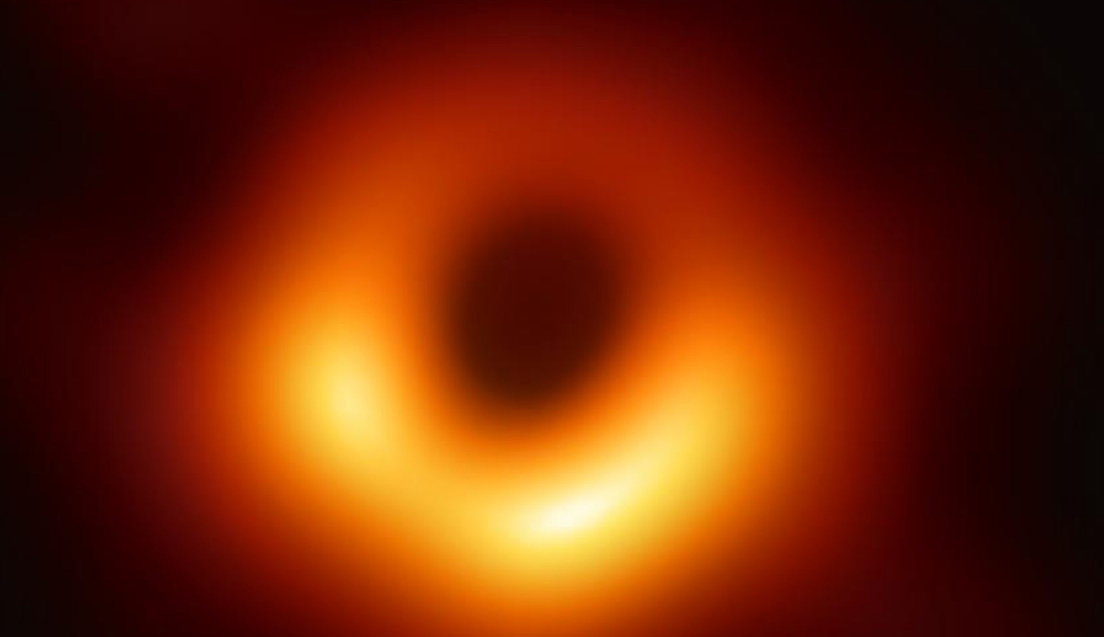
The Shadow of the Supermassive Black Hole



First M87 Event Horizon Telescope Results

Sohn, Bong Won (KASI)
On behalf of the EHT Collaboration

Event Horizon Telescope

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NOVA

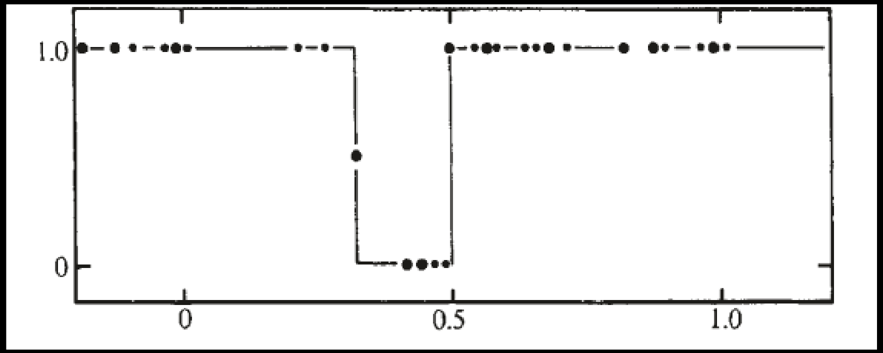
Introduction

- Astronomical Black Holes
  - Stellar mass BHs (up to 100 M_{Sun})
    - Made from Supernova explosion and consequent mergers
    - Keplerian motion + X-ray (Webster & Murdin 1972; Remillard & McClintock 2006)
    - Gravitational-wave measurements (Abbott et al. 2016)
  - Supermassive Black holes (SMBHs; from 10^6 M_{Sun})
    - Seeds? Stellar mass BH or heavier seeds (IMBH) ?
    - exist in the centers of nearly all galaxies (Lynden-Bell 1969; Kormendy & Richstone 1995; Miyoshi et al. 1995)
    - Our Galatic center, Sgr A* (Eckart & Genzel 1997; Ghez et al. 1998; Gravity Collaboration et al. 2018)
    - M87 (Gebhardt et al. 2011; Walsh et al. 2013)
  - Strong evidence of Micro BHs or Intermediate mass BHs is yet to be found

Introduction

- Observational Evidences of BHs
  - Cyg X-1 Radiation from very compact objects
    - Stellar BH - X-ray binary
      - e. g *[Black body radiation] power of 10^{37} erg/s, $L = 4\pi R^2 \sigma T_e^4$*
    - *[X-ray] Peak* around 1 keV (10^7 K),
      - r ~ 10 km (Sun ~ 7 x 10^5km, Earth ~ 6 x 10^3 km)
    - If it radiates at optical-UV,
      - r ~ 10^7 km (a giant star) for given Luminosity

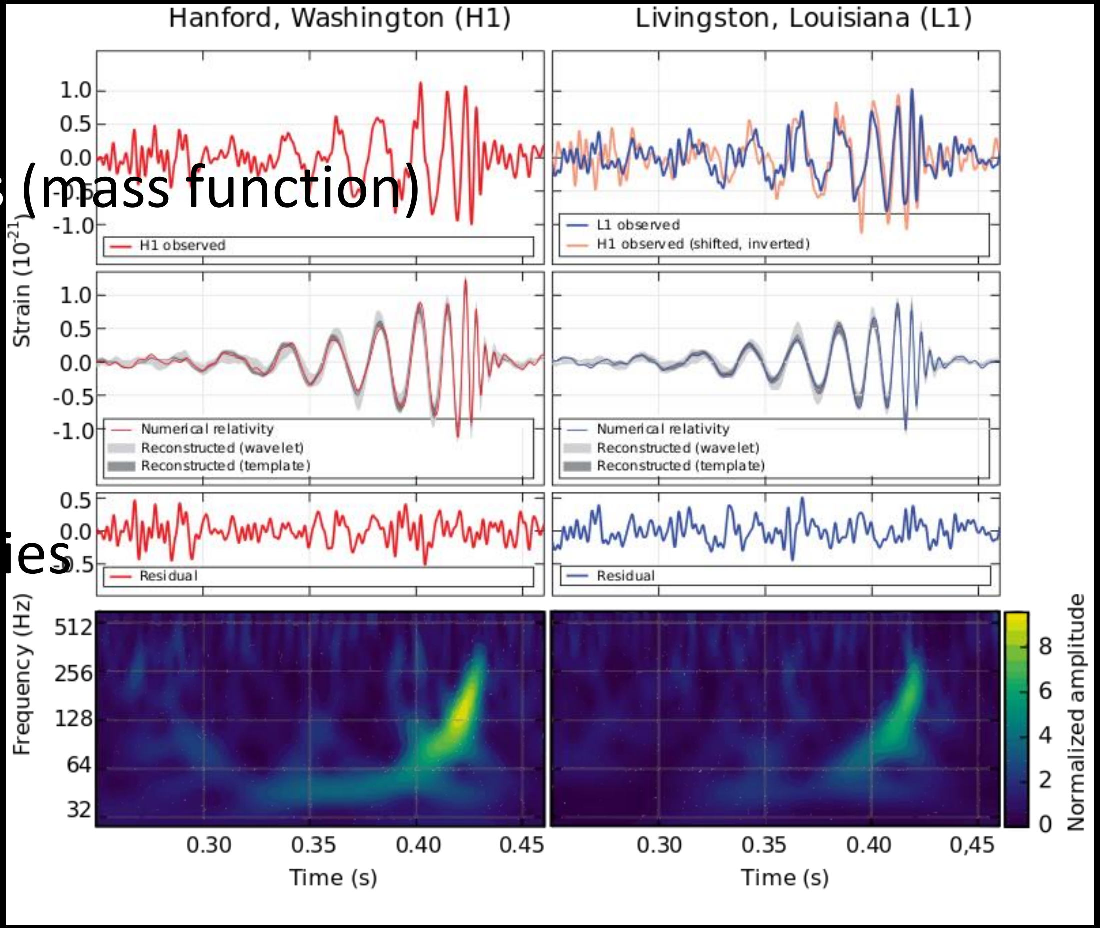
    - Cyg X-1 (Webster & Murdin 1972) > a few solar mass
      - Keplerian motion of companion from spectroscopy



Cyg X-1 X-ray light curve (Agrawal+ 1971)

Introduction

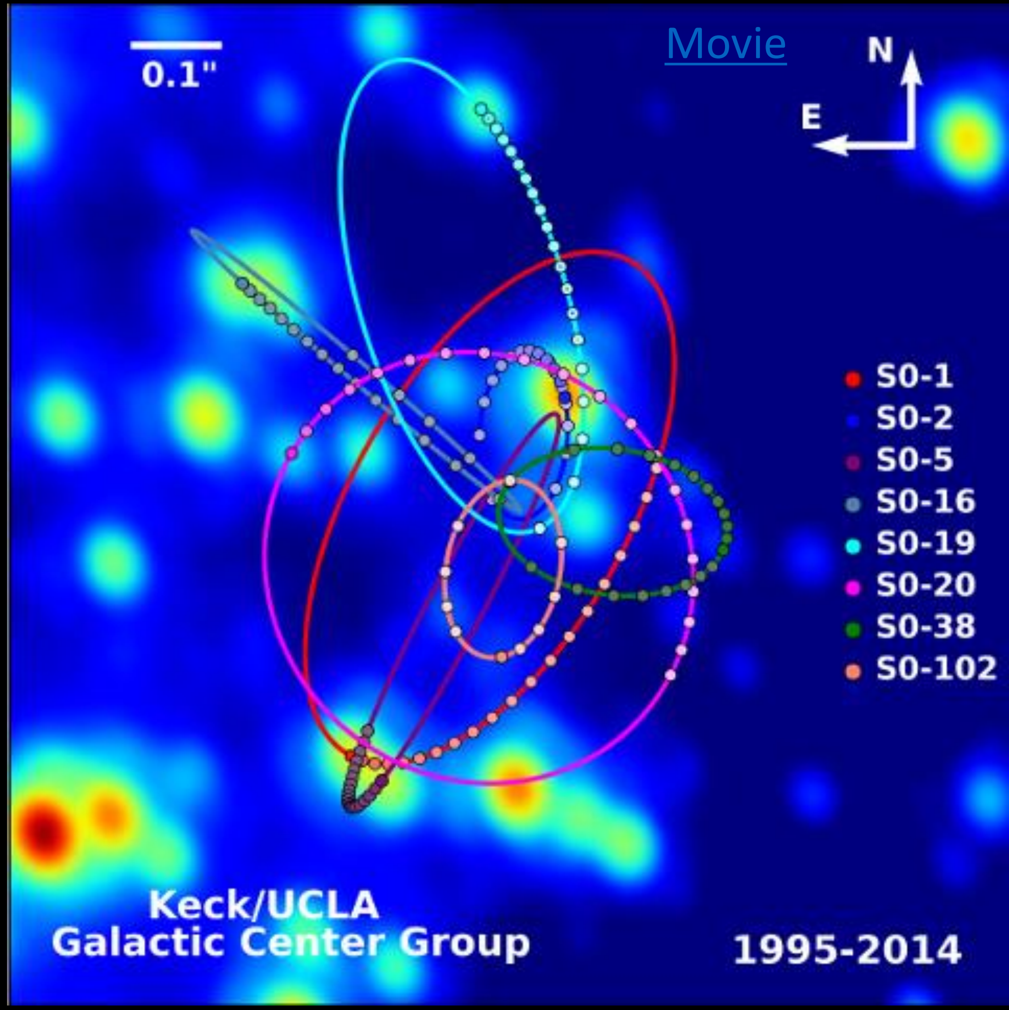
- Observational Evidences
  - Keplerian motion around compact objects (mass function)
    - Stars around SMBH (e.g. Sgr A*)
    - Gas disk around SMBH (e.g. NGC4258(M107))
    - Velocity dispersion (e.g. M87)
  - Gravitational redshift from center of galaxies
    - Star (GRAVITY collaboration 2018), gas
  - Optical, IR, Radio (VLBI) , X-ray, ...
  - Photometry, spectroscopy, Astrometry, ...



Galactic Center Sgr A*

(Eckart & Genzel 1997; Ghez+ 1998; ESO & UCLA GC group)

- Long-term monitoring of star's positons
- In a volume with radius of 60 AU
  - ~ 0.3 mPC ~ 0.00095 ly ~ 8.3 lhr
- M ~ 4.1 ± 0.6 x 10^6 M_{Sun}
  - 0.1 arcsec ~ 850 AU at 8.5 kpc
  - R_{sch} ~ 0.08 AU (0.39 μpc)
- Full phase coverage measured for two stars
  - S0-2 with an orbital period of 15.56 years
  - S0-102 with 11.5 years
  - At the closest approach, S0-2 is only 17 light hours



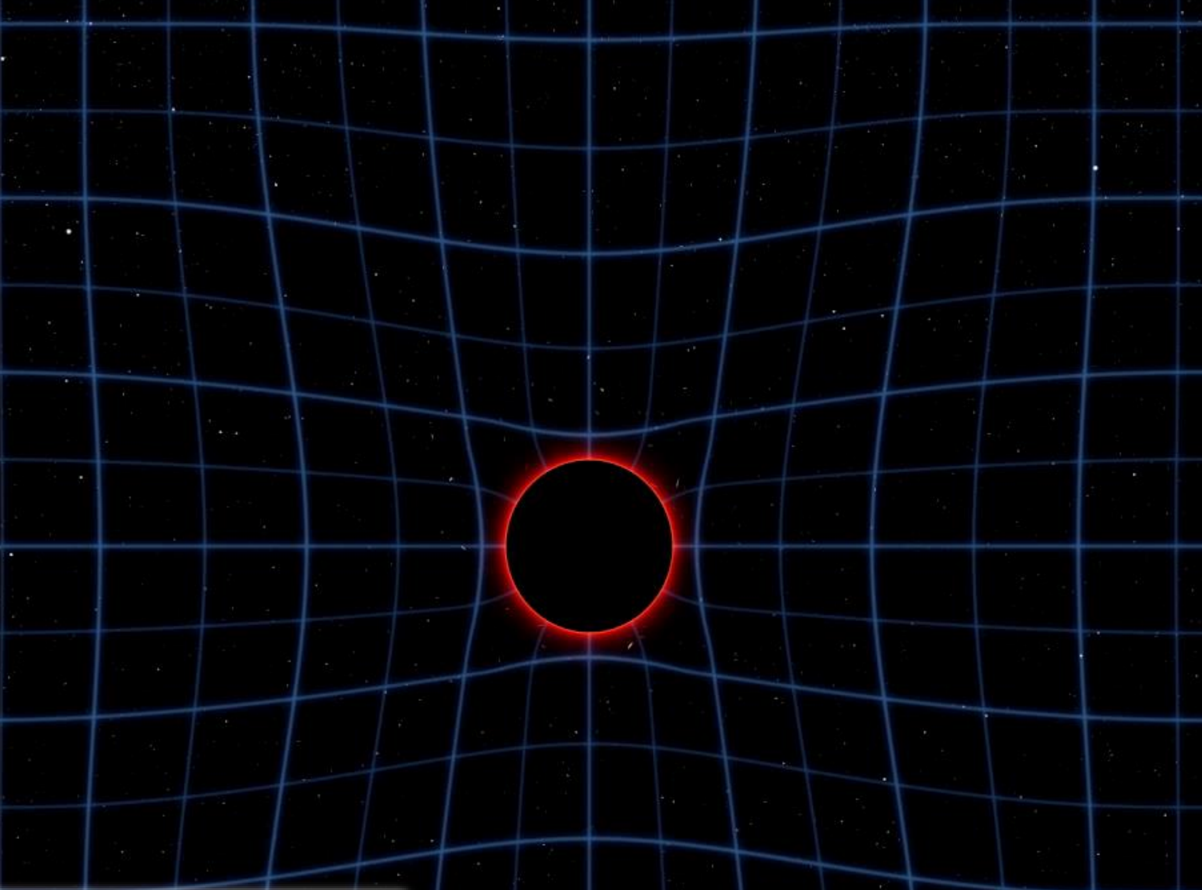
Looking for Best objects for Black Hole Shadow Image

M_BH should be massive ➔ large photon capture ring (BH shadow)

Object should be as close as possible from us → large angular size

Should be compact and bright Synchrotron source ➔ Radio Interferometer

Black Hole Photon Capture (BH Shadow)



Photon Capture Radius (Black Hole Shadow Size)

$R_c = 1.5 \sqrt{3}\ R_{sch} = 3 \sqrt{3}\ GM\_BH / c^2$

Event Horizon Telescope

Apparent Size of Photon Capture Radius

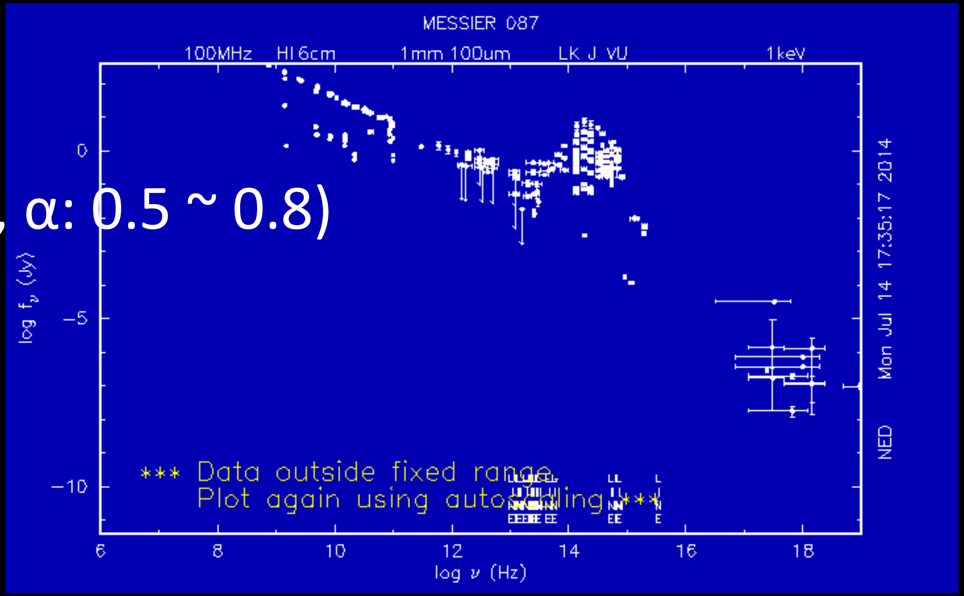
- Apparent Size of Photo Ring
  - $\Theta_c = R_c$ / distance
- Stellar Mass BHs
  - Cygnus X-1
    - M ~ 15 M_{Sun}
    - Distance 1,900 pc
  - SS433 (Stellare BH with Jet)
    - M < 30 M_{Sun}
    - D ~ 5,500 pc
- Supermassive BHs
  - *Sgr A**
    - M ~ 4 x 10^6 M_{Sun}
    - d ~ 8.5 kpc
  - *M87* (Vir A*)*
    - M ~ 6 x 10^9 M_{Sun}
    - d ~ 16.7 Mpc
  - Cen A
    - M ~ 5 x 10^7 M_{Sun}
    - d ~ 4 Mpc

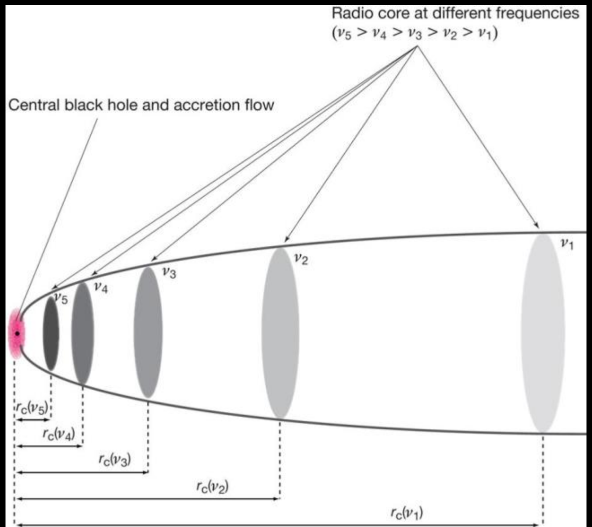
Θ_c of Sgr A*, M87* ~ 40 μarcsec

> 10^4 times larger than stellar BH candidates

Synchrotron radiation around Black Holes

- Synchrotron radiation from SMBH
  - Power law distribution of flux density ($S_\nu \propto \nu^{-\alpha}$, α: 0.5 ~ 0.8)
  - Relatively interstellar extinction free
  - But synchrotron absorption
    - significant in compact region (e.g. near BH)
    - Synchrotron self-absorption (jet)
    - Blandford-Koenigl jet (1979)
    - $S_\nu \propto \nu^{5/2}$
  - Radio frequency → Radio interferometry
  - mm wavelength → higher angular resolution
  - mm wavelength → low synchrotron self-absorption

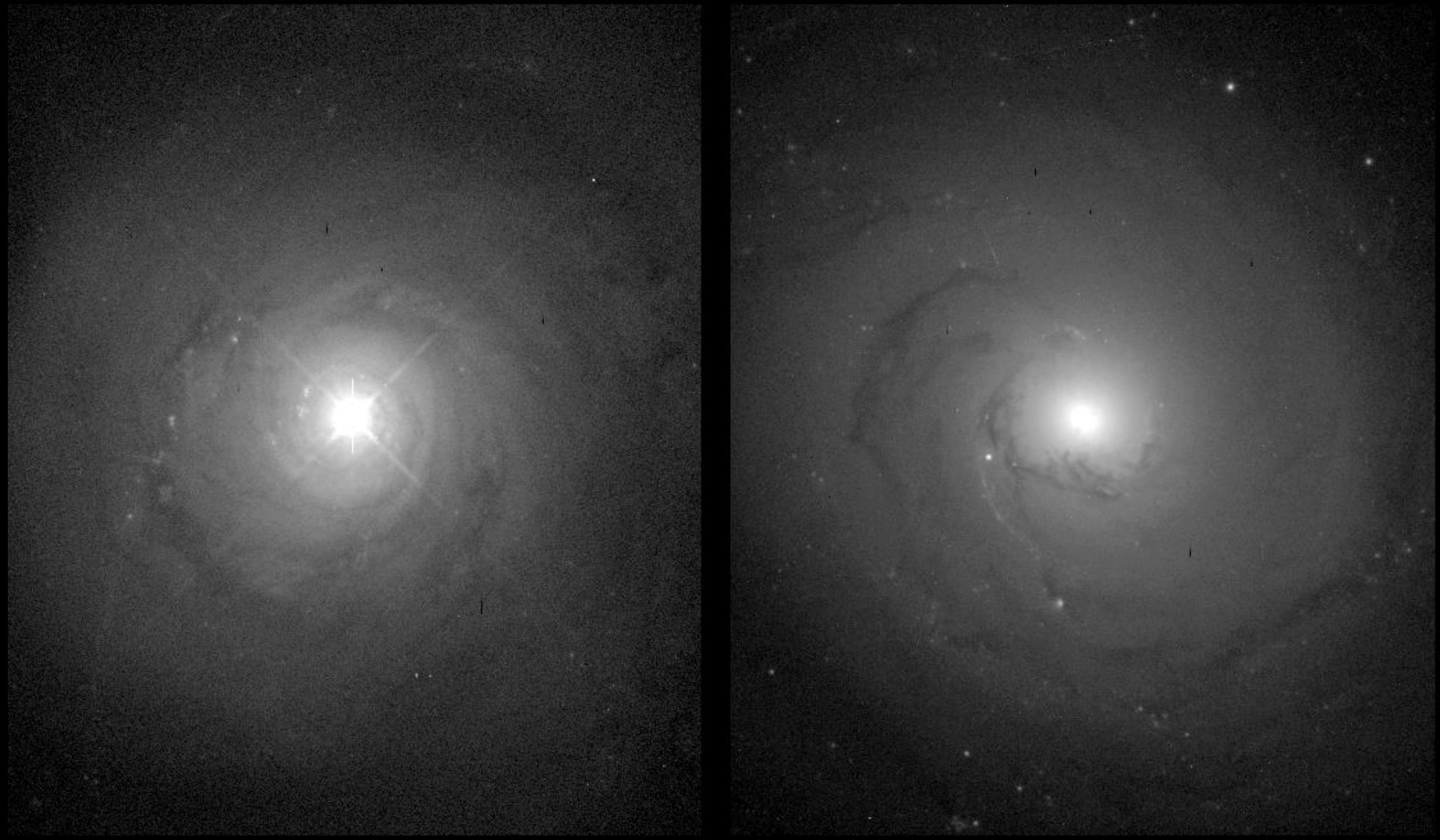




Active Galactic Nuclei (AGNs)

- NGC1068 first discovered by Fath in 1908
- Central bright regions that can outshine the entire stellar population of their host galaxy
- Mass-accreting SMBH and surrounding regions
- Simplified classification
  - High accretion rate Quasars
    - Optically thick, geometrically thin accretion disk (Shakura & Sunyaev 1973; Sun & Malkan 1989)
  - Low accretion rate LLAGN
    - fed by hot, tenuous accretion flows with much lower accretion rates (Ichimaru 1977; Narayan & Yi 1995; Blandford & Begelman 1999; Yuan & Narayan 2014)
  - All together ~10% of whole SMBHs (~90% are not active)

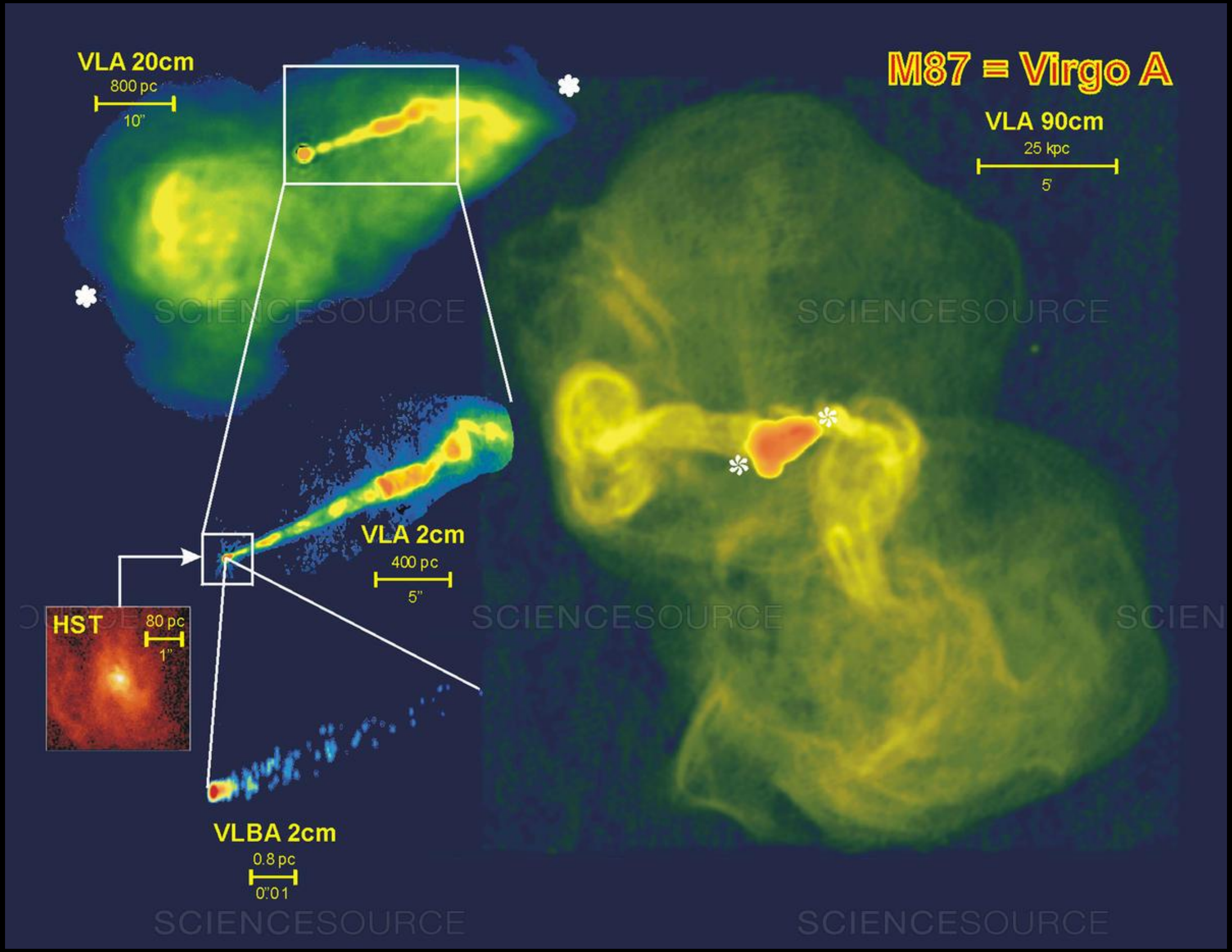
Seyfert Galaxy NGC 5548 (AGN in Spiral Galaxy) versus normal galaxy NGC 3277



And ~10% of 'Active' SMBHs are 'radio loud' (bright synchrotron sources)

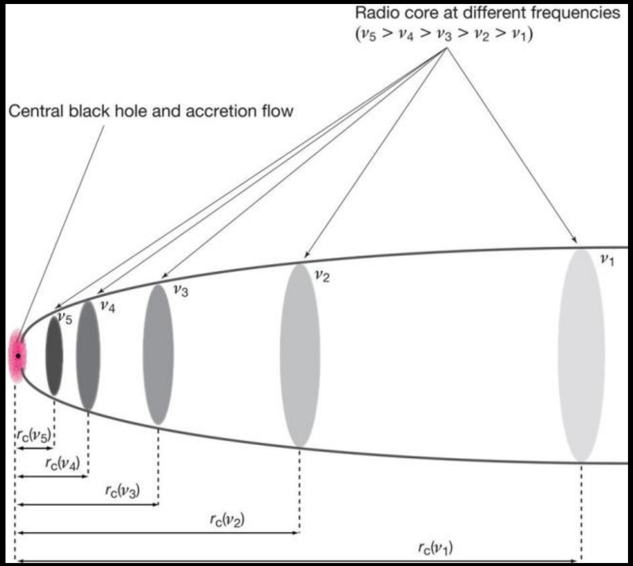
Radio core in M87

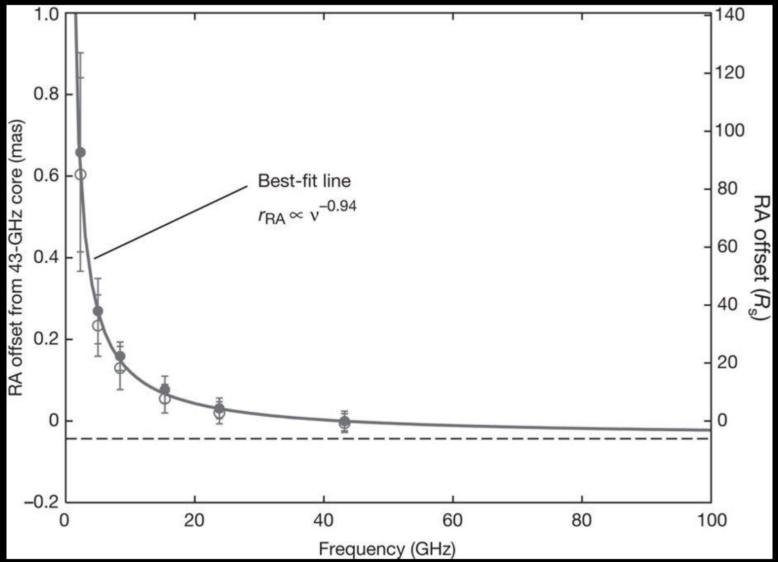
- Linear feature found in M87 by Curtis in 1918
  - Called "jet" by Baade and Minkowski (1954)
  - 65kpc; 40 Myr
    - Power close to 10^45 erg/s (de Gasperin+, 2012)
  - Compact (unresolved) source at the upstream end of the jet – LLAGN

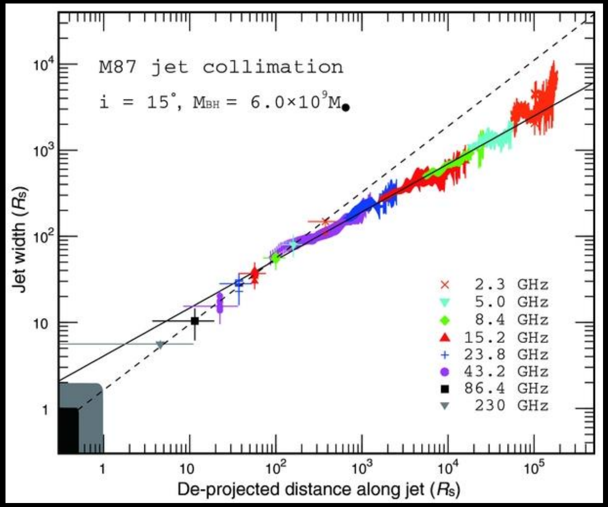


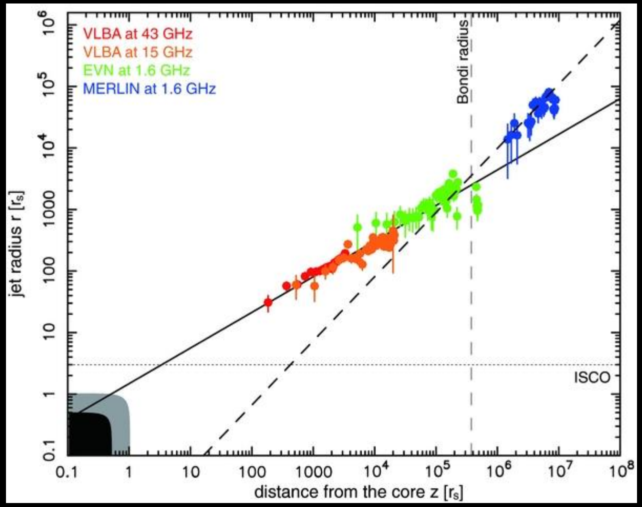
Radio core in M87

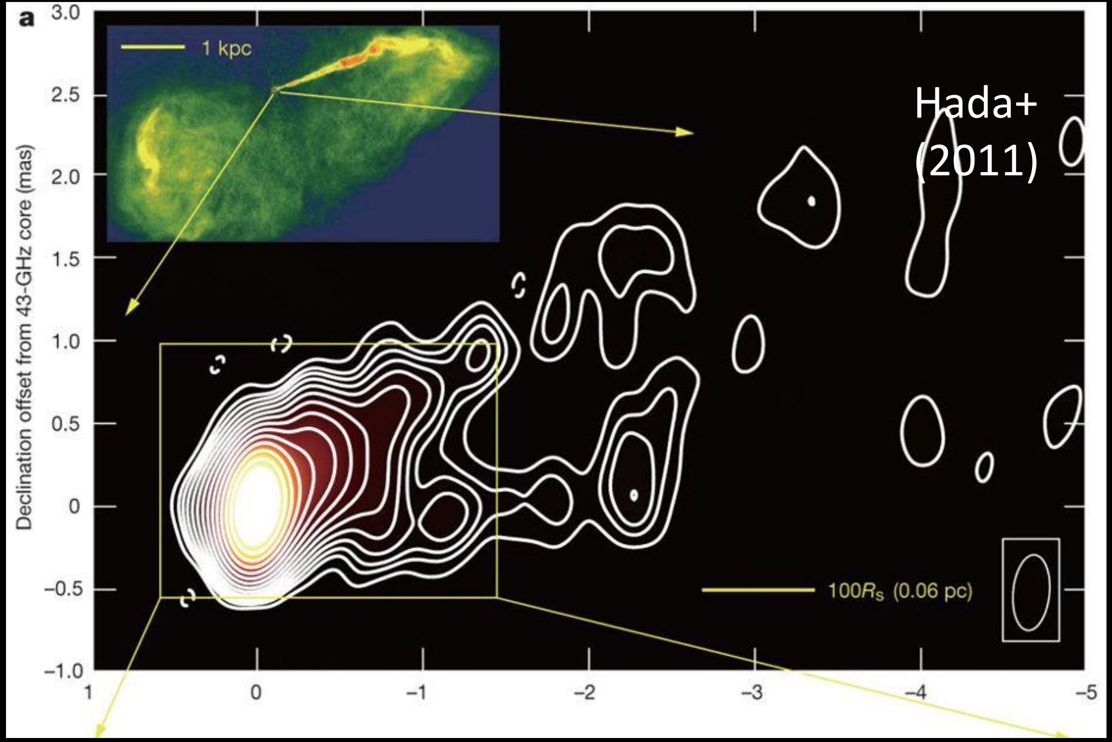
- Blandford-Koenigl (1979) jet
  - Synchrotron self-absorption
  - Confirm (Hada+ 2011)
  - Quasi-parabolic limb shape
    - From 10^5 r_g to 20 r_g (Hada+ 2013)
    - Further to 10^7 r_g (Asada+ 2012)











Hada+ (2011)

Event Horizon Telescope

- A global millimeter VLBI experiment
  - Baseline 160 m to 10,700 km
  - 230GHz; 1.3mm → resolution ~25 μas
  - 6 locations, 8 stations (2017)
  - Sensitivity increase by a factor of ~30 increased over last ten years (ALMA and high performance recorders)

Best targets

Sgr A* : M_{BH} ~ 4 x 10^6 M_{Sun}
d ~ 8.5 kpc

M87* : M_{BH} ~ 4-6 x 10^9 M_{Sun}
d ~ 16.5 Mpc

First radio telescope was an interferometer

Jansky and his Bruce array

Radio interferometer

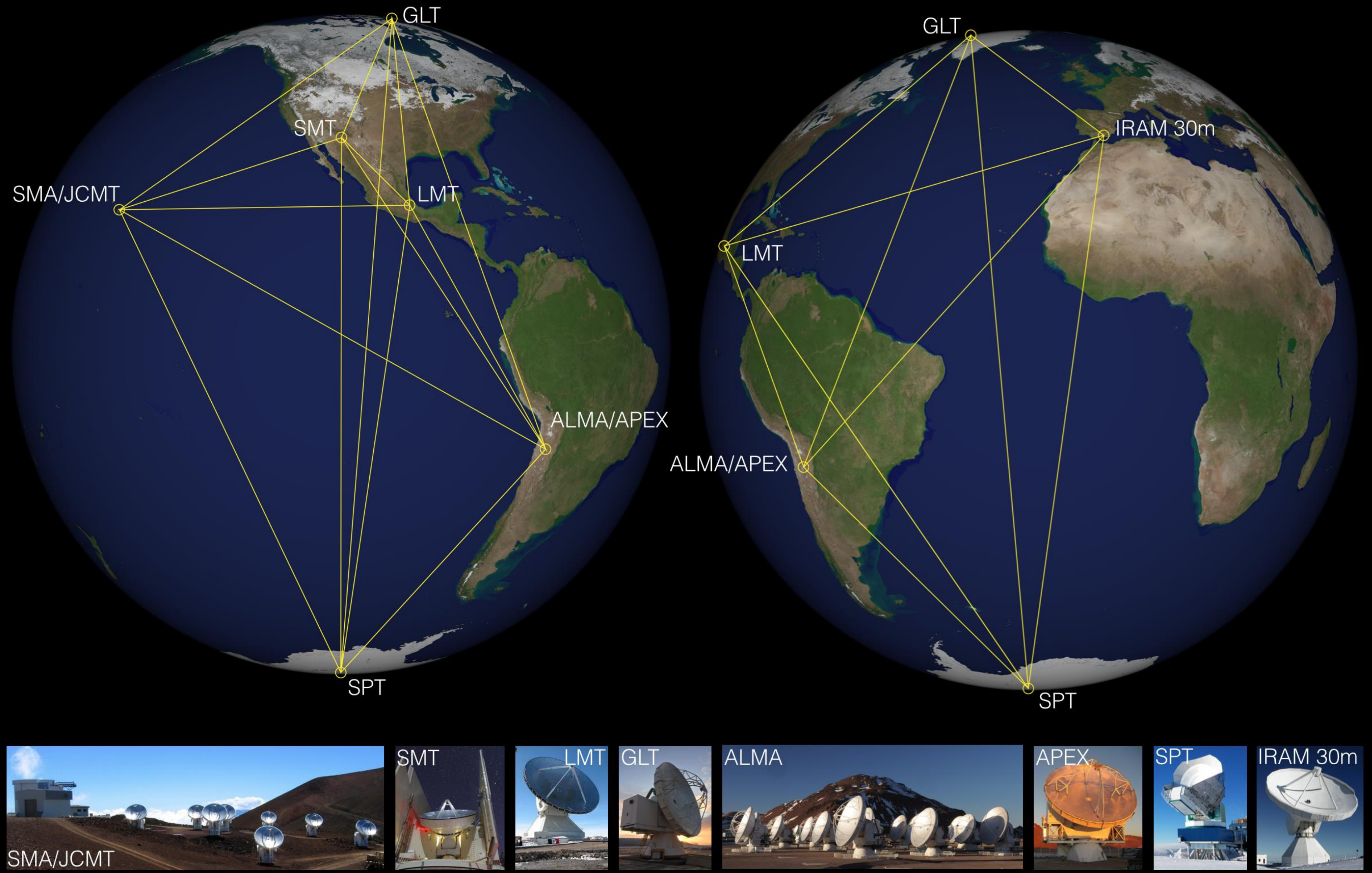
- Interferometer sees ‘visibility’ (e.g. fringes of Young’s experiment)
- Visibility (ν_x, ν_y) FT Image (x, y); FT ‘Fourier Transformation’
- In imaging, transformation between Spatial Frequency and position

$$E(\xi) = \int_{-\infty}^{\infty} \bar{E}(x_\lambda)\, e^{-i2\pi x_\lambda \xi}\, dx_\lambda$$

$$E(x_\lambda) = \int_{-\infty}^{\infty} \bar{E}(\xi)\, e^{+i2\pi \xi x_\lambda}\, d\xi$$

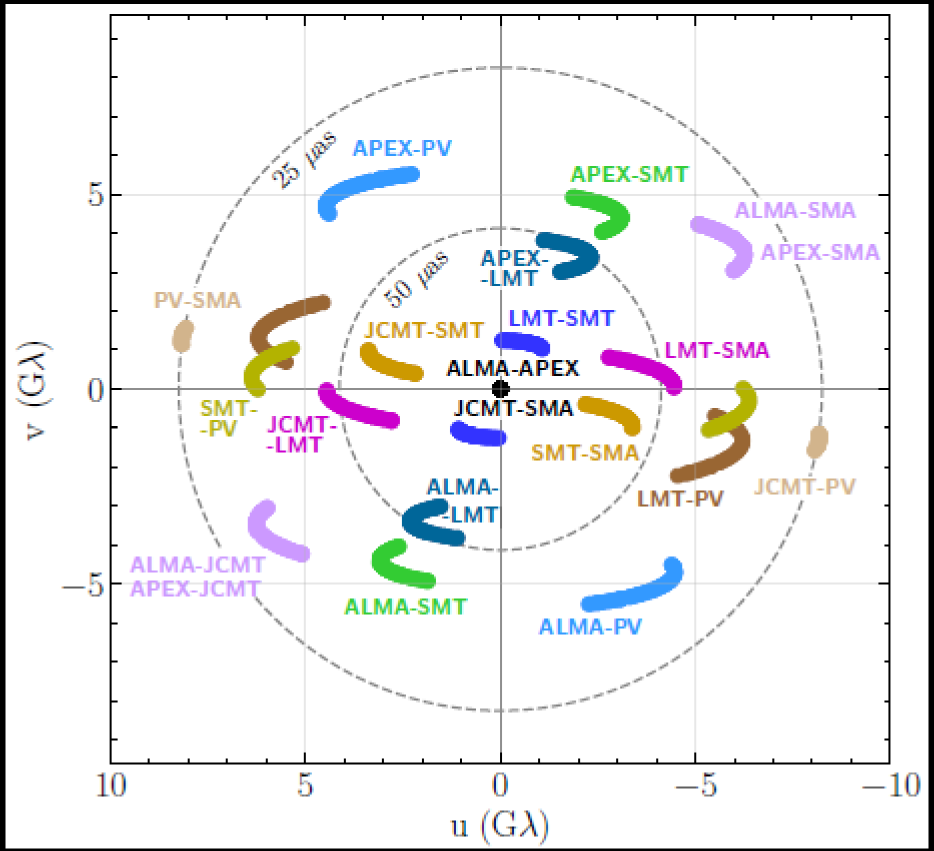
- Radio interferometer with very long baseline
  - ‘Very long’ means separate freq. time standard and incoherent atmosphere
  - At radio wavelength, arbitrary long baseline is possible
- From IR, frequency standard (H-maser clock) accuracy is not sufficient to record waves
  - Plus interstellar extinction and contamination

Event Horizon Telescope



Observation, Correlation and Calibration

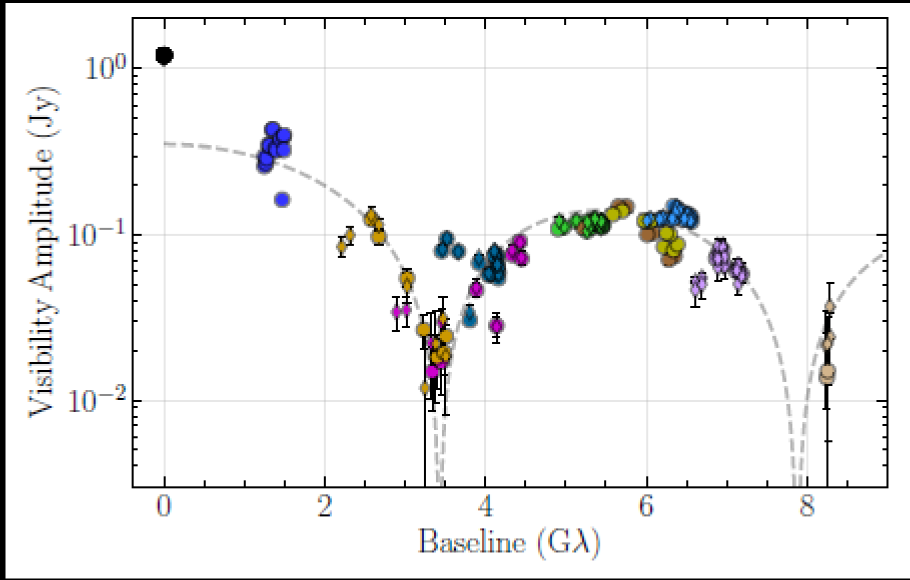
- M87* observed on 2017 April 5, 6, 10 and 11
- τ (opacity) 0.03 ~ 0.28 at 230 GHz
- M87* scans (alias 3C274) interleaved with 3C279
  - A scan 3 to 7 minutes duration
  - Seven scans on April 10, twenty-five scans on April 6
  - Dual circular polarization observation
  - 2GHz BW, centered at 227.1 and 229.1 GHz, digitized and recorded at 32Gbps
  - Typical coherence time ~ 10 s
    - mainly due to water vapor
- Corraleted at MIT Haystack and at MPIfR Bonn
- ALMA as reference station
  - Amplitude accuracies 5 to 10 %



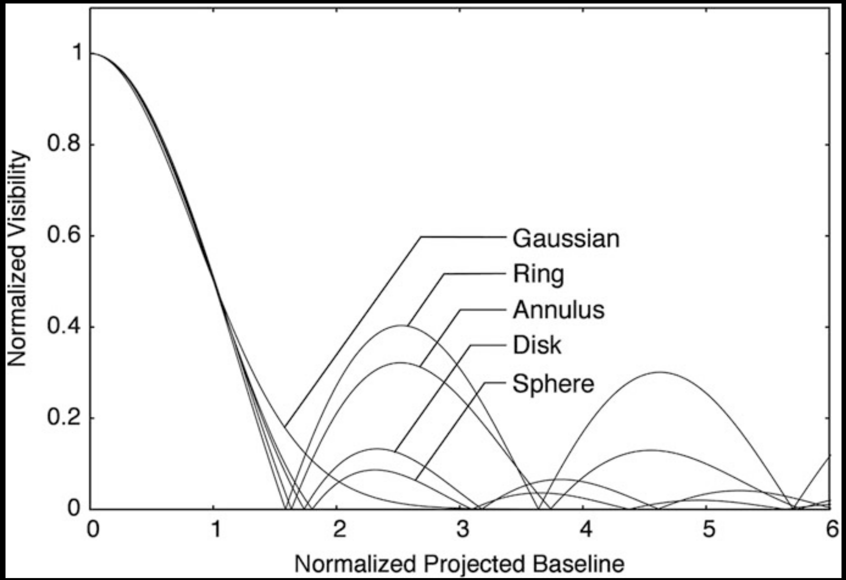
Earth Synthesis

Observation, Correlation and Calibration

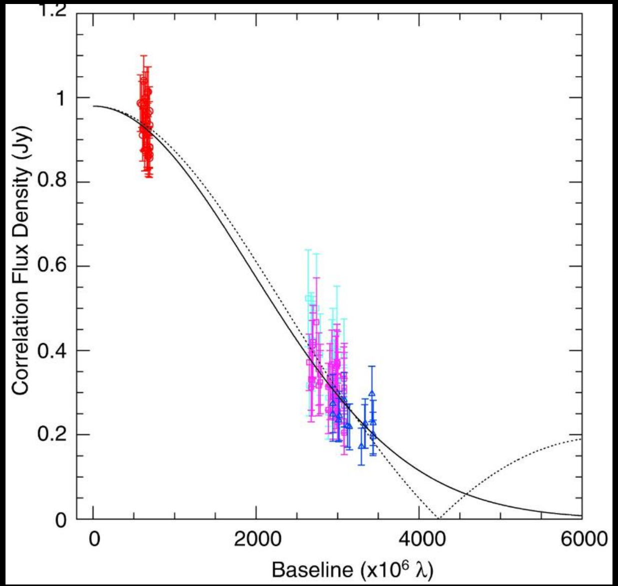
- ALMA baseline SNR > 100, non-ALMA baseline > 10
- 2 bands & 2 polarization, three independent pipelines
  - 1deg phase and 2% amplitude systematic errors
- Visibility distribution (left) resembles a thin ring (middle)
  - Huge improve of UV coverage since 2012 (right)
  - 46 µas diameter, a first null at 3.4 Gλ, but not a simple plain ring
  - 50% flux resolved out, depth of first minima as a function of orientation ➔ asymmetric



EHT collaboration 2019



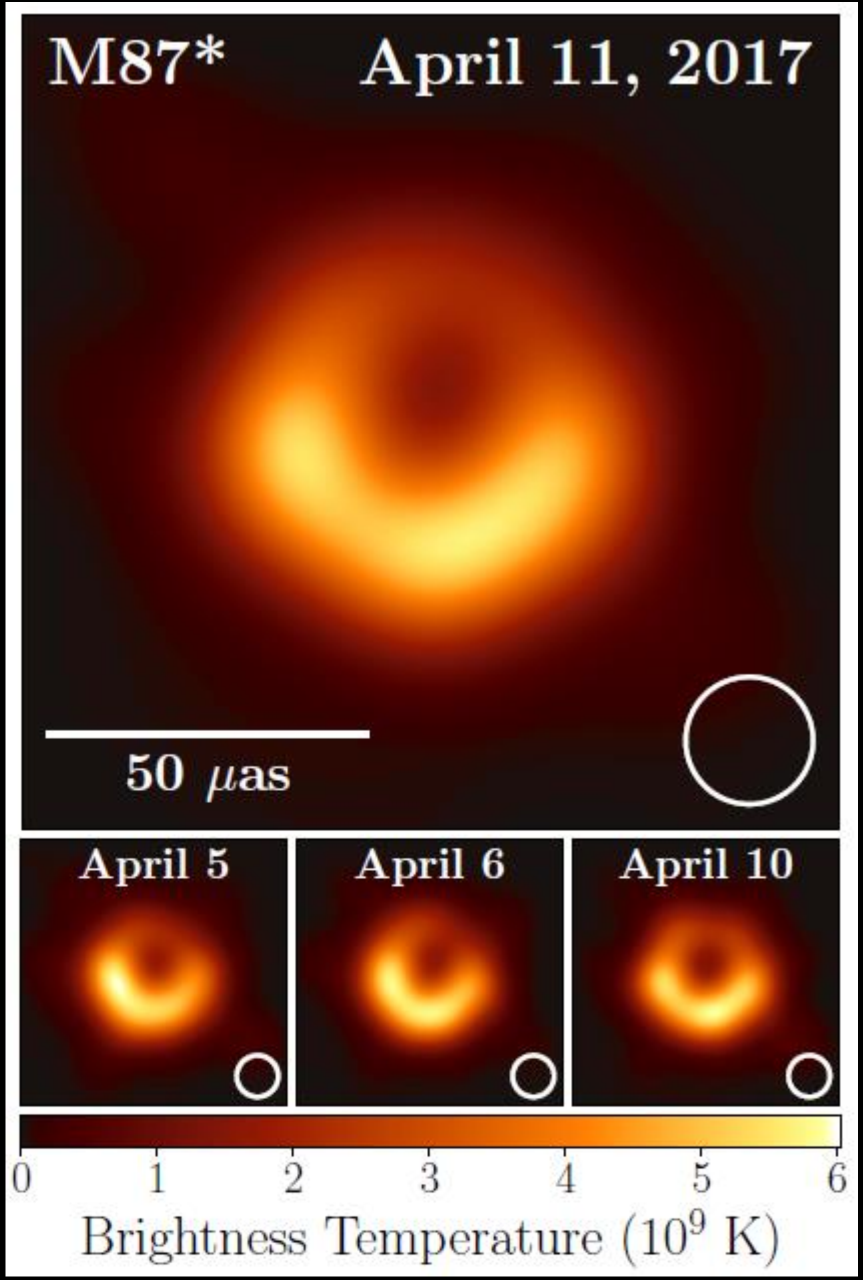
Thompson+ 2017

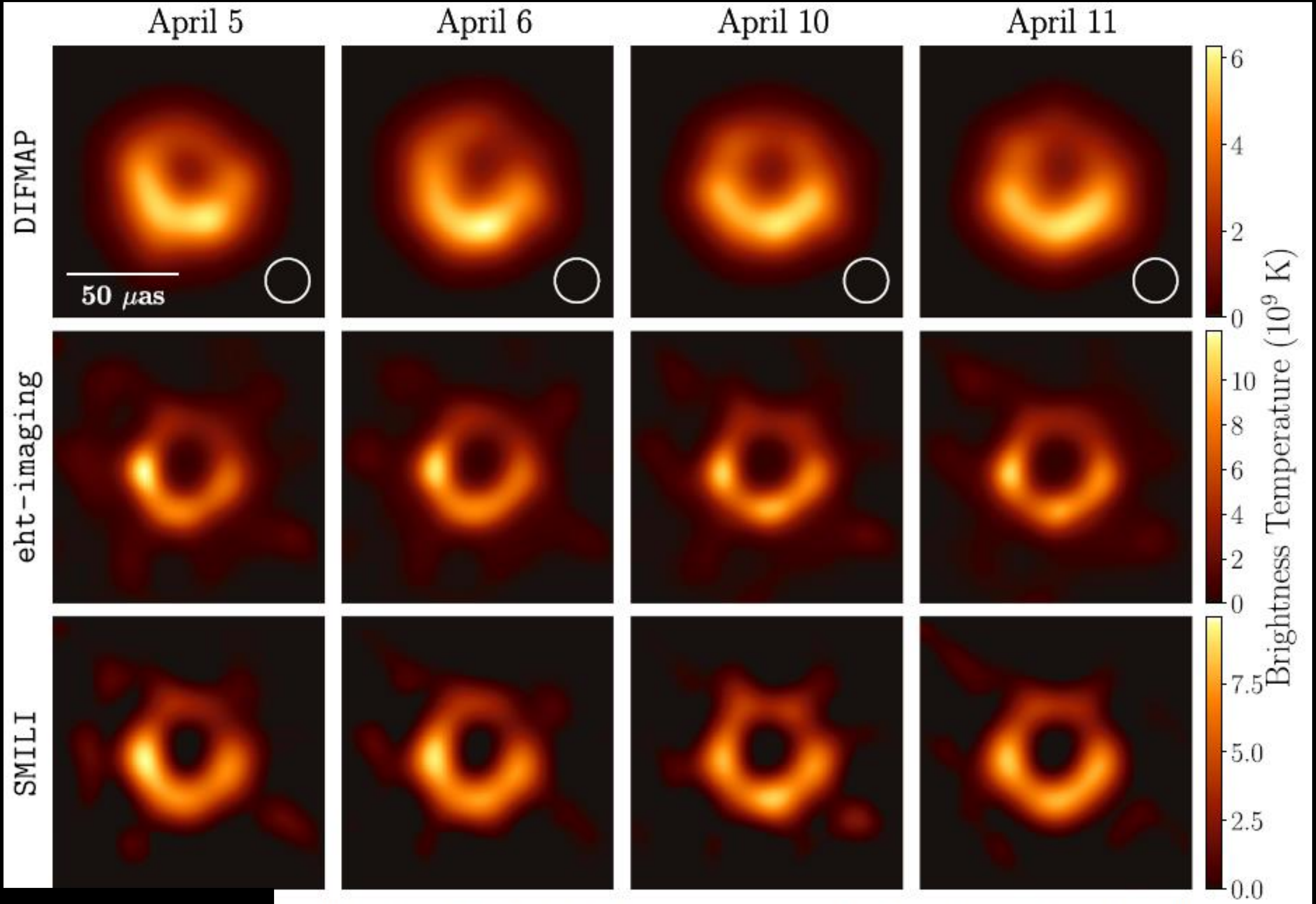


Doeleman+ 2012

Images and Features

- EHT baselines sample a (very) limited range of spatial frequencies
  - 25 to 160 μas
- Two algorithms
  - Inverse-modelling – CLEAN & self-calibration
    - Deconvolve PSF from Visibilities
  - Forward-modelling – RML
    - Searching for images
- Four teams independently imaging
  - Common ring feature 38-44 μas diameter
  - With common enhanced brightness to the South
- Position angle 20deg between 5/6 and 10/11





7 on all four observed days from each of the three imaging pipelines. CLEAN images (from DIFMAP) are shown after convolution ng and SMILI results have no restoring beam applied. Different selected fiducial imaging parameters (e.g., compact flux) result in tures for each method, as indicated by the unique color bars for each row.

Event Horizon Telescope

Paper 4

After beam-convolution of forward modelling data

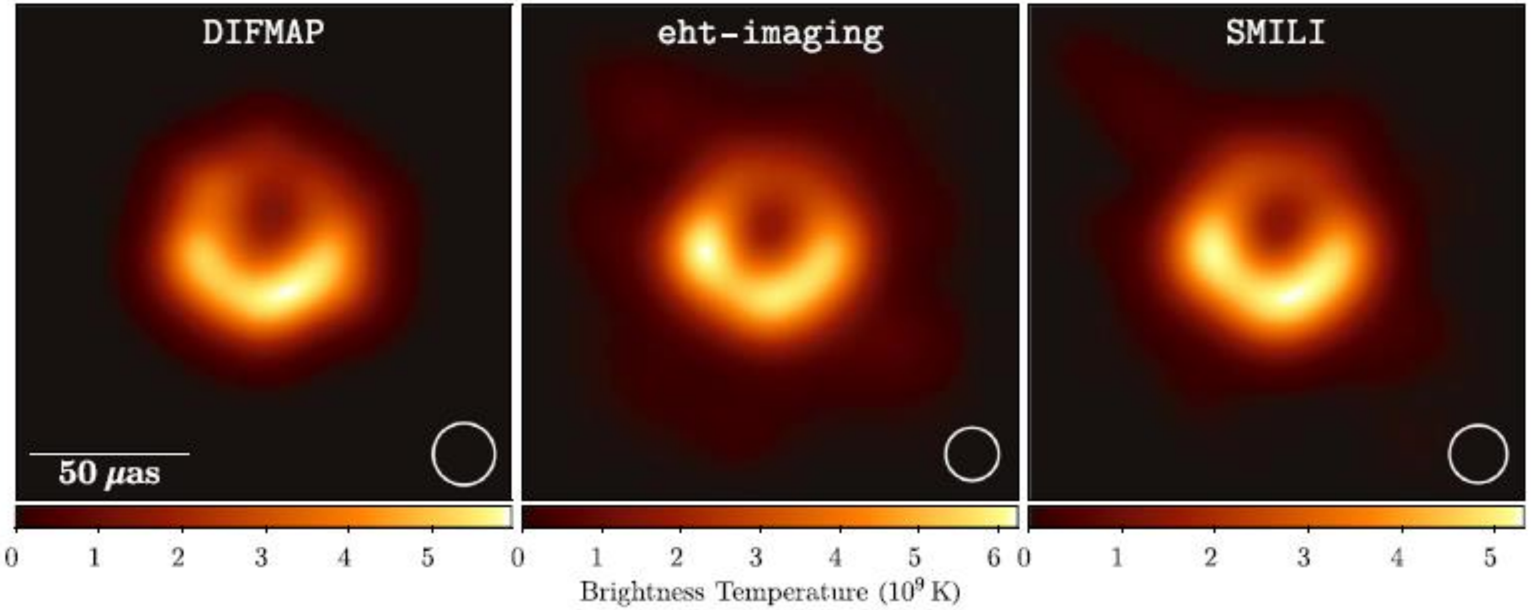
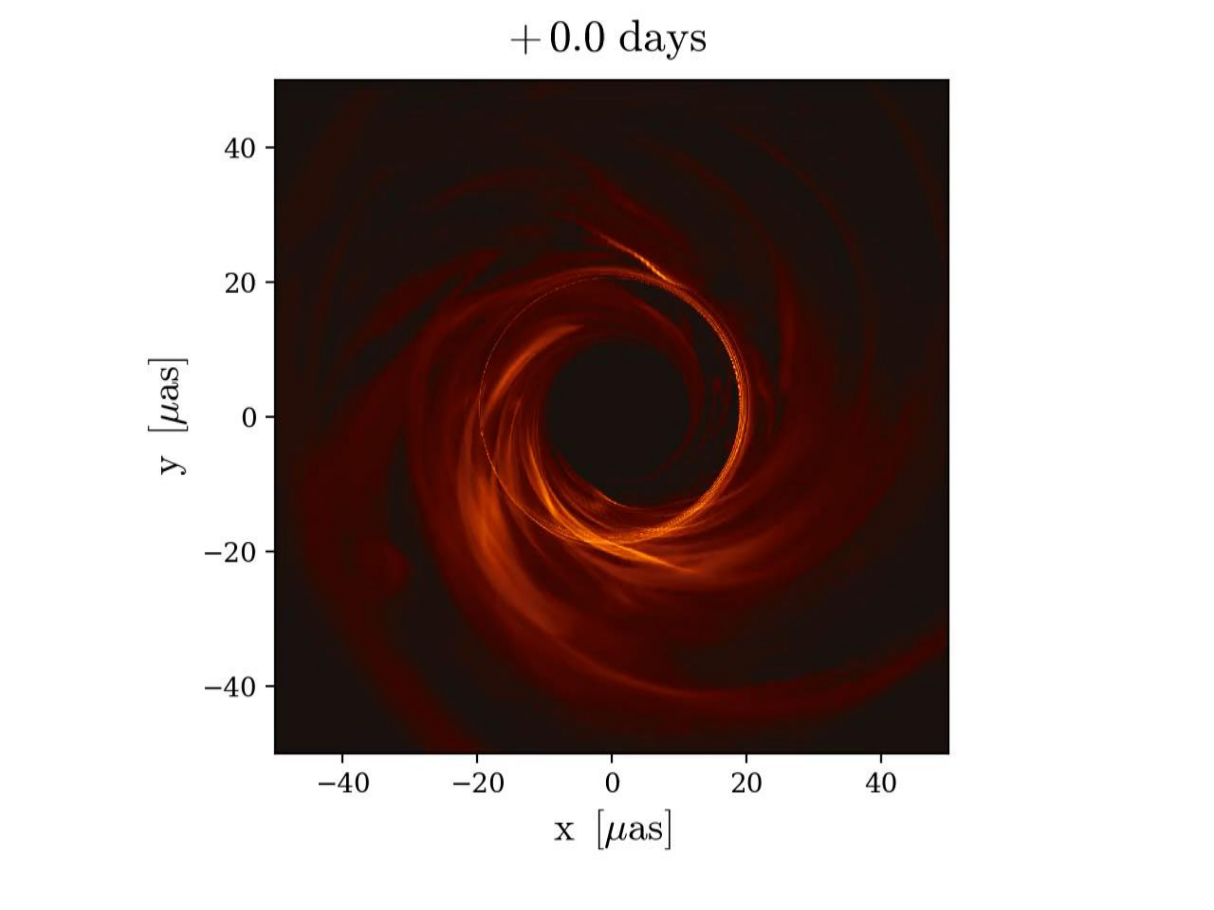


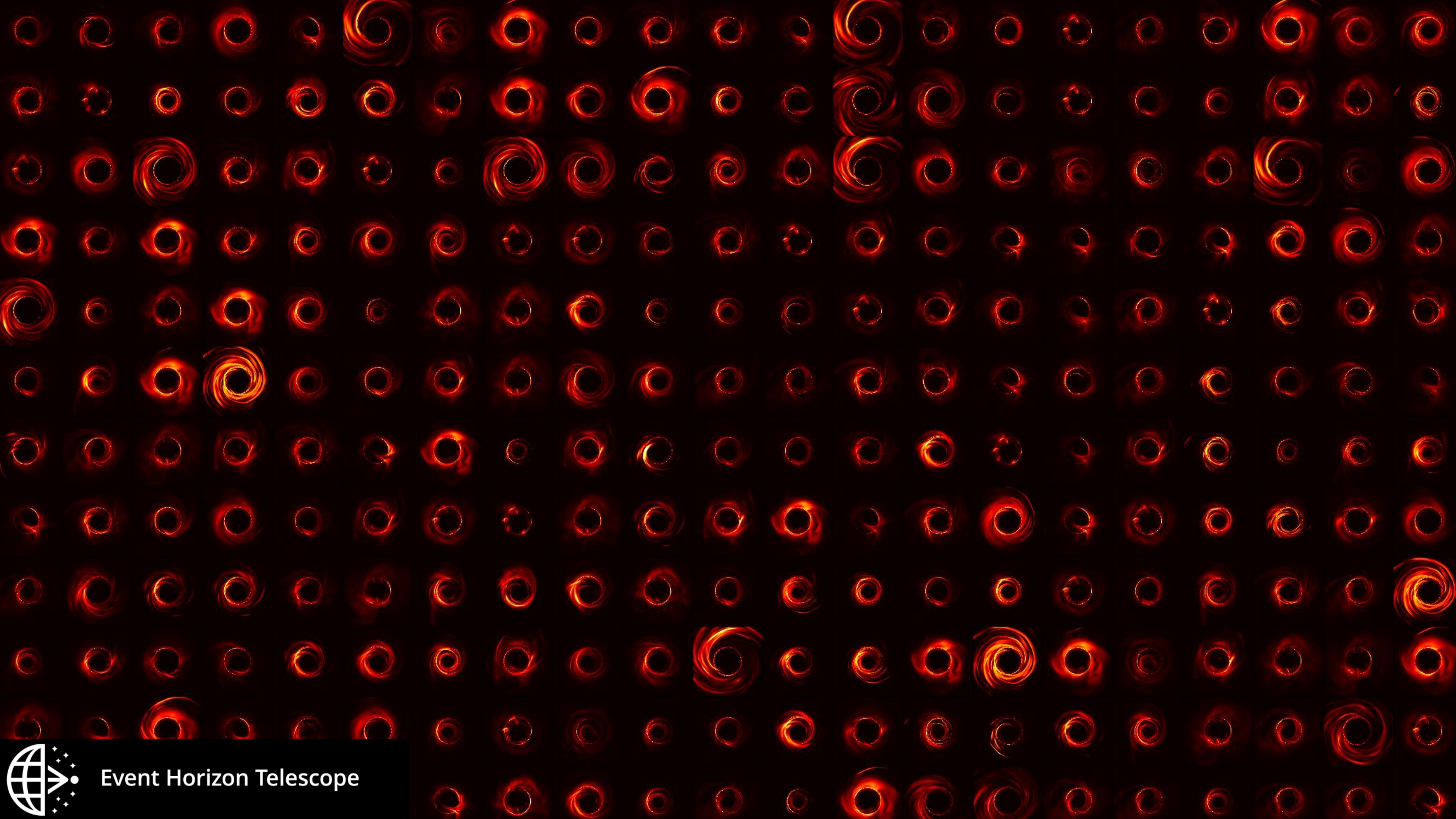
Figure 14. Fiducial images of M87 on April 11 from our three separate imaging pipelines after restoring each to an equivalent resolution. The `eht-imaging` and `SMILI` images have been restored with 17.1 and 18.6 μas FWHM Gaussian beams, respectively, to match the resolution of the `DIFMAP` reconstruction restored with a 20 μas beam.

Theoretical Modeling

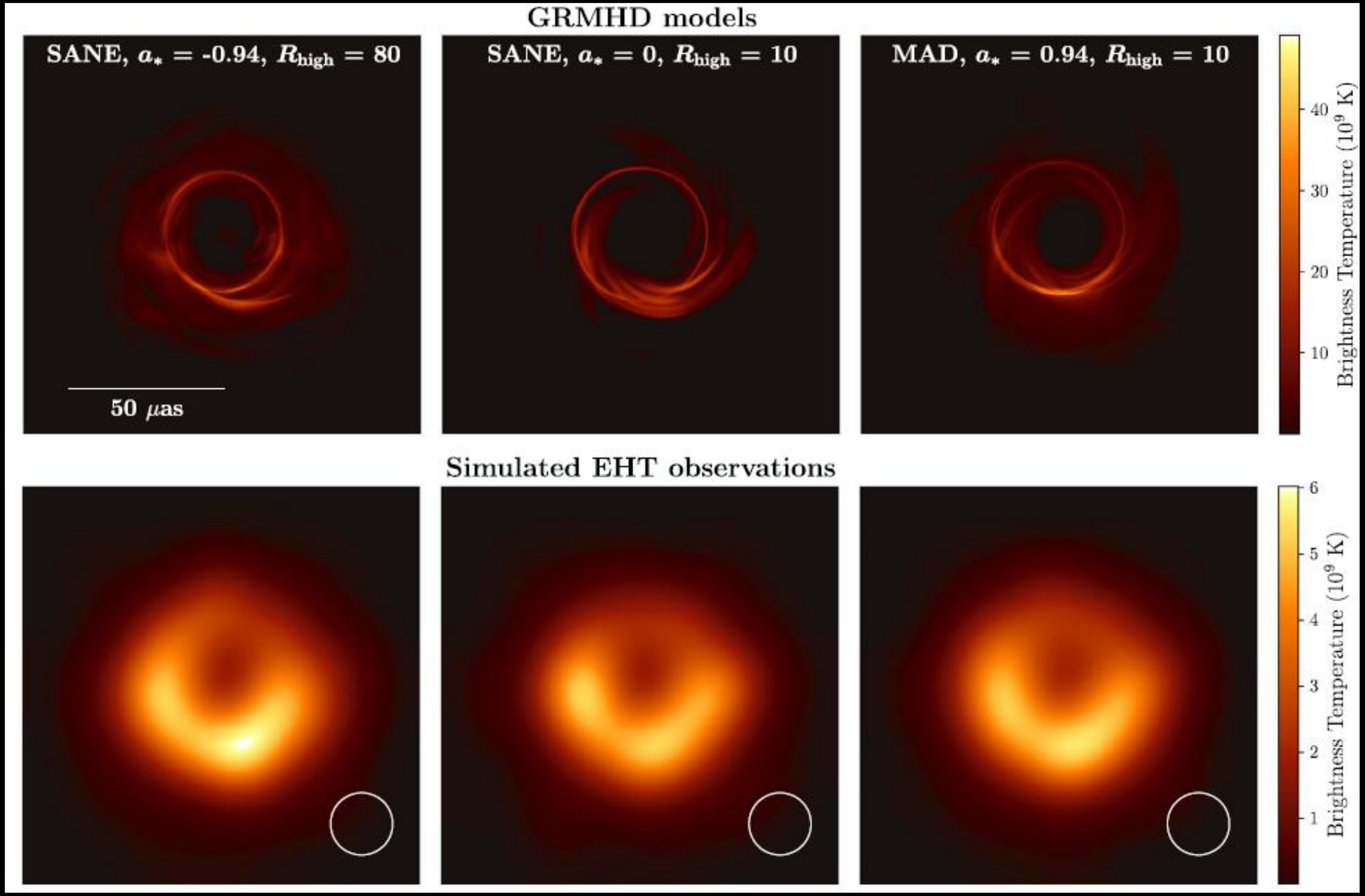
- General-relativistic magneto-hydrodynamics (GRMHD) simulations
  - A turbulent, hot, magnetized disk orbiting a Kerr black hole
  - Powerful jet and the broad-band SED observed in LLAGN
  - a shadow and an asymmetric emission ring predicted
  - Ring – lensed photon ring rather than ISCO
- Synthetic image library built
  - Magnetized accretion flows onto black holes in GR
  - Coupled to three diffrent general-relativistic ray-tracing and radiative-transfer codes



MAD: a=0.94, R_high = 160


Event Horizon Telescope

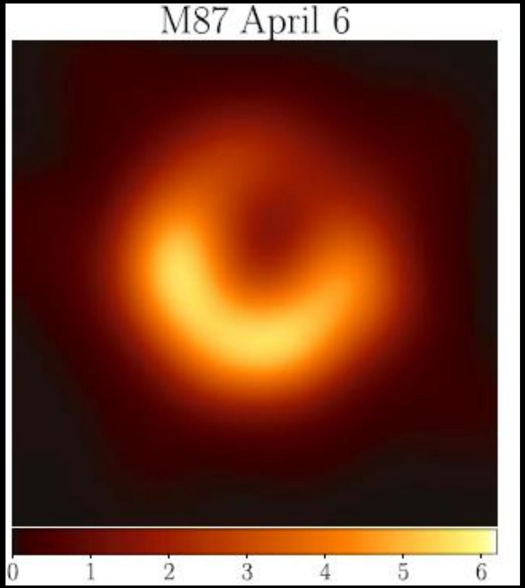
Simulated images rather model-independent

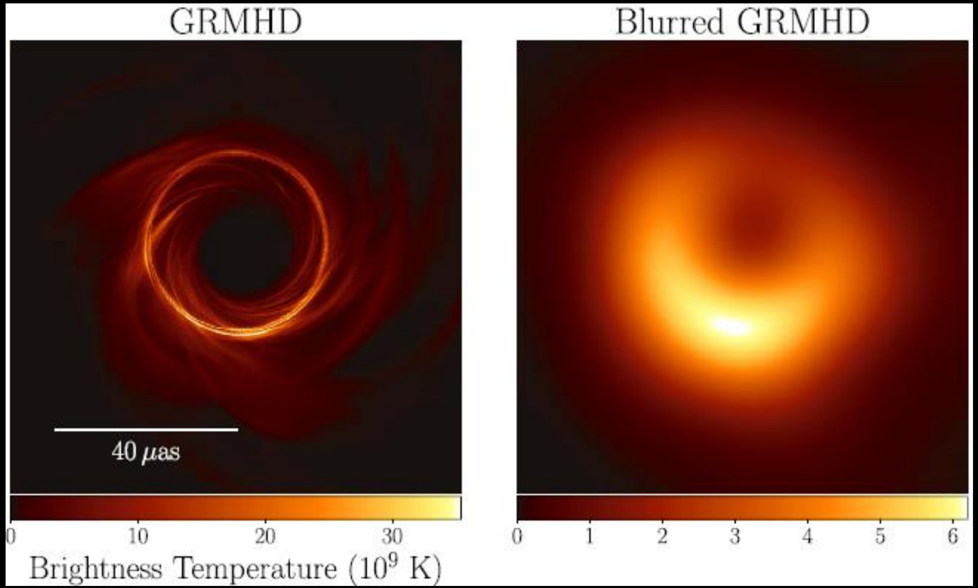


Paper 1

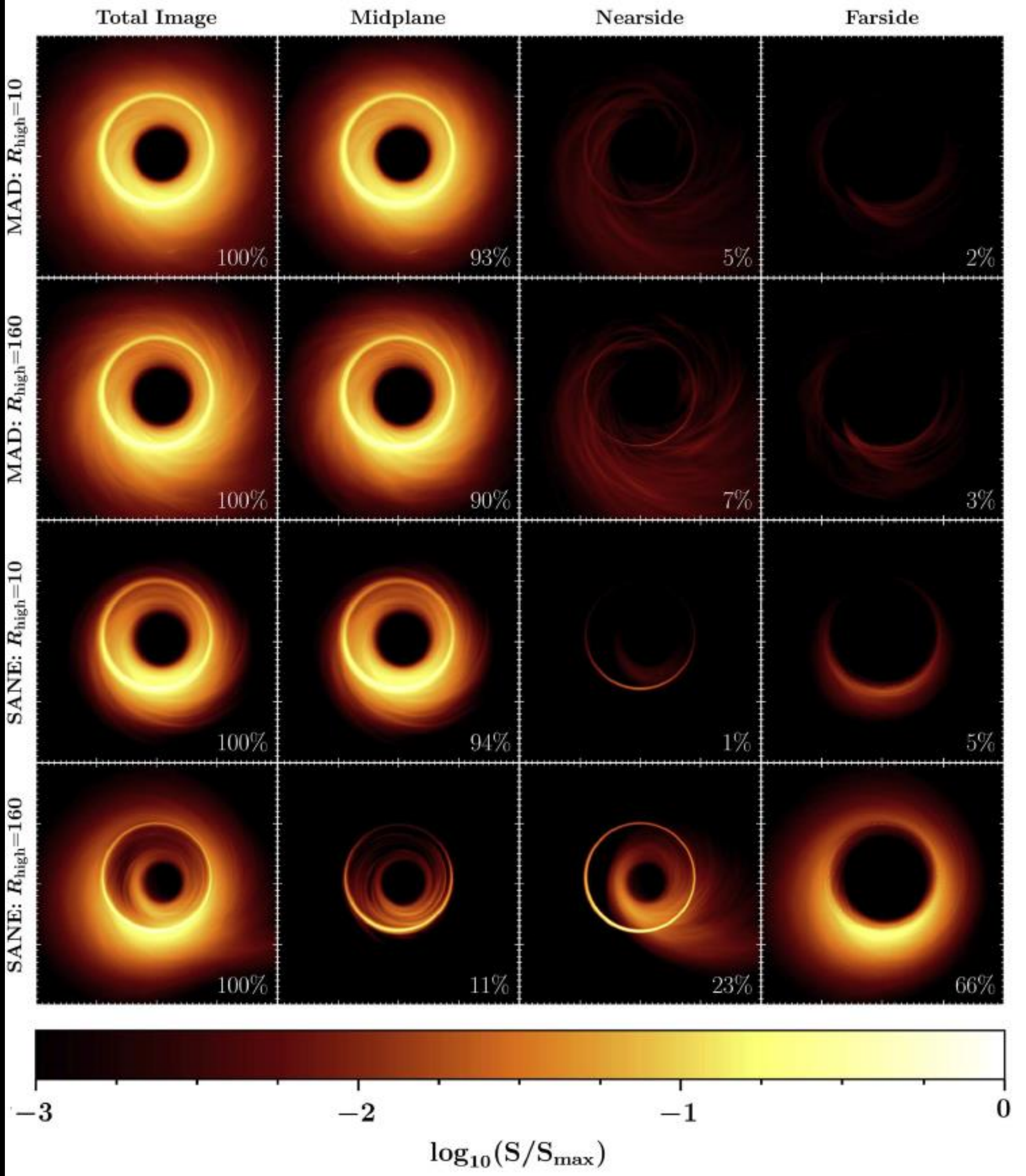
Theoretical Modeling

- Kerr Black hole with accretion flow
  - Initial: Thermal ion, relativistic electron and weakly magnetized torus, axis aligned
  - Outcome: All Corona with $\beta_p \sim 1$ & strongly magnetized poles ($B^2 / \rho c^2$)
  - Schwarzschild BH disfavored : Accretion rate << Jet power
    - Blandford-Payne (1982, accretion disk) not enough
    - Blandford-Znajek (1977, BH spin + B) – Kerr BH
- MAD Highly magnetized
  - Magnetic flux / accretion rate ~ 15
  - ➢ All strongly magnetized
  - ➢ Emission mostly from disk midplane
- SANE Mildly magnetized
  - Magnetic flux / accretion rate ~ 1
  - ➢ Jet (disk) strongly (weakly) magnetized
  - ➢ High (low) R_{high}, emission mostly from jet (disk)





Where the lights come from?



Event Horizon Telescope

Paper 5

Model Comparison and Parameter Estimation

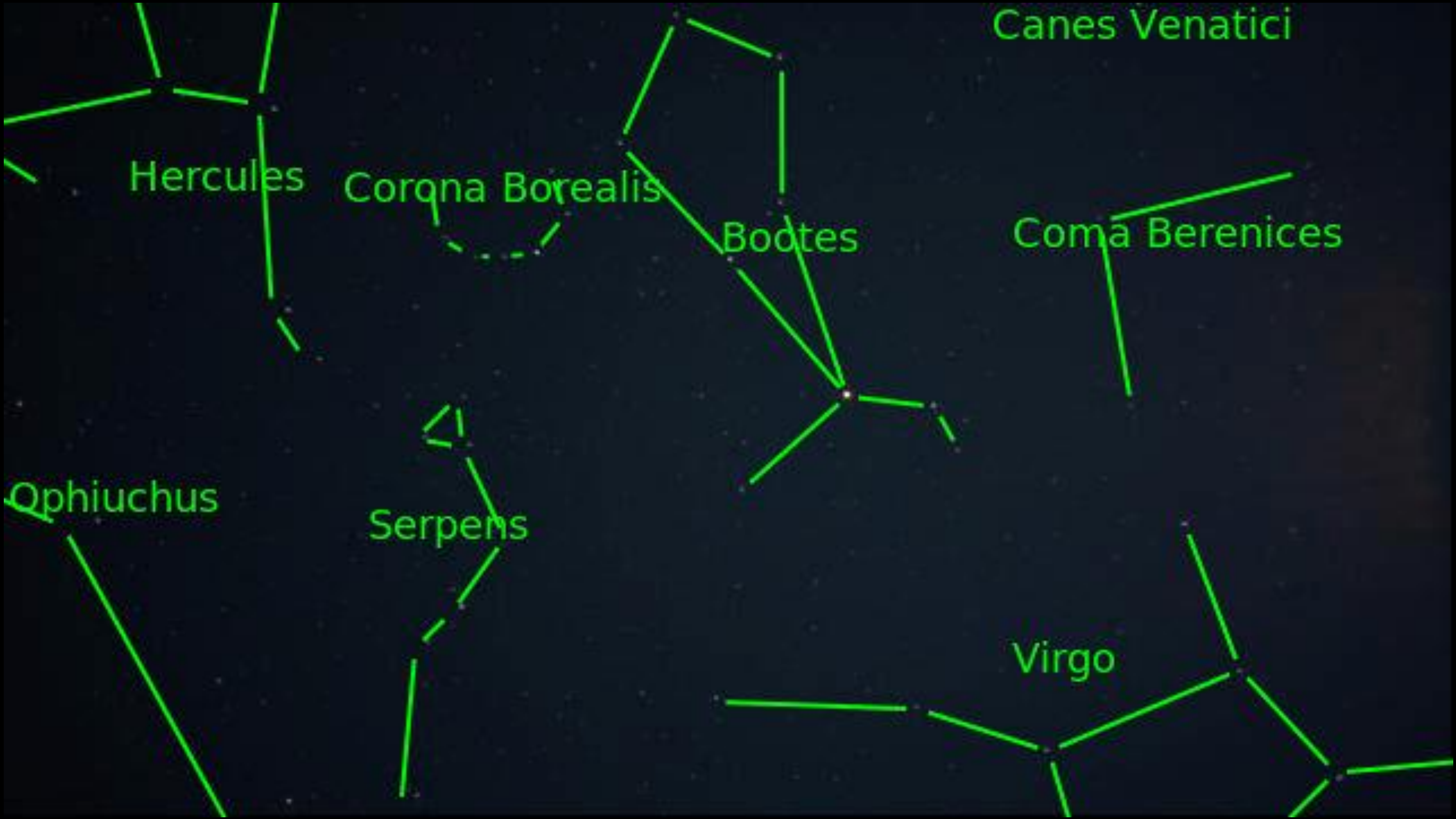
Table 1
Parameters of M87*

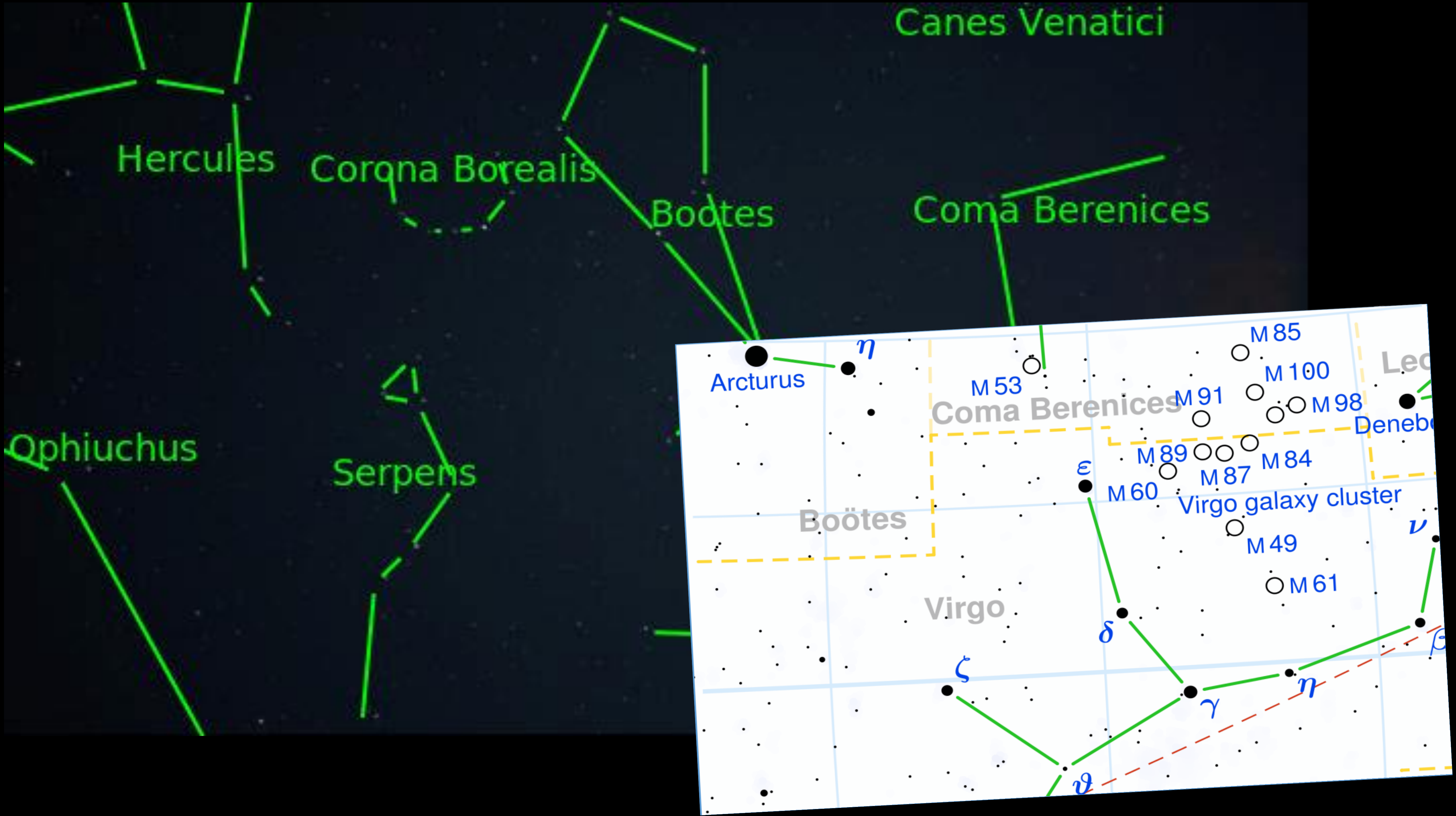
Parameter	Estimate
Ring diameter [a] d	42 ± 3 μas
Ring width [a]	<20 μas
Crescent contrast [b]	$>10:1$
Axial ratio [a]	$<4:3$
Orientation PA	$150°–200°$ east of north
$\theta_g = GM/Dc^2$ [c]	3.8 ± 0.4 μas
$\alpha = d/\theta_g$ [d]	$11^{+0.5}_{-0.3}$
M[c]	$(6.5 \pm 0.7) \times 10^9\ M_\odot$
Parameter	**Prior Estimate**
D [e]	(16.8 ± 0.8) Mpc
M(stars) [e]	$6.2^{+1.1}_{-0.6} \times 10^9\ M_\odot$
M(gas) [e]	$3.5^{+0.9}_{-0.3} \times 10^9\ M_\odot$

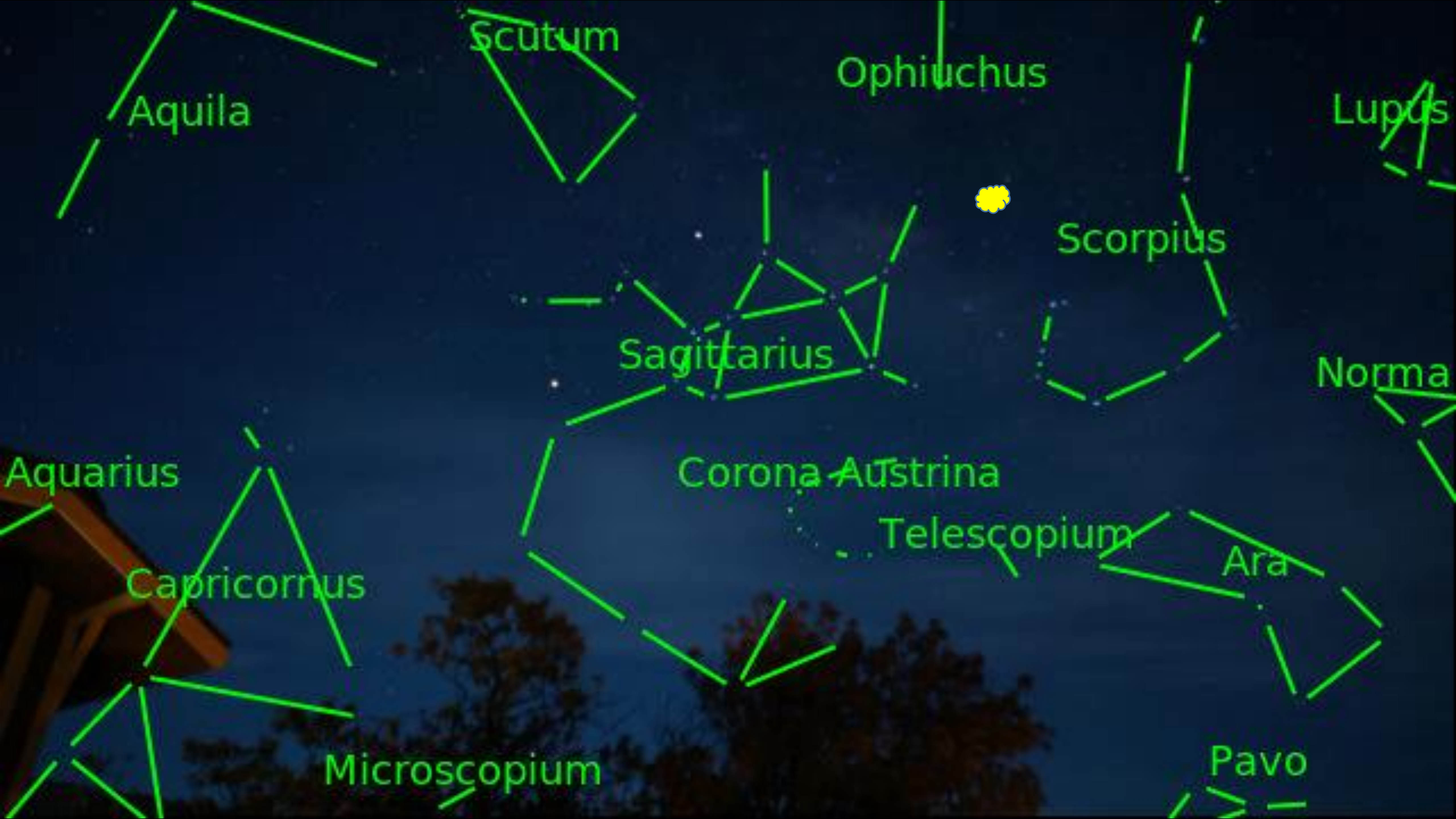
Conclusion and Outlook

- EHT, VLBI at a wavelength of 1.3 mm imaged horizon-scale structures around SMBH candidate in M87
- The image to be dominated by a ring structure of 42±3 μas diameter brighter in the south
- central brightness depression with a contrast of >10:1, which we identify with the black hole shadow
- Extensive library of synthetic images obtained from GRMHD simulations
  - basic features of our image are relatively independent of the detailed astrophysical model
  - black hole mass of 6.5±0.7×10^9M
- rotation of the black hole in the clockwise direction
  - The brightness excess in the south explained as relativistic beaming of material rotating in the clockwise
- To come: Polarization (RM → accretion rate), … Sgr A*! And other jetted AGNs
- And more stations (a KVN?) and higher frequency

Where is M87 ?


Canes Venatici
Hercules
Corona Borealis
Bootes
Coma Berenices
Ophiuchus
Serpens
Virgo


Canes Venatici
Hercules
Corona Borealis
Boötes
Coma Berenices
Ophiuchus
Serpens
Arcturus
η
M 53
M 85
M 100
M 91
M 98
Coma Berenices
Denebo
M 89
M 84
M 87
ε
M 60
Virgo galaxy cluster
Boötes
M 49
ν
M 61
Virgo
δ
ζ
γ
η
ϑ
β


Scutum
Ophiuchus
Aquila
Lupus
Scorpius
Sagittarius
Norma
Aquarius
Corona Australis
Telescopium
Ara
Capricornus
Microscopium
Pavo

(binary) Mass function

- Keplerian 3rd law
  - the centripetal force equal to the gravitational force: $mr\omega^2 = G\frac{mM}{r^2}$
  - $mr(\frac{2\pi}{P})^2 = G\frac{mM}{r^2}$ → $P^2 = \frac{(2\pi)^2}{GM} r^3$ → $\frac{a^3}{P^2}$ = constant (7.5×10^{-6} AU^3/day^2)
  - When m is non-negligible, then M→ M_1 & m→ M_2, M = (M_1 + M_2)
  - Then, $a = a_1 + a_2$, $M_1 a_1 = M_2 a_2$ (the center of the mass location)
  - $a = a_1 \frac{M}{M_2}$; $K = (\frac{2\pi}{P})\, a_1 \sin i$;
  - $\frac{M^3{}_2}{M^2} = \frac{P\ K^3}{2\ \pi\ G} \sin^{-3} i$; mass function $f = \frac{M^3{}_2}{M^2} \sin^3 i = \frac{P\ K^3}{2\ \pi\ G}$;
  - From spectroscopy $v \sin i$
  - For $M_1 << M_2$, f ~ $M_2 \sin^3 i$
  - For $M_1 >> M_2$, f ~ $\frac{M^3{}_2}{M^2{}_1} \sin^3 i$