Event Horizon Telescope Images of Black Holes

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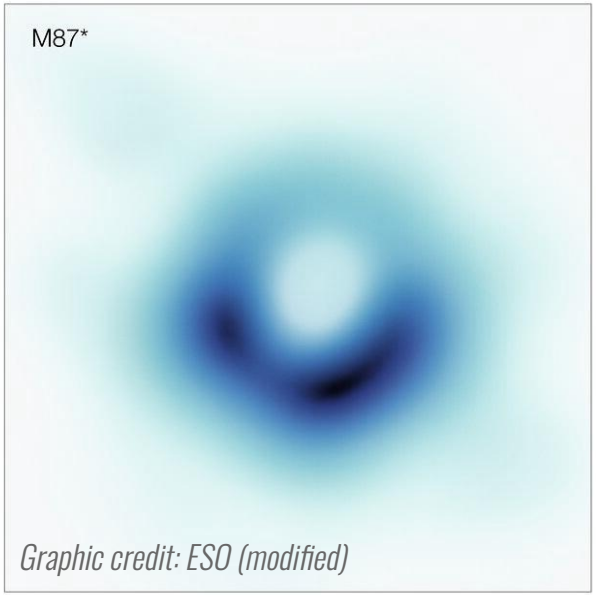
On behalf of the **Event Horizon Telescope Collaboration**

LHC Days in Split, Croatia \ 2022 October 3

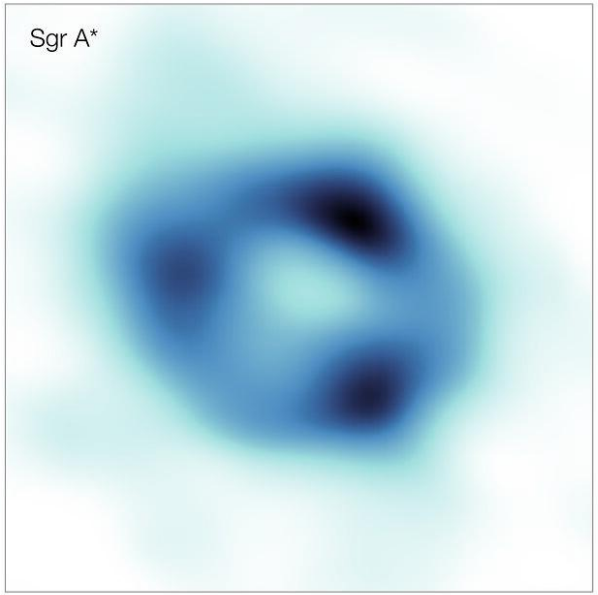
EVENT HORIZON TELESCOPE (EHT) COLLABORATION

- >300 people, ~60 institutions, ~20 countries and regions, *nearly all* continents
- Formalized in 2017 (until 2022) via collaborative agreement between 13 stakeholder institutions
- Funded by many grants of varied size from national and international sources

KEY EHT RESULTS: BLACK HOLE IMAGES



Graphic credit: ESO (modified)



Graphic credit: Eduardo Ros

This talk: how did we get here, what are we seeing, where to look next?

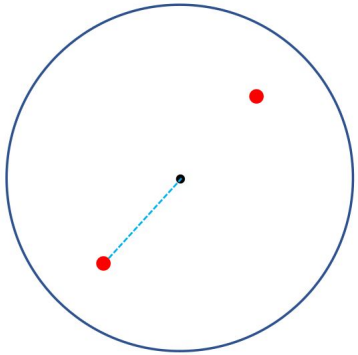
VERY LONG BASELINE INTERFEROMETRY CONCEPT

Photo credit: NRAO

- Baseline length between antenna pairs => (inverse) angular scale
- Wavelength as short as 1 mm, baselines as long as the Earth
- Need precise and stable timing of signal => atomic clocks
- Data streams recorded to local disk banks for offline correlation

Earth as seen from M87*

Single Fourier (a.k.a. UV) plane measurement

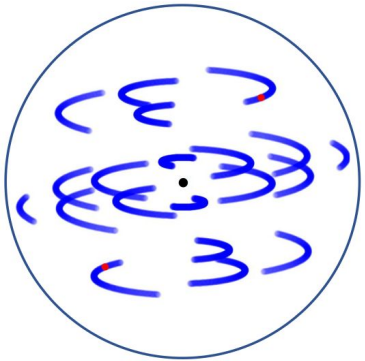


Many telescope pairs
+
Earth rotation

(a.k.a. aperture synthesis)

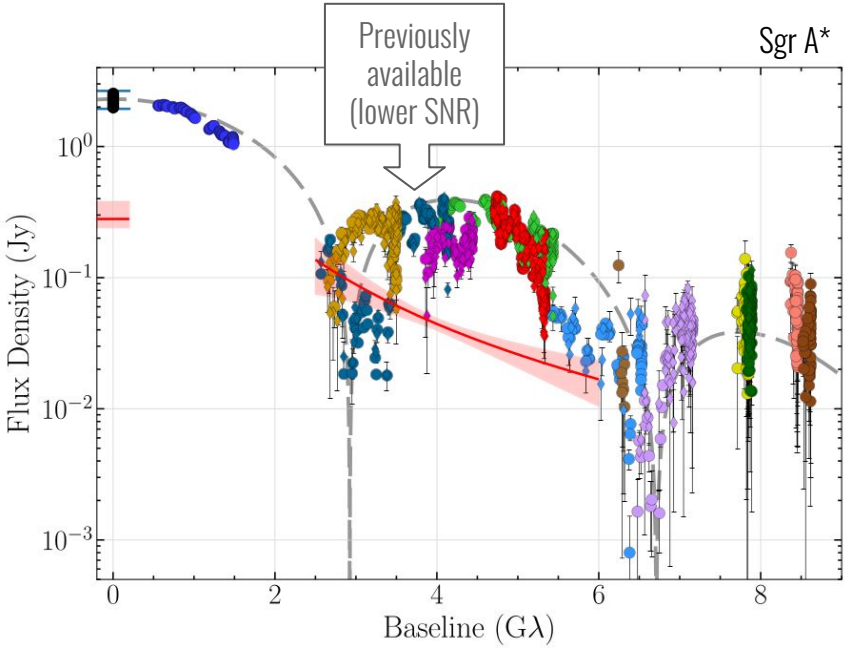
Graphic credit: Dominic Pesce

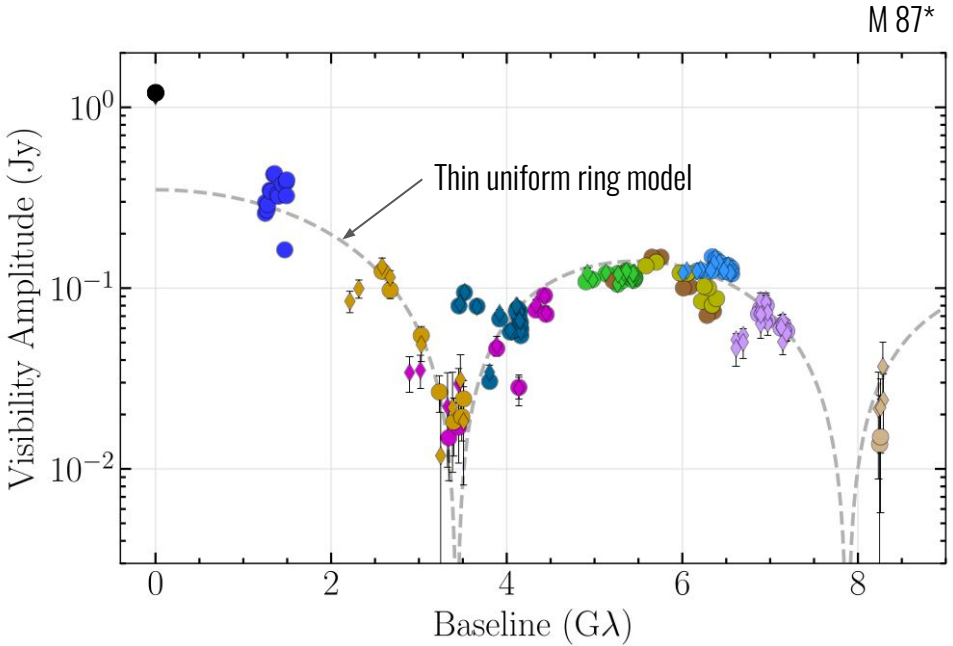
Sparse UV plane coverage



- Incomplete information
- Weak signal
- Integration time against variability

RING OR NO RING... THAT WAS THE QUESTION



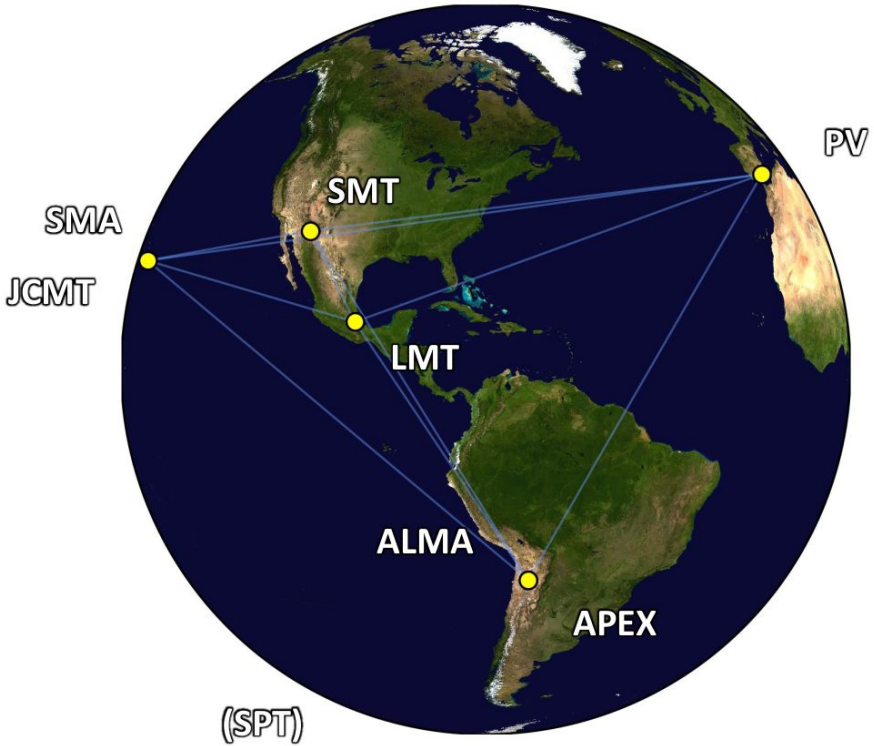


EHT OBSERVING CAMPAIGN IN APRIL 2017

Note: All results published so far are based on 2017 data alone!

- 10 (general-purpose) observatories in 8 locations
- Specialized VLBI equipment distributed
- 5 triggered observations within 10-day window
- Follow-up with major space & ground telescopes
- Overall excellent weather, very few issues
- 32 Gbps per observatory, ~6 PB in total

- *Yearly observing campaigns (skipped 2019 & 2020)*
- *Upgrades & additional observatories*
- *Expanding bandwidth up tp 128 Gbps*
- *Higher-frequency testing*

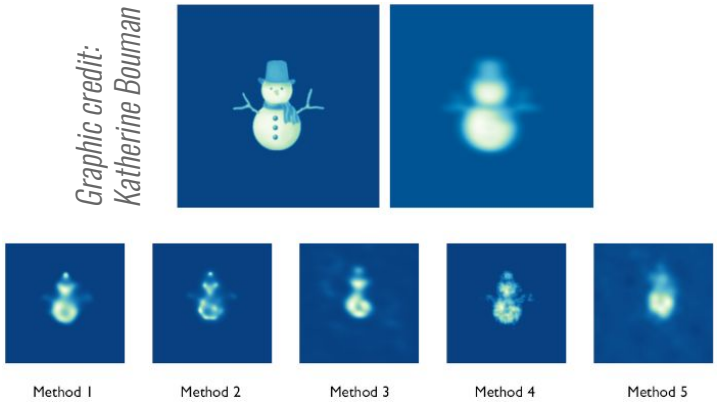


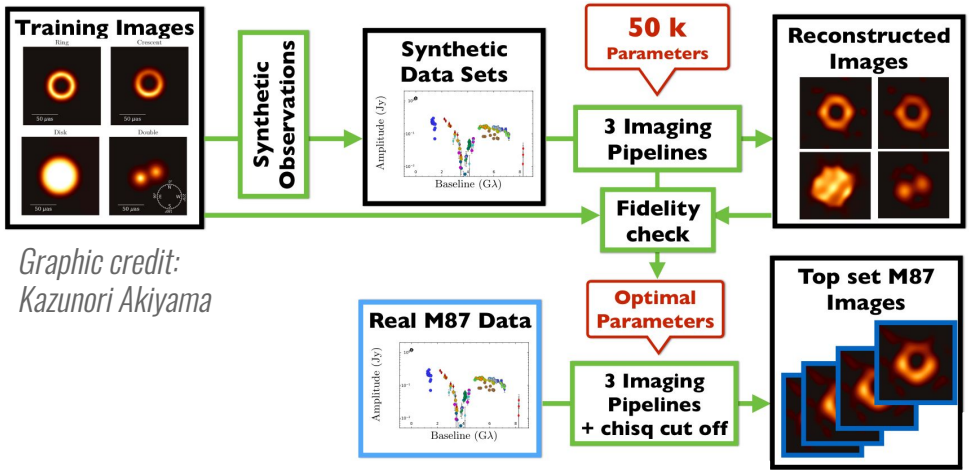
DATA PROCESSING CHAIN(S)

- Physical collection of disks (including the South Pole)
- Correlation
- Calibration & flagging
- Consistency checks & validation
- Pipeline development
- “Imaging” (Image reconstruction)
- Data volume reduced by 12 orders of magnitude

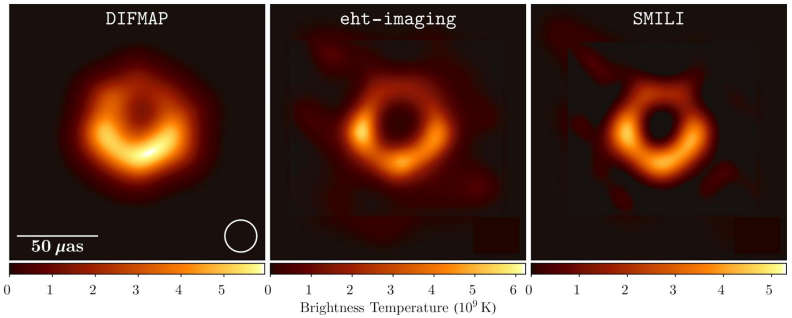
Graphic credit: Lindy Blackburn

THE ART OF MAKING INTERFEROMETRIC IMAGES

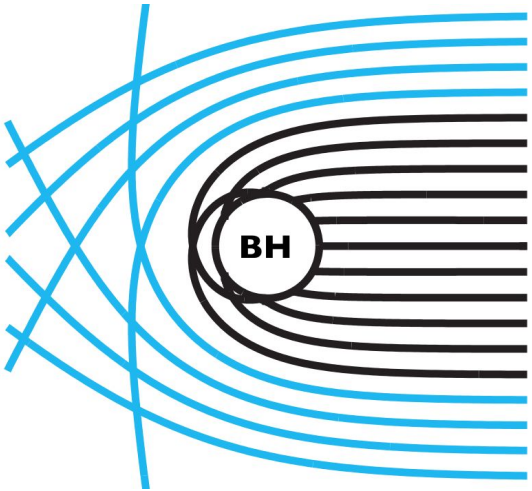




- Blind imaging challenges to assess reliability
- 4 isolated teams using traditional & novel methods
- Countering human bias, methods robustly calibrated
- One average M 87* image per night of observation



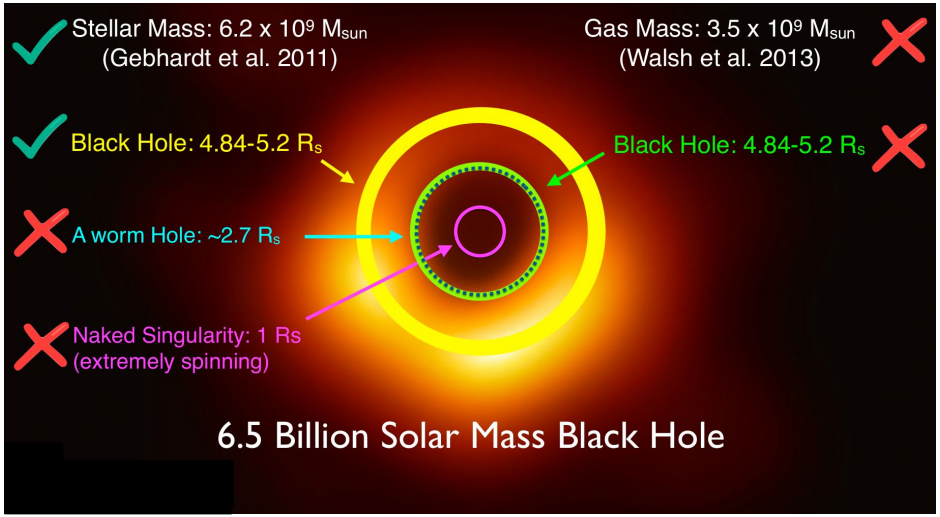
BASIC PROPERTIES OF THE M 87* IMAGE



2x
~5.2 Rs

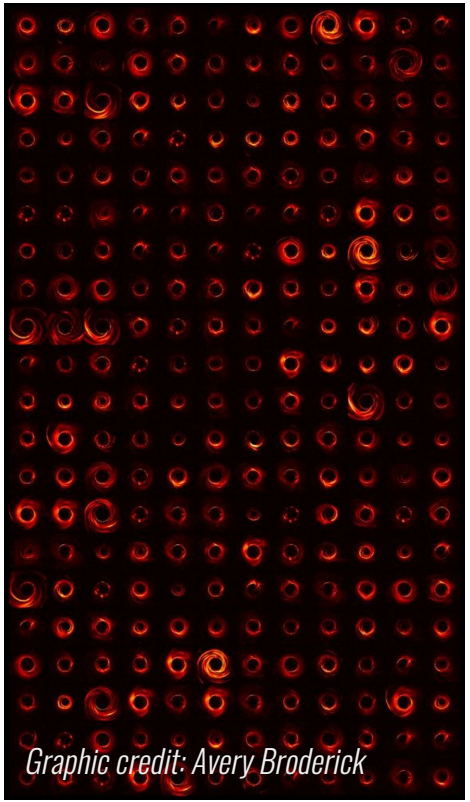
$R_s = 2GM_{BH}/c^2$

Graphic credit:
Hung-Yi Pu



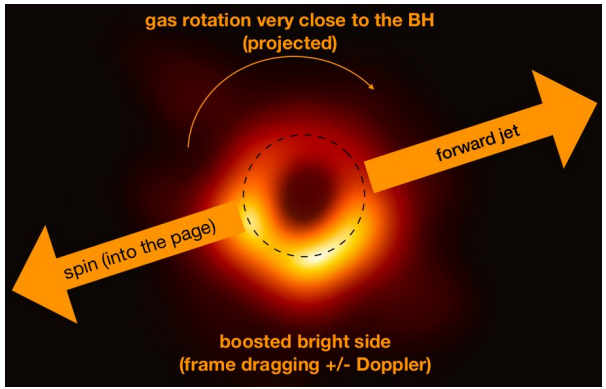
- 42 micro-arcsec diameter
- <10% deviation from a circle
- No significant deviation from GR

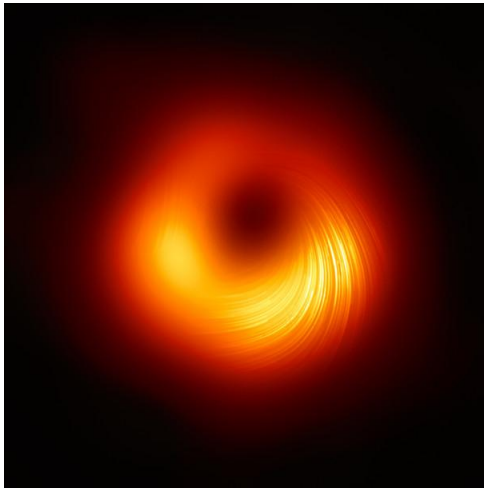
UNDERSTANDING THE M 87*ACCRETION FLOW



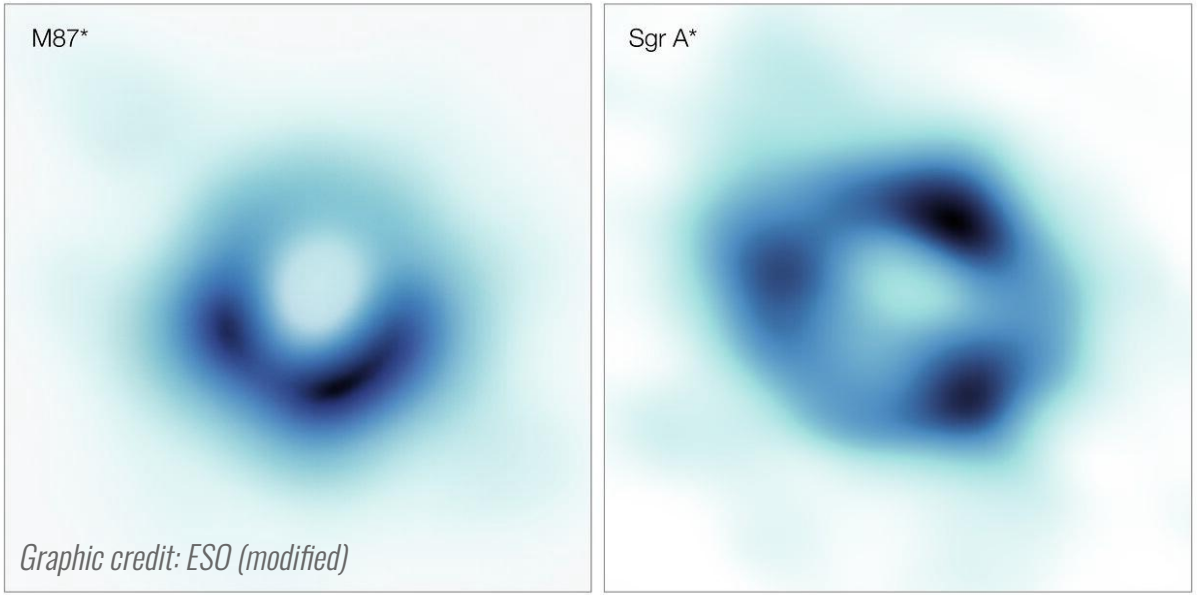
- 60,000 GRMHD simulations to compare the images to
- Consistent with Kerr black hole, has to be spinning prograde
- Additional constraints: variability, jet power, polarization
- Magnetically arrested disk (dynamically important field)

Graphic credit: Shepherd Doeleman





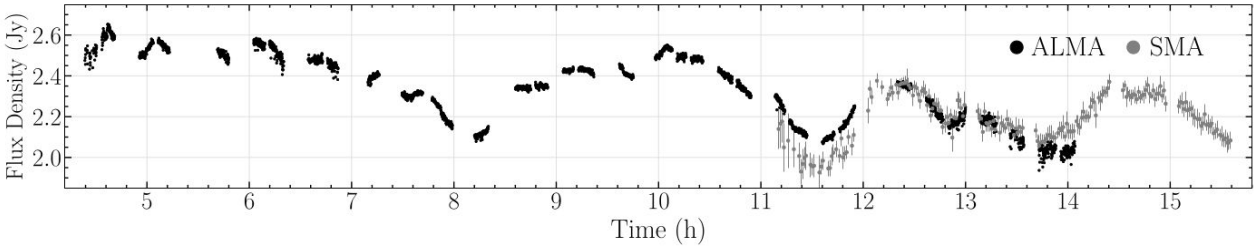
WHY IS IMAGING SGR A* MORE DIFFICULT?



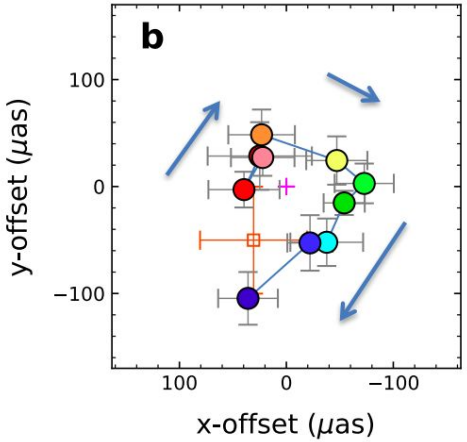
Graphic credit: ESO (modified)

- Less massive, more variable (factor of 1000)
- Turbulent hot gas adds blur
- Lower accretion rate, no jet (?)

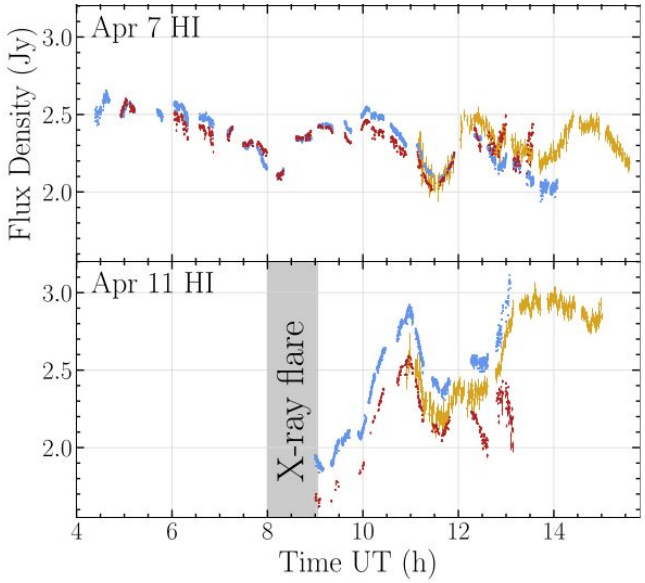
STRUCTURAL VARIABILITY ON SHORT TIMESCALES?



This is a mm-wave light curve showing persistent variability in **unresolved** total flux.



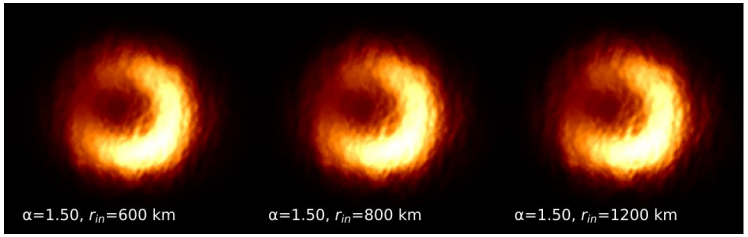
Flaring, polarized, circulating feature observed by the GRAVITY Collaboration (near-infrared interferometer at VLTI) in 2018

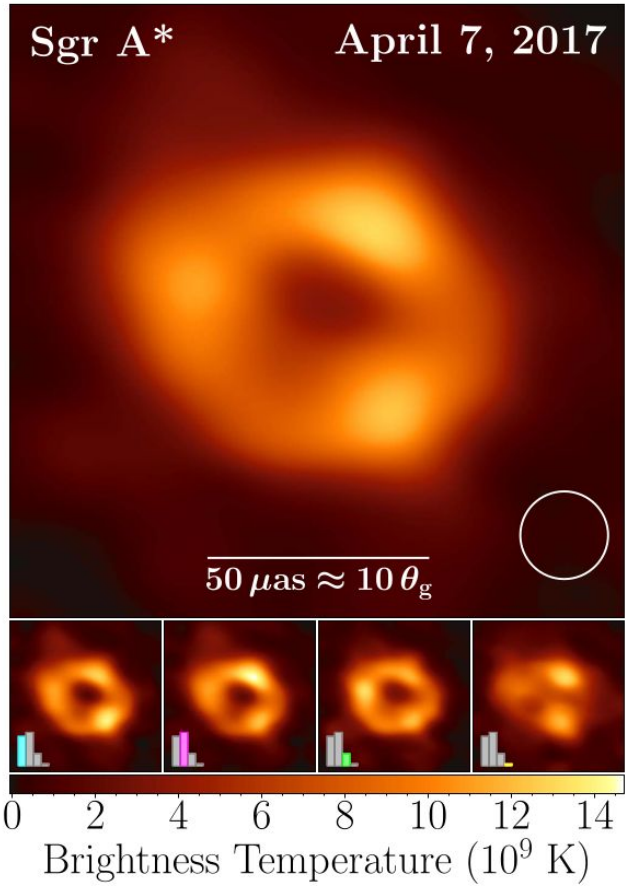


FOUR TYPES OF POSSIBLE SGR A* IMAGES

- Generally consistent with a ring
- 52 micro-arcsec diameter
- Fully in line with the well-constrained black hole mass
- Small fraction of data consistent with non-ring image model

Effect of refractive scattering in the intervening hot gas:

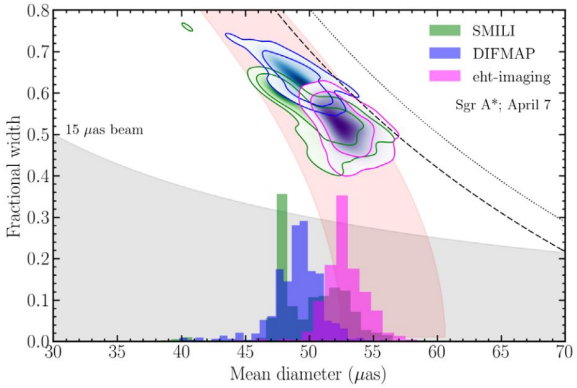


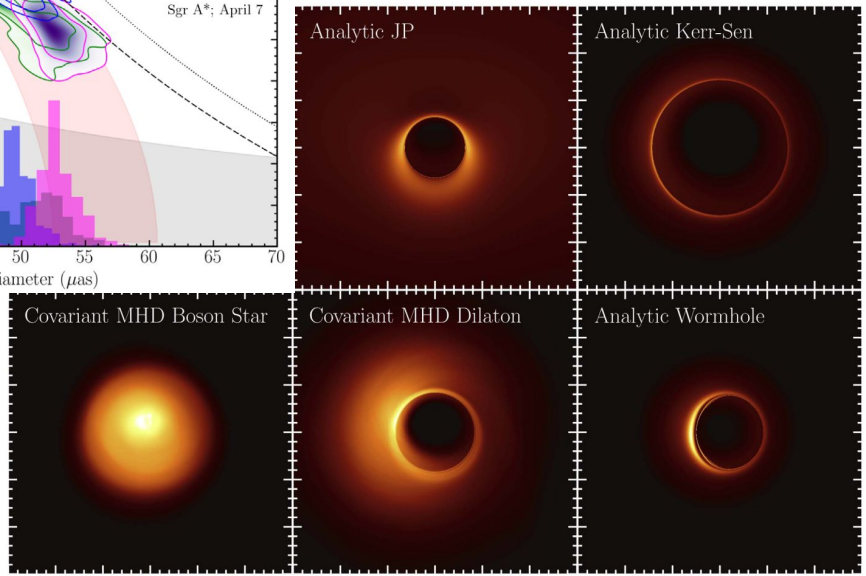


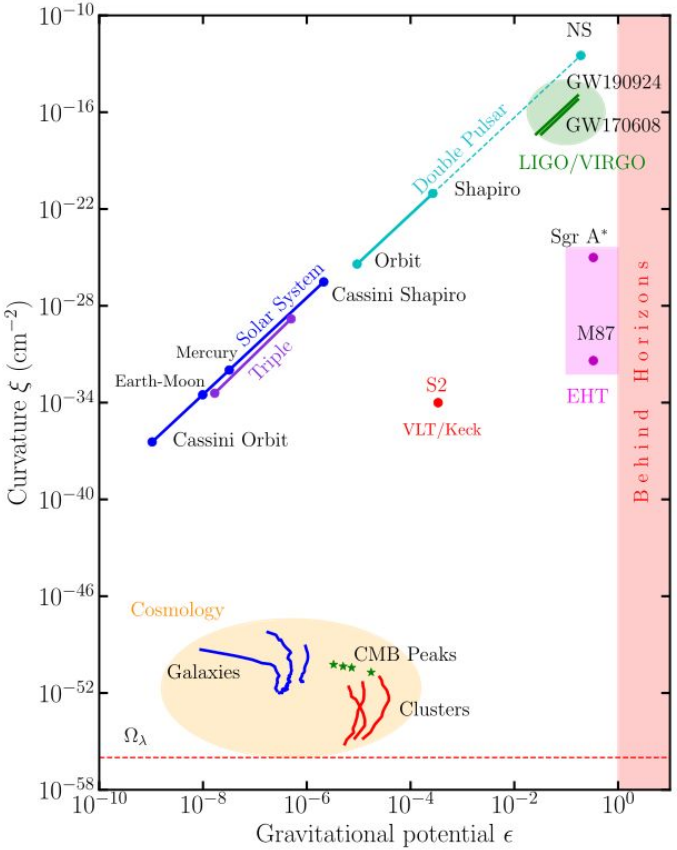
Non-ring model consistent with the data

TESTS OF GENERAL RELATIVITY WITH THE EHT

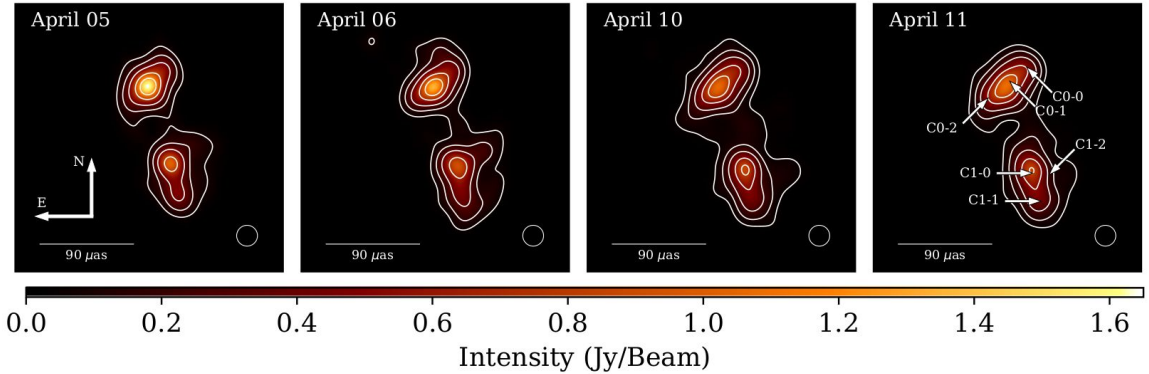
Sgr A* offers more stringent tests of GR due to its accurately measured mass. *GR seems fine for black holes of all masses!*

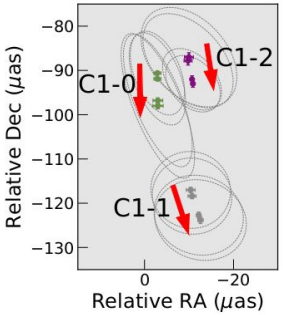


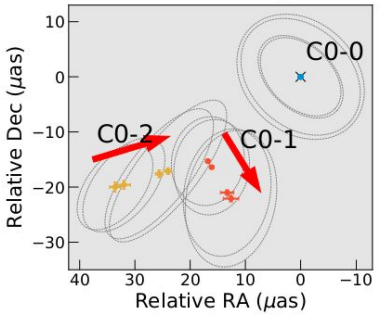




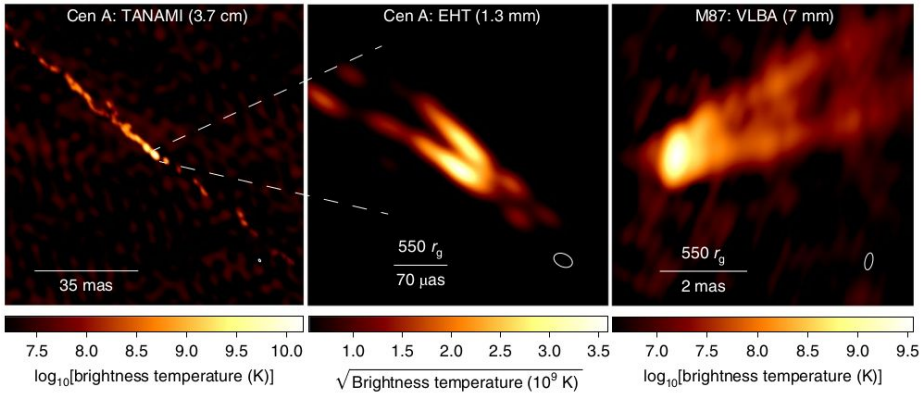
AWAY FROM THE EVENT HORIZON: RELATIVISTIC JETS



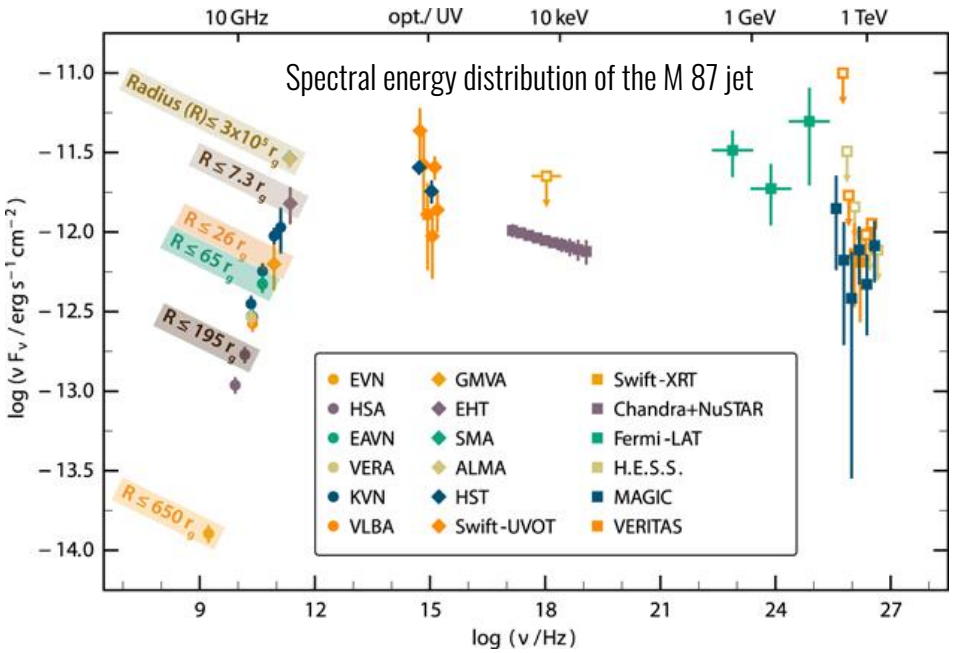




- Peculiar blob motion in 3C 279 (above)
  - Kim et al. 2019
- Edge-brightened jet in Cen A (right)
  - Janssen et al. 2021

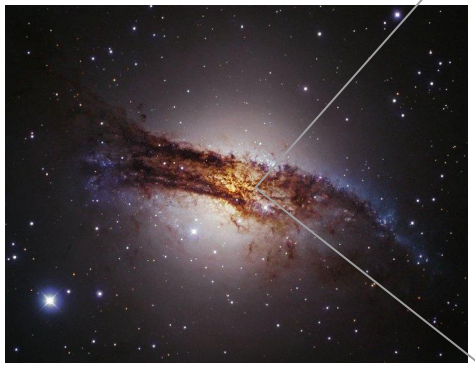


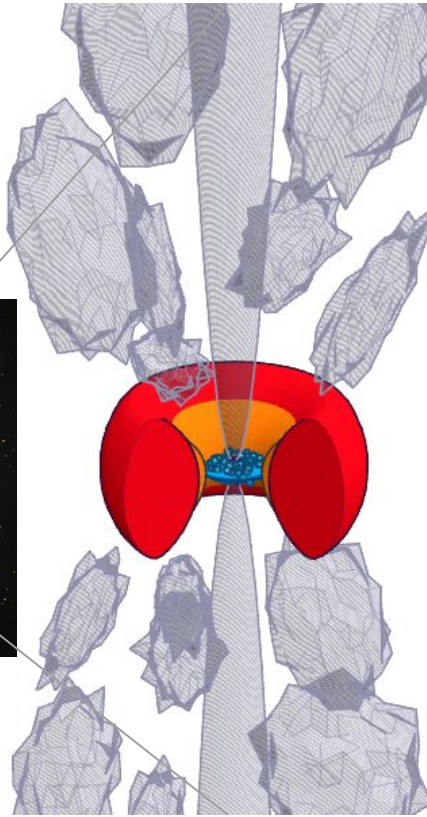
BROADER CONTEXT: AGN AND THEIR ENVIRONMENT



Luminous, accreting AGN + mergers seen by LISA
=> full picture of black hole growth over cosmic time

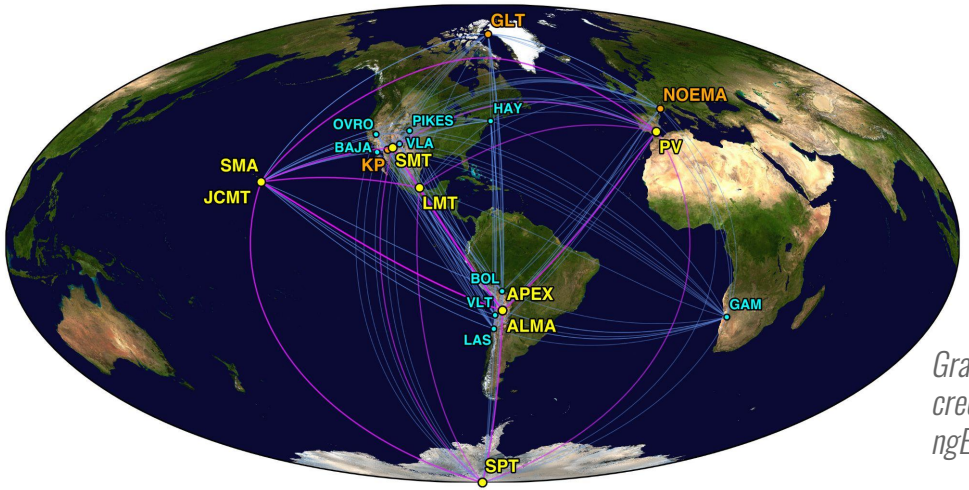
Graphic credit: ESO





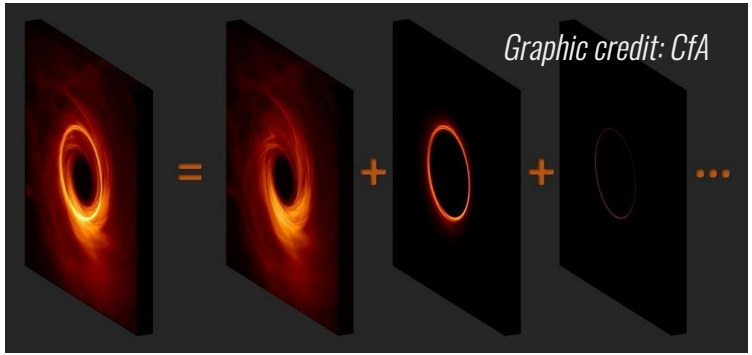
NEXT GENERATION EHT AND FUTURE CHALLENGES

- **ngEHT** study already well underway
- Denser array with smaller dishes
- More observing flexibility
- Multi-band observing
- Real-time correlation



Graphic credit: ngEHT

- Going to space:
  - No atmosphere, extended baselines
  - Fast UV coverage in LEO + outrigger(s)
  - Single dish or flotilla configuration?
  - Fast downlink (laser communications?)



SUMMARY

- EHT Collaboration: built recently on top of >20 years of effort
- Long path from raw data to images and science
- Key results: first black hole images, M 87* and Sgr A*
- No deviations from GR so far, but we just started (only 2017 data)
- Not only black hole images, also relativistic jets
- Lots of space and time for expansion

Thank you!

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