Imaging a supermassive black hole

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Plan of the talk

- How do image a SMBH: **observations?**
- How do image a SMBH: **theory?**
- Comparing **theory** and **observations**
- Alternatives to Einstein and to black holes

A very basic problem

- Black holes are most compact objects in nature: cannot confine mass/energy in a smaller volume

- Luckily, BHs are astronomical objects; unfortunately, they are at astronomical distances

- If you want to take a photo you need a black hole with a resolvable size on the sky

Only solution: need very massive black holes and sufficiently close to us

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

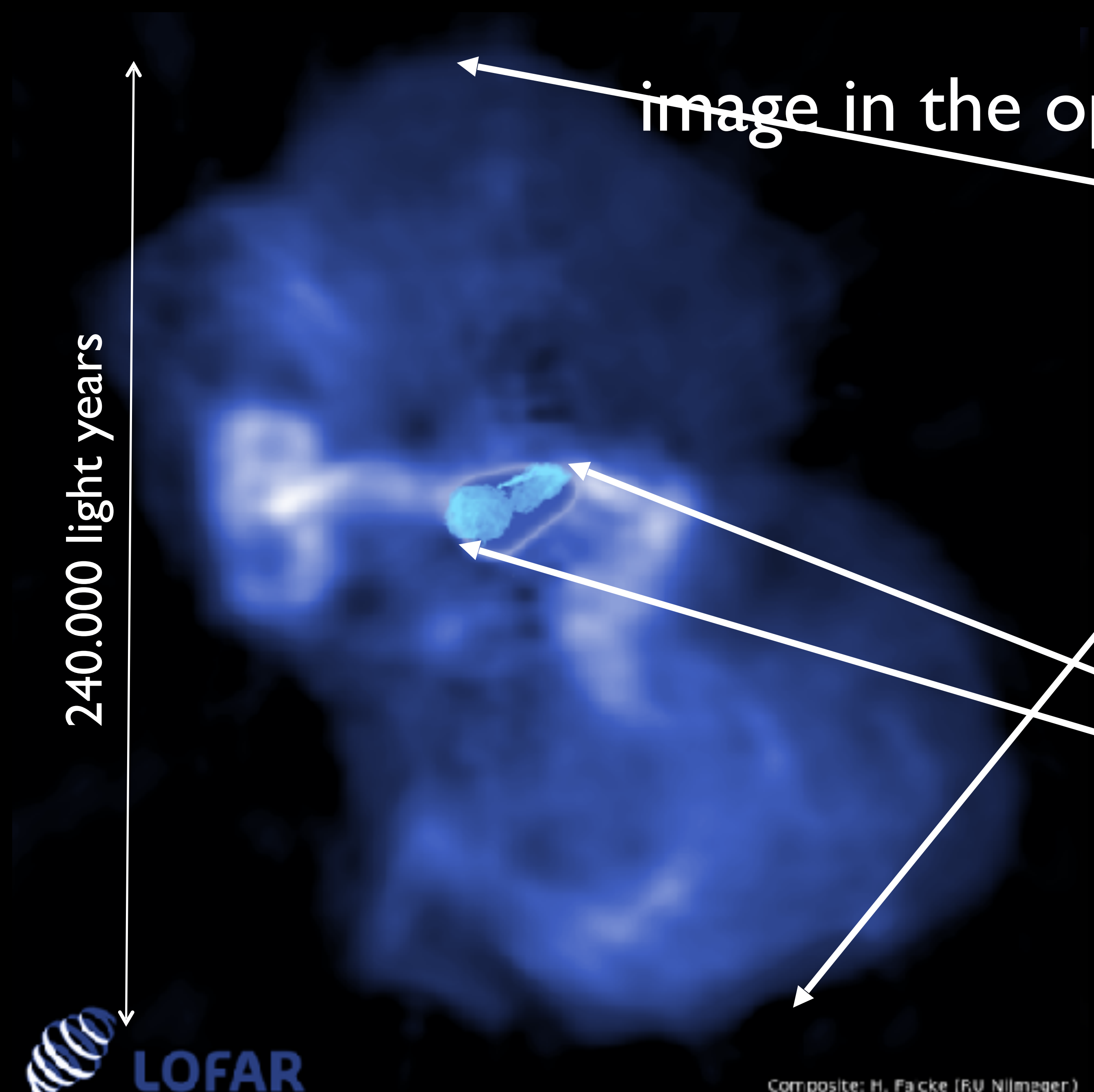

image in the optical

Large-scale radio map (few cm wavelengths)

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

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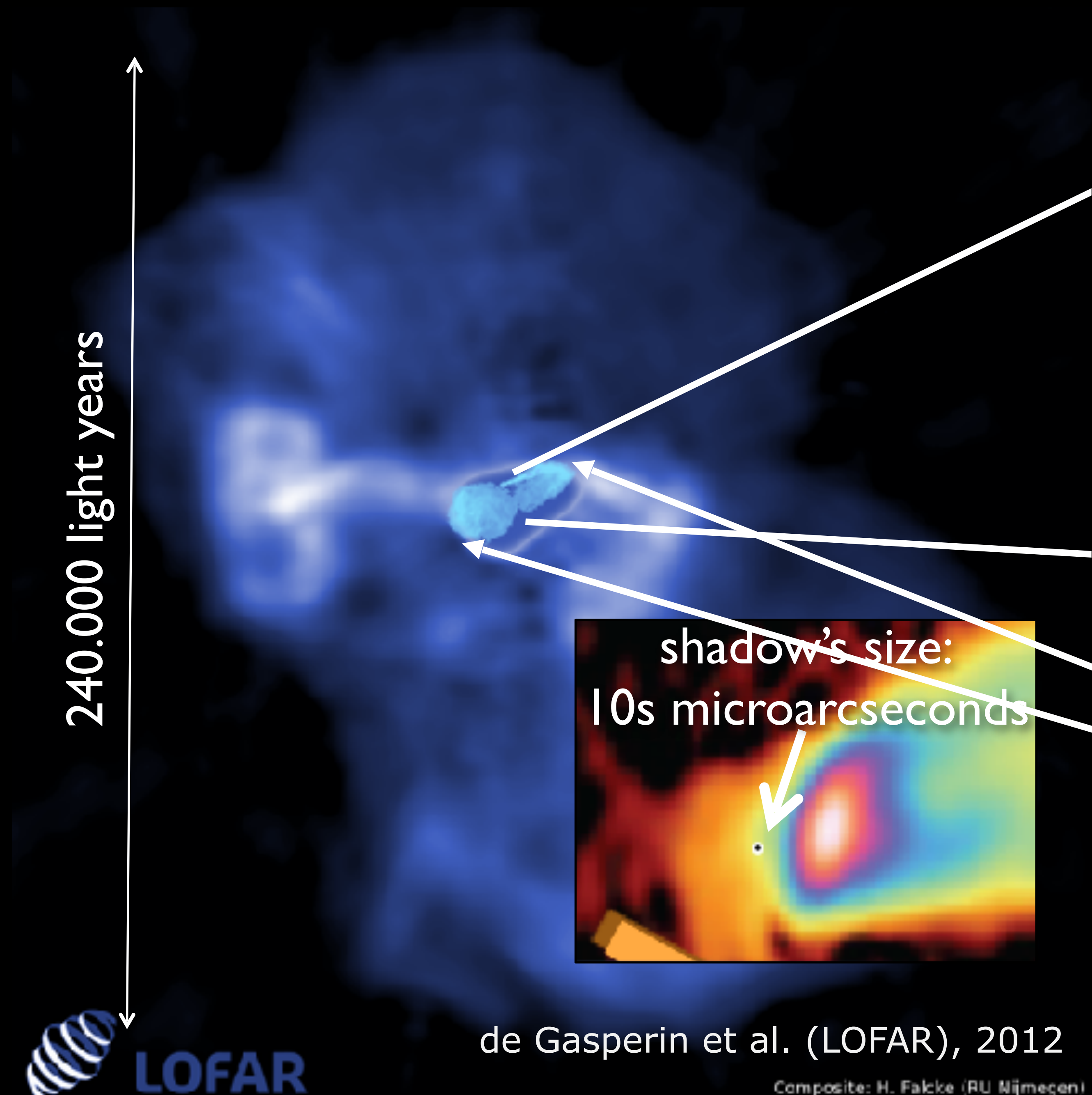
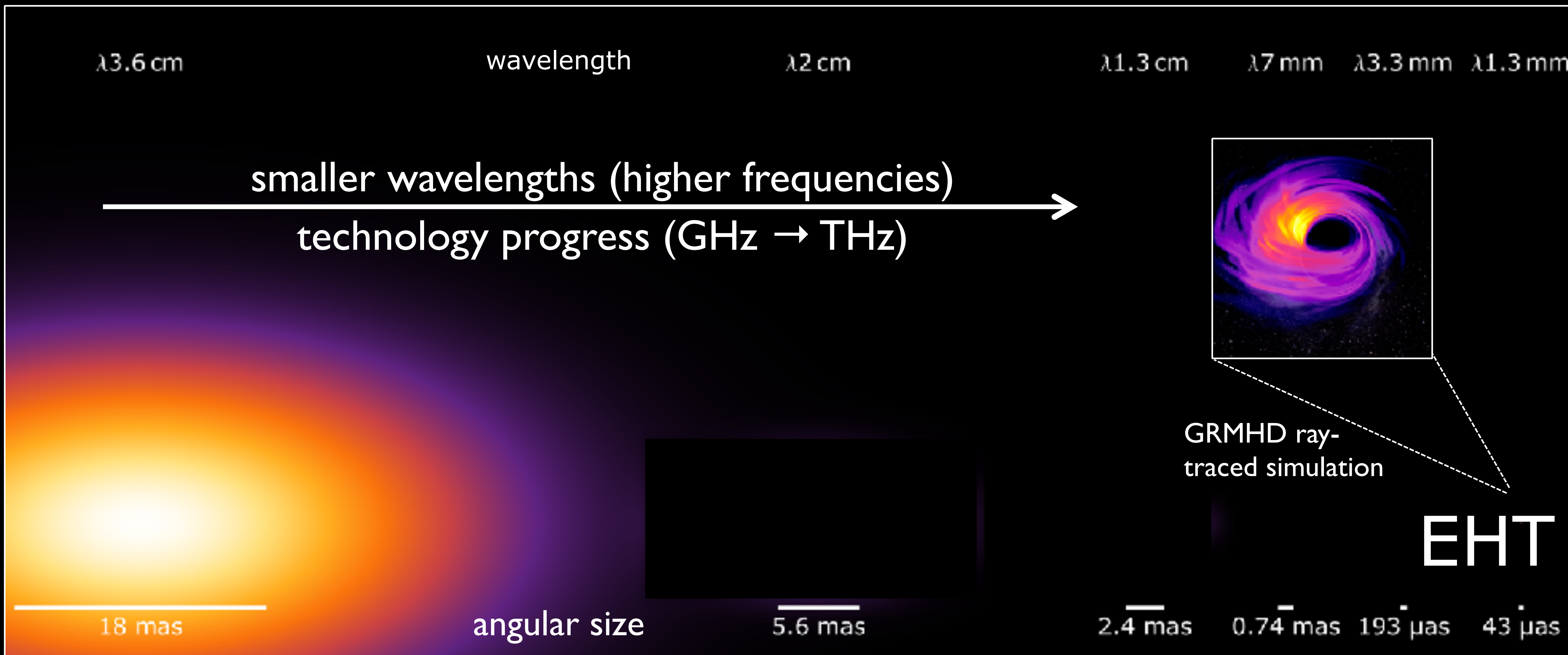


small-scale radio map of the core (cm wavelength)

VLBI: Very Long Baseline Interferometry

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

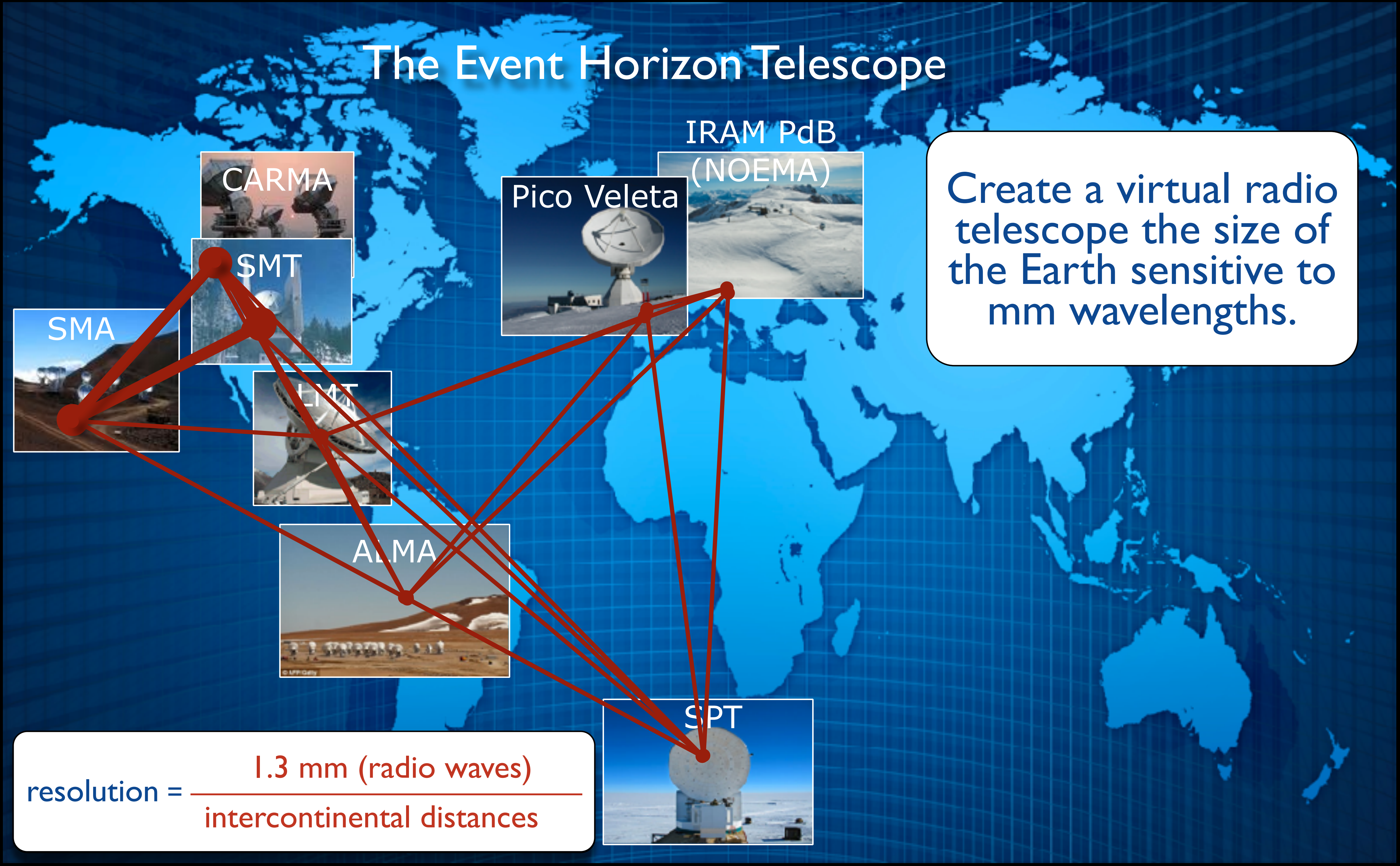


- The shorter the wavelength, the smaller the emitting source
- At 1.3 mm the source becomes of the size of the horizon

mas = milli-arcsecond = 5×10^{-9} rad

μas = micro-arcsecond = 5×10^{-12} rad

VLBI: Very Long Baseline Interferometry

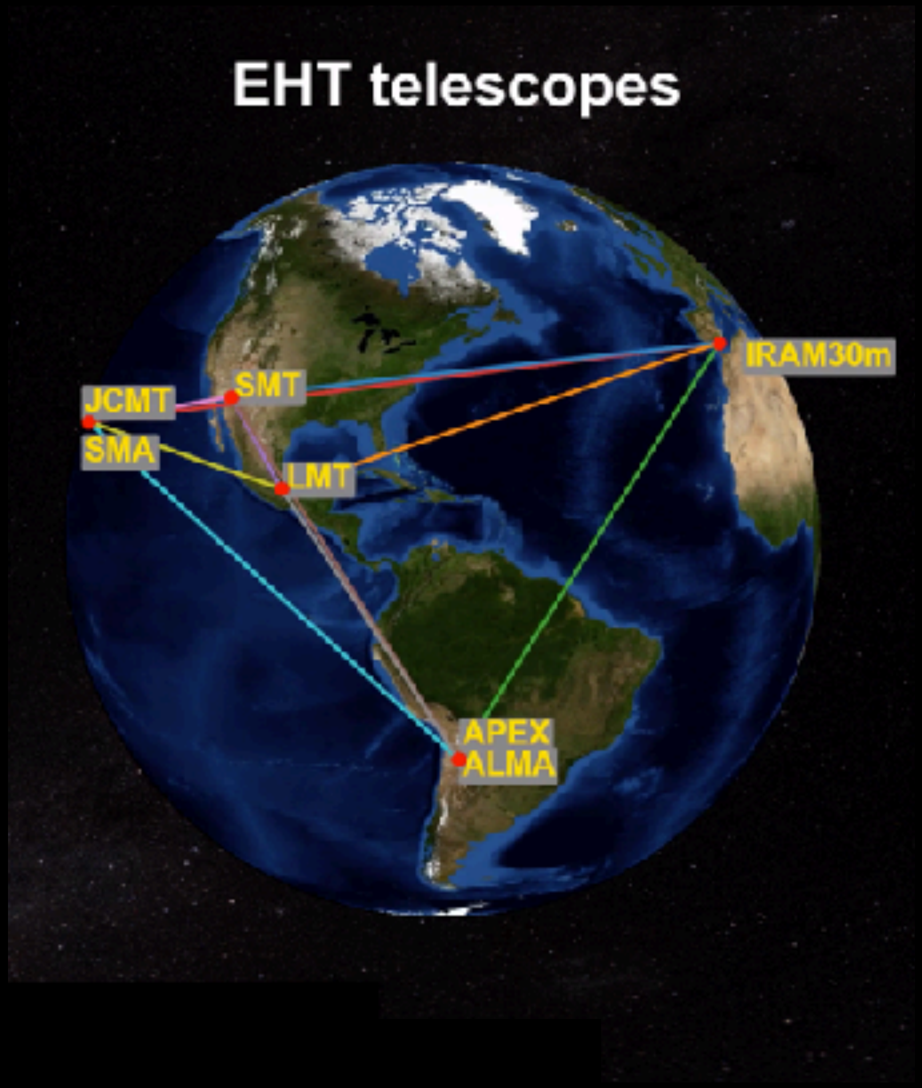


Create a virtual radio telescope the size of the Earth sensitive to mm wavelengths.

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

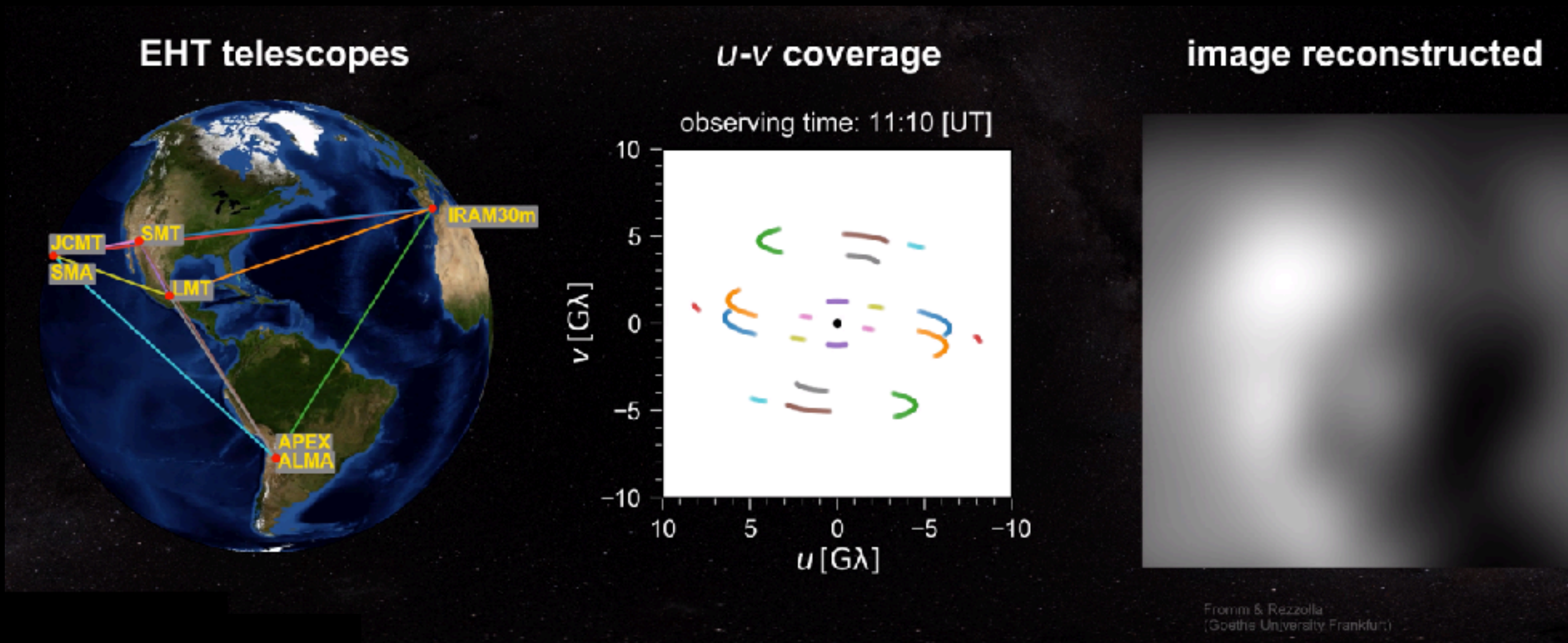
Observations

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



Observations

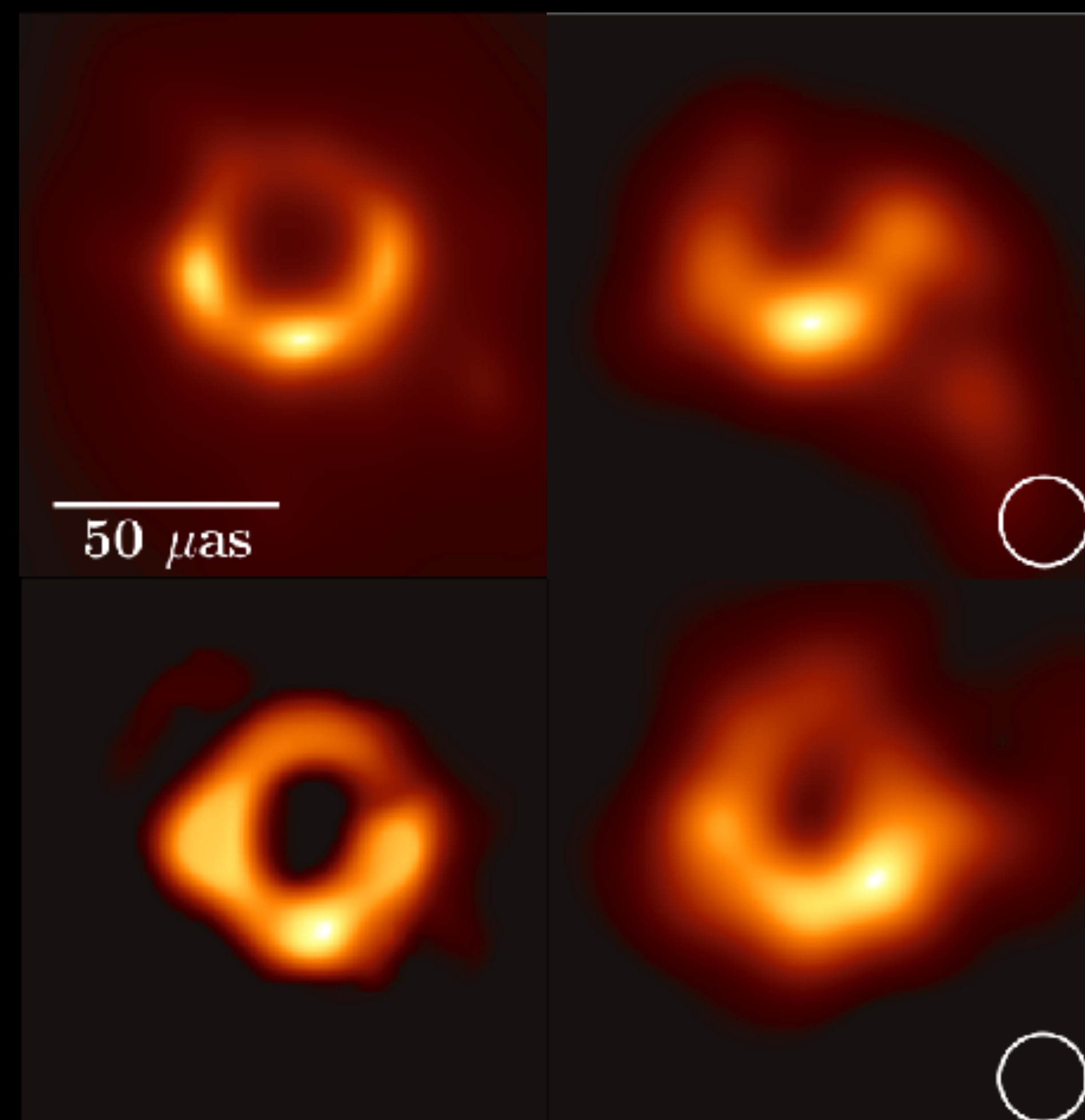
$$\mathcal{V}(u,v) = \int\int e^{-2\pi i(ux+vy)} I(x,y)\,dx\,dy$$



Observations

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

As the data was collected, converted and calibrated four different imaging teams were set with the task of computing an image

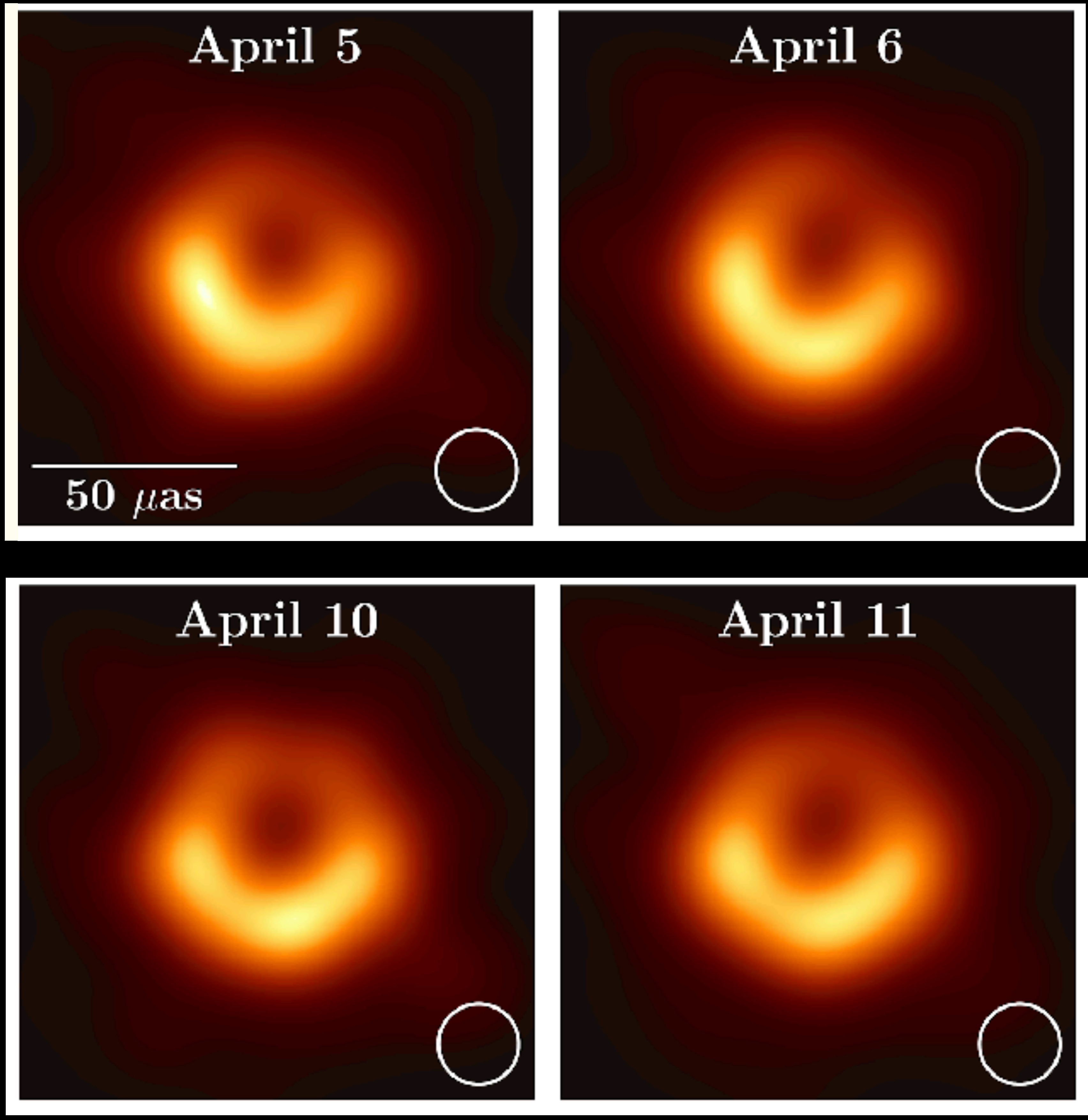


The four teams used multiple software packages and were set to work blindly from each other.

All of the teams recovered a very similar images: asymmetric ring is a robust feature of the image

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.



Three basic steps are needed:

(1) **GRMHD simulations** in arbitrary spacetimes

(2) **ray-traced, radiative-transfer**, **deconvolved images**

(3) **comparison** with **observations**.

BlackHoleCam (LR, Falcke, Kramer), has developed a complete computational infrastructure:

BHAC/BHOSS/GENA

C. Fromm R. Gold Y. Mizuno H. Olivares O. Porth Z. Younsi






now CfA now SDU now Shangai now Radboud now UA now UCL

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...

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

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

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

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

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

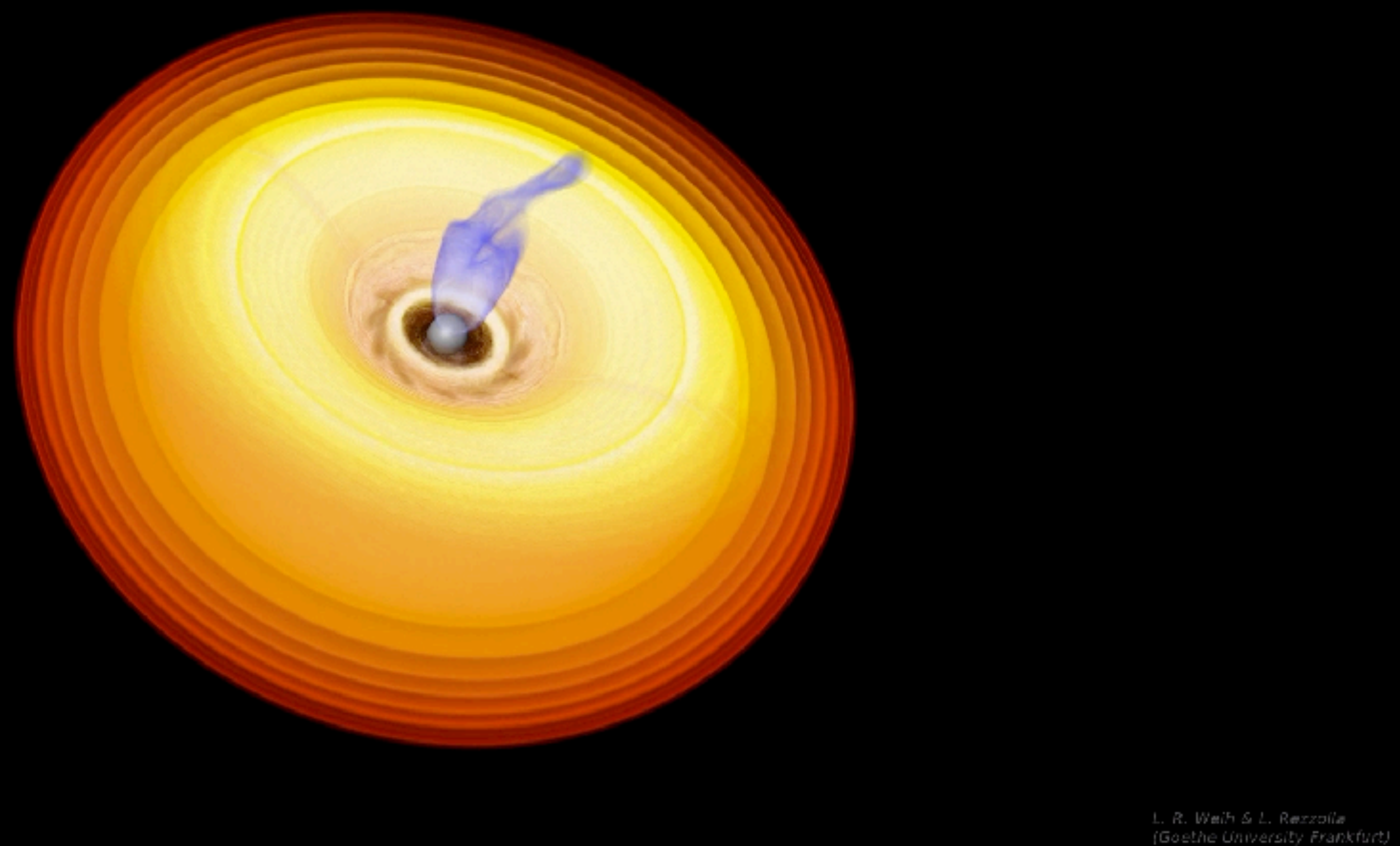
The equations of **general-relativistic radiative transfer (GRRT)** need to be solved in the background spacetime.

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

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

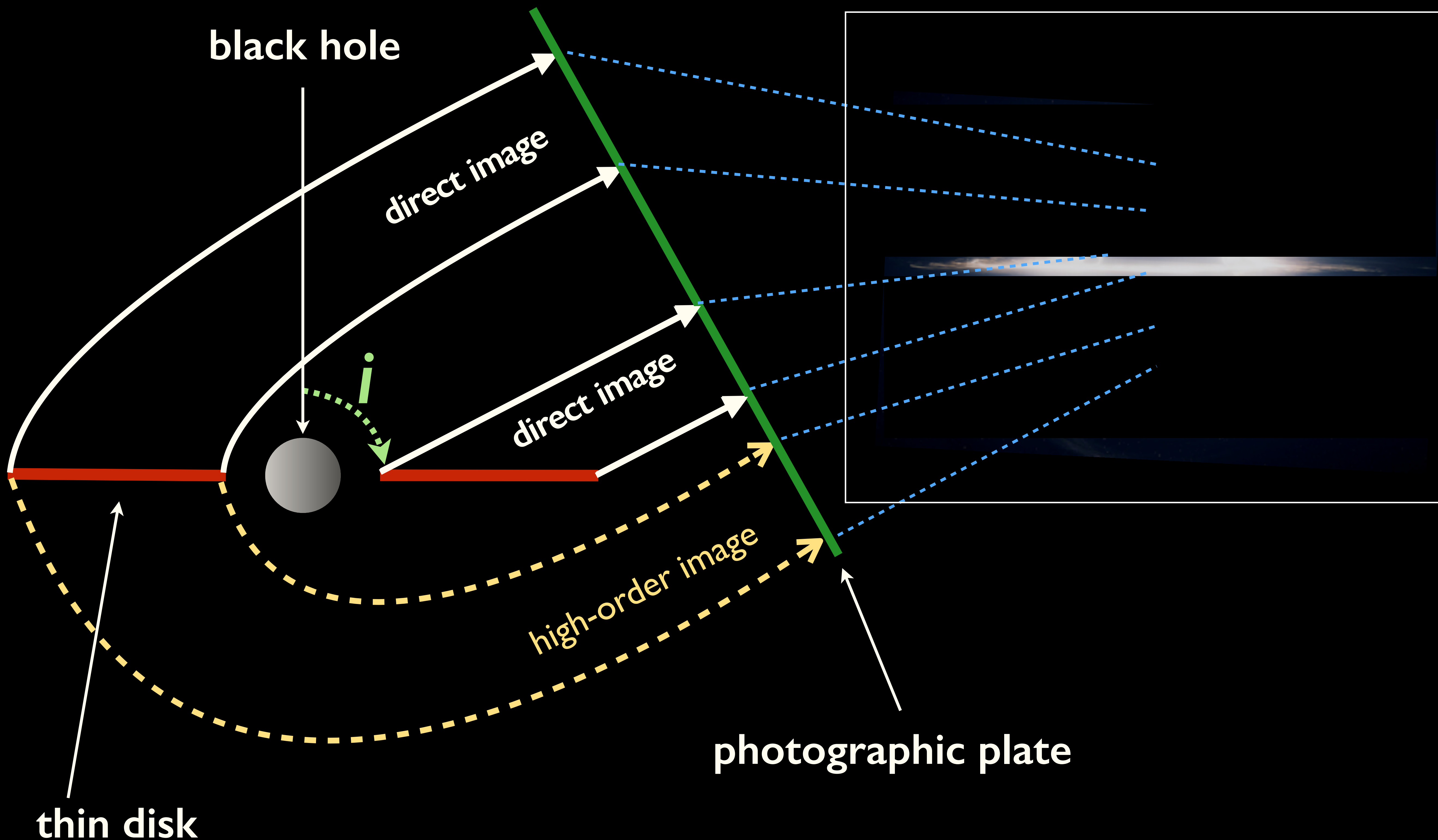
Plasma dynamics:
a typical GRMHD simulation…

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…



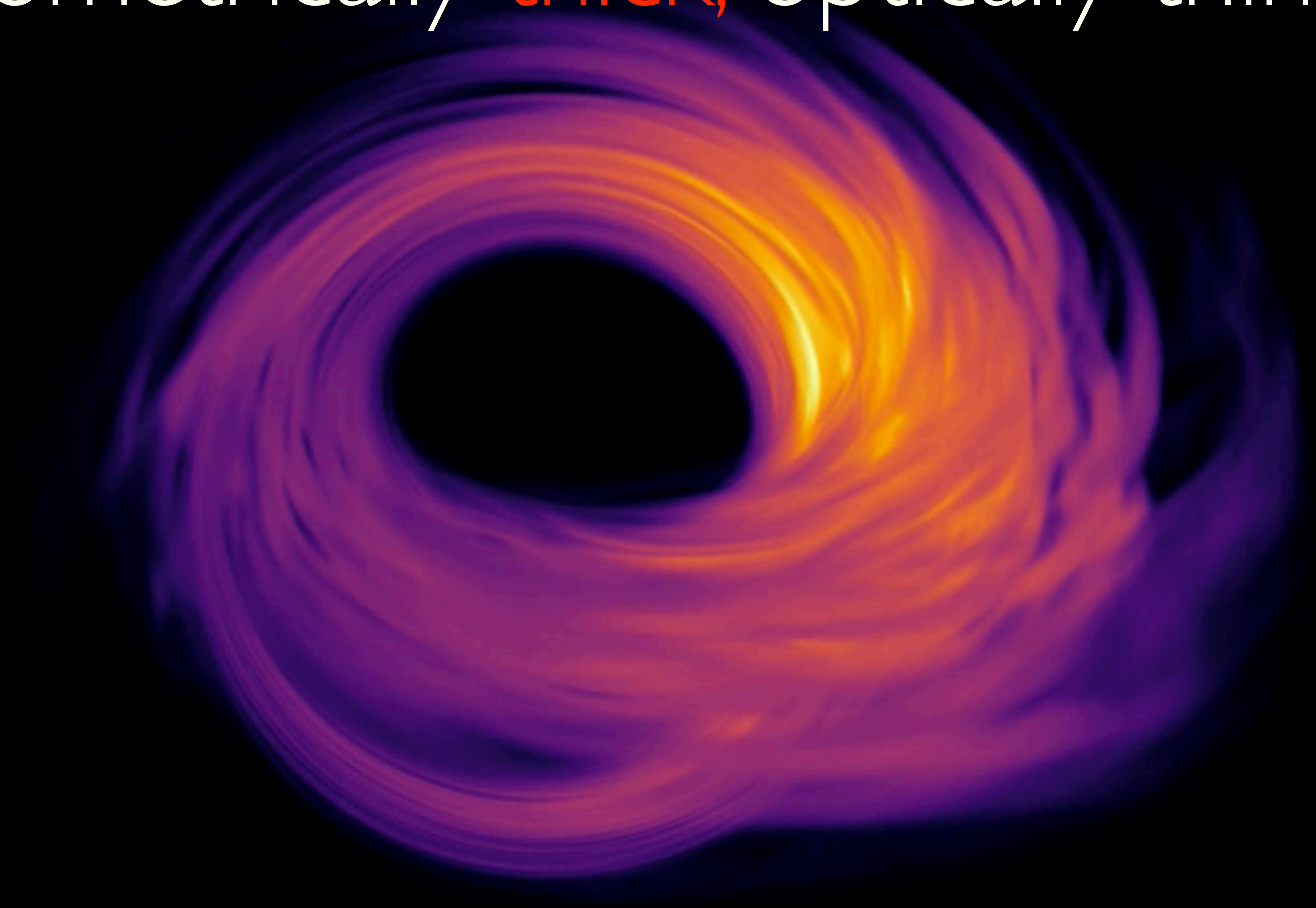
L. Weih, LR

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



Younsi, LR 2019

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



What we have observed is the “shadow”

source of light

photon
circular orbit

event horizon

“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
- alternative to black holes (horizonless without 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": $\beta_p := p_{\mathrm{gas}}/p_{\mathrm{mag}}$

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

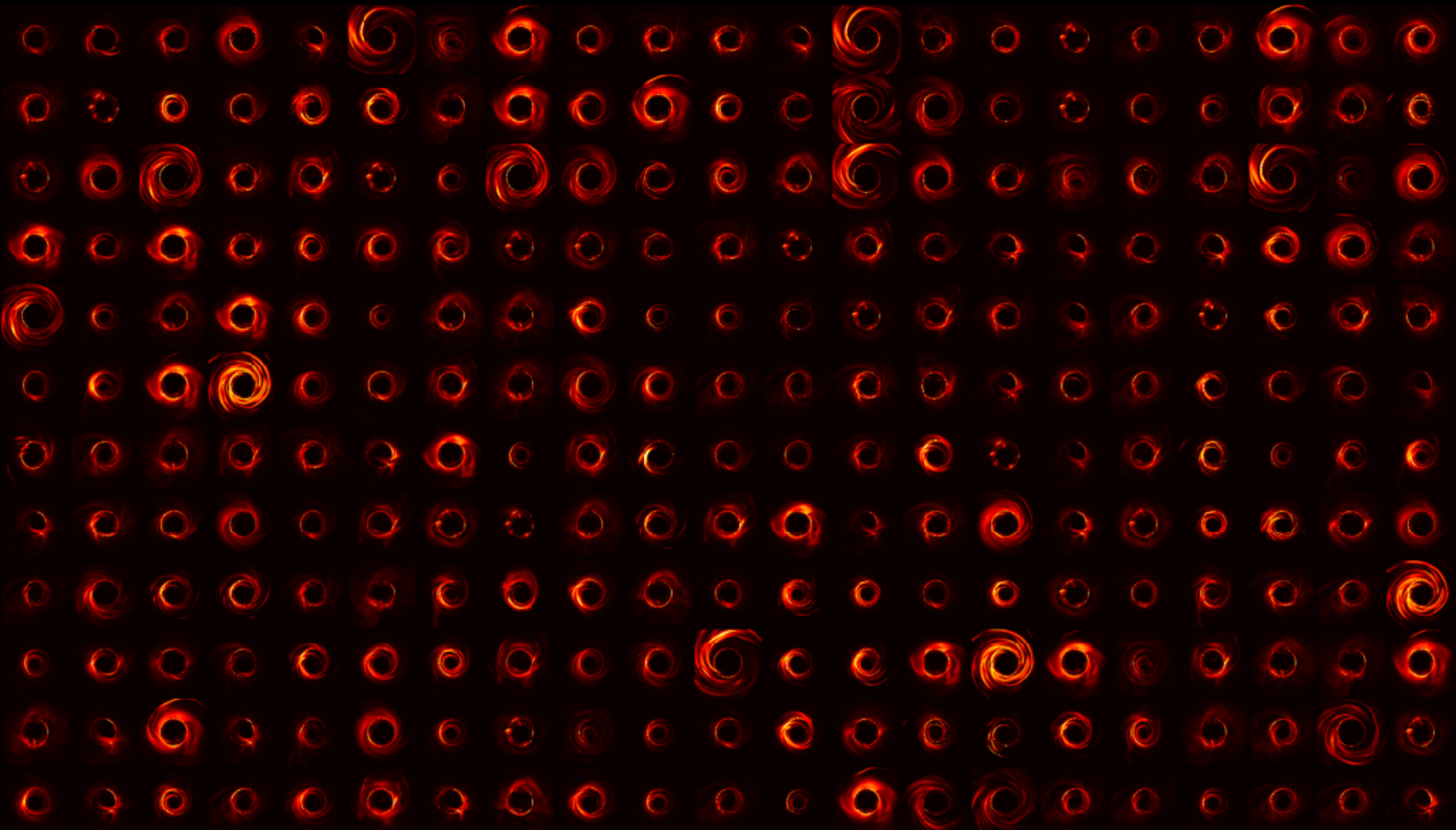
Mościbrodzka+ 2016

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

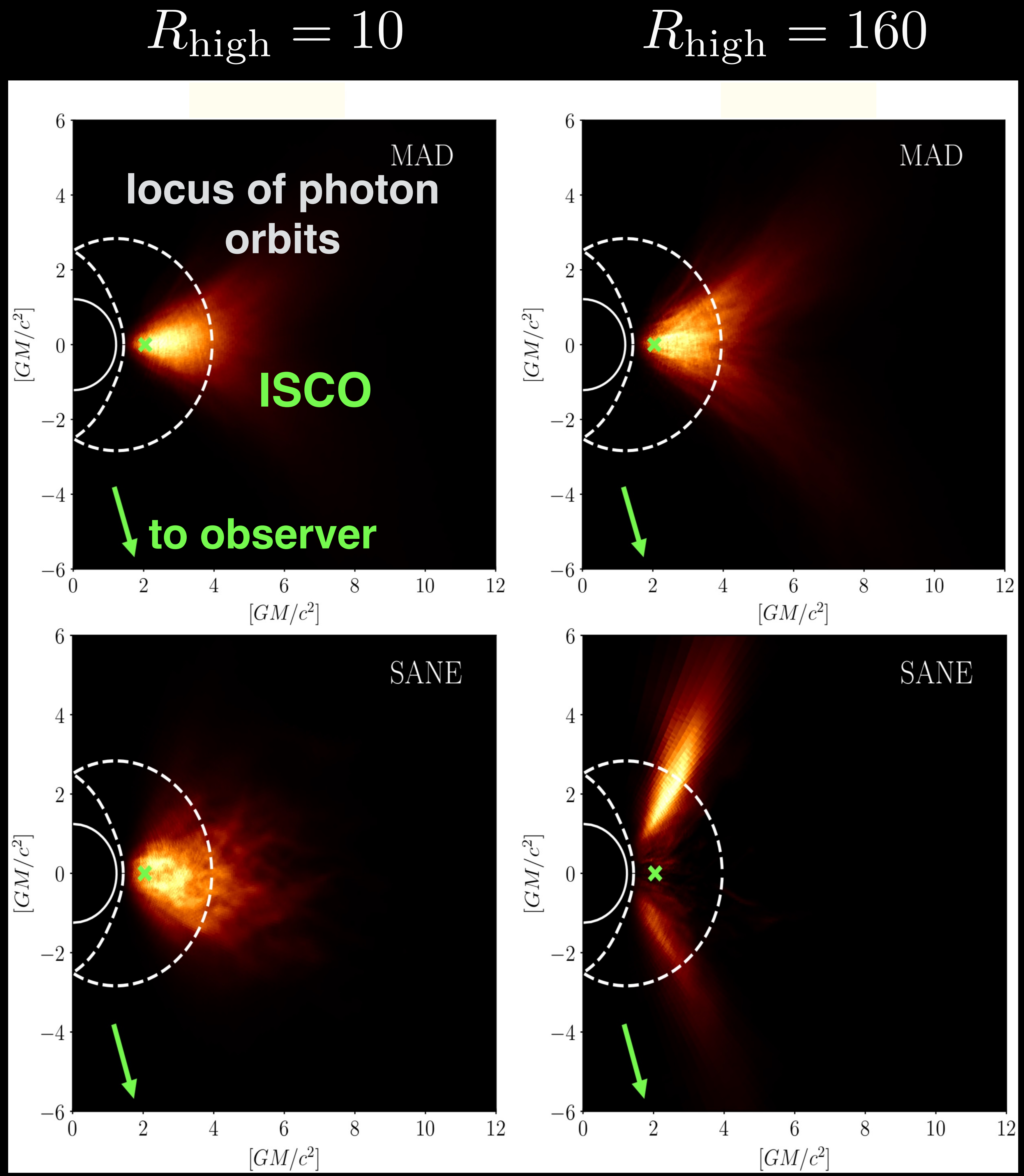
- Given physical assumptions (spin, magnetisation), 3D GRMHD simulations were made: ~ *50 high-res simulations*.

- 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?



MAD: mostly from the equatorial plane

SANE: can switch from equatorial plane to funnel wall

Where do the mm-long photons originate?

Kerr black hole,
$a_* = -0.94$

MAD: mostly but not only from the equatorial plane

SANE: equatorial plane is essentially depleted

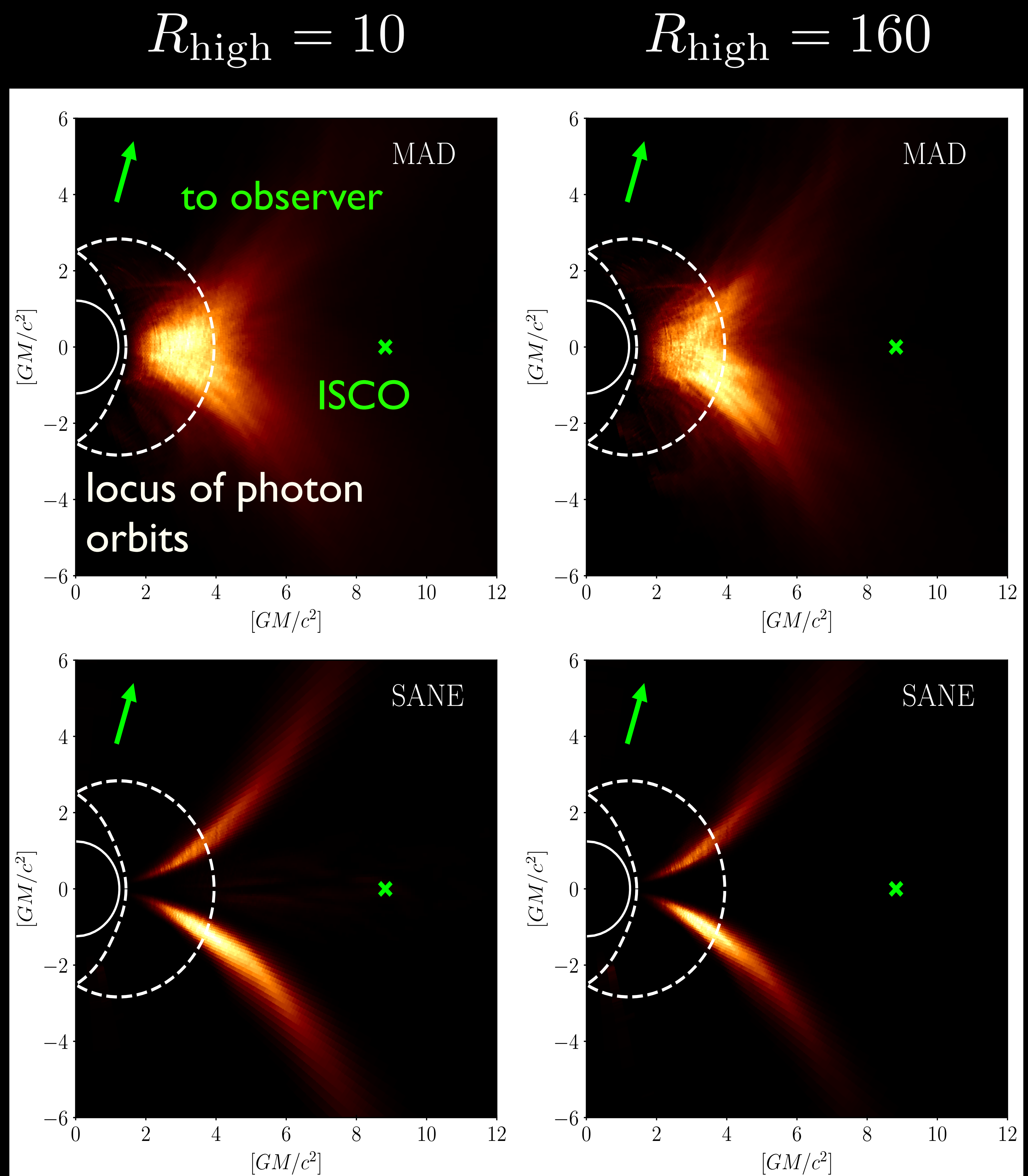
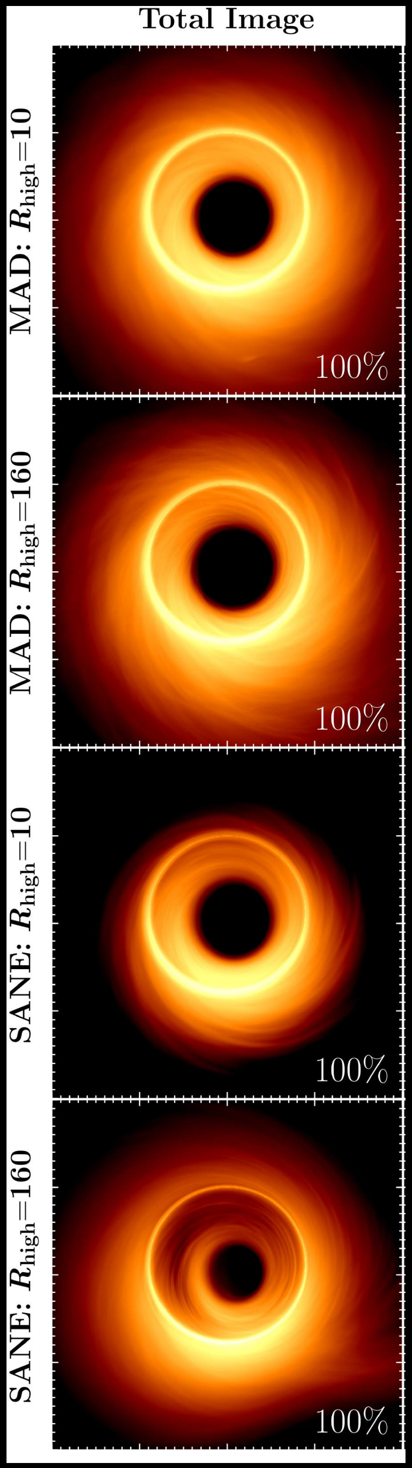


Image is combination of emissions…

- Image decomposed in: midplane, nearside, and farside
- MAD: midplane emission always dominates
- SANE with low R_{high}: midplane emission dominates
- SANE with high R_{high}: farside emission dominates



- 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*.

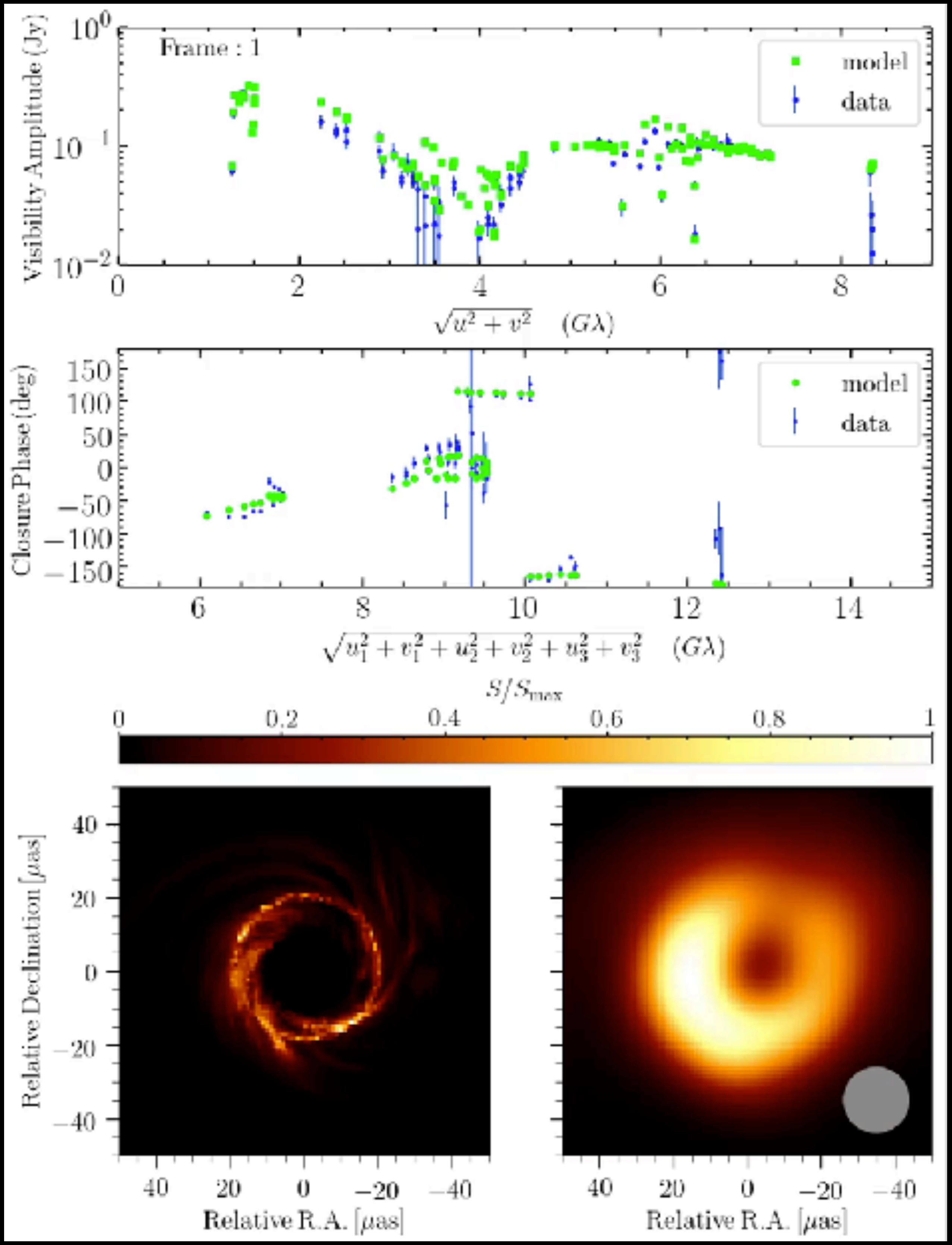
- Genetic algorithms and MCMC pipelines find best match.

Fitting the images to the data

visibility amplitude (VA)

Closure phase (CP)

GRMHD image (left) and convolved image (right)



Fromm, Younsi, LR

Top-10 best matches

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

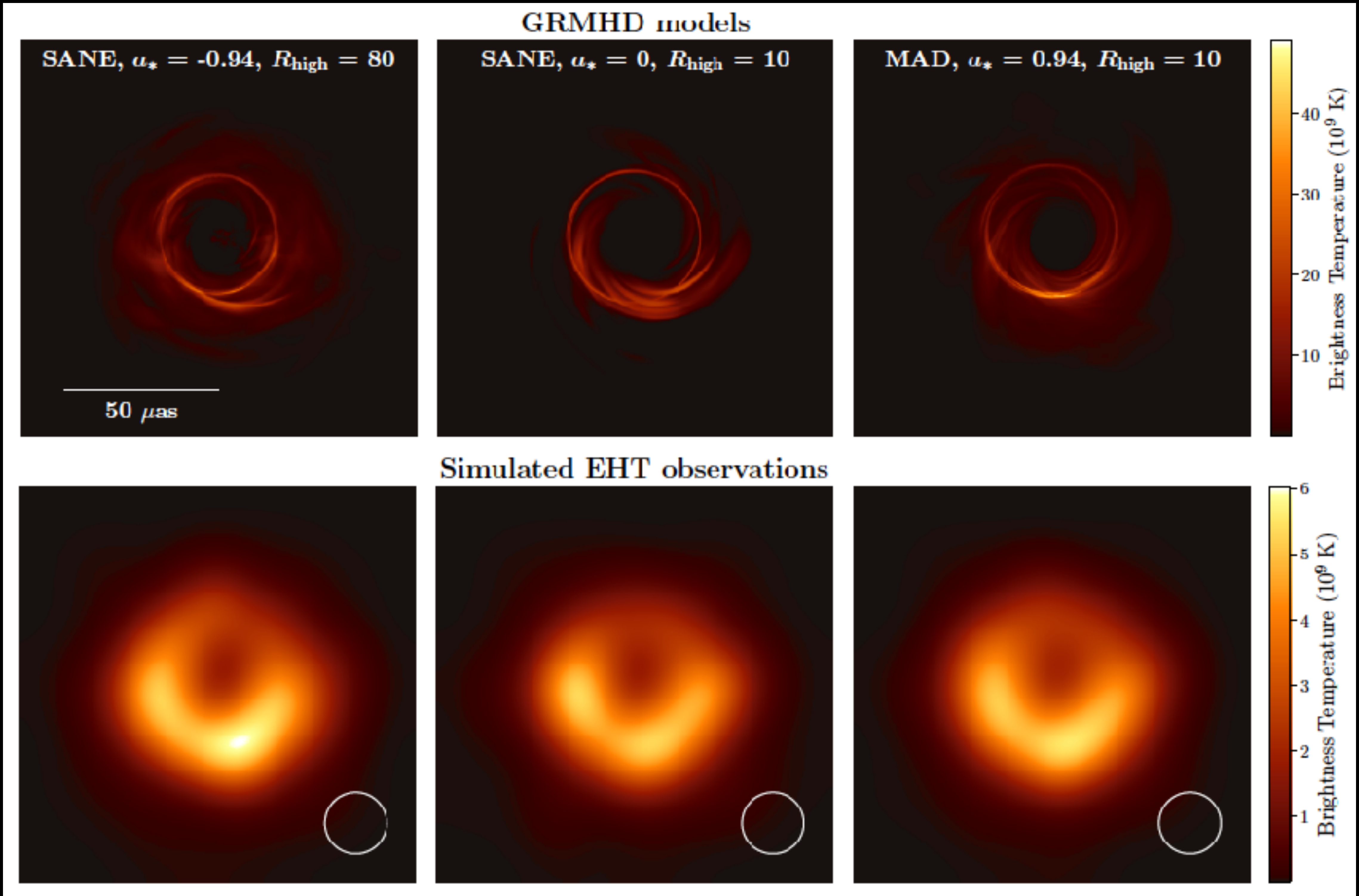
In the image space this would correspond to searching a face in a stadium full of people…

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

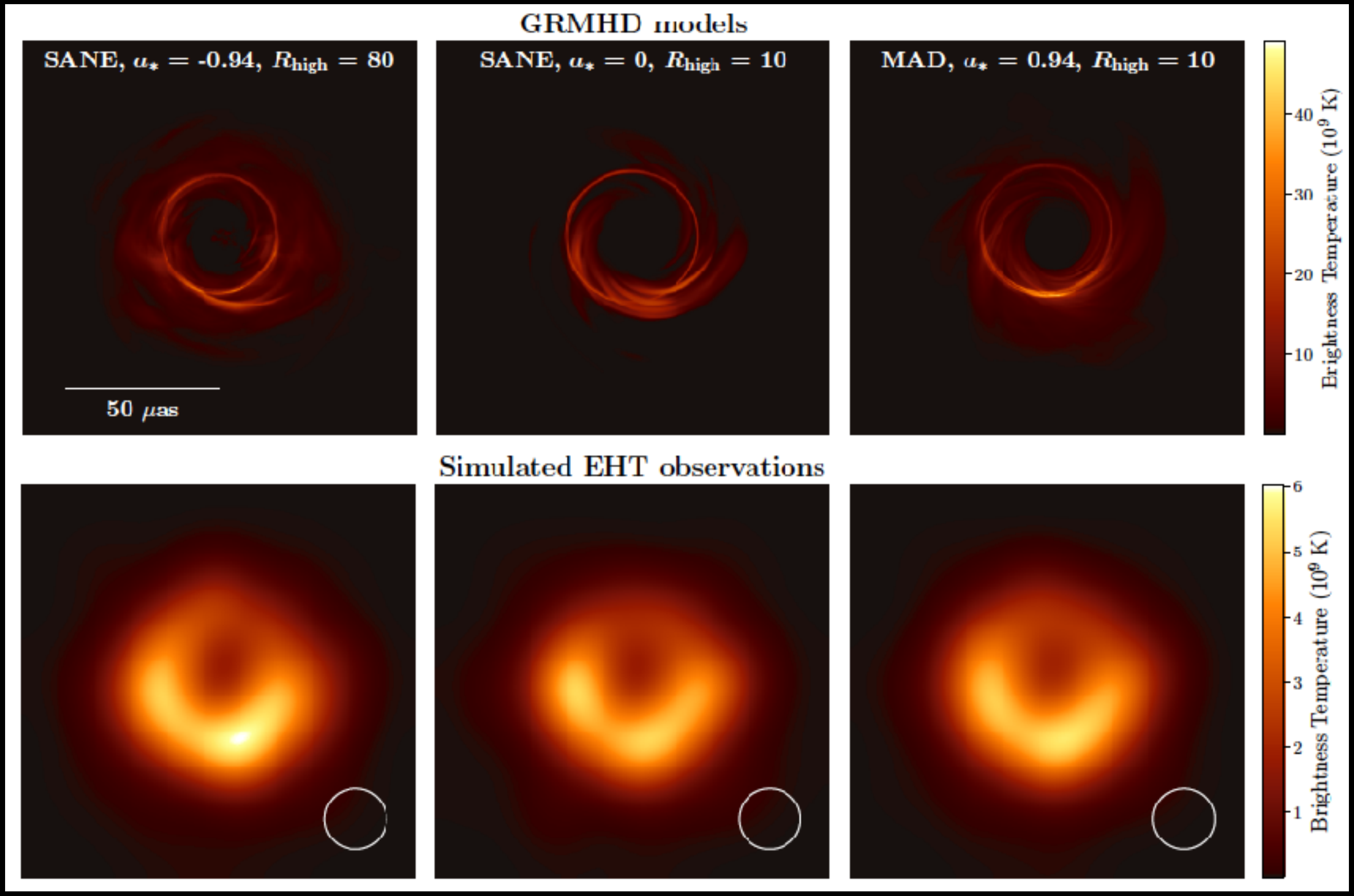
THEORETICAL MODEL



- Degeneracies present in physical conditions and scenarios.

  Good: robustness of conclusions (BHs produce ring)

  Bad: more accurate observations to determine BH spin



Some degeneracies removed with “astronomical priors”

Jet power:

- SANE with $|a| < 0.5$ rejected; MAD with $|a| > 0$ mostly acceptable

X-ray luminosity

- Over-luminous models: mostly SANE with $R_{\rm high} \leq 20$ rejected

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. $\tilde{A}(x) = \dfrac{a_1}{1 + \frac{a_2 x}{1 + \frac{a_3 x}{1 + \dots}}}$

- Few (2-3!) coefficients sufficient for any known metric.

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

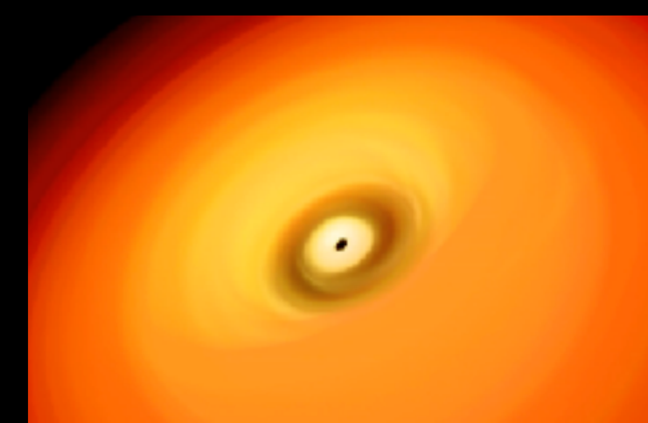
Gnostic approach: alternatives to Kerr bhs:

- accretion onto a **dilaton black hole**

  Mizuno+ 2018

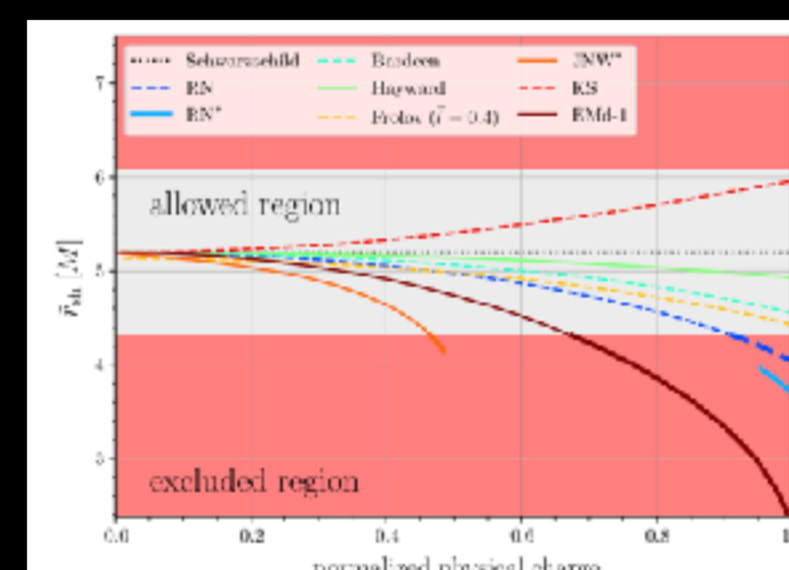
- accretion onto a **boson star**

  Olivares+ 2020



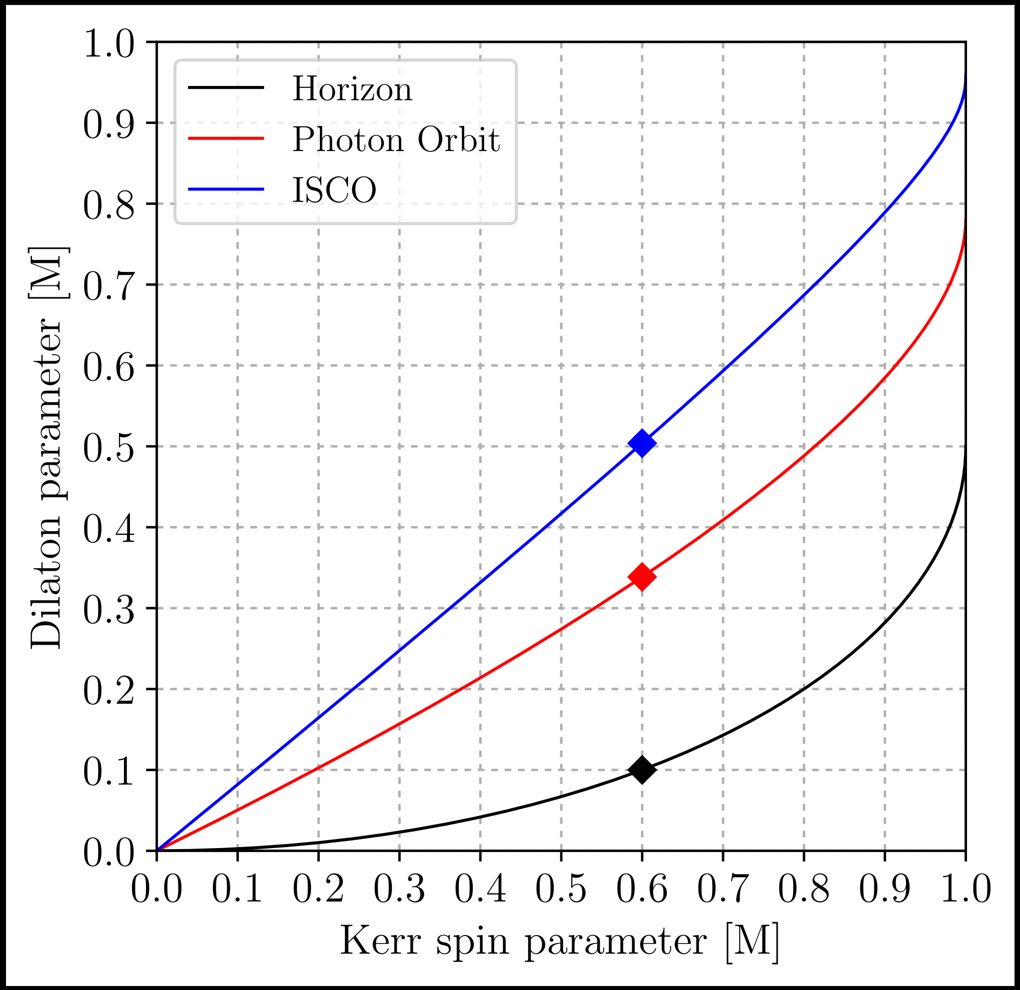
- shadow size on **"charged"** BHs

  Kocherlakota+ 2021



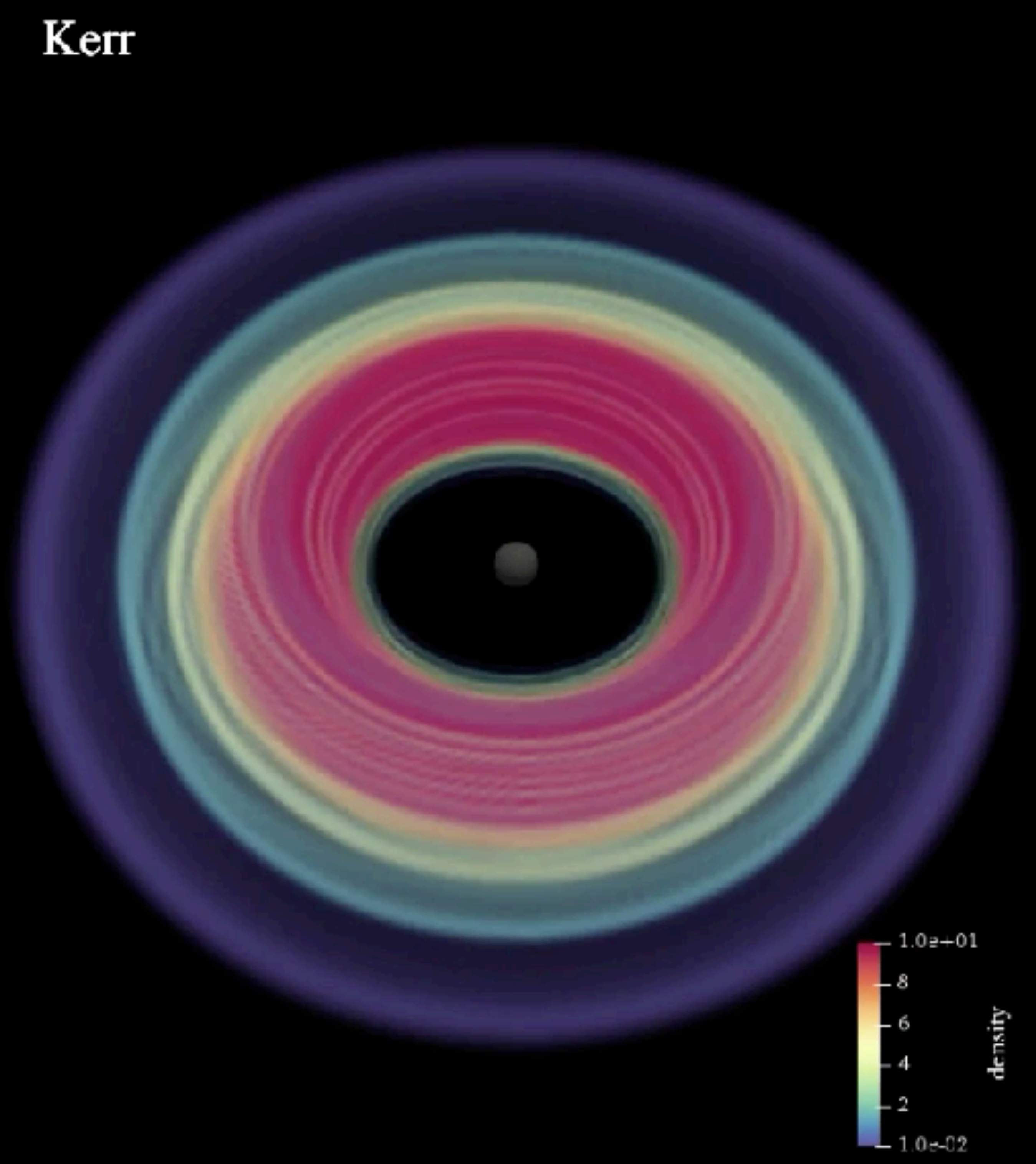
Dilaton vs Kerr black hole

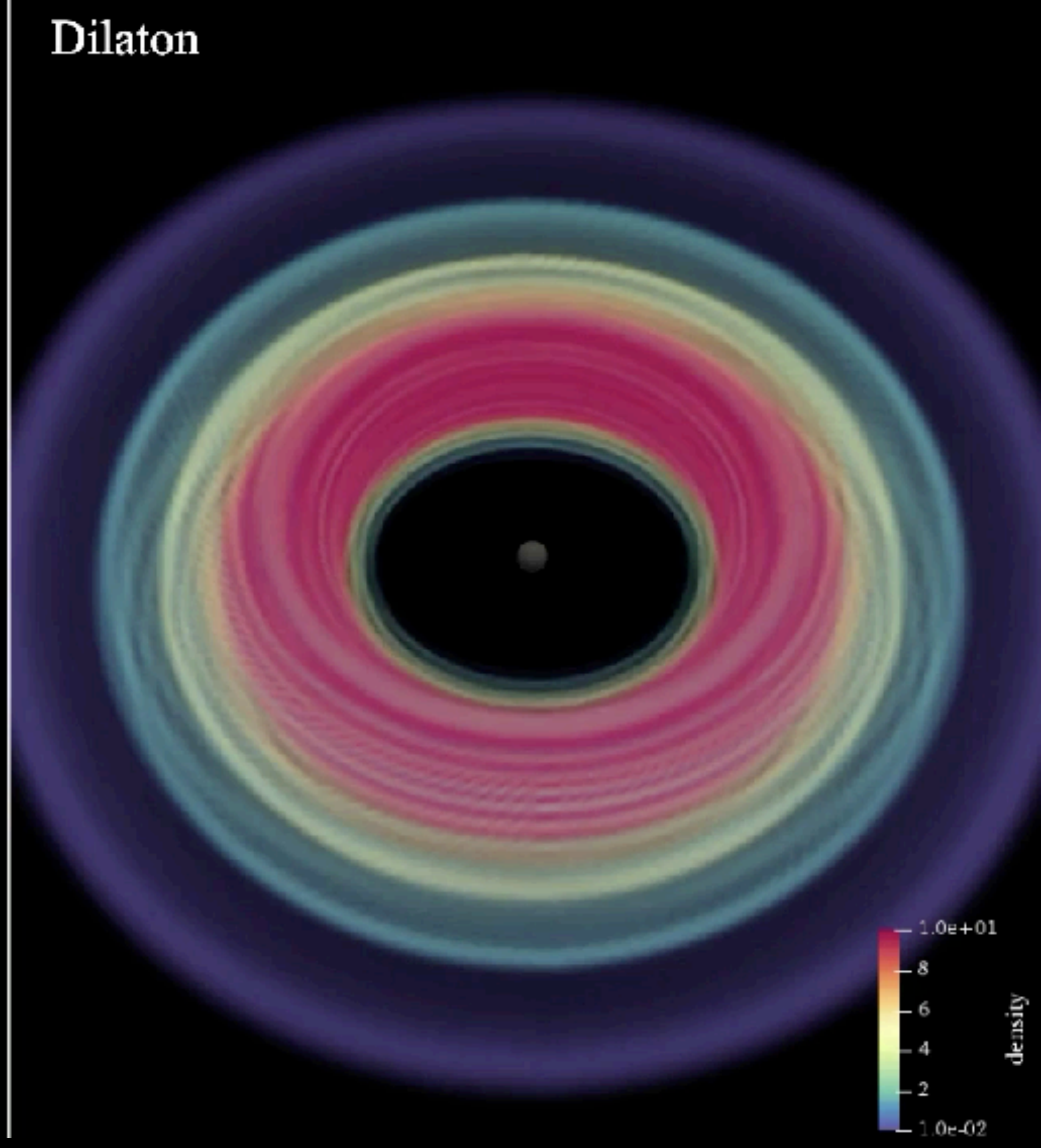
- Fair comparison requires that basic features of the flow are matched.
- Three most important are: **horizon radius, photon orbit, ISCO**
- In general, larger dilaton parameter reduces horizon radius, photon orbit, and ISCO (cf. spin in Kerr).



- Different matches possible but ISCO is most critical since most of the emission comes from around ISCO.

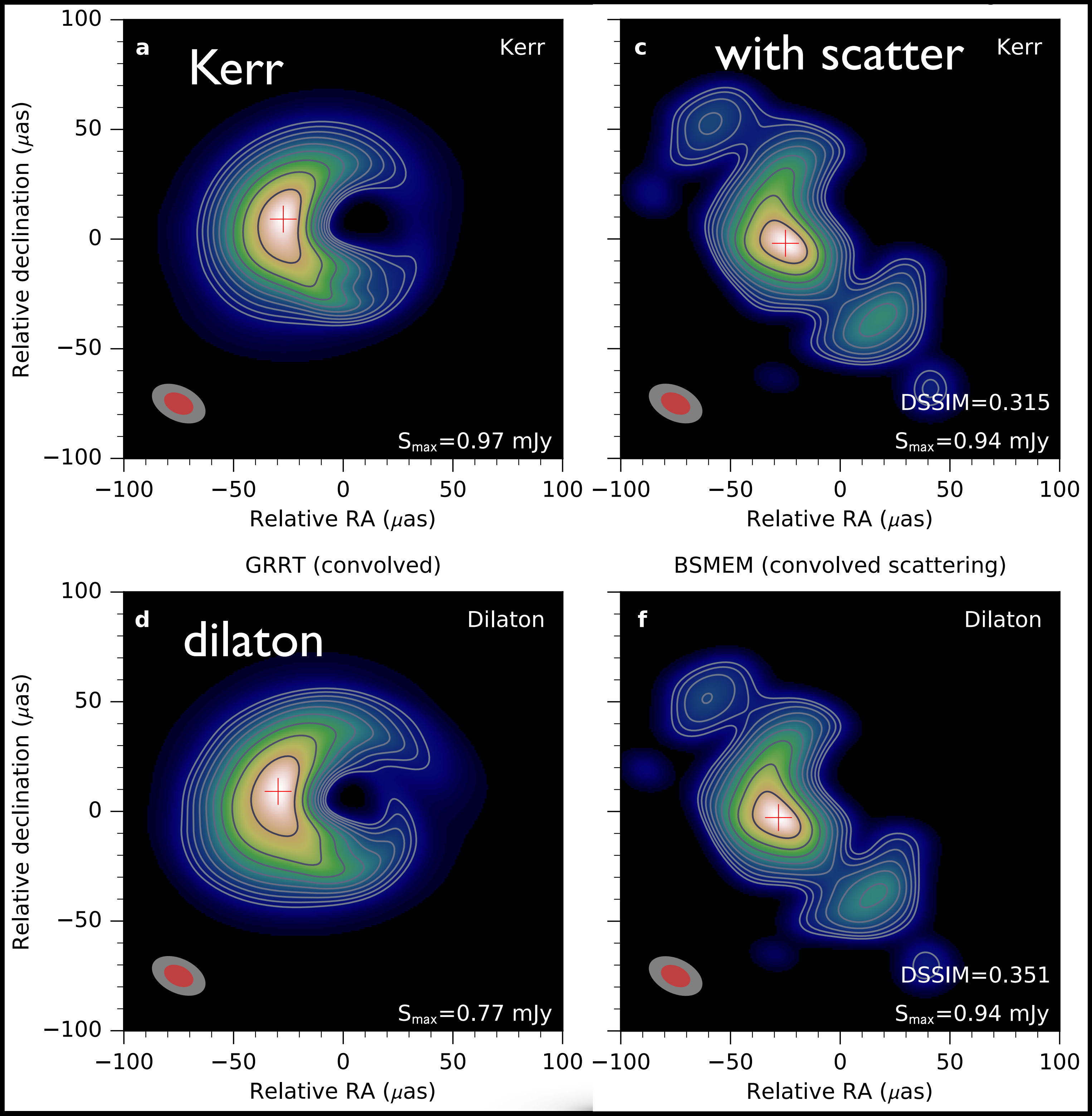
GRMHD simulations





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

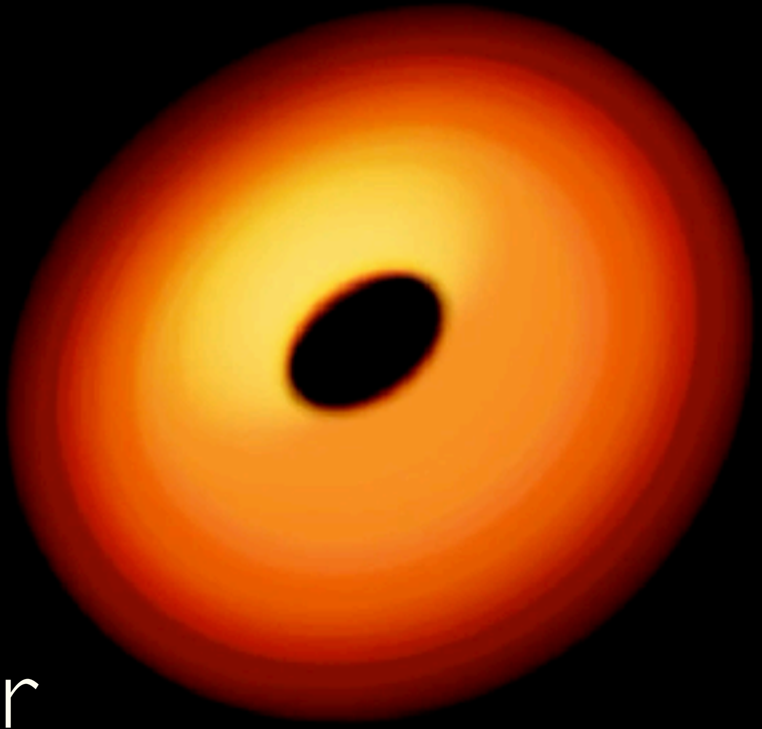


addition of scattering as for Sgr A* makes comparison harder and degeneracy more severe

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

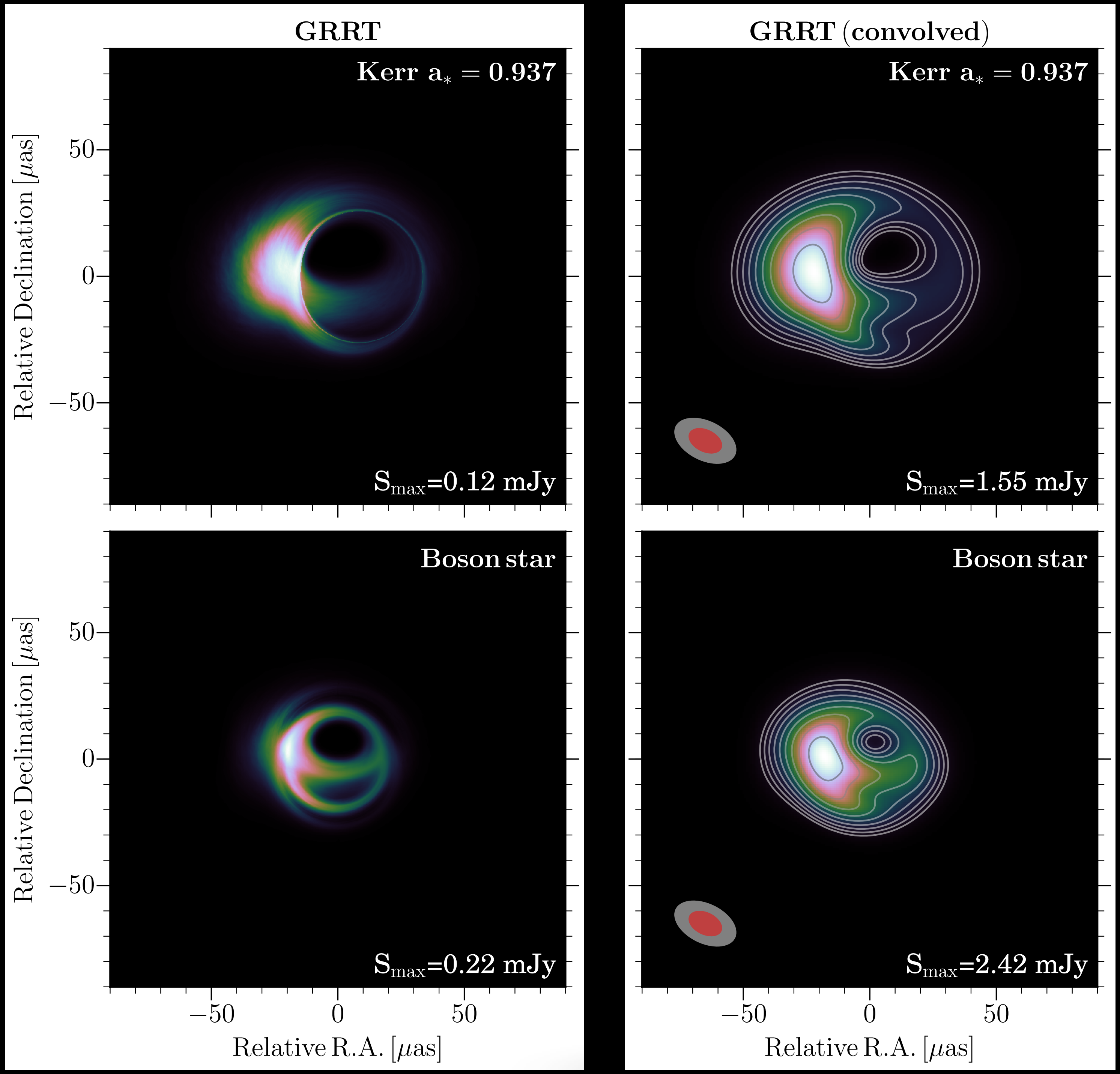


Nonrotating boson star solution of KG equations for a complex scalar field with quadratic potential (mini-boson star):

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

- 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

Conclusions

- ✷ **BlackHoleCam** covered all aspects of these observations, has played a major role in the **EHT** campaign and analysis.
- ✷ 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** and boosted our understanding of accretion in **strong gravity**.

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