Smithsonian Astrophysical Observatory

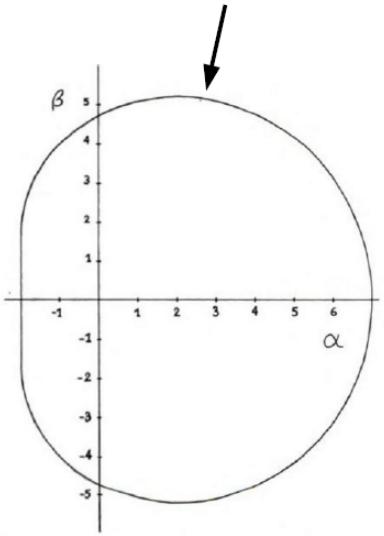
Connecting Blazar Kinematics to Supermassive Black Holes: Dynamical Imaging with the Event Horizon Telescope

Michael Johnson (CfA)
with Katie Bouman, Andrew Chael, Lindy Blackburn, Craig Walker, Daniel Palumbo, Maciek Wielgus, Shep Doeleman, Kazu Akiyama, Alan Marscher, Svetlana Jorstad, and the EHT Imaging Working Group

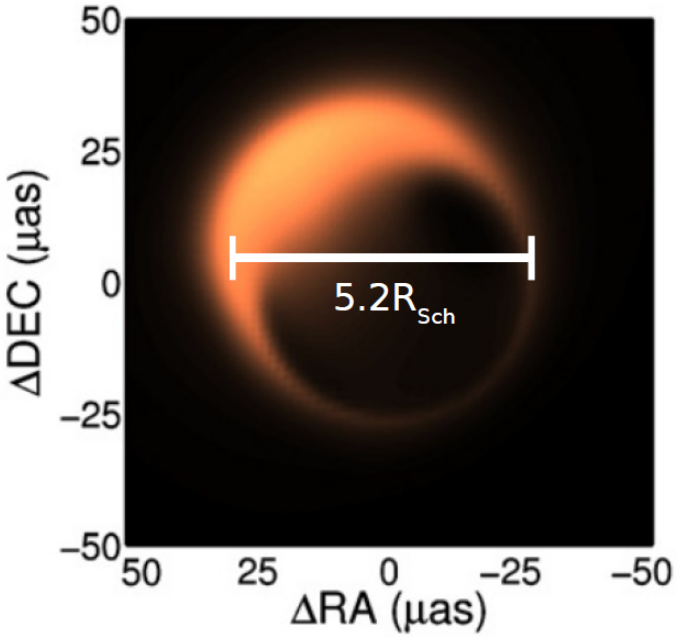
Half a Century of Blazars and Beyond
June 11, 2018

The Image of a Black Hole

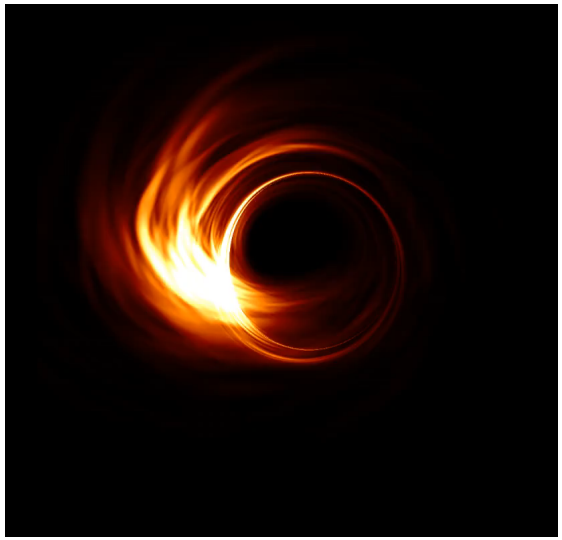
The black hole “shadow”
Changes by only ±4% with BH spin



Bardeen (1973)



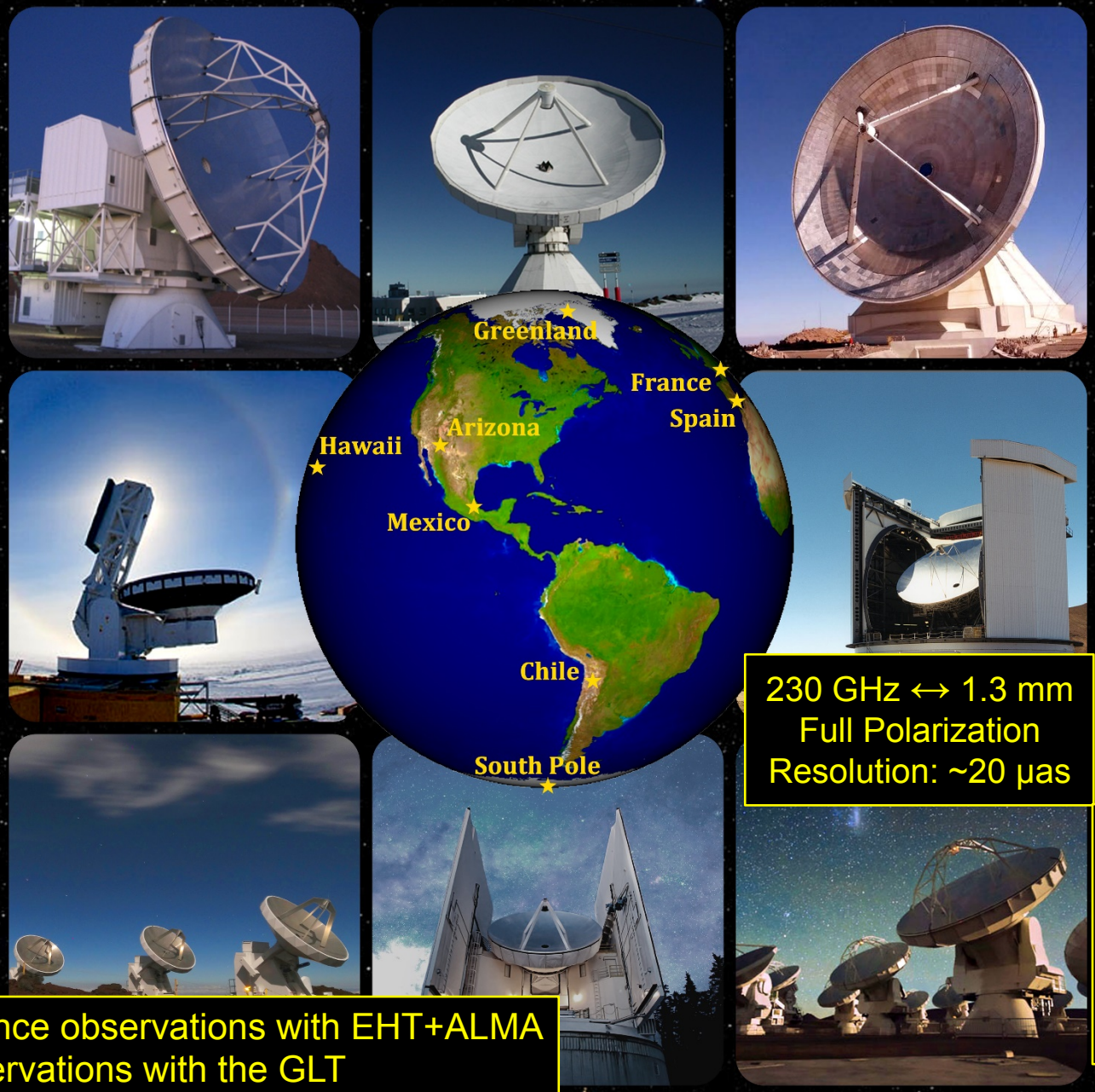
Broderick et al. (2011)



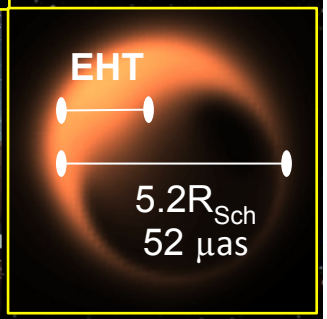
H. Shiokawa

“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



2017: First science observations with EHT+ALMA
2018: First observations with the GLT

Roadmap of the EHT

2008

- 1 GHz BW (4 Gb/s)
- 3 Stations
- Horizon-scale structure

2013

- Phased arrays
- Polarimetry
- Ordered magnetic fields

2017

- 4 GHz BW (32 Gb/s)
- 8 Stations (incl. ALMA)
- 10x sensitivity increase

Roadmap of the EHT

2008

- 1 GHz BW (4 Gb/s)
- 3 Stations
- Horizon-scale structure

2013

- Phased arrays
- Polarimetry
- Ordered magnetic fields

2017

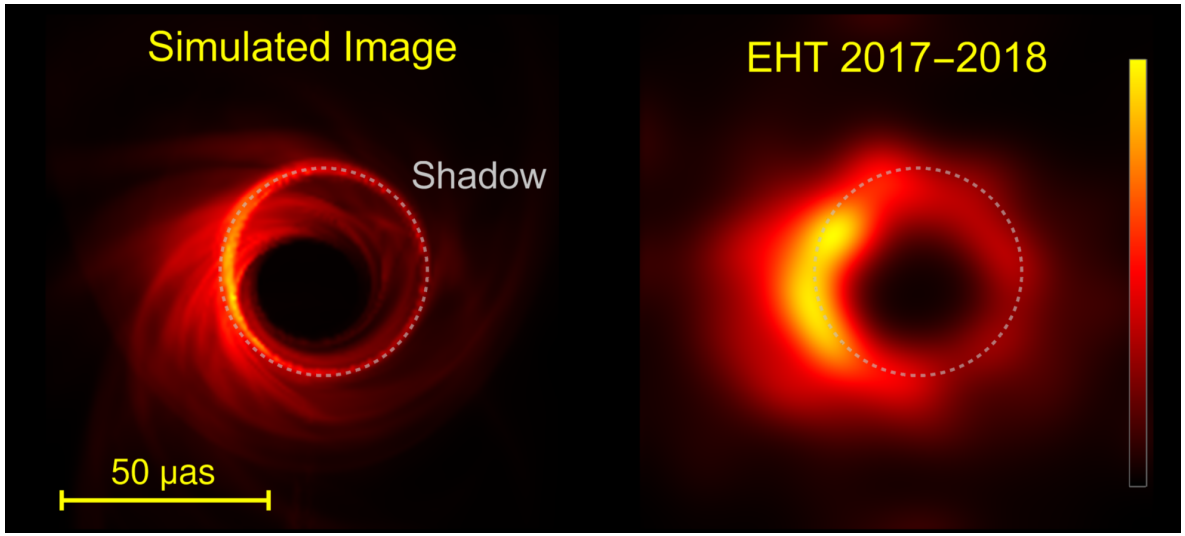
- 4 GHz BW (32 Gb/s)
- 8 Stations (incl. ALMA)
- 10x sensitivity increase

In 2017: 5 observing nights, 80 hours observing, 18 different sources

Excellent weather and performance at all sites

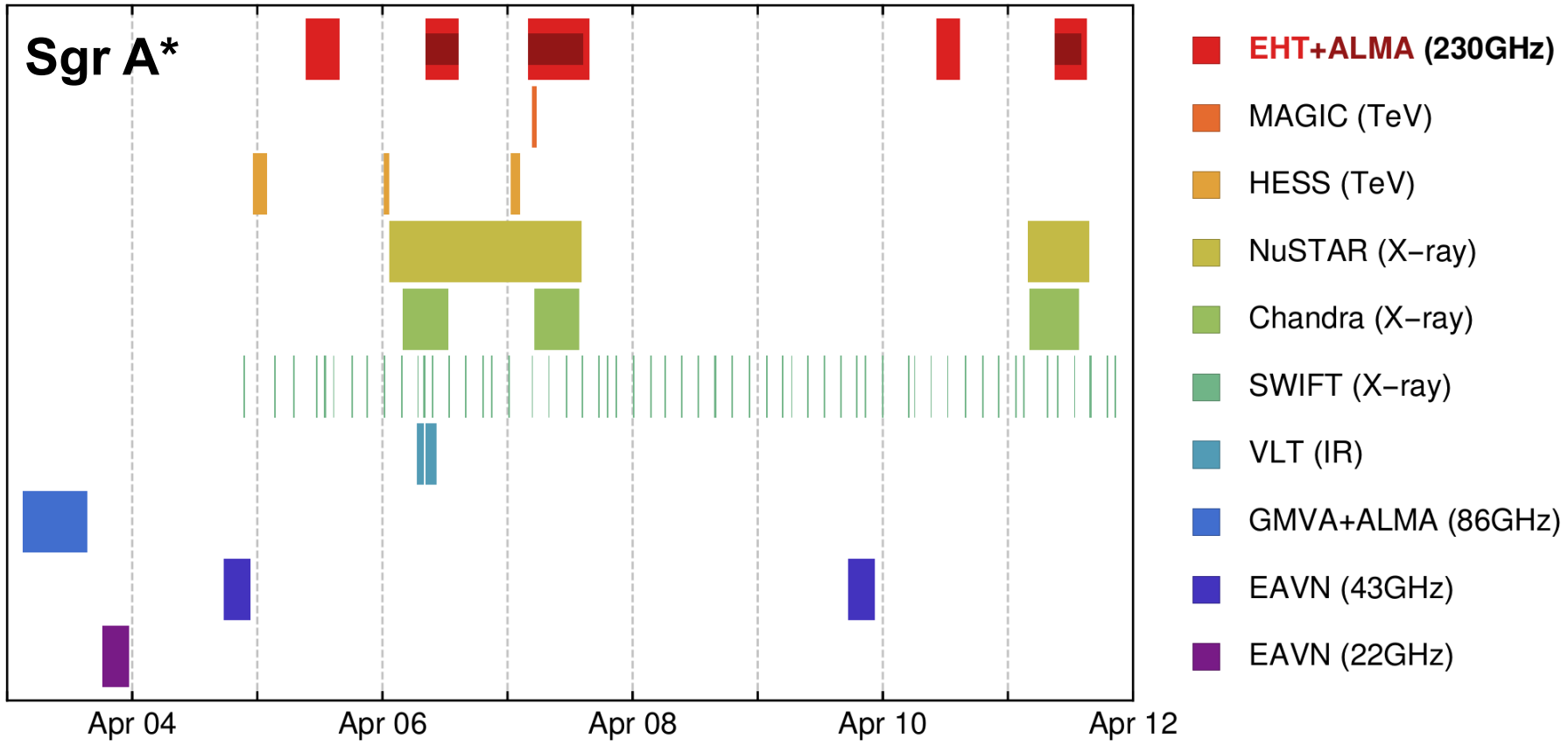
In 2018: BW again doubled (64 Gb/s) with sideband separation; GLT joined

Data analysis and imaging is ongoing!



Flares of Sgr A* in 2017

The 2017 EHT observations prompted a worldwide multi-wavelength campaign

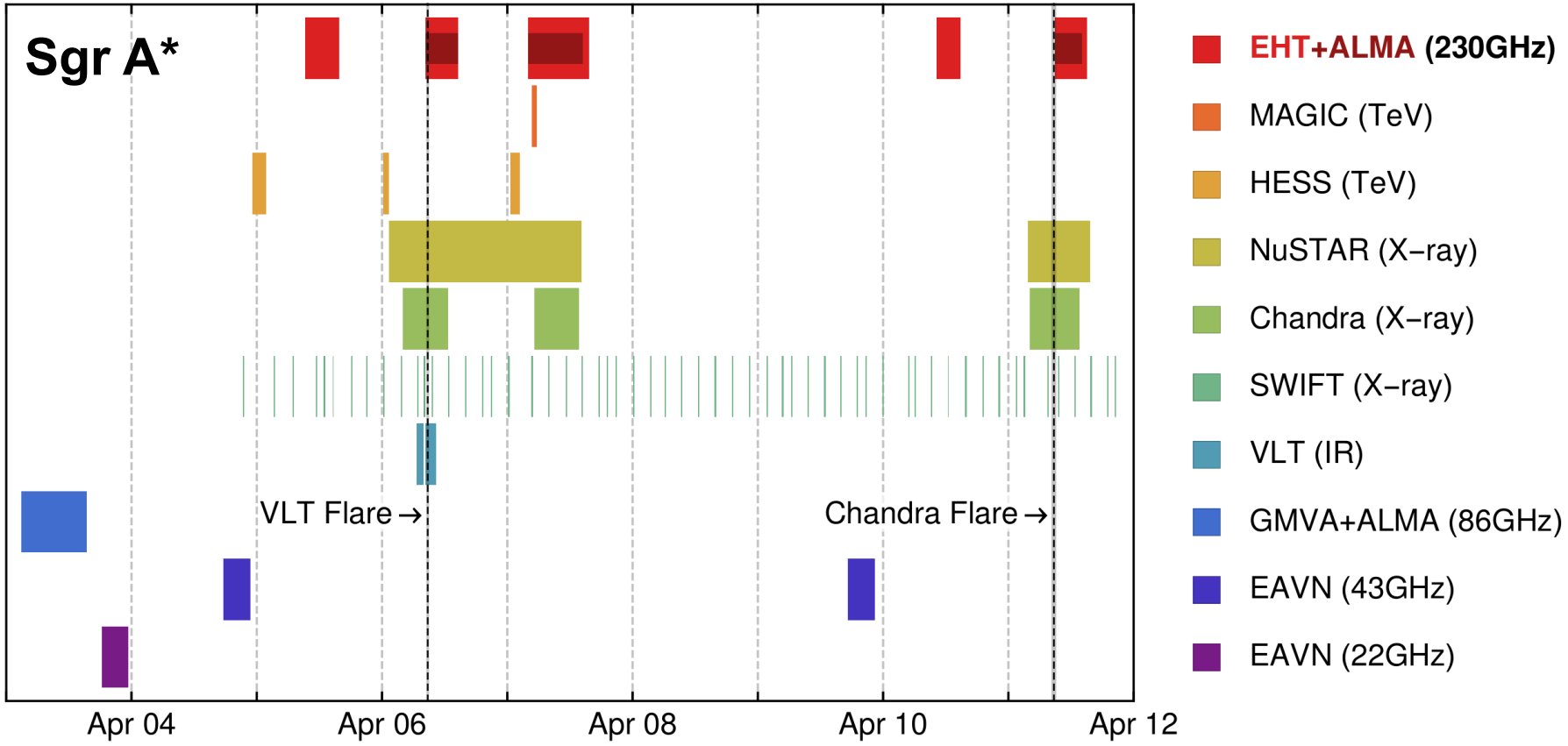


EHT Multiwavelength Working Group

Flares of Sgr A* in 2017

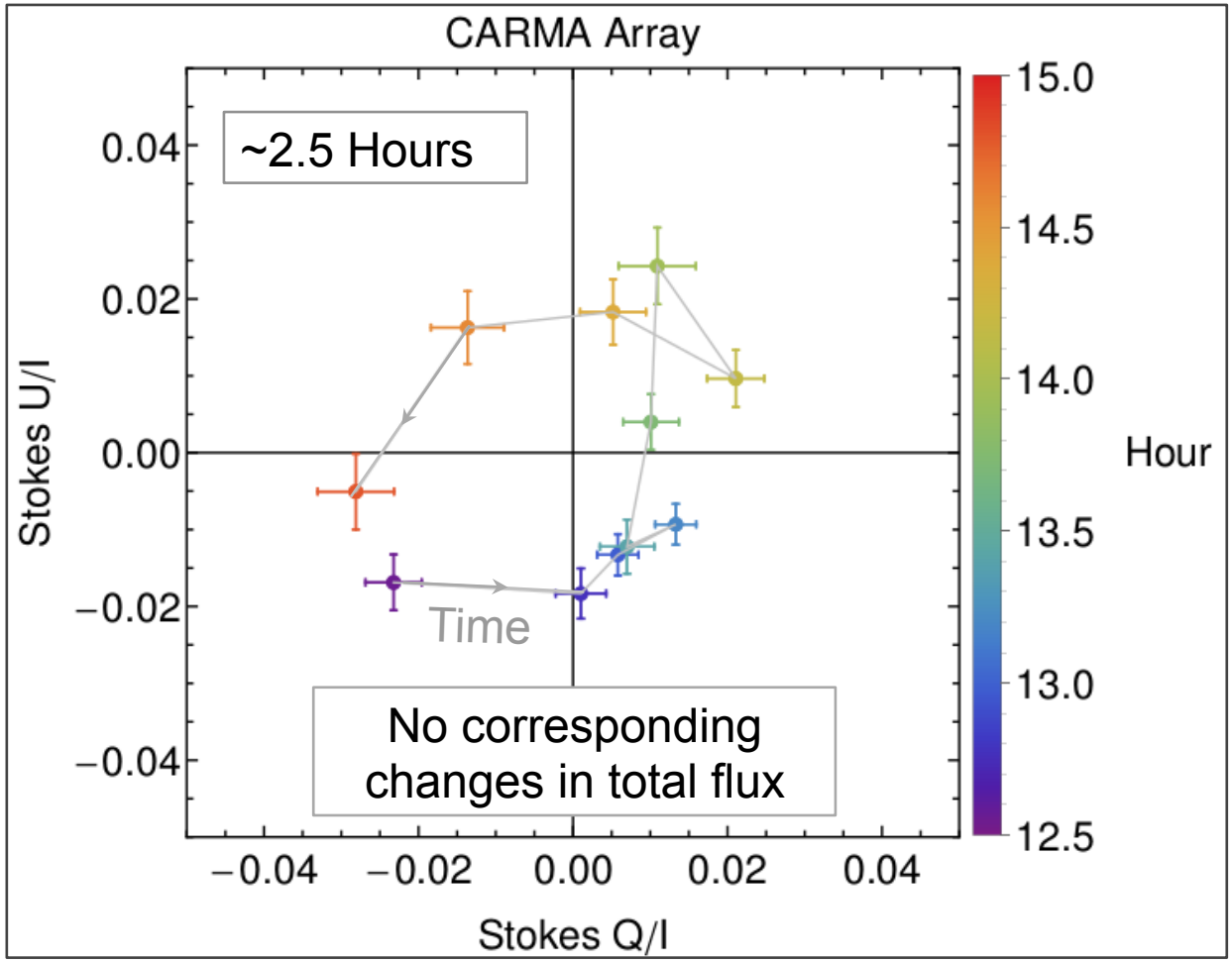
The 2017 EHT observations prompted a worldwide multi-wavelength campaign

Two flares were detected **during** EHT observations



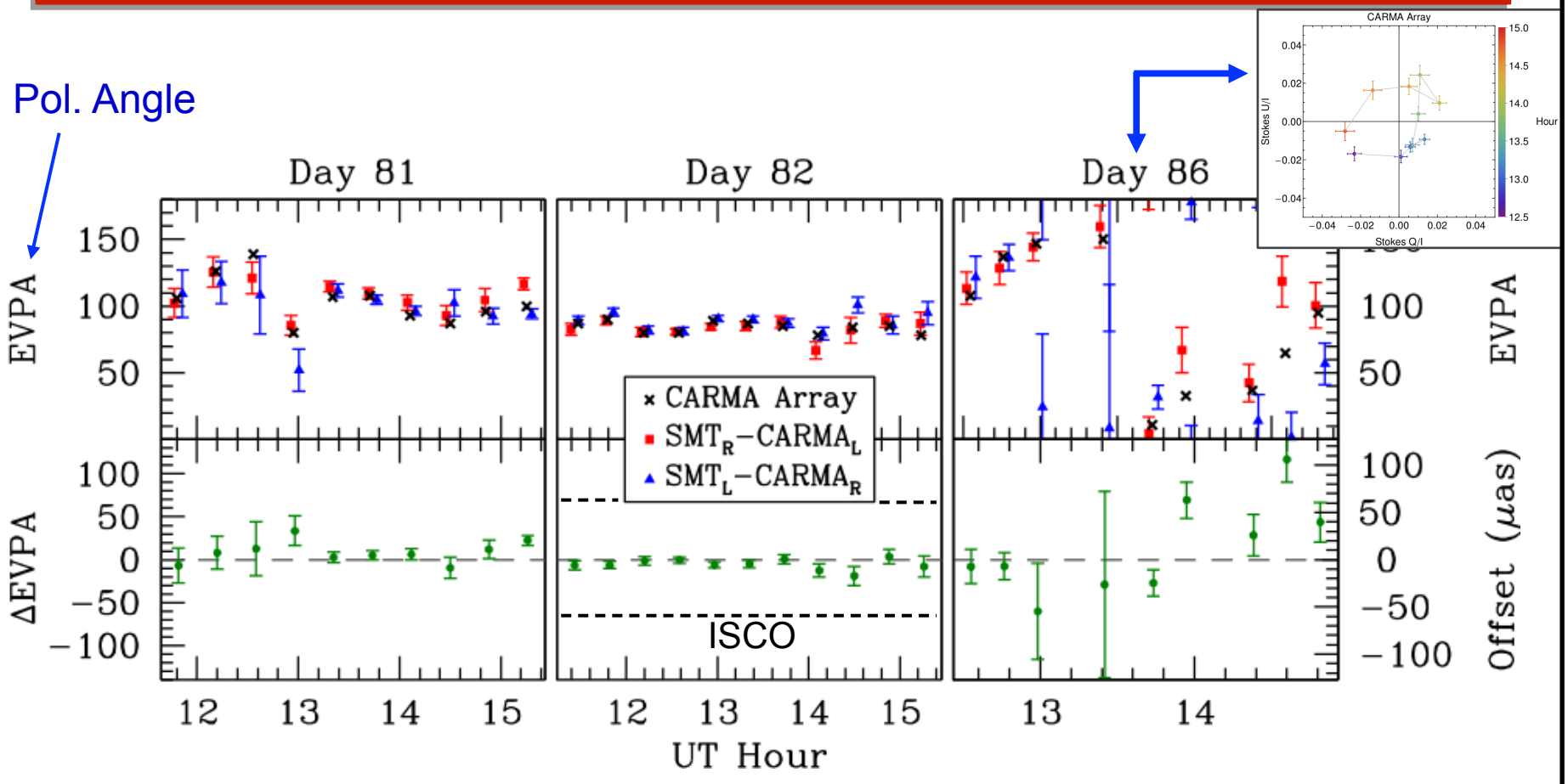
EHT Multiwavelength Working Group

Time Variability of Sgr A*



see also: Marrone et al. (2007), Fish et al. (2009)

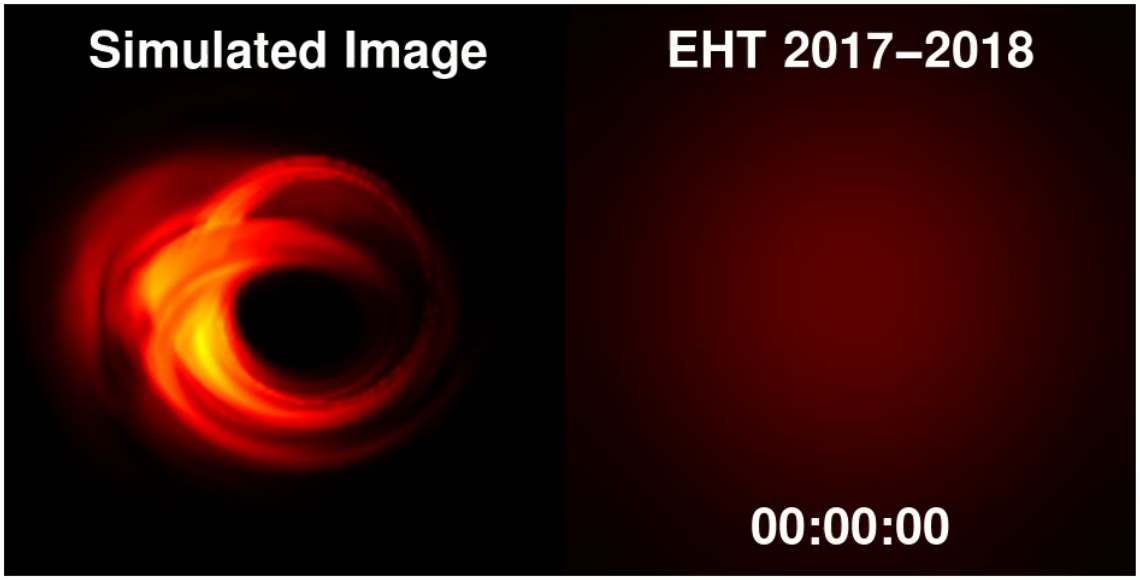
Tracking Dynamical Activity of Sgr A*

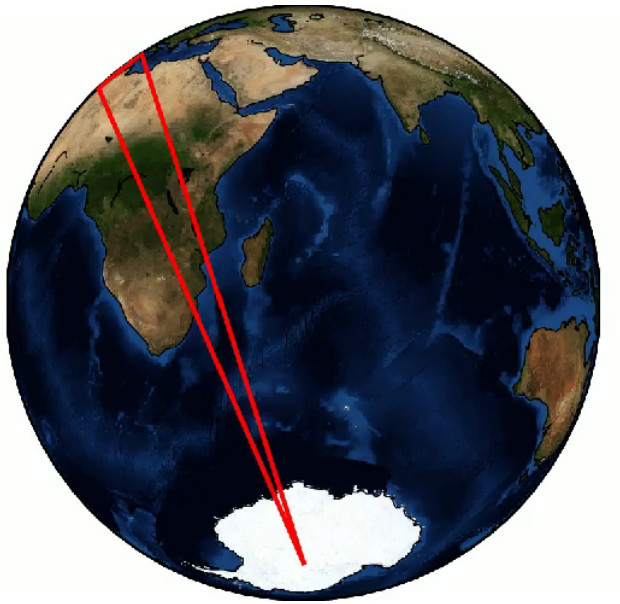


EHT observations show that polarimetric variability in Sgr A* occurs near the black hole and has associated centroid wobble

Johnson et al. (2015)

EHT Imaging



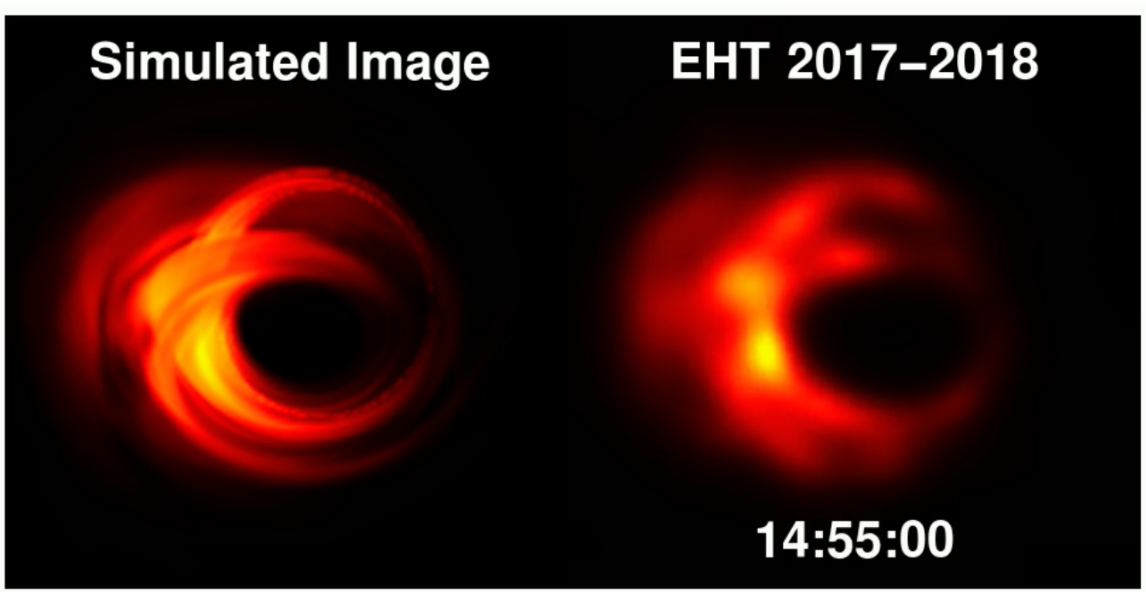


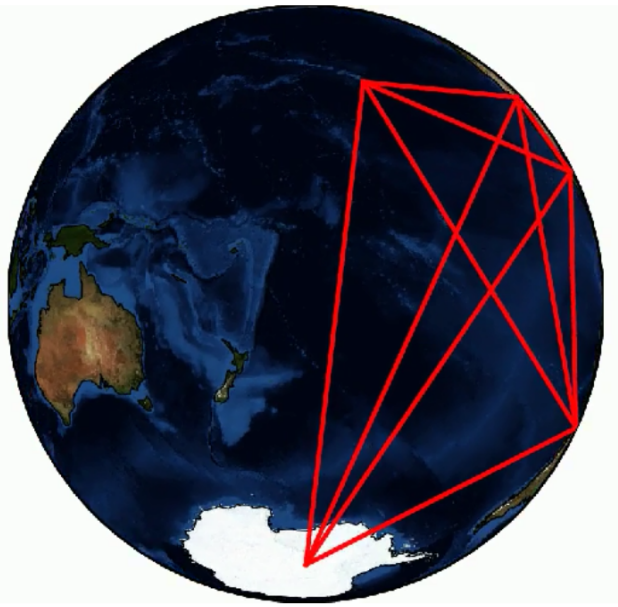
To improve sampling without adding sites, VLBI uses the rotation of the Earth

Projected baselines evolve with rotation, sampling a range of frequencies

The full accumulated coverage is critical for sparse arrays (e.g., the EHT)

EHT Imaging





Earth rotation synthesis assumes that the image is static

- This assumption is unreasonable for Sgr A* (ISCO periods are 4-30 minutes).
- M87 evolves more slowly (ISCO periods are 4-30 days). Even so, a component traveling at ~2*c* would cross the EHT beam in a single day!

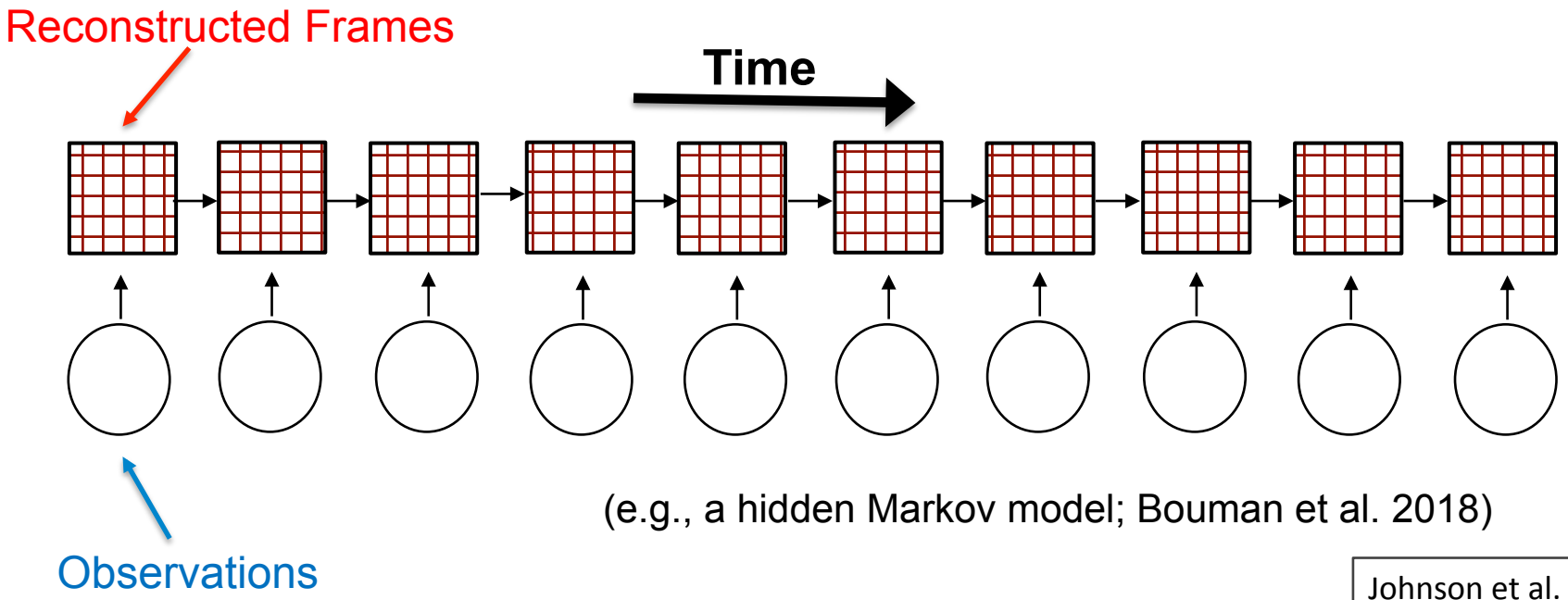
Dynamical Imaging

Basic Idea:

Images are nearby times are **not** independent. All frames should be simultaneously reconstructed with corresponding regularization.

Dynamical imaging strategies depend on the physical system. Options:

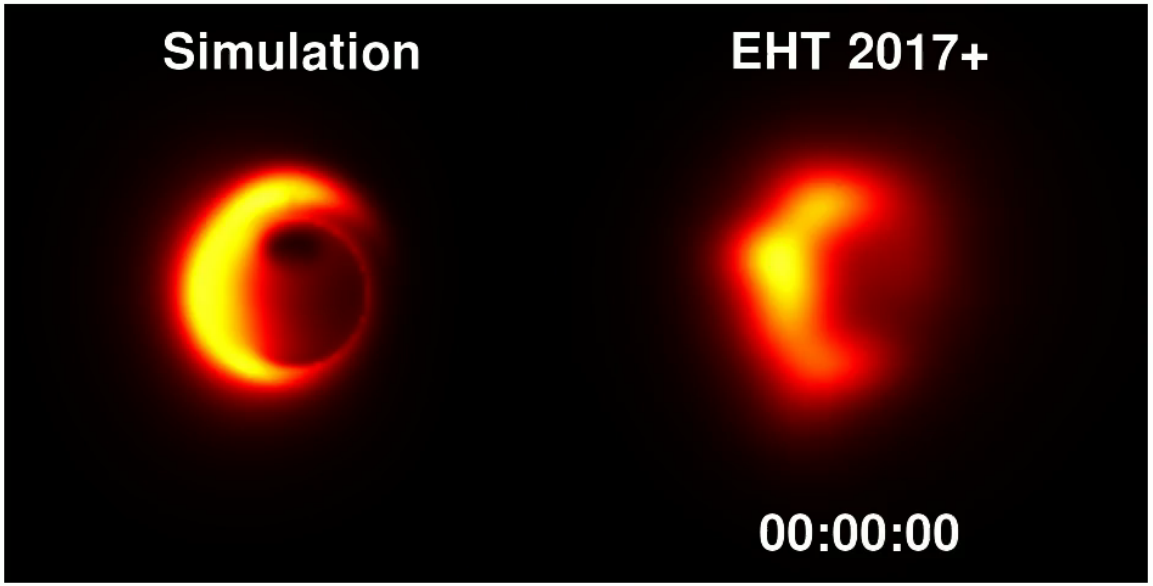
- Favor temporal continuity
- Favor stable average image
- Favor stable flow

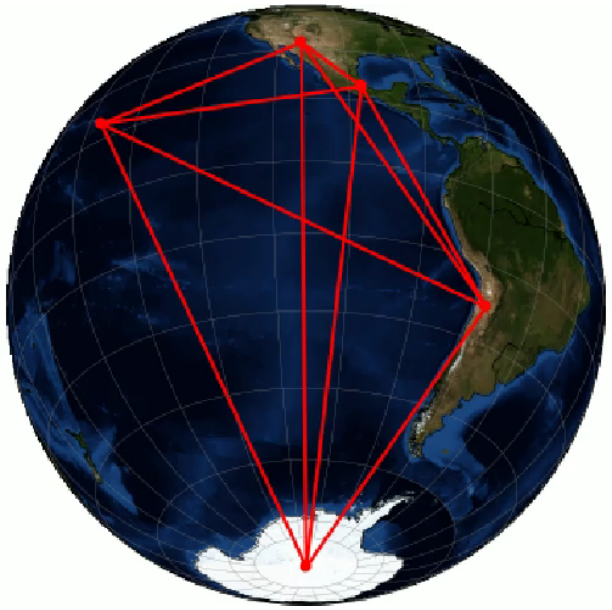


(e.g., a hidden Markov model; Bouman et al. 2018)

Johnson et al. (2017)

Dynamical Imaging





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

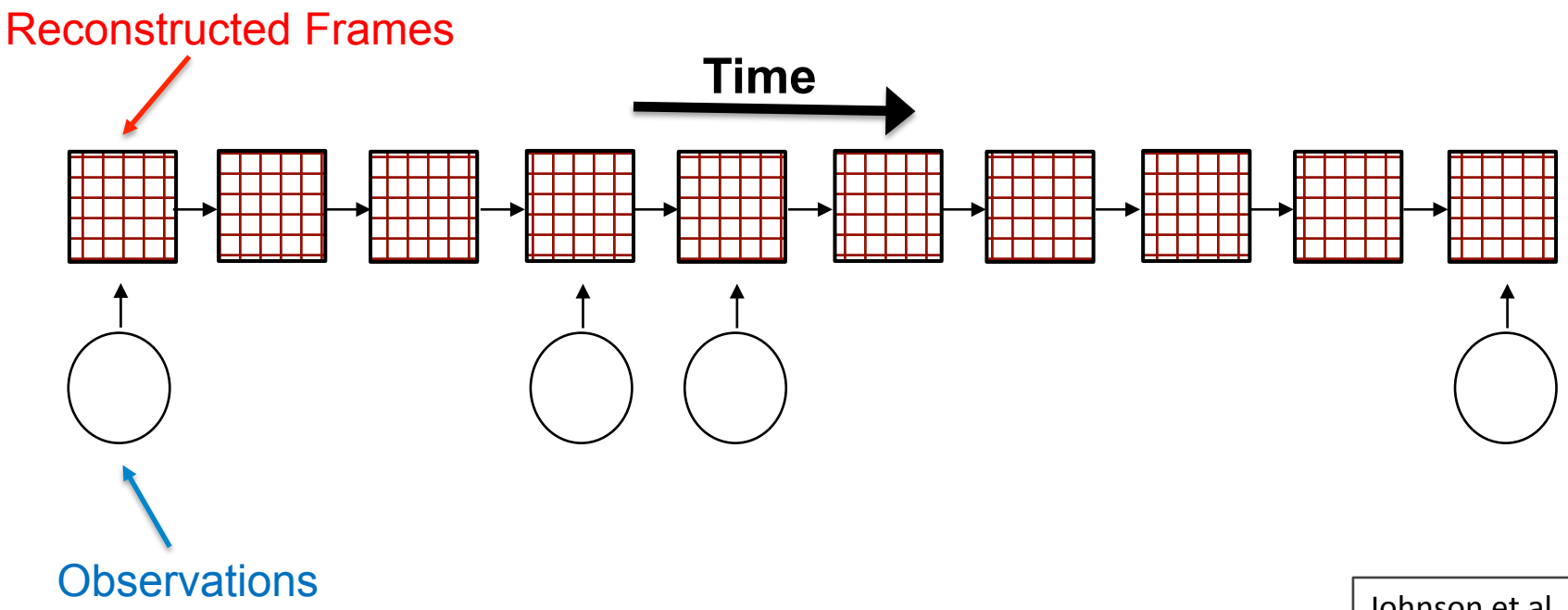
Johnson et al. (2017)

Dynamical Imaging and Interpolation

Dynamical imaging also provides a framework for temporal interpolation

Ideal for multi-epoch VLBI studies:

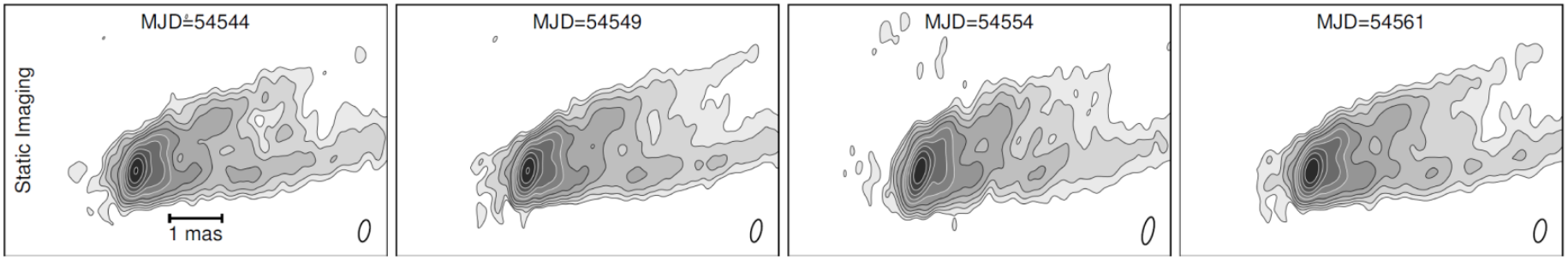
- Solves (including calibration) for a continuous series of images
- Data can be irregularly spaced in time
- Data can have inhomogeneous baseline coverage and quality



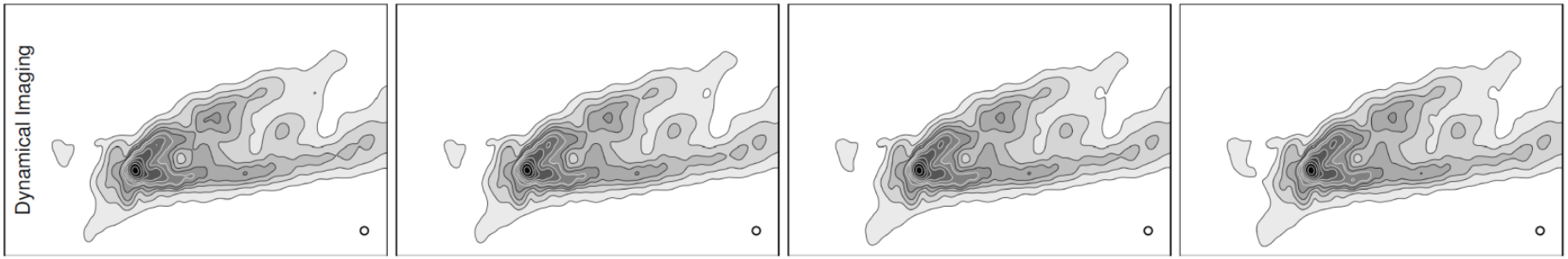
Johnson et al. (2017)

7mm VLBA Observations of M87

Standard Imaging Approach (independent static images with CLEAN)



Dynamical Imaging



17 Days

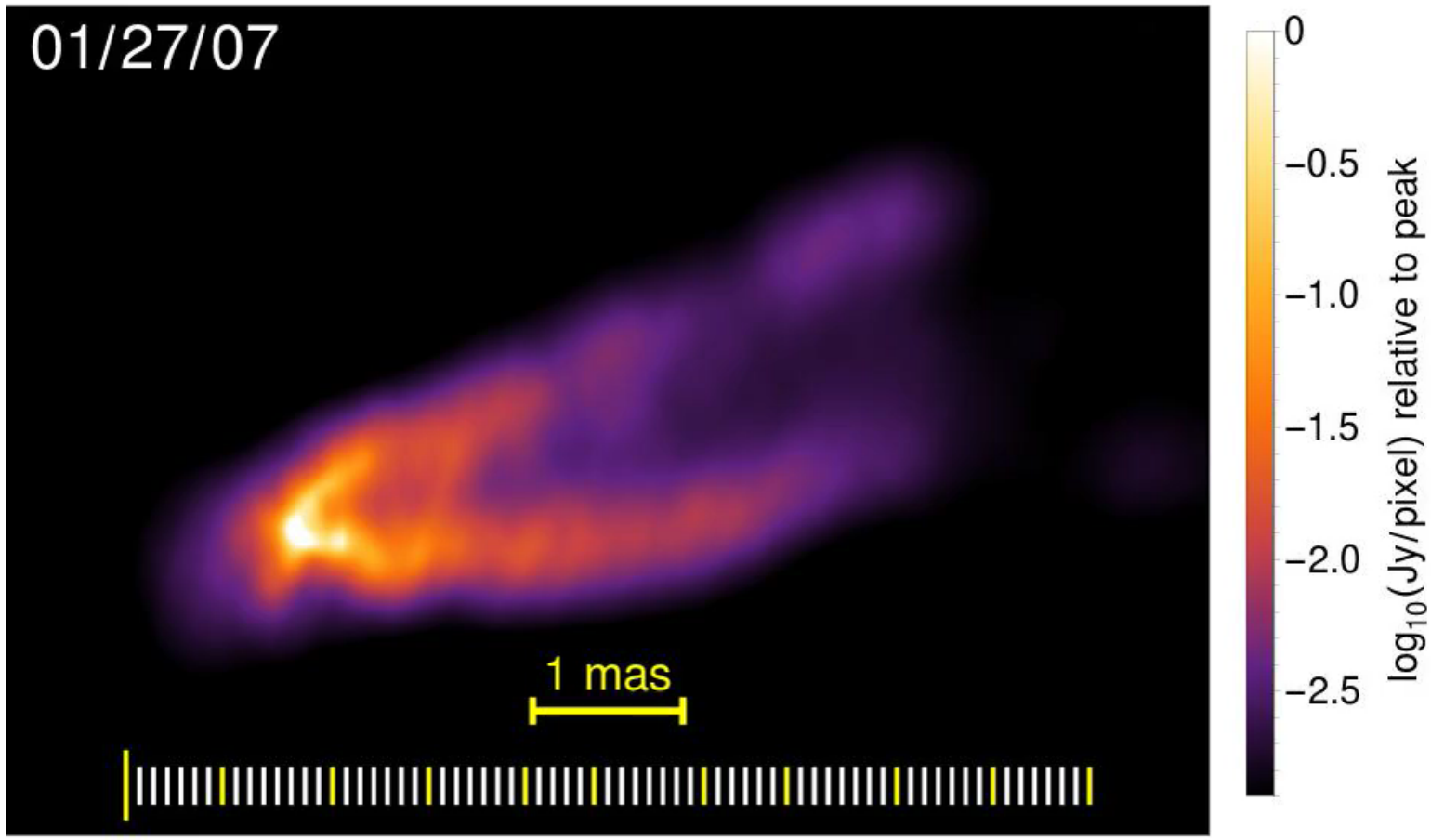
Observed every ~3 weeks in 2007 at 7mm (43 GHz) with the VLBA (Walker et al. 2016, 2018)

Dynamic scheduling – good data quality, but occasionally missing stations

Previous movies provided a “strong visual impression of motion”

Johnson et al. (2017)

7mm VLBA Observations of M87



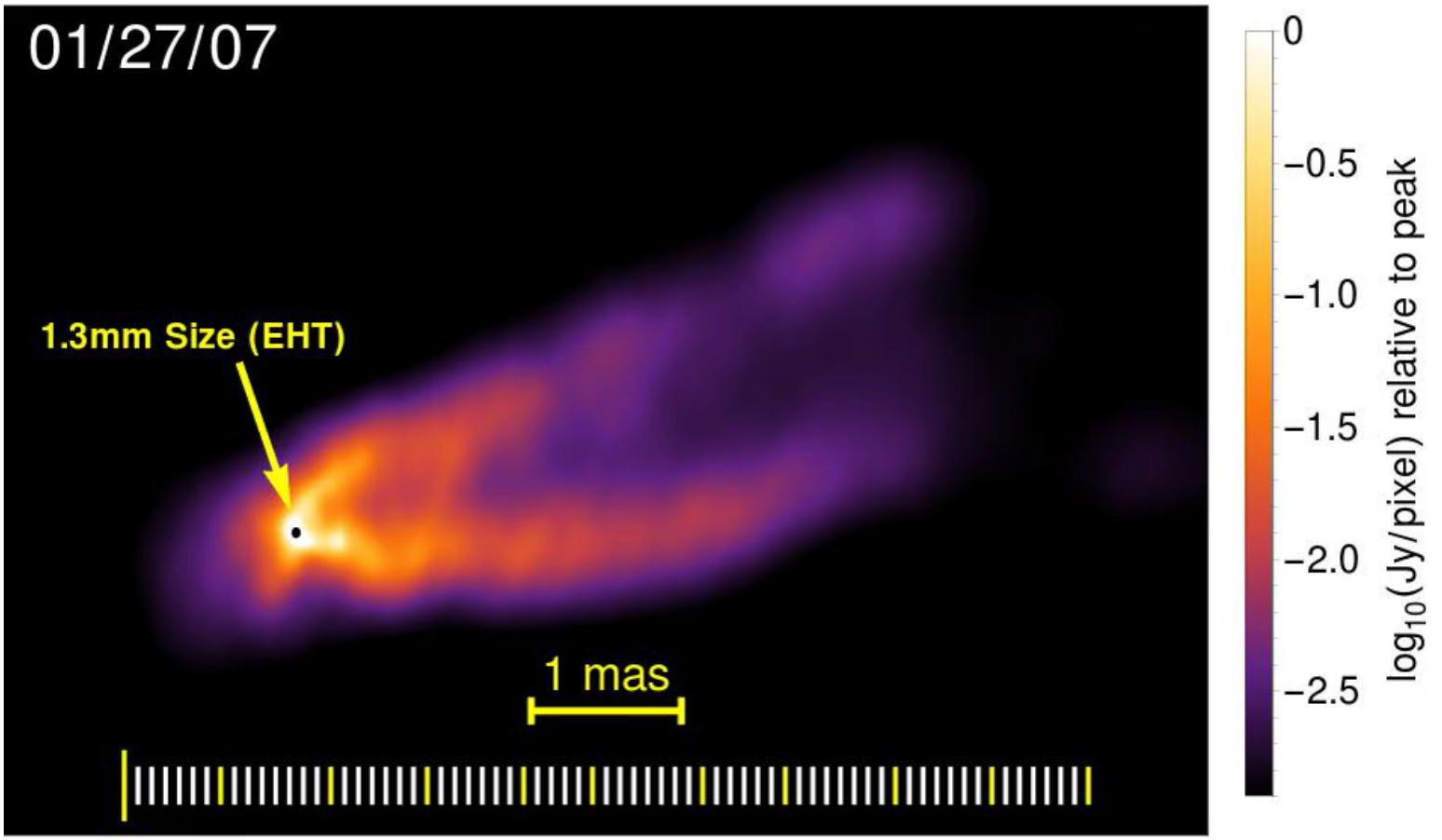
Observed every ~3 weeks in 2007 at 7mm (43 GHz) with the VLBA (Walker et al. 2016, 2018)

Dynamic scheduling – good data quality, but occasionally missing stations

Previous movies provided a “strong visual impression of motion”

Johnson et al. (2017)

7mm VLBA Observations of M87



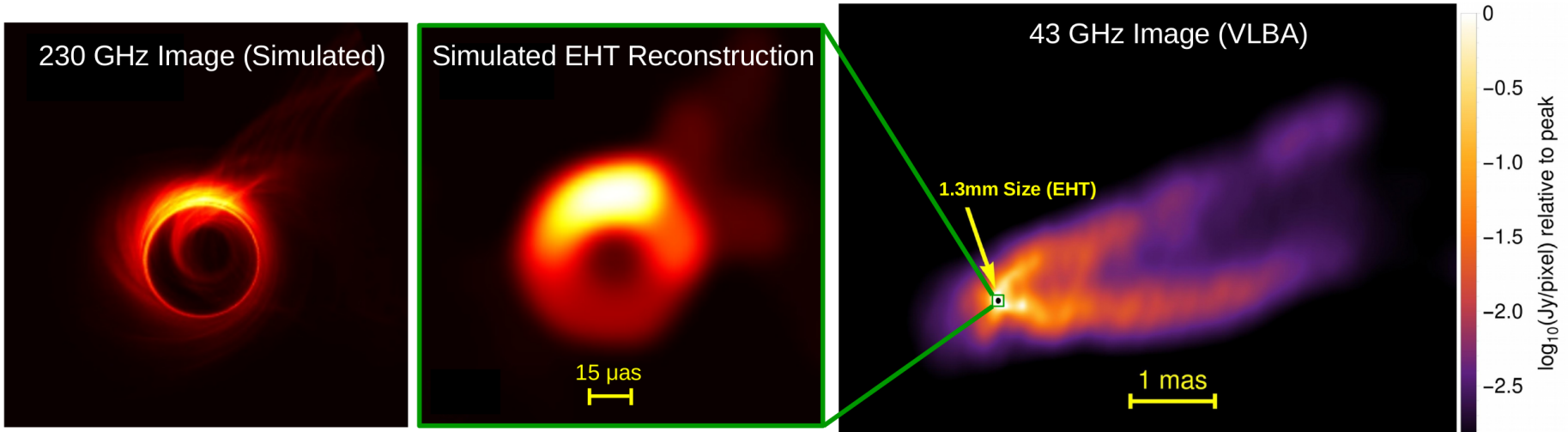
Observed every ~3 weeks in 2007 at 7mm (43 GHz) with the VLBA (Walker et al. 2016, 2018)

Dynamic scheduling – good data quality, but occasionally missing stations

Previous movies provided a “strong visual impression of motion”

Johnson et al. (2017)

7mm VLBA Observations of M87



Mościbrodzka et al. (2016) Akiyama et al. (2017)

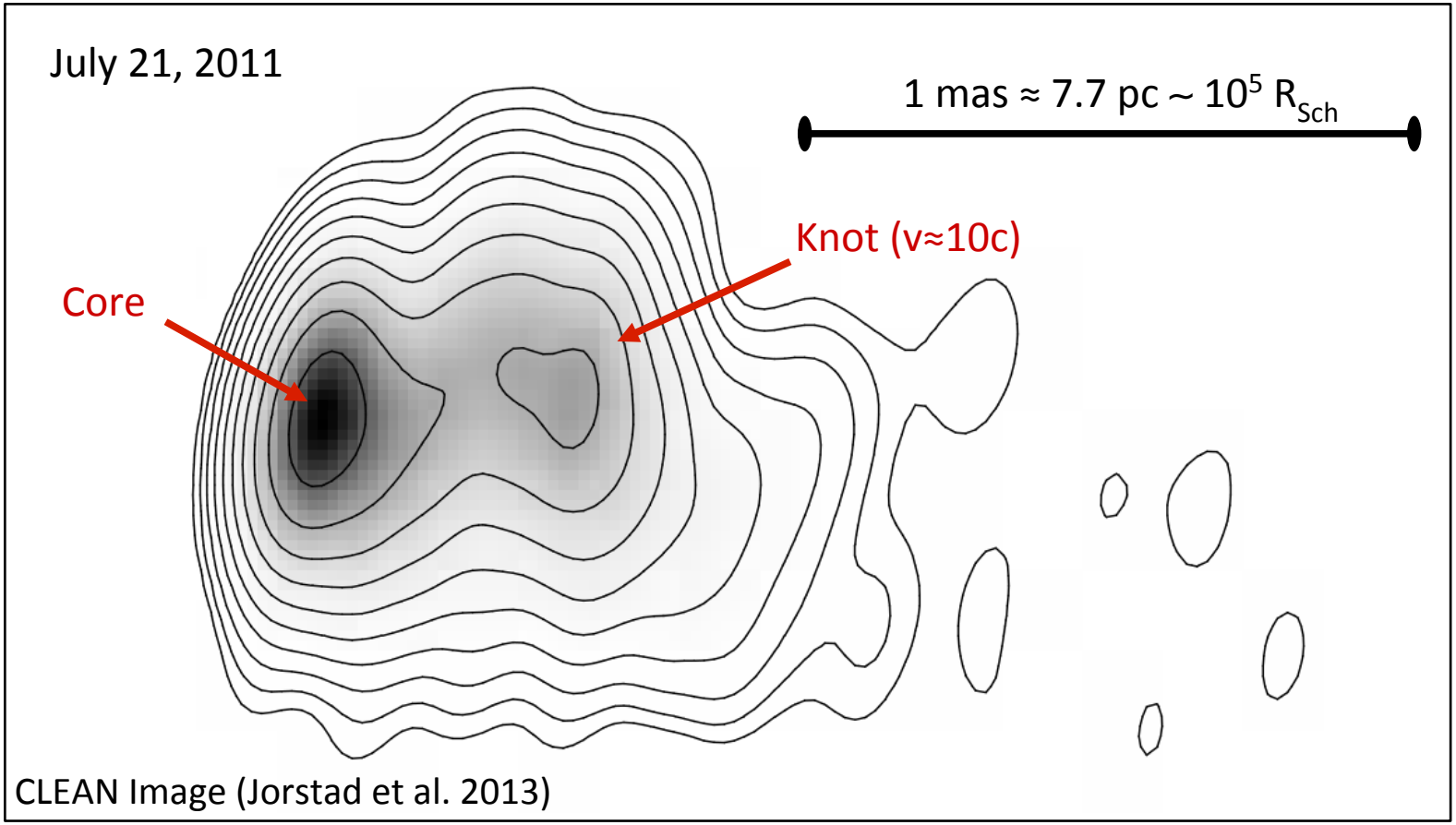
~7 months of observations of M87 are equivalent to **~3 hours** for Sgr A*

Imaging framework is flexible

- Irregularly spaced observations
- Inhomogeneous beam
- Suitable for black holes, blazars, microquasars, SNe

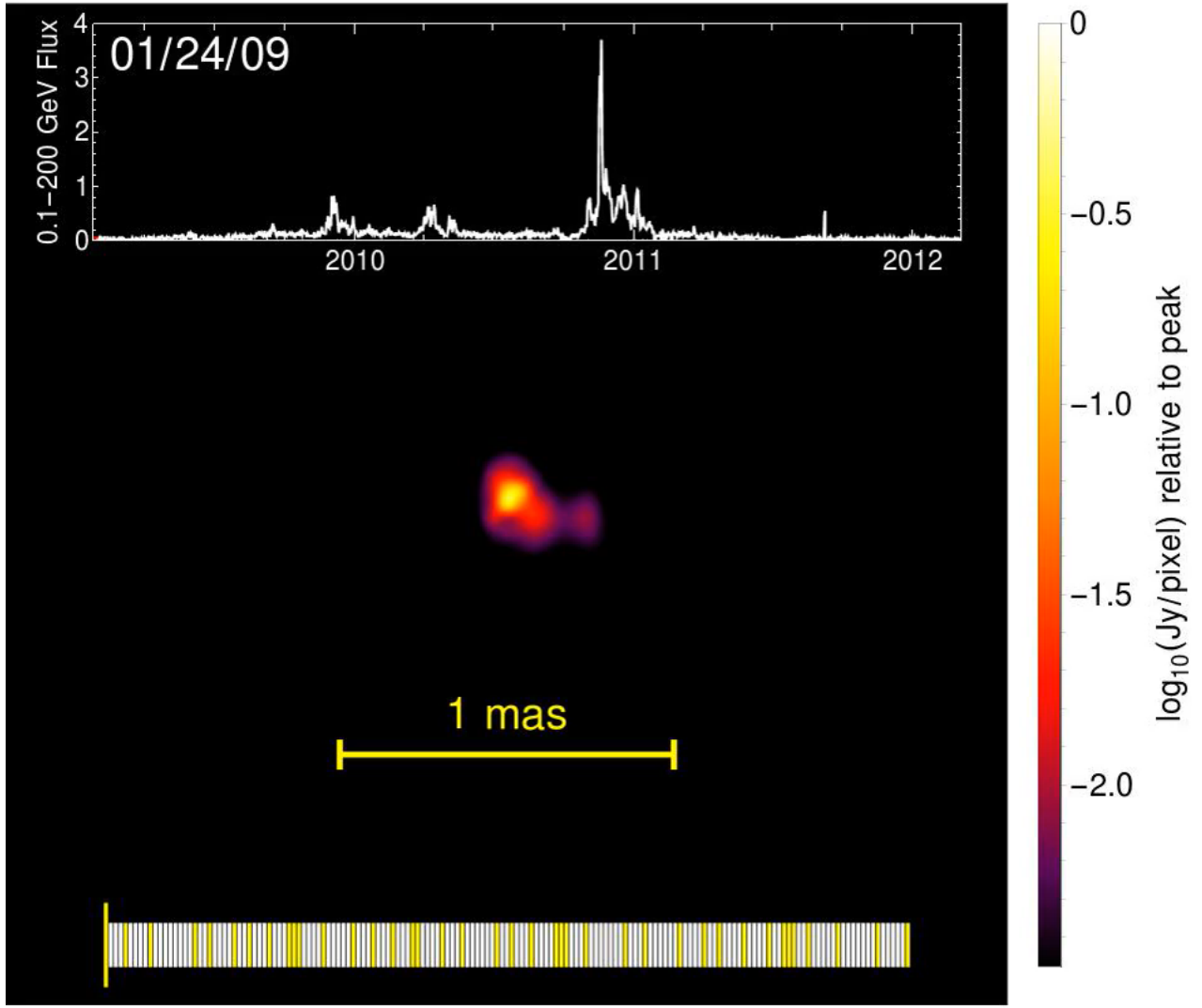
Results can be post-processed to analyze motion; e.g., w/ wavelets (Mertens & Lobanov 2015)

7mm Images of 3C454.3



- Blazar at z=0.859
- Bright in gamma rays. In 2010 November, 3C454.3 underwent a 5-day outburst.
- Reached apparent isotropic luminosity of ~ 10^{50} erg/s.

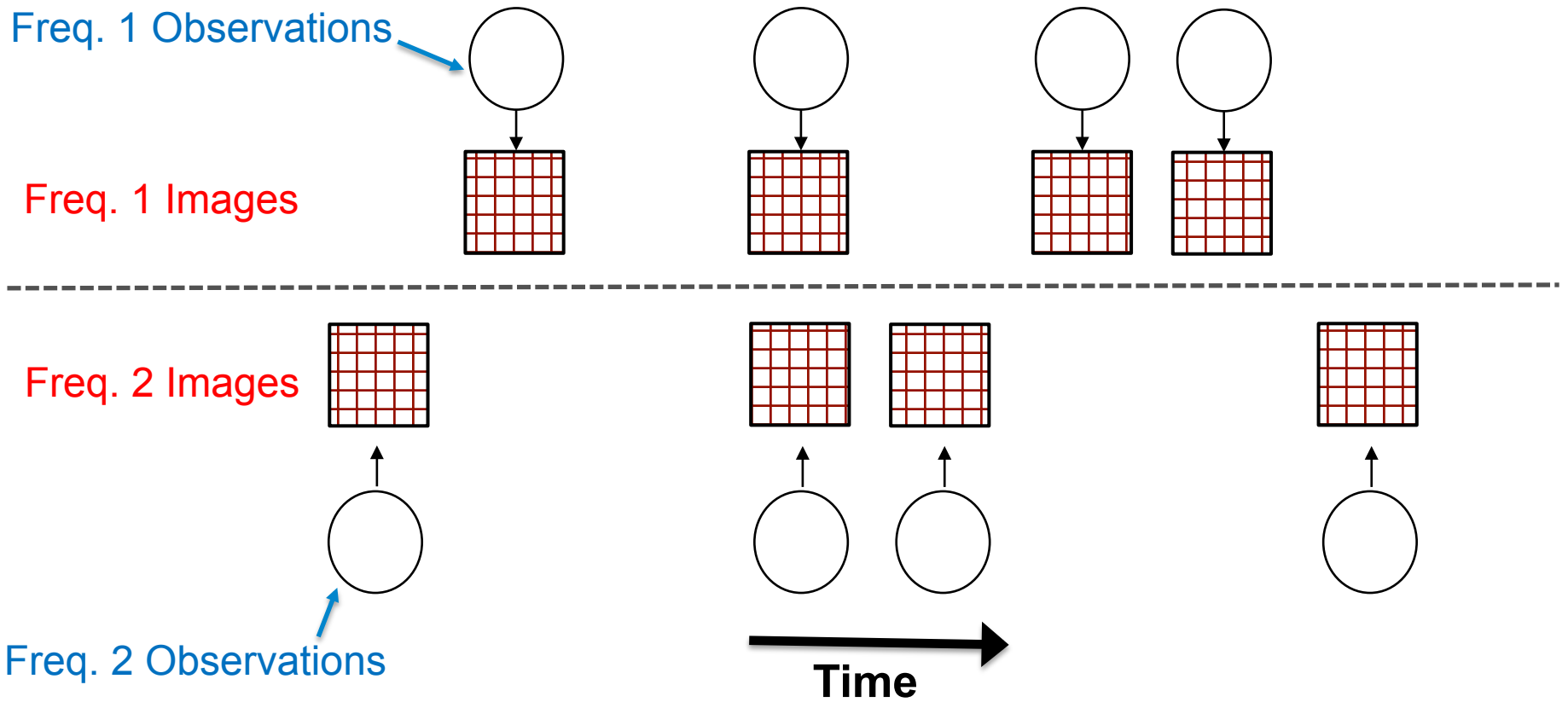
Dynamical Imaging of 3C454.3



Data: BU Blazar Group

Multi-Frequency Dynamical Imaging

Dynamical imaging can be extended to multi-frequency observations

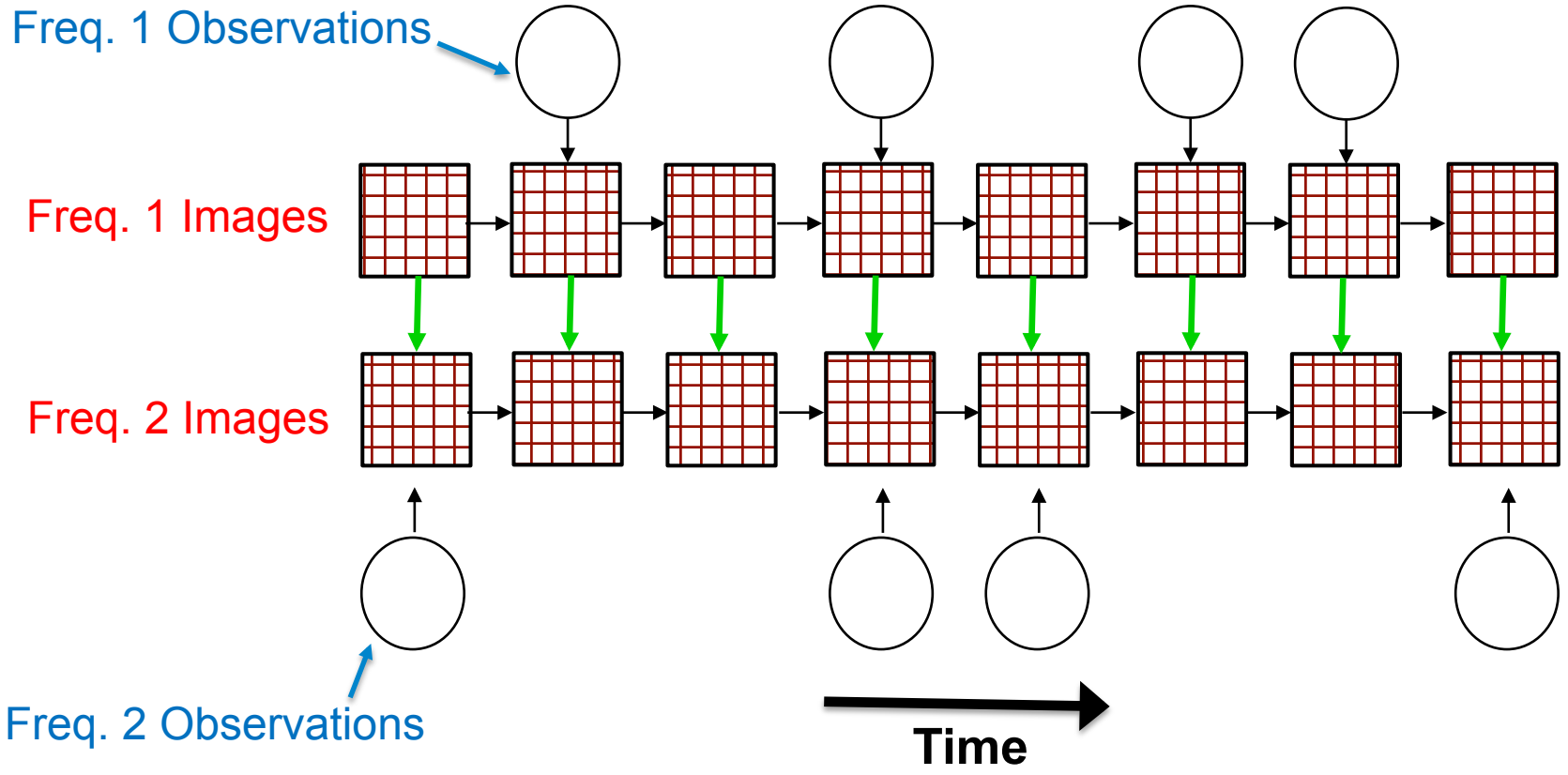


Multi-Frequency Dynamical Imaging

Dynamical imaging can be extended to multi-frequency observations

Idea: Enforce (approximate) spectral continuity in addition to temporal continuity

Ideal for multi-epoch VLBI monitoring studies (e.g., MOJAVE + BU + GMVA + EHT)

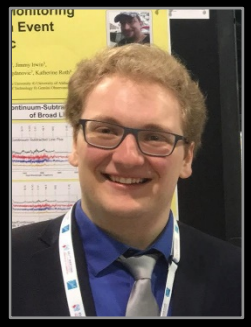


The EHT Collaboration

Katie Bouman
(EHT Postdoc)

Andrew Chael
(Harvard Grad Student)

Lindy Blackburn
(EHT Postdoc)



Daniel Palumbo
(Harvard Grad Student)

Shep Doeleman
(EHT Director)

Summary

2017 observations with EHT+ALMA are expected to lead to the first **EHT images** of Sgr A*, M87, and several other targets (e.g., 3C273, 3C279, and OJ287)

New VLBI imaging algorithms developed in response to challenges faced by the EHT may enrich blazar studies

EHT images probe strong gravity, black hole spin, and accretion dynamics with limited sensitivity to uncertain microphysics

Blazar and jet kinematics likewise provide insights that are not accessible from static images

Continued EHT expansion will enable:

- Images of the black hole shadow, testing the no-hair theorem
- Images of magnetic fields & Faraday rotation
- Movies:

  Flares (energy injection and dissipation)

  Accretion Dynamics (BH rotation curve and turbulence)

  Jet Launching ($\Omega^F=\Omega^H/2$)

All imaging code is available online: https://github.com/achael/eht-imaging