Imaging the Supermassive Black Hole at the Heart of M87 using Global Millimeter VLBI

November 27, 2024
Presenter:
Jongho Park (Kyung Hee University)

Part I: What did we learn about black hole physics from the EHT observations?

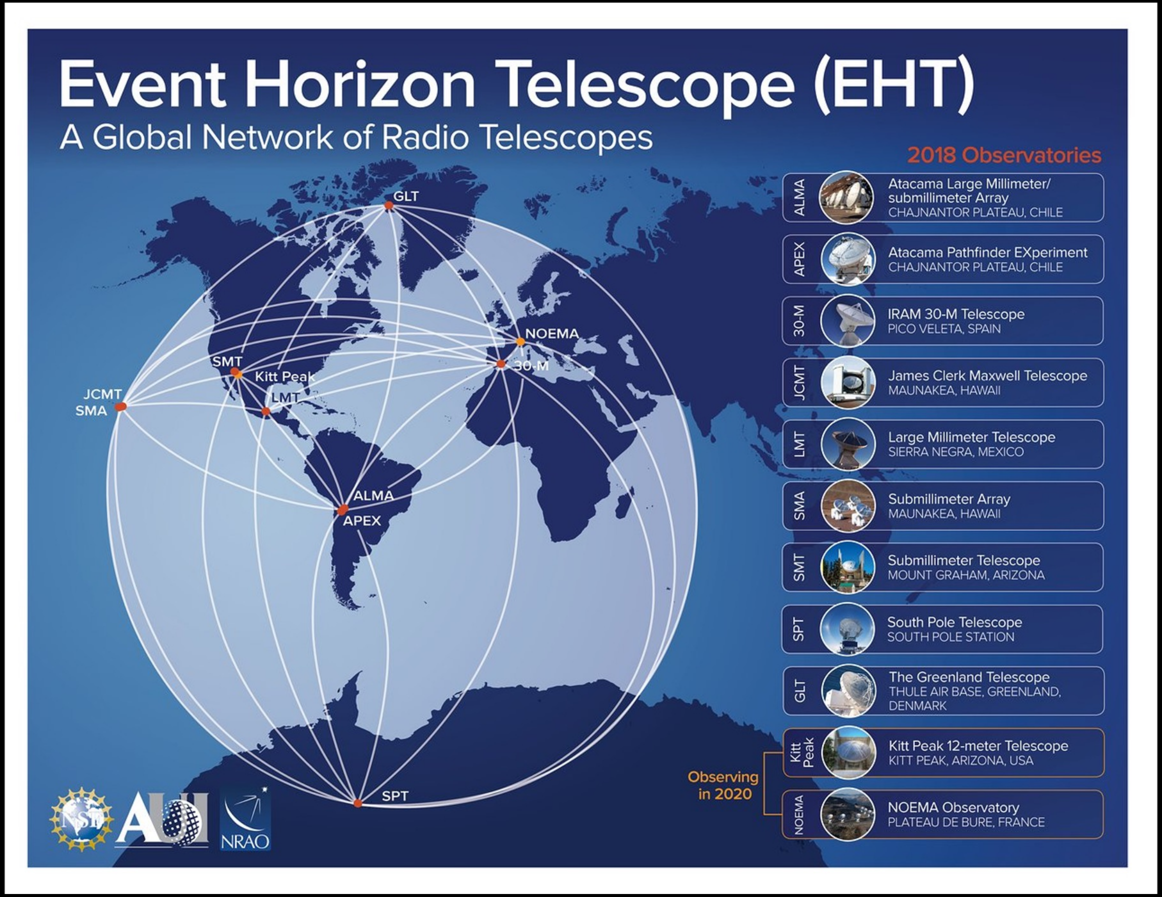
Presenter: Jongho Park (Kyung Hee University)

Part II: Observing the supermassive black hole at the center of M87 using GMVA+ALMA

Presenter: Jongho Park (Kyung Hee University)

The black hole image of M87* revealed by the EHT

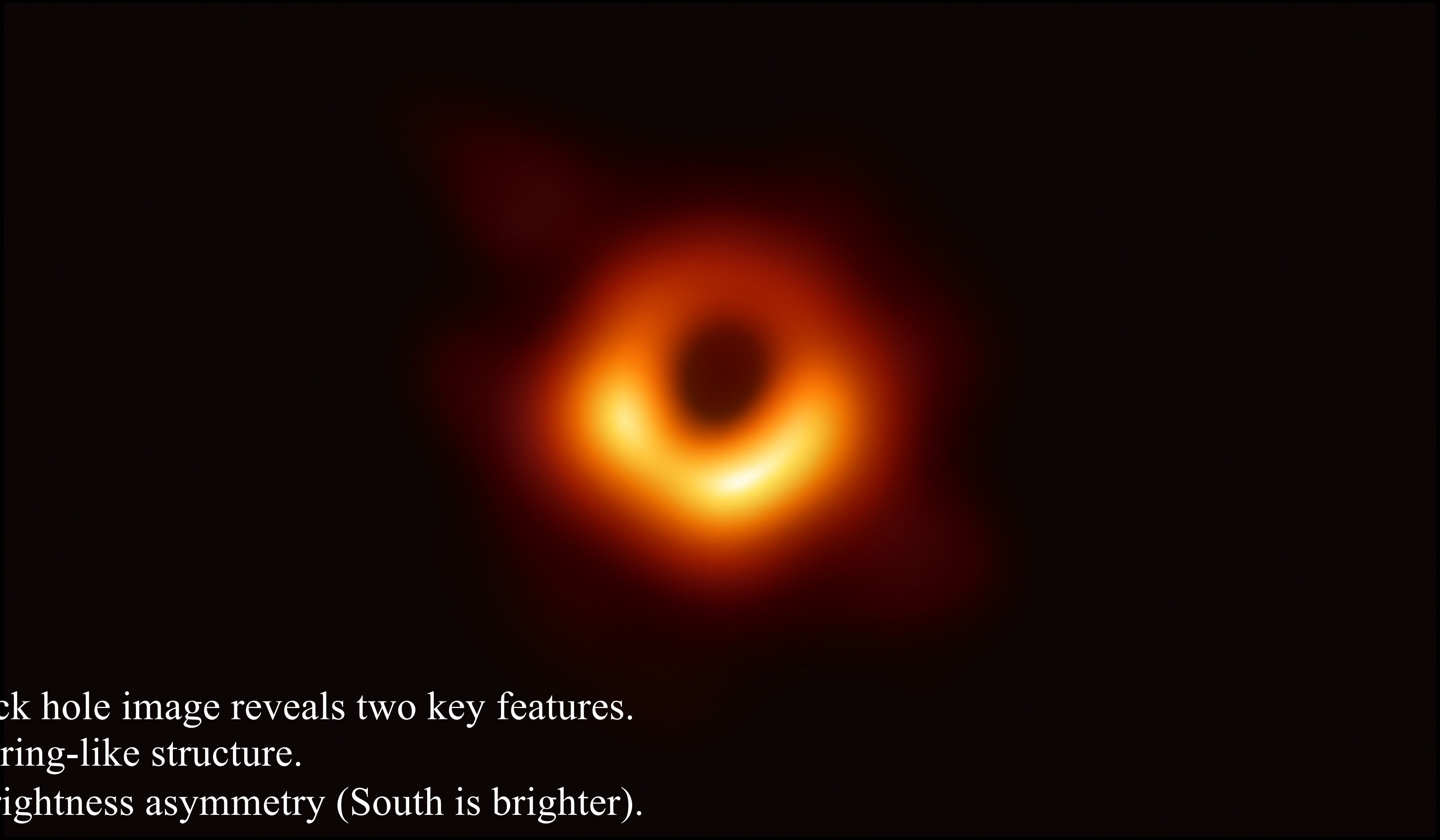
The Event Horizon Telescope



$$\theta_{\mathrm{res}} \propto \frac{\lambda}{B_{\mathrm{max}}}$$

The observing wavelength λ = 1.3 mm.
The maximum baseline length is B_{max} = 11,000 km
The angular resolution is ~ 20 μas

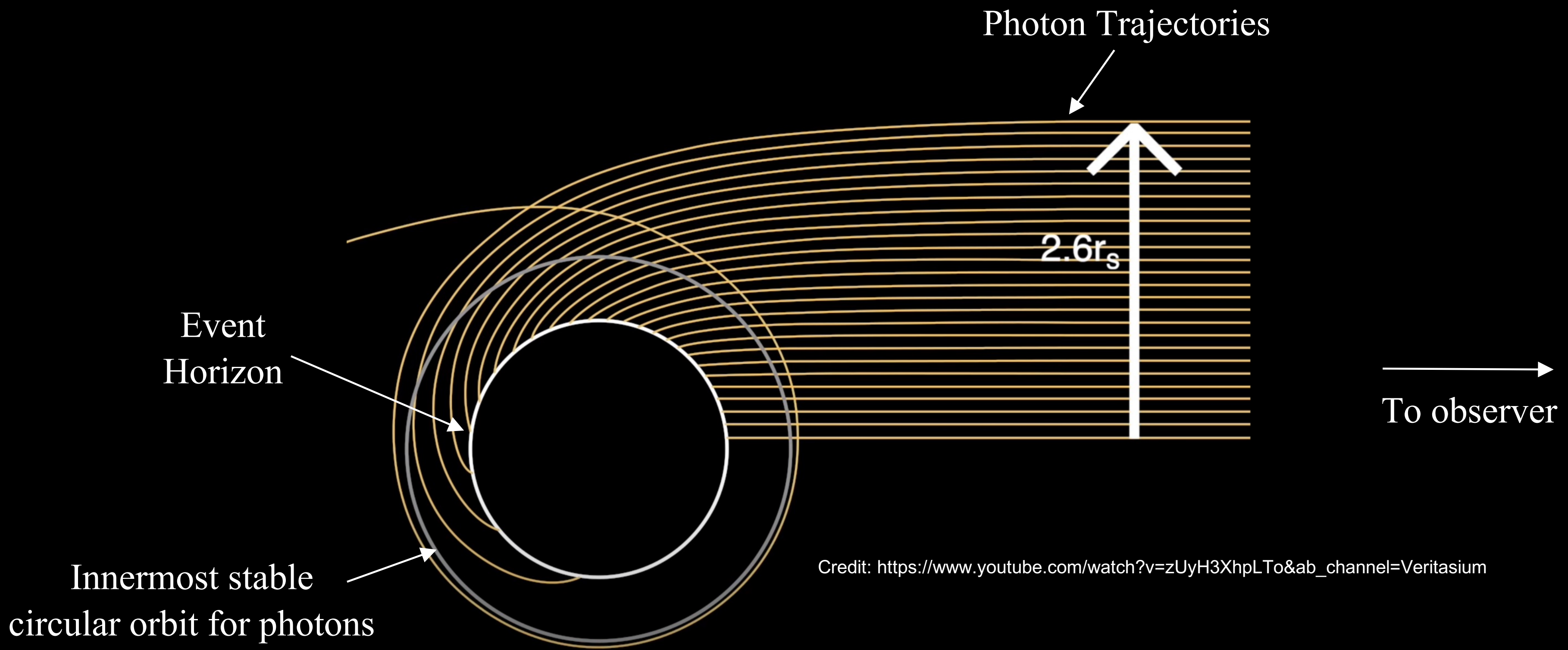
The black hole image of M87* revealed by the EHT



The black hole image reveals two key features.

1. A ring-like structure.
2. Brightness asymmetry (South is brighter).

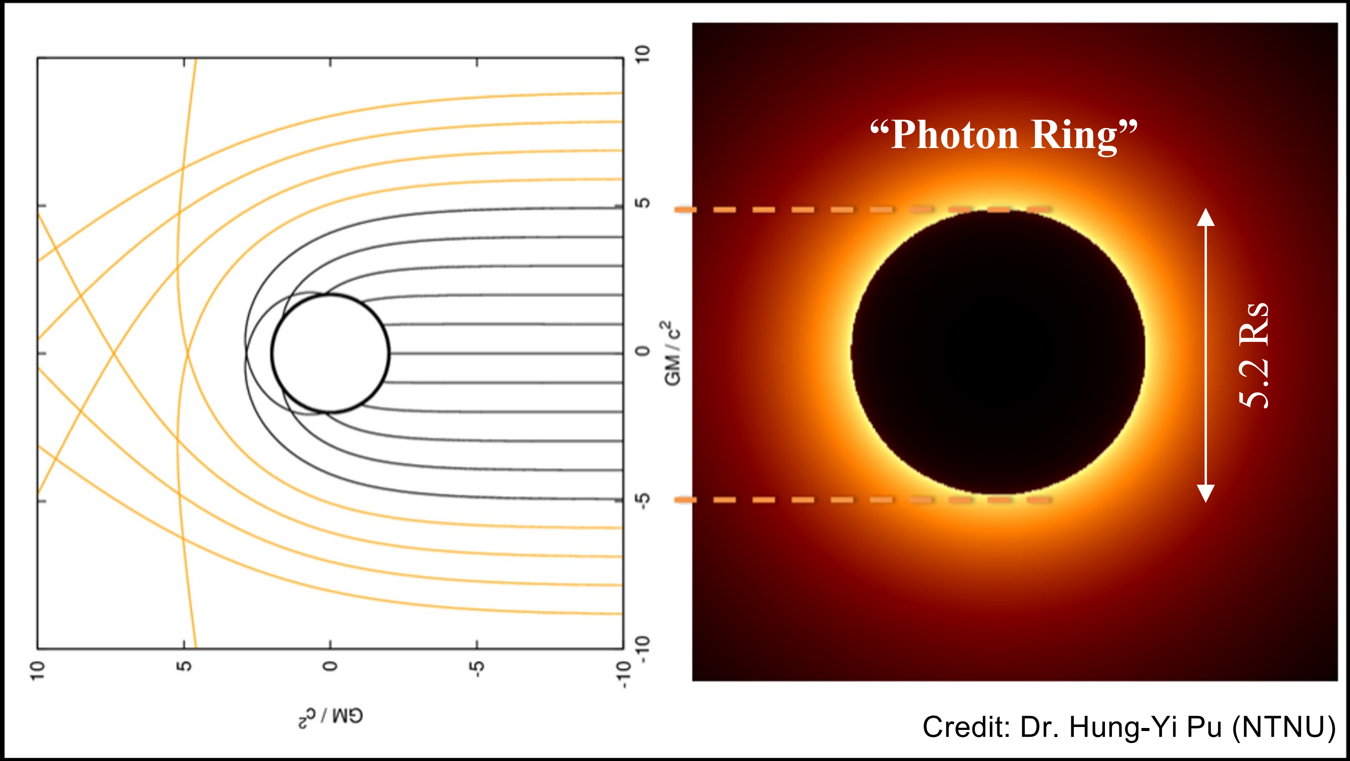
"Photon Ring" and "Black Hole Shadow"



Credit: https://www.youtube.com/watch?v=zUyH3XhpLTo&ab_channel=Veritasium

All the photons within projected distances of ~2.6 Rs from the center of the black hole will pass through the event horizon (we cannot see those photons).

“Photon Ring” and “Black Hole Shadow”

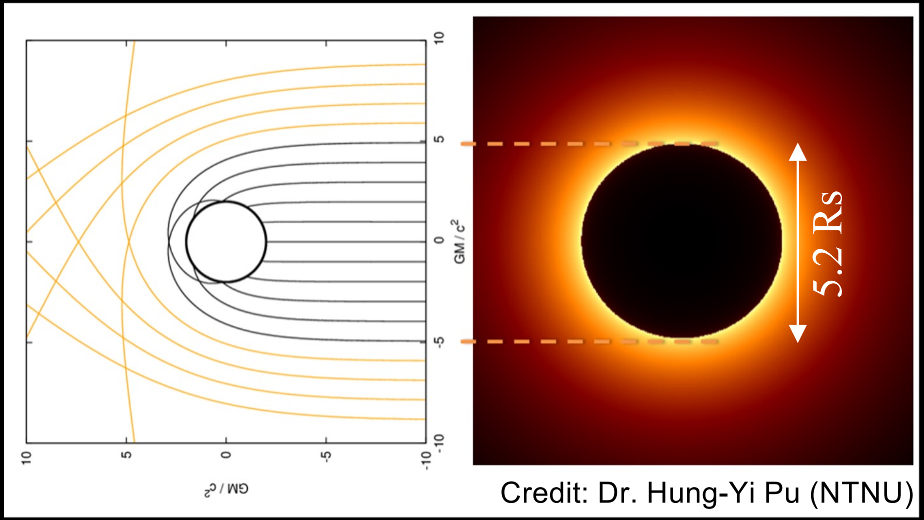


Credit: Dr. Hung-Yi Pu (NTNU)

All the photons within projected distances of ~2.6 Rs from the center of the black hole will pass through the event horizon (we cannot see those photons).

“Photon Ring” and “Black Hole Shadow”

Black hole mass: 6.6e9 Msun (Gebhardt+ 2011)
Distance: 16.8 Mpc (Blakeslee+ 2009)
1 uas ~ 0.129 Rs
(42 ± 3) uas ~ (5.4 ± 0.3) Rs



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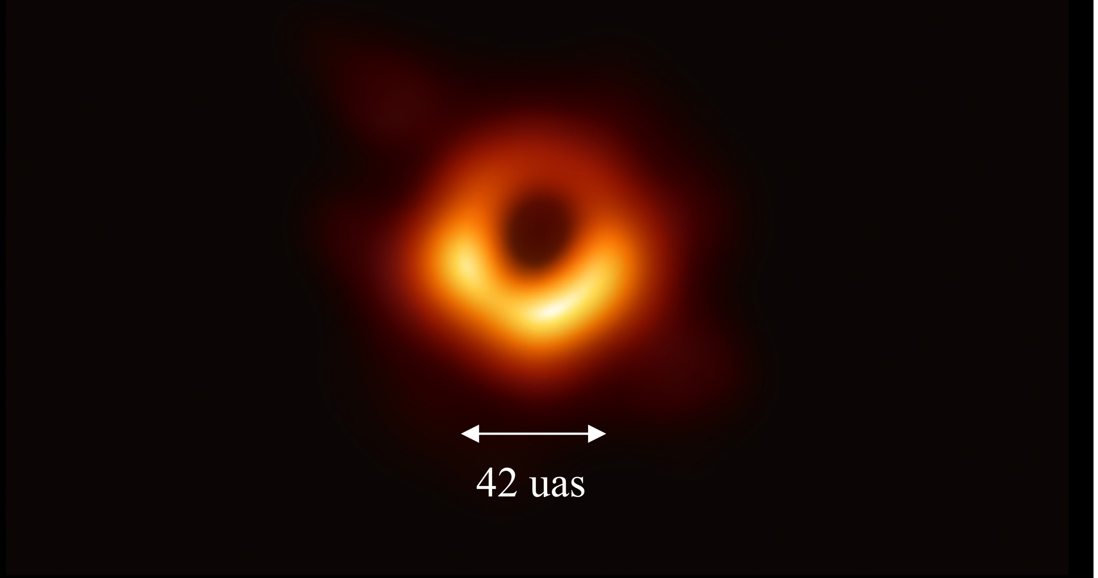
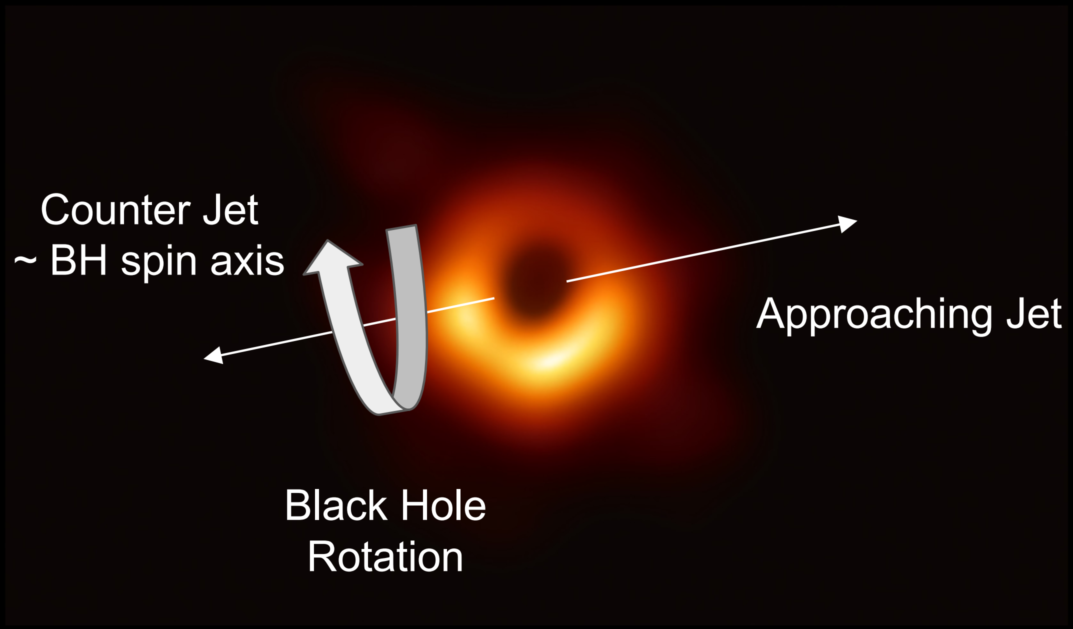
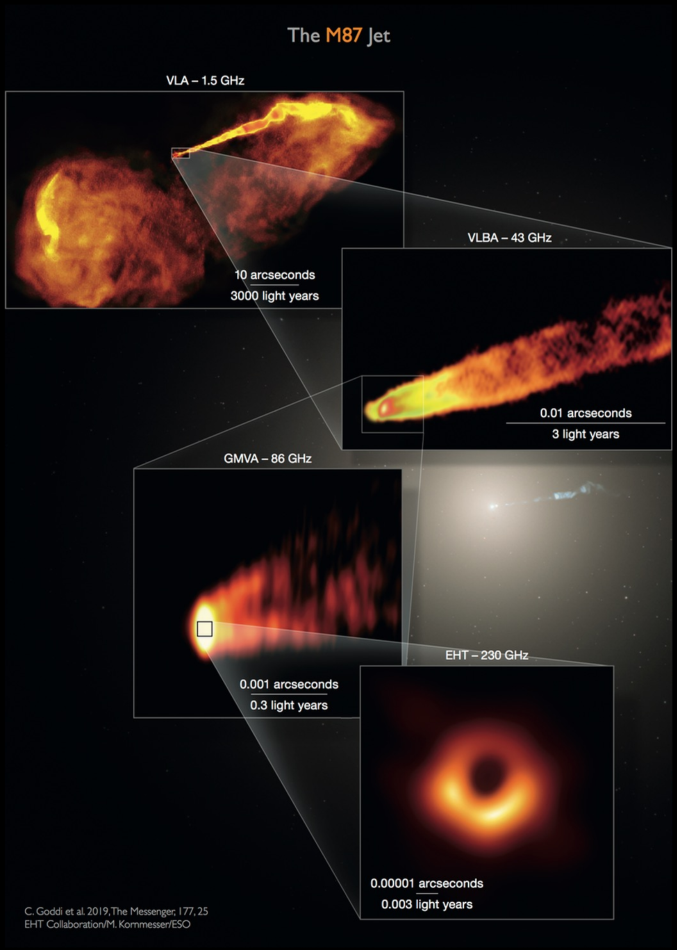


The observed ring-like structure is in good agreement with the prediction of GR.

Doppler Boosting and Brightness Asymmetry

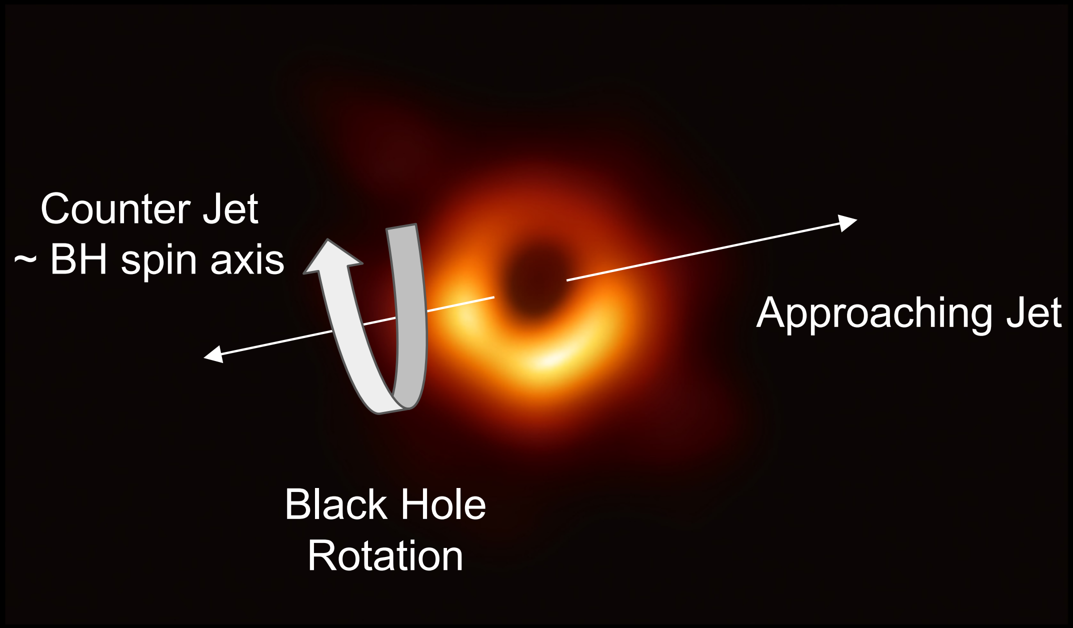




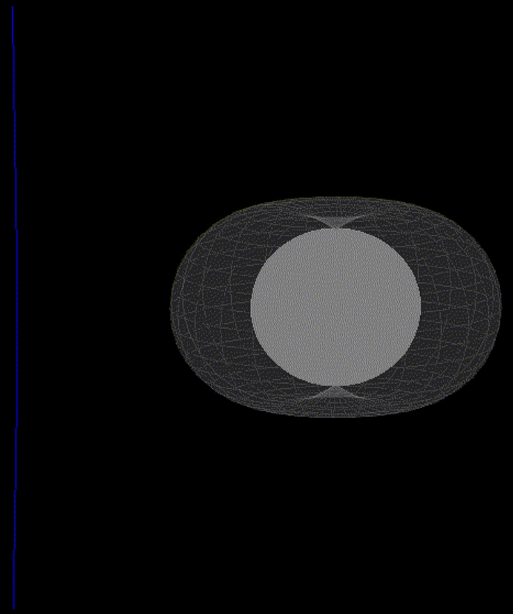
C. Goddi et al. 2019, The Messenger, 177, 25
EHT Collaboration/M. Kornmesser/ESO

The frame-dragging and Doppler boosting effects.

Doppler Boosting and Brightness Asymmetry



Semenov (2004)



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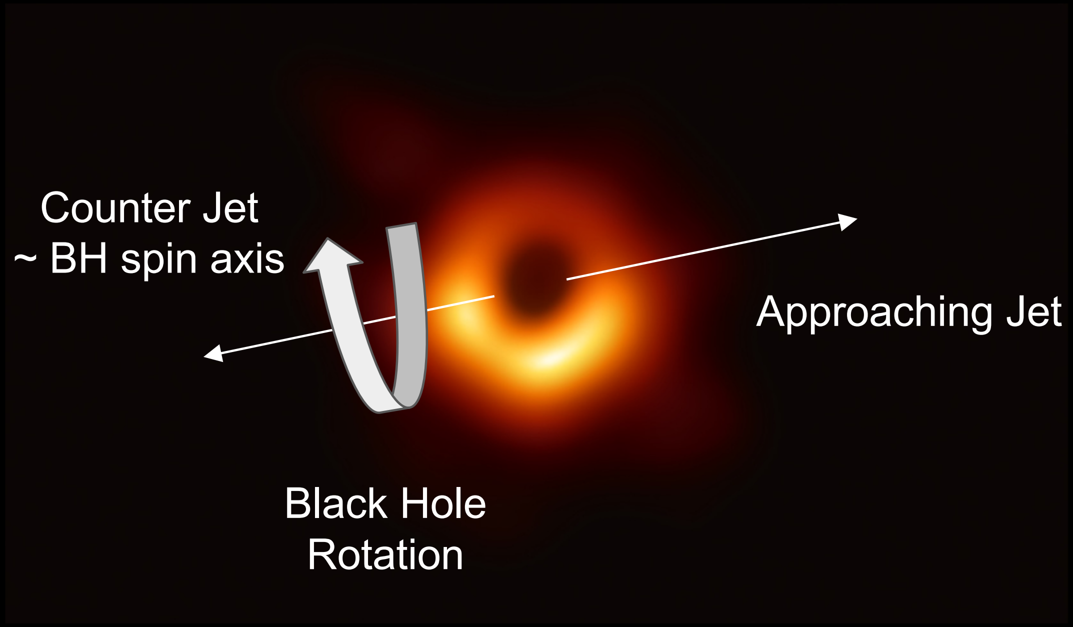

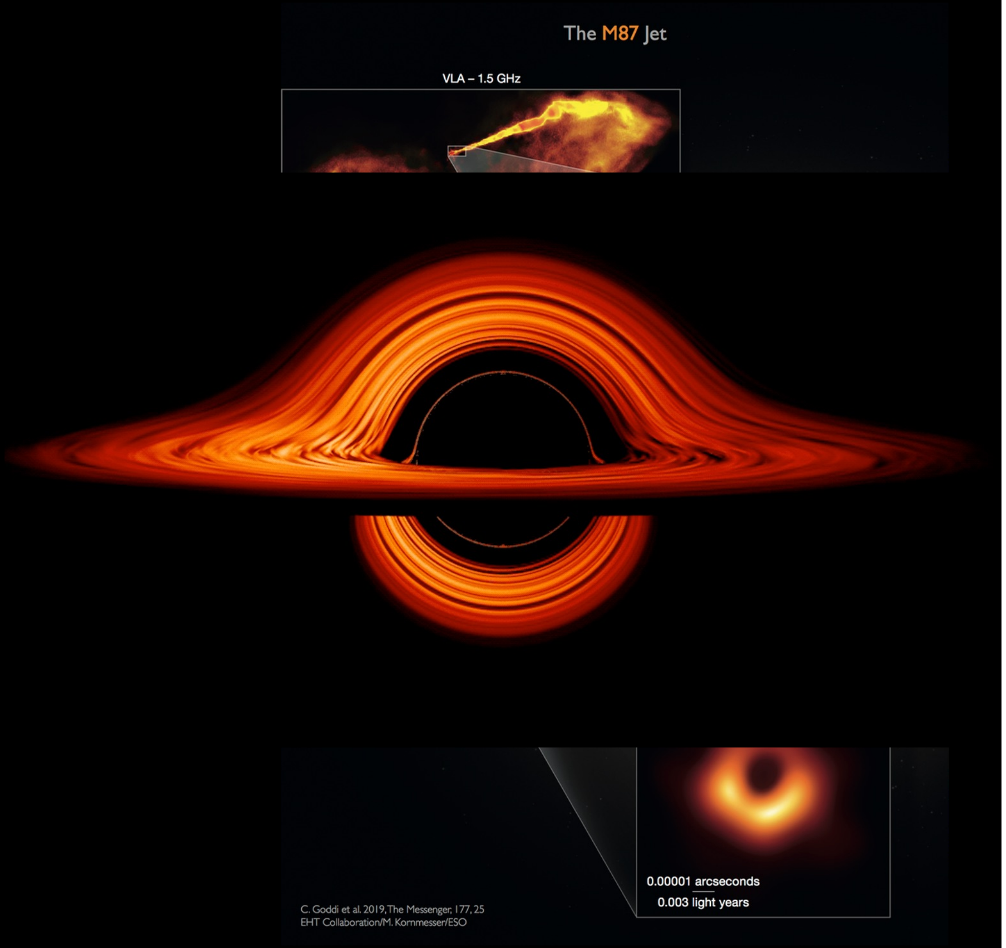

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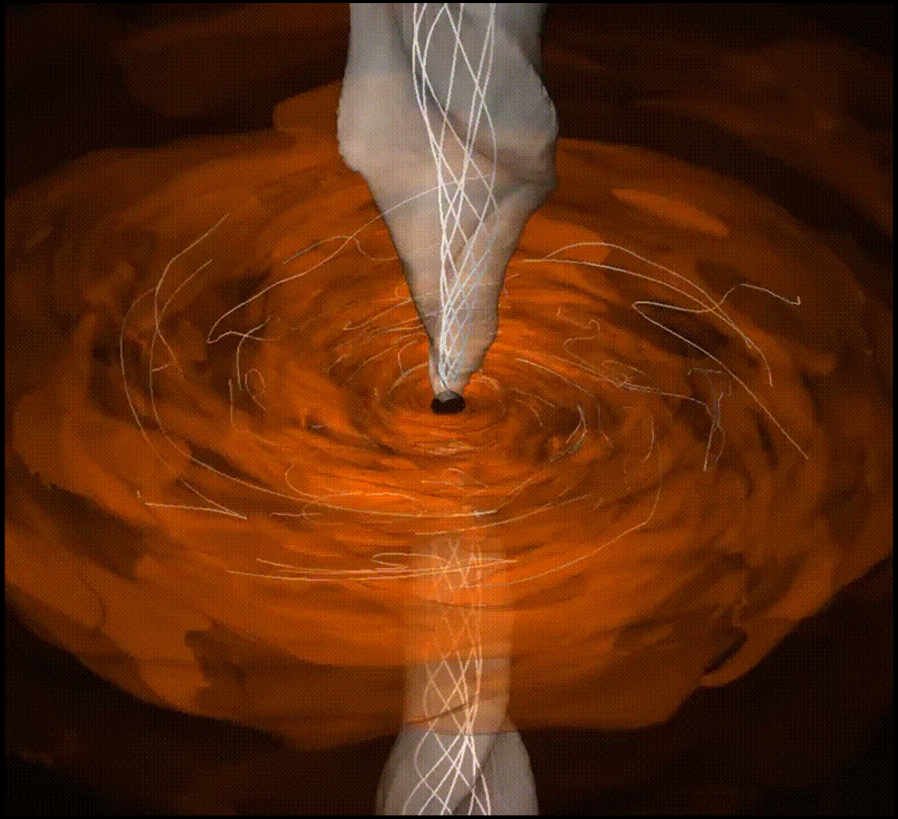
The frame-dragging and Doppler boosting effects.

Remaining Questions in the Black Hole Physics Community

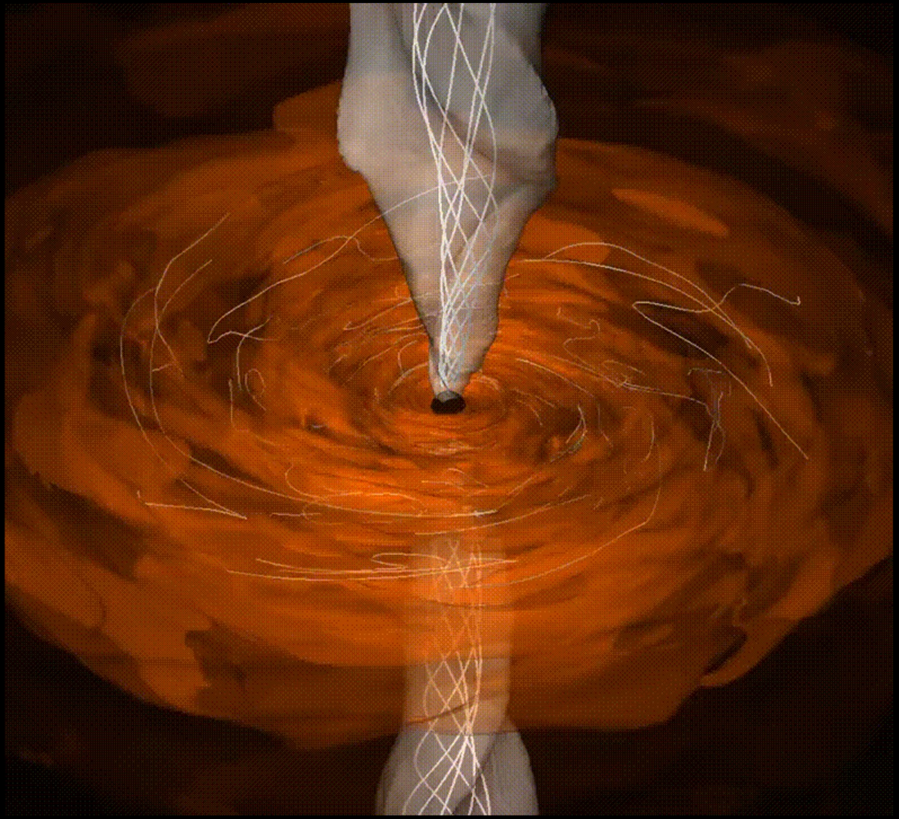


Credit: Shiokawa

The observed black hole images are produced by the interplay between the followings:

1. Accretion Flows & Jets.
2. Magnetic Fields.
3. Curved Spacetime around the black hole.

Remaining Questions in the Black Hole Physics Community



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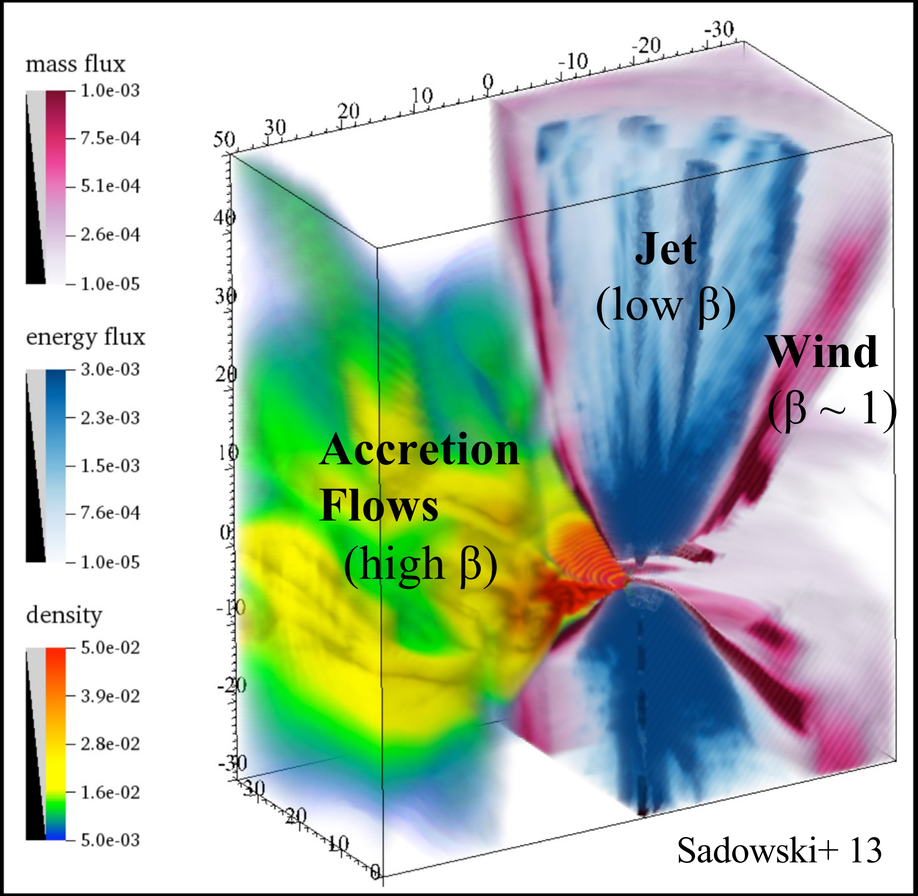
How do the particles in the accretion flows and jets behave?
→ R_{high}

Remaining Questions in the Black Hole Physics Community



Sadowski+ 13

Low-Luminosity AGNs like M87 and Sgr A*

→ Hot and Geometrically Thick Accretion Flows.

- Low Density & High Pressure
- Very weak Coulomb Collisions between the Ions and Electrons

$$R \equiv T_i / T_e$$

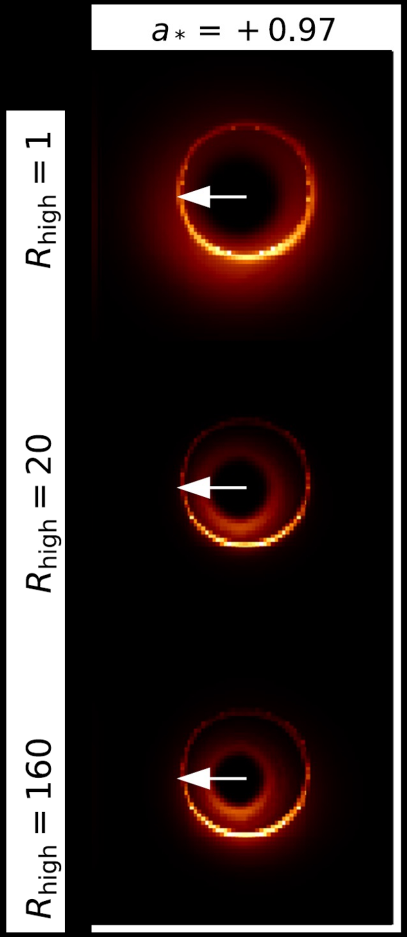
$$R = R_{\mathrm{high}} \frac{\beta_{\mathrm{p}}^2}{1+\beta_{\mathrm{p}}^2} + \frac{1}{1+\beta_{\mathrm{p}}^2}$$

$$\beta_{\mathrm{p}} \equiv p_{\mathrm{gas}} / p_{\mathrm{mag}}$$

$R \sim R_{\mathrm{high}}$ at high beta

$R \sim 1$ at low beta

Remaining Questions in the Black Hole Physics Community



$R_{\rm high}$ ↑

Electron T in the Accretion Disk ↓

Jet Emission becomes prominent

Low-Luminosity AGNs like M87 and Sgr A*
→ Hot and Geometrically Thick Accretion Flows.

- Low Density & High Pressure
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$$R \equiv T_i / T_e$$

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R ~ $R_{\rm high}$ at high beta
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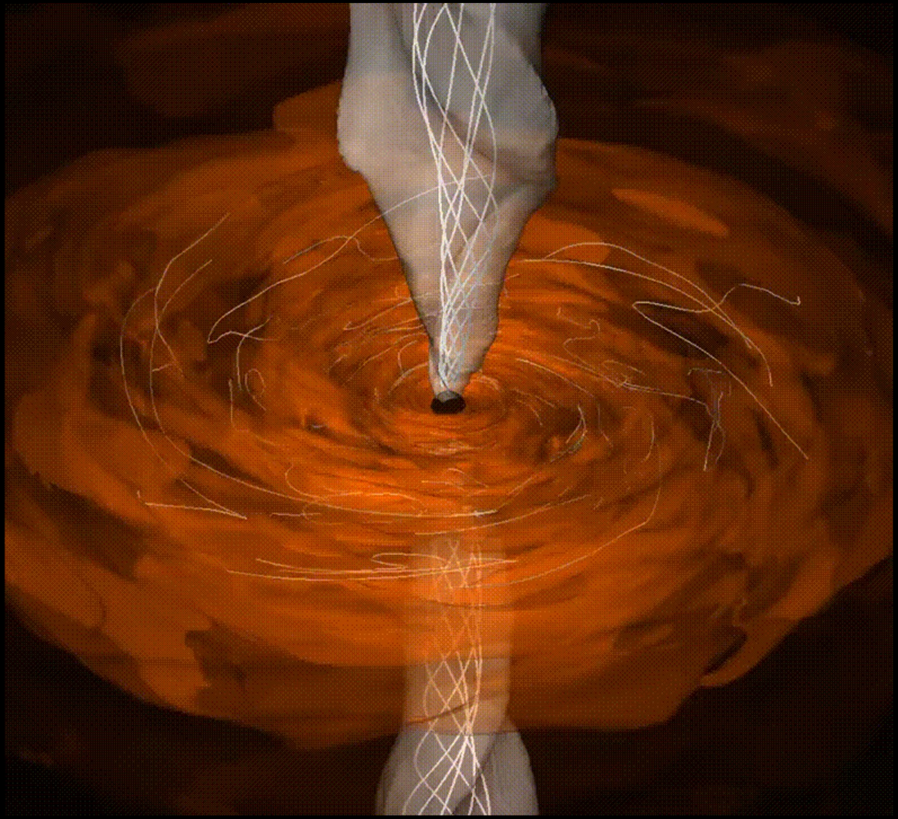
Remaining Questions in the Black Hole Physics Community



Credit: Shiokawa

The observed black hole images are produced by the interplay between the followings:

1. Accretion Flows & Jets.
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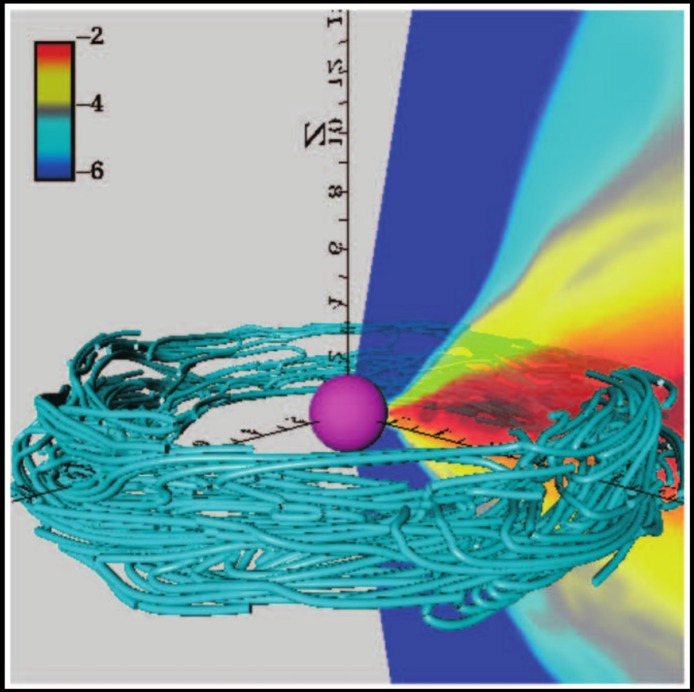
What is the configuration and strength of the magnetic field around the black hole?
→ SANE or MAD?

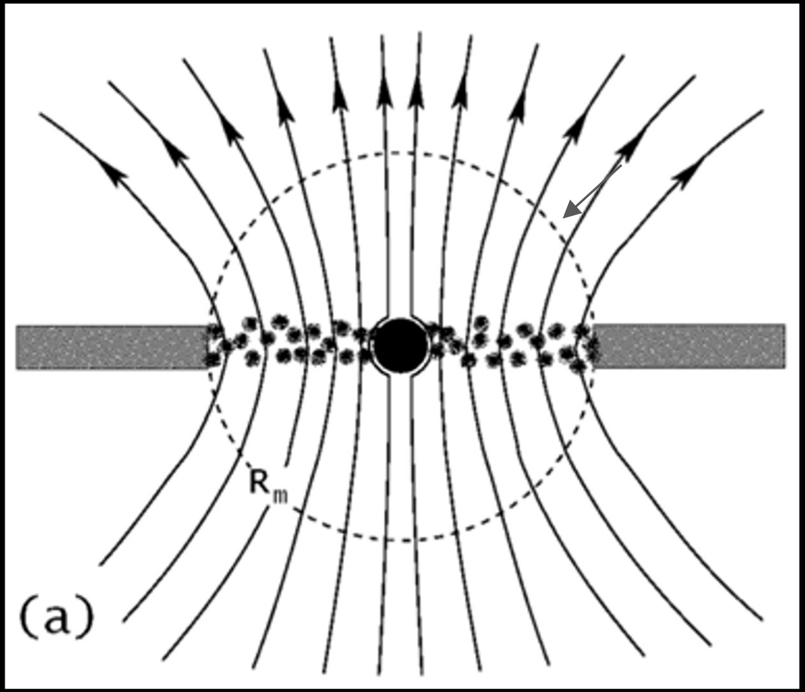
Remaining Questions in the Black Hole Physics Community

Standard and Normal Evolution
(SANE)



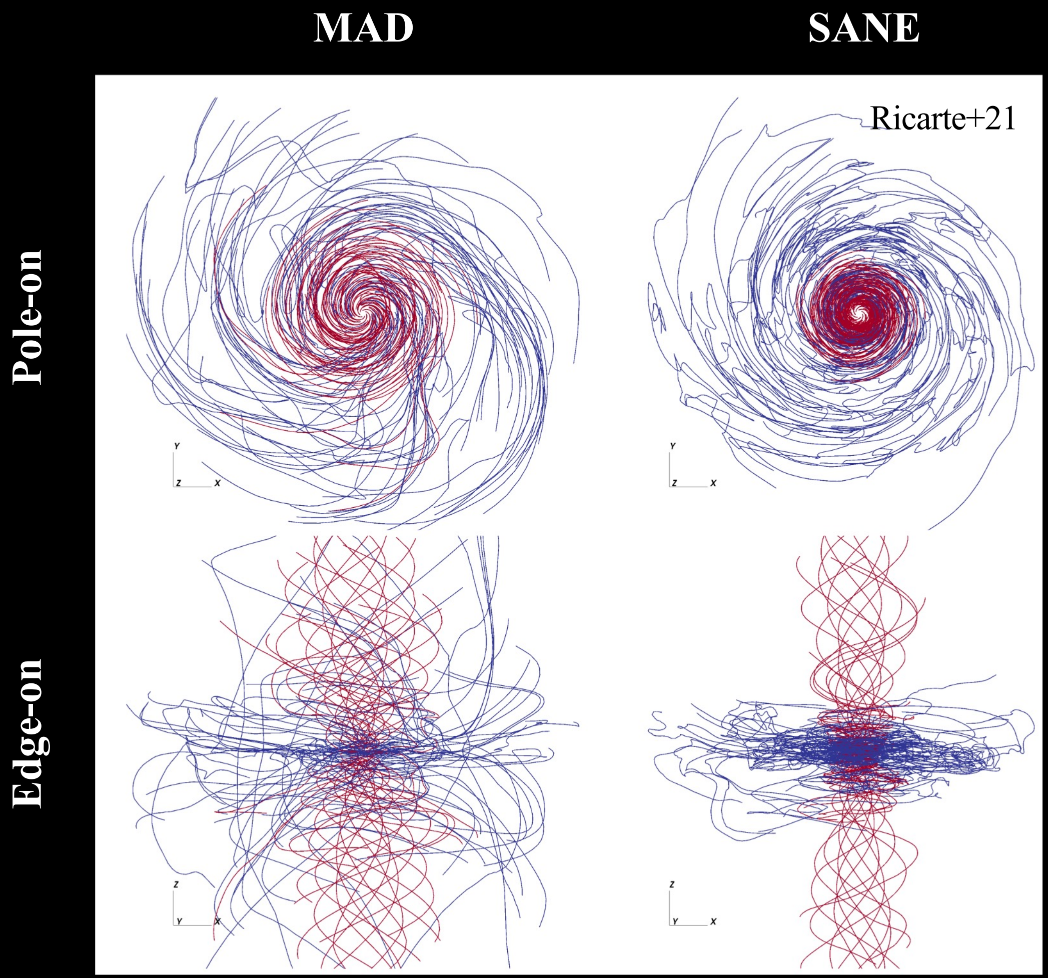
Turbulent, weak, and toroidal-dominated B fields

Magnetically Arrested Disk
(MAD)



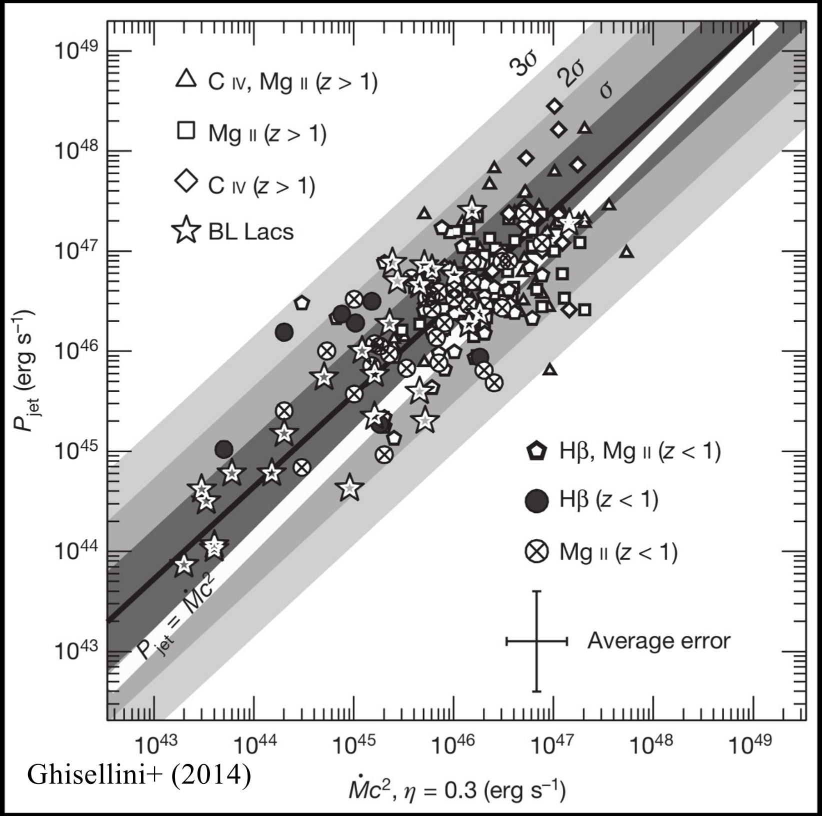
Ordered, strong, and poloidal-dominated B fields

Remaining Questions in the Black Hole Physics Community



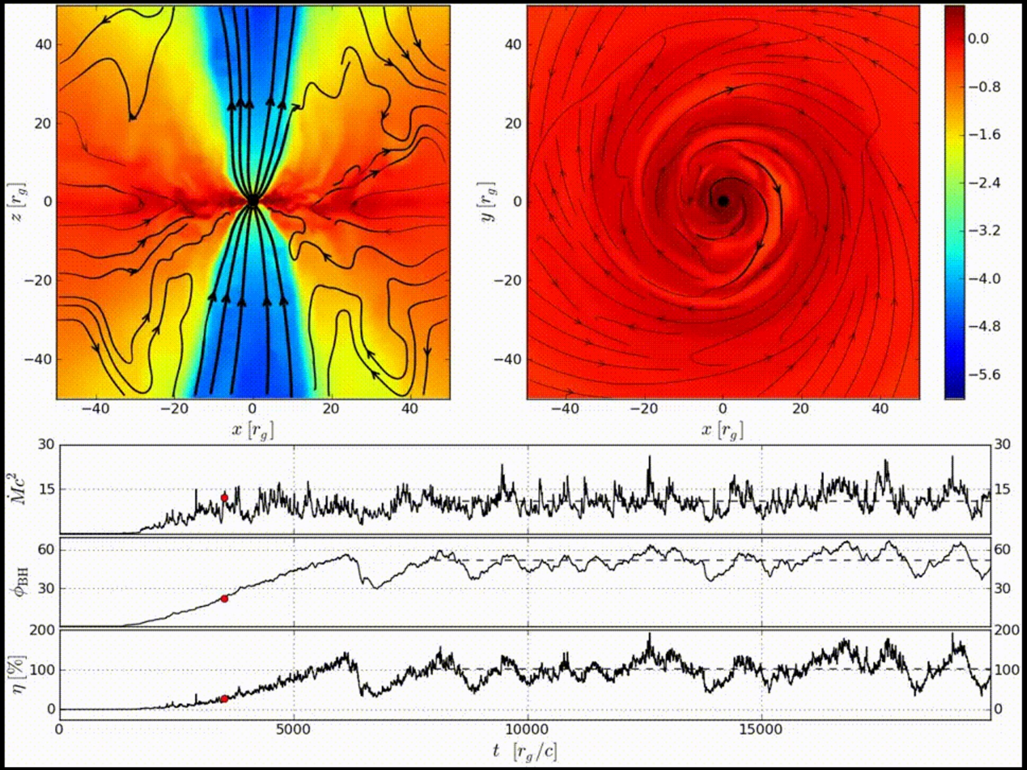
Remaining Questions in the Black Hole Physics Community

Jet Power



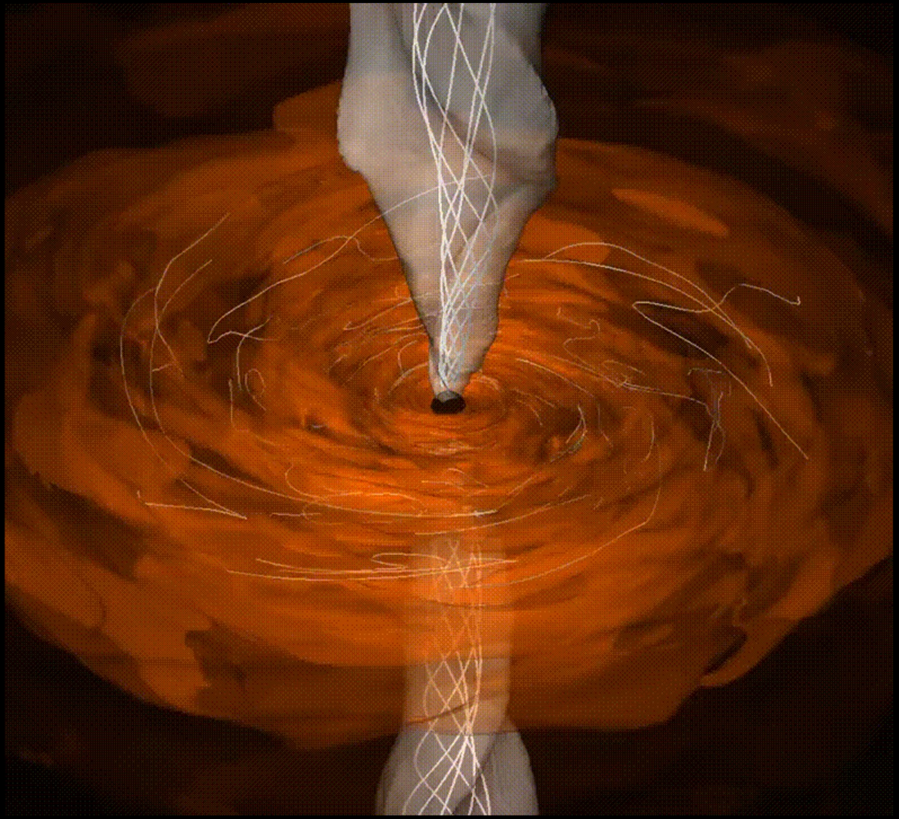
Ghisellini+ (2014)

Accretion Power



Tchekhovskoy+ (2011)

Remaining Questions in the Black Hole Physics Community



Credit: Shiokawa

The observed black hole images are produced by the interplay between the followings:

1. Accretion Flows & Jets.
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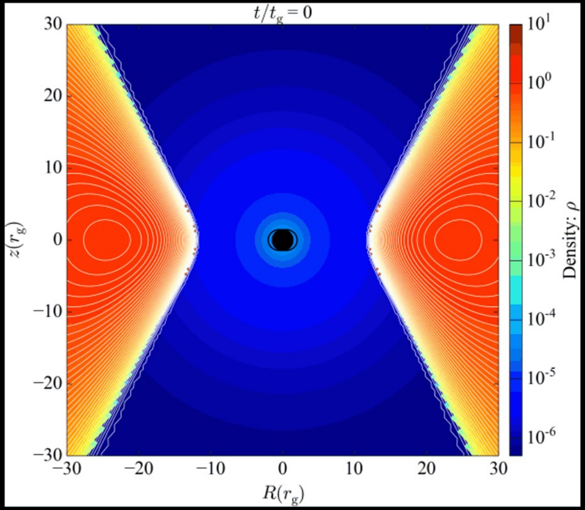
What is the spin of the black hole?
→ α

GRMHD simulations + GRRT calculation

General Relativistic Magnetohydrodynamic Simulations

Credit: Nakamura+



Particle Density, Temperature, Velocity,
Magnetic Fields in each cell

General Relativistic Radiative Transfer Calculation

Credit: Gammie+

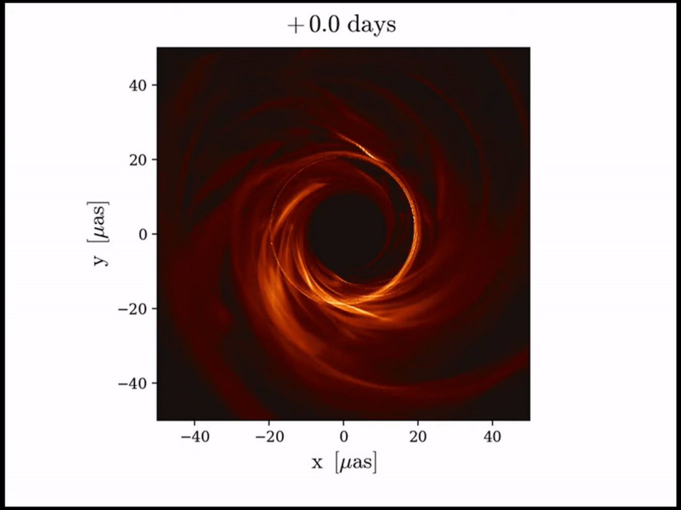
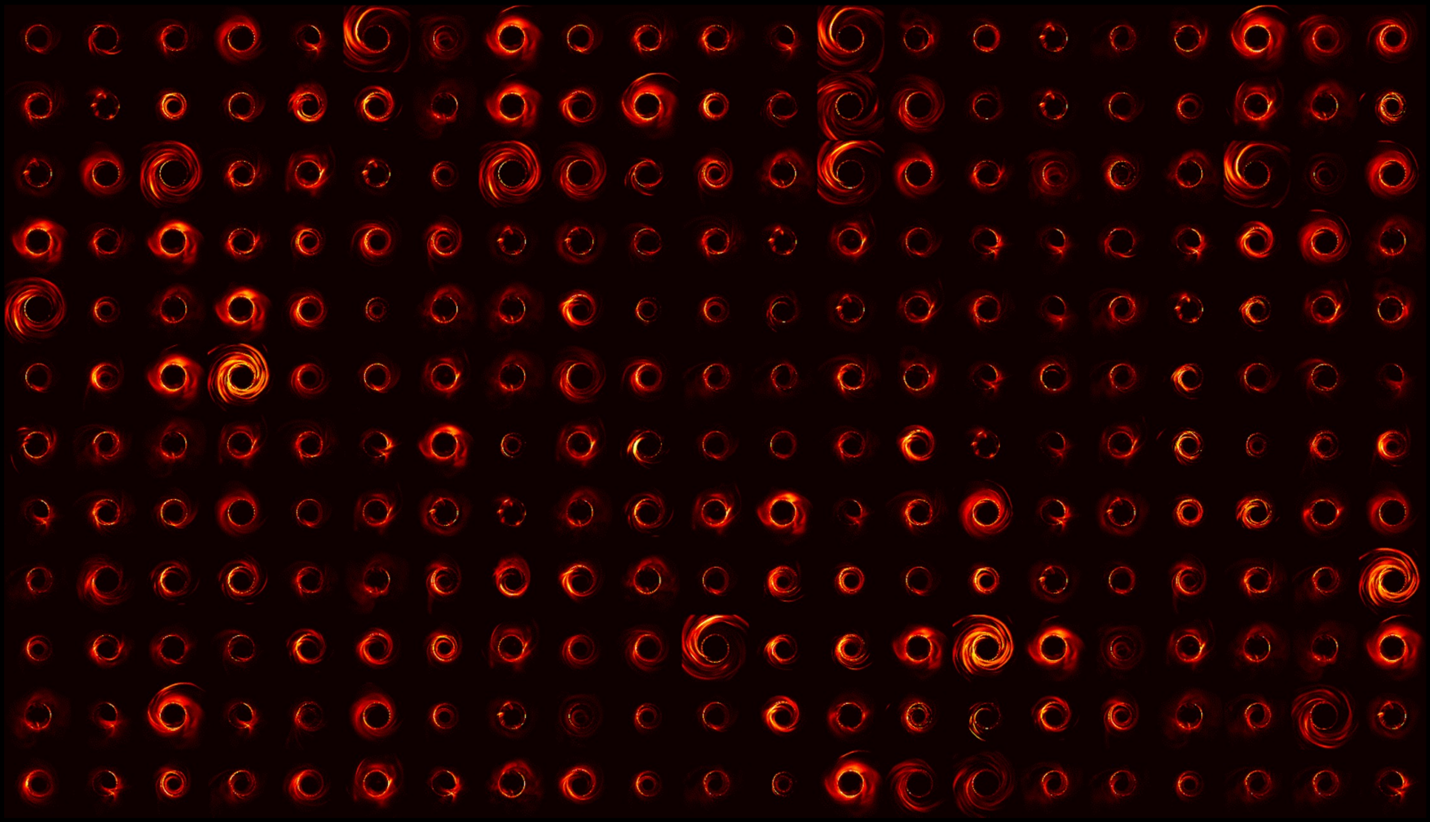


Image of the black hole

GRMHD simulations + GRRT calculation

Credit: the EHT collaboration

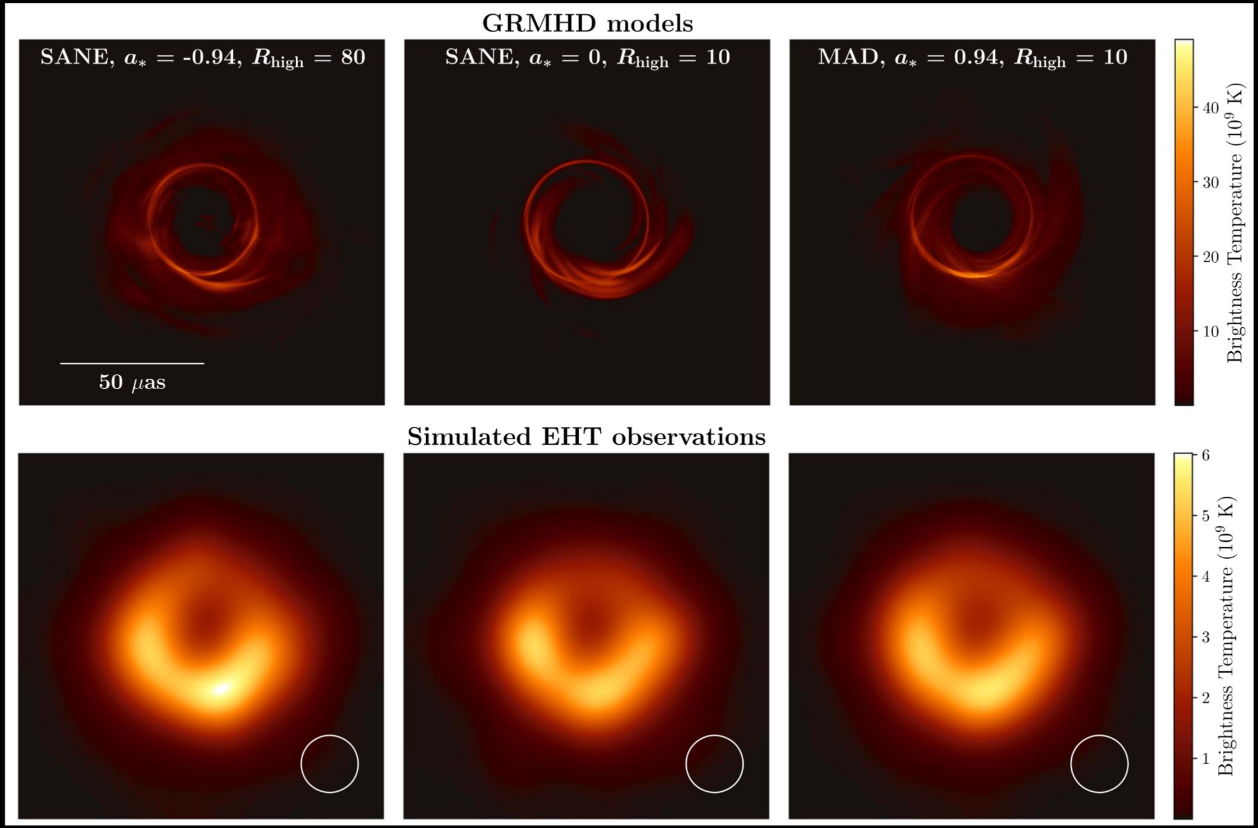


→ Which model can reproduce the observed black hole image?

GRMHD simulations + GRRT calculation

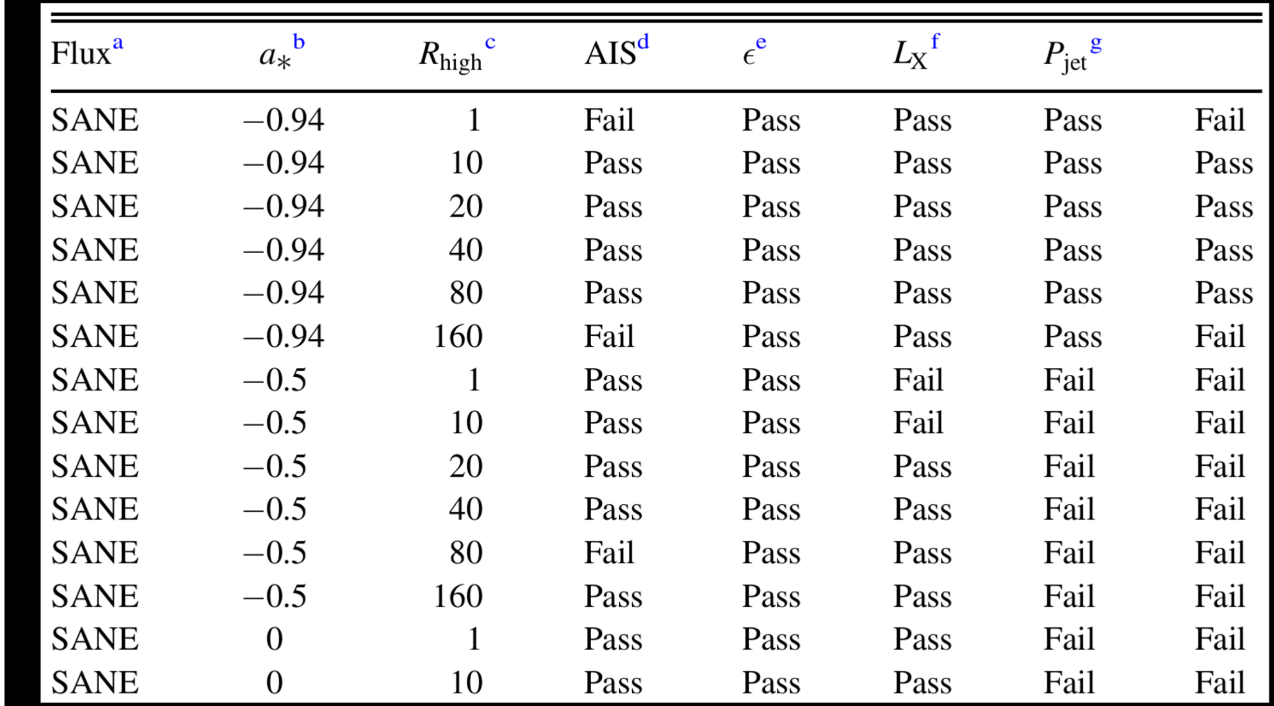
Simulation

“Blurred”
Images



→ Which model can reproduce the observed black hole image?

Modeling of the observed black hole image



			2	3	4	5	
Flux[a]	a_*[b]	$R_{\rm high}$[c]	AIS[d]	ϵ[e]	L_X[f]	$P_{\rm jet}$[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

From a GRMHD simulation library consisting of 72,000 images, find the models which meet the following criteria.

1. Total flux of 0.5 Jy.
2. The model must produce similar images to the observed ones.
3. The radiative efficiency should not be too high.
4. The model should not produce too high X-ray flux.
5. The model should produce enough jet power $P_{\rm jet} \geq 10^{42} {\rm erg\ s^{-1}}$.

Conclusions: a detailed modeling of the black hole shadow image using the state-of-the-art GRMHD simulation could not constrain the physical parameters tightly.

he observed black hole image

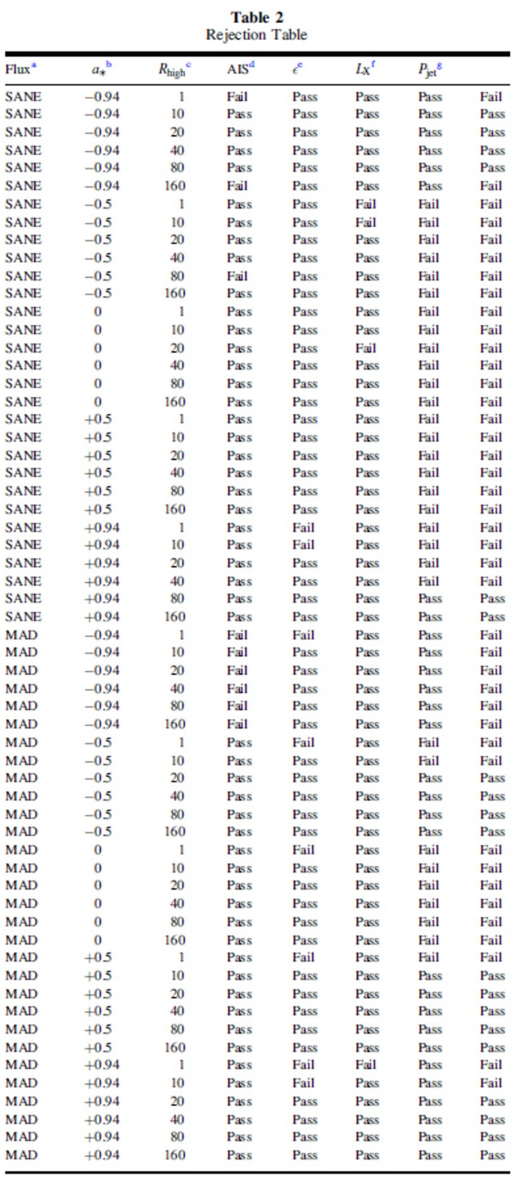


Table 2
Rejection Table

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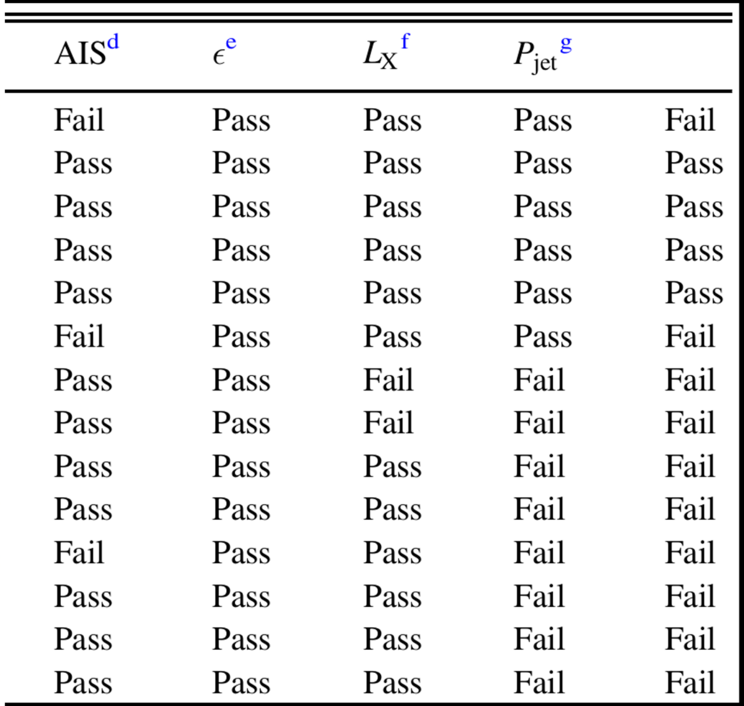
MAD	+0.94	1	Pass	Fail	Fail	Pass	Fail
MAD	+0.94	10	Pass	Fail	Pass	Pass	Fail
MAD	+0.94	20	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	40	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	80	Pass	Pass	Pass	Pass	Pass
MAD	+0.94	160	Pass	Pass	Pass	Pass	Pass

2 3 4 5



AIS[d]	ϵ[e]	L_X[f]	$P_{\rm jet}$[g]	
Fail	Pass	Pass	Pass	Fail
Pass	Pass	Pass	Pass	Pass
Pass	Pass	Pass	Pass	Pass
Pass	Pass	Pass	Pass	Pass
Pass	Pass	Pass	Pass	Pass
Fail	Pass	Pass	Pass	Fail
Pass	Pass	Fail	Fail	Fail
Pass	Pass	Fail	Fail	Fail
Pass	Pass	Pass	Fail	Fail
Pass	Pass	Pass	Fail	Fail
Fail	Pass	Pass	Fail	Fail
Pass	Pass	Pass	Fail	Fail
Pass	Pass	Pass	Fail	Fail
Pass	Pass	Pass	Fail	Fail

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nodeling of the black hole shadow image using the state-of-the-art GRMHD strain the physical parameters tightly.

The Linear Polarization of the M87* Black Hole

First M87 Event Horizon Telescope Results. VII. Polarization of the Ring (ApJL, 910, L12, 2021 March 20)
First M87 Event Horizon Telescope Results. VIII. Magnetic Field Structure near The Event Horizon (ApJL, 910, L13, 2021 March 20)

Paper VII writing team

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(Perimeter)

John
Wardle
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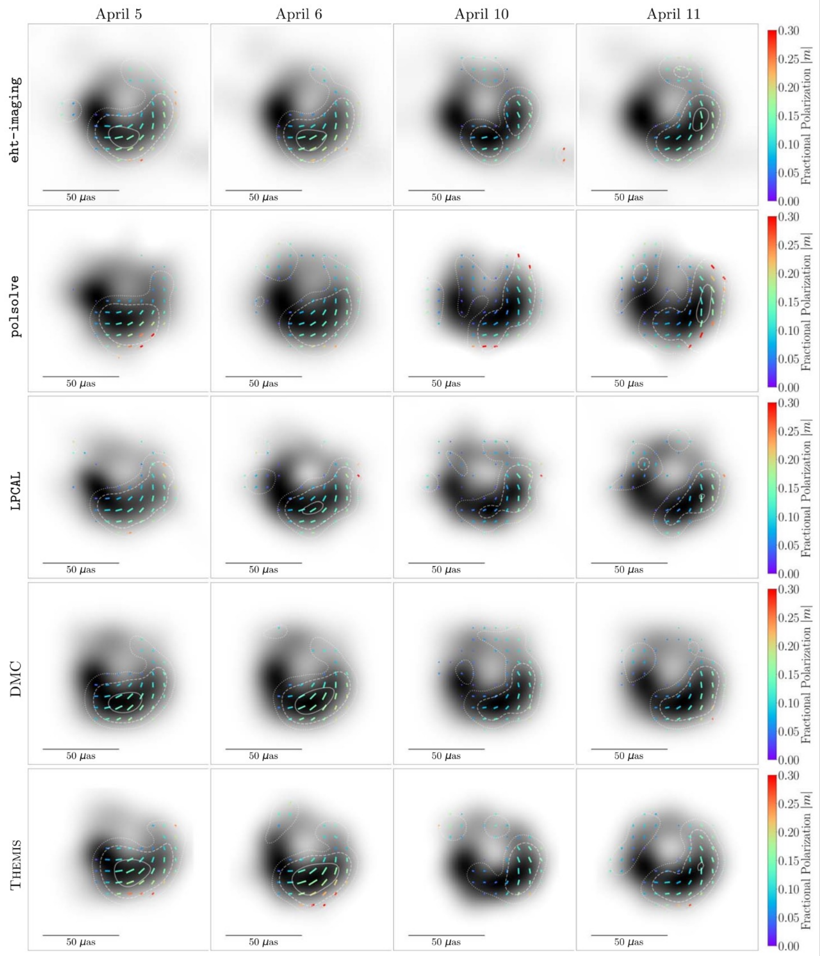
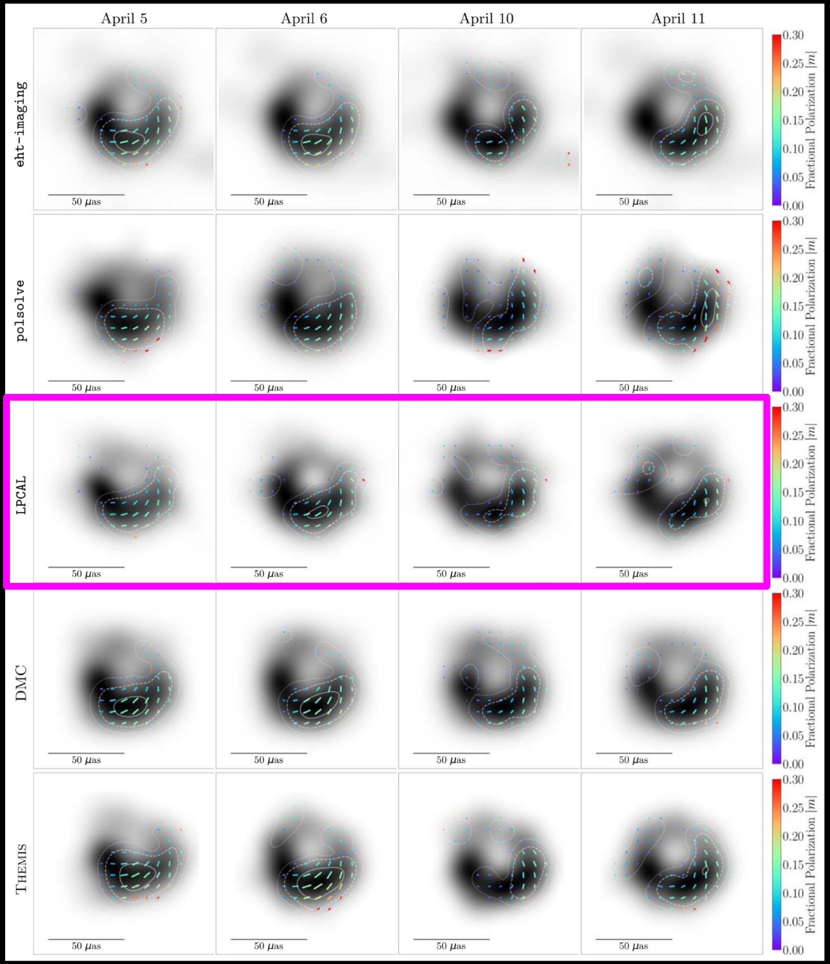
Univ.)

VLBI Polarimetry

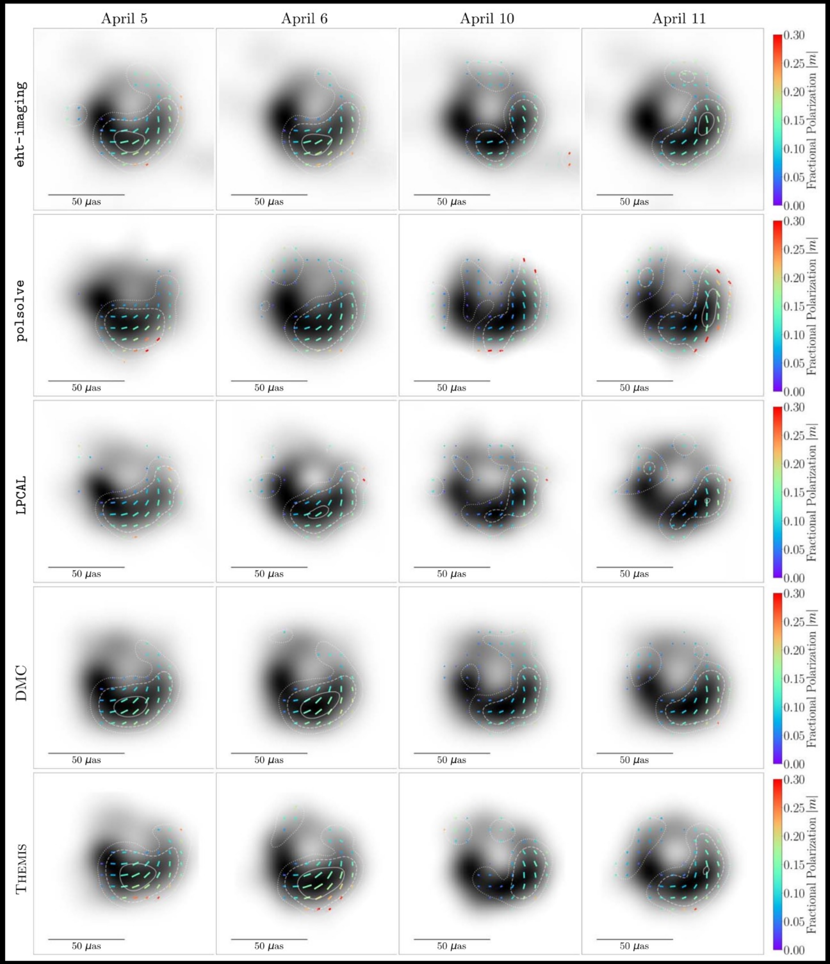


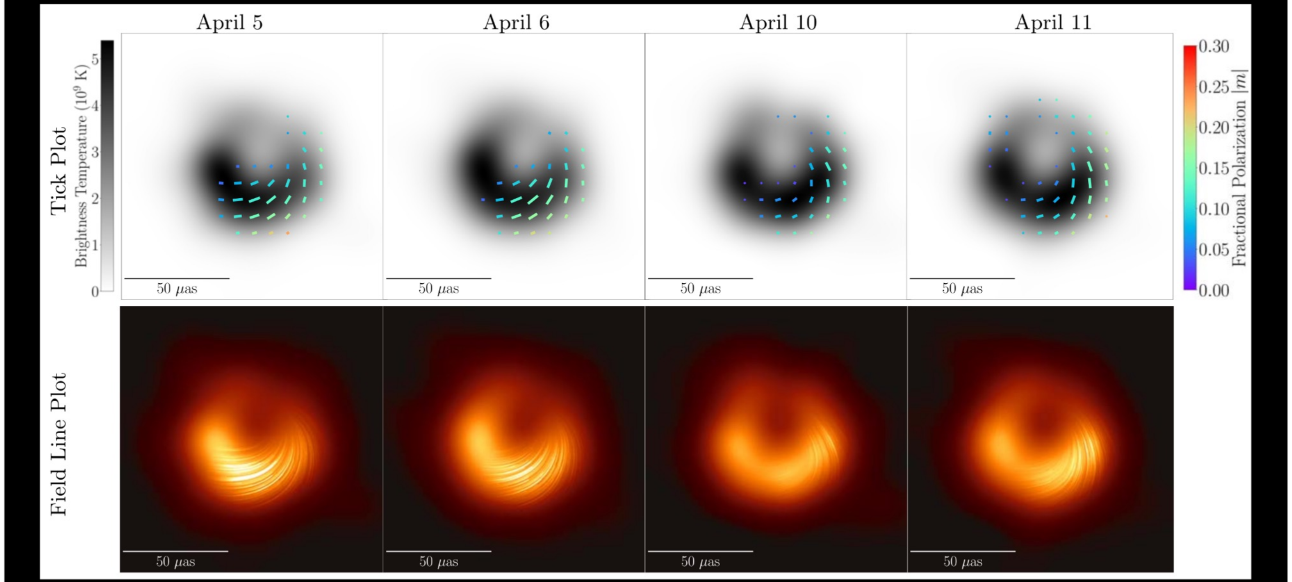
VLBI Polarimetry



← Leader of this team

VLBI Polarimetry

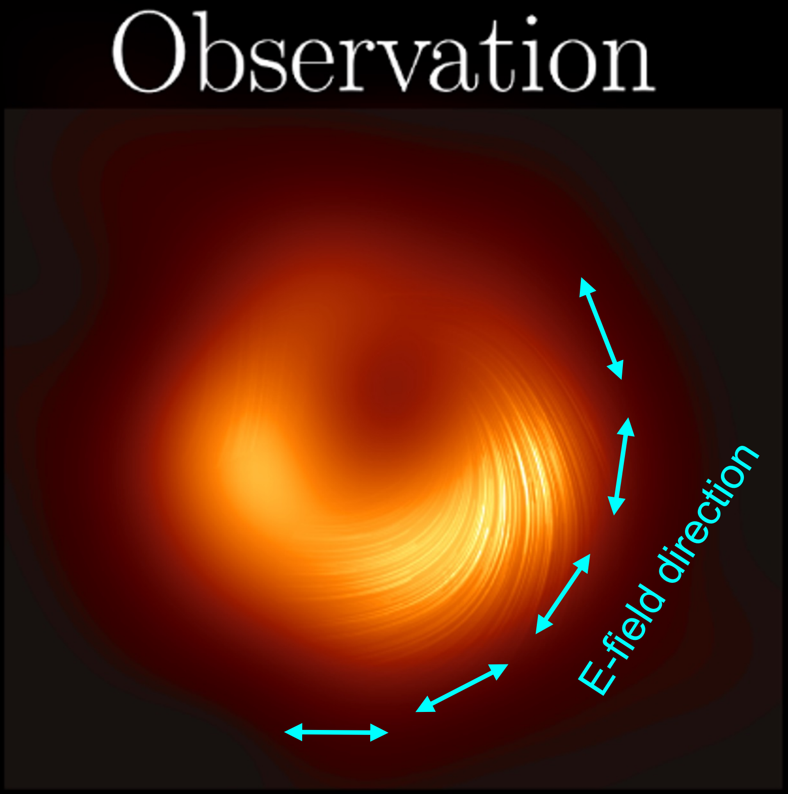




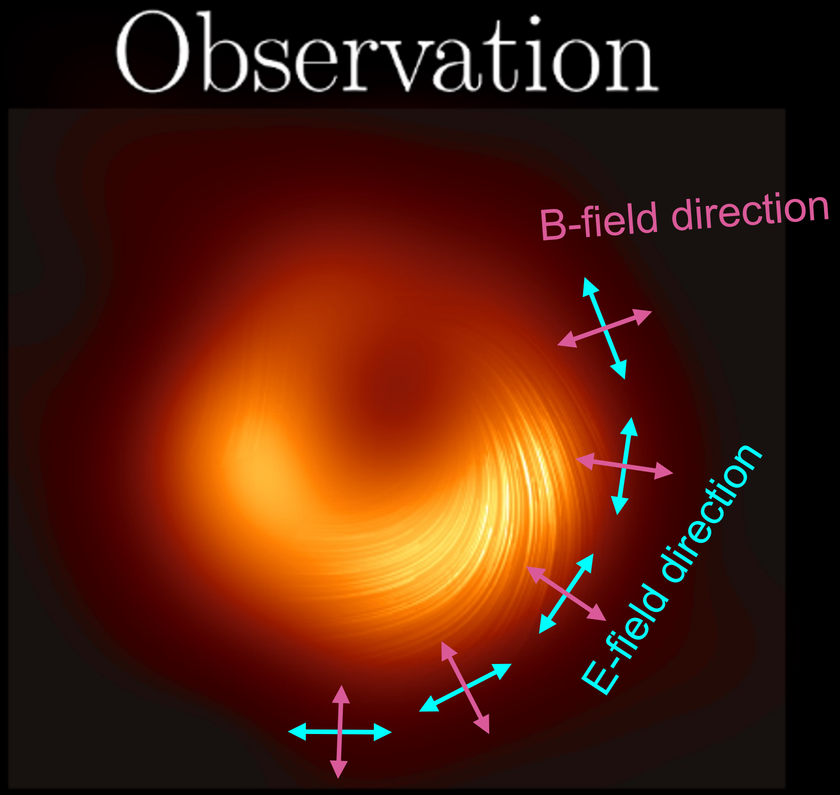
Modeling of the linear polarization image

Observation

Modeling of the linear polarization image

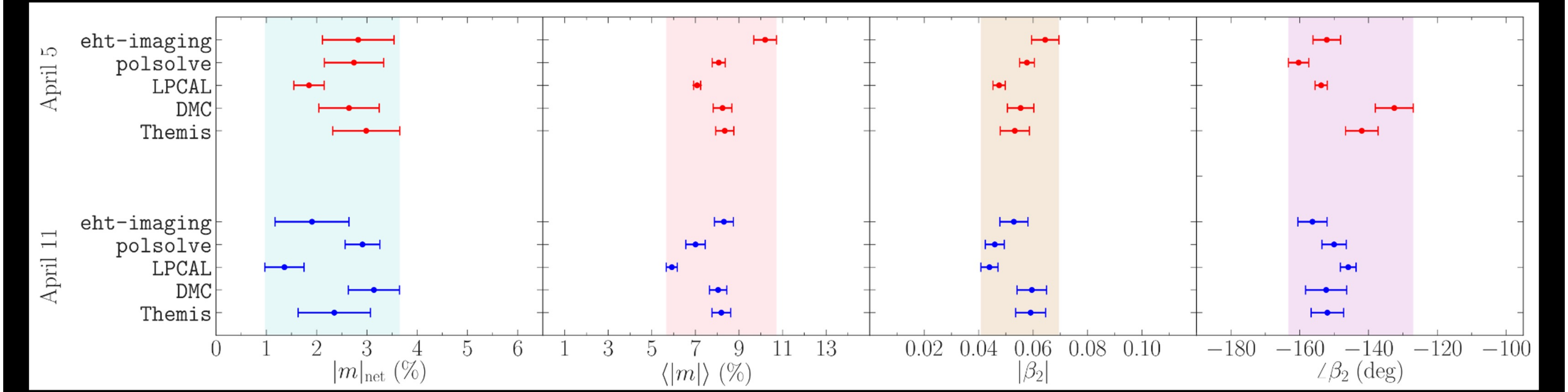


Modeling of the linear polarization image



Poloidal-dominated B Fields are preferred!

Modeling of the linear polarization image



We obtained four quantities and define “conservative” ranges to be compared with the model.

$$|m|_{\rm net} = \frac{\sqrt{\left(\sum_i Q_i\right)^2 + \left(\sum_i U_i\right)^2}}{\sum_i I_i}$$

“Net” frac. pol.

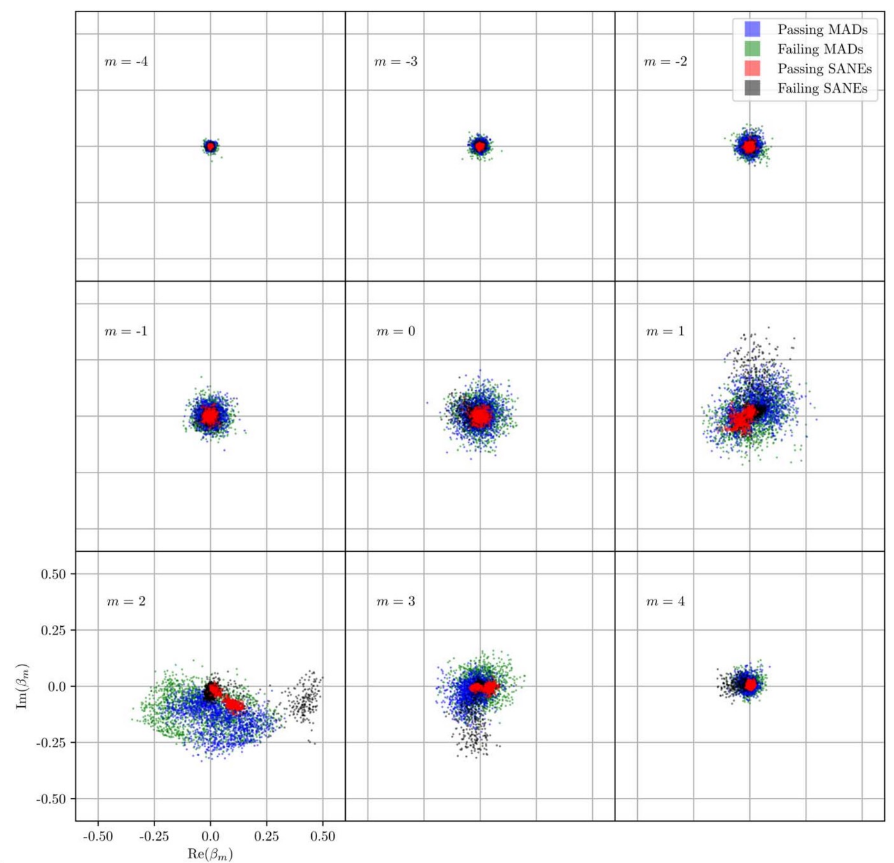
$$\langle |m| \rangle = \frac{\sum_i \sqrt{Q_i^2 + U_i^2}}{\sum_i I_i}$$

Intensity-weighted frac. pol.

$$\beta_2 = \frac{1}{I_{\rm ring}} \int_{\rho_{\rm min}}^{\rho_{\rm max}} \int_0^{2\pi} P(\rho,\, \varphi)\, e^{-2i\varphi}\, \rho d\varphi d\rho$$

m=2 mode of azimuthal decomposition of the polarized ring structure

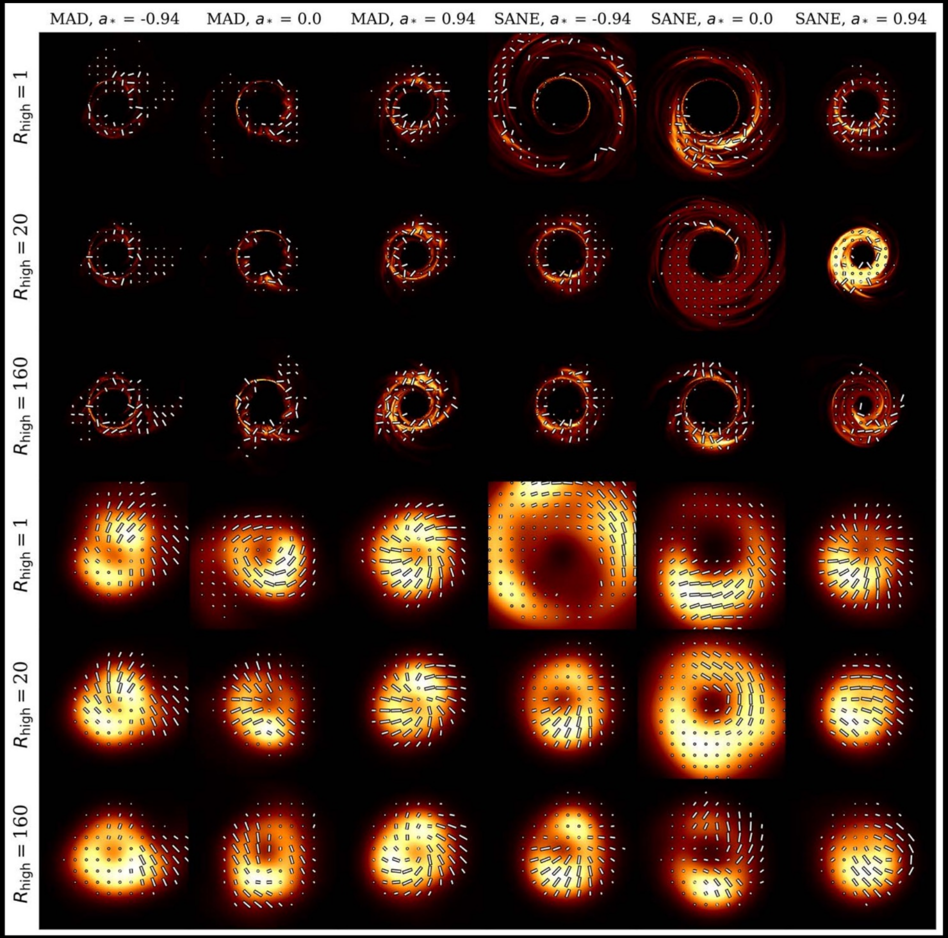
Modeling of the linear polarization image



Palumbo+ 2020

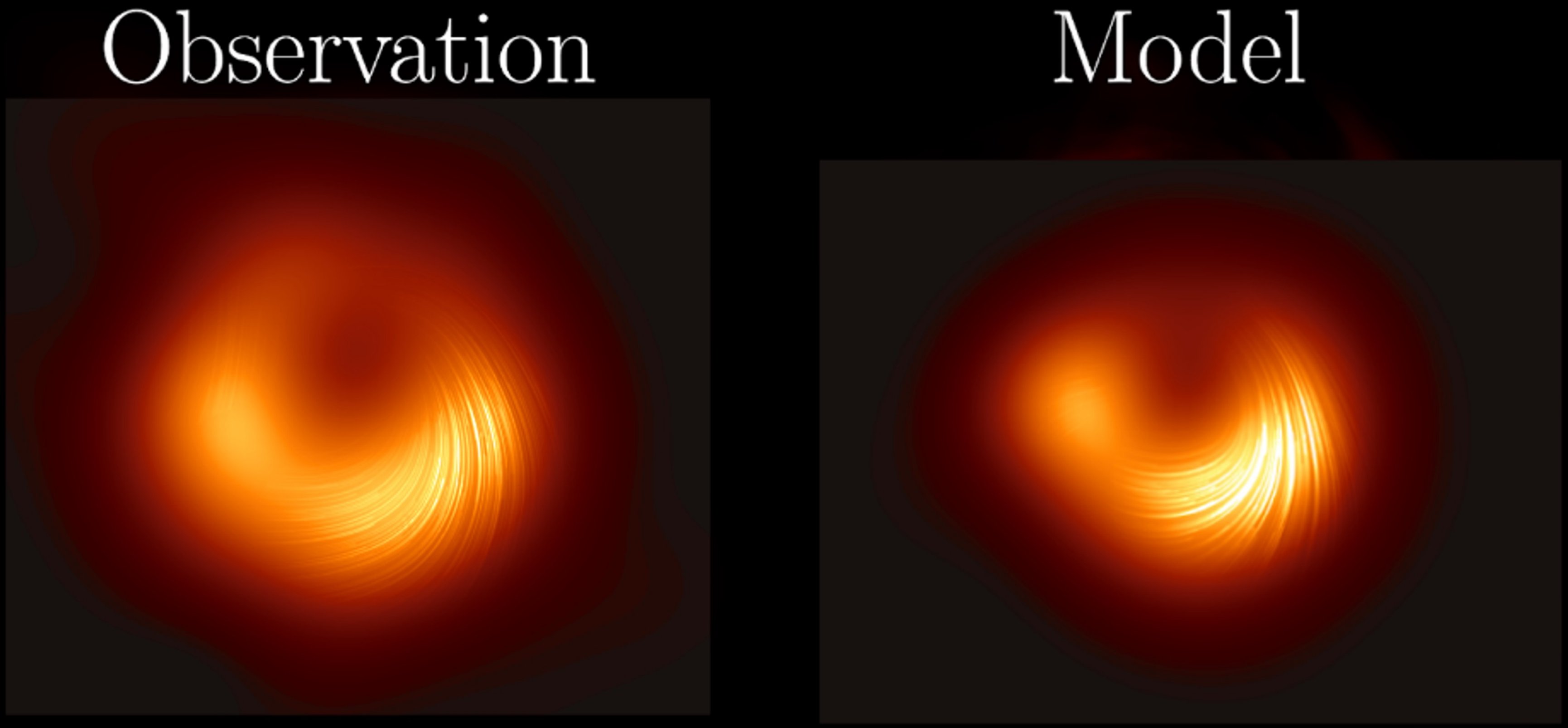
GRMHD simulations are most sensitive to the m=2 mode.

Modeling of the linear polarization image



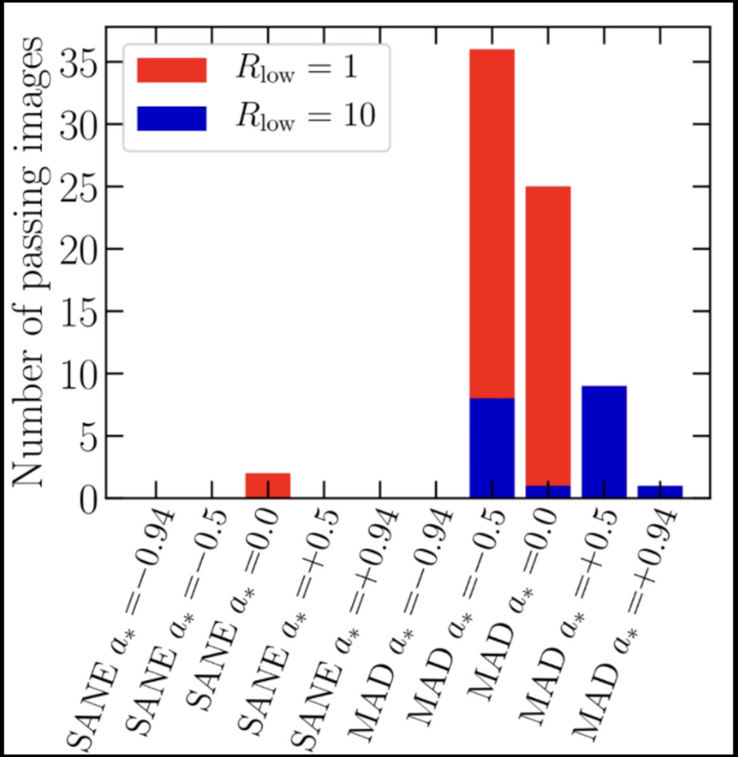
Including relativistic effects (space-time curvature, light bending), Faraday rotation/conversion effects, etc.

Modeling of the linear polarization image


Observation

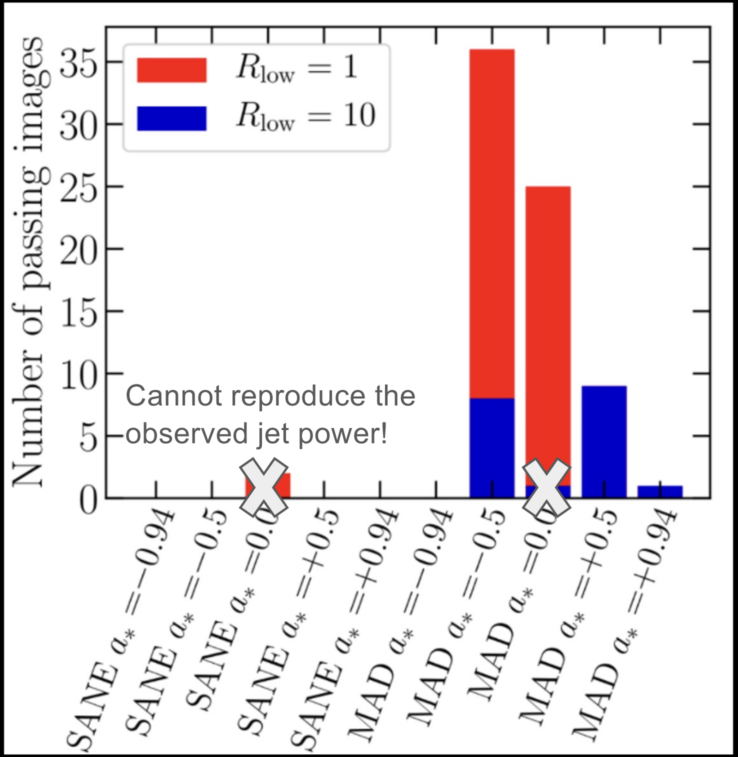
Model

Modeling of the linear polarization image



Nearly all SANE models are rejected because they could not easily reproduce the observed twisted polarization pattern and the relatively high (<~10%) fractional polarization.

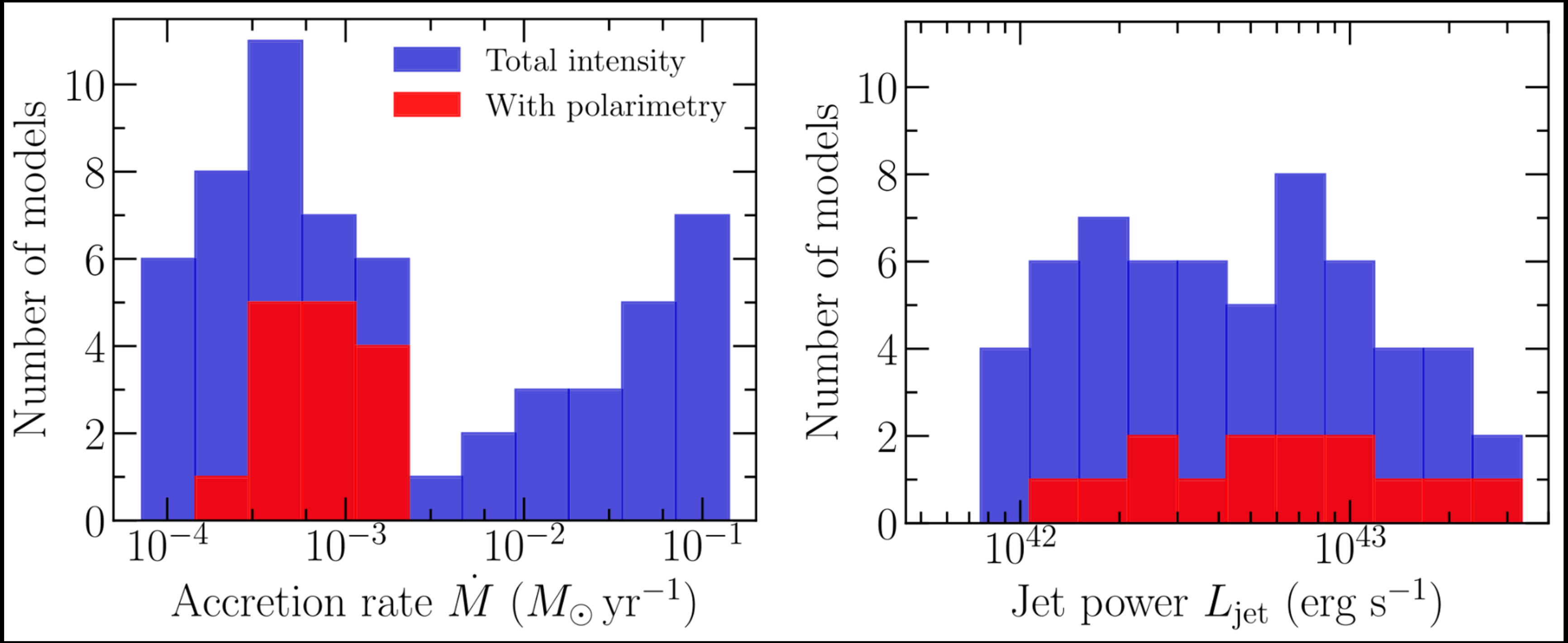
Modeling of the linear polarization image



Still degeneracy in $R_{\rm high}$

Nearly all SANE models are rejected because they could not easily reproduce the observed twisted polarization pattern and the relatively high (<~10%) fractional polarization.

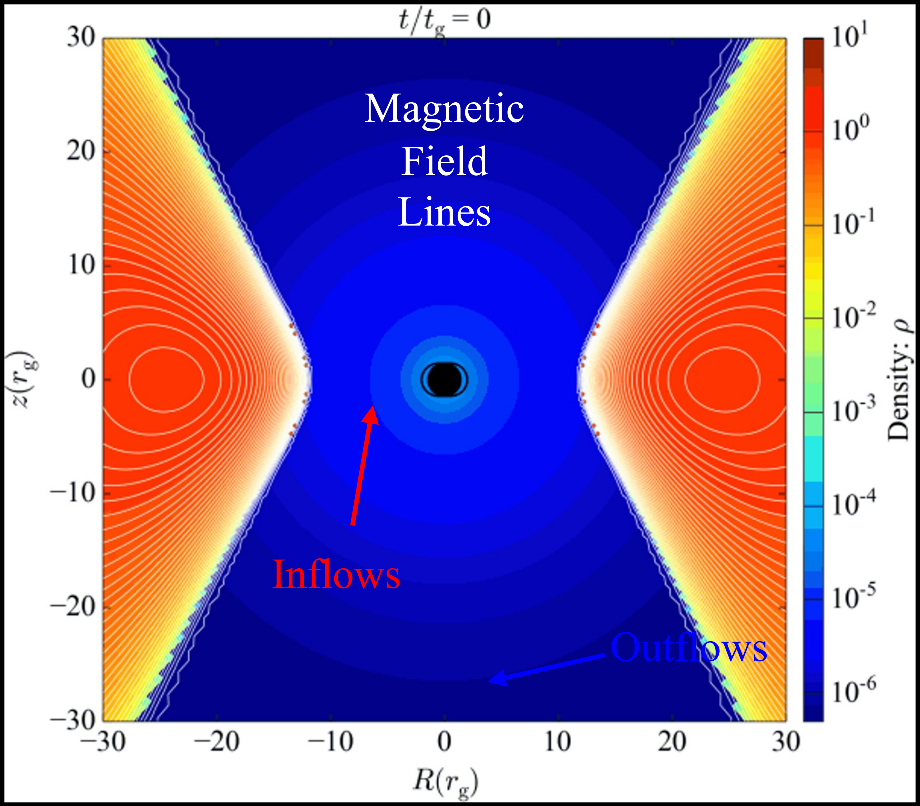
Modeling of the linear polarization image



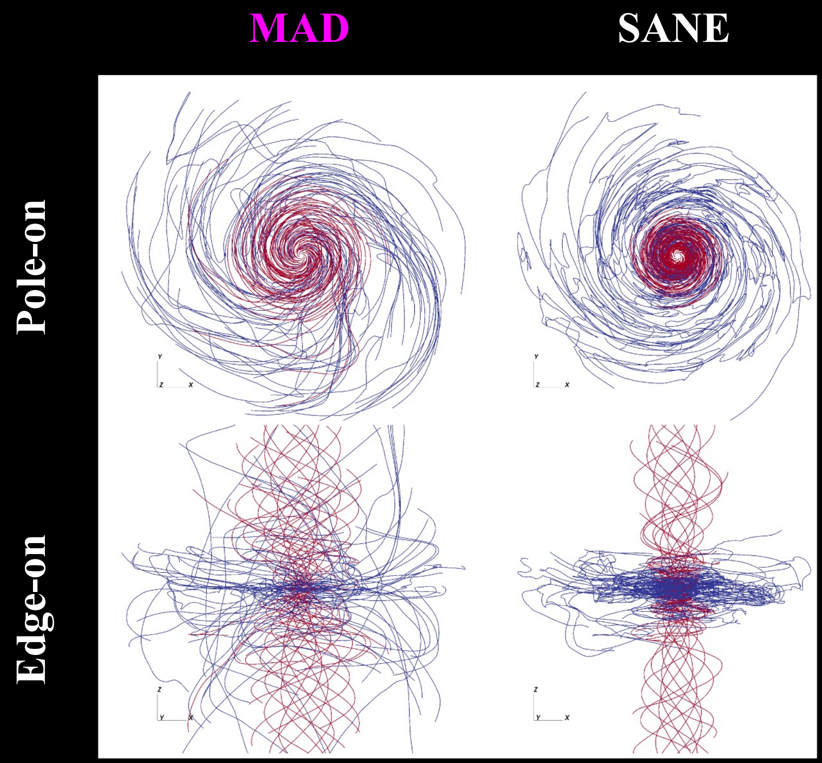
Polarimetry puts a stronger constraint on the physical quantities. The Bondi accretion rate for M87 is $\sim 0.1 M_\odot\ \mathrm{yr}^{-1}$ (Russell+2015). The black hole accretion rate is much smaller than this, which implies that a significant fraction of gas captured by the black hole’s gravity cannot reach the event horizon.

M87 is **MAD!**

Numerical simulation of Jet Formation (M. Nakamura)



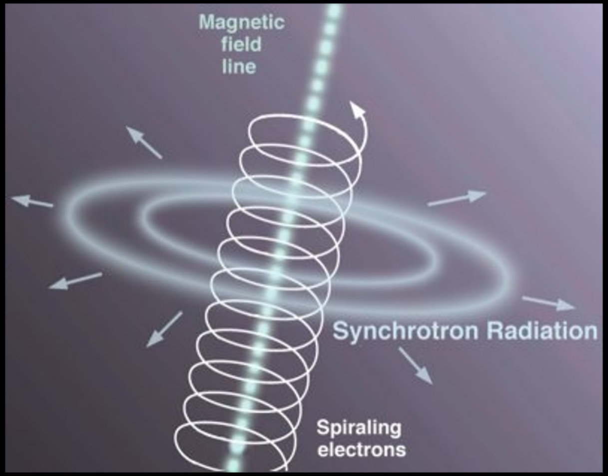
The data is consistent with the model that produces powerful jets due to the rotation of the black hole and strong, radial magnetic fields around the black hole.



Circular Polarization Observations of the M87* black hole

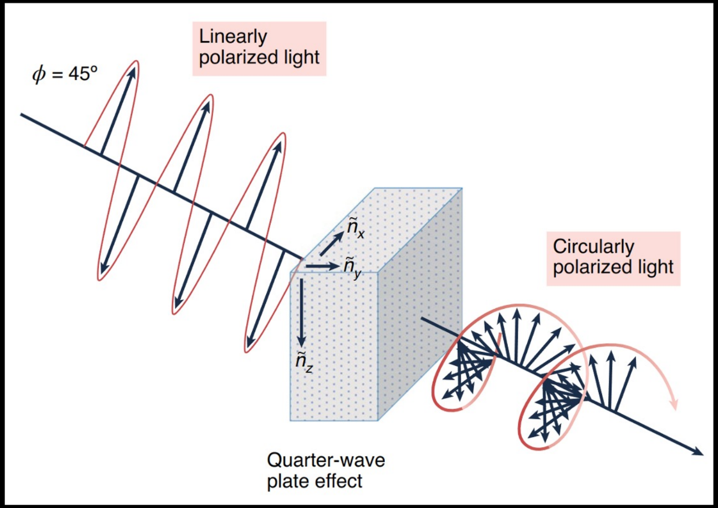
Mechanisms for producing Circular Polarization near the vicinity of the black hole

1. Intrinsic Circular Polarization



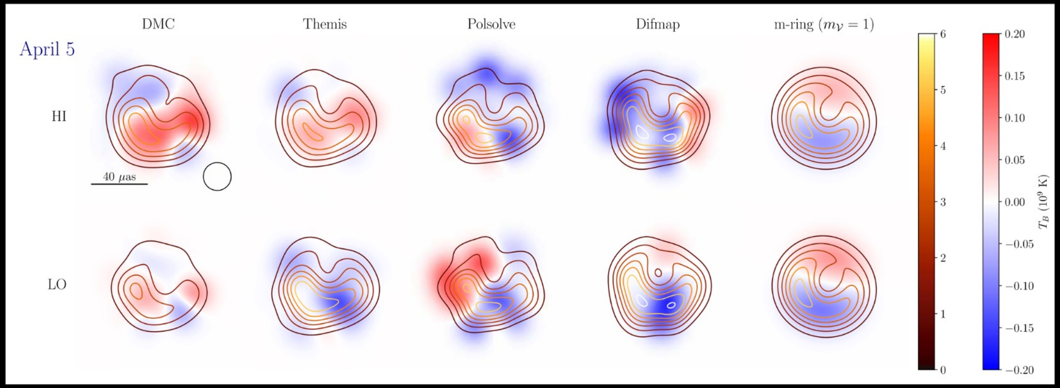
https://astronomyonline.org/Stars/SupernovaRemnant.asp

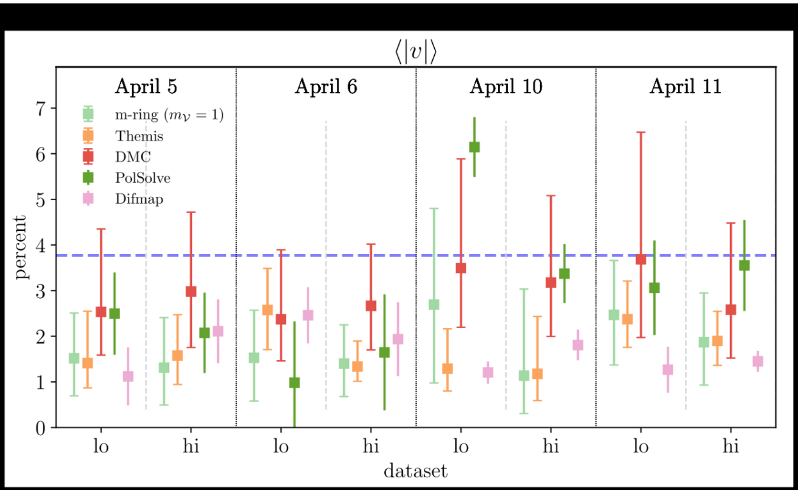
2. Faraday Conversion



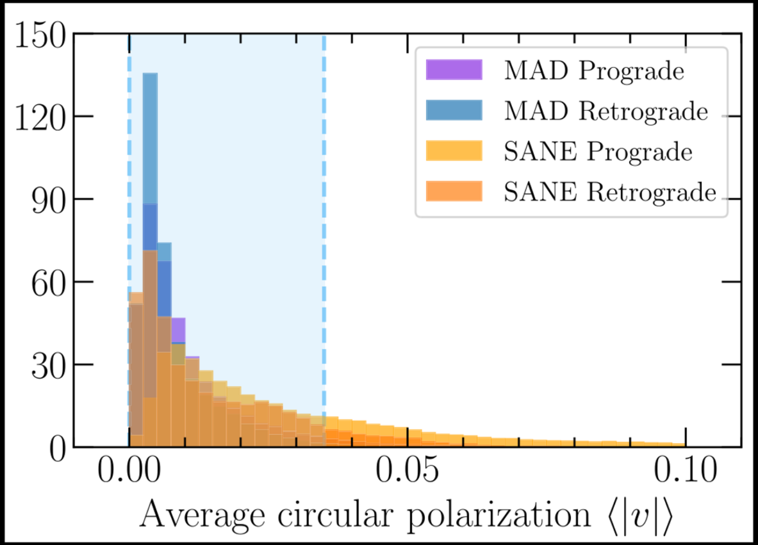
Sabatini & Lakhwani (2021)

Circular Polarization Observations of the M87* black hole



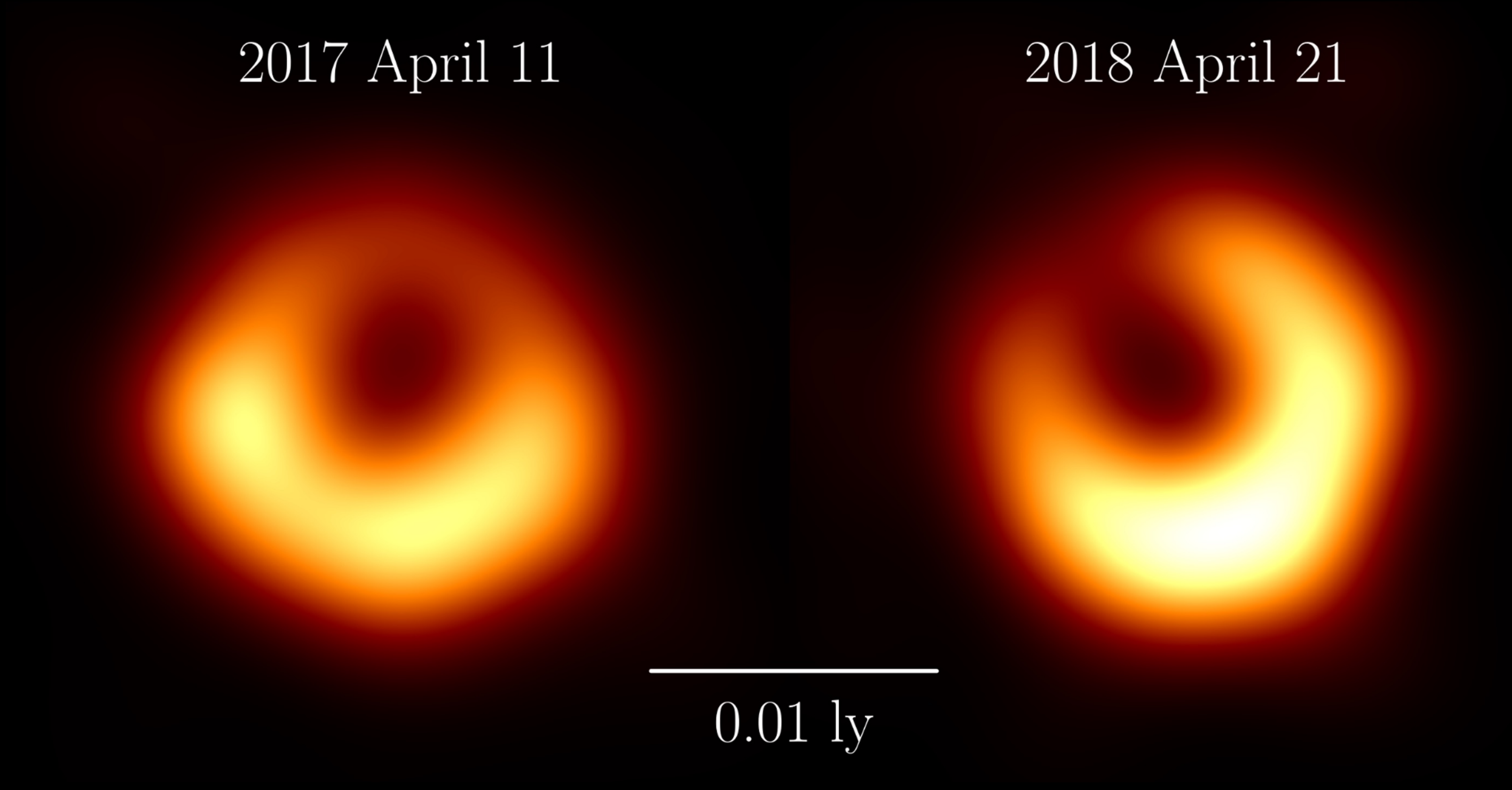


Observation: low levels of circular polarization



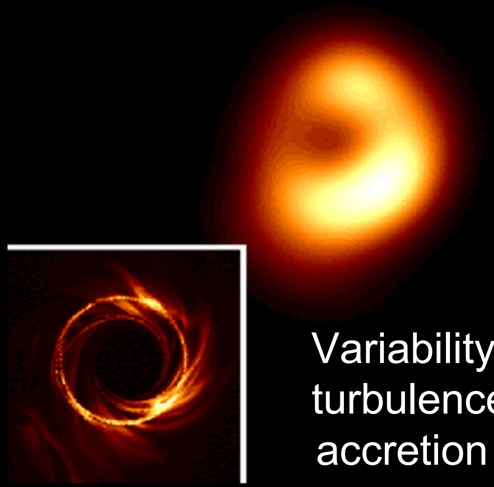
Theory: most models naturally exhibit low Stokes V emission due to the finite EHT beam.

Annual Evolution of the M87* Ring Structure

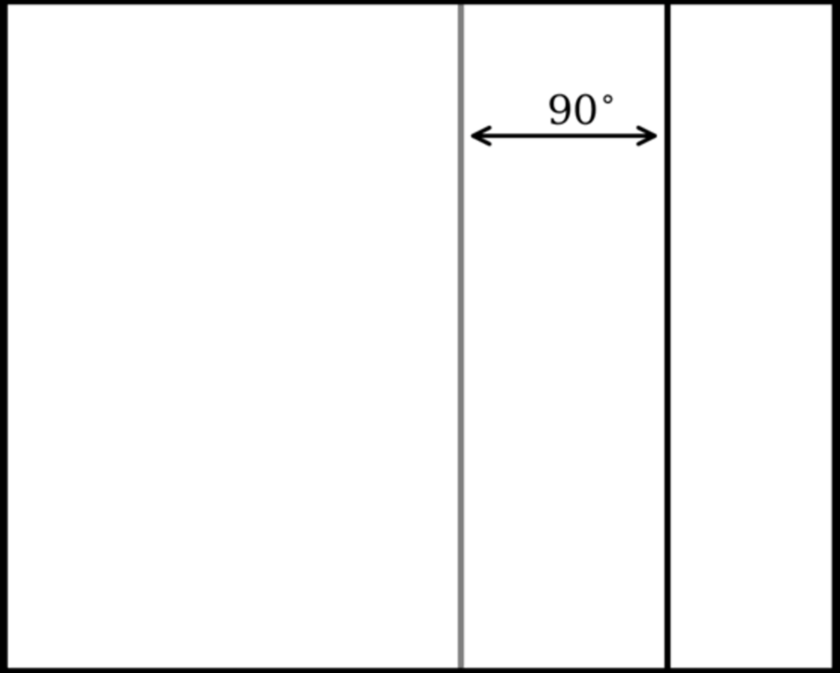


Annual Evolution of the M87* Ring Structure

Credit: Hung-Yi Pu (NTNU)

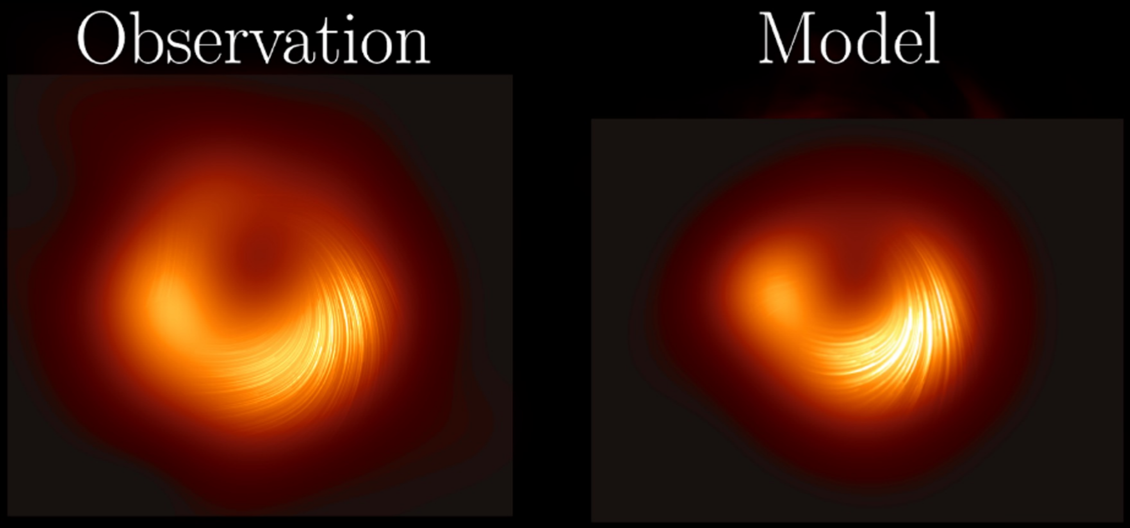


Variability due to turbulence in the accretion flows?



Our theory paper has just been accepted for publication in A&A. Please stay tuned for the press release!

Summary

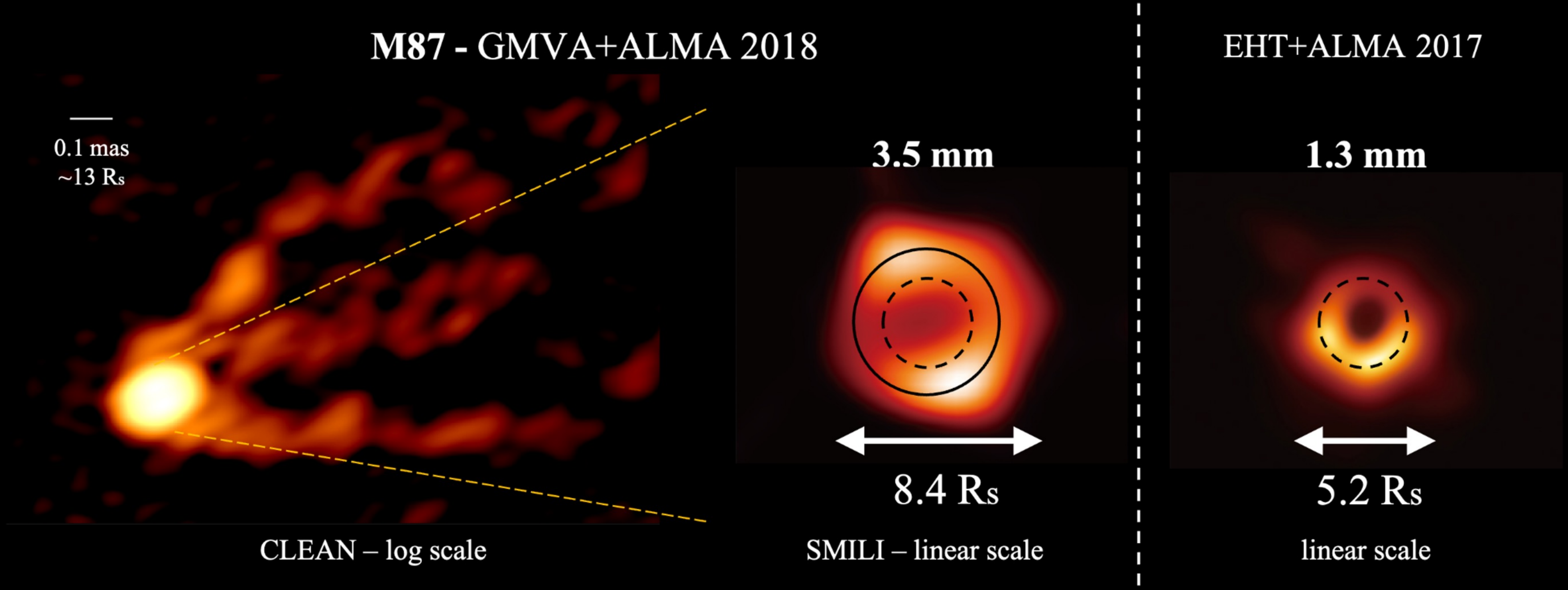

Observation

Model

The state-of-the-art GRMHD simulations + GRRT calculations enable us to directly compare the observed black hole images with the models. The conclusions derived from the modeling are:

- The black hole spin: The M87 black hole is highly likely spinning ($|\alpha| > 0$).
- The magnetic field configuration: M87 is highly likely MAD, surrounded by large-scale poloidal B fields.
- The electron-to-ion temperature ratio: is still very uncertain and not well understood.
  → Spectral Information could be a key to understand this physics.

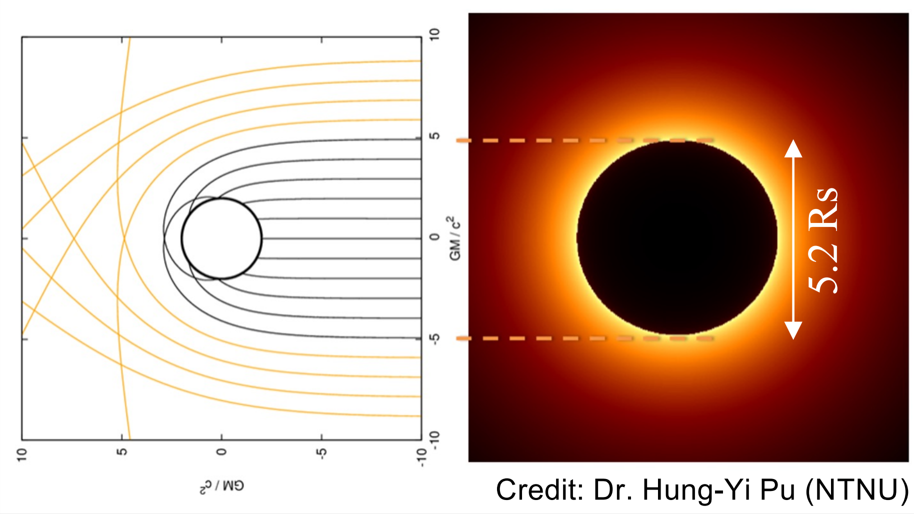
Observing the Supermassive Black Hole at the Center of M87 using GMVA+ALMA



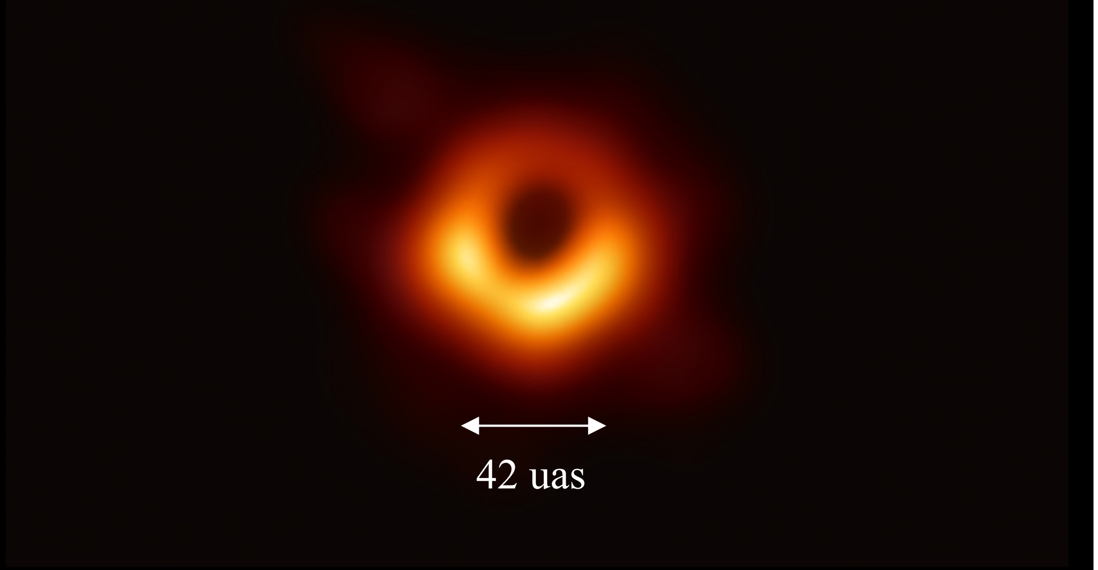
Jongho Park (Kyung Hee University) on behalf of
the EHT Collaboration and the GMVA-M87 Collaboration

"Photon Ring" and "Black Hole Shadow"

Black hole mass: 6.6e9 Msun (Gebhardt+ 2011)
Distance: 16.8 Mpc (Blakeslee+ 2009)
1 uas ~ 0.129 Rs
(42 ± 3) uas ~ (5.4 ± 0.3) Rs



Credit: Dr. Hung-Yi Pu (NTNU)



The observed ring-like structure is in good agreement with the prediction of GR.

What constitutes the observed ring-like structure?

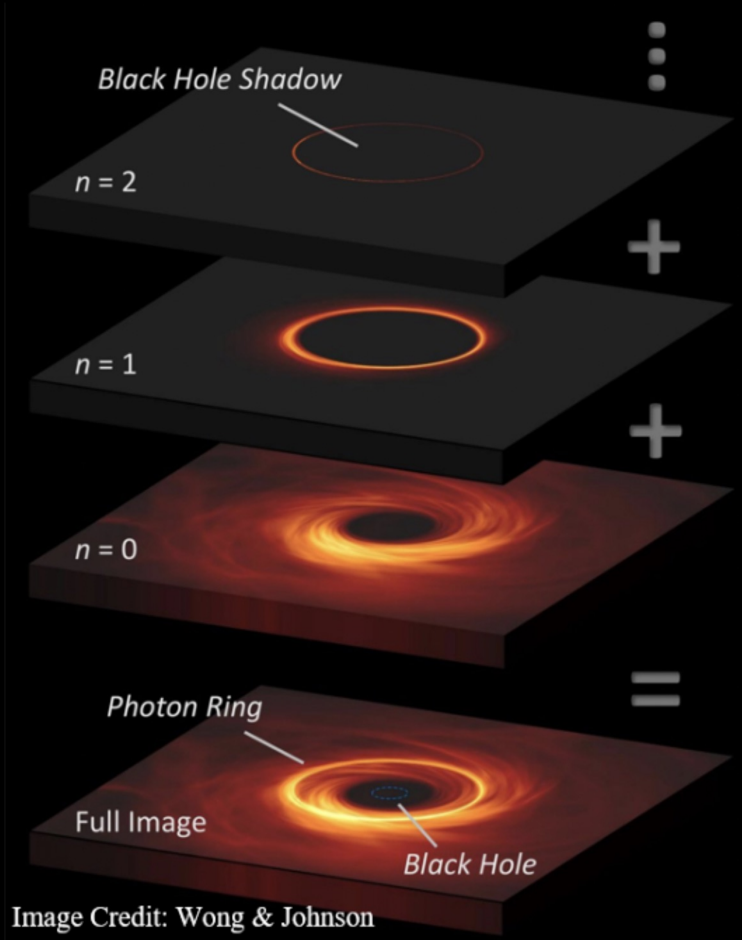
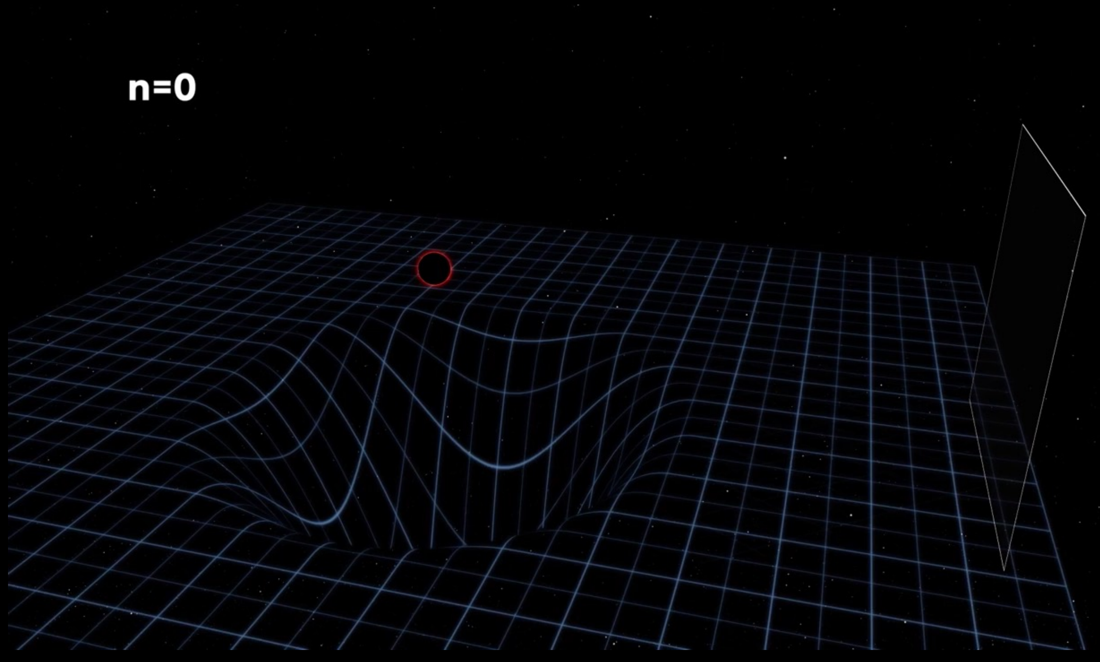


Image Credit: Wong & Johnson



Credit: the EHT collaboration

What constitutes the observed ring-like structure?

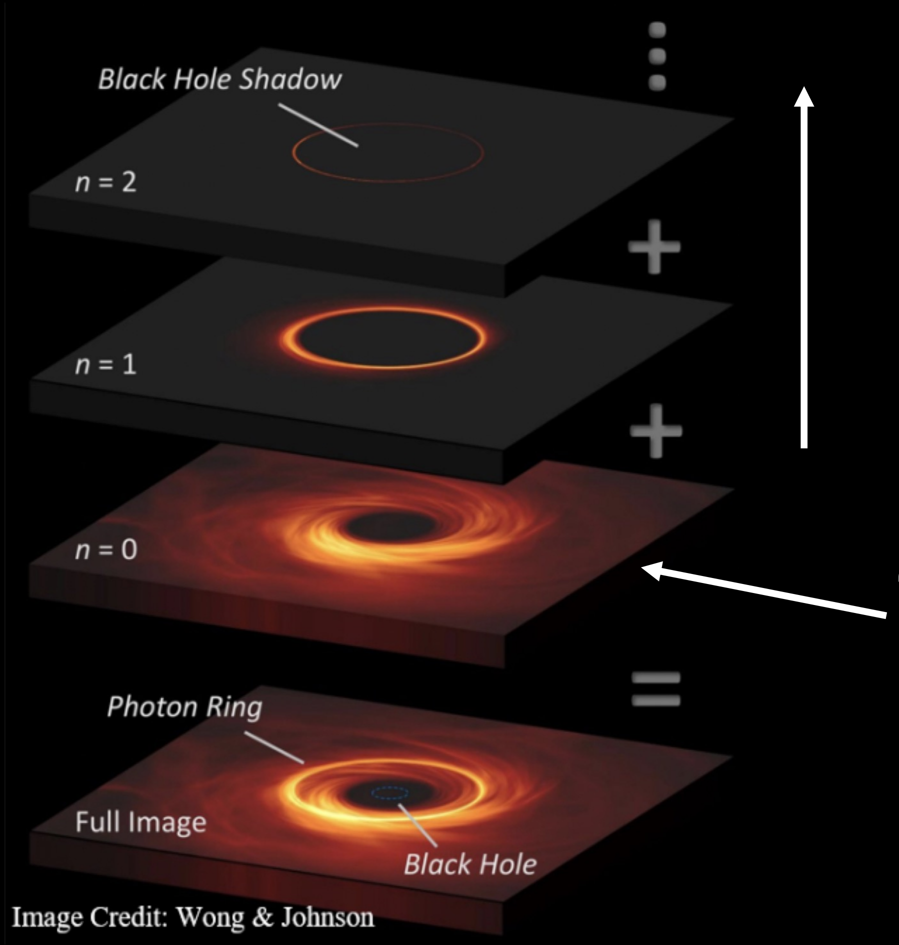


Image Credit: Wong & Johnson

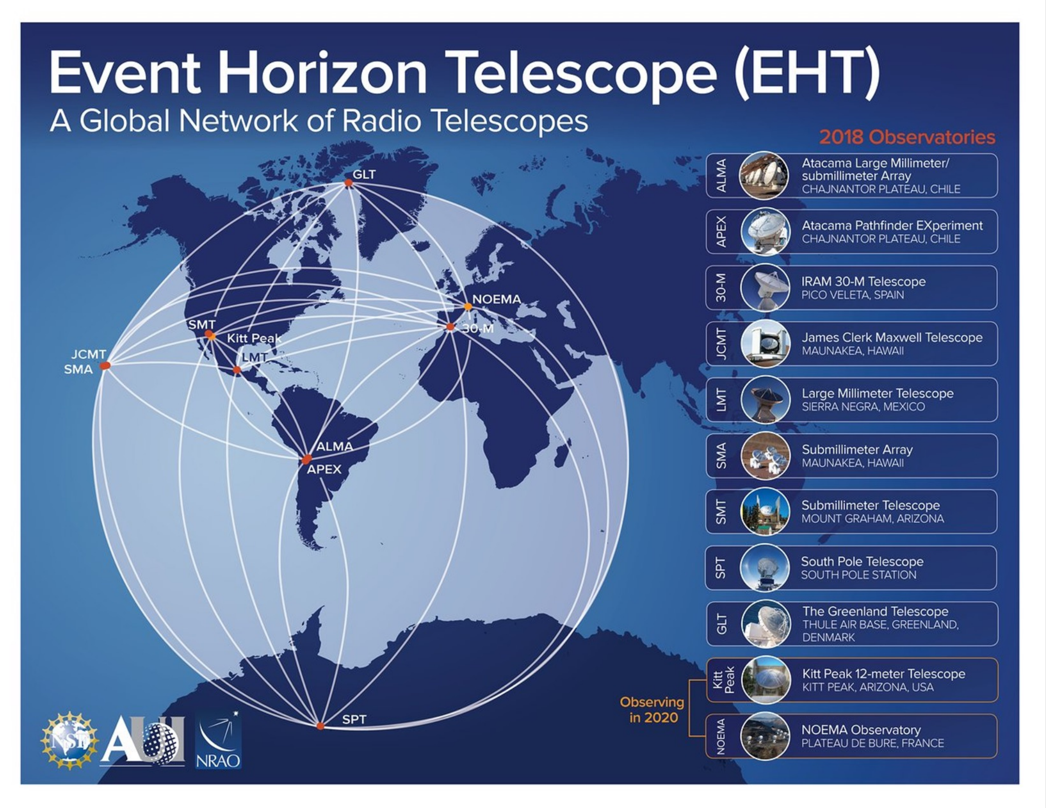
Photon Ring

“Gastrophysical” Ring (Accretion, Jet)

n = 0? n >= 1?

Credit: the EHT collaboration

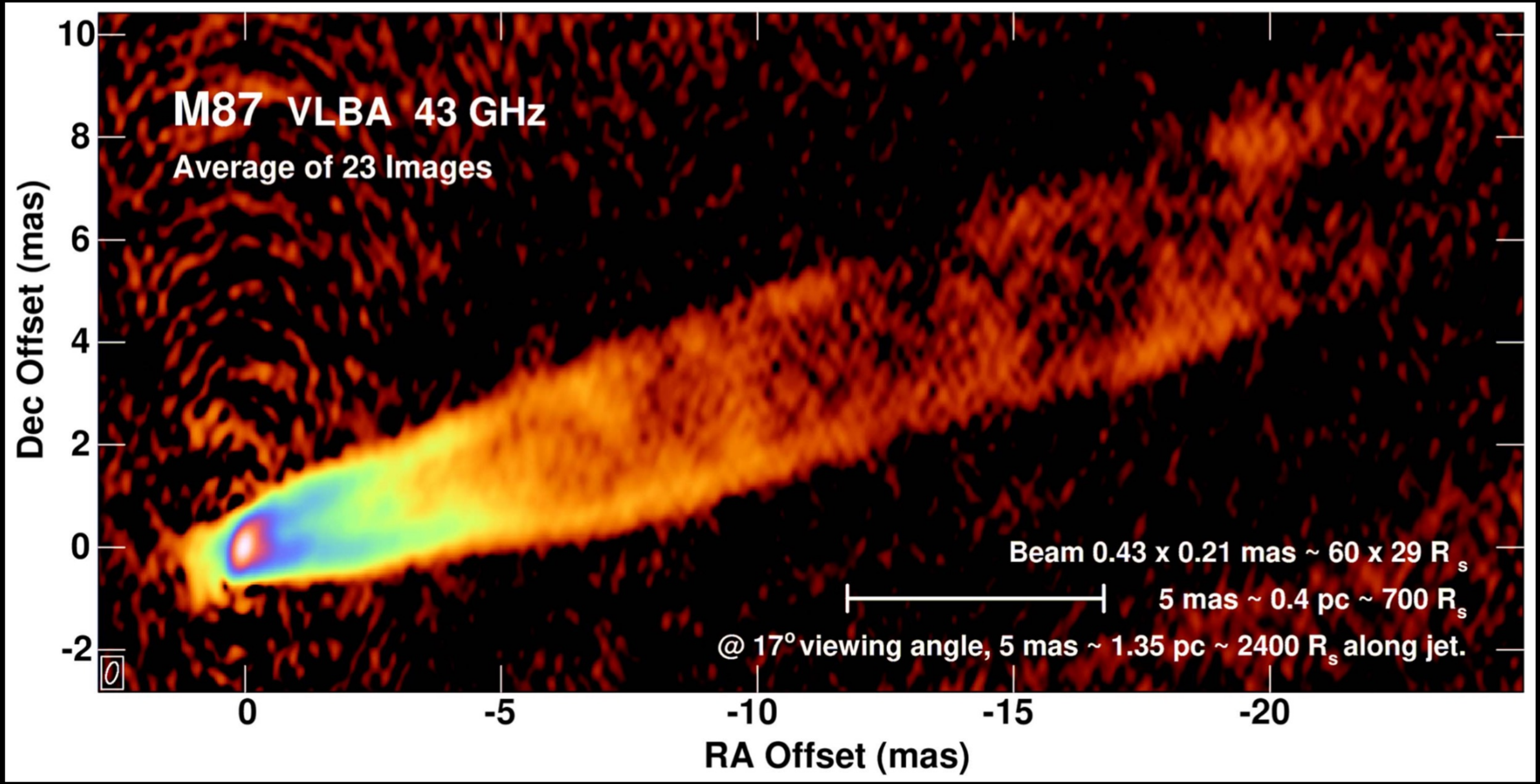
The Global Millimeter VLBI Array (GMVA) at 3.5 mm



EHT, 1.3 mm, Angular resolution: ~20 μas

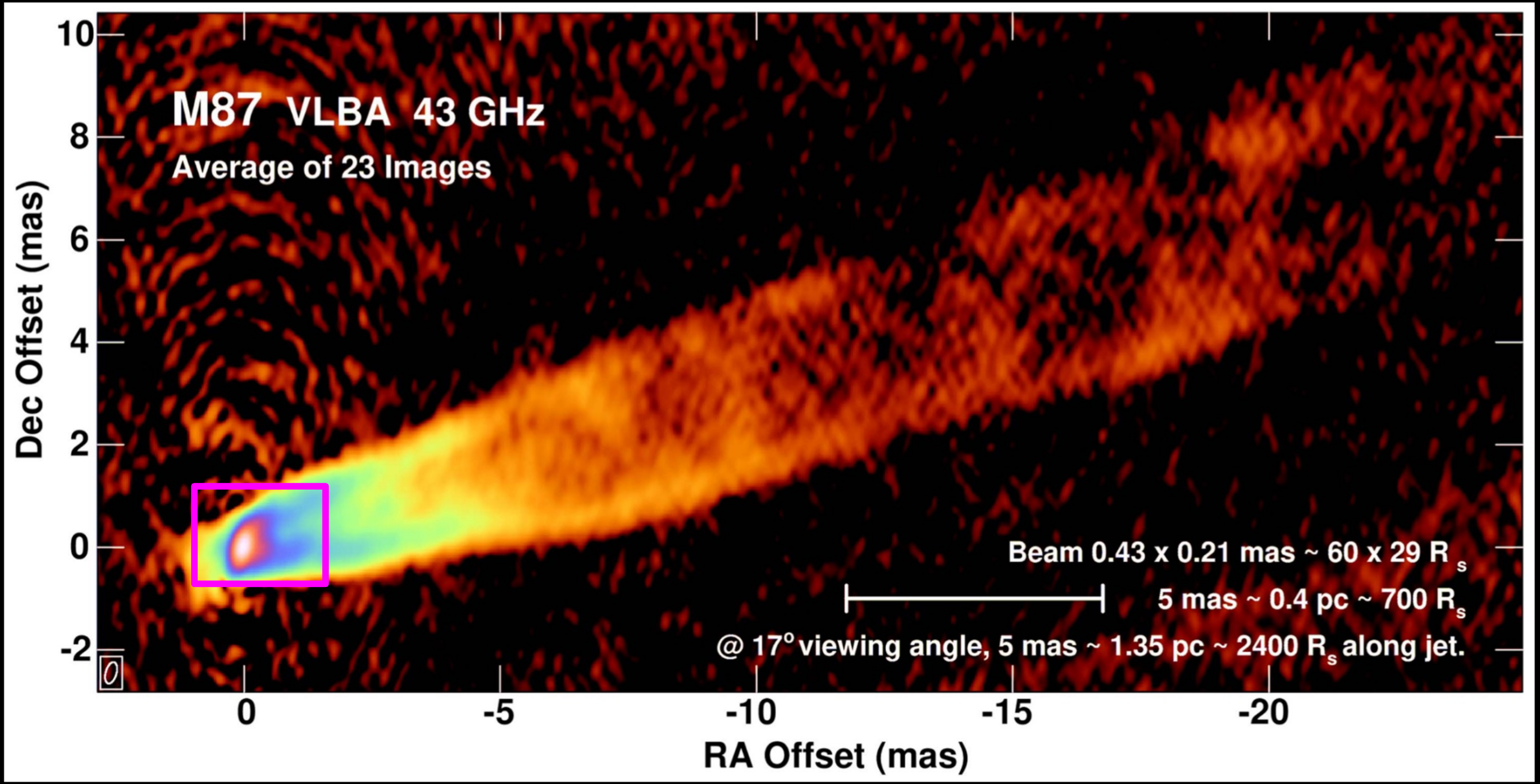
GMVA+ALMA, 3 mm, Angular resolution: ~40 μas

The Global Millimeter VLBI Array (GMVA) at 3.5 mm



Walker et al. (2018)

The Global Millimeter VLBI Array (GMVA) at 3.5 mm



Walker et al. (2018)

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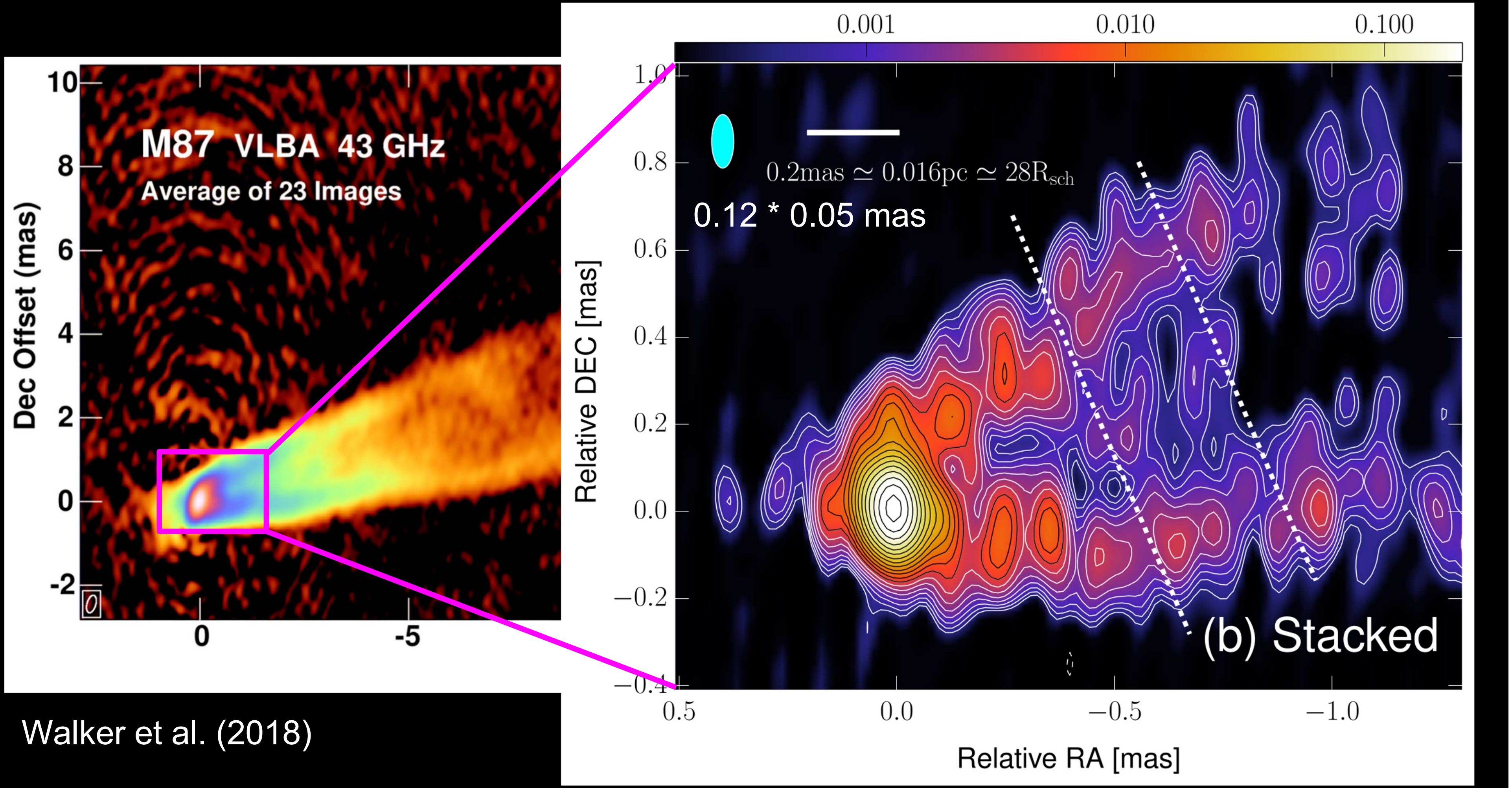
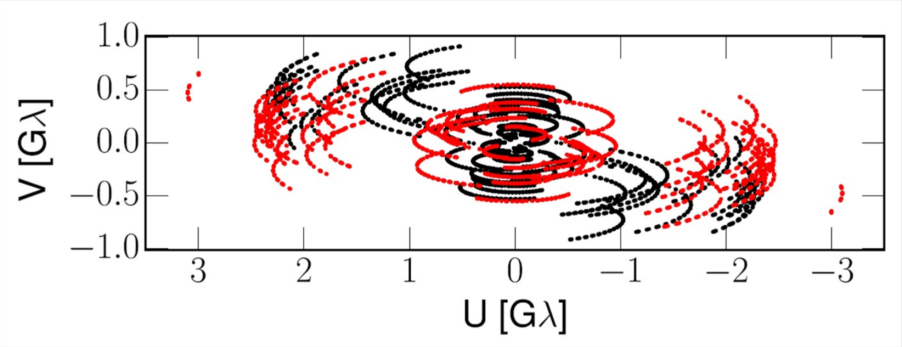


Walker et al. (2018)

GMVA 86 GHz Kim et al. (2018)

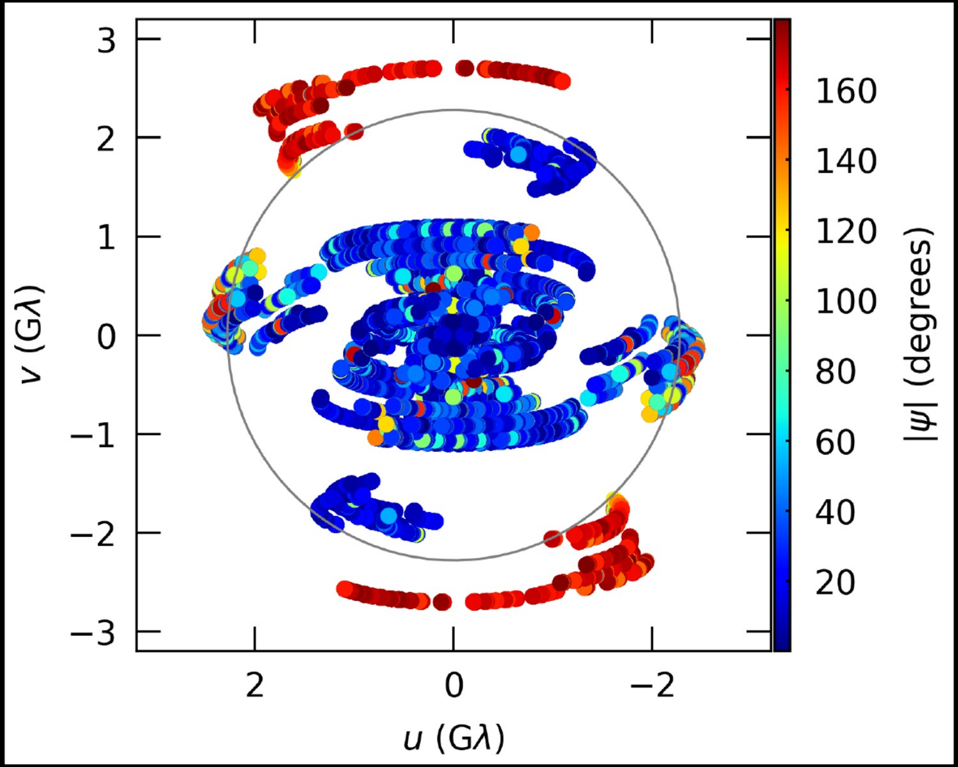
The Global Millimeter VLBI Array (GMVA) at 3.5 mm

GMVA



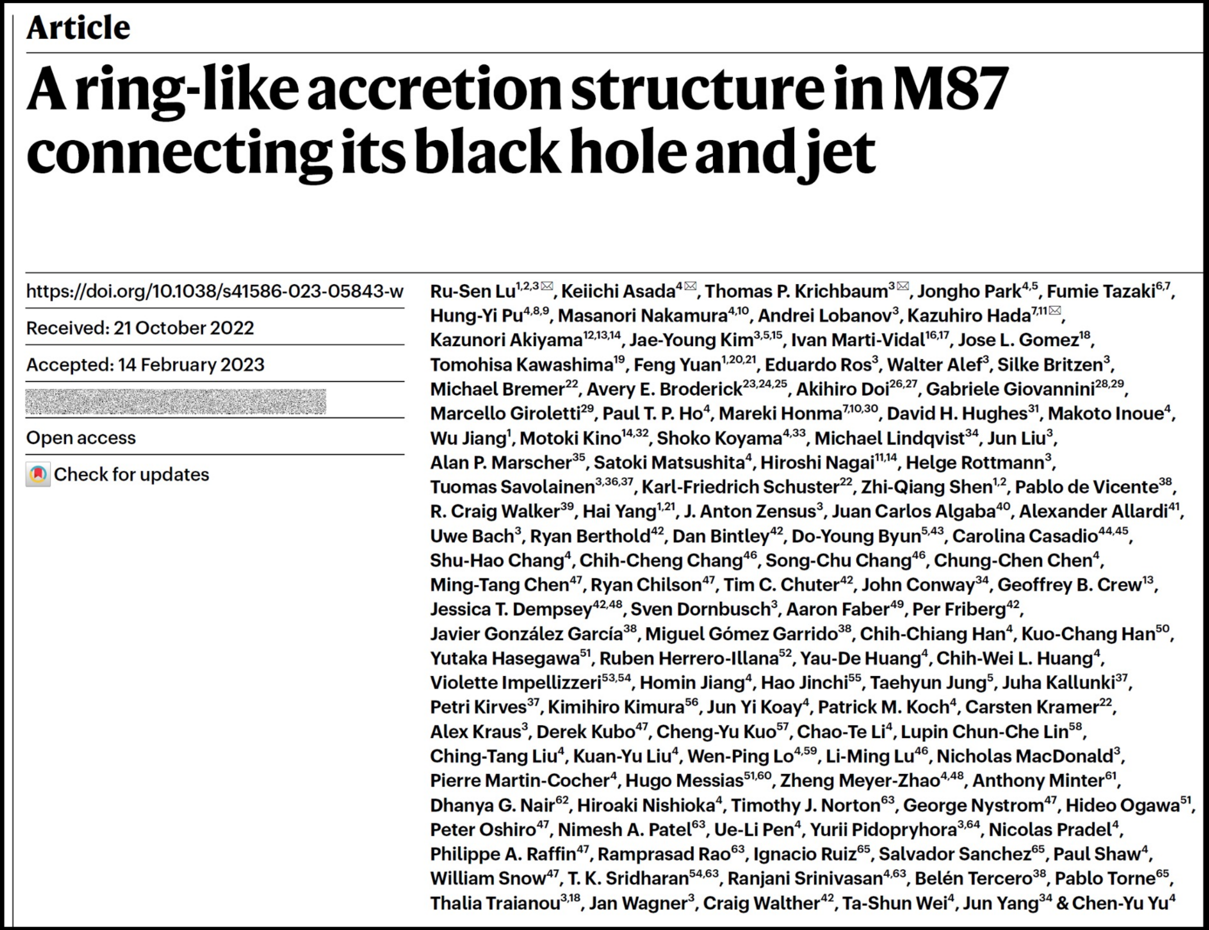
Kim et al. (2018)

GMVA+ALMA+GLT



- The longest baselines determine the angular resolution.
- The (u,v) coverage determines the image fidelity.

GMVA+ALMA+GLT observation of M87 in 2018



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경희대학교 박종호

UNIST 김재영

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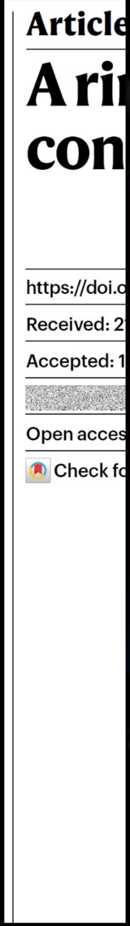

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인터스텔라(영화)에서 나온 것과 같은 거라고 생각하시면 될 거 같습니다.

nearly

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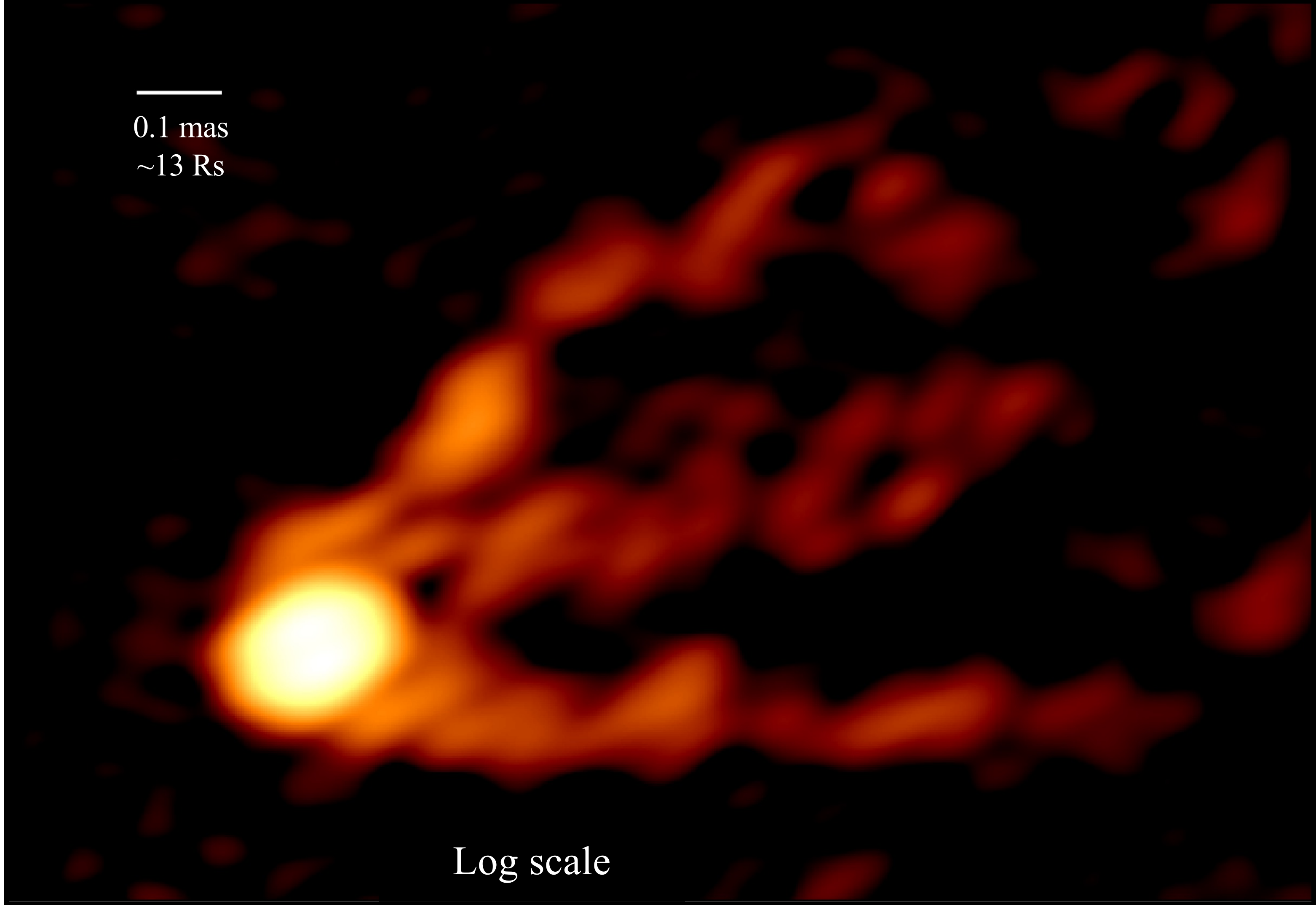
orea,

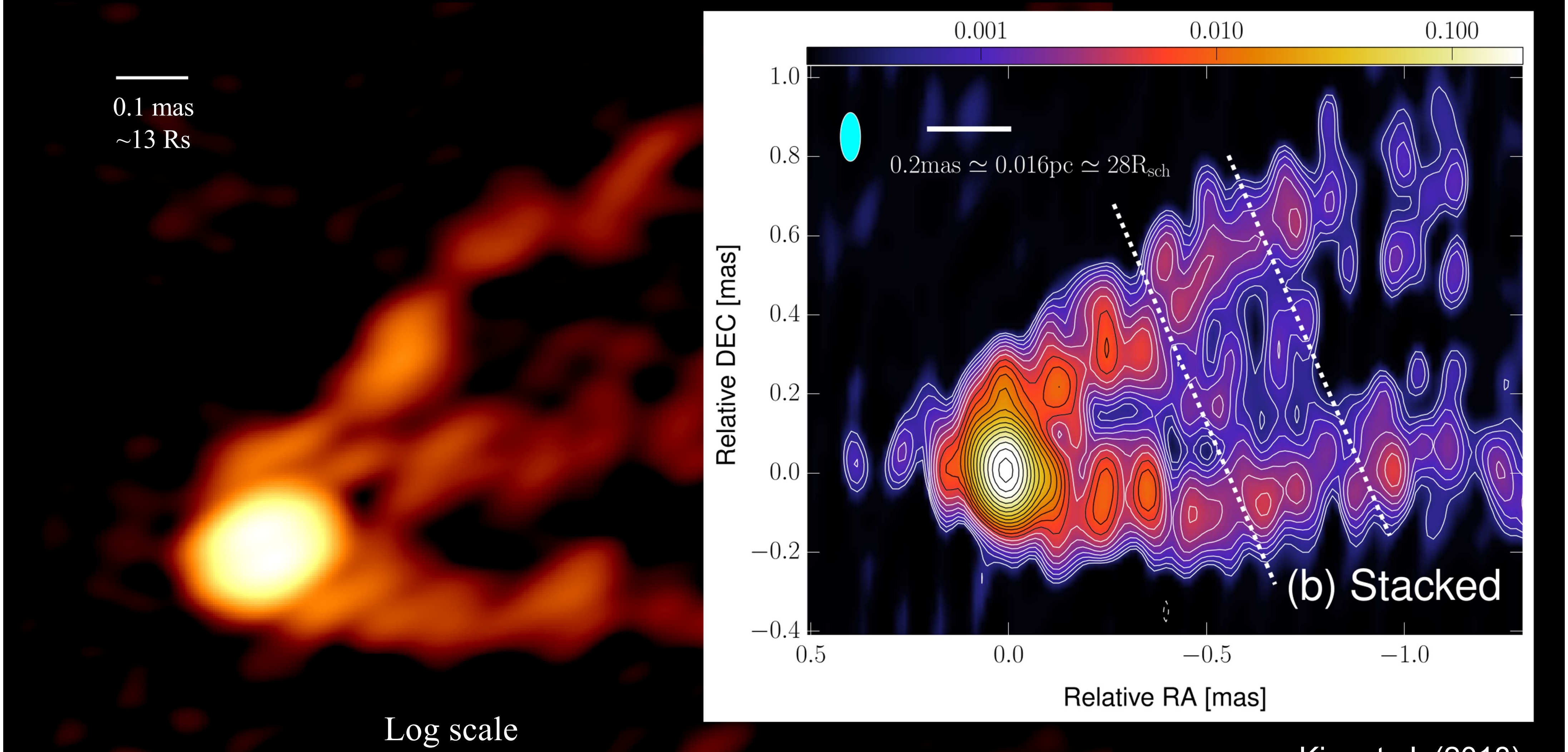
김재

Publis

GMVA+ALMA+GLT observation of M87 in 2018

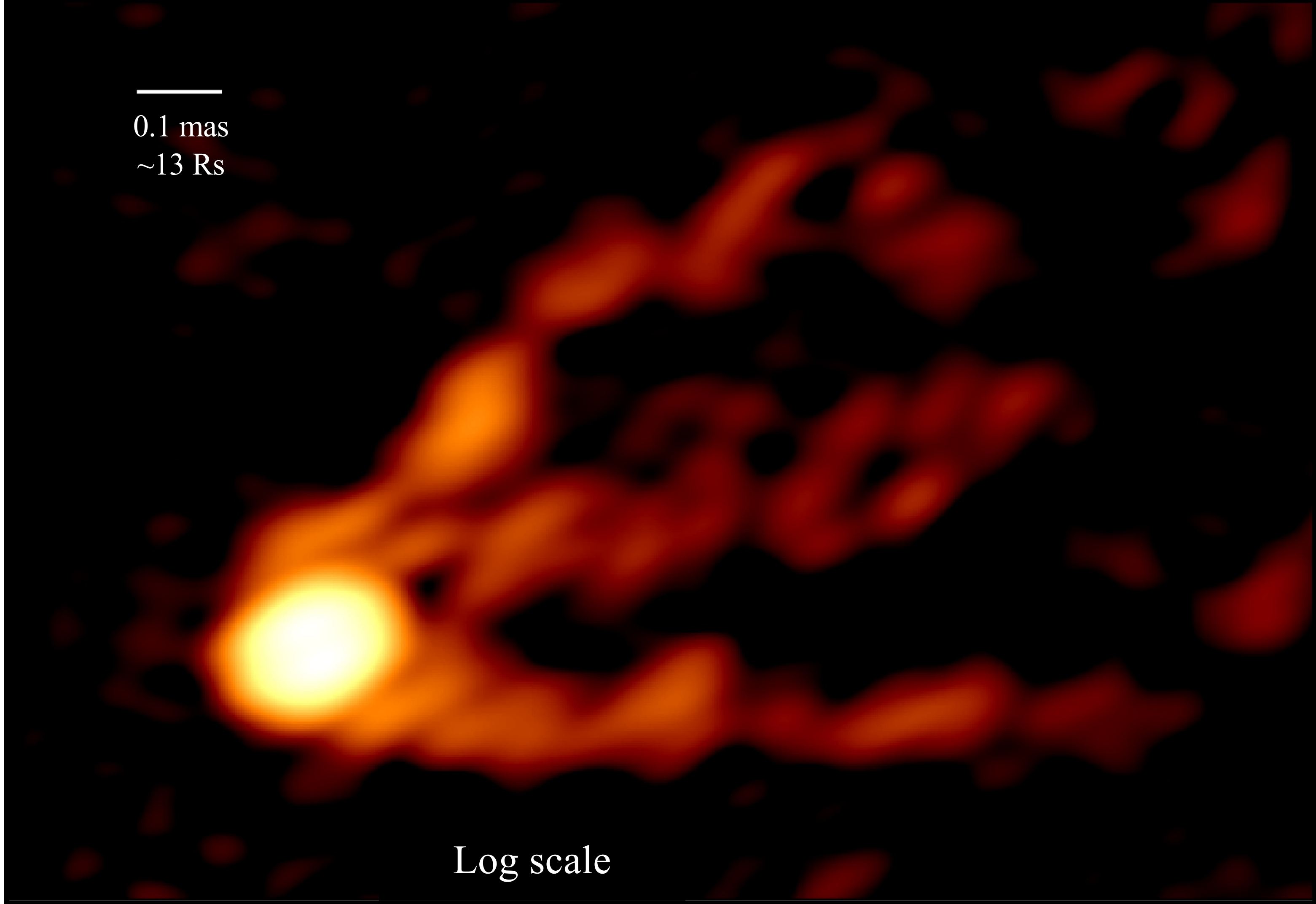


GMVA+ALMA+GLT observation of M87 in 2018



Kim et al. (2018)

GMVA+ALMA+GLT observation of M87 in 2018



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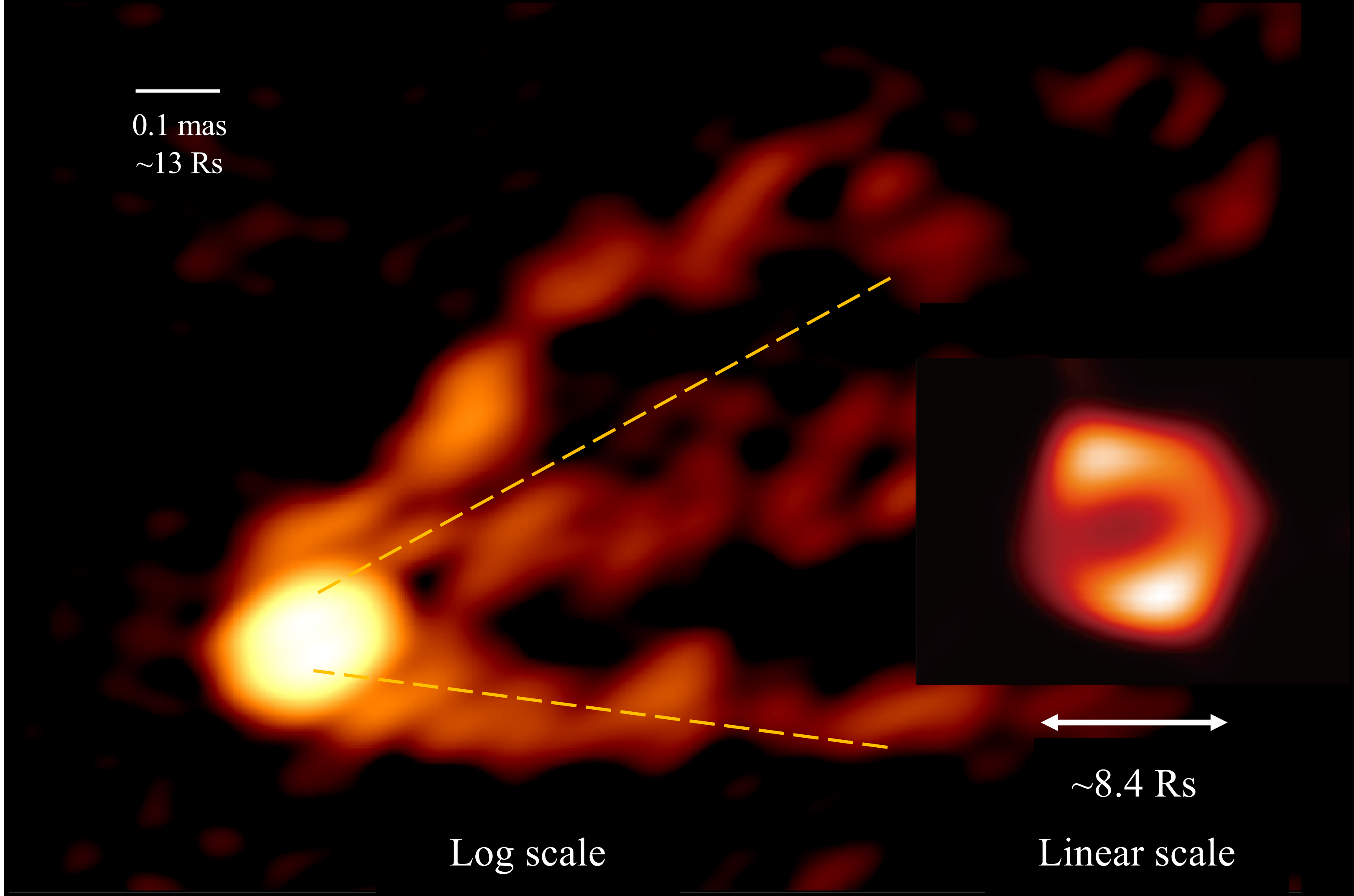
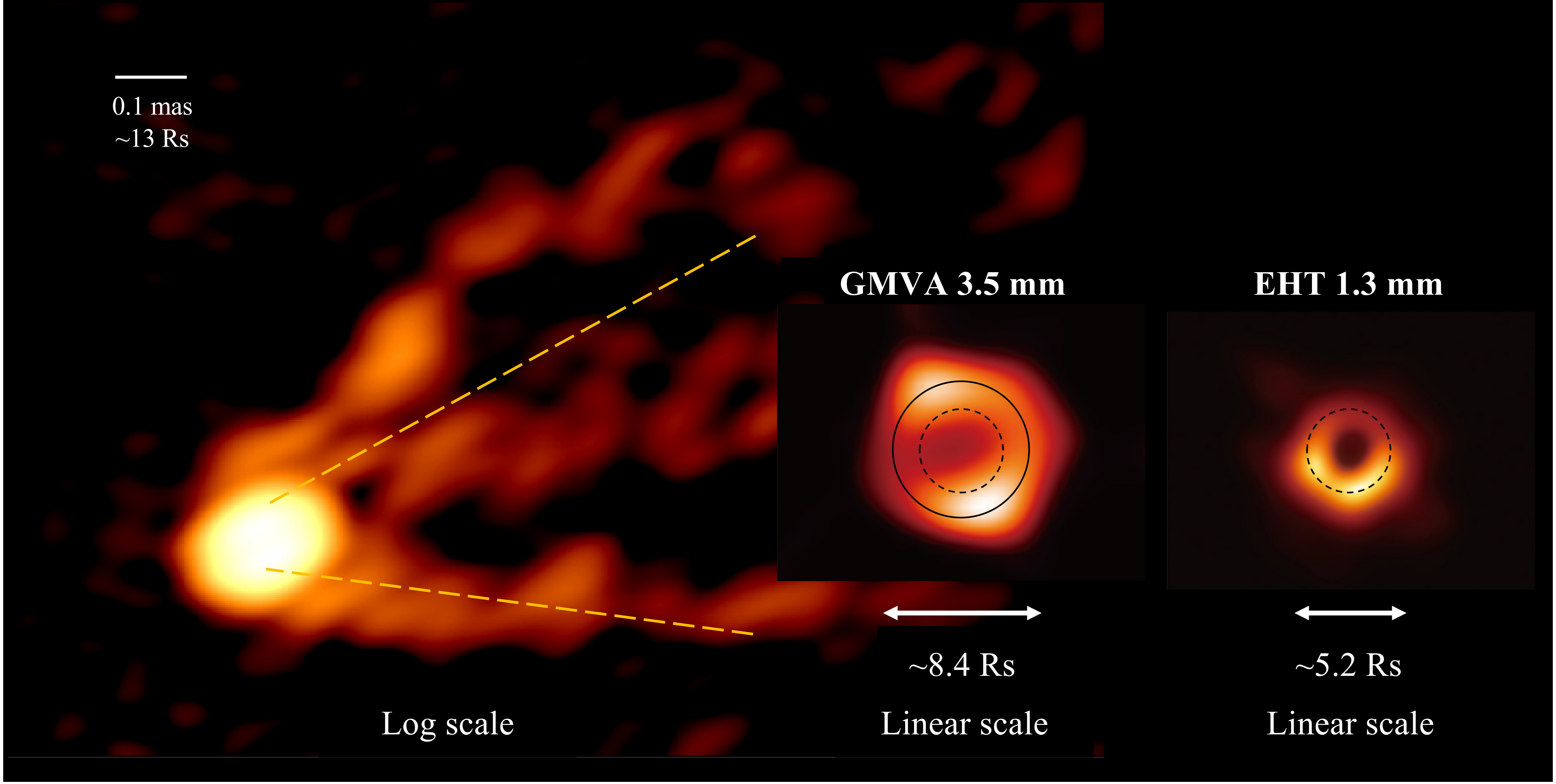
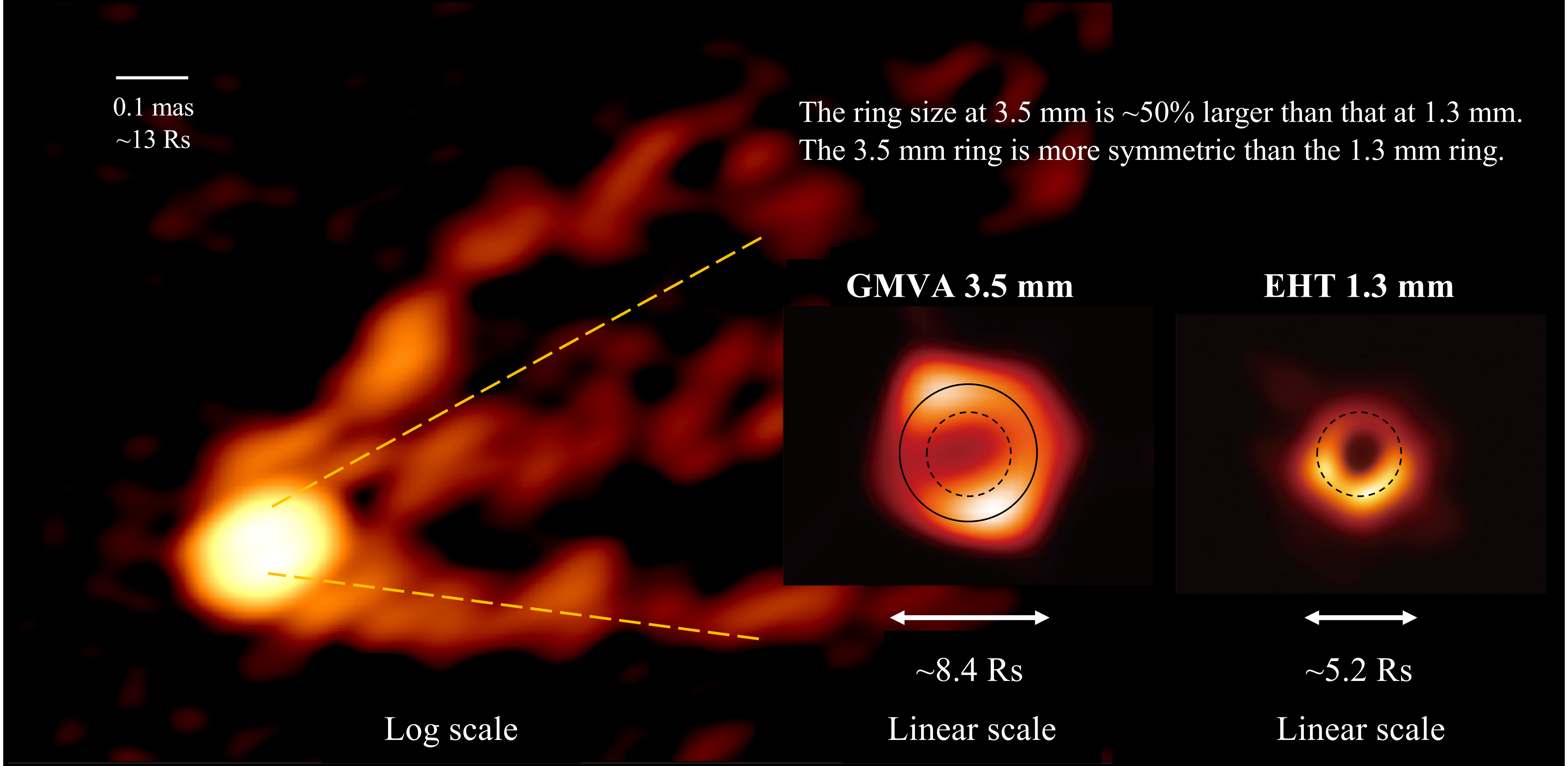


GMVA+ALMA+GLT observation of M87 in 2018

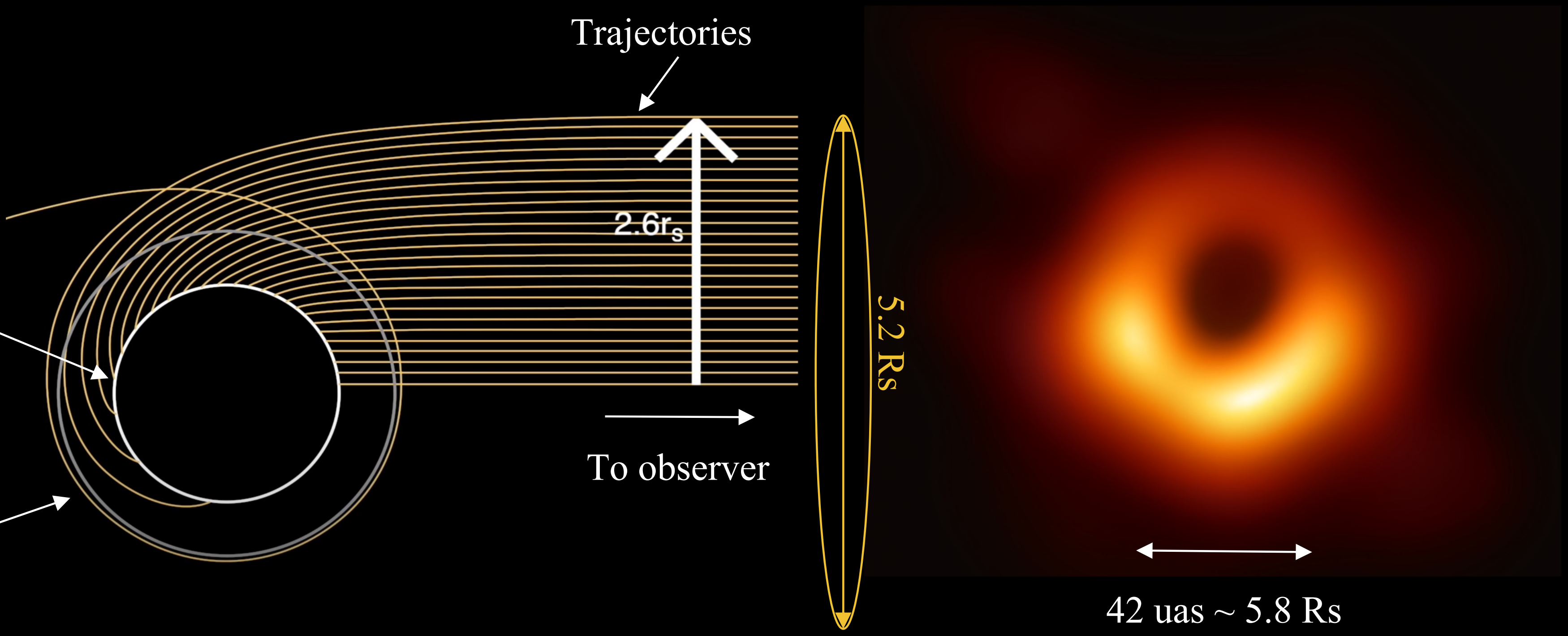


GMVA+ALMA+GLT observation of M87 in 2018



The ring size at 3.5 mm is ~50% larger than that at 1.3 mm.
The 3.5 mm ring is more symmetric than the 1.3 mm ring.

“Photon ring” and “Black Hole Shadow”



Photon Trajectories

Event Horizon

Innermost stable circular orbit for photons

$2.6r_s$

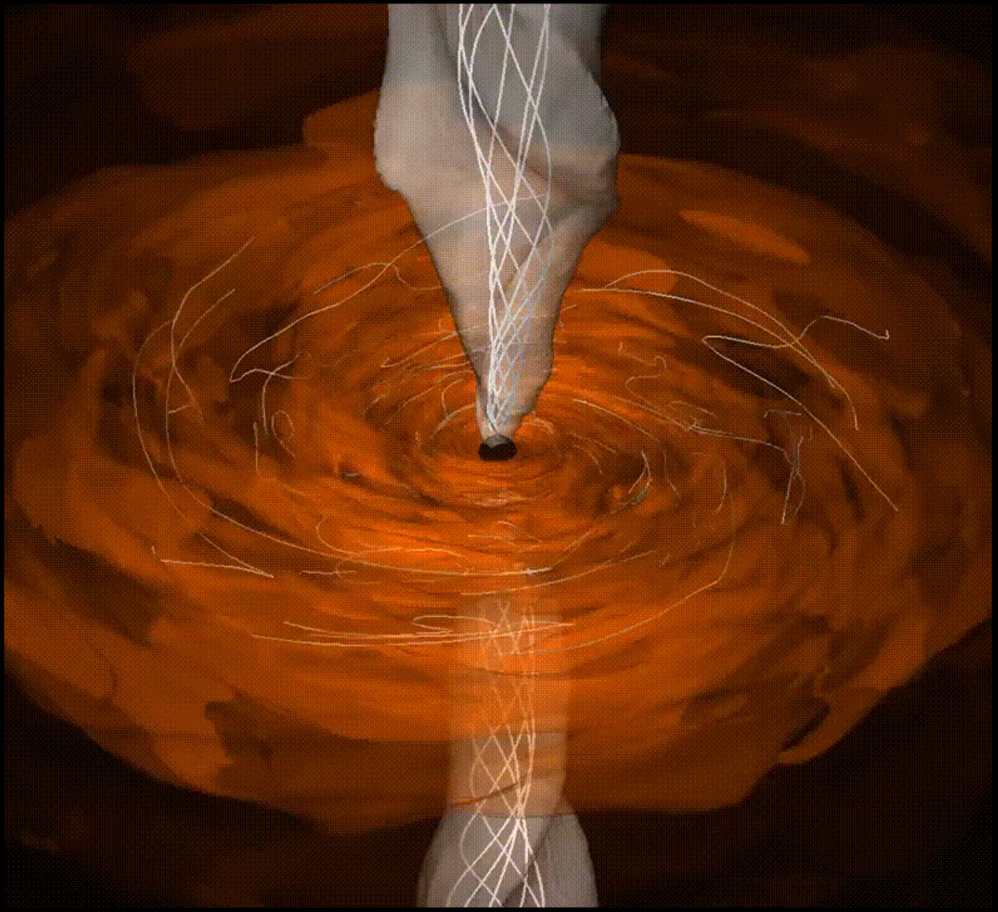
To observer

5.2 Rs

“Photon Ring”

42 uas ~ 5.8 Rs

What constitutes the observed ring-like structure?



Credit: Shiokawa

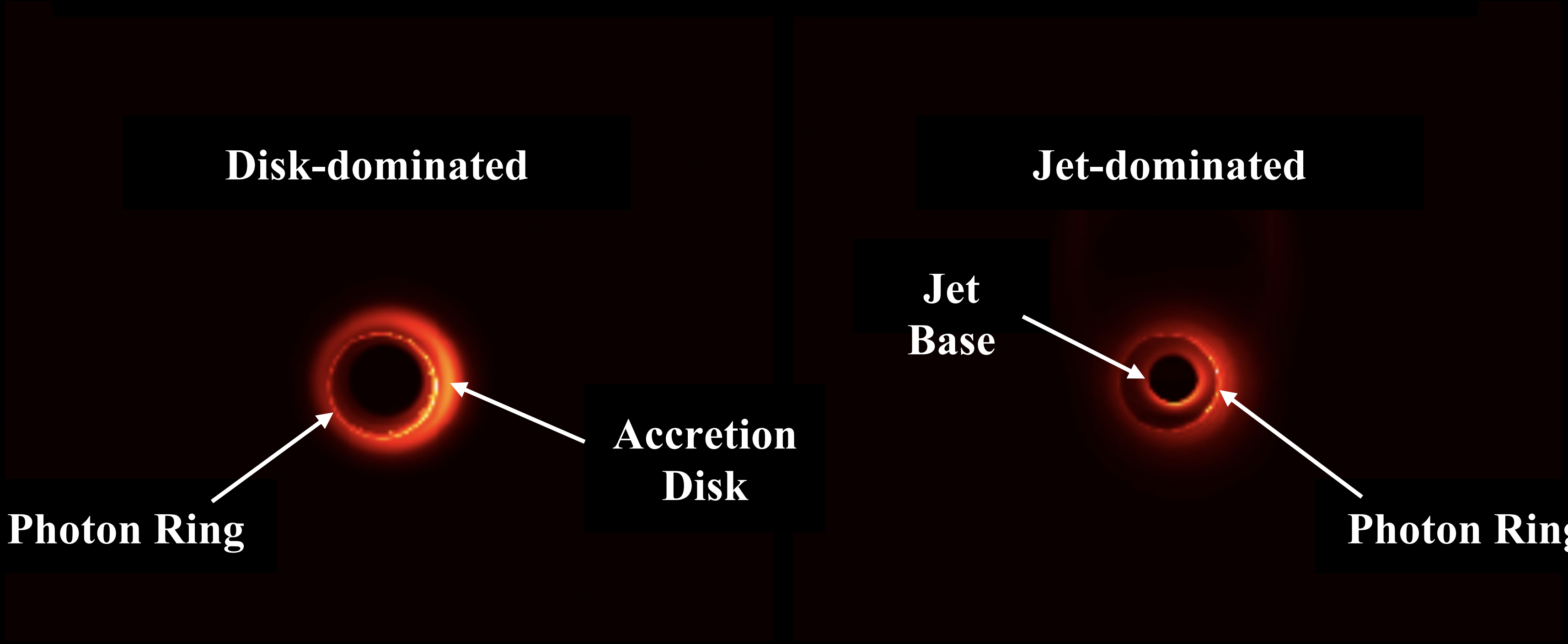
The ring-like structure is believed to originate from synchrotron emission in the plasma around the black hole.

- Accretion Flows (thermal synchrotron)
- Jets (Nonthermal synchrotron)
- Photon capture at the Event Horizon (geometric effect)

What constitutes the observed ring-like structure?

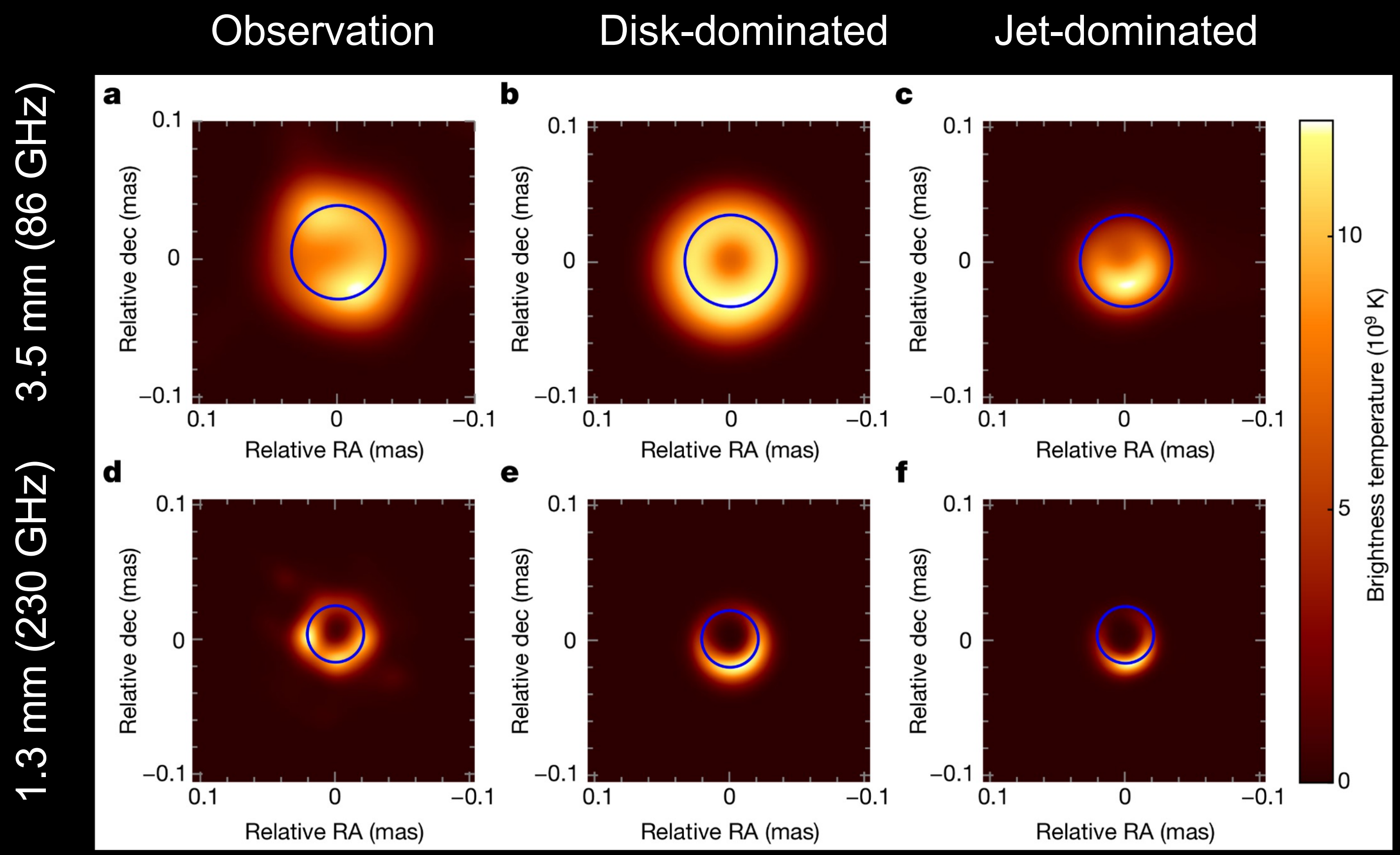
Credit: Pu & Nakamura

Same GRMHD model but with different post-processing



- The photon ring emission + outer disk emission become more dominant in the disk-dominated model.
- The photon ring emission + forward jet base emission become more dominant in the jet-dominated model.

What constitutes the observed ring-like structure?

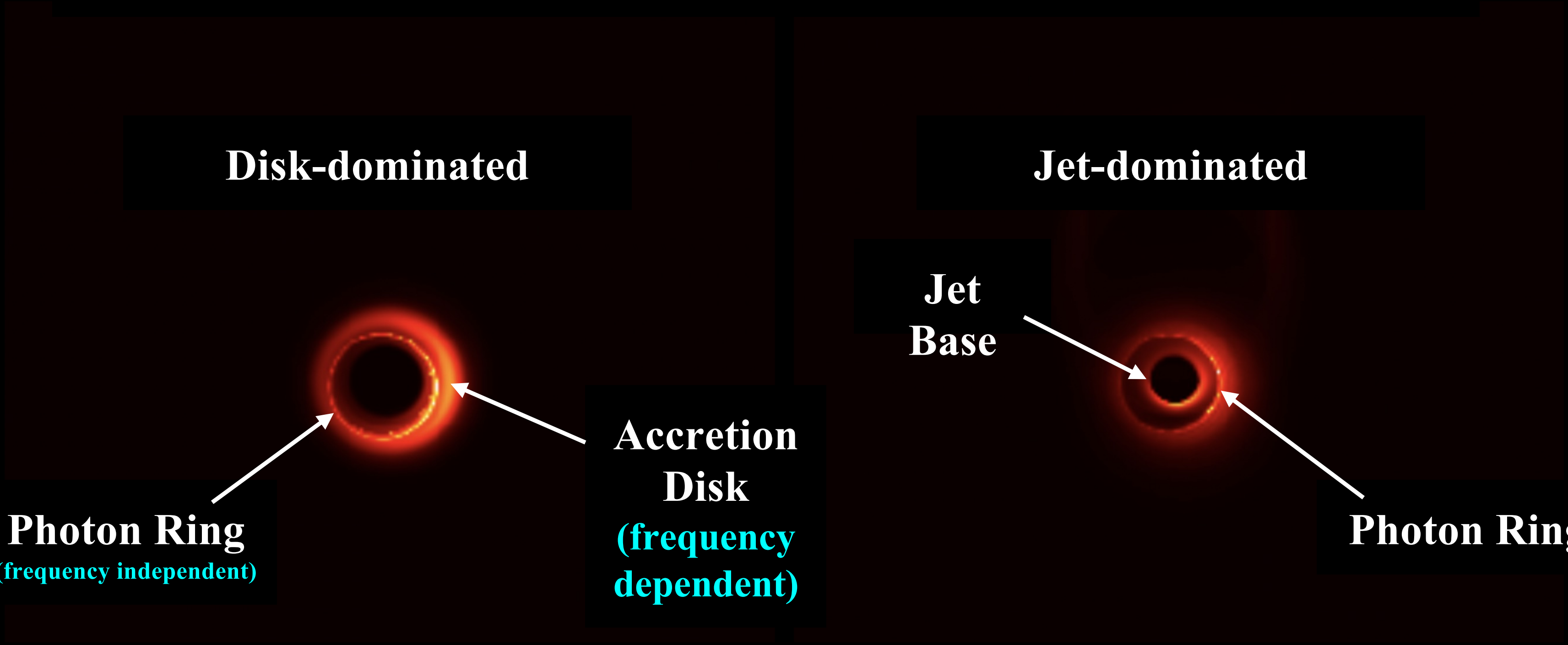


- At 230 GHz, the photon ring emission is dominant in both models.
- At 86 GHz, the innermost accretion disk emission and the photon ring emission become optically thick in the disk model. The forward jet base emission is dominant in the jet model.

What constitutes the observed ring-like structure?

Credit: Pu & Nakamura

Same GRMHD model but with different post-processing



Disk-dominated

Photon Ring
(frequency independent)

Accretion Disk
(frequency dependent)

Jet-dominated

Jet Base

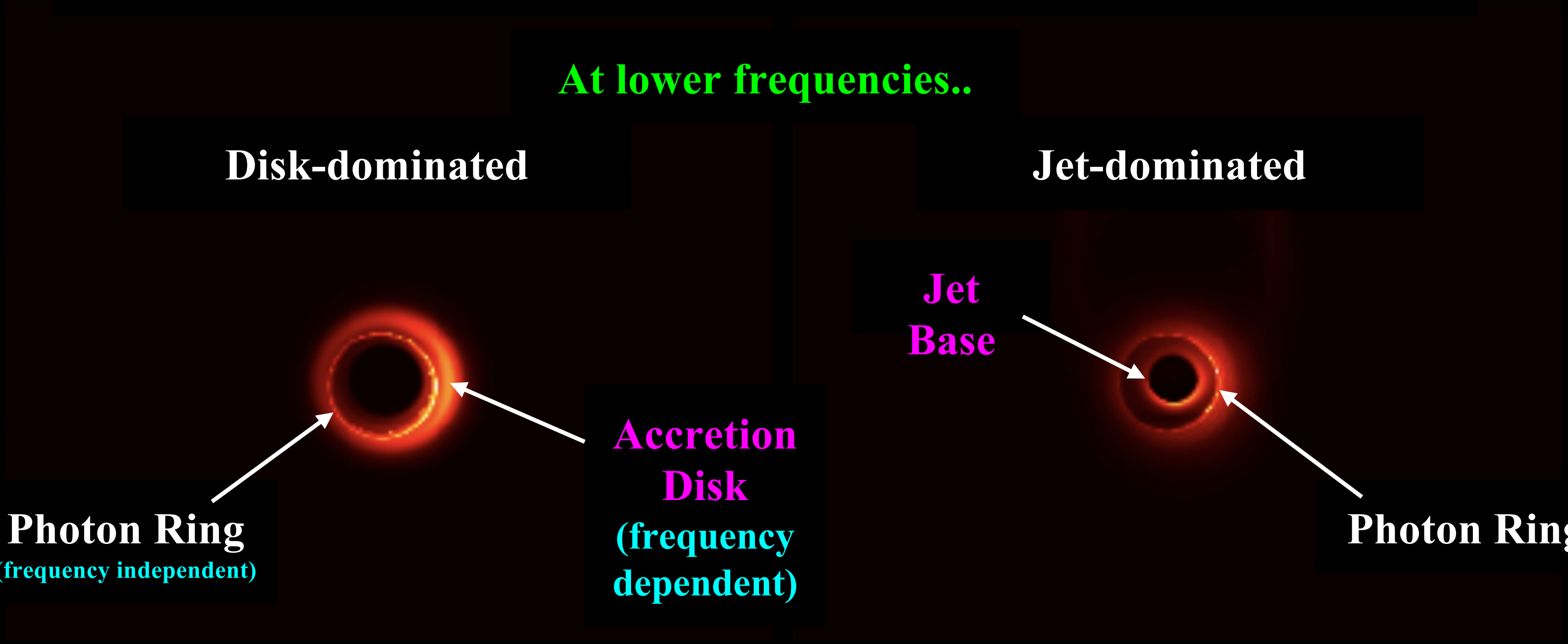
Photon Ring

- The photon ring emission + outer disk emission become more dominant in the disk-dominated model.
- The photon ring emission + forward jet base emission become more dominant in the jet-dominated model.

What constitutes the observed ring-like structure?

Credit: Pu & Nakamura

Same GRMHD model but with different post-processing



At lower frequencies..

Disk-dominated

Jet-dominated

Jet Base

Accretion Disk (frequency dependent)

Photon Ring (frequency independent)

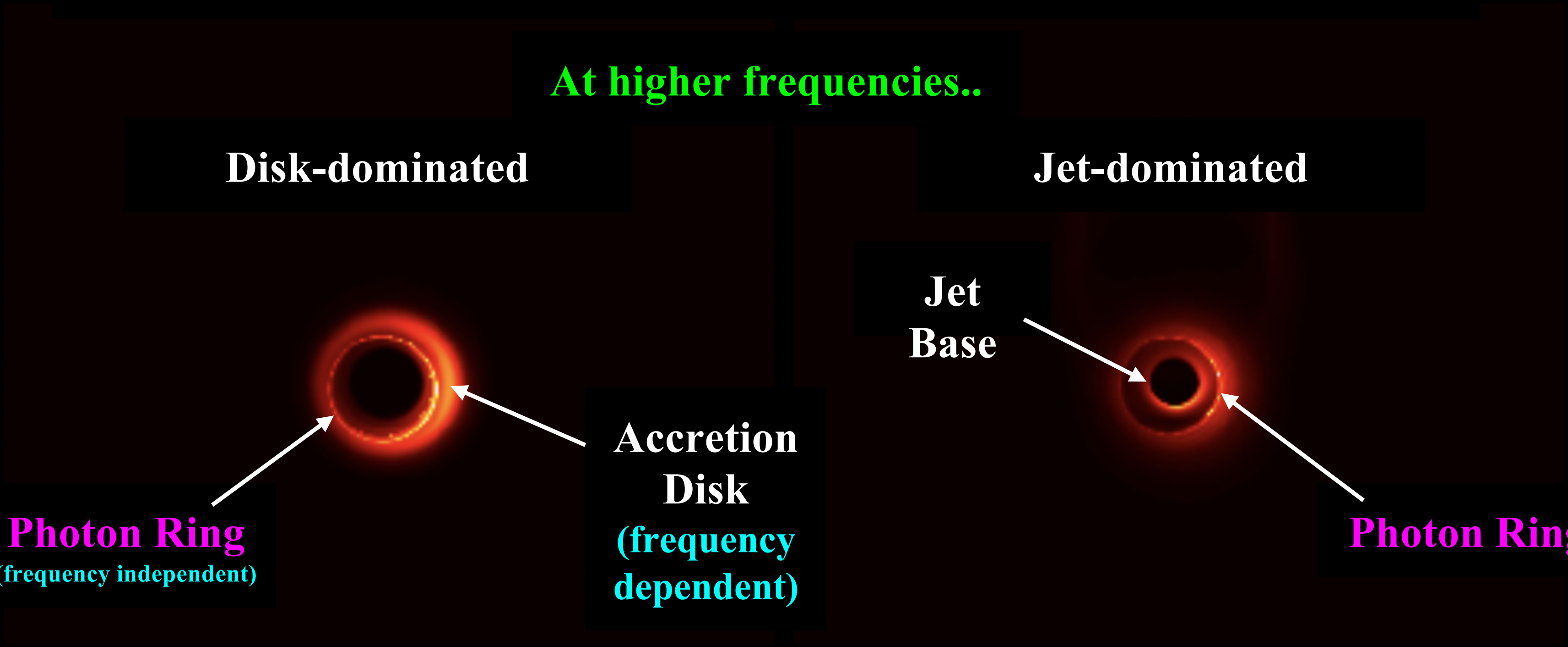
Photon Ring

- The photon ring emission + outer disk emission become more dominant in the disk-dominated model.
- The photon ring emission + forward jet base emission become more dominant in the jet-dominated model.

What constitutes the observed ring-like structure?

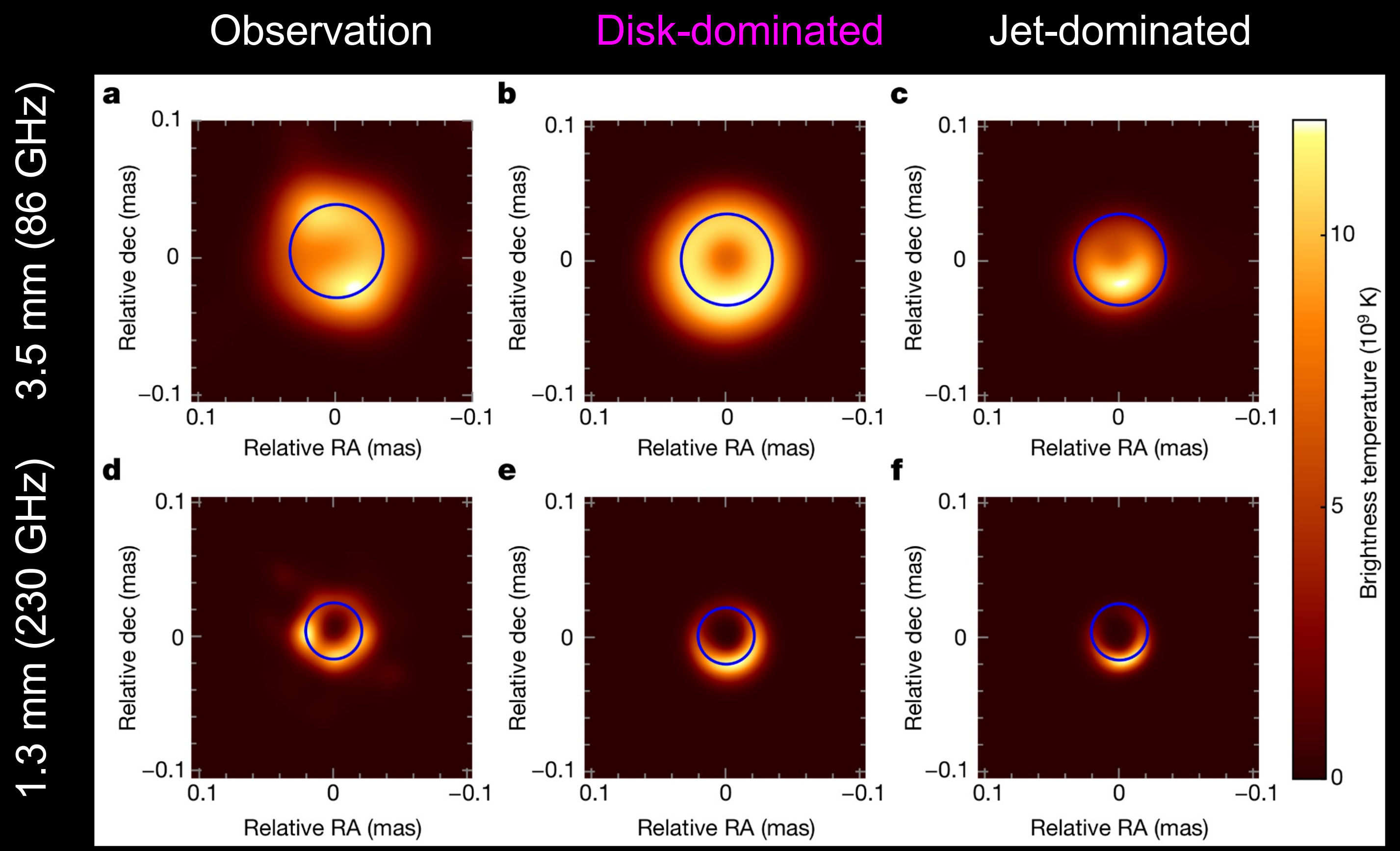
Credit: Pu & Nakamura

Same GRMHD model but with different post-processing



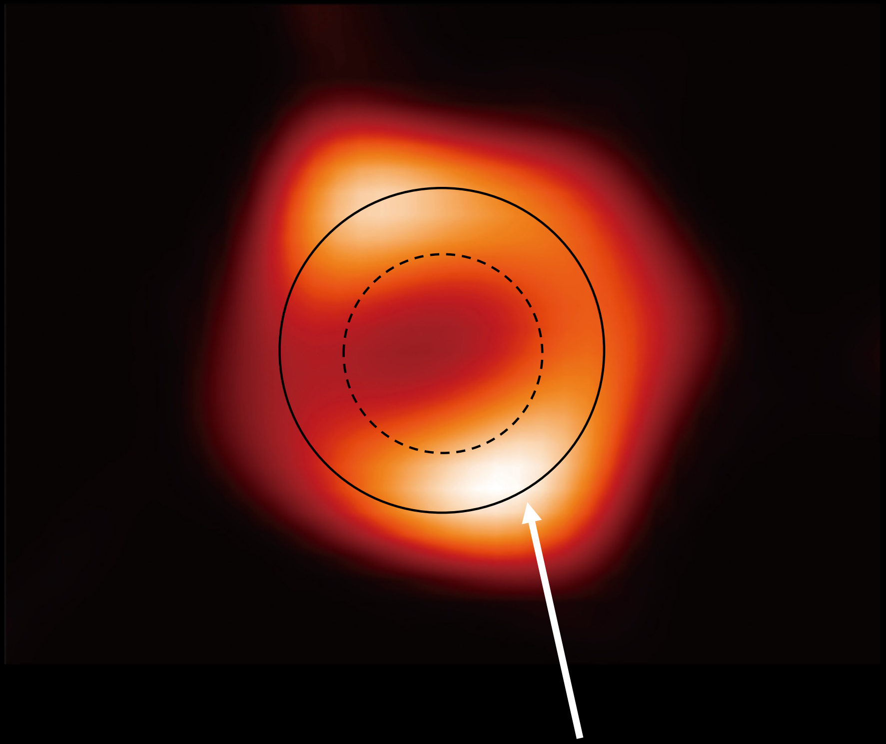
- The photon ring emission + outer disk emission become more dominant in the disk-dominated model.
- The photon ring emission + forward jet base emission become more dominant in the jet-dominated model.

What constitutes the observed ring-like structure?

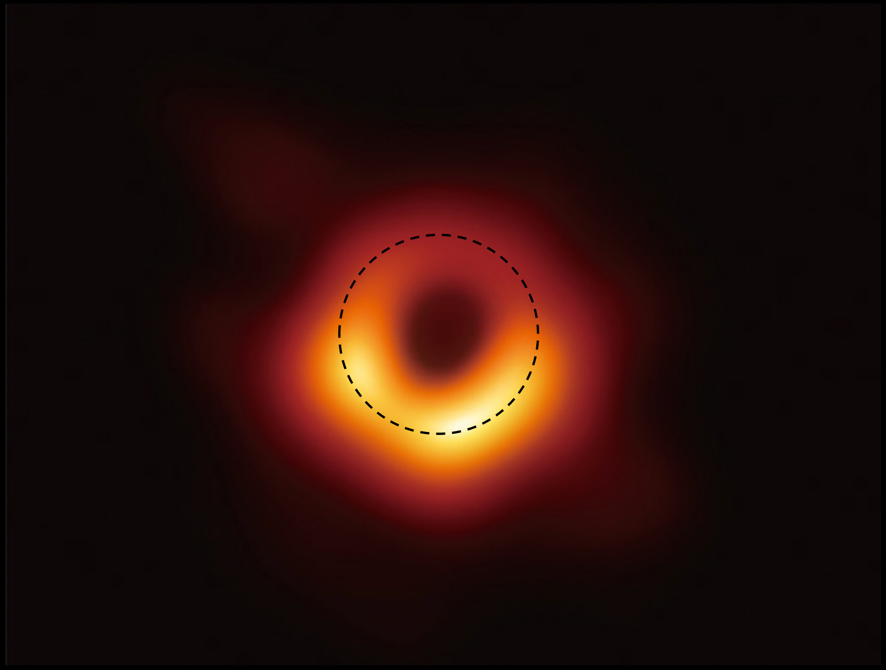


- The ring-like structure revealed by GMVA+ALMA at 86 GHz indicates the accretion structure that was not very evident in the EHT 230 GHz images.
- We don’t see clear brightness asymmetry as the emission is dominated by the outer accretion disk.

GMVA 3.5 mm



EHT 1.3 mm



Significant contribution from
the outer part of the Accretion Disk

→

Larger Diameter &
Symmetric Brightness

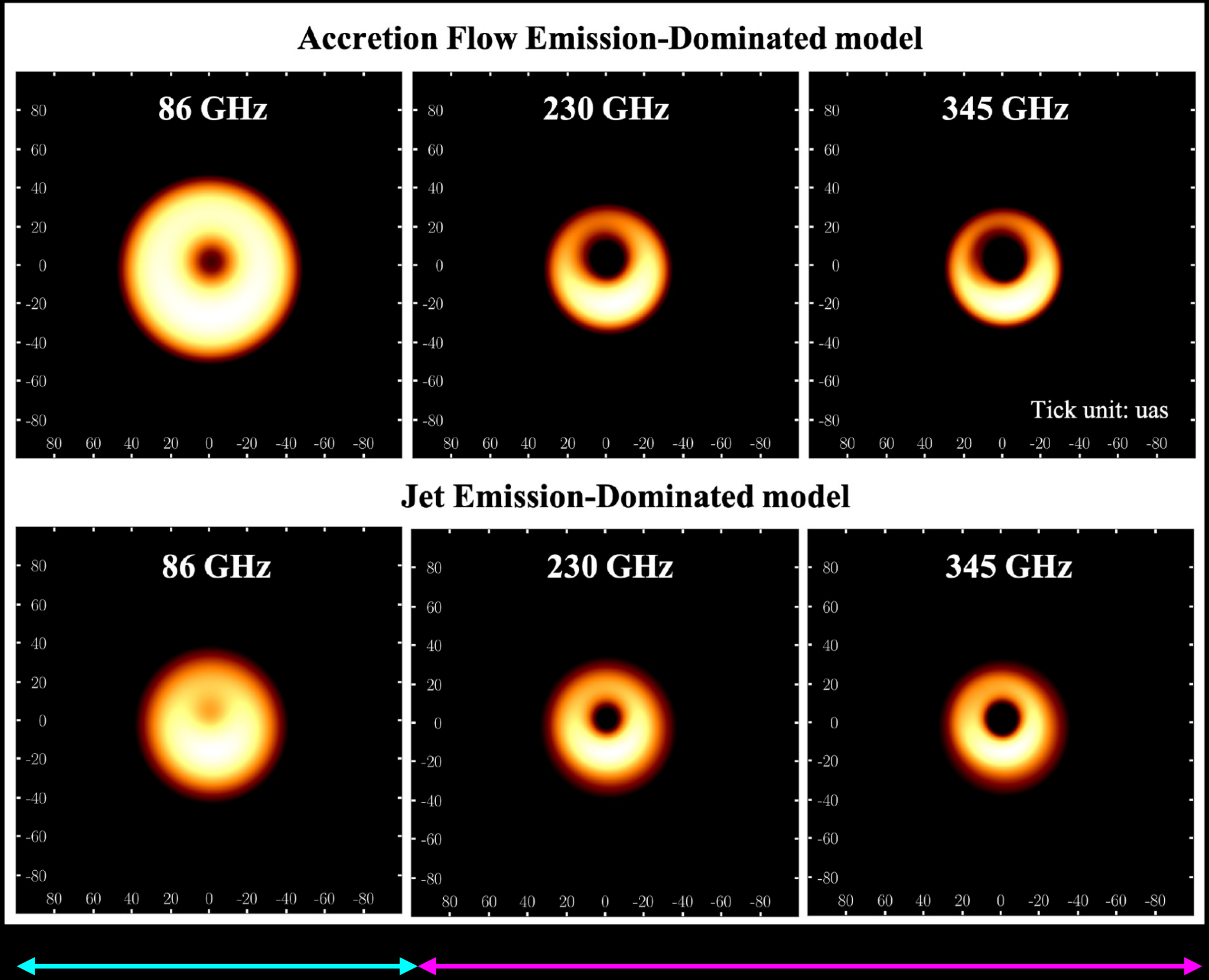
Future Prospects: the M87 black hole images in multiple colors

GMVA+ALMA
43/86 GHz
(PI: J. Park)

+

EHT
230/345 GHz

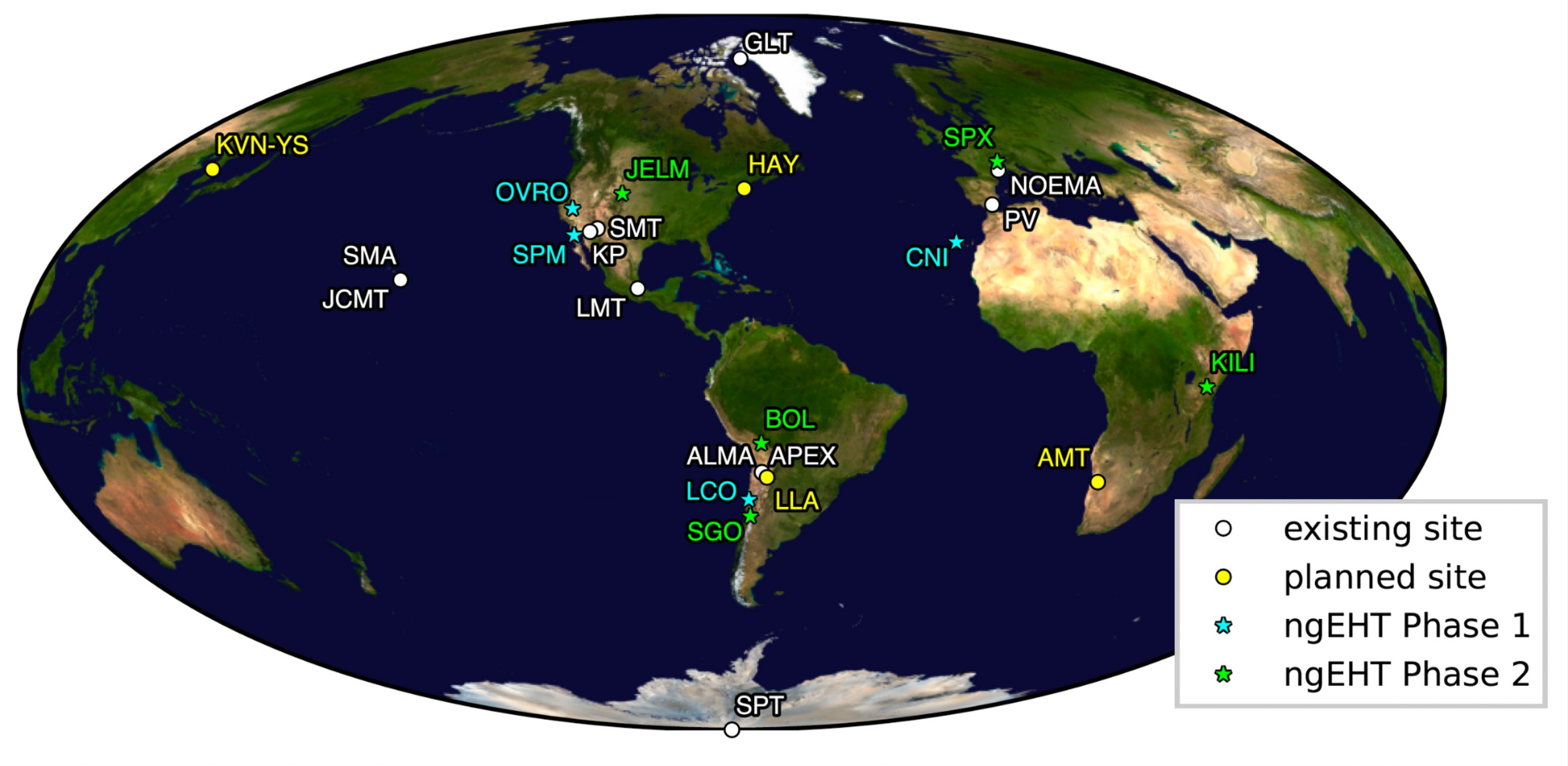
in 2024/2025



n = 0 ring dominated?

Photon-ring (n >= 1) dominated?

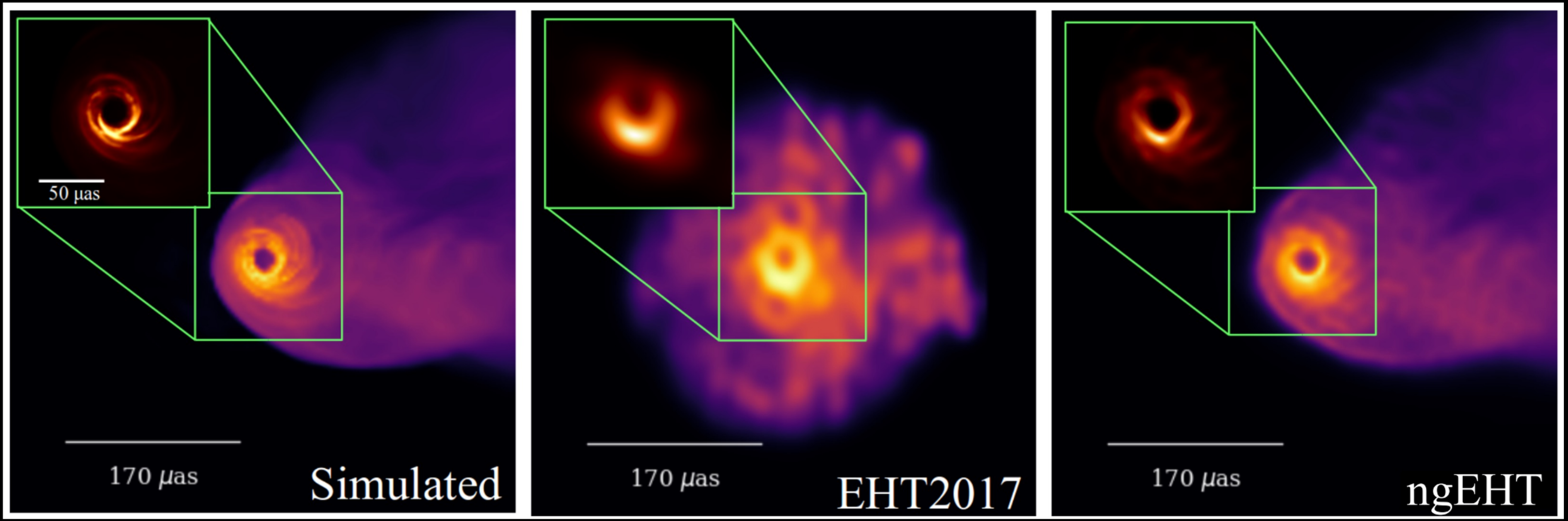
Future Prospects: the M87 black hole movie obtained by the next-generation EHT



The ngEHT project (https://www.ngeht.org)

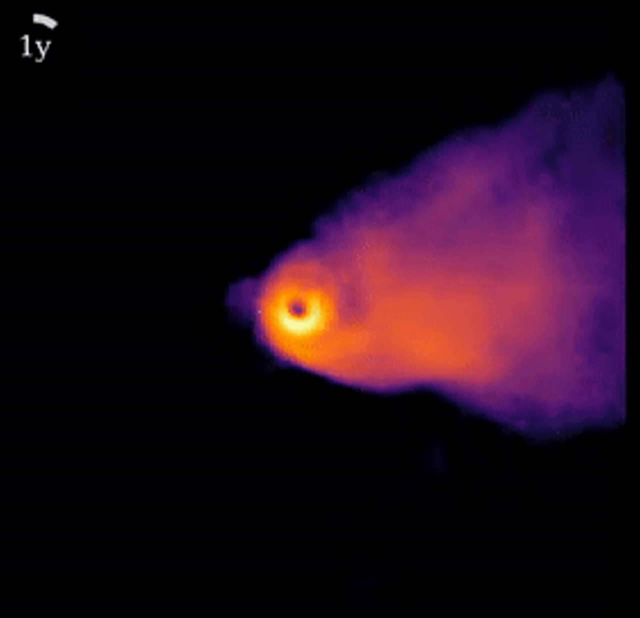
Johnson et al. 2023

Future Prospects: the M87 black hole movie obtained by the next-generation EHT



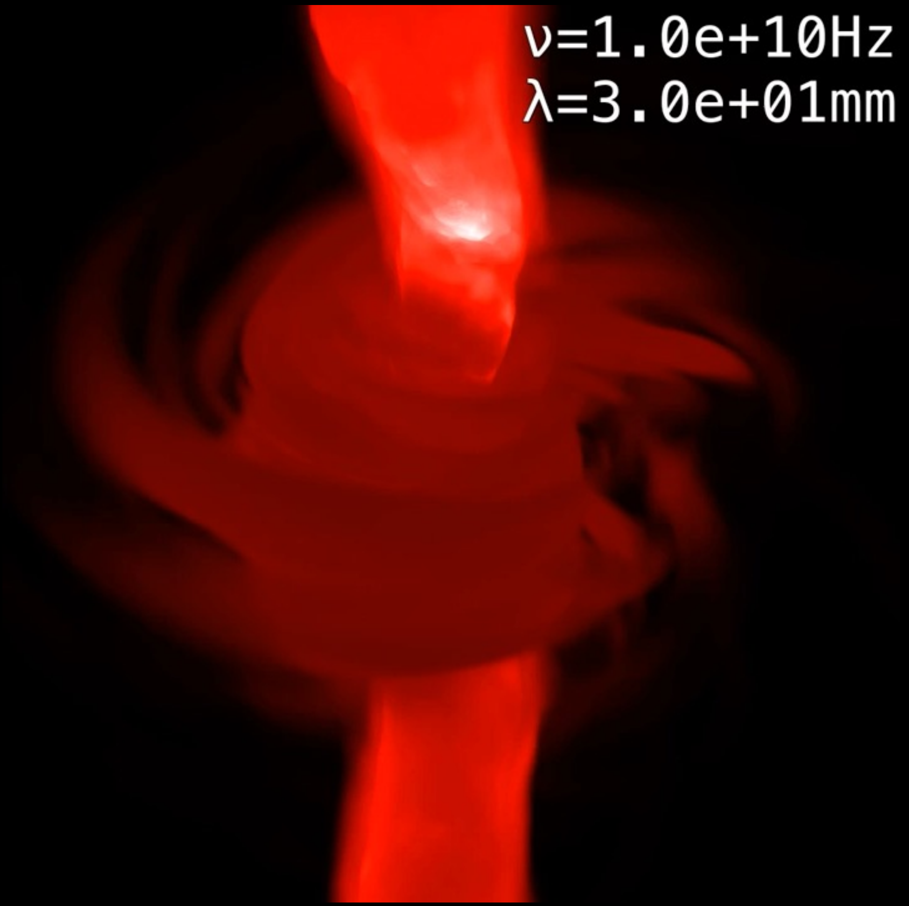
Blackburn et al. (2019)

Future Prospects: the M87 black hole movie obtained by the next-generation EHT

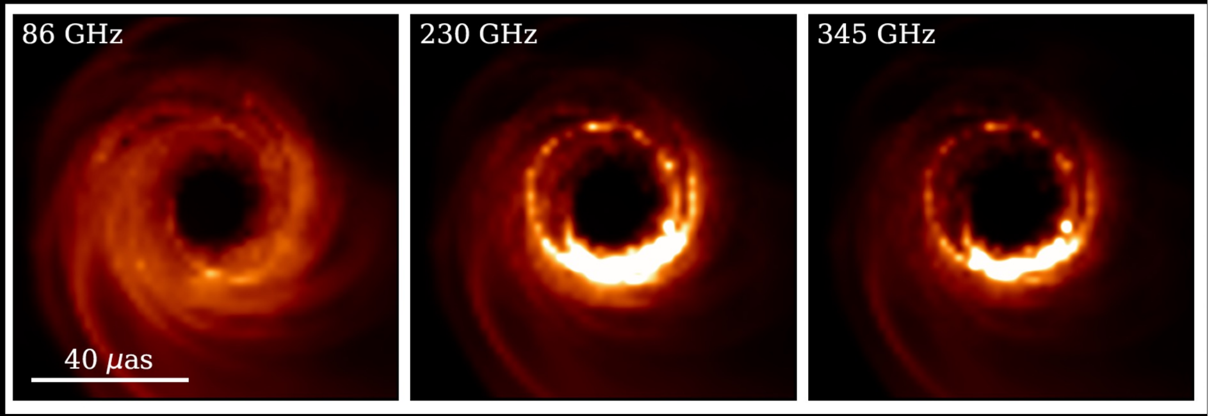


The M87 movie created based on GRMHD simulations
Credit: the ngEHT collaboration

Future Prospects: the M87 black hole images in multiple colors

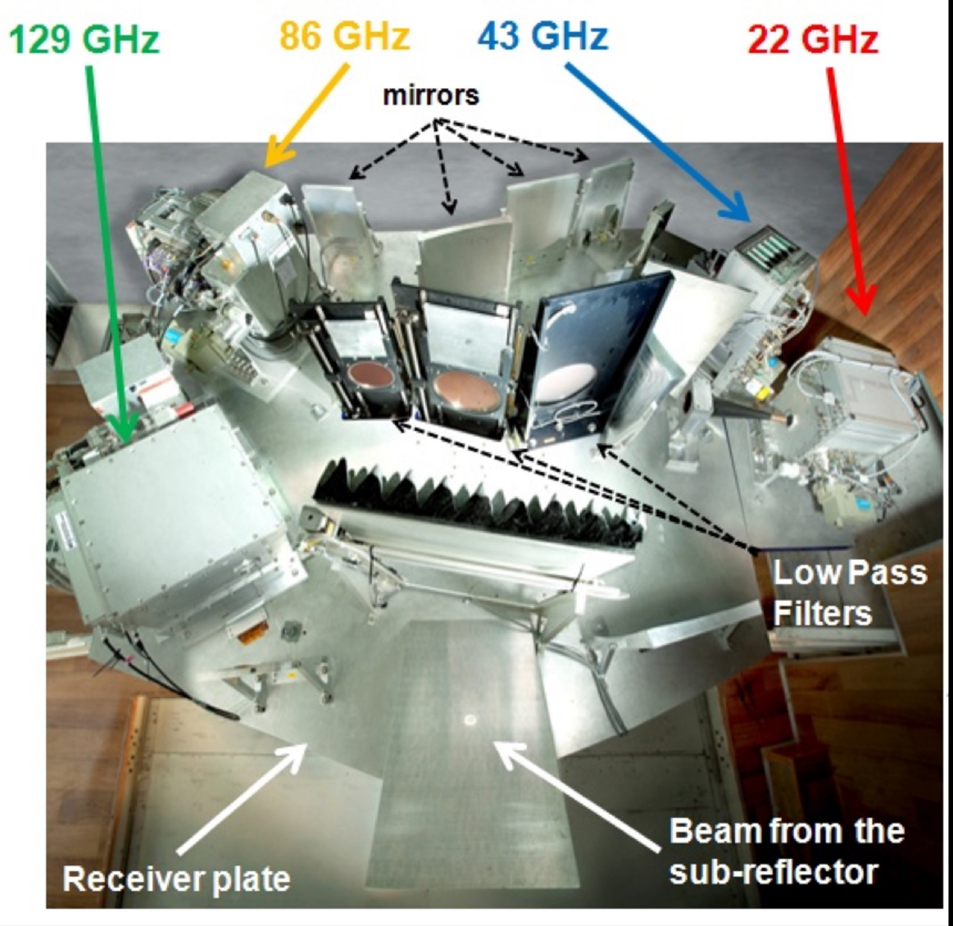


Credit: CK Chan



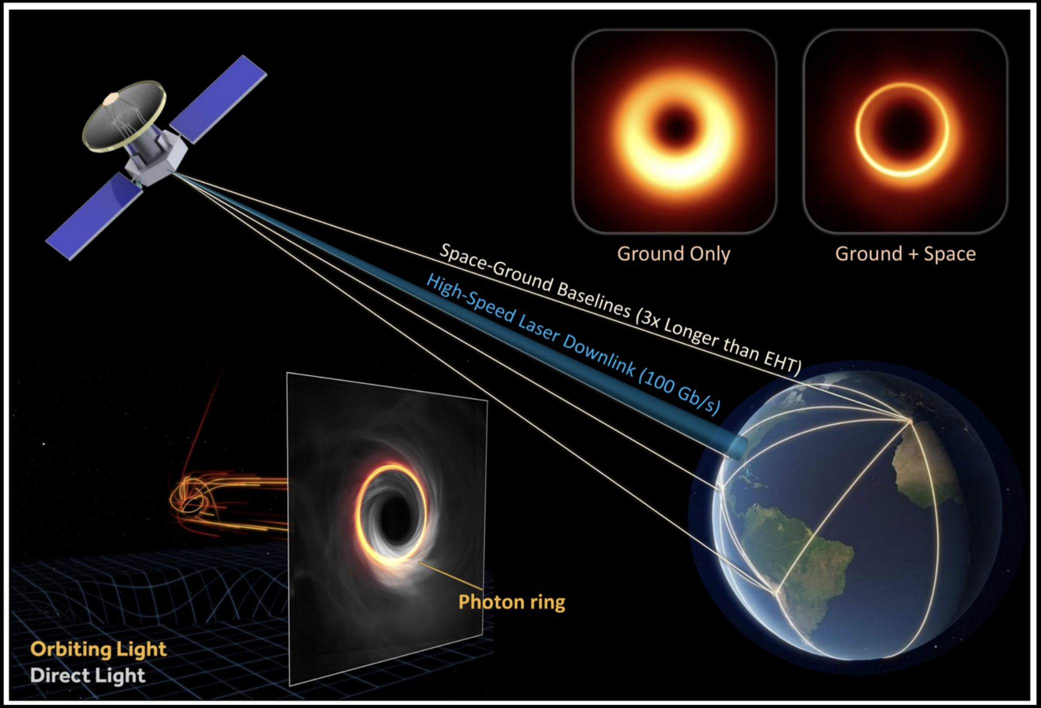
Issaoun et al. (2023)

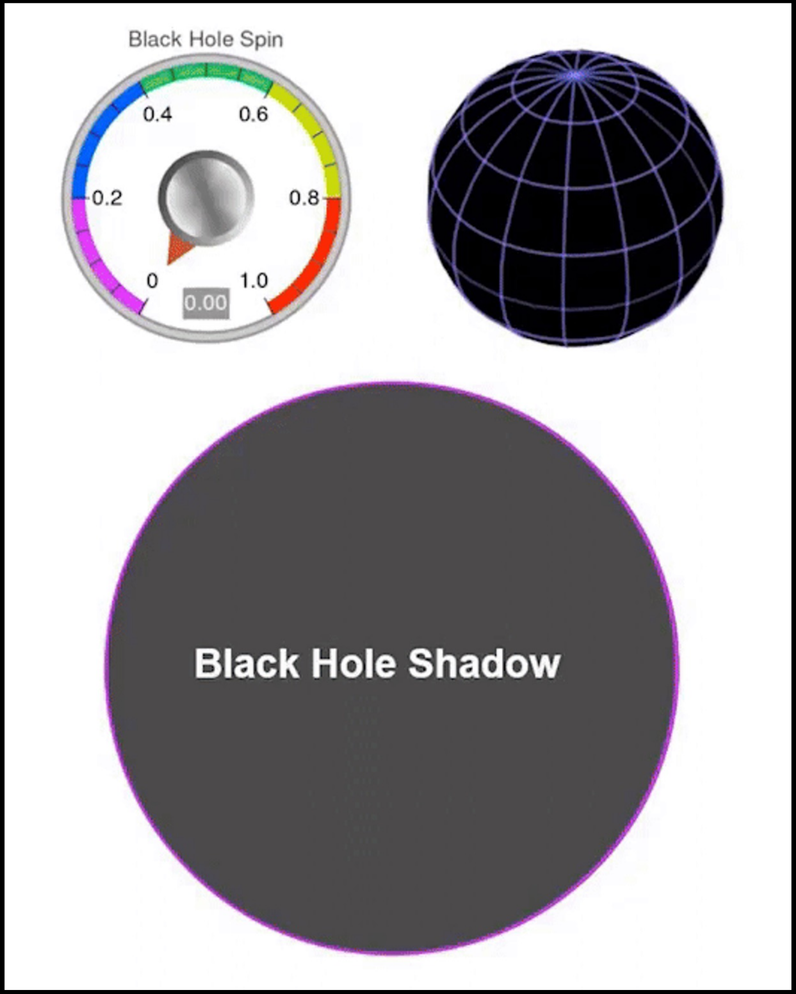
Future Prospects: the M87 black hole images in multiple colors



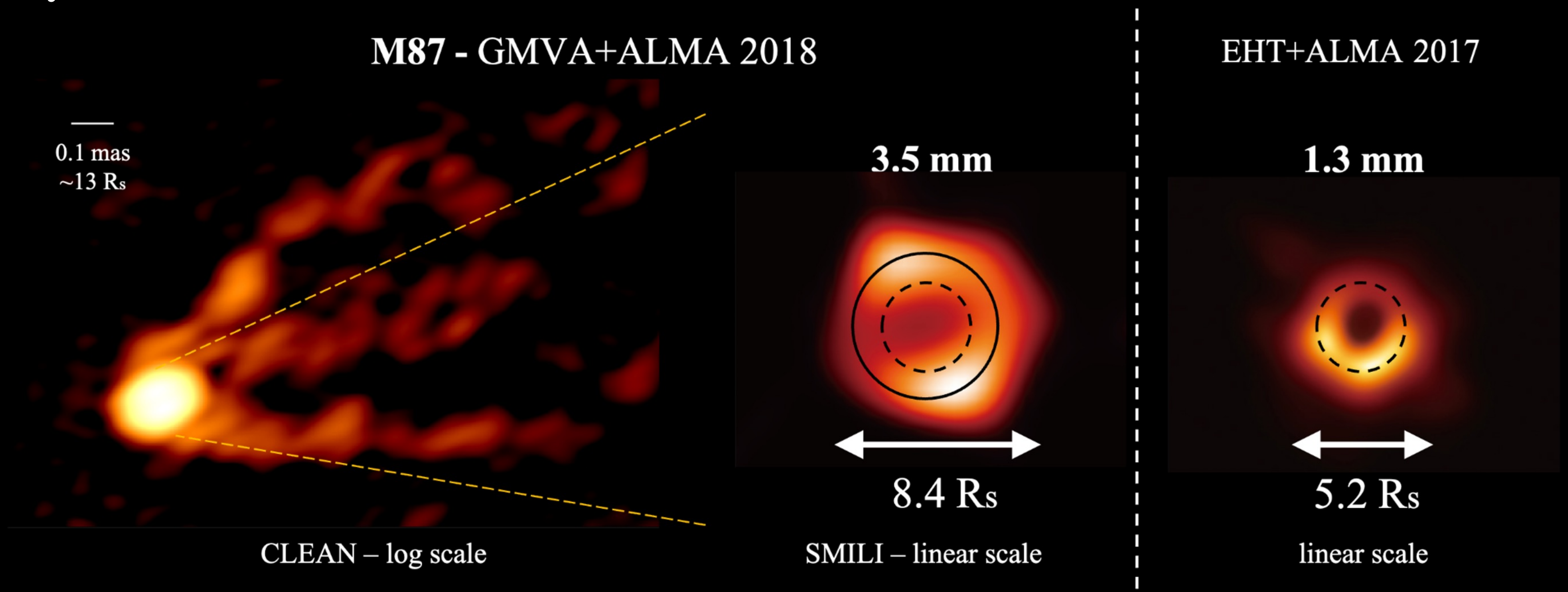
- A bottleneck of high frequency VLBI observations is a short atmospheric coherence time.
- We can dramatically increase the coherence time using simultaneous multi-frequency observations.
- The KVN has demonstrated the power of this system at 22/43/86/129 GHz, and KASI is developing a new system for 86/230/345 GHz (submm-Compact Triple Receiver; submm-CTR; PI: 이정원)

The Black Hole Explorer (BHEX)





Summary



M87 - GMVA+ALMA 2018

EHT+ALMA 2017

CLEAN – log scale

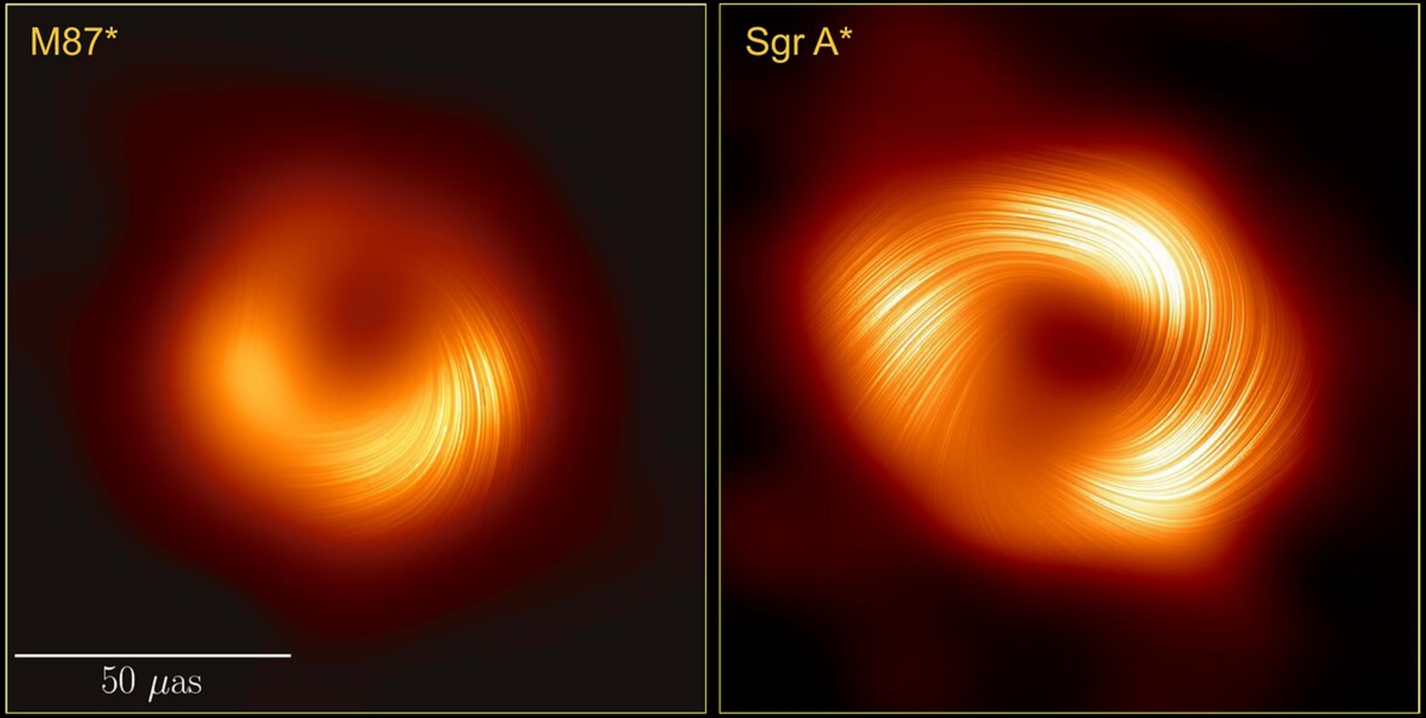
SMILI – linear scale

linear scale

- We revealed a ring-like structure at the center of M87 at 3.5 mm with the GMVA+ALMA.
- The observed size of the ring at 3.5 mm is ~50% larger than that of the EHT ring at 1.3 mm.
- The discrepancy can be reconciled if (i) the photon ring emission is dominant at 1.3 mm and (ii) the photon ring emission is optically thick and the outer accretion disk emission is more dominant at 3.5 mm.
- We plan to extensively investigate the M87 black hole and jet in the frequency and time domain in the future, and KASI and Korea will play a critical role.

Backup Slides

Sagittarius A*

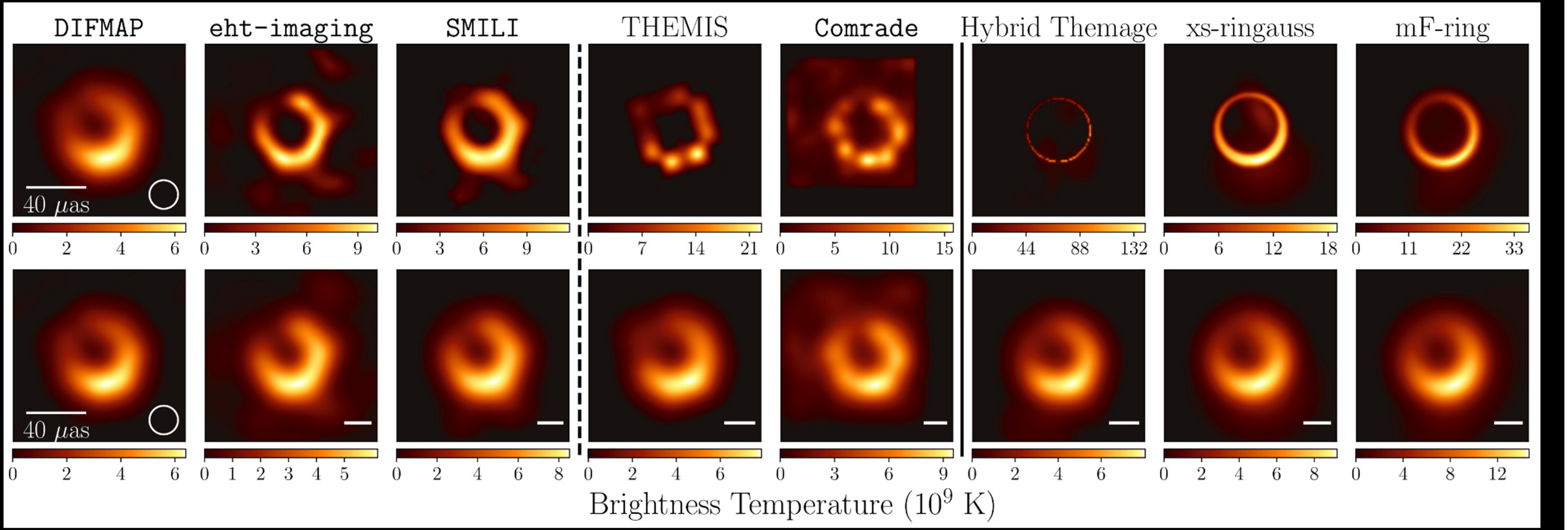


MAD, a = 0.94, i = 150 degrees

Annual Evolution of the M87* Ring Structure

Original

Blurred



Team Leaders

Ilje Cho
(KASI/Yonsei Univ.)

What constitutes the observed ring-like structure?

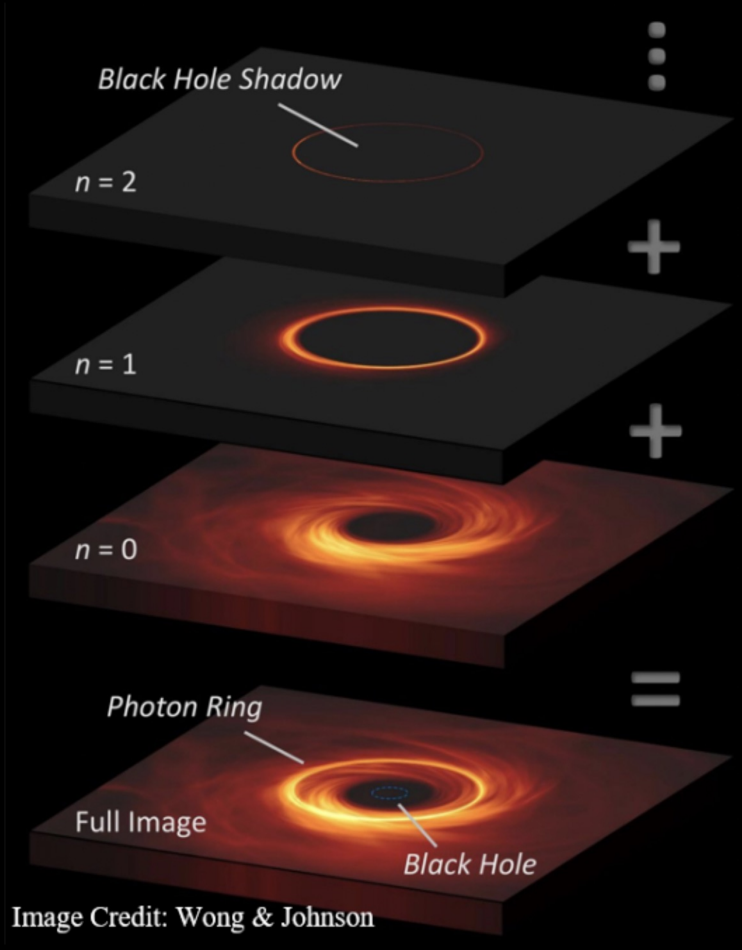
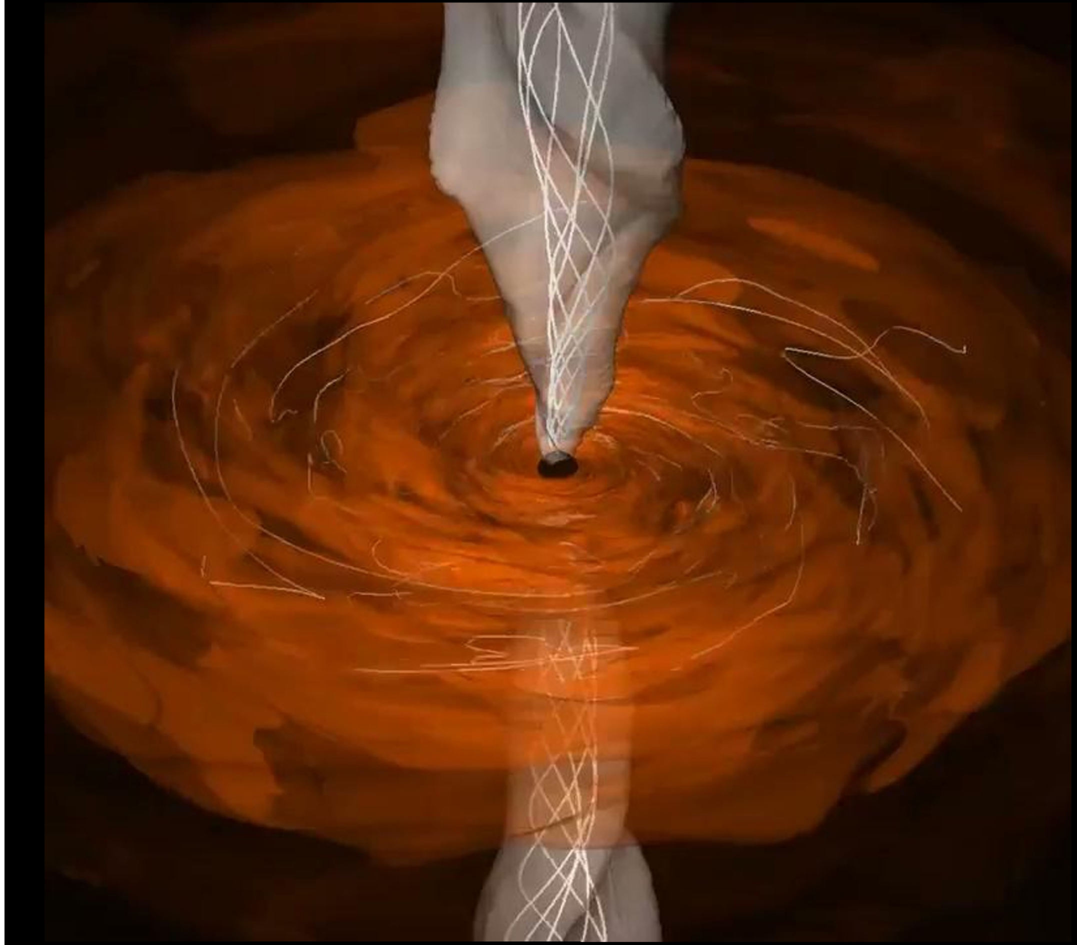


Image Credit: Wong & Johnson

Credit: the EHT collaboration

What constitutes the observed ring-like structure?



Credit: Shiokawa

The ring-like structure is believed to originate from synchrotron emission in the plasma around the black hole.

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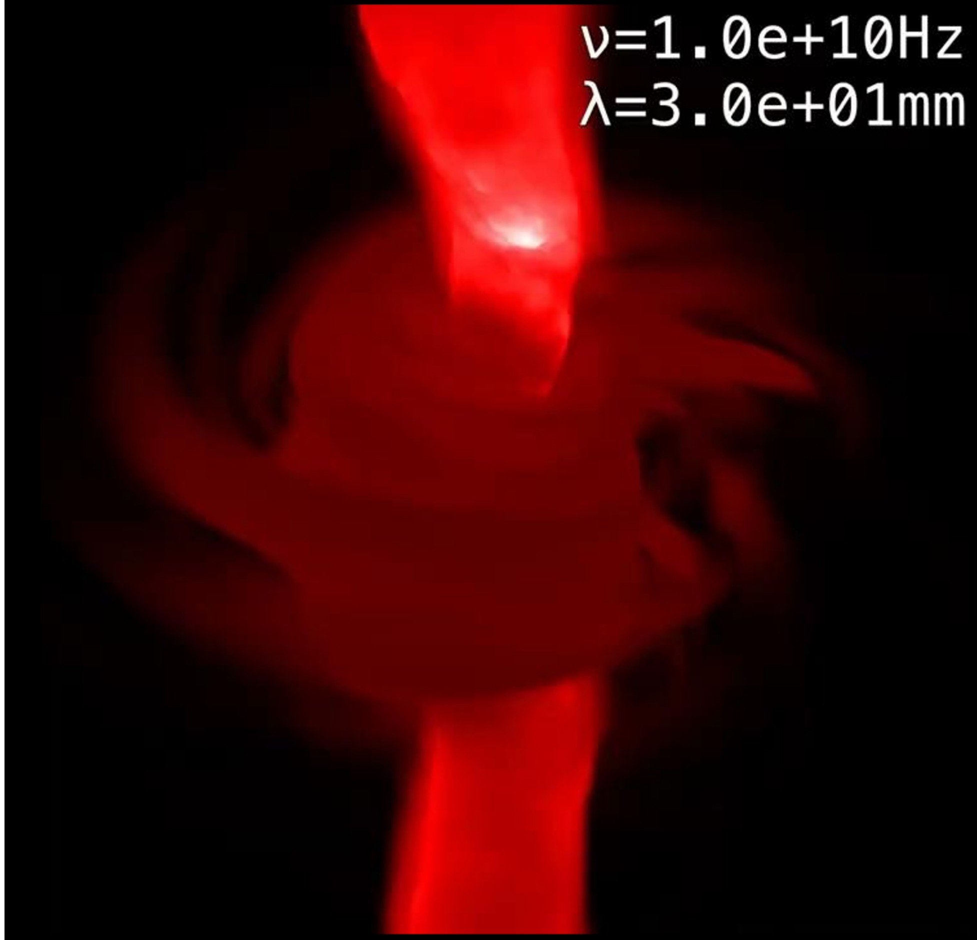
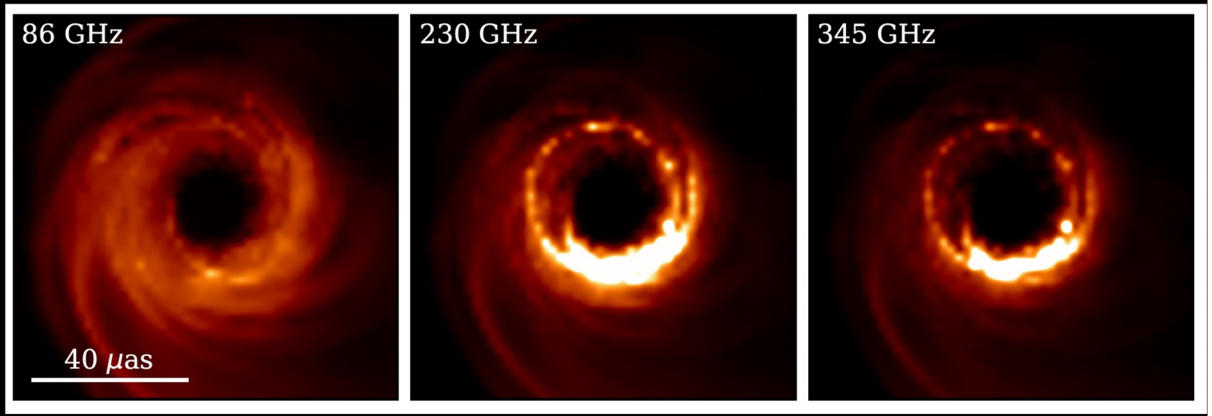


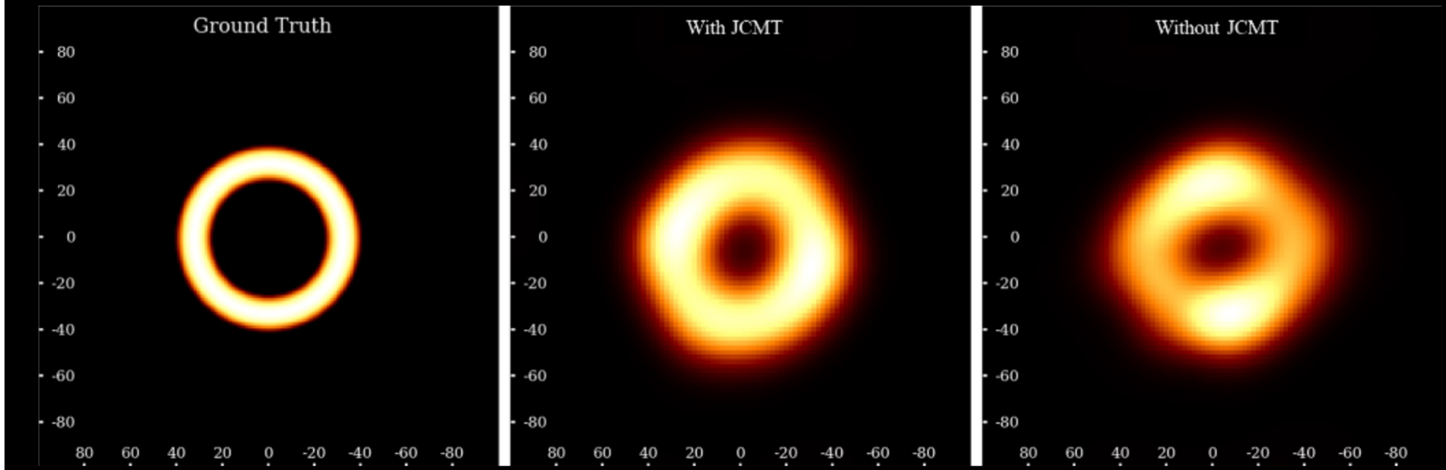
Credit: CK Chan



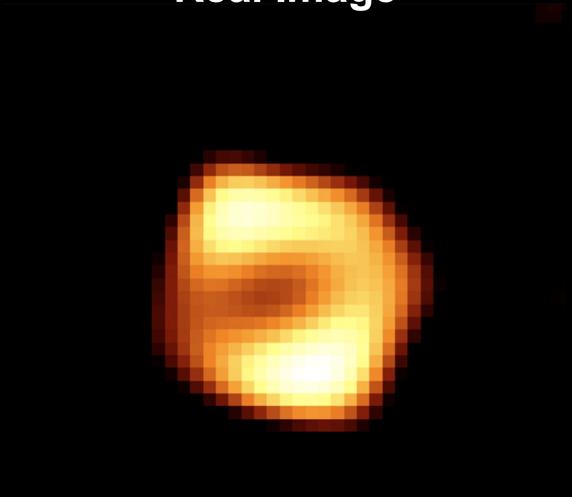
Issaoun et al. (2023)

Future Prospects: Testing the Jet Launching Mechanism for M87 through Monitoring Observations.

Simulation Images



Real Image



- Reconstructing a ring-like structure can be greatly affected by the (u,v)-coverage.
- The JCMT, providing high SNR very long baselines along the EW direction, plays a crucial role in accurately reconstructing the structure.

What constitutes the observed ring-like structure?

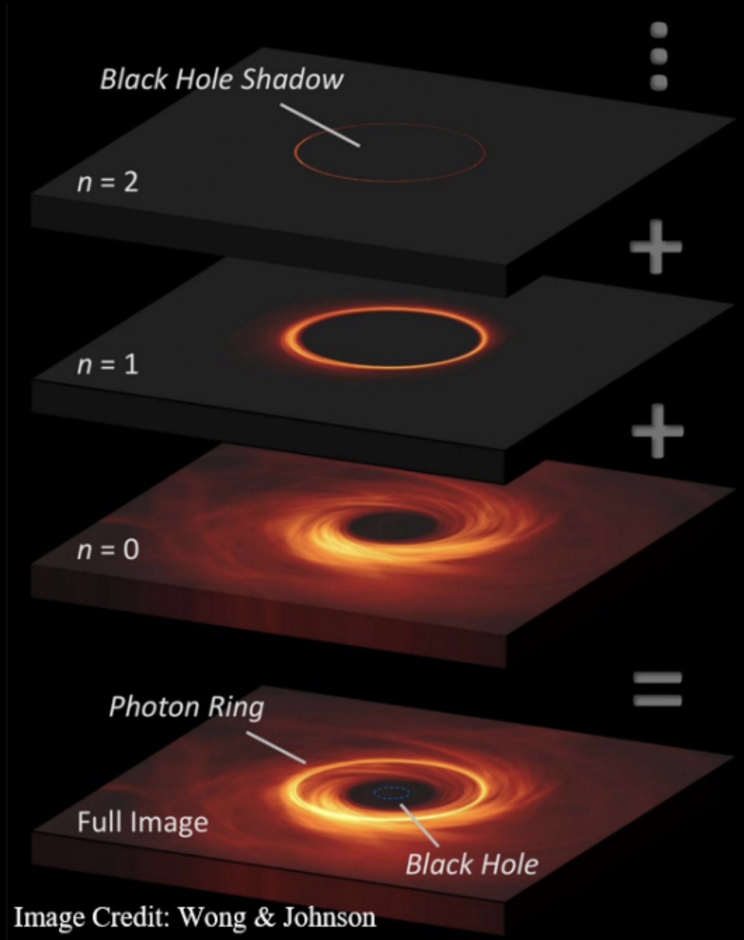
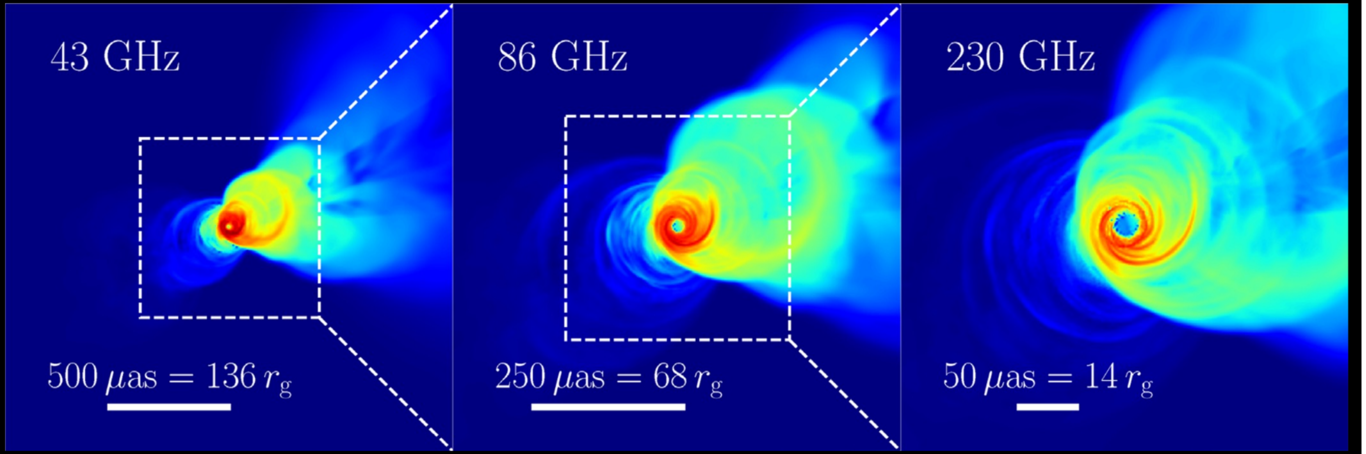
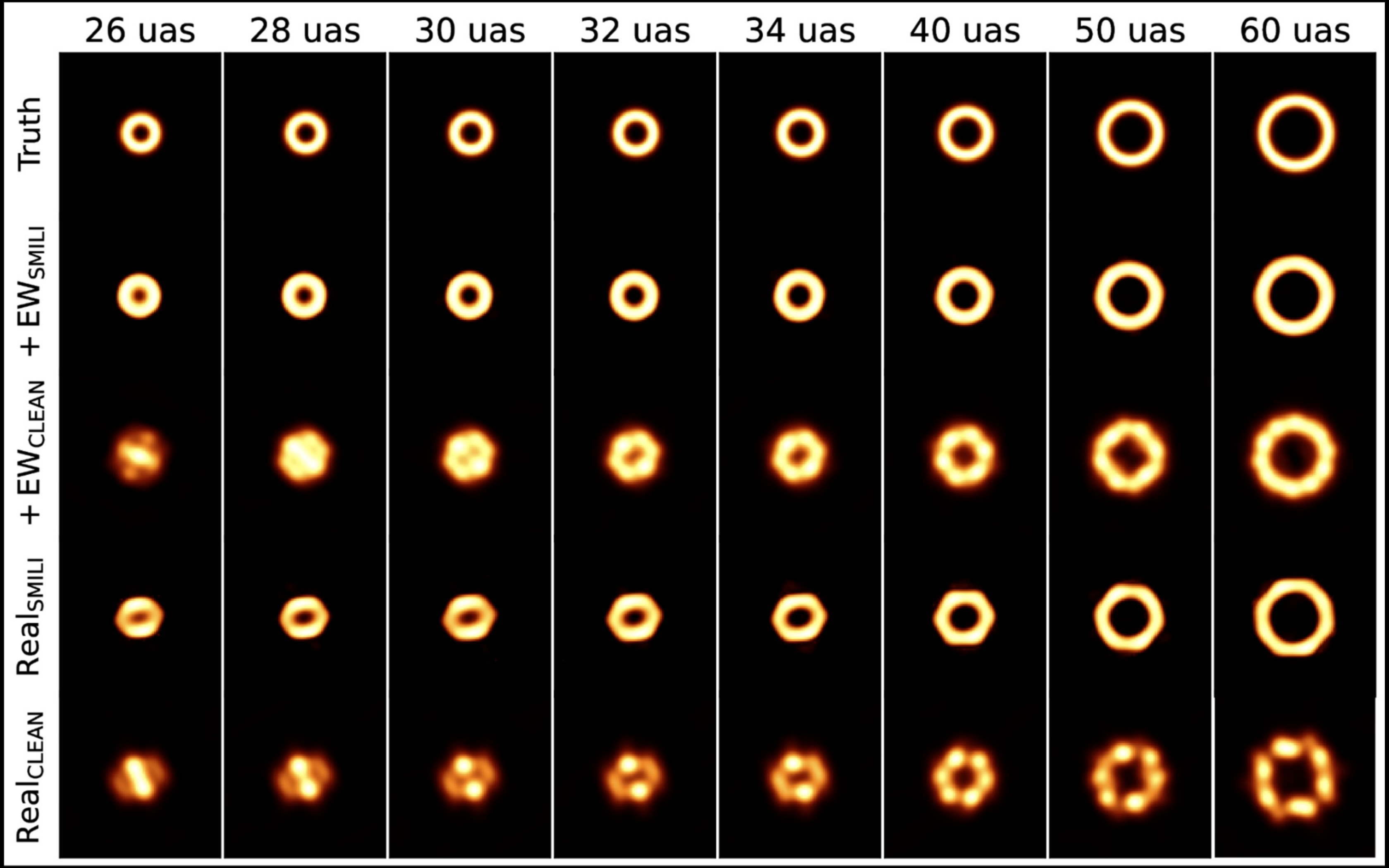
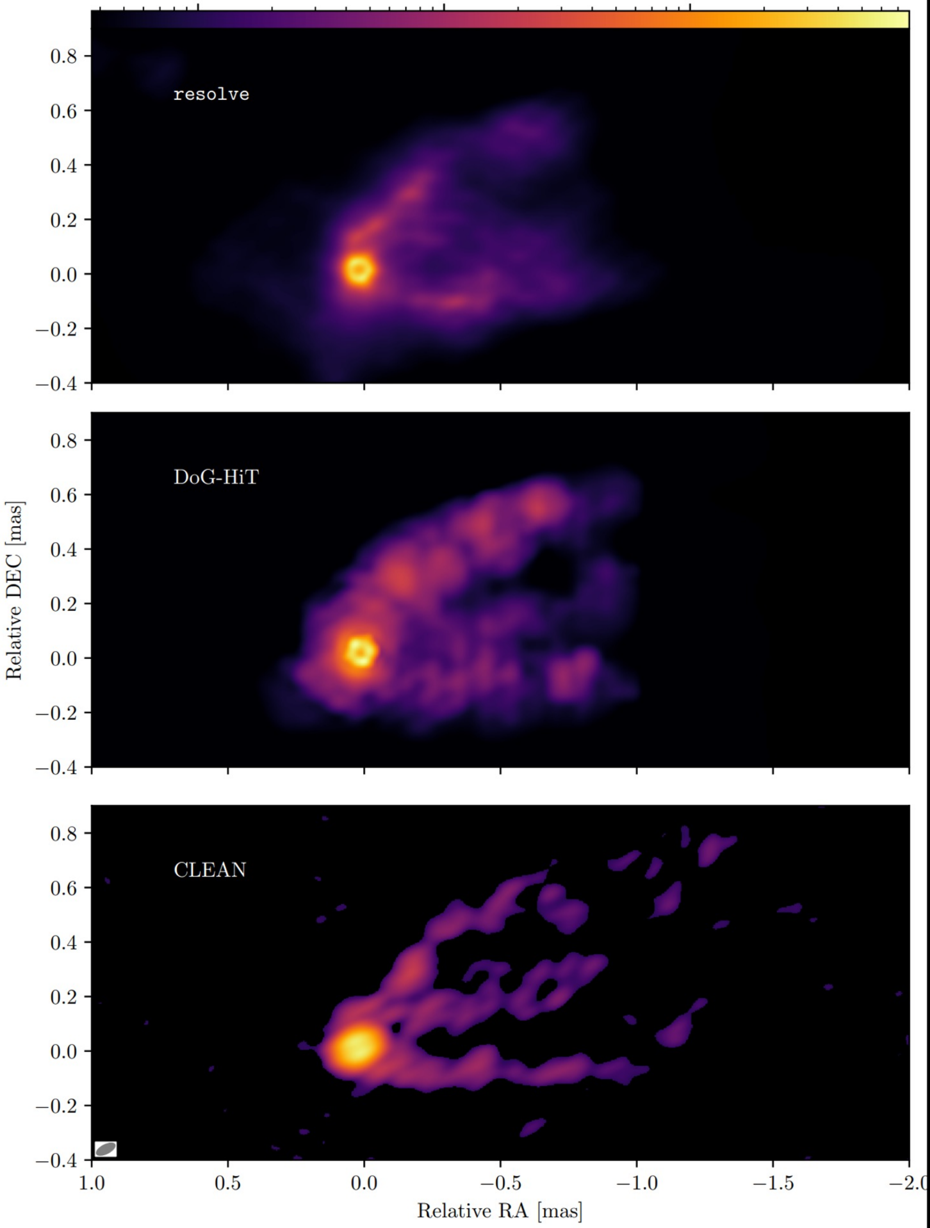


Image Credit: Wong & Johnson

Credit: the EHT collaboration




26 uas
28 uas
30 uas
32 uas
34 uas
40 uas
50 uas
60 uas
Truth
+ EW$_{\mathrm{SMILI}}$
+ EW$_{\mathrm{CLEAN}}$
Real$_{\mathrm{SMILI}}$
Real$_{\mathrm{CLEAN}}$



Jong-seo Kim et al. (2024)

GVA Observations

$$\boxed{I'(x,y) = A(x,y)\, I(x,y) = \int_{-\infty}^{\infty} V(u,v,0)\, \mathrm{e}^{-\mathrm{i}2\pi(ux+vy)}\, \mathrm{d}u\, \mathrm{d}v}$$

the van Cittert-Zernike relation

$$I(x,y) \xleftrightarrow{\text{F.T.}} V(u,v)$$

Imaging & Deconvolution

$$V(u,v) \xleftrightarrow{\text{F.T.}} I(l,m) \quad S(u,v) \xleftrightarrow{\text{F.T.}} s(l,m)$$

measurements

$$\begin{tikzcd} V(u,v)S(u,v) \arrow[d, leftrightarrow, "\text{F.T.}"] \\ I^D(l,m) = I(l,m) * s(l,m) \end{tikzcd}$$

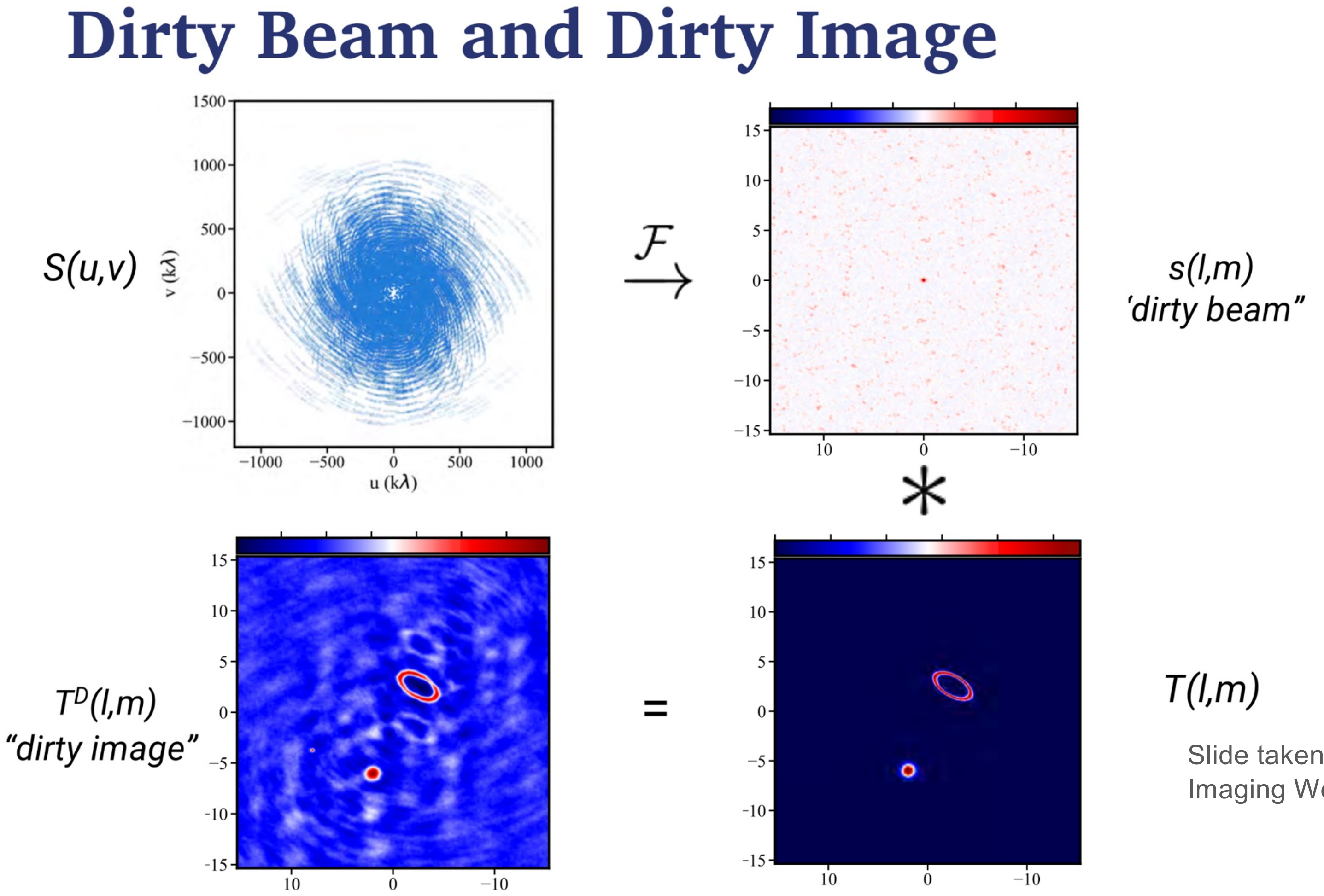
$S(u,v) = 1$ if there is data

$S(u,v) = 0$ if there is no data

dirty beam

dirty image

Imaging & Deconvolution



Dirty Beam and Dirty Image

$S(u,v)$ $\xrightarrow{\mathcal{F}}$ $s(l,m)$ 'dirty beam”

$*$

$T^D(l,m)$ “dirty image” = $T(l,m)$

Slide taken from NRAO Synthesis Imaging Workshop

Imaging & Deconvolution

$$V(u,v)S(u,v) \xrightarrow{\mathcal{F}} T^D(l,m)$$

$$T(l,m) * s(l,m) = T^D(l,m)$$

How to derive T(l, m)?

1. Deconvolution using s(l, m)

- CLEAN (Hogbom 1974)
- Assume that the source consists of a sum of point sources
- Conventional Method
- Successful but Limitation

2. Forward "Modeling"

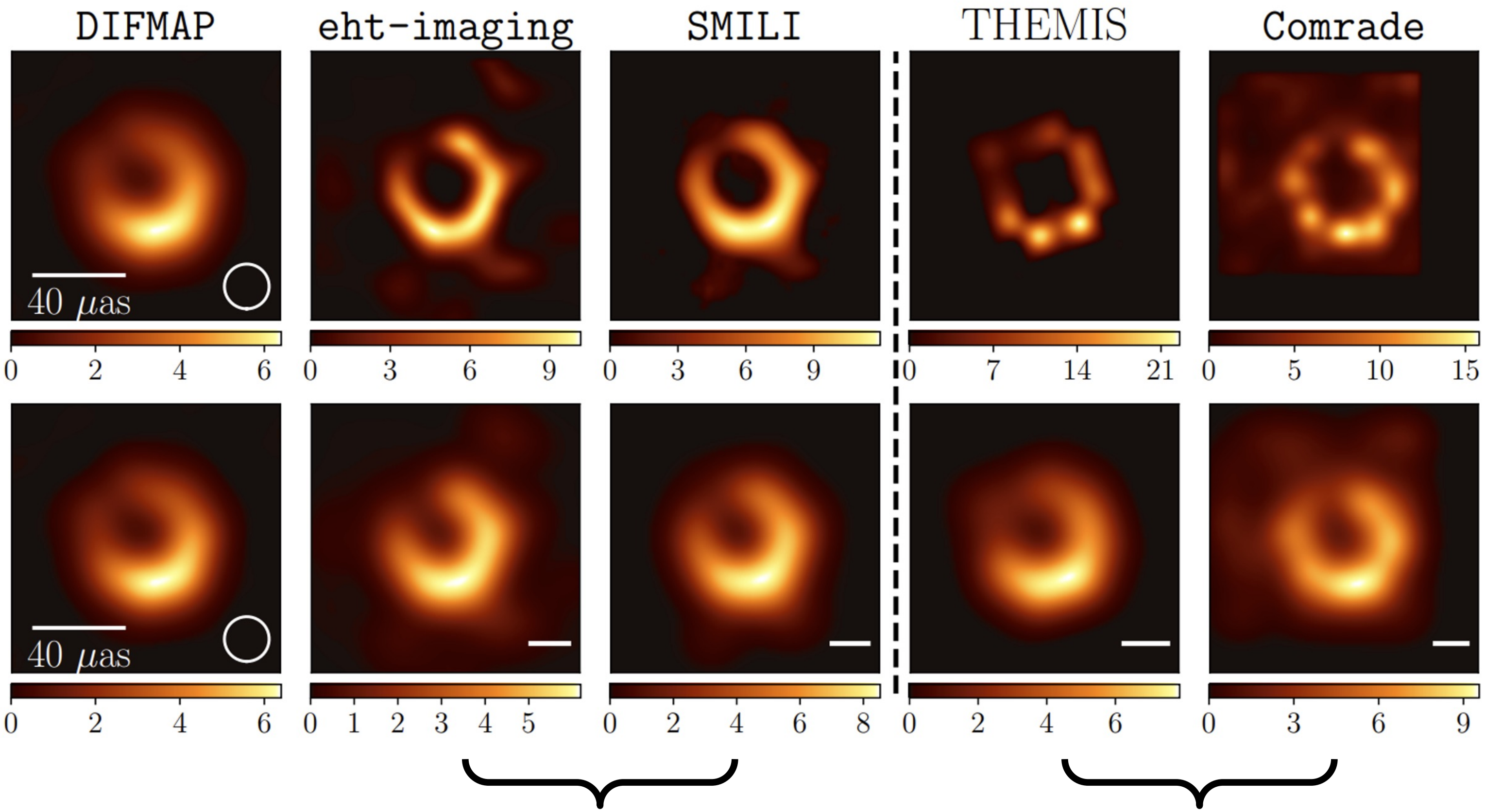
- Regularized Maximum Likelihood (RML) method
- Construct model images and directly fit them to the visibilities
- "Super-resolution" is possible
- Have not been extensively tested.

Imaging & Deconvolution

The EHT Collaboration et al. (2024)

“natural” resolution

after convolution

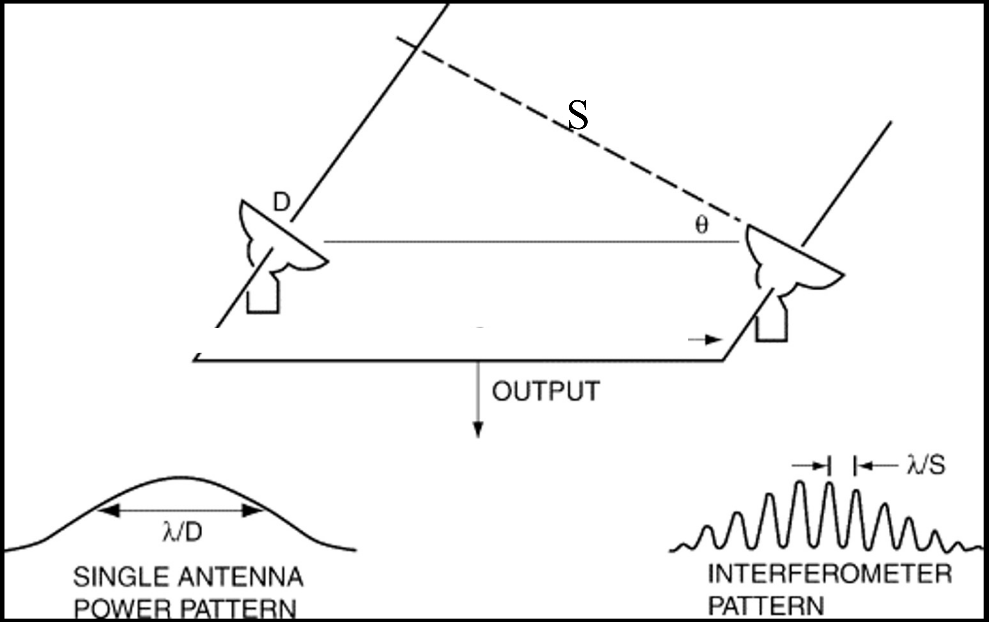


CLEAN

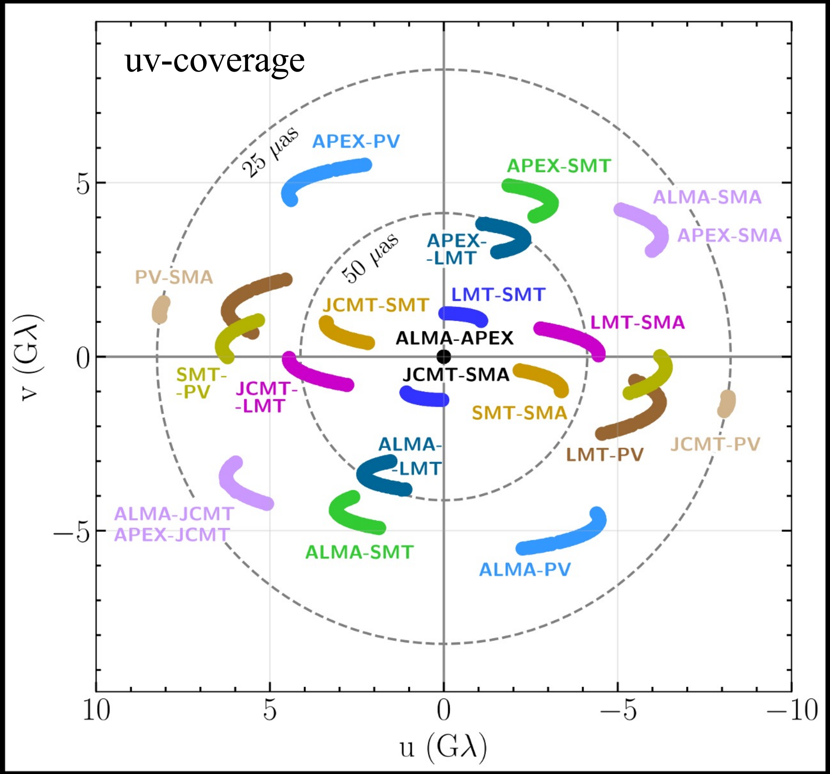
RML

Bayesian

Very Long Baseline Interferometry & Event Horizon Telescope



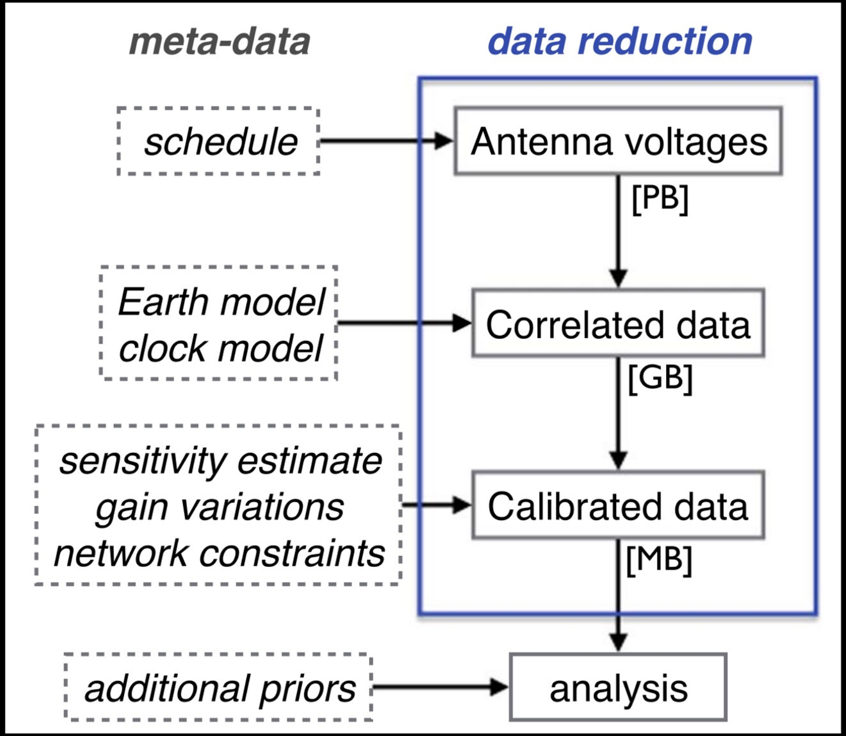
Credit: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/radio-astronomy



Interference of radio signals received at two separated telescopes allows us to capture the source structure at a high resolution. The Fourier transform of the correlated signals for different baseline vectors (on the u-v plane) can provide a source image.

$$T(l,m) = \int\int V(u,v) e^{i2\pi(ul+vm)} du dv$$

Very Long Baseline Interferometry & Event Horizon Telescope



meta-data

data reduction

schedule

Antenna voltages

[PB]

Earth model
clock model

Correlated data

[GB]

sensitivity estimate
gain variations
network constraints

Calibrated data

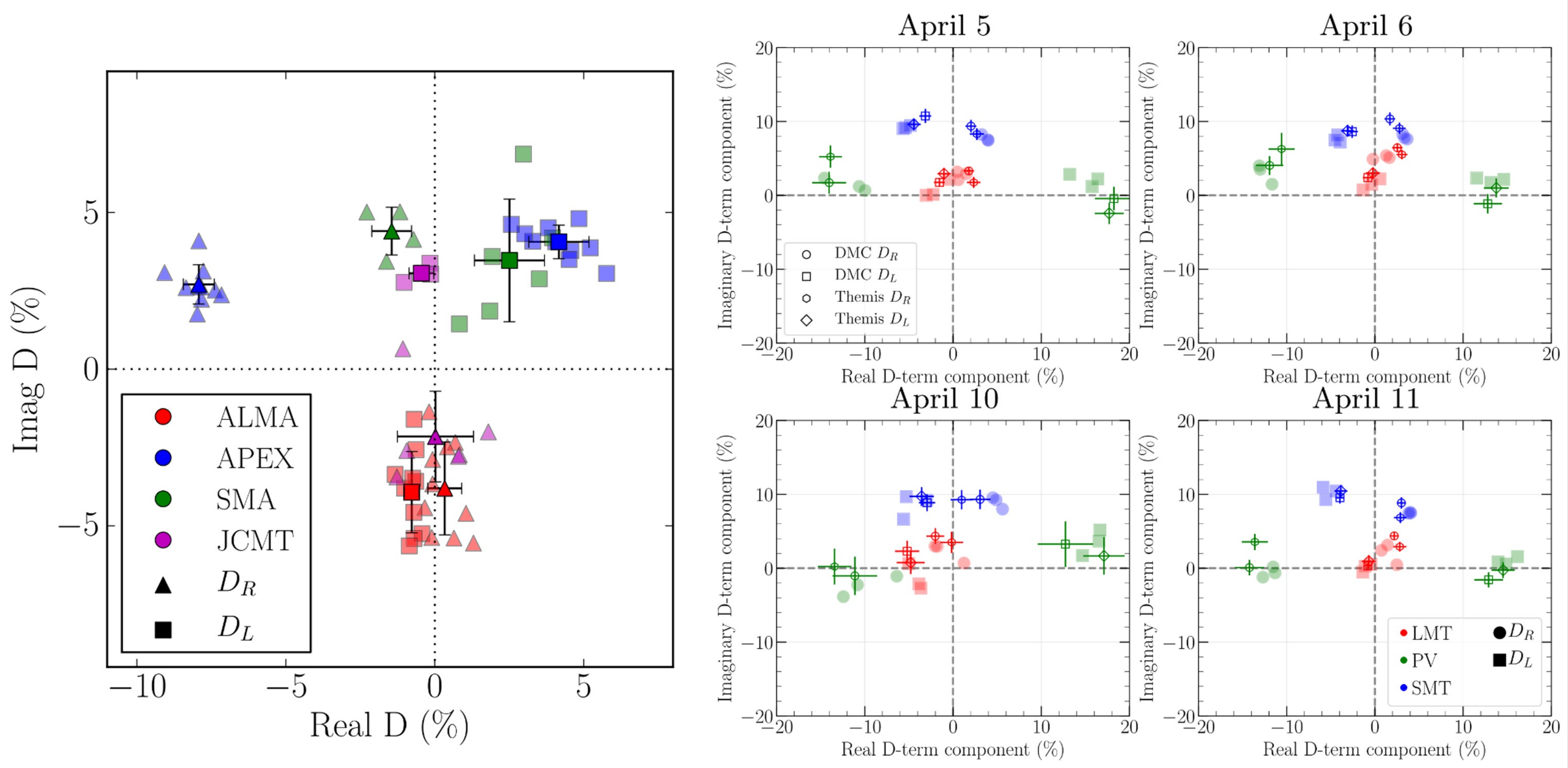
[MB]

additional priors

analysis

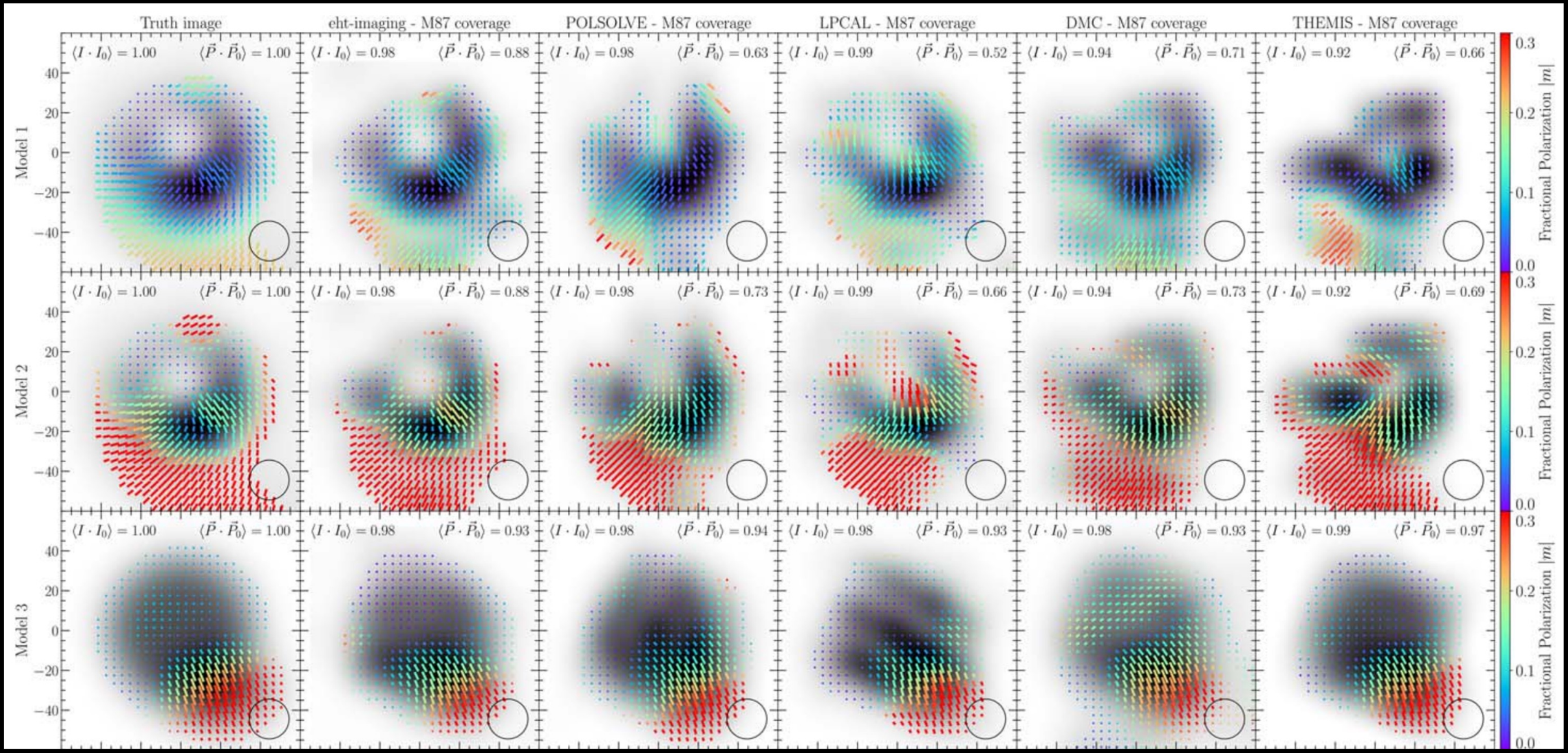
Very long baseline interferometry (VLBI) is a radio interferometer of telescopes separated by very long distances. One has to save the voltage data to hard drives at each station, bring the disks to the same place, and compute correlations (interference) of the signals.

How to remove instrumental signals from the data?



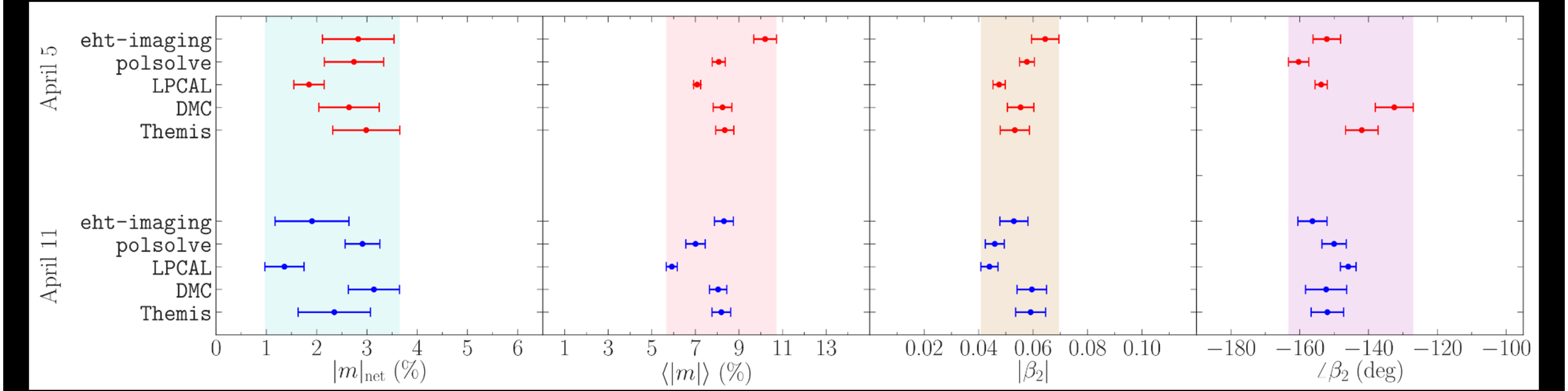
The derived D-terms from different sources, days, and softwares are consistent with each other.

Verification using synthetic data



We verified softwares and optimized parameters using various simulated data.

Linear Polarization Quantities



We obtained four quantities and define “conservative” ranges to be compared with the model.

$$|m|_{\rm net} = \frac{\sqrt{\left(\sum_i Q_i\right)^2 + \left(\sum_i U_i\right)^2}}{\sum_i I_i}$$

“Net” frac. pol.

$$\langle |m| \rangle = \frac{\sum_i \sqrt{Q_i^2 + U_i^2}}{\sum_i I_i}$$

Intensity-weighted frac. pol.

$$\beta_2 = \frac{1}{I_{\rm ring}} \int_{\rho_{\rm min}}^{\rho_{\rm max}} \int_0^{2\pi} P(\rho,\, \varphi)\, e^{-2i\varphi}\, \rho d\varphi d\rho$$

m=2 mode of azimuthal decomposition of the polarized ring structure