# Zooming in on Black Holes with the Event Horizon Telescope

Huib Jan van Langevelde JIVE Dwingeloo & Sterrewacht Leiden

## Introducing

- Chief Scientist at JIVE: Joint Institute for VLBI ERIC
  - · Hosted by ASTRON, Dwingeloo
  - · Collaboration of nations with radio facilities, supported by radio-astrono
  - EVN: European VLBI Network
    - Consortium of (European) Telescopes operators
- Professor Galactic Radio Astronomy Sterrewacht Leiden, Leiden University
  - ·Oldest astronomy department in the world
- Affiliated staff University of New Mexico, Albuquerque







oint Institute for VLBI ERIC





## JIVE team got involved in the EHT

### • European BlackHoleCam project

·Working on the CASA based calibration pipeline

· Used in parallel with HOPS and AIPS based schemes

### • Rooted in earlier work on VLBI software

- ·JIVE runs independent SFXC software correlator
- · Developed ParselTongue Python AIPS interface
- pySched python version of Sched
- · jive5ab VLBI recording software
  - for simultaneous recording and streaming
- "casa-fication" of VLBI processing

· VLBI casa workshop last week attended by









### JIVE (software) team members of EHTC





## Lezing Alkmaar 24 Nov 2017:

### Can resolve at 1mm

- Expected to see the 'shadow' of the black hole
  - Relativistic beaming and gravitational lensing
  - of the accretion disk (and jet)
- Expected response depends on:
  - Brightness of accretion disk, jet
  - Inclination of the system
  - State of the activity
    - G2 cloud interaction
  - Nature of the Black Hole
    - Just spin expected



Een telescoop zo groot als Europa, Alkmaar, 24 November 2017









## The Event Horizon Telescope

- Project Director since mid 2020
- Key roles for other NL scientists
  - Nijmegen: initiated project, simulations, calibration, new initiatives
  - ·Amsterdam: models, organising simultaneous observations other wavelengths
  - ·Leiden: ALMA support, calibration methods
  - ·JIVE: VLBI software
- Key contributions largely funded through European BlackHoleCam project
  - New projects centred on African Millimeter Telescope



### The sky appears full of stars, but beyond are billions of galaxies

eld in Tucan





### The radio sky is dominated by bright radio galaxies in far universe



Radio sky over Green Bank radio telescopes

Moon to scale on LOFAR field



Hercules A = 3C348 at 1 billion light years, observed with the VLA





### Centaurus A = NGC5128 at 10 million lightyears, various observing wavelengths







### Zooming in on the engines of radio galaxies





### First M87 Event Horizon Telescope Results I. The Shadow of the Supermassive Black Hole

Distance to M87: 54 million lyr Black Hole mass: 6.5 10<sup>9</sup> M<sub>o</sub>

Observations at 1.3 mm  $\approx$  230 GHz Brightness temperature: 6 10<sup>9</sup>K 42 µas ≈ 700 au = 98 lh





galaxies

## stars in orbit

supermassive black holes

# And now the latest EHT result: The Black Hole in the centre of our Galaxy

# radio emission

# millimeter telescopes

very long baseline interferometry





### Einstein's relativity special: nothing will go faster than light general: even light will feel gravity









- that nothing can escape



- The boundary is called Event
- - Collapse when they have no fuel left











## **Really?**

- Active galaxies producing energetic jets
- Binary stars with dark companions
- Some AGN have observed fast rotating disks
- Gravitational waves of compact mergers
- The Galactic centre









## The Milky Way, our Galaxy

### Spiral arms

Sun







Orbits of Infrared stars in orbit around black hole

### With GRAVITY on ESO's VLT in Chile



### THE NOBEL PRIZE IN PHYSICS 2020



### Roger Penrose

"for the discovery that black hole formation is a robust prediction of the general theory of relativity"

### Reinhard Genzel

"for the discovery of a supermassive compact object at the centre of our galaxy"



Supermassive black hole (4 million solar masses)

20 billion kilometres = 120 × Earth-Sun

.

.

Closest approach 19 May 2018



### Radio golven kunnen net als licht door de dampkring





### • Big radio telescopes

- Detect weaker signals
- Resolve smaller details
  - But with waves 100.000 longer than in optical
- Similar resolution requires
  radio telescopes 100km diameter





## VLBI: make a giant telescope

- Very long baseline interferometry
- Measures interference patterns between pairs of telescopes
- Atmosphere transparent for radio emission 100M - 100GHz
- Big telescopes more sensitive, long baselines high resolution
- Sample, digitise and record and tag very accurate time
- Send to correlator, measure interference

maser clock

• Compute image back from measurements



### But we also took data of Sagittarius A\*, the Black Hole at the centre of the Milky Way. That can be observed from the Southern hemisphere



Inner square arcsin at 22 GHz (NRAO, VLA)

The inner Galaxy observed with MeerKAT, the SKA precursor



### Now to the Galactic Center, SgrA\*



## Event Horizon Telescope

SM

JCMT

- 8 telescopes at best sites
  - working together
- · Recording high bandwidth
  - · 32 Giga bit per sec
- Good weather · around the world
- New image processing
  - · Checked by simulations
- Simulations
  - GRMHD codes
  - relativistic ray tracing









### Now try this with millimeter telescopes

















### **Optical light**



# The Black Hole in the centre of our Galaxy

## What made it difficult?

## Why is this more fundamental?



# Interstellar scattering

- Limits view on SgrA\* at longer wavelengths
  - Where it is optically thick anyway
- Becomes sub-dominant at 1mm
  - Where it is optically thin
  - And global VLBI reaches 20µas





# Variability

Q-metric measures closure phase statistics

- Total flux variability
  - Can be estimated robustly from interferometers
- Structural variability
  - Must be estimated from redundant visibilities
    - Between days
    - Baseline crossings
  - Or from modelling
    - Using closure properties



![](_page_37_Picture_11.jpeg)

![](_page_37_Figure_12.jpeg)

Interferometrically measured total flux variations, Wielgus et al., 2022

NVWS Alkmaar, 31 Mar 2023

![](_page_37_Figure_15.jpeg)

![](_page_37_Picture_16.jpeg)

### M87\*

![](_page_38_Picture_1.jpeg)

![](_page_38_Picture_2.jpeg)

![](_page_38_Picture_3.jpeg)

![](_page_38_Figure_4.jpeg)

### Simulation

![](_page_39_Picture_0.jpeg)

![](_page_39_Picture_1.jpeg)

![](_page_39_Picture_2.jpeg)

![](_page_39_Picture_3.jpeg)

![](_page_39_Picture_4.jpeg)

![](_page_39_Picture_5.jpeg)

![](_page_39_Picture_6.jpeg)

![](_page_39_Picture_7.jpeg)

![](_page_39_Picture_8.jpeg)

![](_page_39_Picture_9.jpeg)

![](_page_40_Picture_0.jpeg)

# Dynamic imaging

- Promising but not conclusive
  - Focusing on 100 minutes with best coverage
  - Stable results on April 6
  - Azimuthal evolution on April 7
  - Still not very consistent results
  - But hopeful for future

![](_page_41_Figure_7.jpeg)

![](_page_41_Picture_8.jpeg)

Event Horizon Telescope

# Interpreting ring sizes

- Angular size of gravitational radius:
- Schwartzschild diameter:
- ISCO diameter
  - for non-rotating:
  - Innermost Stable Circular Orbit
  - ISCO diameter Kerr
- Photon ring
  - Non rotating
  - Cross section for shadow
  - Kerr photon ring
    - Depending on orientation
- From simulations
  - Convolved with beam...

![](_page_42_Picture_14.jpeg)

### Event Horizon Telescope

 $c^2D$  $4\theta_g$ 

 $12\theta_{g}$  $< 18 \theta_{g}$ 

 $d = \alpha \theta_{g}$ 

 $/27 \theta_g = 10.4 \theta_g$ 

θ

 $9.6 - 10.4 \theta_{o}$ 

![](_page_42_Picture_20.jpeg)

an welchem jeder herankommende Lichtstrahl endigt (ist doch dort die Lichtgeschwindigkeit 0), ferner  $r = \frac{1}{2} \alpha$  und  $r = \frac{3+3}{2} \alpha$ , stabe der r, zwischen  $\alpha$  und  $\frac{3}{2} \alpha$  liegt, so vergrößert, daß sie ihm den " zu haben scheint. Überhaupt alle Kugeln werden Halbmesser optisch vergrößert. Die im Text folgende Rechnung gibt für die rela-

Max von Laue (1921): "Die Relativitätstheorie. Zweiter Band", Vieweg, 1921

![](_page_42_Picture_24.jpeg)

### Image from gravitational lensing

n=0

![](_page_43_Picture_2.jpeg)

# Astrophysics with the SgrA\* Black Hole we know quite precisely it is at a distance of 26 thousand lightyear...

last stable orbit of gas in orbit around Black Hole

Event Horizon, radius of the Black Hole, no return from here

Photon Ring, where we see the photons that have gone – round the Black Hole once or multiple times

![](_page_44_Picture_4.jpeg)

resolution of the EHT, we cannot resolve smaller details image follows circle, as predicted by General Relativity

diameter equals 51 µas, because we know the mass and distance, this is precisely correct!

Source is variable, azimuthal structure uncertain; almost face on?

![](_page_45_Figure_0.jpeg)

![](_page_45_Picture_1.jpeg)

# Checking against predictions

- $\theta_g$  estimates can be compared Remember it is basically M/D that is measured
- Can be compared in various ways
  - Treat Genzel EHTC al., Ghez et al., separately
    - Using independent distance from Reid et al. 2019
- Result comfortably within errors
  - Consistent with Einstein's GR

![](_page_46_Picture_7.jpeg)

Event Horizon Telescope

![](_page_46_Figure_13.jpeg)

![](_page_46_Picture_14.jpeg)

![](_page_47_Figure_0.jpeg)

C. M. Fromm (Würzburg), Y. Mizuno (Shanghai), Z. Younsi (London), O. Porth (Amsterdam)

H. Olivares (Nijmegen), A. Nathanail (Athens), A. Cruz-Osorio, L. Weih and L. Rezzolla (Frankfurt)

![](_page_47_Figure_3.jpeg)

![](_page_47_Picture_4.jpeg)

![](_page_48_Picture_0.jpeg)

# Low inclination is intriguing

- Means rotation axis not aligned (at all) with Galaxy disk
  - If there is a jet at all, could be pointed towards us
- Consistent with shifting IR position during flare
  - As observed with GRAVITY

![](_page_49_Figure_5.jpeg)

![](_page_49_Picture_6.jpeg)

Event Horizon Telescope

Motions of IR flares at ISCO Gravity collaboration 2018

![](_page_49_Picture_10.jpeg)

NVWS Alkmaar, 31 Mar 2023

![](_page_49_Picture_12.jpeg)

![](_page_50_Picture_0.jpeg)

![](_page_50_Picture_1.jpeg)

![](_page_51_Picture_1.jpeg)

# Also did tests against non-Kerr metrics

- Trying to constrain alternatives for Black Holes
- Consistent with GR over 3 orders of magnitude BH mass

![](_page_52_Figure_3.jpeg)

![](_page_52_Picture_4.jpeg)

![](_page_52_Figure_6.jpeg)

![](_page_52_Picture_9.jpeg)

Tax Actumentation Journal Letting, 998.12 (202) May 30 © 103. The Anderith Milliard System American Advanced Scotts **OPEN ACCESS** 

https://doi.org/10.3847/2041-8213/ac6674

![](_page_53_Picture_3.jpeg)

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### First Sagittarius A" Event Horizon Telescope Results. I. The Shadow of the Supern Black Hole in the Center of the Milky Way

The Event Hostzon Telescope Collaboration

(See the end matter for the full list of authors.) Necdival 2022 March 25; annual 2022 April 4; acapted 2022 April 8; published 2022 May 12

### Abstract

We present the fast Event Horizon Telescope (EHT) diservations of Sagittains A\* (Sgr A\*), the Galactic center source associated with a supermanave black hole. These observations were conducted to 2017 using a global interferometric array of eight telescopes opening in a wavelength of  $\lambda = 1.3$  nm. The EHT data resolve a compact emission region wid intrahour variability. A variety of imaging and modeling analyses all support as image that is dominated by a bright, thick may with a diameter of 51.8  $\pm$  2.3  $\mu$ as (48% credible interval). The mag has madest azimuthal high trens asymmetry and a comparatively day interior. Using a large suite of mone-field standardow, we demonstrate that the EHT images of Sg A" are consistent with the expected appearance of a Kerr black hole with man ~4 × 80° M\_ which is inferred to exist at this location based on previous infrared observations of individual stellar orbits, as well as maser proper-motion andies. Our model comparisons distance scenarios where the black hole is viewed at high inclination (1>50°), as well a murphising black holes and those with settingende accestion disks. Our results provide discrete vidence for the presence of a supermusive black hole at the center of the Milky Way, and for the fint time we consert the predictions from dynamical measurements of nellar orbits on scales of 107-107 gravitational radii to event hodron-scale images and variability. Parthermore, a comparison with the 3917 results for the supermanise black hole M87\* shows consistency with the predictions of general relativity spanning over three orders of magnitude in central mass.

Unified Astronomy Thesaurae concepts: Black Soles (162); Kerr black Joles (206); Rotating black holes (1406) Heterodyne ist effermiet ry (72b); Galactic center (565)

### 1. Introduction

Black holes are among the buildest and most perdoand predictions of Hinstein's theory of general selativity (CR), Einstein 1915). Originally studied as a mathematical connequesce of GR rather than as physically relevant objects (Schwartschild 1916), they are now believed to be generic and sometimes inevitable autoones of gravitational collapse (Opperheimer & Snyder 1939; Penrote 1965), In GR, the spacetime around astrophysical black holes is predicted to be uniquely described by the Kerv metale, which is entirely specified by the blackhole's mass and angular momentum or "spin" (Kery 1963).

The first empirical evidence for their existence was through stellar-mass black holes, beginning with observations of X-my binary orbits (Bolton 1972; Webster & Muslin 1972; McClistock & Remillard 1985) and culminating in the detection of guivitational waves from merging mellar-mass black holes (Abbott et al. 2016). In parallel, the discovery that quasars are not stellar in nature but are rather extremely luminous, compact objects located in the centers of distant galaxies (Schmidt 1963) led to an intensive effort to identify and measure the supermassive black holes (SMBHs) energetically favored to power them (Lynden-Bell 1979). Observations now suggest that SMBHs not only lie at the center of nearly every galaxy (Richstone et al. 1998) but also may play a role in their evolution (see, e.g., Magorrian et al. 1998; Fabian 2012; Kormendy & Ho 2013), though how exactly the

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ebbs and flows of black hole activity and growth pe major constanting question is the field.

With the advert of the Event Hoston Telescope (EHT can now be statied with direct imaging (fivest Horizon Collaboration et al. 2019a, 2019b, 2019c, 2019 30796, 302 la, 202 lb, hereafter MSJ\* Papers I-VIII). The tion of an event hostom and strong lensing near blad predicted to produce distinctive gravitational signature inages (e.g., Hilbert 1917, Badeen 1973; Lund Januaryushi & Kuspiewski 1997; Falche et al. 2000), In simulated images of black holes typically have a central dependence mint he hy a height emission ring. The mag is near the gravitationally leased photon orbits that housdary of what we have after refer to as the black hole The findow has an angular diameter  $d_{\rm ab} \approx 10 GM/G^2$ where G is the gravin focal constant, c is the speed of the black hole mass, and D is the black hole distance.

From the first endeaton that SMBHs could power bright ratio ones in many galactic nuclei (Lynden-Hell 1969, and references Bereith), the search has been on to identify them. Within our own Calury, the compact source Sgr A" has been intensely studied as a caulidate SMBH since its discovery as a bright source of radio emission located near the Galactic center (Halick & Brown 1974, Hien et al. 1975; Loer al. 1975). Decades of monitoing its proper motion, as well as motions of individual stars is orbit around it. have revealed SgrA\* to be an extremely dense oncentration of main  $(M \approx 4 \times 10^6 M_{\odot})$  that is located at and nearly motionless. with respect to the dynamical center of the Galaxy (Dis Silpe). poviding stong evidence that it is the nuclear SMBH in our Galaxy (eg., Do et al. 2019; Granty Collaboration et al. 2019; Reid & Branthaler 2020). As the searest SMBH, SgrA\* provides a unique opportunity to directly image such an object, together

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> First Sagitarius A' Event Horizon Telescope Results. II, EHT and Multiwavelength Observations, Data Processing, and Calibration

> > The Fires/ Husbon Telescore Collidoration (See the end mater for the full fait of authors.) Bridnet 2021 Advance by revised 2022 April 4: excepted 2022 April 10: published 2022 May /2.

### Abilitant

We cannot itsue bistone Valences (MMV) 1.3 mm measurements of the radio source lossed at the position of (Sg A'), collected during the 2017 April 5-21 campaign. The ties it as loostons screa the gide. Novel calibration methods are by. The manyity of the 1.3 mm mission artist from looknot scales. brook in the add of minute interes. The effects of intertellar band to be subloosingst to instenic grave structure. The caliburat s of the visibility mission, are broadly consistent with a blazed stog in later works in this agries. Controportations multiwardength h, and 86 (199) and at series in Bared and X cay scattering flat. Revenue also, not at low significance loady with fiwith no 3017 April 7 and # TAR on 2017 April 11. The trighter April 11 flate is not discreted a significant increase in millimetre flex variability inumediately after tion is the emission physics user the event harizon. We compare migh to its historical spectral energy distribution and find that took consistent with to keig-term behavior.

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### 1. Introduction

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First Sagiturias A\* Event Rosizon Telescope Results. III. Imaging of the Galactic Center

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### Abstract

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### First Sagittarios &" Event Horizon Teles the Galactic

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### 1. Introduction

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et al. 1993; Pakke & Markoff 2003. Milleli. If suggested KLAPs/ADAPs have been constructed soling terminalitytic proscriptions (e.g., Nanoya et al. 1987; Onti-rtat. 2000; Novletc's et al. 2009; 30: 2) and using losse depende at general elabore: magnetalphistopamon (CRADE))

to bears (e.g., Genzel e 2011; Neihen et al. DIT). The multimeters 2017 12HT divervice of Telescope Calabaratio The potential for rat analysis of EHT observ andiomits for sparse apotare synthesis, whe accusulated as Earth orientation with strate 2117). This shutery static duroughout the accusolisted data meat SgrA" violates this mastel. After sevenal inege structure in Se Georgiev et al. 207. inconstructions from reconstruction time-and Telescope Collaboration Depite de second encour, the data ibservation epoch are i of the variable emissio analgasi of observation

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### First Sagitarius A" Event Hortzon Telescope Results. M. Testing the Black Hole Metric

The liver Heaton Telescope Collaboration

Januard 2017 March 12; probat 2017 April 12; prograf 2012 April 22; published 2012 May 12

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mpe//doi.org/10.1047/2041-0213/w6716

### First Sagittarius A' Event Horizon Telescope Results. IV. Variability, Morphology, and Black Hole Mass

The Event Hotton Telescope Collaboration Oce the end matter for the full list of authors.)

Research 2012 March (1): sectual 2022 April (2): securited 2022 April (2): published 2023 Marc 12

### A betract

In this paper we quantify the temporal variability and image morphology of the horizon scale estimics from Sgt A", so observed by the EHT in 2017 April at a wavelength of 1.3 mm. We find that the Sgt A" data exhibit valability that exceeds what can be explained by the uncertainties in the data or by the effects of interstellar scattering. The magnitude of this variability can be a anisotantial function of the constants flux density, searbing ~100% on some baselines. Through an exploration of simple geometric analysis andels, we demonstrate that ronglike morphologies provide hener fits to the 5 g A\* data that do other asophologies with comparable complexity We develop two strategies for fitting static geometric may models to the time-variable S y A\* data, one strategy fits modelate short segments of data over which the source is static and averages these independent fits, while the other fits midels to the full data set using a parametric model for the structural variability power spectrum among the average source structure. Both geometric modeling and image domain thatan extraction inclusions detensive file dog Gameter to be 51.8 ± 2.3 µms (68% credible intervals), with the dog thickness constrained to have an P WHM. herenes. -- 10% and 50% of the mig-diameter. To being the diameter parameter sectors a common physical acule, we calificate firm using synthetic data generated from GRMHD simulations. This calibration constrains the angular size of the gravitational radius to be  $4.3^{+1.2}_{-1.2}$  µm, which we combine with an independent distance measurement from mater panillaxes to determine the mass of Sgr A' to be 4.0.44 × 10<sup>6</sup> M<sub>c</sub>.

Unified Astronomy Thistanus concepts: Black holes (182)

### 1. Introduction

Sogitation A" (Sgr A"), the radio associated with the supremanive black hole (SMBH) at the center of the Milky Way, is hought to adhead the largest segular size of all black losies in the sky. At a dottane of Dwillips and with a nam of M == 4 × 10" M., (Do et al. 2019; Gavity Colliboration et al. 2019, 2020). Sg A\* has a Schwarzschild radius of ~10 µm. Models of optically this spheaked accretion three around SMBHs: generally peellet that they will appear to dottast choreten as bight sings of ensusion surrounding a darker central "shadow" (e.g. Bauben 1973; Laminer 1979; de Viter 2000; Falcke et al. (D) Bodetick & Loth 2005; Bodetick & Namyan 2004; Brodelick et al. 2011, 2016; National et al. 2019), and a variety of more grand acceptors flow annihilious have demonstrated that the dianeter of this mig is typically ~5 times larger than the Schwattichell milita in g., Frent Harton Telescope Collebration et al. 2019; The Event Horizon Telescope (EHT) collaboration piereded charavational verification of this picture, using a global very long fascine interlationary (VLBD arrows of radio telescopes observing at a frequency of ~200 GHz to searche the --40 pas story of emission around the MID\* SMBH (Event Hosten) Telesope Colabonition et al. 2019a, 2019b, 2019c, 2019d. 2019c, 2019f, 2021a, 2023b, heading MR7' Payon 1-VIII).

The predicted stag classes for Sgr A" is ~50 µm, about 25% larger that what the EHT observed for MIT". However, because Sar A" is more than three outers of magnitude less mans or than MS7", all dynamical timoscales in the system are

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and an incruit. He apprendiction is deliver by the conduction promit, this is called in determining the observational appearance of the source in particular, the energy pervision in may be made with latitude to the first, leading to a jet or -setting the numbers is spaced intere-

The question of whether empirics is dominant for as achieve to cotting it interactly tol to the publics of allog attent a author, if they is one, a GRMHD simulation of Mult hole appendes the strangth of the continue dapends securities y on the Mach fulle suit (e.g., Event Hisrians Telescope Collaboration at al. 2019c, here fro MRT\* Paper V.; Nampios et al. 2023). Ac

Supermassive Black Hole

### inter line of product / got

![](_page_53_Picture_84.jpeg)

### More results

![](_page_54_Figure_7.jpeg)

![](_page_54_Figure_8.jpeg)

![](_page_54_Figure_11.jpeg)

![](_page_54_Figure_12.jpeg)

First M87 Event Horizon Telescope Results I. The Shadow of the Supermassive Black Hole

Distance to M87: 16.8 Mpc Black Hole mass: 6.5 10<sup>9</sup> M<sub>o</sub>

Observations at 1.3 mm  $\approx$  230 GHz Brightness temperature: 6 10<sup>9</sup>K 42 μas ≈ 700 au = 98 lh

### Hotspot in orbit around SgrA\* inferred from polarisation variations

![](_page_56_Picture_1.jpeg)

![](_page_56_Figure_2.jpeg)

![](_page_57_Picture_0.jpeg)

Radboud University/ESO/WFI/MPIfR//APEX/NASA/CXC/CfA/EHT/M. Janssen et al.

## Future outlook!

### More/better data in hand

- ·2018, 2021, 2022
  - preparing for April 2023 campaign
- · Introducing NOEMA, Greenland Telescope, Kitt Peak, AZ
- Option to use higher frequency

· 345 GHz: 1.5x better resolution

- 2024+ possibly more observatories:
  - Owens Valley, Haystack, South-Korea, Africa Millimeter Telescope (Dutch project!), Llama (Argentina), Canary Islands
  - $\cdot \text{Time sampled images}$
- But space submm-VLBI for:
  - $\cdot$  Other targets
  - · Resolving direct image from photon rings

![](_page_58_Picture_13.jpeg)

![](_page_59_Picture_0.jpeg)

## Conclusions

- SgrA\* displays convincingly the predicted ring
  - But data processing was quite involved
- $\cdot$  It is a more fundamental measurement
  - Because we know distance and mass a priori
  - Consistent with GR at these scales
- SgrA\* modeling points towards
  - · Magnetically arrested, prograde spinning, low inclination
  - ·Very low accretion, but still could have a jet

![](_page_60_Picture_9.jpeg)

Brought to you by a large, global, distributed team

![](_page_60_Picture_13.jpeg)

![](_page_60_Picture_14.jpeg)

![](_page_60_Picture_15.jpeg)

### Huib van Langevelde acknowledges support from:

![](_page_61_Picture_1.jpeg)

![](_page_61_Picture_2.jpeg)

THE UNIVERSITY OF NEW MEXICO.

### EHT stakeholders are:

![](_page_61_Picture_5.jpeg)

![](_page_61_Picture_6.jpeg)

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![](_page_61_Picture_13.jpeg)

![](_page_61_Picture_14.jpeg)

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Universiteit Leiden

### **JIVE** Joint Institute for VLBI ERIC

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![](_page_61_Picture_24.jpeg)

ANTON PANNEKOEK INSTITUTE

### EHT affiliated institutes are:

![](_page_61_Picture_27.jpeg)