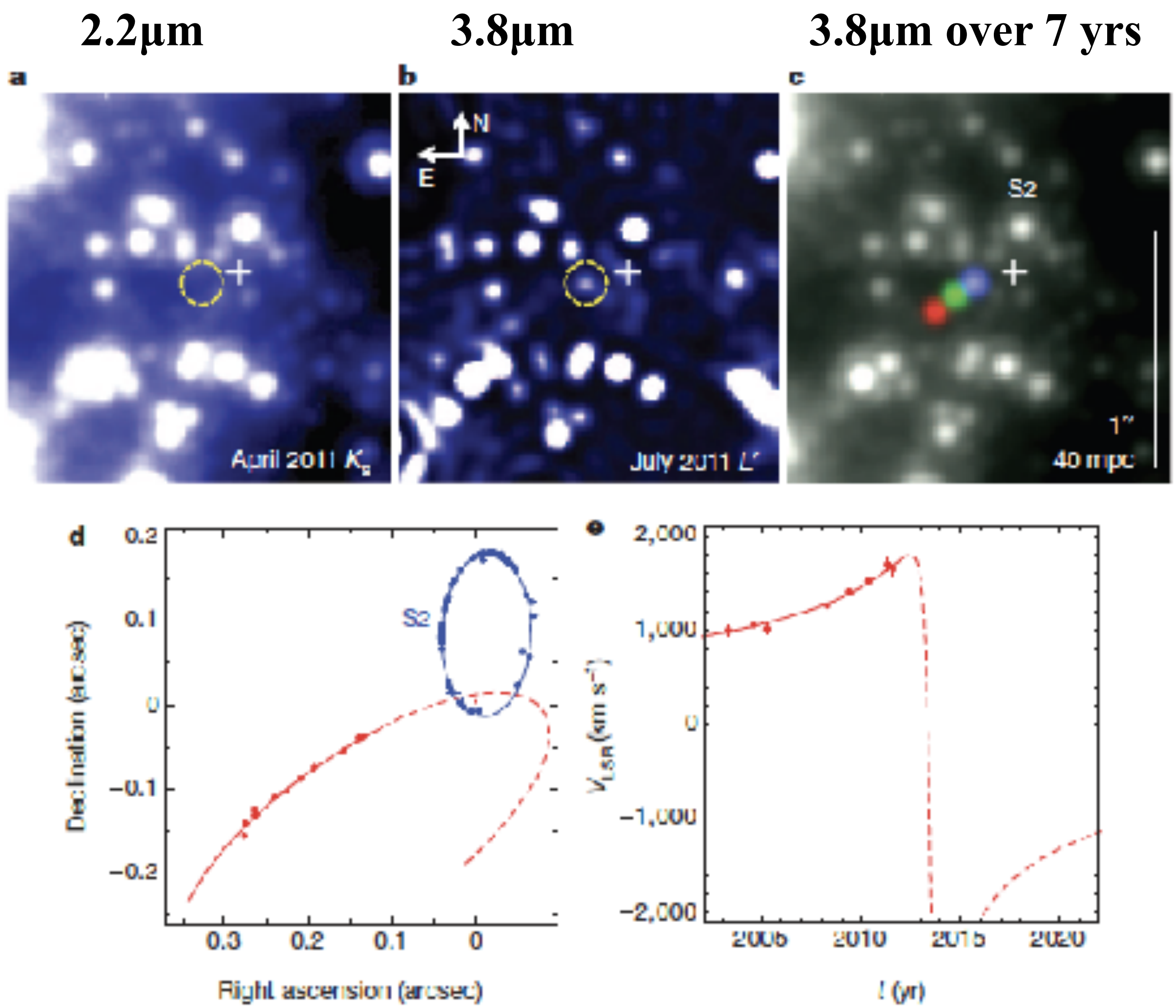

**Precision Improved by a factor of 100 !**

***because* of Interferometry**

# 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

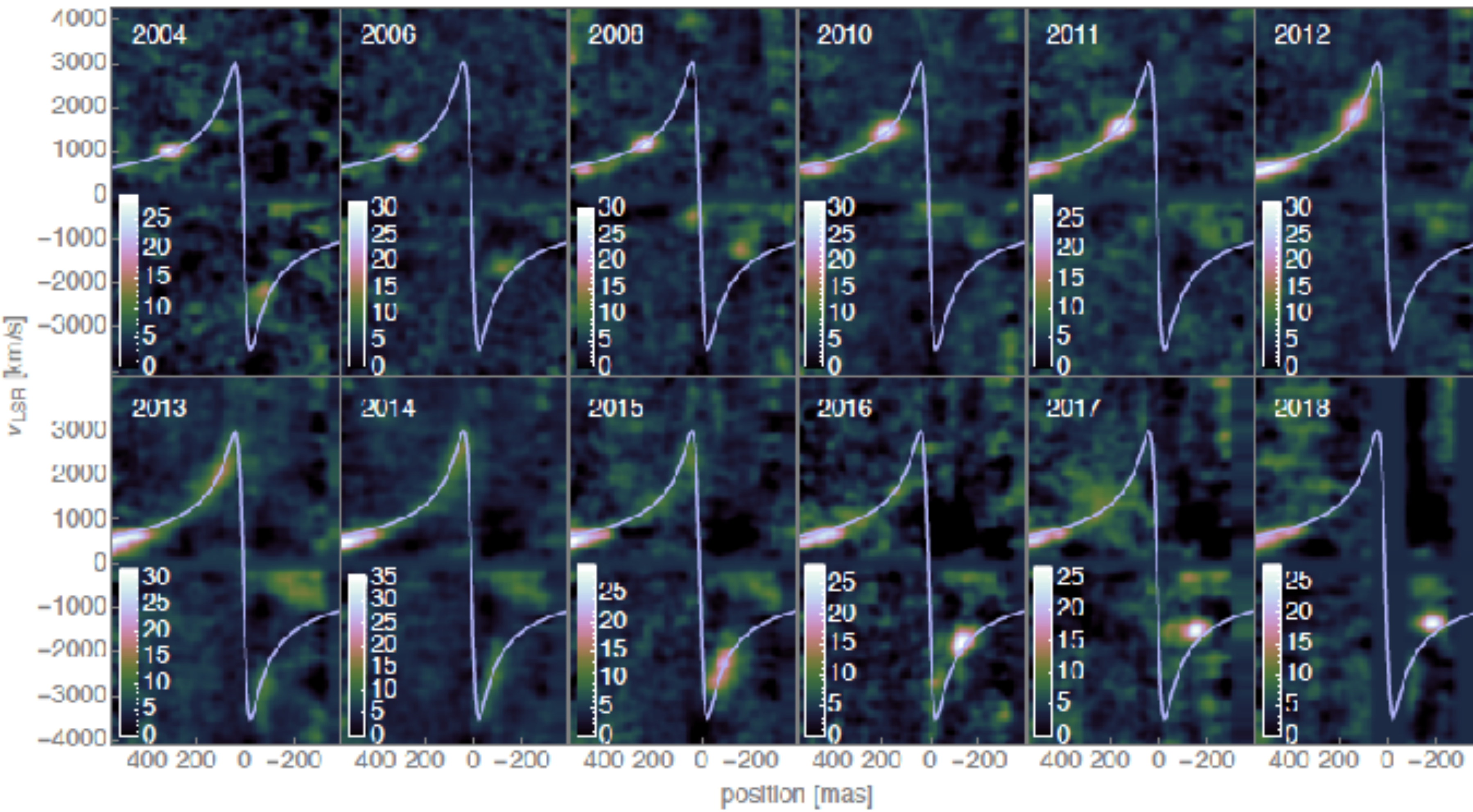
# Ionized Gas Gloud G2 near SgrA*




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

# Back Story on "Feeling Gravity"

- 1967: Charles **Townes** moves to UC Berkeley from MIT
- 1980: Townes group detect motions around Galactic Center with mid-infrared spectroscopy of ionized gas

- 1980: Reinhard **Genzel** joins Townes group
  — Genzel moves from VLBI to infrared astronomy
  (— I moved to Submm Interferometry)
- 1992: Genzel Starts Measuring Orbit of S2 around SgrA*
- 2002: 15.2 year Orbit defined
- 2018: Gravity Instrument measures motions near Event Horizon of Sgr A* : Lasers and Interferometry
- Nobel Prize awarded to **Genzel** and **Ghez** for discovering Black Hole: **~50 years** of laser + interferometry research

(— I worked on Imaging Black Hole)

# Summary

- **Nobel Prize Winning Work defined by Precision**
- **Science typically addresses Fundamental Physics**
- **Science typically discovers Important Phenomena**
- **Discoveries typically leads to further Important Discoveries**
- **Discoveries typically enabled by New Technology**

- **Some Nobel Prize Winners stimulate more Prize Winning Work. Why?**
- **Some Problems have multiple Prize Winning Work. Why?**

# 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: $\sim 5R_{sch} \sim 40 \times 10^{-6}\,''$)**
- **Very Long Baseline Interferometry**

  **at Submm Wavelength**

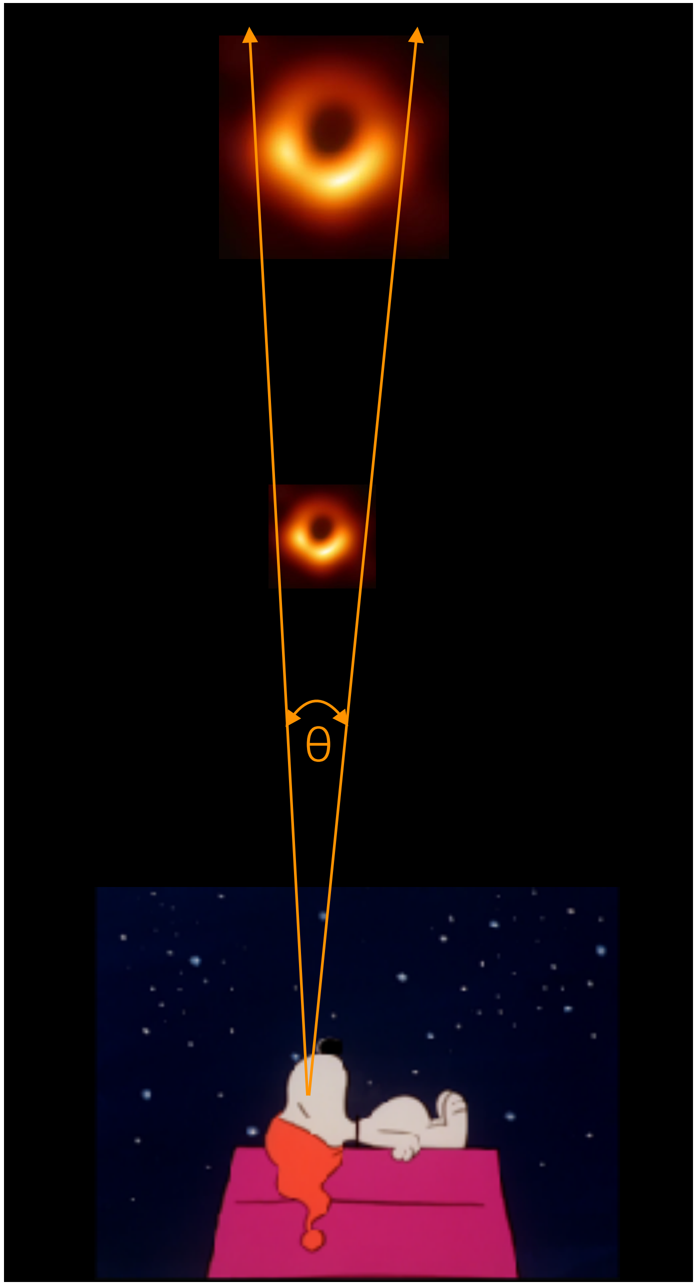
**Precision $\sim 10^{-10}$**

# 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:

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

**<u>DIFFRACTION PROBLEM</u>**

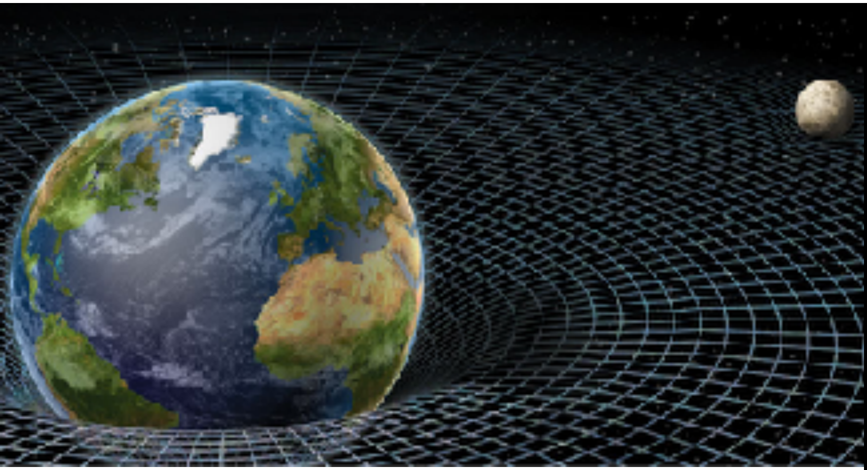


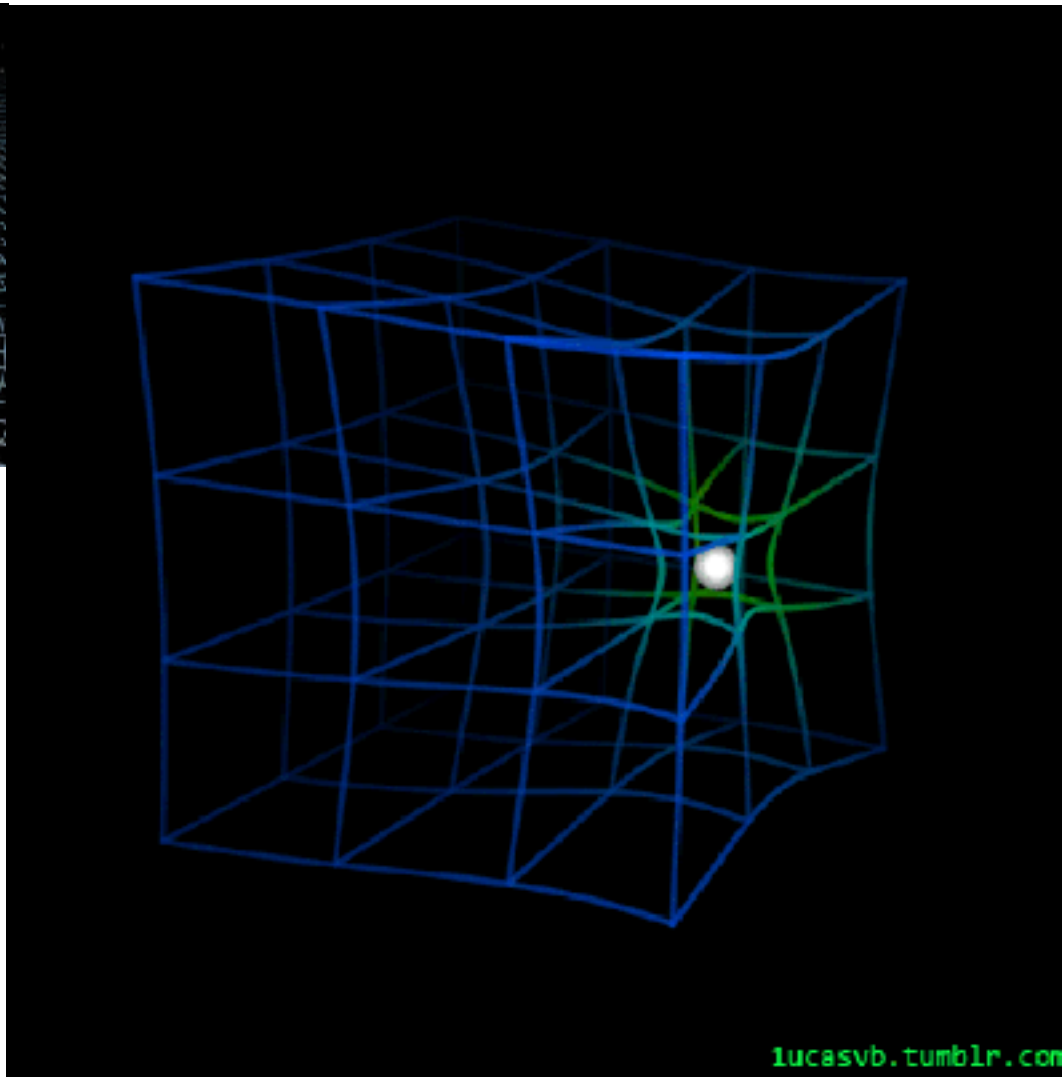
# Very Long Baseline Interferometer

- **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) — <u>IMAGE RECONSTRUCTION</u>**

# Gravity affects Geometry of Space

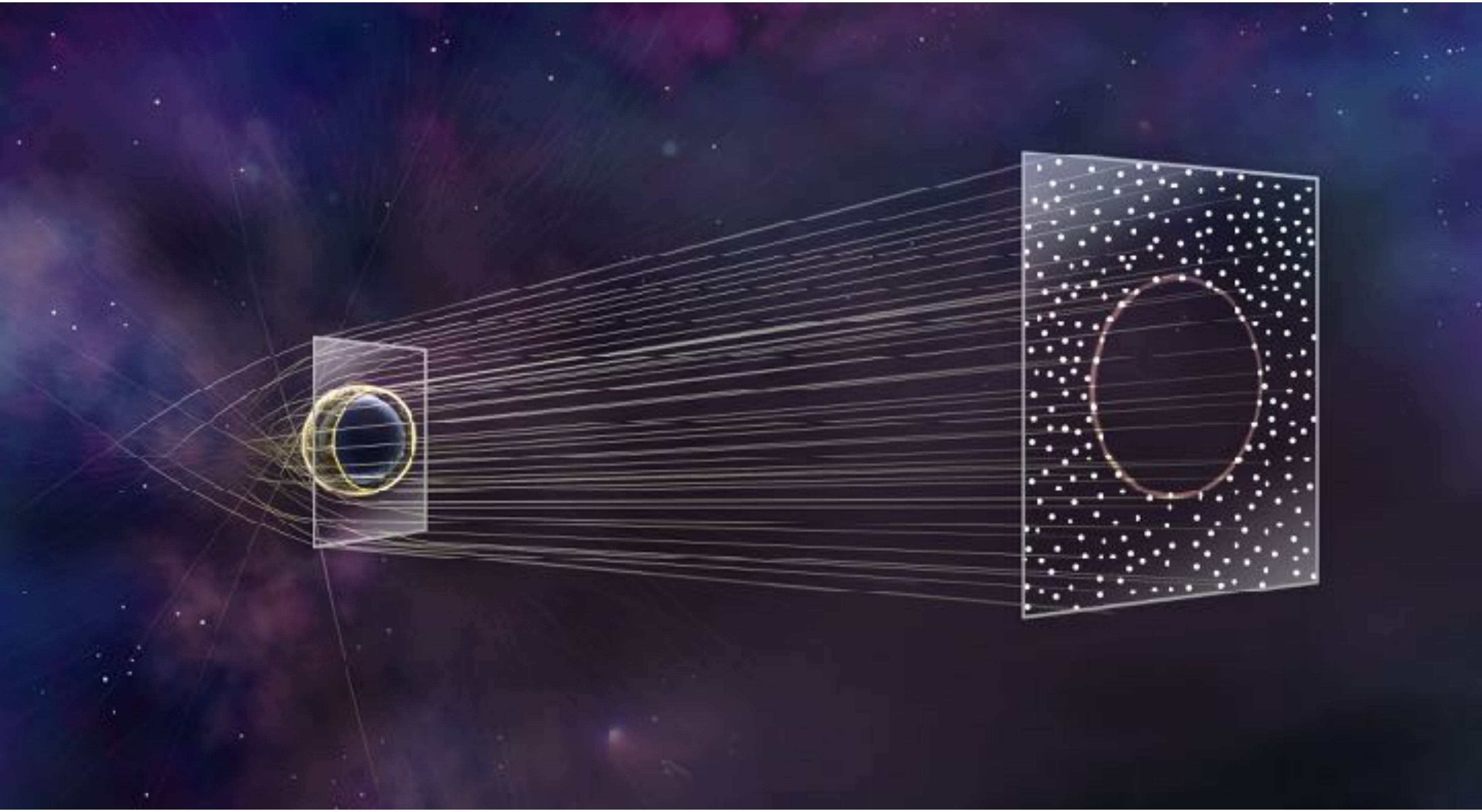




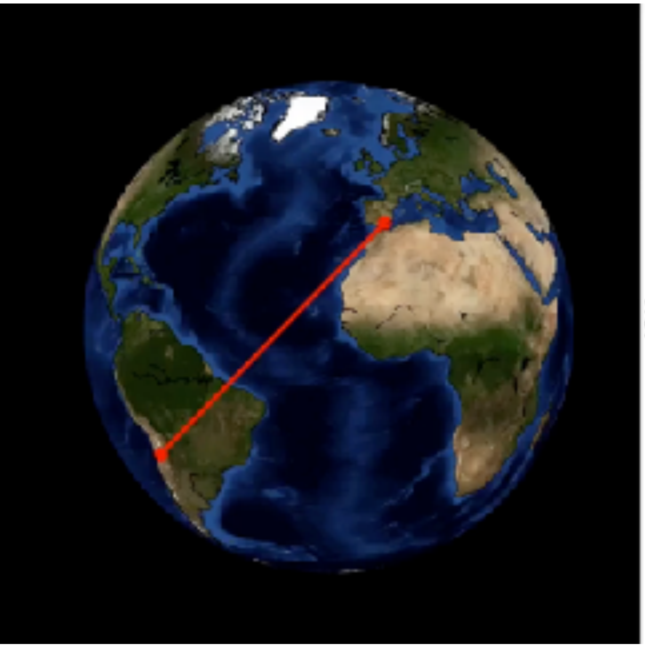

- Mass will distort space-time until even light cannot escape
- Einstein predicted the existence of black holes - though even he was not comfortable with the conclusions from his equations

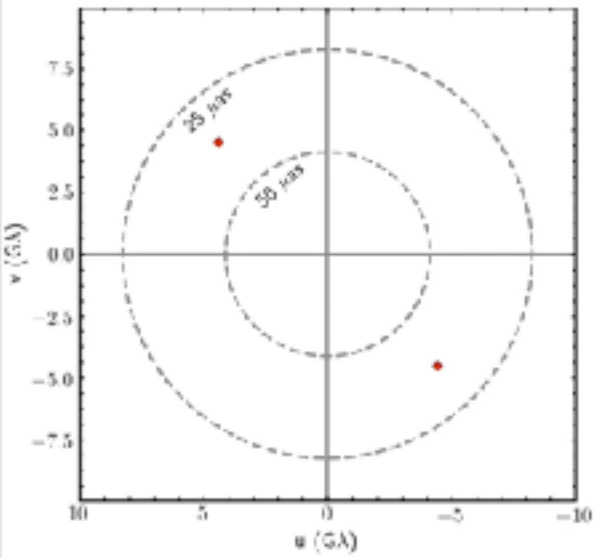
**Gravity/Geometry instead of Material/Dielectric to bend Light**

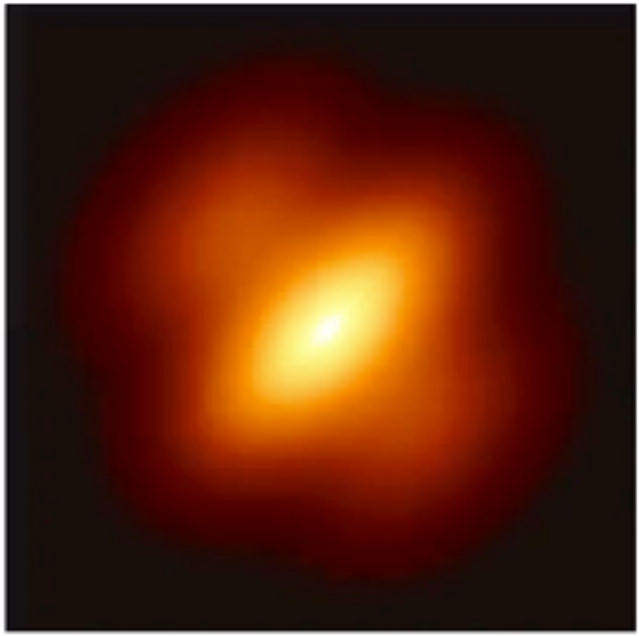
# Shadow comes from General Relativity
# Shadow Diameter ~ 5.2 $R_{sch}$



Event Horizon Telescope





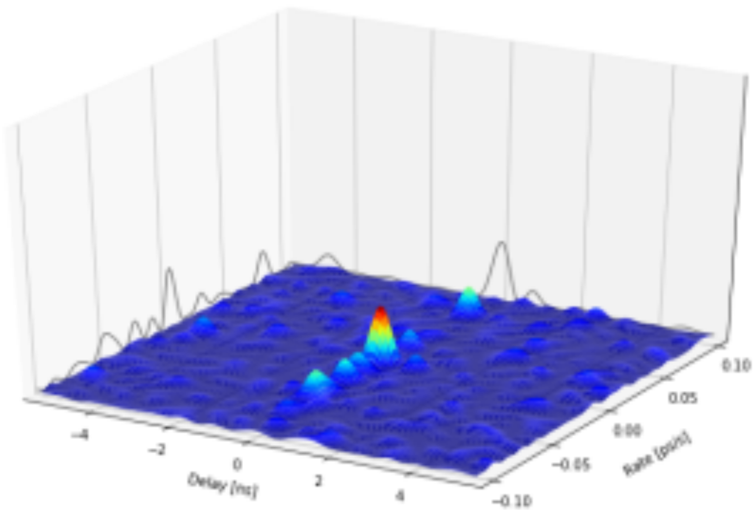
# Aperture Synthesis: Building up UV Coverage

## Visibility = Sampling · Source + Error

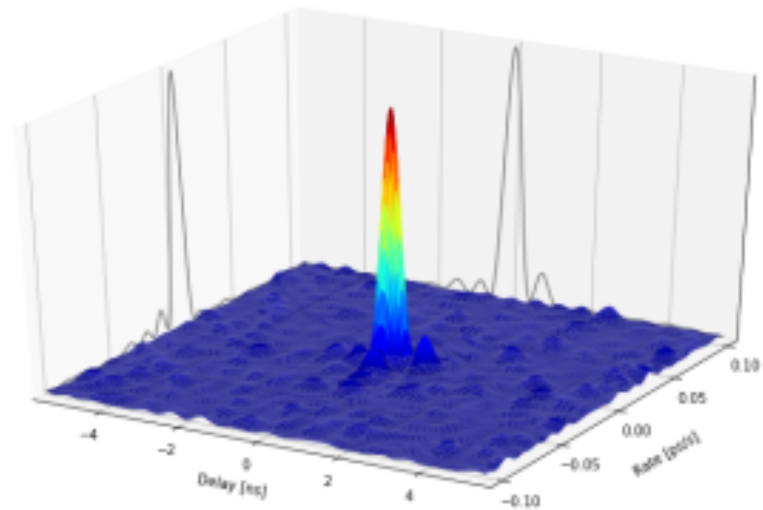
# Removing "Errors"

## Radio Version of Adaptive Optics

**before** ad-hoc phasing




**after** ad-hoc phasing

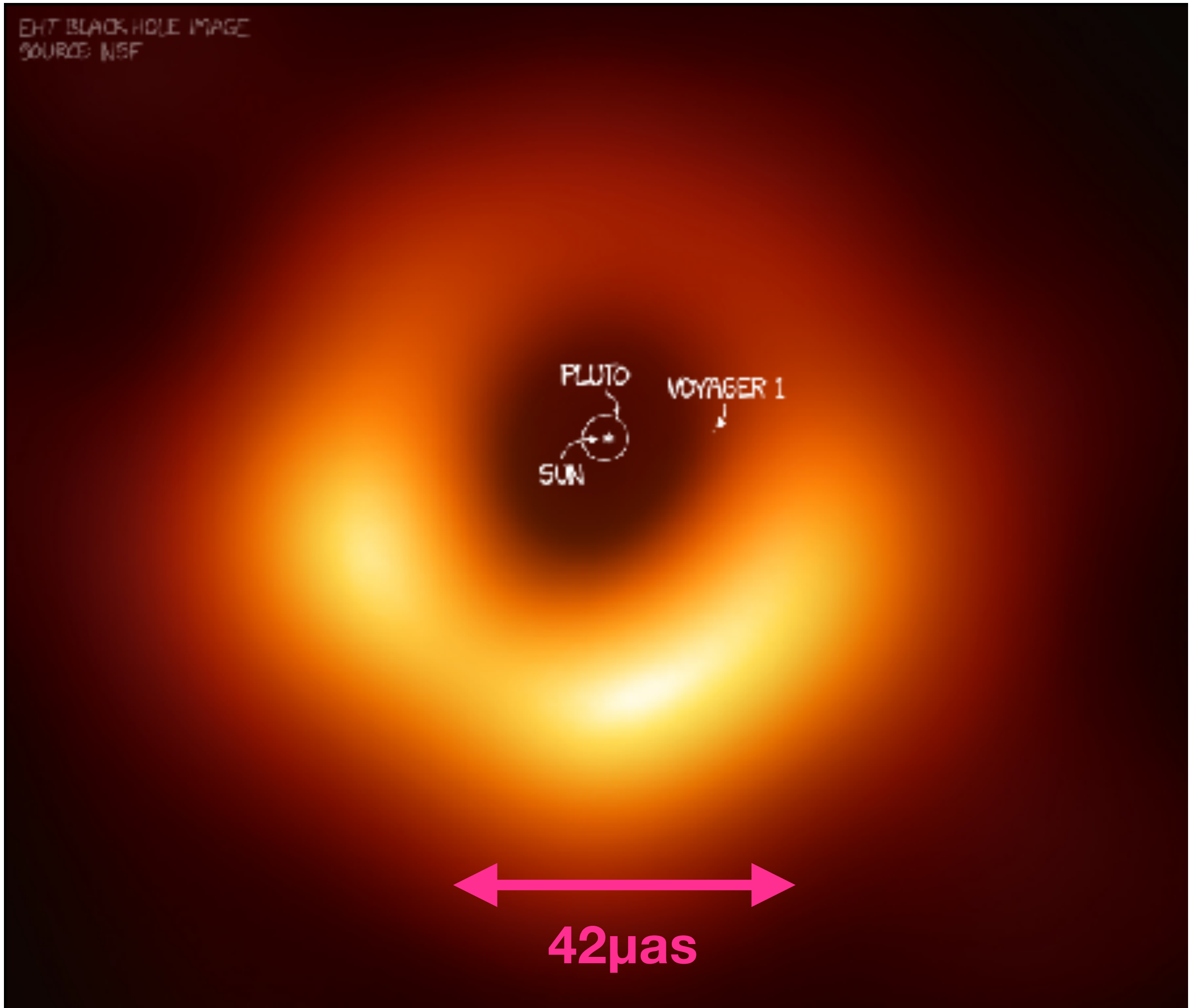



Blazar OJ 287; Hawaii-Spain (SMA-IRAM) baseline 420-second integration

**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

# 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**

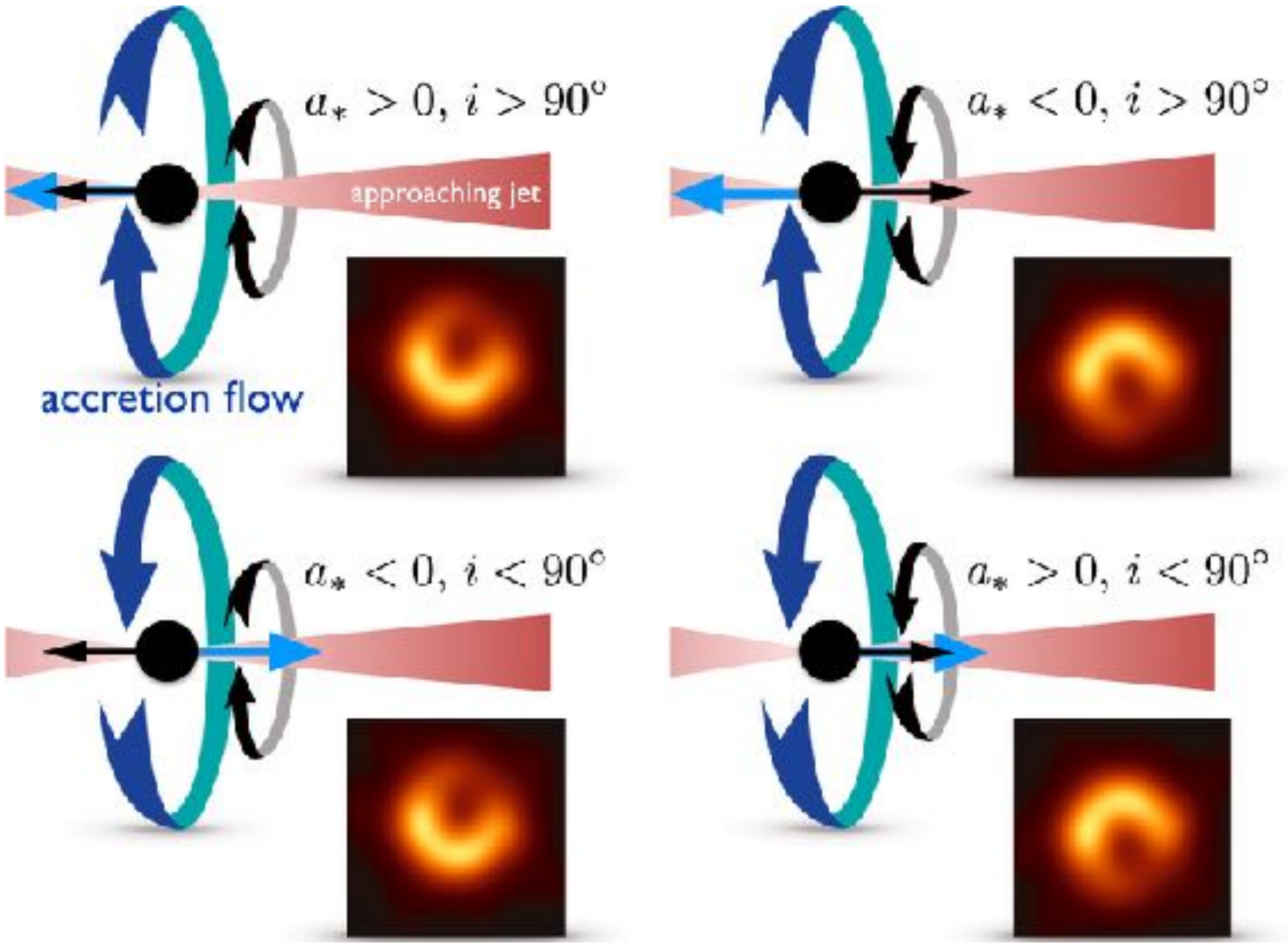
—— **deduced mass ~ 6.5 billion solar mass**

- **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**

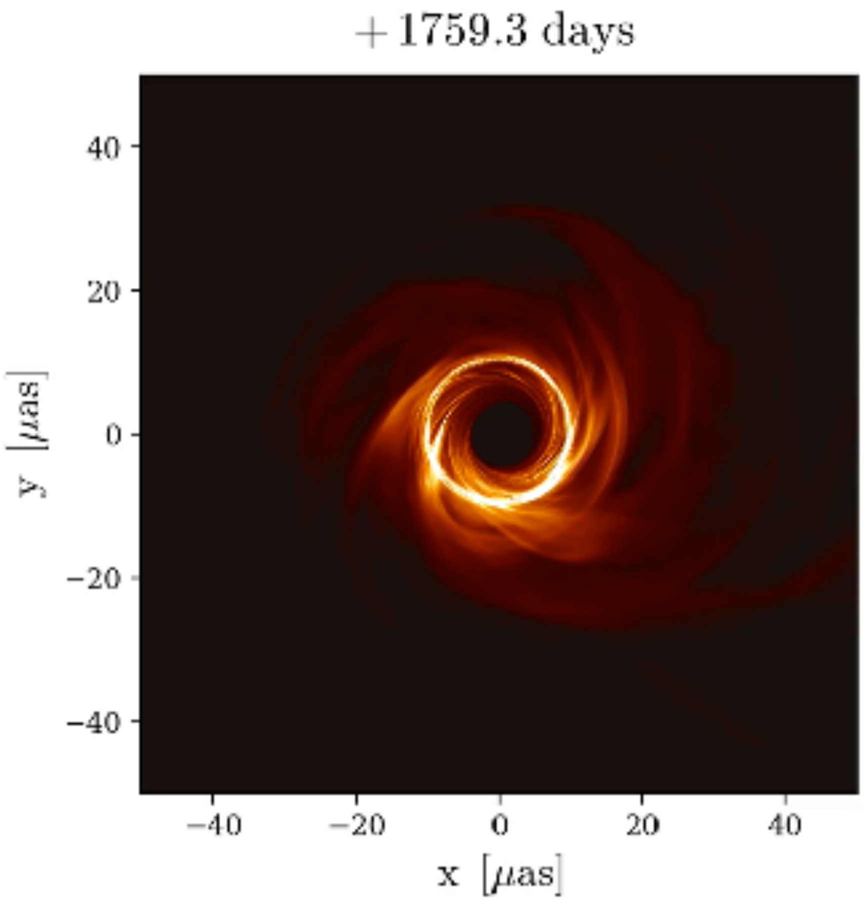
- **Tipped Disk: Perpendicular to Relativistic Jet**
- **Spin of Black Hole: Pointed away from Earth**

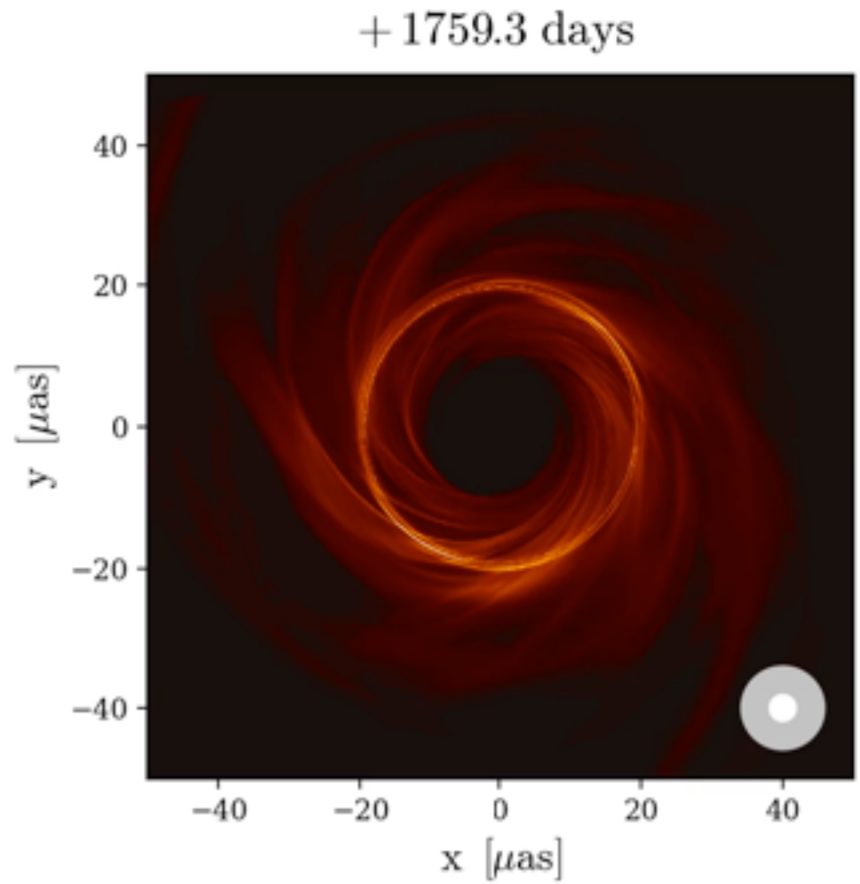
# Doppler Boosting of Approaching Part of Rotating Ring



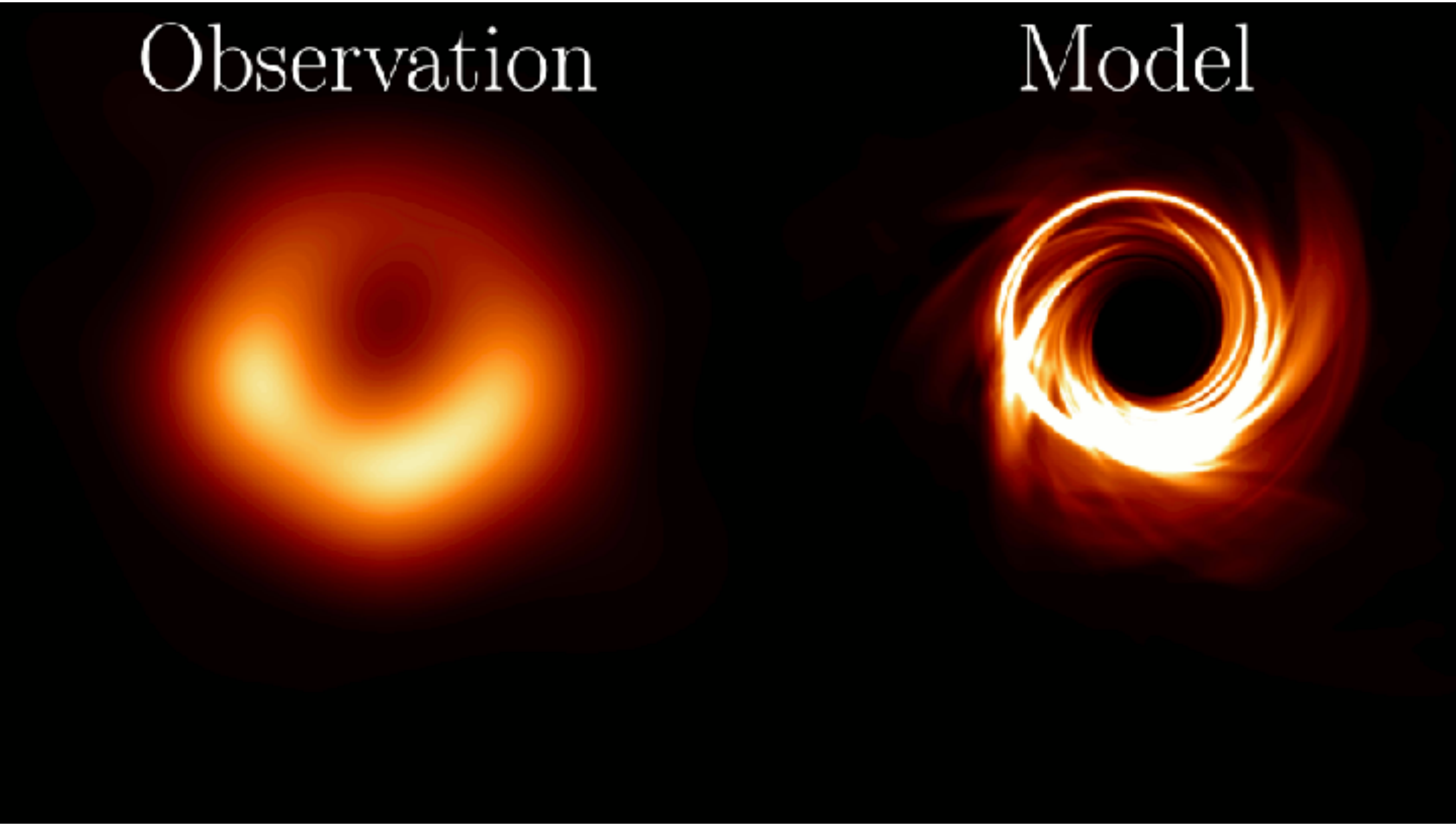

**Inner Rotation must lock to Black Hole Rotation**

# Simulation of Doppler Boosting



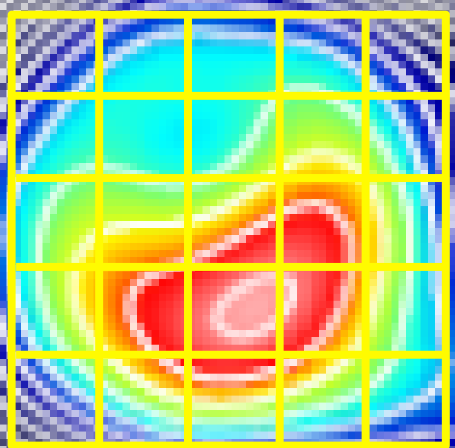




G. Wong, B. Prather, C. Gammie (Illinois)

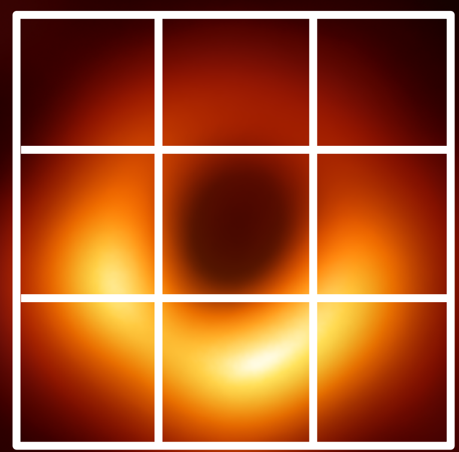

Observation
Model

# Current and Future Resolution of EHT with GLT and JCMT

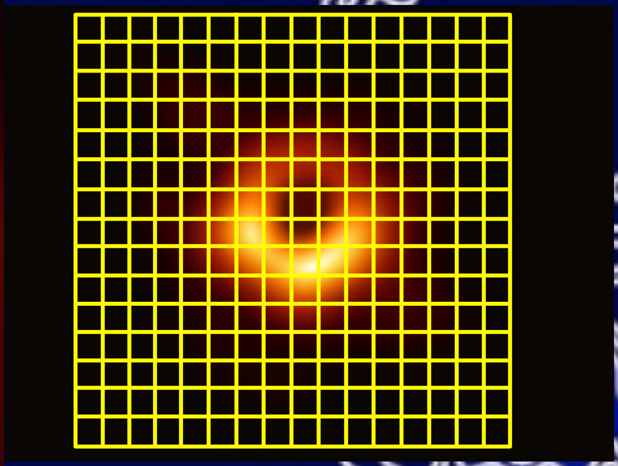
EHT with GLT
220 GHz
5 x 5 pix (25 pix)



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



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



M31 (Andromeda)
Black Hole

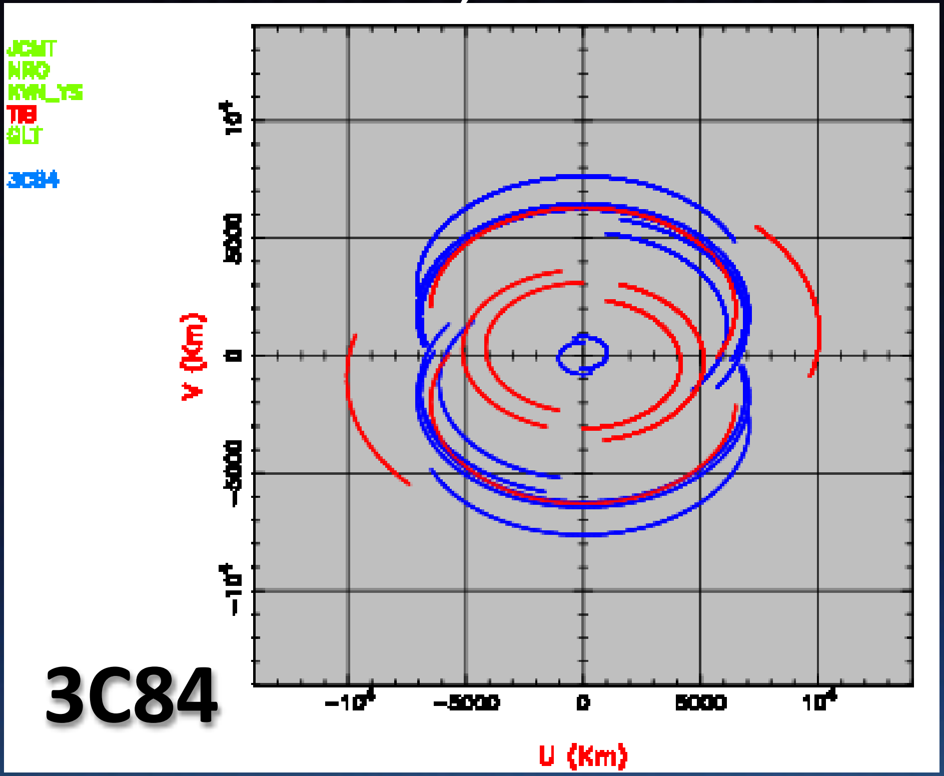
We will have better resolution & sensitivity on M87 black hole shadow & jet.

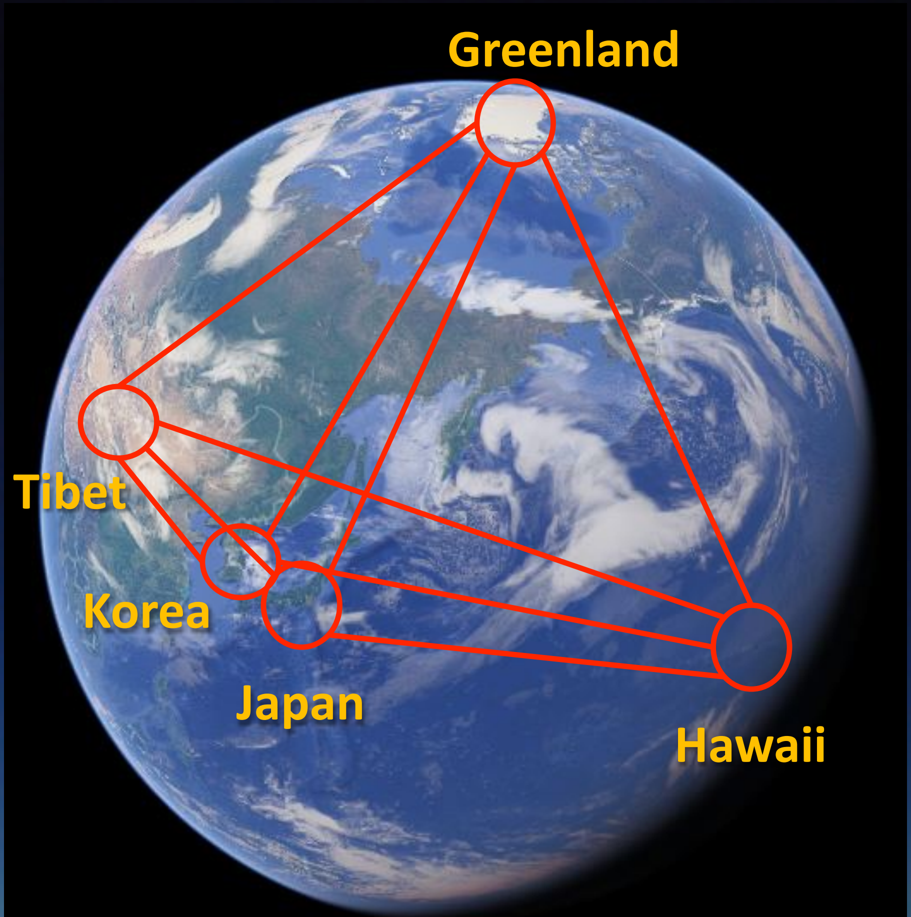
We will have much better resolution for black hole shadows in various galaxies.

# Another Initiative

# East Asian Submm-VLBI Network

- With Tibet, we can have



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- **Discoveries typically enabled by New Technology**

- **Some Nobel Prize Winners stimulate more Prize Winning Work. Why?**
- **Some Problems have multiple Prize Winning Work. Why?**
- **EAO/JCMT will continue to push the EHT experiments, with *new receivers, new broad band processing, and higher frequencies***
- **Moon Based Telescope — 30 - 100 times better linear resolution**

# 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!