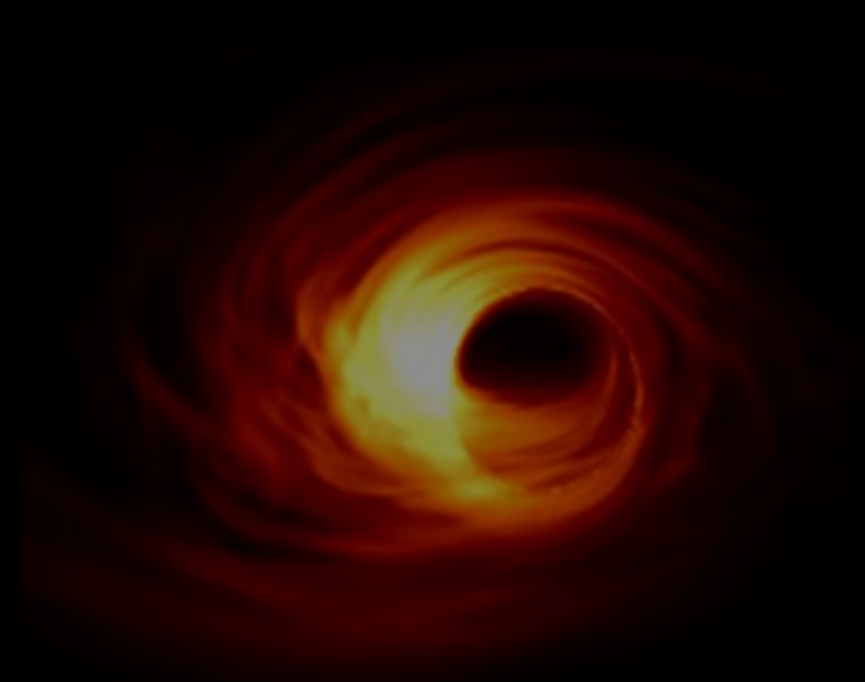
The Size, Shape, and Scattering of Sagittarius A*



By M. Moscibrodzka

Sara Issaoun

With M. Johnson, L. Blackburn, C. Brinkerink, M. Moscibrodzka, A. Chael, S. Doeleman, H. Falcke and 3 mm project team

June 1, 2020

Event Horizon Telescope

BLACK HOLE CAM

erc European Research Council

Smithsonian Astrophysical Observatory

Radboud University

IN DEI NOMINE FELICITER

The Event Horizon Telescope Collaboration

300+ members, 60+ institutes, 18 countries and regions in Europe, Asia, Africa, North and South America.

The Event Horizon Telescope Collaboration

- 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 physics and dynamics to multi-wavelength variability/flares

Animation credit: ESO

The Event Horizon Telescope

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

The Event Horizon Telescope Multiwavelength Effort

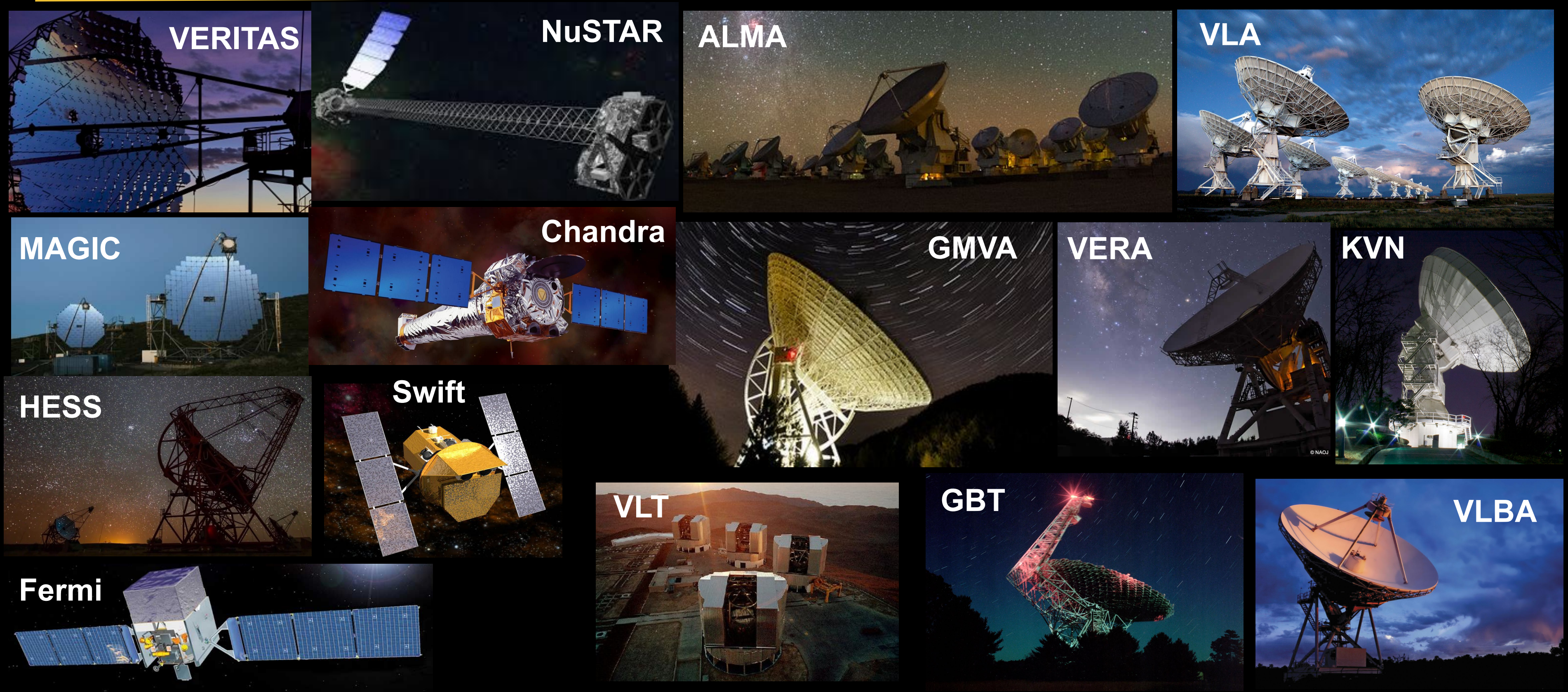
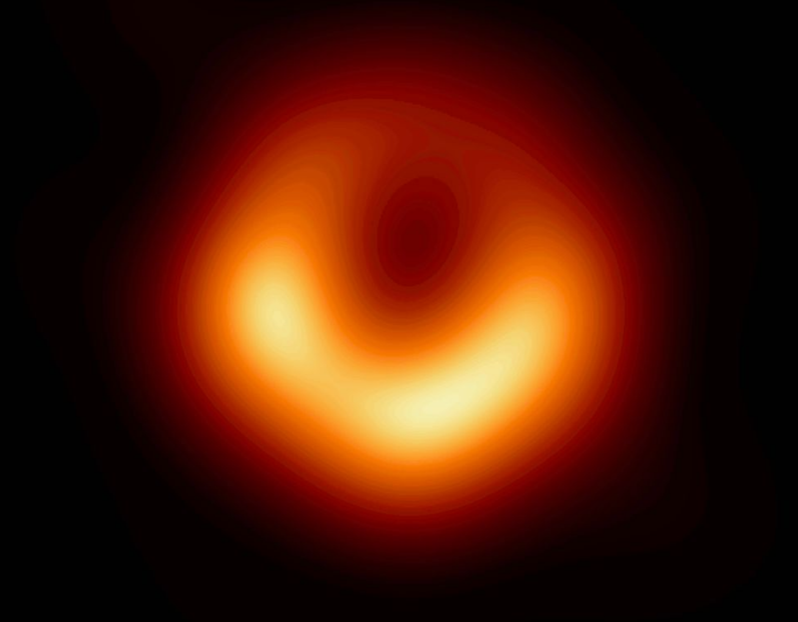


Image credits: NSF/VERITAS, Juan Cortina, Vikas Chander, NASA, NASA/JPL-Caltech, NASA/CXC/SAO, NASA, ESO, P. Kranzler & A. Phelps, NRAO/AUI/NSF, HyeRyung, NAOJ, MPIfR/N. Tacken

How well can we replicate nature?

Observation



Model

Animation credit: S. Issaoun, F. Roelofs, M. Moscibrodzka, Radboud

What is the mass of the M87 black hole?

6.5 ± 0.7 **billion** solar masses

The supermassive black hole Sagittarius A*

Closest supermassive black hole

- Mass: 4.1x10^6 solar masses
- Distance: 8.1 kpc

(Gravity Collaboration+ 2018)

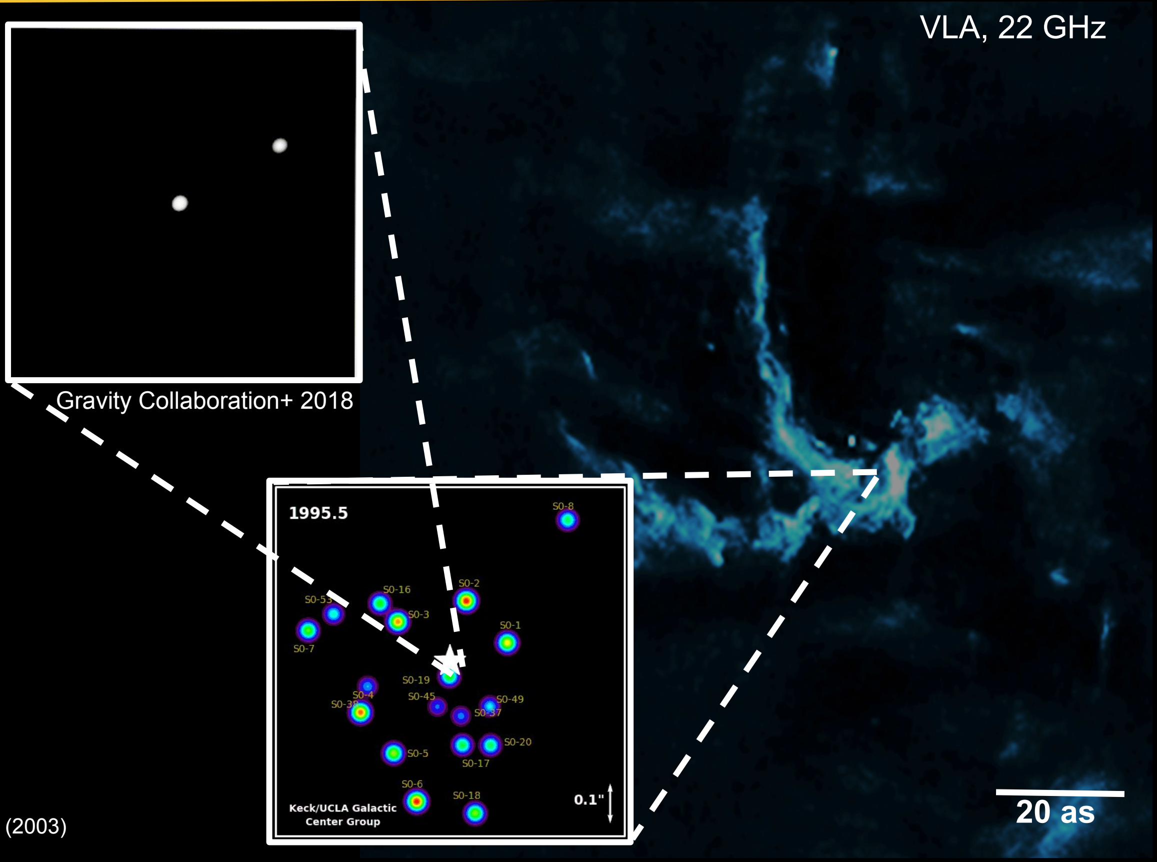


Image Credits:
X-ray: NASA/CXC/UCLA/Z. Li et al
Radio 22 GHz: NRAO/VLA
S-stars: UCLA Galactic Center Group (Keck), Genzel et al. (2010), Yuan et al. (2003)
S2: Gravity Collaboration+ 2018, ESO/Gravity

The supermassive black hole Sagittarius A*

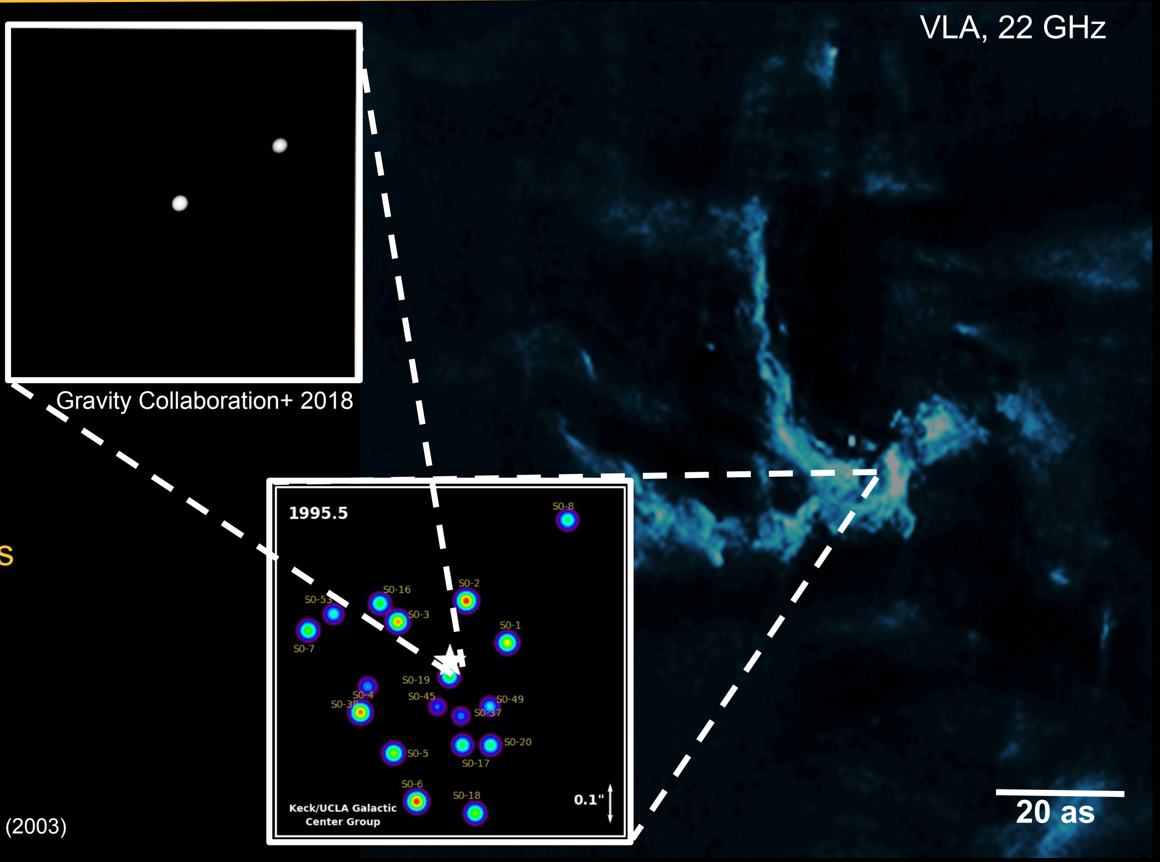
What does Sgr A* look like?

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)?



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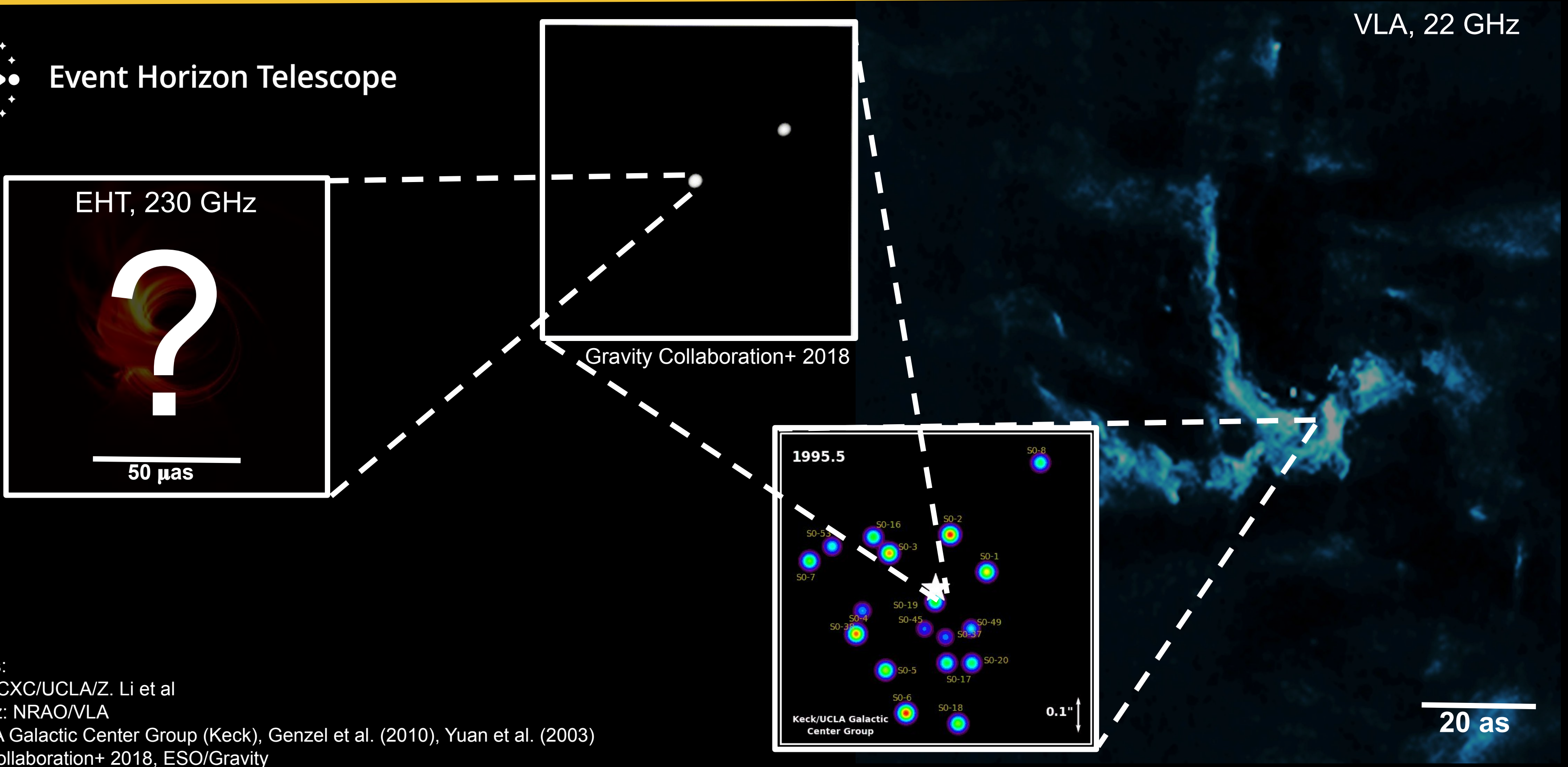
The supermassive black hole Sagittarius A*

Event Horizon Telescope



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S-stars: UCLA Galactic Center Group (Keck), Genzel et al. (2010), Yuan et al. (2003)
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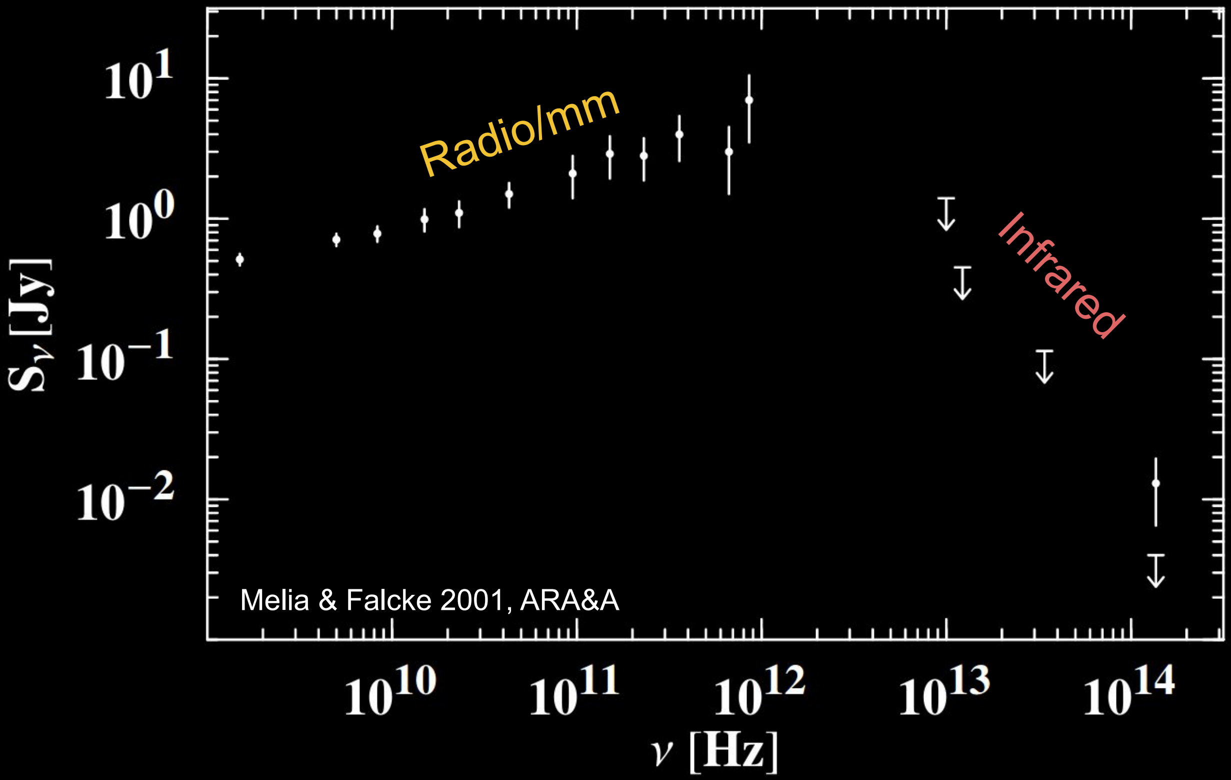
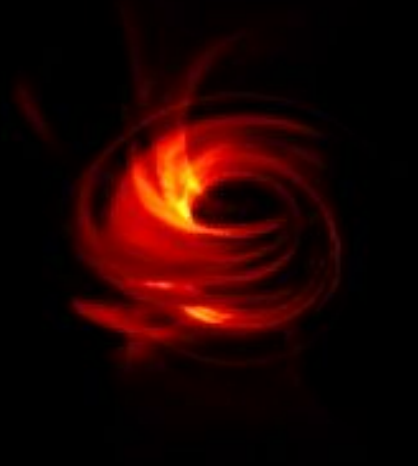
The supermassive black hole Sagittarius A*

Time-averaged Spectral Energy Distribution



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

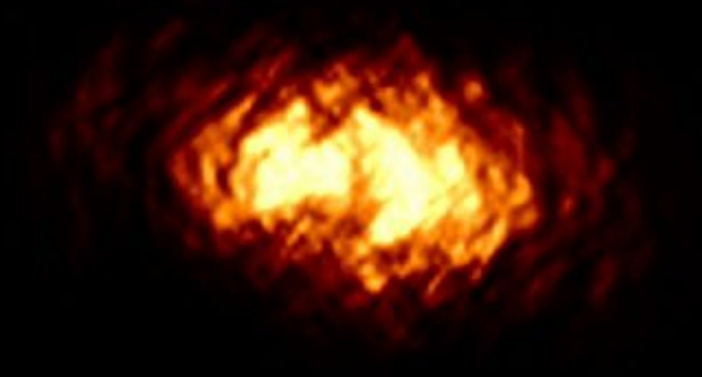
3.5 mm: **Accretion disk dominated** **versus** **Jet dominated**

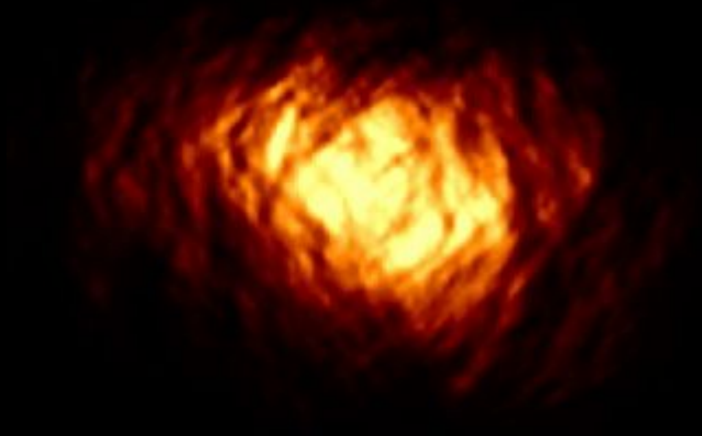
Credit: M. Moscibrodzka

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!



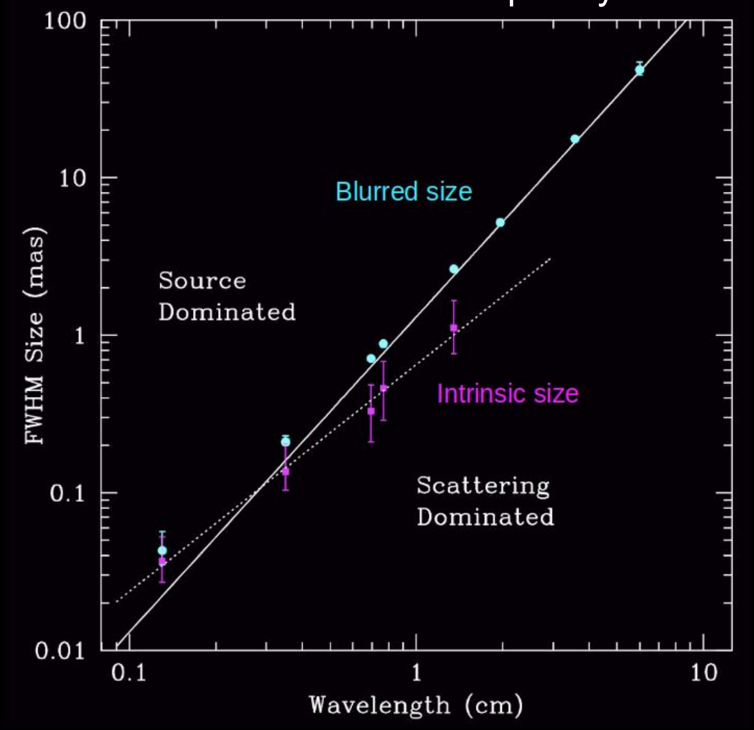


3.5 mm: **Accretion disk dominated** **versus** **Jet dominated**

Credit: M. Moscibrodzka, M. Johnson

Previous constraints on scattering toward GC

Blurred size vs frequency

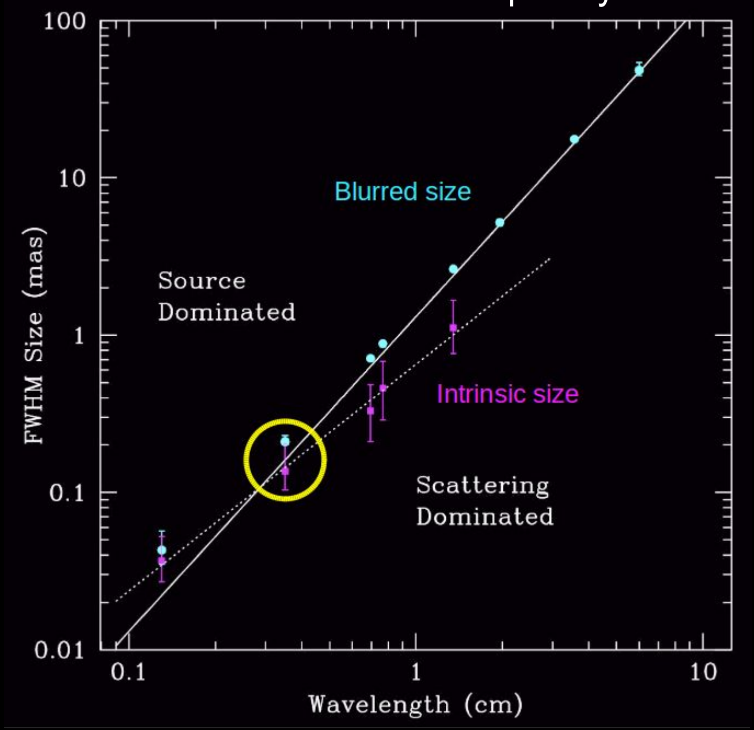


Shen+ 2005, Bower+ 2006, Doeleman+ 2008

- **Scattered size scales as λ^2**

Previous constraints on scattering toward GC

Blurred size vs frequency

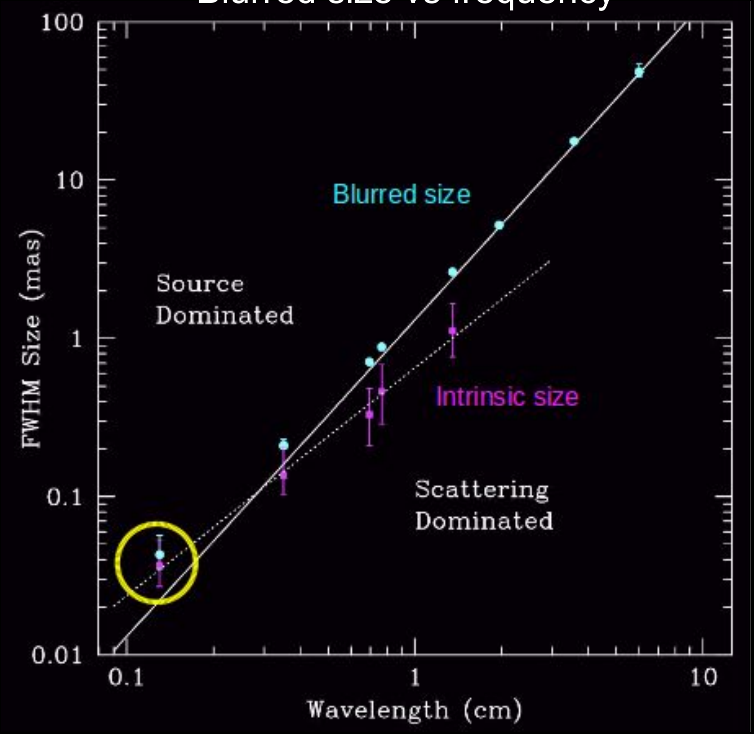


Shen+ 2005, Bower+ 2006, Doeleman+ 2008

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

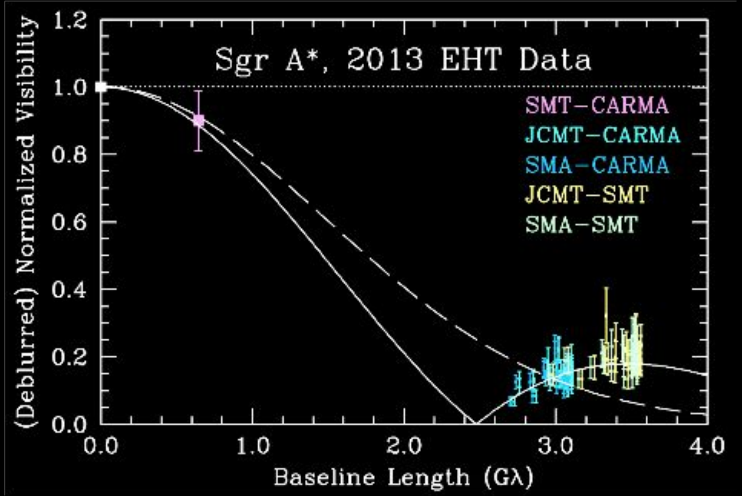
Previous constraints on scattering toward GC

Blurred size vs frequency



Shen+ 2005, Bower+ 2006, Doeleman+ 2008

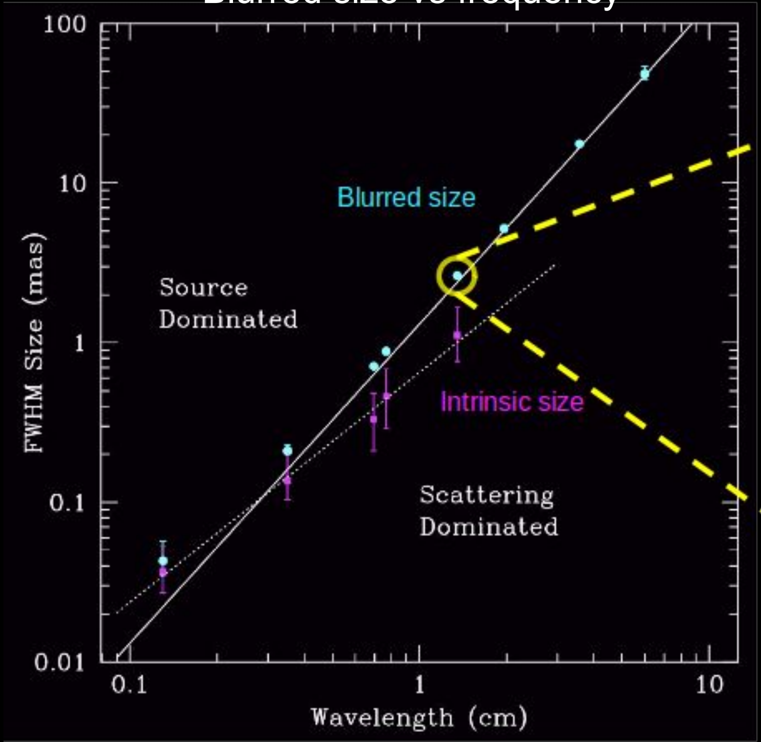
- Scattered size scales as λ^2
- 3.5mm: intrinsic size comparable to blurring kernel
- 1.3mm: intrinsic size dominates



Johnson+ 2015

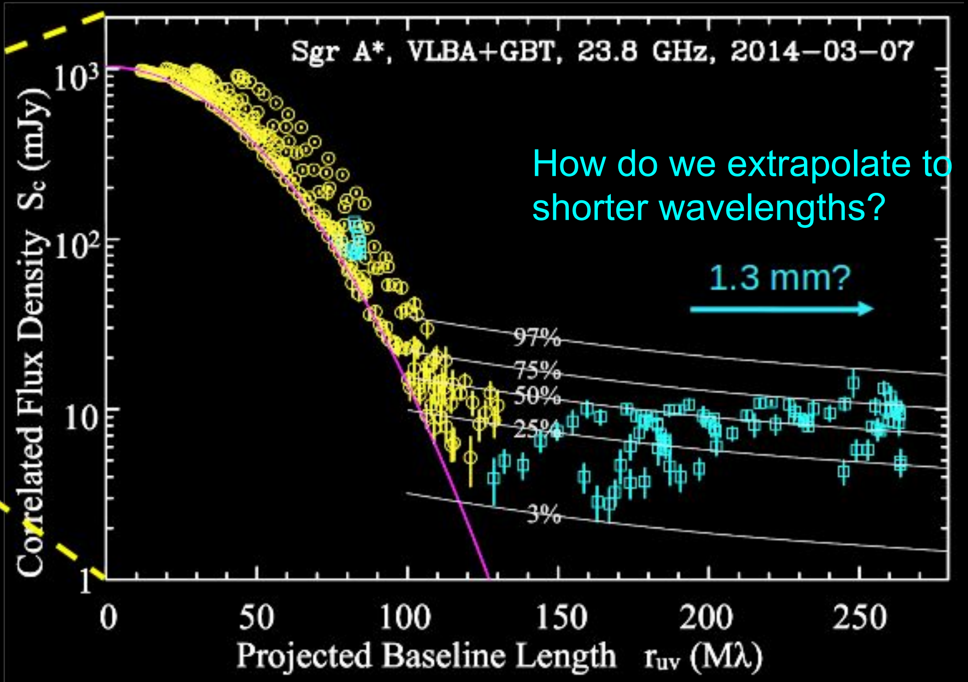
Previous constraints on scattering toward GC

Blurred size vs frequency



Shen+ 2005, Bower+ 2006, Doeleman+ 2008

Refractive substructure at 1.3cm

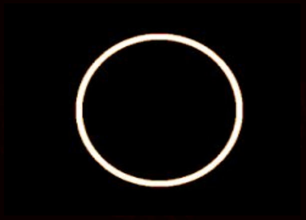


Gwinn+ 2014

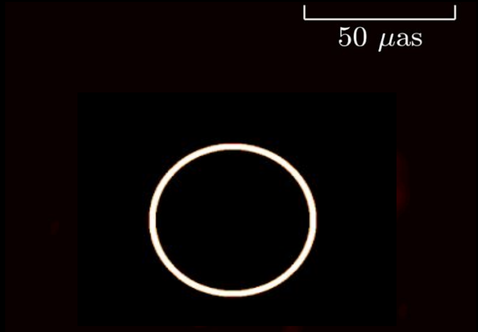
Previous constraints on scattering toward GC

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)



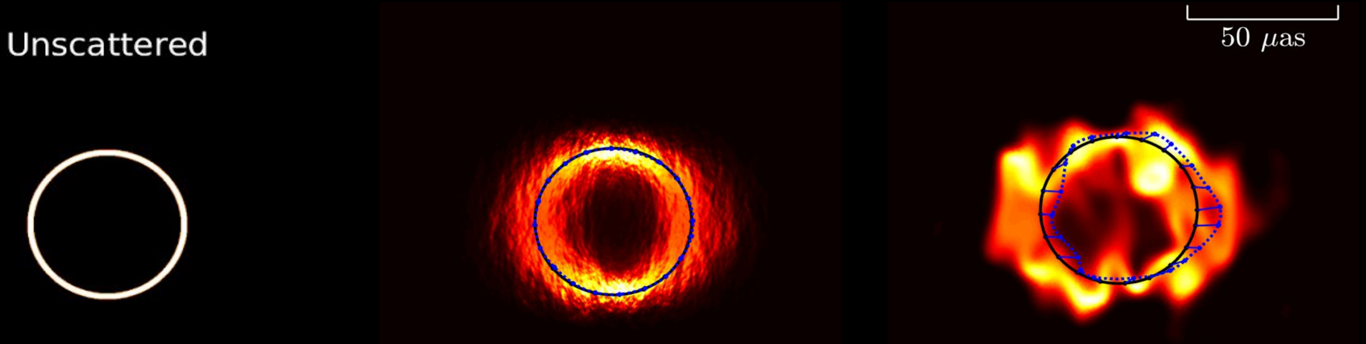
GS06 model (Goldreich & Sridhar 2006)

Zhu, Johnson & Narayan 2019

Both scattering models fit observational constraints to date

Previous constraints on scattering toward GC

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)

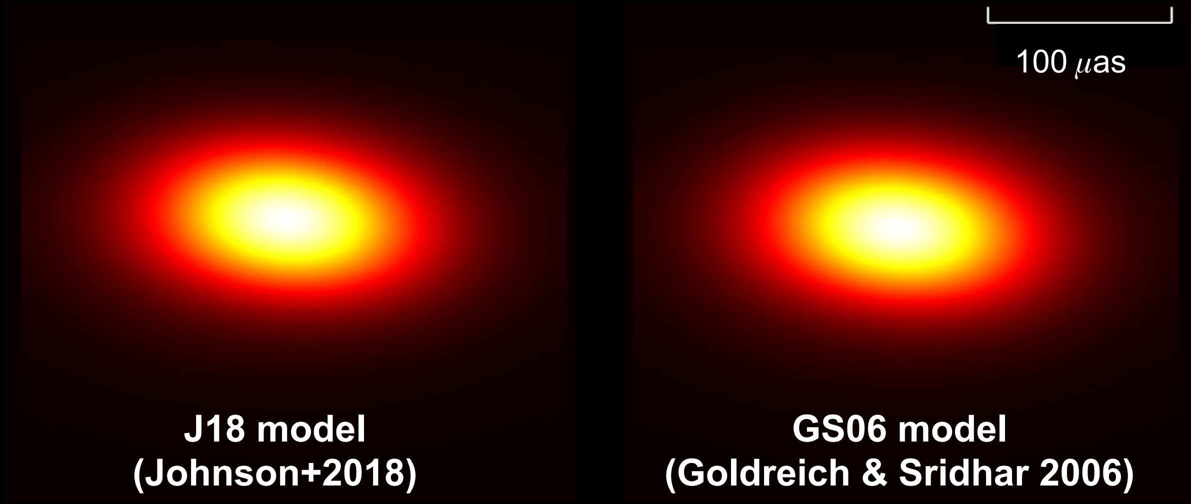
GS06 model (Goldreich & Sridhar 2006)

Zhu, Johnson & Narayan 2019

Both scattering models fit observational constraints to date

Previous constraints on scattering toward GC

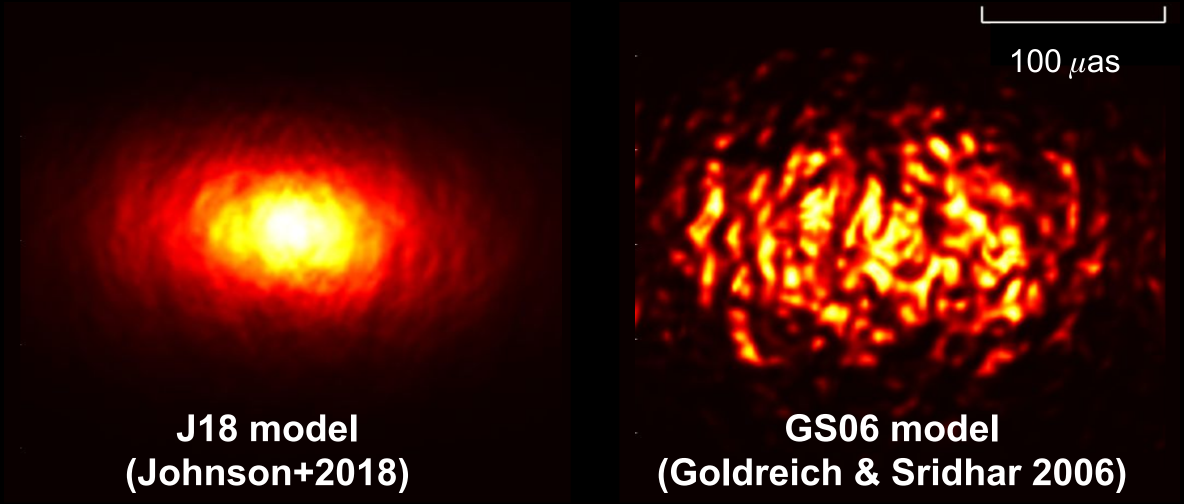
The two scattering models at 3.5mm as observed to date



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

Previous constraints on scattering toward GC

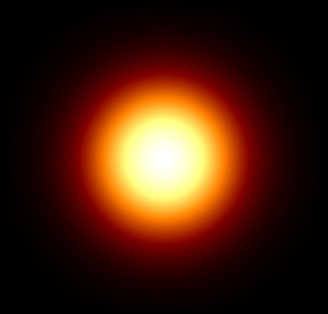
The two scattering models at 3.5mm if we could pick up on long-baseline refractive properties



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

Sagittarius A* from model-fitting: first detections

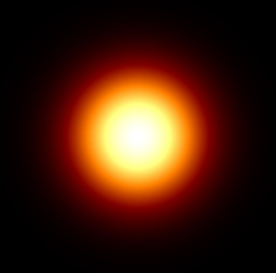
Scattered size



150 x 150 μas

Rogers et al. 1994

Intrinsic size

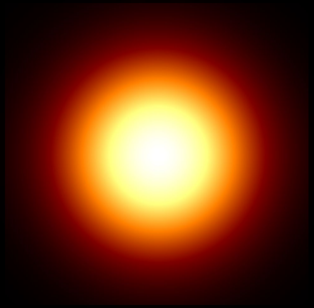


< 130 x 130 μas

- Two- or three-station arrays
- Short baselines
- Zero closure phases (symmetrical)

Sagittarius A* from model-fitting: first detections

Scattered size | **Krichbaum et al. 1998** | **Intrinsic size**



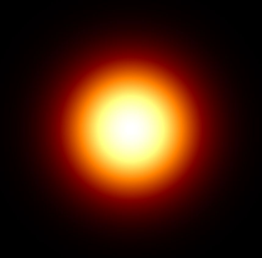
190 x 190 μas

- Two- or three-station arrays
- Short baselines
- Zero closure phases (symmetrical)

Sagittarius A* from model-fitting: first detections

Scattered size | **Doeleman et al. 2001** | **Intrinsic size**

180 x 180 μas



< 130 x 130 μas

- Two- or three-station arrays
- Short baselines
- Zero closure phases (symmetrical)

Sagittarius A* from model-fitting: VLBA era

Scattered size **Shen et al. 2005** **Intrinsic size**

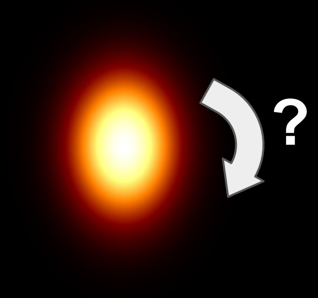
210 x 130 μas

- Multiple-station arrays, good East-West resolution, bad North-South
- VLBA era multi-epoch measurements
- Stable source size, elongated in the East-West, major axis well-constrained

Sagittarius A* from model-fitting: VLBA era

Scattered size | **Lu et al. 2011** | **Intrinsic size**

210 x 130 μas



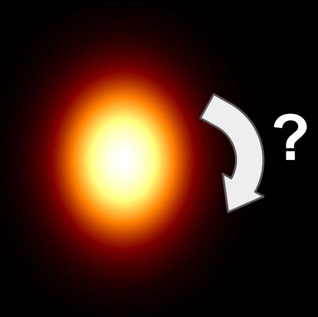
139 x 102 μas

- Multiple-station arrays, good East-West resolution, bad North-South
- VLBA era multi-epoch measurements
- Stable source size, elongated in the East-West, major axis well-constrained

Sagittarius A* from model-fitting: LMT+GBT era

Scattered size | **Ortiz-Leon et al. 2016 C** | **Intrinsic size**

213 x 138 μas



142 x 114 μas

- East-West array but LMT and GBT improve sensitivity and North-South resolution
- Stable source size, elongated in the East-West, minor axis better constrained

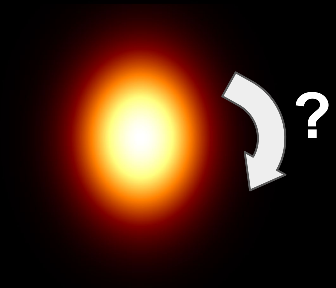
Sagittarius A* from model-fitting: LMT+GBT era

Scattered size

222 x 156 μas

Ortiz-Leon et al. 2016 D

Intrinsic size



155 x 122 μas

- East-West array but LMT and GBT improve sensitivity and North-South resolution
- Stable source size, elongated in the East-West, minor axis better constrained
- Ortiz-Leon+ 2016 and Brinkerink+ 2016 detect slightly non-zero closure phases

Sagittarius A* from model-fitting: LMT+GBT era

Scattered size | **Brinkerink et al. 2018** | **Intrinsic size**

215 x 145 μas

- East-West array but LMT and GBT improve sensitivity and North-South resolution
- Stable source size, elongated in the East-West, minor axis better constrained
- Ortiz-Leon+ 2016 and Brinkerink+ 2016 detect slightly non-zero closure phases
- Brinkerink+ 2018 detect 1% excess flux that deviates from Gaussian morphology

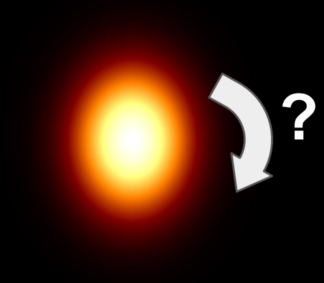
Sagittarius A* from model-fitting: LMT+GBT era

Scattered size

215 x 139 μas

Johnson et al. 2018

Intrinsic size



143 x 114 μas

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- Stable source size, elongated in the East-West, minor axis better constrained
- Ortiz-Leon+ 2016 and Brinkerink+ 2016 detect slightly non-zero closure phases
- Brinkerink+ 2018 detect 1% excess flux that deviates from Gaussian morphology

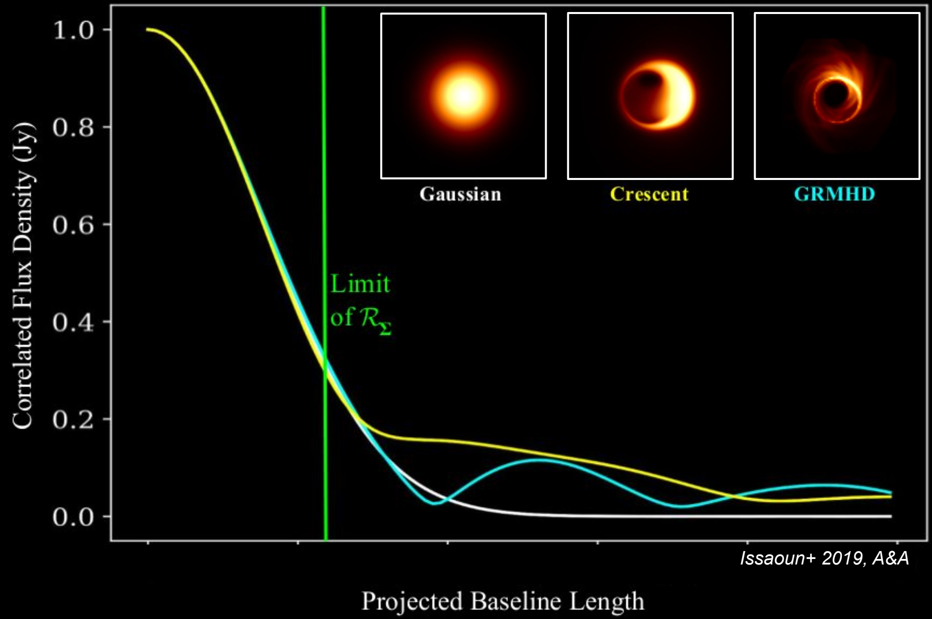
Is a Gaussian model suitable for Sgr A*?

Imaging is the next step

Sagittarius A* from imaging?

What does Sagittarius A* really look like at 86 GHz?

- No baselines above 1 Gλ, observed (scattered) source looks Gaussian
- Need longer baselines to probe non-Gaussian structure



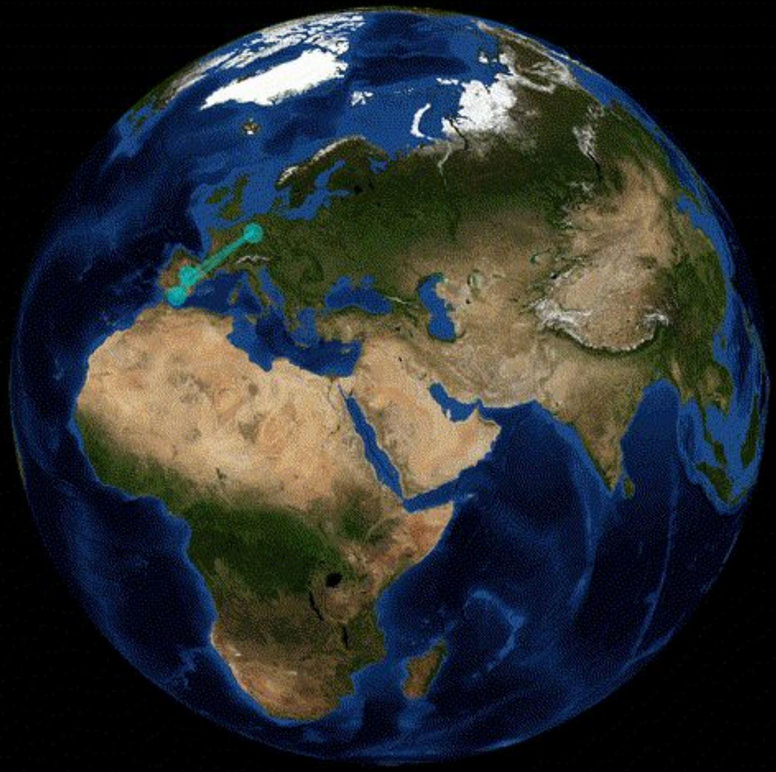
Issaoun+ 2019, A&A

April 2017: First VLBI with ALMA (+GMVA)

The Global Millimeter VLBI Array (GMVA)

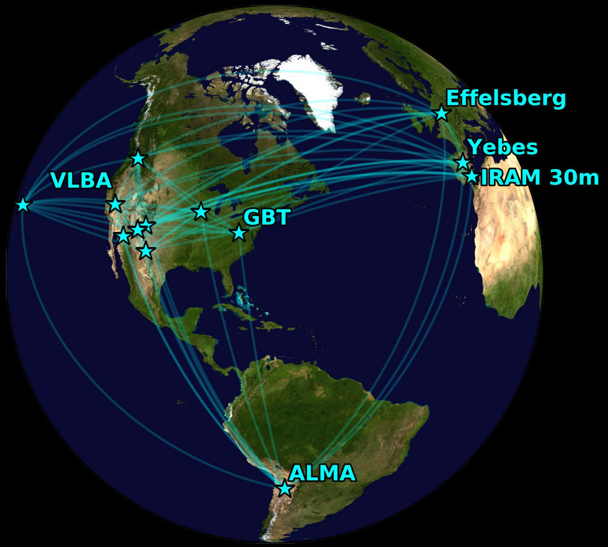
- European mm-wave facilities
- Very Long Baseline Array (US)
- Green Bank Telescope (US)
- ALMA (Chile) equipped for VLBI by the ALMA Phasing Project (Matthews+ 2018)

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

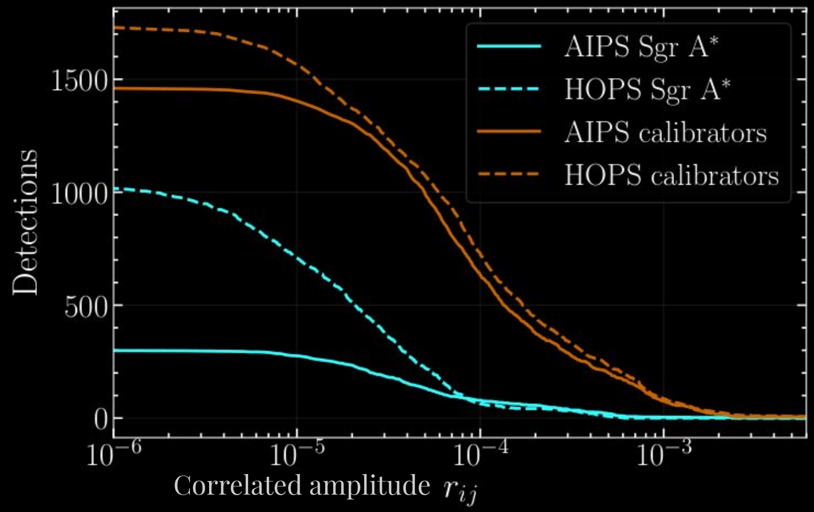


GMVA+ALMA observations

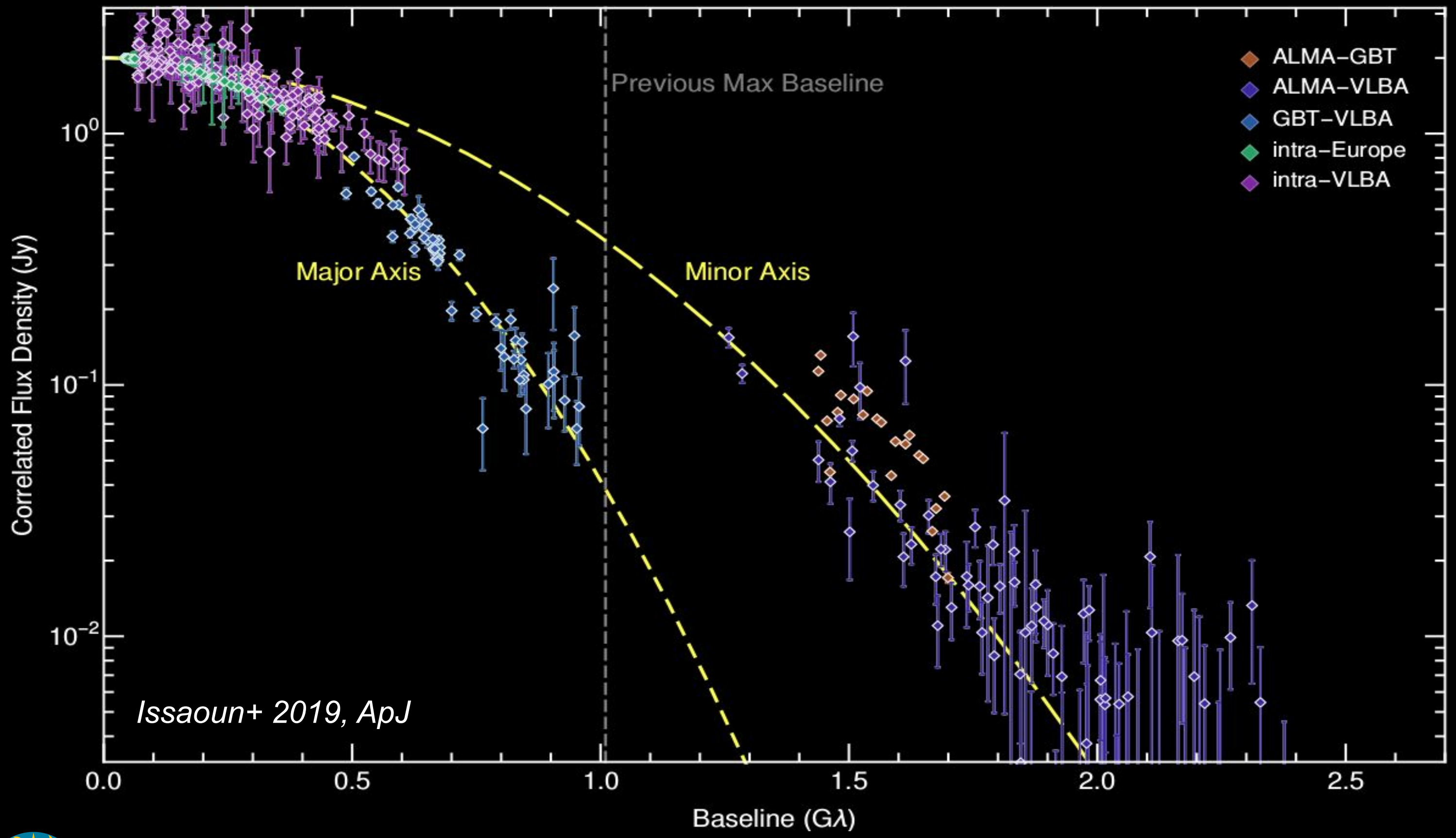
- April 3 2017 (12 hours, 8 with ALMA)
- Sagittarius A*, NRAO530, J1924-2914
- 13 participating stations
- 256 MHz bandwidth, full-polarization, 2Gbps recording



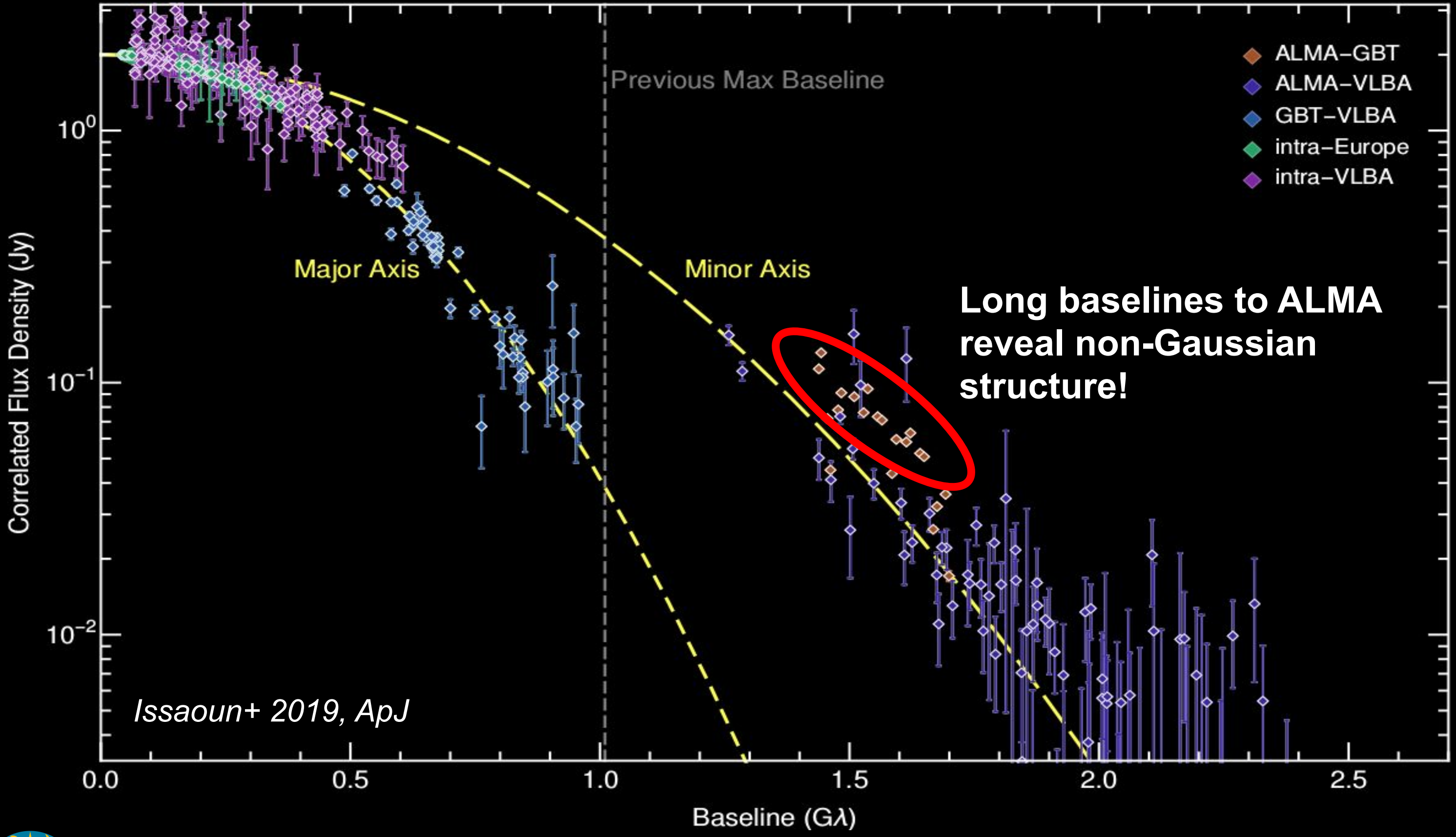
- Data reduction with *EHT-HOPS* pipeline (Blackburn+ 2019, ApJ)
- Processing checks with *AIPS*
- Imaging with *eht-imaging* library (Chael+ 2016, 2018)



Sgr A* amplitudes reveal scattering properties

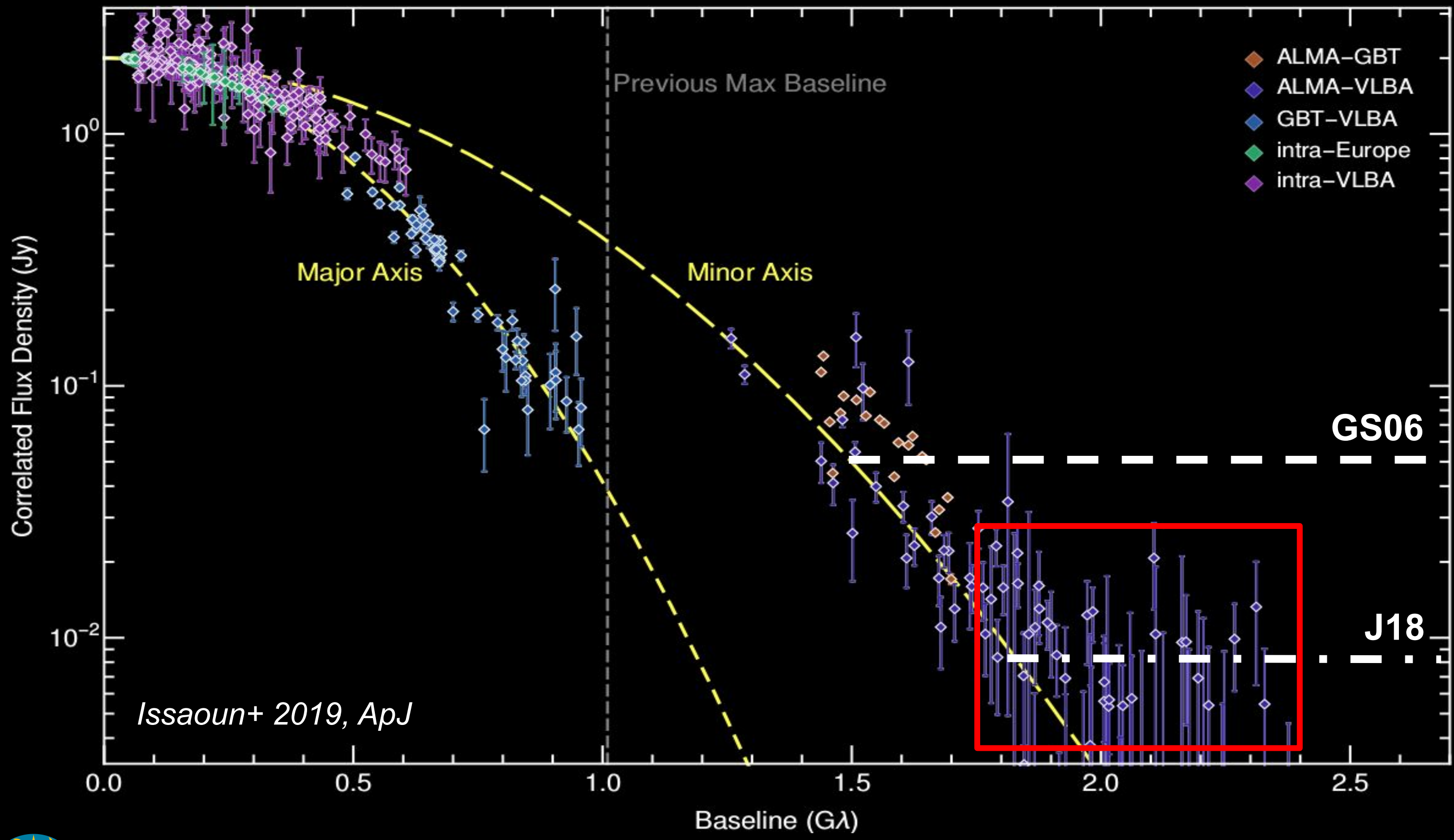


Sgr A* amplitudes reveal scattering properties



Long baselines to ALMA reveal non-Gaussian structure!

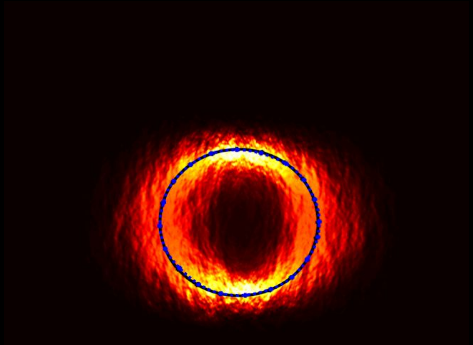
Sgr A* amplitudes reveal scattering properties



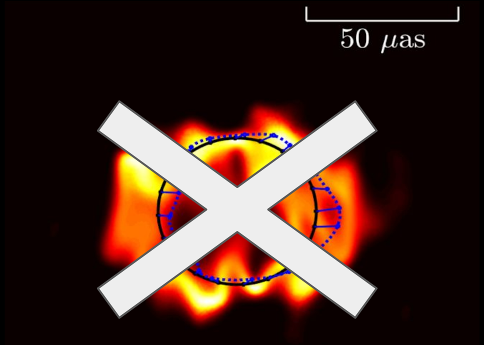
Sgr A*: The Scattering

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)

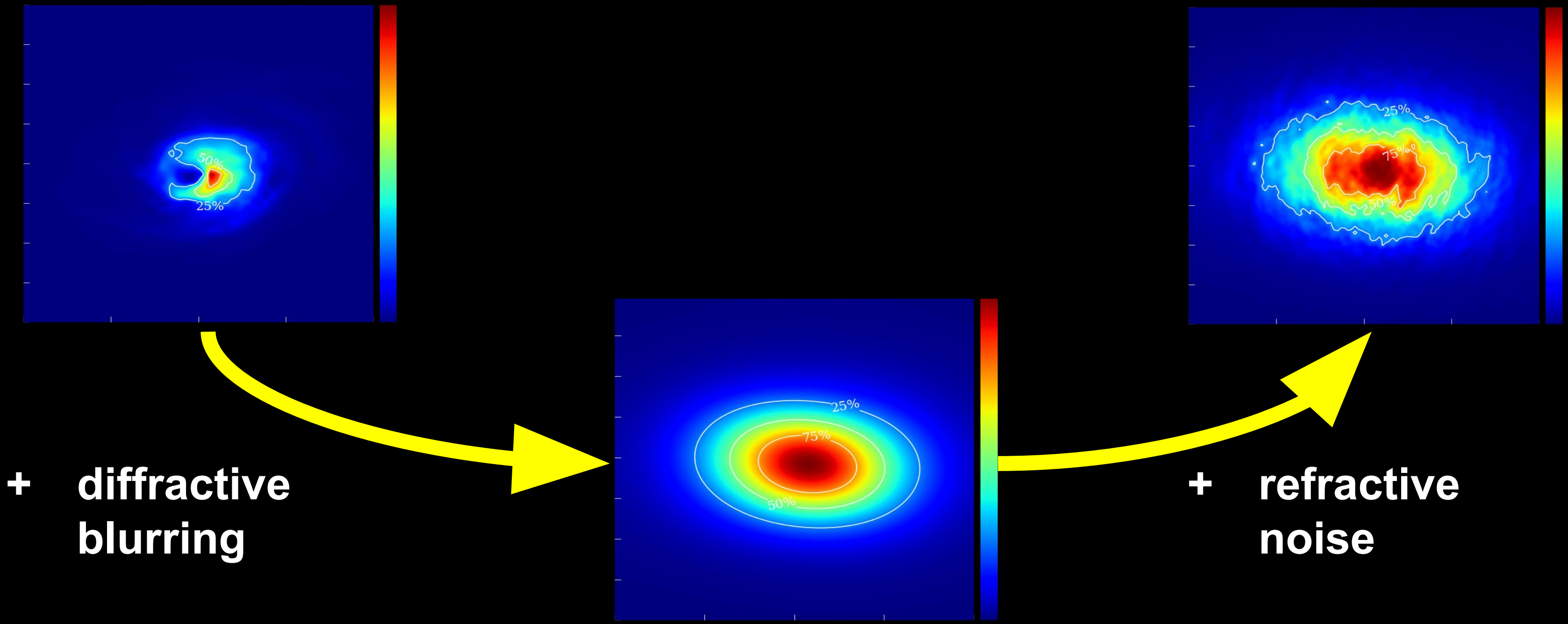


GS06 model
(Goldreich & Sridhar 2006)

Zhu, Johnson & Narayan 2019

Reconstructing an unscattered image: J18

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



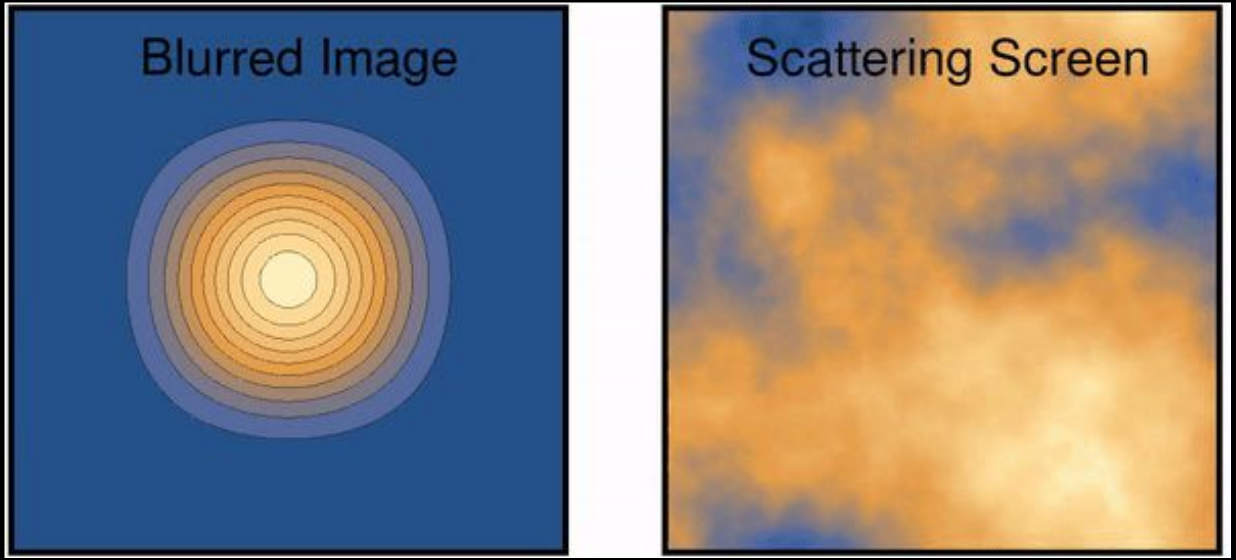
Reconstructing an unscattered image: J18

J18 scattering model:

non-Gaussian scattering kernel + stochastically varying refractive noise

1) Solving for stochastic variations in the scattering screen

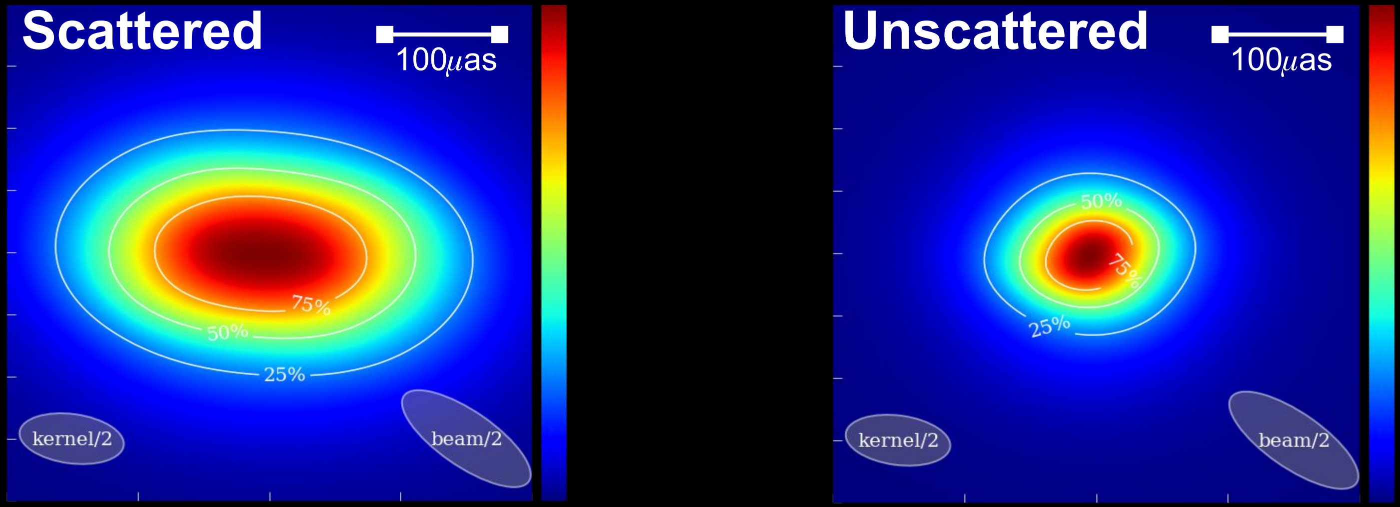
2) Deconvolving with the scattering kernel



Credit: M. Johnson

Sgr A*: The Size

Issaoun+ 2019, ApJ



215 x 140 μas, PA 80º

120 x 100 μas, PA 96º

All closure phases are consistent with zero within 3σ, indicating no apparent asymmetry

Emission at 86 GHz originates within

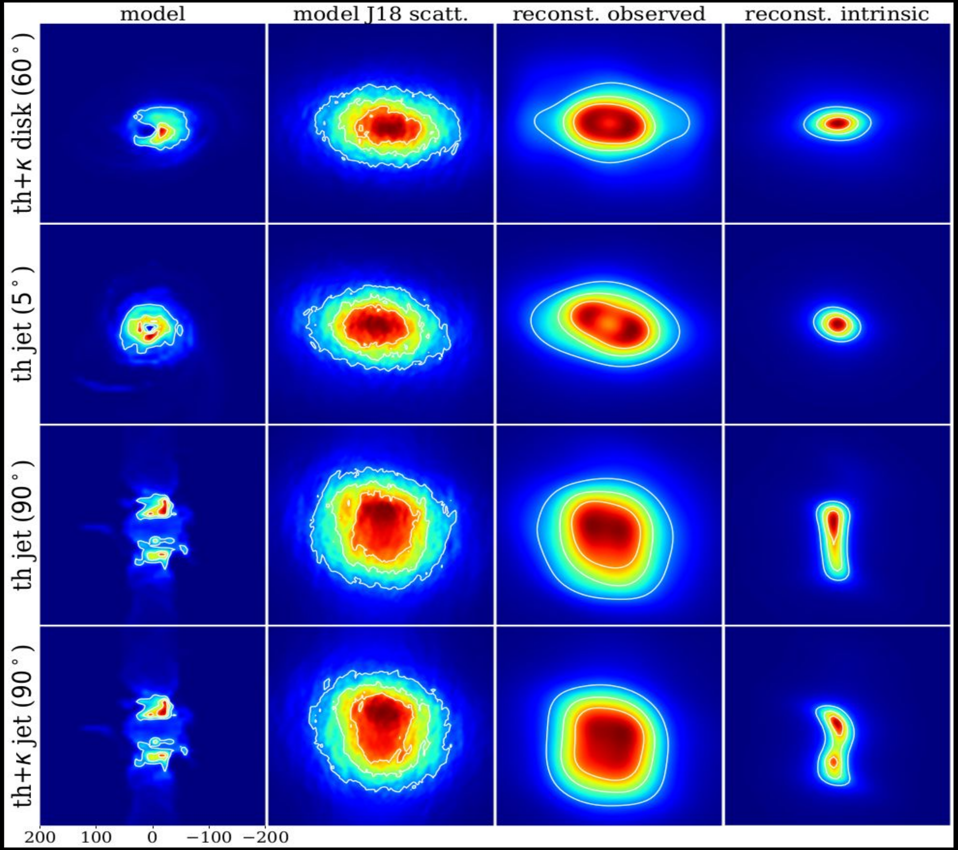
~12 Schwarzschild radii of the black hole

Sgr A*: The Shape

GRMHD simulations (from M. Moscibrodzka) sampling disk vs jet dominated emission at 86 GHz, varying electron acceleration

Diffractive and refractive scattering with *stochastic optics* (Johnson 2016)

Image reconstructions with *eht-imaging* library (Chael+ 2016, 2018), identical to real Sgr A* imaging

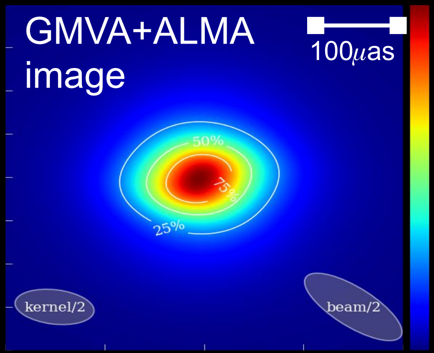


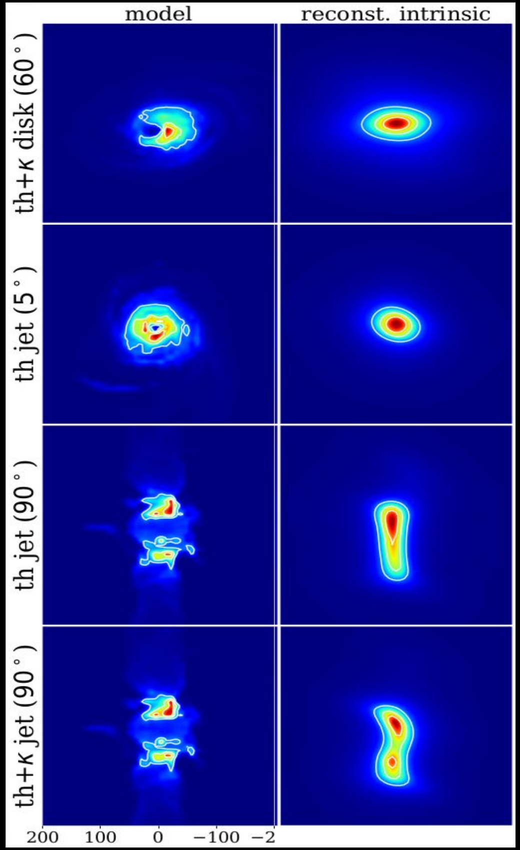
Sgr A*: The Shape

8 simulations were tested against the source size/shape:

- 4 looking at electron acceleration in disks/jets (Davelaar+ 2018)
- 4 looking at electron heating prescription and spin (Chael+ 2018)

If jet dominated, emission must be face-on (< 20 degrees)





Sgr A*: The Shape

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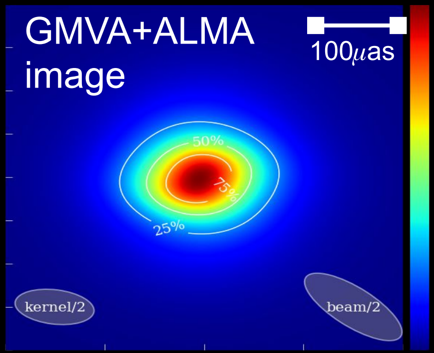
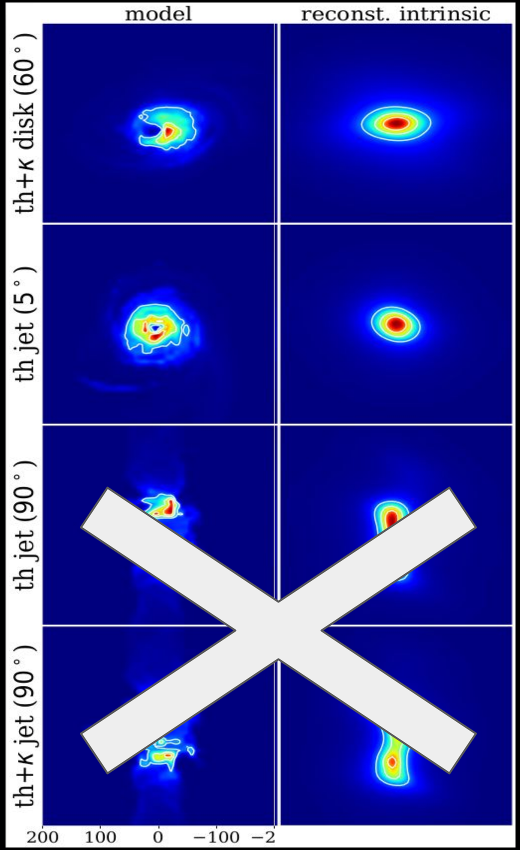




GMVA+ALMA in 2018

Two observations (2x6hrs) separated by 3 days, to explore dynamic properties of refractive scattering

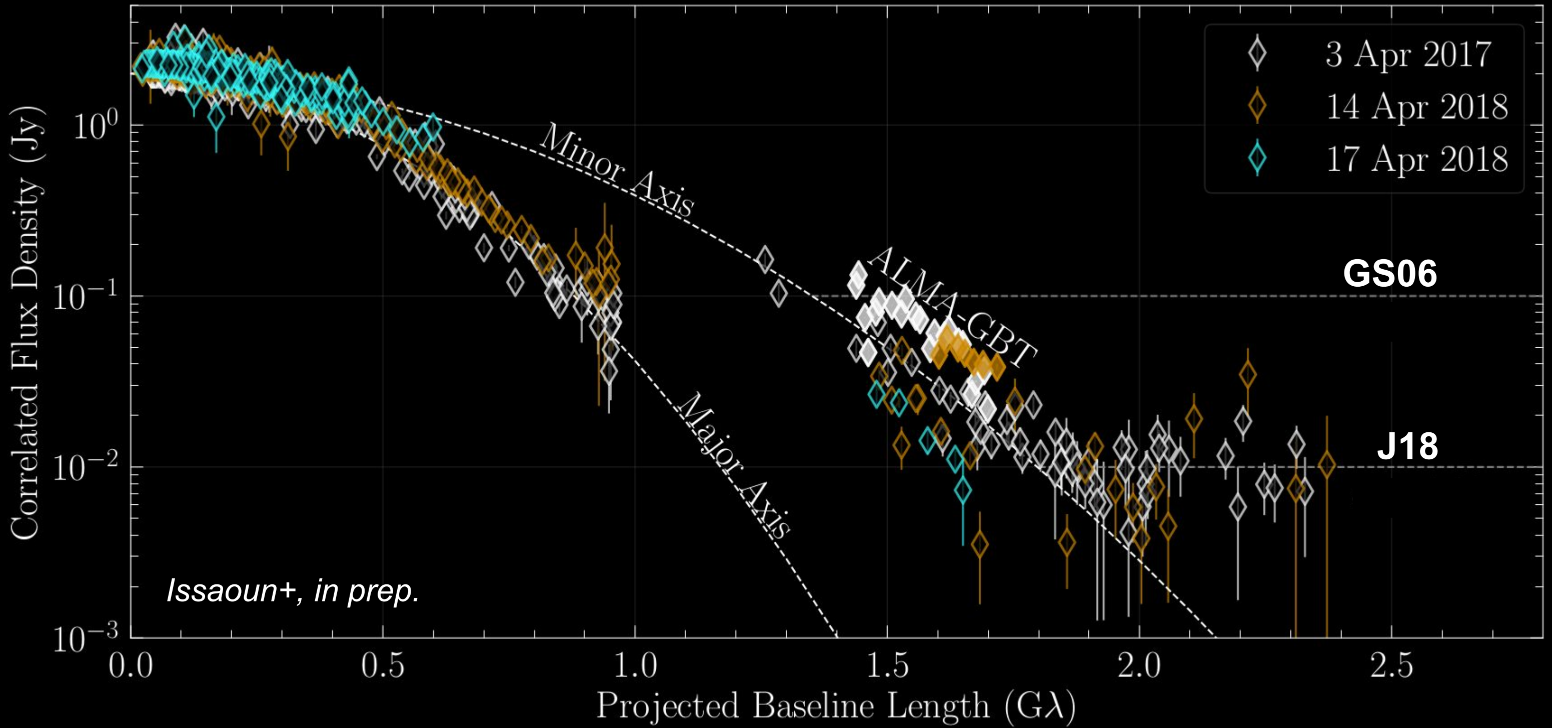
April 14, 2018

April 17, 2018

GBT lost due to disk failure

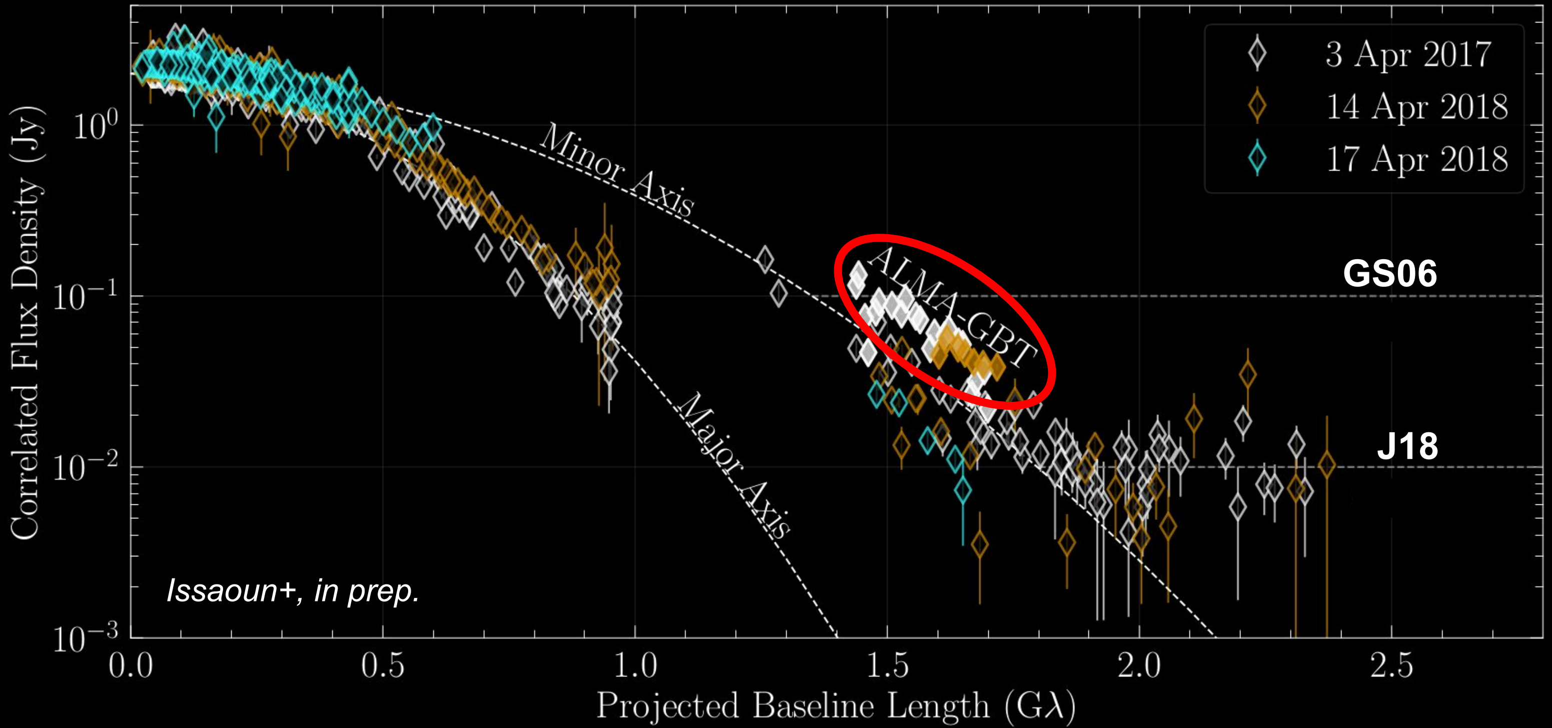
GMVA+ALMA in 2018

Two observations (2x6hrs) separated by 3 days, to explore dynamic properties of refractive scattering



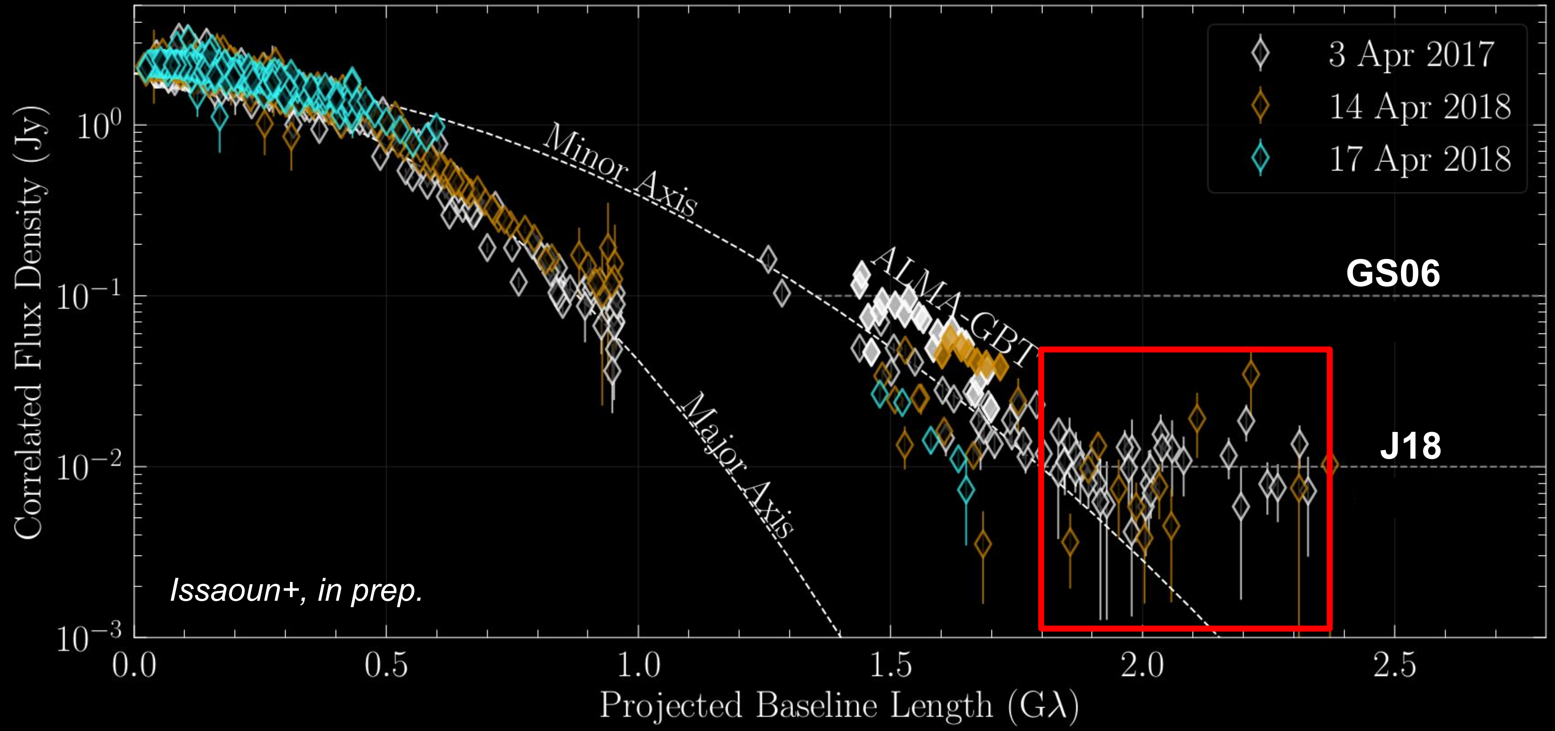
GMVA+ALMA in 2018

Two observations (2x6hrs) separated by 3 days, to explore dynamic properties of refractive scattering



GMVA+ALMA in 2018

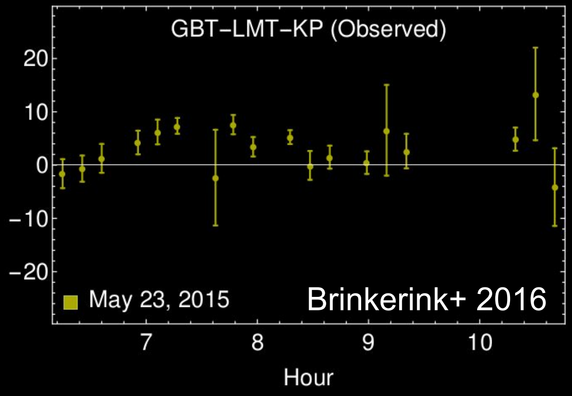
Two observations (2x6hrs) separated by 3 days, to explore dynamic properties of refractive scattering

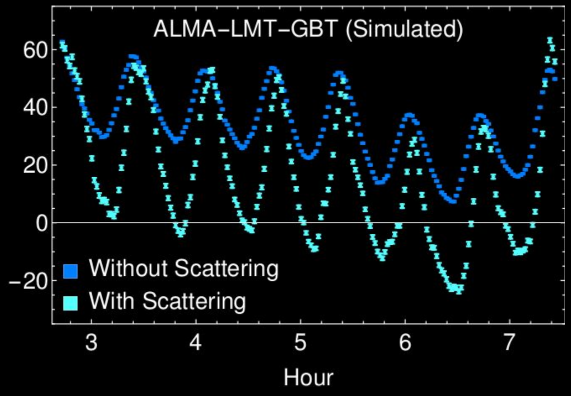


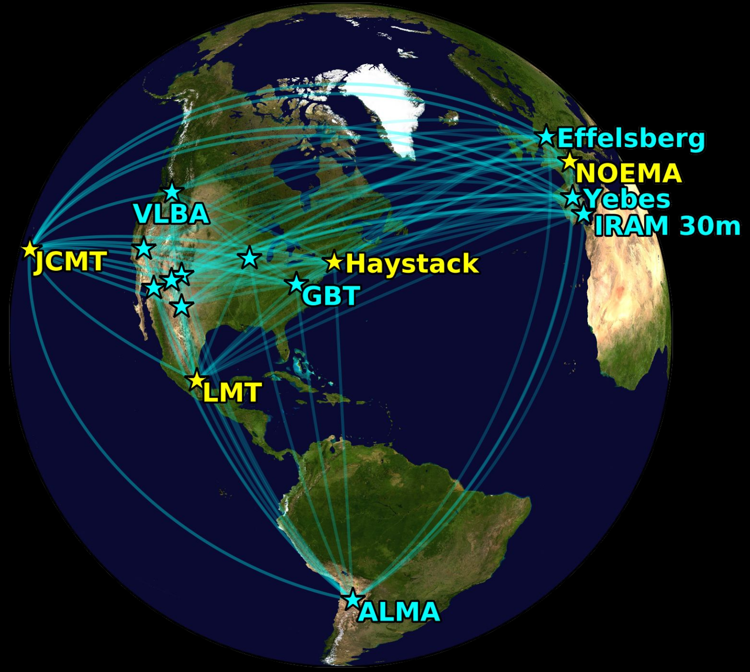
GMVA+ALMA in the future

Expanding GMVA+ALMA to more sensitive stations

- Higher sensitivity on long baselines to Europe/Hawaii
- Higher sensitivity in North-South direction
- Highly sensitive triangles for time-domain analysis of closure phase variability







GMVA+ALMA in 2021+

Zooming into Sagittarius A*

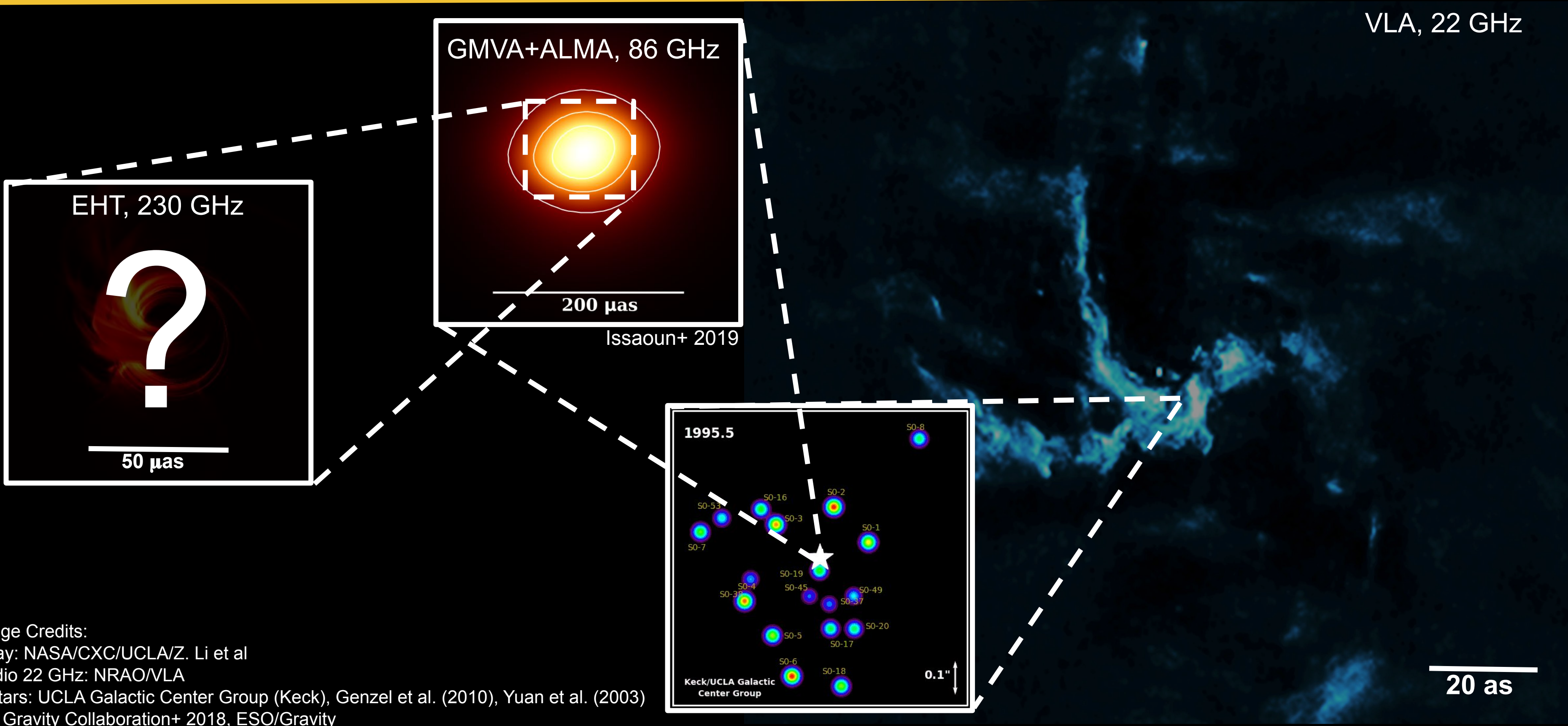


Image Credits:
X-ray: NASA/CXC/UCLA/Z. Li et al
Radio 22 GHz: NRAO/VLA
S-stars: UCLA Galactic Center Group (Keck), Genzel et al. (2010), Yuan et al. (2003)
S2: Gravity Collaboration+ 2018, ESO/Gravity

Summary

- The size:
  - The radio emission at 86 GHz originates in a compact region of ~12 Schwarzschild radii
- The shape:
  - We obtain a highly symmetrical morphology
  - Jet-dominated emission models do not fit the 3 mm observations, unless they are < 20° of face-on (consistent with Gravity Collaboration+ 2019 flare results)
- The scattering:
  - The GS06 model over-estimated flux on ALMA baselines and was successfully ruled out
  - The J18 model is consistent with our measurements
  - Good prospects for the Event Horizon Telescope