Zooming in on
Black Holes
with the Event Horizon Telescope

Huib Jan van Langevelde
JIVE Dwingeloo & Sterrewacht Leiden

Introducing

- Chief Scientist at JIVE:
  Joint Institute for VLBI ERIC
  - Hosted by ASTRON, Dwingeloo
  - Collaboration of nations with radio facilities, supported by radio-astrono
  - EVN: European VLBI Network
    - Consortium of (European) Telescopes operators
- Professor Galactic Radio Astronomy
  Sterrewacht Leiden, Leiden University
  - Oldest astronomy department in the world
- Affiliated staff
  University of New Mexico, Albuquerque

JIVE team got involved in the EHT

- European BlackHoleCam project
  - Working on the CASA based calibration pipeline
  - Used in parallel with HOPS and AIPS based schemes

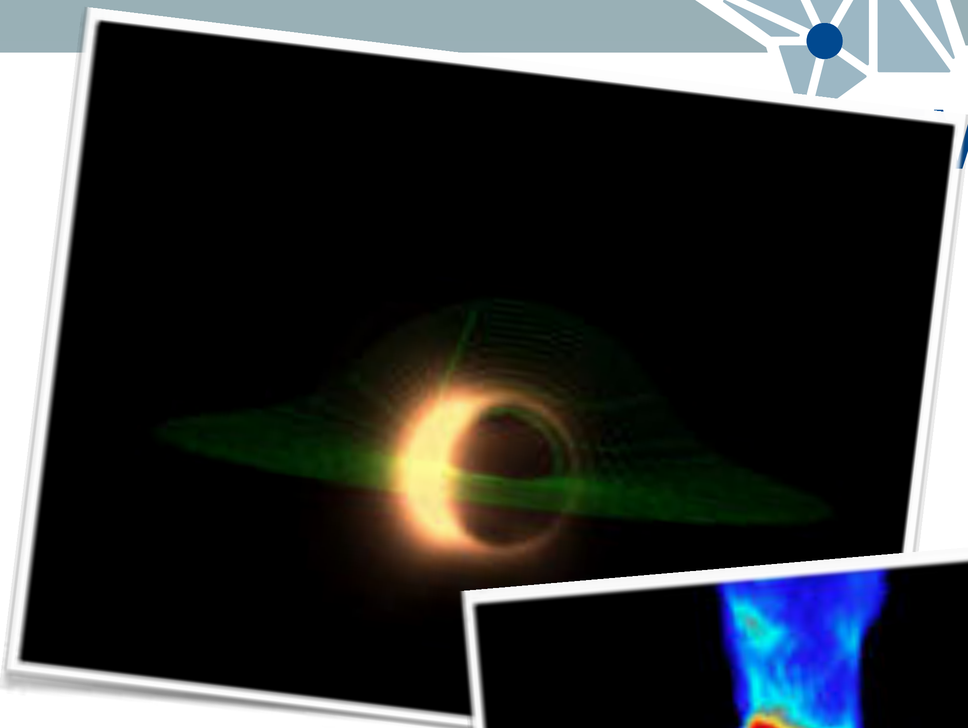
- Rooted in earlier work on VLBI software
  - JIVE runs independent SFXC software correlator
  - Developed ParselTongue Python AIPS interface
  - pySched python version of Sched
  - jive5ab VLBI recording software
    - for simultaneous recording and streaming
  - "casa-fication" of VLBI processing
    - VLBI casa workshop last week attended by

JIVE (software) team members of EHTC

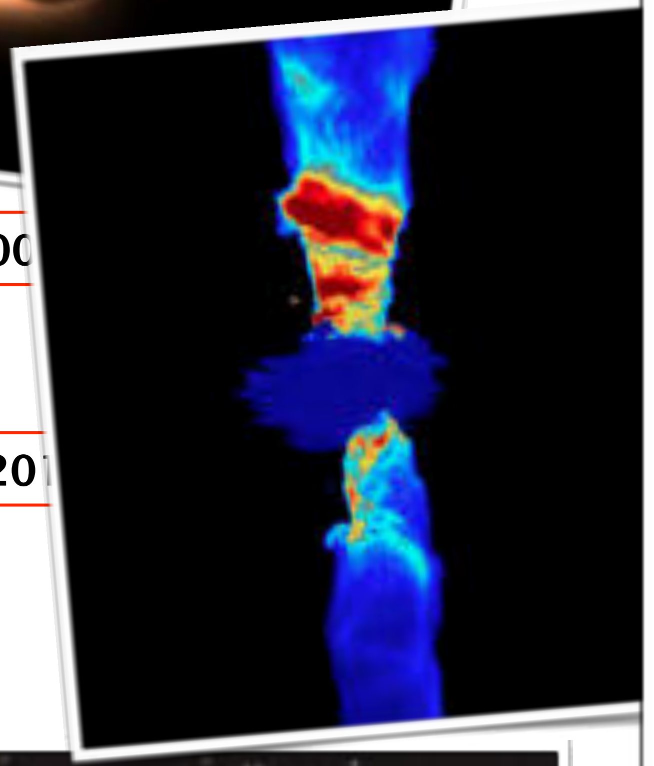
Lezing Alkmaar 24 Nov 2017:

Can resolve at 1mm

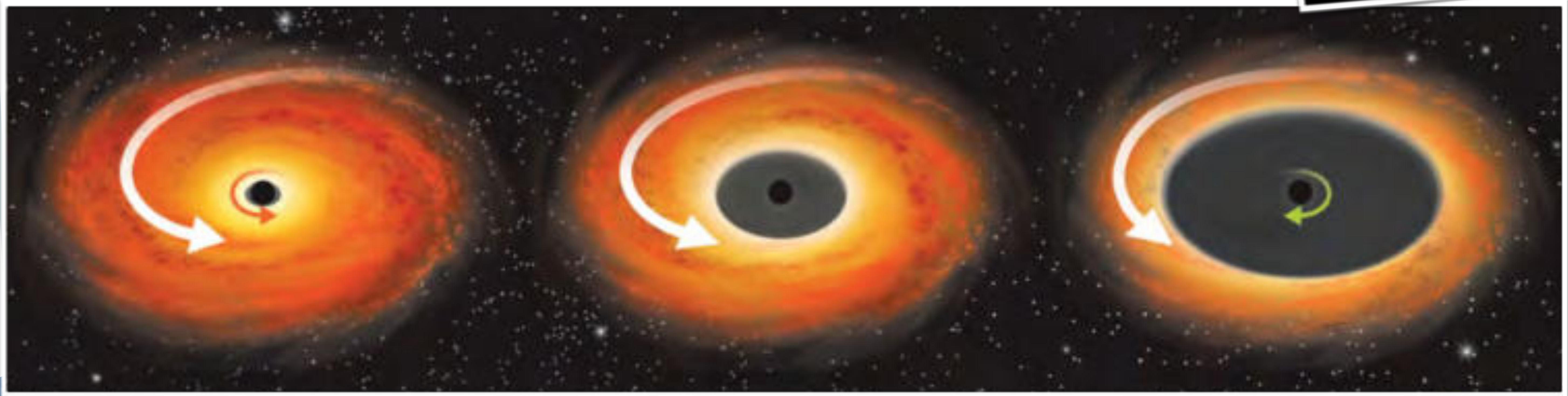
- Expected to see the ‘shadow’ of the black hole
  - Relativistic beaming and gravitational lensing
  - of the accretion disk (and jet)
- Expected response depends on:
  - Brightness of accretion disk, jet
  - Inclination of the system
  - State of the activity
    - G2 cloud interaction
  - Nature of the Black Hole
    - Just spin expected



Broderick & Loeb, 200

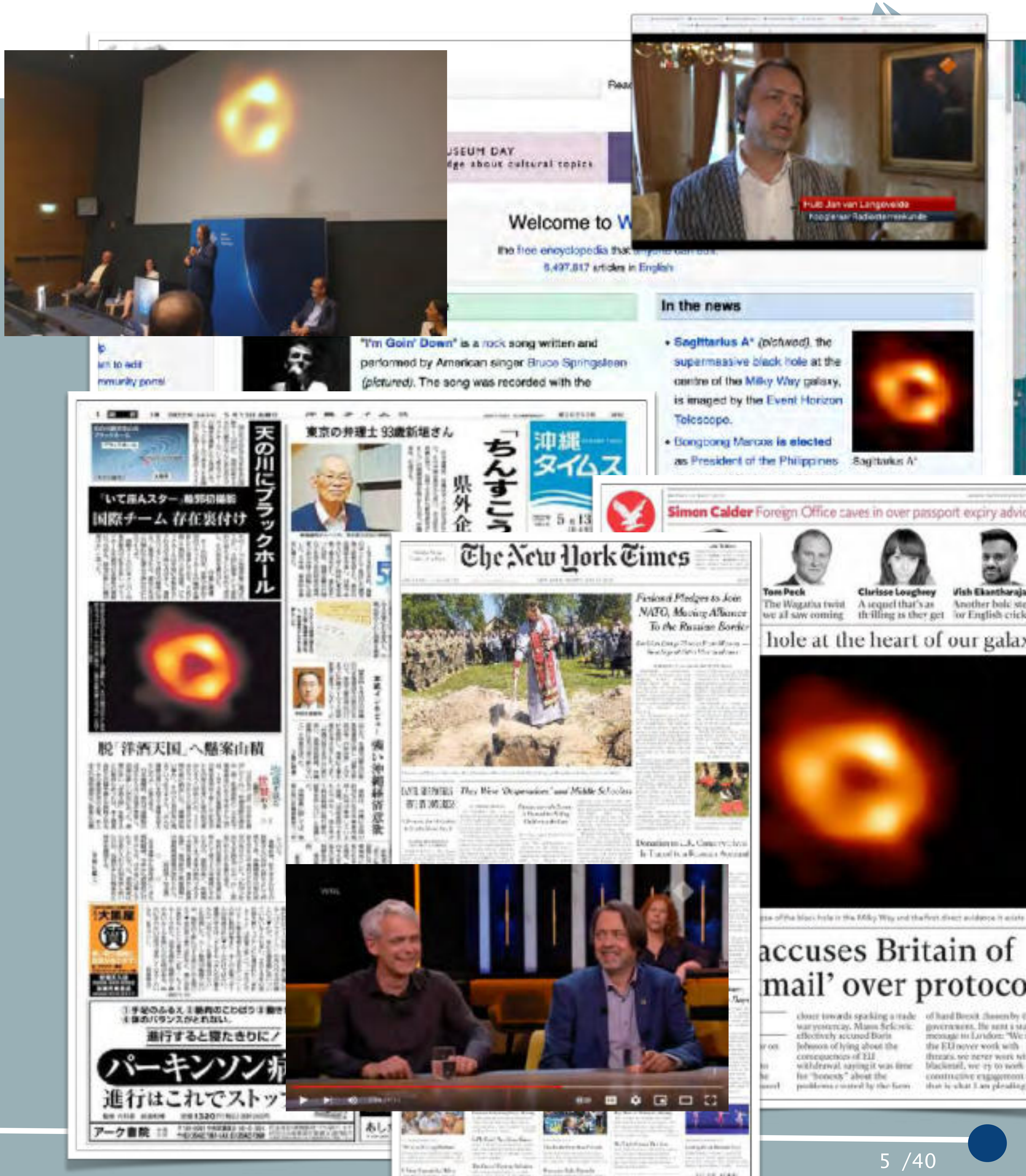


Moscibrodzka et al. 20



The Event Horizon Telescope

- Project Director since mid 2020
- Key roles for other NL scientists
  - Nijmegen: initiated project, simulations, calibration, new initiatives
  - Amsterdam: models, organising simultaneous observations other wavelengths
  - Leiden: ALMA support, calibration methods
  - JIVE: VLBI software
- Key contributions largely funded through European BlackHoleCam project
  - New projects centred on African Millimeter Telescope



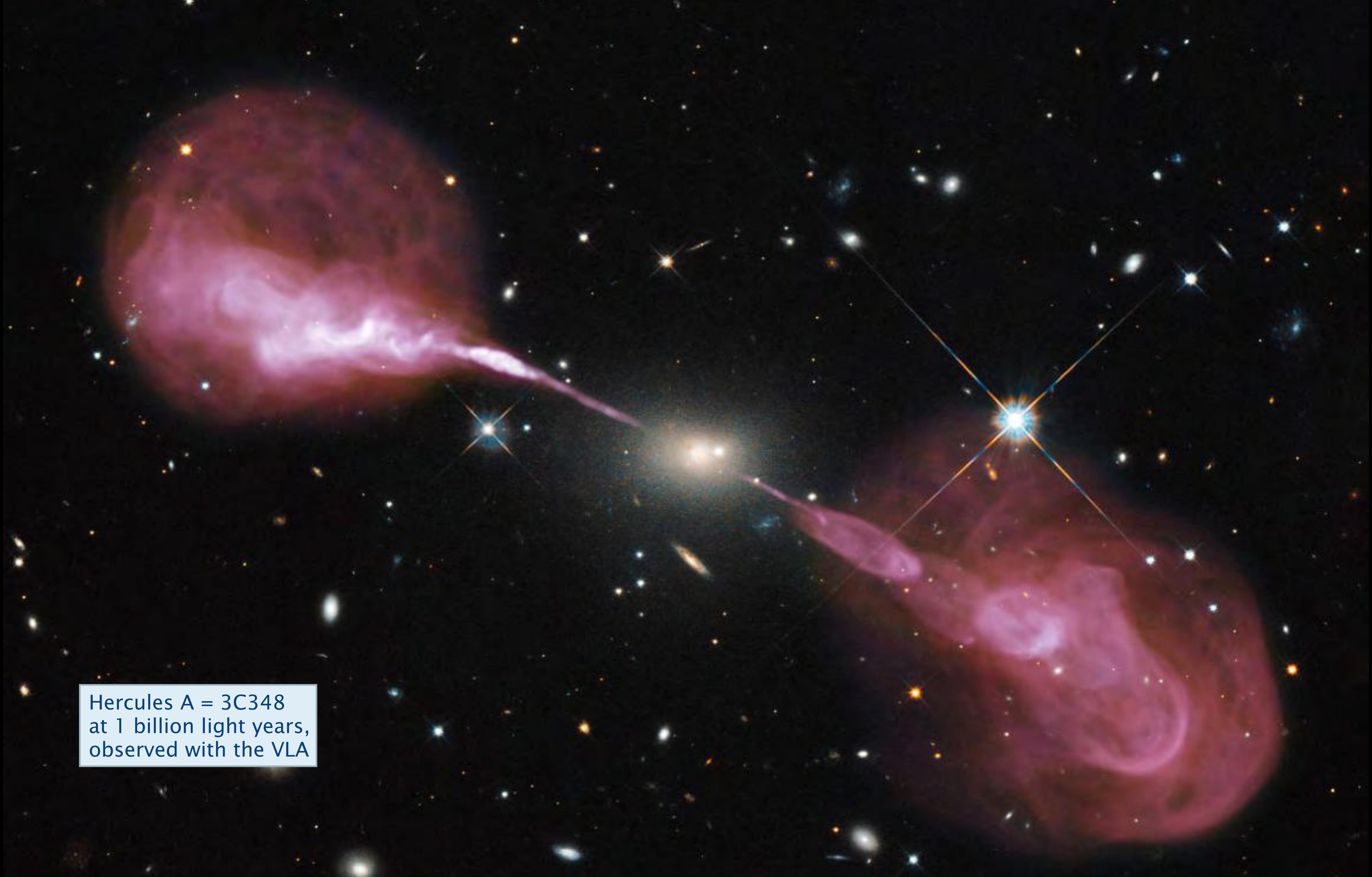
The sky appears full of stars, but beyond are billions of galaxies

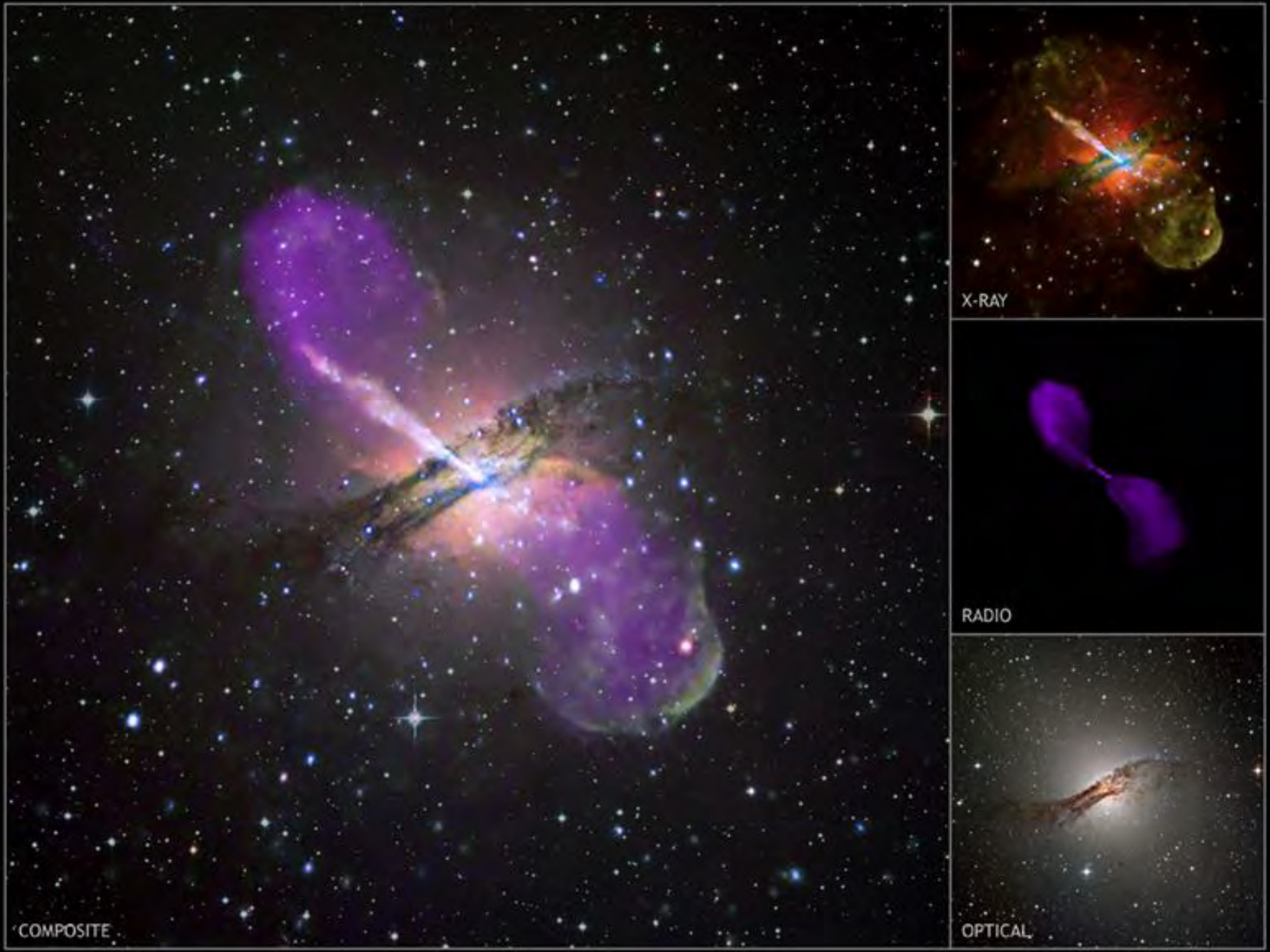
Hubble image of field in Tucana

The radio sky is dominated
by bright radio galaxies in far universe

Radio sky over Green Bank radio telescopes

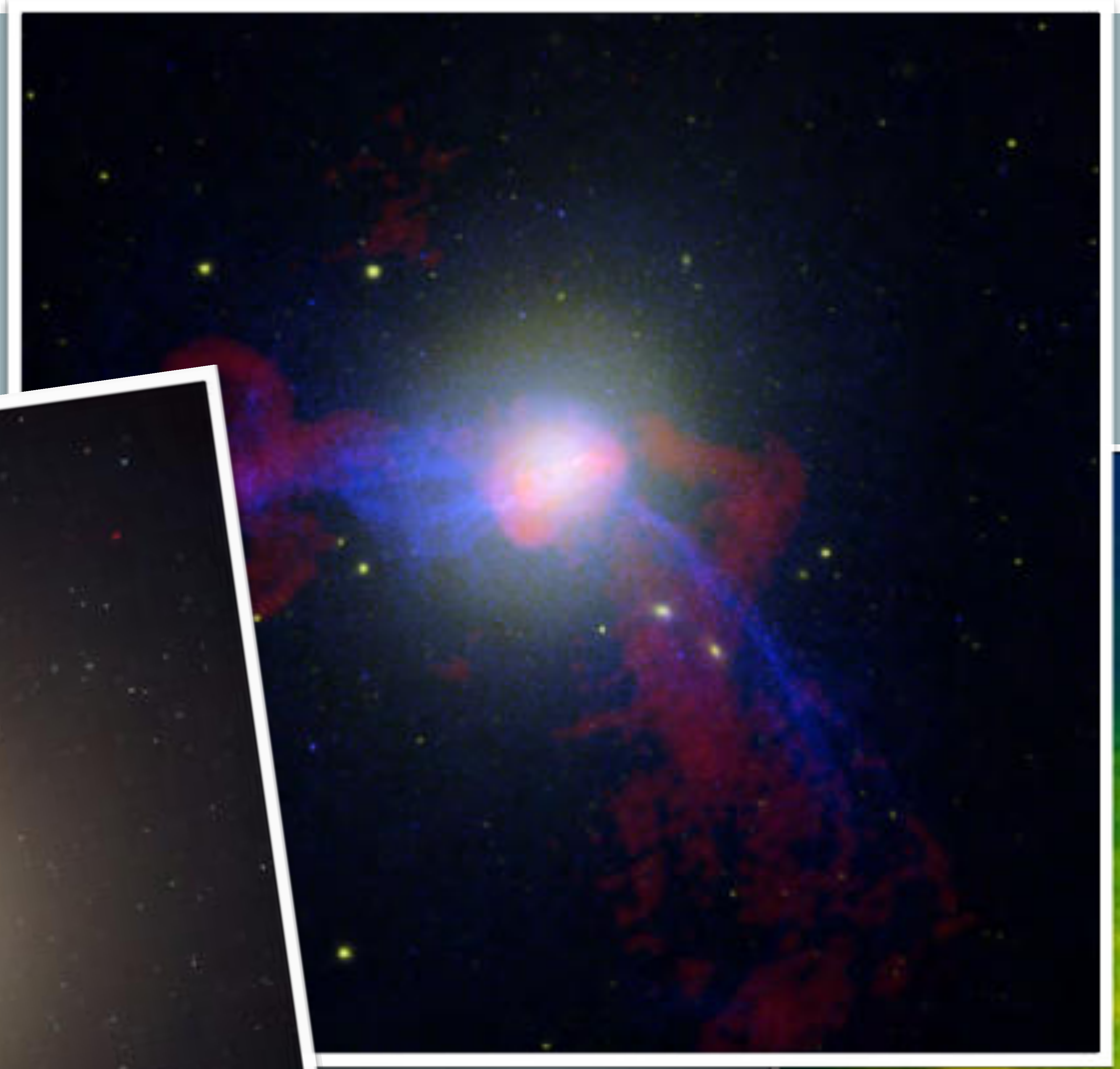
Moon to scale on LOFAR field

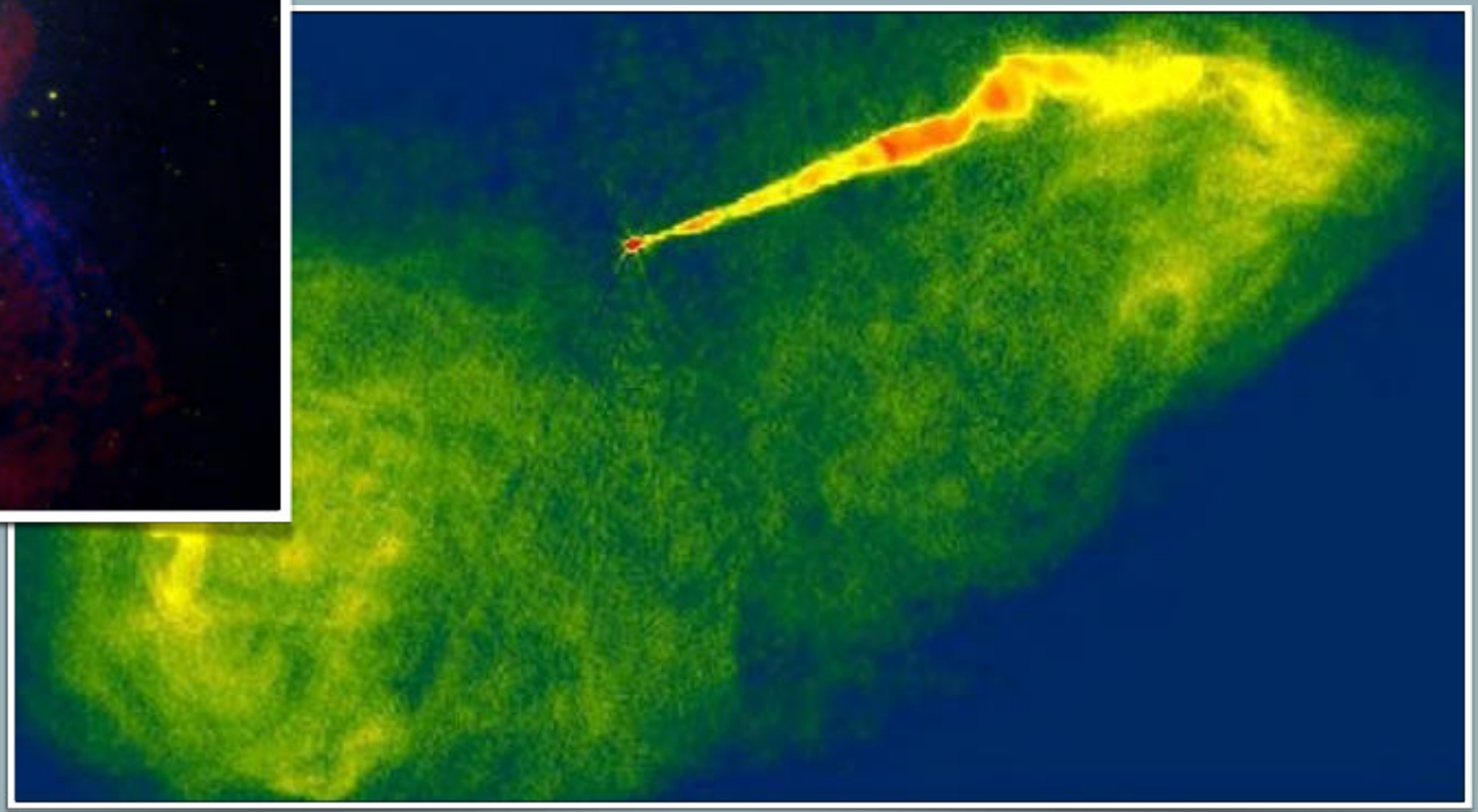

Hercules A = 3C348
at 1 billion light years,
observed with the VLA



Centaurus A = NGC5128
at 10 million lightyears,
various observing wavelengths

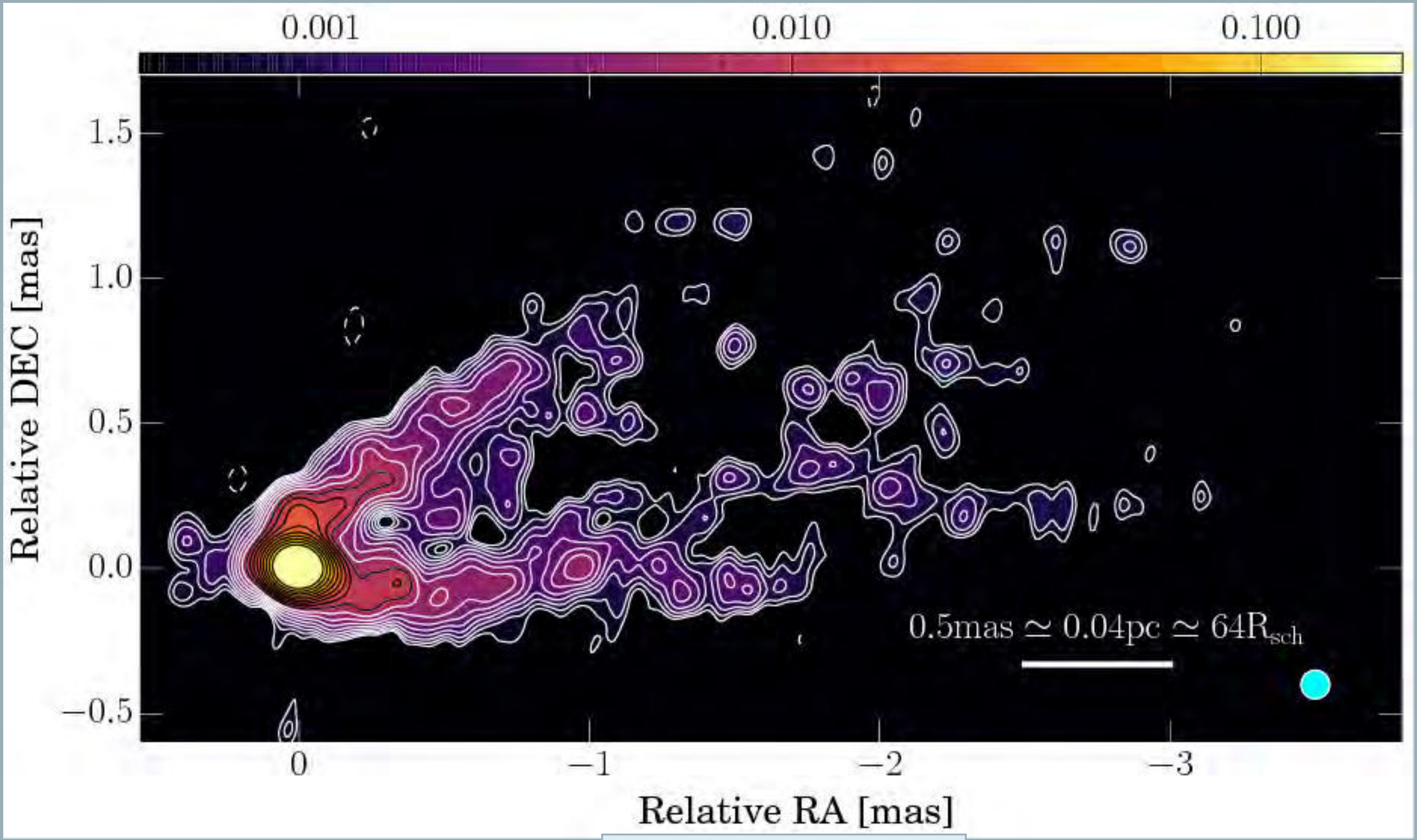
Messier 87 = Virgo A





Hubble LOFAR + optical VLA

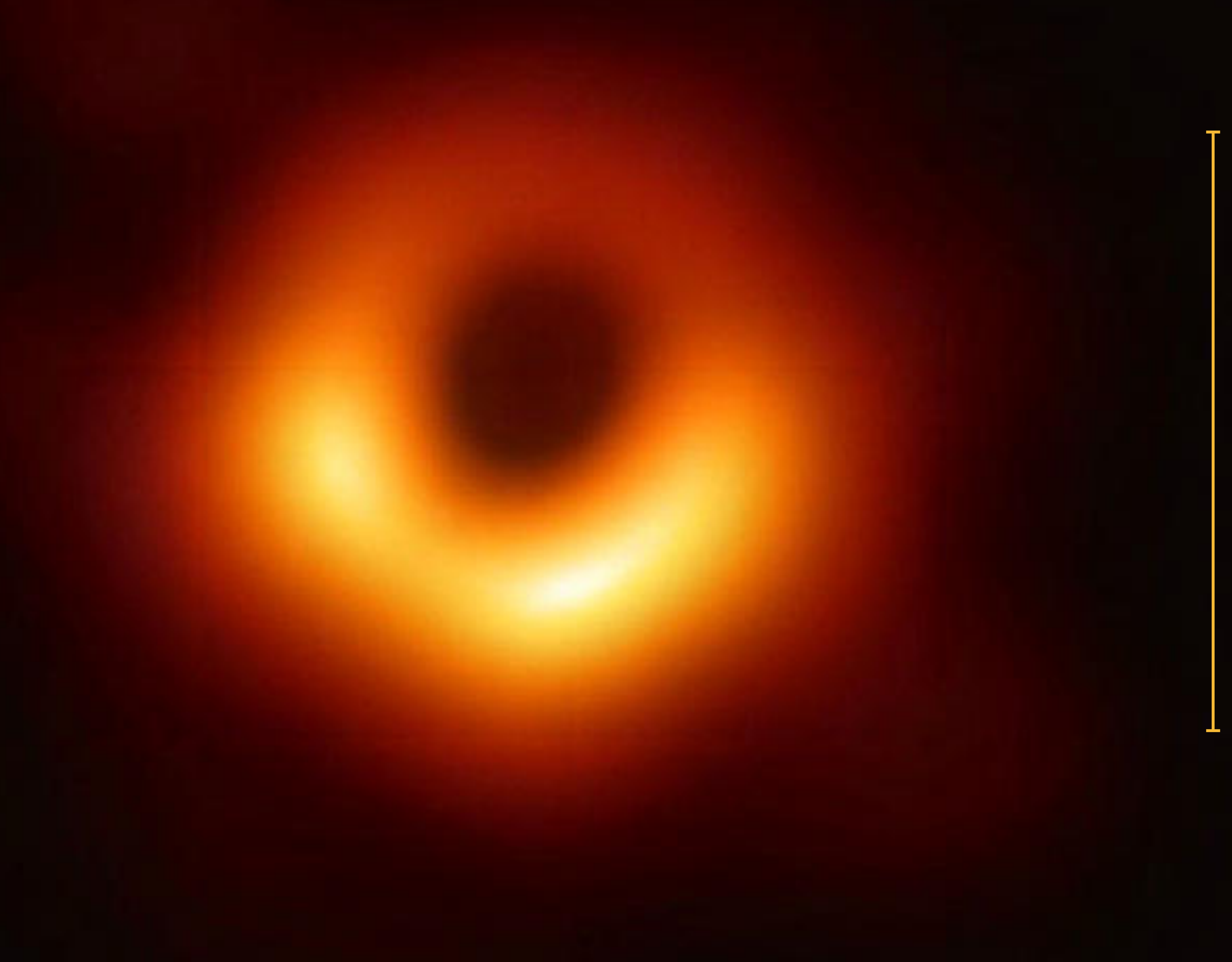
Zooming in on the engines of radio galaxies



Virgo A M87, Kim, Jae-Young et al. 2016

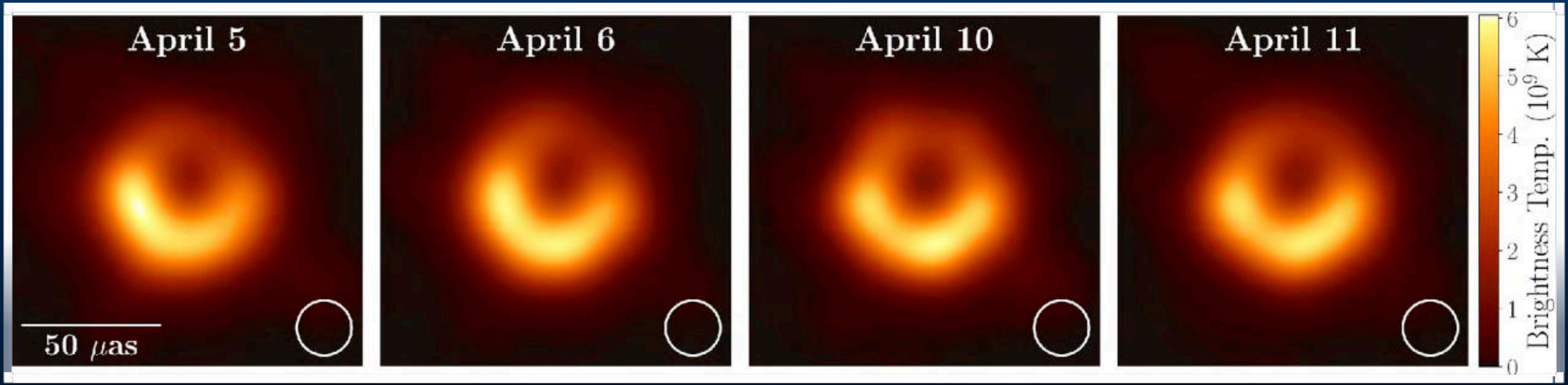
First M87 Event Horizon Telescope Results I. The Shadow of the Supermassive Black Hole

Distance to M87: 54 million lyr
Black Hole mass: $6.5\ 10^9\ M_\odot$



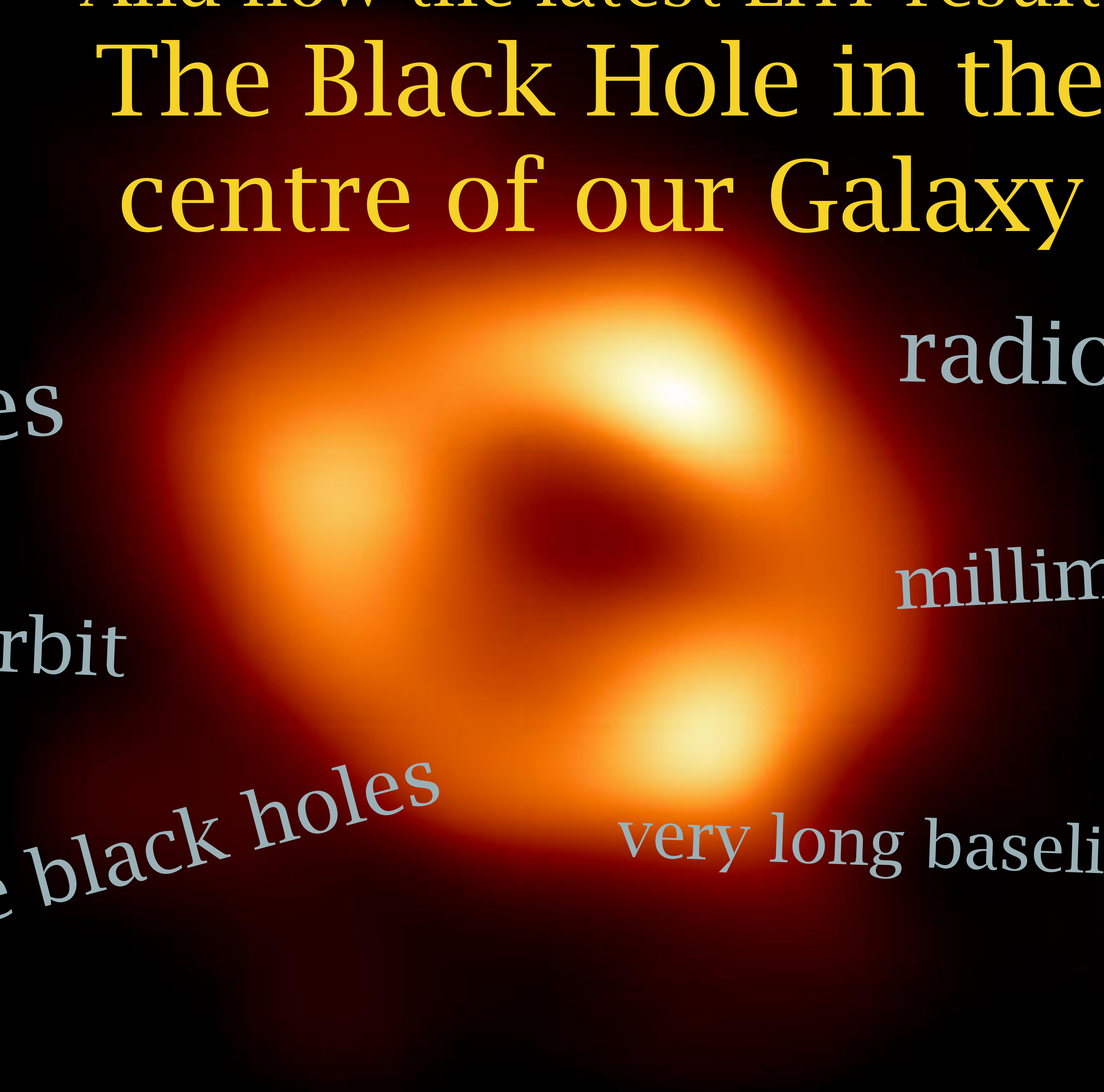
42 μas
≈ 700 au
= 98 lh

Observations at 1.3 mm ≃ 230 GHz
Brightness temperature: $6\ 10^9$K

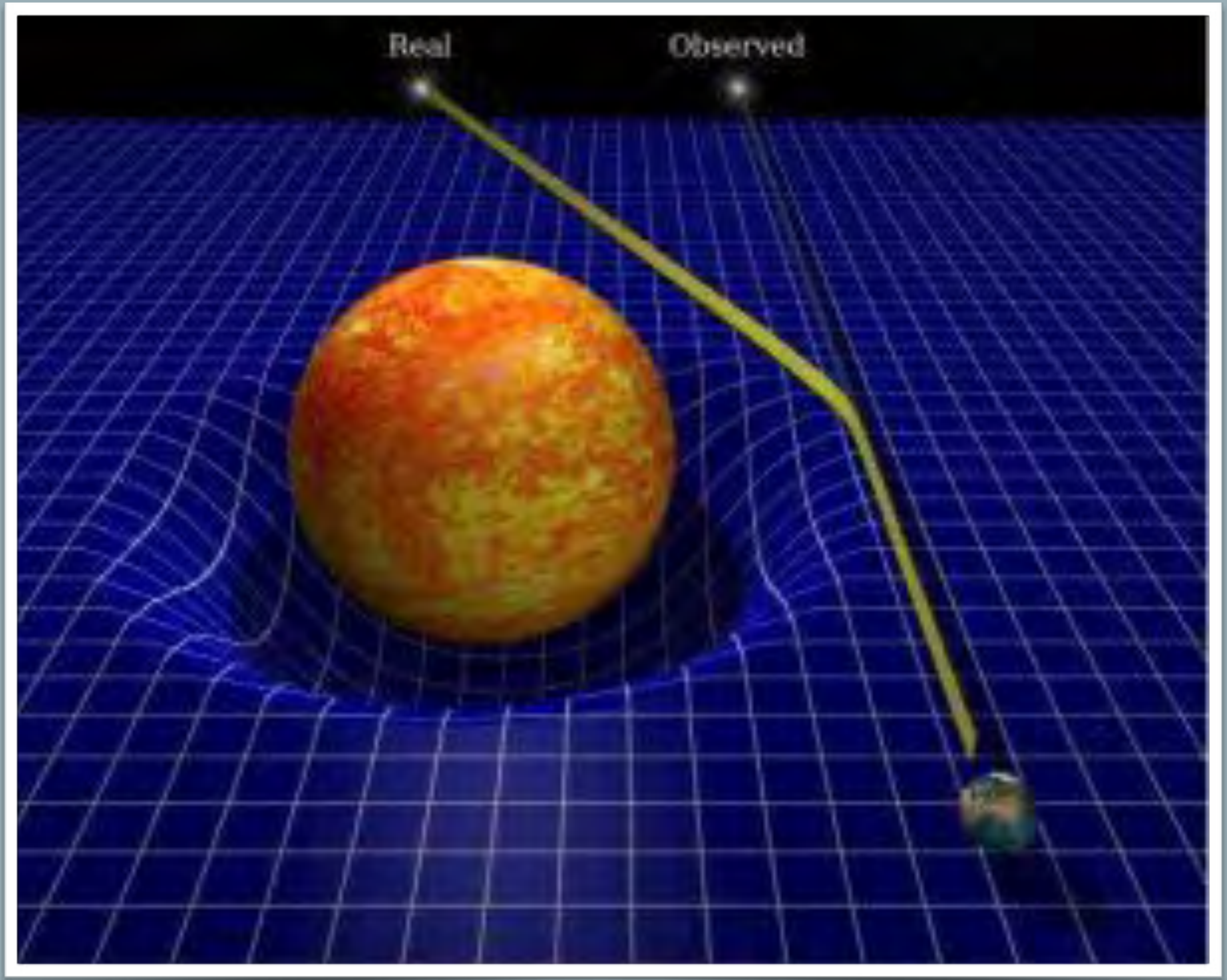

April 5
April 6
April 10
April 11
50 μas
Brightness Temp. (10^9 K)
0
1
2
3
4
5
6

And now the latest EHT result:

The Black Hole in the centre of our Galaxy

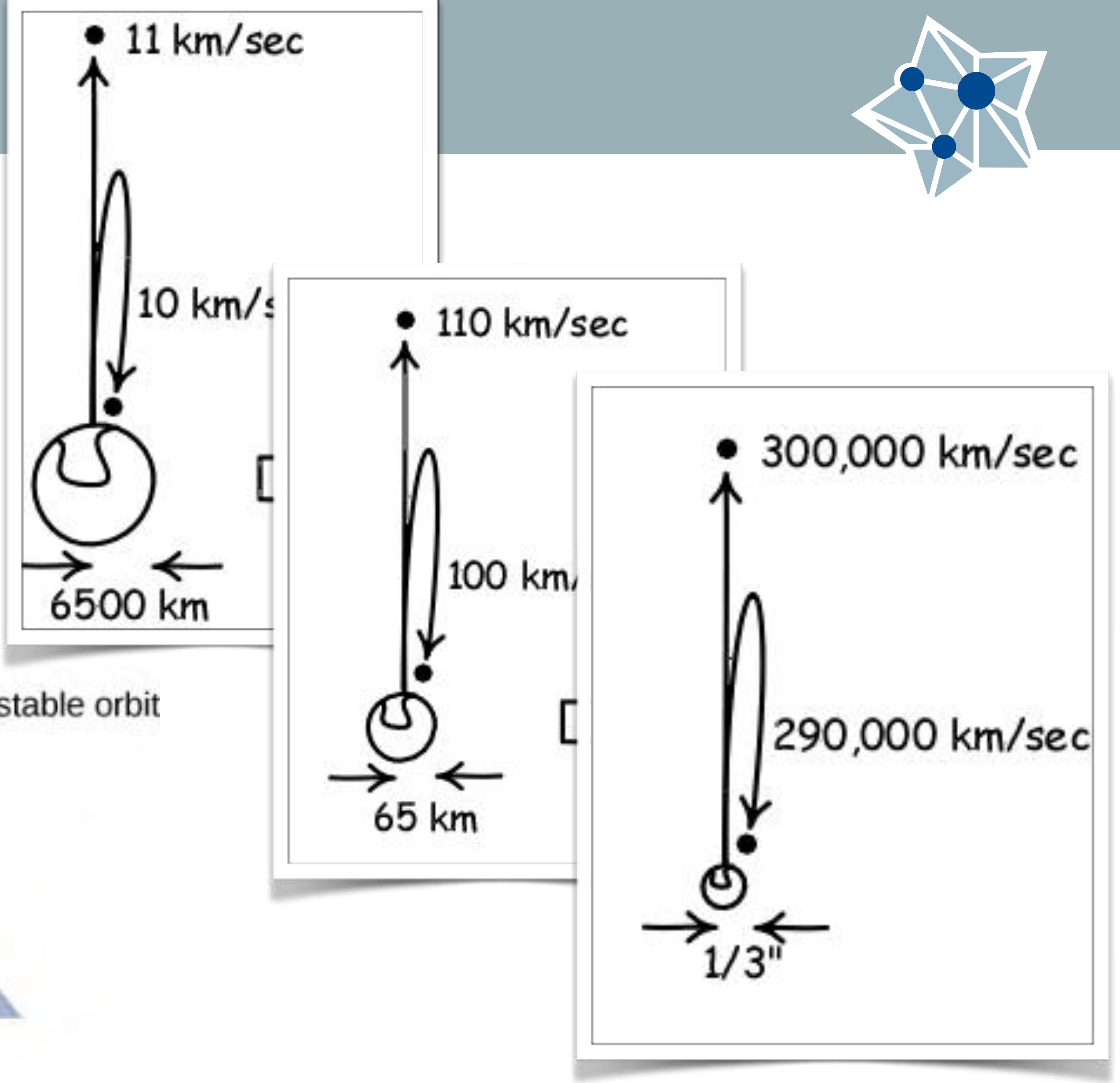


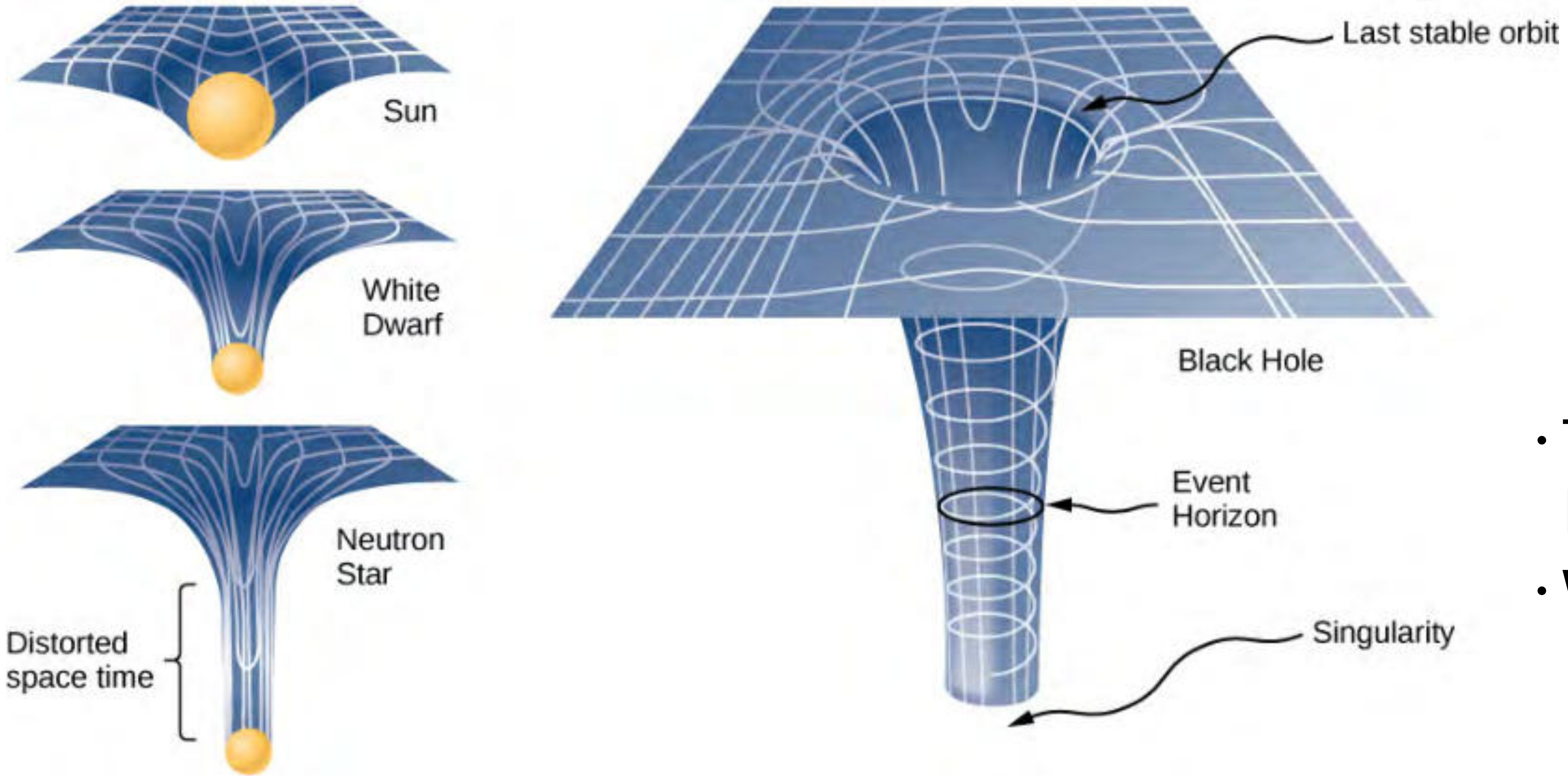
Einstein’s relativity
special: nothing will go faster than light
general: even light will feel gravity



Absurd consequence: Black Holes

- Make gravity so concentrated that nothing can escape
  - Not even light…
  - No information…



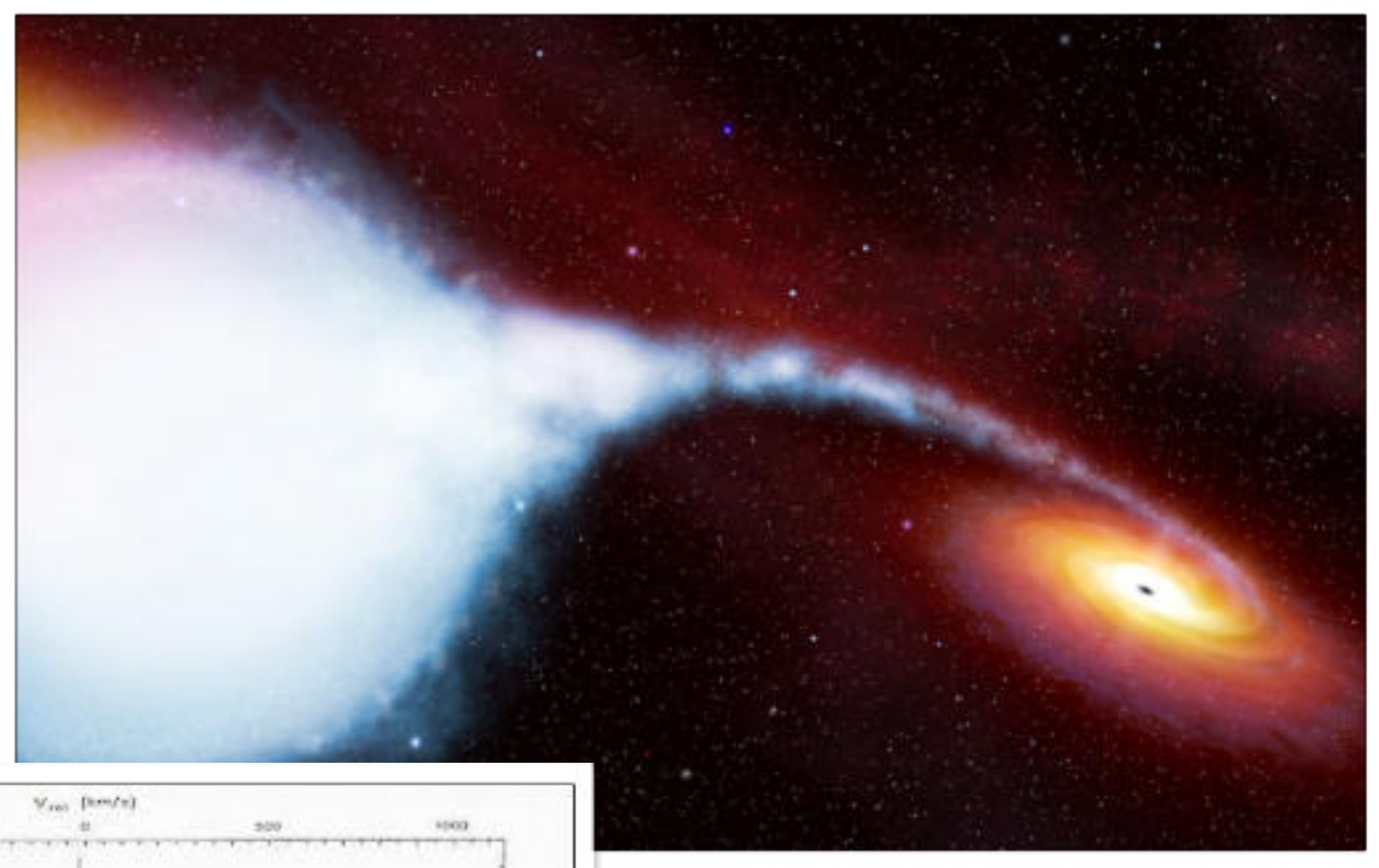


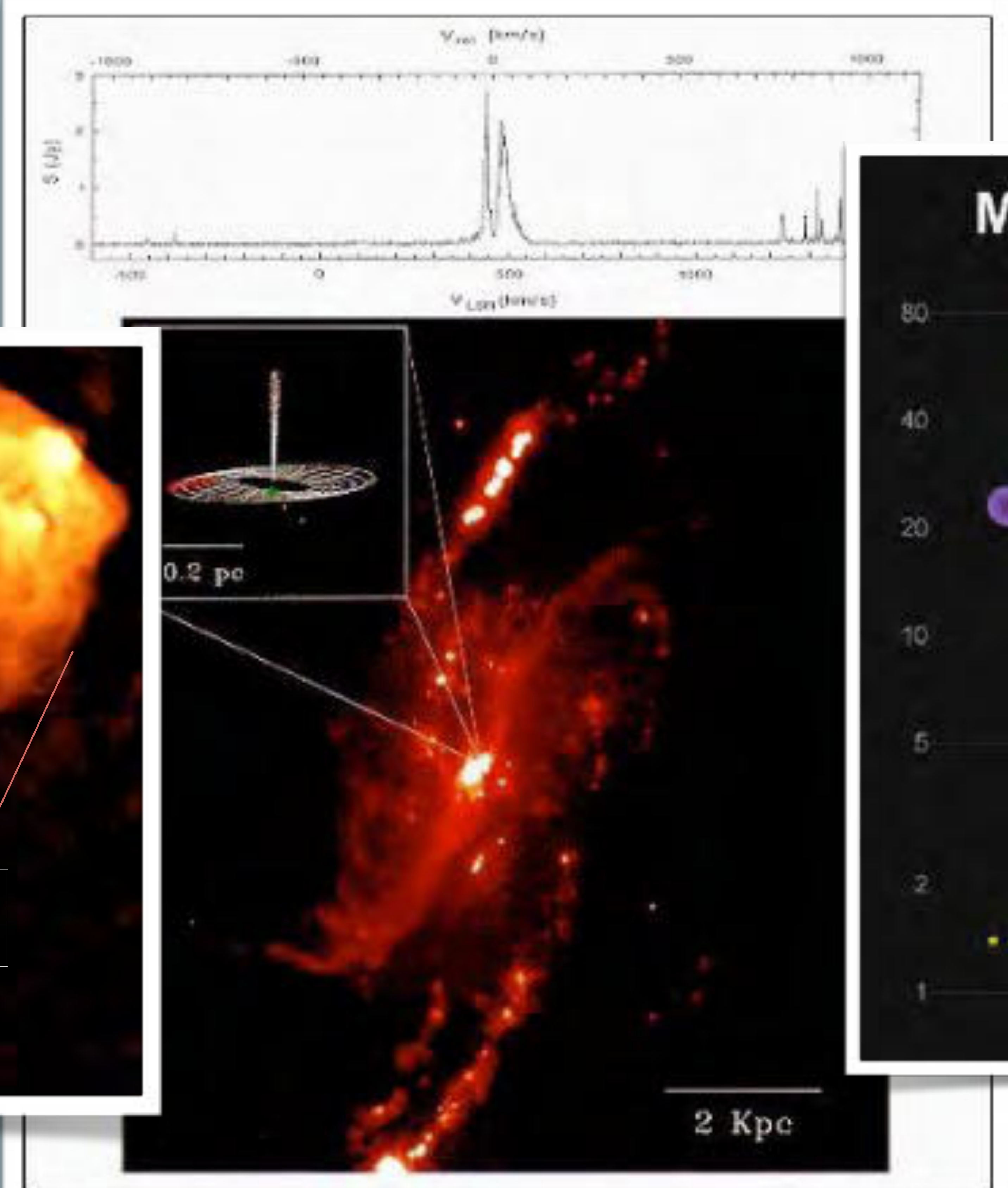
- The boundary is called Event Horizon
- We have learned this can happen for stars
  - Collapse when they have no fuel left

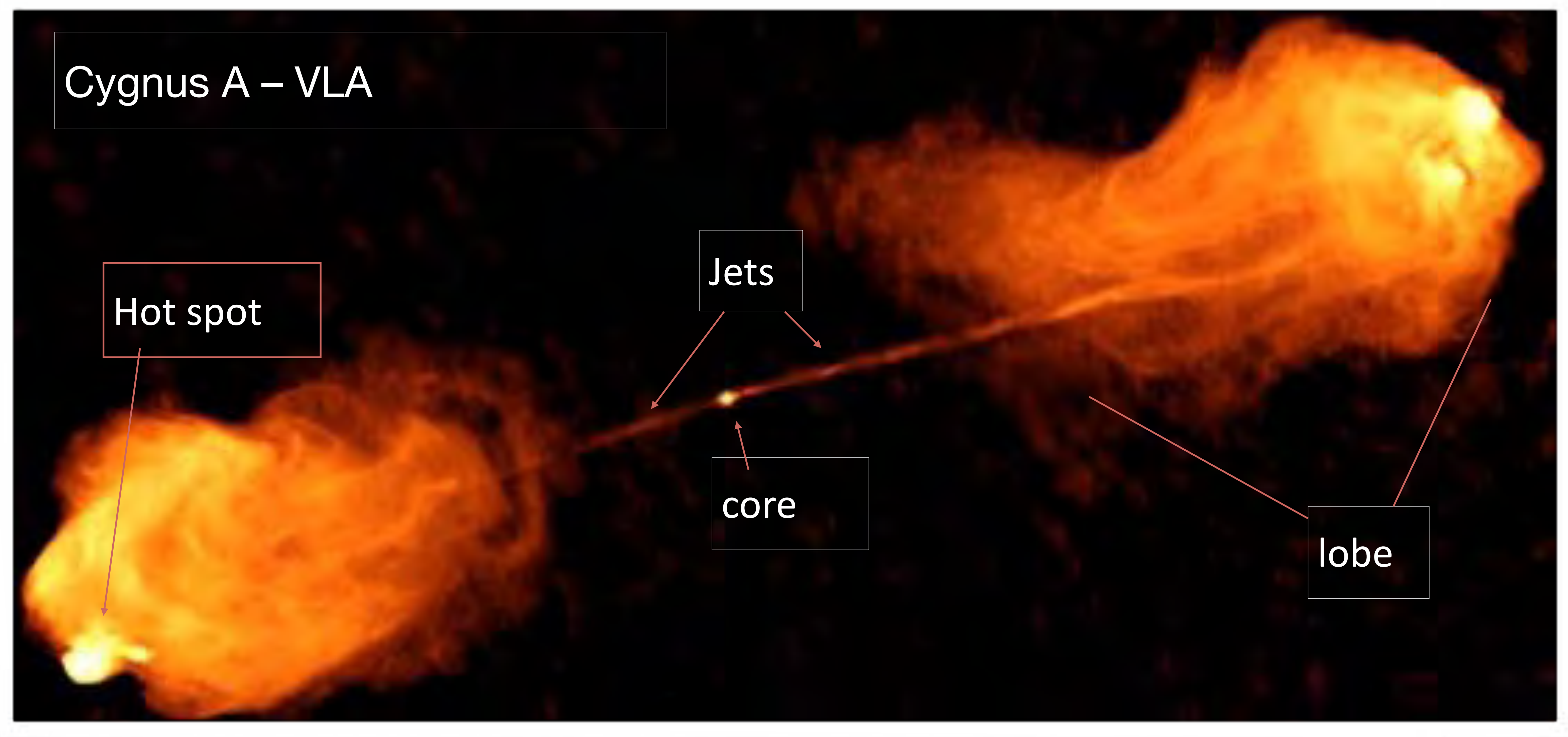

HAVE YOU EVER HEARD OF A "BLACK HOLE", CAPTAIN?
I'M AFRAID NOT, MR. SPOCK! PLEASE EXPLAIN!

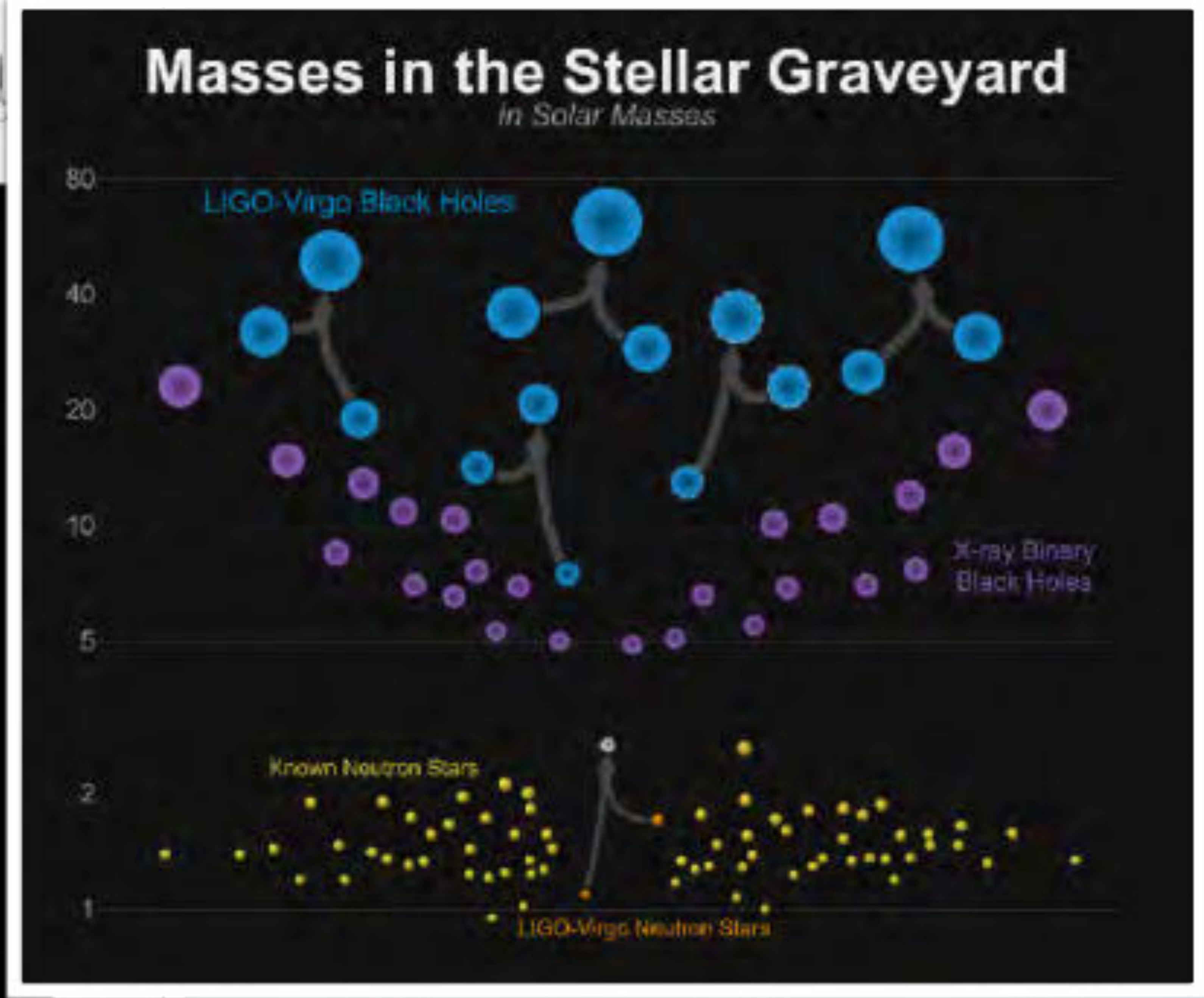
Really?

- Active galaxies producing energetic jets
- Binary stars with dark companions
- Some AGN have observed fast rotating disks
- Gravitational waves of compact mergers
- The Galactic centre

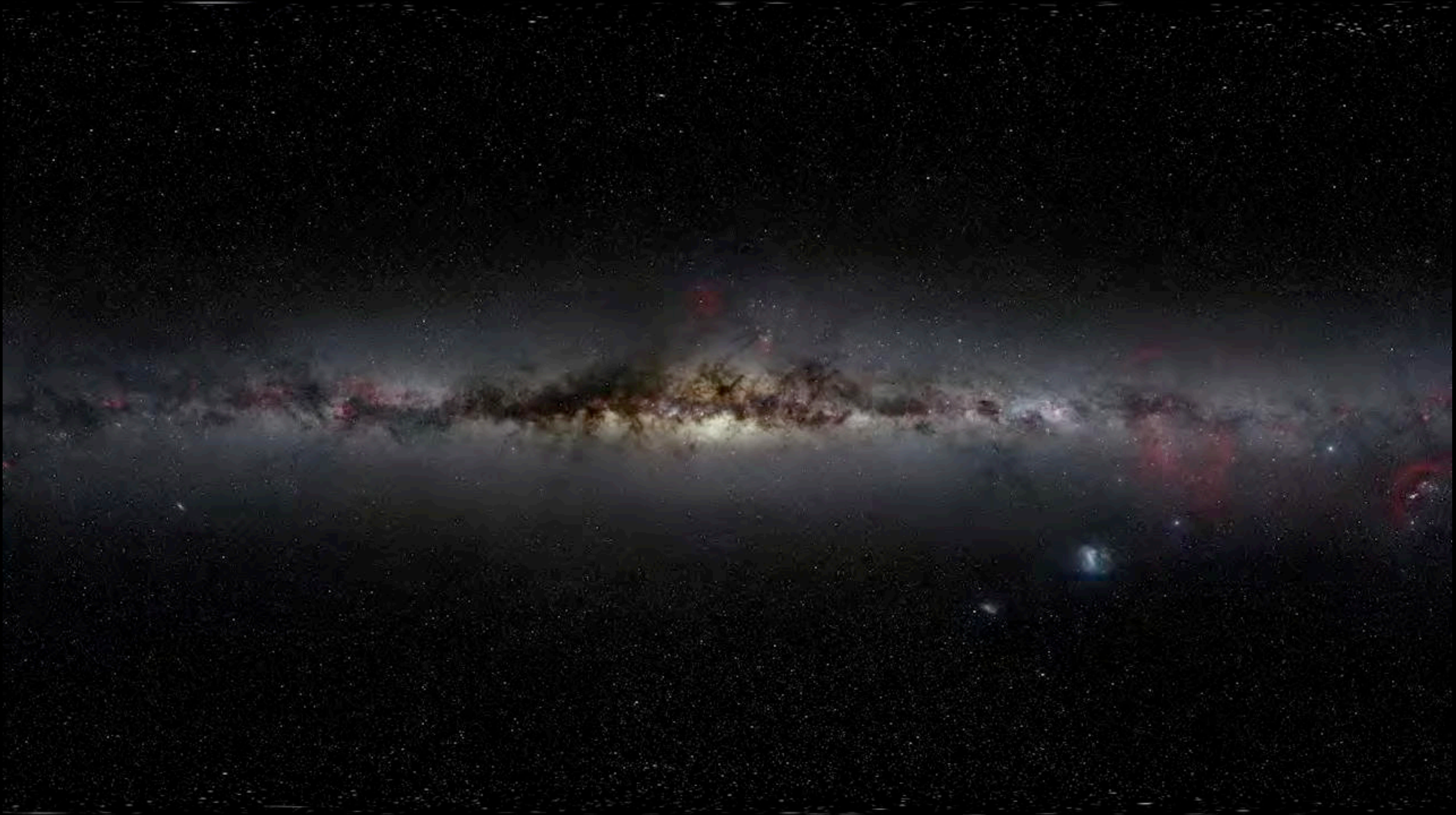


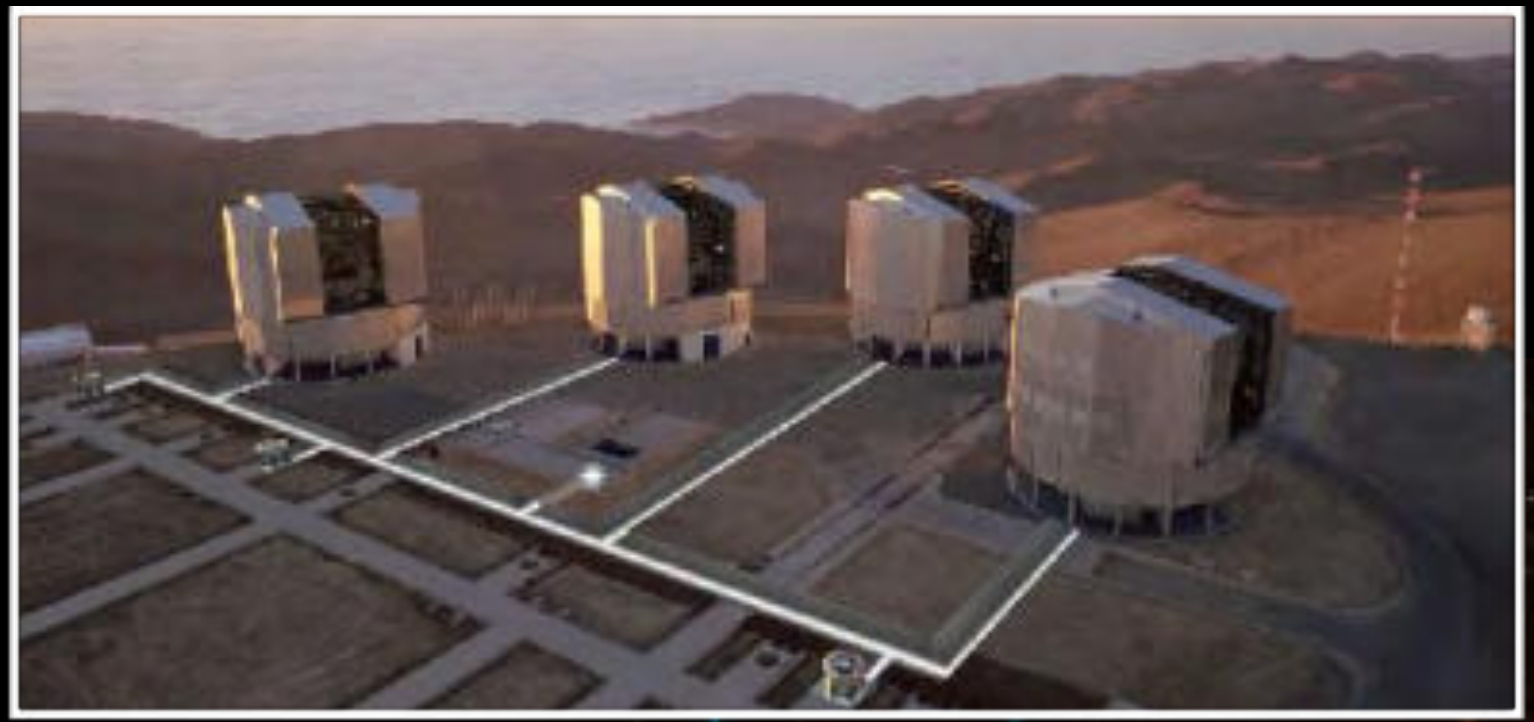




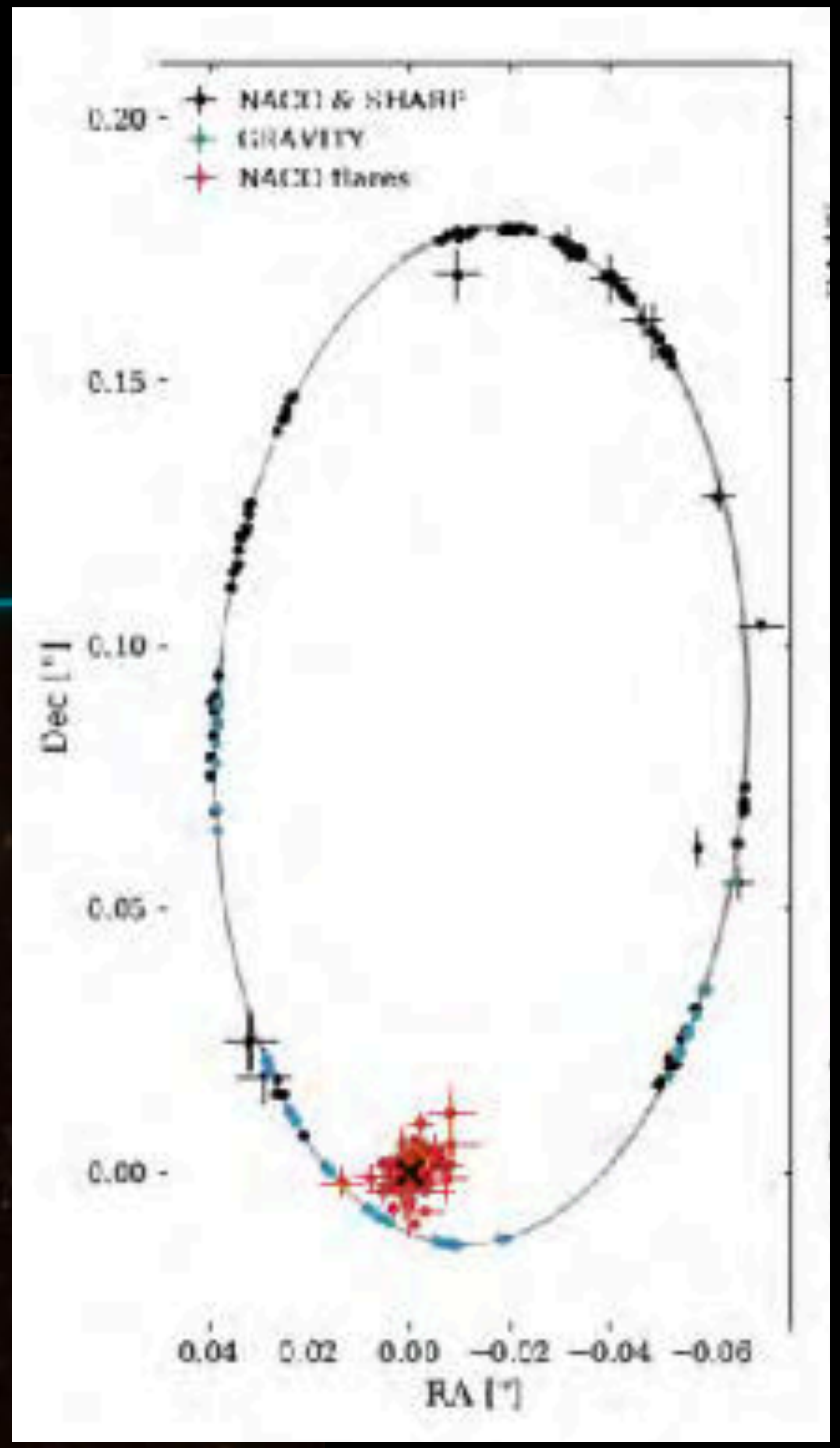


The Milky Way, our Galaxy

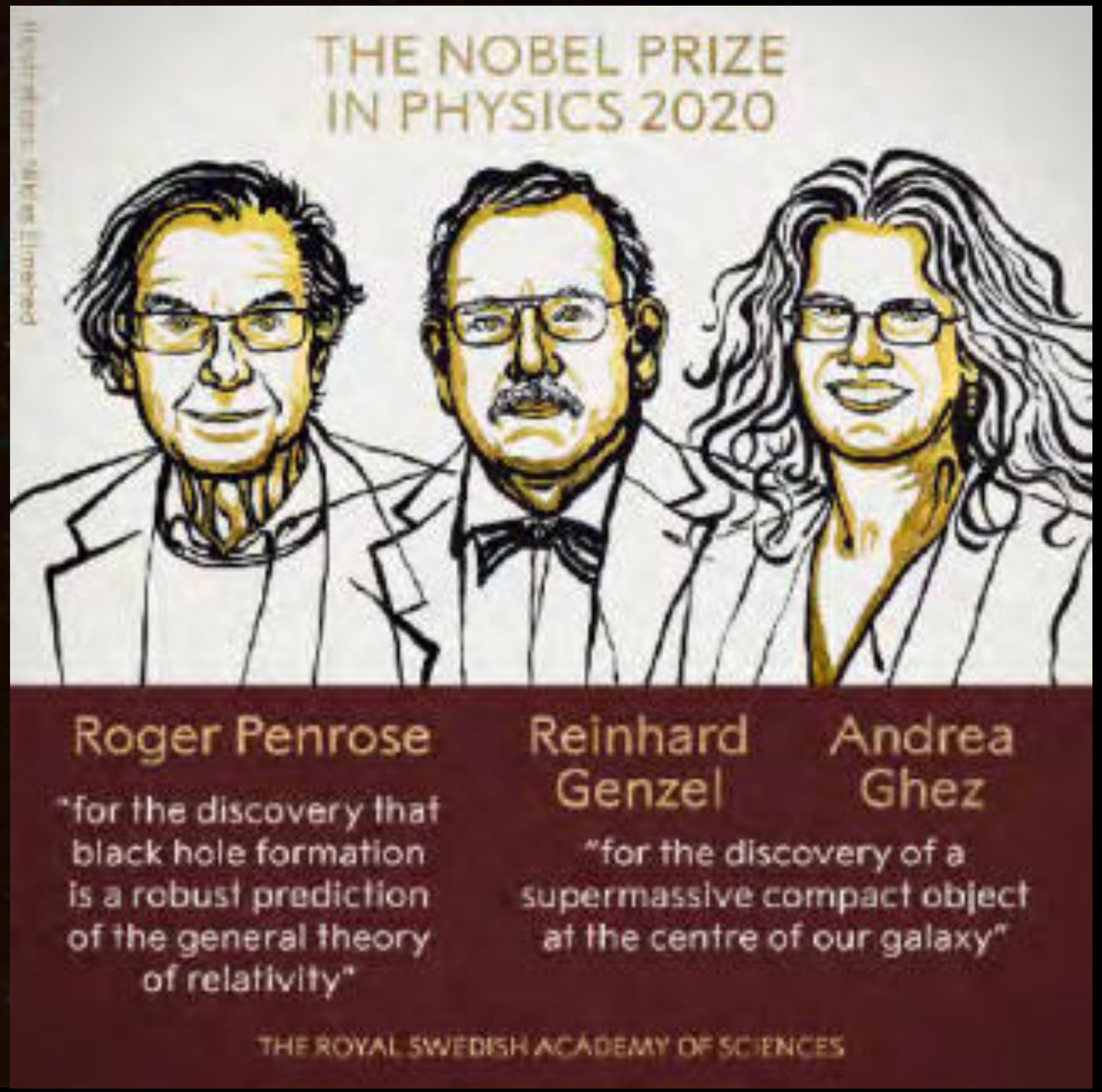


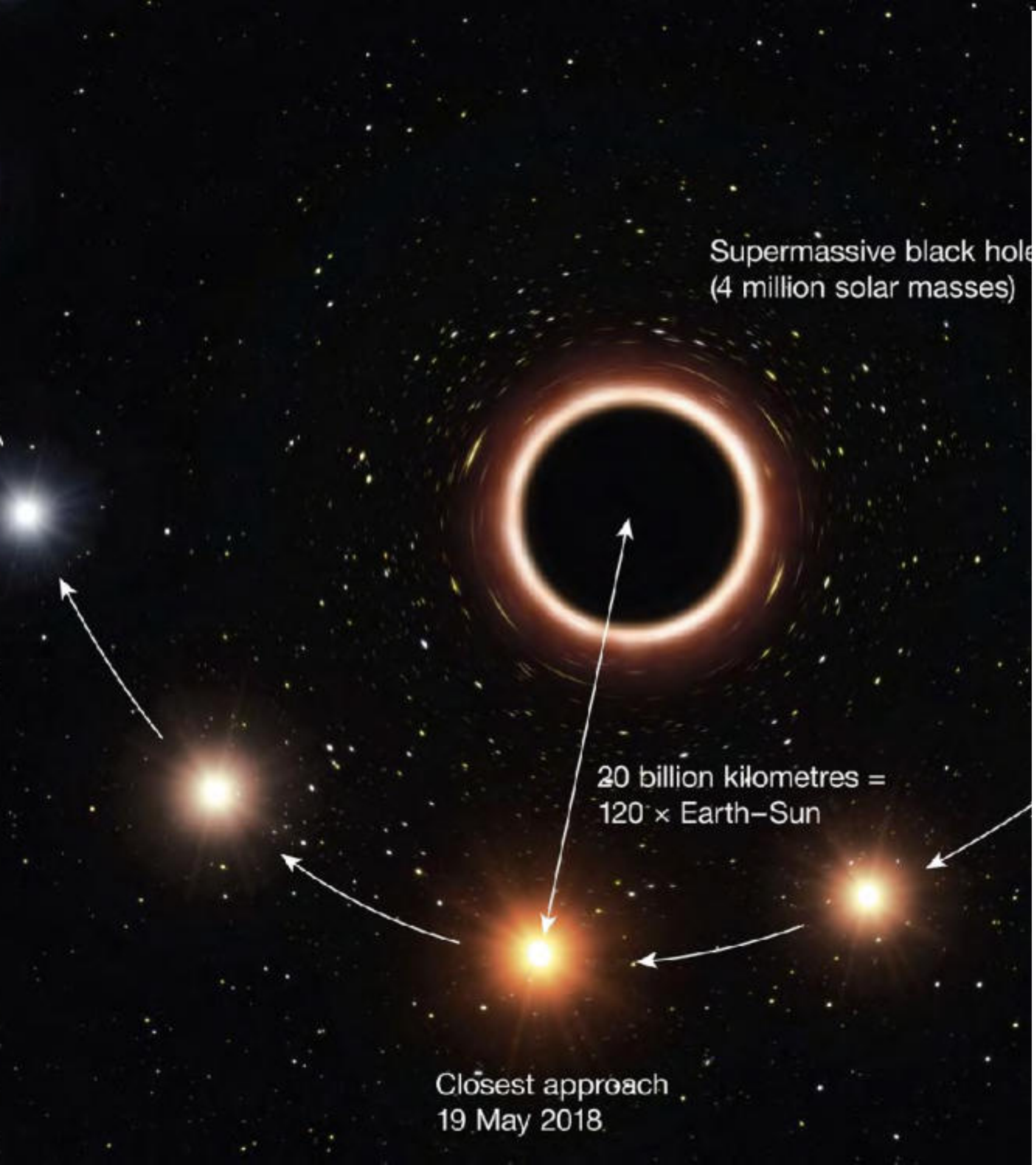


With GRAVITY on ESO’s VLT
in Chile

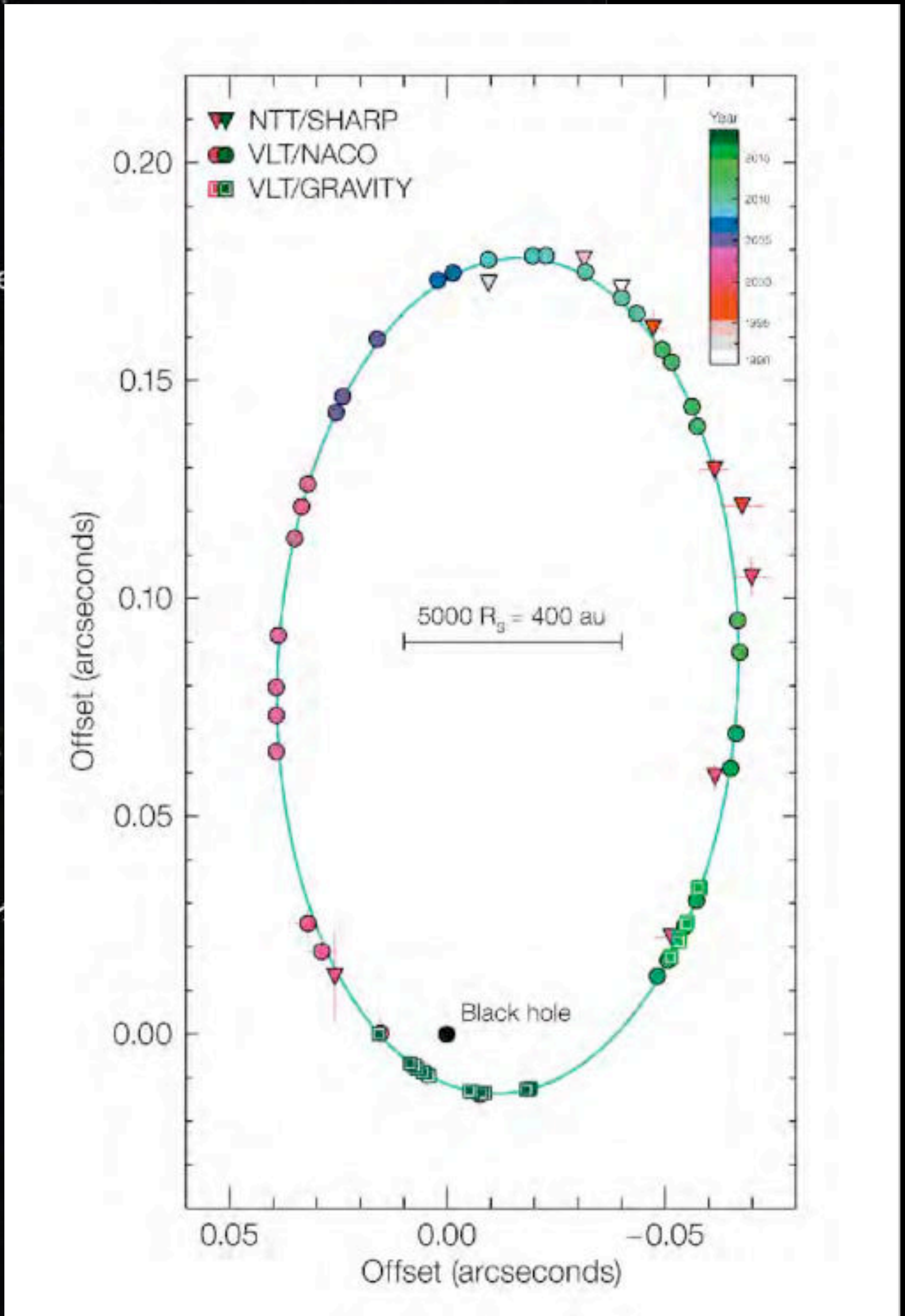


Orbits of Infrared stars
in orbit around black hole



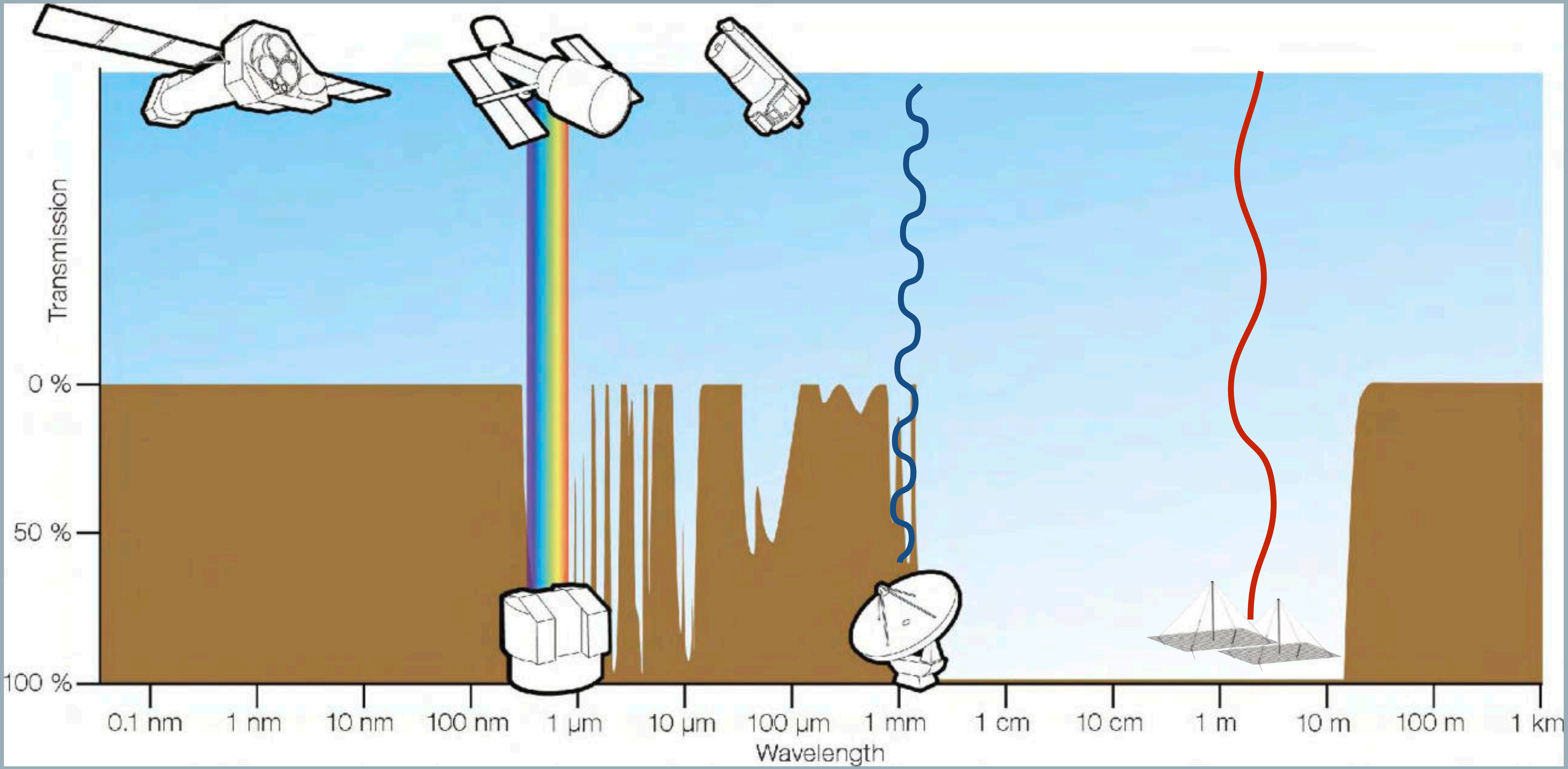


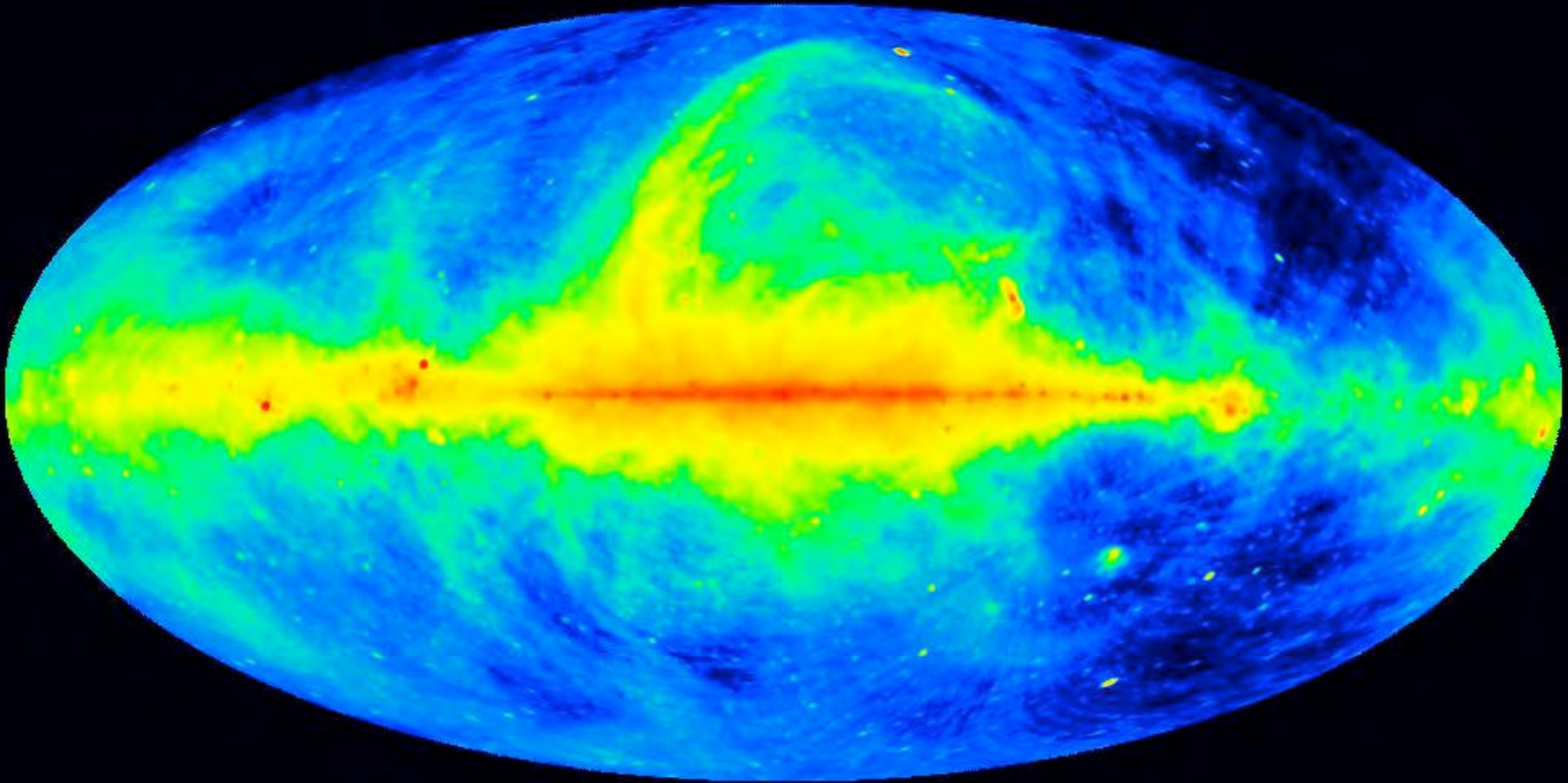
Supermassive black hole
(4 million solar masses)
20 billion kilometres =
120 × Earth–Sun
Closest approach
19 May 2018



NTT/SHARP
VLT/NACO
VLT/GRAVITY
0.20
0.15
0.10
0.05
0.00
Offset (arcseconds)
5000 R_g = 400 au
Black hole
0.05
0.00
−0.05
Offset (arcseconds)

Radio golven kunnen net als licht door de dampkring

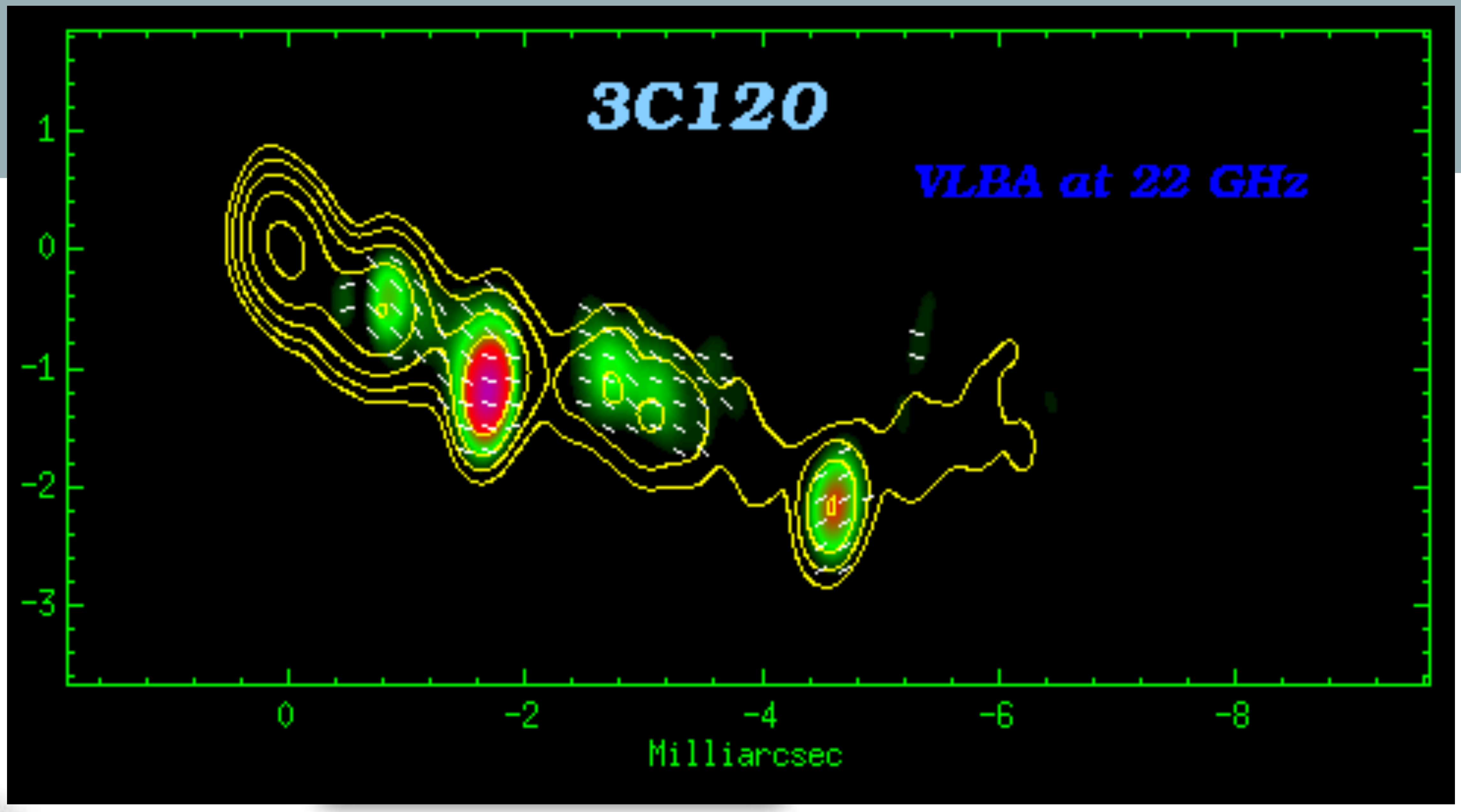


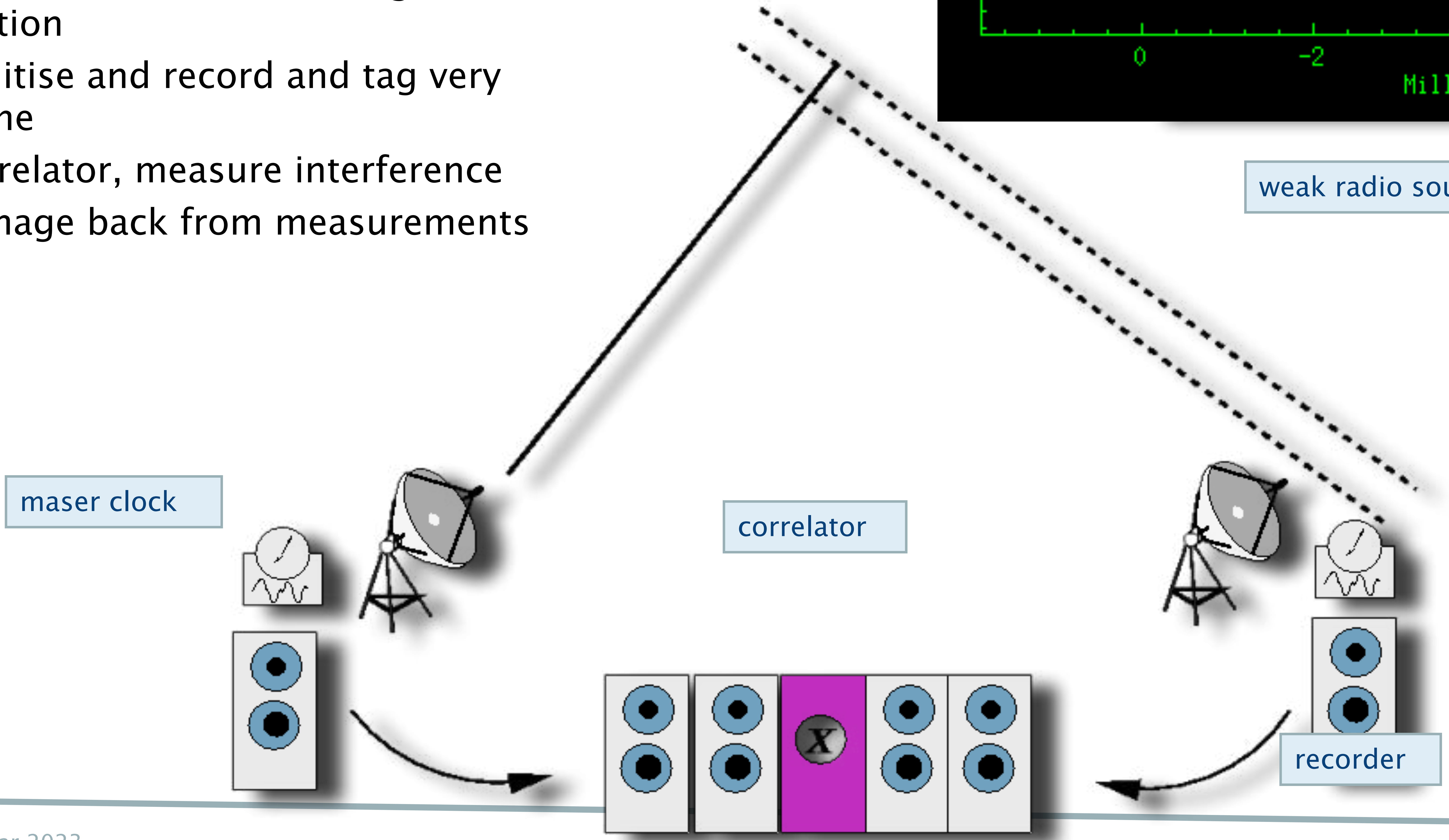


- **Big radio telescopes**
  - Detect weaker signals
  - Resolve smaller details
    - But with waves100.000 longer than in optical
  - Similar resolution requires radio telescopes 100km diameter

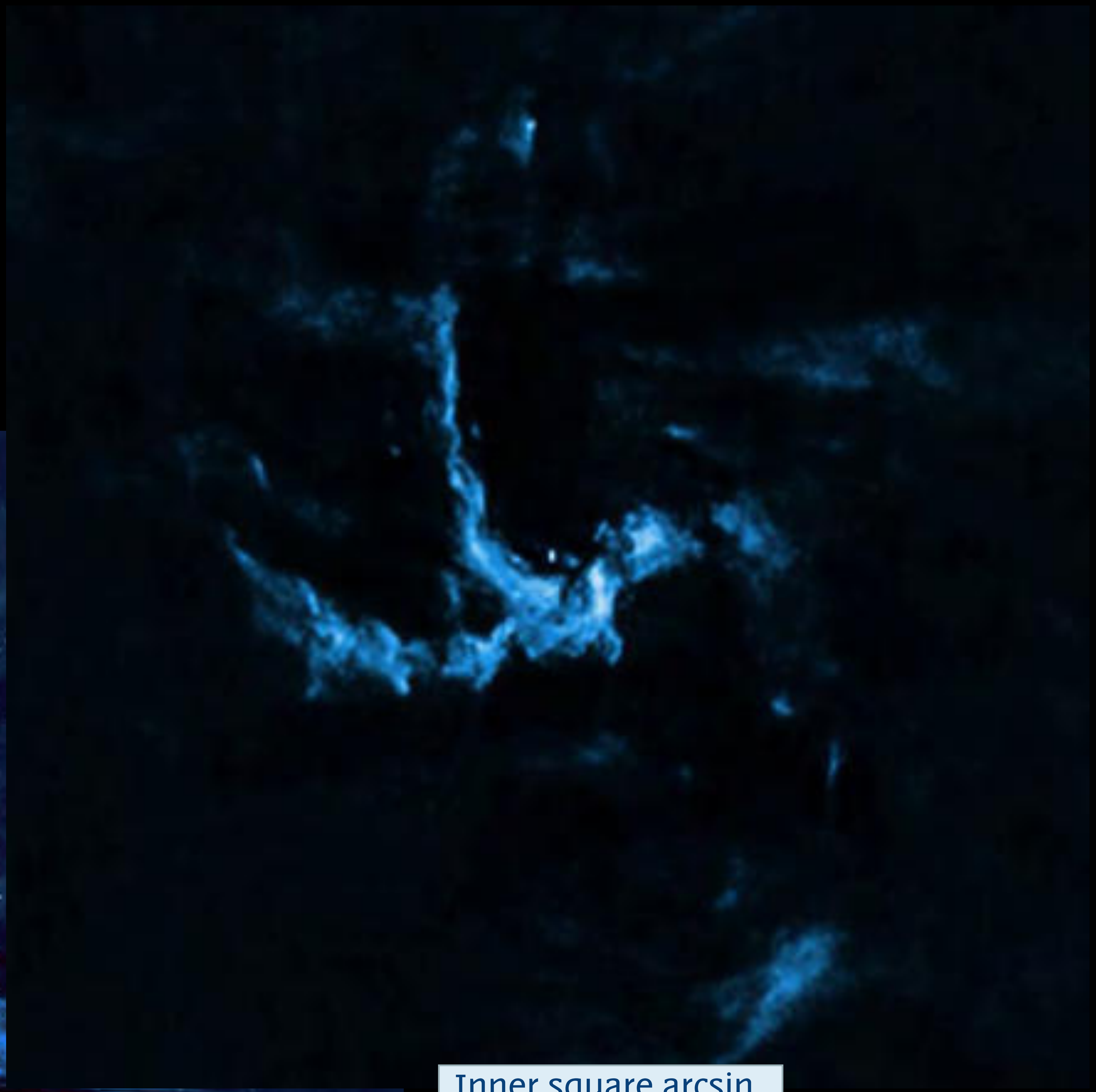
VLBI: make a giant telescope

- Very long baseline interferometry
- Measures interference patterns between pairs of telescopes
- Atmosphere transparent for radio emission 100M - 100GHz
- Big telescopes more sensitive, long baselines high resolution
- Sample, digitise and record and tag very accurate time
- Send to correlator, measure interference
- Compute image back from measurements

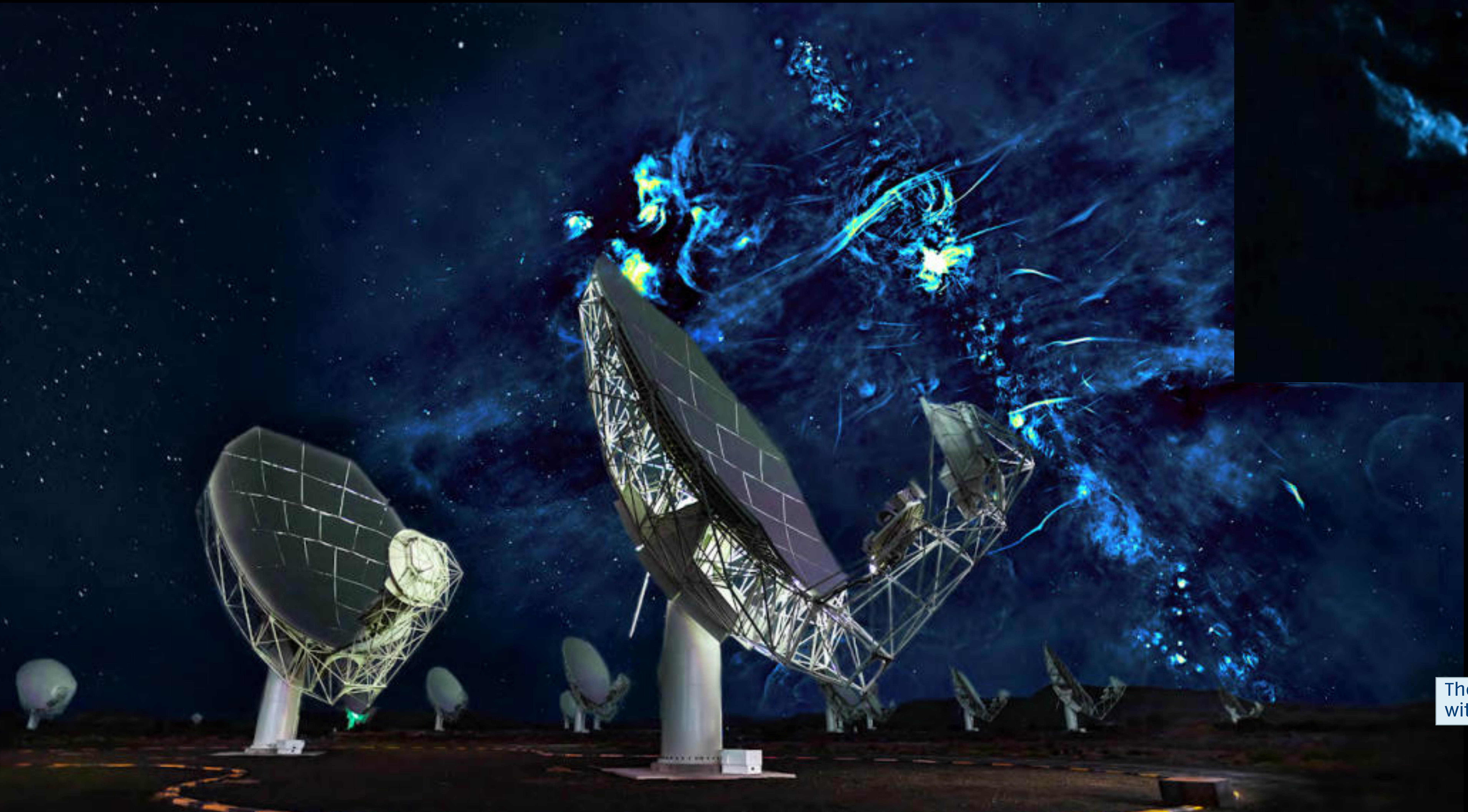




But we also took data of Sagittarius A*, the Black Hole at the centre of the Milky Way. That can be observed from the Southern hemisphere



Inner square arcsin at 22 GHz (NRAO, VLA)

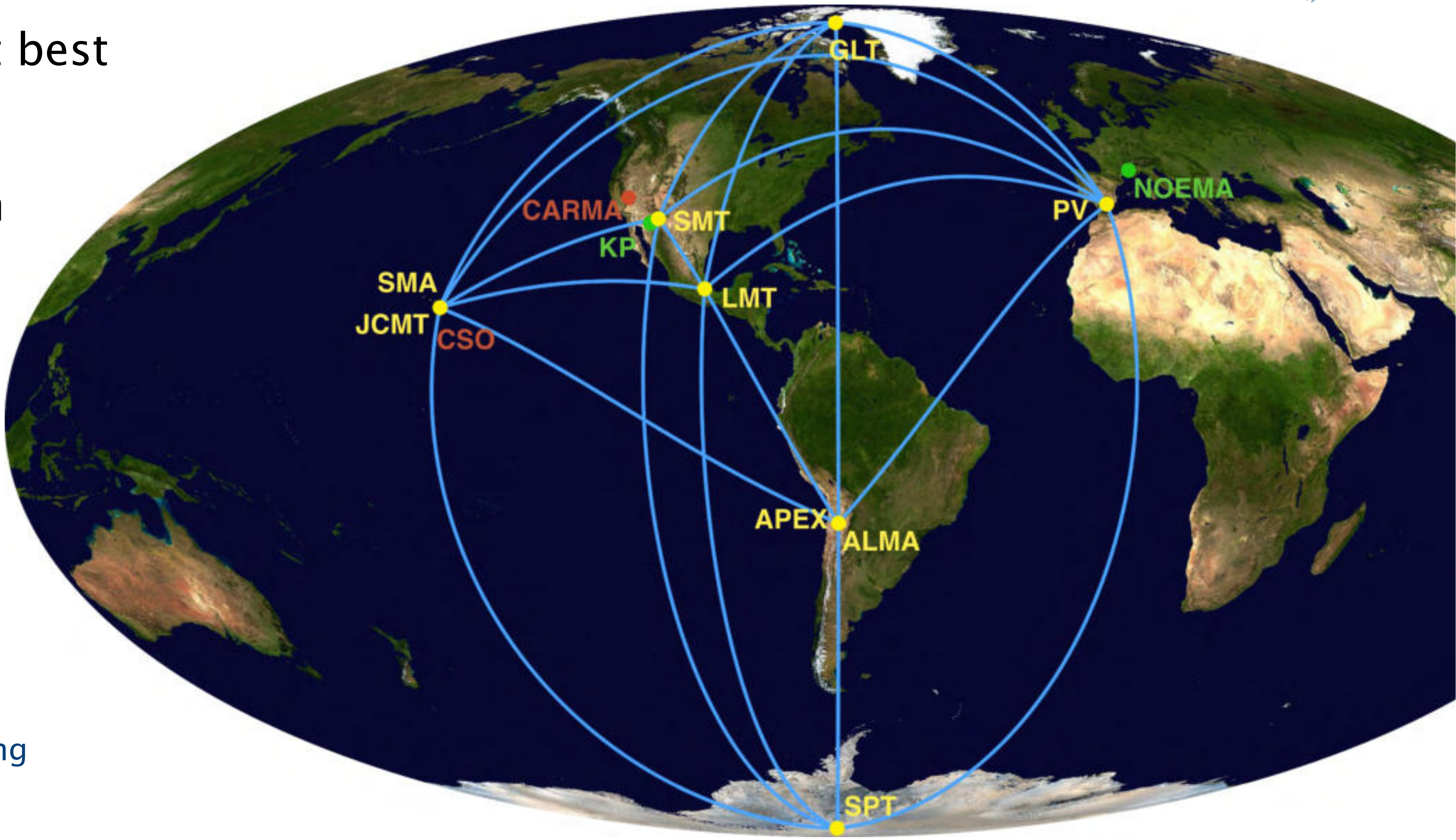


The inner Galaxy observed with MeerKAT, the SKA precursor

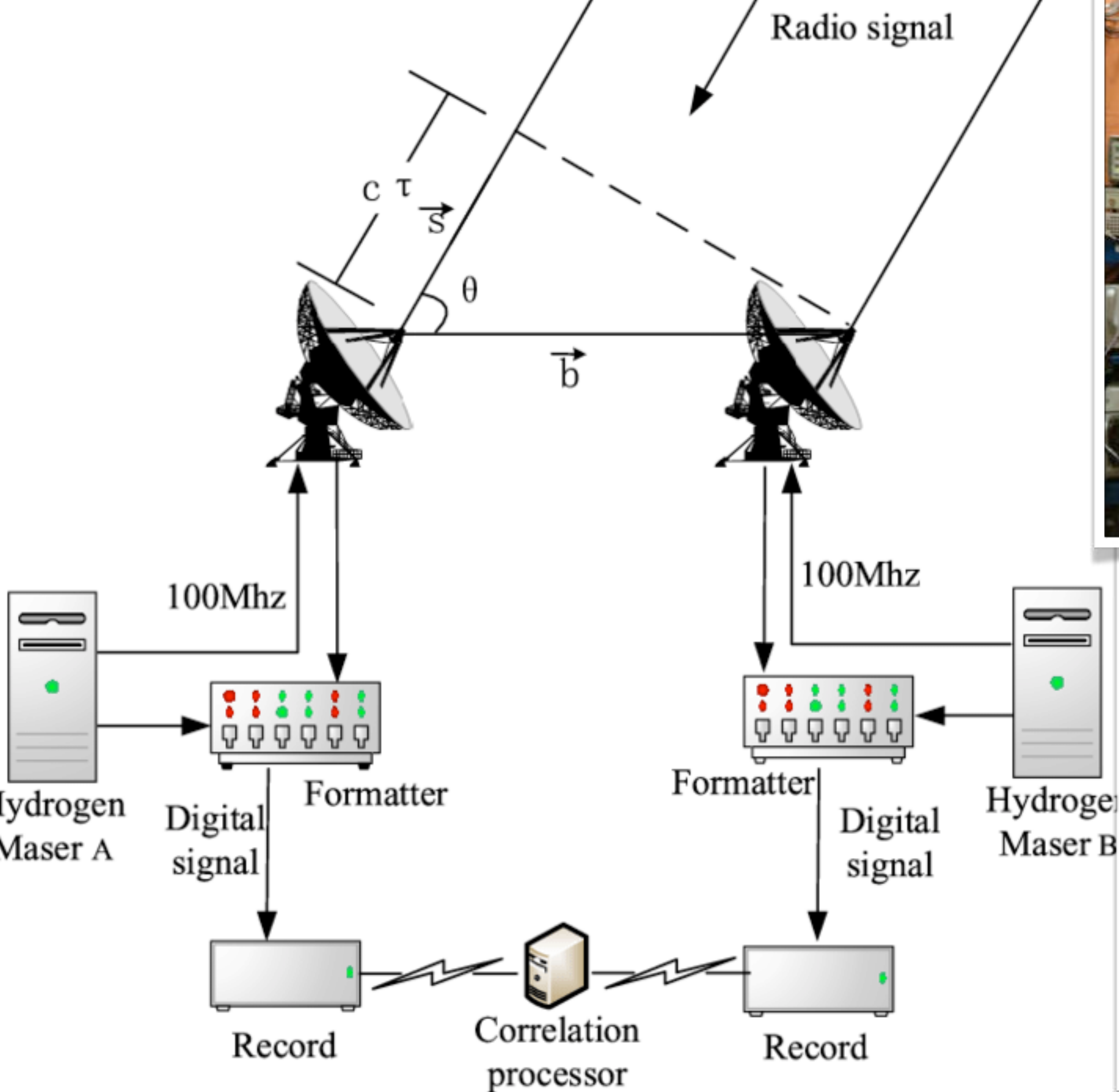
Now to the Galactic Center, SgrA*

Event Horizon Telescope

- 8 telescopes at best sites
  - working together
- Recording high bandwidth
  - 32 Giga bit per sec
- Good weather
  - around the world
- New image processing
  - Checked by simulations
- Simulations
  - GRMHD codes
  - relativistic ray tracing



Now try this with millimeter telescopes


Radio signal
c τ
s
θ
b
100Mhz
100Mhz
Formatter
Formatter
Digital signal
Digital signal
Maser A
Maser B
Record
Record
Correlation processor


Optical light

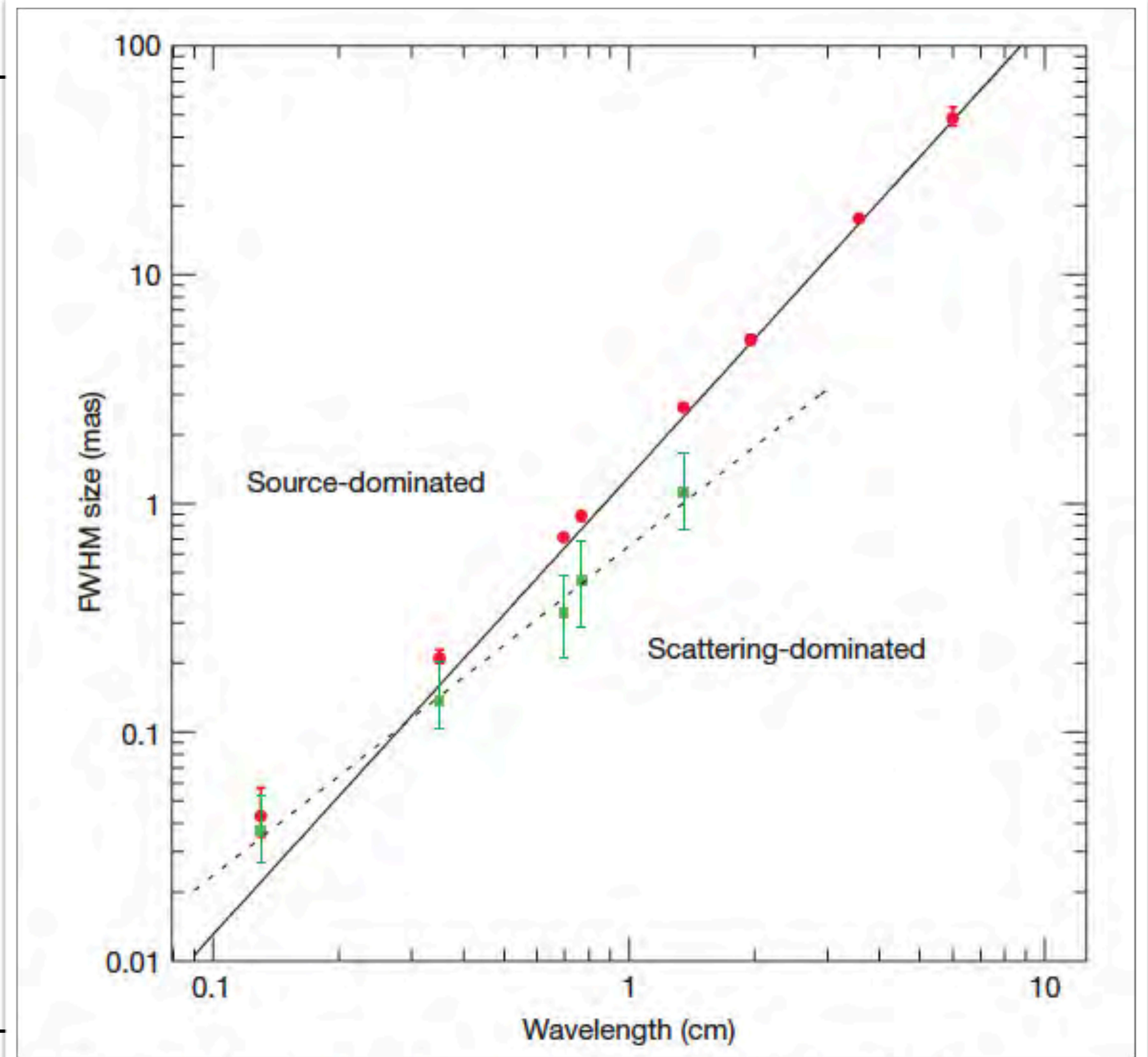
The Black Hole in the centre of our Galaxy

What made it difficult?

Why is this more fundamental?

Interstellar scattering

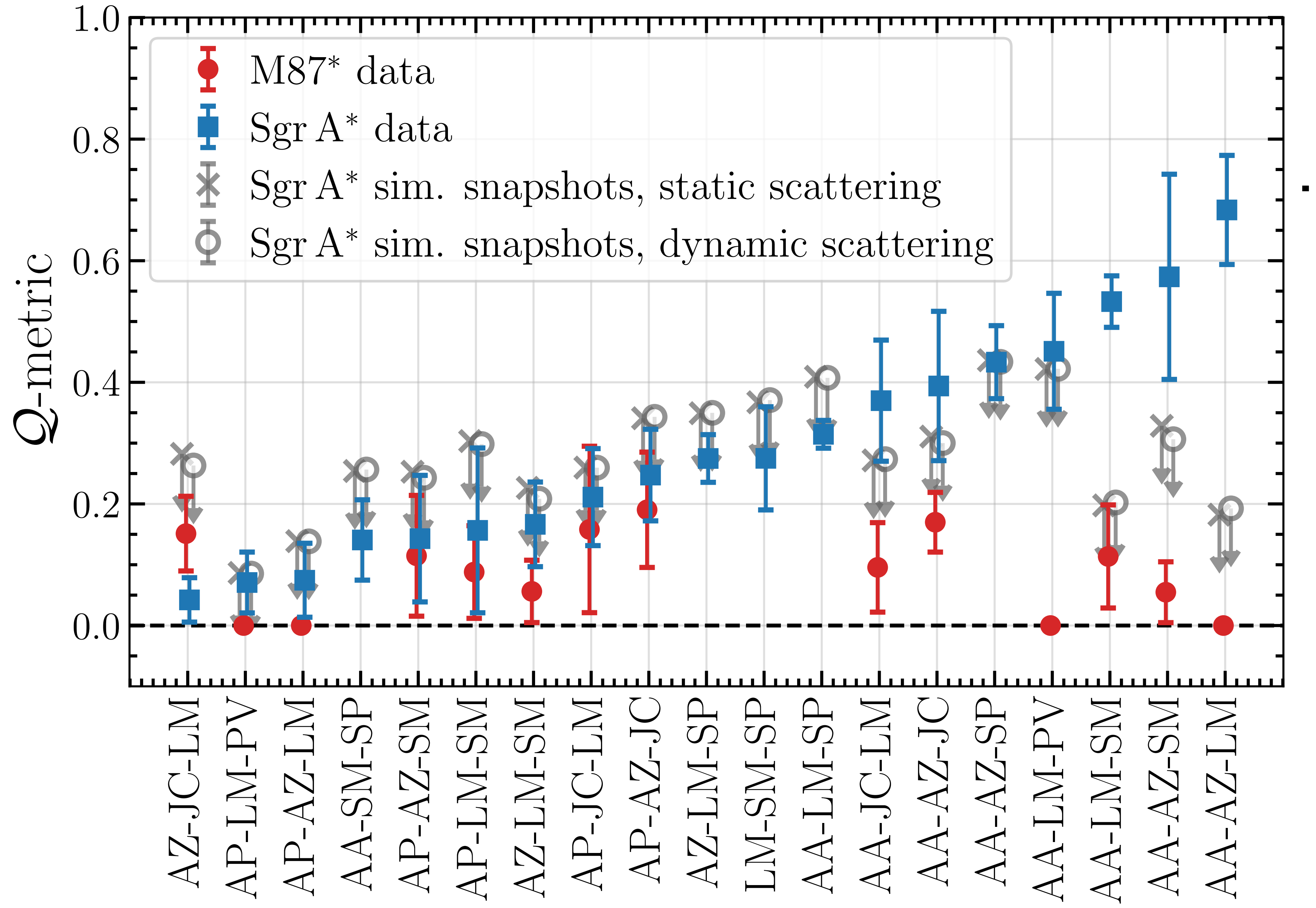
- Limits view on SgrA* at longer wavelengths
  - Where it is optically thick anyway
- Becomes sub-dominant at 1mm
  - Where it is optically thin
  - And global VLBI reaches 20μas



Doeleman et al. 2008

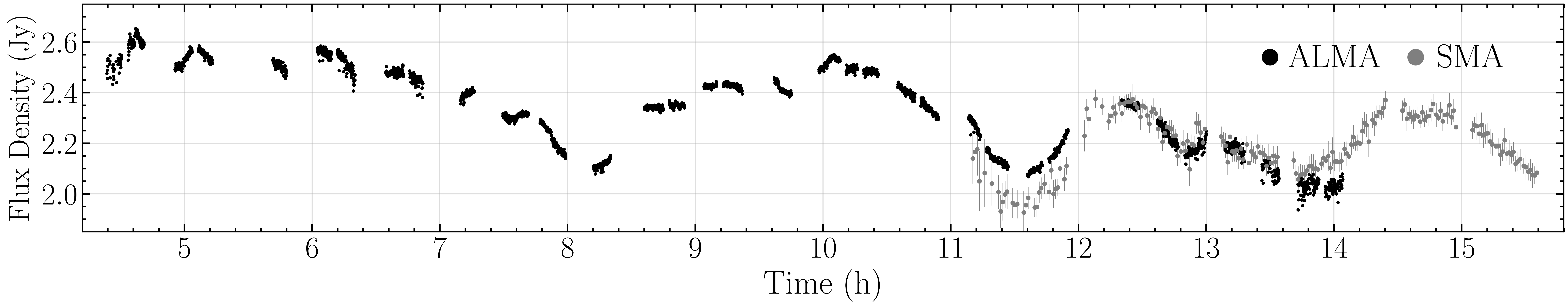
Variability

Q-metric measures closure phase statistics (Roelofs et al., 2017), shows SgrA* variability on long baselines

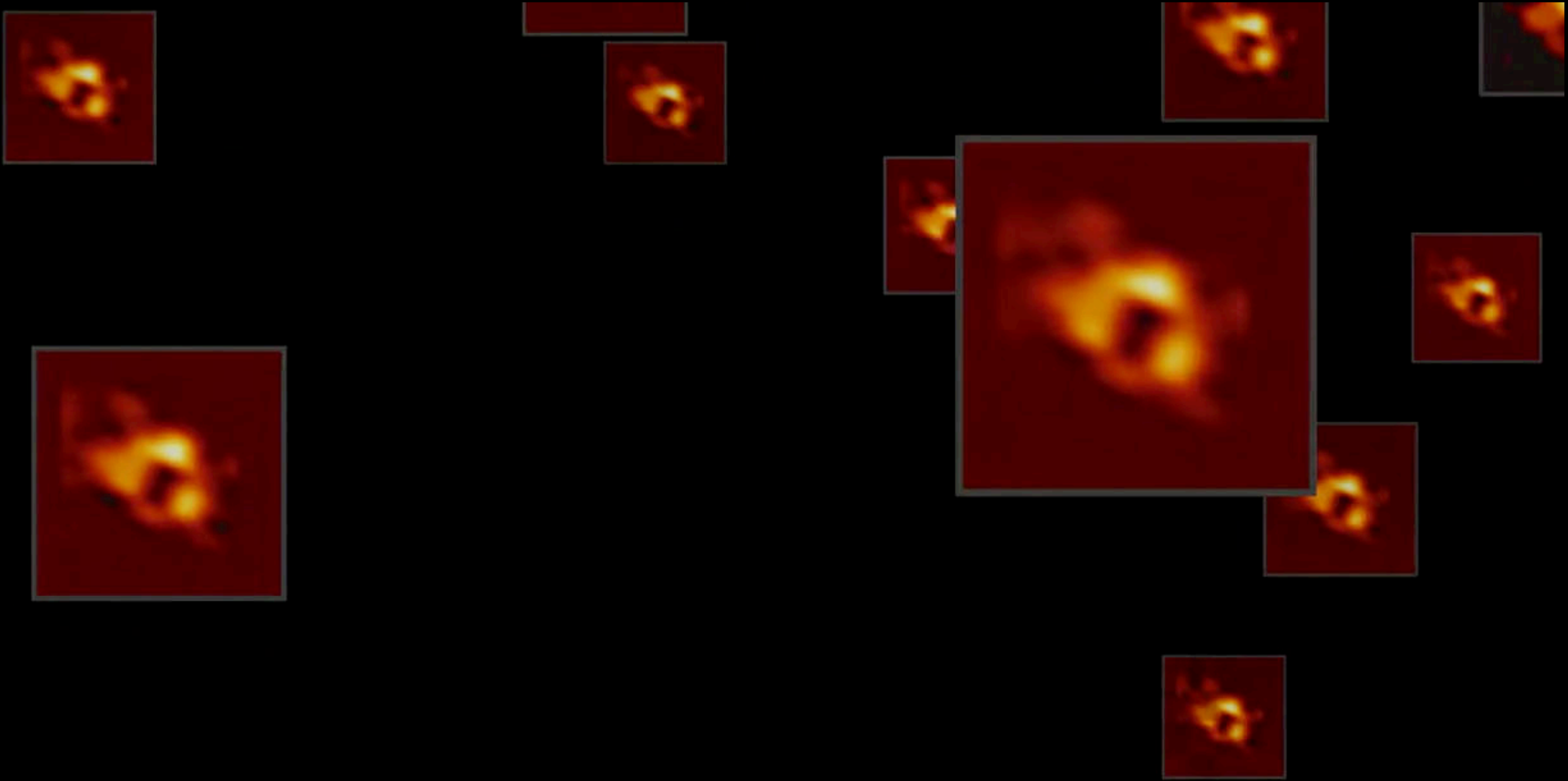


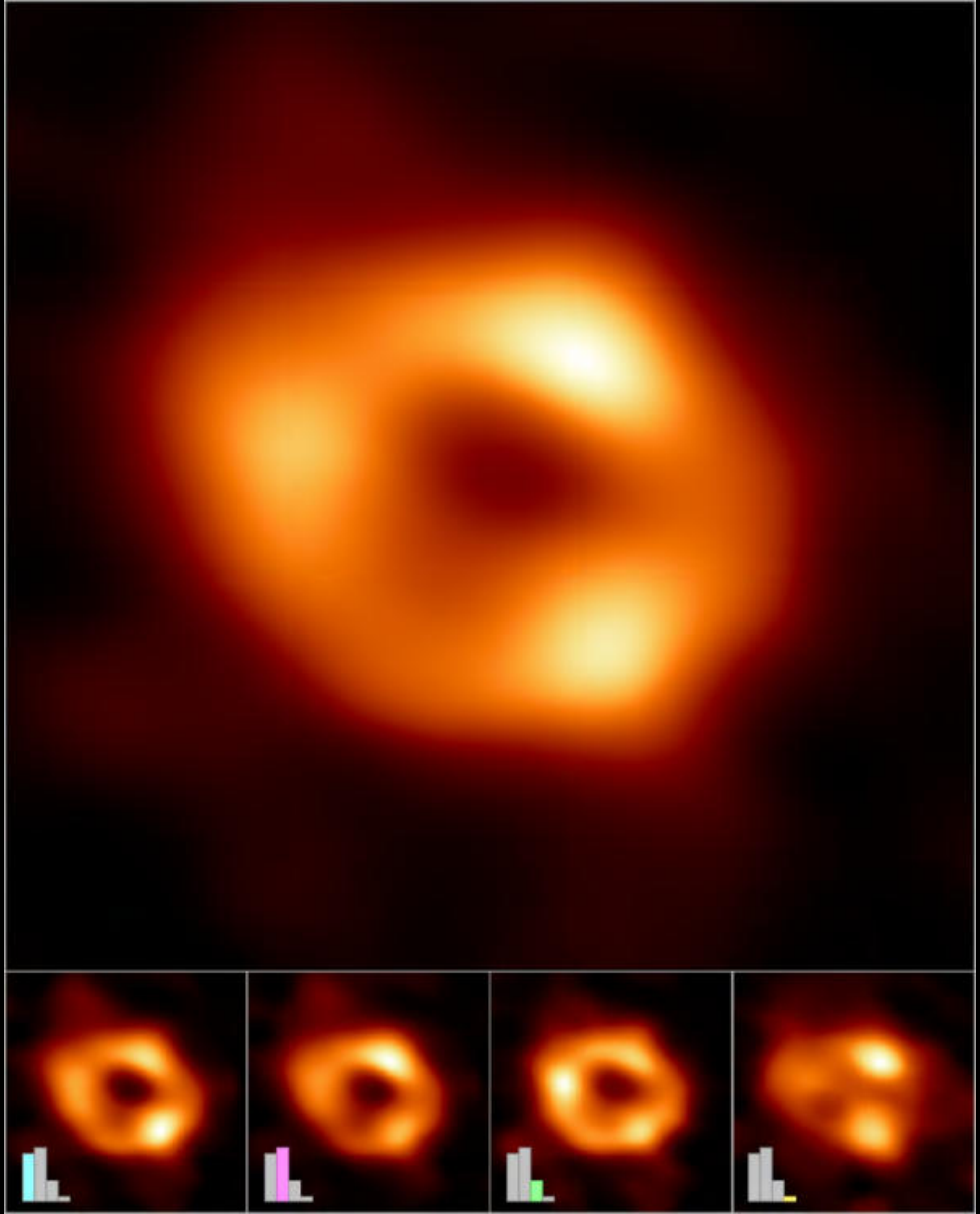
- Total flux variability
  - Can be estimated robustly from interferometers
- Structural variability
  - Must be estimated from redundant visibilities
    - Between days
    - Baseline crossings
  - Or from modelling
    - Using closure properties

Interferometrically measured total flux variations, Wielgus et al., 2022



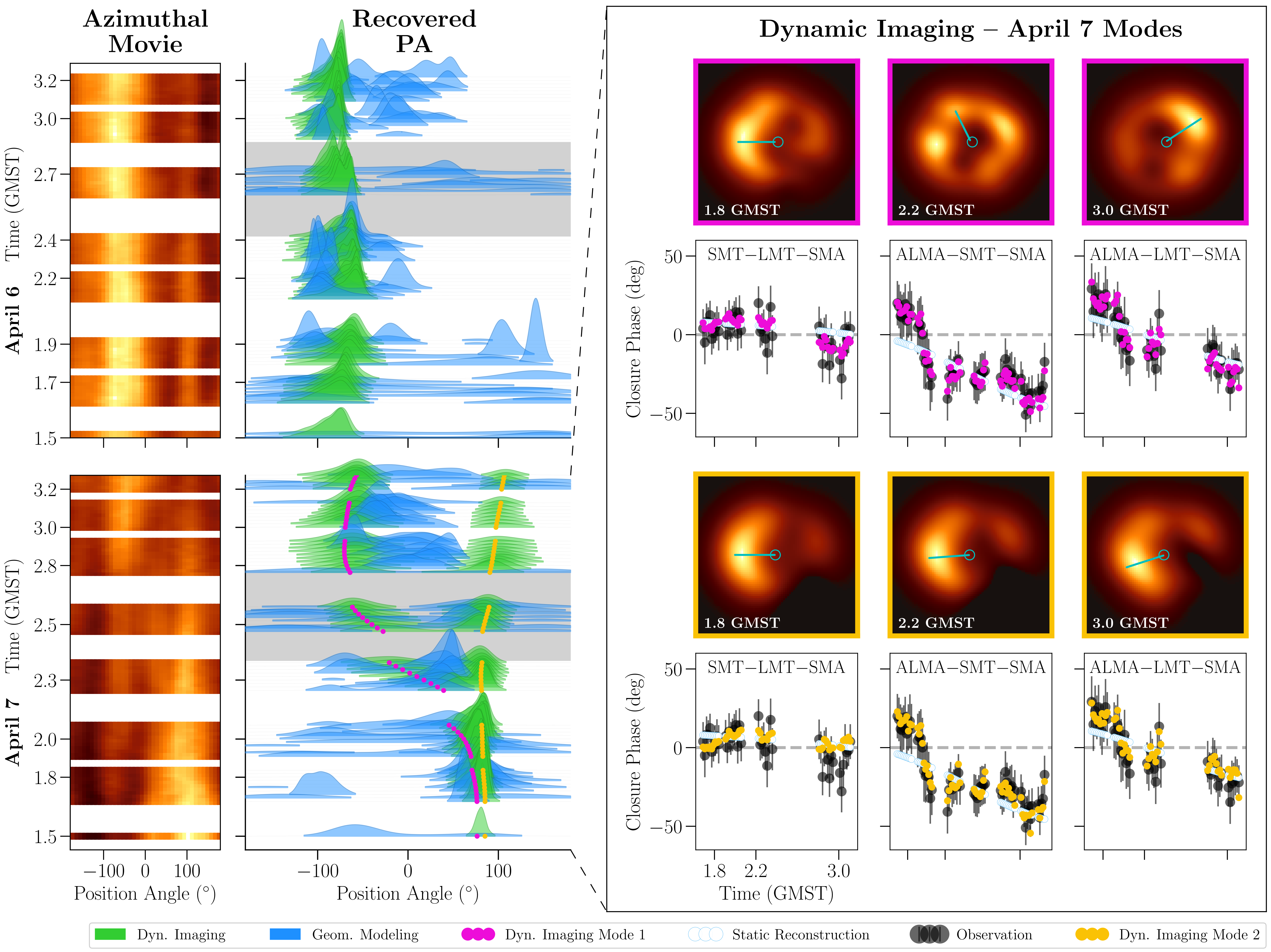

M87*
Sgr A*
Simulation





Dynamic imaging

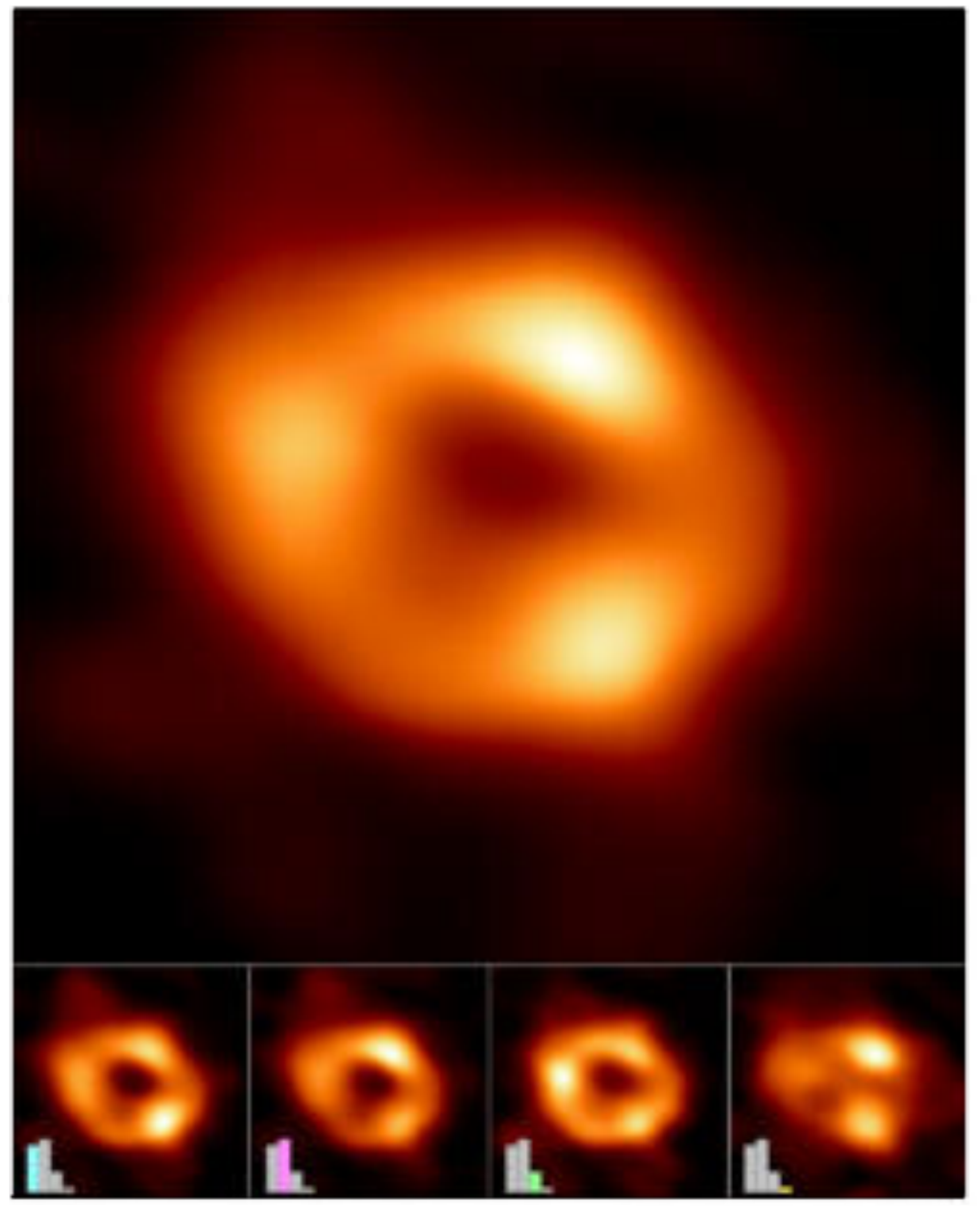
- Promising but not conclusive
  - Focusing on 100 minutes with best coverage
  - Stable results on April 6
  - Azimuthal evolution on April 7
  - Still not very consistent results
  - But hopeful for future

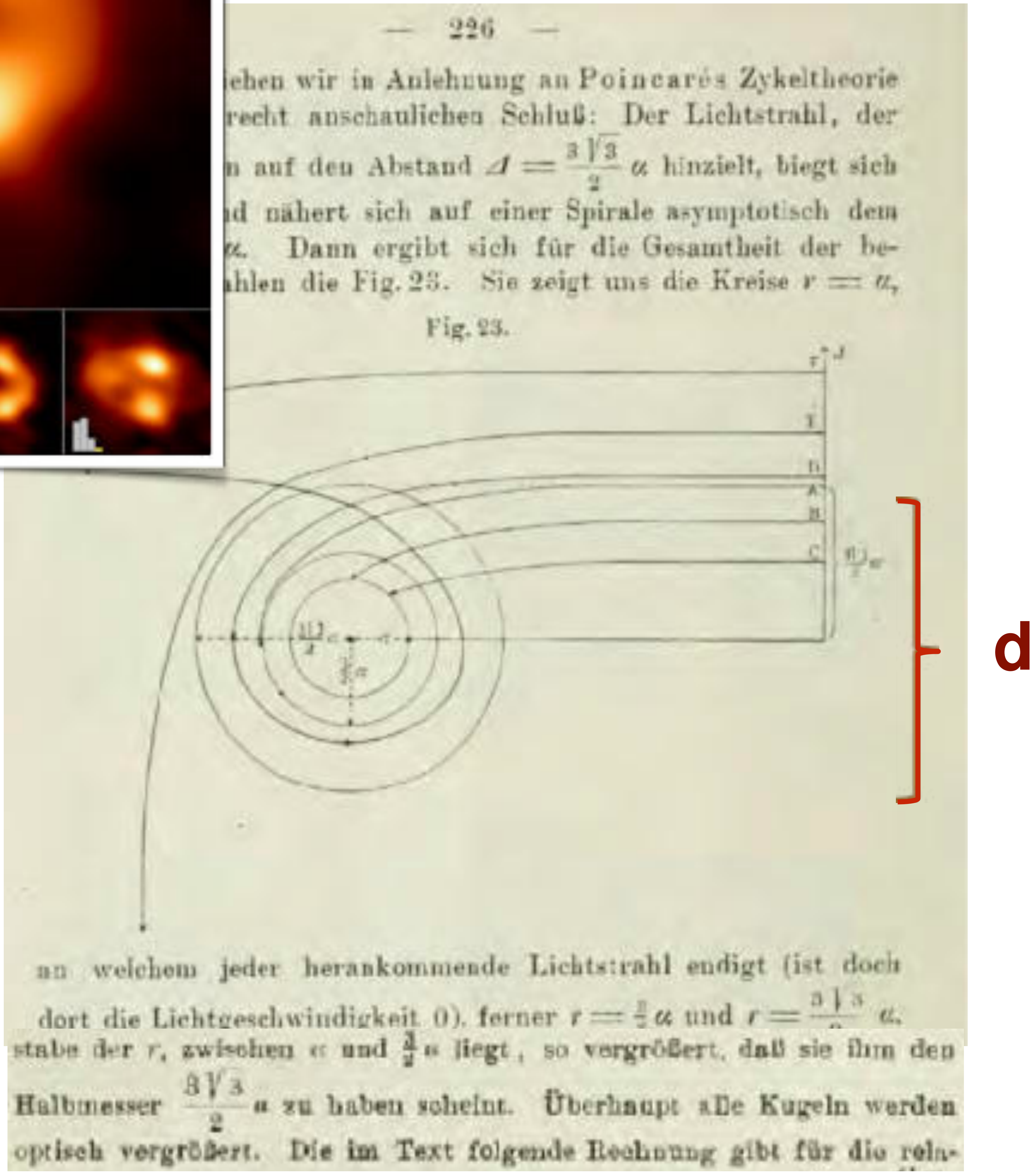


Event Horizon Telescope

Interpreting ring sizes

- Angular size of gravitational radius: $\theta_g = \frac{GM}{c^2 D}$
- Schwartzschild diameter: $4\,\theta_g$
- ISCO diameter
  - for non-rotating: $12\,\theta_g$
  - Innermost Stable Circular Orbit
  - ISCO diameter Kerr $< 18\,\theta_g$
- Photon ring
  - Non - rotating $2\sqrt{27}\,\theta_g = 10.4\,\theta_g$
  - Cross section for shadow
  - Kerr photon ring $9.6 - 10.4\ \theta_g$
    - Depending on orientation
- From simulations
  - Convolved with beam… $d = \alpha\,\theta_g$





— 226 —

…ehen wir in Anlehnung an Poincarés Zykeltheorie …recht anschaulichen Schluß: Der Lichtstrahl, der …n auf den Abstand $\Delta = \frac{3\sqrt{3}}{2}\alpha$ hinzielt, biegt sich …d nähert sich auf einer Spirale asymptotisch dem …α. Dann ergibt sich für die Gesamtheit der be…ahlen die Fig. 23. Sie zeigt uns die Kreise $r = \alpha$,

Fig. 23.

an welchem jeder herankommende Lichtstrahl endigt (ist doch dort die Lichtgeschwindigkeit 0), ferner $r = \frac{3}{2}\alpha$ und $r = \frac{3\sqrt{3}}{2}\alpha$.

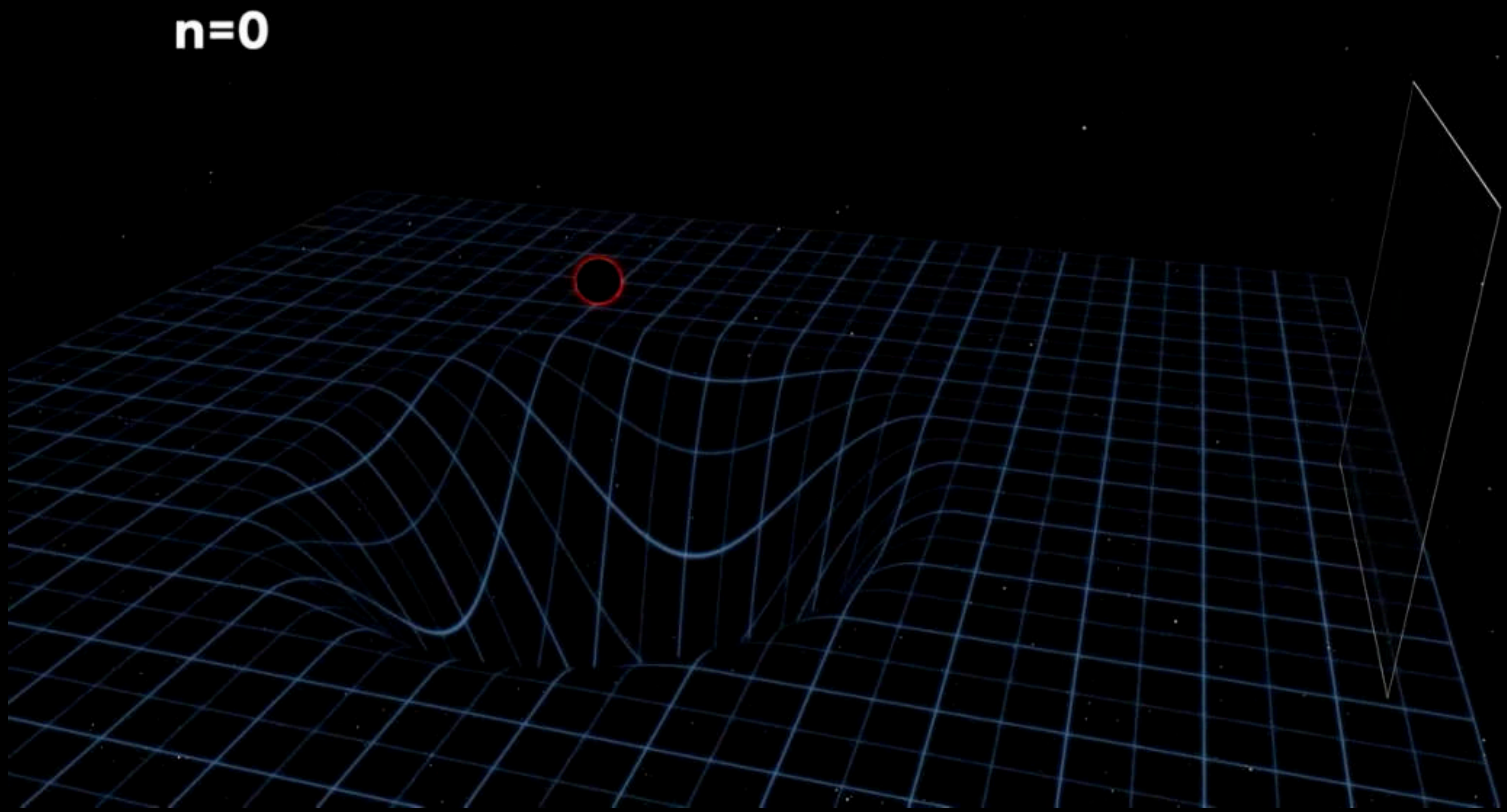
…stabe der r, zwischen α und $\frac{3}{2}\alpha$ liegt, so vergrößert, daß sie ihm den Halbmesser $\frac{3\sqrt{3}}{2}\alpha$ zu haben scheint. Überhaupt alle Kugeln werden optisch vergrößert. Die im Text folgende Rechnung gibt für die rela-

Max von Laue (1921):
"Die Relativitätstheorie. Zweiter Band", Vieweg, 1921

Event Horizon Telescope

NVWS Alkmaar, 31 Mar 2023

Image from gravitational lensing



Astrophysics with the SgrA* Black Hole

we know quite precisely it is at a distance of 26 thousand lightyear…

last stable orbit
of gas in orbit around
Black Hole

Event Horizon,
radius of the Black Hole,
no return from here

Photon Ring,
where we see the
photons that have gone
round the Black Hole
once or multiple times

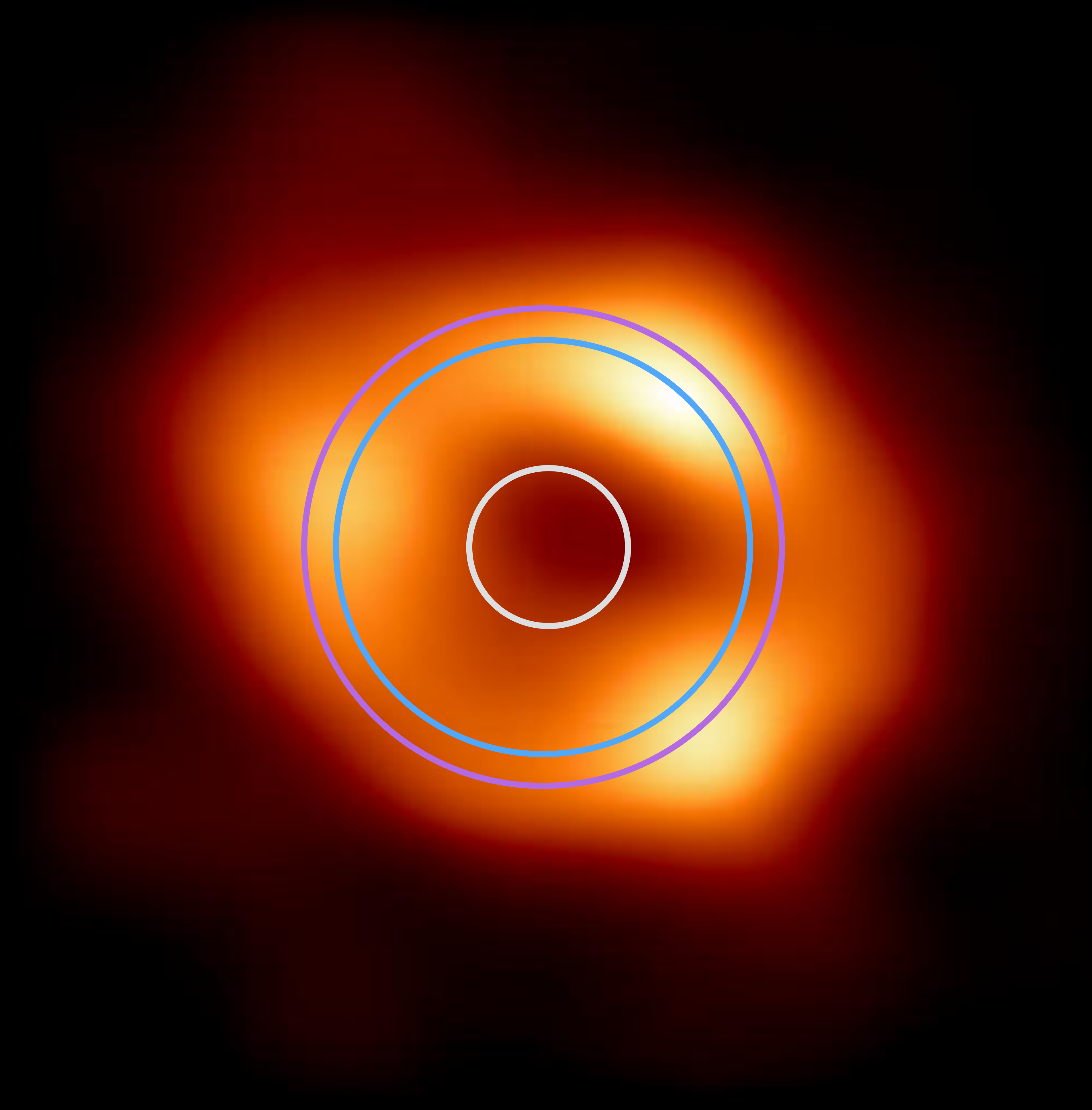
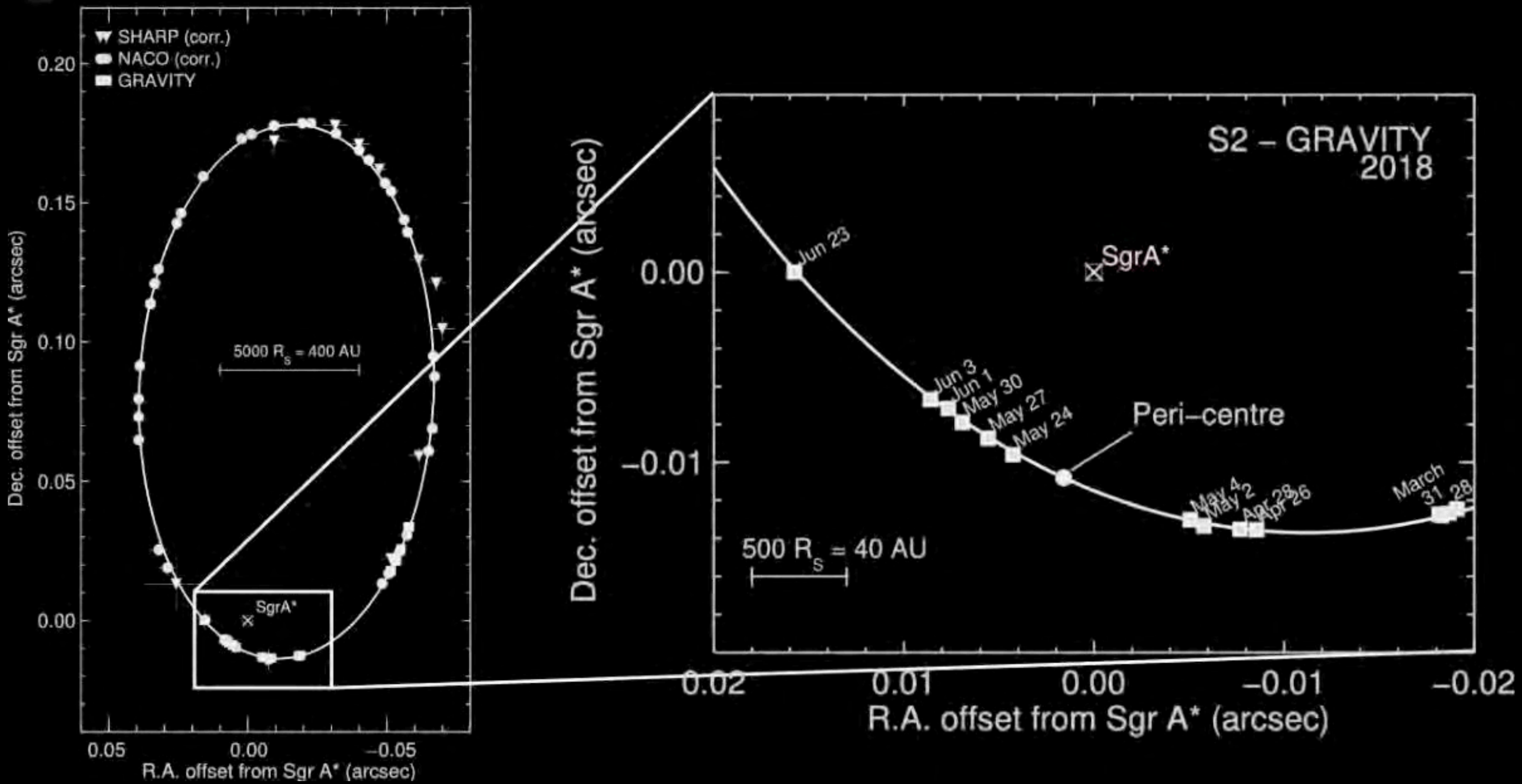


image follows circle,
as predicted by General
Relativity

diameter equals 51 μas,
because we know the
mass and distance, this
is precisely correct!

Source is variable,
azimuthal structure
uncertain;
almost face on?

resolution of the EHT, we cannot
resolve smaller details



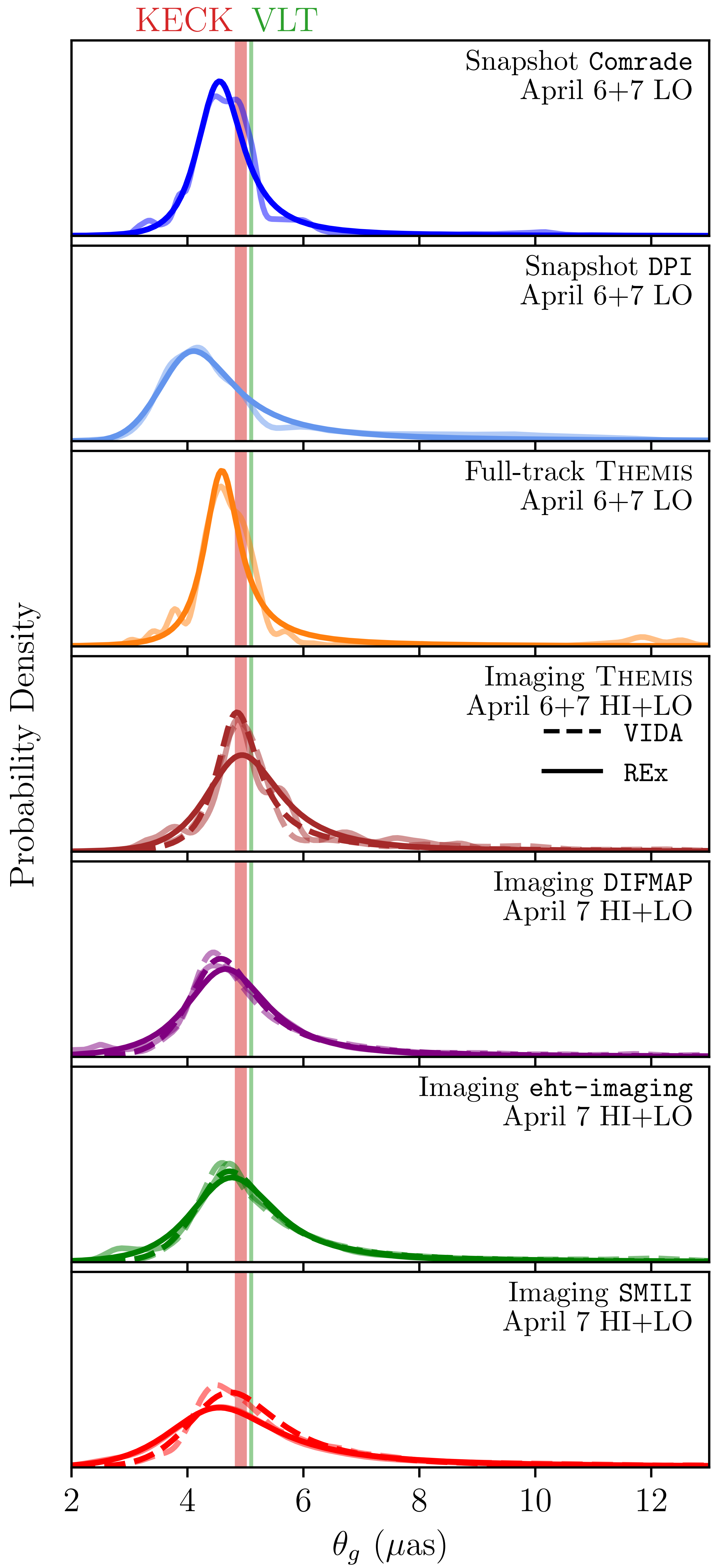
SHARP (corr.)
NACO (corr.)
GRAVITY
0.20
0.15
0.10
0.05
0.00
Dec. offset from Sgr A* (arcsec)
5000 R_S = 400 AU
SgrA*
0.05
0.00
-0.05
R.A. offset from Sgr A* (arcsec)
S2 – GRAVITY
2018
Jun 23
SgrA*
Jun 3
Jun 1
May 30
May 27
May 24
Peri-centre
May 4
May 2
Apr 28
Apr 26
March
31
28
500 R_S = 40 AU
0.00
-0.01
Dec. offset from Sgr A* (arcsec)
0.02
0.01
0.00
-0.01
-0.02
R.A. offset from Sgr A* (arcsec)

Checking against predictions

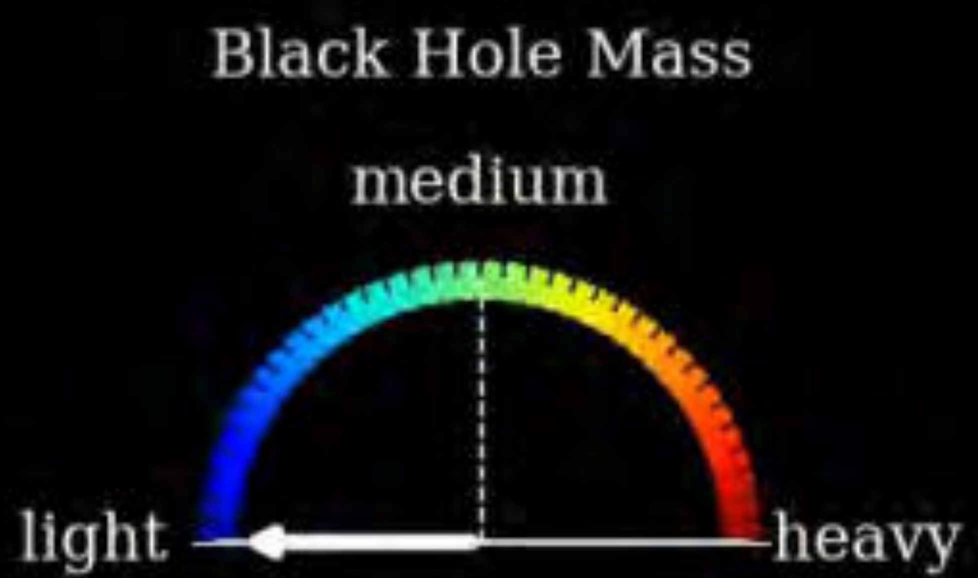
- θ_g estimates can be compared
  Remember it is basically M/D that is measured

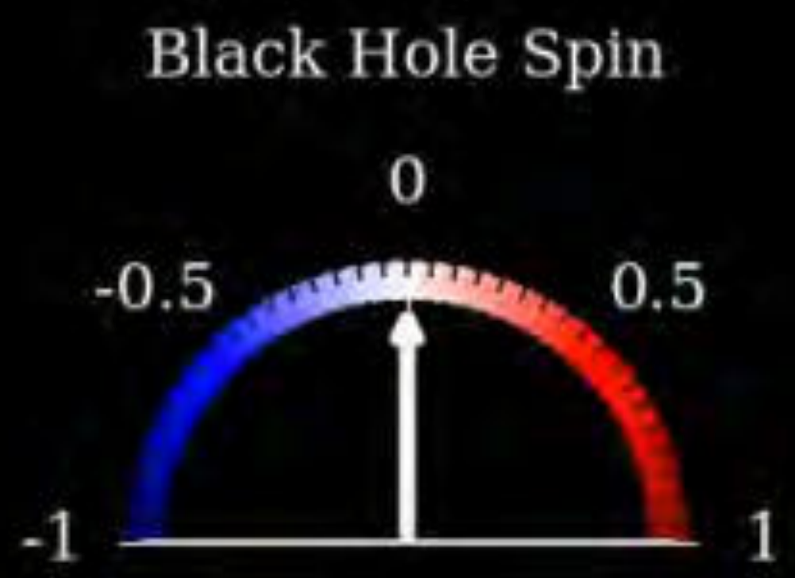
- Can be compared in various ways
  - Treat Genzel EHTC al., Ghez et al., separately
    - Using independent distance from Reid et al. 2019

- Result comfortably within errors
  - Consistent with Einstein's GR



Event Horizon Telescope

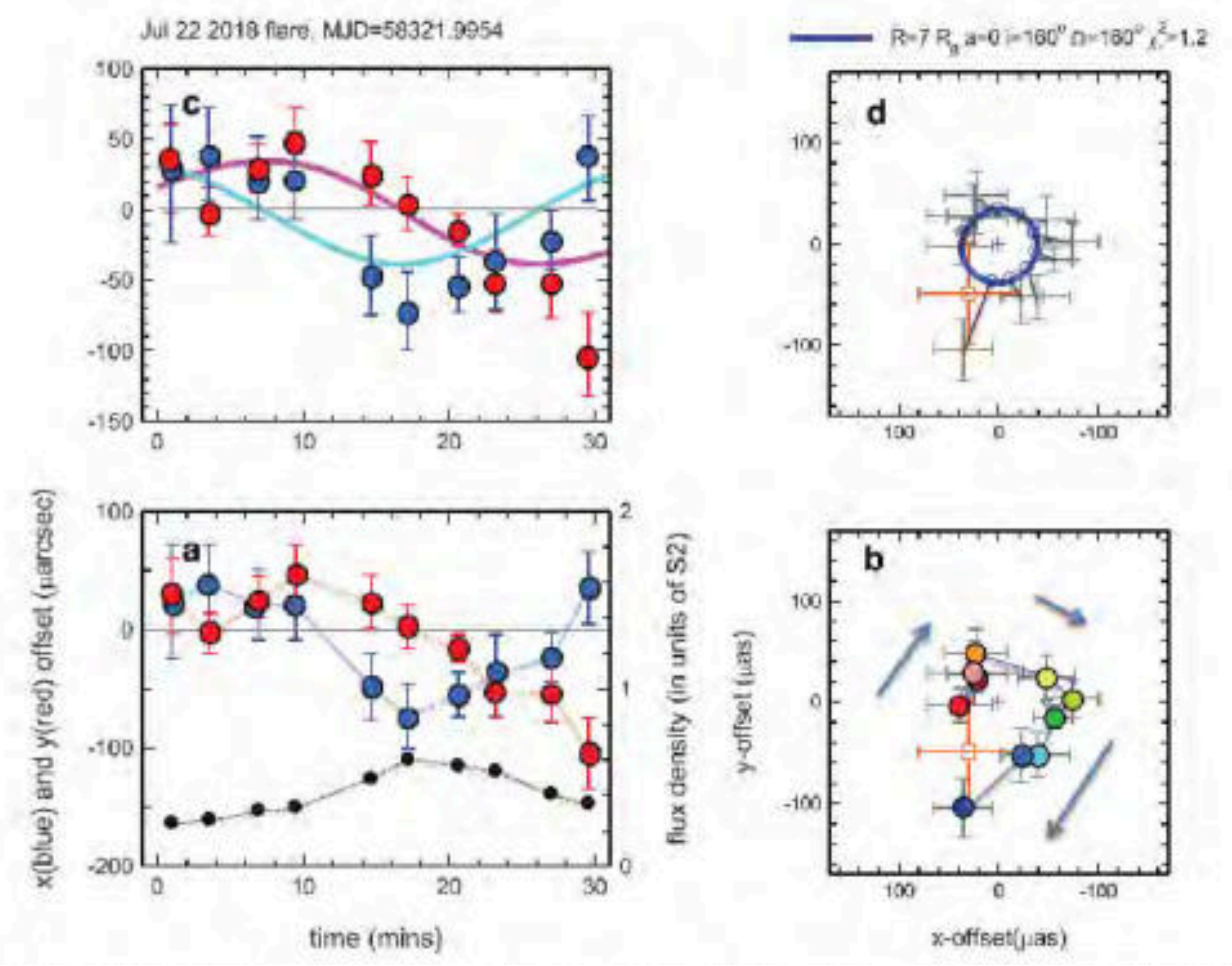




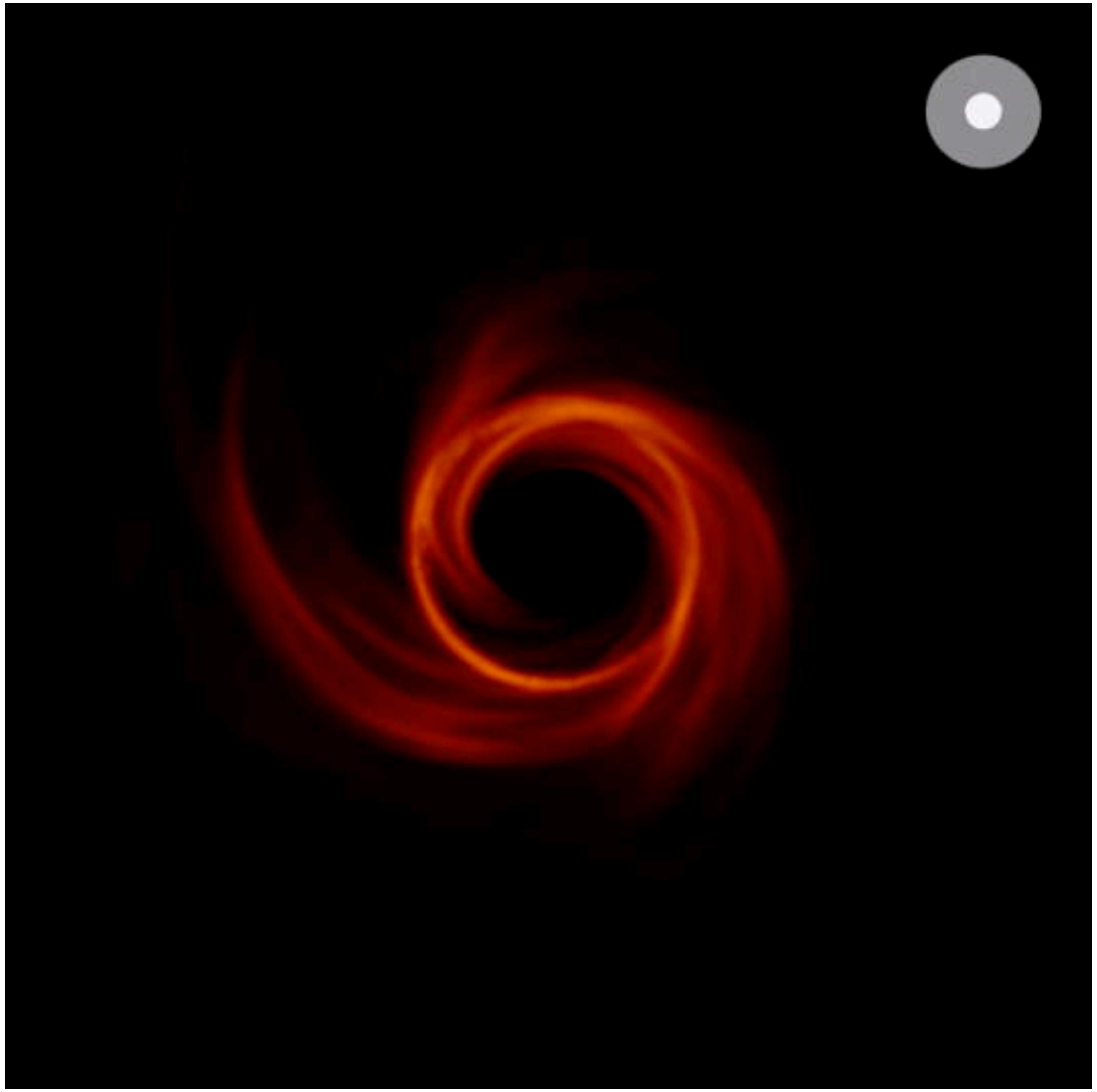
C. M. Fromm (Würzburg), Y. Mizuno (Shanghai), Z. Younsi (London), O. Porth (Amsterdam)
H. Olivares (Nijmegen), A. Nathanail (Athens), A. Cruz-Osorio, L. Weih and L. Rezzolla (Frankfurt)

Low inclination is intriguing

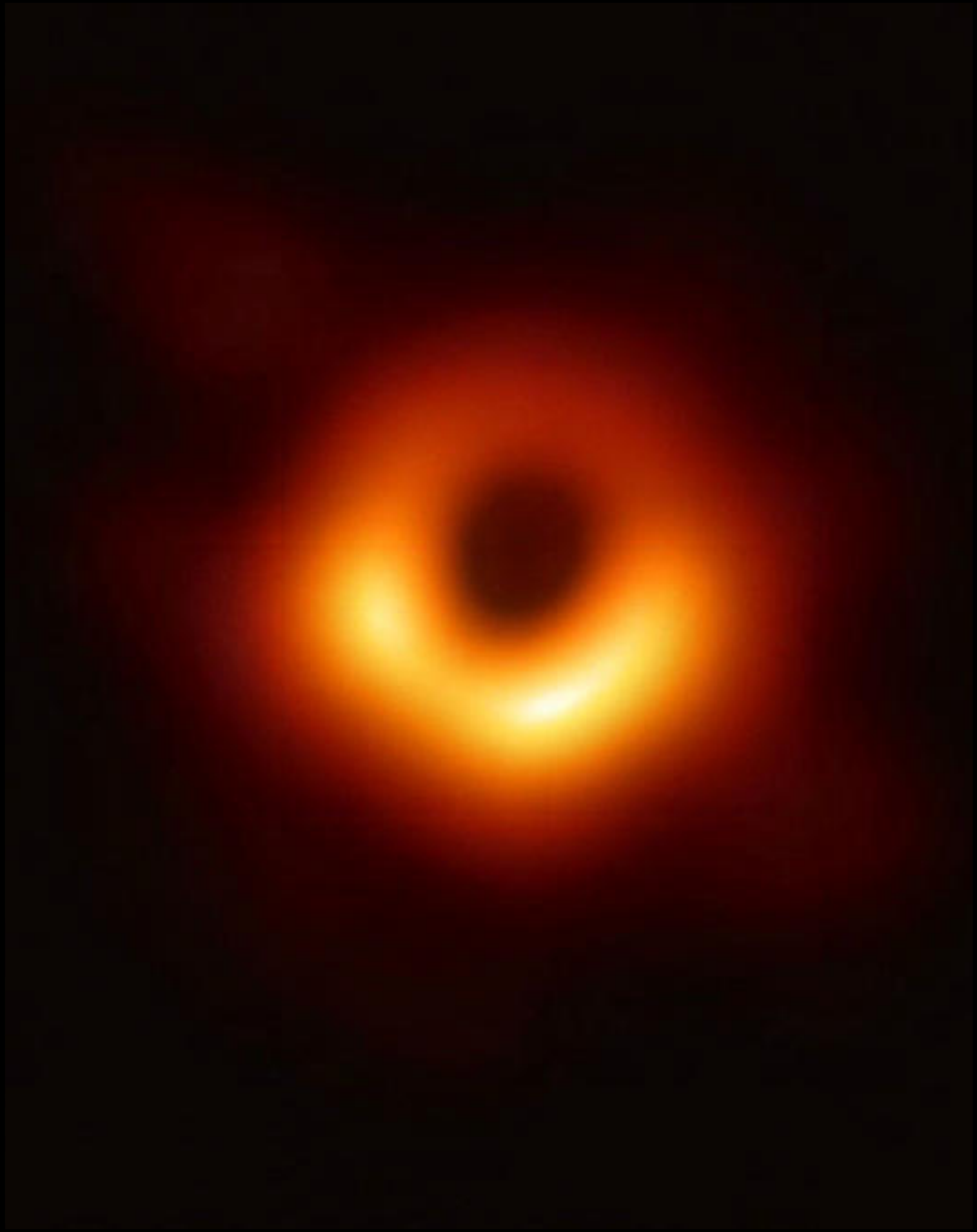
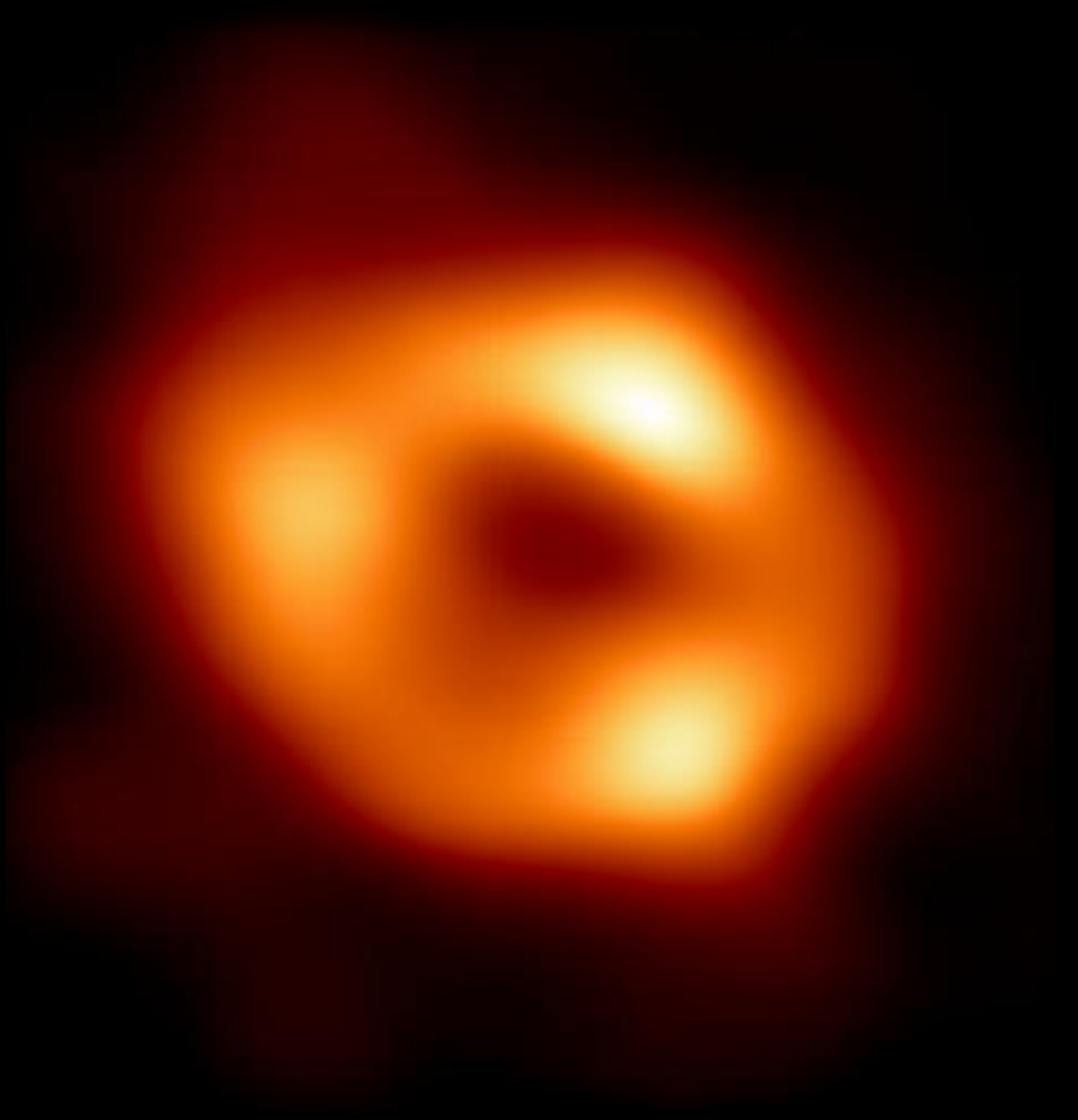
- Means rotation axis not aligned (at all) with Galaxy disk
  - If there is a jet at all, could be pointed towards us
- Consistent with shifting IR position during flare
  - As observed with GRAVITY



Motions of IR flares at ISCO
Gravity collaboration 2018

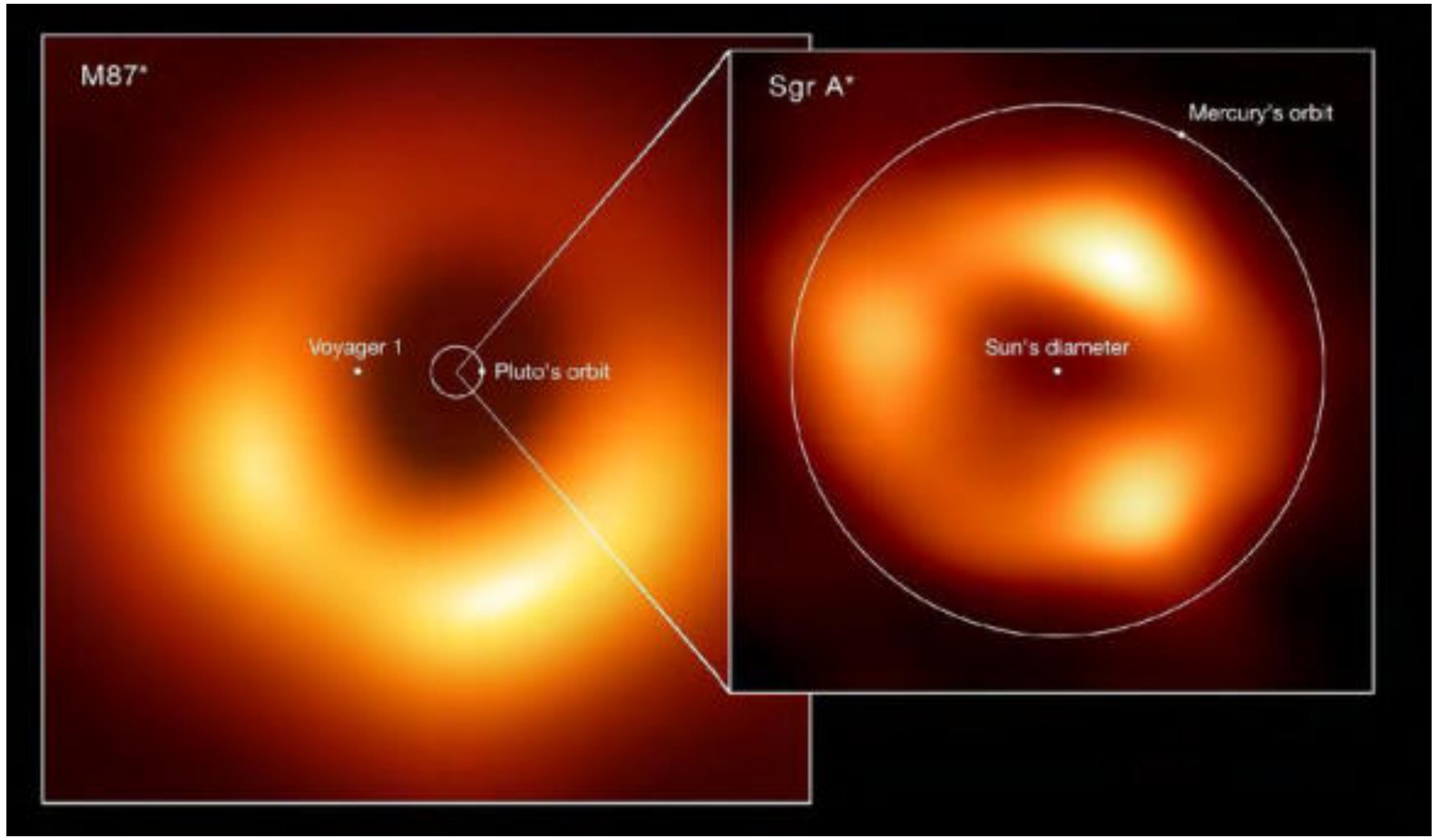


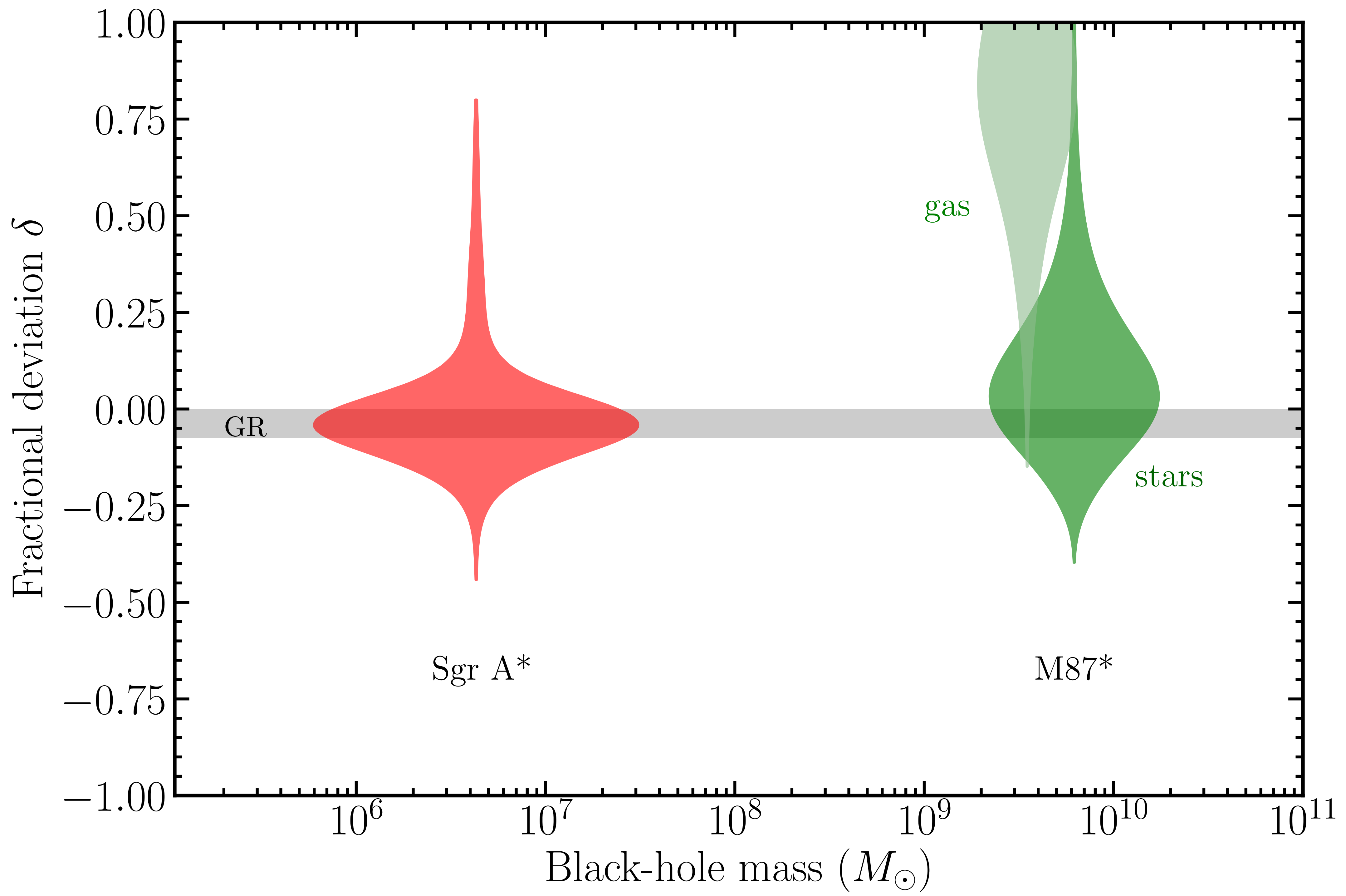
Event Horizon Telescope

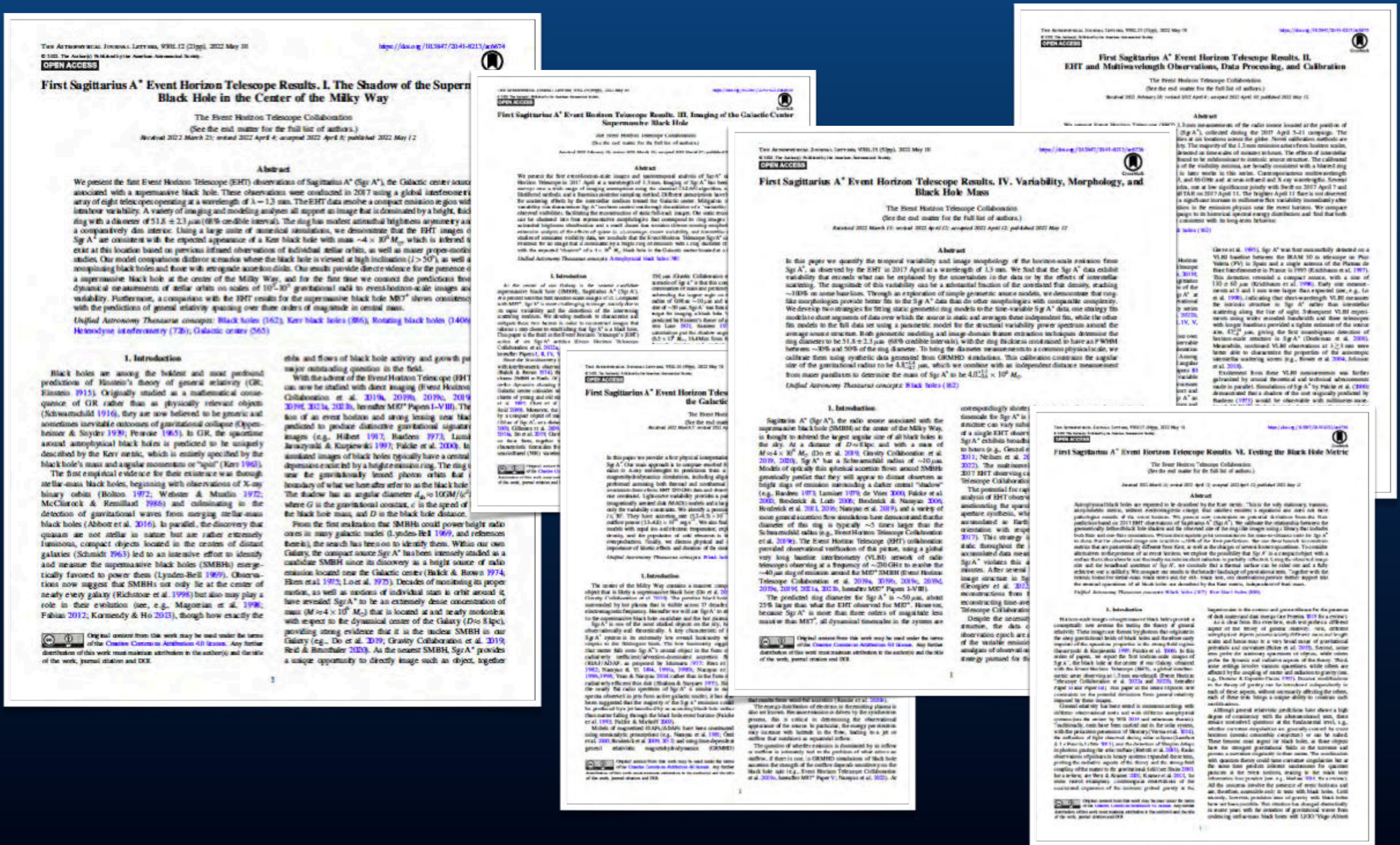



Also did tests against non-Kerr metrics

- Trying to constrain alternatives for Black Holes
- Consistent with GR over 3 orders of magnitude BH mass



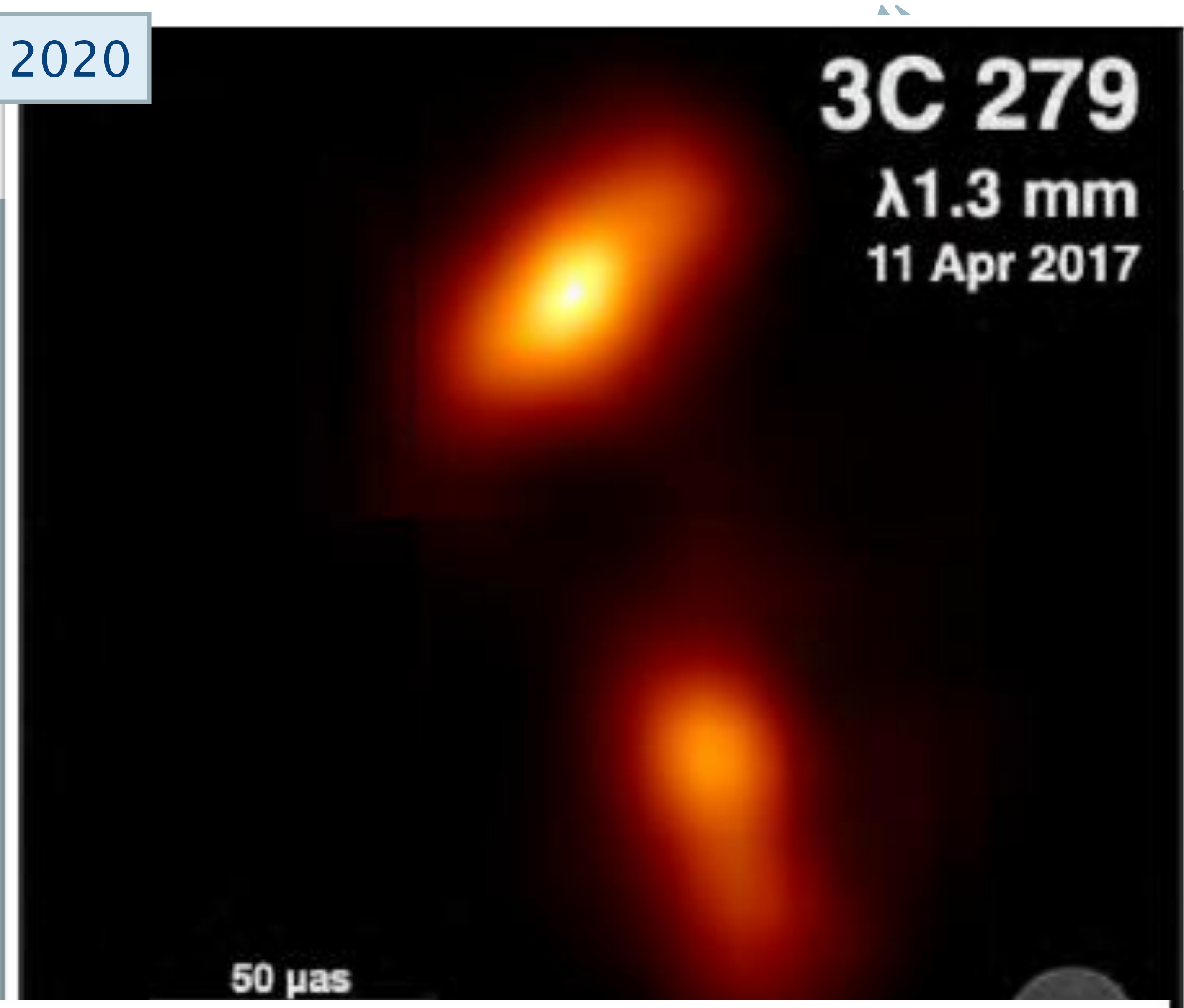


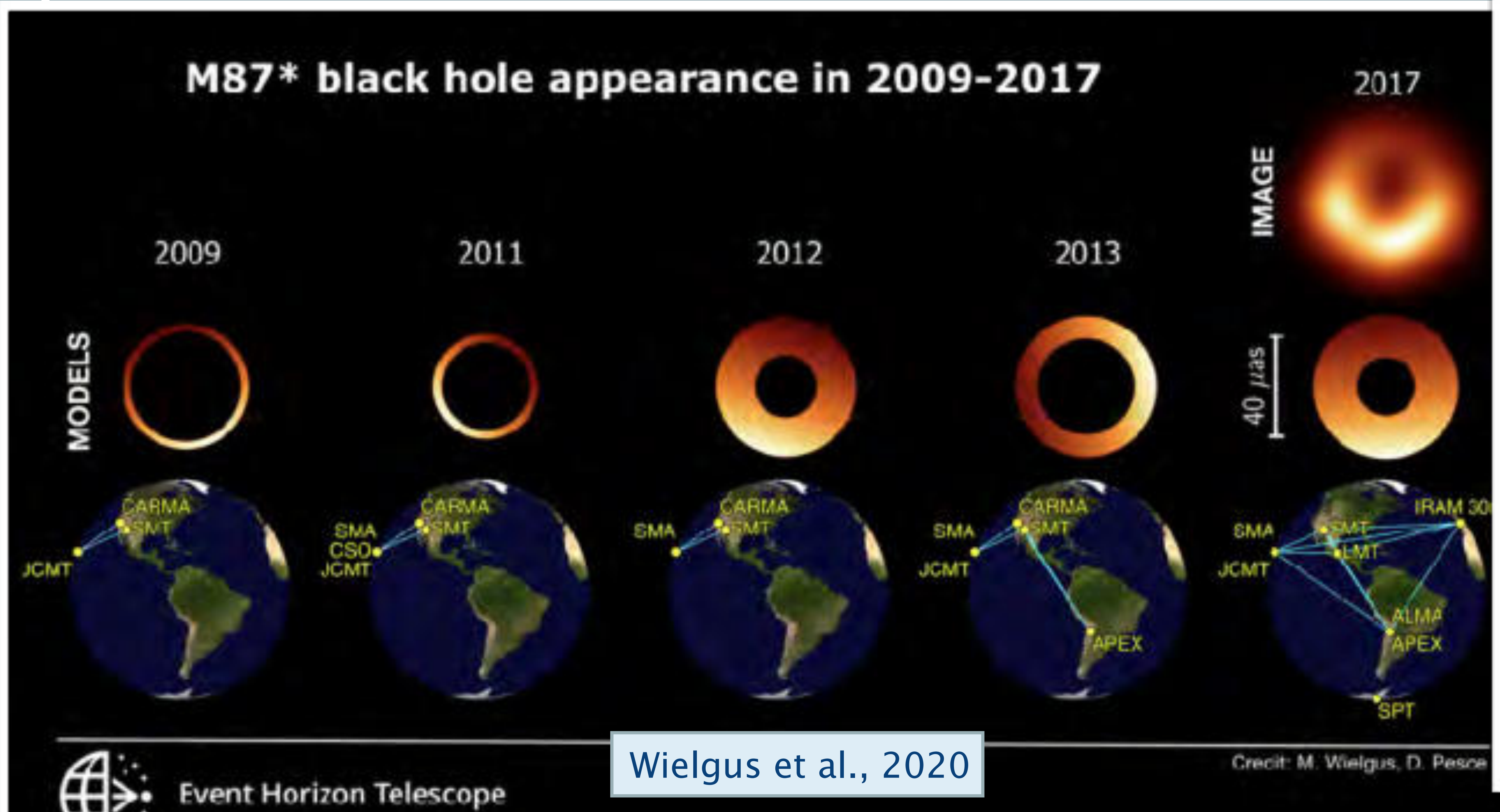

First Sagittarius A* Event Horizon Telescope Results. I. The Shadow of the Superm
Black Hole in the Center of the Milky Way
First Sagittarius A* Event Horizon Telescope Results. II. EHT and Multiwavelength Observations, Data Processing, and Calibration
First Sagittarius A* Event Horizon Telescope Results. III. Imaging of the Galactic Center Supermassive Black Hole
First Sagittarius A* Event Horizon Telescope Results. IV. Variability, Morphology, and Black Hole Mass
First Sagittarius A* Event Horizon Telescope Results. VI. Testing the Black Hole Metric

More results

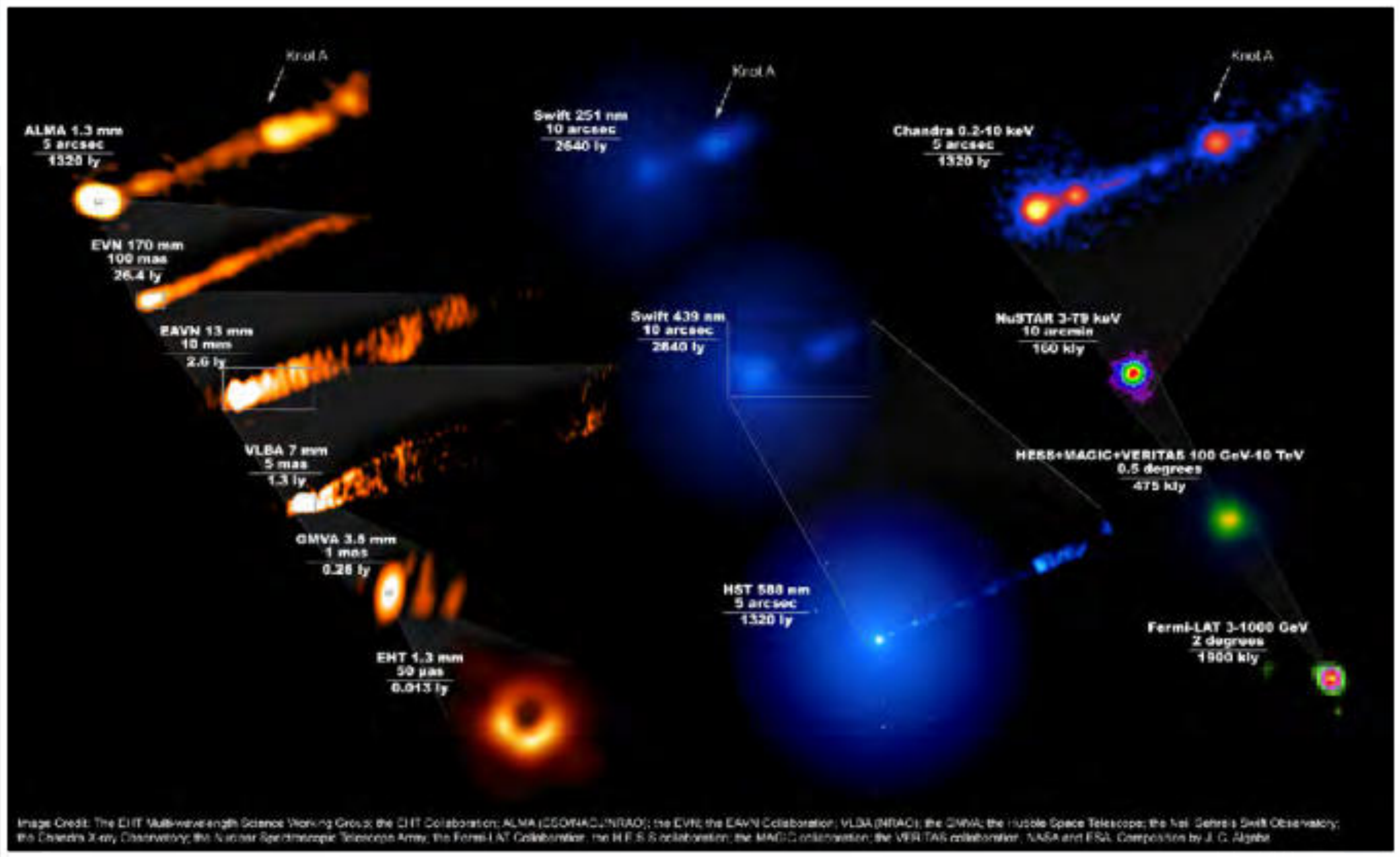
- Main results in 'collaboration papers'
  - More coming from 2017 data
- Several 'official papers'
  - Backing up main results, also on AGN, historic data, GR constraints
- Many tens of 'related papers'
  - Documenting algorithms and models

Kim et al 2020



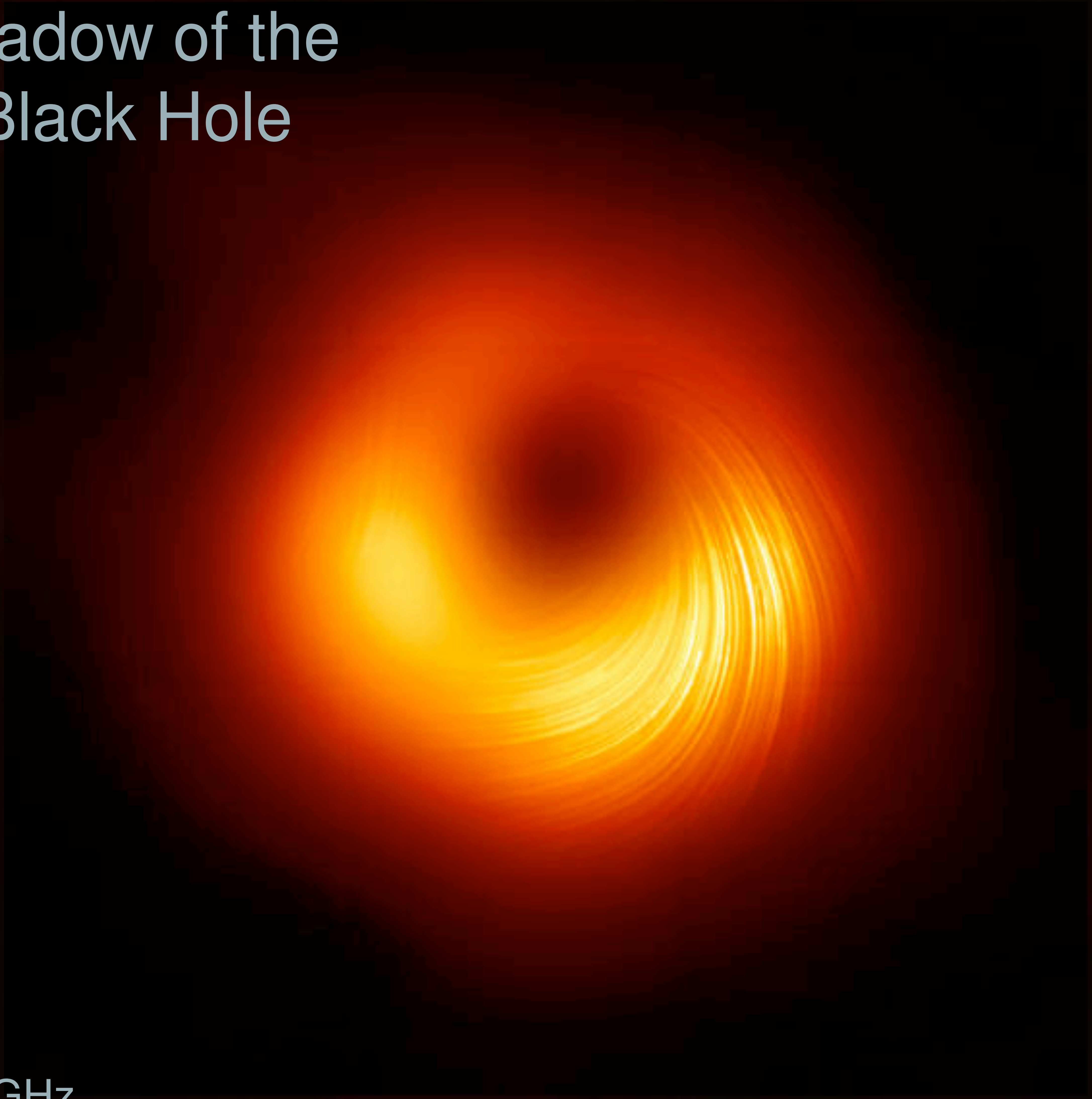


Wielgus et al., 2020



First M87 Event Horizon Telescope Results I. The Shadow of the Supermassive Black Hole

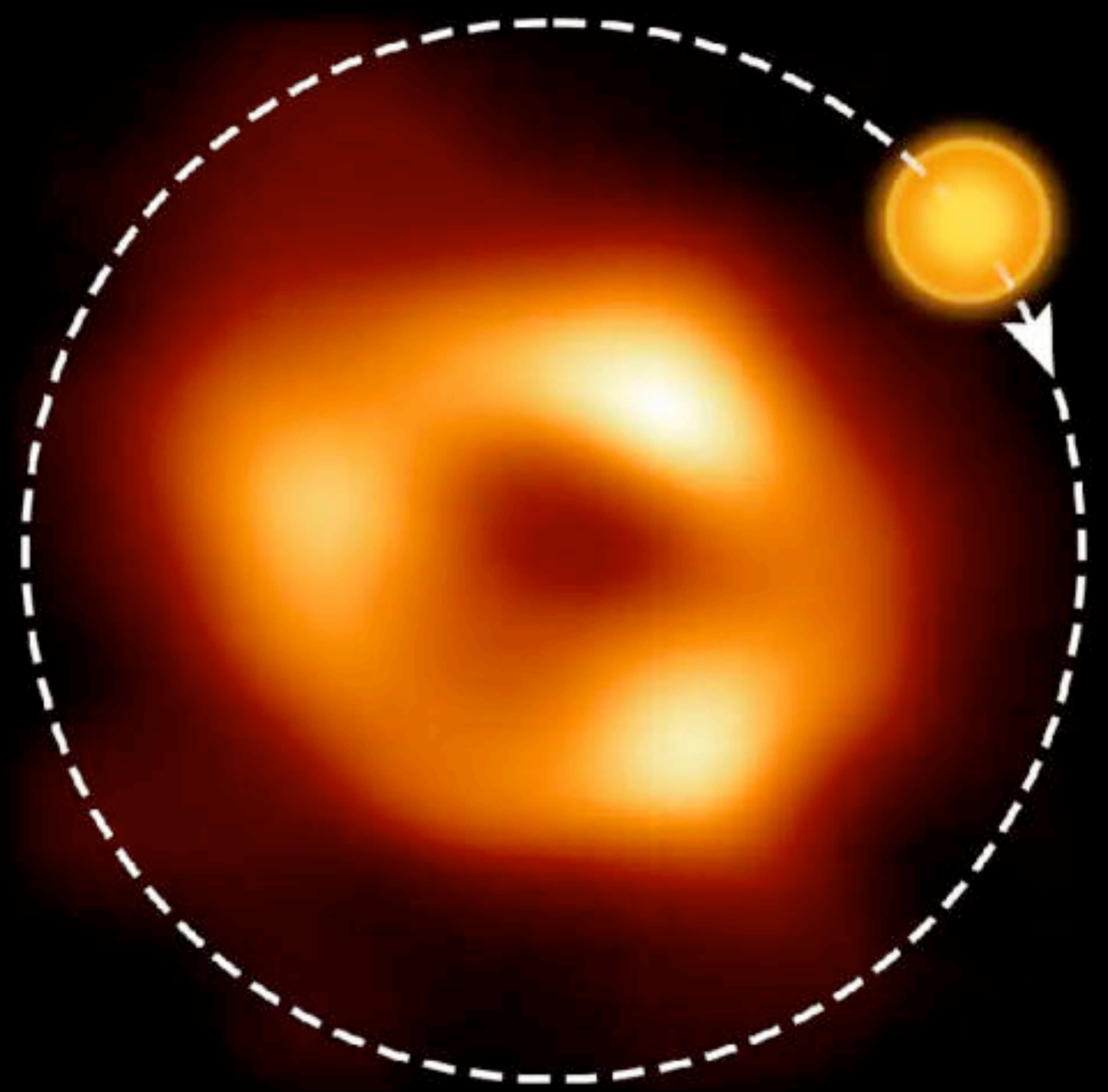
Distance to M87: 16.8 Mpc
Black Hole mass: $6.5\ 10^{9}\ M_{\odot}$



42 μas
≈ 700 au
= 98 lh

Observations at 1.3 mm ≍ 230 GHz
Brightness temperature: $6\ 10^{9}$K

Hotspot in orbit around SgrA*
inferred from polarisation variations



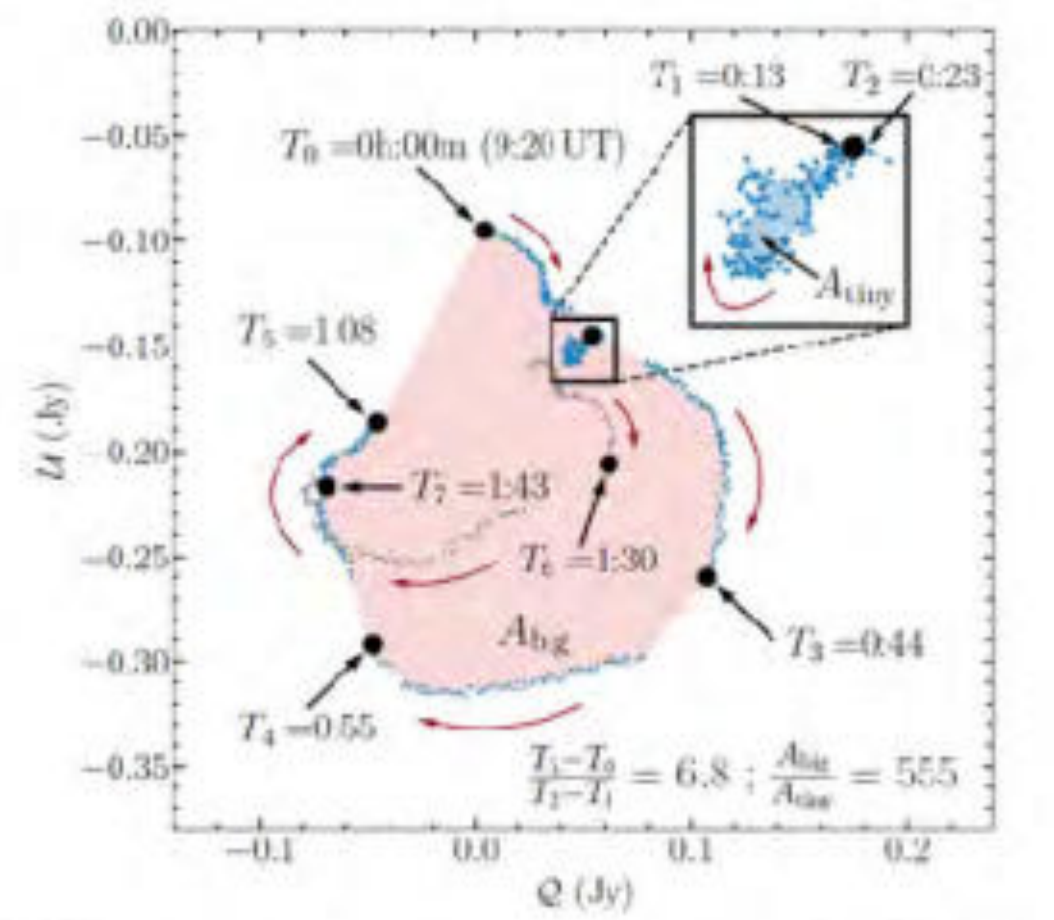
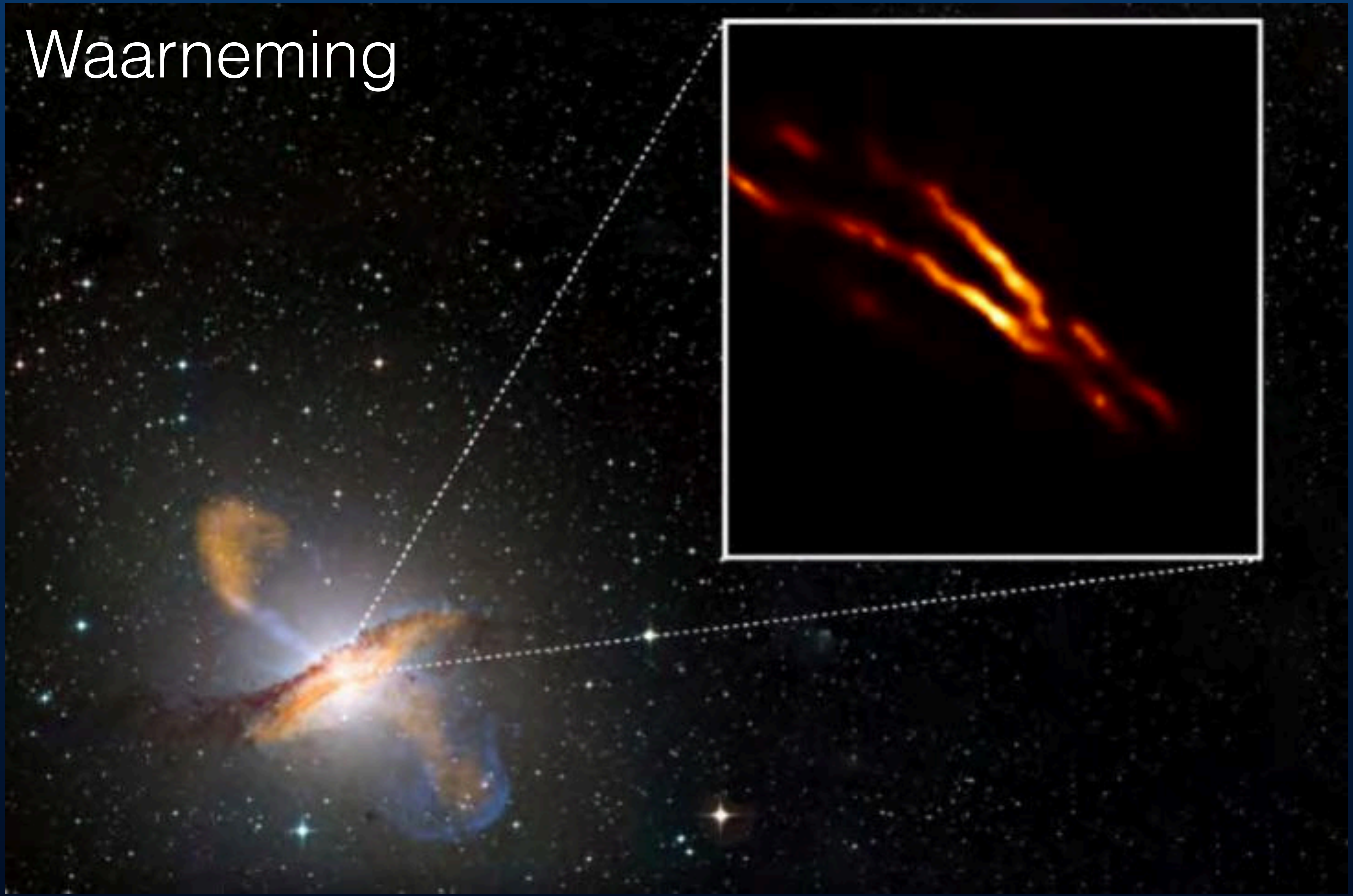


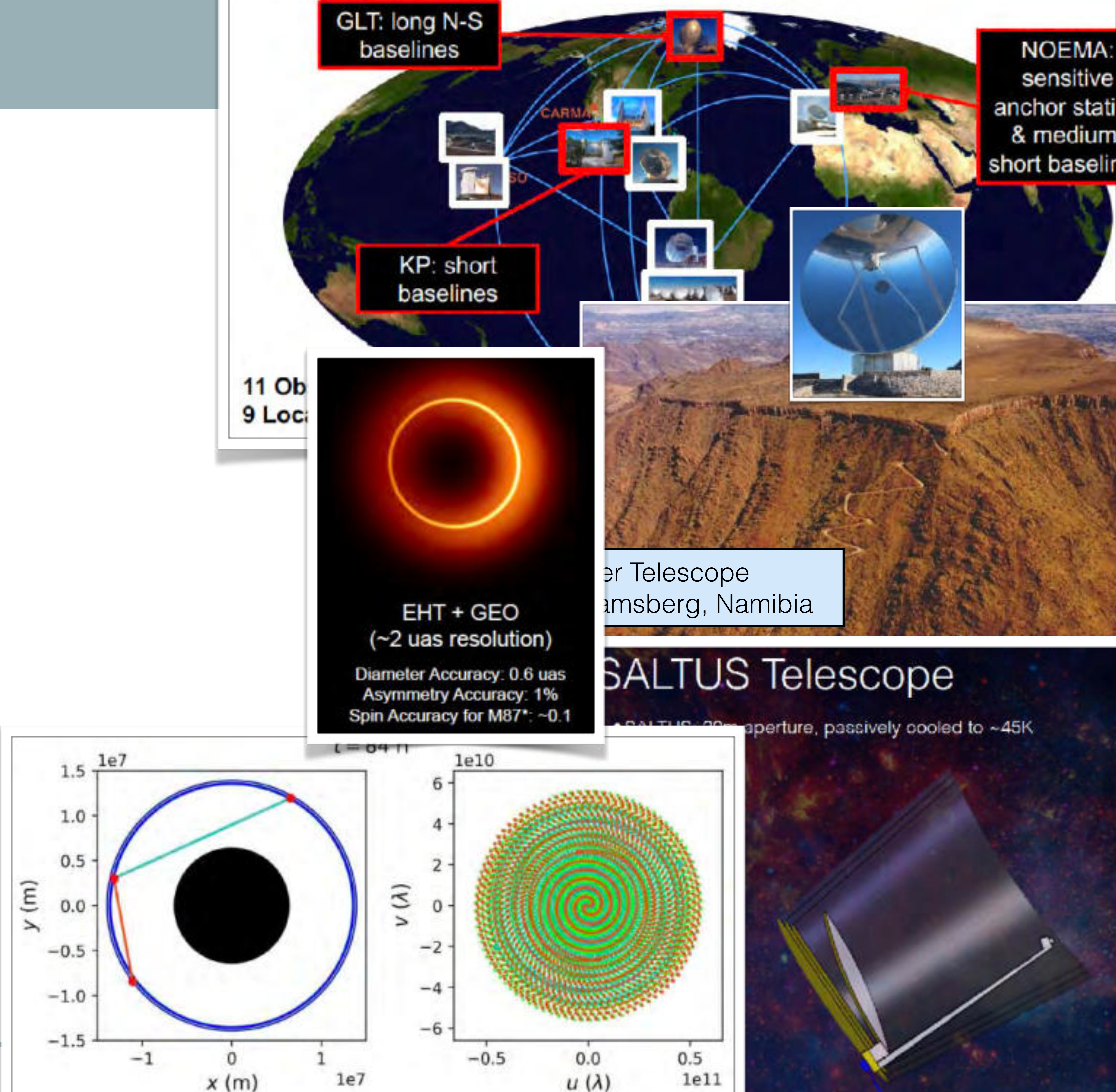
Fig. 2. Polarimetric loops observed by ALMA at 229 GHz on 2017 Apr. 11. The observations began at T_0 = 9:20 UT (MJD 57854.39), 30 min after the peak of the X-ray flare. We highlight the small inner loop A_{tiny}. Following the full loop A_{big} between T_0 and T_5, a similar pattern continues between T_5 and T_7, with a decreased period and reduced LP.



Radboud University/ESO/WFI/MPIfR//APEX/NASA/CXC/CfA/EHT/M. Janssen et al.

Future outlook!

- More/better data in hand
  - 2018, 2021, 2022
    - preparing for April 2023 campaign
  - Introducing NOEMA, Greenland Telescope, Kitt Peak, AZ
- Option to use higher frequency
  - 345 GHz: 1.5x better resolution
- 2024+ possibly more observatories:
  - Owens Valley, Haystack, South-Korea, Africa Millimeter Telescope (Dutch project!), Llama (Argentina), Canary Islands
  - Time sampled images
- But space submm-VLBI for:
  - Other targets
  - Resolving direct image from photon rings



Conclusions

- SgrA* displays convincingly the predicted ring
  - But data processing was quite involved
- It is a more fundamental measurement
  - Because we know distance and mass a priori
  - Consistent with GR at these scales
- SgrA* modeling points towards
  - Magnetically arrested, prograde spinning, low inclination
  - Very low accretion, but still could have a jet

Brought to you by a large, global, distributed team

Huib van Langevelde acknowledges support from:

EHT stakeholders are:

EHT affiliated institutes are: