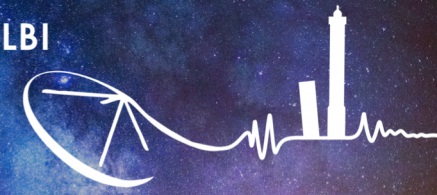




Bologna VLBI

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NEXT GENERATION EVENT HORIZON TELESCOPE Entering a New Era of Black Hole Cinema

Sara Issaoun

NHFP Einstein Fellow

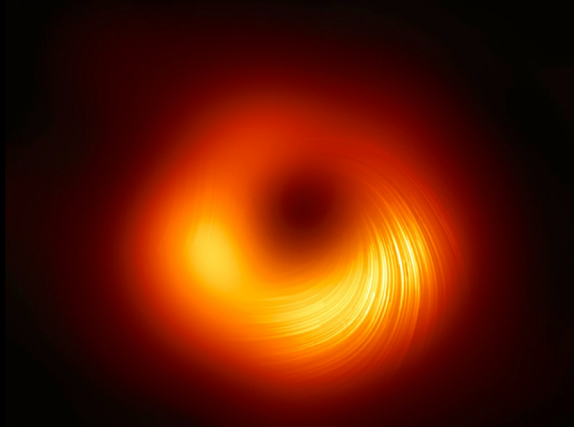
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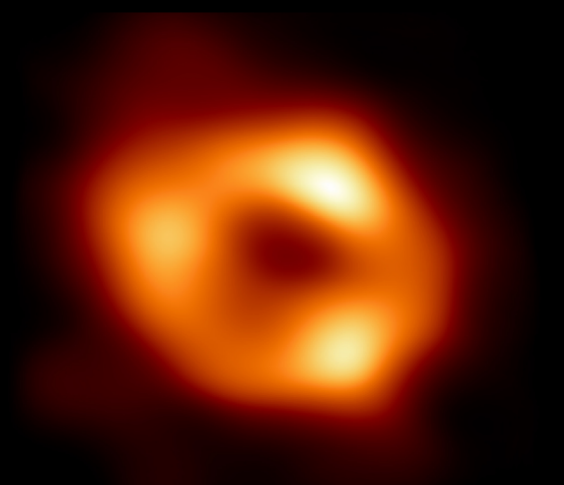
The Black Holes of the EHT Campaign



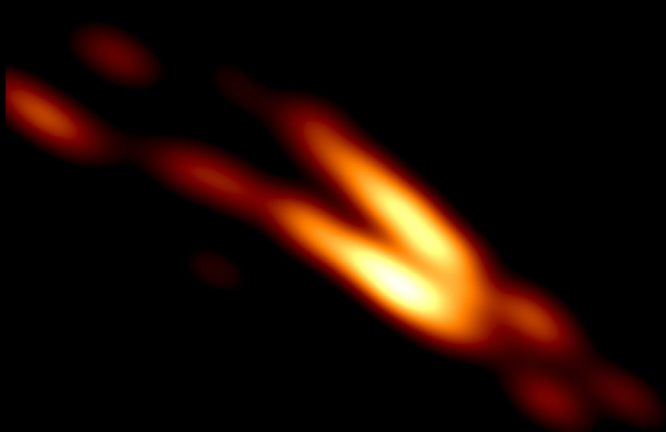
M87* - EHTC+ 2019, 2021



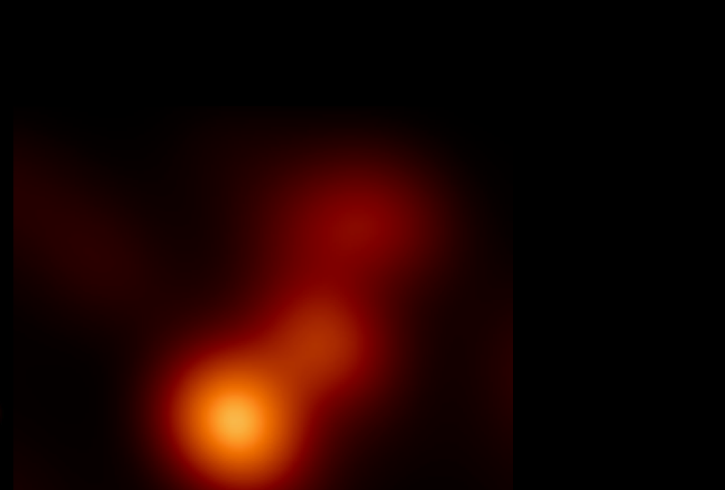
3C 279 - Kim+ 2020



Sgr A* - EHTC+ 2022



Cen A - Janssen+ 2021



J1924 - Issaoun, Wielgus+ 2022



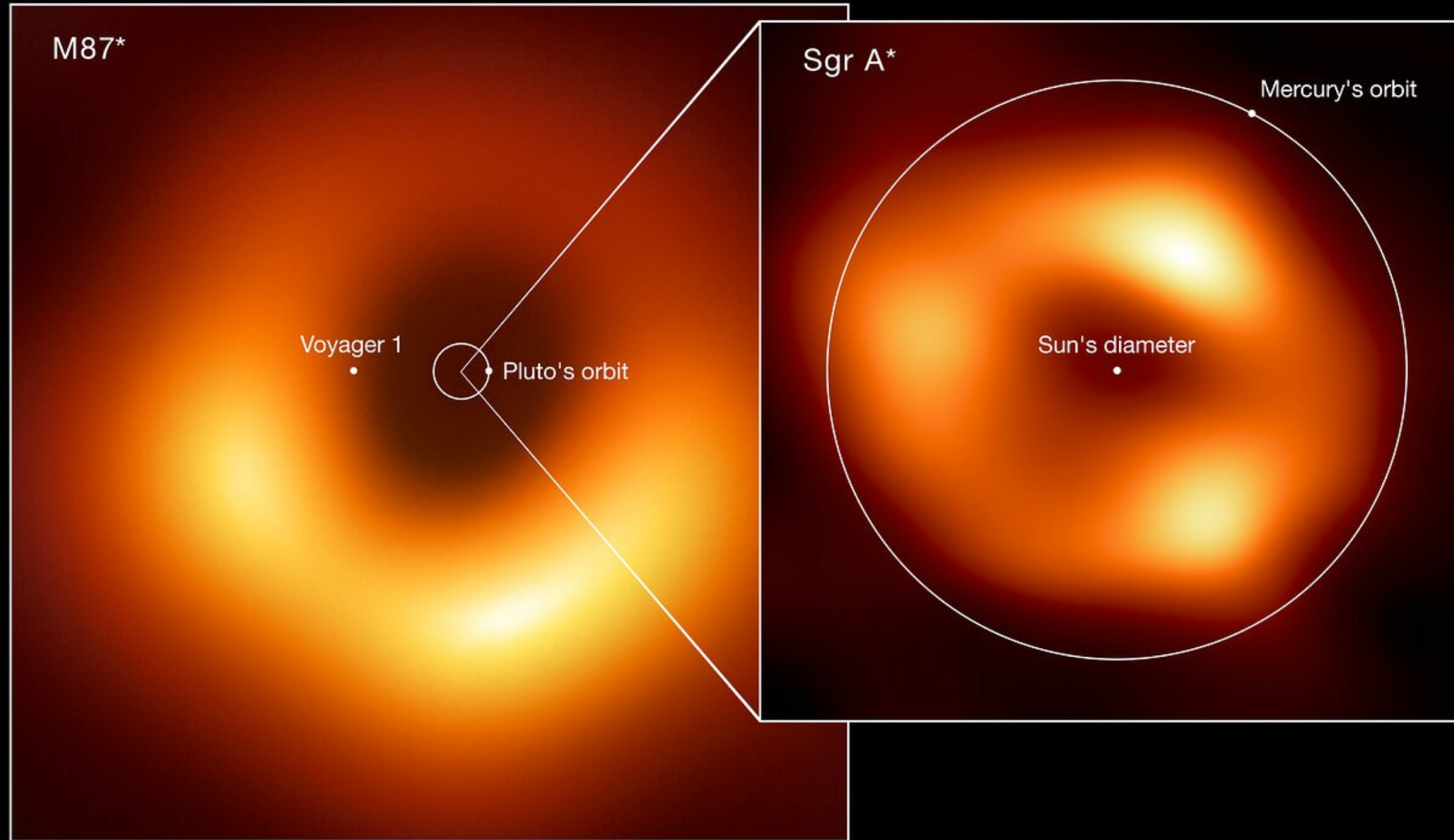
NRAO530 - Jorstad, Wielgus+ 2023



OJ 287 - Gomez+ 202?



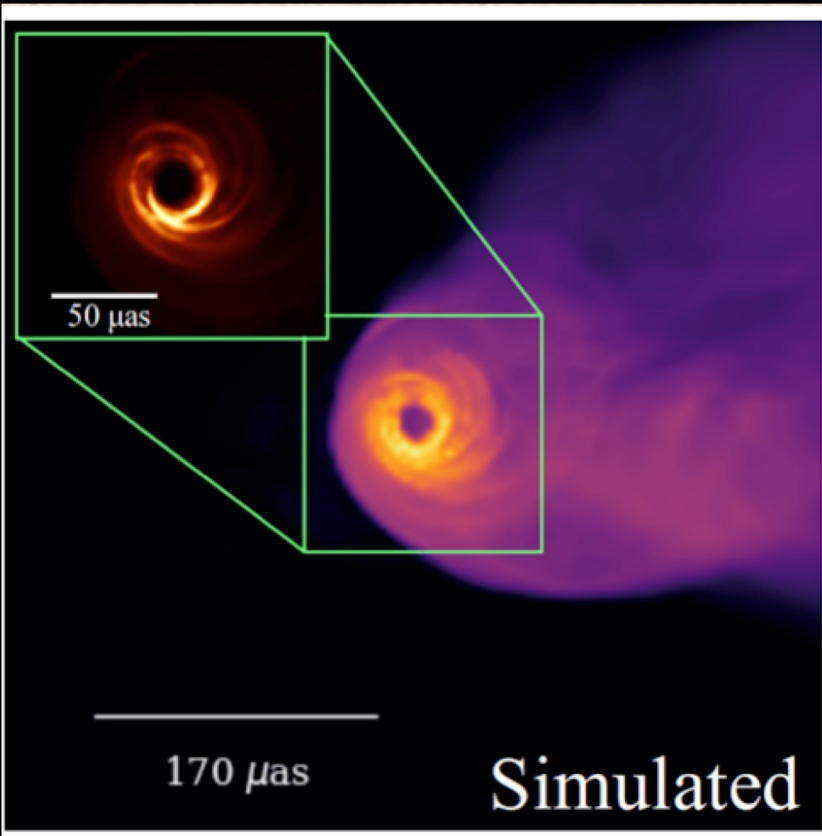
A Tale of Two Black Holes



Visualization by L. Medeiros, IAS/ xkcd

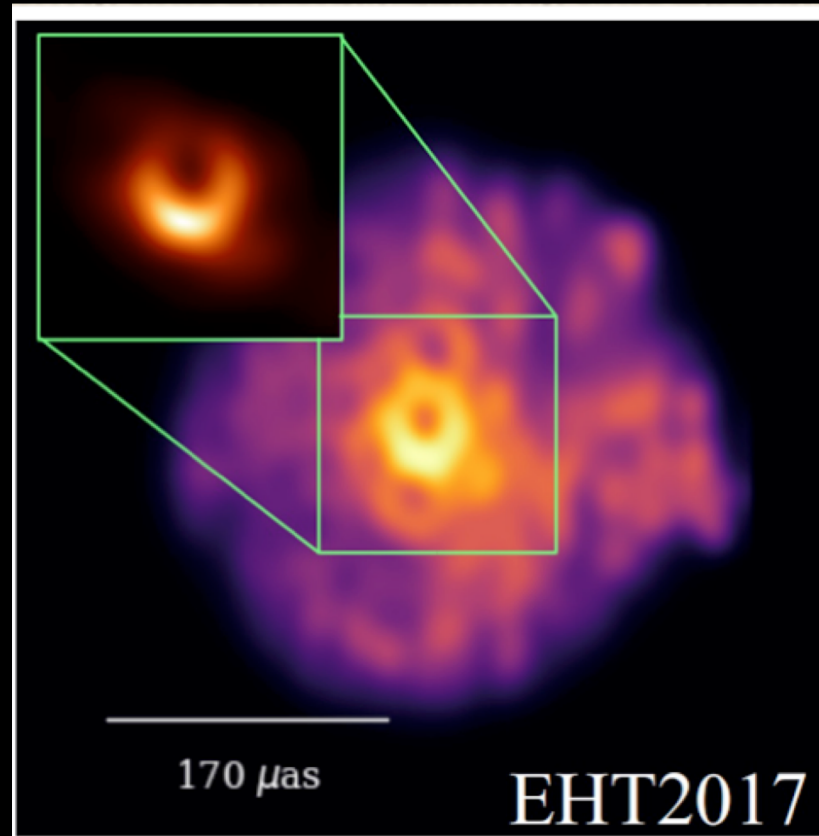
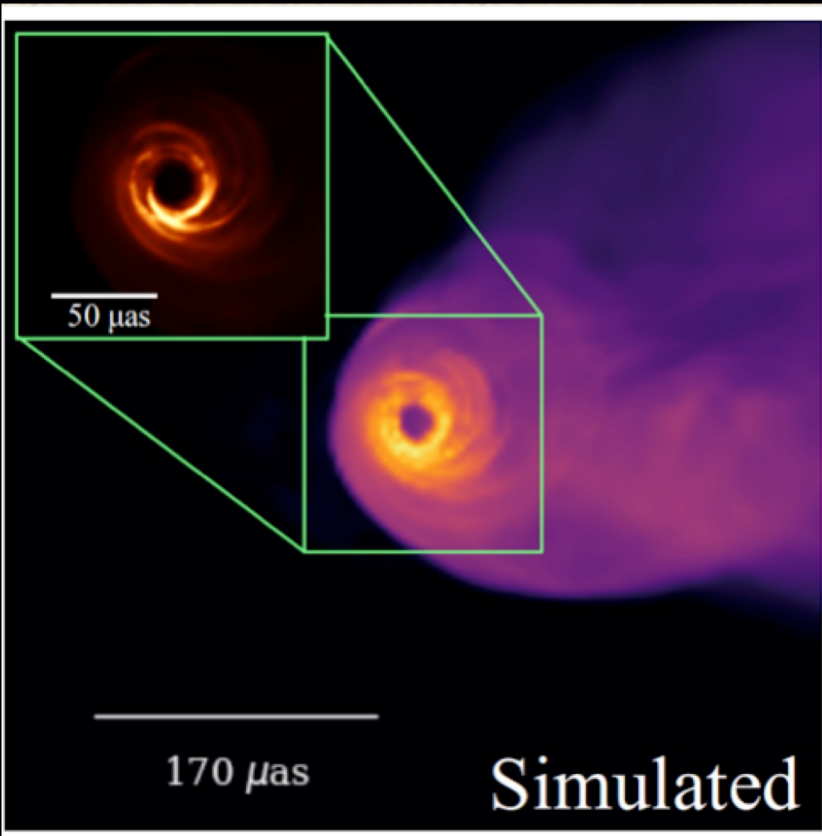


The Era of Black Hole Cinema



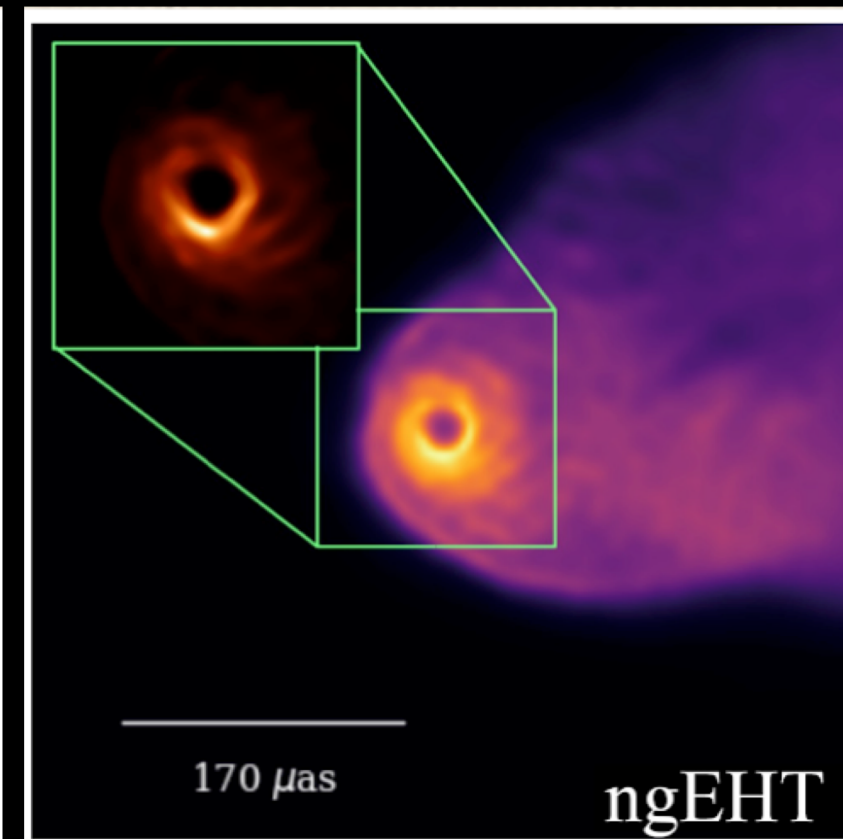
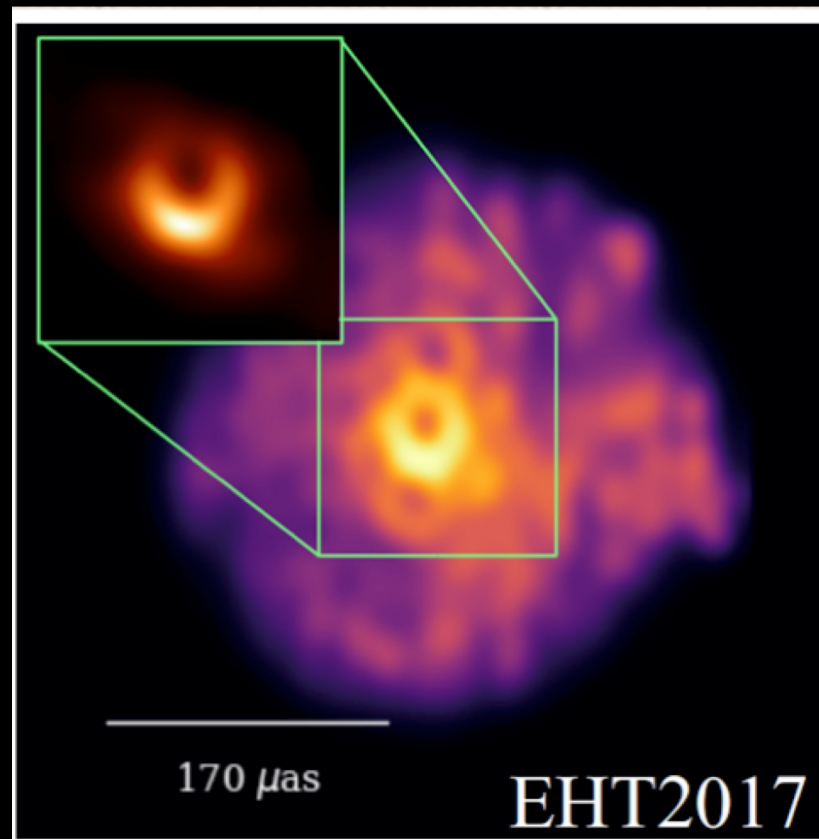


The Era of Black Hole Cinema





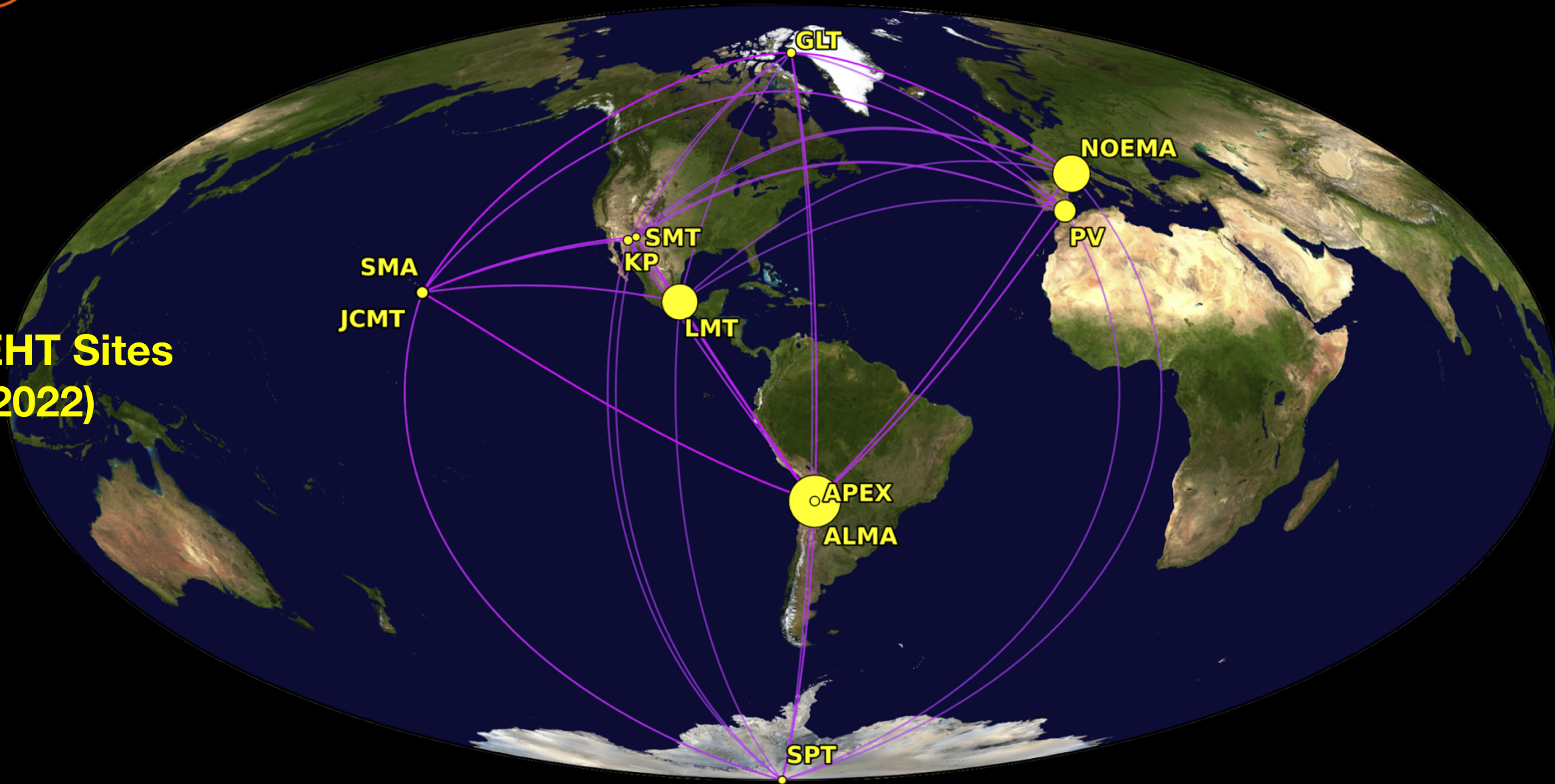
The Era of Black Hole Cinema





The Next Generation Event Horizon Telescope

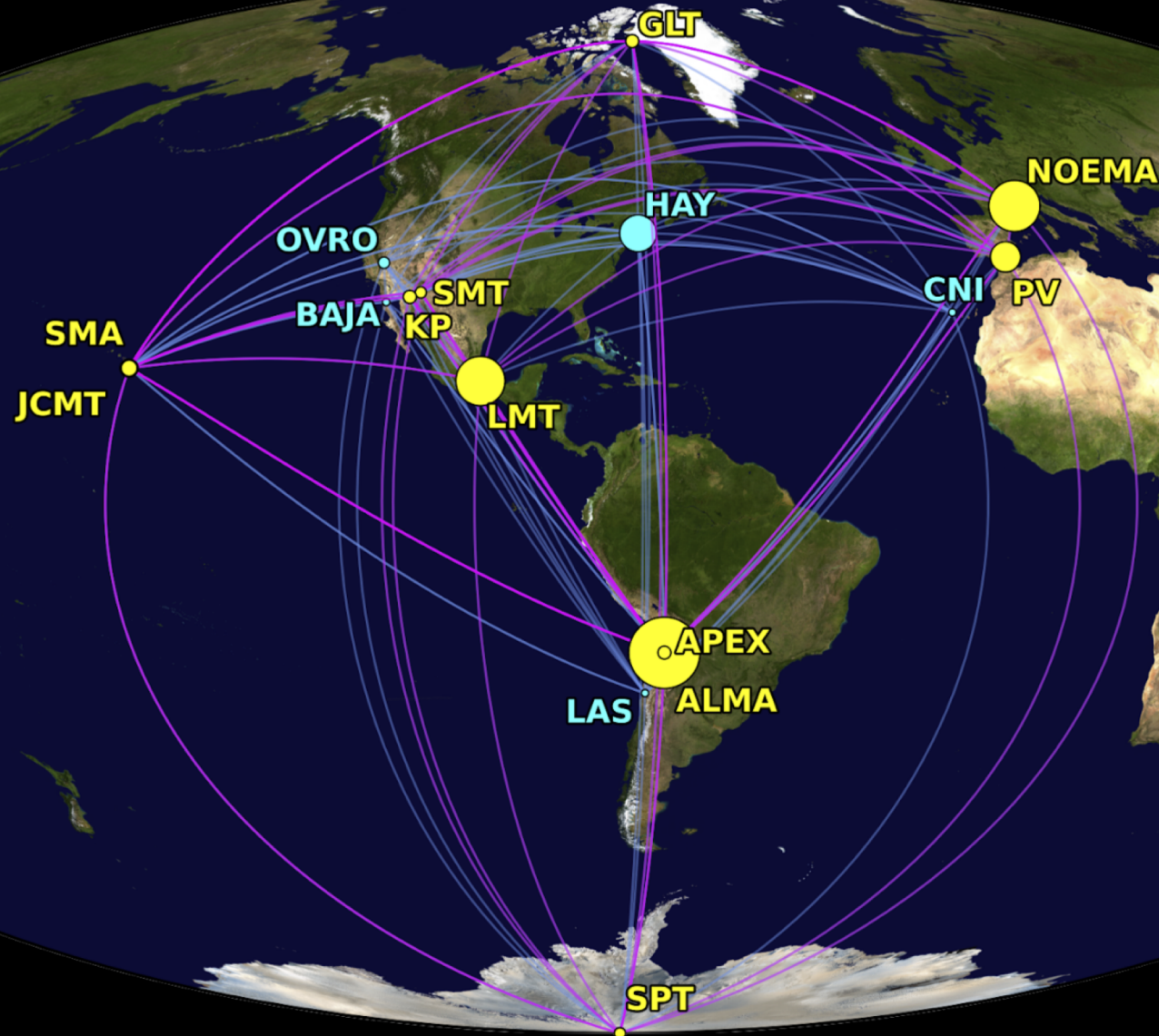
**EHT Sites
(2022)**





The Next Generation Event Horizon Telescope

EHT Sites
ngEHT concept
(Phase 1)

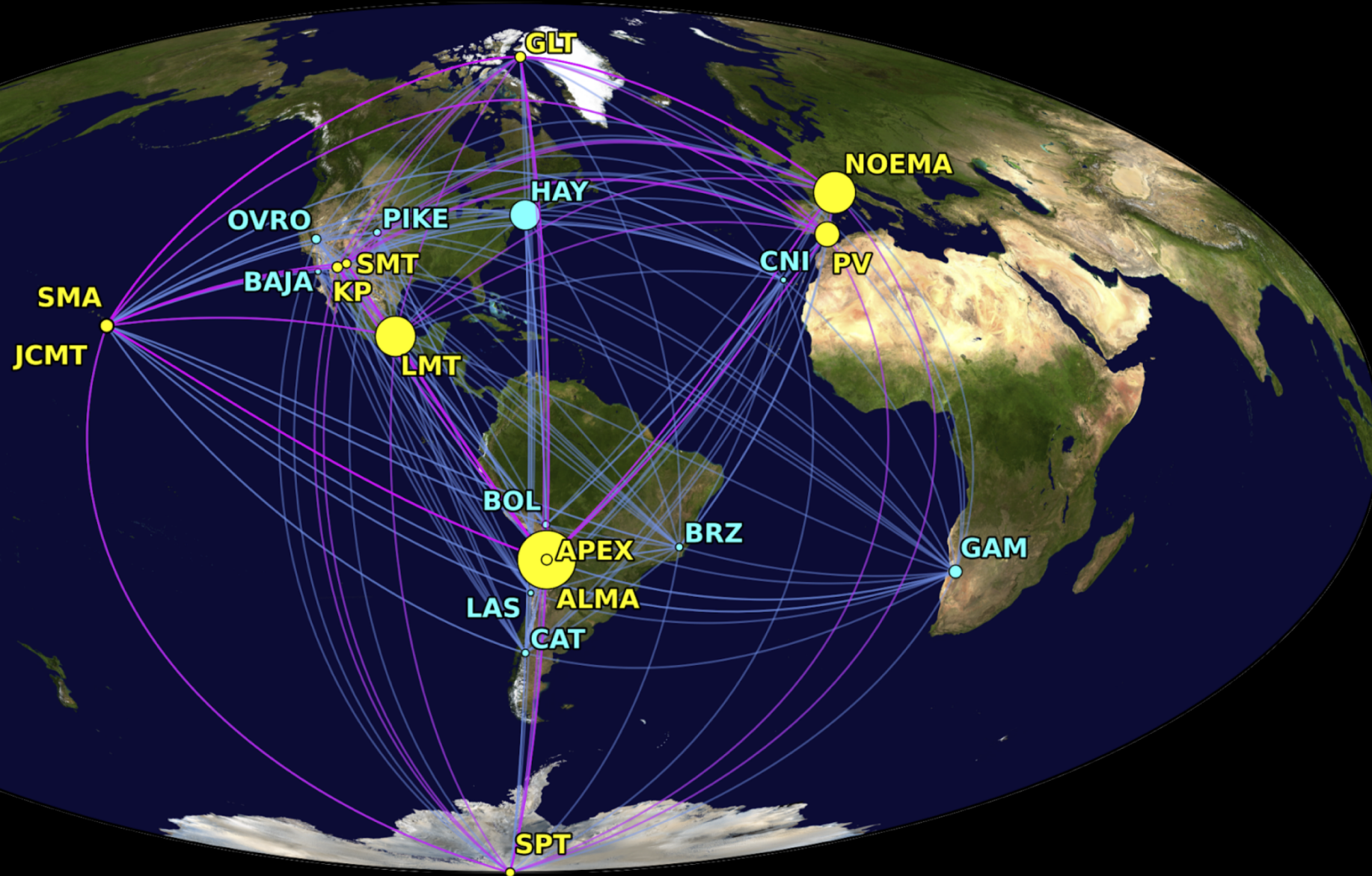


~5 additional sites
230 + 345 GHz (256 Gbps)
Multiple months of
observing



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:

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- No publication charges
- Open access

25 published papers including seminal array and science goals papers

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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

Invitation to submit

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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 description.

1. INTRODUCTION

On April 10, 2019, the Event Horizon Telescope project (EHT) released images of the supermassive black hole at the heart of galaxy M87 (Event Horizon Telescope Collaboration et al. 2019a,b,c,d,e,f). The observed ring of emission, formed by radio waves lensed in the gravitational field of a 6.5 billion solar mass black hole, has dimensions that match the predictions of General Relativity. Images of Sgr A*, the 4 million solar mass black hole at the center of the Milky Way, also exhibit a ring morphology with diameters anticipated by theory (Event Horizon Telescope Collaboration et al. 2022a,b,c,d,e,f). These results confirm that the EHT has observed the strong gravitational lensing signature of supermassive black holes (Darwin 1973; Lunmet 1979; Falcke et al. 2000; Takahashi 2004; Broderick & Loeb 2005), and these images have opened a new field of precision black hole studies on horizon scales.

This work built upon decades of technical development and precursor observations. Pioneering first Very Long Baseline Interferometry (VLBI) experiments at wavelengths of 1.3mm (Padin et al. 1990; Krichbaum et al. 1995) demonstrated that observations with the required resolution were possible at frequencies where AGN are likely to be optically thin. Discovery of horizon-scale structure in both Sgr A* and M87 with purpose-built ultra-high bandwidth systems on early EHT arrays (Doeleman et al. 2008, 2012) confirmed that imaging these sources was feasible. Subsequent observations revealed time-variability and ordered magnetic fields on Schwarzschild radius dimensions (Fish et al. 2011; Johnson et al. 2015). Emergence of the

EHT to a full imaging array grew from building community through decadal review processes (Doeleman et al. 2009), efforts to modify large scale international facilities, such as ALMA, through global cooperation (Matthews et al. 2018), and work to enable VLBI capability at the most remote observations on the planet (Inoue et al. 2014; Kim et al. 2018). Over the course of two decades, all the technical, logistical, organizational and analytical aspects of the full EHT were implemented by an expert team that grew from a few 10's to over 200 collaborators worldwide.

Building upon this legacy, the next-generation EHT (ngEHT), described here, goes far beyond incremental advances planned for the current EHT, delivering a transformative new instrument capable of envisaging real-time black hole movies. Where the EHT used existing mm/sub-mm facilities to form a first imaging array, the ngEHT will take the next step by designing and locating new dishes to optimize performance and scientific return. This vision offers excellent opportunities to engage the curious public on many levels. It is estimated that over a billion people have now seen the M87 image (Christensen et al. 2019). We anticipate that the long term public and STEM education engagement as the ngEHT builds to its goal of black hole 'cinema' will be similar in scope.

Technical advances in several areas make design and implementation of the ngEHT within this decade a realistic goal. Over most of the past two decades, the bandwidth of VLBI systems has kept pace with Moore's Law - a doubling of capacity and speed approximately every 18 months (see, e.g., Event Horizon Telescope Col-

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Key Science Goals for the Next-Generation Event Horizon Telescope

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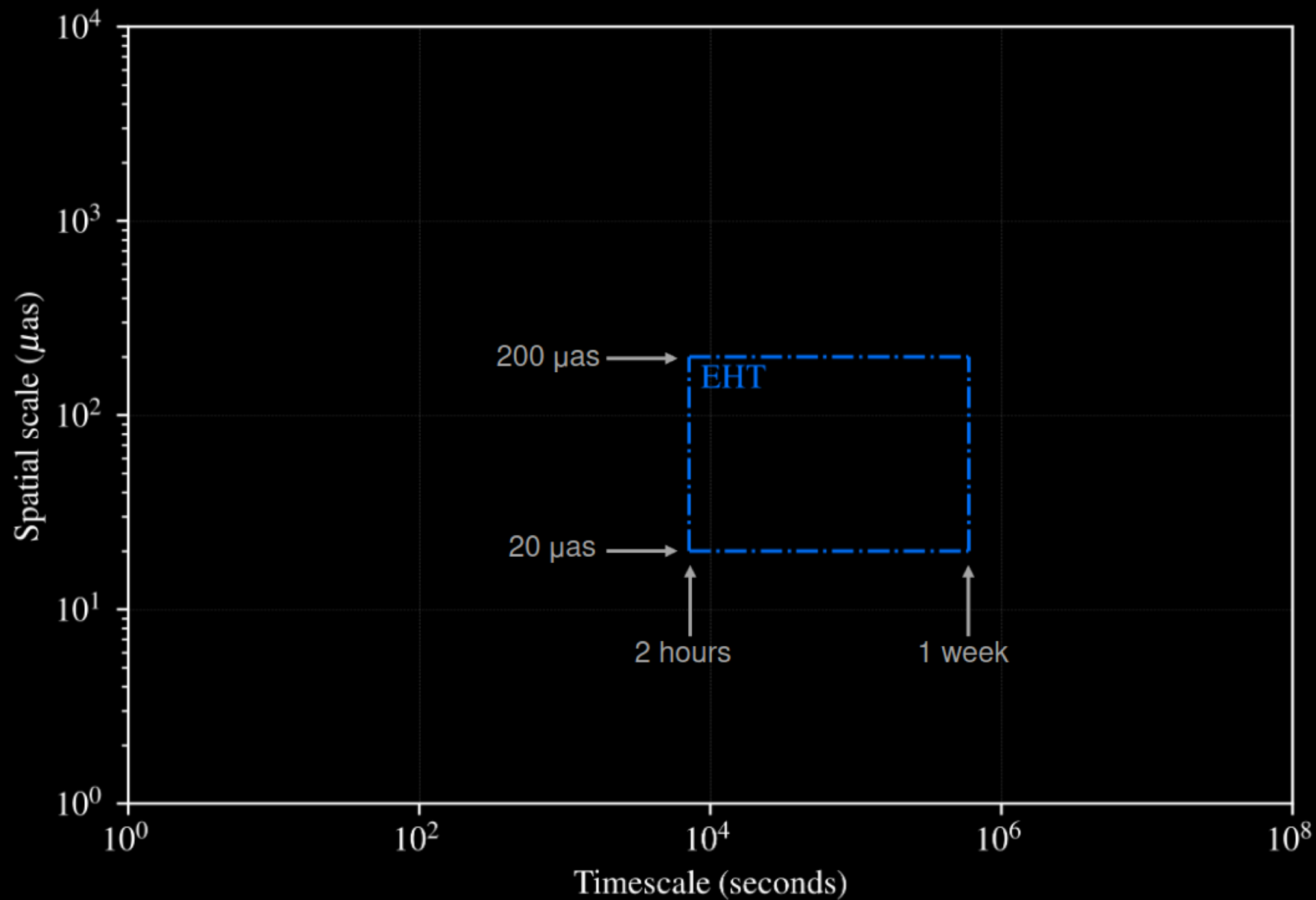
Corresponding author: Michael D. Johnson
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ngEHT Reference Array

ngEHT Key Science Goals

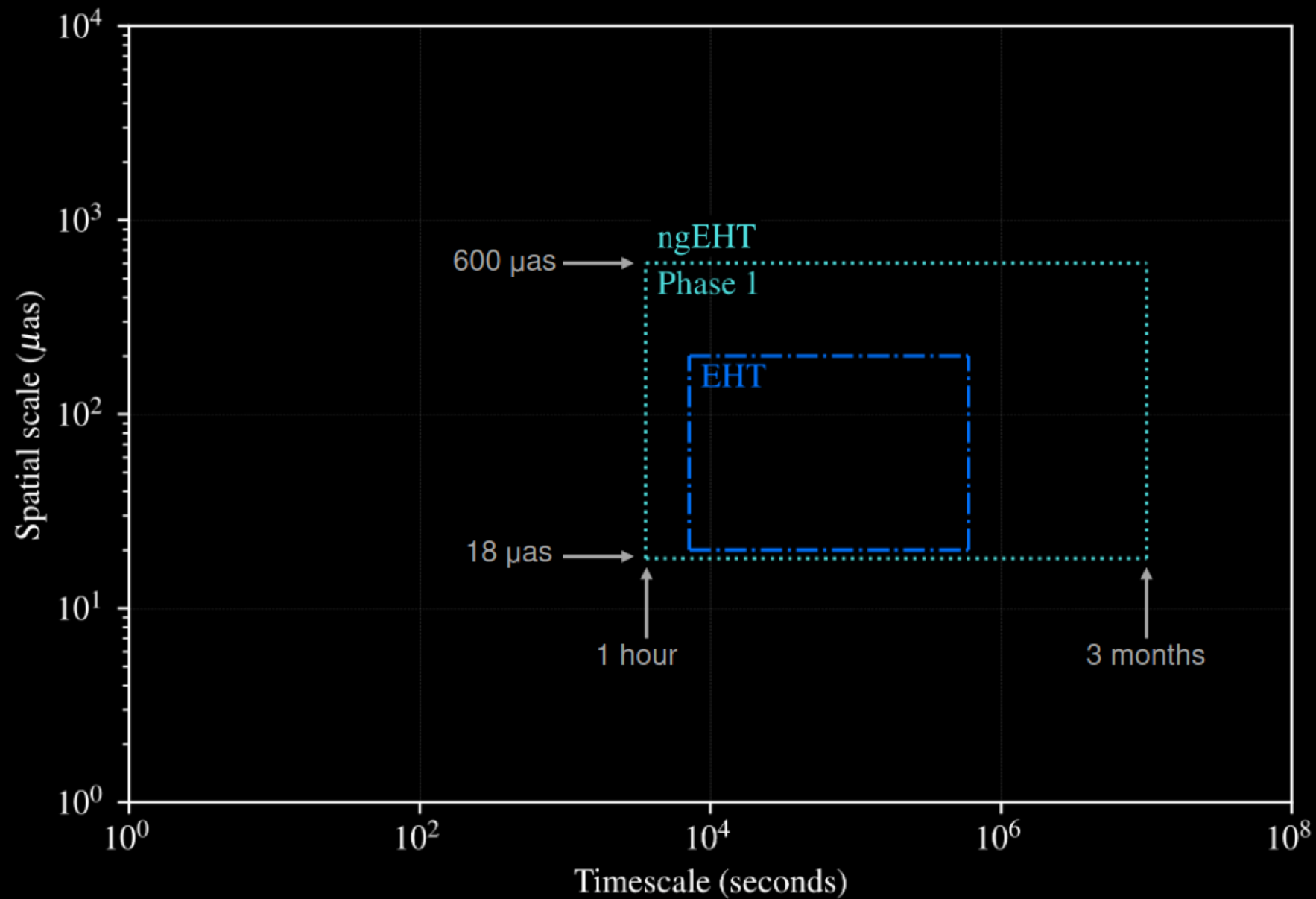


The ngEHT Key Science Goals



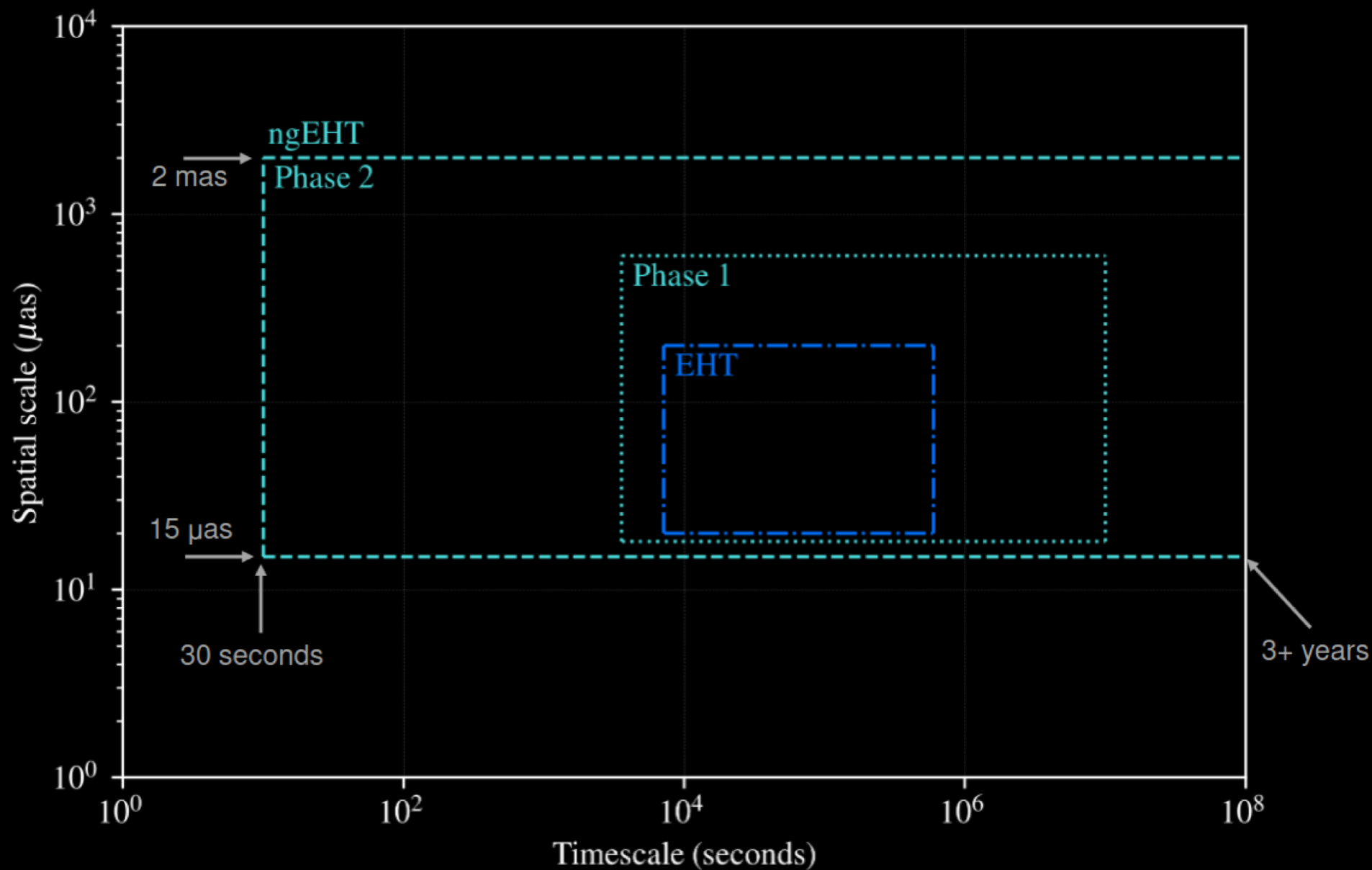


The ngEHT Key Science Goals



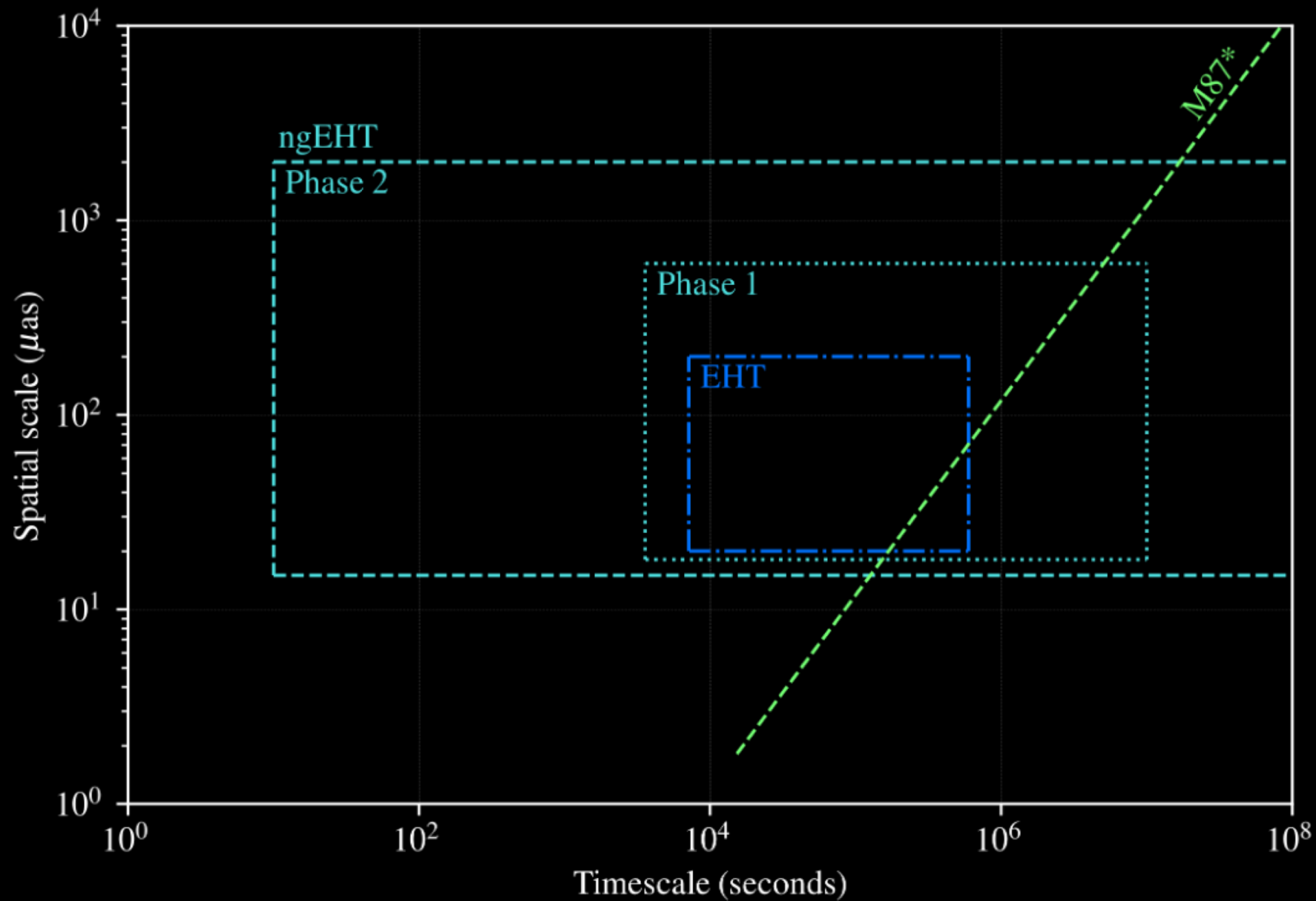


The ngEHT Key Science Goals



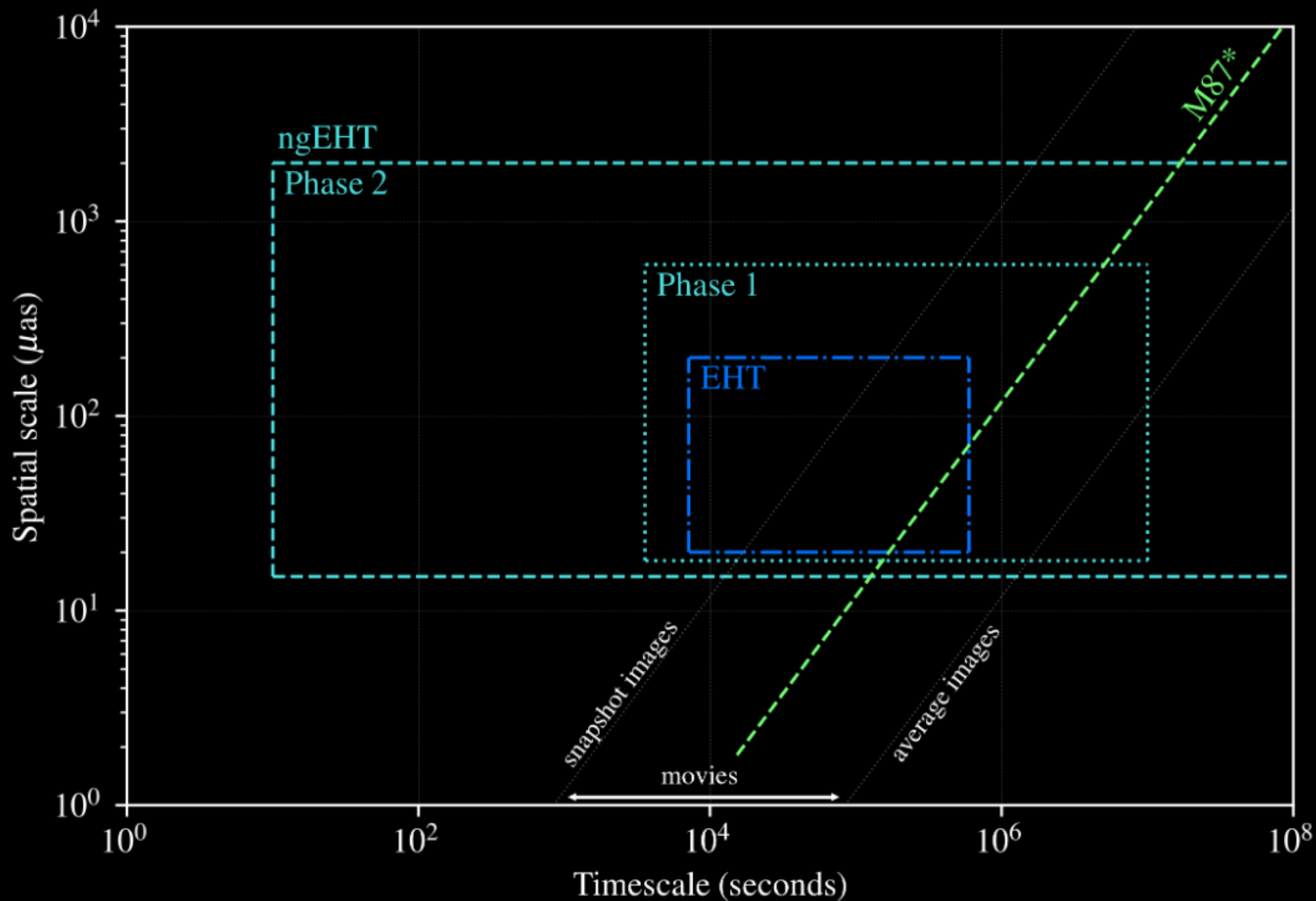


The ngEHT Key Science Goals



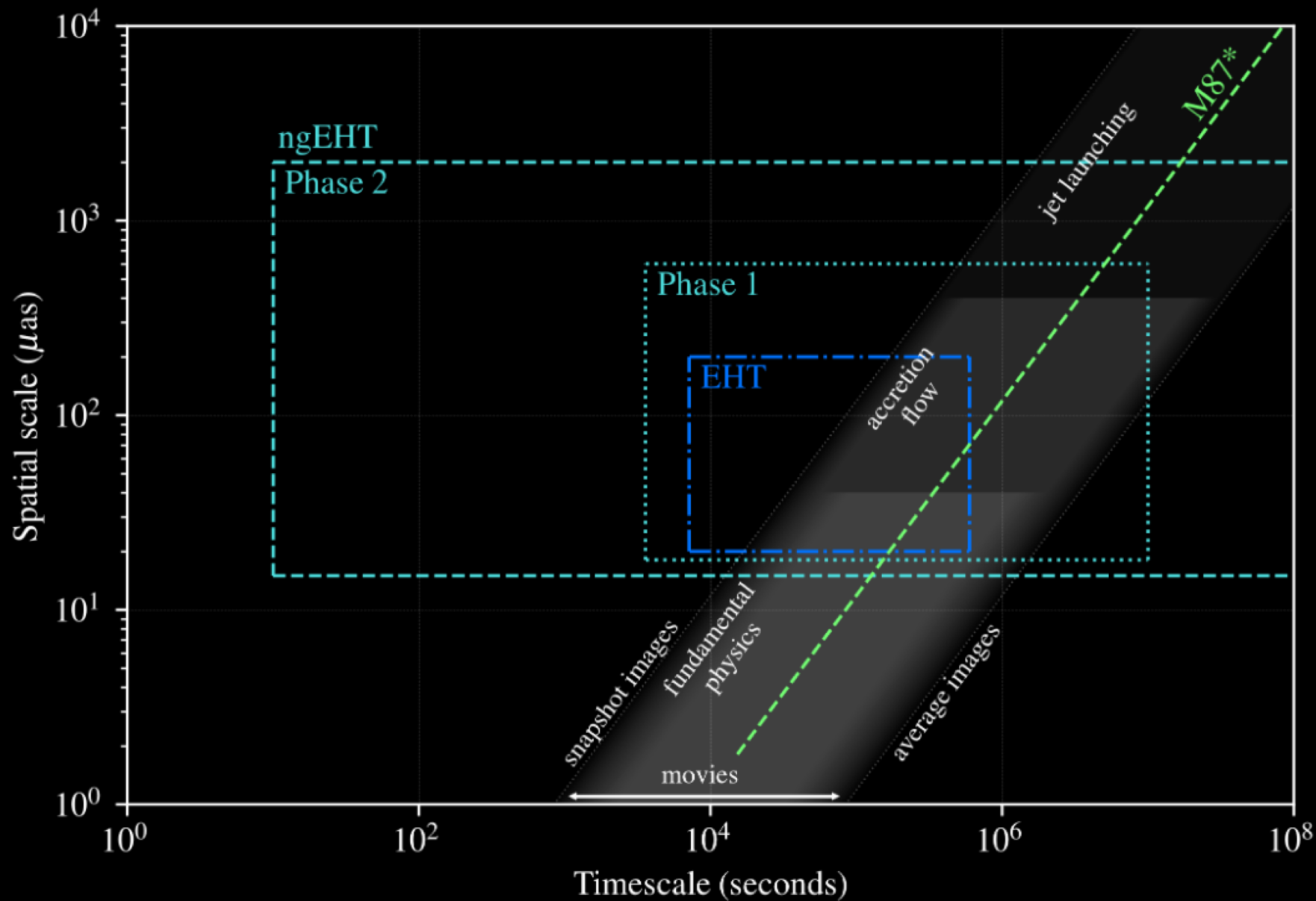


The ngEHT Key Science Goals



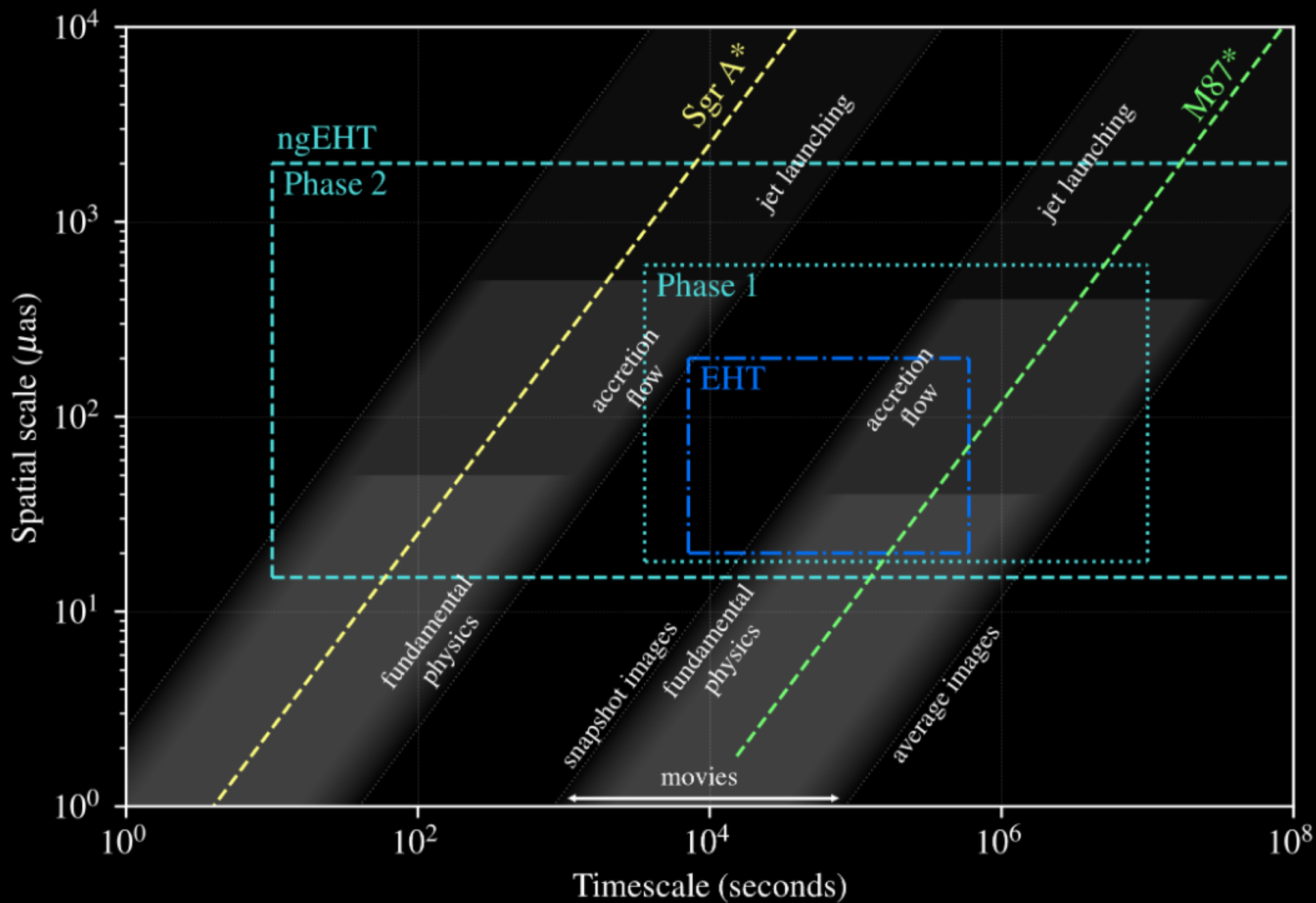


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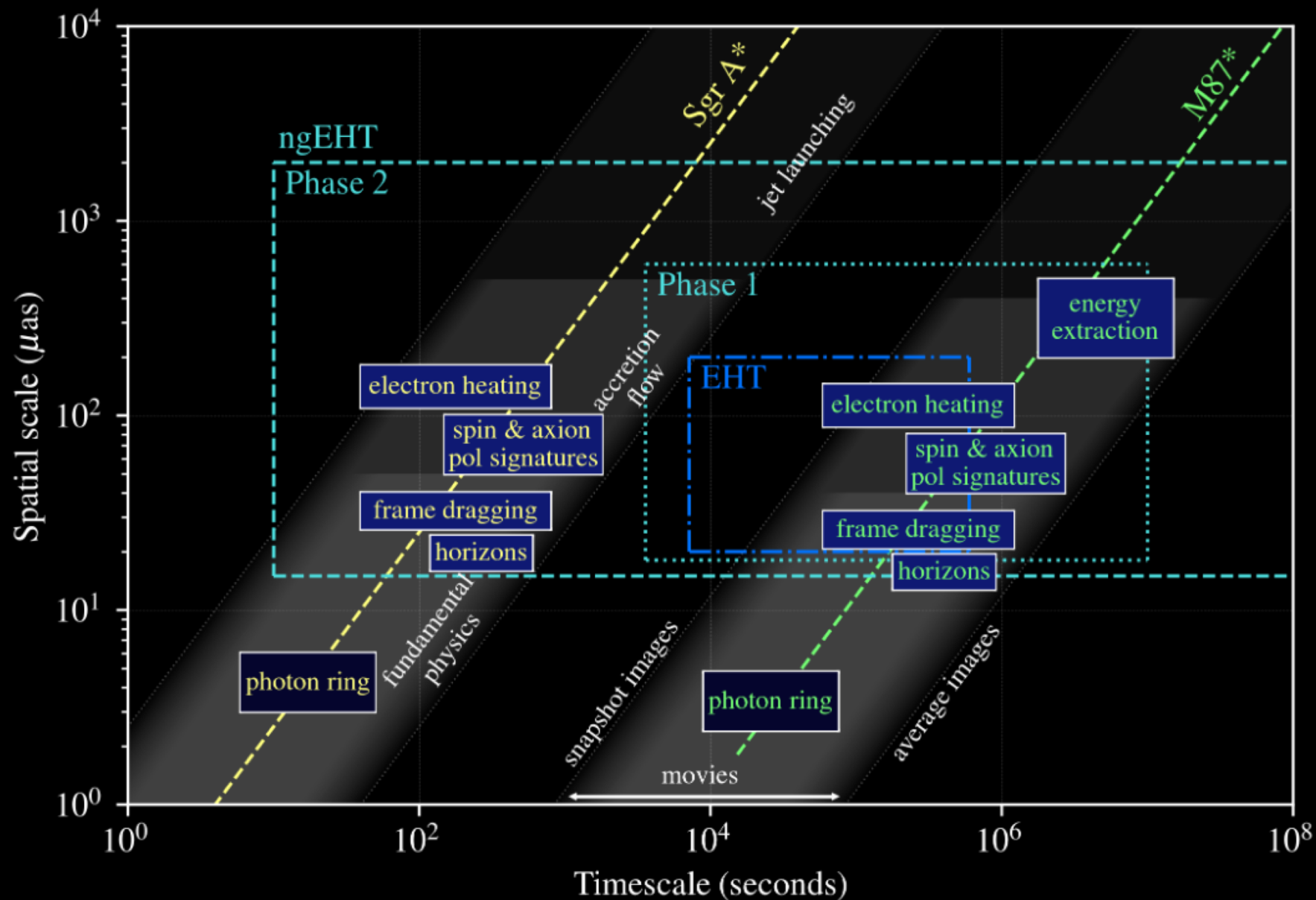


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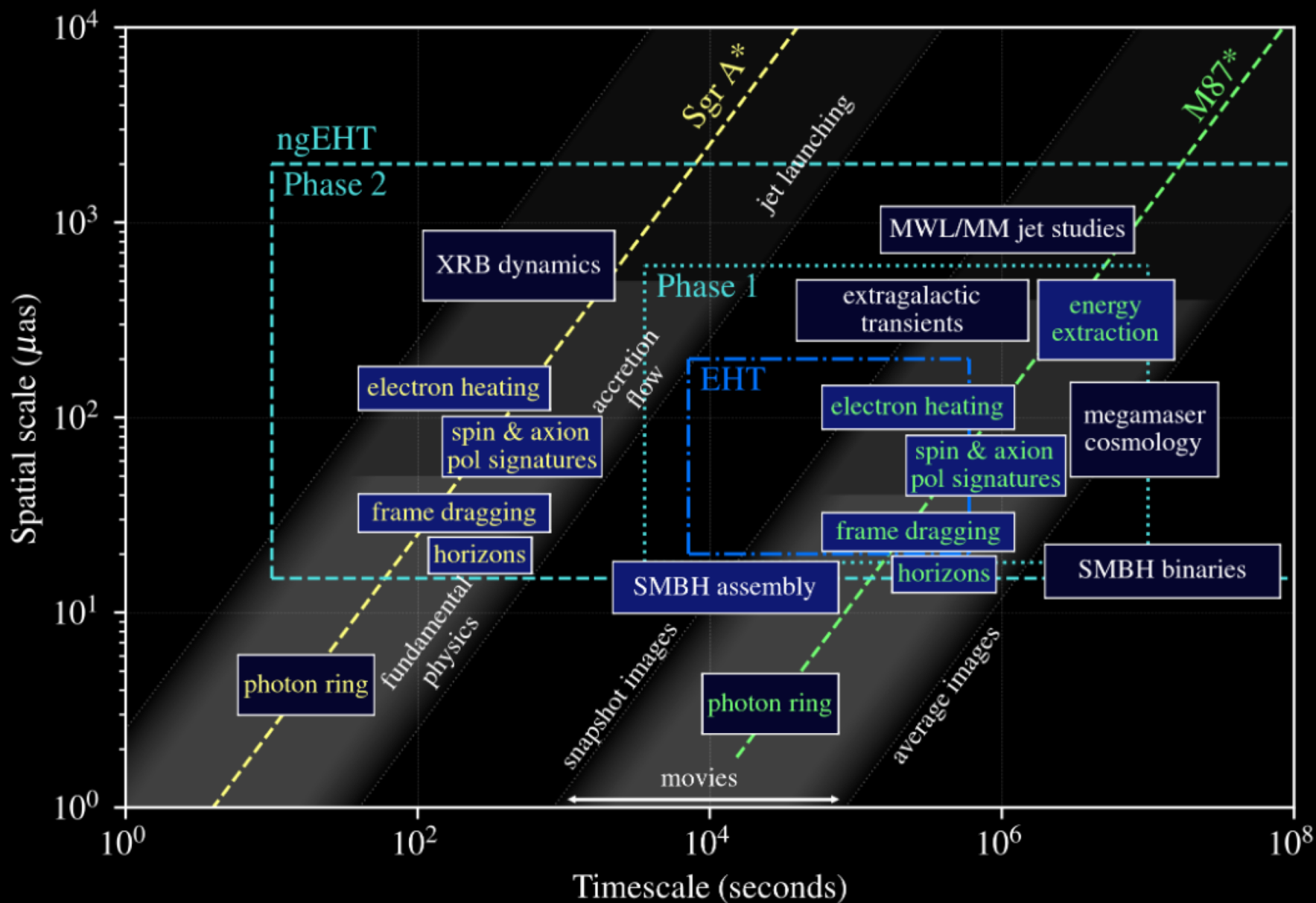


The ngEHT Key Science Goals





The ngEHT Key Science Goals

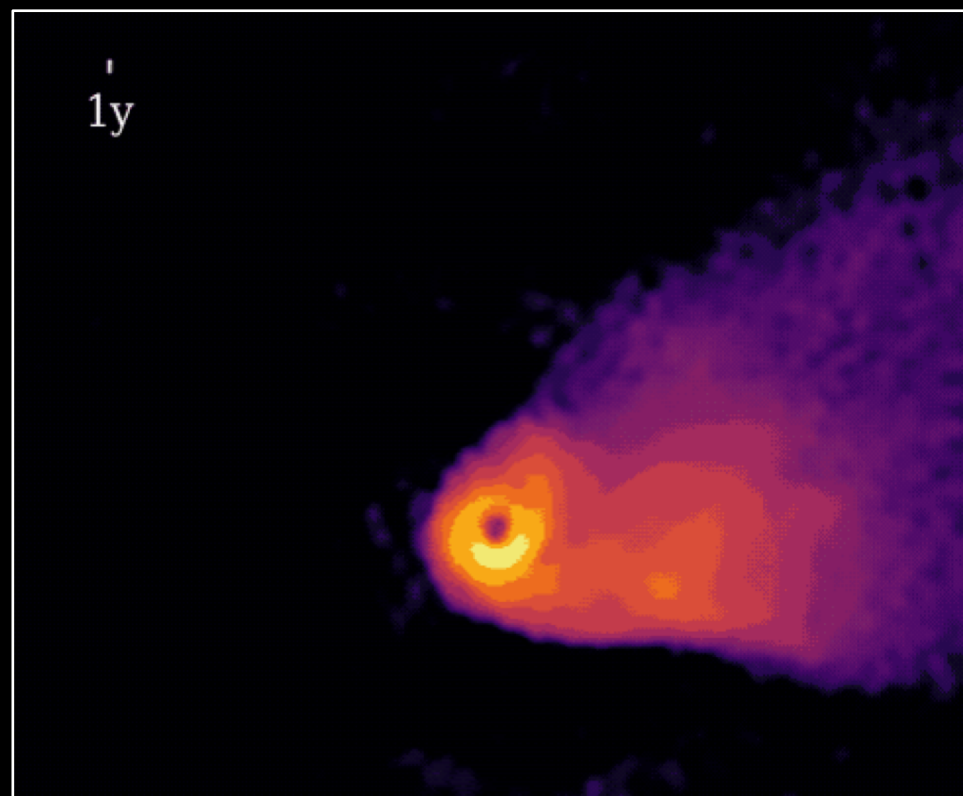
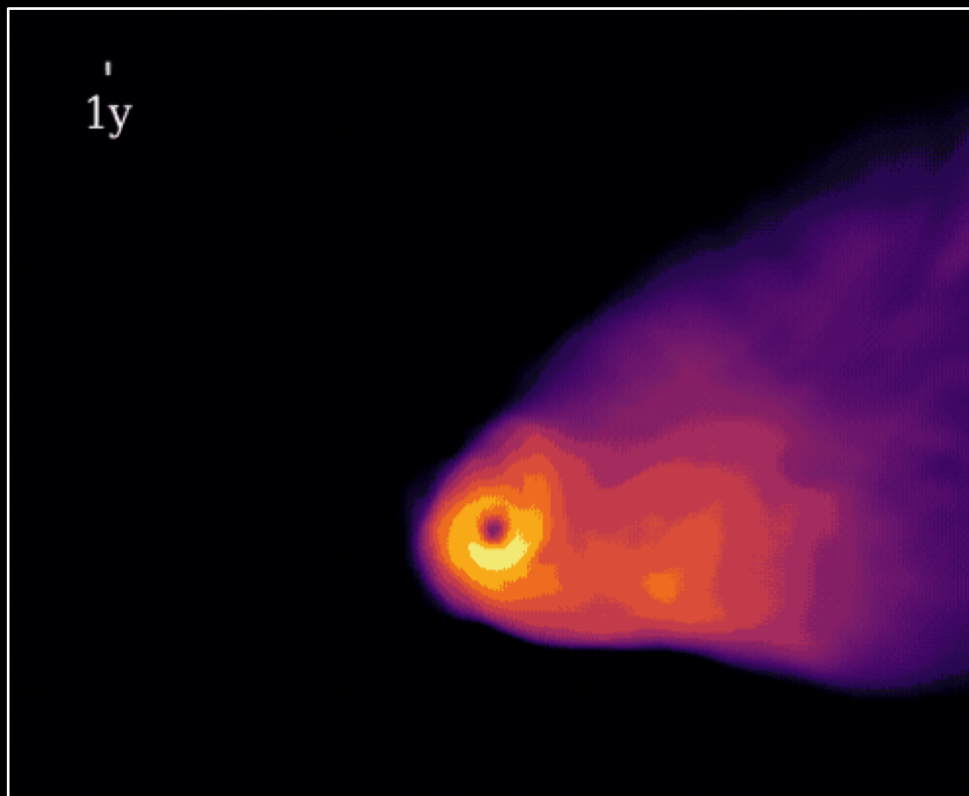




The Era of Black Hole Cinema (Accretion & Jet Launching)

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

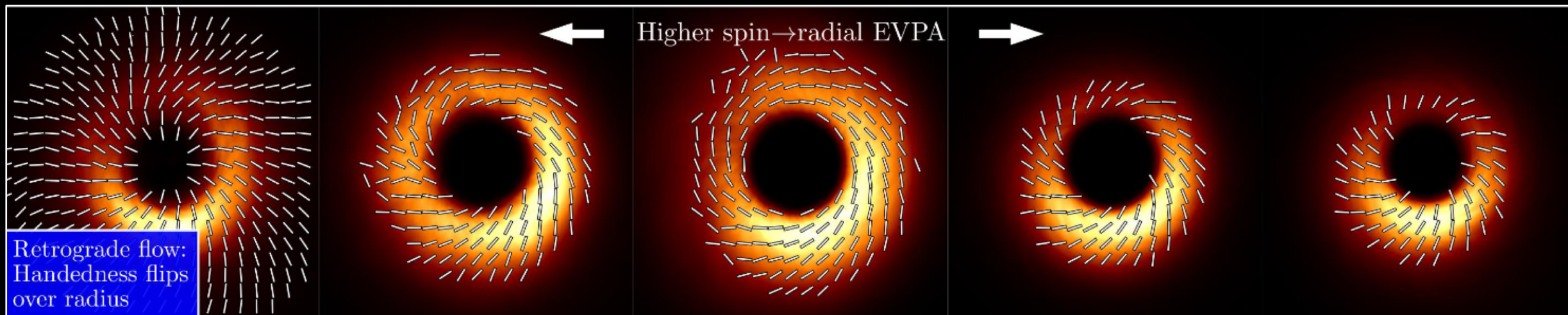
Retrograde High Spin

Retrograde Med. Spin

Schwarzschild

Prograde Med. Spin

Prograde High Spin



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

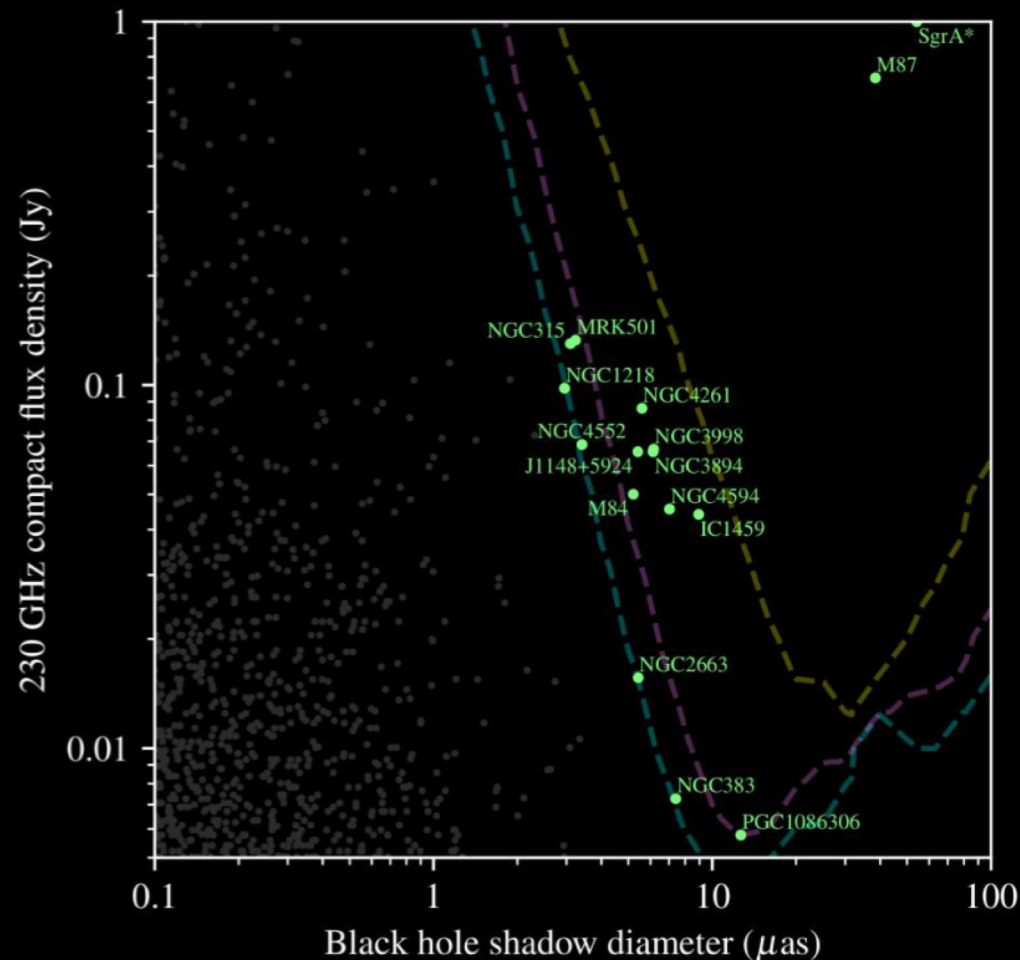
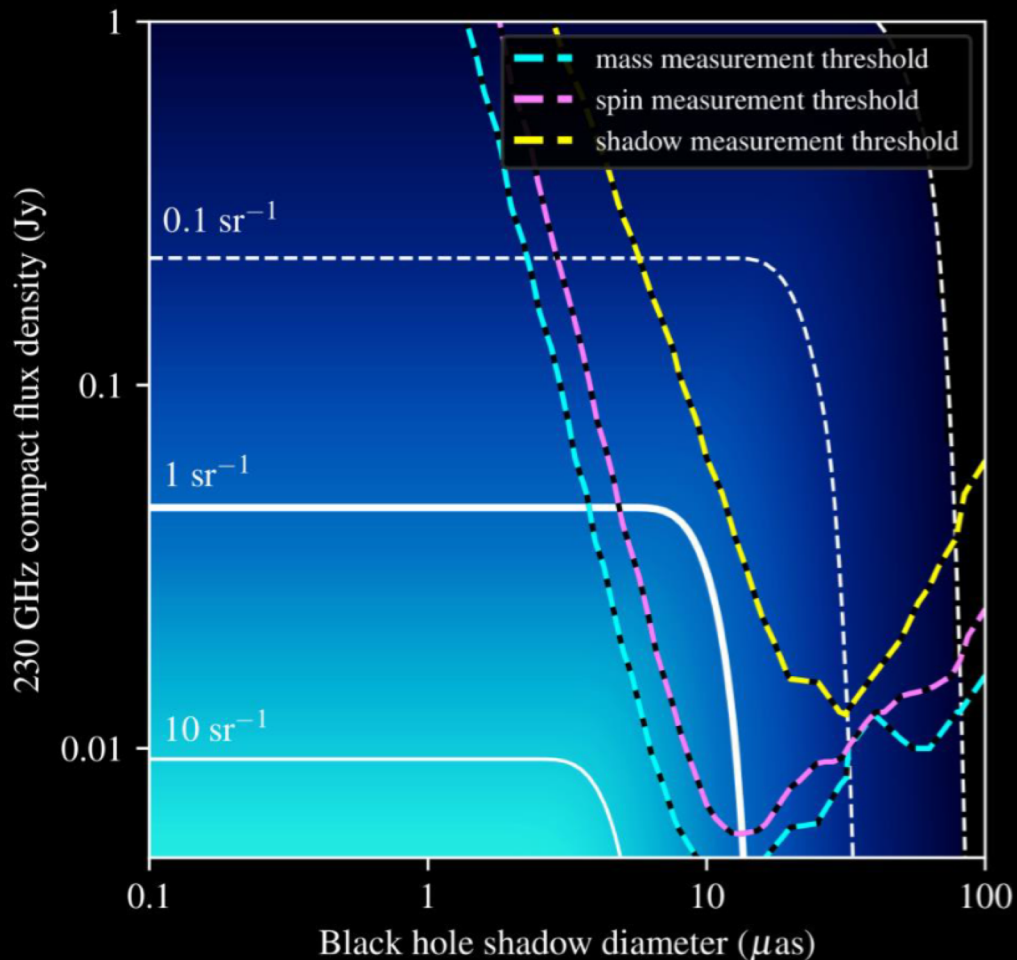


Black Hole Demographics

Black Holes and their Cosmic Context

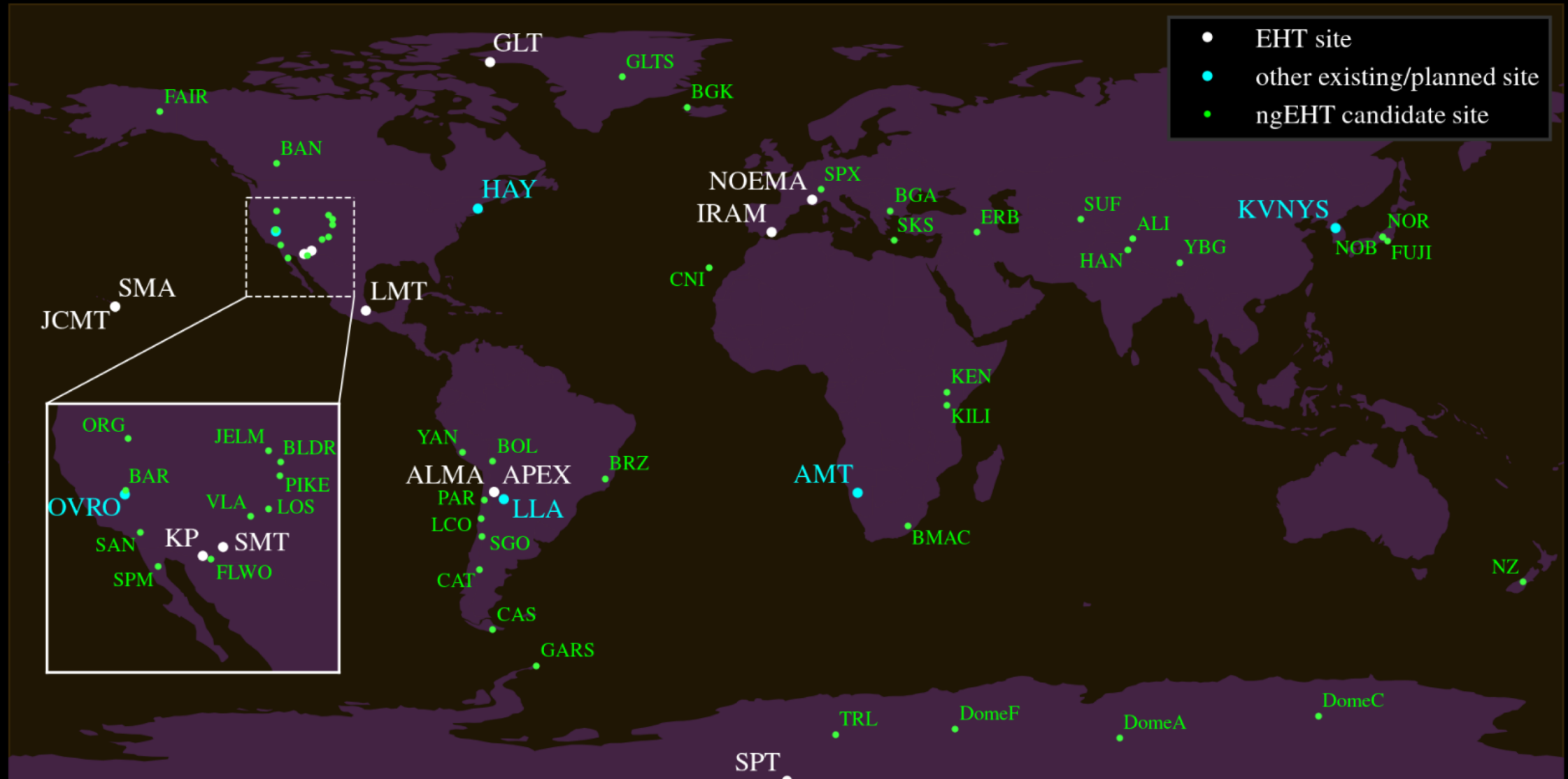
- Reveal Black Hole-Galaxy Formation, Growth, and Coevolution

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





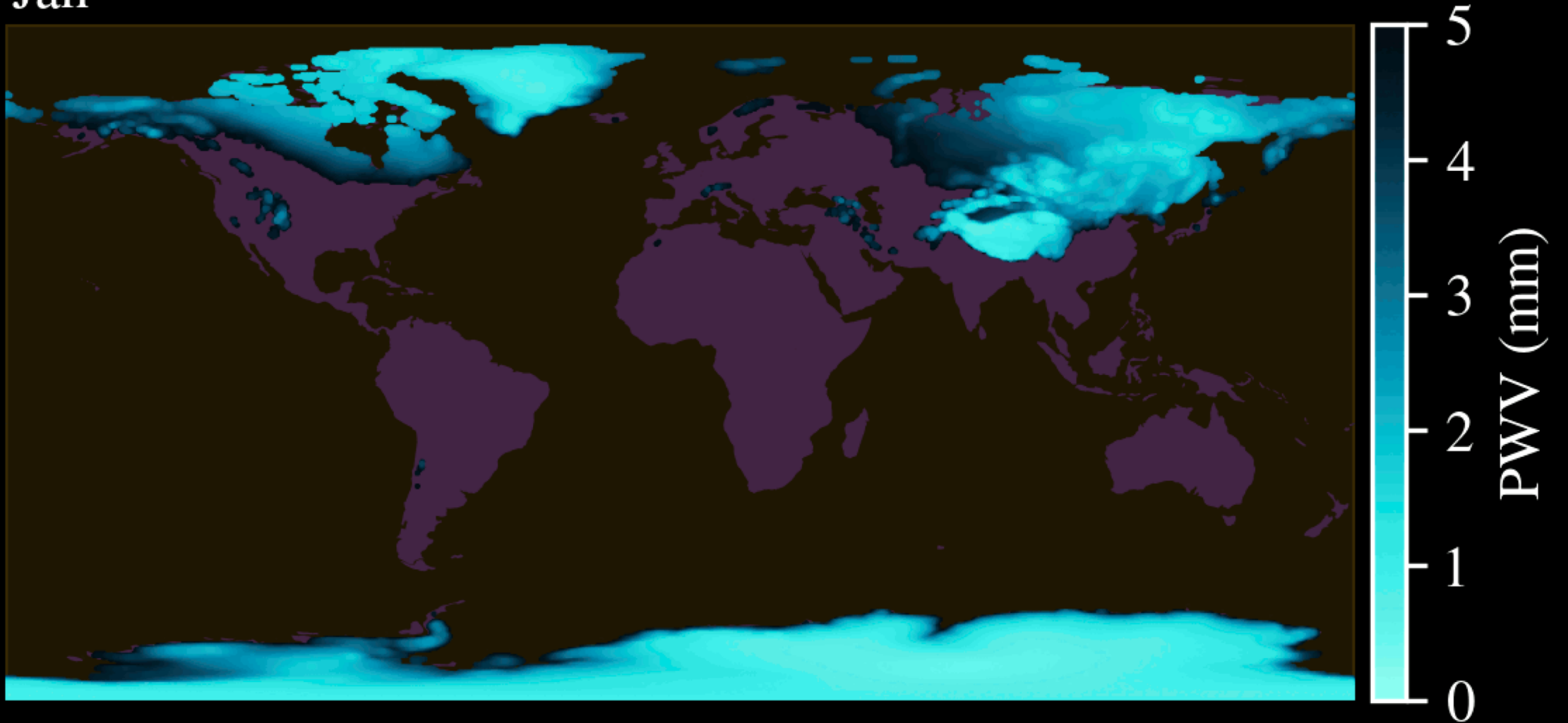
Phase 1 Site Selection





Phase 1 Site Selection

Jan





Phase 1 Site Selection

Considerations for the addition of three 6-meter dishes

The array must perform well:

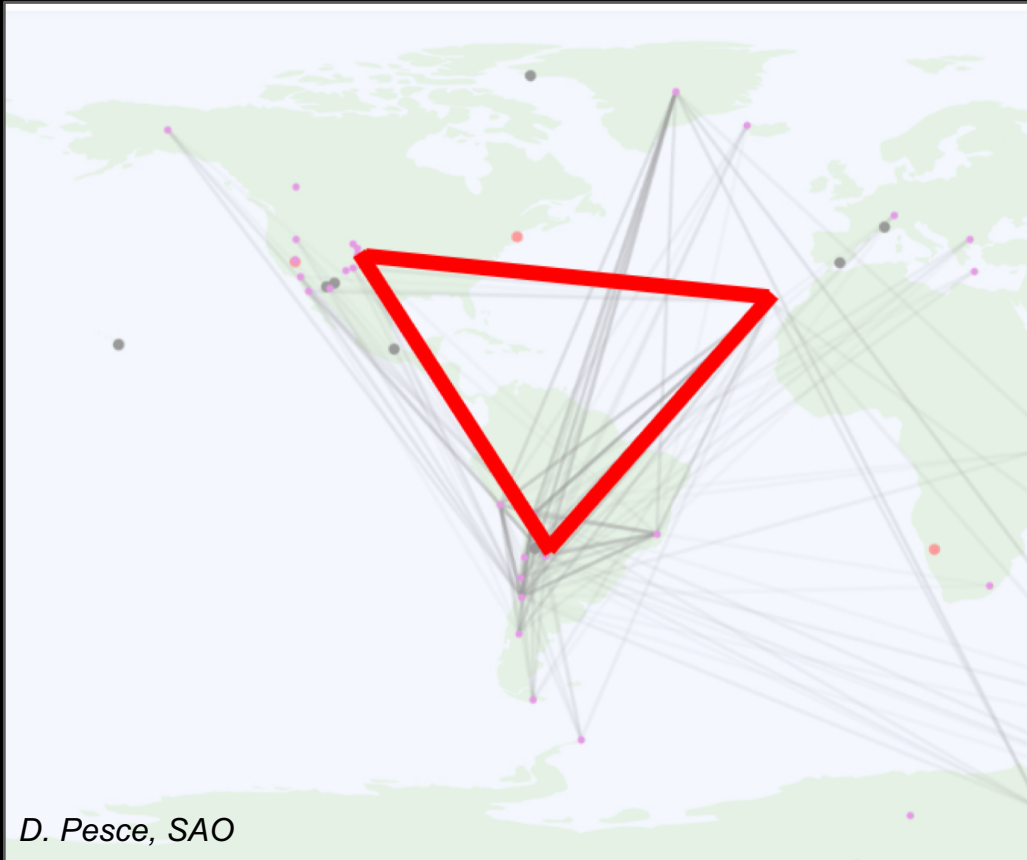
- when observing both M87 and Sgr A*
- when observing in any season of the year (with varying weather conditions)
- when observing alongside the full EHT, no EHT, or an EHT subset

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)

Article

Enabling transformational ngEHT science via the inclusion of 86 GHz capabilities

Sara Issaoun^{1,2,*}, Dominic W. Pesce^{1,3}, Freek Roelofs^{1,3,4}, Andrew Chael^{5,2}, Richard Dodson⁶, Maria J. Rioja^{7,8,9}, Kazunori Akiyama^{9,10,3}, Romy Aran^{11,1}, Lindy Blackburn^{1,3}, Sheperd S. Doeleman^{1,3}, Vincent L. Fish⁹, Garret Fitzpatrick¹, Michael D. Johnson^{1,3}, Gopal Narayanan¹², Alexander W. Raymond^{1,3}, Remo P. J. Tilanus^{13,14,15,16}

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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.

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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Version January 18, 2023 submitted to *Galaxies* <https://www.mdpi.com/journal/galaxies>



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

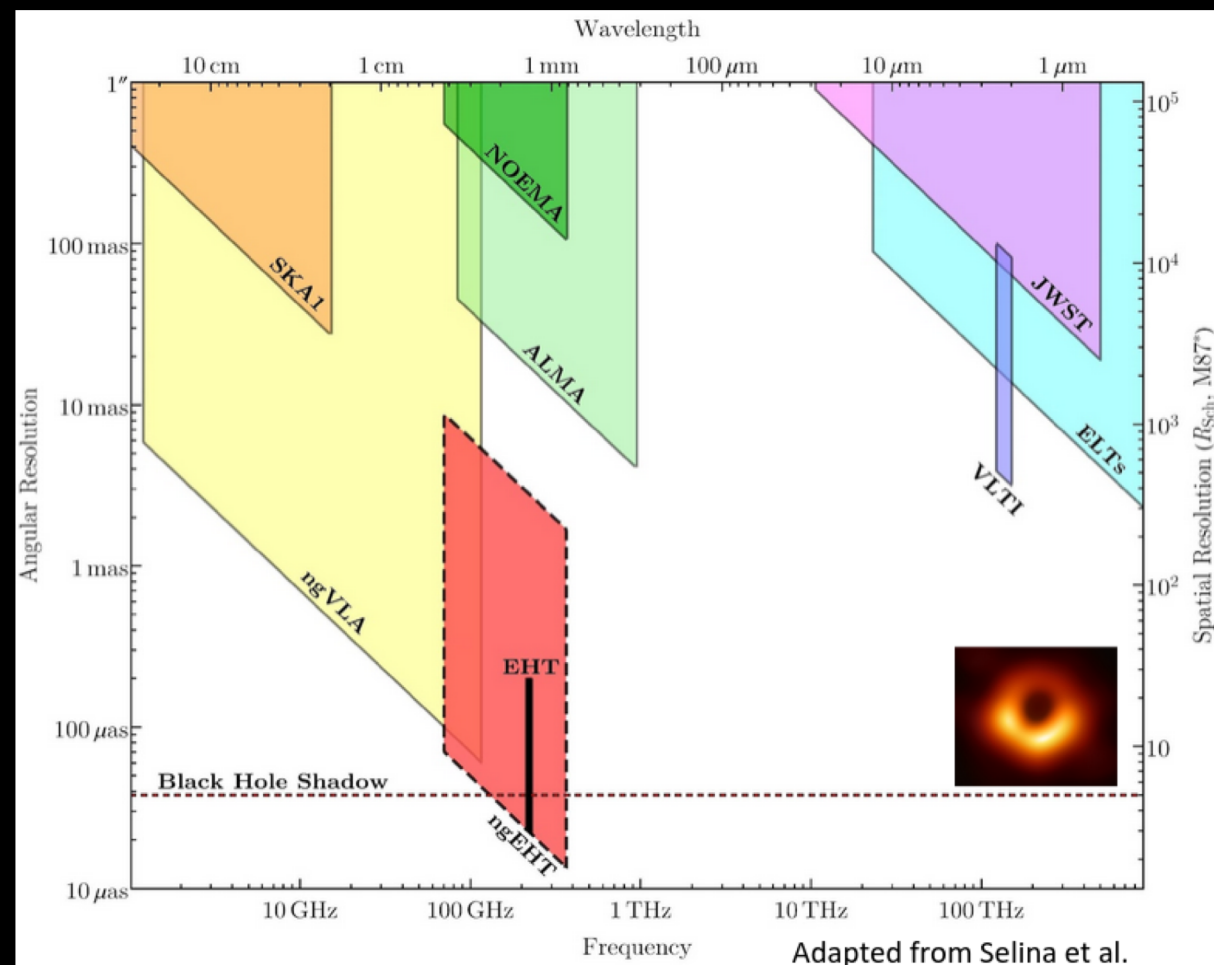
- Flexibility and reliability in observing schedules for black hole movies; many observations throughout the year
- Less dependent on external partner facilities with other science programs (e.g., ALMA)

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

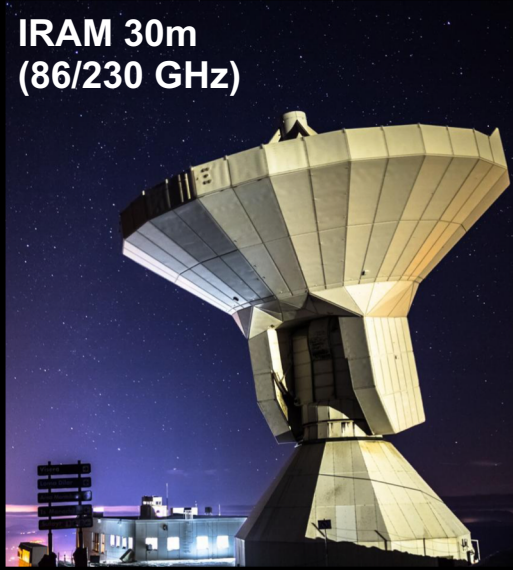
Overall improvement in quality and quantity of science!



Path forward: First FPT to 230 GHz



KVN Yonsei
(86/230 GHz)



IRAM 30m
(86/230 GHz)



JCMT
(86 GHz)



GLT
(86 GHz)



SMA
(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

