First results from the Event Horizon Telescope

Dom Pesce

On behalf of the Event Horizon Telescope collaboration

March 10, 2020
EDSU conference

Event Horizon Telescope

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

The goal (ca. 2017)

The goal is to take a picture of a black hole

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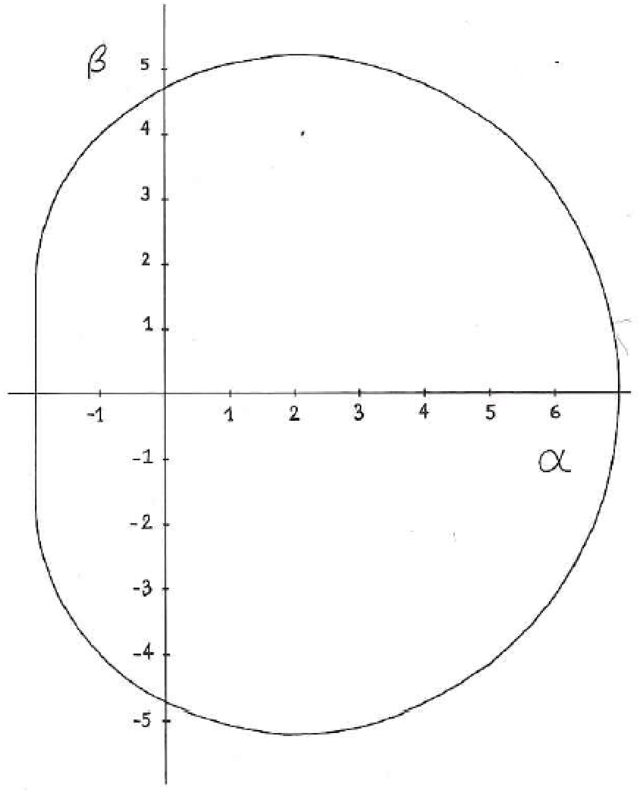
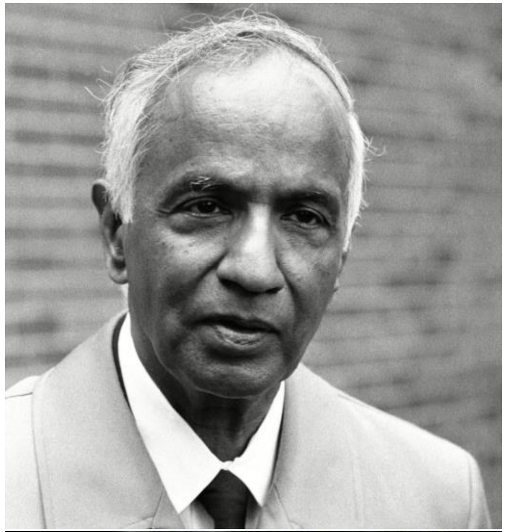
- General relativity makes a prediction for the apparent shape of a black hole

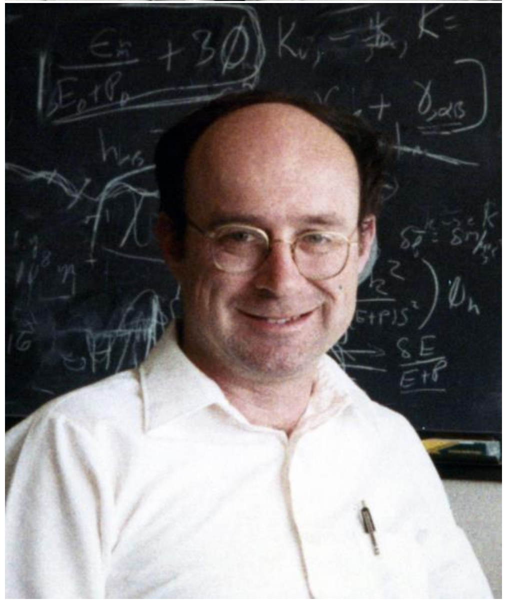


"It is conceptually interesting, if not astrophysically very important, to calculate the precise apparent shape of the black hole… Unfortunately, there seems to be no hope of observing this effect."

- James Bardeen, 1973

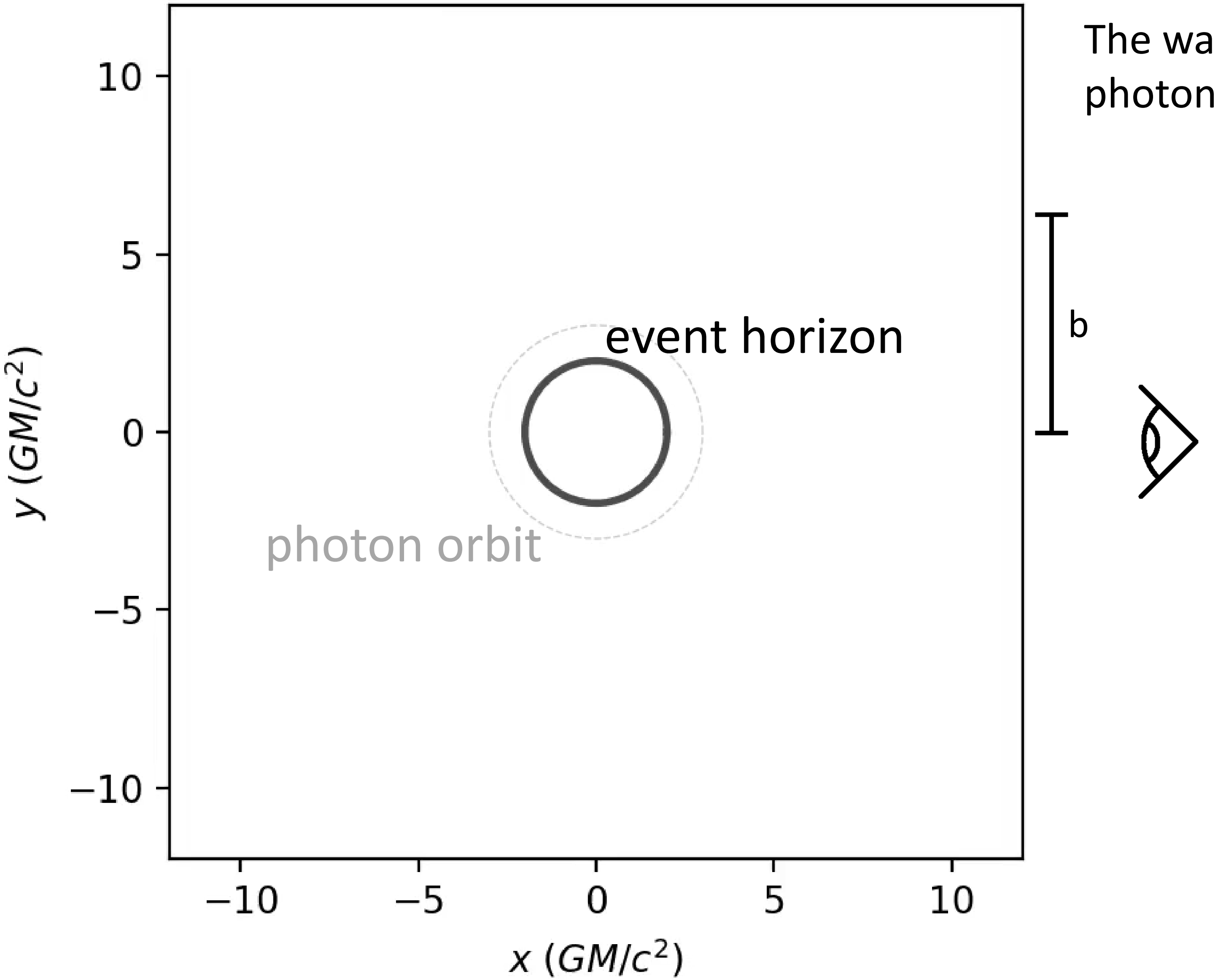
Subrahmanyan Chandrasekhar





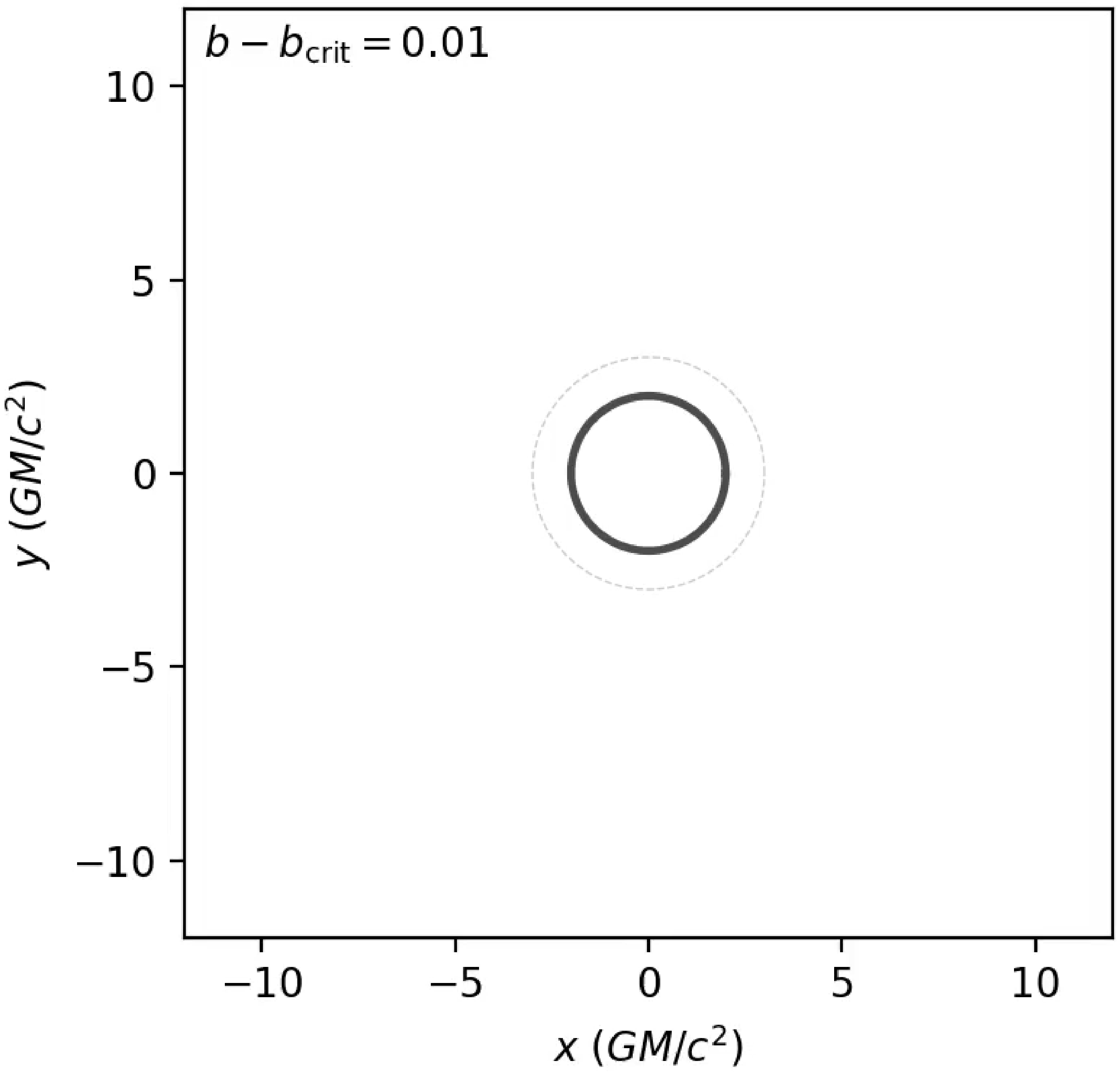
James Bardeen

Photon ring and black hole shadow



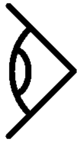
The warped spacetime around a black hole causes photon trajectories to bend

Photon ring and black hole shadow



The warped spacetime around a black hole causes photon trajectories to bend

The closer these trajectories get to a critical impact parameter, the more tightly wound they become



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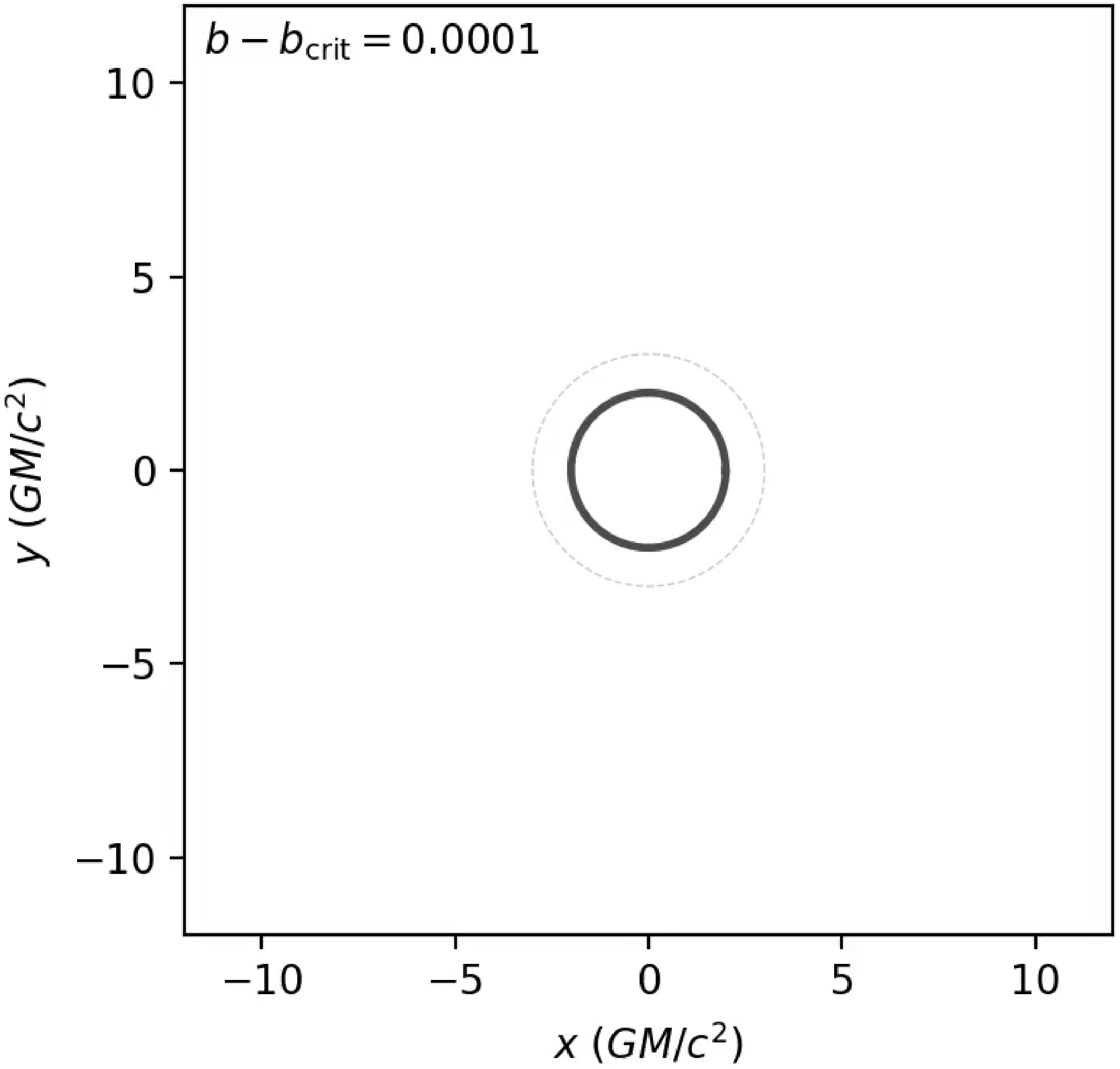

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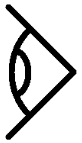

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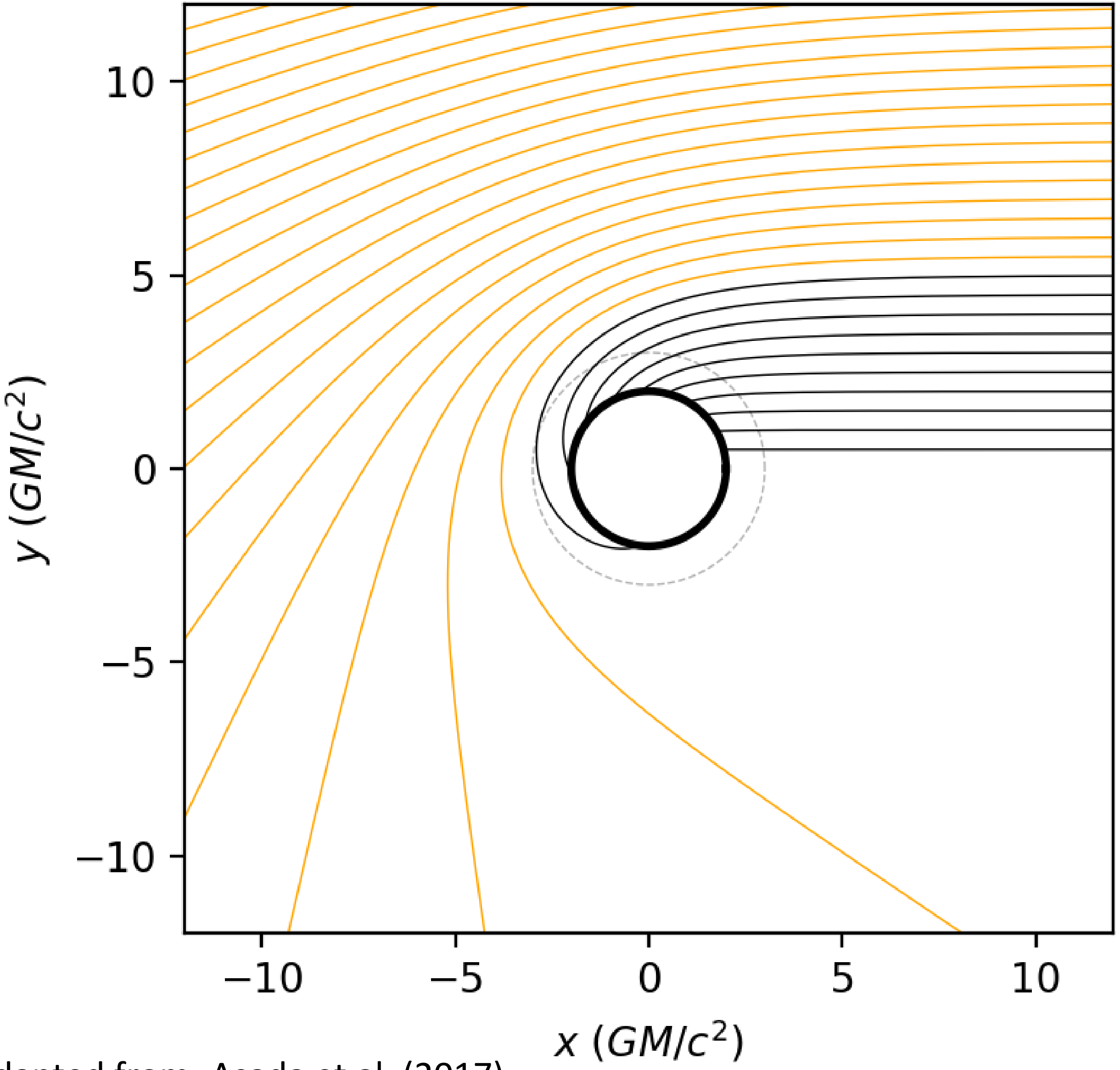

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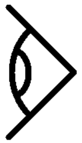
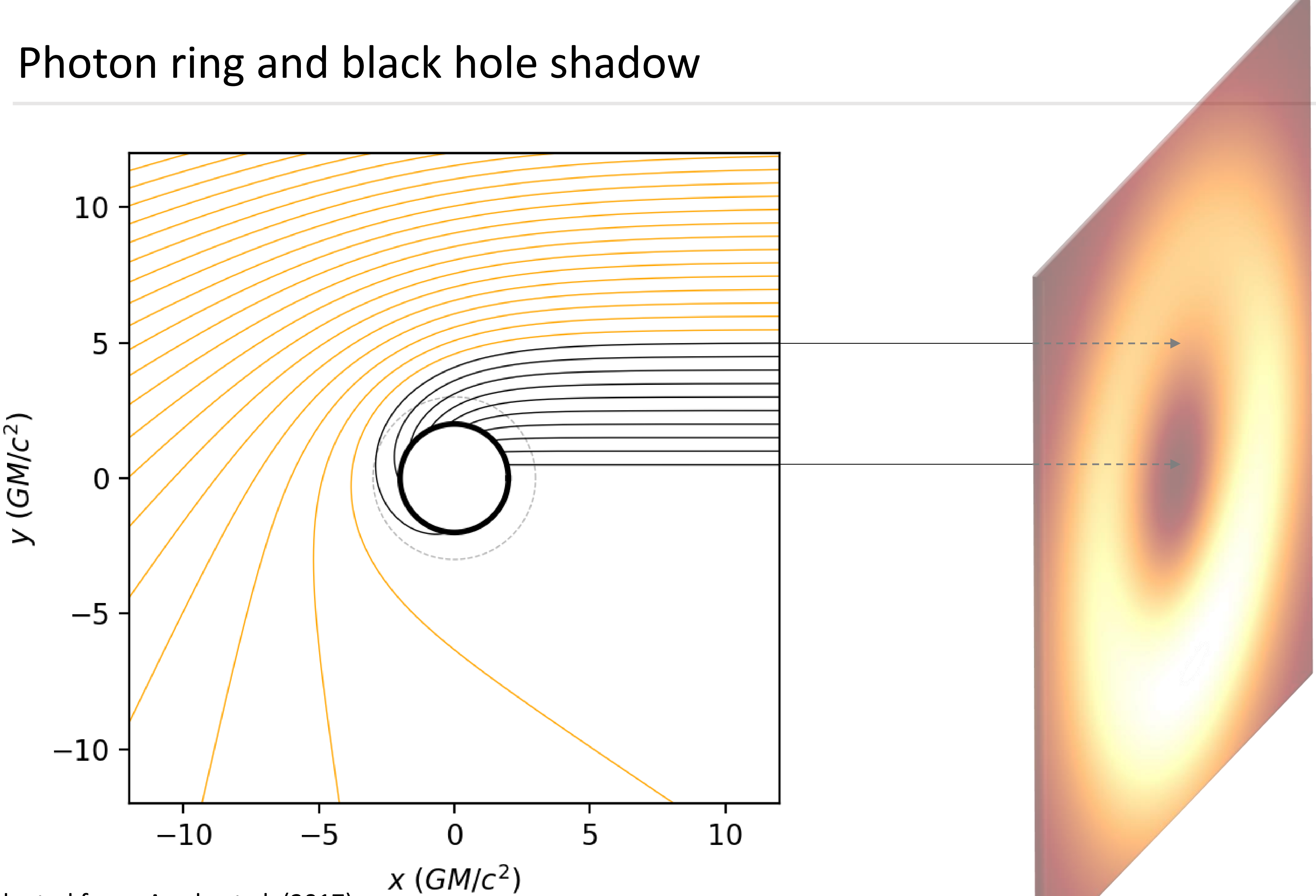


The trajectories interior to this critical impact parameter intersect the horizon, and these collectively form the black hole "shadow" (Falcke, Melia, & Agol 2000) while the bright surrounding region constitutes the "photon ring"

Adapted from: Asada et al. (2017)

Photon ring and black hole shadow



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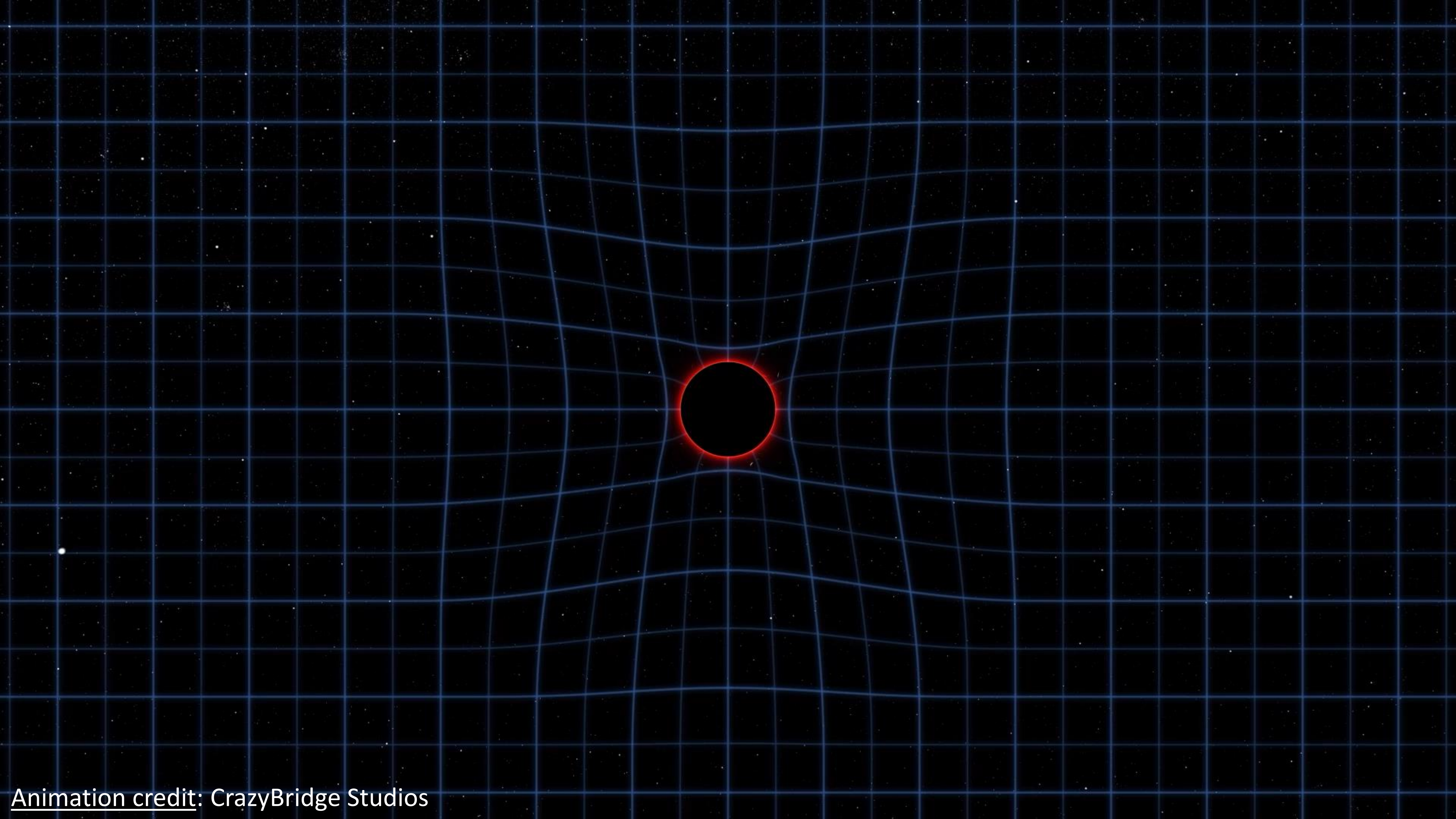

Animation credit: CrazyBridge Studios

The challenge

The challenge is that black holes are tiny

- The black holes with the largest angular sizes (i.e., Sgr A*, M87) subtend only 40-50 μas

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"Cosmic conspiracy" steers us towards an observing wavelength of ~1mm (230 GHz):

1. The angular resolution of Earth-diameter VLBI at this wavelength is sufficient to resolve the shadows of Sgr A* and M87
2. The atmosphere at high-altitude sites is reliably transparent enough for global VLBI at this wavelength
3. The accretion flows around both Sgr A* and M87 start to become optically thin at mm wavelengths
4. For Sgr A*, interstellar scattering only becomes subdominant at wavelengths < ~1 mm

The EHT array as seen from M87 in 2017

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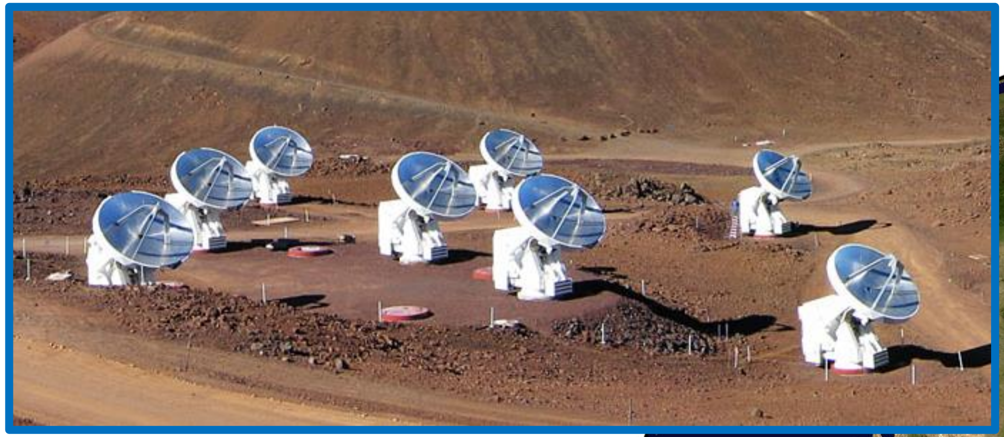

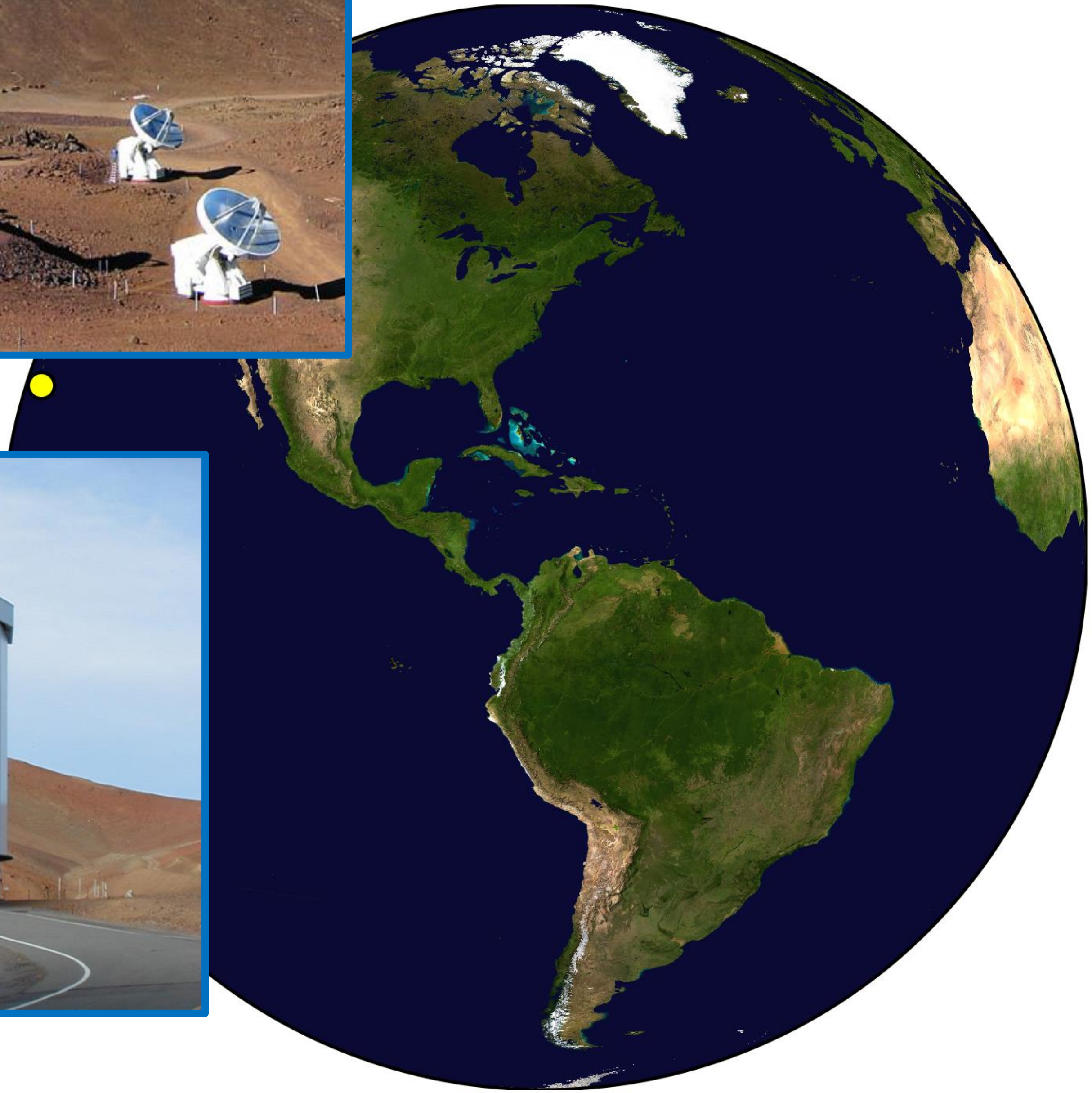

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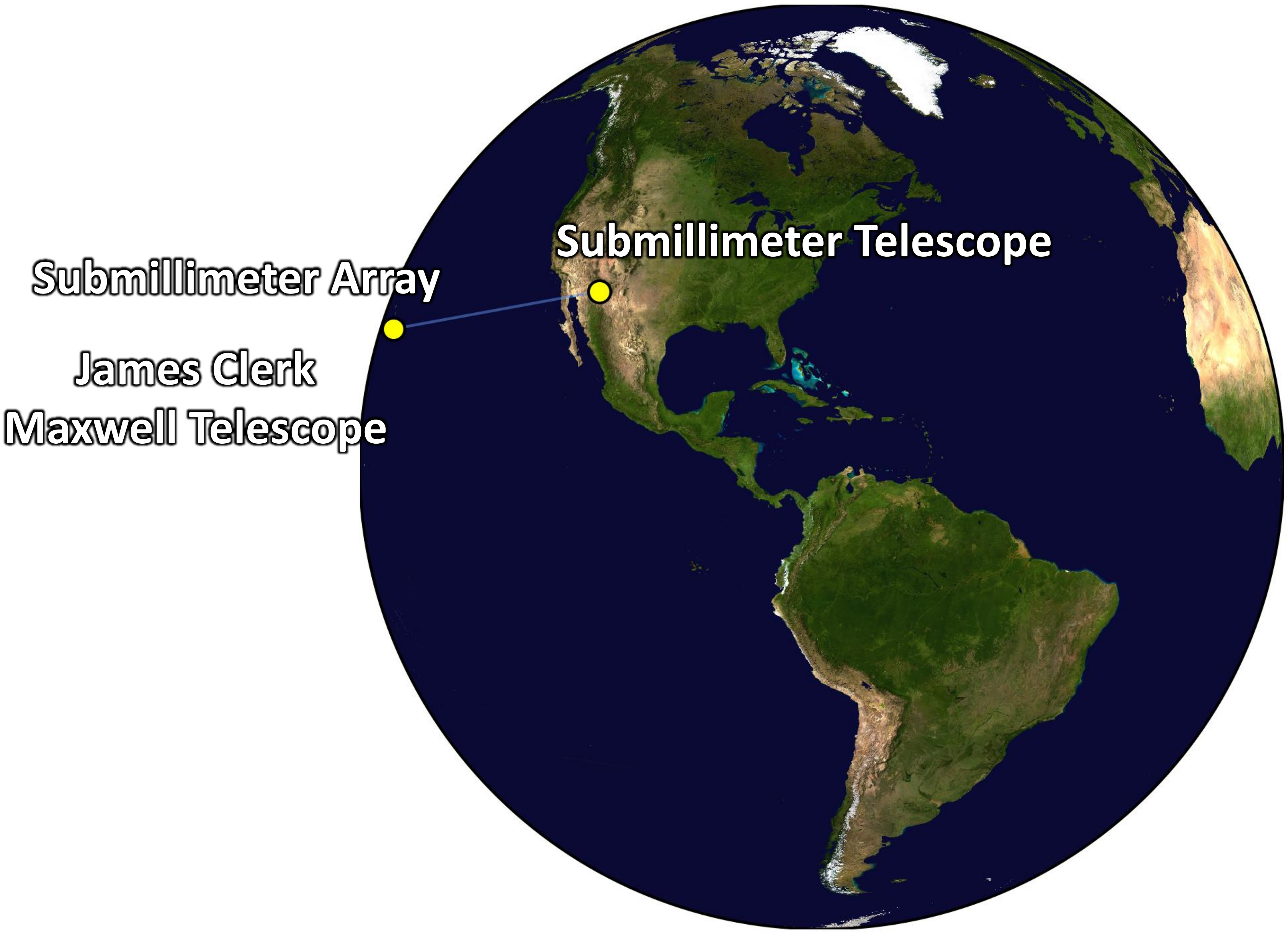

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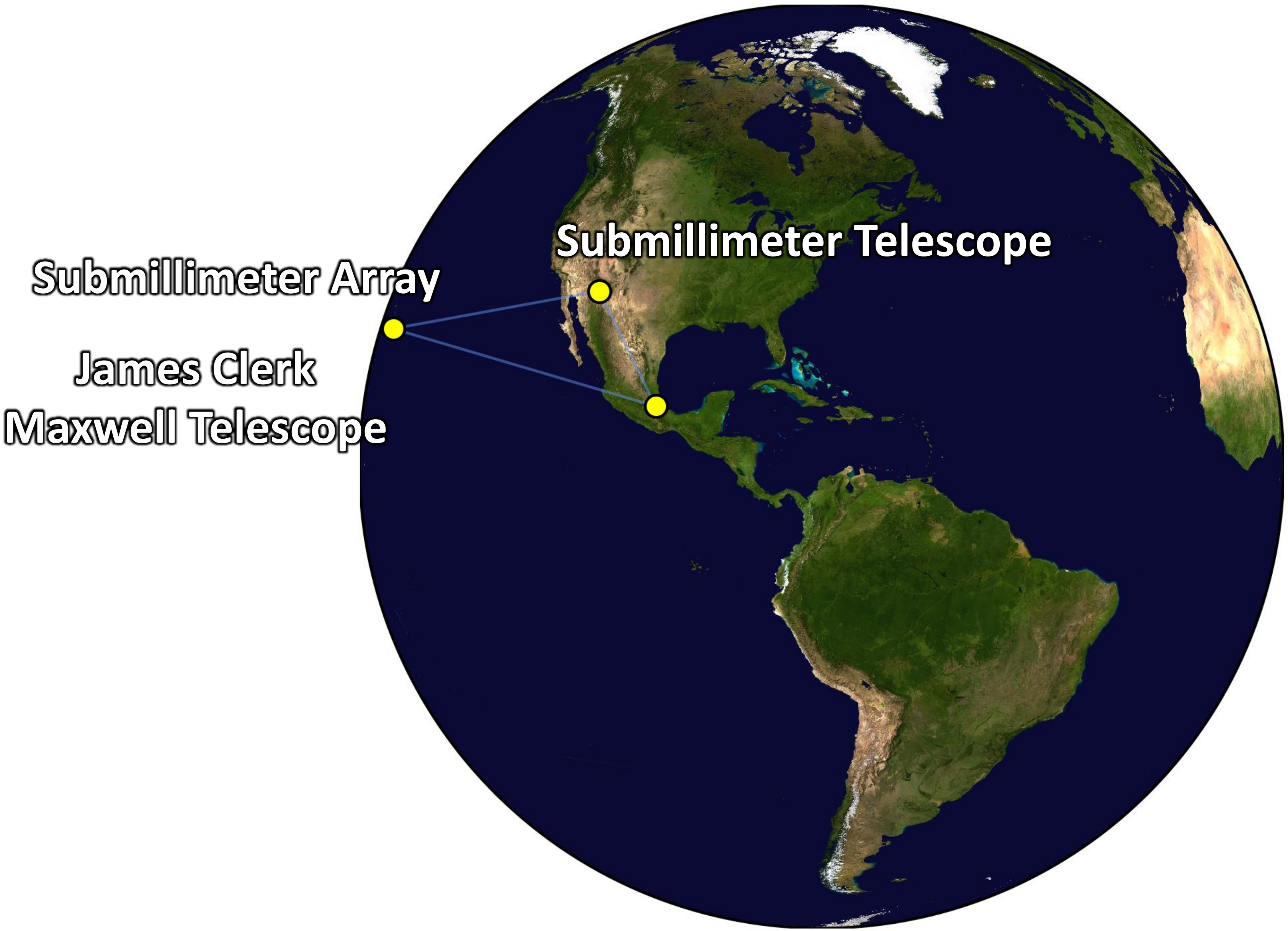

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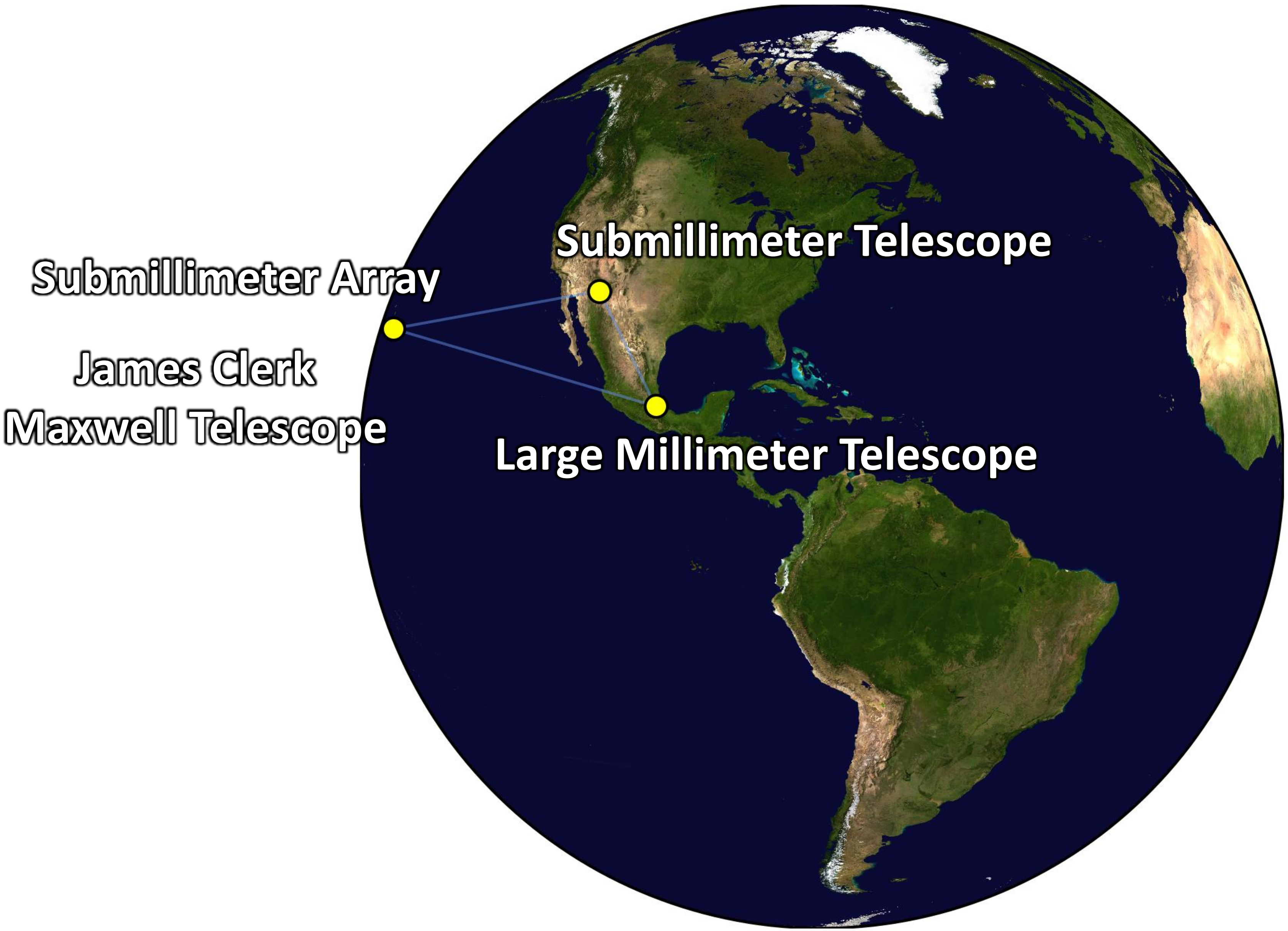

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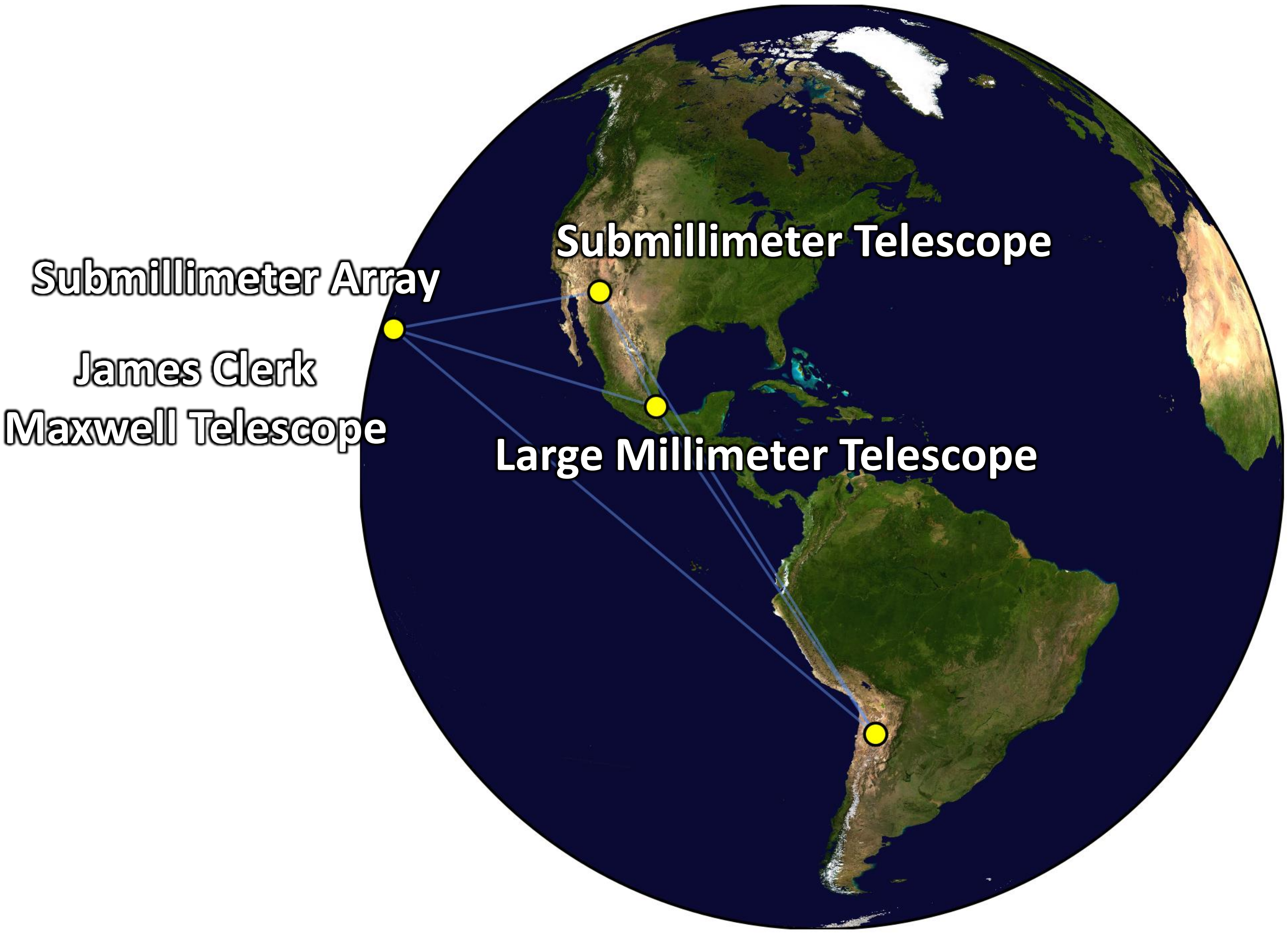

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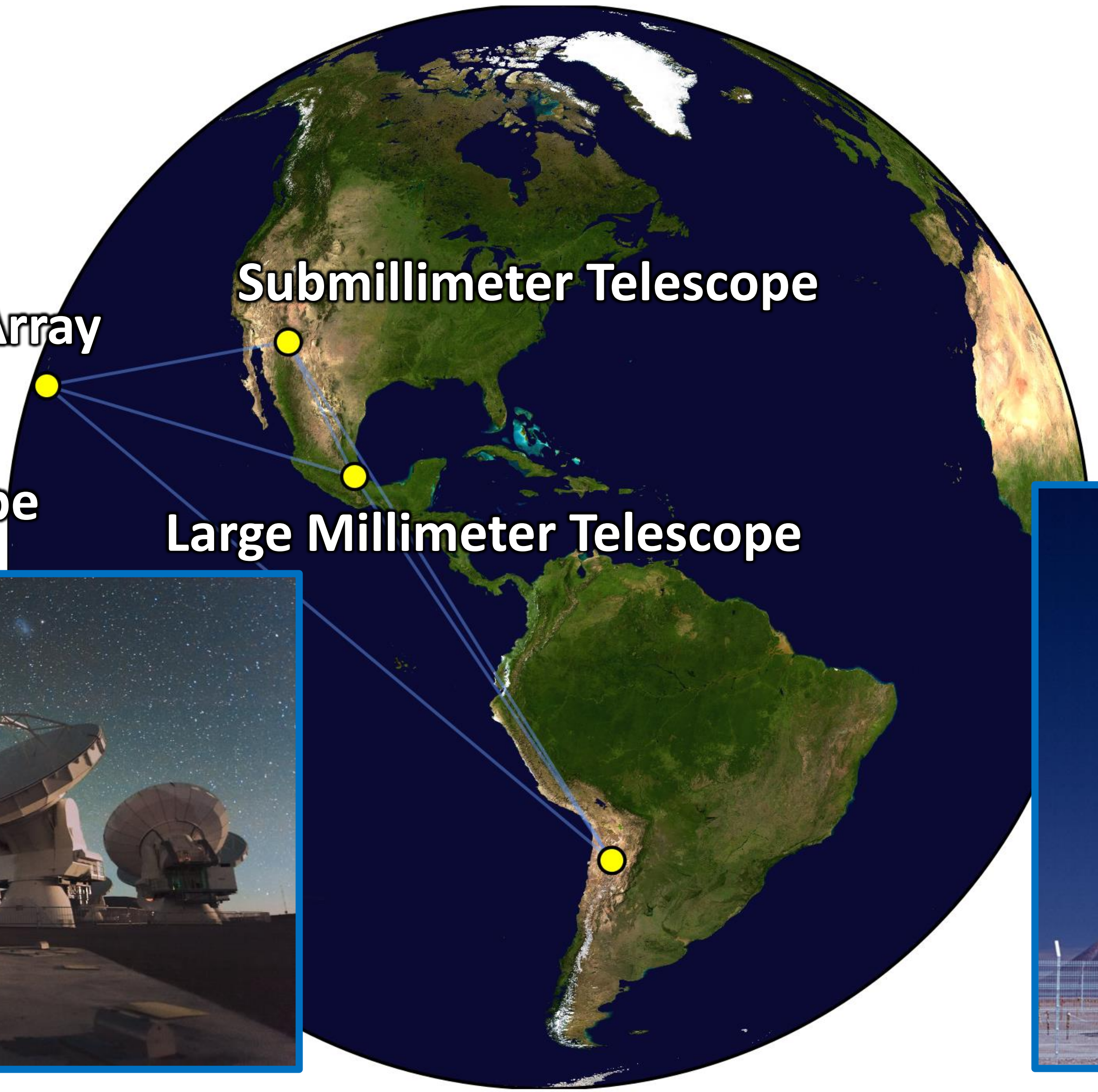

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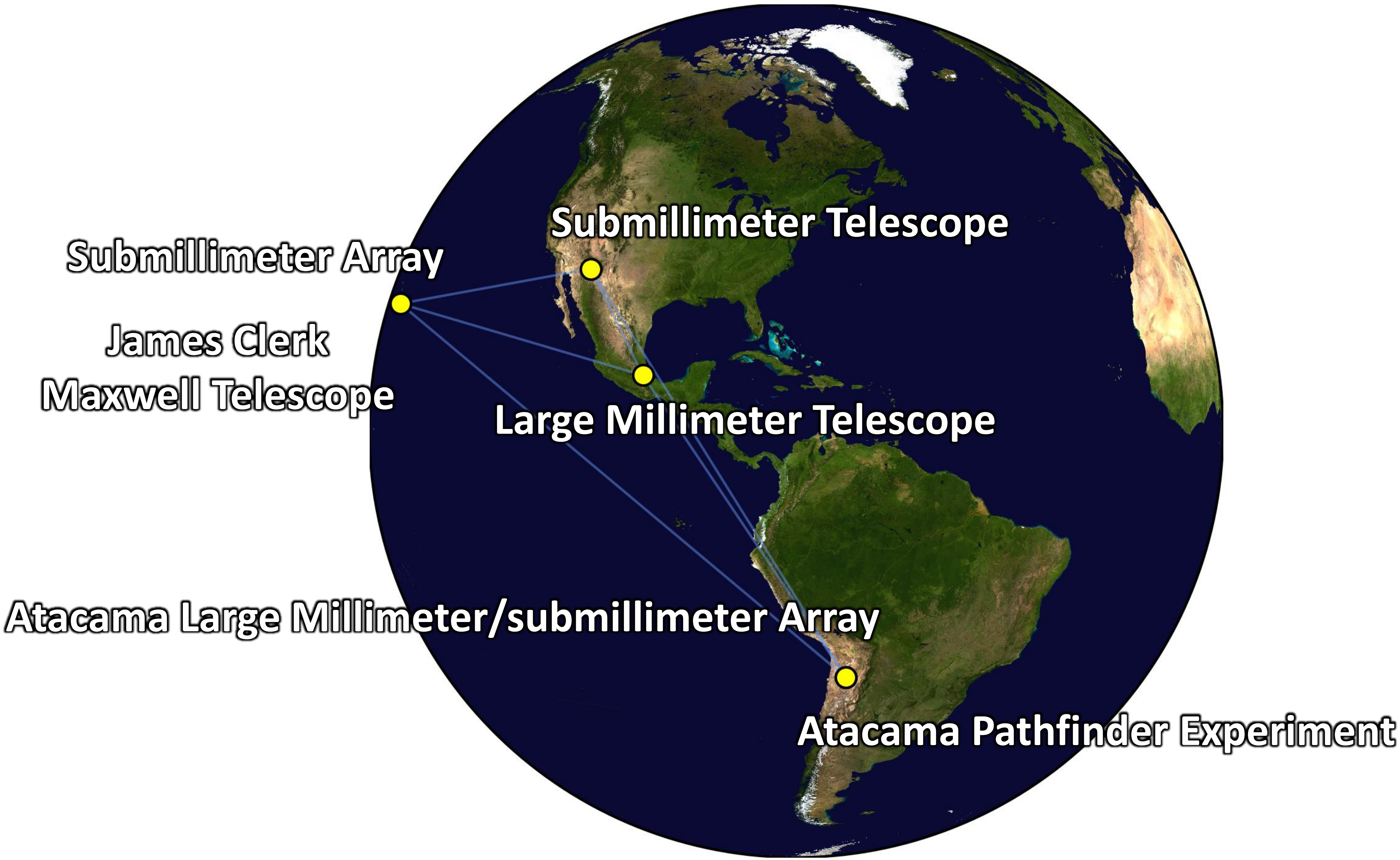

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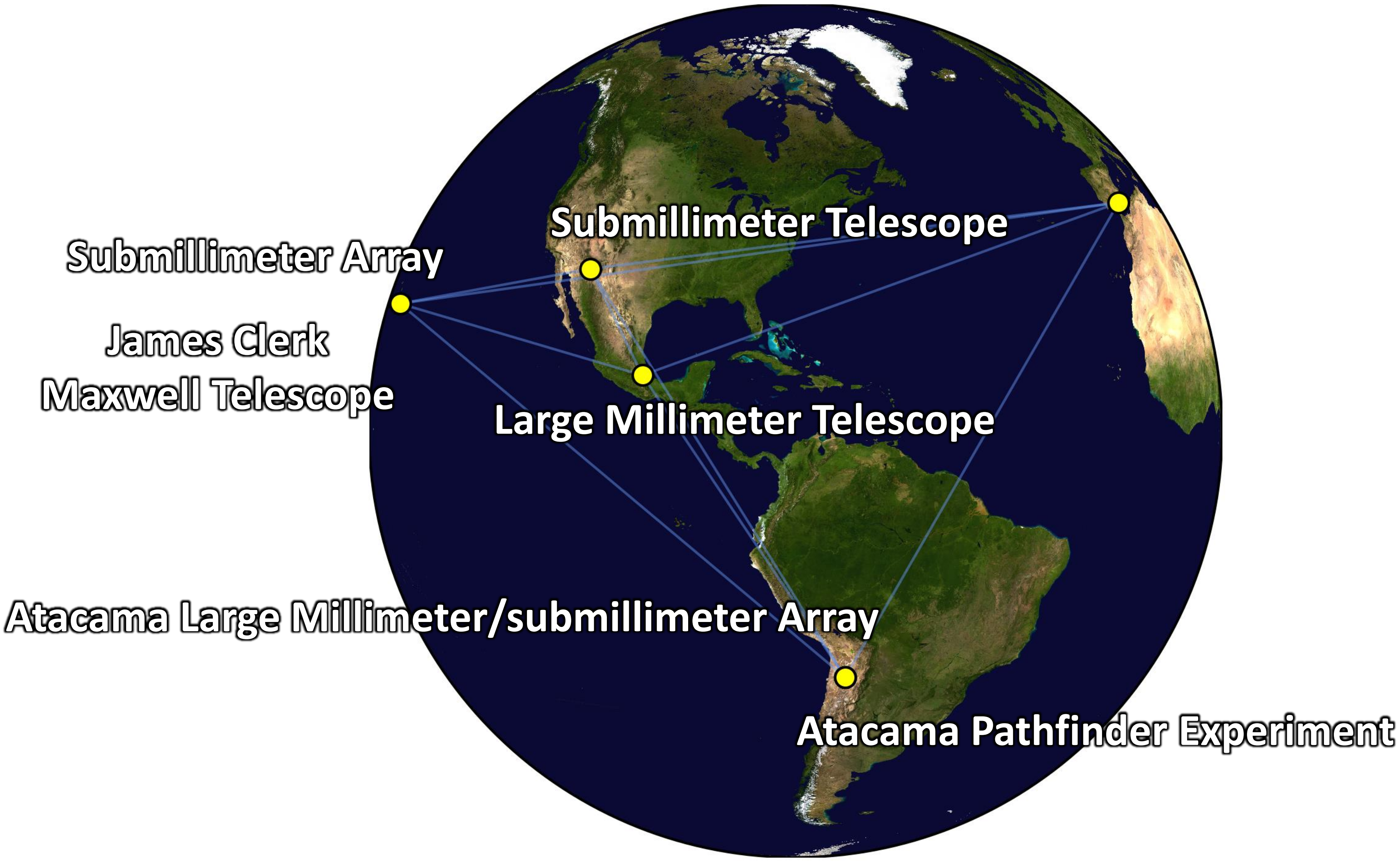

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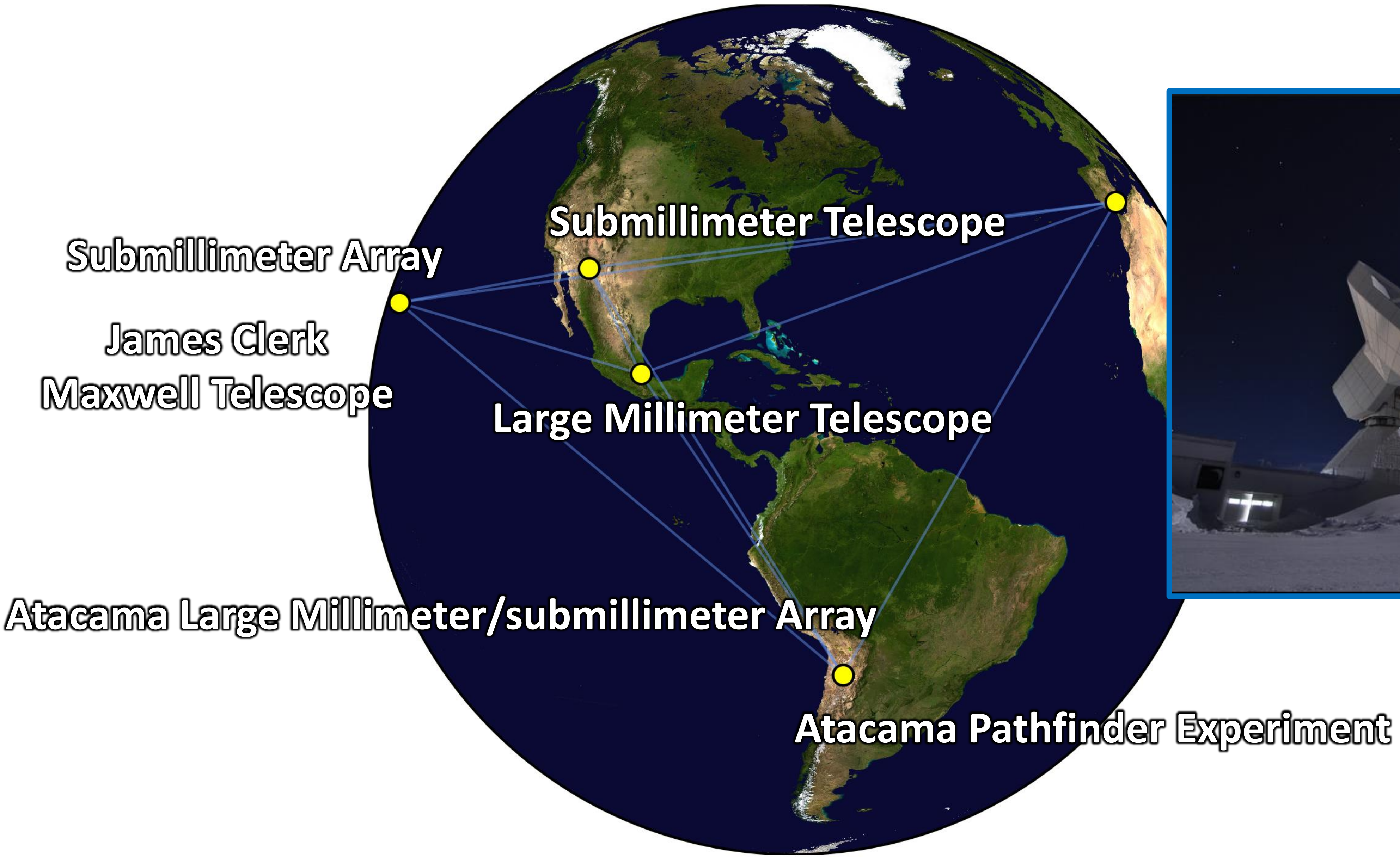

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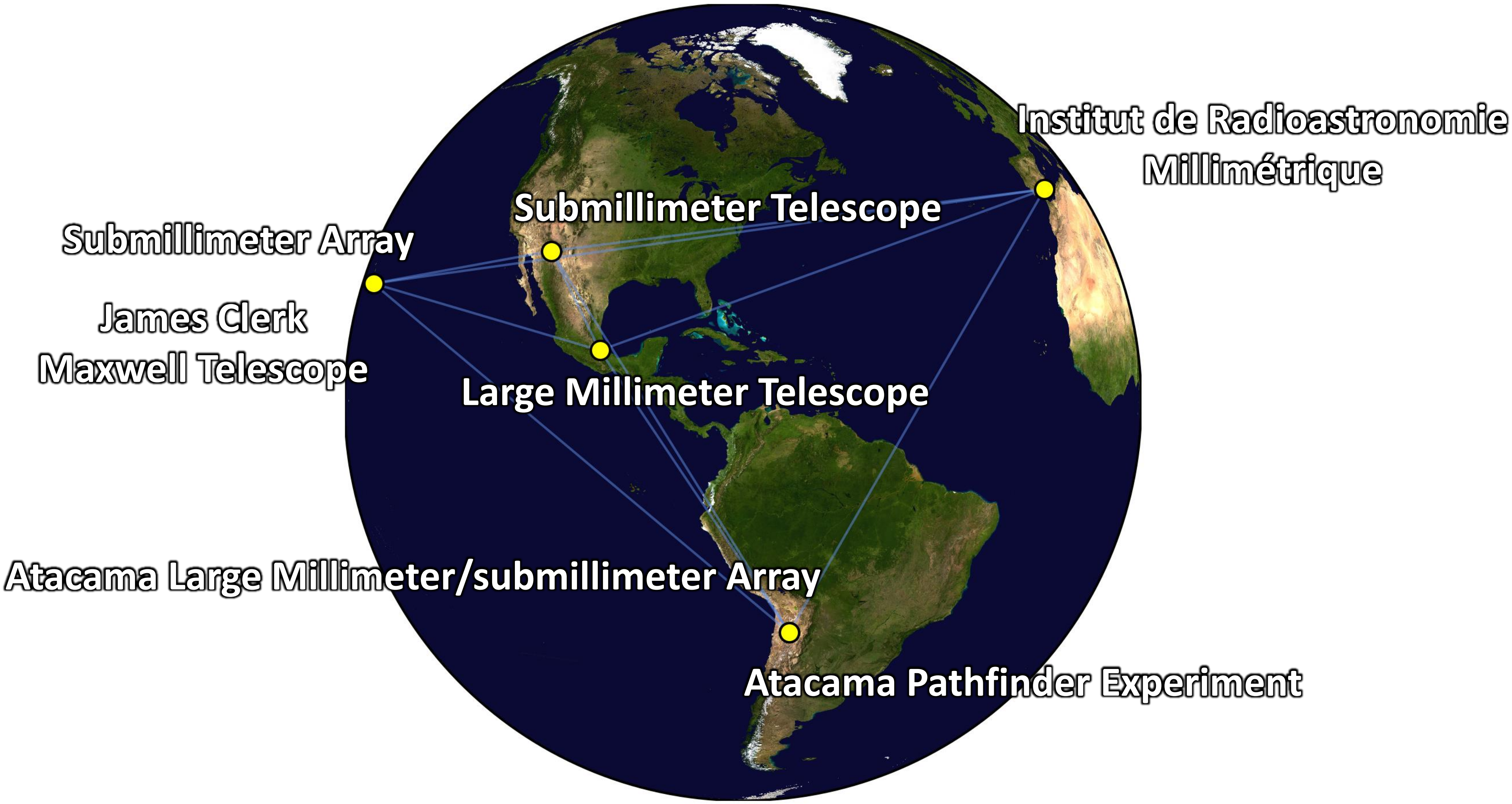
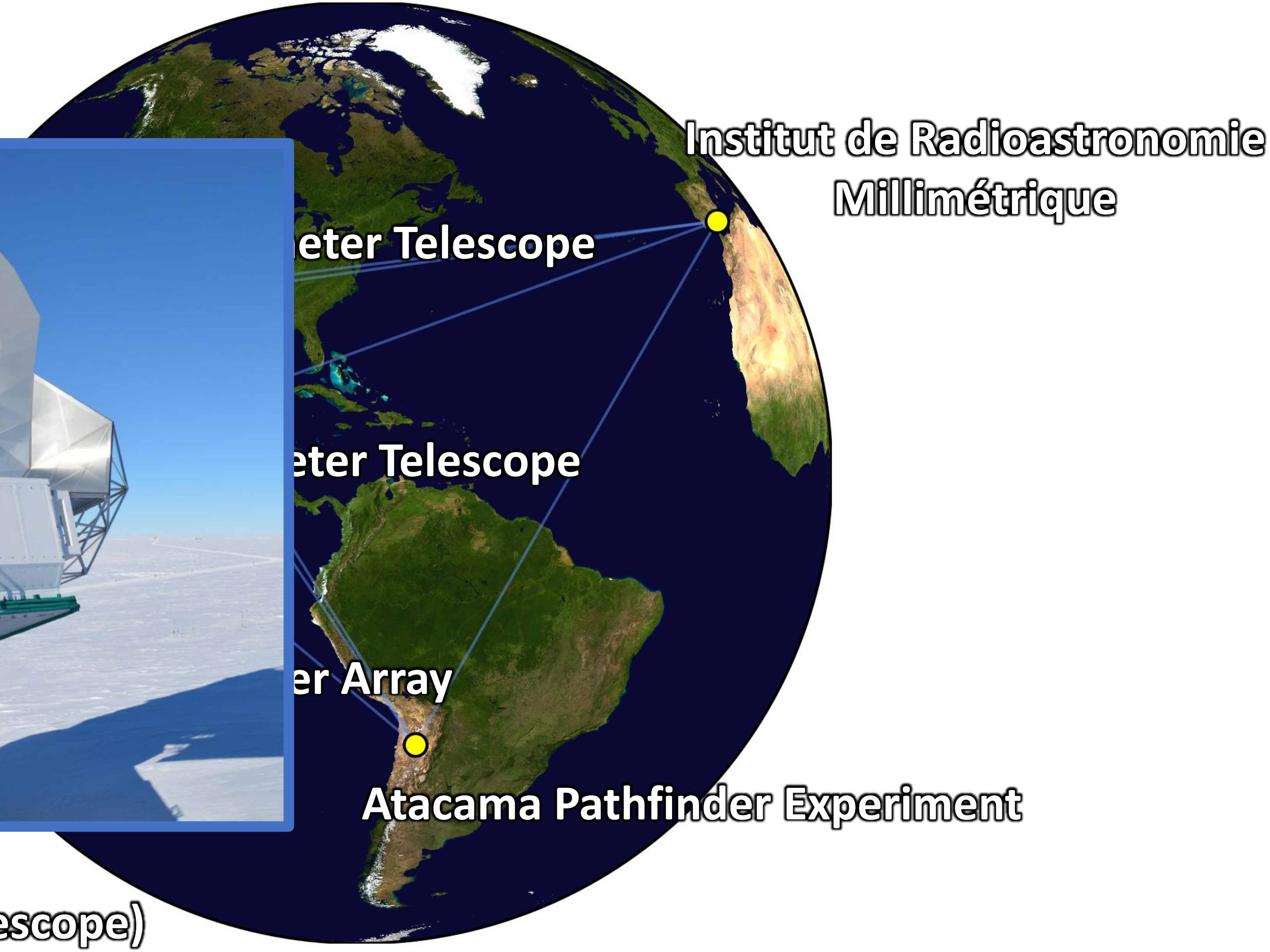
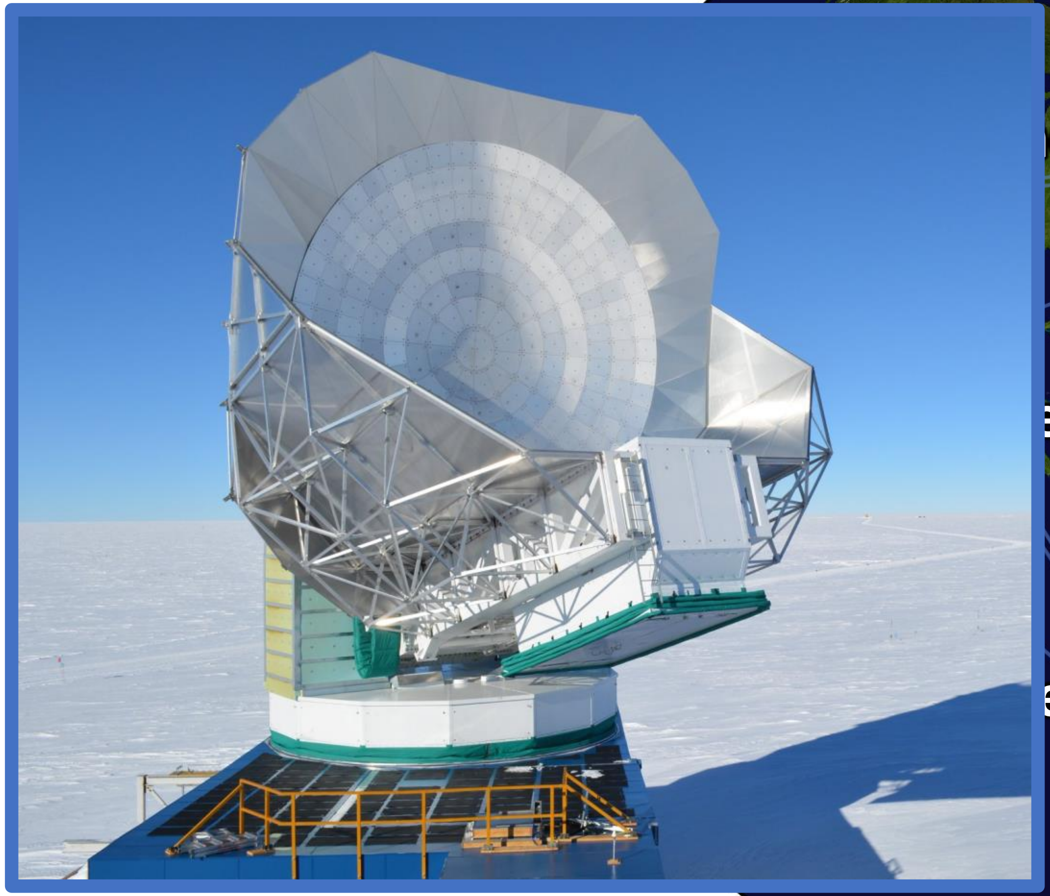


Assembling the Event Horizon Telescope





(South Pole Telescope)

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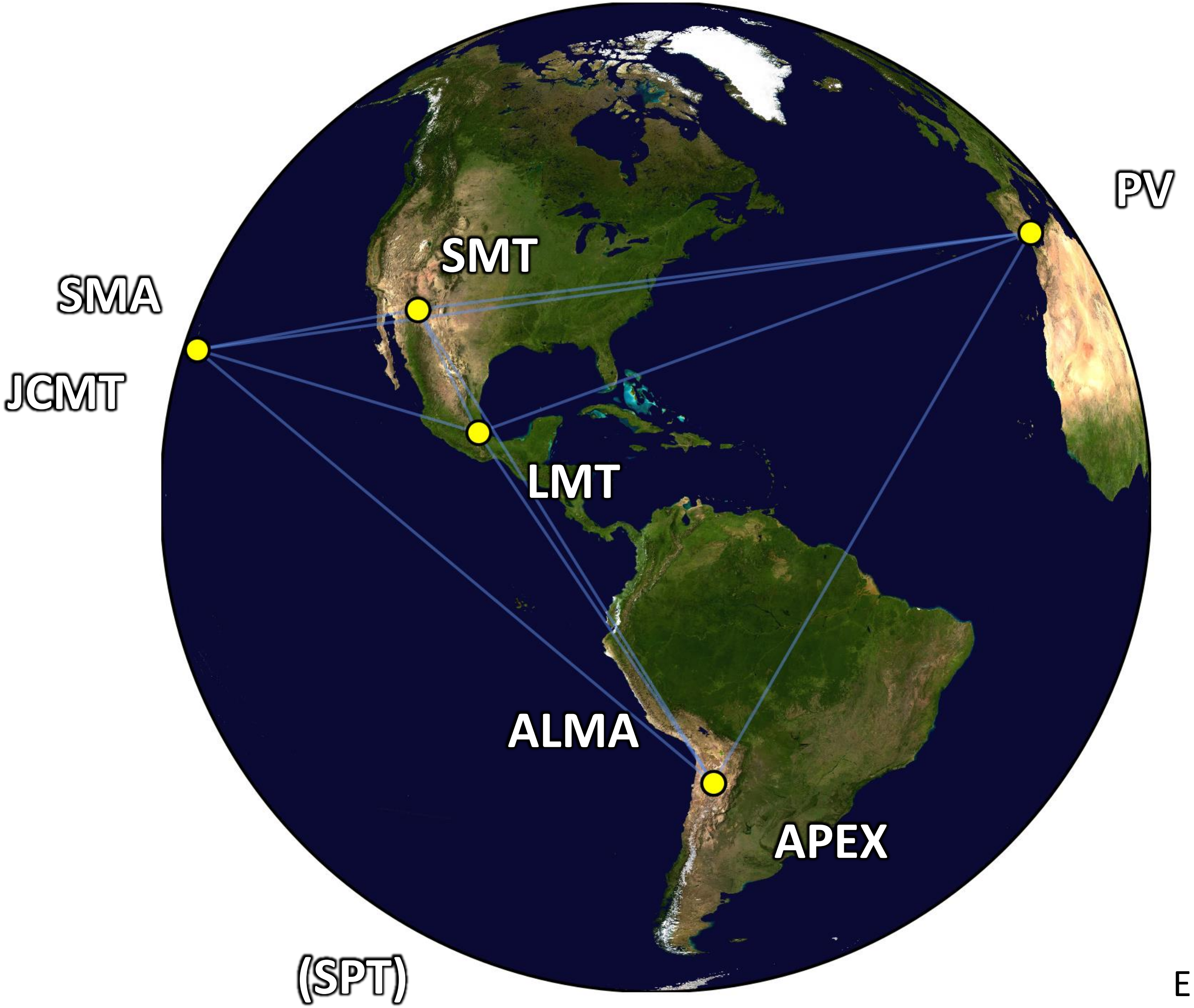
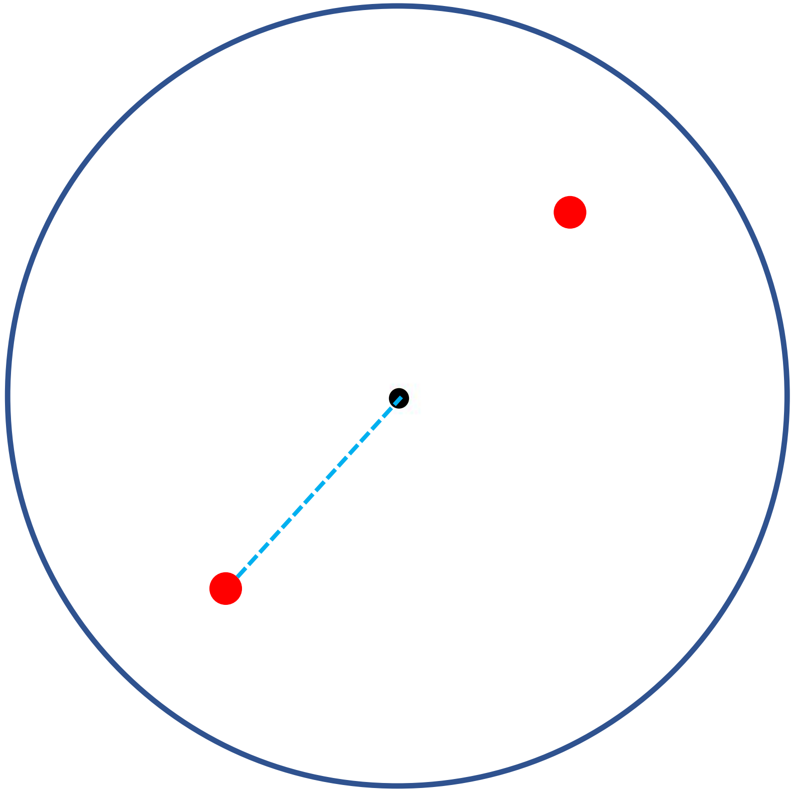


EHT Collaboration et al. (2019b)

Brief review of very long baseline interferometry (VLBI)

The EHT array operates as a network of interferometers, with each pair of telescopes contributing a single Fourier mode measurement

Earth as viewed from M87



Fourier coverage

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- A technique called “Earth aperture synthesis” is used to improve the Fourier sampling

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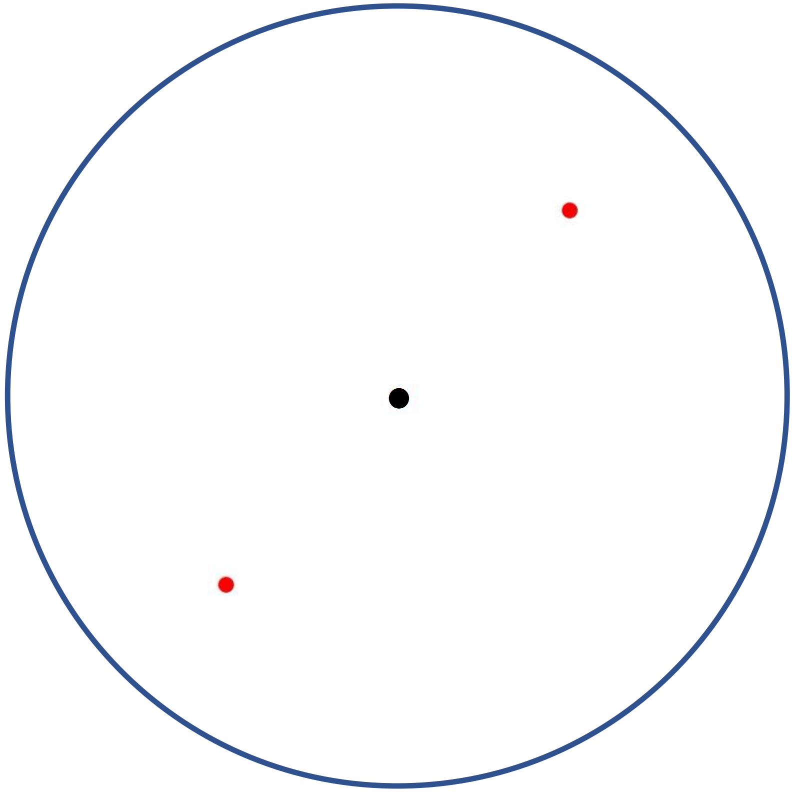

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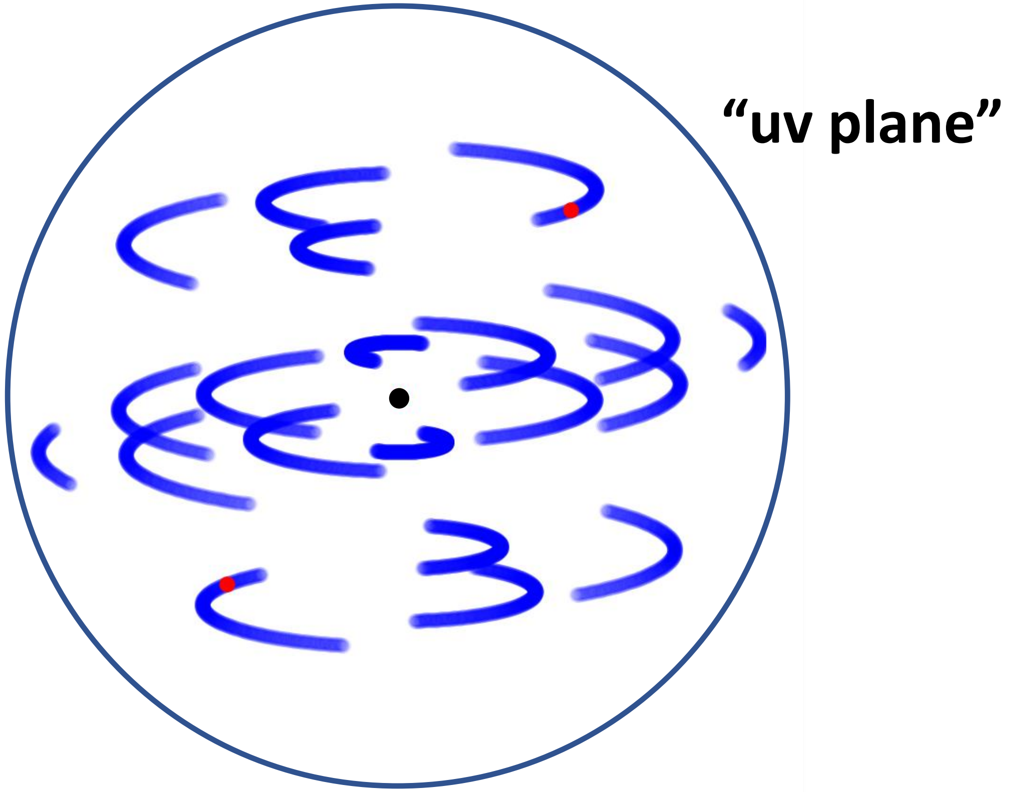

Fourier coverage

Data journey at a glance

Credit: Lindy Blackburn

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Raw signals
[PB]

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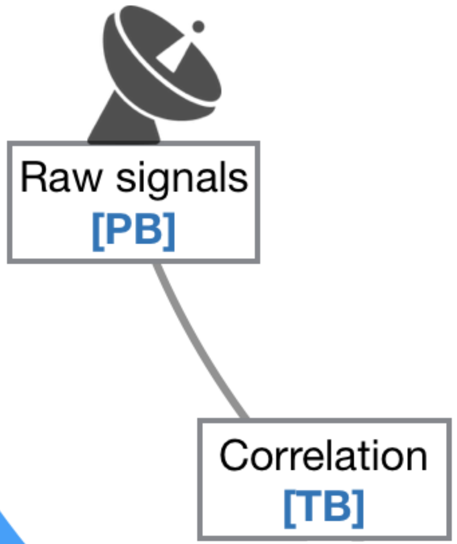

Don Sousa

Credit: Lindy Blackburn

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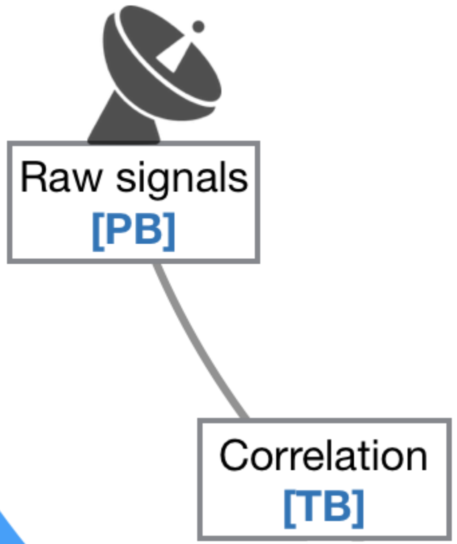

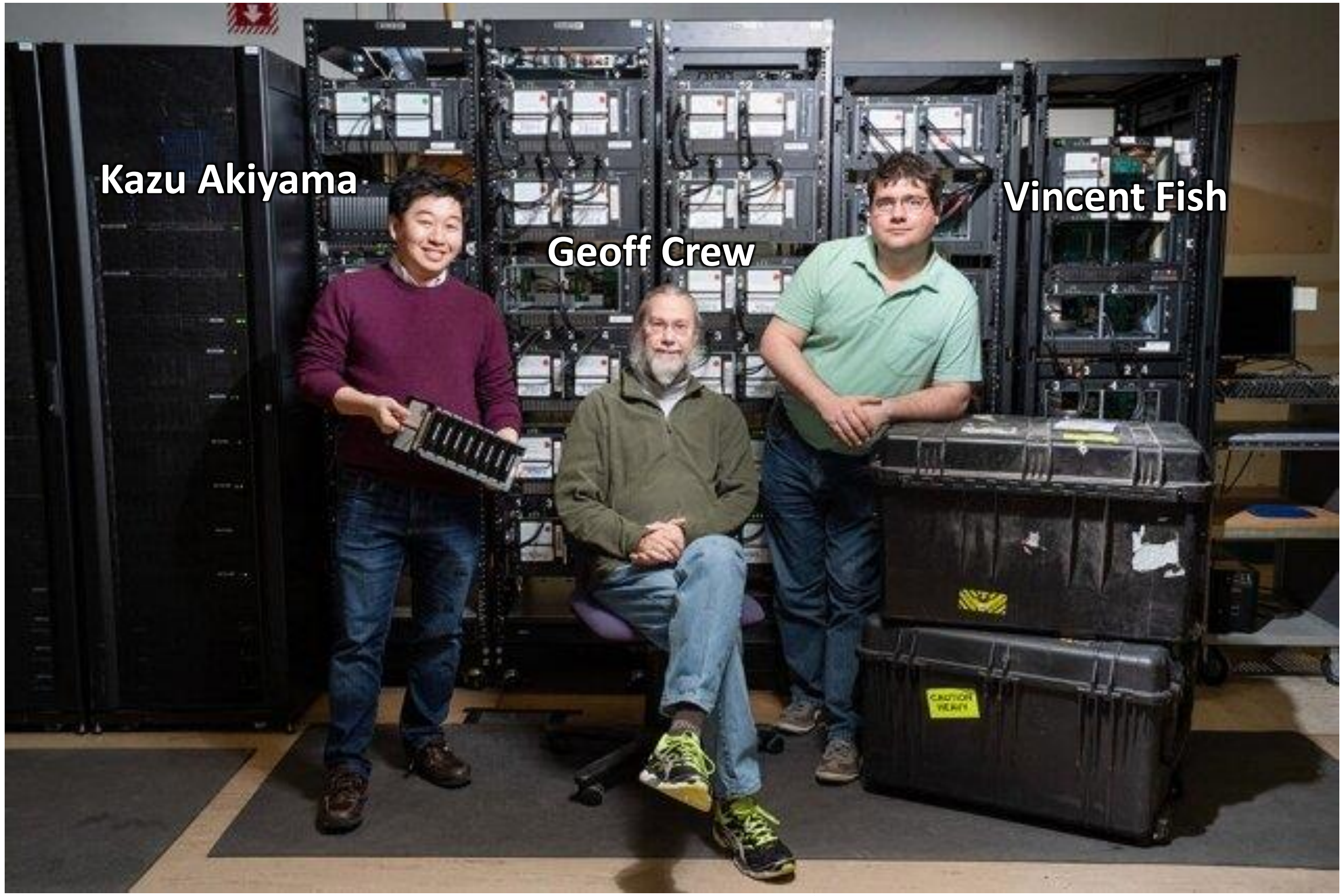

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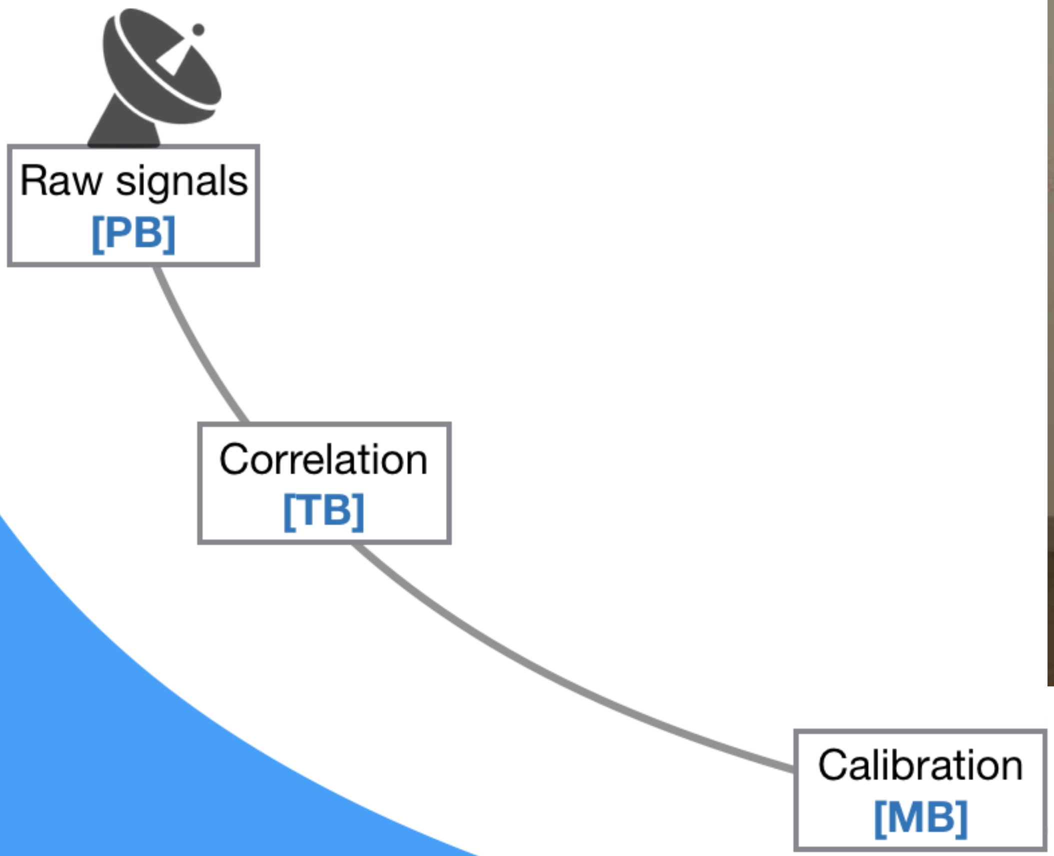

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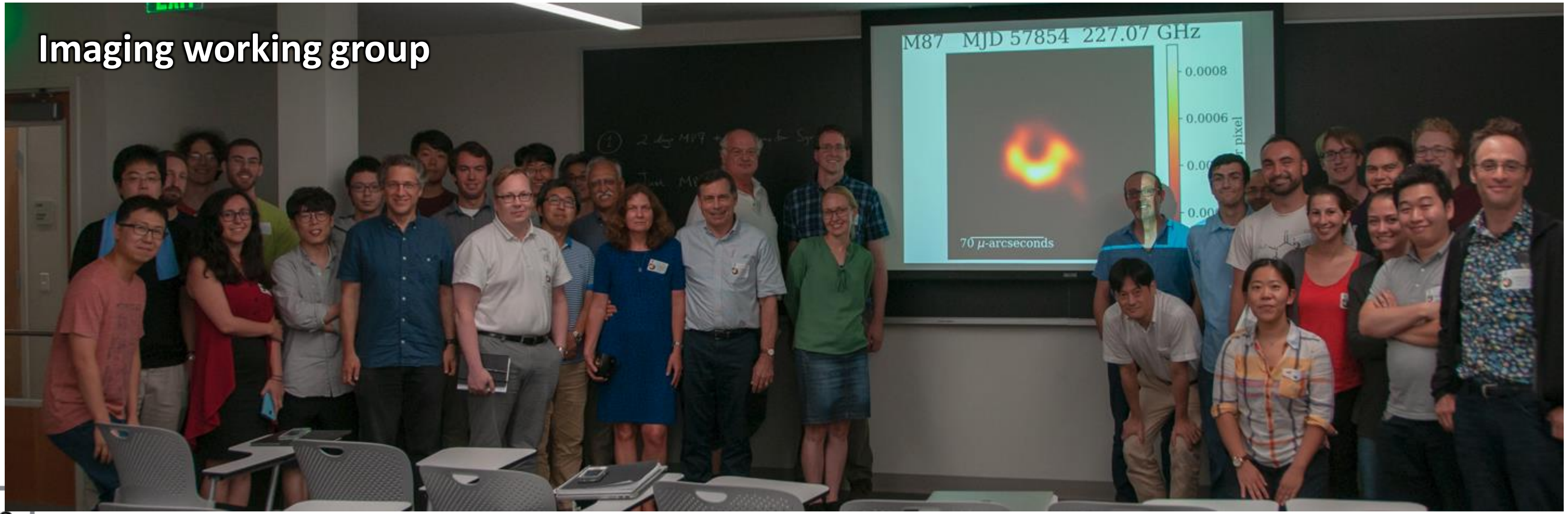
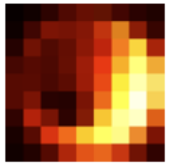


Raw signals
[PB]

Correlation
[TB]

Calibration
[MB]

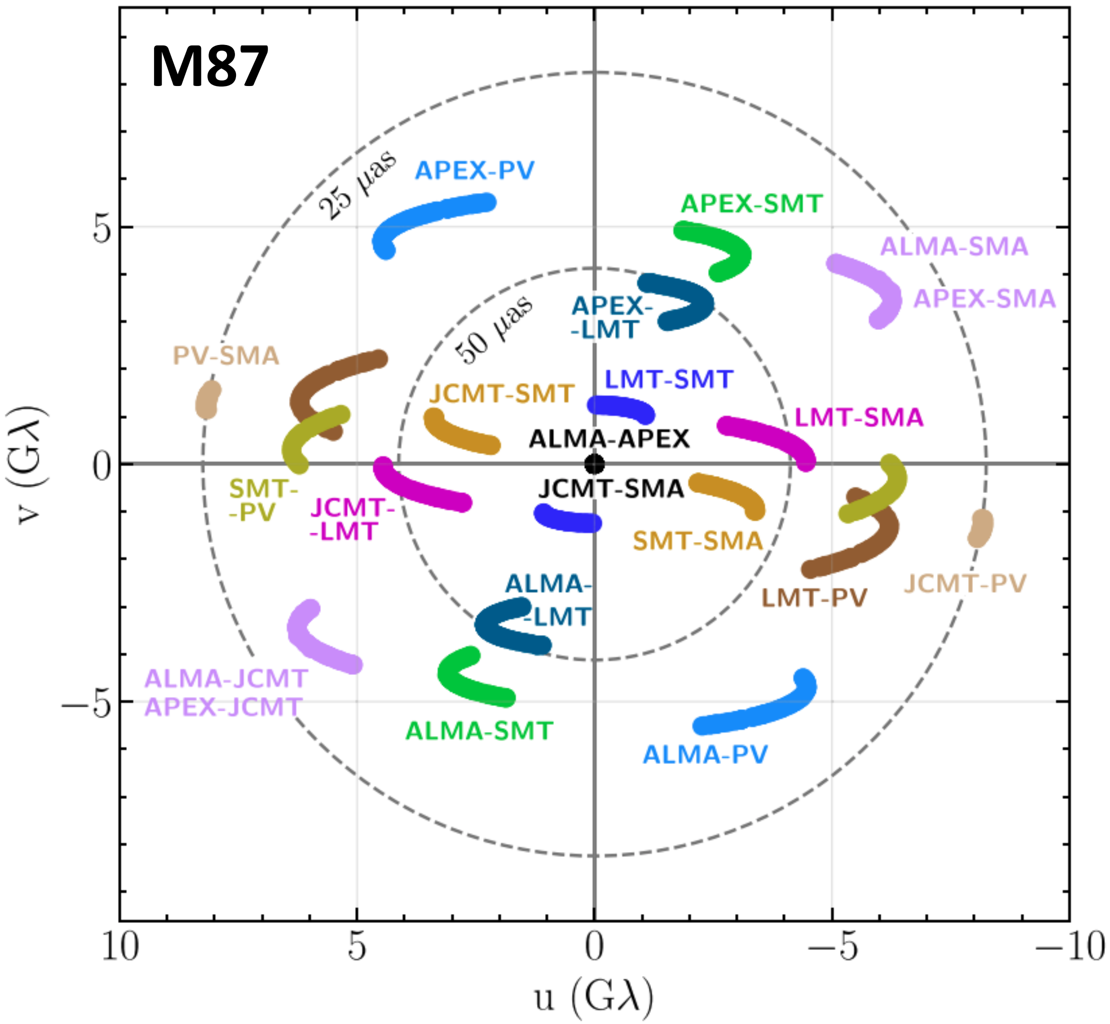
Image
[kB]



Credit: Lindy Blackburn

Challenge: sparse coverage

Our uv-plane coverage is limited by the small number of stations



EHT Collaboration et al. (2019c)

Imaging

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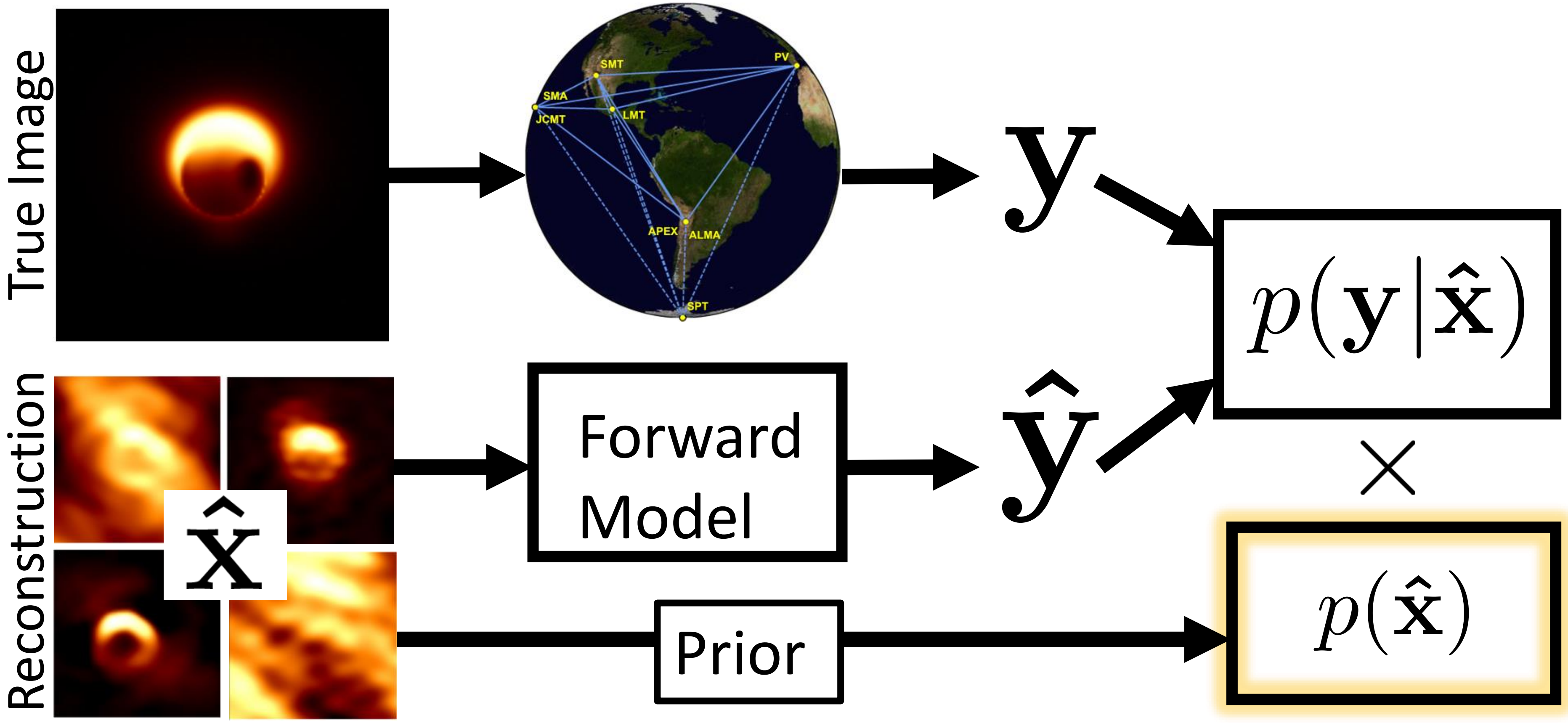
Mitigation strategy #1: regularized forward-modeling of the source emission structure



Credit: Katie Bouman, Avery Broderick

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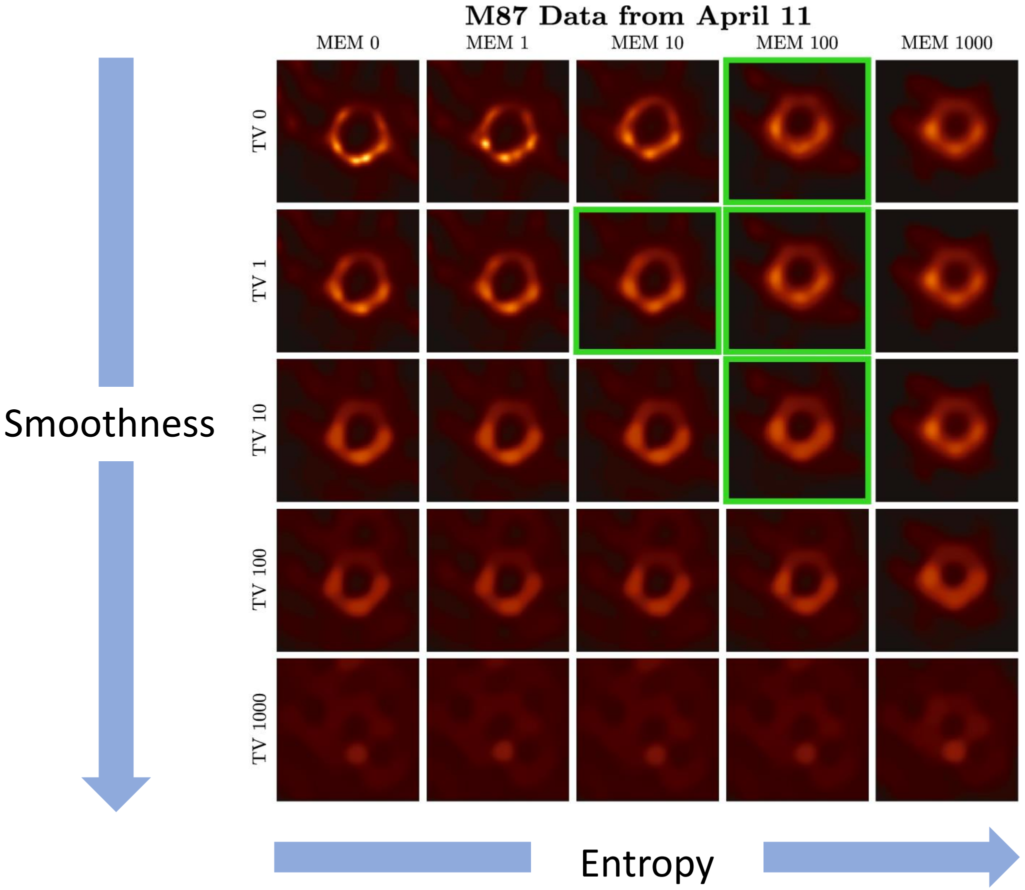
Mitigation strategy #1: regularized forward-modeling of the source emission structure

Sparsity:
Favors the image to be mostly empty space

Smoothness:
Favors an image that varies slowly over small spatial scales

Maximum Entropy:
Favors compatibility with a specified "prior" image
(which can be flat)



Credit: Andrew Chael

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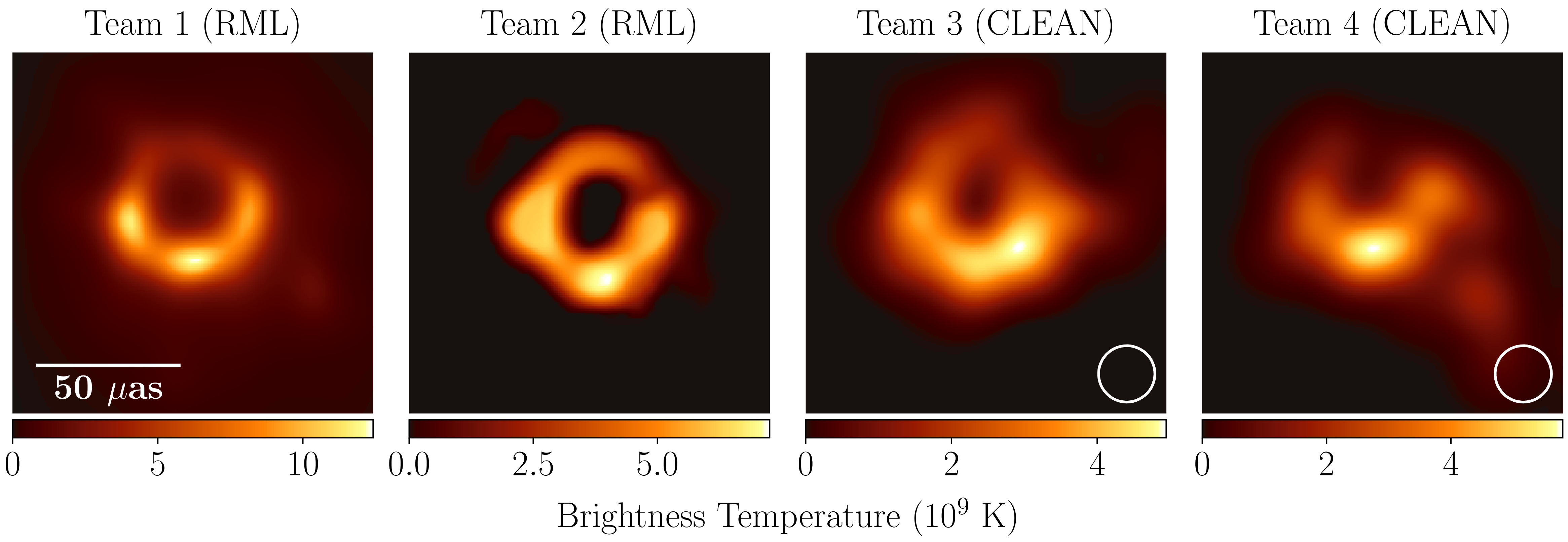
Mitigation strategy #1: regularized forward-modeling of the source emission structure

Mitigation strategy #2: multi-team blind imaging



EHT Collaboration et al. (2019d)

Imaging

Our uv-plane

- No u

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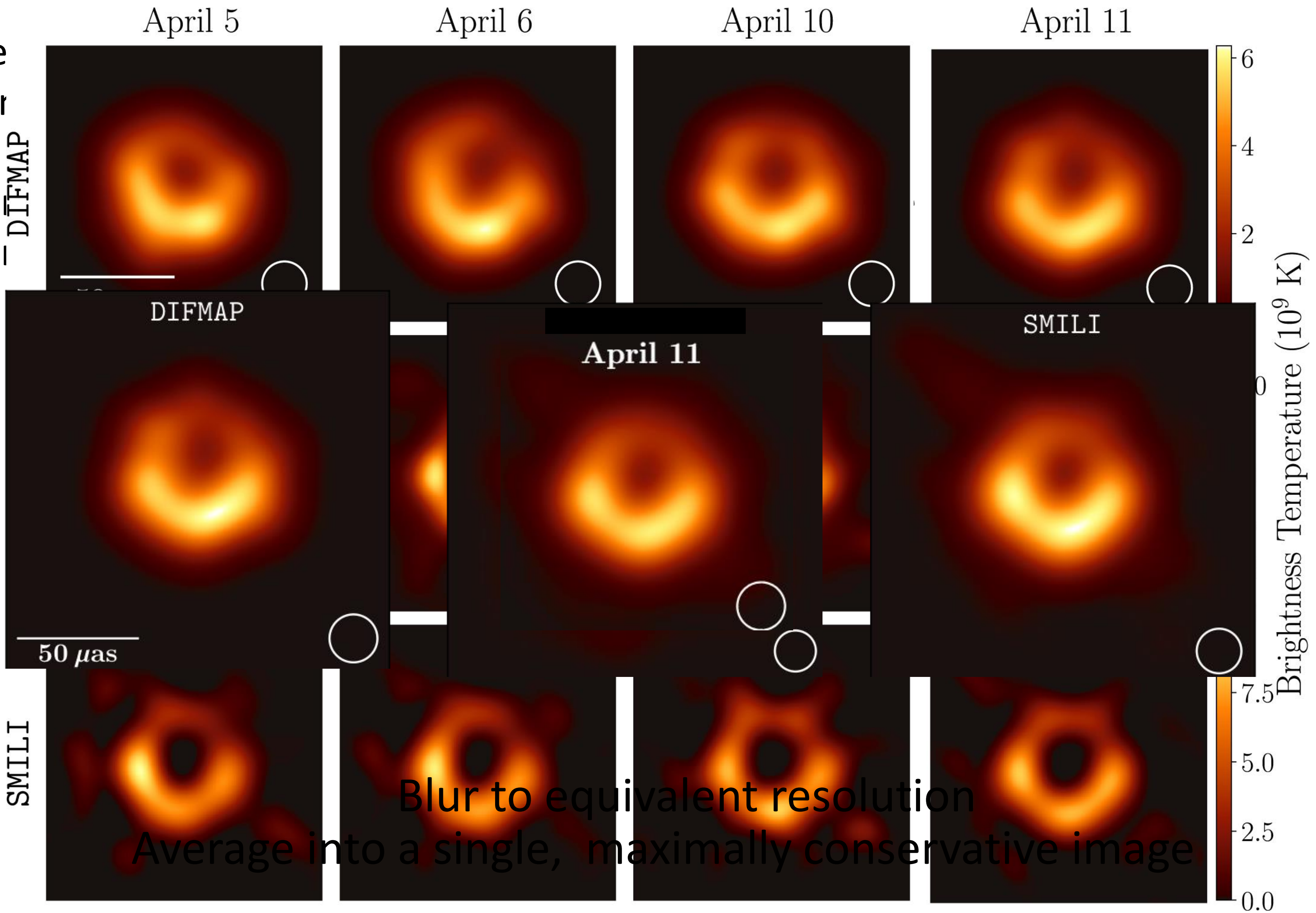

Blur to equivalent resolution

Average into a single, maximally conservative image

Credit: Katie Bouman, Andrew Chael, Daniel Palumbo

What does the image tell us?

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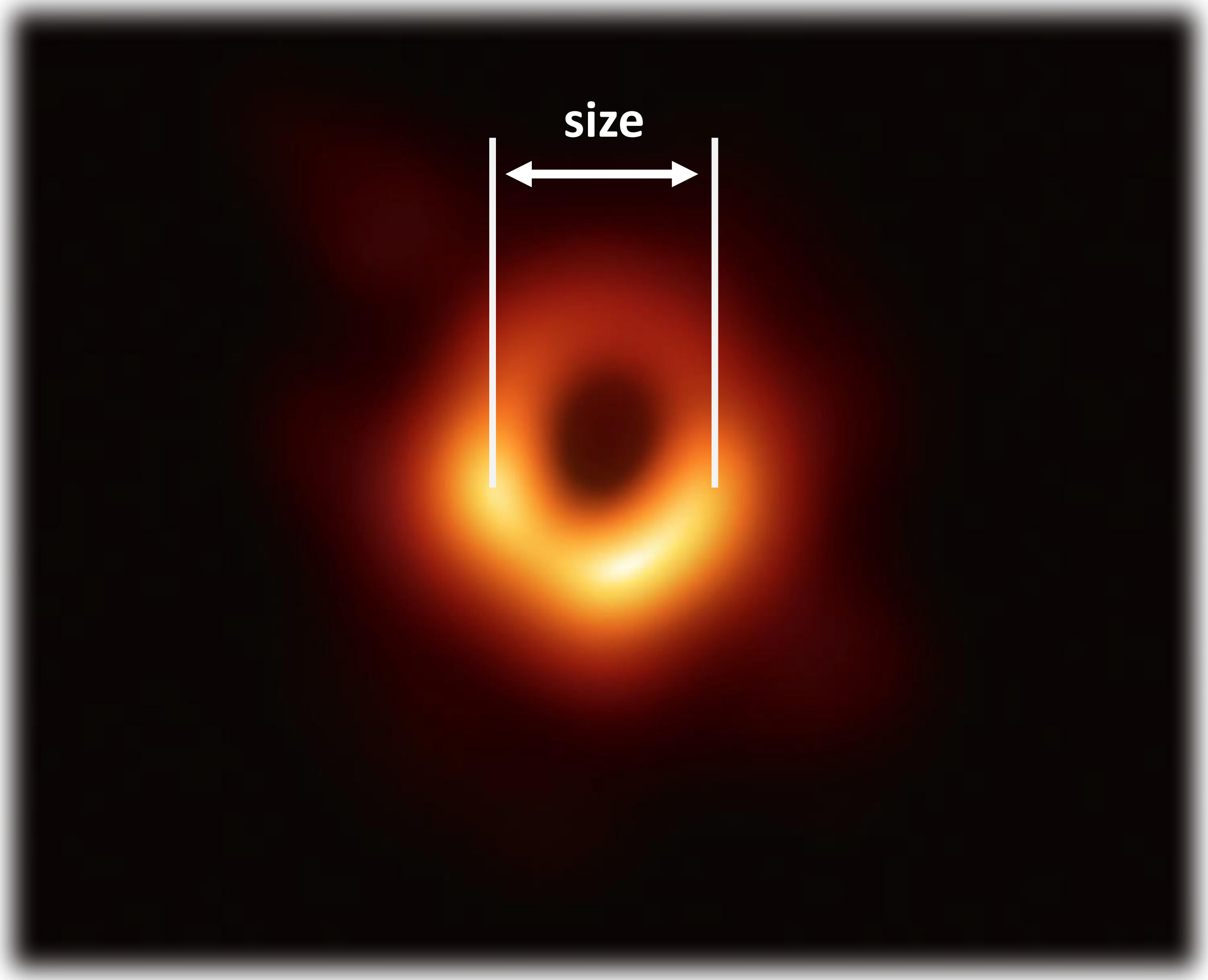
The diameter of the emission region tells us about the mass of the black hole

- We measure the mass to be 6.5 (±0.7) billion solar masses



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The diameter of the emission region tells us about the mass of the black hole

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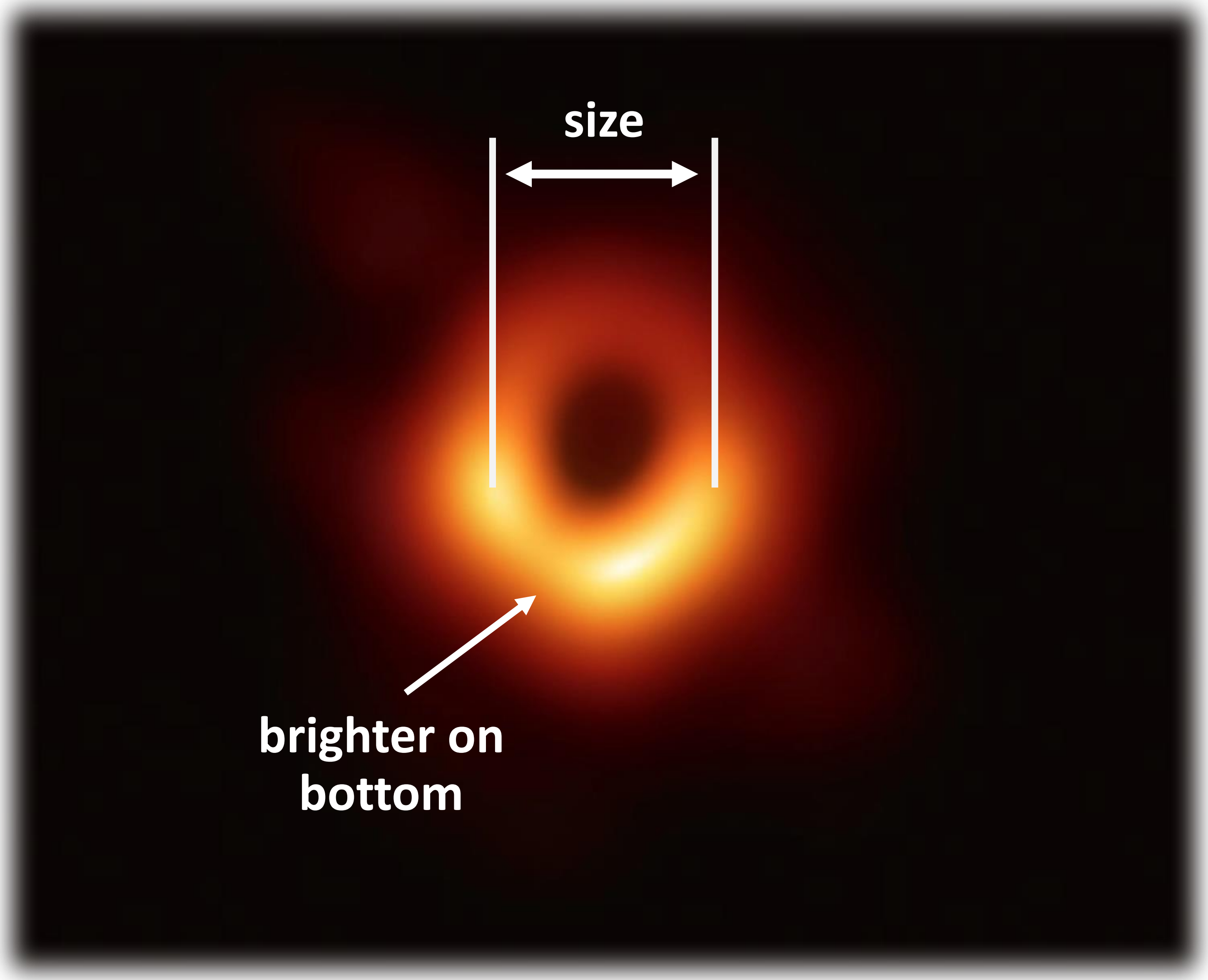
The asymmetry of the emission tells us about the black hole's angular momentum

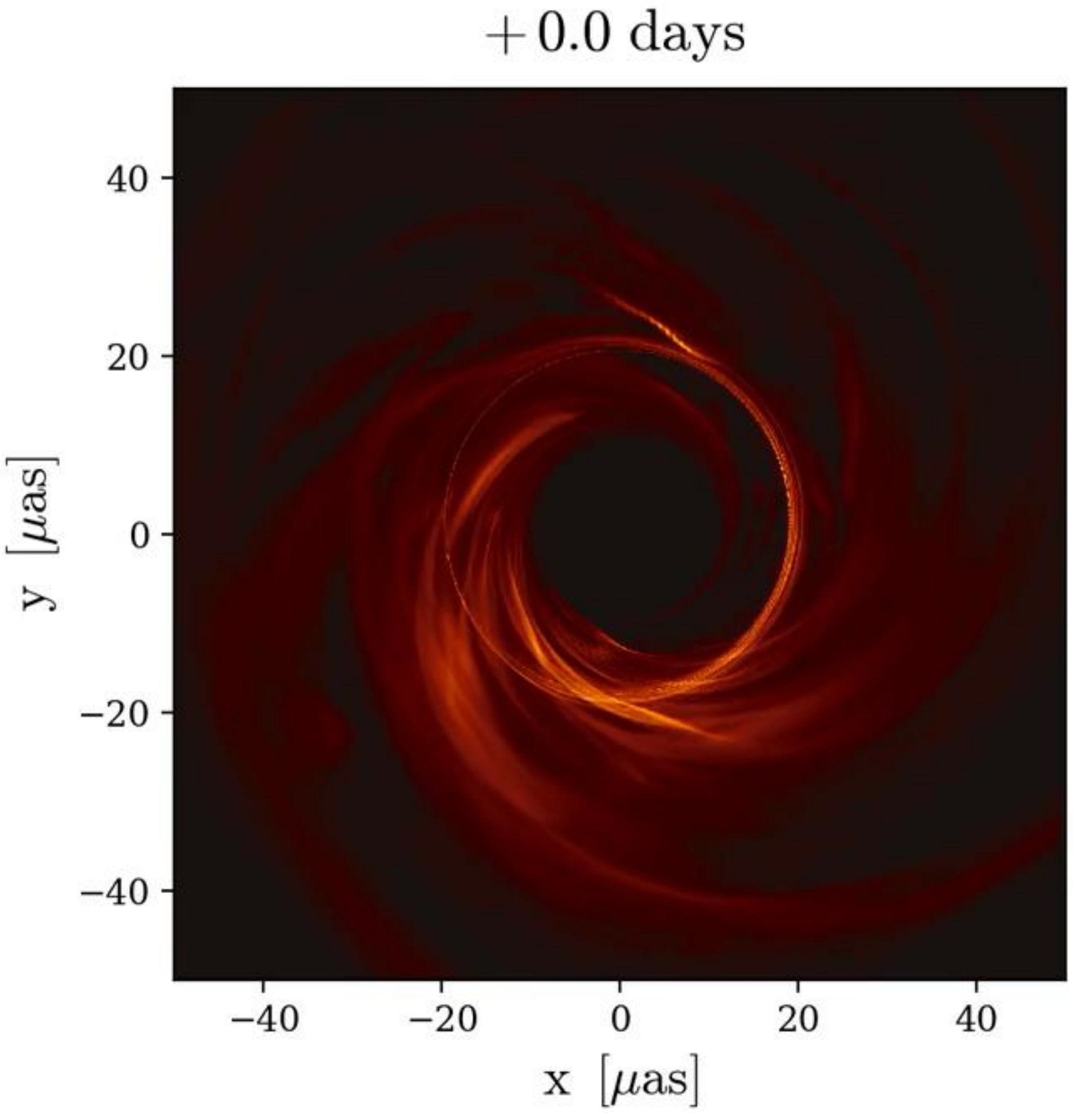
- The black hole spin axis points away from Earth



What does the image+theory tell us?

Guided by a library of general relativistic magnetohydrodynamic simulations, we find that:

- the EHT data are consistent with the image of a black hole shadow in a **Kerr spacetime**
- models that are simultaneously consistent with the EHT data and prior jet power constraints suggest that the black hole is spinning and that the jet is powered by the **Blandford-Znajek mechanism**
- the ring size, shape, and orientation are primarily set by black hole properties and thus **should not vary** from year to year



Credit: George Wong

EHT Collaboration et al. (2019e)

Summary and next steps

The 2017 EHT observing campaign successfully targeted M87, producing high-quality data

- an image of the emission region was produced
- we find that the structure is consistent with that of a 6.5 billion solar mass Kerr black hole powering a Blandford-Znajek jet

<u>Next steps</u>

Images of Sgr A*

- source is highly variable; more sophisticated algorithms are required

Full-polarization images

- Access to magnetic field structure, accretion flow physics

Add more stations to the ground array

- 2018 observations included Greenland Telescope
- 2020 observations (just a couple of weeks away!) will include Kitt Peak and NOEMA

Move to higher observing frequencies

- improved angular resolution and scattering mitigation
- multi-frequency observations