

Recovering Movies of Black Holes

(by expanding the Event Horizon Telescope to space)

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Caltech & Harvard-Smithsonian



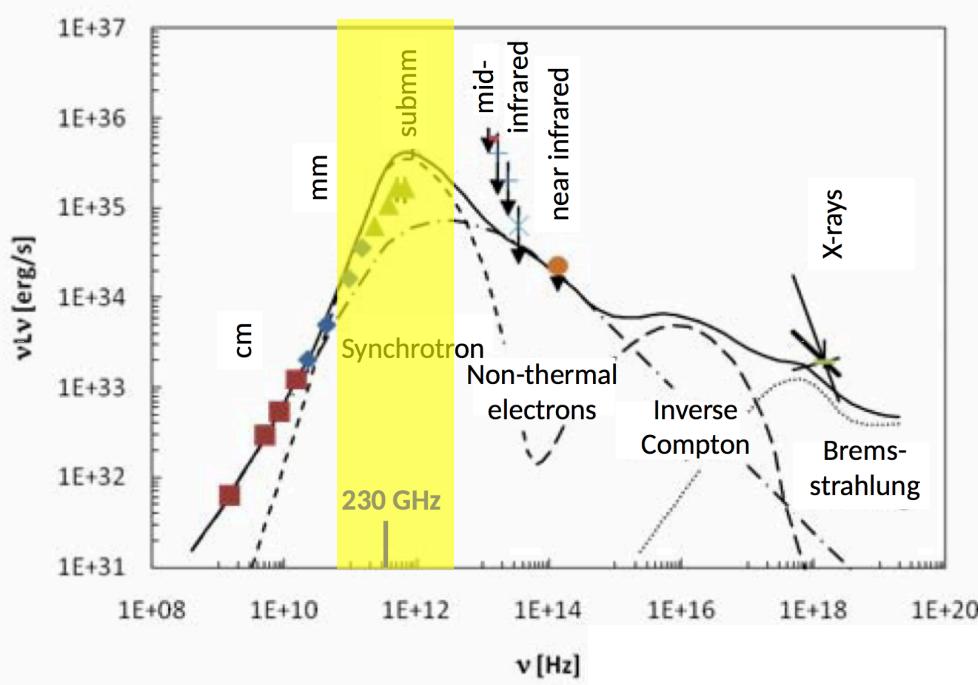
Joint work with: Michael Johnson (CFA), Daniel Palumbo (Harvard), Andrew Chael (Harvard), Sheperd Doeleman (CFA), Bill Freeman (MIT), Adrian Dalca (MiT), Freek Roelofs (Radboud), Vincent Fish (MIT), Kazu Akiyama (MIT), Joseph Lazio (JPL)



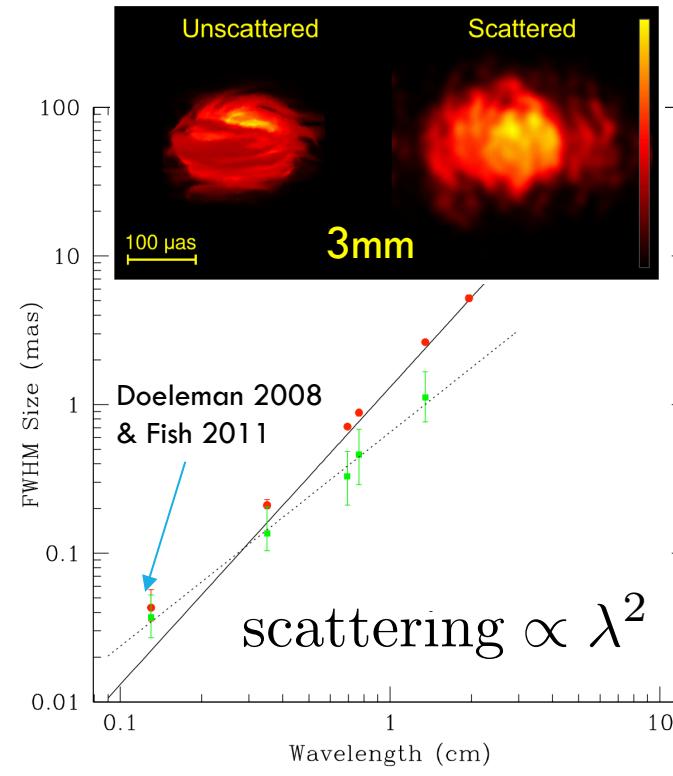
Simulation of SgrA*

Photo courtesy of Hotaka Shiokawa

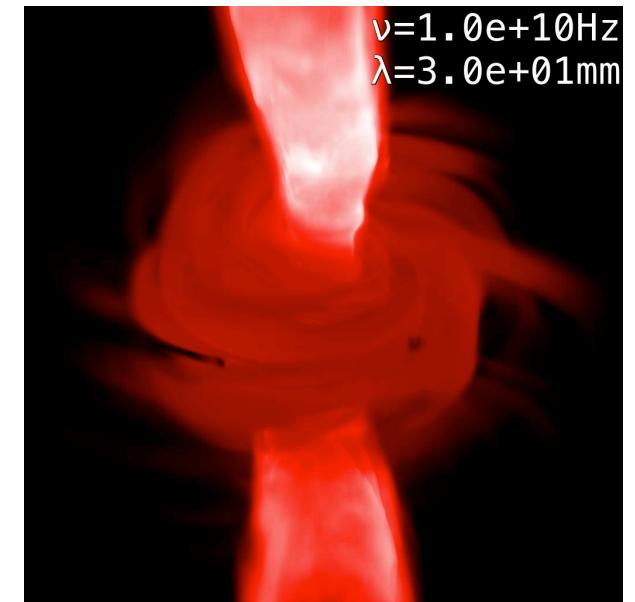
What Wavelength Should We Observe? ≈ 1 mm



Finding the Peak
of the Spectrum



Piercing the
Scattering Screen



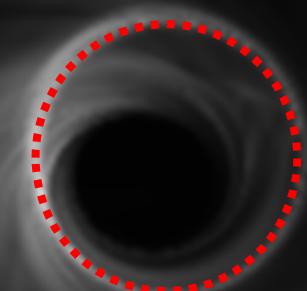
Finding Where the
Shadow is Visible

How Big Must Our Telescope Be? **Earth Sized**

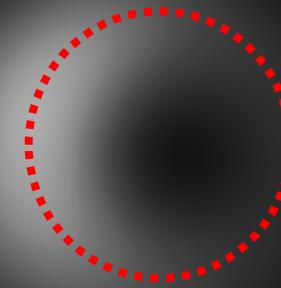
Telescope-Size \propto

$$\frac{Wavelength}{Angular Resolution}$$

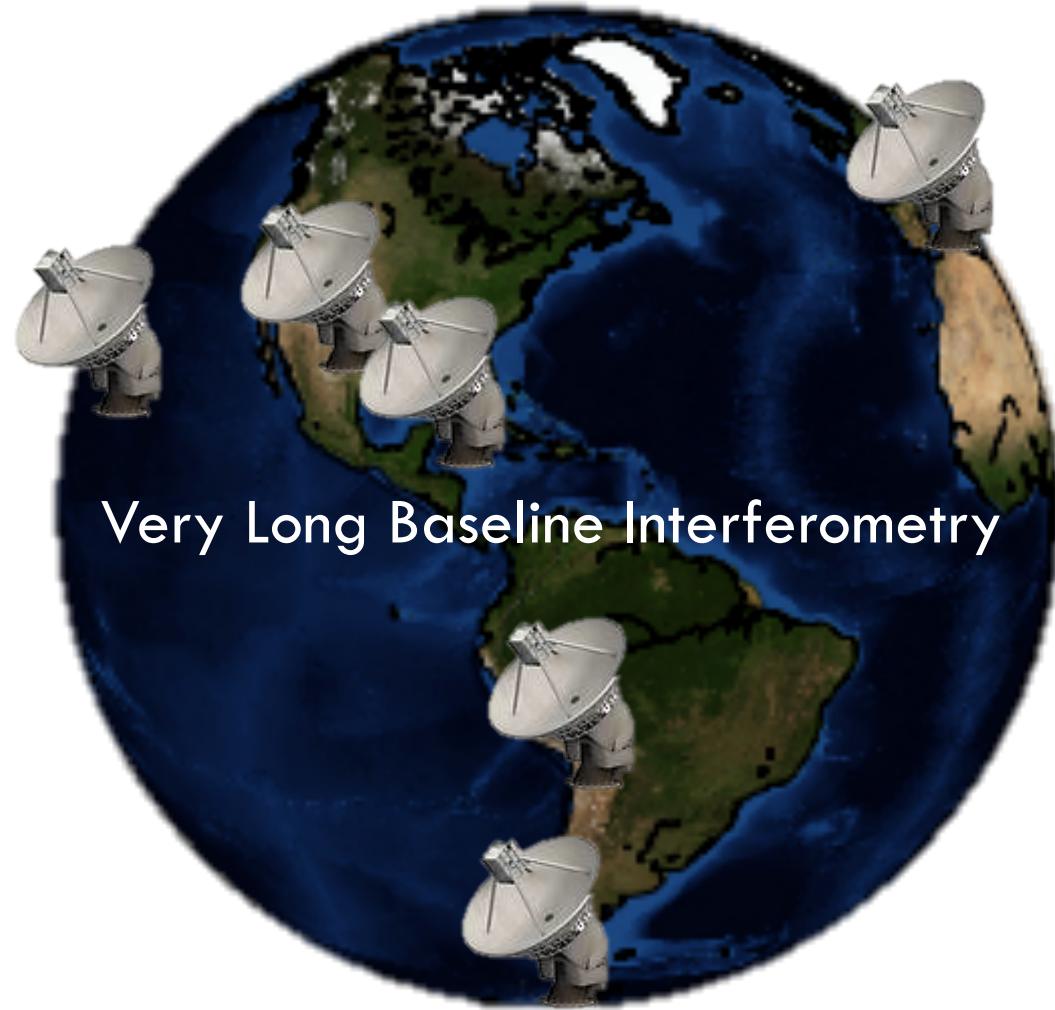
Simulation of SgrA*



Ideal Image with
Earth-Sized Telescope

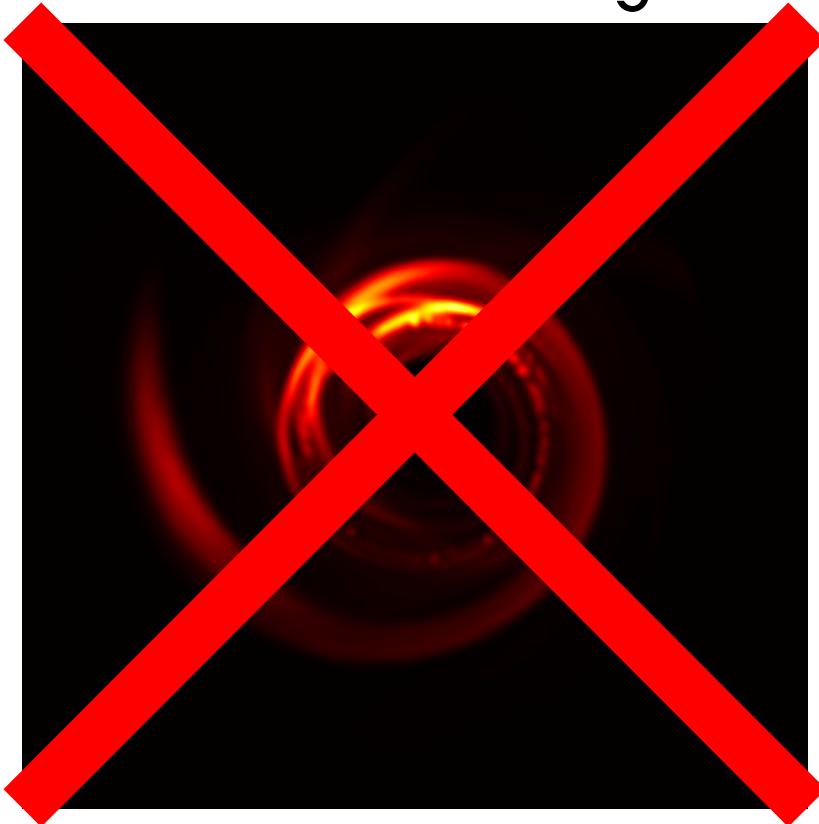


The Event Horizon Telescope (EHT)

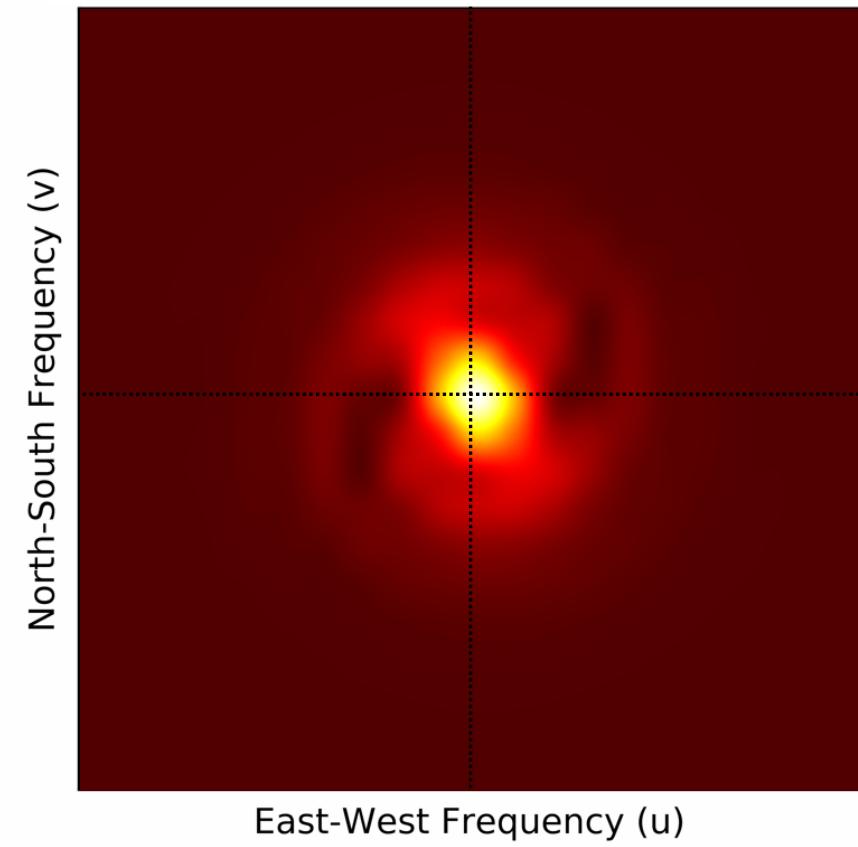


Very Long Baseline Interferometry (VLBI)

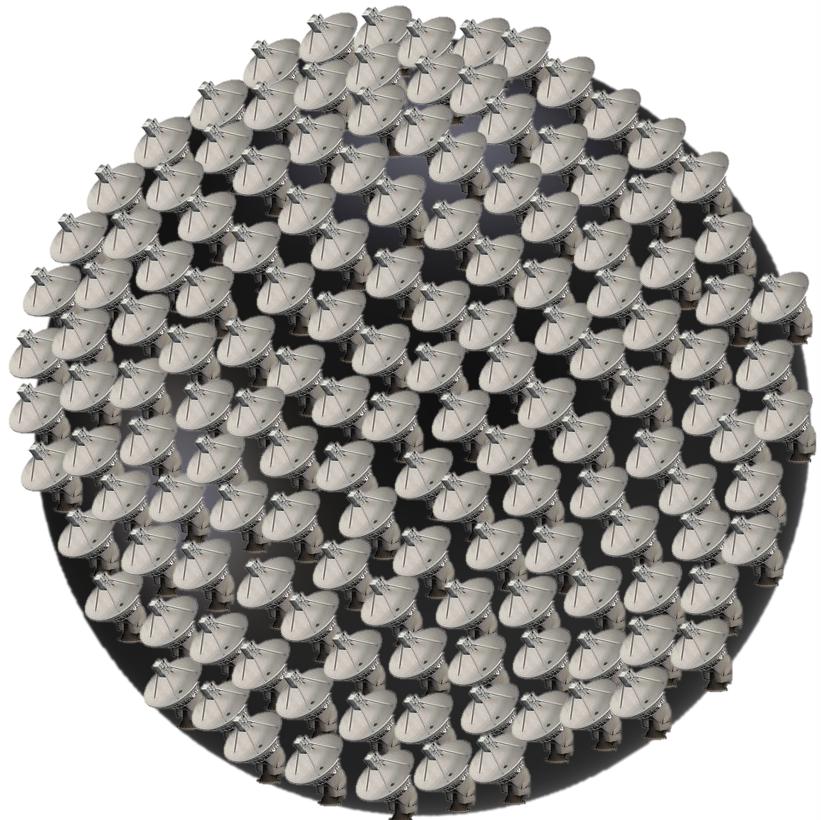
Black Hole Image



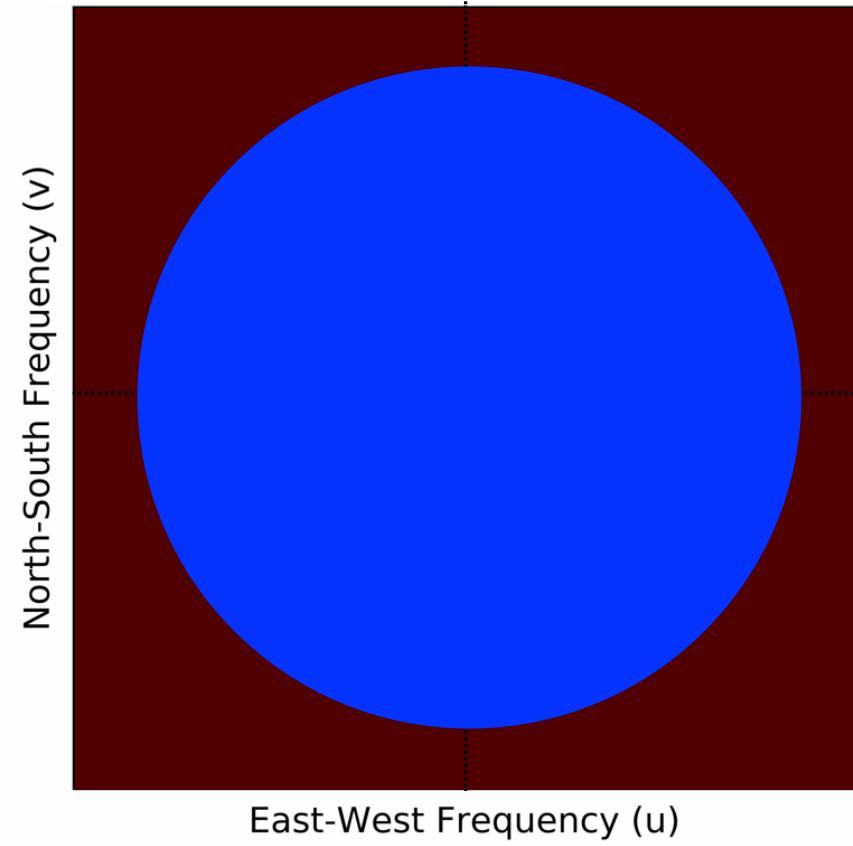
Frequency Measurements



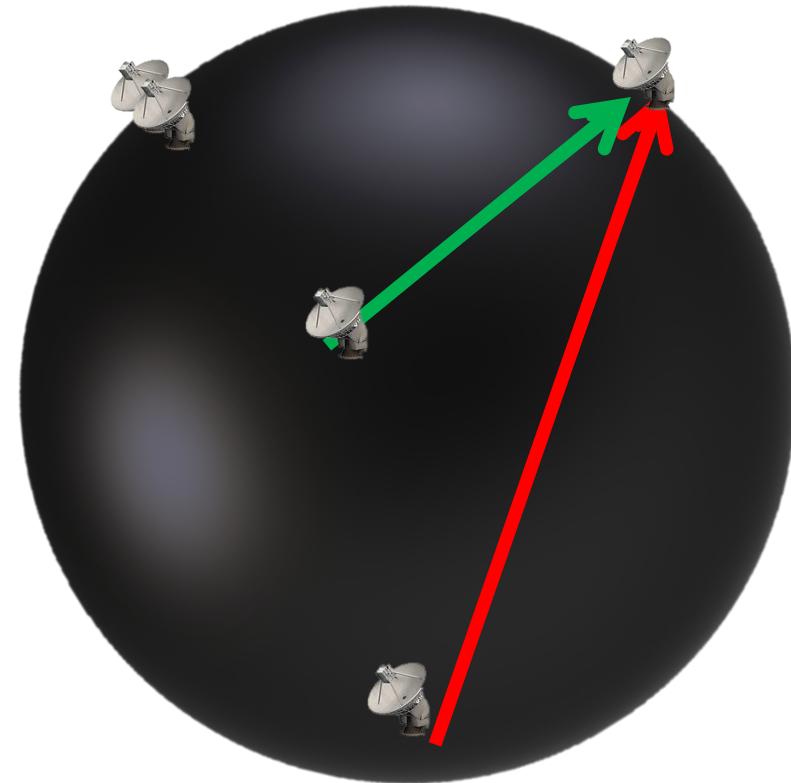
Very Long Baseline Interferometry (VLBI)



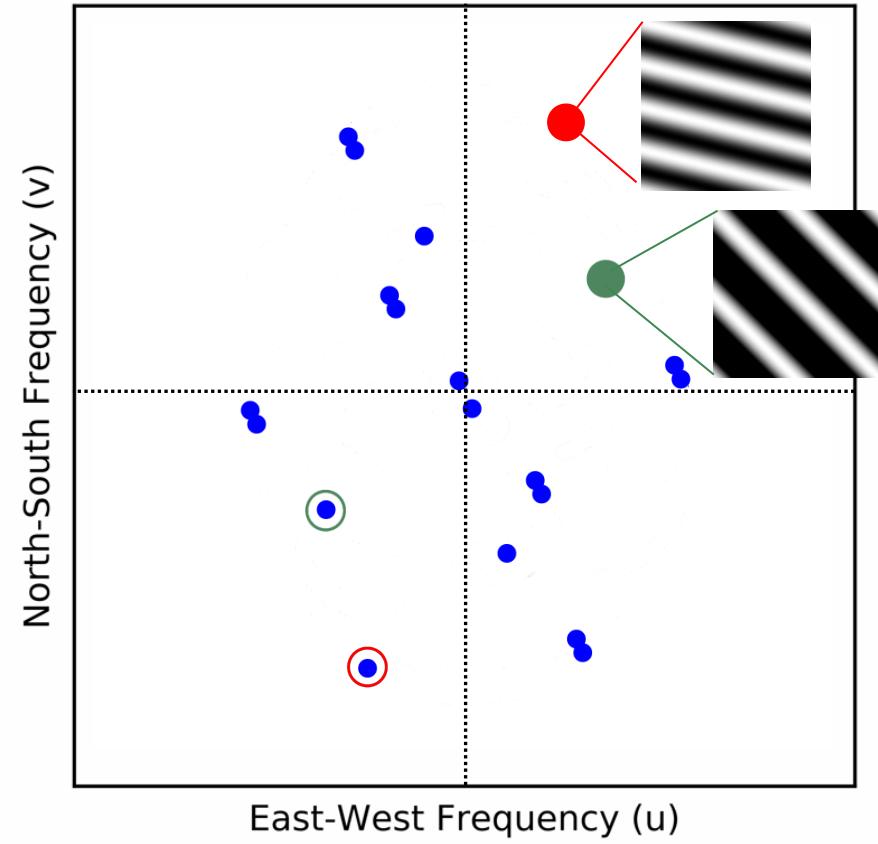
Frequency Measurements



Very Long Baseline Interferometry (VLBI)



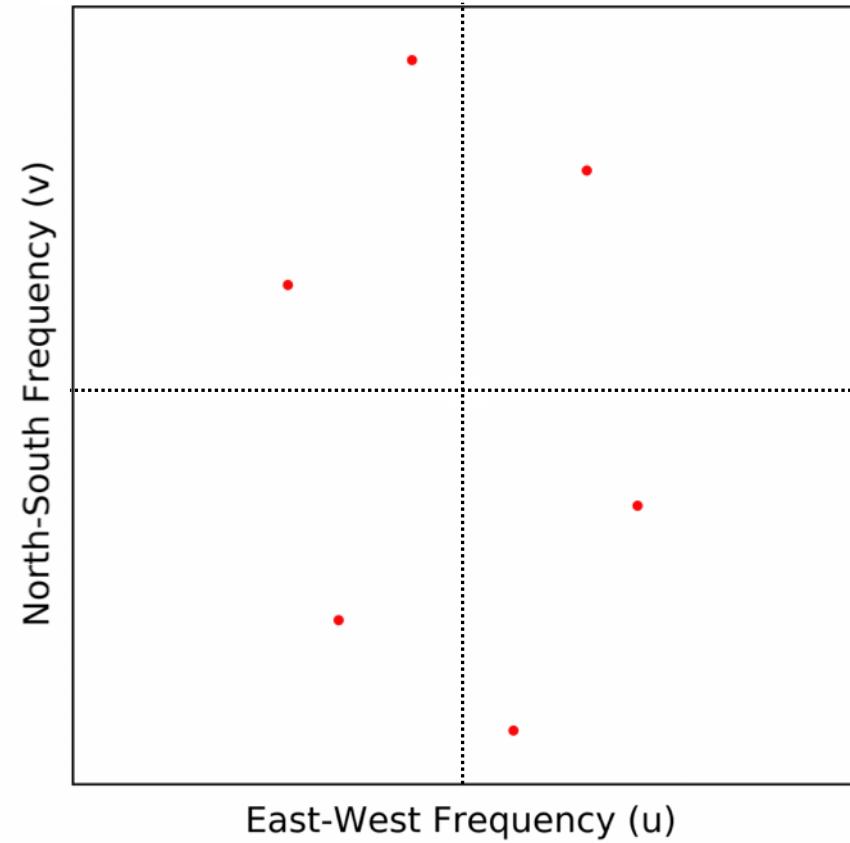
Frequency Measurements



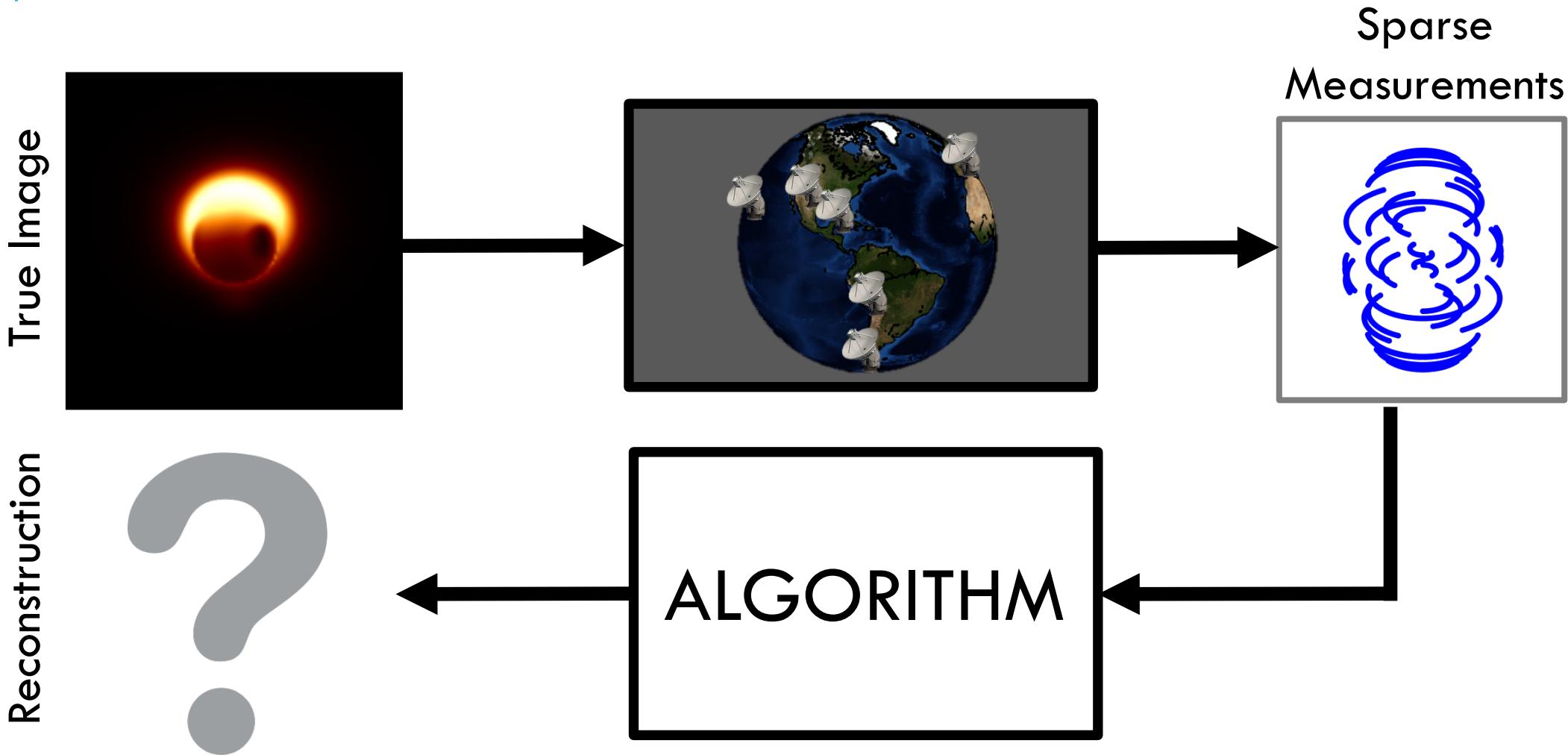
Very Long Baseline Interferometry (VLBI)



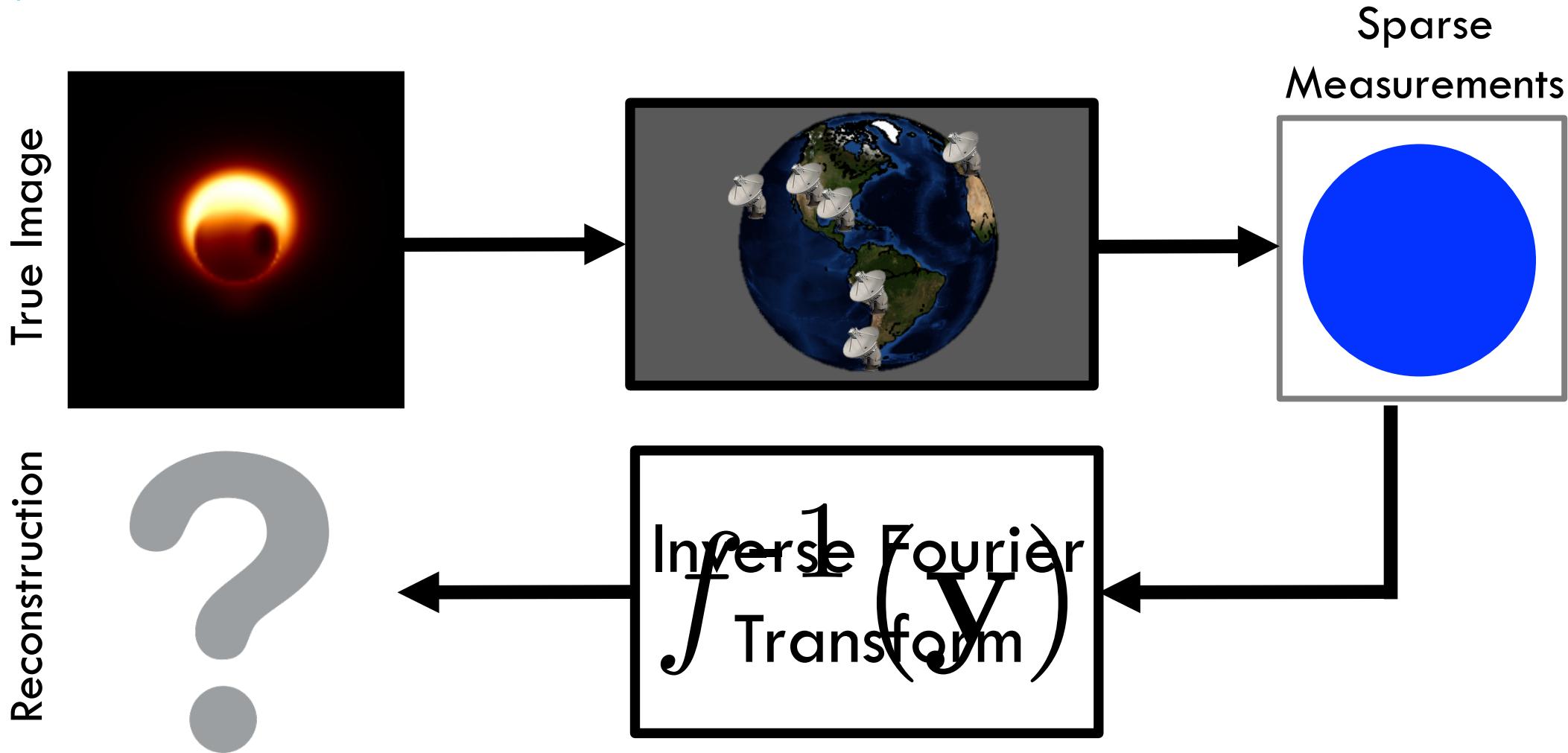
Frequency Measurements



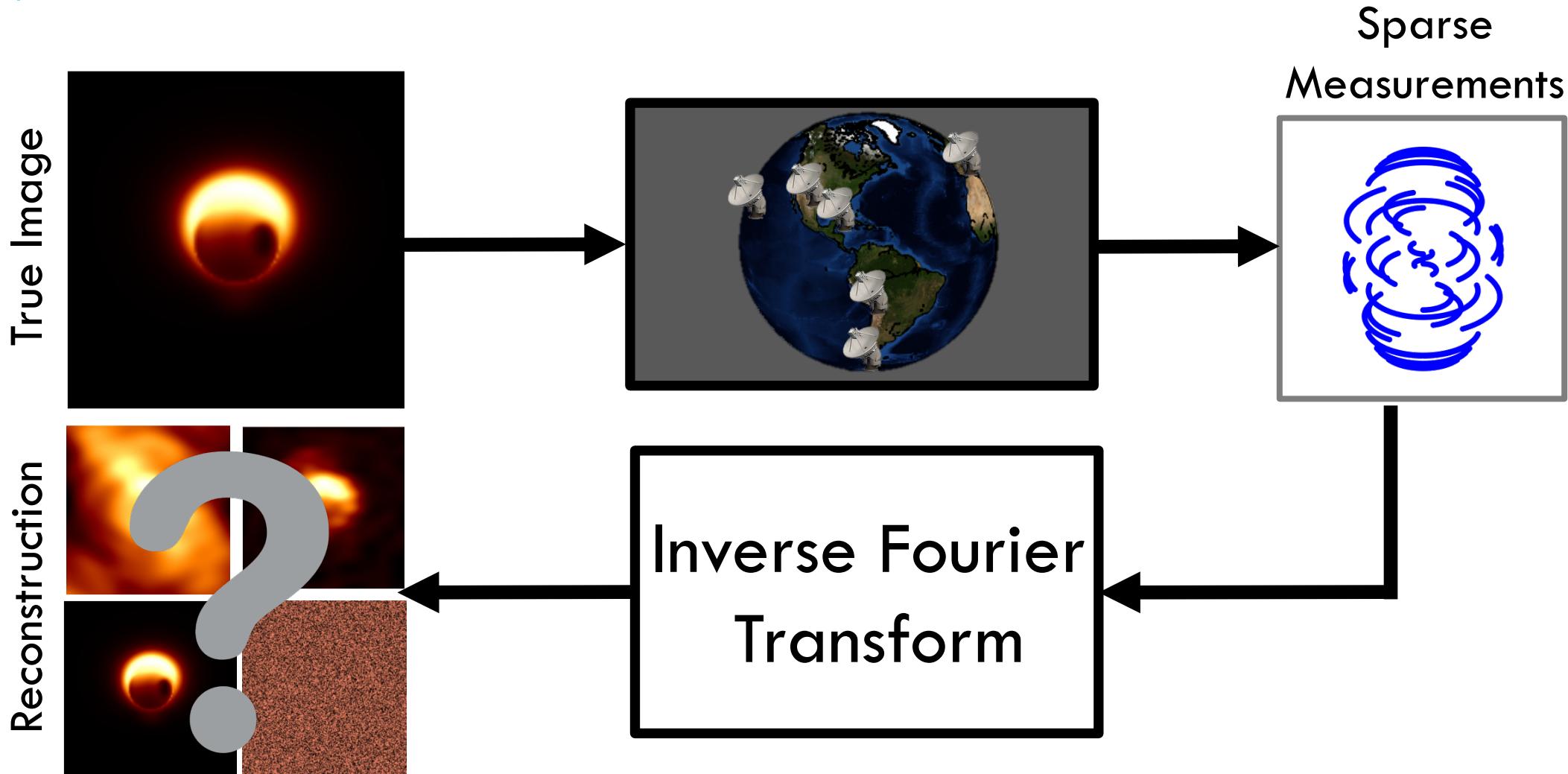
Unconventional Imaging: The EHT



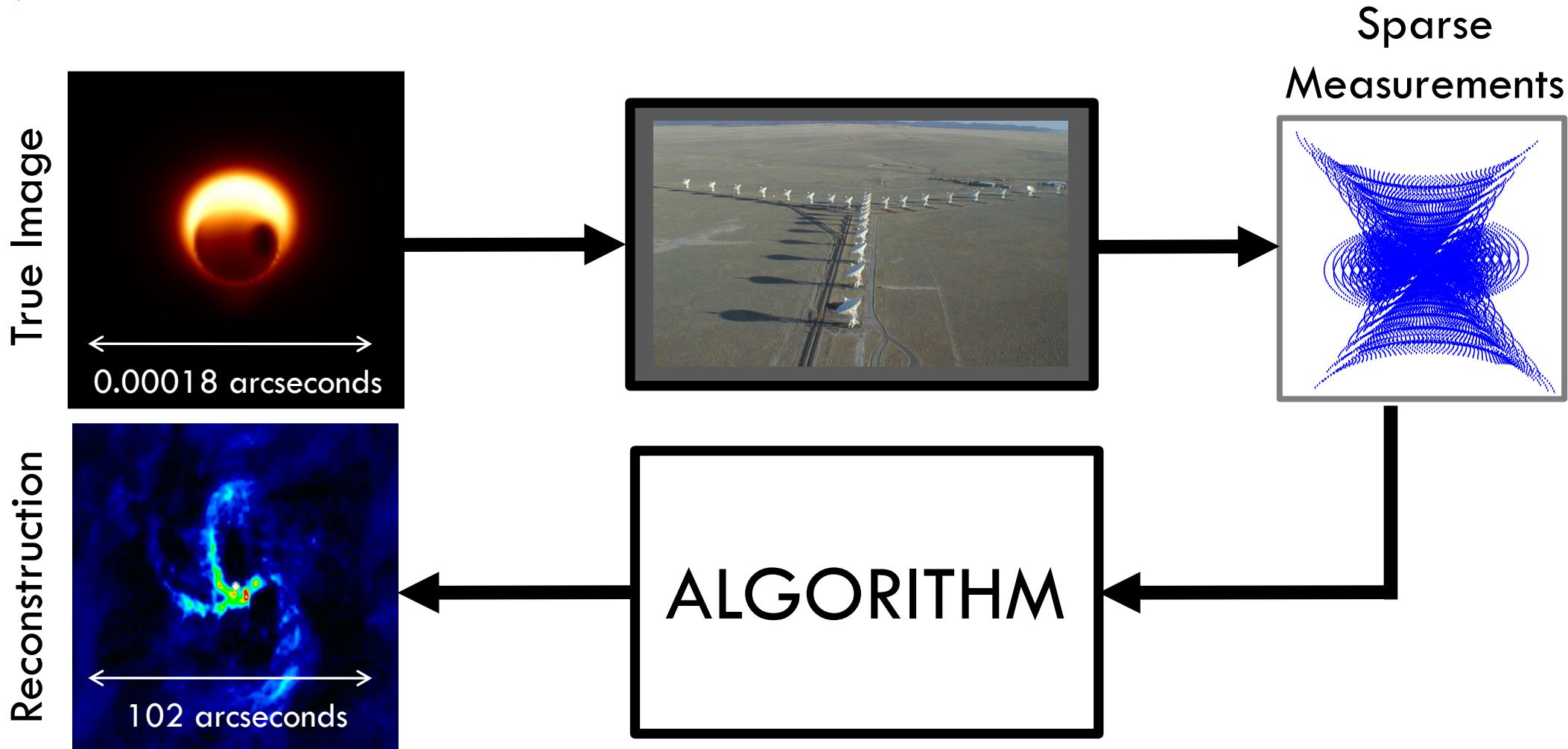
Inverting the EHT Imaging System



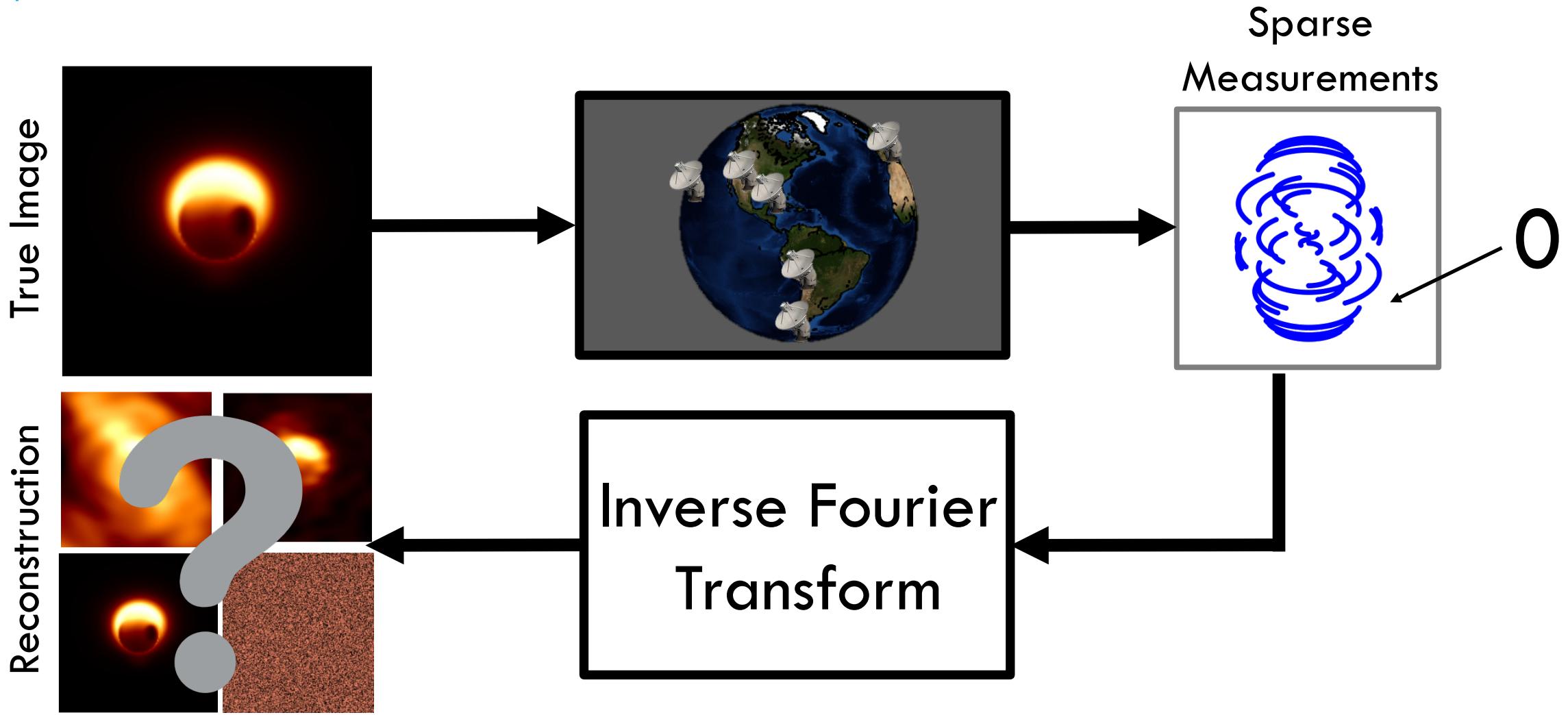
Inverting the Imaging System: Ambiguity



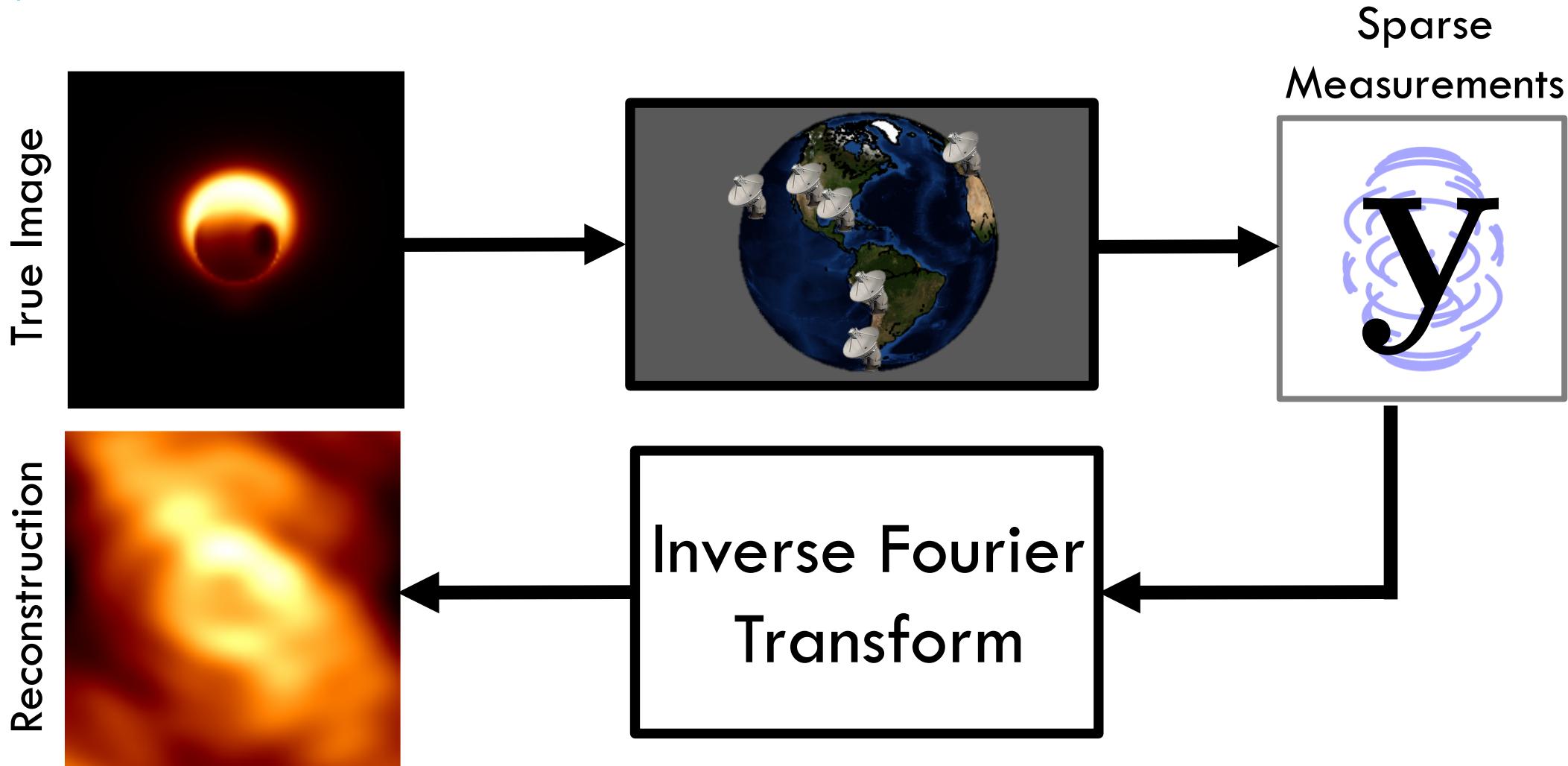
Unconventional Imaging: The VLA



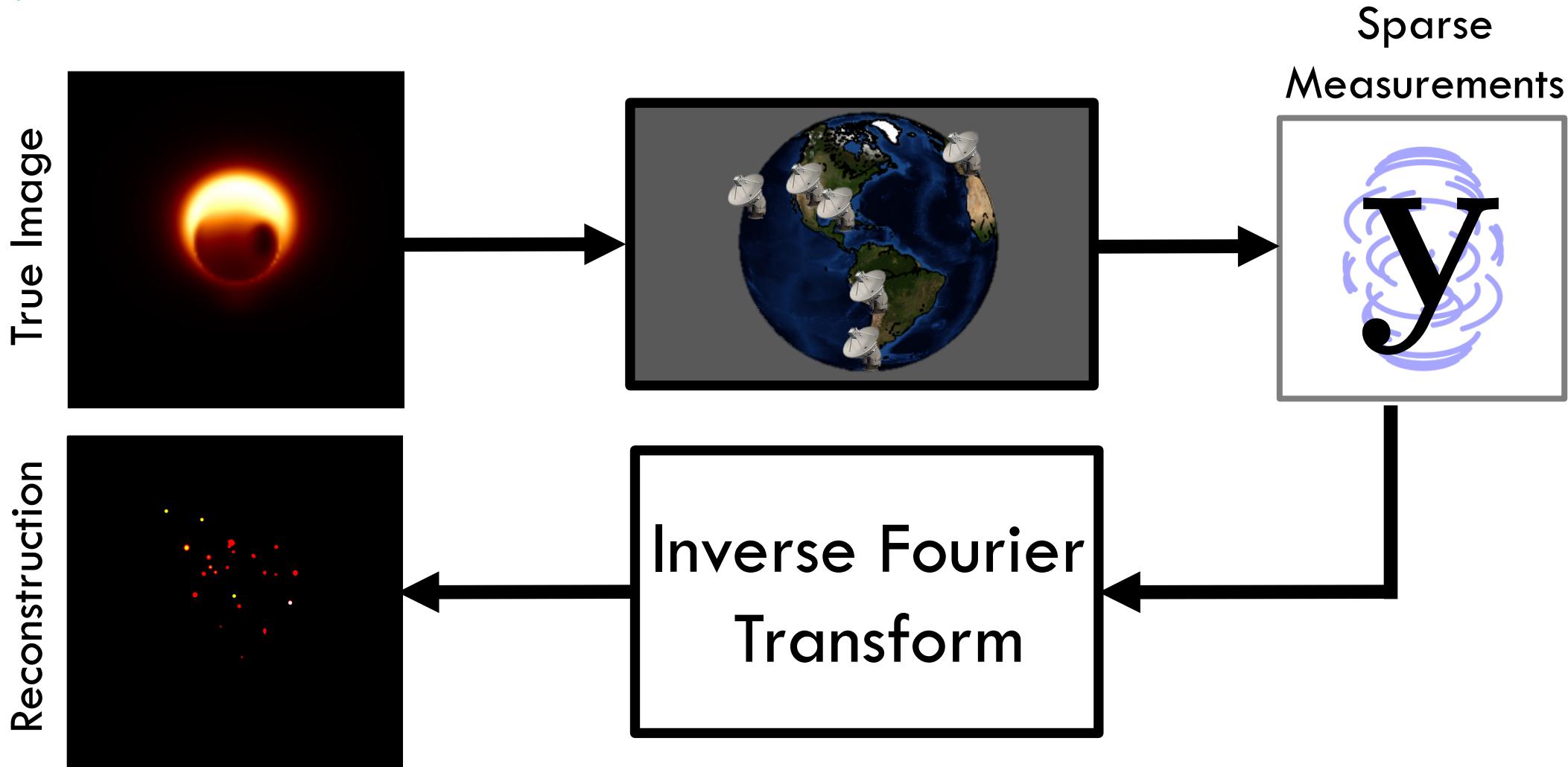
Traditional Approach: CLEAN



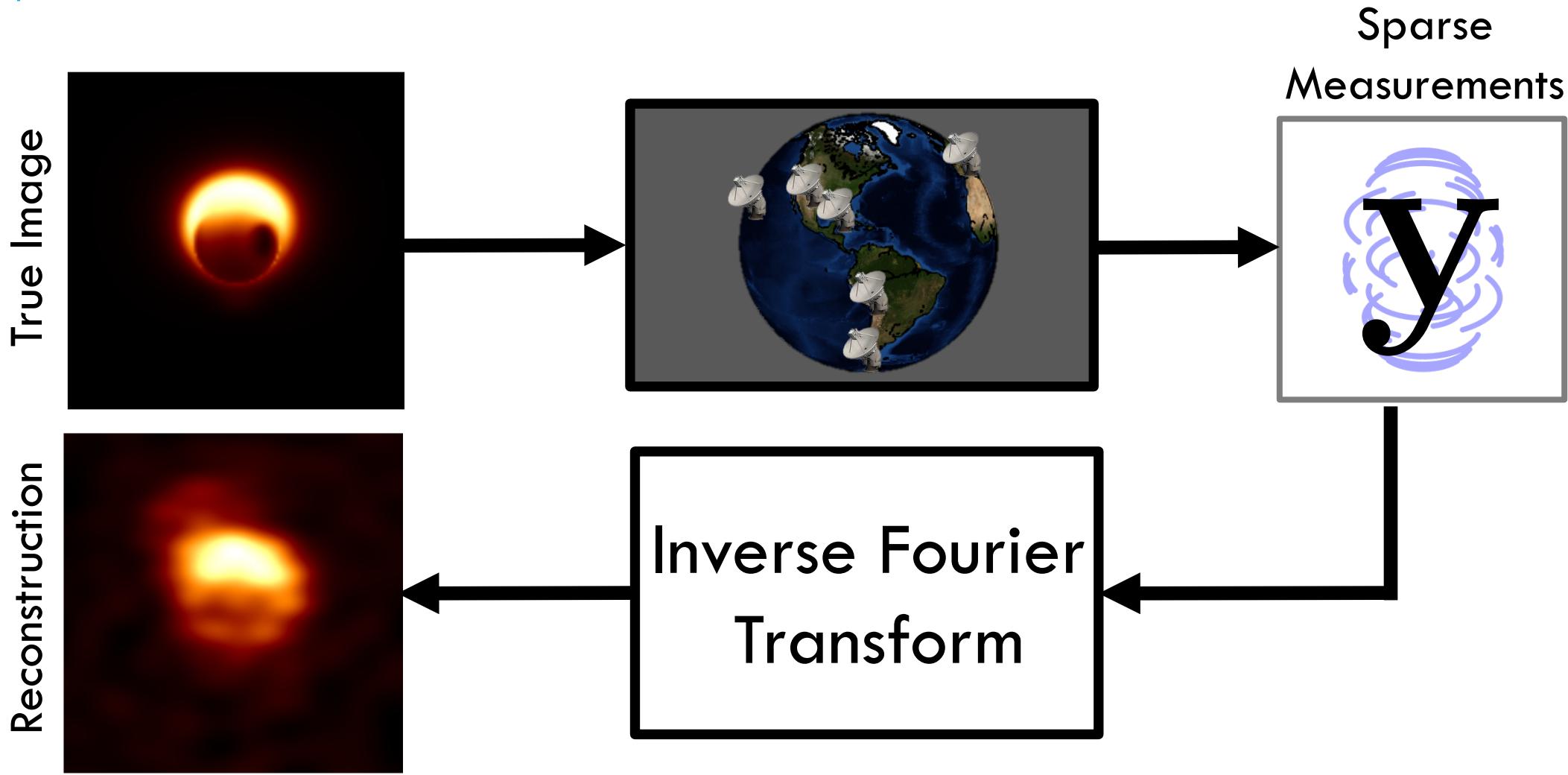
Traditional Approach: CLEAN

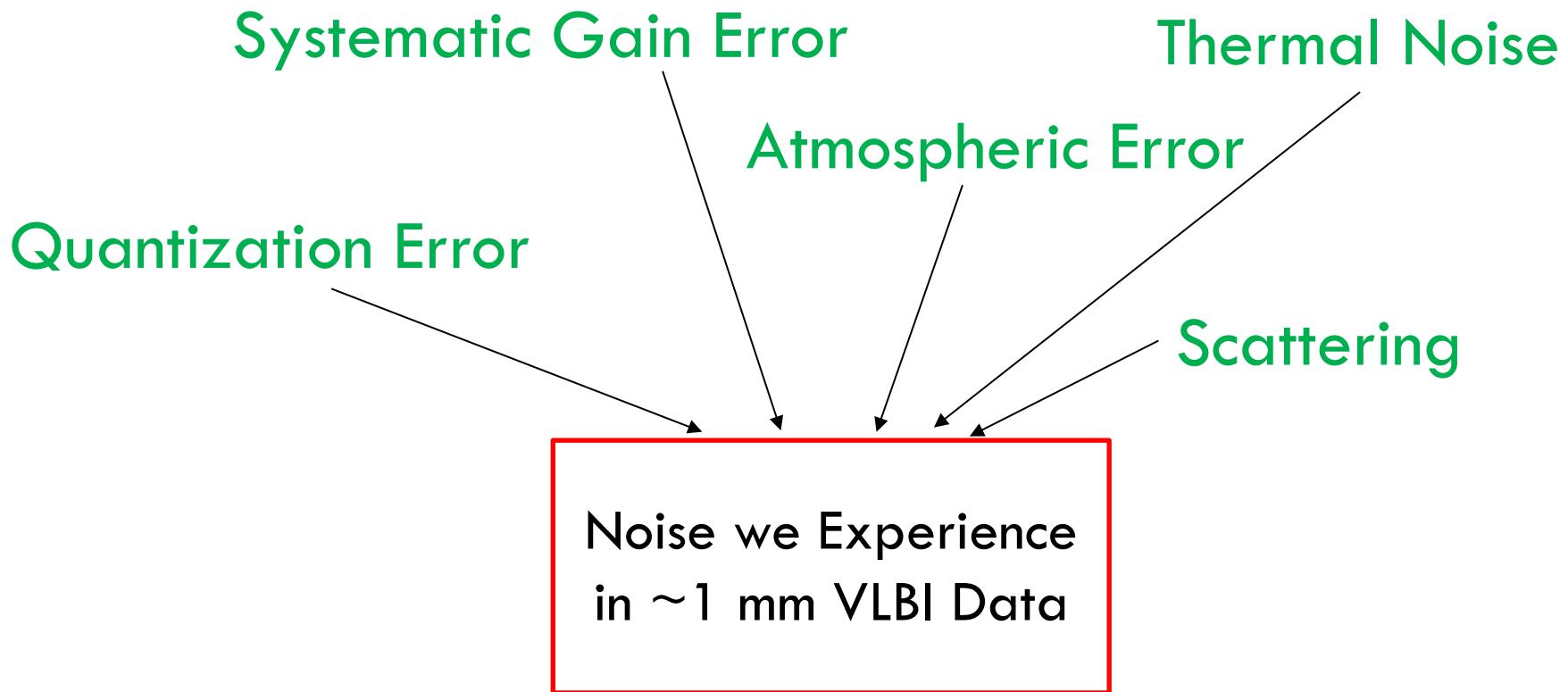


Traditional Approach: CLEAN

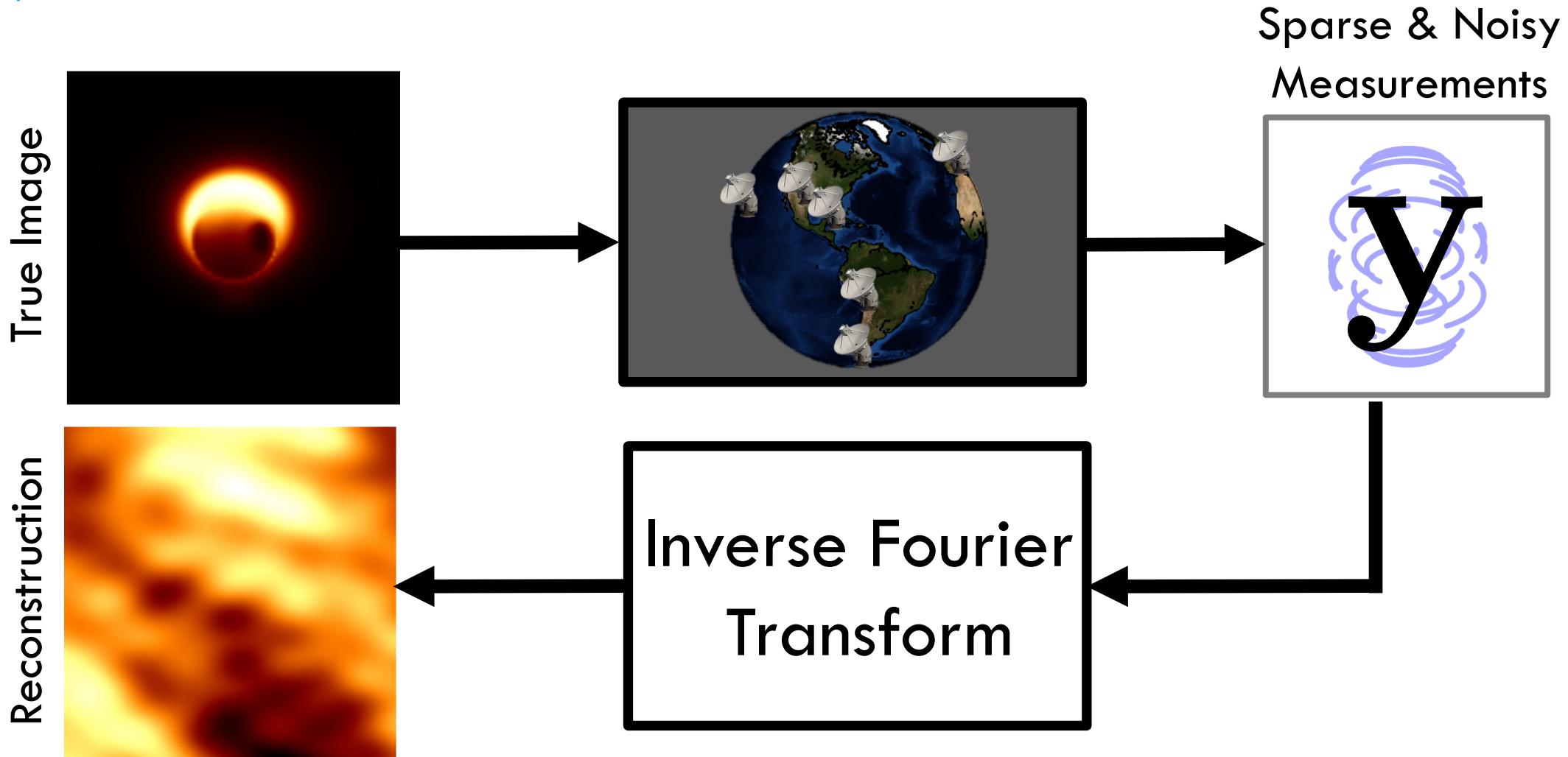


Traditional Approach: CLEAN





Atmospheric Error: The Effect

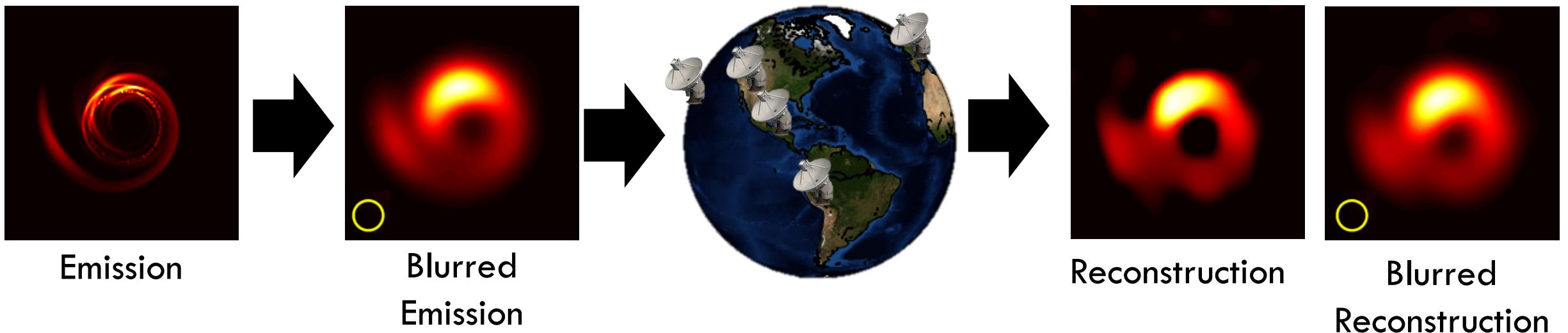


Bayesian Model Inversion

$$\hat{\mathbf{x}}_{\text{MAP}} = \operatorname{argmax}_{\mathbf{x}} [\log p(\mathbf{y}|\mathbf{x}) + \log p(\mathbf{x})]$$

The diagram illustrates the components of the Bayesian model inversion formula. Five error terms are shown in red text: "Systematic Gain Error", "Atmospheric Error", "Thermal Noise", "Scattering", and "Quantization Error". Arrows point from each of these error terms to the $\log p(\mathbf{y}|\mathbf{x})$ term in the equation above, indicating that it represents the sum of the log likelihood and the log prior.

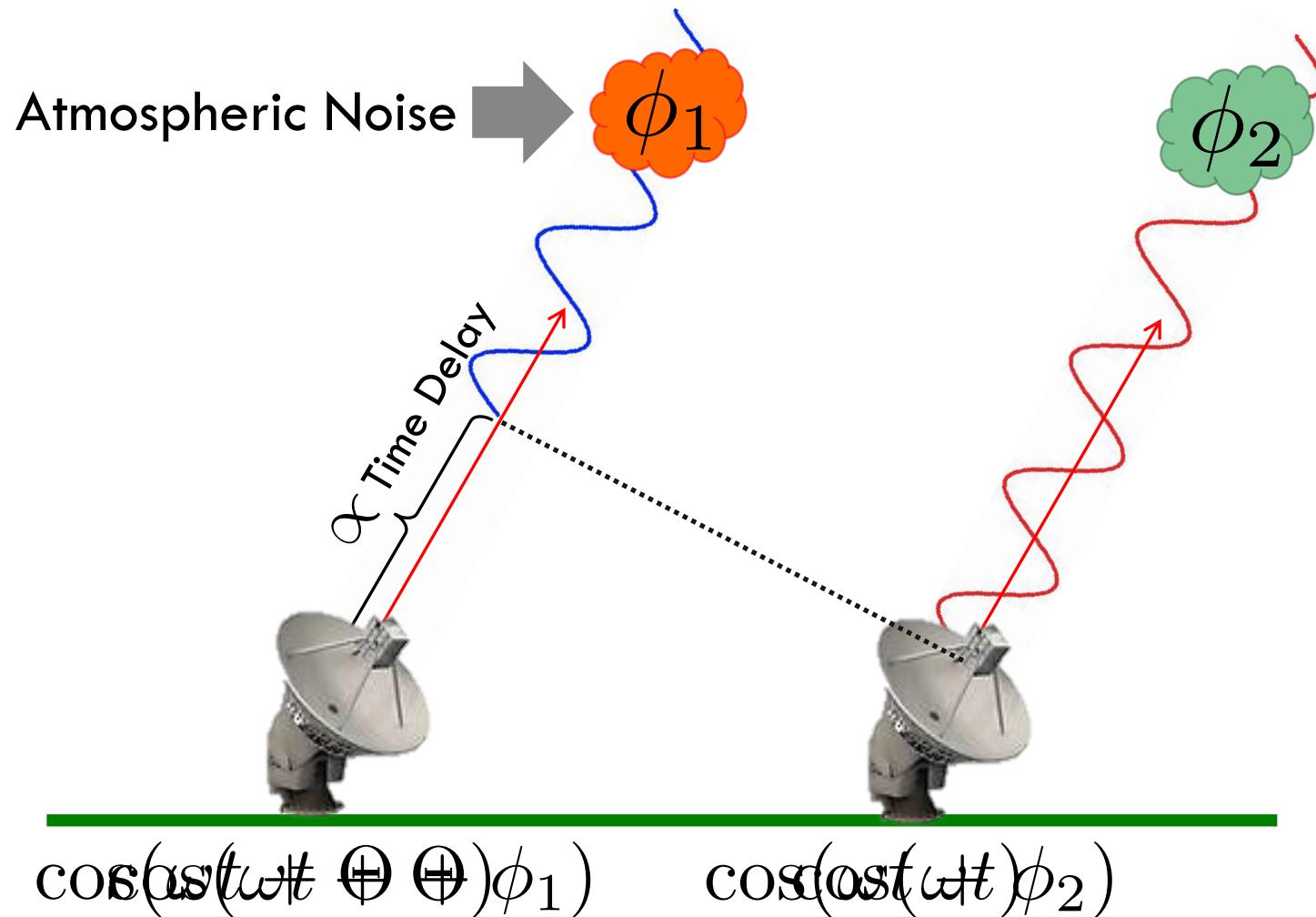
Simulated EHT Image Reconstruction



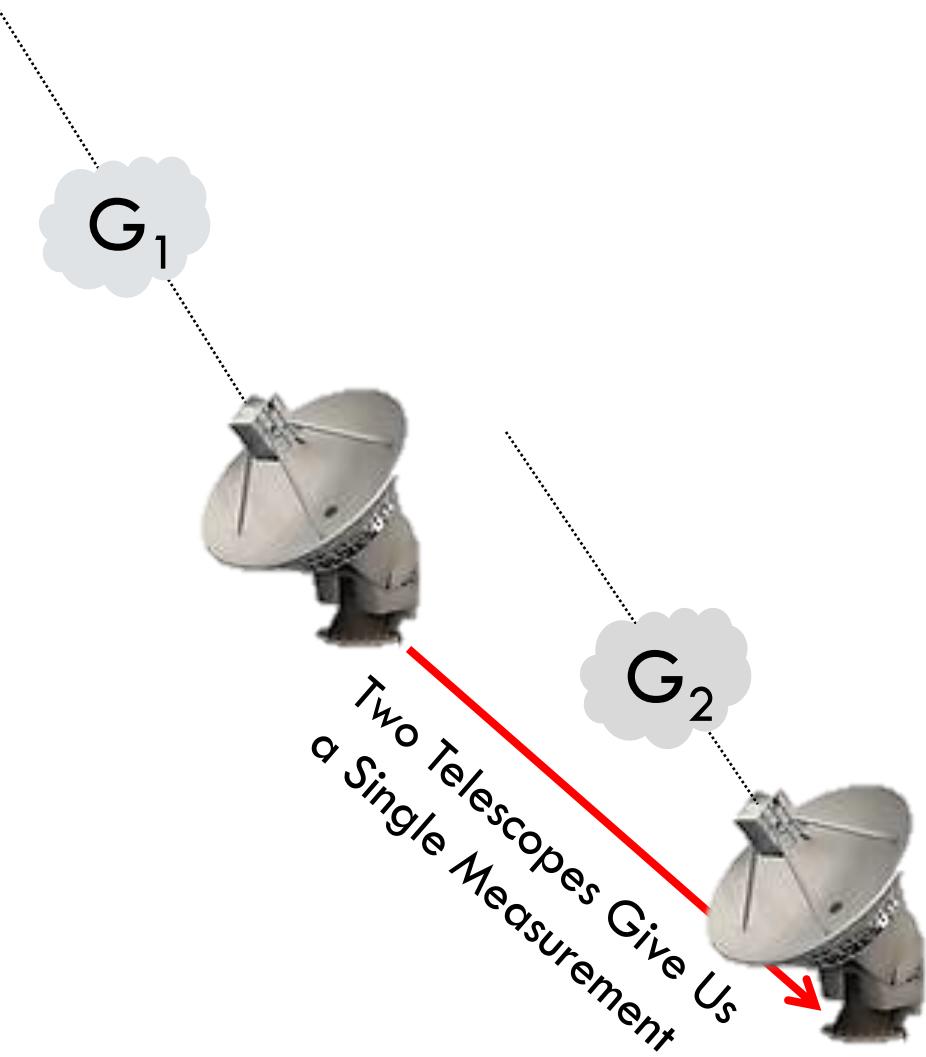
Calibration-Free Imaging

“Interferometric Imaging Directly with Closure Phases and Closure Amplitudes”

Atmospheric Phase Error



Systematic Gain Error



$$|V_{1,2}^{\text{meas}}| \approx |V_{1,2}^{\text{ideal}}| V_{1,2}^{\text{ideal}} |G_1| G_2$$

Atmospheric + Systematic Gain Error

$$V_{1,2}^{\text{meas}} \approx V_{1,2}^{\text{ideal}} G_1 G_2 \exp(\phi_1 - \phi_2)$$

Amplitude Errors Phase Error



Atmospheric + Systematic Gain Error

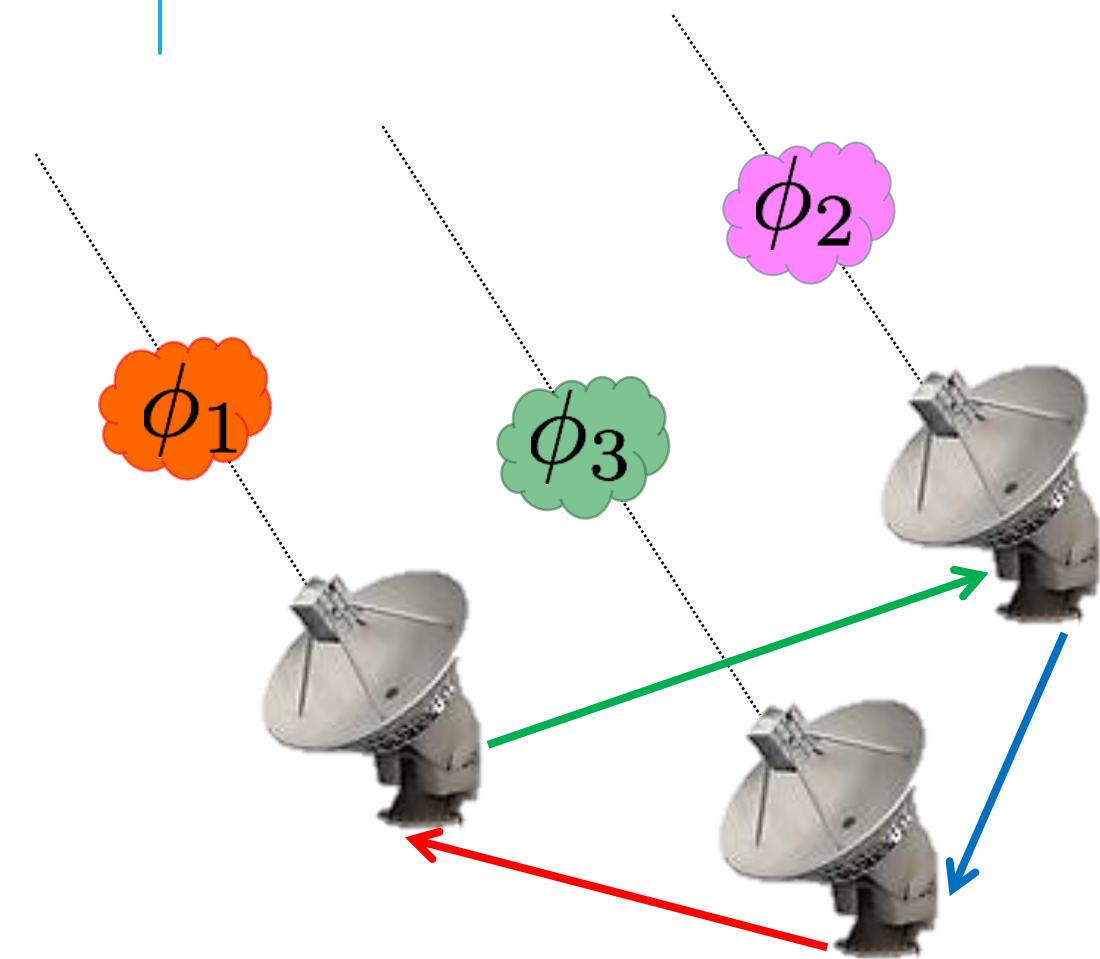
$$V_{1,\frac{2}{3}}^{\text{meas}} \approx V_{1,\frac{2}{3}}^{\text{ideal}} G_1 G_{\frac{2}{3}} \exp(\phi_1 - \phi_{\frac{2}{3}})$$

Amplitude Errors

Phase Error

The diagram illustrates the components of the measured voltage. It starts with the measured voltage $V_{1,\frac{2}{3}}^{\text{meas}}$, which is approximately equal to the ideal voltage $V_{1,\frac{2}{3}}^{\text{ideal}}$. The ideal voltage is multiplied by two gain terms, G_1 and $G_{\frac{2}{3}}$. The difference in phase between ϕ_1 and $\phi_{\frac{2}{3}}$ is also included. A red crossed-out term $V_{1,2/3}^{\text{ideal}}$ is shown above the ideal term. Below the measured voltage, two blue curly braces group terms: G_1 and $G_{\frac{2}{3}}$ under the heading 'Amplitude Errors', and $\exp(\phi_1 - \phi_{\frac{2}{3}})$ under the heading 'Phase Error'.

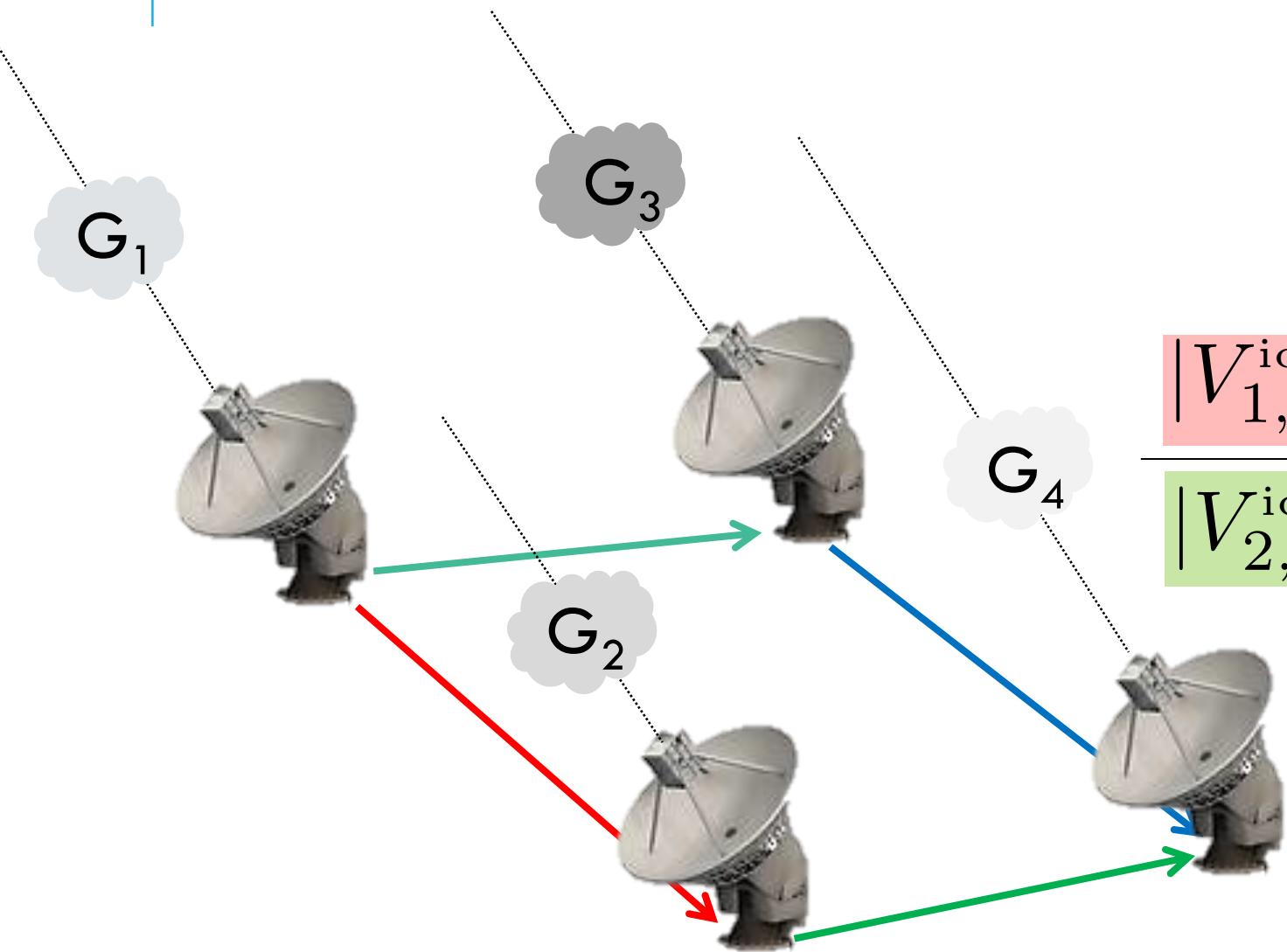
Atmospheric Phase Error: Phase Closure



The diagram illustrates the concept of atmospheric phase error in radio astronomy. Three silver satellite dishes are arranged in a triangle. Dotted lines connect each dish to three colored clouds labeled ϕ_1 (orange), ϕ_2 (pink), and ϕ_3 (green). A green arrow points from the top-right dish to the bottom-left dish, and a blue arrow points from the bottom-right dish to the bottom-left dish.

$$\frac{\Theta_{12} + \cancel{\phi_1} - \cancel{\phi_2}}{+\Theta_{23} + \cancel{\phi_2} - \cancel{\phi_3}} + \frac{\Theta_{31} + \cancel{\phi_3} - \cancel{\phi_1}}{\Theta_{12} + \Theta_{23} + \Theta_{31}}$$

Systematic Gain Error: Closure Amplitude



$$\frac{|V_{1,2}^{\text{meas}}| \quad |V_{3,4}^{\text{meas}}|}{|V_{2,4}^{\text{meas}}| \quad |V_{1,3}^{\text{meas}}|} \approx$$

$$\frac{|V_{1,2}^{\text{ideal}}| \quad \cancel{G_1} \quad \cancel{G_2} \quad |V_{3,4}^{\text{ideal}}| \quad \cancel{G_3} \quad \cancel{G_4}}{|V_{2,4}^{\text{ideal}}| \quad \cancel{G_2} \quad \cancel{G_4} \quad |V_{1,3}^{\text{ideal}}| \quad \cancel{G_1} \quad \cancel{G_3}}$$

$$\approx \frac{|V_{1,2}^{\text{meas}}| \quad |V_{3,4}^{\text{meas}}|}{|V_{2,4}^{\text{meas}}| \quad |V_{1,3}^{\text{meas}}|}$$

Constraining:

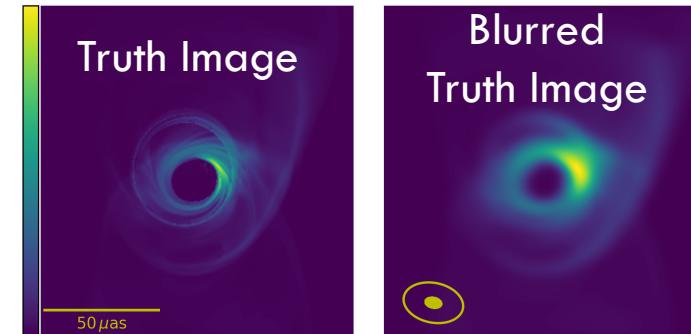
Closure
Amplitudes
+ Closure Phase



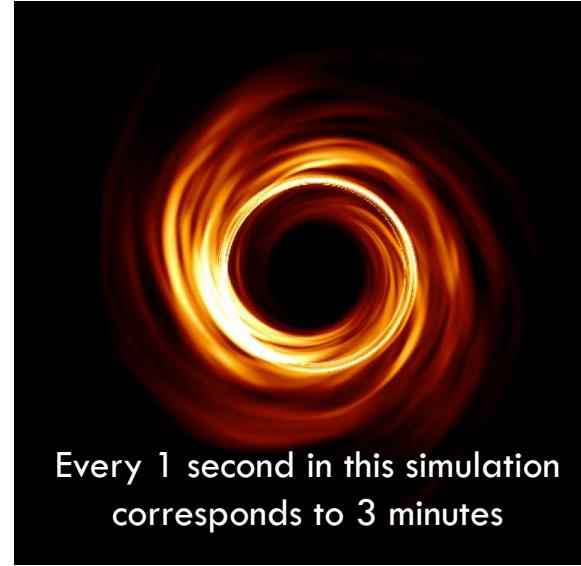
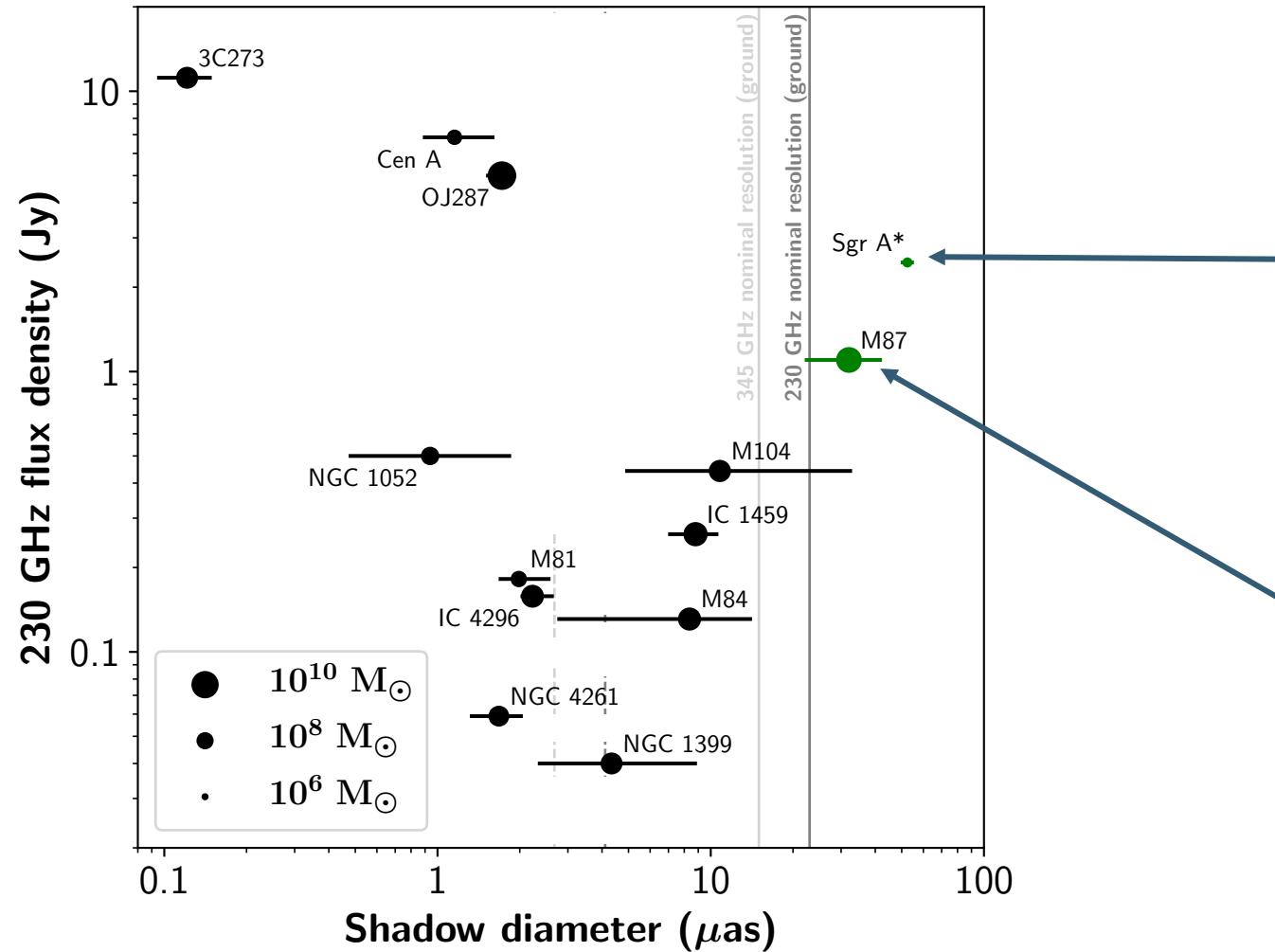
0% 5% 10% 25% 50% 75% 100%

Percentage of Systematic Gain Error

Calibration Free Imaging



The EHT's Black Hole Targets



Sagittarius A* (Sgr A*)
4 Million Solar Masses
Orbital Period: 4 – 30 minutes

M87
6 Billion Solar Masses
Orbital Period: 4 – 30 days

Testing General Relativity

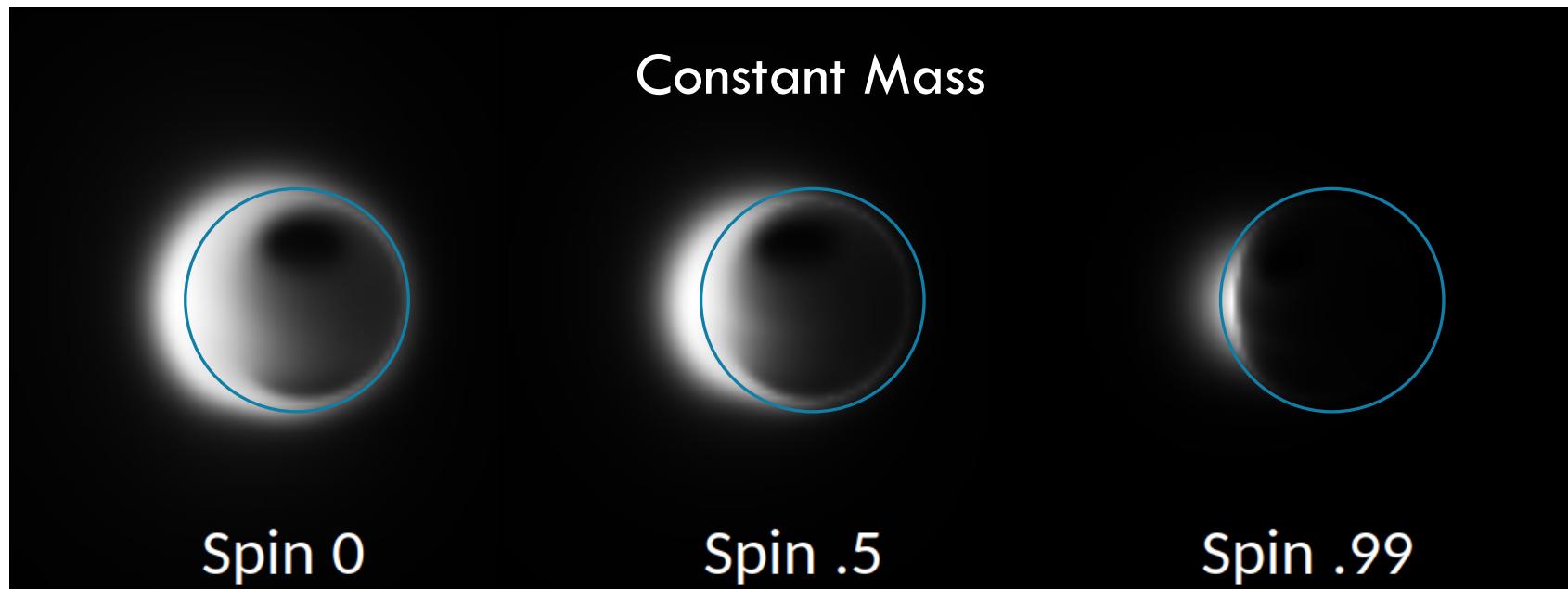
The “No Hair” Theorem

The spacetime surrounding a black hole can be fully characterized by three numbers:

Mass

Angular Momentum (spin)

~~Charge~~

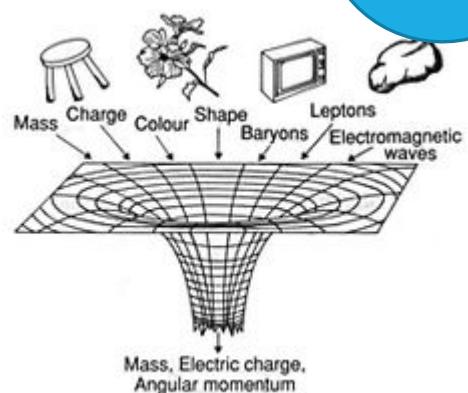


Spin changes shadow size by +/- 4%

The Information Paradox

(don't ask me too much 😊)

No Hair Theorem
(Black Hole spacetime
fully described by
mass and spin)



Hawking Radiation
(Black Holes can
evaporate)

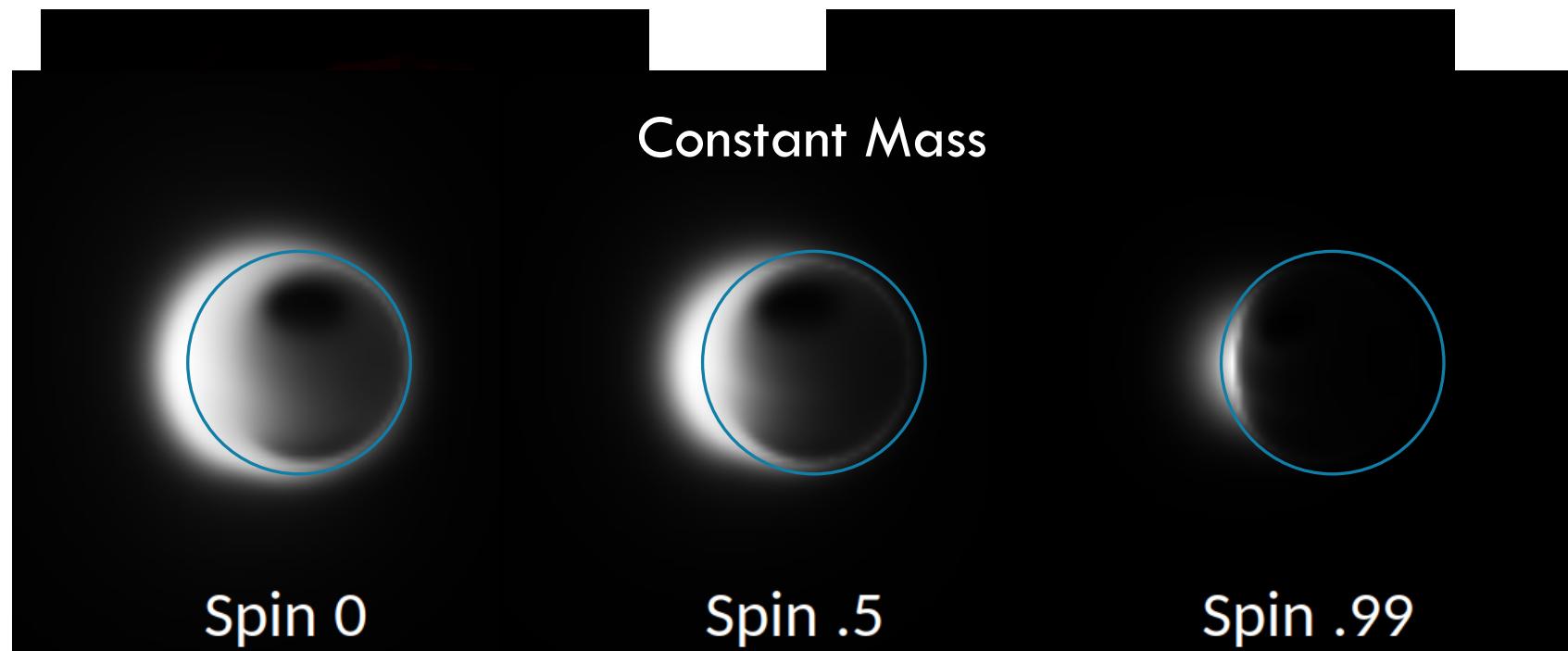
Quantum Theory's
Conservation
of Information

Information
Can Disappear!



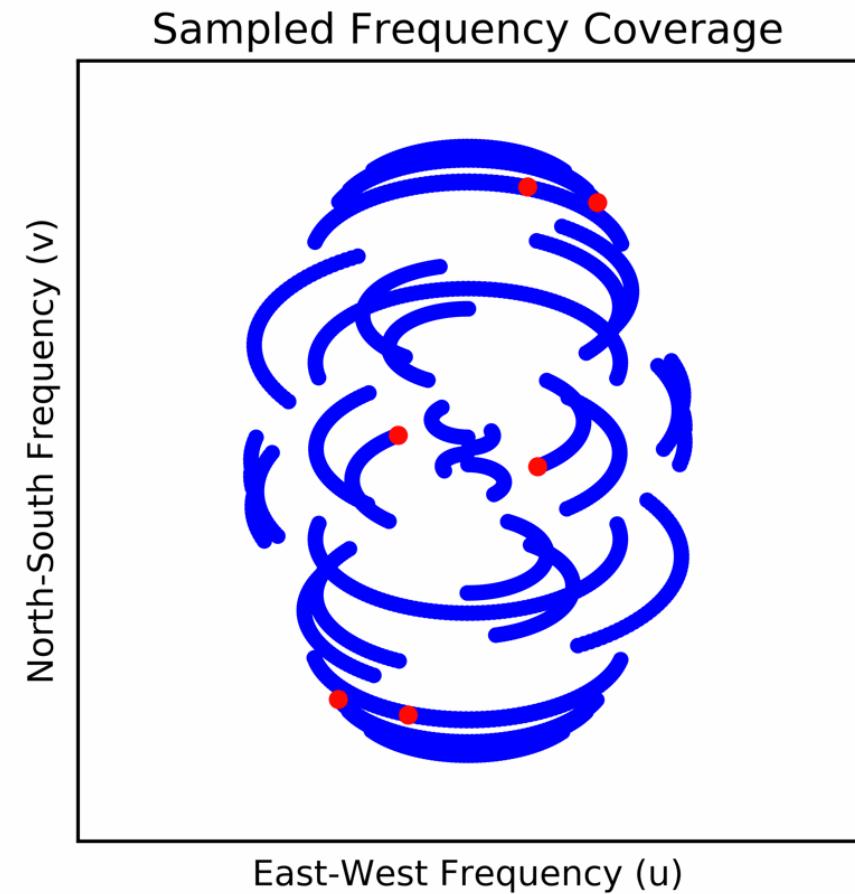
Measuring the Black Hole Spin to Probe Spacetime

Spin Changes a shadow by +/- 4% Which is only 2 microarcseconds
(the highest spatial frequency we measure corresponds to 25 microarcseconds)

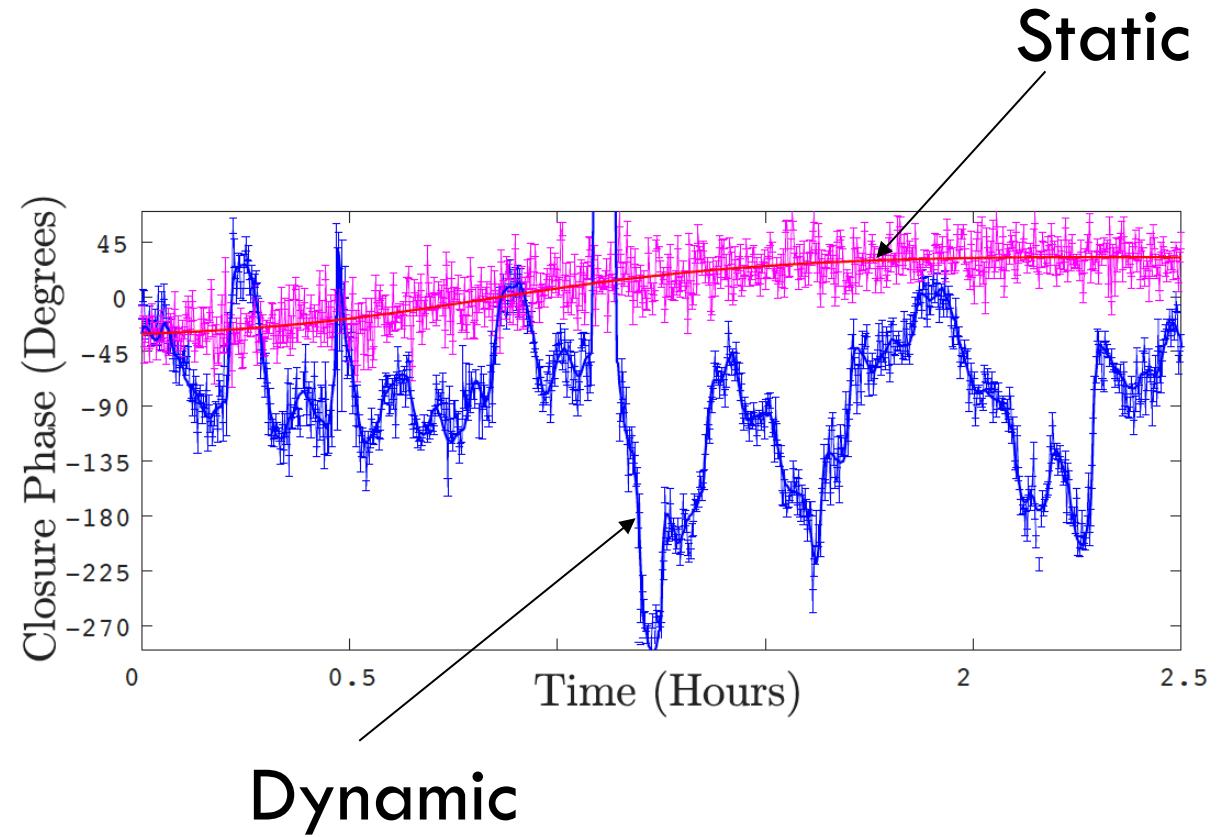


The Black Hole Spin Has a Much Bigger Effect on the Rotation of Gas Around the Back Hole
Spin changes shadow size by +/- 4%

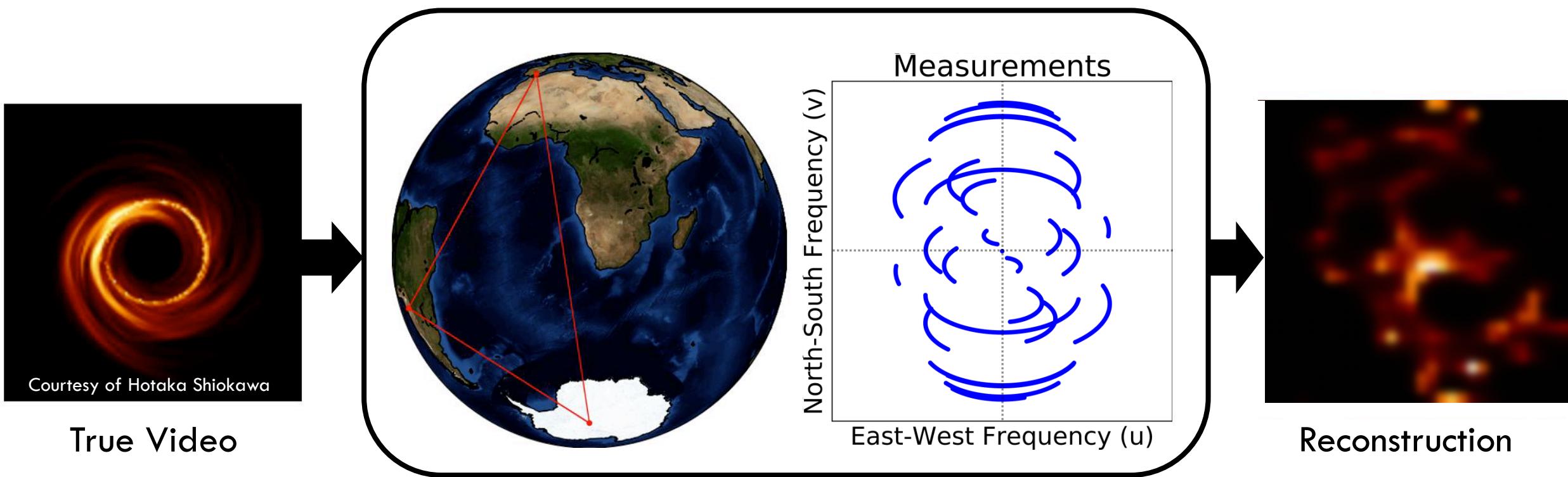
Observing an Evolving Source



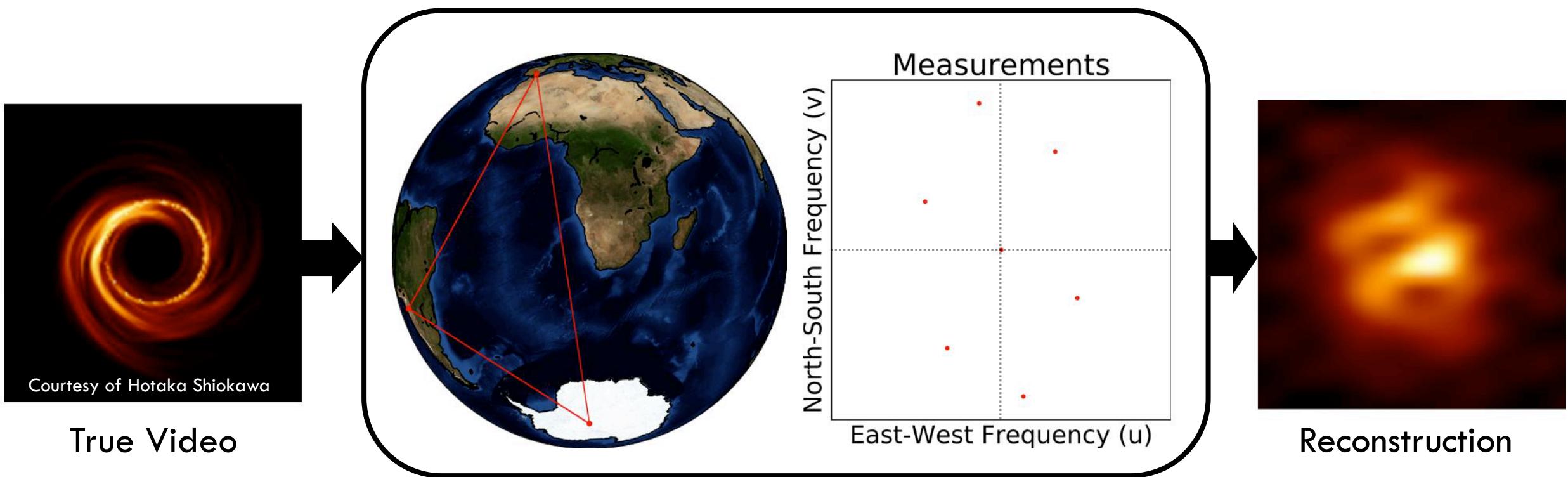
Observing an Evolving Source



Imaging a Time-Varying Source as a Static Image



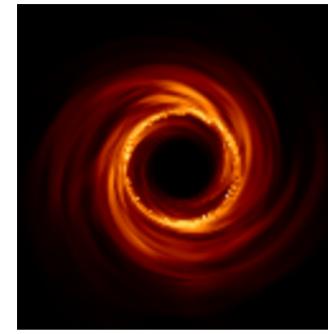
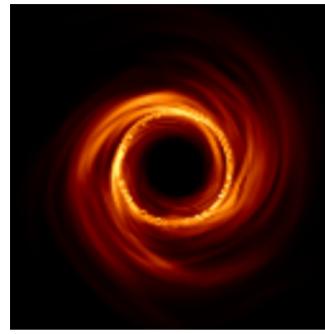
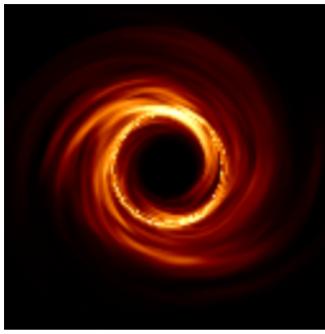
Imaging a Time-Varying Source as Snapshots



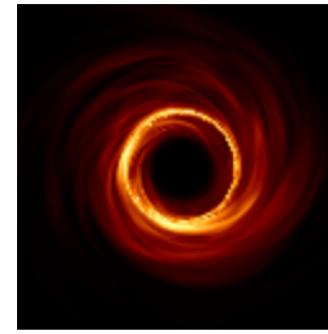
Time-Variable Imaging

“Reconstructing Video of Time-Varying Sources from Radio Interferometric Measurements ”

Different Images Over Time



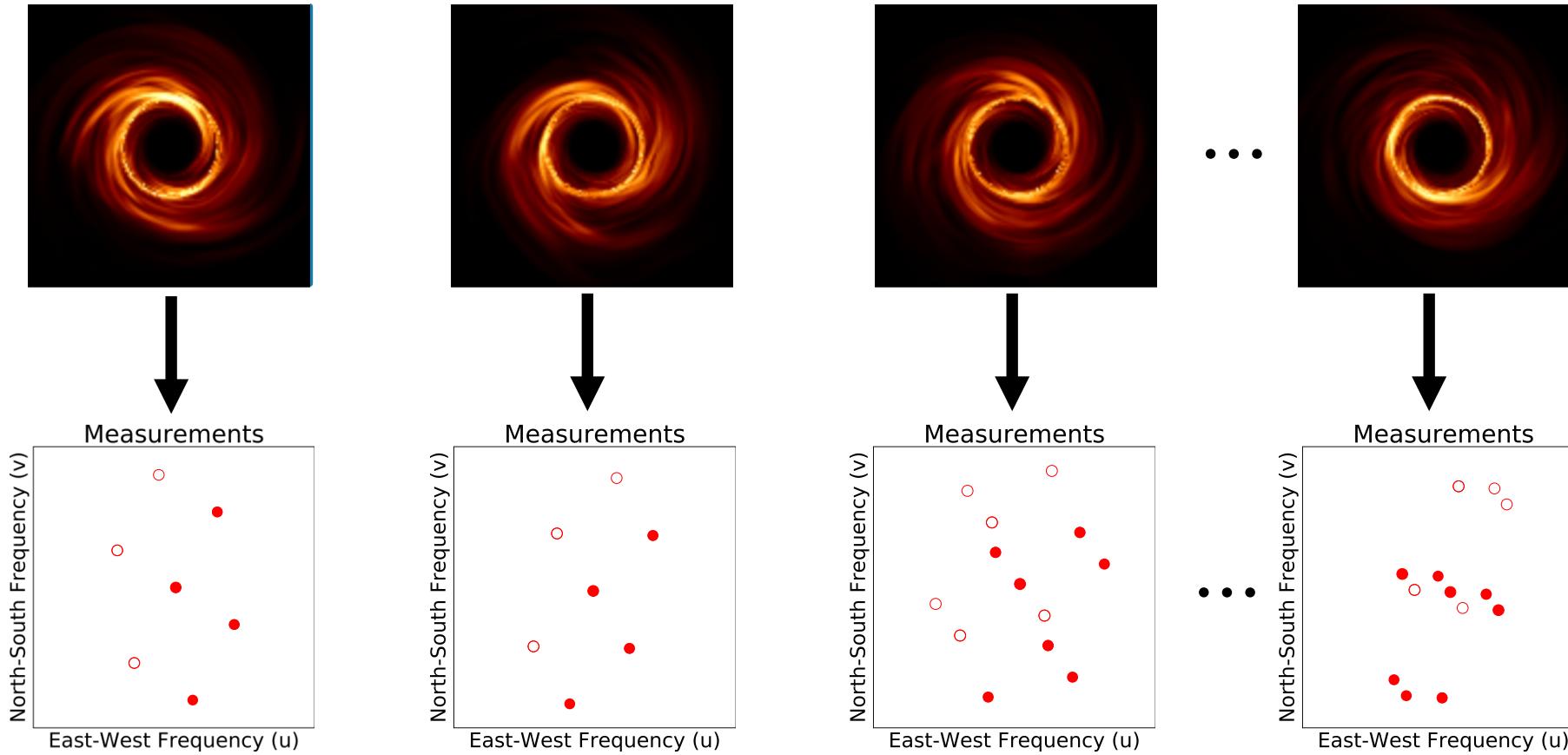
...



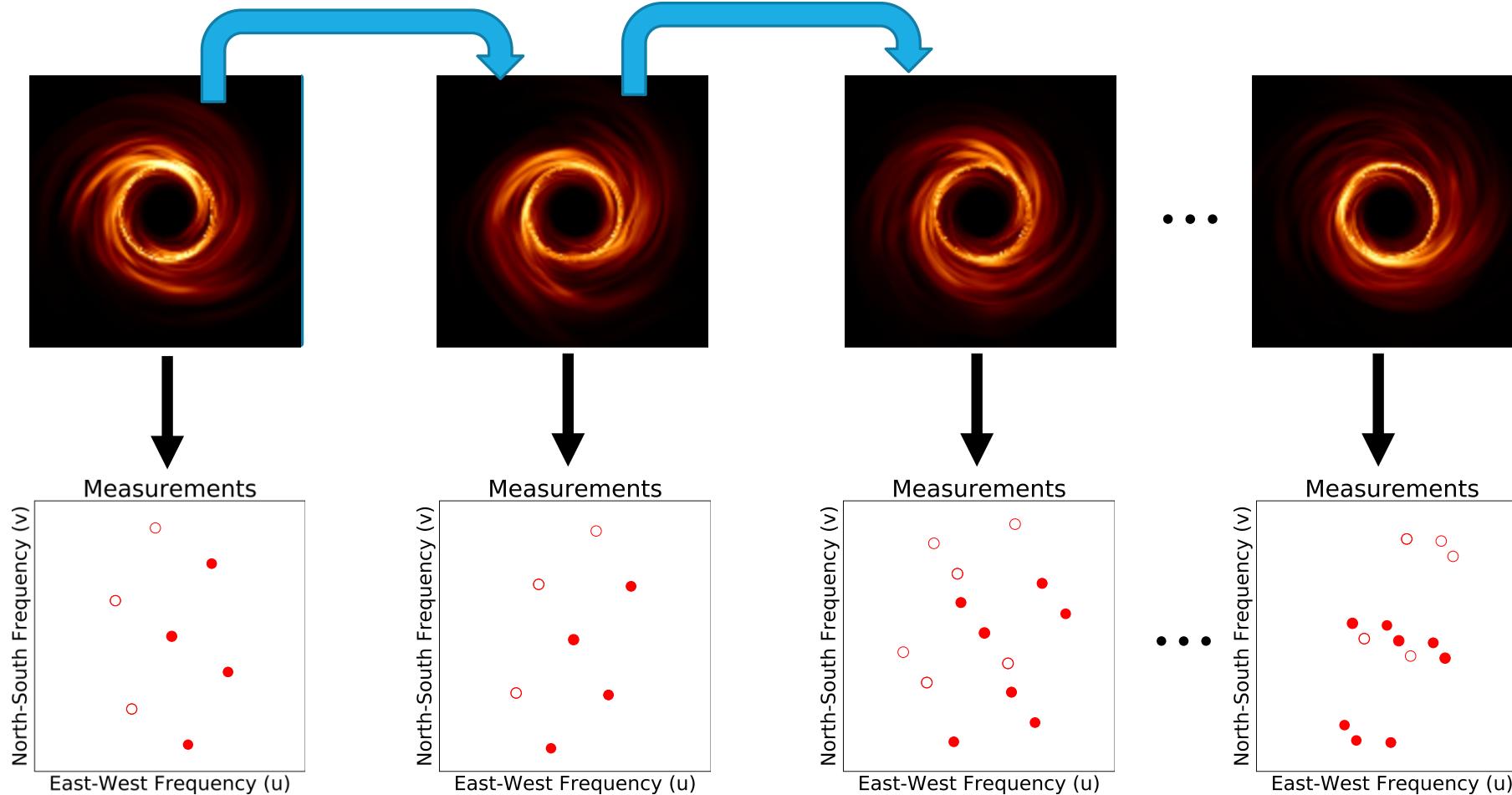
TIME



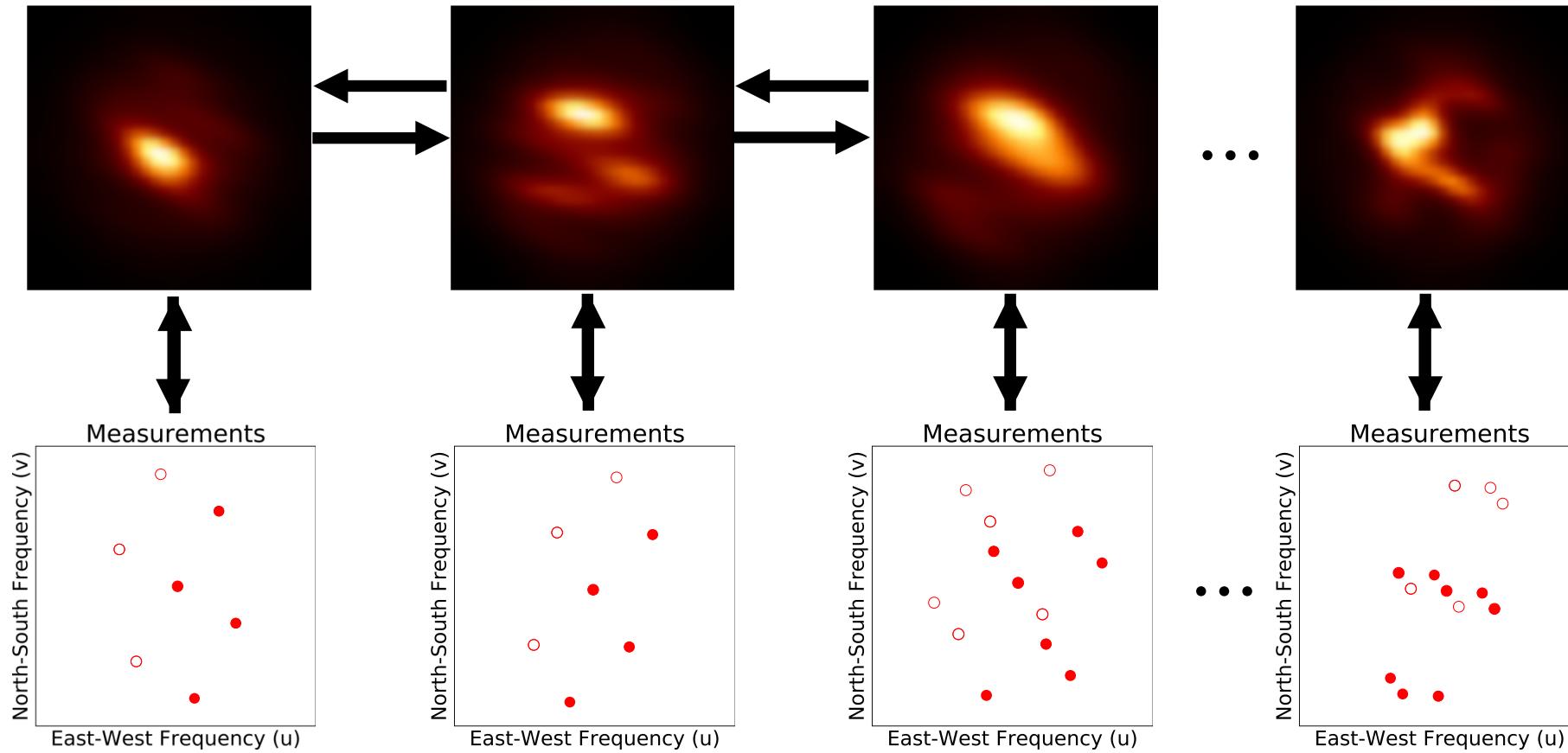
New Observation at Each Time



Small Appearance Change Over Time

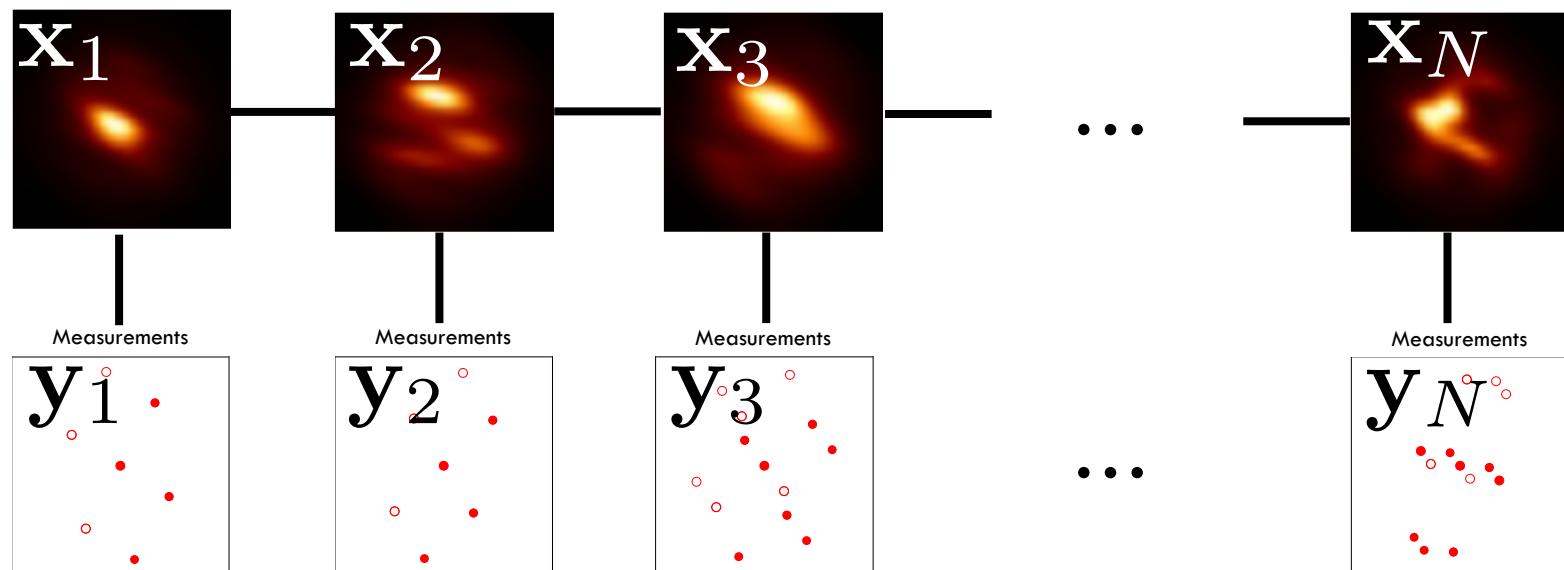


Reconstructing Each Snapshot



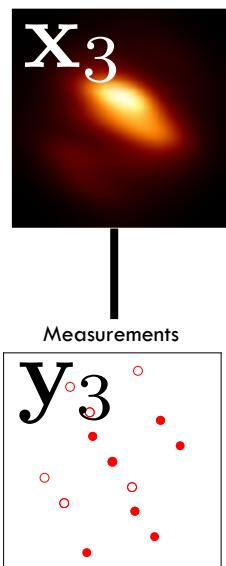
Solving for the Video

$$p(\mathbf{X}, \mathbf{Y}) \propto \prod_{t=1}^N \varphi_{\mathbf{y}_t | \mathbf{x}_t} \prod_{t=1}^N \varphi_{\mathbf{x}_t} \prod_{t=2}^N \varphi_{\mathbf{x}_t | \mathbf{x}_{t-1}}$$



Solving for the Video: Data Consistency

$$p(\mathbf{X}, \mathbf{Y}) \propto \prod_{t=1}^N \varphi_{\mathbf{y}_t | \mathbf{x}_t} \prod_{t=1}^N \varphi_{\mathbf{x}_t} \prod_{t=2}^N \varphi_{\mathbf{x}_t | \mathbf{x}_{t-1}}$$



DATA CONSISTENCY:
Each video frame should be consistent
with the data taken at it's
corresponding time

Solving for the Video: Image Prior

$$p(\mathbf{X}, \mathbf{Y}) \propto \prod_{t=1}^N \varphi_{\mathbf{y}_t | \mathbf{x}_t} \prod_{t=1}^N \varphi_{\mathbf{x}_t} \prod_{t=2}^N \varphi_{\mathbf{x}_t | \mathbf{x}_{t-1}}$$

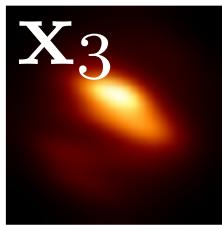
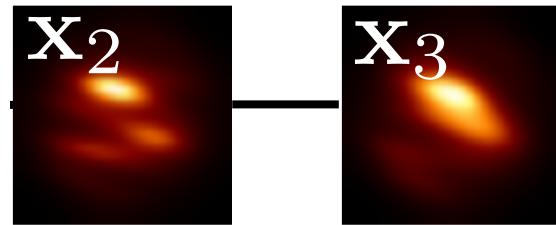


IMAGE PRIOR:
Each video frame should look like
how we expect images to look

Solving for the Video: Frame Similarity

$$p(\mathbf{X}, \mathbf{Y}) \propto \prod_{t=1}^N \varphi_{\mathbf{y}_t | \mathbf{x}_t} \prod_{t=1}^N \varphi_{\mathbf{x}_t} \prod_{t=2}^N \varphi_{\mathbf{x}_t | \mathbf{x}_{t-1}}$$

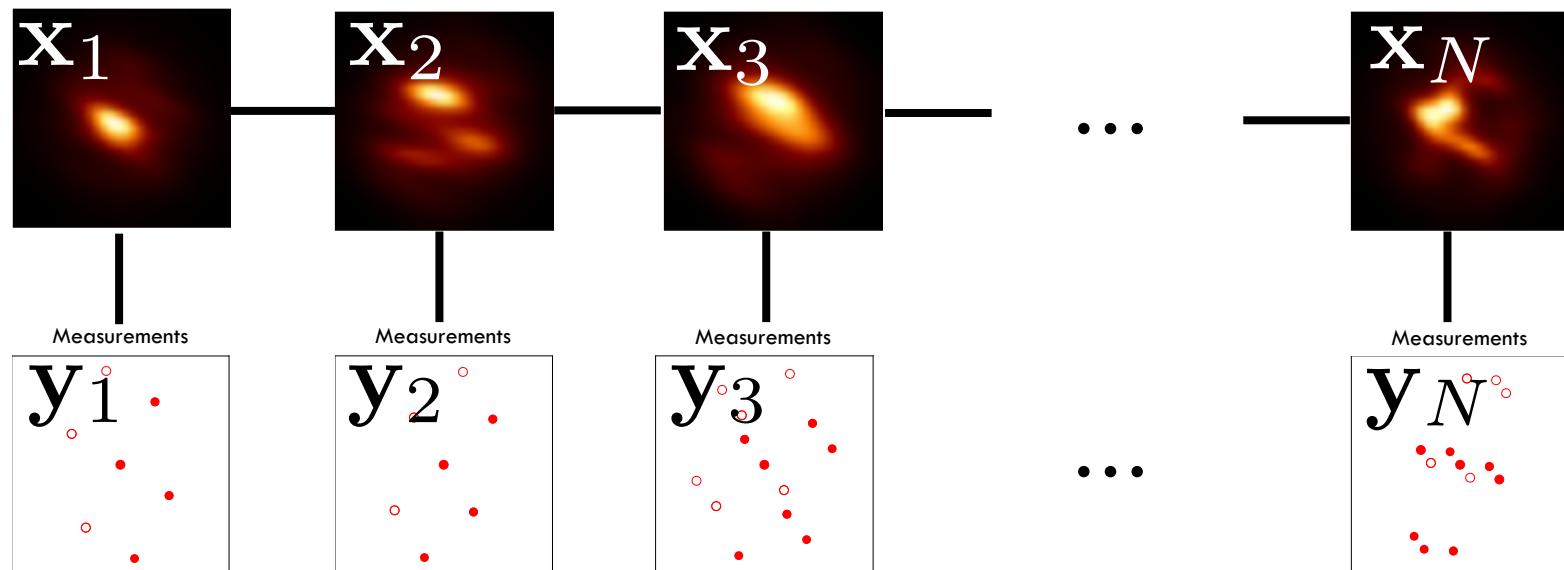


FRAME SIMILARITY:

Each video frame should look similar
to its adjacent video frames

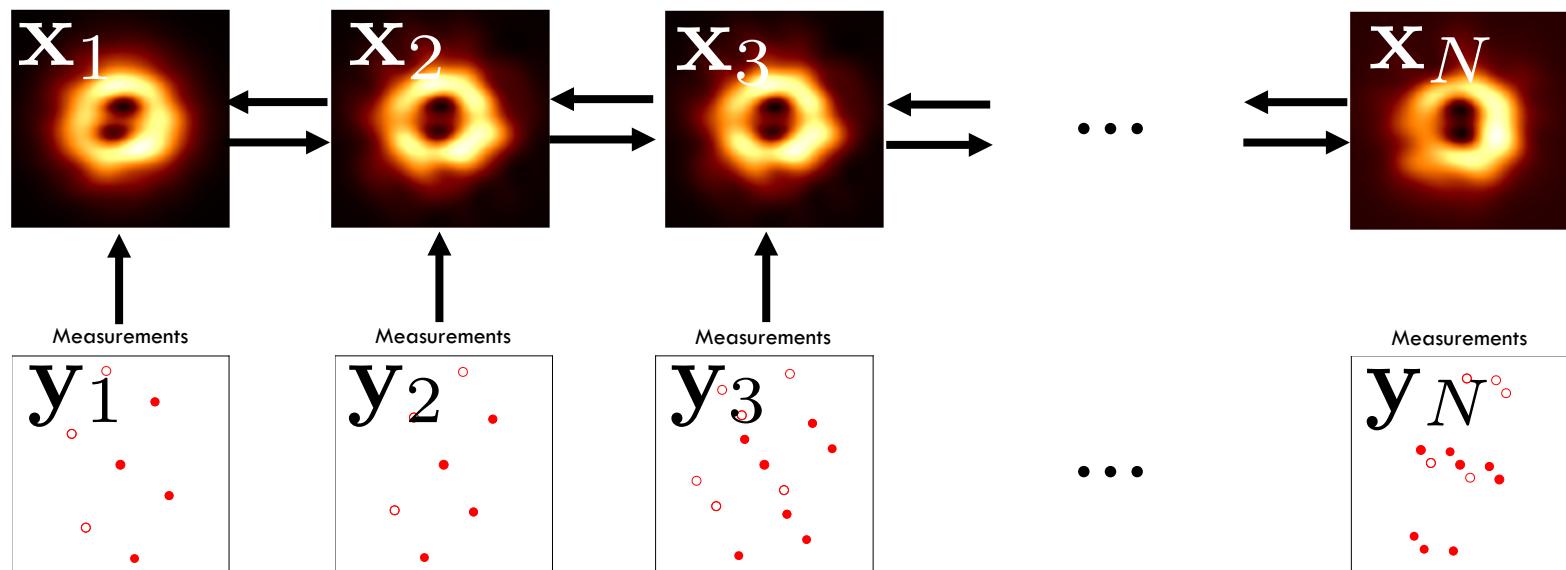
Solving for the Video

$$p(\mathbf{X}, \mathbf{Y}) \propto \prod_{t=1}^N \varphi_{\mathbf{y}_t | \mathbf{x}_t} \prod_{t=1}^N \varphi_{\mathbf{x}_t} \prod_{t=2}^N \varphi_{\mathbf{x}_t | \mathbf{x}_{t-1}}$$

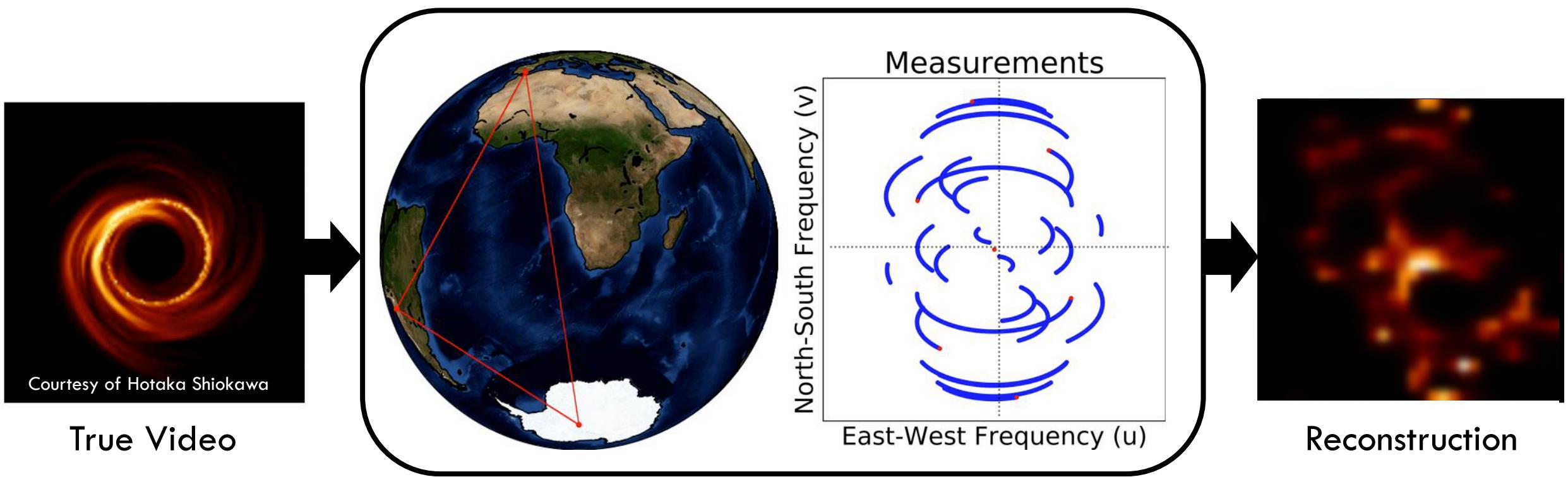


Solving for the Video

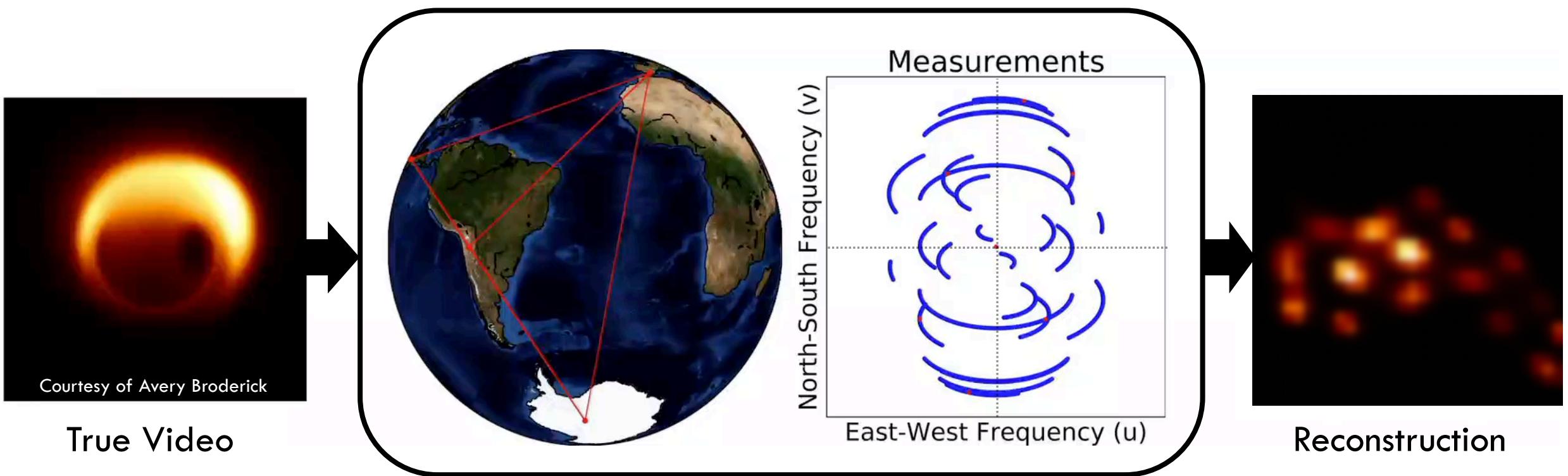
$$p(\mathbf{X}, \mathbf{Y}) \propto \prod_{t=1}^N \varphi_{\mathbf{y}_t | \mathbf{x}_t} \prod_{t=1}^N \varphi_{\mathbf{x}_t} \prod_{t=2}^N \varphi_{\mathbf{x}_t | \mathbf{x}_{t-1}}$$



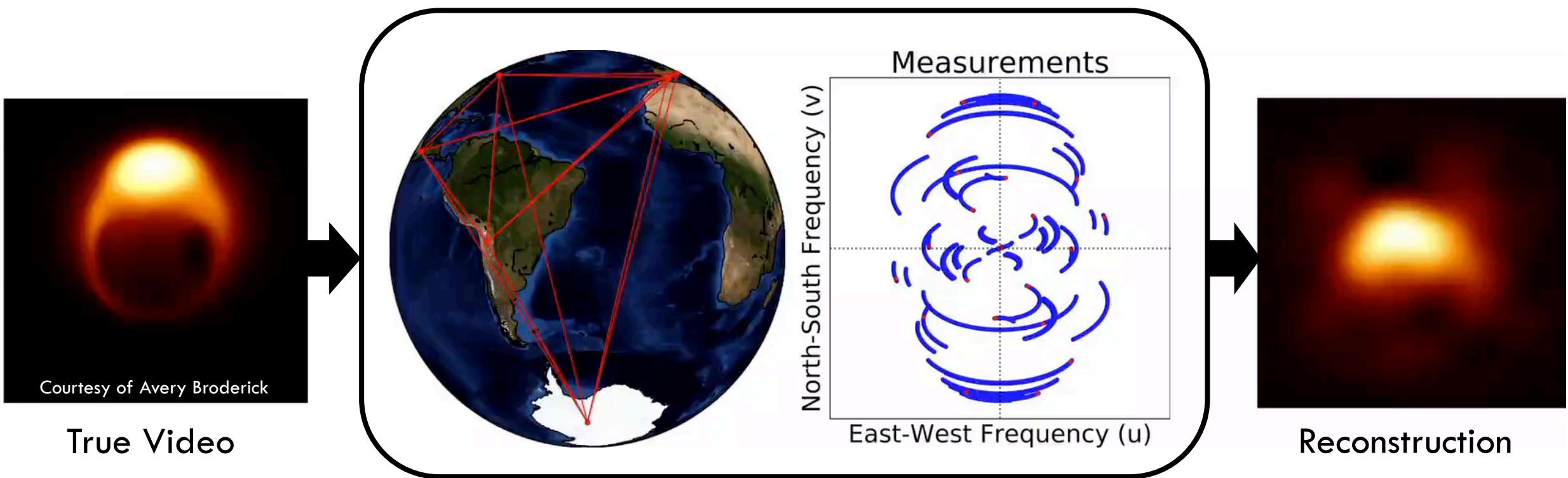
Video Reconstruction: EHT 2017 Array



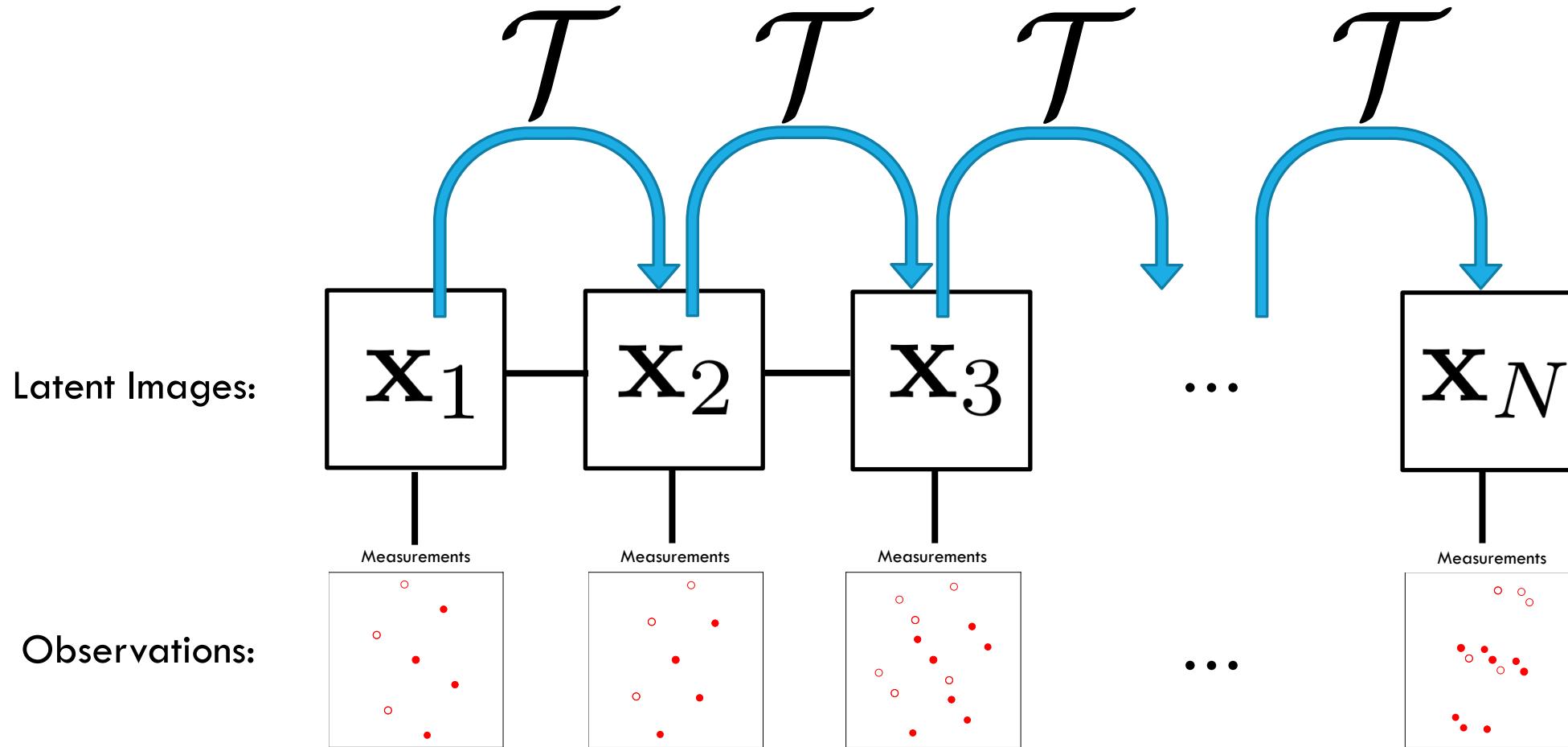
Video Reconstruction: EHT 2017 Array



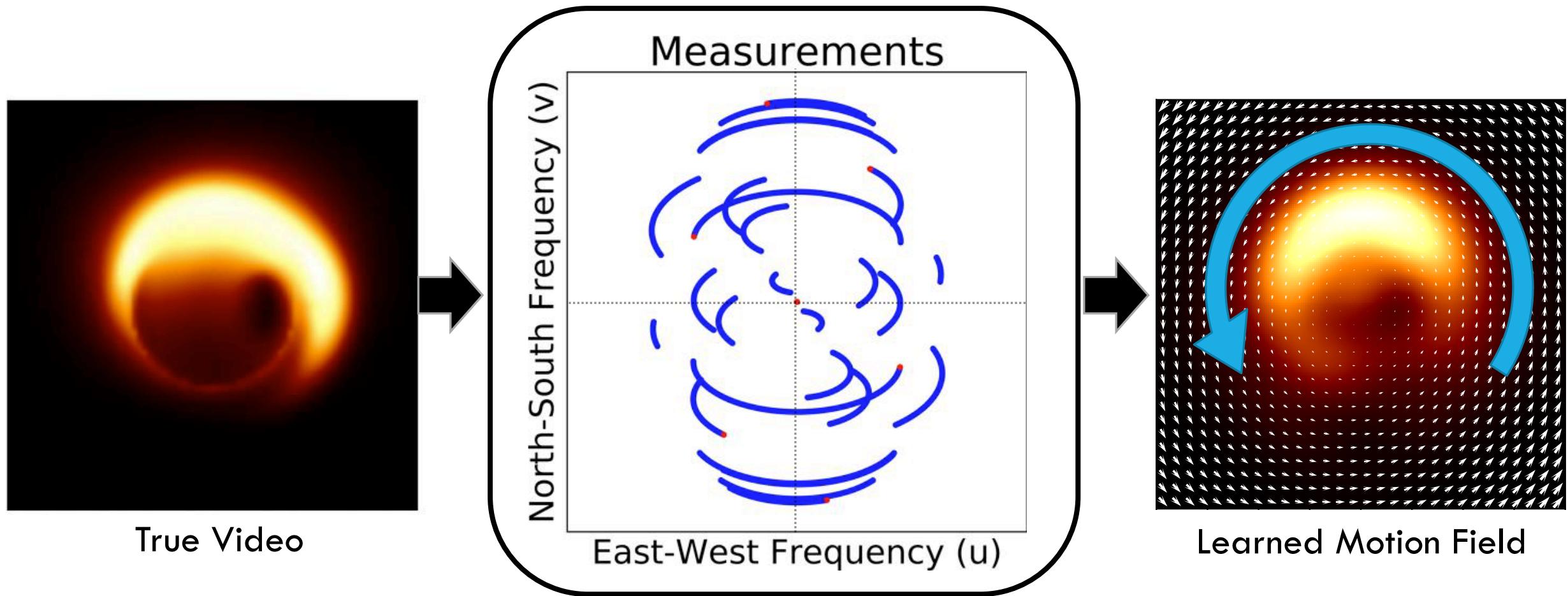
Video Reconstruction: EHT 2017++ Array



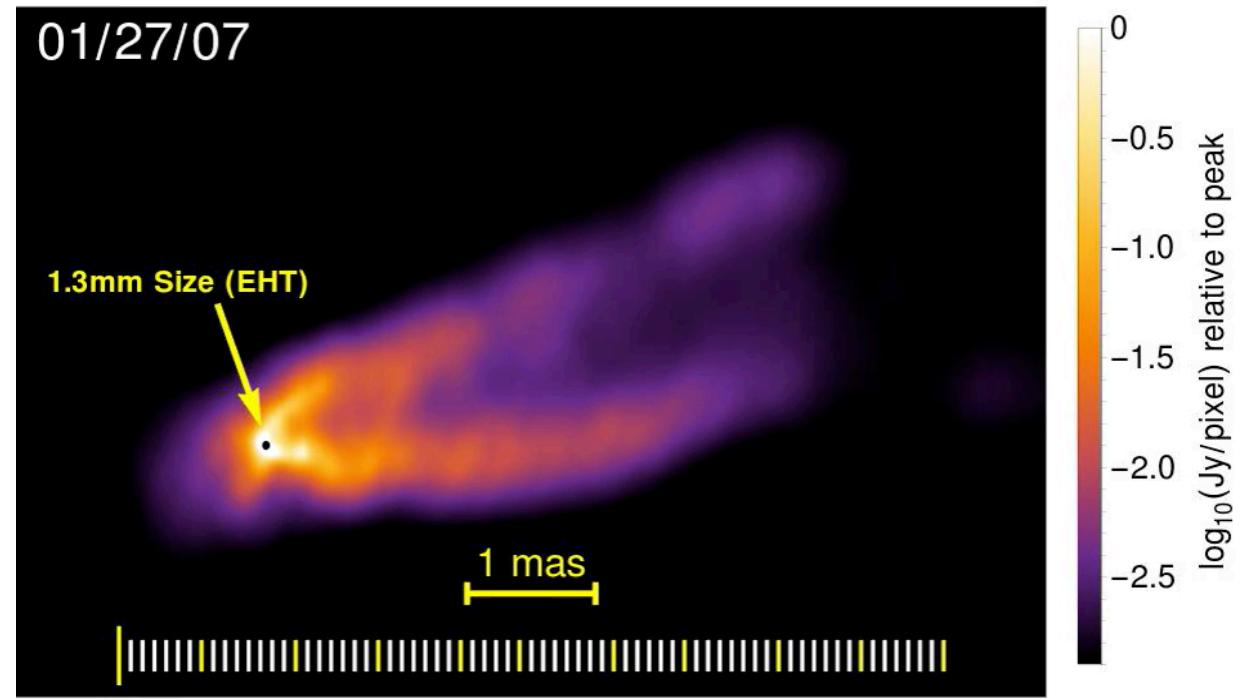
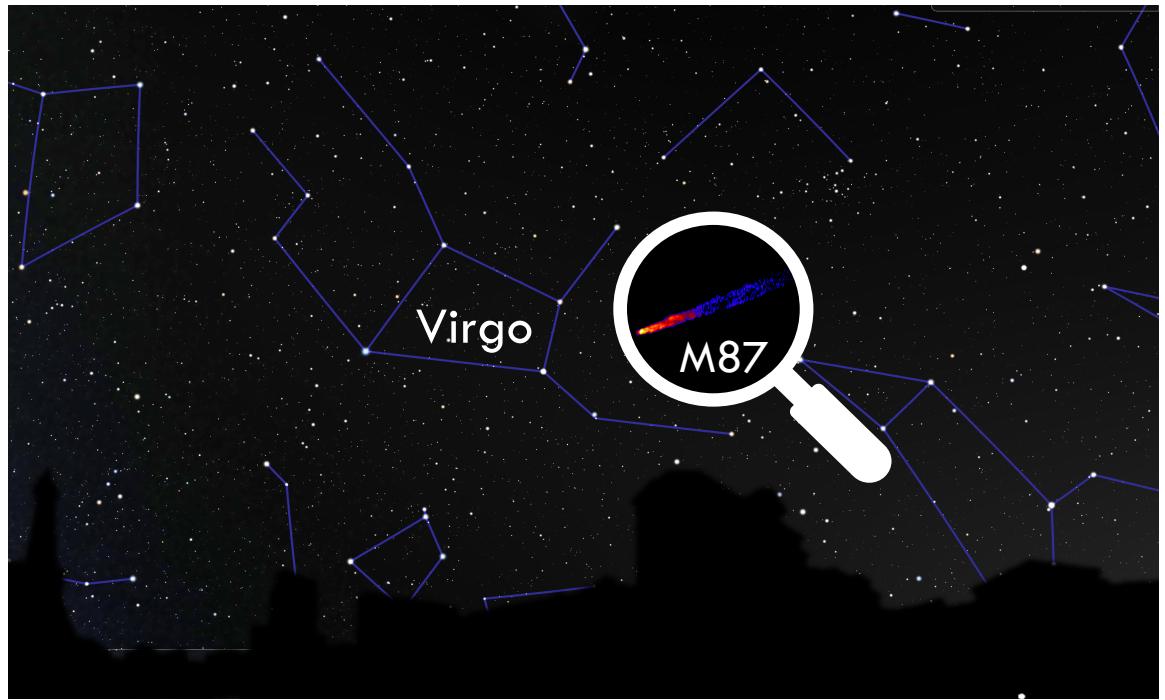
Simultaneously Solve for Motion Transformation



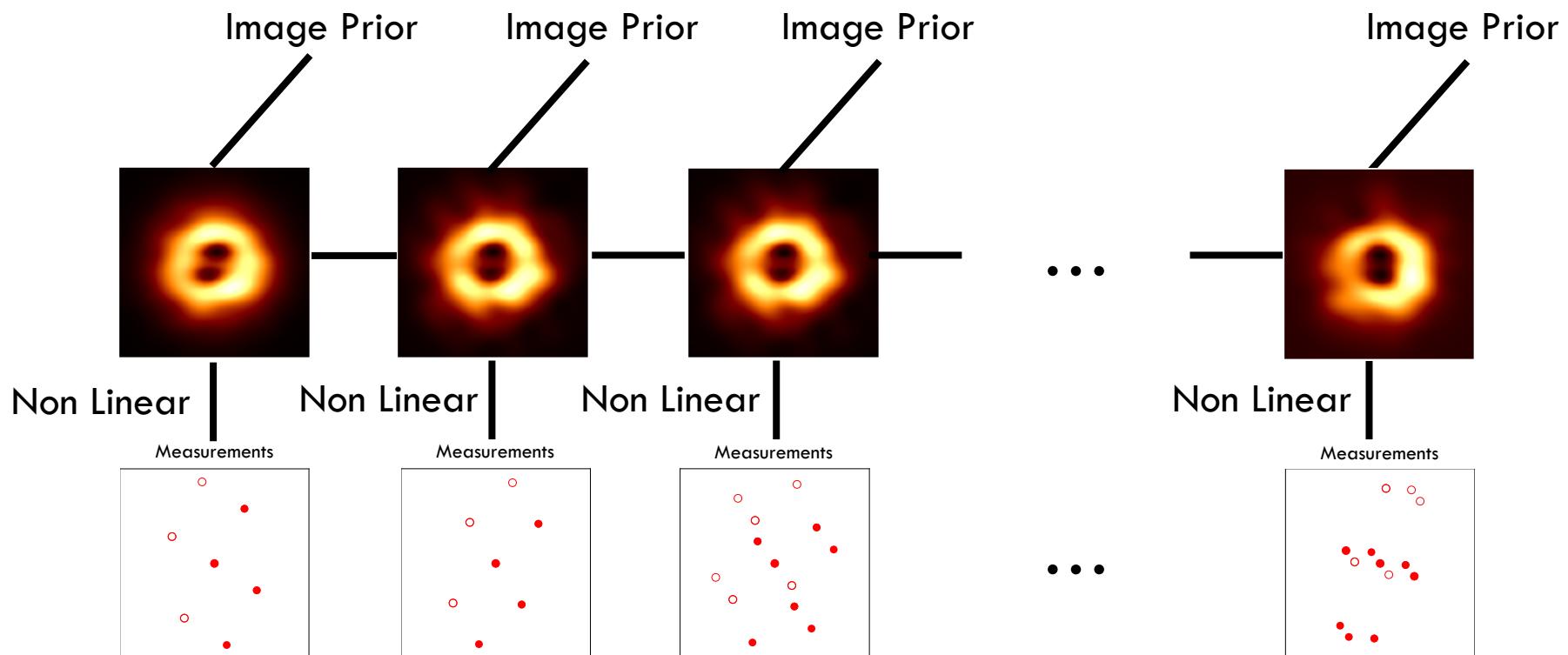
Learning the Approximate Persistent Motion



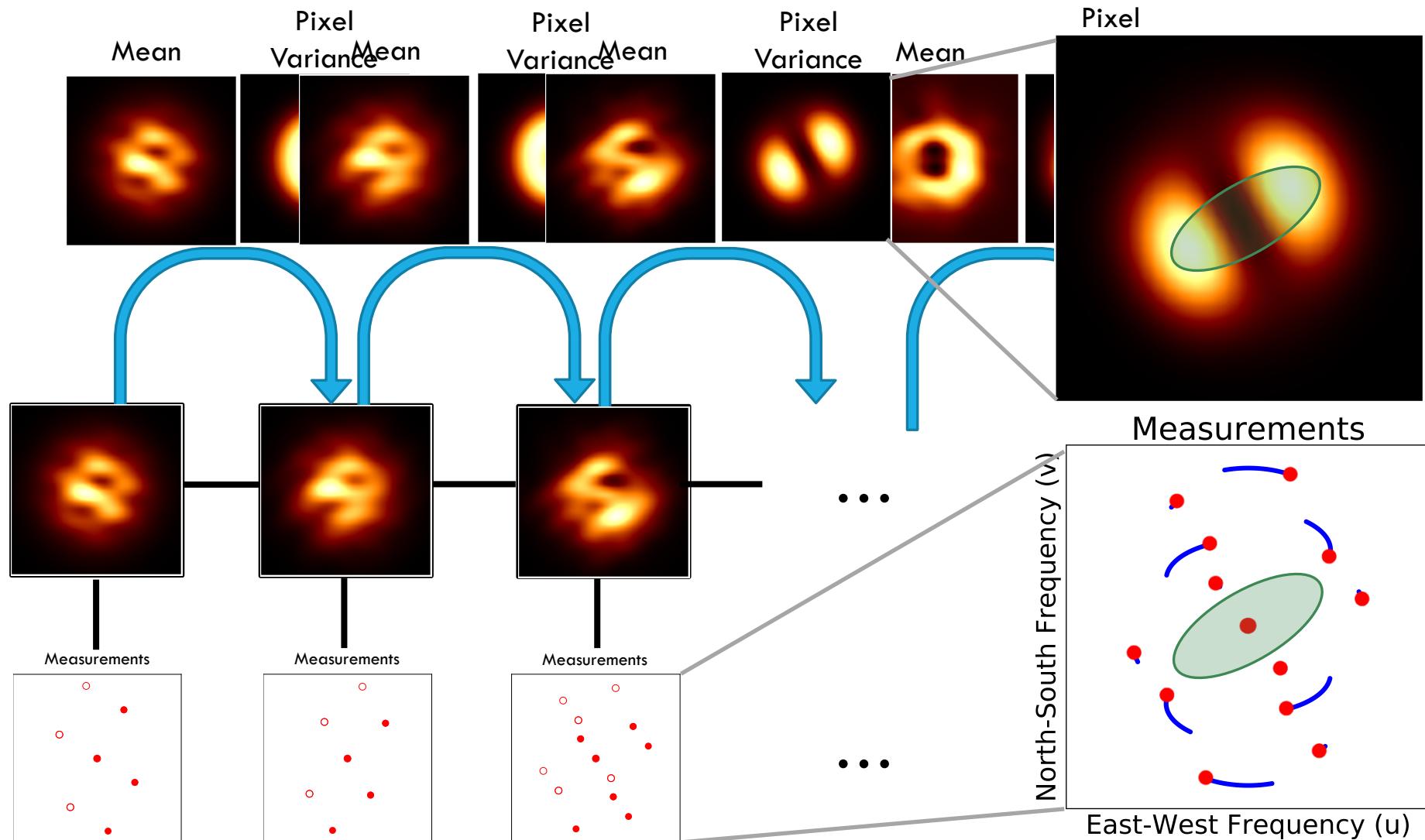
Generating Movies from Real Radio Data



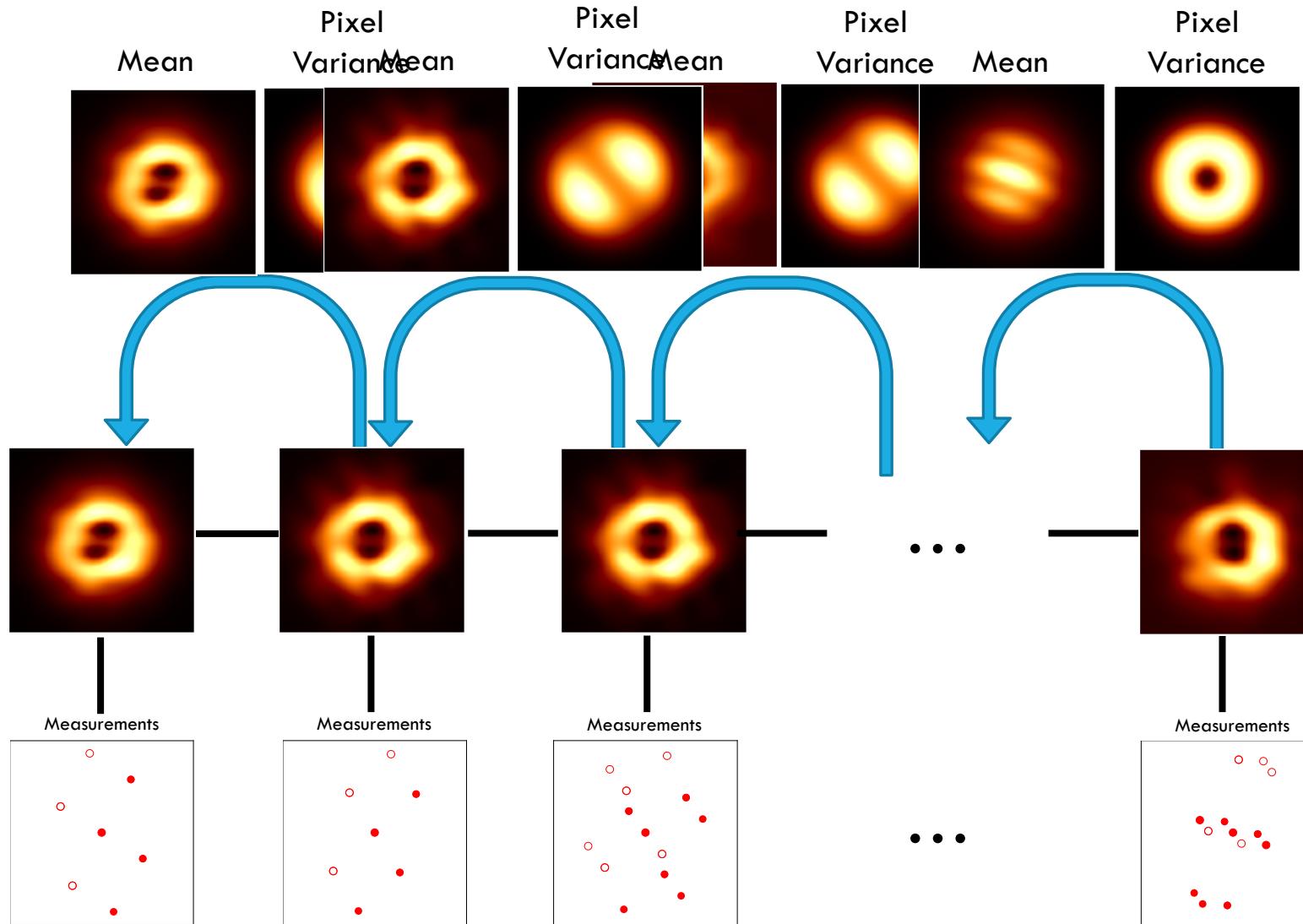
Forward-Backward Optimization to Find Most Likely Image Given All Measurements



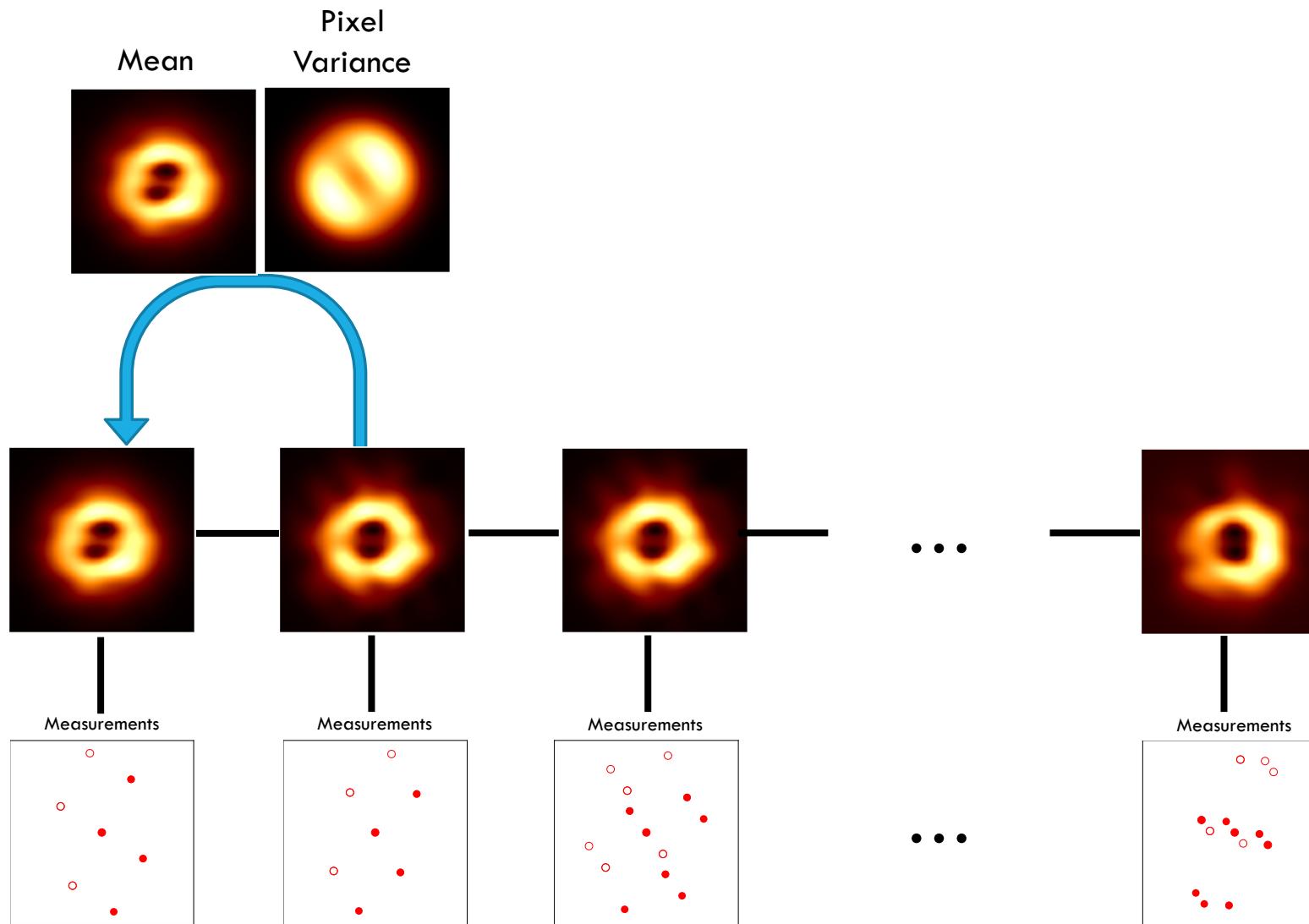
Solving for the Video: Optimization



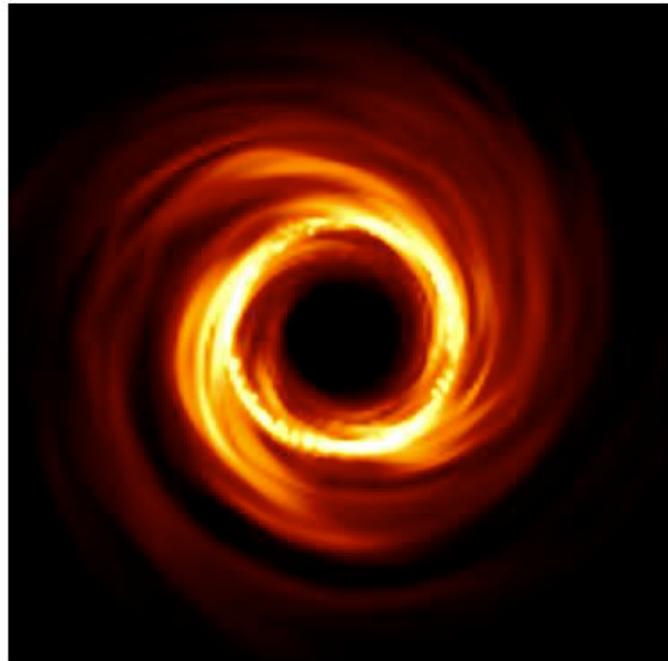
Solving for the Video: Optimization



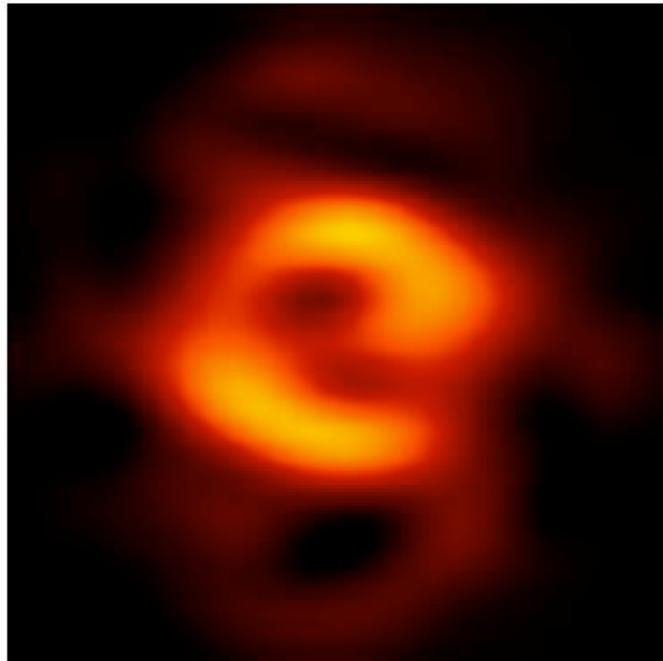
Solving for the Video: Optimization



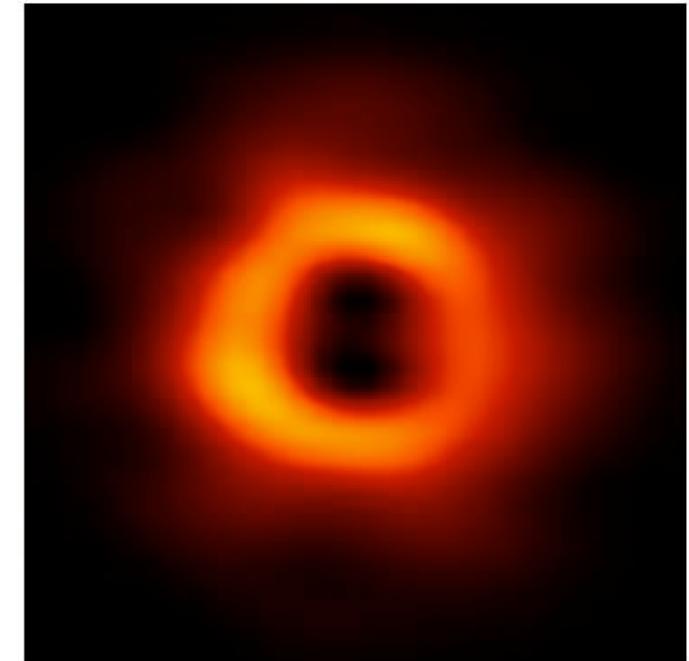
Propagating Uncertainty



Ground Truth Video

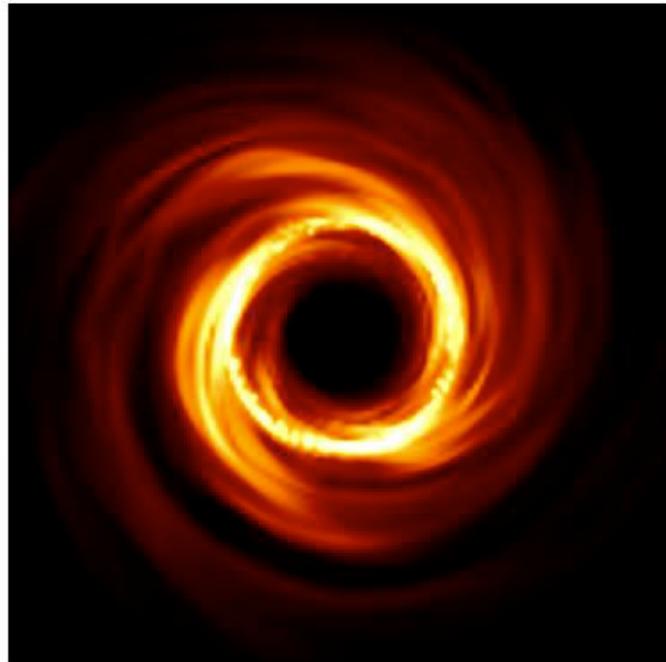


No Propagation
of Uncertainty

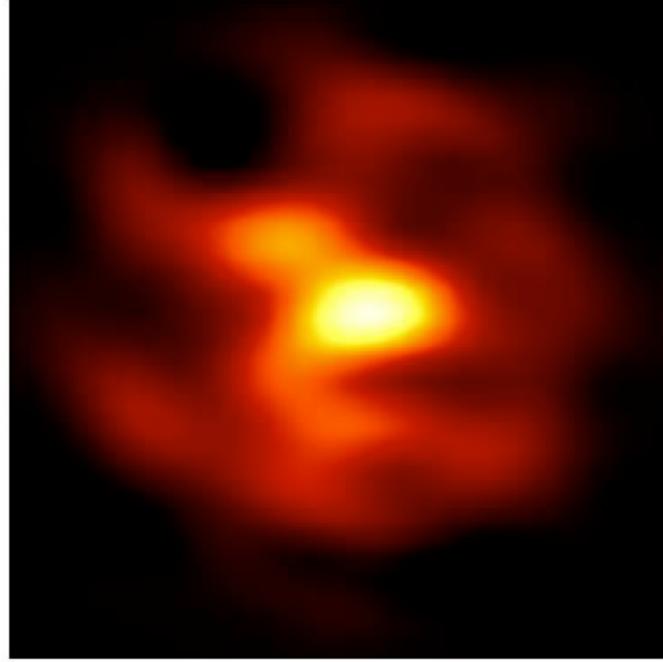


Our Method

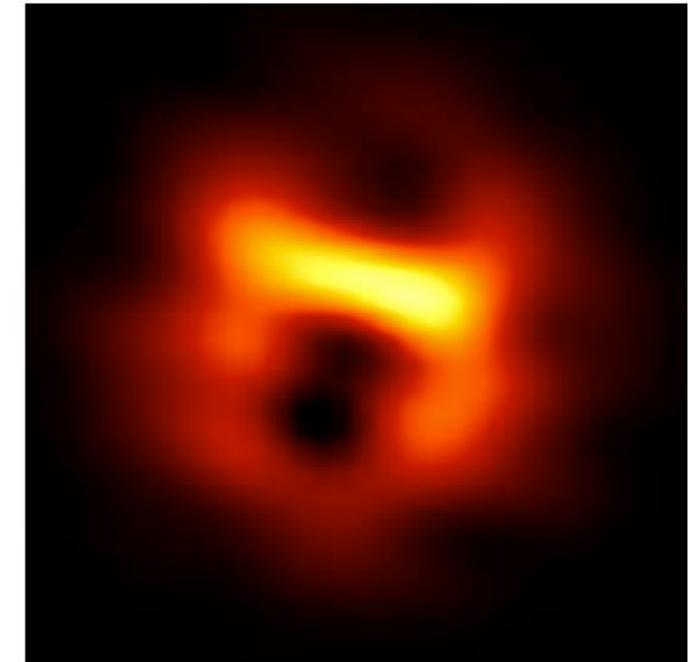
Propagating Uncertainty: More Realistic Data



Ground Truth Video

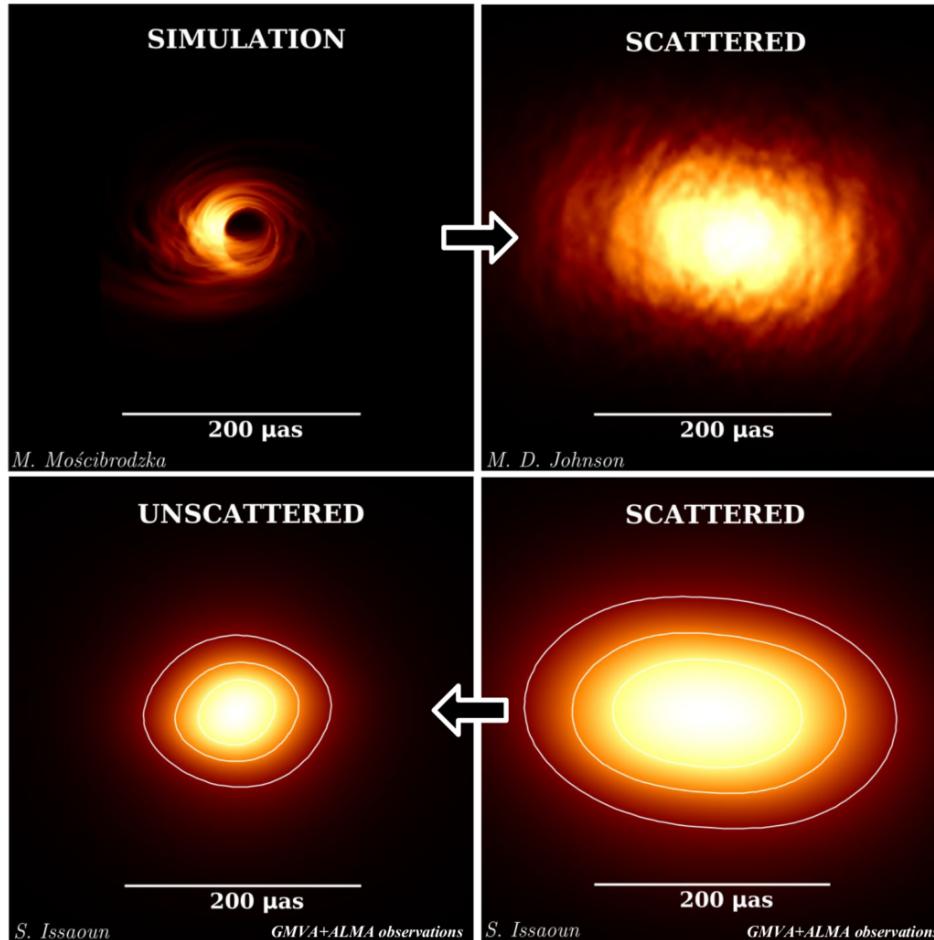
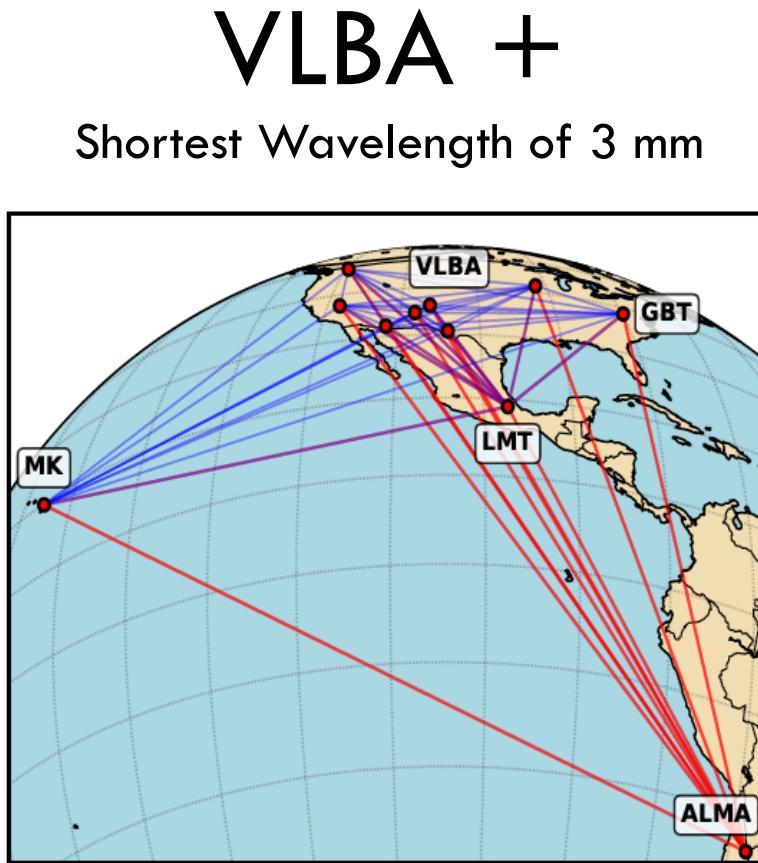


No Propagation
of Uncertainty



Our Method

Can We Easily Add Other Telescopes?



~~Can We Easily Add Other Telescopes?~~

Option 1: Build/Equip New Ground Sites

There are a limited number of high-altitude locations suitable for siting antennas that observe at ~ 1 mm

Option 2: Go to Space! Build/Launch Low-Earth Orbiters

Expanding the EHT to Space

“Metrics and Motivations for Earth-Space VLBI: Time-Resolving Sgr A* with the Event Horizon Telescope” (in submission)

A Brief History of Space-VLBI

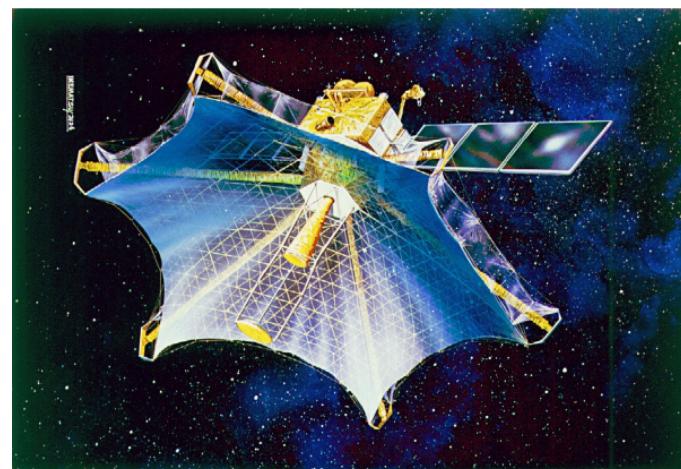
1986-1988



Tracking and Data Relay Satellite (TDRSS)

- Shortest wavelength of 2 cm
- Baseline of 2.2 Earth Diameters
- 24 hour period
- 5.8 m dish

1997-2003



VLBI Space Observatory Program (VSOP)

- Shortest wavelength of 6 cm
- Baseline of 3 Earth Diameters
- 6.3 hour period
- 8.8 m dish

2011-2019

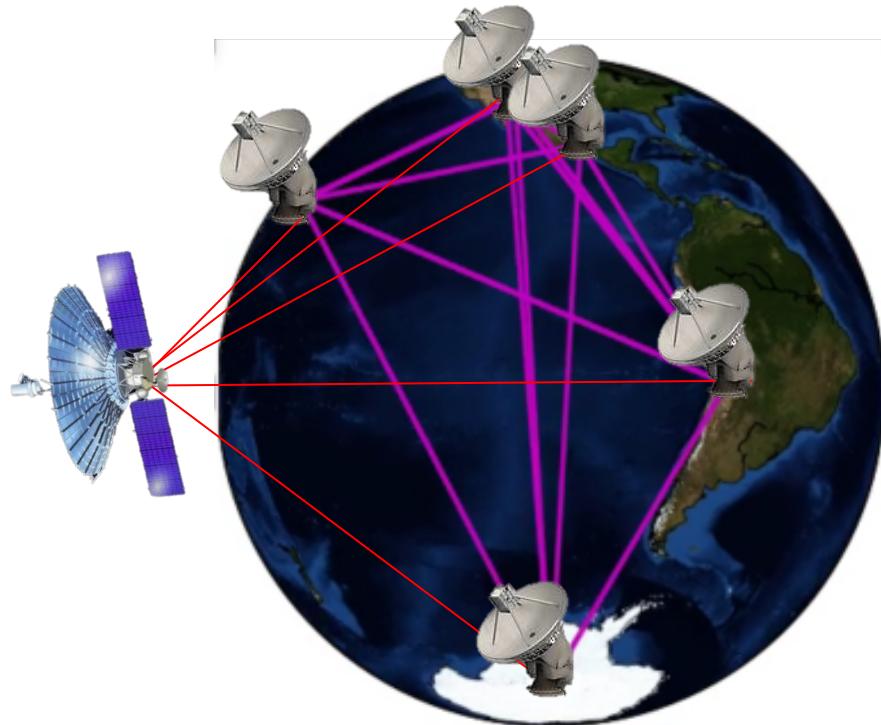


RadioAstron

- Shortest wavelength of 1.3 cm
- Baseline of 28 Earth Diameters
- 8.5 day period
- 10 m dish

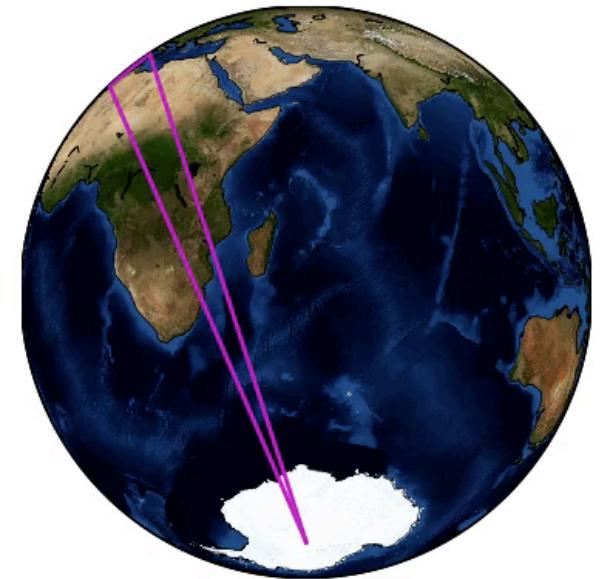
Angular resolution of ~10 uas....
but at 1.3 CENTIMETERS...NOT MILLIMETERS

Adding Face-On Low Earth Orbiters

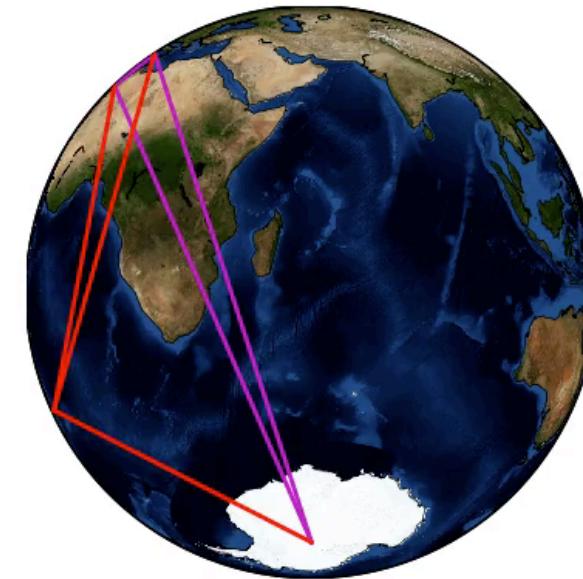


- Observes at 0.8-1.3 mm wavelength
- Baseline of \sim 1 Earth Diameter
- Has a Fast Period of \sim 90 minutes
- Always in the line of sight of the black hole

Low Earth Orbiters: 90 minute period

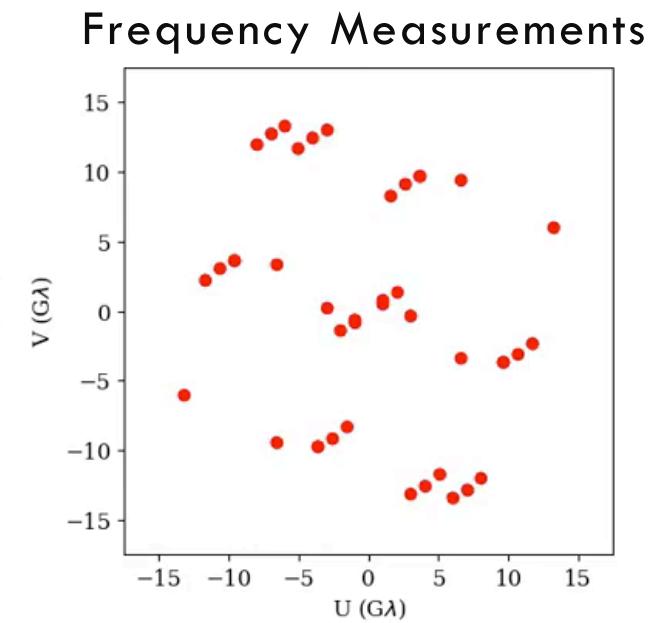
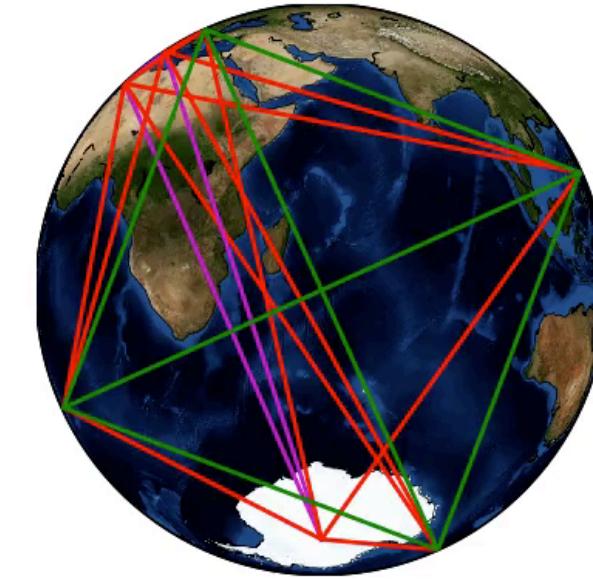
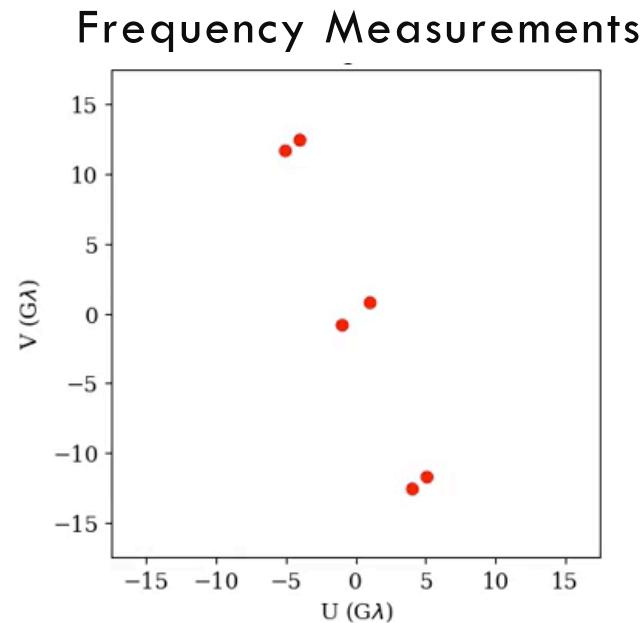
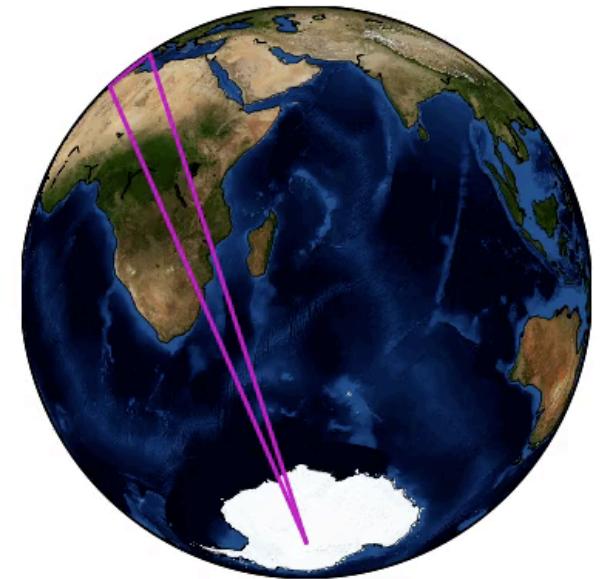


EHT's Current Ground Based Sites



EHT's Current Ground Based Sites
+ 1 Low-Earth Orbiter

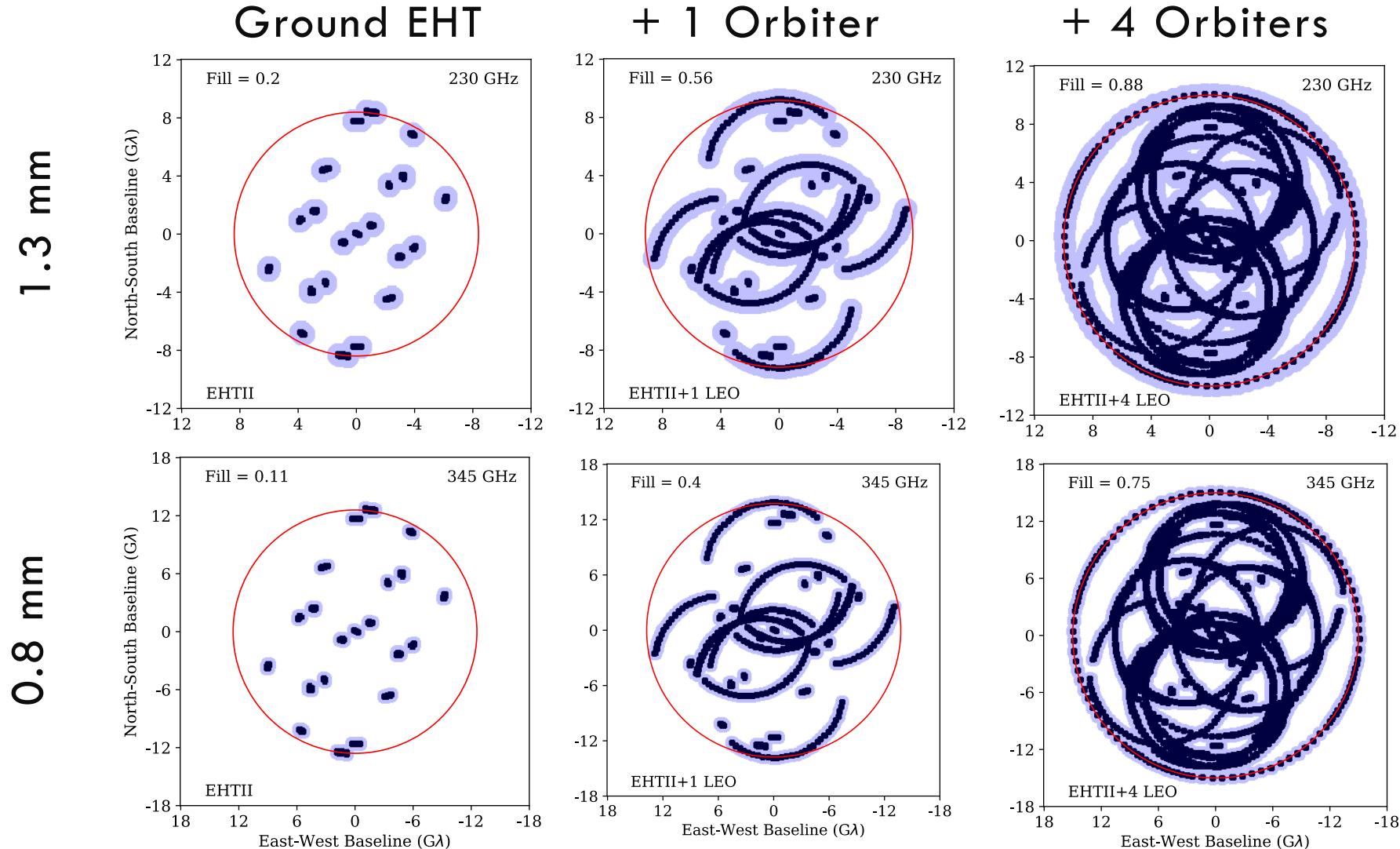
Low Earth Orbiters: 90 minute period



EHT's Current Ground Based Sites

EHT's Current Ground Based Sites
+ 4 Low-Earth Orbiter

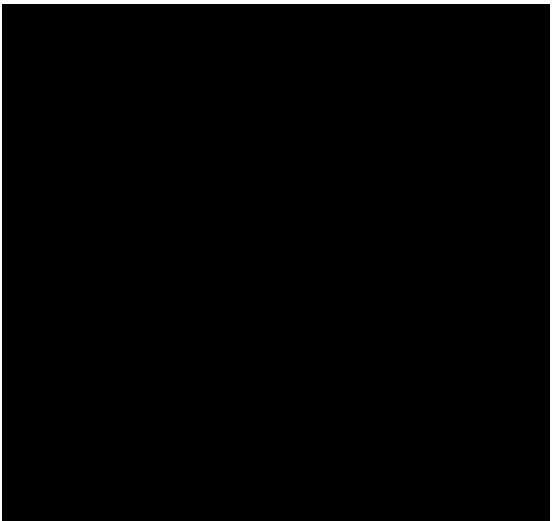
Fourier Coverage Within 30 minutes



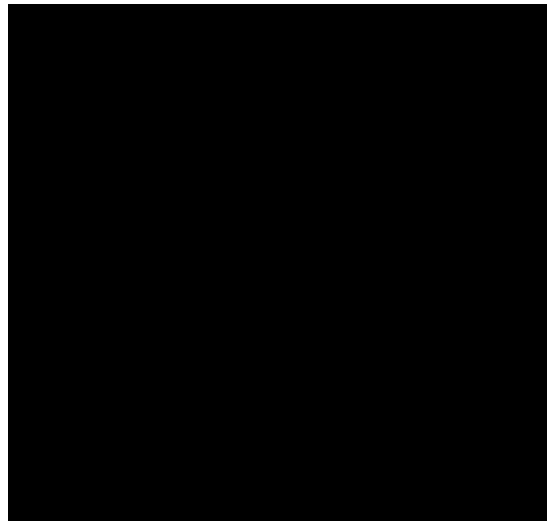
$$\approx \frac{\text{Wavelength}}{\text{Maximum Baseline}}$$

Reconstructions: Face on Turbulence

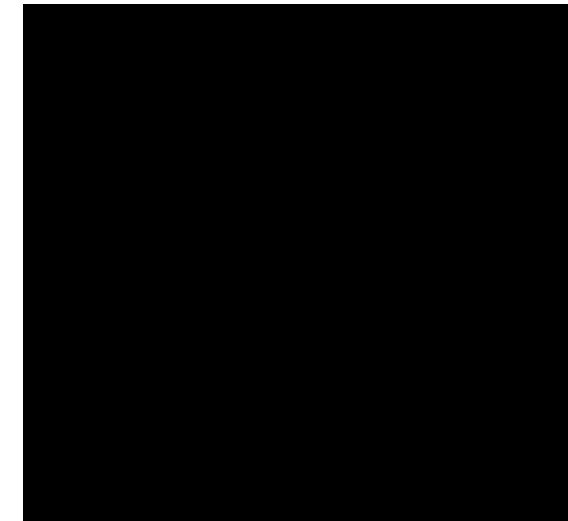
Truth Video



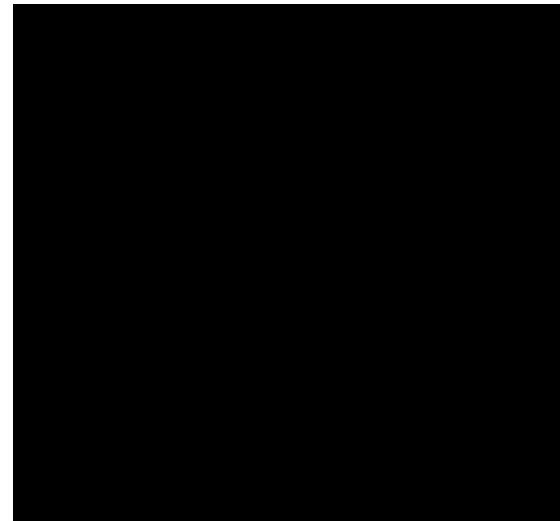
EHT Ground Sites



+ 1 Orbiter

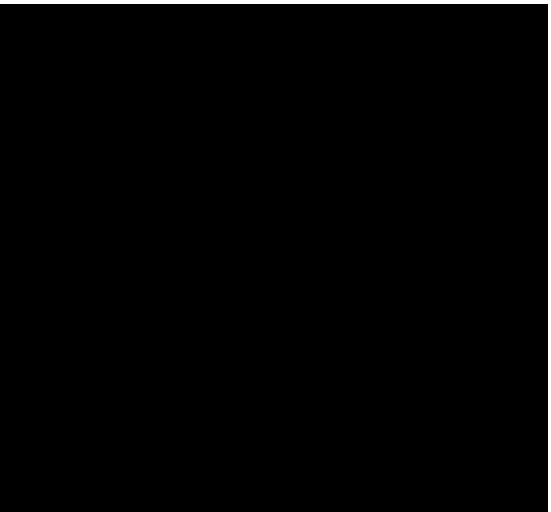


+ 4 Orbiters

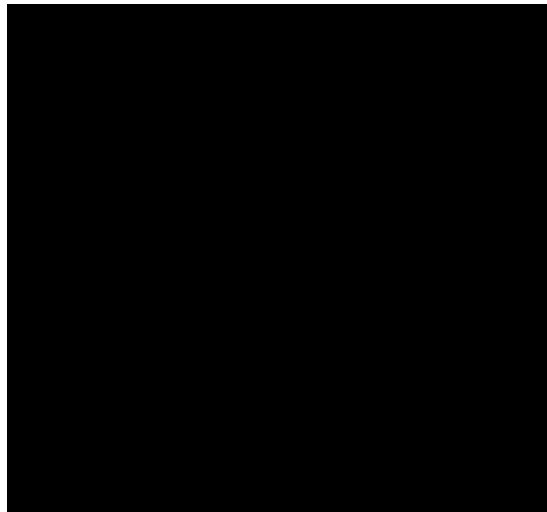


Reconstructions: Hot Spot

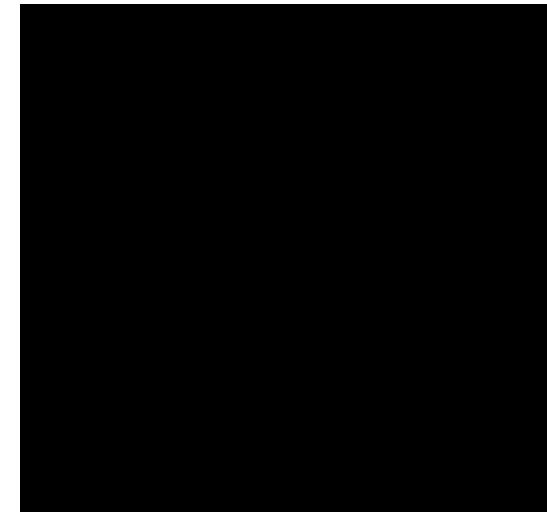
Truth Video



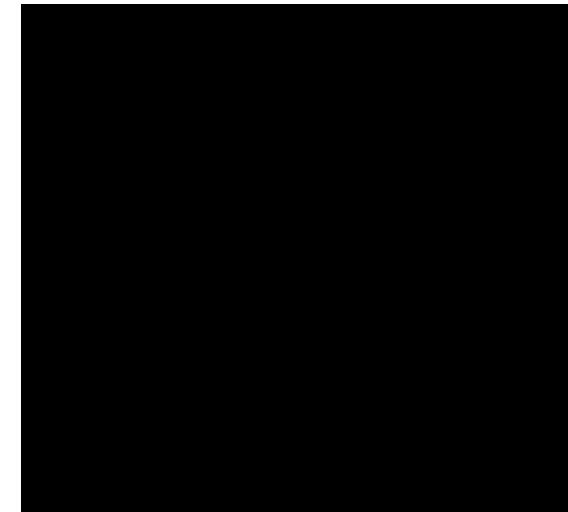
EHT Ground Sites



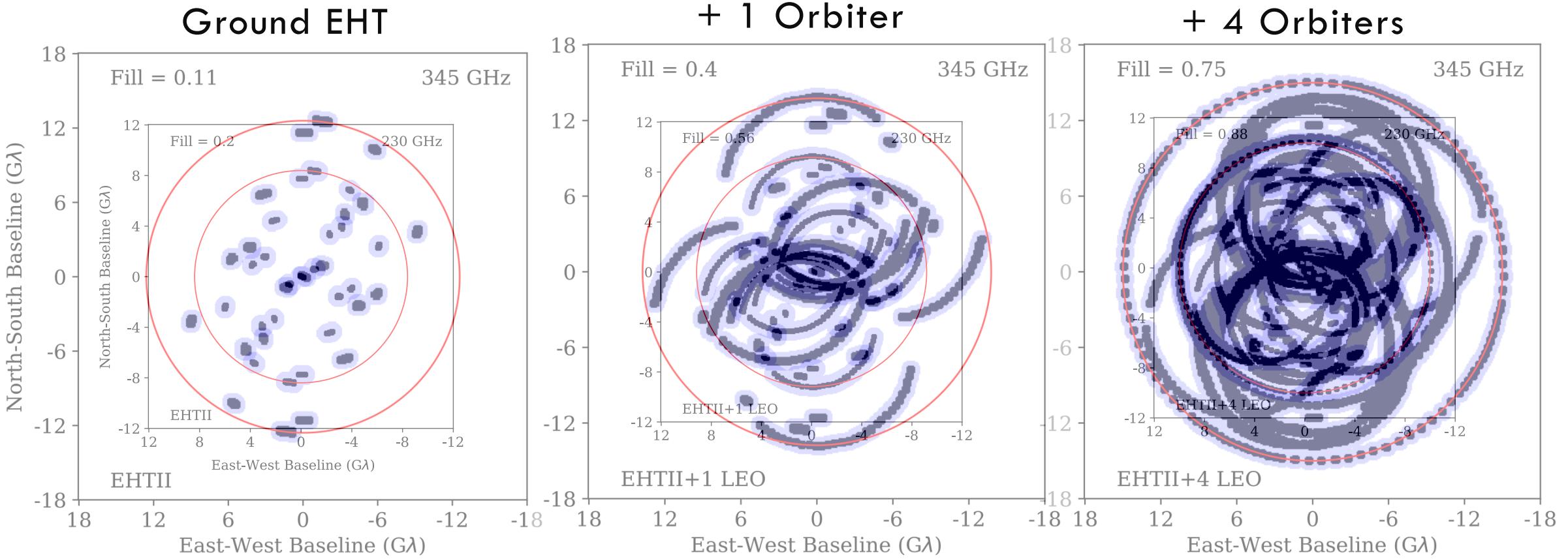
+ 1 Orbiter



+ 4 Orbiters



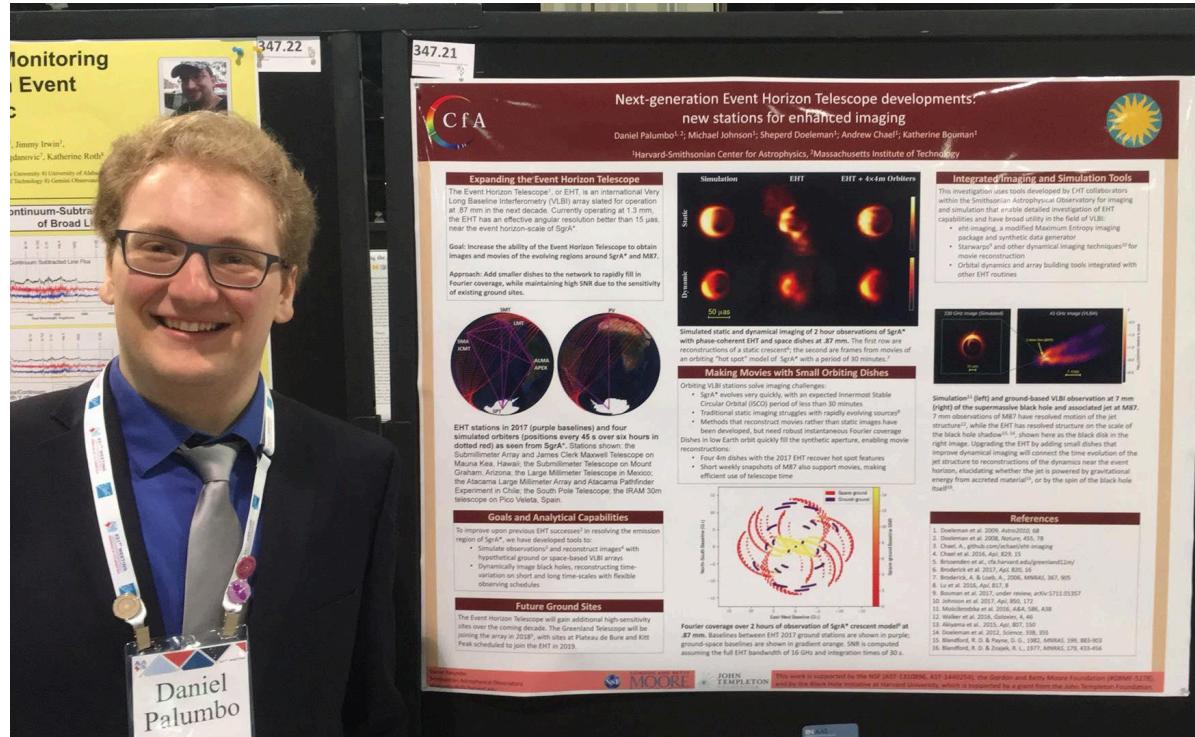
Merging the 0.8 and 1.3 mm Coverage



Hardware Needs/Limitations

Goal: Thermal Noise should be < 20 mJy

- Averaging Time (coherence time)
 - Ground sites are limited by the atmosphere
 - Space orbiters are limited by how much you can average in an image's frequency space without encountering phase wraps (more compact images allow longer averaging)
- Bandwidth around observed light frequency
- Dish and Receiver Quality (SEFD)
 - Dish Size
 - 4 meter can fit in Space X Falcon 9
 - Dish Efficiency
 - Receiver Temperature

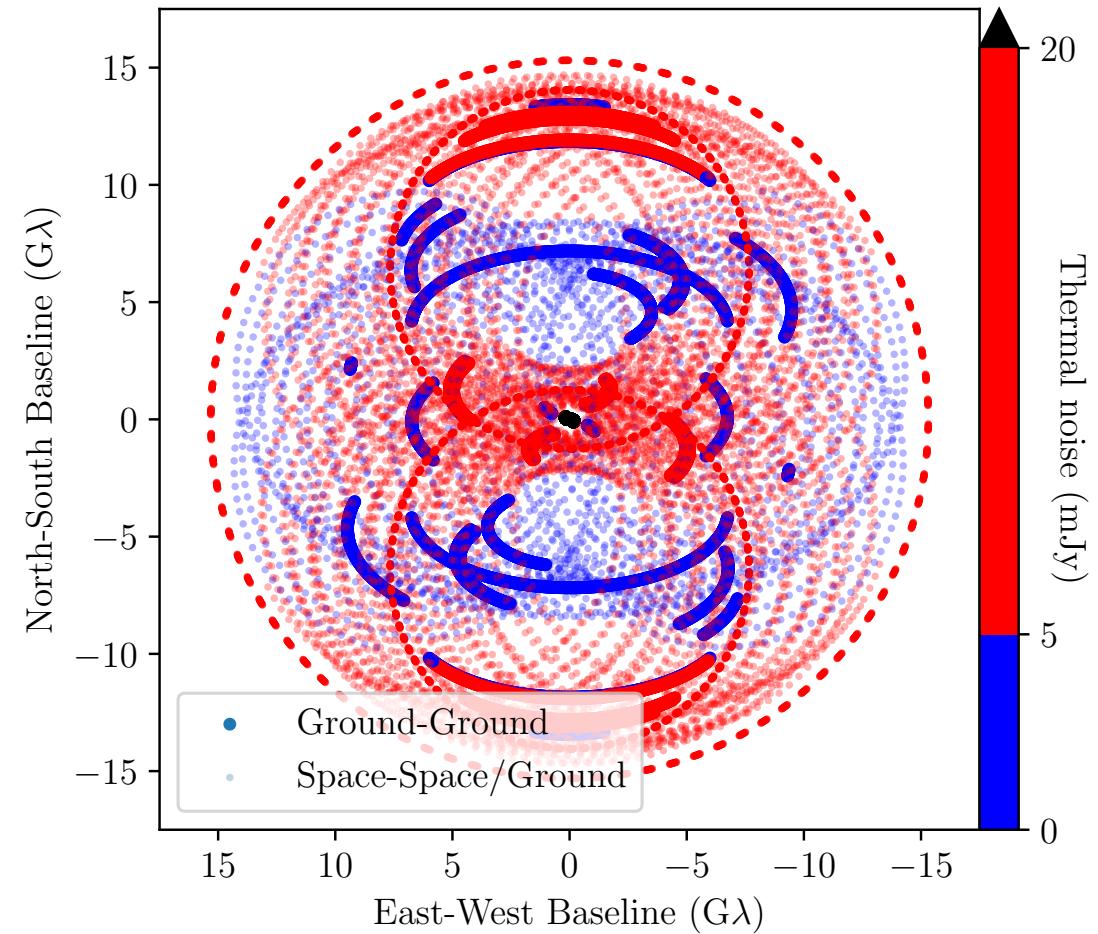


Daniel Palumbo

Hardware Needs/Limitations

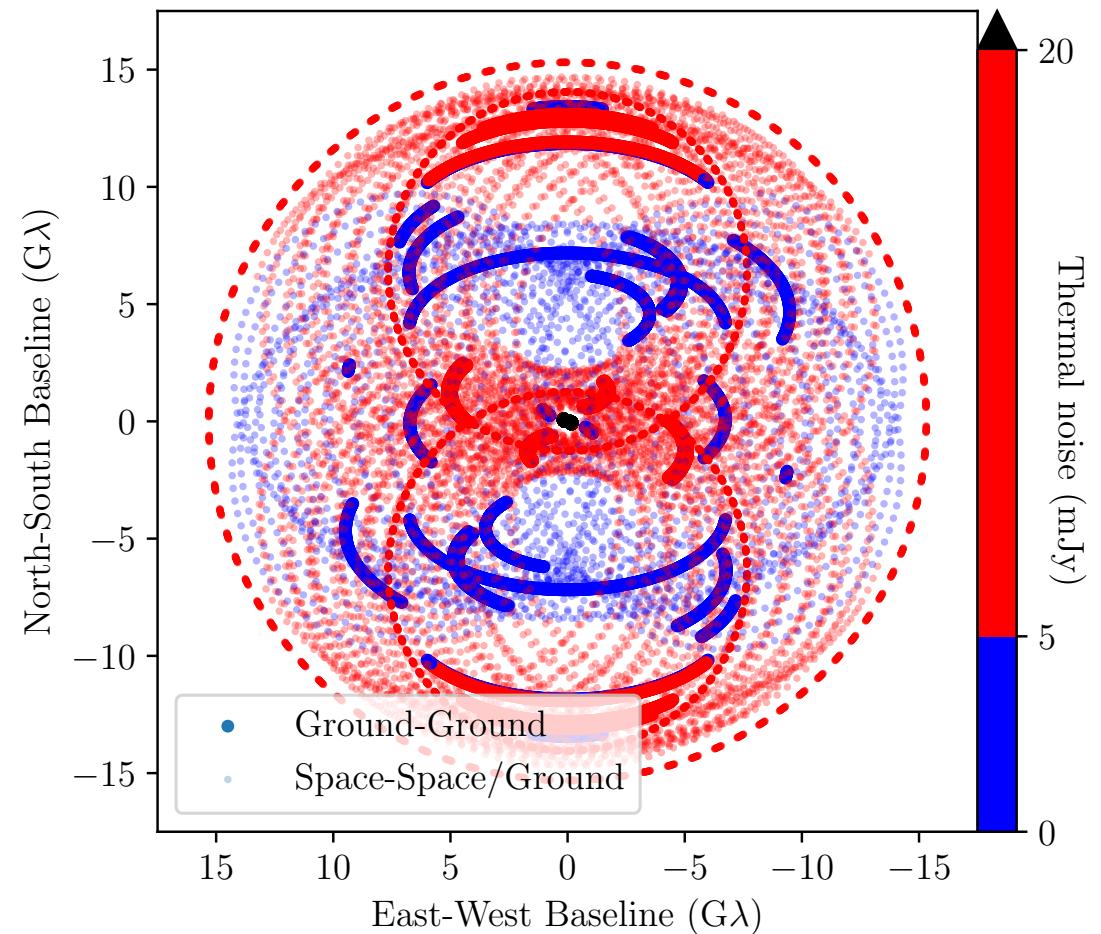
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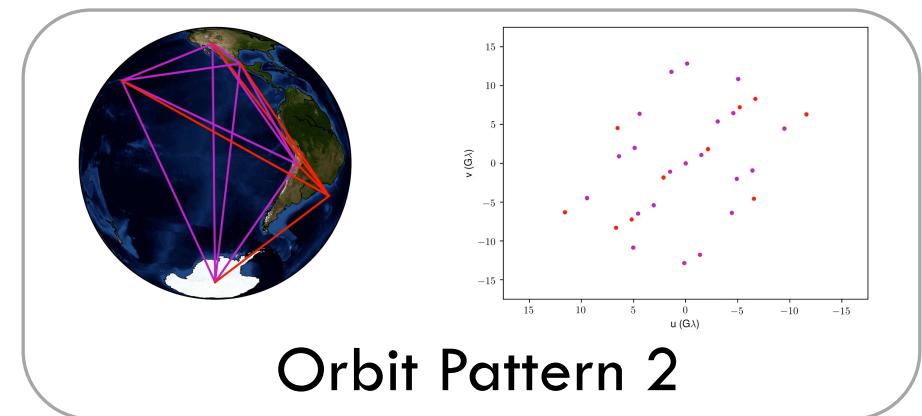
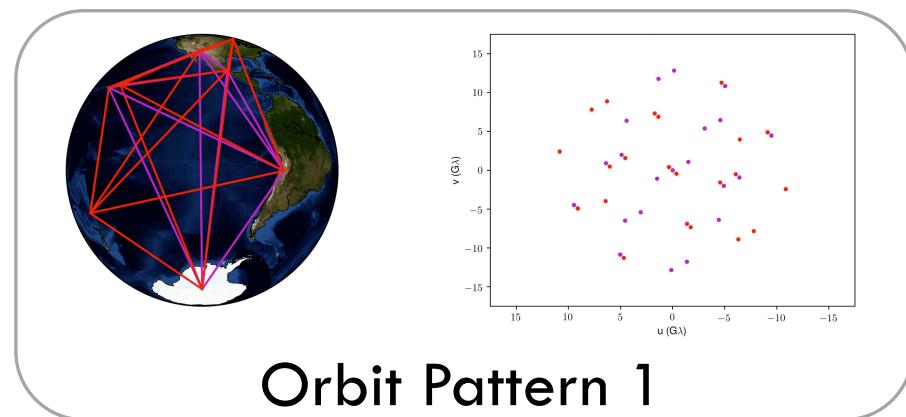
Hardware Needs/Limitations Continued

- Data Recording Rate
 - Currently recording 64 Gbit/sec
 - Plan to expand to 256 Gbit/sec
- Precise Timing
 - Ground sites use atomic clocks
- Data Storage
 - ~200 TB with 25% duty cycle
- Transfer Data
 - Lasercom?

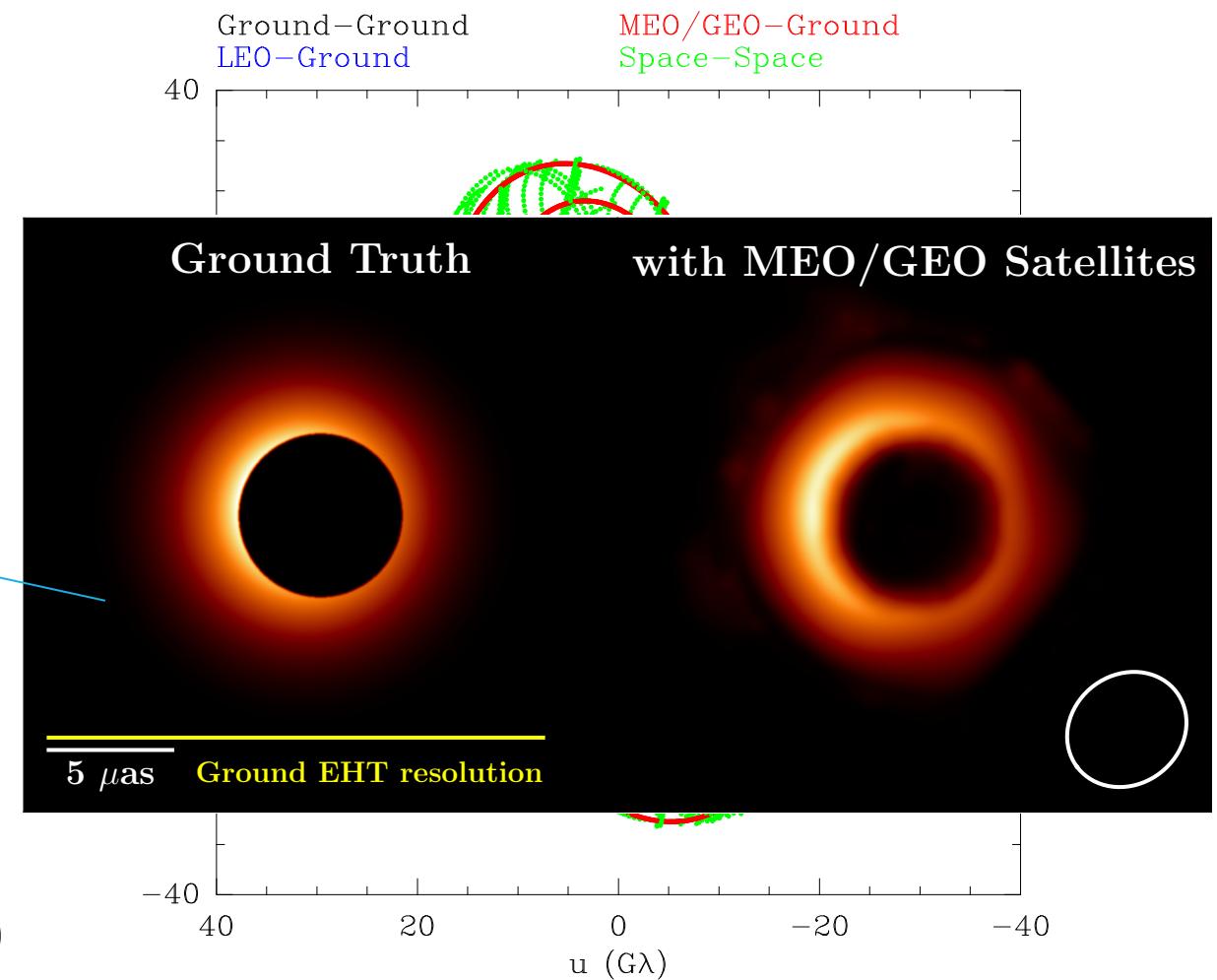
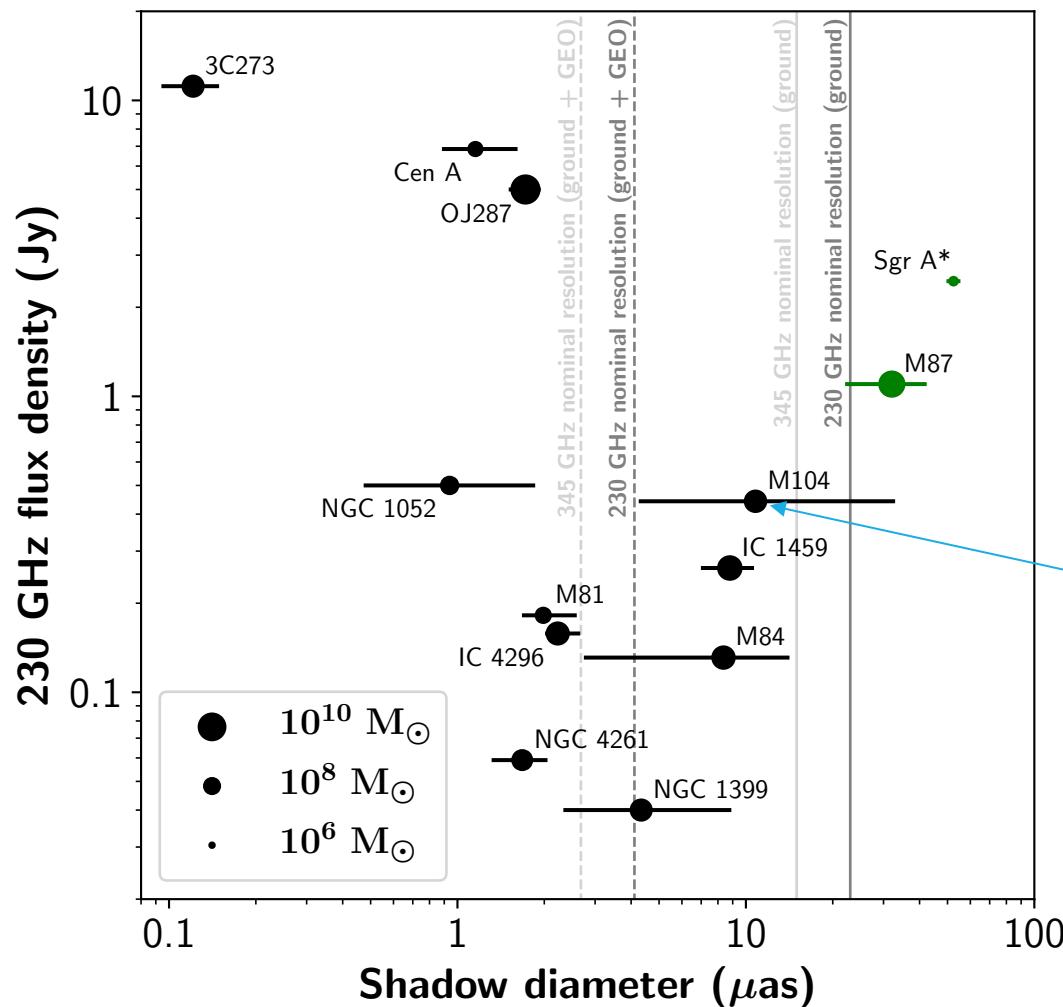


Optimizing the Hardware with the Orbit Pattern

How to best optimize for all the observed sources?



What Other BHs Become Visible with Space-VLBI?





Simulated Image Courtesy of Hotaka Shiokawa



Joint work with: Michael Johnson, Daniel Palumbo, Andrew Chael, Sheperd Doeleman, Bill Freeman, Adrian Dalca,
Freek Roelofs, Vincent Fish, Kazu Akiyama, and the

Event Horizon Telescope Collaboration