Imaging black holes and jets from space

Freek Roelofs

With Heino Falcke

FIR 2025, Leiden, 4 April 2025

Link to slides with animations:
https://docs.google.com/presentation/d/1wtHAV9h1V7c1X9M2anVo3lwHNnk3t5MICRrMdFUjmTQ/edit?usp=sharing

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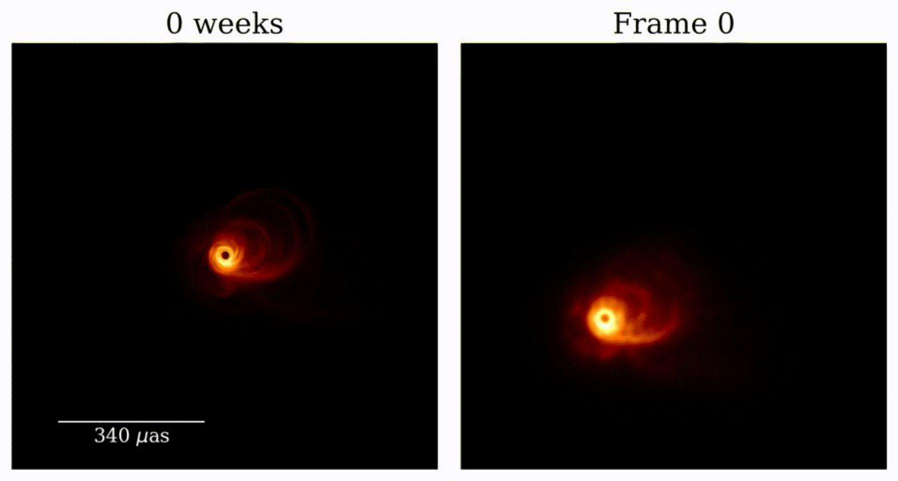
Black hole imaging with the EHT

EHT extensions: jet imaging and movie making

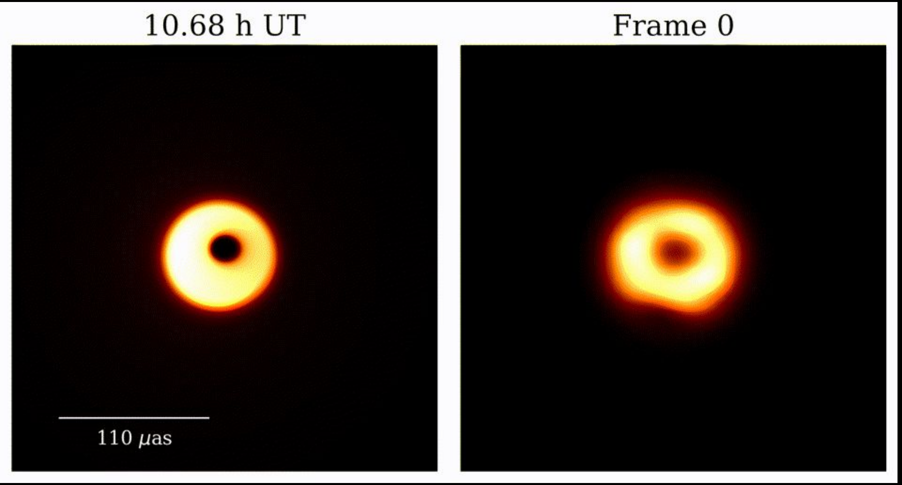
M87*



K. Chatterjee, R. Emami

P. Arras, J. Knollmüller; resolve

Sgr A*



P. Tiede

A. Fuentes; StarWarps

EHT2022 array + 10 additional sites

ngEHT Analysis Challenges: Roelofs+ (2023)

See also Doeleman+ (2023), Johnson+ (2023)

Why space?

The Earth's size and atmospheric absorption + turbulence make observing at baselines > 14 Glambda (15 μas resolution) very difficult

In space, we can extend baseline lengths significantly, and higher frequencies are accessible (no atmosphere)

Most importantly, **there is unique and exciting science to be done from space**, especially in fundamental physics!

Key science questions

Are black hole spacetimes described by the Kerr metric and can we extract energy from it?

- ➢ Requires measuring the size and shape of the n=1 photon ring, light echos
- ➢ Identify Blandford-Znajek Process and understand jet launching → polarization

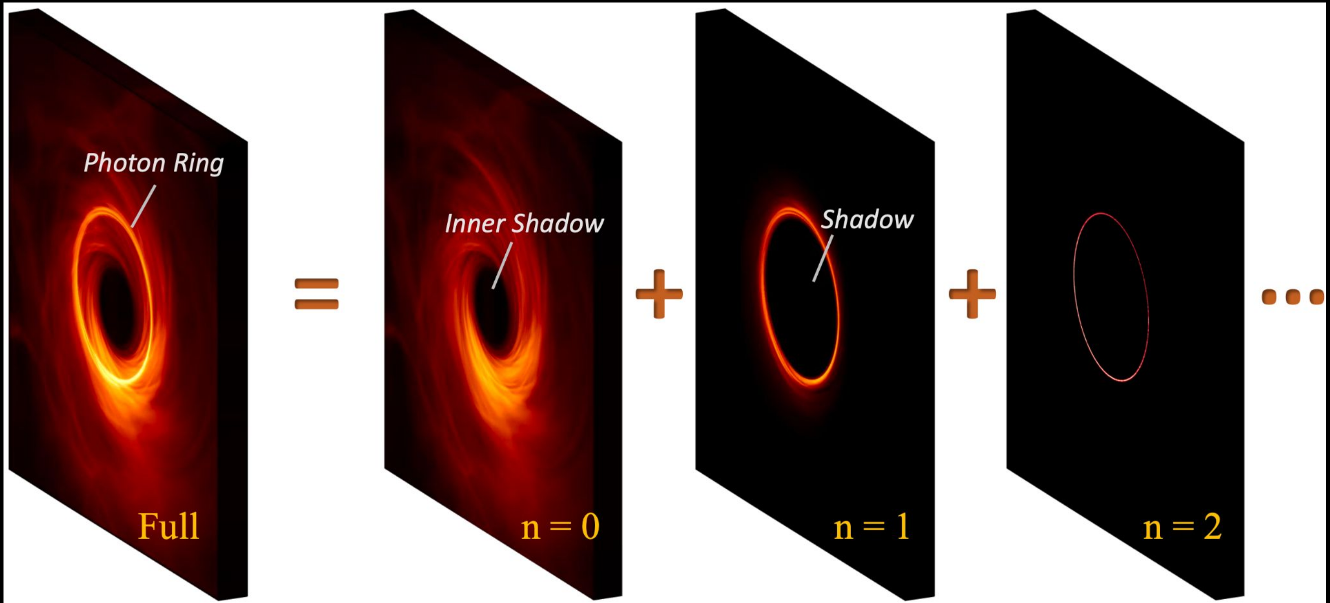
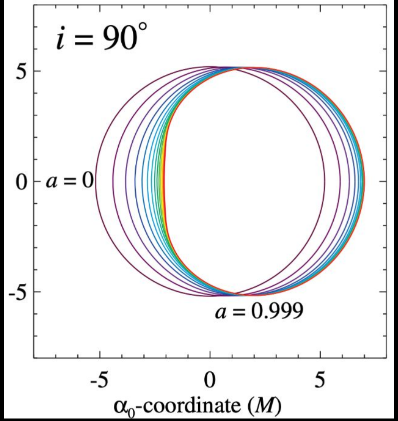


Image: Johnson+ 2023

n = number of half-orbits light makes around the black hole before reaching us

Photon ring for different spins (Chan+ 2013)



EHT images
Astrophysics

Gravity ⟶

Mission concepts

Space-Space	Space-Ground
THz-regime frequencies become accessible	Limited to ~345 GHz
Excellent and flexible uv-coverage for imaging	Limited uv-coverage for imaging
Operations and data quality independent of weather and ground site availability	Operations and data quality constrained by weather and ground site availability
Limited data downlink (if correlating on-board)	All data needs to be sent to ground (high bandwidth downlink)
Limited sensitivity	Leverage high-sensitivity ground-based telescopes
Need to launch at least two dishes, more costly	Need to launch only one dish
New way of observing	Has been done before (e.g. RadioAstron)

← See BHEX poster by Paul Grimes

Event Horizon Imager (EHI)

Space-Space VLBI: no ground-based telescopes involved

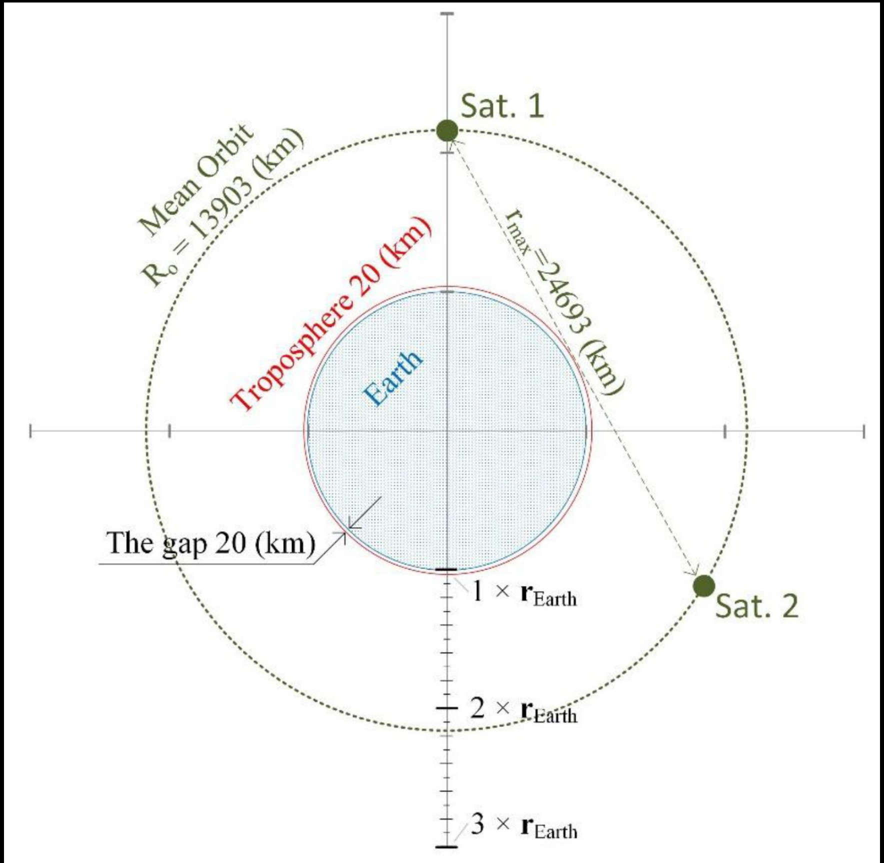
Ideas developed in collaboration with ESTEC (M. Martin-Neira, V. Kudriashov)

Two satellites at slightly different orbital radii (MEO), observing at high frequencies up to ~690 GHz

Satellites send data and correlate on the fly

Orbits determined by GNSS satellites, fringe fitting in post-processing on ground

Joining forces with Eric Villard and broader community on related ESA M8 proposal (next talk!)



Martin-Neira+ 2017, Roelofs+ 2019, Kudriashov+ 2021

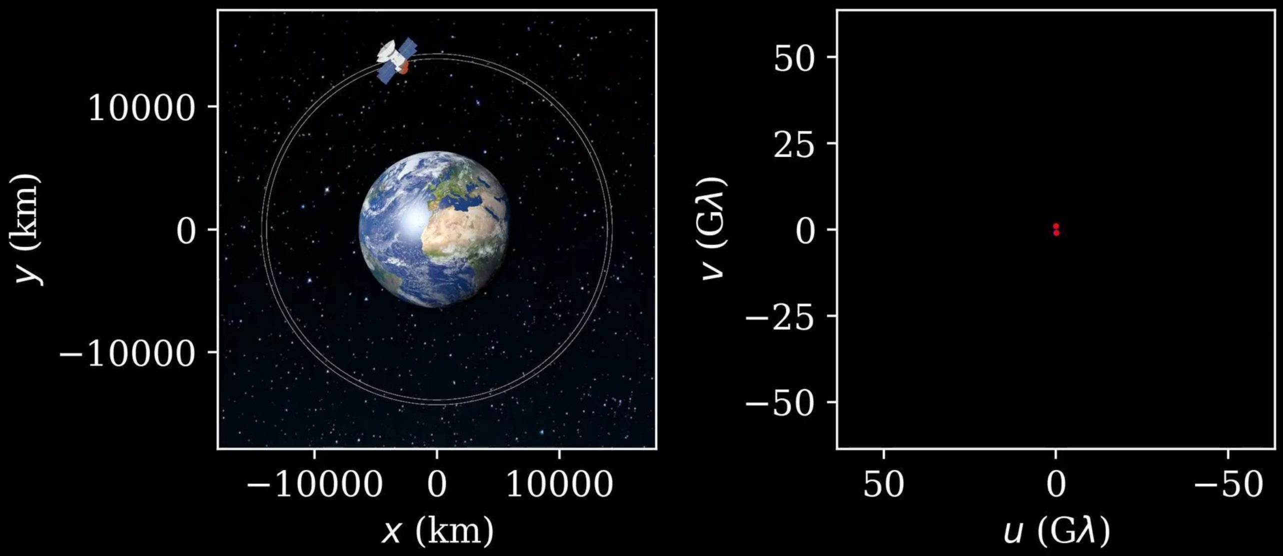
Uv-coverage, with only 2 satellites

Two (or three) satellites in circular orbits with slightly different radius

Dense spiral-shaped uv-coverage

~3.5 μas nominal resolution at 690 GHz

$t = 0.2$ h



Roelofs+ 2019

Imaging: Sgr A*

Excellent imaging, limited by sensitivity

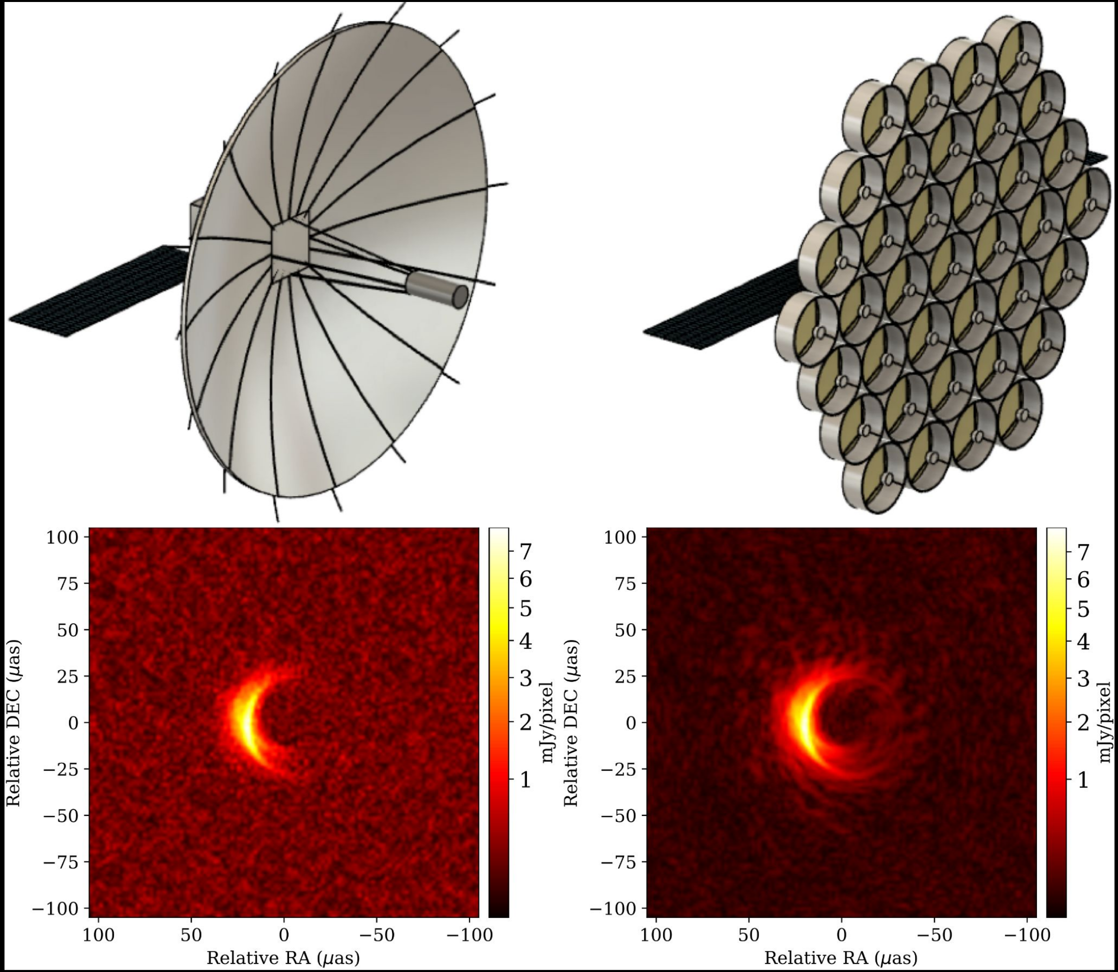
Static photon ring imaging, averaging over variability

Ideal laboratory for gravitational physics because of precise distance knowledge

Roelofs+ 2019, Gurvits+ 2022

4 m dish, 1 month

15.7 m dish, 1 month



Movie Making: M87

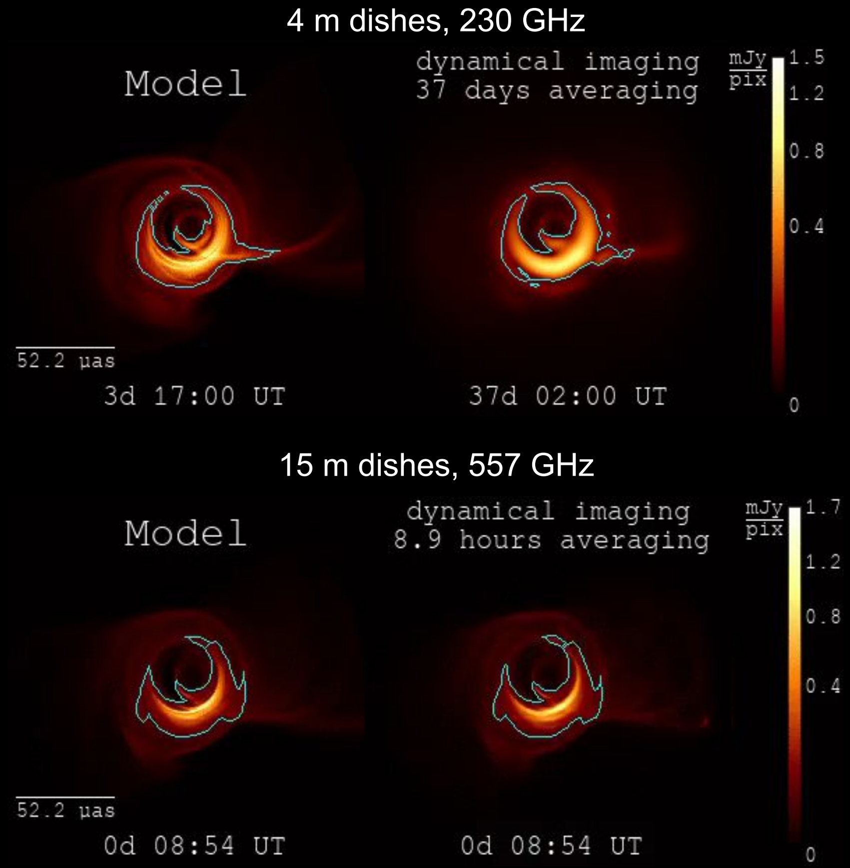
Movies of jet launching, black hole energy extraction

Distance between orbits can be optimized to fill uv-plane fast enough for movie making (~400 km for M87)

Determine spin from photon ring

Use full polarization to get structure and motion of magnetic fields

See whether B-fields are anchored in ergosphere and, how fast matter rotates, how and whether energy is transferred from ergosphere to jet

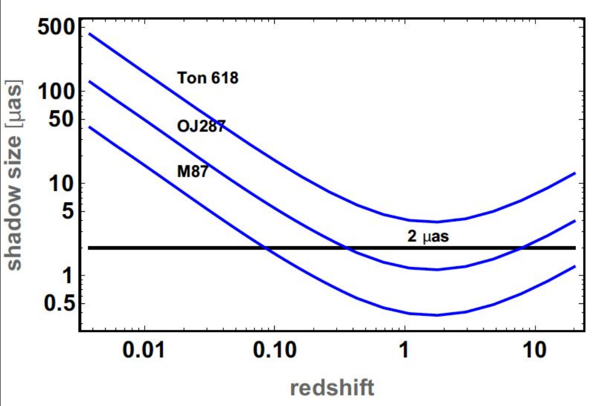


Shlentsova, Roelofs+ (2024)

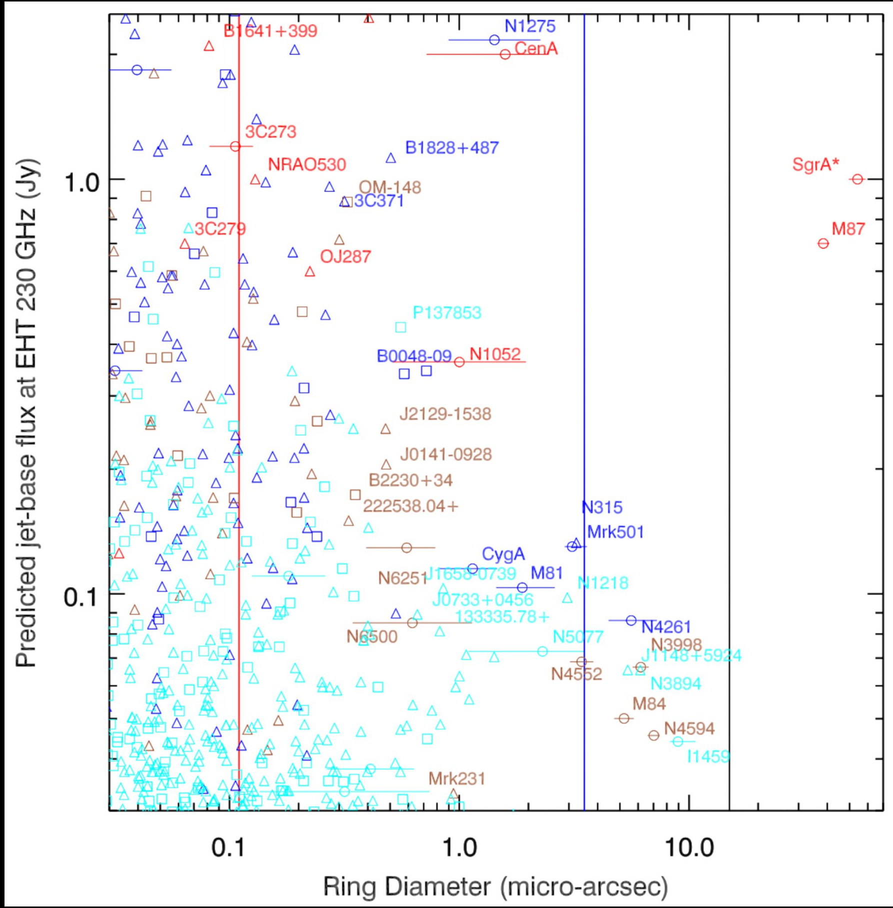
Additional science

How different are different black holes?

- Imaging and measuring black hole shadows for a larger sample
  - Seven black hole shadows exists with a **diameter between 5 and 10 μas and flux densities between 20 and 100 mJy at 230 GHz**
  - Potential targets are M84, M104, 3C270, and NGC3998



Gurvits et al. (2021, ESA WP)



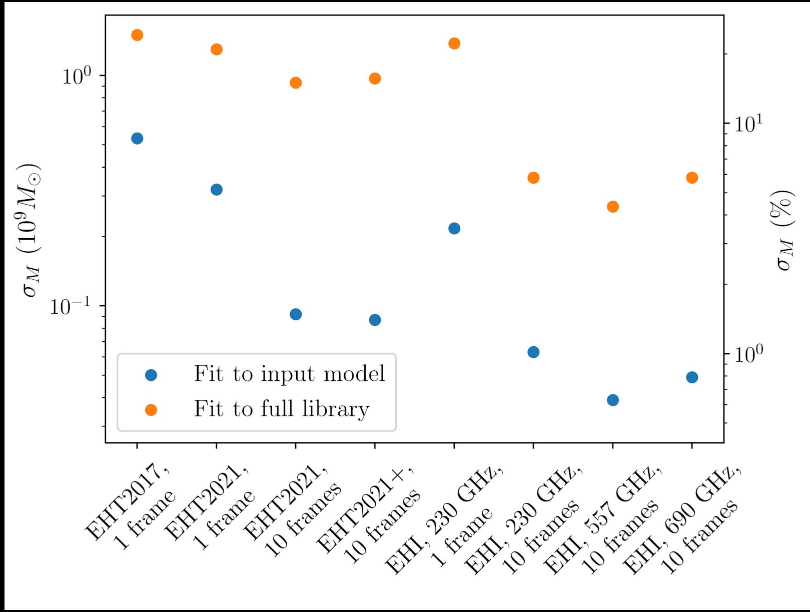
Ramakrishnan+ (2023)

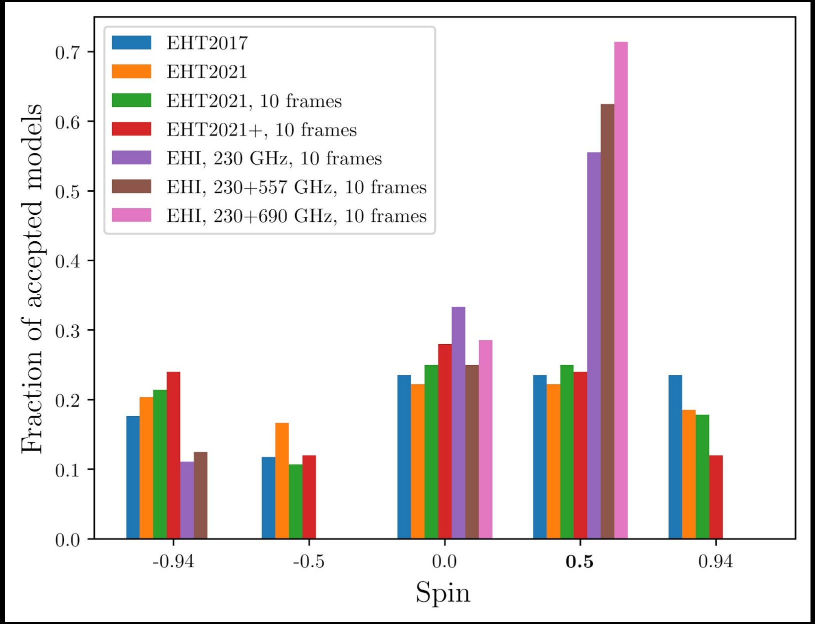
Additional science

- Imaging non-horizon AGN with order-of-magnitude better resolution: jet base, corona, connection to multi-messenger science
- Imaging protoplanetary disks (?) using short baselines by keeping the constellation compact through small orbital changes
- Single dish spectroscopy (?)
- Join long and short-baseline concepts and science in one mission
  - See also Eric Villard’s talk!

Parameter Estimation

Fitting an M87 GRMHD model library to simulated data with different arrays and # of observations
Using EHT M87 Paper VI scoring framework





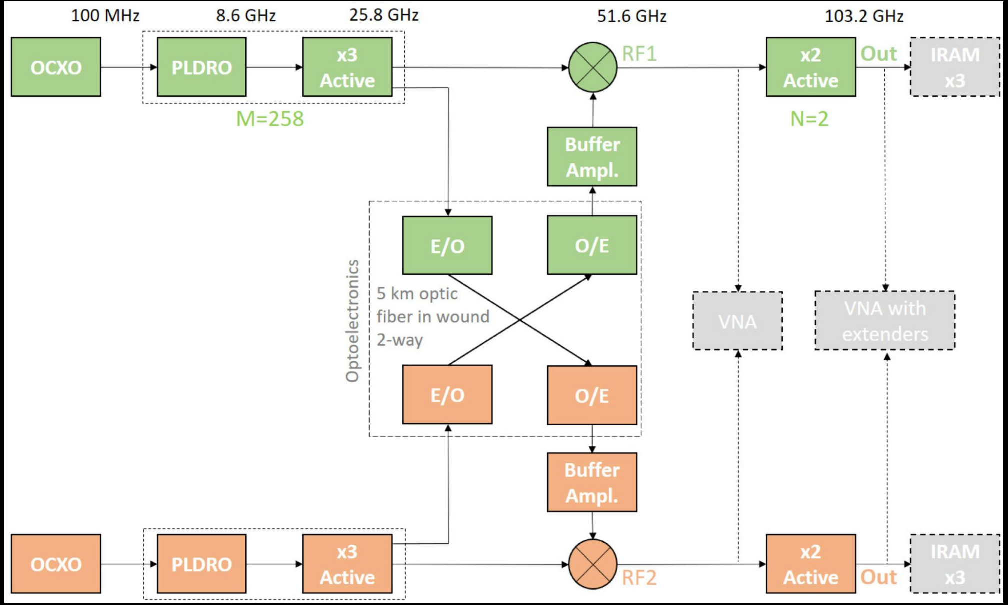
Repeated observations help getting a significantly better mass measurement (averaging variability)

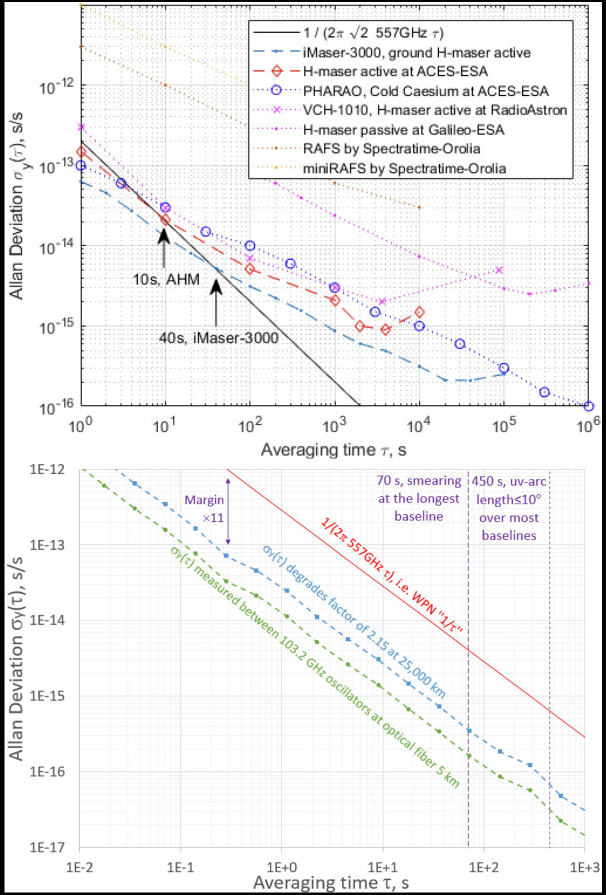
Constraints on black hole spin and other GRMHD parameters

Sub-percent precision mass measurements with EHI → GR tests

Roelofs+ 2021

“Connected interferometer in space” concept





Satellites send data and correlate on the fly

Positions (cm-level) determined by GNSS satellites

Fringe fitting in post-processing on ground

Make use of intersatellite laser link for distance measurements and synchronization of clock signals

Kudriashov+ (2021)

Technology Demonstrator: EHI Pathfinder (EHIP)

Demonstrating the clock sharing and on-board correlation concept in-orbit

First space-space VLBI experiment!

Idea: small (~1-meter) dishes imaging jets at cm wavelength, possibly on CubeSats

Both on-board correlation and direct data downlink

Initial studies started, proposal for ESA OSIP small systems study in progress

(Science) ideas welcome, both for full mission and demonstrator!

ESA RACE double CubeSat mission

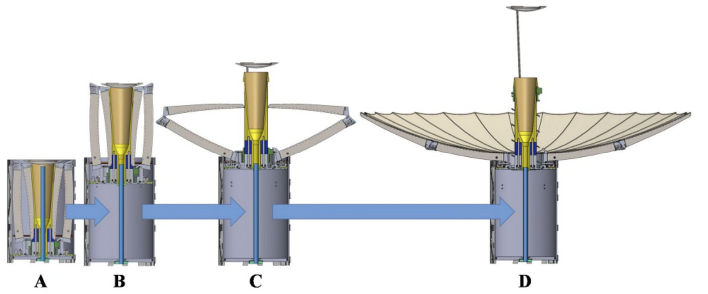
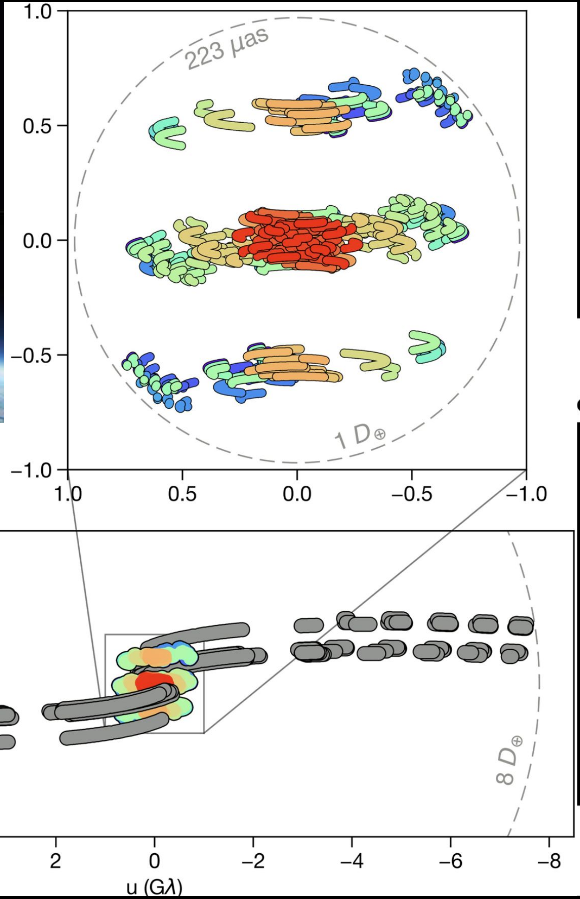
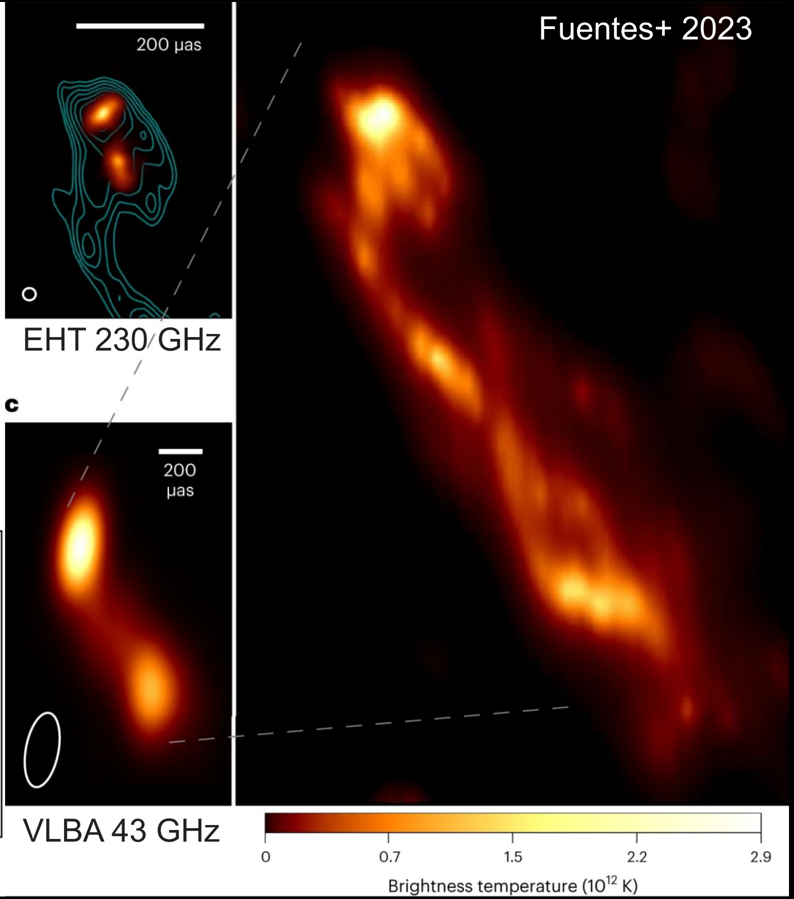


Figure 2. KaPDA Deployment Sequence

First test case: 3C279 at 22 GHz

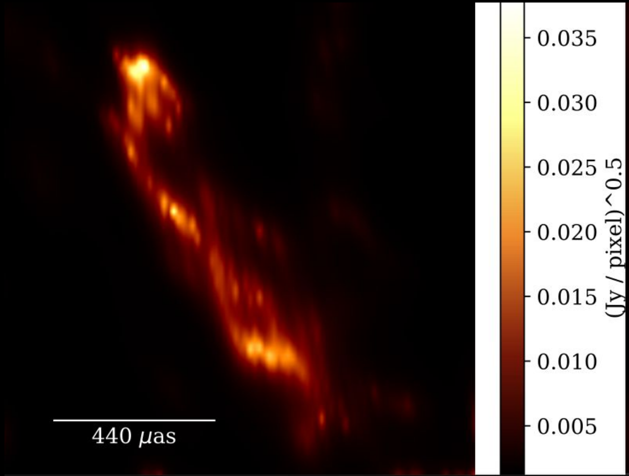




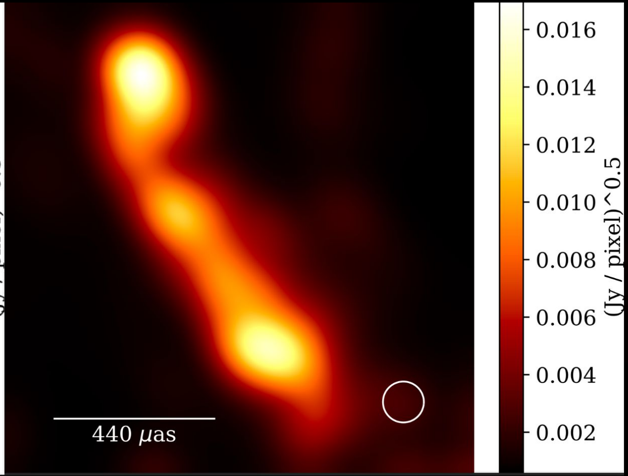
3C279 EHIP simulations

Two 0.6-meter dishes
22 GHz
MEO orbits separated by 30 km
20 days of observing
Tsys 120 K, 5 GHz bandwidth

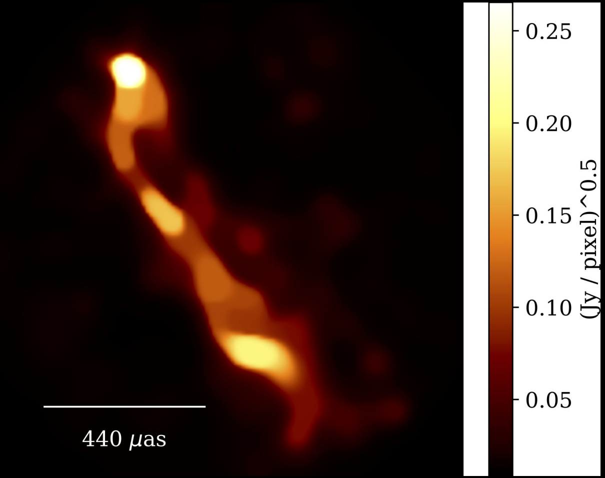
Ground Truth (Fuentes+ 2023)



Blurred to nominal EHIP resolution



EHIP Imaging

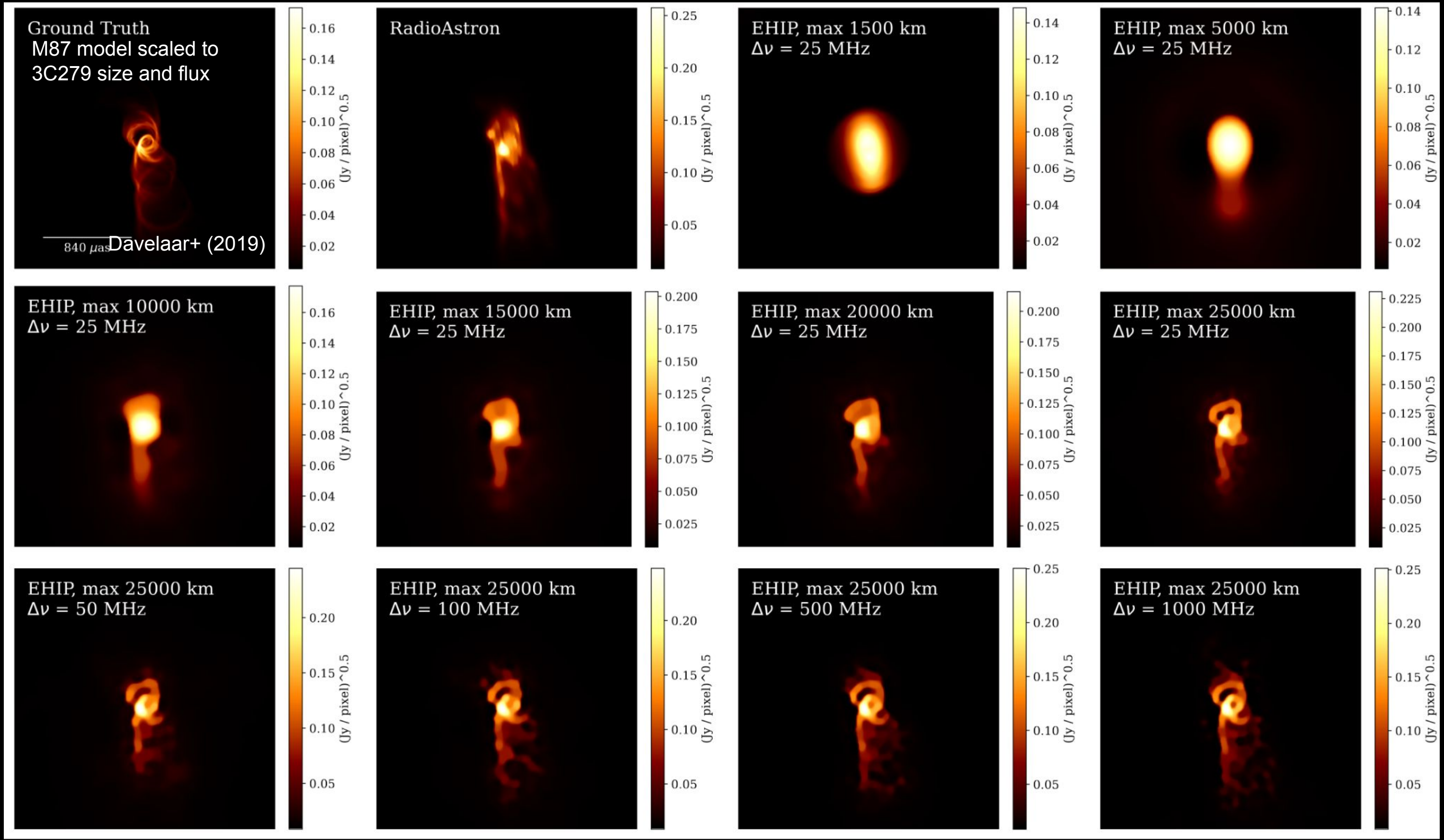


RadioAstron observed image
10 m dish + full ground array
7.6 Gλ baselines

Two 0.6 m dishes
1.8 Gλ baseline

Thanks to EHIP's excellent uv-coverage, we can see similar features as RadioAstron with just 2 small dishes and shorter baselines, independently of ground conditions

A different source model



With sufficient inter-satellite distance and bandwidth, EHIP can recover image features that were not accessible to RadioAstron

Summary and next steps

Prospects for space-based black hole imaging are excellent: exciting science, sharp images, and viable mission concepts

ESA M-class proposal under construction (see also Eric Villard’s talk)

First jet imaging simulations of EHI Pathfinder are cause for optimism, with ESA OSIP small systems study proposal to be submitted

Science ideas are welcome!