Black Hole Explorer (BHEX) Mission

秦 和弘（国立天文台 水沢）

内容

- 地上ミリ波VLBI(EHT)によるSMBH観測
- スペースミリ波VLBI(BHEX)：動機とミッション概要

超巨大ブラックホールの根源的問い

Perimeter Institute for Theoretical Physics

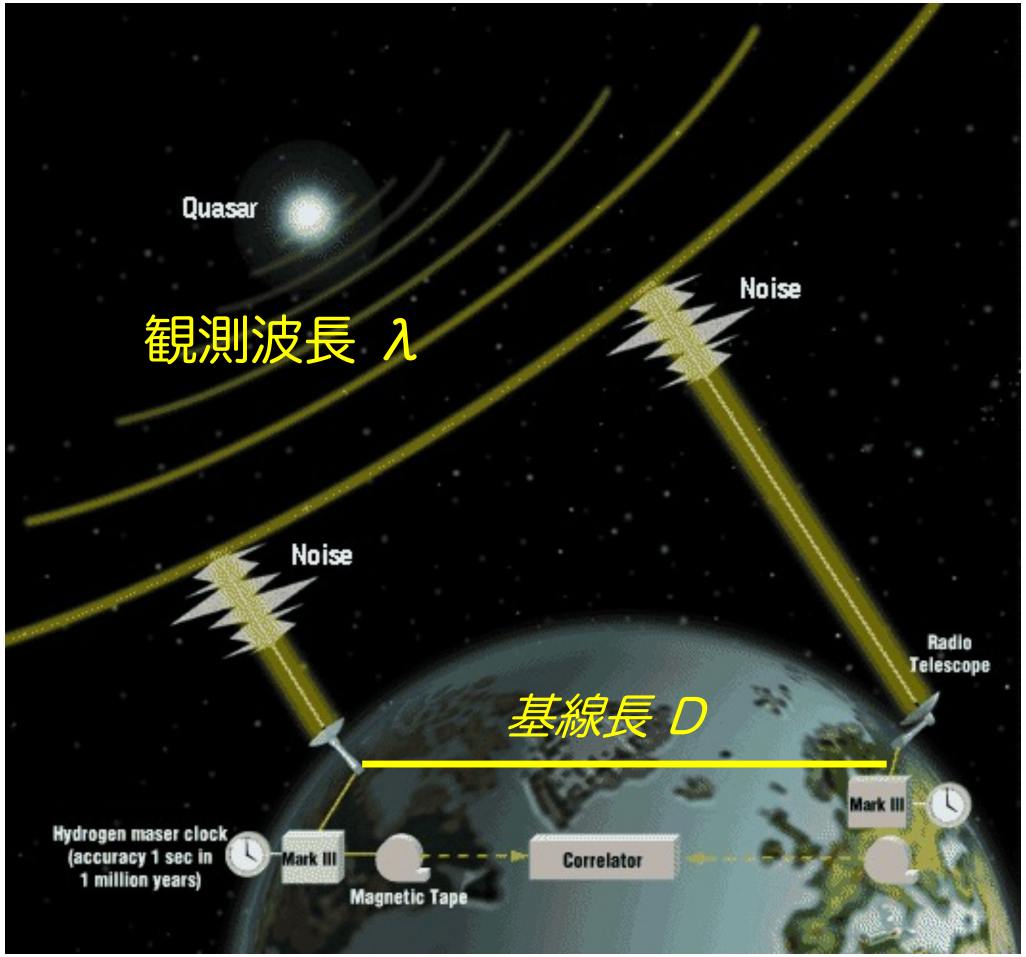
- SMBHはどのように物質を吸い込むのか?
- SMBHはどのように物質を噴出するのか?
- SMBH周辺の時空構造は？
- SMBHの活動性・多様性をもたらすキーパラメタは何か?

SMBH近傍まで直接空間分解できる観測が重要

$R \sim 10R_g \sim 0.01\mathrm{mas}$ @ $D = 10\mathrm{Mpc}$, $M_{BH}=10^9M_{sun}$

電波によるVLBI観測が現状(ほぼ)唯一の手段

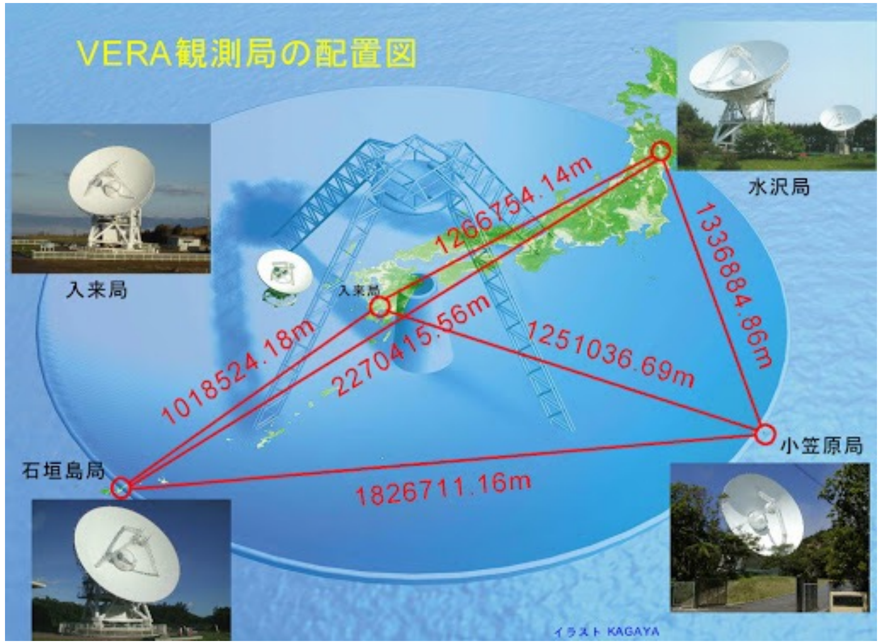
超長基線電波干渉計 (VLBI)



NASA

$$\theta = \lambda / D$$

日本のVLBIネットワーク VERA

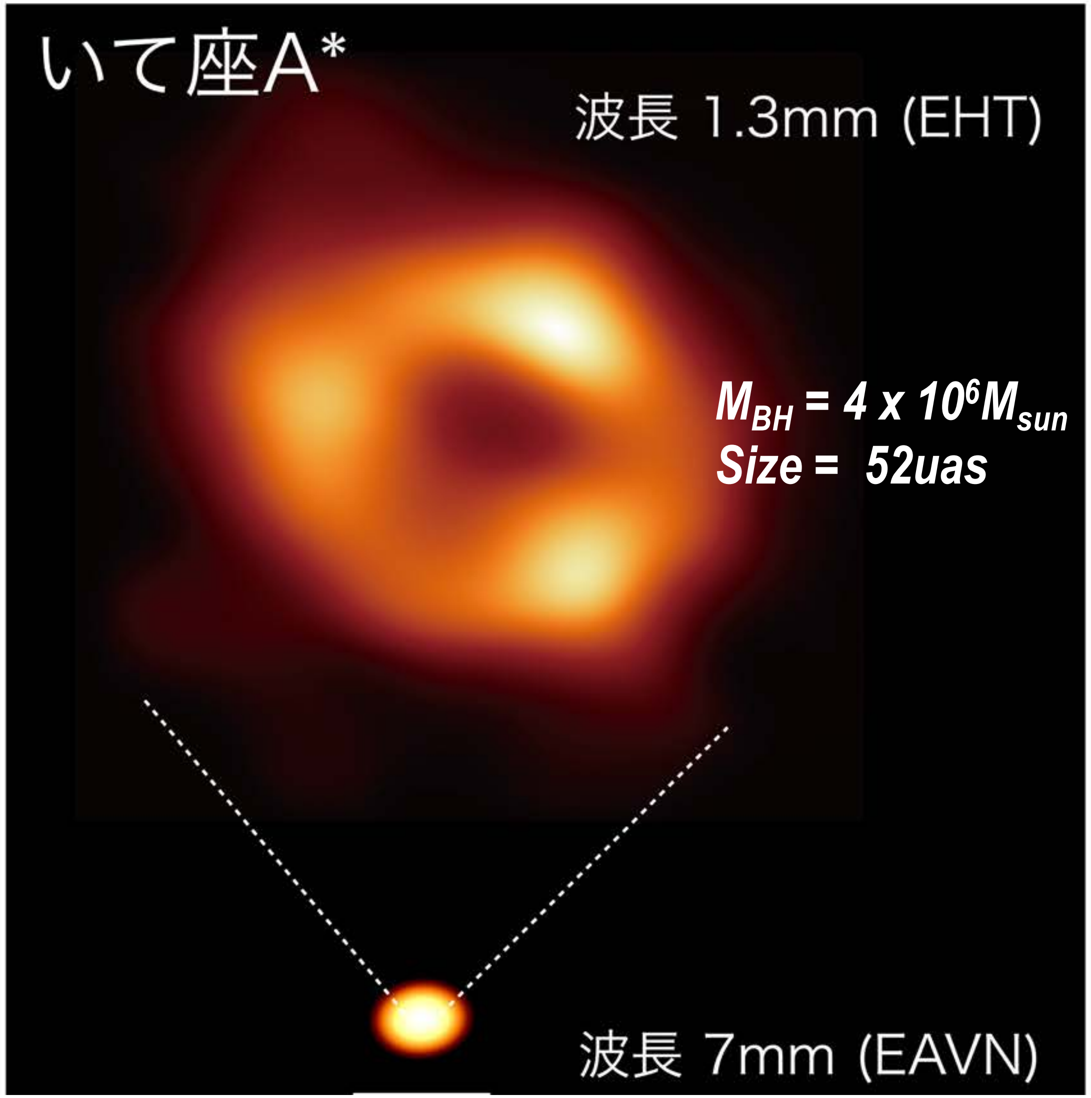


- D ~ 2300km
- λ ~1.3cm (22GHz)
- θ ~ 1 mas

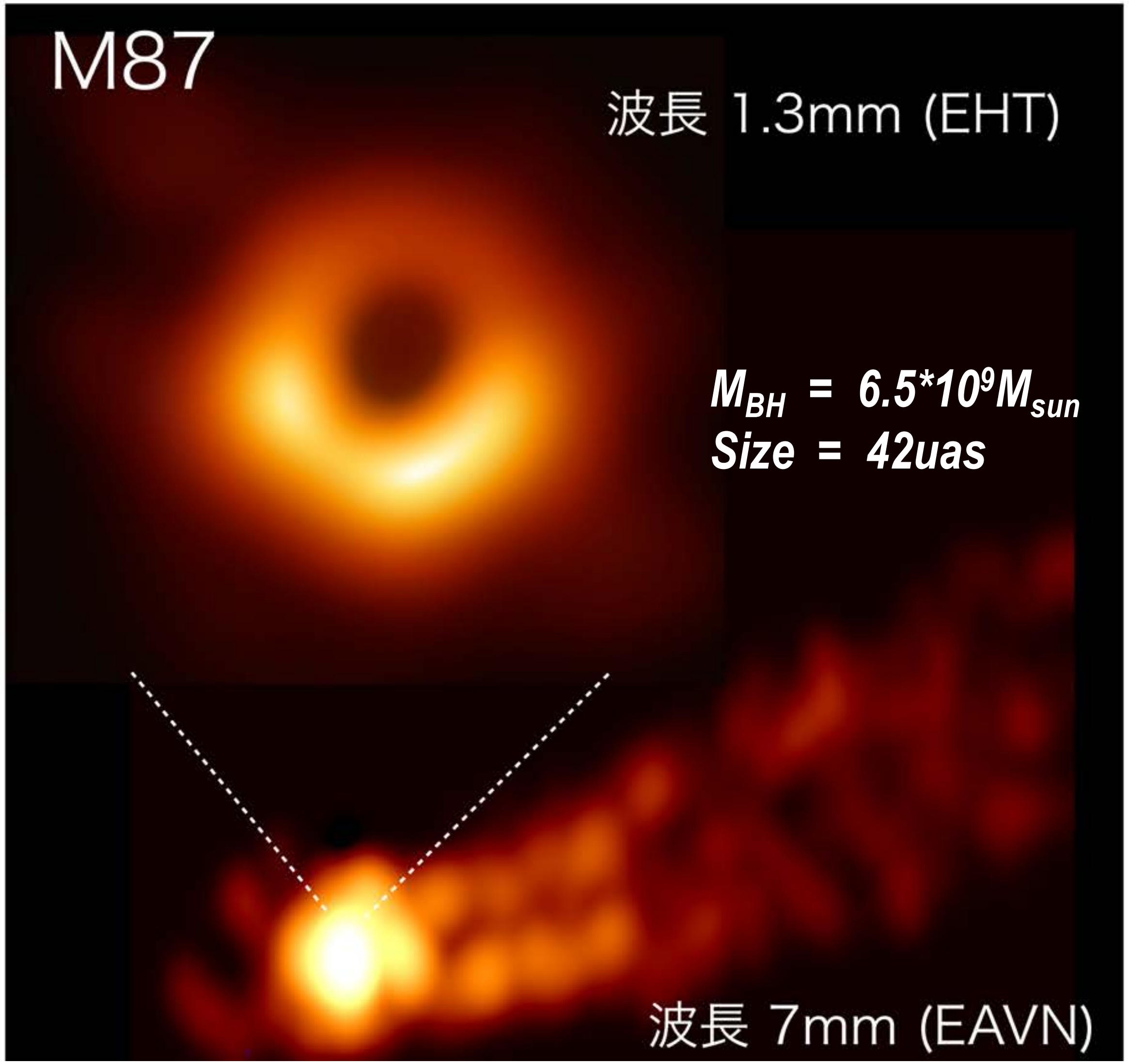
Event Horizon Telescope (EHT)

- 波長1.3mm (230GHz)帯のグローバルVLBI観測網
- 空間分解能 ~25uas
- 11局 (2024年現在)
- 一部の局では870um (345GHz)帯での運用も開始

EHTの初期成果

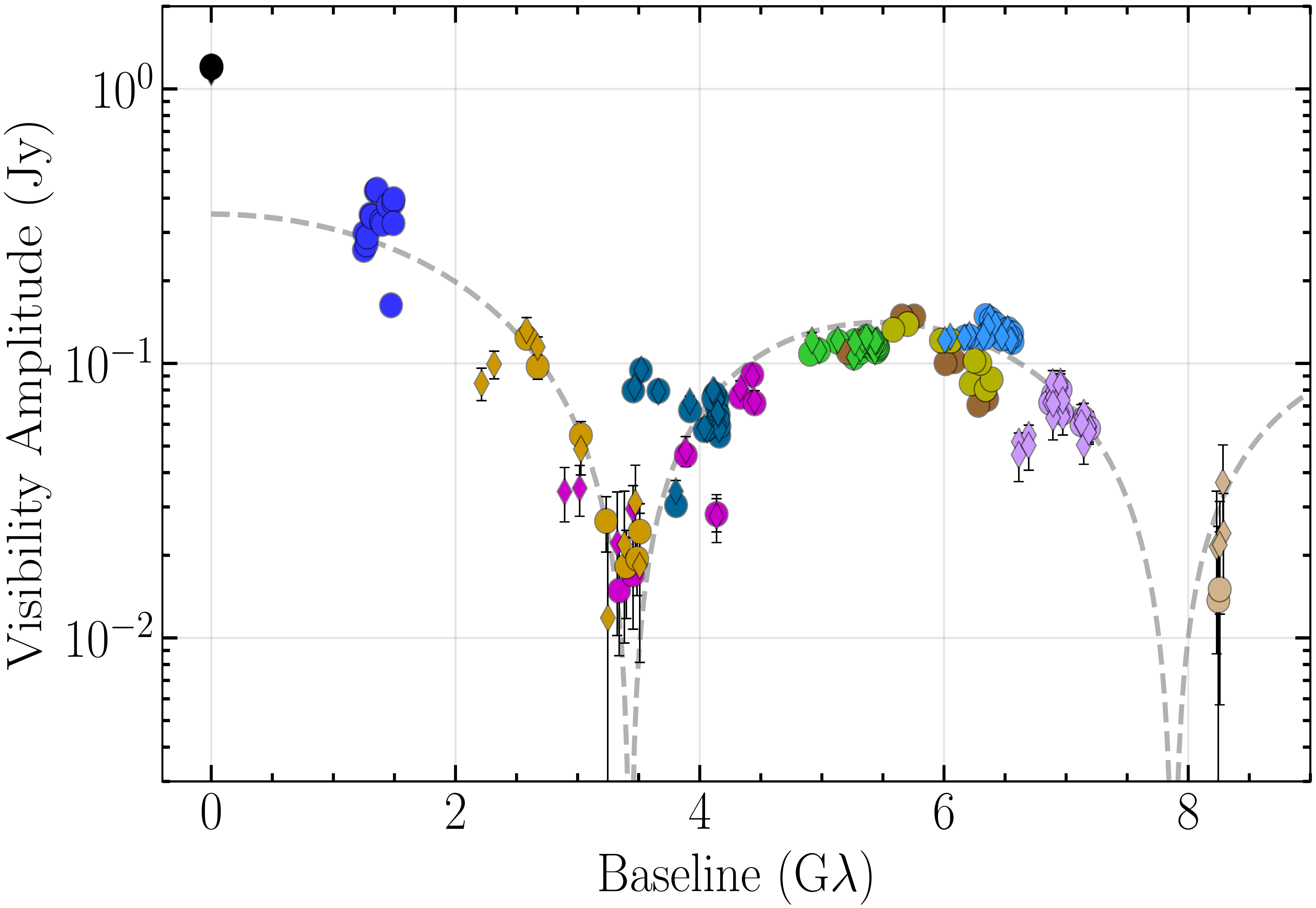


EHTC+2022

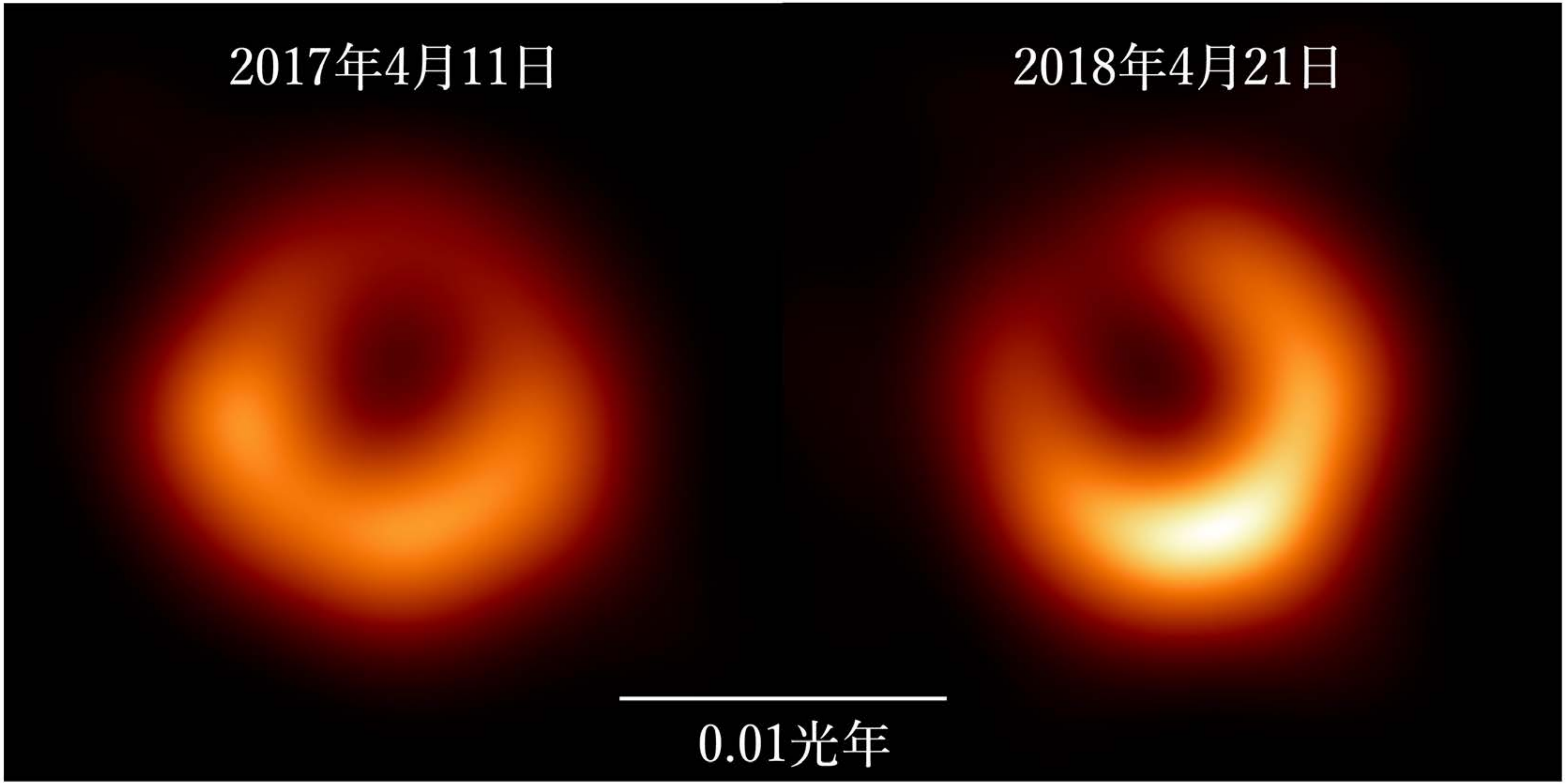


EHTC+2019

EHT Collaboration 2019

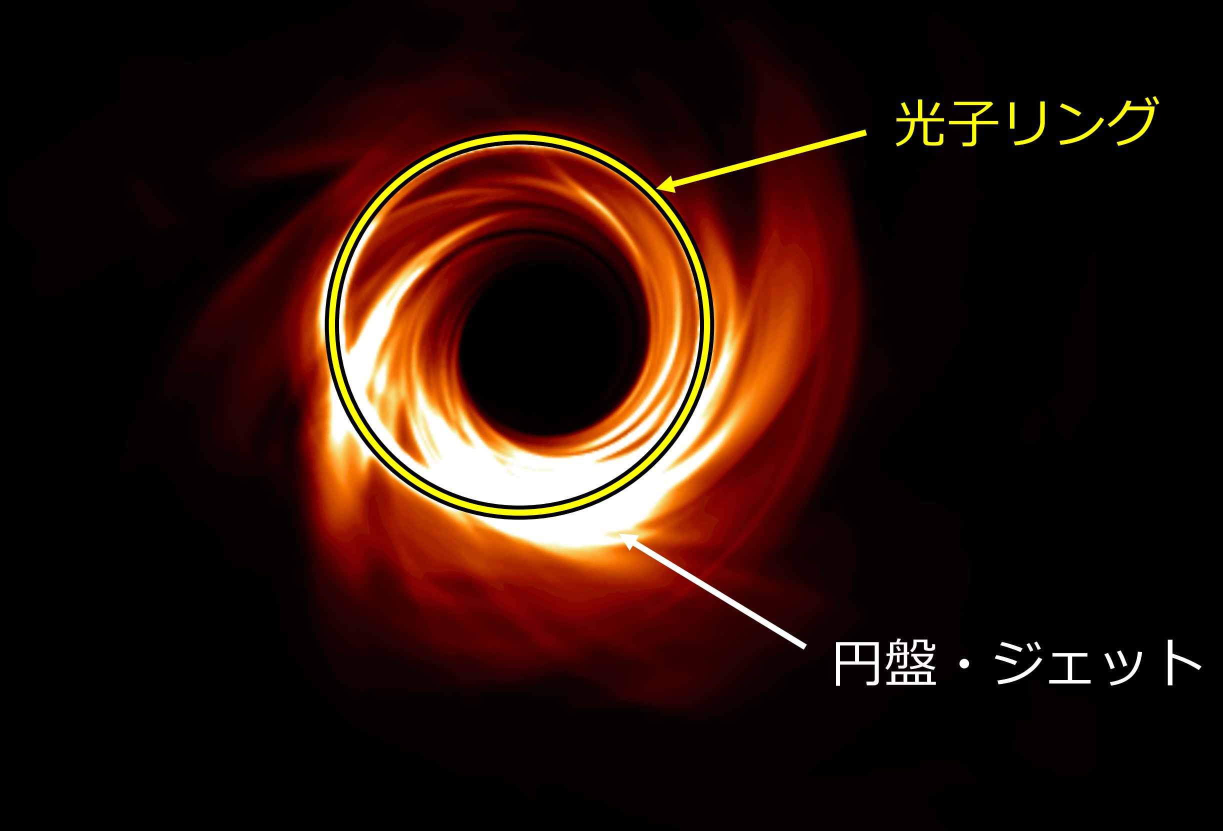


M87最新成果 (EHTC+2024)



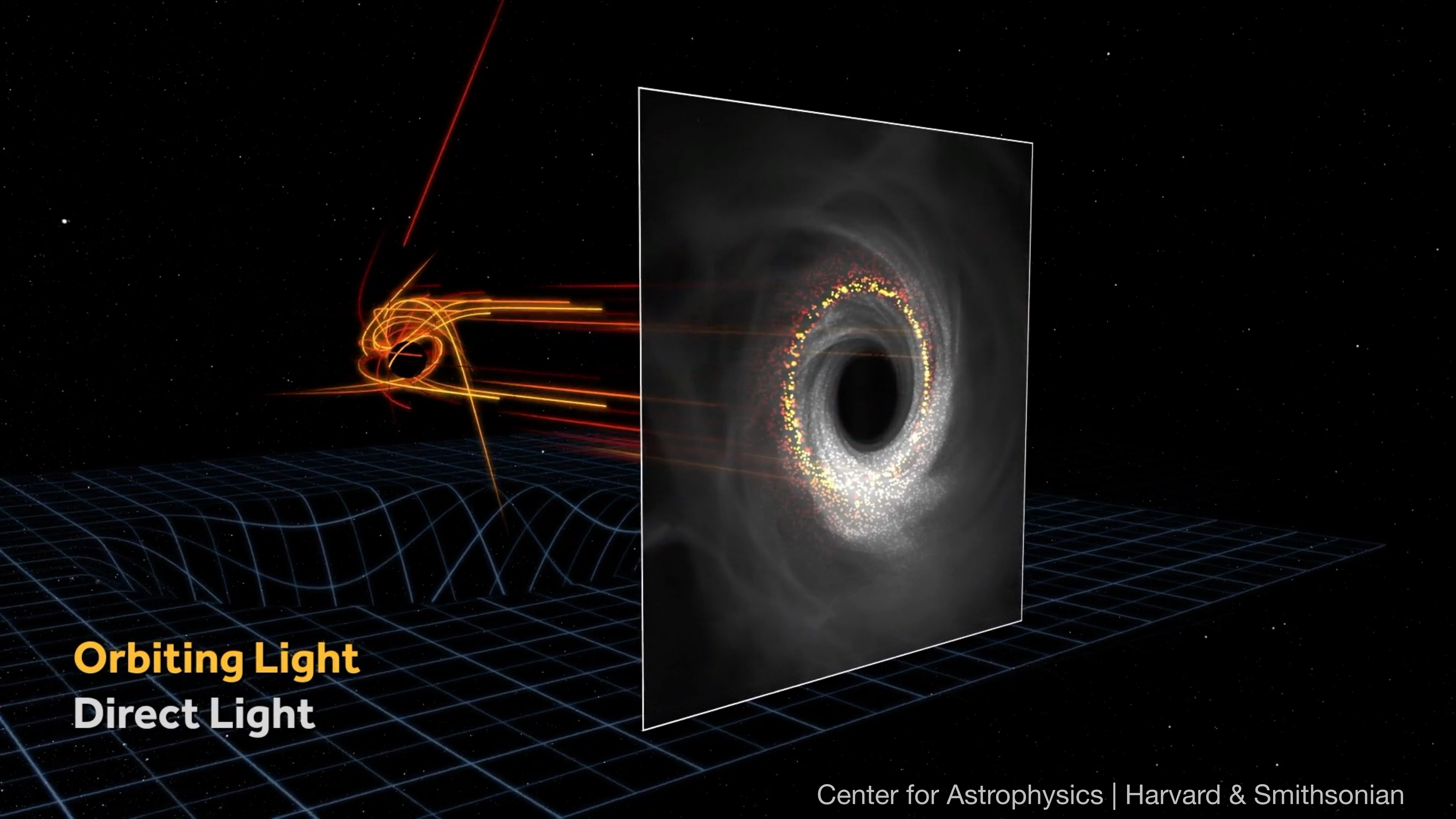
Observation

Model



- 実際の観測は有限の空間分解能
- 地上EHT画像では、光子リングと周囲の放射（円盤・ジェット）が完全には分離できていない

EHT Collaboration


Orbiting Light
Direct Light
Center for Astrophysics | Harvard & Smithsonian

Black Hole Explorer (BHEX) Mission

BHEX will achieve the highest angular resolution in history and would reveal a black hole's "photon ring" for the first time

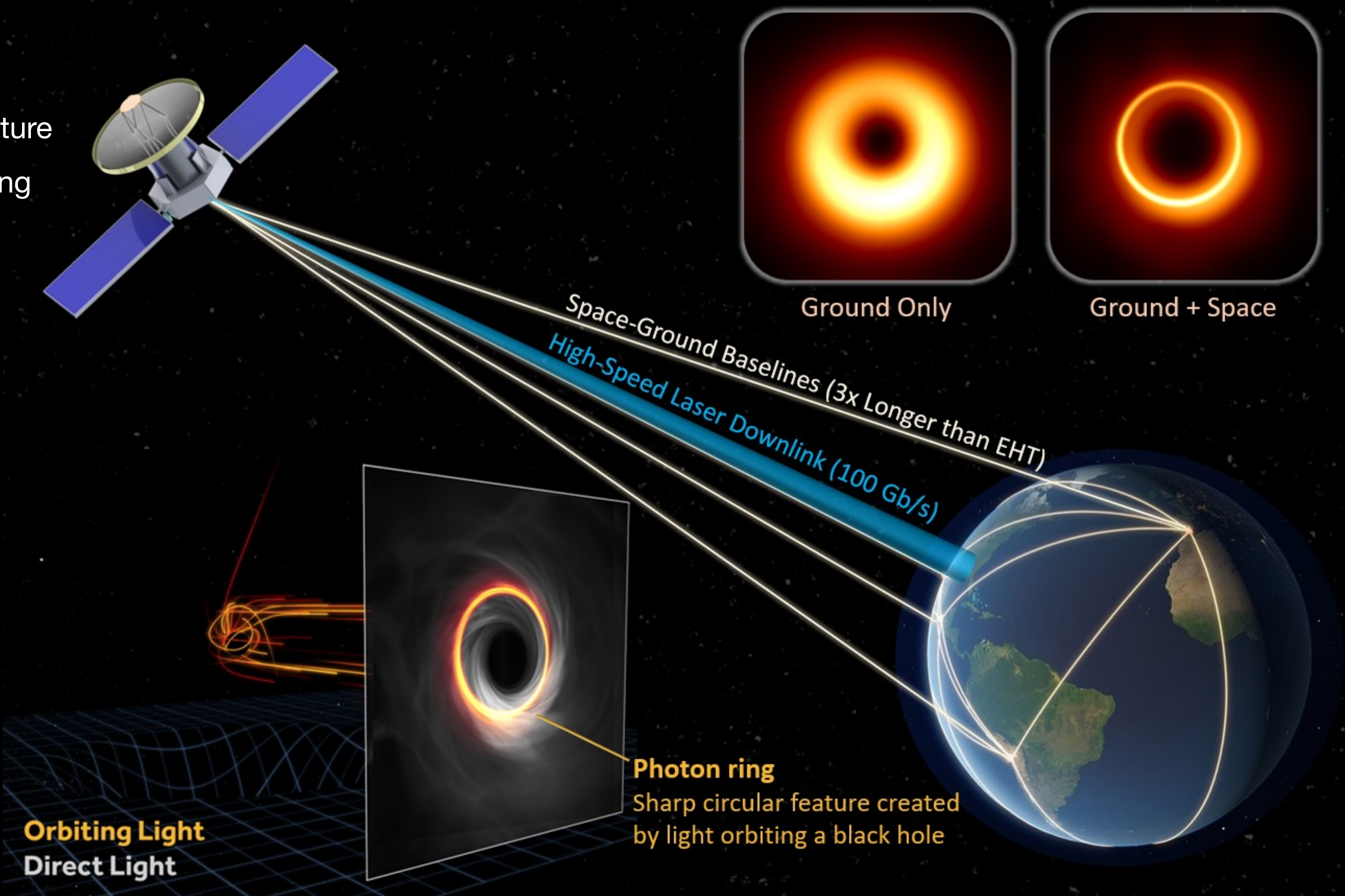
- First direct measurement of a black hole's spin
- Opportunity to study *dozens* of black holes
- Leverages billions of dollars of ground infrastructure
- Explosion of community interest in the photon ring
- Targeting a 2025 SMEX proposal

Science Goals

- ➢ Discover a black hole's photon ring
- ➢ Make direct measurements of a black hole's mass and spin
- ➢ Reveal the shadows of *dozens* of supermassive black holes

Necessary Parameters for Space-VLBI

- ➢ High radio frequencies (>100 GHz)
- ➢ Orbits of at least ~30,000 km
- ➢ High-speed (~100 Gb/s) downlink



Credit: Michael Johnson, Center for Astrophysics | Harvard & Smithsonian

Johnson et al 2020

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RESEARCH ARTICLE | ASTRONOMY

Universal interferometric signatures of a black hole's photon ring

MICHAEL D. JOHNSON, ALEXANDRU LUPSASCA, ANDREW STROMINGER, GEORGE N. WONG, SHAHAR HADAR, DANIEL KAPEC, RAMESH NARAYAN, ANDREW CHAEL, CHARLES F. GAMMIE, [...], AND JAMES M. MORAN +7 authors Authors Info & Affiliations

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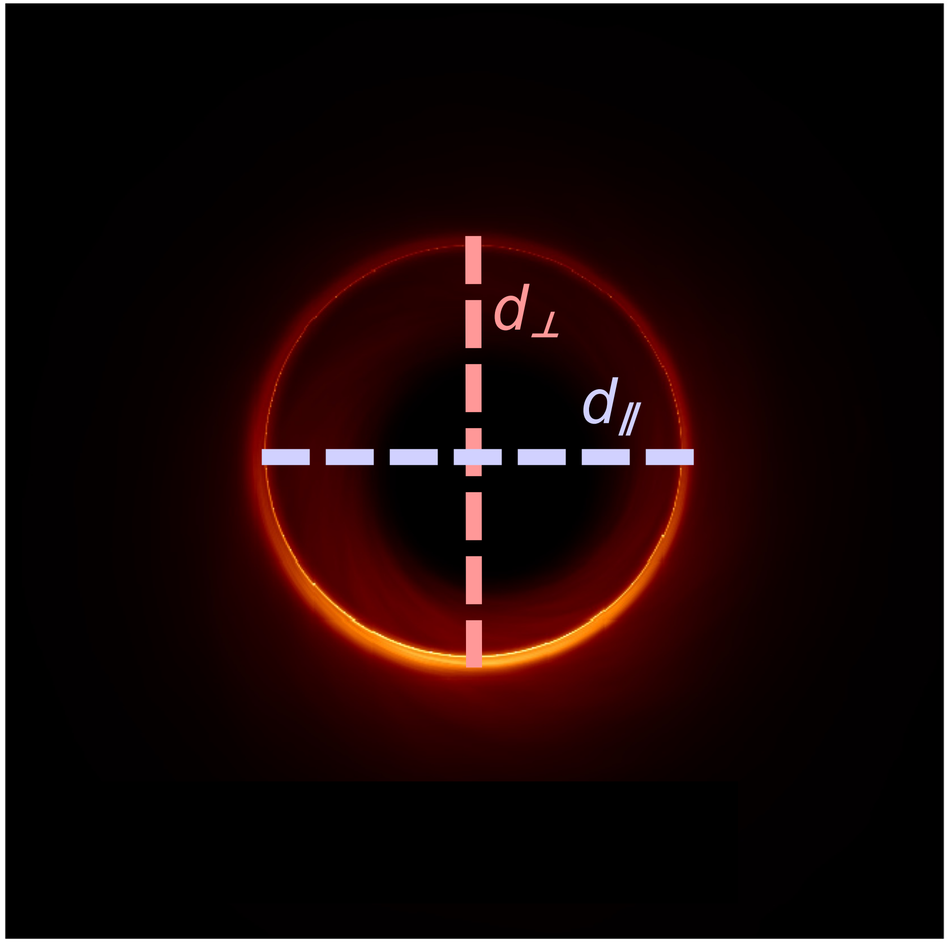
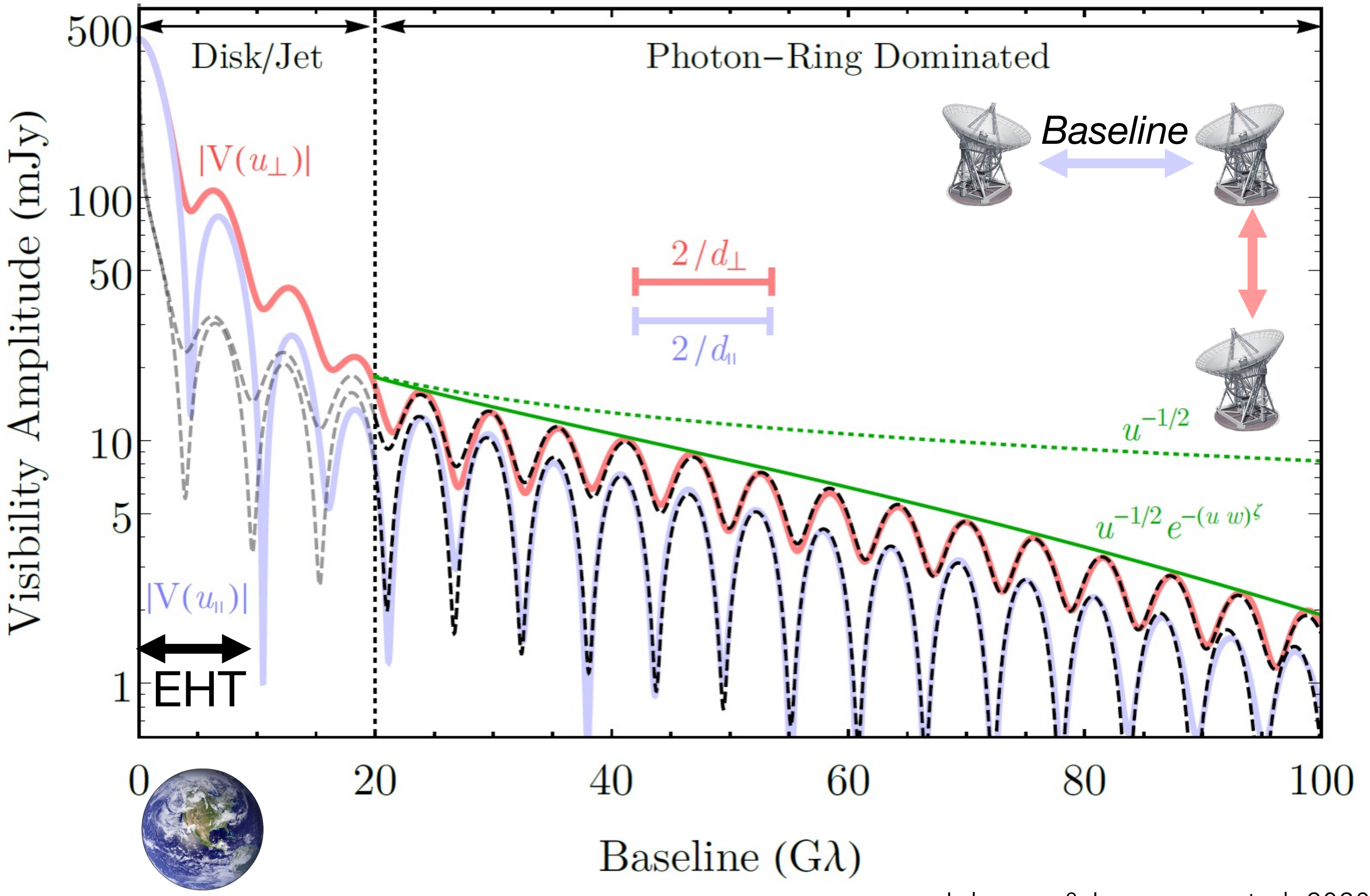
6,085 113

Abstract

The Event Horizon Telescope image of the supermassive black hole in the galaxy M87 is dominated by a bright, unresolved ring. General relativity predicts that embedded within this image lies a thin "photon ring," which is composed of an infinite sequence of self-similar subrings that are indexed by the number of photon orbits around the black hole. The subrings approach the edge of the black hole "shadow," becoming exponentially narrower but weaker with increasing orbit number, with seemingly negligible contributions from high-order subrings. Here, we show that these subrings produce strong and universal signatures on long interferometric baselines. These signatures offer the possibility of precise measurements of black hole mass and spin, as well as tests of general relativity, using only a sparse interferometric array.

Seeing Photon Subrings with an Interferometer





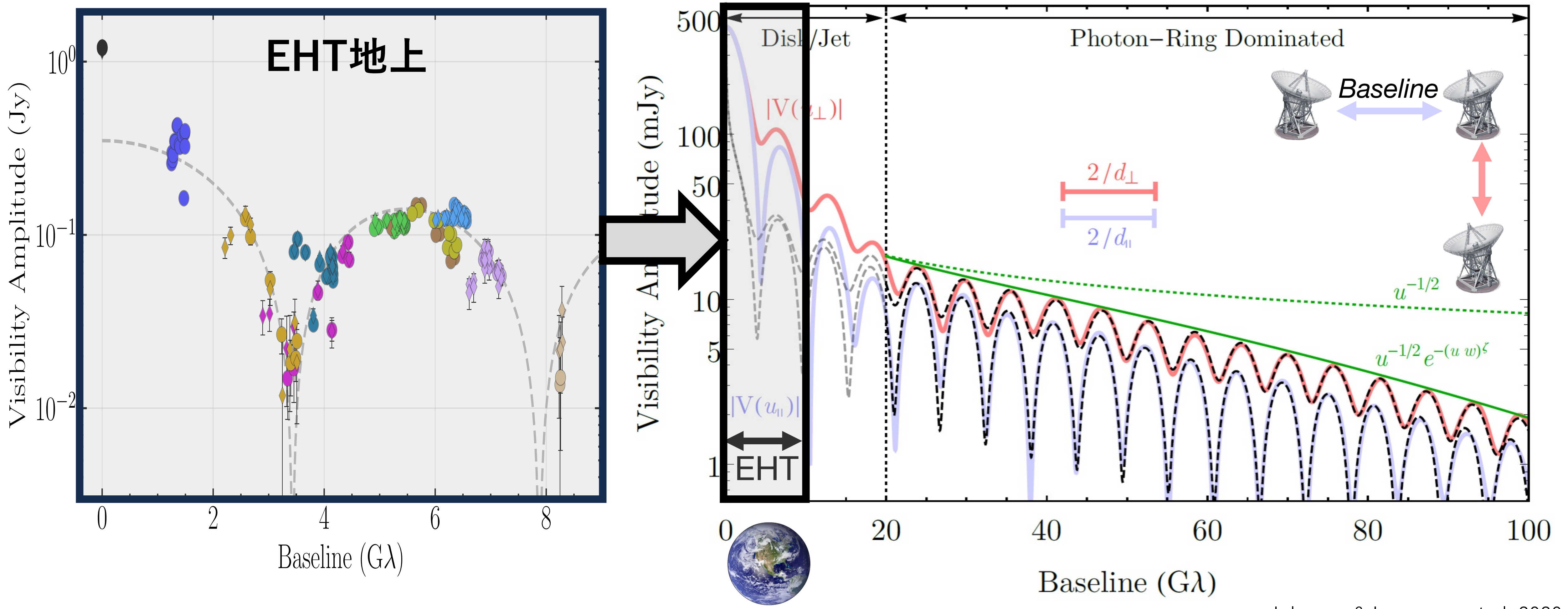
Johnson & Lupsasca et al. 2020

Subrings are negligible for images but give a strong signal for an **interferometer**

A single long baseline can measure the subring properties

Slide: M. Johnson

Seeing Photon Subrings with an Interferometer



Johnson & Lupsasca et al. 2020

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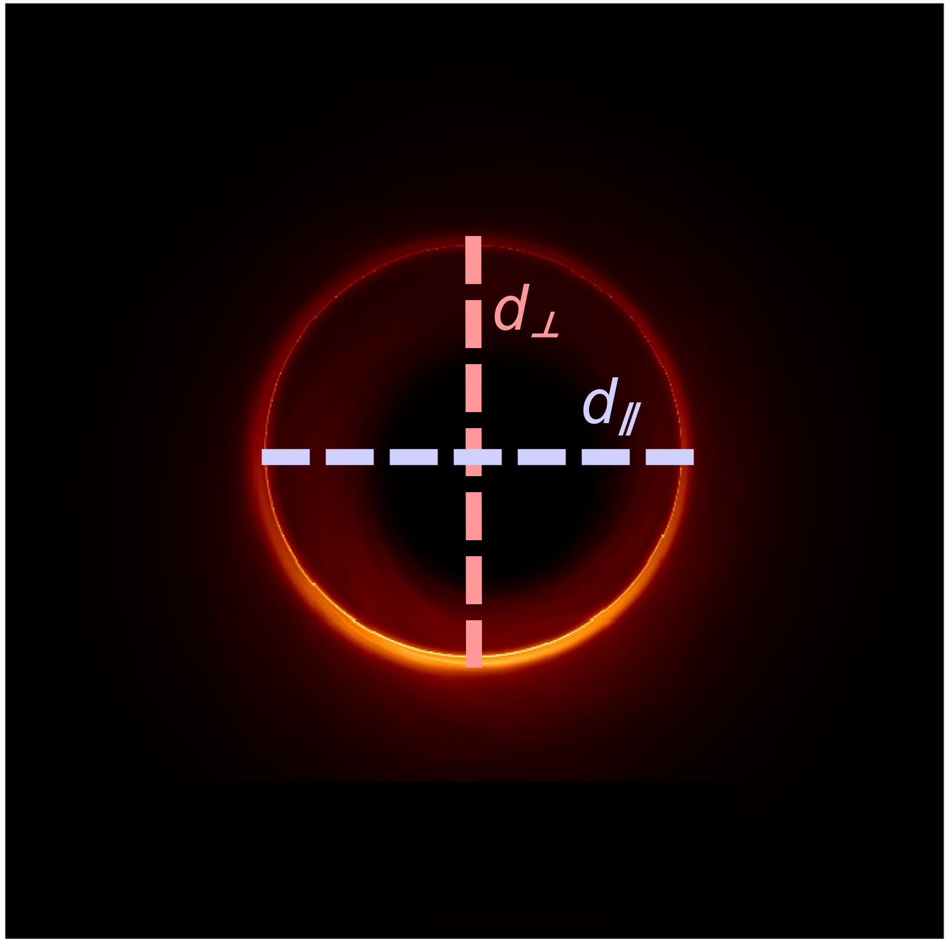

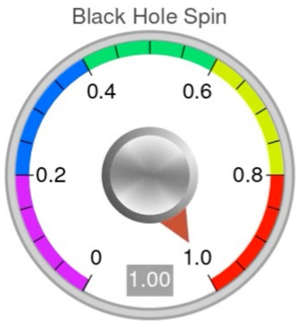

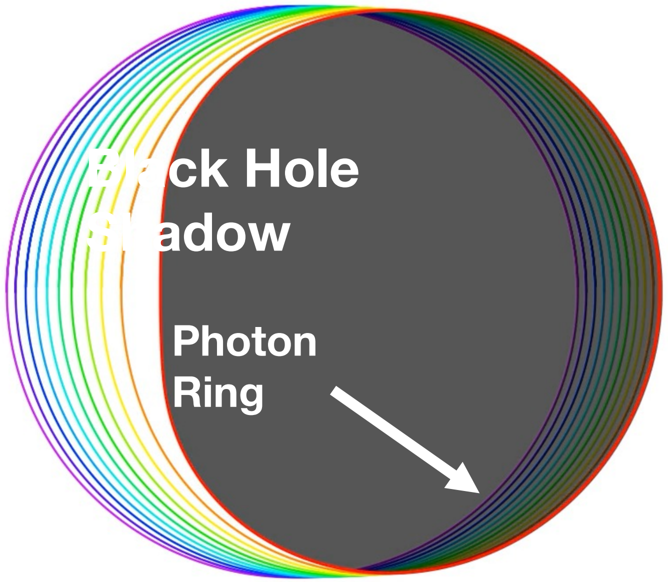

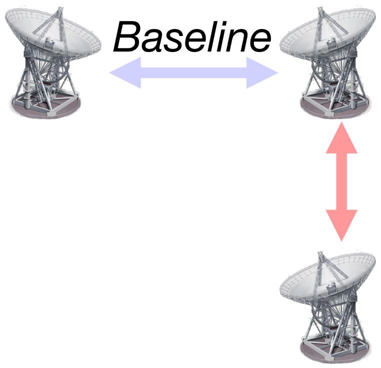

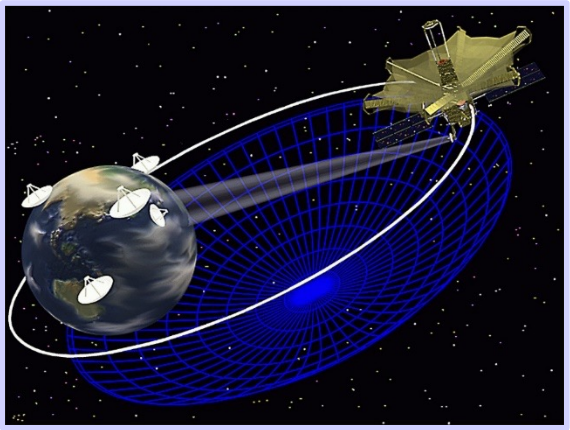

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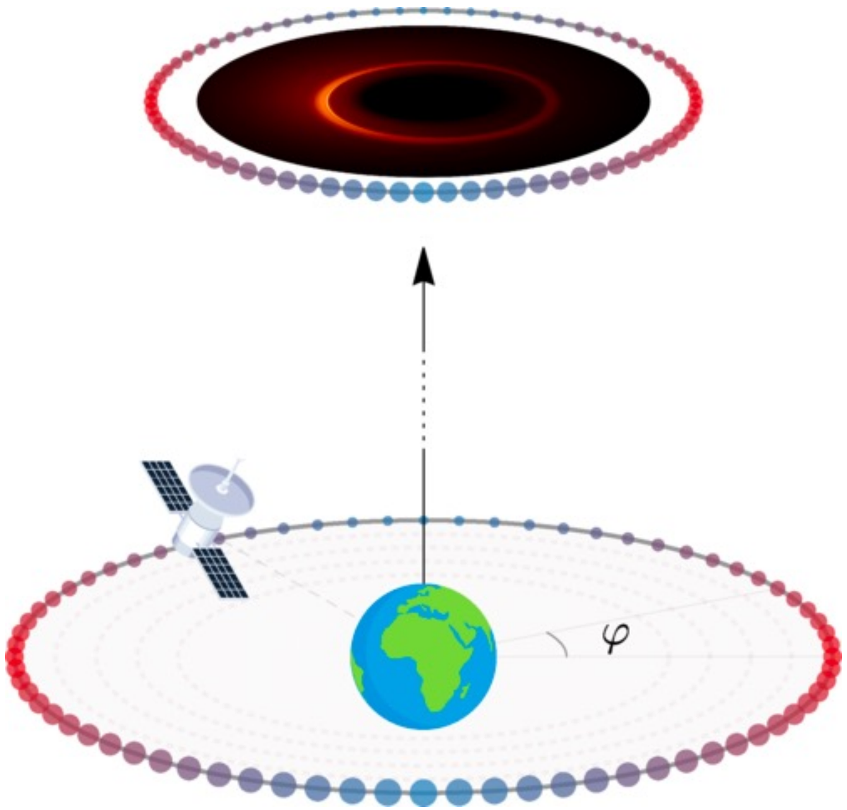
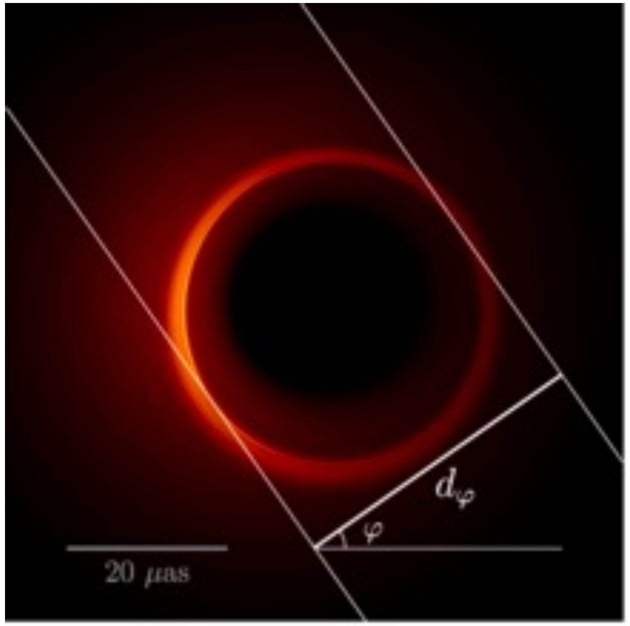
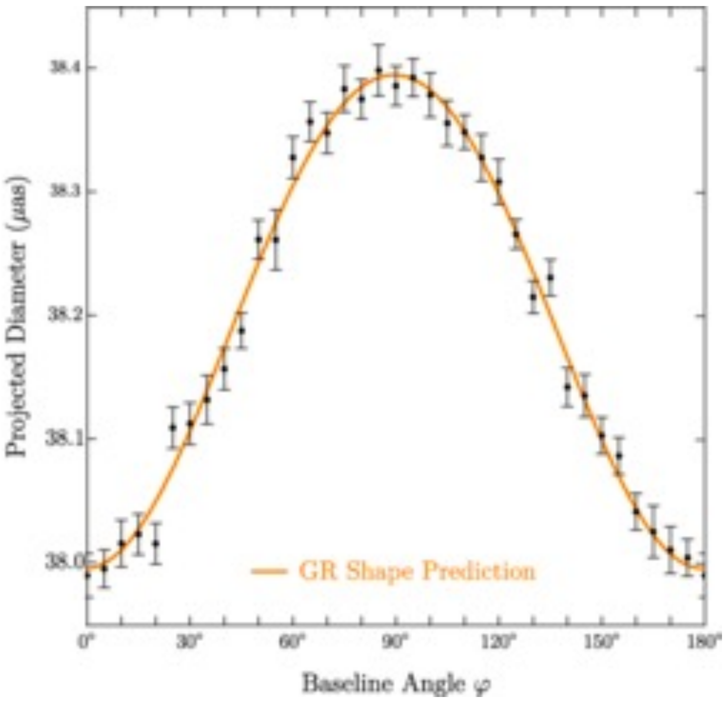
Seeing Photon Subrings with an Interferometer







Gralla, Lupsasca, & Marrone 2020

Subrings are negligible for images but give a strong signal for an **interferometer**

A <u>single</u> long baseline can measure the subring properties

Black Hole Photon Ring: A New Research Area in 2020s

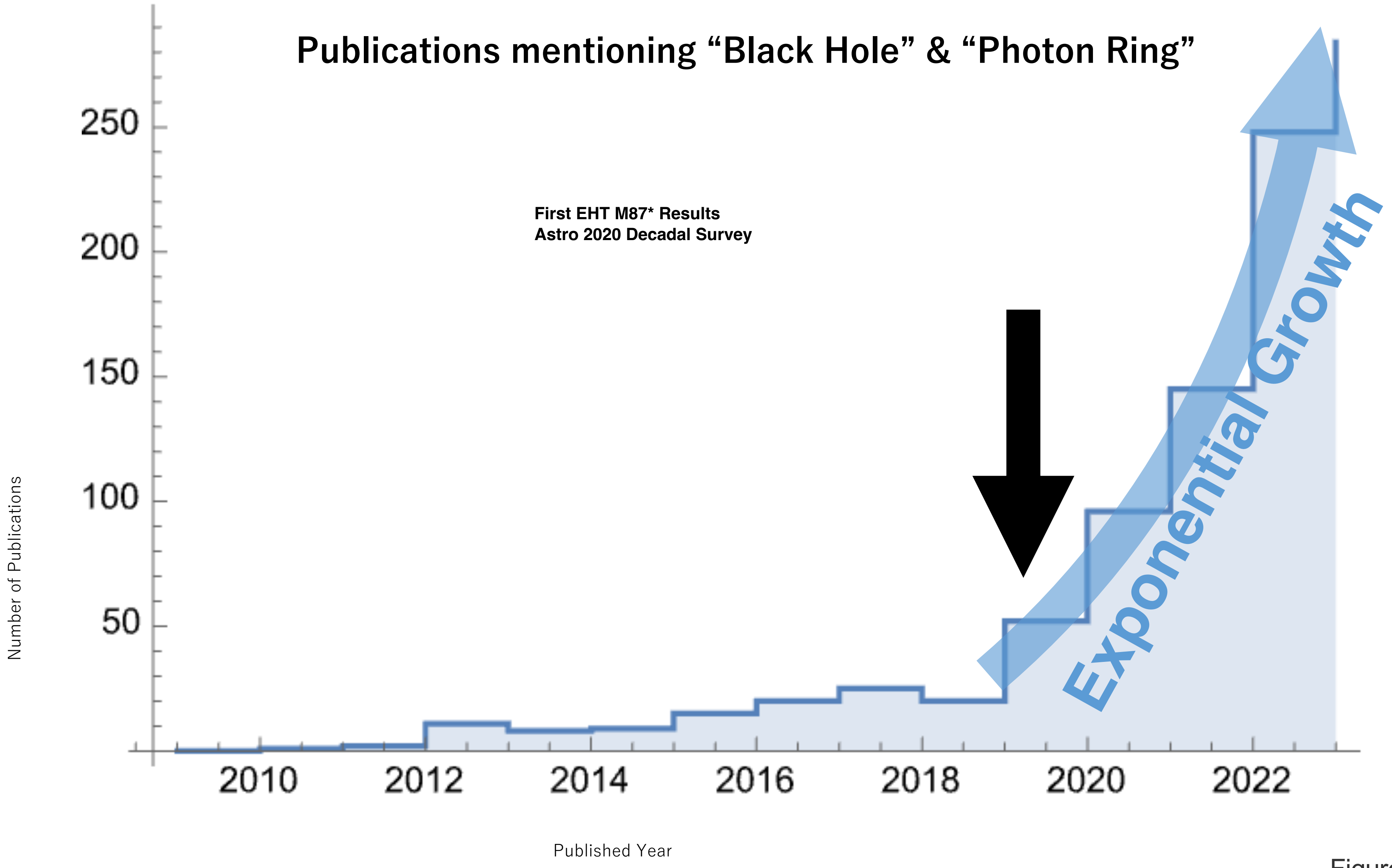


Figure Credit: A. Lupsasca

Crucial Enabling Technology

Increasing signal bandwidth has been essential to the EHT

BHEX will transmit 750x more data than RadioAstron

RadioAstron: 128 Mb/s
(64MHz bandwidth, 1bit)

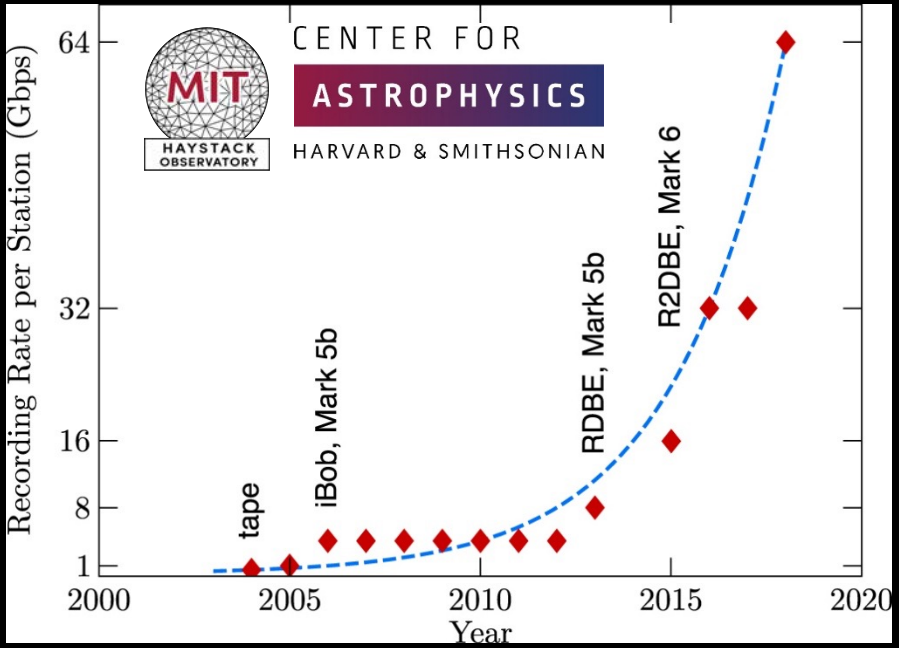
EHT in 2008: 4 Gb/s [x6 sensitivity]
(1 GHz, 2bit)

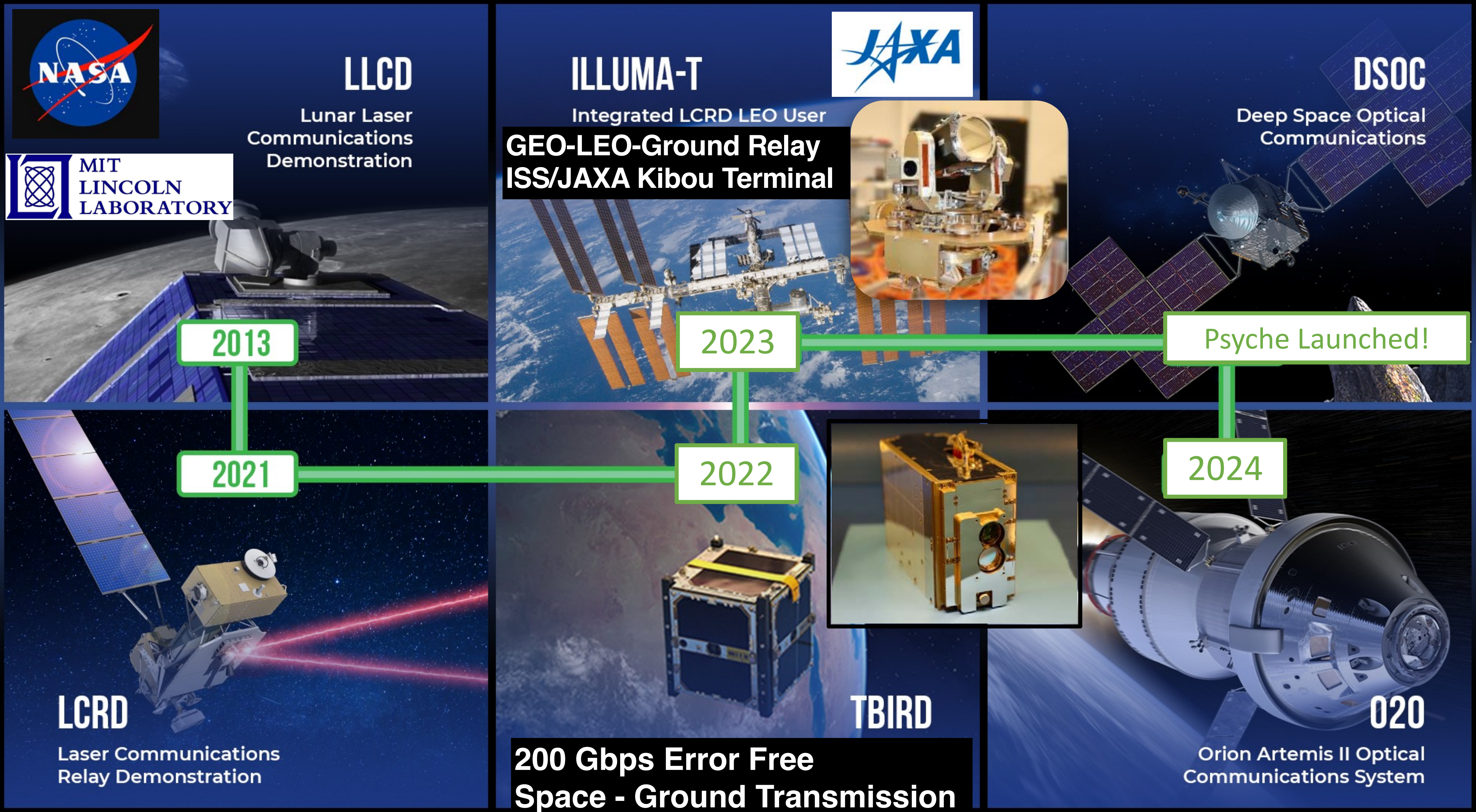
EHT in 2017: 32 Gb/s [x16 sensitivity]
(2x4 GHz, 2bit)

EHT in 2018+: 64 Gb/s [x23 sensitivity]
(4x4 GHz, 2bit)

BHEX Target: 96 Gb/s [x36 sensitivity, multiband]
(2x8+4x8 GHz, 1bit)

VLBI recording rate over time




NASA
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LINCOLN
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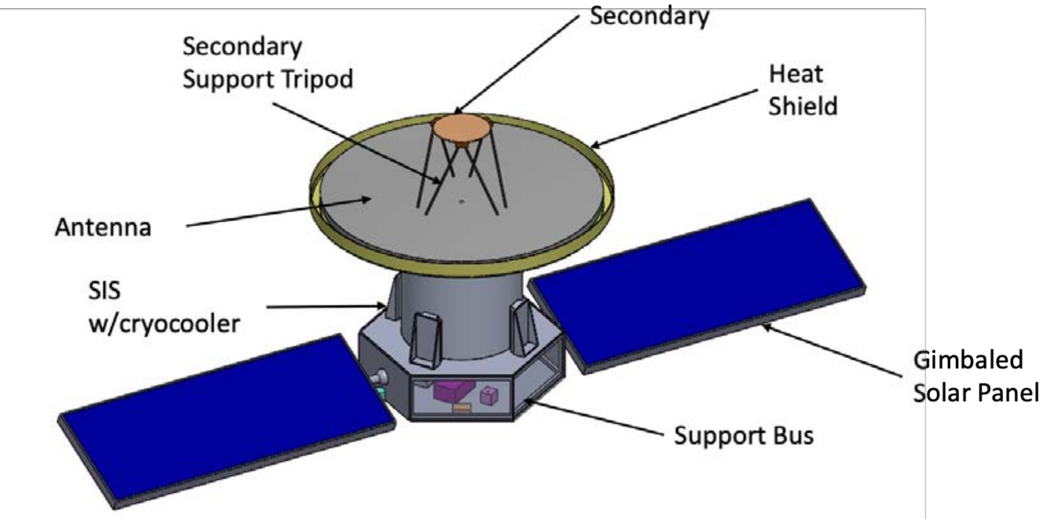
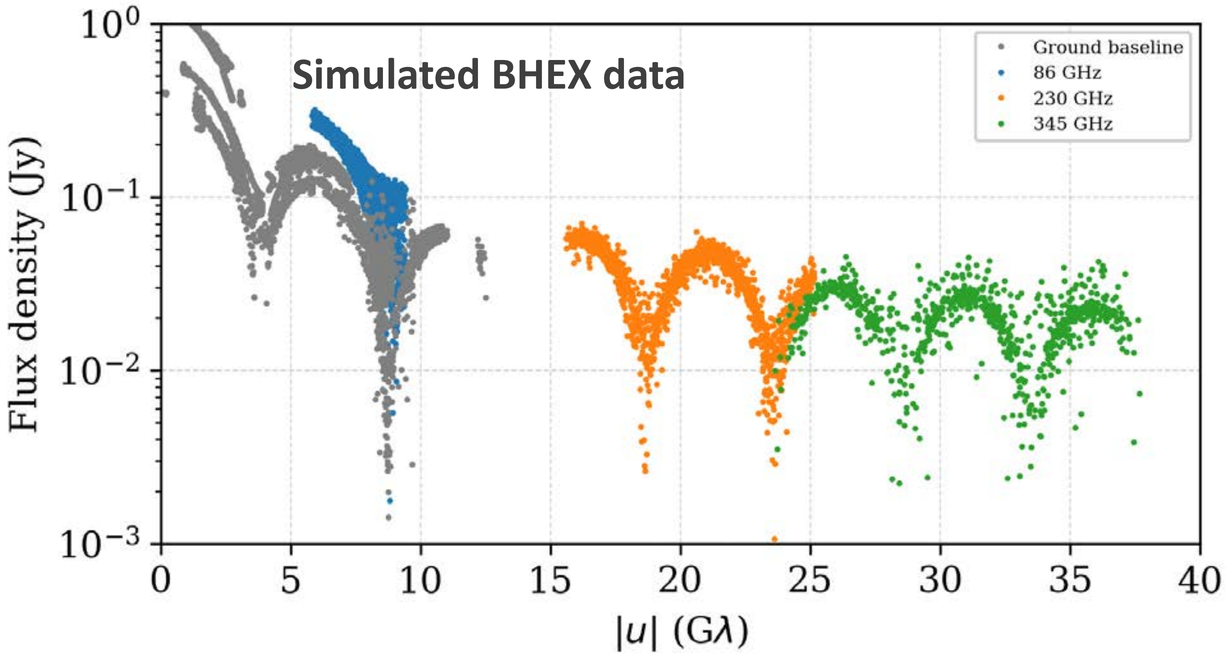
LLCD
Lunar Laser
Communications
Demonstration
ILLUMA-T
Integrated LCRD LEO User
GEO-LEO-Ground Relay
ISS/JAXA Kibou Terminal
JAXA
DSOC
Deep Space Optical
Communications
2013
2023
Psyche Launched!
2021
2022
2024
LCRD
Laser Communications
Relay Demonstration
TBIRD
200 Gbps Error Free
Space - Ground Transmission
O2O
Orion Artemis II Optical
Communications System

BHEX 衛星概要



Mission Parameters

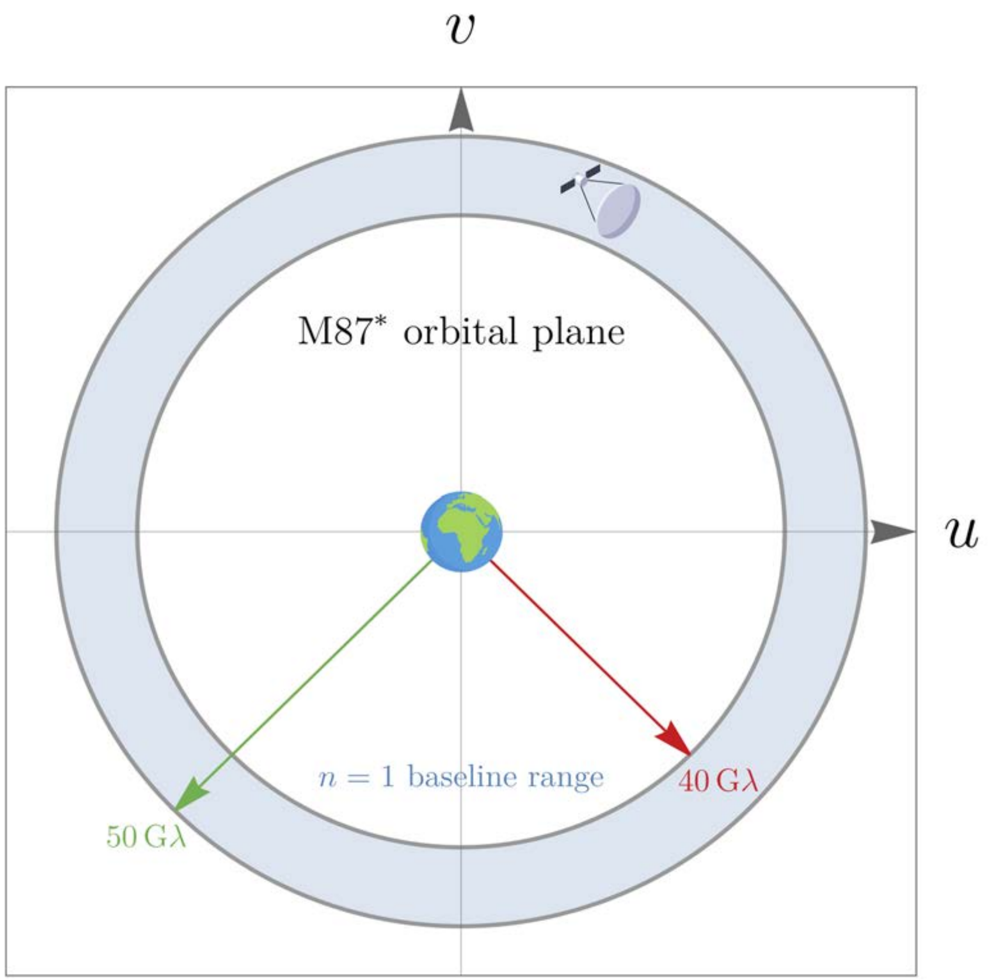
- 3.5m Antenna, 30μm surface, shaded
- Simultaneous dual-band observations (86 + 230/345 GHz)
- Operations synchronized with ground telescopes (“hybrid observatory”)
- Orbit: ~25,000 km altitude
- Lifetime: 2+ years
- Telemetry: 100 Gbps using laser communications



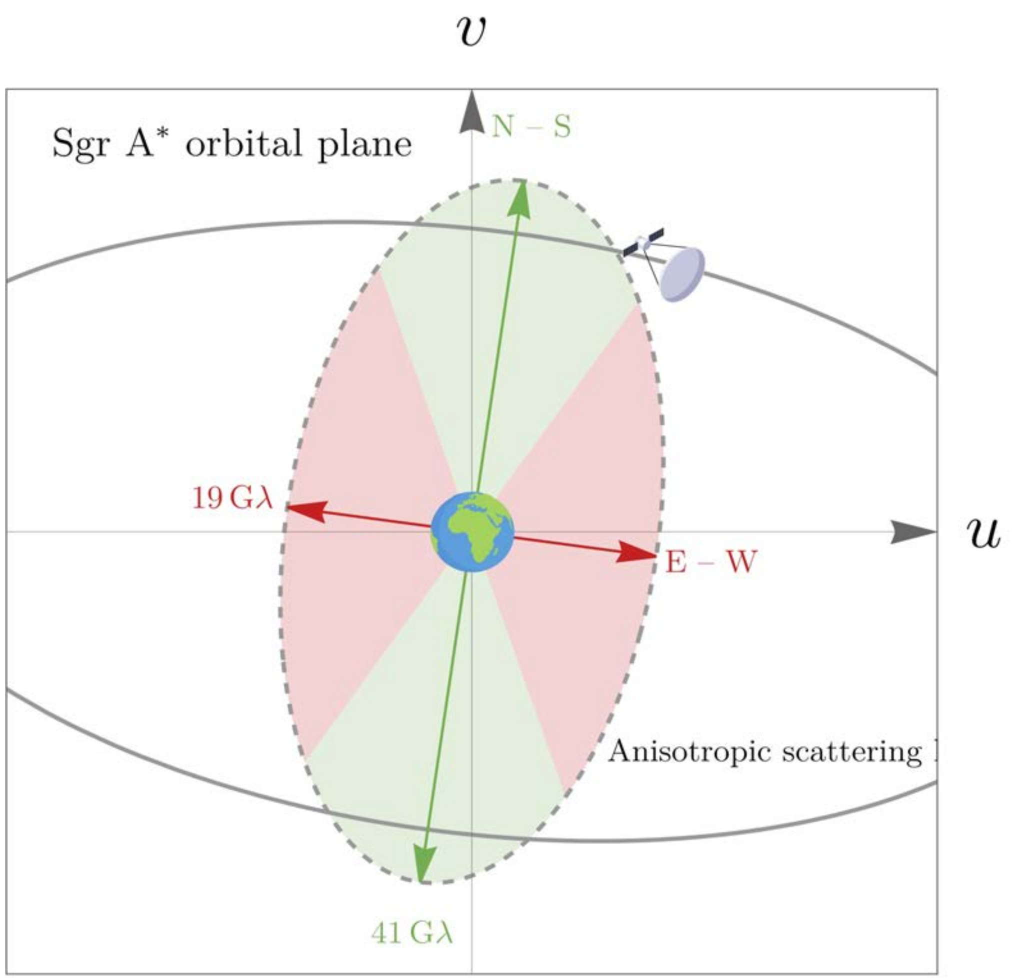
Simulations: Daniel Palumbo and Paul Tiede

Orbital Requirements

M87



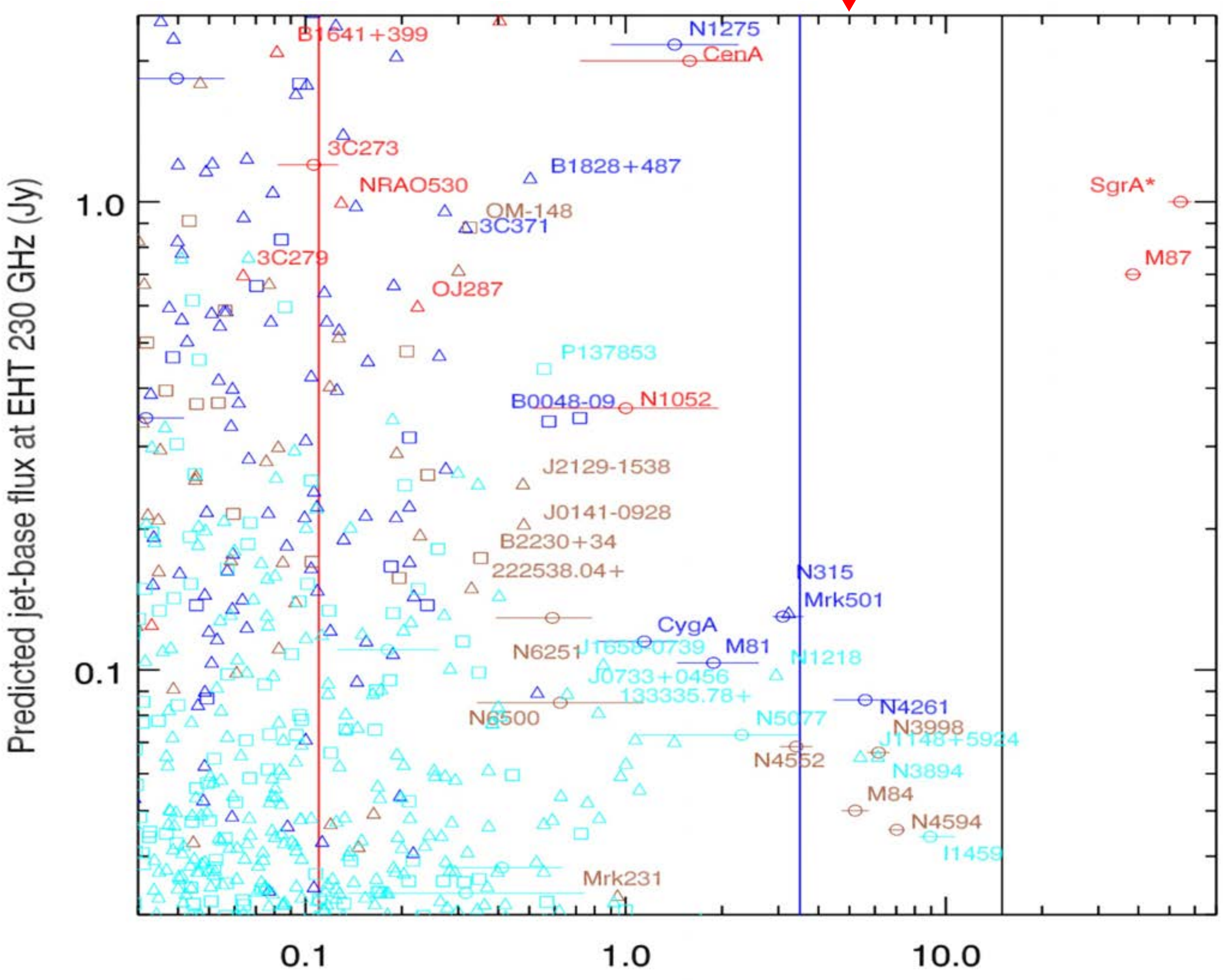
SgrA*



Credit: Goddard EHE WS 2023

Beyond M87/SgrA*

BHEX分解能 (5~7uas)



予想されるBHシャドウ直径 (マイクロ秒角)

近傍AGN >10天体のBHシャドウ検出が可能に

一部のクエーサー系も数10Rsまで空間分解可能

Ramakrishnan+2023

代表的なサイエンスケース

- M87/SgrA*の光子リング成分の分離・精密モデリング
- 近傍(LL)AGN ~10天体のBHシャドウイメージング
- 高Mdot天体 (クエーサー、FR-II)の降着円盤スケール、ジェット加速・収束領域スケールのイメージング

Black Hole Explorer Team

BHEX


Michael Johnson
PI


Kari Haworth
Deputy PI


Dan Marrone
Instrument Scientist


Janice Houston
Lead Systems Engineer


Alex Lupsasca
Deputy Project Scientist


Peter Galison
Science Team Lead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Science Operations Lead


John Mather
Science Advisor


Peter Kurczynski
Formulation Manager


Eliad Peretz
Mission Architect


Ranjani Srinivasan
Data Processing co-Lead


Jonathan Weintroub
Data Processing co-Lead


Edward Tong
Receivers Lead


Jade Wang
Downlink Lead


T. K. Sridharan
Antenna Lead


Kazunori Akiyama
Japan-EHE Lead


Rebecca Baturin
Project Manager

BHEX

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

HARVARD

ARIZONA

PRINCETON UNIVERSITY

VANDERBILT UNIVERSITY

MIT HAYSTACK OBSERVATORY

NASA Goddard SPACE FLIGHT CENTER

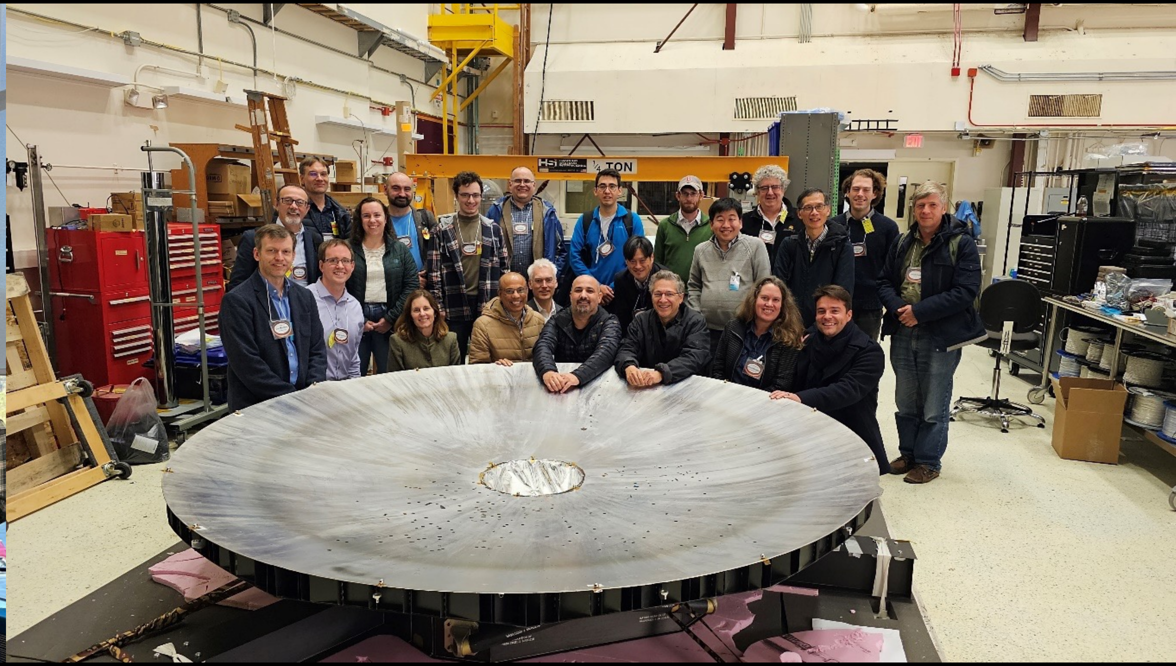
MIT LINCOLN LABORATORY

NRAO National Radio Astronomy Observatory

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Black Hole Explorer Team

BHEX



BHEX

CENTER FOR ASTROPHYSICS | HARVARD & SMITHSONIAN

HARVARD

ARIZONA

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MIT HAYSTACK OBSERVATORY

NASA Goddard SPACE FLIGHT CENTER

MIT LINCOLN LABORATORY

NRAO National Radio Astronomy Observatory

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

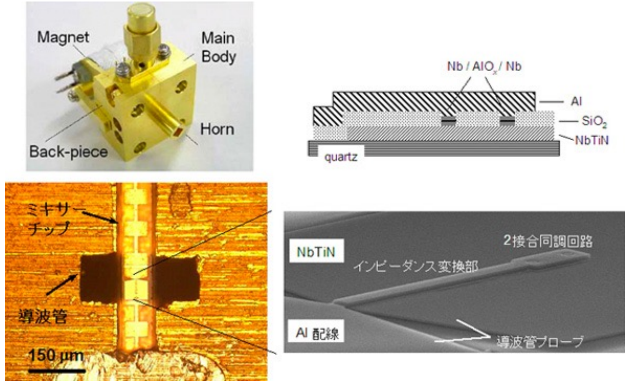
Why is Japanese participation crutial?

BHEX

JAXA

Sumitomo
Heavy Industries, Ltd.

4K Cryocooler (Hitomi/XRISM/LiteBIRD)



国立天文台
NAOJ

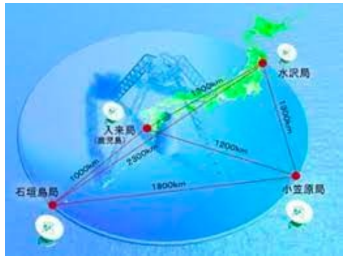
自然科学研究機構 国立天文台
ATC
先端技術センター

SIS Mixer (ALMA / ALMA2)

NICT
国立研究開発法人
情報通信研究機構

Optical Laser Downlink

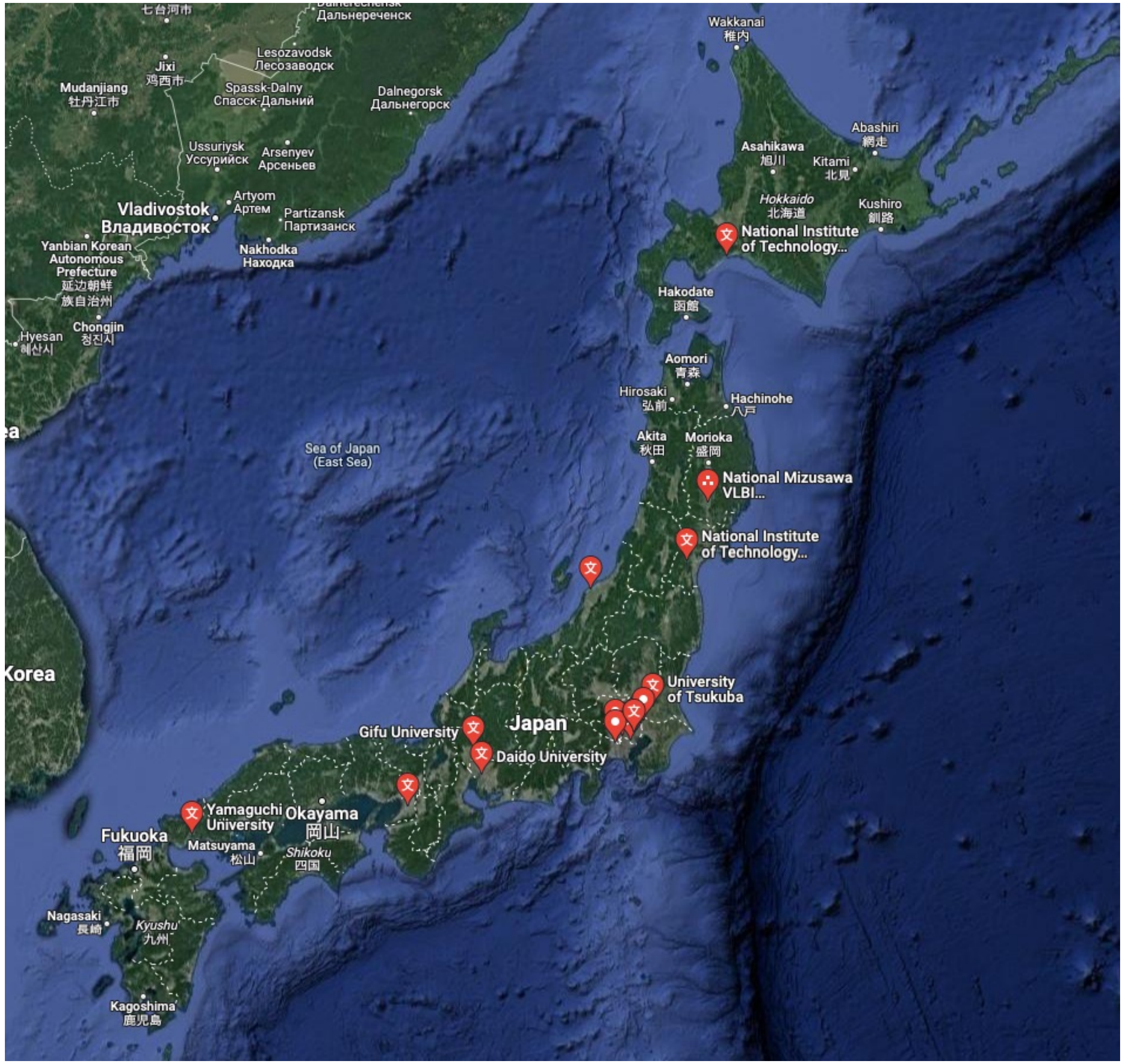
国立天文台
NAOJ



ACA Total Power Array / Ground mm stations

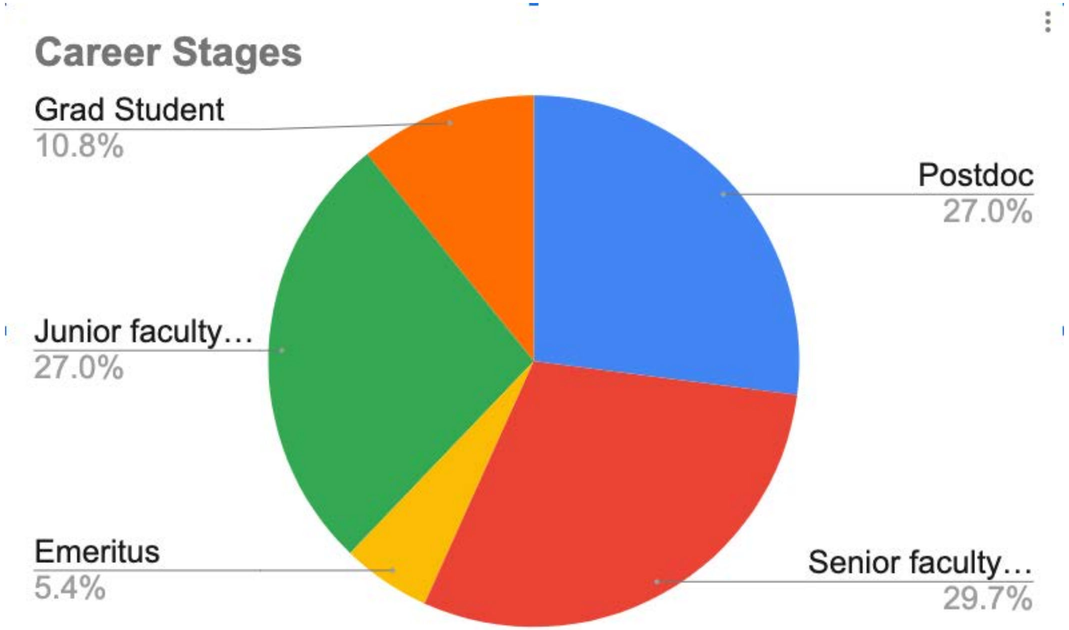
These are all **strategically** developed in Japan

BHEX Japan Group



Exploring the Japanese Role in the Mission

60+ Scientists from 20+ Institutes



Three Science Working Groups

Aiming to establish a WG/RG under JAXA

BHEX Japan Team

Kazuhiro Hada
NAOJ Mizusawa
BHEX-J Co-lead

Kotaro Niinuma
Yamaguchi U.
BHEX-J Co-lead

Kazu Akiyama
MIT Haystack / NAOJ
BHEX-J Co-lead
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NAOJ ATC
SIS Mixer Development

Shoko Koyama
Niigata U.

Yoshiaki Hagiwara
Toyo U.

AGN SWG Leads

Tomoaki Kawasima
U. Tokyo ICRR

Ken Ohsuga
Tsukuba U.

Yuh Tsunetoe
Harvard BHI

GR / Accretion & Jet Launching SWG Leads

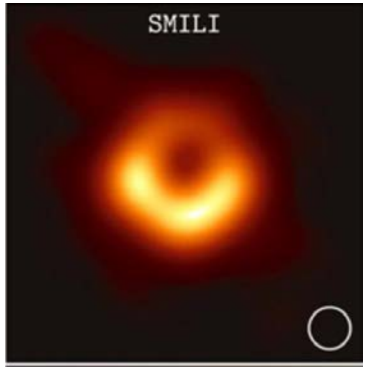
Aya Higuchi
Tokyo Denki U.

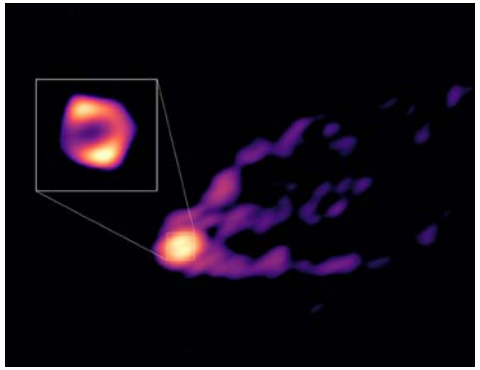
Hidetoshi Sano
Gifu U.

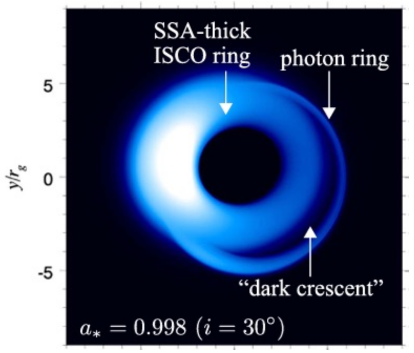
Single Dish / Molecular SWG

Major Areas of the BHEX Japan Science

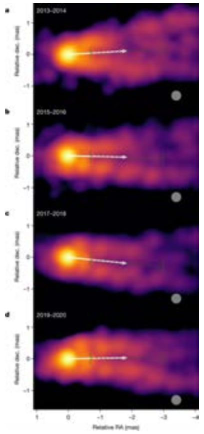
Gravitational Physics
Accretion and Jet Launching

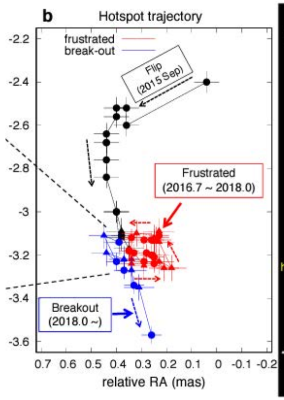


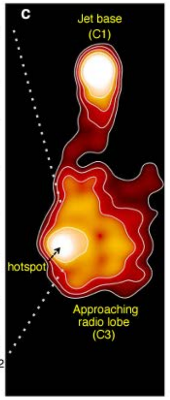


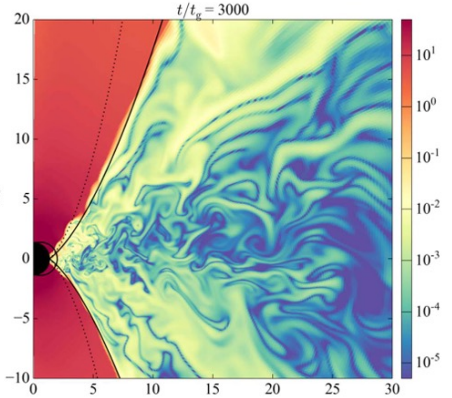


AGN Jet Studies

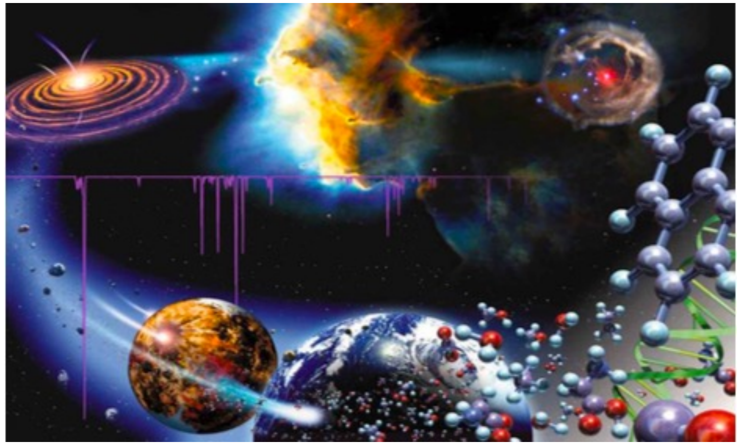




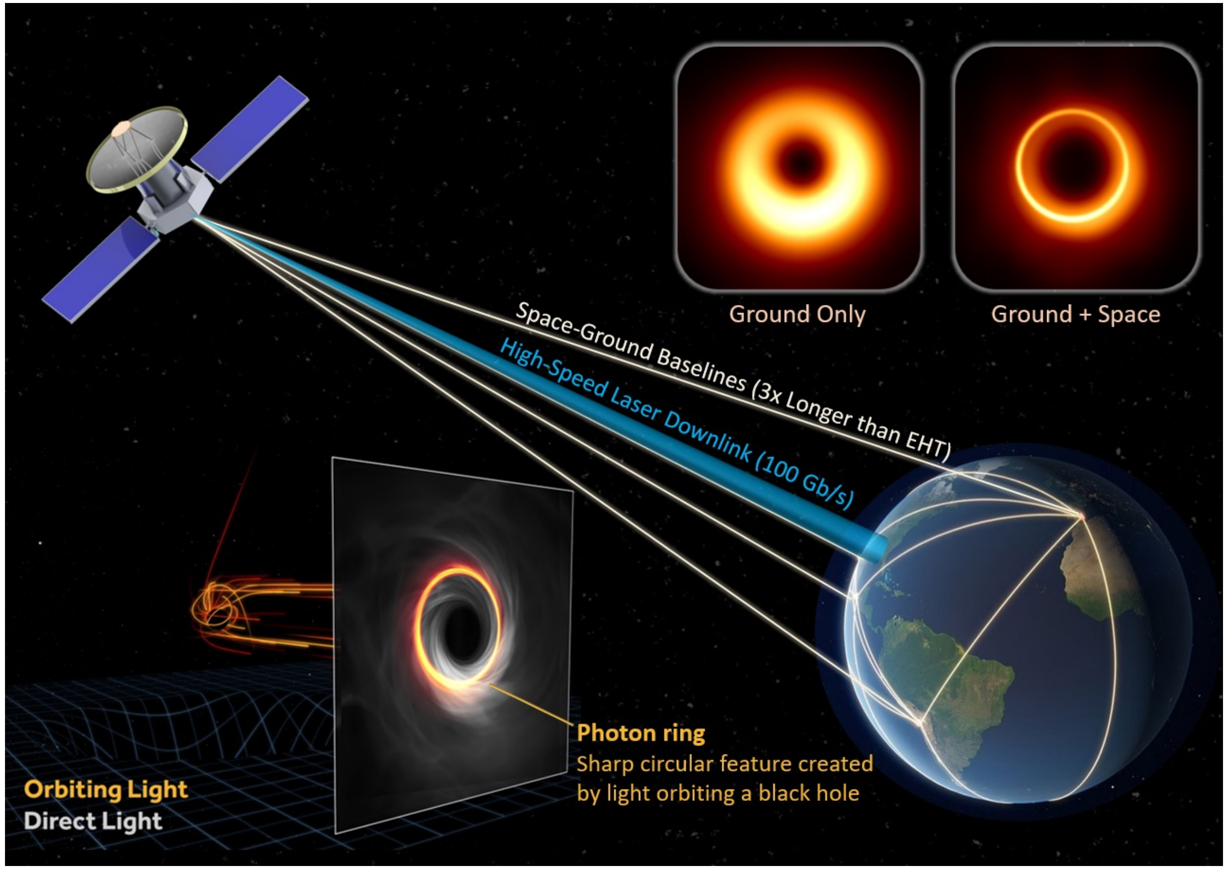




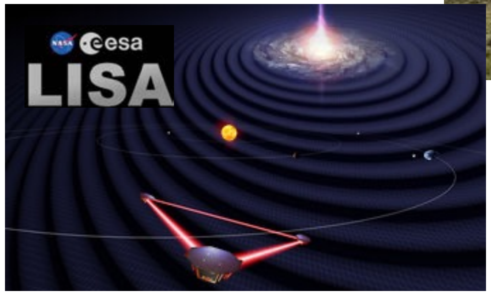
Astrochemistry Science with Potential Single Dish Mode



MWL & MMS in 2030s



Credit: Michael Johnson, Center for Astrophysics | Harvard & Smithsonian



まとめ

- 地上ミリ波VLBI（EHT）の進展により、直接撮像による SMBH観測新時代が幕開け

- 次の一手としてスペースへの展開（BHEX）が本格始動
  - 解像度さらに4-5倍。光子リングのイメージングを精密化。BH質量、スピンの精密測定へ

- 日本へ大きな期待
  - 冷凍機、受信機、レーザー通信、地上局
  - サイエンス => WG設立

BHEX Japan Workshop at NAOJ from June 24-25, 2024

Registration is now open! (4/1締切)

Website: sites.mit.edu/bhex-japan-workshop-2024