Title: Special Guest Talk - 'How to take a picture of a black hole'

Speakers: Shep Doeleman

Collection: The Day of Discovery

Date: October 20, 2022 - 11:05 AM

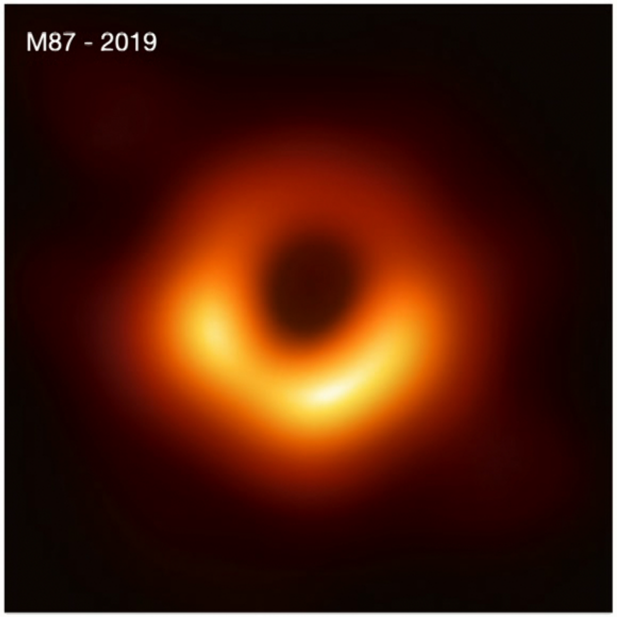
URL: https://pirsa.org/22100066

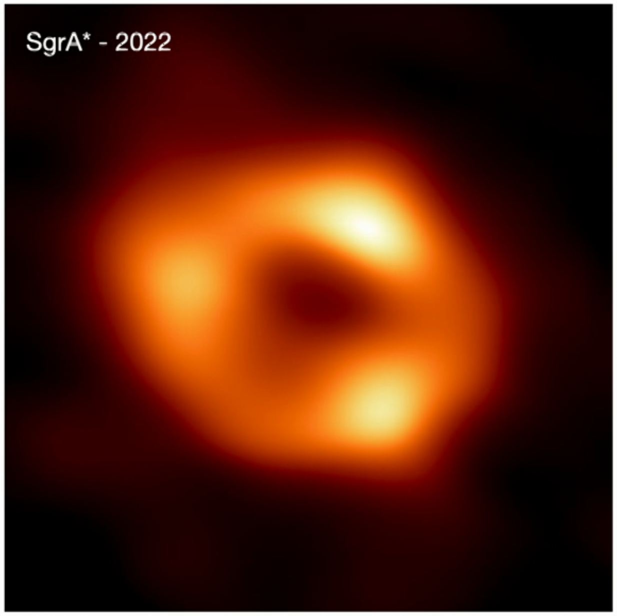
CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

Event Horizon Telescope

How to take a picture of a Black Hole.

Shep Doeleman
EHT Founding Director





EHT Results on behalf of the EHT Collaboration.

The black hole impact parameter

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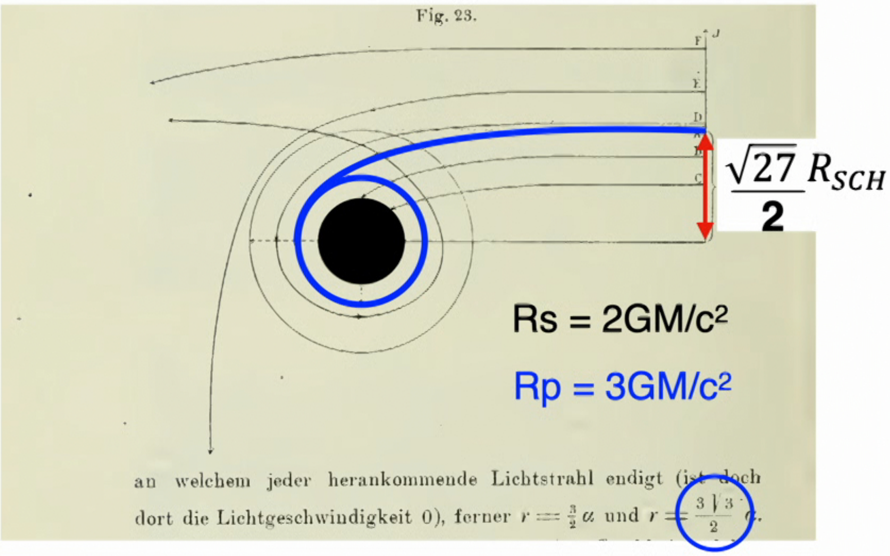
Event Horizon Telescope



Max van Laue 1921

Non-spinning (a=0)

$$D_{SH} = \sqrt{27}\, R_{SCH}$$

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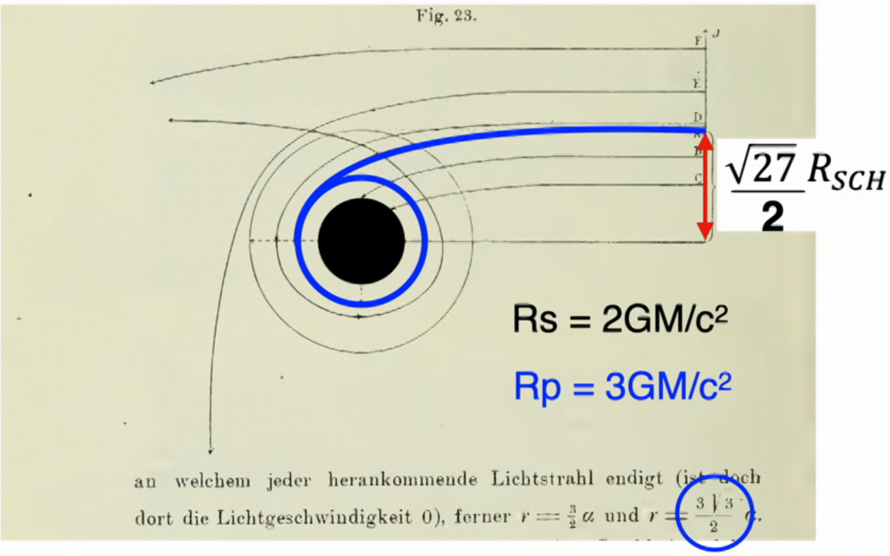
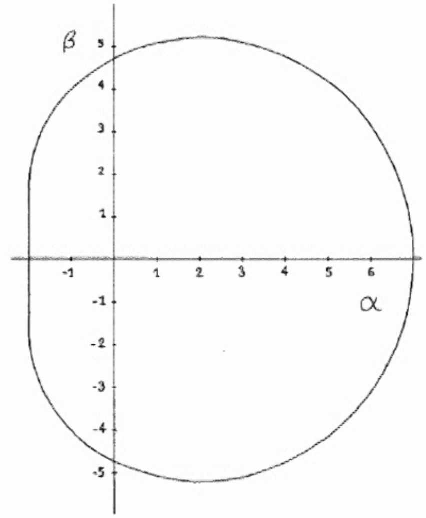
Event Horizon Telescope





Max van Laue 1921

Non-spinning (a=0)

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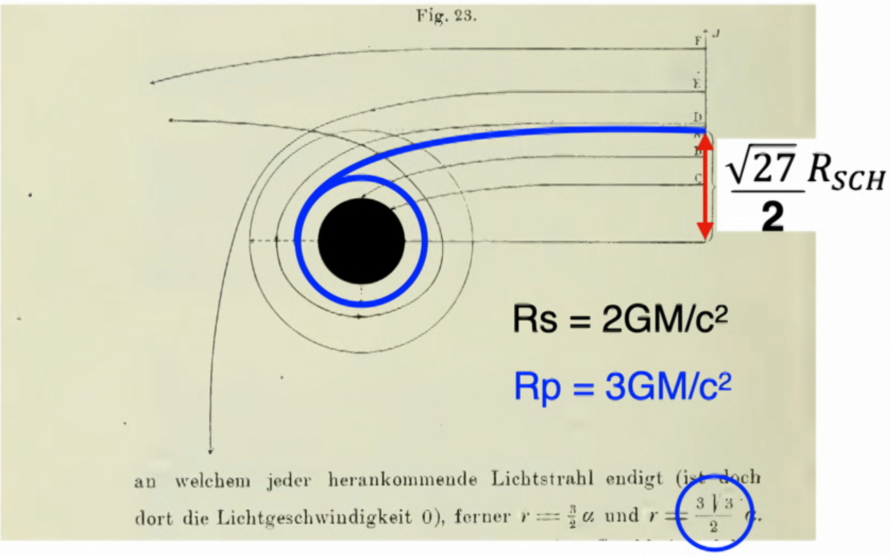
James Bardeen 1973

Spinning (a=1)

$D_{SH} = 9/2 * R_{SCH}$

The black hole impact parameter



Max van Laue 1921

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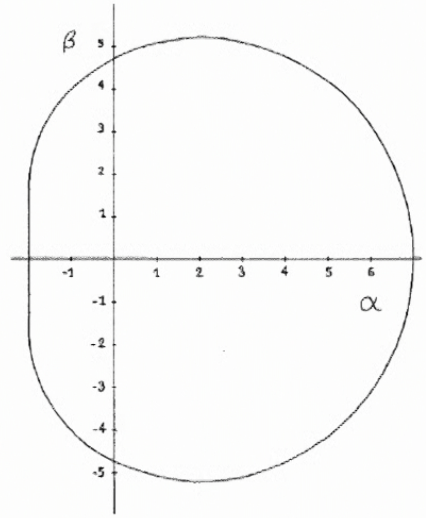

James Bardeen 1973

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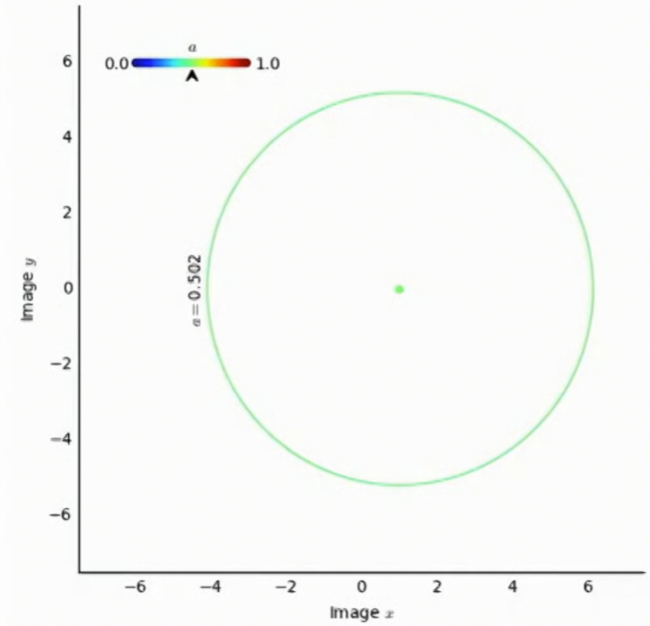
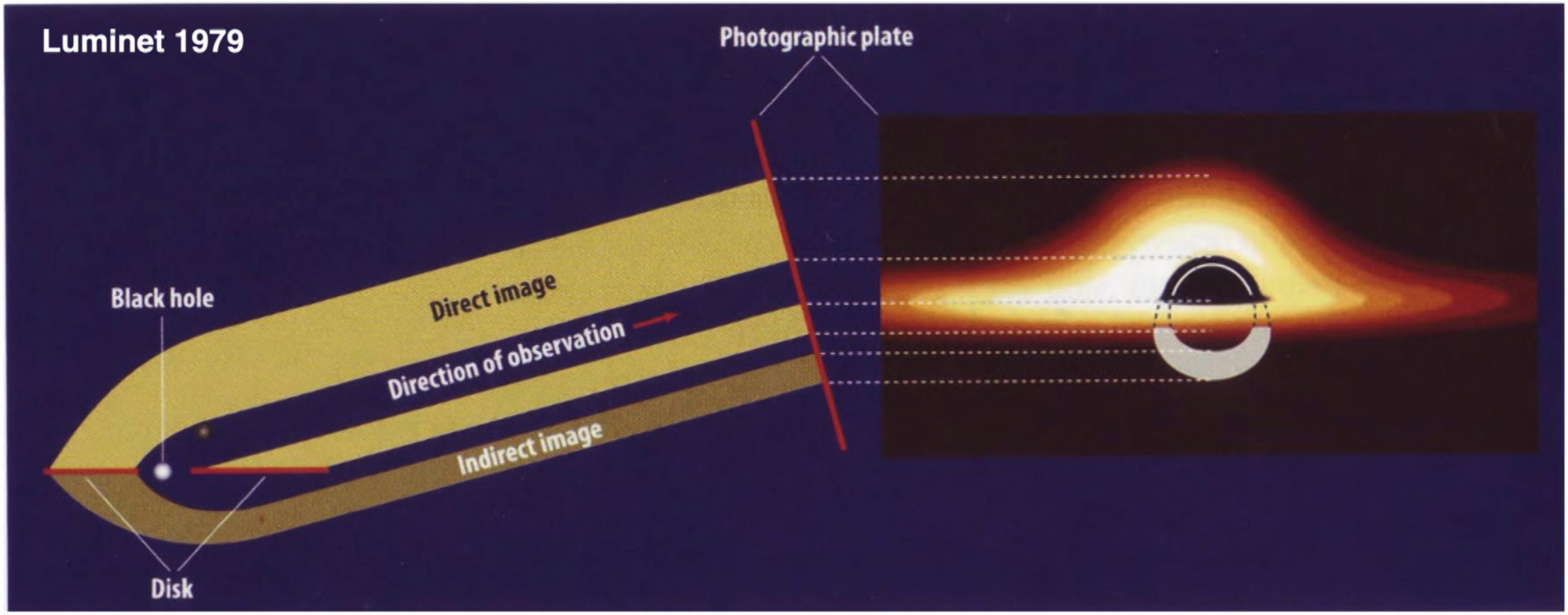


Farah et al 2020

Shadow size and shape encodes GR and BH spin.


Luminet 1979
Photographic plate
Black hole
Direct image
Direction of observation
Indirect image
Disk

A first dynamical simulation

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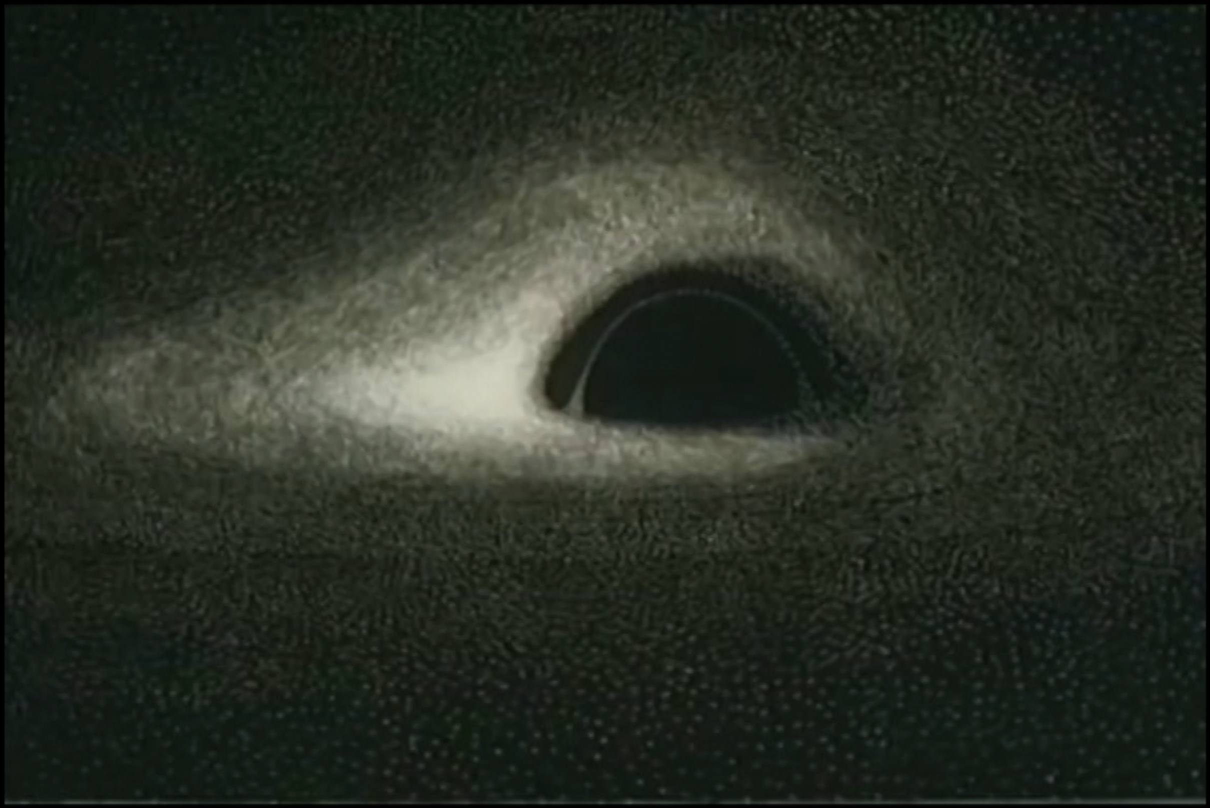
Event Horizon Telescope



Jean-Pierre Luminet (1979)

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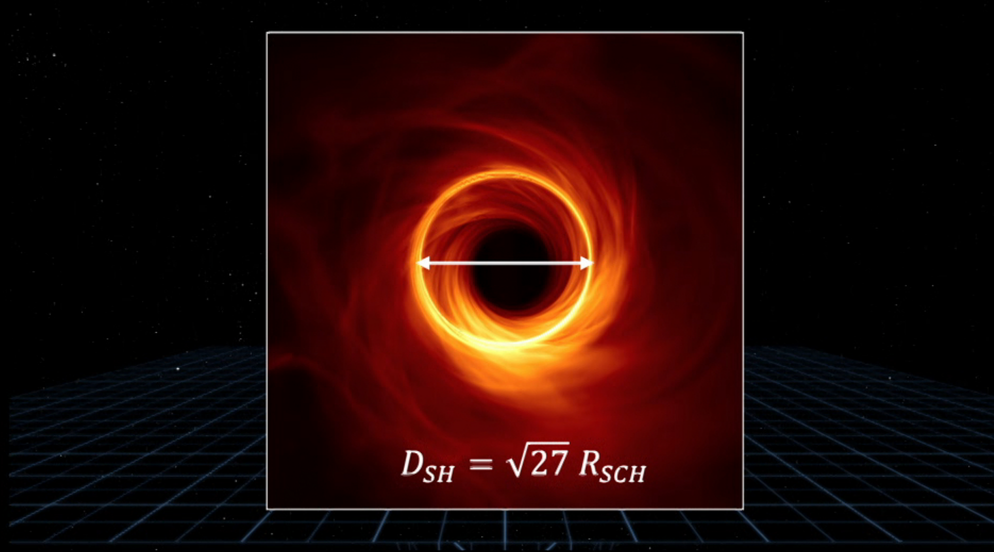
Event Horizon Telescope



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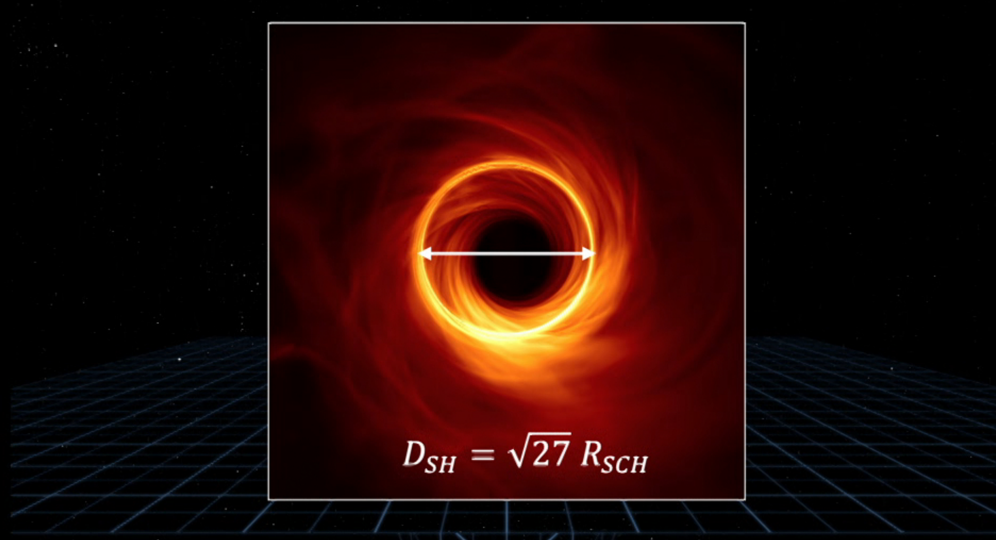
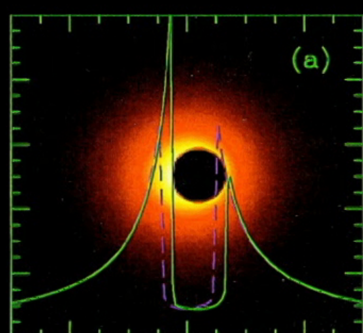
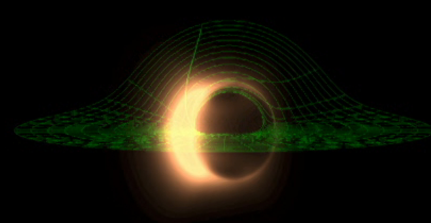
Event Horizon Telescope

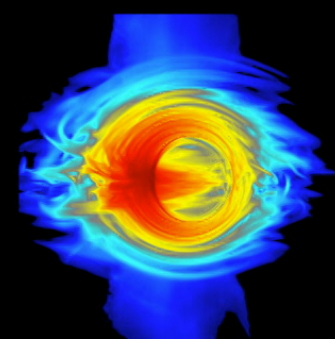




Falcke, Melia & Agol 2000



Broderick et al (2006-)



Dolence, Gammie et al (2009)

The Milky Way: A. Ghez & R. Genzel

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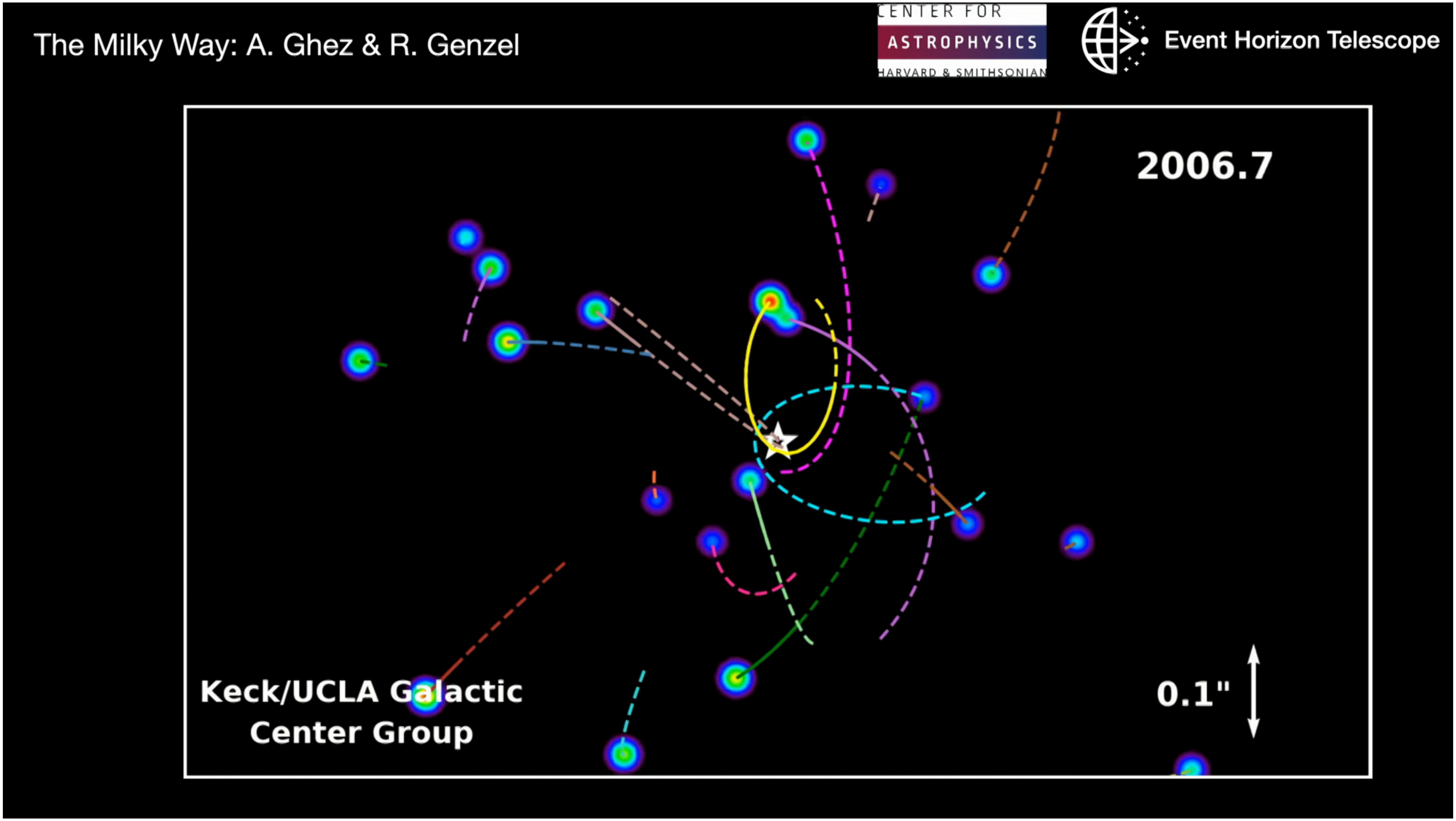
Event Horizon Telescope


The Milky Way: A. Ghez & R. Genzel
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ASTROPHYSICS
HARVARD & SMITHSONIAN
Event Horizon Telescope
2006.7
Keck/UCLA Galactic
Center Group
0.1"

The Milky Way: A. Ghez & R. Genzel

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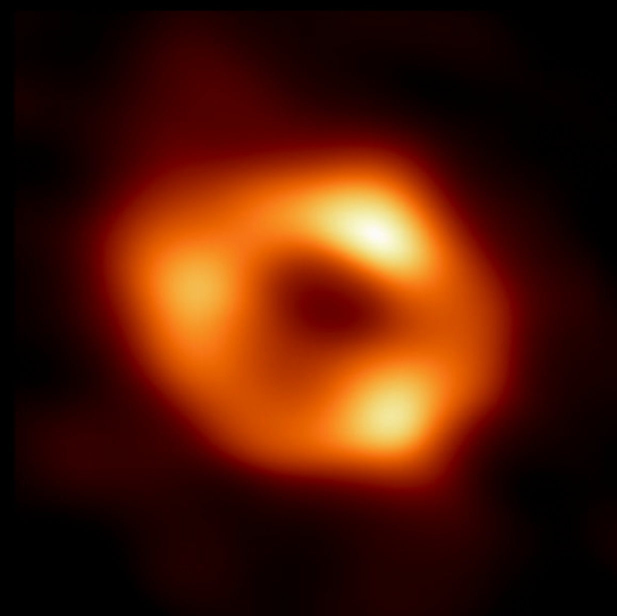
Event Horizon Telescope



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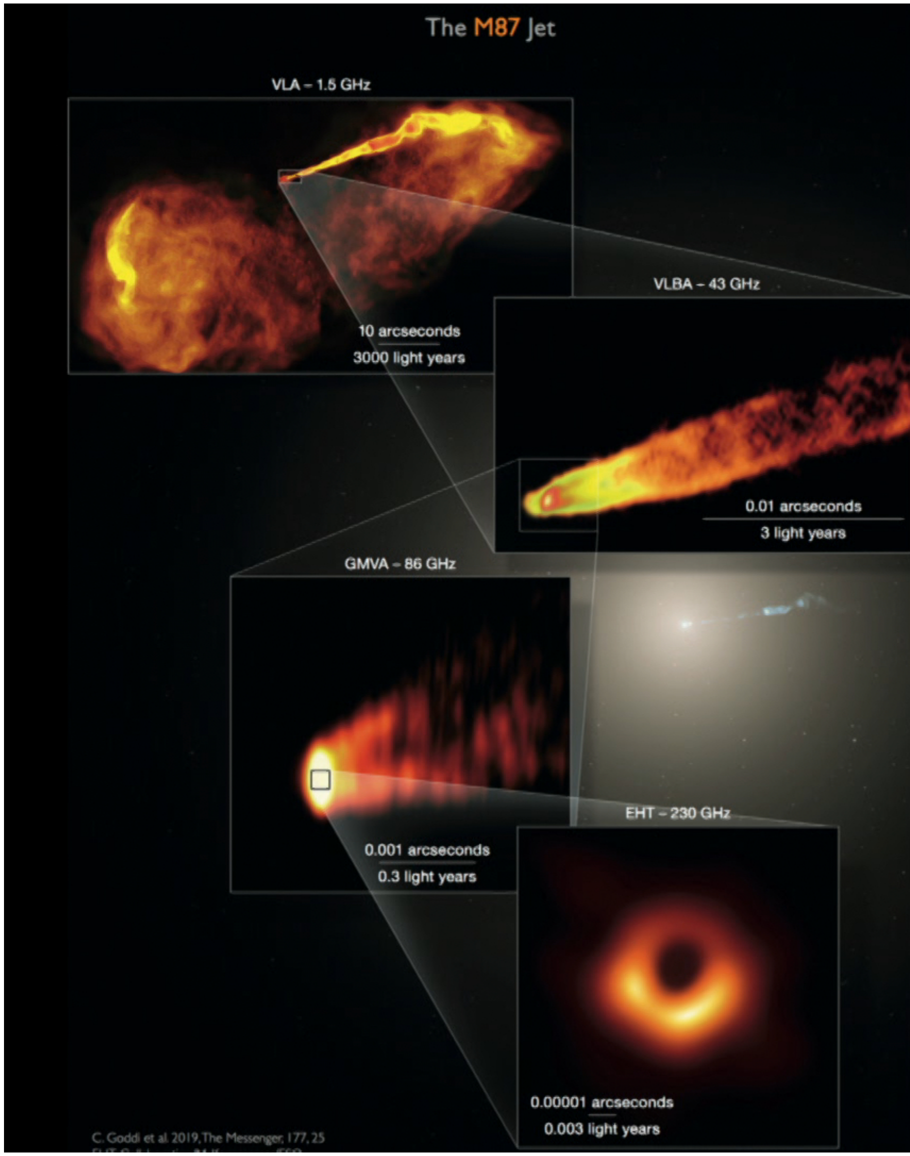
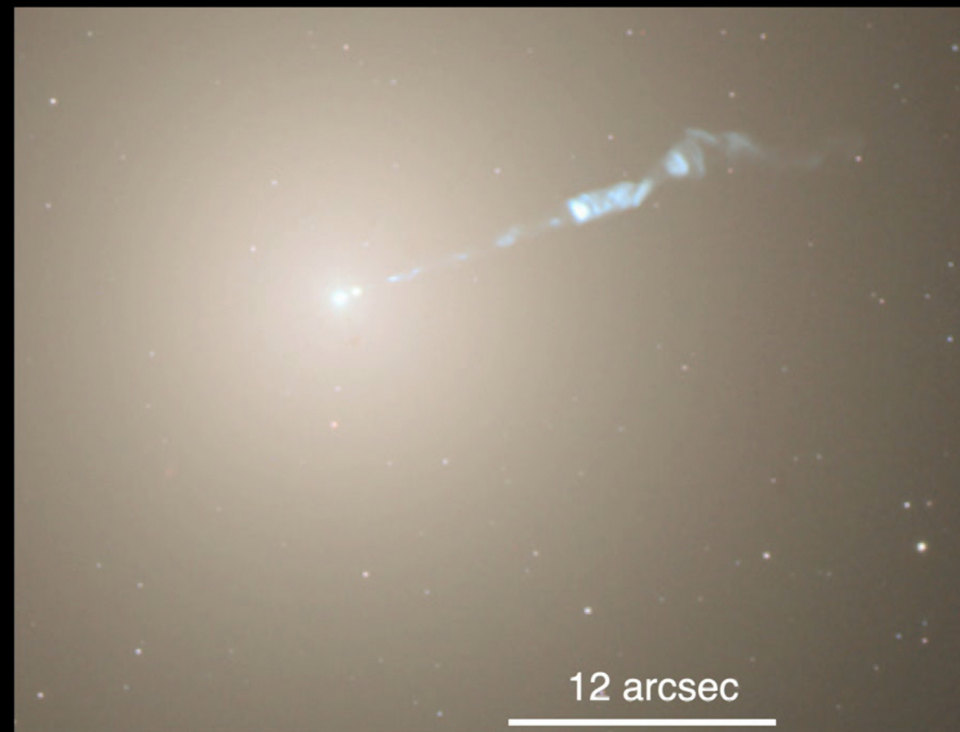
Event Horizon Telescope





Hubble Space Telescope

The object must be bright and surrounding gas must be transparent: observe at 1mm wavelength.

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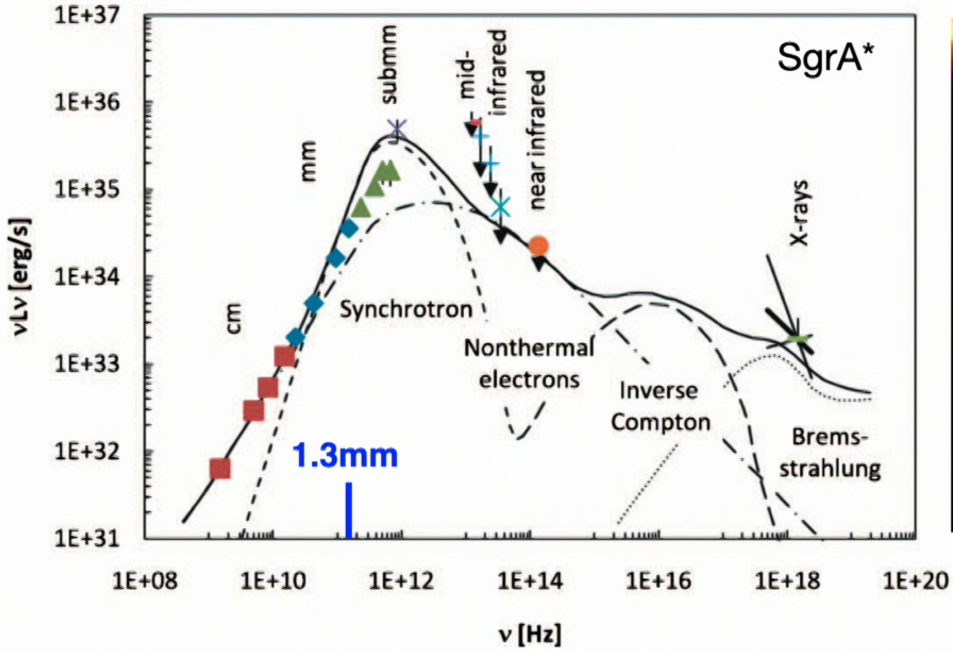
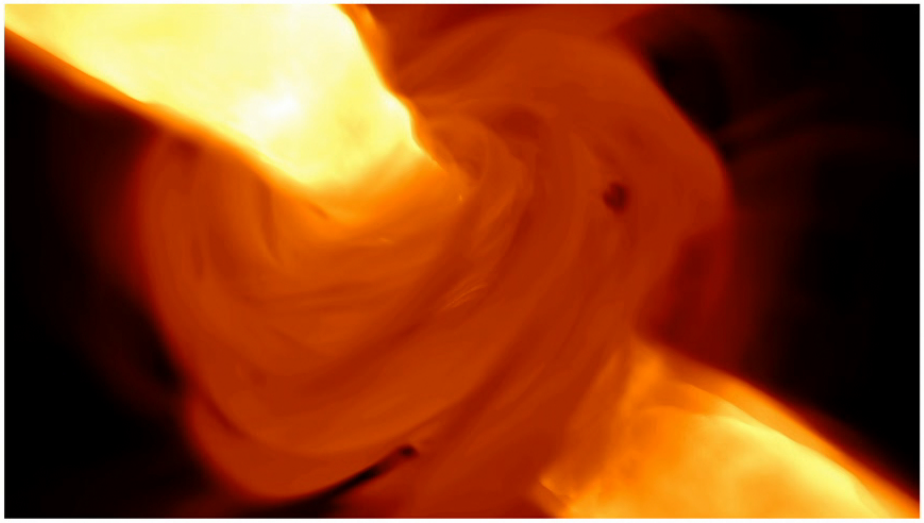
Event Horizon Telescope





Yuan & Narayan 2014

CK Chan et al, University of Arizona

The object must be bright and surrounding gas must be transparent: observe at 1mm wavelength.

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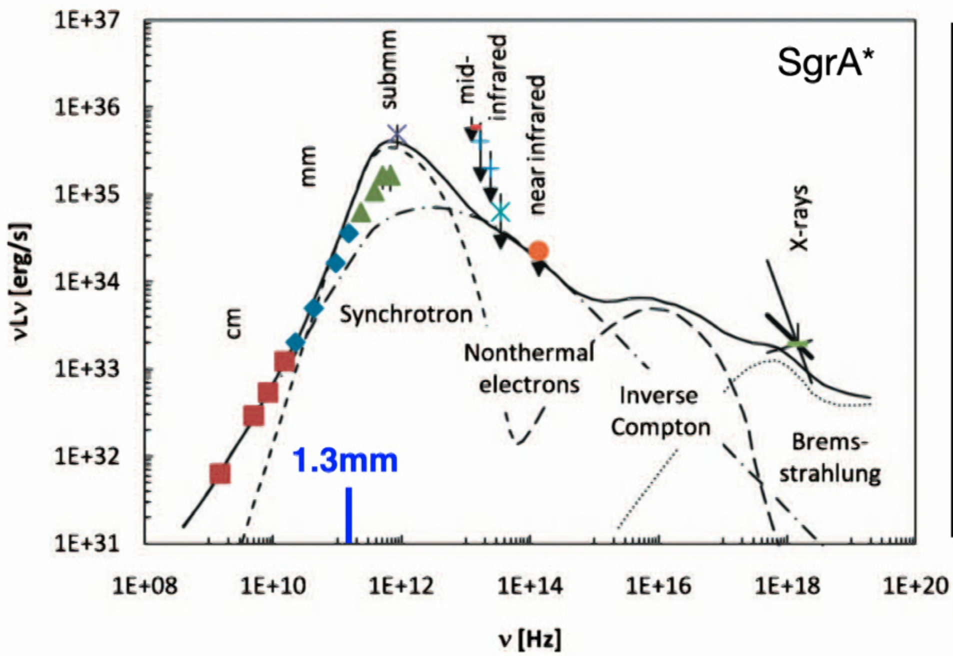
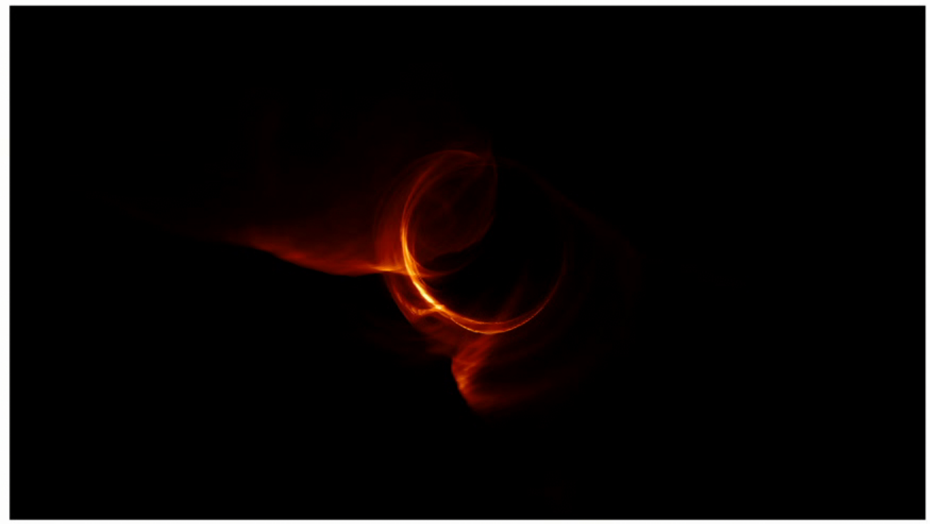
Event Horizon Telescope



Yuan & Narayan 2014



CK Chan et al, University of Arizona

SgrA* is harder: Interstellar Scattering

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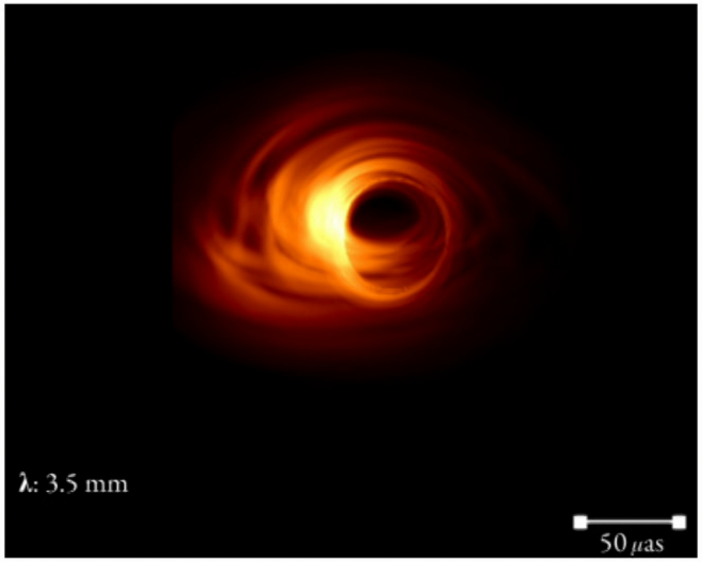
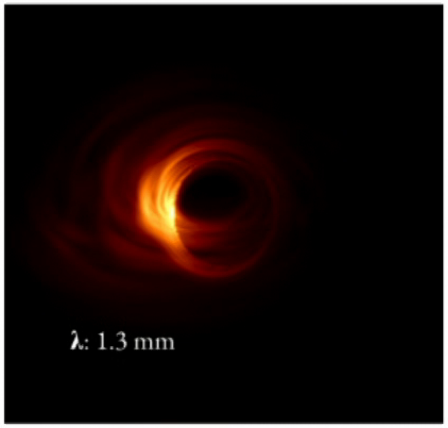
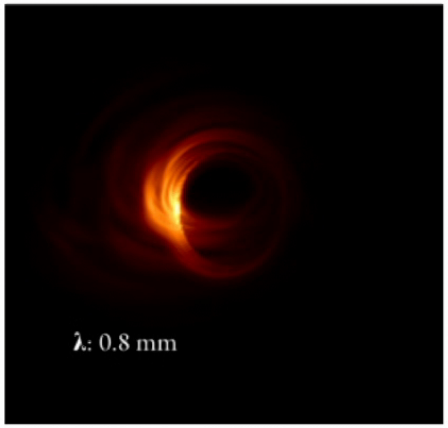
Event Horizon Telescope







SgrA* is harder: Interstellar Scattering

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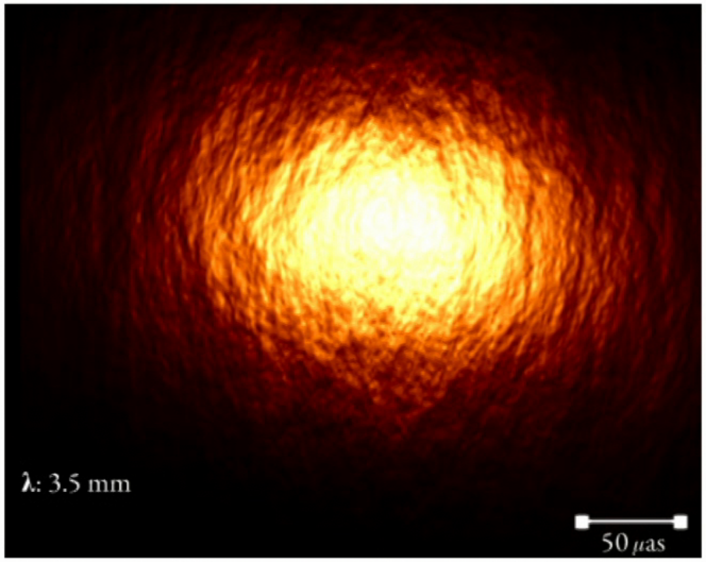
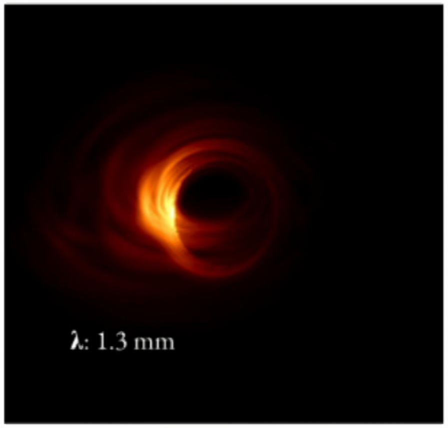
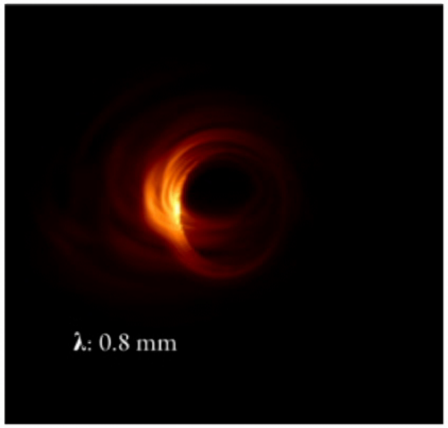
Event Horizon Telescope







Very Long Baseline Interferometry: An Earth Sized Telescope

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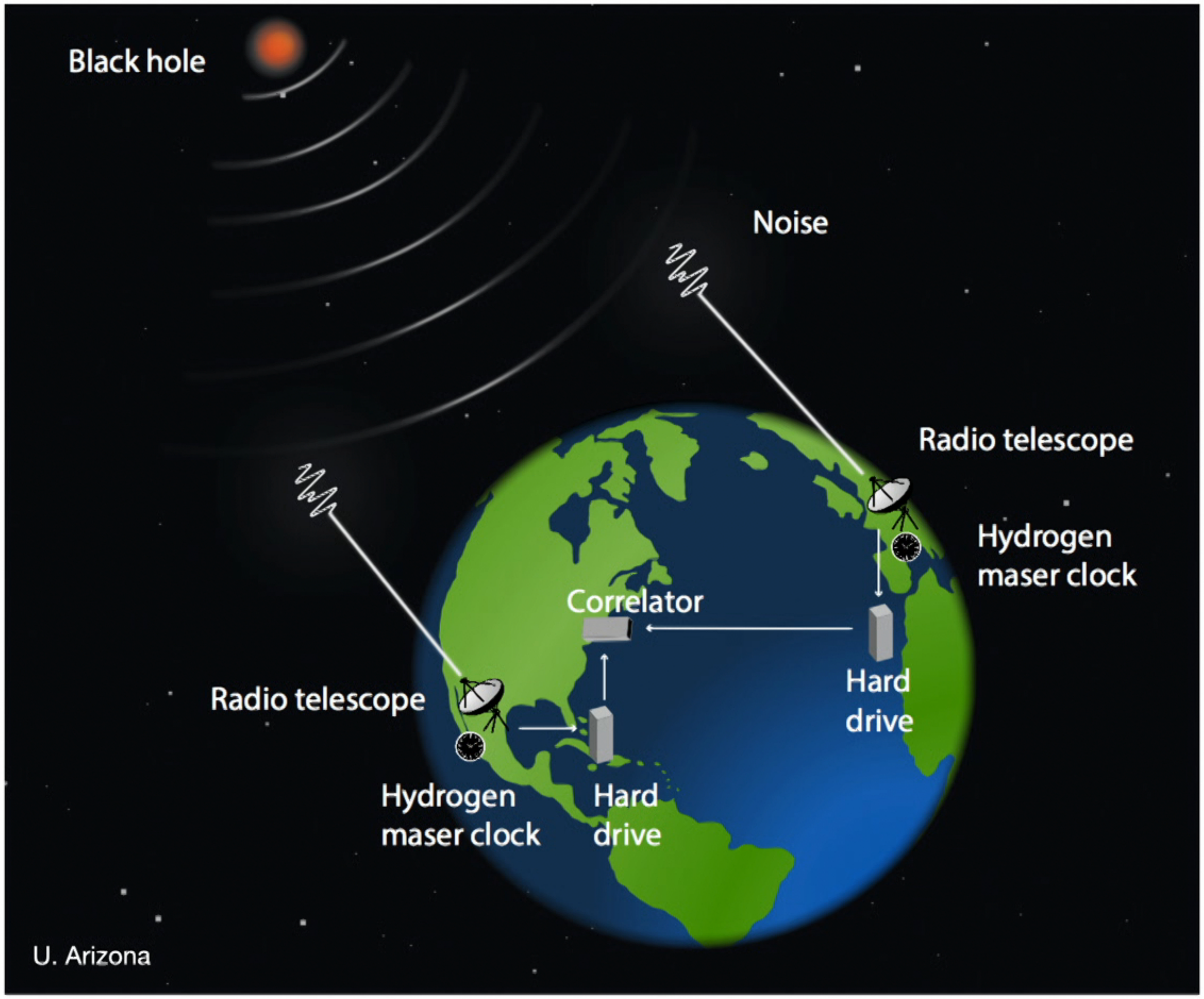
Event Horizon Telescope



M87 Shadow ~ 42 μas
SgrA* Shadow ~ 52 μas

Observing Wavelength ~ 1mm

A telescope of 10,000km diameter is needed

Data recorded at each site must be transported to a central processing facility.

No compression possible.

Many PBytes/station.

Earth Rotation Aperture Synthesis

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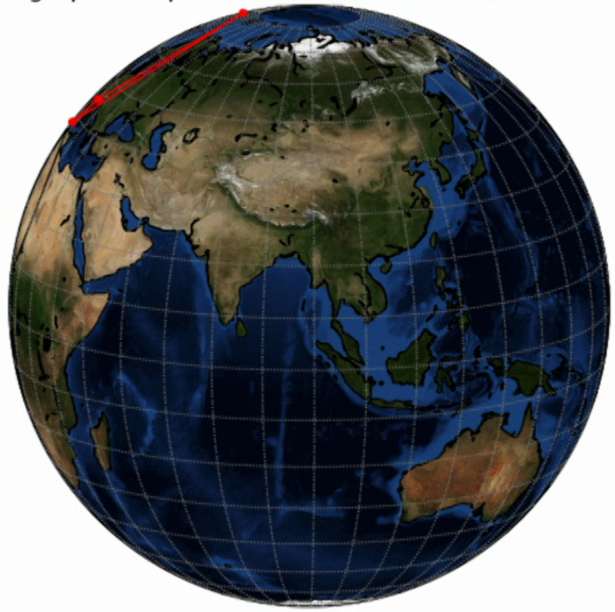
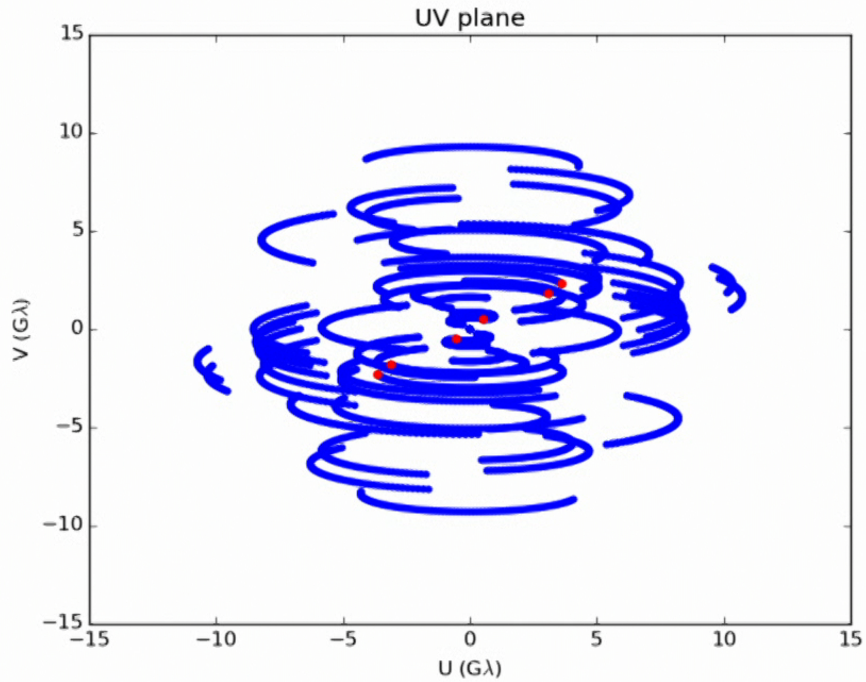
Event Horizon Telescope

Orthographic Map Centered on Lon=94, Lat=12.391123





Animation: Laura Vertatschitsch

Detection of SgrA* on Long Baselines: Horizon Scale Structure

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Event Horizon Telescope

Doeleman et al 2008

Detection of SgrA* on Long Baselines: Horizon Scale Structure

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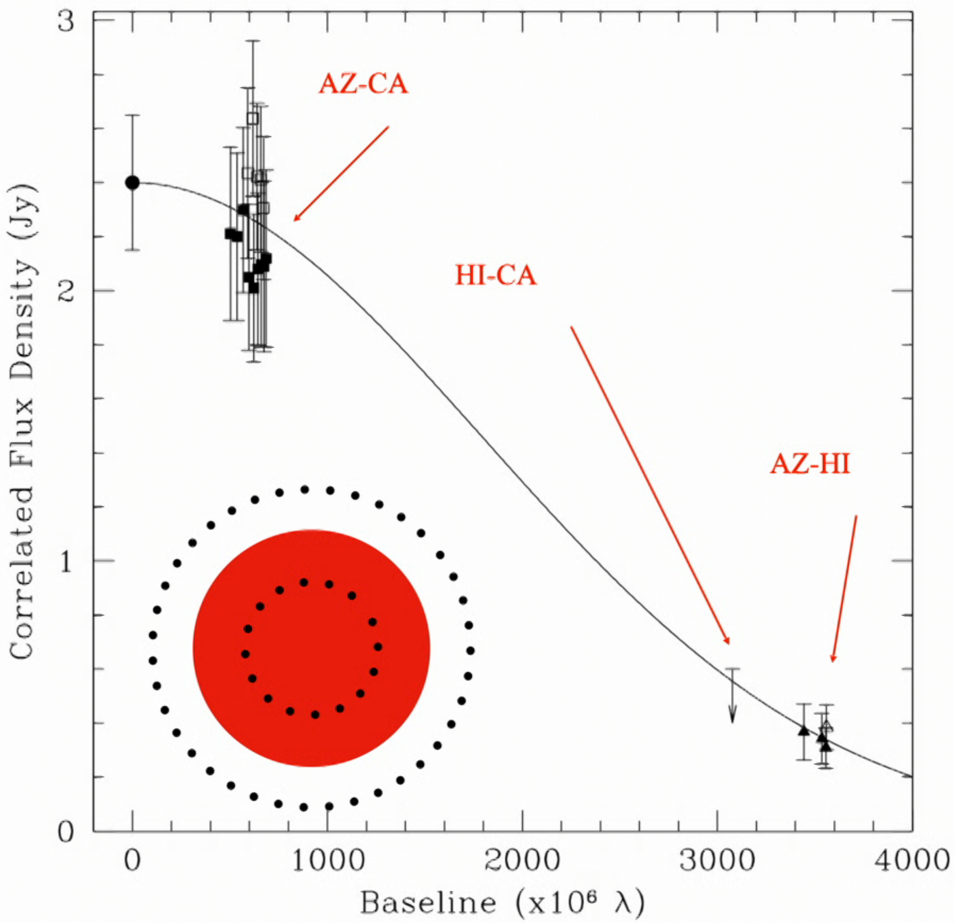
Event Horizon Telescope



Size = 3.7 Schwarzschild radii (37 µas)

Doeleman et al 2008

Detecting Horizon-Scale Structure in M87 (2012)

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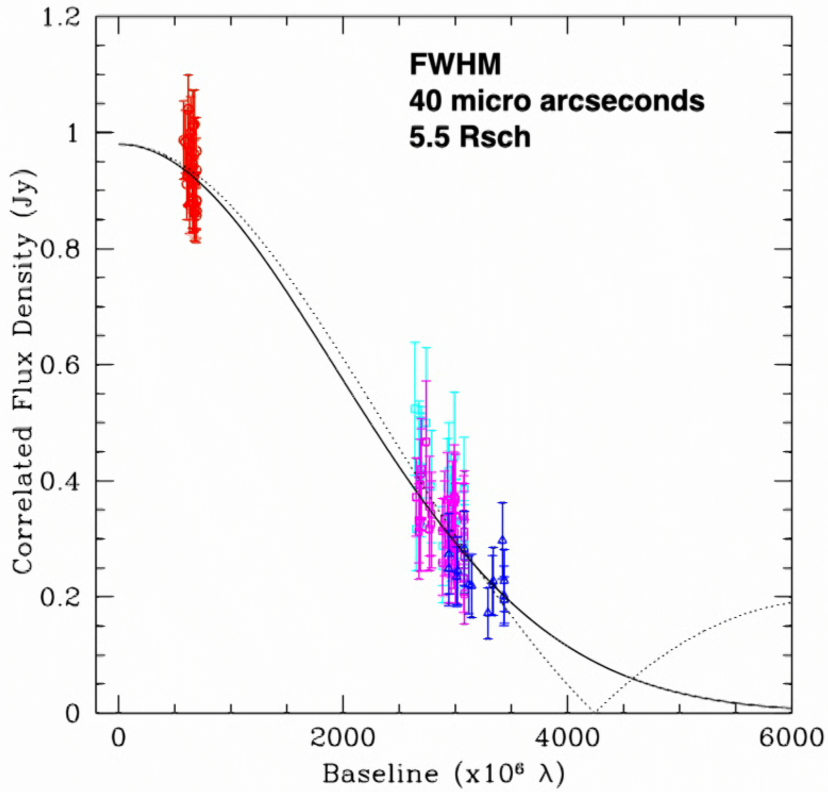
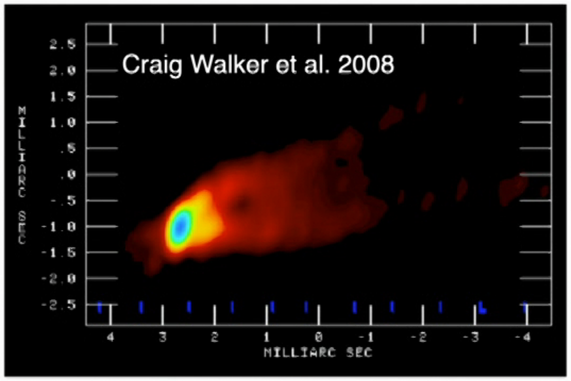
Event Horizon Telescope



Doeleman et al 2012



EHT Sensitivity Breakthrough: Bandwidth

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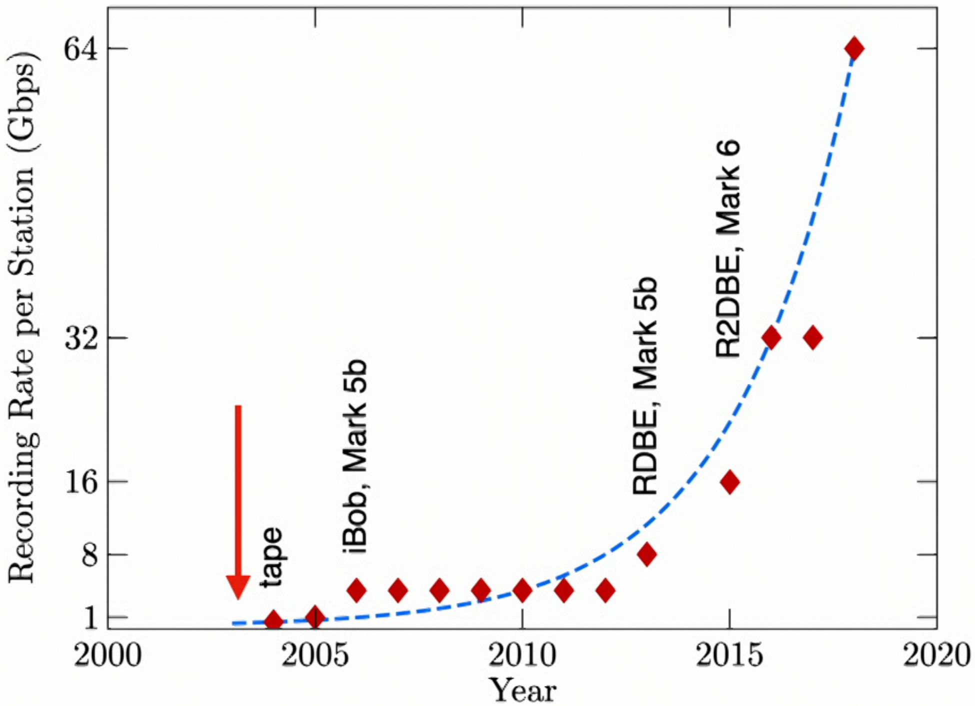
Event Horizon Telescope



COTS:
Bandwidth increases by x150
Cost decreases by x10.

EHT Sensitivity Breakthrough: Bandwidth

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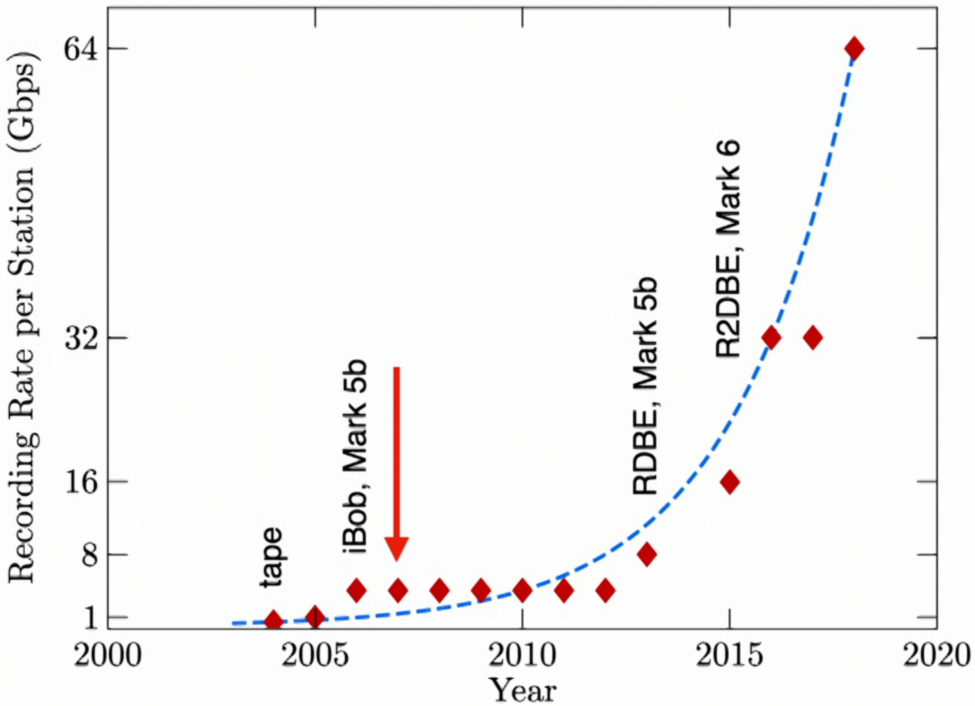
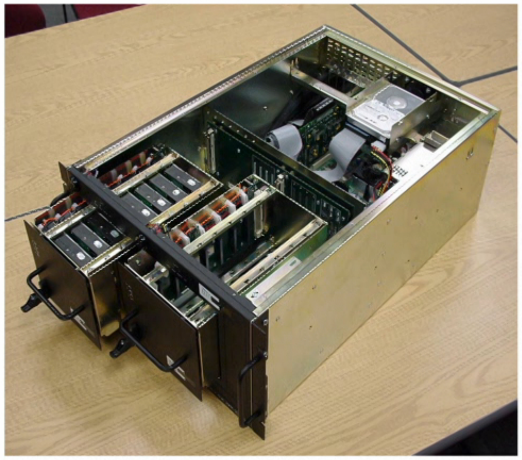
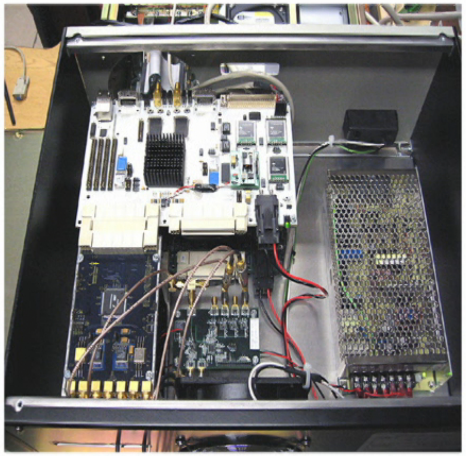
Event Horizon Telescope







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EHT Sensitivity Breakthrough: Bandwidth

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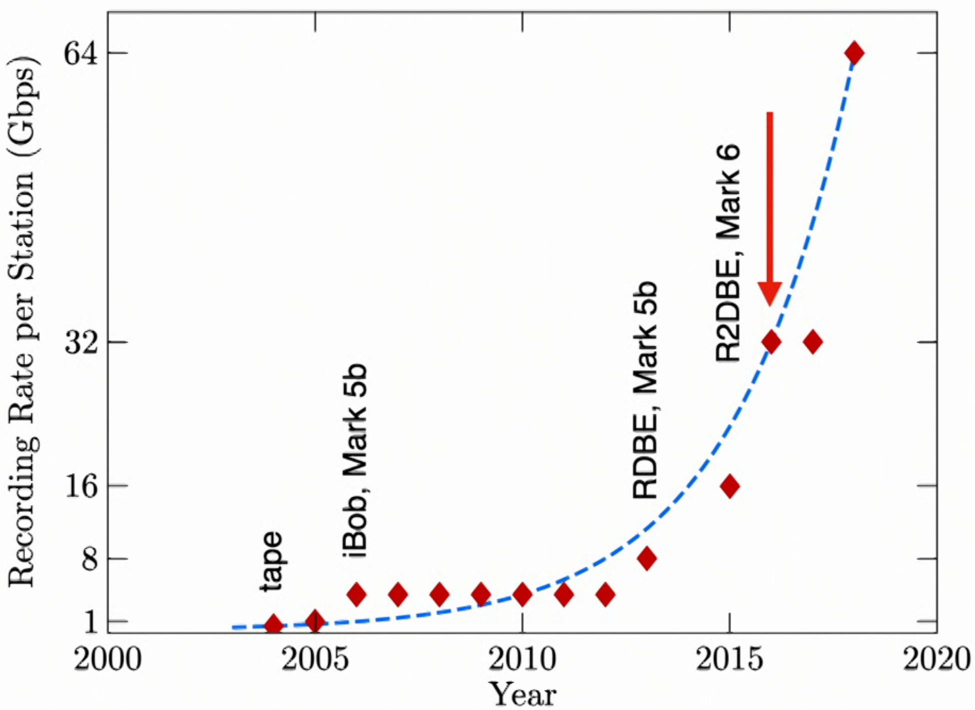
Event Horizon Telescope



COTS:
Bandwidth increases by x150
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- ALMA Phasing 2009-2017

First Full EHT Observations: April 2017

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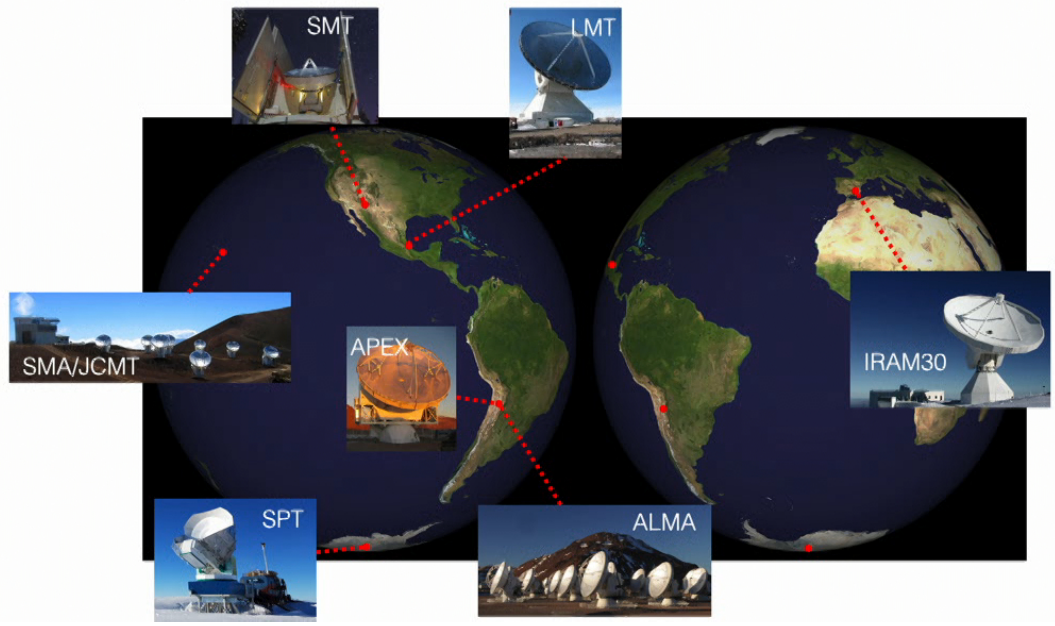
Event Horizon Telescope

- ALMA Phasing 2009-2017

- 8-Station EHT Array: APEX, SPT, ALMA, LMT, SMTO, JCMT, SMA, Pico Veleta.
- Dates: April 5-14, with 5 days ‘triggered’ on good weather.
- Weather: Fantastic.
- Successful: Detections to all 8 participating telescopes.



Transporting data from the South Pole

Andrew Nadolski at Pole

Disks arrive at Haystack

Unloading disks.

Disks coming up to temperature.

Unpacking

5 MegaBytes of Storage in 1956

Strong signature apparent.

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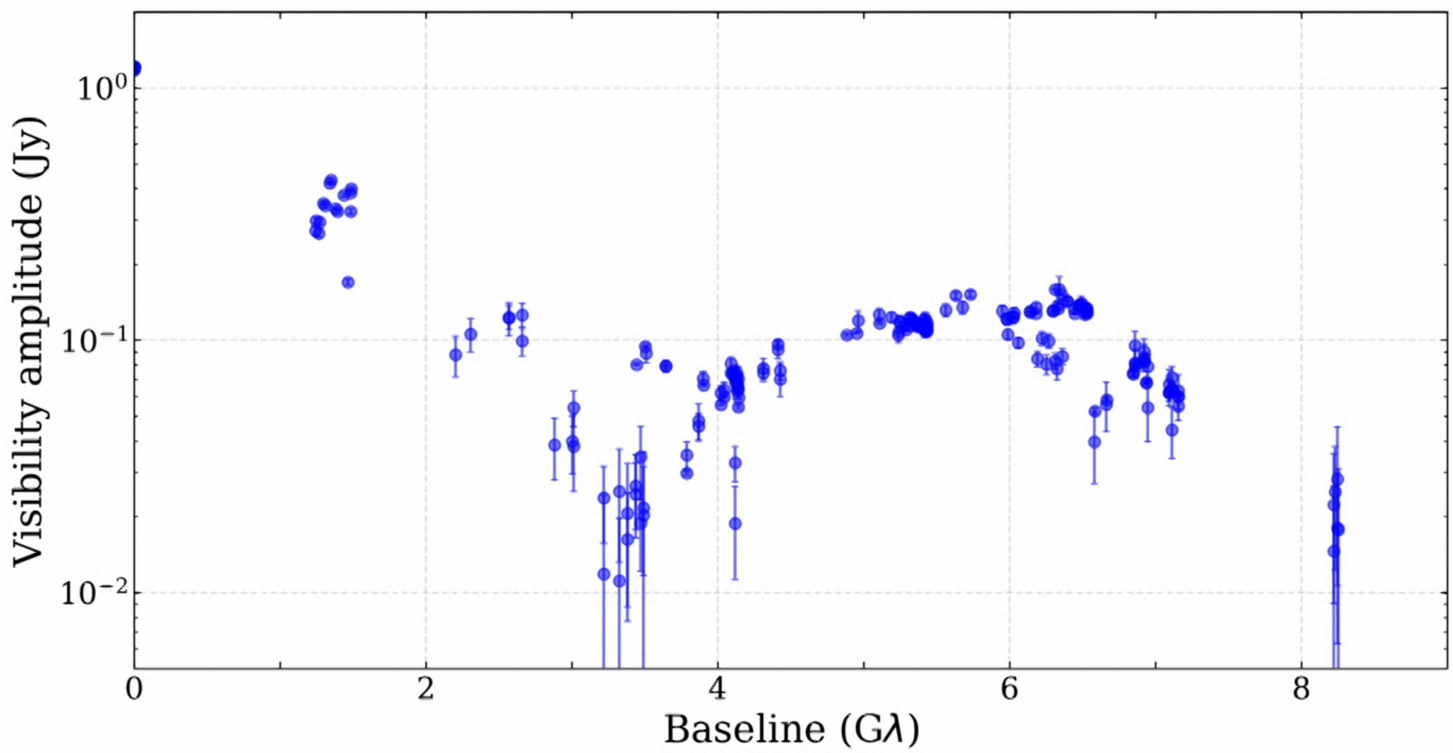
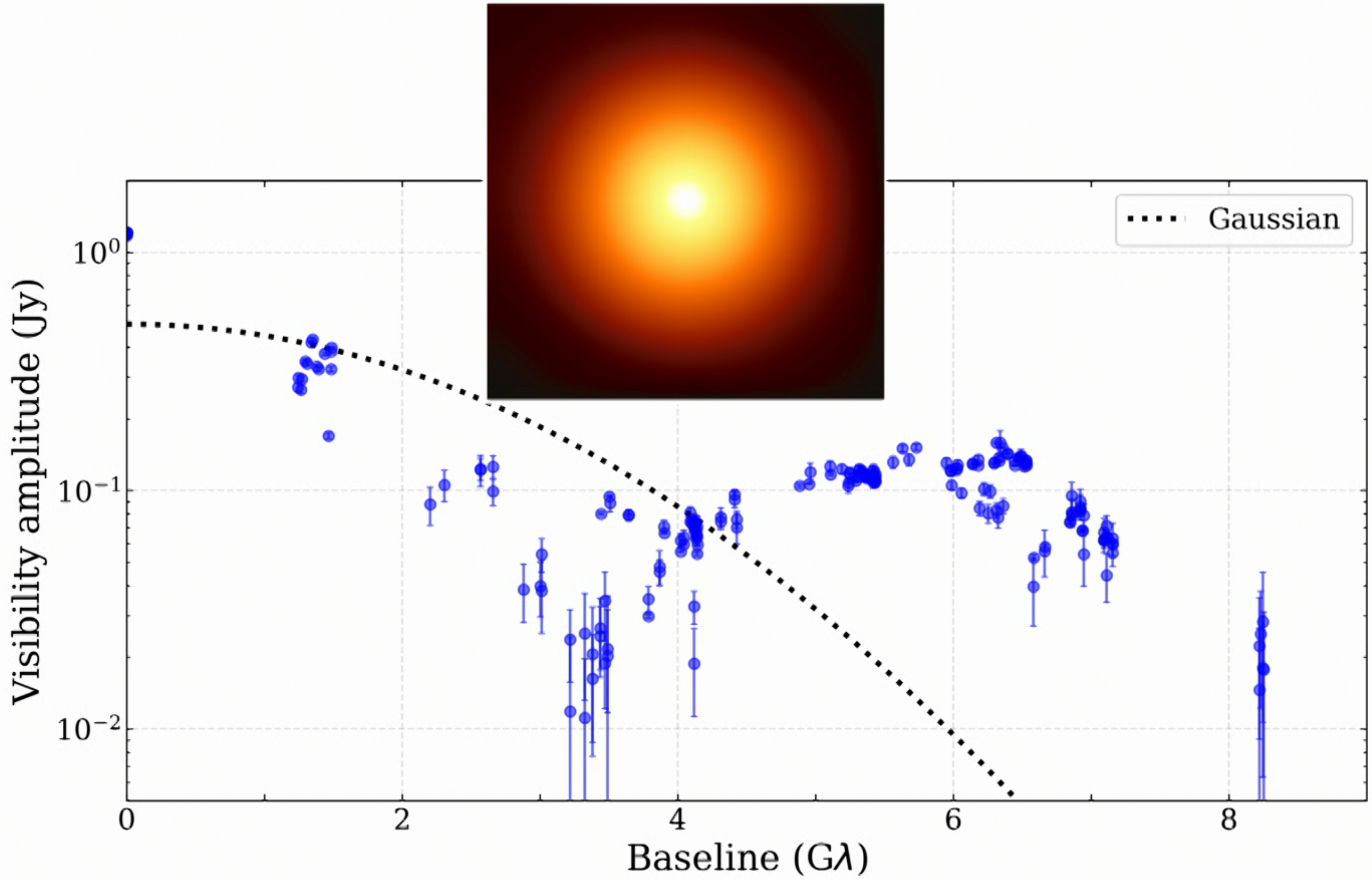
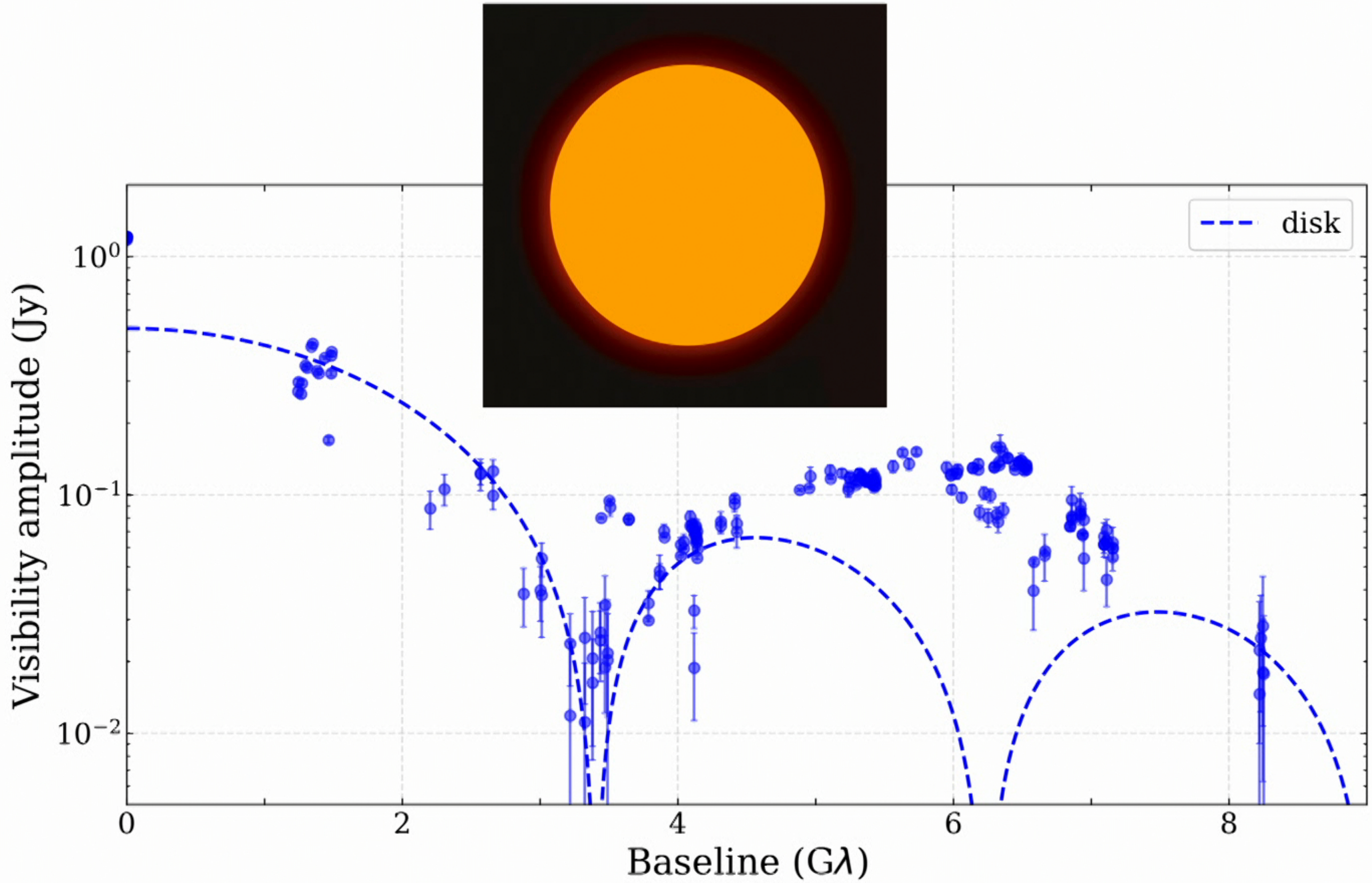
Event Horizon Telescope



Strong signature apparent.




disk
10^0
10^{-1}
10^{-2}
Visibility amplitude (Jy)
0
2
4
6
8
Baseline (Gλ)

Strong signature apparent.

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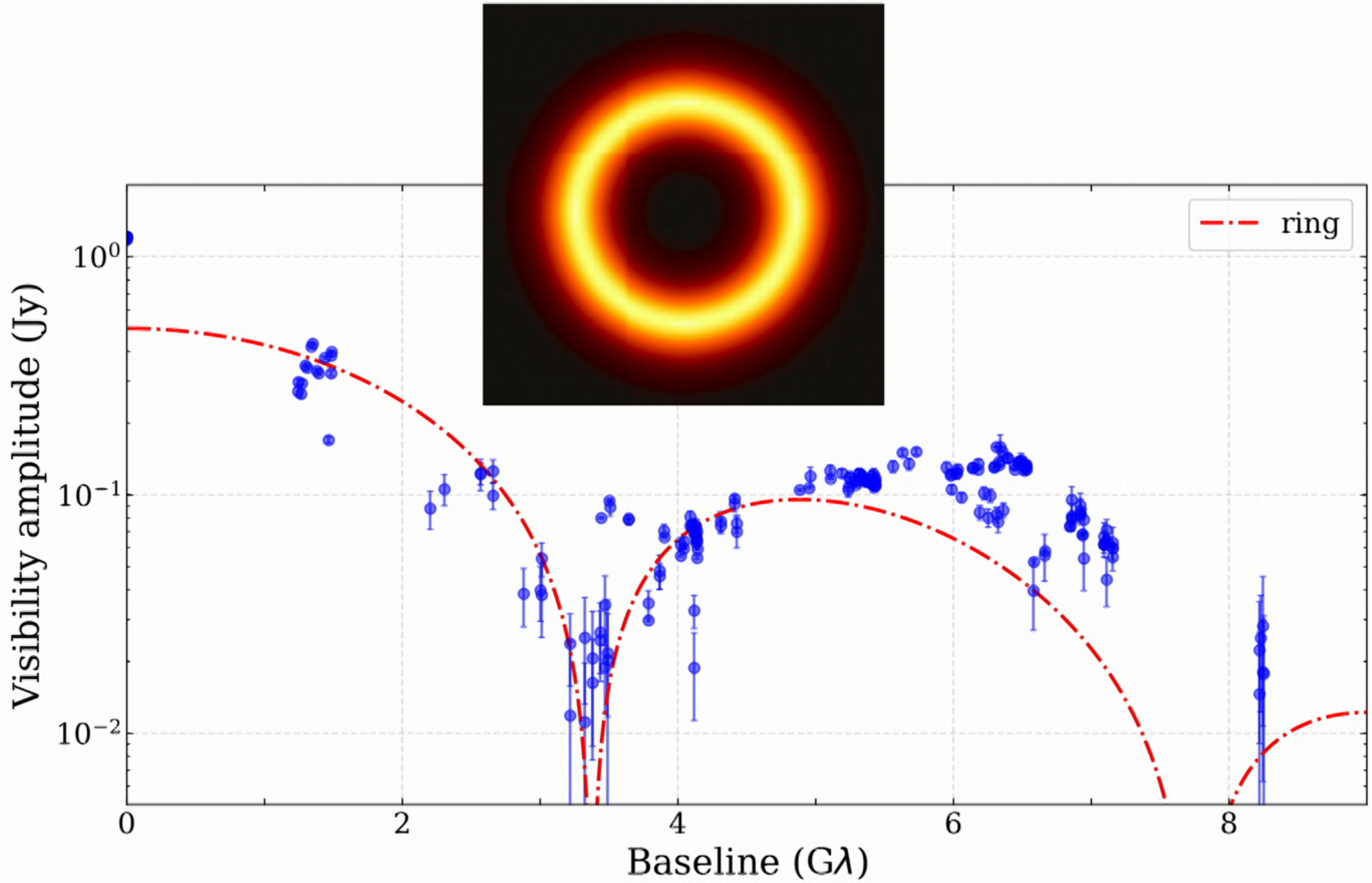
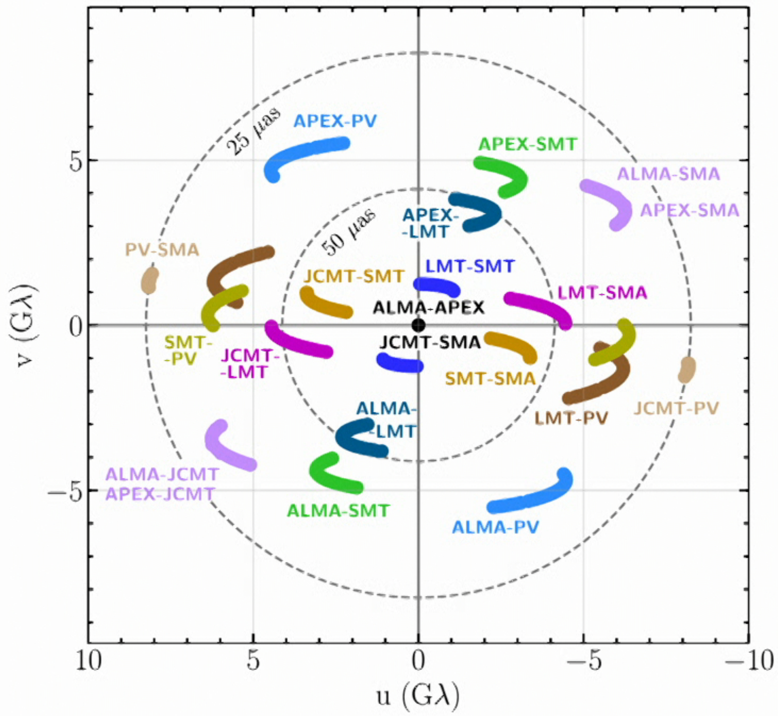
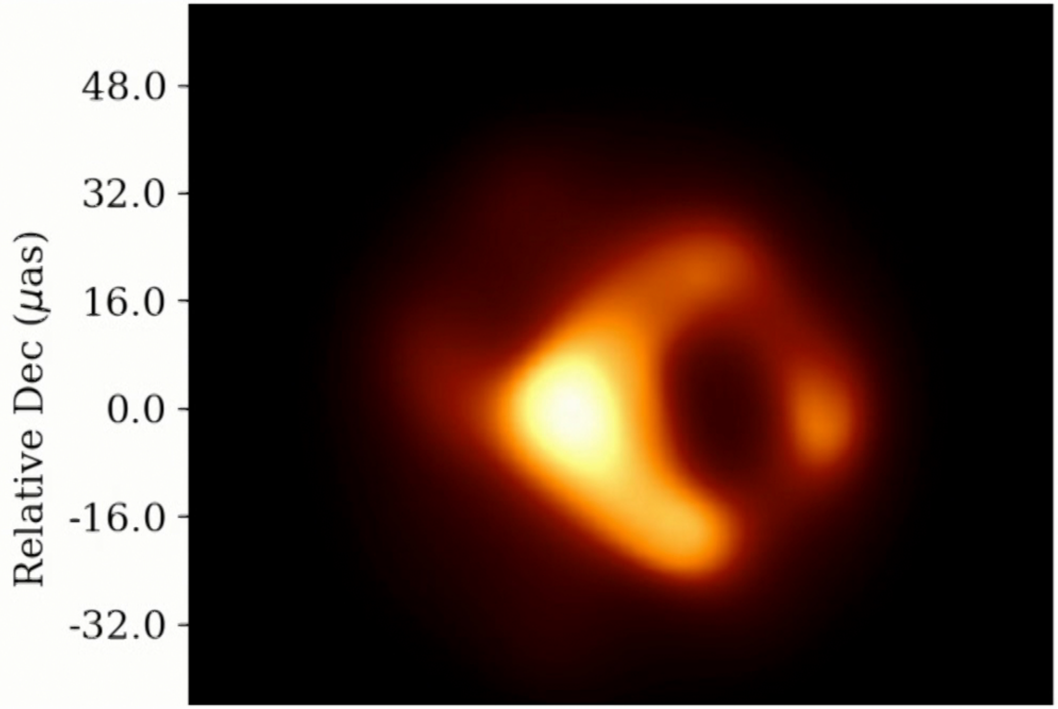
Event Horizon Telescope



$$J(I) = \underbrace{\sum}_{\text{data terms}} \alpha_D \chi^2_D(I) - \underbrace{\sum}_{\text{regularizers}} \beta_R S_R(I)$$





Imaging Challenges: Exploring Algorithms

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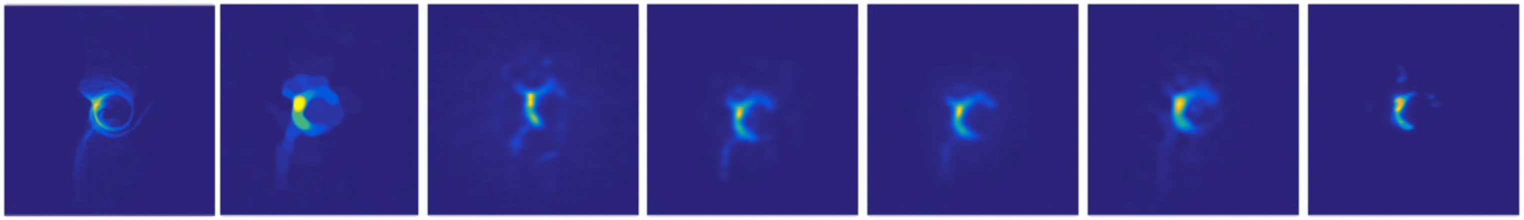
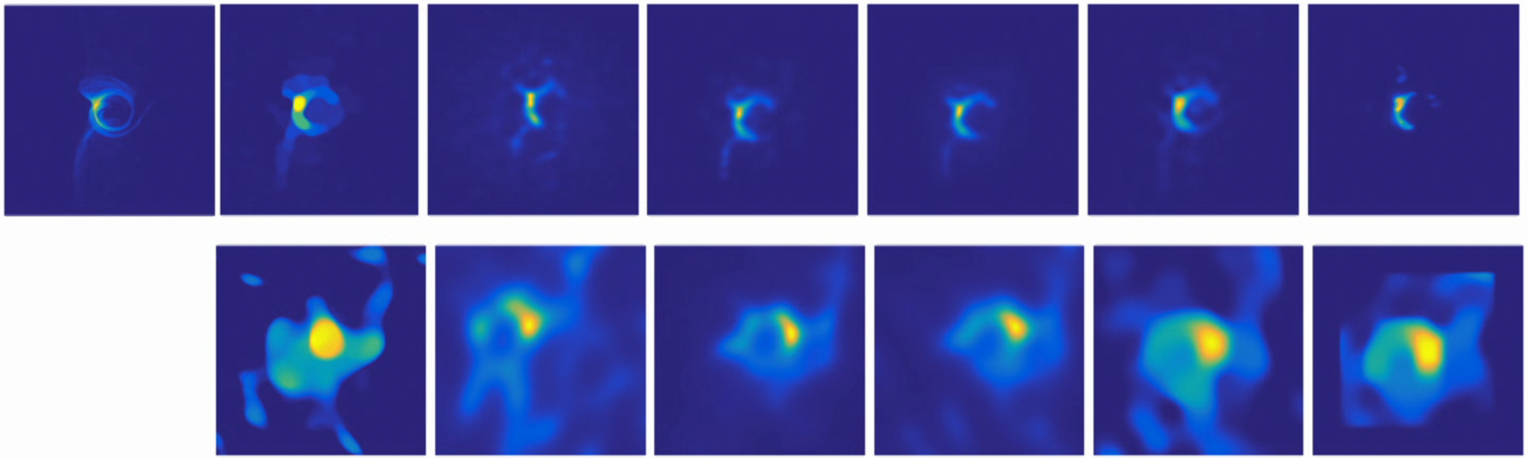
Event Horizon Telescope

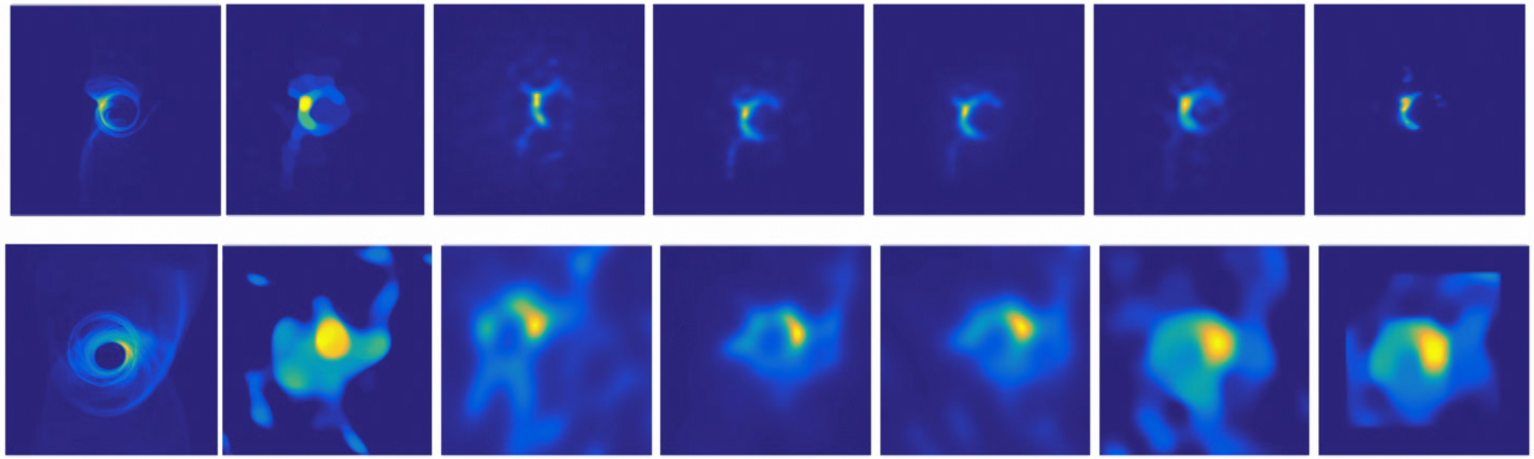


K. Bouman, M. Johnson, A. Chael, K. Akiyama et al

Imaging Challenges: Exploring Algorithms



K. Bouman, M. Johnson, A. Chael, K. Akiyama et al



K. **Bouman**, M. Johnson, A. Chael, K. Akiyama et al

Imaging Challenges: Exploring Algorithms

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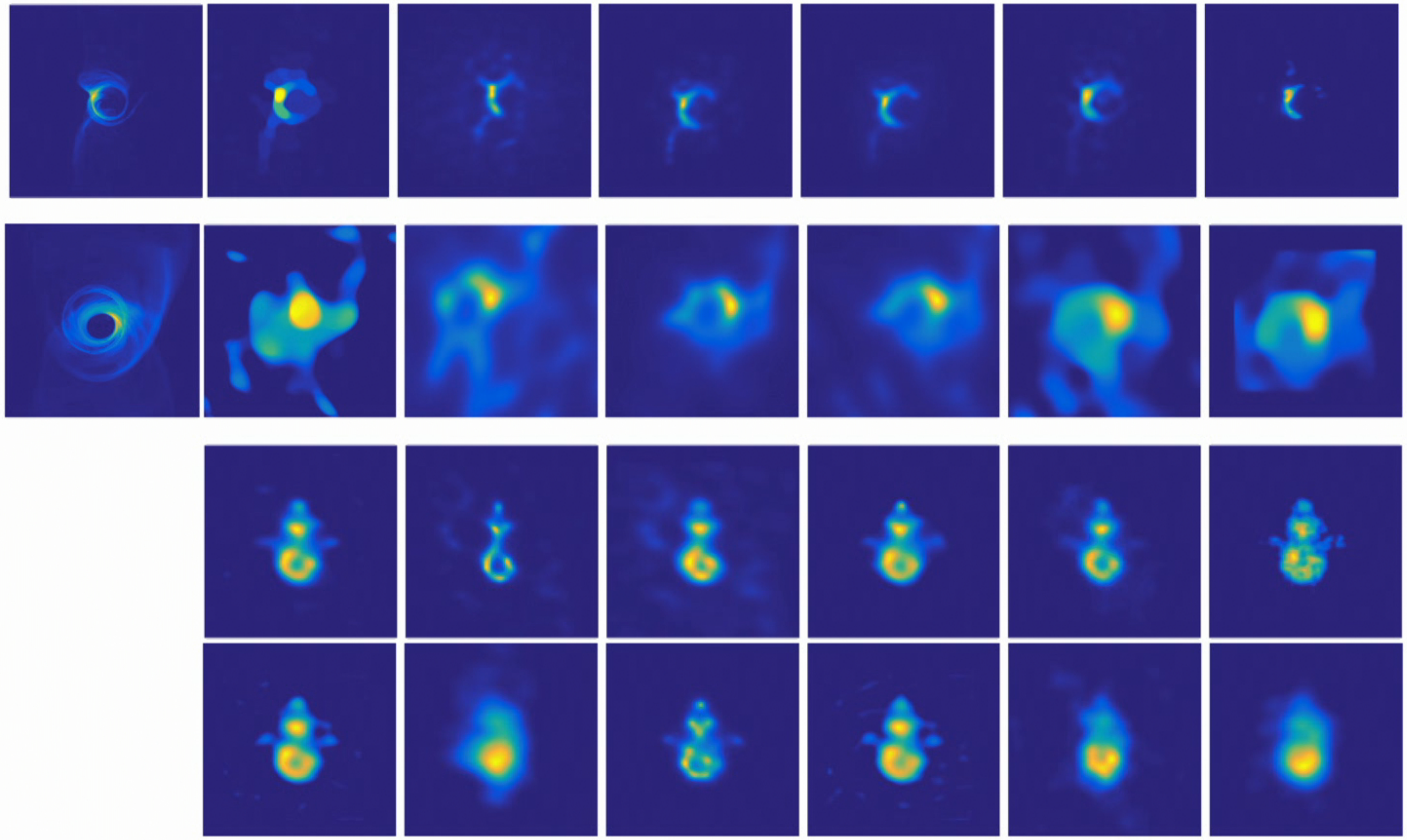
Event Horizon Telescope



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Imaging Challenges: Exploring Algorithms

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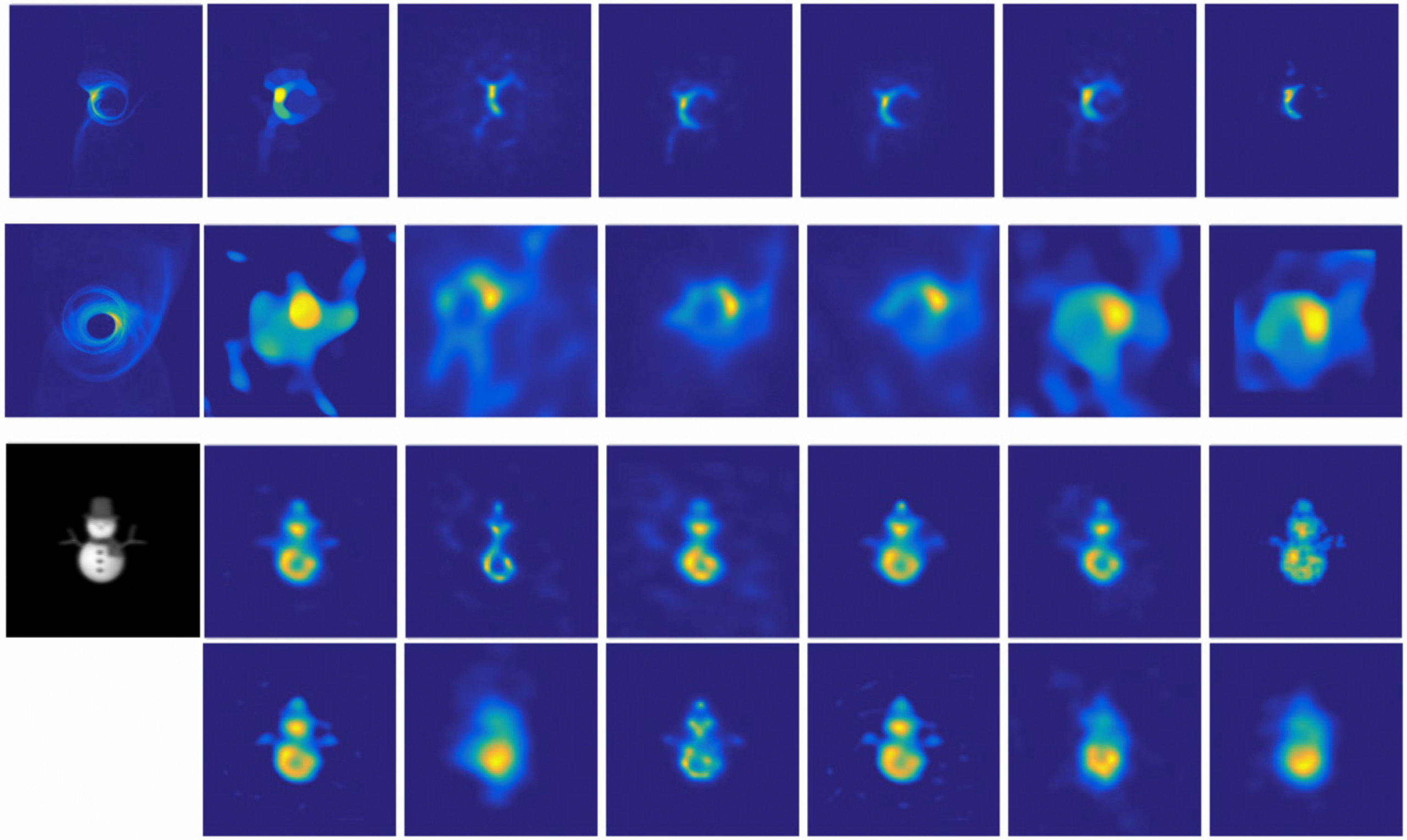
Event Horizon Telescope



K. Bouman, M. Johnson, A. Chael, K. Akiyama et al

Four Independent Imaging Teams

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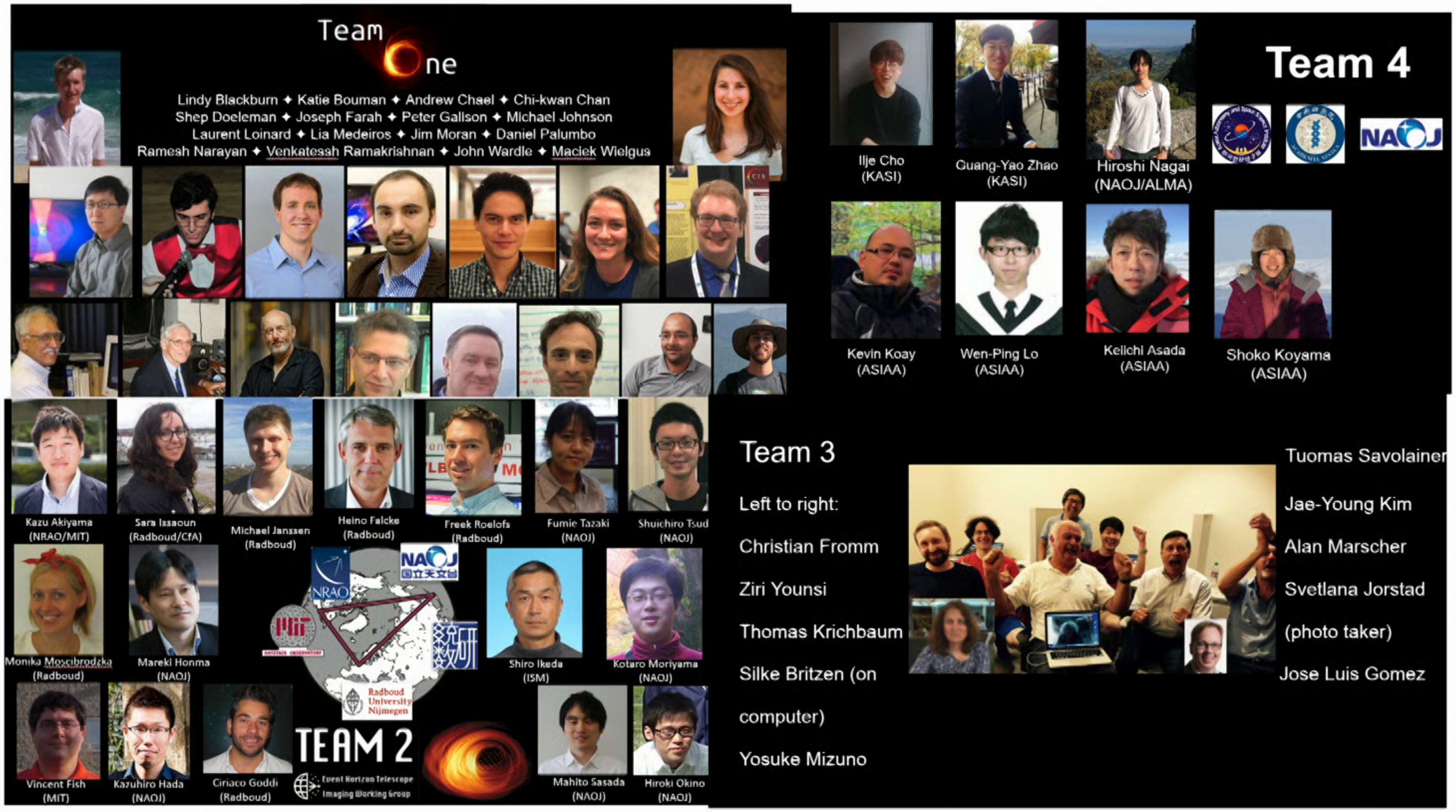
Event Horizon Telescope



Removing Human Bias

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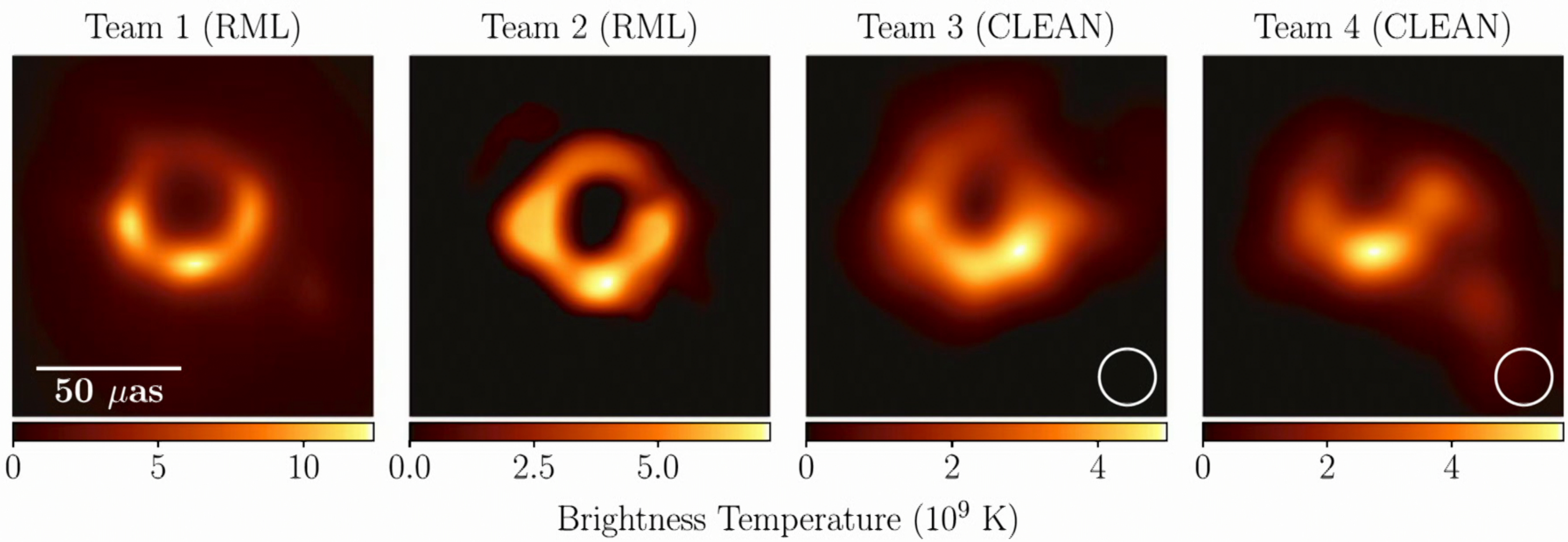
Event Horizon Telescope

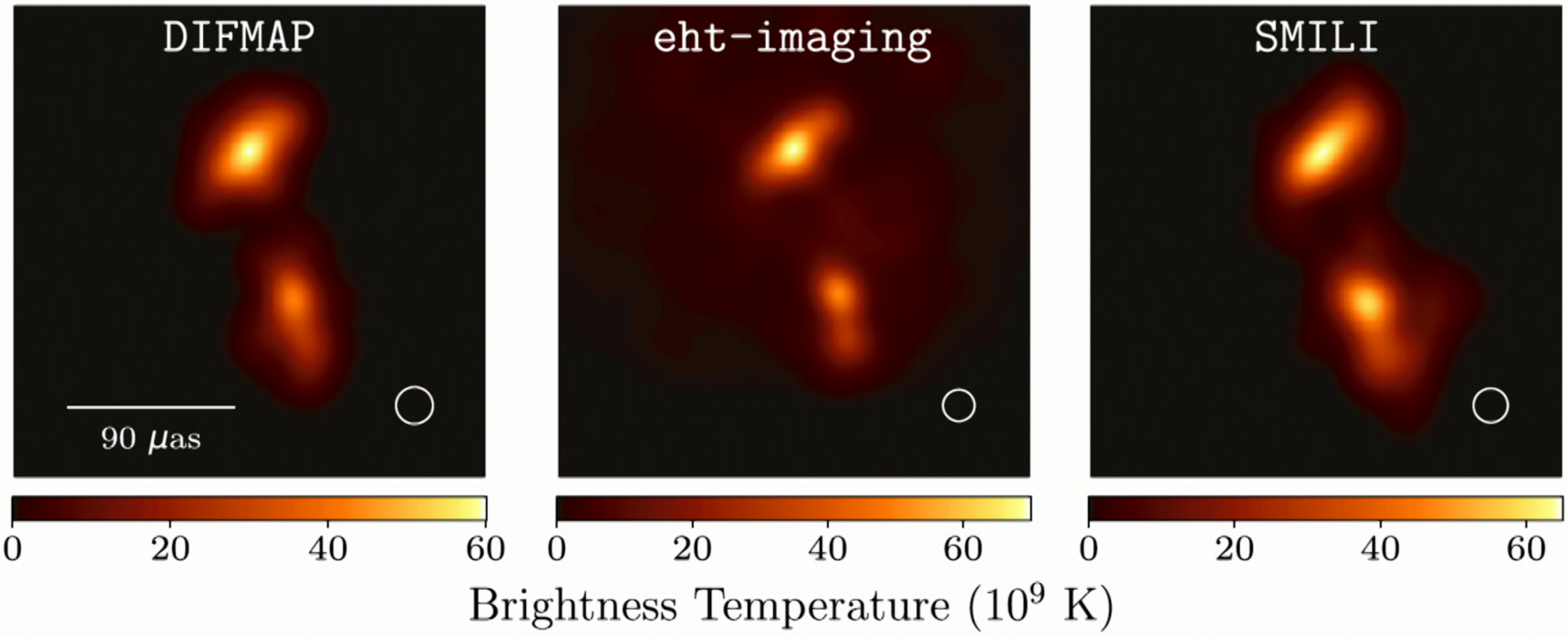
Artificial intelligence struggles to tell difference between fried chicken and Labradoodles.

Removing Human Bias

Black Hole Initiative
Harvard University
July 24, 2018



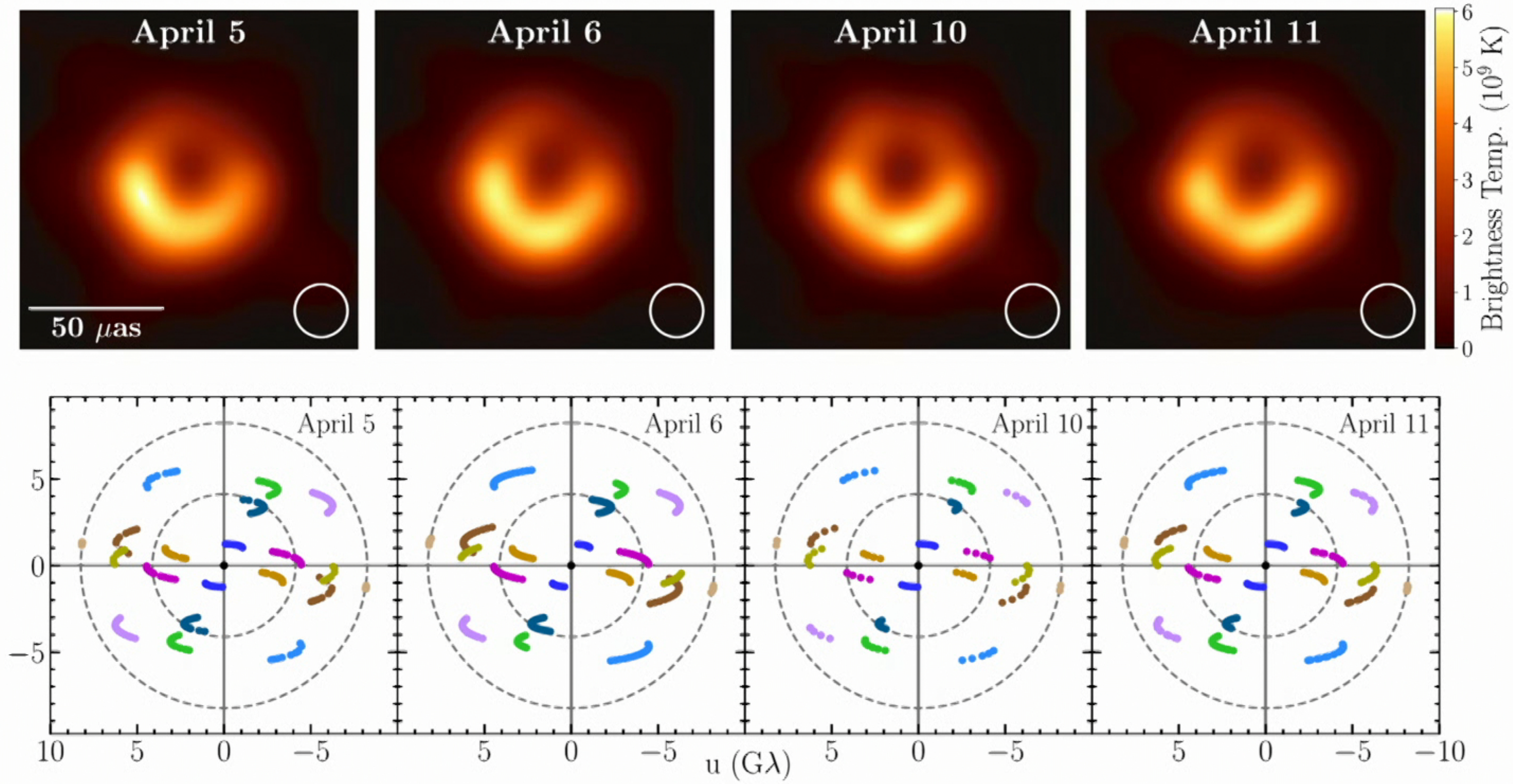
Imaging Calibration Targets: Quasar 3C279



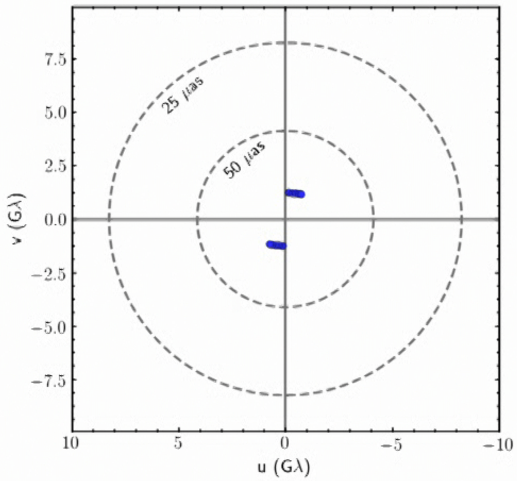
EHT Paper 4

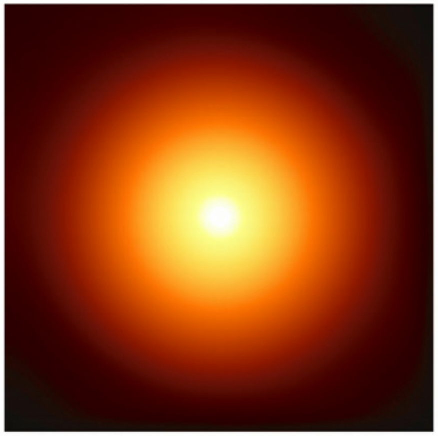
Kim, Krichbaum, Broderick et al (2020)

Repeatable over four days.



Data → Image: the Importance of New Sites

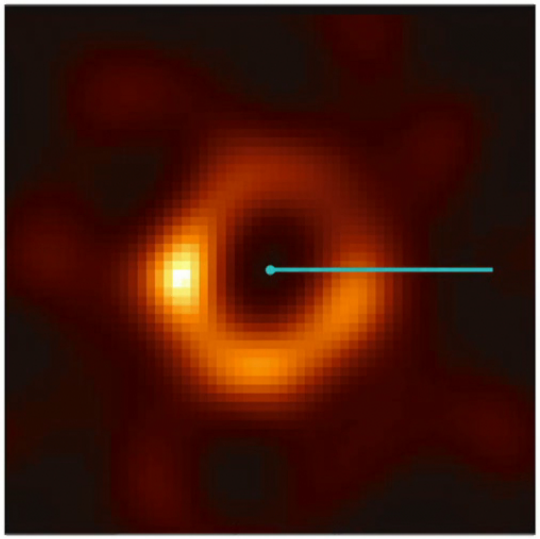


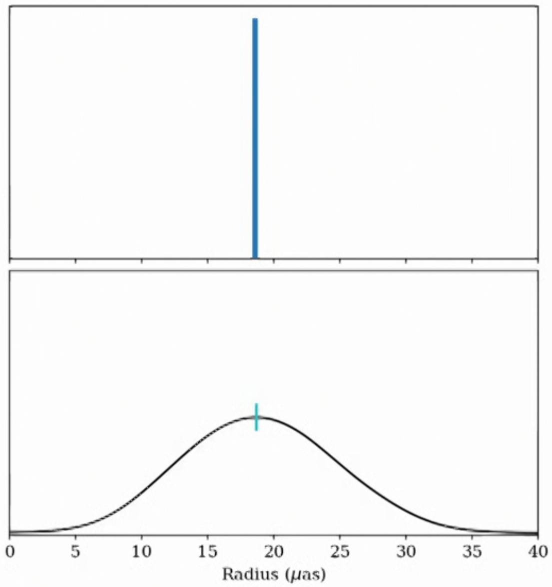


2 Sites ↔ 1 Baseline

D. Palumbo, M. Wielgus, M. Johnson

We can measure the diameter directly from images





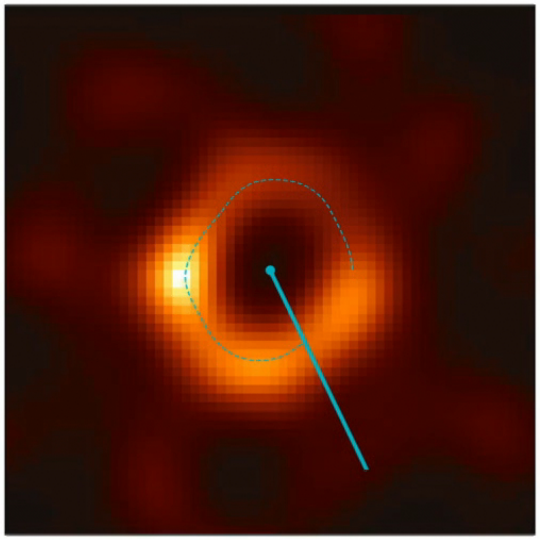
For Schwarzschild (a=0)

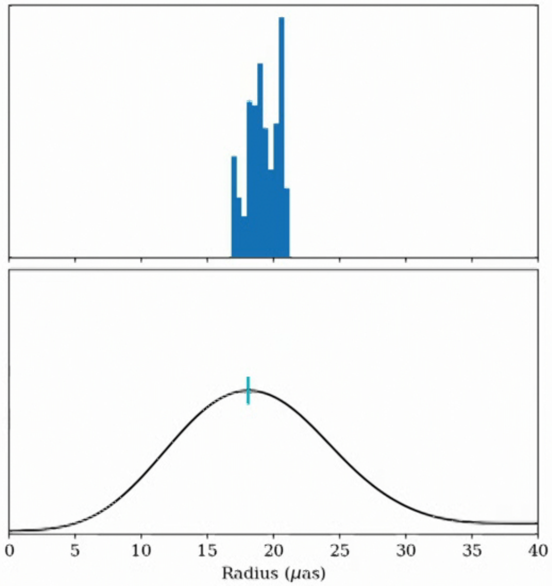
$$\text{Ang Shadow Diameter} = 2\sqrt{27}\left(\frac{GM}{Dc^2}\right)$$

$$\text{Ang Shadow Diameter} = 2\sqrt{27}(\theta_g)$$

D. Pesce

We can measure the diameter directly from images





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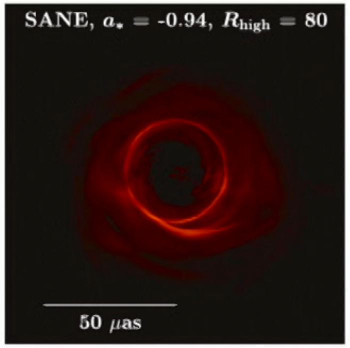
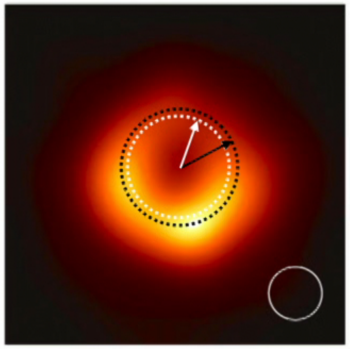
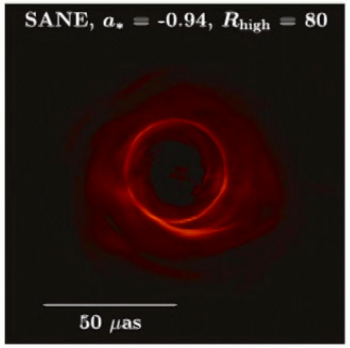
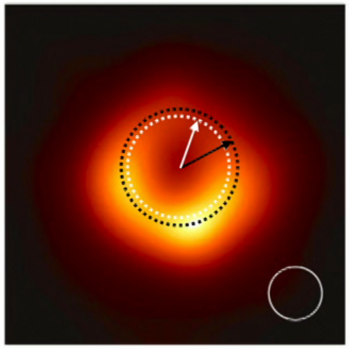




$$\text{Ang Shadow Diameter} = \alpha\theta_g$$

Empirically calibrate α using 100's of GRMHD simulations: spin, ion-electron temperature, B-Field configuration.





Ang Shadow Diameter $= \alpha\theta_g$

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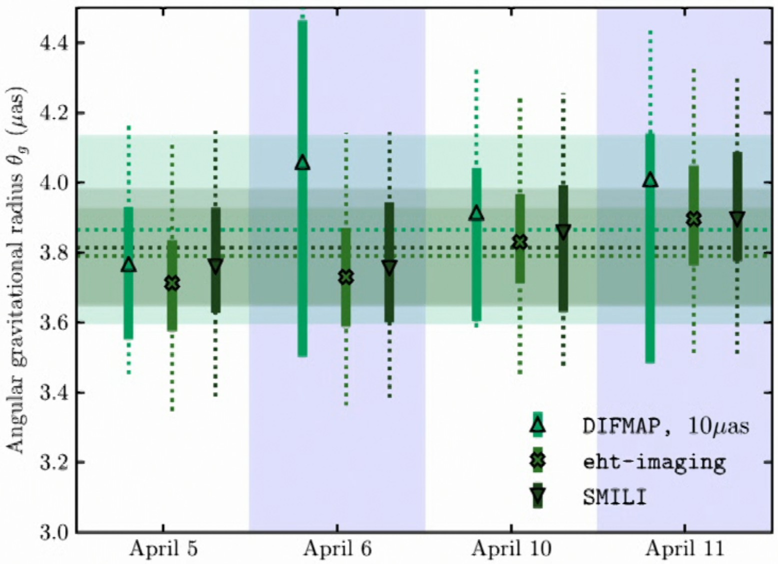
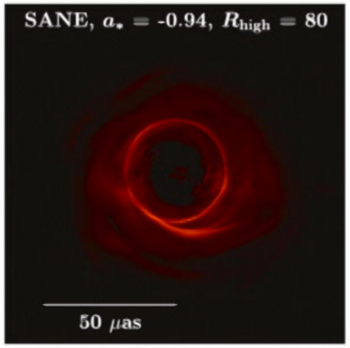
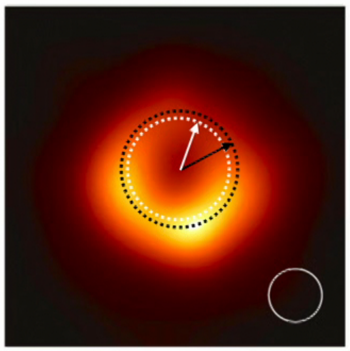


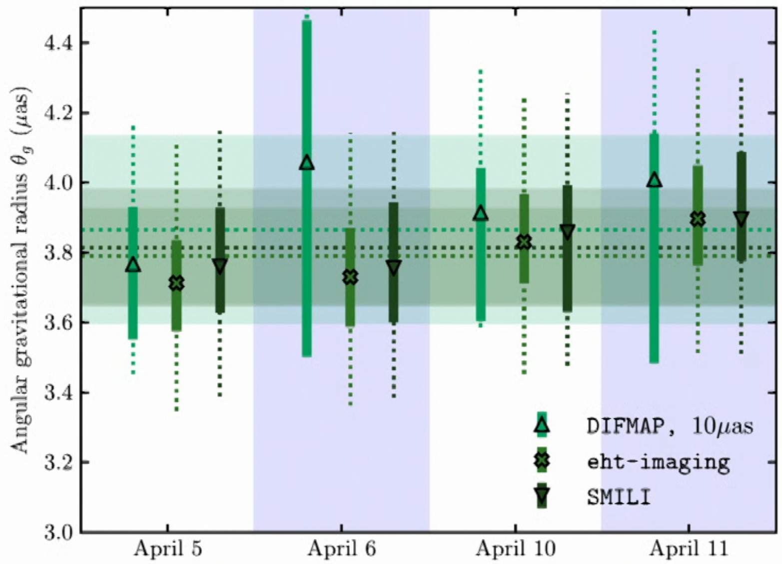
EHT Paper 6





$$\text{Ang Shadow Diameter} = \alpha\theta_g$$

Empirically calibrate α using 100's of GRMHD simulations: spin, ion-electron temperature, B-Field configuration.



EHT Paper 6

D = 16.8 (+.8/-.7) Mpc

M = 6.5 (+.8/-.7) x 10^9 Msol

Is this the shadow of a black hole?

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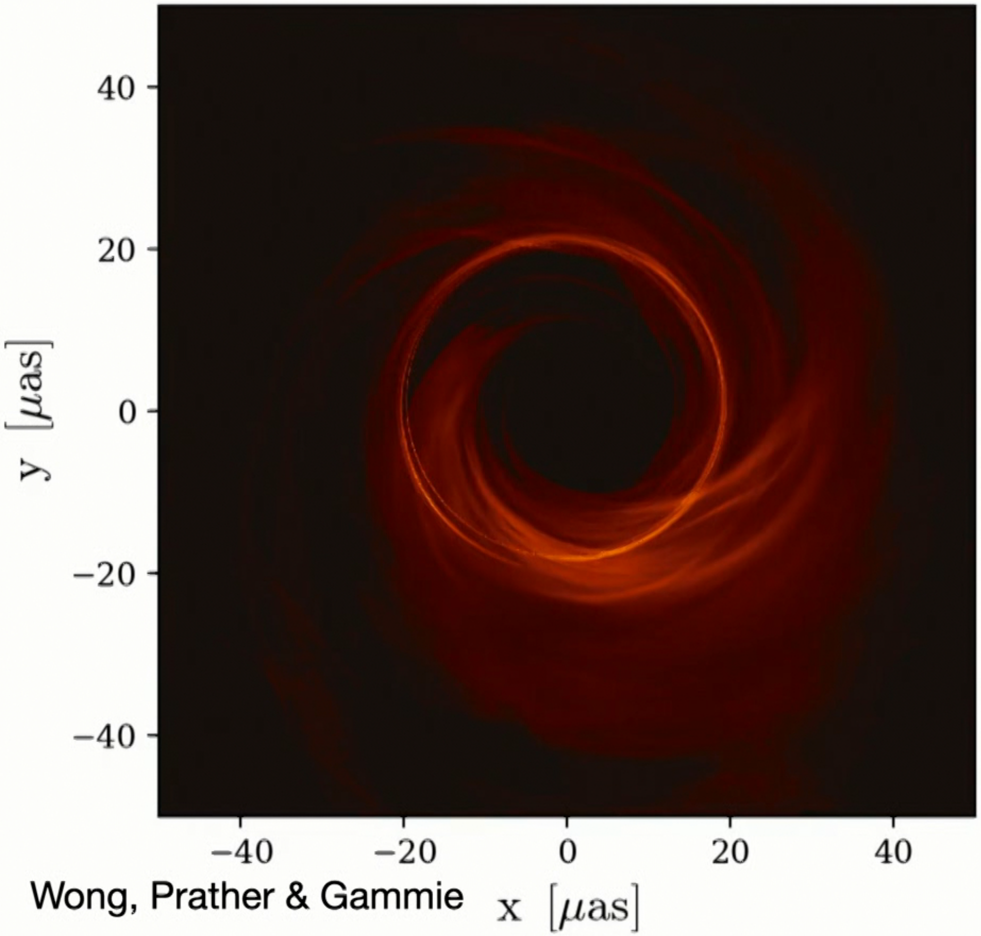
Event Horizon Telescope

- Mass from GR = 6.5 (+/-0.7) x 10^9 M$\odot$
  - Agrees with dynamical measurements.
- Circular to 10% -expected due to inclination of jet.
- Asymmetry due to near light-speed motions of gas near the event horizon.
- Consistent with Einstein's theory at the 17% level.
- We can do much better with future instruments and observations.
- Allows us to study the details of flow around the black hole.

Time variability challenges the current EHT

ngEHT
Science at the Horizon



Wong, Prather & Gammie

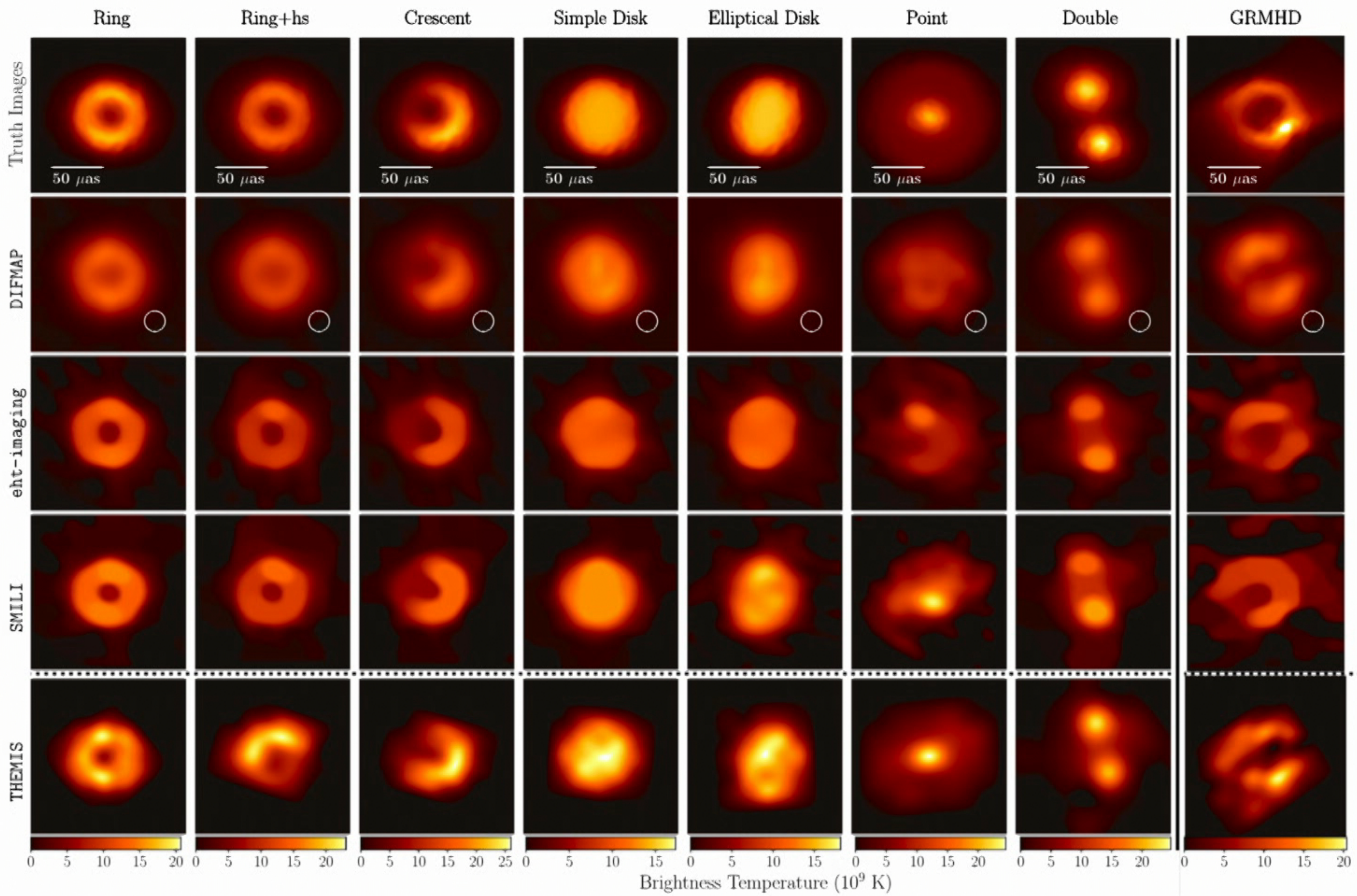
For SgrA*:

- Orbital Period of Matter = 1/2 hour.
- It changes its appearance many times during a night of observing.

SgrA* Imaging Strategy

ngEHT
Science at the Horizon

- Each image method is tuned to reproduce the right input structure.
- Multiple methods of scattering and time variability mitigation are attempted.
- Over **<u>100k</u>** images are produced from the SgrA* data.



SgrA*: Strong Evidence for a Ring

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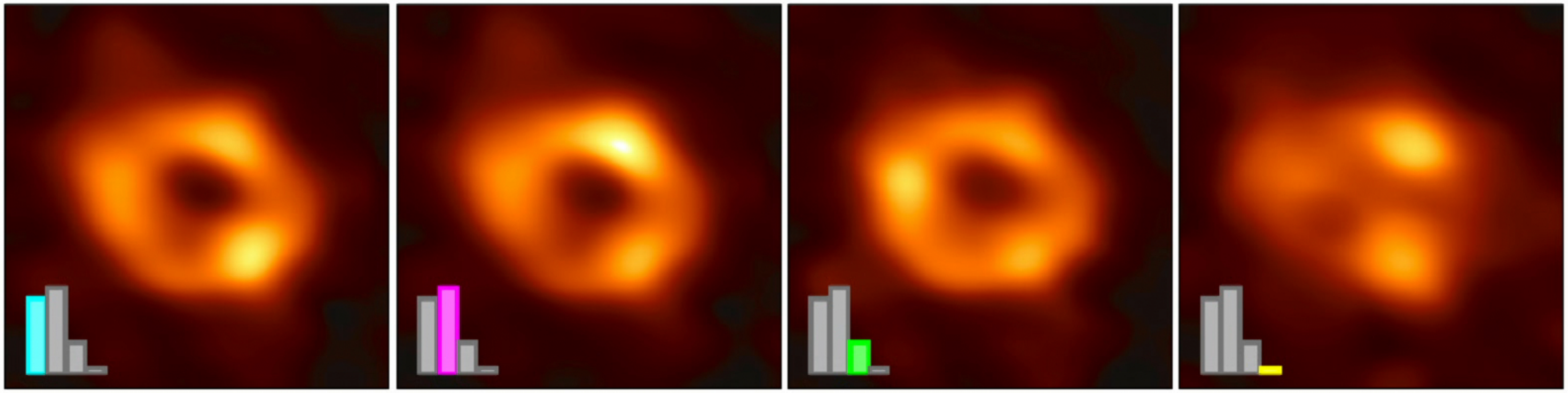
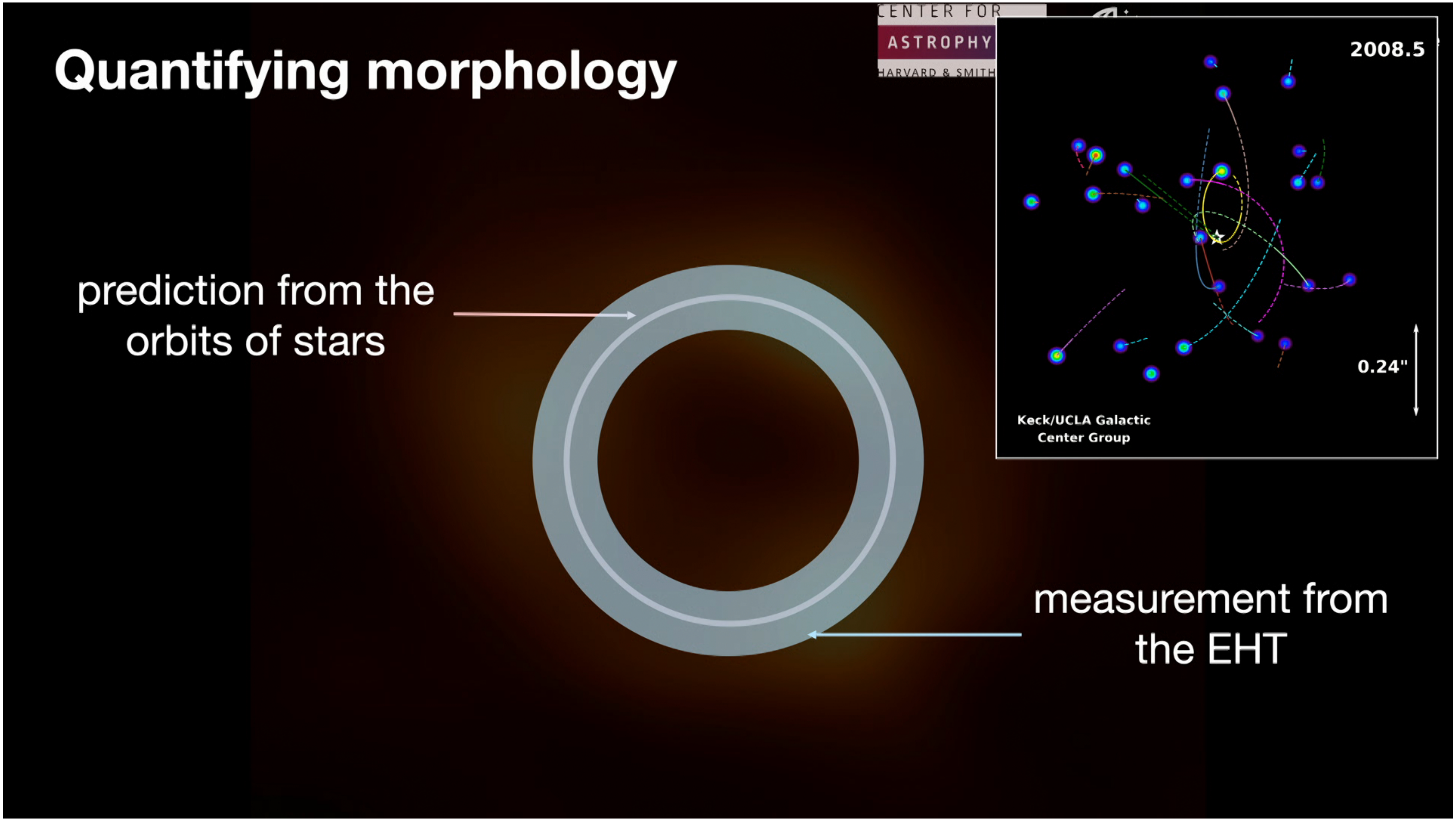
Science at the Horizon



- Four major clusters identified (based on azimuthal structure): ~2% are non-ring.
- Ring structure is NOT likely produced by intrinsic non-ring morphology. Non-ring synthetic data does not produce rings, and synthetic ring data produces ~2% non-rings.
- Scattering does not strongly affect ring structure.
- Non-rings most likely caused by variability.



Quantifying morphology
prediction from the orbits of stars
measurement from the EHT
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN
2008.5
0.24"
Keck/UCLA Galactic Center Group

SgrA*: Still a Ring but more complex.

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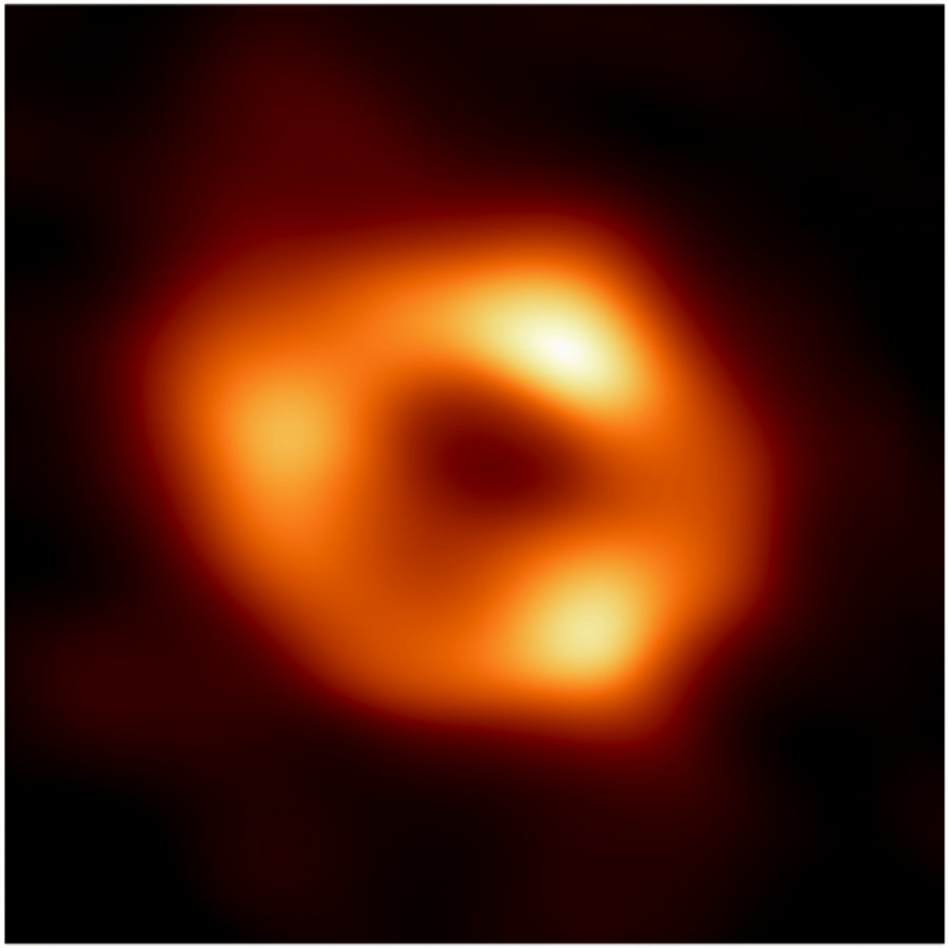

- SgrA* ring diameter =51.8 ± 2.3 μas. Width ~30%.
- Derived mass = 4.0 (+1.1,-0.6) x 10^6 $M_\odot$
- Mass from stellar orbits = 4.1 x 10^6 $M_\odot$
- Corroborates GR at 10% level.
- Two sources now that corroborate Einstein's gravity at the horizon.
- **Best evidence for the existence of supermassive black holes.**
- A jet has not yet been seen but the ring has a low inclination (near face-on), so the jet may be aligned towards us.

The Next-Generation EHT: What's Next?

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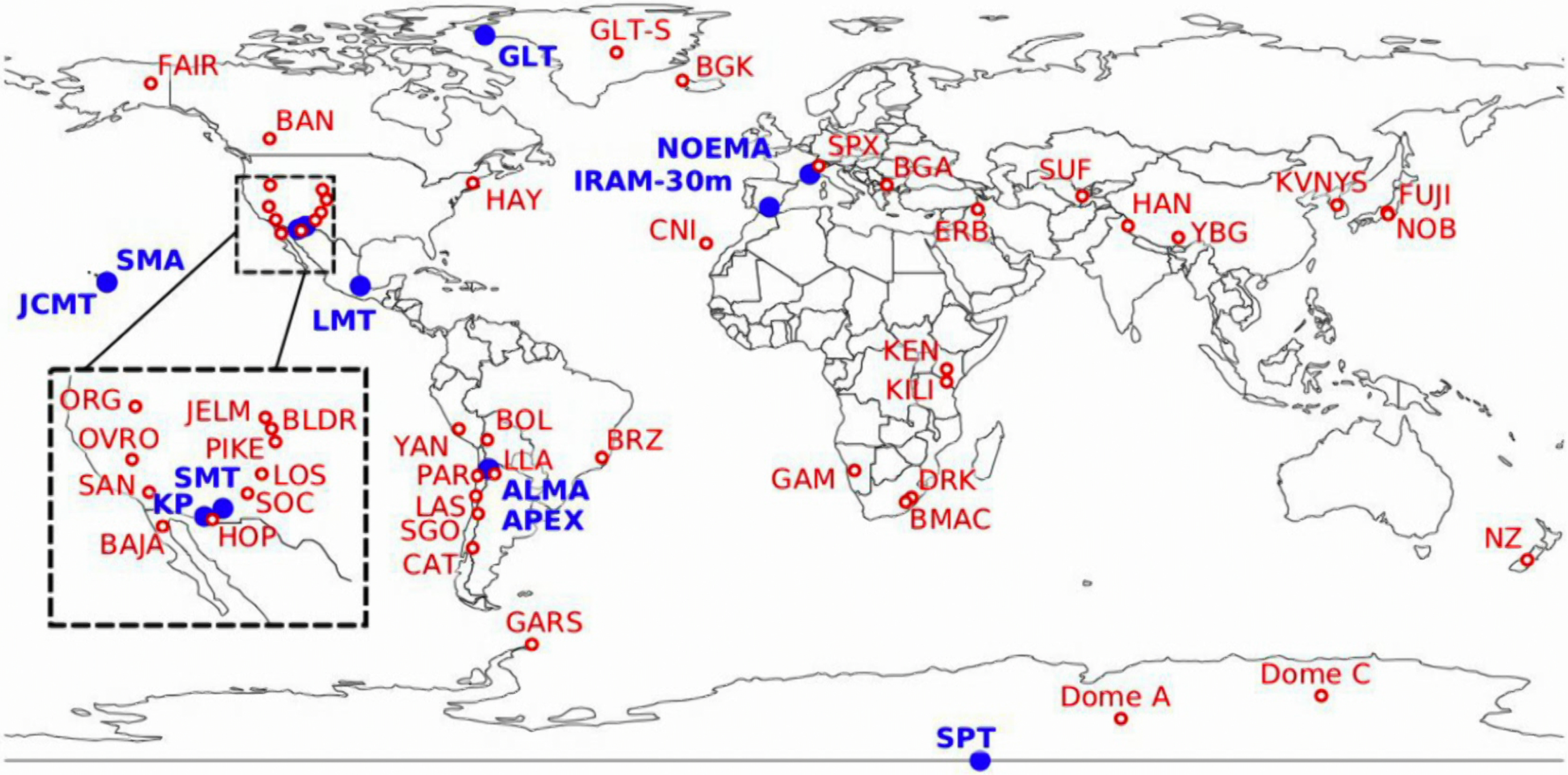

A. Raymond, D. Pesce, G. Lindahl, D. Palumbo, ngEHT team.

M87: Transformative ngEHT imaging fidelity

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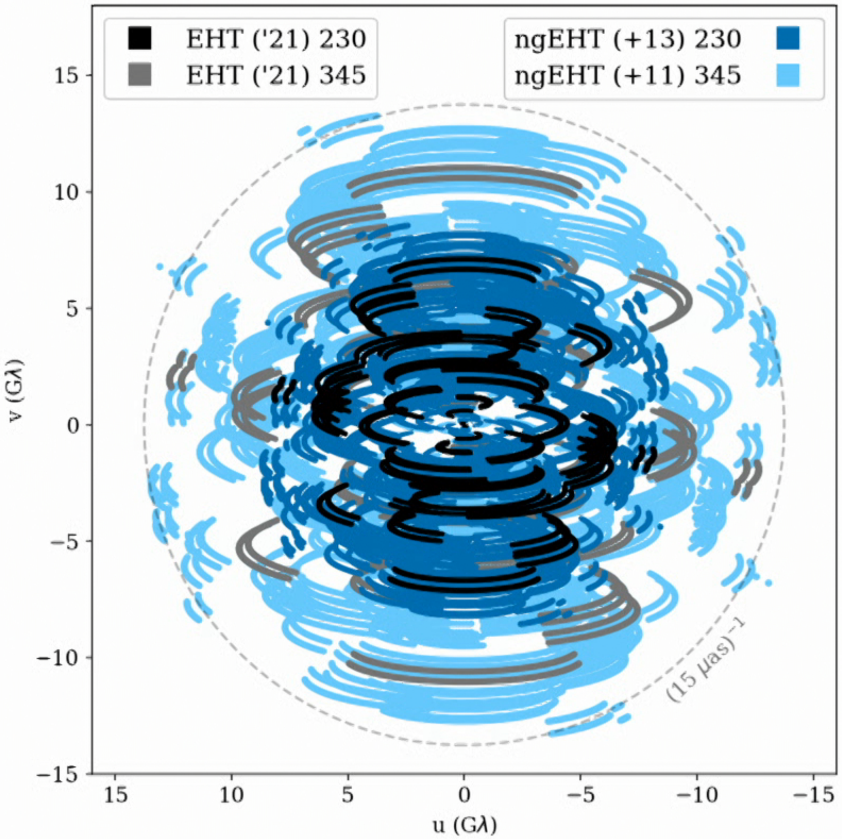
Event Horizon Telescope

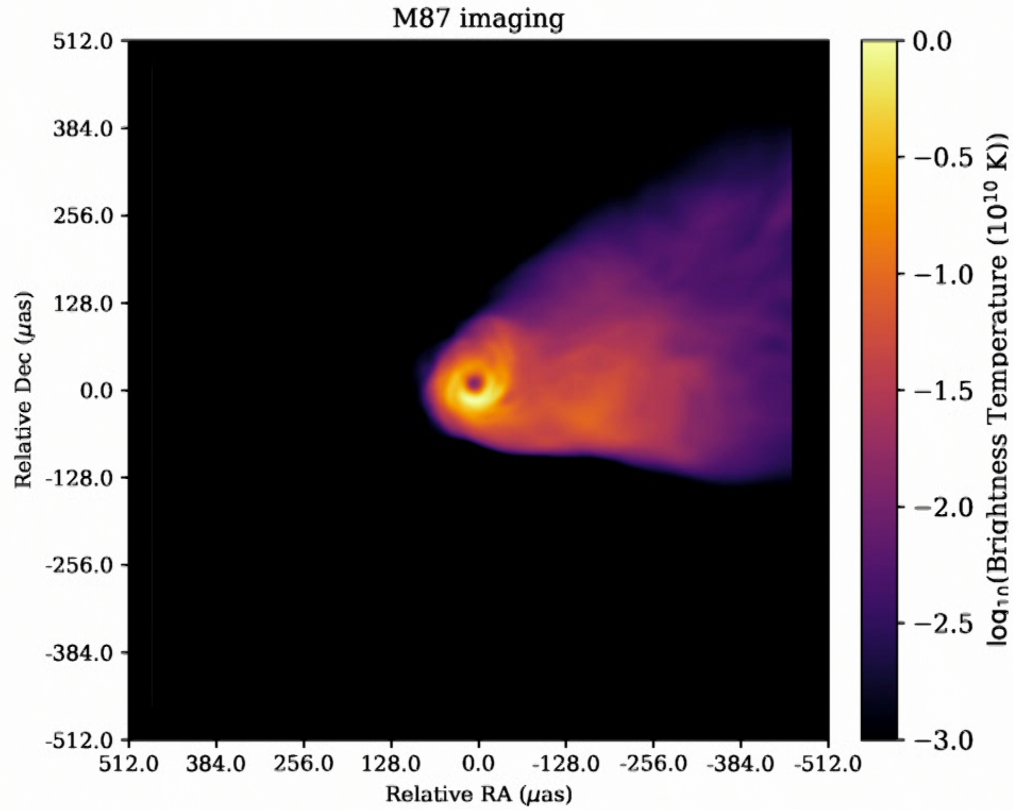
L. Blackburn & A. Chael

ngEHT (+13)

APEX SMA JCMT SMT LMT PV PDB SPT GLT [KP] (no ALMA)
SGO KEN NZ CNI CAT BMAC KILI BRZ GLT-S YBG SPX [HAY OVRO]
ngEHT sites with zenith $SEFD_{230}$ = 10,000 (8-10m)

eht-imaging
closure phases
5% amplitude calibration





Black Hole Movies to Study Event Horizon Dynamics

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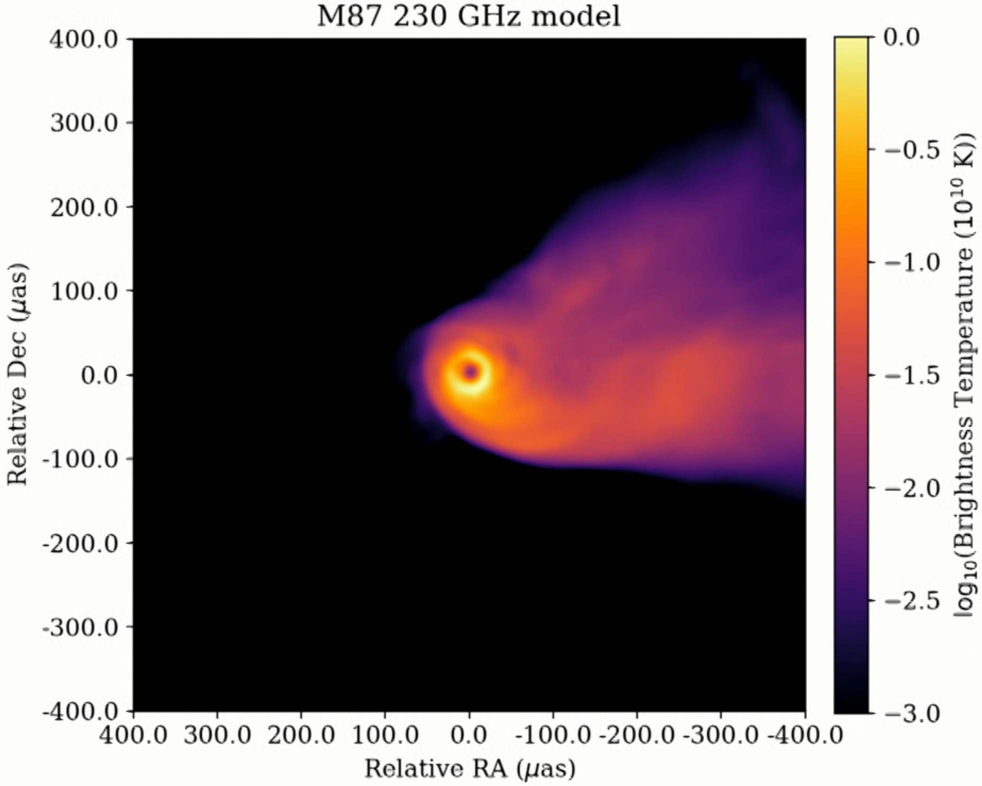
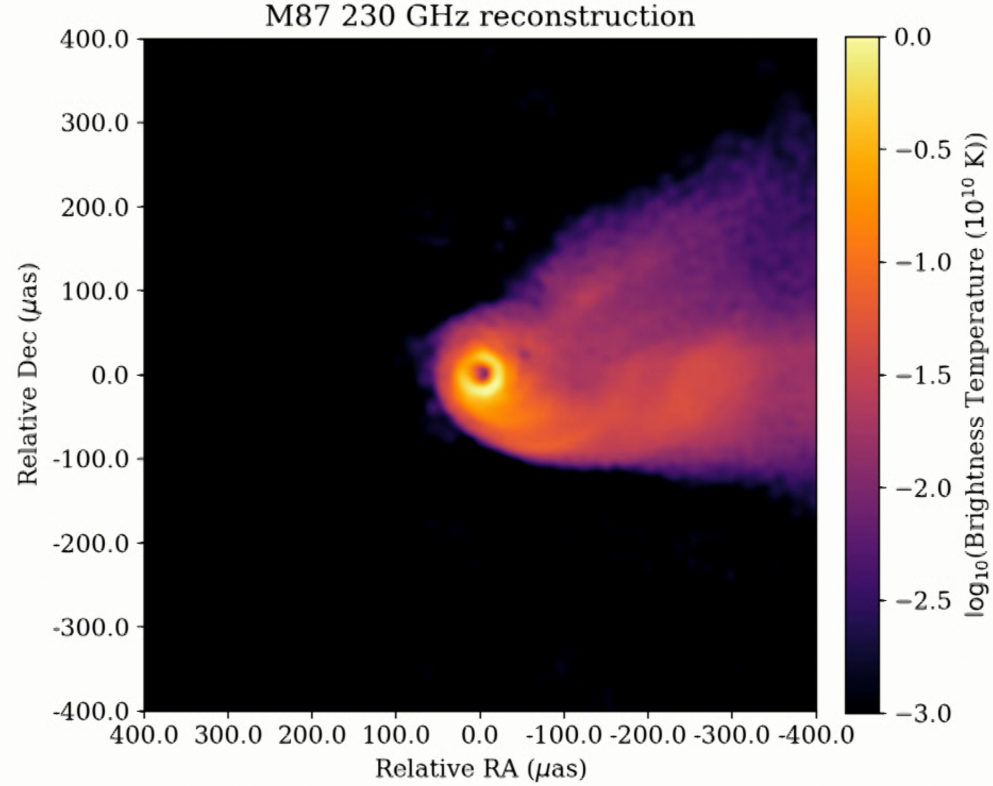
Science at the Horizon

Movie duration: 5 years, 10M=3.5 day sampling.

non-thermal jet model [Chael et al 2019]



ngEHT monitoring campaign (no ALMA)



Real Time Black Hole Video: SgrA* (GM/c³ = 20 sec)

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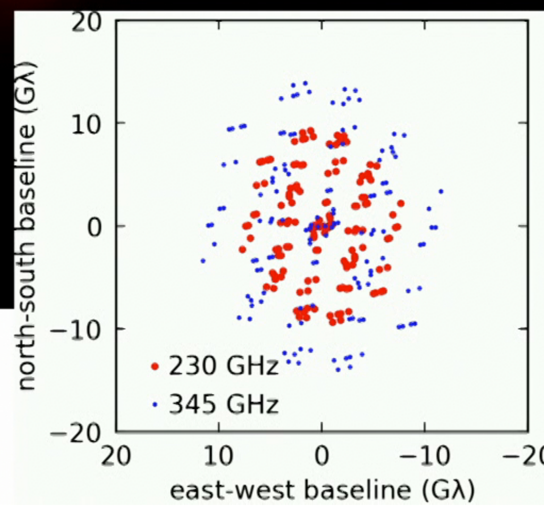
Event Horizon Telescope

Simulation | Blurred | Reconstruction

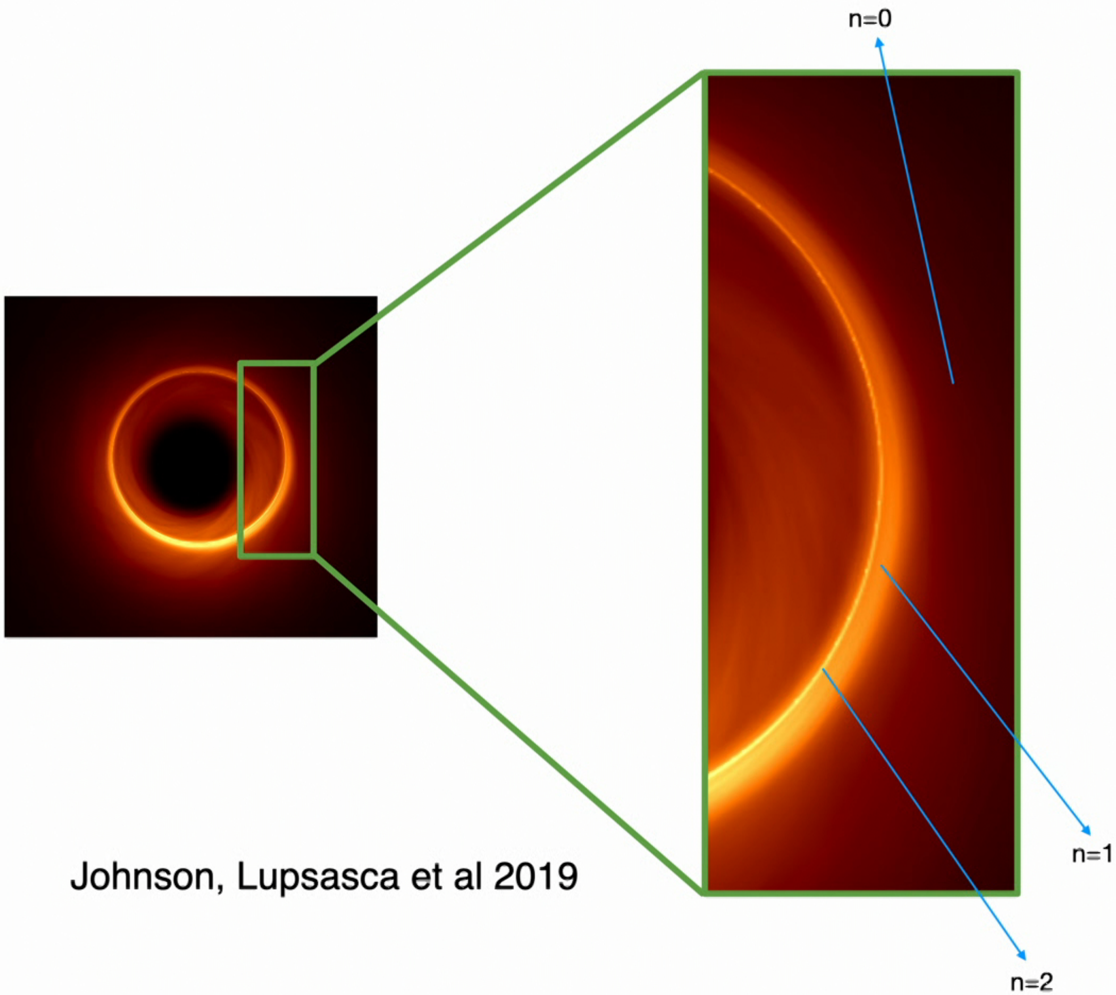
Lindy Blackburn
Katie Bouman
Christian Fromm
Zachary Gelles
Michael Johnson
Alex Raymond



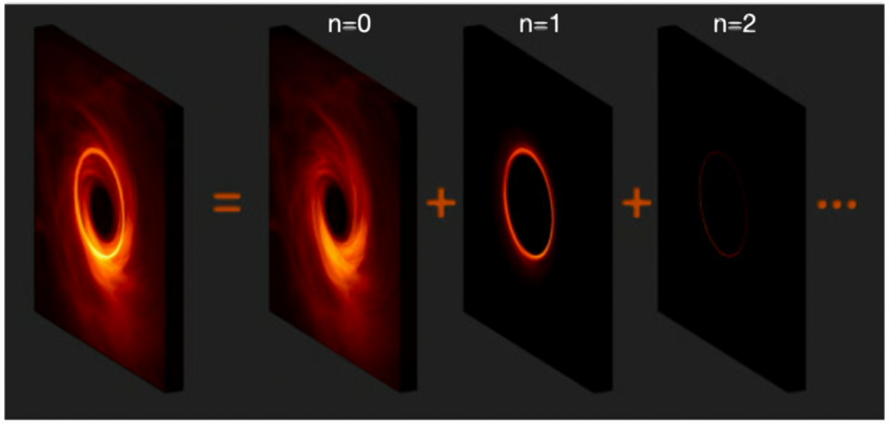
- Horizon scale flares
- Magnetic field dynamics.
- Precision black hole orbits.

Can we test GR to better precision? Inner photon rings.

ngEHT Science at the Horizon



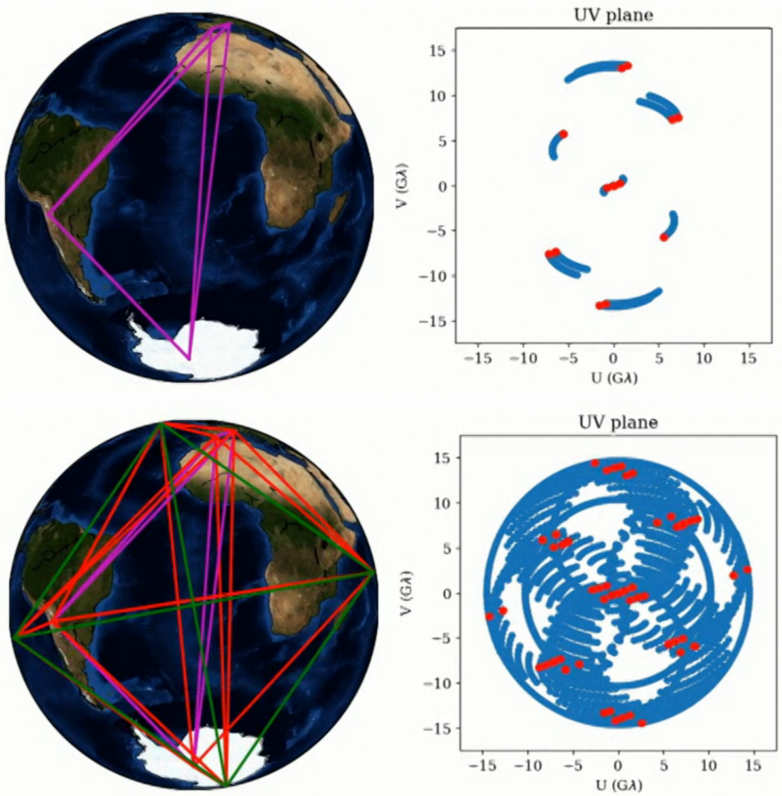
Johnson, Lupsasca et al 2019



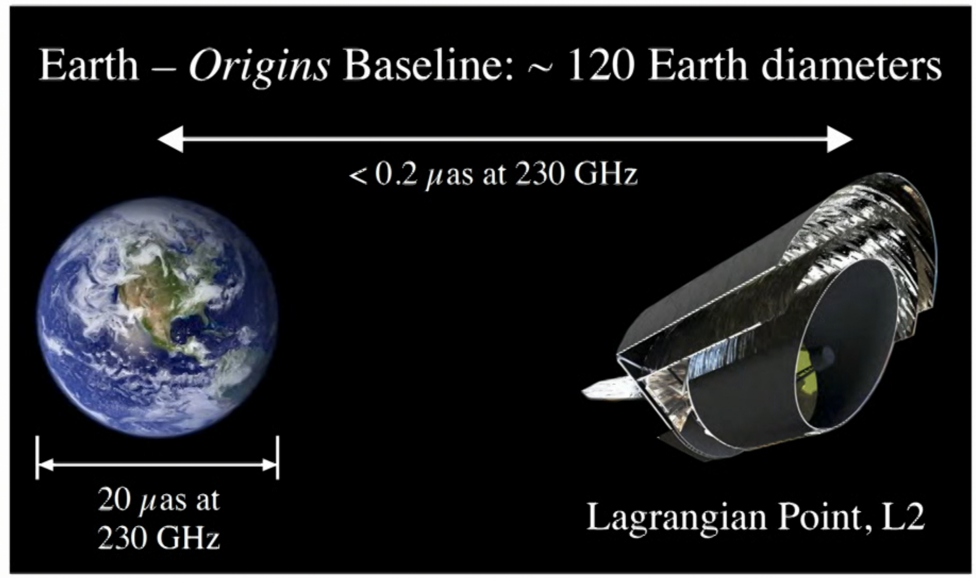
Extension of EHT to Space Transforms Our Capabilities

ngEHT
Science at the Horizon

Space-EHT enables real time black hole video and detection of thousands of black holes.



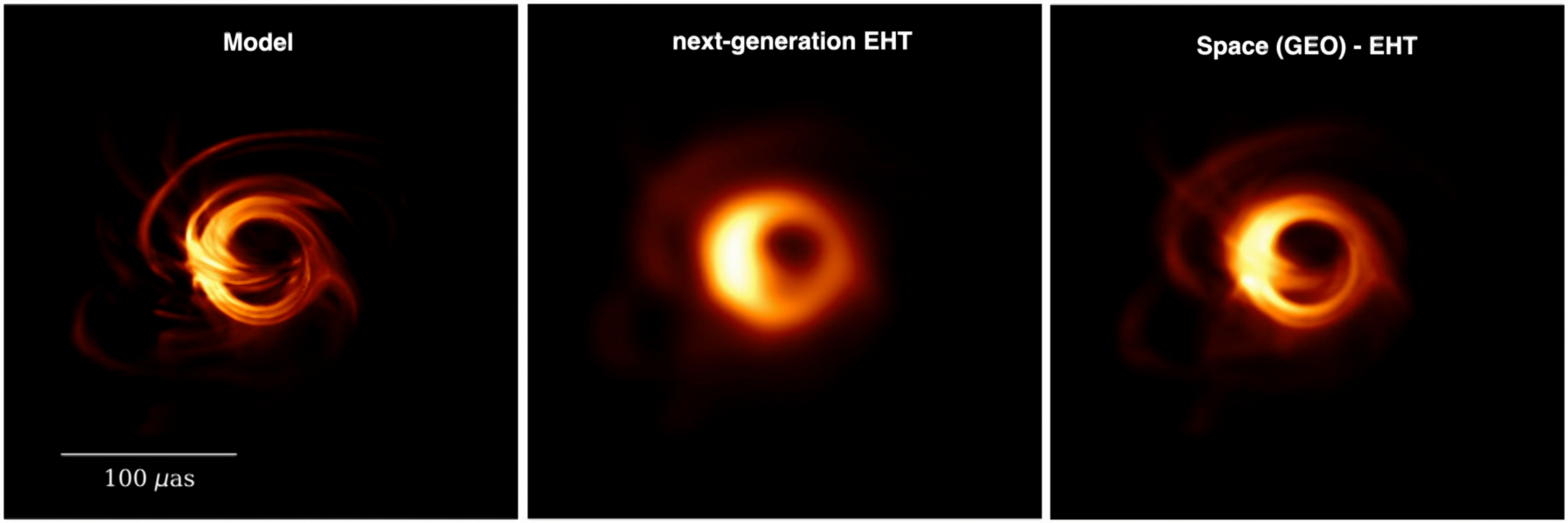
Adding 4 Low Earth Orbiters allows snapshots every 100 seconds.



A 1.5 million km telescope : the event horizons of 10's of thousands of black holes could be resolved. This allows us to study black hole mass and spin over cosmic times.

SgrA*: Black Hole Cinema

ngEHT
Science at the Horizon



ngEHT Team

- >200 members - 60 institutes - 20 countries/regions
- Significant contributions by early career researchers.

EHT 2020 Early Career Awards

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Event Horizon Telescope

EARLY CAREER
Kazunori Akiyama
(NRAO/MIT Haystack)

EARLY CAREER
Lindy Blackburn
(Center for Astrophysics | Harvard & Smithsonian)

EARLY CAREER
Katherine L. Bouman
(California Institute of Technology)

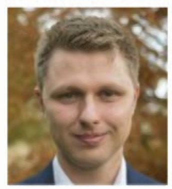
EARLY CAREER
& OUTSTANDING PhD (Analysis)
Andrew Chael
(Princeton University)
Graduated at Harvard Univ.

OUTSTANDING PhD (Theory)
Jordy Davelaar
(Radboud Universiteit Nijmegen)

EARLY CAREER
Jason Dexter
(University of Colorado Boulder)

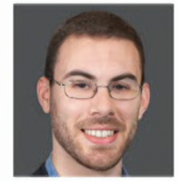
EARLY CAREER
Christian M. Fromm
(Goethe-Universität Frankfurt)

EARLY CAREER
Sara Issaoun
(Radboud Universiteit Nijmegen)



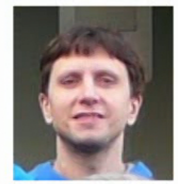
EARLY CAREER
Michael Janßen
(Radboud Universiteit Nijmegen)

OUTSTANDING PhD (Instrumentation)
Junhan Kim
(California Institute of Technology)
Graduated at Univ. of Arizona

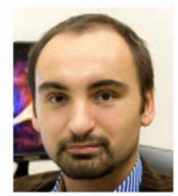


EARLY CAREER
Dominic Pesce
(Center for Astrophysics | Harvard & Smithsonian)

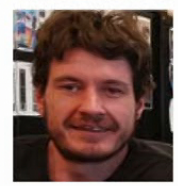
EARLY CAREER
Hung-Yi Pu
(Perimeter Institute/ National Taiwan Normal Univ.)



EARLY CAREER
Jan Wagner
(MPI für Radioastronomie)



EARLY CAREER
Maciek Wielgus
(Center for Astrophysics | Harvard & Smithsonian)



EARLY CAREER
André Young
(Radboud Universiteit Nijmegen)

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Event Horizon Telescope