CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

NEXT GENERATION EVENT HORIZON TELESCOPE

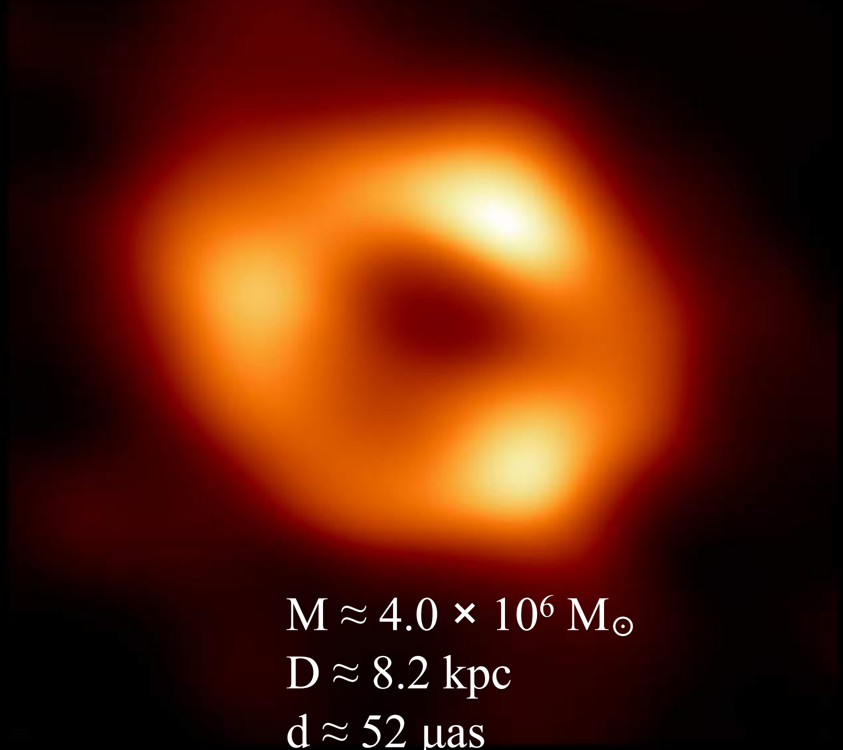
Lindy Blackburn (CfA)

On behalf of the ngEHT project

Oct 17, 2022
Next Generation Space VLBI Workshop – ASTRON/JIVE

Black Hole Images with the EHT

Sgr A*



$M \approx 4.0 \times 10^6\ M_\odot$
$D \approx 8.2$ kpc
$d \approx 52\ \mu as$

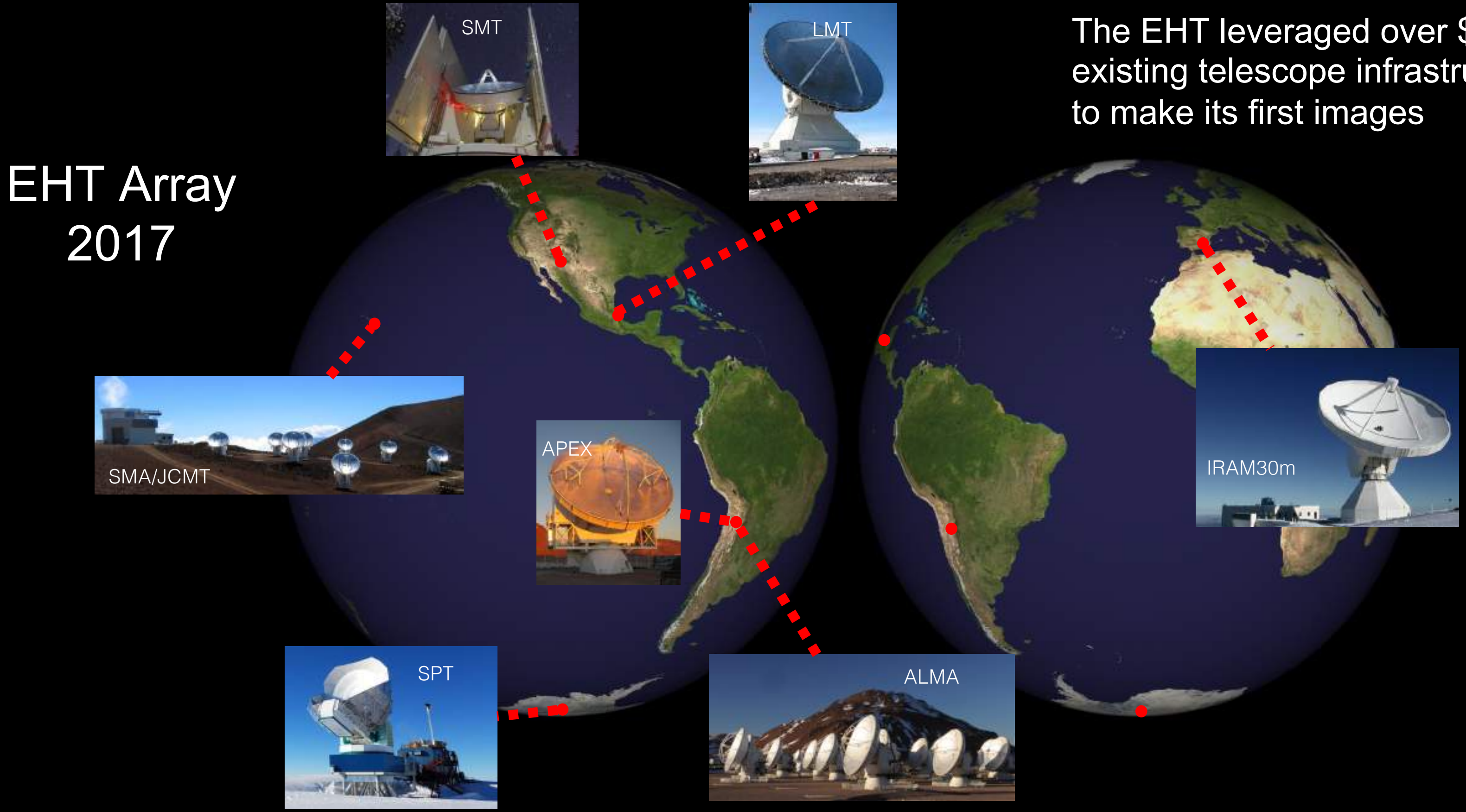
M87*

$M \approx 6.5 \times 10^9\ M_\odot$
$D \approx 17$ Mpc
$d \approx 42\ \mu as$

Event Horizon Telescope

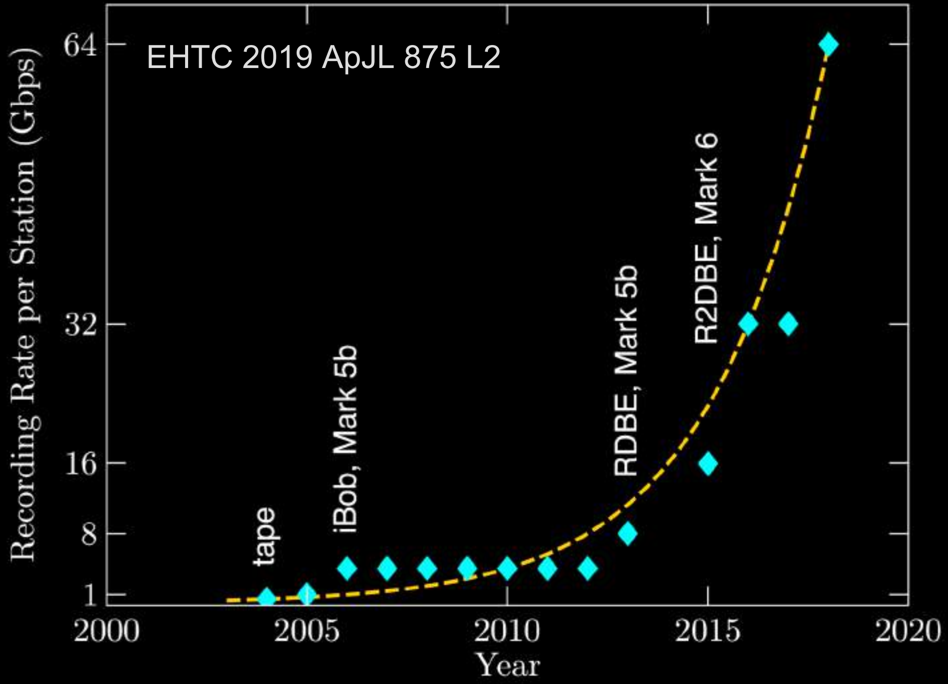
Building the EHT: Use of existing infrastructure

The EHT leveraged over $1B of existing telescope infrastructure to make its first images



ALMA Phasing Project: 2009-2017

Sensitivity through bandwidth: Moore's Law

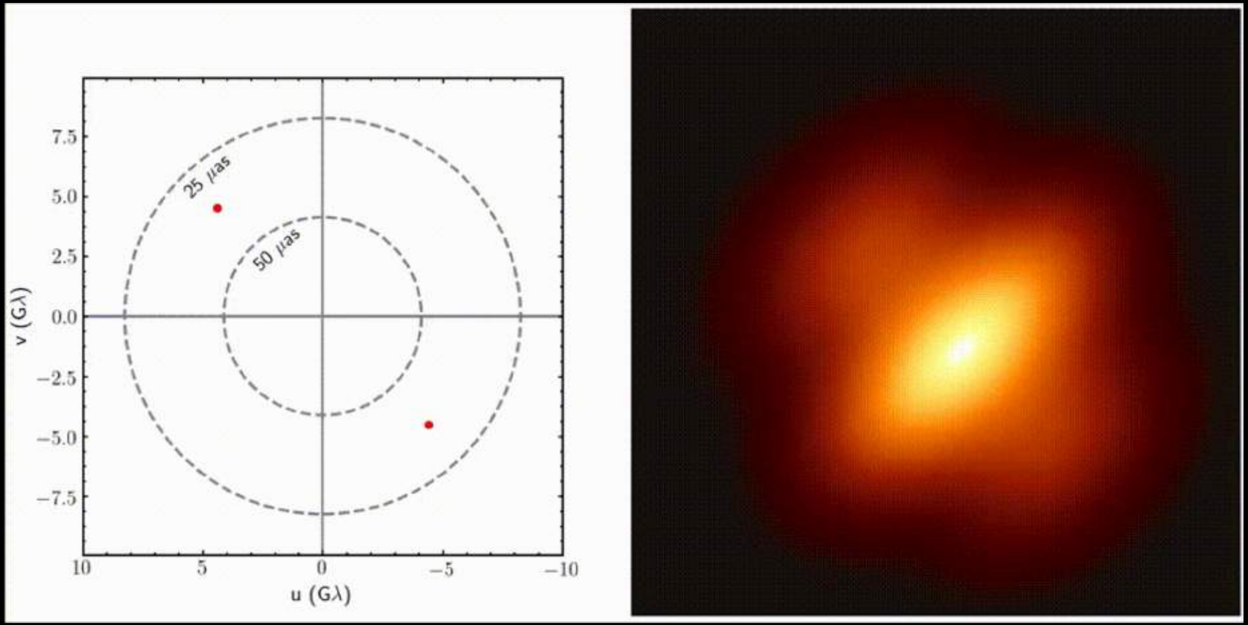


EHT integrated off-the-shelf electronics to enable an exponential increase in bandwidth (sensitivity)

EHT backend at IRAM 30M

Imaging with a VLBI array

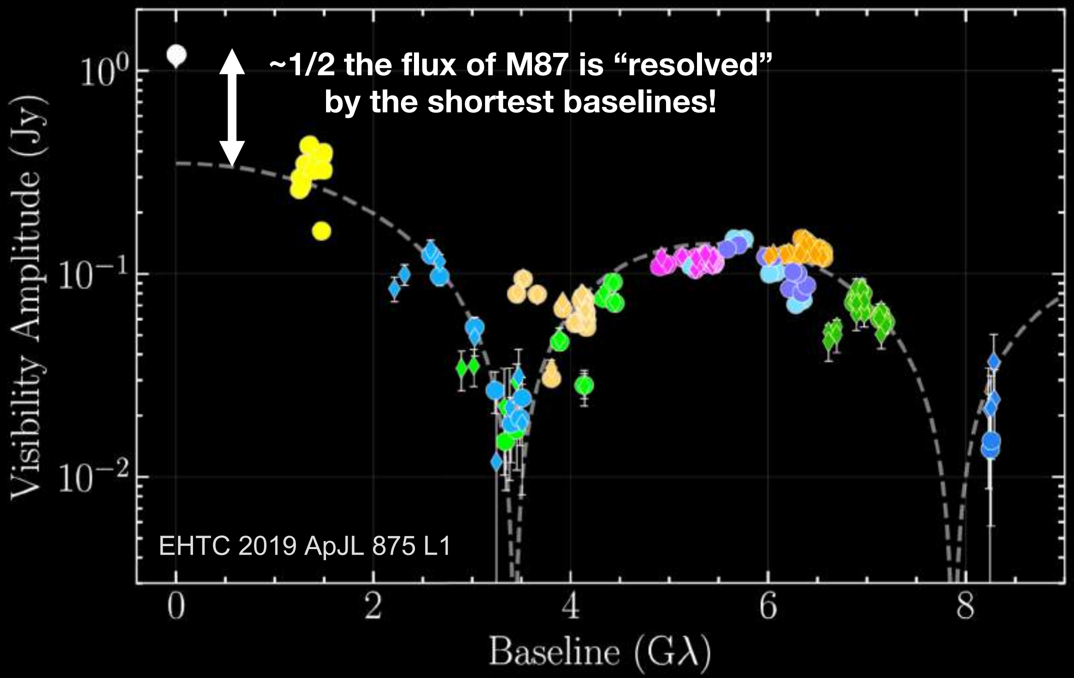
Five geographic locations are sufficient to capture M87’s ring
(Earth rotation aperture synthesis)

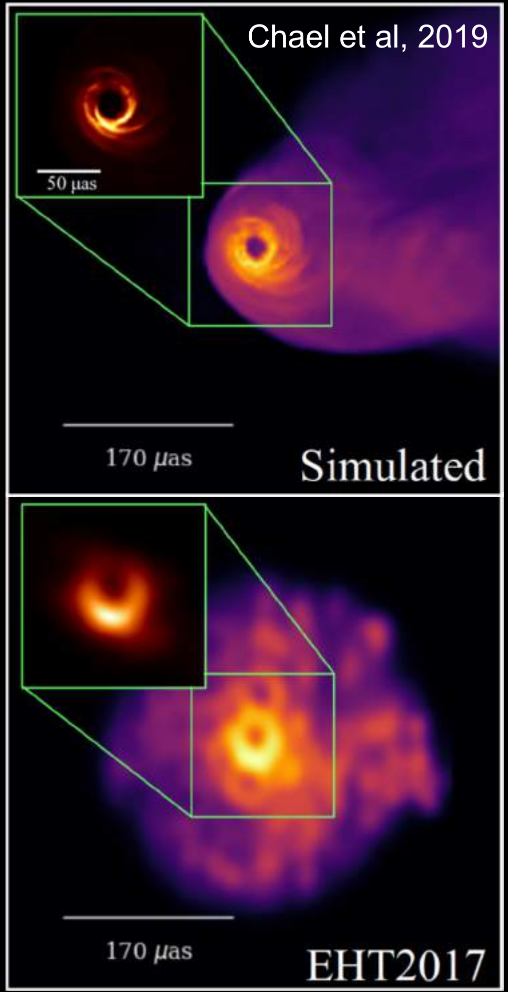


Animation: D. Palumbo, M. Wielgus

Event Horizon Telescope

Detecting the jet in M87





Imaging the jet base of M87 requires short baselines, dense coverage for a dynamic range ~1000:1 over 1 mas

Tracking dynamics in SgrA* and M87

H. Shiokawa

BH spacetime is stationary, but our sources vary on the dynamical timescale set by the BH mass & spin

Dynamical measurements trace accretion and jet physics, and probe BH spacetime

SgrA

GM/c^3 = 20 seconds

Requires snapshot imaging capability

(dense instantaneous coverage)

M87

GM/c^3 = 8 hours

Requires observations every ~few days for weeks/months

(monitoring campaign)

Secondary images and the black hole photon ring

Lensed images of the emission asymptotically approach the black hole "photon ring" at the edge of the black hole shadow.

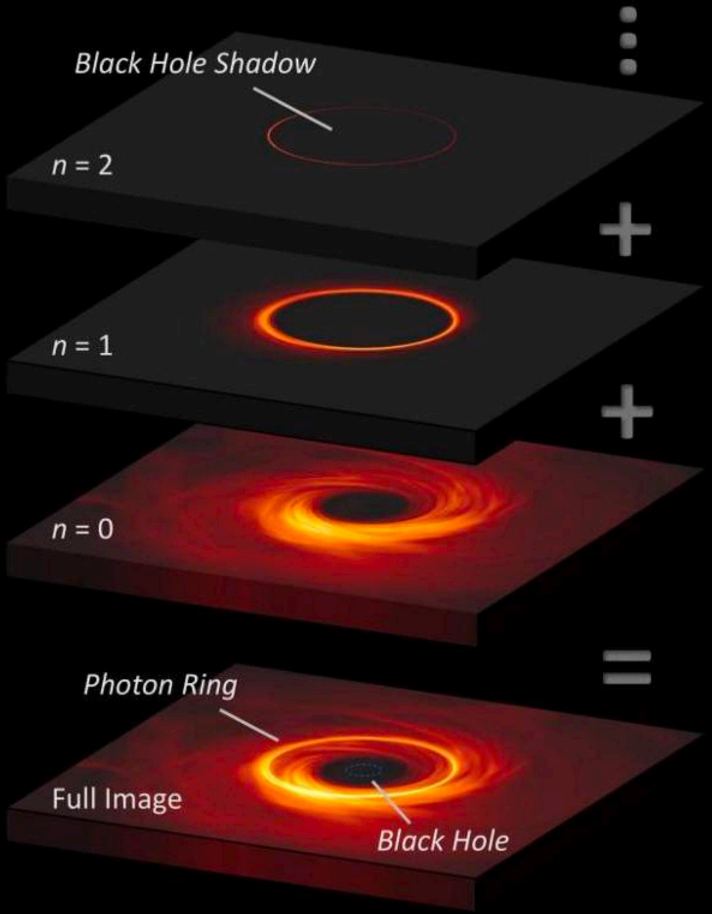
Size and shape completely determined by metric.

Can be extracted via modeling, but requires:

Robust 345 GHz VLBI (resolution)

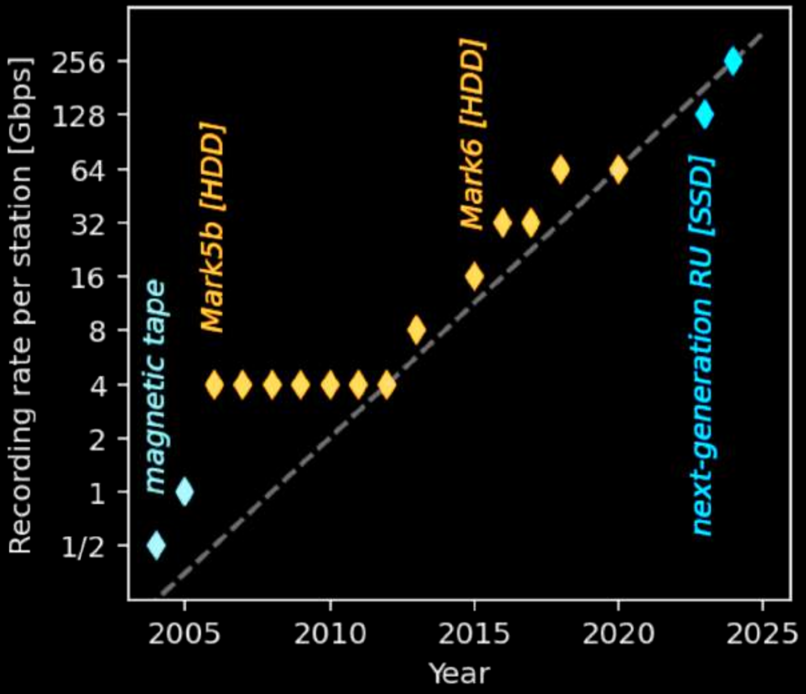
Better coverage (for direct emission)

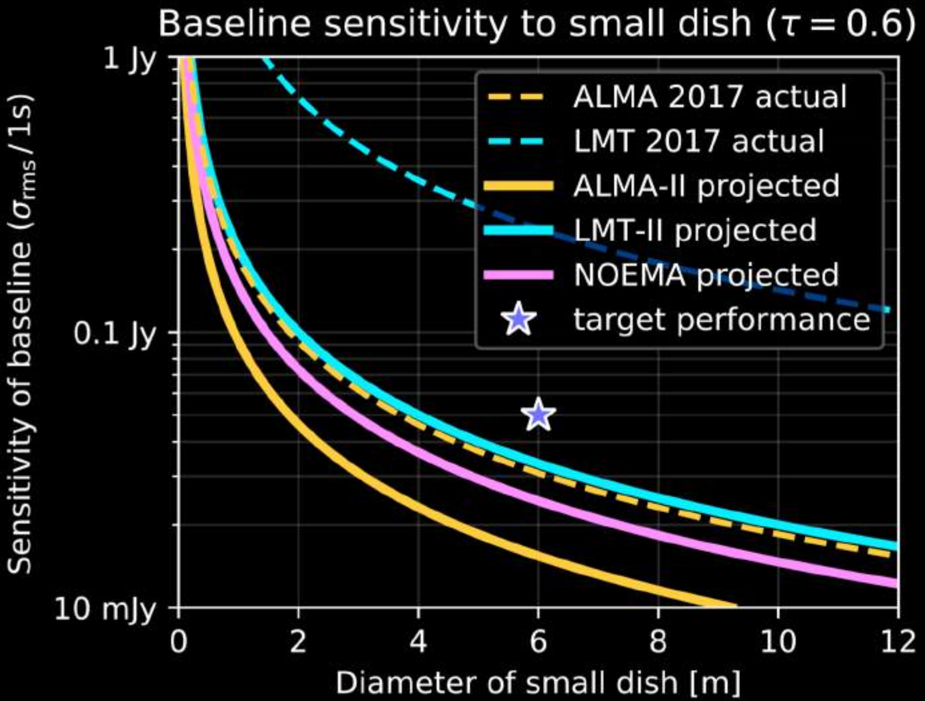
Many observations to identify stationary features



M. D. Johnson, G. N. Wong

Next-generation data rates and volumes





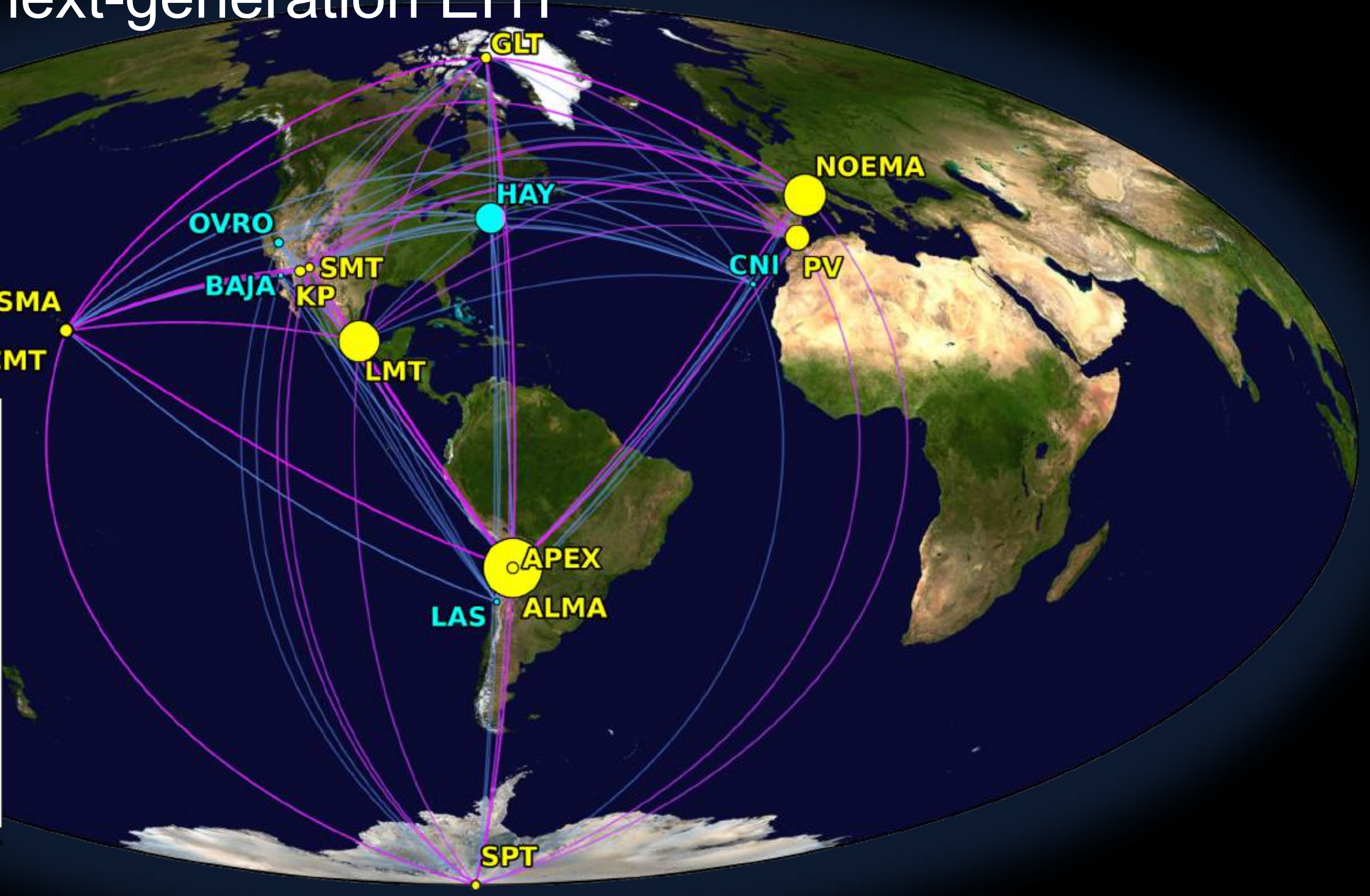
- High sensitivity required to track atmospheric phase at (sub)-mm
- High sensitivity required for fainter targets, lower image noise

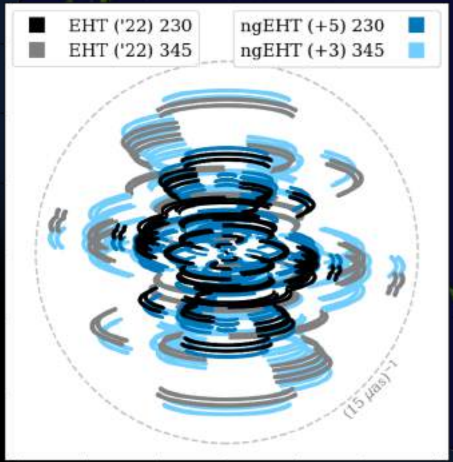
Toward a next-generation EHT

EHT Sites
(2022)

Toward a next-generation EHT

EHT Sites
ngEHT concept
(Phase 1)

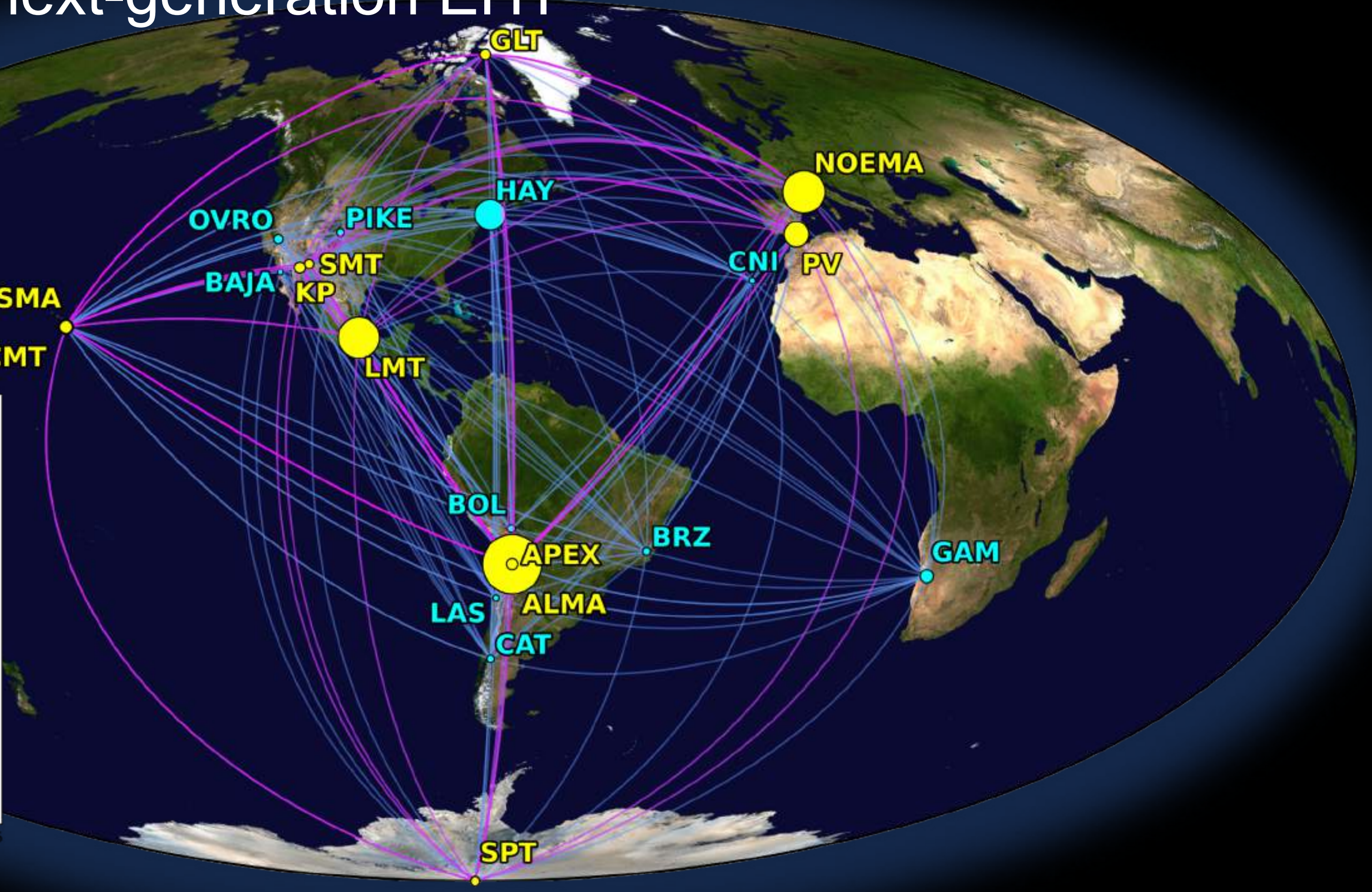


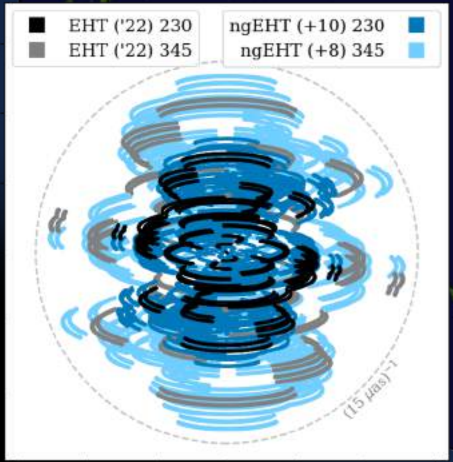


~5 additional sites
230 + 345 GHz (256 Gbps)
Multiple months of observing

Toward a next-generation EHT

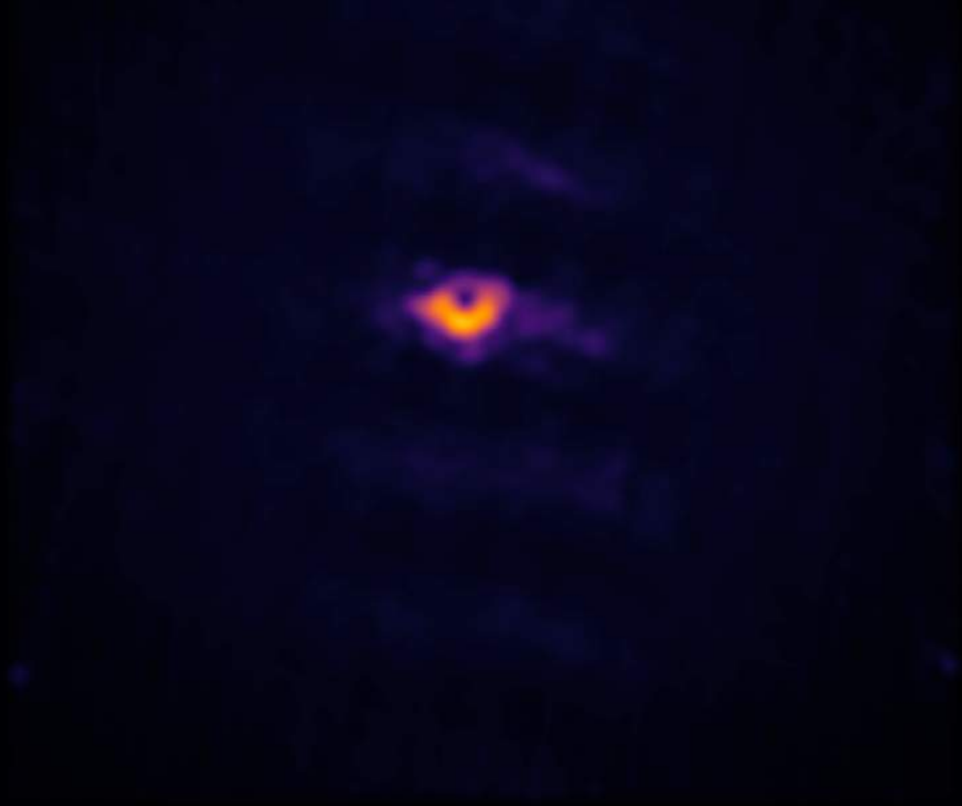
EHT Sites
ngEHT concept
(Phase 2)

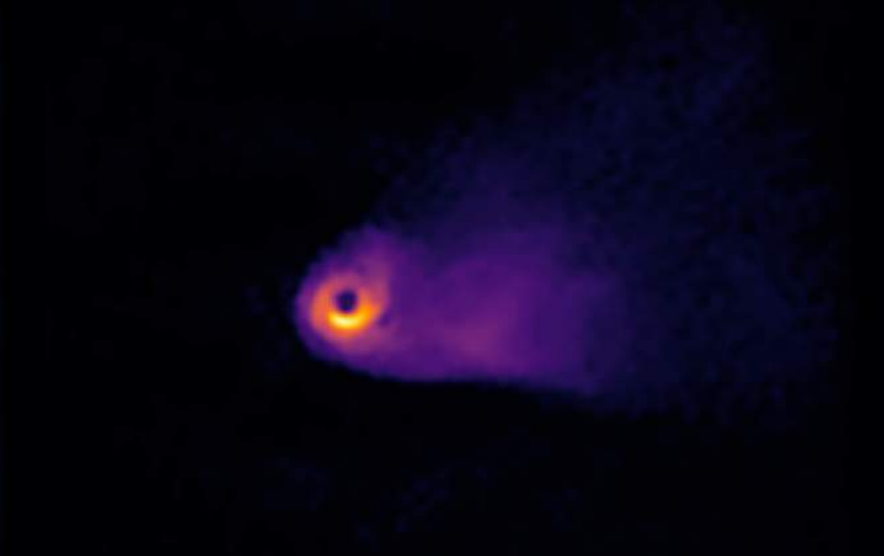




~10 additional sites
230 + 345 GHz (256 Gbps)
Multiple months of observing

ngEHT monitoring of the M87 jet

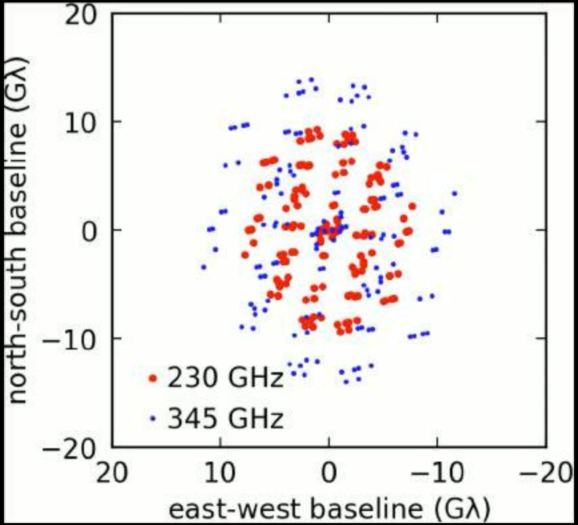




- Jet morphology and velocity profile
- Electron distribution and magnetic fields

Capturing a movie of Sgr A*

ngEHT Instantaneous Coverage



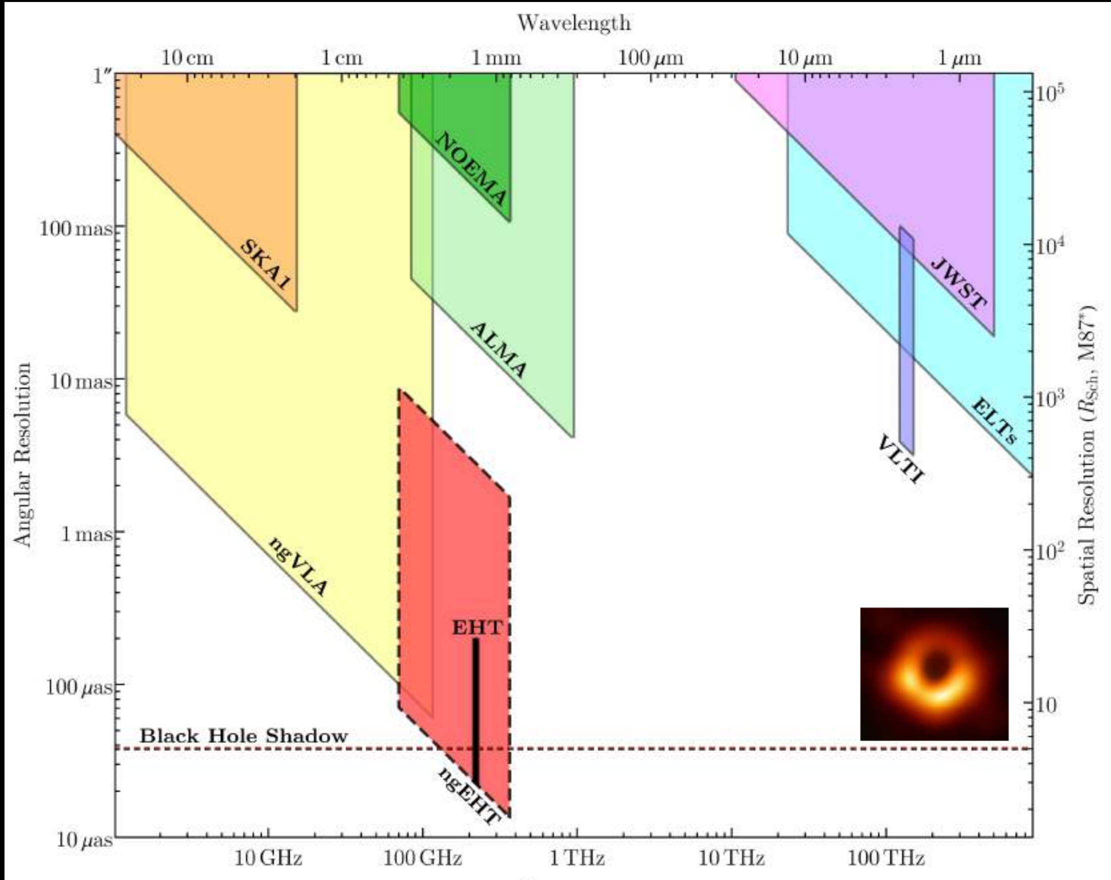
Simulation (Blurred)

ngEHT reconstruction

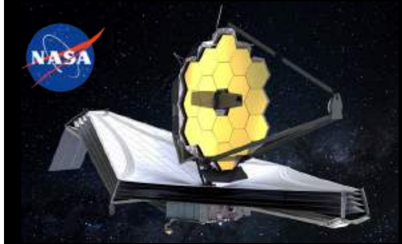
- Accretion dynamics
- Origin of flares..

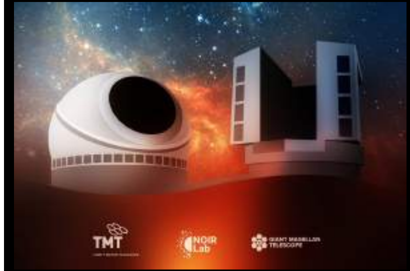
K. Bouman
A. Raymond

Next-Generation Astronomy



Adapted from Selina et al. (2018)

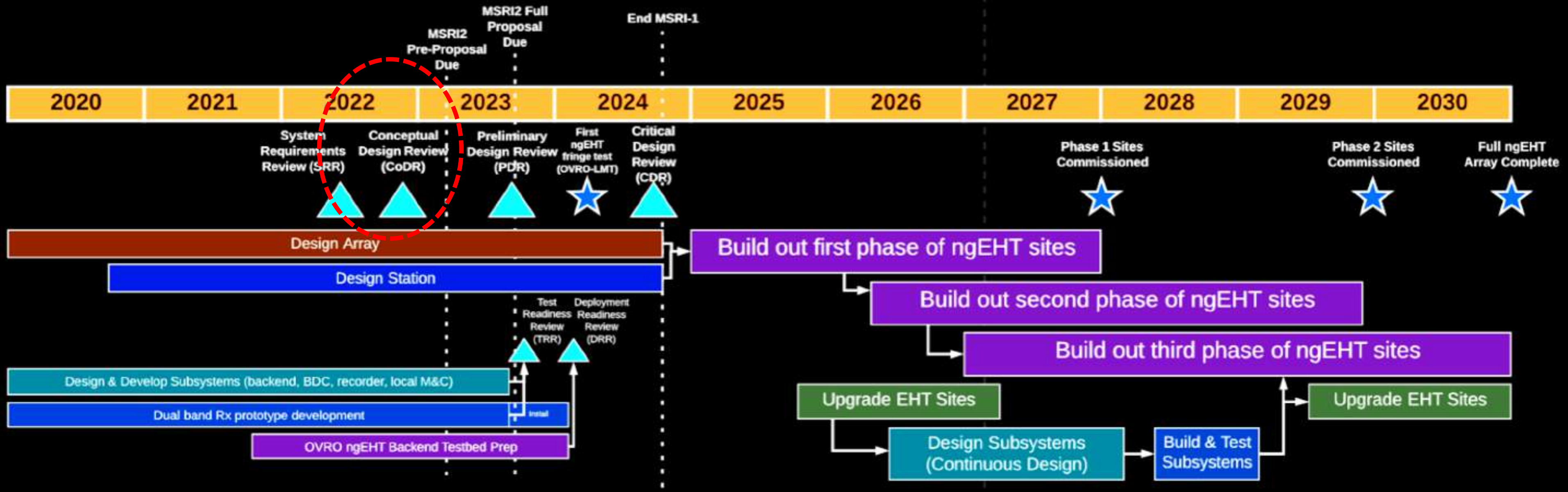




ngEHT Design and Timeline

ngEHT Project Office coordinates initial design efforts (support via NSF MSRI-I & GBMF)

- S. Doeleman (PI), M. D. Johnson (PS), G. Fitzpatrick (PE)
- Technical WGs on Receivers, Backends, Data Management, Antennas, Site selection



ngEHT Community Science Working Groups

The ngEHT has 8 science working groups:

- Fundamental Physics (Vitor Cardoso, Ziri Younsi)
- Black Holes & Cosmic Context (Jose Gomez, Priya Natarajan)
- Jet Launching (Matt Lister, Christian Fromm)
- Accretion (Ramesh Narayan)
- Transients (Rob Fender, Daryl Haggard, Sera Markoff)
- New Horizons (Andrei Lobanov, Lindy Blackburn)
- Algorithms & Inference (Katie Bouman, Dom Pesce, Kazu Akiyama)
- History, Philosophy, and Culture (Peter Galison)

Responsible for developing the Level-0 Science Requirements


Vitor Cardoso


Ziri Younsi

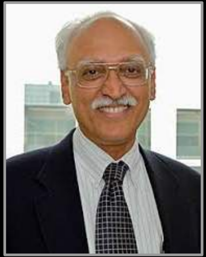

Priyamvada Natarajan


Jose L. Gomez


Rob Fender


Matt Lister


Christian Fromm


Ramesh Narayan


Daryl Haggard


Andrei Lobanov


Sera Markoff


Lindy Blackburn


Peter Galison


Kazunori Akiyama


Katie Bouman


Dom Pesce

Science Requirements Review (Feb 4, 2022)

Fundamental Physics Key Science Goals

Opening Remarks

Black holes (BHs) are the most simple, compact, and physically elusive macroscopic objects in the Universe. Among astronomical targets, BHs are extraordinary in their ability to convert energy into electromagnetic and gravitational radiation. Meanwhile, the study of BH stability and dynamics challenges our knowledge of partial differential equations, of numerical methods, and of the interplay between quantum field theory and the geometry of spacetime. The BH information paradox and the existence of unresolved singularities in classical general relativity point to deep inconsistencies in our current understandi…
conceptual problem…
Astrophysical BH s…

Metric	Range	Min. Acceptable	Importance	Rationale
Baseline Sensitivity	0.1-1000 mJy	1-10 mJy	4 - Very	Based on known X-ray binary population, and typical SNe/TBDTs fluxes. GRBs/TDEs events may be too far away/too faint.
Point Source Sensitivity	0.1-100 mJy	1-10 mJy	4 - Very	
Angular Resolution	10-100 µas	50	4 - Very	Range of angular sizes needed to track expanding components before resolved out (require long + short baselines). Need to balance between probing smaller scales and extending the time over which we can track component motion. Opening ang <5 deg, exp. rates 0.1-10 mas/dy, resolved out 20 min-9 hrs.
Field of View/Max …	50-10000 µas	1000-10000 µas	5-extremely …	Defines ability to track jet components out to longer distances from BH (separation speeds of 1-100mas /day), and connect mm-VLBI to cm-VLBI. …

Science Case for the ngEHT: Black Hole Accretion

Introduction

Electromagnetic radiation from astrophysical black holes originates in hot gas, which is brought close to the black hole by an accretion disk. Some of the same gas is also expelled in relativistic jets or winds. Spatially resolved still images of the disk, better yet dynamical movies, provide the most direct way to study accretion physics.

Black hole accretion disks are believed to operate with the help of the magnetorotational instability, which amplifies the magnetic field in the plasma and uses the associated shear stress to transport angular momentum outward. Signatures of the magnetic field are revealed via linear and circular polarization of the emitted radiation. Spatially-resolved and time-resolved spectropolarimetric observations are thus the ultimate tool for studying the inner workings of black hole accretion.

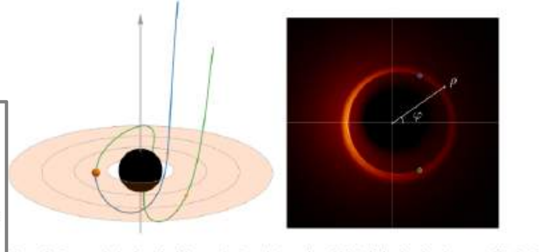
We do not at present have even a single spatially-resolved image of any black hole accretion disk. The closest we have come is with Event Horizon Telescope (EHT) observations of M87*. The …arized EHT image of M87* is justly famous for confirming strong light … hole. However, the angular resolution and dynamic range achieved so far …nd it is unclear what part of the observed radiation is from the accretion disk

Supermassive Black Holes and their Cosmic Context Science Cases for the ngEHT

ngEHT Science Working Group

Scientific Rationale

Electromagnetic and gravitational wave observations of galaxy mergers and the associated supermassive binary black holes at their centers offer unique insights into galaxy formation and evolution, as well as on black hole demographics and growth across cosmic times. In the current galaxy formation paradigm, feedback from accretion onto supermassive black holes (SMBHs) is required to regulate gas cooling and star formation in massive galaxies (e.g., Haehnelt et al., 1998; Di Matteo et al., 2005; Croton et al., 2006). At present, however, the details of these processes are poorly understood and are the largest source of uncertainty in understanding the combined mass assembly history and evolution of galaxies and their central SMBHs. This strongly motivates detailed studies of the central engines as will be permitted by the ngEHT for extracting information on their masses, spins, and accretion rates, to better constrain models. SMBHs grow via gas accretion as well as mergers, and the spins of SMBHs encode th…



…igure 2: Two geodesics launched from a single emitting point which both land at the observer, offset by the …half-orbital time lag (left). Semi-analytic accretion model with arrival positions of diagrammed geodesics (right). …

Science case for ngEHT: Transients

Introduction

Astrophysical transients are the sites of some of the extreme physics in the present-day universe, including accreting sources such as black hole X-ray binaries and Tidal Disruption Events, explosive events such as supernova as well as the LIGO gravitational wave bursts associated with neutron star-neutron star mergers such as GW170817.

In essentia… all cases the radio emission from these transients traces the synchrotron … relativistic electrons spiralling in magnetic fields either in the jet or in …ch have been energised by the jet. As with supermassive black holes in AGN, …rmation, propagation and ultimate energetics of these jets is a central to … the physics of black holes and how they take infalling matter and its …ease of gravitational potential energy, and convert it into these powerful …flows.

Figure 1: Conceptual illustration of the science cases that 'Black holes and their cosmic context' ngEHT group is focused on. BH growth, binary BHs and gravitational waves, and MWL studies of black holes and jets. Credits from left to right: Perimeter Institute, NASA's Goddard Space Flight Center/Jeremy Schnittman and Brian P. Powell, J. C. Algaba for the EHT Collaboration. Composition: Thalia Traianou, IAA-CSIC.

ngEHT Key Science Goals Draft Document: Jet Launching

Feb 3, 2022

Authors: Christian Fromm and Matthew Lister

Relativistic jets are among the most energetic phenomena… radiation throughout the entire electromagnetic spectrum f… the γ-ray regime, and even accelerated particles to highes… most powerful jets can be found in Active Galactic Nuclei (… centers supermassive black holes (SMBH) weighing up to … which serve as the launching engines of relativistic jets. Th…

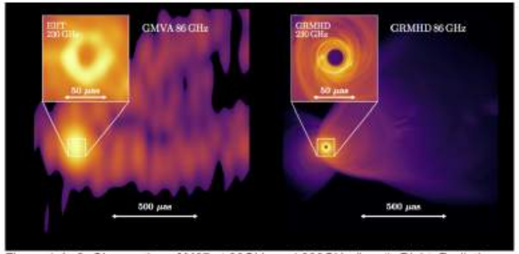


Figure 1. Left: Observation of M87 at 86GHz and 230GHz (inset); Right: Radiative signature of GRMHD model of a magnetically arrested disk around a black hole with spin a_* = 0.94 at 86 GHz and 230 GHz (inset). In this simulation, the jet is powered by spin-energy extraction from the SMBH. (References: EHT, Kim and Fromm et al. 2022.)

ngEHT Science Kickoff Meeting: February 22-26, 2021

- 500+ Registrants
- 86 Presentations
- 8 Discussion Sessions
- 1 Day of Group Brainstorming

https://www.ngeht.org/ngeht-meeting-2021

Science at the Horizon, Feb 22-26 2021

From Vision to Instrument: November 1-5, 2021

- 500+ Registrants
- >100 Presentations
- 3 Interactive Science/Engineering Sessions

https://www.ngeht.org/ngeht-meeting-november-2021

From Vision to Instrument:
Designing the ngEHT to Transform Black Hole Science

galaxies

an Open Access Journal by MDPI

CITESCORE 2.8 SCOPUS

From Vision to Instrument: Creating a Next - Generation Event Horizon Telescope for a New Era of Black Hole Science

Guest Editors

Dr. Michael D. Johnson, Dr. Shep Doeleman, Dr. Jose L. Gómez

Deadline

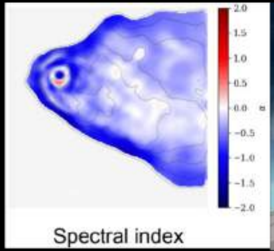
22 June 2022

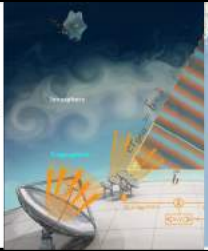
Special Issue

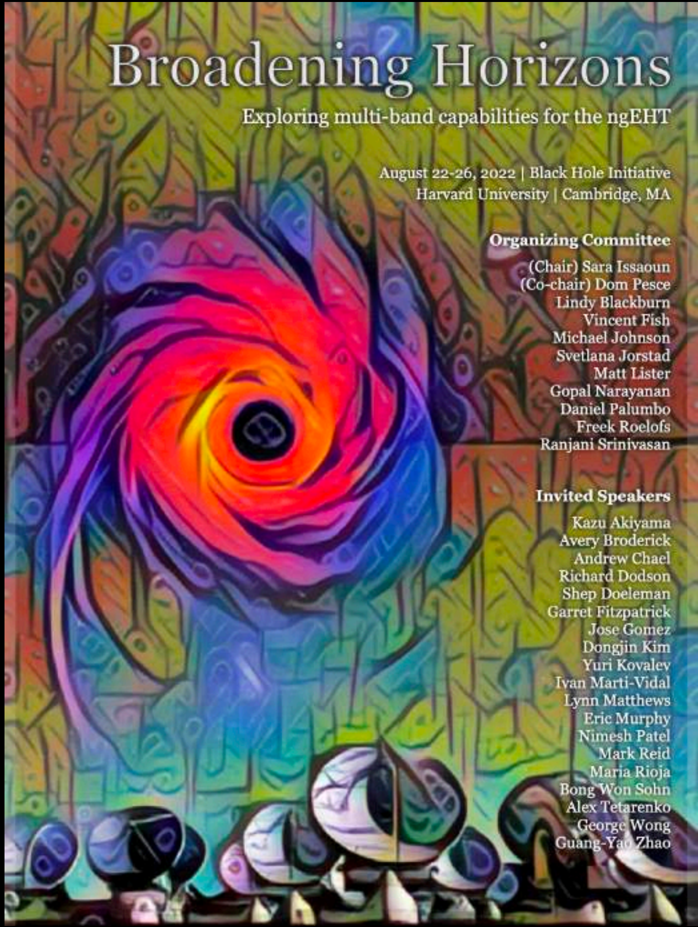
mdpi.com/si/118926

Invitation to submit

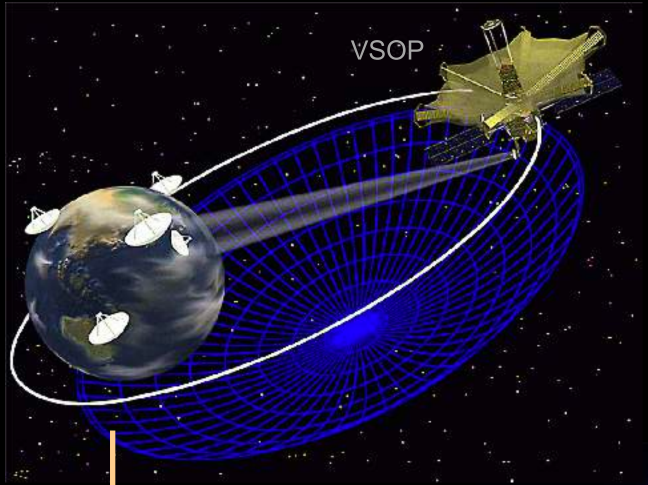
ngEHT 86 GHz Workshop







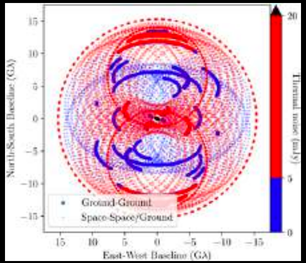
ngEHT + Space



Long baselines,
highest resolution

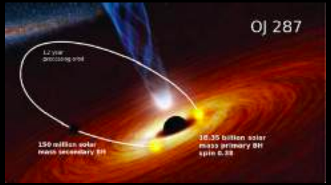
Johnson+ 2020

LEO/MEO orbit,
rapid u-v filling



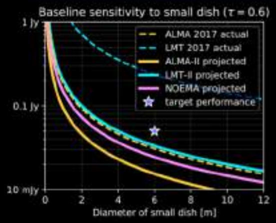
Palumbo+ 2019

No atmosphere,
stable phases
astrometric referencing
beyond 345+ GHz



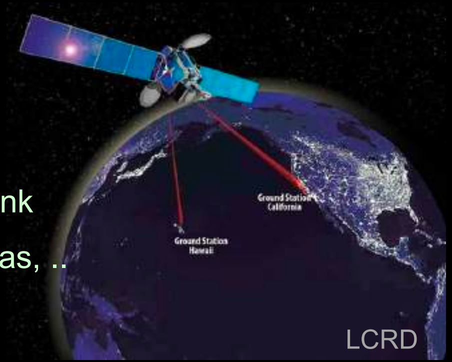
Multiple antennas,
dense u-v coverage
high-D/R imaging

Large apertures,
sensitivity



Enabling technologies

- Free Space Optical (FSO) Downlink
- Clocks/transfer, Rx, DSP, Antennas, ..



Summary

The Next-Generation EHT aims to design a transformative VLBI array for black-hole science, providing order(s) of magnitude increase in dynamic range, frequency span, field-of-view, and observing time

The basic concept calls for ~10 new dedicated ground sites to augment the current EHT, and expansion to 256+ Gbps 86+230+345 GHz simultaneous observations

An open, global scientific community is actively engaged in defining the Key Science Goals and L0 Science Requirements for the array

One or more Space VLBI antennas can bring ultra-high frequency VLBI and ~orders of magnitude improvements to resolution, u-v filling rate, integration time – providing strong synergy with a next-generation ground array.

https://www.ngeht.org