CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

Sagittarius A* Across The Radio Band

Sara Issaoun
NHFP Einstein Fellow
Center for Astrophysics | Harvard & Smithsonian

MeerKAT's view of the Galactic Center
Credit: I. Heywood, SARAO.

The Event Horizon Telescope Collaboration

300+ members, 60 institutes, 20 countries in Europe, Asia, Africa, North and South America.

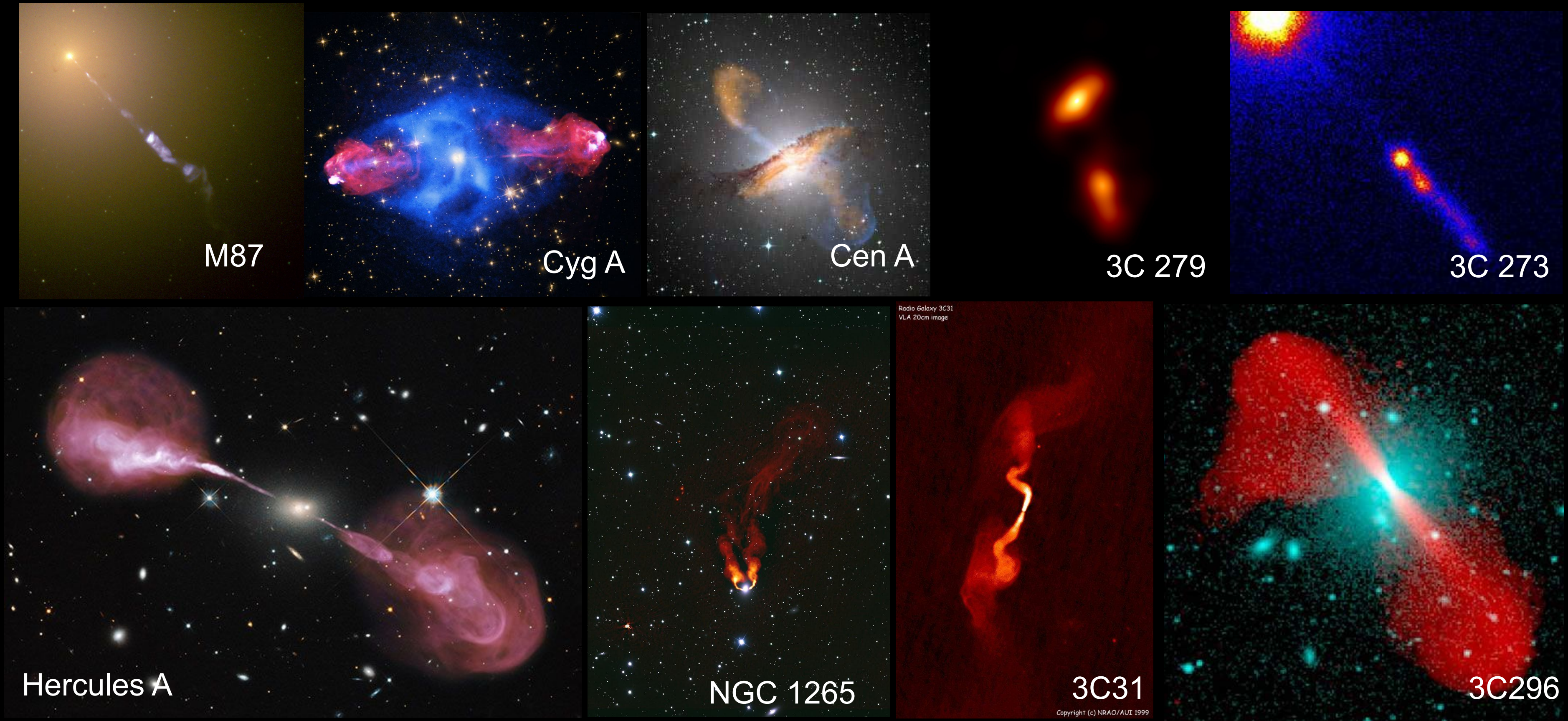
Slide credit: E. Traianou, MPIfR

The Event Horizon Telescope Collaboration

Direct imaging of black holes to:

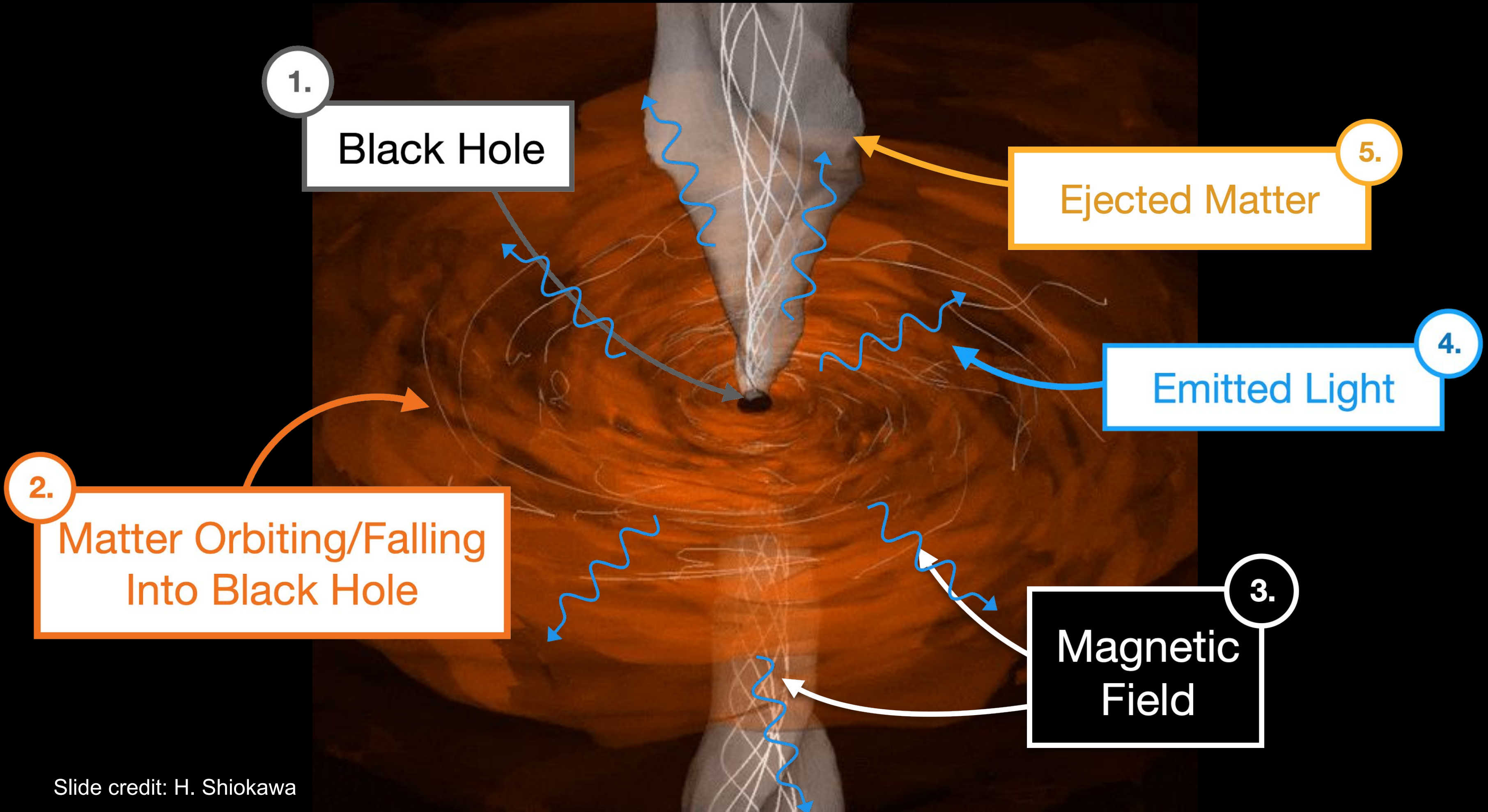
- Test theories of gravity in the vicinity of a supermassive black hole
- Connect horizon-scale physics to launching mechanisms of relativistic jets
- Connect horizon-scale dynamics to multi-wavelength variability/flares

Why are we interested in imaging a black hole?



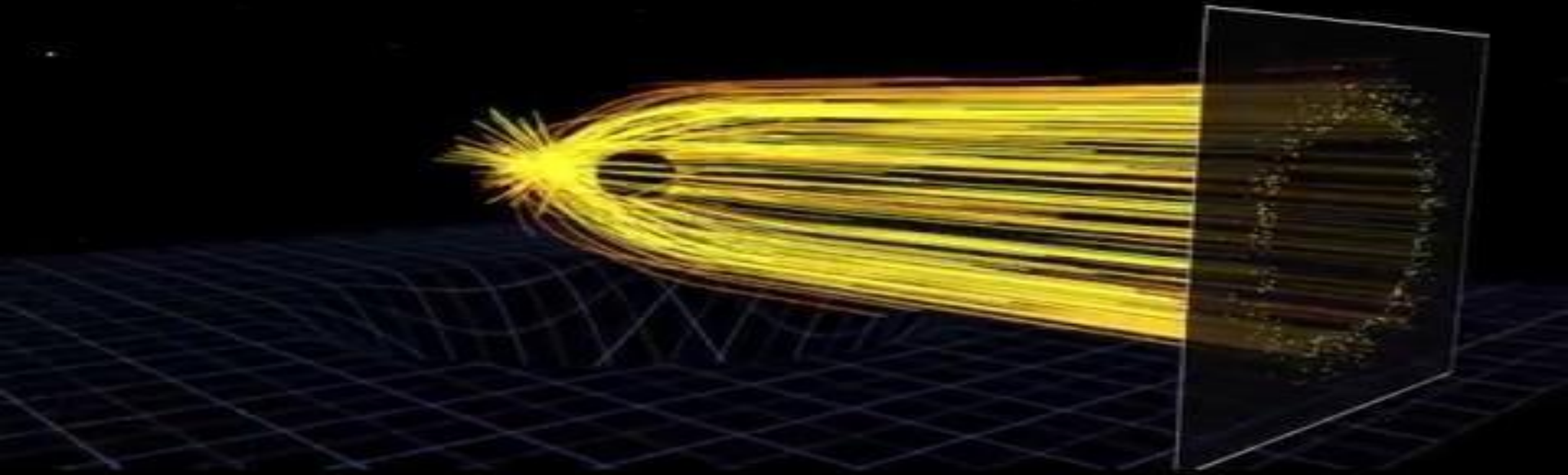
Credits: (M87: HST), (Cyg A: Chandra/HST/VLA (Cyg A), (Cen A: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)), (NGC 1265: M. Gendron-Marsolais et al.; S. Dagnello, NRAO/AUI/NSF; Sloan Digital Sky Survey),(3C279, EHT),(3C293, Chandra),(Hercules A, HST/VLA),(NGC1265,M. Gendron-Marsolais et al.; S. Dagnello, NRAO/AUI/NSF; SDSS), (3C31, VLA), (3C296, AUI, NRAO)

Simulating a black hole and its environment



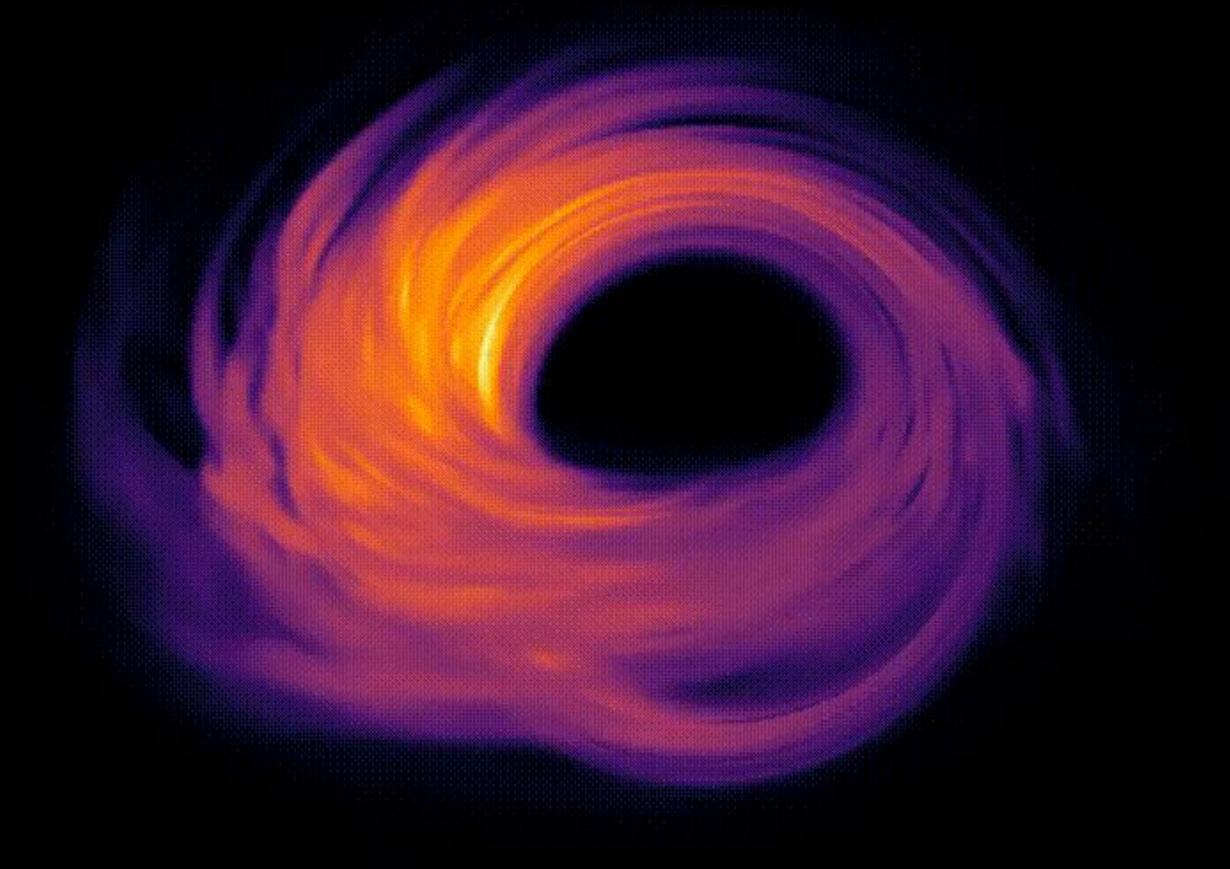
Slide credit: H. Shiokawa

What is the black hole shadow?



Animation credit: CrazyBridge Studios

What is the black hole shadow?



Animation credit: Z. Younsi, T. Bronzwaer & J. Davelaar, Frankfurt/Radboud/U.Columbia

Horizon-scale targets: M87* and Sagittarius A*

Inclination

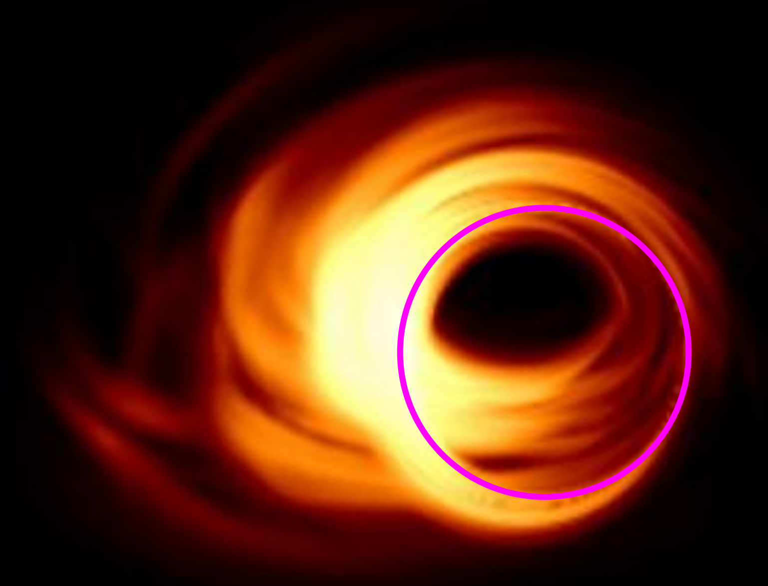
Mass

Spin

Distance

Scattering

Astrophysics



M. Moscibrodzka, Radboud U.
Moscibrodzka & Gammie 2018

Horizon-scale targets: M87* and Sagittarius A*


43 GHz with the Very Long Baseline Array/ Walker et al. 2018


22 GHz with the Very Large Array/ NRAO

M87*

- Mass
- Distance
- Inclination
- Spin
- Astrophysical model

Sagittarius A*

- Mass
- Distance
- Inclination
- Spin
- Astrophysical model

Horizon-scale targets: M87* and Sagittarius A*

43 GHz with the Very Long Baseline Array/ Walker et al. 2018

22 GHz with the Very Large Array/ NRAO

M87

- Mass
- Distance
- Inclination
- Spin
- Astrophysical model

Sagittarius A*

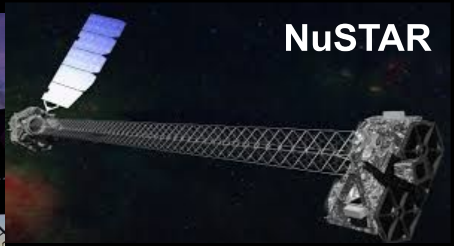
- Mass
- Distance
- Inclination
- Spin
- Astrophysical model
- Variability
- Scattering

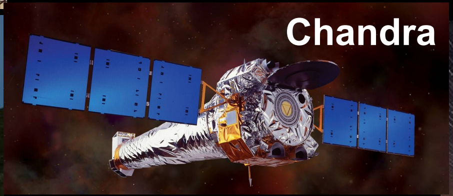
The Event Horizon Telescope in 2017

6 different locations
6 single-dish telescopes
2 phased arrays

Photos: ALMA, Sven Dornbusch, Junhan Kim, Helge Rottmann, David Sanchez, Daniel Michalik, Jonathan Weintroub, William Montgomerie, Tom Lowe, Serge Brunier

Our Multi-Wavelength Partners





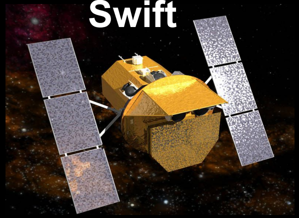


Image credits: NSF/VERITAS, Juan Cortina, Vikas Chander, NASA, NASA/JPL-Caltech, NASA/CXC/SAO, NASA, ESO, P. Kranzler & A. Phelps, NRAO/AUI/NSF, HyeRyung, NAOJ, MPIfR/N. Tacken

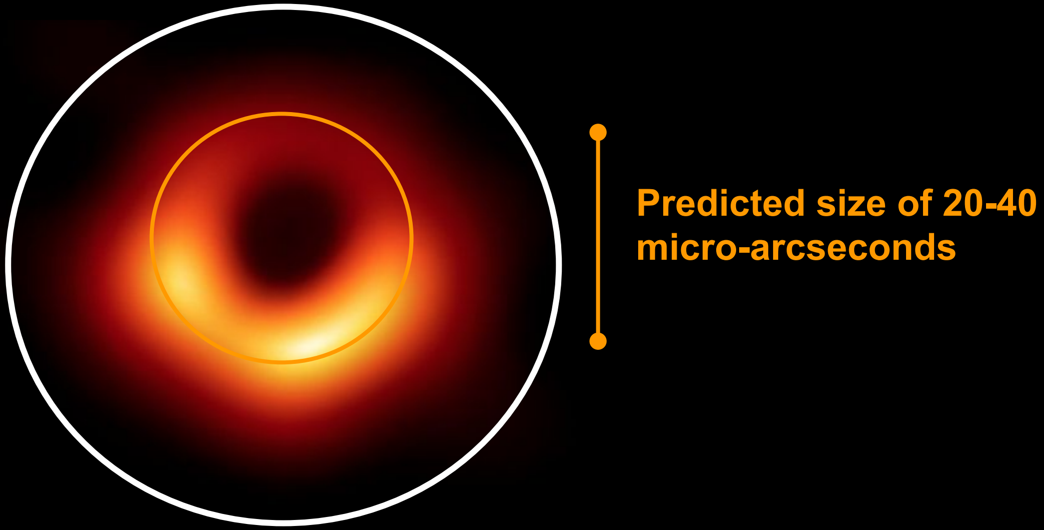
Our Multi-Wavelength Partners

Image credits: NSF/VERITAS, Juan Cortina, Vikas Chander, NASA, NASA/JPL-Caltech, NASA/CXC/SAO, NASA, ESO, P. Kranzler & A. Phelps, NRAO/AUI/NSF, HyeRyung, NAOJ, MPIfR/N. Tacken

Animation credit: ESO

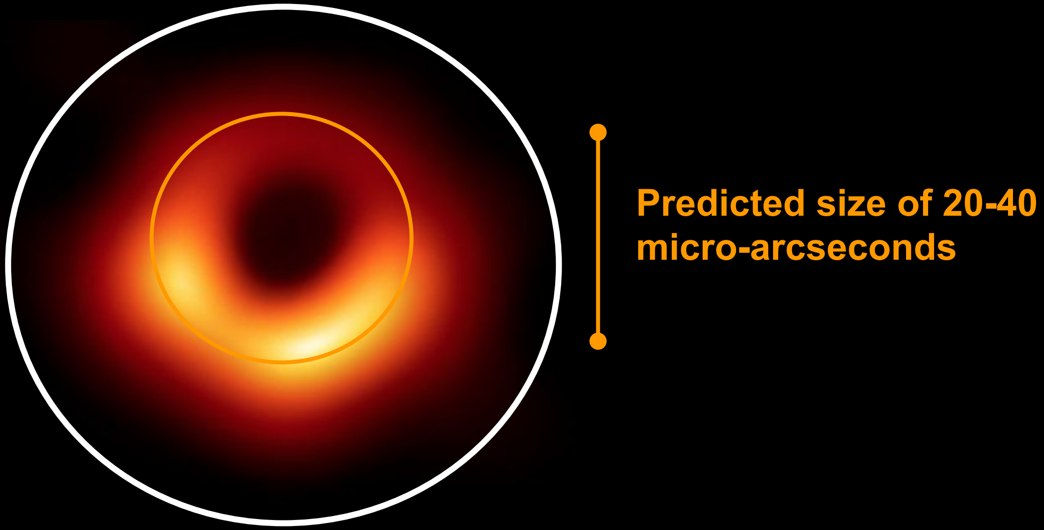
How Big Must our Telescope Be?

$$\text{Telescope Size} \propto \frac{\text{Observing Wavelength}}{\text{Angular Resolution}}$$



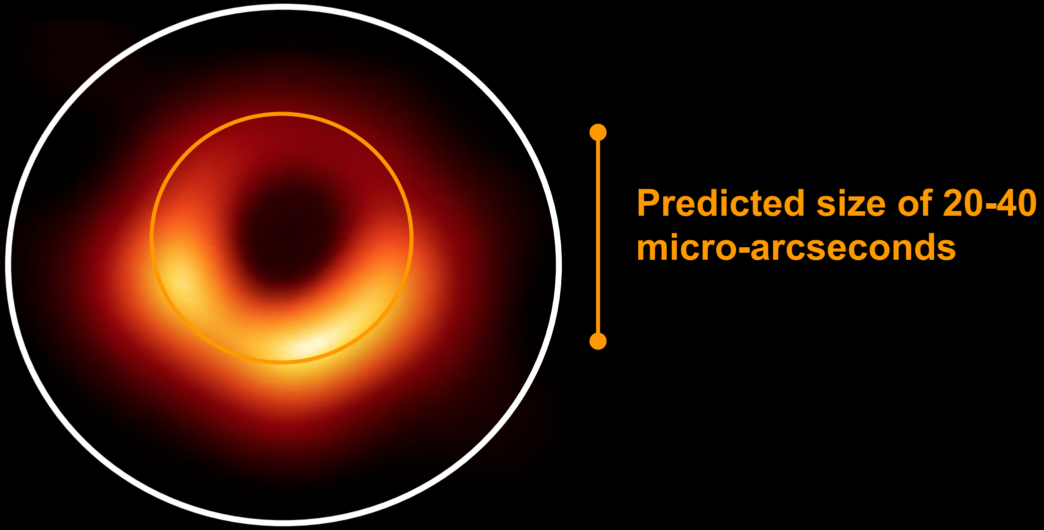
How Big Must our Telescope Be?

$$\text{Telescope Size} \propto \frac{\text{Observing Wavelength}}{\color{red}{\text{20 micro-arcseconds}}}$$



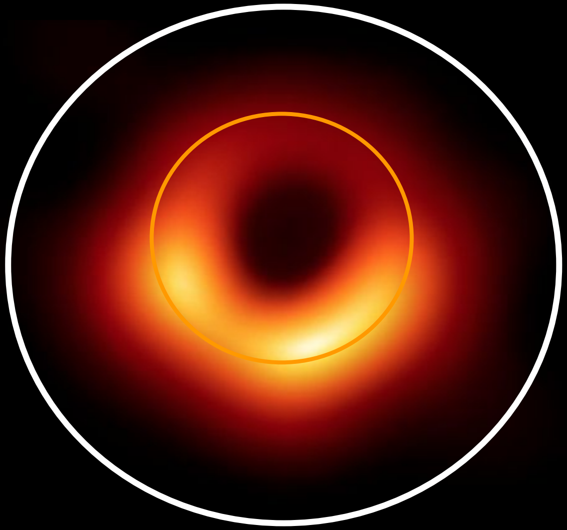
How Big Must our Telescope Be?

$$\text{Telescope Size} \propto \frac{\text{1.3 millimeters}}{\text{20 micro-arcseconds}}$$



How Big Must our Telescope Be?

$$\text{13 million meters} \propto \frac{\text{1.3 millimeters}}{\text{20 micro-arcseconds}}$$



Predicted size of 20-40 micro-arcseconds

Animation credit: ESO

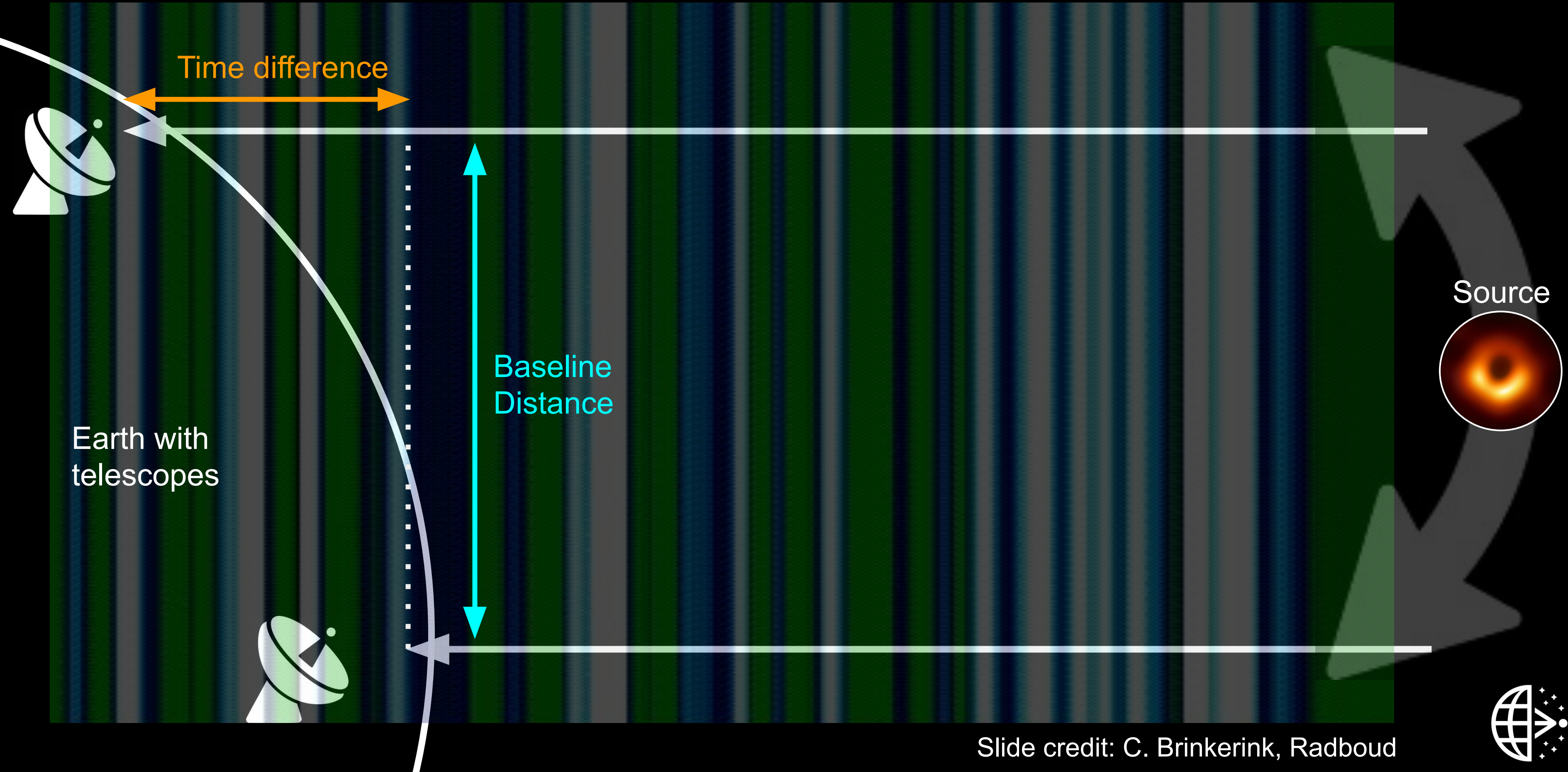
Very Long Baseline Interferometry

Slide credit: C. Brinkerink, Radboud

Very Long Baseline Interferometry

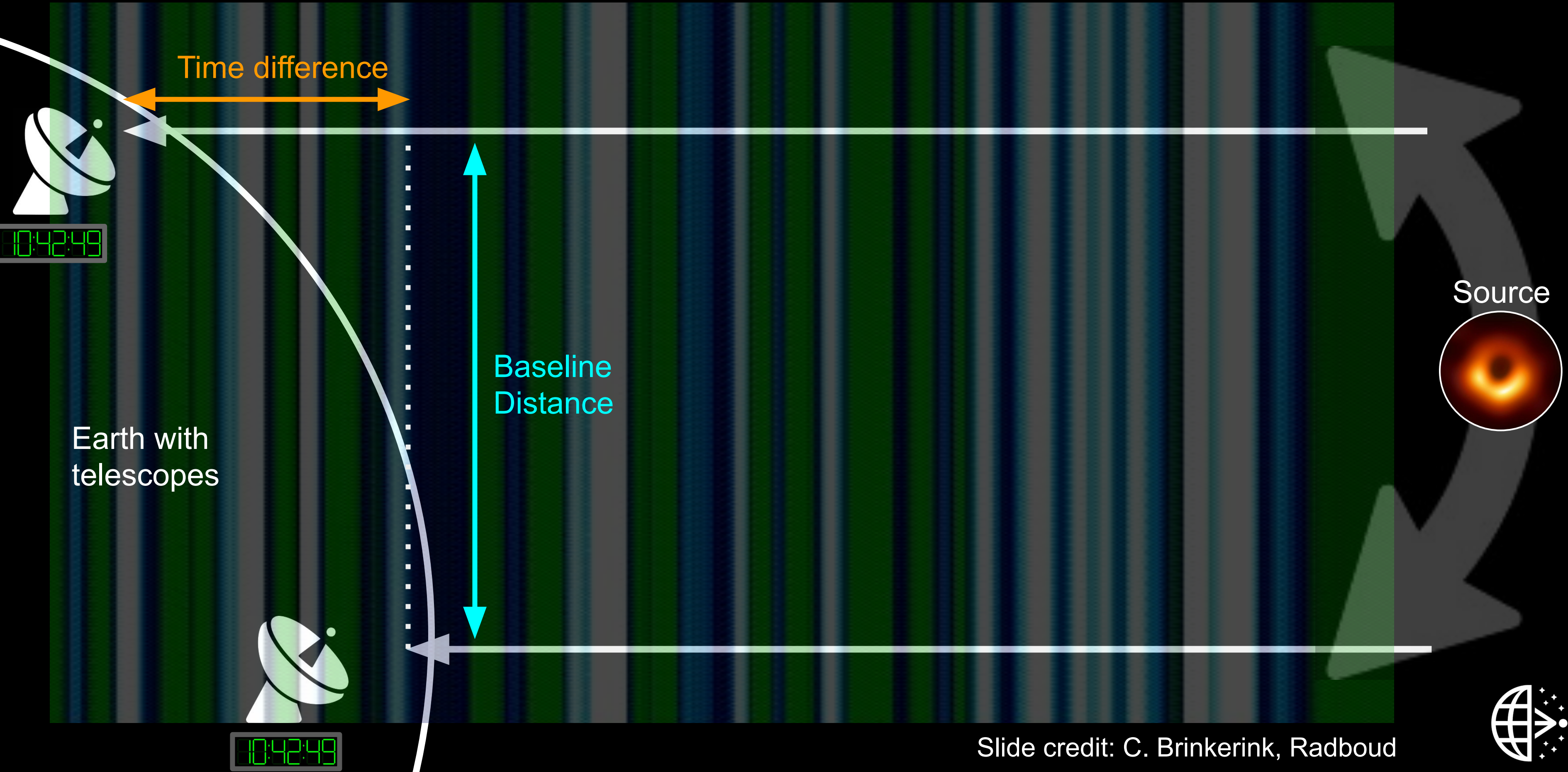
Slide credit: C. Brinkerink, Radboud

Very Long Baseline Interferometry



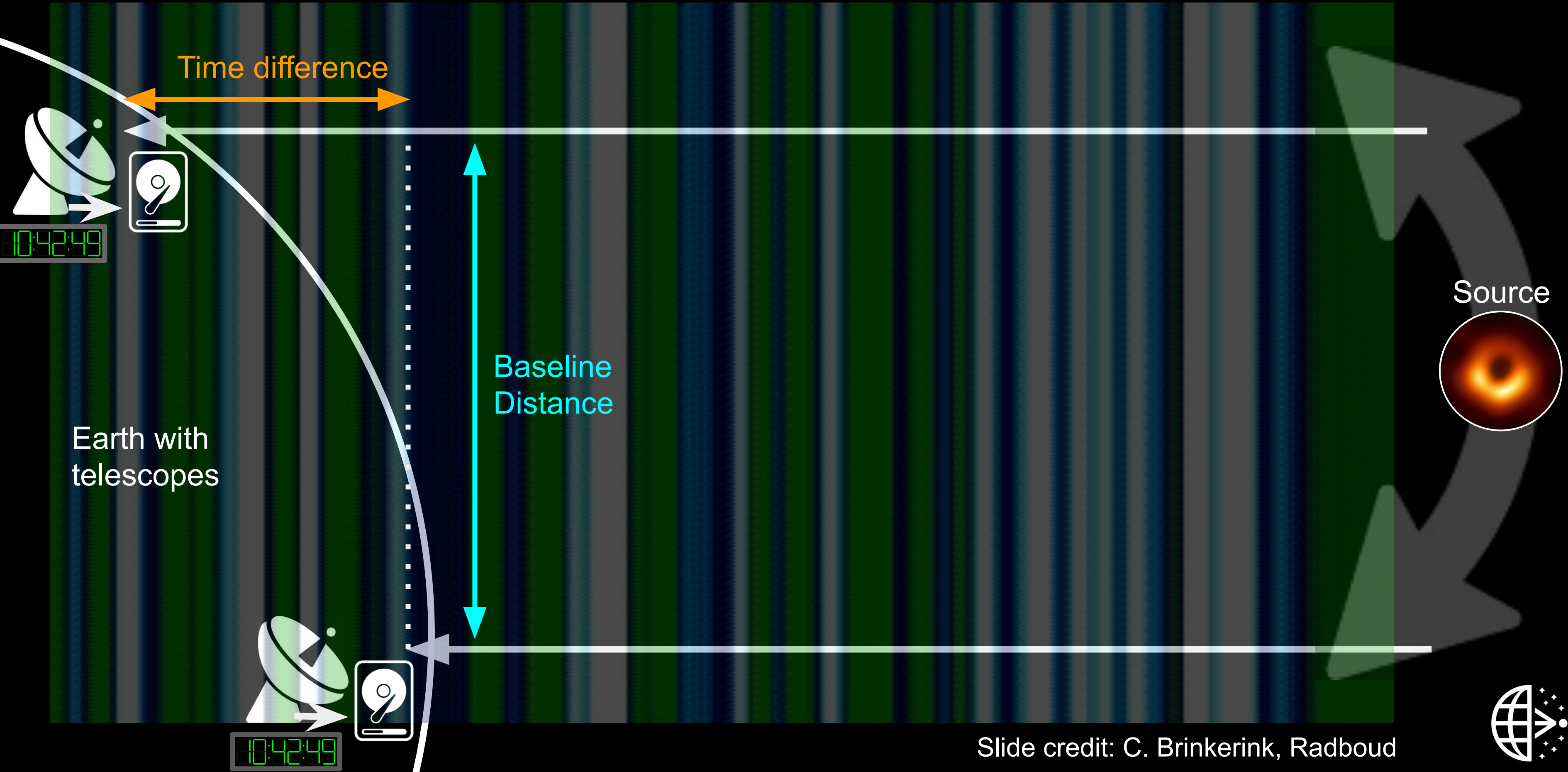
Slide credit: C. Brinkerink, Radboud

Very Long Baseline Interferometry



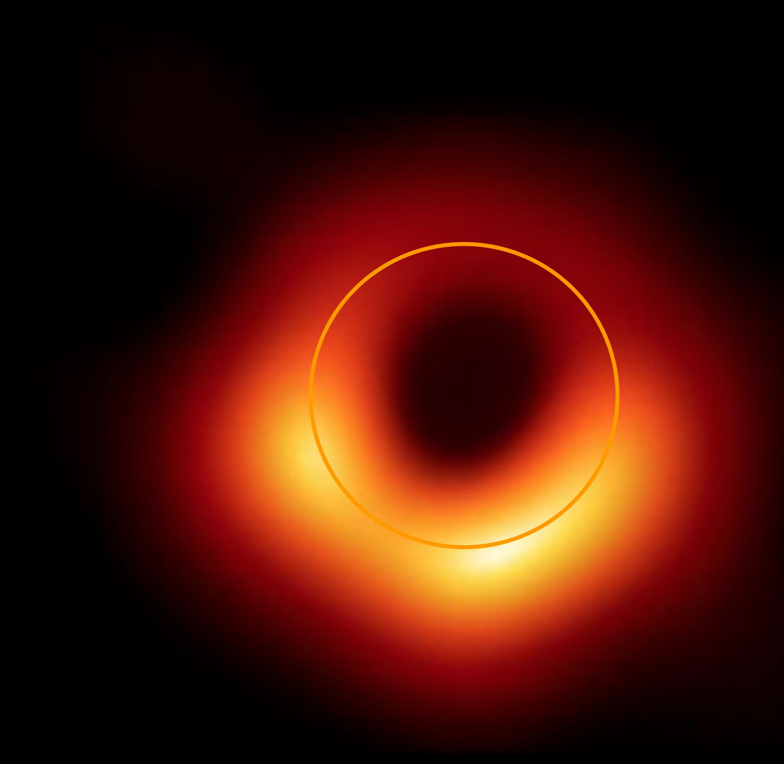
Slide credit: C. Brinkerink, Radboud

Very Long Baseline Interferometry



Slide credit: C. Brinkerink, Radboud

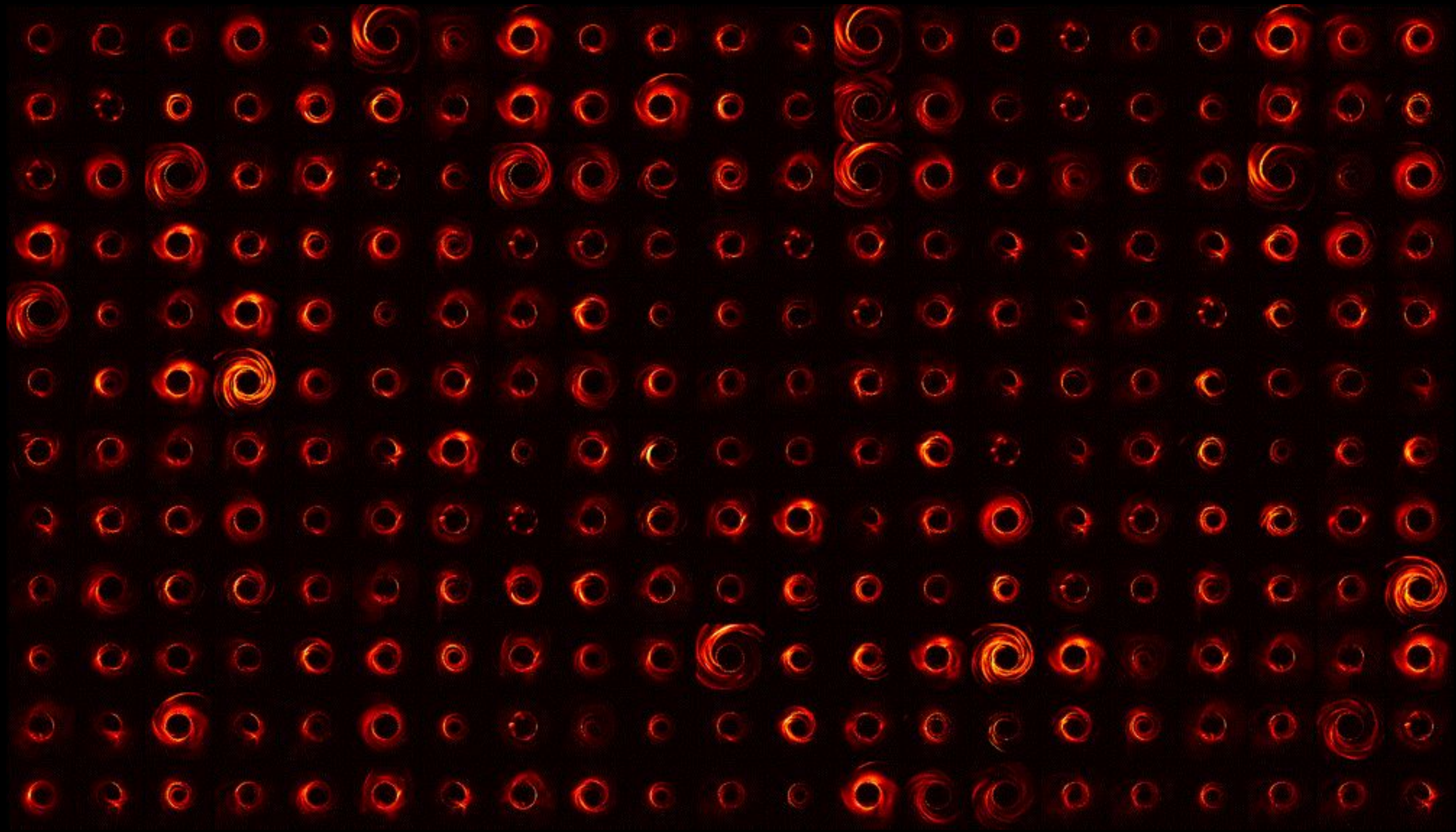
The first target: the M87 black hole



6.5 ± 0.7 **billion** solar masses

EHTC+ 2019. ApJL, 875, L6 (Paper VI)

How well can we replicate nature?



Animation credit: A. Broderick, Perimeter

EHTC+ 2019. ApJL, 875, L5 (Paper V)

The 2017 observations

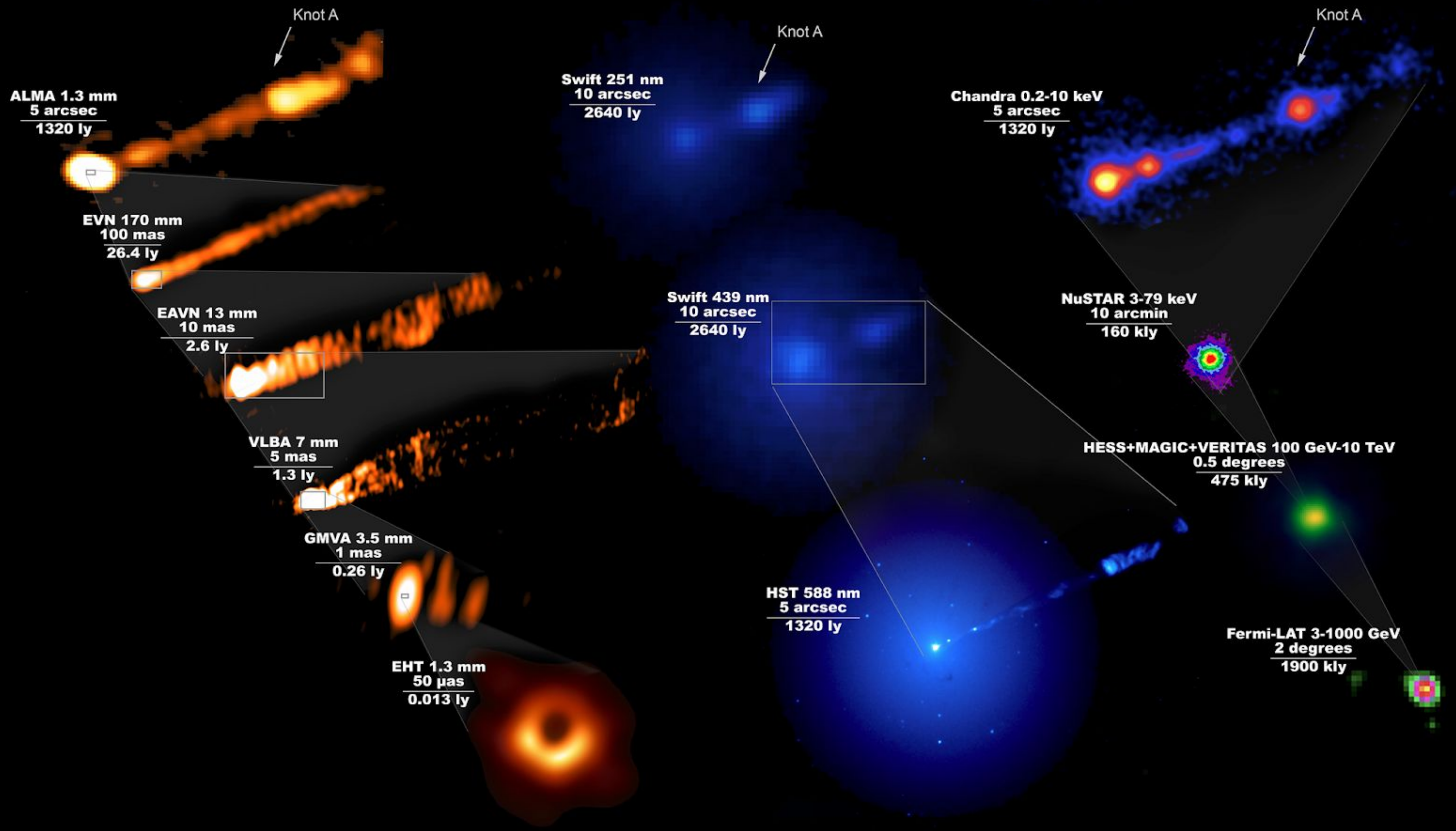


Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array;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

The first target: the M87 black hole

Longer wavelength radio inform jet physics

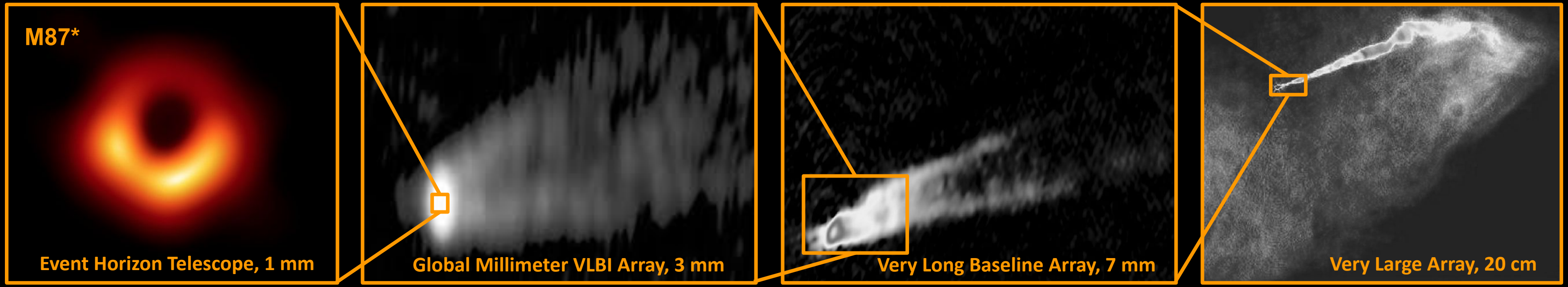


Image credits: EHT Collaboration/Kim et al. 2018/Walker et al. 2018/NRAO VLA

Many theoretical models are able to reproduce the EHT signatures, but could not make it past multi-wavelength X-ray and broadband radio jet constraints.

EHTC+ 2019. ApJL, 875, L1 (Paper V)

So how much did we learn?

Rejection Table

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

EHT data

Thin disk limit

X-ray flux

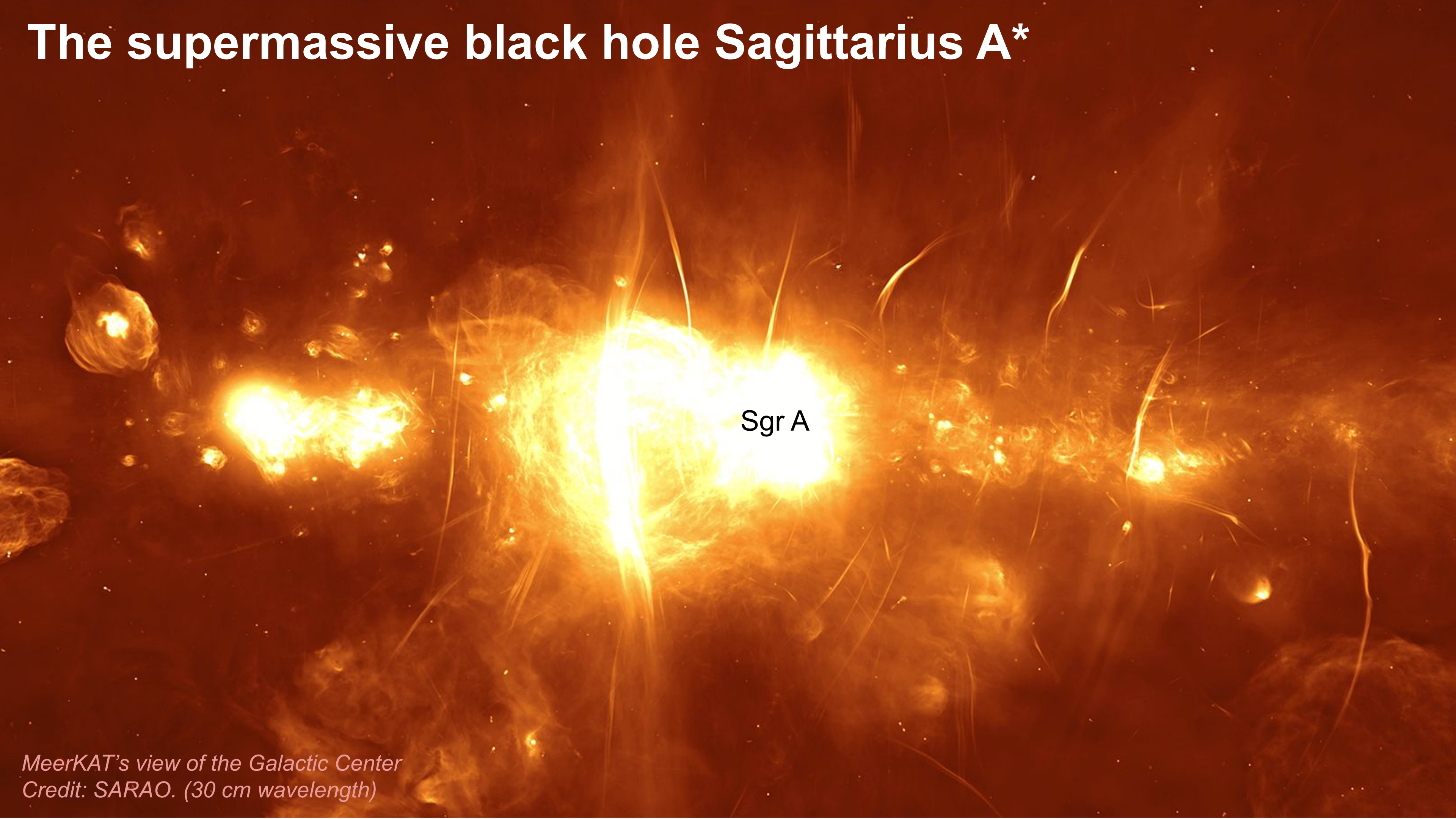
Large-scale jet

Rejection Table

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

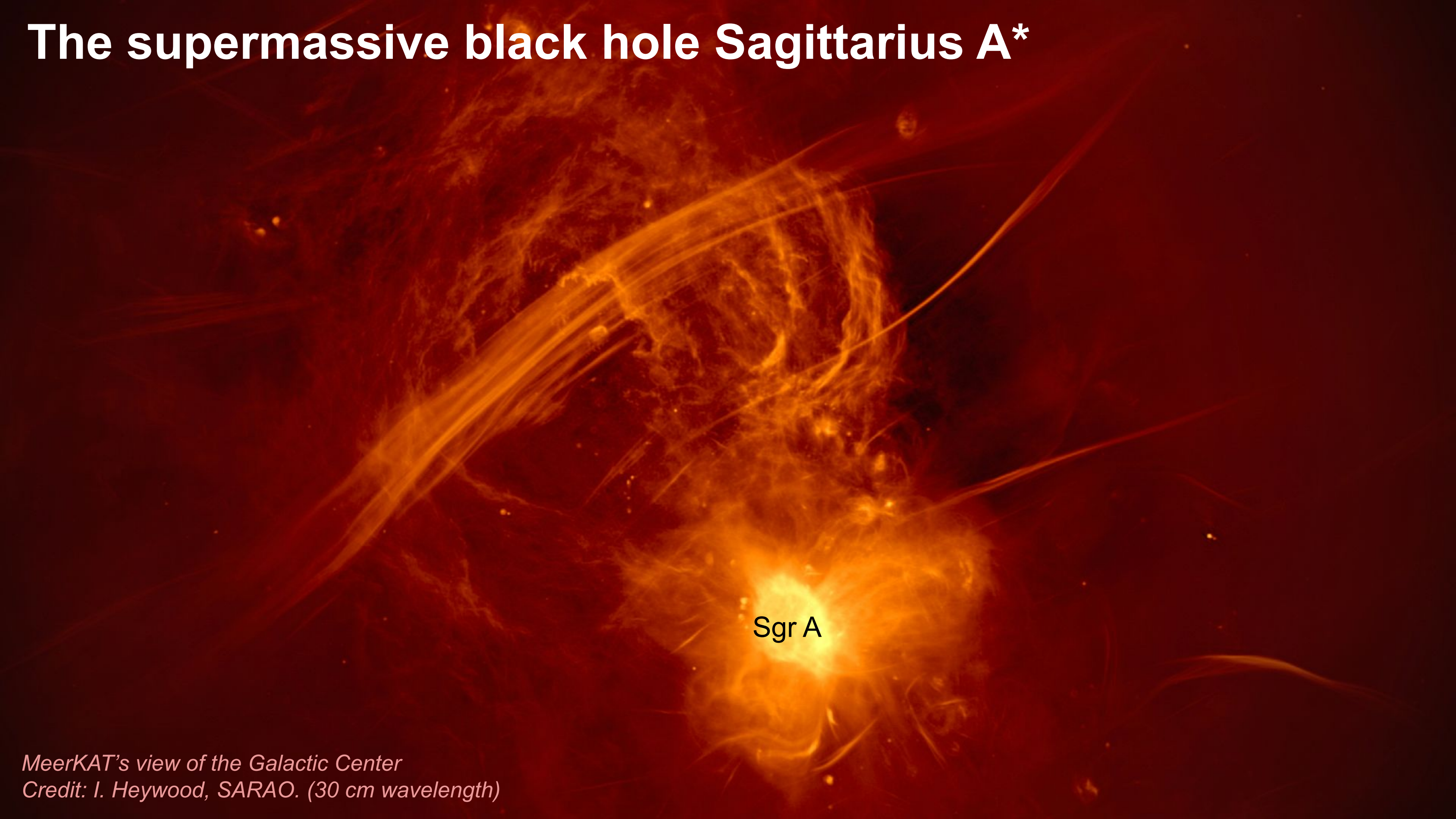
EHTC+ 2019. ApJL, 875, L5 (Paper V)

The supermassive black hole Sagittarius A*



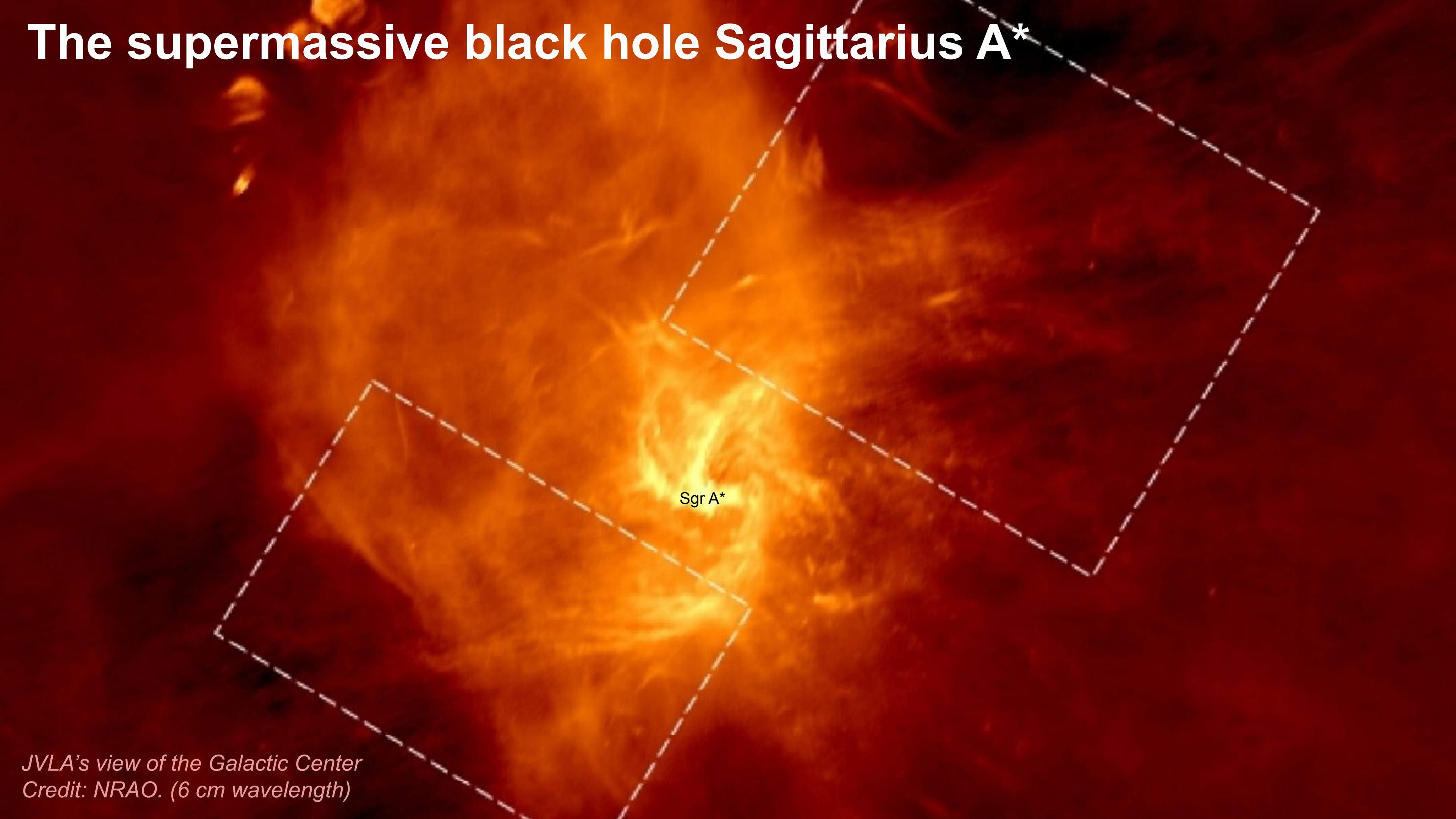
MeerKAT's view of the Galactic Center
Credit: SARAO. (30 cm wavelength)

The supermassive black hole Sagittarius A*



MeerKAT's view of the Galactic Center
Credit: I. Heywood, SARAO. (30 cm wavelength)

The supermassive black hole Sagittarius A*



JVLA's view of the Galactic Center
Credit: NRAO. (6 cm wavelength)

The supermassive black hole Sagittarius A*

Closest supermassive black hole

- Mass: 4.1×10^6 solar masses
- Distance: 8.1 kpc

(Gravity Collaboration+ 2019, Do+ 2019)

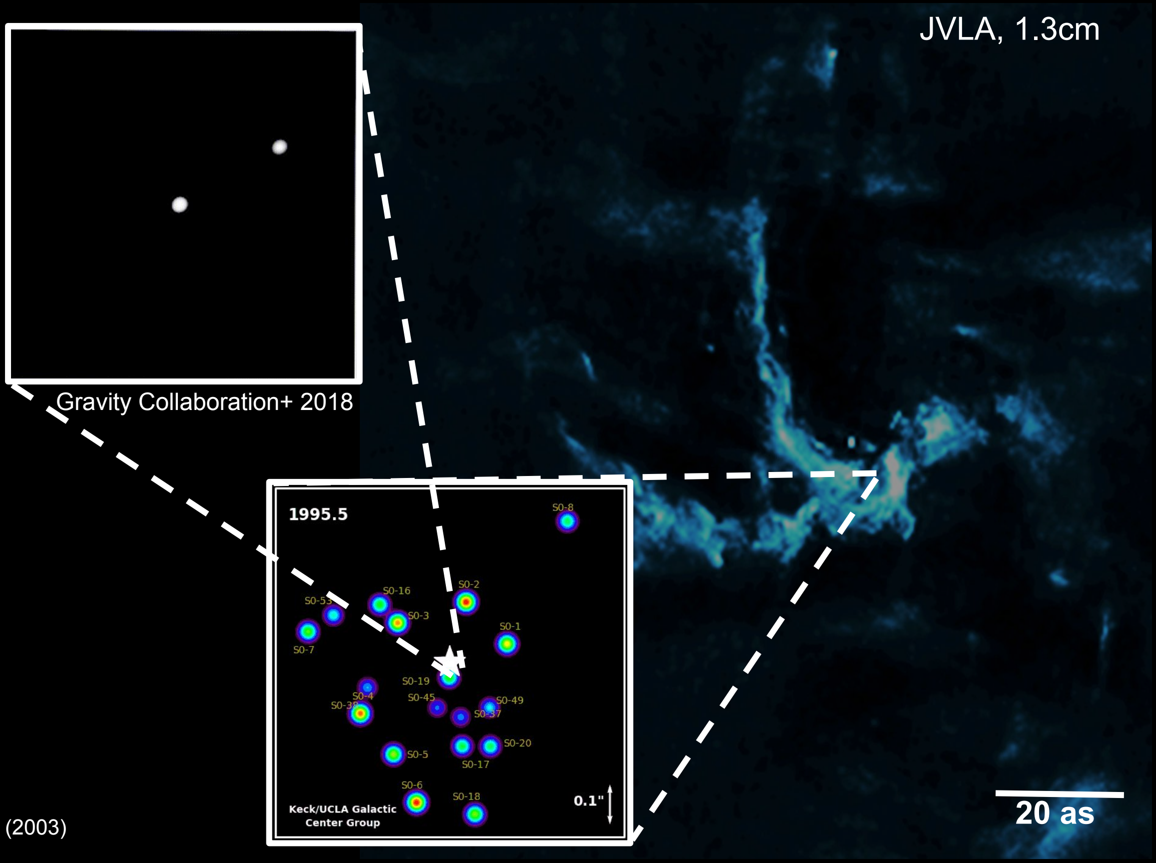


Image Credits:
X-ray: NASA/CXC/UCLA/Z. Li et al
Radio 22 GHz: NRAO/VLA
S-stars: UCLA Galactic Center Group (Keck), Genzel et al. (2010), Yuan et al. (2003)
S2: Gravity Collaboration+ 2018, ESO/Gravity

The supermassive black hole Sagittarius A*

What does Sgr A* look like?

Expected size of the shadow of Sgr A*:
~50 μas ~ 5 Schwarzschild radii

(Falcke+2000, Doeleman+2008, Fish+2011, Johnson+2015, Fish+2016, Lu+ 2018)

What is the orientation of the black hole?
Is it spinning?

Long-standing debate: what emission process dominates in the radio (disk versus jet)?

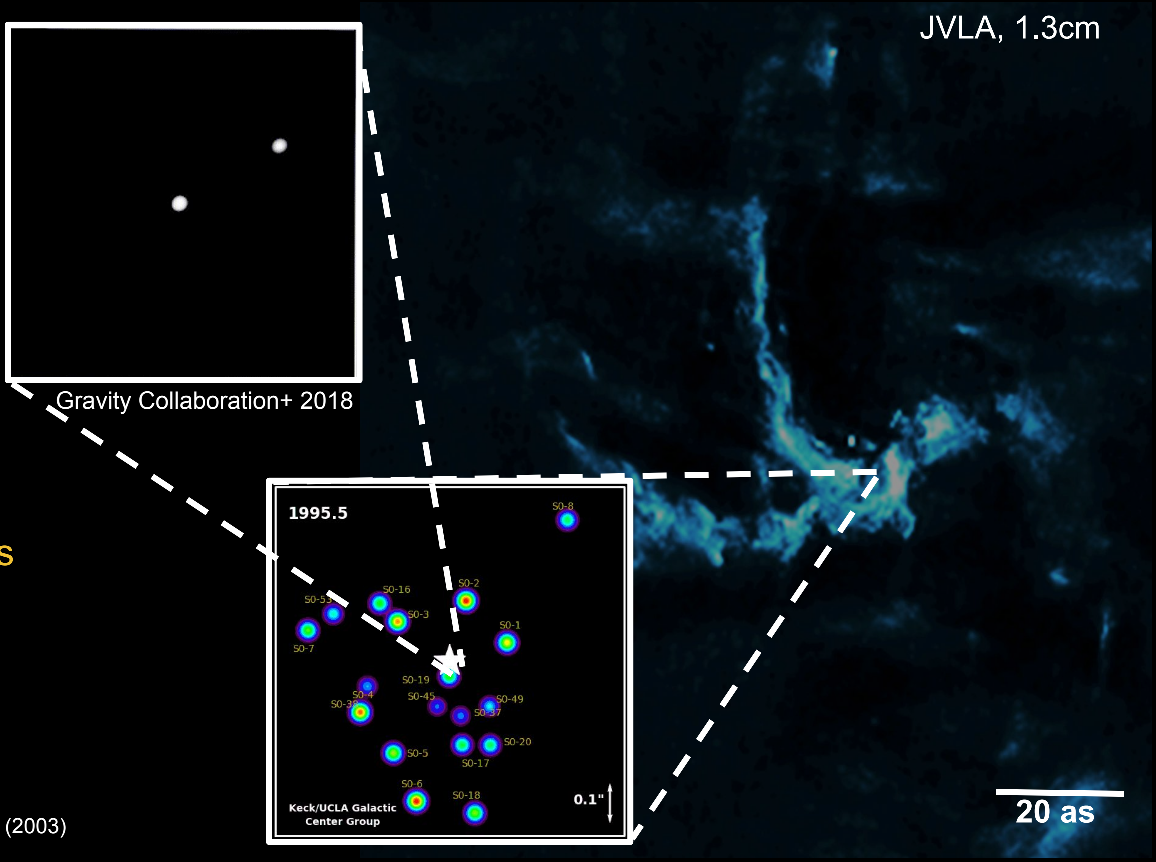


Image Credits:
X-ray: NASA/CXC/UCLA/Z. Li et al
Radio 22 GHz: NRAO/VLA
S-stars: UCLA Galactic Center Group (Keck), Genzel et al. (2010), Yuan et al. (2003)
S2: Gravity Collaboration+ 2018, ESO/Gravity

The supermassive black hole Sagittarius A*

Event Horizon Telescope

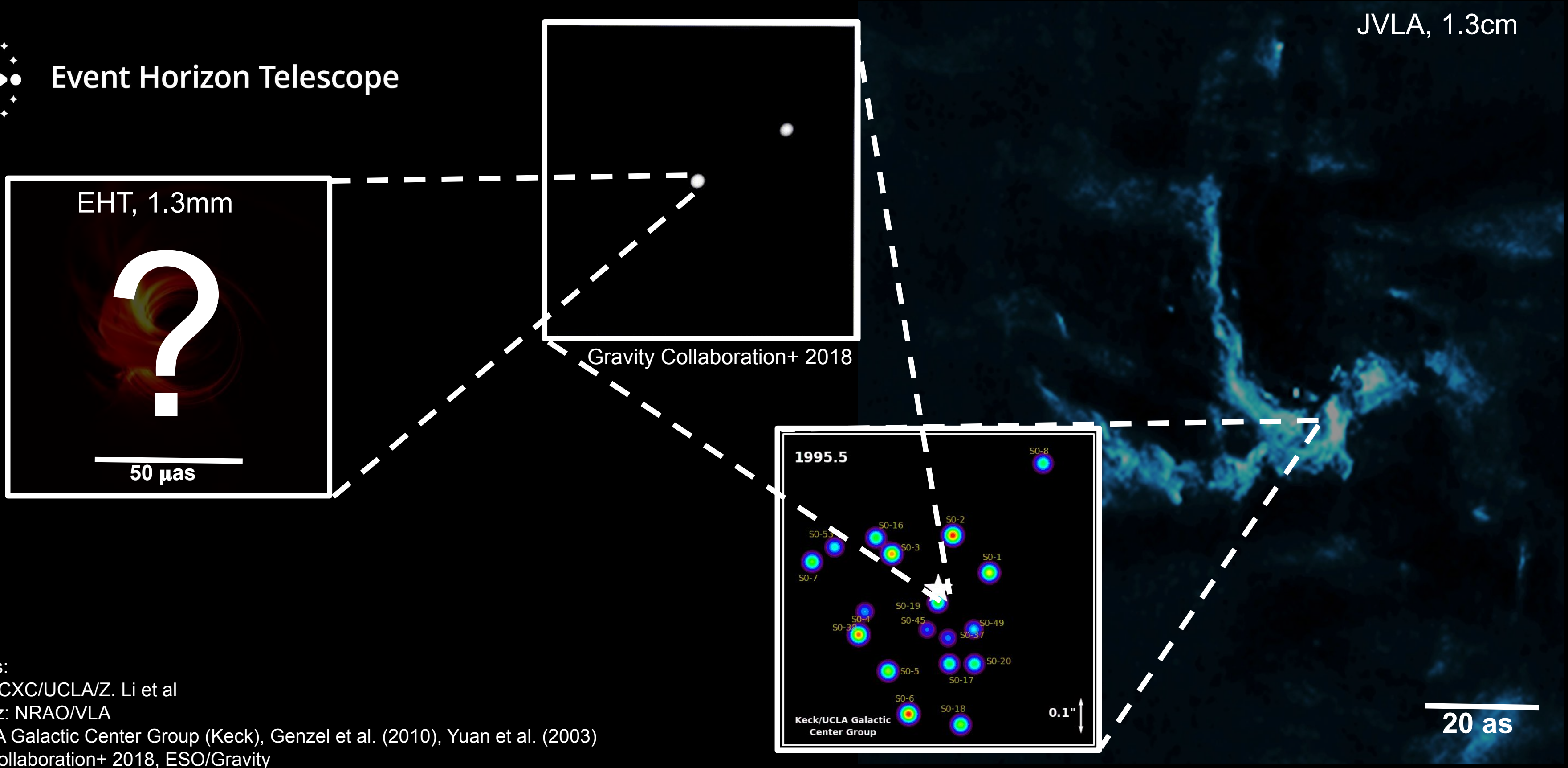
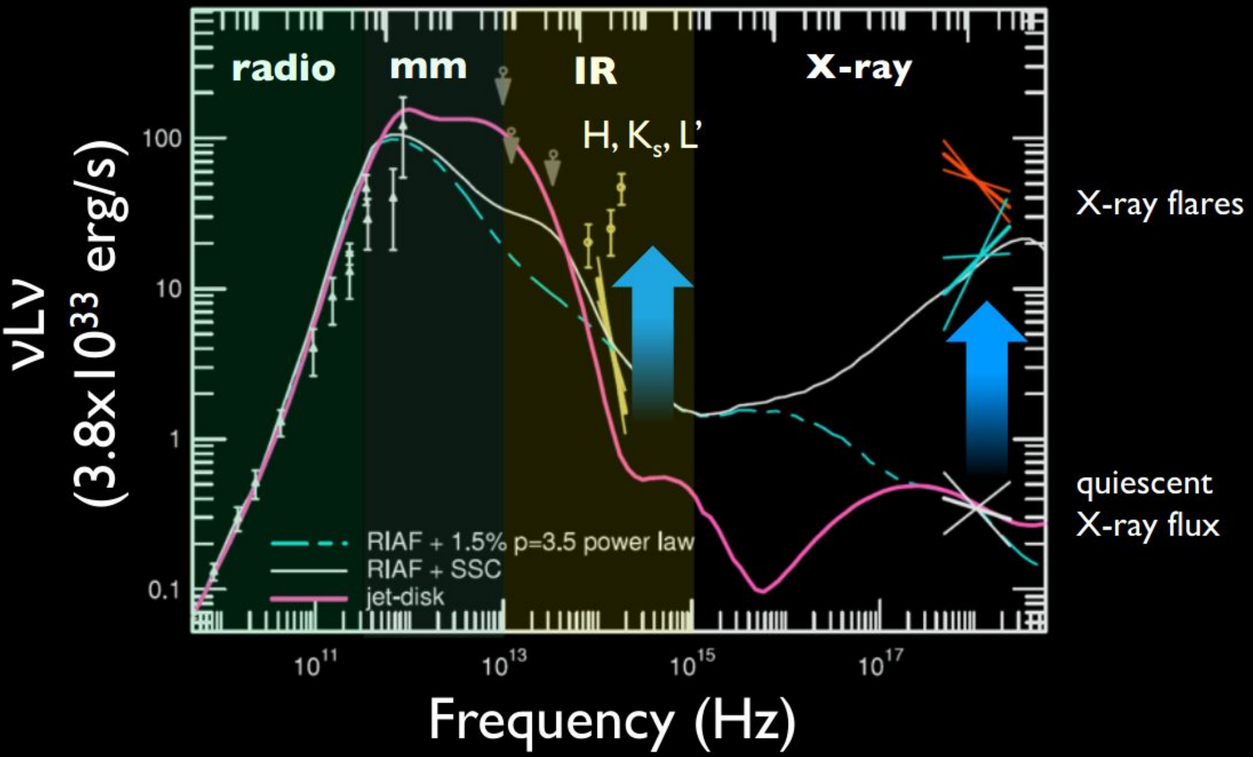


Image Credits:
X-ray: NASA/CXC/UCLA/Z. Li et al
Radio 22 GHz: NRAO/VLA
S-stars: UCLA Galactic Center Group (Keck), Genzel et al. (2010), Yuan et al. (2003)
S2: Gravity Collaboration+ 2018, ESO/Gravity

The supermassive black hole Sagittarius A*

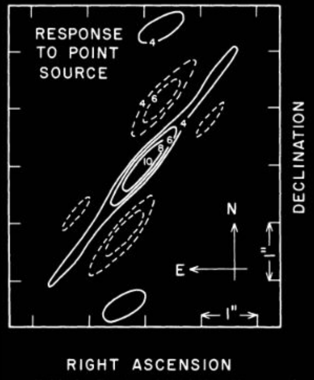
The SED of Sgr A* is highly variable, simultaneous coverage is crucial for modeling

[Genzel, et al. 2003; Yuan et al. 2004]

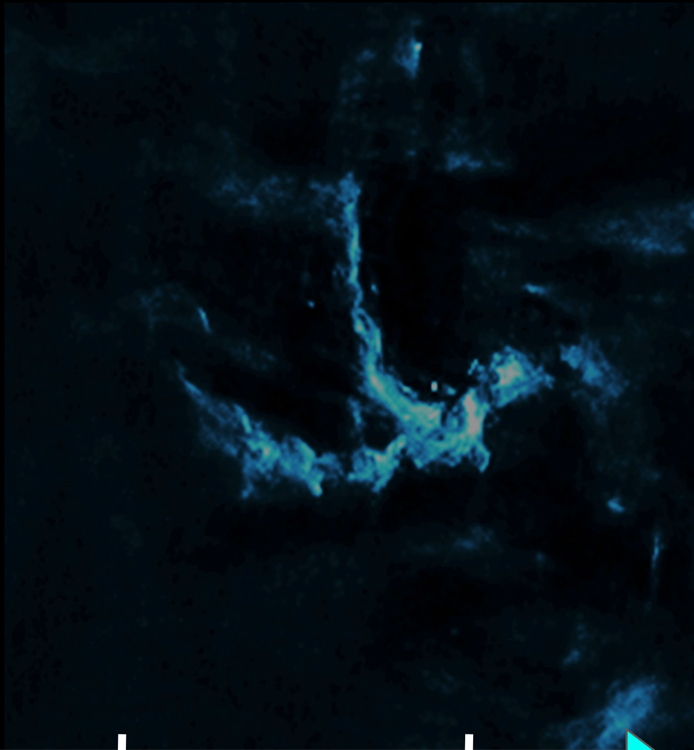


Slide credit: D. Haggard, McGill / EHT MWL Science WG

The Galactic Center Across The Radio Band

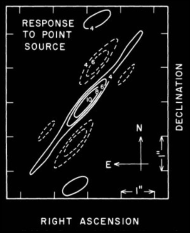


Radio source first detected in the Galactic Center at 11 and 3.7 cm (Balick & Brown 1974)

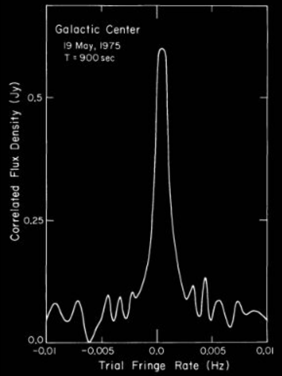


1970 1980 1990 2000 2010

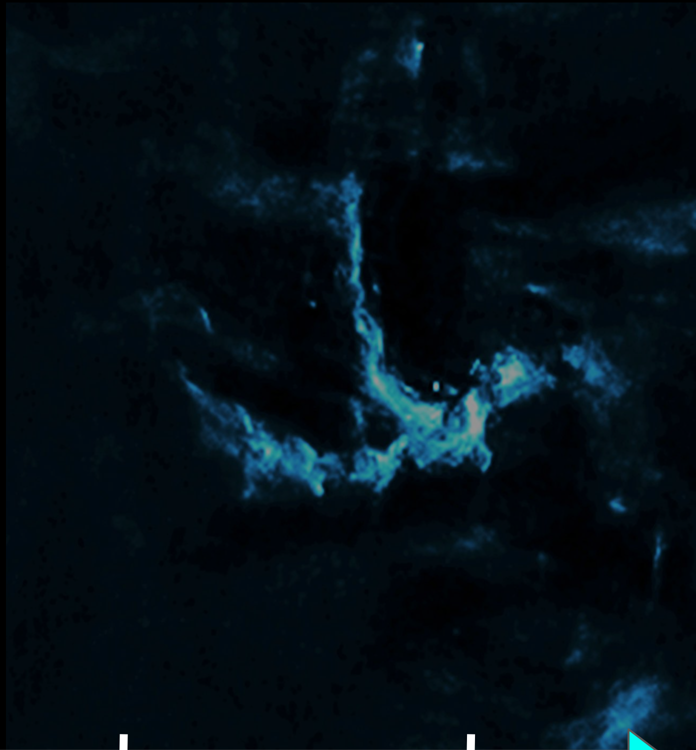
The Galactic Center Across The Radio Band

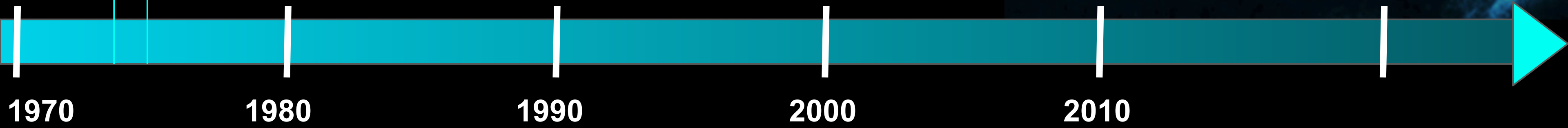


Radio source first detected in the Galactic Center at 11 and 3.7 cm (Balick & Brown 1974)

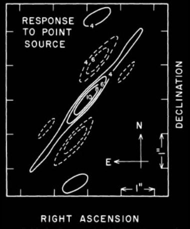


First VLBI detection of the radio source (Lo+ 1975)

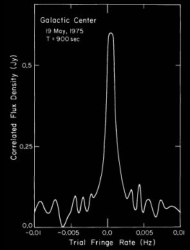




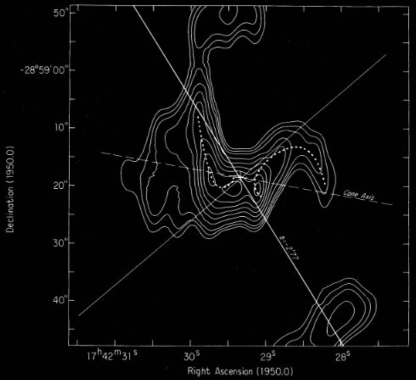
The Galactic Center Across The Radio Band



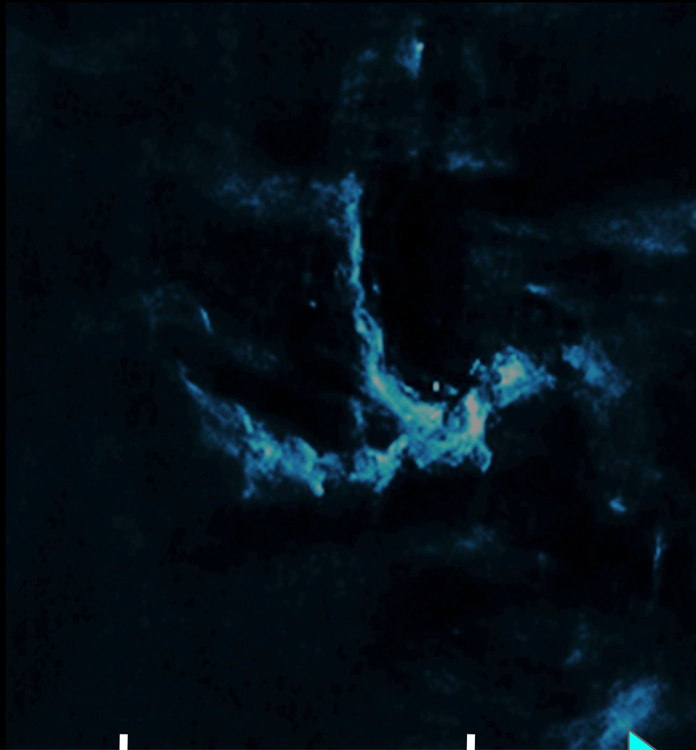
Radio source first detected in the Galactic Center at 11 and 3.7 cm (Balick & Brown 1974)



First VLBI detection of the radio source (Lo+ 1975)

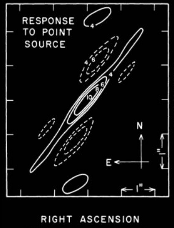


The non-thermal radio source is named Sagittarius A* (Brown 1982)

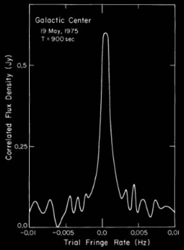


1970 1980 1990 2000 2010

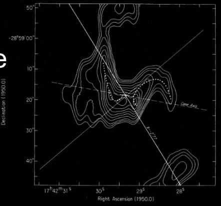
The Galactic Center Across The Radio Band



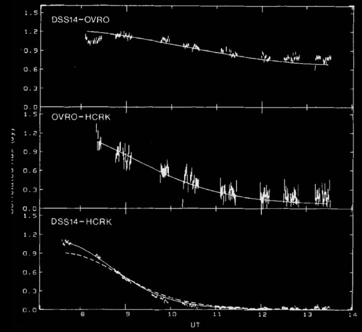
Radio source first detected in the Galactic Center at 11 and 3.7 cm (Balick & Brown 1974)



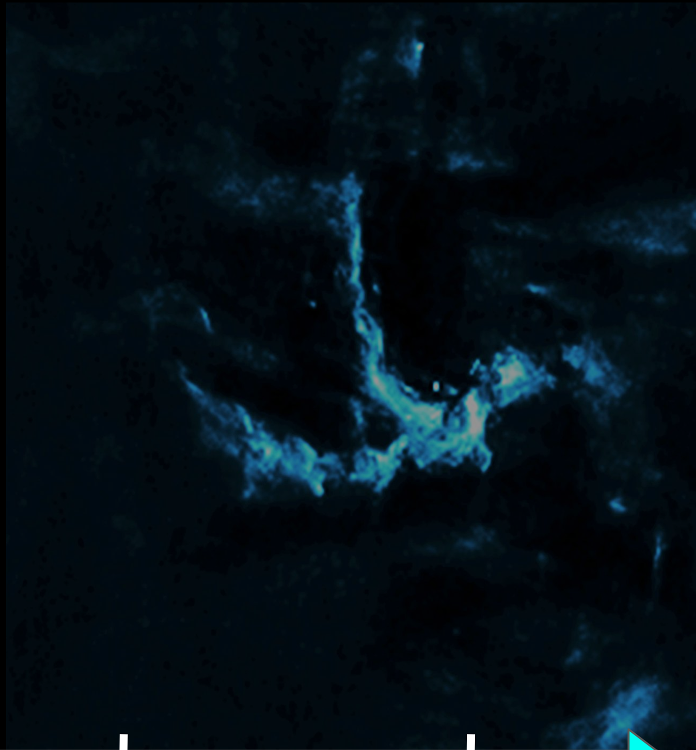
First VLBI detection of the radio source (Lo+ 1975)



The non-thermal radio source is named Sagittarius A* (Brown 1982)

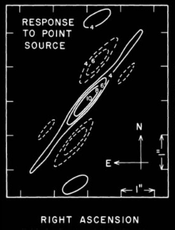


First observation of an elongated structure at 3.6 cm (Lo+ 1985)

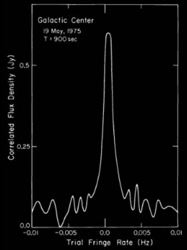


1970 1980 1990 2000 2010

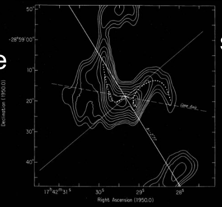
The Galactic Center Across The Radio Band



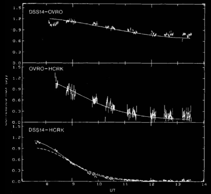
Radio source first detected in the Galactic Center at 11 and 3.7 cm (Balick & Brown 1974)



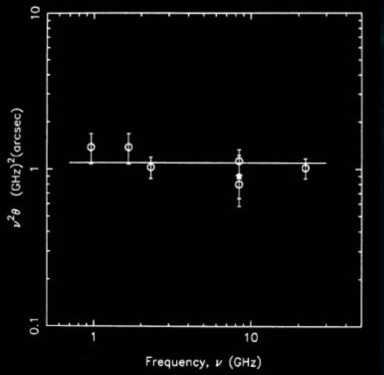
First VLBI detection of the radio source (Lo+ 1975)



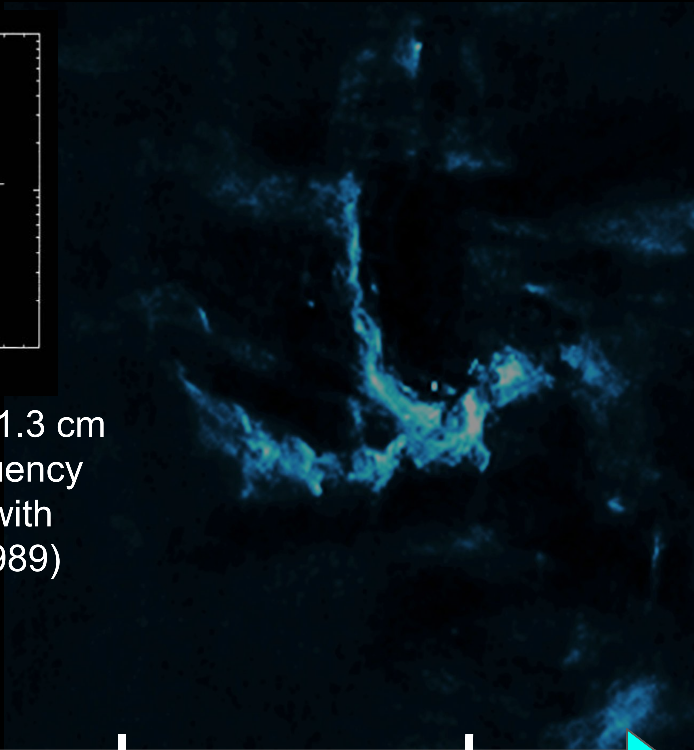
The non-thermal radio source is named Sagittarius A* (Brown 1982)



First observation of an elongated structure at 3.6 cm (Lo+ 1985)

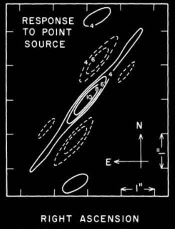


Observations from 30 to 1.3 cm show that the size-frequency relation is consistent with scattering (Jauncy+ 1989)

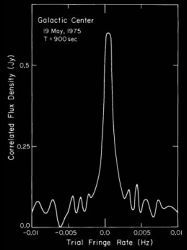


1970 1980 1990 2000 2010

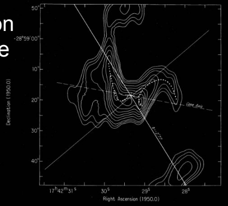
The Galactic Center Across The Radio Band



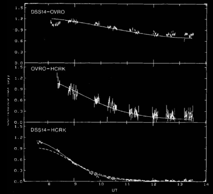
Radio source first detected in the Galactic Center at 11 and 3.7 cm (Balick & Brown 1974)



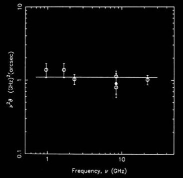
First VLBI detection of the radio source (Lo+ 1975)



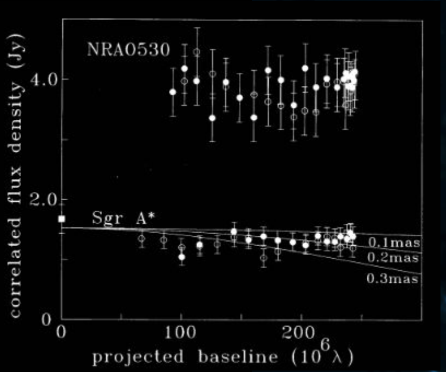
The non-thermal radio source is named Sagittarius A* (Brown 1982)



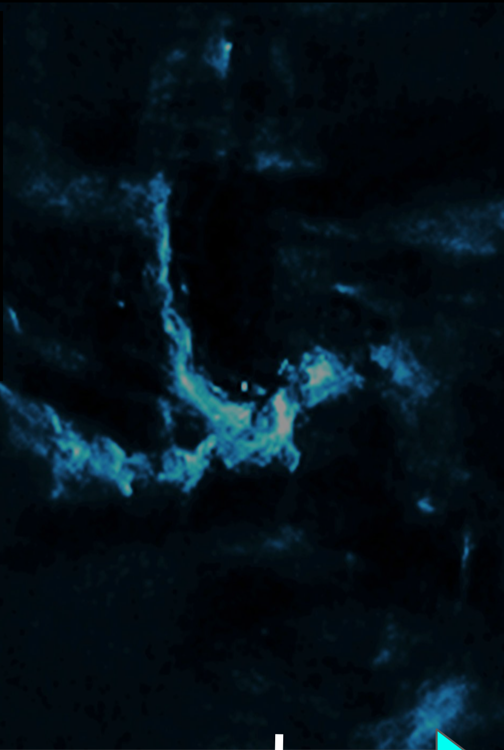
First observation of an elongated structure at 3.6 cm (Lo+ 1985)



Observations from 30 to 1.3 cm show that the size-frequency relation is consistent with scattering (Jauncy+ 1989)

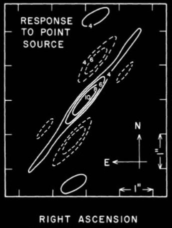


First VLBI detection at 3mm (Rogers+ 1994)

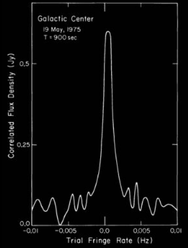


1970 1980 1990 2000 2010

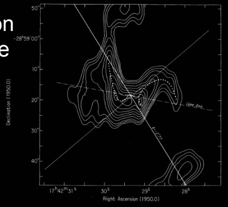
The Galactic Center Across The Radio Band



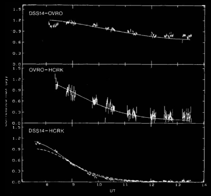
Radio source first detected in the Galactic Center at 11 and 3.7 cm (Balick & Brown 1974)



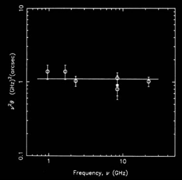
First VLBI detection of the radio source (Lo+ 1975)



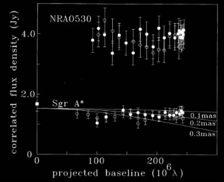
The non-thermal radio source is named Sagittarius A* (Brown 1982)



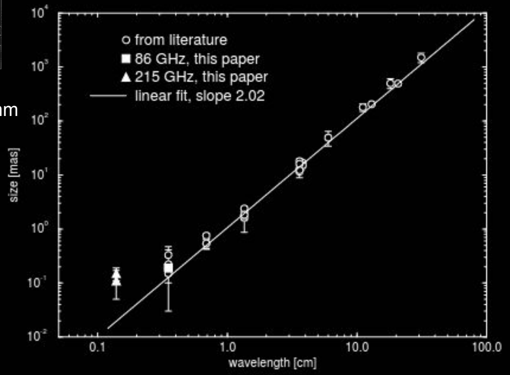
First observation of an elongated structure at 3.6 cm (Lo+ 1985)



Observations from 30 to 1.3 cm show that the size-frequency relation is consistent with scattering (Jauncy+ 1989)



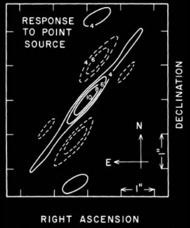
First VLBI detection at 3mm (Rogers+ 1994)



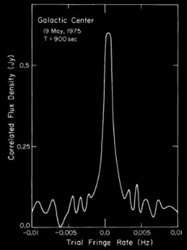
First VLBI detection at 1mm (Krichbaum+ 1998)

1970 1980 1990 2000 2010

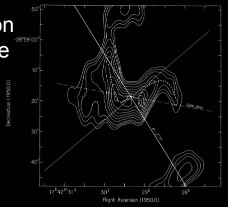
The Galactic Center Across The Radio Band



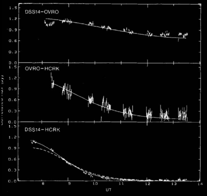
Radio source first detected in the Galactic Center at 11 and 3.7 cm (Balick & Brown 1974)



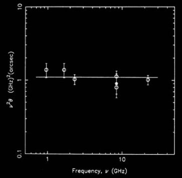
First VLBI detection of the radio source (Lo+ 1975)



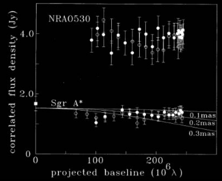
The non-thermal radio source is named Sagittarius A* (Brown 1982)



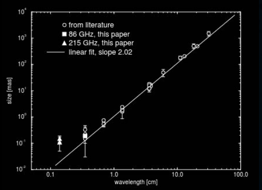
First observation of an elongated structure at 3.6 cm (Lo+ 1985)



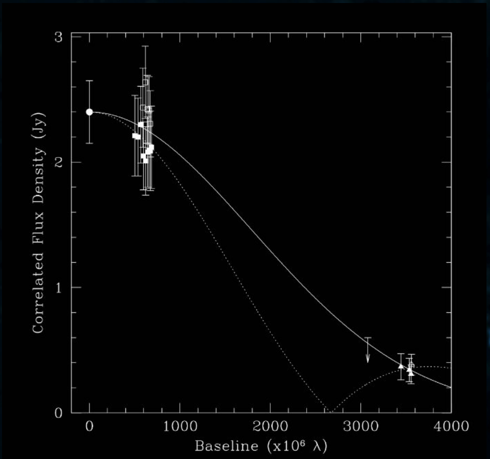
Observations from 30 to 1.3 cm show that the size-frequency relation is consistent with scattering (Jauncy+ 1989)



First VLBI detection at 3mm (Rogers+ 1994)



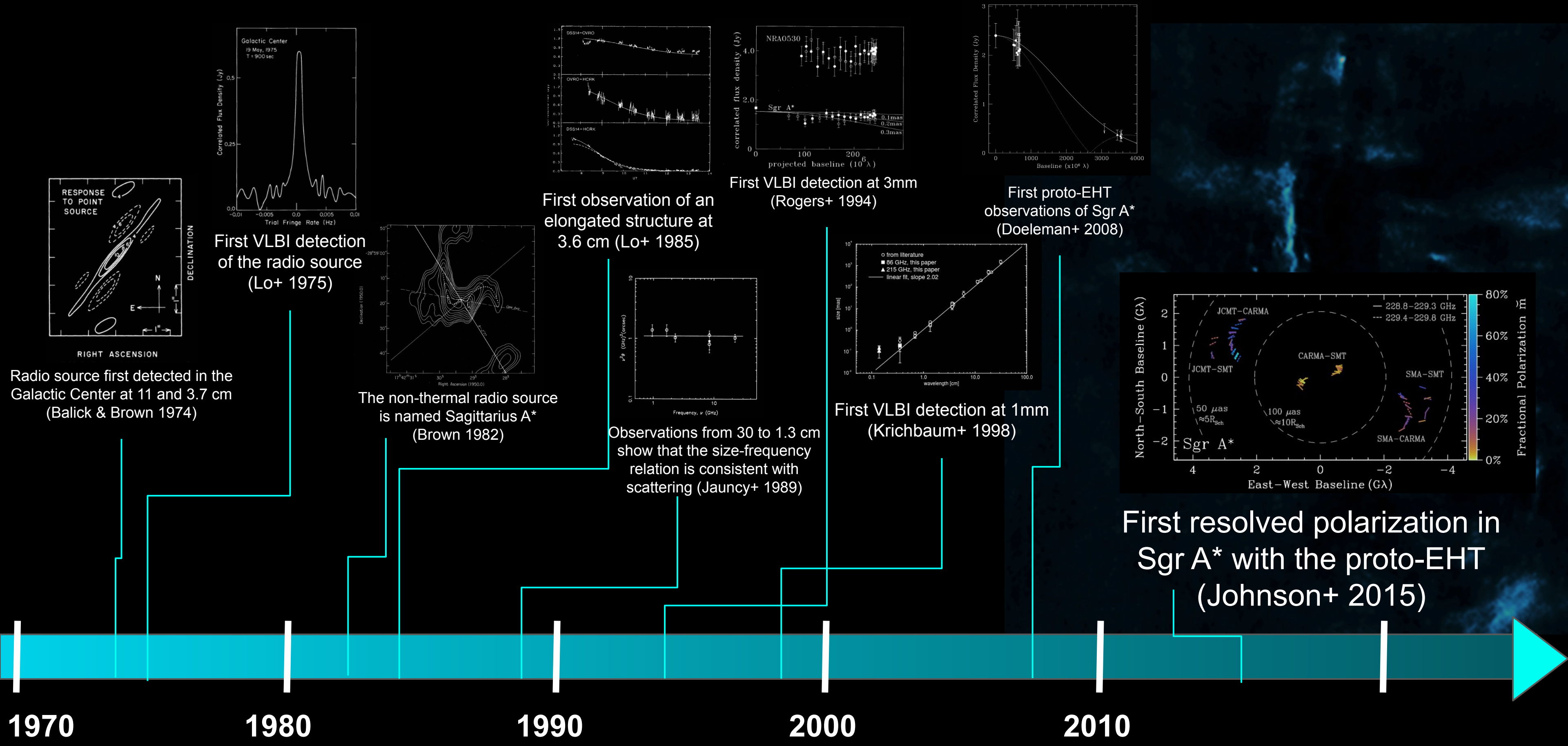
First VLBI detection at 1mm (Krichbaum+ 1998)



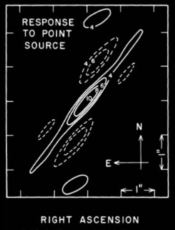
First proto-EHT observations of Sgr A* (Doeleman+ 2008)

1970 1980 1990 2000 2010

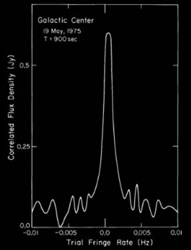
The Galactic Center Across The Radio Band



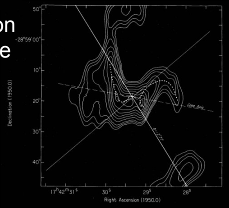
The Galactic Center Across The Radio Band



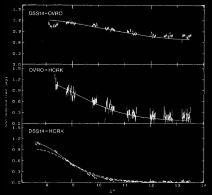
Radio source first detected in the Galactic Center at 11 and 3.7 cm (Balick & Brown 1974)



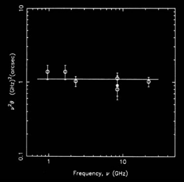
First VLBI detection of the radio source (Lo+ 1975)



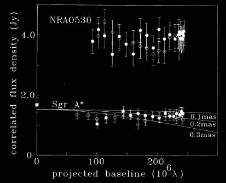
The non-thermal radio source is named Sagittarius A* (Brown 1982)



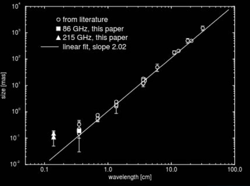
First observation of an elongated structure at 3.6 cm (Lo+ 1985)



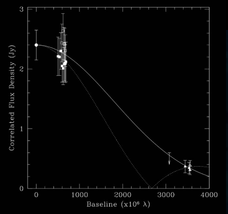
Observations from 30 to 1.3 cm show that the size-frequency relation is consistent with scattering (Jauncy+ 1989)



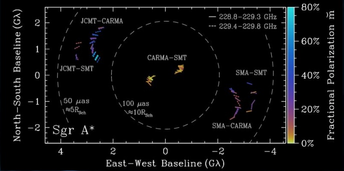
First VLBI detection at 3mm (Rogers+ 1994)



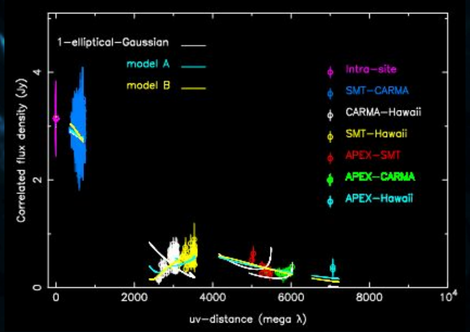
First VLBI detection at 1mm (Krichbaum+ 1998)



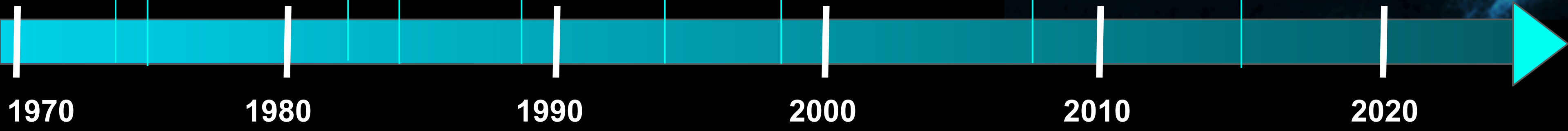
First proto-EHT observations of Sgr A* (Doeleman+ 2008)



First resolved polarization in Sgr A* with the proto-EHT (Johnson+ 2015)



Highest resolution observations of Sgr A* to date with proto-EHT (Lu+ 2018)



Synergy with 1.3mm VLBI

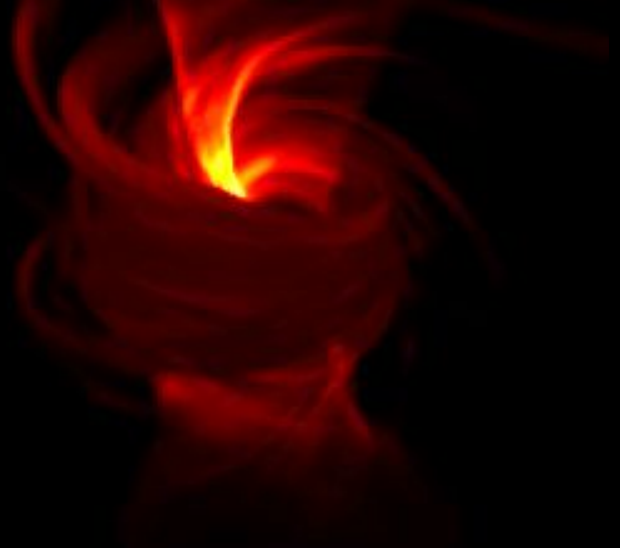
The origin of the radio emission in Sagittarius A* is still unknown
At 1.3 mm, the shadow is the dominating feature

1.3 mm: **Accretion disk dominated** **versus** **Jet dominated**

Credit: M. Moscibrodzka

Synergy with 1.3mm VLBI

The origin of the radio emission in Sagittarius A* is still unknown
At 3.5 mm, accretion flow differences are more apparent



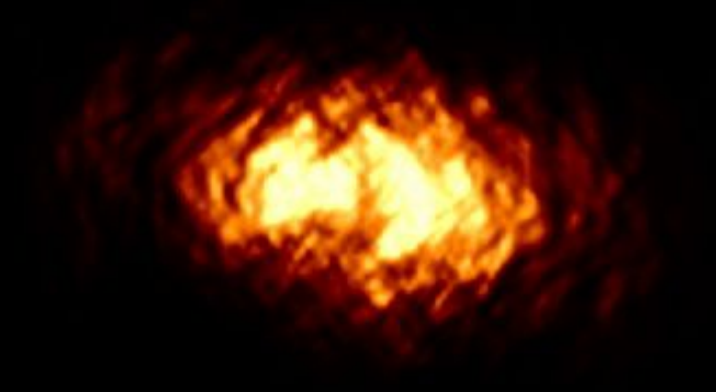
3.5 mm: **Accretion disk dominated** **versus** **Jet dominated**

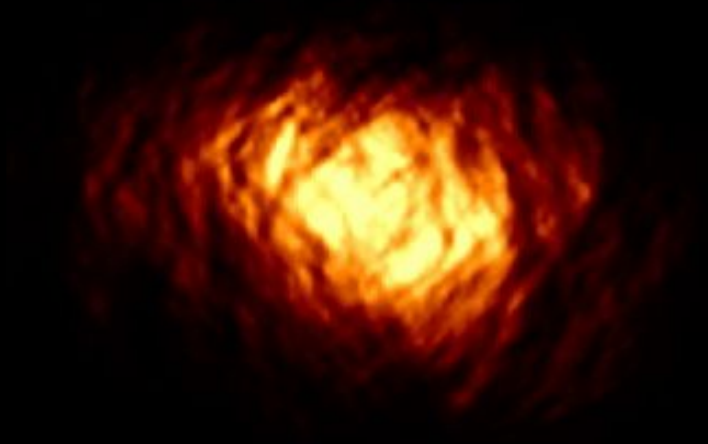
Credit: M. Moscibrodzka

Longer wavelengths go beyond the realm of GRMHD simulations

Synergy with 1.3mm VLBI

But Sagittarius A* is subject to interstellar scattering, stronger with increasing wavelength!



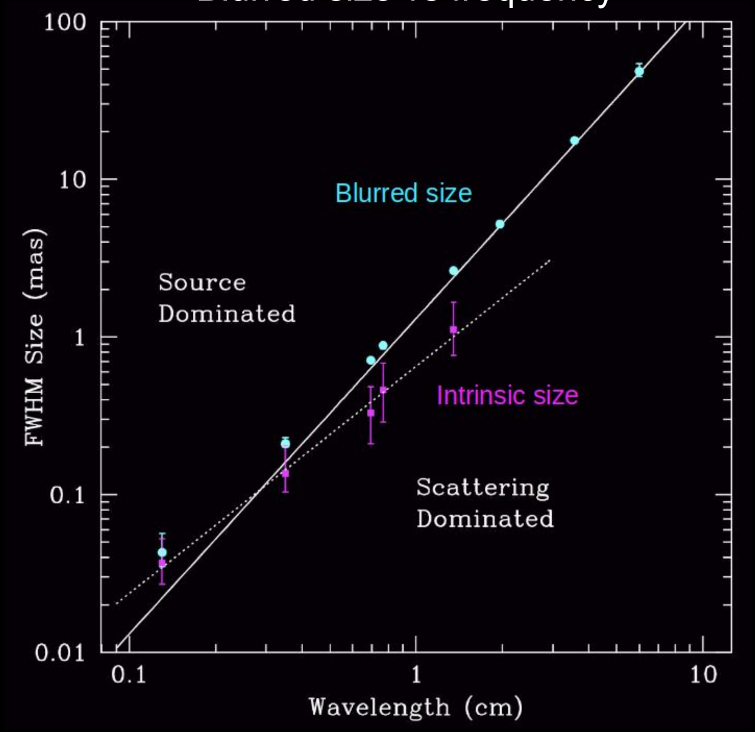


3.5 mm: **Accretion disk dominated** **versus** **Jet dominated**

Credit: M. Moscibrodzka, M. Johnson

Lifting the veil on Sgr A* with longer wavelength radio

Blurred size vs frequency

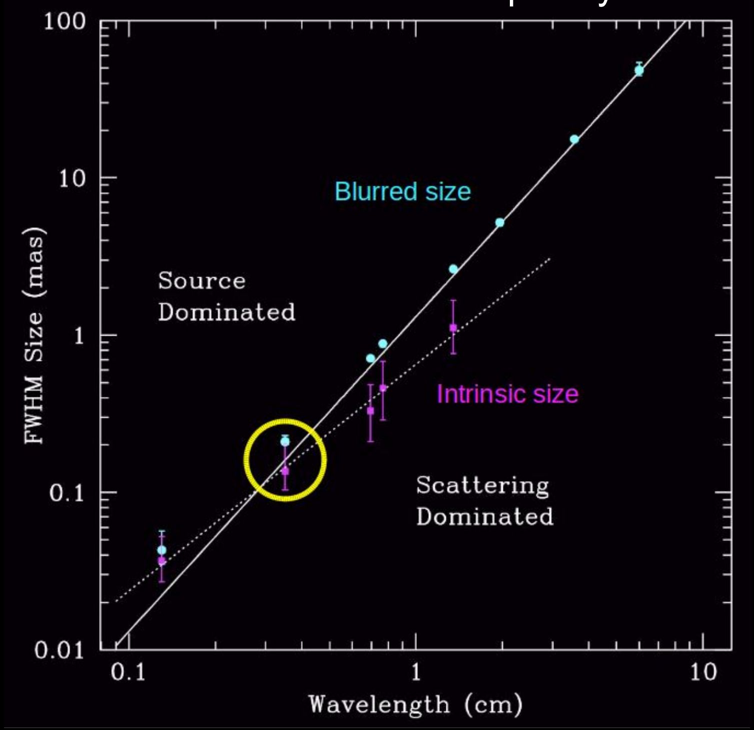


Shen+ 2005, Bower+ 2006, Doeleman+ 2008

- **Scattered size scales as λ^2**

Lifting the veil on Sgr A* with longer wavelength radio

Blurred size vs frequency

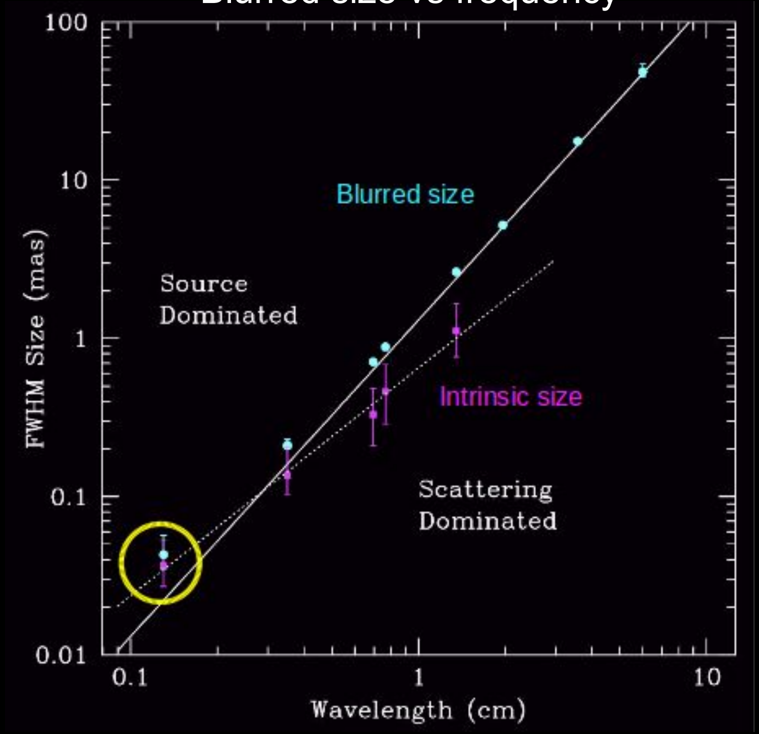


Shen+ 2005, Bower+ 2006, Doeleman+ 2008

- Scattered size scales as λ^2
- 3.5mm: intrinsic size comparable to blurring kernel

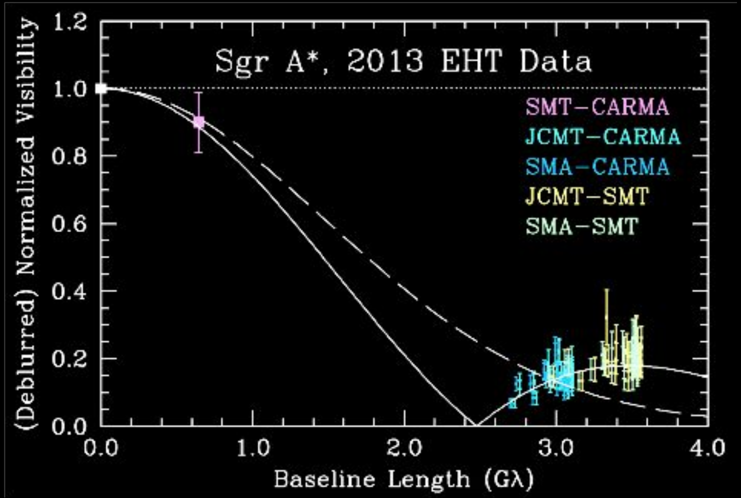
Lifting the veil on Sgr A* with longer wavelength radio

Blurred size vs frequency



Shen+ 2005, Bower+ 2006, Doeleman+ 2008

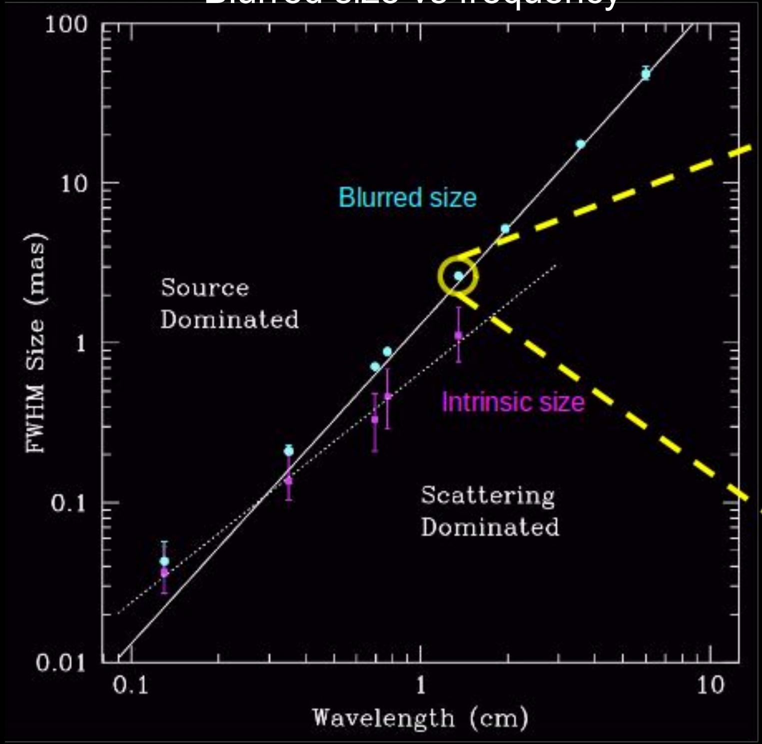
- **Scattered size scales as λ^2**
- **3.5mm: intrinsic size comparable to blurring kernel**
- **1.3mm: intrinsic size dominates**



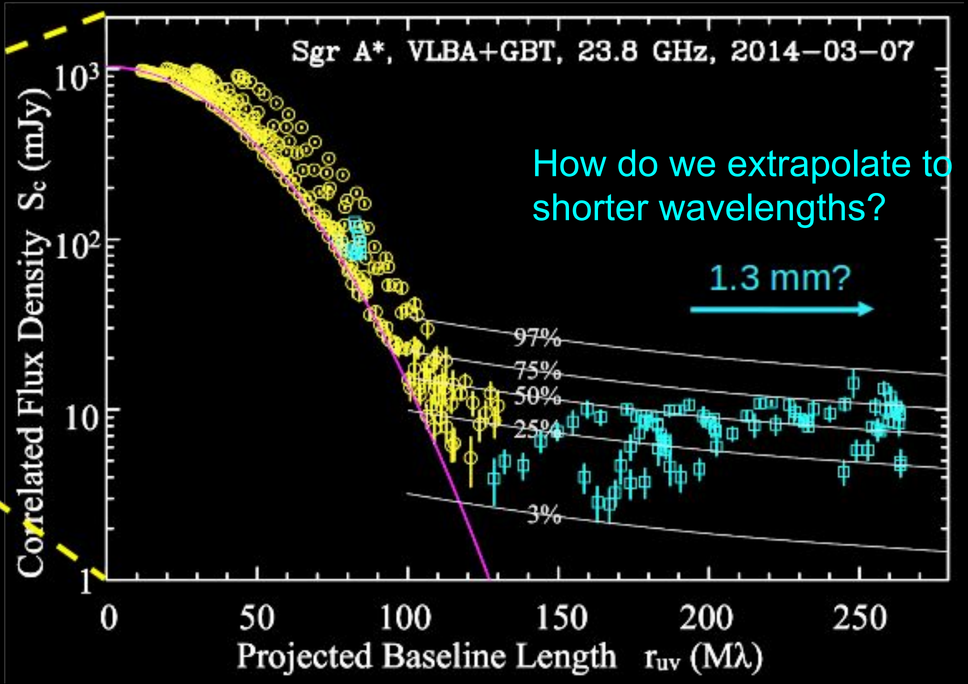
Johnson+ 2015

Lifting the veil on Sgr A* with longer wavelength radio

Blurred size vs frequency



Refractive substructure at 1.3cm



Gwinn+ 2014

Lifting the veil on Sgr A* with longer wavelength radio

There is more to worry about: depending on the scattering theory, interstellar scattering may contaminate tests of GR with EHT images

Simple ring at 1.3mm

J18 model (Johnson+2018)

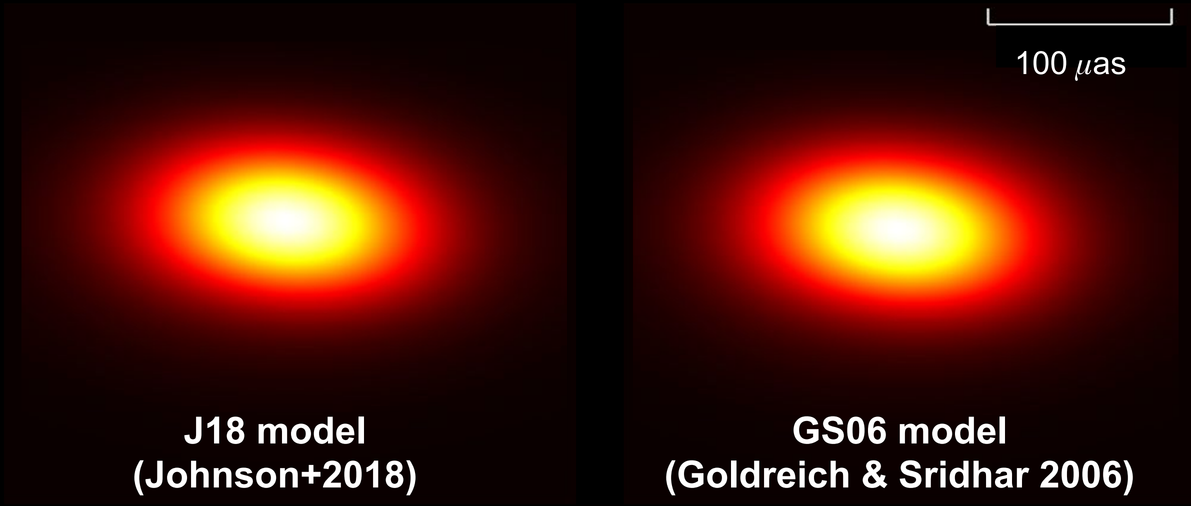
GS06 model (Goldreich & Sridhar 2006)

Zhu, Johnson & Narayan 2019

Both scattering models fit observational constraints prior to 2017

Lifting the veil on Sgr A* with longer wavelength radio

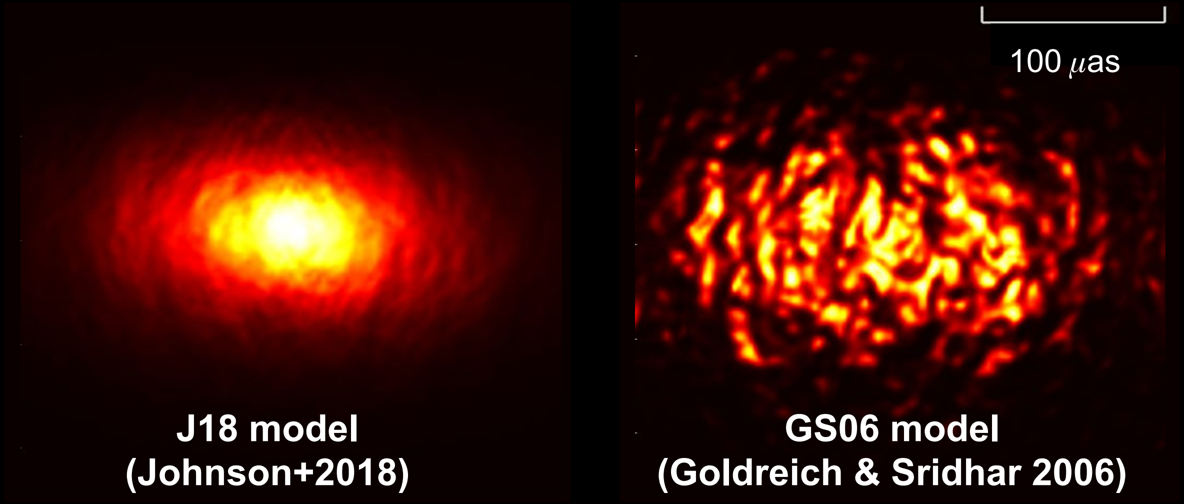
The two scattering models at 3.5mm as observed to date



Both scattering models show the same diffractive blurring (diffraction or bending of the waves as they pass through the ISM)

Lifting the veil on Sgr A* with longer wavelength radio

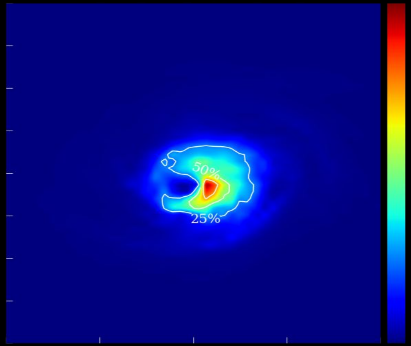
The two scattering models at 3.5mm if we could pick up on long-baseline refractive properties



Both scattering models differ in refractive sub-structure (refraction through over-densities causing the waves to bend)

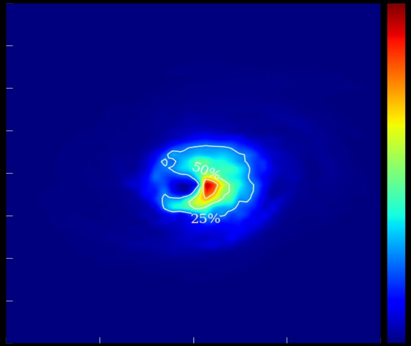
Reconstructing an unscattered image

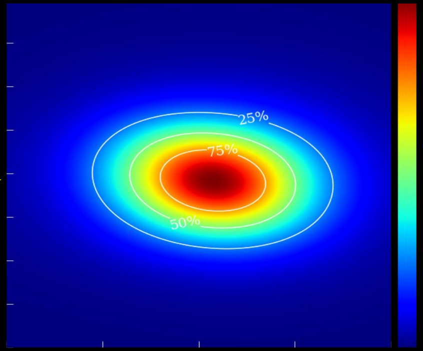
How can we reconstruct the unscattered image? → *stochastic optics* (Johnson 2016)
Similar to adaptive optics, but we can do it in post-processing!



Reconstructing an unscattered image

How can we reconstruct the unscattered image? → *stochastic optics* (Johnson 2016)
Similar to adaptive optics, but we can do it in post-processing!

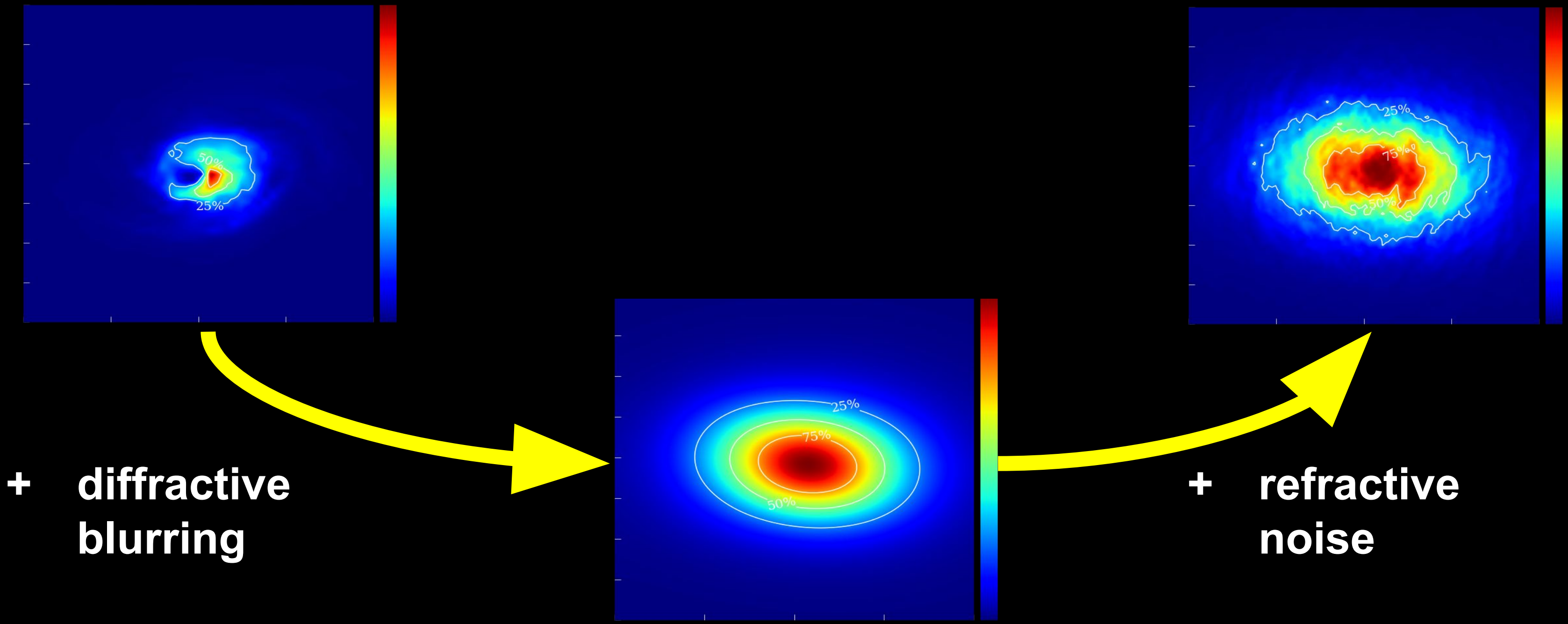




+ diffractive blurring

Reconstructing an unscattered image

How can we reconstruct the unscattered image? → *stochastic optics* (Johnson 2016)
Similar to adaptive optics, but we can do it in post-processing!

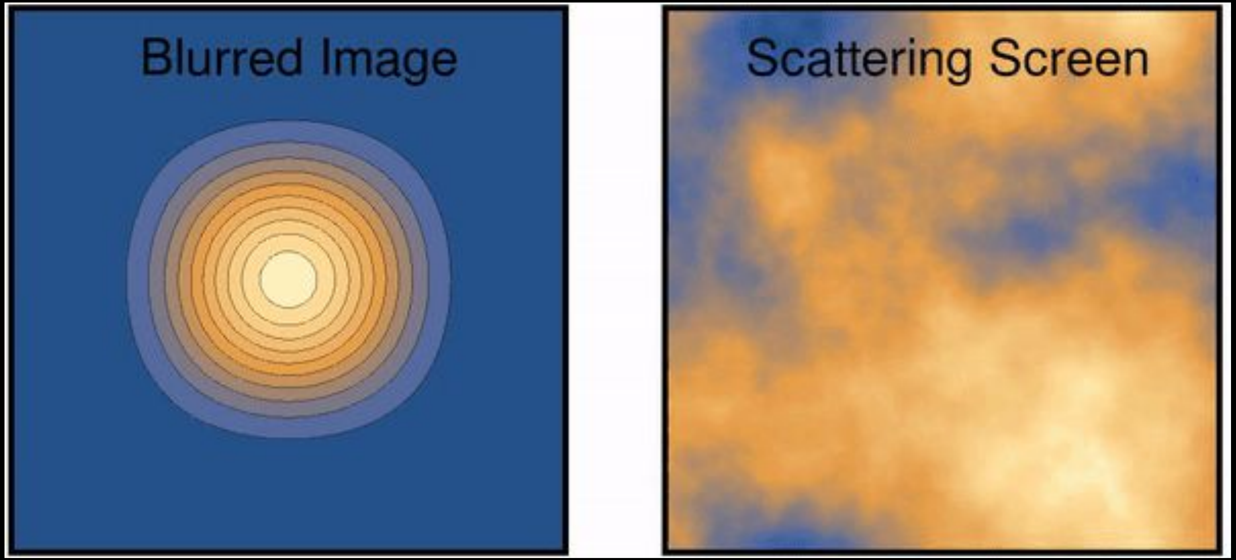


Reconstructing an unscattered image

Scattering model: non-Gaussian scattering kernel + stochastically varying refractive noise

1) Solving for stochastic variations in the scattering screen

2) Deconvolving with the scattering kernel

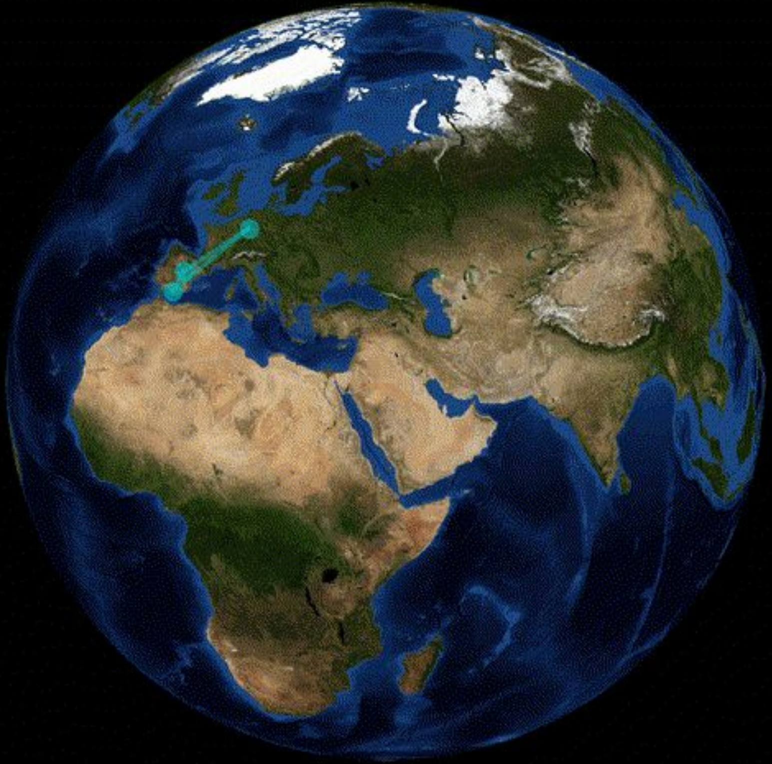


Credit: M. Johnson

Lifting the veil on Sgr A* with longer wavelength radio

Observing Sgr A* at 3.5 mm in 2017/2018 with the Global Millimeter VLBI Array (GMVA)

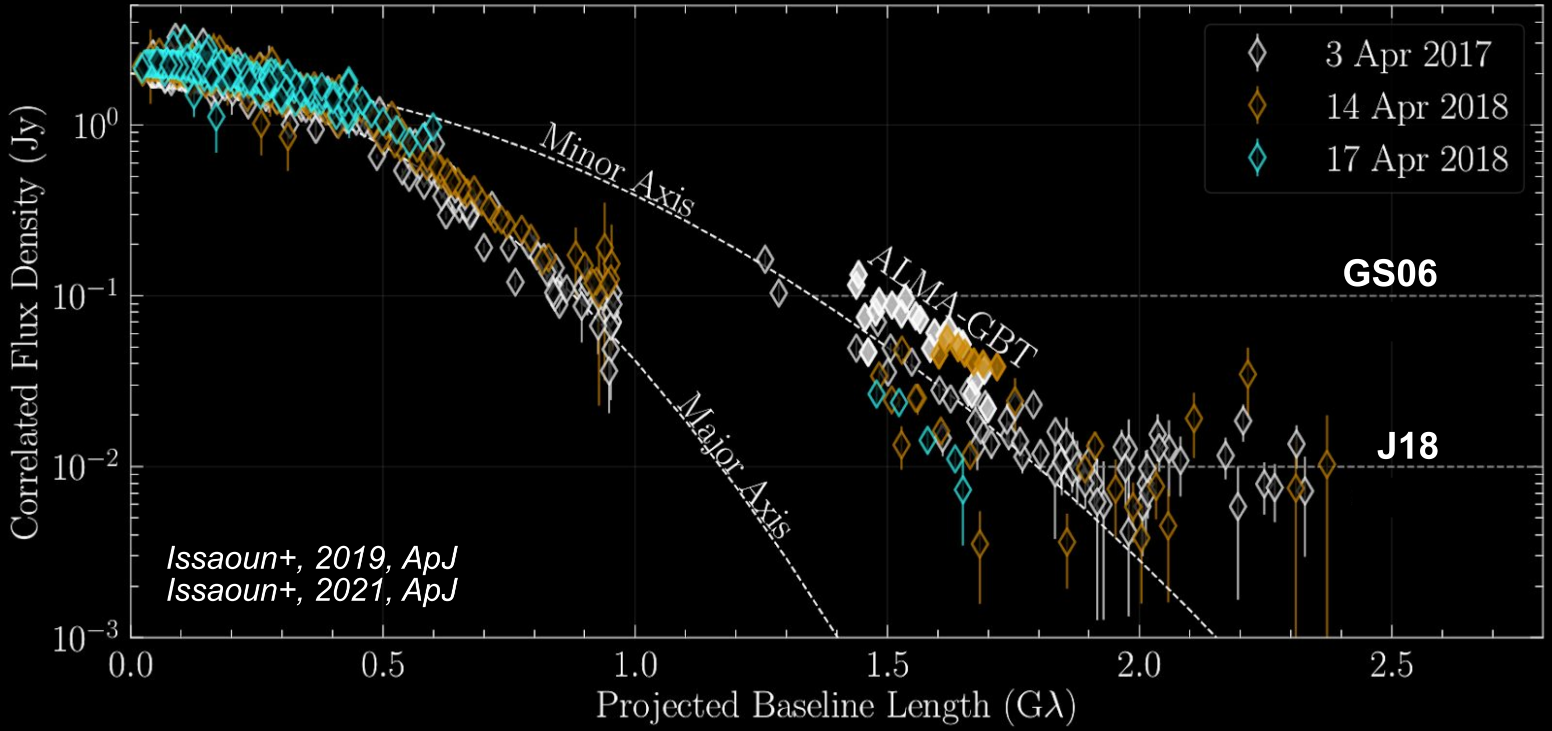
- European mm-wave facilities
- Very Long Baseline Array (US)
- Green Bank Telescope (US)
- ALMA (Chile)
  equipped for VLBI by the ALMA Phasing Project (Matthews+ 2018)



ALMA is a game-changer for sensitivity, north-south coverage, and long inter-continental baselines!

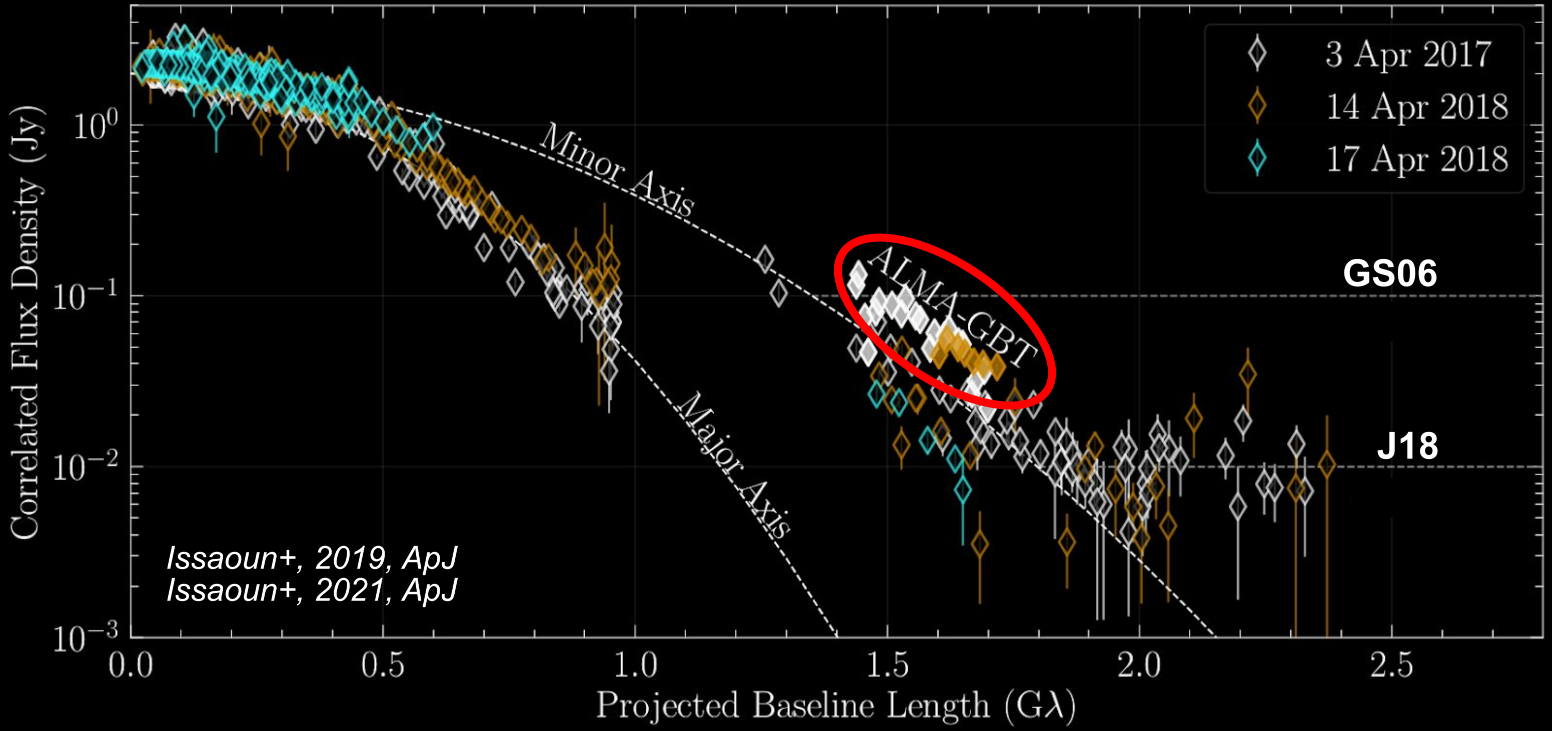
Sagittarius A* at 3mm

1 observation in April 2017, 2 observations separated by 3 days in 2018



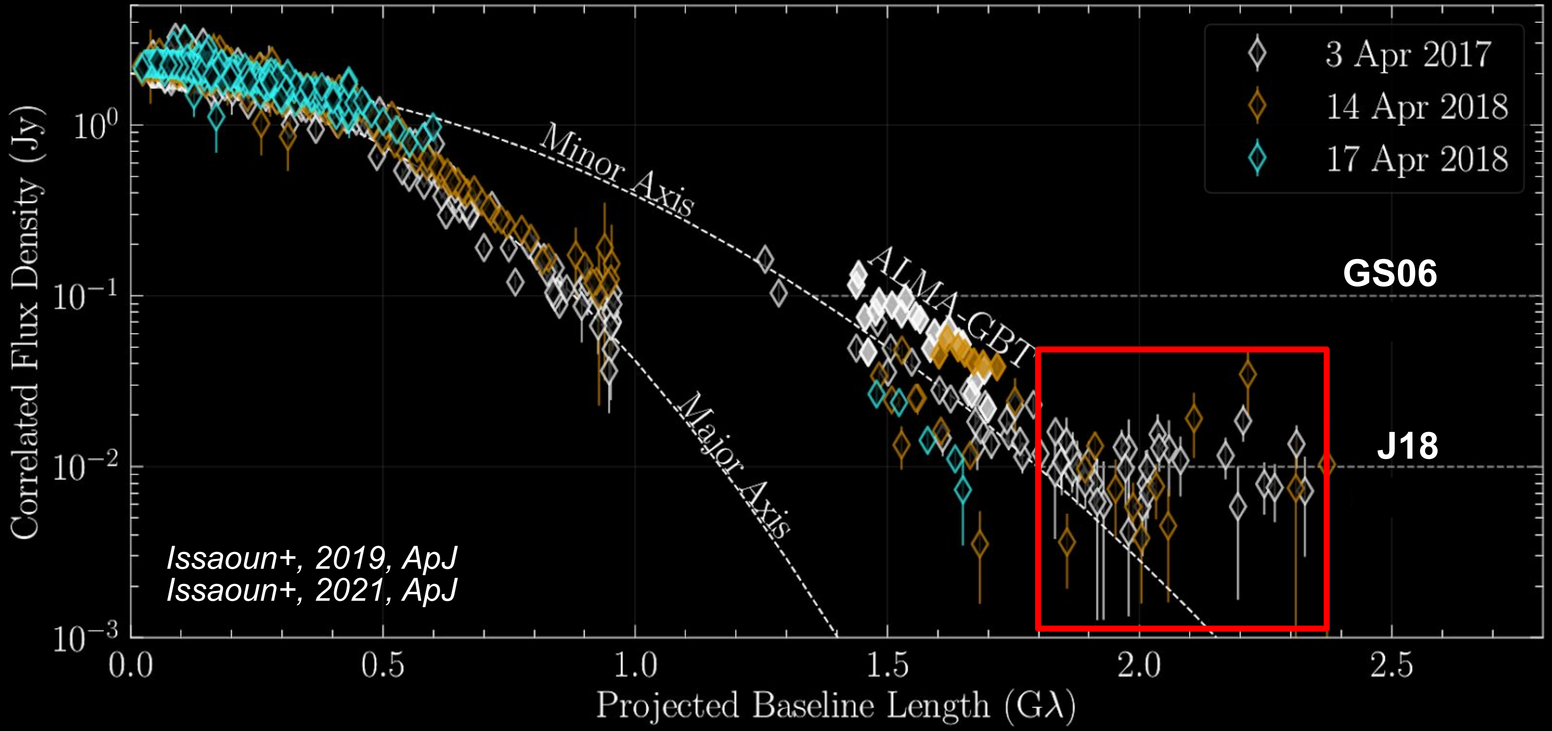
Sagittarius A* at 3mm

1 observation in April 2017, 2 observations separated by 3 days in 2018



Sagittarius A* at 3mm

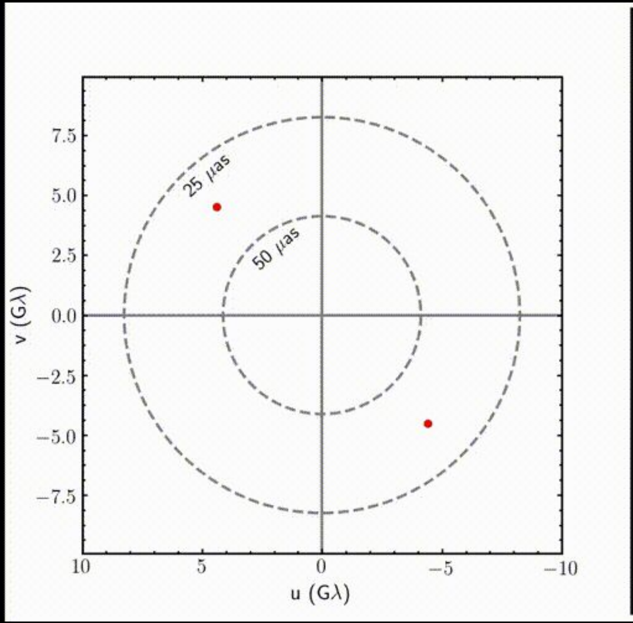
1 observation in April 2017, 2 observations separated by 3 days in 2018



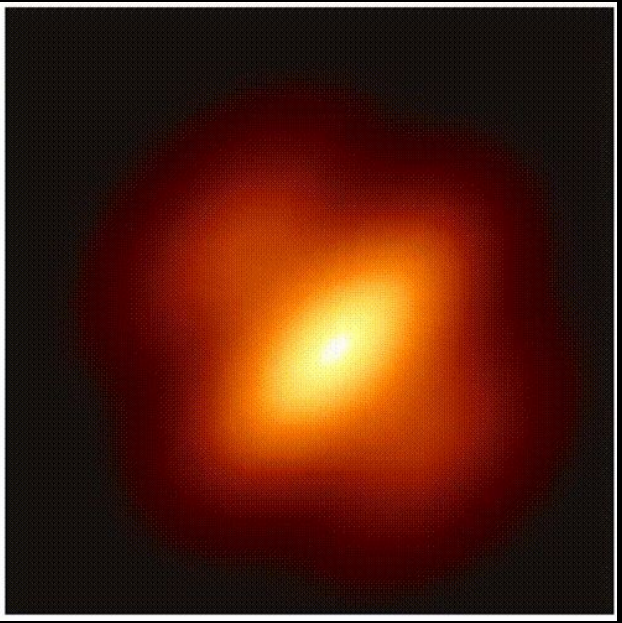
What is imaging?

Aperture synthesis: Earth rotation helps us fill our virtual mirror and combine data on multiple temporal and spatial scales

M87 becomes visible to stations as Earth rotates



Our coverage, or "virtual mirror" fills up

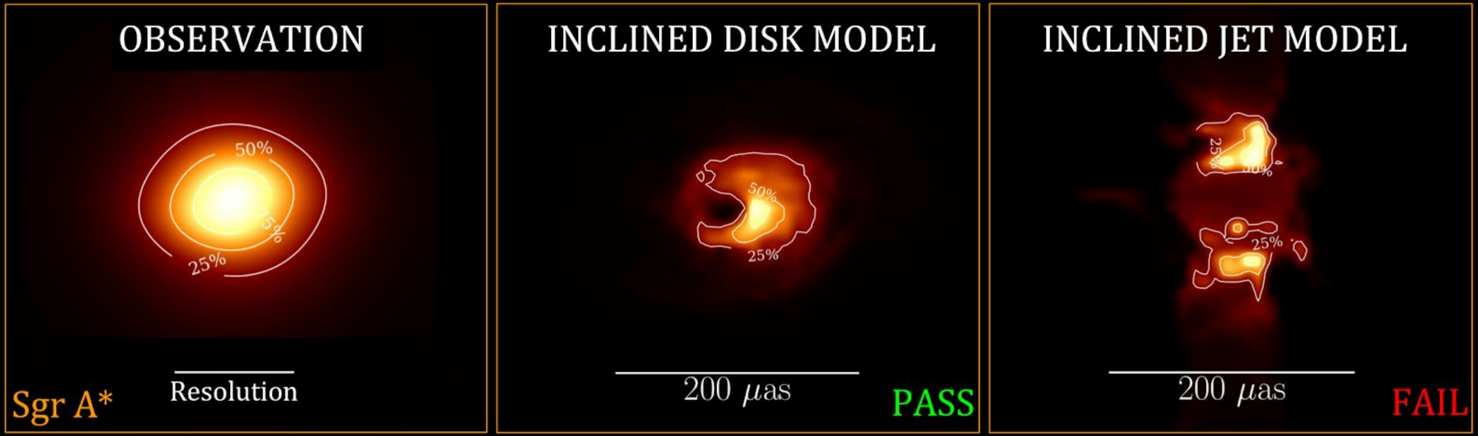


Our image improves

Animation credit: D. Palumbo, M. Wielgus, Harvard

The first intrinsic image of Sgr A* at 3.5 mm

Issaoun+ 2019



120 x 100 μas, PA 96º

Radio emission at 3mm originates within

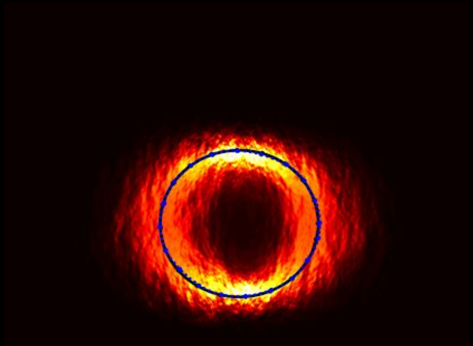
~12 Schwarzschild radii of the black hole

Jet-dominated models with inclination > 20º were ruled out

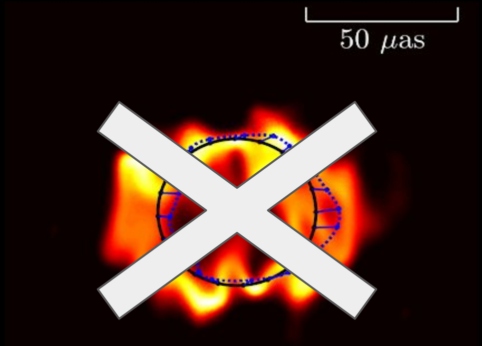
The first intrinsic image of Sgr A* at 3.5 mm

ALMA detections at 3mm rule out the GS06 scattering model for Sgr A*
Encouraging for EHT science!

Simple ring at 1.3mm



J18 model (Johnson+2018)



GS06 model (Goldreich & Sridhar 2006)

Zhu, Johnson & Narayan 2019

Combining 3.5 mm scattering constraints with longer-wavelength constraints showed that a single scattering model can explain behavior in the cm and mm regime *(Psaltis+ 2018, Johnson+ 2018, Issaoun+ 2021)*

Zooming into Sagittarius A*

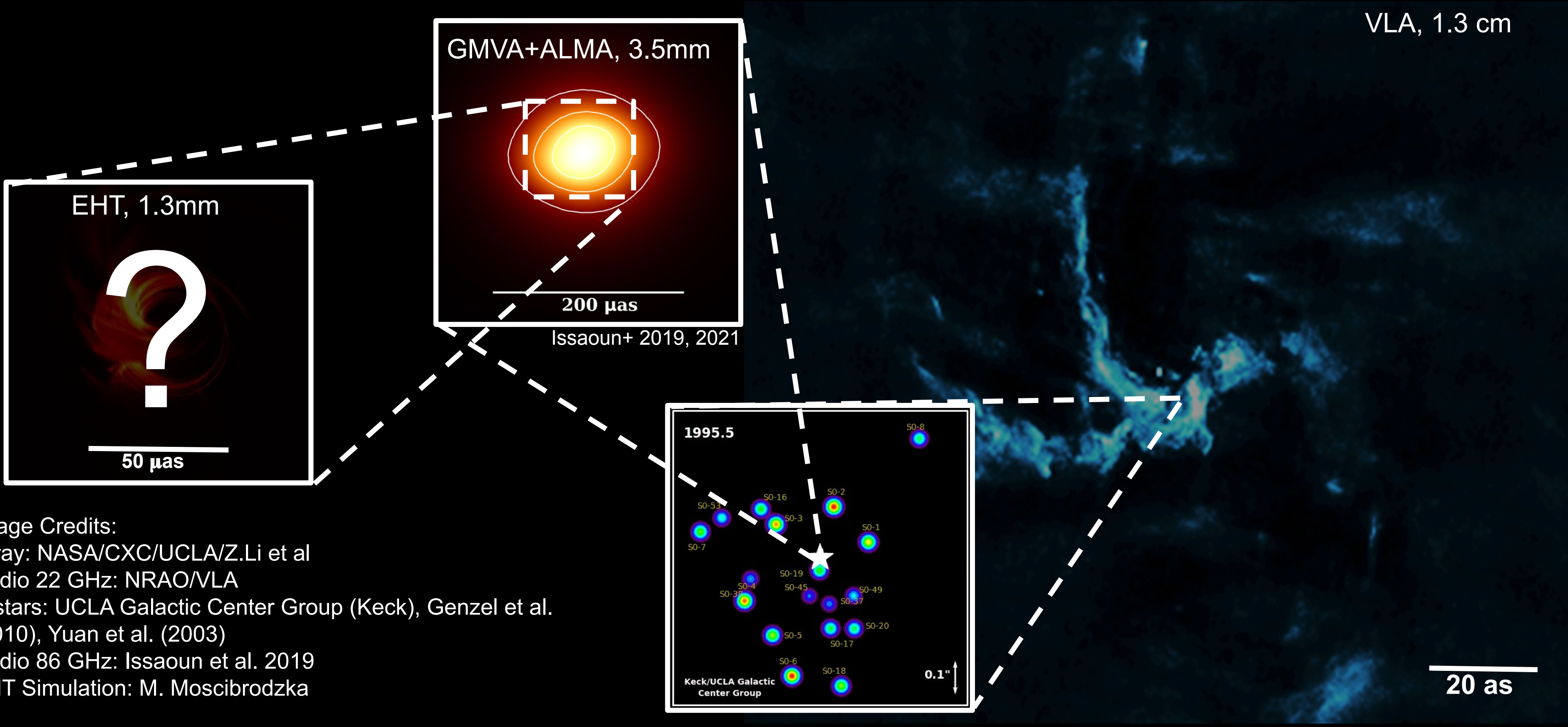


Image Credits:
X-ray: NASA/CXC/UCLA/Z.Li et al
Radio 22 GHz: NRAO/VLA
S-stars: UCLA Galactic Center Group (Keck), Genzel et al. (2010), Yuan et al. (2003)
Radio 86 GHz: Issaoun et al. 2019
EHT Simulation: M. Moscibrodzka

Summary

- Sagittarius A* and its environment offer an exciting look into black hole physics
- Unlike for M87*, imaging Sagittarius A* requires a deep understanding of variability and interstellar scattering
- Observations across the radio band are crucial to disentangle scattering and intrinsic source structure
- Observations at 3.5 mm are the sweet spot to connect to 1.3 mm observations with the Event Horizon Telescope

→ A wealth of information still remains to be extracted at longer radio wavelengths to understand the accretion flow of Sagittarius A* and the scattering in the interstellar medium