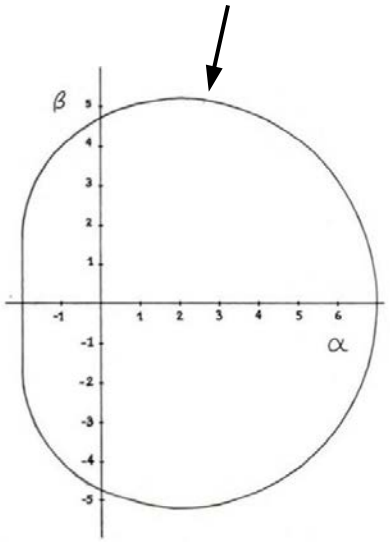
Imaging the Structure and Dynamics near the Event Horizon of a Black Hole

Michael Johnson (CfA)
On Behalf of the Event Horizon Telescope Collaboration

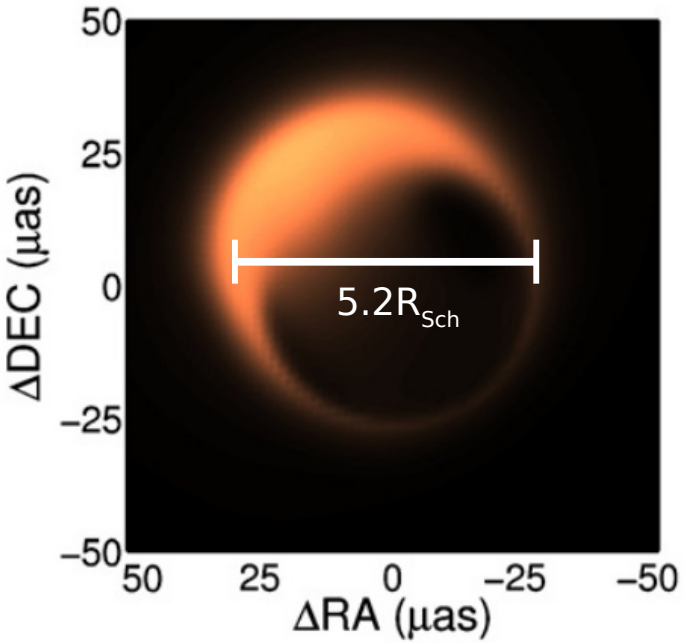
NEROC
November 8, 2017

The Image of a Black Hole

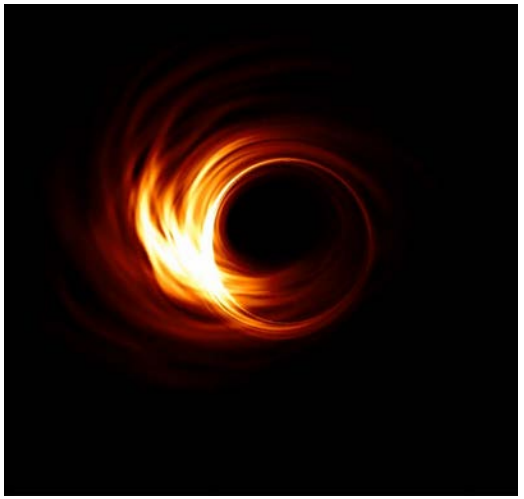
The black hole “shadow”
Changes by only ±4% with BH spin



Bardeen (1973)



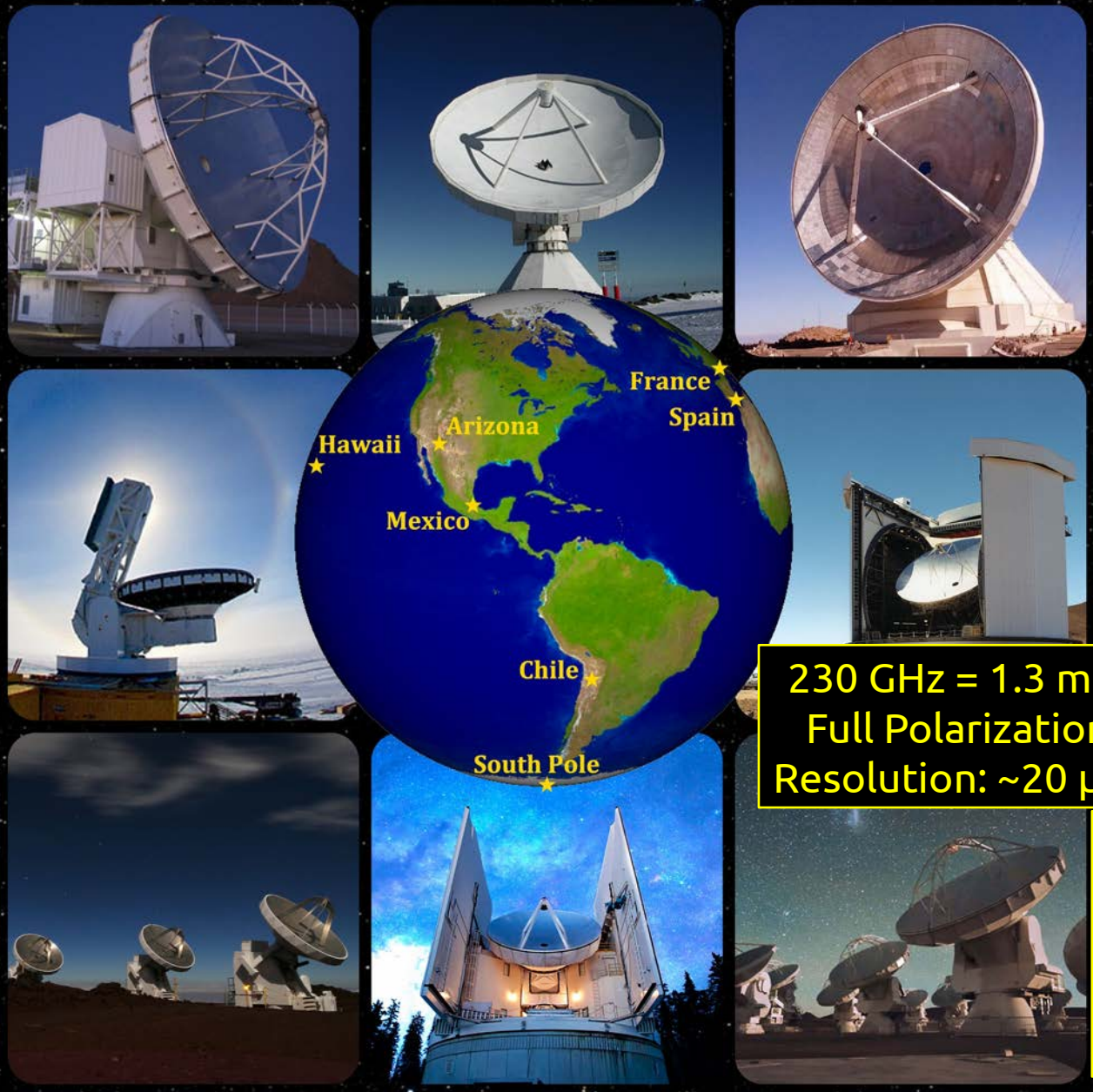
Broderick et al. (2011)



H. Shiokawa

“It is conceptually interesting, if not astrophysically very important, to calculate the precise apparent shape of the black hole... Unfortunately, there seems to be no hope of observing this effect.” (Bardeen 1973,1974)

The Event Horizon Telescope



230 GHz = 1.3 mm
Full Polarization
Resolution: ~20 μas

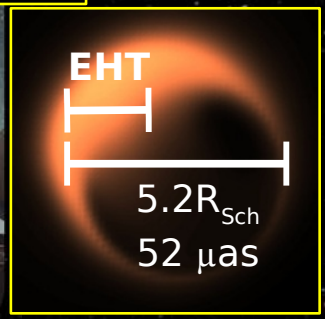
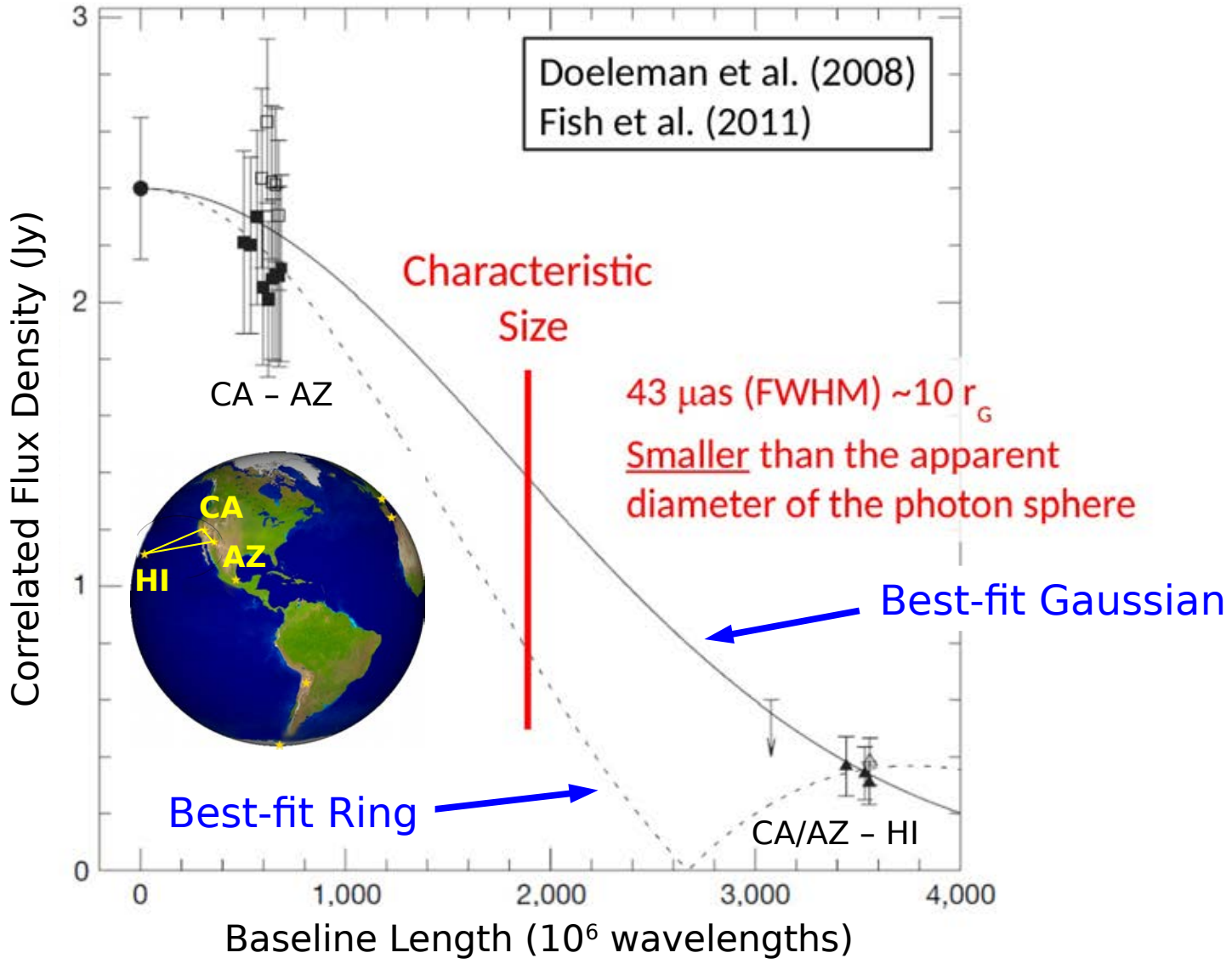


Image Credit: APEX, IRAM, G. Narayanan, J. McMahon, JCMT/JAC, S. Hostler, D. Harvey, ESO/C. Malin

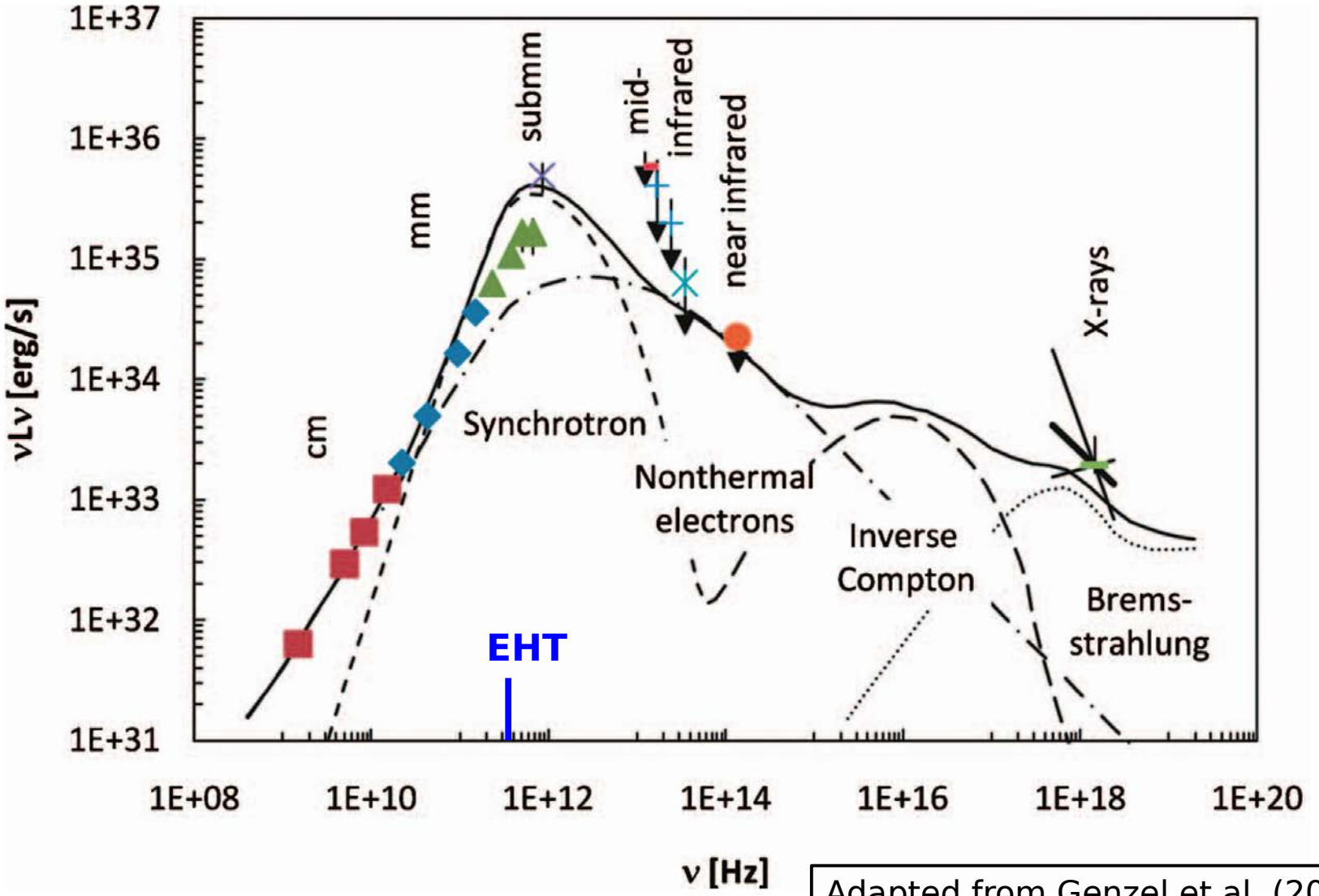
Past Results with the EHT

Image Credit: APEX, IRAM, G. Narayanan, J. McMahon, JCMT/JAC, S. Hostler, D. Harvey, ESO/C. Malin

Studying Sgr A* with the EHT

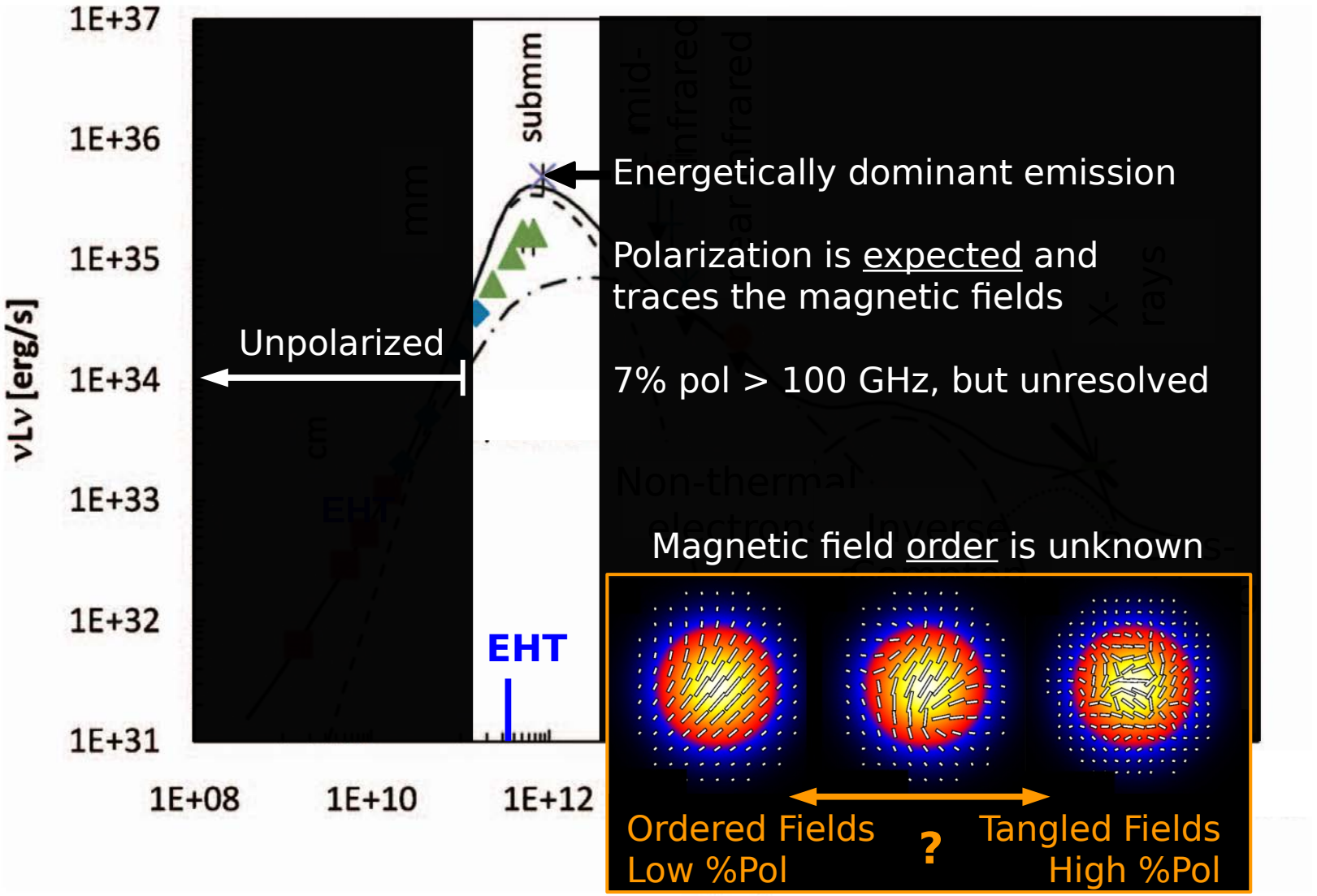


The SED of Sgr A*

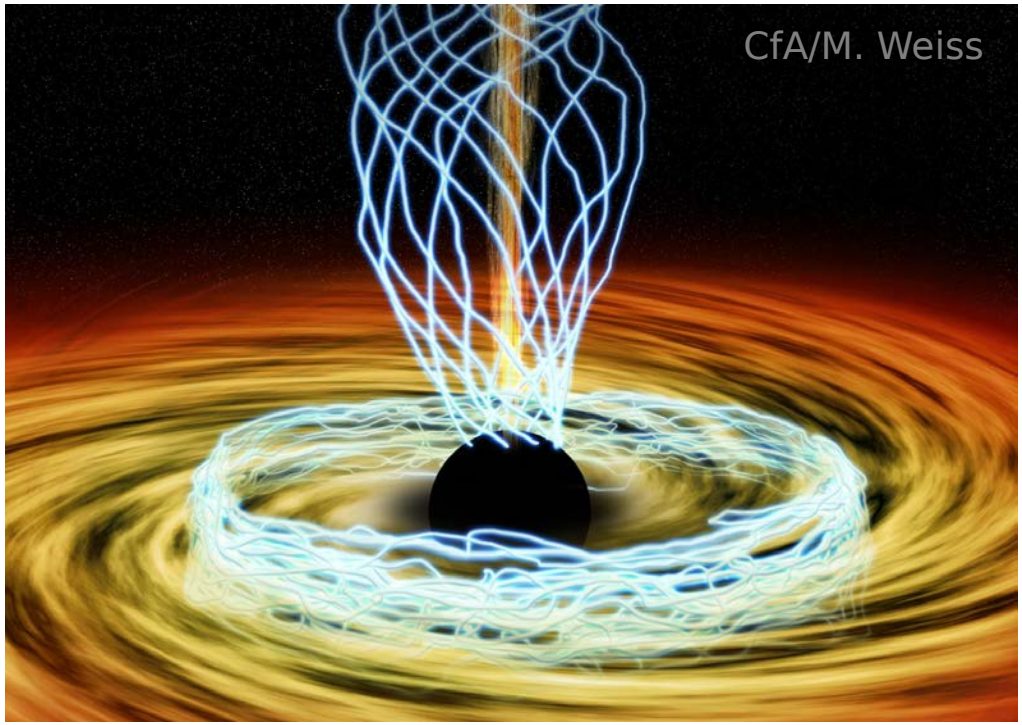


Adapted from Genzel et al. (2010)

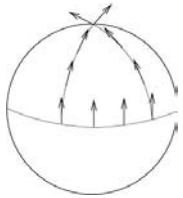
The SED of Sgr A*



Why Study Polarization?

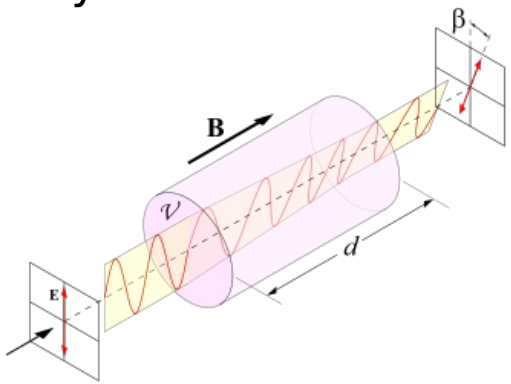


Strong Gravity:
- Parallel Transport
- Relativistic Aberration



BH Accretion and Outflow:
- Field morphology
- Turbulence

Global Accretion:
- Faraday rotation & conversion

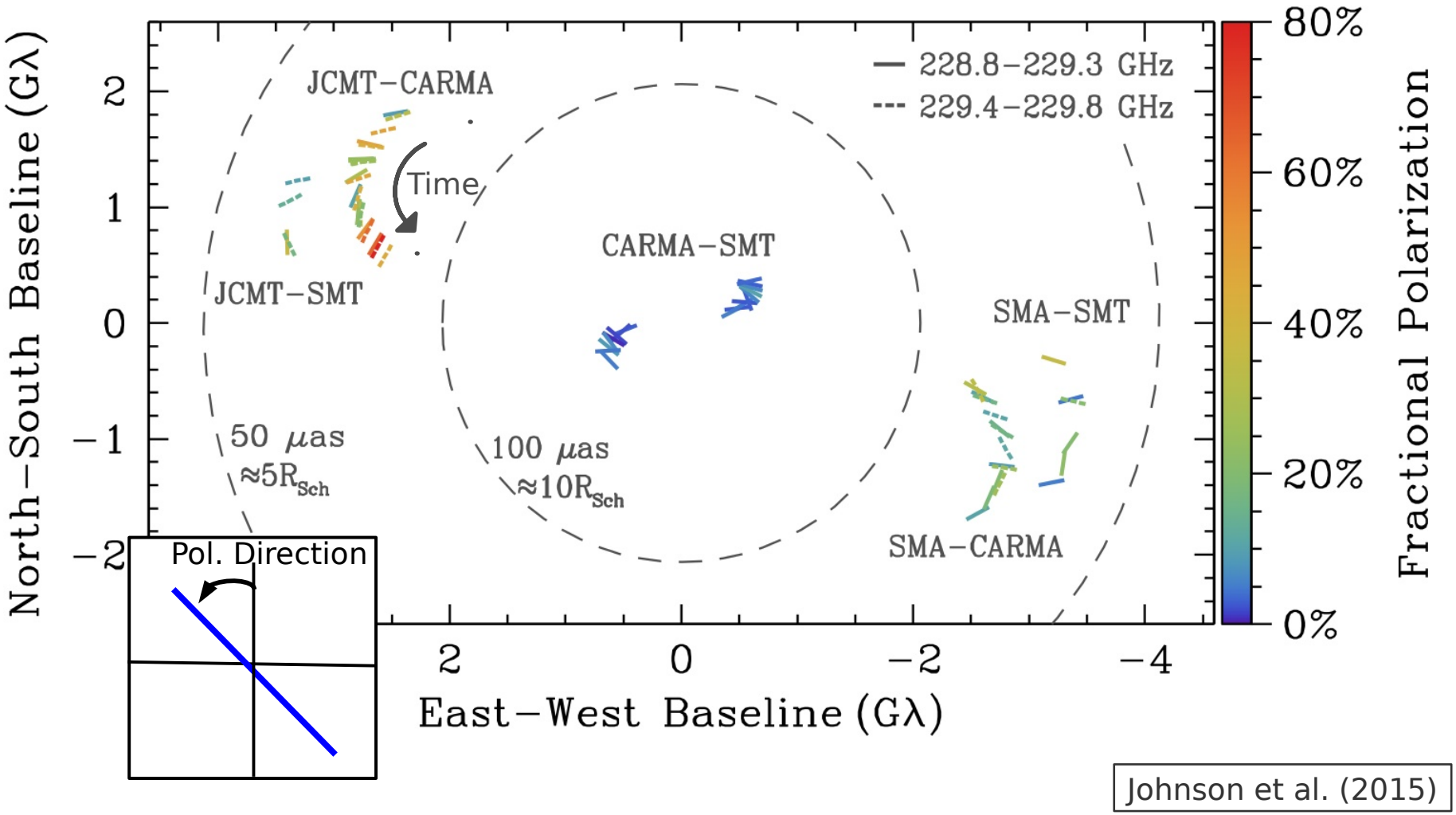


The accretion rate of Sgr A* was not determined until submillimeter polarization was detected!

(Aitken et al. 2000; Marrone et al. 2007)

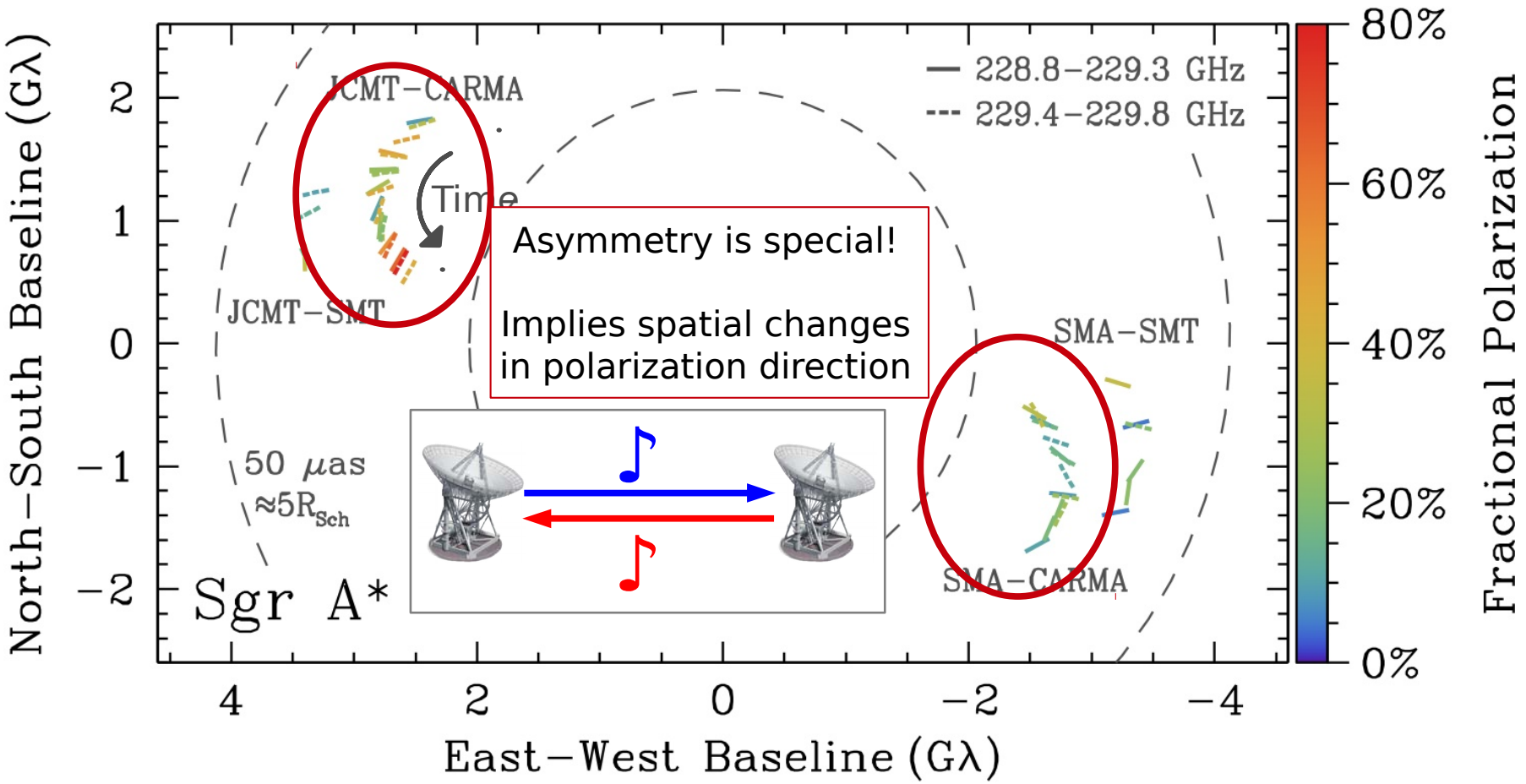
Resolving Sgr A* with the EHT

First polarimetric VLBI at 230 GHz;
First resolved polarization of Sgr A* at <u>any</u> wavelength

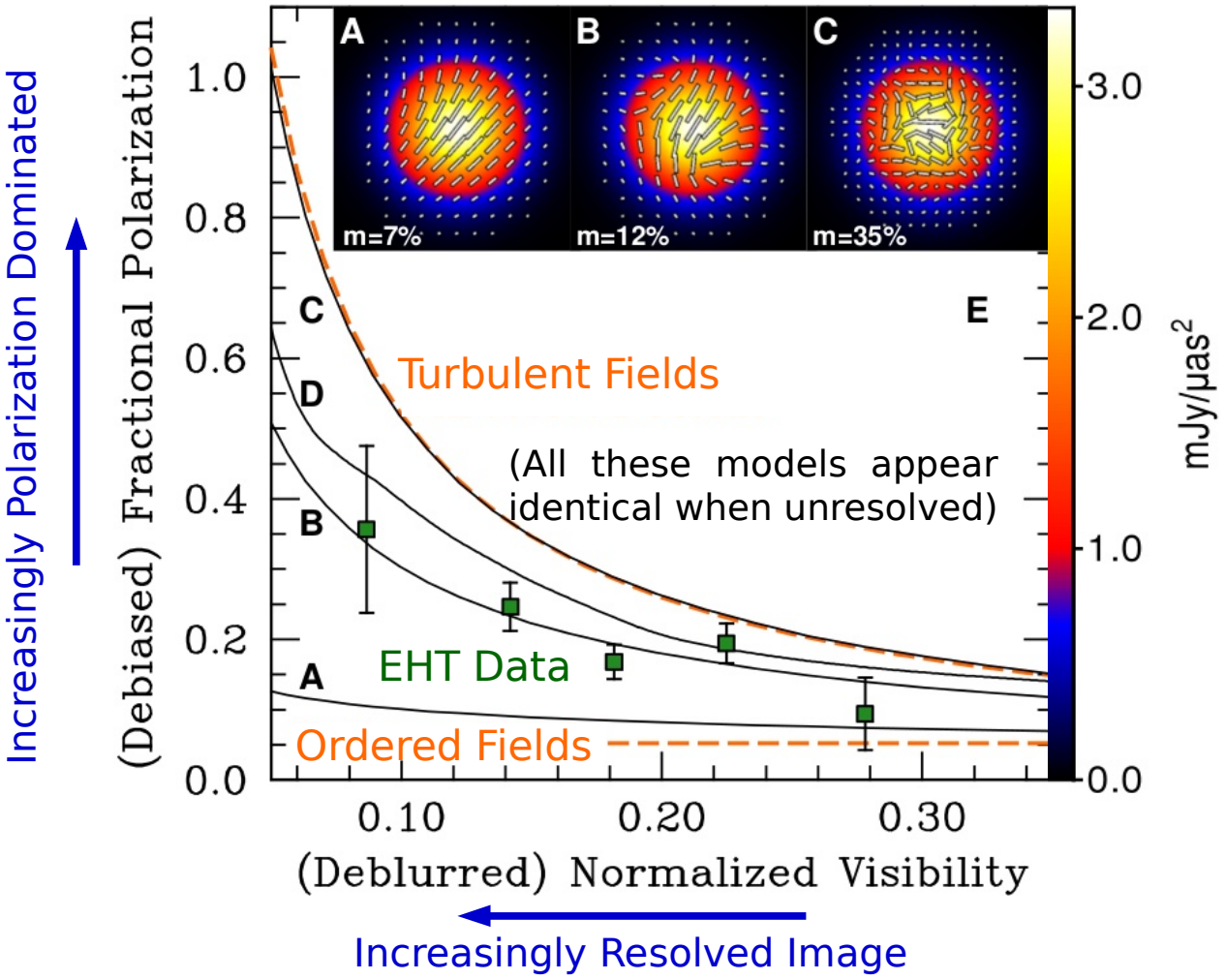


Johnson et al. (2015)

Resolving Sgr A* with the EHT



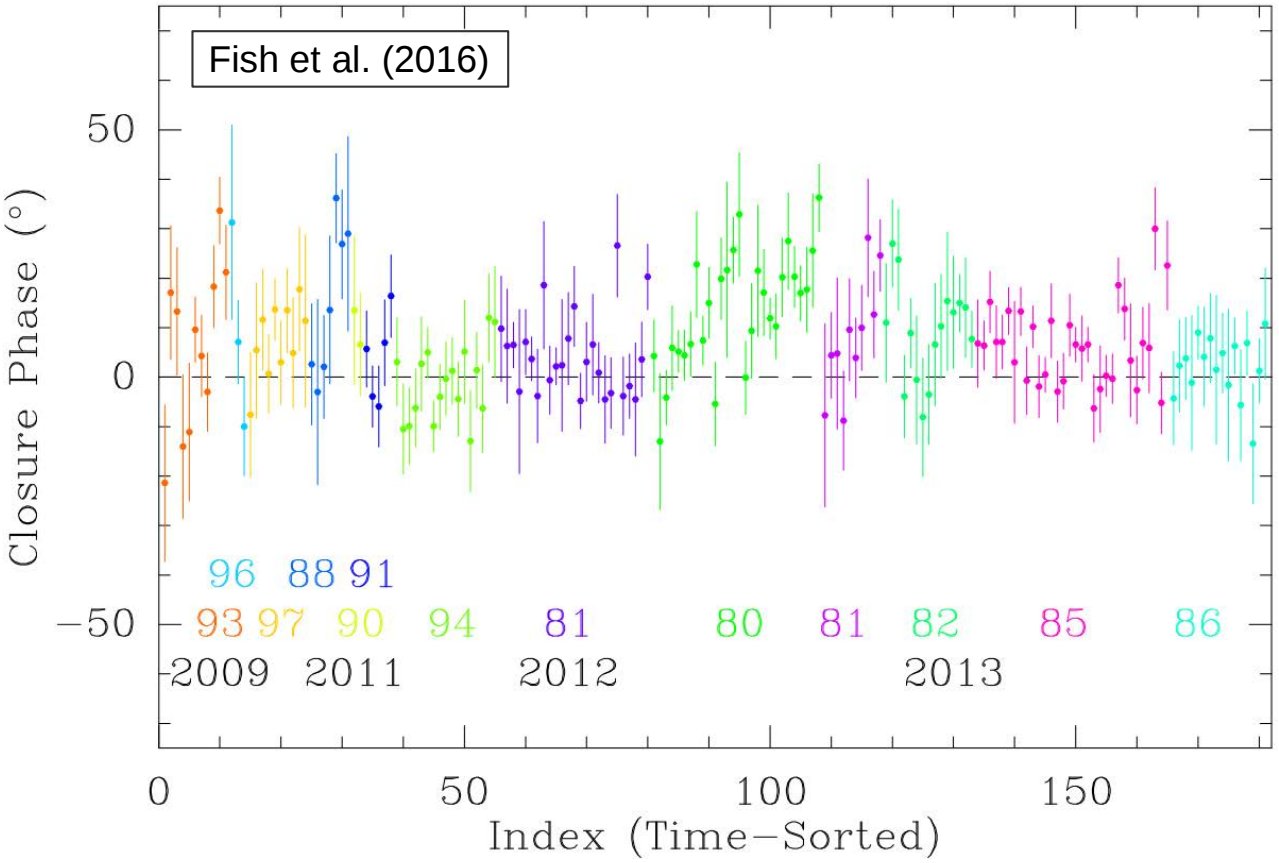
Ordered Fields Near the Horizon

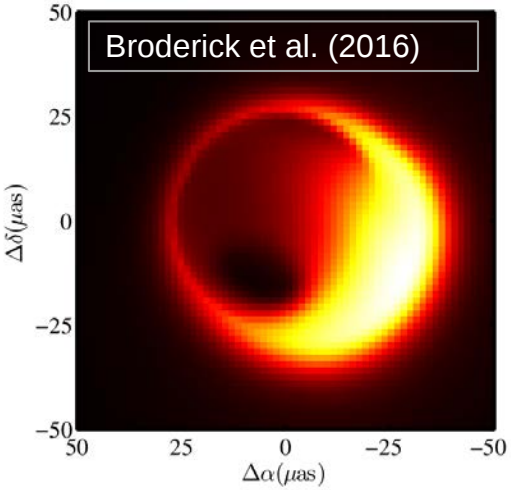


Closure Phases of Sgr A*

Non-zero closure phases detected in 2009-2013

Persistent, asymmetric structure (first ever for Sgr A*)





Example of a compatible model

Roadmap of the EHT

2008

- 1 GHz BW (4 Gb/s)
- 3 Stations
- Detection of horizon-scale structure in Sgr A*

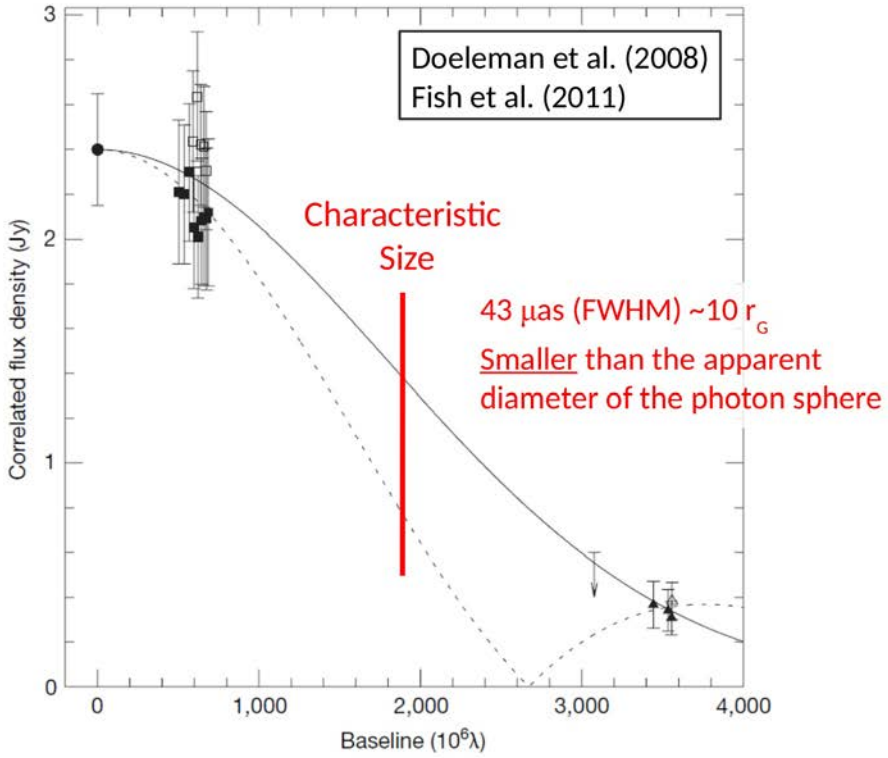


Table 1 | VLBI detections of Sgr A* on the ARO/SMT–JCMT baseline at 1.3 mm wavelength

Date (UT)	Correlated flux density (Jy)	SNR	Residual delay (ns)
10 April 2007 12:20	0.38	5.8	−4.9
11 April 2007 11:00	0.37	5.0	−7.2
11 April 2007 11:40	0.34	5.4	−7.9
11 April 2007 12:00	0.31	5.8	−8.0

Doeleman et al. (2008)

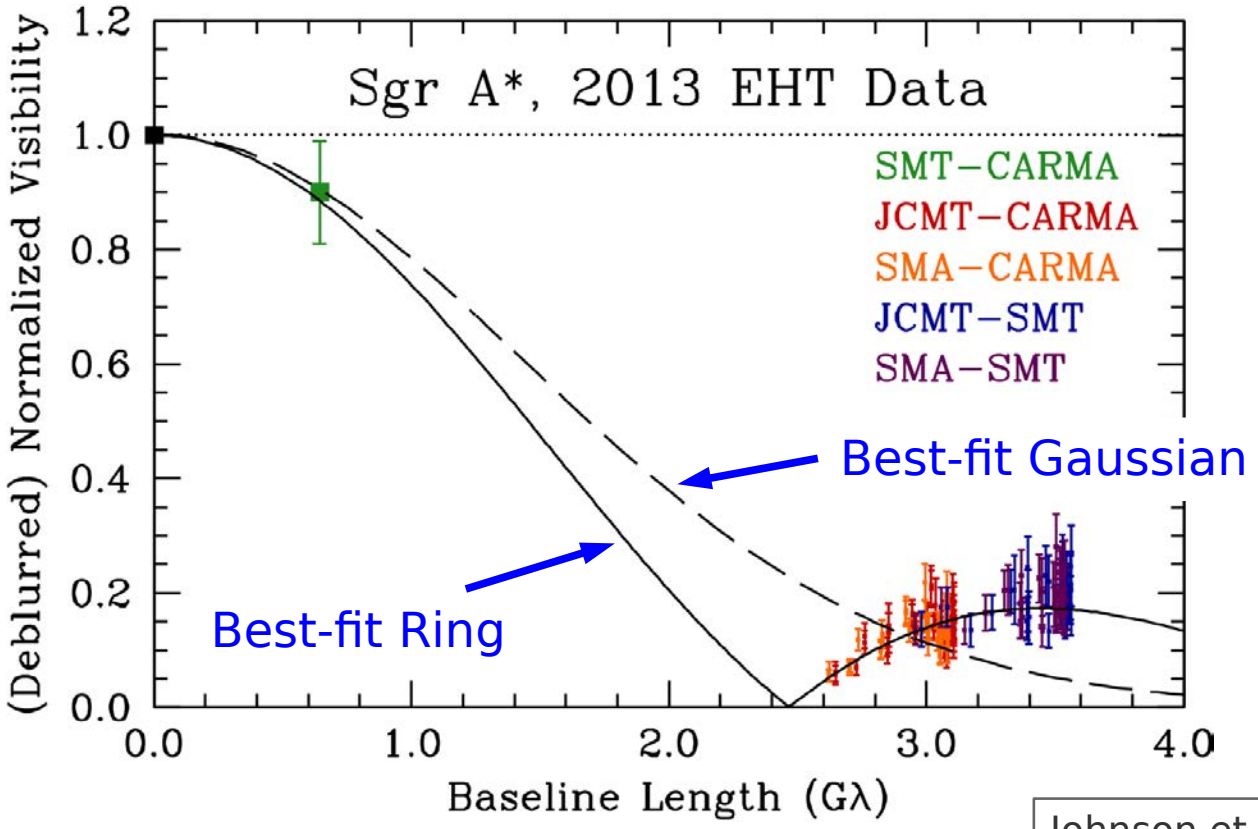
Roadmap of the EHT

2008

- 1 GHz BW (4 Gb/s)
- 3 Stations
- ~4R_{Sch} structure in Sgr A*

2013

- Phased arrays (CARMA, SMA) w/ dual-pol (8 Gb/s)
- Enabled Science: Polarimetry
- Ordered magnetic fields near Sgr A*



Johnson et al. (2015)

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- 1 GHz BW (4 Gb/s)
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2013

- Phased arrays
- Polarimetry
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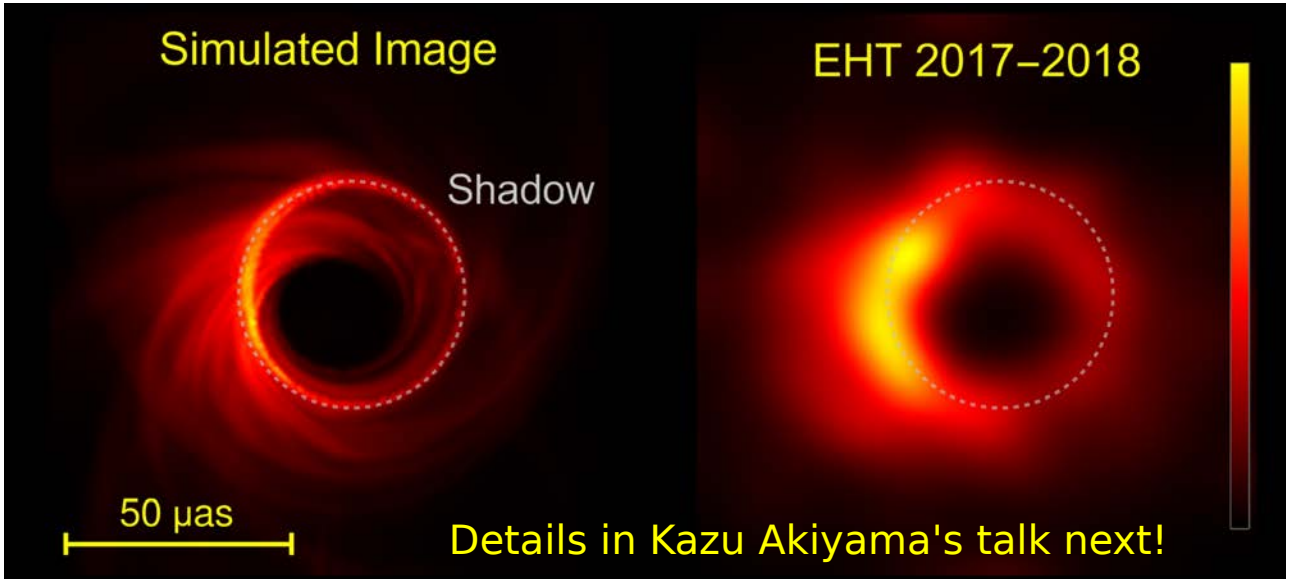
2017

- 4 GHz BW (32 Gb/s)
- ALMA!
- Images of Sgr A* and M87

5 observing nights, 80 hours observing, 18 different sources



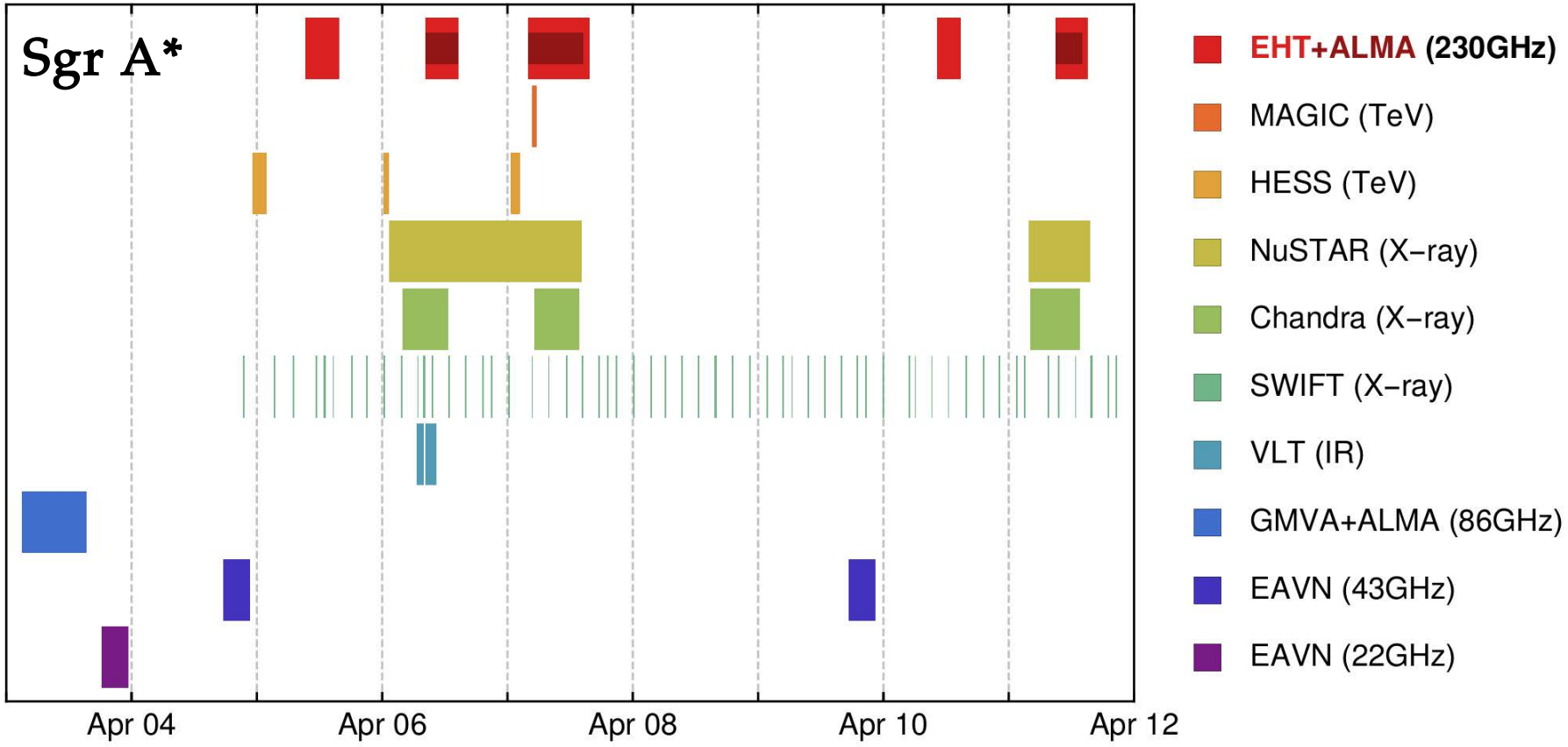
The 2017 EHT Campaign was this April

We have already successfully detected fringes to all sites with unprecedented SNR

Roadmap of the EHT

2008 2013 2017

The 2017 EHT observations prompted a worldwide multiwavelength campaign



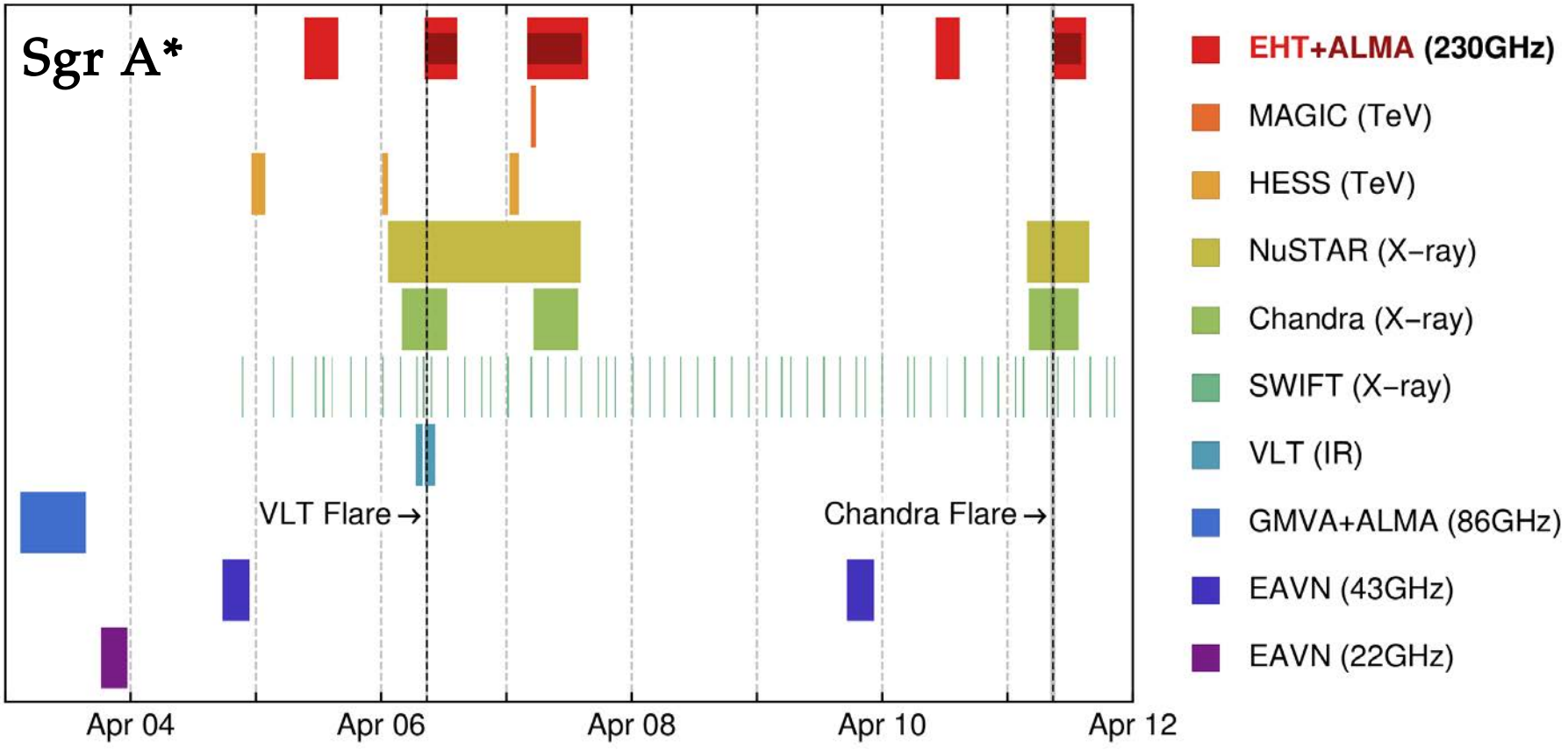
Successful detection of interferometric fringes to all sites

Roadmap of the EHT

2008 2013 2017

The 2017 EHT observations prompted a worldwide multiwavelength campaign

Two flares were detected during EHT observations with ALMA



Successful detection of interferometric fringes to all sites

Roadmap of the EHT

2008

- 1 GHz BW (4 Gb/s)
- 3 Stations
- ~4R_{Sch} structure in Sgr A*

2013

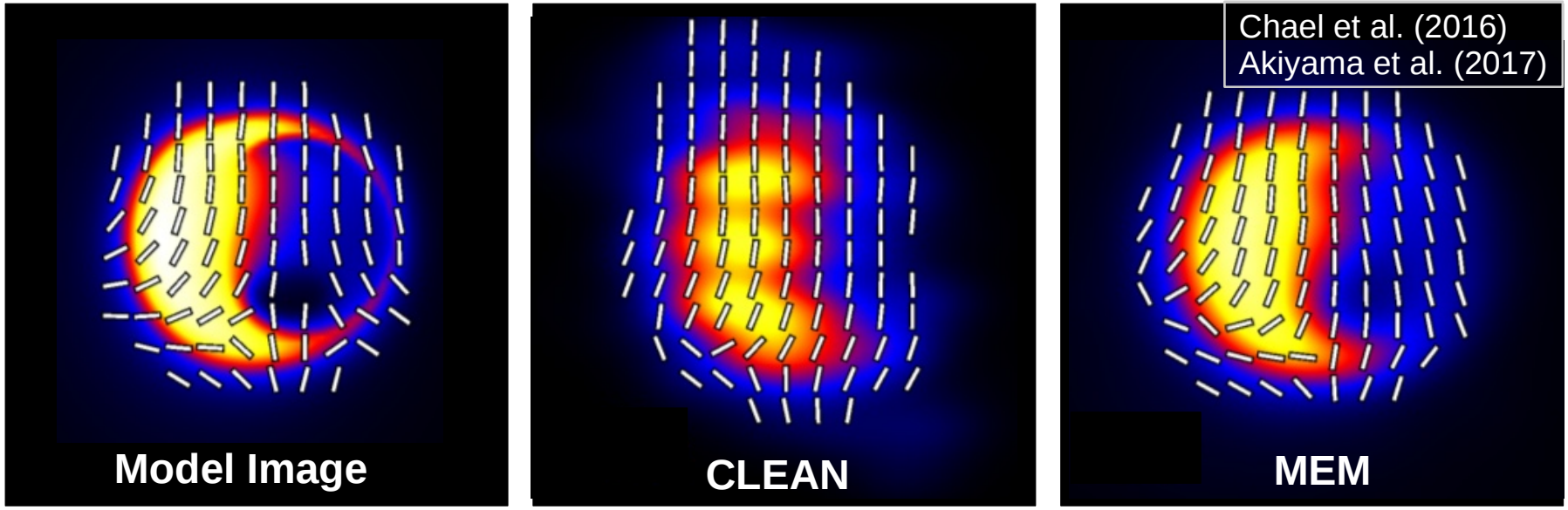
- Phased arrays
- Polarimetry
- Ordered fields near Sgr A*

2017

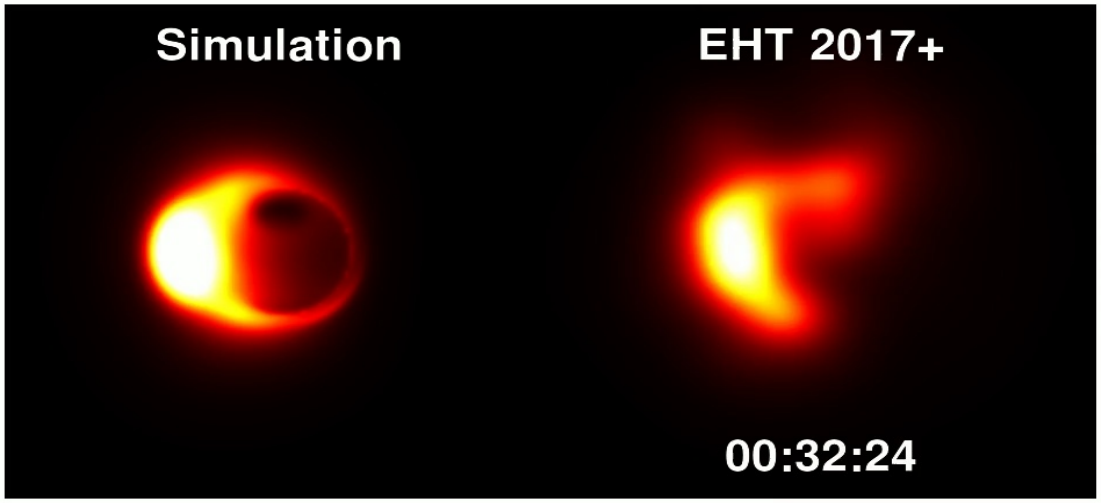
- 4 GHz BW (32 Gb/s)
- ALMA!
- Images of Sgr A* and M87

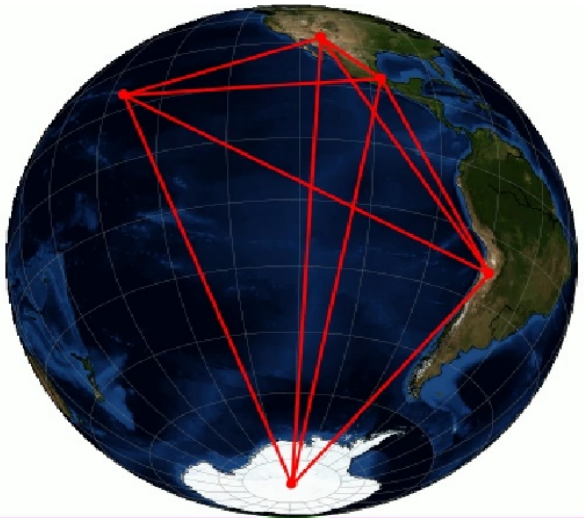
2018+

- 8 GHz BW (64 Gb/s)
- Sideband separation: 18 GHz spanned
- New sites: Greenland Telescope and Kitt Peak
- Extension to 345 GHz



Time Variability: Movies of a Black Hole





Earth-rotation synthesis is inapplicable for Sgr A*!

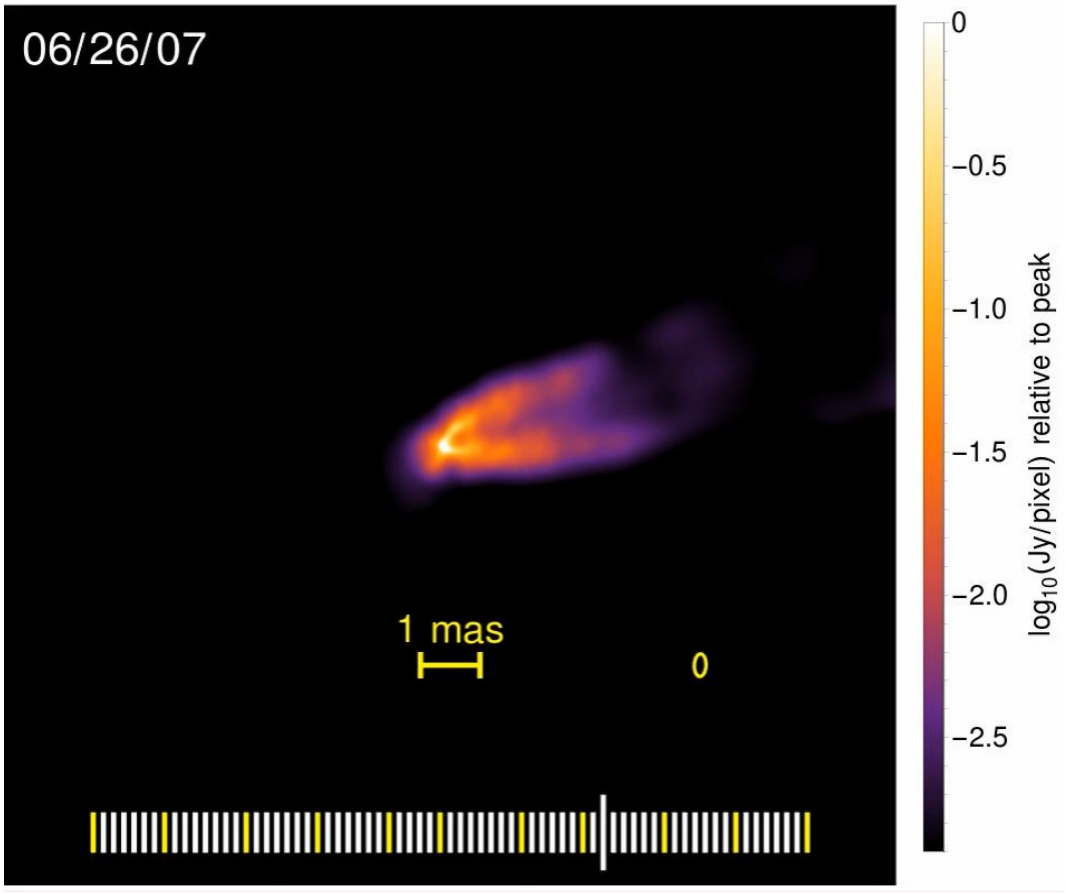
Simulation:

- An orbiting “hot spot” (Broderick & Loeb 2006)
- Earth rotates 7° per hot spot orbit (27 minutes)

Reconstruction:

- Assumes the sites and sensitivities of the expected 2017 EHT
- Snapshot images (~1 minute of data per frame)
- An entire movie is reconstructed, favoring frame-to-frame continuity

7mm VLBA Observations of M87



Computing Time: ~hours

Framework is flexible

- Irregularly spaced obs.
- Inhomogeneous beam

A calibration/imaging framework

Results can be post-processed; e.g., wavelet analyses (Mertens & Lobanov 2015)

← Equivalent to ~3-hr for Sgr A*

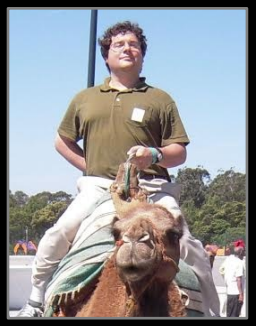
with **Craig Walker**, Andrew Chael, Katie Bouman, Lindy Blackburn, Shep Doeleman

Data: Walker+ (2016, 2017)

The EHT Collaboration

Shep Doeleman
(EHT Director)

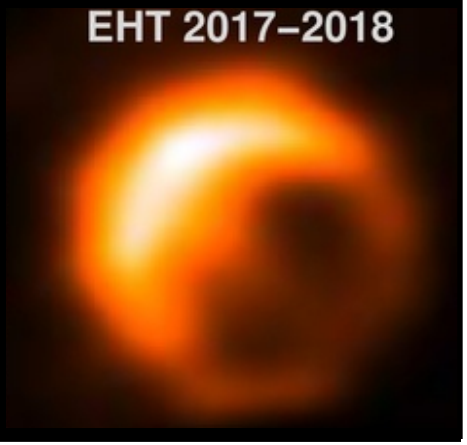
Dimitrios Psaltis
(Project Scientist)



Vincent Fish
(Research Scientist)

Geoff Crew
(APP Software Lead)

Kazu Akiyama
(Jansky Fellow)



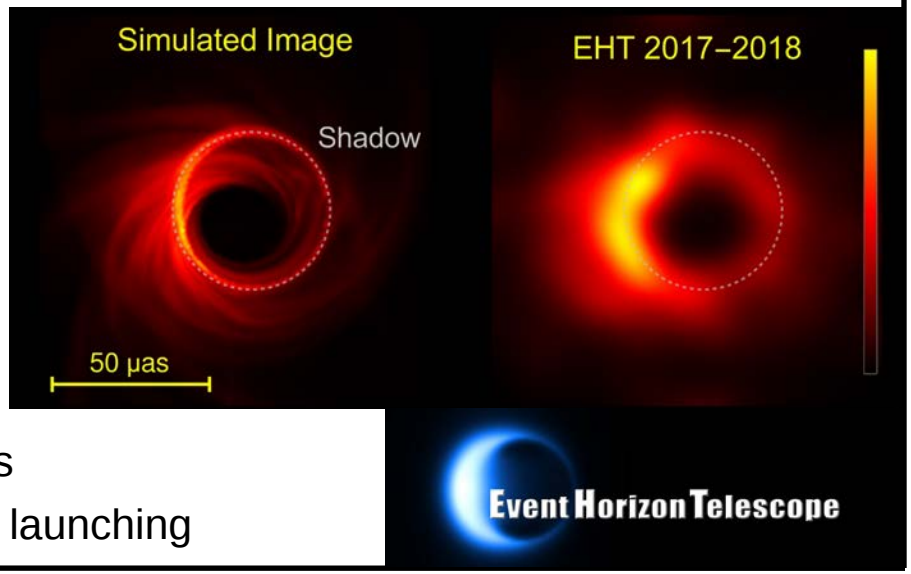
Summary

The EHT is now enabling science that requires horizon-scale observations

Past discoveries include:

- Compact structure in Sgr A* and M87, only ~5 Schwarzschild radii in size
- Persistent complex structure over several years
- Ordered magnetic fields near the event horizon

2017 observations with EHT+ALMA are expected to lead to the first **EHT images** of Sgr A*, M87, and many other targets (e.g., 3C279 and OJ287)



Continued EHT Expansion will enable:

- Imaging at 230 & 345 GHz
- New sites (GLT, KP, and more)
- Triggered observing
- Tests of the no-hair theorem
- Polarimetric and RM images of black holes
- Movies of flares, steady dynamics, and jet launching