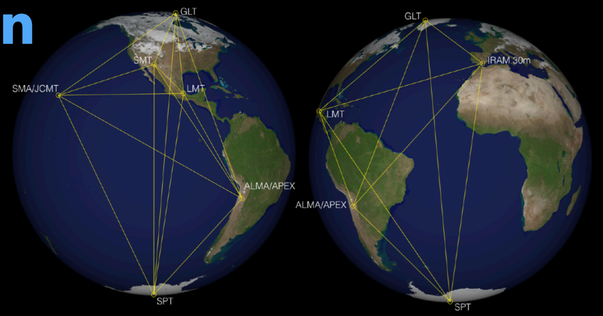
Event Horizon Telescope

Credit: Bronzwaer, Moscibrodzka, Davelaar & Falcke

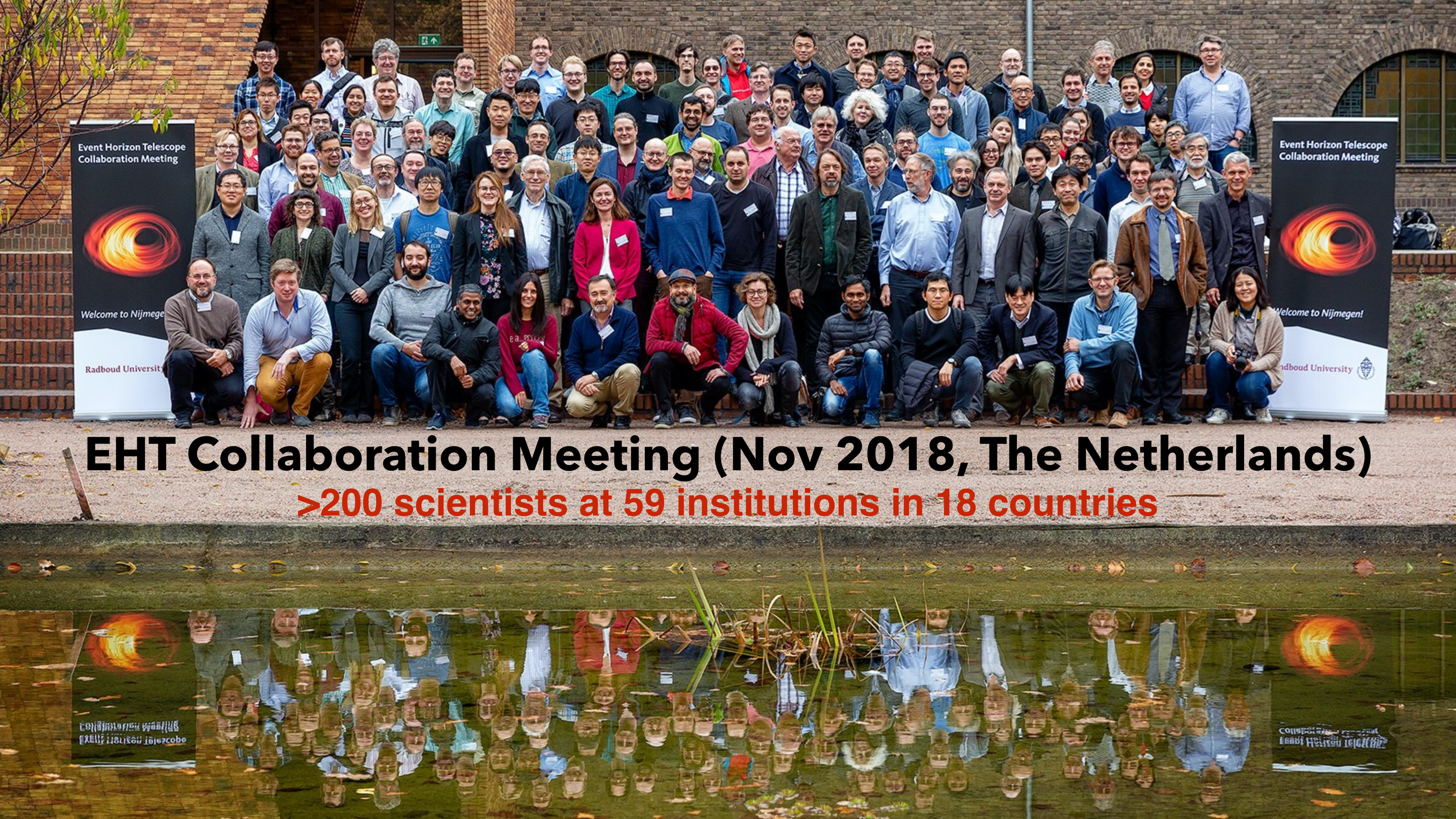
First results and potential African expansion of the Event Horizon Telescope



Roger Deane
University of Pretoria
Visiting Fellow, Rhodes University

On behalf of the EHT Collaboration

EHT Collaboration Meeting (Nov 2018, The Netherlands)



EHT Collaboration Meeting (Nov 2018, The Netherlands)

>200 scientists at 59 institutions in 18 countries

outline

- **EHT Overview:** the instrument and science goals
- **First imaging results on M87:** 
- **The future:** upcoming results and array expansion


中央研究院
ACADEMIA SINICA

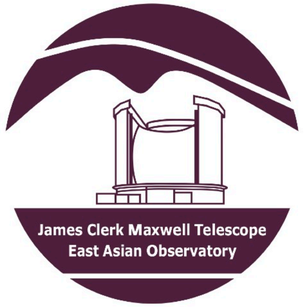

THE UNIVERSITY
OF ARIZONA


THE UNIVERSITY OF
CHICAGO


GOETHE
UNIVERSITÄT
FRANKFURT AM MAIN


iram
Institut de
Radioastronomie
Millimétrique

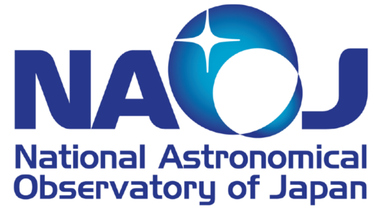

Max-Planck-Institut
für Radioastronomie


James Clerk Maxwell Telescope
East Asian Observatory


Large Millimeter Telescope Alfonso Serrano


Massachusetts
Institute of
Technology


MIT
HAYSTACK
OBSERVATORY


NAOJ
National Astronomical
Observatory of Japan


PERIMETER
INSTITUTE


Radboud University
IN·DEI·NOMINE·FELICITER


Smithsonian
VE RI TAS
HARVARD
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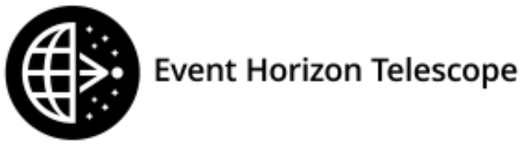
Event Horizon Telescope


Aalto University
School of Electrical Engineering
Brandeis University
BOSTON UNIVERSITY
Los Alamos NATIONAL LABORATORY
Caltech
CIFAR
CITA | ICAT
Canadian Institute for Theoretical Astrophysics
L'Institut Canadien d'astrophysique théorique
NAOC
CHINESE ACADEMY OF SCIENCES
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CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
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ANTON PANNEKOEK INSTITUTE
統計数理研究所
The Institute of Statistical Mathematics
1958
University of Science and Technology of China
University of Massachusetts Amherst
DEPARTAMENTO de ASTRONOMÍA
UNIVERSIDAD DE CONCEPCIÓN
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1885
UNIVERSITEIT VAN PRETORIA
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UST
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FEDERICO II
EHT Associated Logos

Alexander von Humboldt
Stiftung/Foundation

dgapa

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JAPAN SOCIETY FOR THE PROMOTION OF SCIENCE
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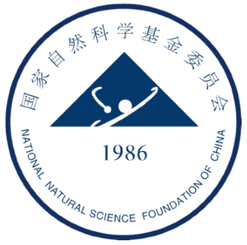
MISTI

中华人民共和国科学技术部
Ministry of Science and Technology of the People's Republic of China

NINS



Innovation, Science and
Economic Development Canada

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Swedish
Research
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Event Horizon Telescope

公益財団法人
東レ科学振興会
Toray Science Foundation

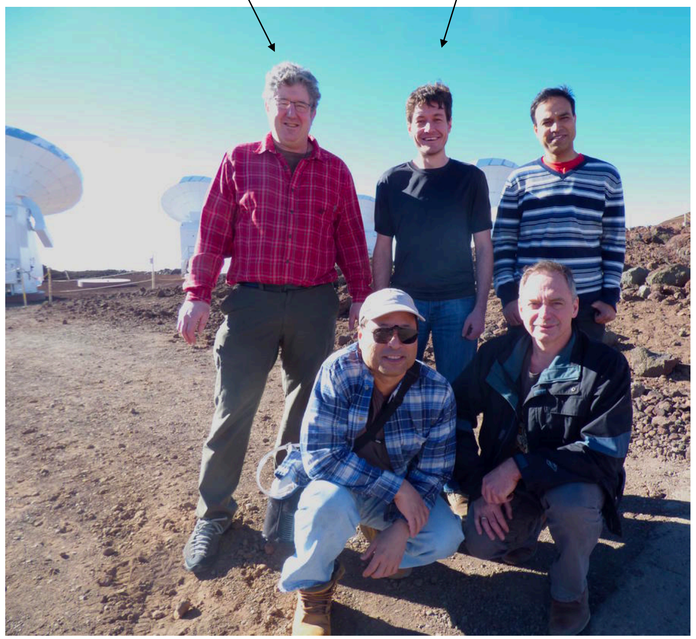
MINISTERO DELL' ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA

Funding Agencies

South African EHT involvement

Andre Young

Jonathan Weintroub



Iniyan Natarajan

Tariq Blecher

Micaela Menegaldo

RPD

Heinrich van Deventer

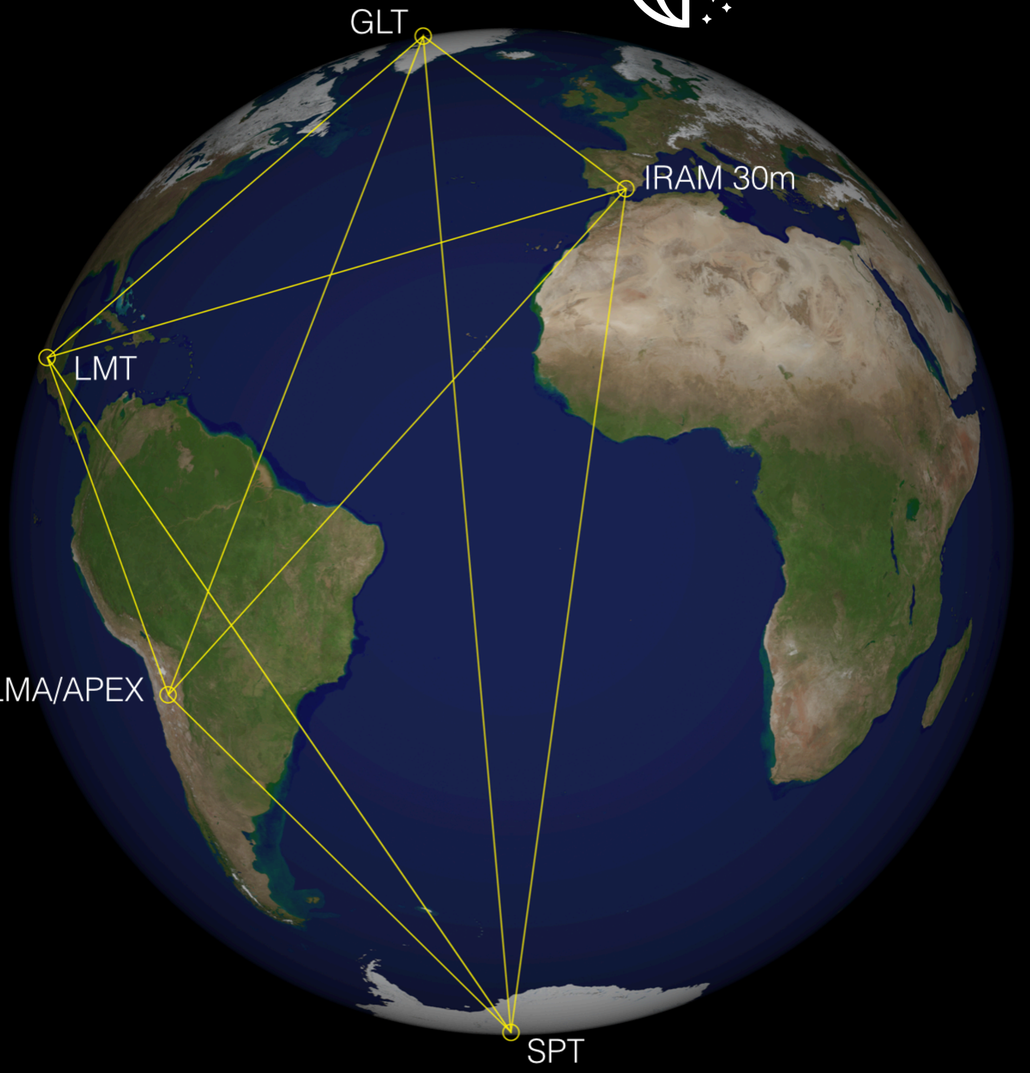
Based at EHT stakeholder institutions

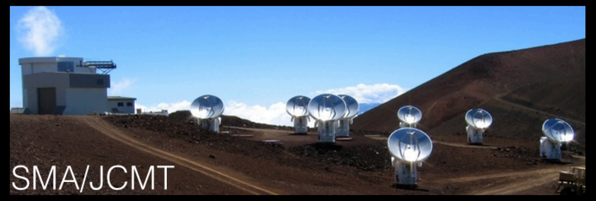
Based in South Africa

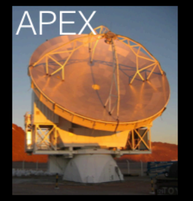
Radio interferometry 101

* history of development of EHT array not covered in this talk

Event Horizon Telescope







Radio interferometers are **not** digital cameras


each antenna pair cross-correlated =
1 sample of 2D Fourier Transform of
sky brightness distribution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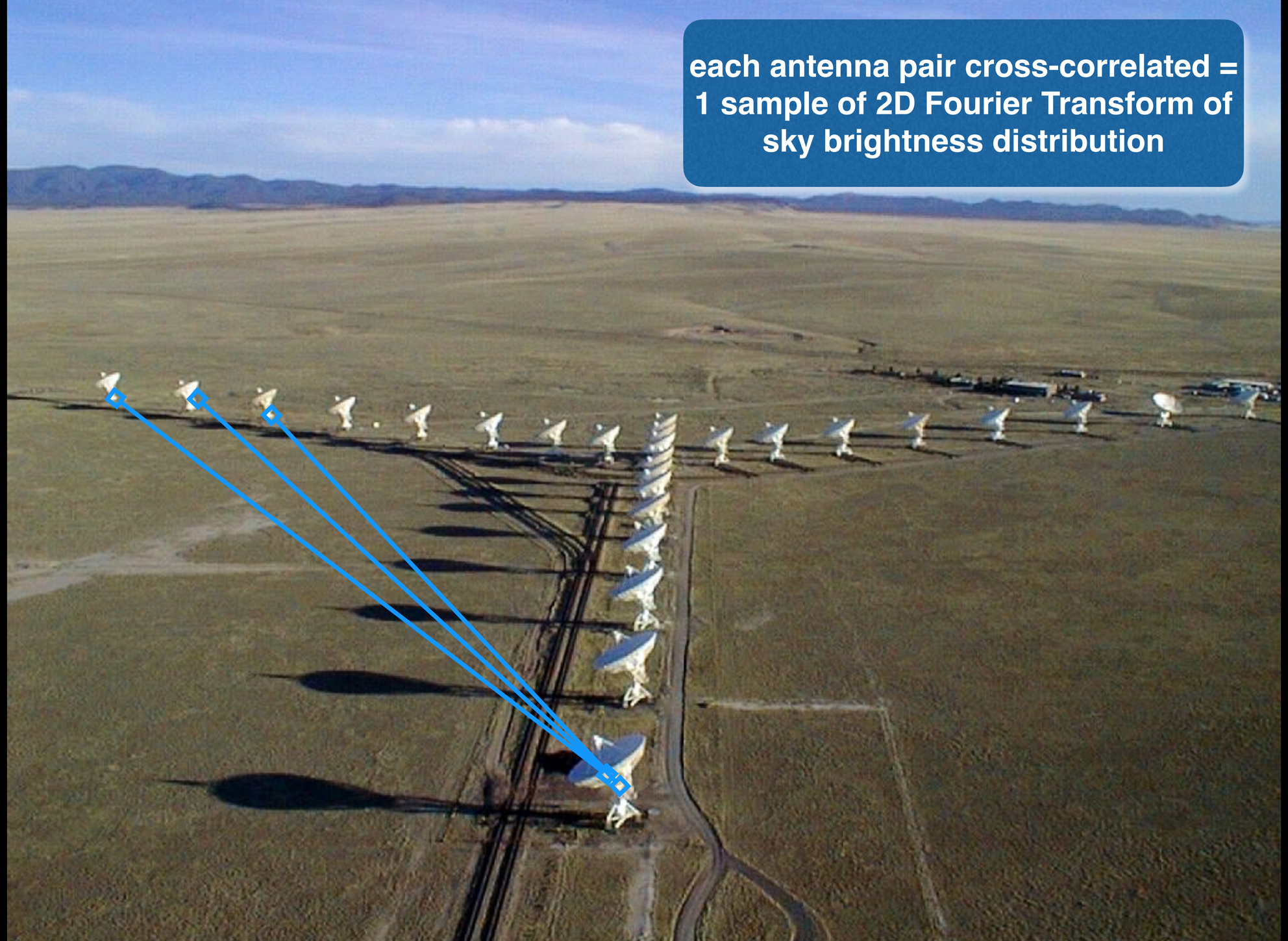
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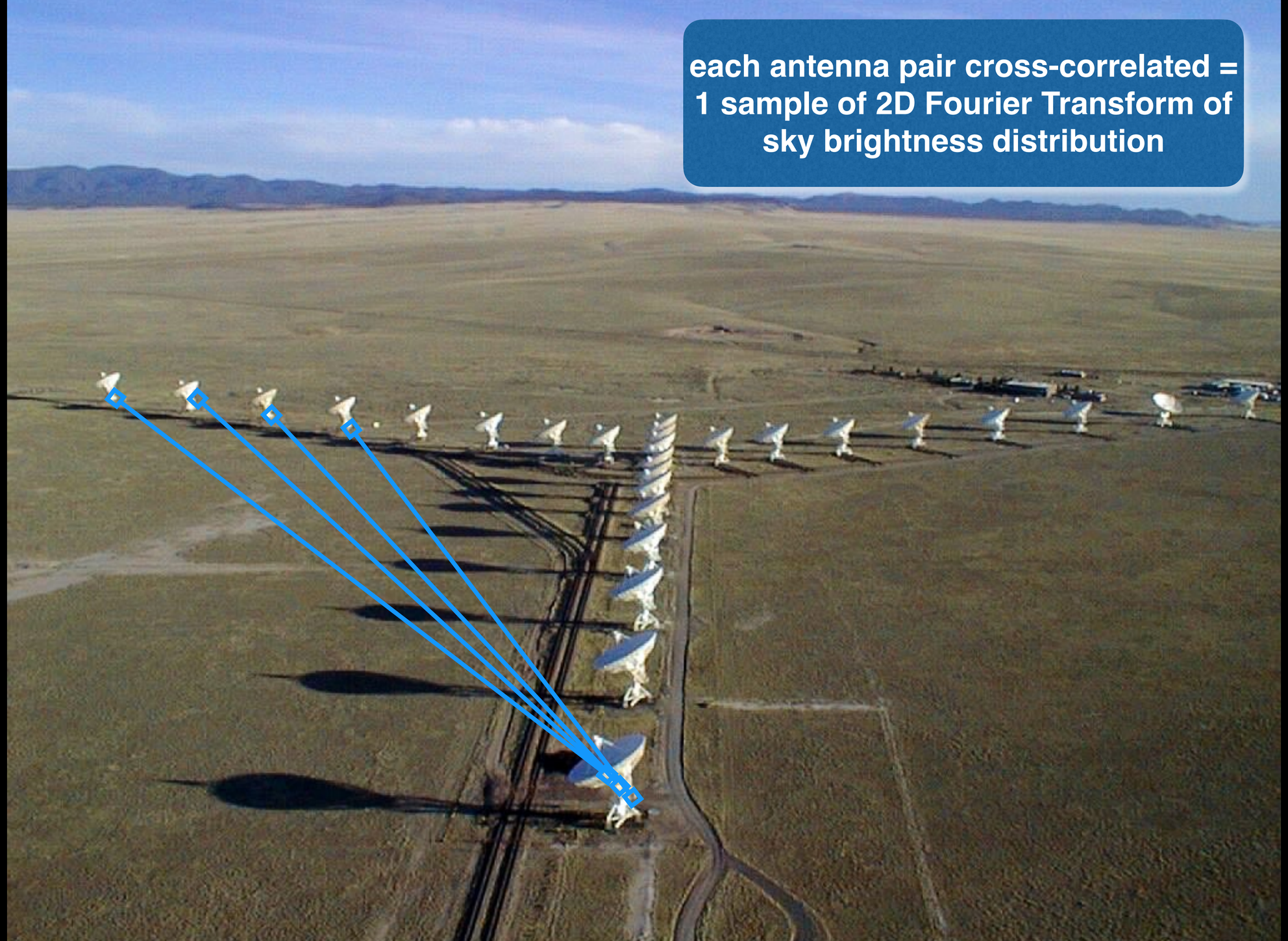
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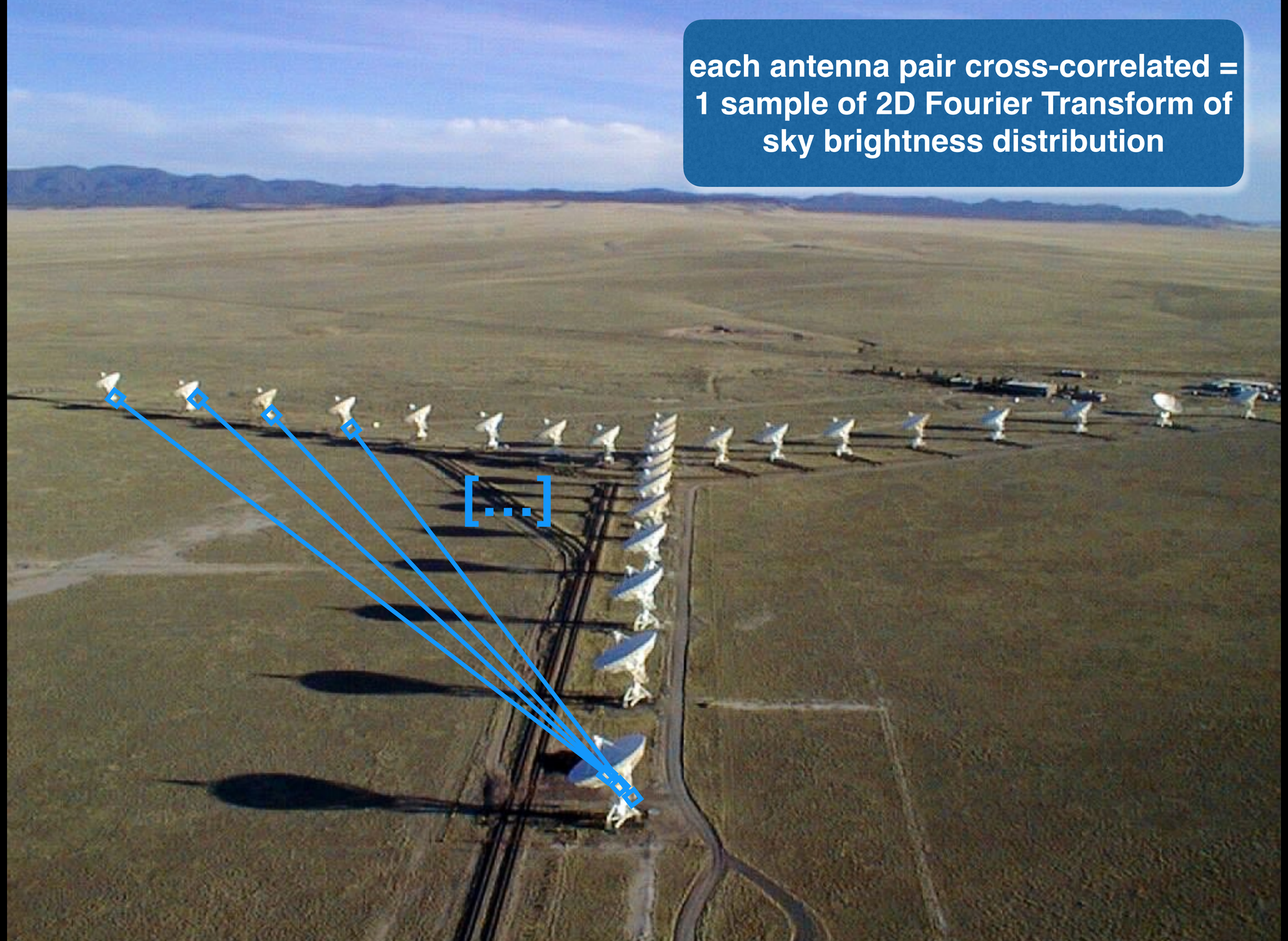
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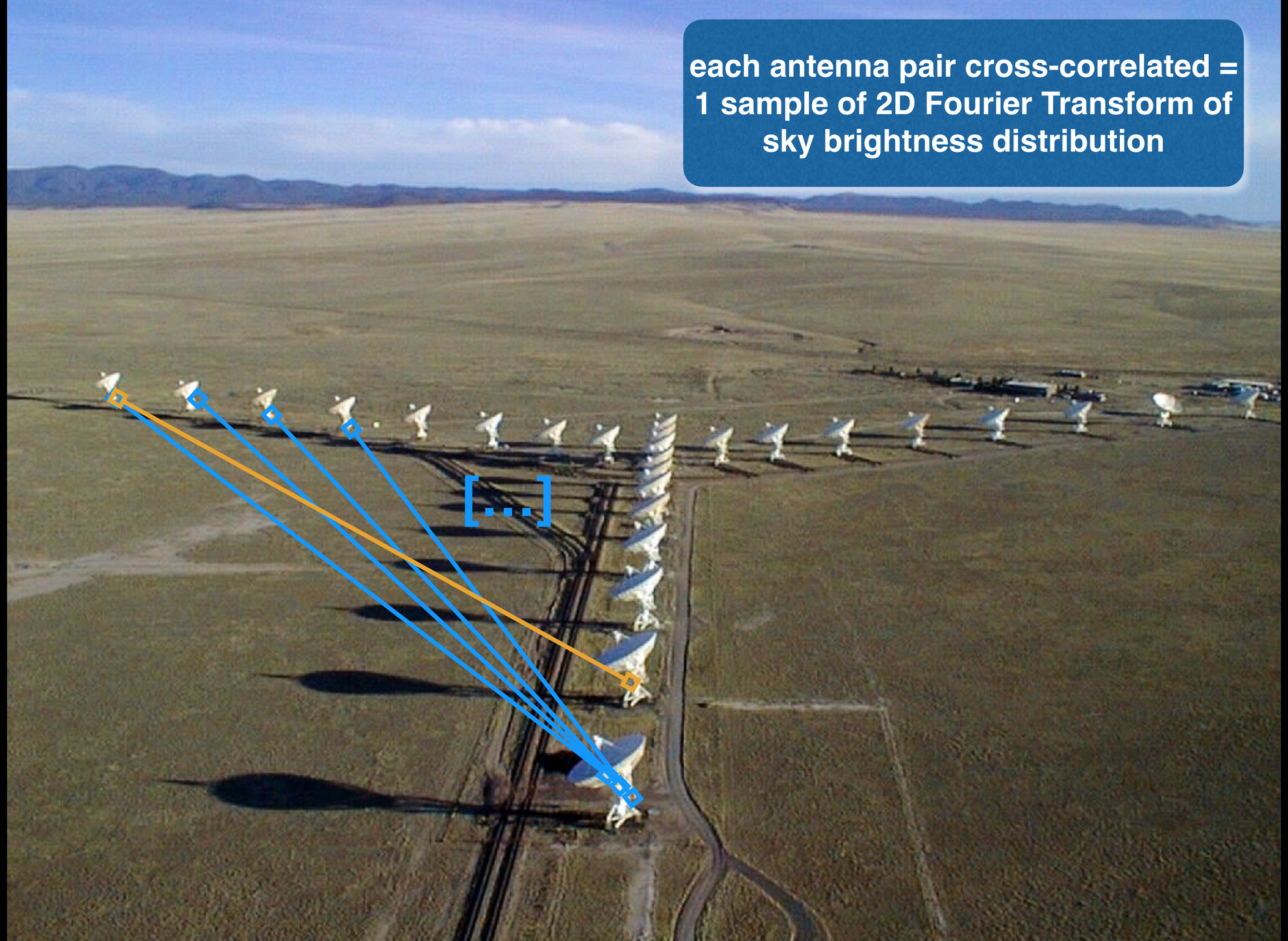
[...]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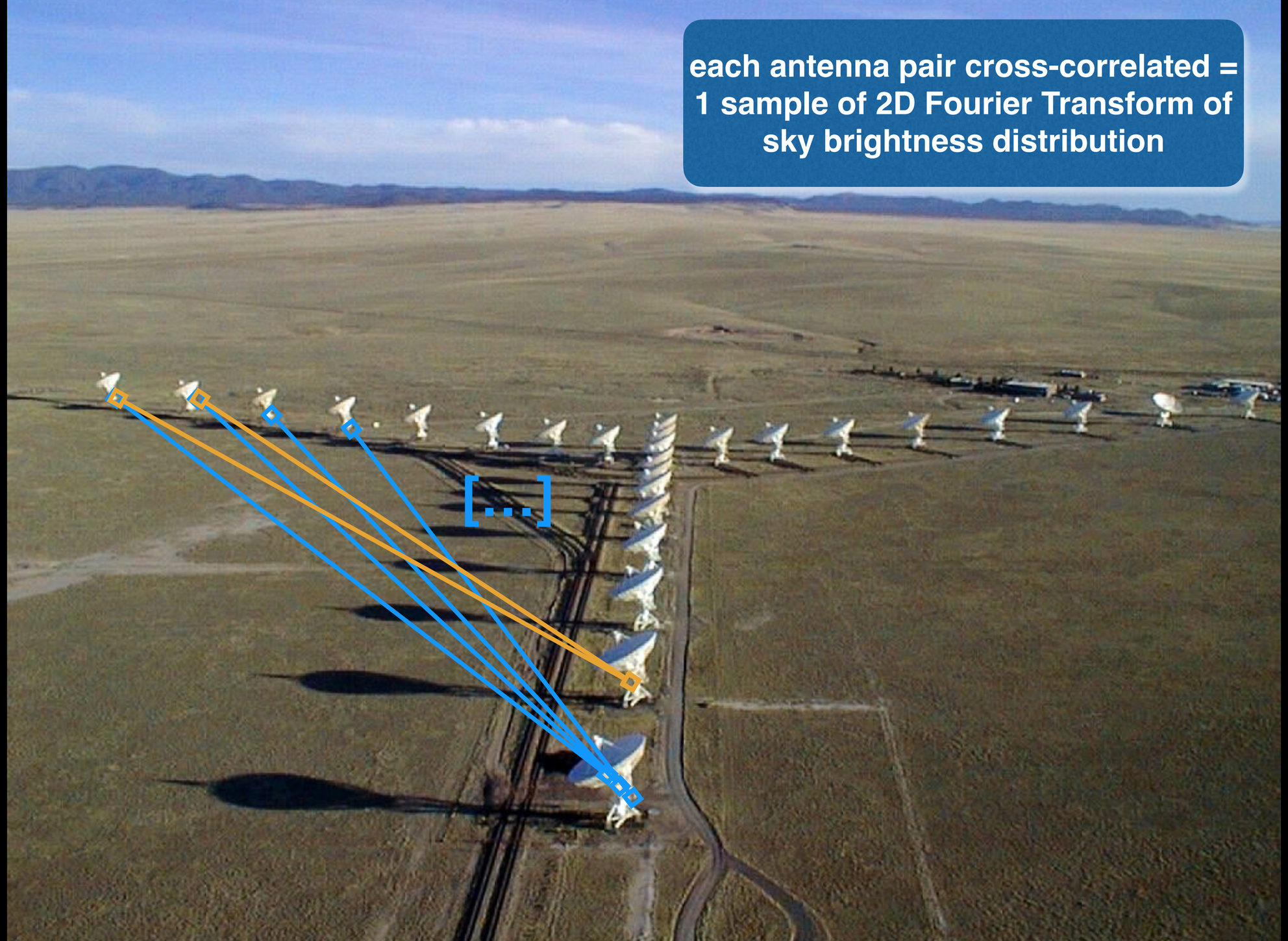
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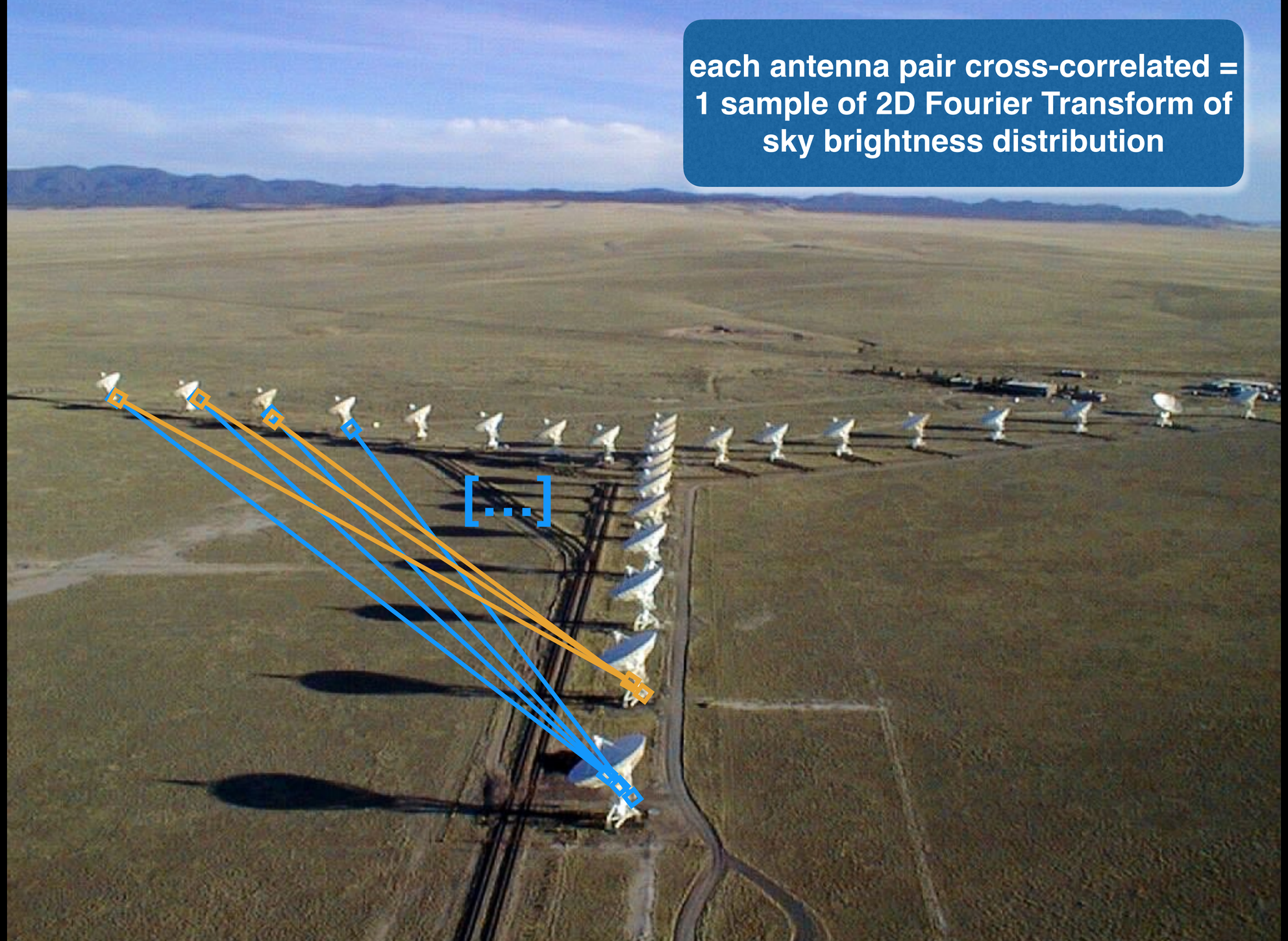
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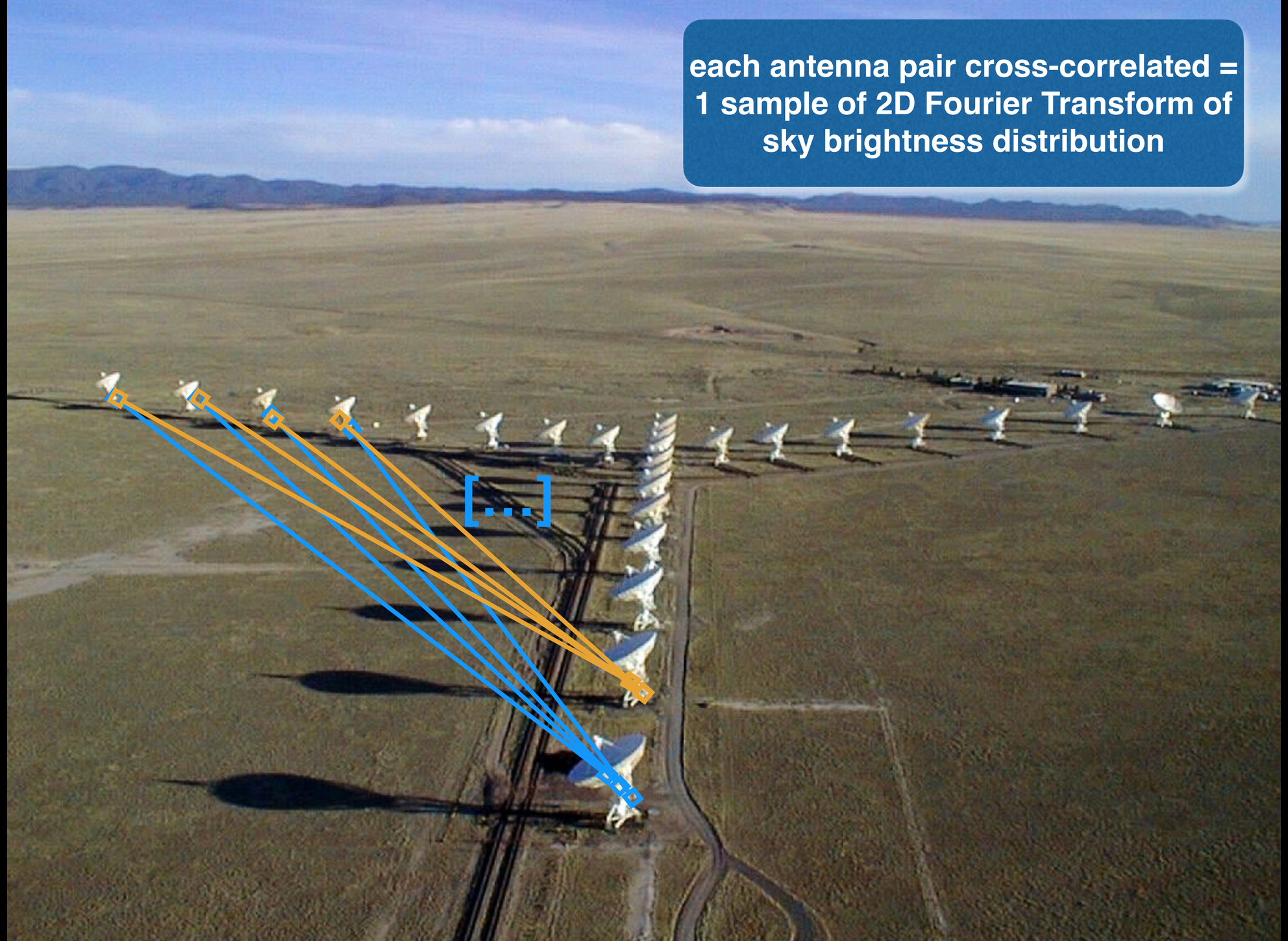
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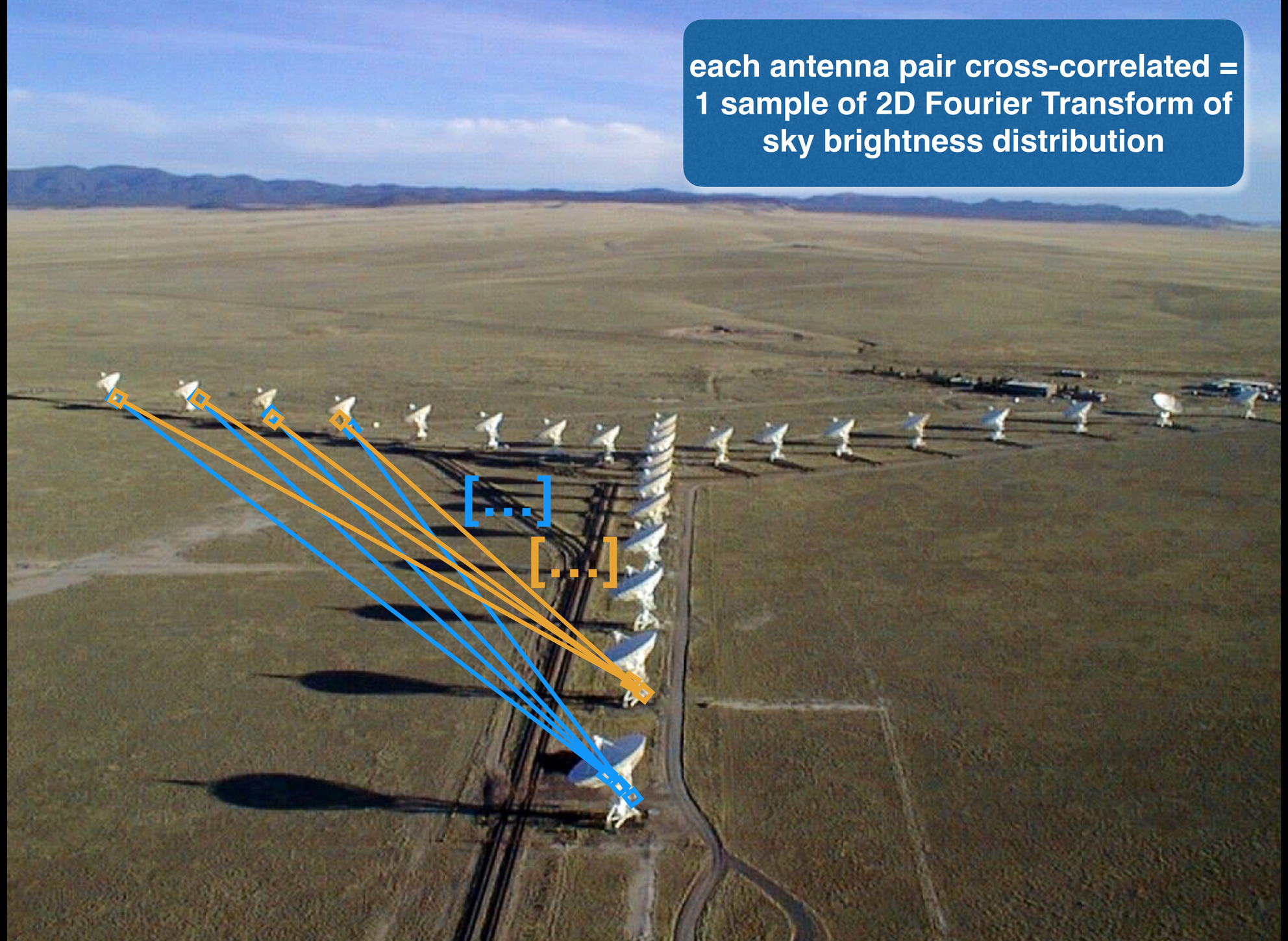
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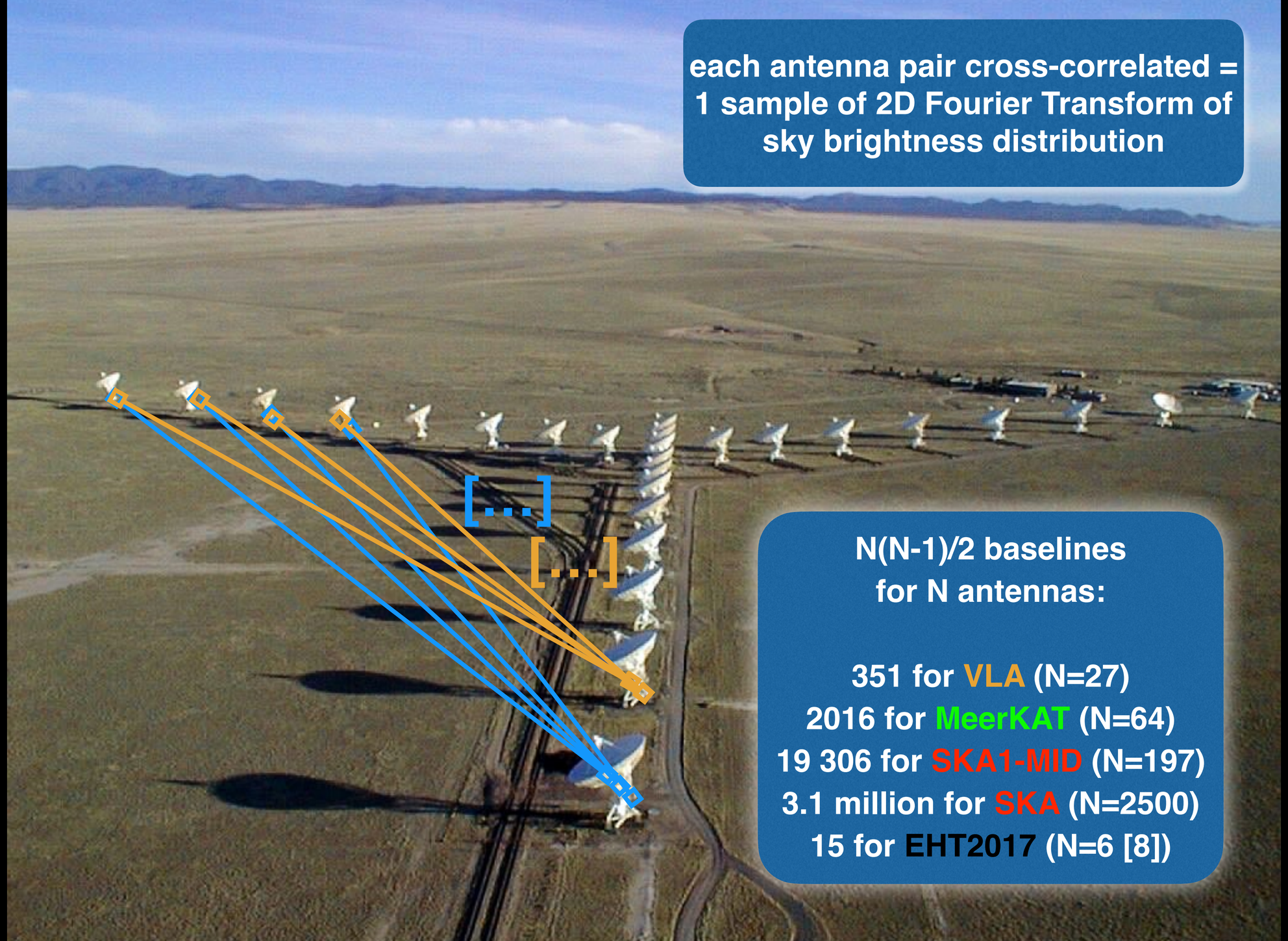
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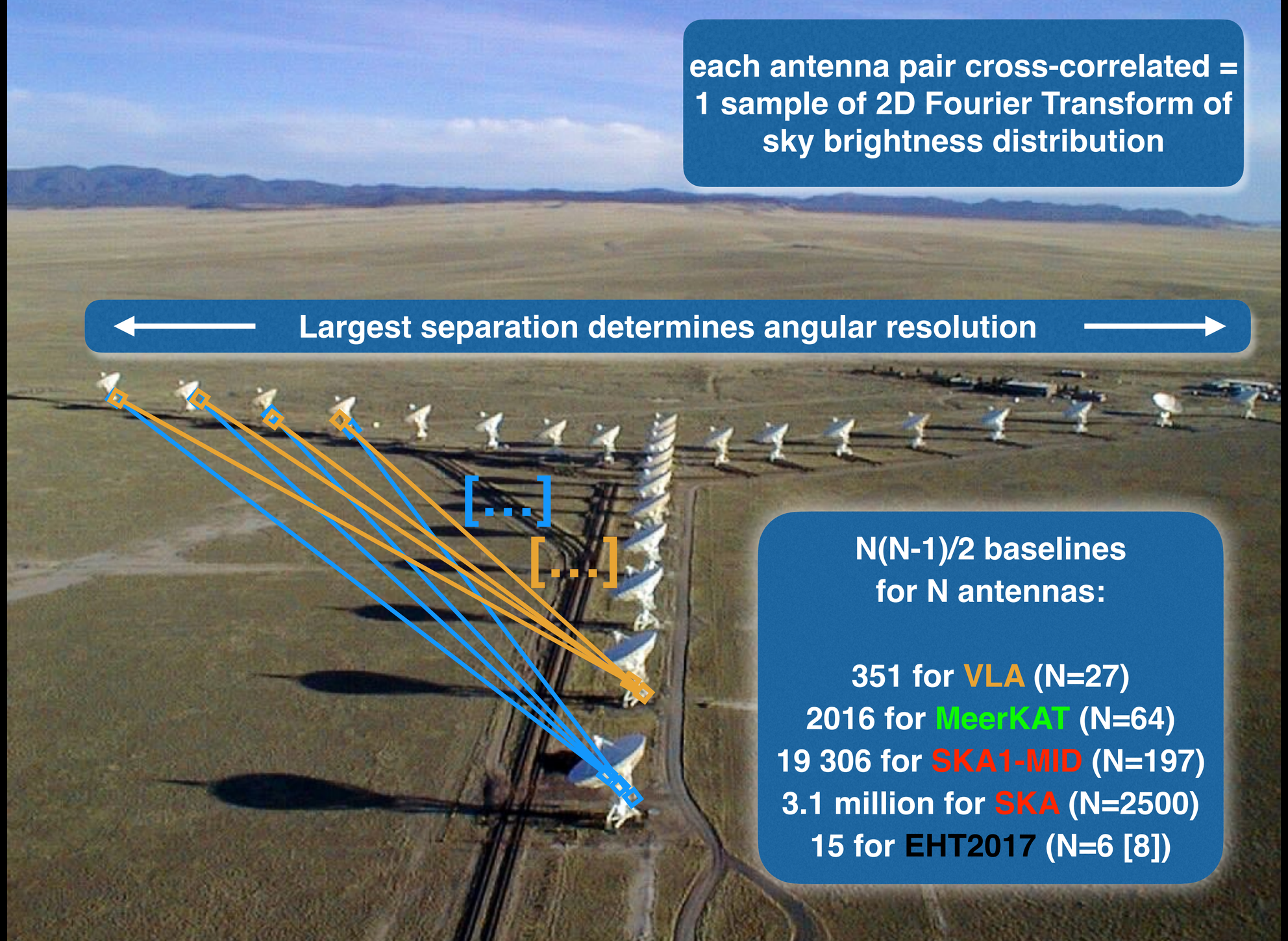
[...]
[...]
N(N-1)/2 baselines
for N antennas:
351 for VLA (N=27)
2016 for MeerKAT (N=64)
19 306 for SKA1-MID (N=197)
3.1 million for SKA (N=2500)
15 for EHT2017 (N=6 [8])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sky brightness distribution
Largest separation determines angular resolution
[...]
[...]
N(N-1)/2 baselines
for N antennas:
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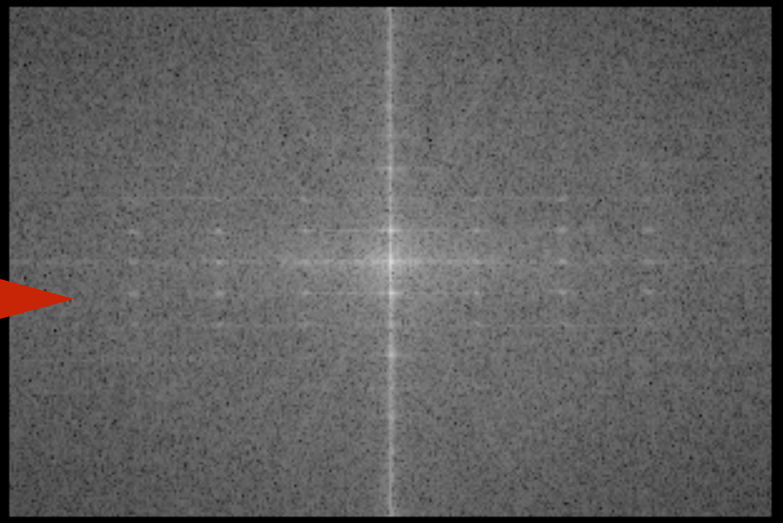
A radio interferometer is a Fourier transform machine

Image

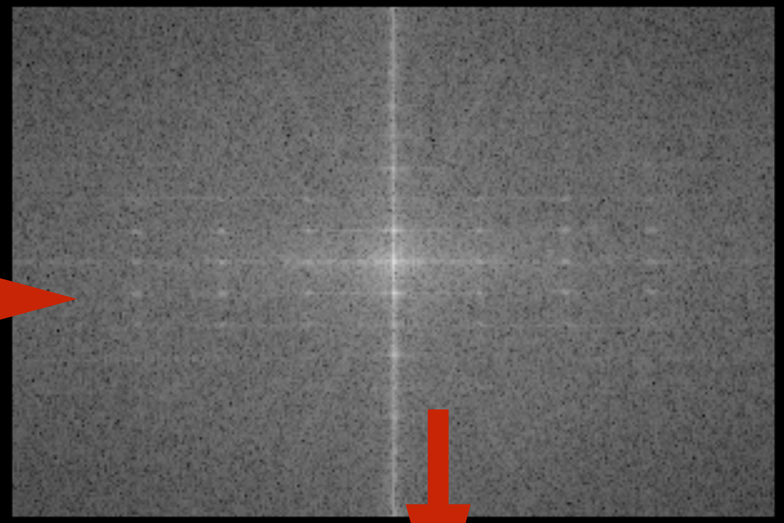
2D FFT



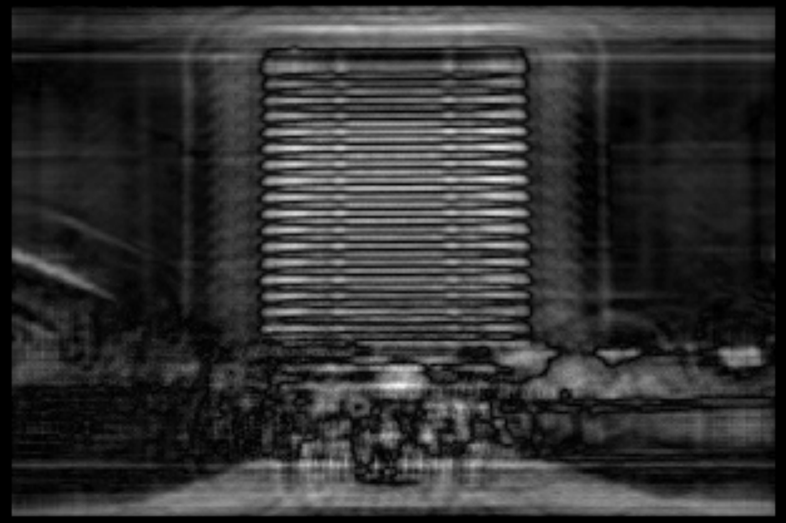
A radio interferometer is a Fourier transform machine

Image

2D FFT



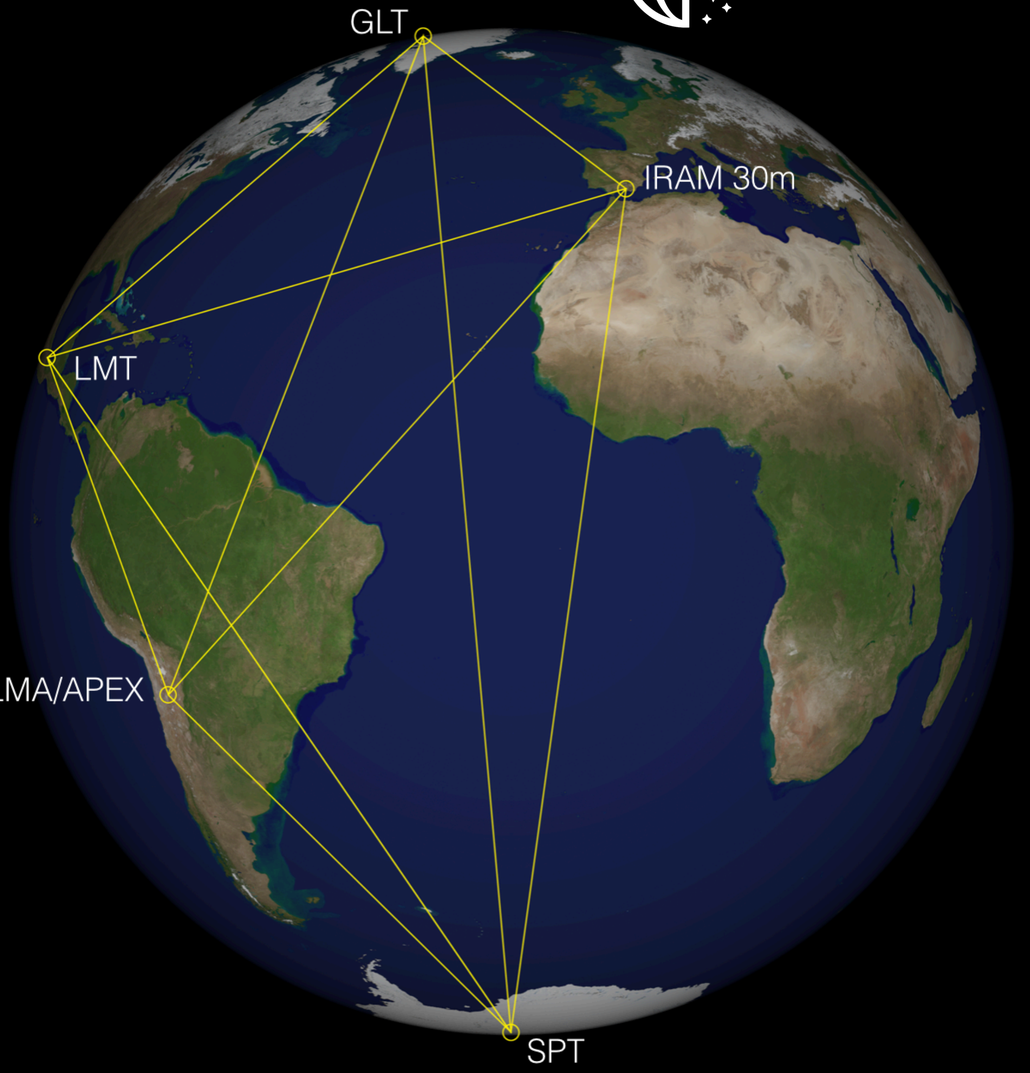
Partially-sampled FFT

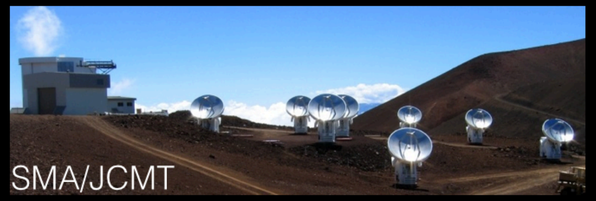


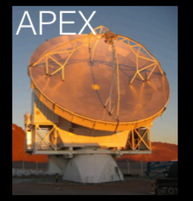
Reconstructed Image

* history of development of EHT array not covered in this talk

Event Horizon Telescope







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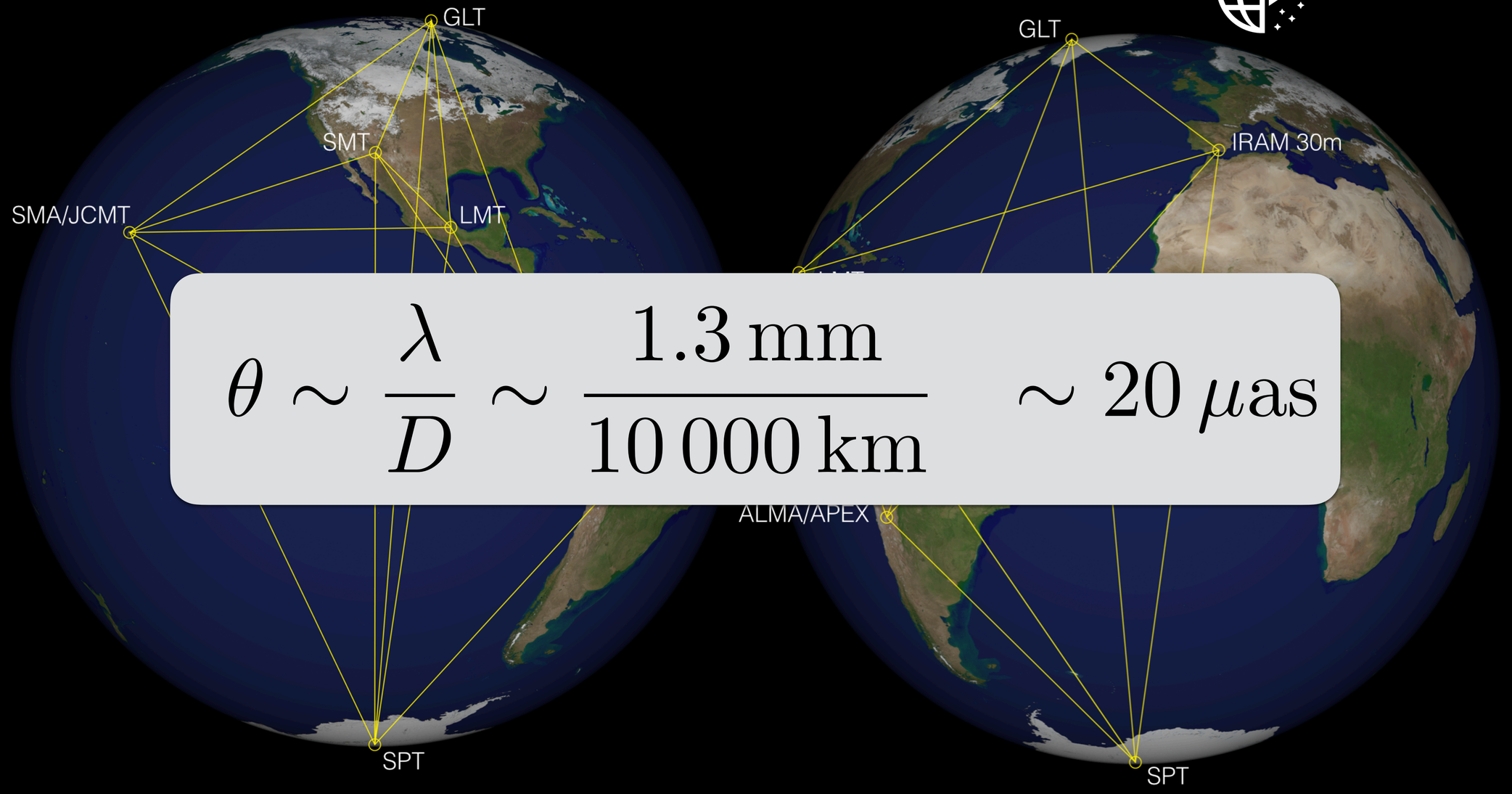
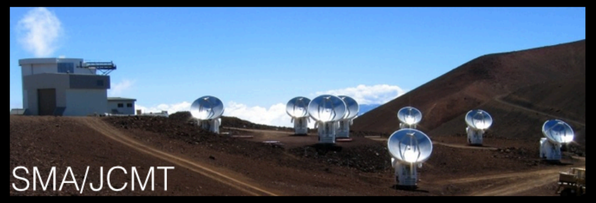
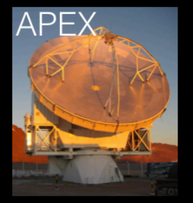
Event Horizon Telescope



$$\theta \sim \frac{\lambda}{D} \sim \frac{1.3\,\mathrm{mm}}{10\,000\,\mathrm{km}} \sim 20\,\mu\mathrm{as}$$

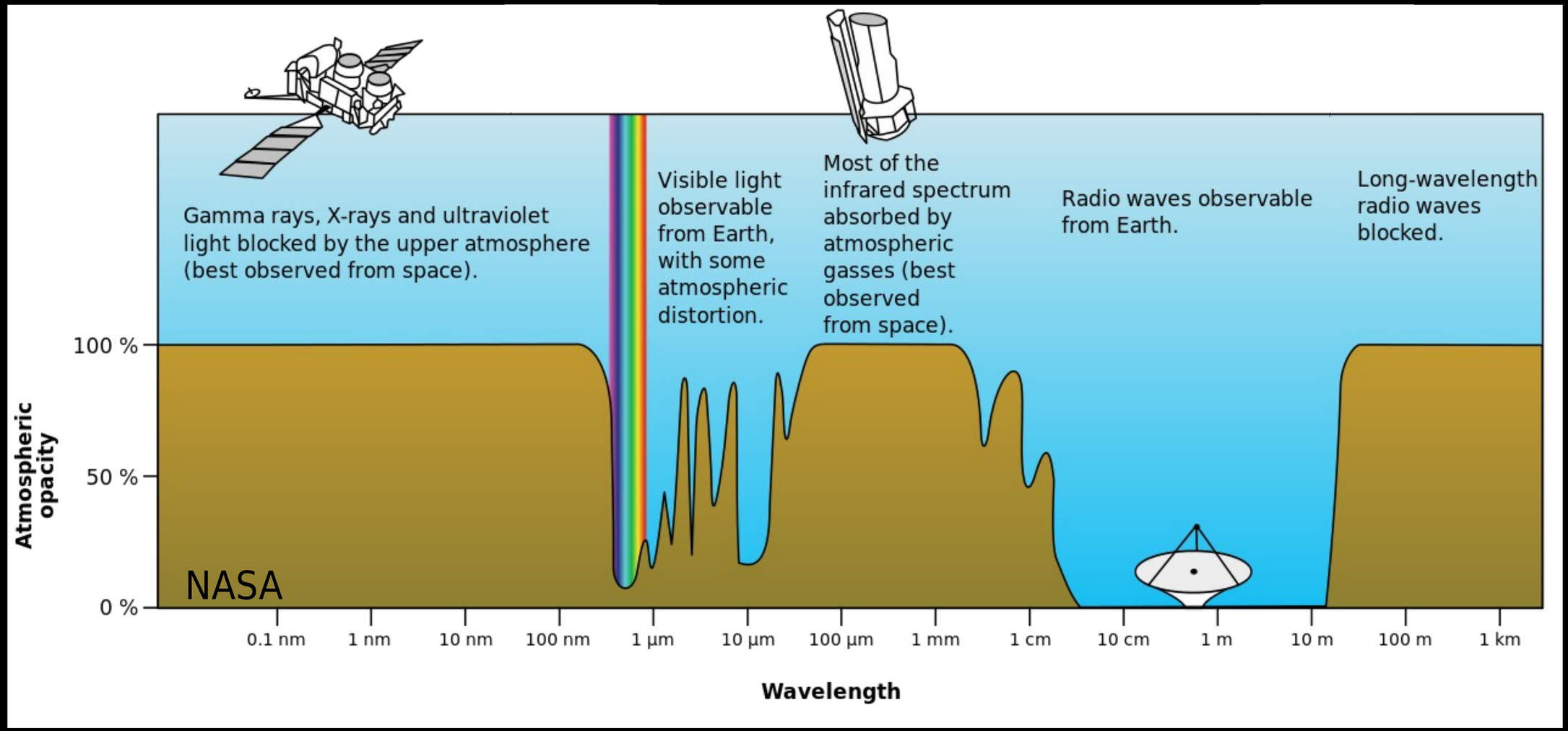




The EHT array

- Earth-sized telescope operating at 230 & 345 GHz
- Achieves an angular resolution of ~20 μas (~1000 times finer than Hubble Space Telescope)
- Primary science goal: spatially resolve event-horizon-scale emission towards Sgr A* and M87
- Test Kerr metric hypothesis (or other theories of gravity) in the strong-field regime and constrain accretion flow / jet-launch physics
- “extreme interferometry” – requires an intense engineering, data processing, calibration, theoretical, and modeling effort

The troublesome (and turbulent) troposphere



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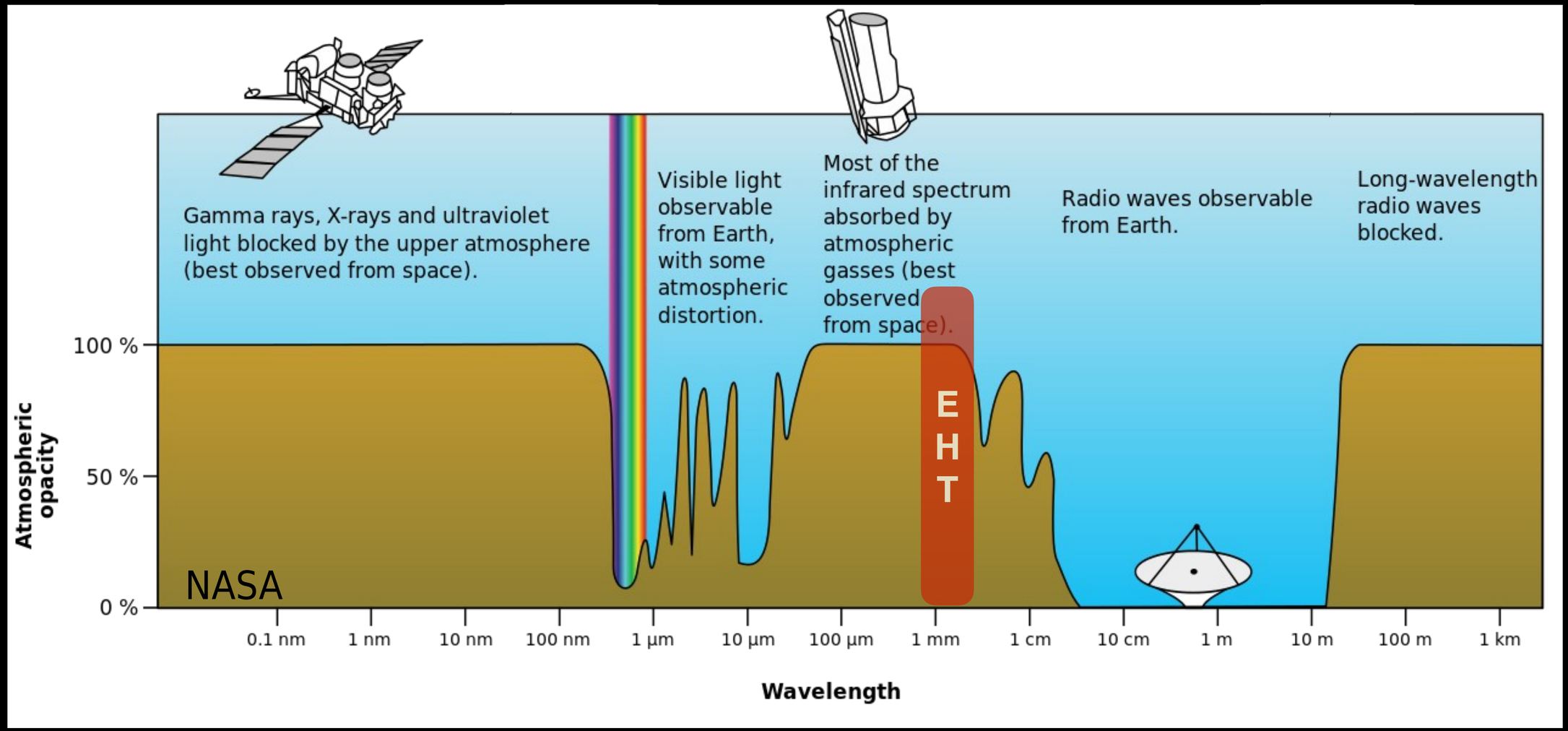
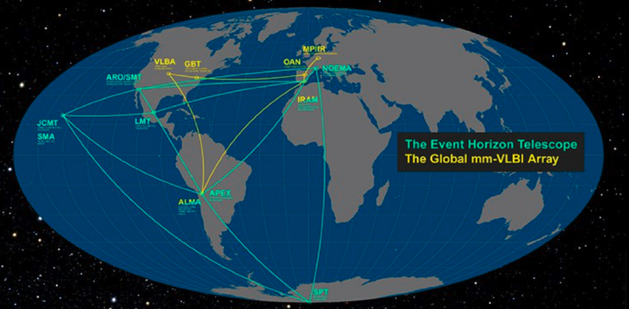


Event Horizon Telescope



Event Horizon Telescope

To image an extreme of physics (black hole shadows), we must go to the extremes of the Earth

A Boeing 747's bandwidth

- Data recorded independently at different sites at very high time and frequency resolution and precision
- Disks brought together at supercomputers at MIT and MPIfR to correlate the signals and form visibilities (fundamental measurement of an interferometer)
- ~4 PB required for entire EHT 2017 observing run
- ~0.5 PB on M87 alone
- This will increase by a factors of a few in the coming years

MIT/Haystack

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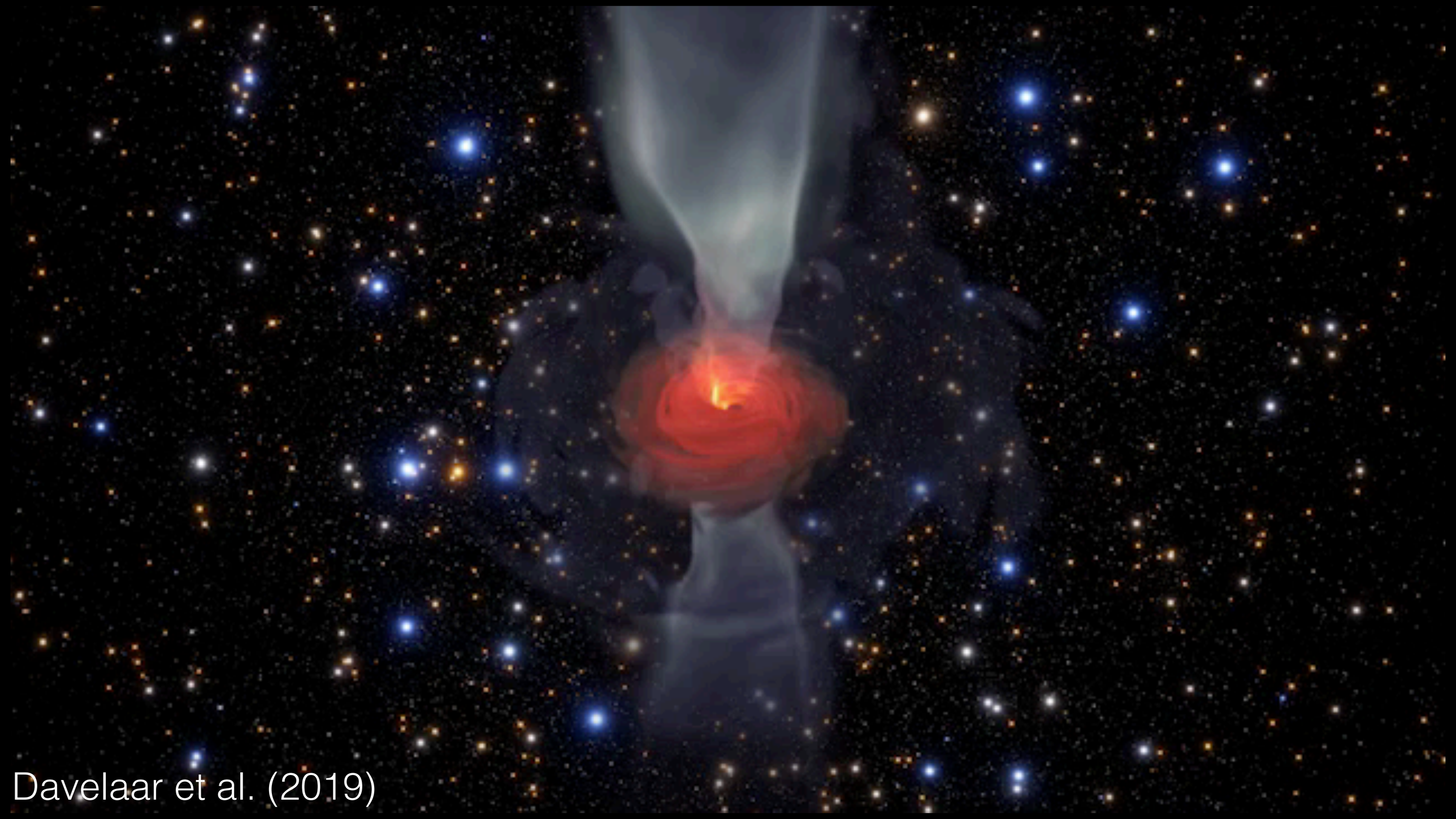
Final image size ~few kiloBytes

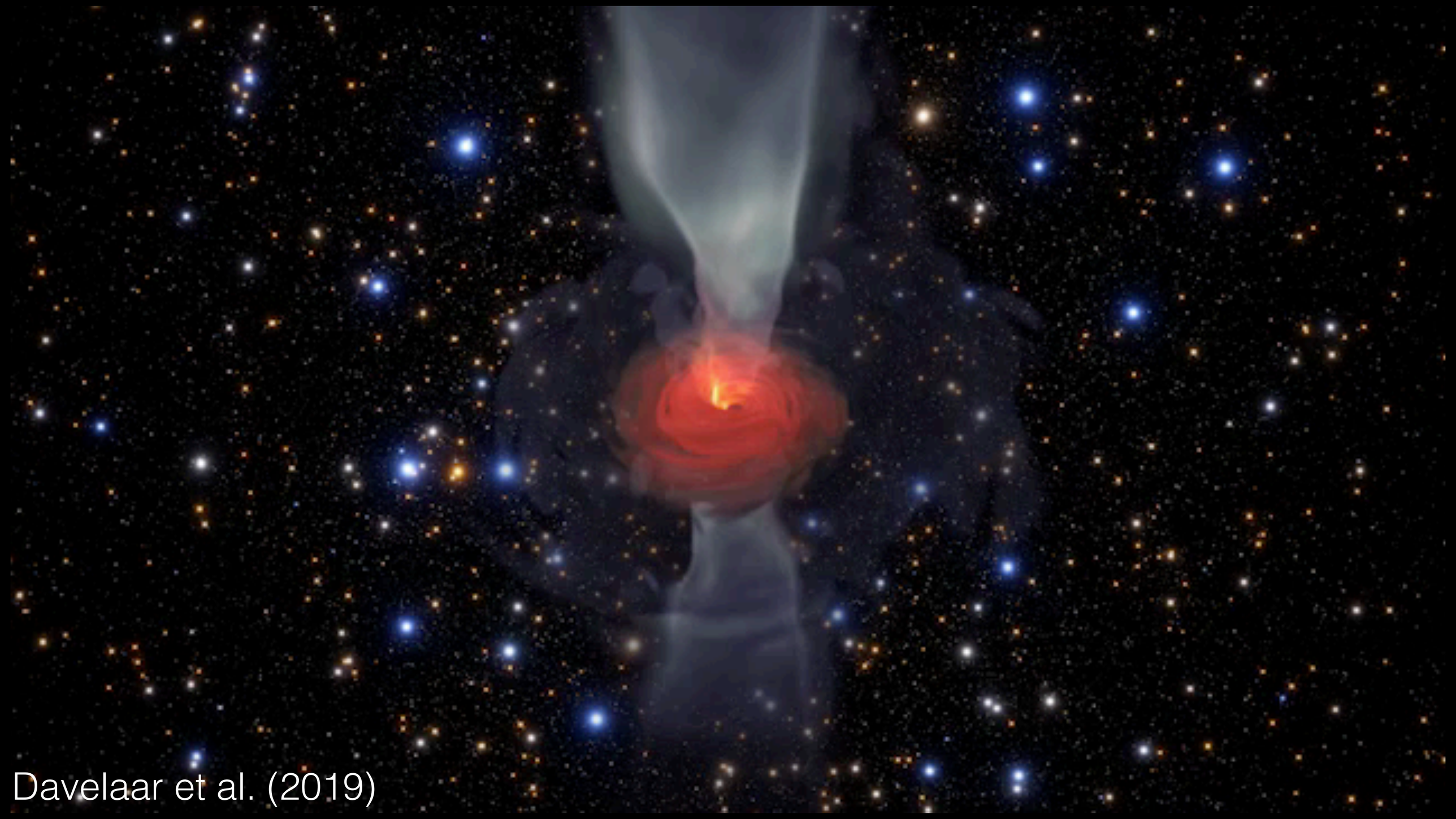
MIT/Haystack

Primary science goal:

Spatially-resolve event horizon scales of nearby supermassive black holes



Davelaar et al. (2019)

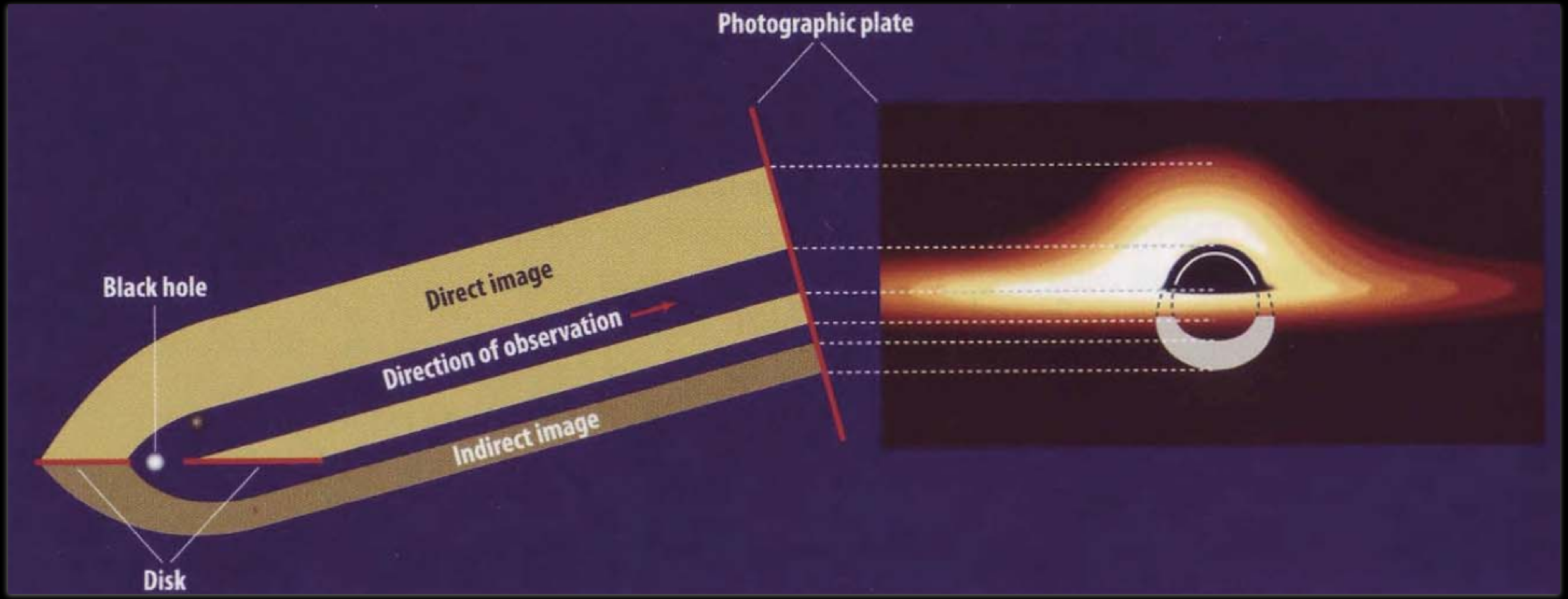


Davelaar et al. (2019)

A black hole shadow?

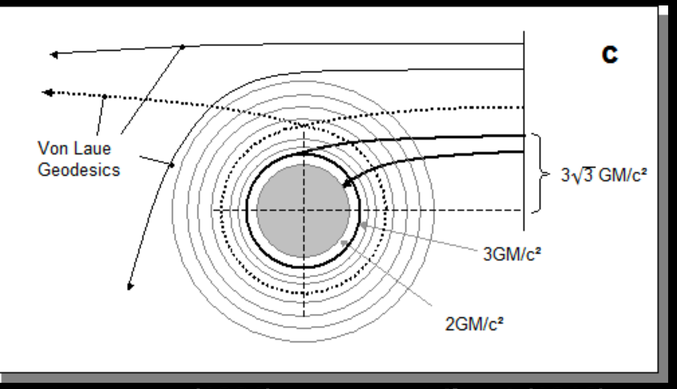
Luminet (1979)

A black hole shadow?

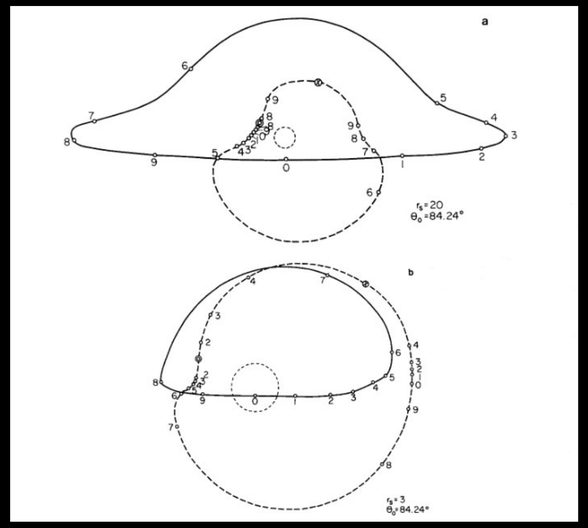


Luminet (1979)

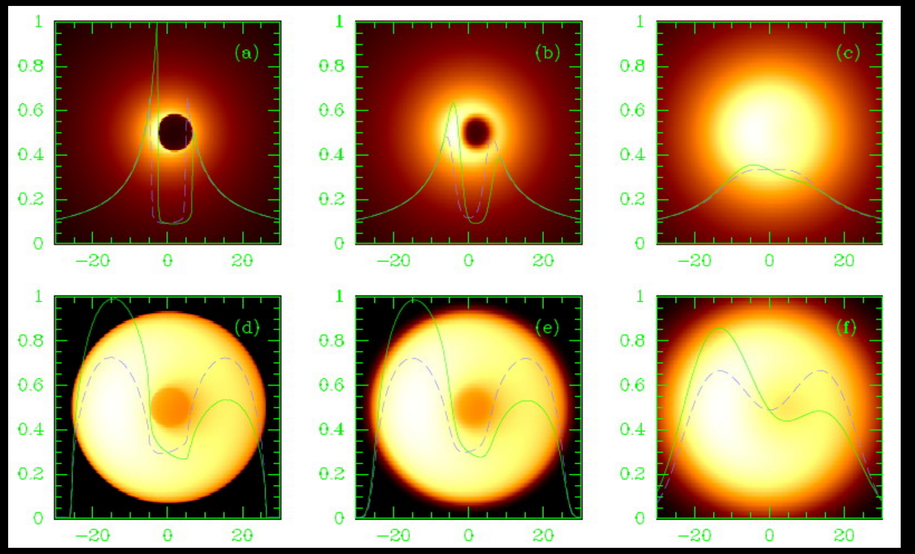
Black hole “shadow” history



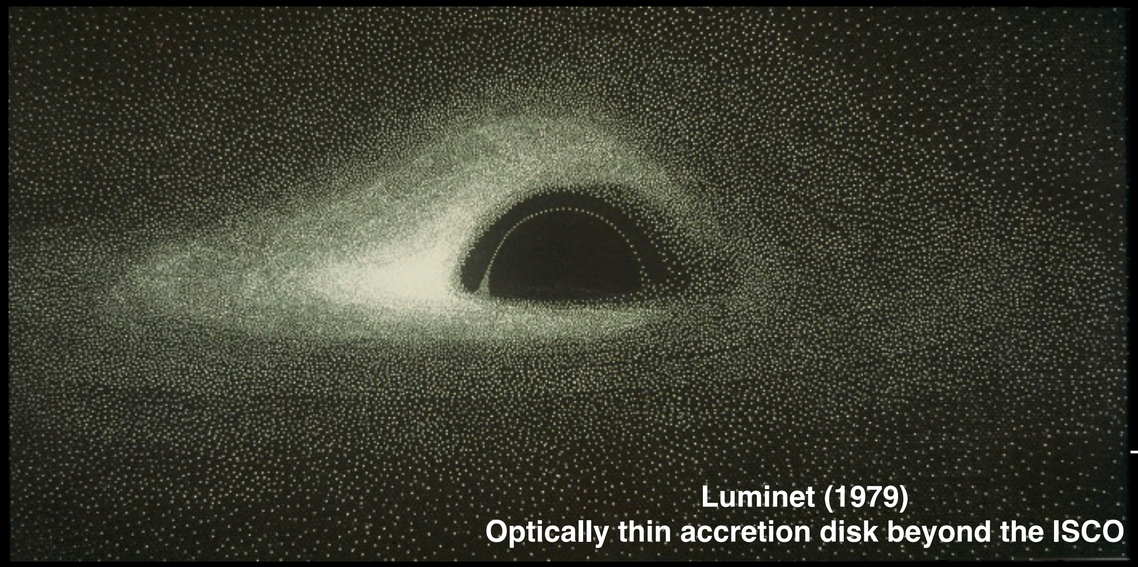
Von Laue (1921) based on Hilbert (1916)
Lights paths that form perfect circles



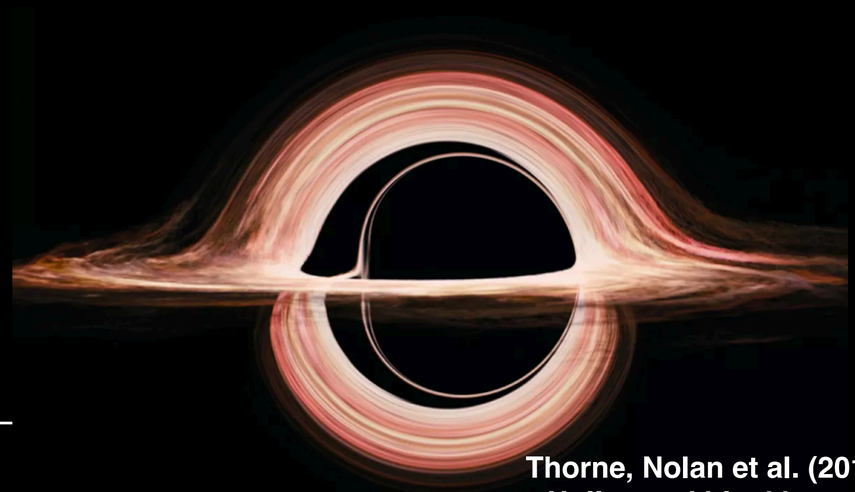
Cunningham & Baarden (1983)
Stellar orbit around a black hole
also, Baarden (1973) lensed star



Falcke et al. (2000)
Optically thin emission, including inside ISCO
Predicted mm-VLBI



Luminet (1979)
Optically thin accretion disk beyond the ISCO

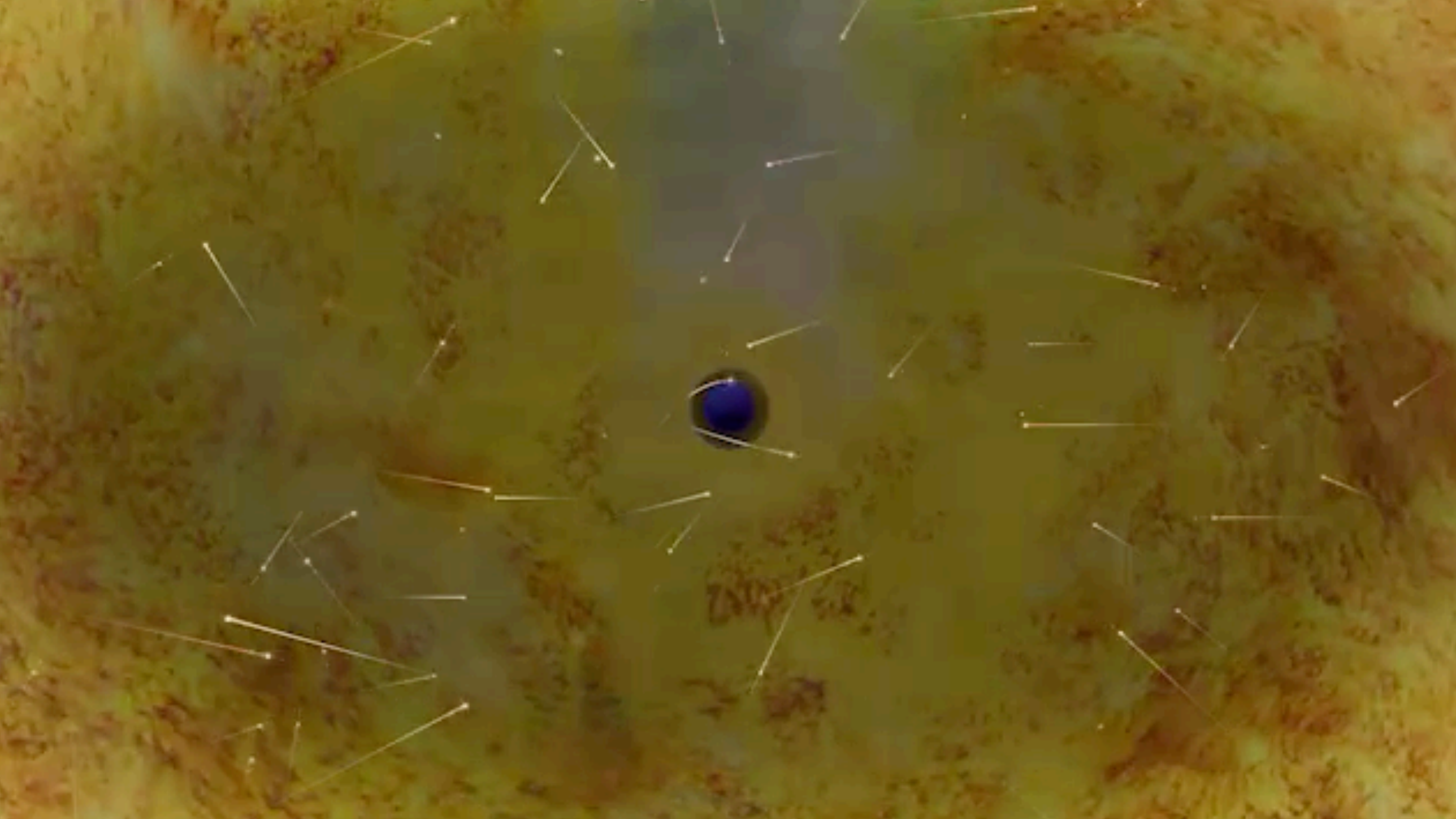


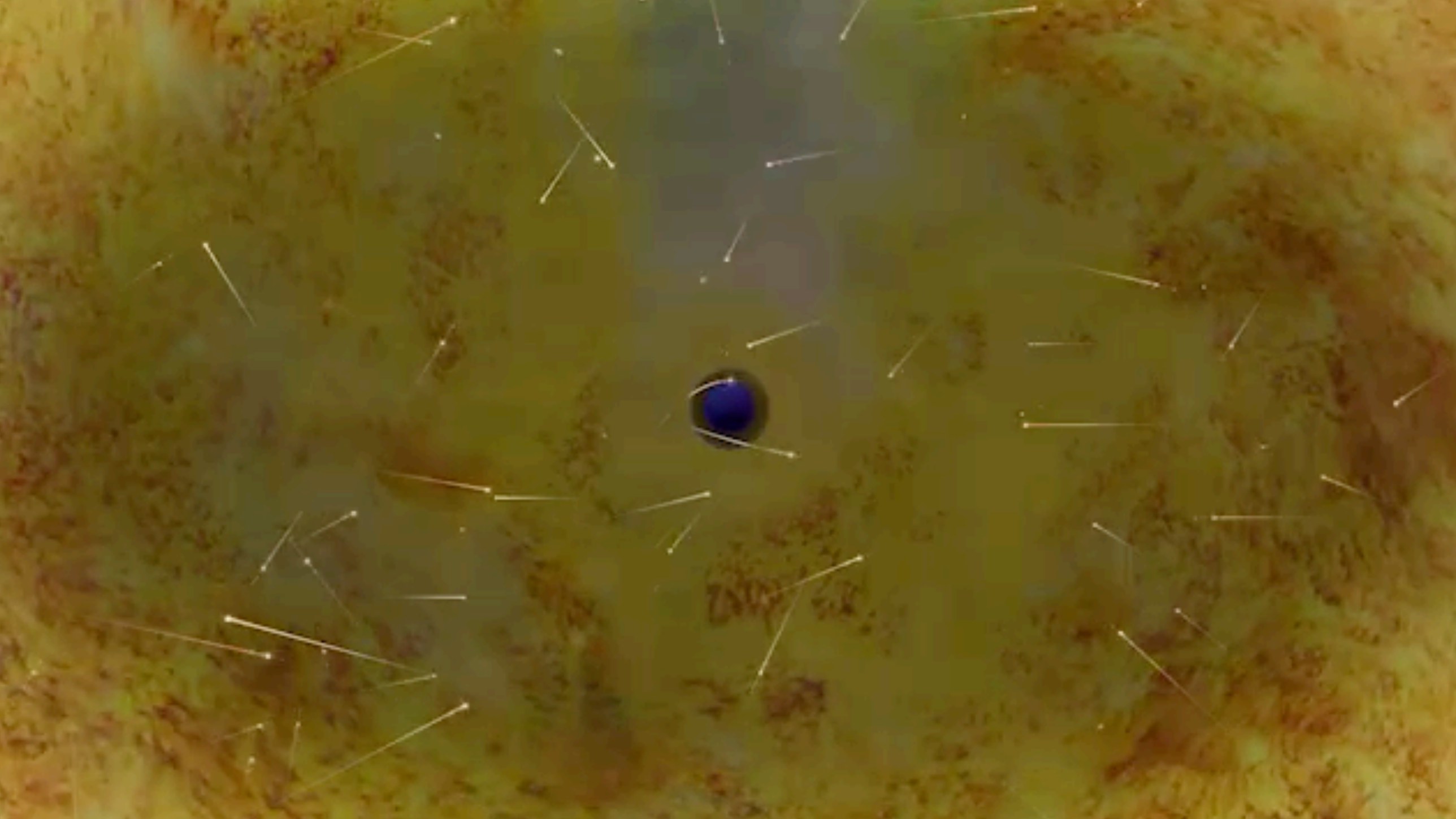
Thorne, Nolan et al. (2014)
Hollywood blockbuster

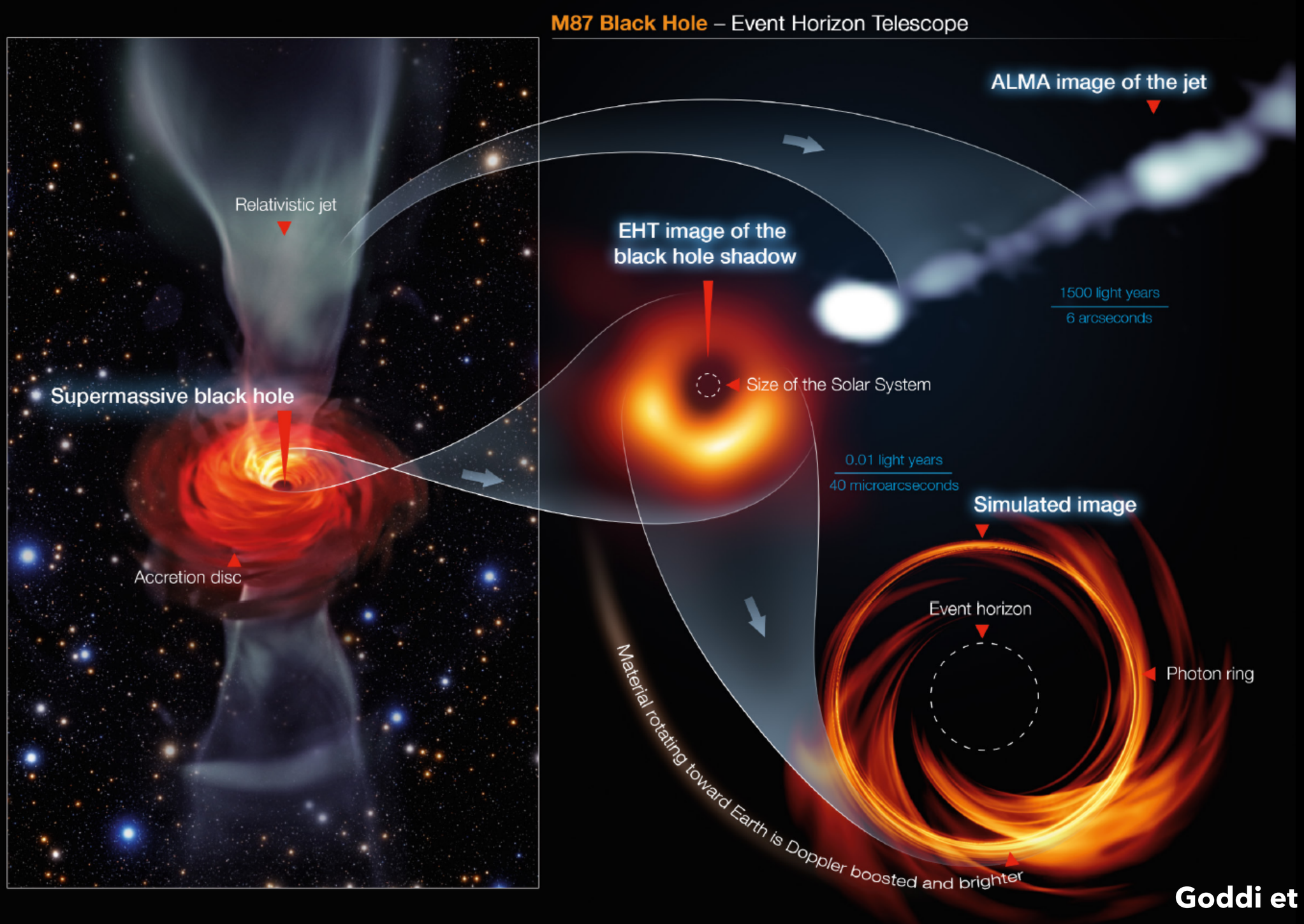
A black hole shadow?

Two key concepts:

1. Light ***bending around*** a black hole
2. Light ***captured by*** a black hole







Goddi et al. (2019)

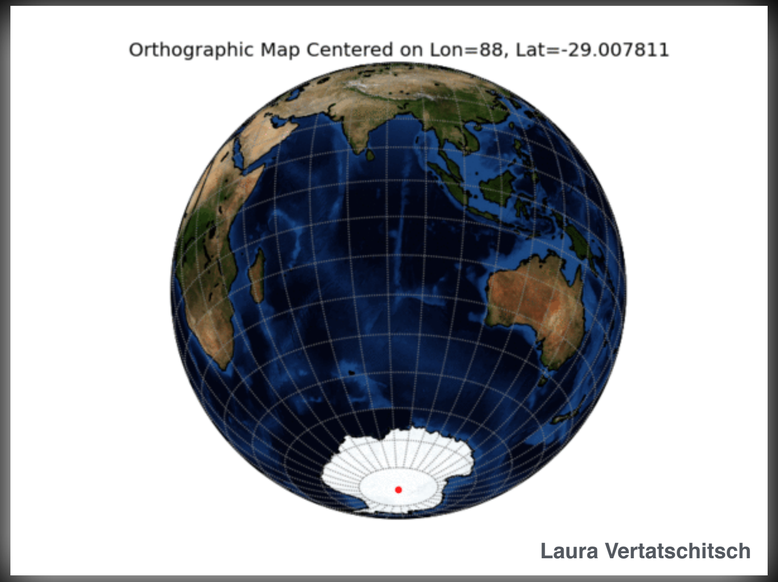
$$\theta_p \equiv \frac{\sqrt{27}\ GM}{c^2 D}$$

for a Schwarzschild metric, ~10% change for spin

Zooming into the Event Horizon

Using this:

Global array of antennas



To image this:

Apparent size of a doughnut on the moon

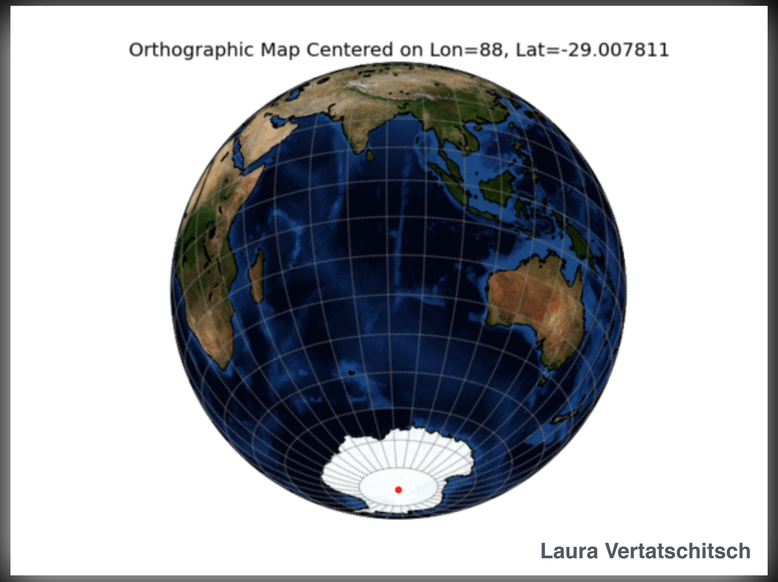
Event Horizon Telescope

credit: Jordy Davelaar & Thomas Bronzwaer
BlackHoleCam

Zooming into the Event Horizon

Using this:

Global array of antennas



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Apparent size of a doughnut on the moon

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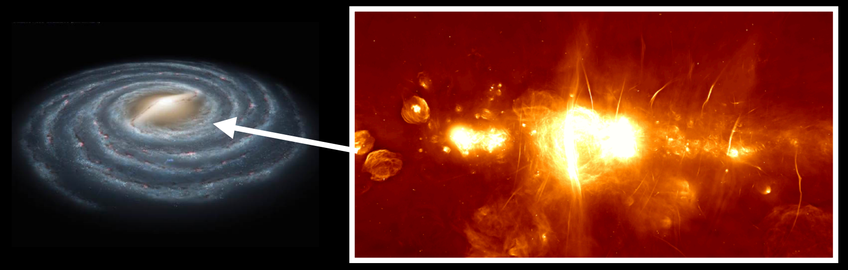
BlackHoleCam

EHT’s two primary targets

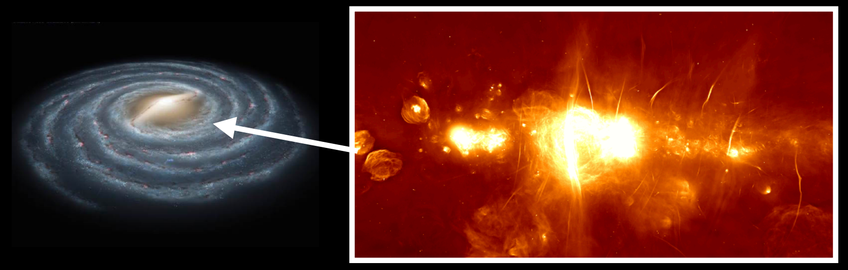
Sgr A*



- M_{BH} ~4 x 10^6 $M_\odot$
- Predicted photon ring ~50 μas
- Shortest orbital timescale: ~minutes

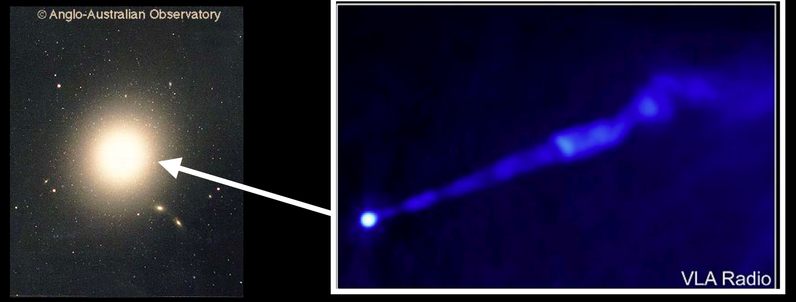
EHT's two primary targets

Sgr A*



- M_{BH} ~4 x 10^6 $M_\odot$
- Predicted photon ring ~50 μas
- Shortest orbital timescale: ~minutes

M87



- M_{BH} ~6 x 10^9 $M_\odot$
- Predicted photon ring ~20-40 μas
- Shortest orbital timescale: ~weeks

outline

- **EHT Overview:** the instrument and science goals
- **First imaging results on M87:** 
- **The future:** upcoming results and array expansion

outline

First imaging results on M87:

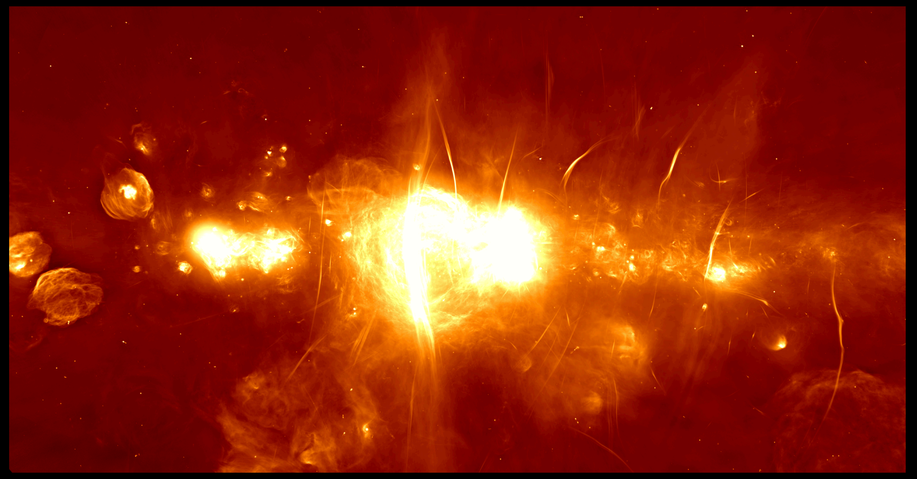
But first some contrast of the imaging challenges with MeerKAT

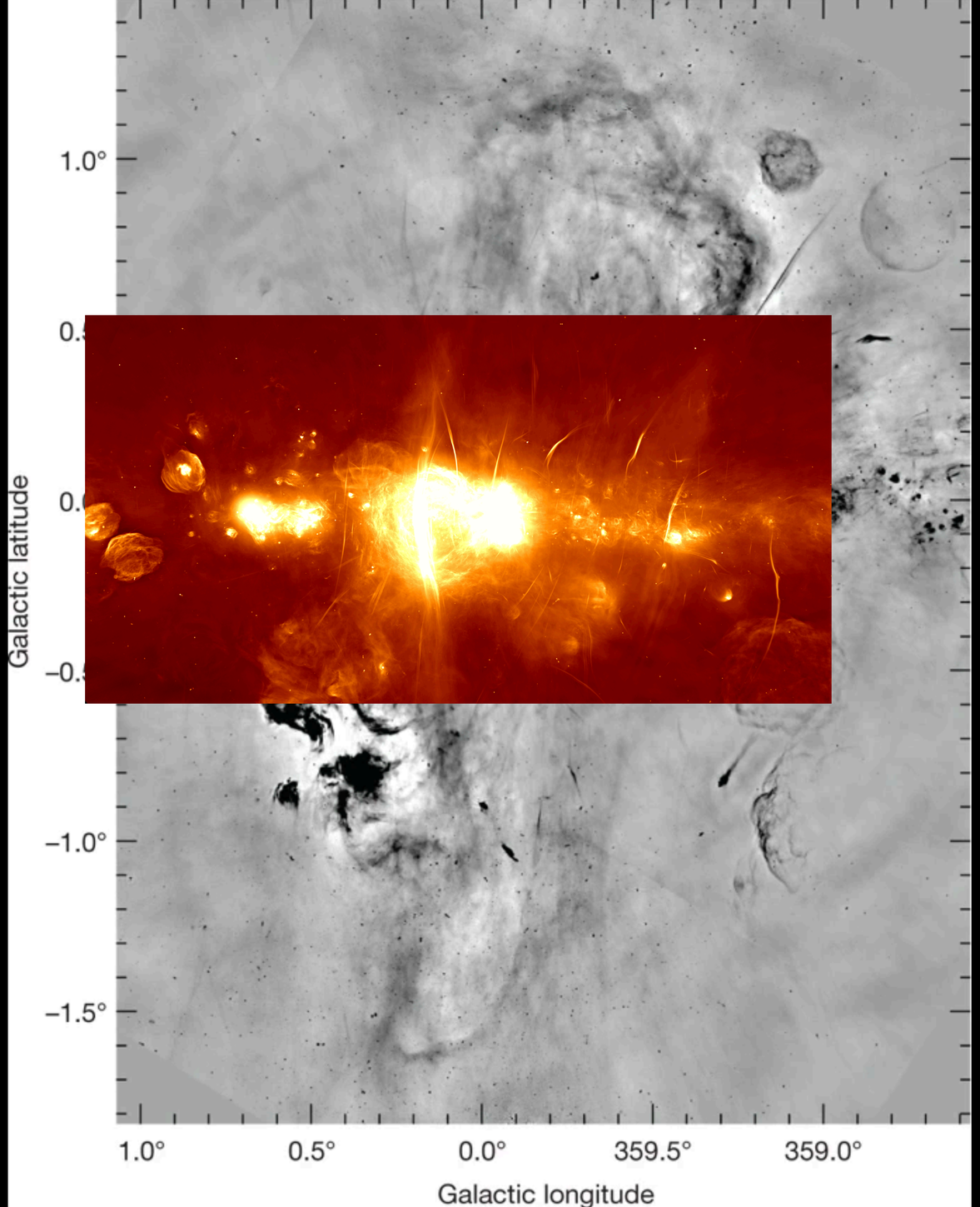
MeerKAT image of the centre of our Galaxy

Image credits: SARAO

MeerKAT image of the centre of our Galaxy

Image credits: SARAO

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Galactic latitude
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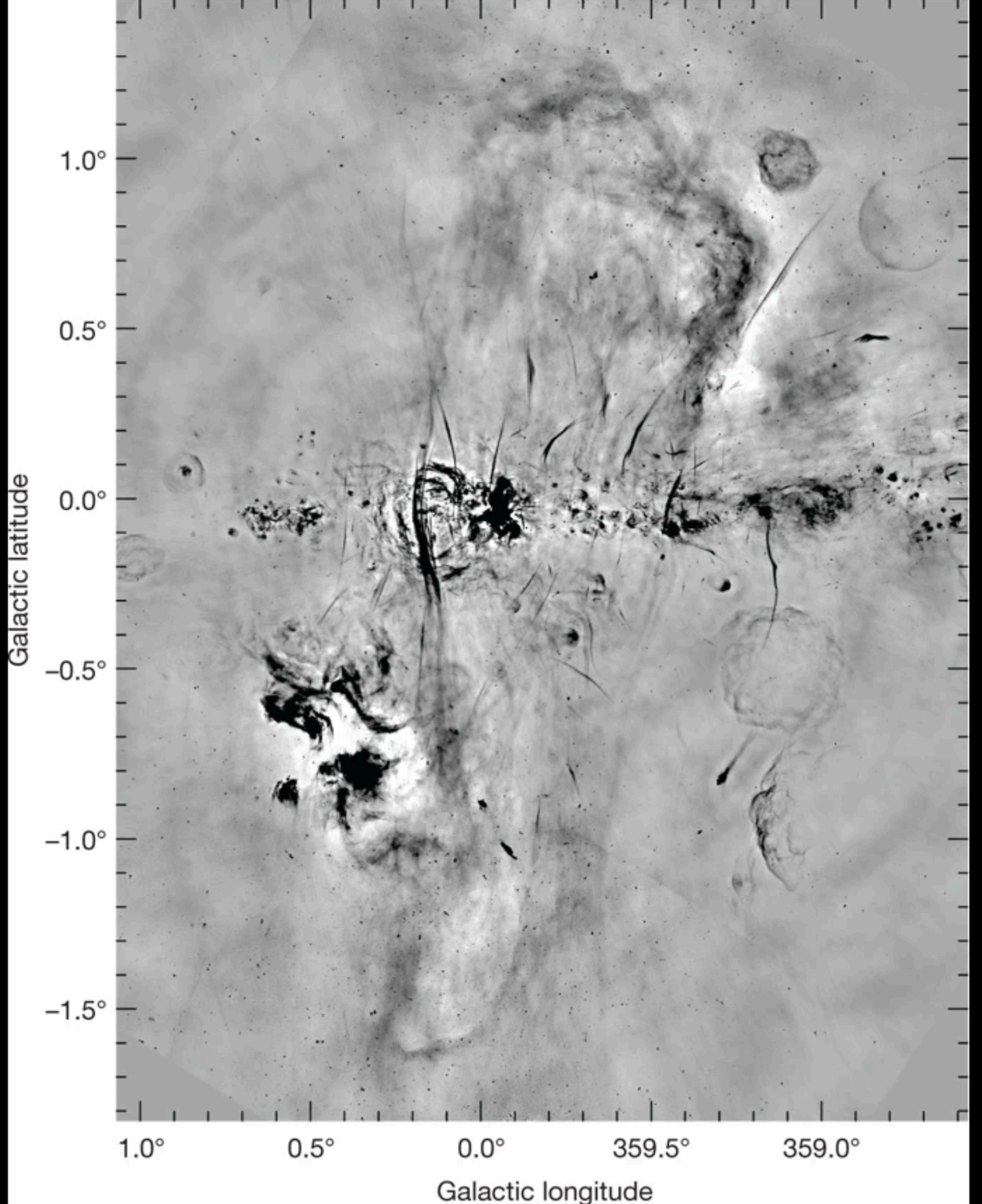
359.0°
Galactic longitude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Galactic latitude
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359.0°
Galactic longitude

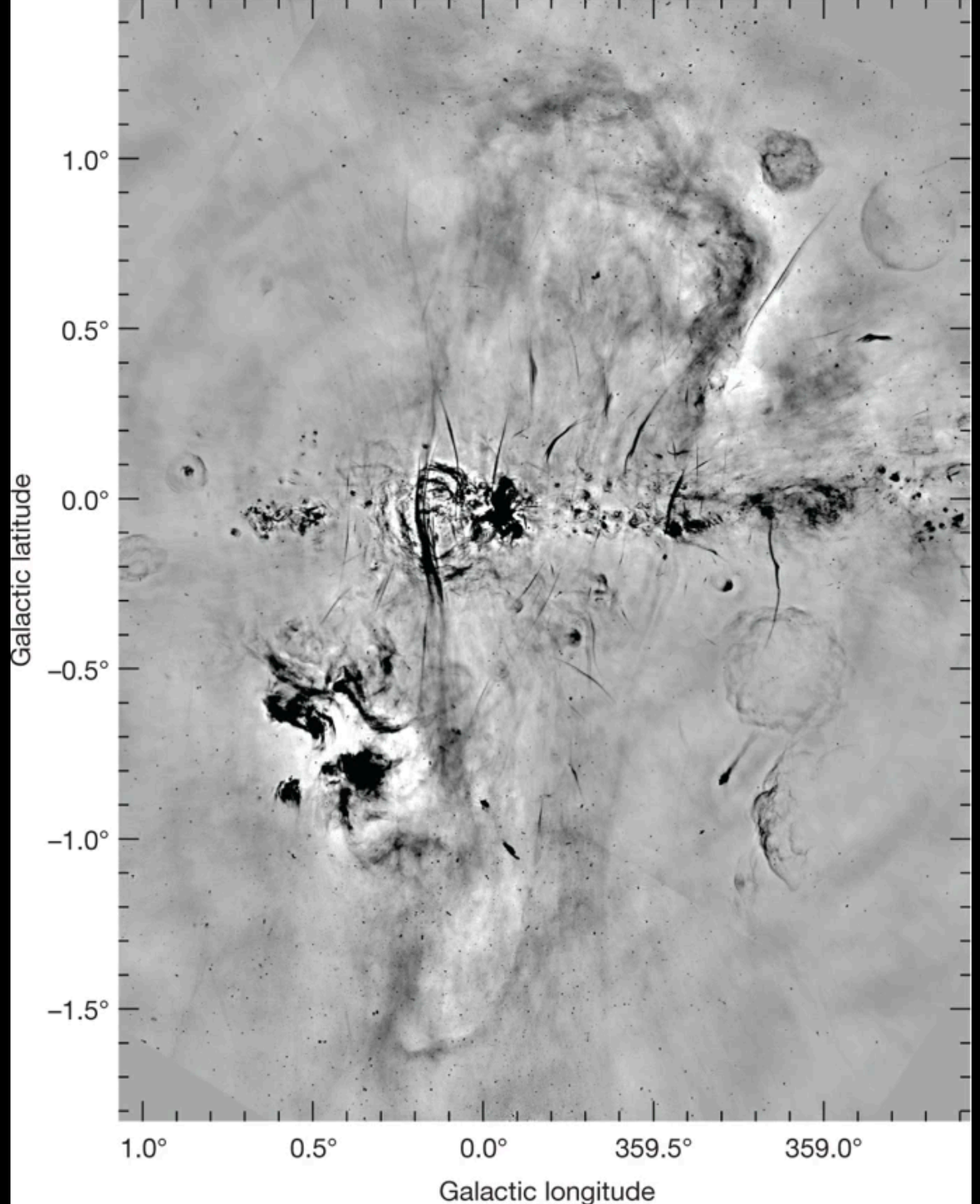
nature
International journal of science

Letter | Published: 11 September 2019

Inflation of 430-parsec bipolar radio bubbles in the Galactic Centre by an energetic event

I. Heywood ✉, F. Camilo ✉, […] L. P. Williams

Nature **573**, 235–237 (2019) | Download Citation ⬇



A more typical MeerKAT map:

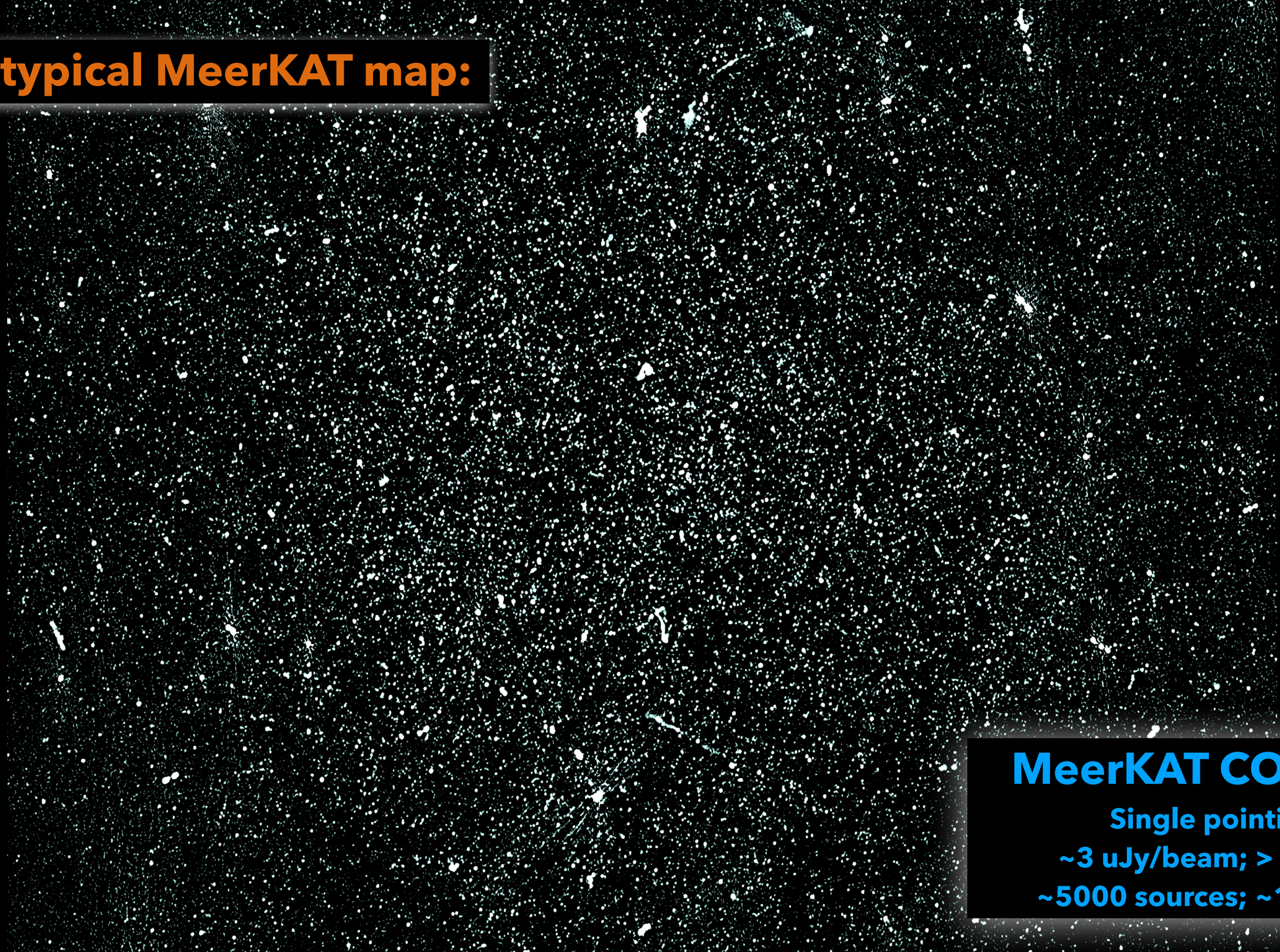


Image courtesy: Ian Heywood & MIGHTEE team

MeerKAT COSMOS

Single pointing

~3 uJy/beam; > 1 deg^2

~5000 sources; ~16 hours

A more typical MeerKAT map:

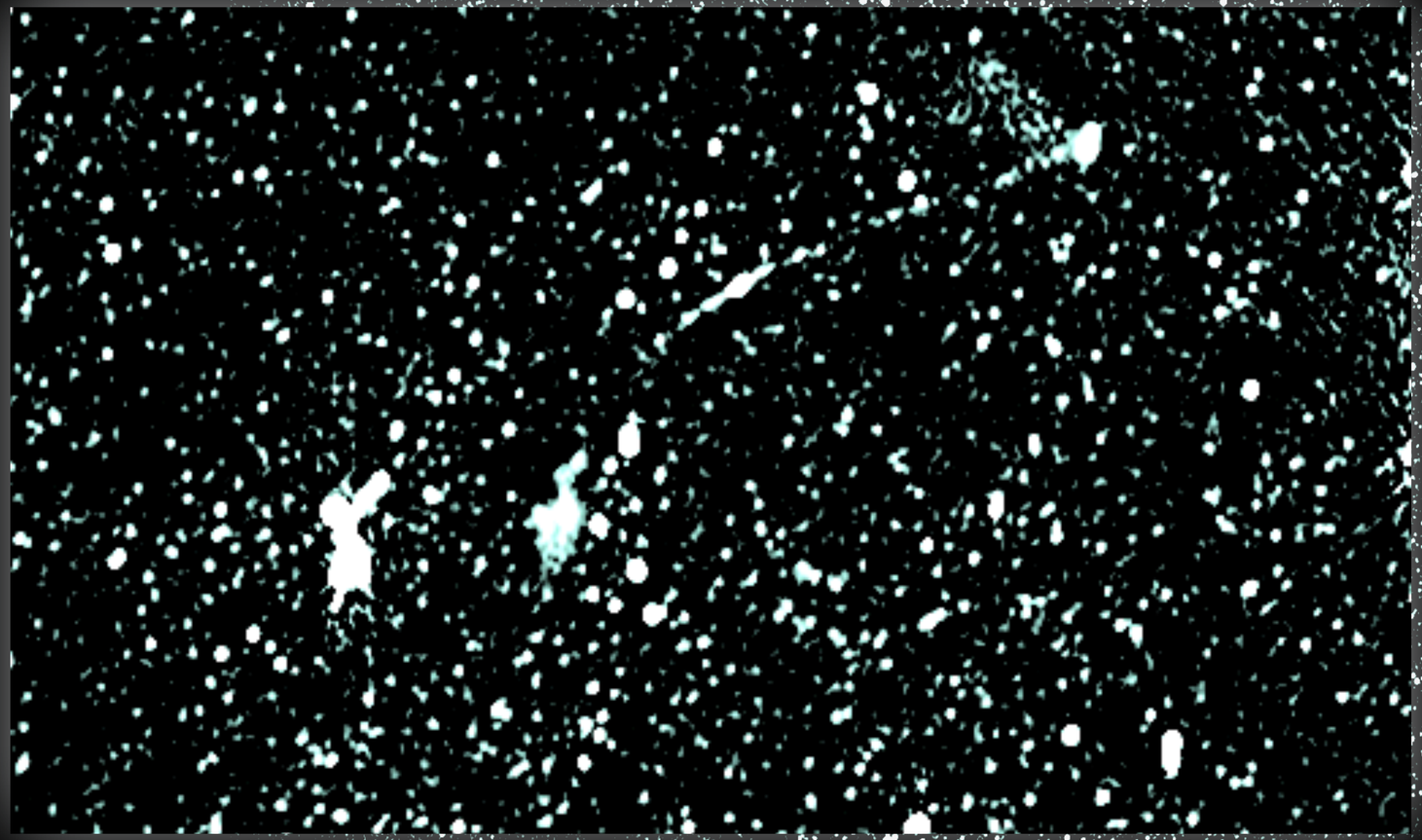


Image courtesy: Ian Heywood & MIGHTEE team

MeerKAT COSMOS

Single pointing

~3 uJy/beam; > 1 deg^2

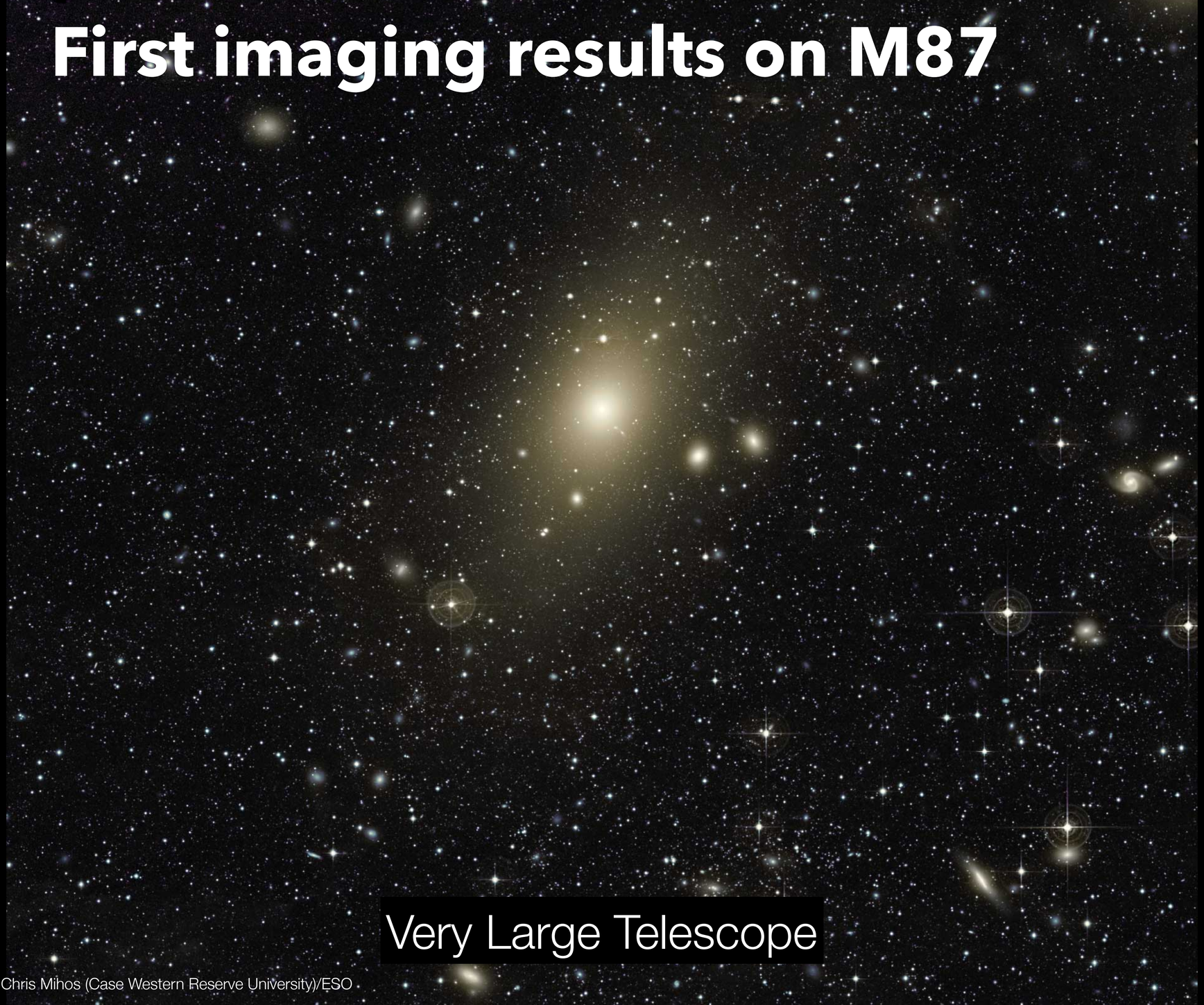
~5000 sources; ~16 hours

EHT has it **easy** *and* **hard**

(time-variable source, gains, propagation effects, but just ~1 source)

versus

First imaging results on M87

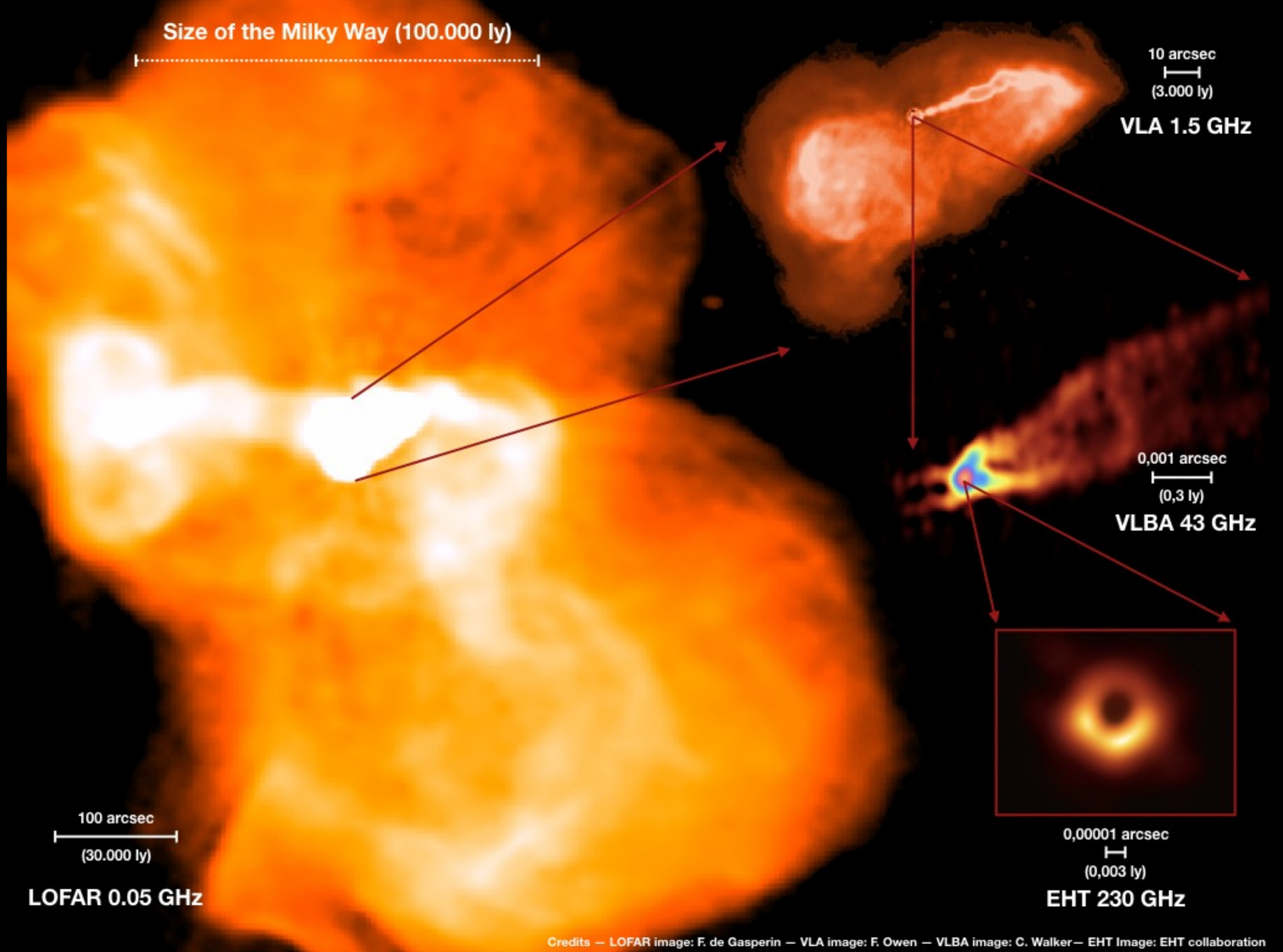


Very Large Telescope

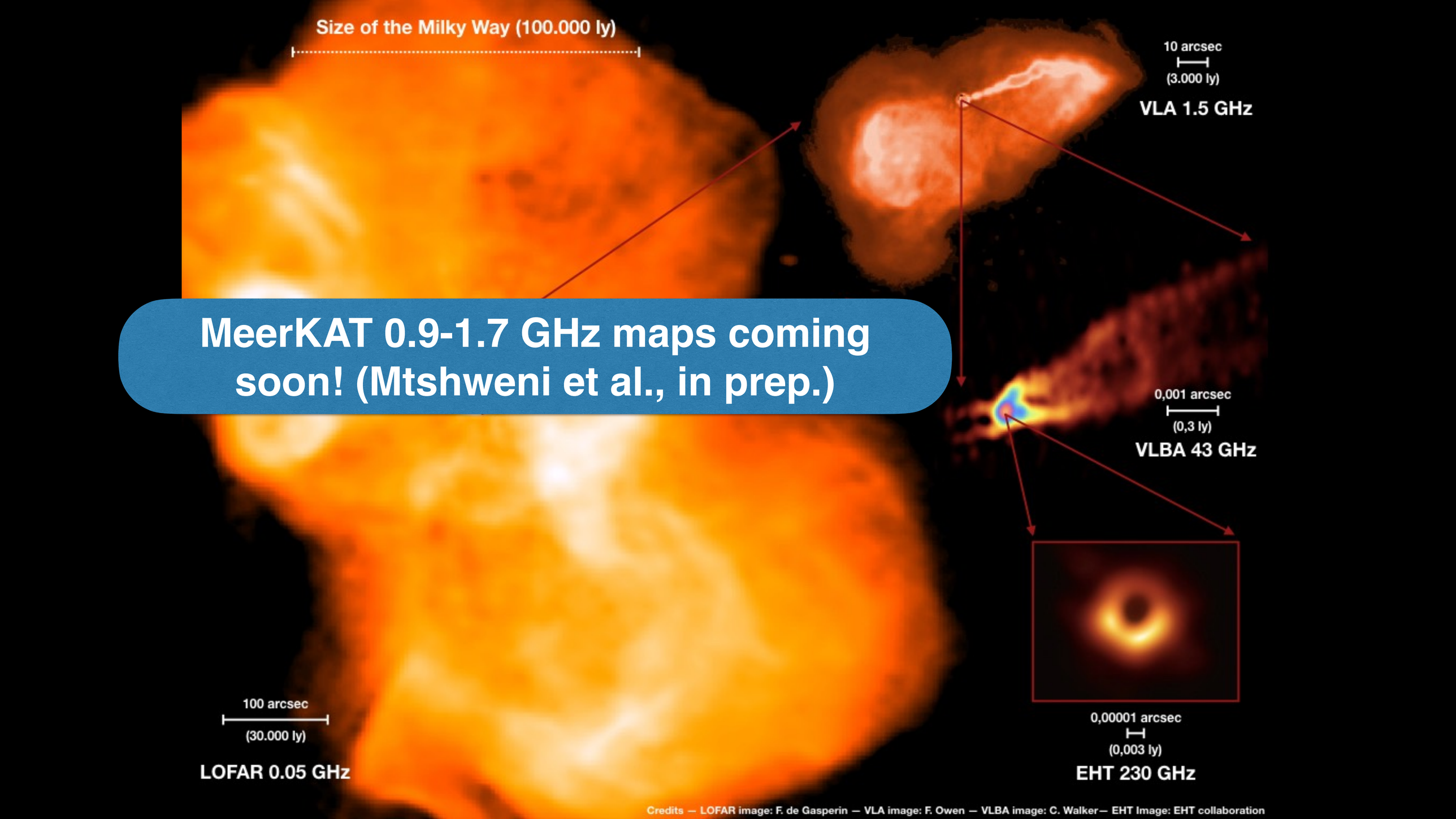
credit: Chris Mihos (Case Western Reserve University)/ESO

Hubble Space Telescope

credit: NASA, ESA and the Hubble Heritage Team (STScI/AURA); Acknowledgment: P. Cote (Herzberg Institute of Astrophysics) and E. Baltz (Stanford University)



Credits — LOFAR image: F. de Gasperin — VLA image: F. Owen — VLBA image: C. Walker— EHT Image: EHT collaboration


Size of the Milky Way (100.000 ly)
10 arcsec
(3.000 ly)
VLA 1.5 GHz
MeerKAT 0.9-1.7 GHz maps coming soon! (Mtshweni et al., in prep.)
0,001 arcsec
(0,3 ly)
VLBA 43 GHz
100 arcsec
(30.000 ly)
LOFAR 0.05 GHz
0,00001 arcsec
(0,003 ly)
EHT 230 GHz
Credits — LOFAR image: F. de Gasperin — VLA image: F. Owen — VLBA image: C. Walker— EHT Image: EHT collaboration

THE WALL STREET JOURNAL

THURSDAY, APRIL 11, 2019 – VOL. CCLXXIII NO. 84

WSJ.com

DOW JONES | DJIA 26157.16 ▲ 6.59 0.03% | NASDAQ 7964.24 ▲ 0.7% | STOXX 600 386.68 ▲ 0.3% | 10-YR. TREAS. ▲ 5/32, Yield 2.479% | OIL $64.61 ▲ $0.63 | GOLD $1,309.10 ▲ $5.60 | EURO $1.12

First Image Illuminates a Black Hole

DARK SIDE: A picture created with data from a network of telescopes reveals the first image of a black hole, 55 million light years away. The dark center inside the ring is where matter and light are trapped. A5

European Union Gives U.K. More Time to Resolve Brexit

Barr to P… 'Spying' … Trump …

Investigation to review whether surveillance in 2016 was 'adequately predicated,' he says

WASHINGTON—Attor… General William Barr tal… would form a team to ex… the origins of a 2016 cmp… telligence investigation… conducted what he te…

By Byron Ta… Sadie Gurman … Aruna Viswa…

"spying" on peo… with the Trump … characterization … was politically … echoed the p… standing critic… Department's …

What's News

Business & Finance

Uber is aiming for a valuation in its coming IPO of as much as $100 billion, below prevlous expectations, as rival Lyft stumbles in its early days of trading as a public company. A1

◆ Fed officials signaled greater conviction at their meeting last month that they don't need to move interest rates up or down. A2

◆ Draghi indicated that the ECB could take fresh action to shore up the eurozone's faltering economy if the outlook darkens. A7

◆ The heads of seven of the largest U.S. banks sparred with Democrats during a joint appearance before the House Financial Services panel. B1

◆ Boeing and U.S. regulators will be seeking what amounts to an international stamp of approval for an expected safety fix for 737 MAX jets. B1

◆ U.S. firms are reporting big swings in what they paid median employees last year, with the reasons for the shifts varying widely. B1

◆ The National Enquirer's parent company said it is exploring a sale of the scandal-plagued tabloid. B1

◆ Stocks in the U.S. edged higher, steadying following Tuesday's decline. The S&P 500 posted a 0.3% gain. B11

◆ U.S. prosecutors charged U.K. drug firm Indivior with organizing a fraud to drive up sales of opioid-addiction treatment Suboxone Film. B4

◆ Norsk Hydro confirmed that hackers used a form of ransomware known as Lock…

The Washington …

Partly sunny 66/54 • Tomorrow: T-storm 73/62 B6

Democracy Dies in Darkness

Scientists revealed the first image of a black hole, assembled with data from a network of radio telescopes around the world

The glowing, doughnut-like ring shows radiation, in the form of high-frequency radio waves, emanating from superheated material outside the event horizon.

The asymmetry of bright and dark sections of the ring is caused by the Doppler effect as the matter is coming toward Earth (brighter) or receding (dimmer).

The ring and the central shadow were anticipated by Einstein's general theory of relativity but had not been seen until now.

EUROPEAN SOUTHERN OBSERVATORY/ AGENCE FRANCE-PRESSE/GET…

A new horizon

Drawn from across the cosmos, the captivating first image of a black hole required a planet-size te…

BY SARAH KAPLAN AND JOEL ACHENBACH

Scientists have finally captured the first image of a black hole, a bottomless pit in the fabric of the universe from which not even light can escape. Black holes are perhaps the strangest things in the cosmos, until now hidden behind dust and gas and the blinding …

… around them.

The highly anticipated portrait, unveiled Wednesday at the National Press Club in Washington and in news conferences in six other cities around the globe, shows an extraordinary, "supermassive" black hole at the center of Messier 87, a gigantic galaxy about 55 million light-years away in the constellation Virgo.

The image was produced by the Event … telescopes spread across the plan… tioning as if it were a single … tuned to high-frequency radio … resents a technical triumph for … involved and inaugurates a n… study of black holes, galaxy … the laws of physics under e… tions.

The M87 black hole app… shadow within a doughnut…

"All the News That's Fit to Print"

The New York Times

VOL. CLXVIII . . . No. 58,294 © 2019 The New York Times Company

THURSDAY, APRIL 11, 2019

Washington Edition

Today, sunshine, and some cloudy, unseasonable, high 66. Tonight, partly cloudy, not as cold, low 54. Tomorrow, milder, late-day thunderstorm, high 73. Weather map, Page B14.

$3.00

Migrants Pour Into a System That's 'on Fire'

U.S. Border Could Be at a Breaking Point

This article is by Michael D. Shear, Miriam Jordan and Manny Fernandez.

SAN YSIDRO, Calif. — It was never like this before.

The migrants come now in the middle of the night or in the bright light of day. Men and women arrive by the hundreds, caked with dirt, with teens and toddlers in tow. They jump the small fences in remote parts of Texas, and they swim across the Rio Grande. They line the pavement at the main border crossing in California. Tired and fearful, they look for either one thing that they pray will allow them to stay in the United States, at least for a while: a Border Patrol agent.

Gone are the days when young, strong men waited on the Tijuana River levees for their chance to wade across the water, evade capture and find work for the summer. These days, thousands of people a day simply walk up to the border and surrender. Most of them are from Central America, seeking to escape gang violence, sexual abuse, death threats and persistent poverty. The smugglers have told them that they will be quickly released, as long as they bring a child, and that they will be allowed to remain in the United States for years while they pursue their asylum cases.

The very nature of immigration to America changed after 2014, when families first began showing up in large numbers. The resulting crisis has overwhelmed a system unable to detain, care for and quickly decide the fate of tens of thousands of people who claim to be fleeing for their lives. For years, both political parties have tried — and failed — to overhaul the nation's immigration laws, mindful that someday the government would reach a breaking point.

That moment has arrived. The country is now unable to provide the necessary humanitarian relief for desperate migrants or even basic controls on the number and

Continued on Page A22

Scientists captured a view of a black hole at the heart of a galaxy known as Messier 87, some 55 million light-years away from Earth.

EVENT HORIZON TELESCOPE COLLABORATION, VIA NATIONAL SCIENCE FOUNDATION

Peering Into Light's Graveyard: The First Image of a Black Hole

BY DENNIS OVERBYE

Astronomers announced on Wednesday that at last they had captured an image of the unobservable: a black hole, a cosmic abyss so deep and dense that not even light can escape it.

For years, and for all the mount… pher Nolan's outer-space epic "Interstellar." Now they are more real than ever.

"We have seen what we thought was unseeable," said Shep Doeleman, an astronomer at the Harvard-Smithsonian Center for Astrophysics, and director of the effort to capture the image, during a …

Linked Antennas Turn Earth Into Telescope

… known as Messier 87, some 55 million light-years away from Earth, resembled the Eye of Sauron, a re… mers reached across intergalactic space to Messier 87, or M87, a giant galaxy in the constellation Virgo. There, a black hole several billion times more massive than the sun is unleashing a violent jet of energy some 5,000 light-years into space.

The image offered a final, ring… age affirmation of an idea so dis…

NEWS ANALYSIS

Israelis Lean On Stability With Leader

Netanyahu Is Symbol of Cherished Security

By DAVID M. HALBFINGER

JERUSALEM — Benjamin Netanyahu's apparent re-election as prime minister of Israel attests to a starkly conservative vision of the Jewish state and its people about where they are and where they are headed.

They prize stability, as well as the military and economic security that Mr. Netanyahu has delivered.

Though in many ways they have never been safer, they remain afraid — especially of Iran and its influence over their neighbors, against which Mr. Netanyahu has relentlessly crusaded. They are persuaded by his portrayal of those who challenge him, whether Arab citizens or the left, as enemies of the state. They take his resemblance to authoritarian leaders around the world as evidence that he was ahead of the curve.

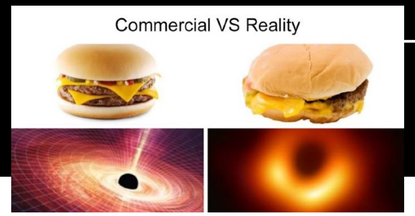
They credit Mr. Netanyahu, whose strategic vision values power and fortitude above all, with piloting Israel to unprecedented diplomatic heights and believe still more is possible. And they are loath to let anyone less experienced take the controls.

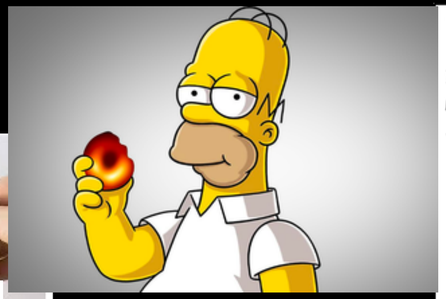
"Let's be honest with ourselves," said Michael B. Oren, a former Israeli ambassador to Washington. "Our economy is excellent, our foreign relations were never better, and we're secure. We've got a guy in politics for 40 years; We know him, the world knows him — even our enemies know him."

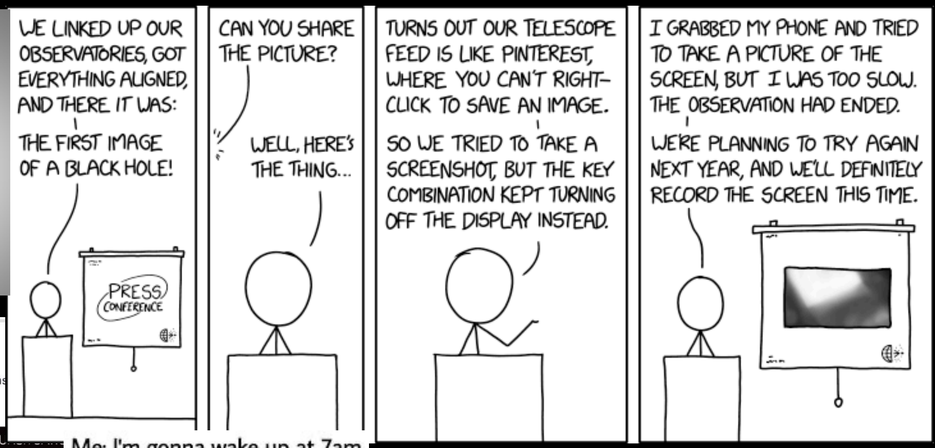
Not everyone is so enamored of him.

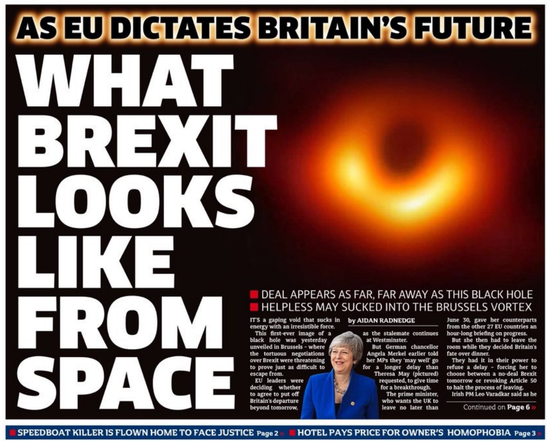
Mr. Netanyahu's coalition appears to have won 65 of the 120 seats in Parliament. But his positions on the issues differed little from those of his main challenger, Benny Gantz, suggesting that close to half of the electorate would have simply preferred someone else in the …

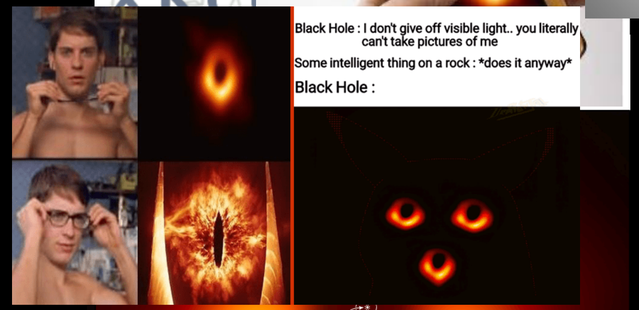
Internet memes...

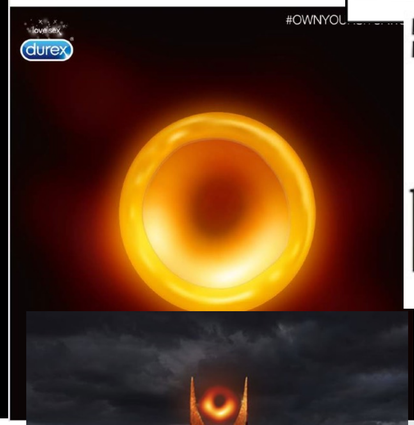


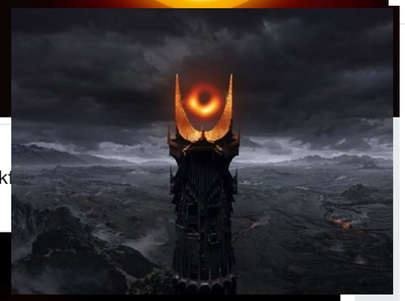


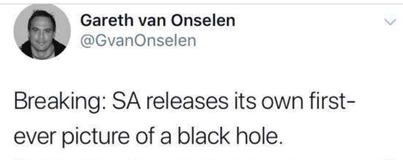


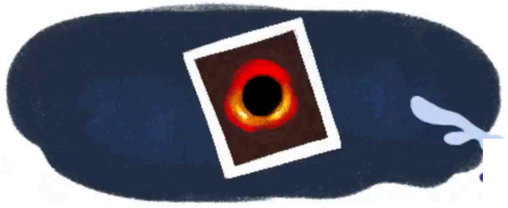


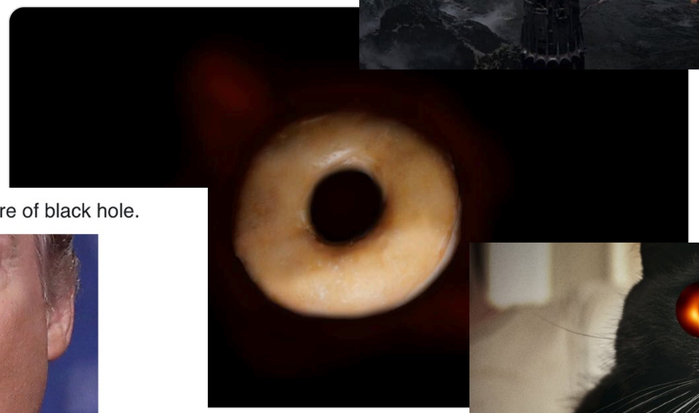


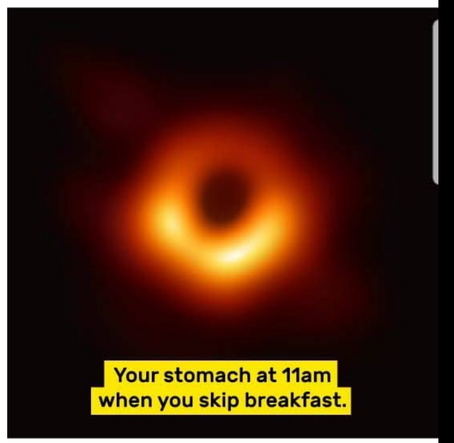


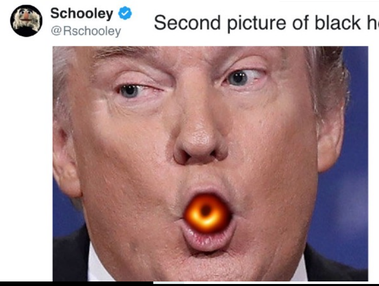


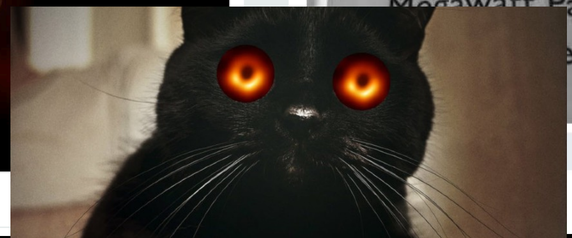




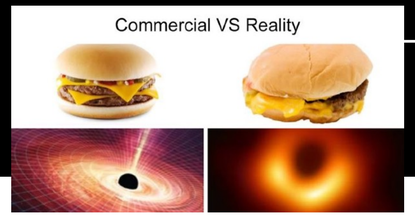


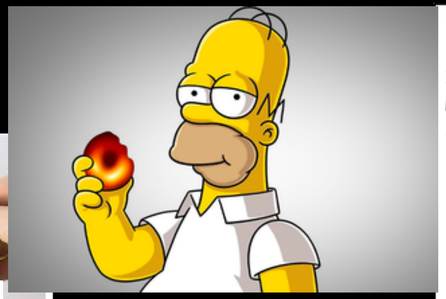


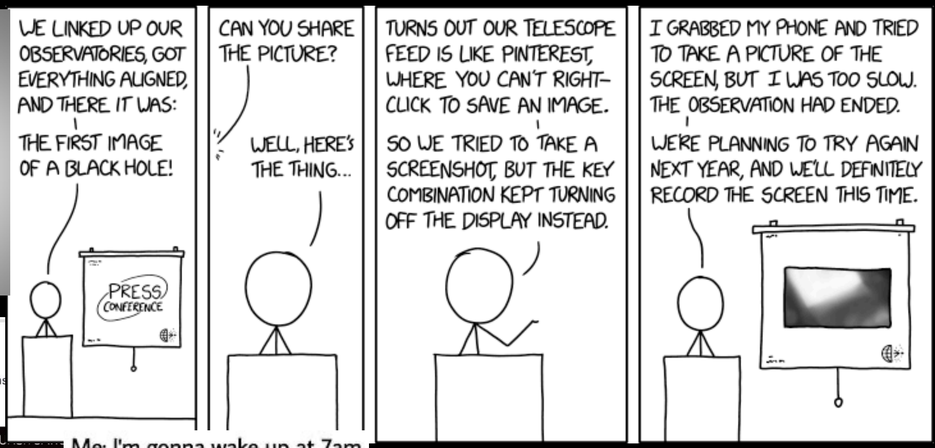


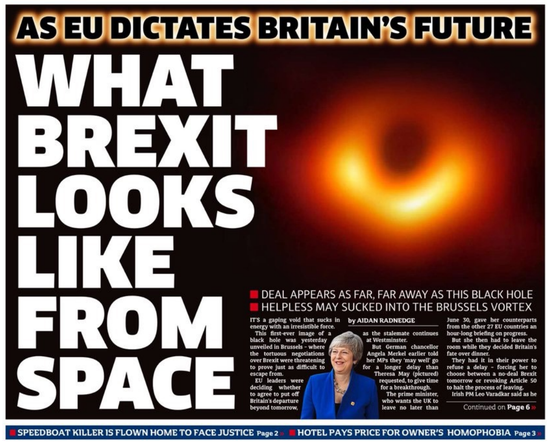


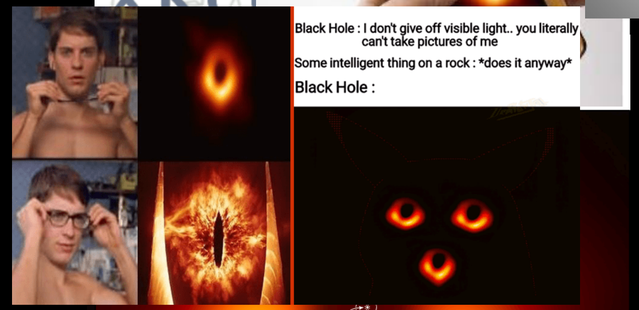
Internet memes...

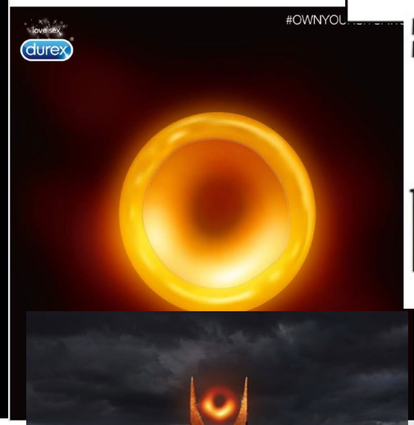


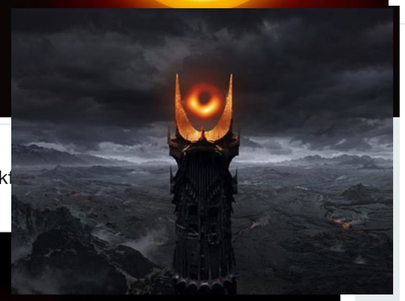


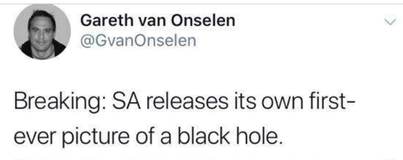


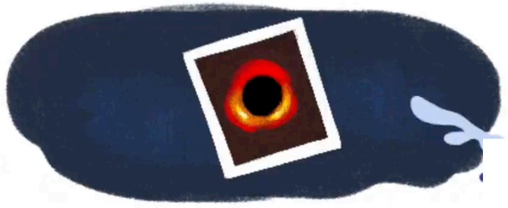


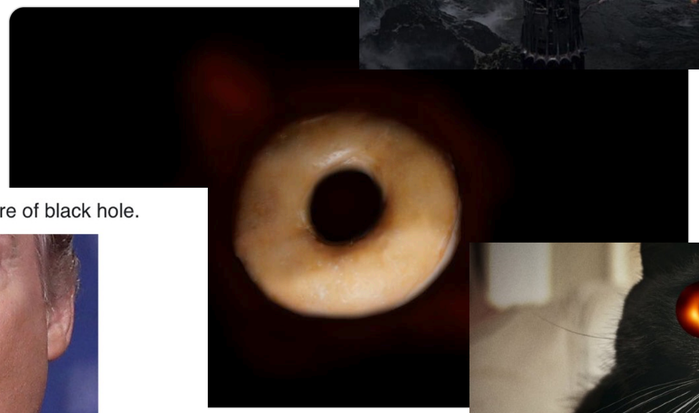


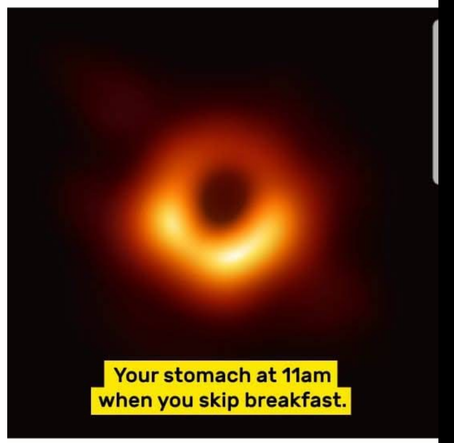


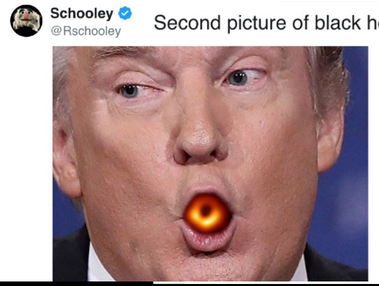


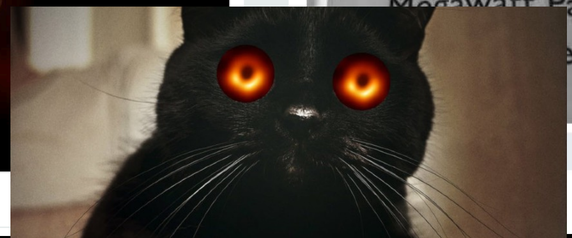












…and six peer-reviewed journal articles

First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole

The Event Horizon Telescope Collaboration *et al.* 2019 *ApJL* **875** L1

First M87 Event Horizon Telescope Results. II. Array and Instrumentation

The Event Horizon Telescope Collaboration *et al.* 2019 *ApJL* **875** L2

First M87 Event Horizon Telescope Results. III. Data Processing and Calibration

The Event Horizon Telescope Collaboration *et al.* 2019 *ApJL* **875** L3

First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole

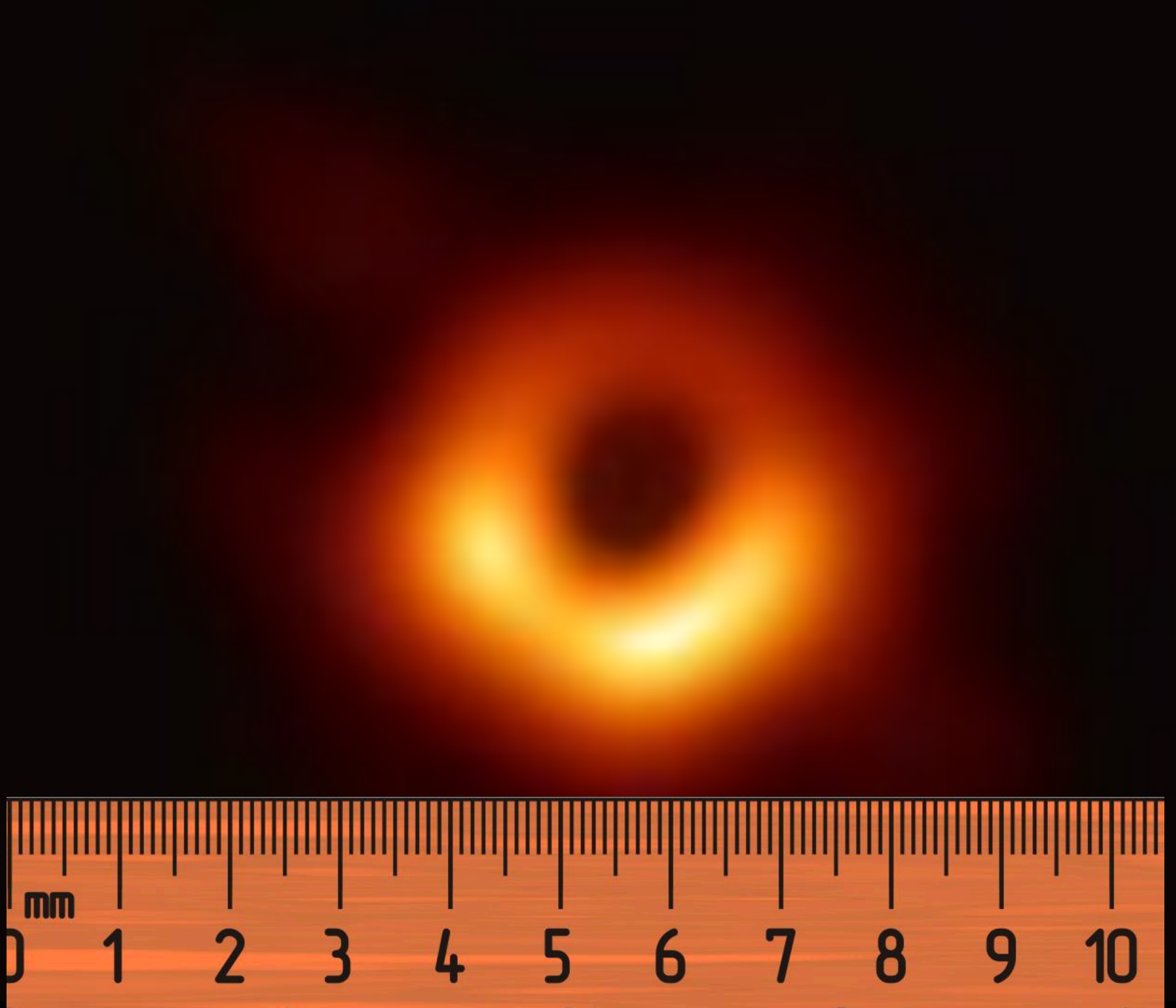
The Event Horizon Telescope Collaboration *et al.* 2019 *ApJL* **875** L4

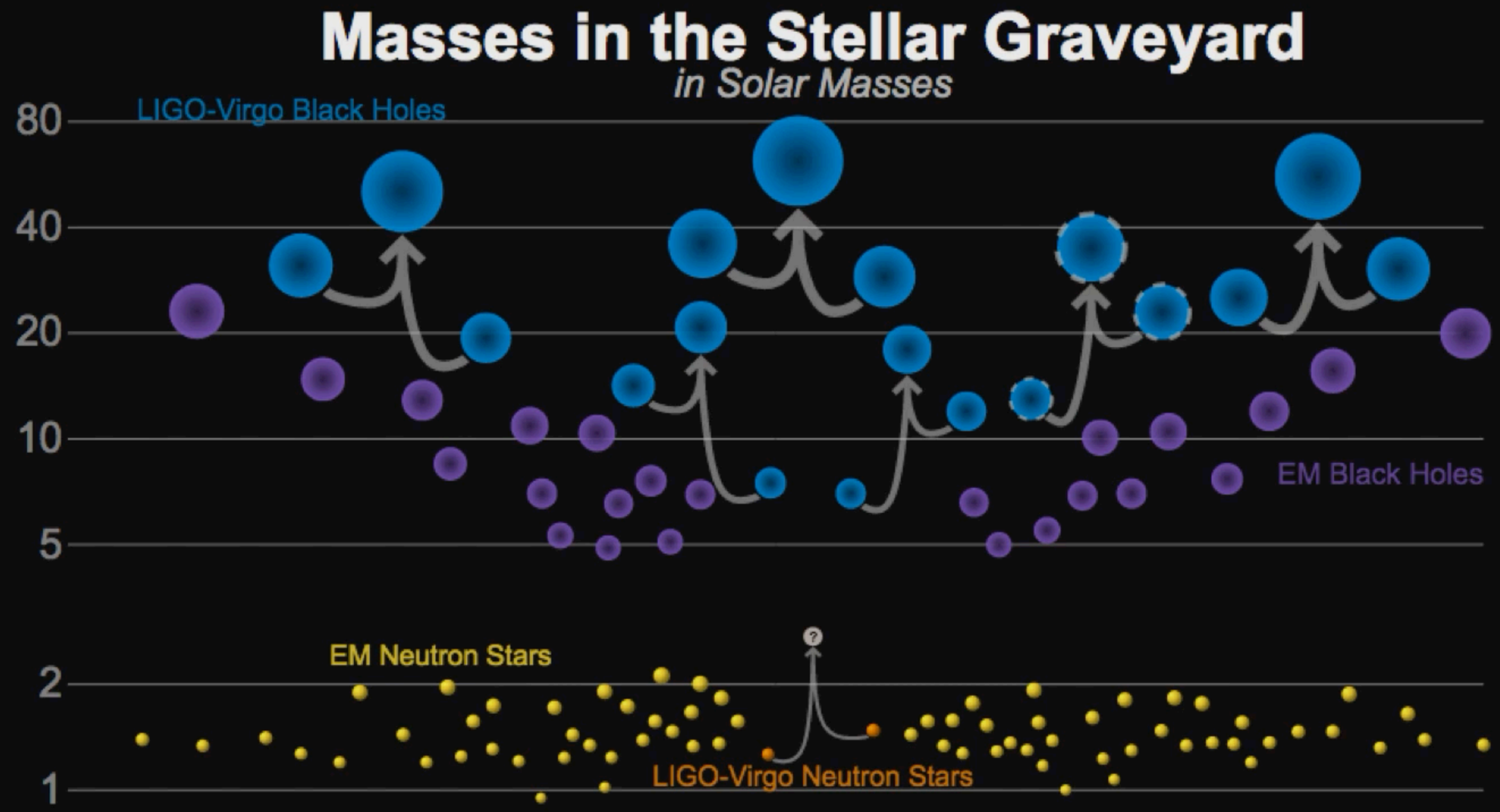
First M87 Event Horizon Telescope Results. V. Physical Origin of the Asymmetric Ring

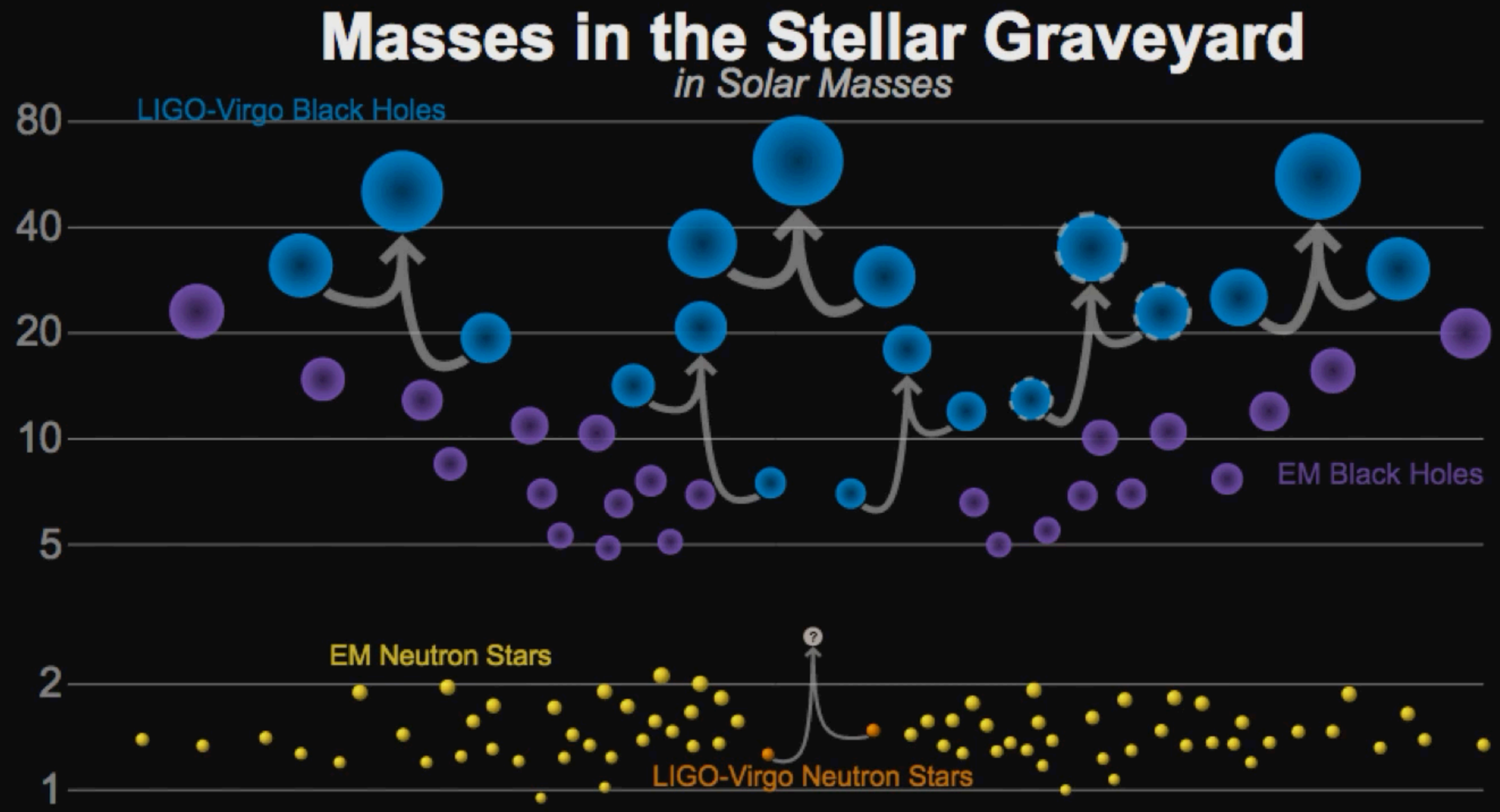
The Event Horizon Telescope Collaboration *et al.* 2019 *ApJL* **875** L5

First M87 Event Horizon Telescope Results. VI. The Shadow and Mass of the Central Black Hole

The Event Horizon Telescope Collaboration *et al.* 2019 *ApJL* **875** L6


mm
0 1 2 3 4 5 6 7 8 9 10


Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
EM Black Holes
EM Neutron Stars
2
1
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern


Masses in the Stellar Graveyard
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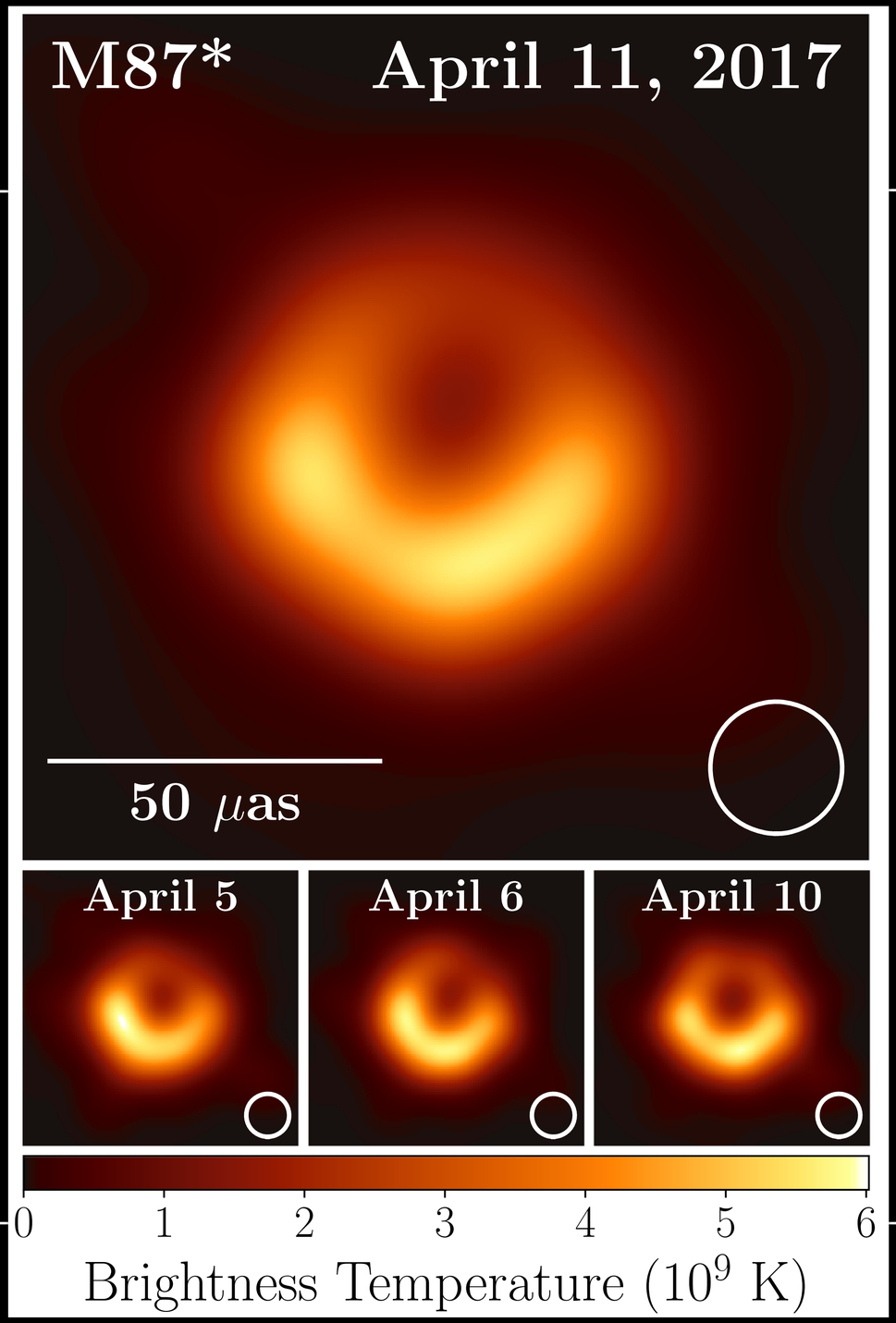
80
40
20
10
5
EM Black Holes
EM Neutron Stars
2
1
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

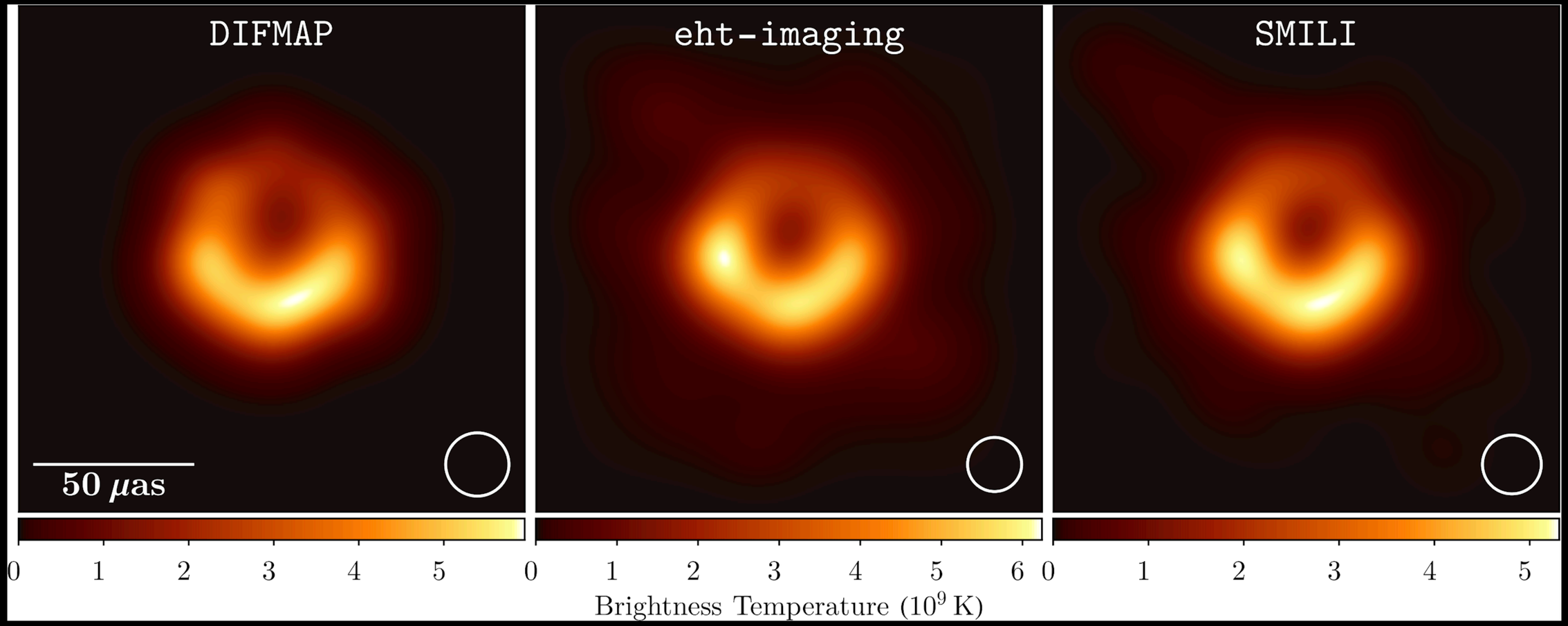
Not just 1 image!

- Average of three different imaging algorithms = consensus image
- Convolved with a 20 uas beam
- Consistent structure over four days, although some super-resolved structure be real
- A next step is to compare static versus dynamic source structure models

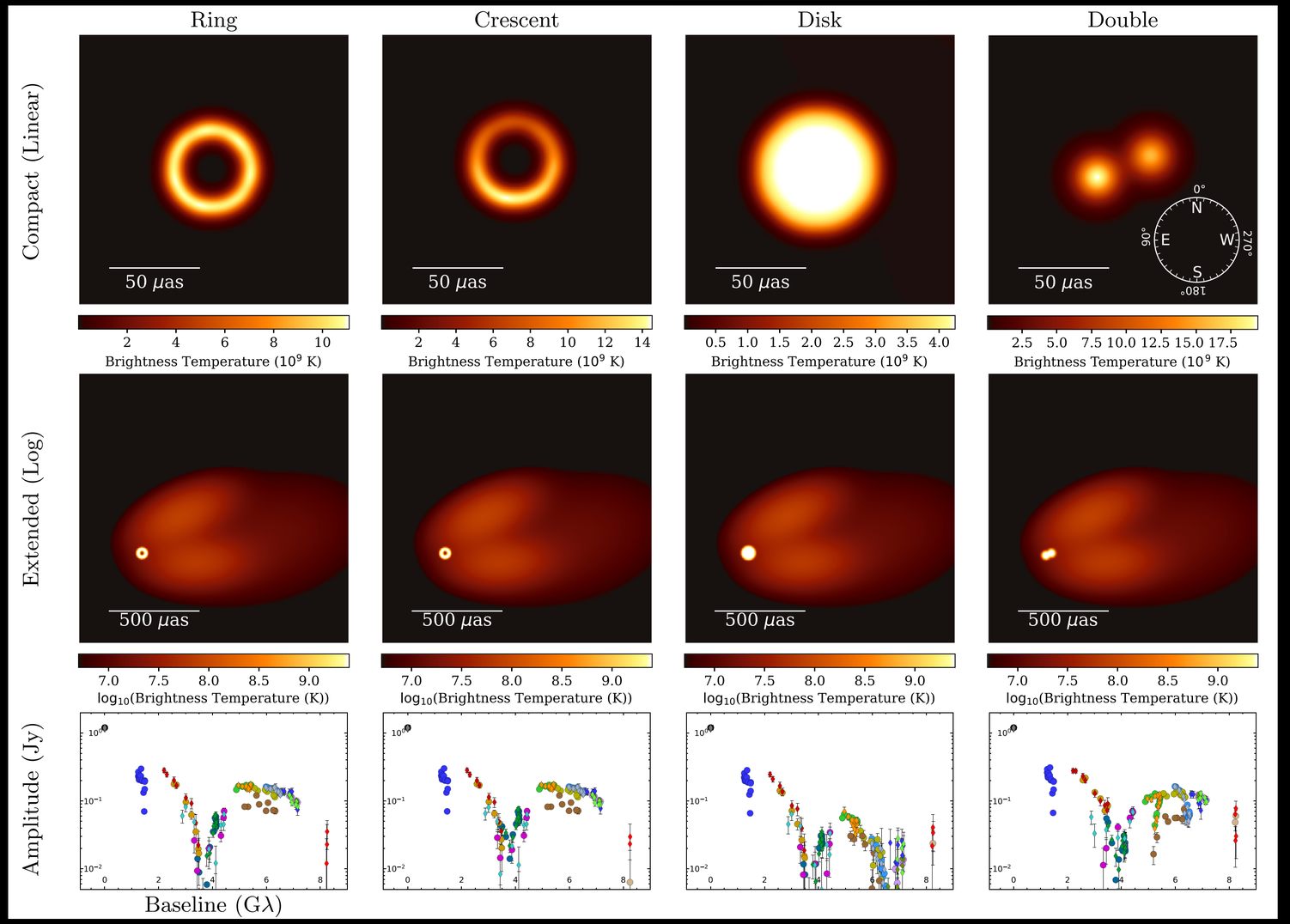


Agreement with a trio of imaging algorithms

Fiducial images of M87 for April 11 restored to an equivalent resolution show remarkably similar structure

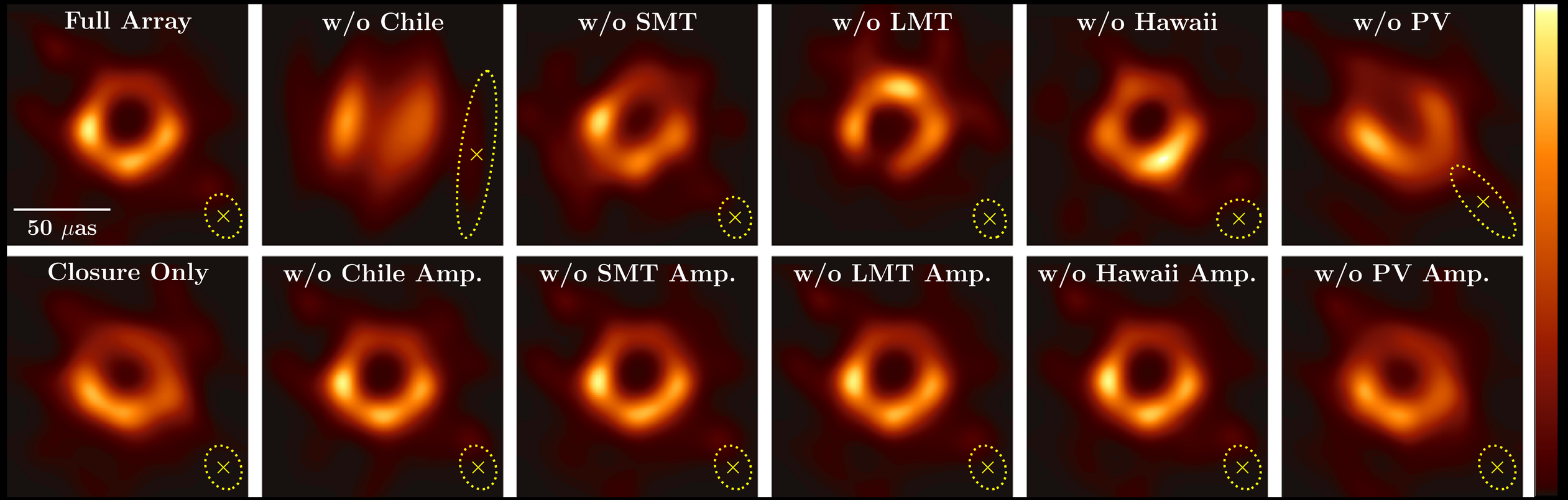


Imaging tests



Event Horizon Telescope

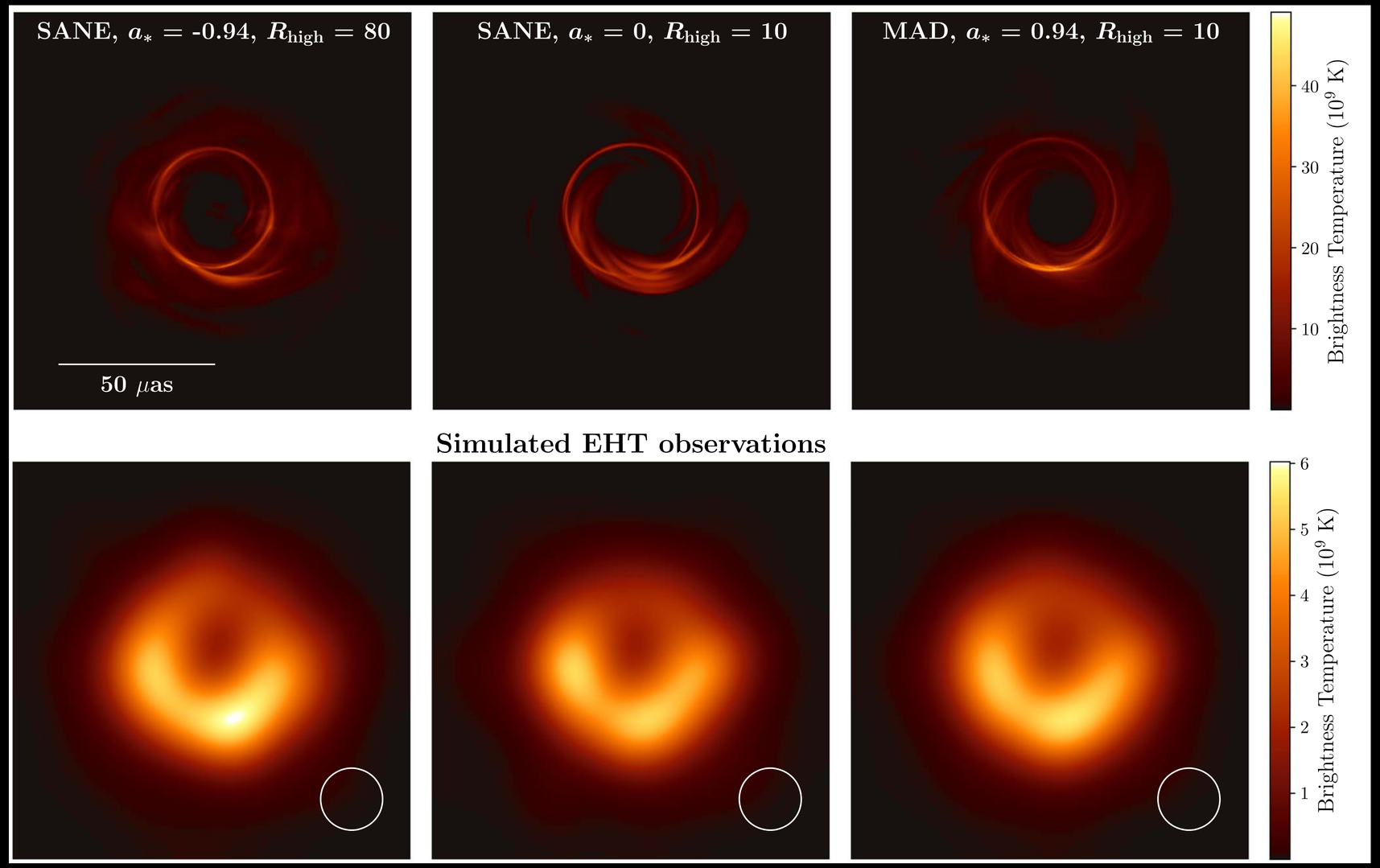
Paper IV


Full Array
w/o Chile
w/o SMT
w/o LMT
w/o Hawaii
w/o PV
50 μas
Closure Only
w/o Chile Amp.
w/o SMT Amp.
w/o LMT Amp.
w/o Hawaii Amp.
w/o PV Amp.

Comparison with simulation

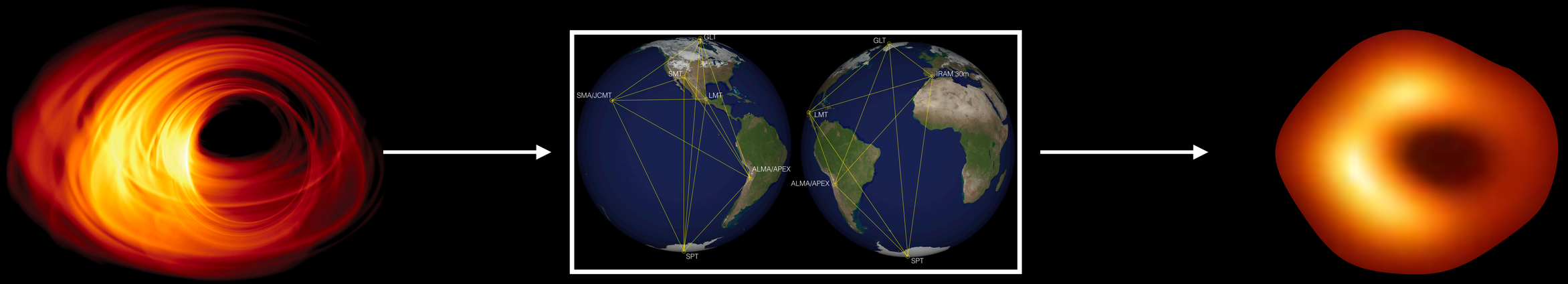
GRMHD simulations generally consistent with image (despite wide range of BH spin, T_e/T_p ratio, magn field model)

Passed through instrument simulator + official EHT calibration and imaging pipeline



Suite of new tools for VLBI (not just for EHT)

Understanding instrumental and propagation transfer functions

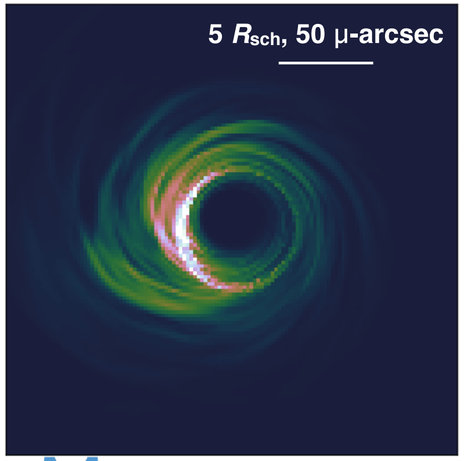


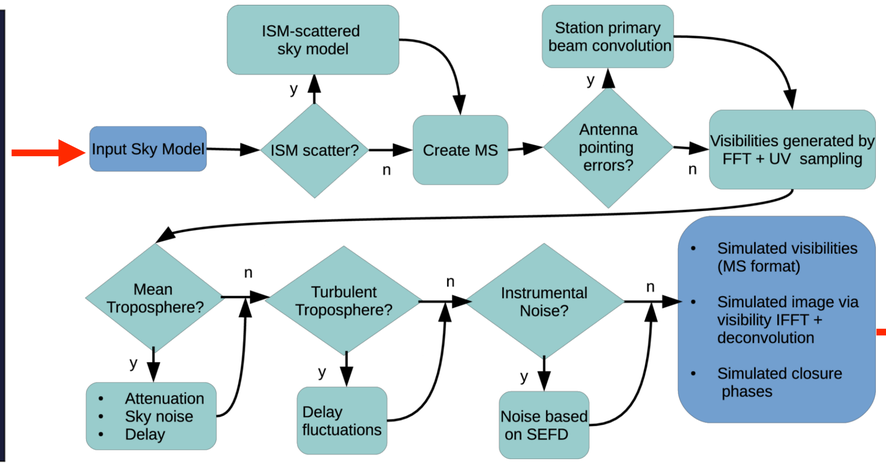
Credit: Bronzwaer, Moscibrodzka, Davelaar & Falcke

EHT synthetic data

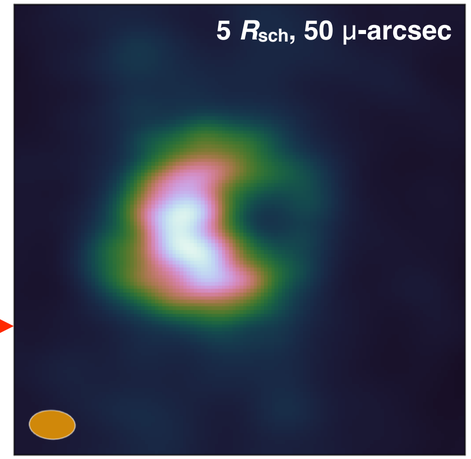
- Given the wide range of stations, propagation effects, calibration uncertainties, and complex source structure, **sophisticated synthetic data is a critical resource for testing purposes**
- These same synthetic data engines are **used in probabilistic modeling** of physical parameters from observables
- My group leads **MeqSilhouette** development for use in the EHT Consortium

input theoretical model





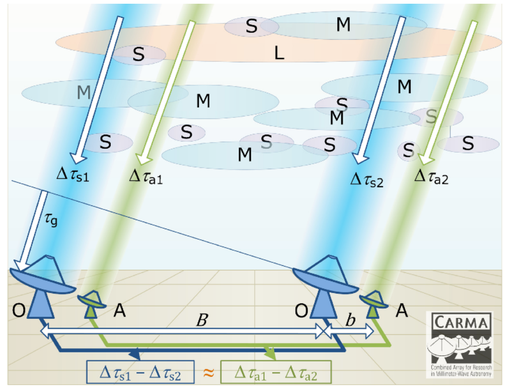
simulated observation

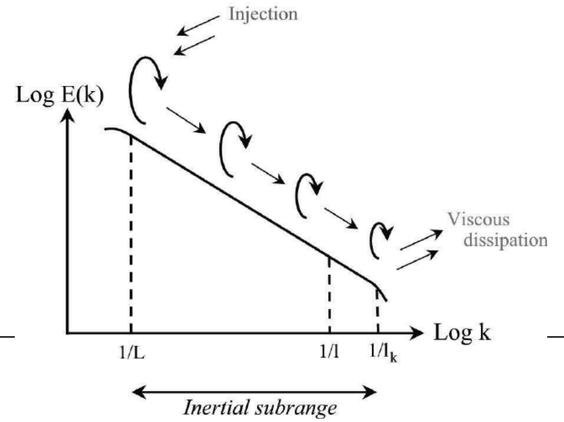


MeqSilhouette

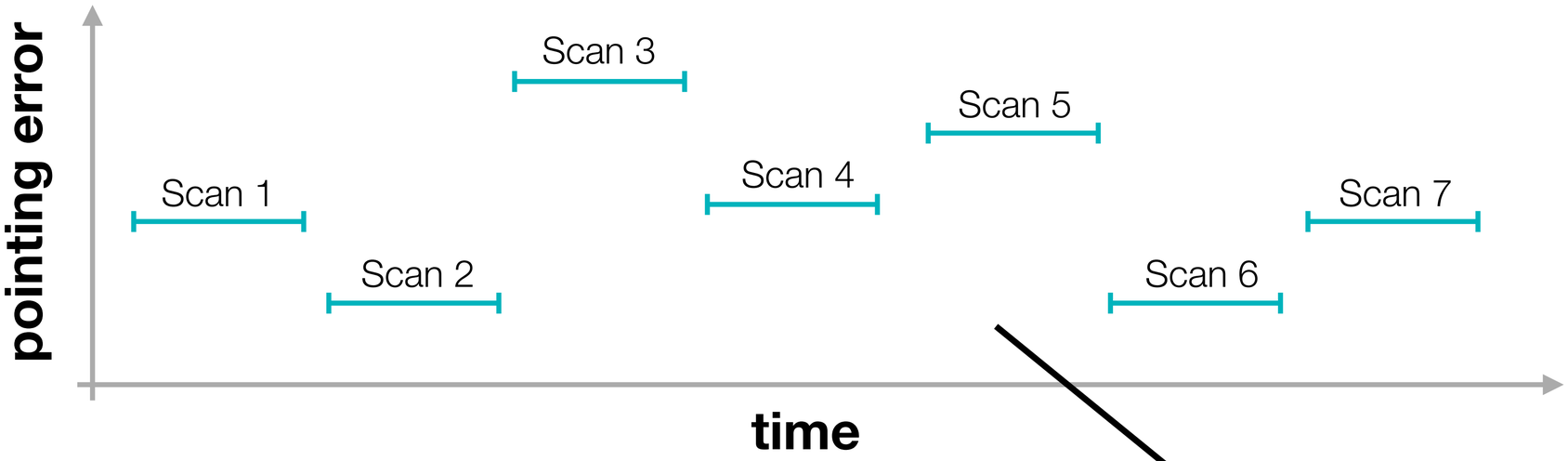
Blecher, Deane et al. (2017)
Natarajan, Deane et al. (in prep.)

Turbulent troposphere

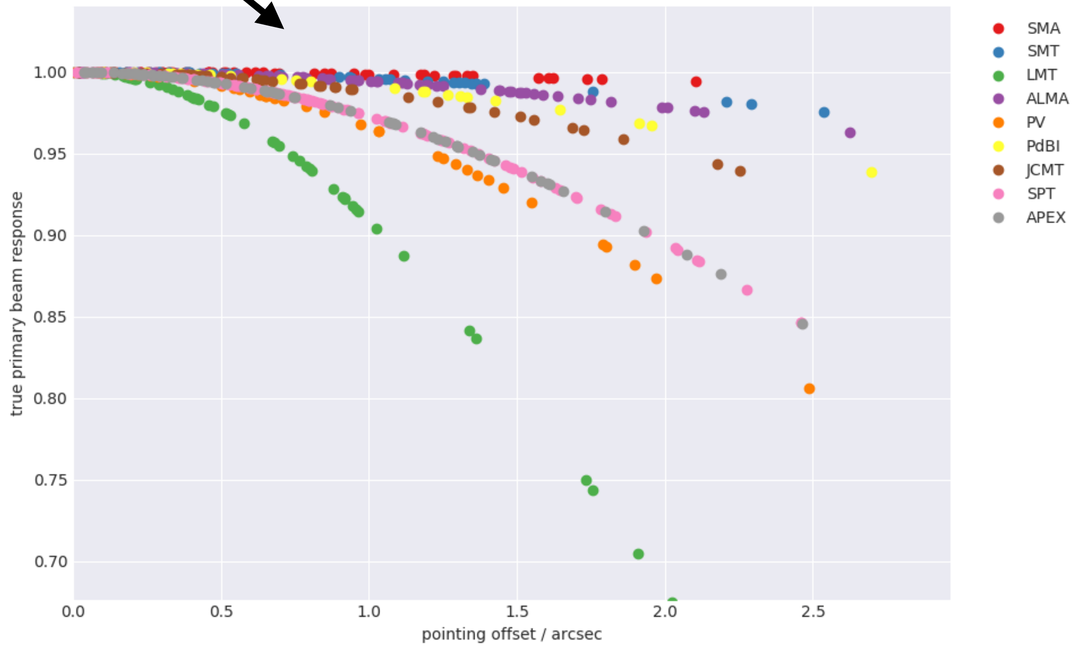




Antenna pointing error



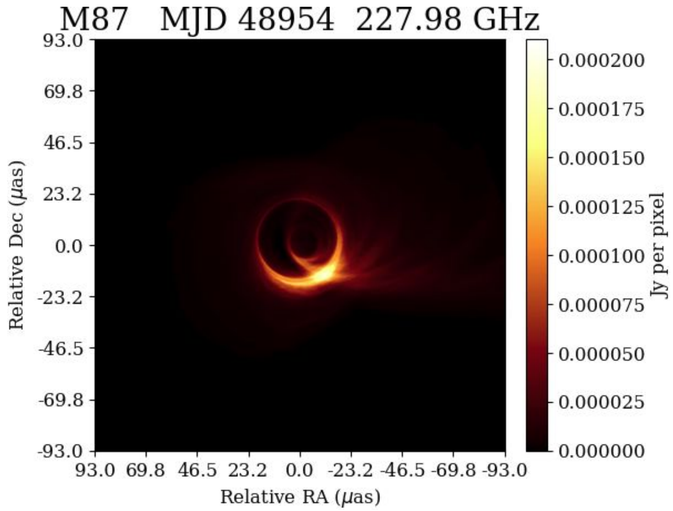
- Time-variable, station-dependent amplitude errors
- Worst off for LMT (biggest dish)
- Introduction of systematics that must be understood
- Using realistic parameter enables feedback into potential array improvements

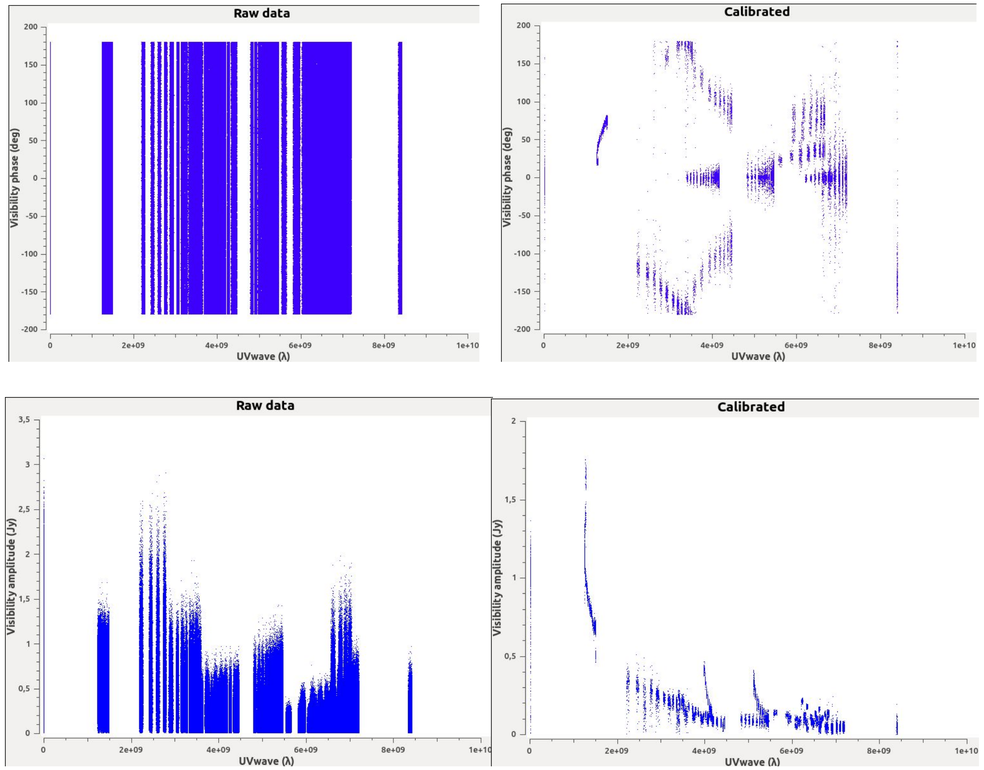


MeqSilhouette + rPICARD = SYMBA

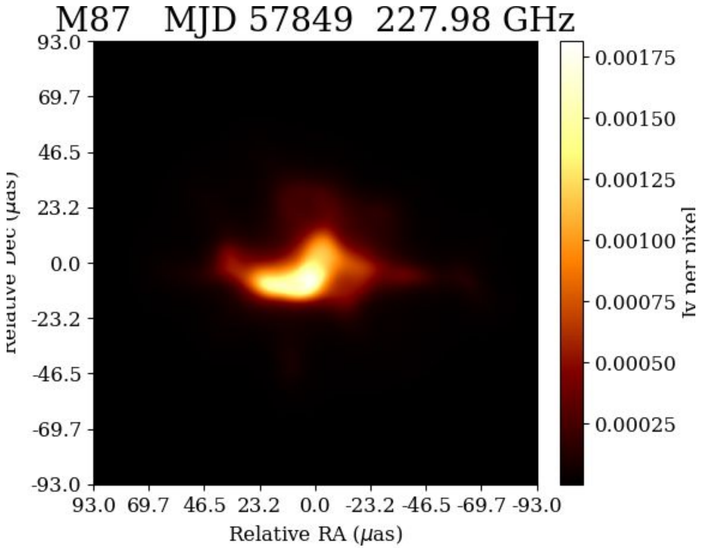
Our synthetic data fed through the real EHT post-processing pipeline

Model image (Davelaar et al. in prep.)





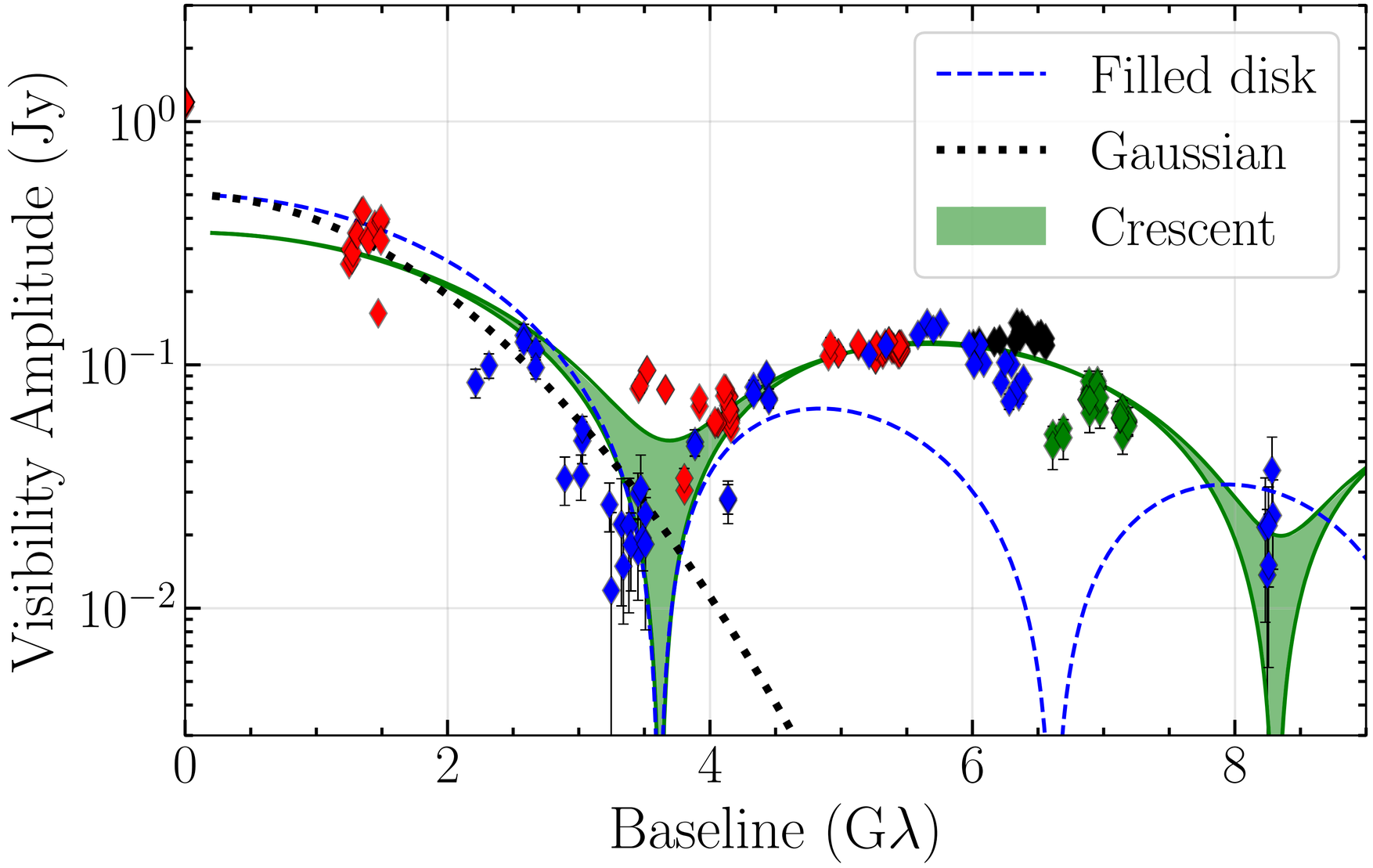
All corruptions



Event Horizon Telescope

Roelofs, Janssen, Natarajan, Deane et al. (2020)
Natarajan, Deane, et al. (in prep.)

Model Comparison: which is most consistent with the data?



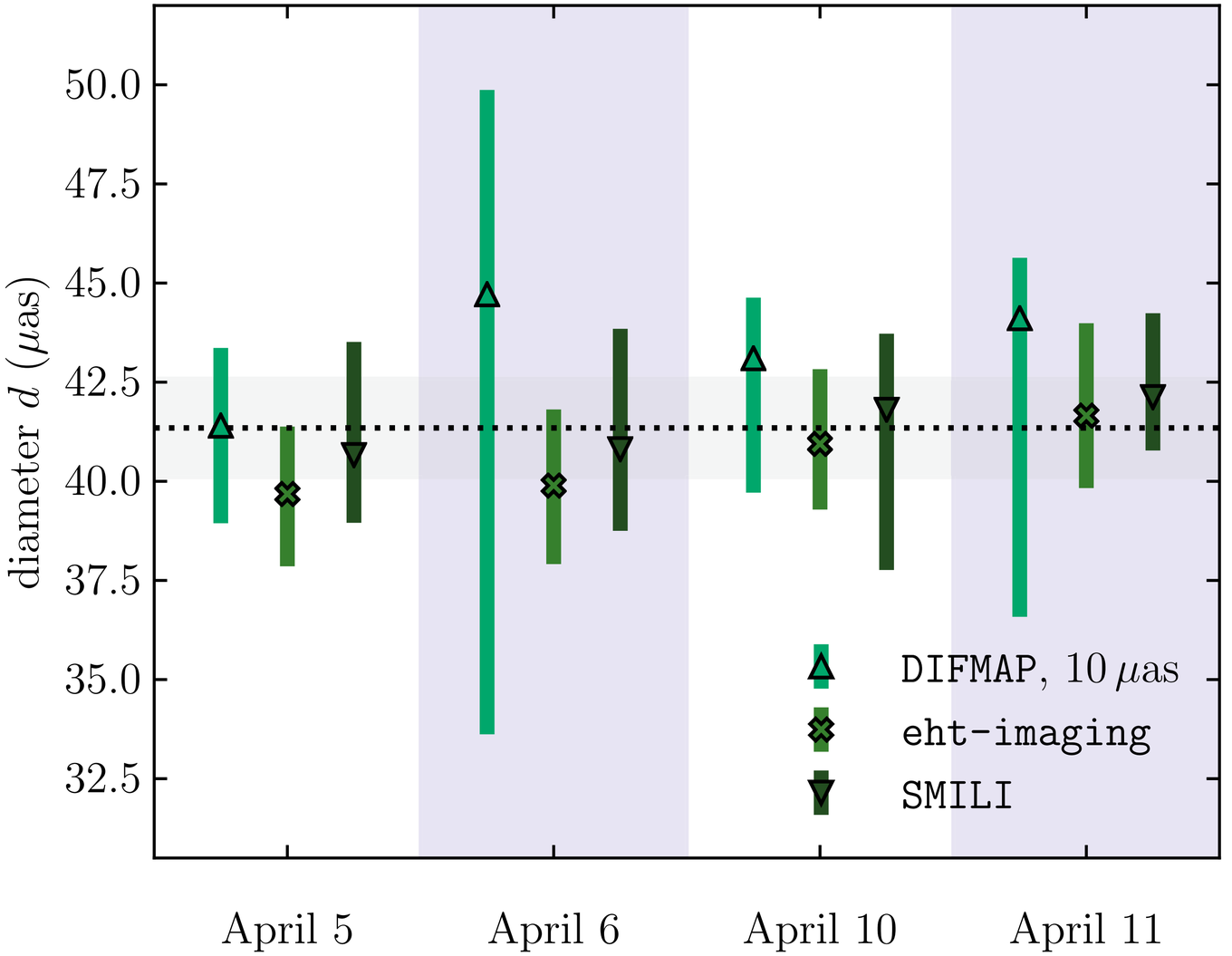
Event Horizon Telescope

EHT Collaboration (2019), Paper VI

image-based fitting results

correlated noise

Consistency across parameter estimation algorithms, frequency bands, observing days



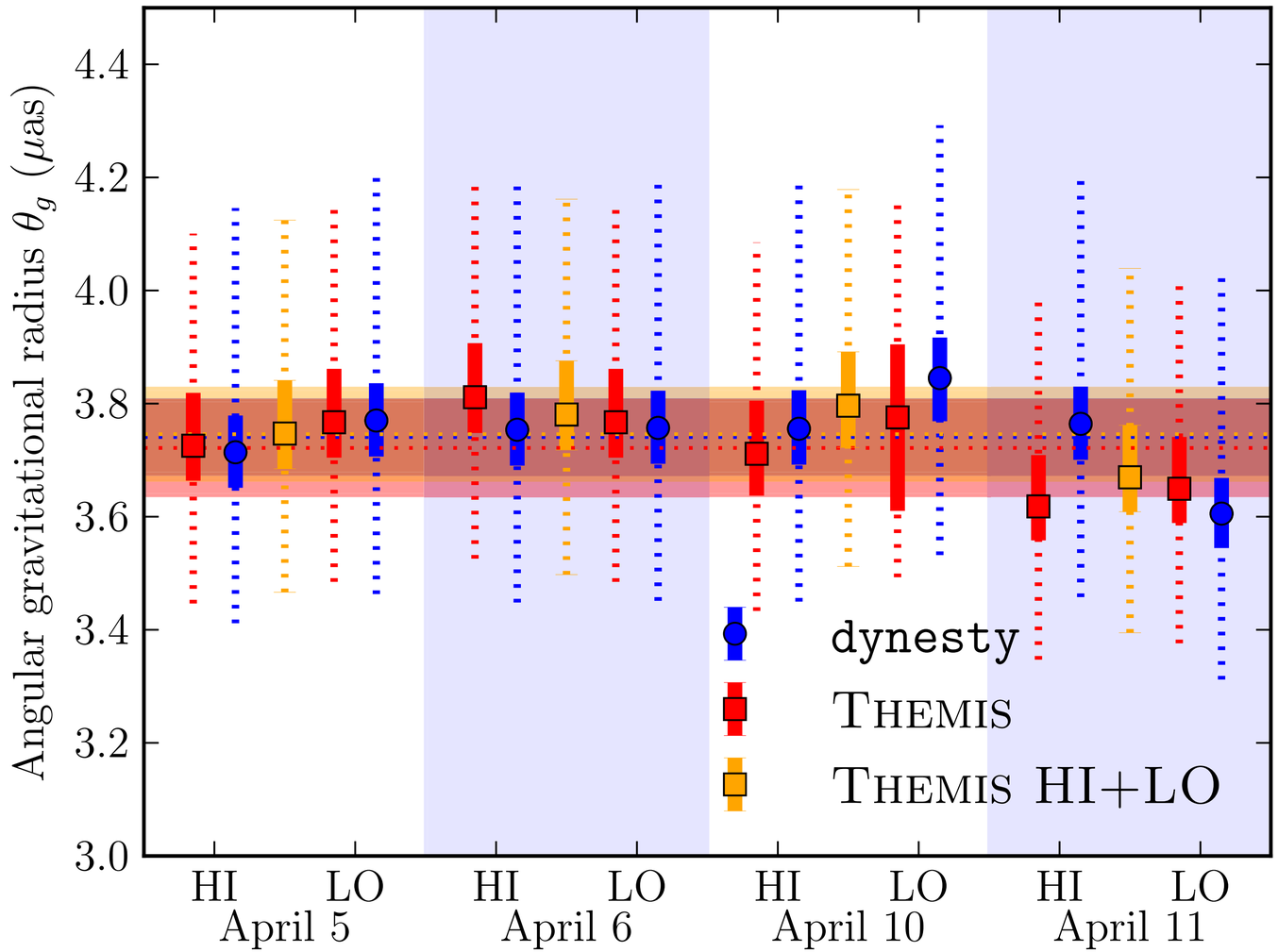
Event Horizon Telescope

EHT Collaboration (2019), Paper IV

Visibility-based fitting results

uncorrelated noise

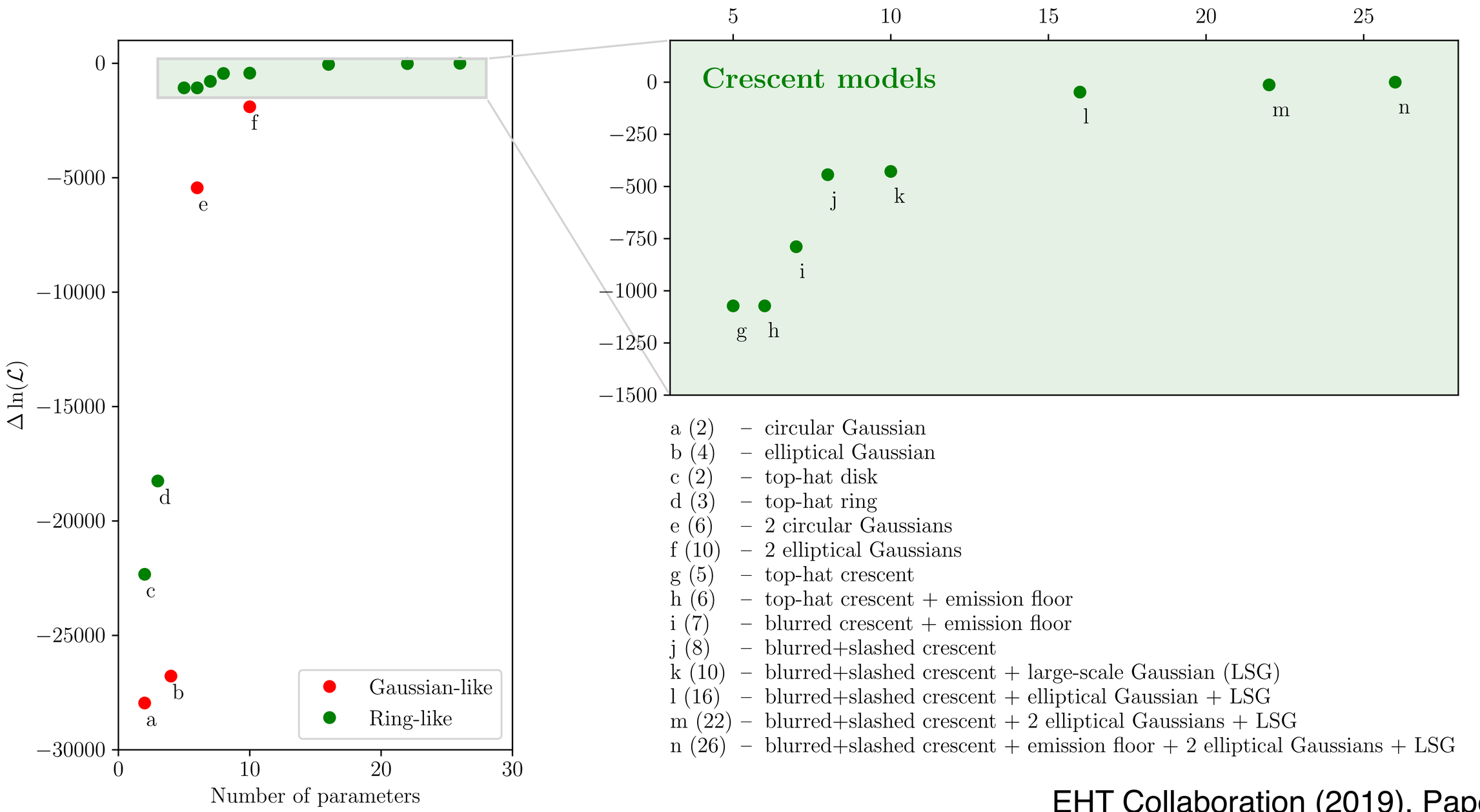
Consistency across parameter estimation algorithms, frequency bands, observing days



Event Horizon Telescope

EHT Collaboration (2019), Paper VI

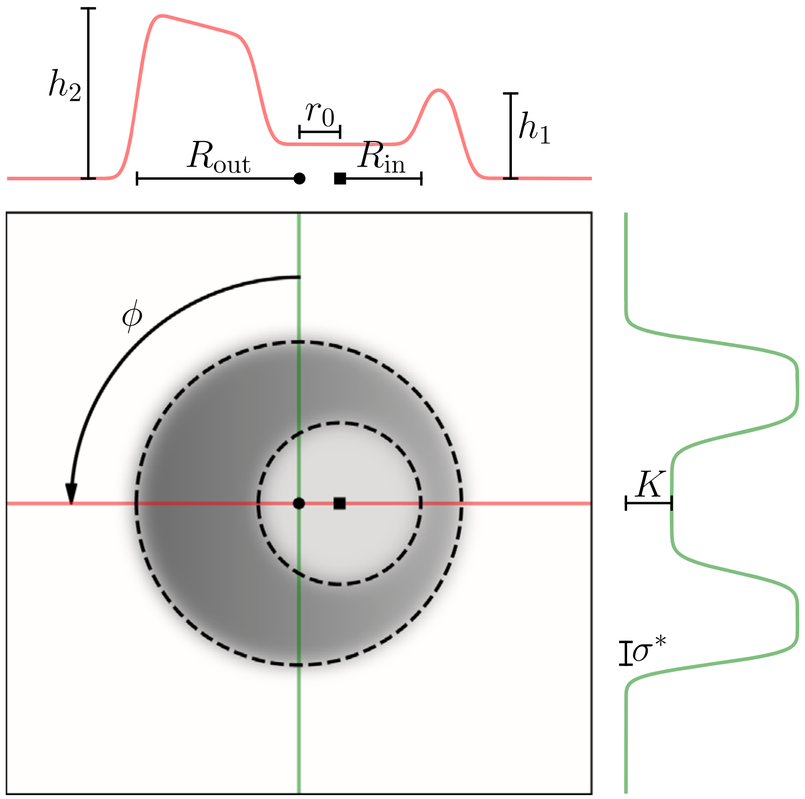
Model Comparison: which is most consistent with the data?



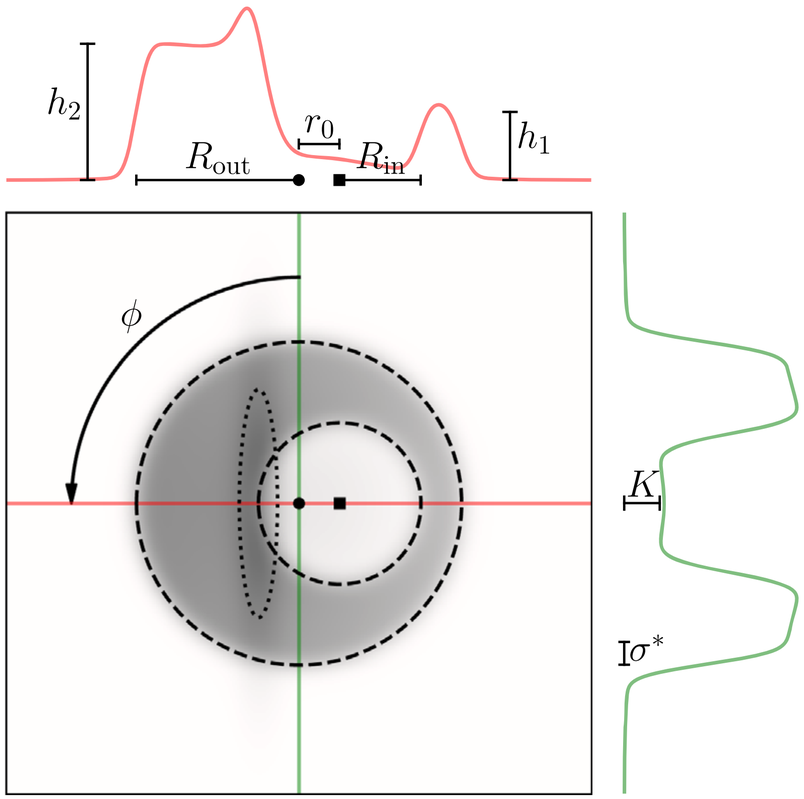
a (2) – circular Gaussian
b (4) – elliptical Gaussian
c (2) – top-hat disk
d (3) – top-hat ring
e (6) – 2 circular Gaussians
f (10) – 2 elliptical Gaussians
g (5) – top-hat crescent
h (6) – top-hat crescent + emission floor
i (7) – blurred crescent + emission floor
j (8) – blurred+slashed crescent
k (10) – blurred+slashed crescent + large-scale Gaussian (LSG)
l (16) – blurred+slashed crescent + elliptical Gaussian + LSG
m (22) – blurred+slashed crescent + 2 elliptical Gaussians + LSG
n (26) – blurred+slashed crescent + emission floor + 2 elliptical Gaussians + LSG

EHT Collaboration (2019), Paper VI

Two primary geometric models used



xs-ring

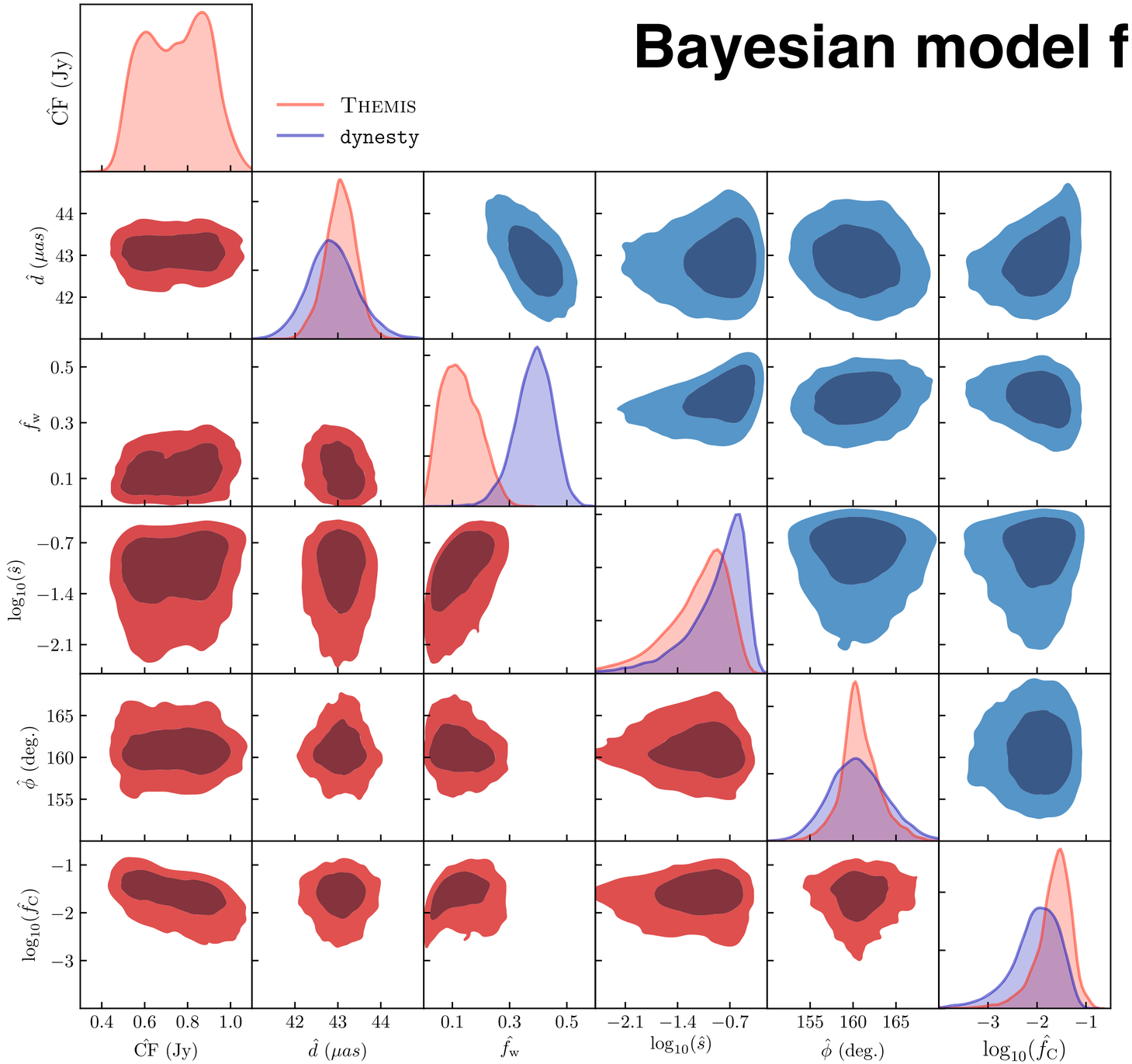


xs-ringauss

Event Horizon Telescope

EHT Collaboration (2019), Paper VI

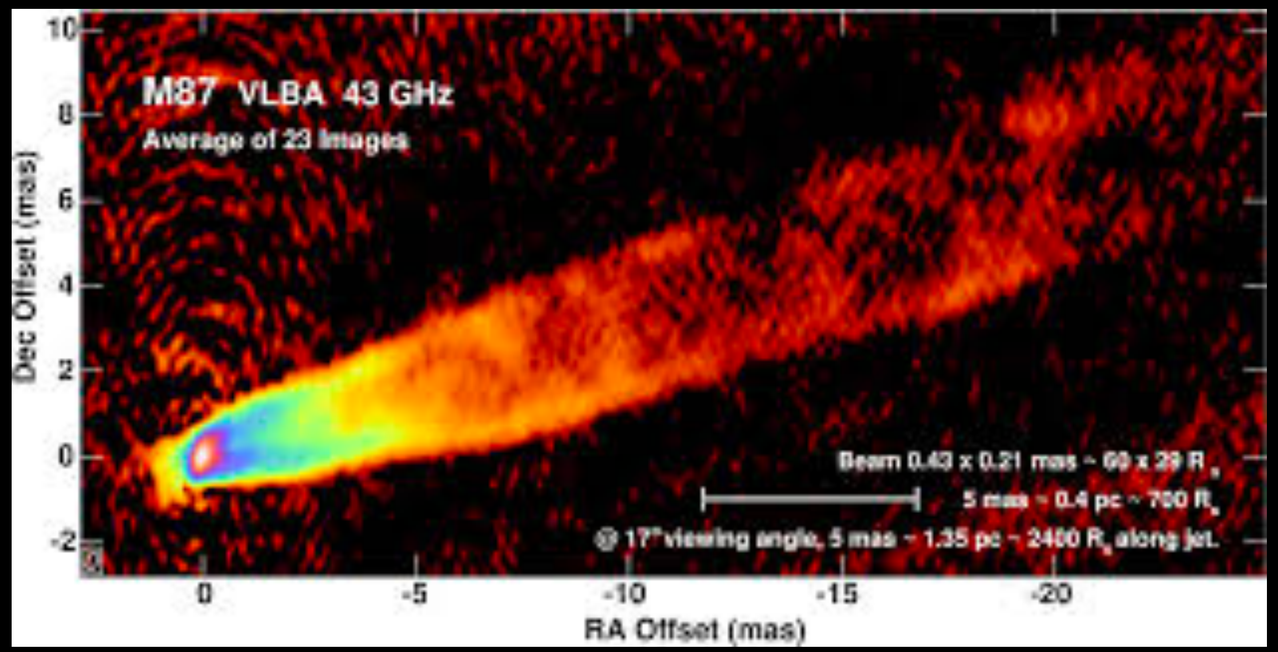
Bayesian model fitting and comparison



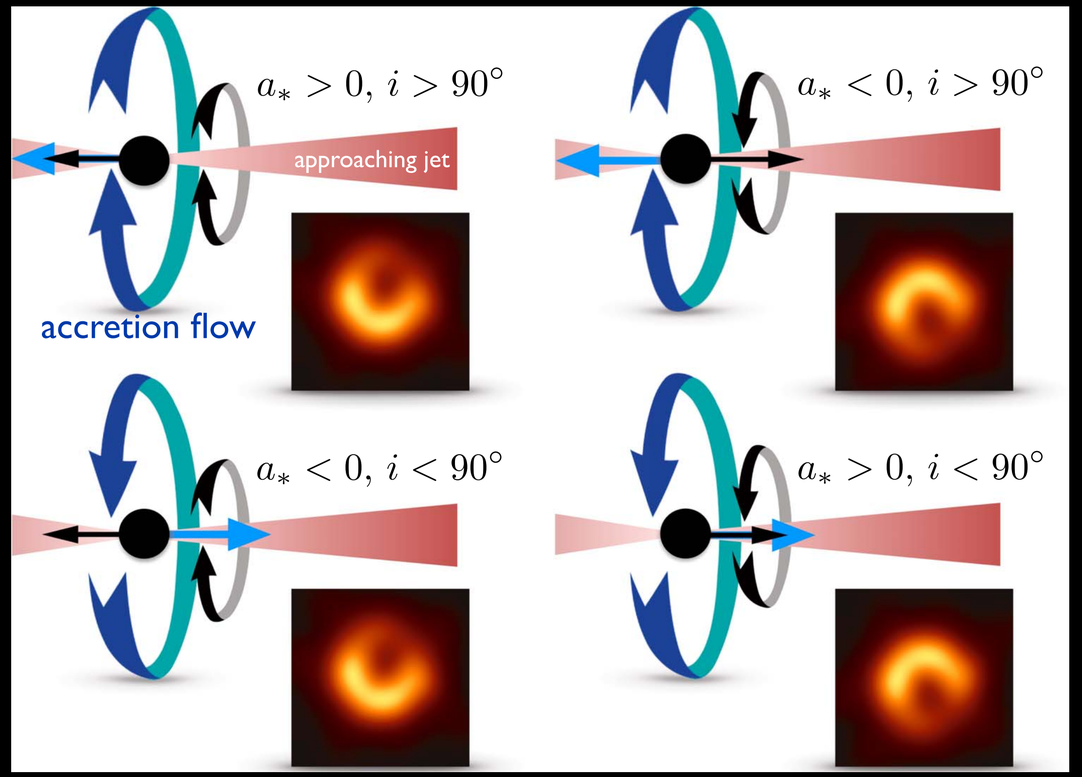
EHT Collaboration (2019), Paper VI

M87 consistency with other observations

Inferred spin vector consistent with jet axis and ionised gas rotation



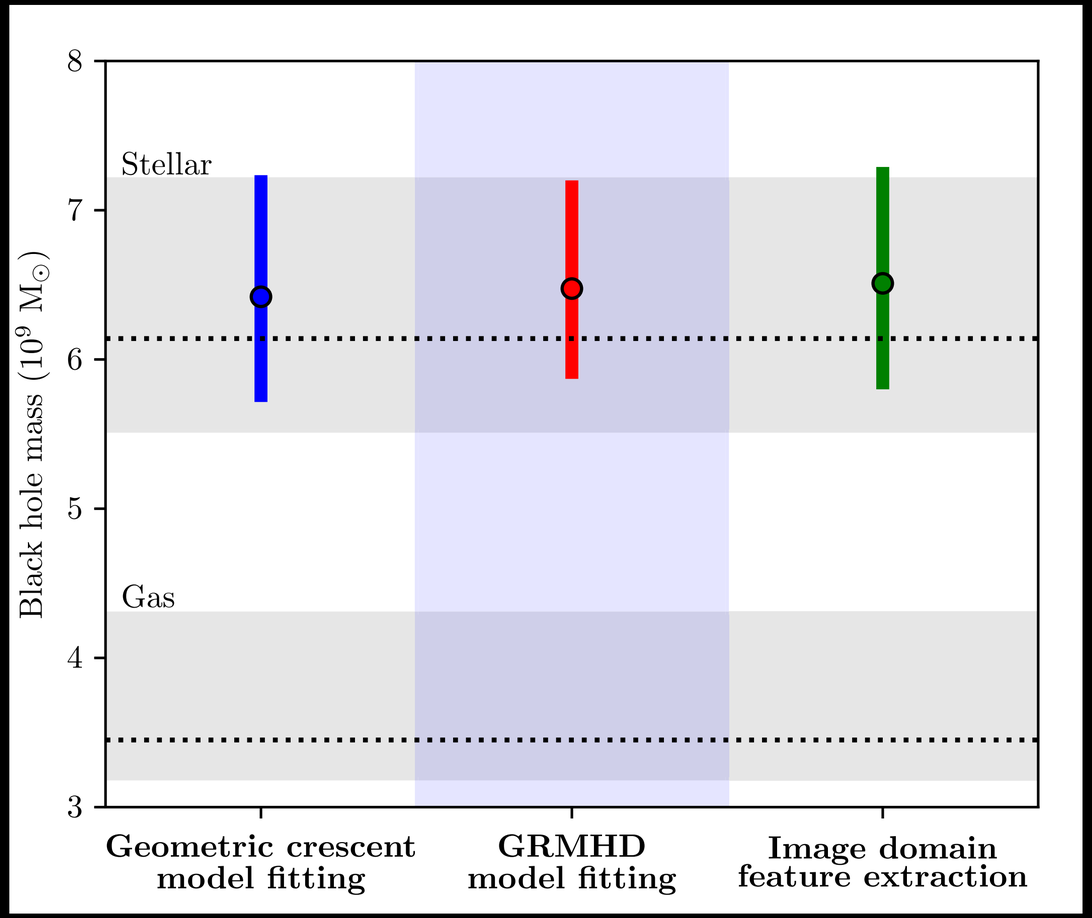
Walker et al. (2008)



EHT Collaboration (2019), Paper V

Consistency with black hole mass estimates

- Factor of ~2 discrepancy between M87 black hole mass estimates based on stellar velocity dispersion and gas dynamics
- Black hole shadow consistent with the larger mass suggested by stellar kinematics
- Assumes 230 GHz emission is not well beyond the shadow radius
- All three methods of black hole mass estimation with EHT data (images and visibility data) are consistent



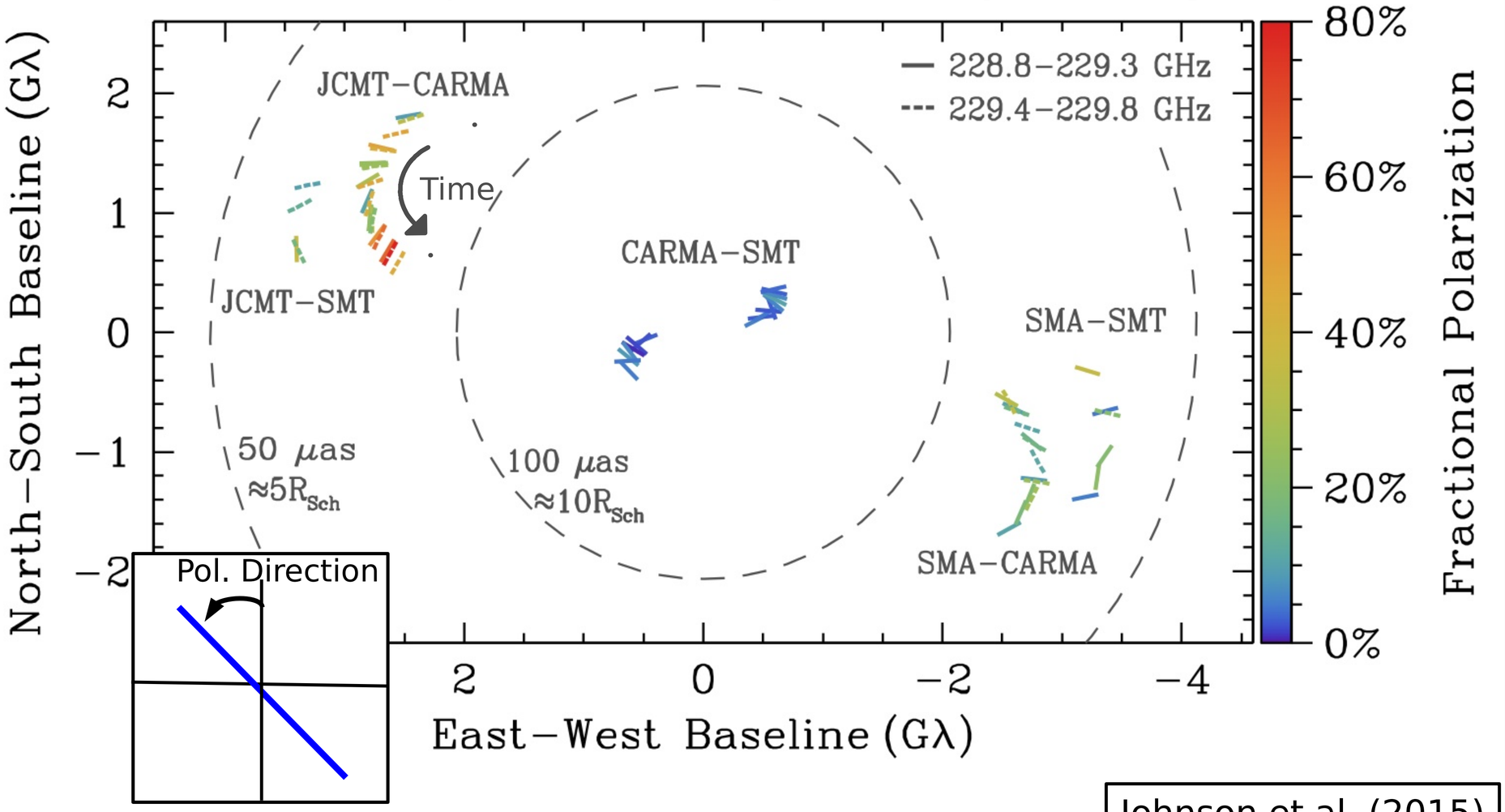
EHT Collaboration (2019), Paper VI

What's next for the EHT?

- **Repeat experiment** to test if ring stable on ~1 year timescales
- Make an ~~image~~ **movie** of Sgr A*
- **Polarimetry** to probe magnetic field structure
- “non-Horizon” science targets (e.g. 3C279 recently published)
- Telescope **array expansion**

Resolving Sgr A* with the EHT

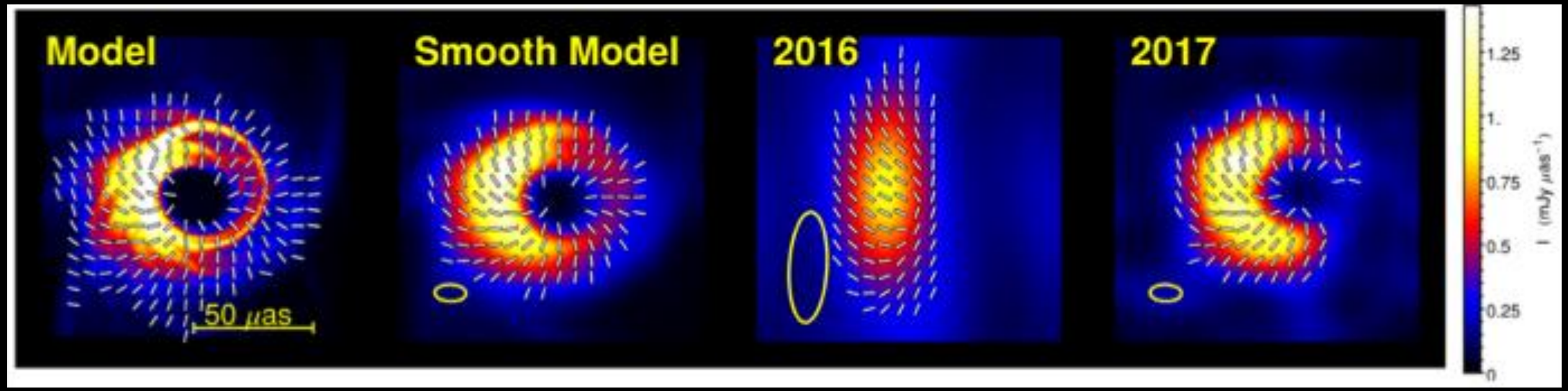
First polarimetric VLBI at 230 GHz
First resolved polarization of Sgr A* at <u>any</u> wavelength



Johnson et al. (2015)

Event Horizo

Imaging polarimetry of M87 (in progress)

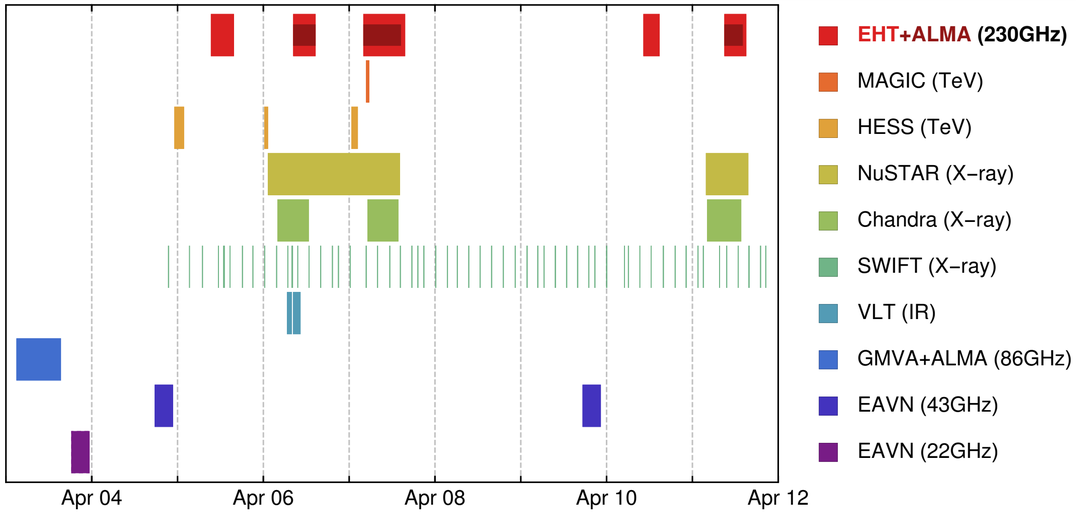


GRMHD simulations:
Jason Dexter

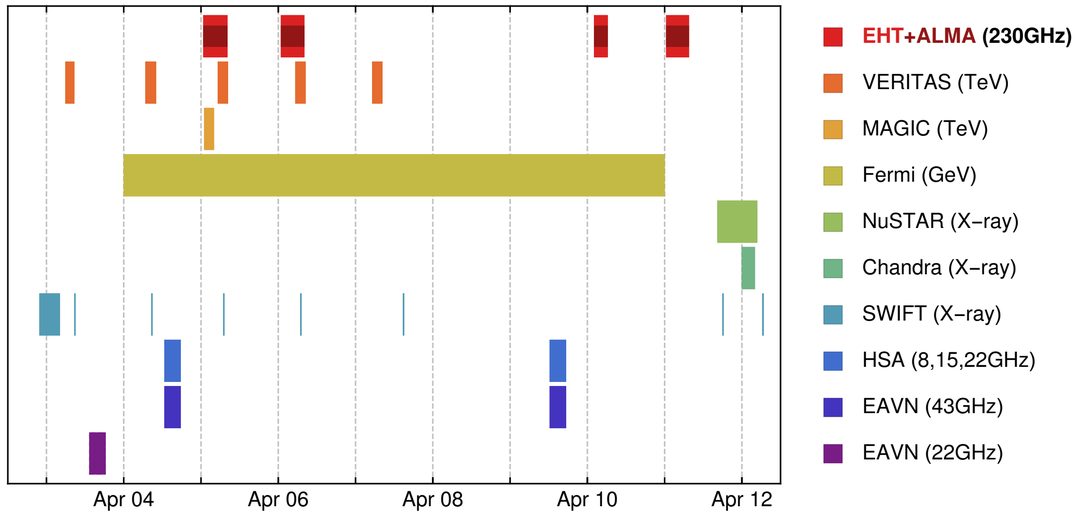
Imaging:
Chael+2016

Multi-wavelength coverage (April, 2017)

Sgr A*



M87



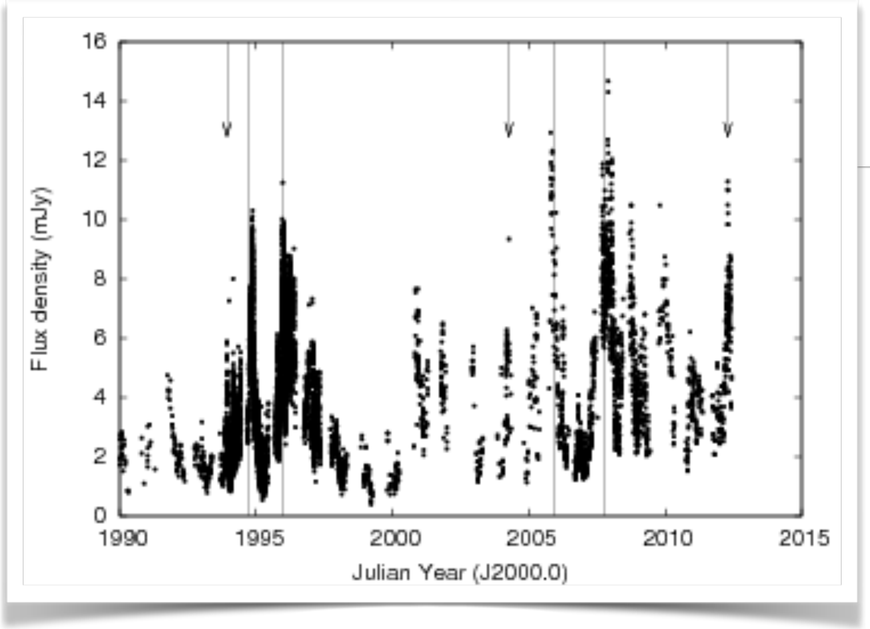
M. Johnson/SAO

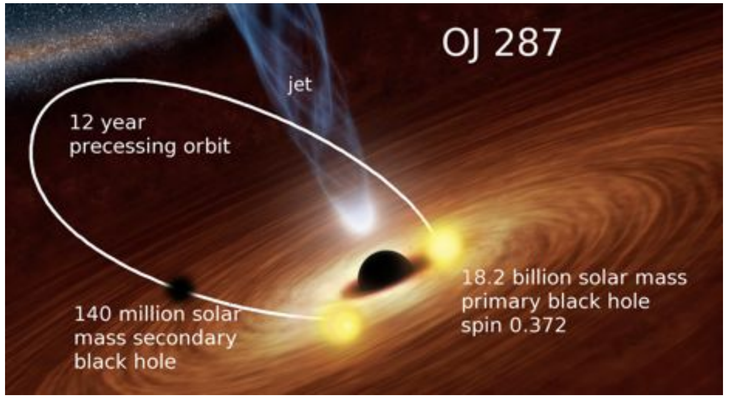
OJ 287 - binary SMBH candidate

OJ287

PI: J.L. Gomez

OJ287 is one of the best candidates for hosting a supermassive binary black hole system (i.e., Valtonen+2016) in an eccentric (ε=0.7) orbit with a major axis of 0.1 pc (~26 μas), which could be spatially resolved by the EHT.





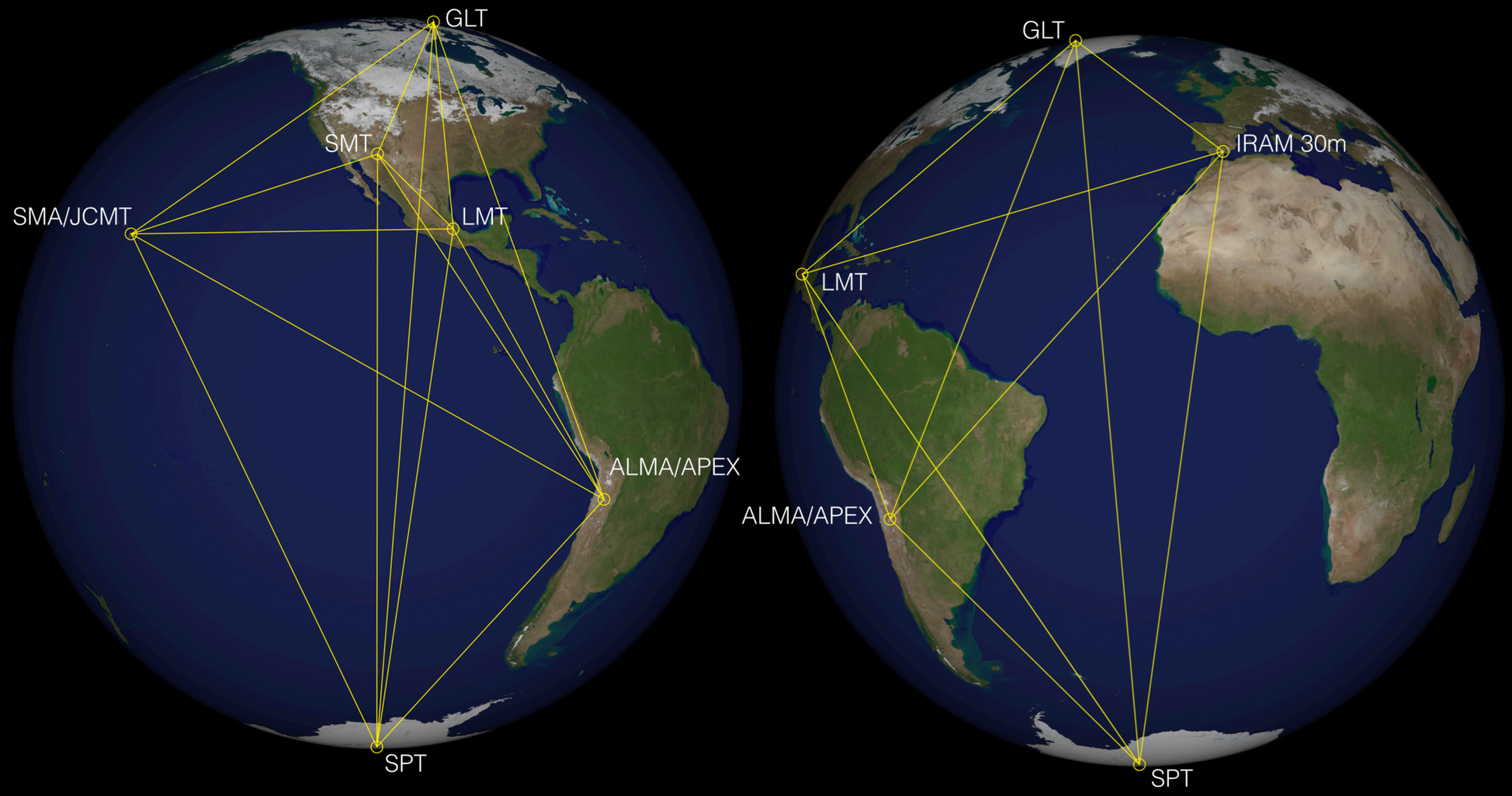
Science goals:

- Confirmation of binary BH system
- Determine magnetic field 3D structure to test jet formation models
- Study collimation profile
- Probe accretion flow

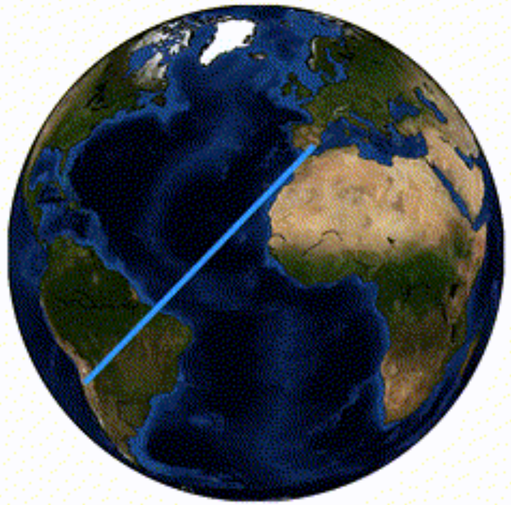
Slide courtesy: T. Krichbaum for non-Horizon/AGN WG

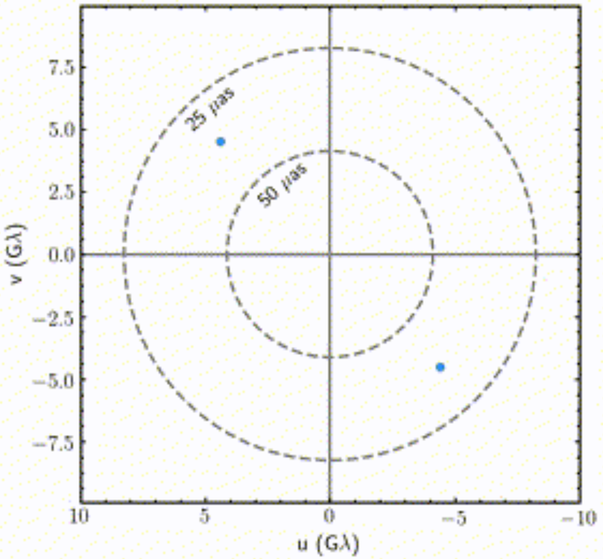
EHT array expansion

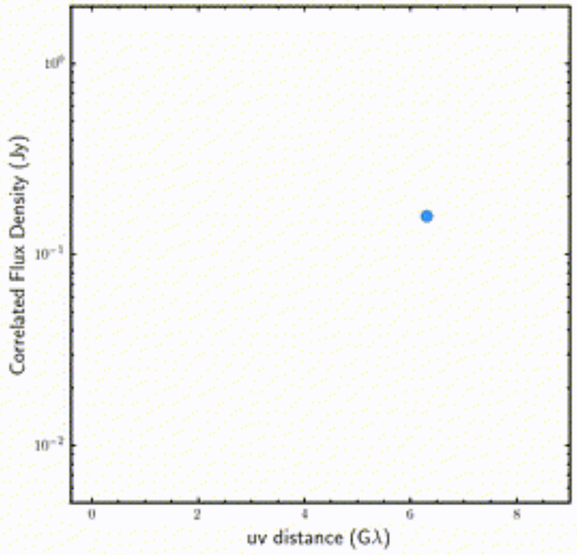
The case for expanding the EHT into Africa

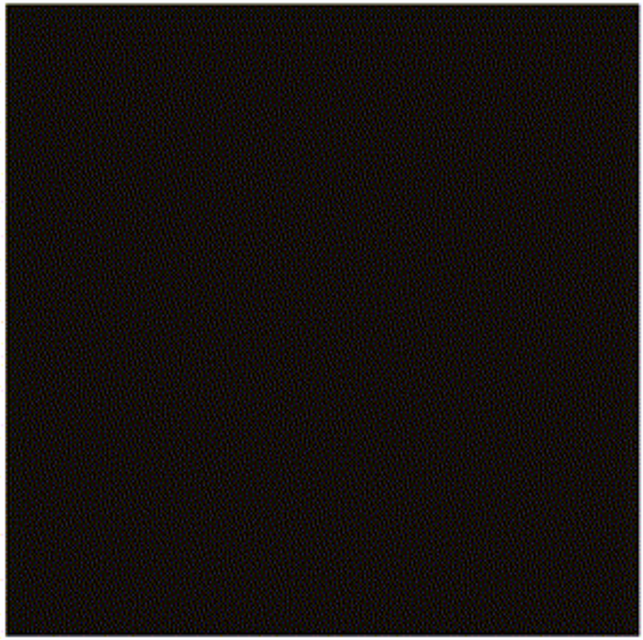


Lo-band eht-imaging on April 11: slowly building up data



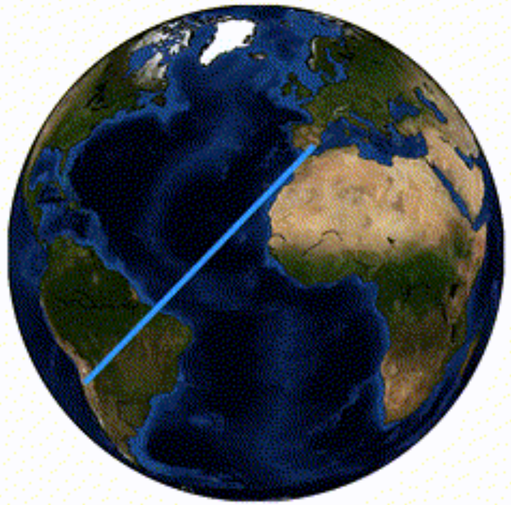


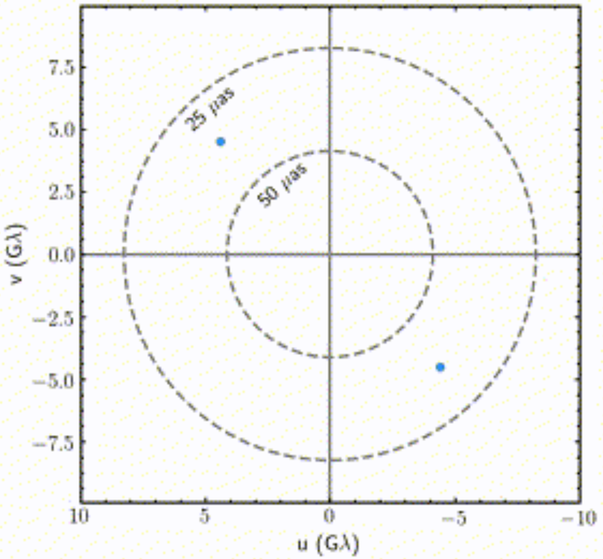


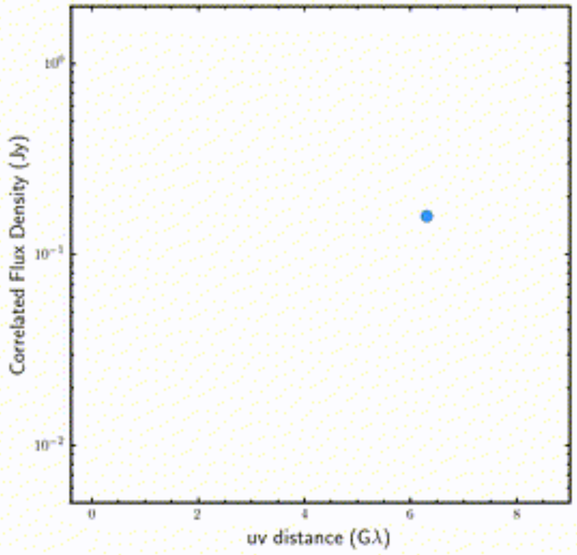


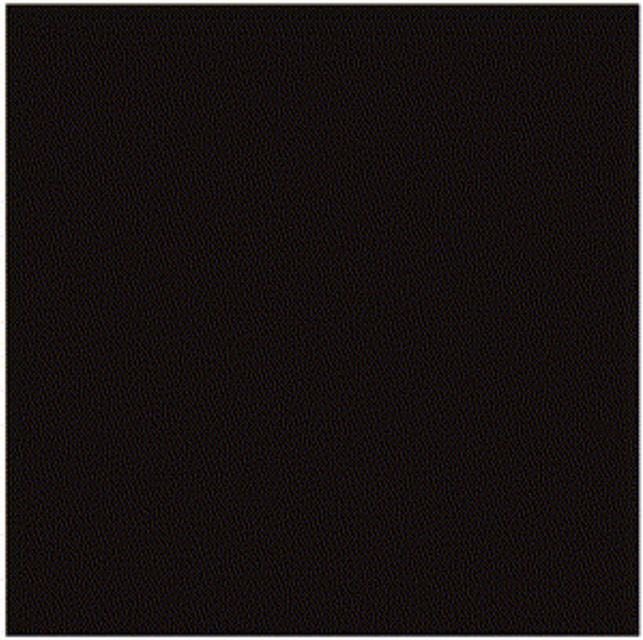
Event Horizon Telescope

Lo-band eht-imaging on April 11: slowly building up data









Event Horizon Telescope

Co-led by Radboud and University of Namibia

Radboud University

Faculty of Science

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Africa Millimetre Telescope

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- Imaging a black hole
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  - The AMT and African science
  - Science with the AMT
- Supporting the AMT
- The scientific team
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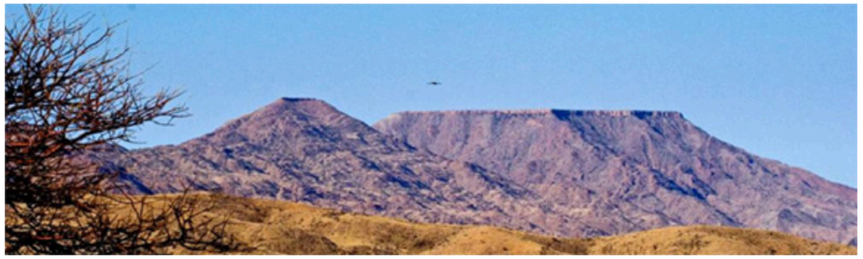
Construction



The AMT is designed as a 15-meter single-dish telescope that will operate at millimeter/submillimeter radio wavelengths. Observations in this regime require a high altitude and extremely dry atmospheric conditions. It would be built in the GamsbergMountain in Namibia.

Leading Scientist

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Department of Astrophysics

Research Institute for Mathematics, Astrophysics and Particle Physics
Radboud University Nijmegen

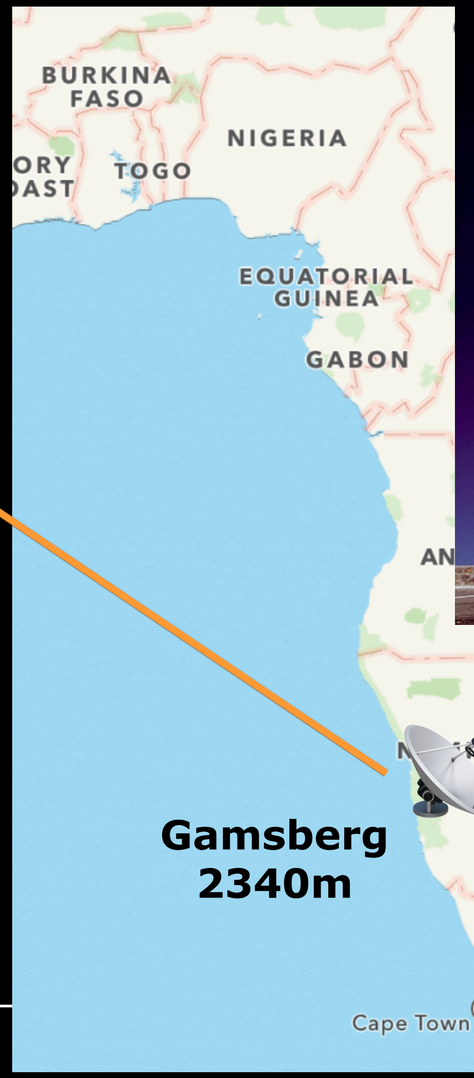
Heijendaalseweg 135

Prospective site for the African Millimetre Telescope

Proposed site for AMT project

Courtesy: Heino Falcke

Proposed site for AMT pro



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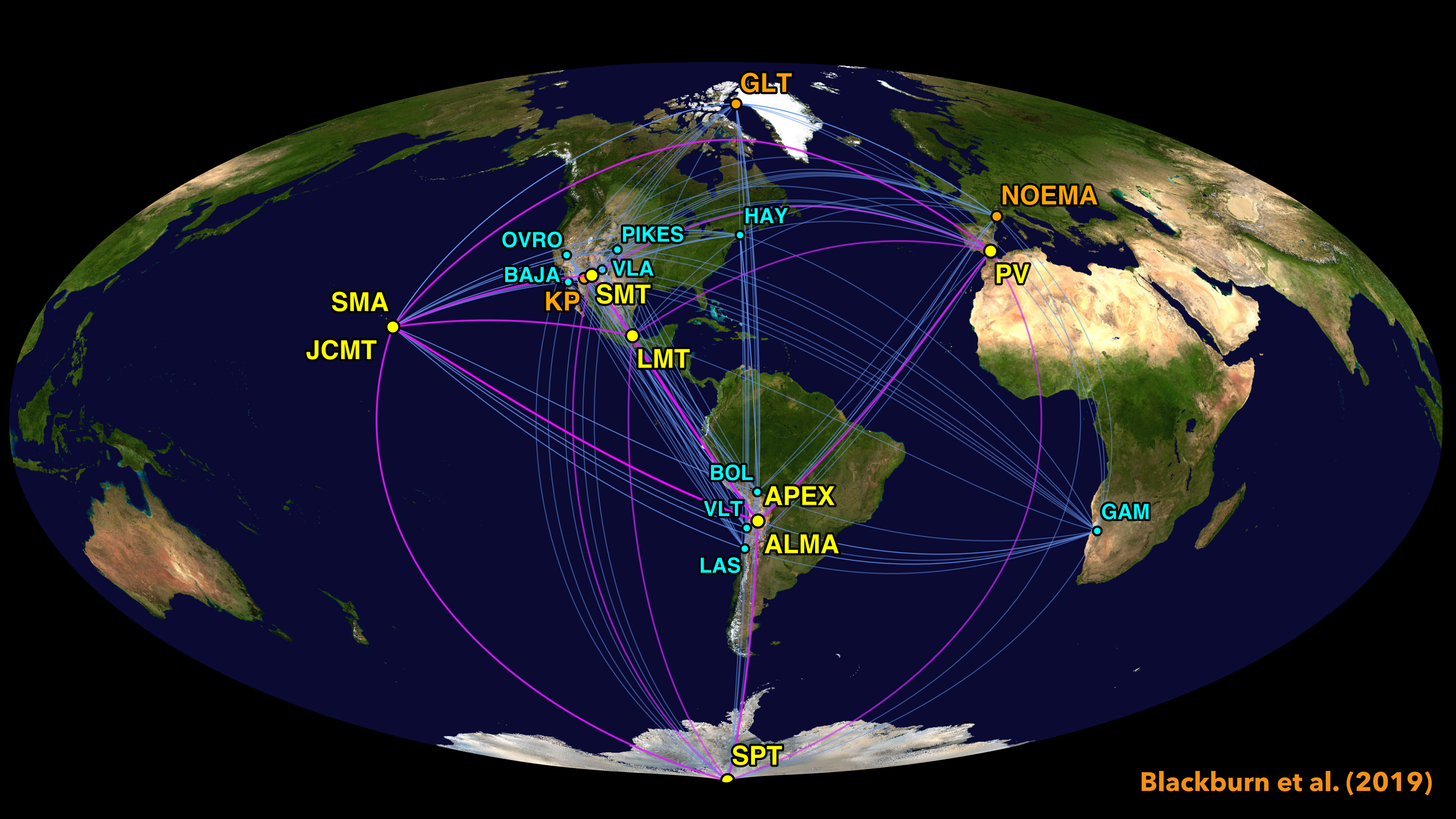
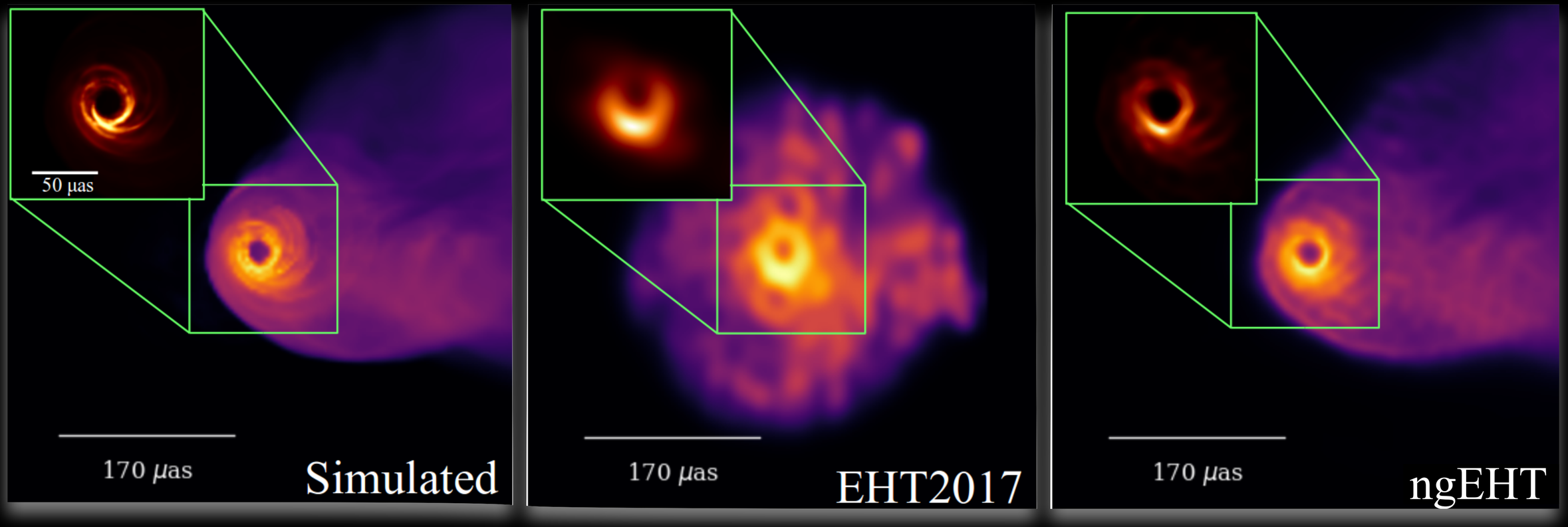


Blackburn et al. (2019)

Next-generation EHT

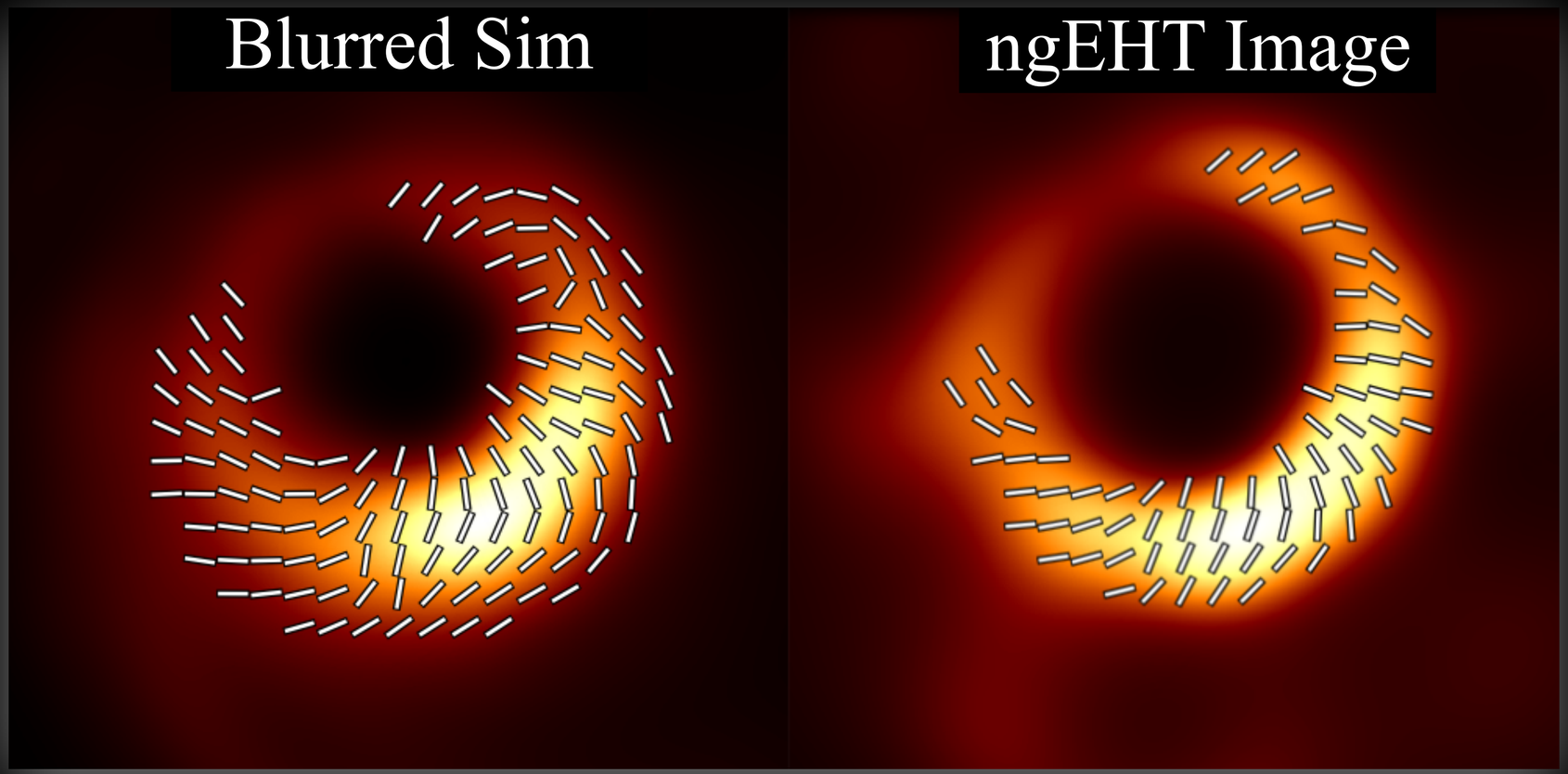
(as SKA-VLBI is to SKA, ngEHT is to ngVLA)



Blackburn et al. (2019)

Next-generation EHT

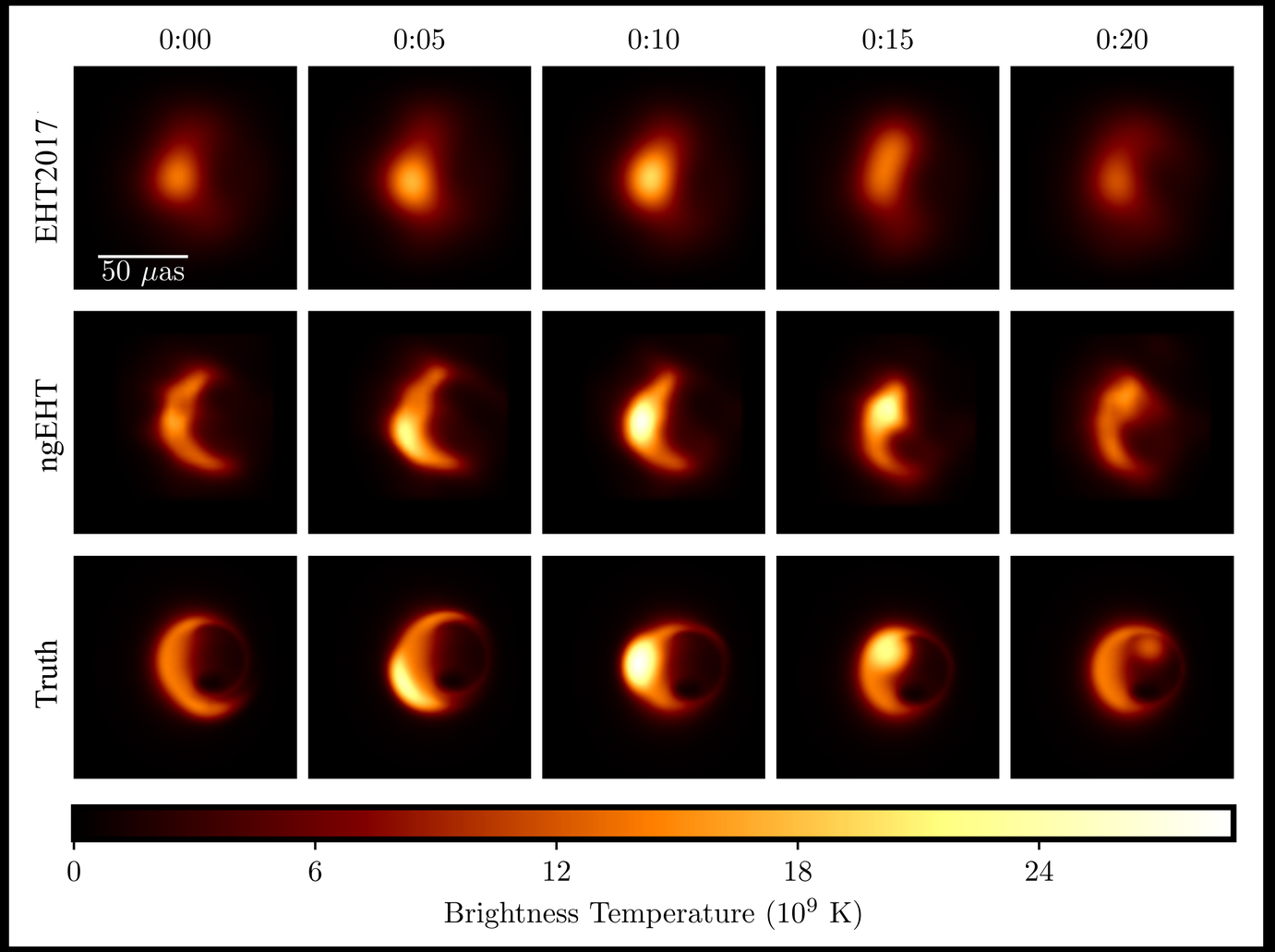
Polarimetric imaging capability



Blackburn et al. (2019)

Next-generation EHT

Imaging orbiting hotspots around Sgr A*



Blackburn et al. (2019)

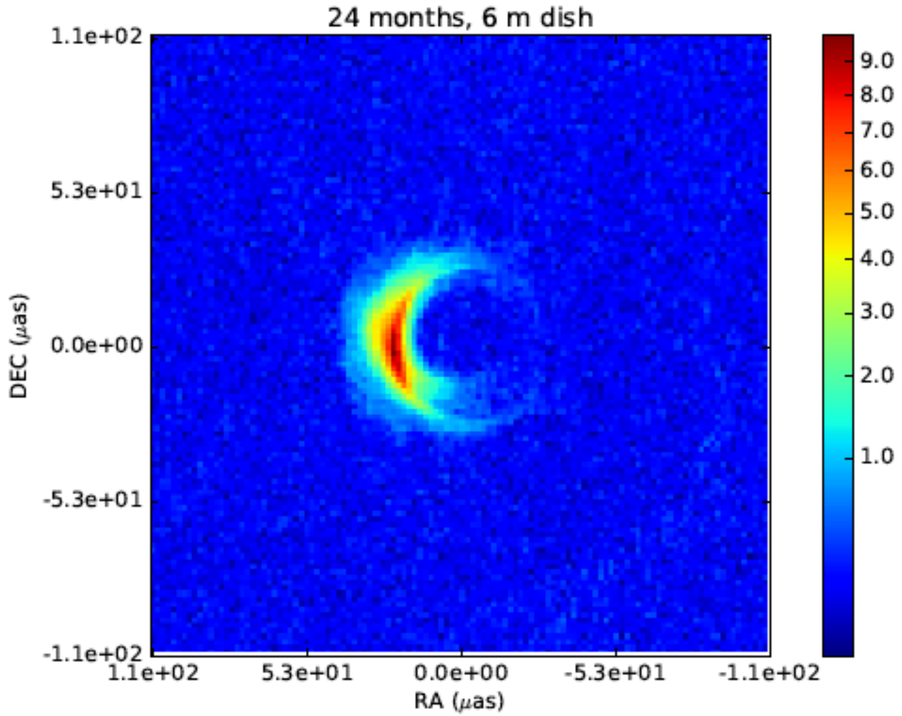
To space!

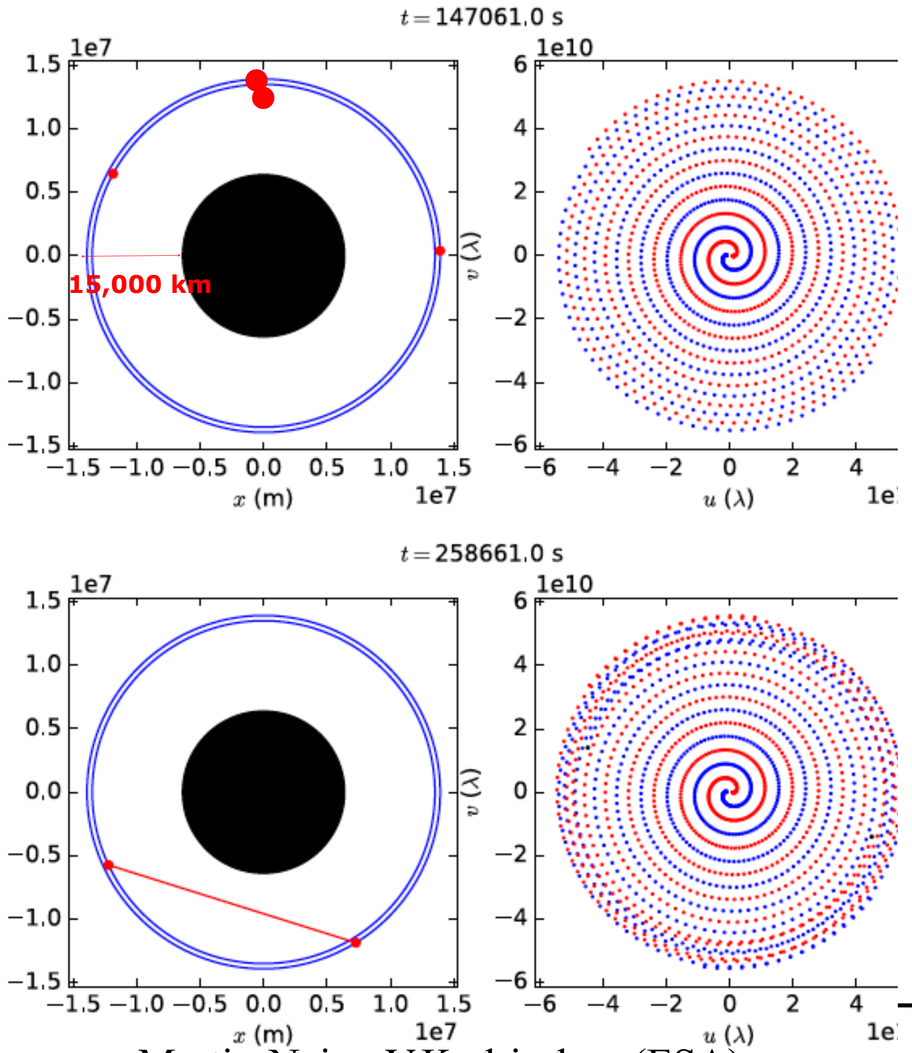
ESA-Radboud study:Event Horizon Imager (EHI)

Radboud University Nijmegen

Reconstructed Space-VLBI image

Includes variability due to scattering and source variations





Roelofs et al. (2019)

Event Horizon Telescope

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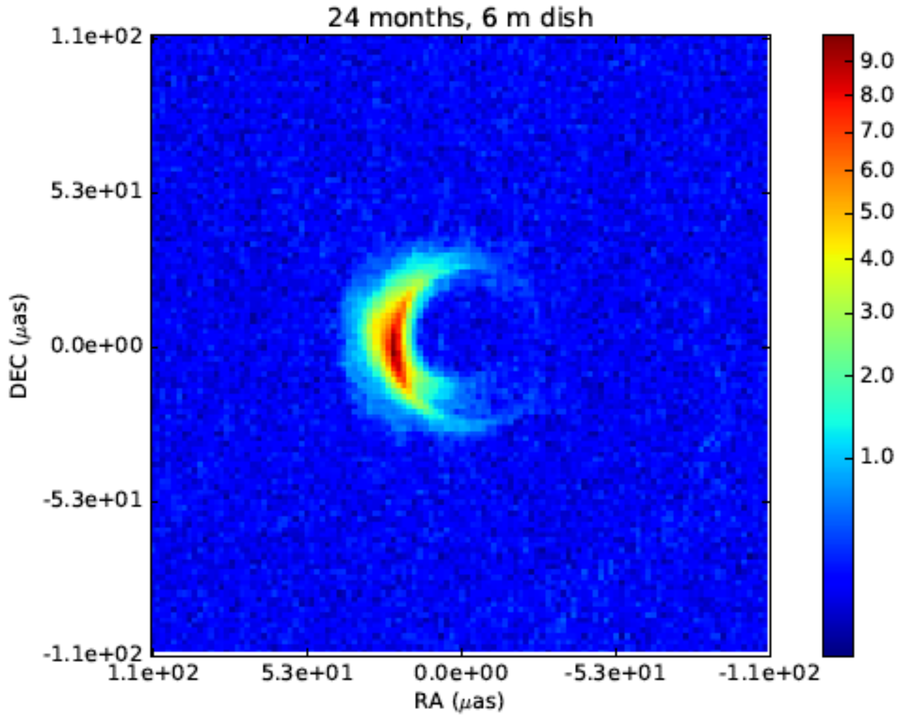

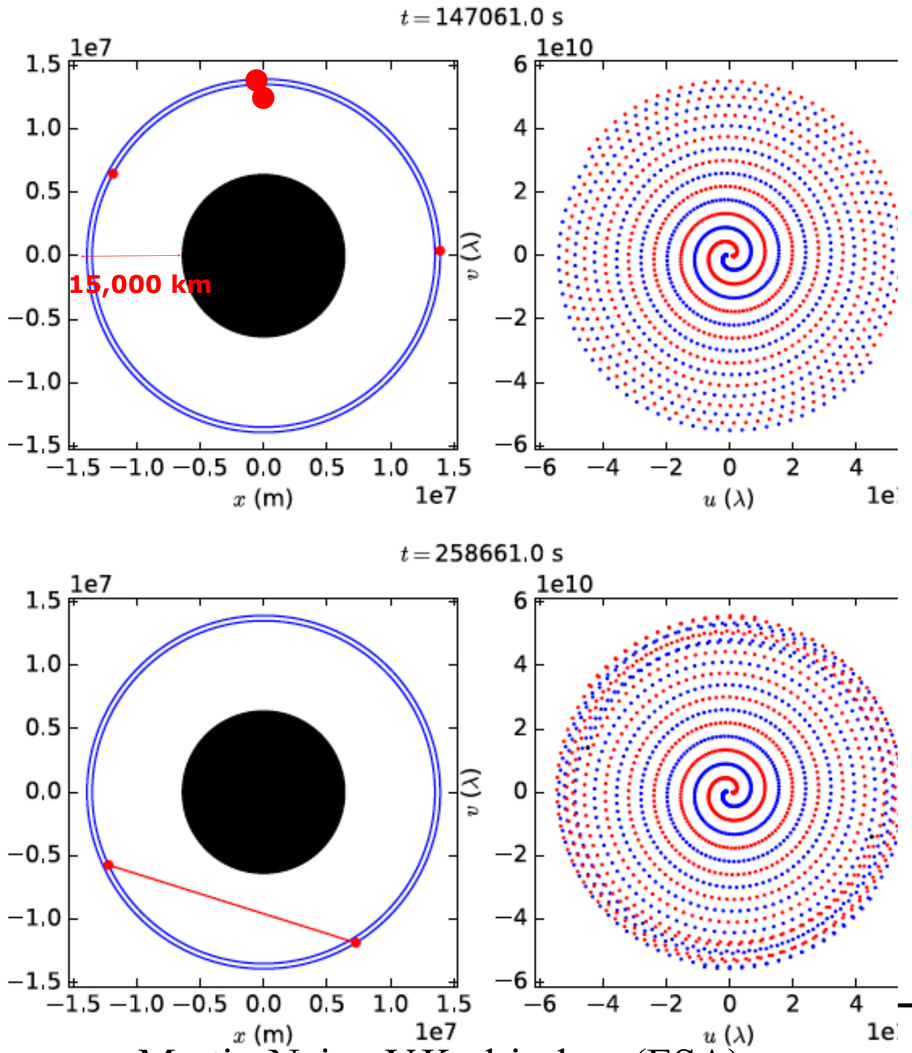

Roelofs et al. (2019)

Event Horizon Telescope

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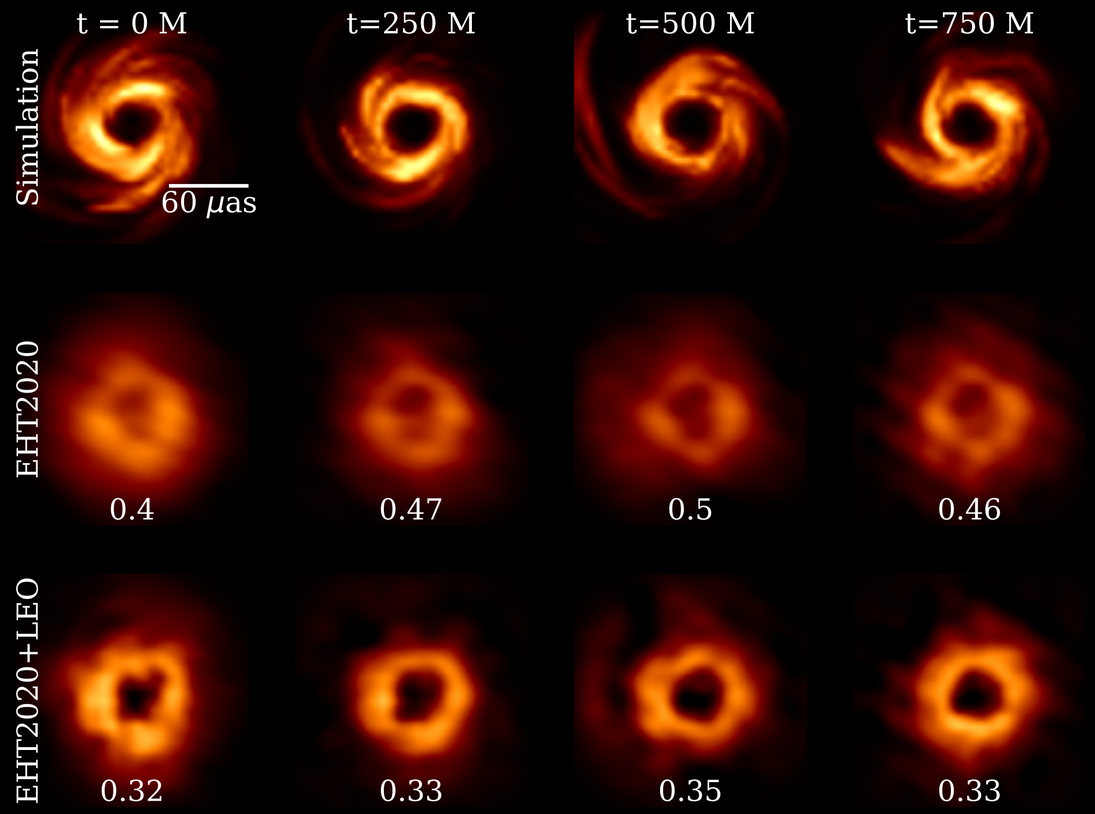
The enormous potential of mm-space VLBI



Event Horizon Telescope

Johnson et al. (2019, 2020)

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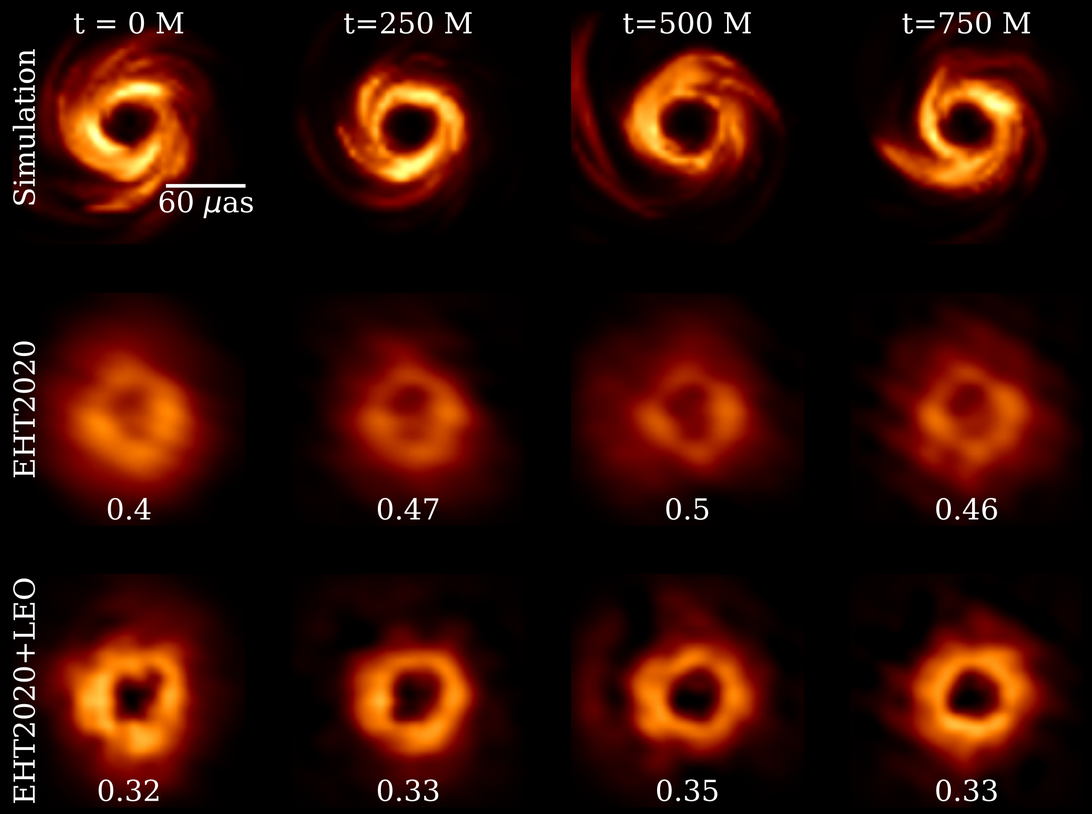

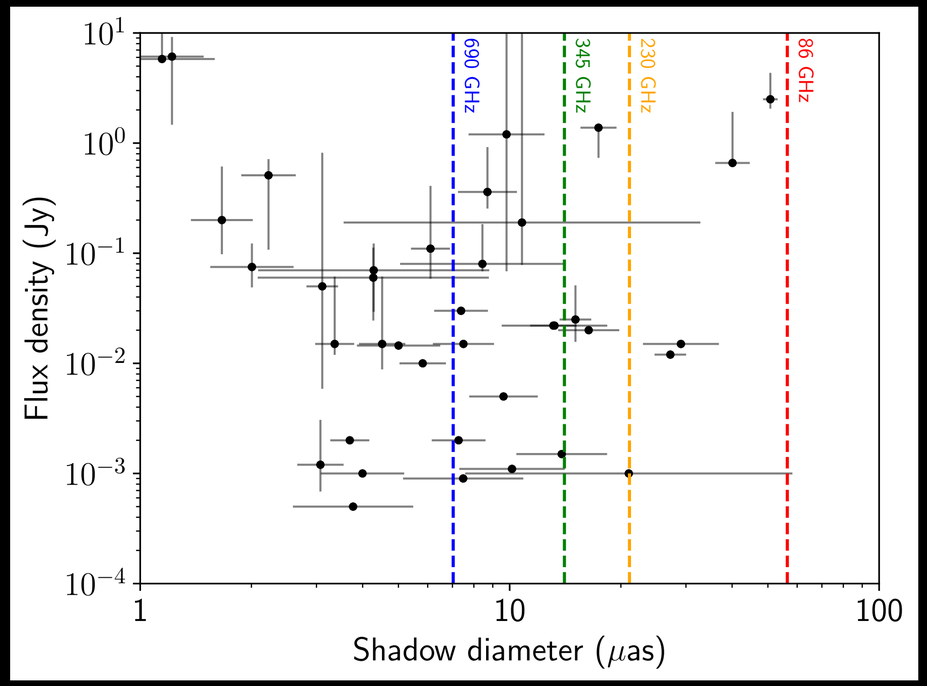

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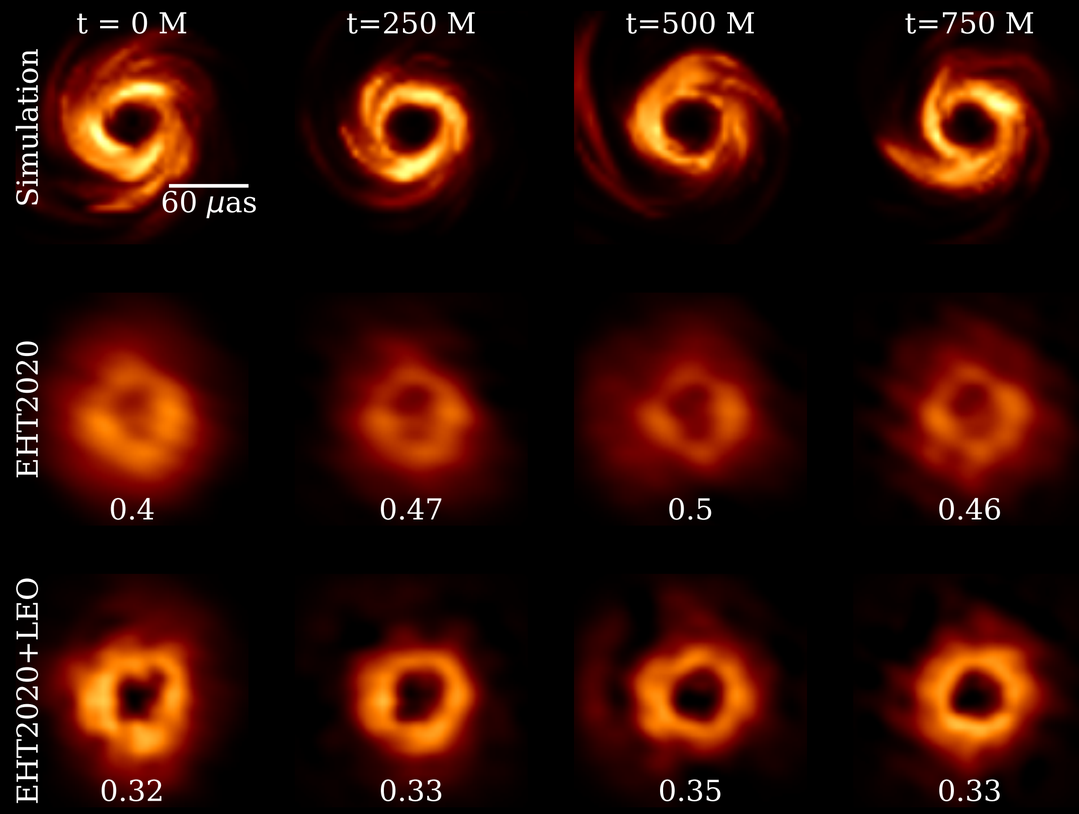
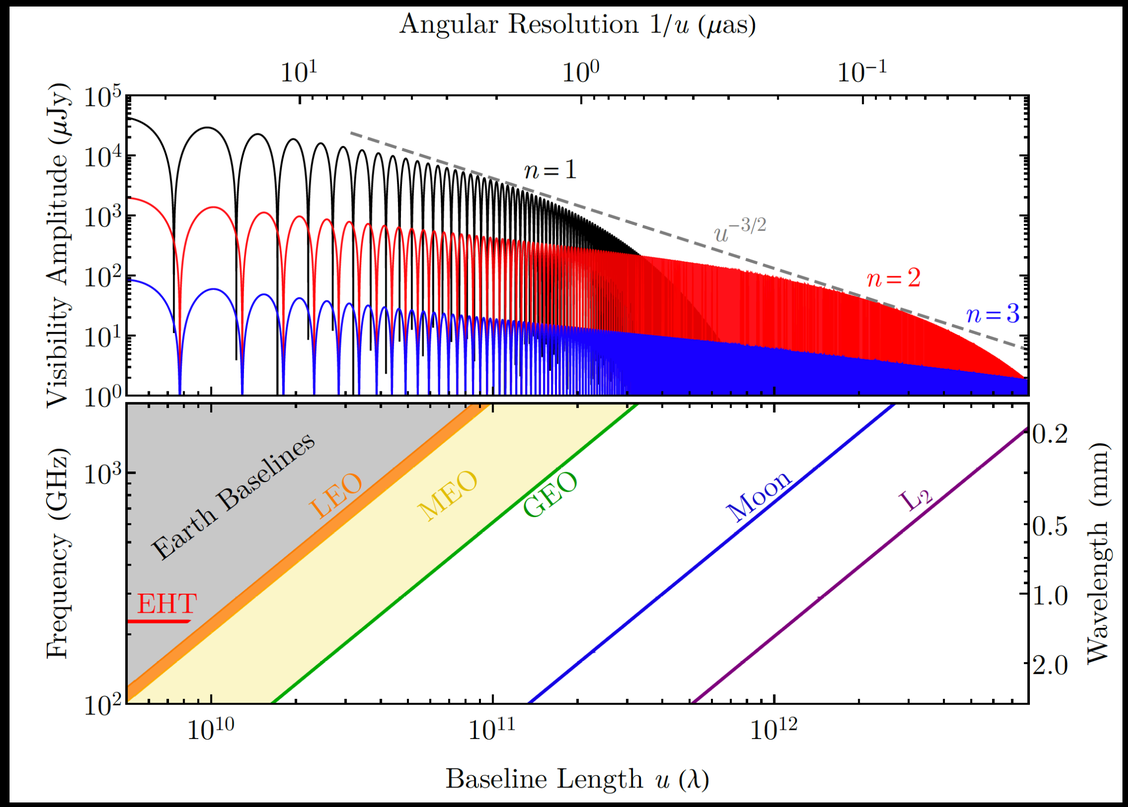
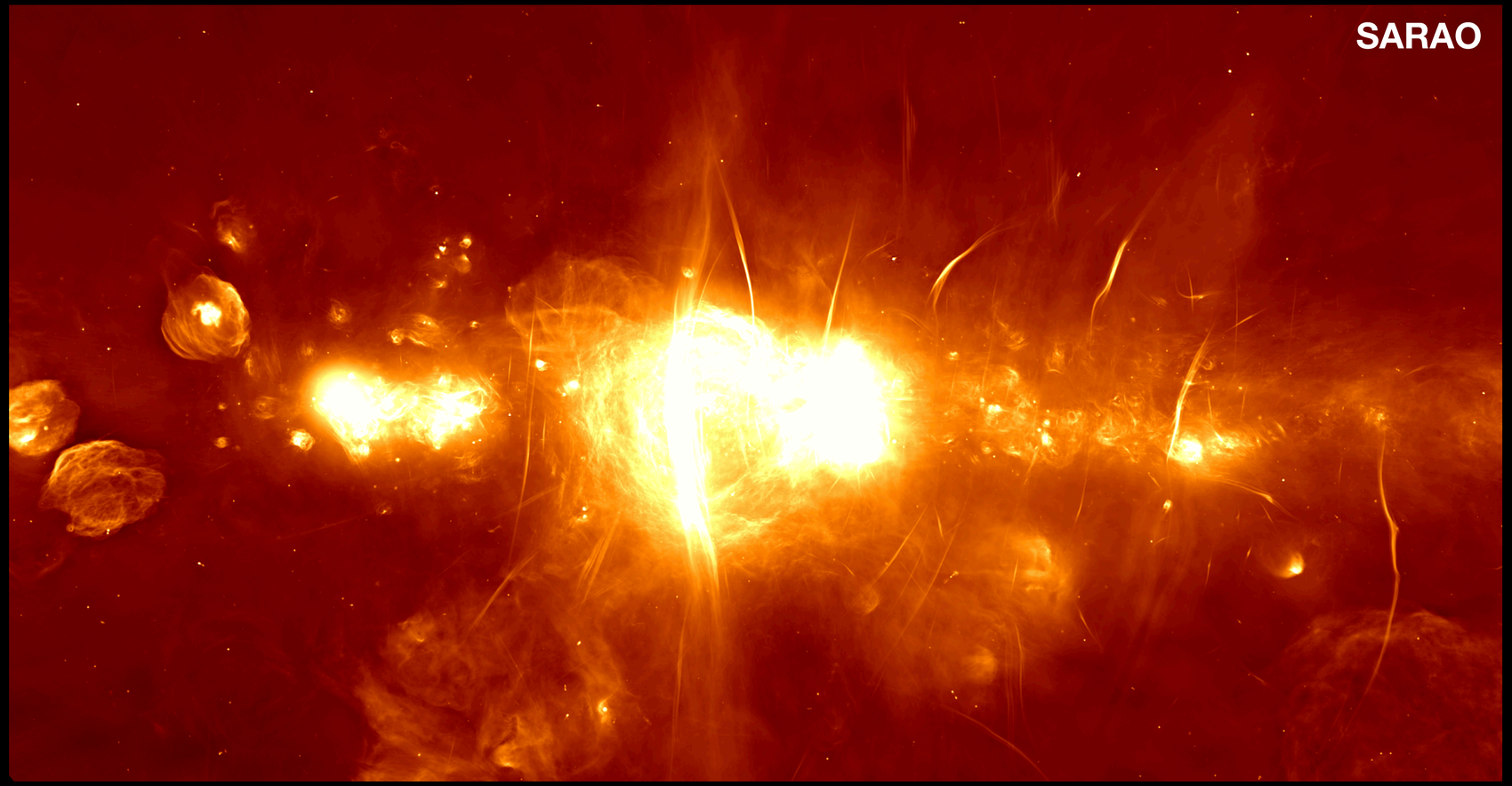
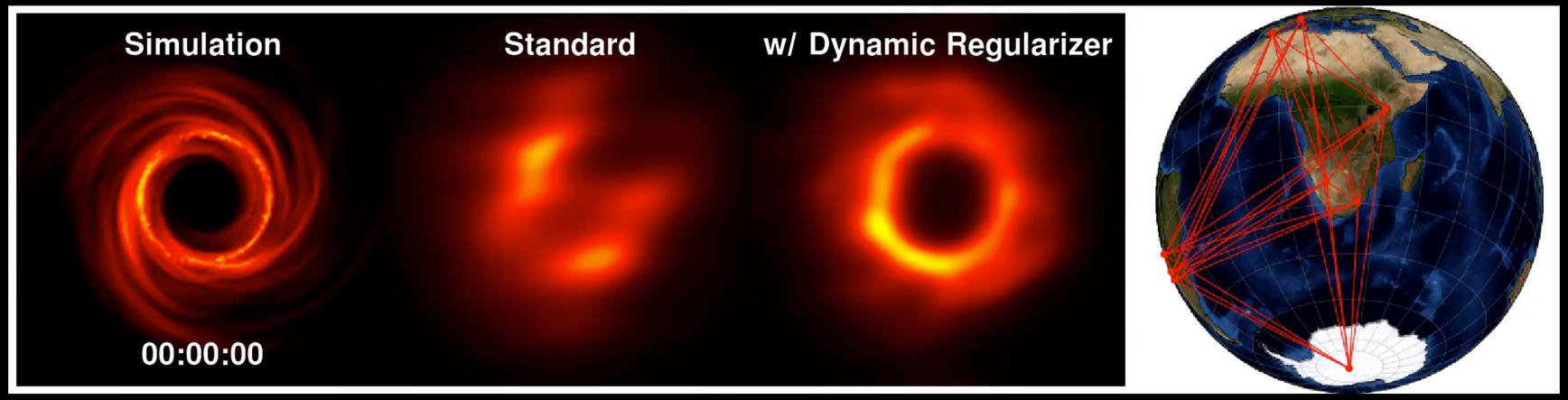




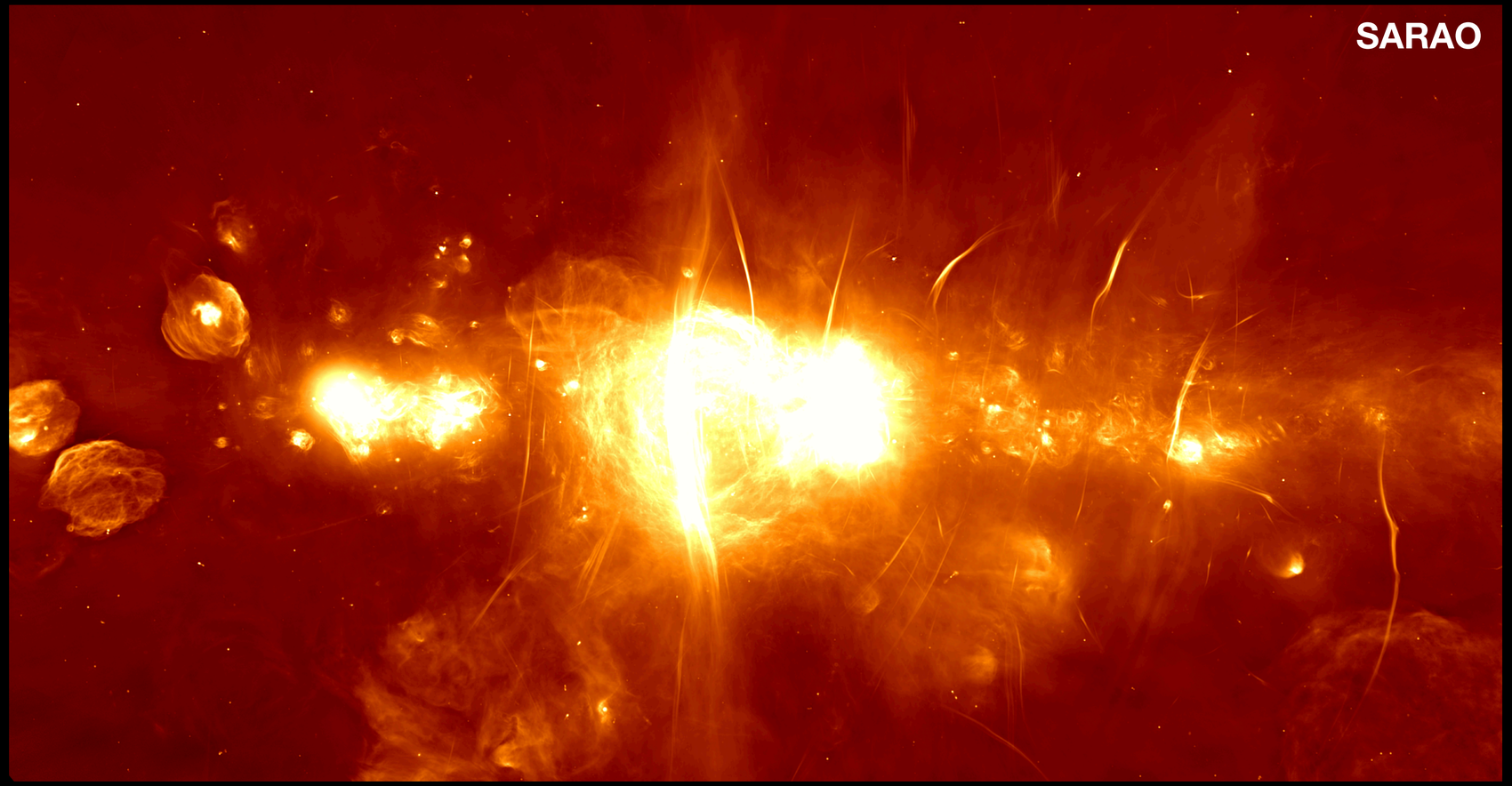
Event Horizon Telescope

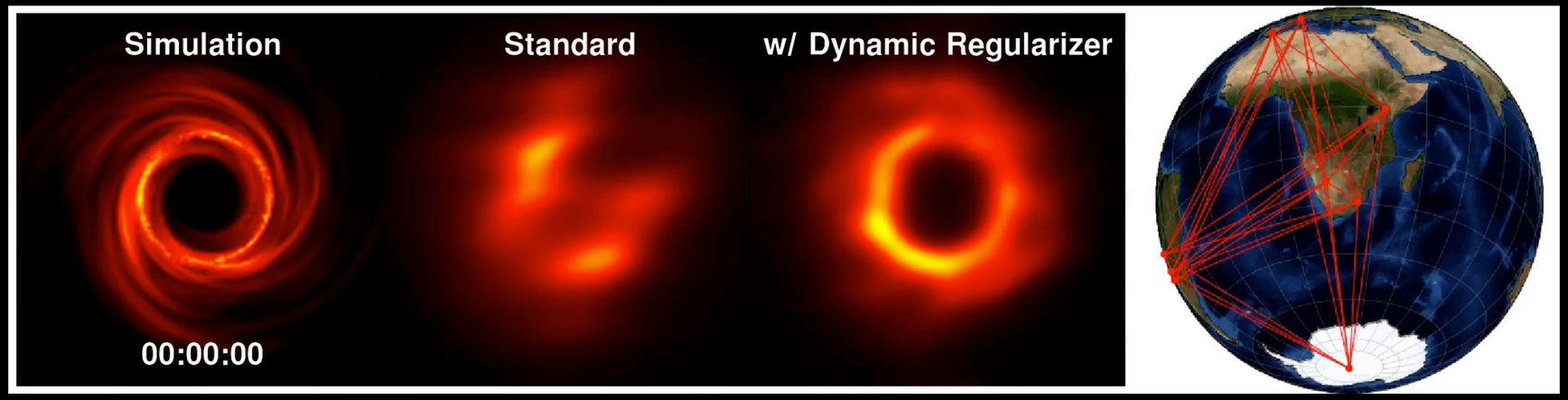
Johnson et al. (2019, 2020)





credit: Michael Johnson (Harvard)





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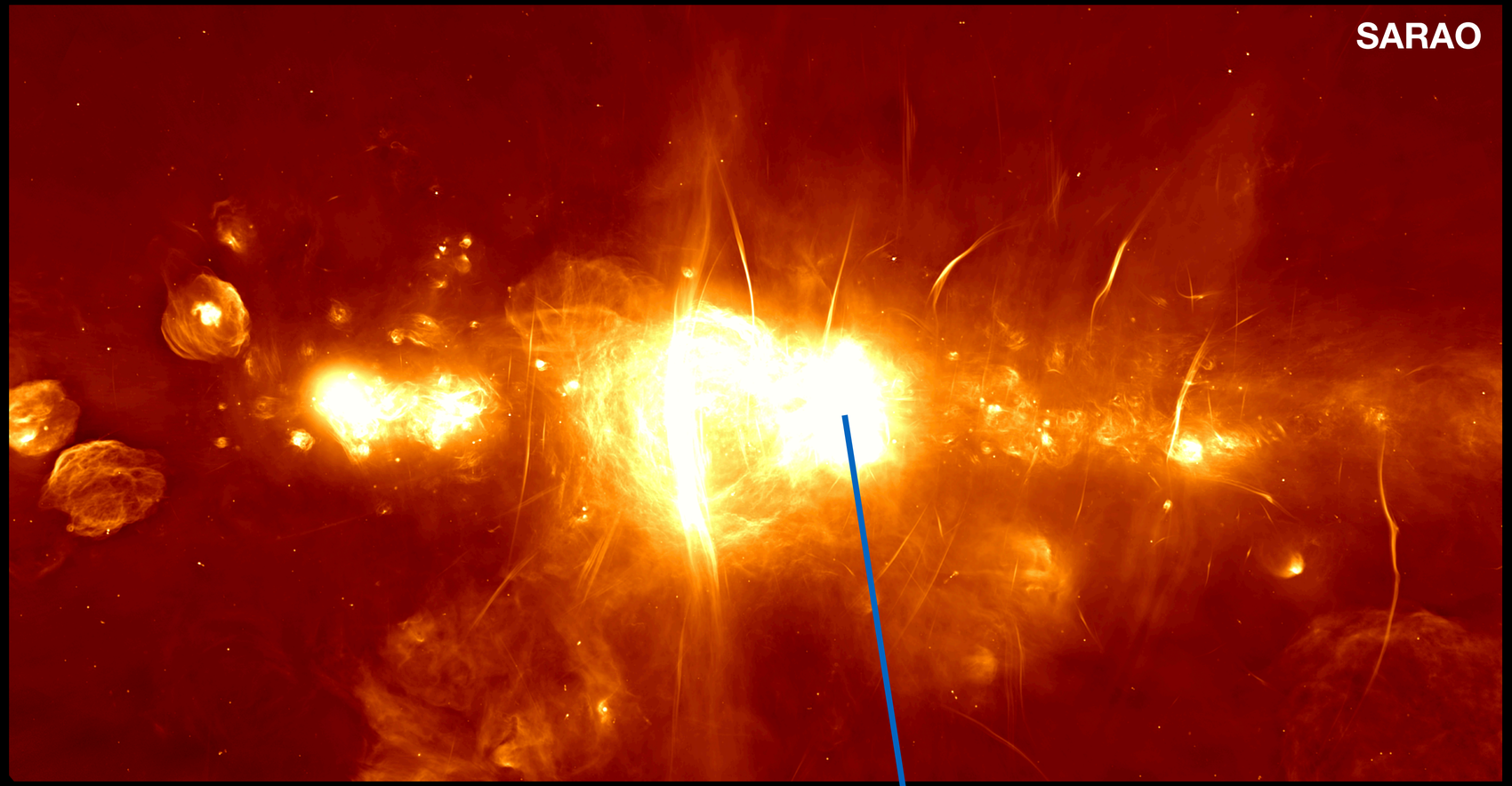

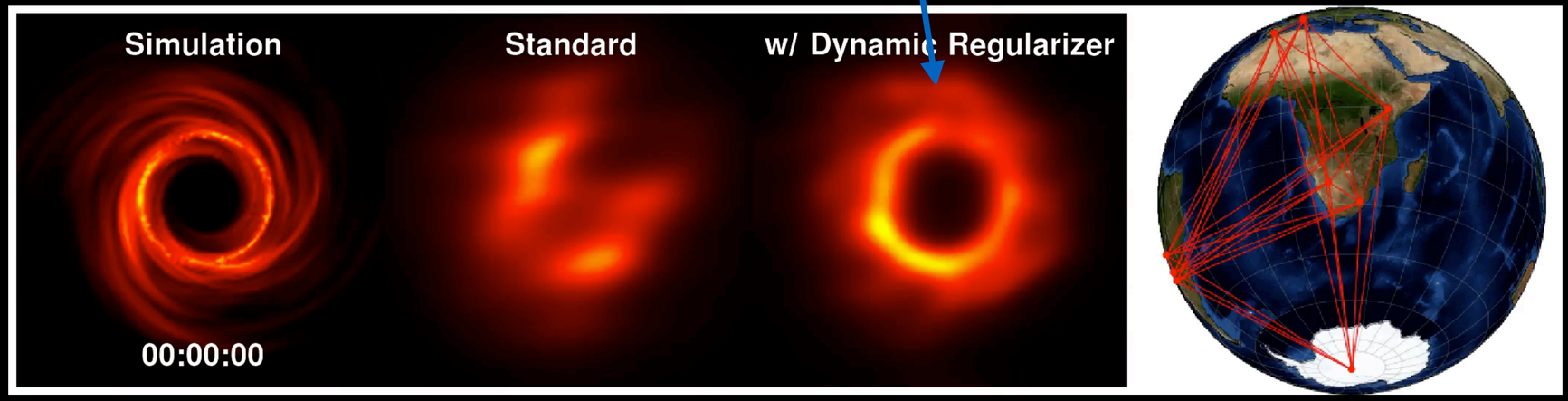

credit: Michael Johnson (Harvard)

summary

- The EHT has a strong record of high impact science built on engineering excellence
- Achieved its primary goal: captured the first image of a black hole!
  But much more to come…
- With current imaging quality, black hole mass consistent with stellar kinematics; and the shape is consistent with GR
- Experiment mode for now (shadow imaging), but large range of unique science on many sources possible, especially as array expands
- The tools and techniques developed with the EHT project ~~will have~~ ***have had*** a much broader impact on VLBI
- EHT expansion (including in Africa and space-VLBI) will significantly sharpen tests of gravity