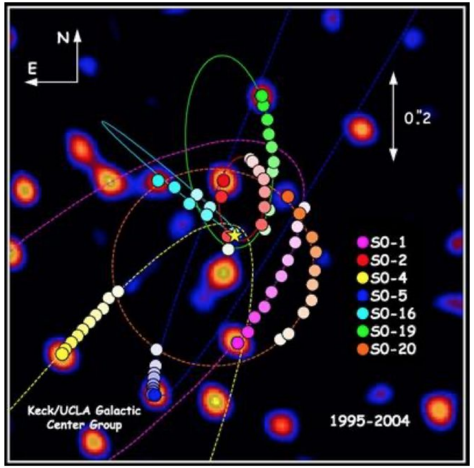
EAVN observations toward Sgr A*

:The intrinsic structure of Sgr A* at 13 and 7 mm

Ilje Cho (UST/KASI),
on behalf of the KaVA/EAVN AGN SWG, EHT MWL WG

Our Galactic Center: Sagittarius A* (Sgr A*)

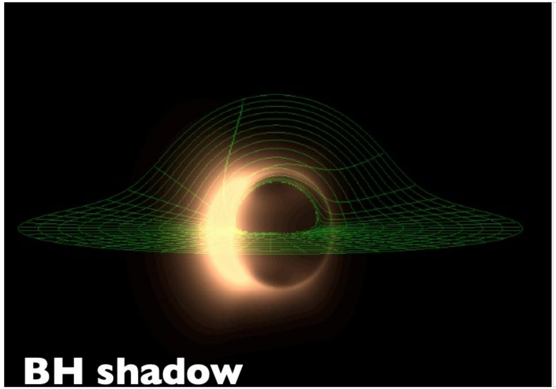


The Closest SMBH from us

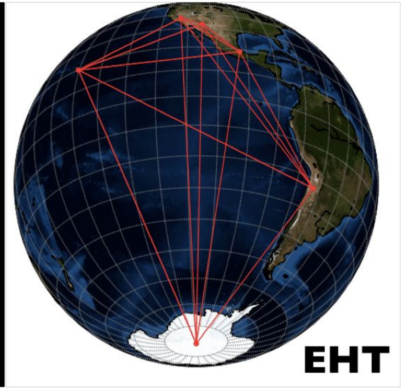
(~8 kpc away: Reid 1993; Ghez+ 2005, 2008; Gillessen+ 2009)

- **Mass ~ 4 x 10^6 M_{sun}**
  (Genzel+ 2010; Falcke & Markoff 2013)
- **R_{sch} ~ 10 uas / visible by lensing up to 50 uas**
  (e.g., Falcke+ 2000)
- **Low Eddington ratio** (L ~ 10^{36} erg/s ~10^{-9} L_{edd})
  (Falcke+ 1993; Quartaert & Gruzinov 2000)
- **Mass accretion rate** (2 x $10^{-7\sim9}$ M_{sun}/yr)
  (Marrone+ 2007)

Thanks to
its proximity,
we can directly study
the environment of
vicinity of SMBH.



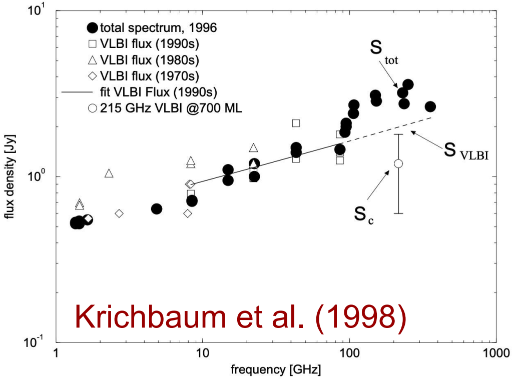
(Bardeen 1973; Luminet 1979;
Shen+ 2005; Broderick & Loeb 2006)

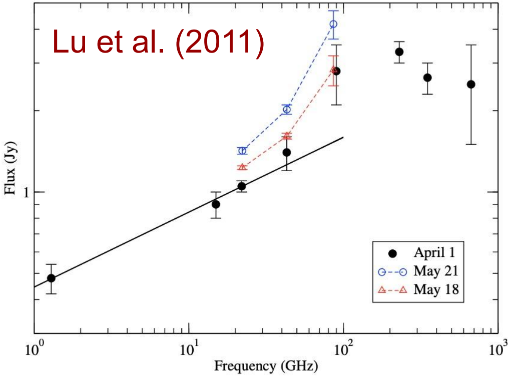


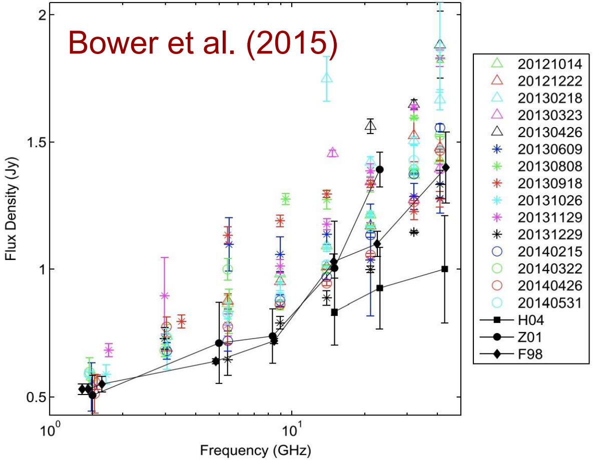
(Johnson+2015; Fish+ 2016;
Chael+ 2016; Broderick+ 2016)

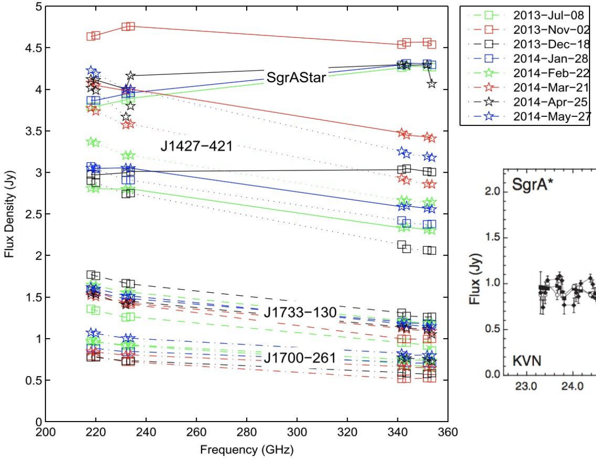
Our Galactic Center: Sagittarius A* (Sgr A*)

Flux densities at cm~sub-mm wavelengths







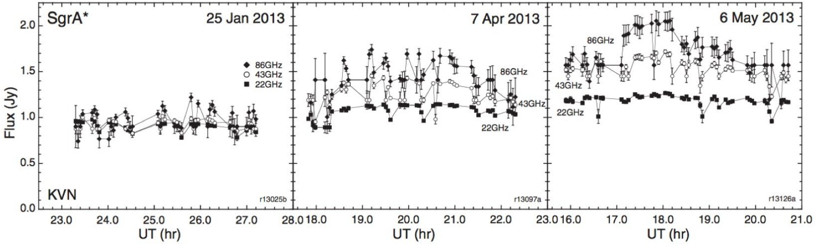


* Inverted synchrotron spectrum in the radio with the turn-over frequency at 200~300 GHz
: stratified, self-absorbed geometry

* Compact but scatter broadened structure

* Fast variation of flux density

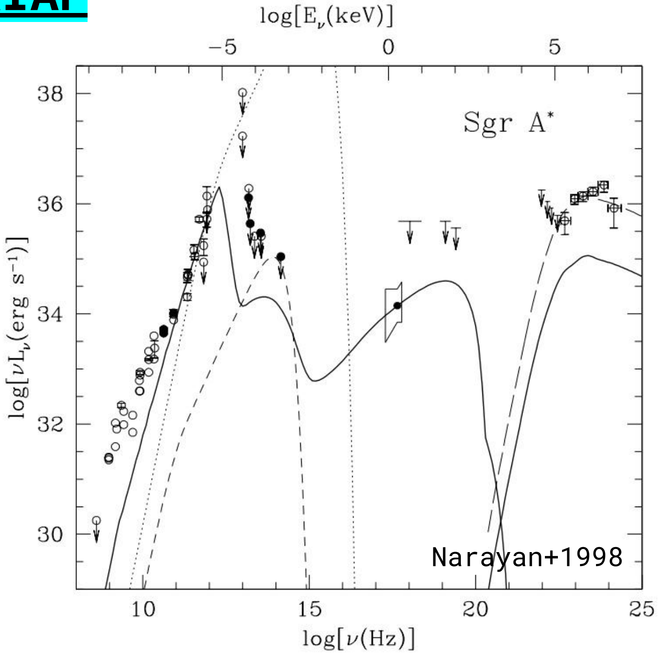
Miyazaki et al. (2014)



Our Galactic Center: Sagittarius A* (Sgr A*)

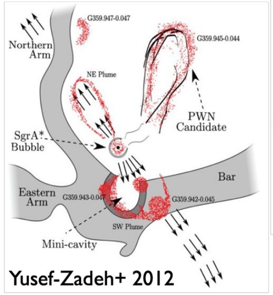
Long-lived Question: What is the origin of radio emission ?

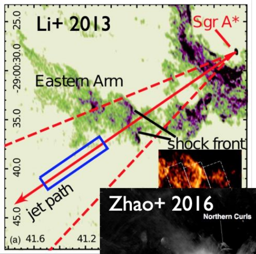
RIAF

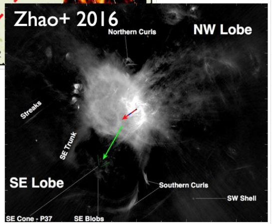


Jet

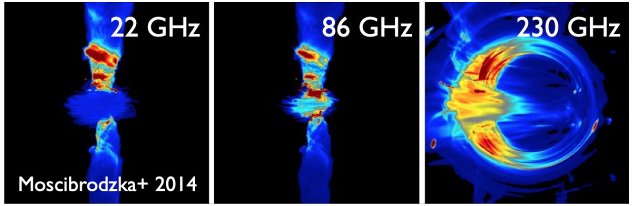
Ambient medium in pc-scale





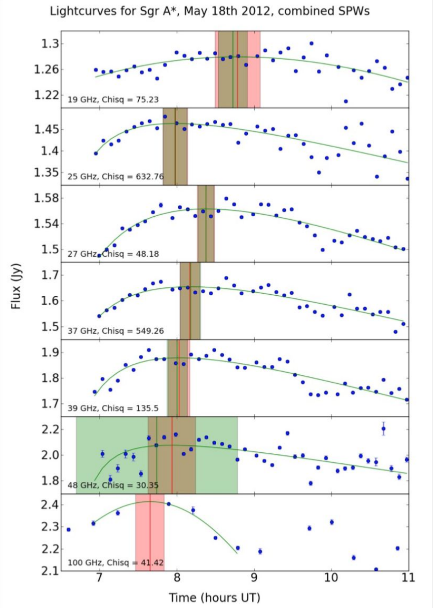


GRMHD simulation including jet model



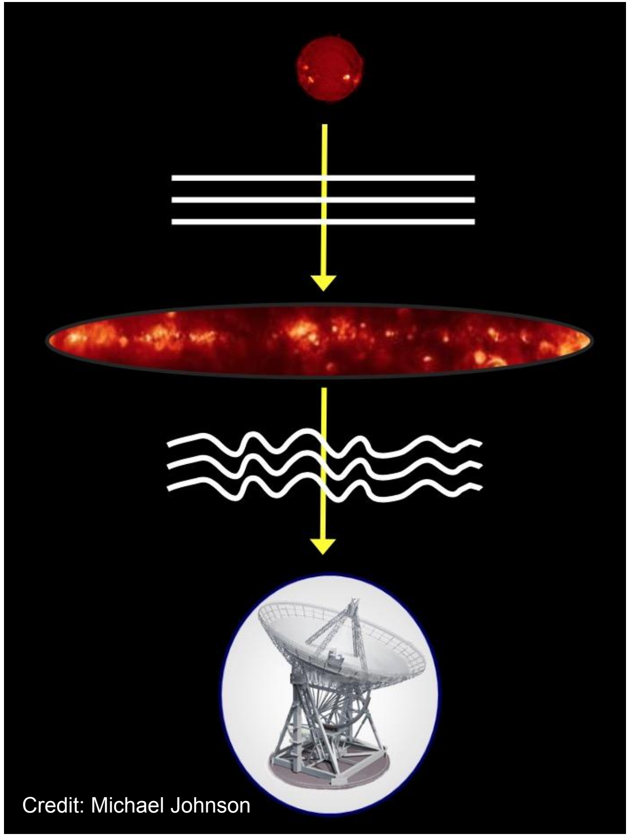
Time delay of flux increase depending on frequency

(Brinkerink+ 2015)



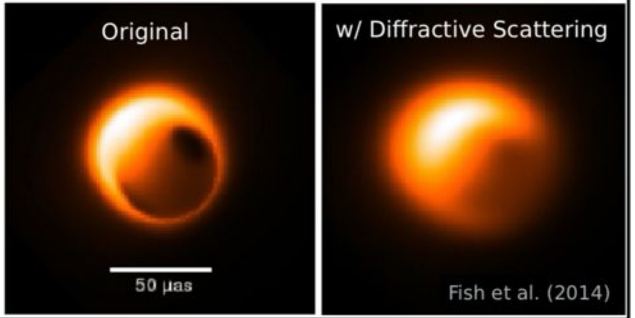
Intrinsic structure of Sgr A* at 13 and 7 mm

Sgr A* together with scattering effects



Effects of Scattering

Two Effects of Interstellar Scattering



1. Blurring ("diffractive"):

- Deterministic and invertible
- Weaker at higher frequencies
- Doesn't affect some observables, such as phase

2. Substructure ("refractive"):

- Stochastic and time-variable
- Stronger at higher frequencies
- Unexpectedly strong effect on VLBI!

(Narayan & Goodman 1989; Johnson & Gwinn 2015)

Credit: Michael Johnson

Intrinsic structure of Sgr A* at 13 and 7 mm

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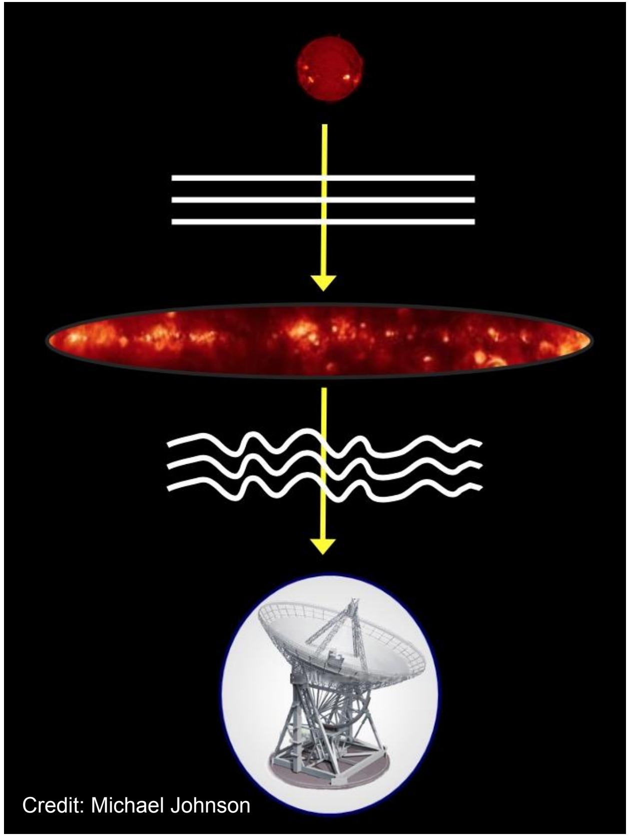
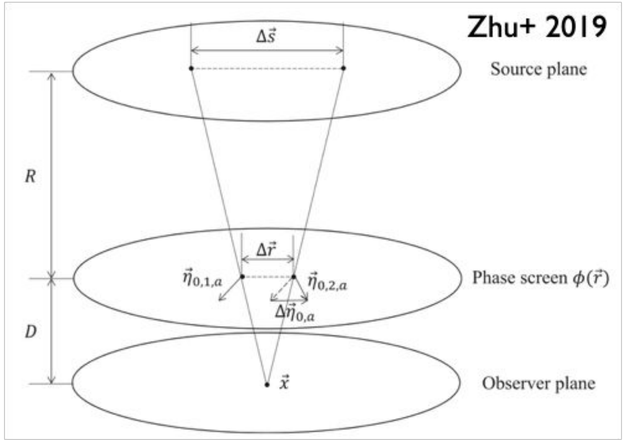




- Density inhomogenities in the ionized ISM makes phase change, $\delta\phi$
- Single thin phase screen, $\phi(r)$, and its power spectrum, $Q(q) \propto |q|^{-\beta}$ (where $r_{in} < r < r_{out}$)
- Phase structure function, $D_\phi \equiv \langle[\phi(r' + r) - \phi(r)]^2\rangle \propto \lambda^2$

- For baseline lengths (b),
  - $b < (1+M)r_{in}$: anisotropic Gaussian blurring ($\theta_{scatt} \propto \lambda^2$)
  - $b > (1+M)r_{in}$: non-Gaussian ($\theta_{scatt} \propto \lambda^{1+2/\alpha}$)

  (where $M \equiv D/R$)

- Scattering model parameters:
  - $\theta_{maj}, \theta_{min}, \phi_{PA}$ (Gaussian broadening)
  - α, r_{in}, r_{out} (r_{out} can be assumed as ~infinity)

Based on,
- Psaltis+18,
- Johnson+18,
- Issaoun+19

Intrinsic structure of Sgr A* at 13 and 7 mm

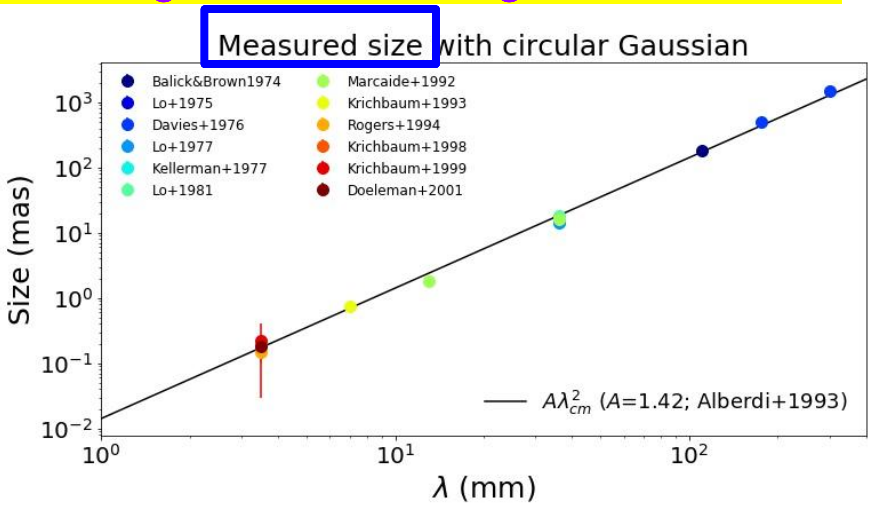
Historical VLBI sizes of Sgr A*: modeling with a single Gaussian

Discovery and lambda^2 relation

- Balick & Brown (1974): discovery of Sgr A* with the interferometric observations at 11 and 3.7 cm
- Davies, Walsh & Booth (1976): lambda^2 relation of the measured size (up to ~2 cm)

$$(\theta_{meas})^2 = (\theta_{scat})^2 + (\theta_{int})^2$$

$$\theta_{scat} \propto \lambda^{\zeta} (\zeta \approx 2)$$



Intrinsic structure of Sgr A* at 13 and 7 mm

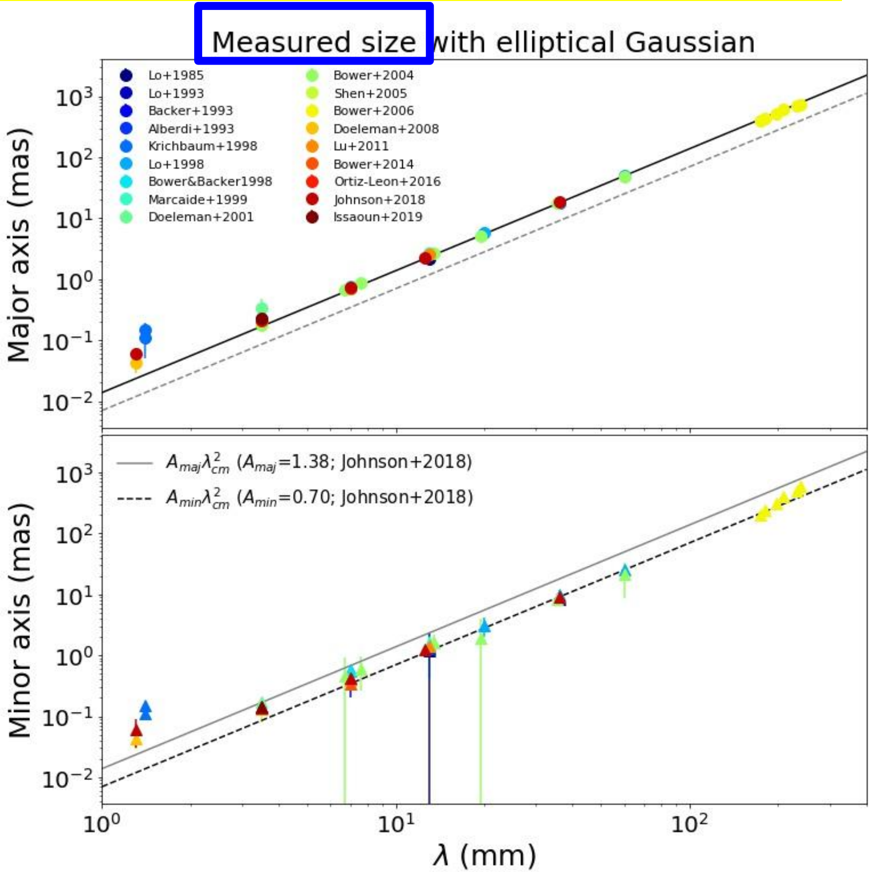
Historical VLBI sizes of Sgr A*: modeling with a single Gaussian

East-West elongated structure

- At 3.6 cm (Lo et al. 1985), 1.3 cm (axial ratio~0.5; Alberdi et al. 1993), and 0.7 cm (axial ratio~0.73; Bower & Backer 1998)

Marginal detection of intrinsic structure (i.e. observed size is larger than the extrapolated lambda^2)

- At 0.7, 0.3 and 0.14 cm (Krichbaum et al. 1998; Lo et al. 1998; Doeleman et al. 2001)
- 2-dimensional lambda^2 relation (Lo et al. 1998): coefficients (i.e., scatter sizes at 1 cm in mas) are 1.43 and 0.76 for major and minor axis, respectively.



Intrinsic structure of Sgr A* at 13 and 7 mm

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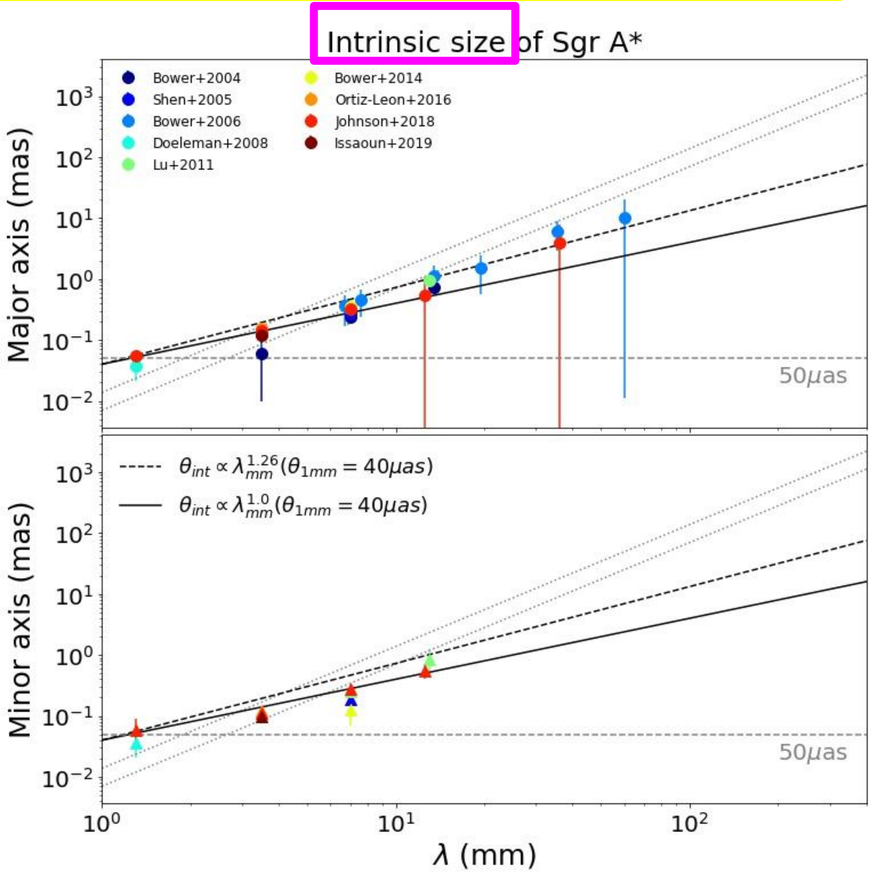
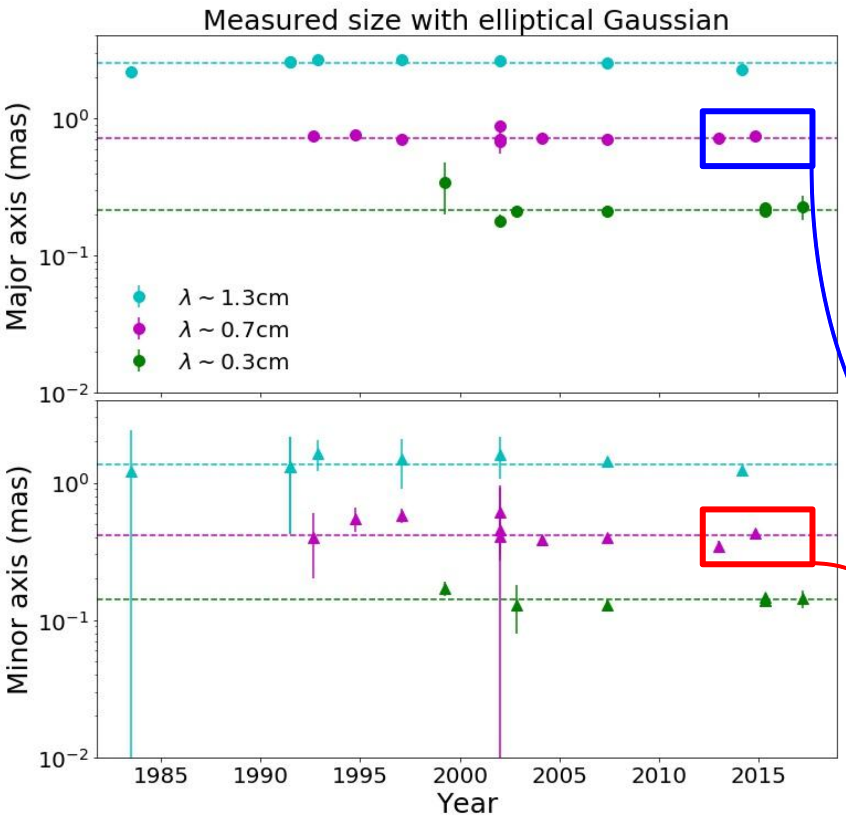
Intrinsic size of Sgr A* by deblurring the scattering kernel model



Intrinsic structure of Sgr A* at 13 and 7 mm

Is the size variable ?



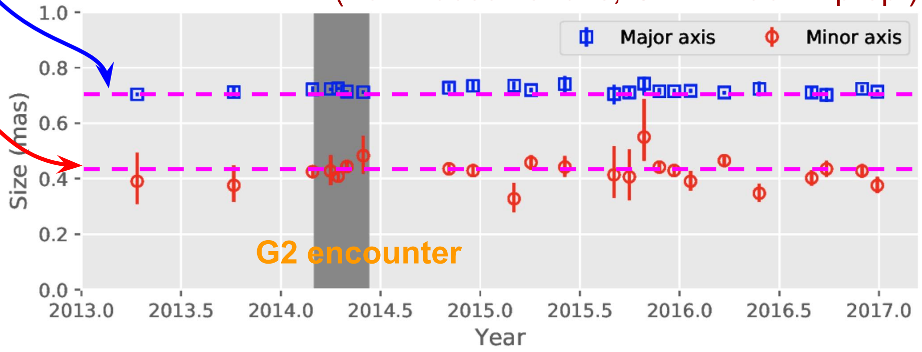
<u>* Stable source structure, e.g.,</u>

- Marcaide et al. (1999): stable over a decade (at 13 mm)
- Lu et al. (2011): stable major axis size over 10 days (at 13/7/3.5 mm)
- Bower et al. (2014): no relation with NIR flares (at 7mm)

<u>* Size variation at 7 mm</u>

- Bower et al. (2004): 60% increase in intrinsic size
- Akiyama et al. (2013): ~19% rms variation
- G.-Y. Zhao et al. (in prep.): Mostly stable for ~4 years but marginal variation of minor-axis size.

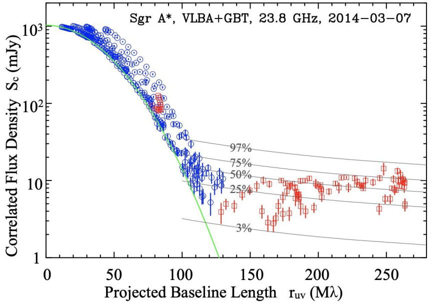
(KaVA observations; G.-Y. Zhao+in prep.)



Intrinsic structure of Sgr A* at 13 and 7 mm

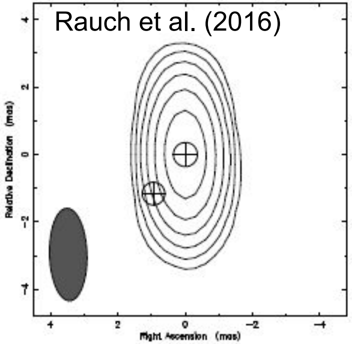
Beyond a single Gaussian model: intrinsic, or refractive feature ?

1.3 cm



Gwinn et al. (2014)
: refractive sub-structure.

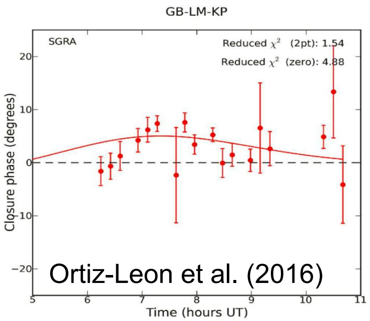
0.7 cm



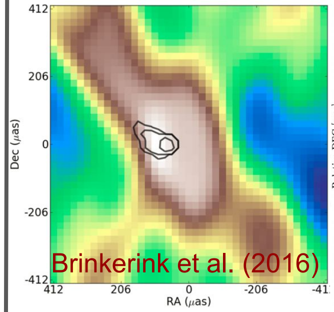
: secondary component which may related to a NIR flare ~4.5 hrs ahead (e.g., adiabatically expanding jet feature ?)

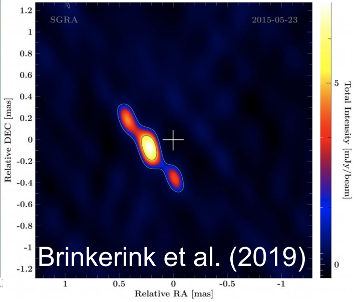
More MWL-coordinated VLBI observations
: KaVA/EAVN (at 7 mm) observations in 2019-2020 (PI: I. Cho)

0.35 cm



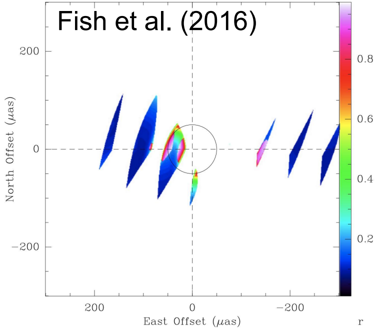
: non-zero closure phases which may consistent with the refractive sub-structure.

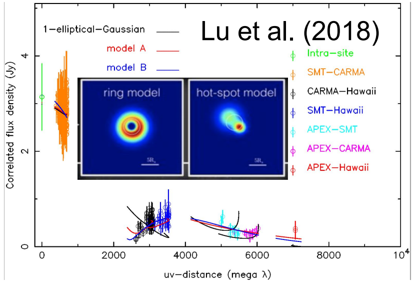




: However, the intrinsic asymmetry cannot be excluded, especially towards east-west.

0.13 cm



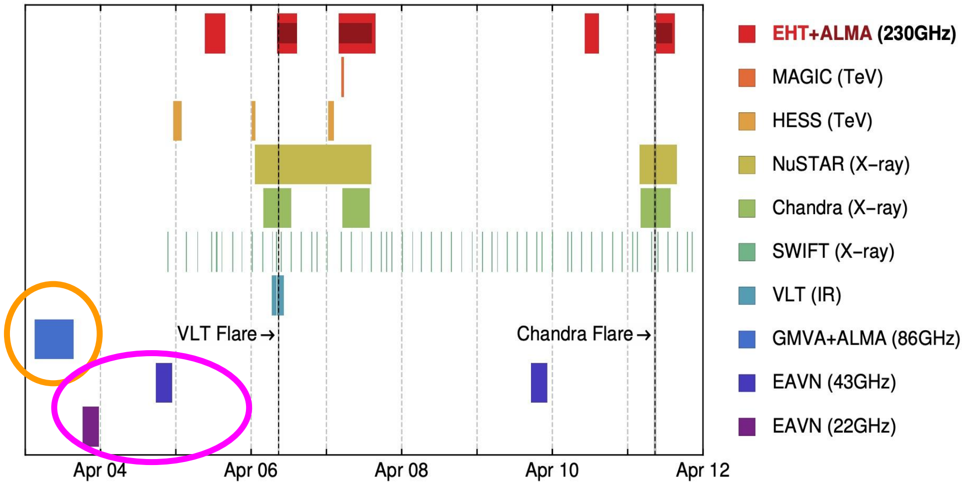


: more likely an asymmetric structure of Sgr A*.

Intrinsic structure of Sgr A* at 13 and 7 mm

Multi-wavelength (MWL) campaign for Sgr A* in 2017 April

2017 EHT window



Array	Date (2017)	λ (cm)	References
EAVN	Apr 03	1.35	This work
EAVN	Apr 04	0.70	This work
GMVA+ALMA	Apr 03	0.35	Issaoun et al. (2019)
EHT	Apr 05-11	0.13	–

Table 1. EAVN and related observations for Sgr A* in 2017 April.

EAVN observations in 2017 April

Intrinsic structure of Sgr A* at 13 and 7 mm

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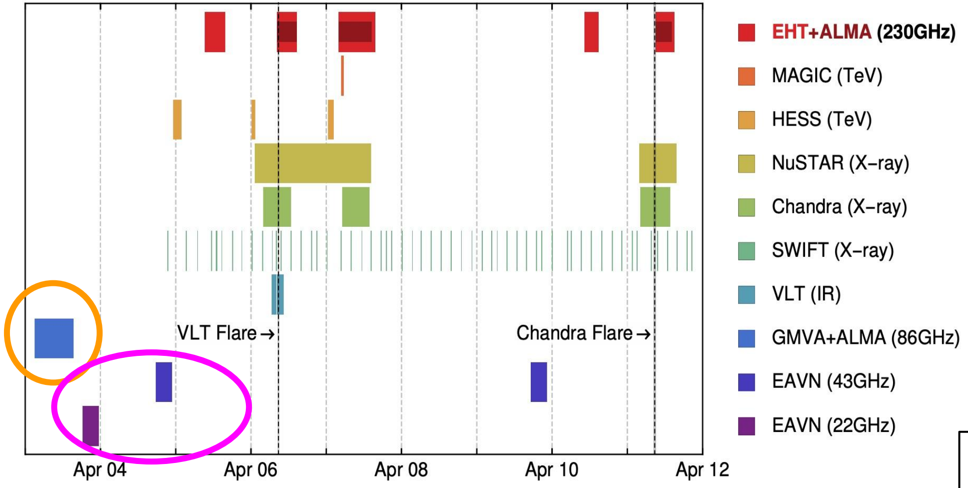

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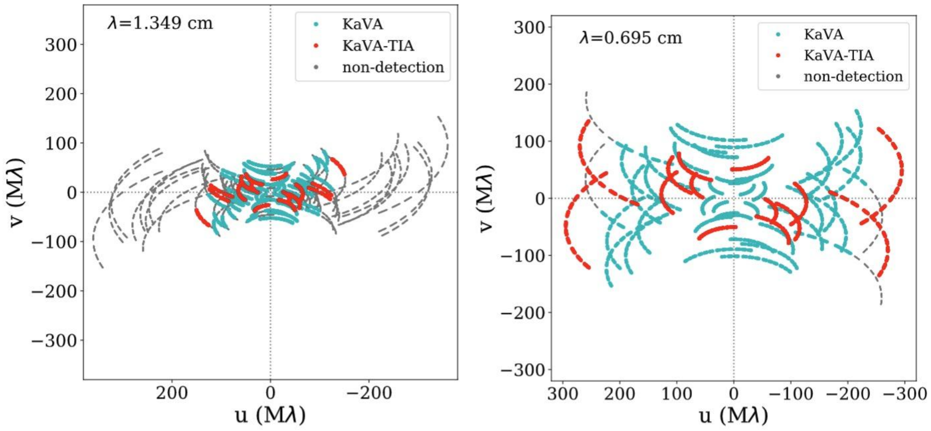


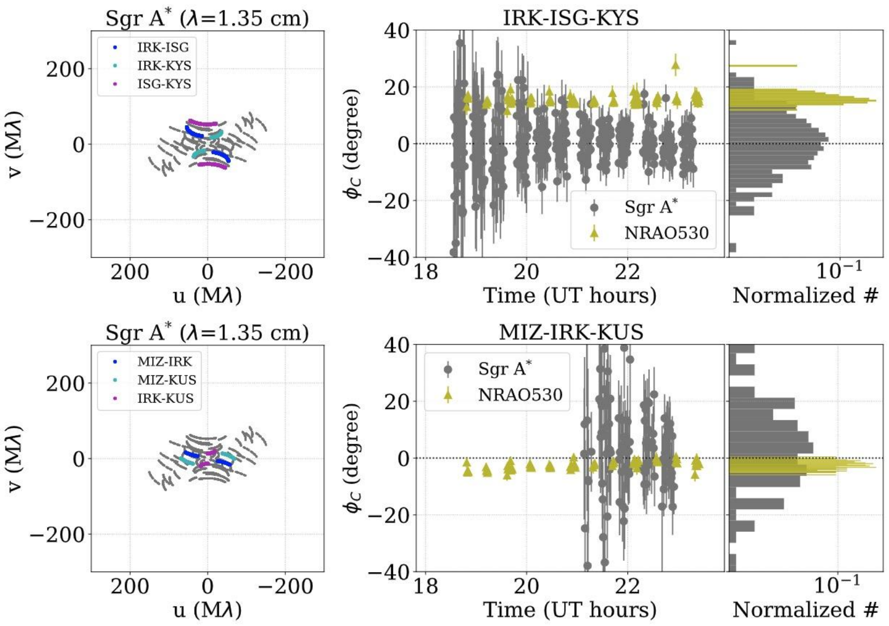
- The observations towards Sgr A* have been conducted as a part of the KaVA/EAVN Large Program.
- The observing wavelengths are 1.3 and 0.7 cm, with 256 MHz total bandwidth.
- 8 telescopes (7 KaVA + Tianma) have successfully detected Sgr A* at both wavelengths.

Intrinsic structure of Sgr A* at 13 and 7 mm

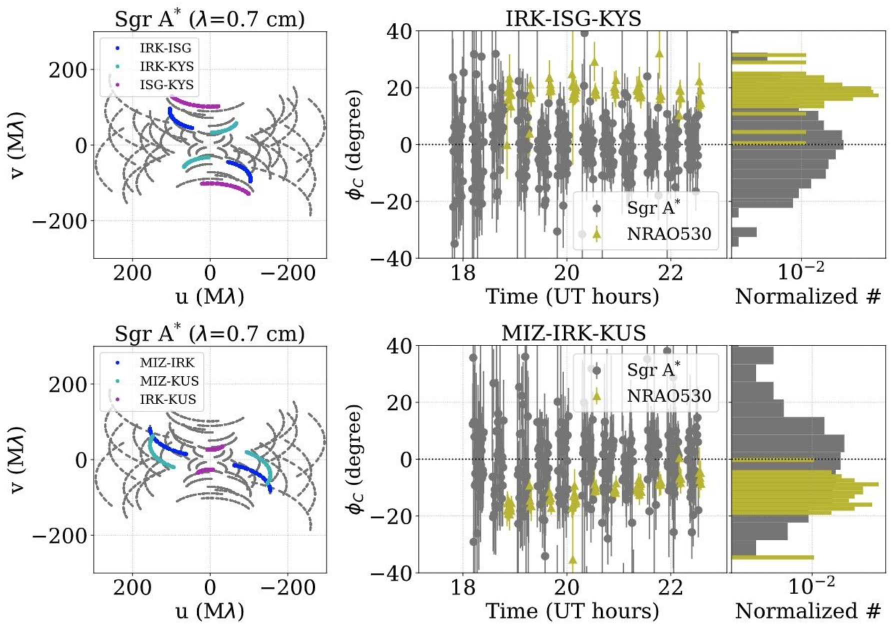
A single Gaussian assumption

* Non-zero closure phases (CP) are not found for Sgr A*, so that its structure can be reasonably assumed as a point or symmetric (e.g., single Gaussian).

1.3 cm



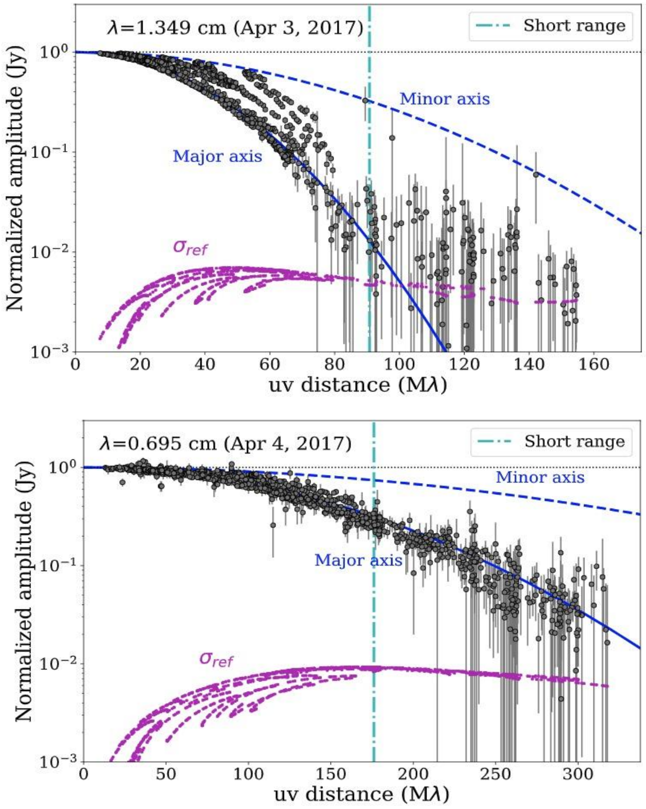
0.7 cm



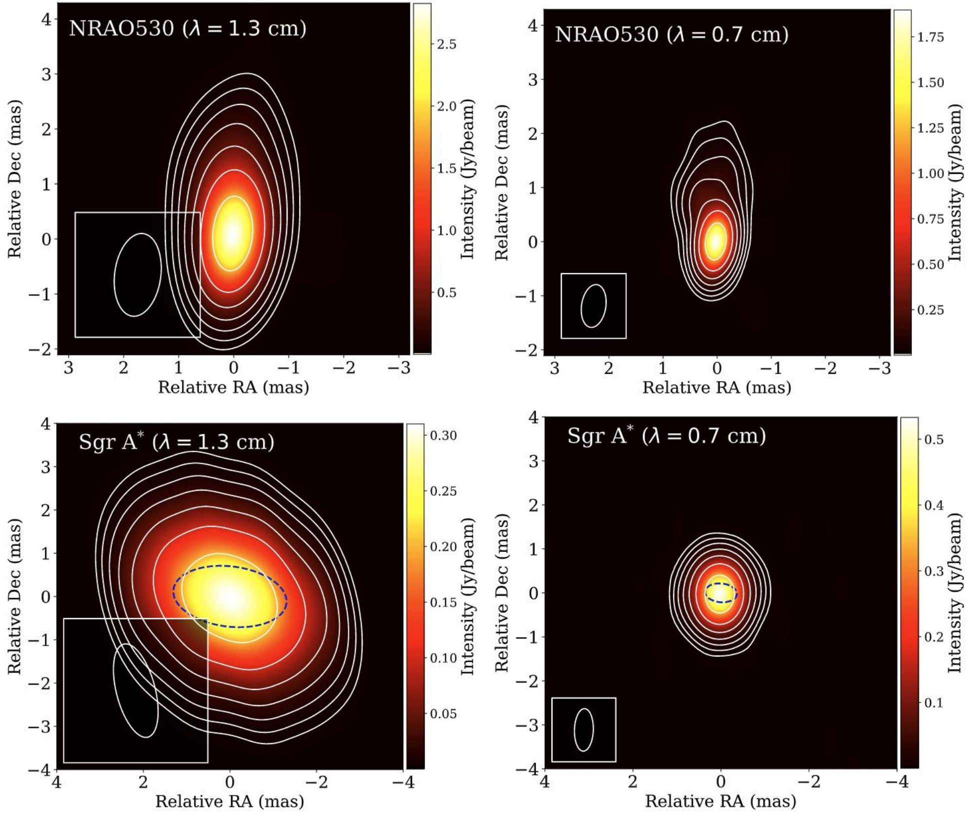
Intrinsic structure of Sgr A* at 13 and 7 mm

Self-calibration results & Images

Visibility amplitudes



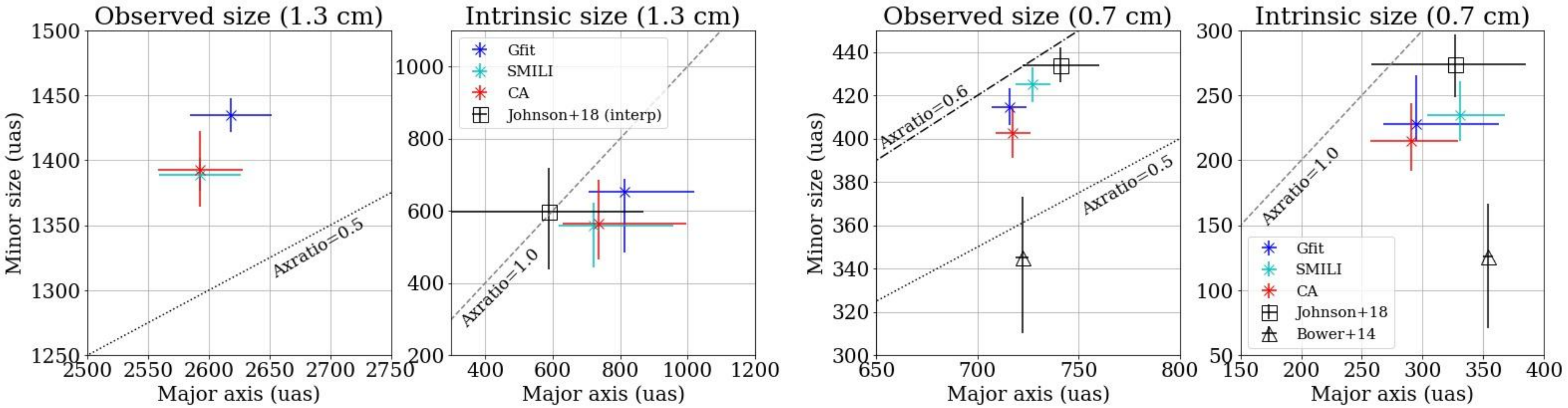
“Observed” images



Intrinsic structure of Sgr A* at 13 and 7 mm

Observed & Intrinsic structure of Sgr A*

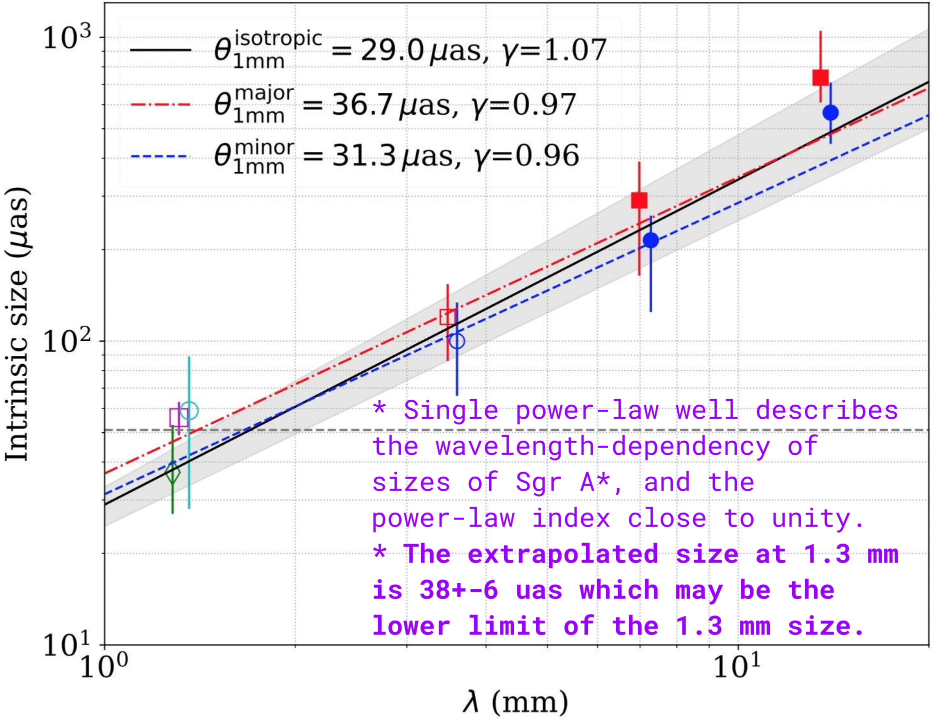
22 GHz **43 GHz**



		Flux	Observed (i.e., scattered) structure				Intrinsic structure			
λ (cm)	Method	S_ν^{tot} (Jy)	θ_{maj}^{obs} (μas)	θ_{min}^{obs} (μas)	r^{obs}	θ_{PA}^{obs} (deg)	θ_{maj}^{int} (μas)	θ_{min}^{int} (μas)	r^{int}	θ_{PA}^{int} (deg)
1.349	Gfit/Amp	1.07 ± 0.11	2618.3 ± 33.8	1434.8 ± 13.3	1.82 ± 0.02	82.6 ± 0.5	$813.7^{+207.9}_{-107.7}$	$652.9^{+34.5}_{-167.2}$	$1.25^{+0.32}_{-0.17}$	$95.6^{+16.8}_{-12.3}$
	SMILI/Amp	1.04 ± 0.10	2592.9 ± 33.8	$1389.1^{+12.4}_{-12.6}$	1.87 ± 0.02	82.0 ± 0.5	$720.9^{+238.3}_{-102.7}$	$559.4^{+62.0}_{-115.9}$	$1.29^{+0.42}_{-0.19}$	$81.6^{+18.0}_{-10.3}$
	CA	-	2592.7 ± 35.1	$1392.3^{+30.6}_{-27.6}$	$1.86^{+0.02}_{-0.03}$	82.6 ± 0.7	$736.7^{+261.3}_{-105.8}$	$564.9^{+121.2}_{-99.3}$	$1.33^{+0.44}_{-0.21}$	$95.0^{+26.6}_{-15.0}$
0.695	Gfit/Amp	1.35 ± 0.14	715.7 ± 25.5	414.7 ± 10.6	1.73 ± 0.06	84.2 ± 0.5	$295.2^{+88.4}_{-63.0}$	$227.8^{+39.7}_{-18.2}$	$1.30^{+0.38}_{-0.28}$	109.6 ± 6.3
	SMILI/Amp	1.30 ± 0.13	727.3 ± 25.5	425.1 ± 10.1	1.71 ± 0.06	85.7 ± 0.5	$331.2^{+67.8}_{-63.0}$	$234.8^{+29.2}_{-23.7}$	$1.41^{+0.29}_{-0.27}$	112.5 ± 4.0
	CA	-	717.5 ± 25.5	402.9 ± 13.5	1.78 ± 0.06	83.0 ± 0.6	$290.5^{+82.8}_{-105.2}$	$214.9^{+36.3}_{-75.3}$	$1.36^{+0.37}_{-0.50}$	$95.1^{+5.1}_{-7.6}$

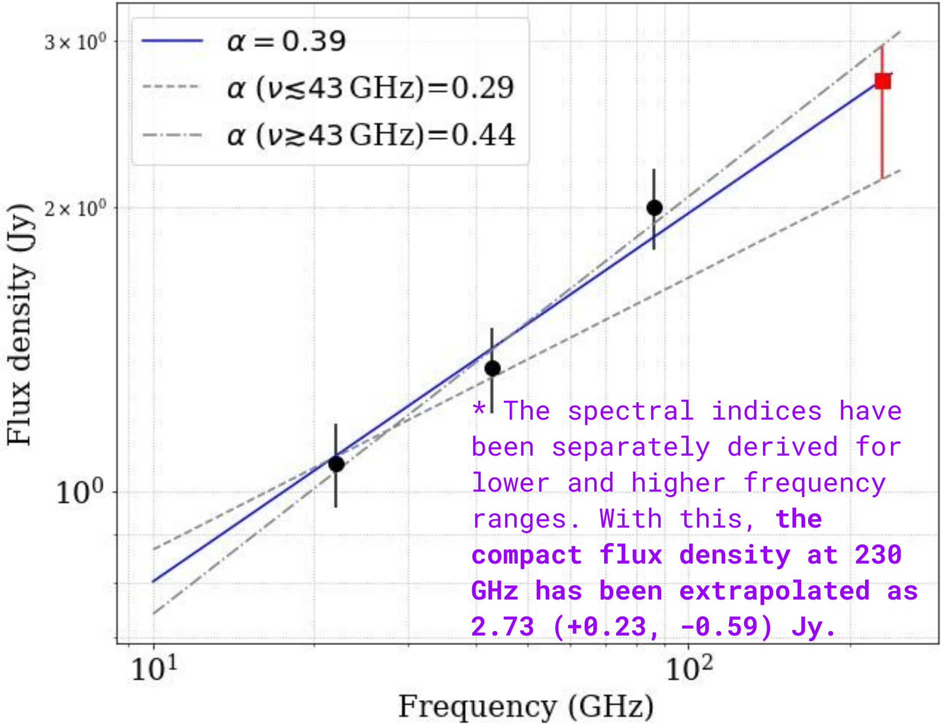
Intrinsic structure of Sgr A* at 13 and 7 mm

Wavelength-dependent size



* Single power-law well describes the wavelength-dependency of sizes of Sgr A*, and the power-law index close to unity.
*** The extrapolated size at 1.3 mm is 38+-6 uas which may be the lower limit of the 1.3 mm size.**

Extrapolated compact flux density at 230 GHz

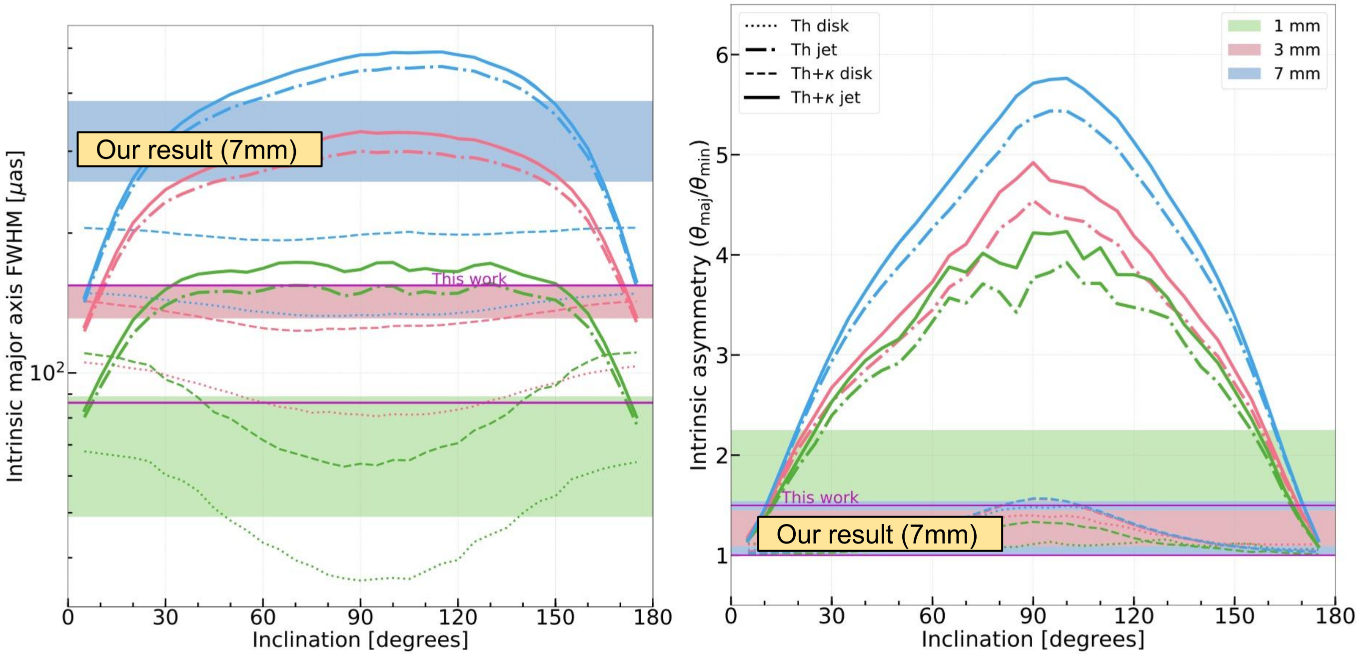


* The spectral indices have been separately derived for lower and higher frequency ranges. With this, **the compact flux density at 230 GHz has been extrapolated as 2.73 (+0.23, -0.59) Jy.**

Intrinsic structure of Sgr A* at 13 and 7 mm

Constraints on the dominant emission models

3D GRMHD simulation (Issaoun+19)



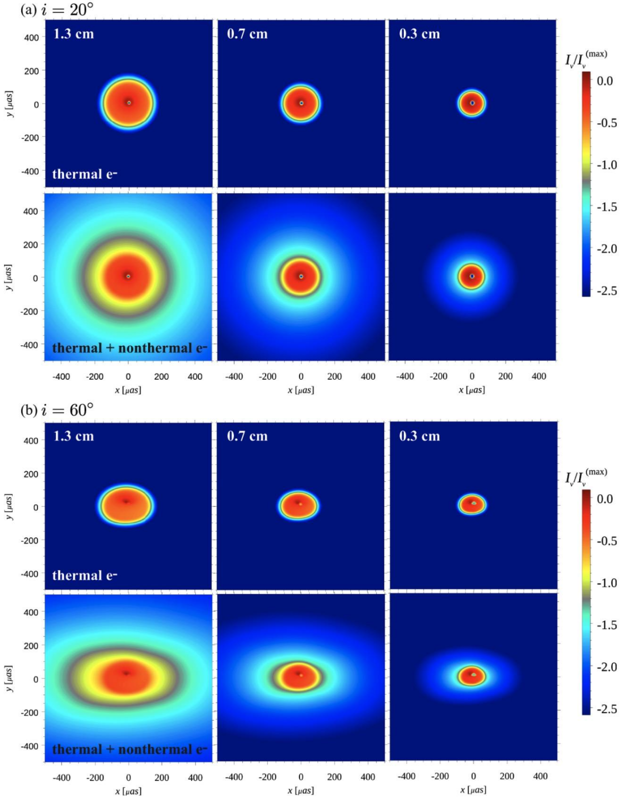
* In comparison of the major axis size at 7 mm, the “Th” disk or jet is preferred, with the inclination angle of ~20-40 deg.

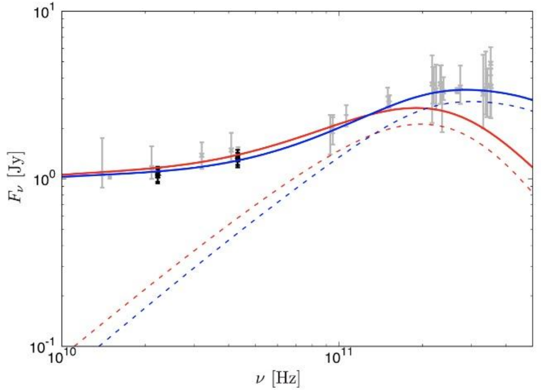
* As for the “Th” jet model, the inclination angle is further constrained as ~< 10 deg, by the axial ratio.

Intrinsic structure of Sgr A* at 13 and 7 mm

Constraints on the dominant emission models

RIAF w/ Keplerian shell model (Kawashima+)





Spectrum of Sgr A*
Viewing angle = 20 deg
Viewing angle = 60 deg

(broken)
Only thermal electrons

(solid) thermal+non-thermal electrons

* In the simulation with RIAF+Keplerian shell model, the accretion flow can also reproduce the measured size and axial ratio.

* However, **the non-thermal electron components become important and the small viewing angle is also preferred (T.Kawashima et al. in prep.).**

Intrinsic structure of Sgr A* at 13 and 7 mm

Summary

* The intrinsic structures of Sgr A* at 13 and 7 mm wavelengths have been found as **a single, isotropic Gaussian** shape.

* A simple isotropic model which the size is **linearly proportional to the observing wavelengths** well describes the results. This implies the stratified, self-absorbed geometry of Sgr A*.

* Both a jet and accretion flow models can explain our results, but the **small viewing angle** is favored at both cases. This is consistent with the previous results from the GRAVITY Collaboration+2018.

* The quasi-simultaneous VLBI observations at lower frequencies (i.e., 22, 43, and 86 GHz) provide a **pre-imaging consideration** of Sgr A* at 230 GHz.