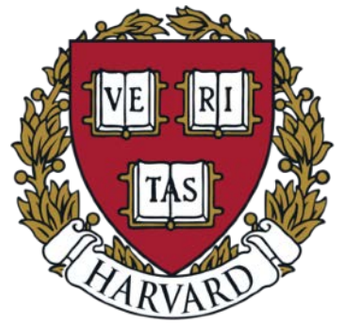
Event Horizon Telescope
- expansion plans

Maciek Wielgus

on behalf of the EHT Collaboration

Black Hole Initiative, Harvard University

Smithsonian Astrophysical Observatory



NEROC, Haystack
1 November 2019

Event Horizon Telescope: the Team

Nijmegen, Netherlands, November 2018

- over 200 scientists
- contributors from 18 countries
- over 60 institutions

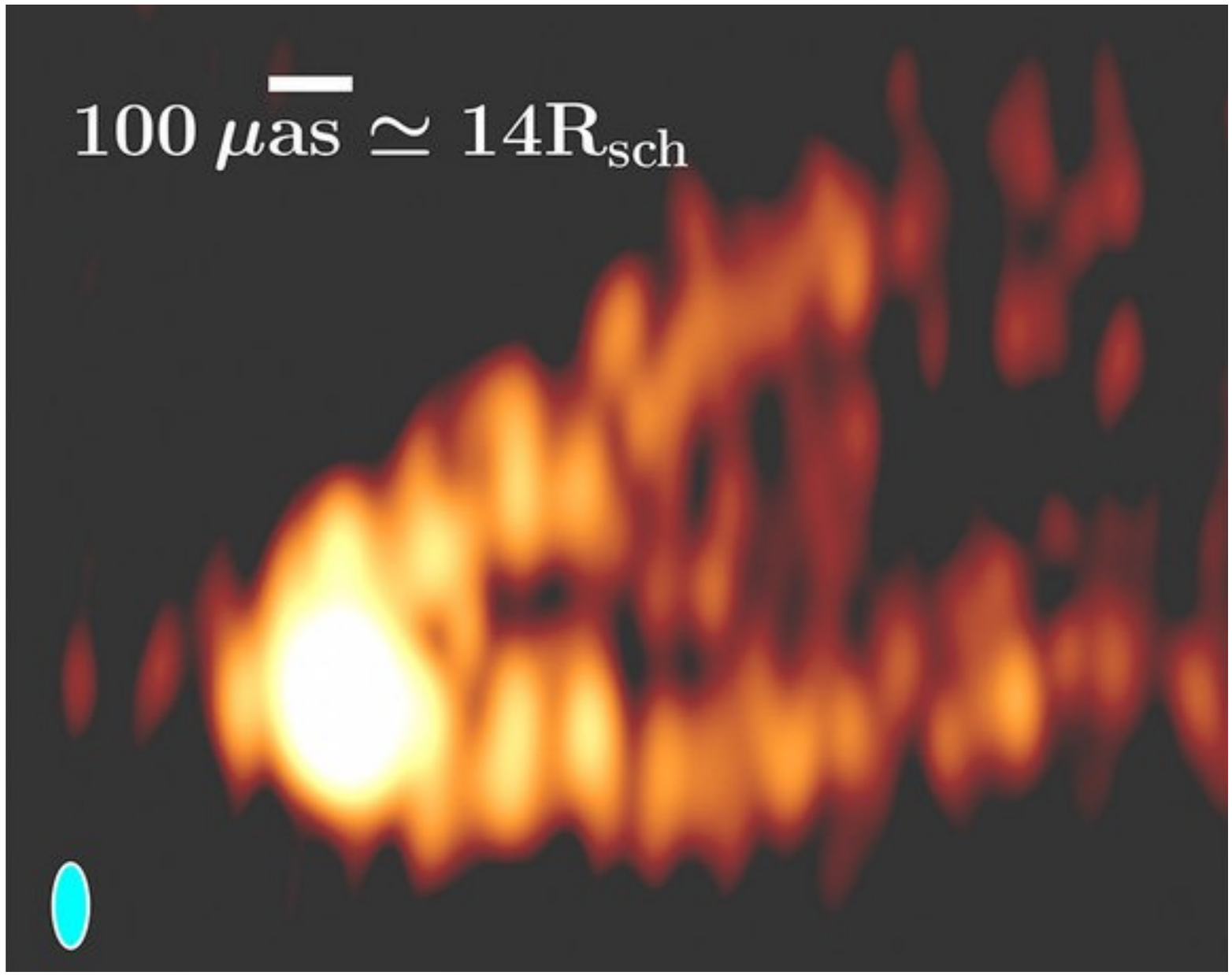
Results so far: M87 (EHTC+)

Nearby LLAGN

Redshift: 0.00428 (53 mln ly)

BH mass: $6.5 \times 10^9 M_{sol}$

EHT resolution: 400 au ~ 3 R_S



Kim et al. 2018

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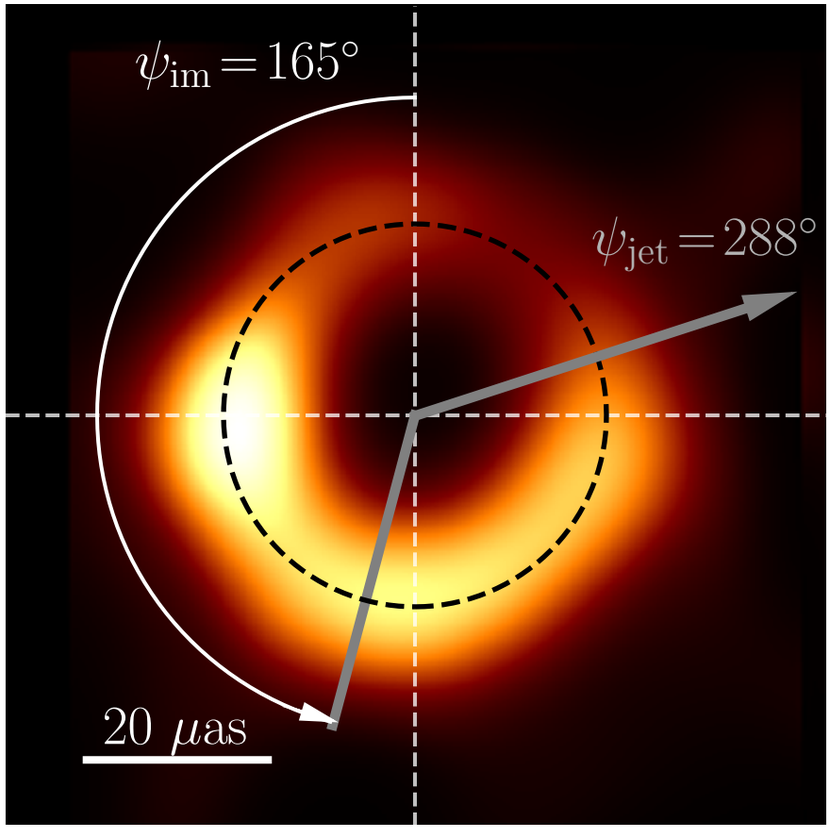

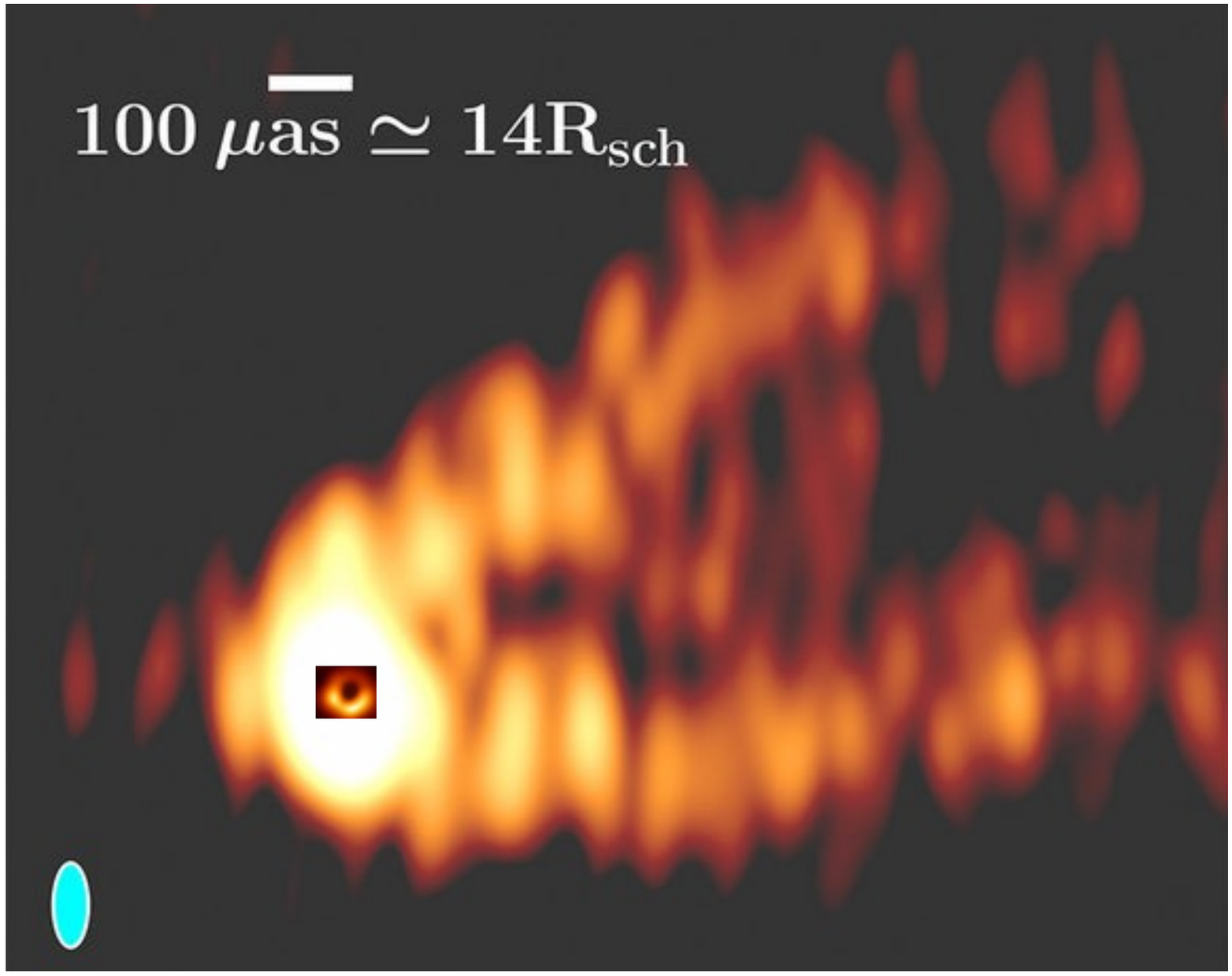

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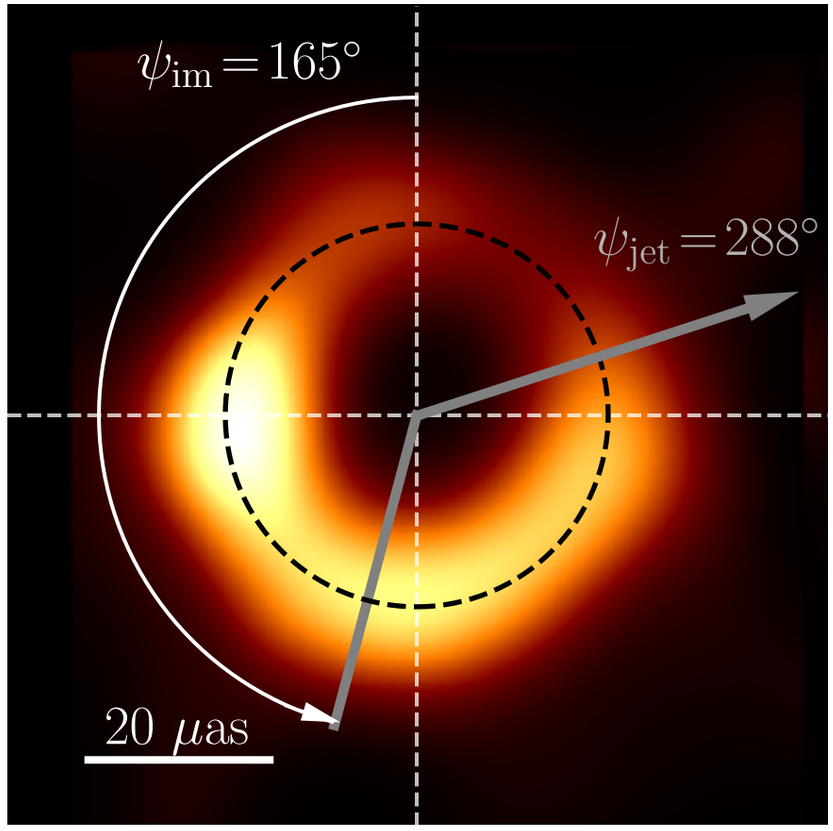

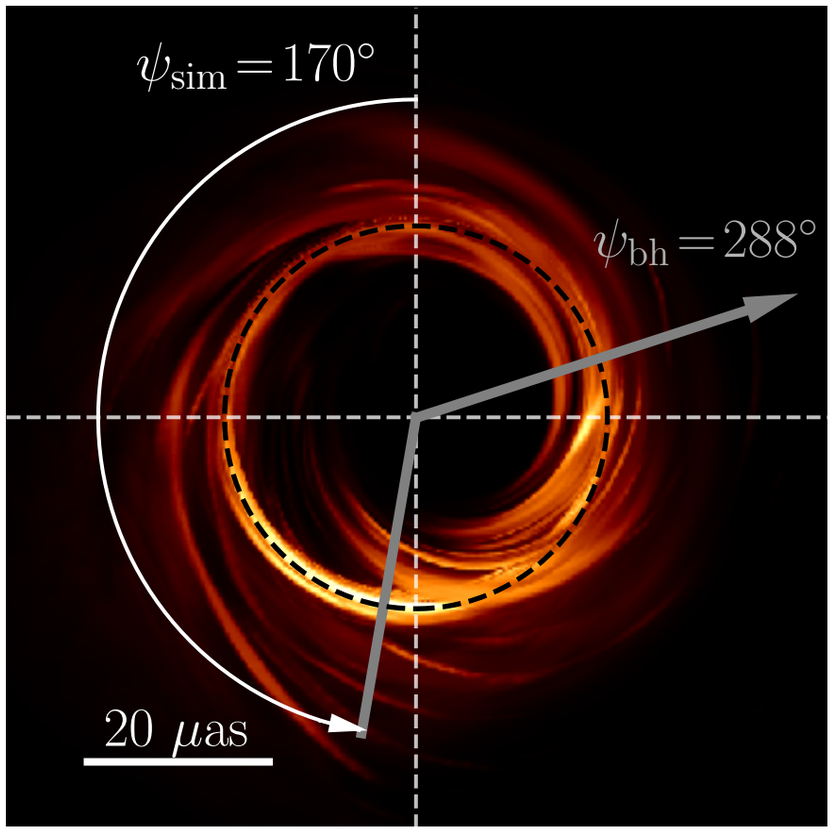

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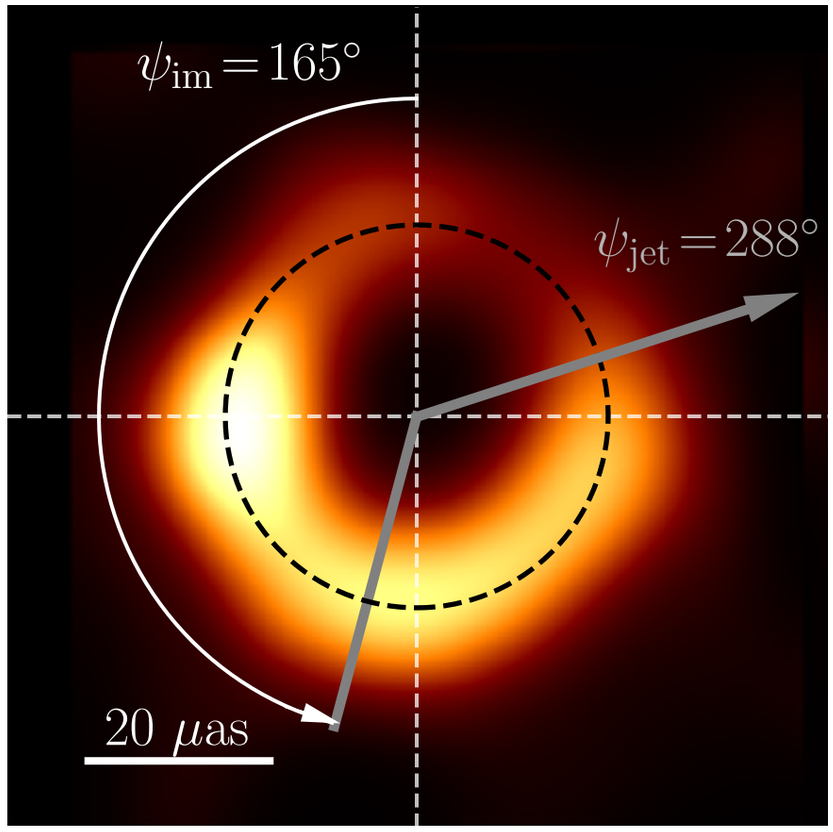
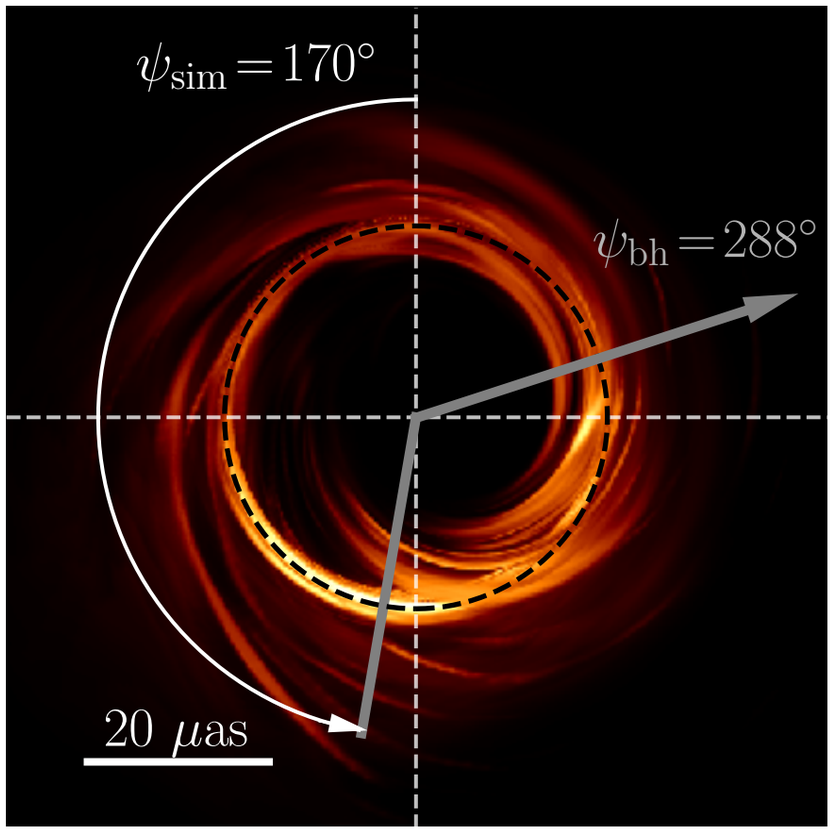
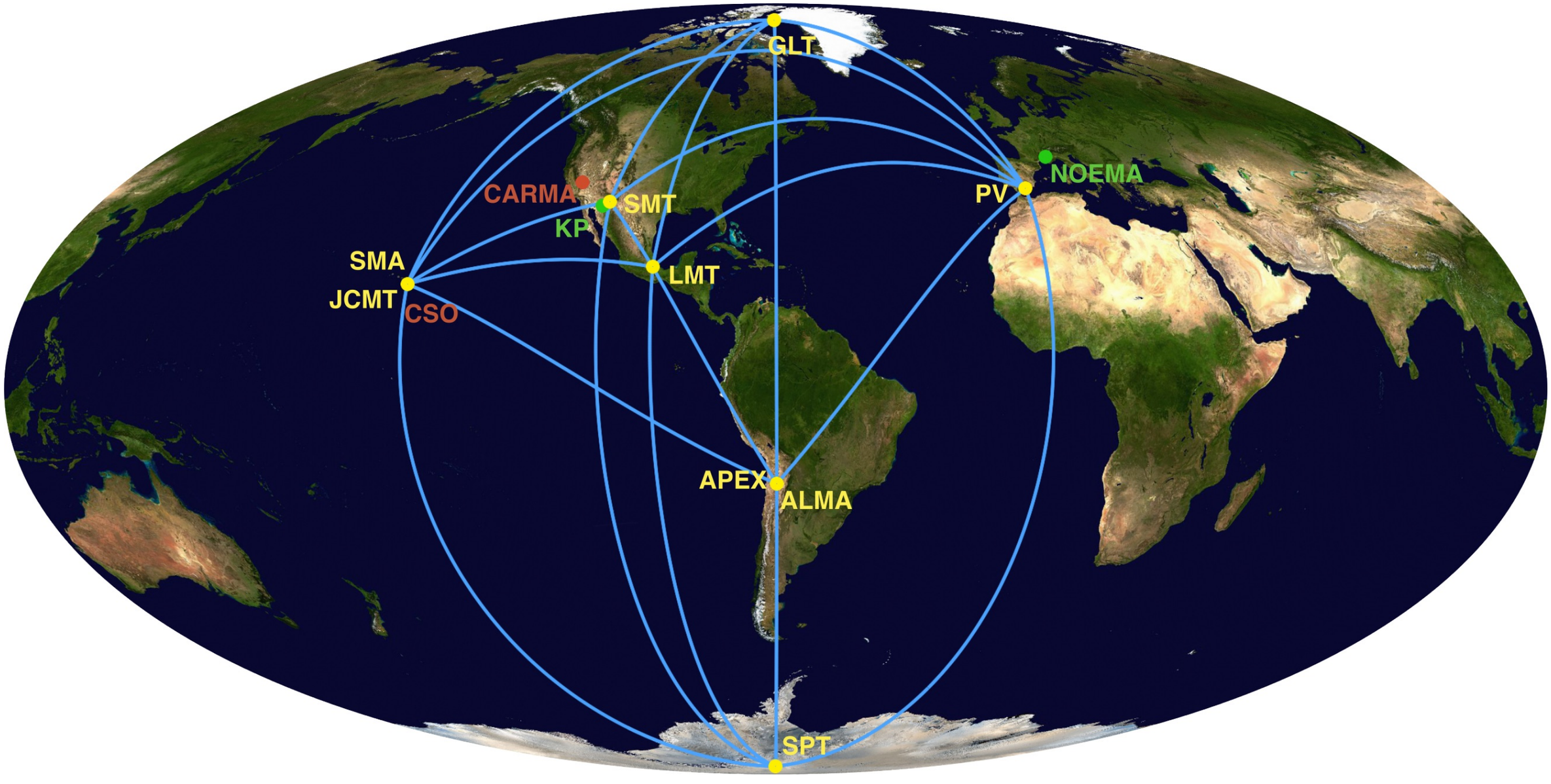




EHT published so far on about 5% of the 2017 campaign data, MUCH MORE to come!

Event Horizon Telescope



EHT 2019. Paper II. Instrument

Improvement considerations

1. **Coverage:**
   N telescopes gives N(N-1)/2 visibility measurements

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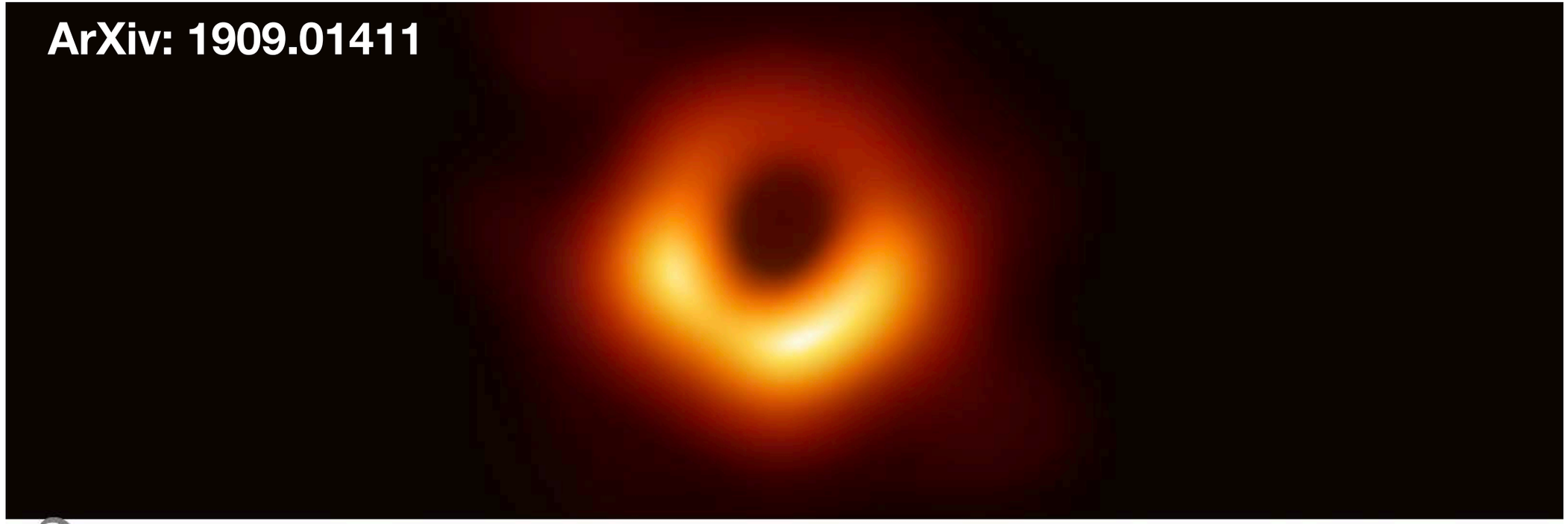
6. **Algorithmic improvements:**
   Will reduce systematics and increase sensitivity



Astro2020 APC White Paper

Studying Black Holes on Horizon Scales with VLBI Ground Arrays

Lindy Blackburn[1,2,*] Sheperd Doeleman[1,2,*], Jason Dexter[12], José L. Gómez[16], Michael D. Johnson[1,2], Daniel C. Palumbo[1,2], Jonathan Weintroub[1,2], Joseph R. Farah[1,2,21], Vincent Fish[4], Laurent Loinard[18,19], Colin Lonsdale[4], Gopal Narayanan[28], Nimesh A. Patel[2], Dominic W. Pesce[1,2], Alexander Raymond[1,2], Remo Tilanus[17,22,23], Maciek Wielgus[1,2], Kazunori Akiyama[1,3,4,5], Geoffrey Bower[6], Avery Broderick[7,8,9], Roger Deane[10,11], Christian Michael Fromm[13], Charles Gammie[14,15], Roman Gold[13], Michael Janssen[17], Tomohisa Kawashima[4], Thomas Krichbaum[29], Daniel P. Marrone[20], Lynn D. Matthews[4], Yosuke Mizuno[13], Luciano Rezzolla[13], Freek Roelofs[17], Eduardo Ros[29], Tuomas K. Savolainen[29,30,31], Feng Yuan[24,25,26], Guangyao Zhao[27]

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[2] *Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA*
[3] *National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA*
[4] *Massachusetts Institute of Technology, Haystack Observatory, 99 Millstone Road, Westford, MA 01886, USA*
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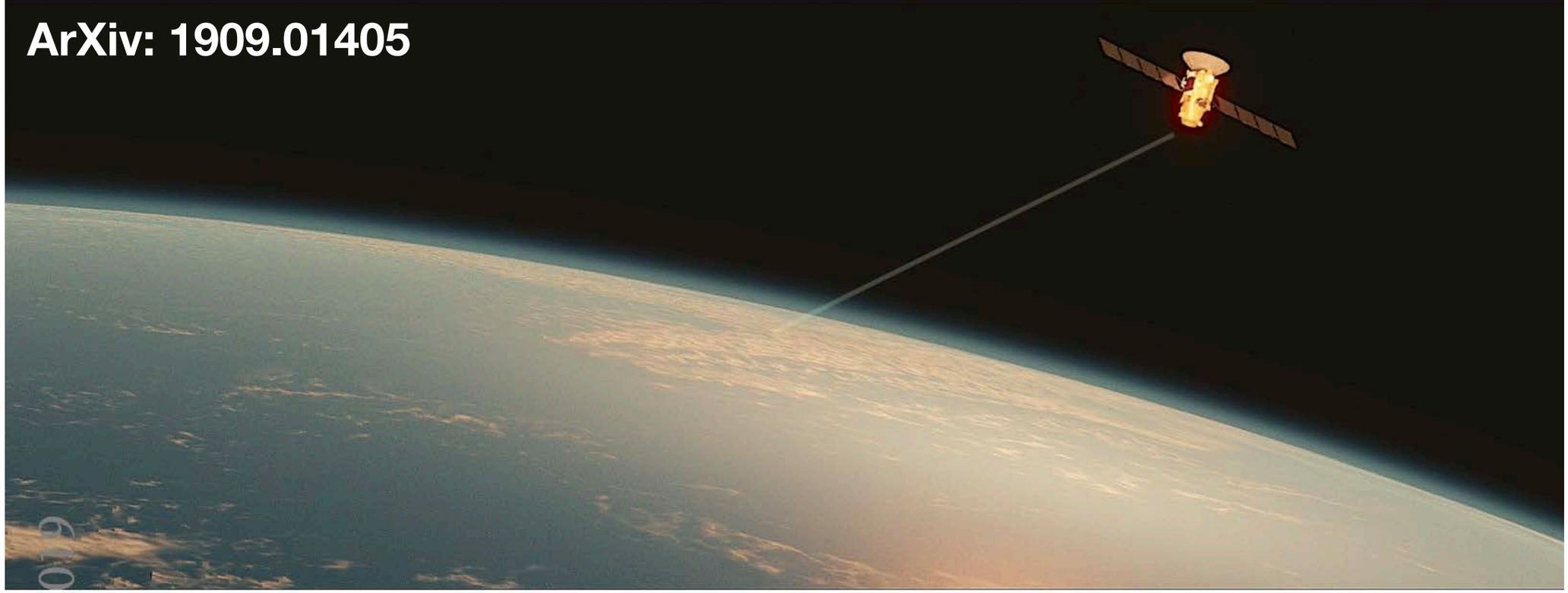
[8] *Department of Physics and Astronomy, University of Waterloo, 200*
[18] *Instituto de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Morelia 58089, México*
[19] *Instituto de Astronomía, Universidad Nacional Autónoma de México, CdMx 04510, México*
[20] *Steward Observatory and Department of Astronomy, University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721, USA*
[21] *University of Massachusetts Boston, 100 William T, Morrissey Blvd, Boston, MA 02125, USA*
[22] *Leiden Observatory—Allegro, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands*
[23] *Netherlands Organisation for Scientific Research (NWO), Postbus 93138, 2509 AC Den Haag , The Netherlands*
[24] *Shanghai Astronomical Observatory, Chinese Academy of Sciences,*
and Particle Physics (IMAPP), Radboud University, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands



Astro2020 APC White Paper

Studying black holes on horizon scales with space-VLBI

Kari Haworth[1,*], Michael D. Johnson[1,2,*], Dominic W. Pesce[1,2], Daniel C. M. Palumbo[1,2], Lindy Blackburn[1,2], Kazunori Akiyama[2,3,4,5], Don Boroson[6], Katherine L. Bouman[7], Joseph R. Farah[1,2,8], Vincent L. Fish[3], Mareki Honma[10,11], Tomohisa Kawashima[5], Motoki Kino[5,9], Alexander Raymond[1,2], Mark Silver[6], Jonathan Weintroub[1,2], Maciek Wielgus[1,2], Sheperd S. Doeleman[1,2], José L. Gómez[13], Jens Kauffmann[3], Garrett K. Keating[1], Thomas P. Krichbaum[14], Laurent Loinard[18,19], Gopal Narayanan[12], Akihiro Doi[16], David J. James[1,2], Daniel P. Marrone[15], Yosuke Mizuno[17], Hiroshi Nagai[5]

[1] *Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA*
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[3] *Massachusetts Institute of Technology, Haystack Observatory, 99 Millstone Road, Westford, MA 01886, USA*
[11] *Department of Astronomical Science, The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*
[12] *Department of Astronomy, University of Massachusetts, 01003, Amherst, MA, USA*
[13] *Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la*

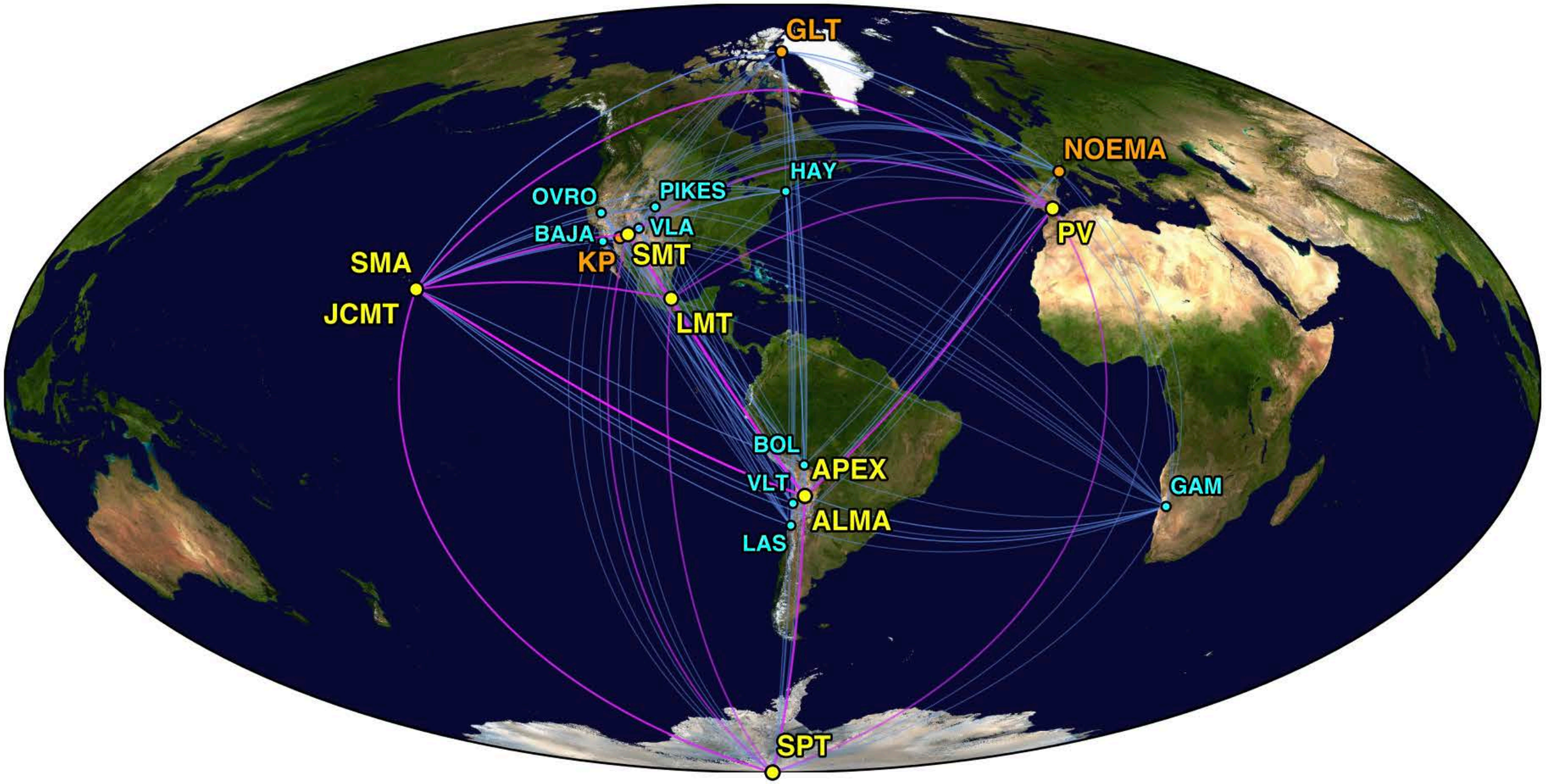
Astro2020 APC White Paper

Extremely long baseline interferometry with Origins Space Telescope

Dominic W. Pesce[†1,2], Kari Haworth[1], Gary J. Melnick[1], Lindy Blackburn[1,2], Maciek Wielgus[1,2], Michael D. Johnson[1,2], Alexander Raymond[1,2], Jonathan Weintroub[1], Daniel C. M. Palumbo[1,2], Sheperd S. Doeleman[1,2], David J. James[1,2]

Abstract: Operating 1.5×10^6 km from Earth at the Sun-Earth L2 Lagrange point, the Origins Space Telescope equipped with a slightly modified version of its HERO heterodyne instrument could function as a uniquely valuable node in a VLBI network. The unprecedented angular resolution resulting from the combination of Origins with existing ground-based millimeter/submillimeter telescope arrays would increase the number of spatially resolvable black holes by a factor of 10^6, permit the study of these black holes across all of cosmic history, and enable new tests of general relativity by unveiling the photon ring substructure in the nearest black holes.

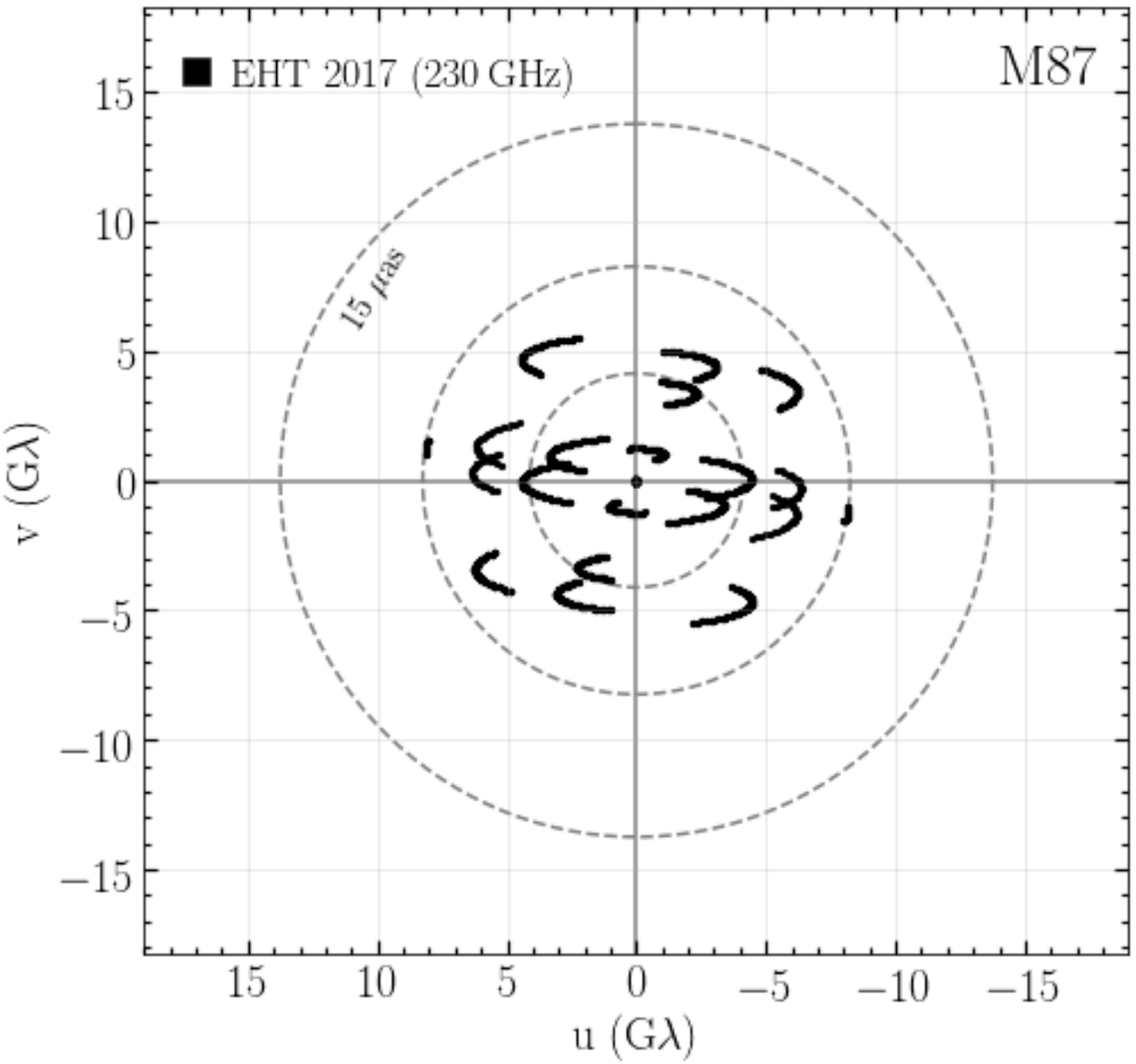
Array expansion

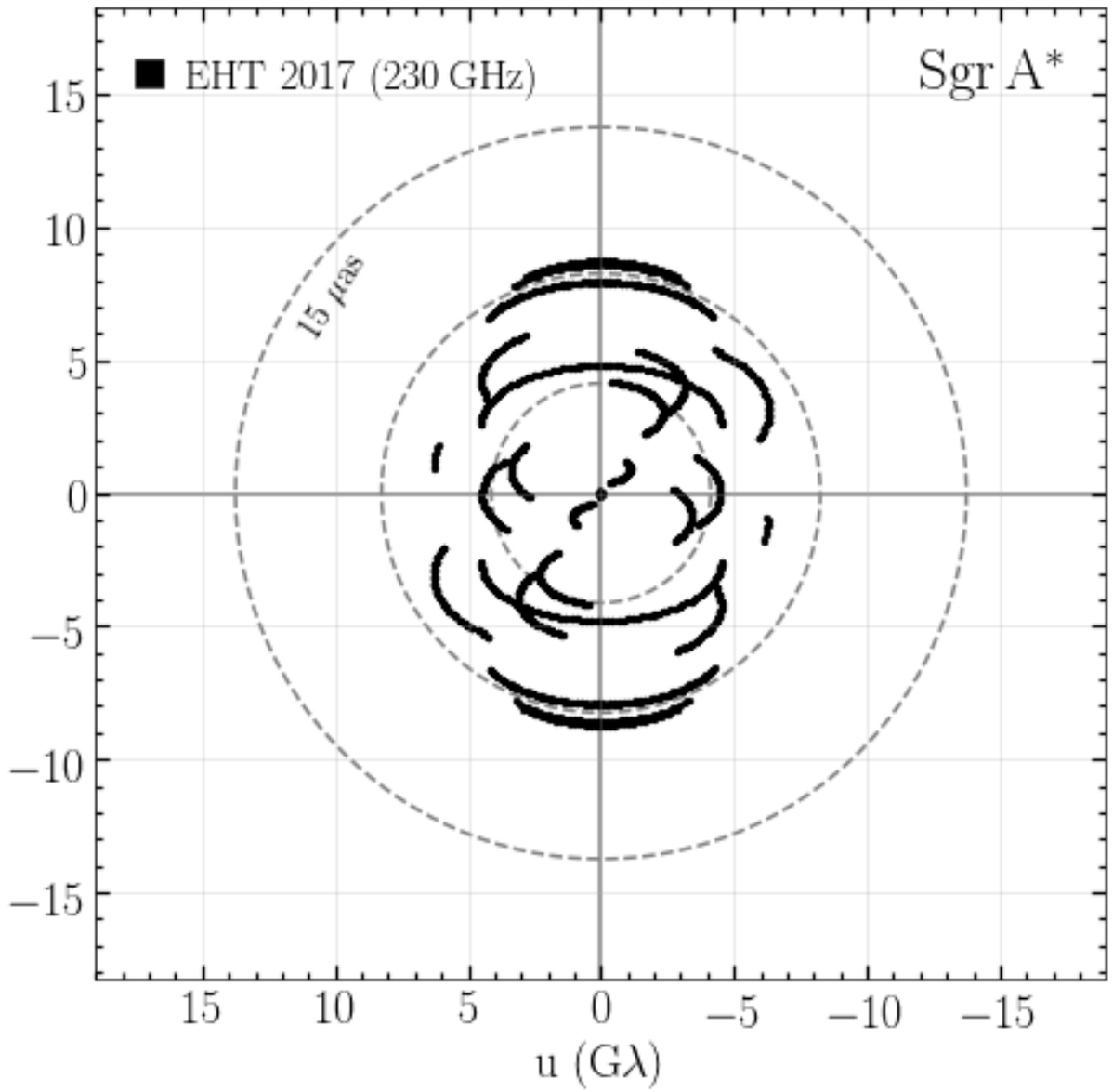


Astro2020 White Paper, ArXiv: 1909.01411

Studying Black Holes on Horizon Scales with VLBI Ground Arrays

Array expansion





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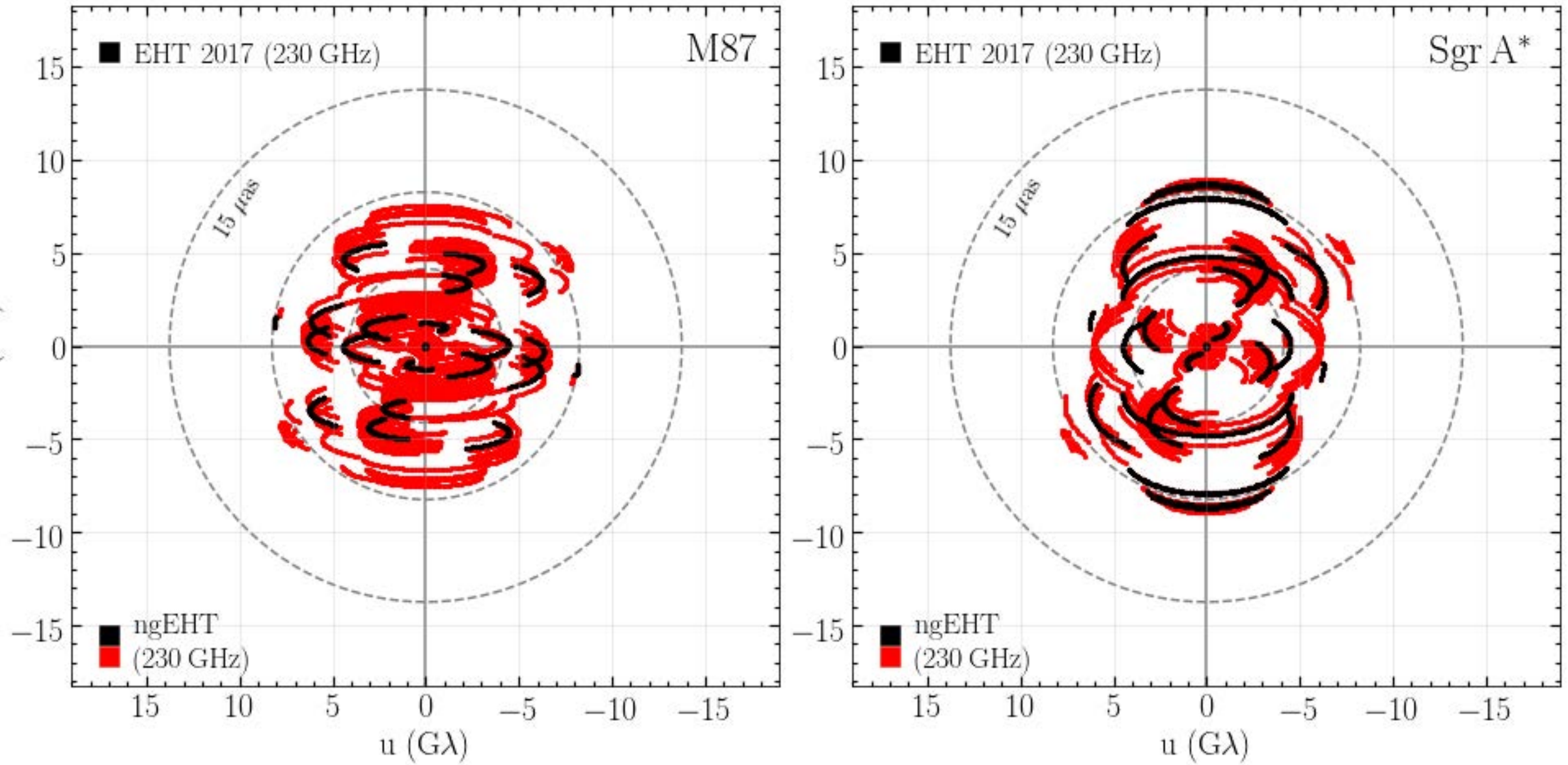
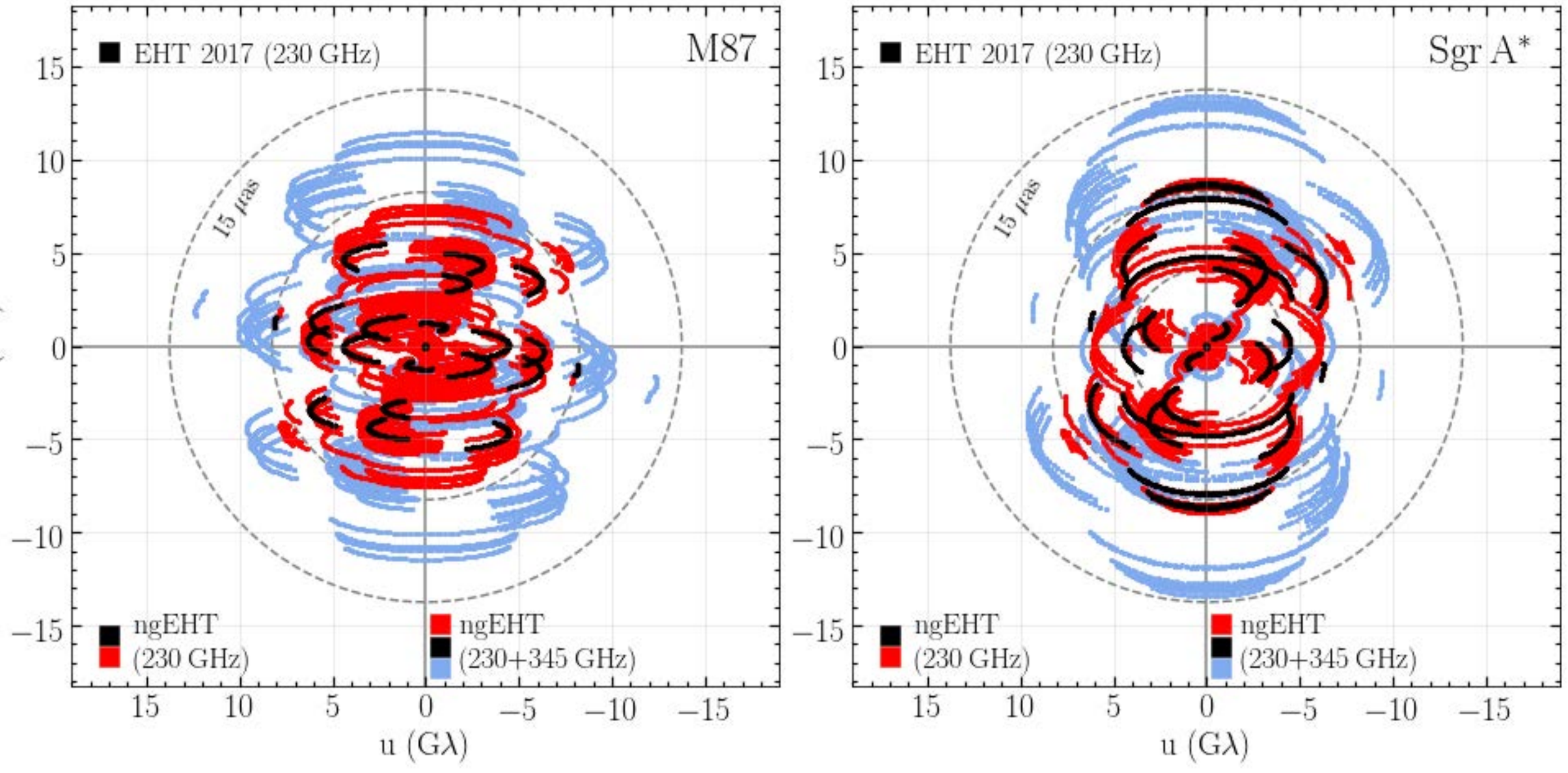


Astro2020 White Paper, ArXiv: 1909.01411

Studying Black Holes on Horizon Scales with VLBI Ground Arrays

Array expansion + dual frequency



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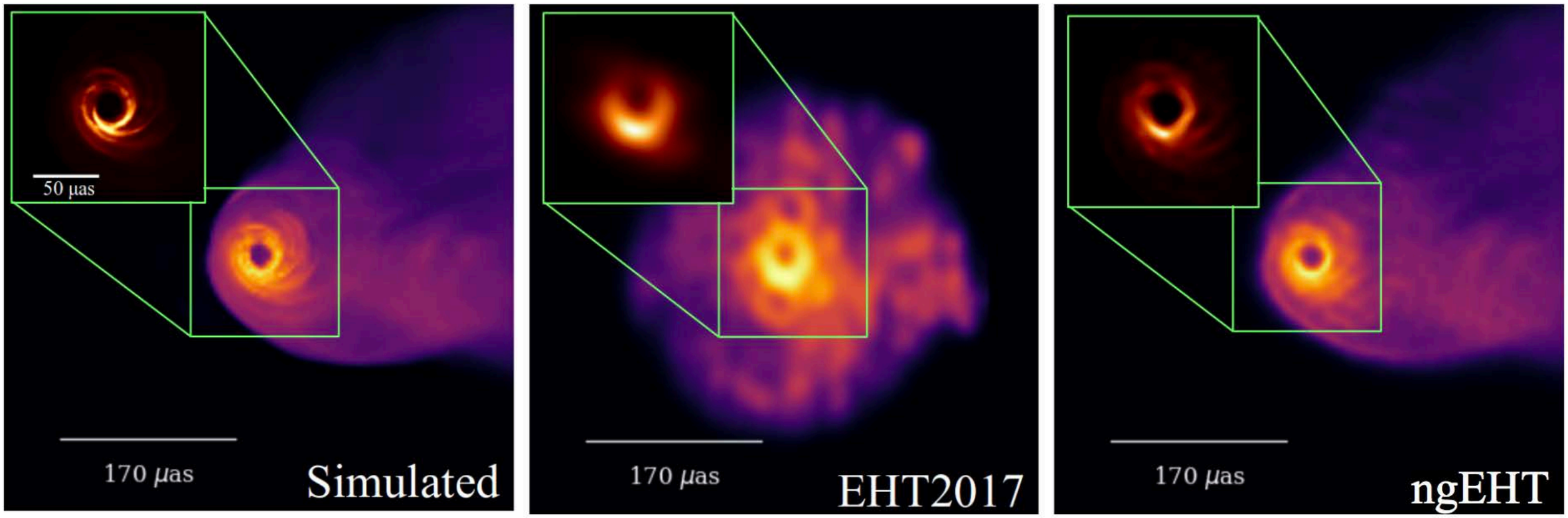
Dynamic range improvement



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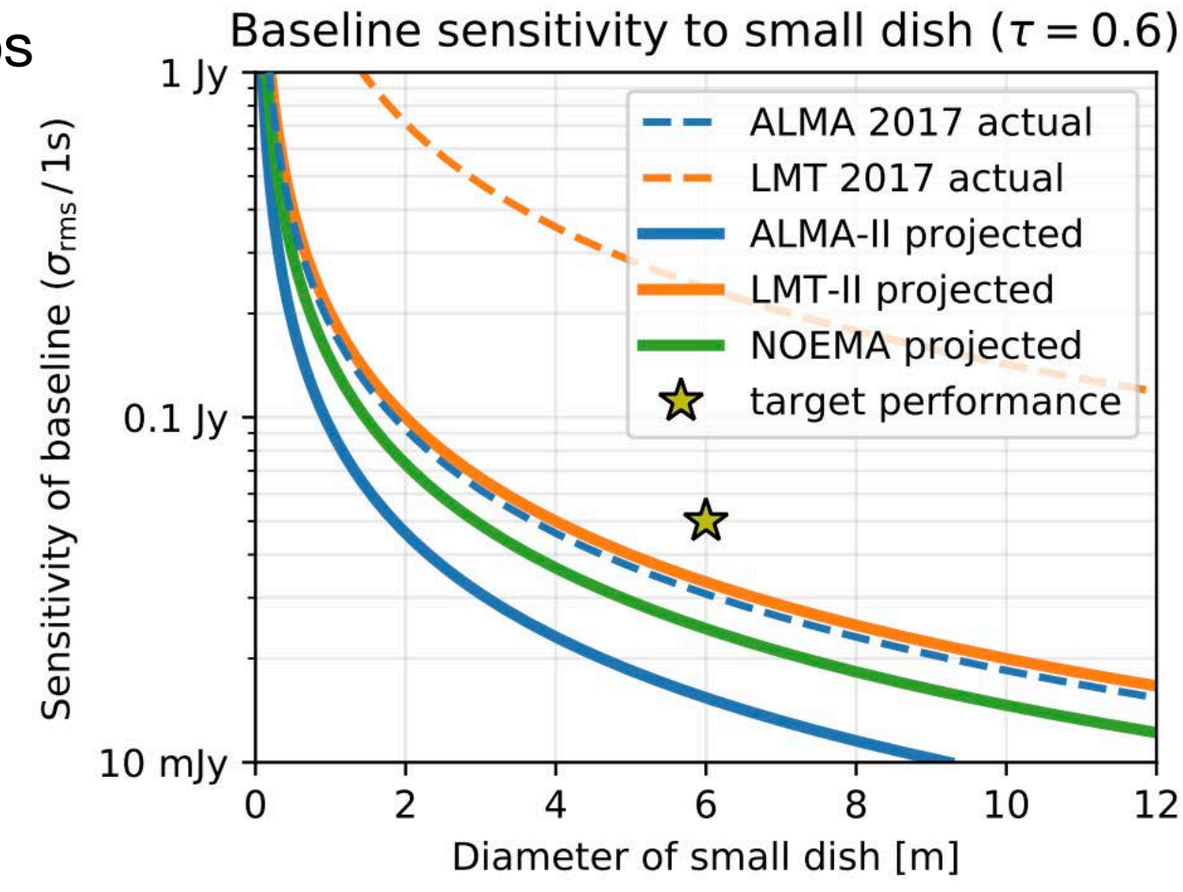
Studying Black Holes on Horizon Scales with VLBI Ground Arrays

Expansion of the EHT ground array

- multiple new sites with 6-12 m dishes,
- upgrading powerful anchor stations, able to connect weaker array elements,
- developing double-frequency technology,
- expanding bandwidth, possibly to 256 Gbps
- data transport developments



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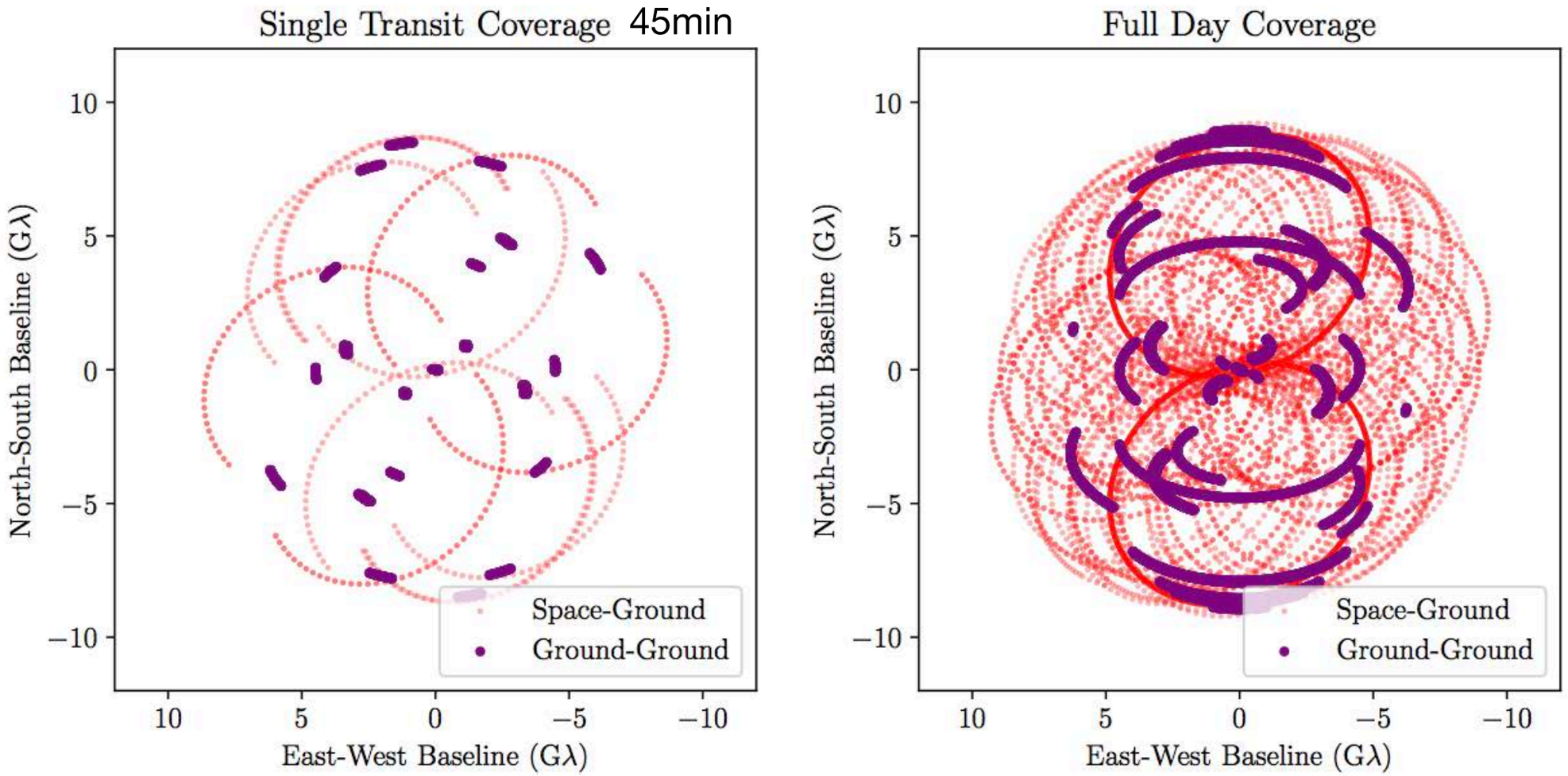
Studying Black Holes on Horizon Scales with VLBI Ground Arrays

Adding a LEO dish: aperture synthesis speed

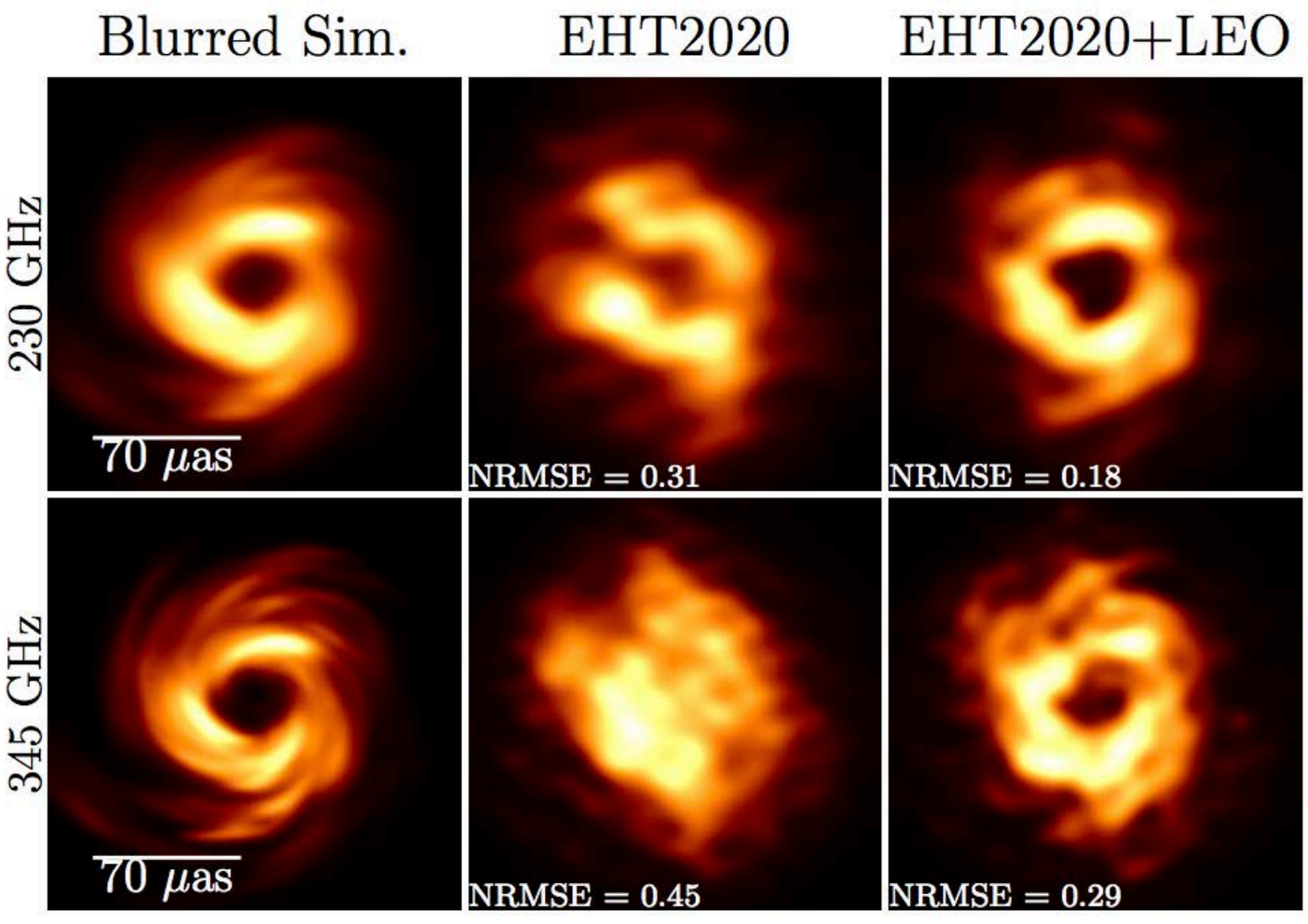


Astro2020 White Paper, ArXiv: 1909.01405

Studying black holes on horizon scales with space-VLBI

Adding a LEO dish: aperture synthesis speed

Observing rapidly varying Sgr A*

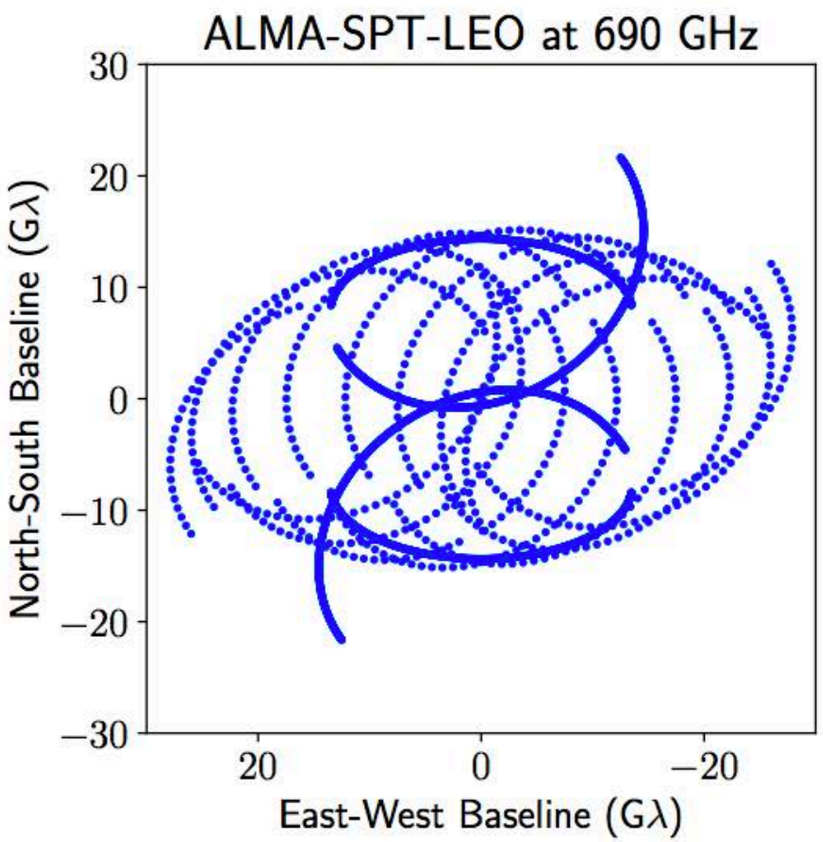


45min of observations

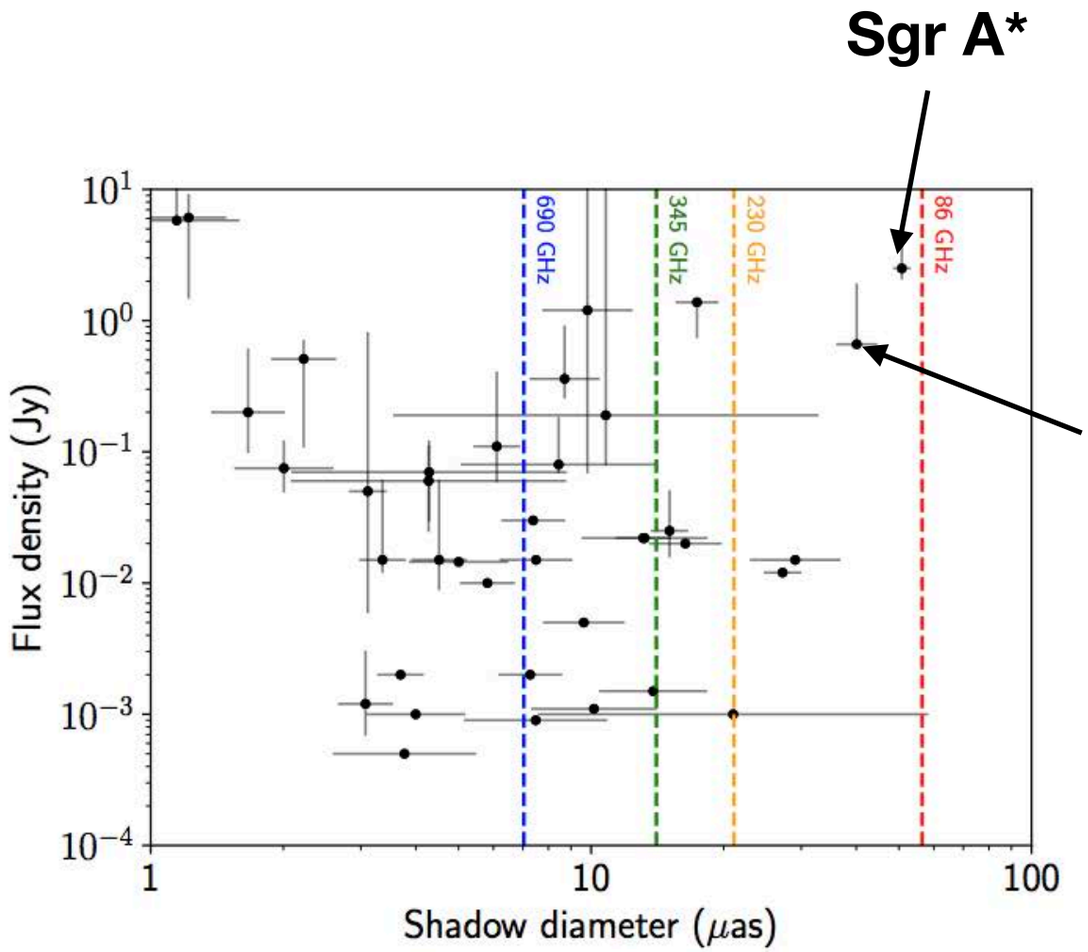
Astro2020 White Paper, ArXiv: 1909.01405

Studying black holes on horizon scales with space-VLBI

More shadows with higher resolution!



Sgr A* coverage



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Studying black holes on horizon scales with space-VLBI

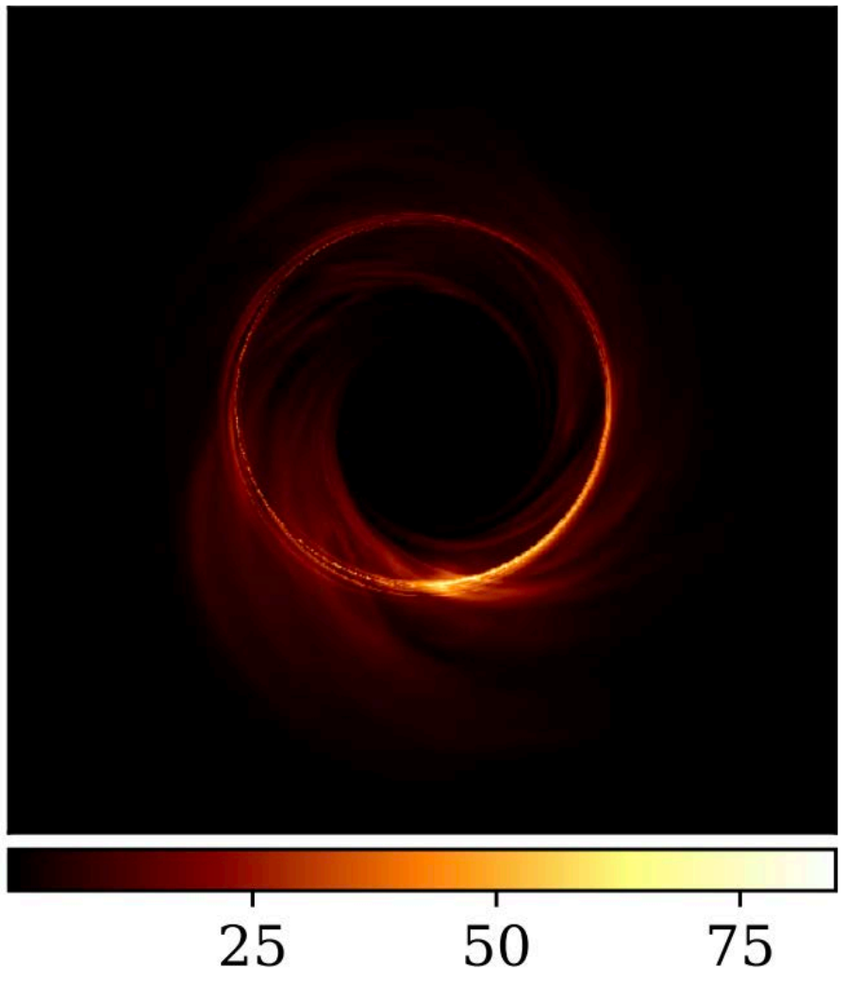
EHT expansion with a LEO antenna

- single 3-4 m dish on the low Earth orbit,
- strong anchor stations (ALMA, NOEMA, LMT) allow for small orbiting dish,
- 2 polarizations x 2 bands x 8 GHz,
- enabling observations in up to 690 GHz frequency with detections to limited number of suitable ground stations (ALMA, SPT),
- technical developments on digital processing system and local oscillator(e.g. high-performance oven-controlled quartz crystal oscillators),
- solid state recorders,
- laser downlink (hundreds Gbps),
- possibly computationally challenging fringe fitting with imperfect position information

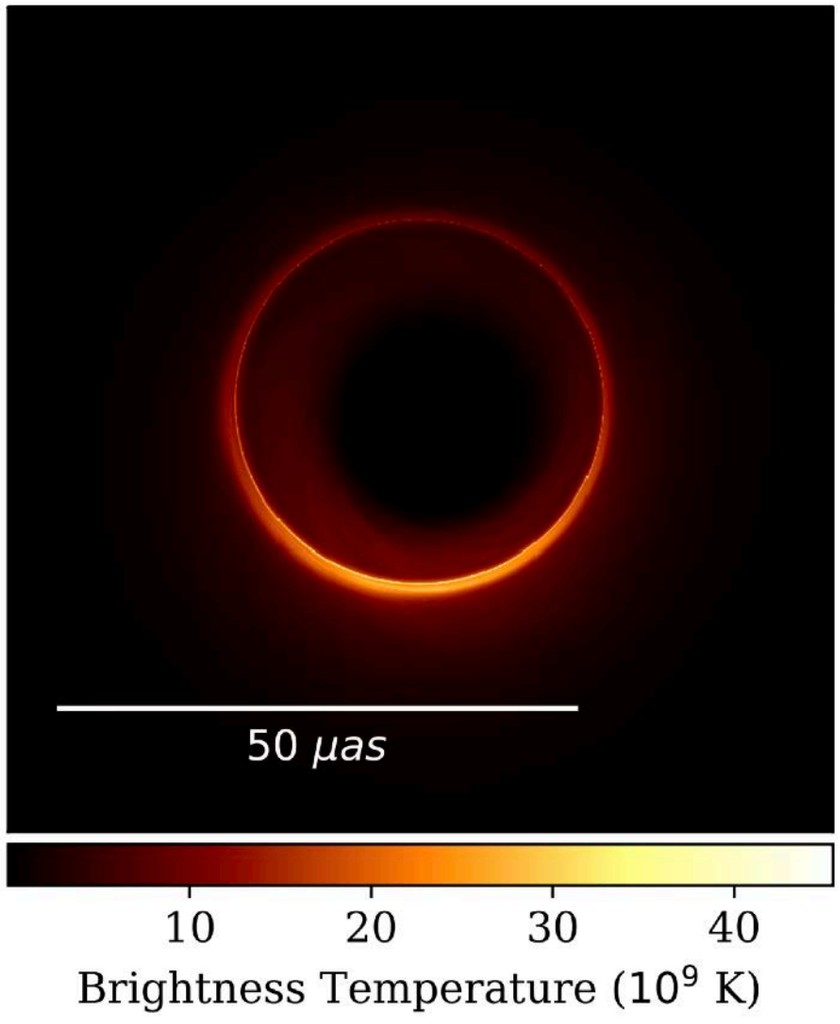
Astro2020 White Paper, ArXiv: 1909.01405
Studying black holes on horizon scales with space-VLBI

VLBI on extreme space baselines

Snapshot



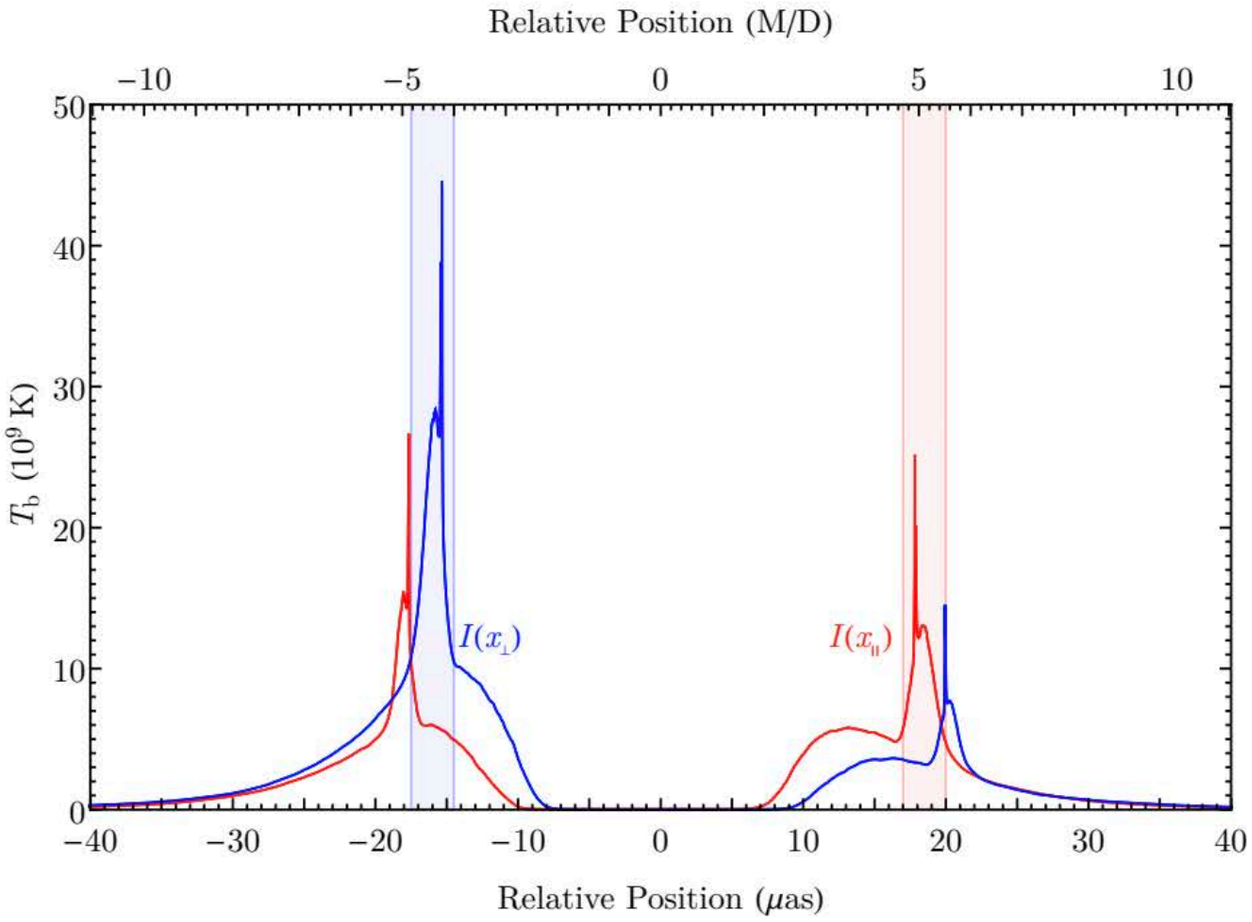
Averaged

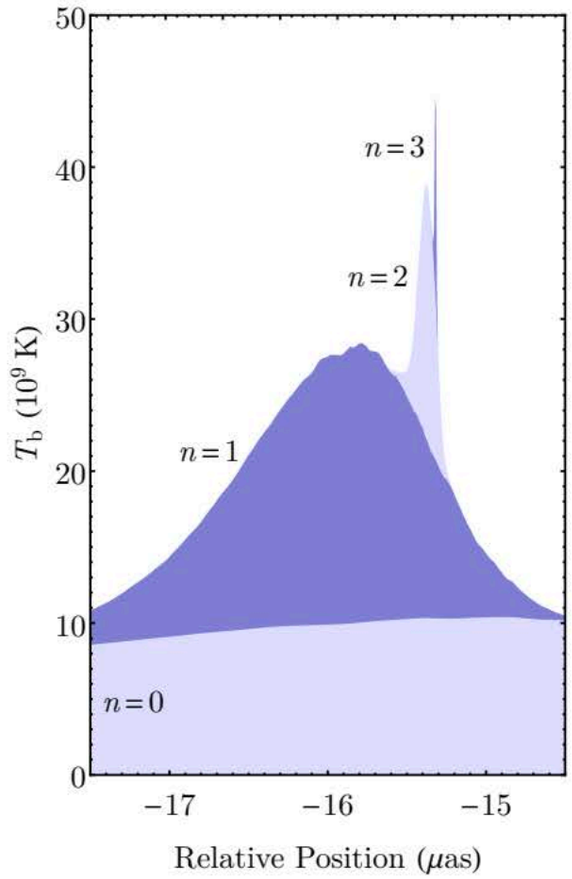


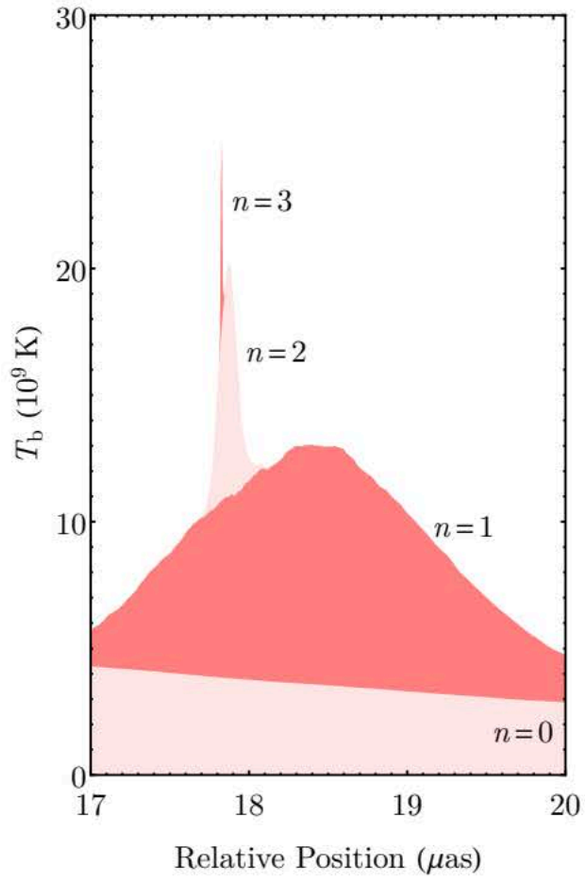
Astro2020 White Paper, ArXiv: 1909.01408
Extremely long baseline interferometry with Origins Space Telescope

Johnson et al. ArXiv: 1907.04329
Universal interferometric signatures of as black hole's photon ring

VLBI on extreme space baselines







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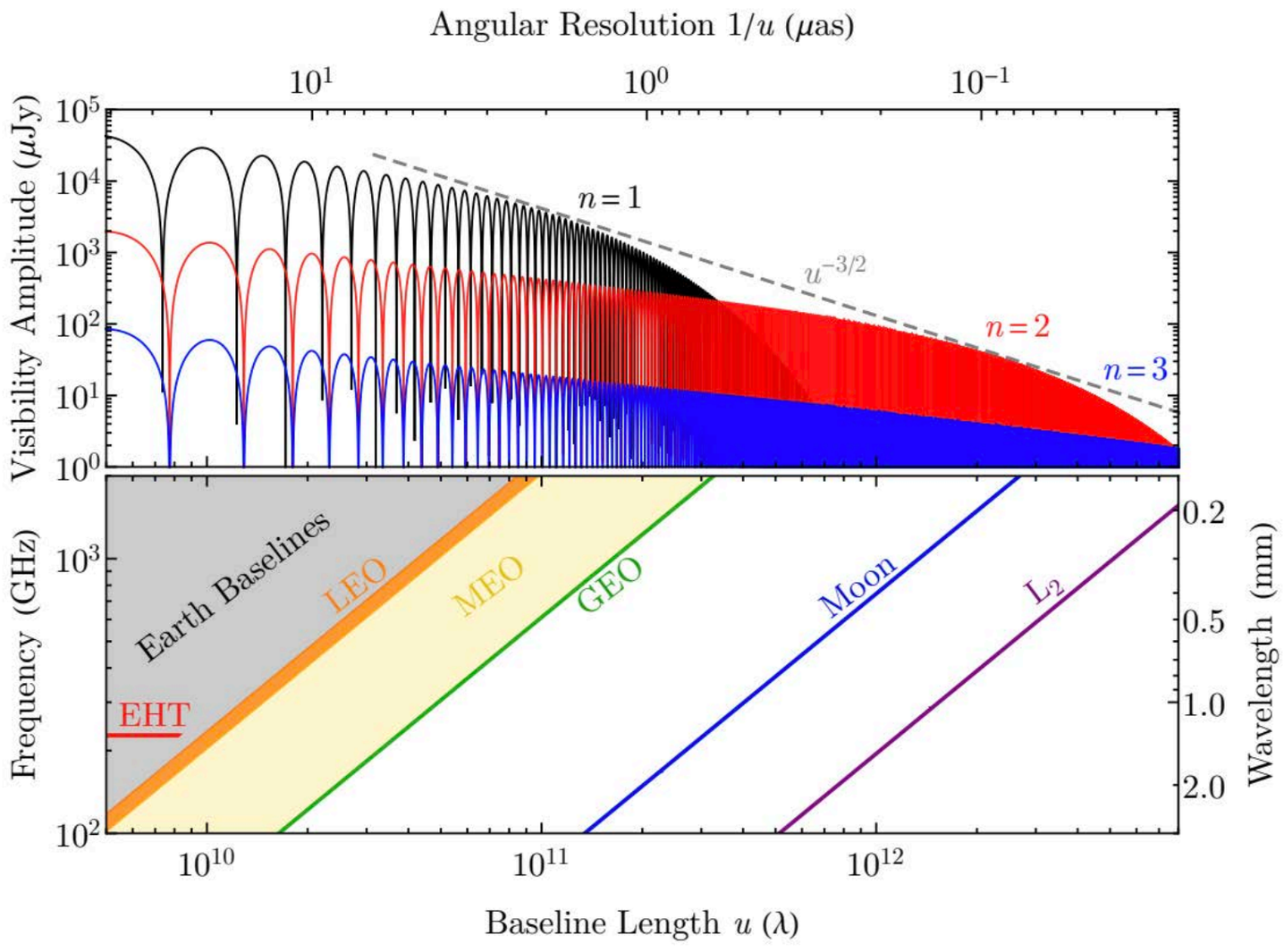

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Thanks!

Also check out
Lindy Blackburn's poster
on the future of the EHT