Event Horizon Telescope

The EHT tale of two black hole images: recent results and future prospects

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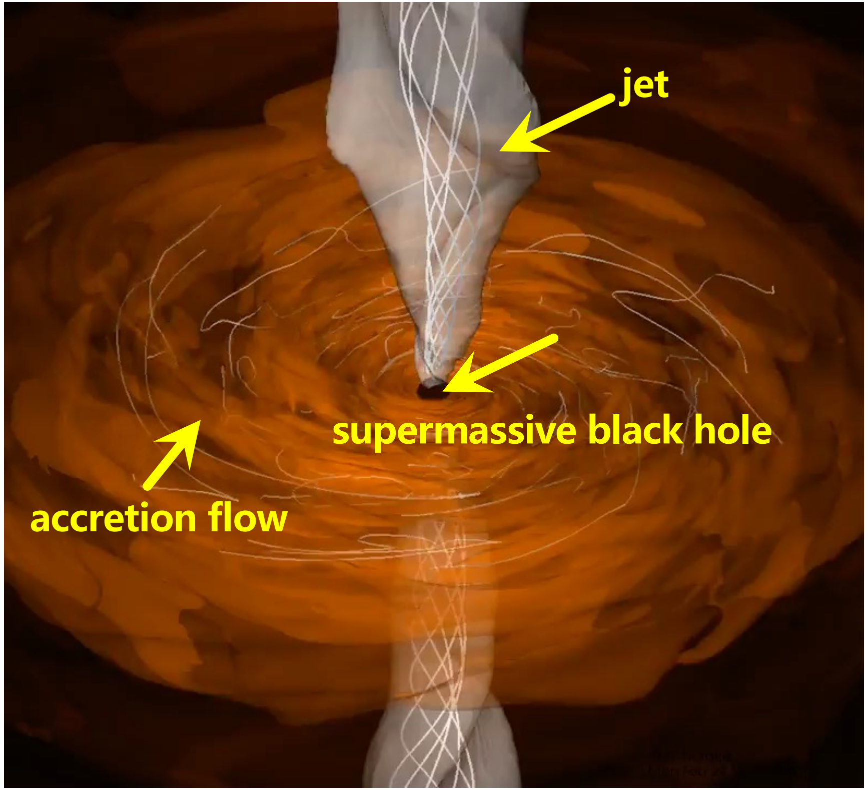
*on behalf of the Event Horizon Telescope Collaboration

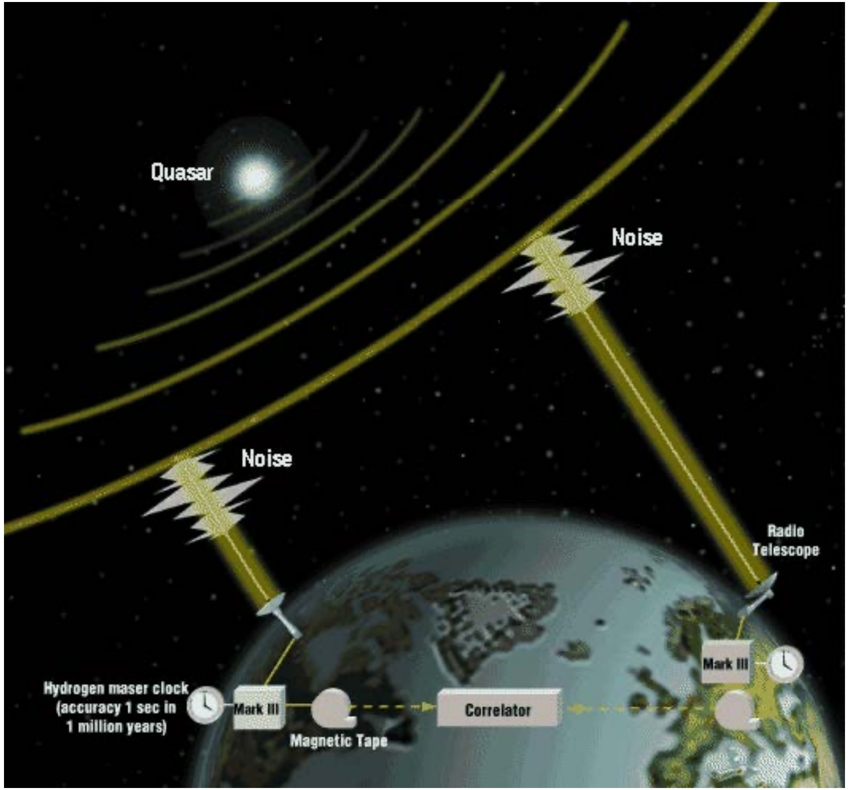
Mini-symposium on accretion process around compact objects within the 32nd Texas Symposium, 2023/12/13, Shanghai

Peering into the hearts of AGN with VLBI



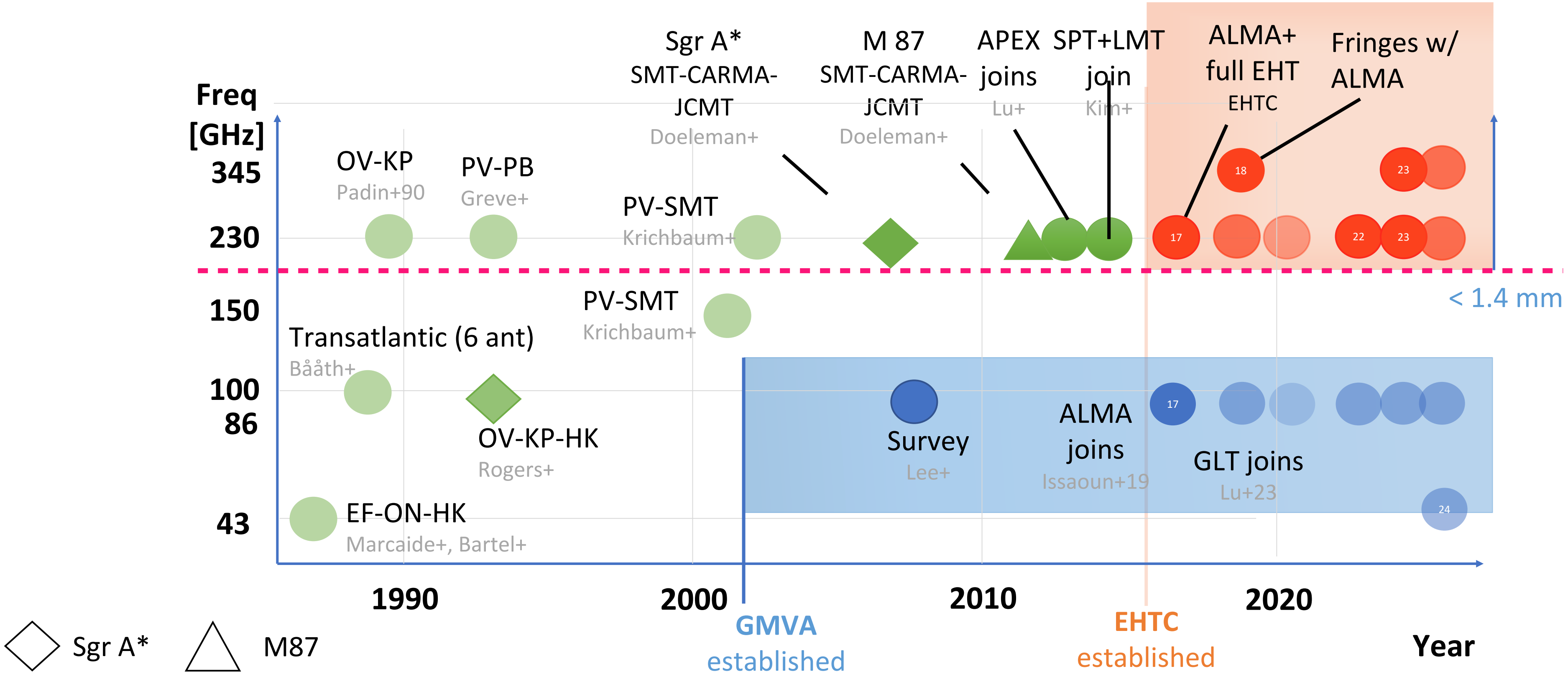
credit: Hotaka Shiokawa

AGN central engine



Very Long Baseline Interferometry

mm-VLBI was developed for about 40 years



Observatories:

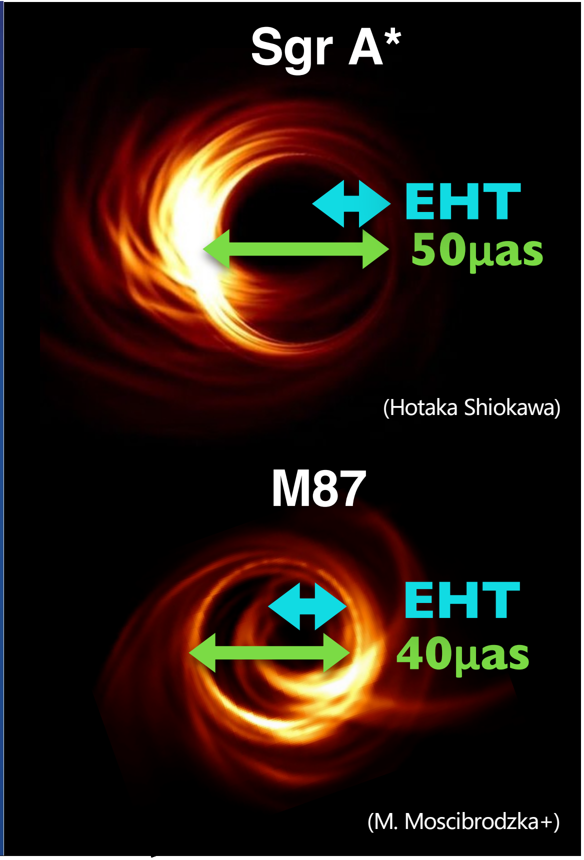
APEX: Atacama Pathfinder Experiment (North Chile) **CARMA**: Combined Array for mm Astronomy (California) **EF: Effelsberg (MPIfR Bonn) HK:** Haystack (Massachusetts) **JCMT:** James Clerk Maxwell Telescope (Hawaii) **KP**: Kit Peak (Arizona) **LMT**: Large mm Telescope (Mexico) **ON**: Onsala (Sweden) **OV**: Owens Valley (California) **PB**: Plateau de Bure (France) **PV**: Pico Veleta (Spain) **SMT**: Submm Telescope (Arizona) **SPT**: South Pole Telescope **GLT**: Greenland Telescope

slide credit: Eduardo Ros

The Event Horizon Telescope Collaboration

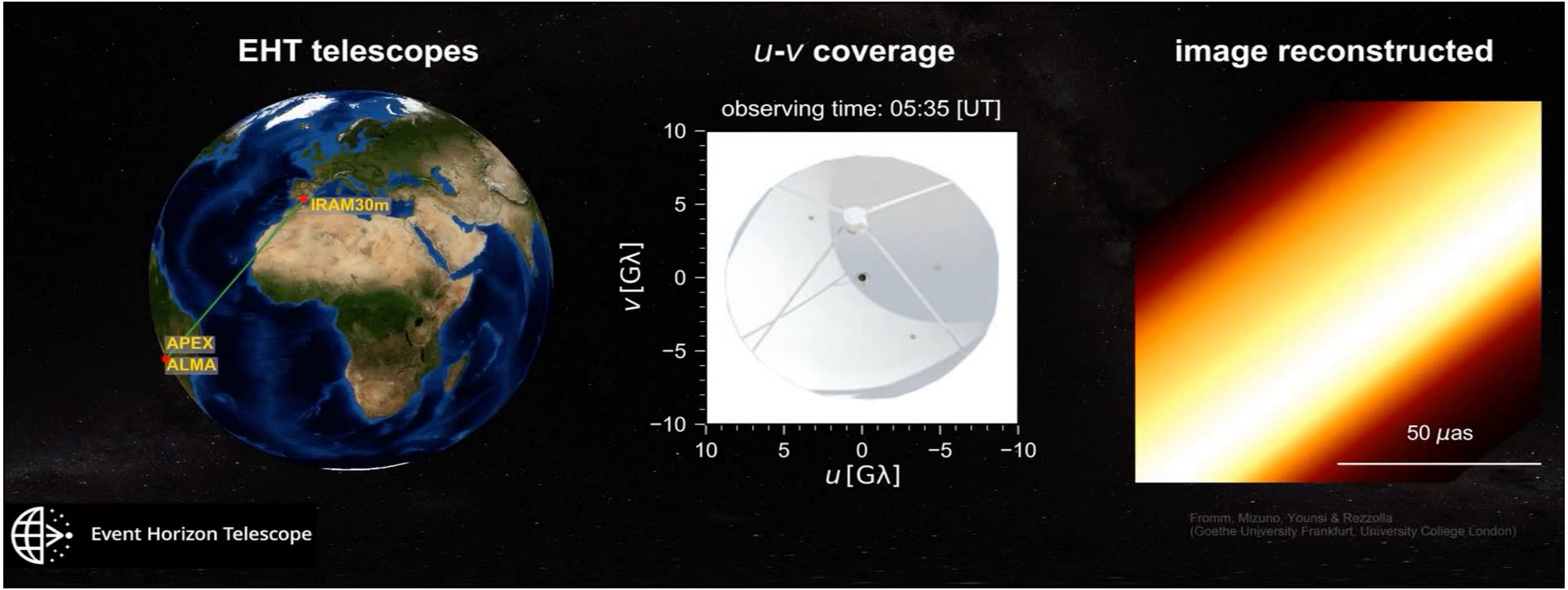
2018 EHT collaboration meeting

Event Horizon Telescope



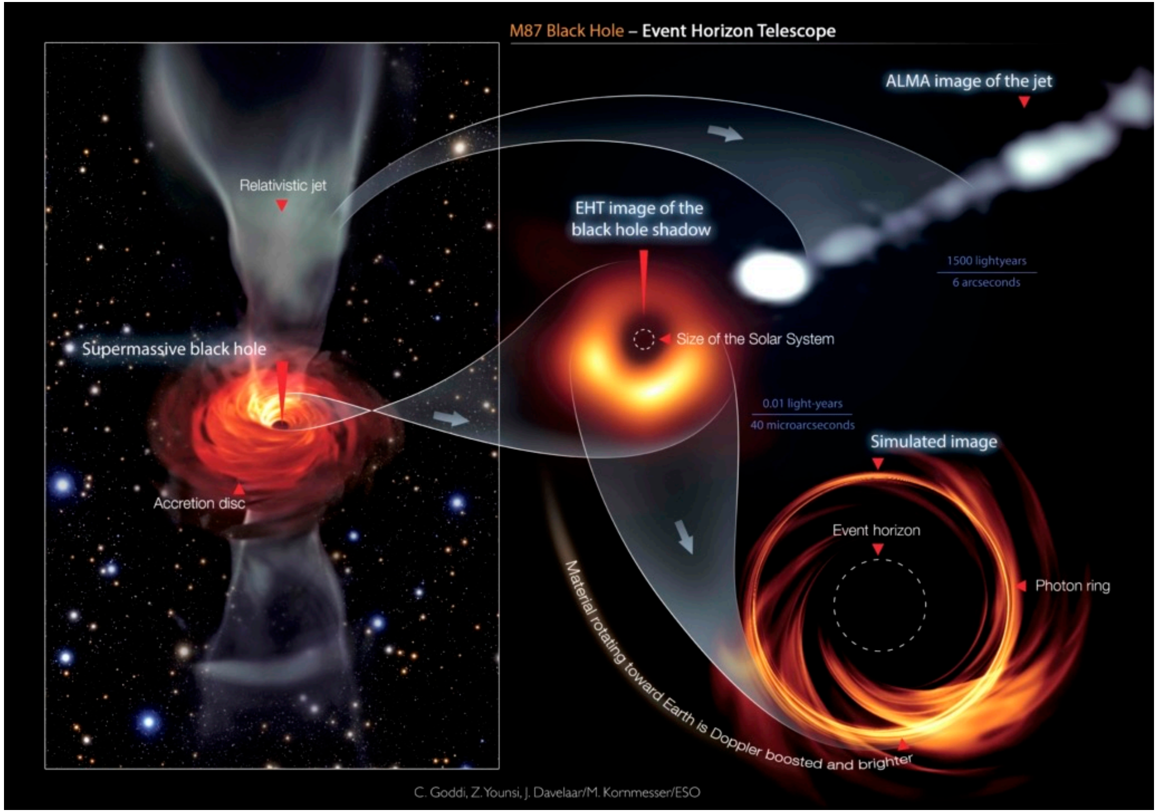
(Slide credit: Eduardo Ros)

How does EHT work?



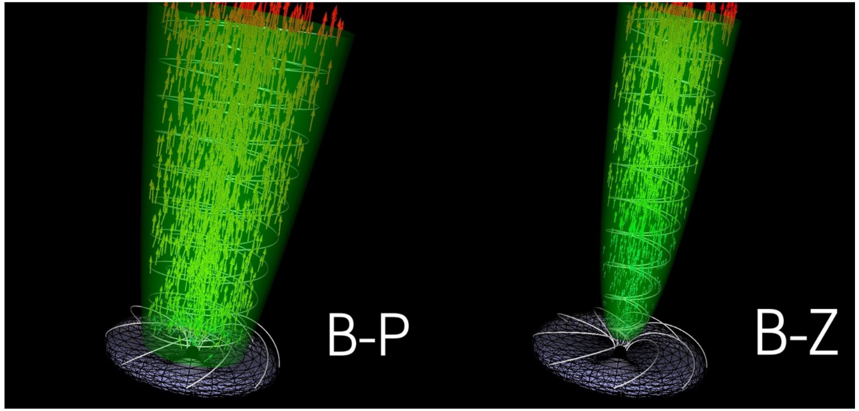
Credit: Fromm, Mizuno, Younsi & Rezzolla

Main objectives



- Black hole imaging/Testing General Relativity in the strong-field regime
- Detailed processes of black hole accretion and jet formation on event horizon scales

Jet formation: Accretion dynamics and ejection processes



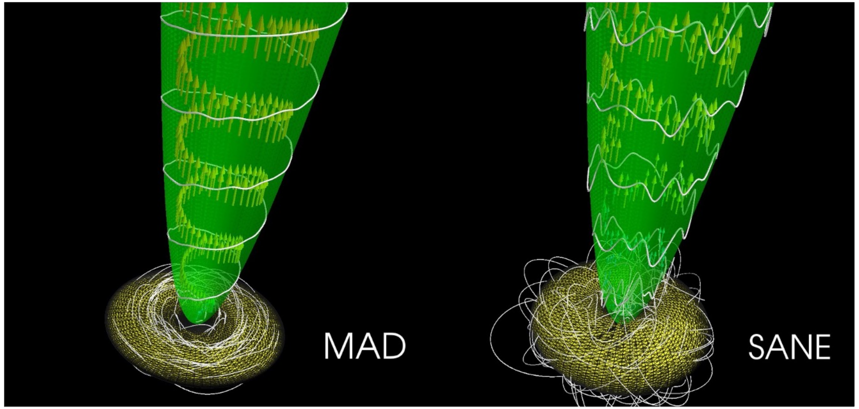
wider jet more narrow jet

BP (Blandford-Payne): energy extracted from accretion disk, magnetic fields collimate and accelerate a disk wind

BZ (Blandford-Znajek): energy extracted directly from rotating black hole, jet launched through electromagnetic forces

MAD: *Magnetically Arrested Disks*
dominated by magnetic energy

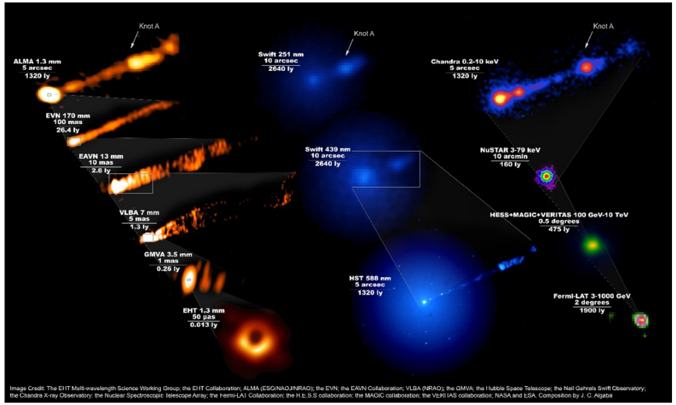
SANE: *Standard And Normal Evolution*
dominated by energy of particles



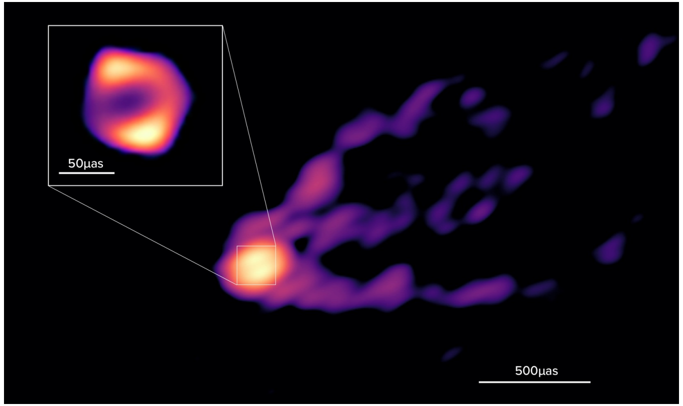
Slide credit: T. Krichbaum

M87: the "Rosetta Stone" for studying an AGN central engine

- The first cosmic jet discovered (Curtis 1918)
- 1Rs = 7.6 µas for M=6.5e9 $M_\odot$ and D_L=16.8 Mpc
- Well studied at many wavelengths (Radio to TeV) since decades
- Edge-brightened structure on VLBI scales, wide initial jet opening angle
- Well studied for jet formation, collimation and acceleration

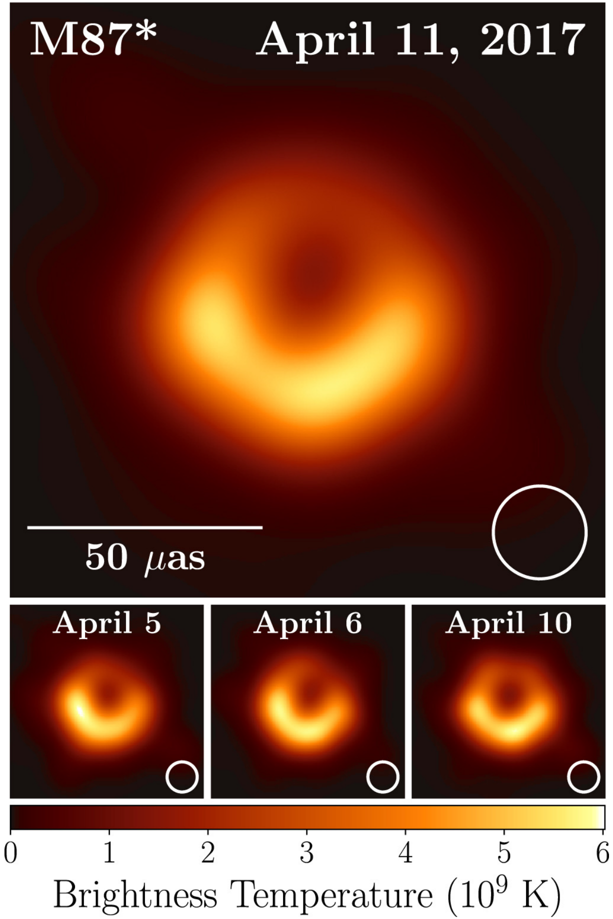


EHT MWL WG et al. 2021



Lu et al. 2023, Nature

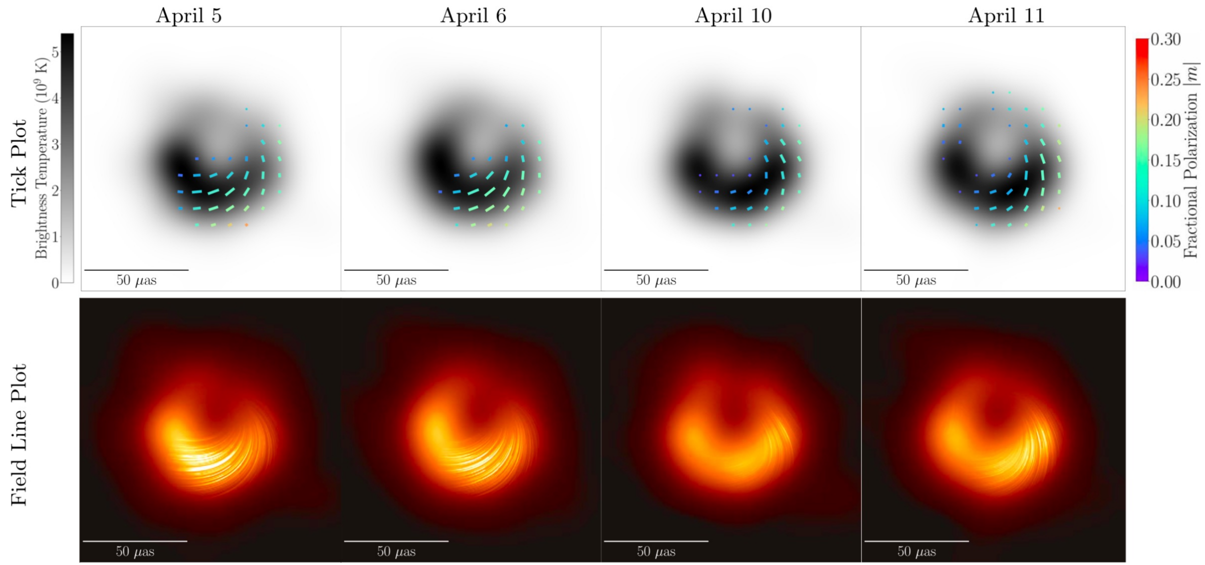
EHT results on M87 from 2017 observations



- First image of a black hole shadow
  - Imaging by four independent teams
  - All images show an asymmetric ring structure
  - Evidence for minor evolution in the ring
  - Data are insensitive to emission on larger scales
- Size (diameter) ~42μas
  - Consistent with a 6.5e9 $M_\odot$ black hole
- Brightness asymmetry
  - The black spin points away from Earth

EHTC et al. 2019 (I-VI)

(Linear) Polarization of the Ring

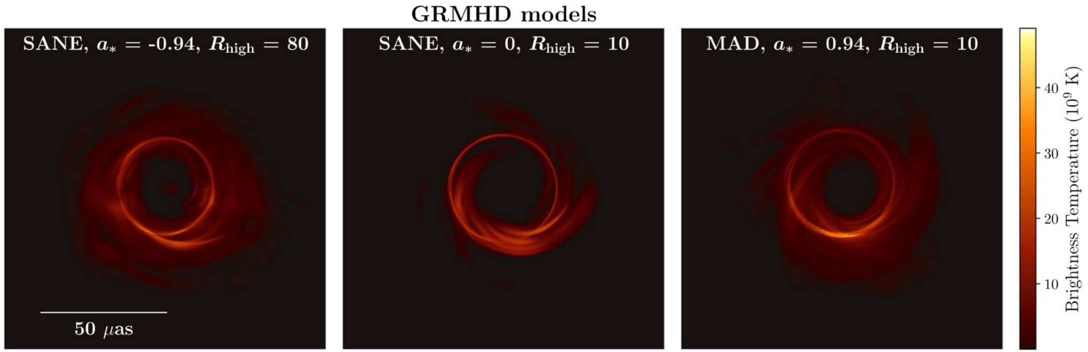


- ➢ A part of the ring is significantly polarized (southwest part of the ring), up to ~15%
- ➢ Pol. position angles are arranged in a nearly azimuthal pattern
- ➢ Temporal evolution of the polarized source structure over one week

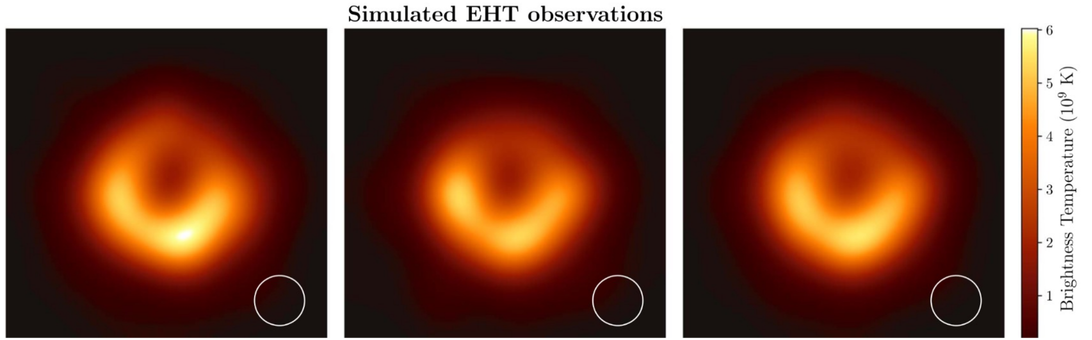
Probes the B-field structure and the plasma properties near the event horizon

EHTC et al. 2021 (VII-VIII)

Comparison of images with 3D GRMHD simulations



Simulations at native resolution



Simulations at EHT resolution

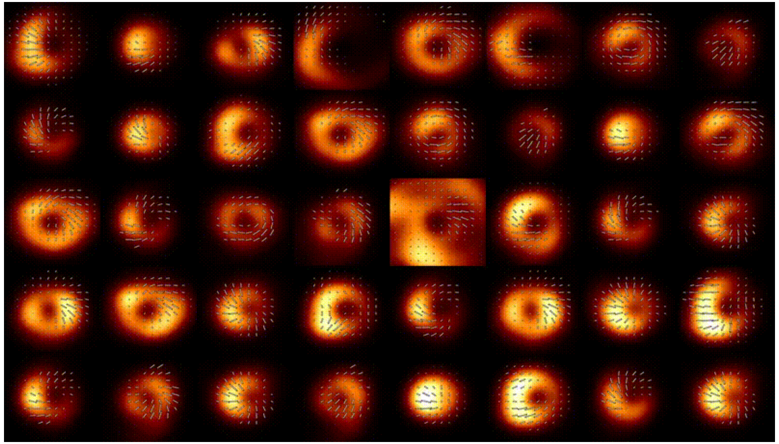
Simulation library: 72K images

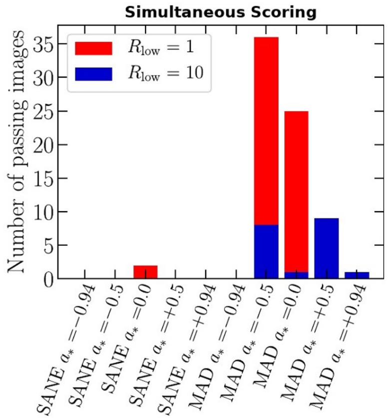
- Most models can survive under the constraint of the total intensity observations alone

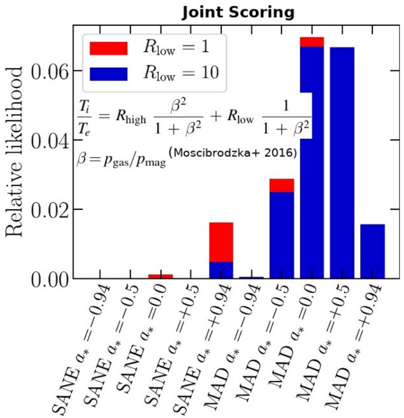
- Some models can be rejected by other constraints (e.g., jet power, X-ray luminosity)
  - Jet power (10^{42} erg/s) rejects all a*=0 models
  - SANE models with a* < 0.5 are rejected; most |a*| > 0 MAD models are acceptable.

Comparison of images with 3D GRMHD simulations

credit: George Wong



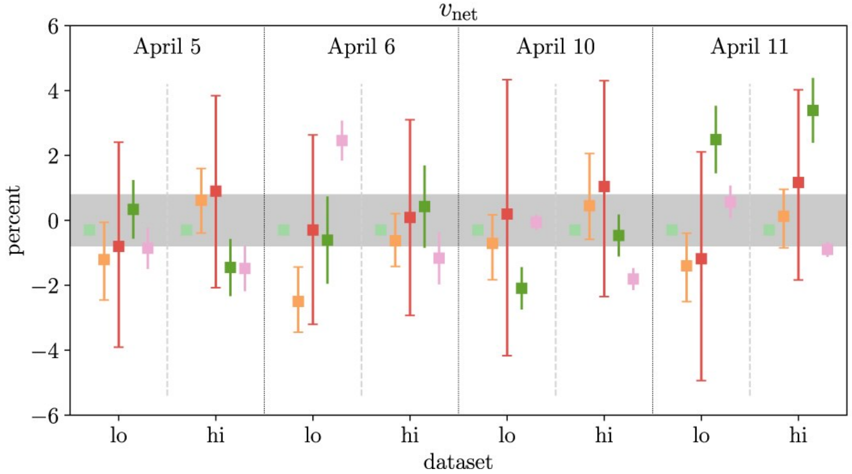


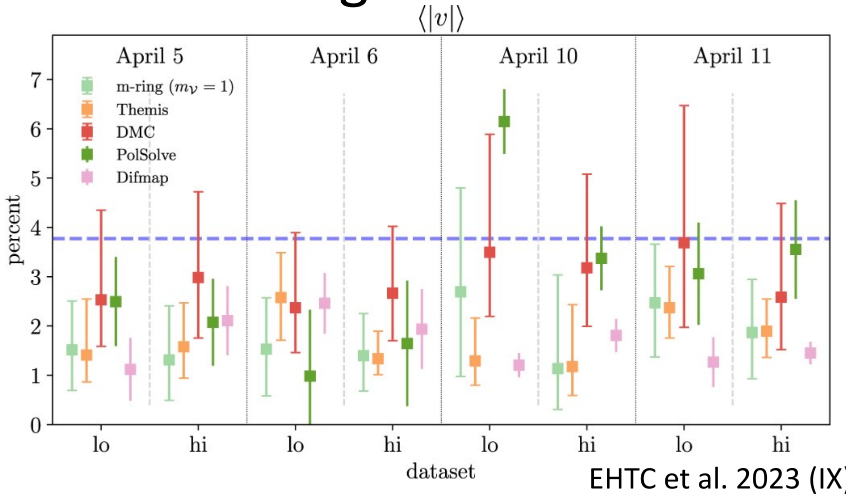


- M87* seems to be MAD!
  (MAD is preferred over SANE for all scoring methods. When other constraints are considered (e.g., jet power lower limit), all SANE model are rejected)
- Magnetic field with a strong poloidal component
- Important hints of the Blandford-Znajek mechanism
- Accretion rate: $\dot{M} \sim (3 - 20) \times 10^{-4} M_{\odot} \mathrm{yr}^{-1}$ ($\sim 10^{-5}\ \dot{M}_{\rm Edd}$)
- Magnetic field: $|B| \sim (7 - 30)$G
- Plasma density: $n \sim 10^{4-5} \mathrm{cm}^{-3}$

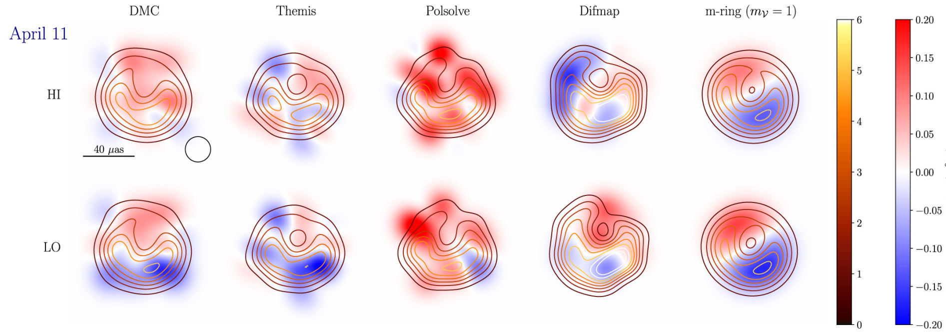
EHTC et al. 2021 (VII-VIII)

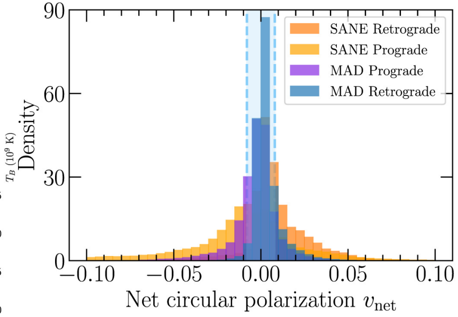
Circular Polarization of the Ring

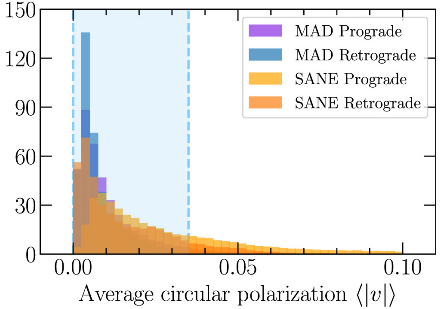




EHTC et al. 2023 (IX)





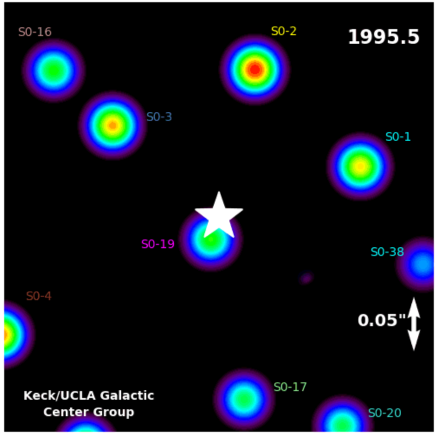


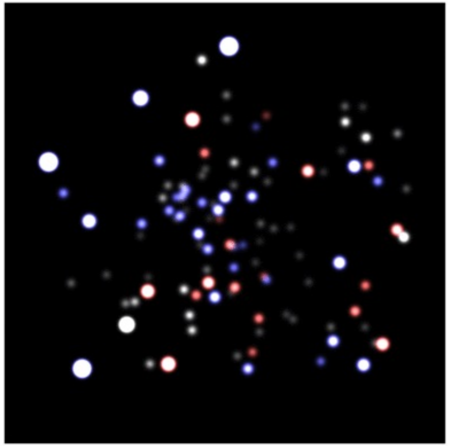
- Moderate level of resolved circular polarization across the image (〈|*v*|〉 < 3.7%)
- MAD models remain favored when this upper limit is included for model comparison

The Galactic center black hole Sgr A*:

- Strong evidence for supermassive black hole from stellar obits, proper motion and VLBI imaging studies
  - Nobel prize in physics 2020 (R. Genzel and A. Ghez)
  - Best distance and mass estimate (~8 kpc and ~4e6 $M_\odot$)
  - Unique source for high-accuracy tests of GR

- Astrophysical nature of the comact radio emssion: accretion flow or jet?



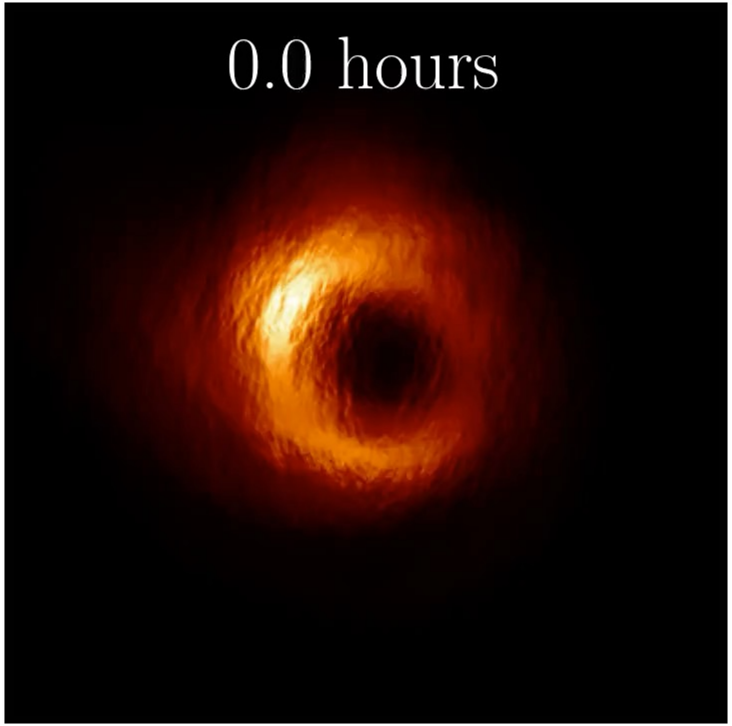


Credit: MPG

Sgr A* imaging: two unique challenges:

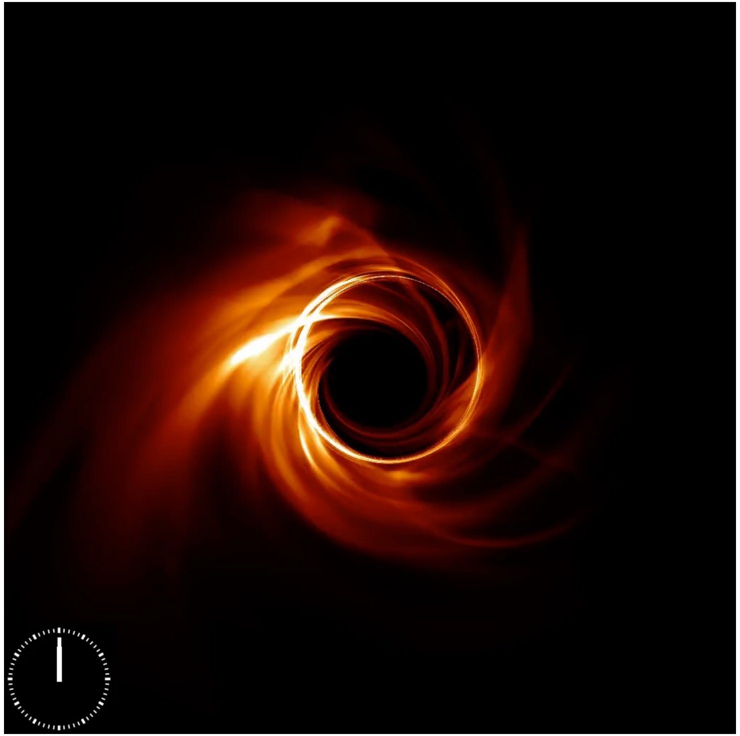
Interstellar Scattering

- Diffractive scat. (angular broadening)
- Refractive scat. (stochastic substructures)



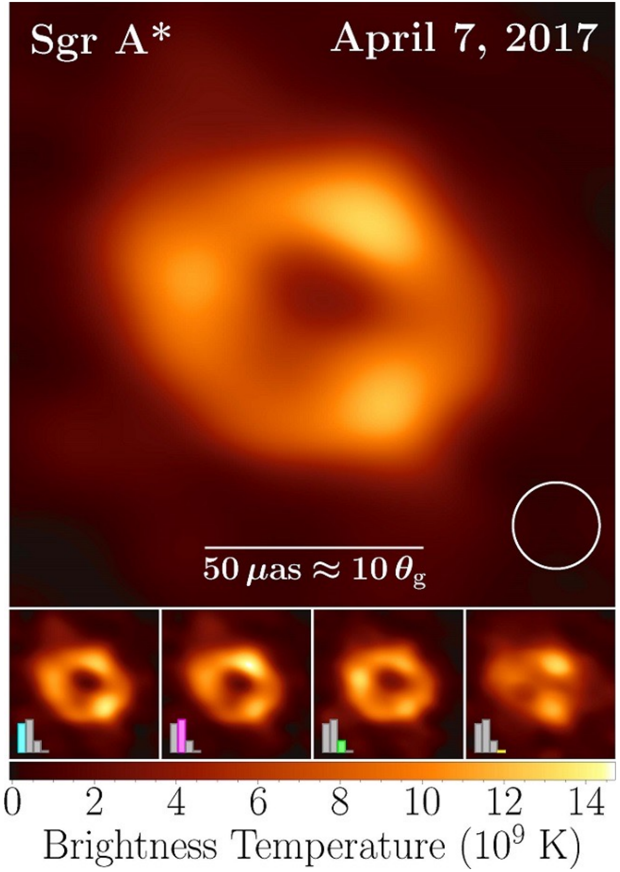
Time variability

- Flux variation (ALMA + Vis Amp)
- Structural variation (closure phases)



Slide credit: R. Lico

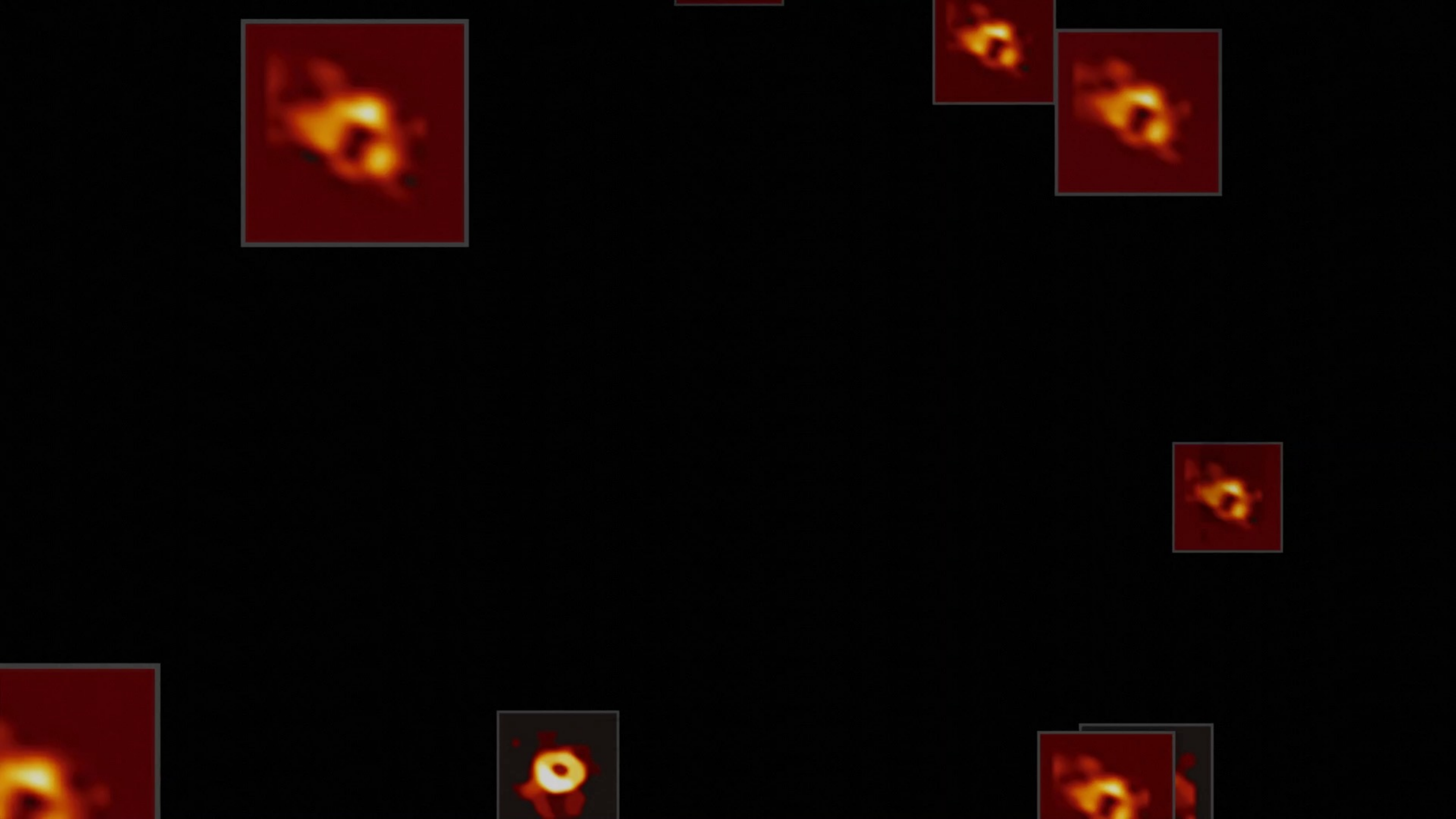
EHT imaging of Sgr A*



- Source variability is challenging:
  - A changing source structure during the observations violates the basic assumption needed for aperture synthesis
  - The reconstructed image is not unique, although the vast majority of images (95−98%) are rings
  - Difficult to recover consistent azimuthal structure

- Strong evidence for a ring with a diameter of ~50 µas, consistent with the expected "shadow" from BH mass and distance and consistent with GR

EHTC et al. 2022 (I-VI)
see also Farah et al. 2022 , Wielgus et al. 2022, Georgiev et al. 2022, and Broderick et al. 2022



Constraining the Sgr A* model

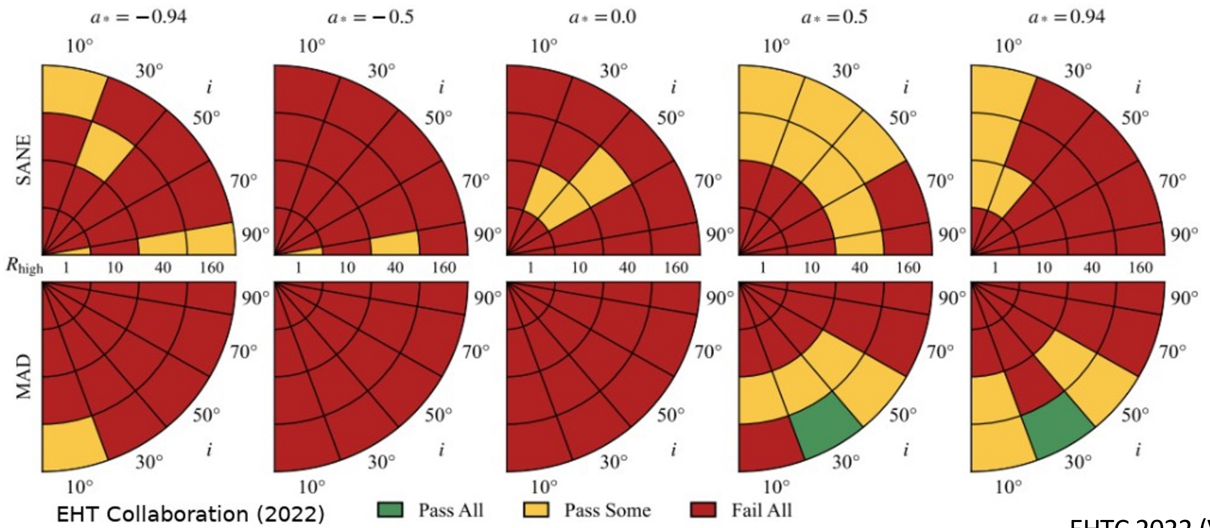
(excluding variability)

- Library of source models: ~PB of GRMHD simulations, images, and SEDs
- Tested against 11 observational constraints:

EHT data (5):
-230 GHz source size
-Vis. Ampl. morphology
-ring diameter, width, asymmetry

MWL data (4):
-86 GHz image size, flux density
-2μm flux density
-X-ray flux density

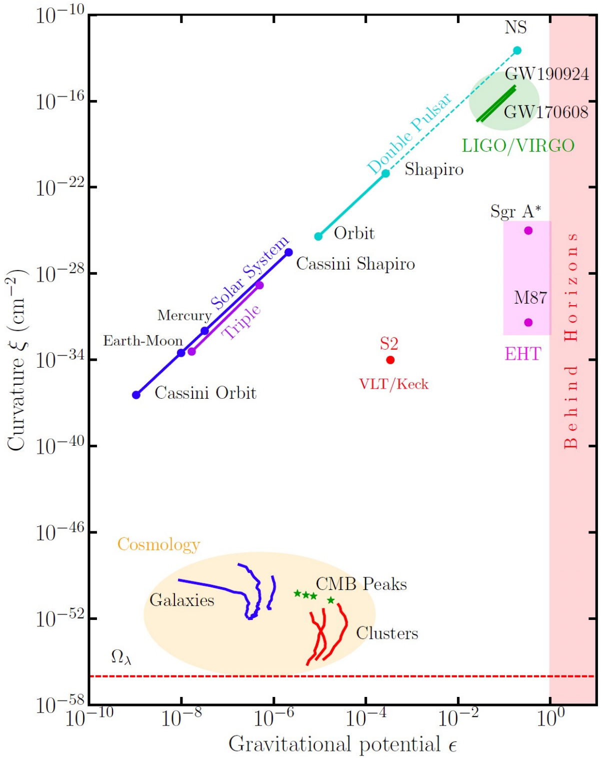
Variability (2):
-230 GHz light-curve
-structural variability



EHTC 2022 (V)

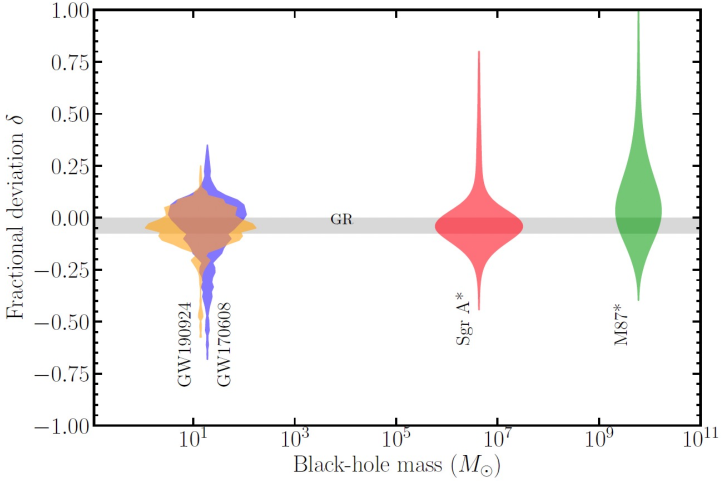
- Best-bet models: MAD, prograde (a* > 0), low inclination (i < 30deg) and cool electrons (R_{high} = 160)

Gravitational tests



Different tests of gravity probe vastly different regimes of gravitational potential and curvature

Comparison of the posterior distributions for the fractional deviation from the Schwarzschild predictions.



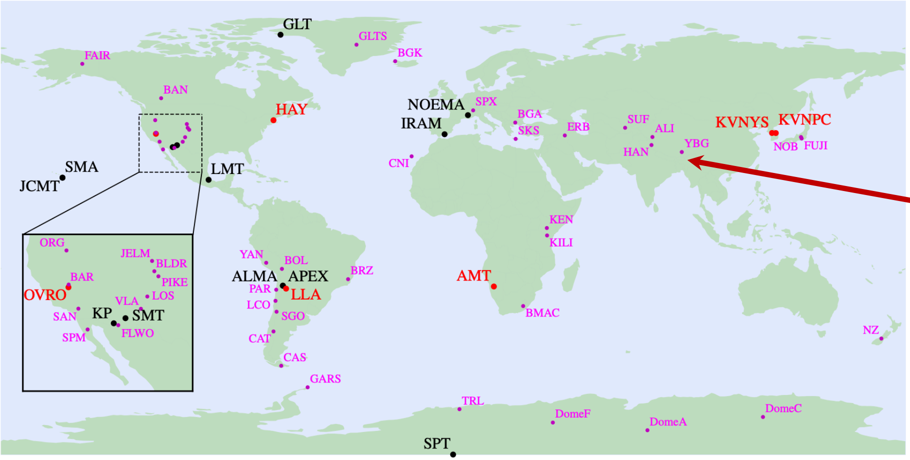
EHTC et al. 2022 (VI)

- Tests with gravitational waves and black hole images span a BH mass range of ~10-11 orders of magnitude
- All tests are consistent with the GR predictions that all BHs are described by the same metric, independent of their mass

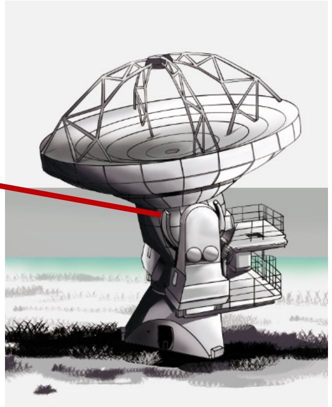
Slide credit: R. Lico

Future outlook

- More (and better) data
  - 2018, 2021, 2022, 2023 obs., +New telescopes (GLT, NOEMA, KP), 2x BW (32 -> 64 Gb/s)
- More telescopes (towards ngEHT)



Doeleman et al. 2023



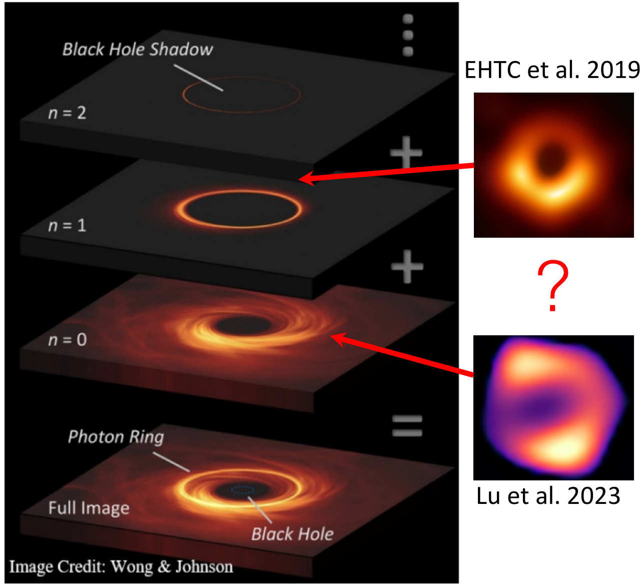
Future outlook

➢ Multi-color

- 345GHz: fringes have been obtained for a few sites; Sgr A* has been observed this year
- 86GHz: Global observations have imaged the ring-like structure in M87
- Simultaneous multi-frequency observations

➢ Movies

- Time resolved horizon-scale structure



Summary

- With Very Long Baseline Interferometry, the EHT has imaged the black hole at the center of M87 and Sgr A*
- Both M87 and Sgr A* show convincingly the predicted ring. GR test with EHT probes three orders of magnitude in black hole mass.
- For both M87 and Sgr A*, GRMHD modeling points towards MAD with dynamically important magnetic fields
- More exciting results to come with future multi-frequency, time-resolved black hole imaging