Instrumentation and Technology supporting the Event Horizon Telescope

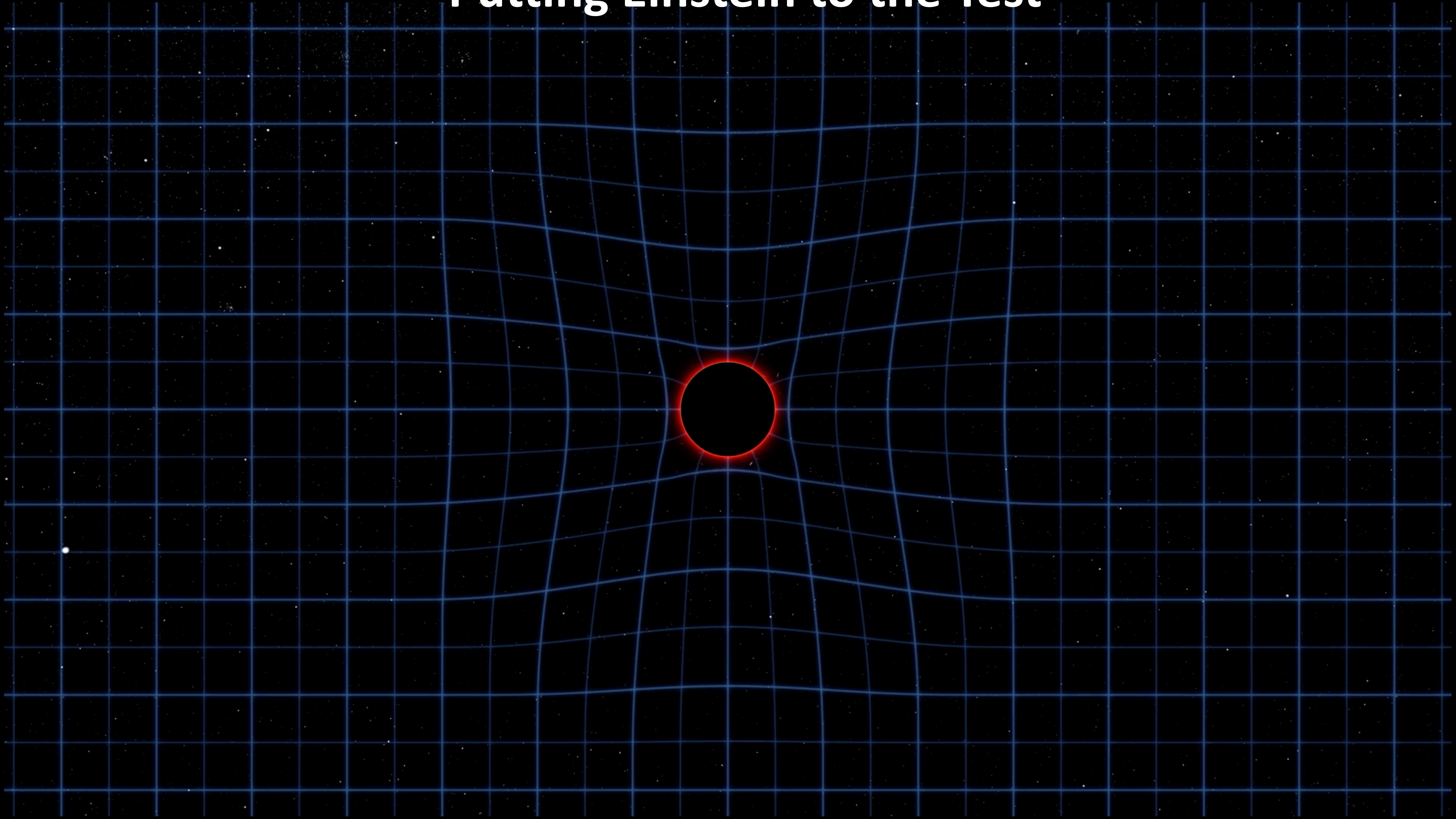
Jonathan Weintroub, on behalf of the EHT Collaboration
Center for Astrophysics | Harvard & Smithsonian

NSF Cyber-Physical Systems PI Meeting
22 November 2019

photo credit: Robbie Singal

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

Putting Einstein to the Test



Cyber-physical systems are new to me

Cyber-physical systems are new to me

https://en.wikipedia.org/wiki/Cyber-physical_system

A **cyber-physical system** (**CPS**) is a mechanism that is controlled or monitored by computer-based algorithms, tightly integrated with the Internet and its users.

Cyber-physical systems are new to me

https://en.wikipedia.org/wiki/Cyber-physical_system

A **cyber-physical system** (**CPS**) is a mechanism that is controlled or monitored by computer-based algorithms, tightly integrated with the Internet and its users.

cyberphysicalsystems.org

Cyber-Physical Systems (CPS) are integrations of computation, networking, and **physical** processes. Embedded computers and networks monitor and control the **physical** processes, with feedback loops where **physical** processes affect computations and vice versa.

Cyber-physical systems are new to me

https://en.wikipedia.org/wiki/Cyber-physical_system

A **cyber-physical system** (**CPS**) is a mechanism that is controlled or monitored by computer-based algorithms, tightly integrated with the Internet and its users.

cyberphysicalsystems.org

Cyber-Physical Systems (CPS) are integrations of computation, networking, and **physical** processes. Embedded computers and networks monitor and control the **physical** processes, with feedback loops where **physical** processes affect computations and vice versa.

- In this talk I will frame (parts of) the Event Horizon Telescope (EHT) as a cyber-physical system.

Cyber-physical systems are new to me

https://en.wikipedia.org/wiki/Cyber-physical_system

A **cyber-physical system** (**CPS**) is a mechanism that is controlled or monitored by computer-based algorithms, tightly integrated with the Internet and its users.

cyberphysicalsystems.org

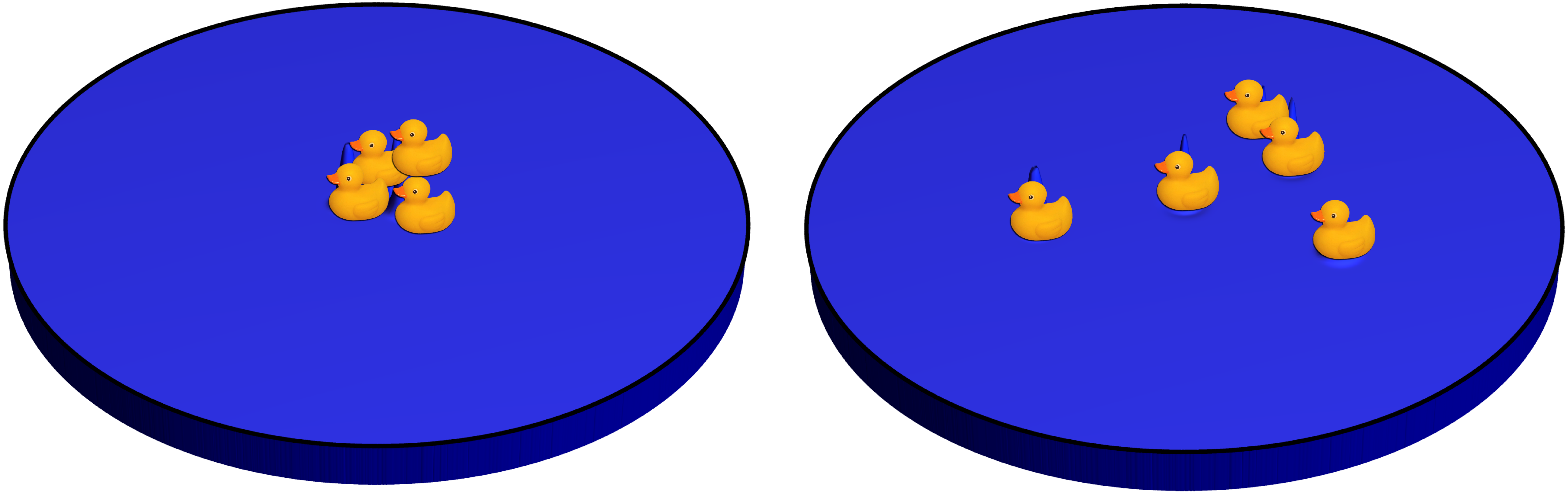
Cyber-Physical Systems (CPS) are integrations of computation, networking, and **physical** processes. Embedded computers and networks monitor and control the **physical** processes, with feedback loops where **physical** processes affect computations and vice versa.

- In this talk I will frame (parts of) the Event Horizon Telescope (EHT) as a cyber-physical system.
- First, lets learn about the technique of (radio) interferometry, on which the EHT depends

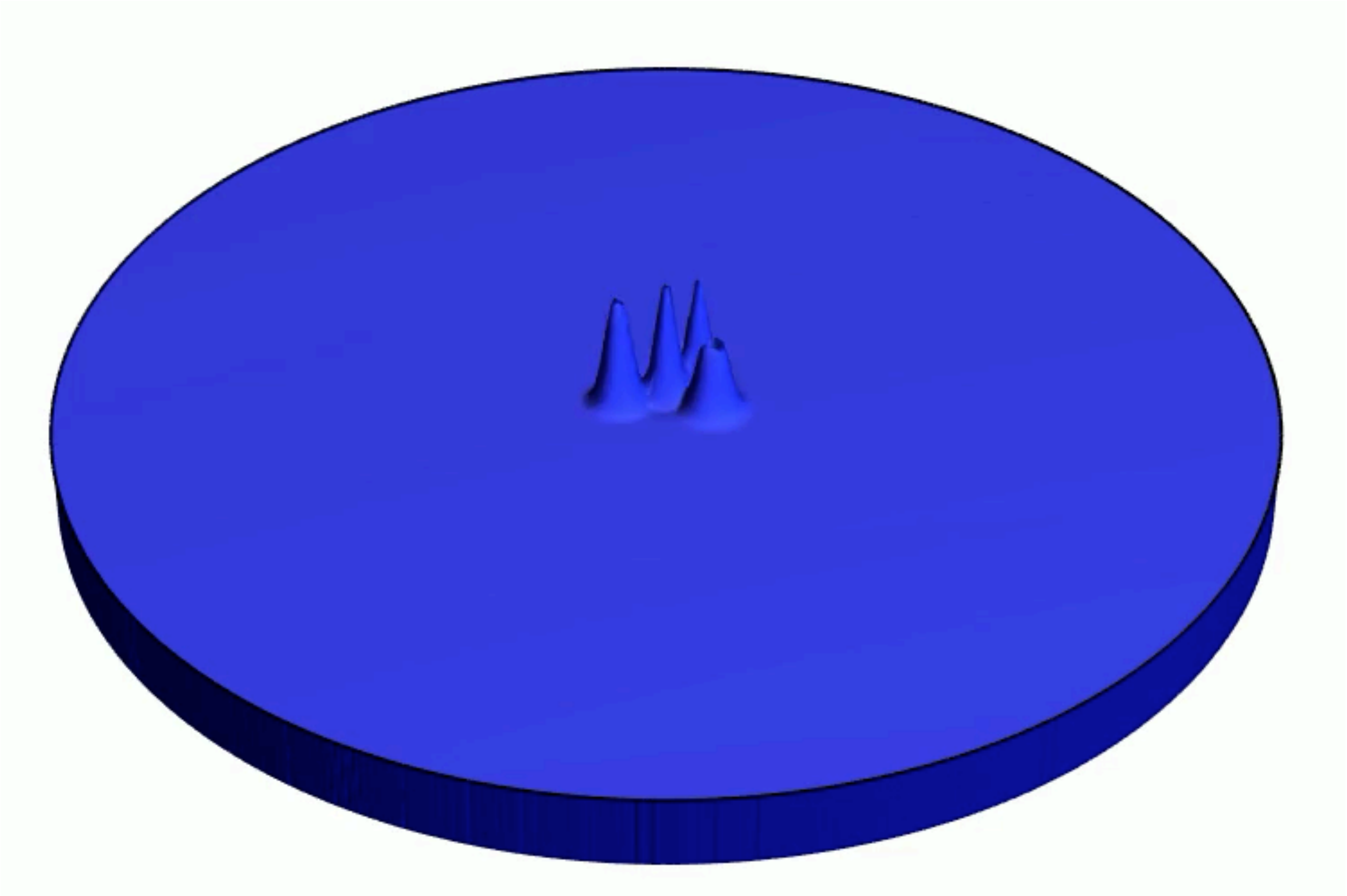
Learning Interferometry from Ducks

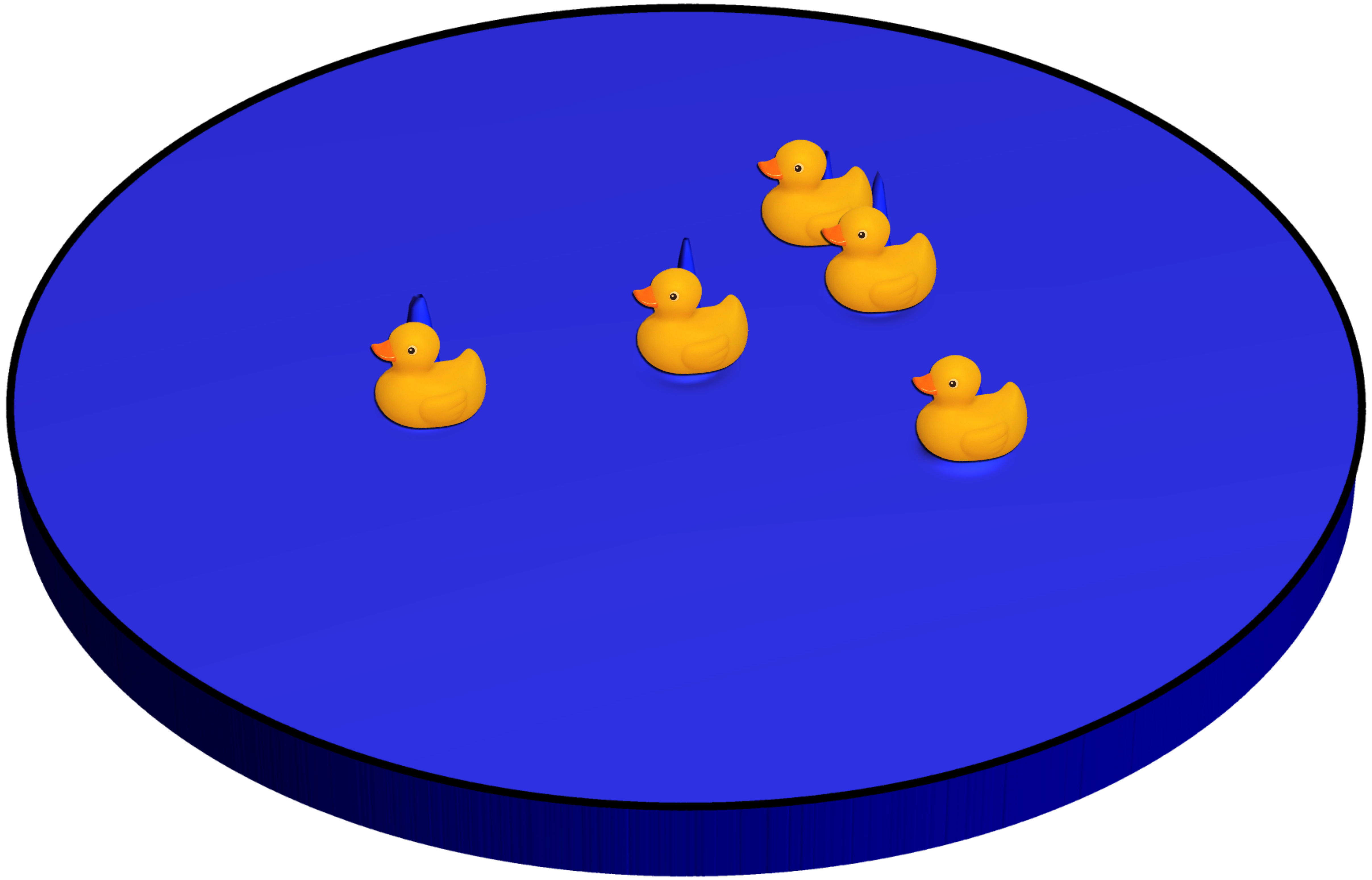
Knox et al., "Spatial coherence from ducks", Physics Today, March 2010

Learning Interferometry from Ducks

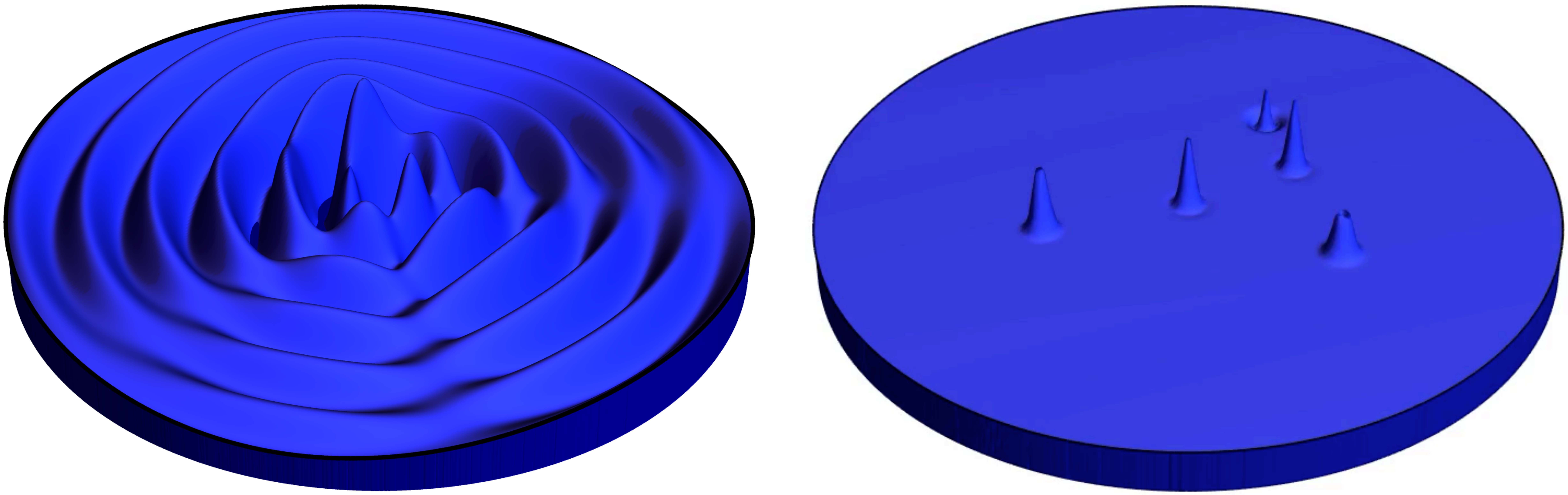


Learning Interferometry from Ducks

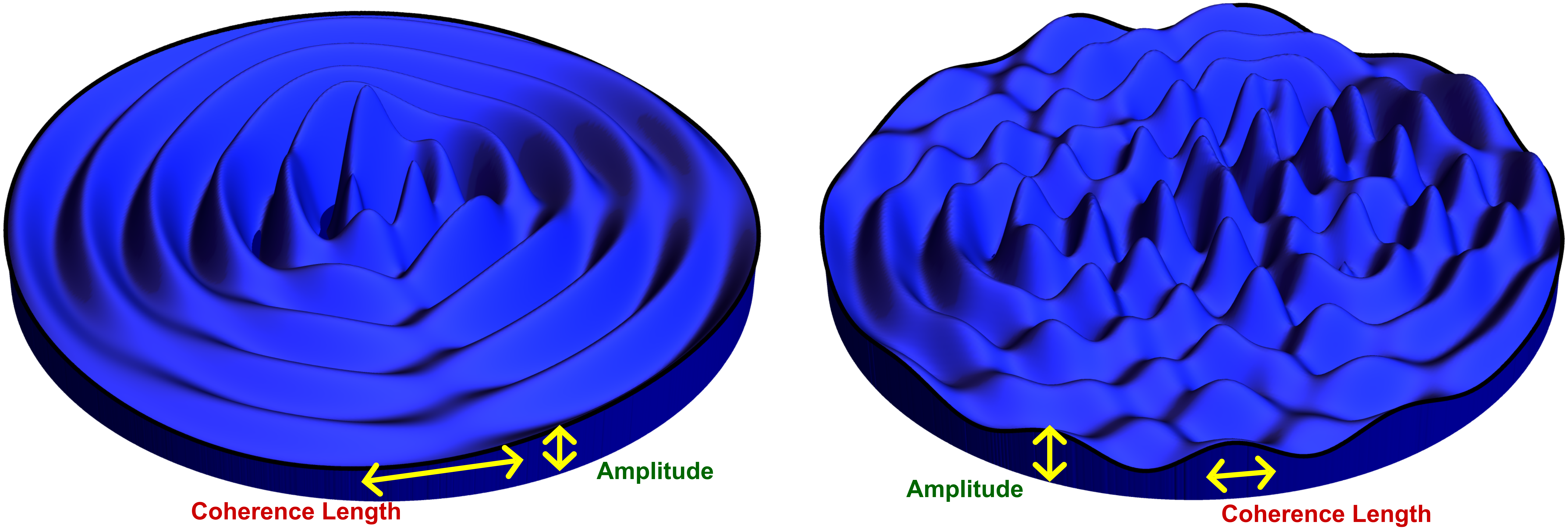




Learning Interferometry from Ducks



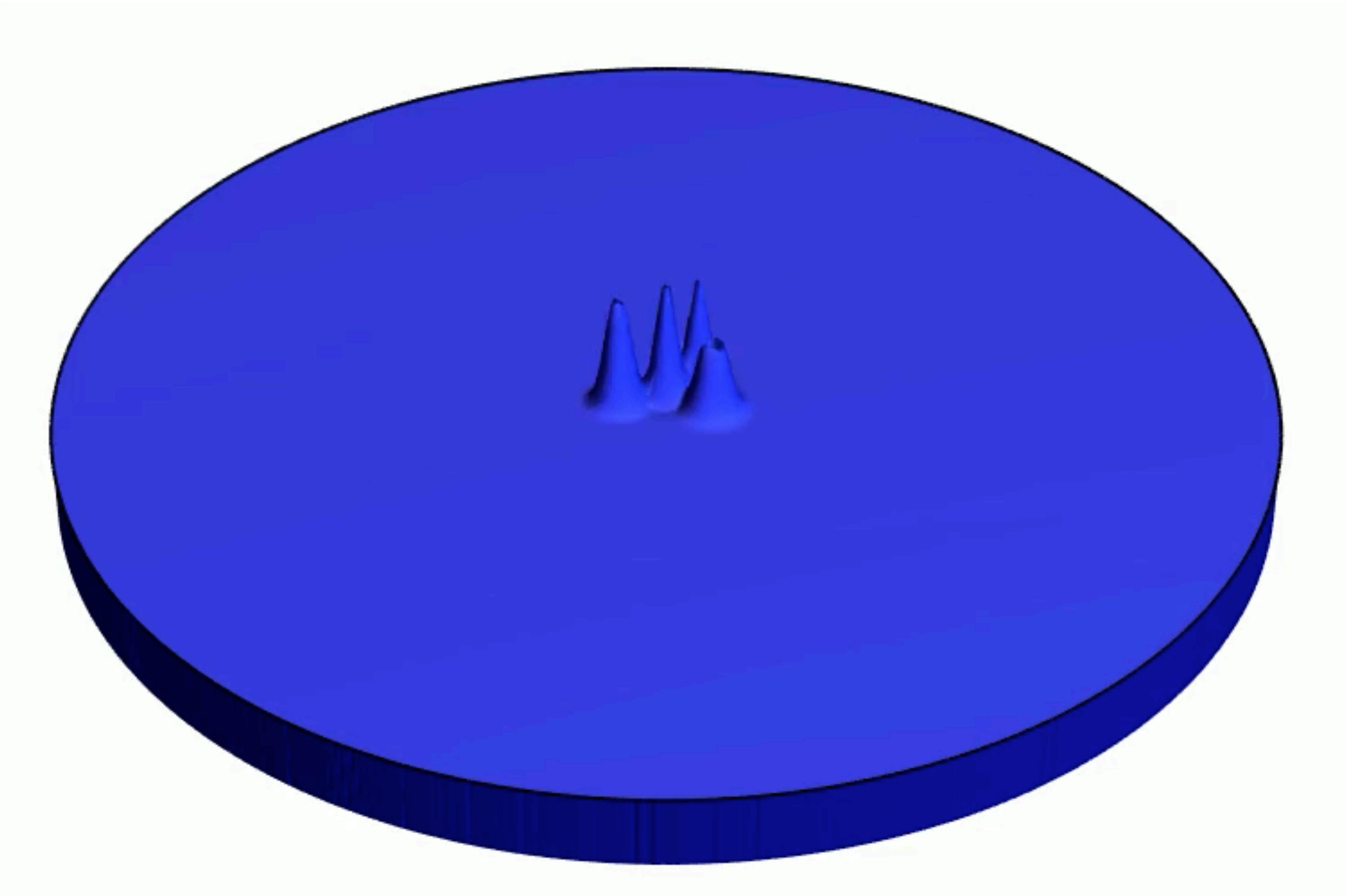
Learning Interferometry from Ducks

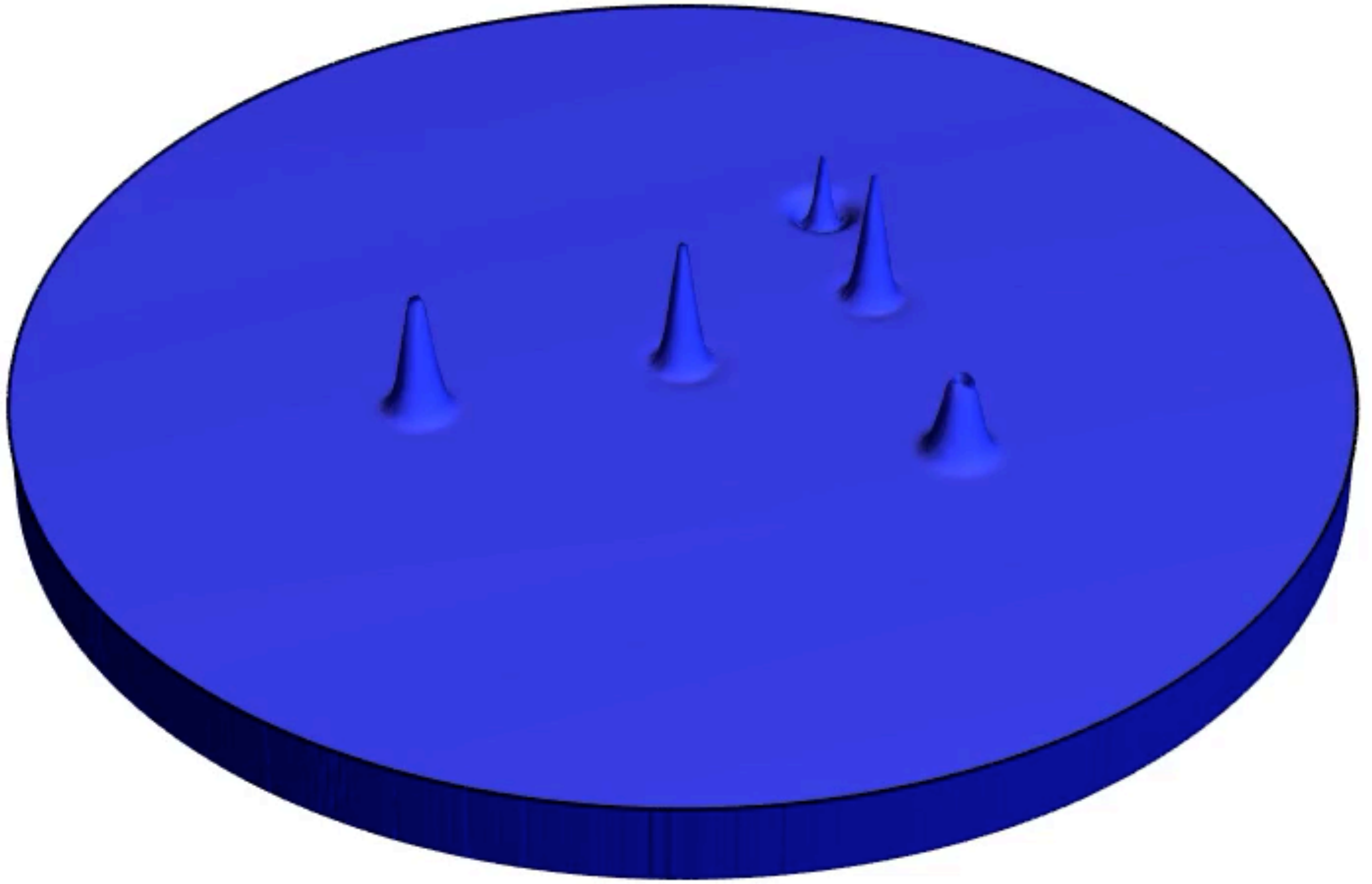


Amplitude: Tells us how many ducks are splashing (and how strongly)

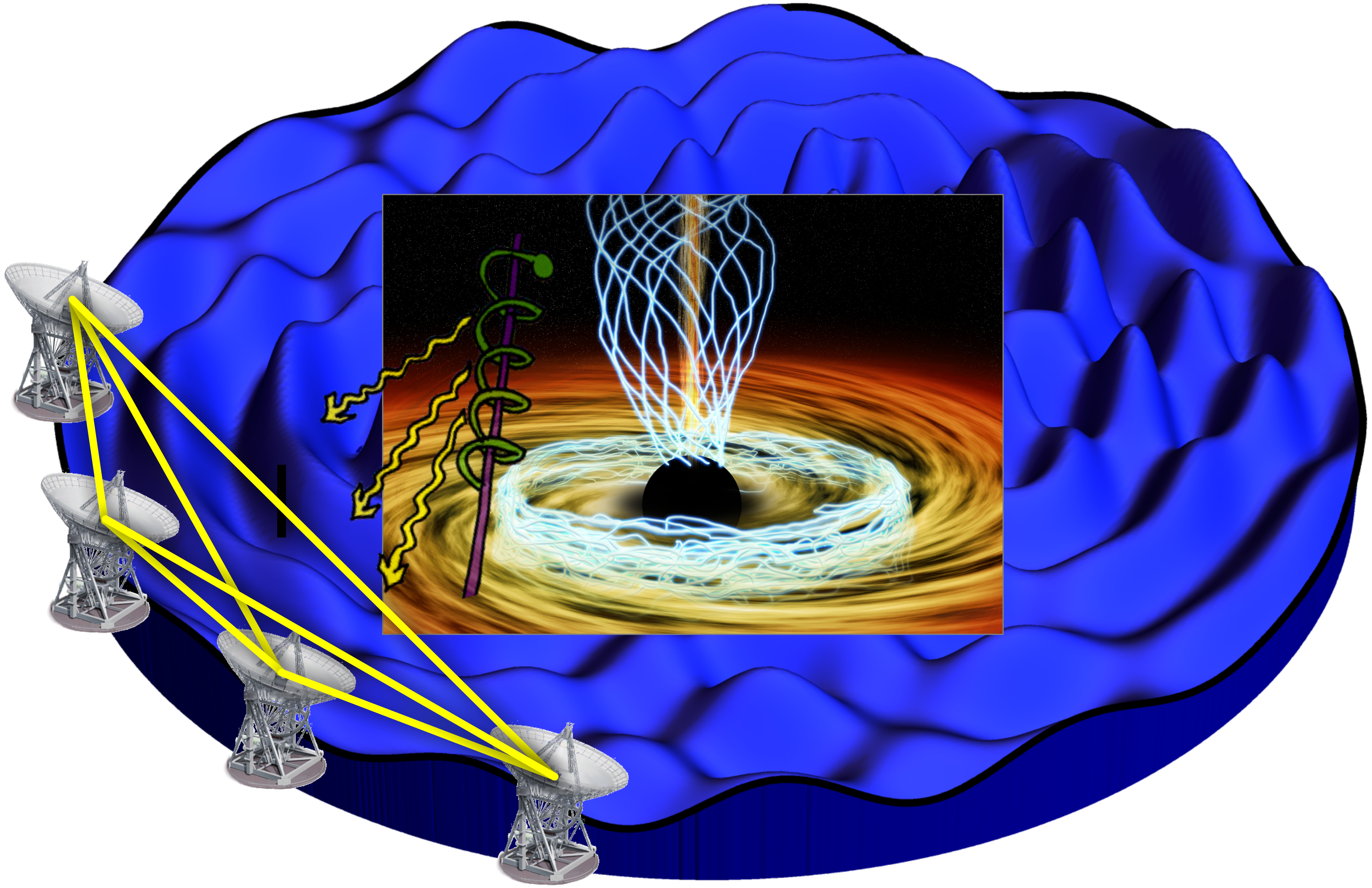
Coherence Length: Tells us how spread out they are

Learning Interferometry from Ducks

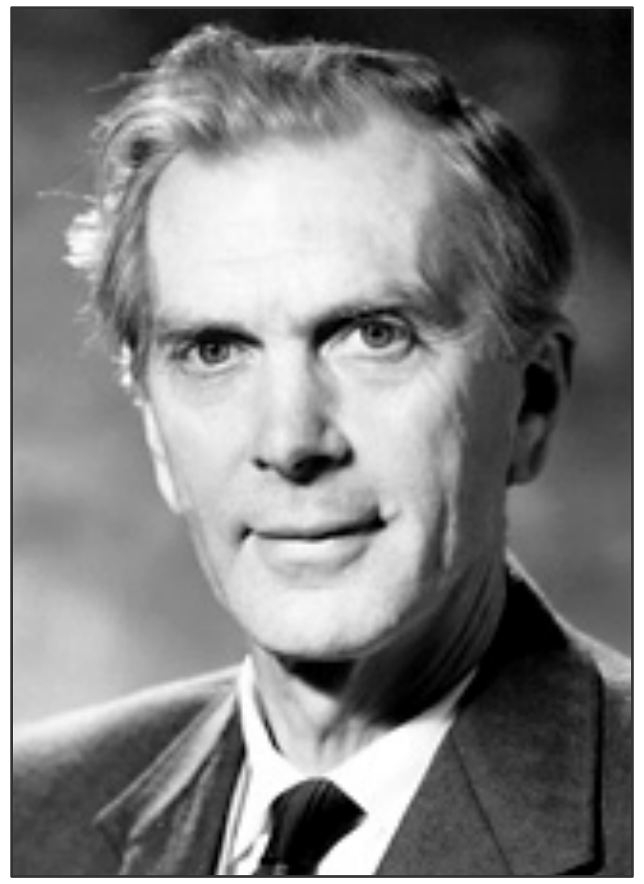




Learning Interferometry from Ducks



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



Martin Ryle
1974 Nobel Prize

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

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)

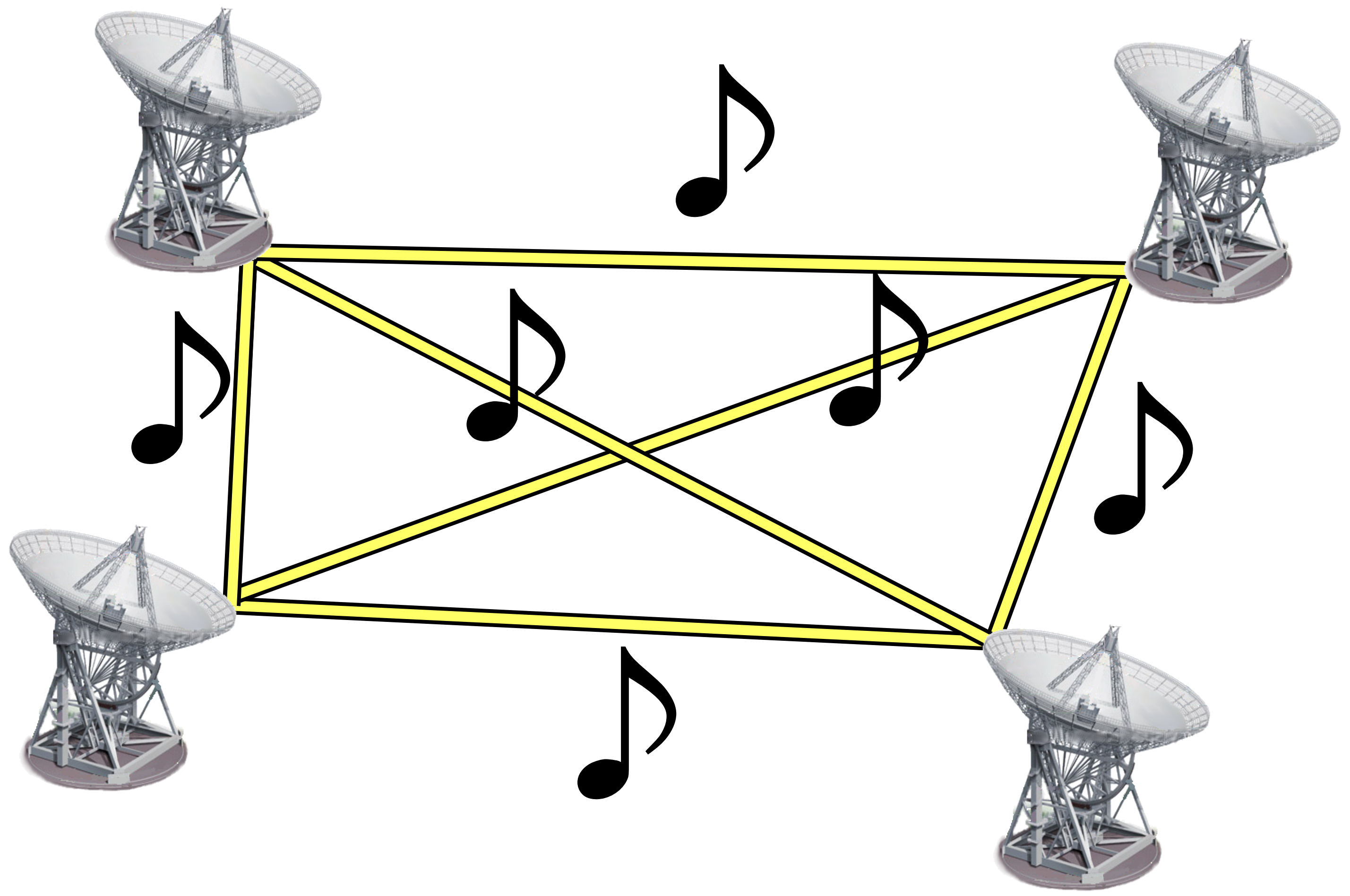
Interferometric Imaging:

Resolution depends on wavelength (λ) and separation of telescopes (B; *baseline*): λ/B

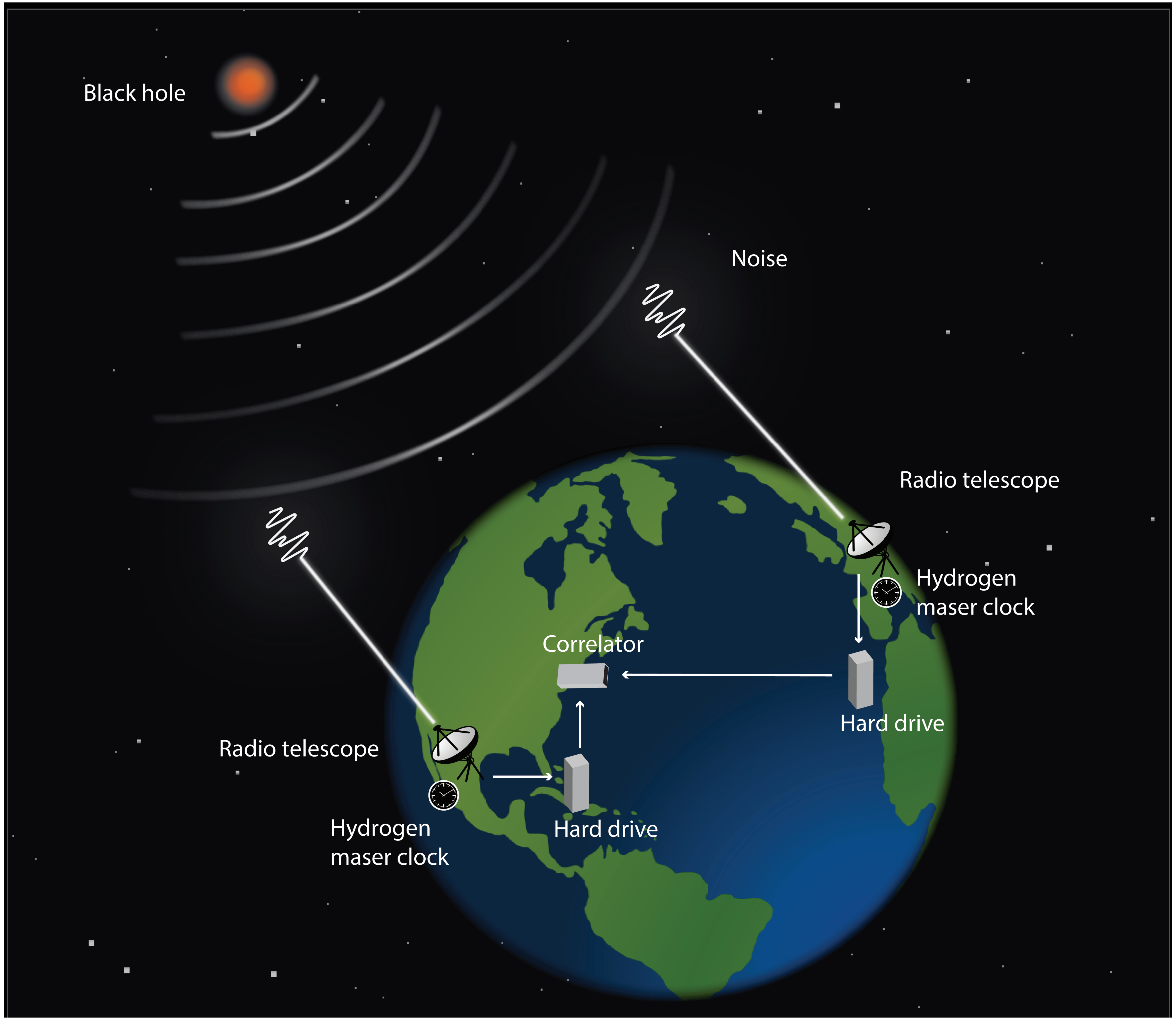
Longer baselines = Higher angular resolution

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

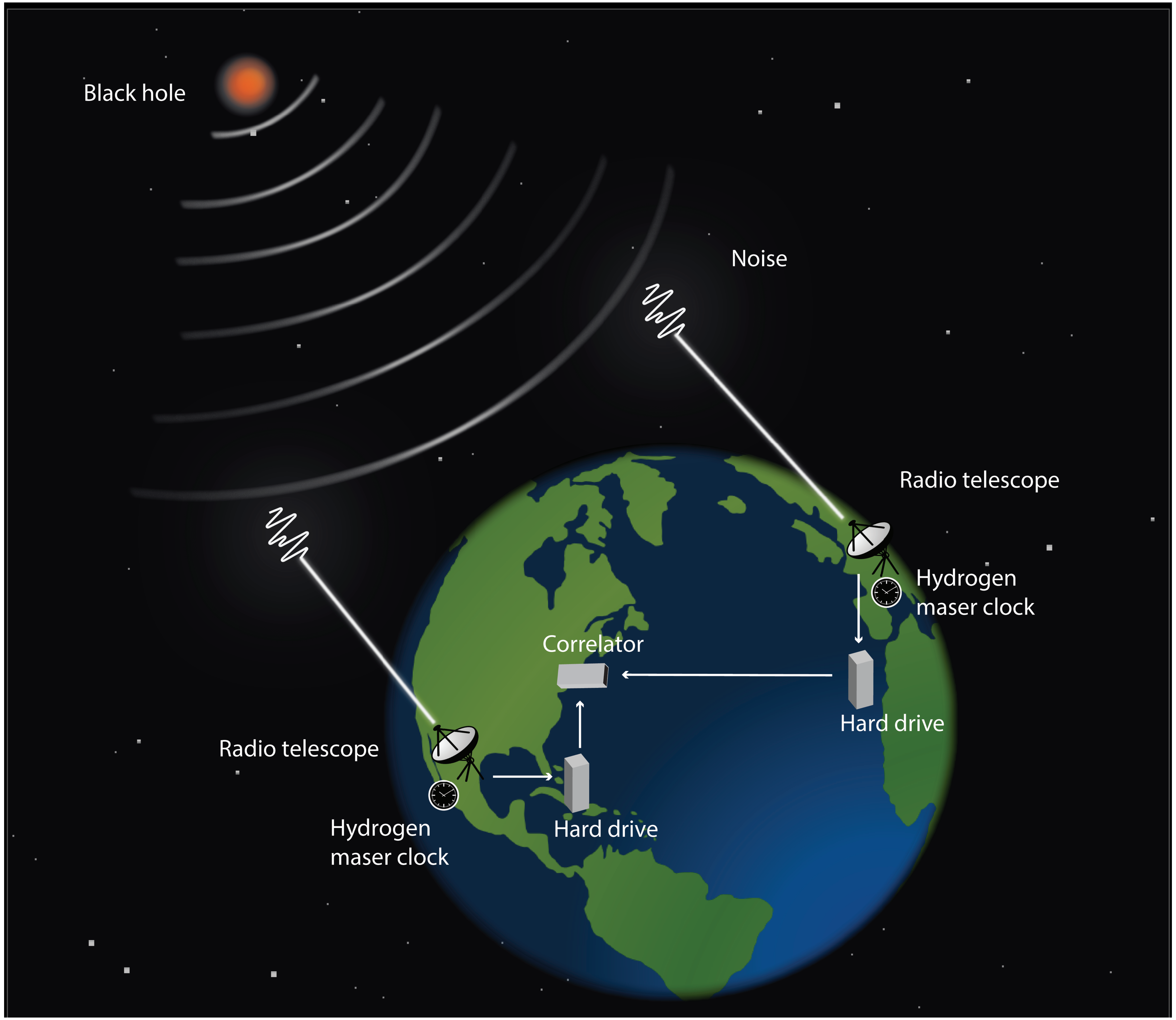
Each baseline only samples one frequency



Very Long Baseline Interferometry Concept

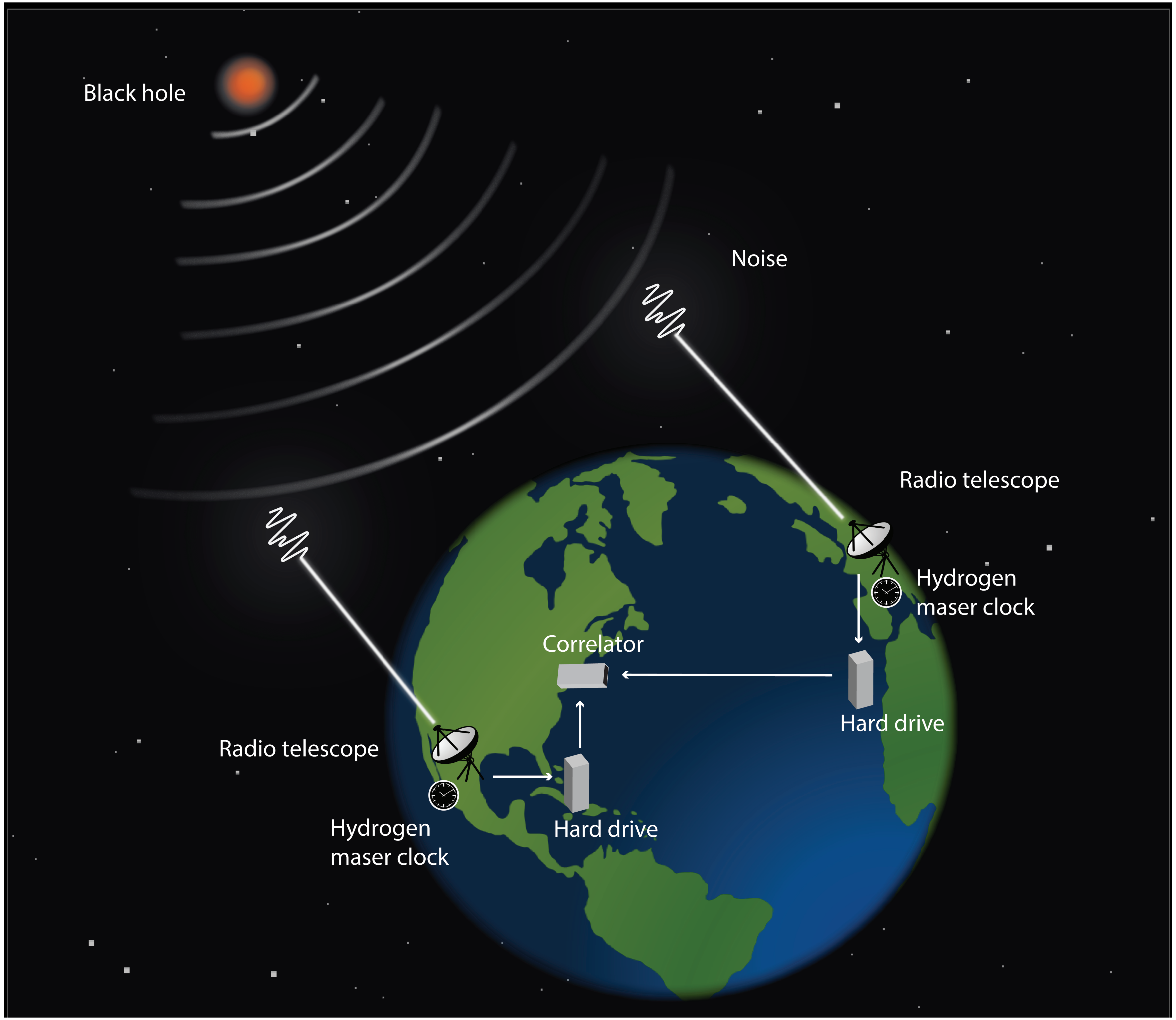


Very Long Baseline Interferometry Concept

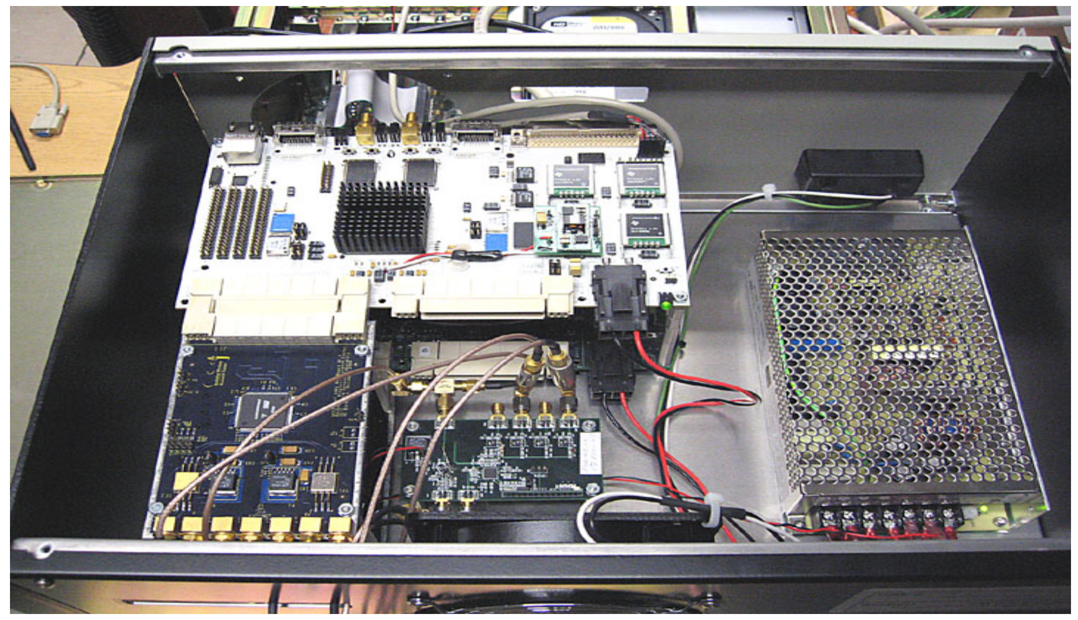


- The Event Horizon Telescope pushed the VLBI concept to the shortest radio wavelengths ~1 mm
- λ/D for ~1 mm and ~ 10,000km: ~10s of microarcseconds.
- A cosmic coincidence: This is of the order of the Schwartzschild radius of the nearest Super Massive Black Holes.
- (This happens to be where their emission peaks and the surrounding hot gas becomes optically thin.)
- 1 mm radio astronomy is hard (technology and weather) and VLBI at these wavelengths a real technical challenge

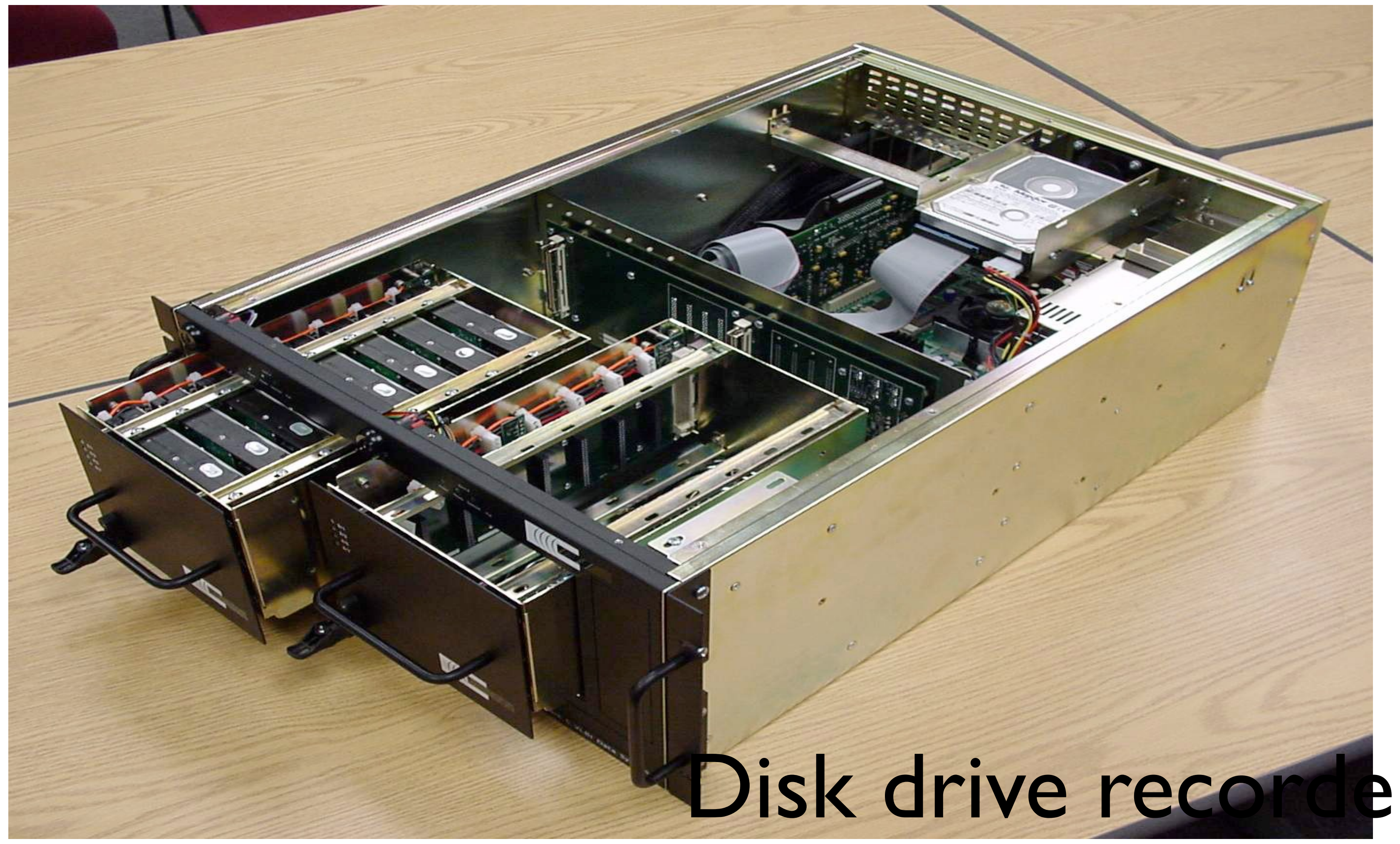
Very Long Baseline Interferometry Concept



Hydrogen Maser Clock (1970s)



Fast Data Samplers

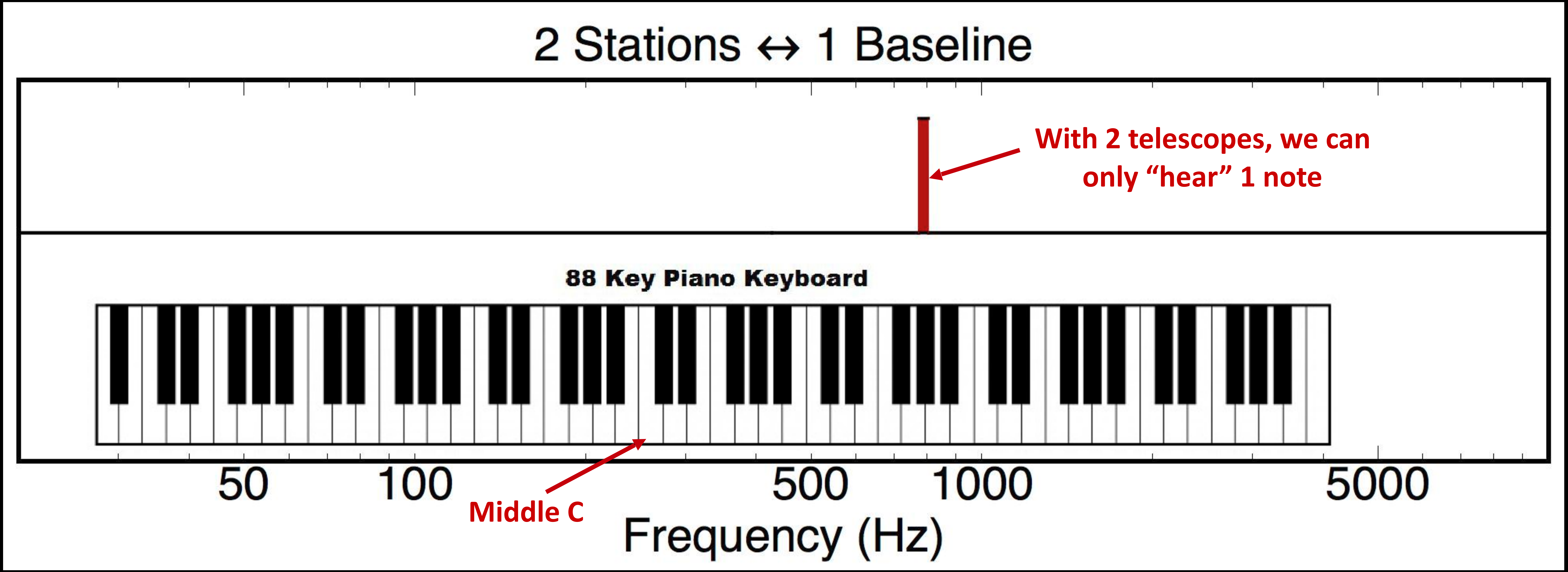


Disk drive recorder

Despite its global scope, EHT is a *very* sparse array

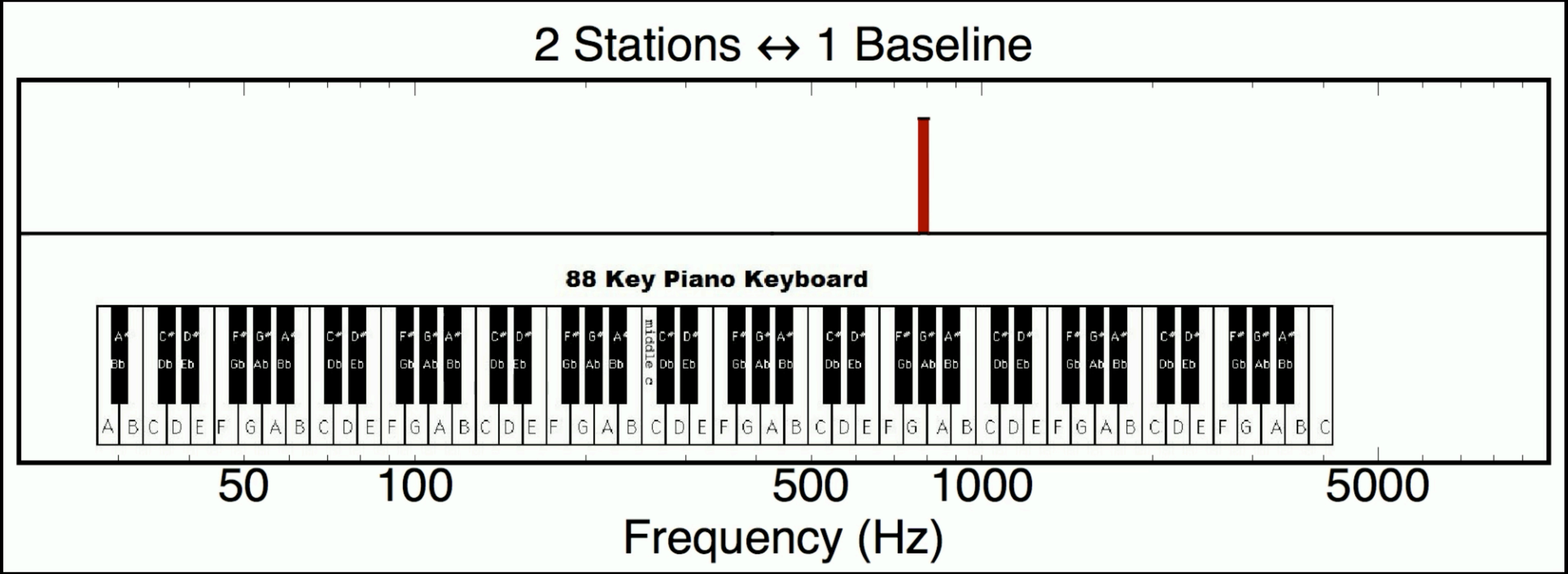
Sparse Interferometric Imaging

Can you identify the song?



Sparse Interferometric Imaging

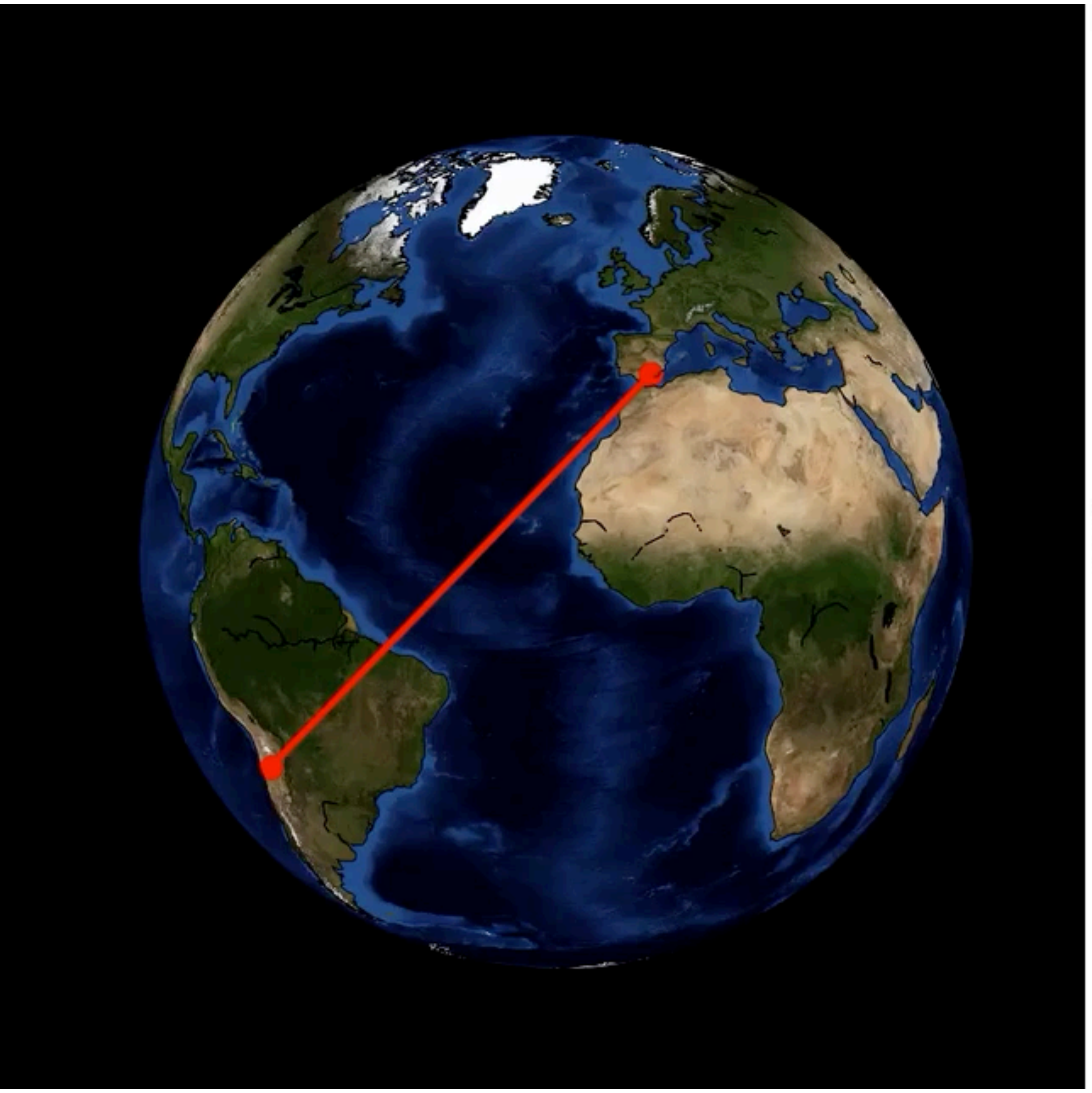
Raise your hand when you recognize what's playing!

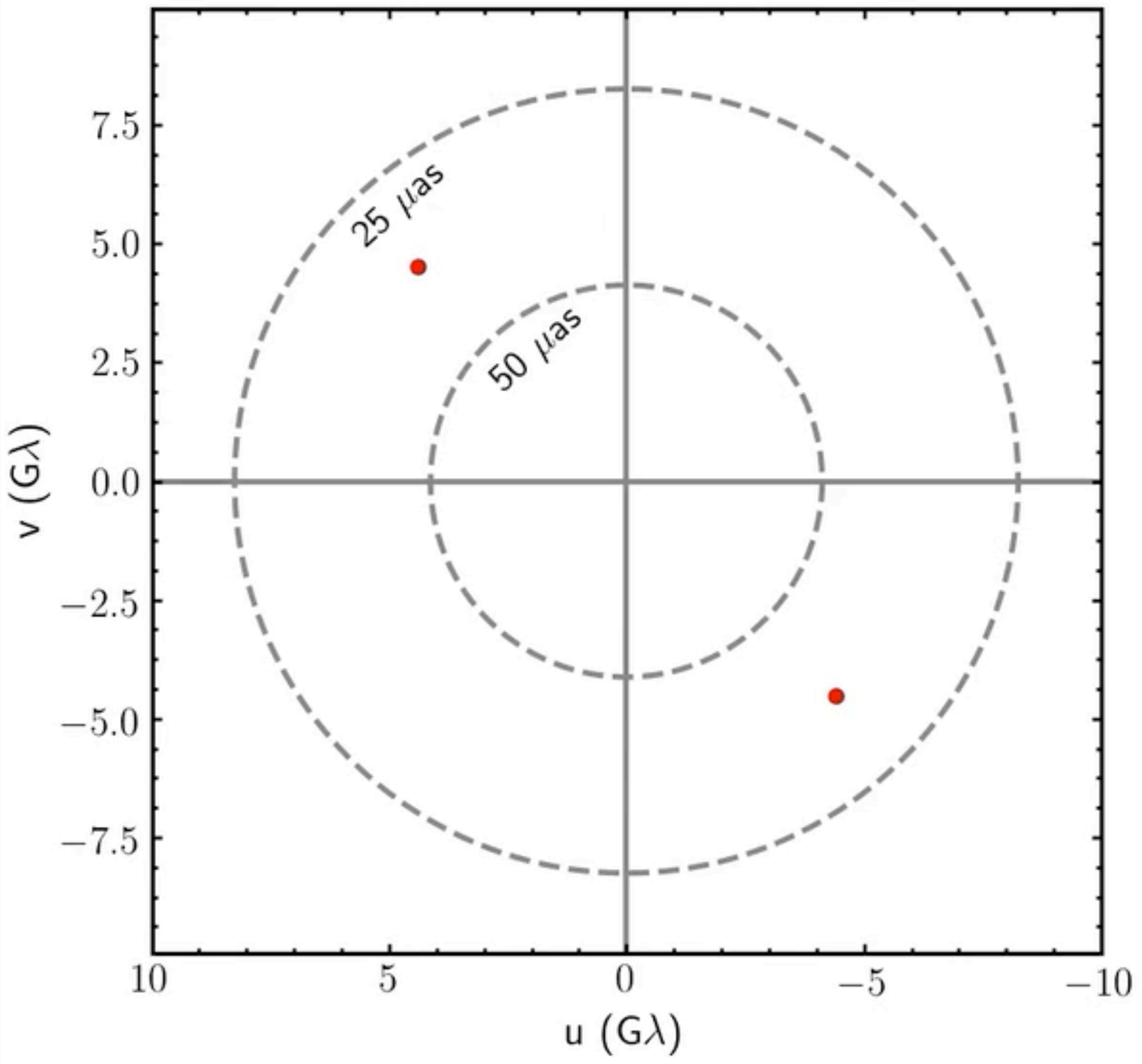


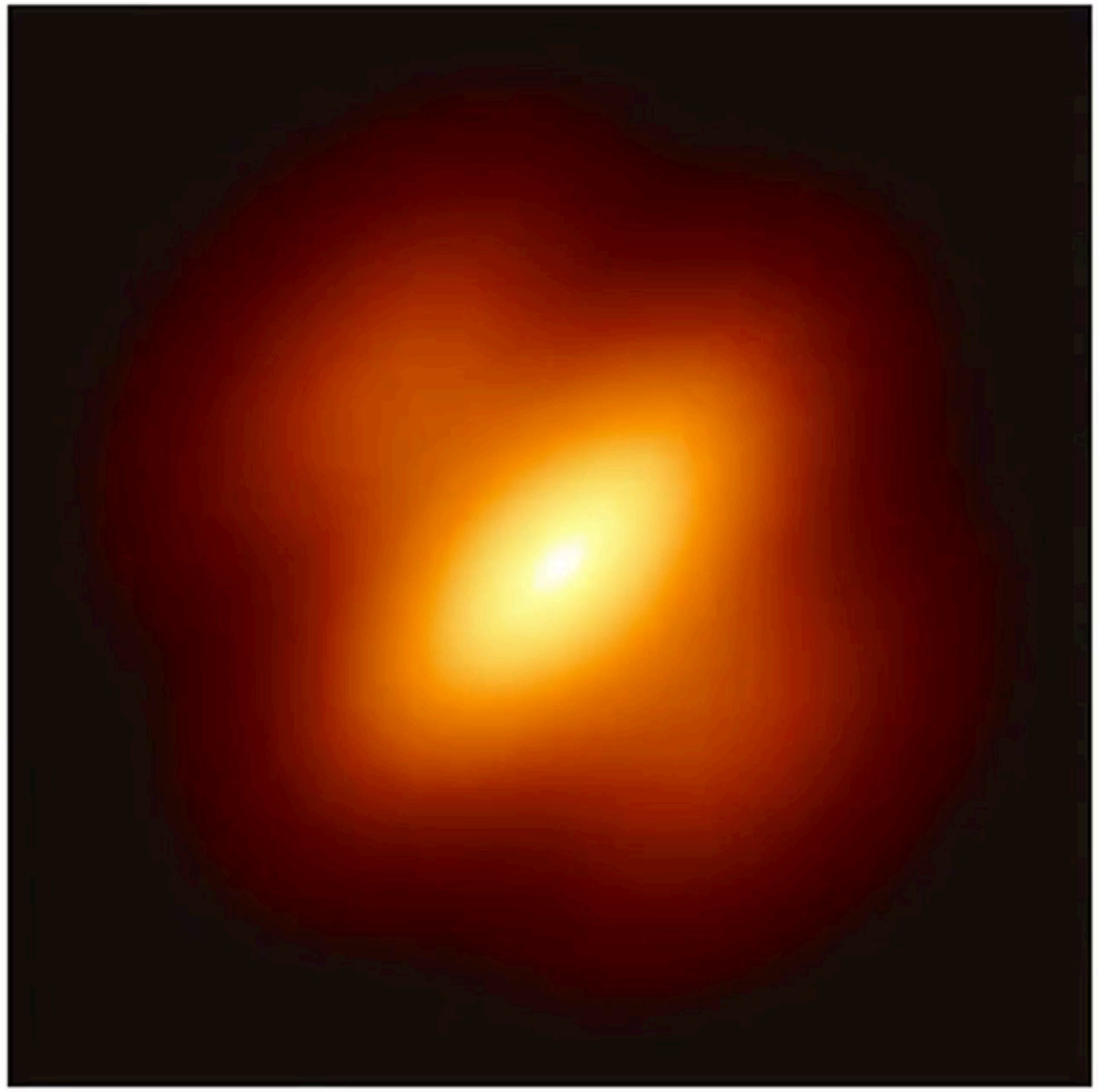
Credit: Michael Johnson

Make earth part of instrument: sample more spatial frequencies

"earth rotation aperture synthesis" to "fill the u-v plane"





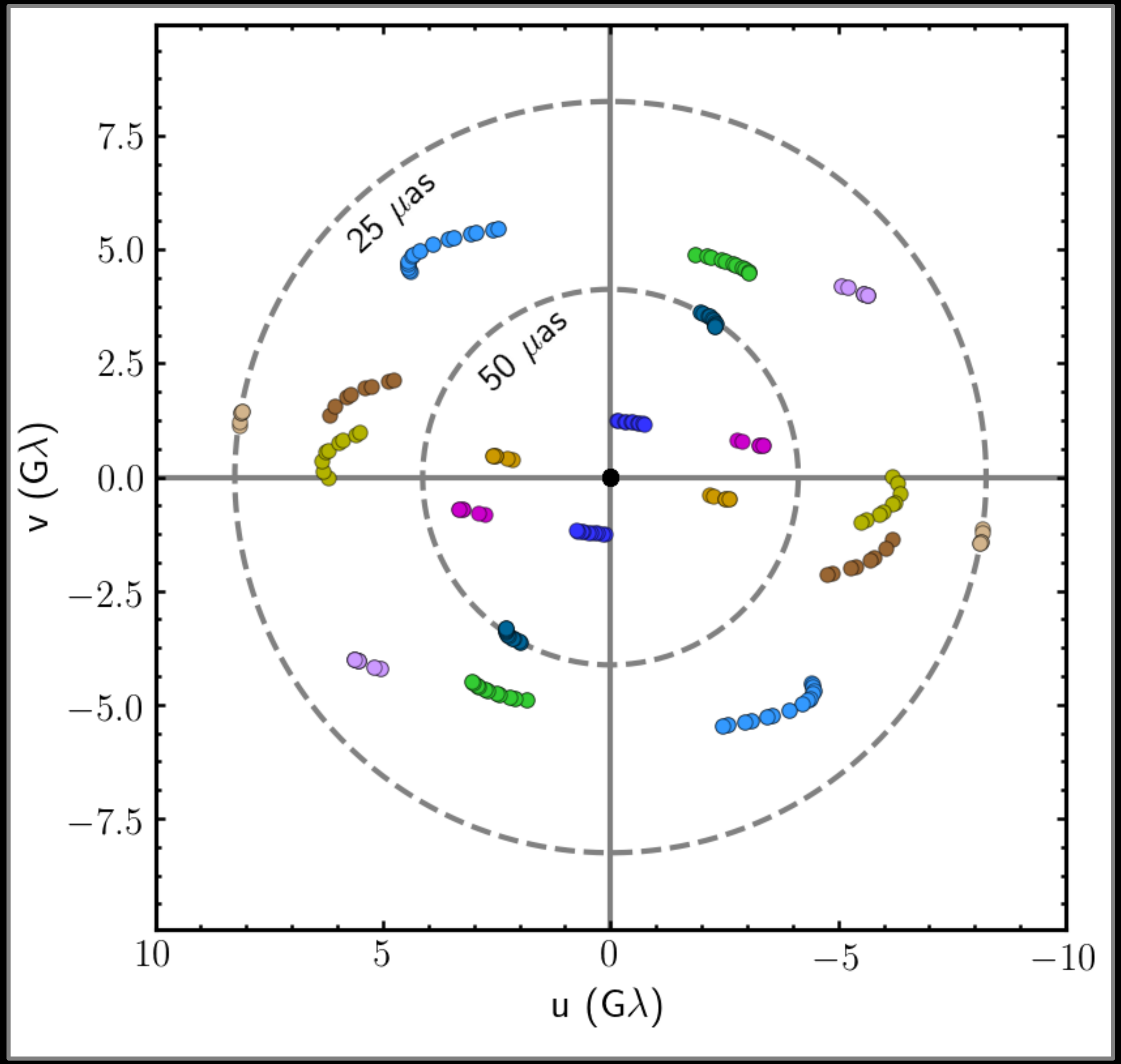


Animation credit: Daniel Palumbo, Katie Bouman, Maciek Wielgus

Turning Data into an Image

We are trying to take a picture of something that has never been seen, using only a handful of measurements that are difficult to calibrate, with an instrument that has never been used.

How can we ensure that our results are reliable?



First Step: Blind Imaging Comparisons

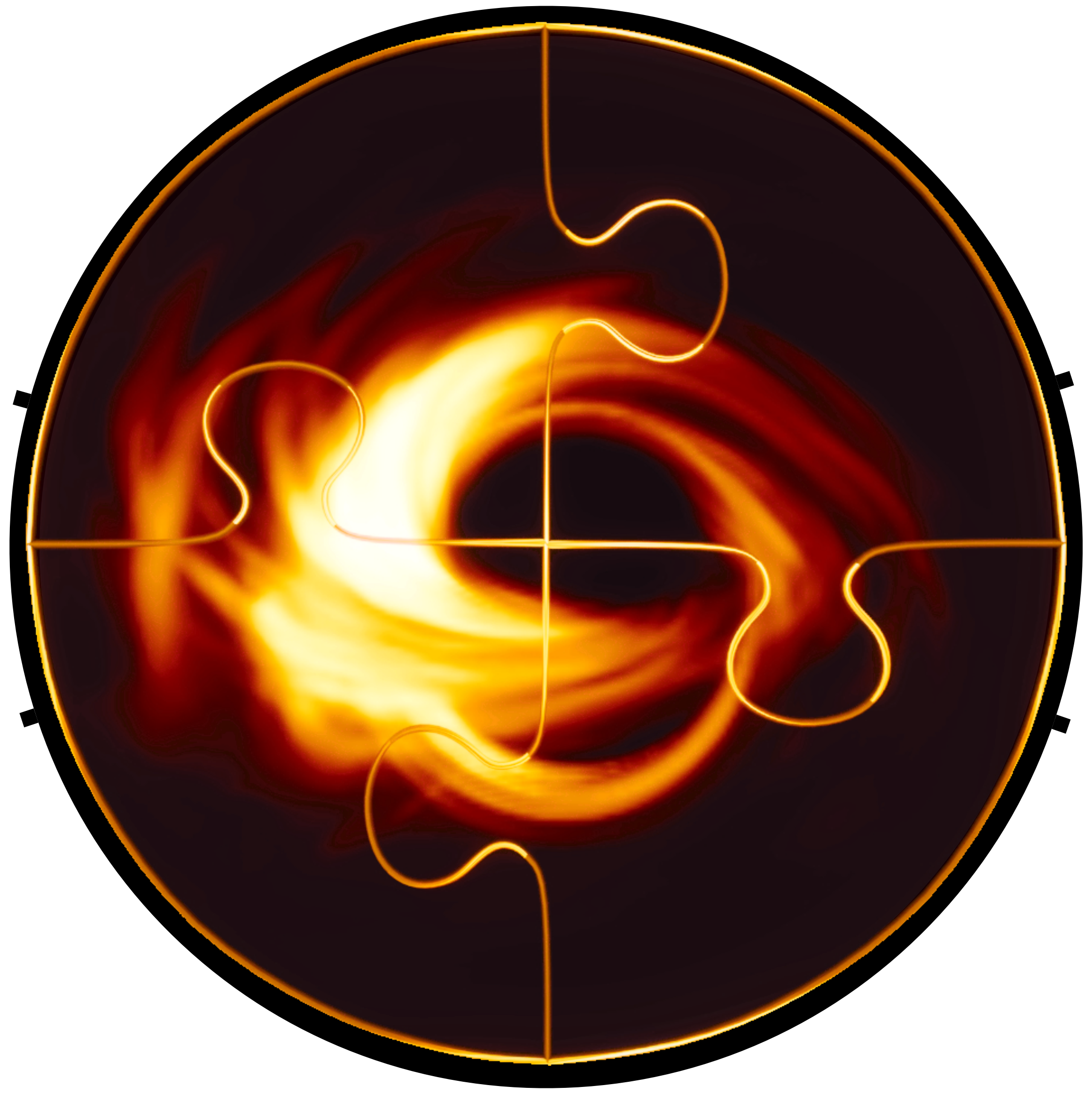
The Imaging WG was divided into four independent teams

Team 1

Region:
The Americas
(SAO, UoA, U.Concepcion)

Team 2

Region:
Global
(MIT Haystack, Radboud U, NAOJ)



Team 3

Region:
East Asia (ASIAA, KASI, NAOJ)

Team 4

Region:
Cross-Atlantic
(MPIfR, Boston U, IAA, Aalto)

Each team blindly reconstructed images

Goal: Assess human bias

First Step: Blind Imaging Comparisons

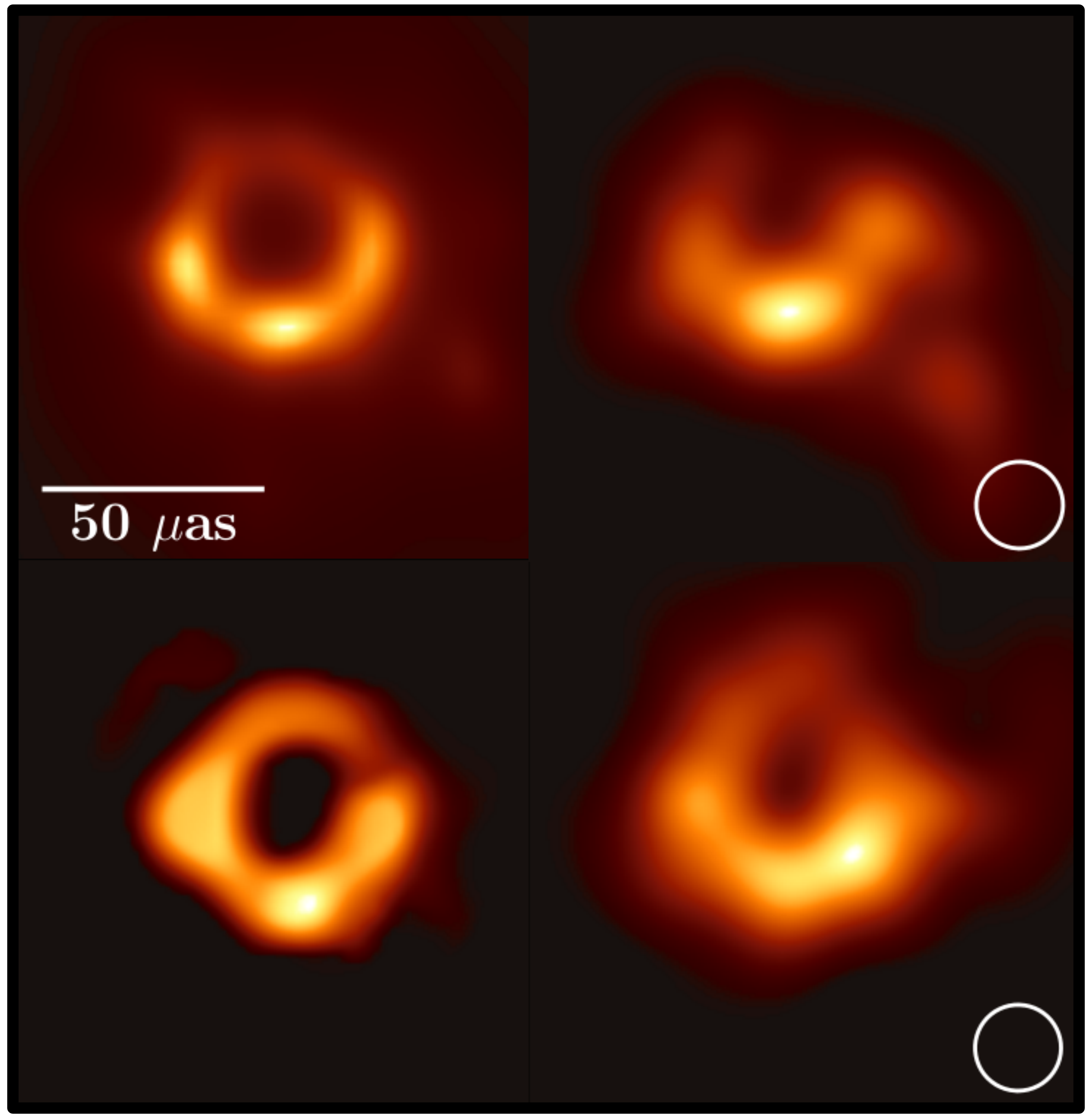
The Imaging WG was divided into four independent teams

Team 1

Region:
The Americas
(SAO, UoA, U.Concepcion)

Team 2

Region:
Global
(MIT Haystack, Radboud U, NAOJ)



Team 3

Region:
East Asia (ASIAA, KASI, NAOJ)

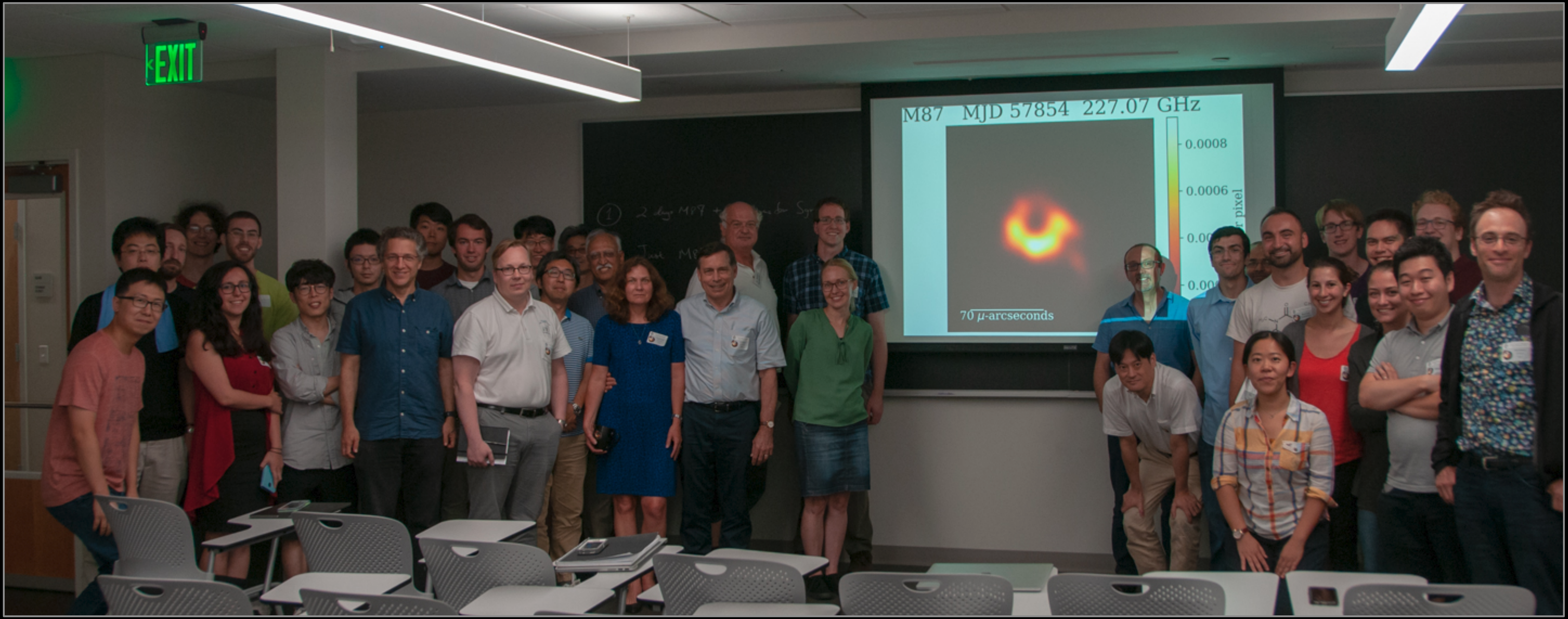
Team 4

Region:
Cross-Atlantic
(MPIfR, Boston U, IAA, Aalto)

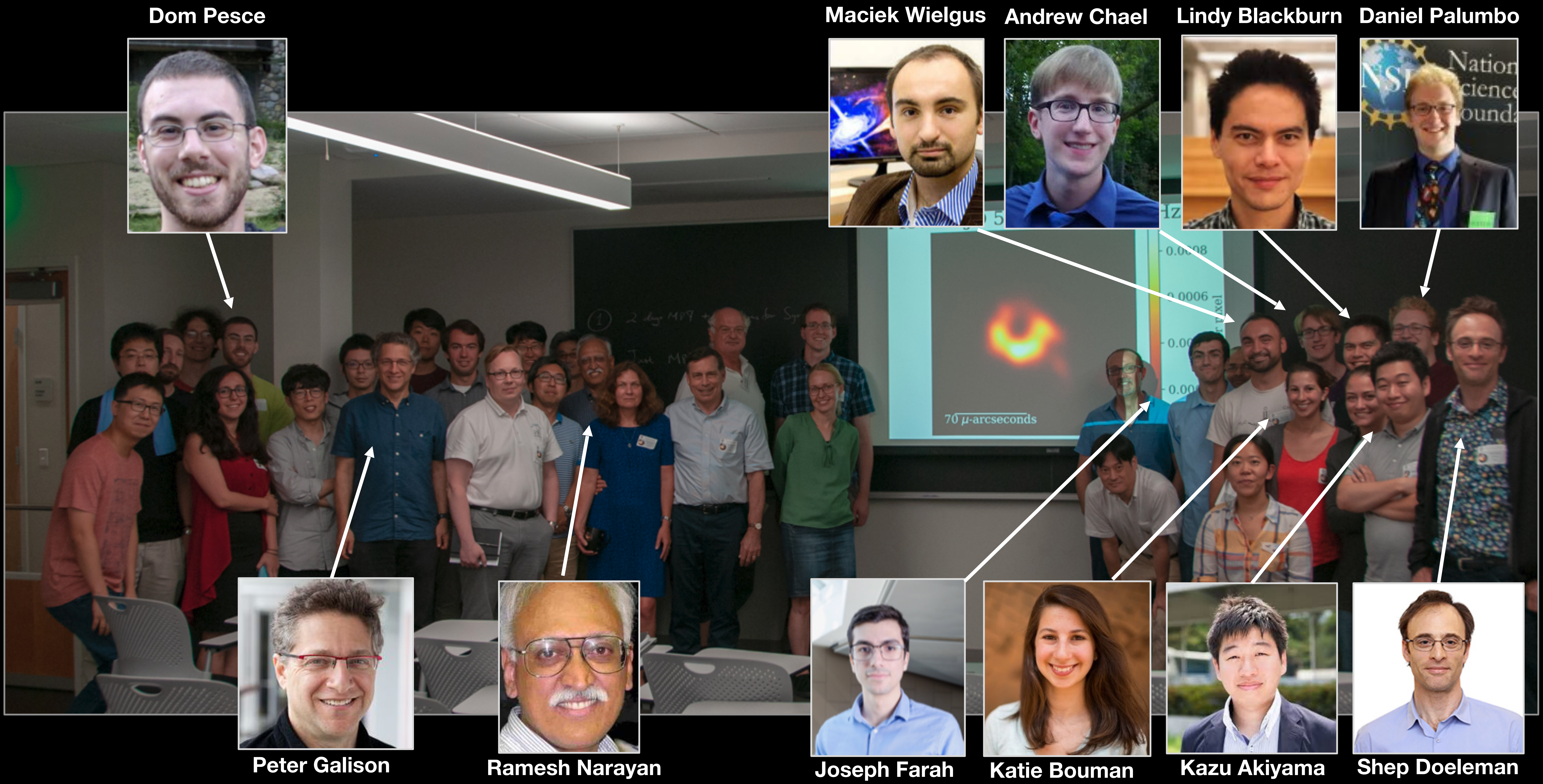
Each team blindly reconstructed images

Goal: Assess human bias

The First EHT Images of M87
July 24, 2018

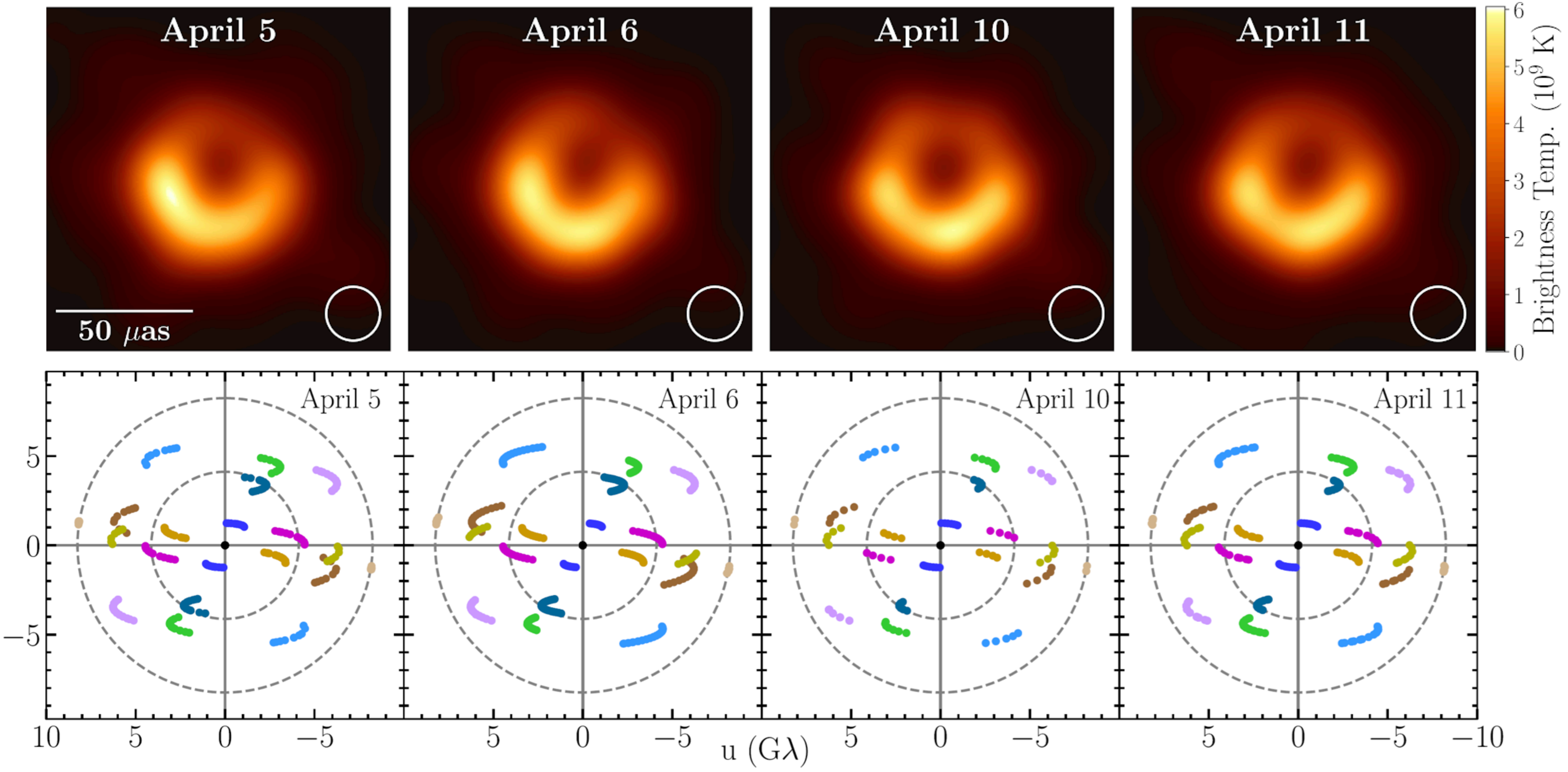


2nd EHT Imaging Workshop



2nd EHT Imaging Workshop

Four Days = Four Experiments



A short personal history of my association with EHT

Submillimeter Array and James Clerk Maxwell Telescope, Mauna Kea, HI

photo credit: Nimesh Patel

2007 1.3 mm “proto-EHT” Array Map

2007 Hawaii-Arizona SgrA* Fringe

Published 2008:

nature Vol 455|4 September 2008|doi:10.1038/nature07245

LETTERS

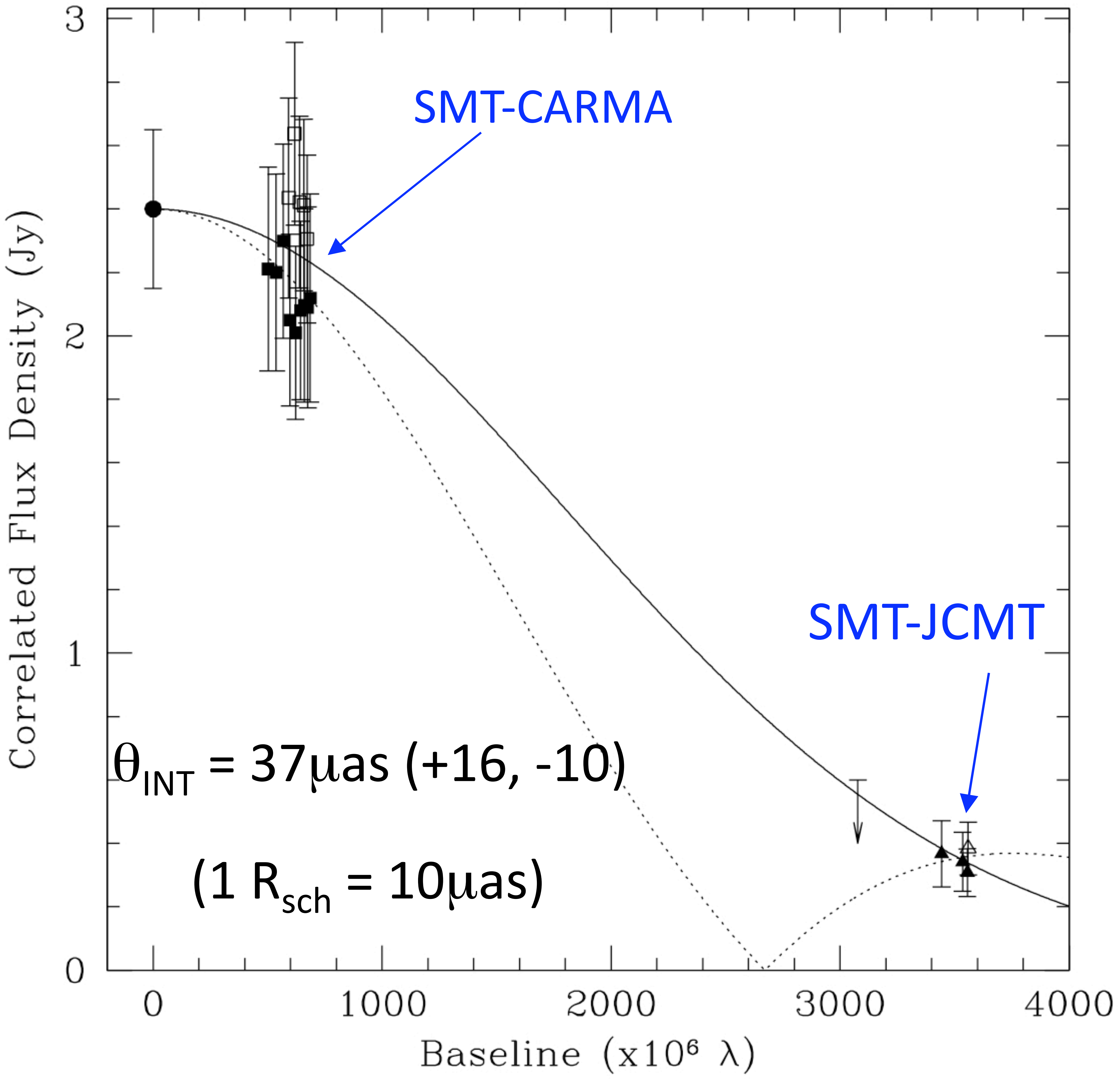
Event-horizon-scale structure in the supermassive black hole candidate at the Galactic Centre

Sheperd S. Doeleman[1], Jonathan Weintroub[2], Alan E. E. Rogers[1], Richard Plambeck[3], Robert Freund[4], Remo P. J. Tilanus[5,6], Per Friberg[5], Lucy M. Ziurys[4], James M. Moran[2], Brian Corey[1], Ken H. Young[2], Daniel L. Smythe[1], Michael Titus[1], Daniel P. Marrone[7,8], Roger J. Cappallo[1], Douglas C.-J. Bock[9], Geoffrey C. Bower[3], Richard Chamberlin[10], Gary R. Davis[5], Thomas P. Krichbaum[11], James Lamb[12], Holly Maness[3], Arthur E. Niell[1], Alan Roy[11], Peter Strittmatter[4], Daniel Werthimer[13], Alan R. Whitney[1] & David Woody[12]

The cores of most galaxies are thought to harbour supermassive black holes, which power galactic nuclei by converting the gravitational energy of accreting matter into radiation[1]. Sagittarius A* (Sgr A*), the compact source of radio, infrared and X-ray emission at the centre of the Milky Way, is the closest example of this phenomenon, with an estimated black hole mass that is 4,000,000 times that of the Sun[2,3]. A long-standing astronomical

uncertainties resulted in a range for the derived size of 50–170 μas (ref. 12).

On 10 and 11 April 2007, we observed Sgr A* at 1.3 mm wavelength with a three-station VLBI array consisting of the Arizona Radio Observatory 10-m Submillimetre Telescope (ARO/SMT) on Mount Graham in Arizona, one 10-m element of the Combined Array for Research in Millimeter-wave Astronomy (CARMA) in



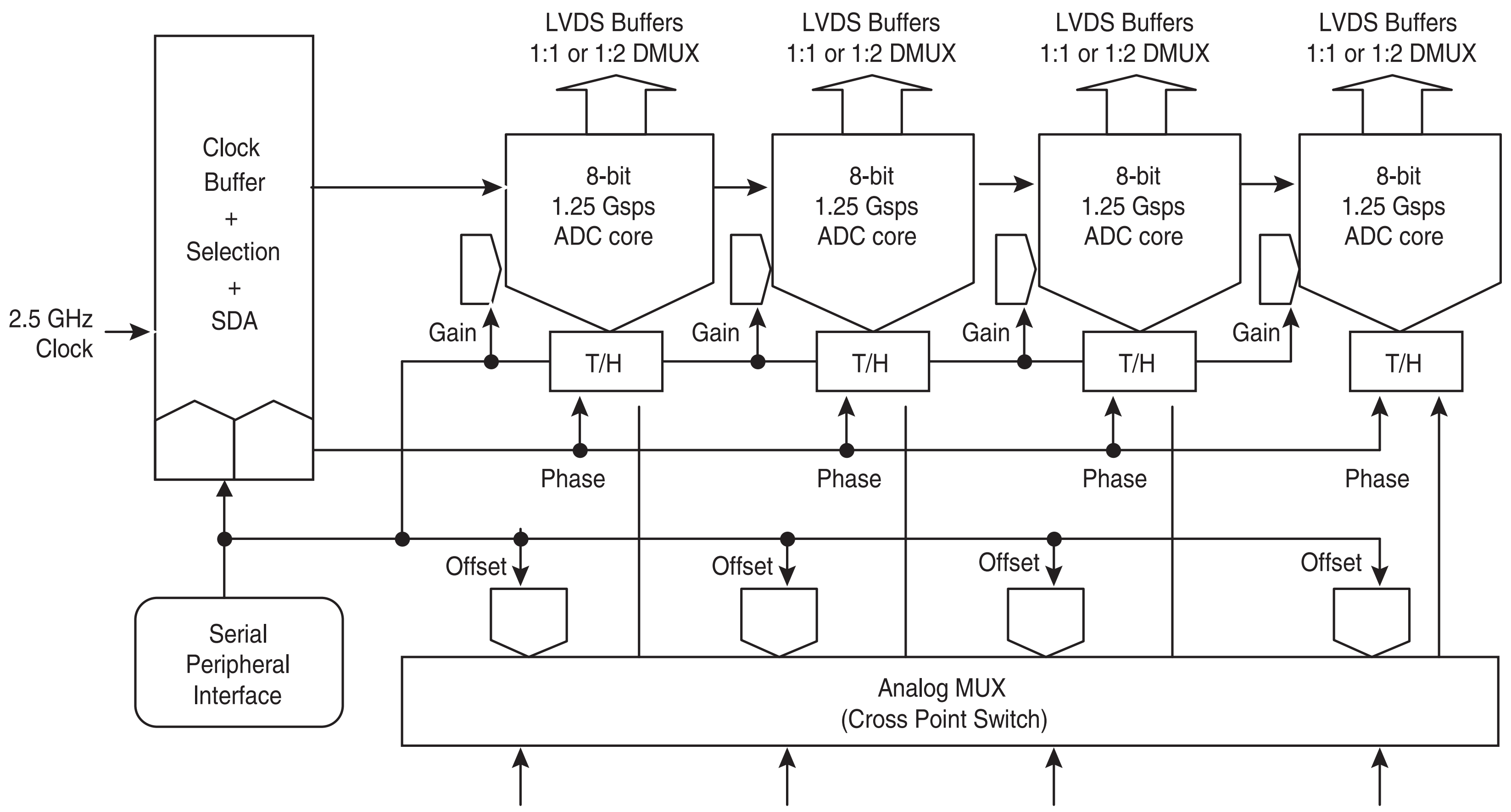
- This result confirmed event-horizon-scale structures exists, and are observable—retired risk
- Result very much on the margin, sensitivity limited, one transpacific baseline had few detections, the other none at all. Array could barely be more sparse.
- Our technical focus turned to improving sensitivity and adding sites.

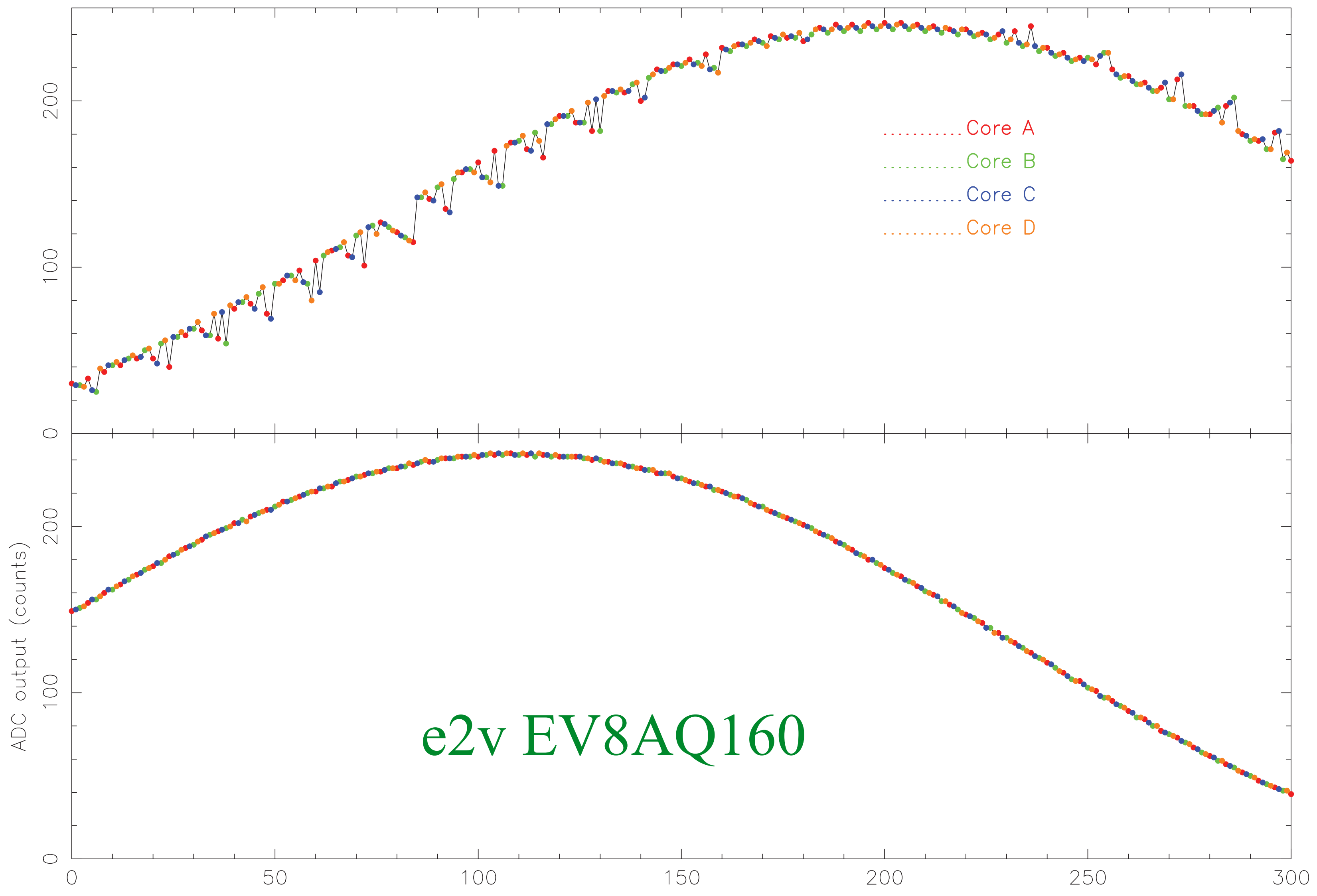
Open Source "Collaboration for Astronomy Signal Processing and Electronics Research"

ROACH2, 5 GSa/s ADC becomes Wideband Tech for 64 Gbps EHT

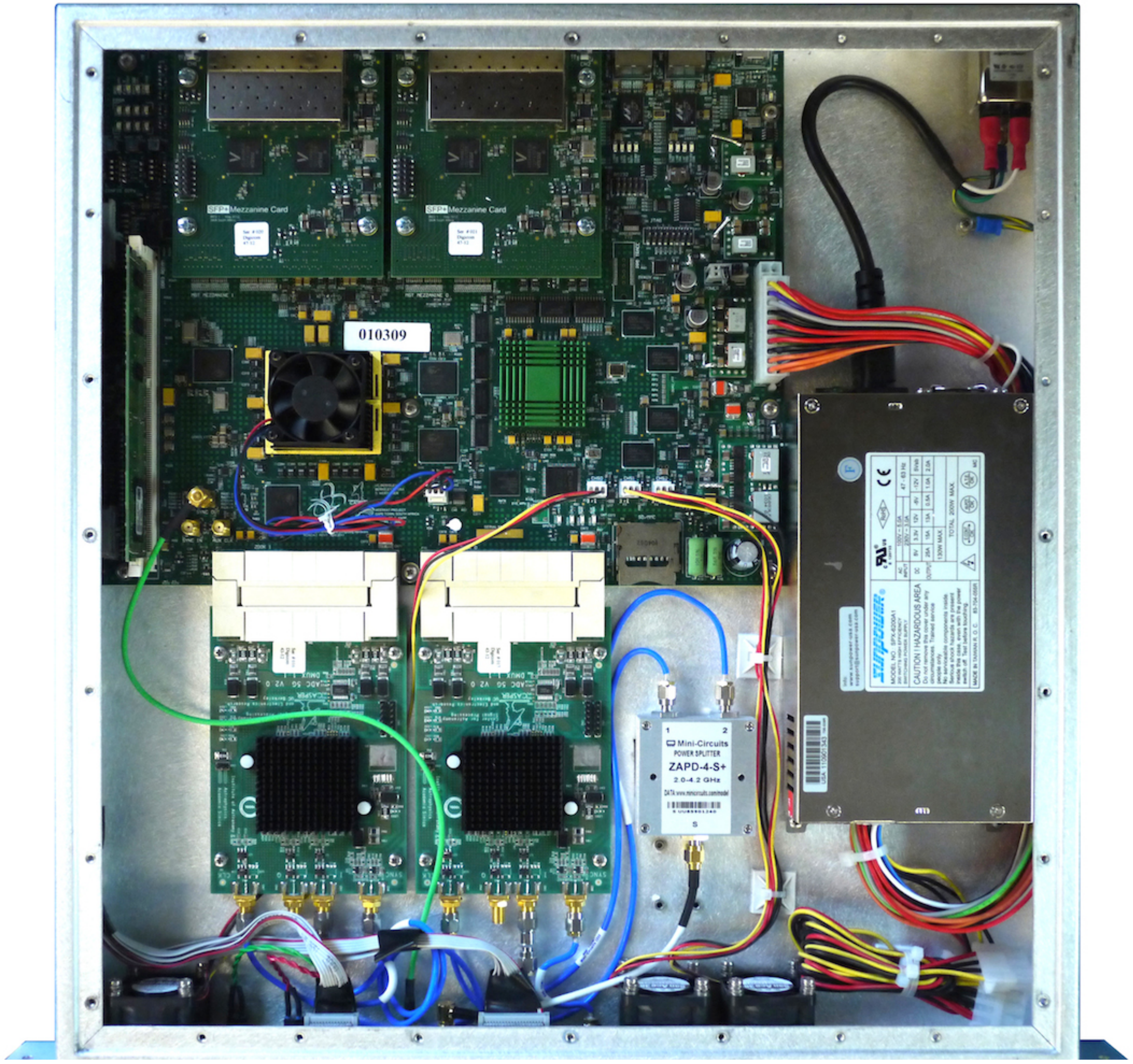
(Jiang et al., PASP 126, 761; 2014; Patel et al., JAI 3, 1 2014)

Ultra Fast Analog-to-Digital Converters are typically interleaved multi-core devices
This introduces interleaving artifacts which must be calibrated





CASPER ROACH2 with Dual ASIAA ADCs
Photo by Derek Kubo



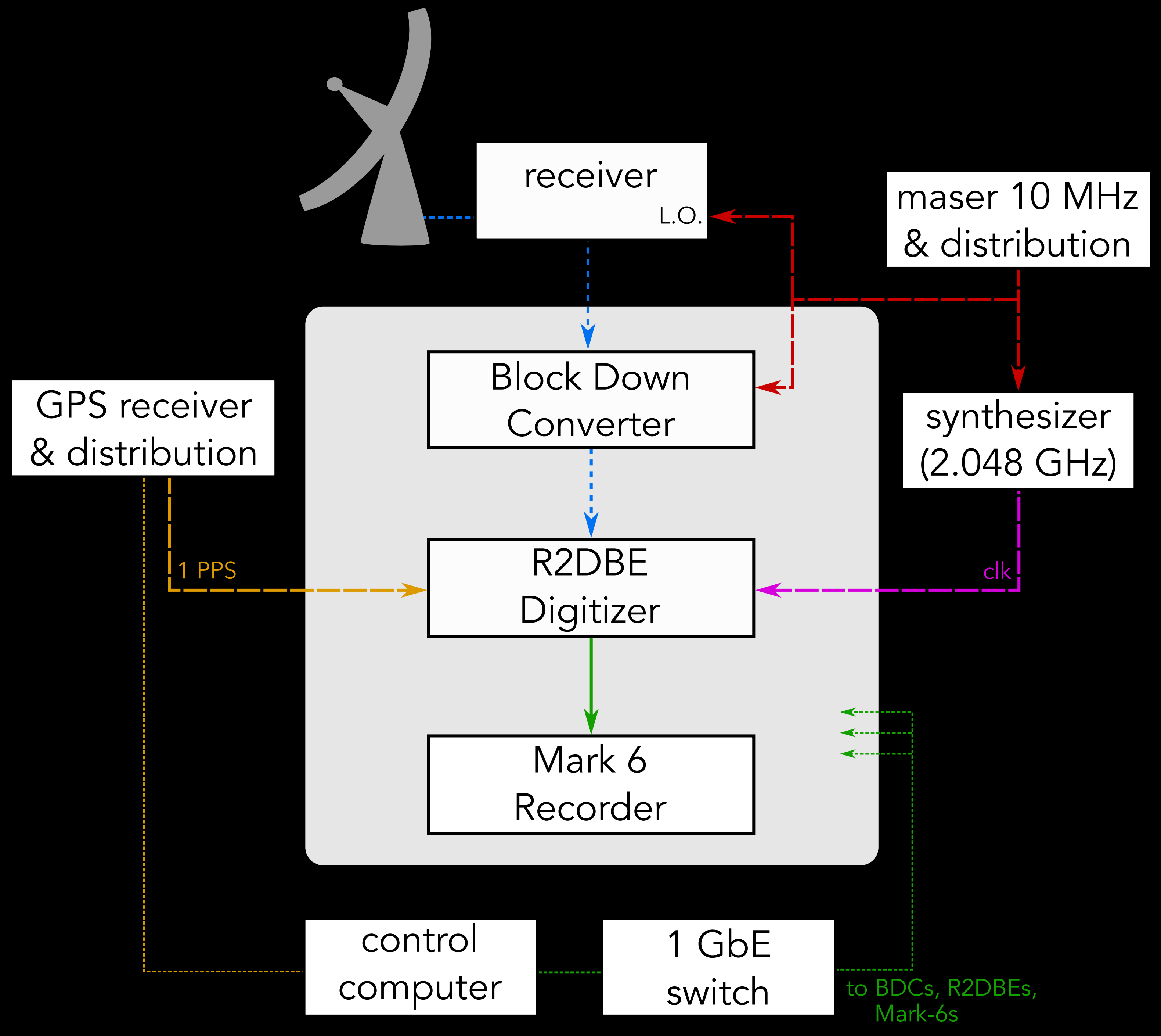
http://casper.berkeley.edu

Hickish et al., Journal of Astronomical Instrumentation, 2016

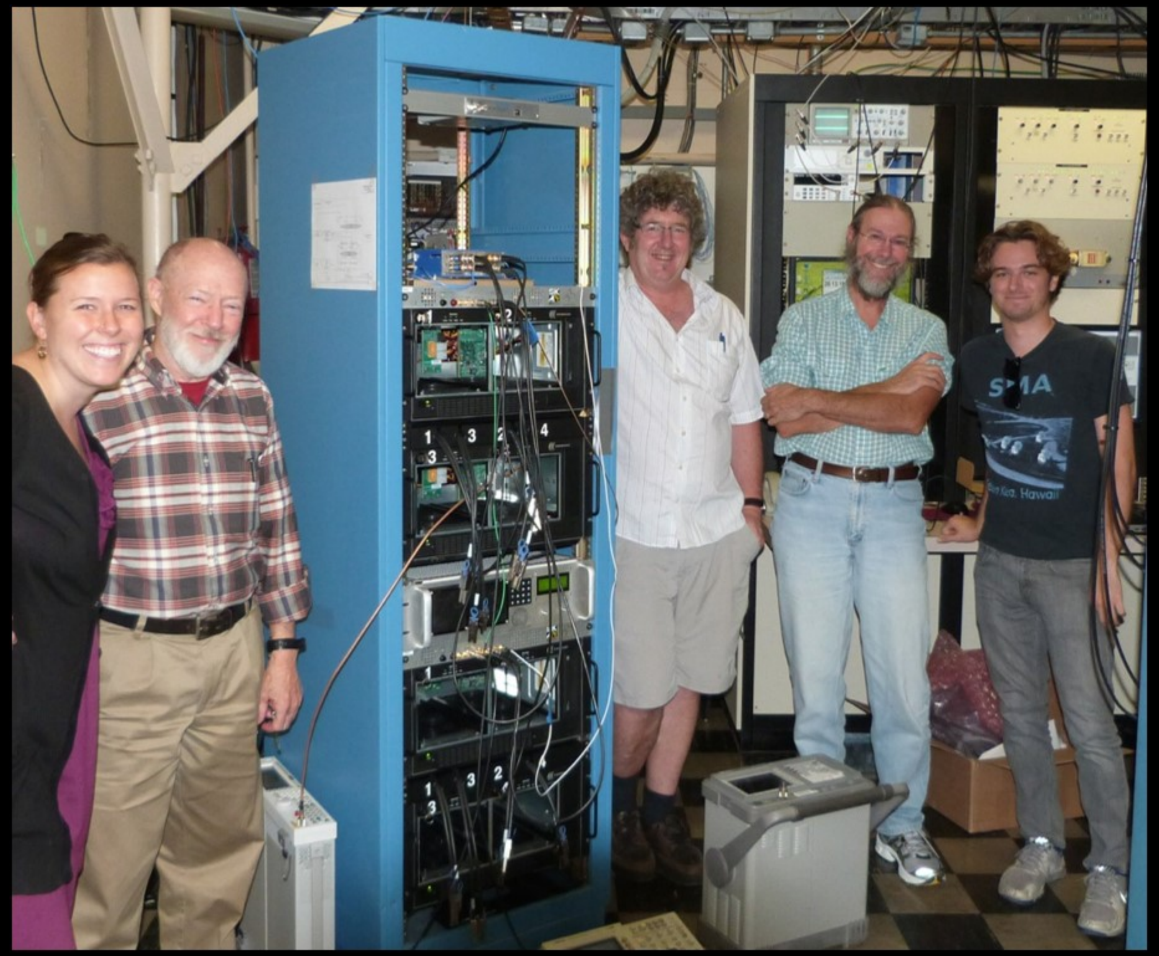
Mark 6 data recorder with expansion ×4

R2DBE digitizer ×4

block down converter ×2



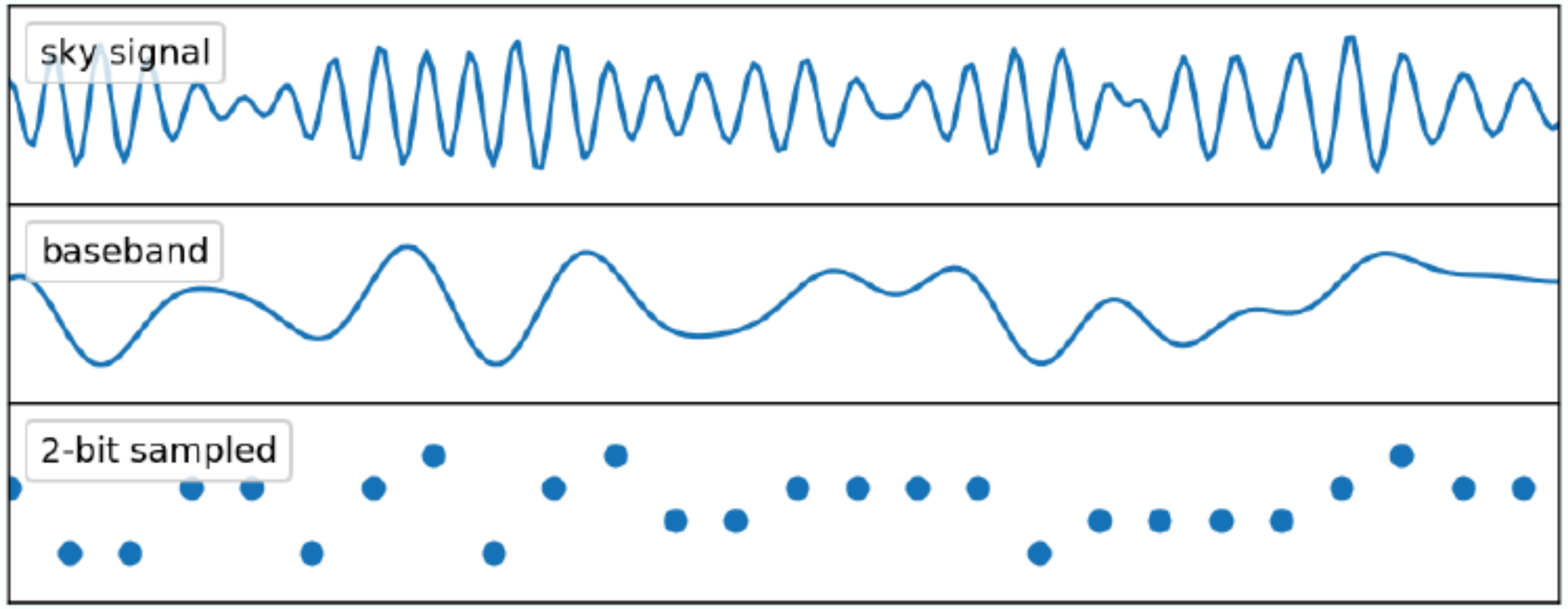
EHTC (2019b) ApJL



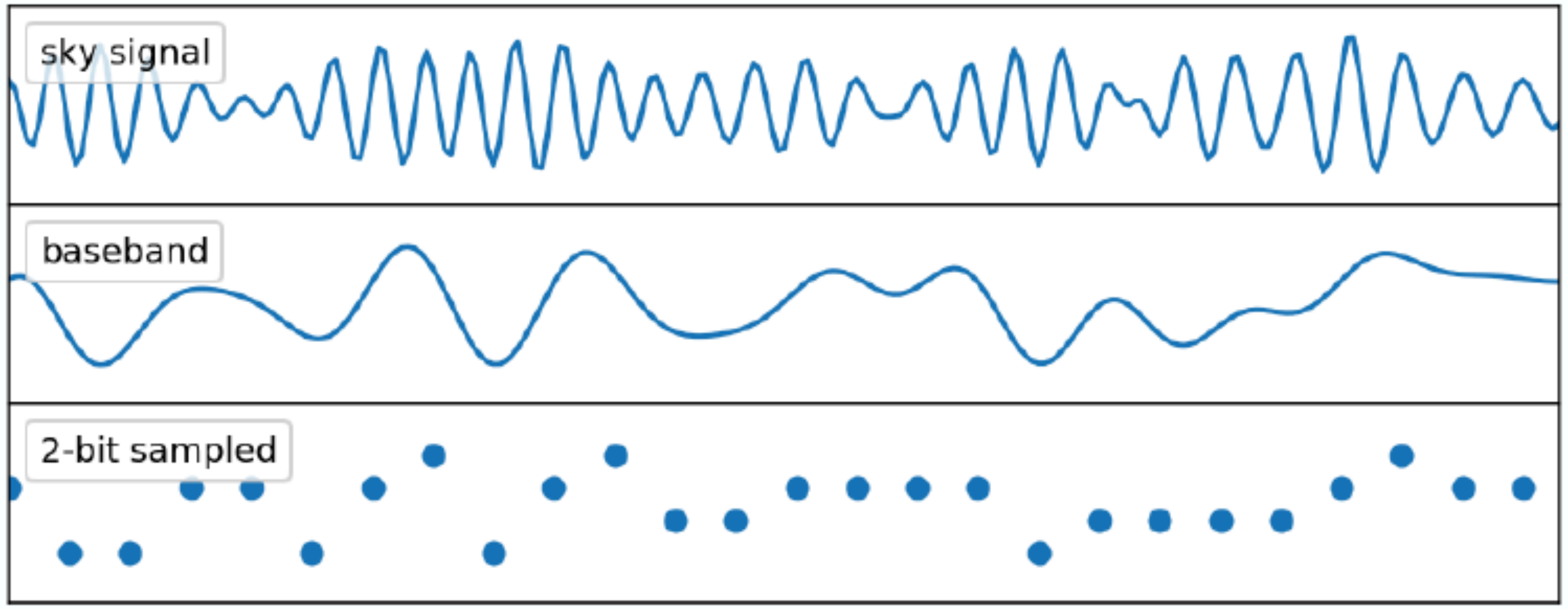
South Pole Telescope

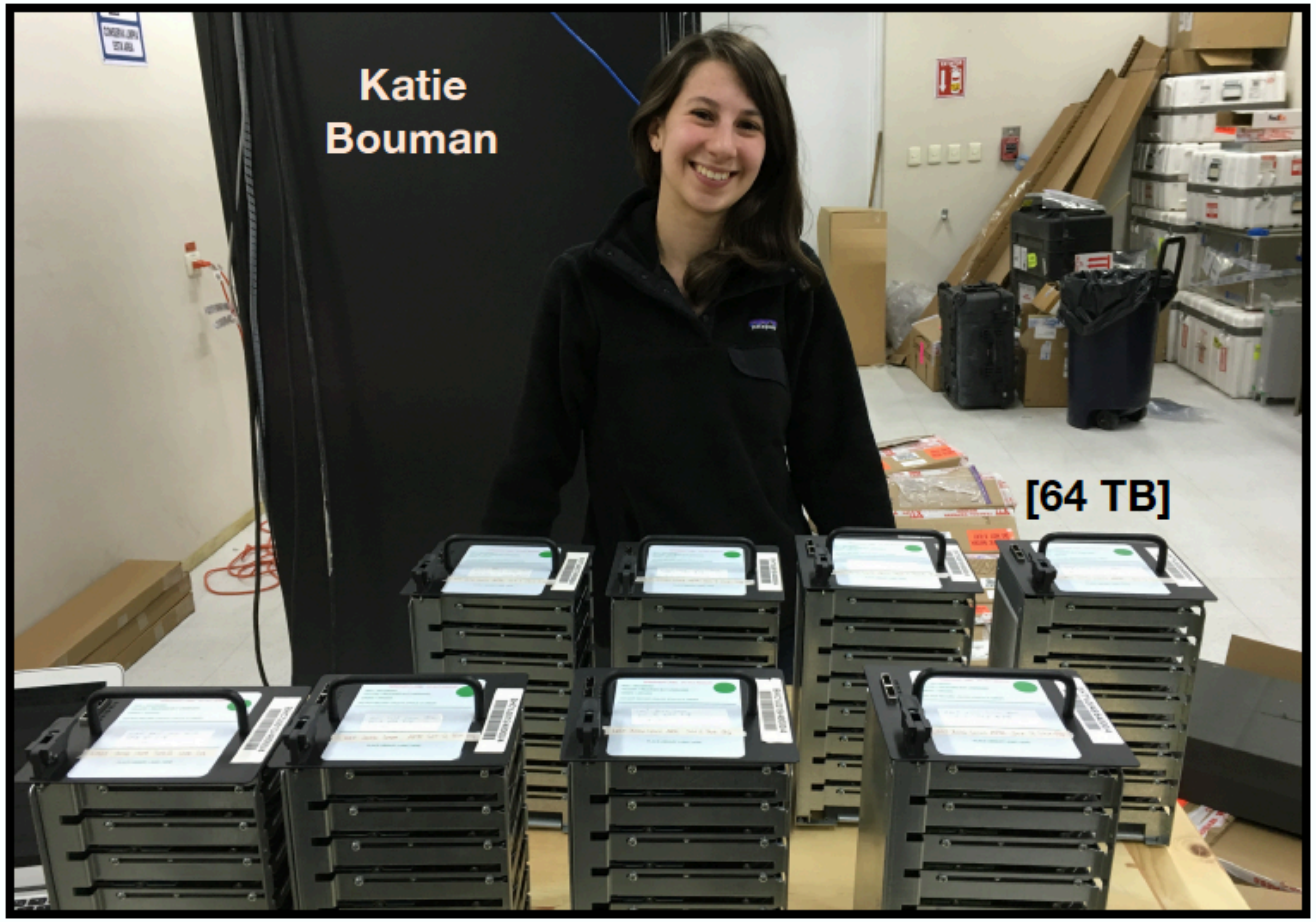
Daniel Palumbo

Daniel Palumbo

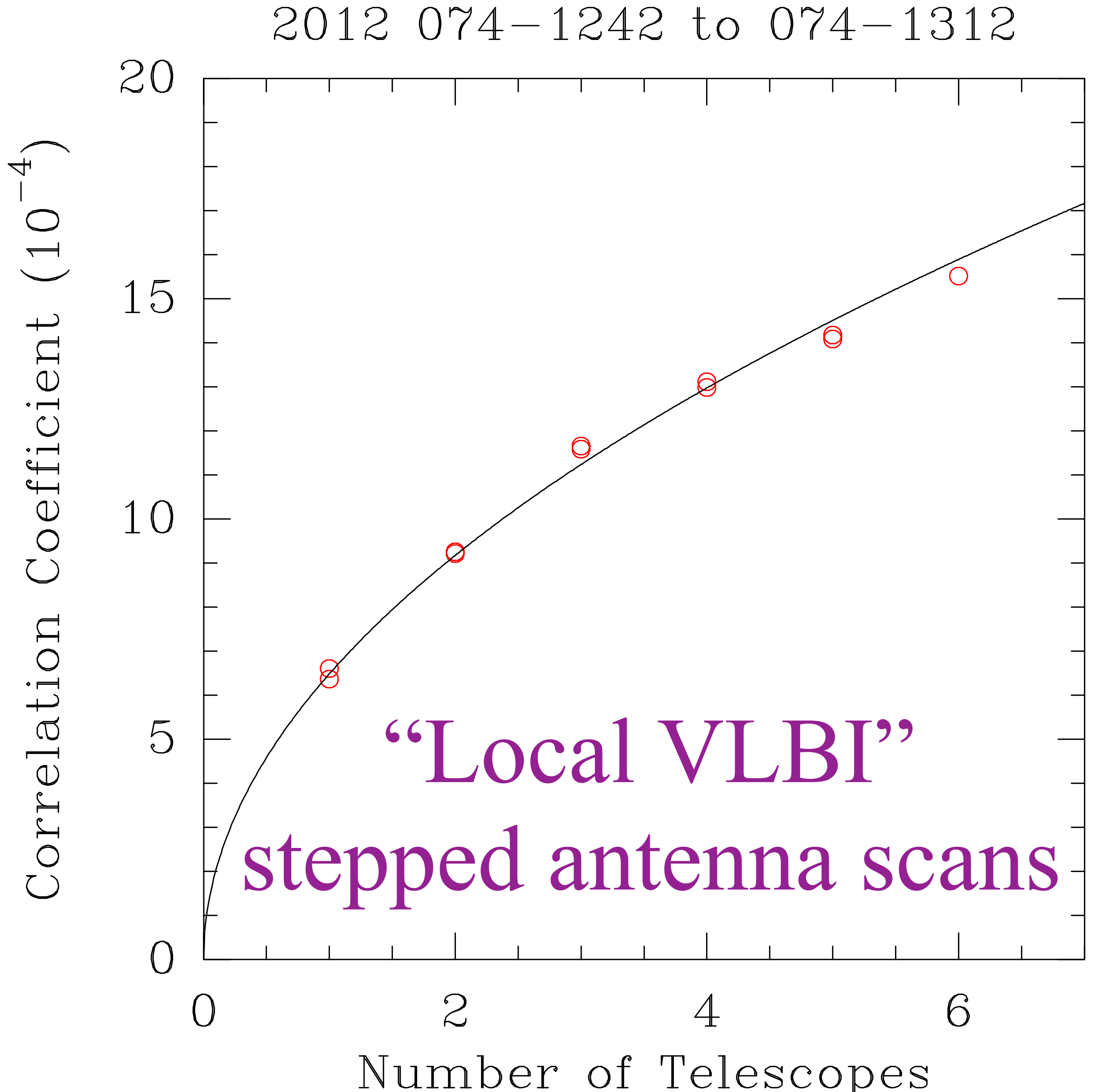



Daniel
Palumbo


sky signal
baseband
2-bit sampled

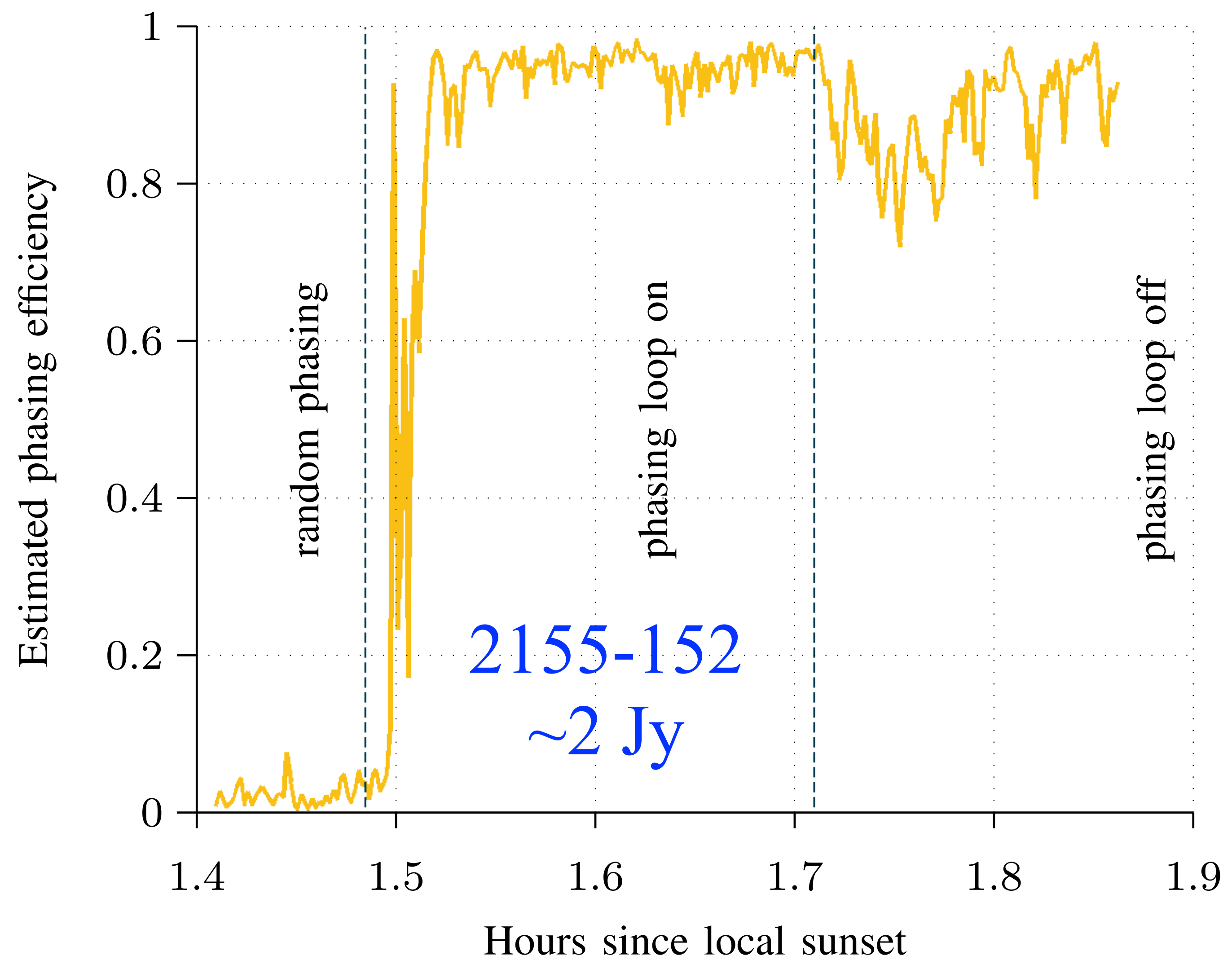

Katie
Bouman
[64 TB]

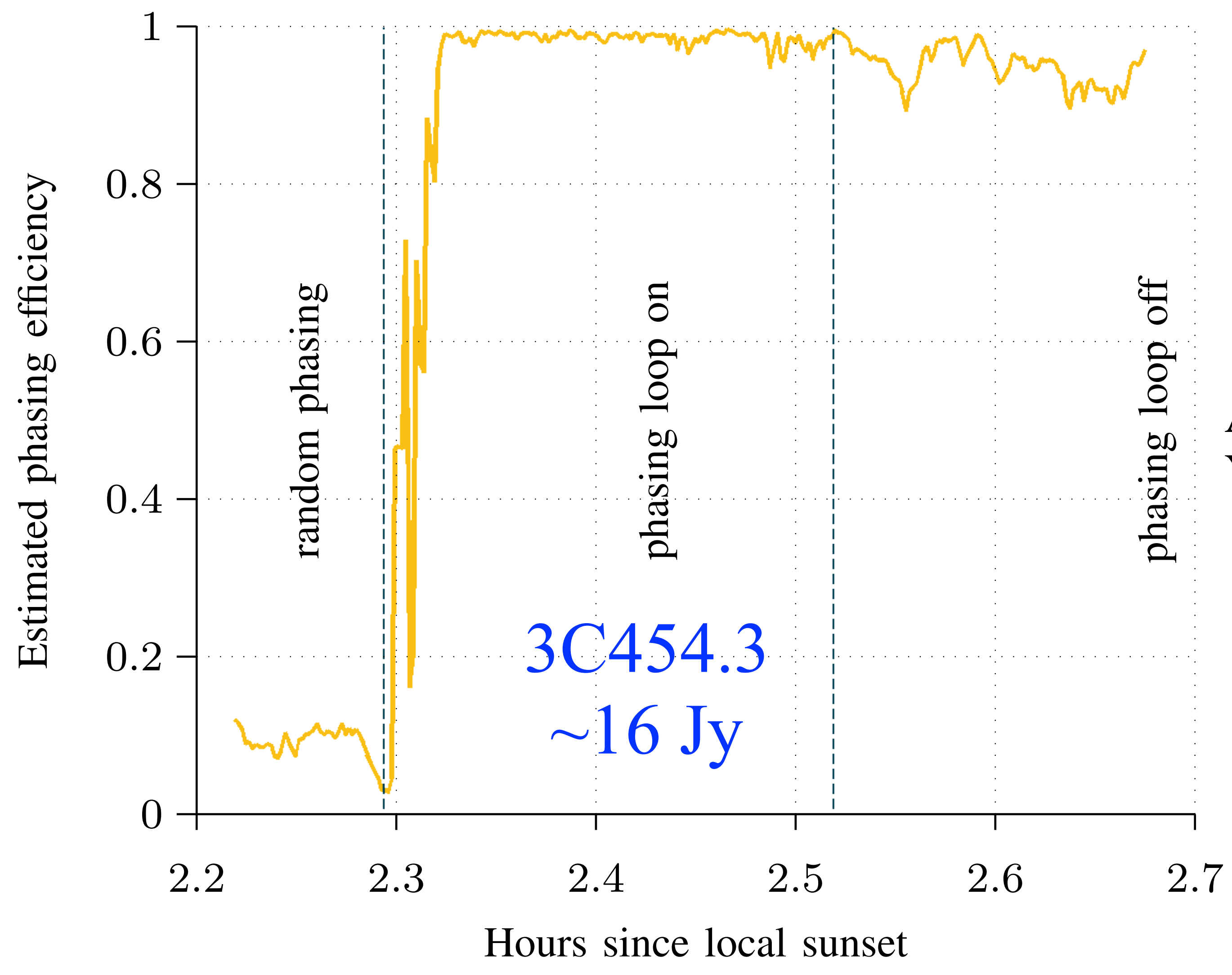
Phased Array on Maunakea



Developed using 2008 CASPER open source technology
https://casper.berkeley.edu
(Nagpal, Primiani, MacMahon, Dexter, Weintroub)

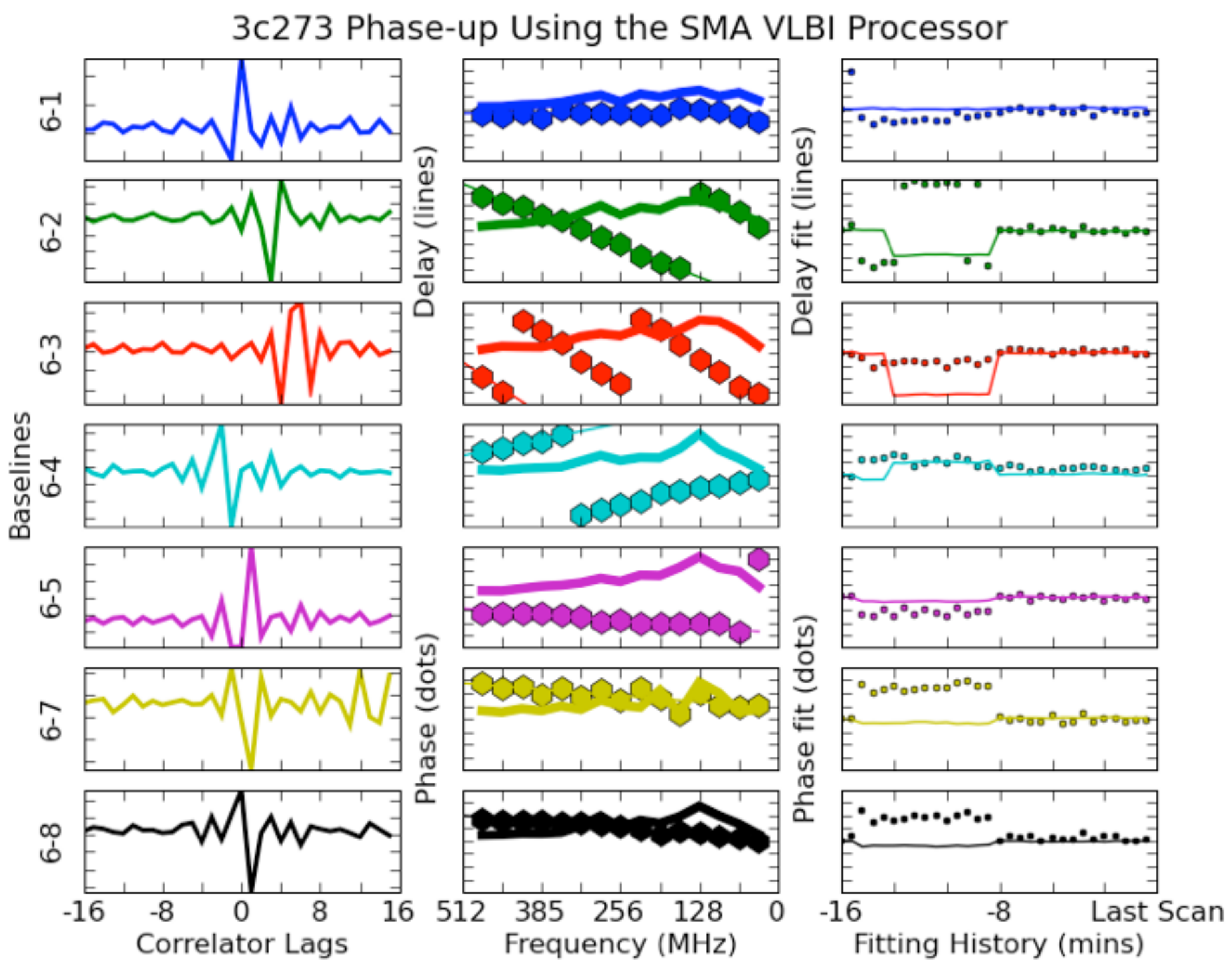
Phased ALMA to SMA Fringe: 22 Jan 2016 (data from test in July 2015)

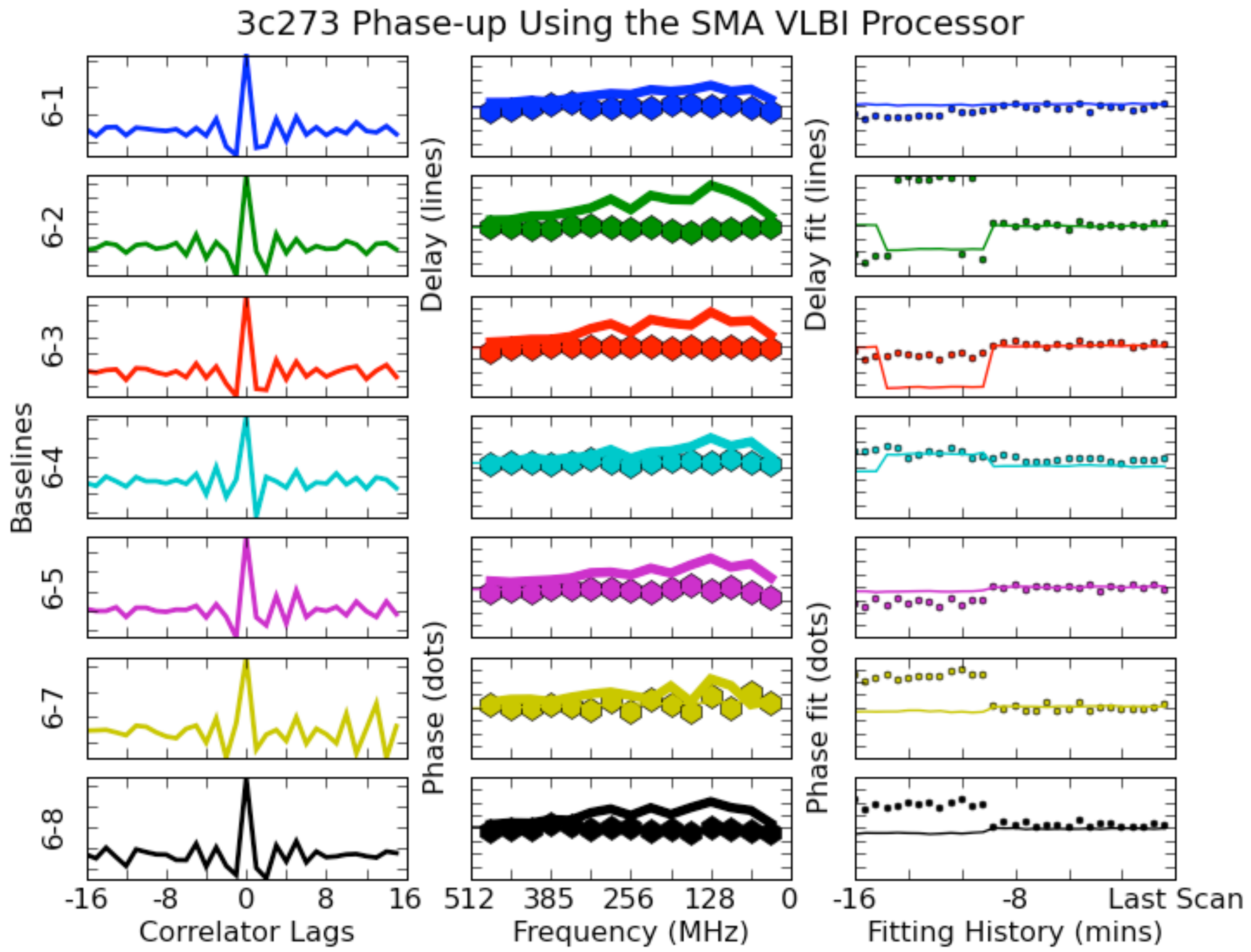




Andre Young, Rurik Primiani, Ken Young, J. Weintroub, et al.

Phased array servo response . . . akin to adaptive optics . . . a CPS for sure

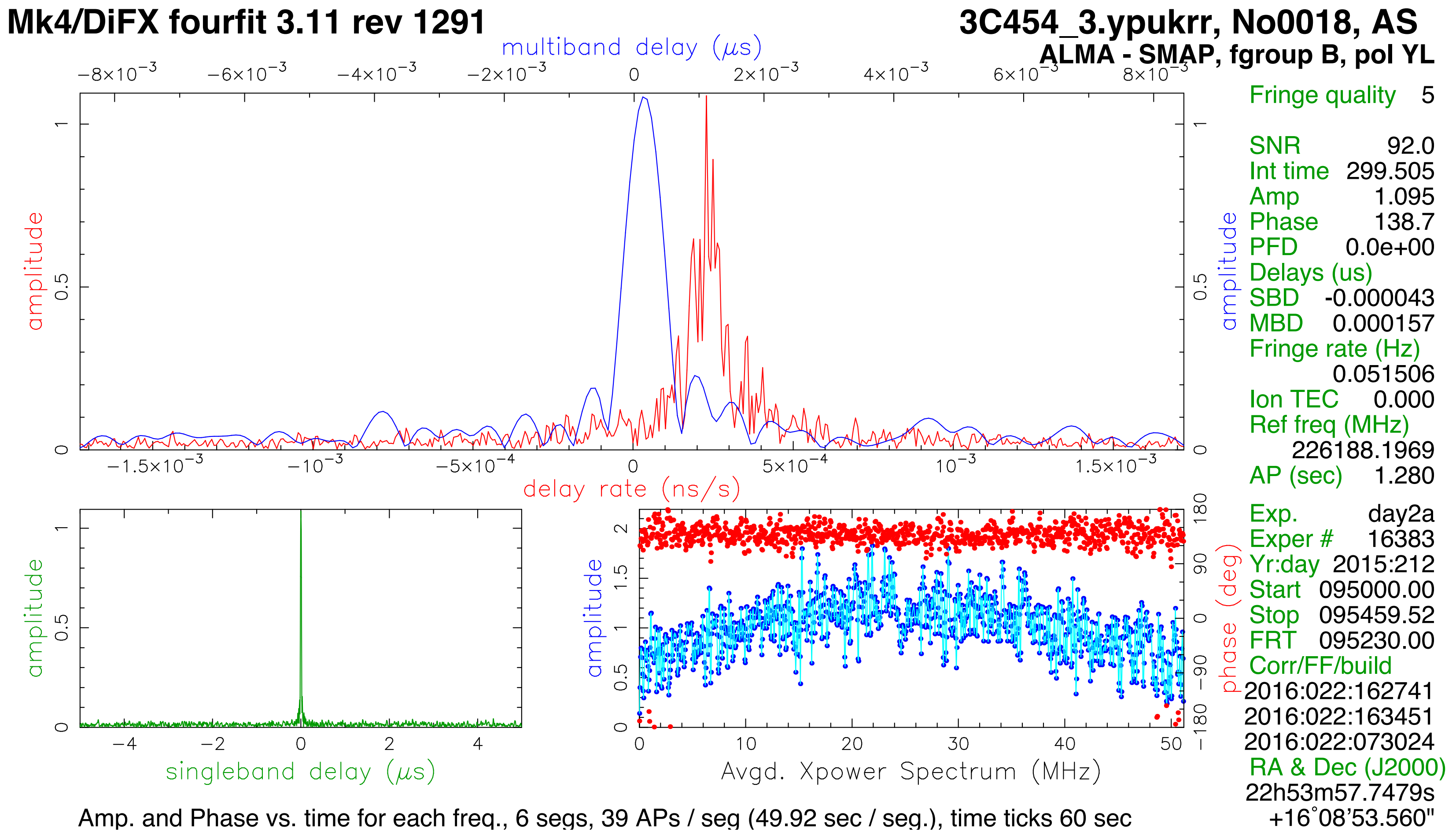




Phased SMA to Phased ALMA fringe

(ALMA Phasing Project, Matthews, Doeleman, Crew, et al.)

First fringe Phased ALMA to Phased SMA July 2015



ALMA: Geoff Crew, Mike Tttus, Roger Cappallo, Adam Deller, ALMA Matthews, and many more!

SMA: Young (x2) , Primiani, Weintroub

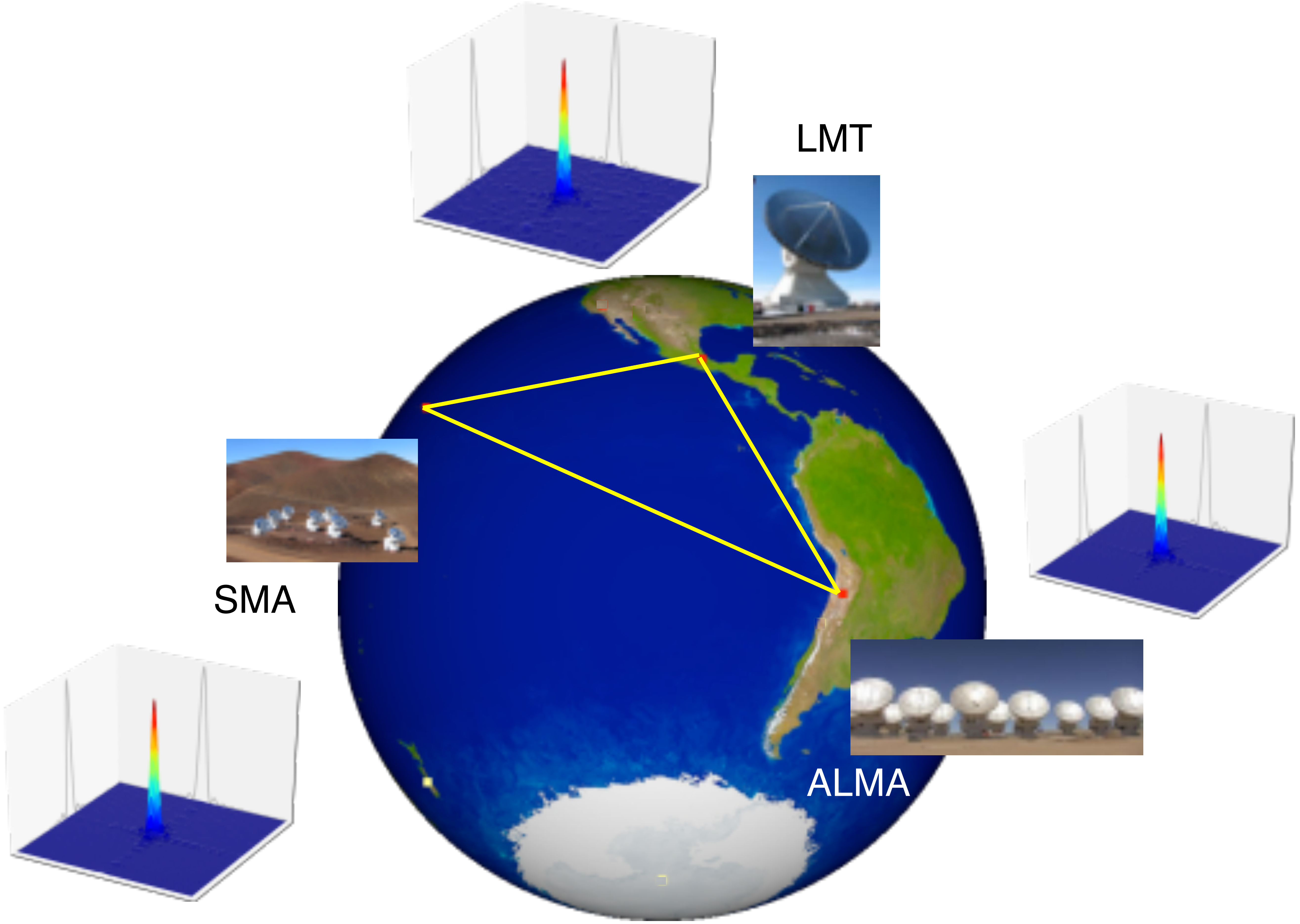
Phase Referencing (Blackburn, et al, 2019, EHTC+ 2019 ApJL 875 L3)

Strong detections to ALMA allow coherent integration on less sensitive baselines.

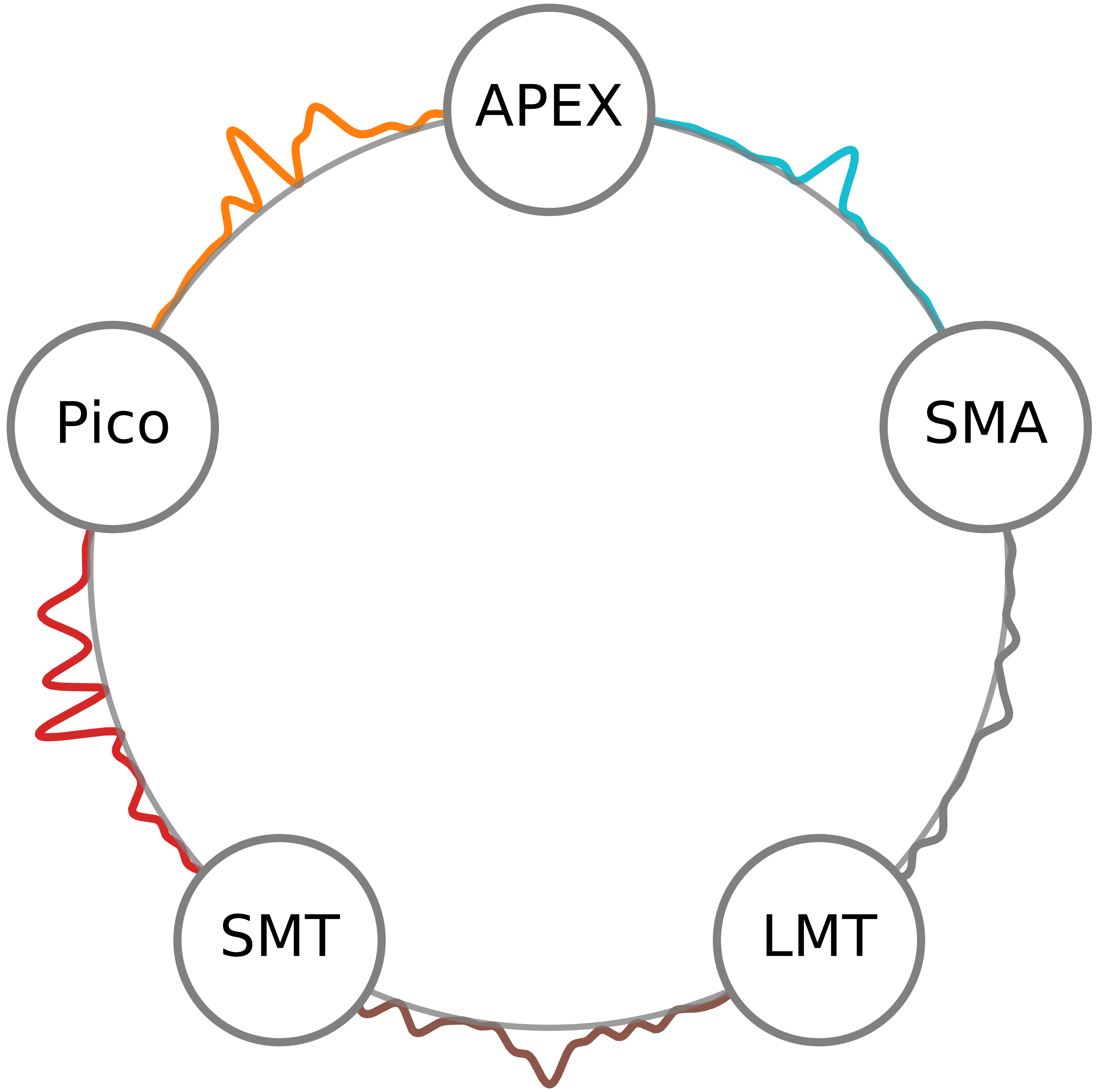
The ALMA baselines to the LMT and SMA enable the atmospheric phase to be tracked and removed on one-second time scales.

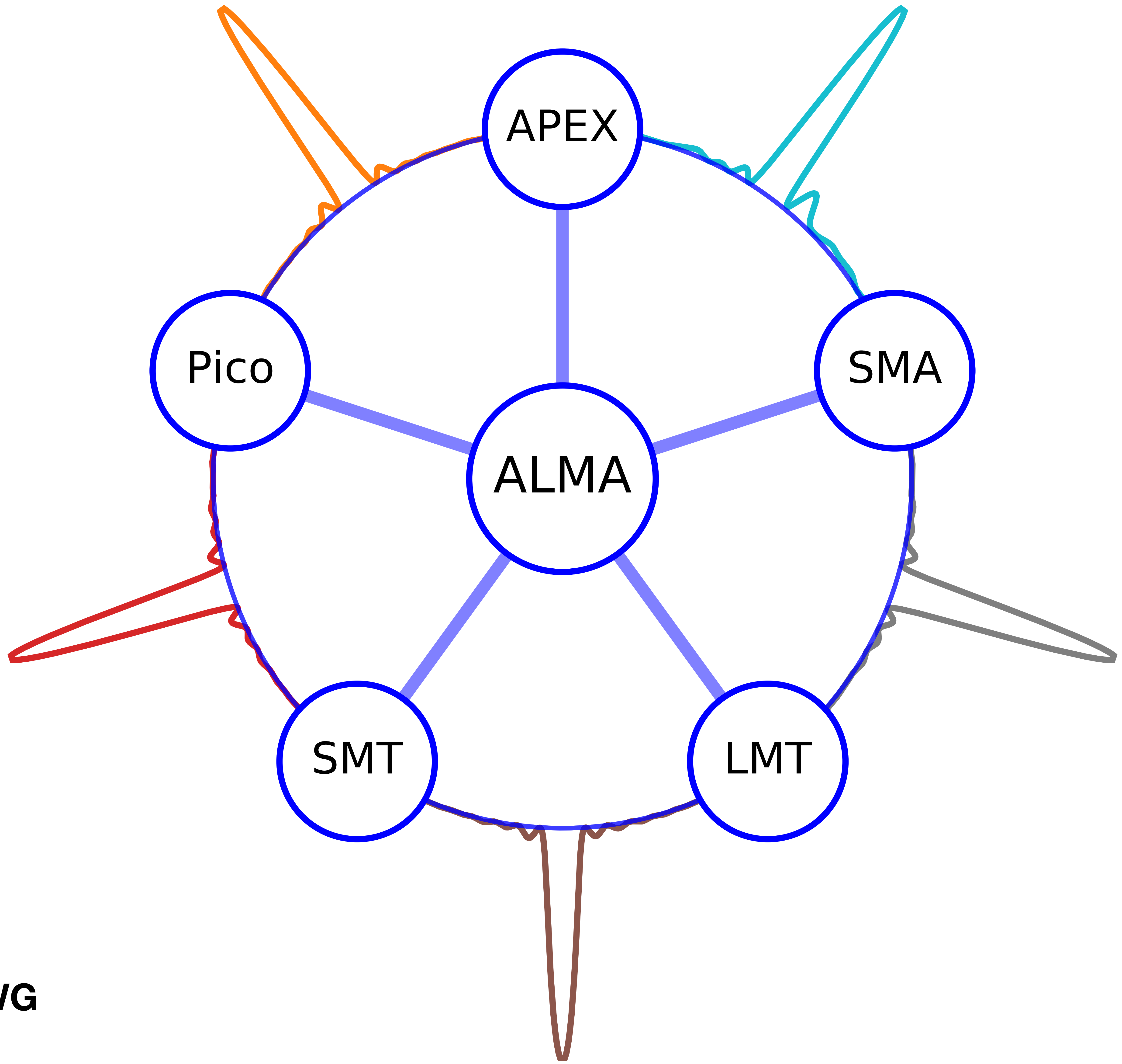
A non-real time phased array on a global scale

EHTC (2019c) ApJL



ALMA Enables New Calibration Scheme: Phase Referencing

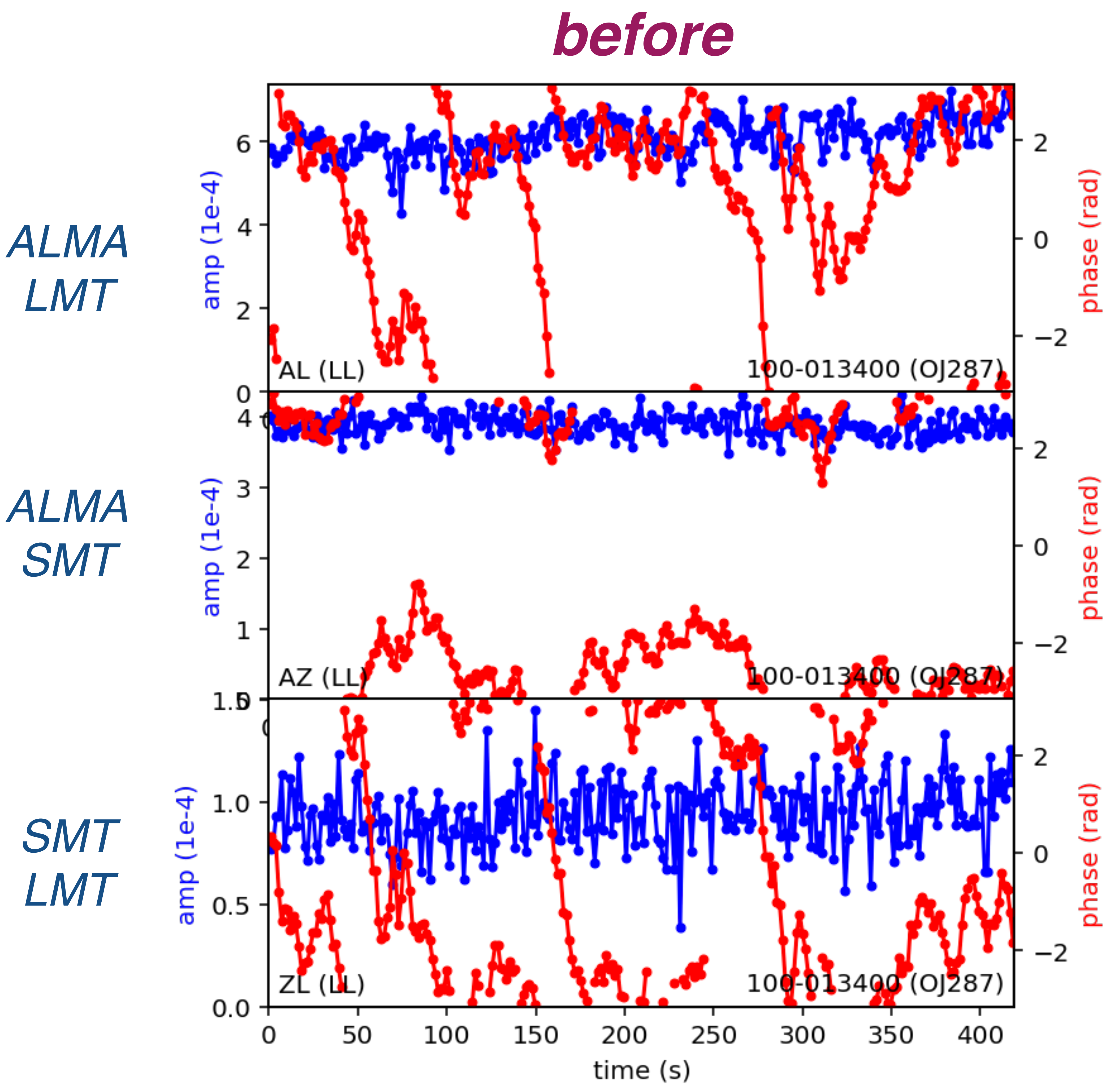


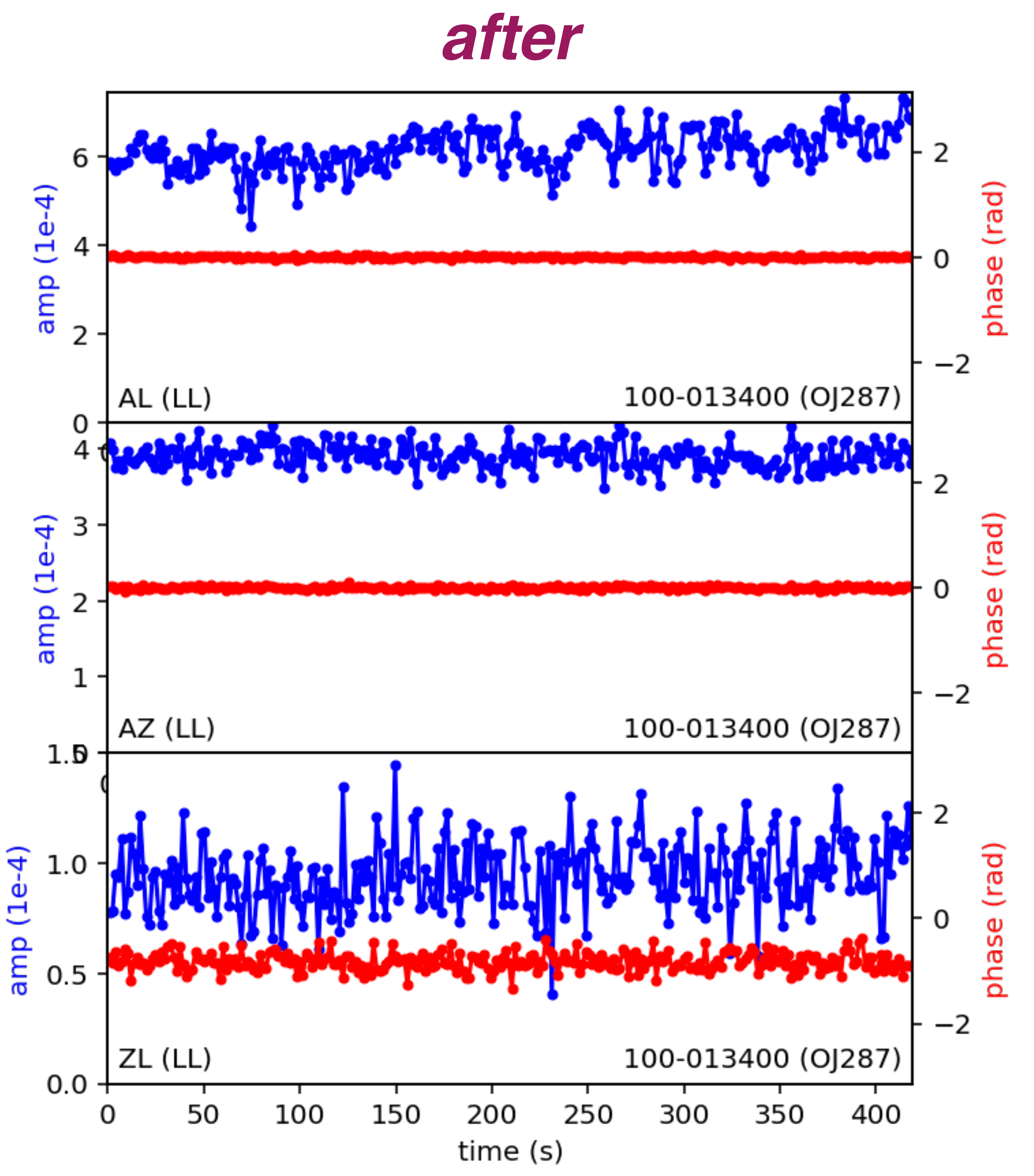


EHT Calibration & Error WG

correcting for atmospheric phase—akin to phased array, but not real time

From a network perspective the EHT is a primitive *sneakernet*



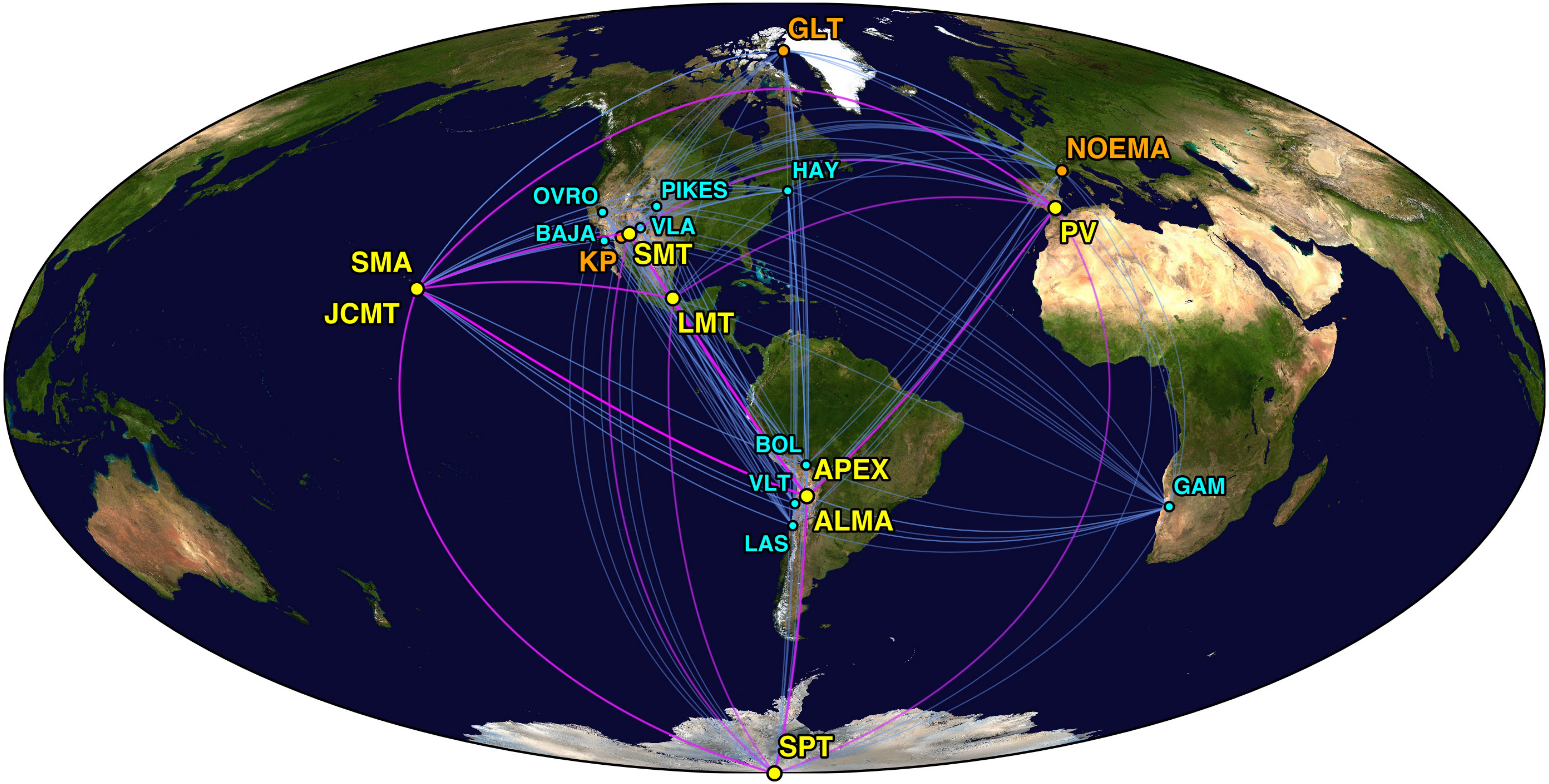


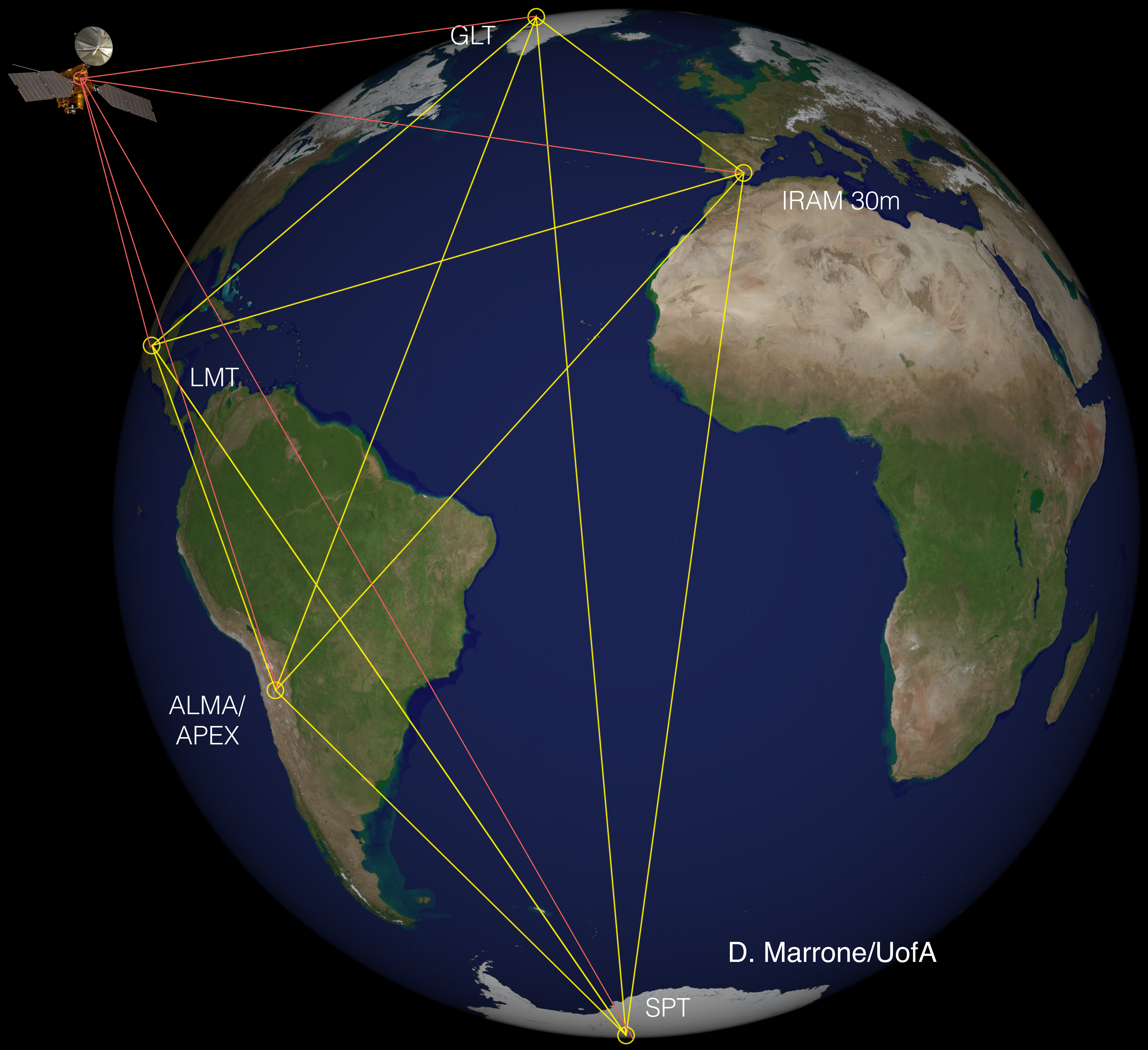
can only average for ~few seconds

can average for entire scan

EHTC+ 2019 ApJL 875 L3, Blackburn et al 2019

What next? next generation EHT as a true real time CPS

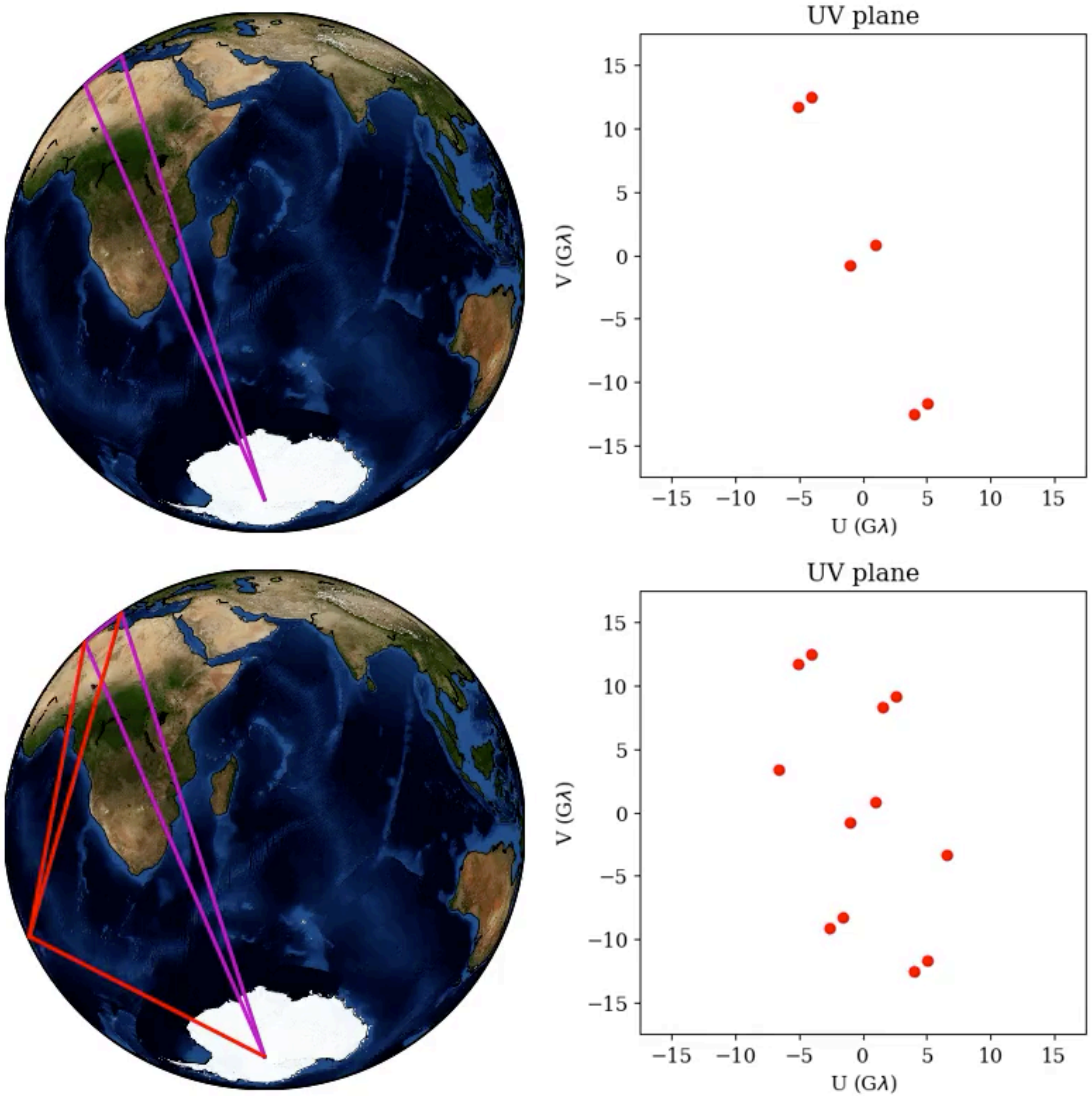




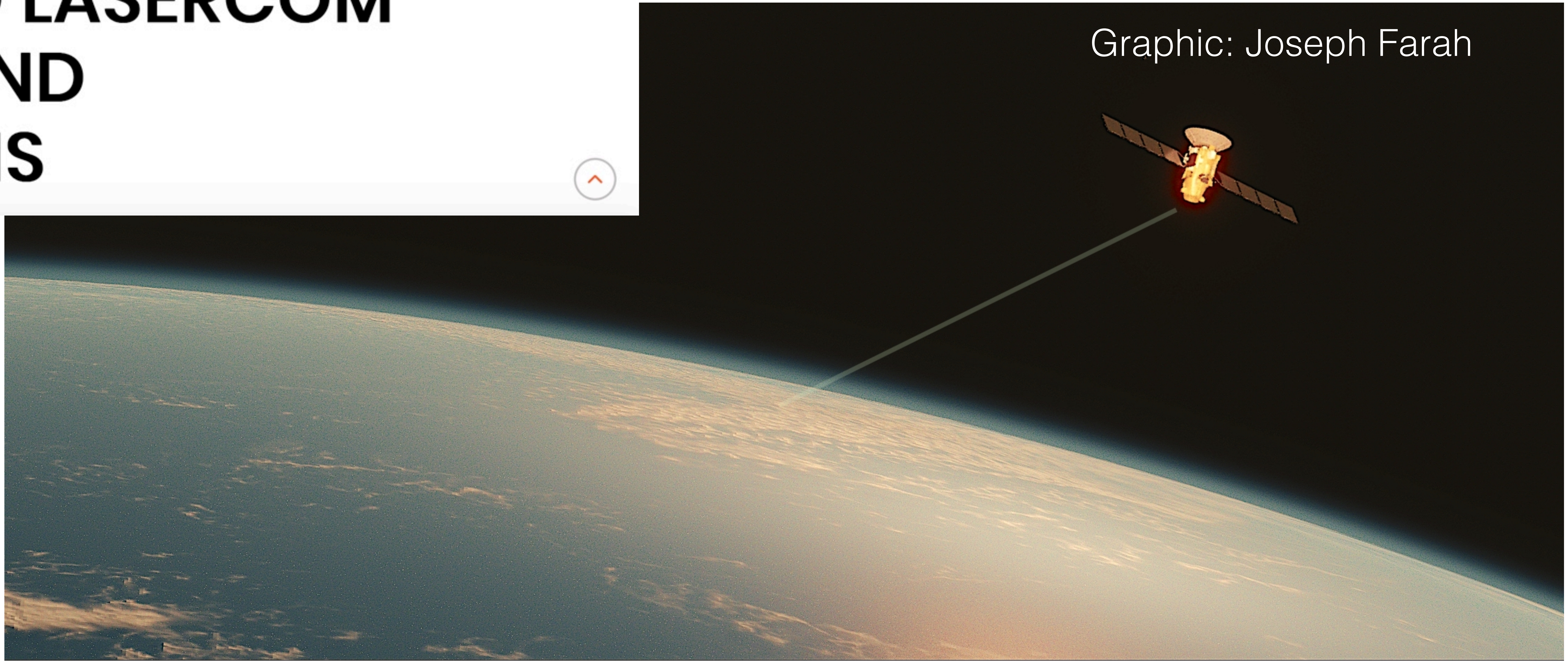
High-frequency orbiting VLBI, dynamical imaging (Daniel Palumbo et al.)

One LEO satellite accelerates population of UV plane (spatial frequencies)

(Daniel Palumbo, et al, 2019)



ngEHT: A truly networked (near) real time EHT using LaserCom (TBIRD from Lincoln Labs)



2018 EHT Collaboration Meeting, Nijmegen, Netherlands

"The future's so bright I gotta wear shades" — Timbuk3

- Open Access Papers: https://iopscience.iop.org/journal/2041-8205/page/Focus_on_EHT
- Wider band EHT: greater sensitivity helps enable smaller dishes and improved dynamic range
- Enable new EHT sites: Kitt Peak, OVRO, Haystack 37m, Namibia, move GLT to Summit
- Add small dish EHT sites across the globe, to improve UV coverage, dynamic range—link the jet to the accretion disk
- EHT space station, LEO and GEO, faster UV-filling for SgrA* snapshots, longer baselines for resolution, use terabyte-per-second downlink by LaserCom
- LaserCom: consider linking earth sites for real time data transport (EHT eVLBI)
- With real time linkage risk is mitigated, operations efficiency improved, and time to science reduced

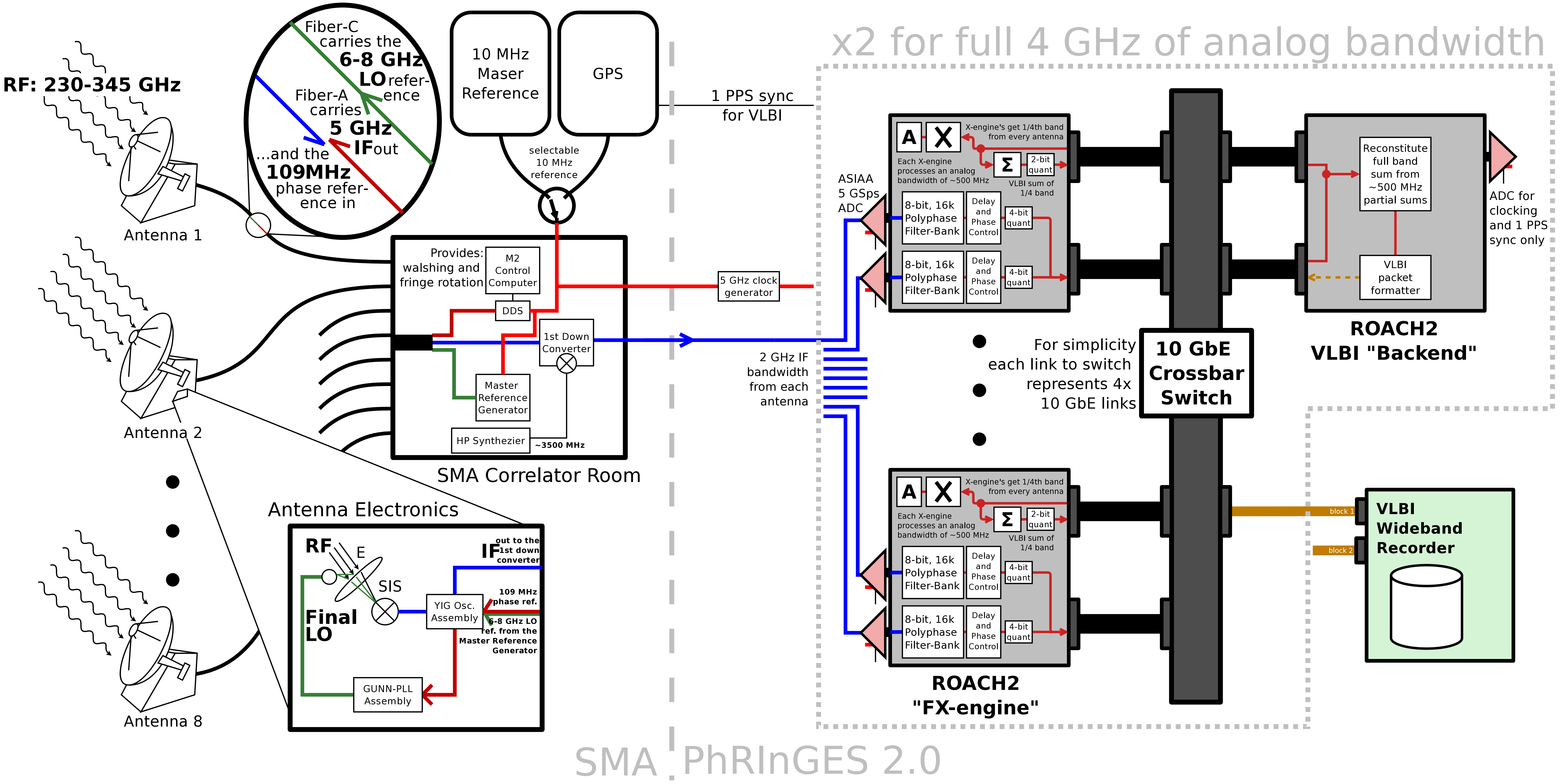

The New York Times
The Washington Post
Frankfurter Allgemeine
THE TIMES
May defies Tory rebels with pledge to stay on
LE FIGARO
THE WALL STREET JOURNAL
EL PAÍS
de Volkskrant
Le Télégramme
VERTIGINEUX !
FOLHA DE S.PAULO
General-Anzeiger
Clarín
DE TIJD
DER STANDARD
ST. LOUIS POST-DISPATCH
Η ΚΑΘΗΜΕΡΙΝΗ
FINANCIAL TIMES
Microsoft under fire over AI work with Chinese military university
ŻYCIE PO UDARZE
wyborcza
EGZAMIN Z KSIĘDZEM I TELEFONEM
DIE WELT
The Guardian
May defies critics with vow to stay on and see Brexit deal through
Los Angeles Times
la Repubblica
La luce in quel pozzo
Italia-Libia il negoziato segreto
the independent
DER TAGESSPIEGEL
Union-Tribune
CHINA DAILY
HOSPODÁŘSKÉ NOVINY
EL MUNDO
THE IRISH TIMES
MORGENAVISEN Jyllands-Posten
IL GAZZETTINO
LA NACION
LA RAZON
La porta de l'Univers
Passauer Neue Presse
Süddeutsche Zeitung
Neue Zürcher Zeitung
EL MERCURIO
Primera imagen de un agujero negro: expertos explican el hito
LA STAMPA
POLITIKEN
THE SUN
GARA
LA VANGUARDIA
La Voz de Galicia
EL CORREO
el Periódico
EL ESPECTADOR
The Boston Globe
La Razón
NATIONAL POST
IDEAL
REGISTER
El Sol de México
Diário de Notícias
The Dallas Morning News

Supplementary Material

Event Horizon Telescope

SWARM: *SMA Wideband Astronomical ROACH2 Machine*

Correlator and 64 Gbps EHT Phased Array for SMA

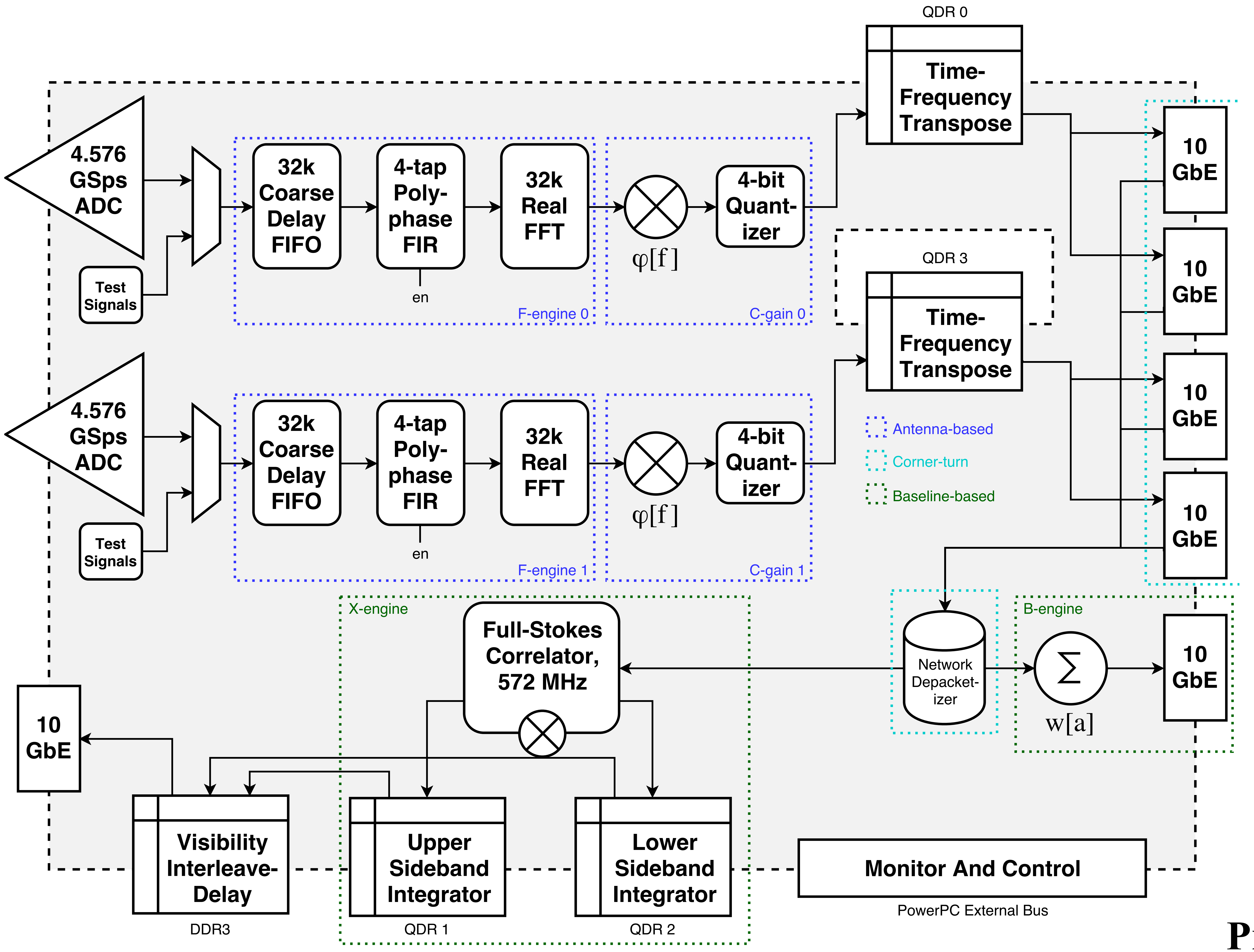


1 "quadrant": 2 GHz per receiver per sideband = 8 GHz; 32 GHz total

1. high uniform spectral resolution with no sacrifice of bandwidth,
2. smaller footprint and power consumption.
3. better digital efficiency with 4-bit cross-correlation
4. 2 GHz wide bands easier to reduce, result in higher quality spectra
5. Natively supports VLBI phasing and recording, 16 Gbps/quadrant
6. Built with CASPER and COTS components

SWARM FPGA logic subsumes substantial DSP complexity

fits in single Virtex 6 SX475T



Primiani et al., JAI, 2016

EHT Funding Agencies Across the Globe

RadioNet

NWO Netherlands Organisation for Scientific Research

JOHN TEMPLETON FOUNDATION

日本学術振興会 Japan Society for the Promotion of Science

MAX-PLANCK-GESELLSCHAFT

NASA

dgapa Dirección General de Asuntos del Personal Académico

MOST 科技部 Ministry of Science and Technology

中国科学院 CHINESE ACADEMY OF SCIENCES

National Research Foundation of Korea

GORDON AND BETTY MOORE FOUNDATION

CONACYT Consejo Nacional de Ciencia y Tecnología

NSFC

ACADEMIA SINICA

erc European Research Council

NSF

Ministry of Science, ICT and Future Planning

NAOJ National Astronomical Observatory of Japan

nst 국가과학기술연구회

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

GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

cnrs Centre National de la Recherche Scientifique

ACADEMY OF FINLAND

KASI 한국천문연구원 Korea Astronomy & Space Science Institute

NOVA