NEXT GENERATION
EVENT HORIZON TELESCOPE

Entering a New Era of Black Hole Cinema

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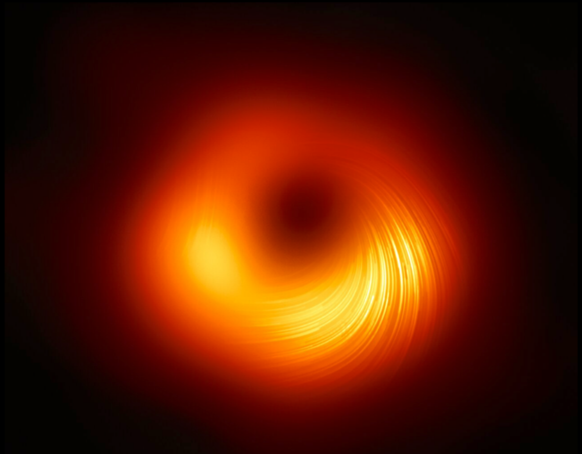
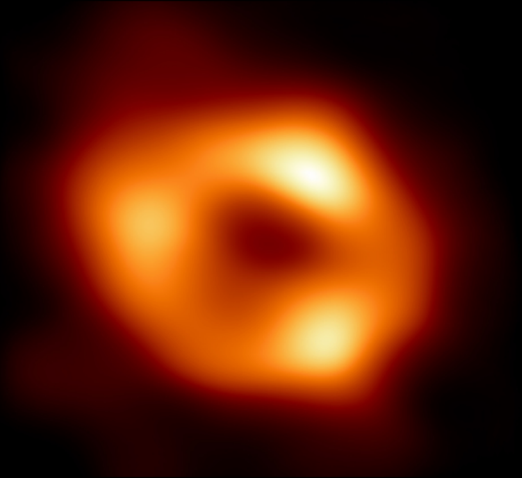
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

The Black Holes of the EHT Campaign

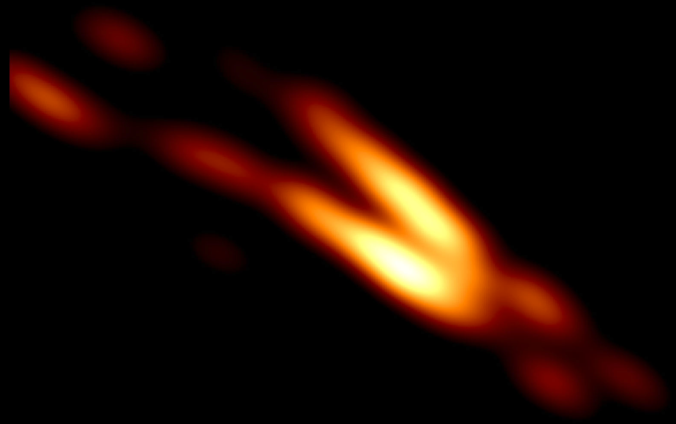


M87* - EHTC+ 2019, 2021

3C 279 - Kim+ 2020



Sgr A* - EHTC+ 2022



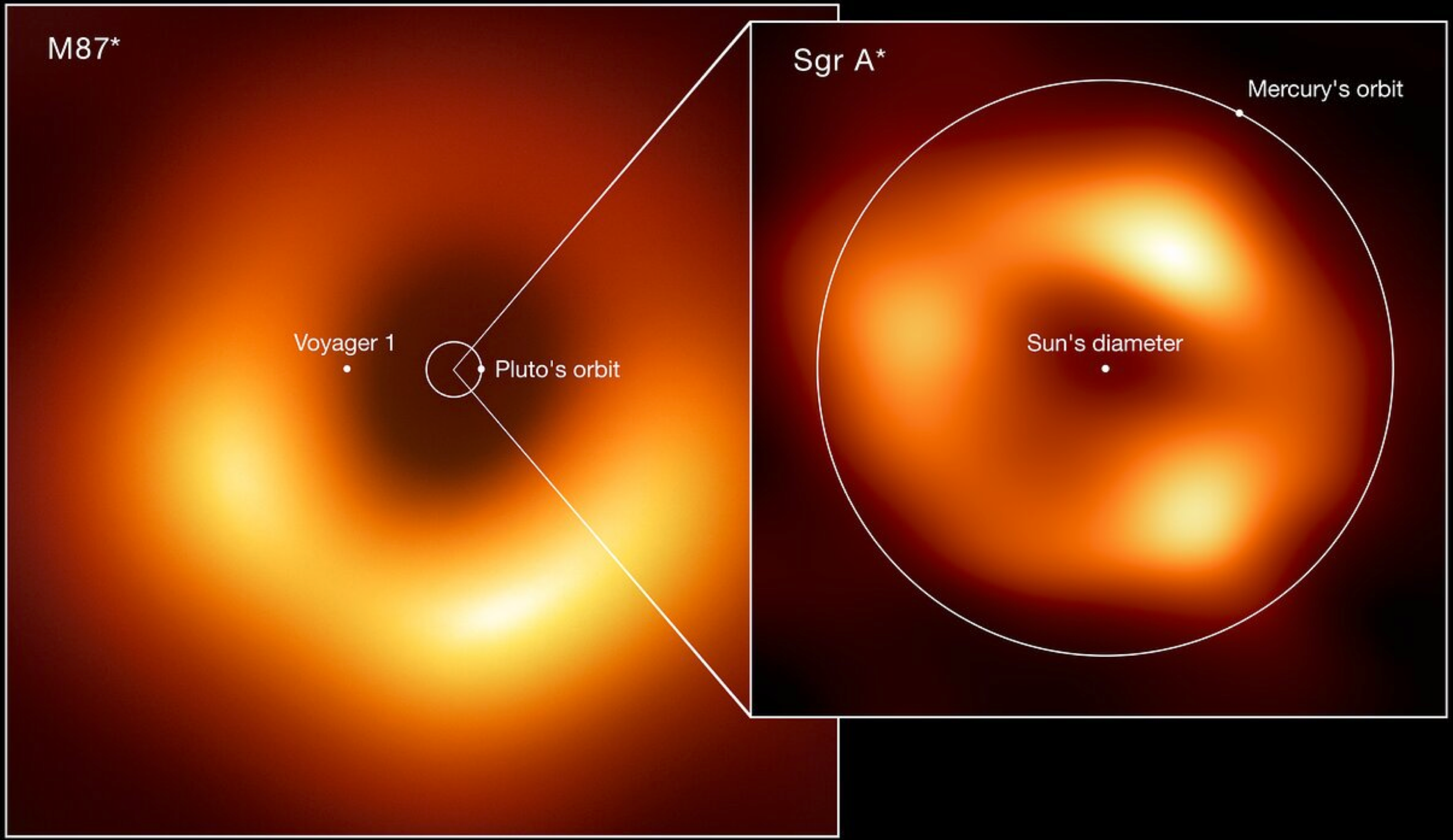
Cen A - Janssen+ 2021

J1924 - Issaoun, Wielgus+ 2022

NRAO530 - Jorstad, Wielgus+ 2023

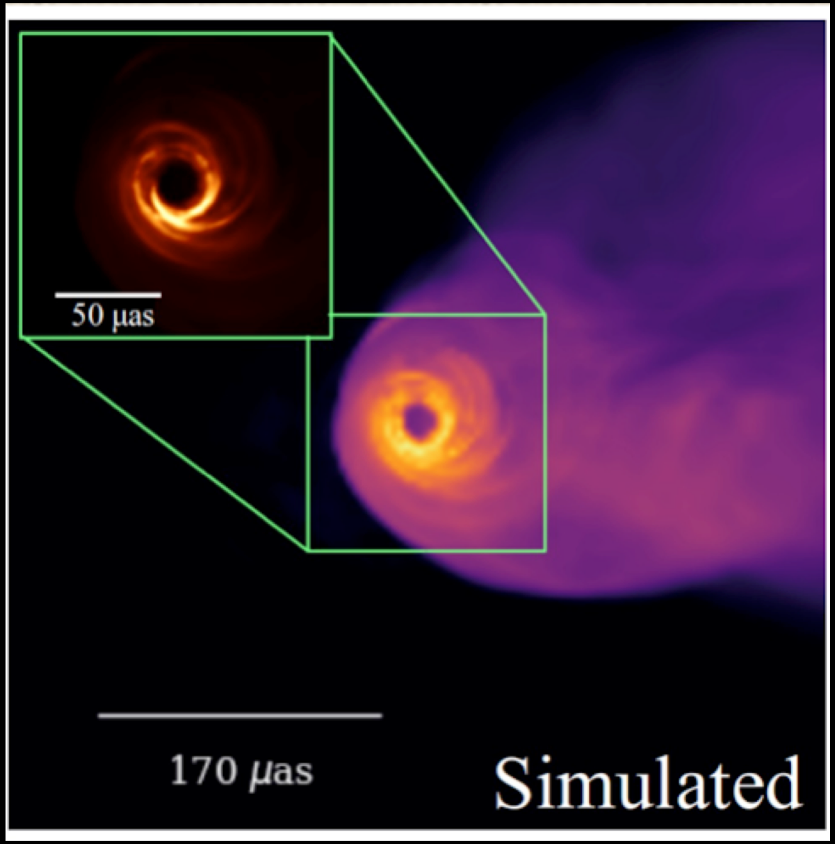
OJ 287 - Gomez+ 202?

A Tale of Two Black Holes



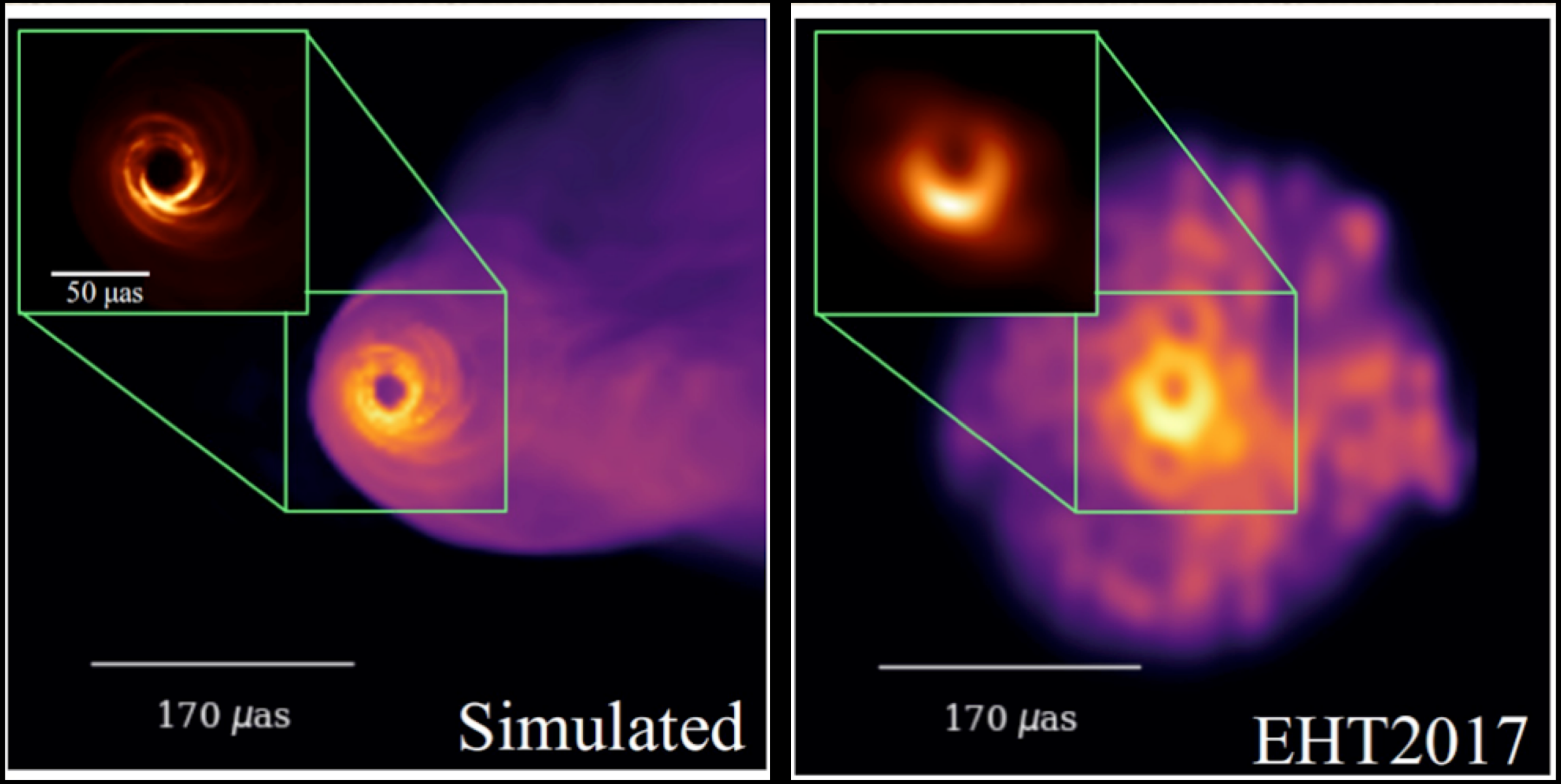
Visualization by L. Medeiros, IAS/ xkcd

The Era of Black Hole Cinema



Slide credit: S. Doeleman, SAO/A. Chael, Princeton

The Era of Black Hole Cinema



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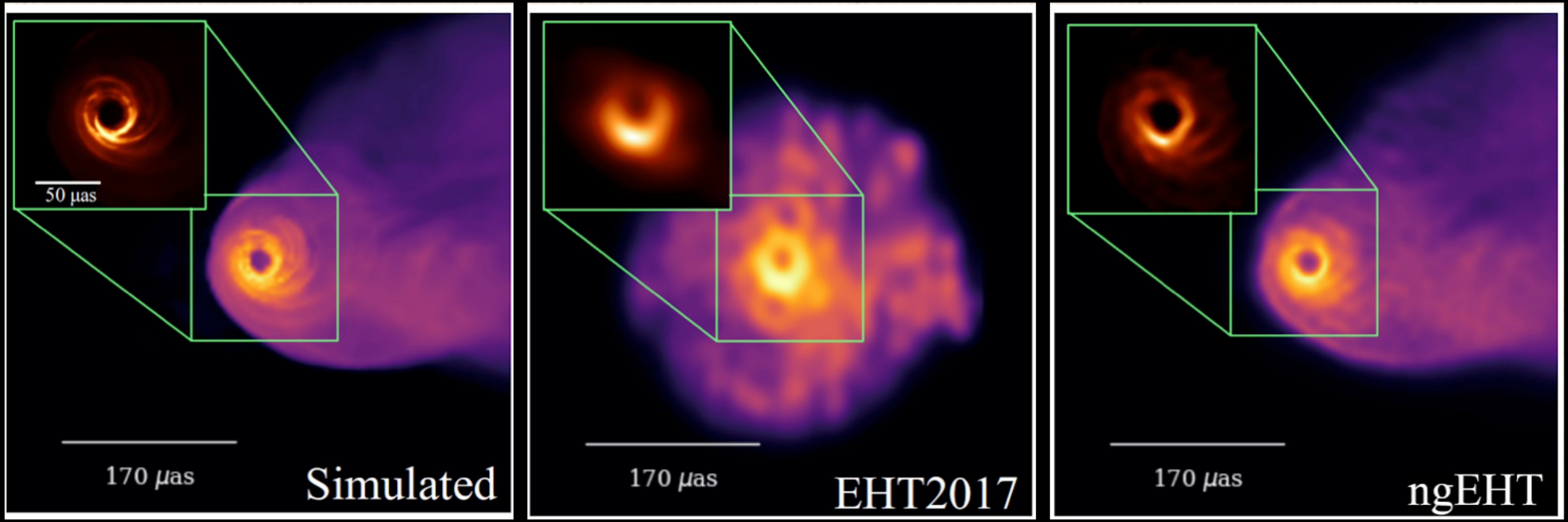
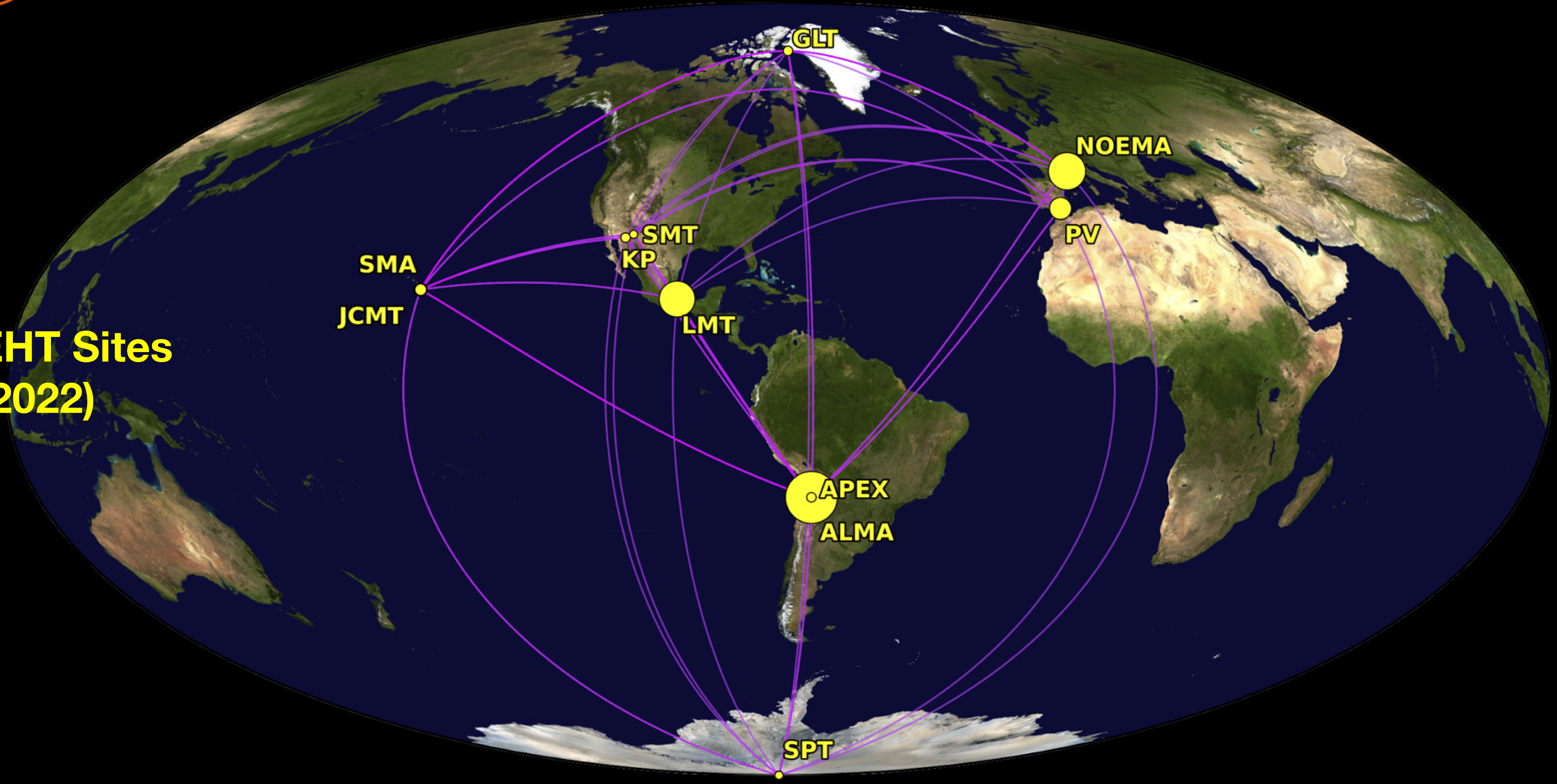
The Era of Black Hole Cinema



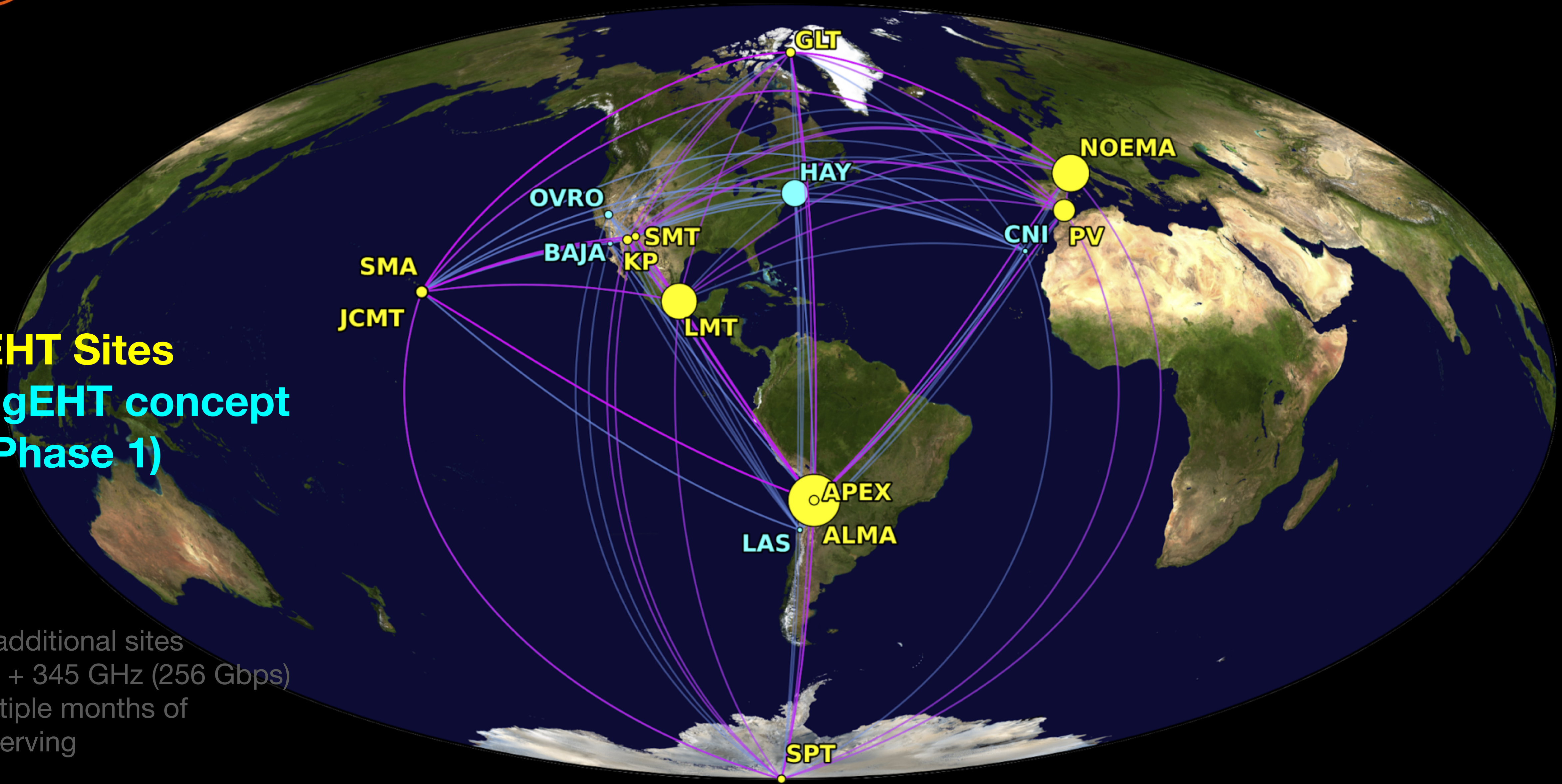
Slide credit: S. Doeleman, SAO/A. Chael, Princeton

The Next Generation Event Horizon Telescope

EHT Sites (2022)



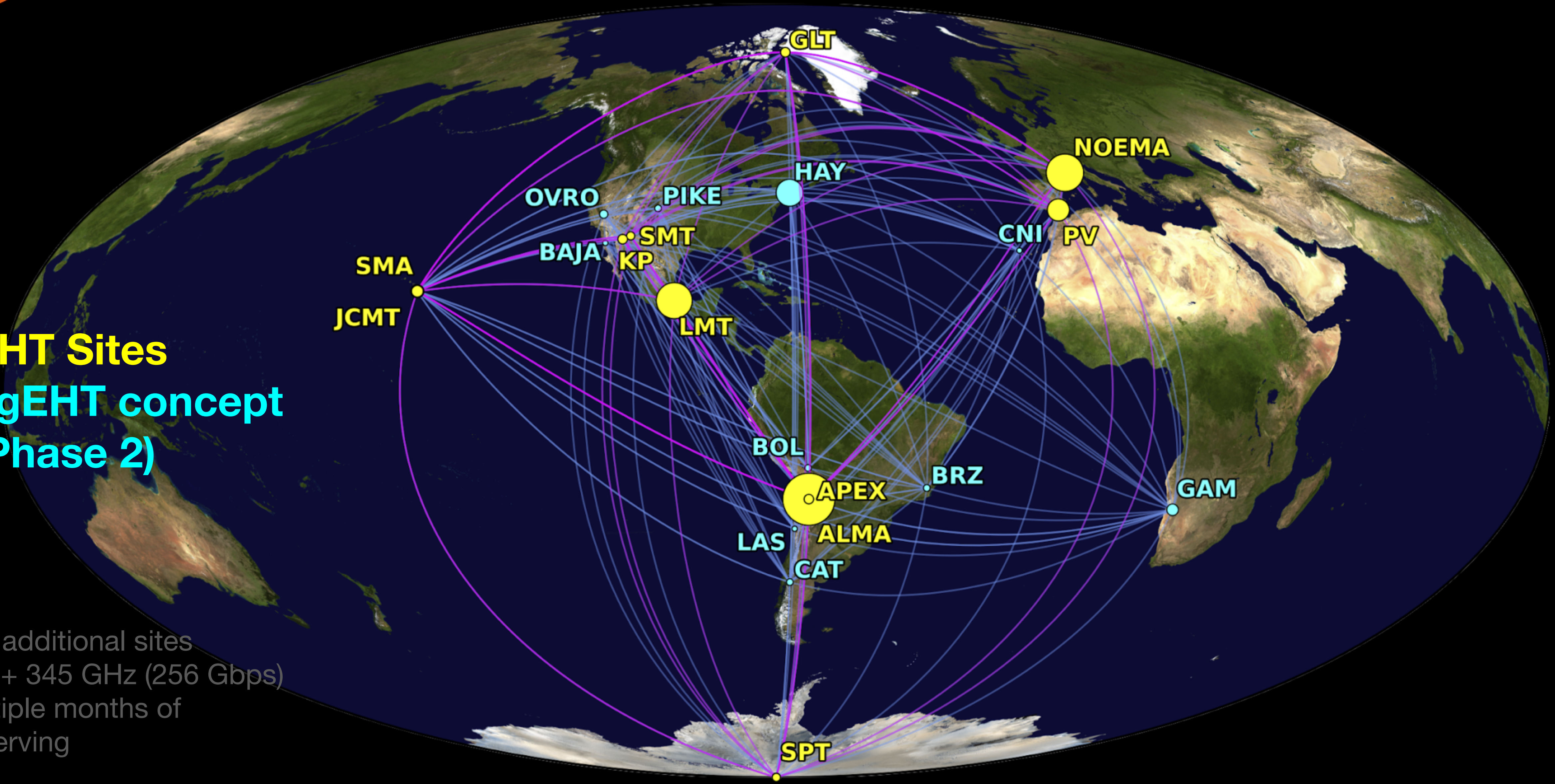
The Next Generation Event Horizon Telescope



EHT Sites
ngEHT concept (Phase 1)

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

The Next Generation Event Horizon Telescope



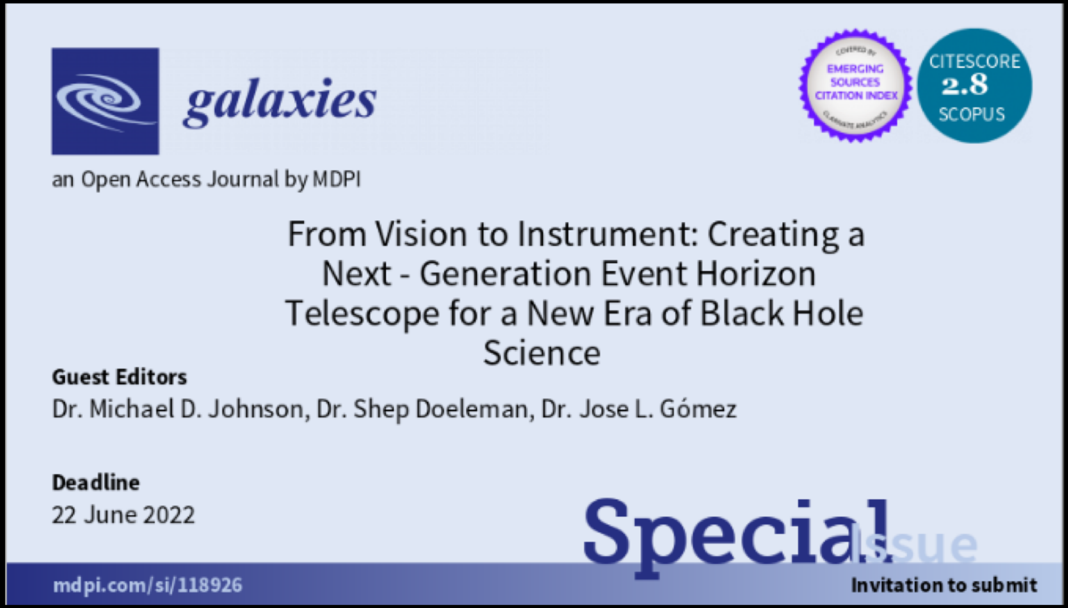
EHT Sites
ngEHT concept
(Phase 2)

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

The ngEHT Special Issue

A special issue was set up in Galaxies for contributions to ngEHT Science:
- Refereed, indexed publications
- No publication charges
- Open access

25 published papers including seminal array and science goals papers
https://www.mdpi.com/journal/galaxies/special_issues/ngEHT_blackholes



Draft version January 24, 2023
Typeset using LaTeX twocolumn style in AASTeX63

Reference Array and Design Consideration for the next-generation Event Horizon Telescope
DRAFT: 24 Jan 2023 - not for distribution

ngEHT Team

ABSTRACT

This white paper outlines a process to design, architect, and implement the next-generation Event Horizon Telescope (ngEHT): a global array of radio dishes that will comprise a virtual Earth-sized telescope capable of making the first real-time movies of supermassive black holes (SMBH) and their emanating jets. This builds upon the EHT principally by deploying additional modest-diameter dishes to optimized geographic locations to enhance the current global mm/submm wavelength Very Long Baseline Interferometric (VLBI) array, which has, to date, utilized mostly pre-existing radio telescopes. The ngEHT will proceed in two phases. In Phase I, three existing 6 m dishes will be refurbished and deployed to realize a significant increase in near-term science capability; in Phase 2, additional new dishes will be added to achieve the full set of ngEHT science goals. Here, the concept, science goals, design considerations, station siting and instrument prototyping is discussed, and a preliminary reference array described.

1. INTRODUCTION

ngEHT Reference Array

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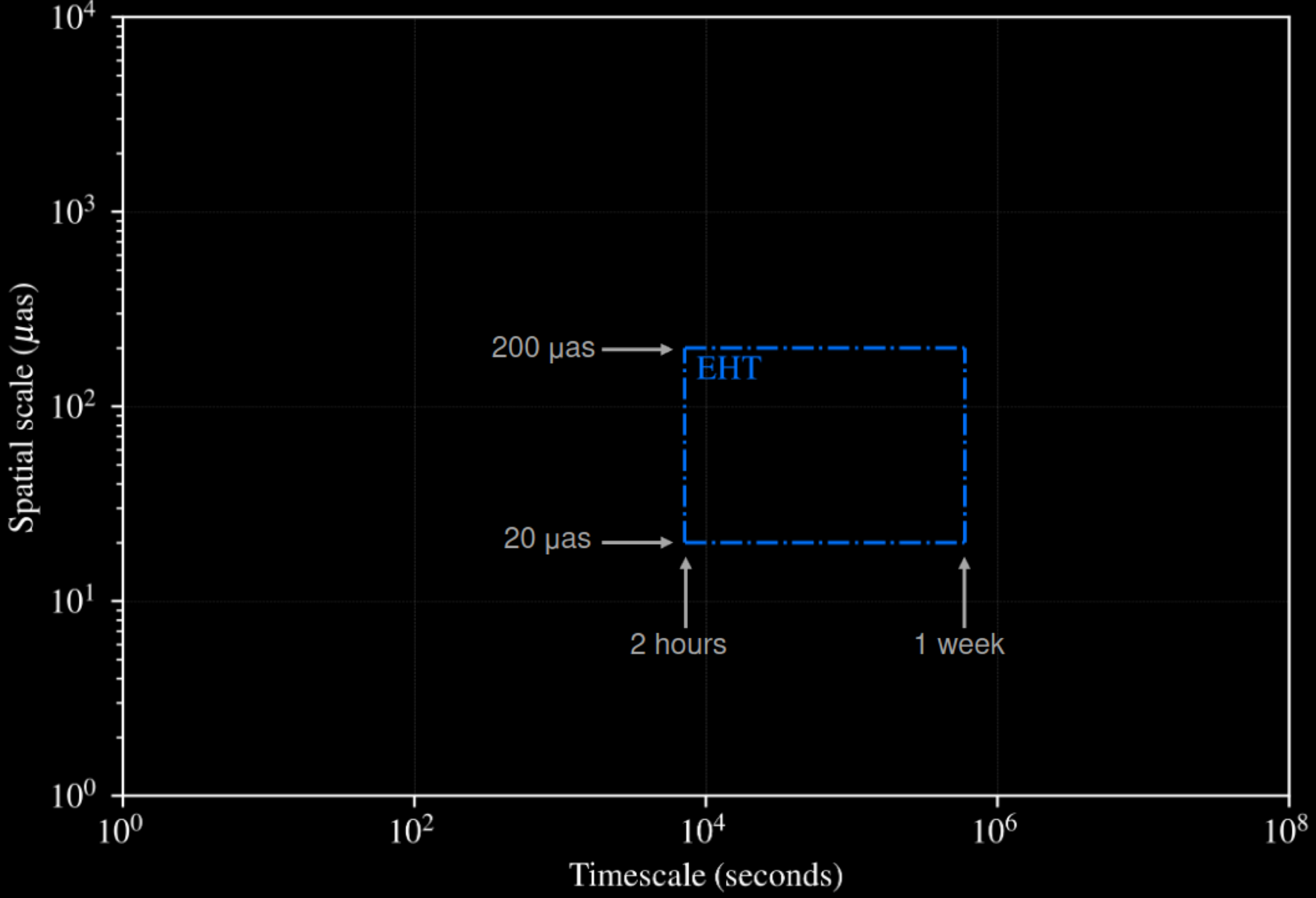
Key Science Goals for the Next-Generation Event Horizon Telescope

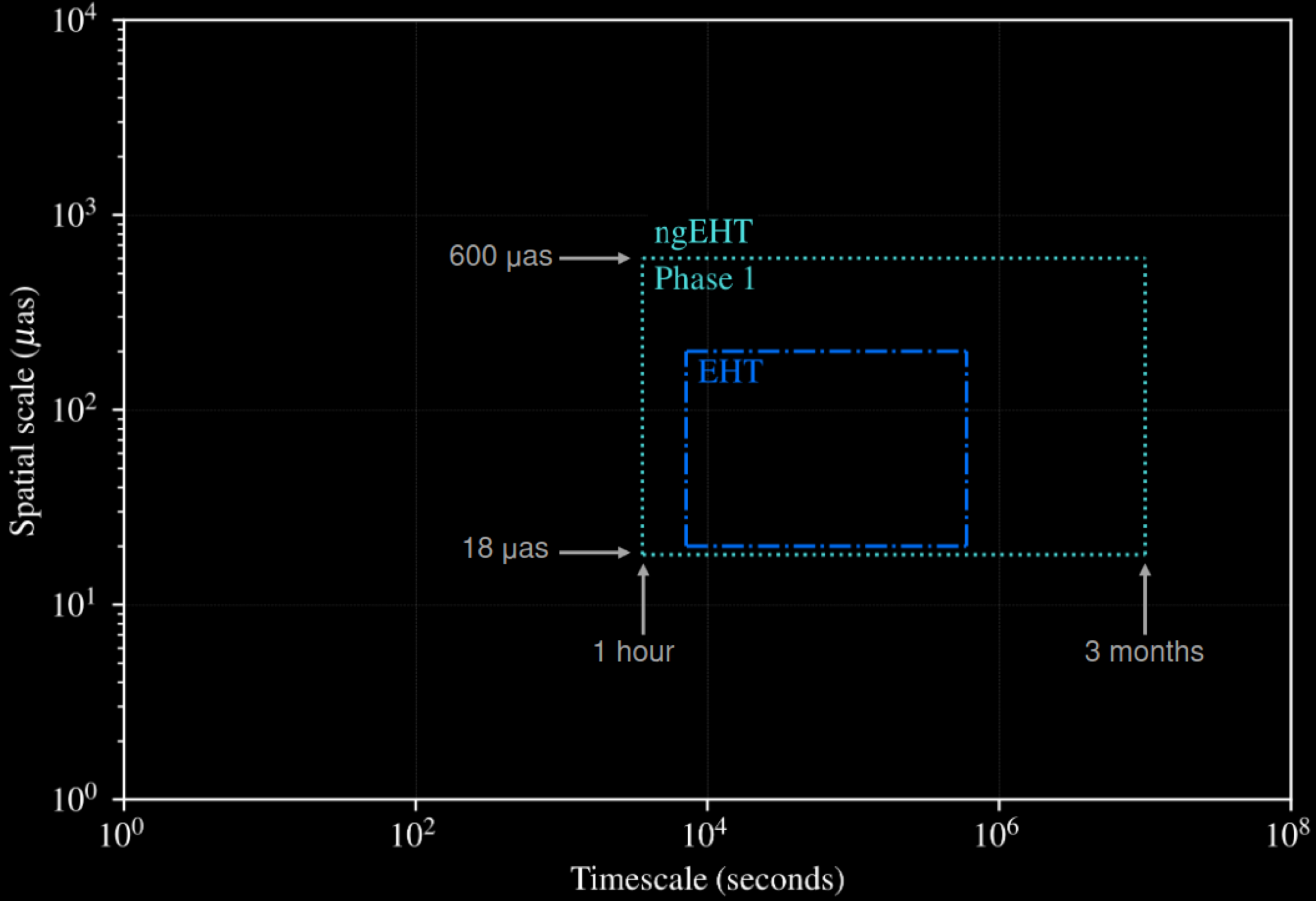
ngEHT Key Science Goals

The ngEHT Key Science Goals



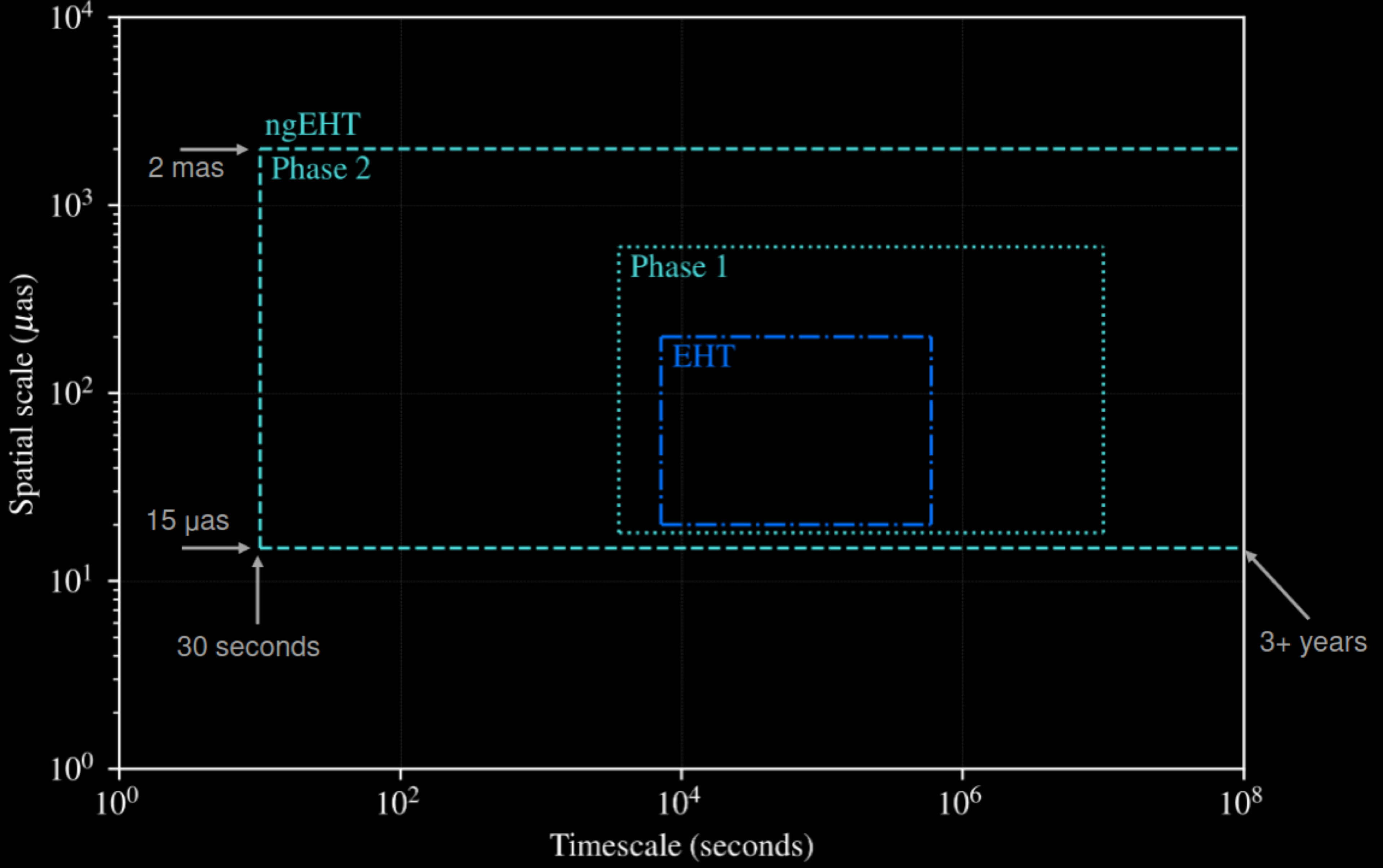
Slide credit: D. Pesce, SAO

The ngEHT Key Science Goals



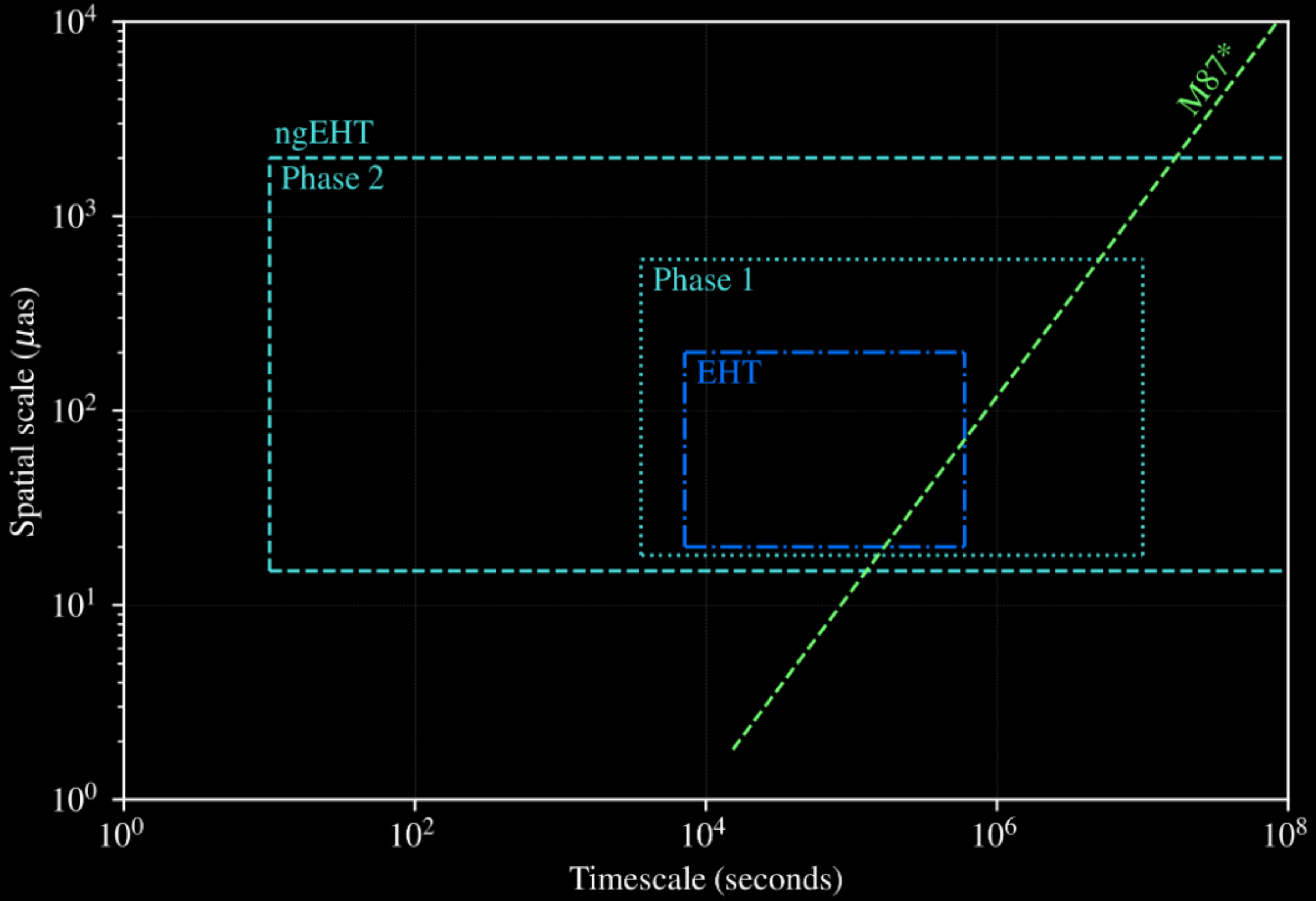
Slide credit: D. Pesce, SAO

The ngEHT Key Science Goals



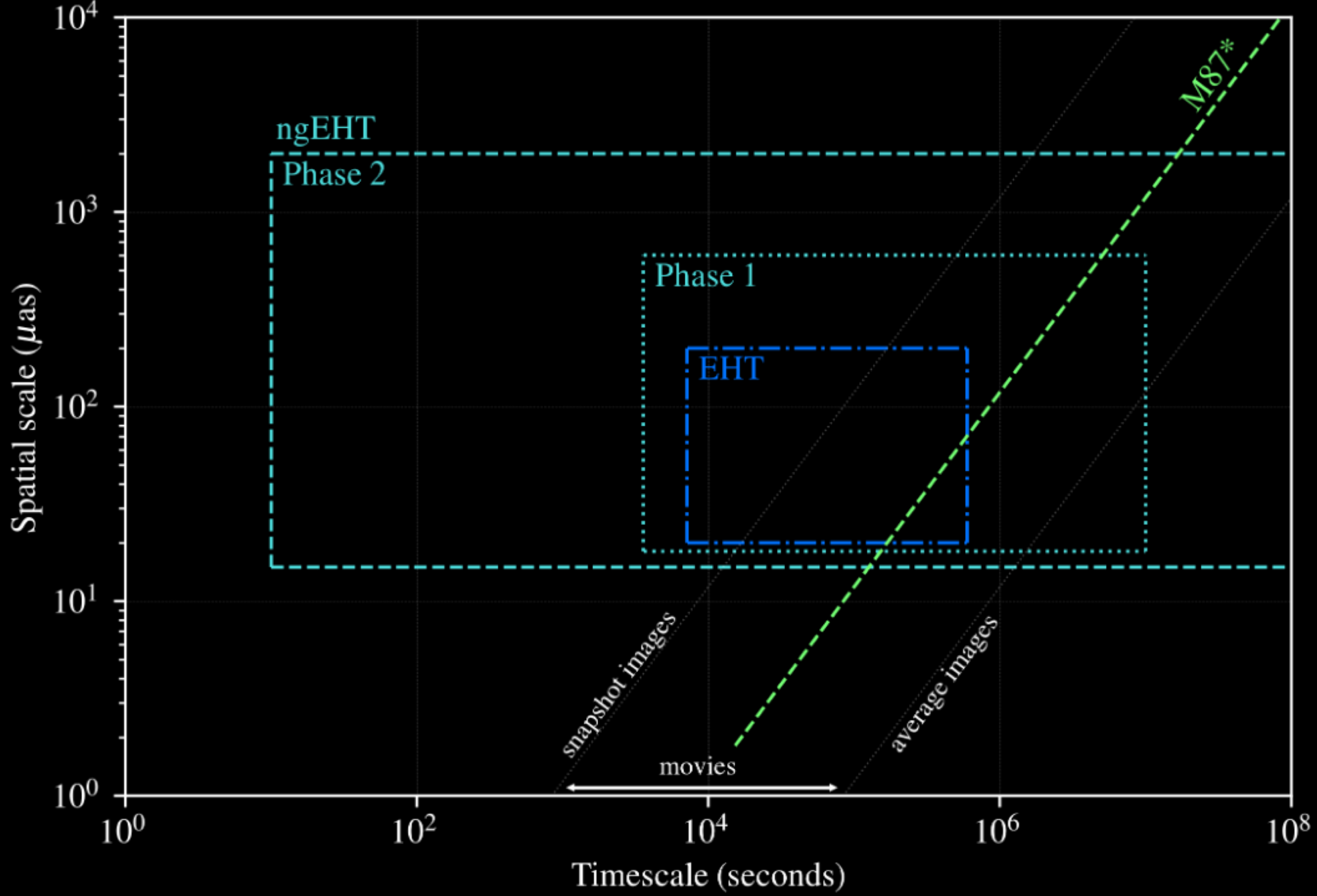
Slide credit: D. Pesce, SAO

The ngEHT Key Science Goals



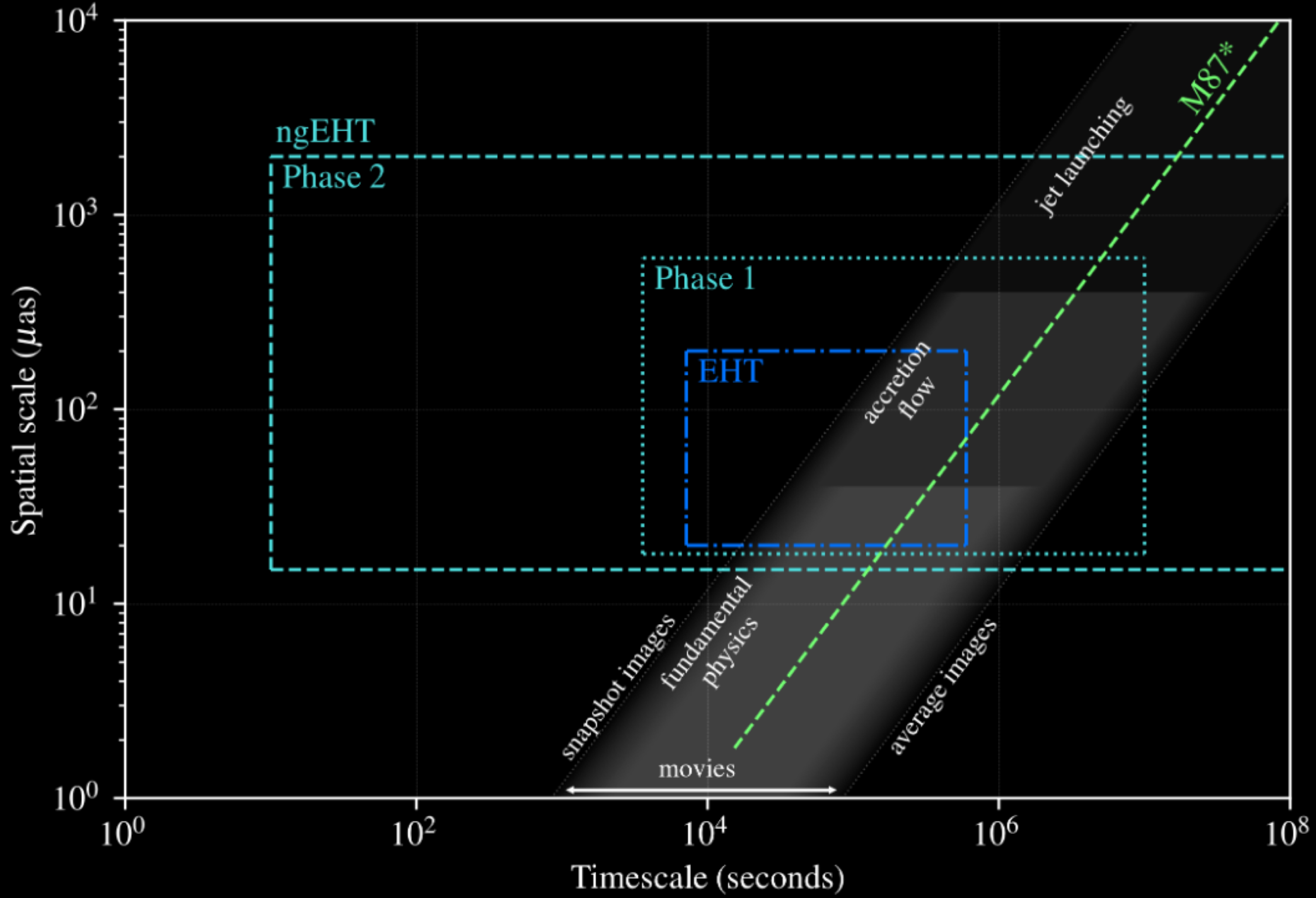
Slide credit: D. Pesce, SAO

The ngEHT Key Science Goals



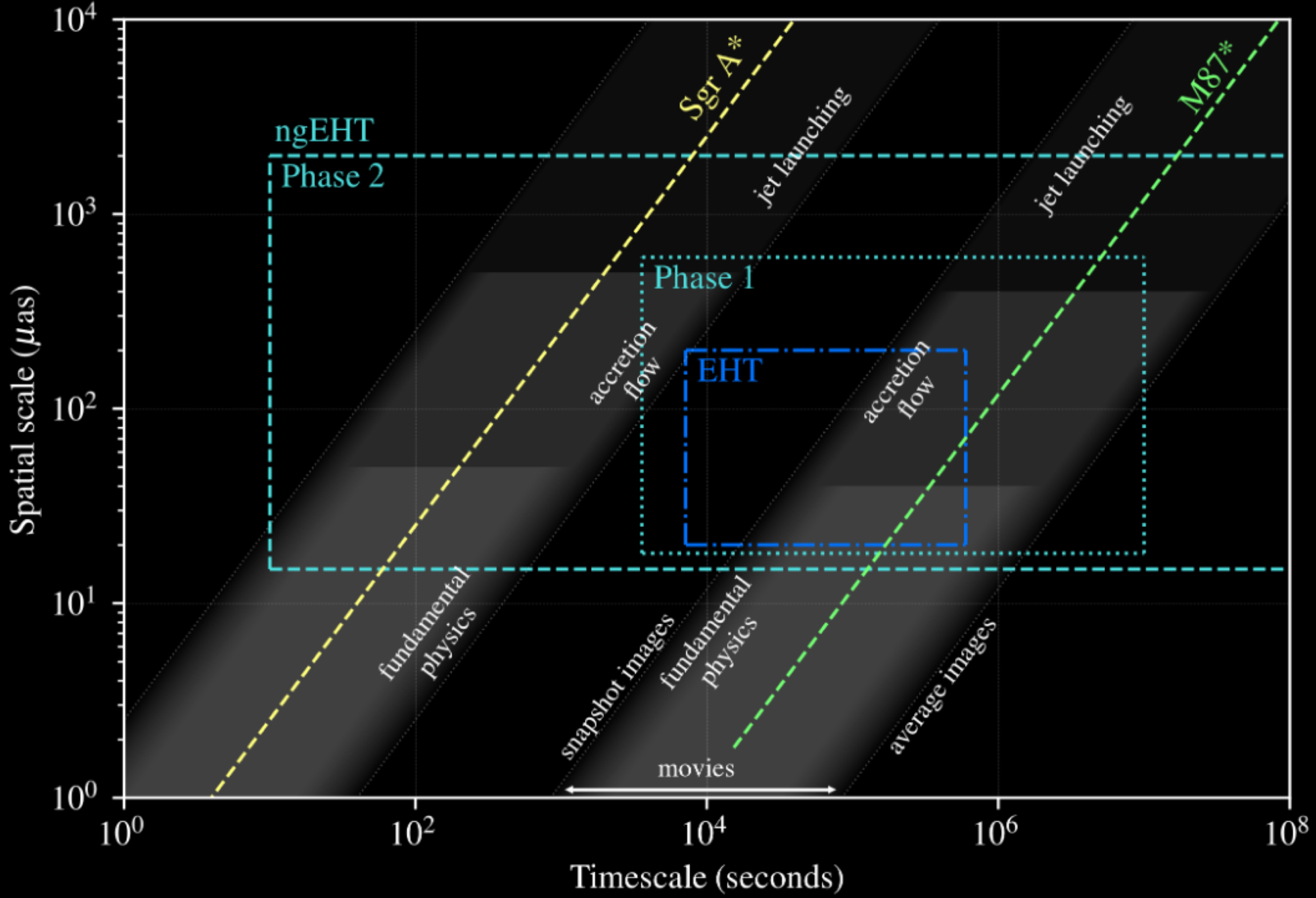
Slide credit: D. Pesce, SAO

The ngEHT Key Science Goals



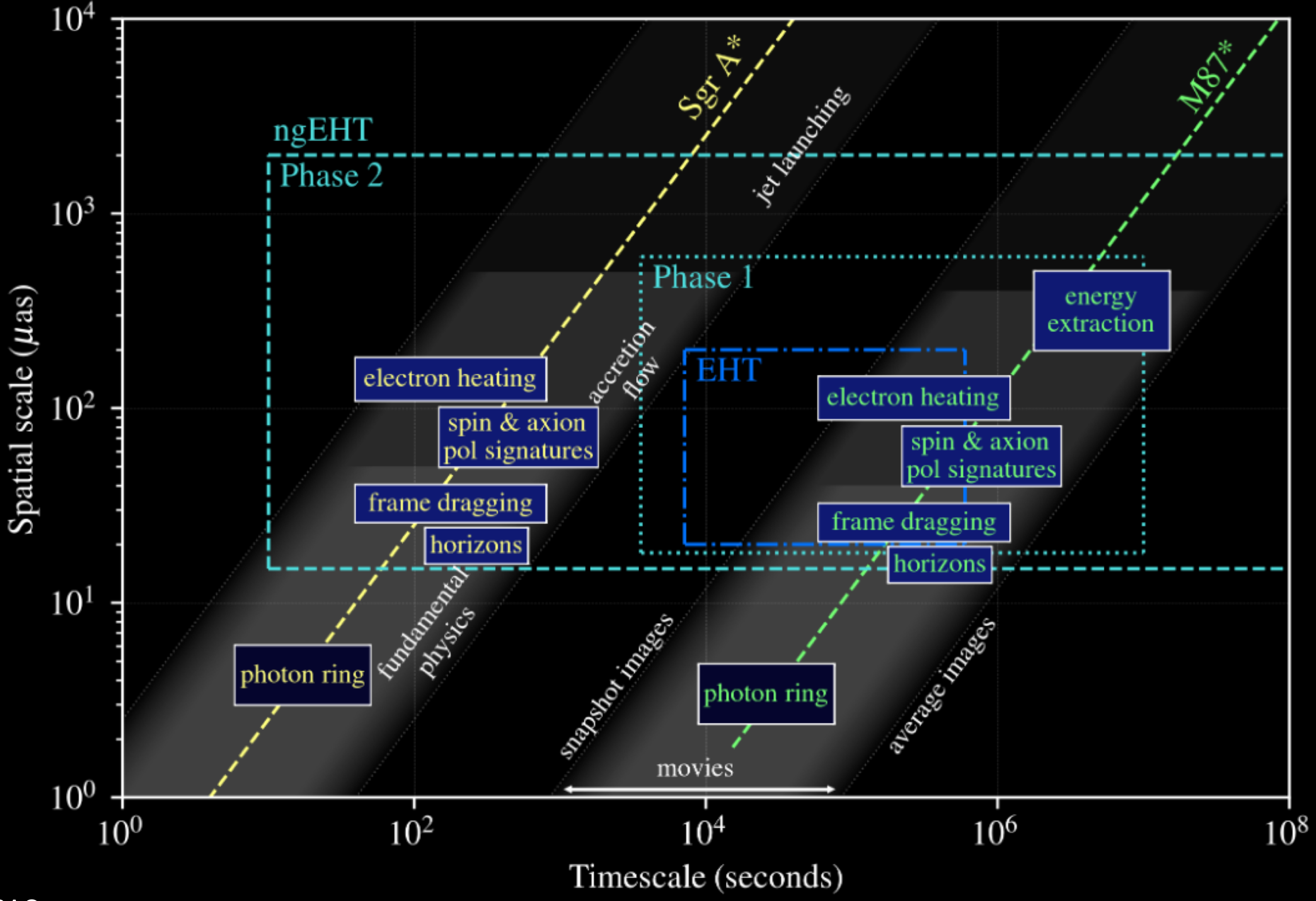
Slide credit: D. Pesce, SAO

The ngEHT Key Science Goals



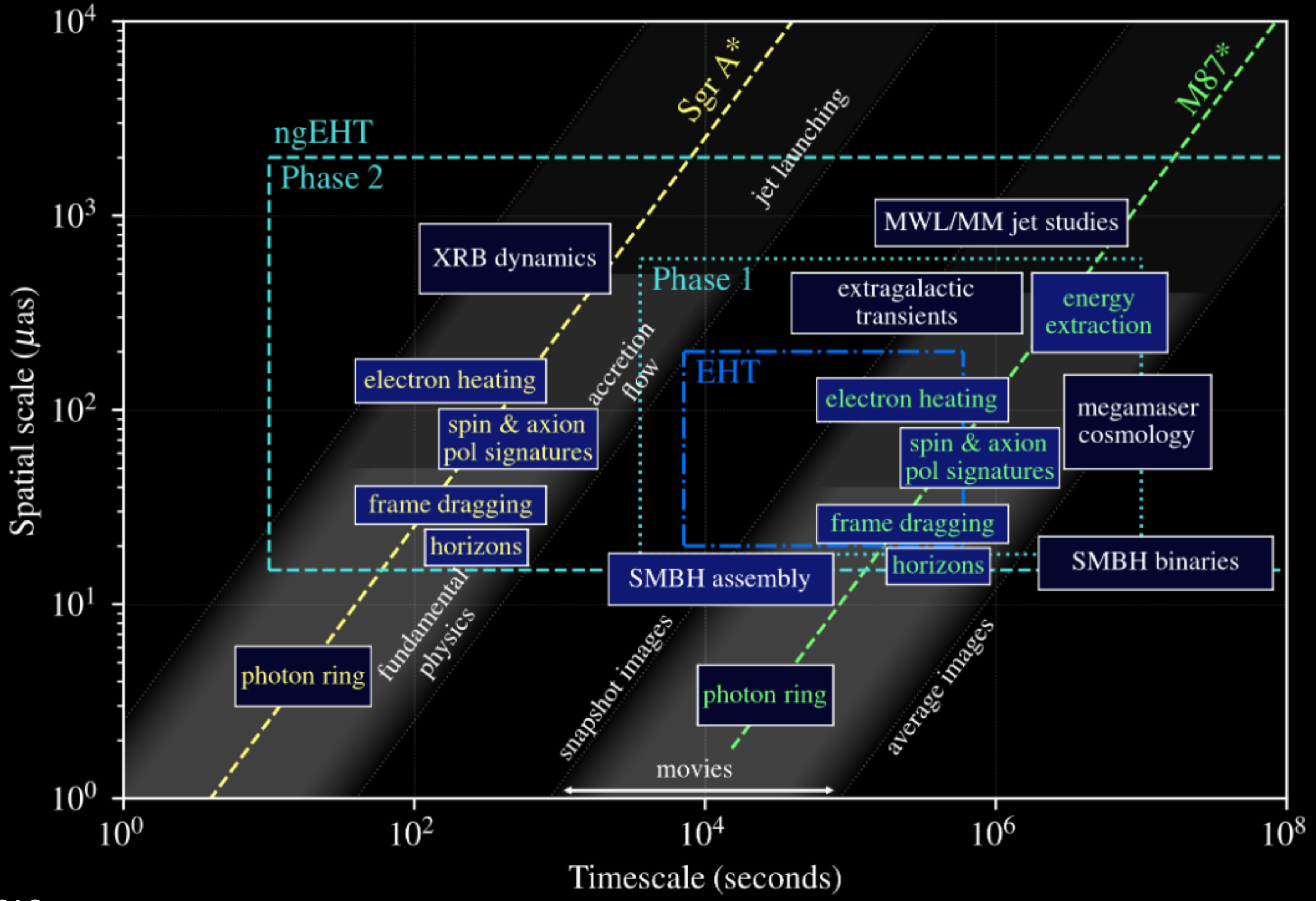
Slide credit: D. Pesce, SAO

The ngEHT Key Science Goals



Slide credit: D. Pesce, SAO

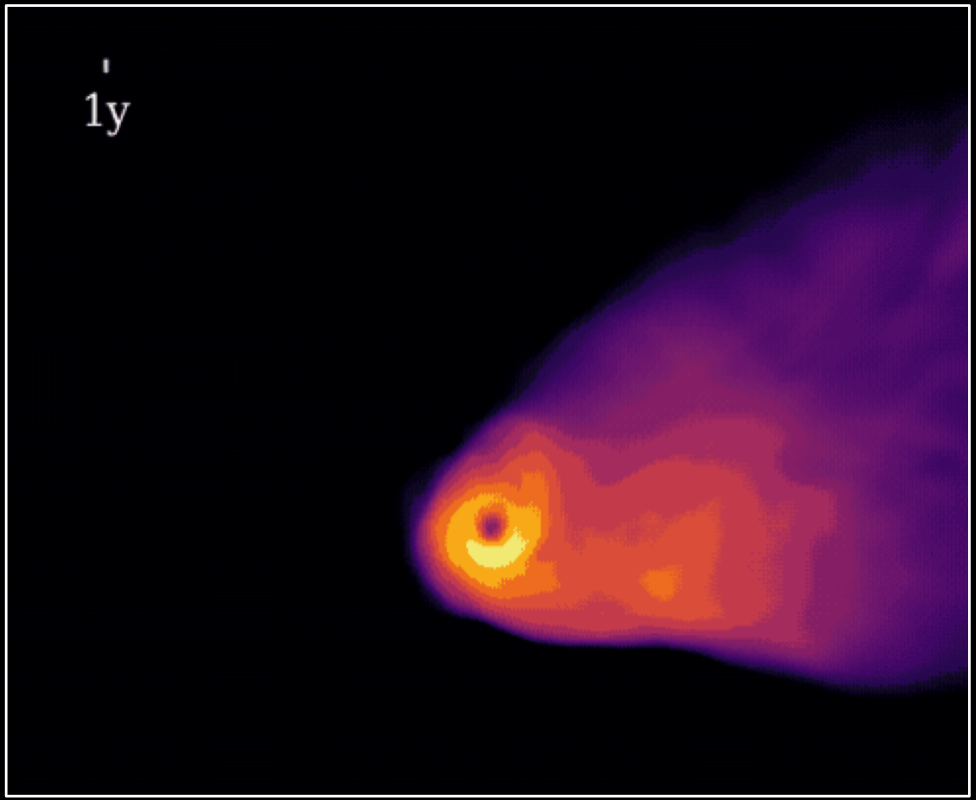
The ngEHT Key Science Goals



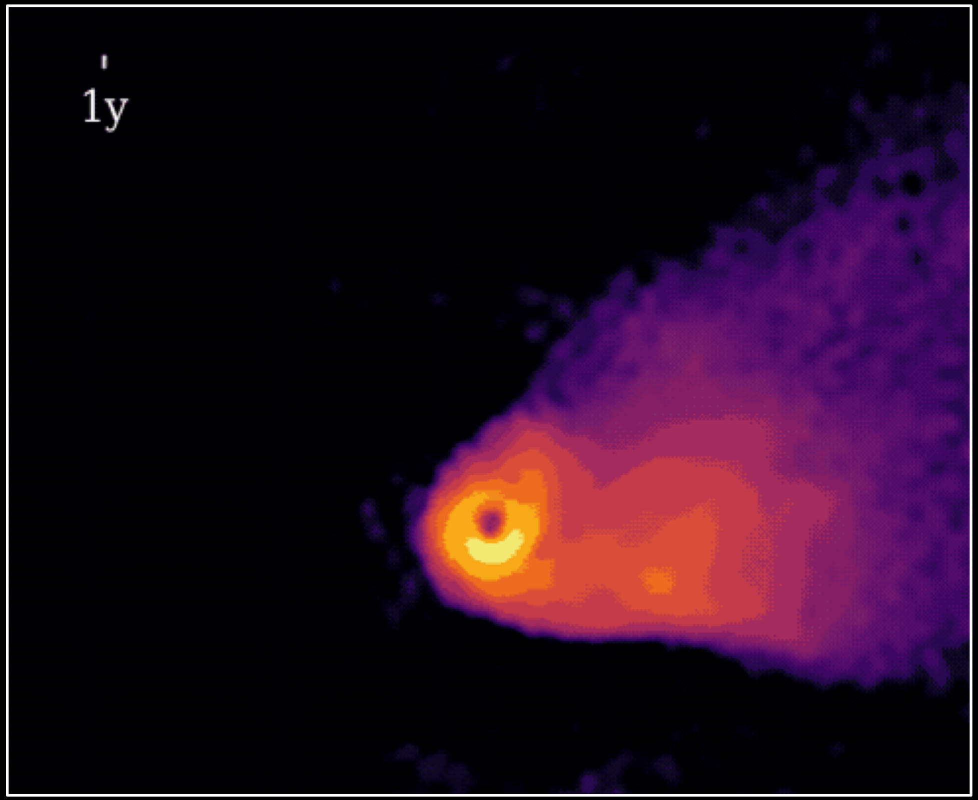
Slide credit: D. Pesce, SAO

The Era of Black Hole Cinema (Accretion & Jet Launching)

Model at 230+345 GHz



Reconstruction at 230+345 GHz



L. Blackburn, K. Chatterjee, SAO

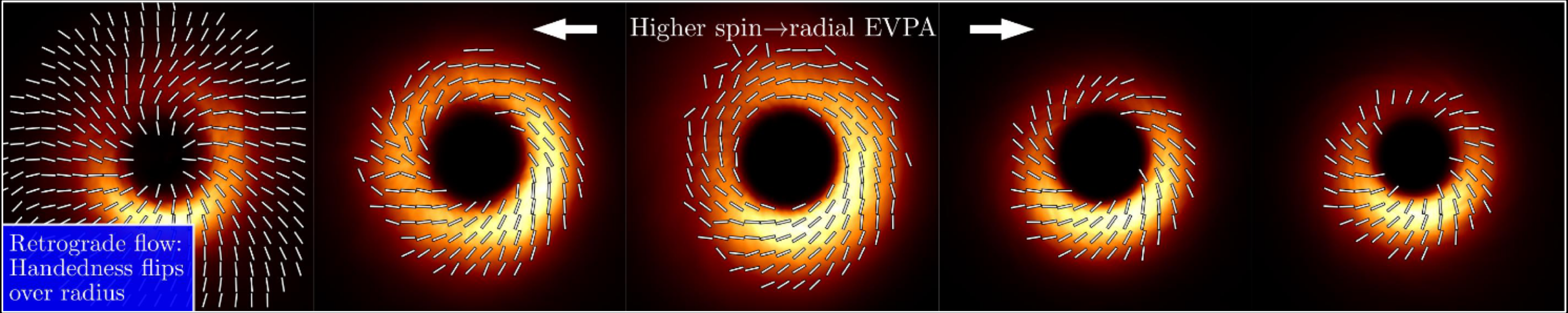
- Reveal how black holes accrete material using resolved movies on event horizon scales
- Observe localized heating and acceleration of relativistic electrons on astrophysical scales
- Determine whether relativistic jets are powered by energy extraction from rotating black holes
- Determine the physical conditions and launching mechanisms of jets

Black Hole Horizons

Fundamental Physics
- Establish the existence and properties of black hole horizons
- Measure the spin of a supermassive black hole

Retrograde High Spin | Retrograde Med. Spin | Schwarzschild | Prograde Med. Spin | Prograde High Spin

Primary Image



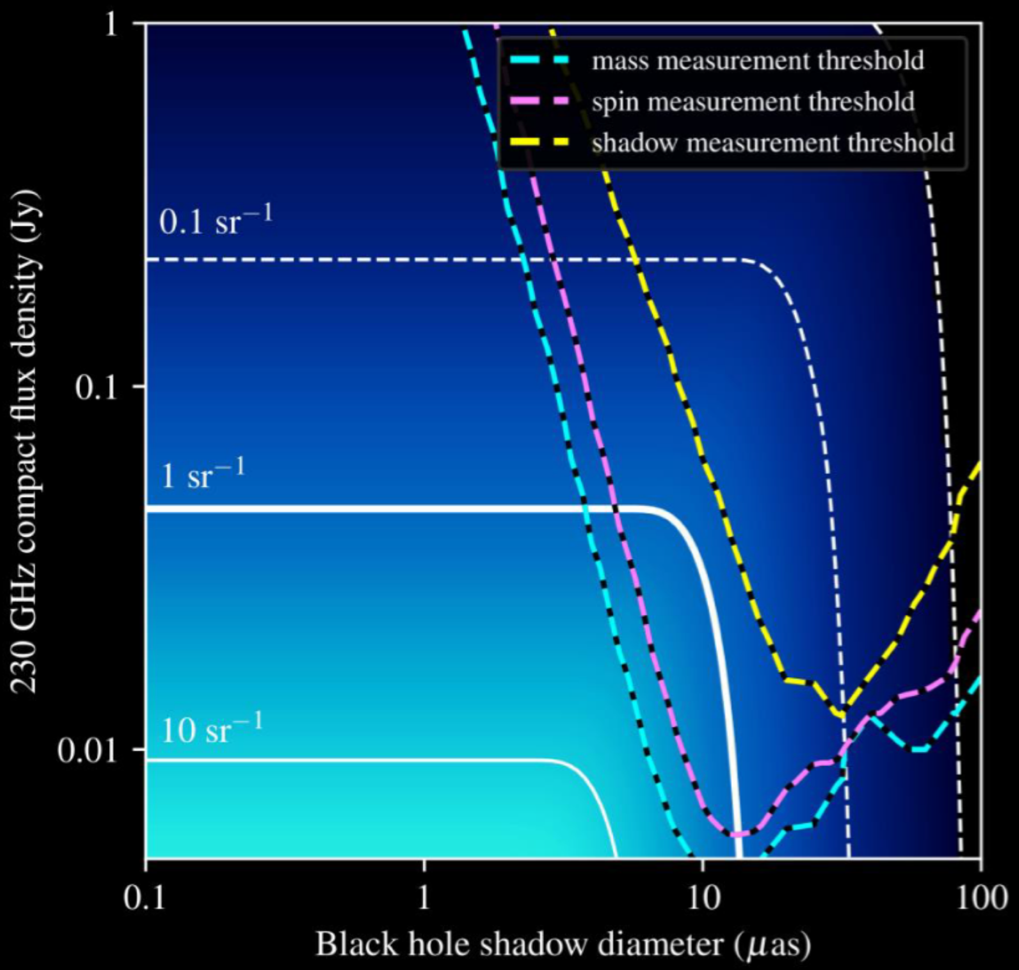
Palumbo, Wong, & Prather (2020); Ricarte+ (2023)

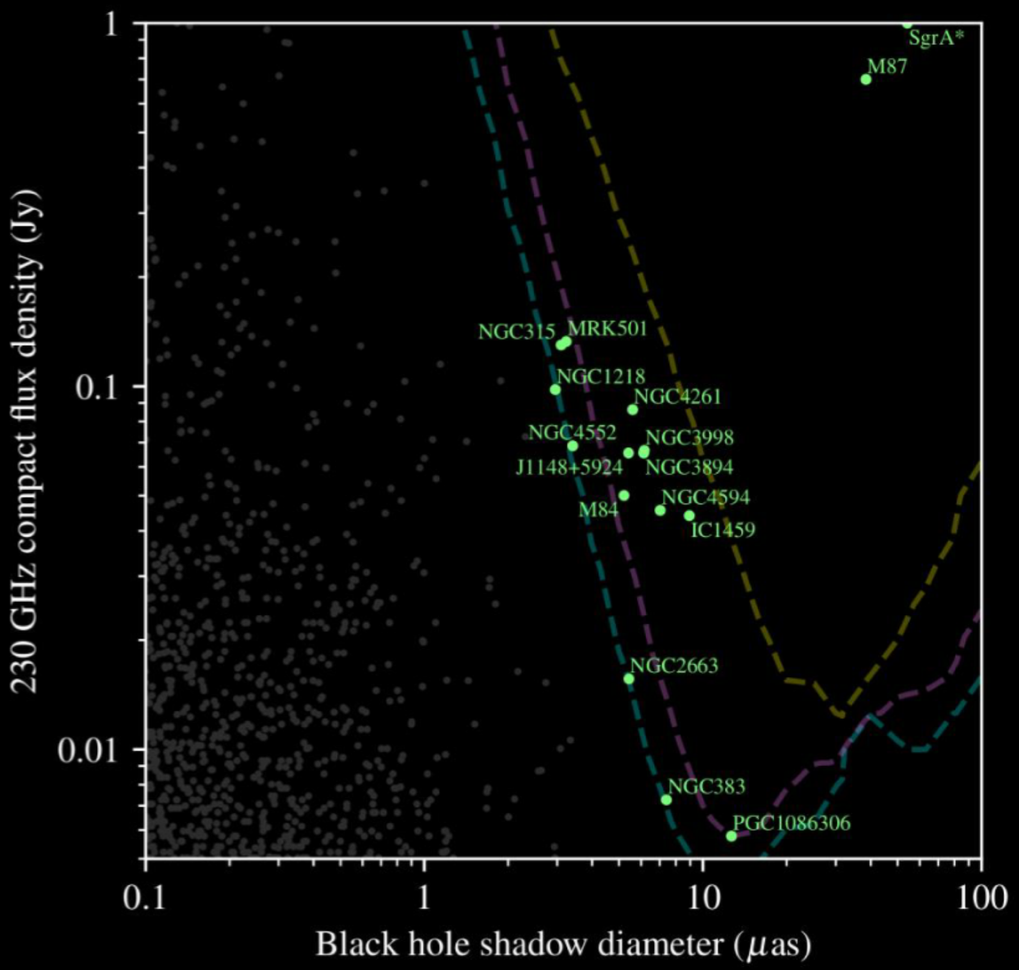
Black Hole Demographics

Black Holes and their Cosmic Context

- Reveal Black Hole-Galaxy Formation, Growth, and Coevolution

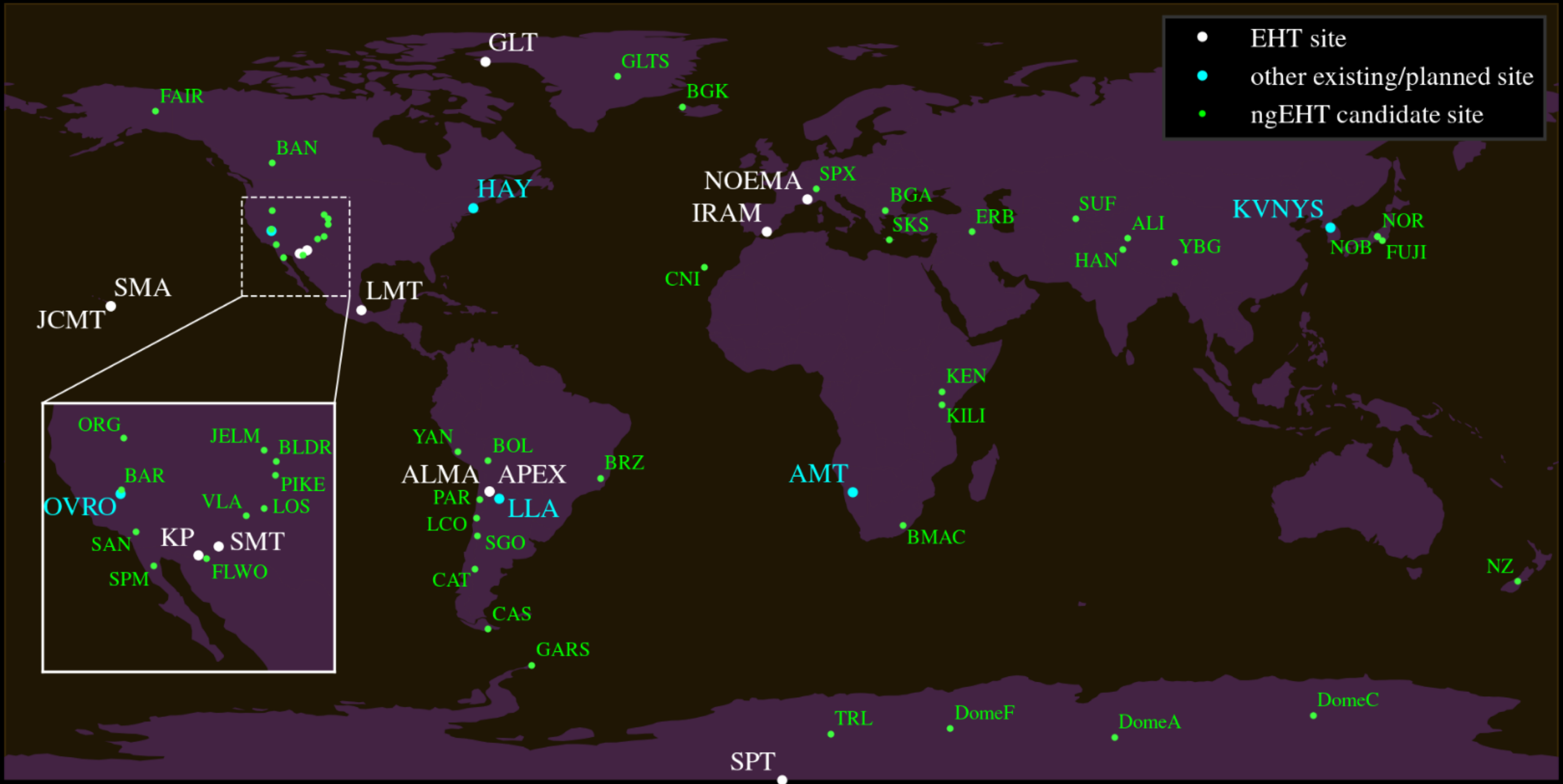
Goal: A sample of >10 SMBH masses and spins to constrain the formation, fueling, and feedback from SMBHs





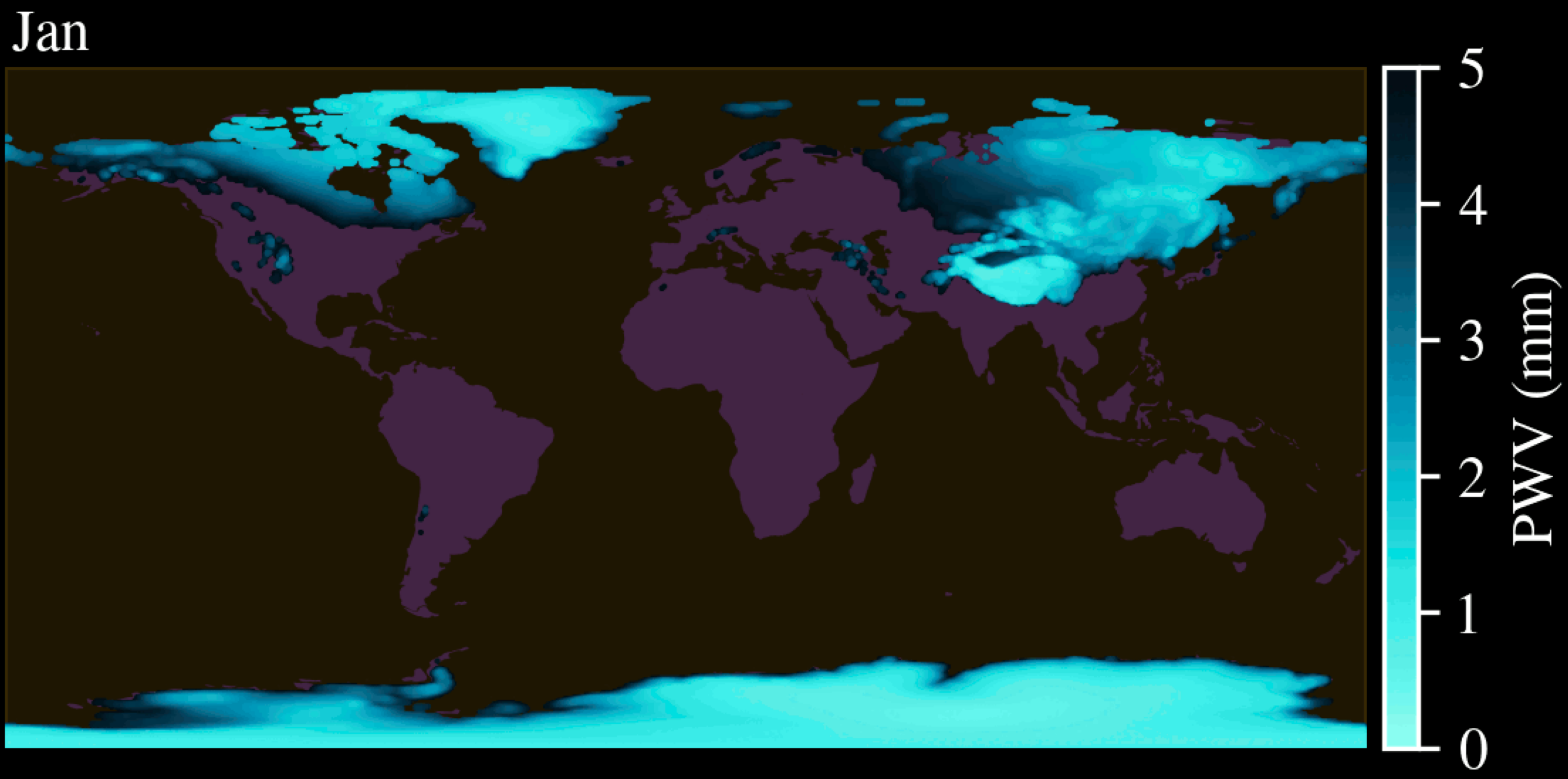
D. Pesce, SAO, V. Ramakrishnan, U Concepcion

Phase 1 Site Selection



Slide credit: D. Pesce, SAO

Phase 1 Site Selection



Slide credit: D. Pesce, SAO

Phase 1 Site Selection

Considerations for the addition of three 6-meter dishes

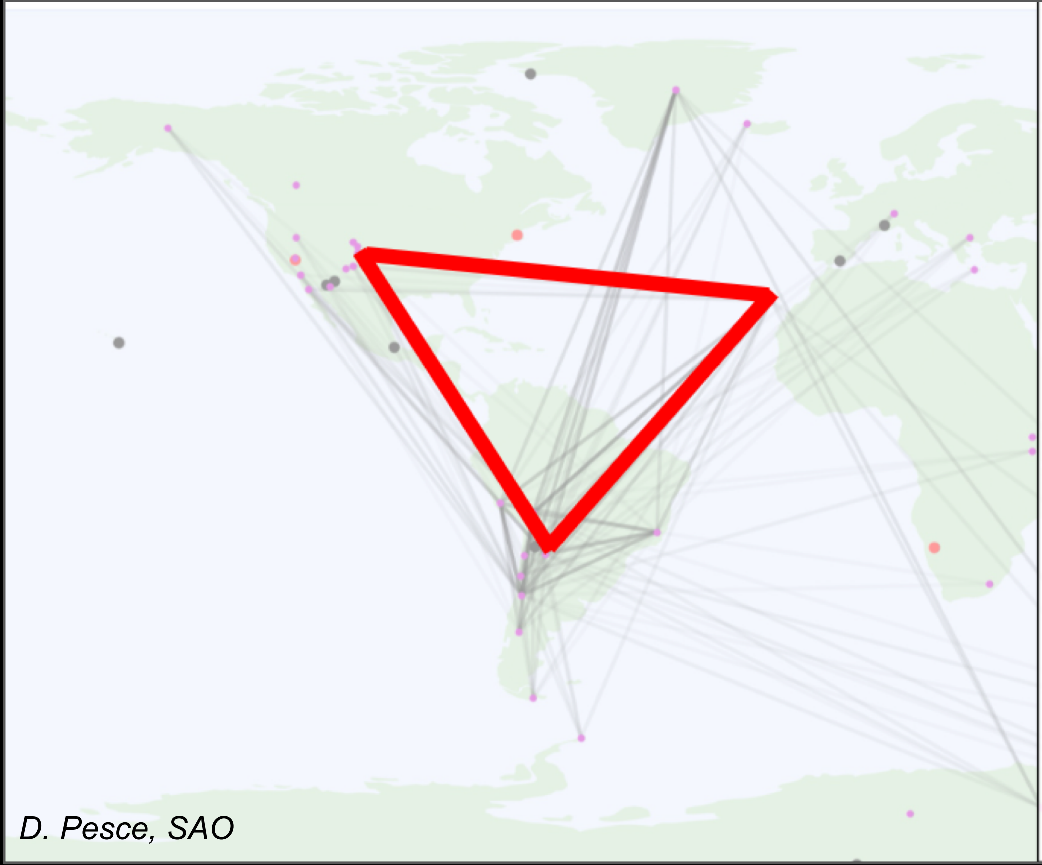
The array must perform well:

- when observing both M87 and Sgr A*
- when observing in any season of the year (with varying weather conditions)
- when observing alongside the full EHT, no EHT, or an EHT subset

The output of this procedure is a large database (~100 million entries for ngEHT Phase 1) of performance metrics for each array+observing mode combination

Cost and infrastructure assessment was folded into the final selection

Phase 1 Site Selection



There are roughly 6 “clusters” of site combinations that make it into the top 5%:

- A “western cluster” containing two sites in South America and one in North America
- A “northern cluster” containing two sites in South America and one in either Greenland or Iceland
- An “eastern cluster” containing two sites in South America and one in Europe
- A “southern cluster” containing two sites in South America and one in Antarctica
- A “polar cluster” containing one site in South America, one site in Antarctica, and one site in Greenland
- **An “equatorial cluster” containing one site in South America, one site in North America, and one in the Canary Islands**

The equatorial cluster provides the most balance in terms of geographical distribution, and it contains one site in each of the three most favored regions

The final selected sites:

- **“SPM” – Observatorio Astronómico Nacional, located in Sierra de San Pedro Mártir, Baja California**
- **“CNI” – On the island of La Palma, Canary Islands**
- **“LCO” – Las Campanas Observatory, located in the Atacama region of Chile**

Phase 2 selection is ongoing, it requires additional responsible environmental and social siting considerations

ngEHT 86 GHz case study

The science and calibration case for adding 86 GHz receivers:

- Enables higher frequency science and observing capabilities
  - multi-frequency imaging is required for M87 jet reconstructions with standalone ngEHT
- Guaranteed coverage and sensitivity the entire year
  - 86GHz enables year-round monitoring at all sites
- Offering both high sensitivity and resolution in combination with current (GMVA) and future (ngVLA) arrays
  - joint ngEHT+ngVLA observations can recover the M87 jet+shadow at 86GHz
- Simultaneity is essential
  - Frequency phase transfer can vastly extend effective coherence times at 230 and 345 GHz (see work by M. Rioja and R. Dodson)

MDPI

Article

Enabling transformational ngEHT science via the inclusion of 86 GHz capabilities

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Abstract: We present a case for significantly enhancing the utility and efficiency of the ngEHT by incorporating an additional 86 GHz observing band. Unlike at 230 GHz or 345 GHz, weather conditions at the ngEHT sites are reliably good enough at 86 GHz to enable year-round observations. Multi-frequency imaging that incorporates 86 GHz observations would sufficiently augment the (u, v)-coverage at 230 GHz and 345 GHz to permit detection of the M87 jet structure without requiring EHT stations to join the array. The general calibration and sensitivity of the ngEHT would also be enhanced by leveraging frequency phase transfer techniques, whereby simultaneous observations at 86 GHz and the higher frequency bands have the potential to increase the effective coherence times from a few seconds to many minutes. When observing at the higher frequencies is not possible, there are opportunities for standalone 86 GHz science such as studies of black hole jets and spectral lines. Finally, the addition of 86 GHz capabilities to the ngEHT would enable it to integrate into a community of other VLBI facilities – such as the GMVA and ngVLA – that are expected to be operating at 86 GHz but not at the higher ngEHT observing frequencies.

Citation: Issaoun et al. ngEHT 86 GHz. *Galaxies* **2022**, 1, 0. https://doi.org/

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1. Introduction

Building upon the success of the Event Horizon Telescope [EHT; e.g., 1,7–9], the next-generation EHT (ngEHT) is a proposed global very long baseline interferometry (VLBI) telescope network that aims to carry out horizon-scale observations of M87 and Sgr A* at (sub)millimeter wavelengths [10]. By adding ~10 new VLBI stations to the EHT array and increasing the overall array sensitivity, the ngEHT will be able to reach high fidelity imaging and even movie-making capabilities. The primary science goals of the ngEHT require an

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Issaoun, et al. 2023

86 GHz Science Highlights

86 GHz capabilities with ngEHT add a suite of new science avenues:

- Spectral index and rotation measure mapping across three frequencies
- Spatially resolving jets in the transverse direction (currently possible only for 3C273)
- Access to spectral lines from a variety of sources (evolved stars, young stellar objects, AGN)
- Absolute 'classic' astrometry is very challenging, but relative astrometry may be possible through FPT
- Relative astrometry could study motion/jitter around a common centroid & jet rotation profiles in AGN
- GRMHD shows emission at 86 GHz is potentially more sensitive to some plasma properties
- Higher sensitivity at 86 GHz could resolve instabilities in the M87 jet in polarization and potential for RM mapping and Faraday tomography
- Flexible and longer observing opens up the realm of mm/sub-mm transient studies of a variety of objects currently mostly unexplored
- Accessibility to weaker sources (AGN) at higher frequencies through FPT

Moving to a tri-band system

The ngEHT array design will include simultaneous tri-band receivers at 86, 230, and 345 GHz.

The addition of the lower frequency band to the ngEHT would enable the first deployment of FPT calibration techniques at higher frequencies

- Increases effective coherence time from several seconds to many minutes

This improved calibration safeguards the array against poor weather conditions

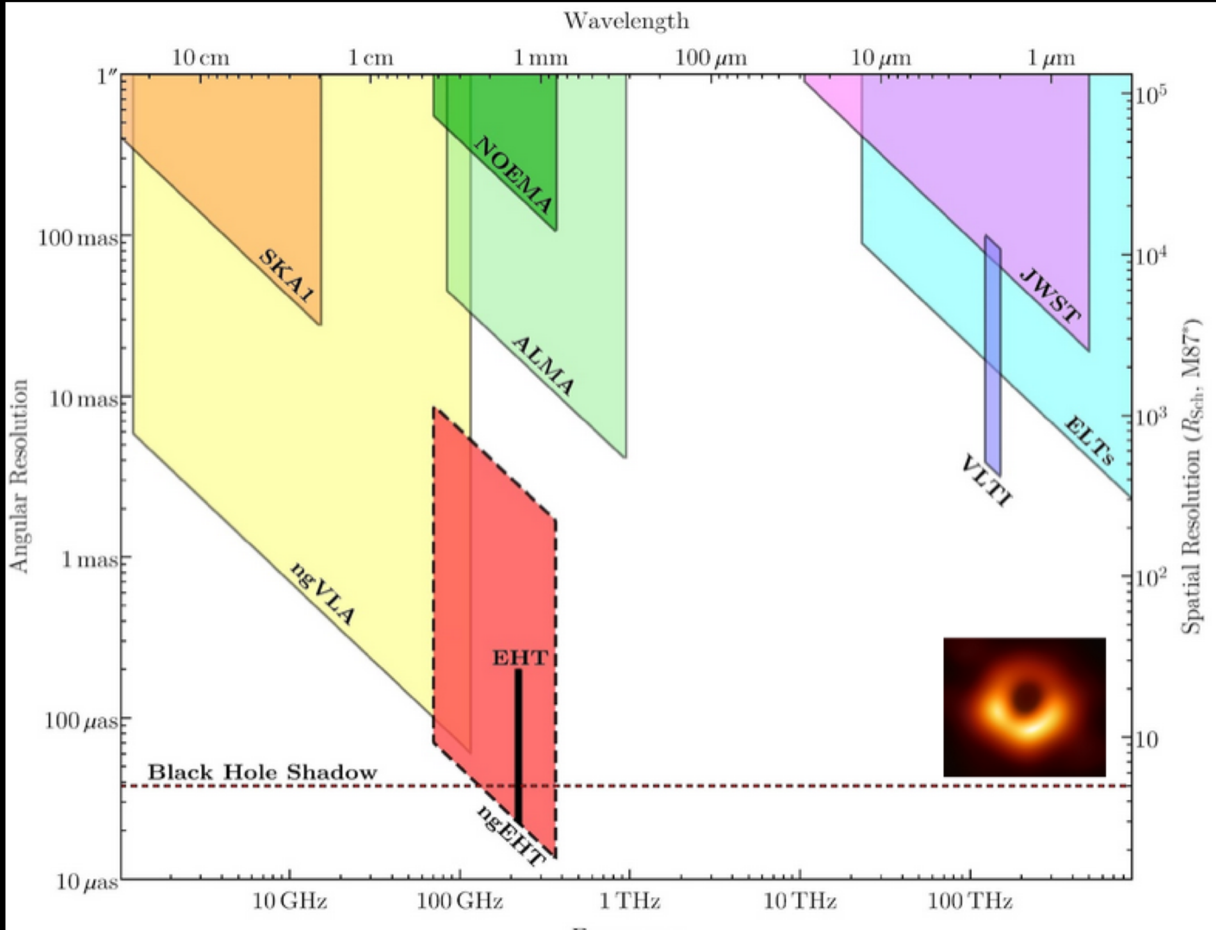
- Flexibility and reliability in observing schedules for black hole movies; many observations throughout the year
- Less dependent on external partner facilities with other science programs (e.g., ALMA)

Moving to a tri-band receiver setup imposes design considerations on the telescope and backend

The added frequency band permits interoperability with contemporary VLBI facilities

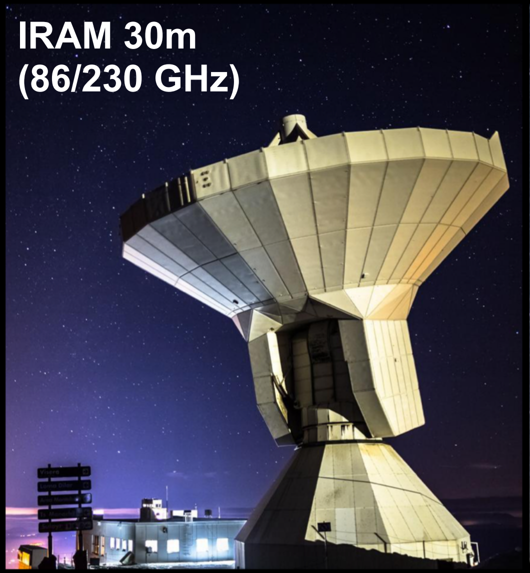
- ngVLA, GMVA, KVN, GBT

Overall improvement in quality and quantity of science!



Adapted from Selina et al.

Path forward: First FPT to 230 GHz



The 86/230 GHz FPTeam

The 86/230 GHz FPTeam

Next steps

Ongoing siting efforts:

- Environmental and social impact investigations of potential phase 2 sites
- Phase 2 site selection surveys

Ongoing engineering efforts:

- 256 Gbps backend development
- LMT dual-band receiver nearly completed
- LMT 86 GHz receiver add-on for tri-band capabilities
- OVRO 86/230 dual-band capabilities

Ongoing technical demonstrations:

- November 2022 FPT observations at the correlation stage, data analysis expected in coming months
- Potential additional 86/230 GHz FPT tests upcoming
- Potential 230/345 GHz FPT tests once dual-band LMT receiver is installed (~mid 2024)

Future efforts:

- Scoping and design of tri-band receiver for additional sites

The Next Generation Event Horizon Telescope will open up new science avenues in the (sub)mm radio