M87* and Sgr A*: Imaging supermassive black holes

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GOETHE UNIVERSITÄT
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RAGTIME
24th Relativistic Astrophysics Group Meeting

Plan of the talk

- How to image a black hole: **observations**
- How to image a black hole: **theory**
- Sgr A* and its differences from M87*
- Implications on gravity and alternatives to BHs

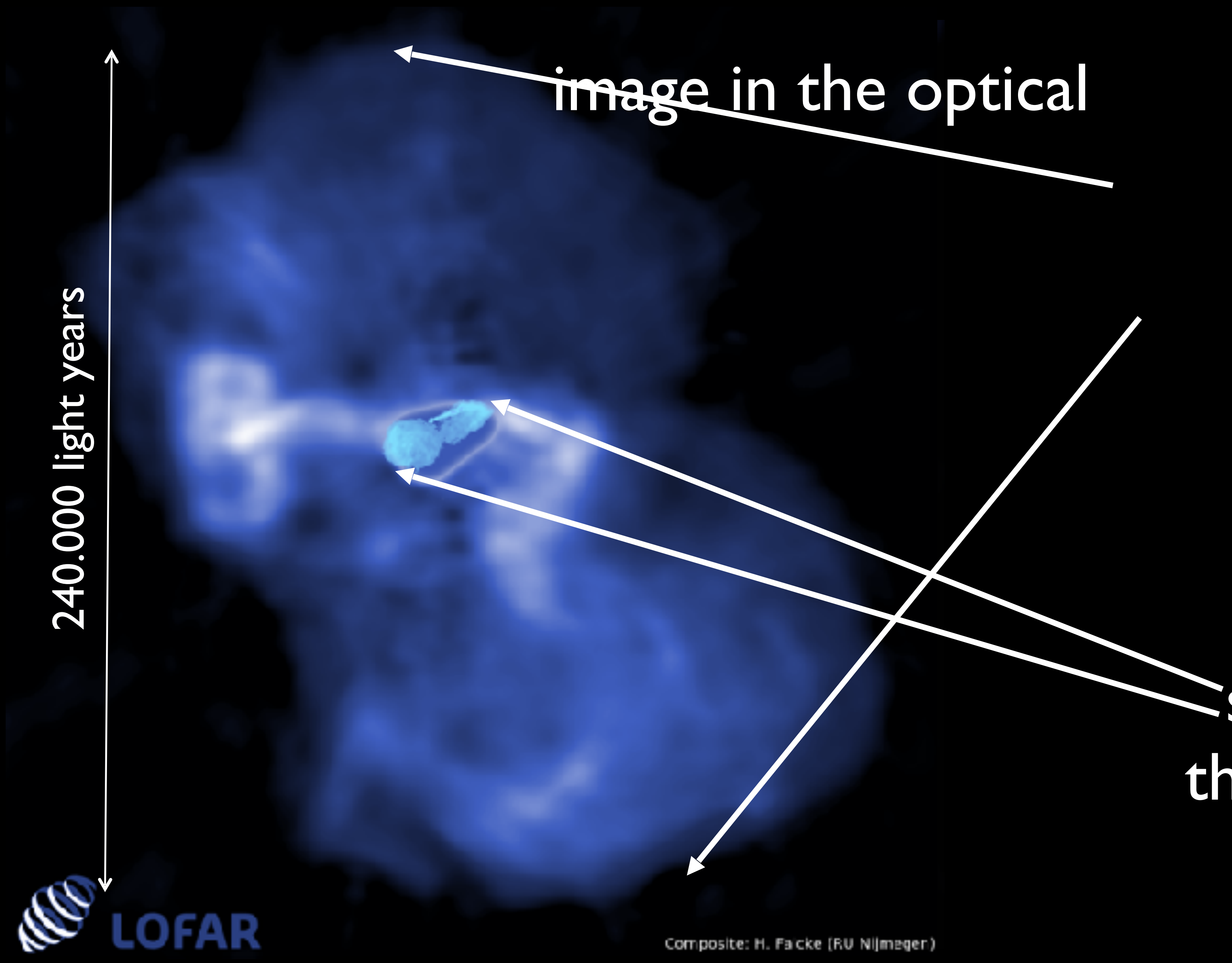
Taking a picture of a black hole: observations

A very basic problem

- Black holes (BHs) are most compact objects known
- BHs are at astronomical distances
- BH must have a resolvable projected size on the sky

Need very massive BHs and sufficiently close to us: M87*, Sgr A*, … IC1459, NGC4594

M87: Elliptical galaxy in center of Virgo cluster (5.5e7 light years); evidence for a “dark” mass of $3\text{-}6\times10^{9}\ M_{sun}$



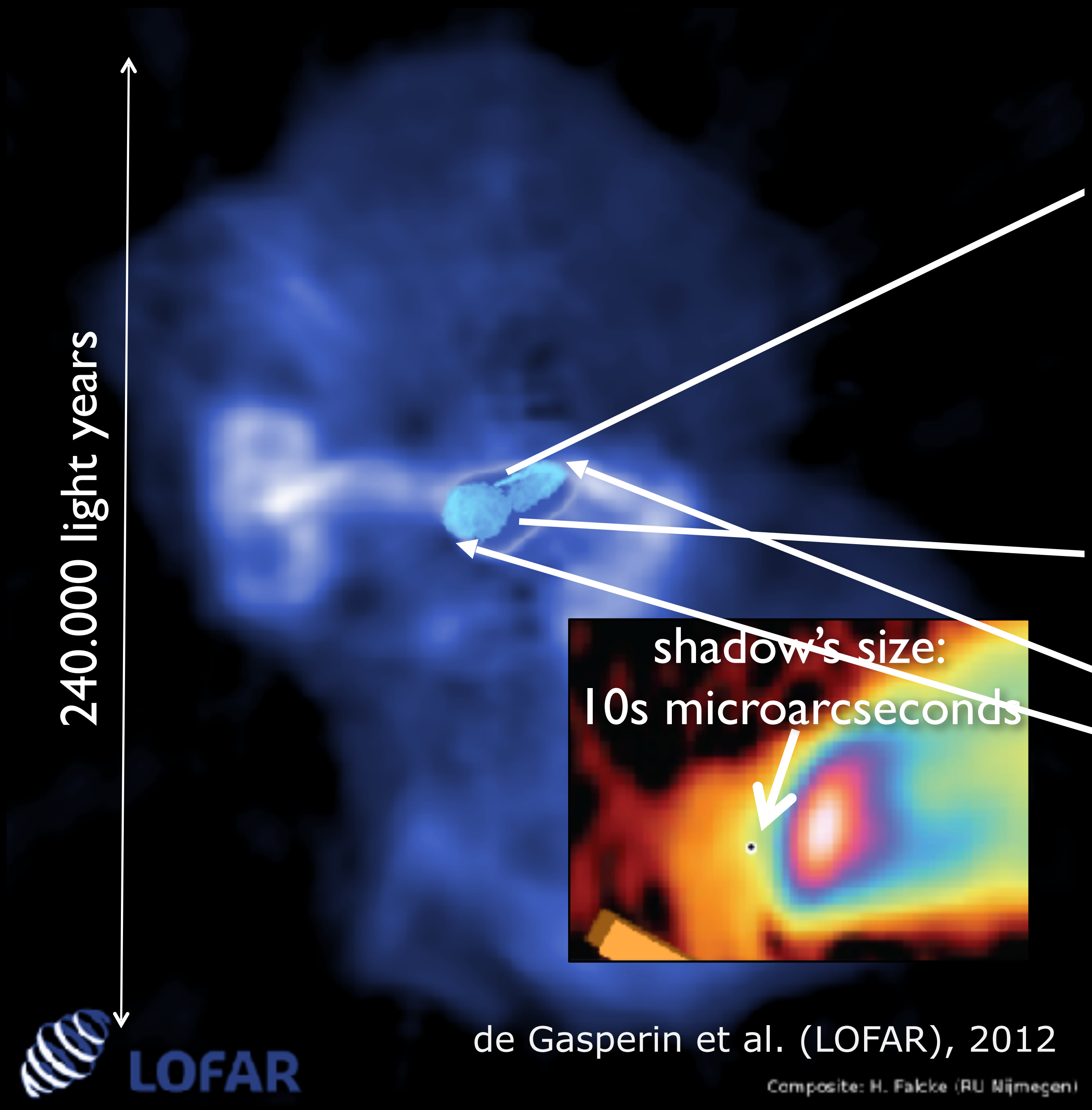
Composite: H. Falcke (RU Nijmegen)

image in the optical

Large-scale radio map (few cm wavelengths)

small-scale radio map of the core (cm wavelength)

M87: Elliptical galaxy in center of Virgo cluster (5.5e7 light years); evidence for a "dark" mass of 3-6×10^9 M_{sun}



small-scale radio map of the core (cm wavelength)

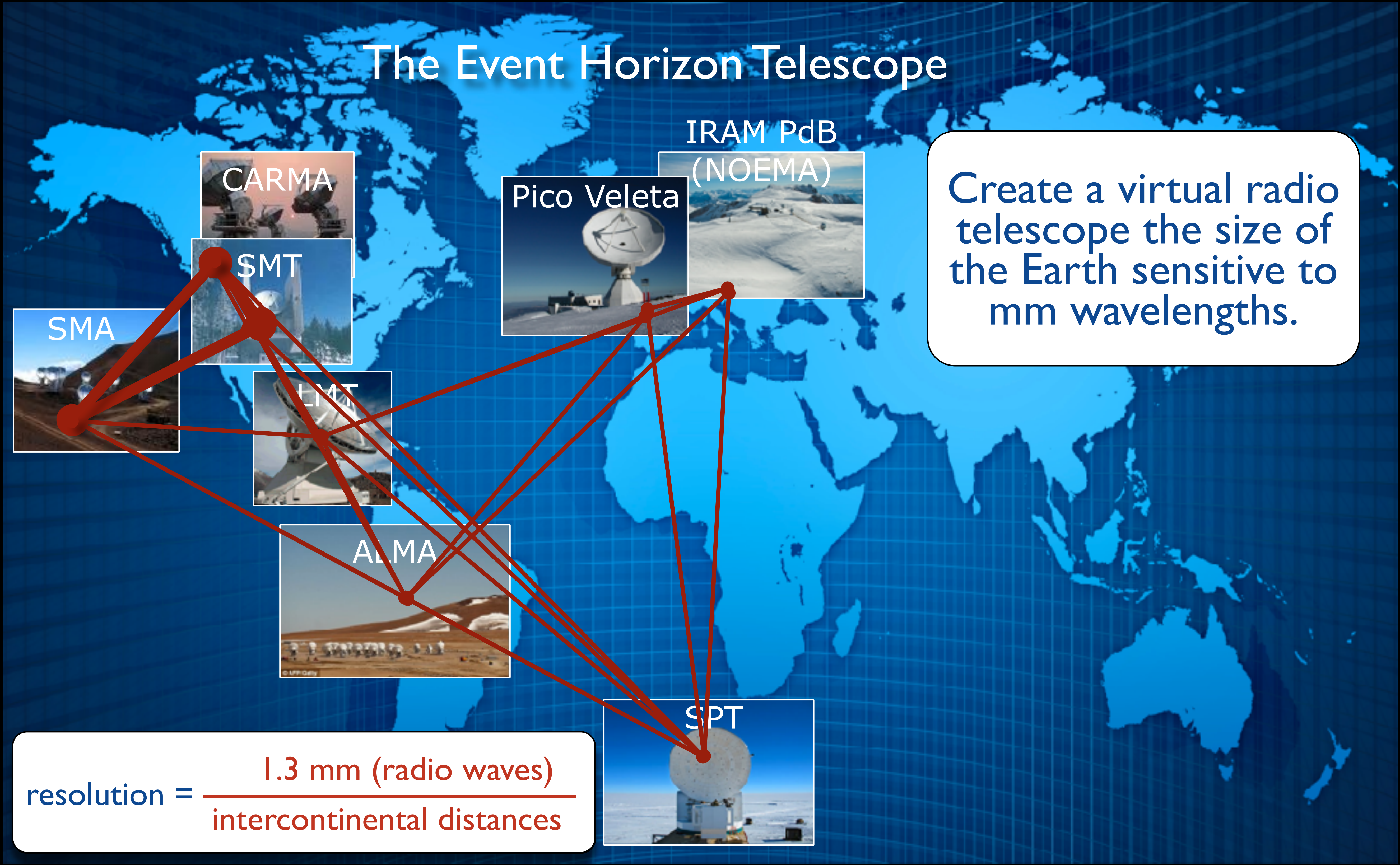
de Gasperin et al. (LOFAR), 2012

Composite: H. Falcke (RU Nijmegen)

VLBI: Very Long Baseline Interferometry

$$\text{resolution} = \frac{\text{wavelength}}{\text{telescope size}}$$

VLBI: Very Long Baseline Interferometry



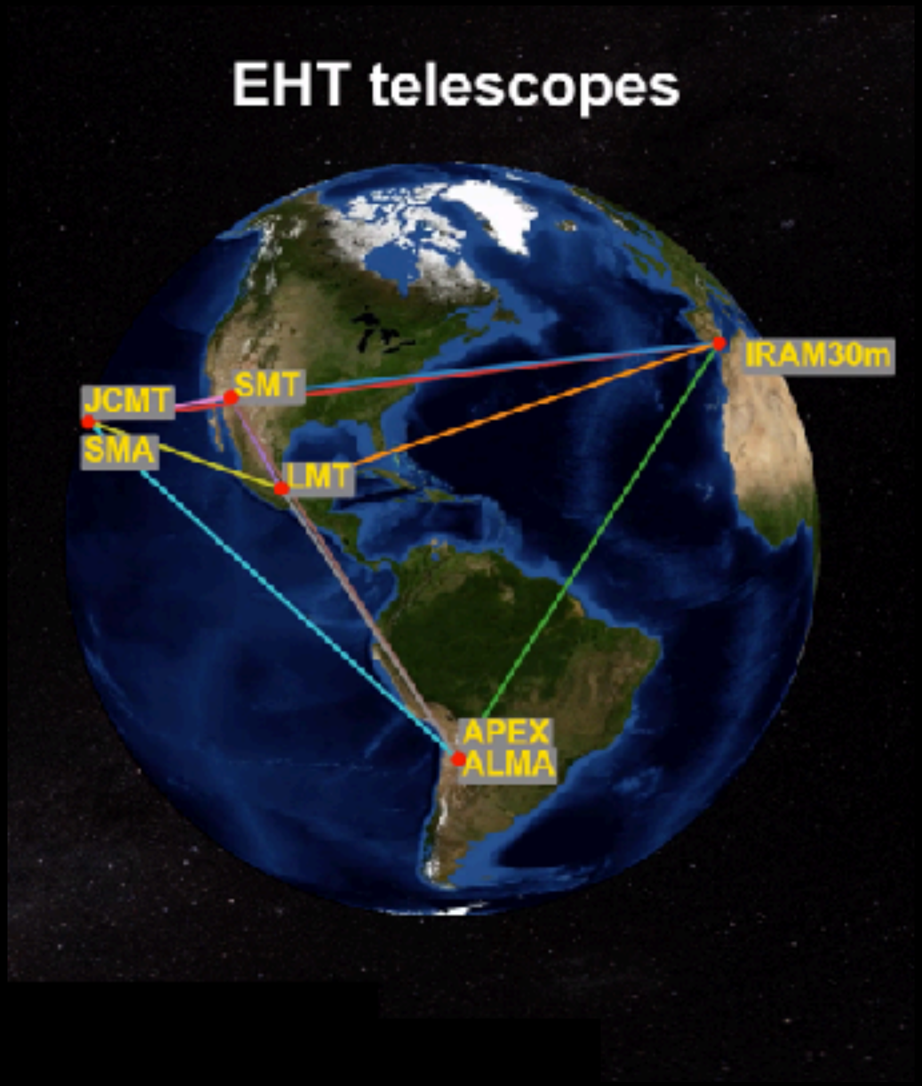
The Event Horizon Telescope

Create a virtual radio telescope the size of the Earth sensitive to mm wavelengths.

$$\text{resolution} = \frac{\text{1.3 mm (radio waves)}}{\text{intercontinental distances}}$$

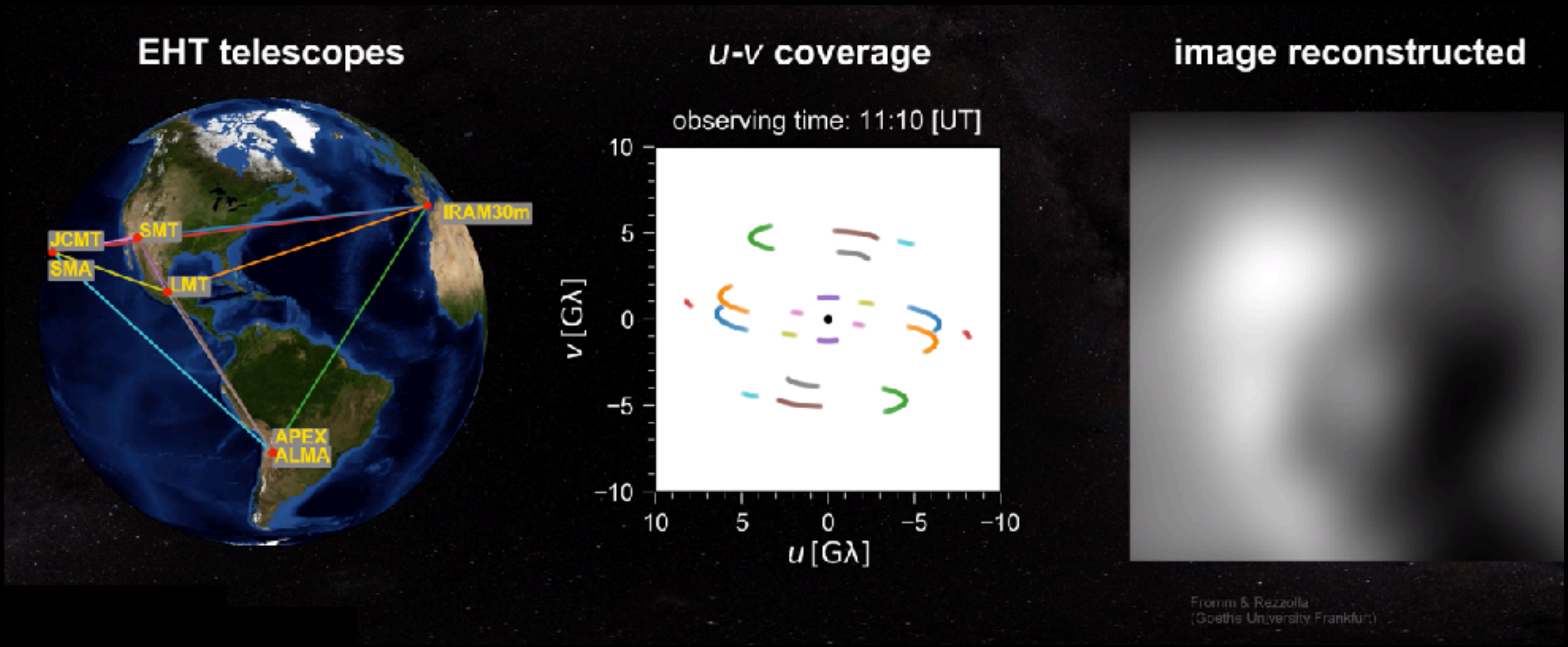
Observations

$$\mathcal{V}(u,v) = \int\int e^{-2\pi i(ux+vy)} I(x,y)\,dx\,dy$$



Observations

$$\mathcal{V}(u,v) = \int\int e^{-2\pi i(ux+vy)} I(x,y)\,dx\,dy$$



EHT telescopes

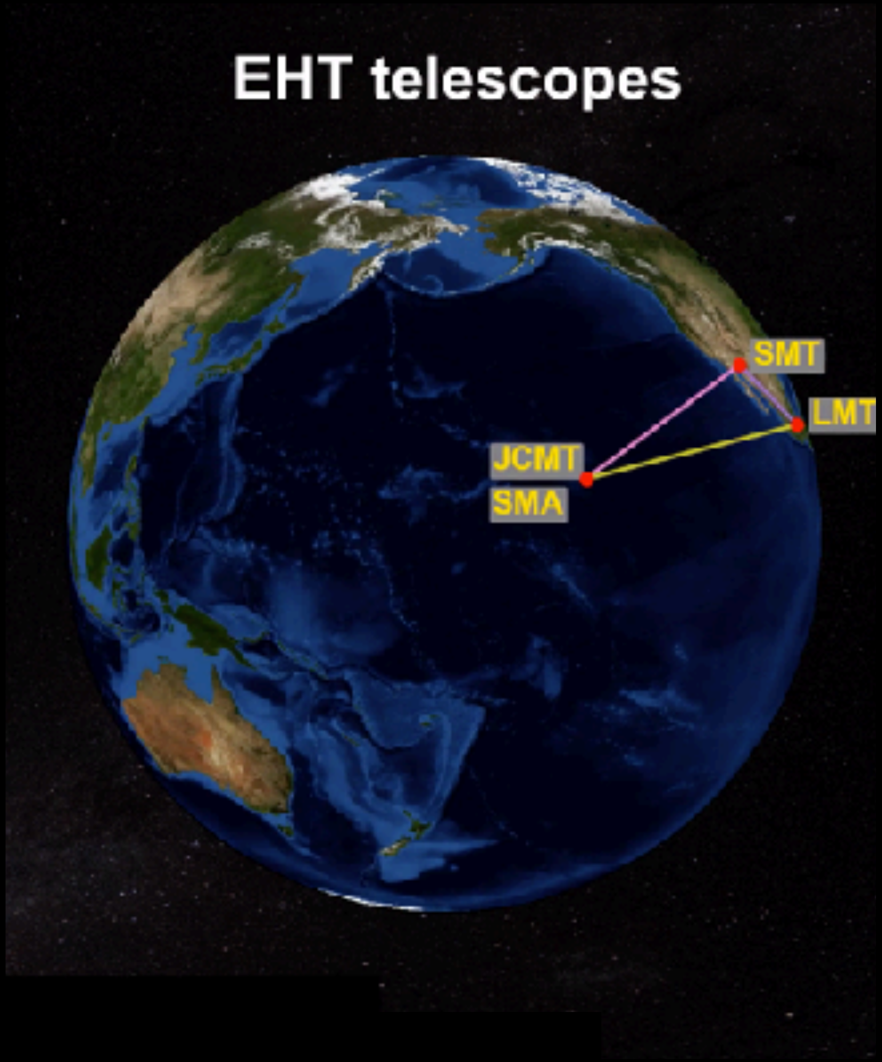
u-*v* coverage

image reconstructed

Fromm & Rezzolla (Goethe University Frankfurt)

Observations

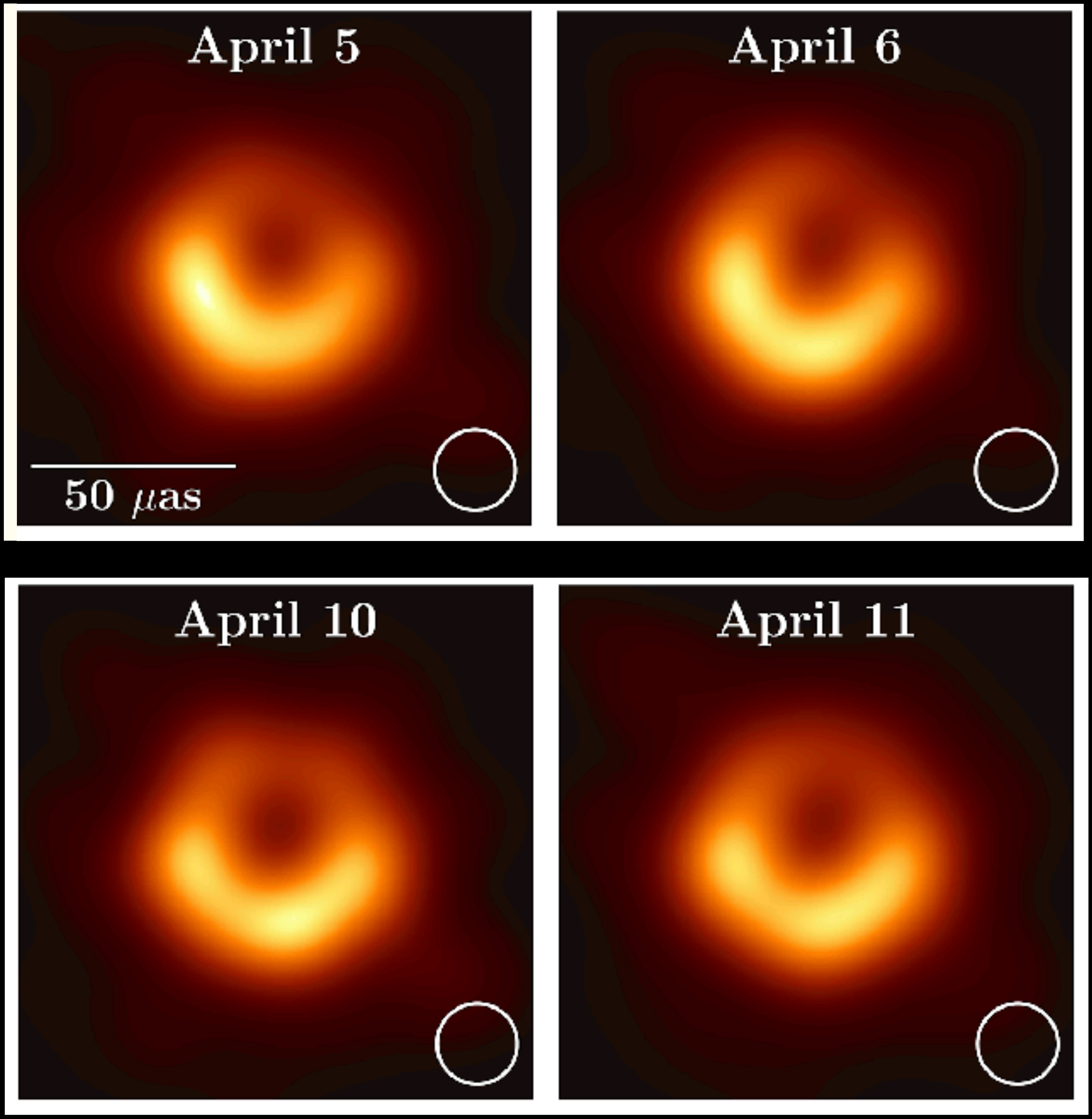
$$\mathcal{V}(u,v) = \int\int e^{-2\pi i(ux+vy)} I(x,y)\,dx\,dy$$



Observations

M87 was observed for several days (eight) and lead to four distinct images.

The images are slightly different but show again that the asymmetric ring emission is stable, as expected on these timescales.



Taking a picture of a black hole: theory

Three basic steps are needed:

1. **GRMHD simulations** in arbitrary spacetimes
(understand how matter falls onto black holes)

2. **ray-traced, radiative-transfer**, **images**

(understand how light is produced and propagates)

3. **comparison** with **observations**.
(compare tens of thousands theoretical images
with a few observed ones)

System of equations to solve...

$$\nabla_\mu T^{\mu\nu} = 0\,, \quad \text{(cons. energy/momentum)}$$

$$\nabla_\mu (\rho u^\mu) = 0\,, \quad \text{(cons. rest mass)}$$

$$p = p(\rho, \epsilon, Y_e, \ldots)\,, \quad \text{(equation of state)}$$

$$\nabla_\nu F^{\mu\nu} = I^\mu\,, \qquad \nabla_\nu^* F^{\mu\nu} = 0\,, \quad \text{(Maxwell equations)}$$

$$T_{\mu\nu} = T_{\mu\nu}^{\text{fluid}} + T_{\mu\nu}^{\text{EM}} + \ldots \quad \text{(energy}-\text{momentum tensor)}$$

These **GRMHD equations** are solved using finite-volume methods with a variety of algorithms in 3+1 dimensions.

In addition…

$$\nabla_\mu T^{\mu\nu} = 0\,, \quad \text{(cons. energy/momentum)}$$

$$\nabla_\mu(\rho u^\mu) = 0\,, \quad \text{(cons. rest mass)}$$

$$p = p(\rho, \epsilon, Y_e, \ldots)\,, \quad \text{(equation of state)}$$

$$\nabla_\nu F^{\mu\nu} = I^\mu\,, \qquad \nabla^*_\nu F^{\mu\nu} = 0\,, \quad \text{(Maxwell equations)}$$

$$T_{\mu\nu} = T^{\rm fluid}_{\mu\nu} + T^{\rm EM}_{\mu\nu} + \ldots \quad \text{(energy}-\text{momentum tensor)}$$

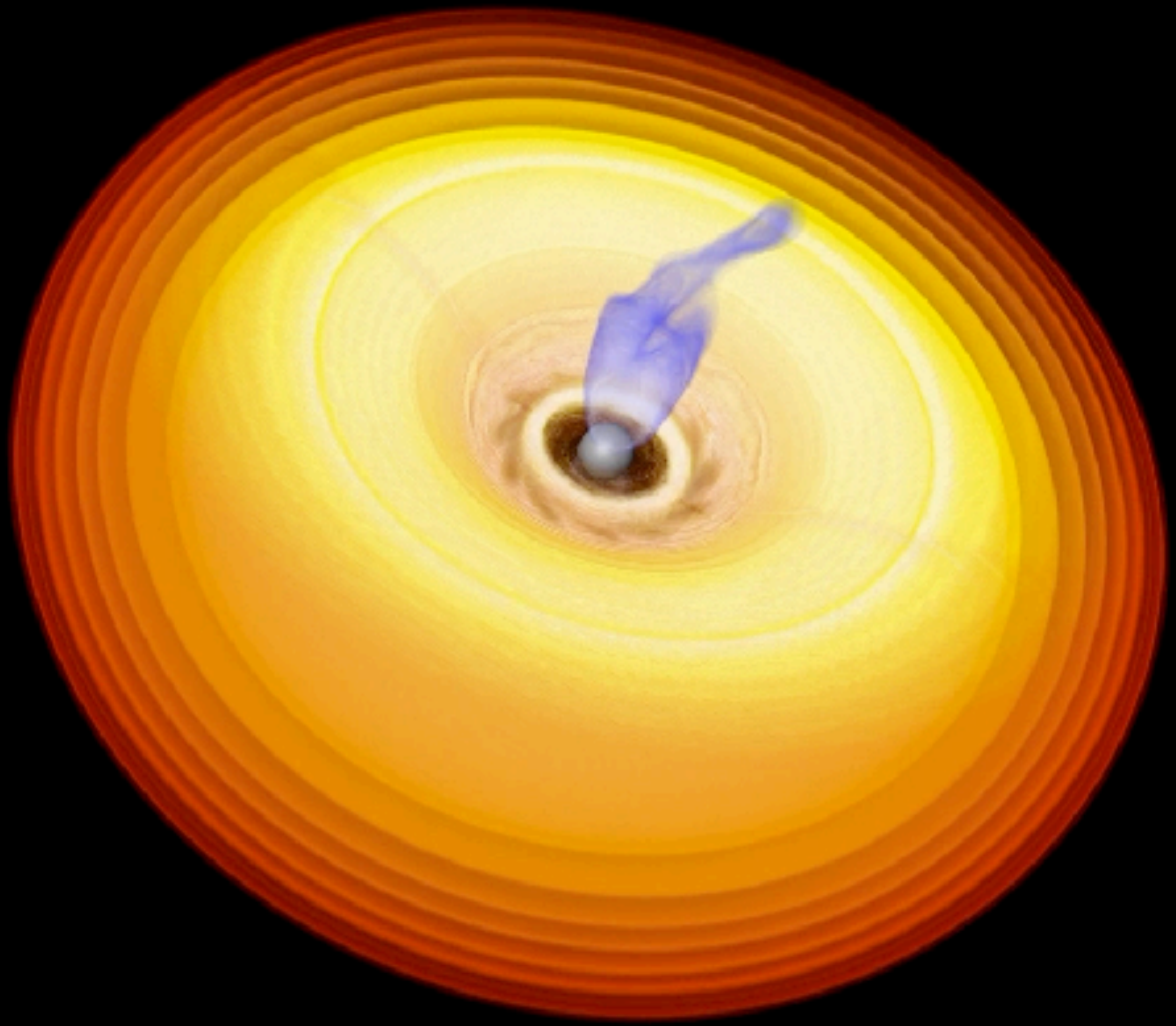
The equations of **general-relativistic radiative transfer (GRRT)** need to be solved in the background spacetime.

$$\frac{d\mathcal{I}}{d\lambda} = -k_\mu u^\mu \left(-\alpha_{\nu,0}\,\mathcal{I} + \frac{j_{\nu,0}}{\nu_0^3}\right) \quad \text{(radiative}-\text{transfer eq.)}$$

$$\mathcal{I} := I_\nu/\nu^3 \qquad \tau_\nu\,(\lambda) = -\int_{\lambda_0}^{\lambda} \alpha_{\nu,0}\,(\lambda')\,k_\mu u^\mu\,d\lambda'$$

1. Plasma dynamics:
a typical GRMHD simulation…

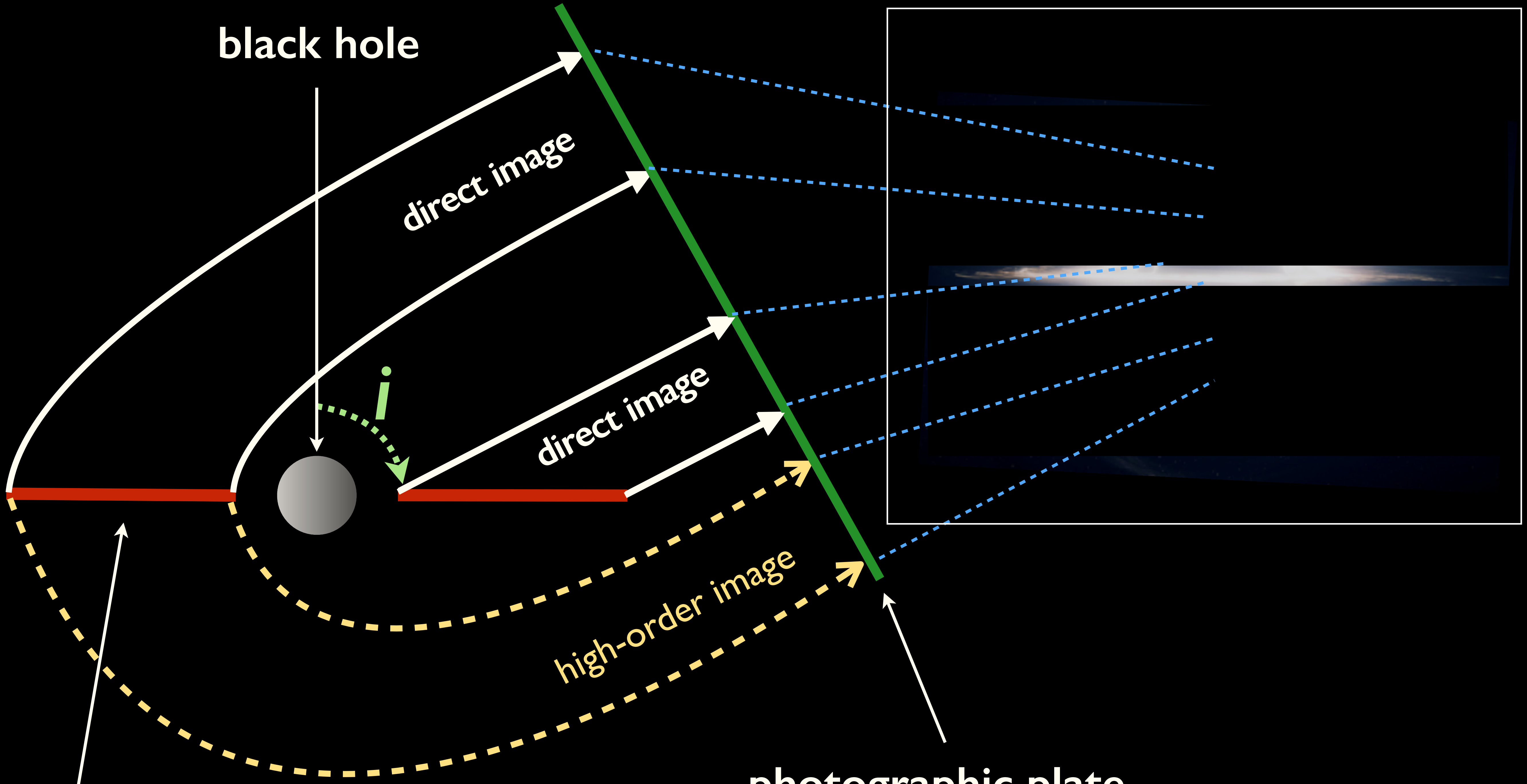
A three-dimensional simulation of a Kerr black hole (a=0.9375) in Kerr-Schild coordinates and an MRI unstable torus would produce results of this type…



L. R. Weih & L. Rezzolla
(Goethe University Frankfurt)

L. Weih, LR

Tracing photons near a BH is **not easy**…



black hole

direct image

i

direct image

high-order image

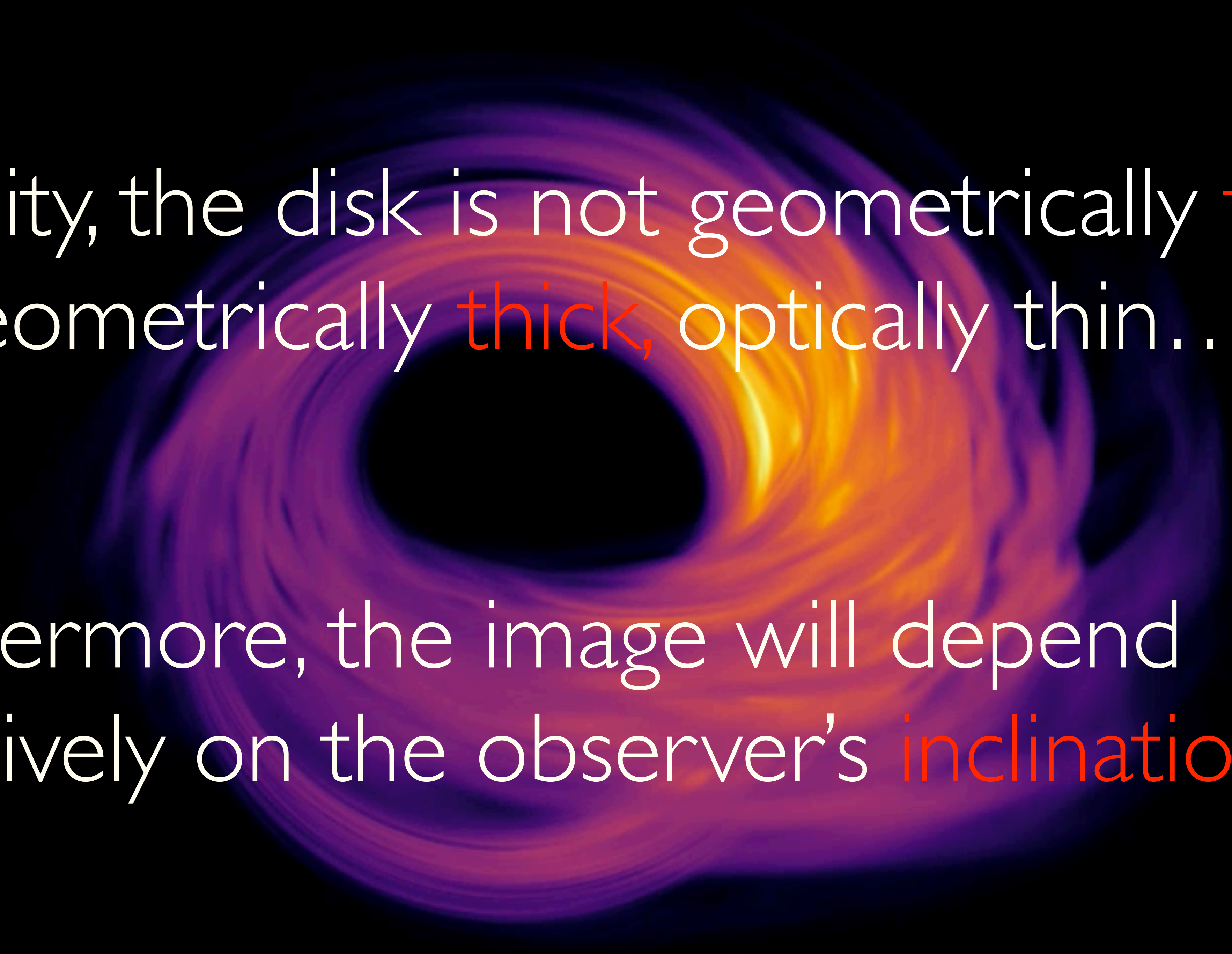
photographic plate

thin disk

Younsi, LR 2019

"Interstellar" (2014)

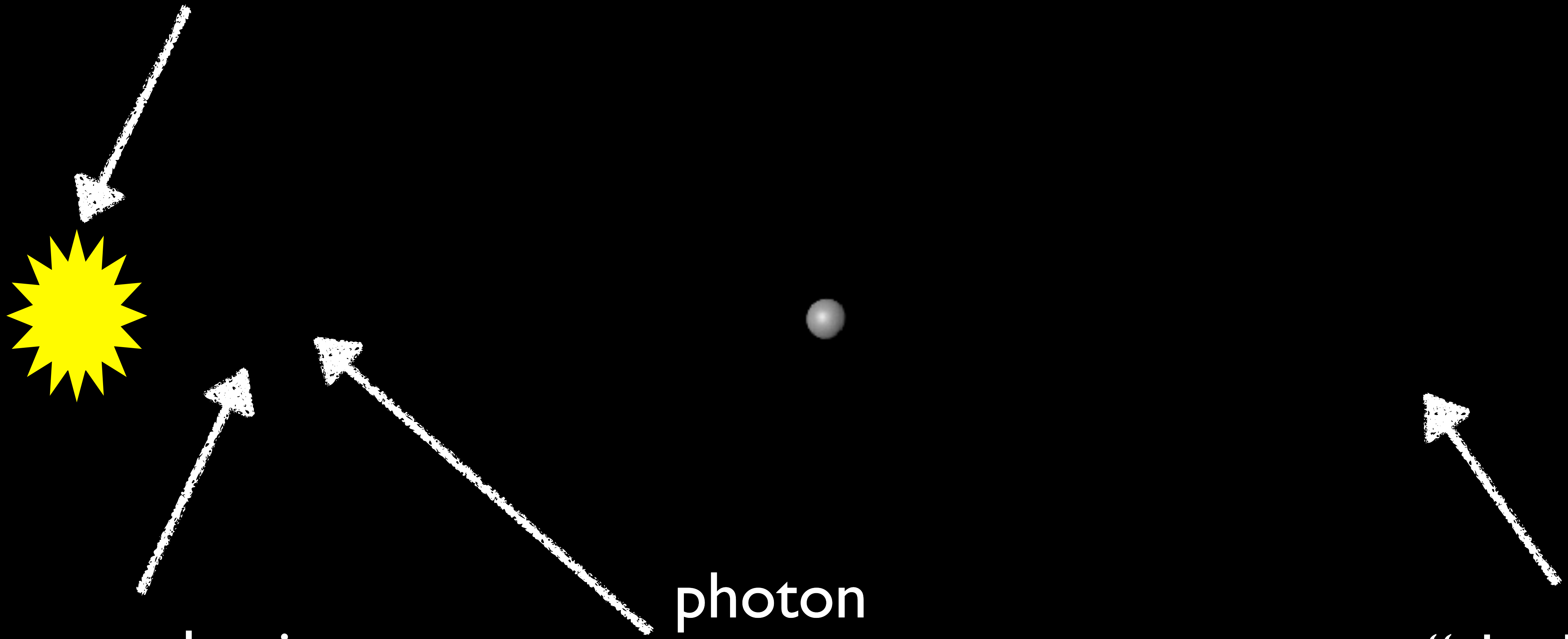
If you have to hide, do not go behind a black hole!…



In reality, the disk is not geometrically thin but geometrically thick, optically thin…

Furthermore, the image will depend sensitively on the observer's inclination

What is the "shadow"?



source of light

event horizon

photon
circular orbit

"shadow"

$$r_{\rm EH} = \frac{2GM}{c^2}$$

$$r_{\rm co} = \frac{3GM}{c^2}; \quad r_{\rm c} := b_{\rm c}\big|_{r_{\rm co}} = \sqrt{27}\left(\frac{GM}{c^2}\right)$$

Müller, Pössel, Weih, LR

Space of parameters

✴ Spacetime properties

- black-hole mass and spin
- black holes in other theories of gravity
- alternatives to black holes (horizonless COs w/ or w/o surface)

✴ Plasma dynamics and properties

- accretion type regulated by importance of magnetic field:
  - ✴ "SANE": standard accretion (thinner disk and slim jets)
  - ✴ "MAD": magnetically arrested (thicker disc and broad jets)

✴ Light dynamics and properties

- microphysics of emission (synchrotron emission, disk/jet component)
- orientation wrt to observer (two free angles)

Electron thermodynamics

- Emission of 1.3 mm radiation expected from synchrotron radiation.
- Simulations evolve temperature of bulk of fluid (ions); electron temperature and energy distribution undetermined.
- Thermal temperature distribution is reasonable approximation.
- T_e deduced from T_i via "plasma parameter": $\beta_p := p_{\rm gas}/p_{\rm mag}$

$$\frac{T_i}{T_e} = R_{\rm high}\frac{\beta_p^2}{1+\beta_p^2} + \frac{1}{1+\beta_p^2}$$

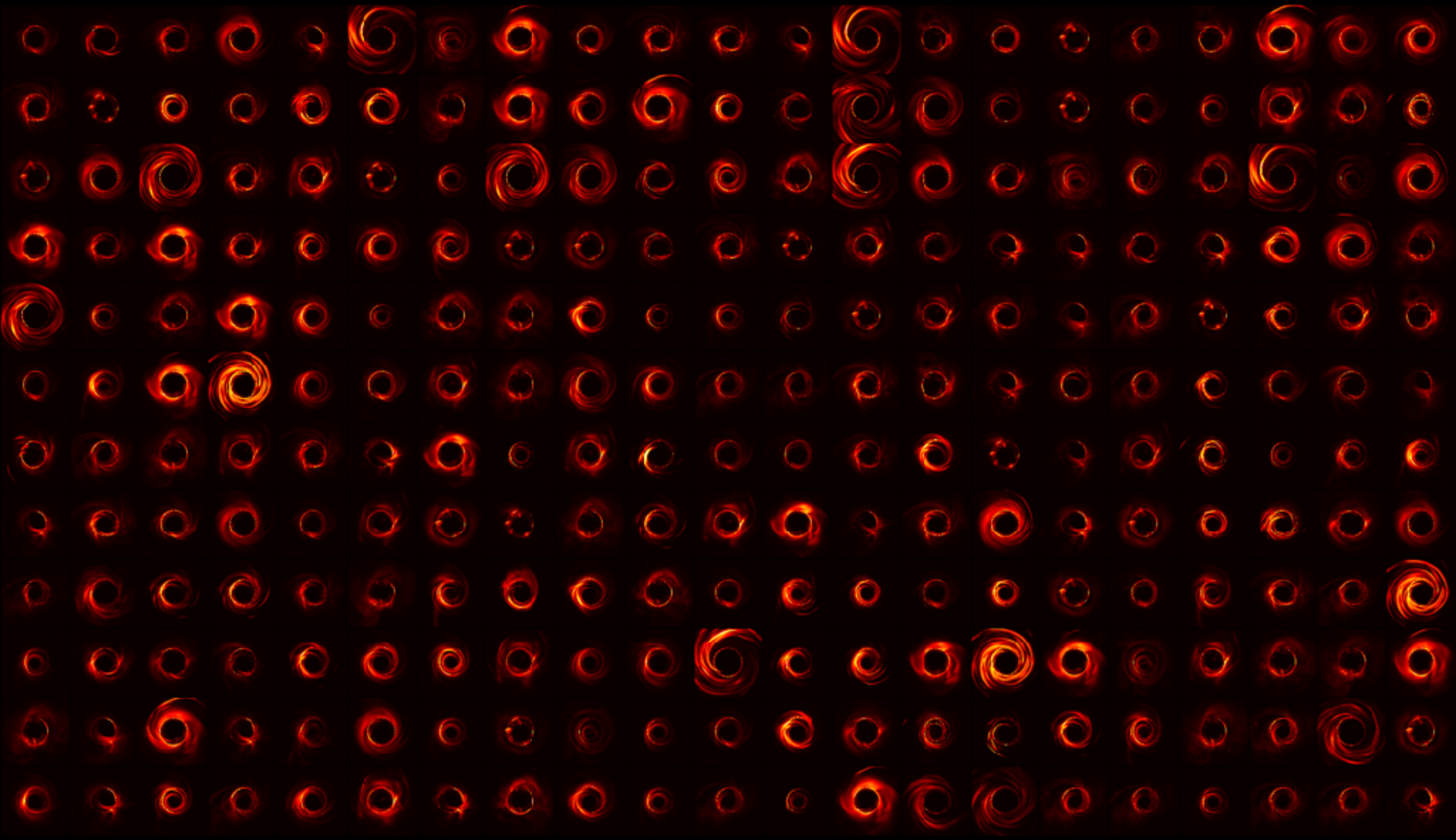
Mościbrodzka+ 2016

- Electrons colder at high beta (i.e., disk), warmer at low beta (i.e., jet).
- $R_{\rm high} = [1, 10, 20, 40, 80, 160]$ treated as free parameter.
- Despite crudeness, prescription recovers well more complex energy distributions (turbulent heating, magnetic reconnection) **Mizuno+ 2021**

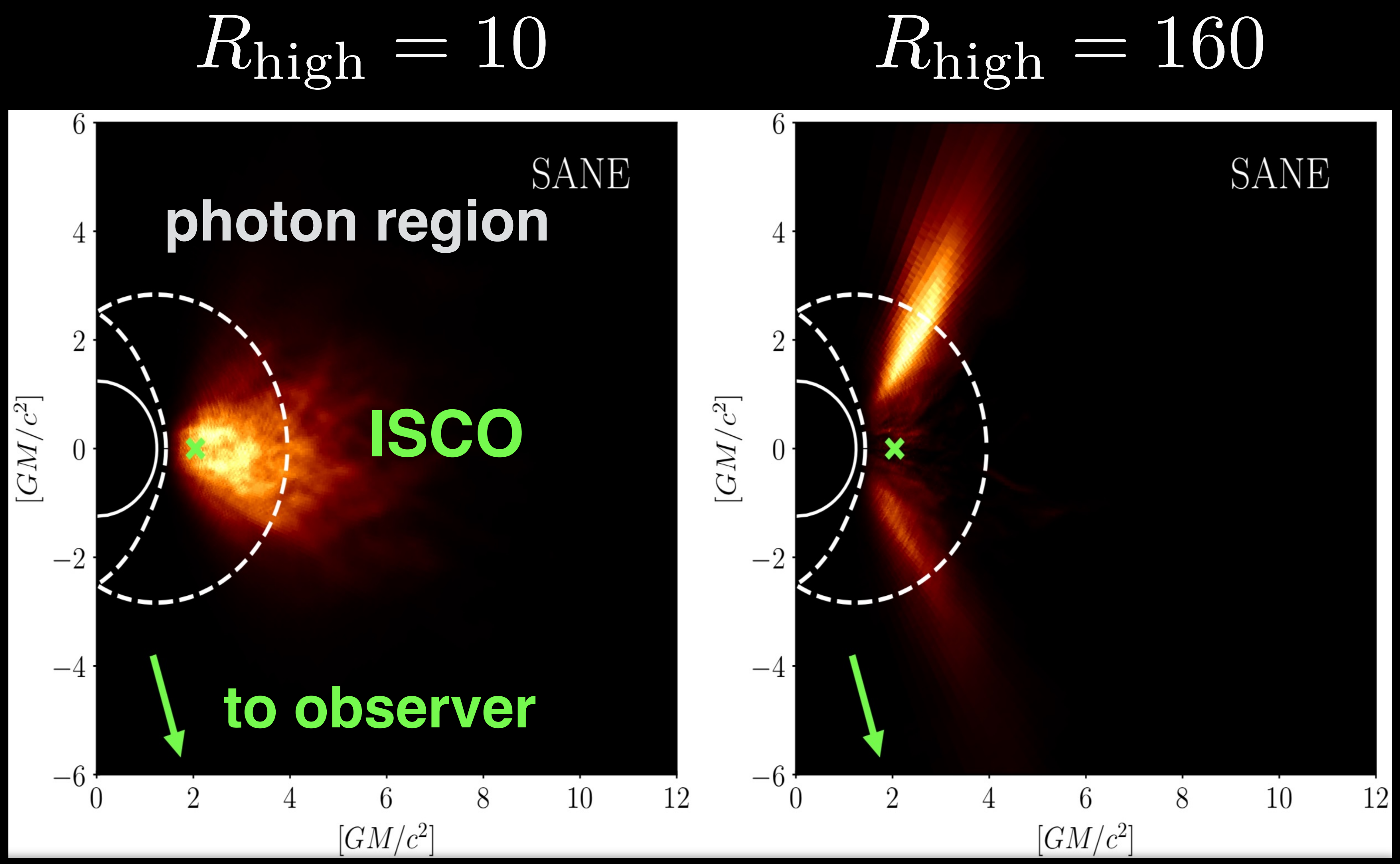
- Given physical assumptions (spin, magnetisation), 3D GRMHD simulations were made: ~ *50 high-res simulations*.

- From each simulation several scenarios are constructed by changing the *thermodynamics of the electrons:* ~ *400* scenarios.

Simulation library (an example...)



Where do the mm-long photons originate?



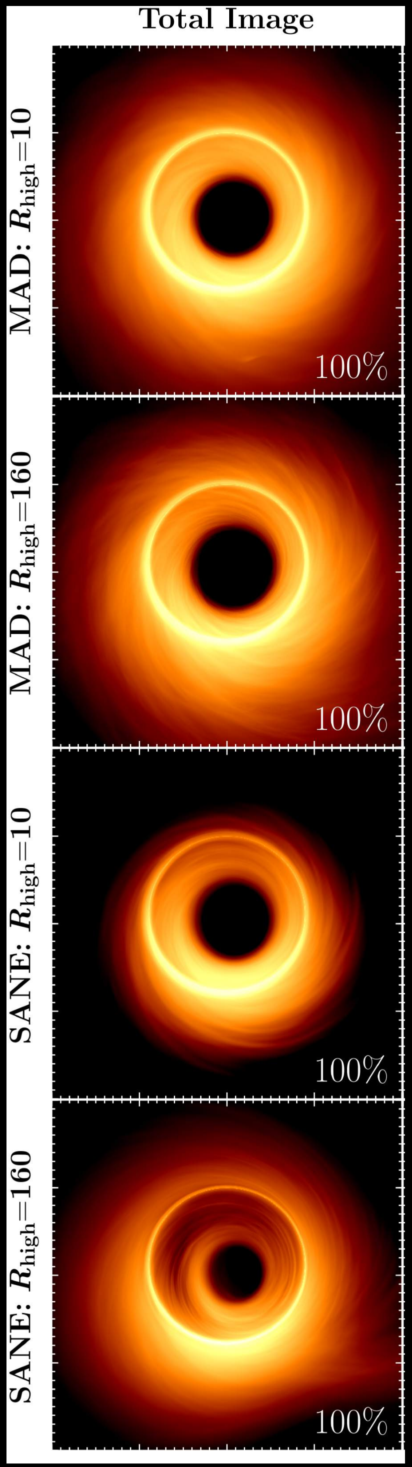
SANE: can switch from equatorial plane to funnel wall

MAD: mostly from the equatorial plane

Image is combination of emissions…

Image decomposed in: **midplane, nearside,** and **farside**

Depending on accretion mode and R_{high} it is possible to have different contributions to dominate, even receding jet!



- Given physical assumptions (spin, magnetisation), 3D GRMHD simulations were made: ~ *50 high-res simulations*.

- From each simulation several scenarios are constructed by changing the *thermodynamics of the electrons*: ~ *400* scenarios.

- From each scenario synthetic images are constructed after radiative transfer and light bending: ~ *60,000 images*.

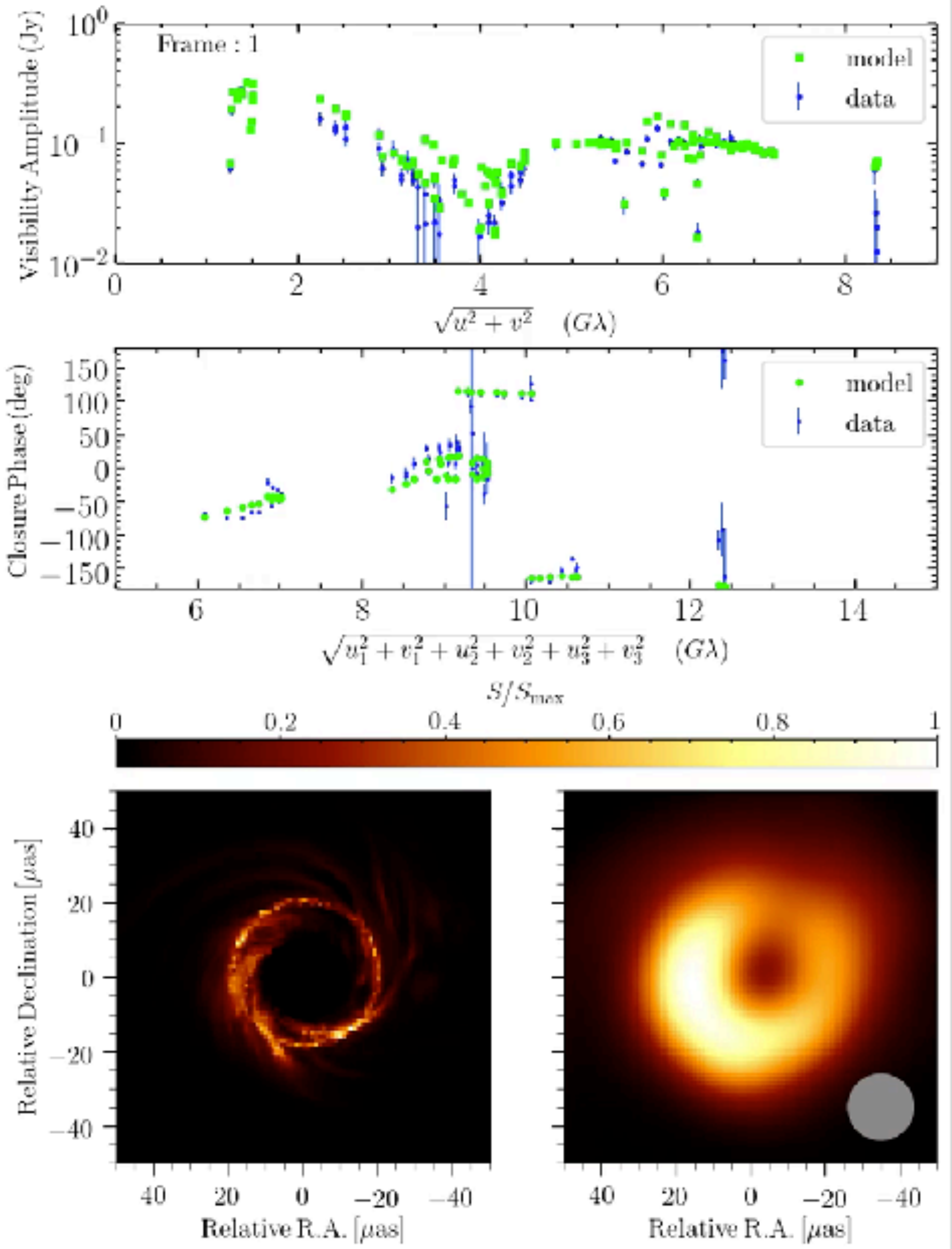
- Genetic algorithms and MCMC pipelines find best match.

Fitting the images to the data

visibility amplitude (VA)

Closure phase (CP)

GRMHD image (left) and convolved image (right)



Fromm, Younsi, LR

original image

test image 0

Top-10 best matches

The match is found in the visibility space, but can also be found in image space.

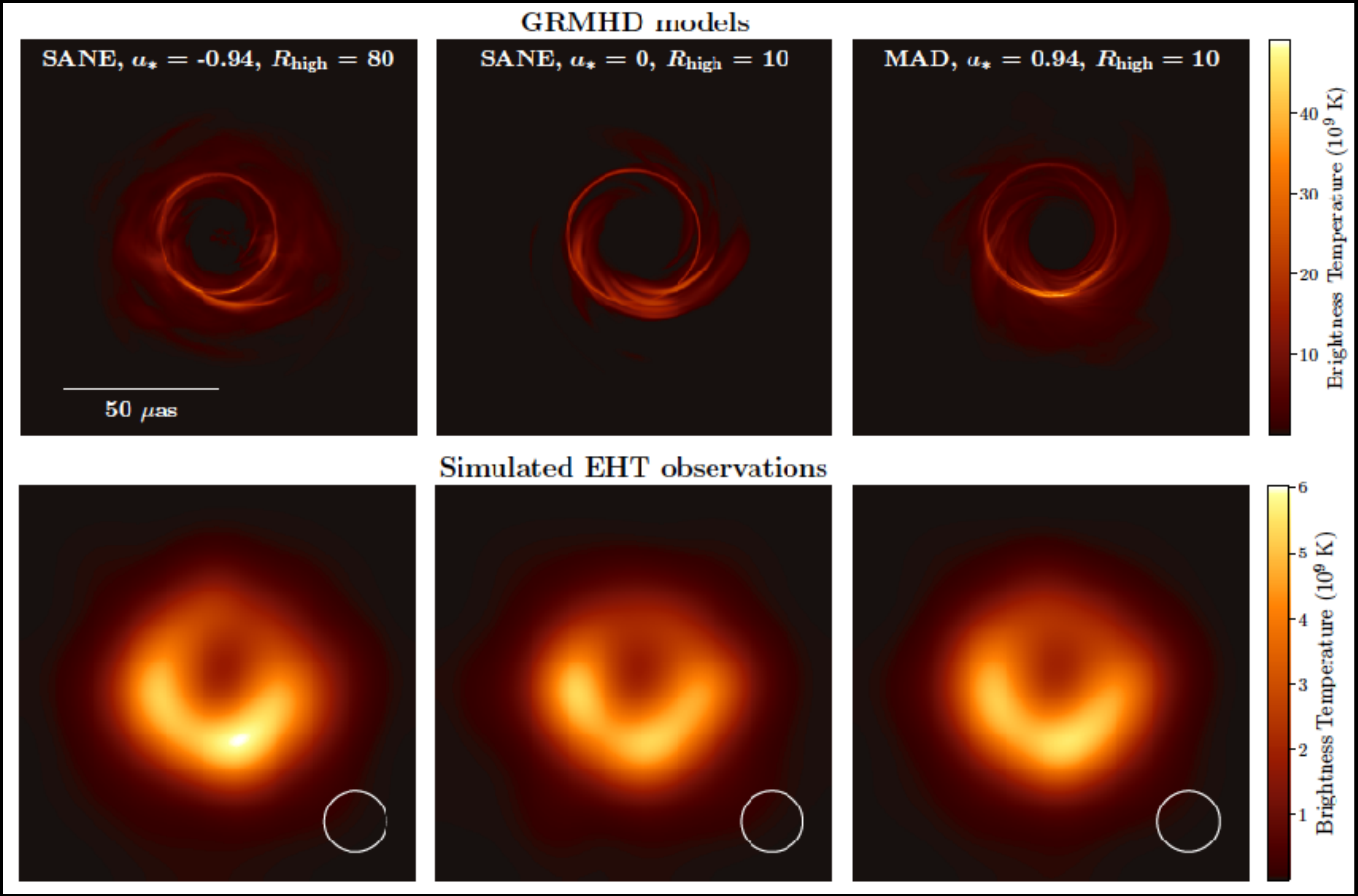
In the image space this would correspond to searching a face in a stadium full of people…

Images:
A Style-Based Generator Architecture for Generative Adversarial Networks
Karras T., Laine S. and Aila T., 2018

The comparison does not provide only **four matches** but to a **distribution** of matches with different chi-squareds

OBSERVATIONS

THEORETICAL MODEL



- Degeneracies present in physical conditions and scenarios.

  Good: robustness of conclusions (BHs produce ring)

  Bad: more accurate observations to determine BH spin

What changes in all this in the case of Sgr A*?

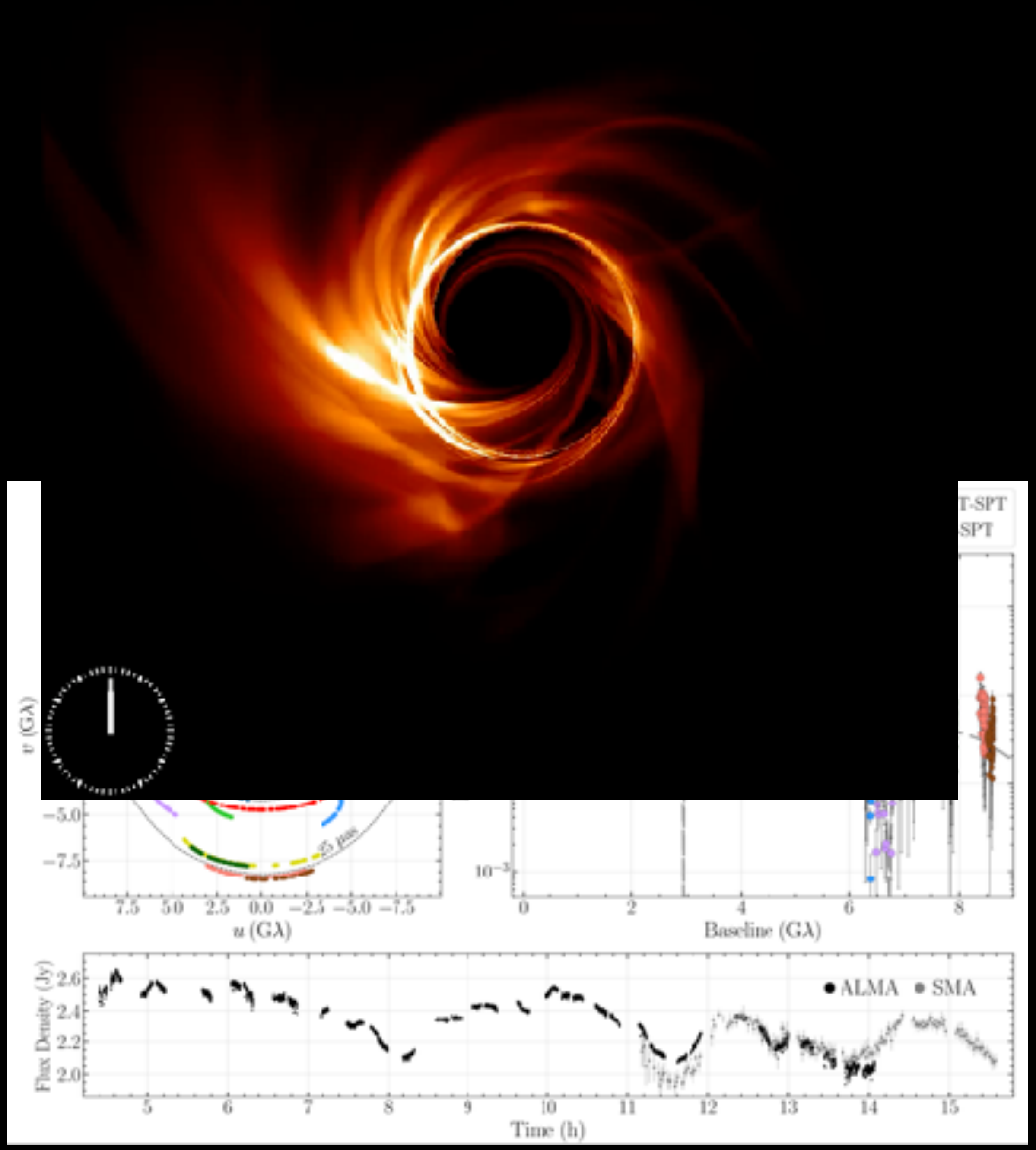
See also Maciek's talk!

Sgr A* observations come with several **disadvantages** and a few **advantages**

- **interstellar scattering:** distorts images and adds small scale features

- **variability:** the source of light has varies on timescales ~ minutes (M87* ~ day): long exposure (8 h) of variable subject

- **partial (u, v) coverage** (as for M87*): ~ 9000 images compatible with data



By contrast, we have a lot of additional **information**

- ✴highly-accurate mass estimate: $3{,}957{,}000\ M_\odot$ (0.2% precision)
- ✴well-known emission at other wavelengths: radio (86 GHz) IR (2 $\mu\mathrm{m}$), X-ray (2-10 keV)
- ✴well-known variability: 1.3 mm light-curve variability on 3 hours; light-curve normalized visibility amplitude variability at~4 Gλ

All in all: **11 constraints** for the simulations

Comparison theory-observations far more involved: **1.6 million images**

- **None of the models passes all constraints!**

- Most models are too variable (although only slightly)

- **Best-bet** models satisfying remaining constraints: MAD, prograde ($a > 0$), low inclination ($i < 70$ deg) and cool electrons ($R_{high} = 160$)

- **Strongly disfavoured**: single-temperature ($R_{high} = 1$); retrograde ($a < 0$); edge-on ($i = 90$ deg)

A conceptual problem

If we have ~ 9,000 images compatible with the data, which one is the correct one?

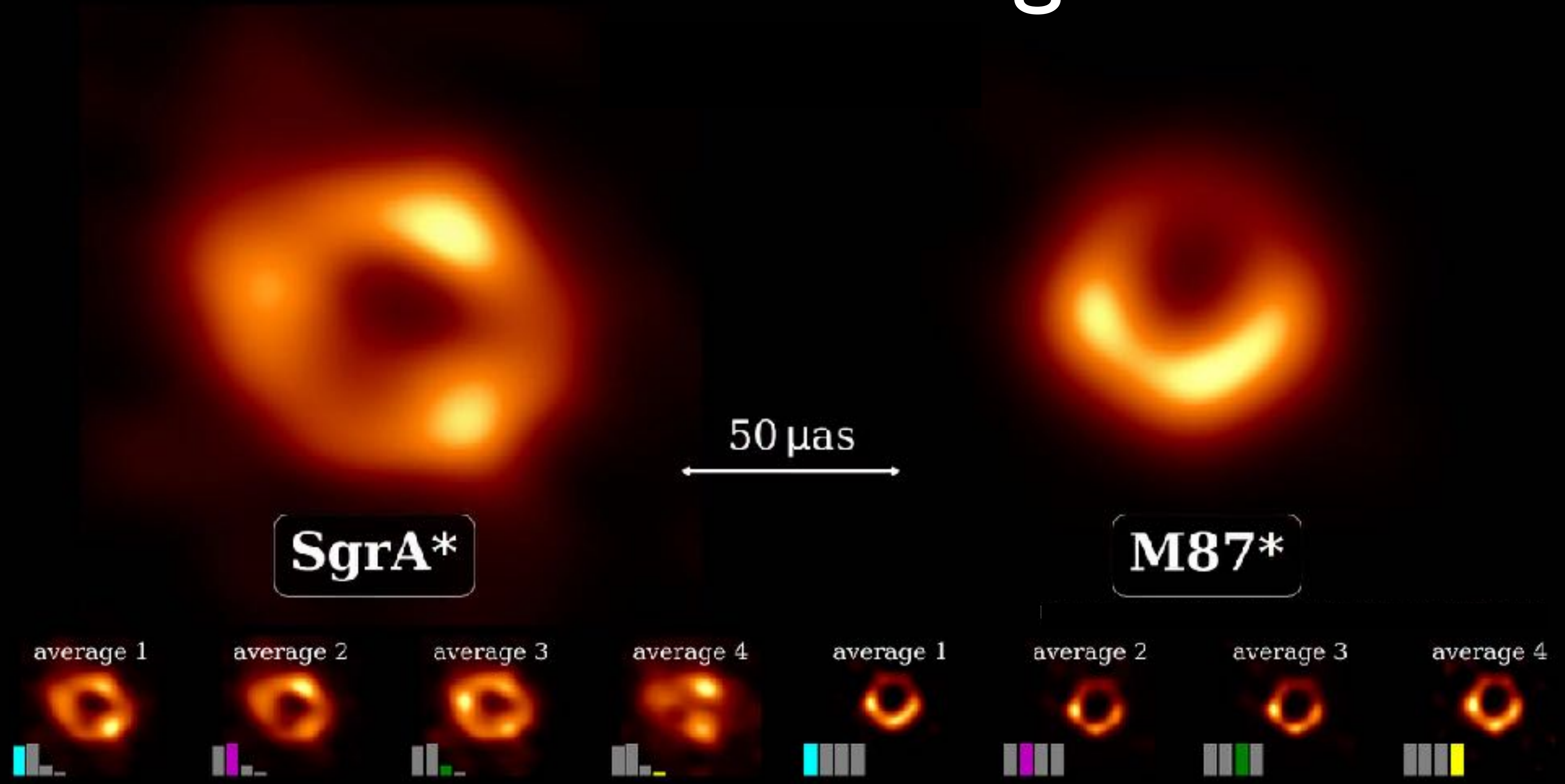
Answer requires new technique: clustering

To appreciate the basics of clustering technique consider the following logical analogy

C. M. Fromm (University Würzburg, Germany) L. Rezzolla (University Frankfurt, Germany)

C. M. Fromm (University Würzburg, Germany), L. Rezzolla (University Frankfurt, Germany) and the EHT Collaboration

Two SMBH at a glance



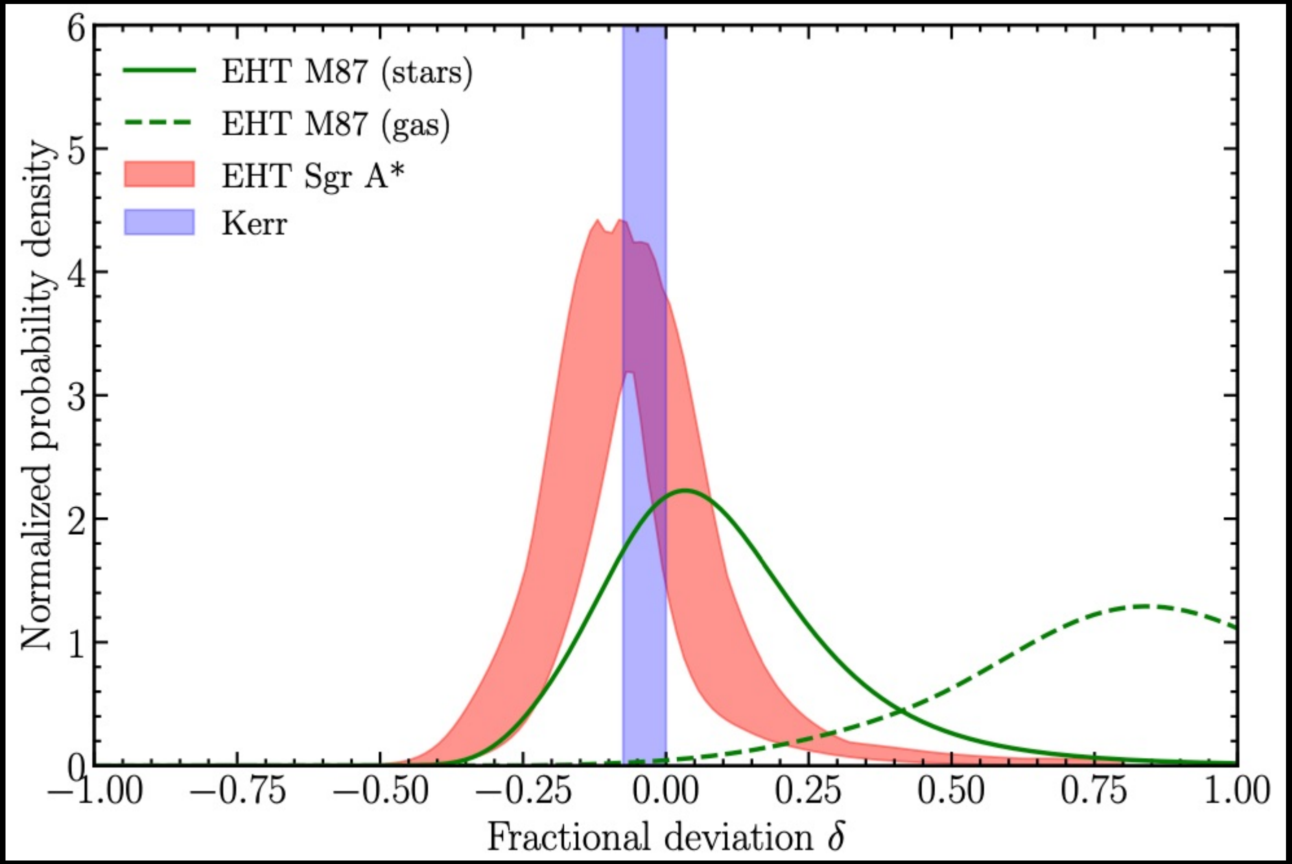
What about gravity?

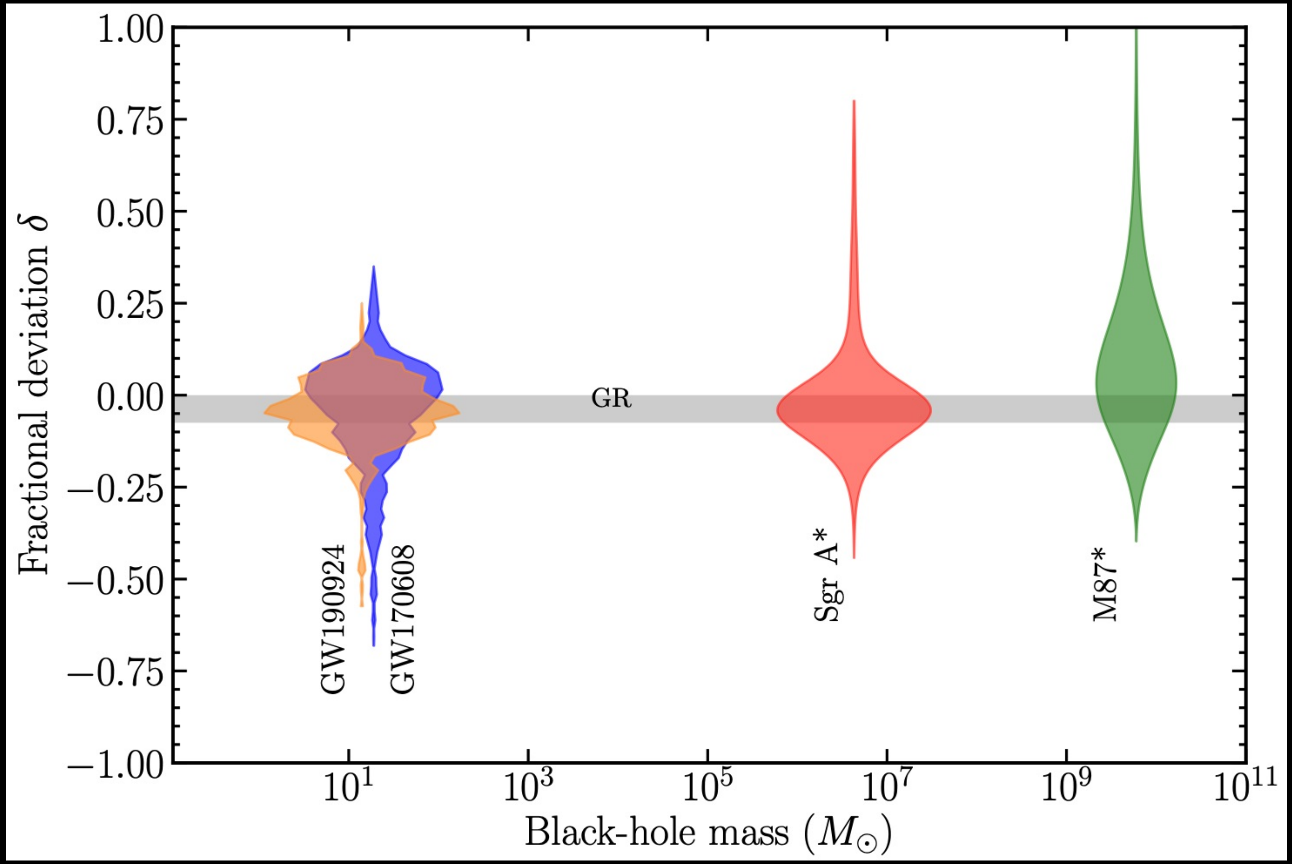
Express deviation from General Relativity via δ

$$\hat{d}_m = \alpha_c\, d_{\mathrm{sh}} = \alpha_c\,(1+\delta)\, d_{\mathrm{sh,Sch}} = \alpha_c\,(1+\delta)\, 6\sqrt{3}\theta_g$$

Sgr A* vs M87*

GWs and imagining





Observations are **consistent** with predictions of **General Relativity**

However, true also for many other theories, compact objects…

Tests of gravity

All we have observed is consistent with a **Kerr black hole** in **general relativity**

Inevitably for an observational science, degenerate explanations are possible.

Testing theory of gravity **not trivial** when hundreds alternatives are available!

Use both **agnostic** and a **gnostic** approach to exclude/allow alternatives.

Agnostic approach

- **Field equations** not necessary thanks to **equivalence principle:** all is needed is background metric: $g_{\mu\nu}(x^\alpha)$
- Device **agnostic approach:** RZ/KRZ metrics to generic static/stationary BH spacetimes: $g_{\mu\nu}(x^\alpha) \to g_{\mu\nu}(x^\alpha, a_i, b_i)$
- GR seen as a possible, reference case: $g_{\mu\nu}(x^\alpha, a_i = 0 = b_i)$
- Two essential ingredients in RZ and KRZ metrics:
  - ★ compactification: $r \to x := 1 - r_0/r; \quad r \in [2, \infty] \to x \in [0, 1]$
  - ★ Pade' expansion at horizon, e.g. $\tilde{A}(x) = \dfrac{a_1}{1 + \frac{a_2 x}{1 + \frac{a_3 x}{1 + \ldots}}}$
- Few (2-3!) coefficients sufficient for any known metric.

LR, Zhidenko 2014; Konoplya, LR, Zhidenko, 2016, Kocherlakota, LR 2020,

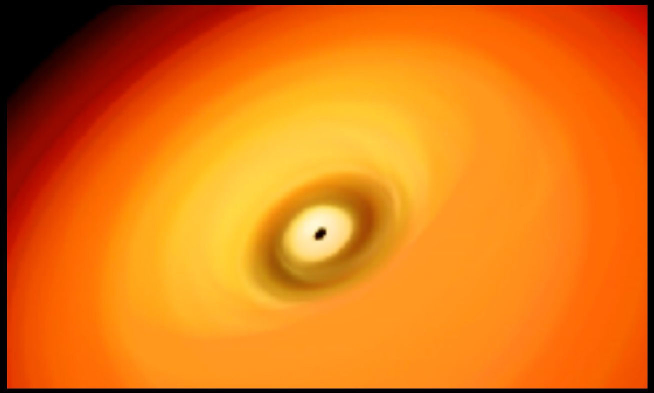
Gnostic approach: alternatives to Kerr bhs:

- accretion onto a **dilaton black hole**

  Mizuno+ 2018

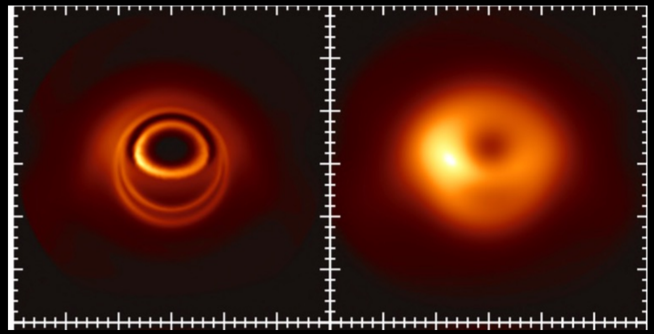
- accretion onto a **boson star**

  Olivares+ 2020



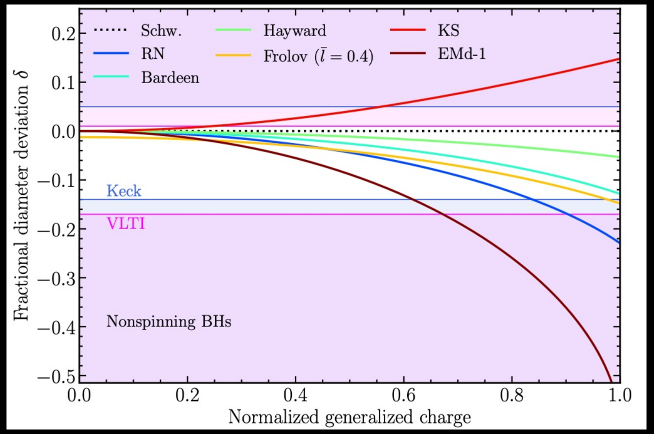
- reflecting hard **surface**

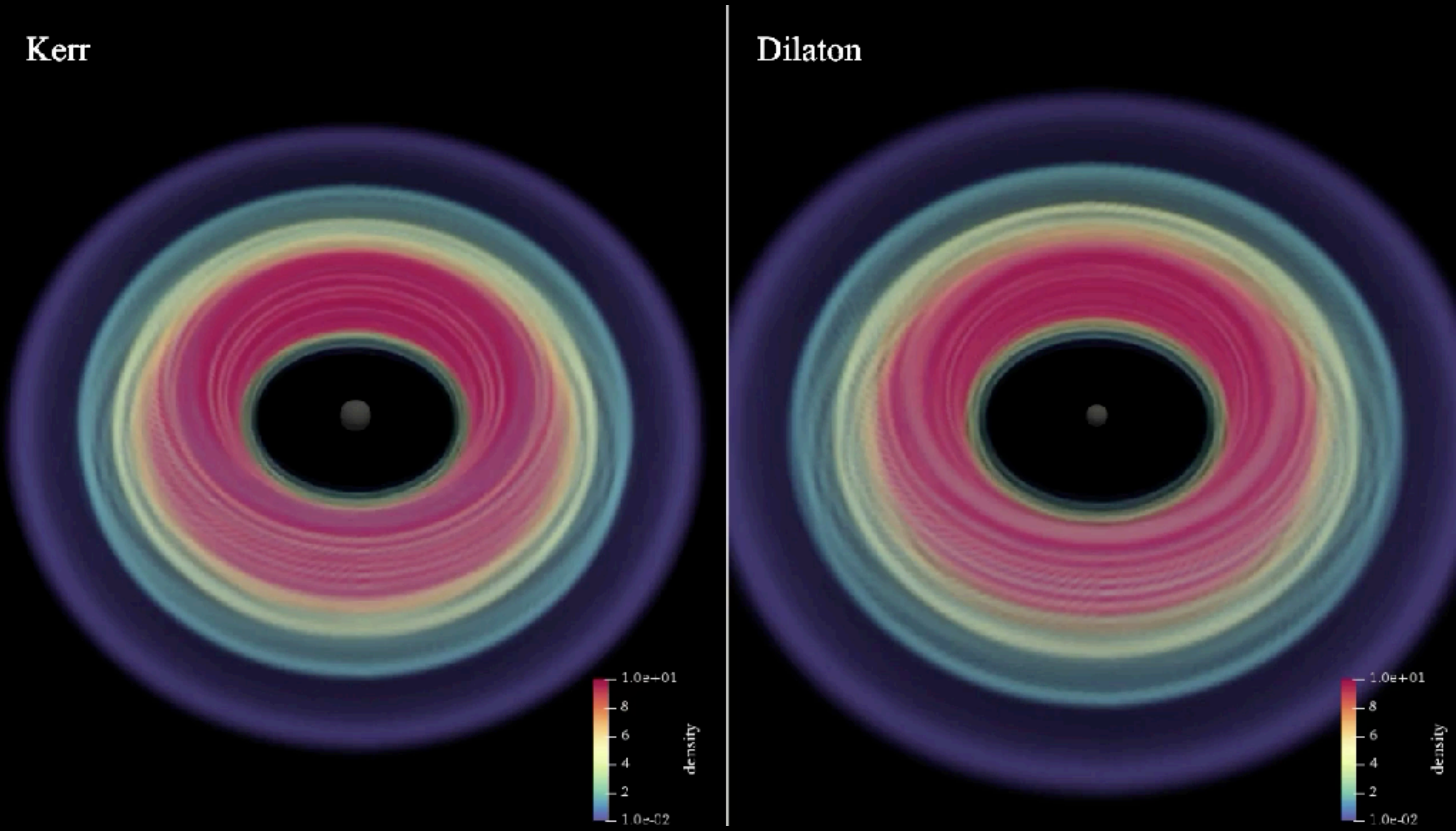
  EHT 2022



- shadow size on **"charged"** BHs

  Kocherlakota+ 2021



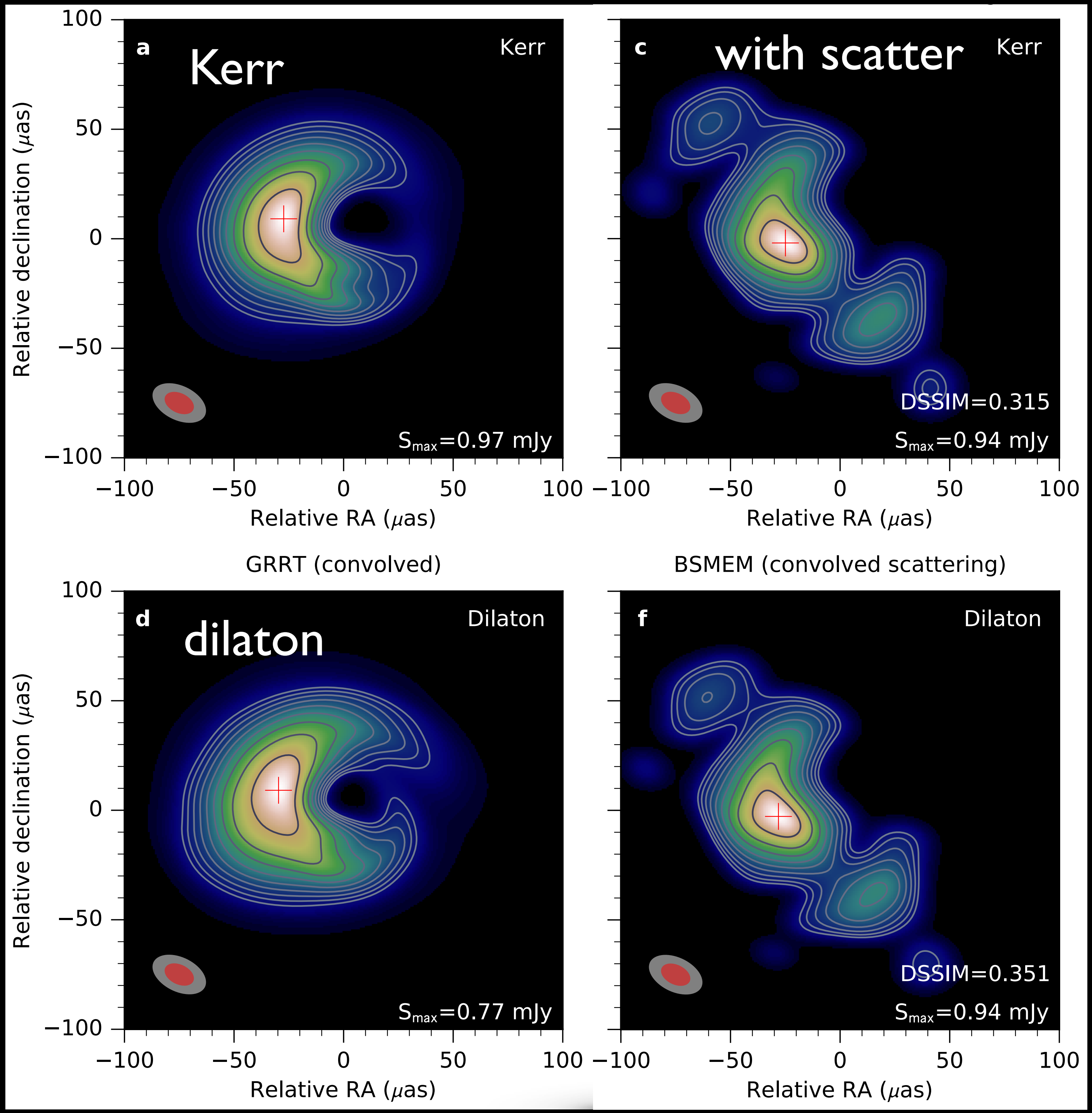


3D GRMHD simulations of magnetized torus with a weak poloidal magnetic field loop accreting onto Kerr BH (*a*=*0.6*) and ISCO-matched dilaton BH (*b*=*0.5*)

cf. Sgr A*

convolved GRRT images; crescent reveals presence of BH. However, degeneracy is present

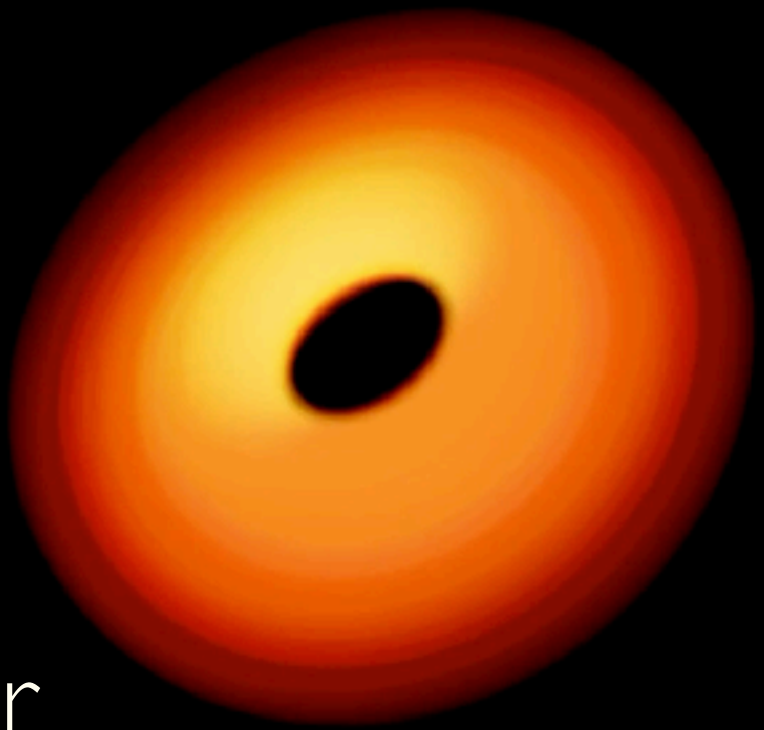
addition of scattering as for Sgr A* makes comparison harder and degeneracy more severe



Overall, at present not possible to distinguish the two BHs

Moving away from black holes: accretion onto a **boson star**

L. Weih, H. Olivares, LR

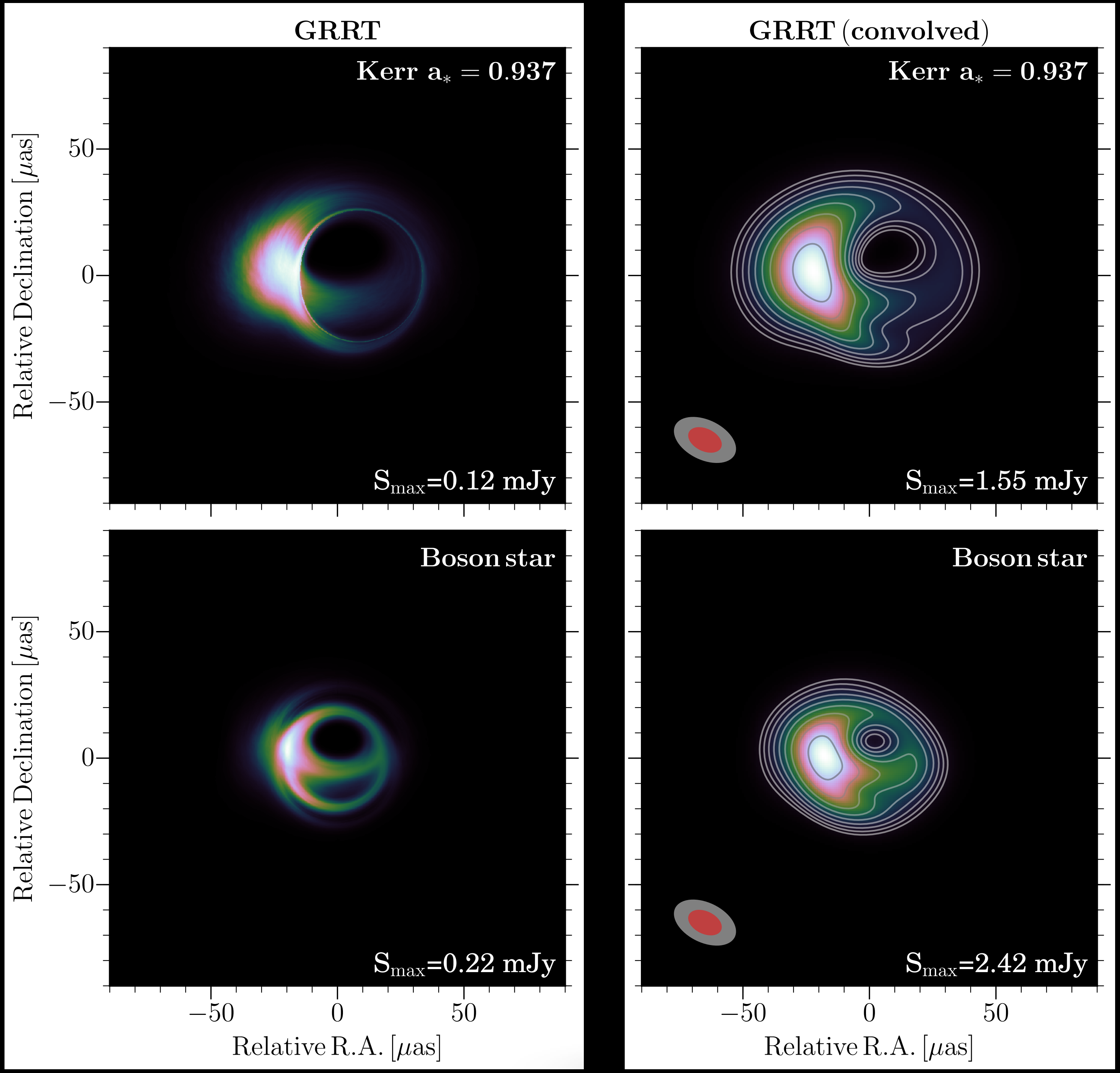


Nonrotating boson star solution of KG equations for a complex scalar field with quadratic potential (mini-boson star):

$$\omega M \approx 0.22;\ m \approx 10^{-17}\,\mathrm{eV}/c^2; \mathcal{C}_{99} \sim 0.064$$

- Left: GRRT images; sharp emission from photon ring visible for BH.

- Right: reconstructed image with scattering and conditions of EHT 2017 campaign.



Reconstructed images shows differences, both in size and structure

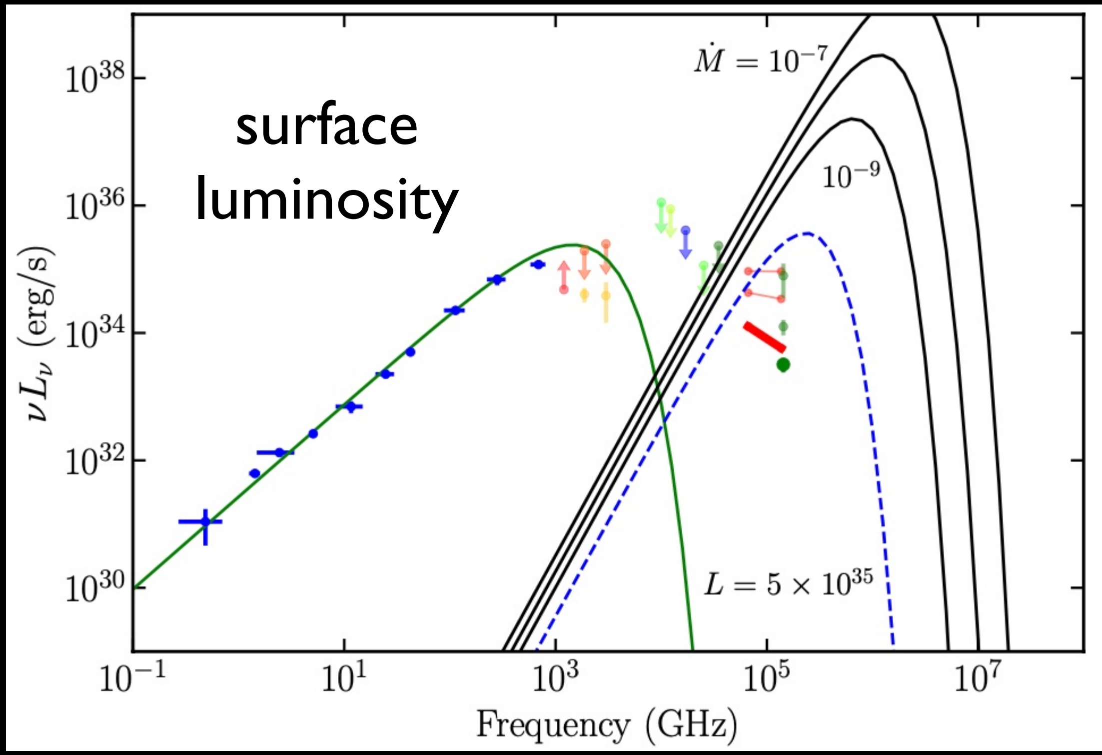
BH image exhibits crescent; boson star emission from inner regions.

Overall, from images alone it is possible to distinguish them

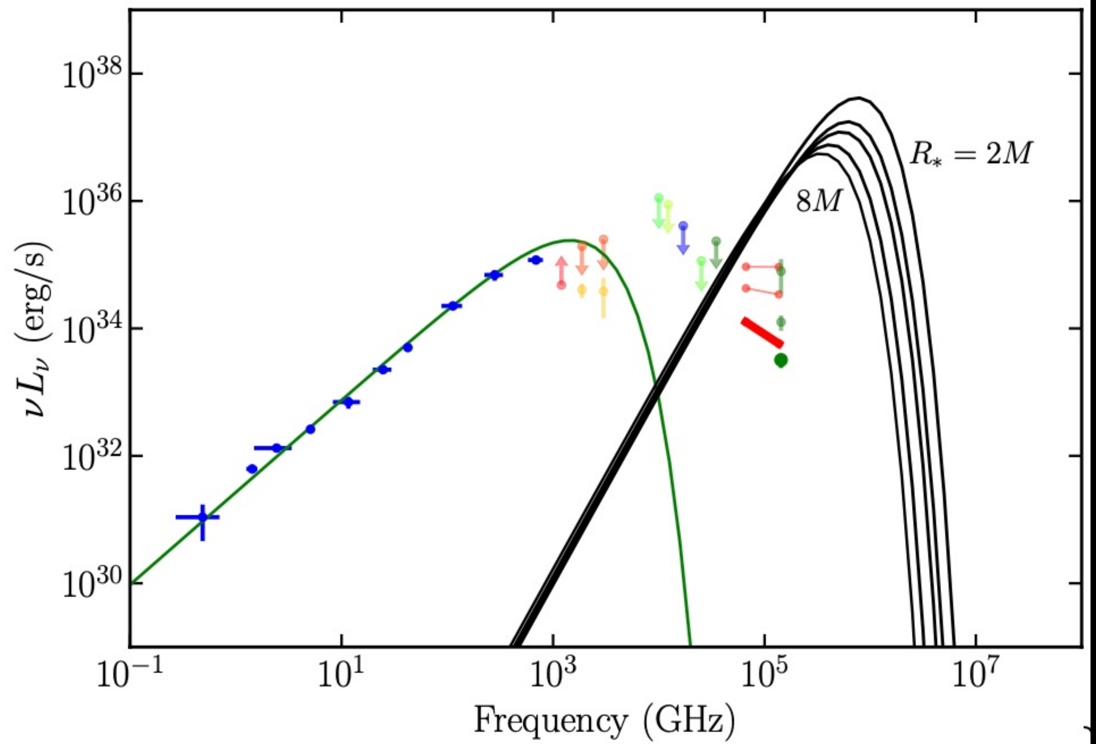
Testing thermalise surface of Sgr A*

If mimicker has a surface, energy will be thermalised and re-radiated.

thermalise surface at *r*=2.5*M*
changing mass accretion rate



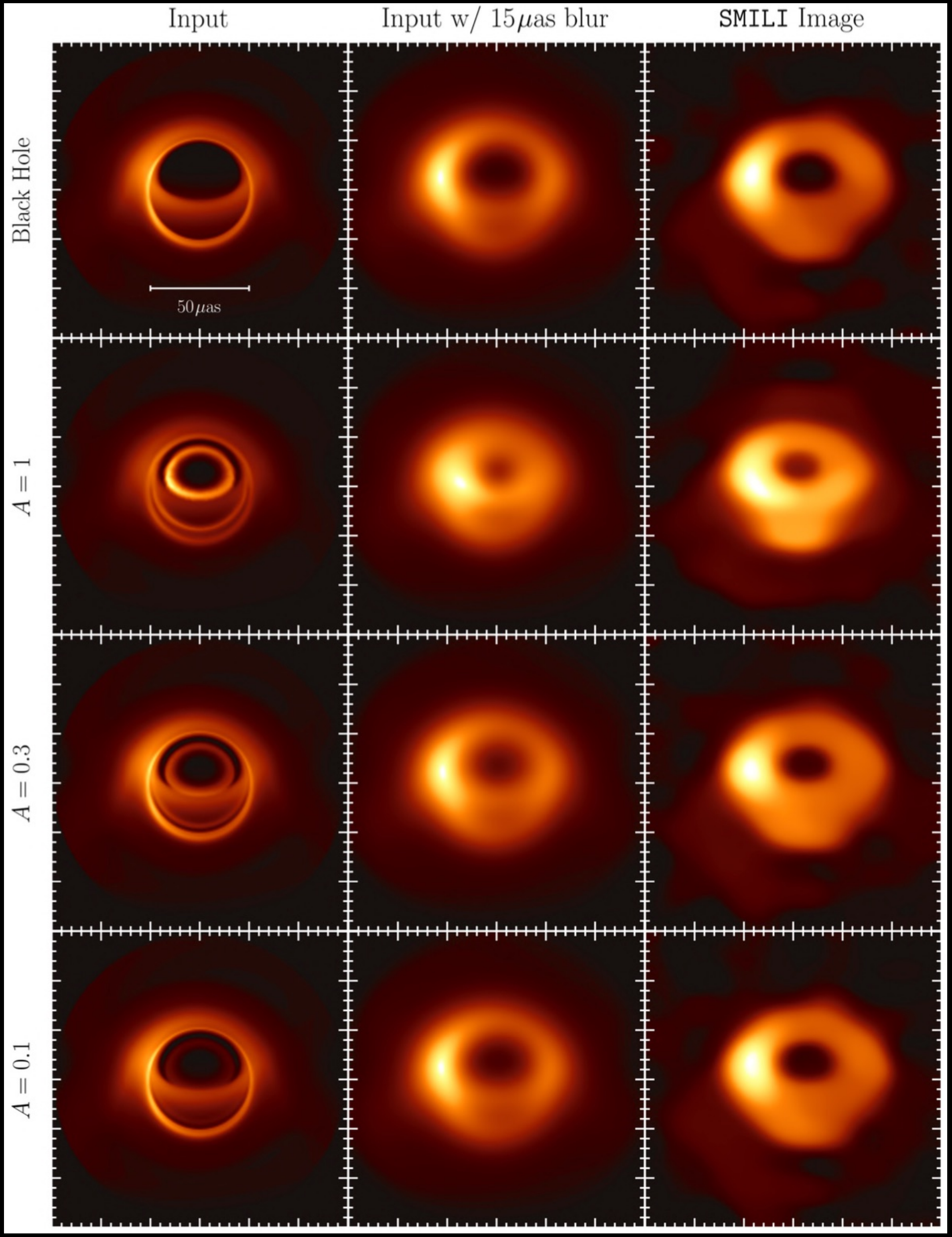
changing thermalise
surface position



Sgr A* does not have thermalised surface

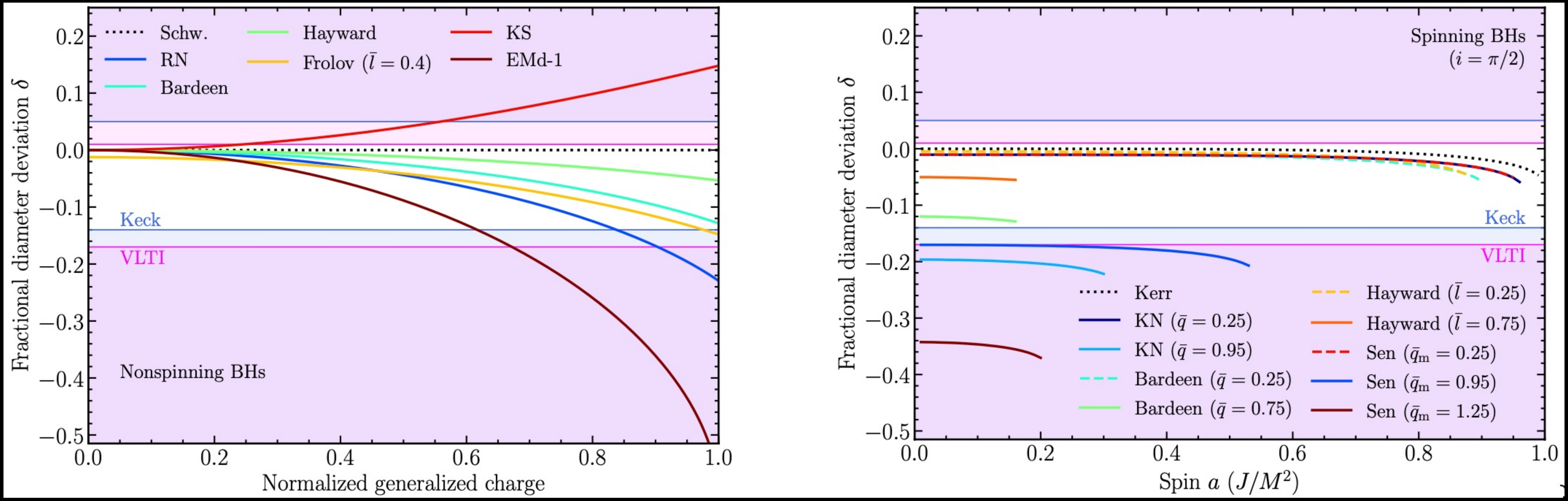
What a reflecting surface looks like

- Assume surface reflects incident radiation
- vary albedo, ***A=1*** is full reflection
- ***A=0.3, 0.1*** are harder to distinguish from the BH case
- Fraction *(1-A)* of radiation falling onto surface is absorbed and re-radiated as thermal emission
- *(1-A) ≥ 0.1:* such thermal emission is ruled out by spectrum constraint

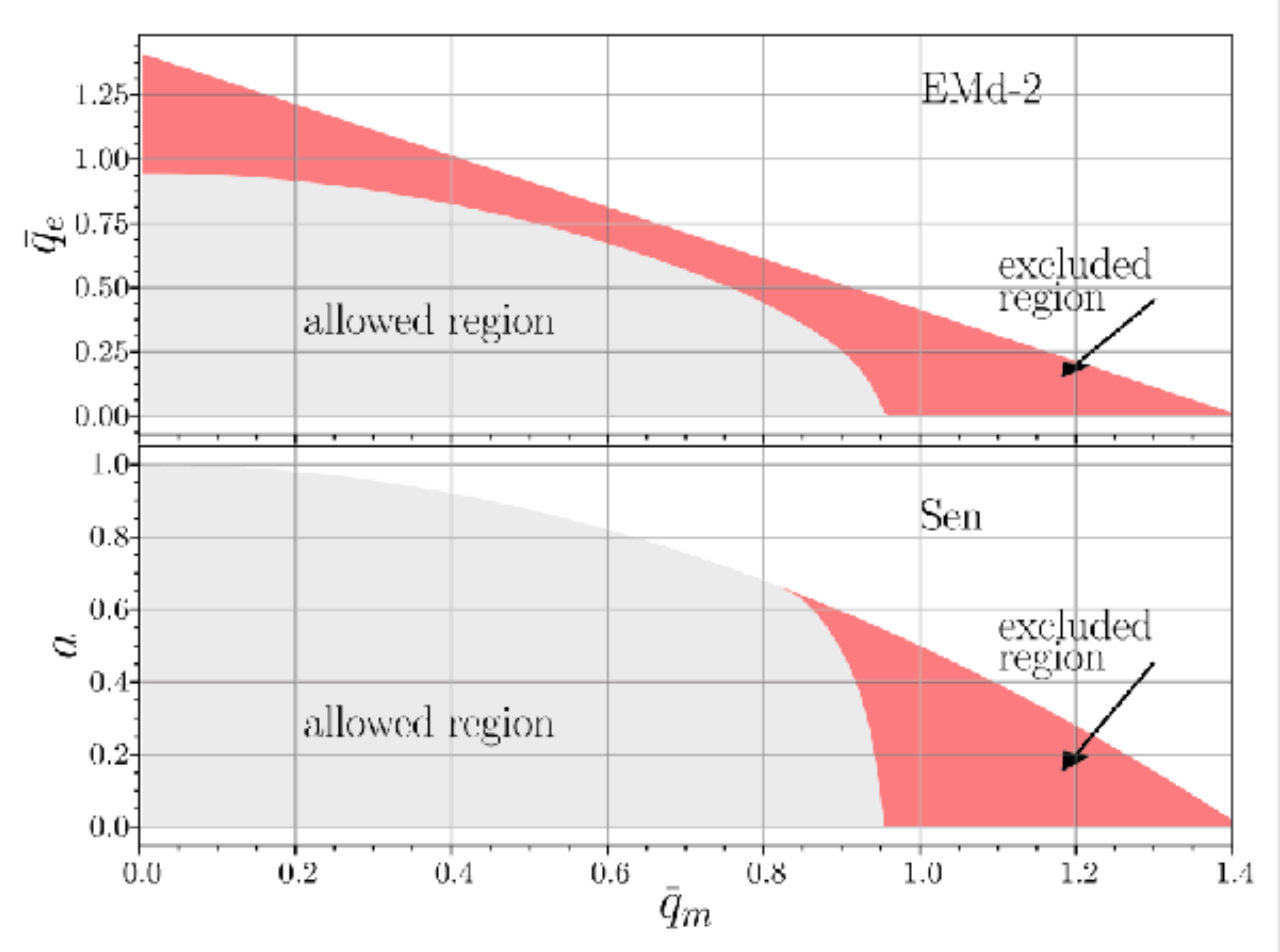


Constraining BH **charges**

Using the shadow size of M87* and Sgr A* we infer constraints on the physical "charges" of a large variety of nonrotating or rotating black holes.



Constraining BH **charges**



For BHs with two physical independent charges, able to exclude considerable regions of the space of parameters; cf. above for the doubly-charged dilaton and the Sen BHs.

Conclusions

- ✳Imaging SMBHs is a complex effort requiring expertise in VLBI, imaging, GRMHD simulations, gravitational physics.

- ✳Accretion onto **Kerr black holes** has been explored extensively in various physical and thermodynamical regimes.

- ✳Exploration of accretion onto **alternatives** to Kerr BHs has started: **boson stars** can be distinguished, **other BHs** cannot.

- ✳EHT has provided **first evidence** existence of **SMBHs** at least in two rather different galaxies.

EHT observations have transformed event horizon from a concept to a testable object.