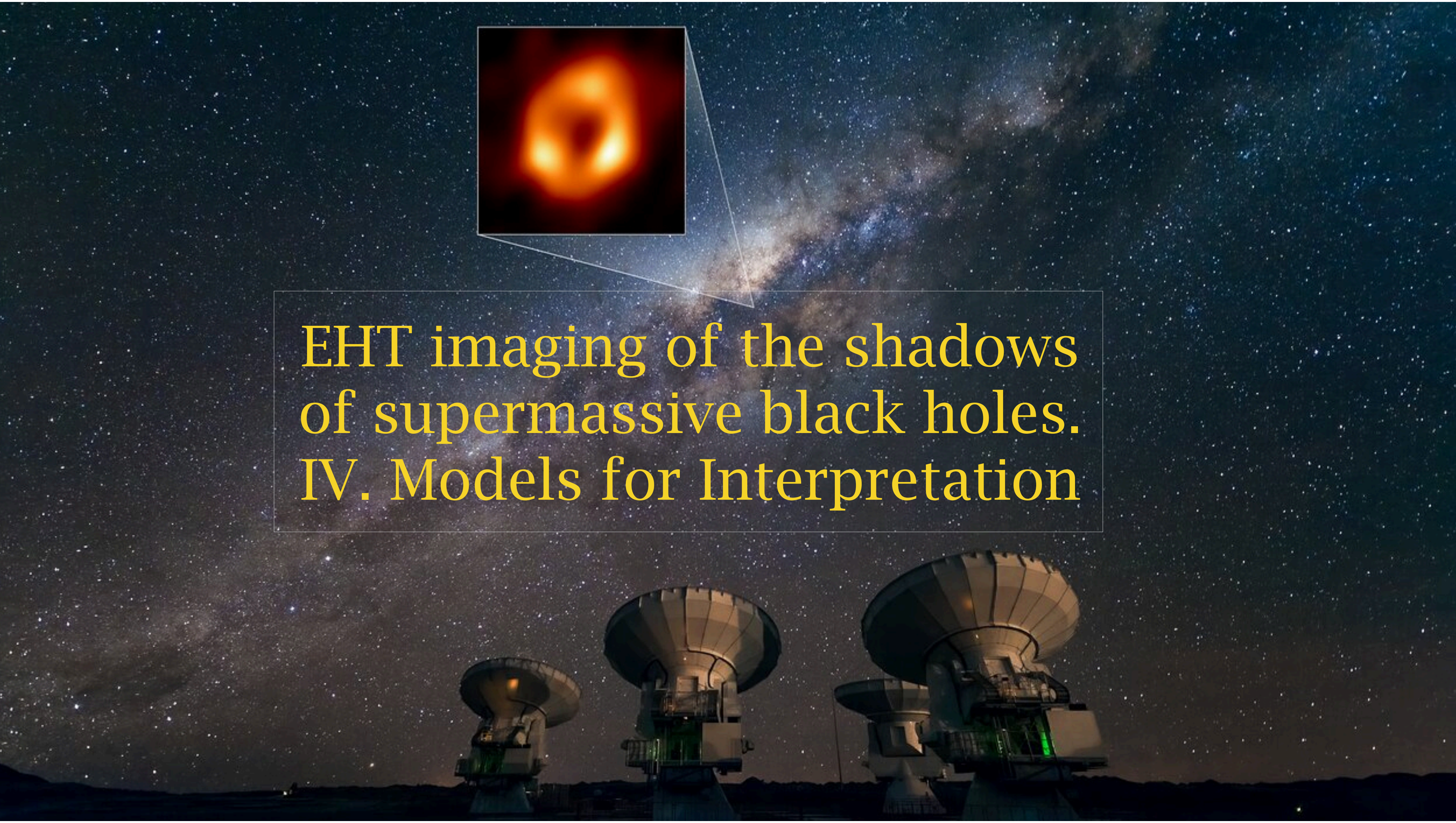
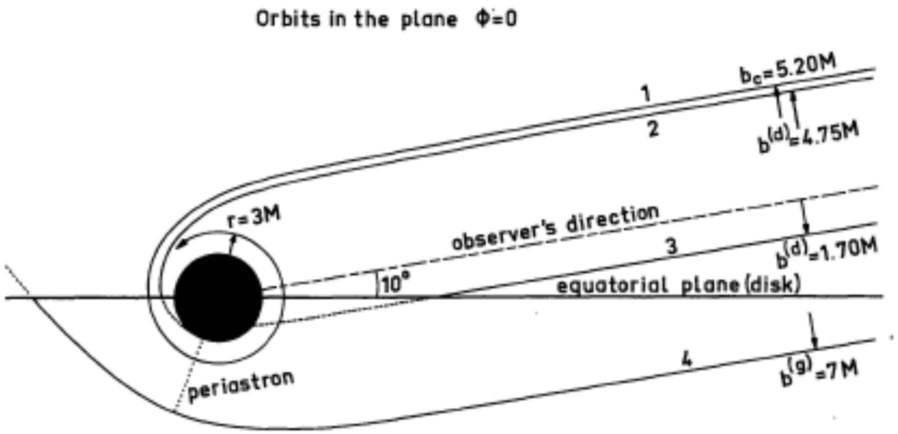

EHT imaging of the shadows
of supermassive black holes.
IV. Models for Interpretation

Today

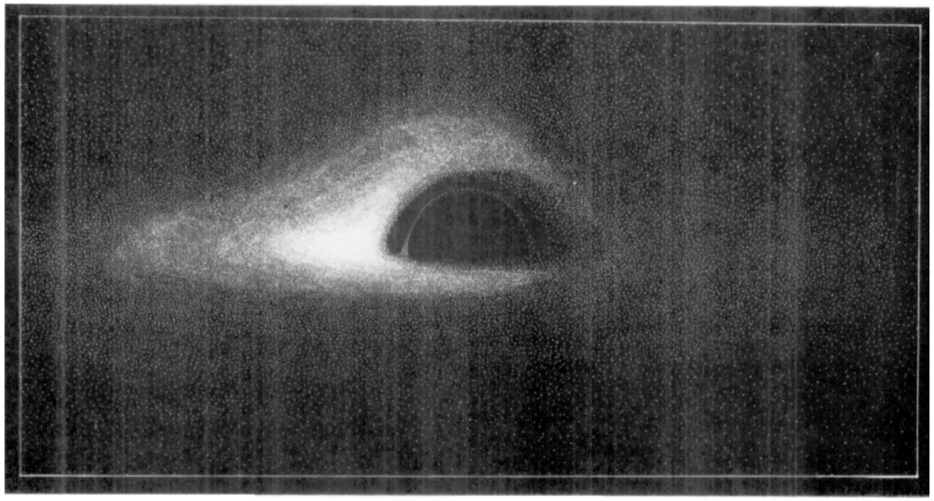
- Overall Objective
  - Introduce the practices of our trade: what it takes to measure the shadow of supermassive black holes

- Today: Models for interpretation
  - What are we looking at?
  - Photon ring
  - BH mass and distances
  - Fitting models
  - α calibration
  - GRMHD models
  - Constraints from GRMHD
  - Spin, inclination
  - Variability crises
  - Future…

How would a Black Hole look like

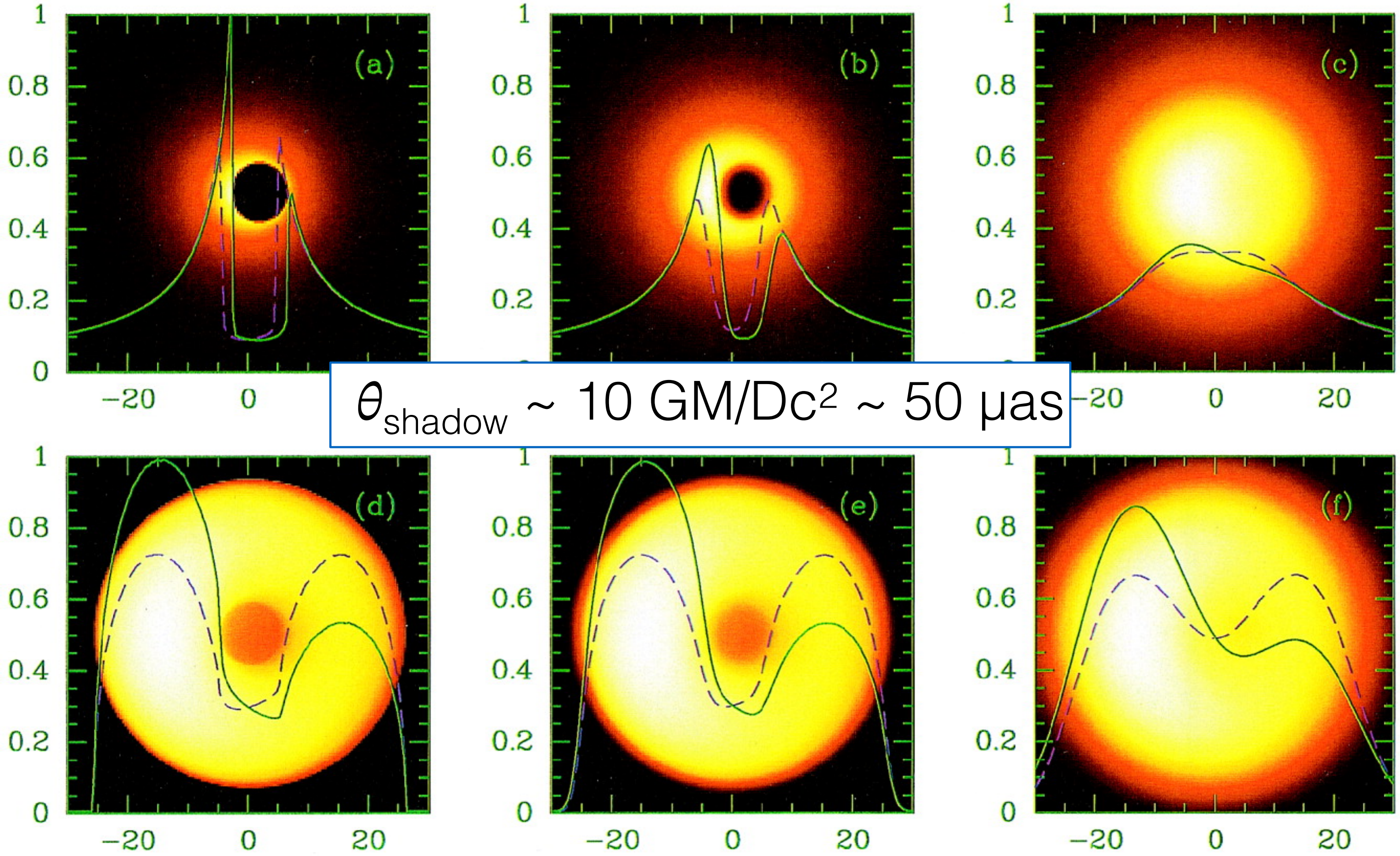


Bardeen 1973



Luminet 1979

And could we ever observe?



θ_{shadow} ~ 10 GM/Dc^2 ~ 50 µas

max rotation

model

0.6mm

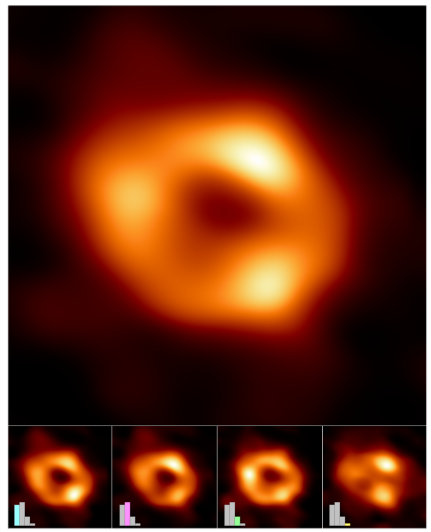
1.3mm

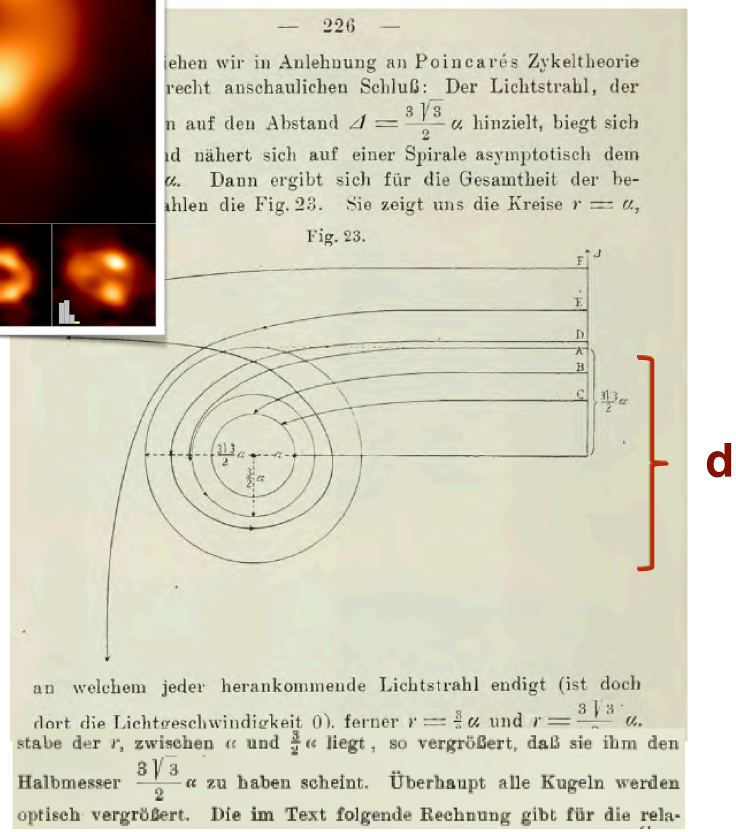
Falcke, Melia, Agol 2000

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 —

…iehen 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 $r = \alpha$,

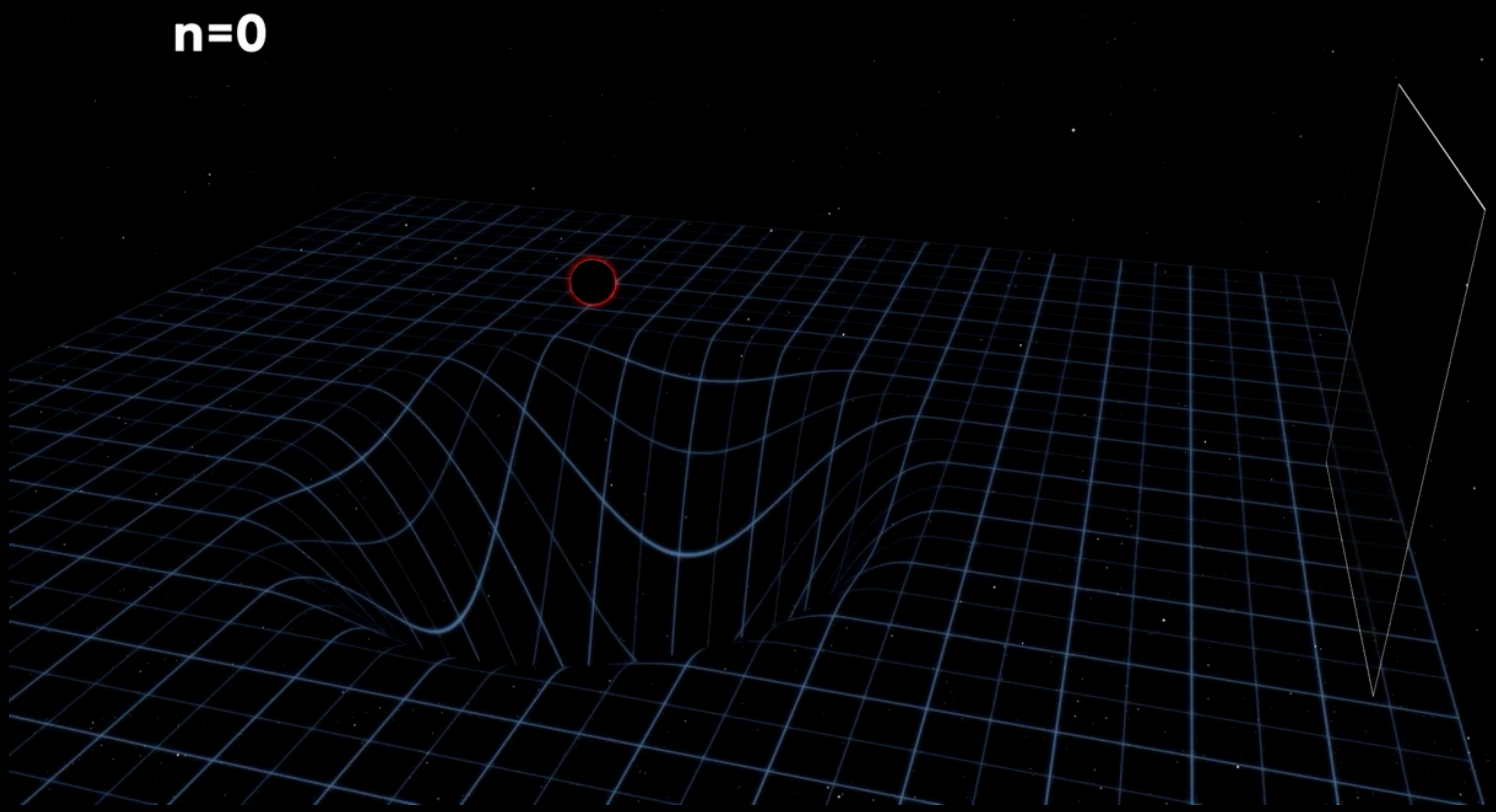
Fig. 23.

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

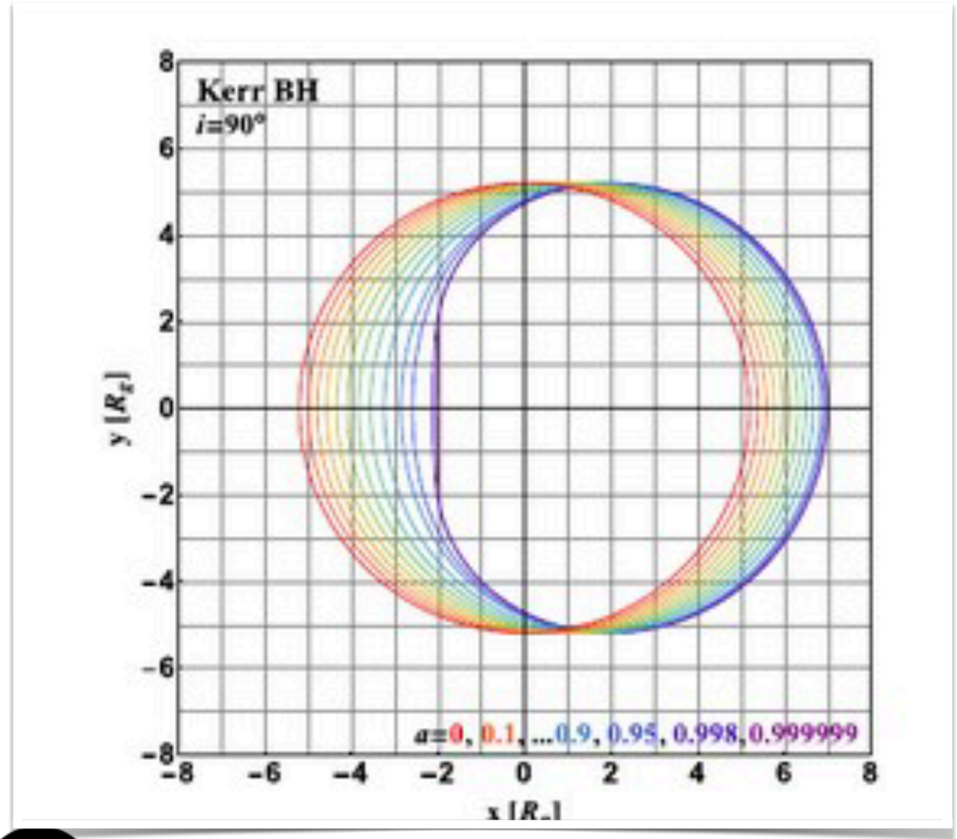
Event Horizon Telescope

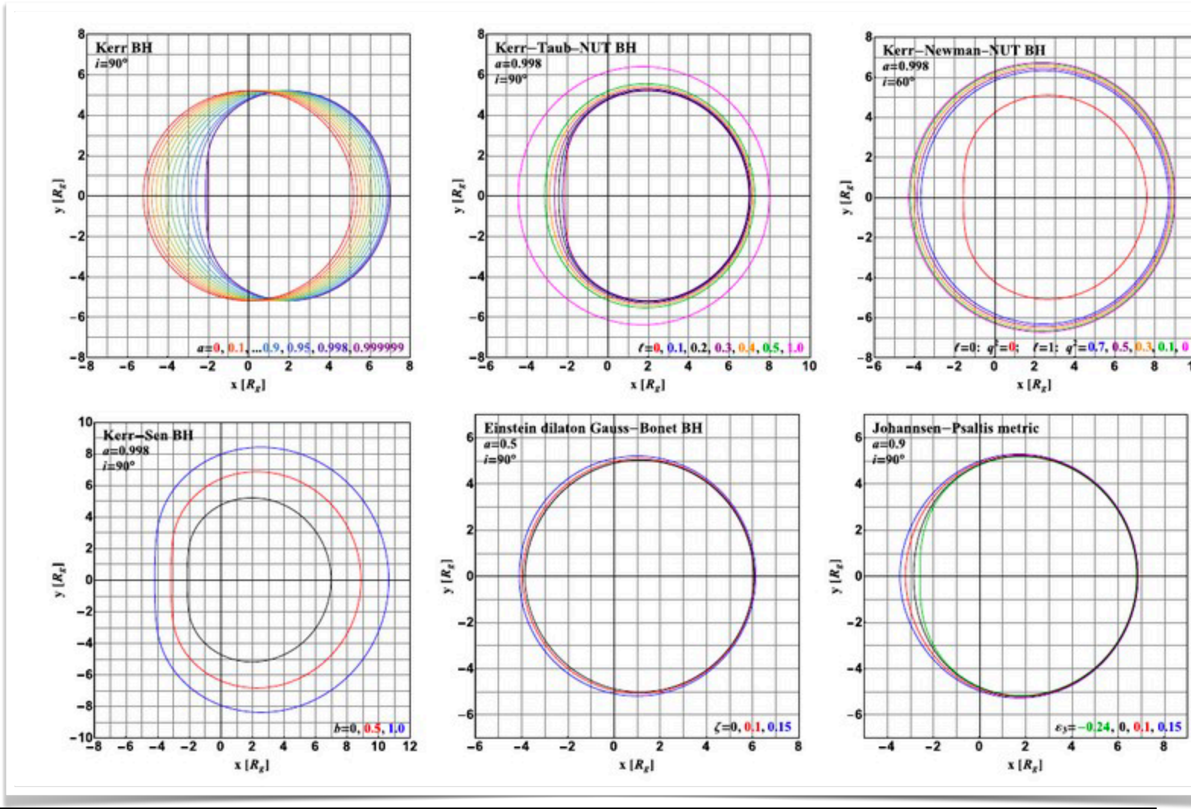
Image from gravitational lensing



Photon rings

- Will deppend on spin… weakly





General Relativistic Magneto Hydro Dynamic Models

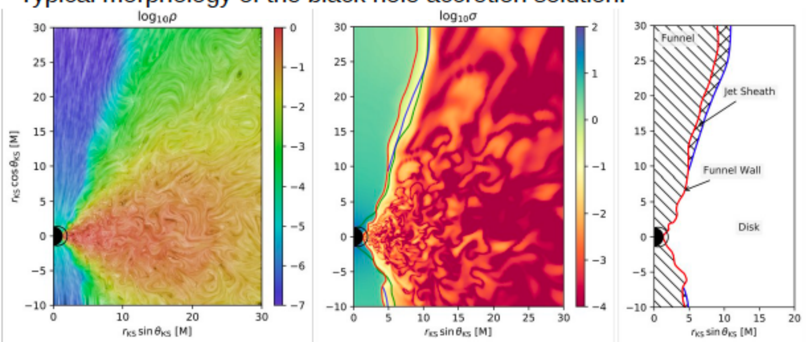
- GRMHD models are really very important for EHT
  - Test imaging and calibration
  - Explain what we look at
  - Calibrate $d = \alpha\, \theta_g$
  - Interpret our images in physical parameters
- Typical inputs
  - spin
  - inclination
  - MAD vs SANE
    - Magnetically Arrested Disks
    - Standard and Normal Evolution
  - Different temperatures electrons/ions

$$\frac{T_\mathrm{p}}{T_\mathrm{e}} = \frac{R_\mathrm{low} + R_\mathrm{high}\, \beta^2}{1 + \beta^2}$$

Standard (EHT) resolutions:
192 x 192 x 192 cells
In r, theta, phi directions

Porth et al. (2019)

Typical morphology of the black hole accretion solution:



Go for SgrA* for best priors

- For M87 large difference between M_{BH} from gas and stellar dynamics
  - Results favour higher mass from stellar measurements
- For SgrA* much more precise, M and D
  - But some controversy Keck & GRAVITY

- M87 inclination 14°
- SgrA* unconstrained
  - Jet is missing…
- Despite scattering
- Despite variability

The Astrophysical Journal Letters, 875:L2 (28pp), 2019 April 10 The EHT Collaboration et al.

Table 1
Assumed Physical Properties of Sgr A* and M87 Used to Establish Technical Goals[a]

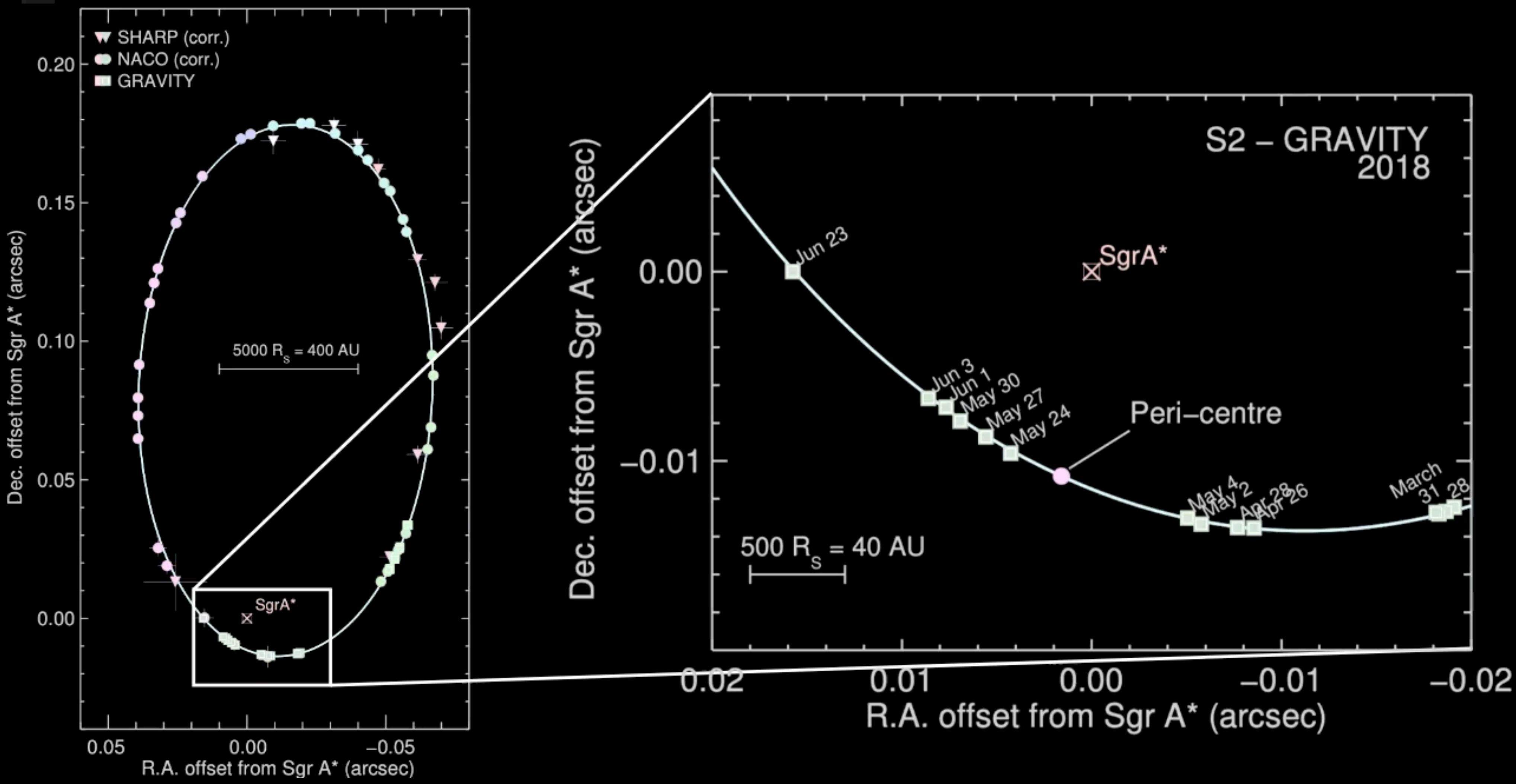
		Sgr A*	M87
Black Hole Mass	M ($M_\odot$)	4.1×10^6 (1)	$(3.3–6.2) \times 10^9$ (5), (6)
Distance	D (pc)	8.34×10^3 (2)	16.8×10^6 (7)
Schwarzschild Radius	R_s (μas)	9.7	3.9–7.3
Shadow Diameter[b]	D_{sh} (μas)	47–50	19–38
Brightness Temperature[c]	T_B (K)	3×10^9 (3)	10^{10} (8)
Period ISCO[d]	P_{ISCO}	4–54 minutes	2.4–57.7 days
Mass Accretion Rate[e]	$\dot{M}$ ($M_\odot$ yr^{-1})	10^{-9}–10^{-7} (4)	$<10^{-3}$ (9)

Notes.
[a] Sgr A*: $\alpha_{J2000.0} = 17^h45^m40^s.0409$, $\delta_{J2000.0} = -29°00'28''.118$ (10); M87: $\alpha_{J2000.0} = 12^h30^m49^s.4234$, $\delta_{J2000.0} = 12°23'28''.044$ (11).
[b] The shadow diameter is within the range 4.8–5.2 R_s depending on black hole spin and orientation to the observer's line of sight (Johannsen & Psaltis 2010).
[c] Brightness temperatures are reported for an observing frequency of 230 GHz.
[d] P_{ISCO} range is given in the case of maximum spin for both prograde (shortest) and retrograde (longest) orbits (Bardeen et al. 1972).
[e] Mass accretion rates $\dot{M}$ are estimated from measurements of Faraday rotation imparted by material in the accretion flow around the black hole.

References. (1) GRAVITY Collaboration et al. (2018a), (2) Reid et al. (2014), (3) Lu et al. (2018), (4) Marrone et al. (2007), (5) Walsh et al. (2013), (6) Gebhardt et al. (2011), (7) Blakeslee et al. (2009), EHT Collaboration et al. (2019e), (8) Akiyama et al. (2015), (9) Kuo et al. (2014), (10) Reid & Brunthaler (2004), (11) Lambert & Gontier (2009).

Event Horizon Telescope

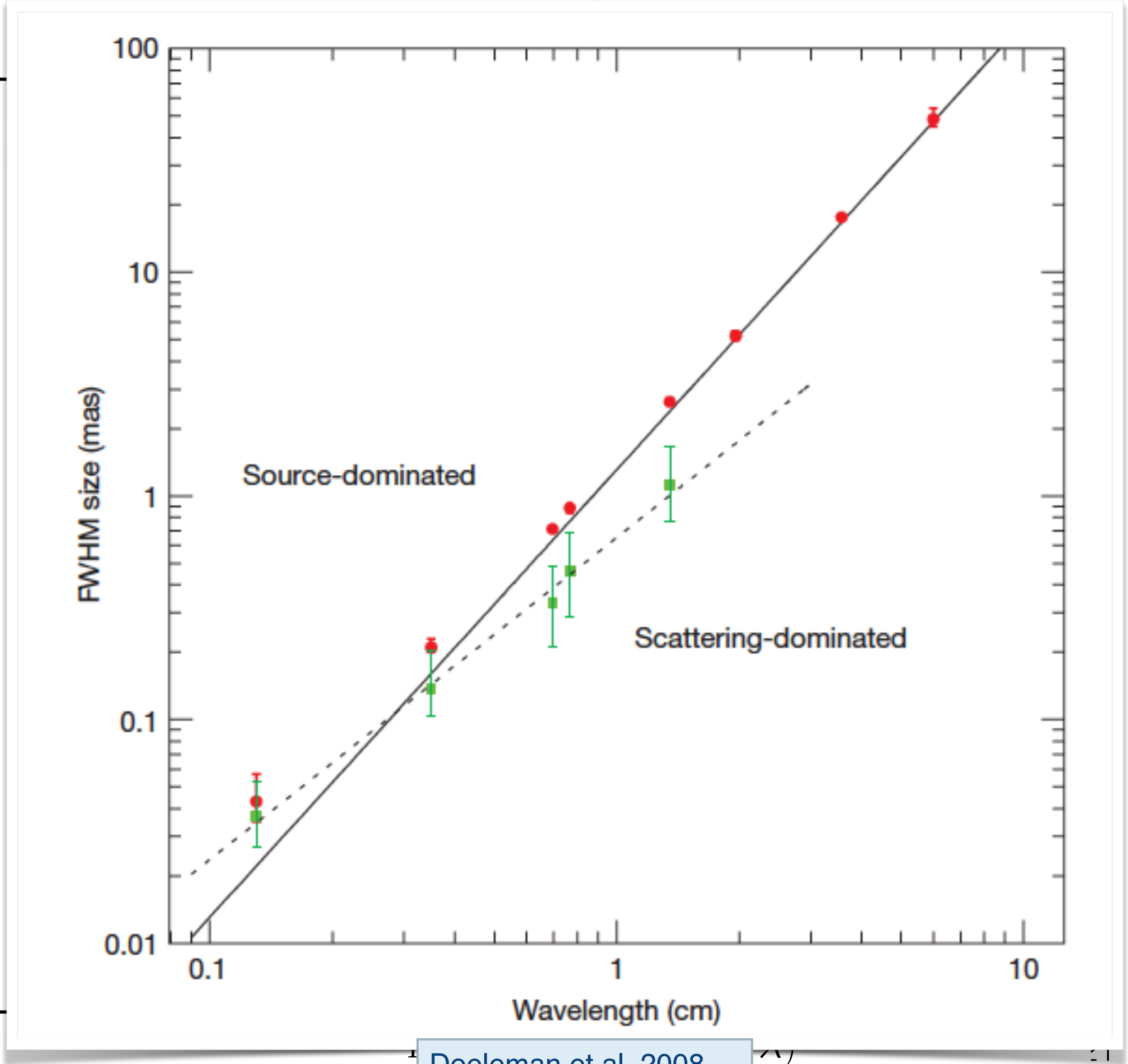
1



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)

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

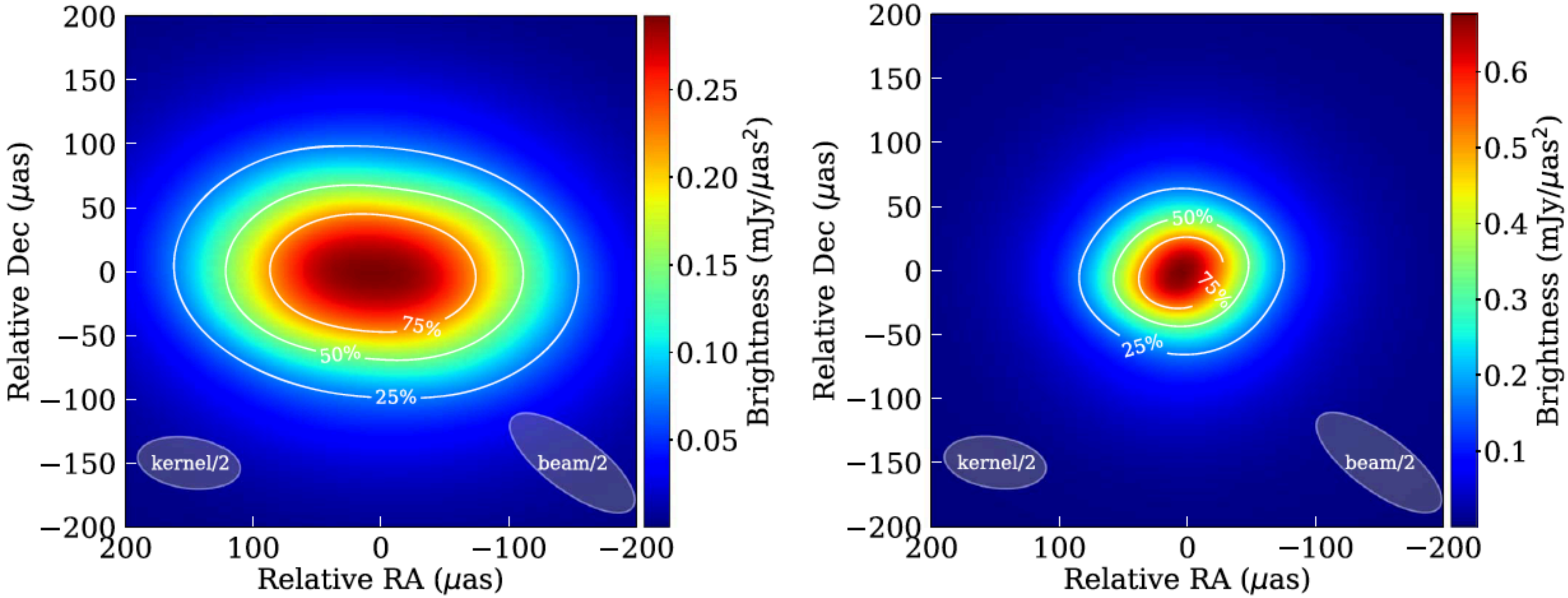


Doeleman et al. 2008

Best SgrA* image published to date

- Global Millimeter VLBI Array (GMVA)
  - At 7mm, including ALMA
  - Favouring (extended) disk models over jet models

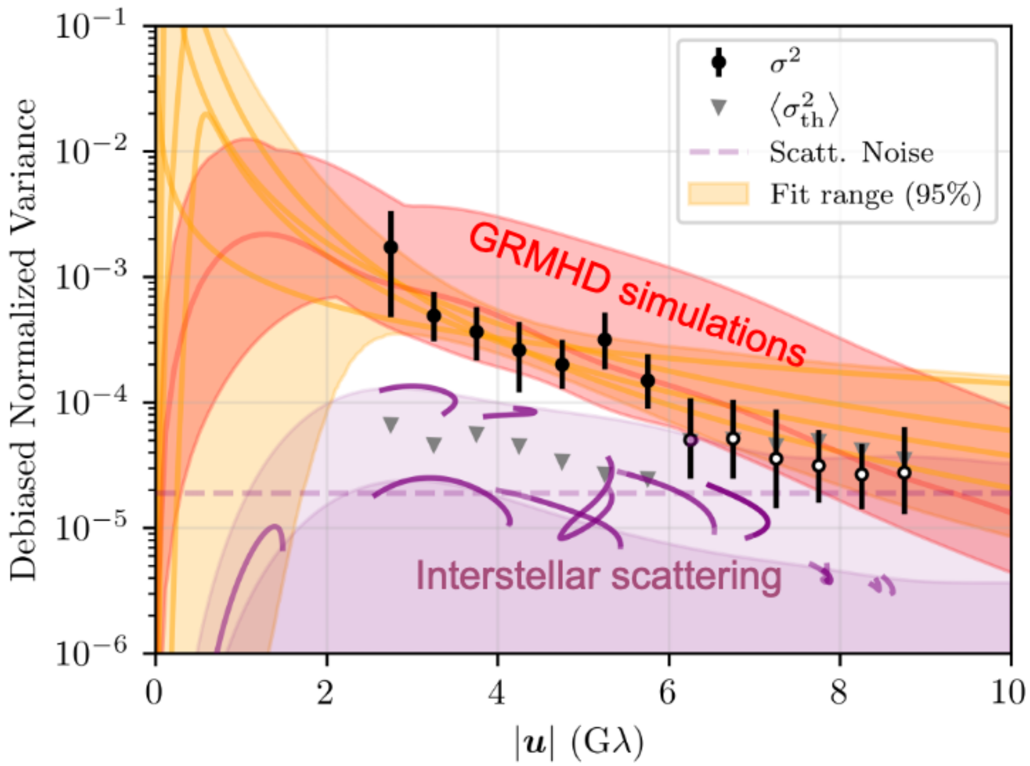
Corrected for interstellar scattering



Issaoun et al., 2019

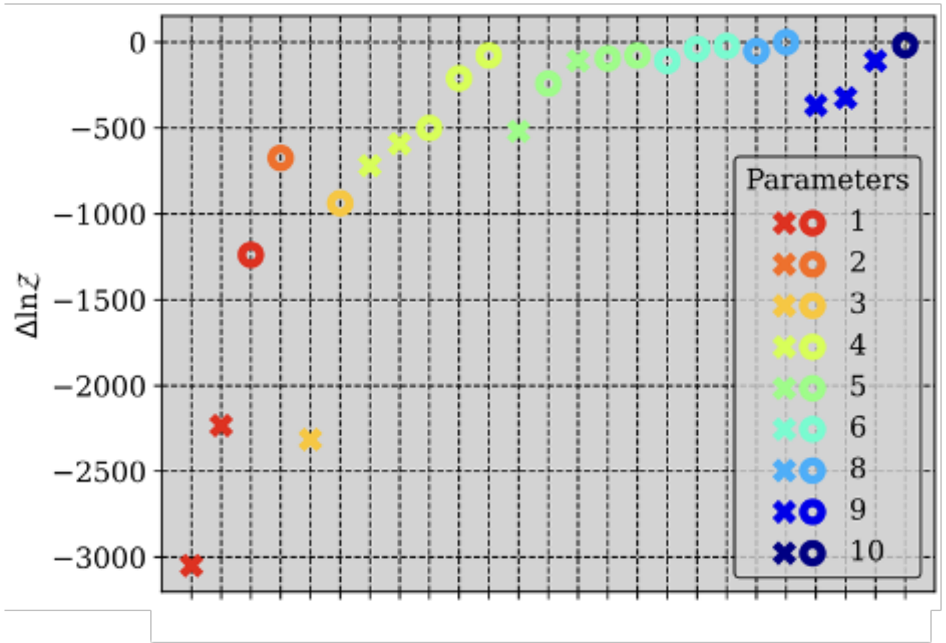
Intrinsic variability is serious

- Visibility amplitudes have extra variance
  - Power-law decline with baseline length
  - As expected from simulations
- Fit to short stretches of data
  - Then average
- Fit with parameter of extra noise contribution



Measure ring diameter

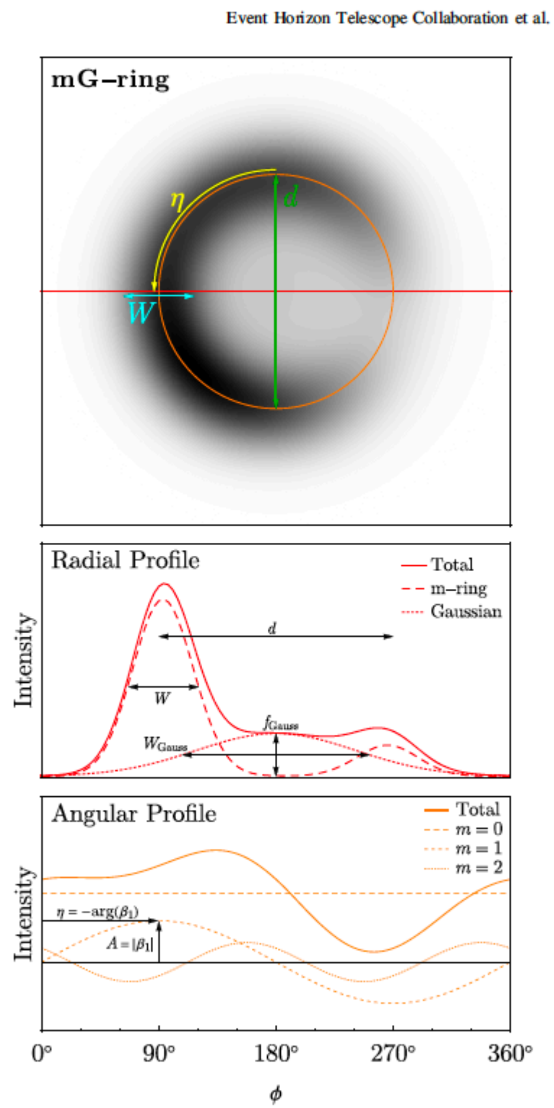
- Most convinced that it is a ring…



ring-like model

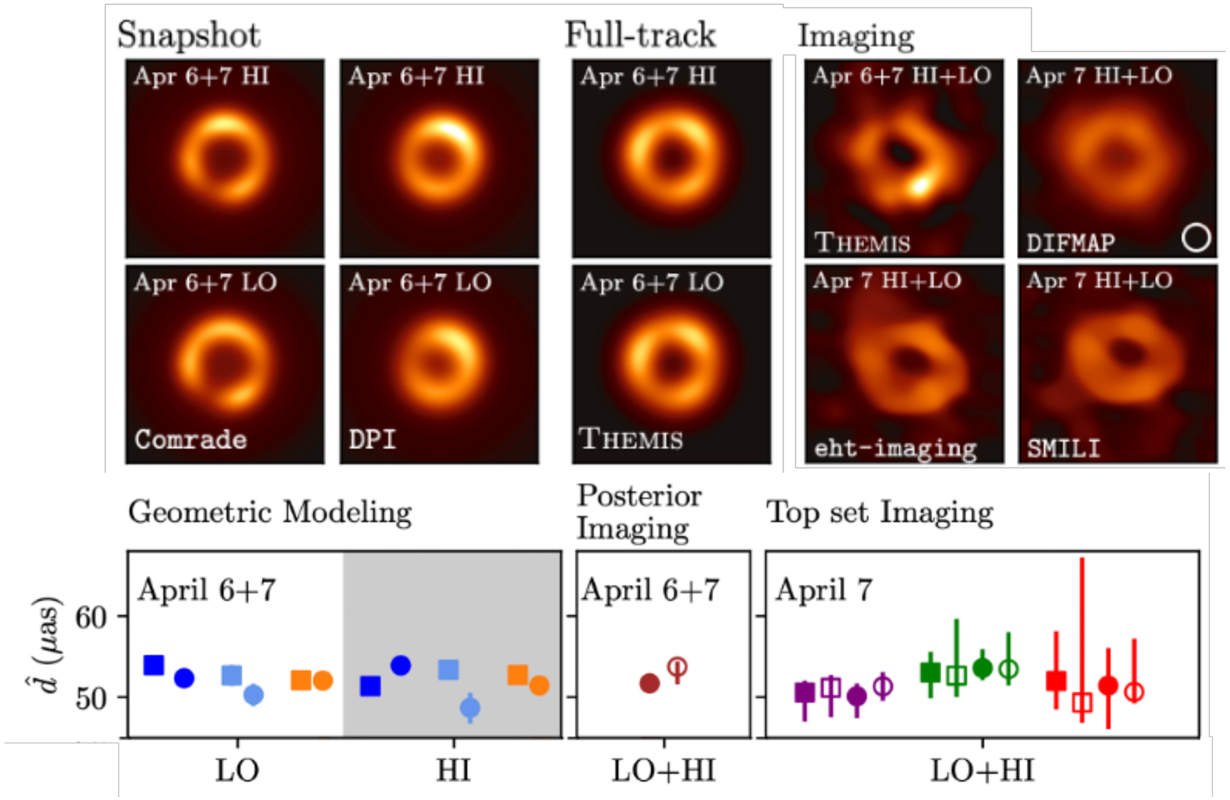
non-ring-like model

Bayesian evidence from closure fitting



Ring properties

- Ring properties from
  - fitting to snapshots
  - fitting to full track
  - fitting to images
- Properties are:
- ring diameter of 51.8 ± 2.3 μas
- thickness FWHM ~30-50% of diameter
- Not so well constrained:
  - asymmetry, magnitude or orientation
  - central depression
-



Compare to previous results

- From GRAVITY (and Keck team)

$$\theta_g = \frac{GM}{c^2 D}$$

- Need to calibrate

$$d = \alpha\,\theta_g$$

Table 5
α Calibration Parameters

Analysis Class	Software	Day	α	$\sigma_\alpha^{(\mathrm{stat})}$	$\sigma_\alpha^{(\mathrm{tot})}$
Snapshot	Comrade	April 6+7	12.0	(+0.2, −0.2)	(+1.6, −1.4)
	DPI	April 6+7	11.0	(+0.8, −0.8)	(+2.2, −4.3)
Full-track	THEMIS	April 6+7	11.7	(+0.1, −0.1)	(+1.3, −1.3)
Imaging	DIFMAP + REx	April 7	10.5	(+0.9, −1.4)	(+2.0, −2.3)
	DIFMAP + VIDA	April 7	10.6	(+1.0, −1.3)	(+1.7, −3.1)
	eht-imaging + REx	April 7	11.0	(+1.4, −1.3)	(+2.1, −2.5)
	eht-imaging + VIDA	April 7	11.0	(+1.2, −1.3)	(+1.7, −3.2)
	SMILI + REx	April 7	10.3	(+2.4, −2.1)	(+2.8, −4.4)
	SMILI + VIDA	April 7	10.4	(+1.4, −1.4)	(+1.8, −3.7)
	THEMIS + REx	April 6+7	10.3	(+0.5, −0.4)	(+1.5, −2.7)
	THEMIS + VIDA	April 6+7	10.6	(+0.4, −0.4)	(+1.2, −3.9)

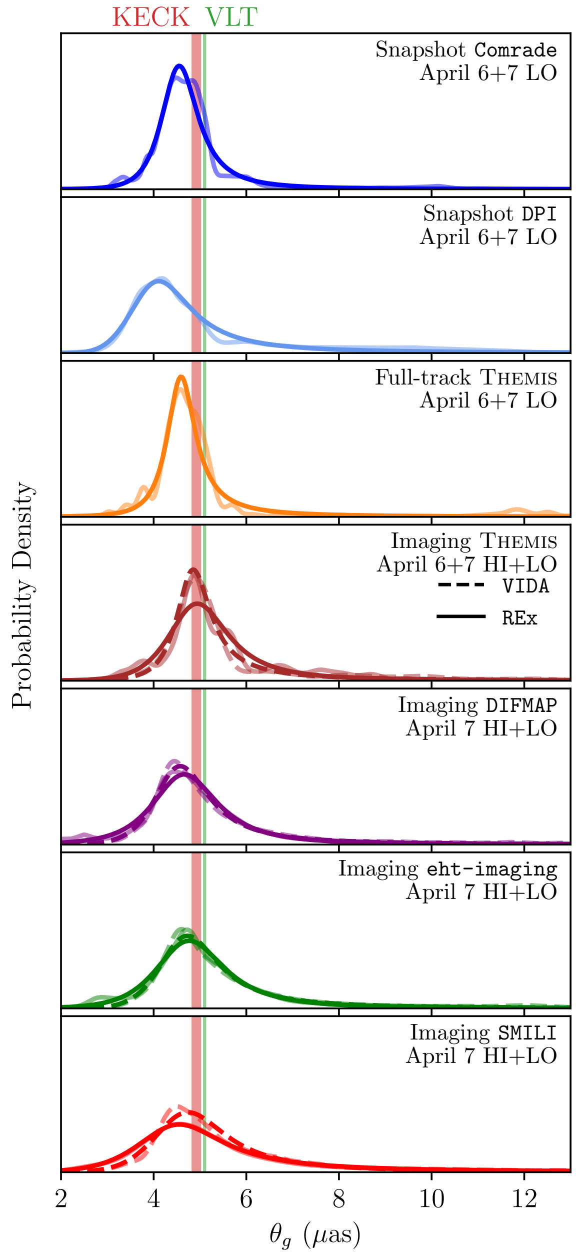
Note. Median values and 68% credible intervals for the calibrated α values, averaged over frequency bands and calibration pipelines.

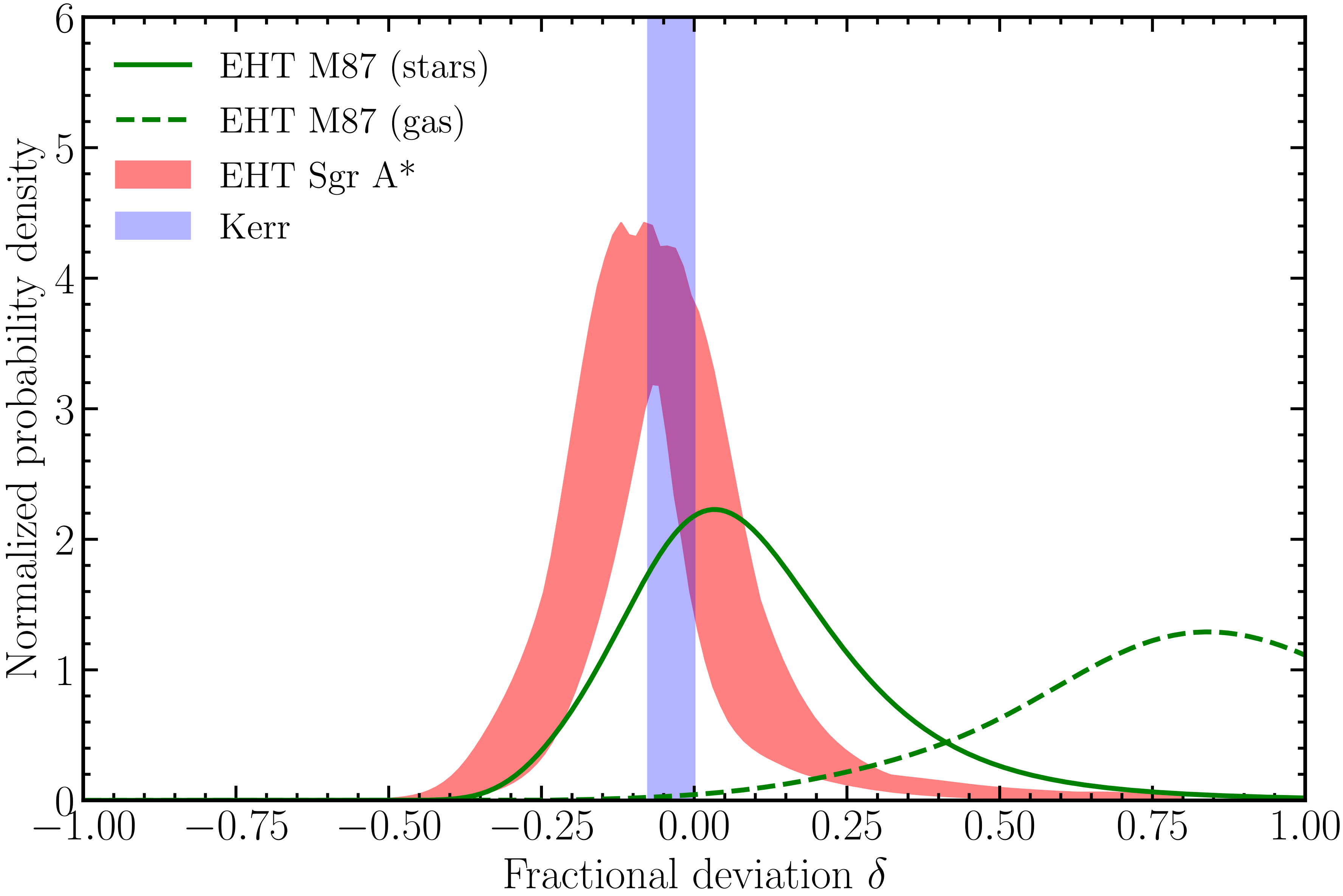
Checking against predictions

- 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

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

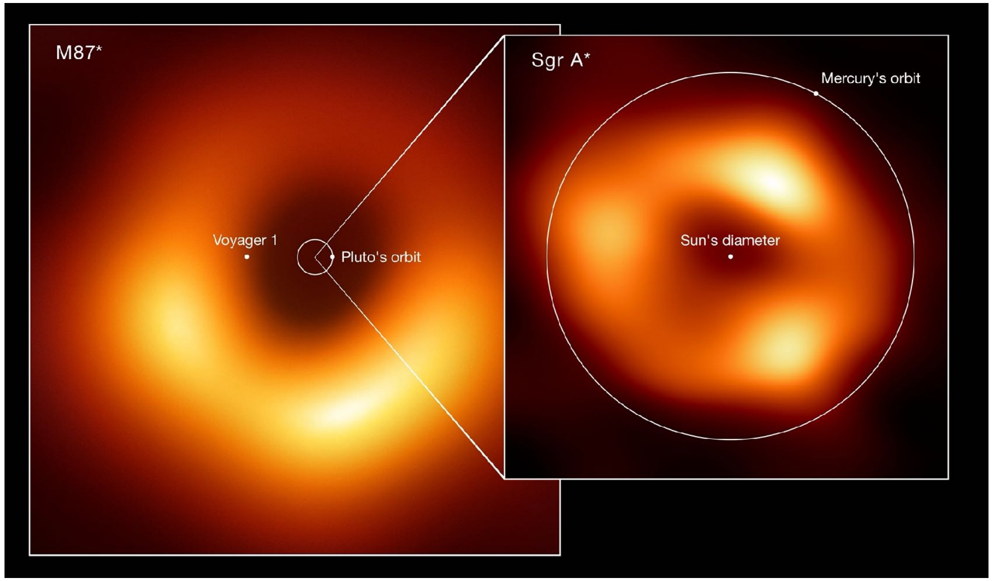


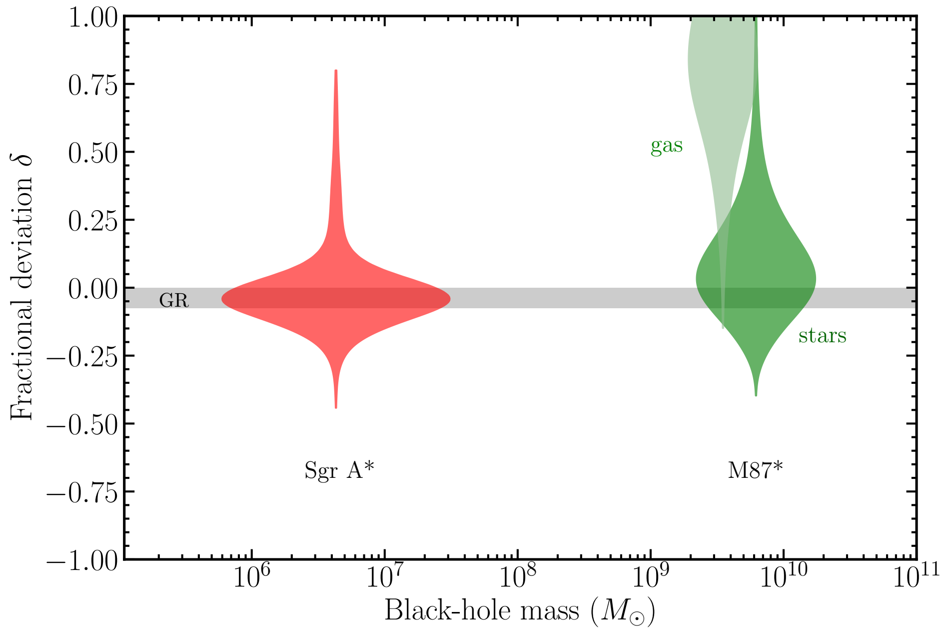


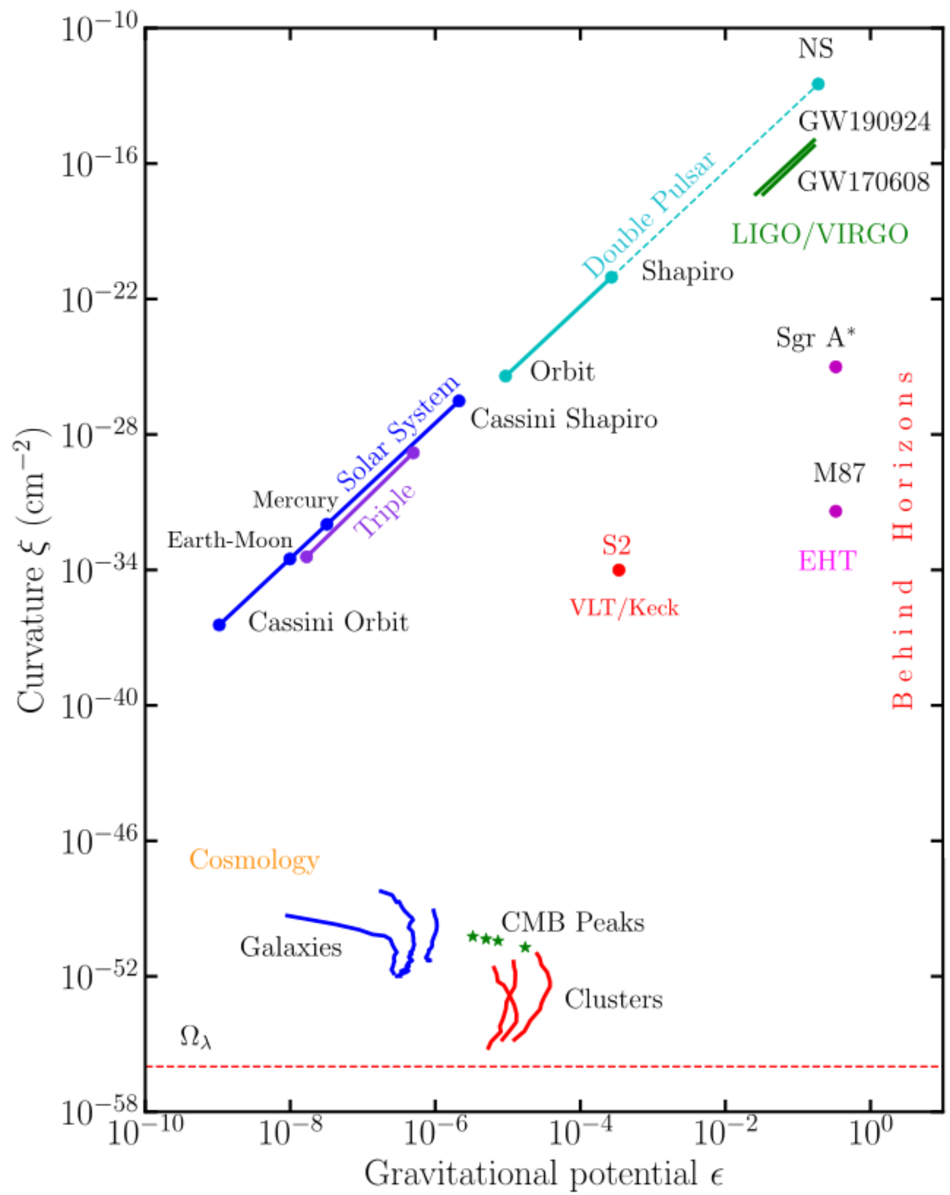
EHT M87 (stars)
EHT M87 (gas)
EHT Sgr A*
Kerr
Normalized probability density
Fractional deviation δ
0
1
2
3
4
5
6
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00

Also did tests against non-Kerr metrics

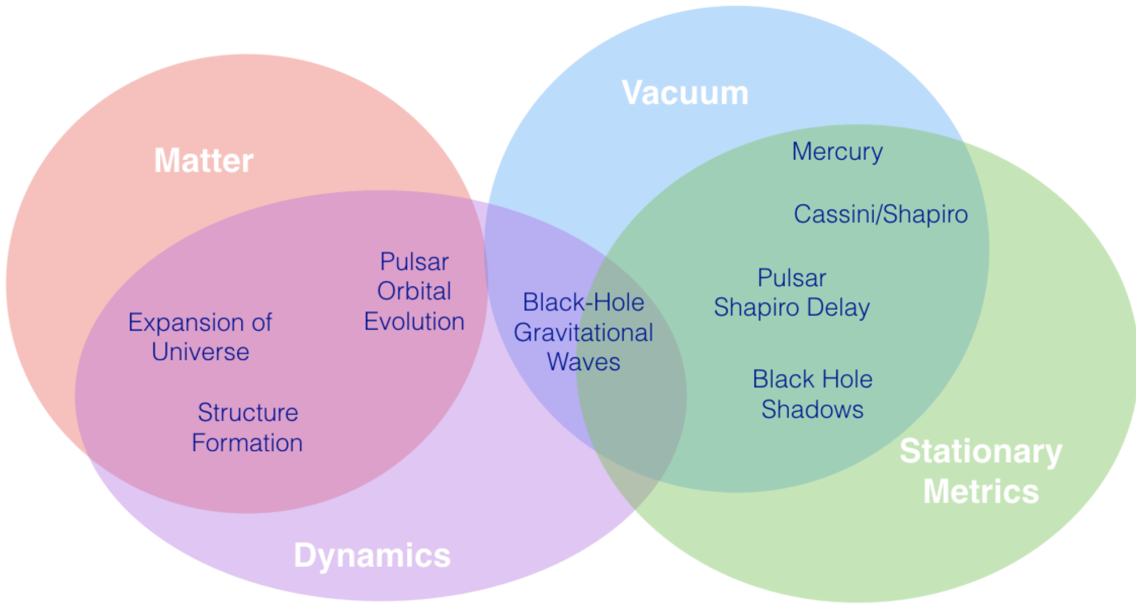
- Trying to constrain alternatives for Black Holes
- Consistent with GR over 3 orders of magnitude BH mass







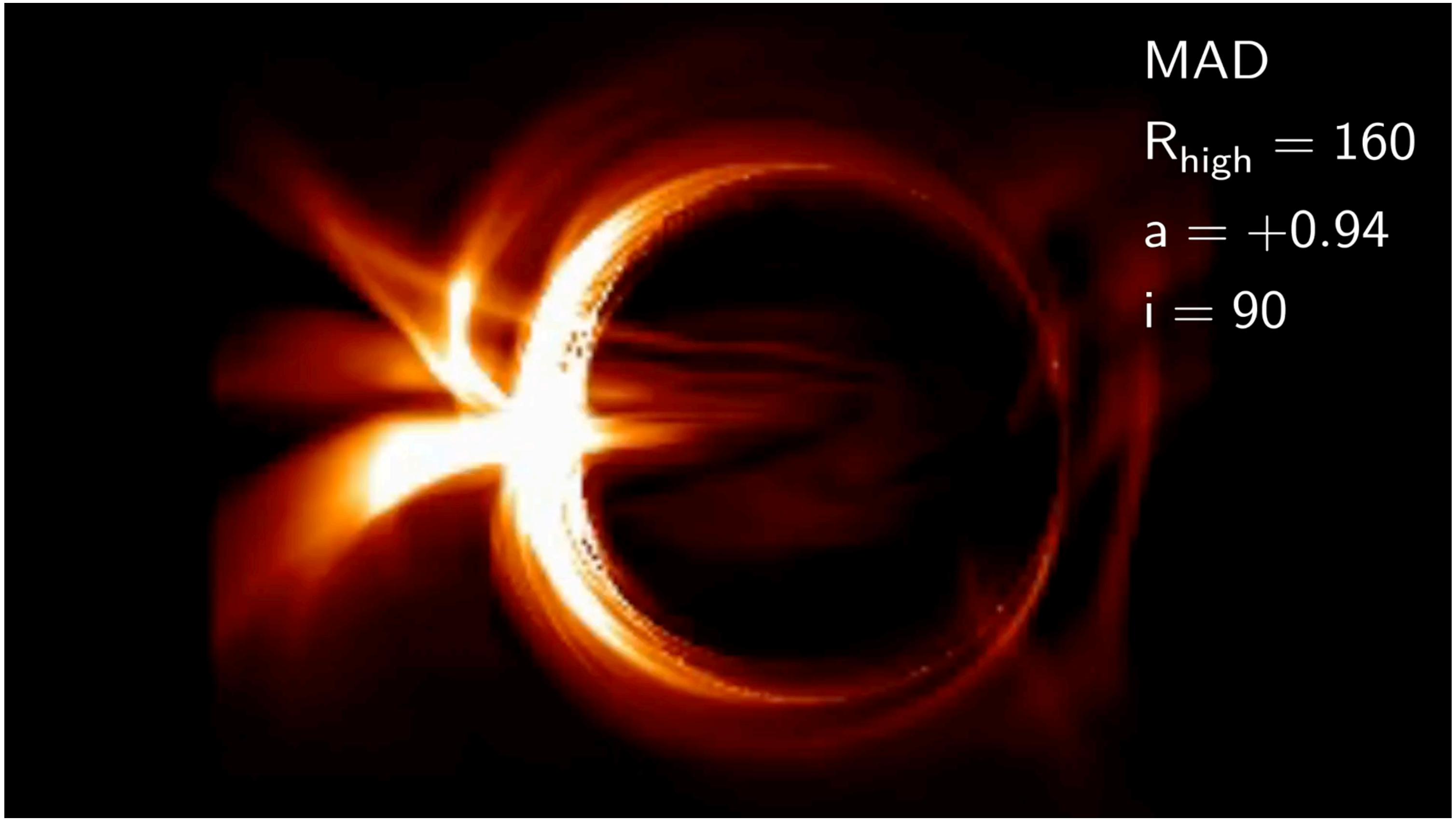
10^{-10}
10^{-16}
10^{-22}
10^{-28}
10^{-34}
10^{-40}
10^{-46}
10^{-52}
10^{-58}
Curvature ξ (cm^{-2})
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
Gravitational potential ϵ
NS
GW190924
GW170608
LIGO/VIRGO
Double Pulsar
Shapiro
Orbit
Sgr A*
Solar System
Cassini Shapiro
M87
Mercury
Triple
Earth-Moon
S2
EHT
VLT/Keck
Cassini Orbit
Behind Horizons
Cosmology
CMB Peaks
Galaxies
Clusters
Ω_λ

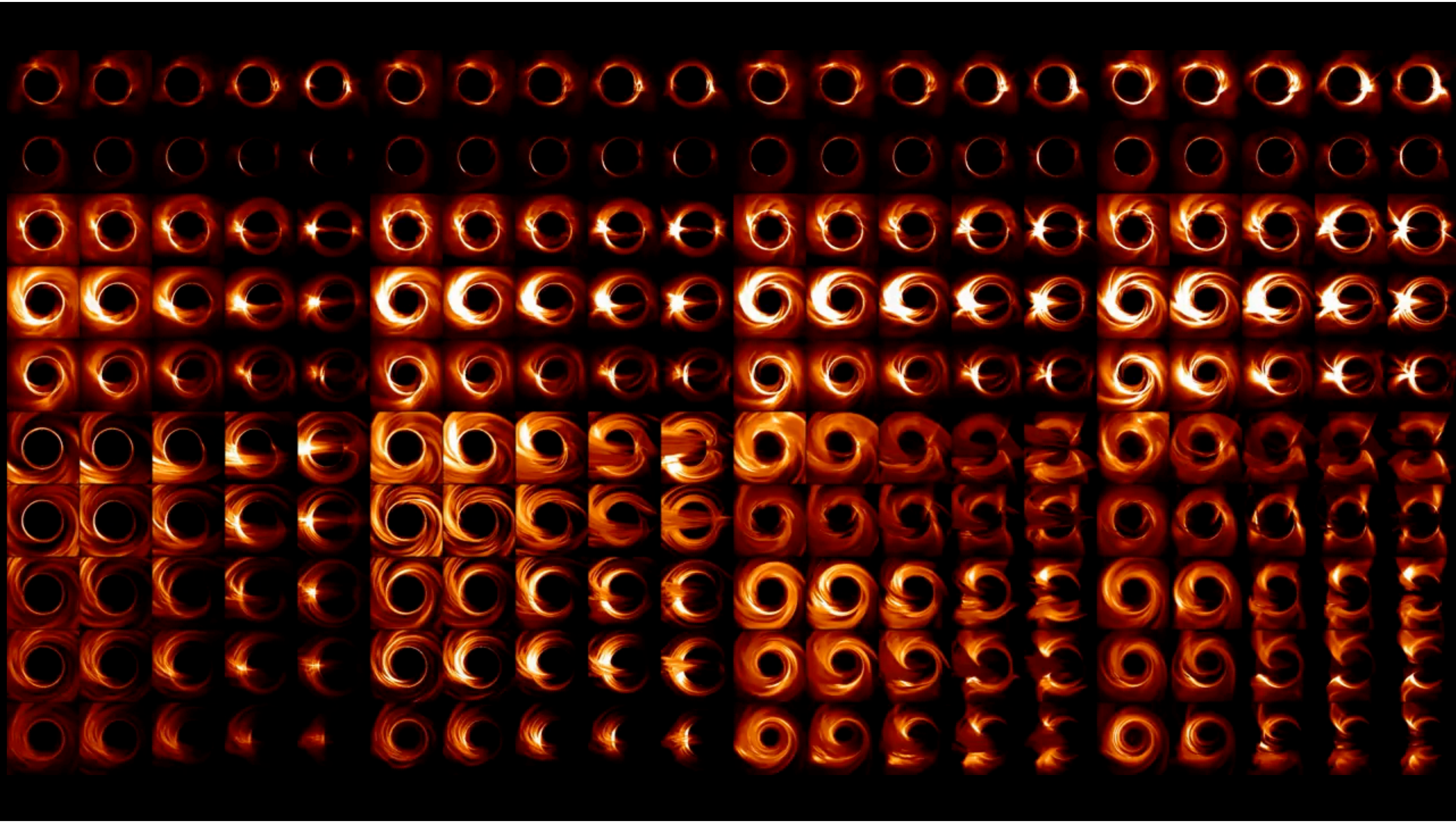


Vacuum
Matter
Mercury
Cassini/Shapiro
Pulsar Orbital Evolution
Expansion of Universe
Black-Hole Gravitational Waves
Pulsar Shapiro Delay
Structure Formation
Black Hole Shadows
Stationary Metrics
Dynamics

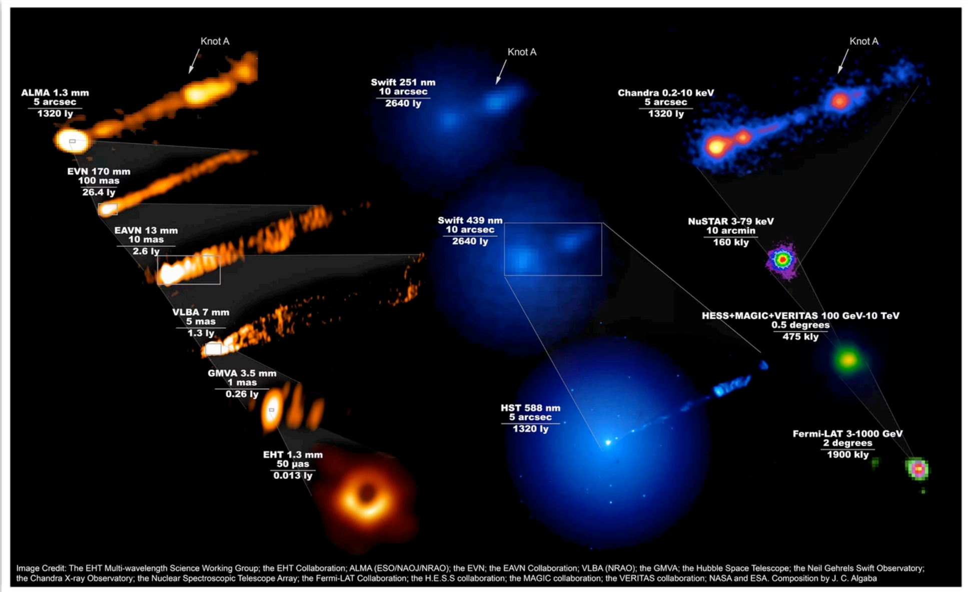
Enormous library of models

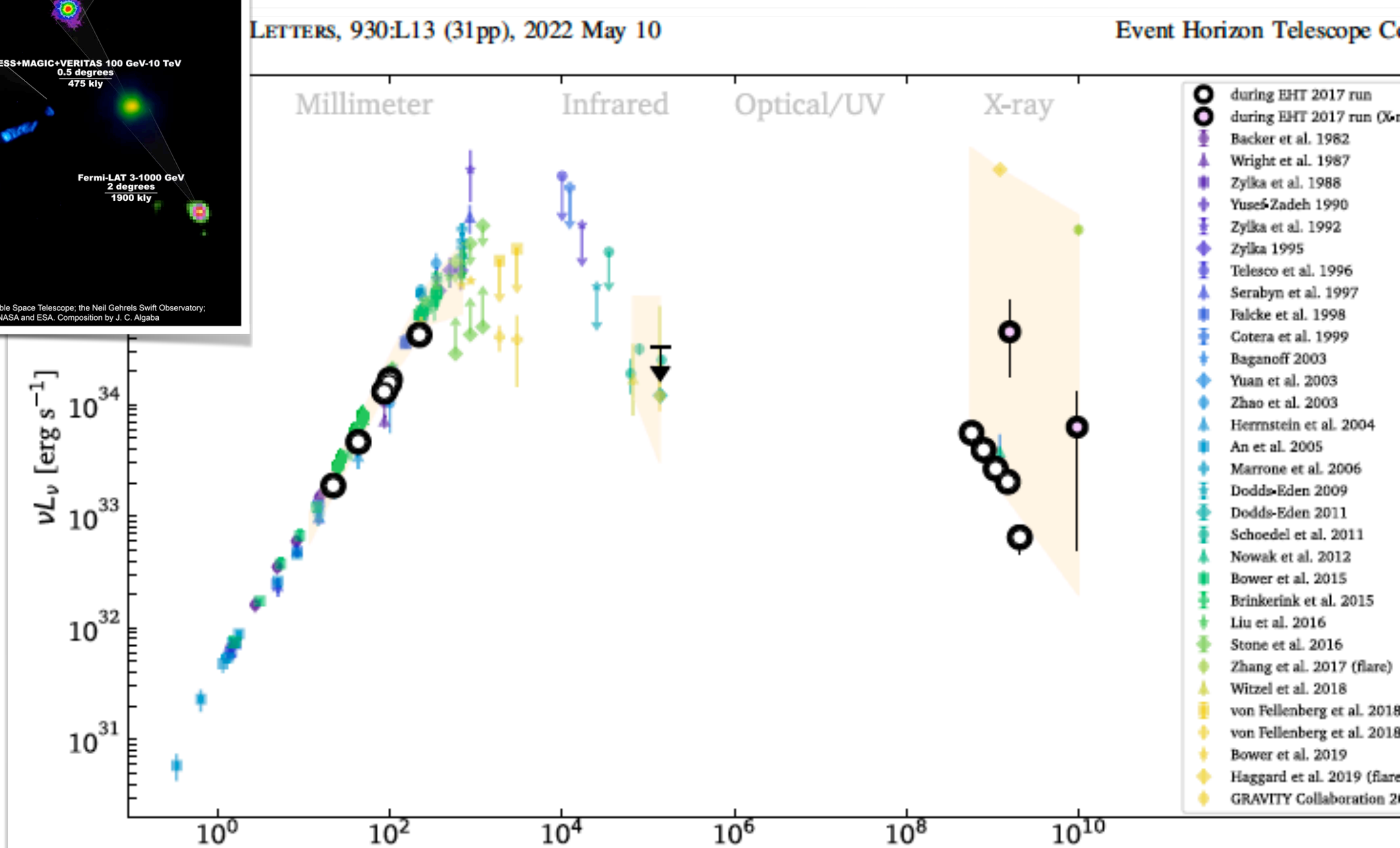
- Aprrox a PetaByte of GRMHD simulations
  - images
  - Spectra Energy Distributions (SED)
- Fiducial Models from KHARMA, BHAC, and H-AMR:
  - MAD vs SANE
  - a_{spin}=±0.94, ±0.5, 0
  - inclination =10, 30, …, 170
  - R_{high}=1, 10, 40, 160
- Exploratory Models:
  - Critical β, nonthermal, variable κ, tilted, stellar wind fed





Constraints from other wavelengths





Scoring different codes

- Data seems to have less variability than models
- Otherwise, MAD models with high spin and low inclination preferred

The Astrophysical Journal Letters, 930:L16 (49pp), 2022 May 10

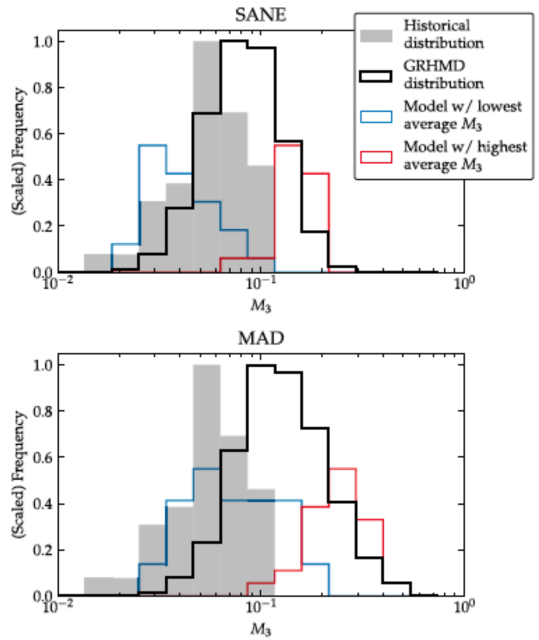


Figure 12. Distributions of 3 hr modulate index M_3 for BHAC, KHARMA, and H-AMR models (black), compared to distributions from historical observations (gray). The distributions for models with the lowest (blue) and highest (red)

rophysical Journal Letters, 930:L16 (49pp), 2022 May 10 Event Horizon Telescope Collaboration et al.

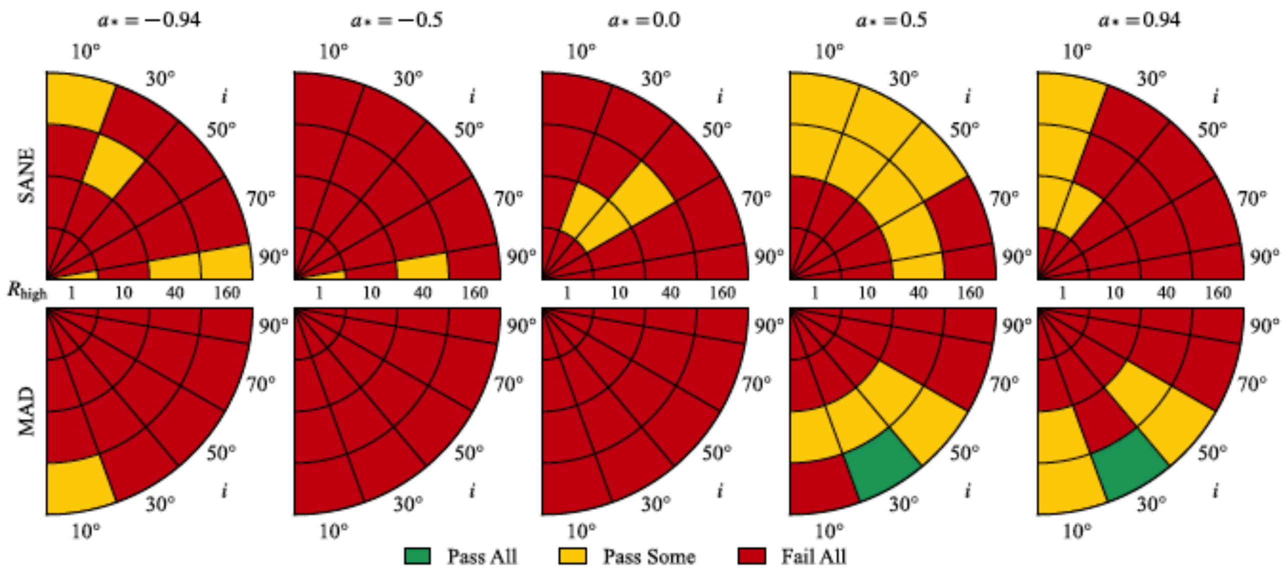
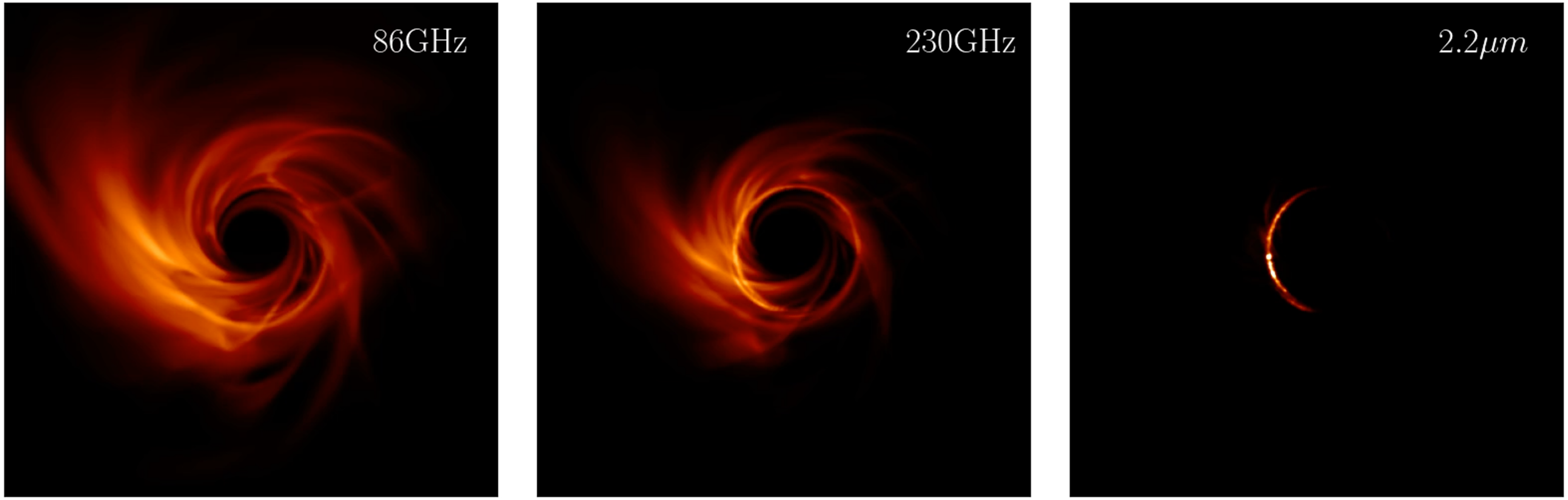


Figure 15. Combined constraints without structural or flux variability. Green indicates that the KHARMA, BHAC, and (for $i = 10°, 50°, 90°$) H-AMR models pass, yellow that one or two of the fiducial models fail, and red that all models fail.

Results

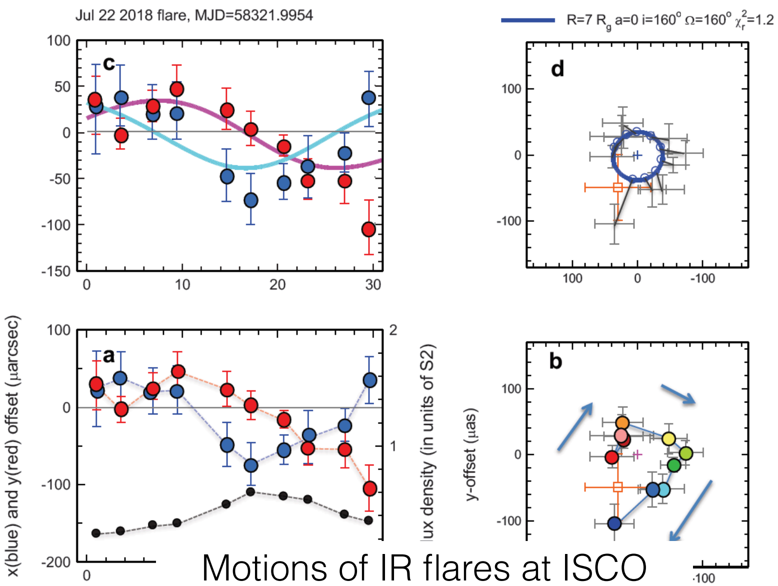
- EHT image is a key constraint; none of the models pass all constraints!
- Most models are too variable. A small reduction in variability would make many models pass



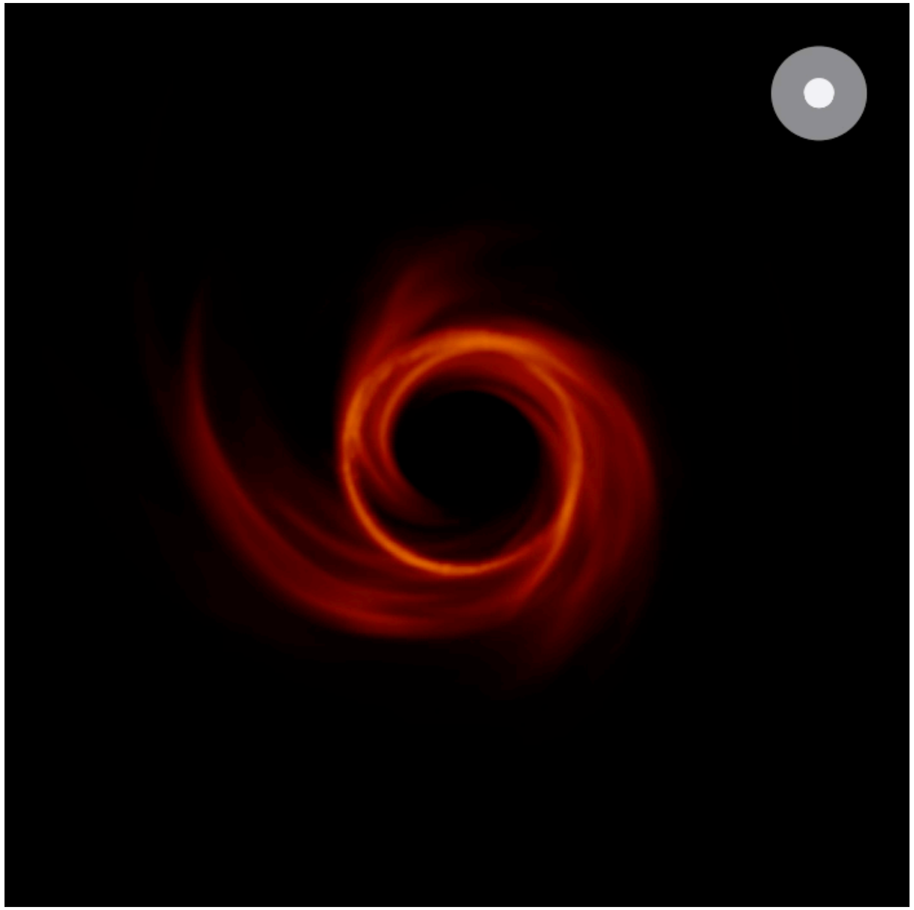
- Setting aside variability, a region of best-bet models that satisfy all remaining constraints: MAD, prograde (a* > 0), low inclination (i < 70deg) and cool electrons (Rhigh = 160)
- Strongly disfavored: single-temperature (Rhigh = 1); edge-on; retrograde

Low inclination is intriguing

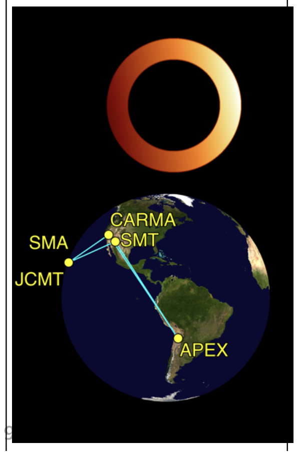
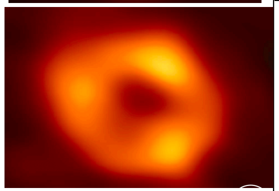
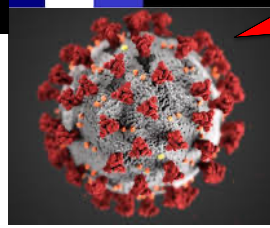
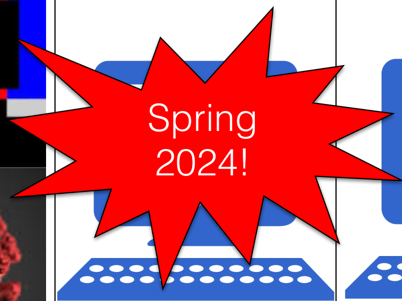
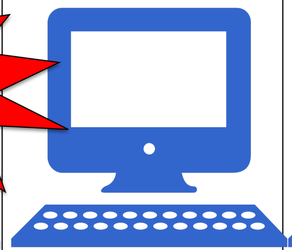
- Means rotation axis not aligned (at all) with Galaxy disk
  - If there is a jet at all, could be pointed towards us
- Consistent with shifting IR position during flare
  - As observed with GRAVITY

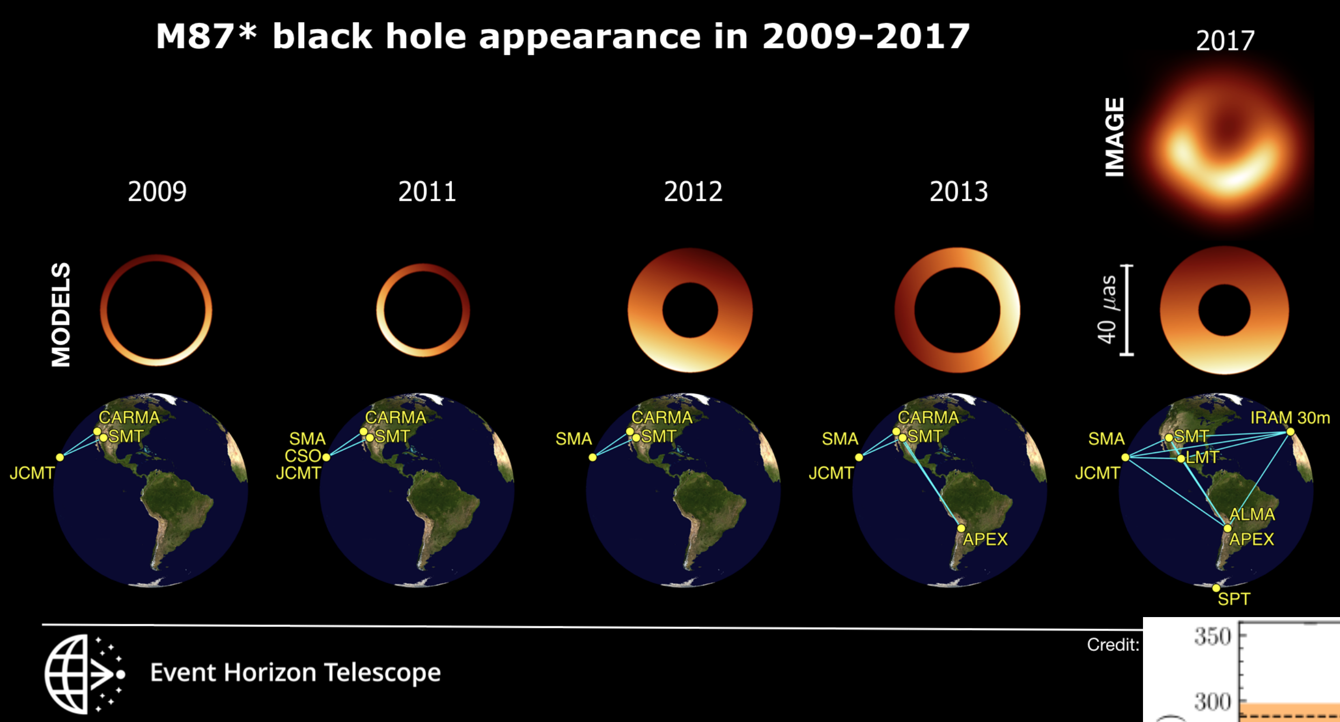


Motions of IR flares at ISCO
Gravity collaboration 2018

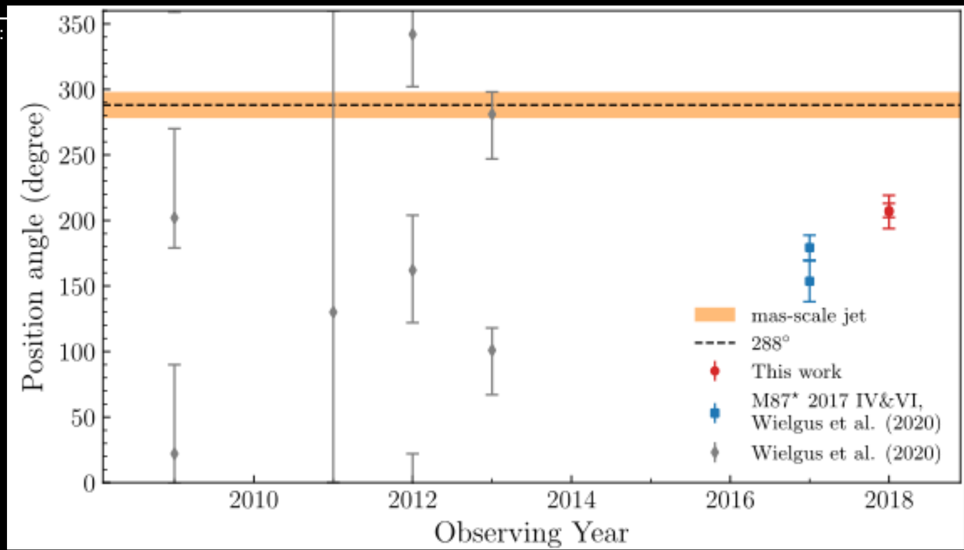


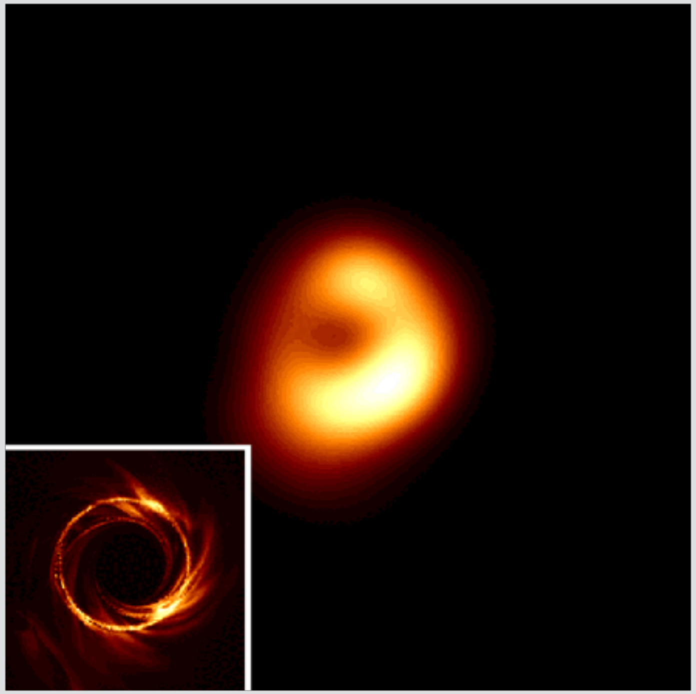
The EHT campaigns

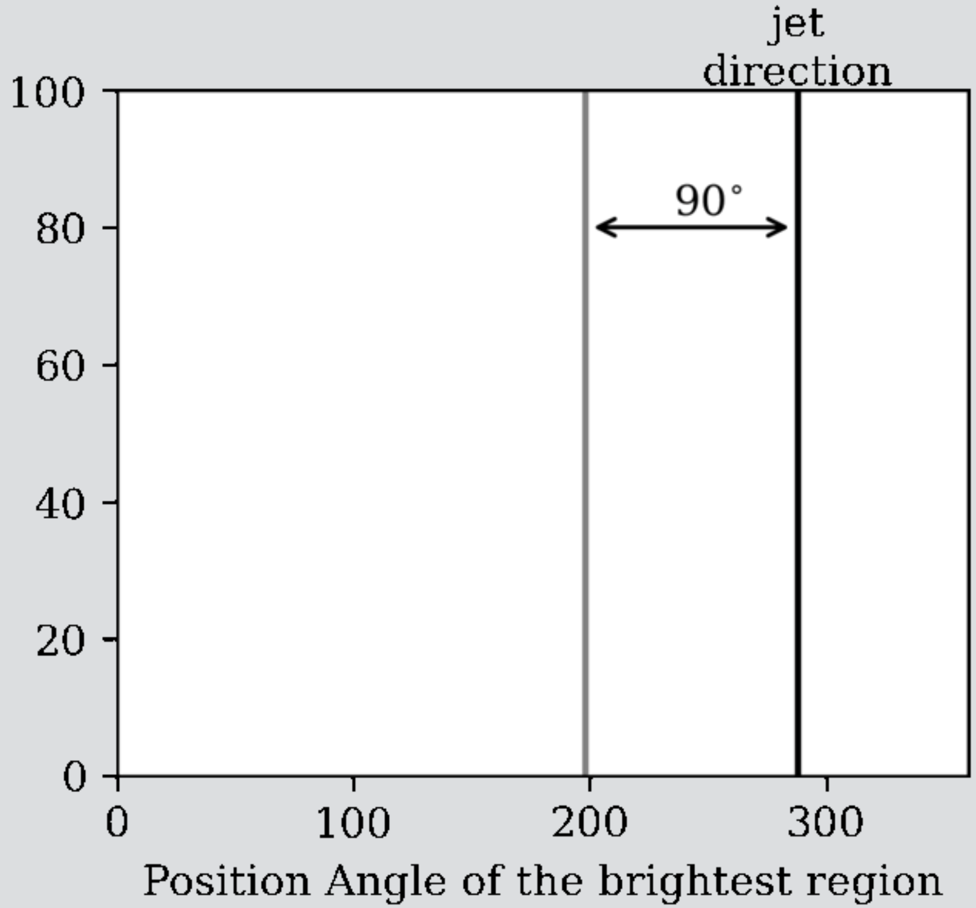
	<2017	2017	2018	2019/ 2020	2021	2022	2023
Stations	SMT, CARMA, SMA, JCMT APEX	SPT, ALMA, APEX, SMA, JCMT, LMT, SMT, PV	SPT, ALMA, APEX, SMA, JCMT, LMT, SMT, PV, GLT		SPT, ALMA, APEX, SMA, JCMT, SMT, PV, GLT, KP, NOEMA	SPT, ALMA, APEX, SMA, JCMT, LMT, SMT, PV, GLT, KP, NOEMA	SPT, ALMA, APEX, SMA, JCMT, LMT, SMT, GLT, KP, NOEMA
Bandwidth		32 Gbps	64 Gbps		64 Gbps	64 Gbps	64 Gbps
		 		 			345 GHz 


M87* black hole appearance in 2009-2017
2009
2011
2012
2013
2017
IMAGE
MODELS
40 μas
CARMA
SMT
JCMT
SMA
CSO
APEX
IRAM 30m
LMT
ALMA
SPT
Event Horizon Telescope
Credit:


2018 April 21


Position angle (degree)
Observing Year
0
50
100
150
200
250
300
350
2010
2012
2014
2016
2018
mas-scale jet
288°
This work
M87* 2017 IV&VI, Wielgus et al. (2020)
Wielgus et al. (2020)





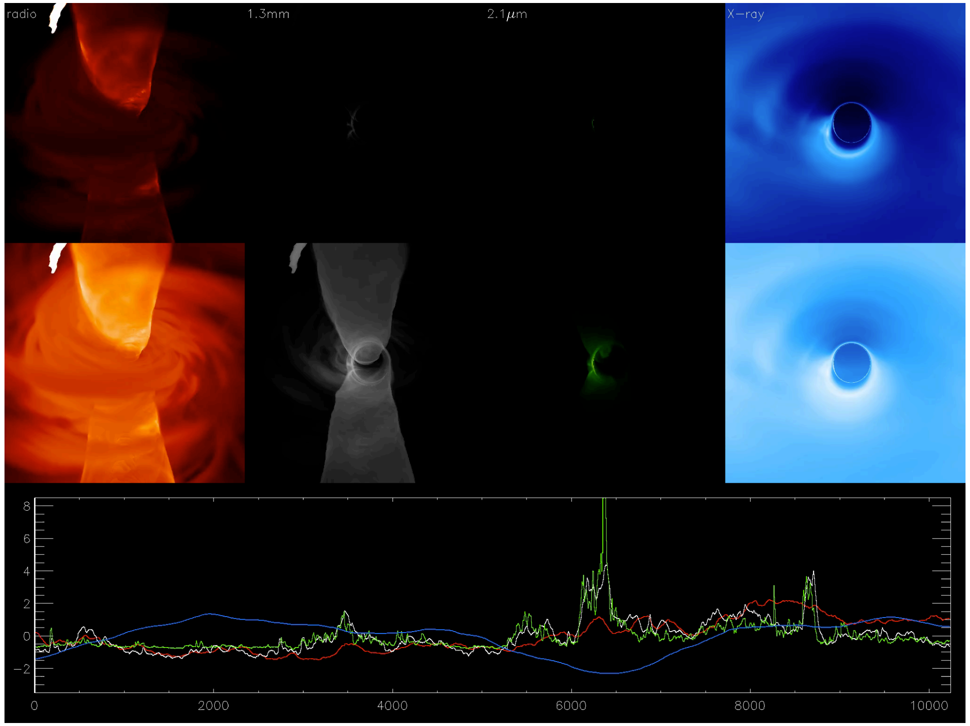
visualization credit: Hung-Yi Pu
simulation credit: Abhishek Joshi & Ben Prather

What we would like to know…

- What are the variability characteristics
  - And how does it relate to jet episodes?
- What is the origin of flares?
- How important are magnetic fields?
- What are the space time properties?
  - Can we measure spin

- Can we address this with current array
  - Improve are observing strategy
  - And calibration and analyse techniques

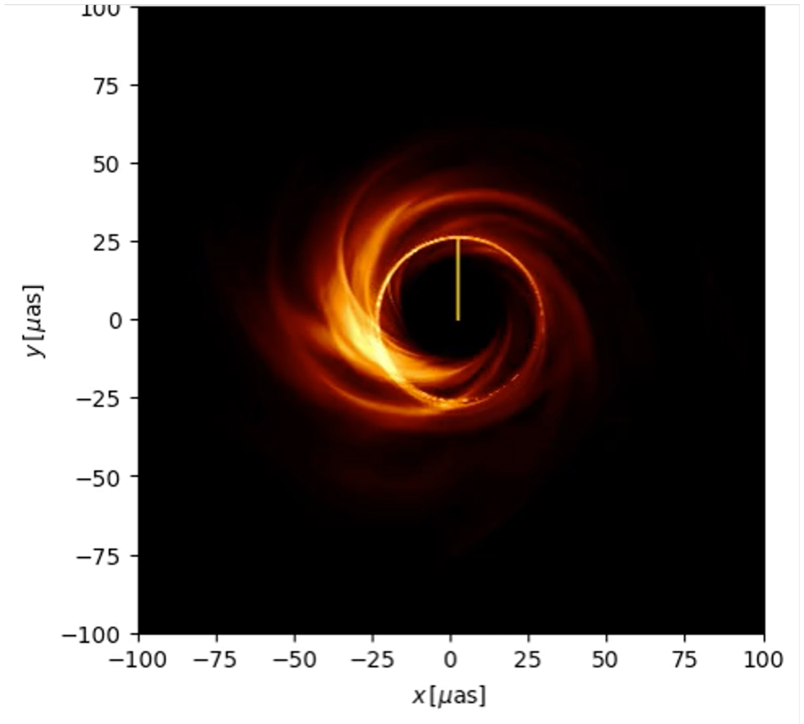
- Before we add many more telescopes
- Or have a space mission



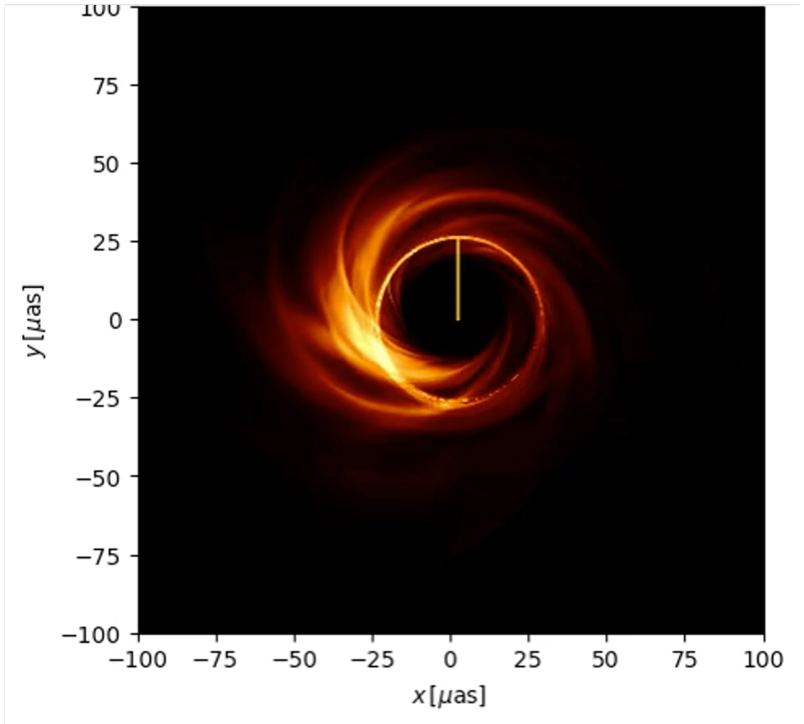
Variability

- Sub-Keplerian variability could be dus to in-spiral of matter

Ω_K



Ω_p

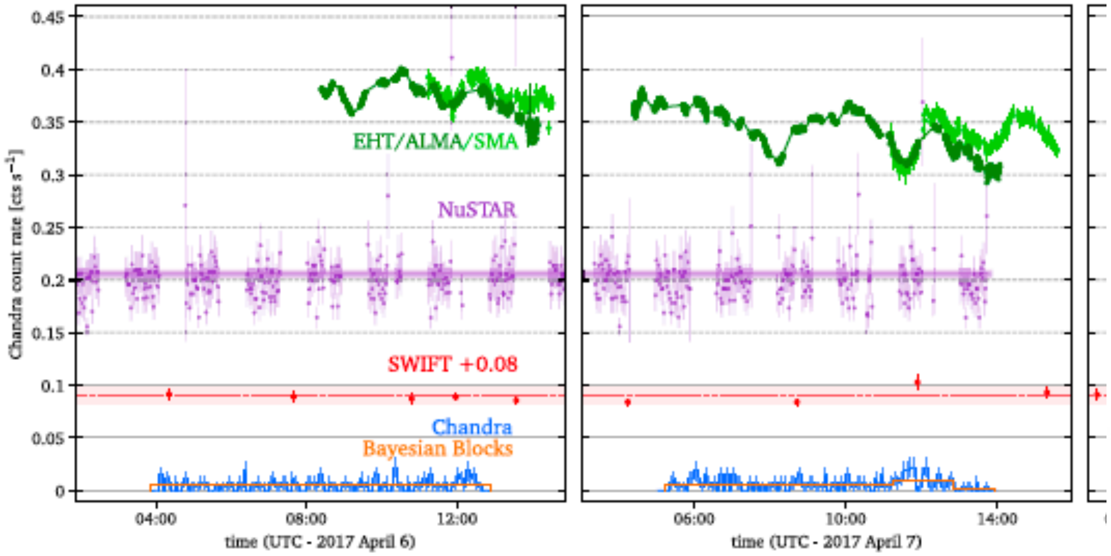


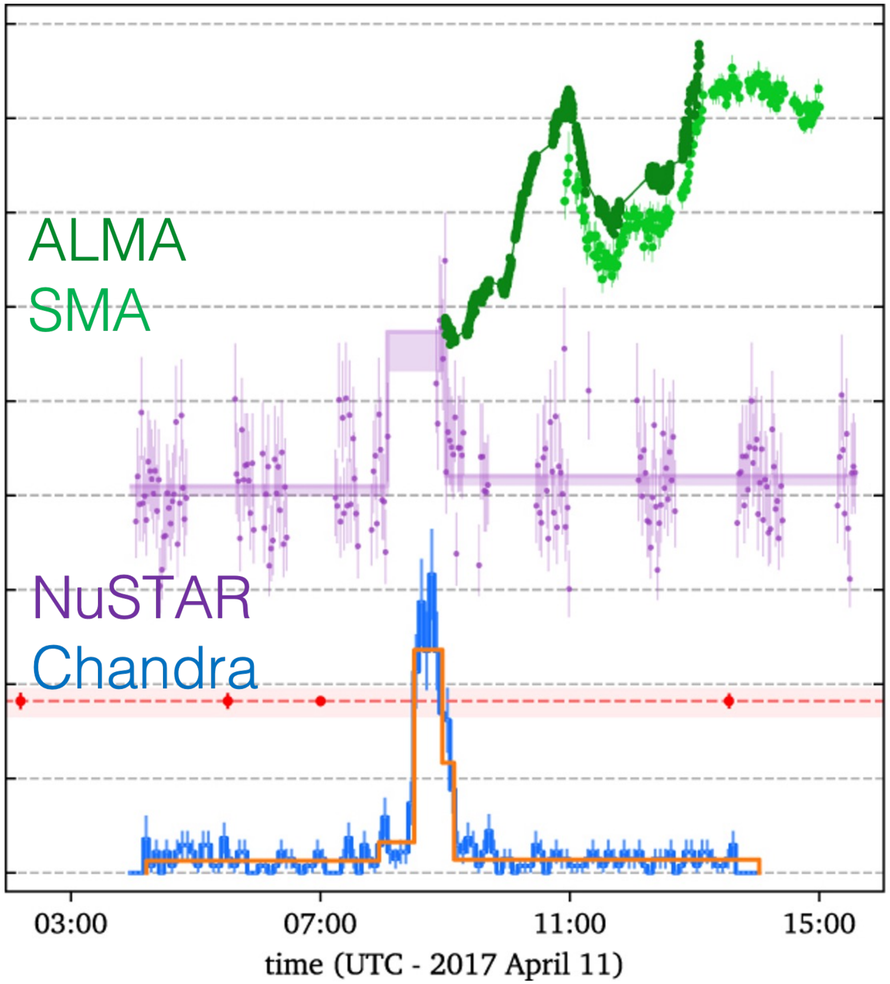
Conroy et al 2023

- Keplerian Velocity Ω_K > Plasma Velocity > Pattern Speed Ω_p
  - Likely ingoing spiral shocks excited by turbulence from r ≈ 15 GM/c^2

Flares

- Related to magnetic phenomena?
  - Link IR and radio motions?

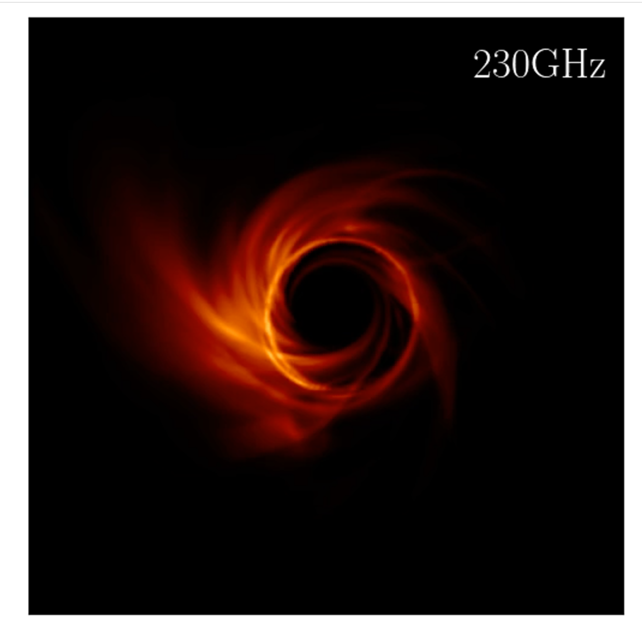




Measuring BH spin

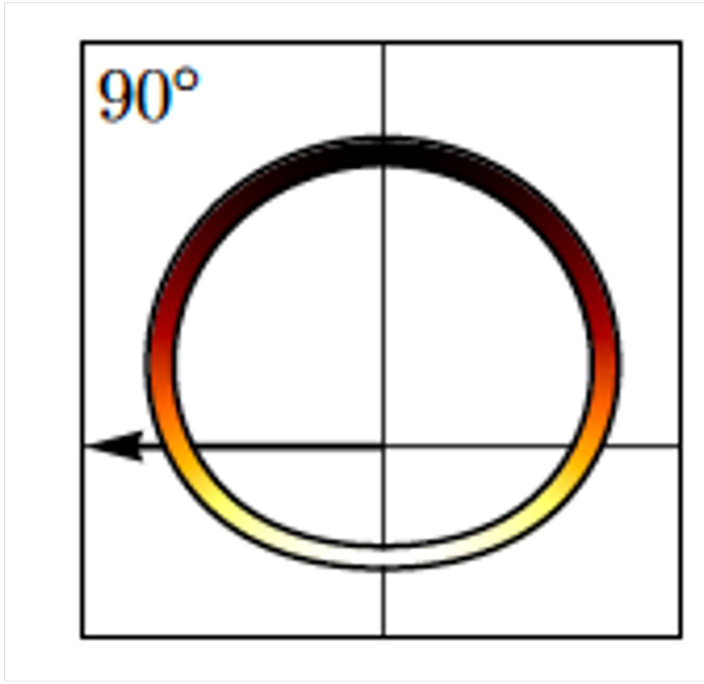
- Various approaches

GRMHD Modeling



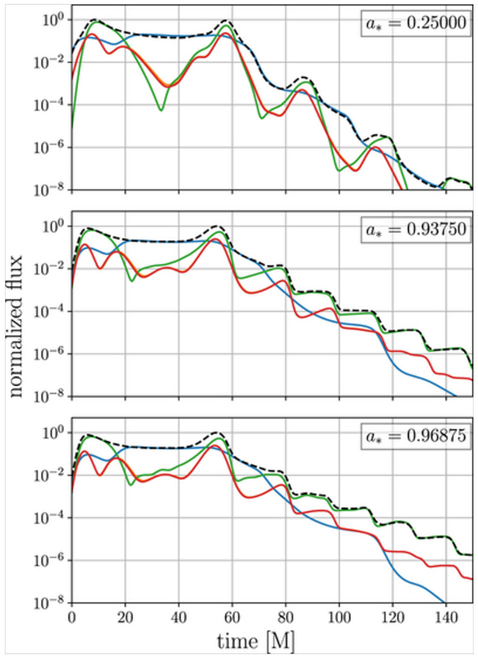
EHTC 2022

Photon Ring Morphology



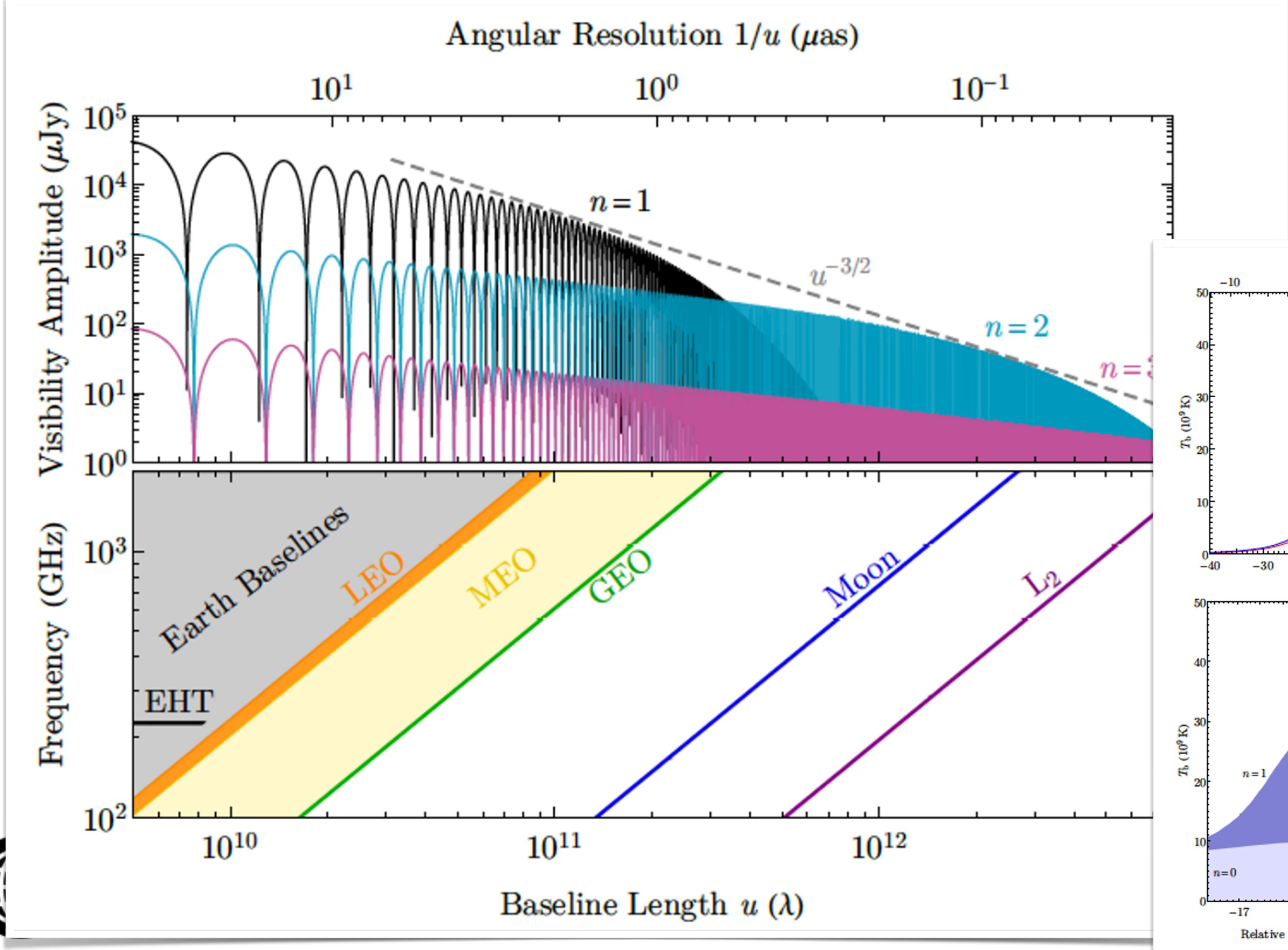
Johnson et al 2020

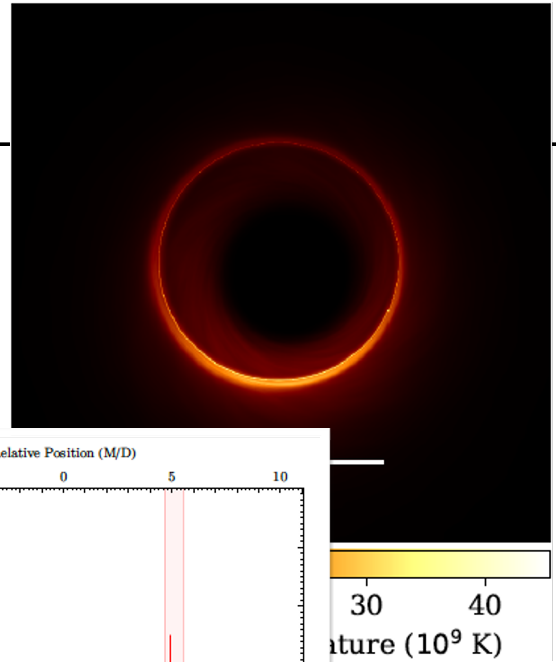
Dynamics

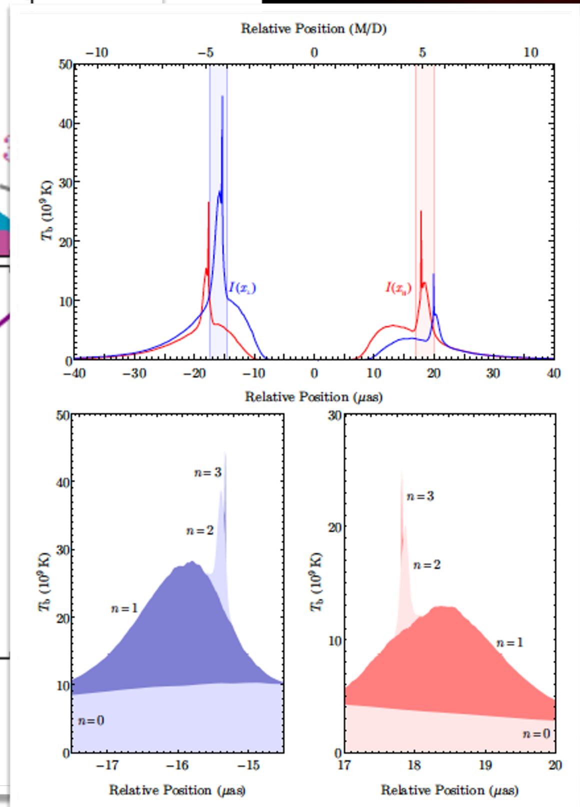


Wong 2021

Multiple order rings…



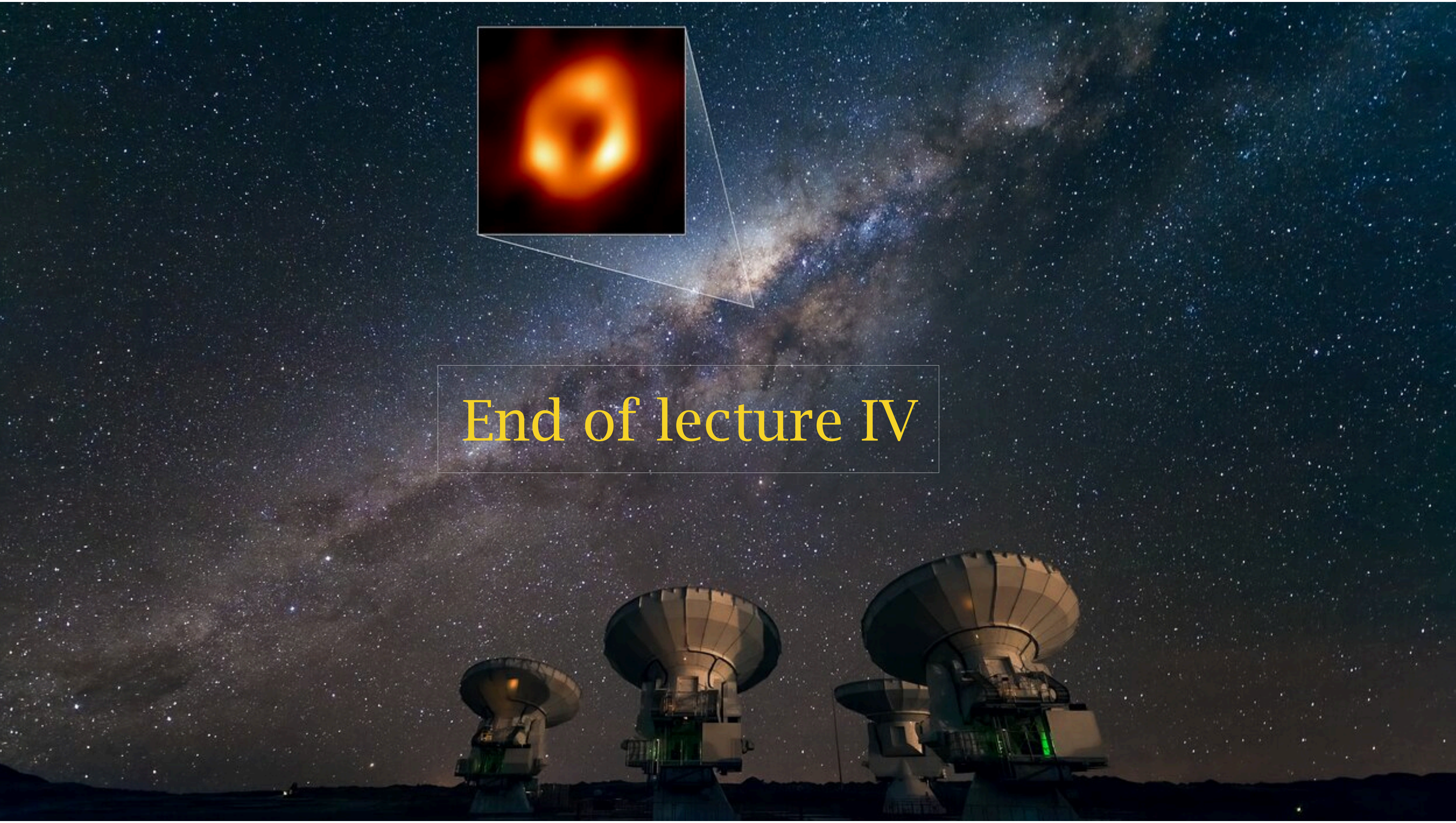




Concluding

- Probed Gravity at extreme conditions
- Nothing indicates that Einstein was not wrong…
  - Confident we did everything right
  - Important to repeat and refine experiments
- Learning a lot about how AGN operate
  - Important force in shaping the Universe
- Many improvements still coming

It is a team effort…


End of lecture IV