Event Horizon Telescope

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

The Event Horizon Telescope

Imaging Black Holes with a Global VLBI Array

Michael Johnson (CfA) on Behalf of the EHT Collaboration

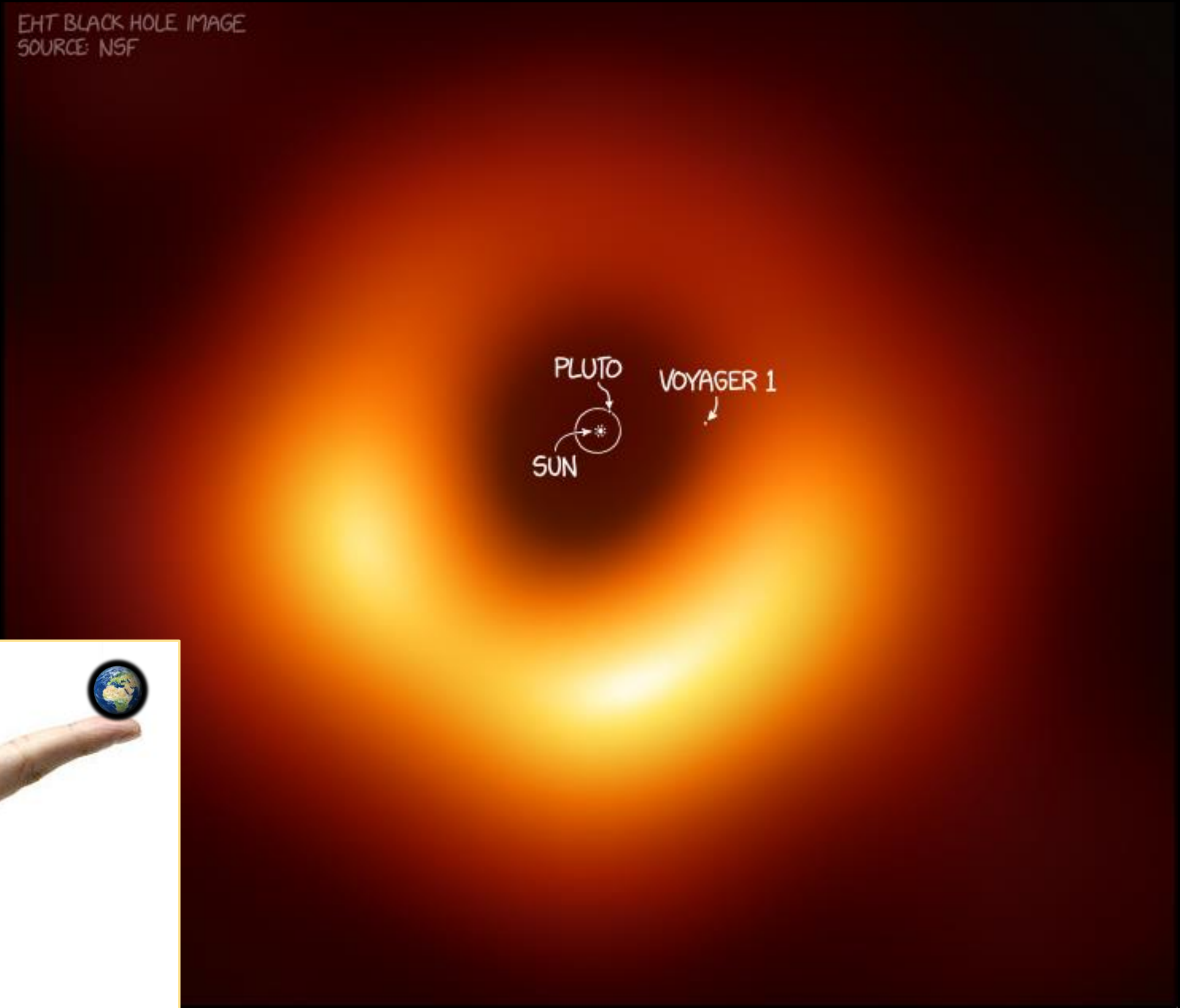
Approaching the Event Horizon: Black Holes and their Effect on the Universe

Keck Institute for Space Studies

September 16, 2019

NSF · JOHN TEMPLETON FOUNDATION · GORDON AND BETTY MOORE FOUNDATION

Credit: ESO/L. Calçada, Digitized Sky Survey 2, ESA/Hubble, RadioAstron, De Gasperin et al., Kim et al., EHT Collaboration.

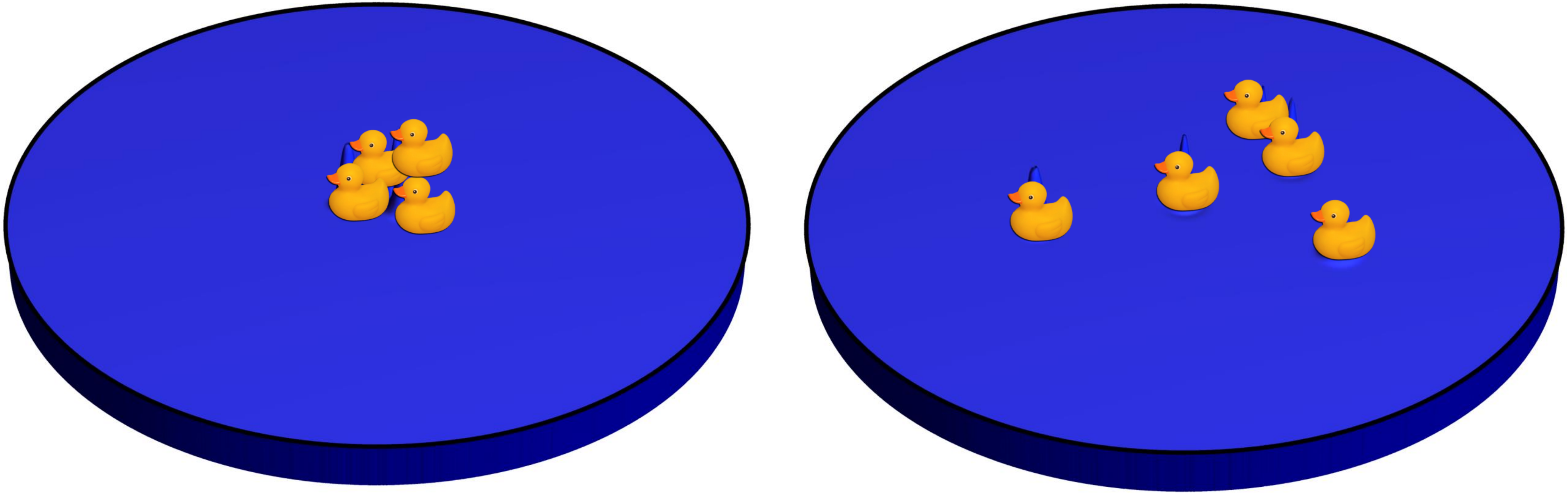


https://xkcd.com/2135/

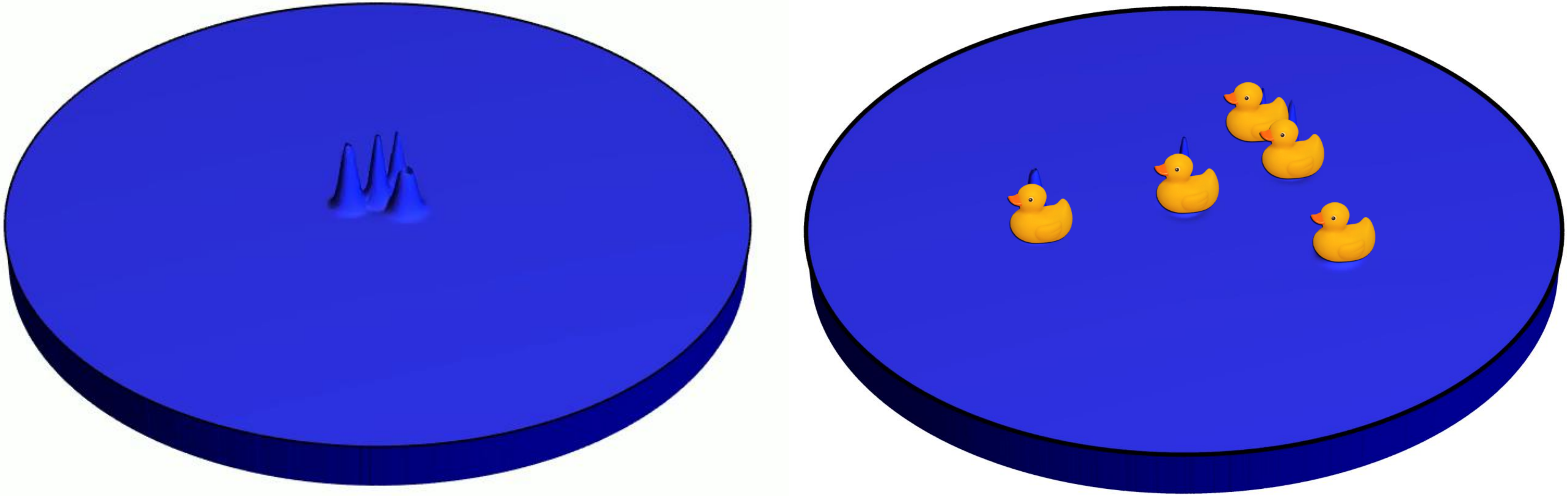
Learning Interferometry from Ducks

Knox et al., "Spatial coherence from ducks", Physics Today, March 2010

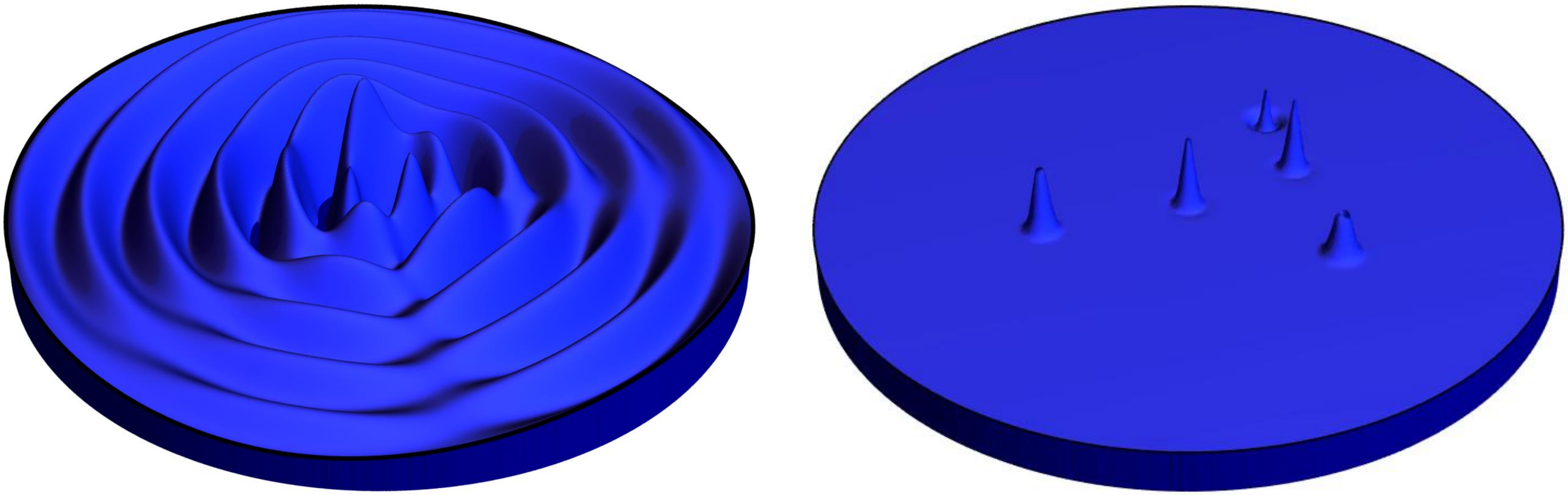
Learning Interferometry from Ducks



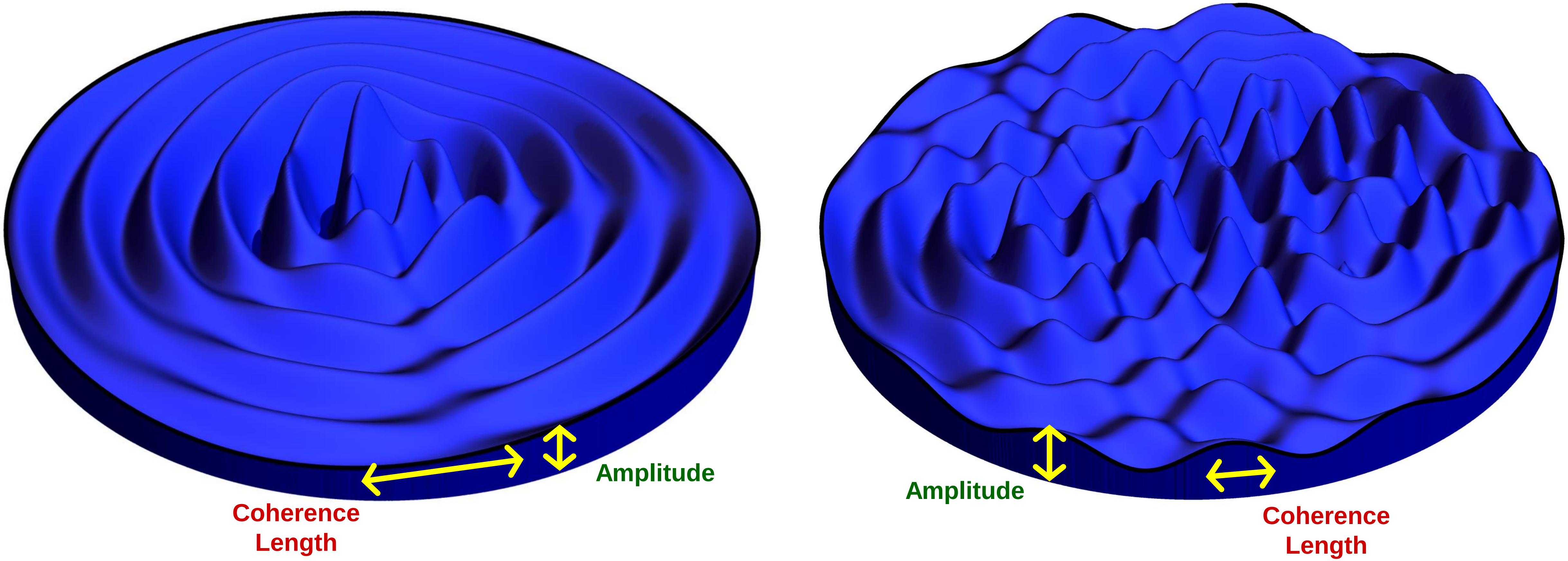
Learning Interferometry from Ducks



Learning Interferometry from Ducks



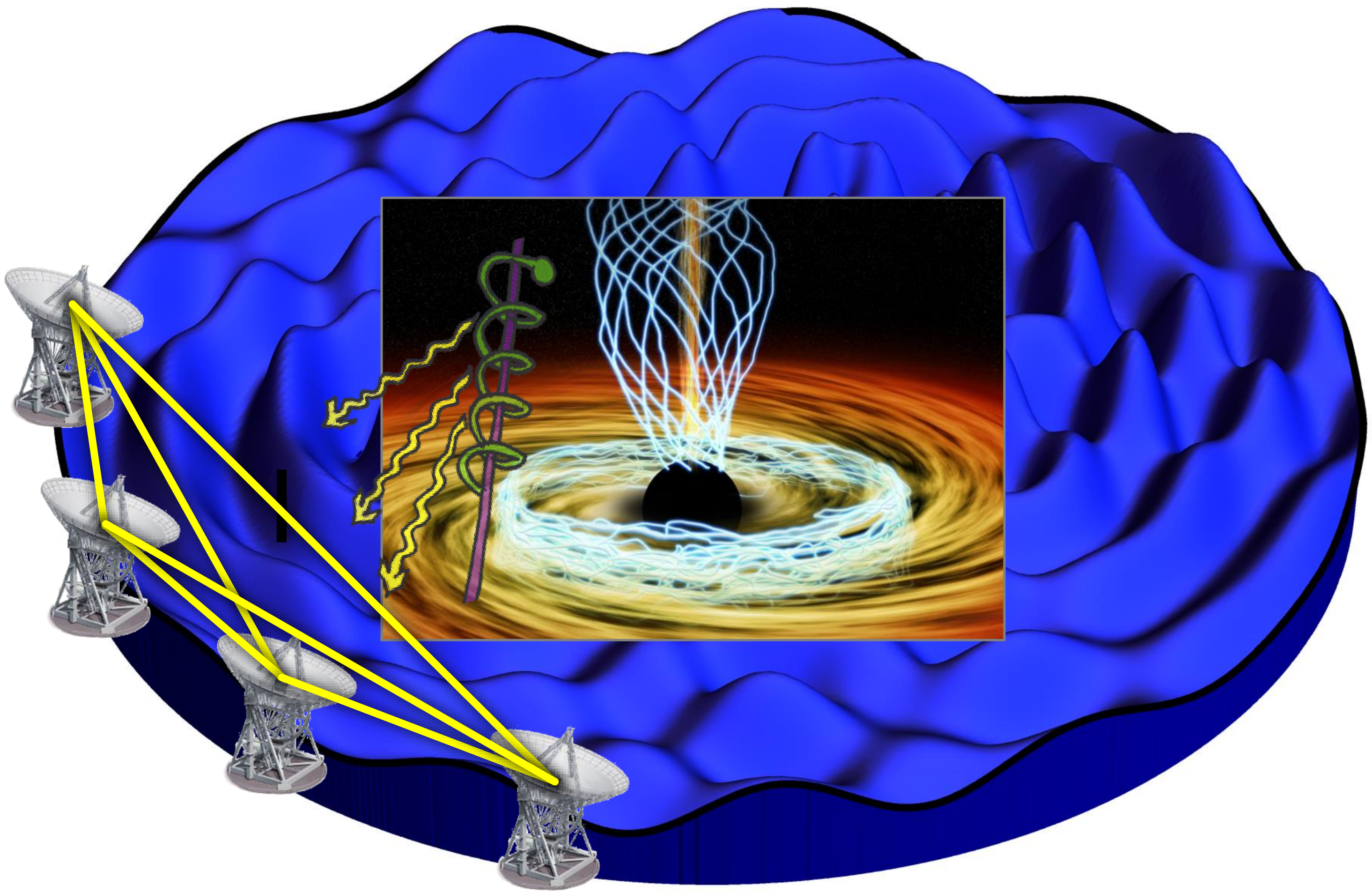
Learning Interferometry from Ducks

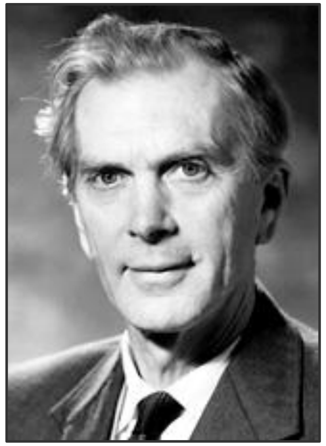


Amplitude: Tells us how many ducks are splashing (and how strongly)

Coherence Length: Tells us how spread out they are

Learning Interferometry from Ducks



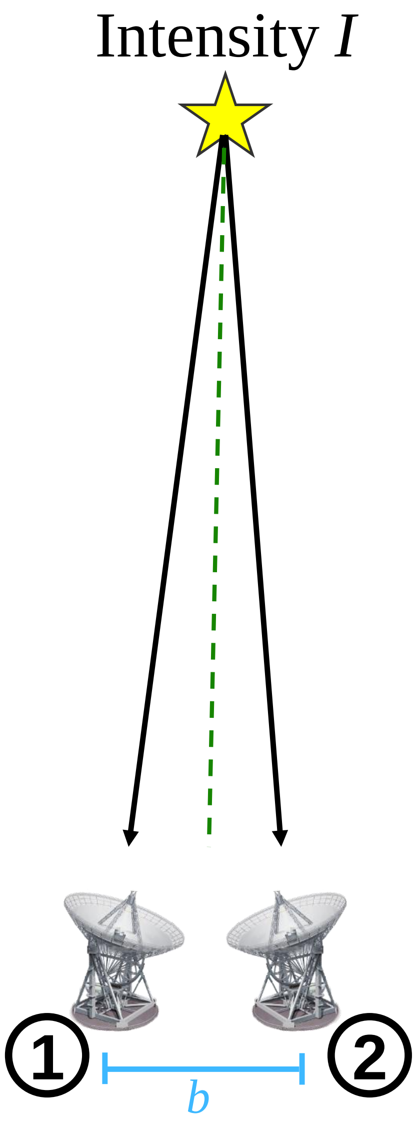


Martin Ryle
1974 Nobel Prize

By studying how fluctuations of electromagnetic waves are correlated among different telescopes, we can make an image of the source!

Image Credit: CfA/M. Weiss; Nobelprize.org

Mutual Coherence and the van Cittert-Zernike Theorem

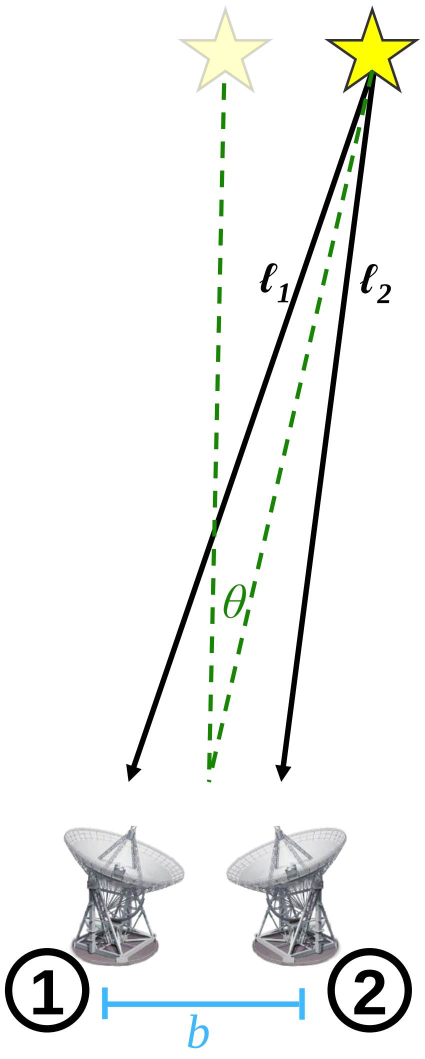


The *interferometric visibility* $V(b)$ is the spatial correlation (or two-point function) of the incident electric field: $V(b) = \langle E_1 E_2^* \rangle$

Key Properties:

- Astrophysical sources emit noise!
- The incident electric field is a Gaussian random variable so is fully characterized by this two-point function
- For a centered point source, the fields are identical and the visibility is just the intensity of the point source no matter what the length of the baseline is: $V(b) = I$

Mutual Coherence and the van Cittert-Zernike Theorem



For a displaced point source, the path lengths to the telescopes are no longer equal: $\boldsymbol{\ell_1 - \ell_2} \approx \boldsymbol{b}\,\theta$

This is equivalent to a differential phase wrap:

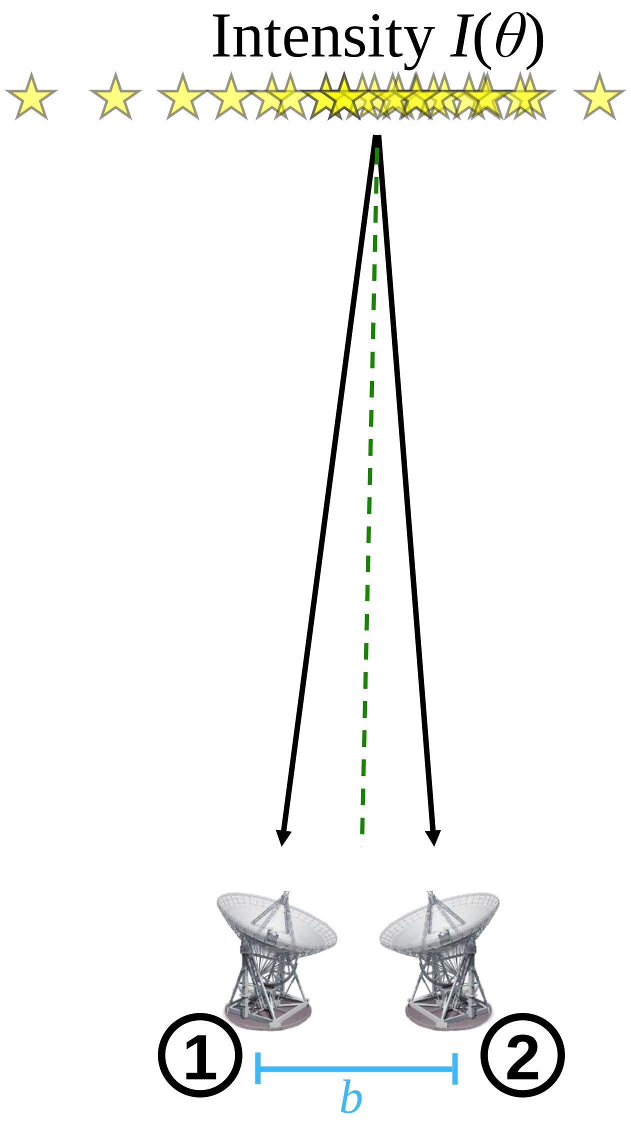
$$V(b) = \langle E_1 E_2^* \rangle$$
$$= I\, e^{-ikb\theta}$$
$$= I\, e^{-2\pi i b\theta/\lambda}$$
$$= I\, e^{-2\pi i u\theta}$$

where k is wavenumber, λ is wavelength, and $u=b/\lambda$ is the (dimensionless) baseline length in wavelengths.

Key Properties:

- The extra visibility phase depends on both the dimensionless baseline length and the angular displacement of the source
- The visibility magnitude $|V(b)|$ is unaffected by displacement
- The characteristic resolution of the interferometer is $1/u = \lambda/b$
- Displacements orthogonal to the baseline have no effect

Mutual Coherence and the van Cittert-Zernike Theorem



A continuous brightness distribution can be written as a sum of point sources, $I(\theta)$:

$$\boxed{V(\vec{u}) = \int \mathrm{d}^2\vec{\theta}\, I(\vec{\theta})e^{-2\pi i \vec{u}\cdot\vec{\theta}}}$$

This is the van Cittert-Zernike Theorem.

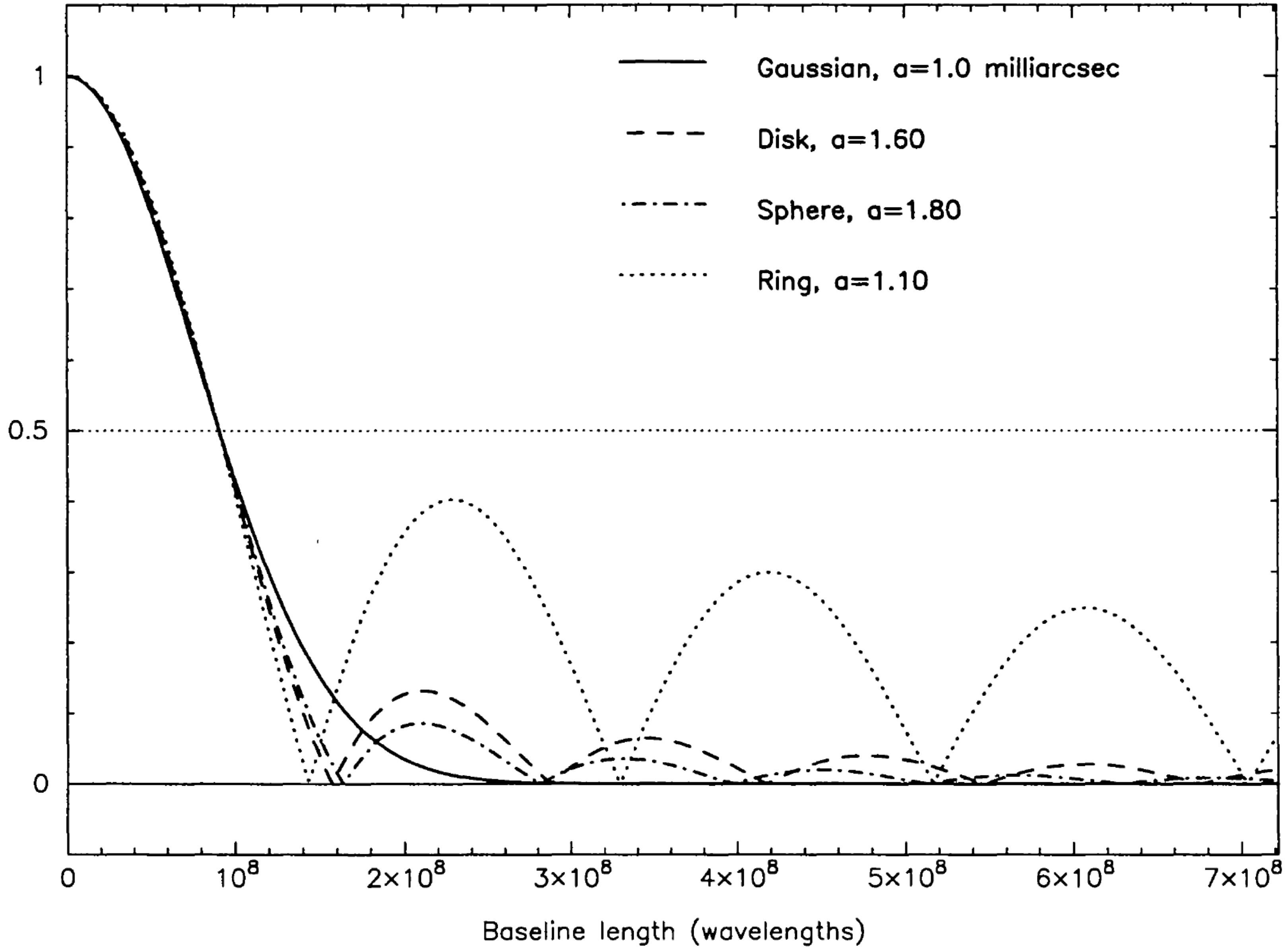
Key Properties:

- The visibility function is the Fourier transform of the image
- The visibility magnitude $|V(u)|$ is maximum at u=0, where it gives the total intensity of the source
- The visibility magnitude $|V(u)|$ falls as baselines begin to resolve the source

Issaoun+ (2019)

Physical Analog	Image Domain		Visibility Domain	
Mass	Total Flux	$\int I(\mathbf{x})d^2\mathbf{x}$	Peak Visibility	$V(\mathbf{0})$
Center of Mass	Centroid ($\boldsymbol{\mu}$)	$V(\mathbf{0})^{-1}\int \mathbf{x}I(\mathbf{x})d^2\mathbf{x}$	Phase Gradient	$(2\pi i V(\mathbf{0}))^{-1}\,\nabla V(\mathbf{u})\rfloor_{\mathbf{u}=\mathbf{0}}$
Moment of Inertia	Covariance ($\boldsymbol{\Sigma}$)	$V(\mathbf{0})^{-1}\int \mathbf{x}\mathbf{x}^{\intercal}I(\mathbf{x})d^2\mathbf{x}$	Amplitude Curvature	$(-4\pi^2 V(\mathbf{0}))^{-1}\,\nabla\nabla^{\intercal}V(\mathbf{u})\rfloor_{\mathbf{u}=\mathbf{0}}$

Example Image-Visibility Pairs



Pearson (1999)

Resolution Limits for Imaging

Ordinary Imaging:

Resolution depends on wavelength (λ) and telescope diameter (D): λ/D

- Human Eye: ~arcminute
- Radio Telescopes: ~arcminutes
- Optical Telescopes: ~50 milliarcseconds (mas)

Resolution Limits for Imaging

Ordinary Imaging:

Resolution depends on wavelength (λ) and telescope diameter (D): λ/D

- Human Eye: ~arcminute
- Radio Telescopes: ~arcminutes
- Optical Telescopes: ~50 milliarcseconds (mas)

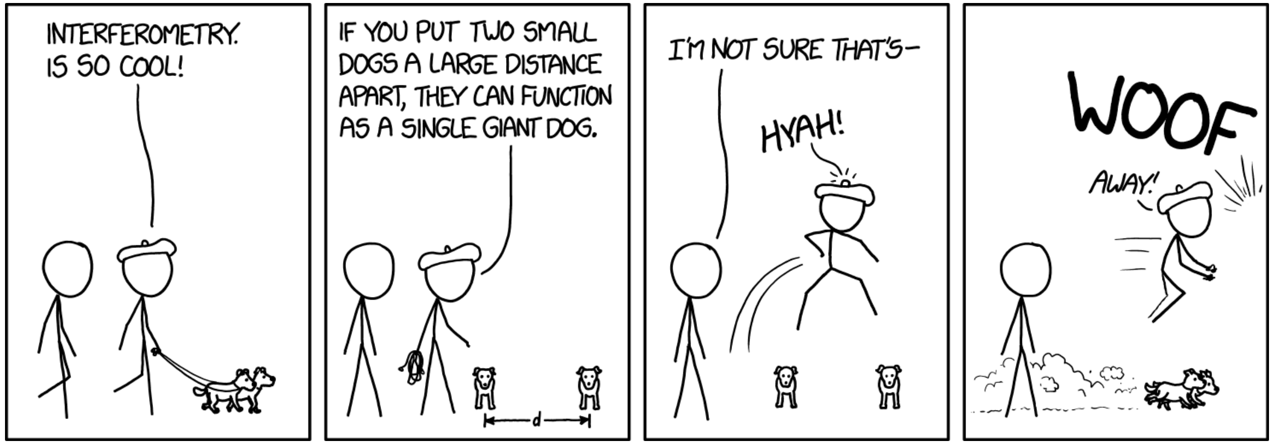
Interferometric Imaging:

Resolution depends on wavelength (λ) and separation of telescopes (b): λ/b

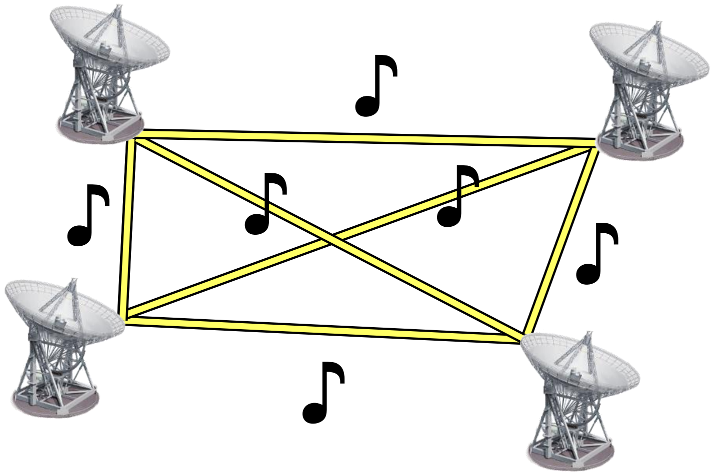
Longer baselines = Higher angular resolution

But there's a price to pay: we don't directly make images

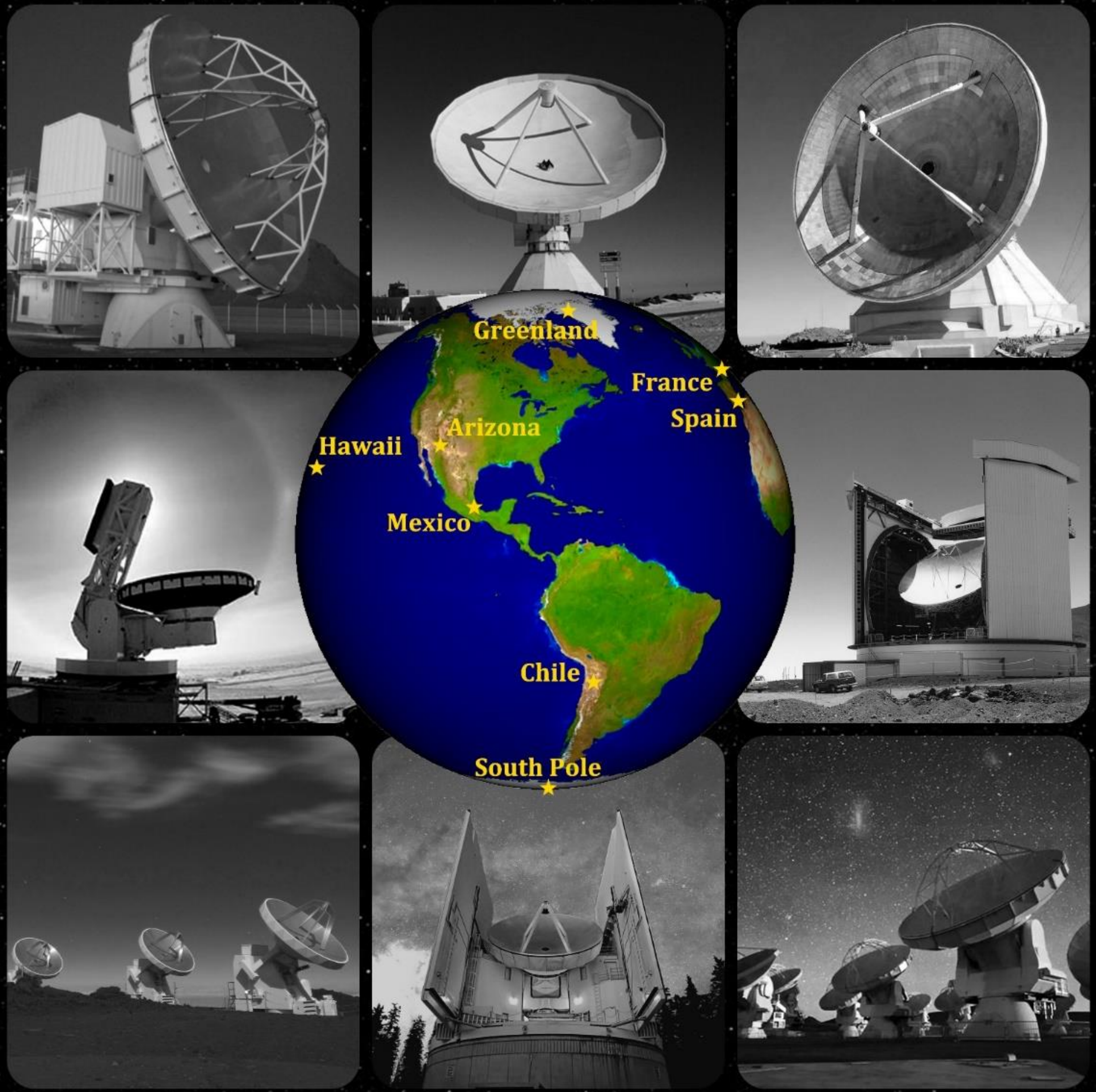
Each baseline only samples one frequency



https://xkcd.com/1922/

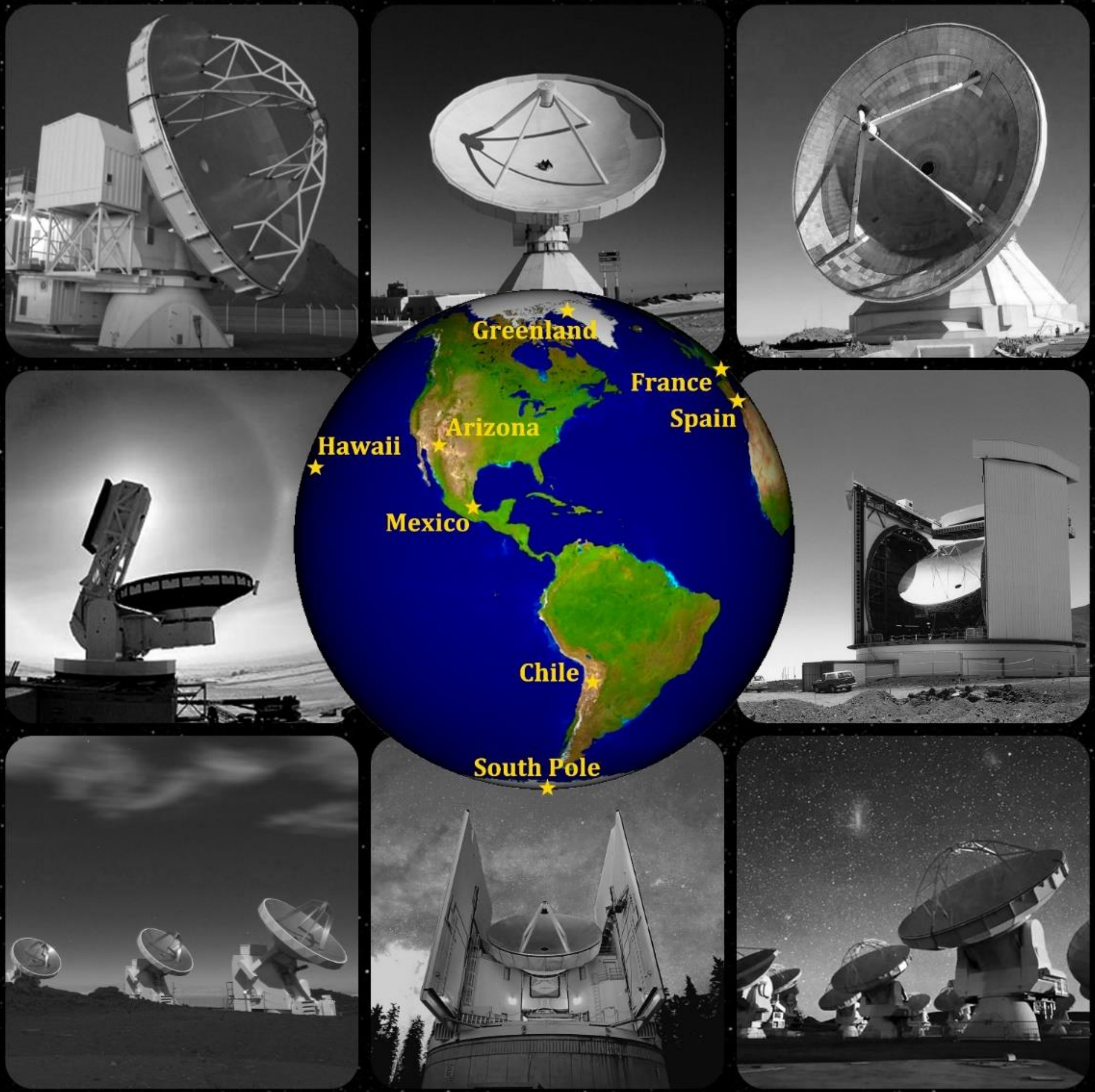


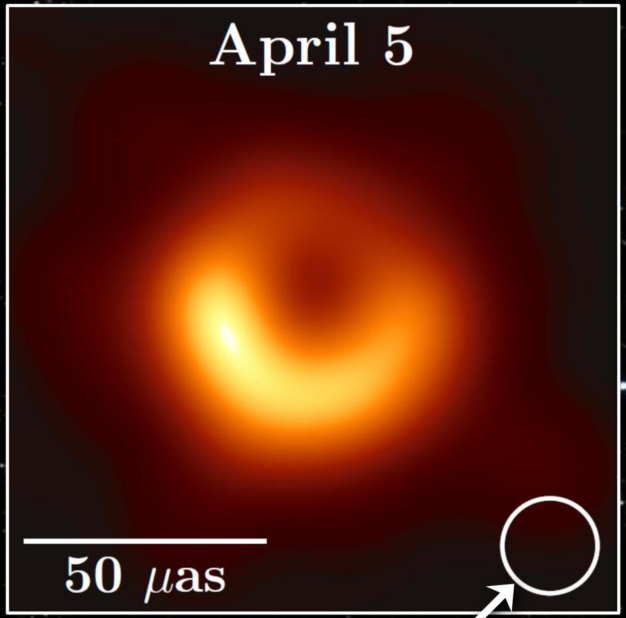
The Event Horizon Telescope



Credit: K. Johnson, APEX, IRAM, G. Narayanan, J. McMahon, JCMT/JAC, S. Hostler, D. Harvey, ESO/C. Malin

The Event Horizon Telescope



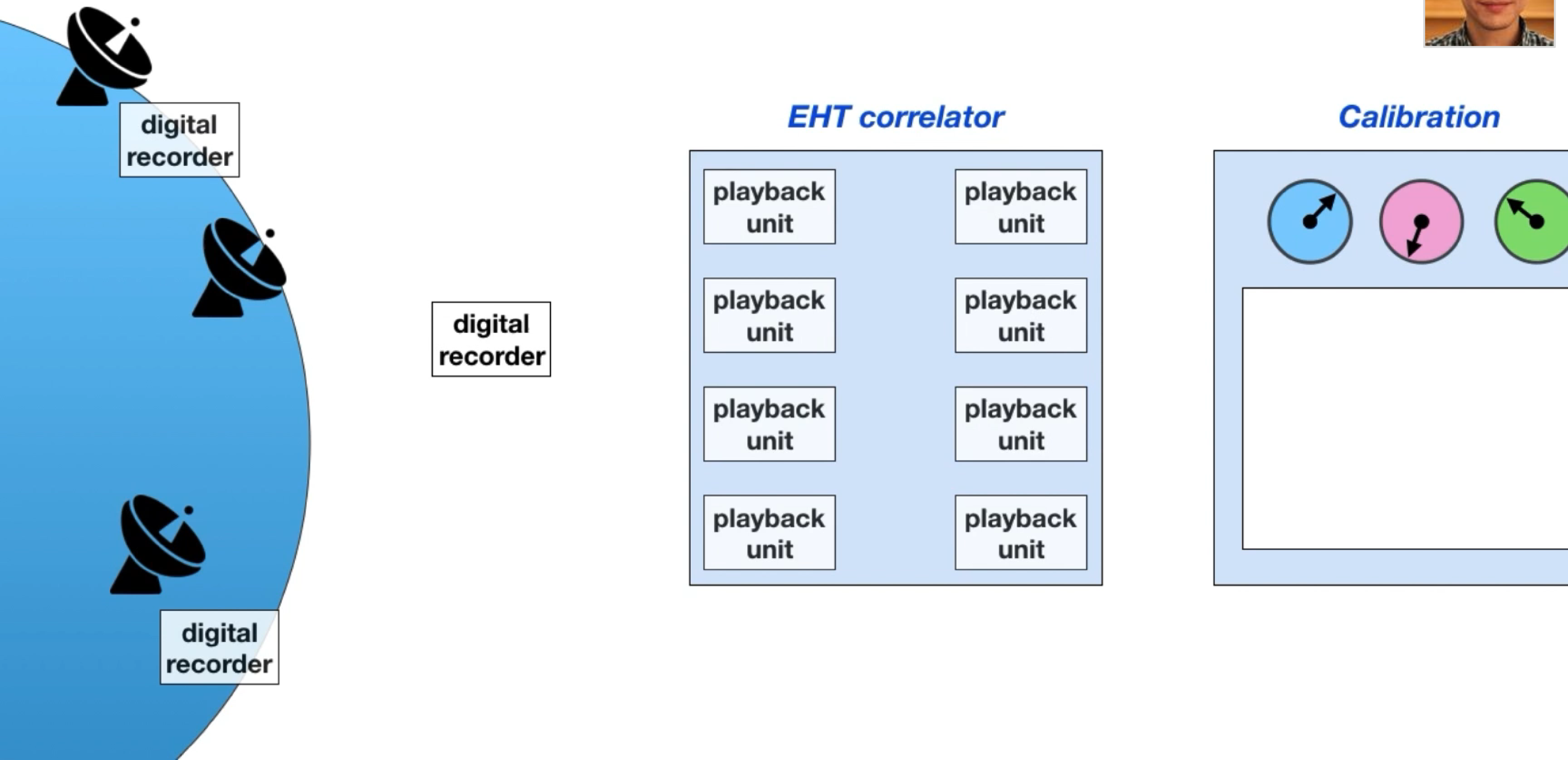


EHT Resolution: ~20 μas

230 GHz ↔ 1.3 mm

Credit: K. Johnson, APEX, IRAM, G. Narayanan, J. McMahon, JCMT/JAC, S. Hostler, D. Harvey, ESO/C. Malin

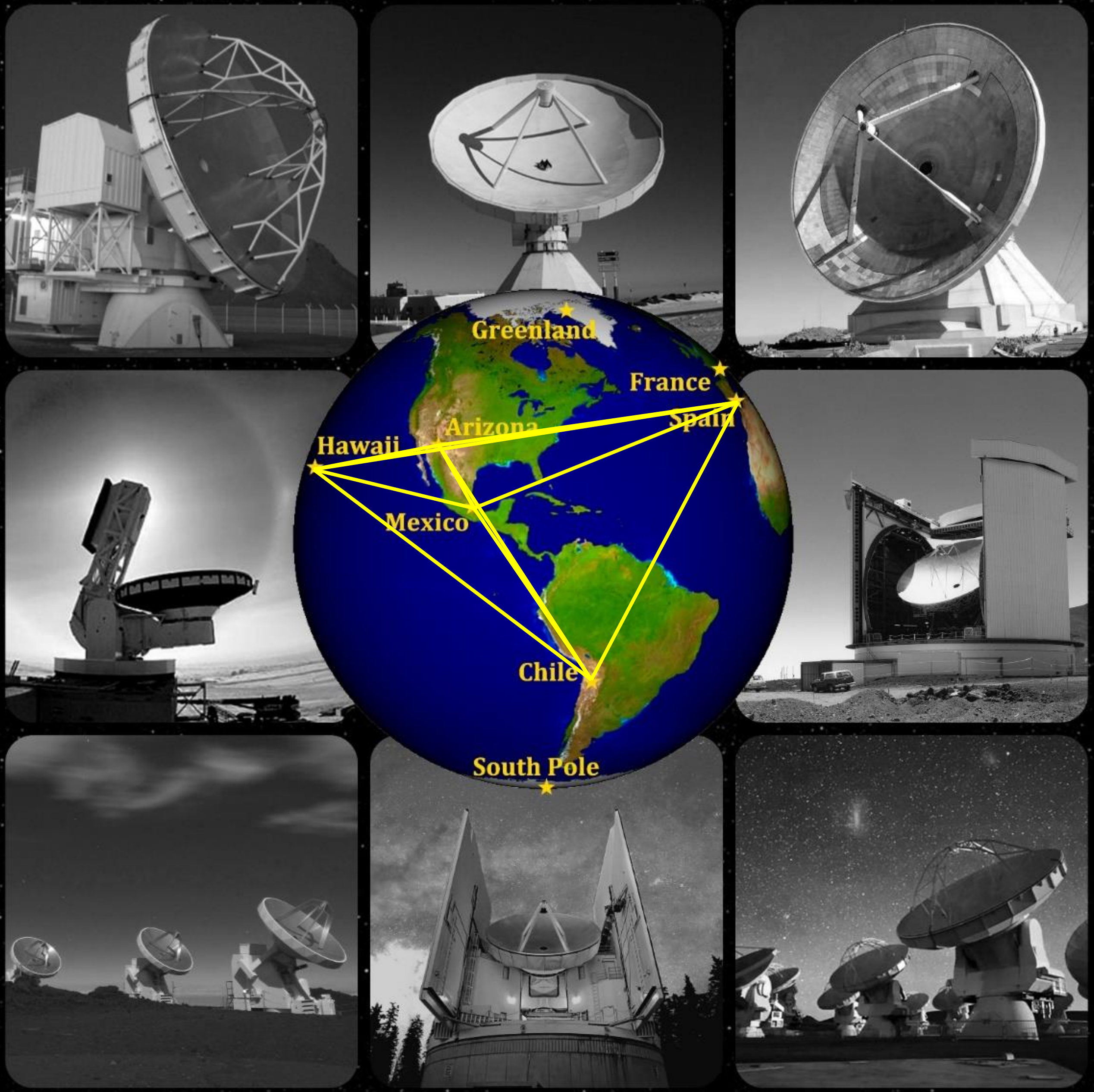
Credit: Lindy Blackburn

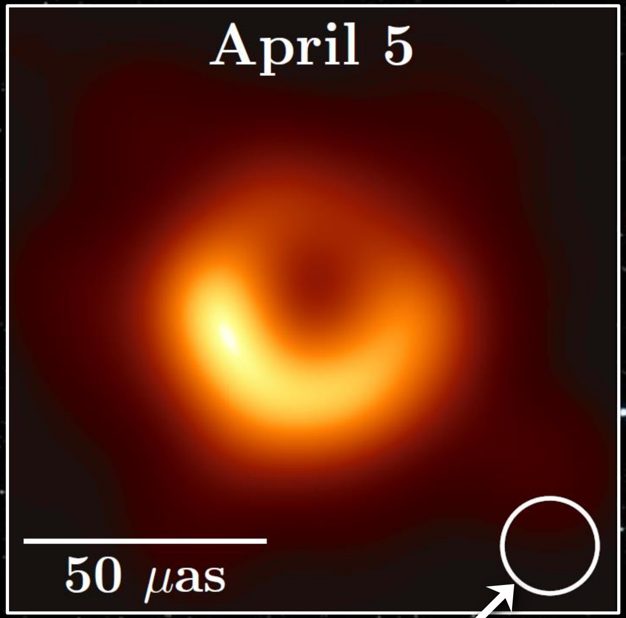


The Event Horizon Telescope

With 5 sites in 2017 that could see M87, the EHT only samples 10 frequencies.

How can that be enough?



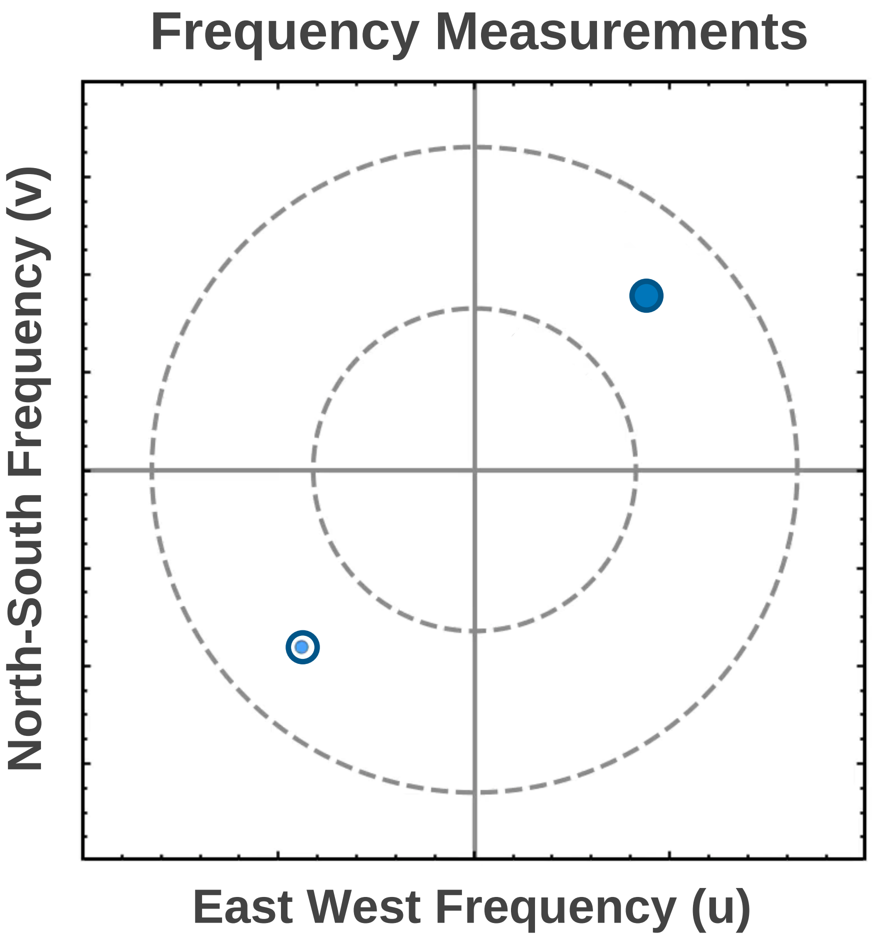


EHT Resolution: ~20 μas

230 GHz ↔ 1.3 mm

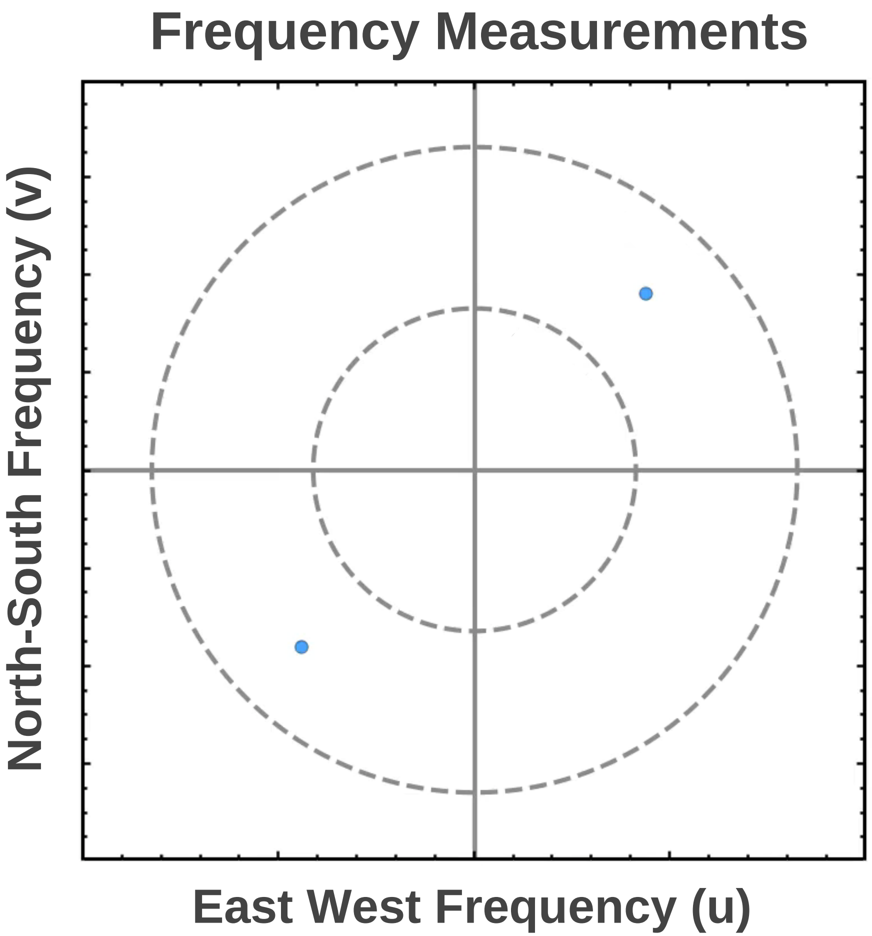
Credit: K. Johnson, APEX, IRAM, G. Narayanan, J. McMahon, JCMT/JAC, S. Hostler, D. Harvey, ESO/C. Malin

We can also make the Earth part of our instrument!



Simulation Credit: Katie Bouman, Daniel Palumbo, Maciek Wielgus

We can also make the Earth part of our instrument!

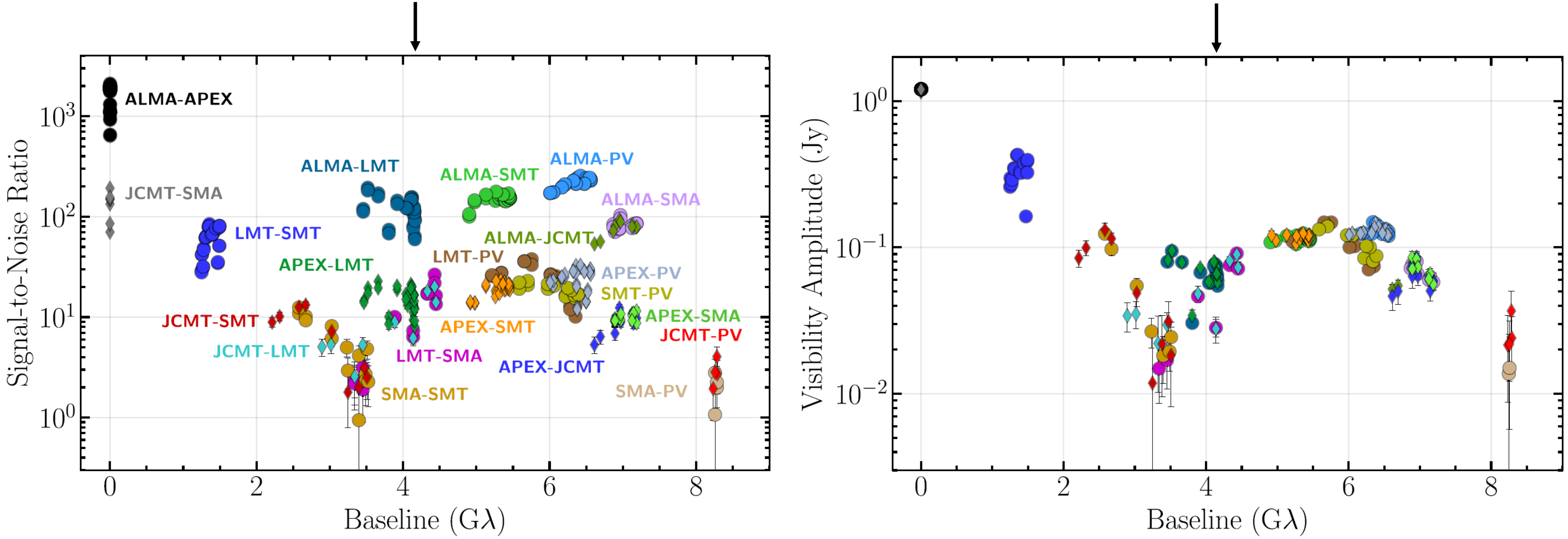


Simulation Credit: Daniel Palumbo, Katie Bouman, Maciek Wielgus

Visibilities for M87

What the EHT directly measures (dimensionless)

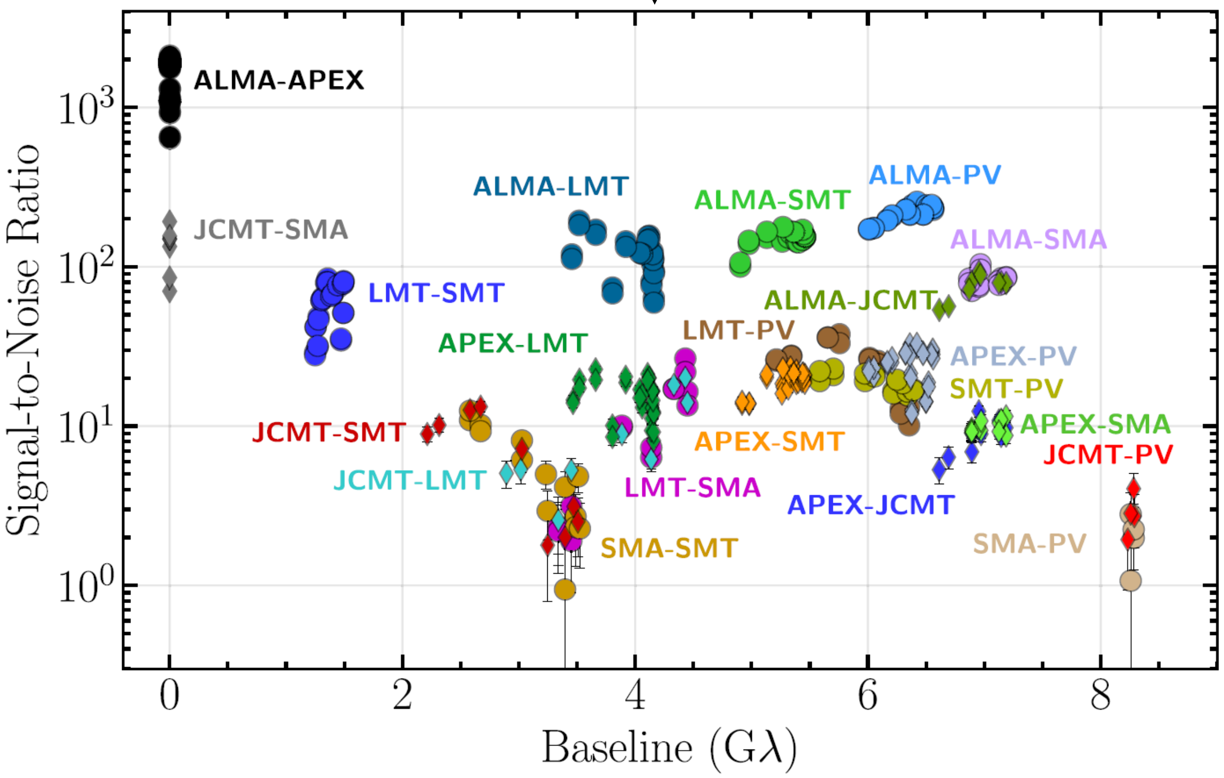
After calibration (units of flux density)



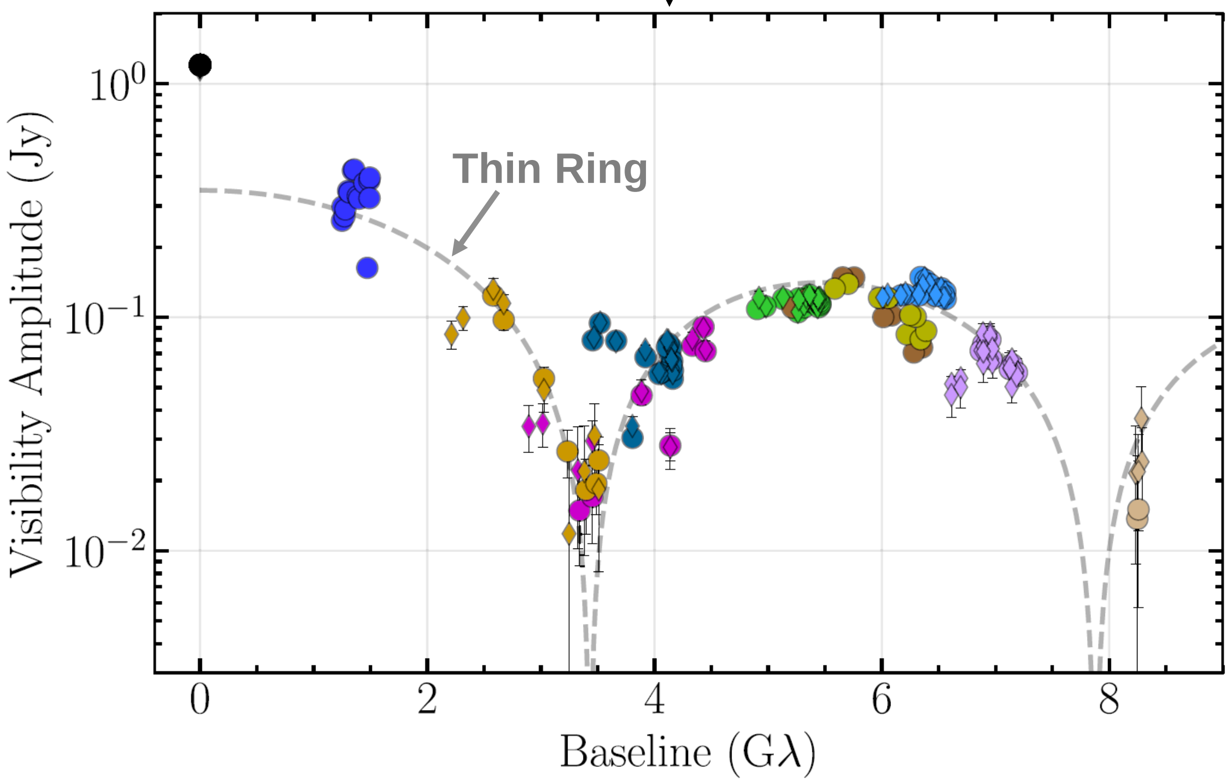
EHTC+ (2019)

Visibilities for M87

What the EHT directly measures (dimensionless)

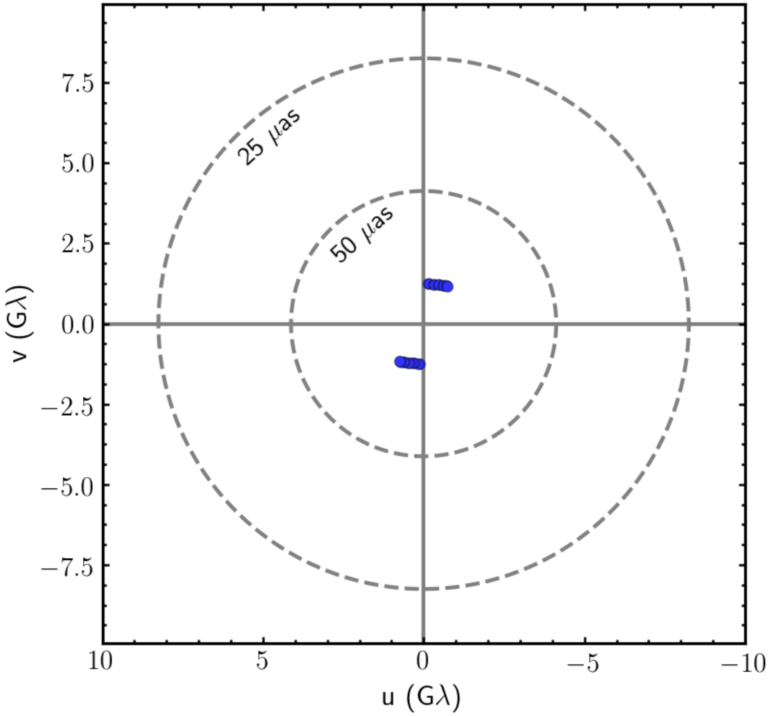


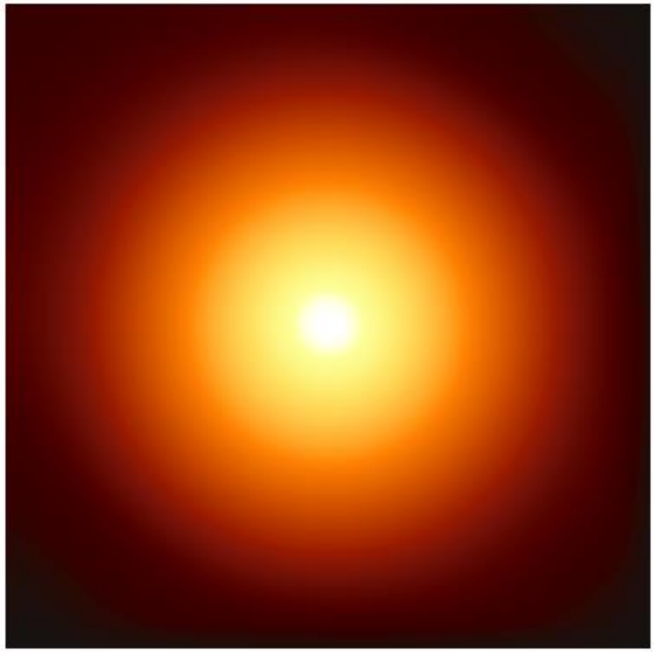
After calibration (units of flux density)



EHTC+ (2019)

Data → Image: the Importance of New Sites

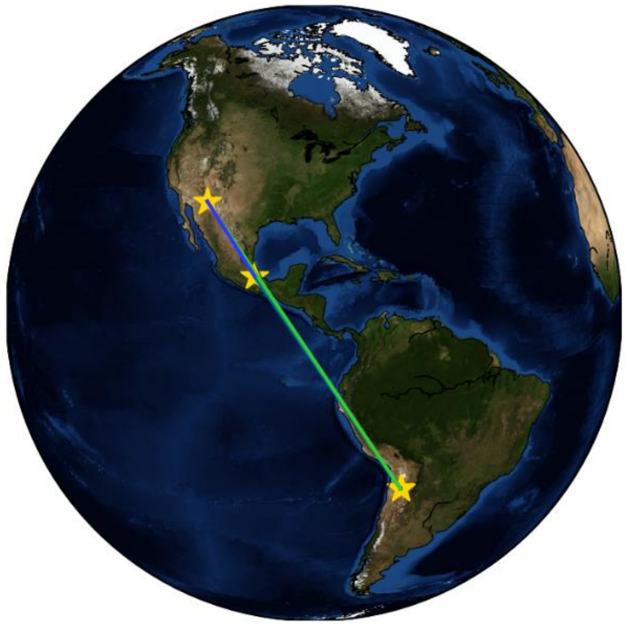


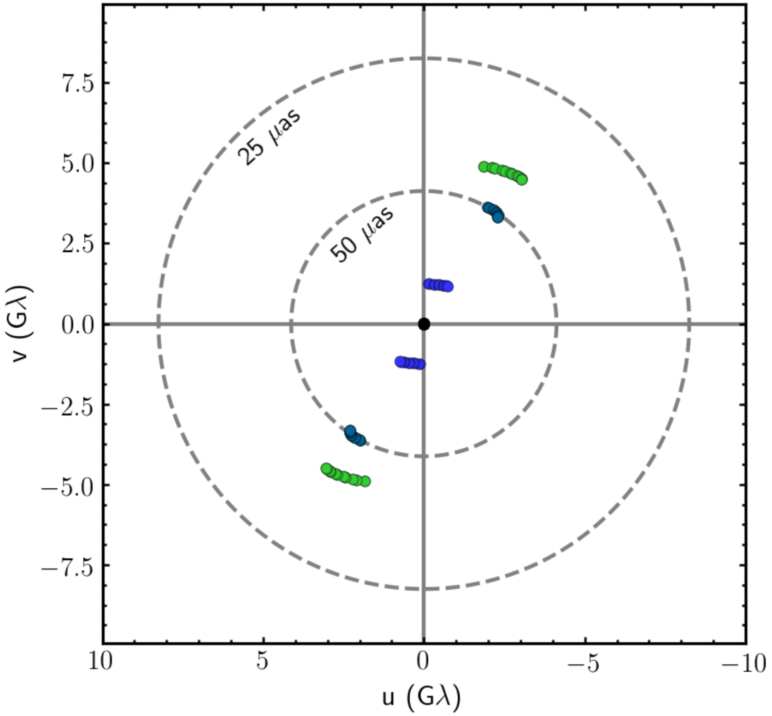


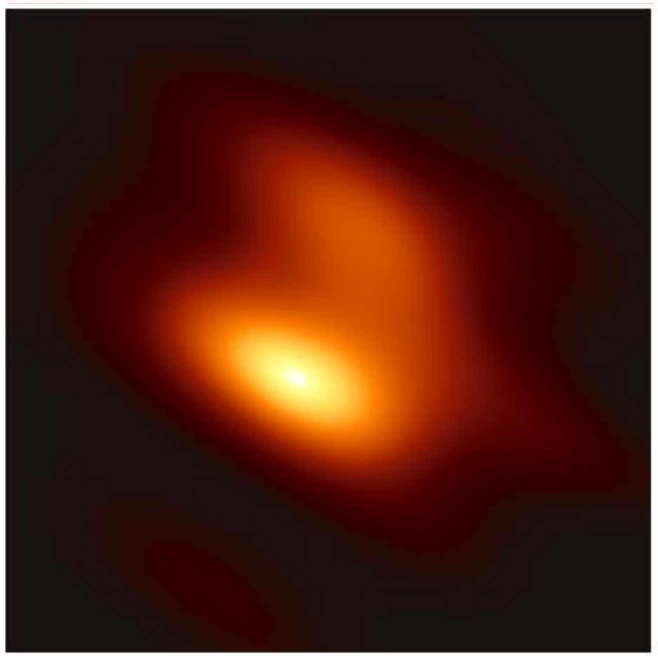
2 Sites ↔ 1 Baseline

Basic Imaging Goal: Find the most conservative image that is consistent with the input data

Data → Image: the Importance of New Sites



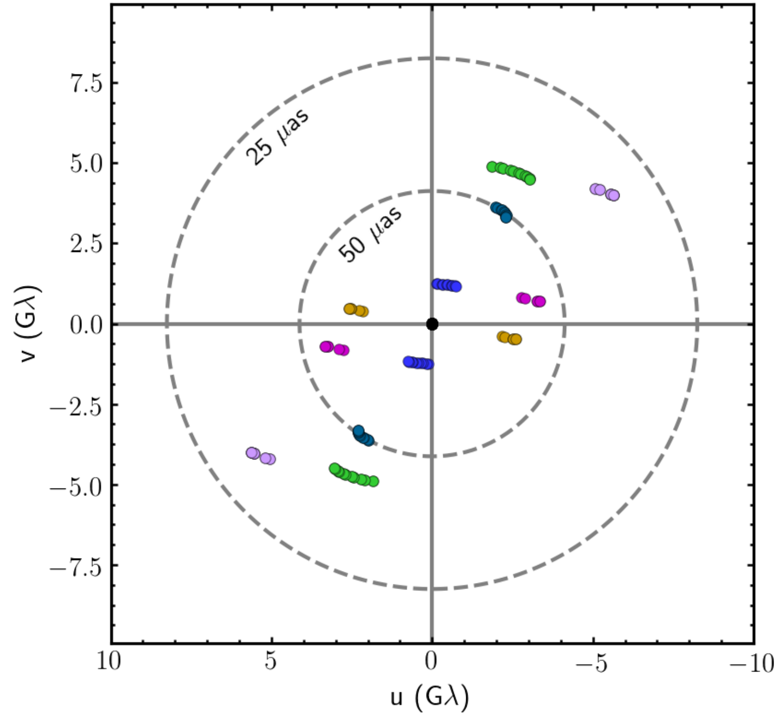


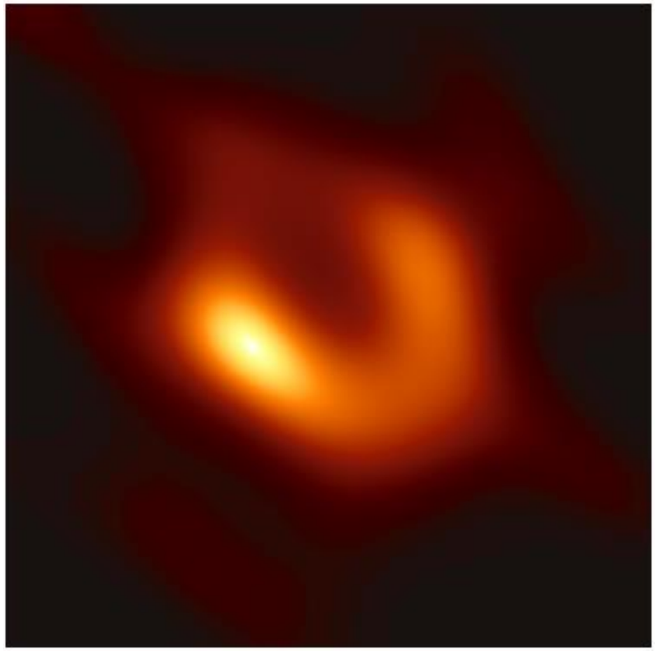


3 Sites ↔ 3 Baselines

Basic Imaging Goal: Find the most conservative image that is consistent with the input data

Data → Image: the Importance of New Sites

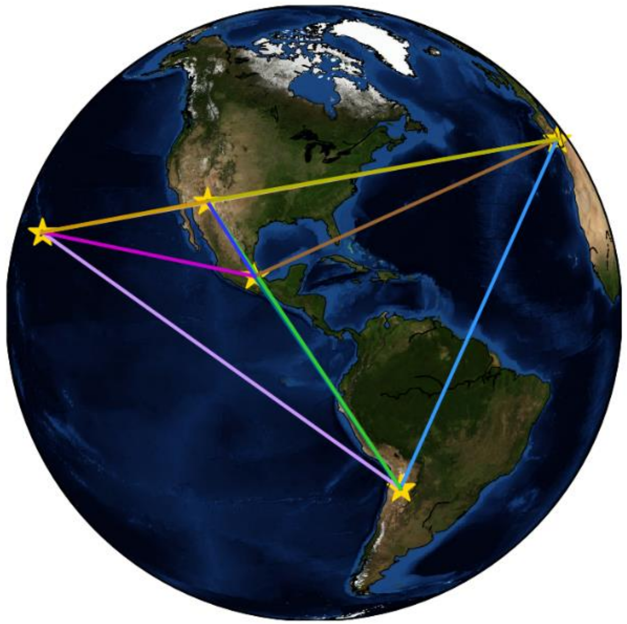


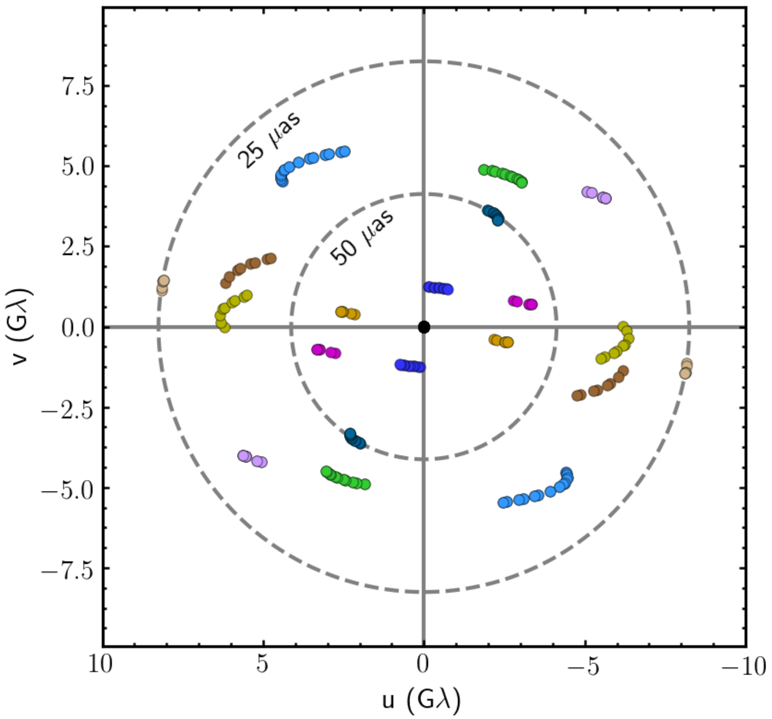


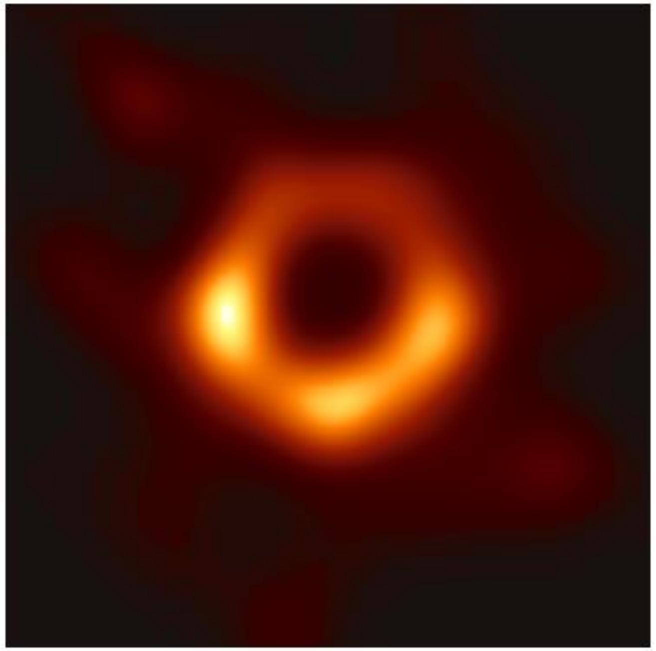
4 Sites ↔ 6 Baselines

Basic Imaging Goal: Find the most conservative image that is consistent with the input data

Data → Image: the Importance of New Sites



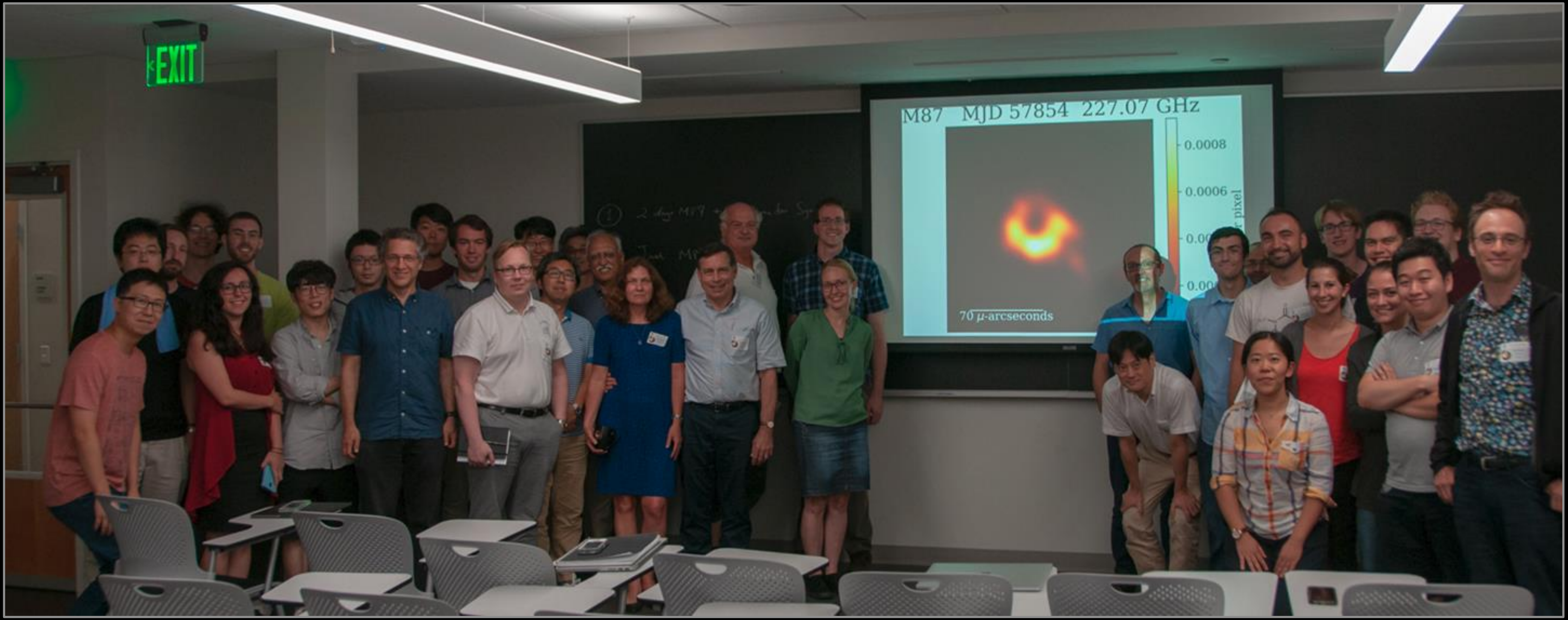




5 Sites ↔ 10 Baselines

Basic Imaging Goal: Find the most conservative image that is consistent with the input data

The First EHT Images of M87
July 24, 2018

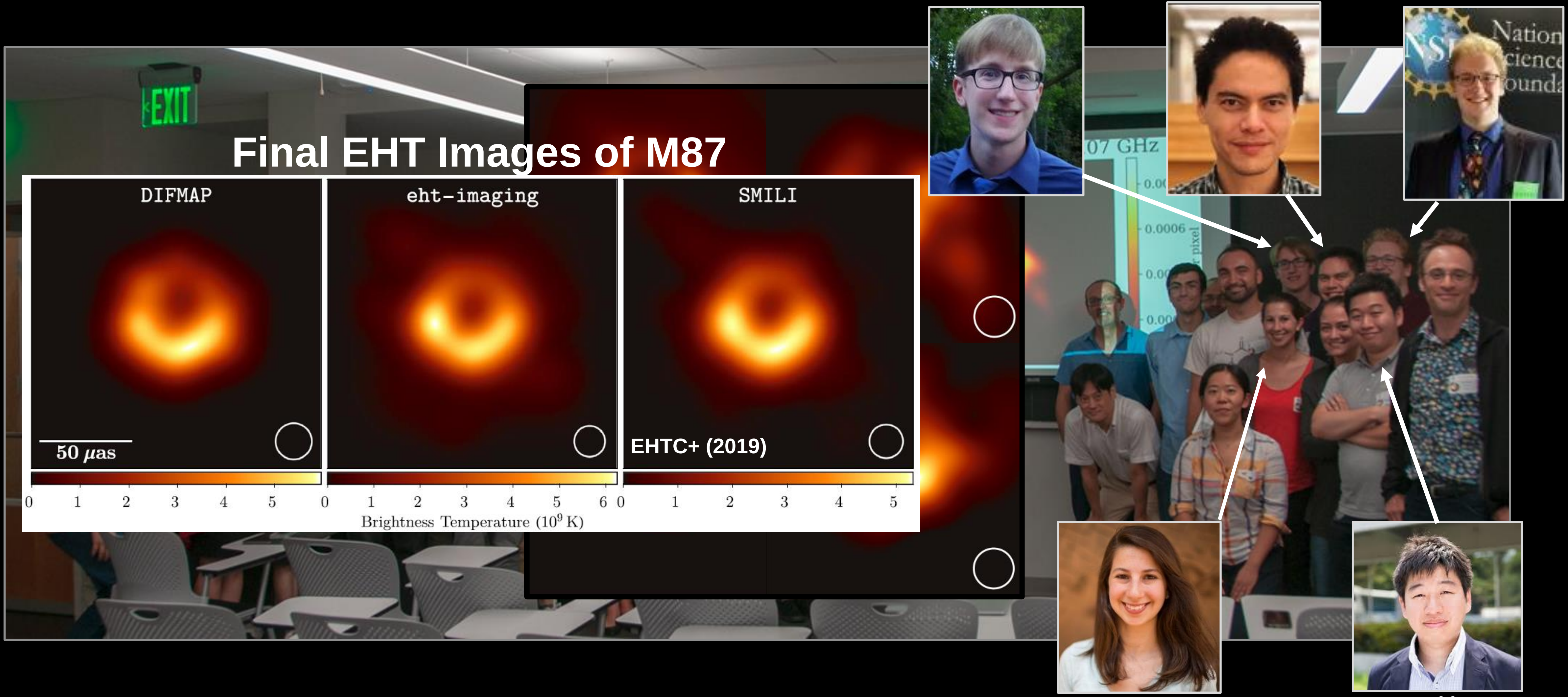


Final EHT Images of M87

Lead developer of `eht-imaging`
https://github.com/achael/eht-imaging
Andrew Chael

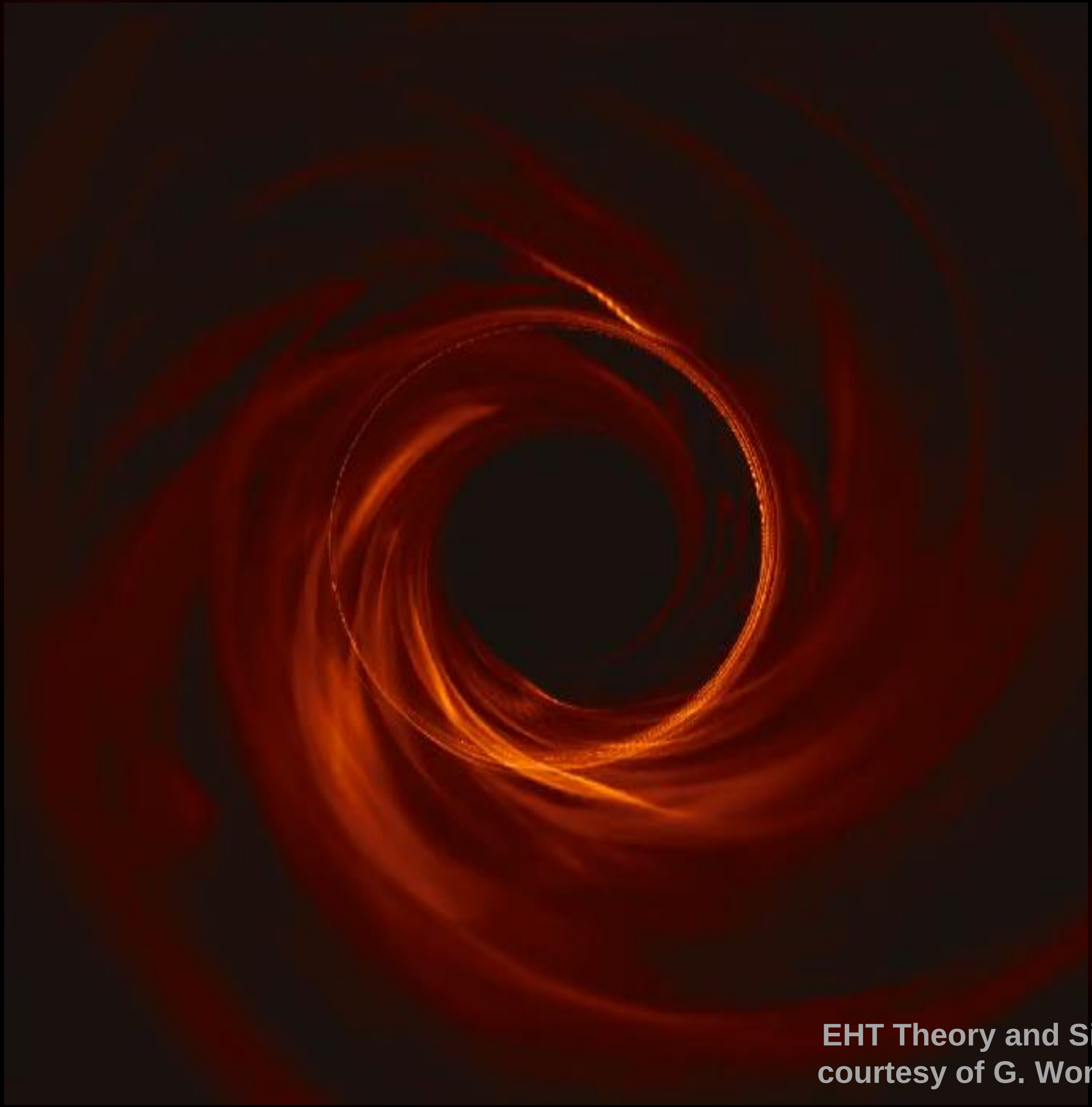
Led EHT Data Processing and Calibration
Lindy Blackburn

Led Imaging Parameter Surveys
Daniel Palumbo



Katie Bouman
Led Synthetic Data & Blind Testing Design

Kazu Akiyama
Lead developer of `SMILI`
https://github.com/astrosmili/smili



EHT Theory and Simulation Working Group
courtesy of G. Wong, B. Prather, C. Gammie

Improving the Event Horizon Telescope

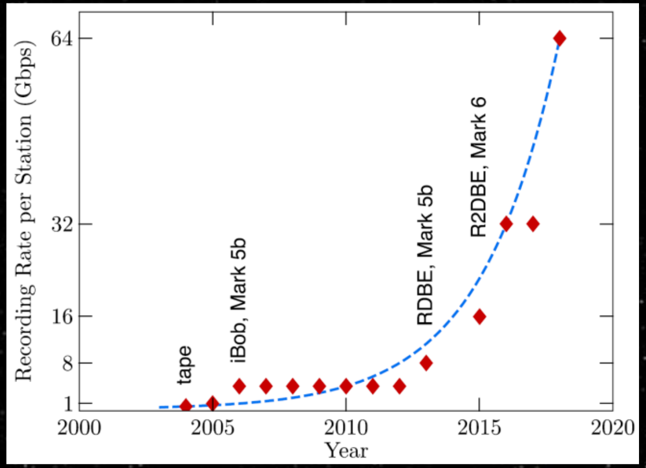
EHT Timeline:

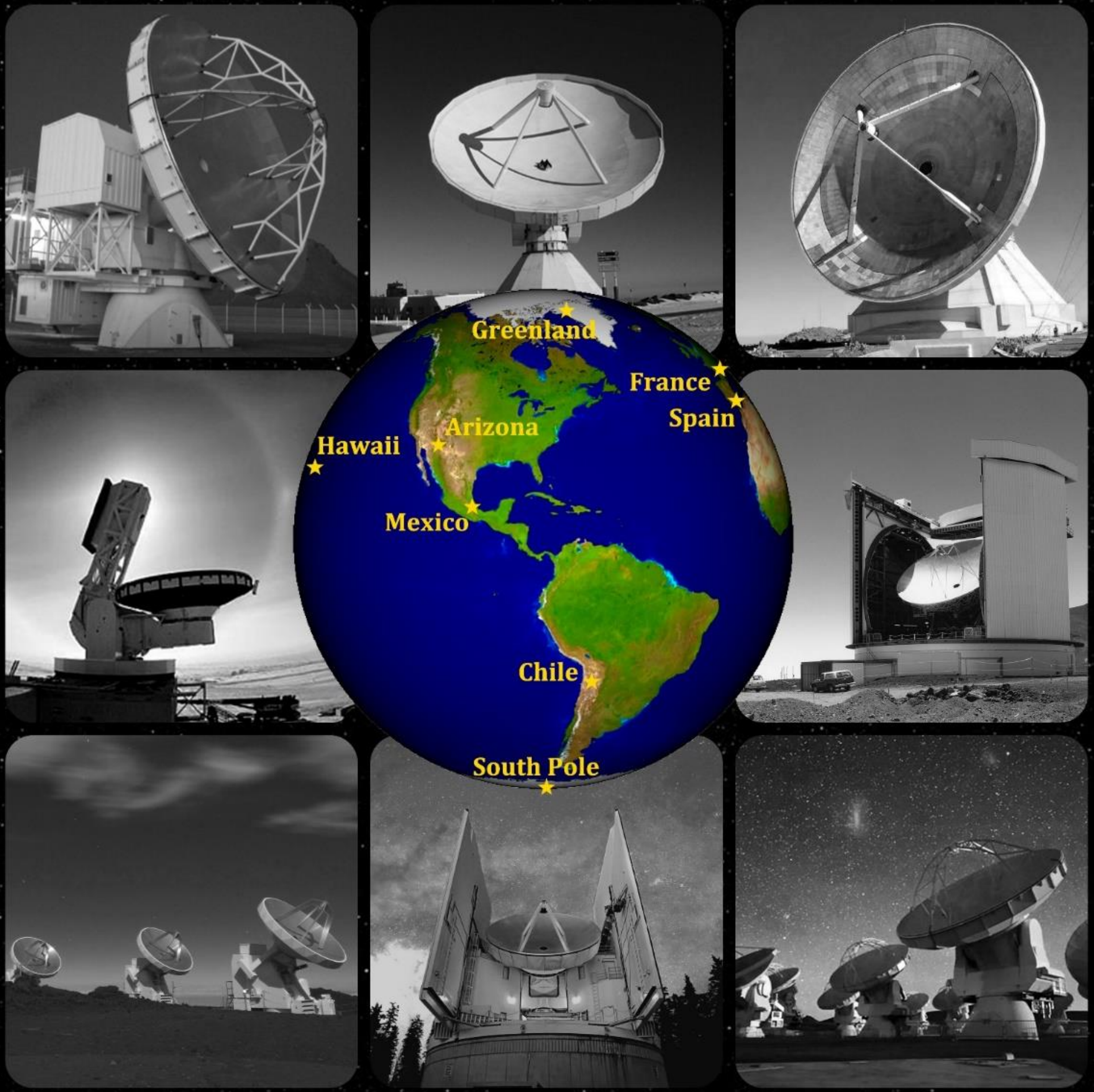
2017: +ALMA, LMT, PV, SPT (32 Gb/s)

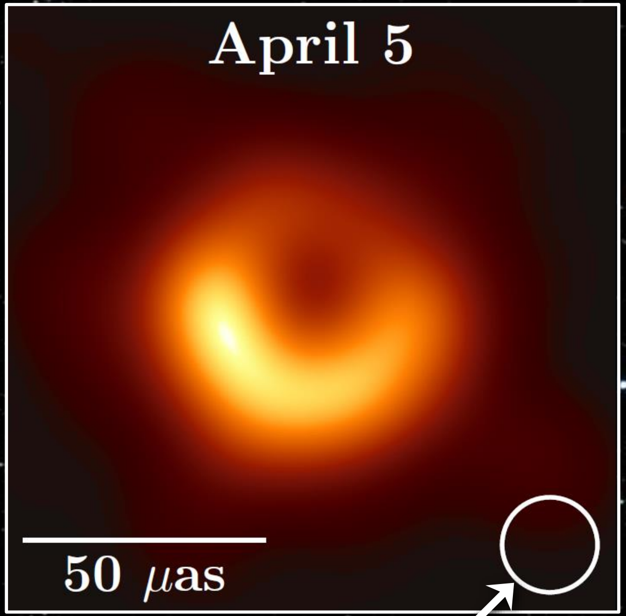
2018: +GLT (64 Gb/s; dual-SB)

2020: +KP, NOEMA (345 GHz tests)

Full-pol. observations since 2013





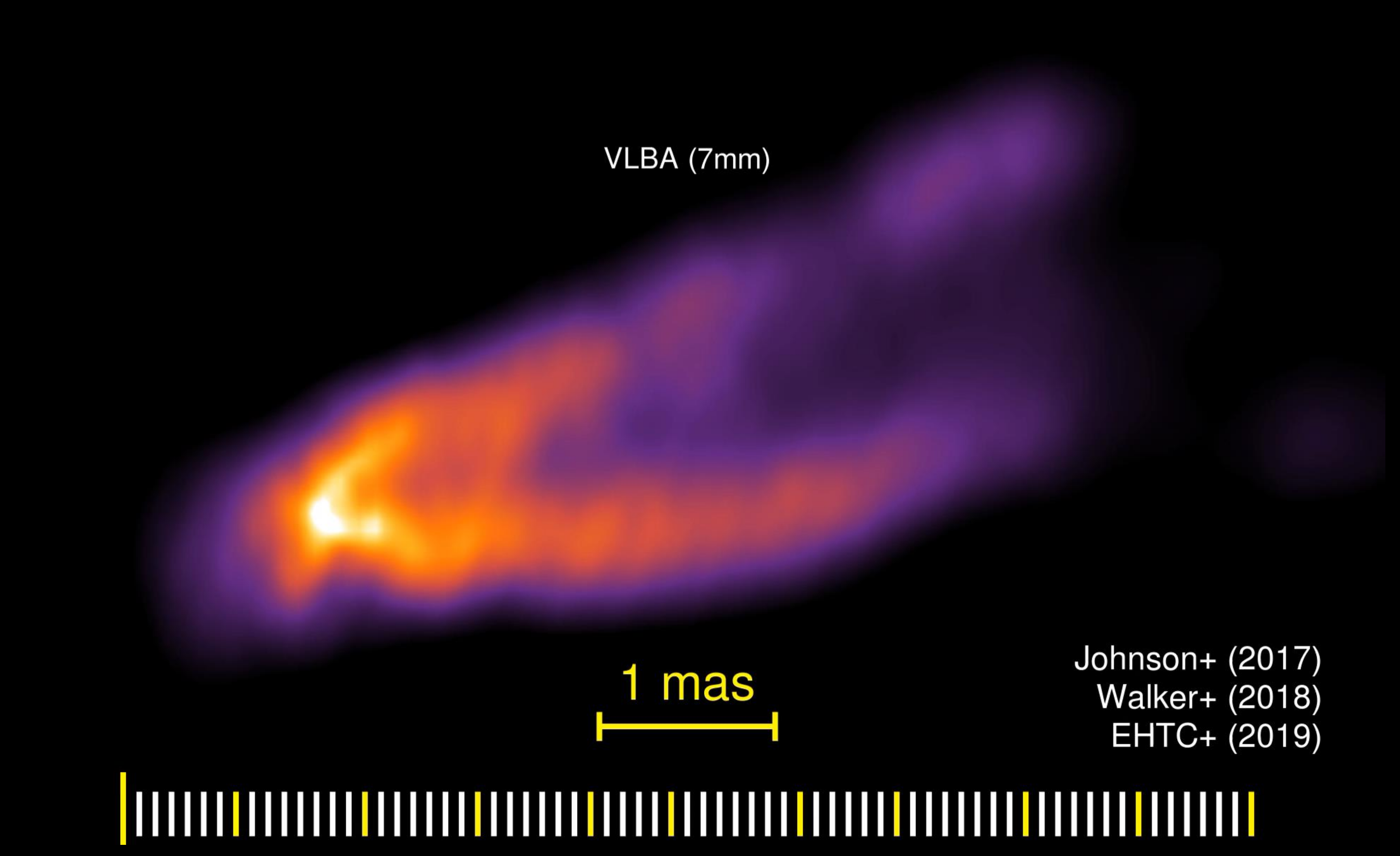


EHT Resolution: ~20 μas

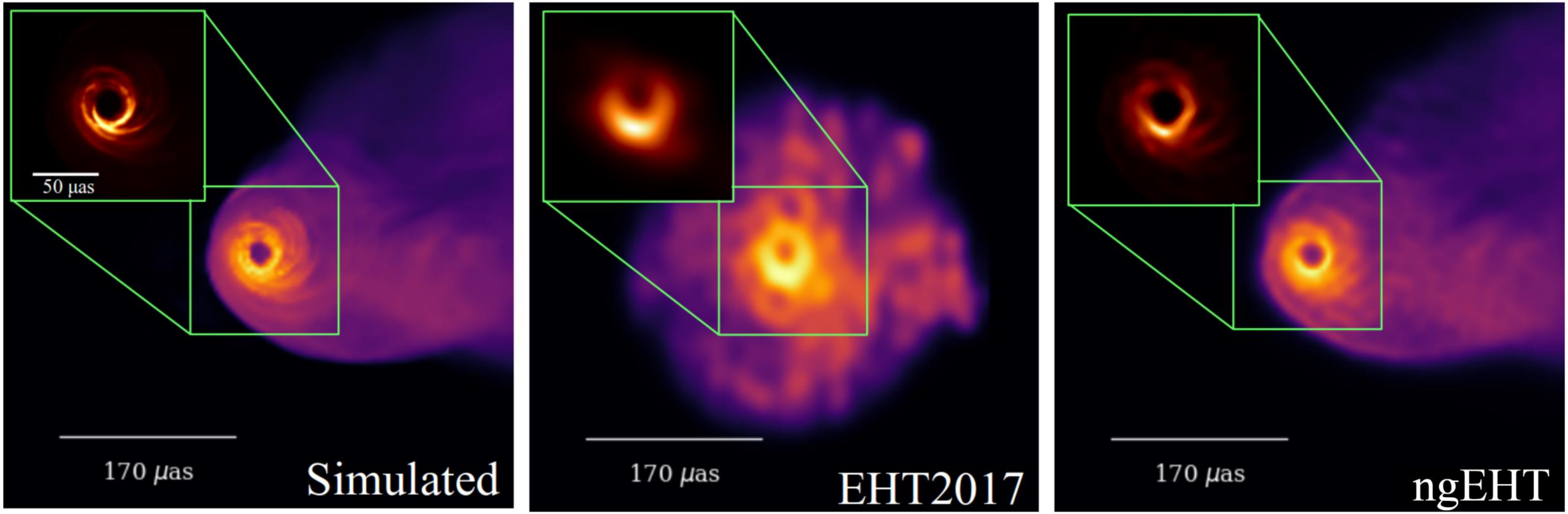
230 GHz ↔ 1.3 mm

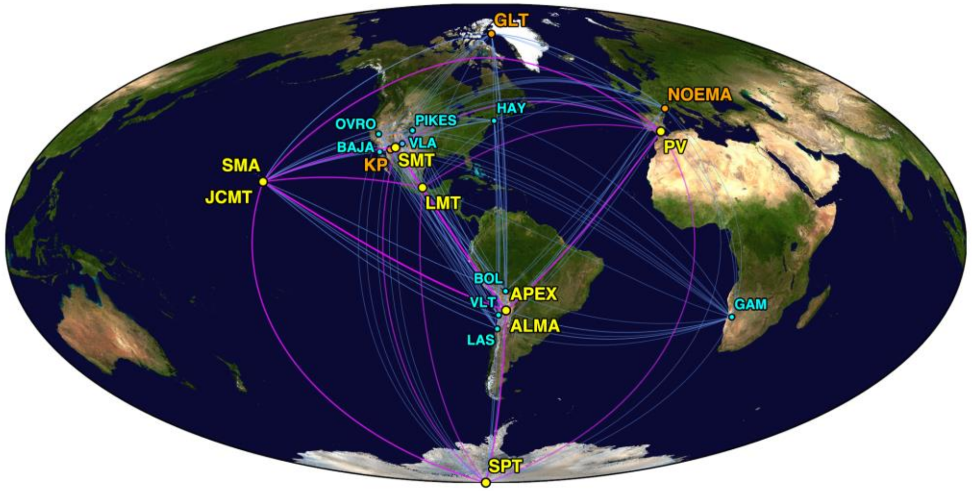
Credit: K. Johnson, APEX, IRAM, G. Narayanan, J. McMahon, JCMT/JAC, S. Hostler, D. Harvey, ESO/C. Malin

Finding the Jet in EHT Images



Finding the Jet in EHT Images





The current EHT lacks <u>short</u> baselines, which are necessary to detect extended structure

Short baselines do not need to be as sensitive as long baselines

Exploring adding a number of small ~6-m dishes to the current array

See: EHT Ground Astro2020 APC White Paper (Blackburn, Doeleman+; arXiv:1909.01411)

Space VLBI with the EHT

Ground-based VLBI is approaching fundamental limits:

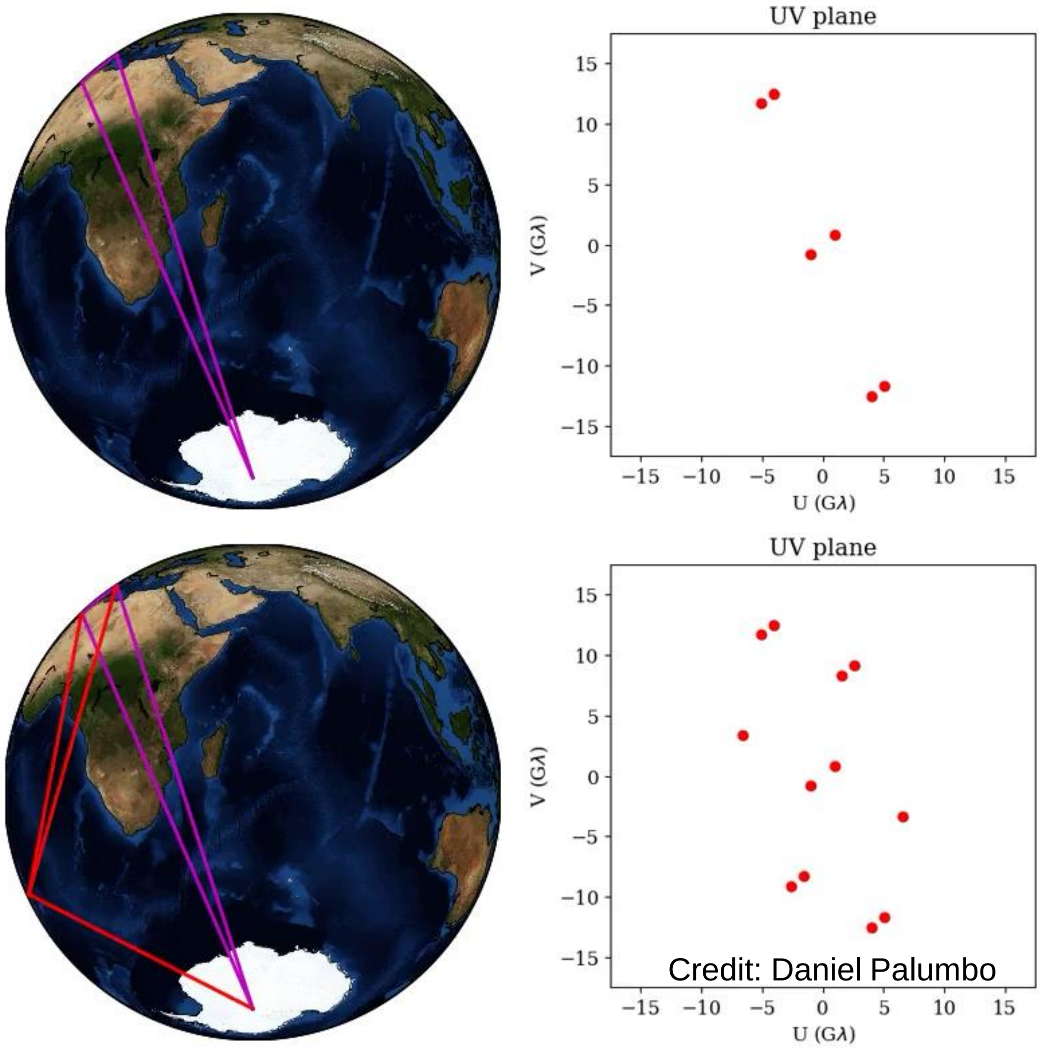
1. Physical baseline lengths cannot exceed the Earth's diameter
2. The atmosphere becomes opaque above a few hundred GHz
3. Interstellar scattering blurs the image of Sgr A*

Space Baselines Could Enable:

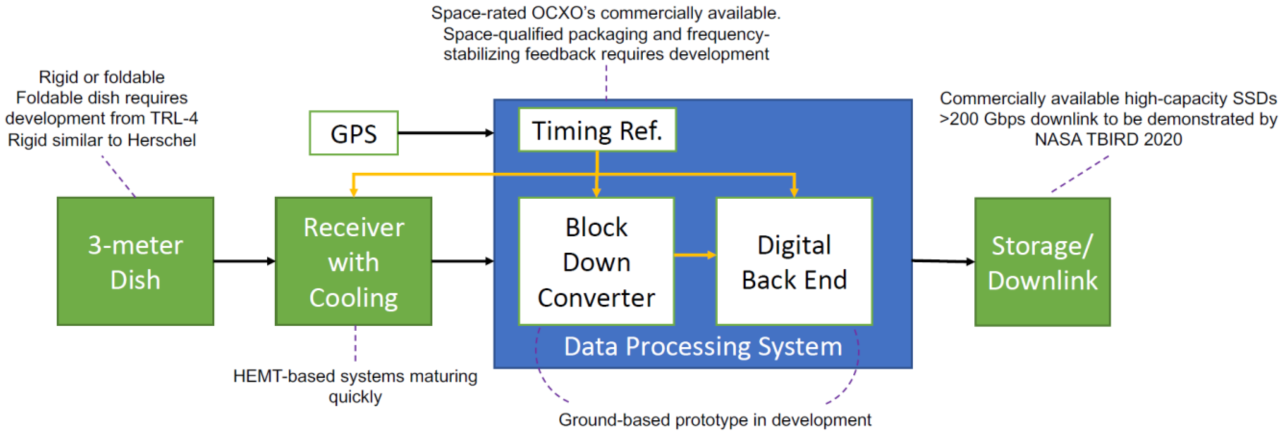
1. Higher frequencies (higher image resolution; weaker scattering)
2. Longer baselines (higher image resolution)
3. Faster sampling of baselines (reconstructed movies!)

Challenges:

1. Sensitivity (smaller dishes, limited bandwidth, shorter coherence times)
2. Orbital modeling and stability
3. Cost



Credit: Daniel Palumbo



See: EHT Space Astro2020 APC White Papers

- Haworth, Johnson+; arXiv:1909.01405
- Pesce+; arXiv:1909.01408

The EHT Collaboration