The first image of a black hole

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BLACK HOLE CAM

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

erc

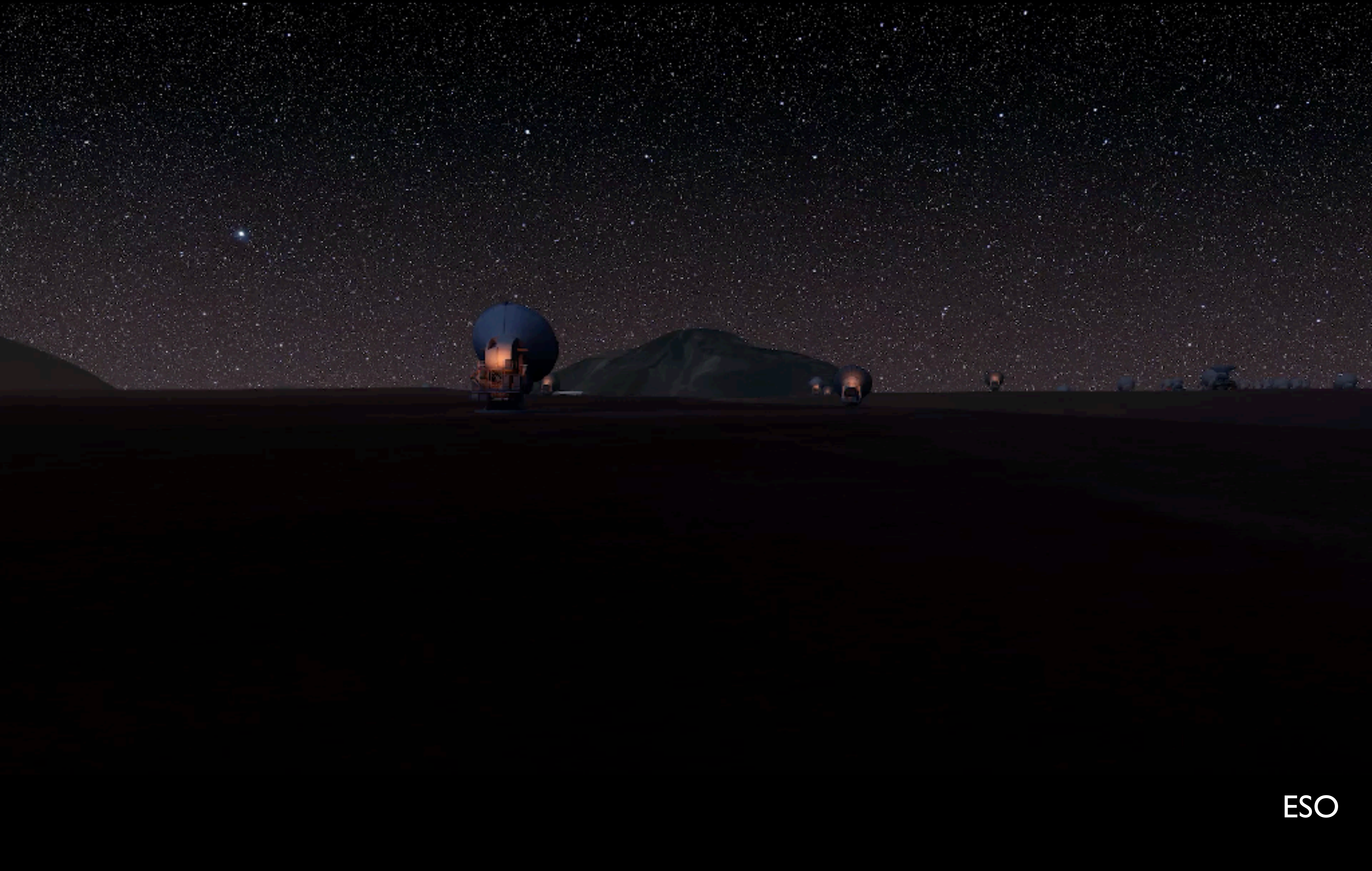
UNIVERSITÀ DI PISA

DIPARTIMENTO DI FISICA

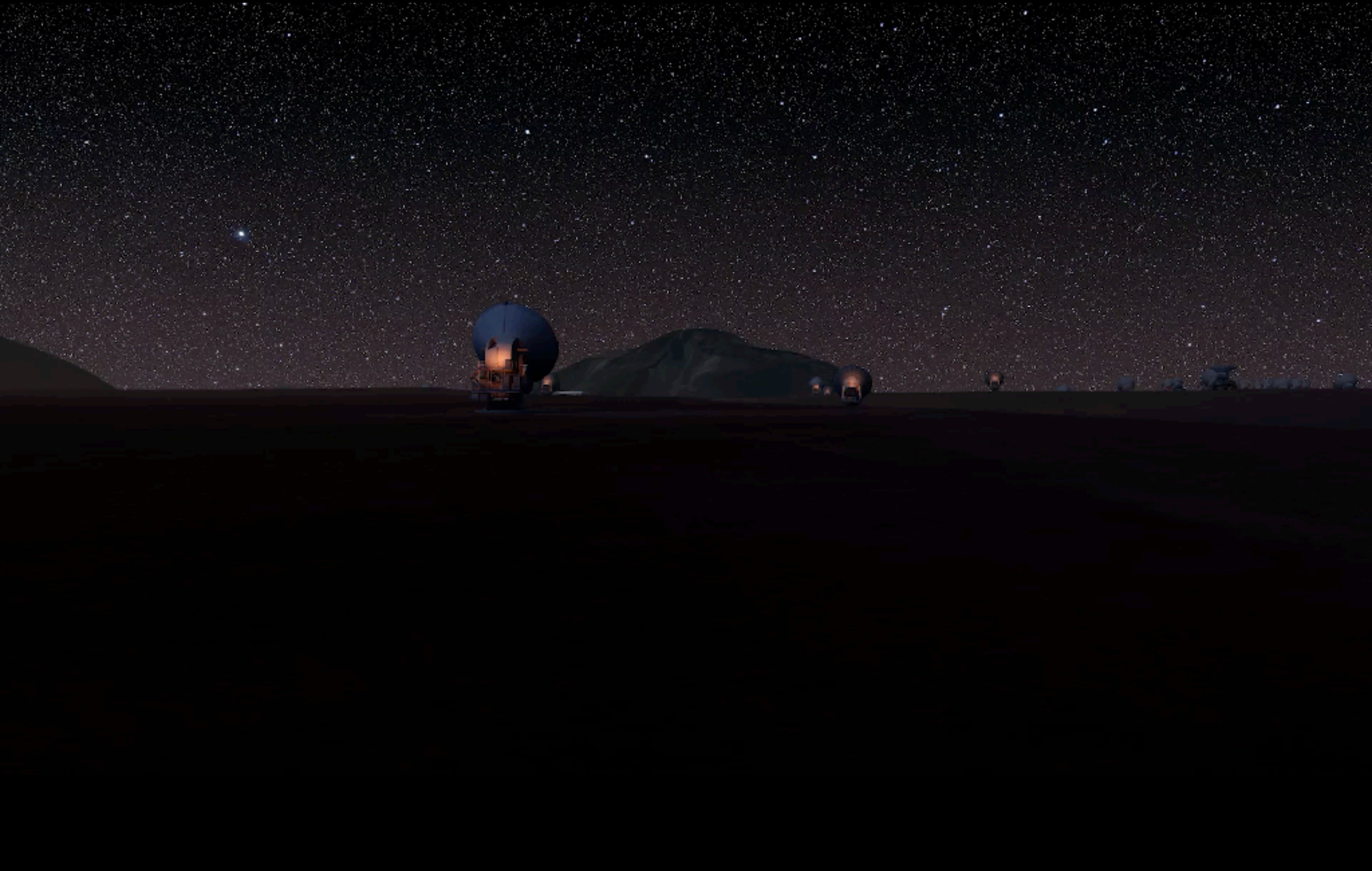
Plan of the talk

- The first image of a black hole: M87*
- How do you take a picture of a BH: **observations?**
- How do you take a picture of a BH: **theory?**
- Alternatives to Einstein and to black holes
- ~~Properties of binary neutron stars~~

M87, center of the Virgo cluster



ESO

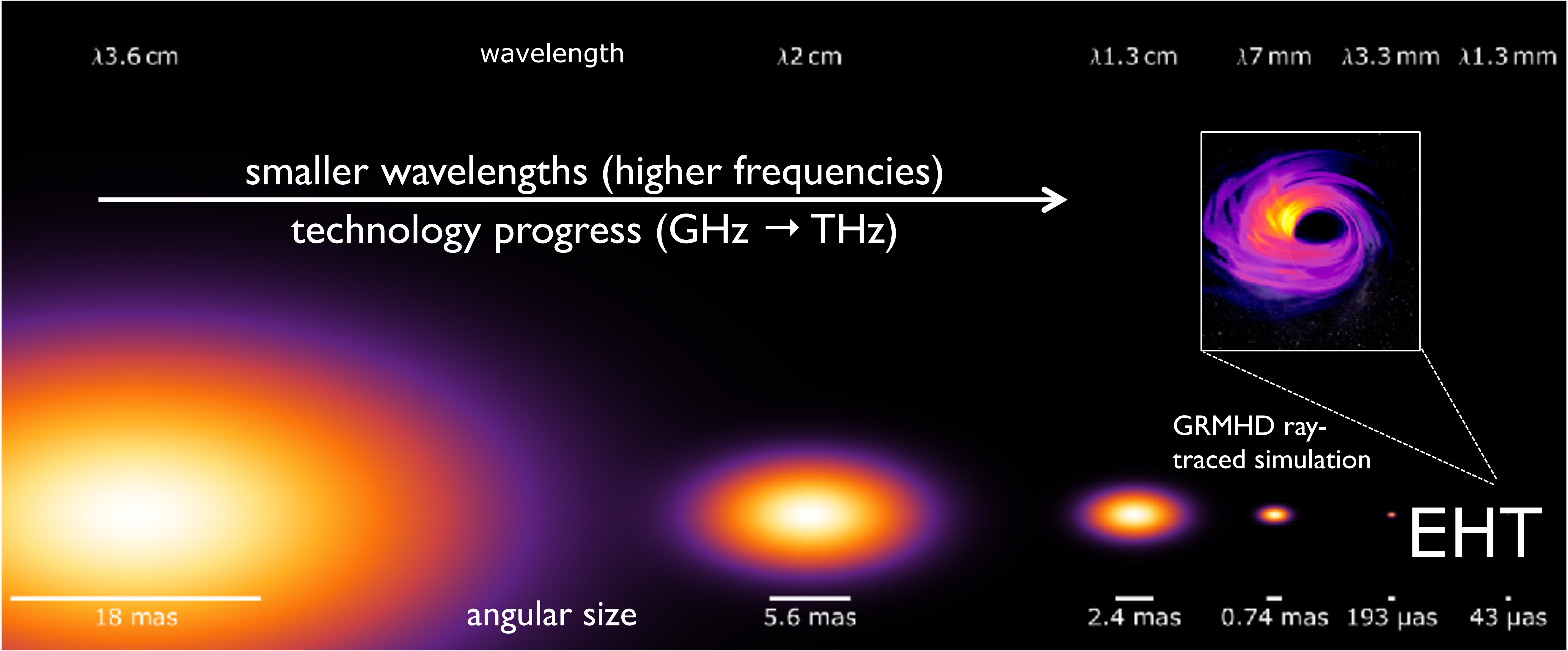


The first image of a black hole

How was this accomplished?

VLBI: Very Long Baseline Interferometry

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

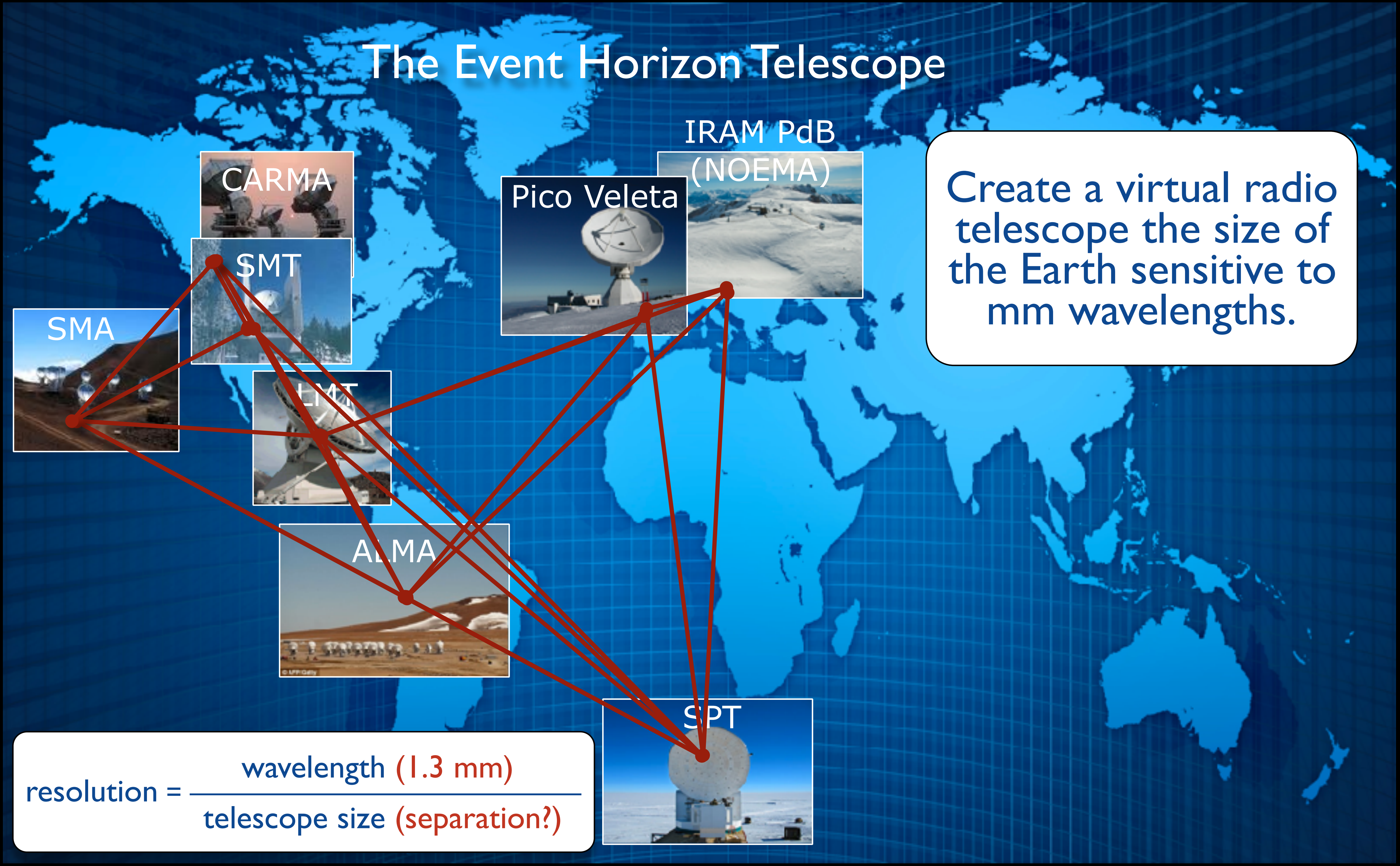


- The shorter the wavelength, the smaller the emitting source
- At 1.3 mm the source becomes of the size of the horizon

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.

$$\text{resolution} = \frac{\text{wavelength (1.3 mm)}}{\text{telescope size (separation?)}}$$

Mexico
(LMT)

Hawaii
(SMA/JCMT)

Arizona
(SMT)

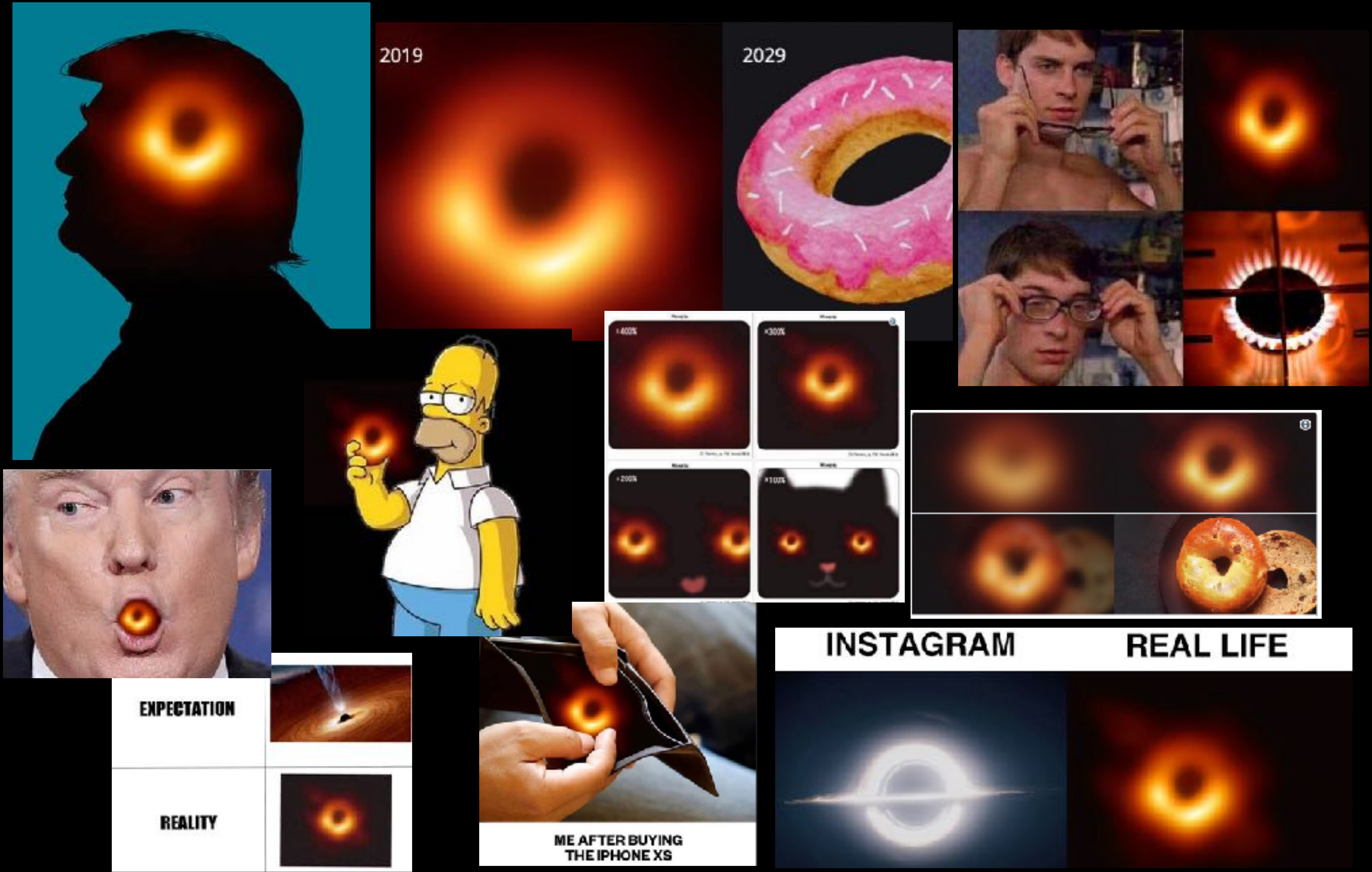
South Pole
(SPT)

Chile
(ALMA/APEX)

Spain
(IRAM 30m,
Pico Veleta)

The image has soon gone around the world…

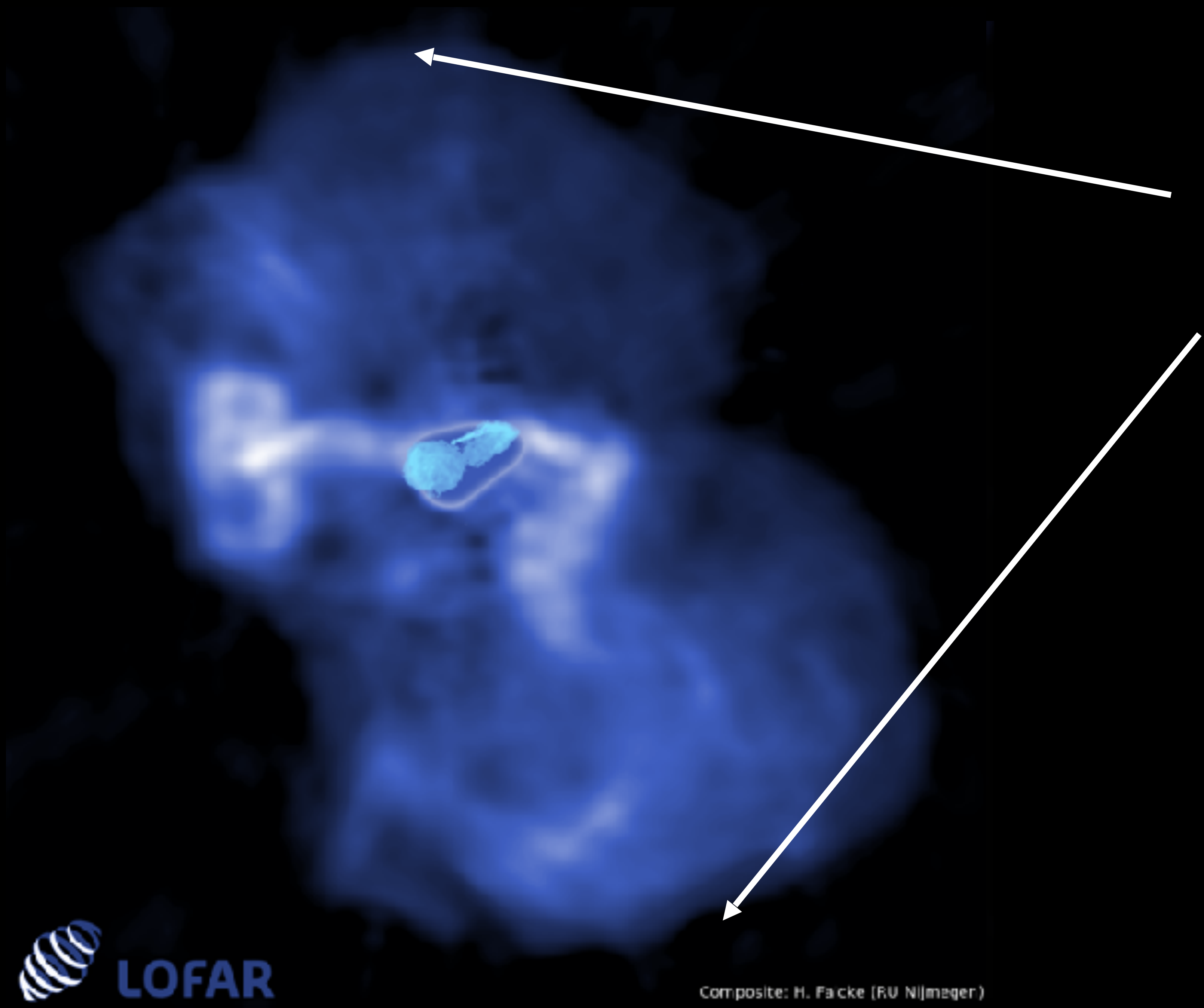
becoming a great resource for social media…



Elliptical galaxy in center of Virgo cluster 50 Million lightyears away
There is evidence for a central dark mass of 3-6×10^9 M_{sun}

image in the optical

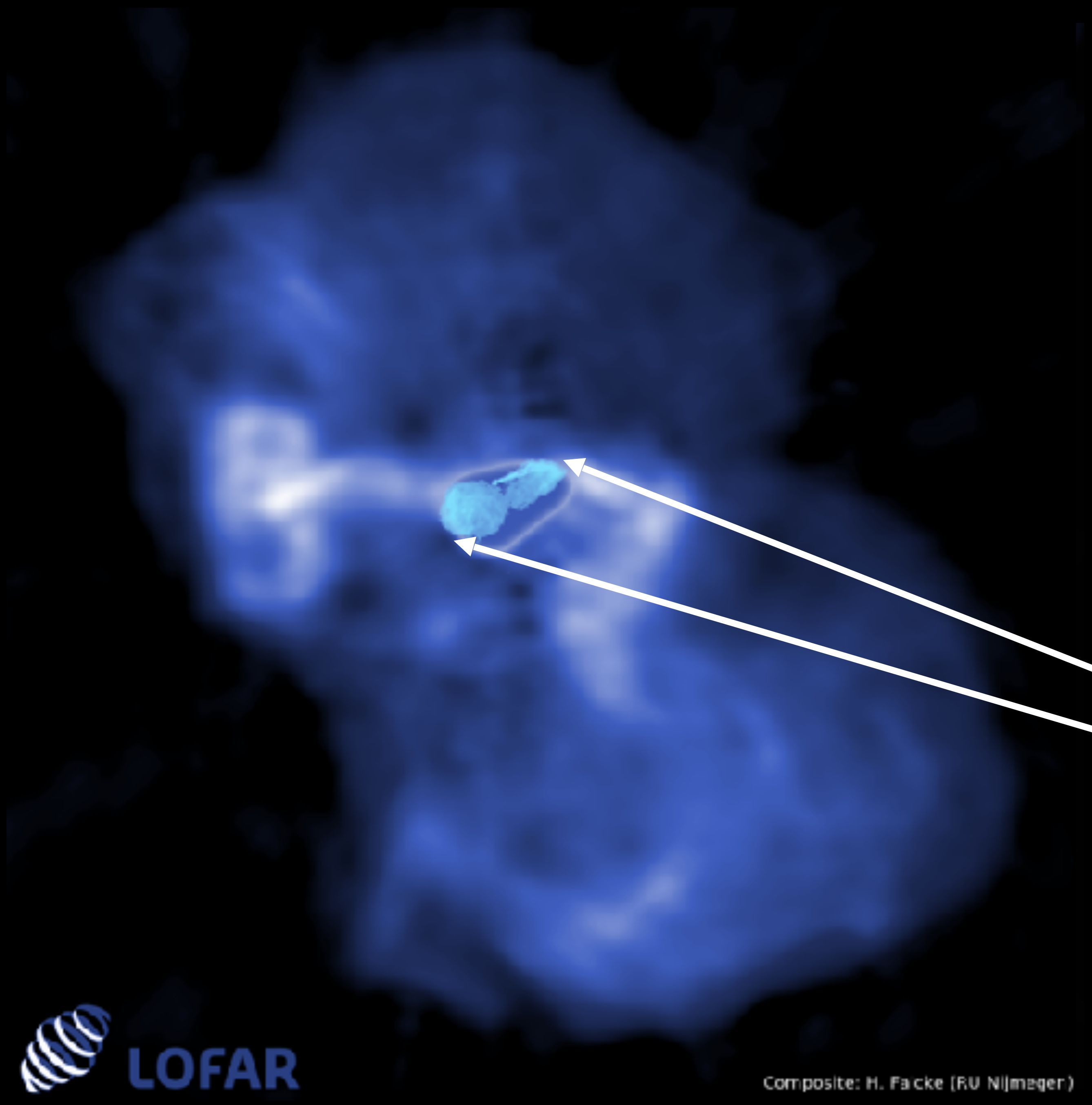
Elliptical galaxy in center of Virgo cluster 50 Million lightyears away
There is evidence for a central dark mass of $3\text{-}6\times10^{9}\ M_{sun}$



Composite: H. Falcke (RU Nijmegen)

Large-scale radio map
(few cm wavelengths)

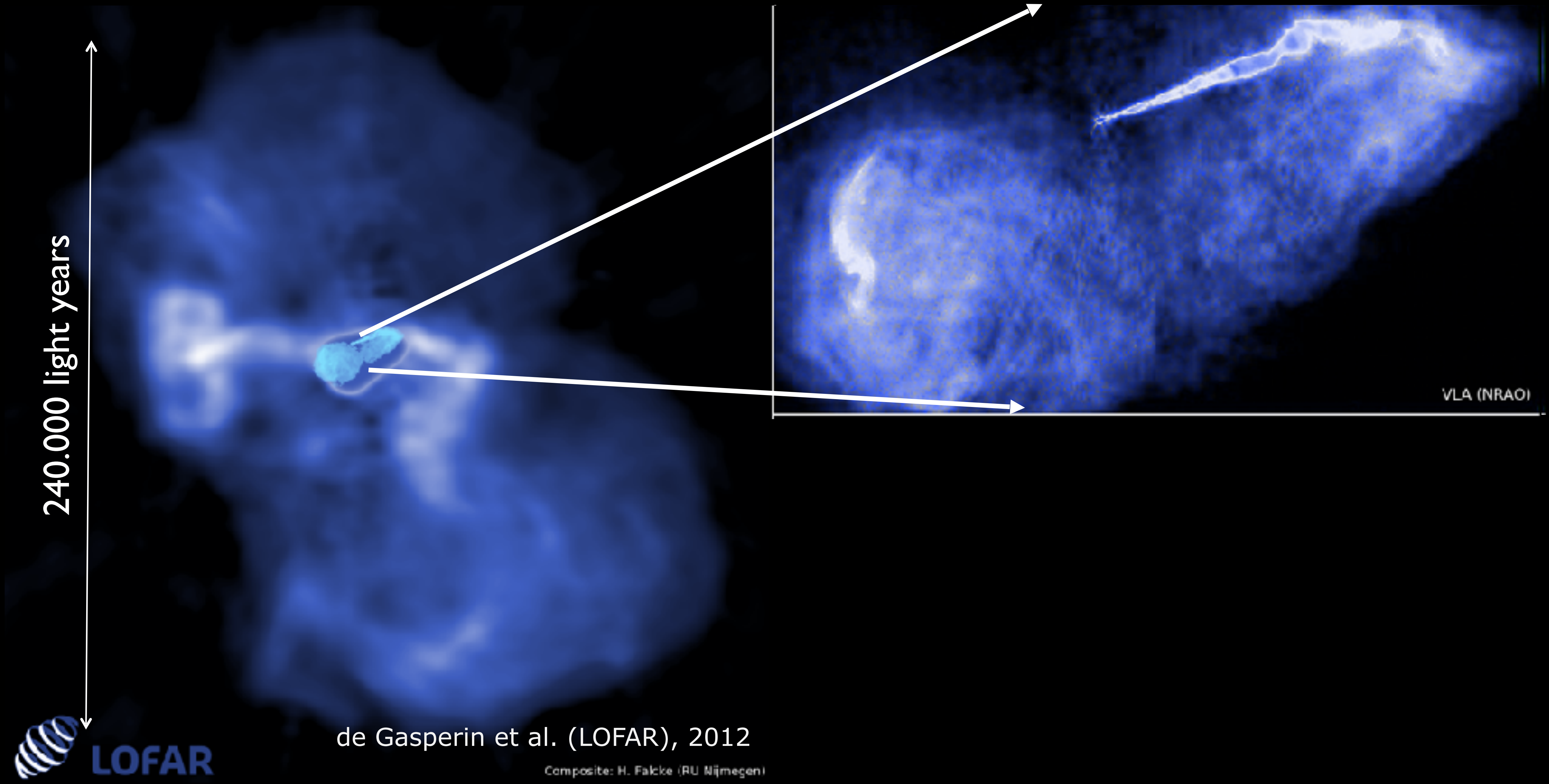
Elliptical galaxy in center of Virgo cluster 50 Million lightyears away
There is evidence for a central dark mass of 3-6×10^9 M_{sun}



Composite: H. Falcke (RU Nijmegen)

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

Elliptical galaxy in center of Virgo cluster 50 Million lightyears away
There is evidence for a central dark mass of $3\text{-}6\times10^9\ M_{\mathrm{sun}}$



de Gasperin et al. (LOFAR), 2012

Composite: H. Falcke (RU Nijmegen)

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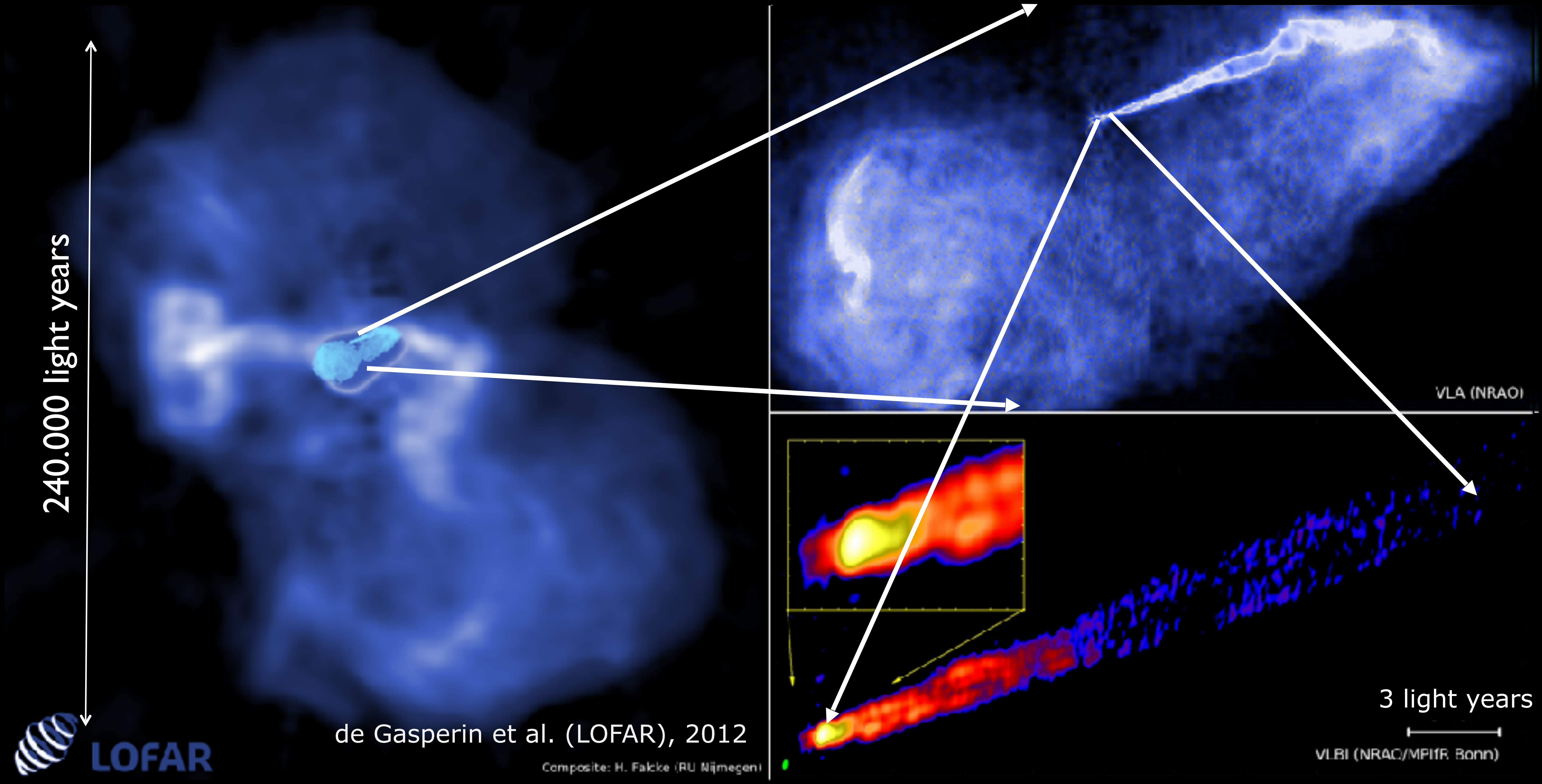

de Gasperin et al. (LOFAR), 2012

Composite: H. Falcke (RU Nijmegen)

VLBI (NRAO/MPIfR Bonn)

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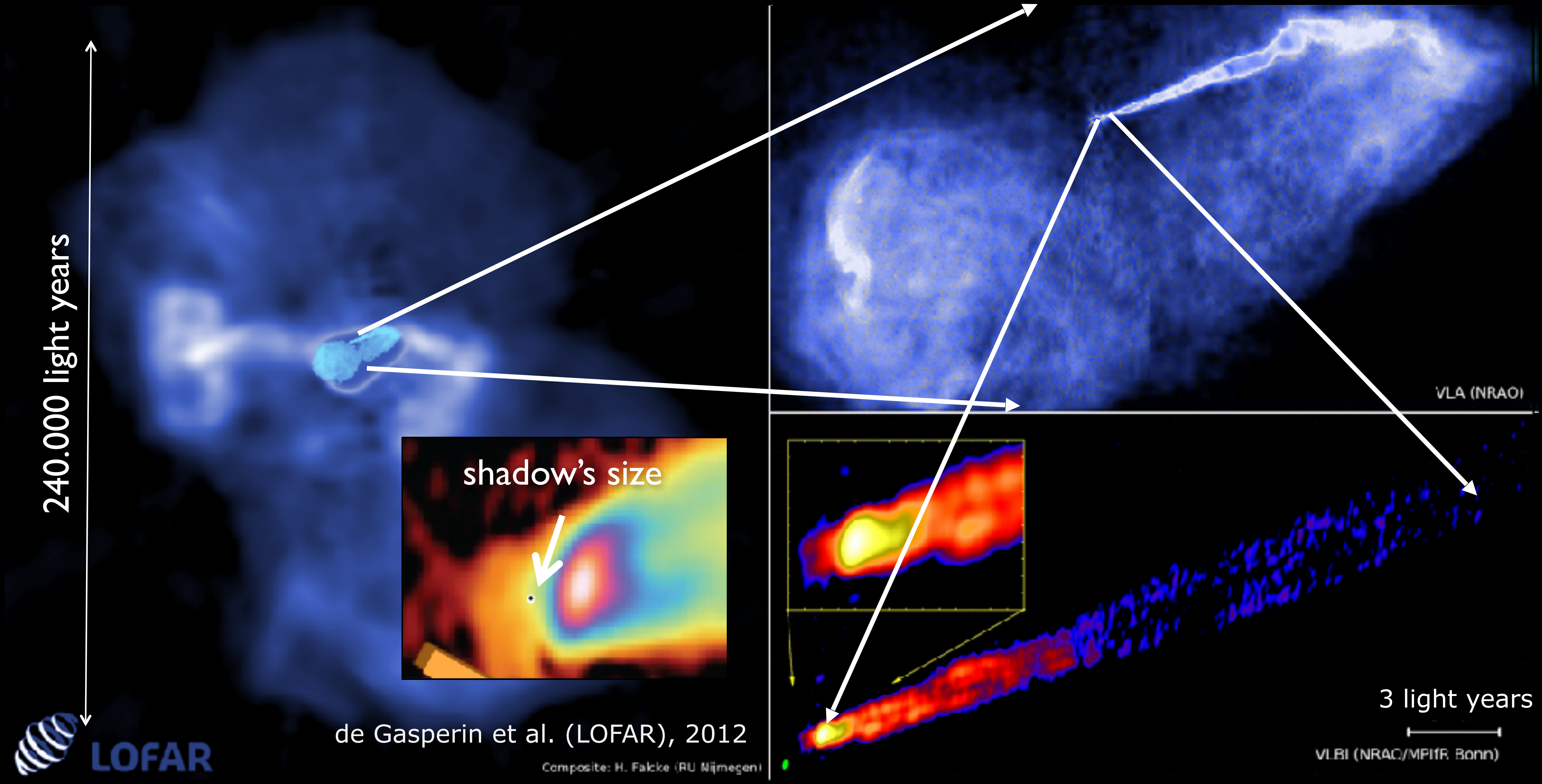


de Gasperin et al. (LOFAR), 2012

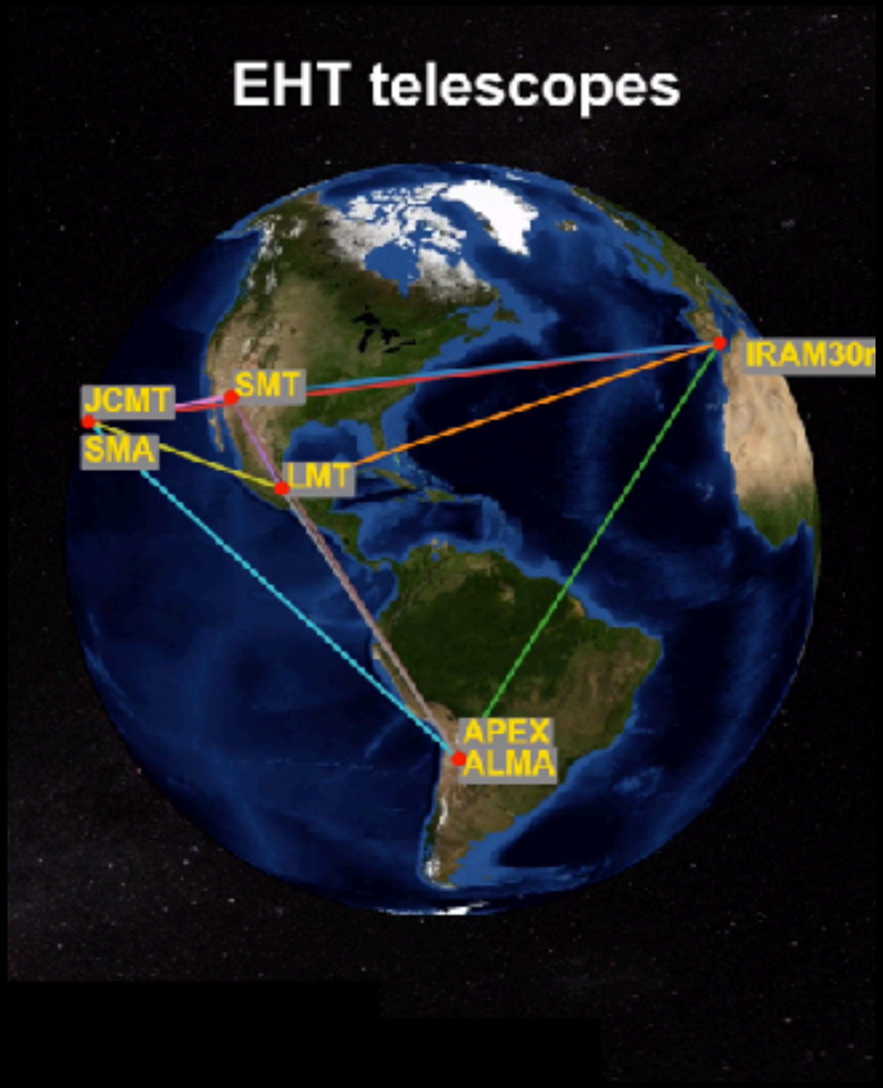
Composite: H. Falcke (RU Nijmegen)

… to have an idea of the scales…

https://xkcd.com/2135/

How do we do this in practice?

Observations



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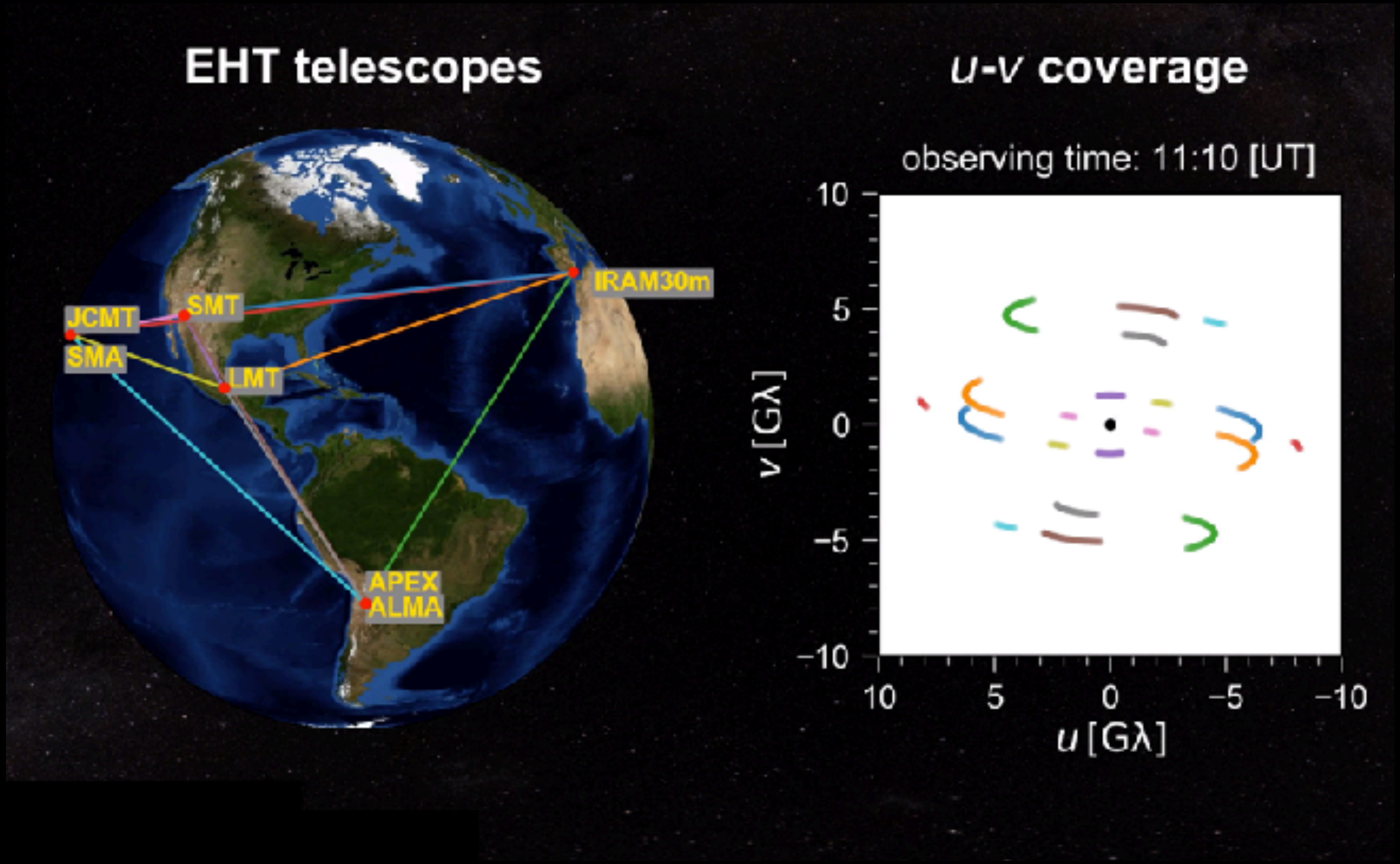


How do we do this in practice?

Observations

$\mathcal{V}(u,v)$: complex visibilities

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

(x,y) : angular coordinates on the sky

(u,v) : projected baseline coordinates on the sky

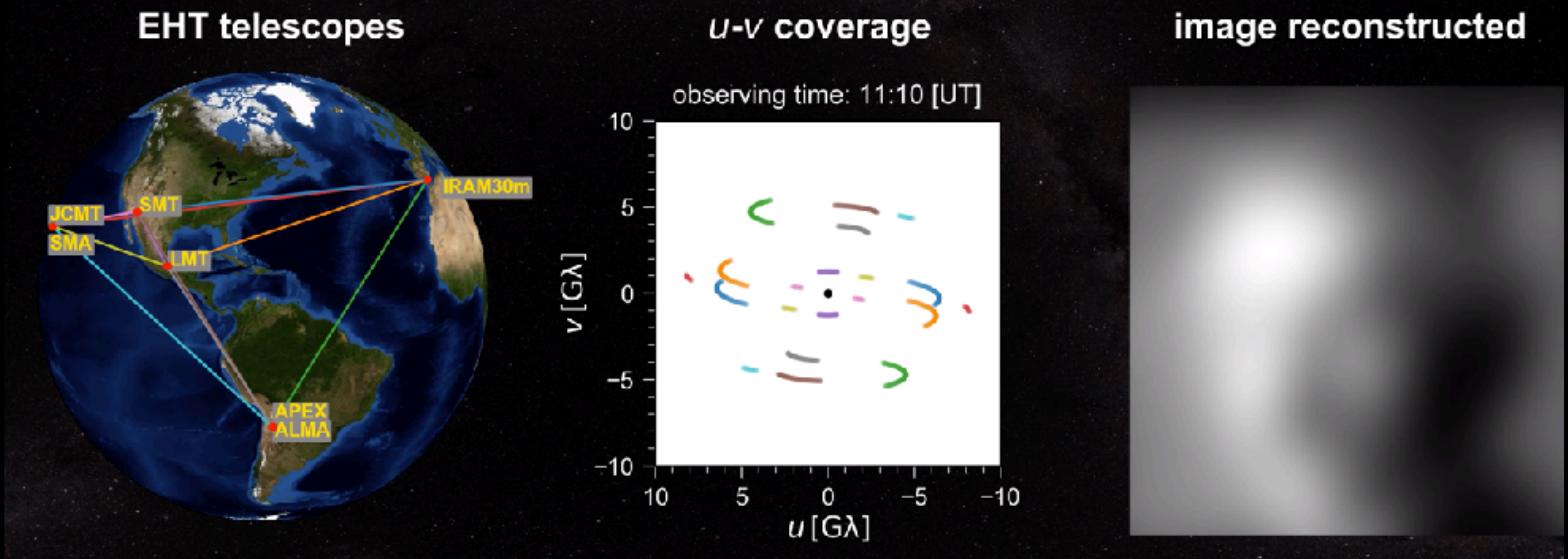
$I(x,y)$: brigthness distribution

$$\mathcal{V}(f) = \int e^{-2\pi i f t} I(t)dt$$

How do we do this in practice?

Observations

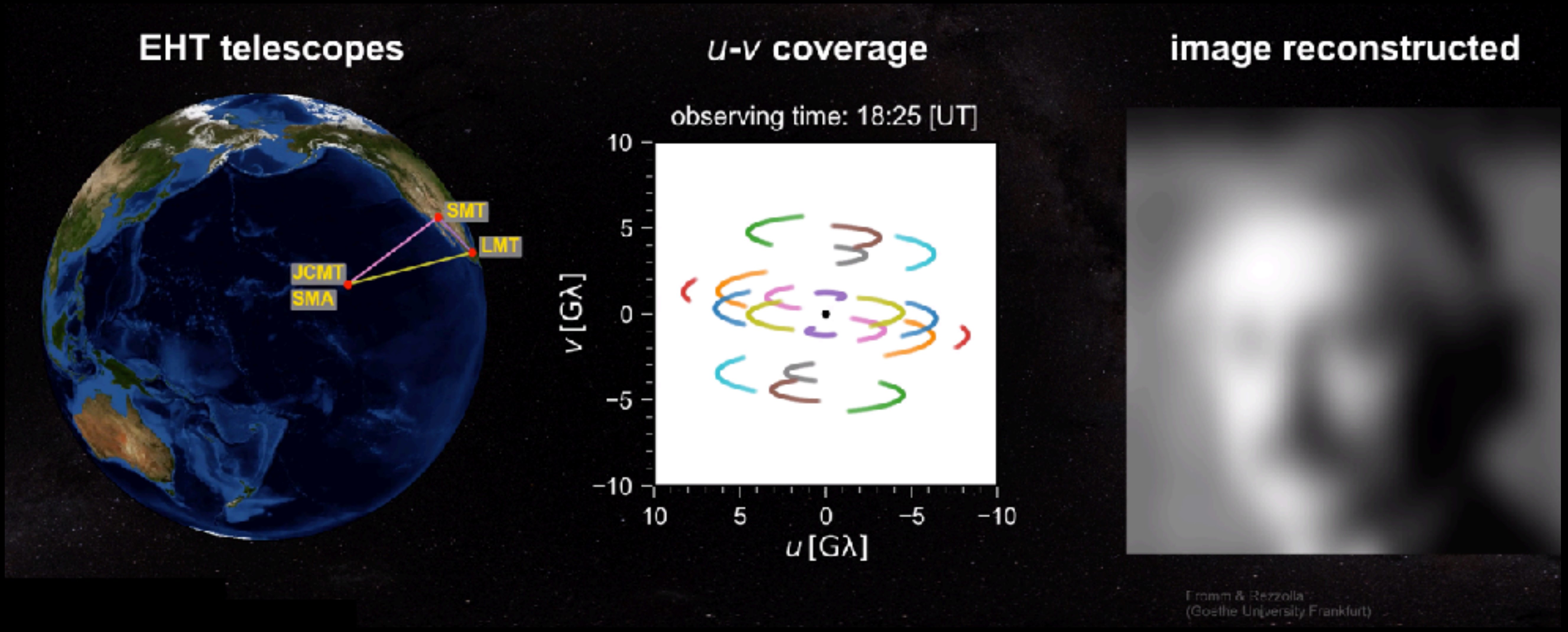
$$\mathcal{V}(u,v) = \int\int e^{-2\pi i(ux+vy)} I(x,y)\,dx\,dy$$



Fromm & Rezzolla
(Goethe University Frankfurt)

How do we do this in practice?

Observations

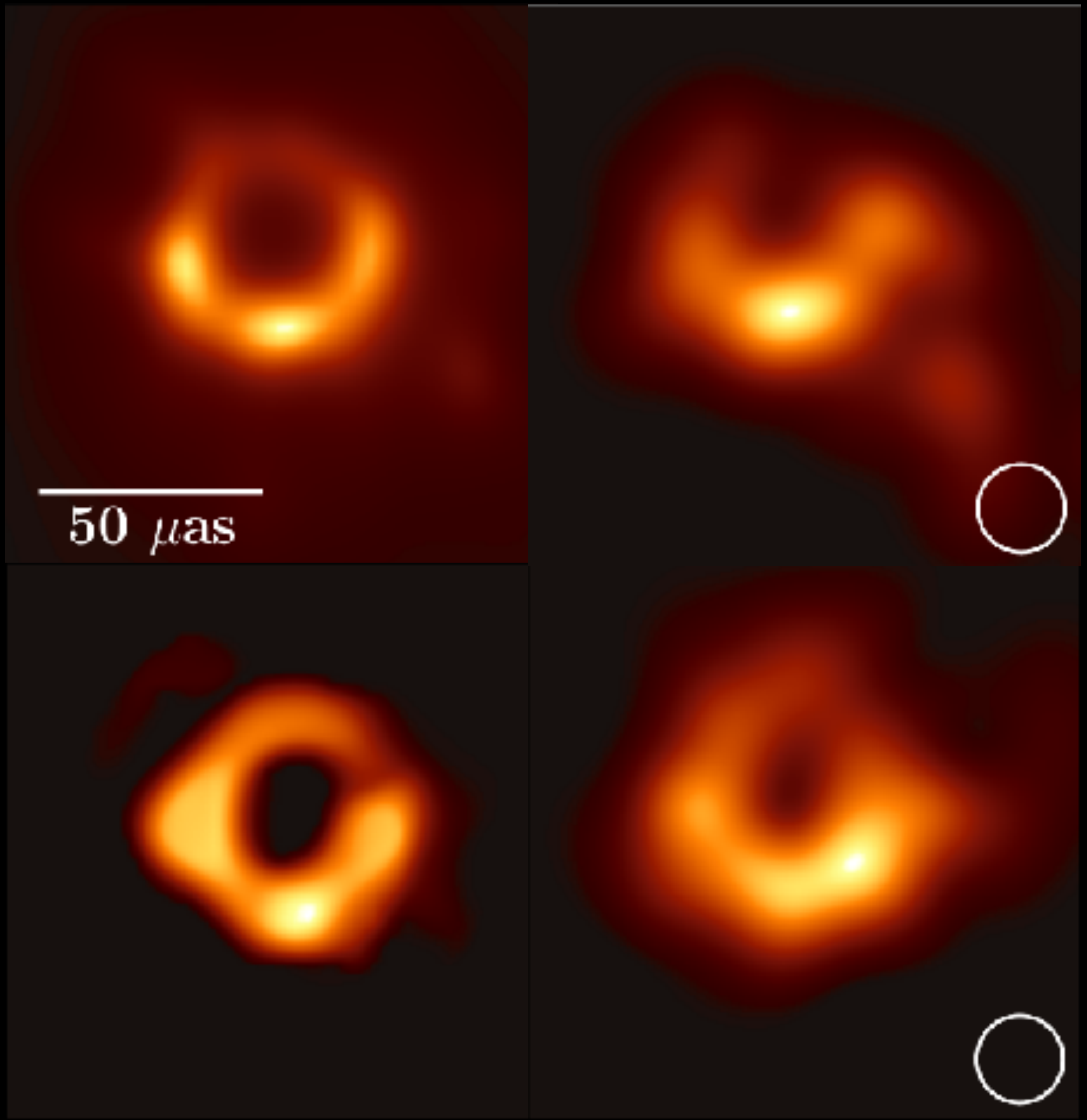


Fromm & Rezzolla
(Goethe University Frankfurt)

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

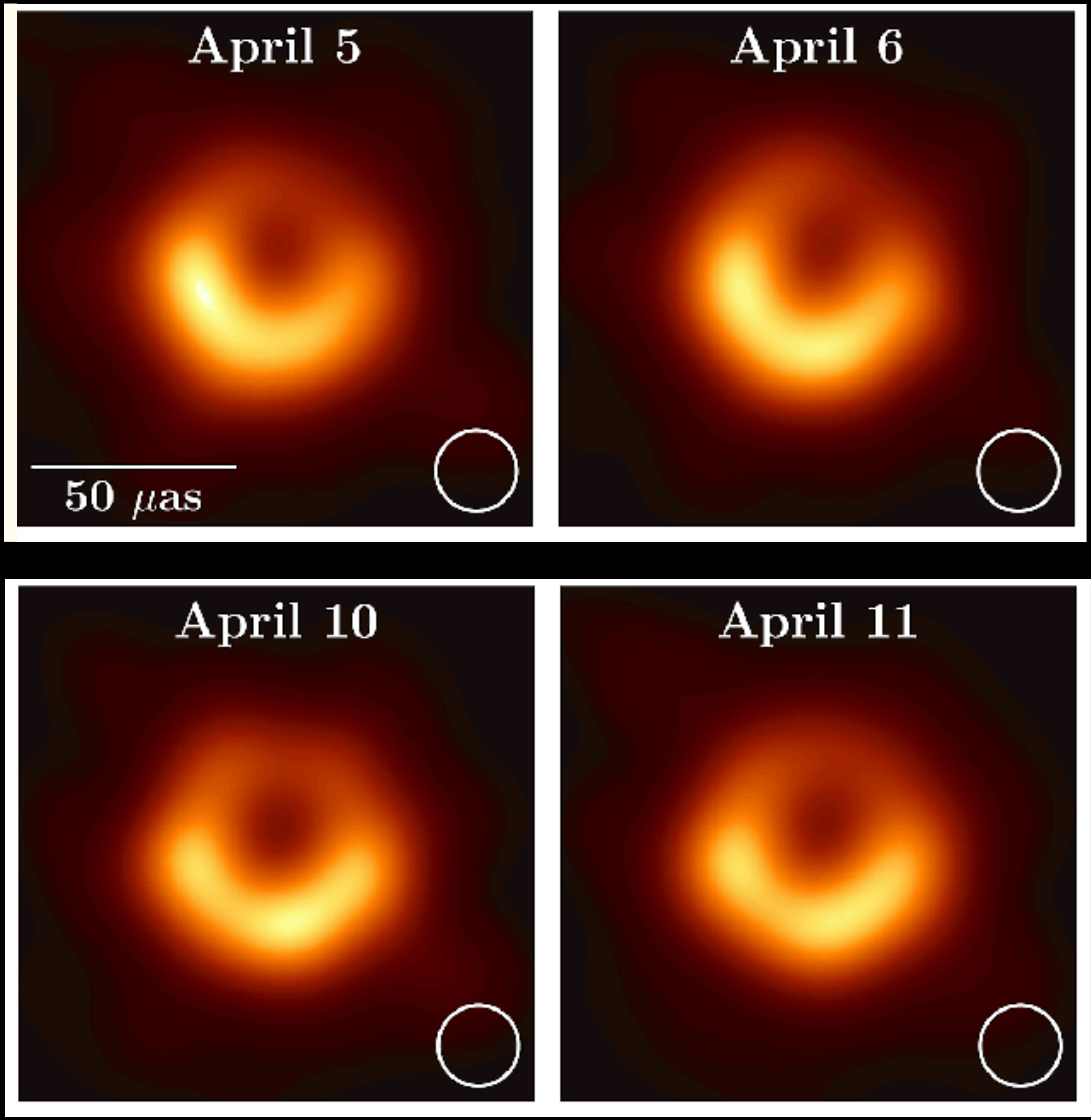
The four teams used multiple software packages and were set to work blindly from each other.

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.**

To do this in **BlackHoleCam,** a complex and complete computational infrastructure was developed:

BHAC/BHOSS/GENA

C. Fromm

R. Gold

Y. Mizuno

H. Olivares

O. Porth

now UA

Z. Younsi

now UCL

BlackHoleCam: Bonn (Kramer), Frankfurt (LR), Nijmegen (Falcke)

- Frankfurt concerned with theoretical modelling of **accretion flows in strong gravity** (GR and alternative theories) and corresponding electromagnetic emission.

- Use **observations** and a complex theoretical pipeline of numerical codes (**`BHAC/BHOSS/GENA`**) to reveal properties of the spacetime.

- These codes are written to solve different sets of PDEs depending on the task considered (1, 2, 3).

System of equations to solve…

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

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

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

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

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

These **GRMHD equations** are solved using finite-volume methods with a variety of algorithms in **2D and 3D**.

In addition...

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

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

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

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

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

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

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

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

Which gravity?…

- Previous eqs. require background **spacetime metric:** $g_{\mu\nu}(x^\alpha)$

- **Field equations** are not necessary as we are exploiting **equivalence principle:** test-particle motion

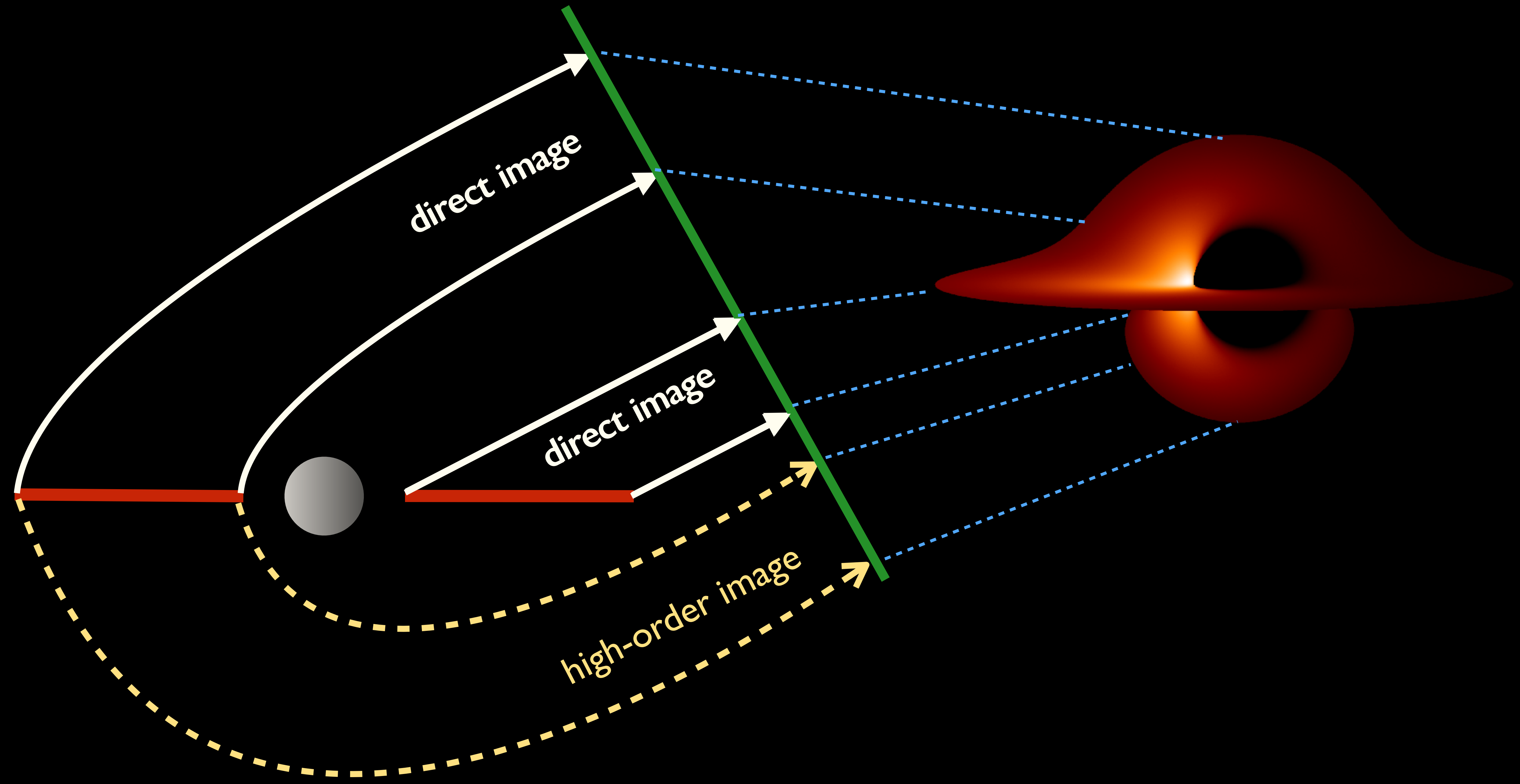
- Testing theory of gravity **not trivial** if hundreds available!

- Opted for **agnostic approach** and built a description able to describe all theories: $g_{\mu\nu}(x^\alpha) \to g_{\mu\nu}(x^\alpha, a_i, b_i)$

- Derive generic expansion exploiting conformal mapping and rapidly converging Pade' expansion

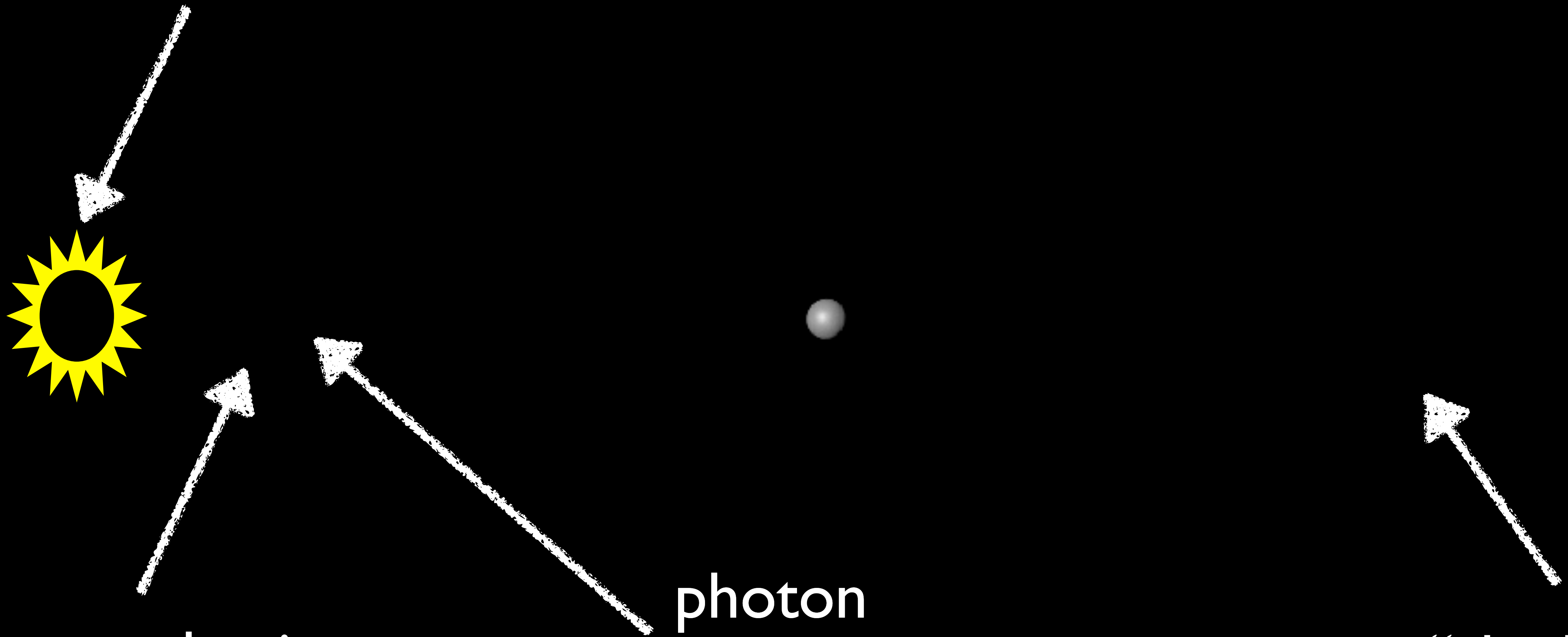
- GR seen as a possible, reference case: $g_{\mu\nu}(x^\alpha, a_i = 0 = b_i)$

LR, Zhidenko, 2014; Konoplya, LR, Zhidenko, 2016



Younsi et al. 2019

source of light



event horizon

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

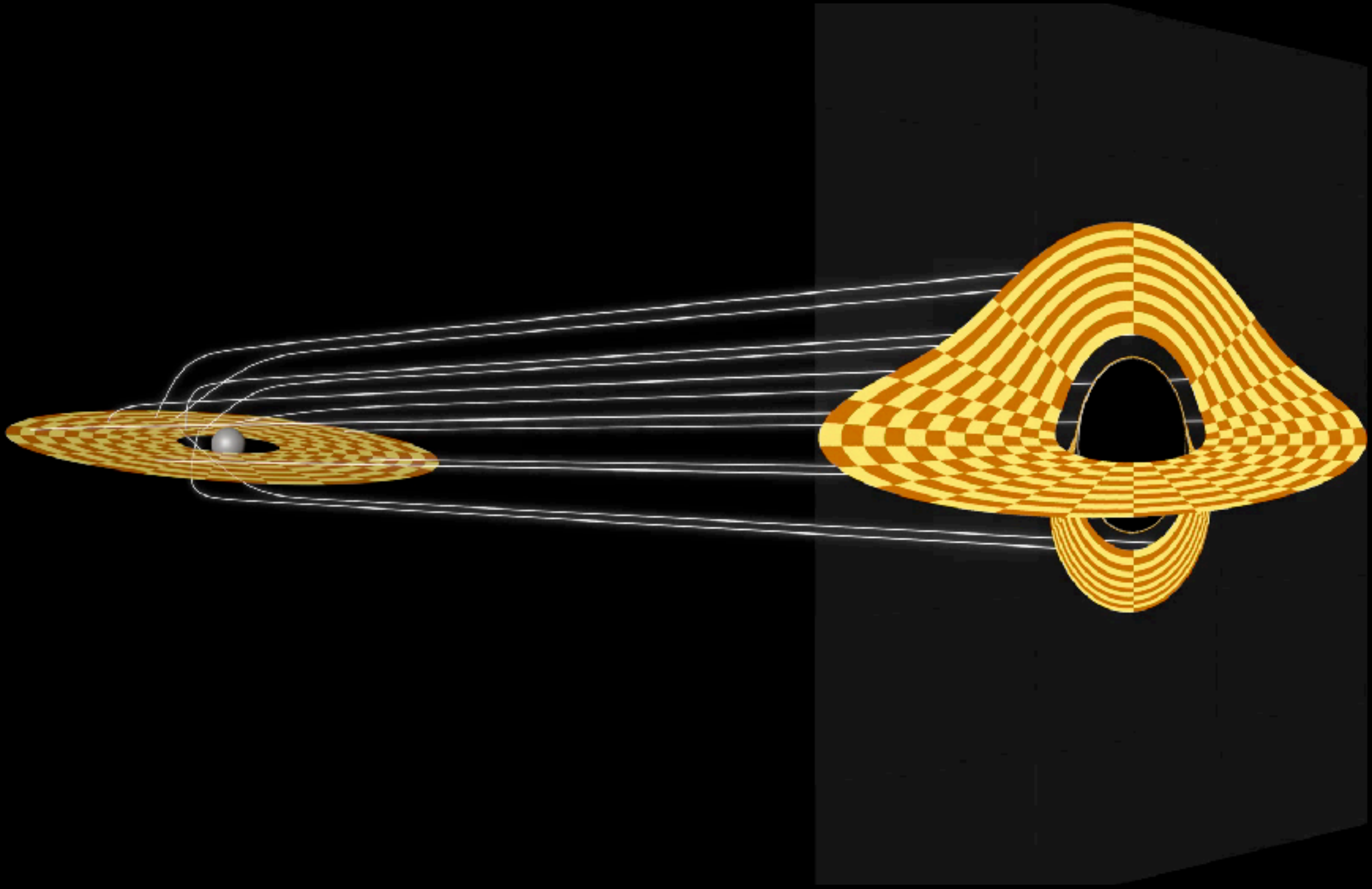
photon
circular orbit

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

“shadow”

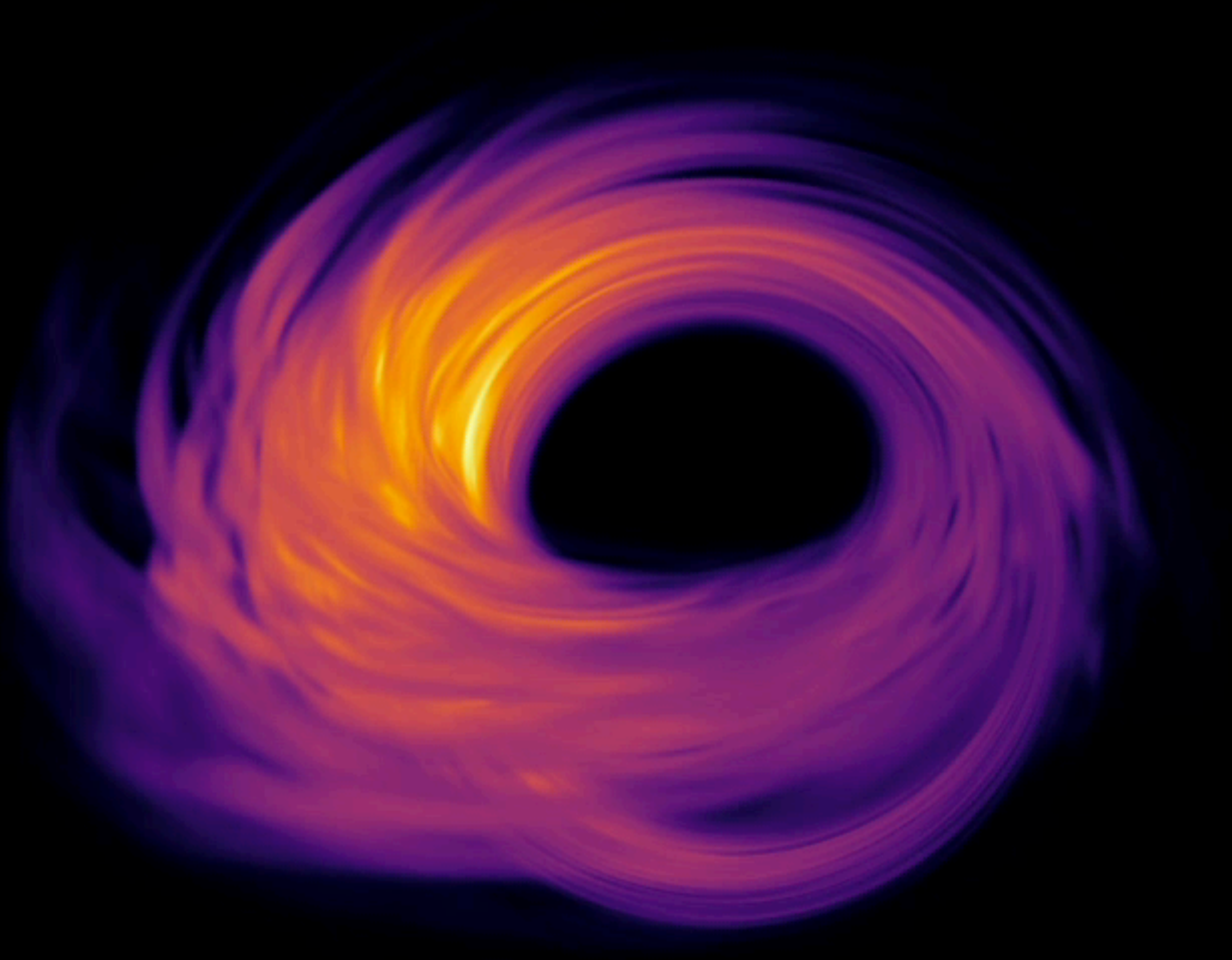
Müller, Pössel, Weih, LR

shadow's size depends also on the inclination



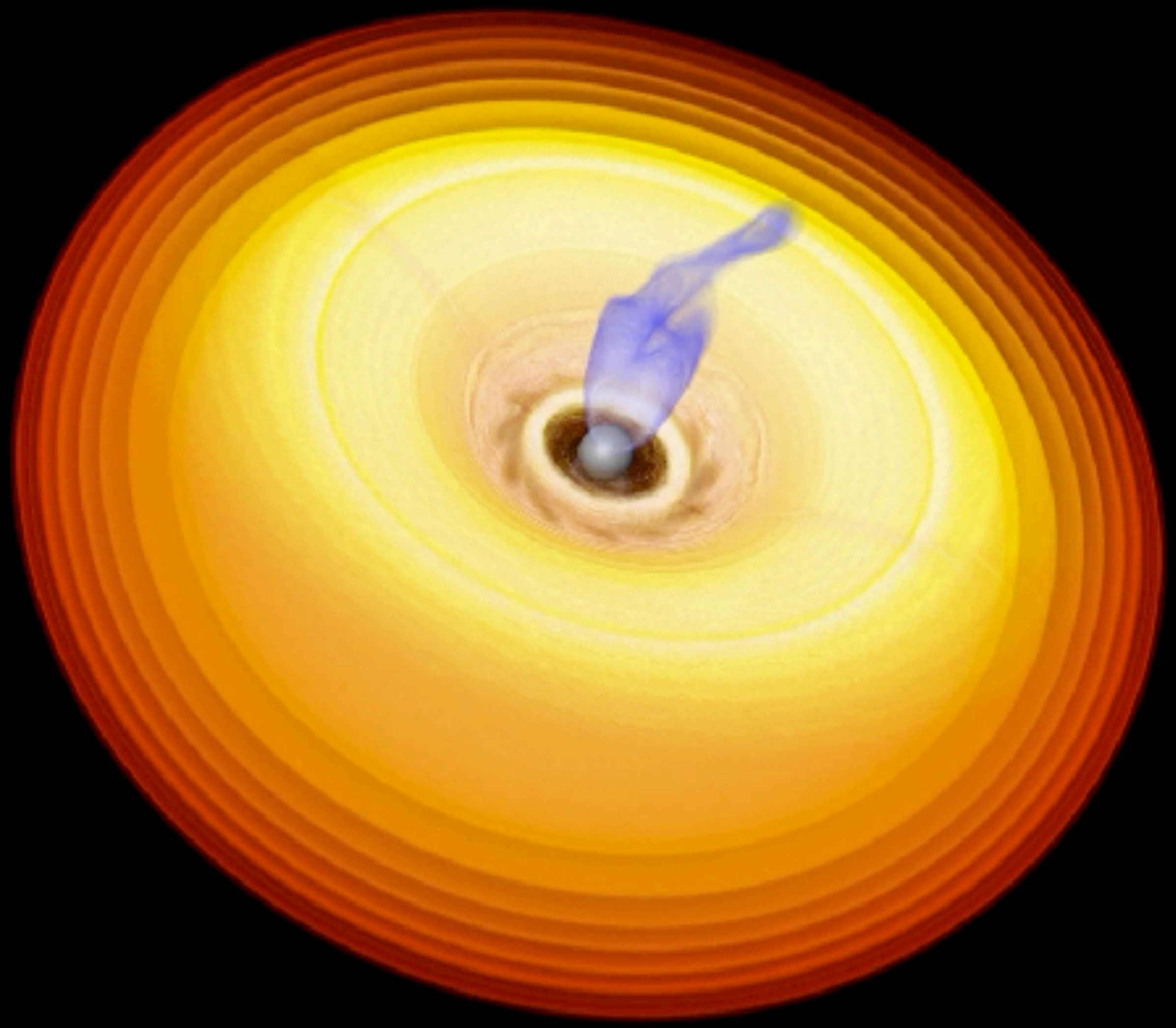
Müller, Pössel, Weih, LR

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



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

Space of parameters

✴Plasma dynamics and properties

- black-hole spin (plasma dynamics depends on it): $-1 < a_* < 1$
- accretion type as regulated by magnetic field (SANE o MAD)

✴Light dynamics and properties

- black-hole mass (sets size of the shadow)
- accretion rate
- microphysics of emission (synchrotron emission, disk/jet component)
- orientation wrt to observer (two free angles)

✴Information from previous observations

- black-hole mass: $6.2 \times 10^9 \, M_\odot$ (stars) or $3.5 \times 10^9 \, M_\odot$ (gas)
- inclination: 17° or 163° , with “position angle” 288°
- X-ray luminosity: $4.4 \times 10^{40} \, \mathrm{erg/s}$
- jet power: $1.0 \times 10^{42} \, \mathrm{erg/s}$

Electron thermodynamics

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

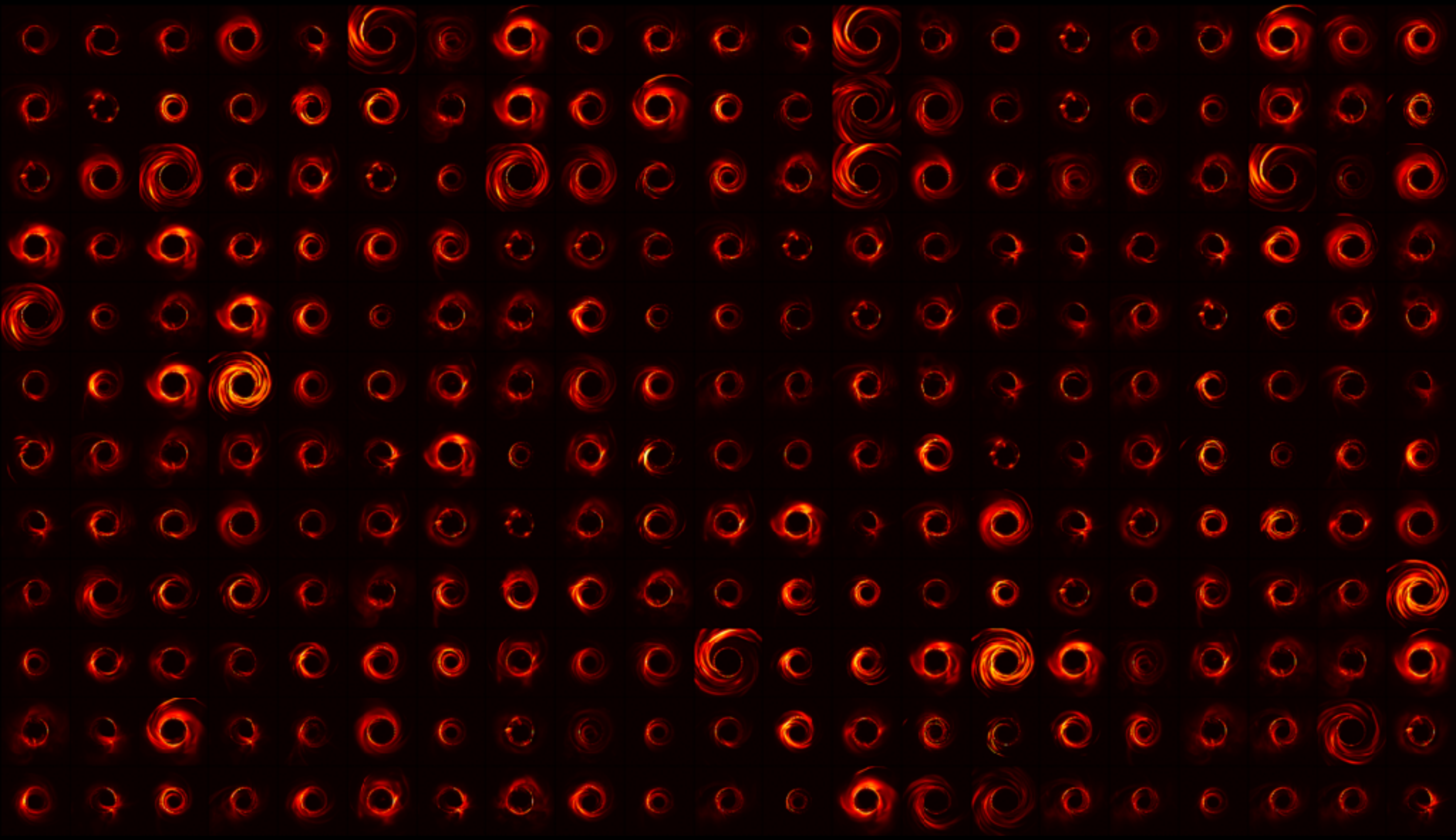
$$\frac{T_i}{T_e} = R_{\rm high}\frac{\beta_p^2}{1+\beta_p^2} + \frac{1}{1+\beta_p^2}$$

Mościbrodzka+ 2016

- Electrons colder at high plasma beta (i.e., disk), warmer at low plasma beta (i.e., jet).
- $R_{\rm high} = [1, 10, 20, 40, 80, 160]$: free parameter

- 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…)



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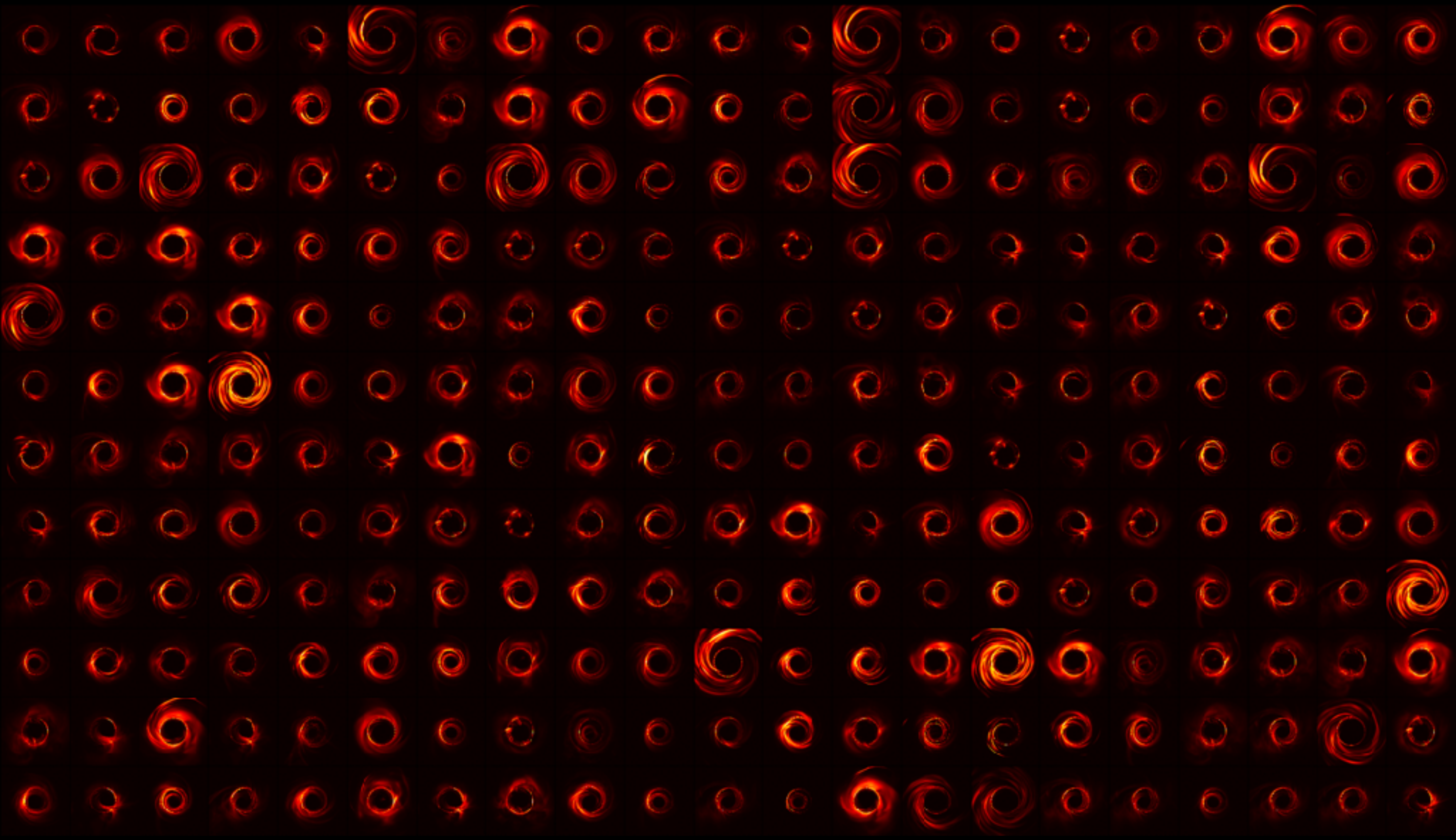

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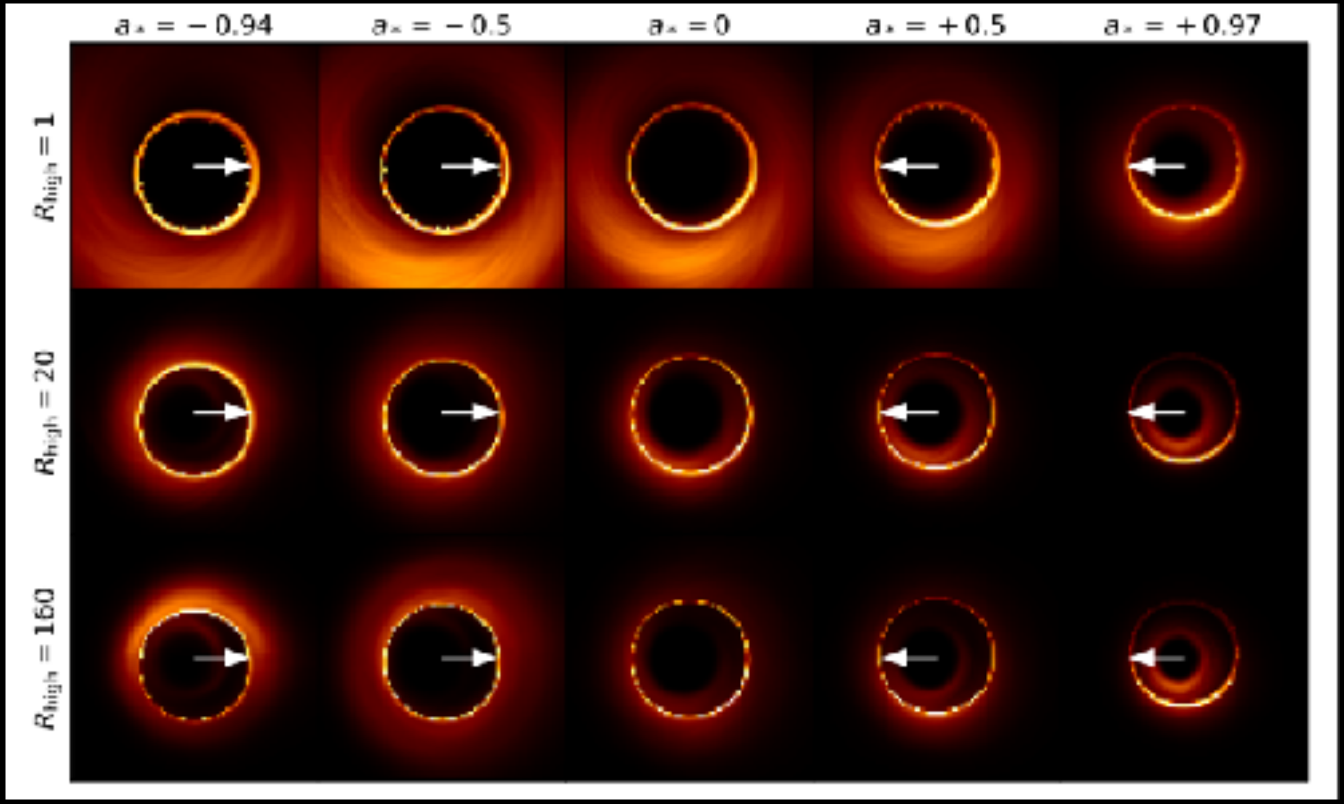
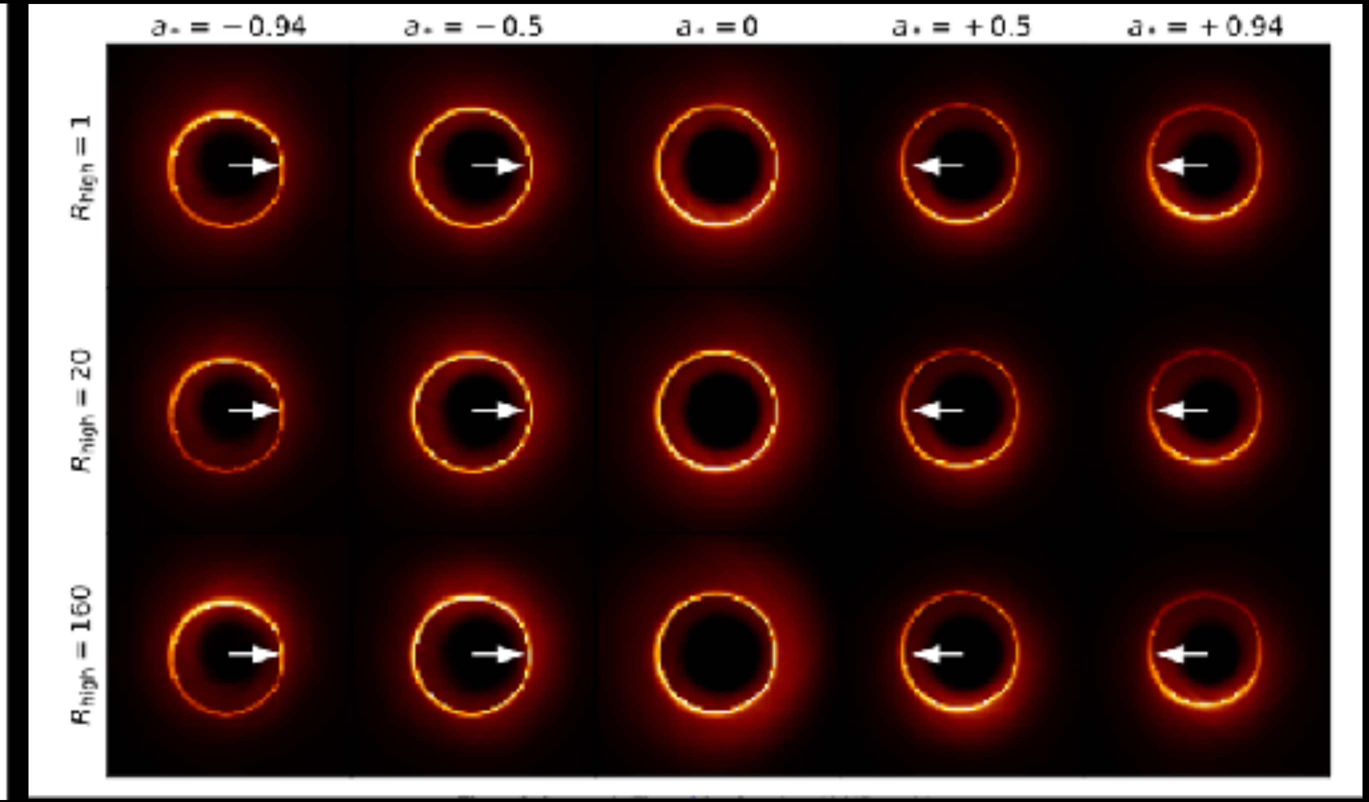


SANE models



MAD models

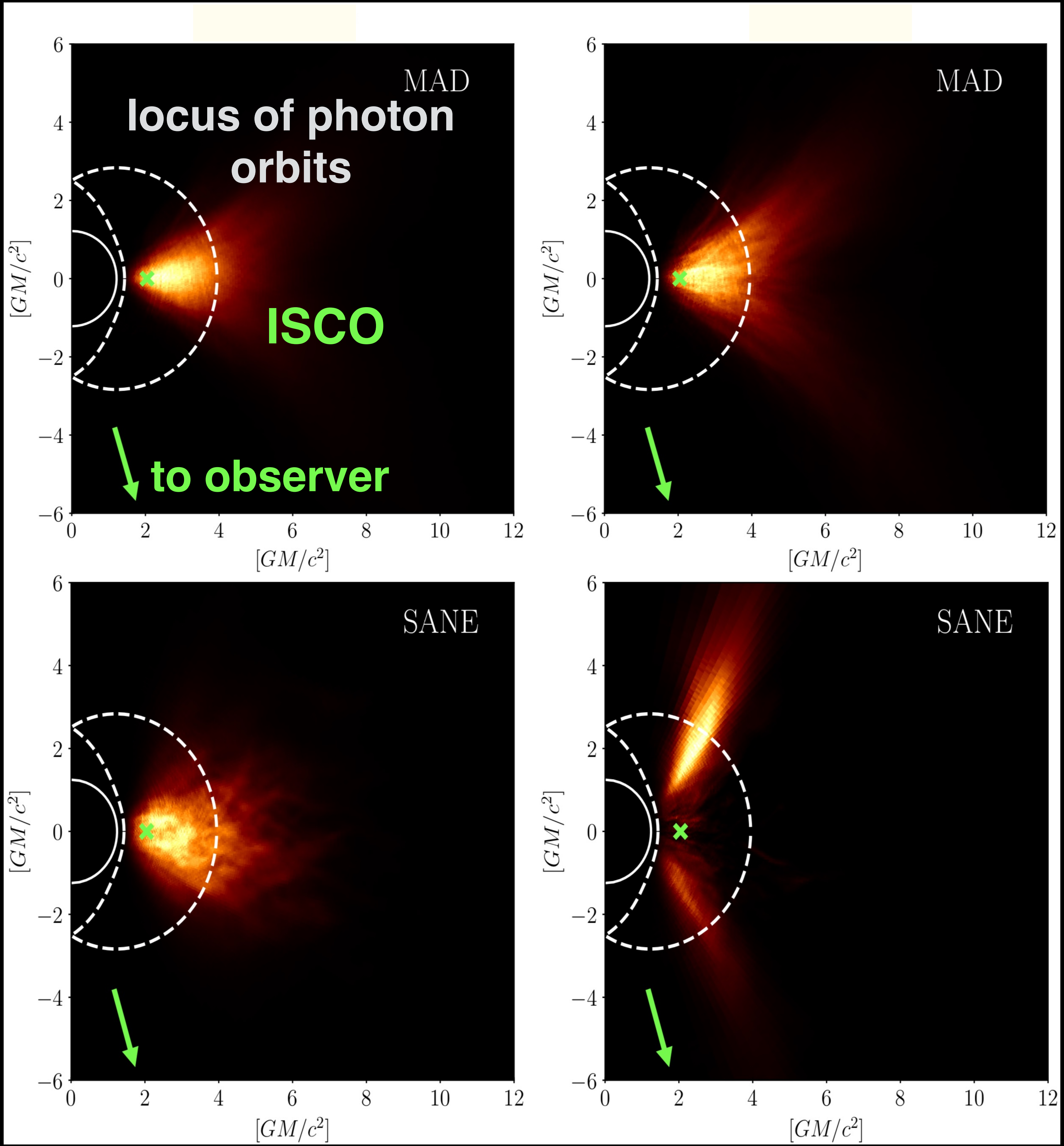
Where do mm-long photons originate?

Kerr black hole,
$a_* = 0.94$

MAD: mostly from the equatorial plane

SANE: can switch from equatorial plane to funnel wall

$R_{\mathrm{high}} = 10$ $R_{\mathrm{high}} = 160$

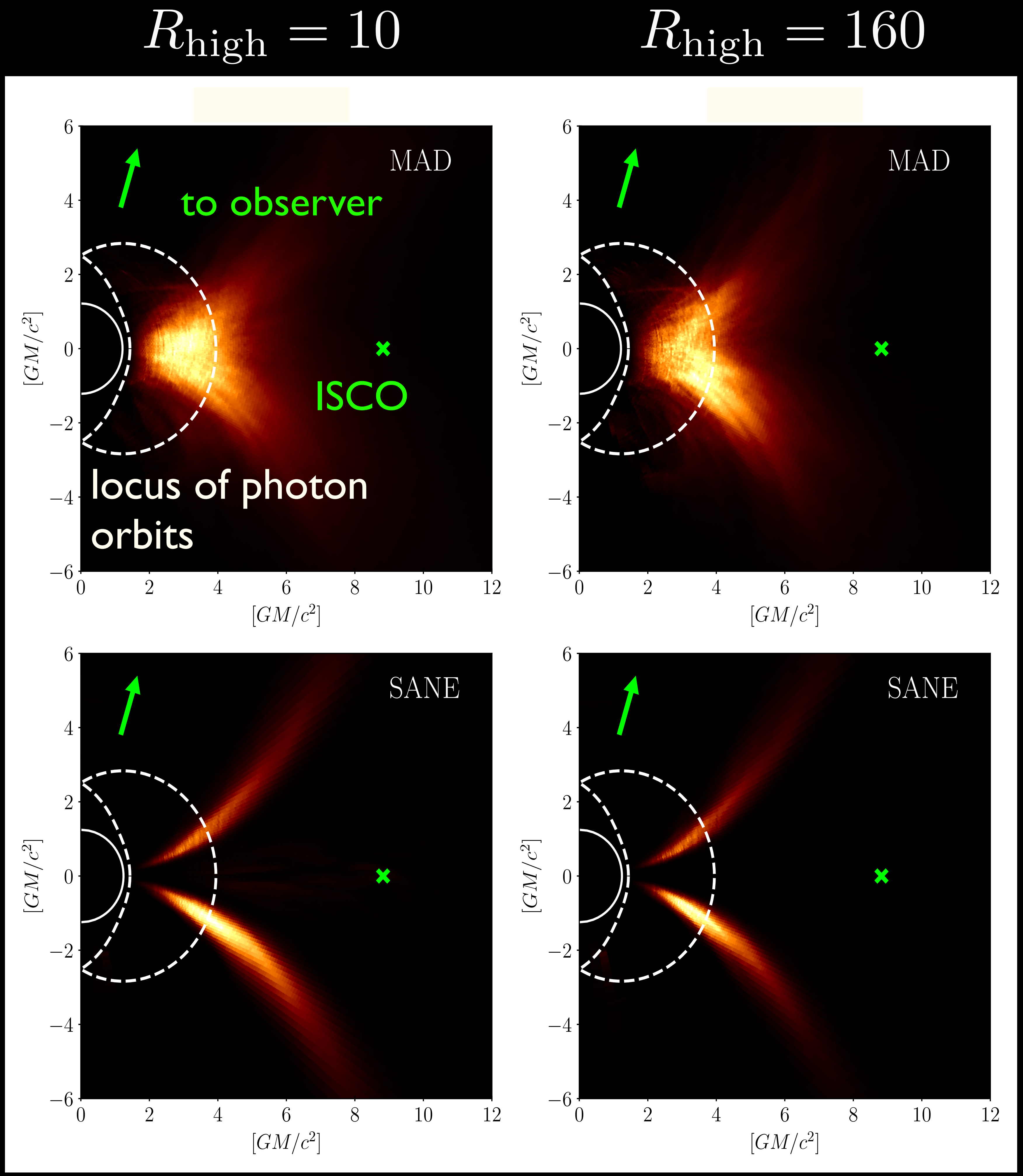


Where do mm-long photons originate?

Kerr black hole, $a_* = -0.94$

MAD: mostly but not only from the equatorial plane

SANE: equatorial plane is essentially depleted



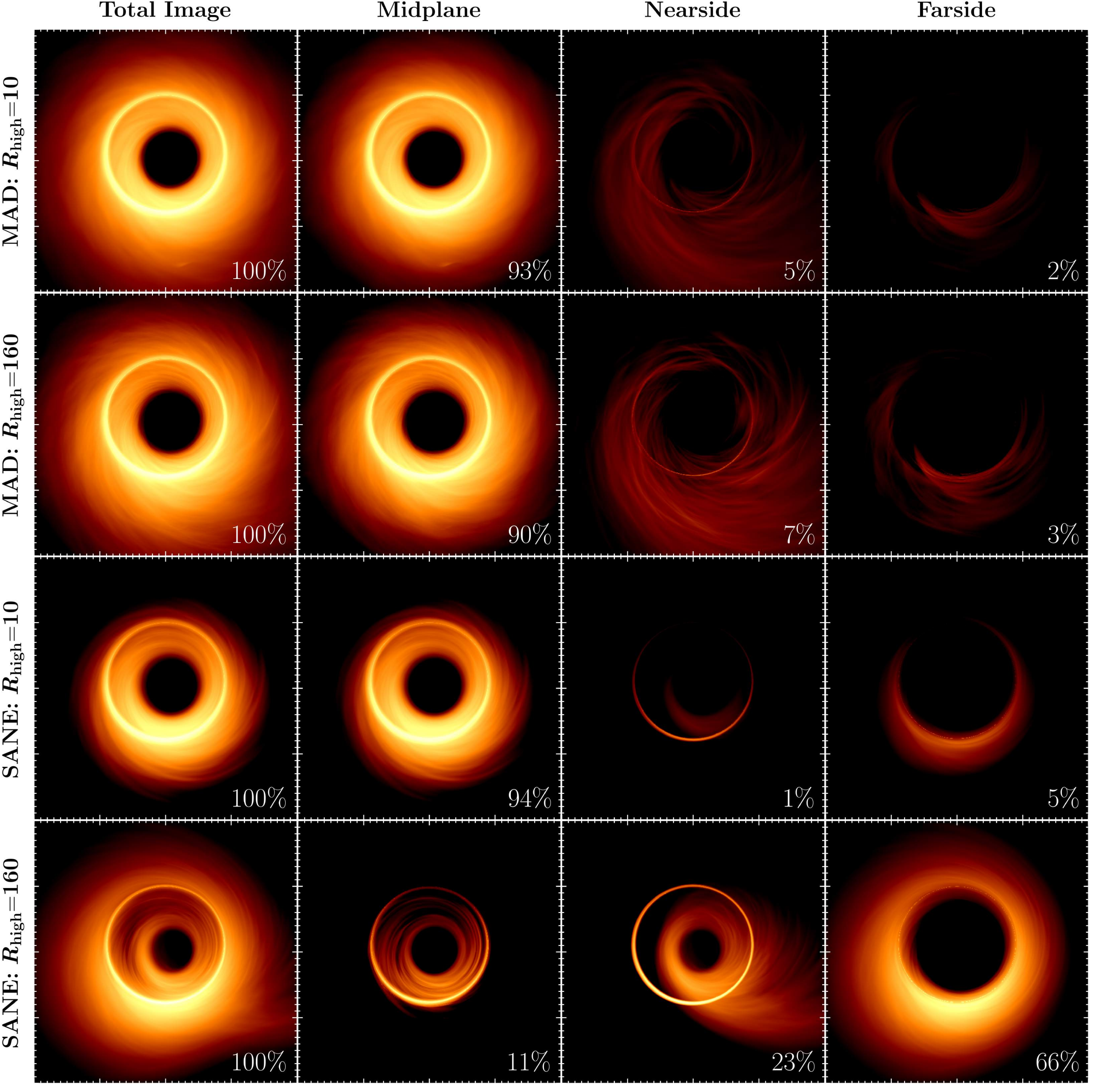
to observer

ISCO

locus of photon orbits

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



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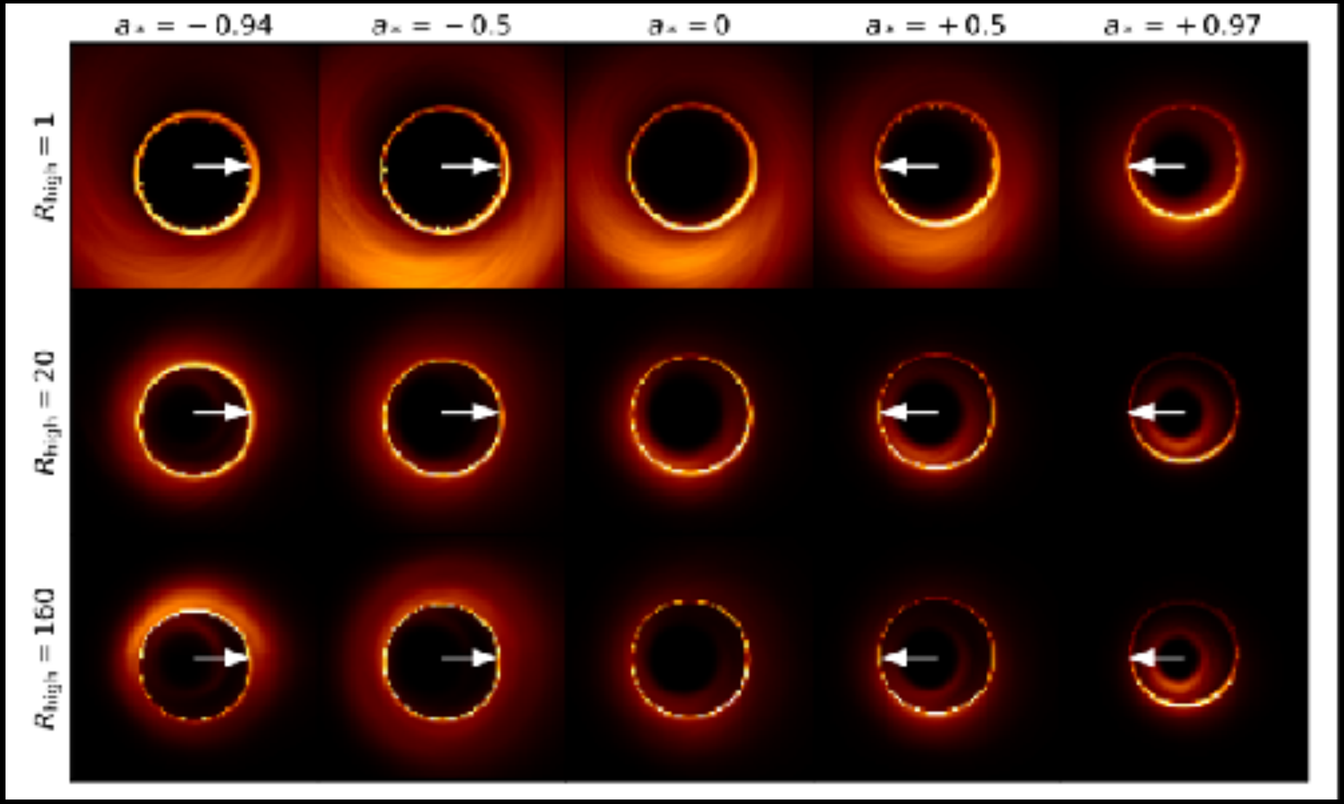
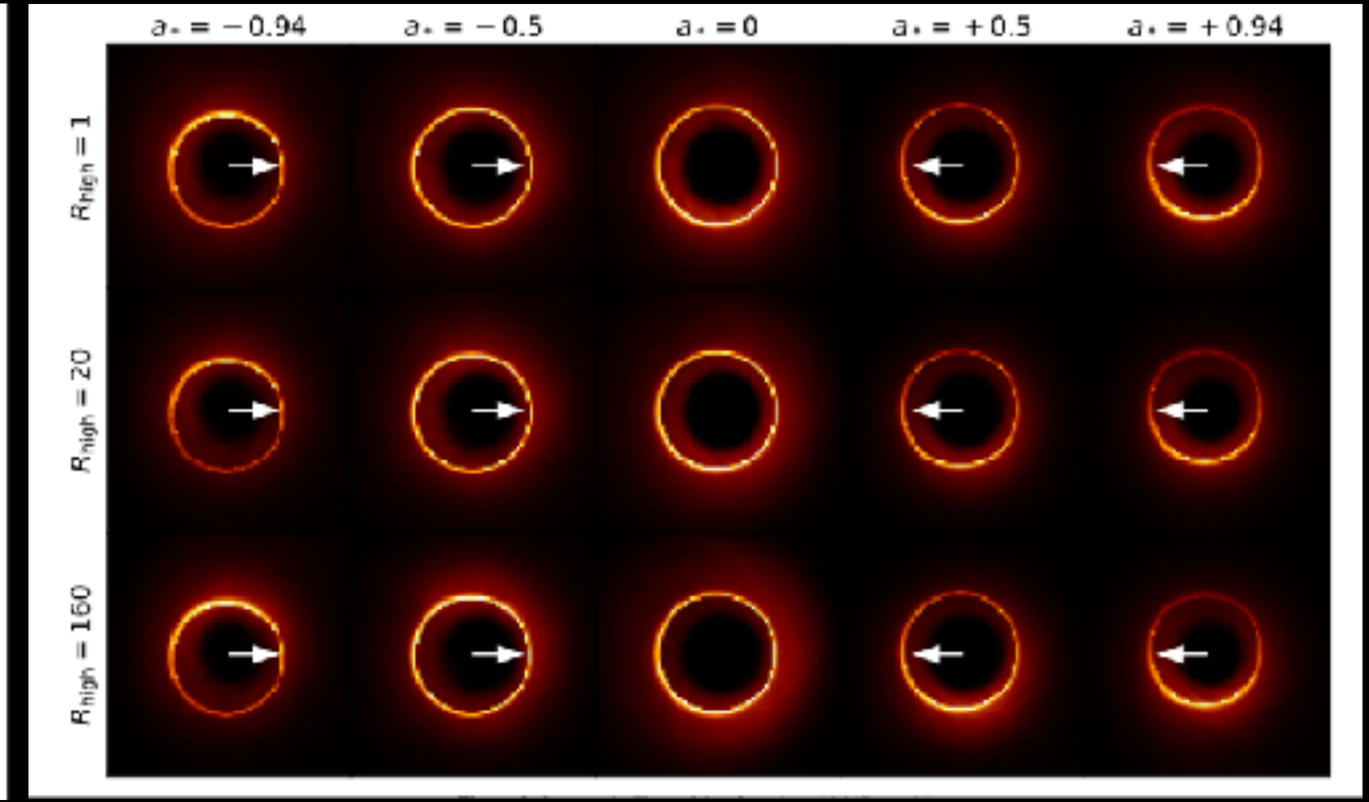


SANE models



MAD models

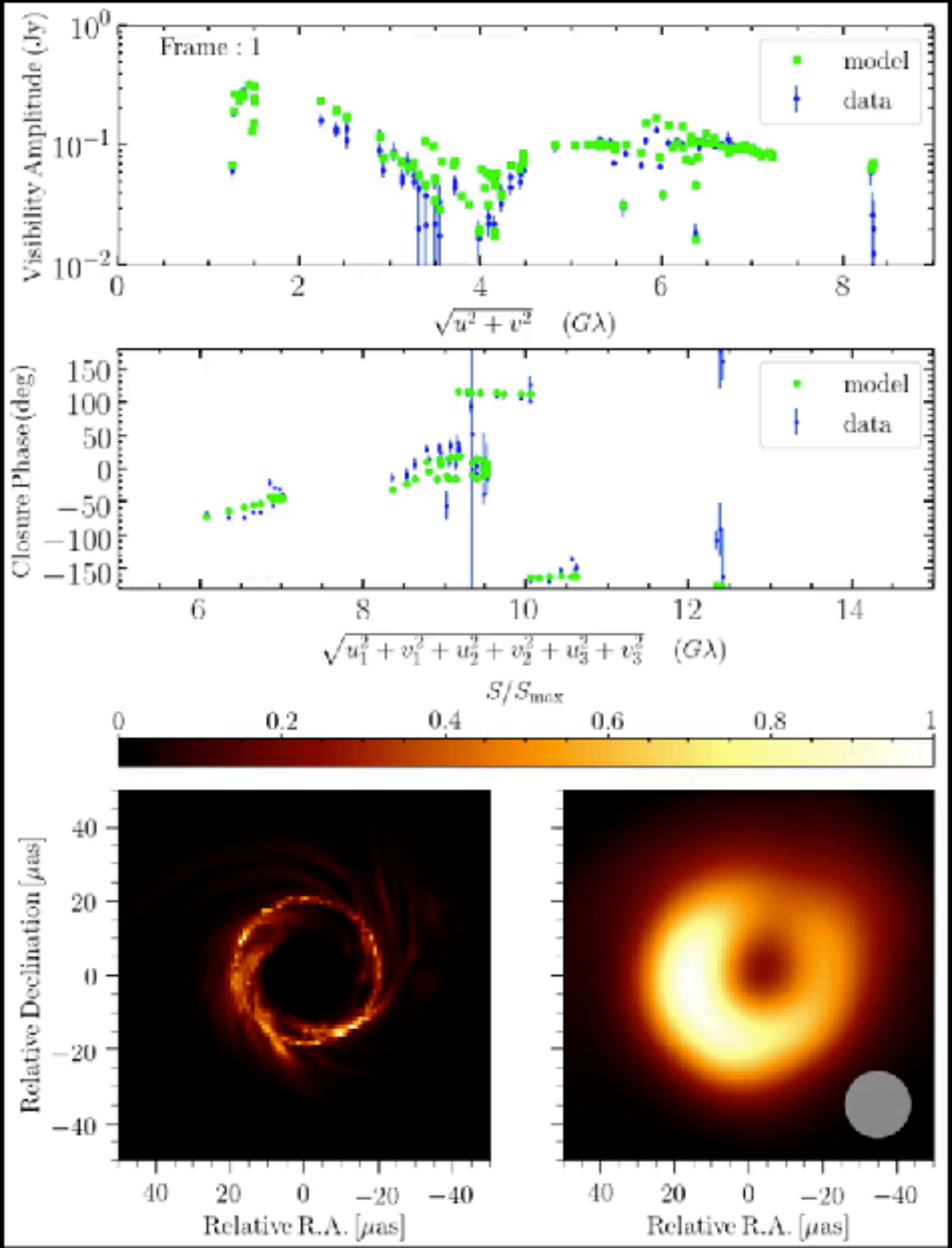
- From each scenario synthetic images are constructed after radiative transfer and light bending: ~ *60,000 images*.
- Genetic algorithms and MCMC pipelines find best match.

Fitting the images to the data

visibility amplitude (VA)

Closure phase (CP)

GRMHD image (left) and convolved image (right)



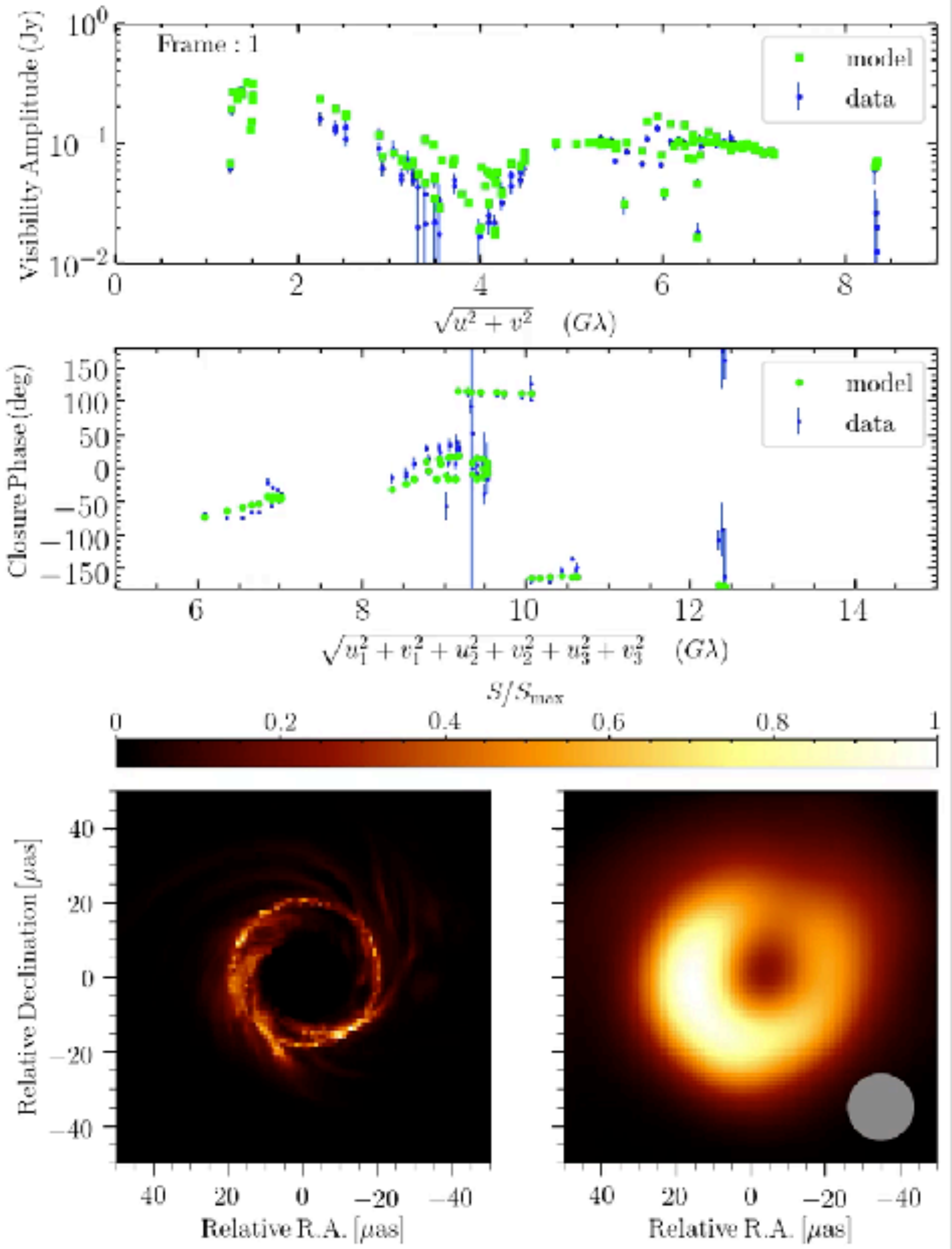
Fromm, Younsi, LR

Fitting the images to the data

visibility amplitude (VA)

Closure phase (CP)

GRMHD image (left) and convolved image (right)



Fromm, Younsi, LR

Fitting the images to the data

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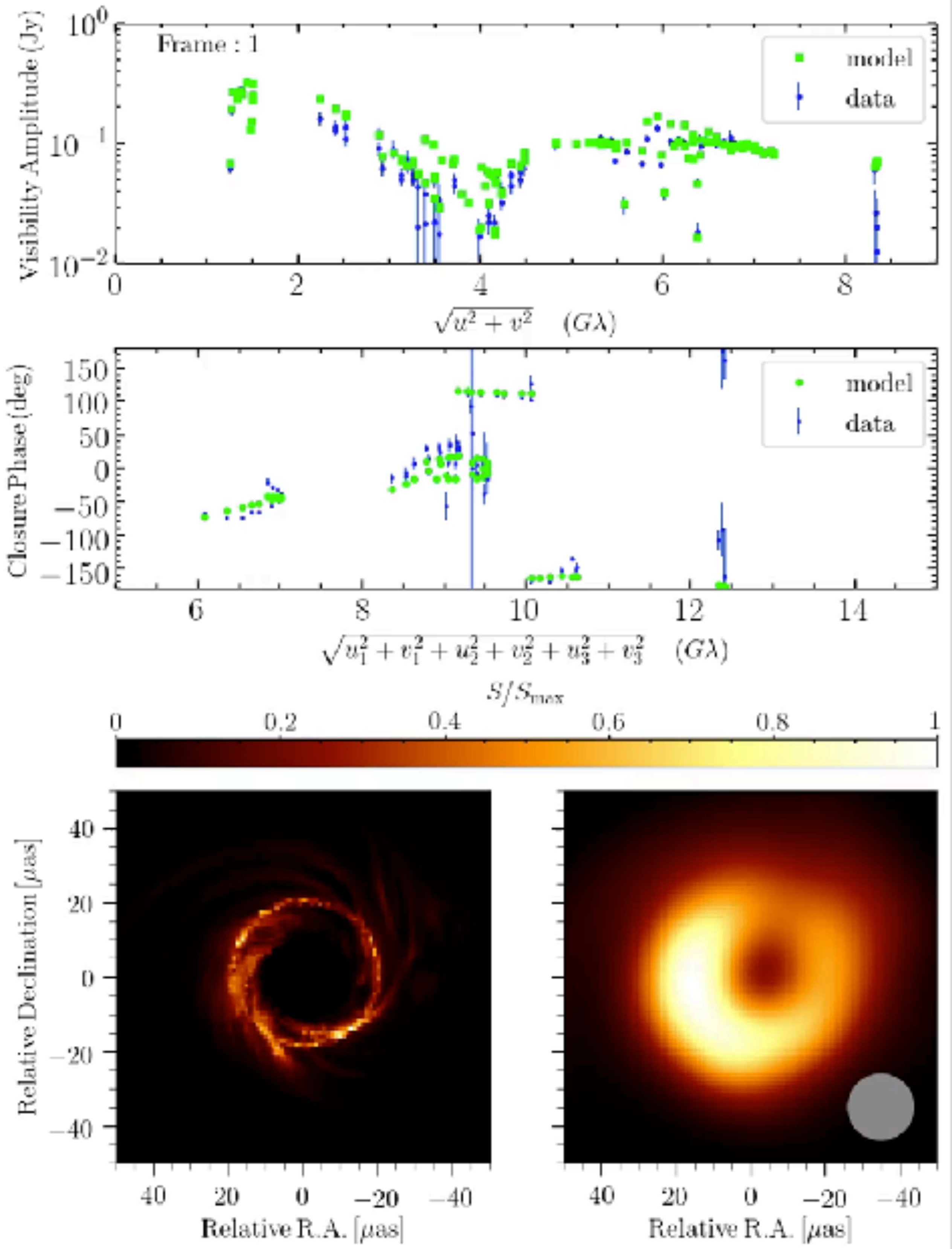


Fromm, Younsi, LR

Note that the match is found in the visibility space.

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

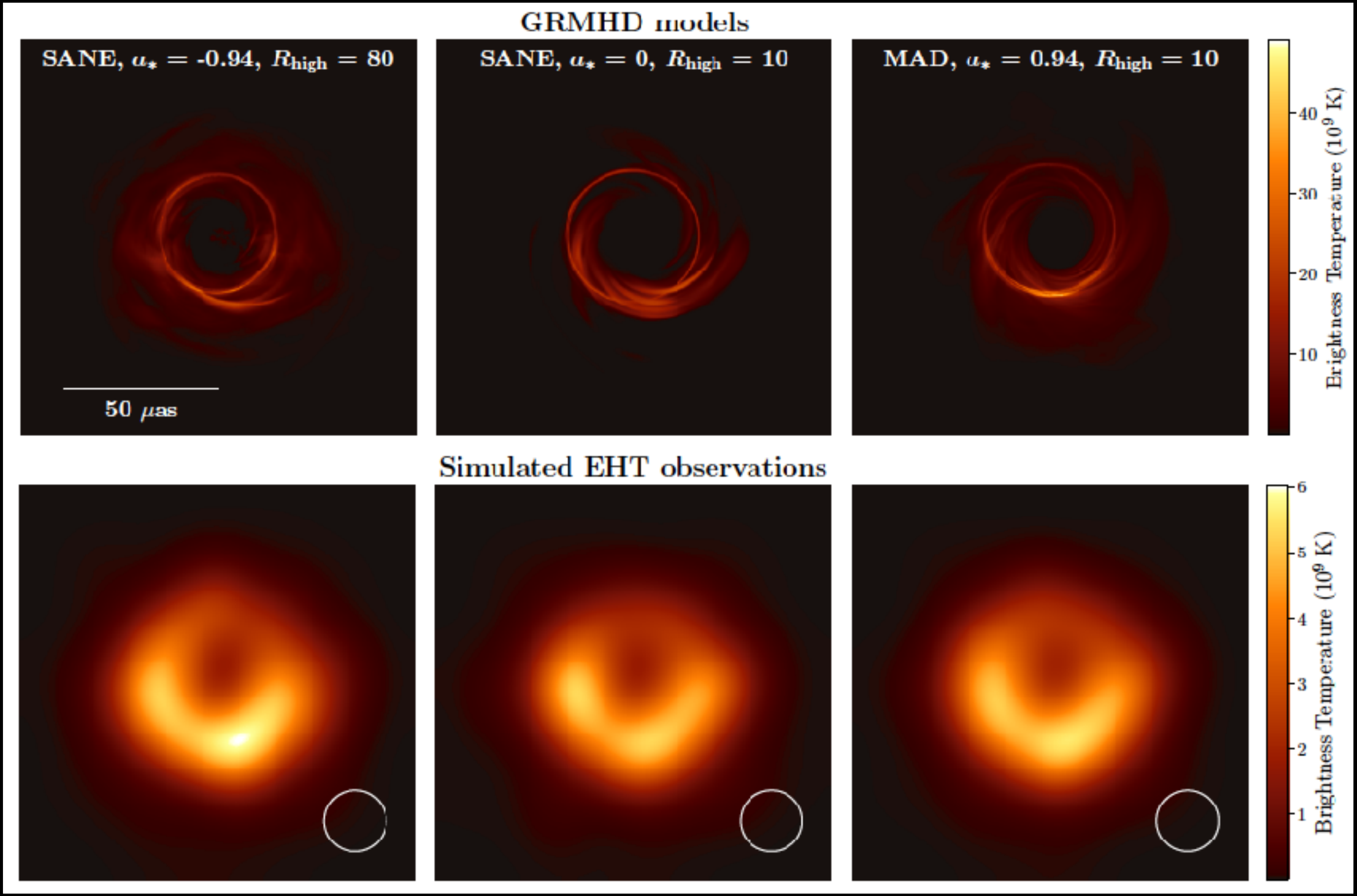
The match is found in the visibility space, but can also be found in image space.

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

OBSERVATIONS

THEORETICAL MODEL



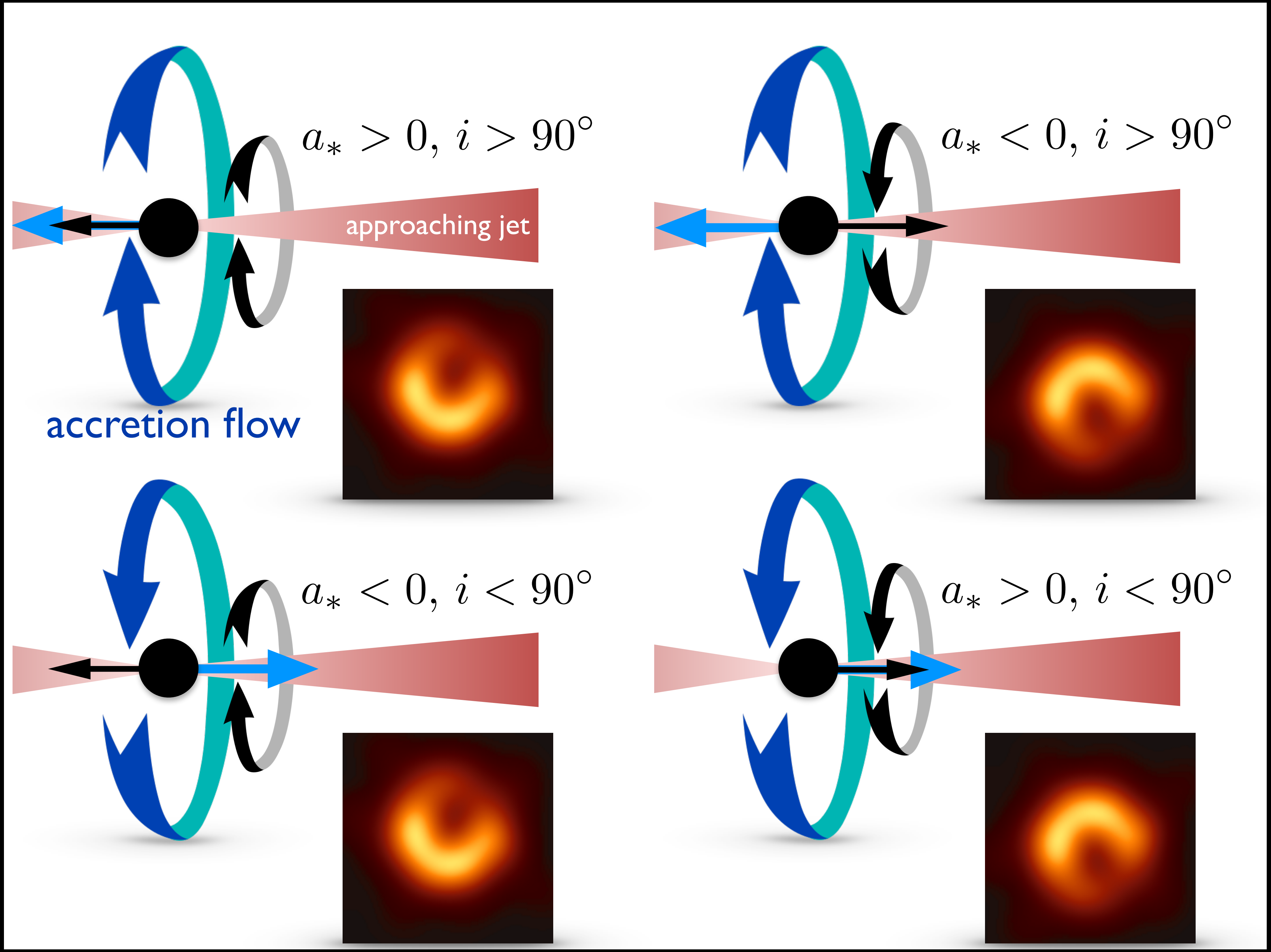
- Degeneracies present in physical conditions and scenarios.

Good: robustness of conclusions (BHs produce ring)

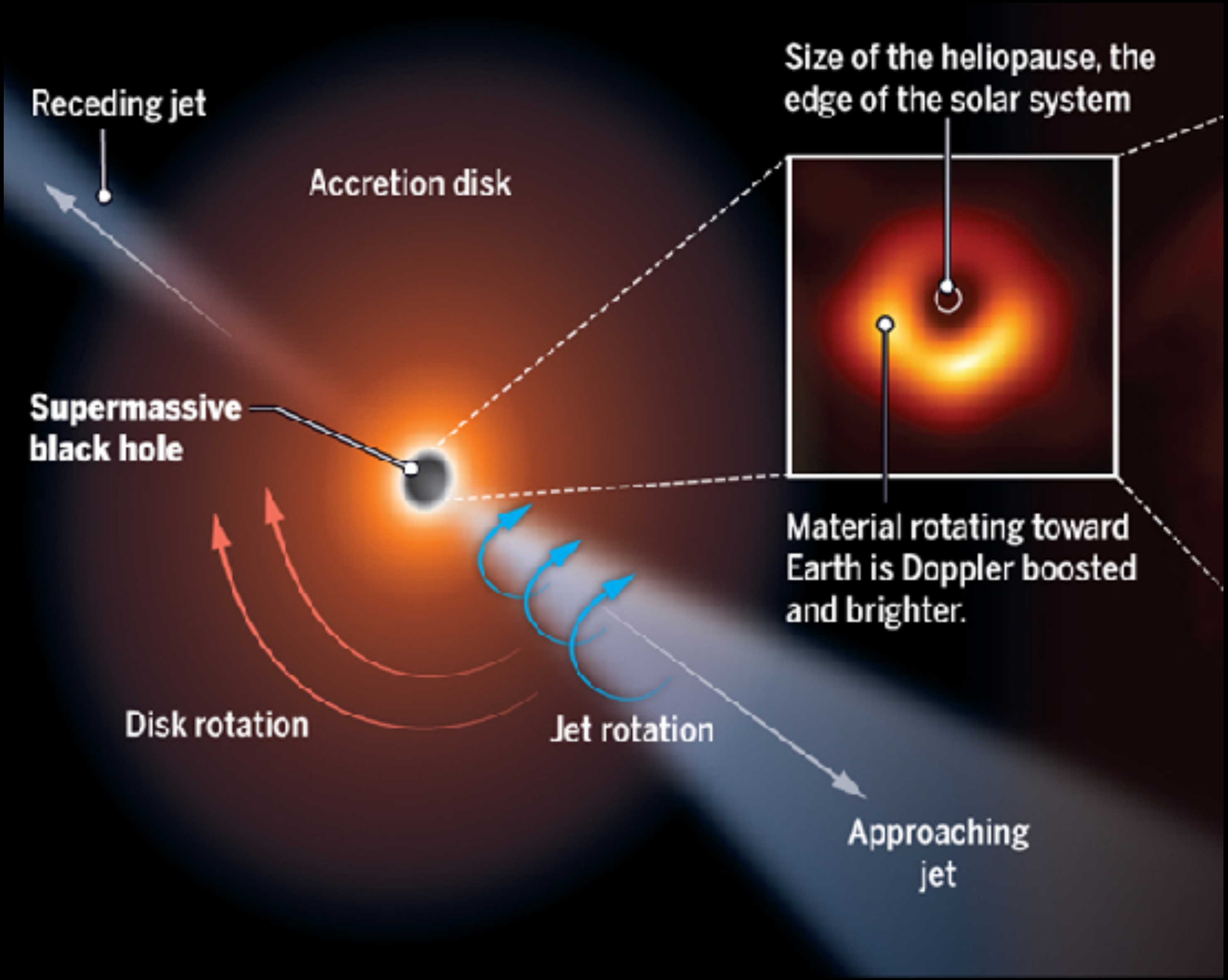
Bad: more accurate observations to determine BH spin

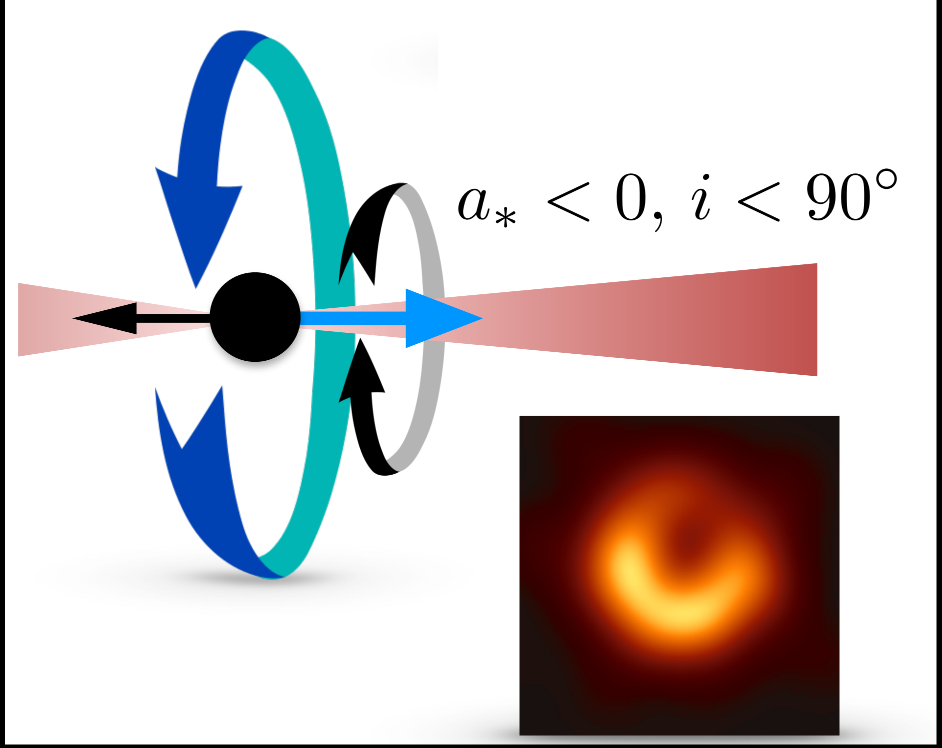
Ring Asymmetry and Black Hole Spin

Conclusions on the spin can still be drawn if one combines "other" information on jet power and orientation

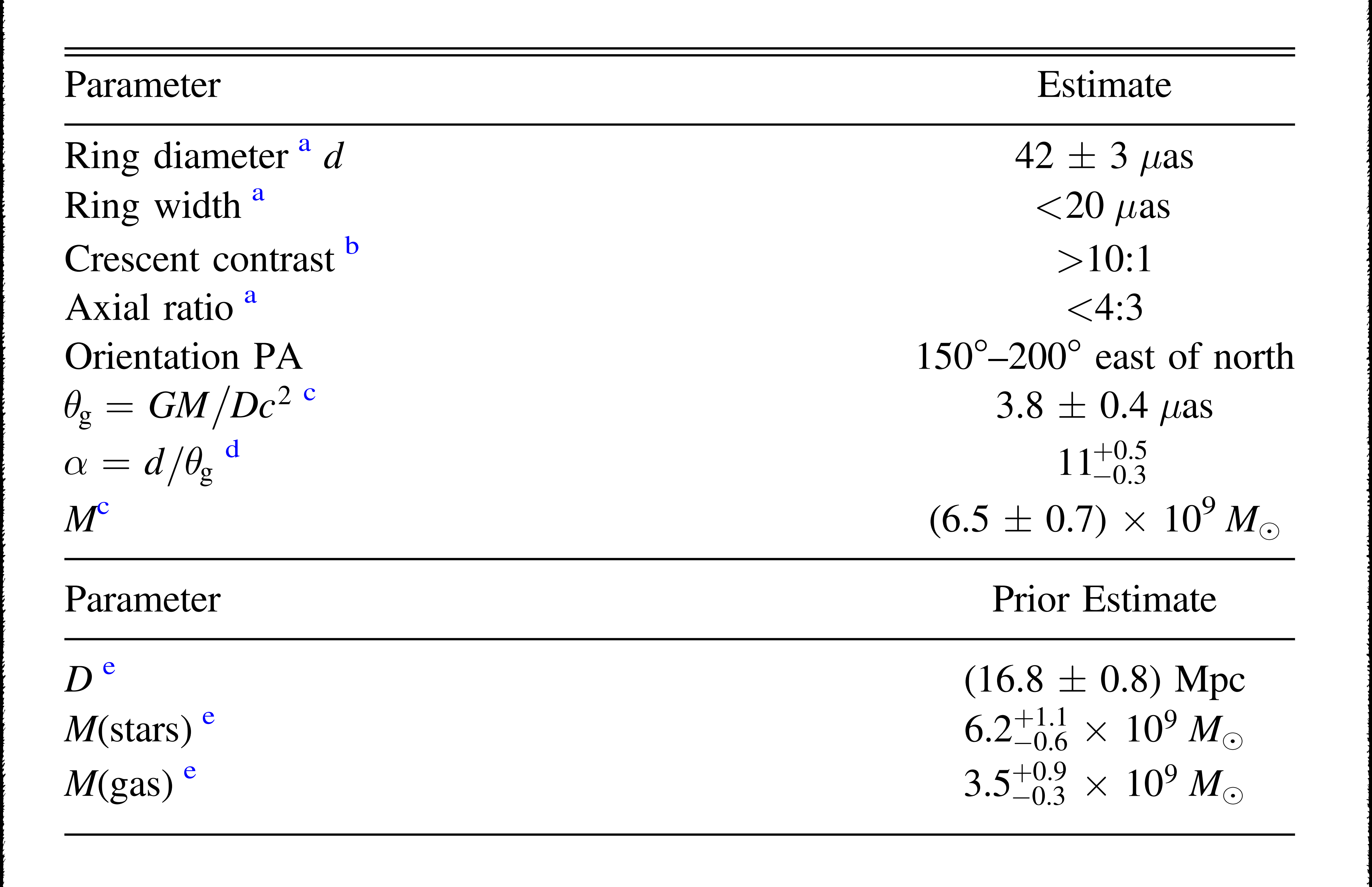


Ring Asymmetry and Black Hole Spin





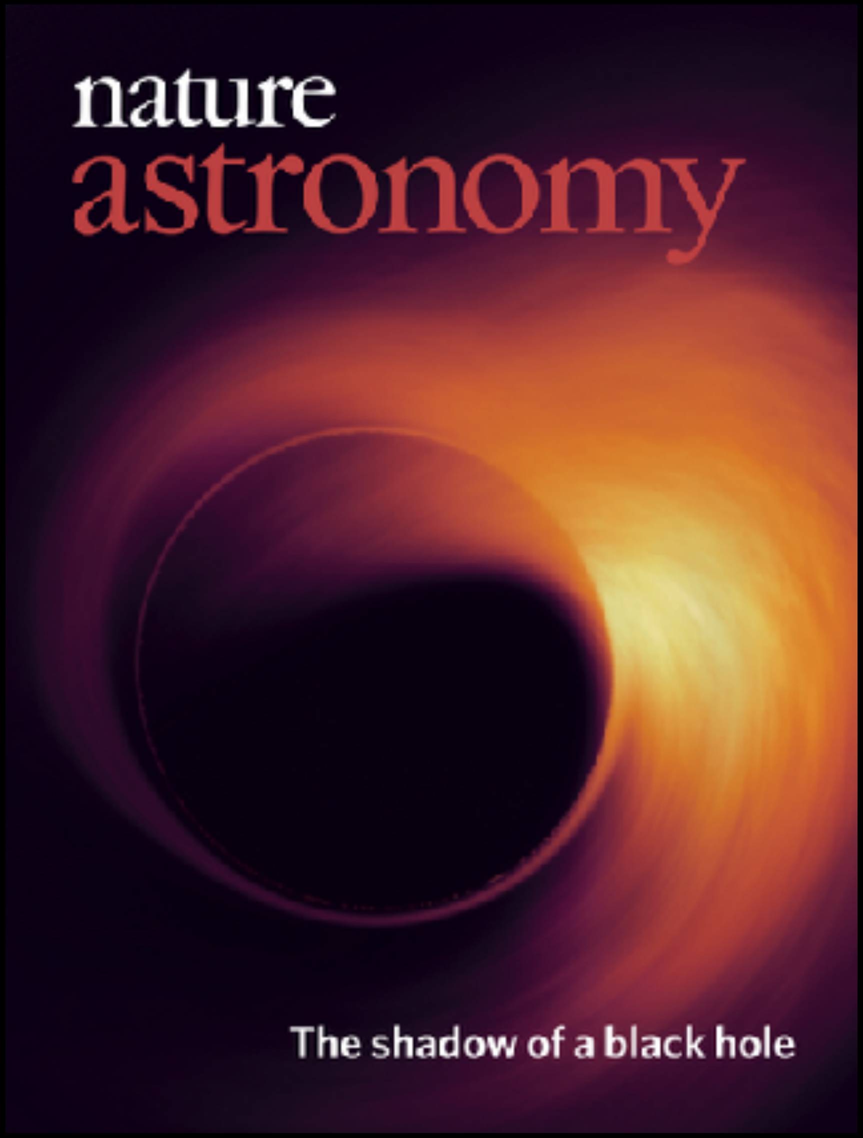
What we measured…



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]	$3.5^{+0.9}_{-0.3} \times 10^9\ M_\odot$

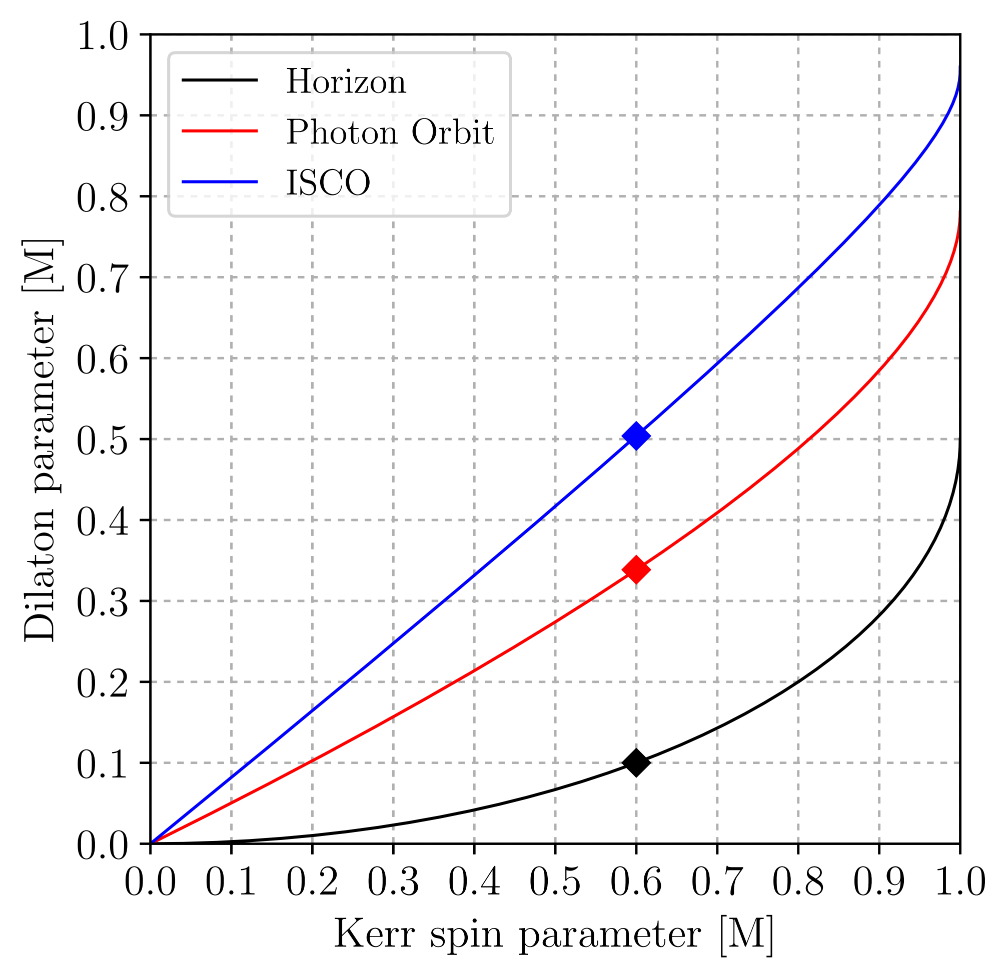
Moving away from Kerr black holes: accretion onto a dilaton black hole



Mizuno+ 2018

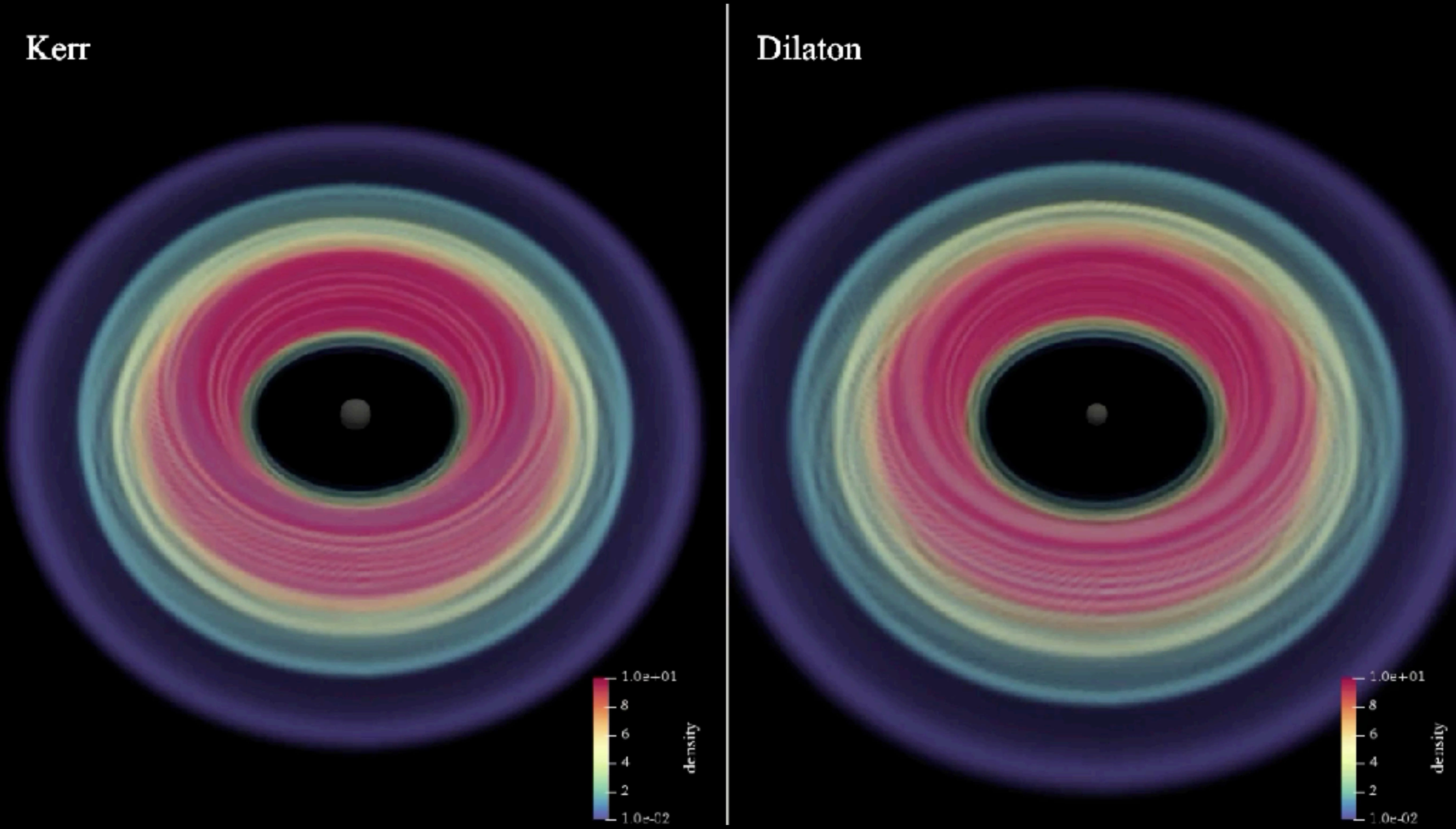
Dilaton vs Kerr black hole

- 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).

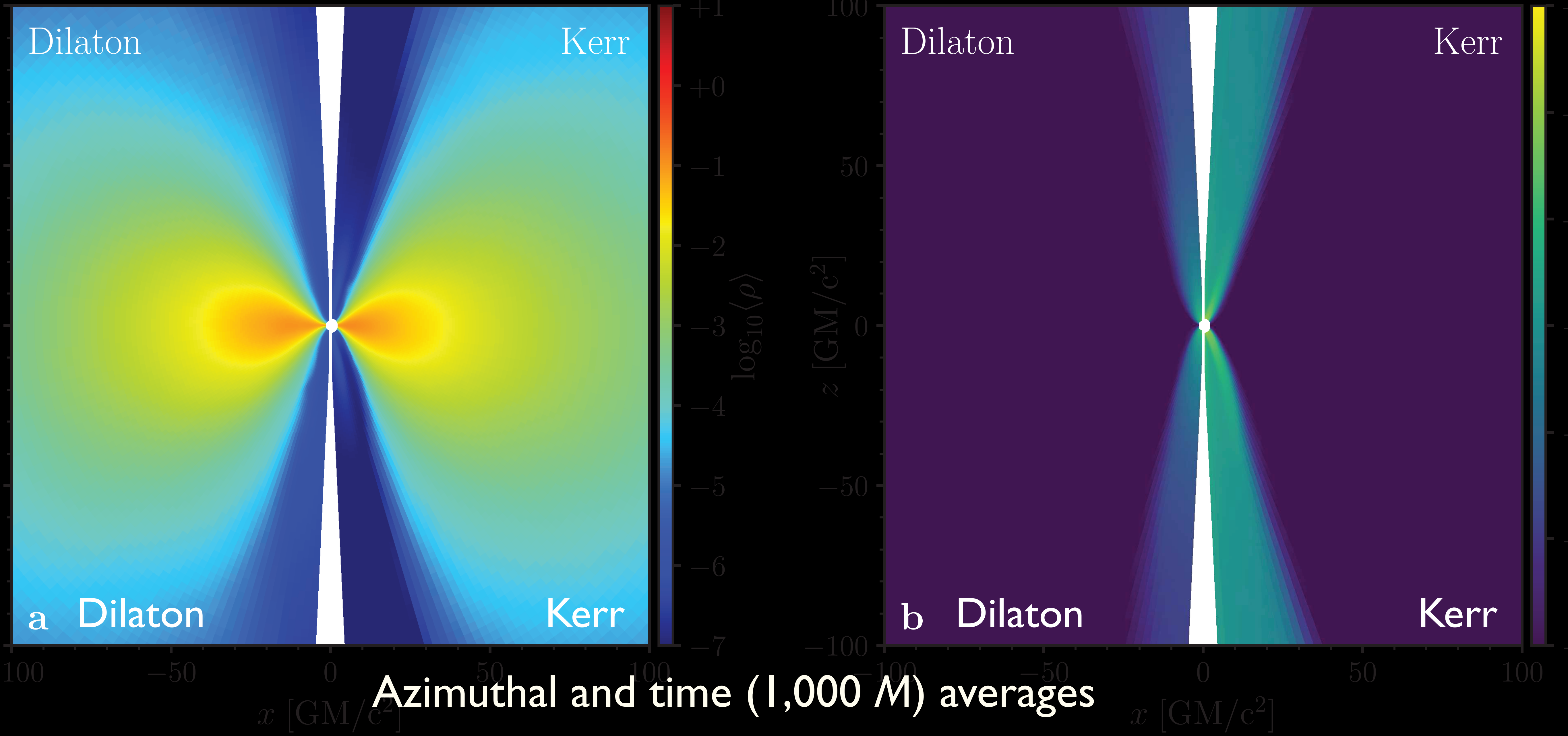


- Different matches possible but ISCO is most critical since most of the emission comes from around ISCO.

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*)



density

magnetization

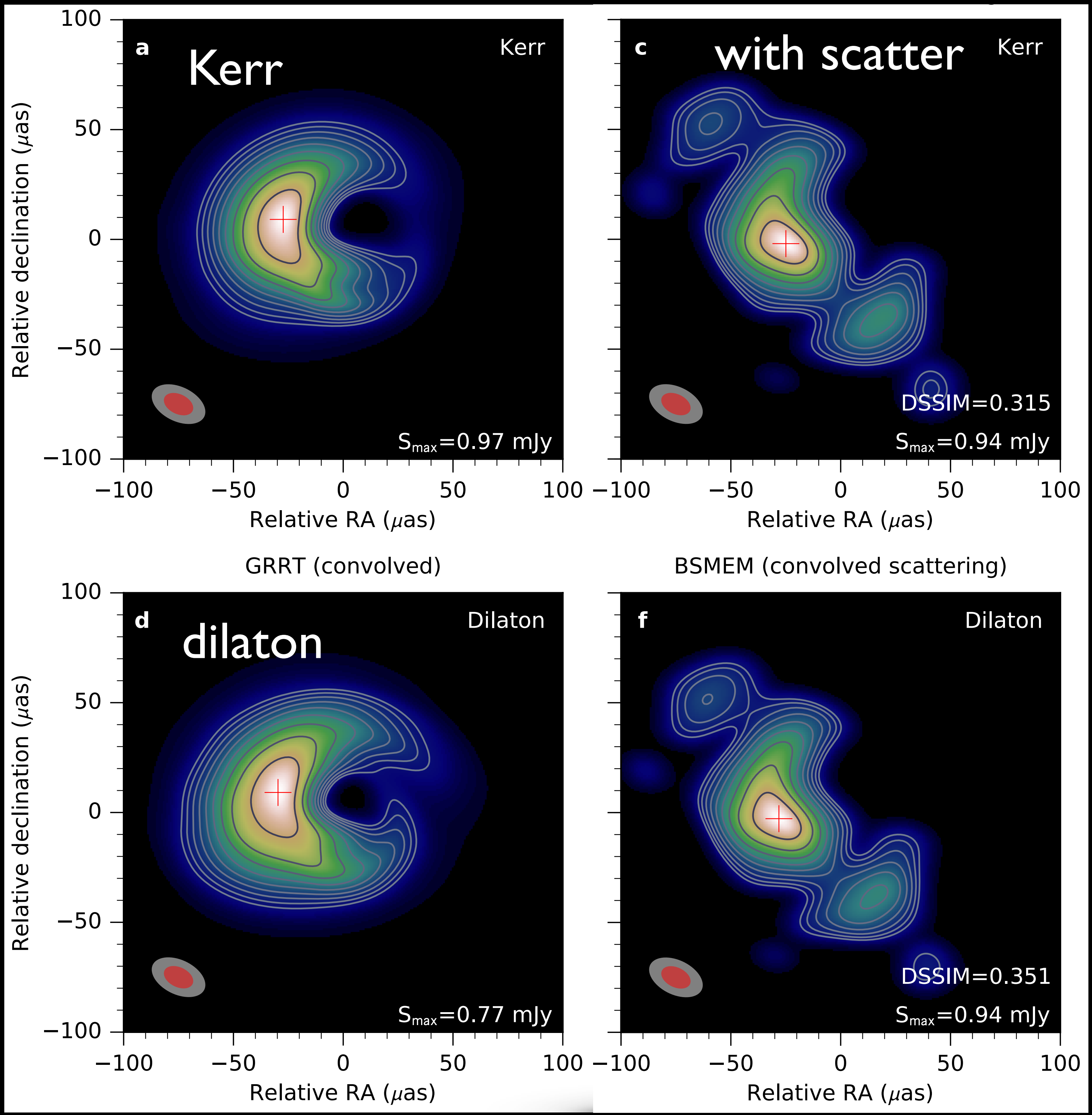
Azimuthal and time (1,000 *M*) averages

- Overall plasma behaviour is very similar.
- Main difference is in the high magnetization region (funnel) but not easy to deduce from observations

cf. Sgr A*

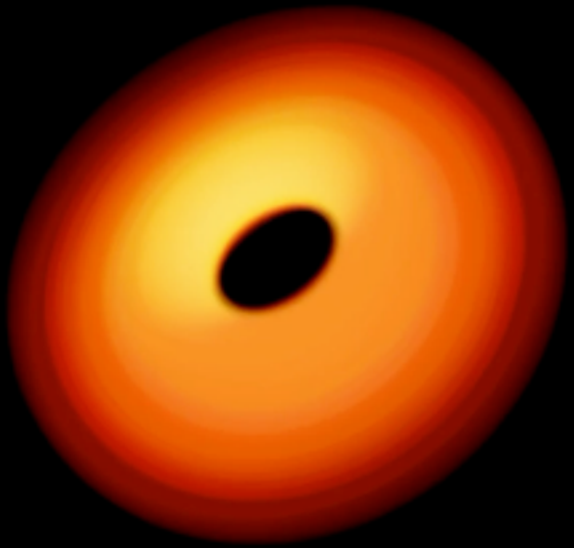
convolved GRRT images; emission features smeared by beam; crescent reveals presence of BH.

BSMEM reconstructed image with scattering; again, presence of a crescent reveals BH.



Overall, at present not possible to distinguish the two BHs

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



Olivares+ 2019

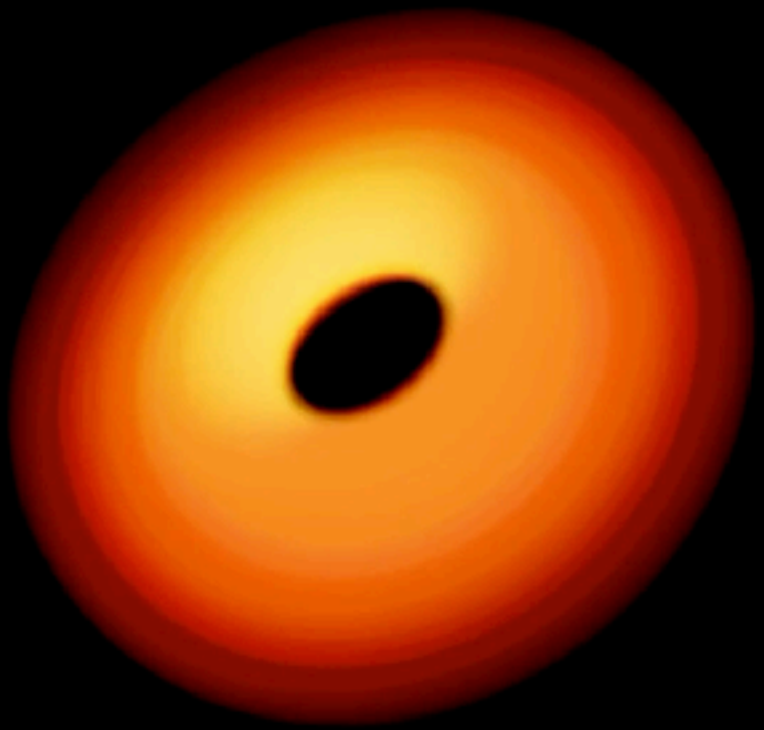
Accretion onto a boson star

- Self-gravitating **horizonless** compact objects composed of scalar field (boson stars) have long since been considered potential candidates for Sgr A* (dark-matter cusp).

- Previous work has considered whether emission from boson stars can be distinguished from that of a black hole.
  - ✴Using spectral features: **not possible to distinguish** (Guzman+ 2010)
  - ✴Using shadow image of a boson star surrounded by torus: **not possible to distinguish** (Vincent+ 2016).

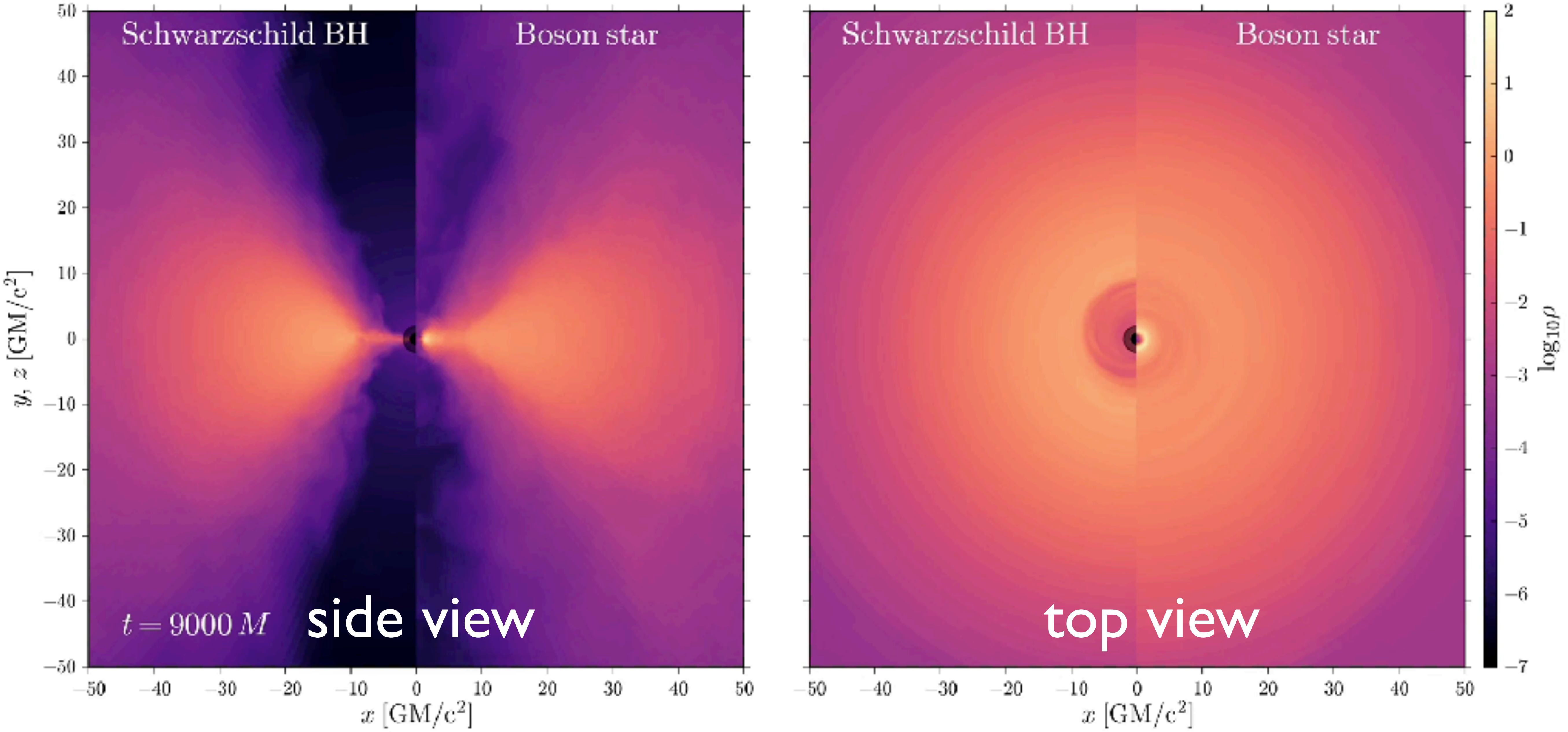
- These works did not consider effects of accretion.

- We performed **first GRMHD** simulations of accreting nonrotating boson stars.



L. Weih, H. Olivares, LR

- Simulations show considerable differences in the dynamics of the accretion flow.
- In the case of the boson star, matter reaches very close to the origin, forming a stalled accretion torus (MRI is quenched).



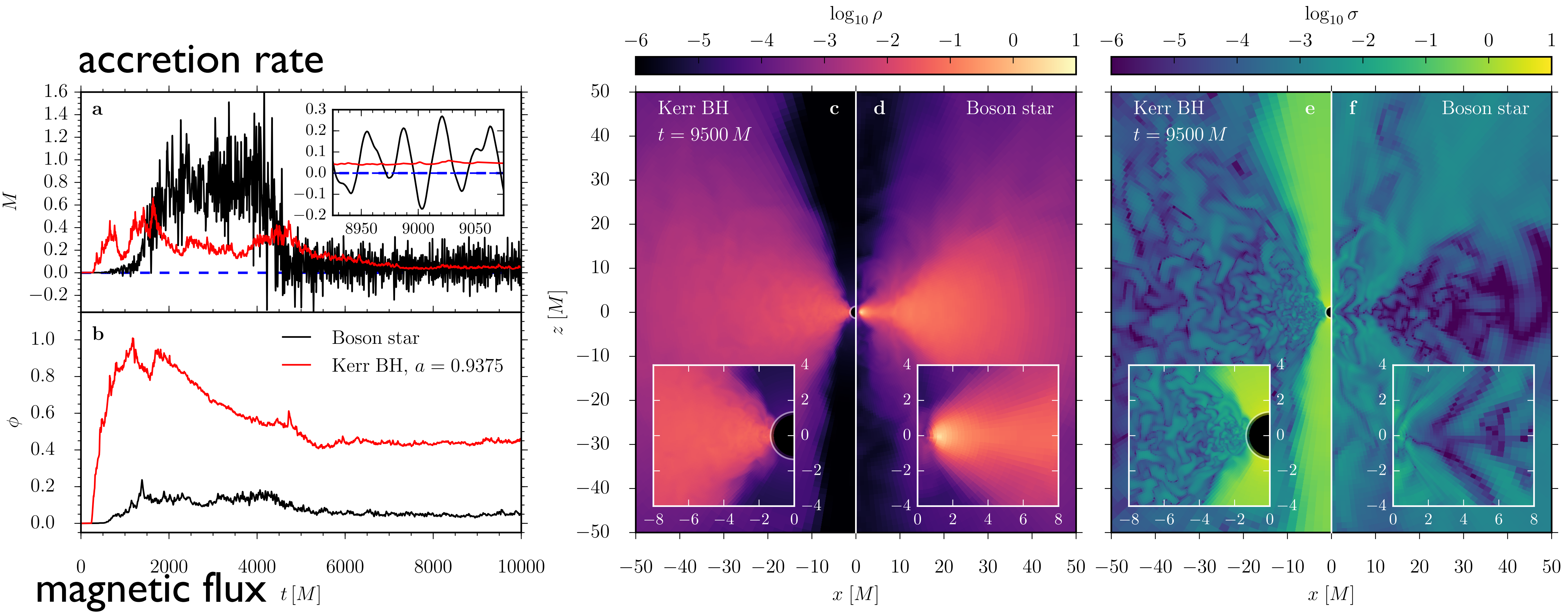
density *(x,z)*

density *(x,y)*

side view

top view

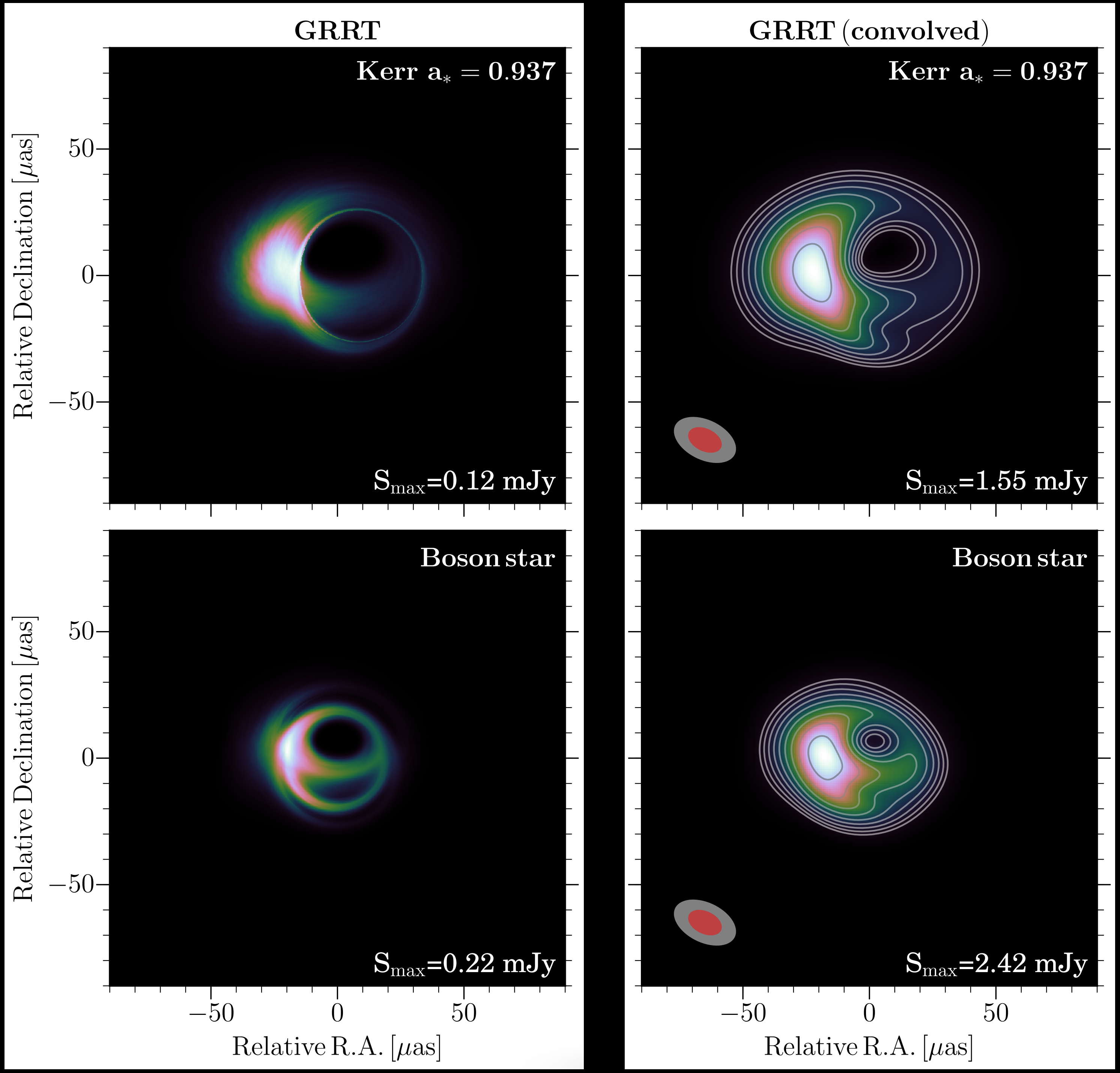
✳compactness is quite high: $\mathcal{C}_{95} := M_{95}/R_{95} = 0.11$



- ✳Mass-accretion rate: **positive** for black hole but **oscillating** for boson star.
- ✳Oscillations produced by stalled torus; correspond to epicyclic frequency.
- ✳No evacuated funnel in polar region in the case of boson star.
- ✳Slow wind flowing from hot and dense interior: **no jet** from boson star.

- 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** covers 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 results have provided first evidence existence of SMBHs and boosted our understanding of accretion in **strong gravity**.

The ability to perform VLBI observations of SMBHs has opened new era of astrophysics. Much more to come!