Imaging black holes with the EHT:
how does it complement studies of strong gravity (2)

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Outline

- Intro -- Tests of GR, Supermassive black holes (SMBH), and VLBI/EHT
- Basics of radio interferometry and EHT data processing
- **Testing GR with the EHT image of M87***
- **Astrophysics of M87(*) and numerical simulations**
- **Ongoing studies with/relevant to the EHT**
- **(Time permits) long-term future perspectives**

Using the EHT M87* image to test GR

Reminder: final images and parameters of M87*

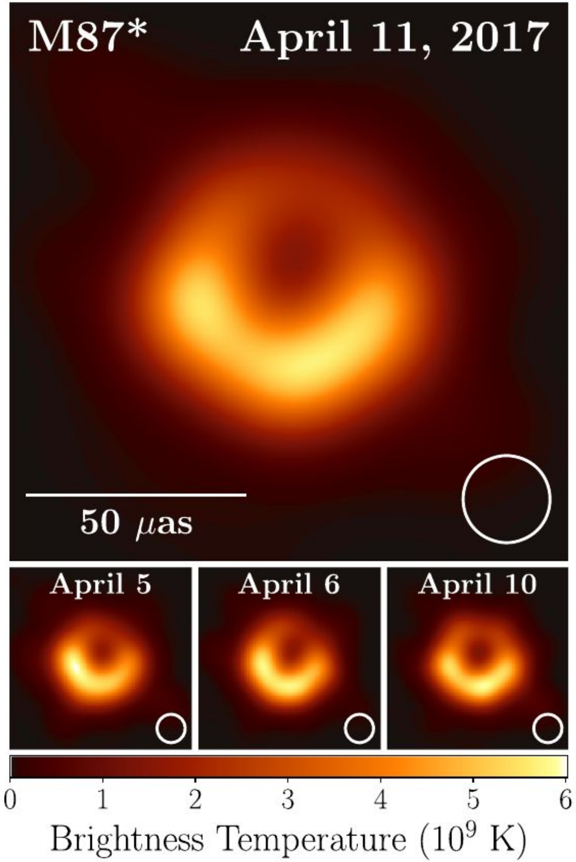

Table 1
Parameters of M87*

Parameter	Estimate
Ring diameter [a] d	$42 \pm 3\ \mu$as
Ring width [a]	$<20\ \mu$as
Crescent contrast [b]	$>10{:}1$
Axial ratio [a]	$<4{:}3$
Orientation PA	150°–200° east of north
$\theta_g = GM/Dc^2$ [c]	$3.8 \pm 0.4\ \mu$as
$\alpha = d/\theta_g$ [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]	$3.5^{+0.9}_{-0.3} \times 10^9\ M_\odot$

Notes.
[a] Derived from the image domain.
[b] Derived from crescent model fitting.
[c] The mass and systematic errors are averages of the three methods (geometric models, GRMHD models, and image domain ring extraction).
[d] The exact value depends on the method used to extract d, which is reflected in the range given.
[e] Rederived from likelihood distributions (Paper VI).

EHTC+2019a

Testing GR with the EHT image of M87*

In the order of most accurately measured parameters:

- **Ring diameter (7% error)**
- **Circularity (<30% axial ratio offsets)**
- **Ring-to-hole contrast (>10:1)**
- Ring width (only upper limit)

Note: distance to the BH and its mass known a-priori (from other astronomical observations)

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
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Testing the Kerr BH scenario -- size

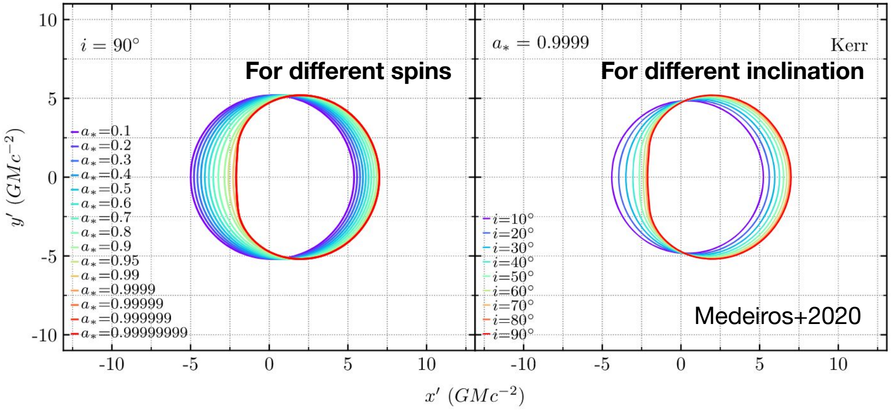
- **Predicted BH shadow size:**
  (insensitive to the spin)

$$\text{radius} = (5.0 \pm 0.2) GM/c^2$$

- Can define difference btw. the **shadow sizes from observation and Kerr prediction**:

$$\delta = \theta_{\rm obs}/\theta_{\rm Kerr} - 1$$

- Note: uncertainties in \delta come from:
  - SMBH mass
  - Ring diameter



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Testing the Kerr BH scenario -- size

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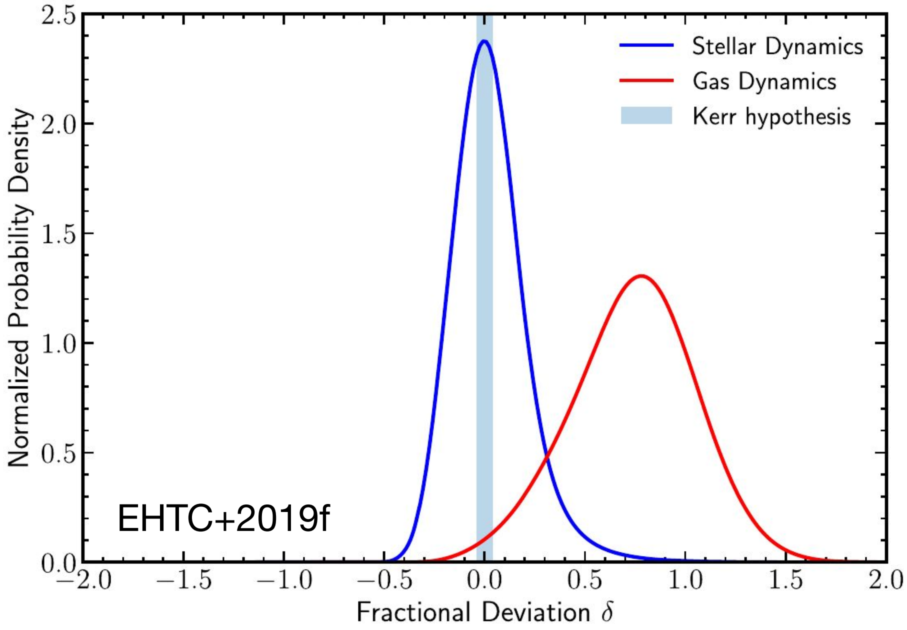


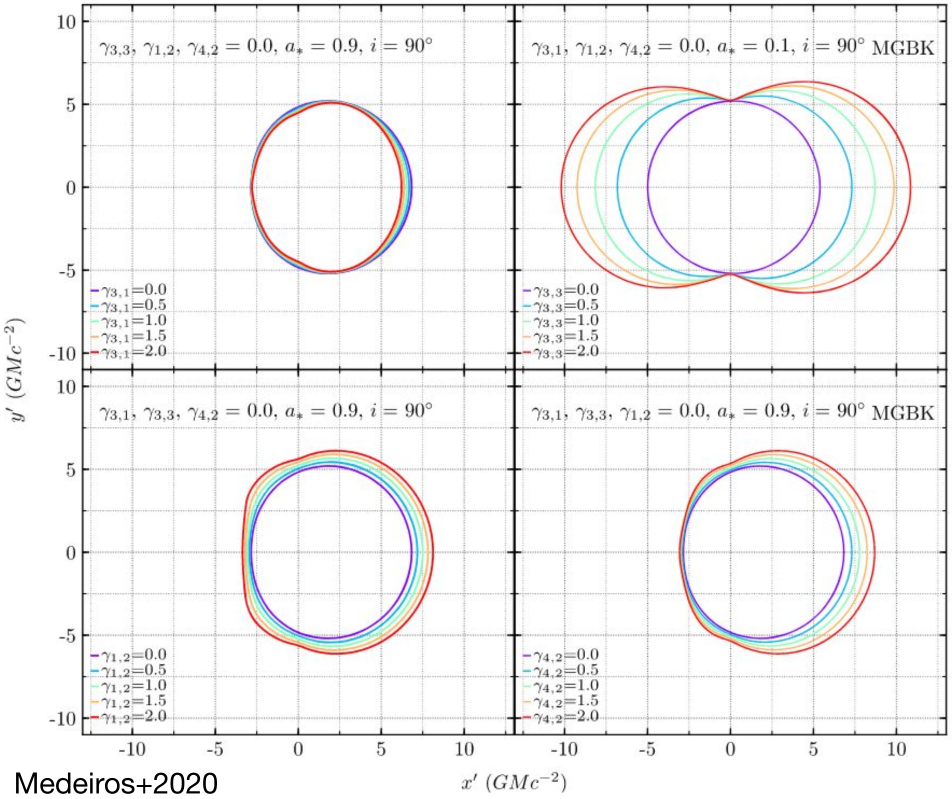
$$\delta = -(0.01 \pm 0.17)$$

Agree with GR prediction within 17%

(note: the large uncertainty comes from the BH mass)

Testing the Kerr BH scenario -- shape

BH shadow morphologies with perturbed Kerr metrics



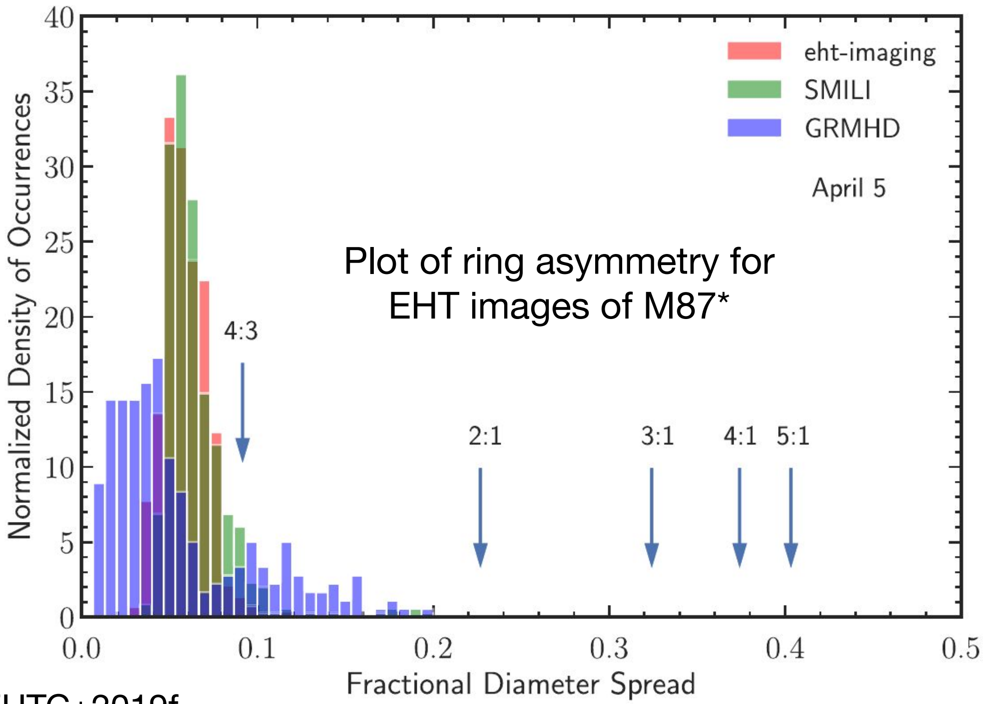
Medeiros+2020

- Black hole shadow can have weird shapes, if Kerr metric parameters are strongly perturbed.

  → **how circular the BH shadow is also tells about how good the Kerr metric case is**

- (Notice changing values of hyper-parameters *gamma*)

Testing the Kerr BH scenario -- shape



EHTC+2019f

- Black hole shadow can have weird shapes, if Kerr metric parameters are strongly perturbed.

  → **how circular the BH shadow is also tells about how good the Kerr metric case is**

- (Notice changing values of hyper-parameters *gamma*)

No significant departure from 1:1
→ <u>the Kerr case is still good</u>

Doing this more quantitatively: Post-Newtonian (PN) approach to GR

GR metric in general form: $$ds^2 = g_{tt}dt^2 + g_{rr}dr^2 + r^2 d\Omega \ .$$

Expanding to high orders of *r*: $$-g_{tt} = 1 - \frac{2}{r} + 2\left(\frac{\bar{\beta} - \bar{\gamma}}{r^2}\right) - 2\left(\frac{\zeta}{r^3}\right) + \mathcal{O}\left(r^{-4}\right)$$

Note: setting *G=c=M=1*

First-order (1PN) correction

Second-order (2PN) correction

BH shadow radius, with 2PN term: $$r_{\rm shadow} = \sqrt{27}(1 + \frac{\zeta}{9})\frac{GM_{\rm BH}}{c^2}$$

Note: not easy at all to "properly" tweak GR and devise a suitable test metric

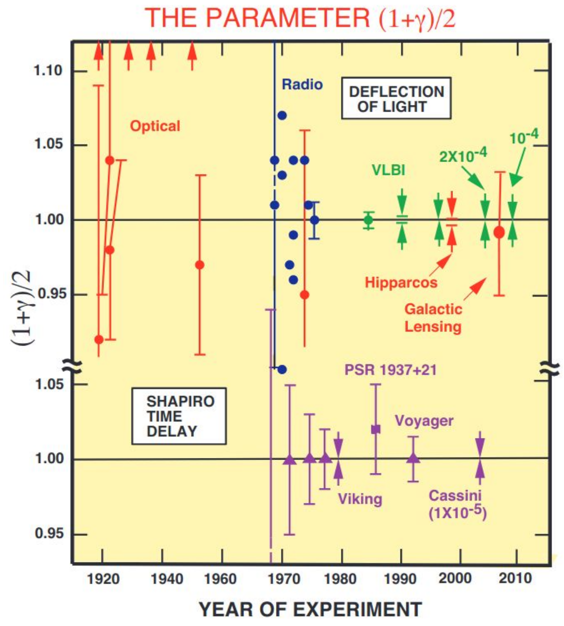
Psaltis+2020

Doing this more quantitatively: Post-Newtonian (PN) approach to GR

Table 3: Metric theories and their PPN parameter values ($\alpha_3 = \zeta_i = 0$ for all cases). The parameters γ', β', α'_1, and α'_2 denote complicated functions of the arbitrary constants and matching parameters.

Theory	Arbitrary functions or constants	Cosmic matching parameters	PPN parameters γ	β	ξ	α_1	α_2
General relativity	none	none	1	1	0	0	0
Scalar-tensor							
Brans–Dicke	ω_{BD}	ϕ_0	$\frac{1+\omega_{BD}}{2+\omega_{BD}}$	1	0	0	0
General, $f(R)$	$A(\varphi)$, $V(\varphi)$	φ_0	$\frac{1+\omega}{2+\omega}$	$1+\frac{\lambda}{4+2\omega}$	0	0	0
Vector-tensor							
Unconstrained	$\omega, c_1, c_2, c_3, c_4$	u	γ'	β'	0	α'_1	α'_2
Einstein-Æther	c_1, c_2, c_3, c_4	none	1	1	0	α'_1	α'_2
Tensor-Vector-Scalar	k, c_1, c_2, c_3, c_4	ϕ_0	1	1	0	α'_1	α'_2

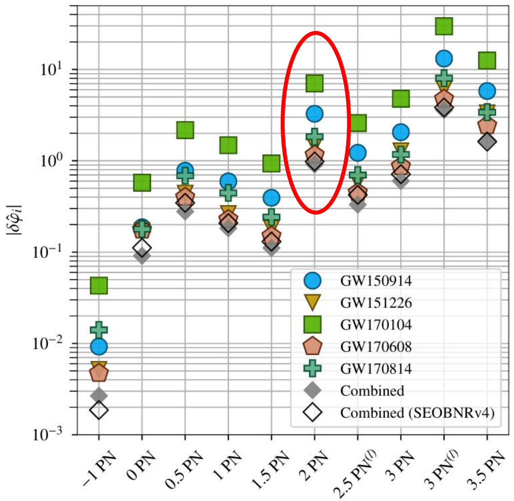
1PN 2PN



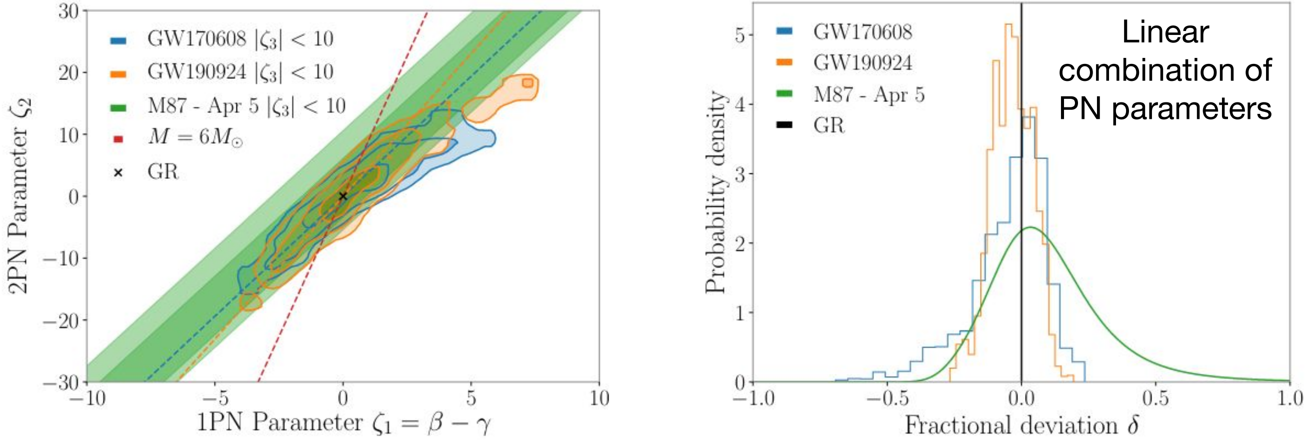
Constraints @ 1PN level

Will 2014

Testing General Relativity at 2PN level



Abbott+2019



Psaltis+2021

<u>GW and EHT BH shadow provide comparable level of tests for GR</u>

(cf. Kowalski+2008, among others, for the importance of independent constraints of GR parameters in cosmology)

Remarks on alternatives theories of gravity + exotic objects (advanced topic)

- The fact that GR passed these tests does **NOT** imply that other alternative theories have immediately failed (e.g., reproducing the M87* sizes)

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Remarks on alternatives theories of gravity + exotic objects (advanced topic)

- The fact that GR passed these tests does **NOT** imply that other alternative theories have immediately failed (e.g., reproducing the M87* sizes)

- ***Mild*** variations: BHs in GR + additional fields (e.g., charges) or (somewhat different) BHs in modified GR + quantum effects.
    - They can still **reproduce M87*-like images**

- ***Extreme*** variations: exotic objects, e.g., naked singularity, boson stars, wormholes, etc.
    - Pretty unknown physical mechanisms to naturally form these objects in the universe
    - **Difficult to predict (and test against) observables**

- **Tough business! (we'll discuss later)**

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Remarks on alternatives theories of gravity + exotic objects (advanced topic)

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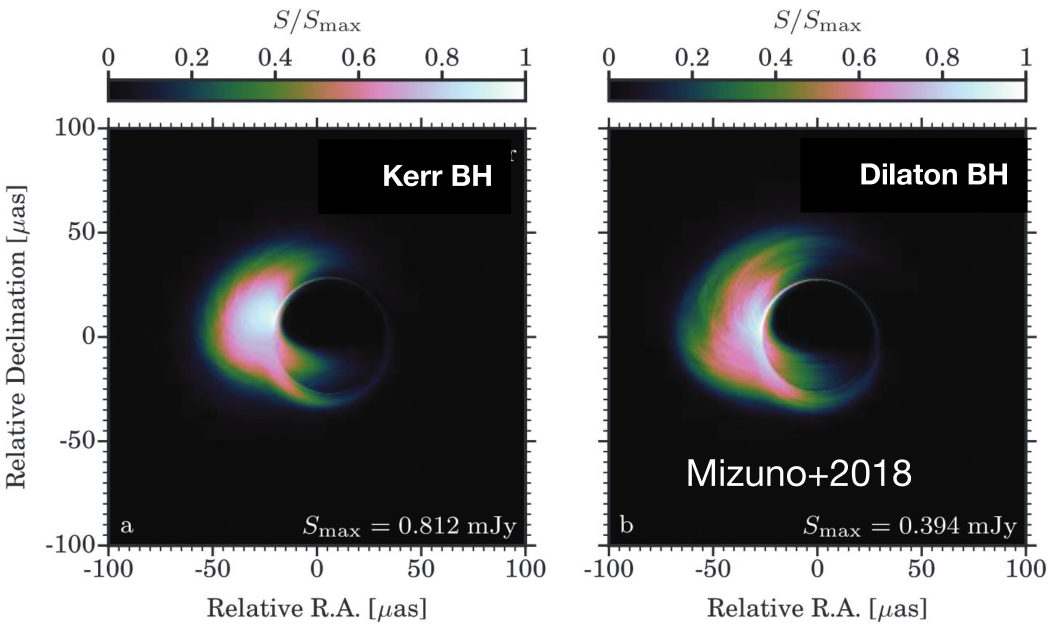

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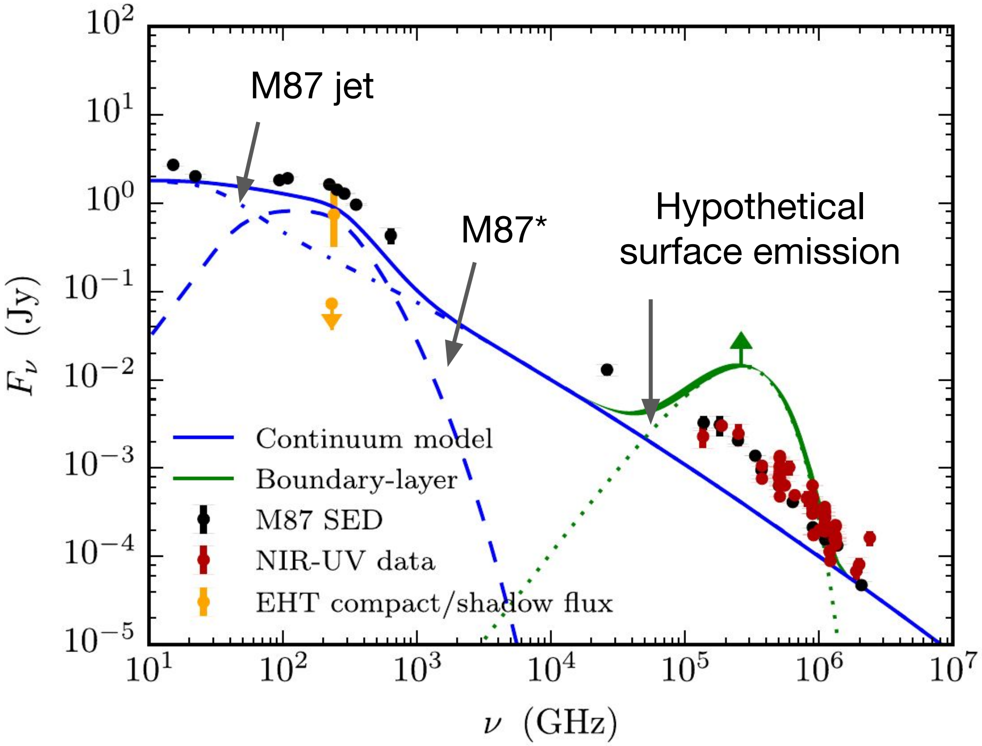
Other ways to test the presence of an event horizon

- Without surface: accreting matter silently falling toward the singularity

- With surface: “accretion power” → “impact luminosity” up to a black body temp. of ~10^4 K; bright emission at optical wavelengths

- **No such emission observed! “Hard” objects can be discarded...**



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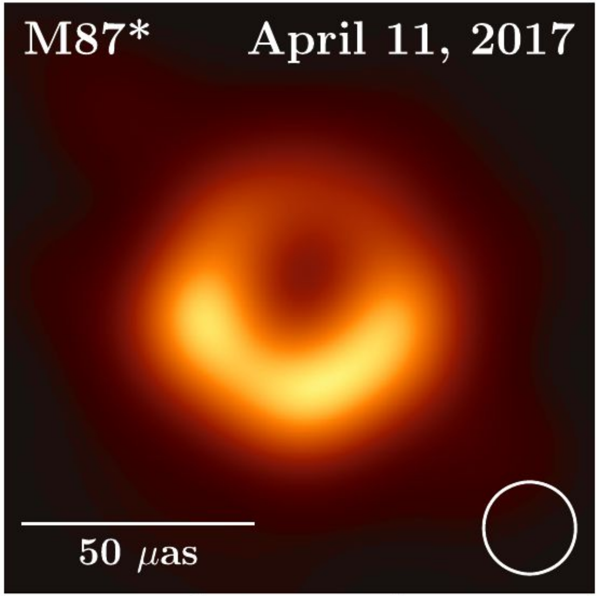
Intermezzo: can details of astrophysics (e.g., accretion flow properties) dominate the M87* image?

- **Sometimes controversial**
  - Partly because of different definitions and assumptions in discussions (see, e.g., Gralla+2019 and especially Narayan+2020)

- **Community consensus: No, as for the dark center and the size of ring with sharp edge**

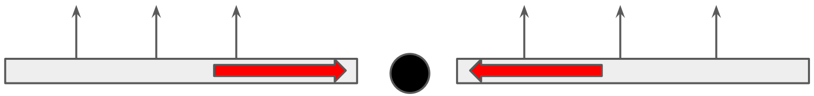
- However, ***some details*** of the photon ring are indeed ***sensitive*** to the surroundings
  - For example, ~2:1 south-to-north brightness asymmetry
  - How would the BH look like “now”?



Astrophysics of M87(*)
and numerical simulations

(advanced topics to follow;
background in astrophysics would help)

The center of M87: "unusual" accretion inflow

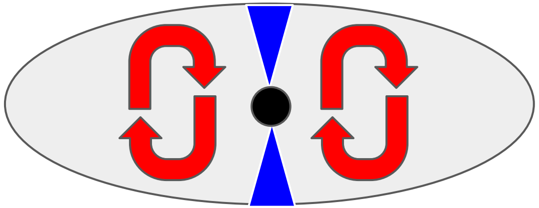


Optically thick, high density:

Grav. E → radiation by viscosity/magnetic fields.

Geometrically thin, relatively cold (~10^5-6 K),

High mass accretion rate



Optically thin, low density inflow:

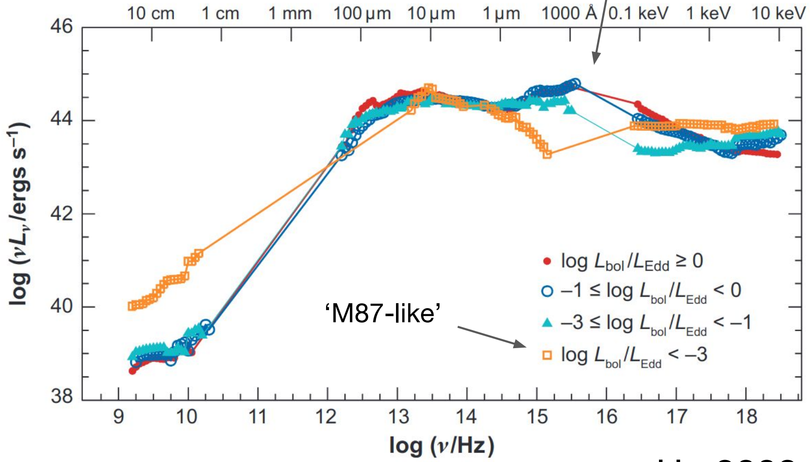
Grav. E → advection (doesn't cool down!).

Geometrically thick, high plasma temperature (up to ~10^9-11 K),

low mass accretion rate. **Often jet!**

'Big blue bump'

(black body spectrum of the slim disk)



Ho 2008

EHT sources

(especially large SMBHs)!

(See also lecture by Minjin Kim)

Further remarks on the advection-dominated accretion flow (ADAF)

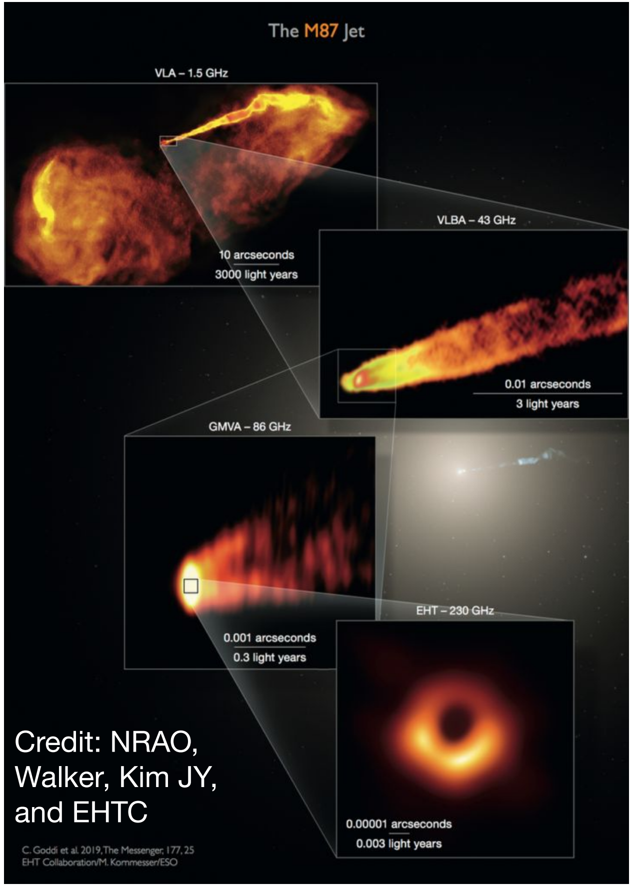
- Outcomes of very low matter density and advection
  - **"Collisionless"** plasma; ions and electrons don't "talk" to each other
  - ***T_ion != T_electron*** → **a great uncertainty in modelling microphysics**
  - Very much pressure dominated (~gravity), **gas only weakly bound to the BH**
  - Gas can **flow** both **in and outward** → **another big uncertainty**

- Why big differences between normal and hot accretion flows?
  - No really clear answer yet; also unclear how a slim disk changes into ADAF

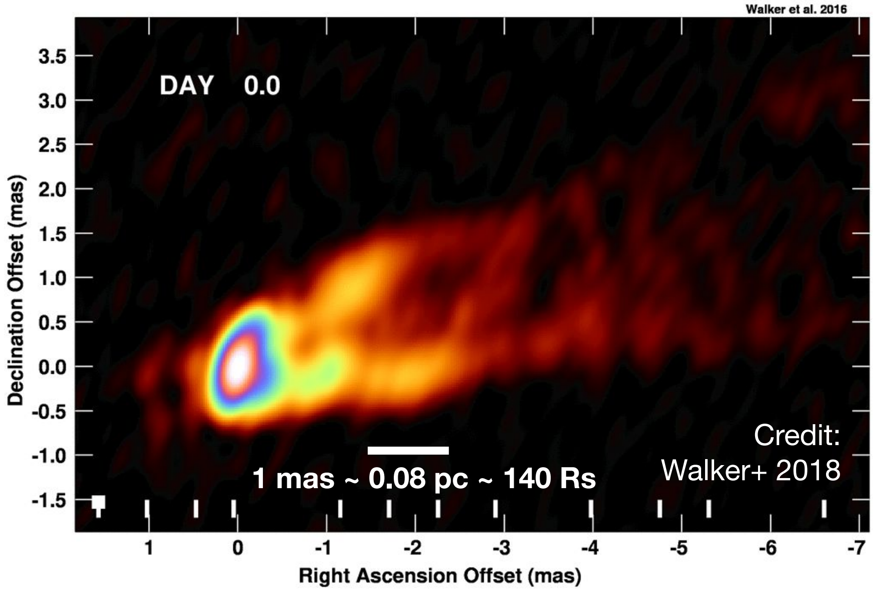
- **EHT and event-horizon-scale images of BHs could greatly help here**

See this webinar for more details

The center of M87: “unusual” relativistic jet



- Very massive black holes with hot accretion flow often show single/two-sided jets up to > Kpc scales
- M87 has one of the first discovered cosmic jets (Curtis 1918; passed 100th birthday in 2018!)



What triggers the jet?

Simulation of a B-field line with free-fall plasma

by Semenov+ 2004
(see Movie S2 therein)

Blandford-Znajek (BZ) mechanism (Blandford & Znajek 1977);
electromagnetic version of the Penrose process (energy extraction from spinning BH)

What controls the jet power?

$$P_{\rm Jet} \propto \Phi_{\rm BH}^2 a_{\rm BH}^2$$

Magnetic field flux threading the BH ergosphere

Normalized black hole spin (|*a*|<1)

- Note: this jet is almost entirely electromagnetic (little mass)
- Also note: there should be certain limits for the B-flux
  - Too strong B-field will push away all the accreting gas, stopping mass accretion
  - This limit is called **Magnetically Arrested Disc (MAD)**
  - The other limit is **Standard And Normal Evolution (SANE)**

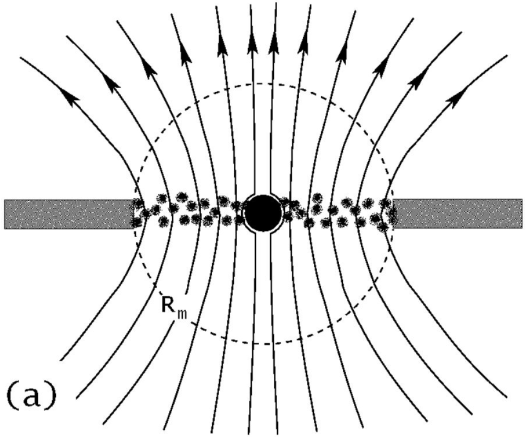
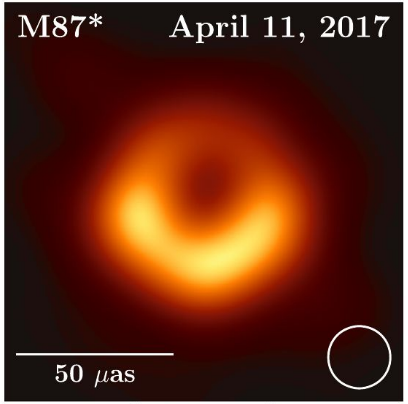
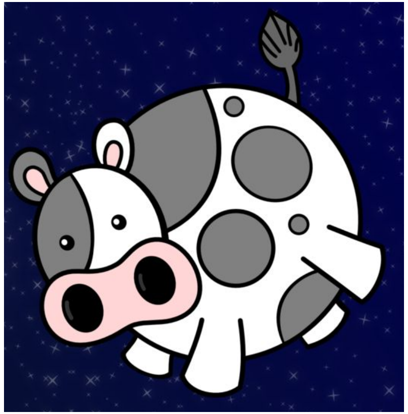


Illustration of MAD
Narayan 2003

Back to M87*: Inferring plasma-physical properties

- **"Ring-like" :** a BH photon ring surrounded by *optically thin*, emitting plasma
- **"Brighter southern limb"** : Doppler beaming due to relativistic rotation of plasma (clockwise on the sky)
- **"Brightness temperature ~ 10^10 *K*"** : consistent with 3mm VLBI "core" and virial temperature of the hot accreting plasma
- **"Total flux ~ 0.5 Jy"** : (with the "spherical cow" assumption) determines $\boldsymbol{n_e}$ (a few 10^4 cm^-3), ***B*** (a few *G*), and mass accretion rate on the horizon scale
- ***Need a fully numerical approach (macro + microphysics) to go beyond***





EHTC+2019e

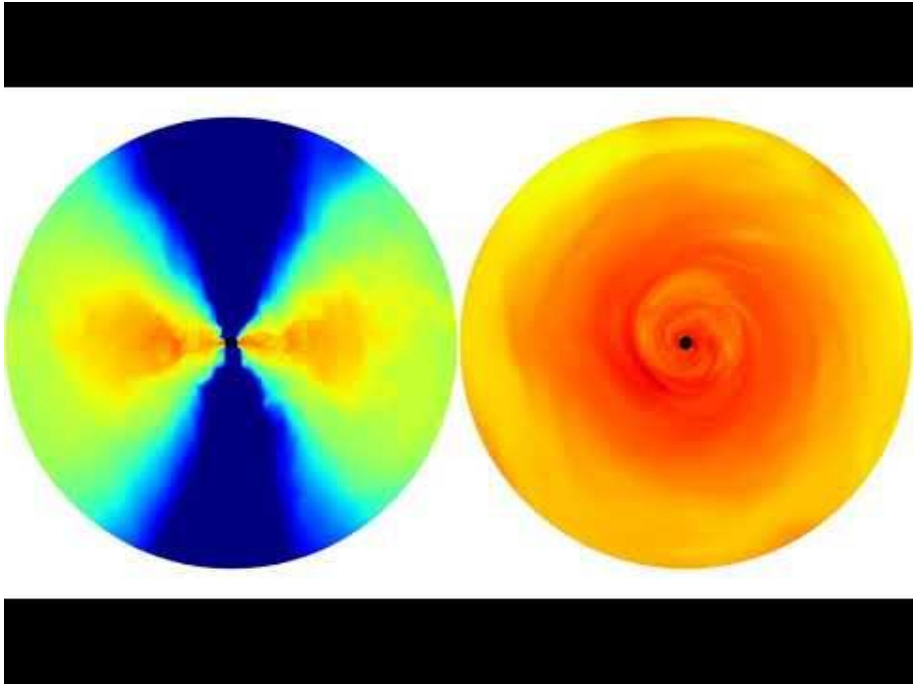
The most common approach:
General-relativistic magnetohydrodynamics (GRMHD) & GR ray-tracing (GRRT) calculations

- Why GRMHD?
  - **Not so monstrous!**
  - Hydrodynamics (fluid approximation)
    - “Prescribe” the microphysics (e.g., distributions of particle E. and temp.)
  - Magnetic field
    - Note: B-field is universal, e.g., in Earth, Sun, interstellar space, and especially compact objects
  - General (curved spacetime) relativistic (high energy plasma, fast speeds, …)
  - <u>**Public codes available**</u>

- Why GRRT?
  - Radiative transfer through curved spacetime around the BH
    - Rays can rotate around a BH even infinite times!
  - <u>**Public codes available**</u>
  - Note: ray-tracing in non-GR metrics is currently challenging and being developed

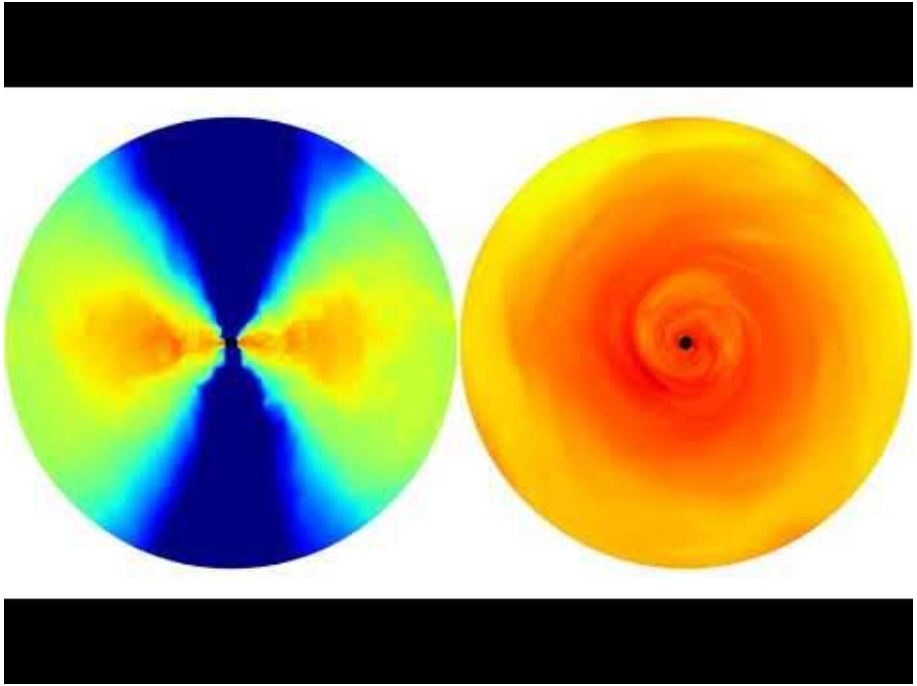
(*Also recall lectures by Young-Hwan Hyun and Jinho Kim*)

Example GRMHD



2D cuts of a 3D simulation
Color: log(density) / **Left**: meridional (x or y=0)
Right: equitorial (z=0) / Credit: U. Illinois

Example GRMHD



2D cuts of a 3D simulation
Color: log(density) / **Left**: meridional (x or y=0)
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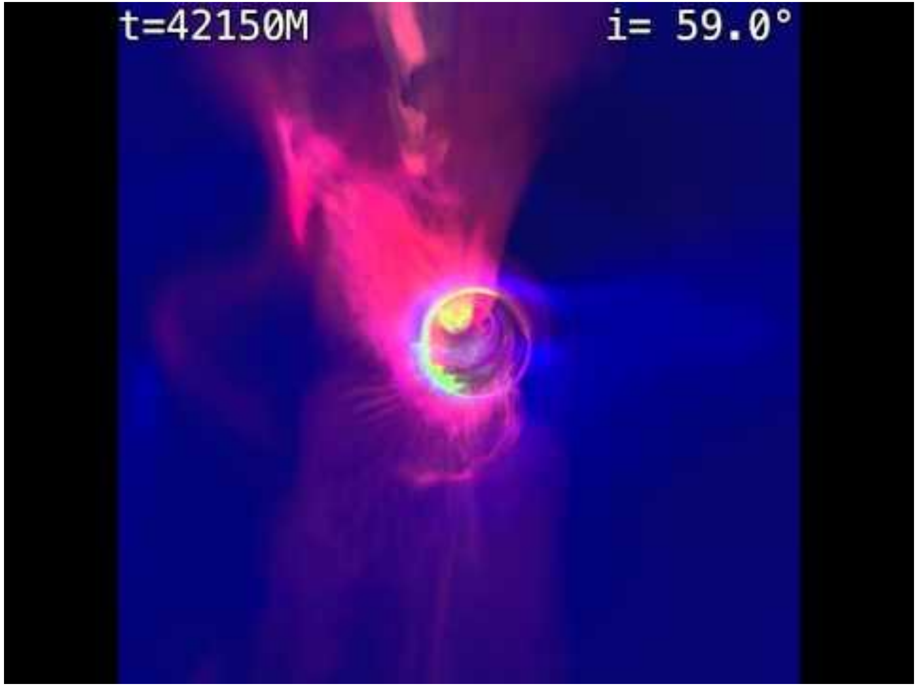
Example GRRT



2D intensity map at various times/angles
Color: log(intensity) / Credit: CK Chan (U. Arizona)
Note: these sims. do not correspond one-to-one

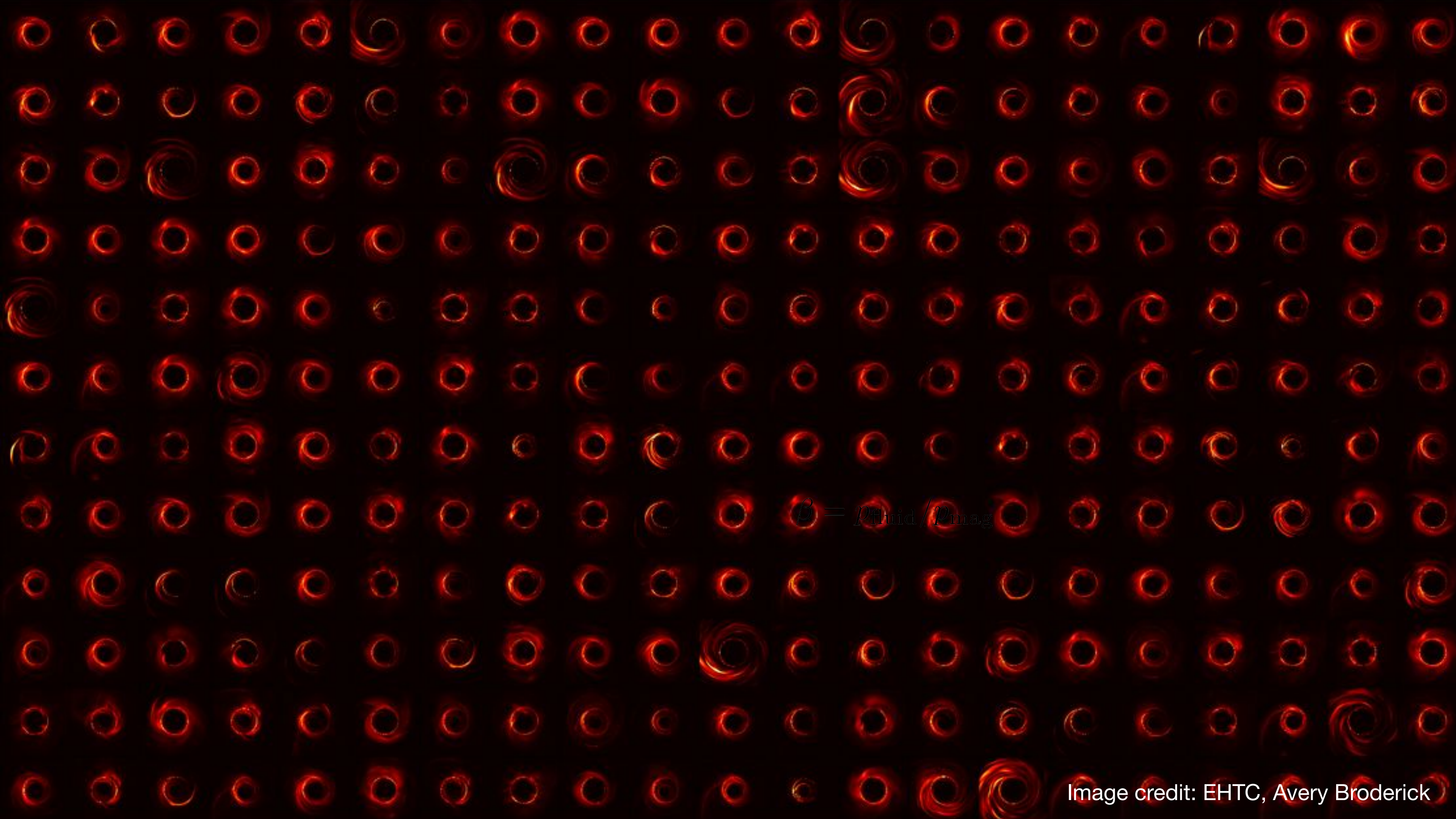


Image credit: EHTC, Avery Broderick

EHT Image Library:

- 43 simulations with different BH spin and accretion state (SANE/MAD)

- Electron Temperatures determined by Mościbrodzka 2016 prescription:

$$\frac{T_i}{T_e} = R_{\rm high}\frac{\beta^2}{1+\beta^2} + R_{\rm low}\frac{1}{1+\beta^2}\ , \quad \beta = p_{\rm fluid}/p_{\rm mag}$$

~70k images we compare to data

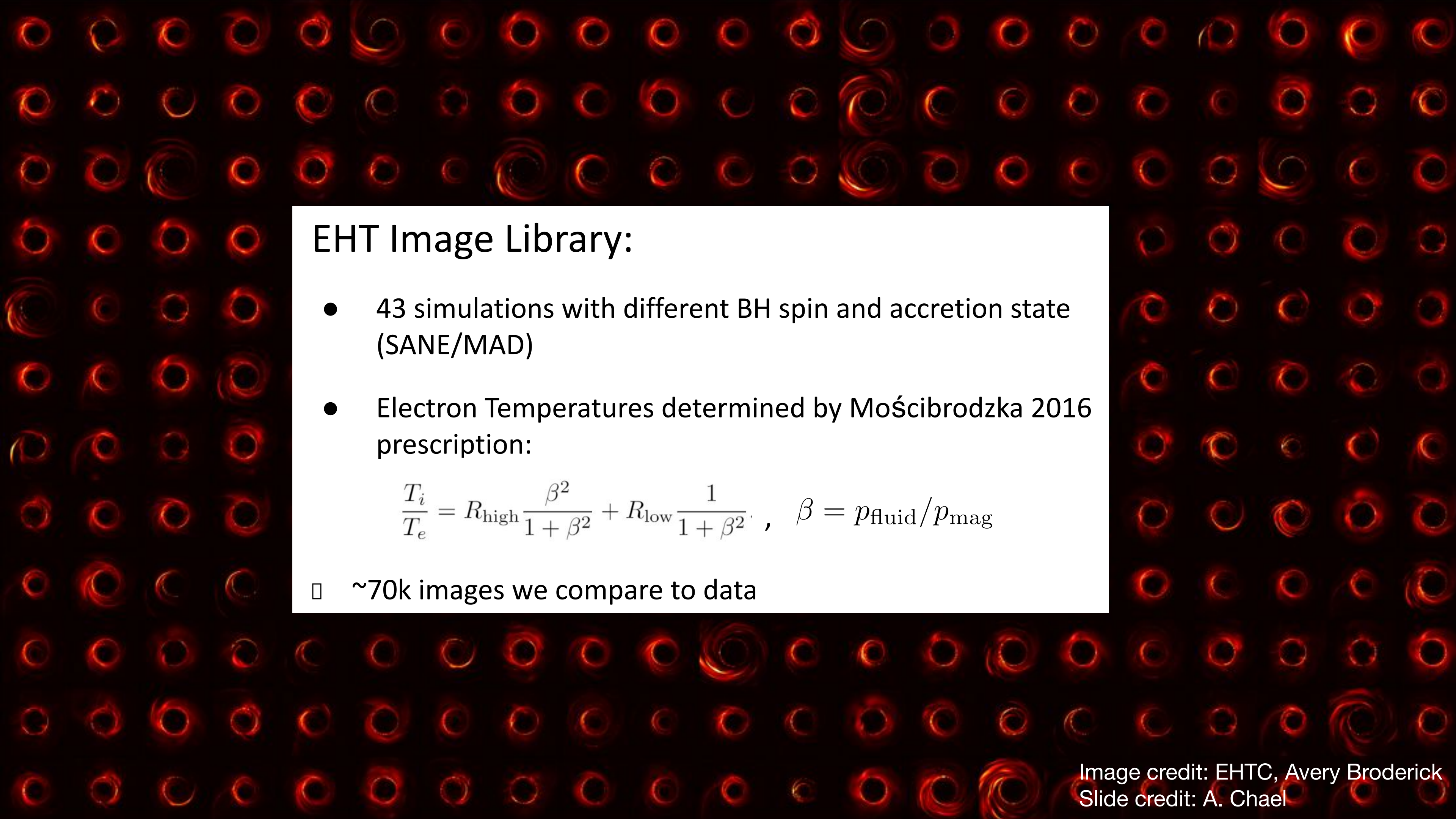
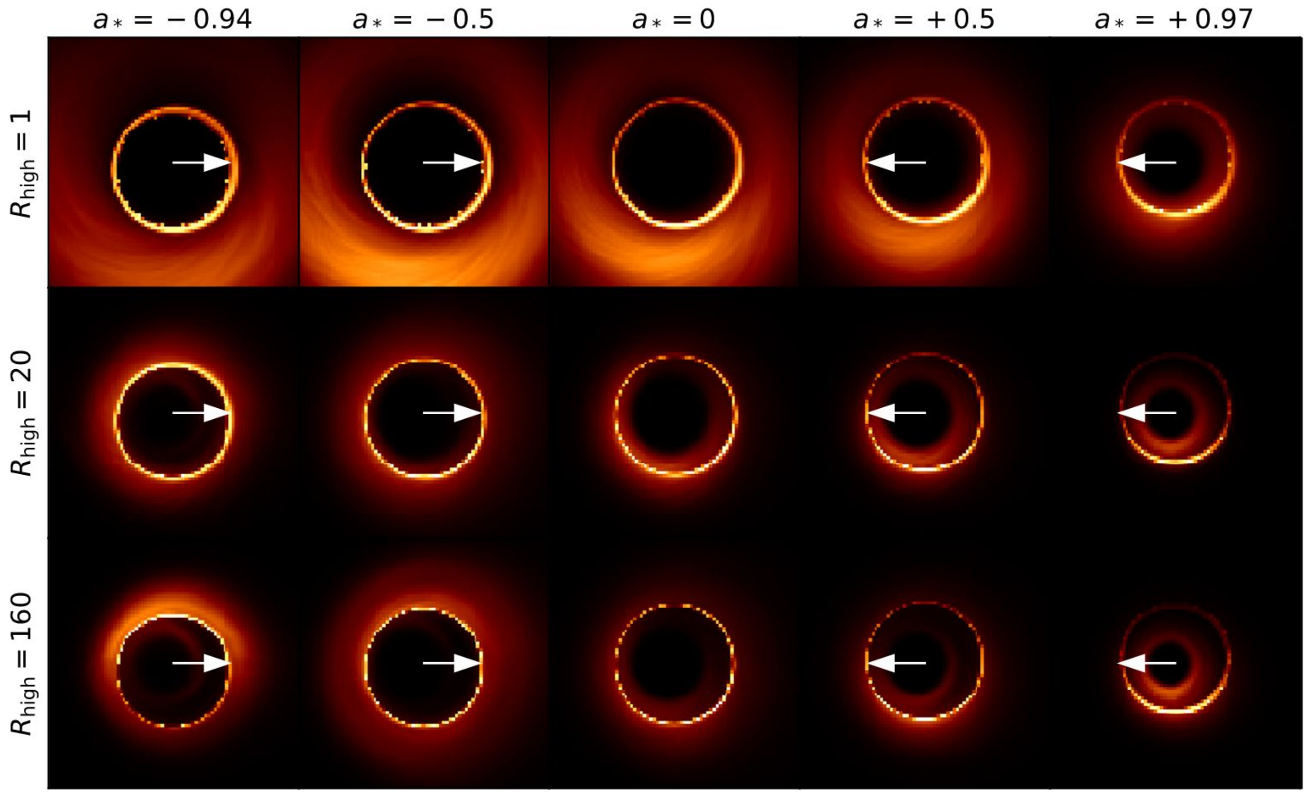


Image credit: EHTC, Avery Broderick
Slide credit: A. Chael

An example set of simulated M87* images



- **White ticks:** sky-projected BH spin direction
- **+/- BH spin (*a*):** Angular momentum
- **R_high:** ~ *T_ion/T_electron* (represent all the microphysics)
- Notice changing sidedness of the ring with varying ***a***

EHTC+2019e

Scoring all the GRMHD simulations vs. observation

Flux[a]	a_*[b]	R_{high}[c]	AIS[d]	ϵ[e]	L_X[f]	P_{jet}[g]	
SANE	−0.94	1	Fail	Pass	Pass	Pass	Fail
SANE	−0.94	10	Pass	Pass	Pass	Pass	Pass
SANE	−0.94	20	Pass	Pass	Pass	Pass	Pass
SANE	−0.94	40	Pass	Pass	Pass	Pass	Pass
SANE	−0.94	80	Pass	Pass	Pass	Pass	Pass
SANE	−0.94	160	Fail	Pass	Pass	Pass	Fail
SANE	−0.5	1	Pass	Pass	Fail	Fail	Fail
SANE	−0.5	10	Pass	Pass	Fail	Fail	Fail
SANE	−0.5	20	Pass	Pass	Pass	Fail	Fail
SANE	−0.5	40	Pass	Pass	Pass	Fail	Fail
SANE	−0.5	80	Fail	Pass	Pass	Fail	Fail
SANE	−0.5	160	Pass	Pass	Pass	Fail	Fail
SANE	0	1	Pass	Pass	Pass	Fail	Fail
SANE	0	10	Pass	Pass	Pass	Fail	Fail
SANE	0	20	Pass	Pass	Fail	Fail	Fail
SANE	0	40	Pass	Pass	Pass	Fail	Fail
SANE	0	80	Pass	Pass	Pass	Fail	Fail
SANE	0	160	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	1	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	10	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	20	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	40	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	80	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	160	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	1	Pass	Fail	Pass	Fail	Fail
SANE	+0.94	10	Pass	Fail	Pass	Fail	Fail
SANE	+0.94	20	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	40	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	80	Pass	Pass	Pass	Pass	Pass
SANE	+0.94	160	Pass	Pass	Pass	Pass	Pass

Flux[a]	a_*[b]	R_{high}[c]	AIS[d]	ϵ[e]	L_X[f]	P_{jet}[g]	
MAD	−0.94	1	Fail	Fail	Pass	Pass	Fail
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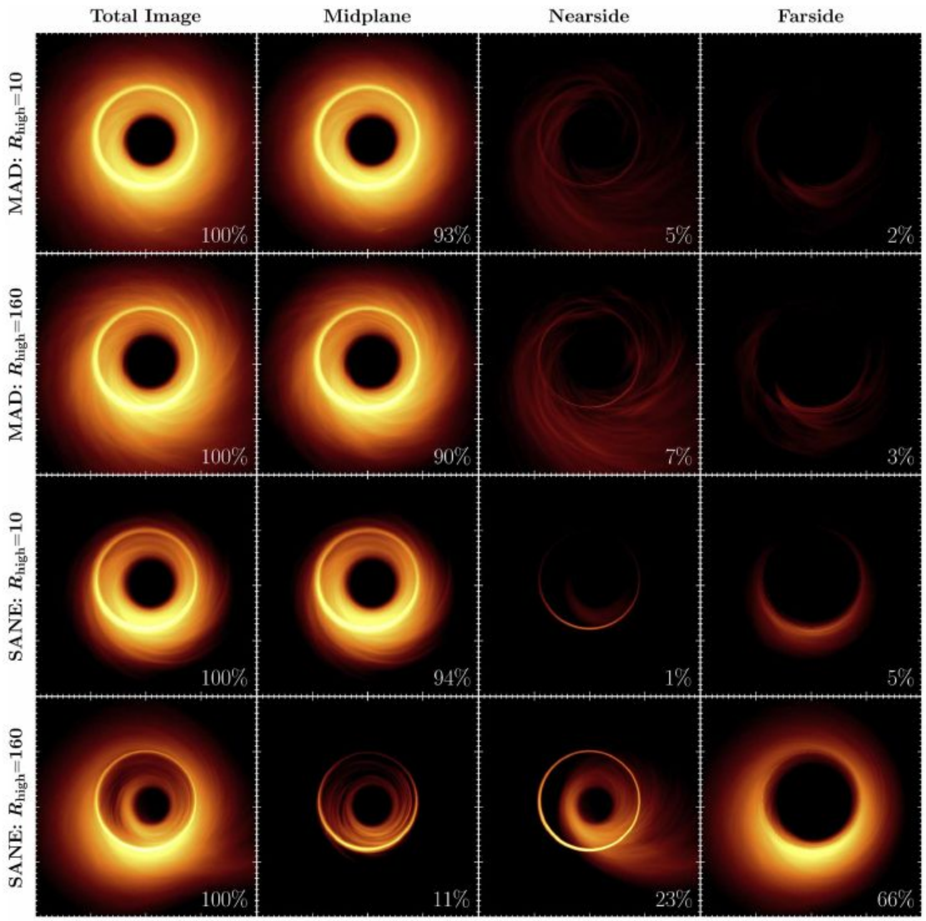
MAD	−0.5	40	Pass	Pass	Pass	Pass	Pass
MAD	−0.5	80	Pass	Pass	Pass	Pass	Pass
MAD	−0.5	160	Pass	Pass	Pass	Pass	Pass
MAD	0	1	Pass	Fail	Pass	Fail	Fail
MAD	0	10	Pass	Pass	Pass	Fail	Fail
MAD	0	20	Pass	Pass	Pass	Fail	Fail
MAD	0	40	Pass	Pass	Pass	Fail	Fail
MAD	0	80	Pass	Pass	Pass	Fail	Fail
MAD	0	160	Pass	Pass	Pass	Fail	Fail
MAD	+0.5	1	Pass	Fail	Pass	Fail	Fail
MAD	+0.5	10	Pass	Pass	Pass	Pass	Pass
MAD	+0.5	20	Pass	Pass	Pass	Pass	Pass
MAD	+0.5	40	Pass	Pass	Pass	Pass	Pass
MAD	+0.5	80	Pass	Pass	Pass	Pass	Pass
MAD	+0.5	160	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	1	Pass	Fail	Fail	Pass	Fail
MAD	+0.94	10	Pass	Fail	Pass	Pass	Fail
MAD	+0.94	20	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	40	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	80	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	160	Pass	Pass	Pass	Pass	Pass

AIS: similarity to image / ***e*:** radiative efficiency / ***L_X* :** X-ray luminosity / **P_{jet} :** Jet power

Looking deeper into individual simulated images



- Changing physical conditions also change dominant sources of the photons
- However, the total images look surprisingly similar -- **“GR always wins over detailed plasma physics”**
- Thus the image similarity is not a very good measure of the goodness of a simulation -- at the angular resolution of ~ 20 uas

EHTC+2019e

Scoring all the GRMHD simulations vs. observation

Flux[a]	a_*[b]	R_{high}[c]	AIS[d]	ϵ[e]	L_X[f]	P_{jet}[g]	
SANE	−0.94	1	Fail	Pass	Pass	Pass	Fail
SANE	−0.94	10	Pass	Pass	Pass	Pass	Pass
SANE	−0.94	20	Pass	Pass	Pass	Pass	Pass
SANE	−0.94	40	Pass	Pass	Pass	Pass	Pass
SANE	−0.94	80	Pass	Pass	Pass	Pass	Pass
SANE	−0.94	160	Fail	Pass	Pass	Pass	Fail
SANE	−0.5	1	Pass	Pass	Fail	Fail	Fail
SANE	−0.5	10	Pass	Pass	Fail	Fail	Fail
SANE	−0.5	20	Pass	Pass	Pass	Fail	Fail
SANE	−0.5	40	Pass	Pass	Pass	Fail	Fail
SANE	−0.5	80	Fail	Pass	Pass	Fail	Fail
SANE	−0.5	160	Pass	Pass	Pass	Fail	Fail
SANE	0	1	Pass	Pass	Pass	Fail	Fail
SANE	0	10	Pass	Pass	Pass	Fail	Fail
SANE	0	20	Pass	Pass	Fail	Fail	Fail
SANE	0	40	Pass	Pass	Pass	Fail	Fail
SANE	0	80	Pass	Pass	Pass	Fail	Fail
SANE	0	160	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	1	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	10	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	20	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	40	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	80	Pass	Pass	Pass	Fail	Fail
SANE	+0.5	160	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	1	Pass	Fail	Pass	Fail	Fail
SANE	+0.94	10	Pass	Fail	Pass	Fail	Fail
SANE	+0.94	20	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	40	Pass	Pass	Pass	Fail	Fail
SANE	+0.94	80	Pass	Pass	Pass	Pass	Pass
SANE	+0.94	160	Pass	Pass	Pass	Pass	Pass

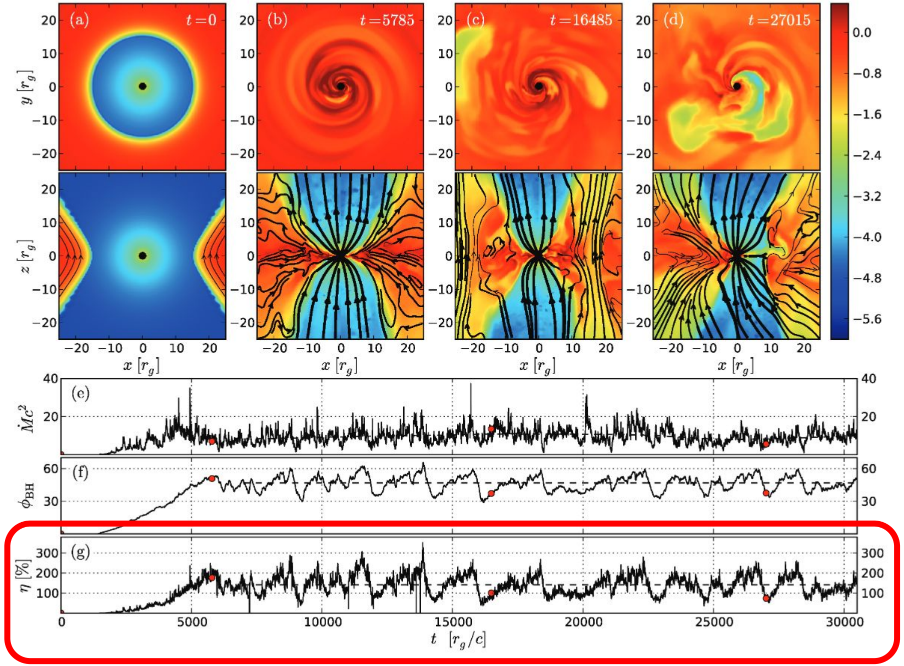
Flux[a]	a_*[b]	R_{high}[c]	AIS[d]	ϵ[e]	L_X[f]	P_{jet}[g]	
MAD	−0.94	1	Fail	Fail	Pass	Pass	Fail
MAD	−0.94	10	Fail	Pass	Pass	Pass	Fail
MAD	−0.94	20	Fail	Pass	Pass	Pass	Fail
MAD	−0.94	40	Fail	Pass	Pass	Pass	Fail
MAD	−0.94	80	Fail	Pass	Pass	Pass	Fail
MAD	−0.94	160	Fail	Pass	Pass	Pass	Fail
MAD	−0.5	1	Pass	Fail	Pass	Fail	Fail
MAD	−0.5	10	Pass	Pass	Pass	Fail	Fail
MAD	−0.5	20	Pass	Pass	Pass	Pass	Pass
MAD	−0.5	40	Pass	Pass	Pass	Pass	Pass
MAD	−0.5	80	Pass	Pass	Pass	Pass	Pass
MAD	−0.5	160	Pass	Pass	Pass	Pass	Pass
MAD	0	1	Pass	Fail	Pass	Fail	Fail
MAD	0	10	Pass	Pass	Pass	Fail	Fail
MAD	0	20	Pass	Pass	Pass	Fail	Fail
MAD	0	40	Pass	Pass	Pass	Fail	Fail
MAD	0	80	Pass	Pass	Pass	Fail	Fail
MAD	0	160	Pass	Pass	Pass	Fail	Fail
MAD	+0.5	1	Pass	Fail	Pass	Fail	Fail
MAD	+0.5	10	Pass	Pass	Pass	Pass	Pass
MAD	+0.5	20	Pass	Pass	Pass	Pass	Pass
MAD	+0.5	40	Pass	Pass	Pass	Pass	Pass
MAD	+0.5	80	Pass	Pass	Pass	Pass	Pass
MAD	+0.5	160	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	1	Pass	Fail	Fail	Pass	Fail
MAD	+0.94	10	Pass	Fail	Pass	Pass	Fail
MAD	+0.94	20	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	40	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	80	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	160	Pass	Pass	Pass	Pass	Pass

AIS: similarity to image / ***e*:** radiative efficiency / ***L_X*:** X-ray luminosity / **P_{jet} :** Jet power

Note: the jet power is the most constraining among all conditions

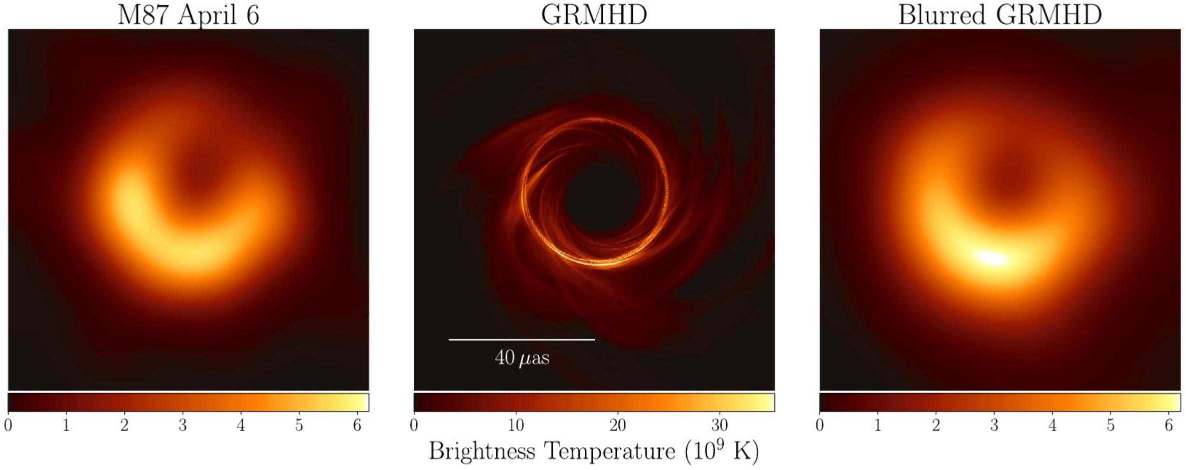
Why so sensitive to the jet power?
Compare with the accretion power (advanced topic)

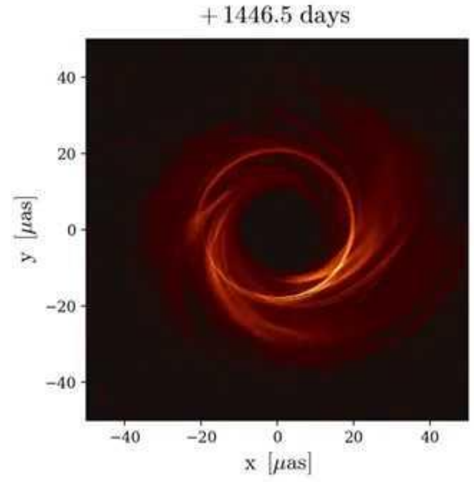
- Observed M87 jet power ~ **10^44 erg/s**
- Maximum power of the mass accretion: converting all of its rest energy
  - Mass accretion rate onto M87*: **Mdot < 0.001 Msun/yr** (e.g., Kuo+ 2014)
  - **Mdot*c^2 < 10^43 erg/s (<10% of the jet power)**
- The jet requires **>100% energy** of the accreting matter; **direct evidence for a rotating SMBH in action**



Tchekhovskoy+2011

One of the best surviving models



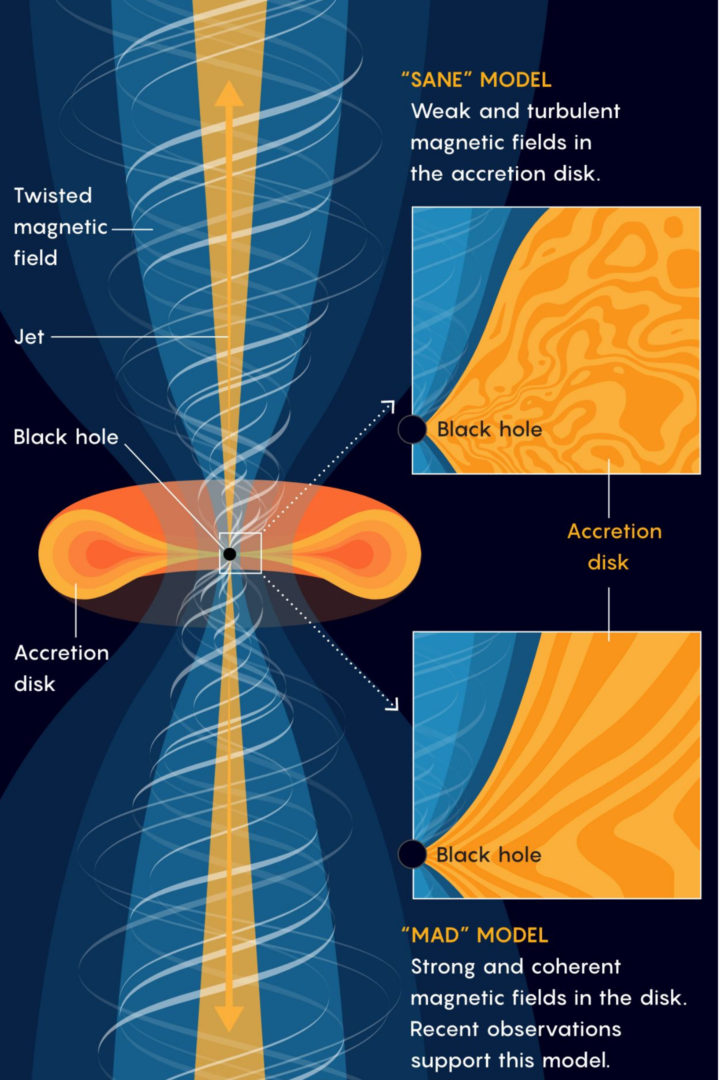


General conclusion: MAD somewhat more likely than SANE & higher BH spin preferred

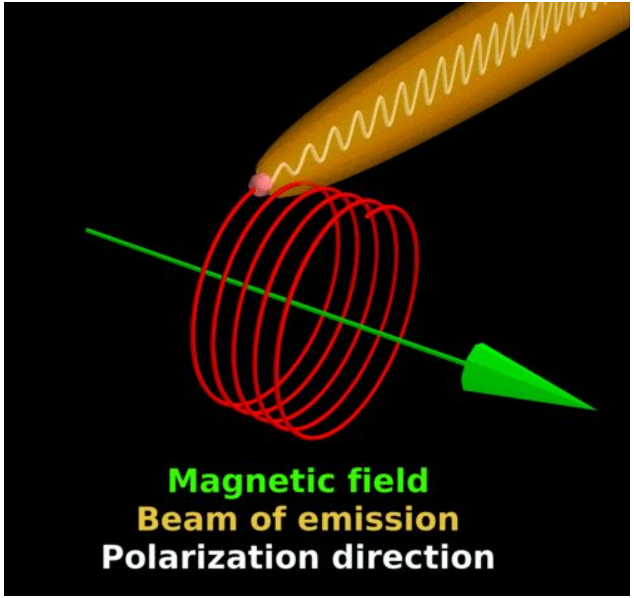
How strong is this statement the case?

Can we do better than this?

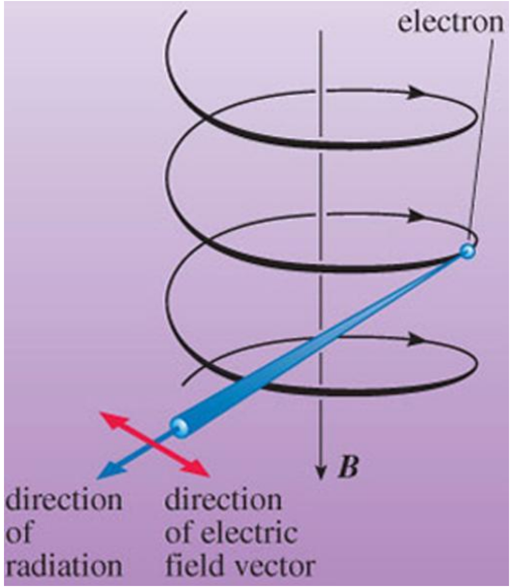
EHTC+2019e



Magnetic field structure matters -- using linear polarization to map the B-field



Credit: I. Marti-Vidal



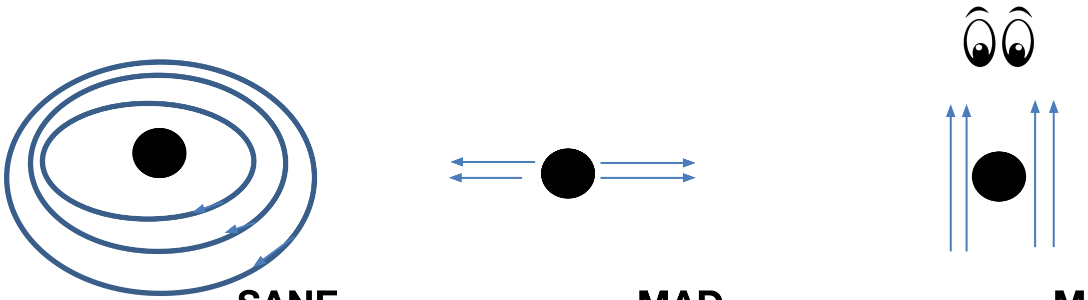
Credit: Open University

Image credit: O'Riordan+ 2017, Quanta Magazine

Possible appearance of M87* in linear polarization (LP)
(advanced topic)

3 simple models, viewed face on

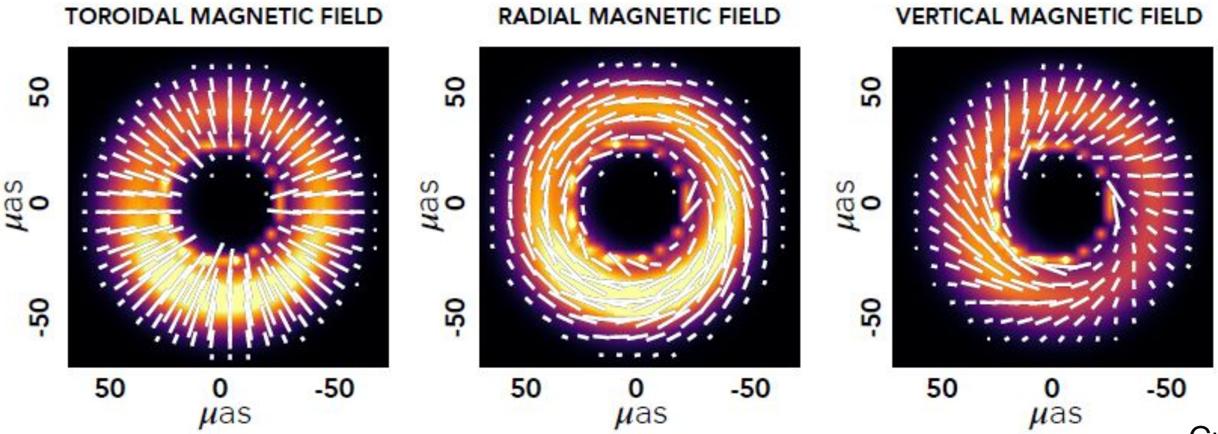
Field structure



~SANE ~MAD ~MAD

(white ticks: strength and direction of LP)

Observed image

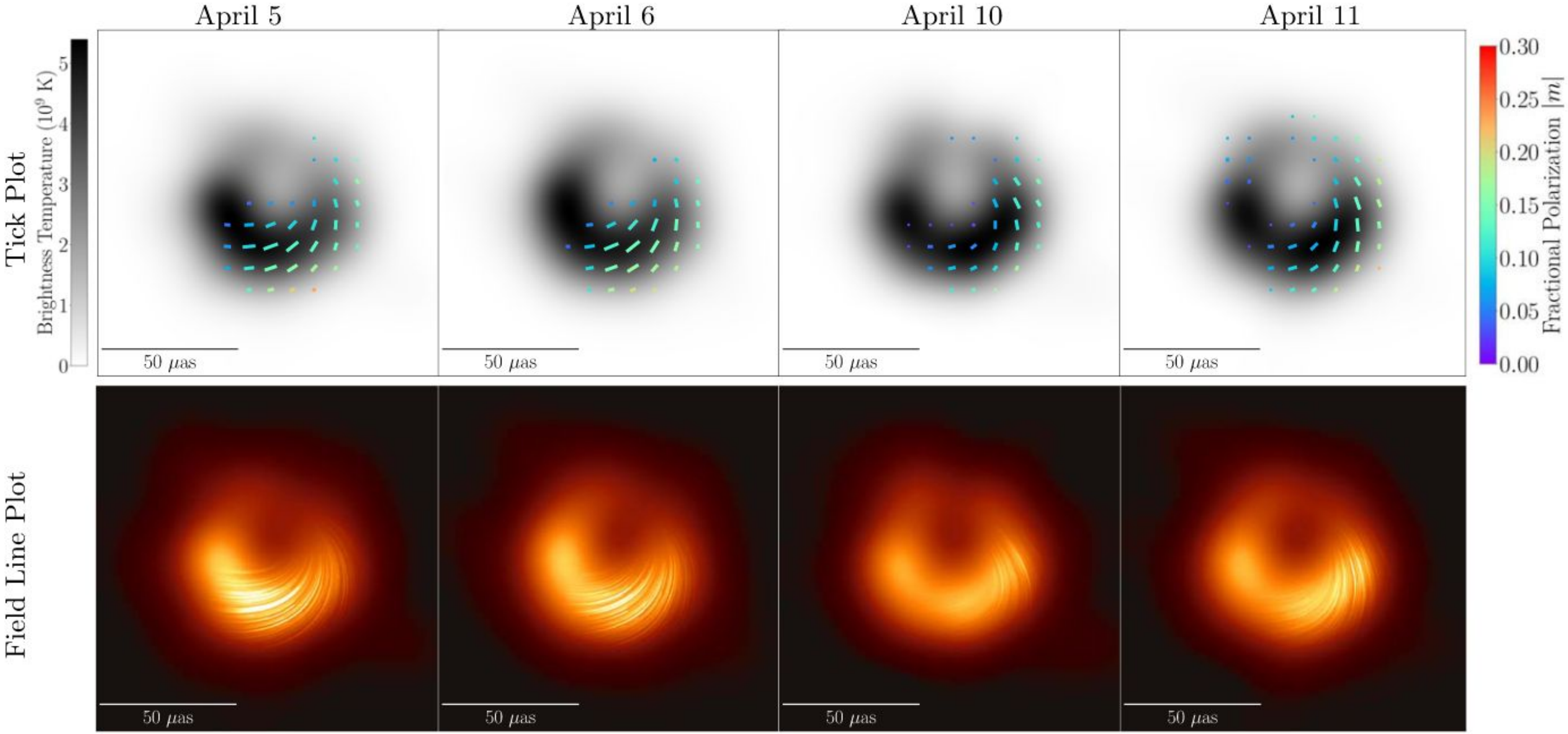


Vertical field scenario would be **unpolarized** without bent photon trajectories!

Slide credit: A. Chael

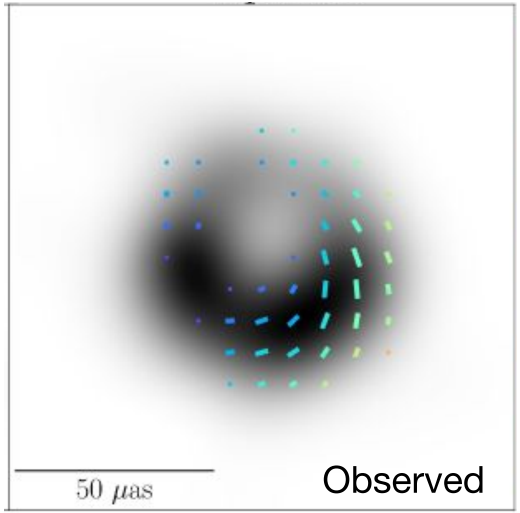
Credit: EHTC 2021 Paper VIII
Jiménez-Rosales+ 2018

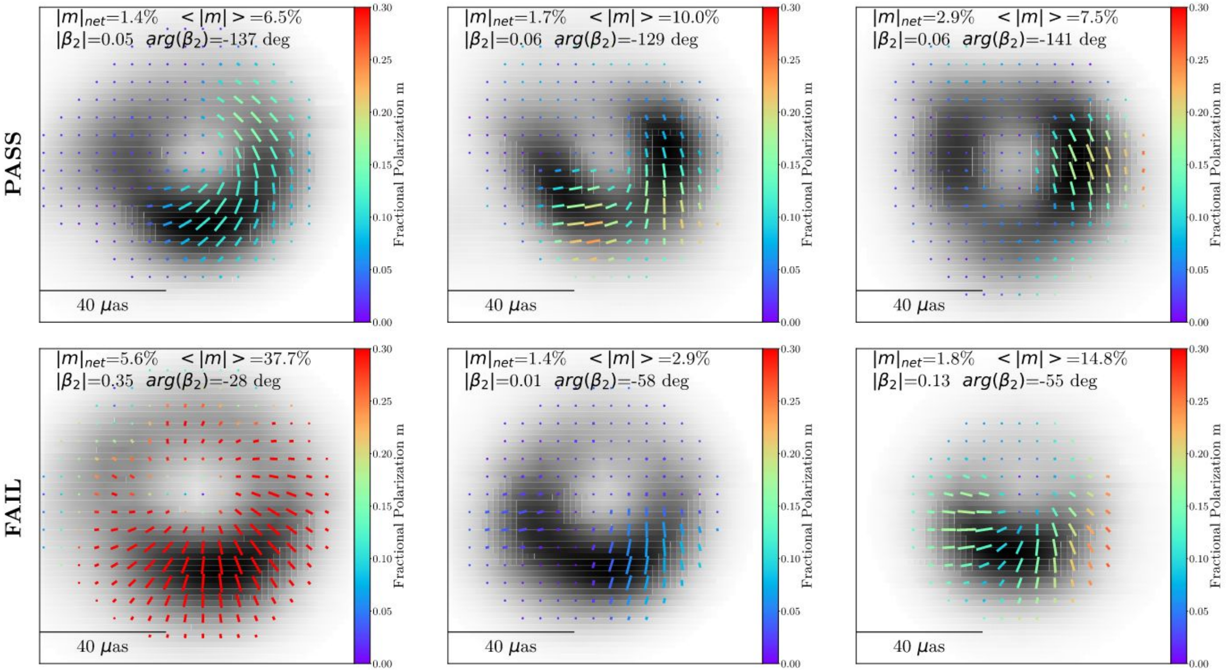
Reminder: real M87* images in LP



EHTC+2021a

Example GRMHD images of M87* in LP

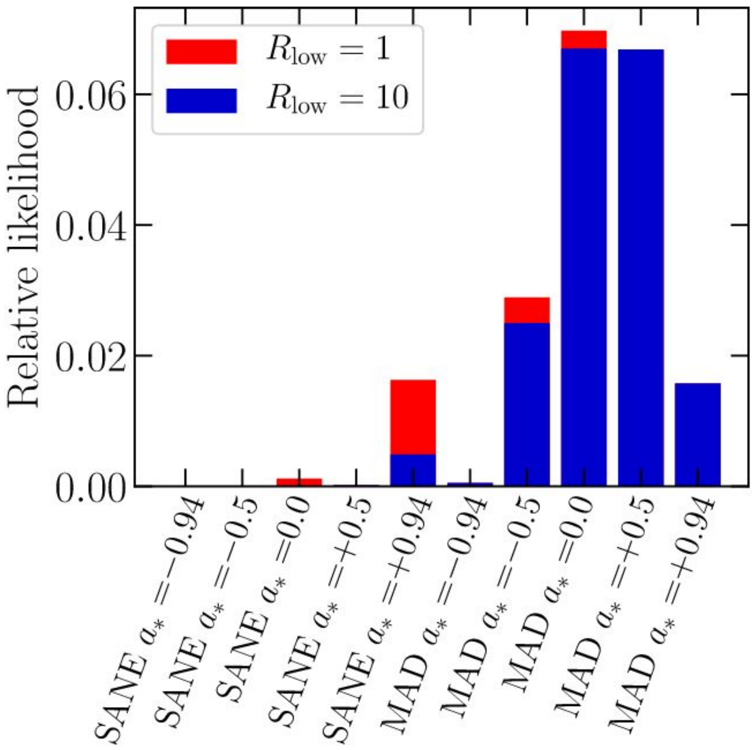




Simulated

EHTC+2021a,b

Scoring again with LP (advanced topic)

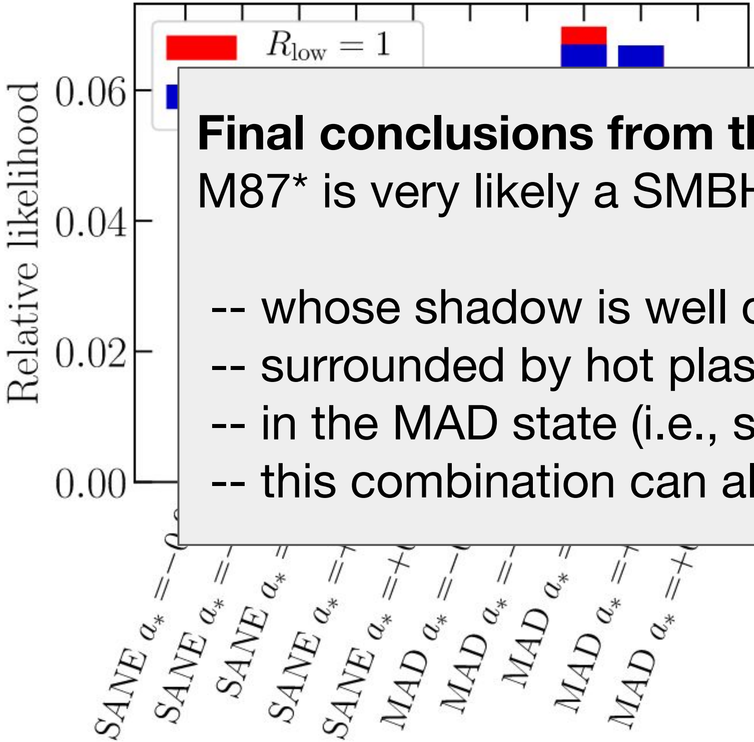


- **Left:** from only total intensity and polarimetric Image comparison

- **Adding the jet power constraint kills all the non-MAD and non-spinning models**

- Why?
    - SANE with incoherent B-field structure → more scrambled and weaker LP
    - MAD with more ordered, vertical B-fields → **stronger LP with winding pattern of the LP angle**

Scoring again with LP (advanced topic)

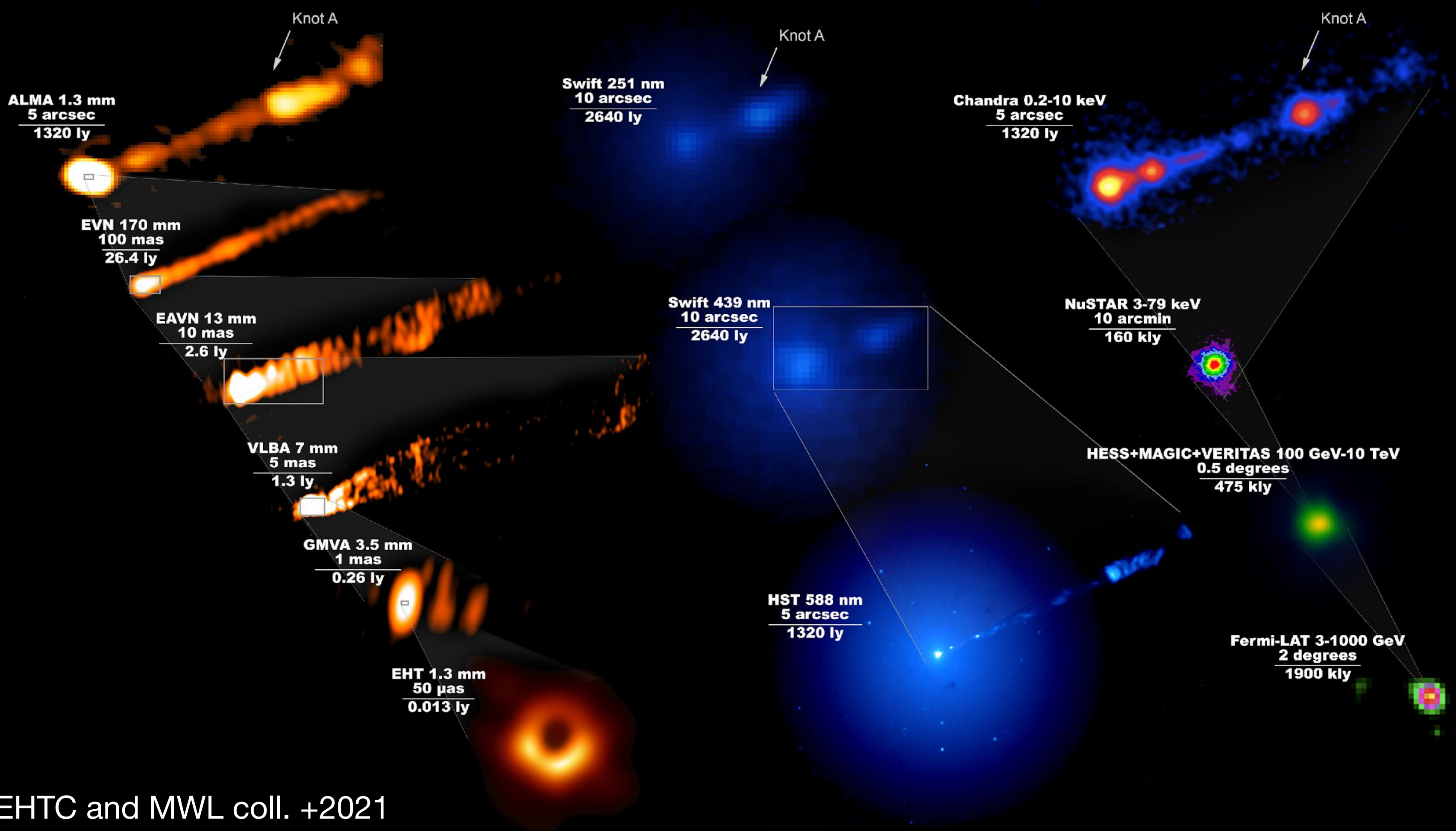


Final conclusions from the EHT 2017 data in 2021:
M87* is very likely a SMBH

-- whose shadow is well described by Kerr metric
-- surrounded by hot plasma accretion flow
-- in the MAD state (i.e., strong magnetic fields)
-- this combination can also well explain the relativistic jet in M87

- **Left:** from only total intensity and polarimetric
  ll
  ls
  ure
  - MAD with more ordered, vertical B-fields **→ stronger LP with winding pattern of the LP angle**

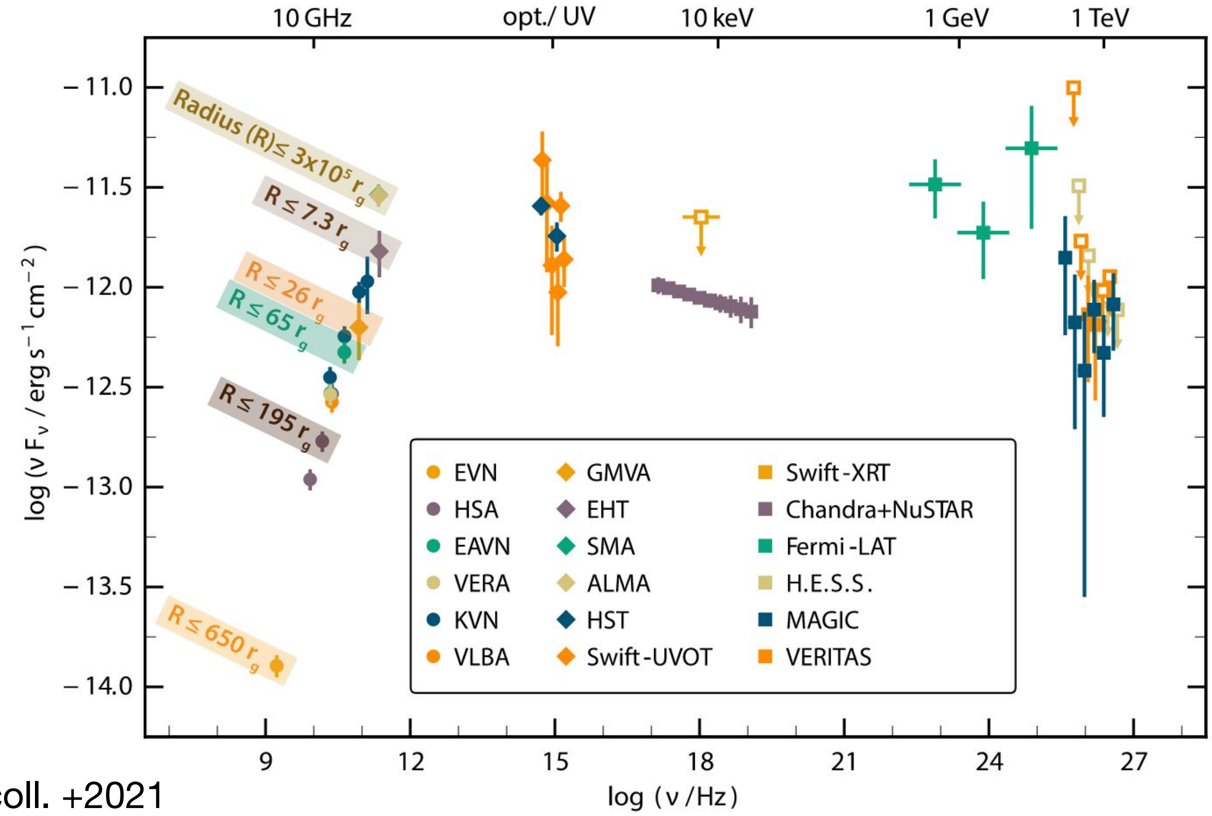
(Selected) areas of actively ongoing research with the EHT



EHTC and MWL coll. +2021

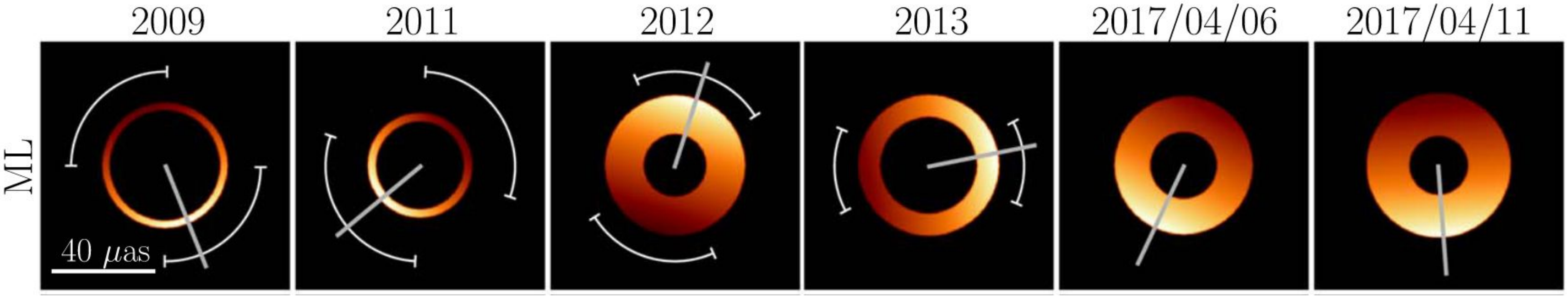
Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

The most simultaneous, “Golden” multiwavelength SED of M87



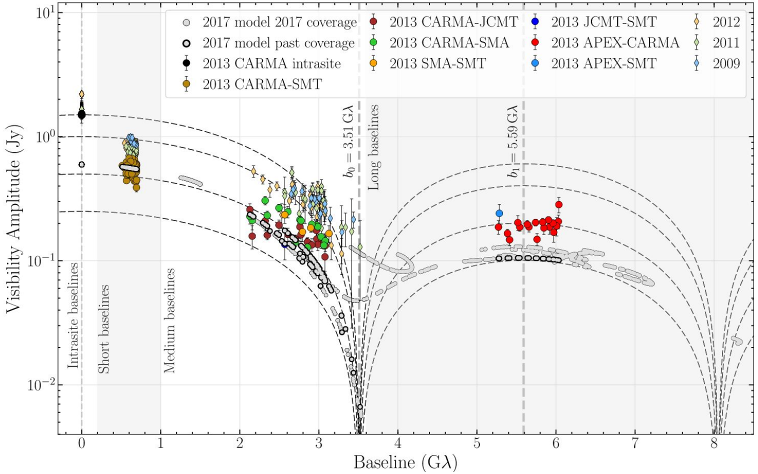
EHTC and MWL coll. +2021

Time variability -- is the M87* ring variable?



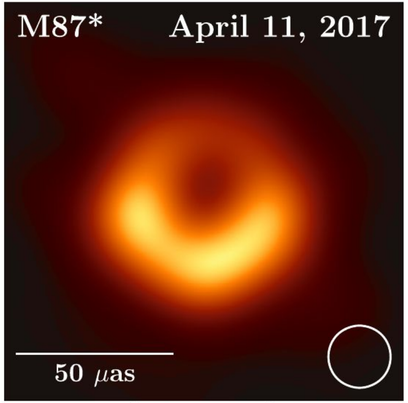
M87* geometric model-fits

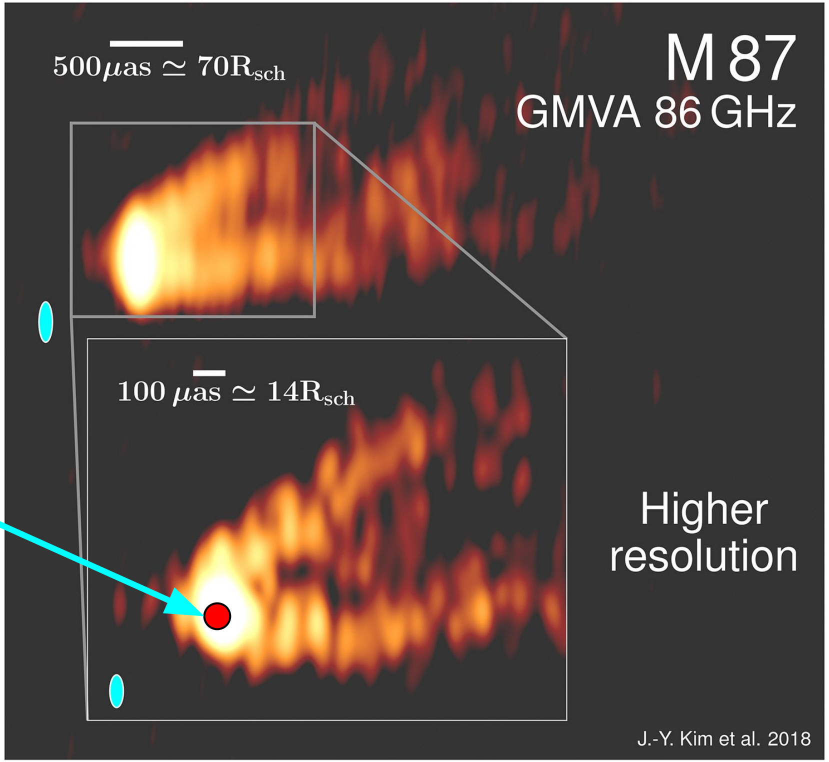
Wielgus+2020



- Fitting proto-EHT data -- before (2017) without phased-ALMA -- with geometric ring model
- Stable diameter, clear flux changes, indications for changes in the position angle of the ring
- Eventually, 2018/2021 data will be beneficial

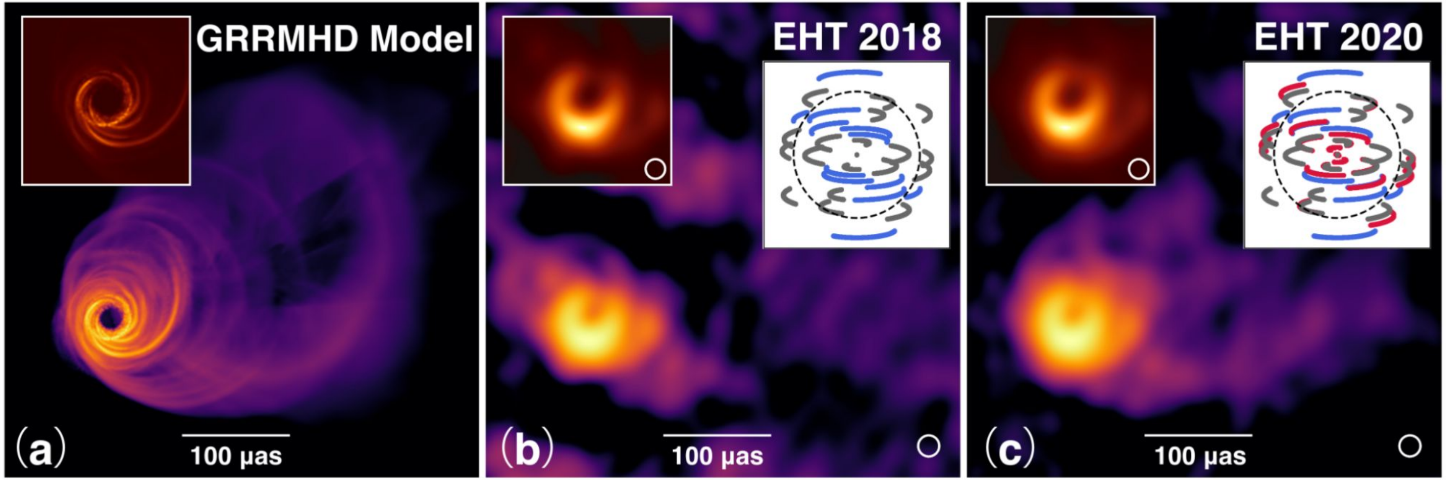
Toward a complete picture of jet formation in M87





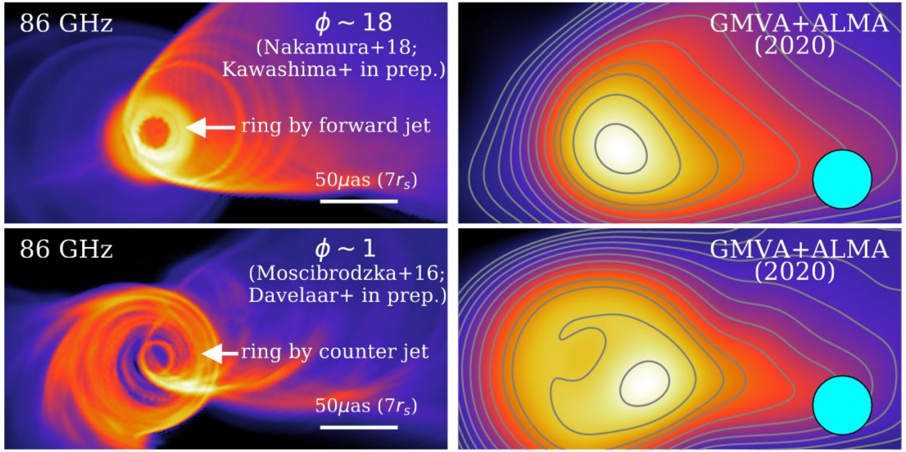
The innermost jet of the nearby giant galaxy M87
(Kim, J.-Y., et al., 2018, A&A, 616, A188)

- **Where is the jet in the EHT image of M87?**
    - Limited imaging fidelity of EHT 2017
- **How will it connect to the ring?**



230 GHz (EHT):
Mapping the direct ring-jet connection

(PI EHTC; observed in ALMA Cy 7 in Spring 2021)



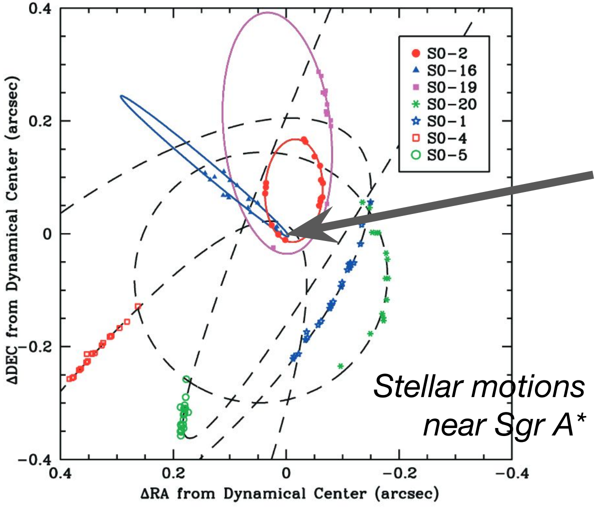
At 86 GHz (traditional global VLBI array):
Resolving the subnuclear structure of the jet "core" at ~40-50 uas resolution

Expect to see some structure, depending on the plasma physics near the jet base

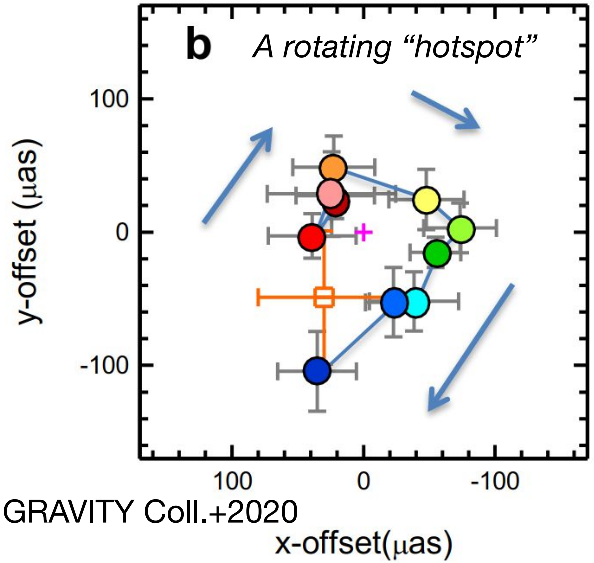
(PI Kim JY; observed in ALMA Cy 7, Spring 2021)

From ALMA Cycle 7 proposal materials

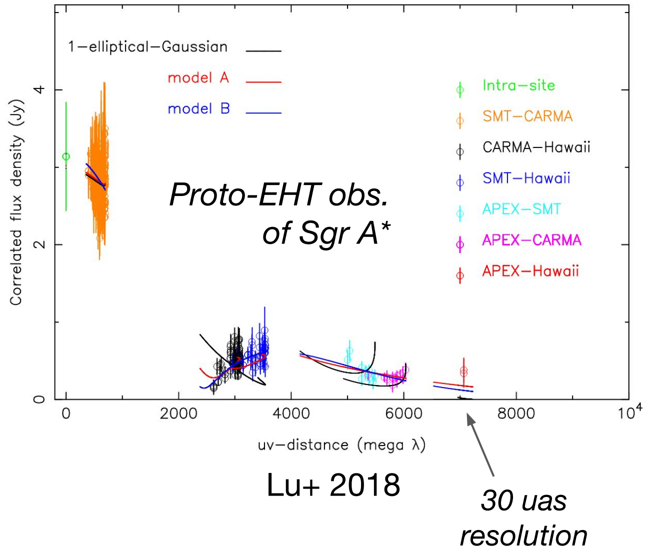
The Galactic Center SMBH Sgr A*: another key laboratory to test GR



Ghez+2005



GRAVITY Coll.+2020



Lu+ 2018

- Best-constrained BH mass of ~4 million Msun (Ghez+; Genzel+; Nobel prize in Physics 2020)
  - Dynamical timescales ~ 10s of minutes to hours
- Detection of motions on the event-horizon scale (GRAVITY Collaboration+) by NIR interferometry
- Proto-EHT observations reveal 3 Schwarzschild-radii scale intrinsic source structure

The EHT image of Sgr A*

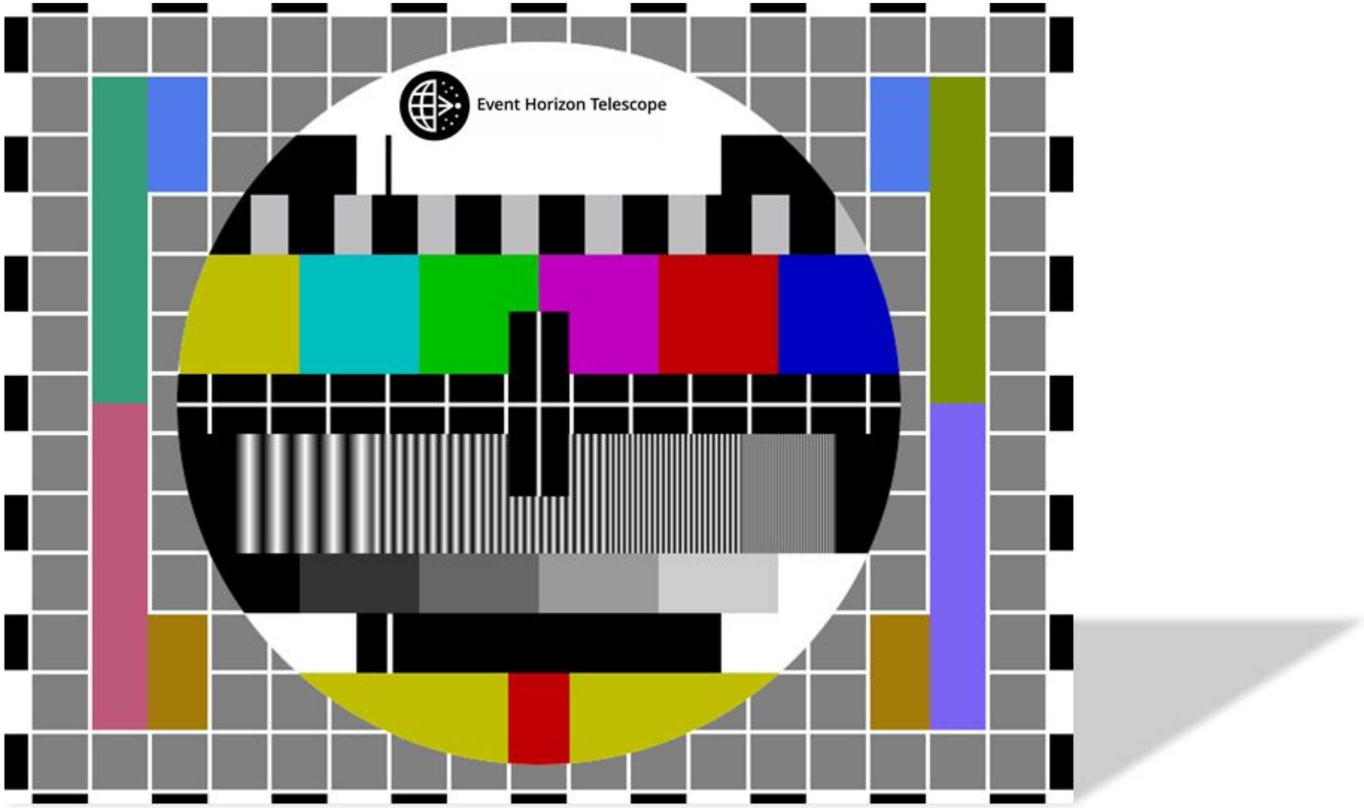


Image credit: E. Ros

Pulsars near Sgr A* for mapping the spacetime

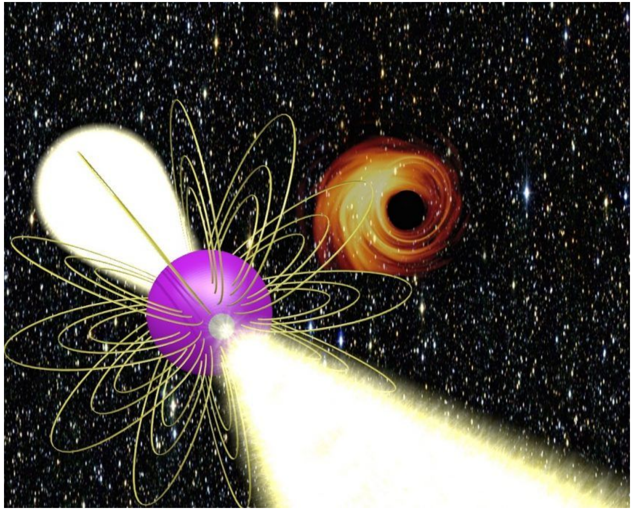
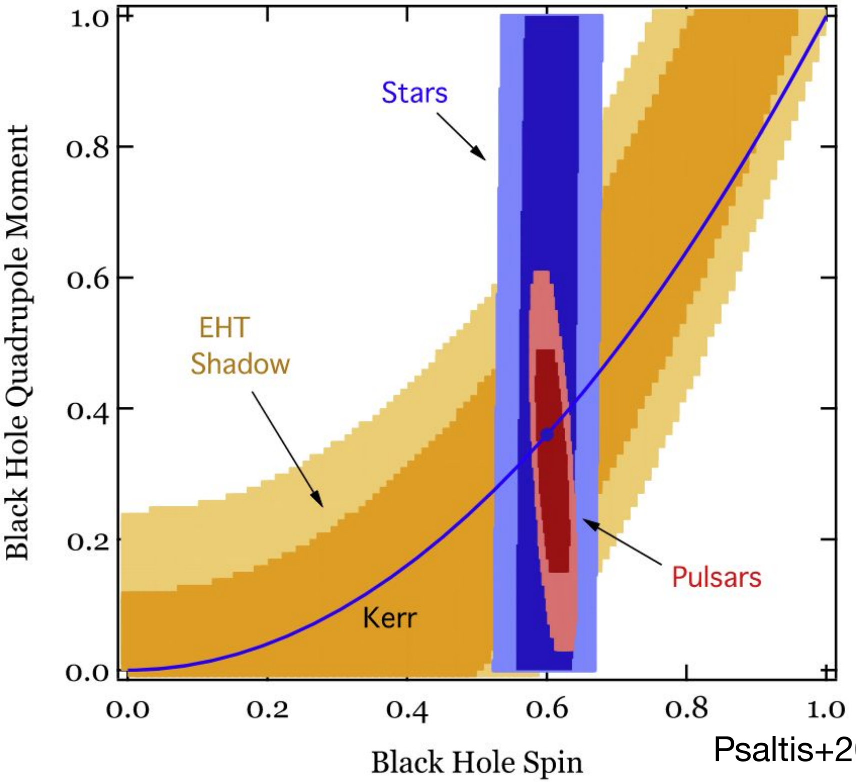


Image credit: Black Hole Cam

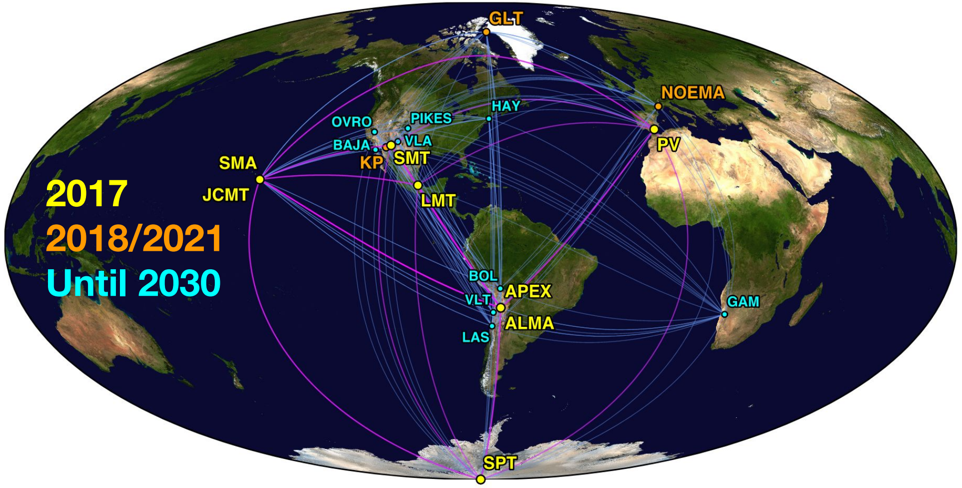
- Pulsars can work as excellent clocks to independently measure spacetime curvature near BH
- Ongoing efforts such as phased ALMA (e.g., Liu K+ 2019)



Psaltis+2016

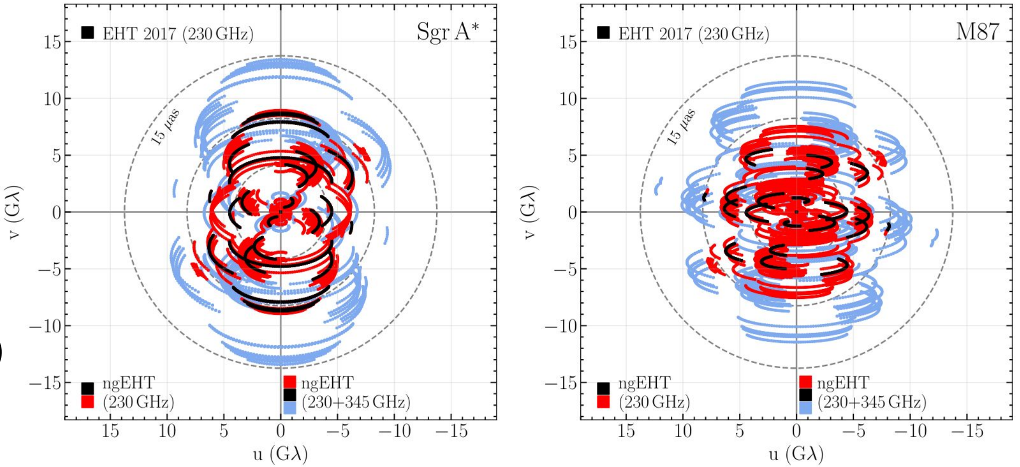
(Time permits)
future perspectives

Expanding the ground array



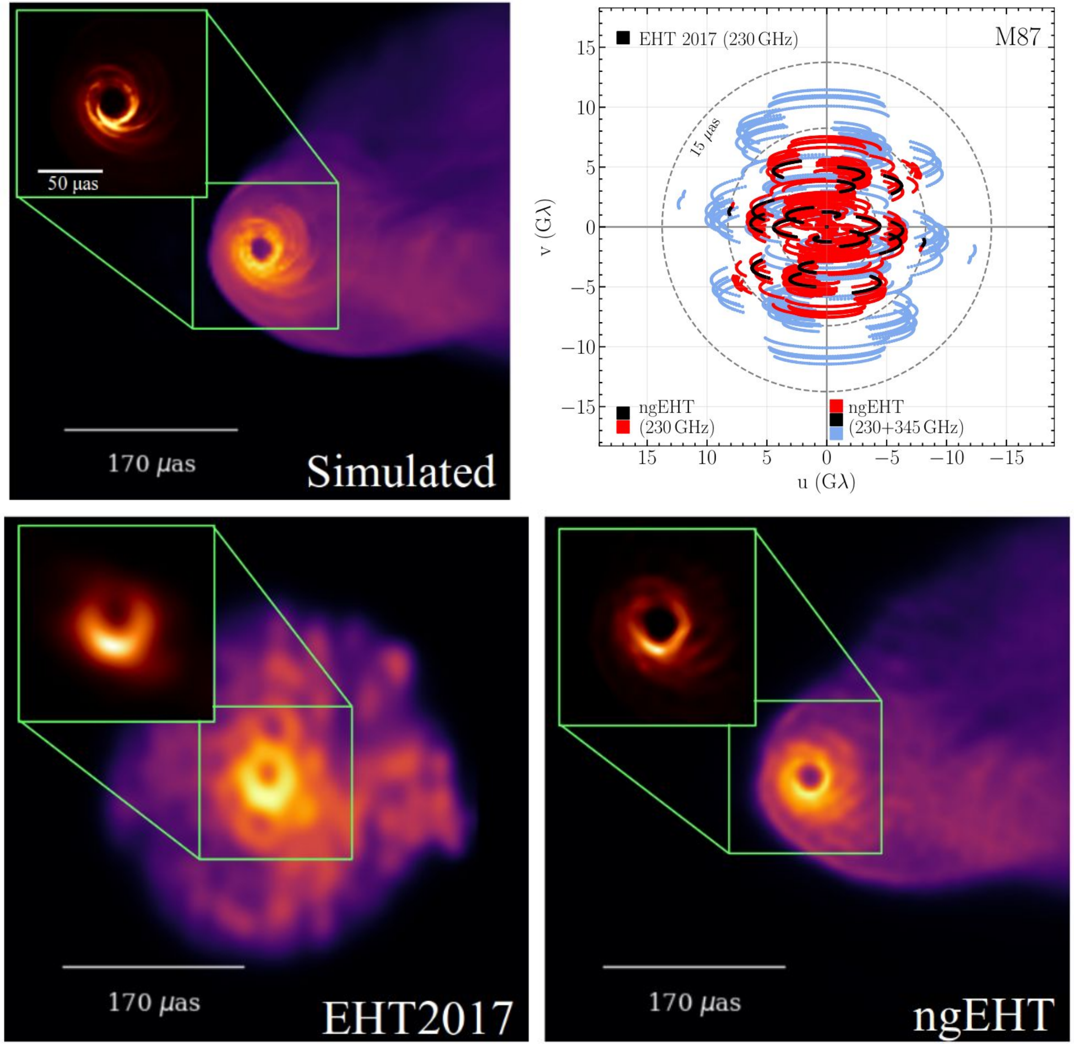
Operating/planned telescopes for 230/345 GHz

Expected improvements of the synthetic aperture (Fourier space coverage)



- Notice: Korea also involved in by the Extended KVN project; serious array design studies are ongoing (e.g., Raymond+21)

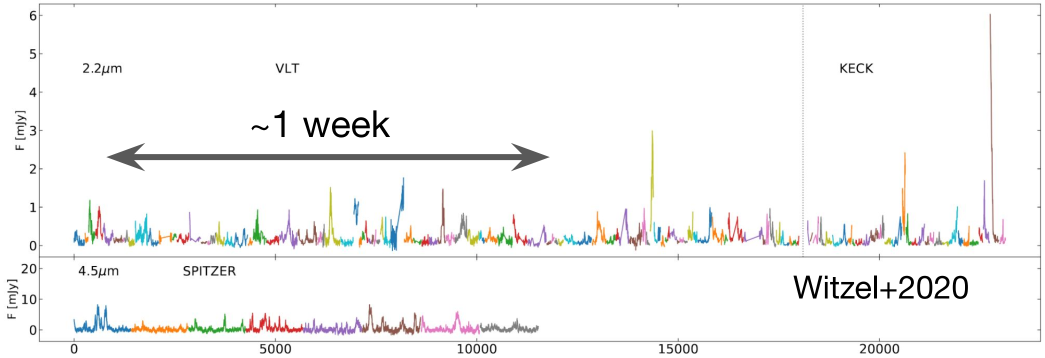
Blackburn+ 2020



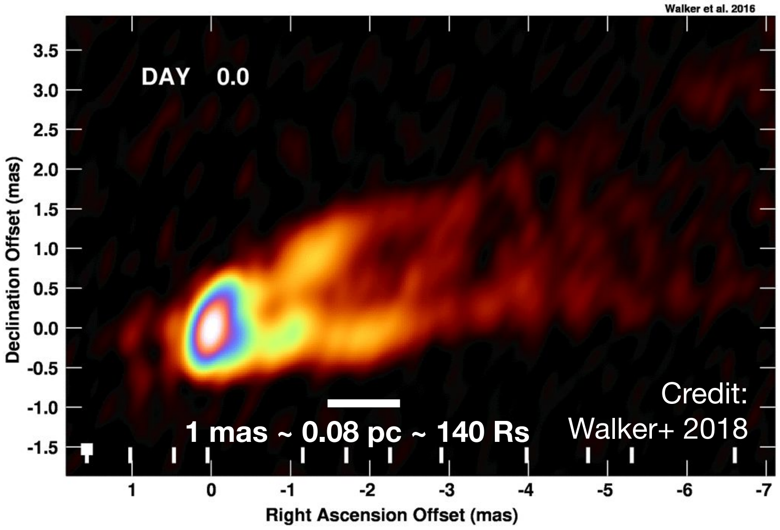
Blackburn+ 2020

Need for further state-of-the-art simulations

A real Sgr A* NIR lightcurve



M87 jet propagation



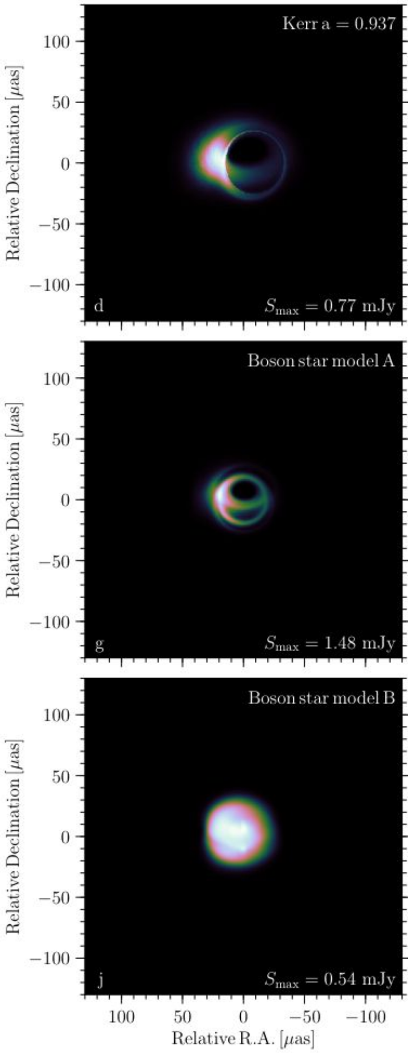
- Real BH accretion flows are likely far more complicated than any simulations
- Current simulations are limited to ~< 100 Rg, while jets propagate >> 1,000 Rg

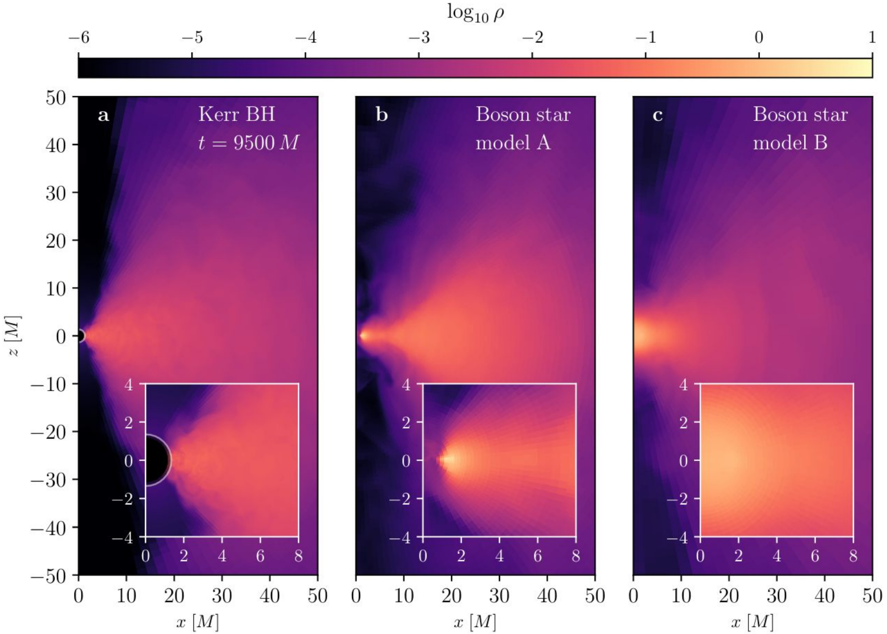
(Unmoderated) list of ongoing improvements in theory

- **Radiation** (e.g., Compton scattering)? → GR Radiation MHD (GRRMHD)
- **Magnetic energy dissipation** (e.g., reconnection)? → Resistive GRMHD (rGRMHD)
- **Particle acceleration** (e.g., non-single power-law)? → Kappa distributions and more
- **Breaking fluid assumption** (notice mean free path length >> Rg for ADAF in general!) → Kinetic particle-in-cell (PIC) plasma simulations
- **Large-scale, long-term, higher resolution** → long-run sim. on GPUs with adaptive meshes, …
- …

(See EHTC+2019e and EHTC+2021b for a brief review)

Testing alternative theories of gravity





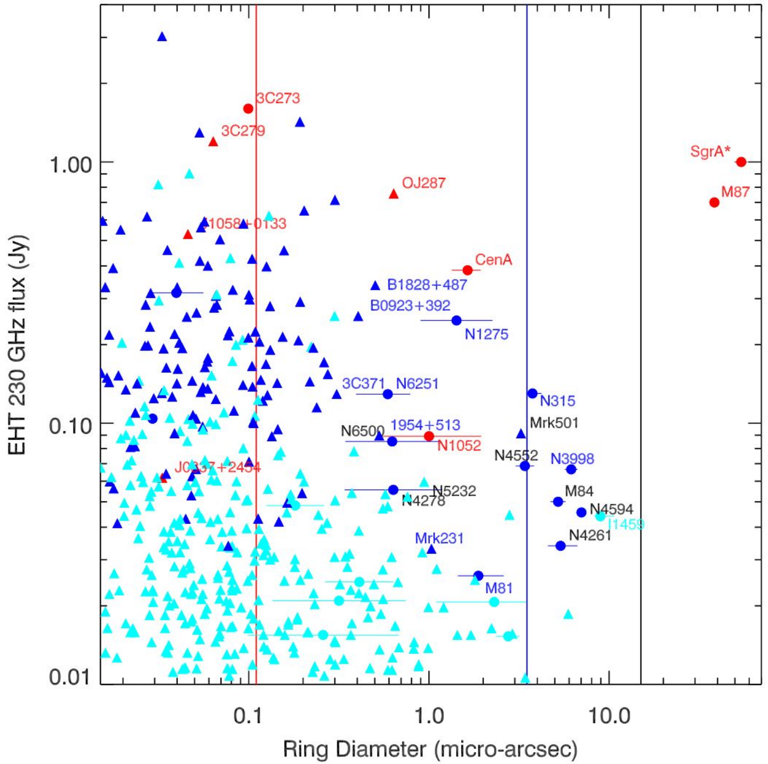
Olivares+2020
color: log(desnity)

- Now beginning to produce serious predictions for exotic objects (e.g., boson star) -- primary difficulty is calculations in strong-field regime with non-GR metrics
- Differences appear due to the surface, mass accumulation, and jet “funnel” magnetization etc.

A “population” study of BH photon rings

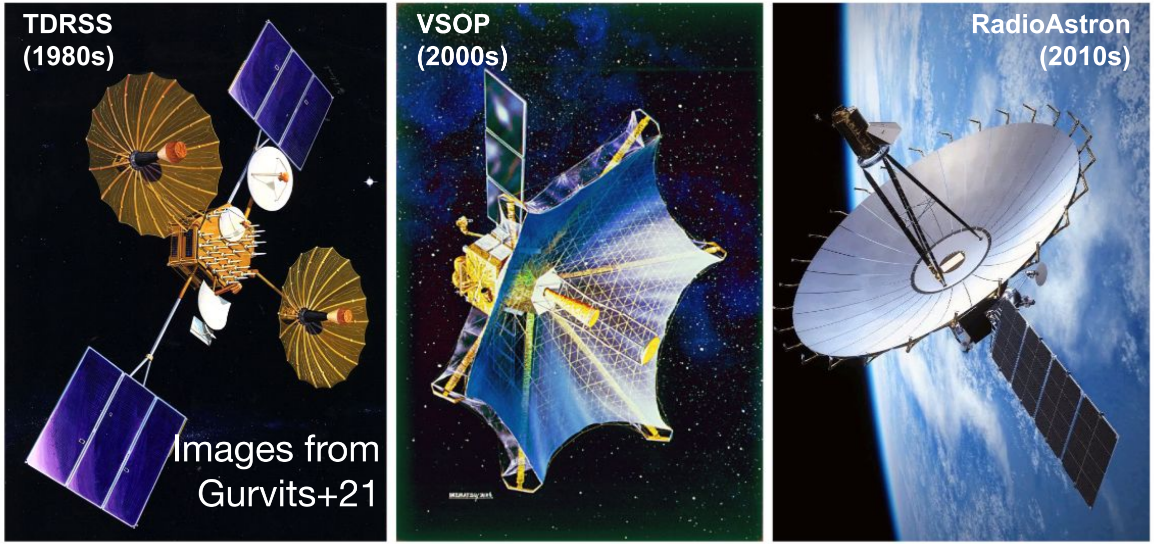
- Can we repeat the whole analysis for more BHs and test GR/astrophysics?
  - Can we observe more BHs?
  - Careful pilot studies with sample construction, size, flux, …

- Expect to find more “unexpected” systems
  - Misaligned BH and accretion flow?
  - Binary SMBHs?
  - SMBH evolution over cosmic time
  - …



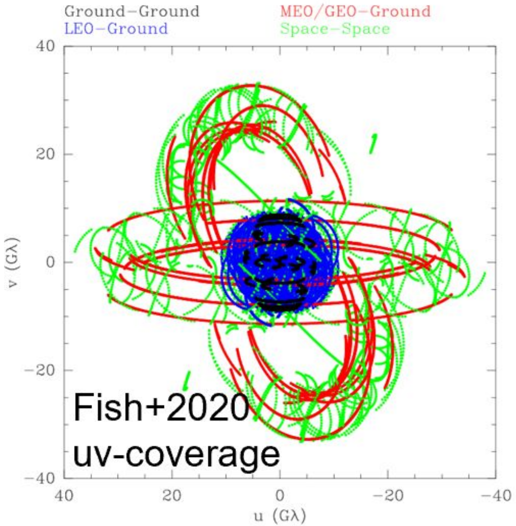
Credit: Nagar, Ramakrishnan+

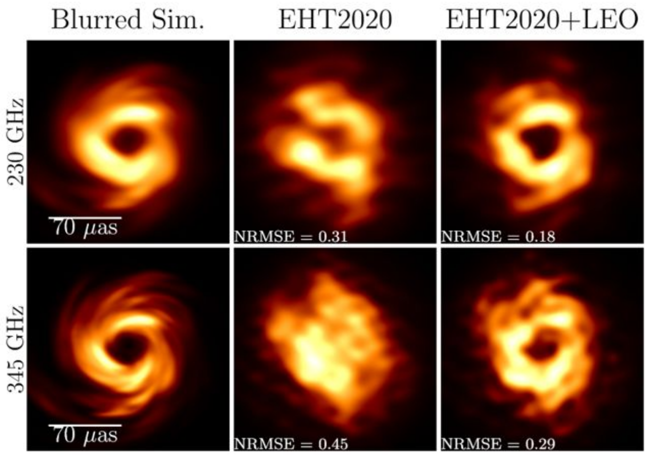
Expanding VLBI array to the space



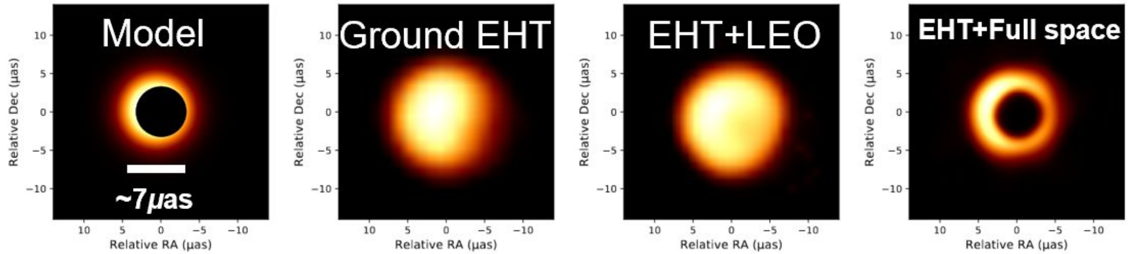
VLBI observations up to 22 GHz (1.3 cm)
already proved and performed in space

Expanding VLBI array to the space (up to mm regime)





Sgr A* 45 min snapshot (Haworth+19)

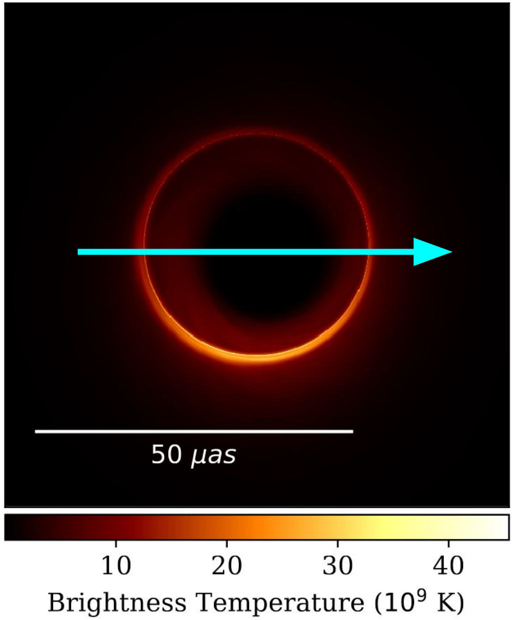


Sombrero Galaxy (shadow size ~ 7 μas; Fish+20)

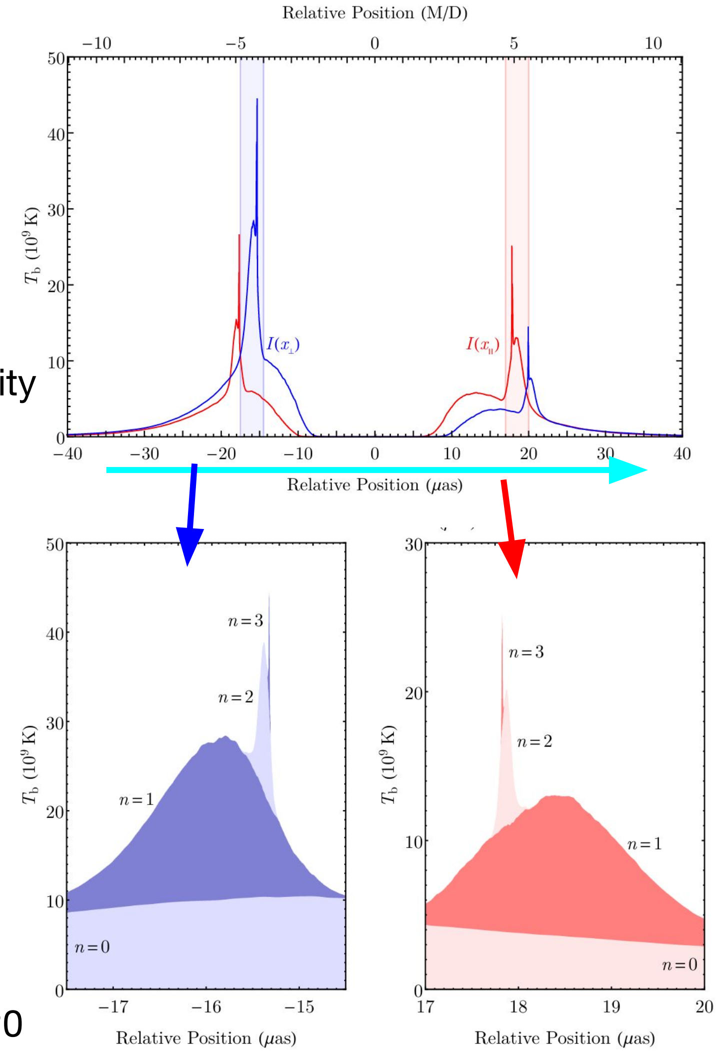
- Orbiting antennas for baselines > 1 Earth Diameter (ED)
- Short (<1ED) baselines: dense uv-coverage to image rapidly variable object (e.g., Sgr A*)
- Long (>1ED) baselines: Significantly higher angular resolution to image more BH shadow candidates
- Decadal developments needed, but likely a productive effort

Sharpening tests of GR: Anatomy of the photon ring

Time-averaged GRMHD sim.



Slice intensity profile



- Some photons can orbit around BH multiple times (n), until it escapes the compact region
- Such paths are narrower for higher n

Johnson+2020

Sharpening tests of GR:

Ar

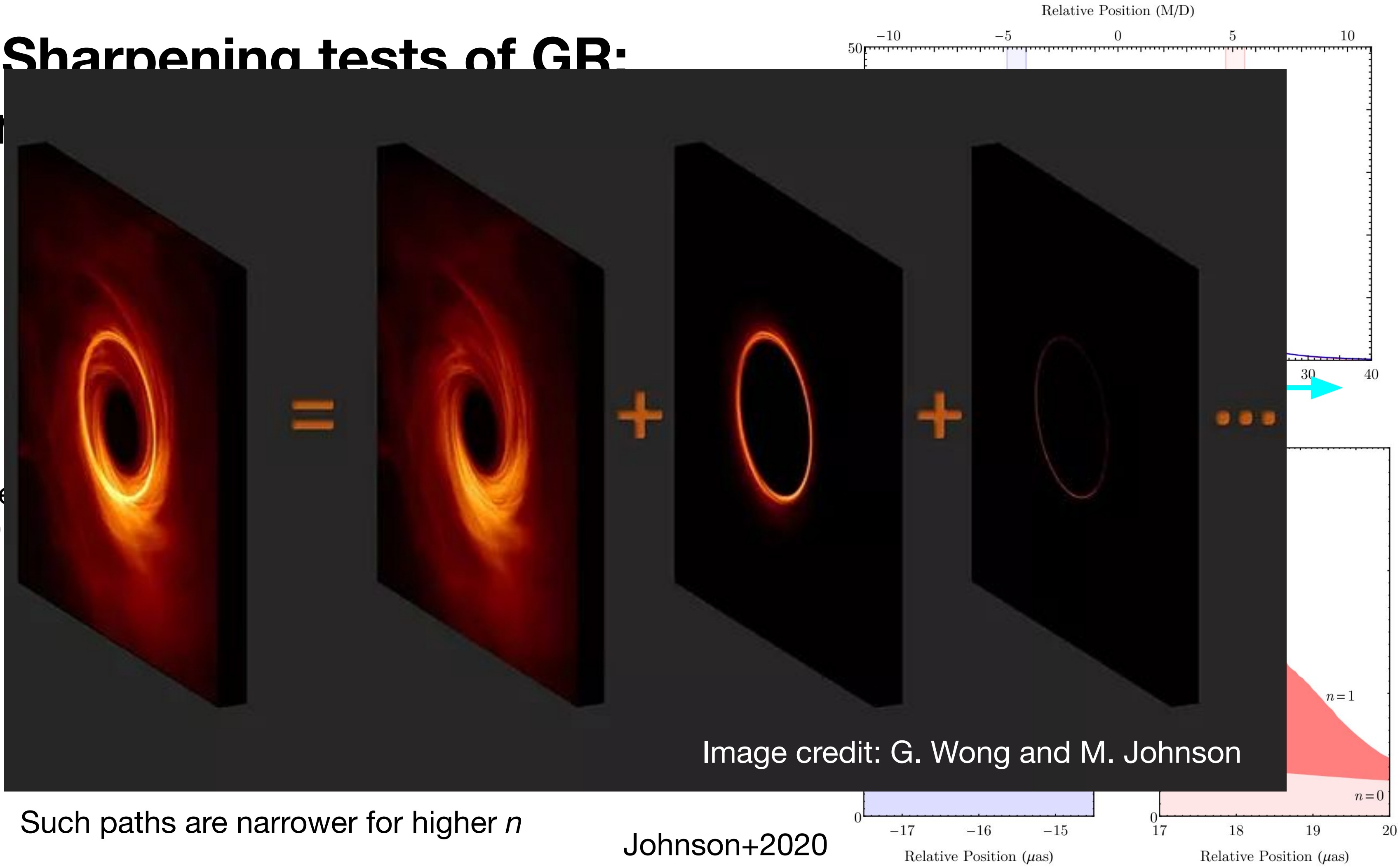


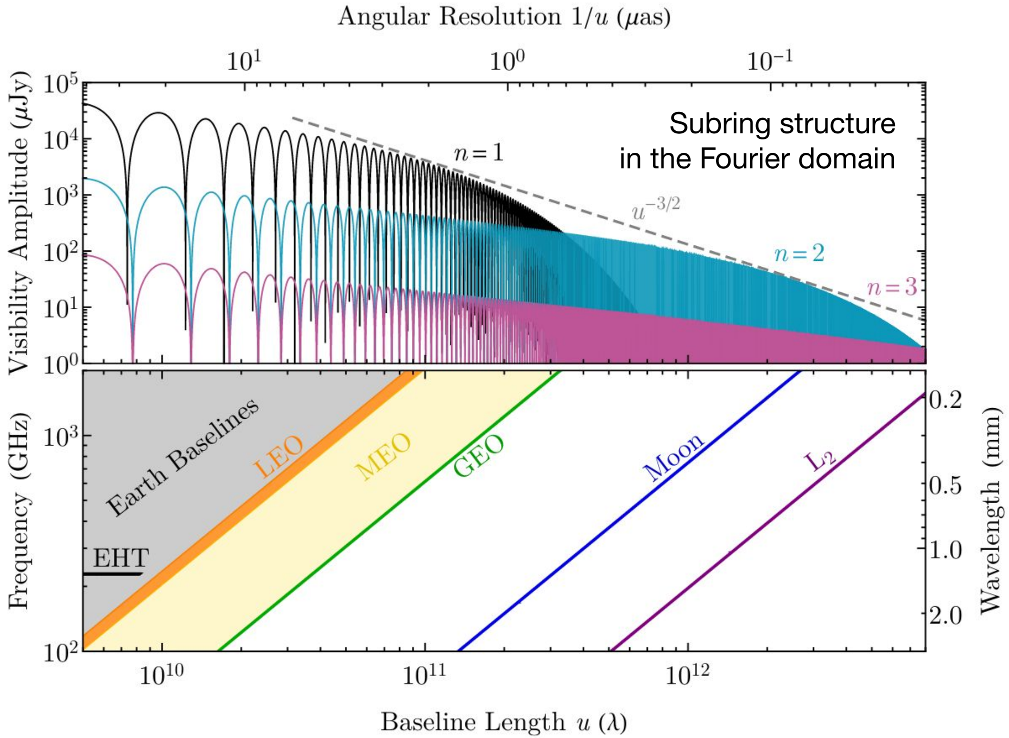
Image credit: G. Wong and M. Johnson

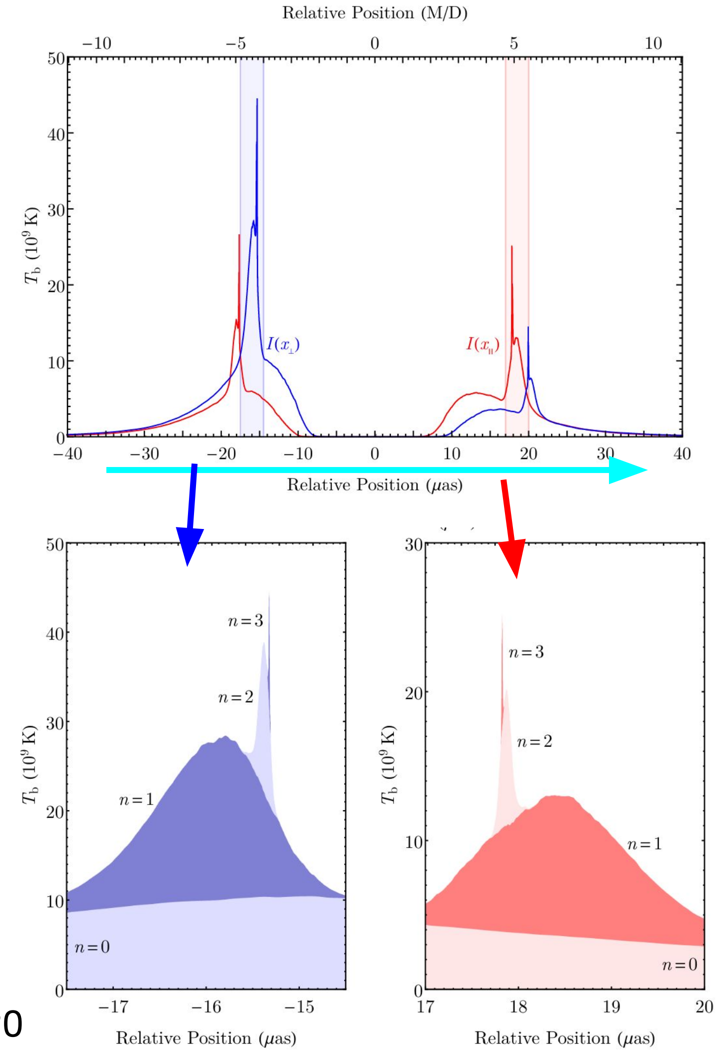
Time-ave
GRMHD

-
- Such paths are narrower for higher *n*

Johnson+2020

Sharpening tests of GR: Anatomy of the photon ring





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Final remarks

- Imaging event-horizon-scale structures in nearest SMBHs is now possible, by VLBI technology at short mm wavelengths

- The new images allow a direct test of the GR as well as sharpening our knowledge of the astrophysics by testing big assumptions

- New answers and new questions: more observations and improved theory to meet at some point

- **The golden era has come to test state-of-the-art theories of gravity and plasma physics by GW and BH with cutting-edge observing instruments**

Enjoy!

Thanks for your attention!