First M87 Event Horizon Telescope Results: Data Calibration to Imaging Central Supermassive Black Hole

- EHT collaboration team

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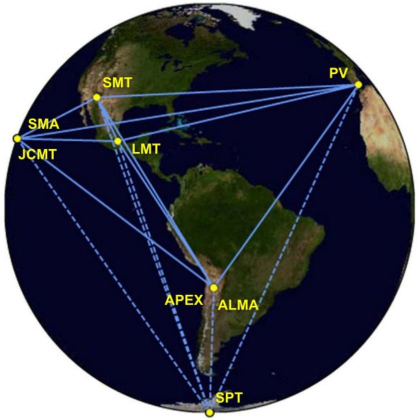
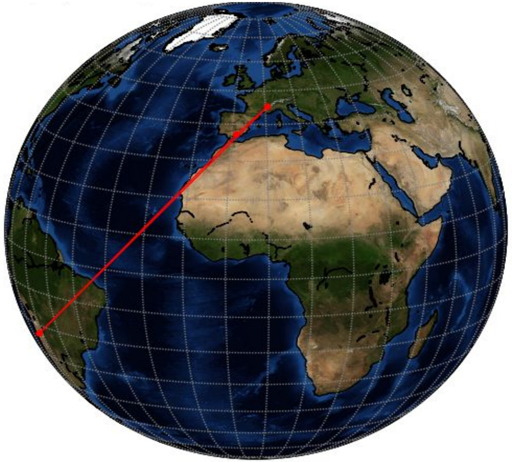
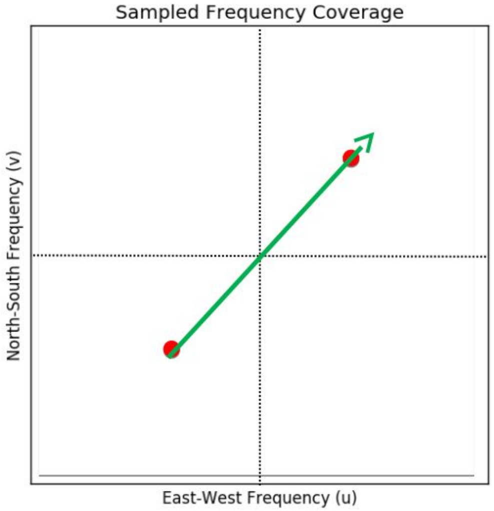
How Big Our Telescopes Must Be?

- Telescope size ∝ Wavelength (1.3mm) / Angular resolution (20-40 μas)
- Telescope size ≅ 13 million meters
- EHT - Computational telescope
  - Very Long Baseline Interferometry array of millimeter and submillimeter wavelength

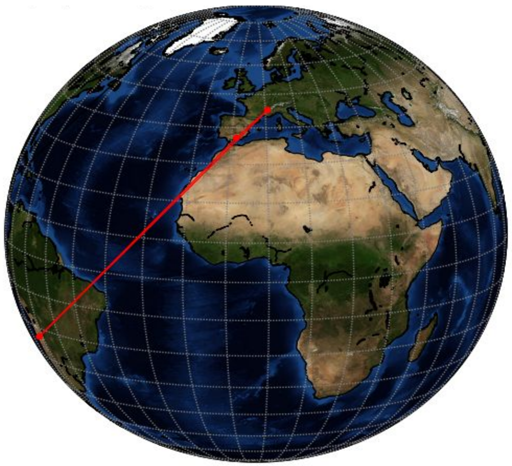


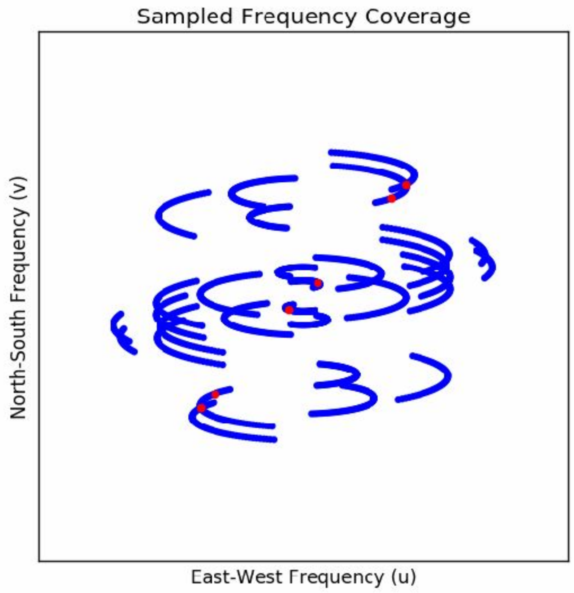
Basics of Interferometry





Basics of Interferometry





Section 1

- Data processing and Calibration
  - Data Flow
  - Correlation
  - Fringe Detection
  - Flux Density calibration
  - Network Calibration

Section 1.1: Data Flow

- Digital Recordering phase
  - Through the receiver and backend electronics at each telescope, the sky signal is mixed to **baseband**, **digitized**, and recorded directly to hard disk.
- Correlator phase
  - The correlator uses an a priori **Earth geometry** and **clock/delay model** to align the signals from each telescope to a common time reference, and estimates the pair-wise complex correlation coefficient

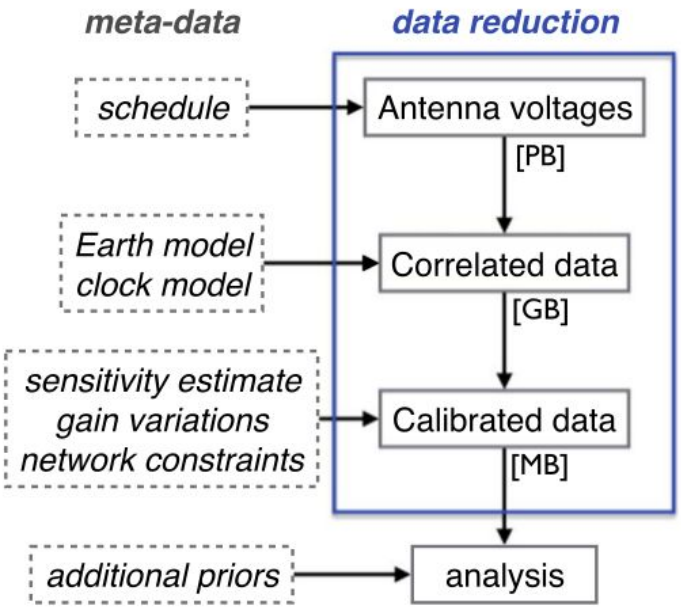
$$r_{ij} = \frac{\langle x_i x_j^* \rangle}{\eta_Q \sqrt{\langle x_i x_i^* \rangle \langle x_j x_j^* \rangle}},$$

Section 1.1: Data Flow

- Calibration phase
  - This process attempts to relate the **pairwise correlation coefficients** r_ij , which are in units of thermal noise of the detector, to correlated **flux density** in units of Jansky (equivalent to 10−26 watts per square metre per hertz).

$$r_{ij} = \gamma_i \gamma_j^* \, V_{ij}.$$

Section 1.1: Data Flow



Section 1.2: Correlation

- Correlator phase
    - The correlator uses an a priori Earth geometry and clock/delay model to align the signals from each telescope to a common time reference, and estimates the pair-wise complex correlation coefficient

$$r_{ij} = \frac{\langle x_i x_j^* \rangle}{\eta_Q \sqrt{\langle x_i x_i^* \rangle \langle x_j x_j^* \rangle}},$$

- Small pre-processing: The delay model very precisely takes into account the **geometry of the observing array at the time of observation and the direction of the source.**

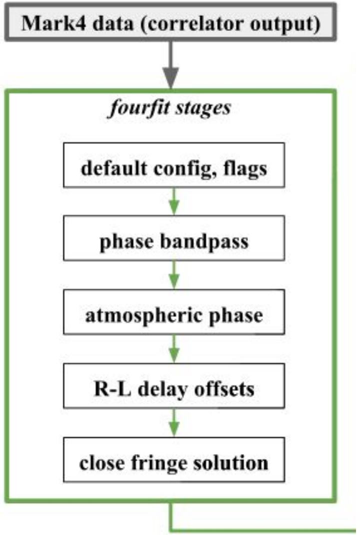
Section 1.2: Correlation

- Example of SMA site: An offline preprocessing pipeline, called the Adaptive Phased-array and Heterogeneous Interpolating Downsampler for SWARM, is used.
    - To perform the necessary filtering, **frequency conversion**, and transformation to the time domain.
        - So that the format of the SMA data delivered to the VLBI correlator is the same as for single-dish stations

Section 1.3: Fringe Detection

- Correlated data could be coherently integrated in time and frequency only if..
  - all correlator delay model parameters were known perfectly ahead of time and there were no atmospheric variations.
- **But sadly that’s not the case. In practice, many of the model parameters are not known exactly at correlation.**
- Examples being,
  - offset from the expected coordinates of the source
  - the position of each telescope may differ from the best estimate
  - variable water content in the atmosphere
- In VLBI, this data processing this process is known as fringe-fitting.
- **Solution: HOPS pipeline!**

Section 1.3: Fringe Detection



- Atmospheric phase:
  - Done at each baseline level.
  - Every baseline will have 32 spectral IF
  - Leave out one cross estimation approach
  - Model gives dist. of phases over 31 IF
- R-L delay offset:
  - Change in the circular polarization of electromagnetic field vectors

Section 1.4: Flux Density Calibration

- The flux density calibration for the EHT is done in two steps and is a common post-processing procedure for the HOPS pipeline.
    - **A Priori Amplitude Calibration**
    - **Network Calibration**

Section 1.4: Priori Amplitude Calibration

- It serves to calibrate visibility amplitudes from correlation coefficients to flux density measurements.
- The SEFD of a radio telescope is the total system noise represented in units of equivalent incident flux density above the atmosphere.

$$\mathrm{SEFD} = \frac{T^{*}_{\mathrm{sys}}}{\mathrm{DPFU} \times \eta_{\mathrm{el}}},$$

Section 1.4: Priori Amplitude Calibration

$$\mathrm{SEFD} = \frac{T^*_{\mathrm{sys}}}{\mathrm{DPFU} \times \eta_{\mathrm{el}}},$$

- Parameter 1: T_{sys}^* the effective system noise temperature describes the total noise characterization of the system corrected for atmospheric attenuation
- Measure via chopper or hot-load method,

$$T^*_{\mathrm{sys}} \simeq e^{\tau}(T_{\mathrm{rx}} + (1 - e^{-\tau})T_{\mathrm{atm}}),$$

$$\frac{P_N}{B} = k_B T$$

Section 1.4: Priori Amplitude Calibration

$$\mathrm{SEFD} = \frac{T^*_{\mathrm{sys}}}{\mathrm{DPFU} \times \eta_{\mathrm{el}}},$$

- Parameter 2: DPFU, the efficiency of the telescope must also be quantified.
- The DPFU relates flux density units incident onto the dish to equivalent degrees of thermal noise power through the following equation:

$$\mathrm{DPFU} = \frac{\eta_{\mathrm{A}} A_{\mathrm{geom}}}{2k_{\mathrm{B}}},$$

- Parameter 3: They separately determine the elevation-dependent efficiency factor η_{el} (or gain curve) due primarily to gravitational deformation of each parabolic dish.

Section 1.4: Priori Amplitude Calibration

- And finally, **Calibrating Visibility Amplitudes**
  - where | V ij | is then the calibrated visibility amplitude in Jy on that baseline.

$$|V_{ij}| = \sqrt{\mathrm{SEFD}_i \times \mathrm{SEFD}_j}\ |r_{ij}|,$$

Section 1.4: Network Calibration

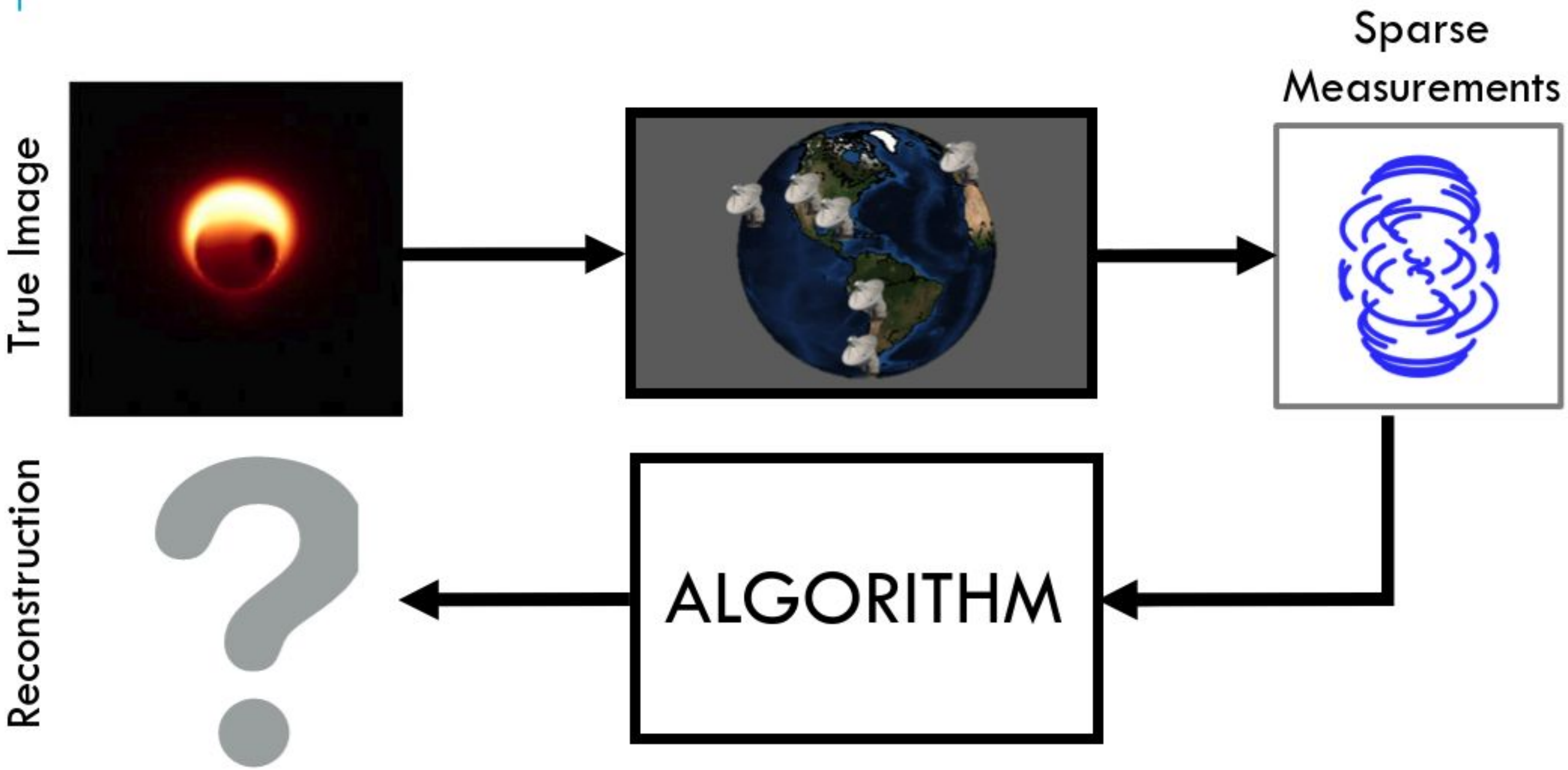
- **Phase closure**:
  - inhomogeneities in the atmosphere cause the light to travel at different velocities towards each telescope.
  - These delays have a significant effect on the phase of measurements

Although absolute phase measurements cannot be used, a clever observation - termed phase closure - allows us to still recover some information from the phases. The atmosphere affects an ideal visibility (spatial frequency measurement) by introducing an additional phase term: $\Gamma_{i,j}^{\text{meas}} = e^{i(\phi_i - \phi_j)}\Gamma_{i,j}^{\text{ideal}}$, where ϕ_i and ϕ_j are the phase delays introduced in the path to telescopes i and j respectively. By multiplying the visibilities from three different telescopes, we obtain an expression that is invariant to the atmosphere, as the unknown phase offsets cancel, see Eq. 2 [14].

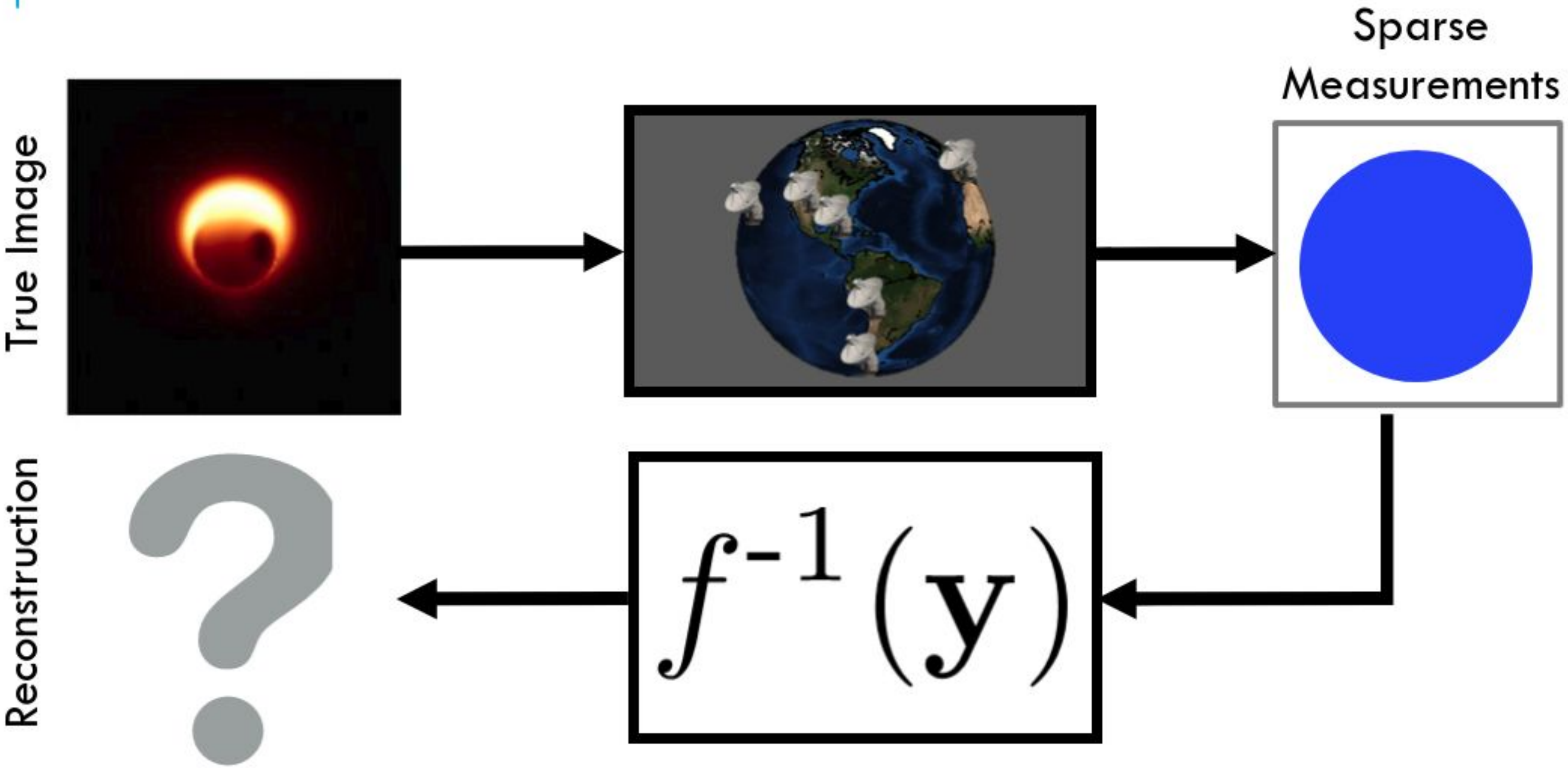
$$\begin{aligned}\Gamma_{i,j}^{\text{meas}}\Gamma_{j,k}^{\text{meas}}\Gamma_{k,i}^{\text{meas}} &= e^{i(\phi_i - \phi_j)}\Gamma_{i,j}^{\text{ideal}}e^{i(\phi_j - \phi_k)}\Gamma_{j,k}^{\text{ideal}}e^{i(\phi_k - \phi_i)}\Gamma_{k,i}^{\text{ideal}} \\ &= \Gamma_{i,j}^{\text{ideal}}\Gamma_{j,k}^{\text{ideal}}\Gamma_{k,i}^{\text{ideal}} \qquad (2)\end{aligned}$$

Section 2: Imaging Central Supermassive Black Hole

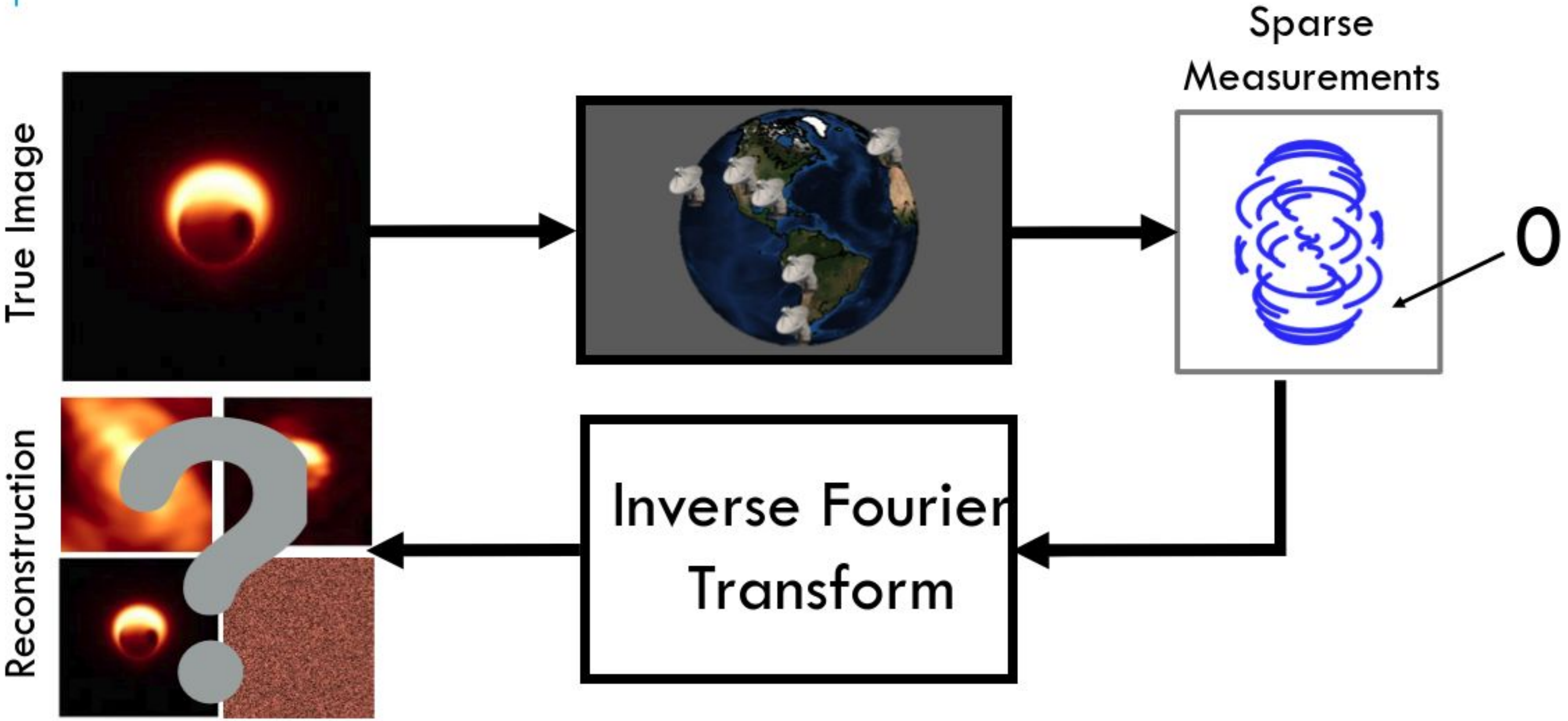
Unconventional Imaging: The EHT



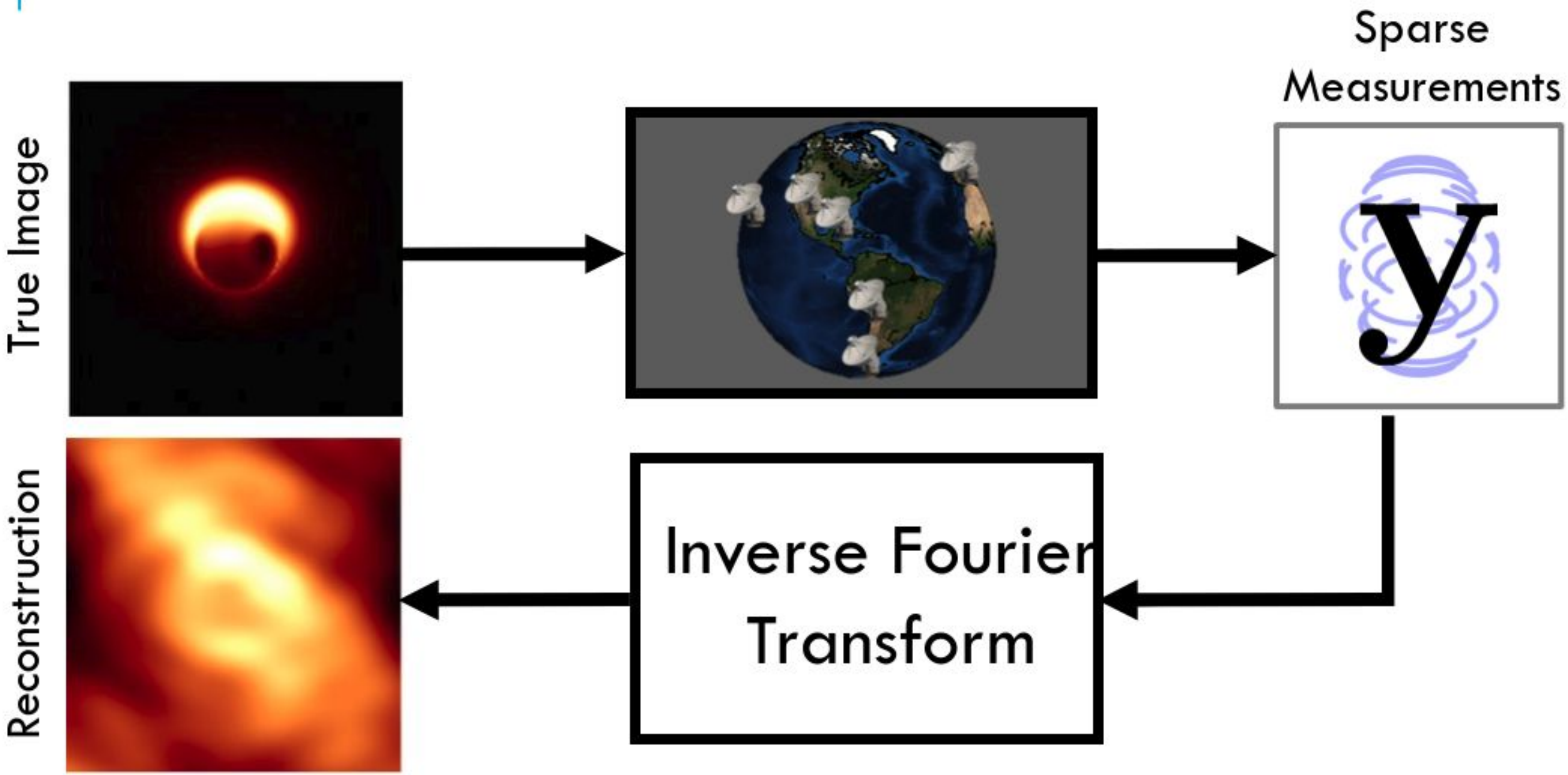
Inverting the EHT Imaging System



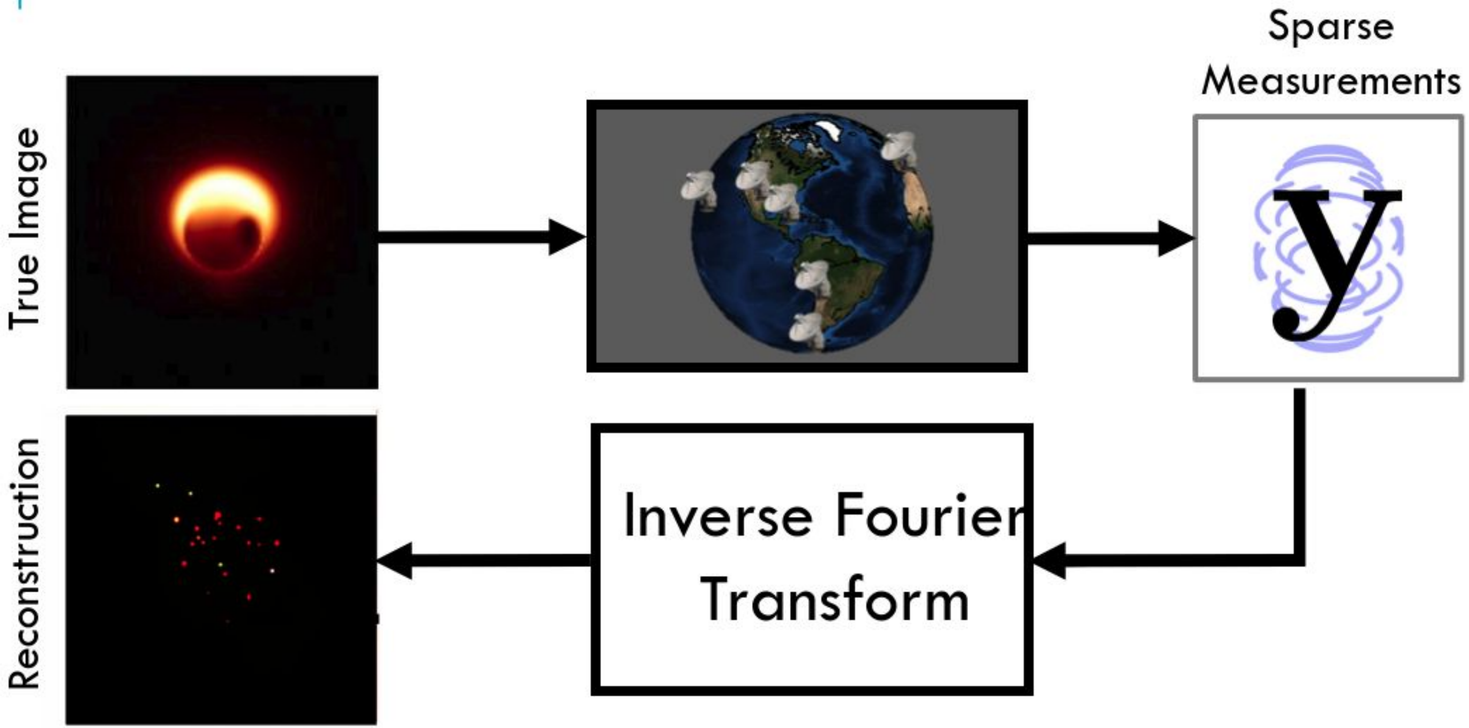
Inverting the Imaging System: CLEAN



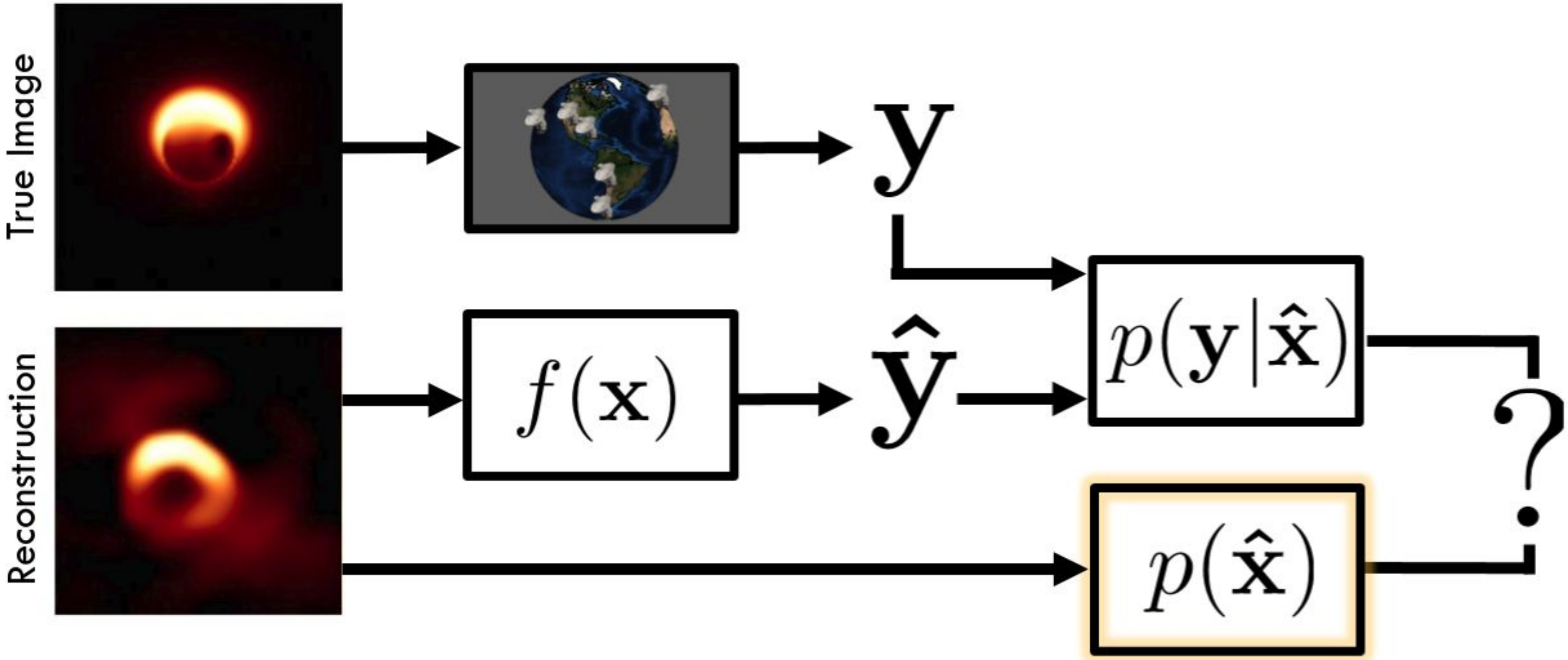
Traditional Approach: CLEAN



Traditional Approach: CLEAN



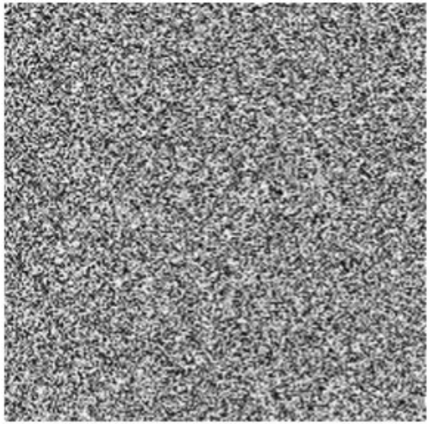
Bayesian Model Inversion



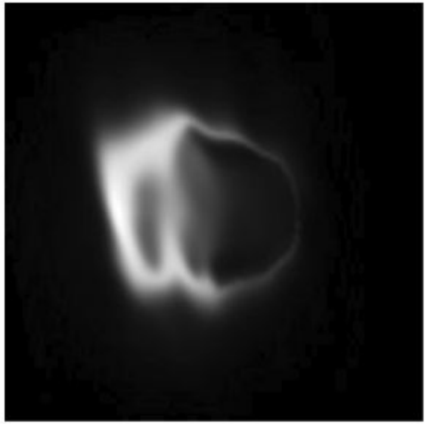
$$\overbrace{\hat{\mathbf{x}}_{\mathrm{MAP}}}^{\text{Best Image}} = \operatorname{argmax}_{\mathbf{x}} \left[\log \underbrace{p(\mathbf{y}|\mathbf{x})}_{\text{Likelihood}} + \log \underbrace{p(\mathbf{x})}_{\text{Prior}} \right]$$

Section 3: How do we make sure that we are not biasing our image too much!

What is a Likely Black Hole Image?



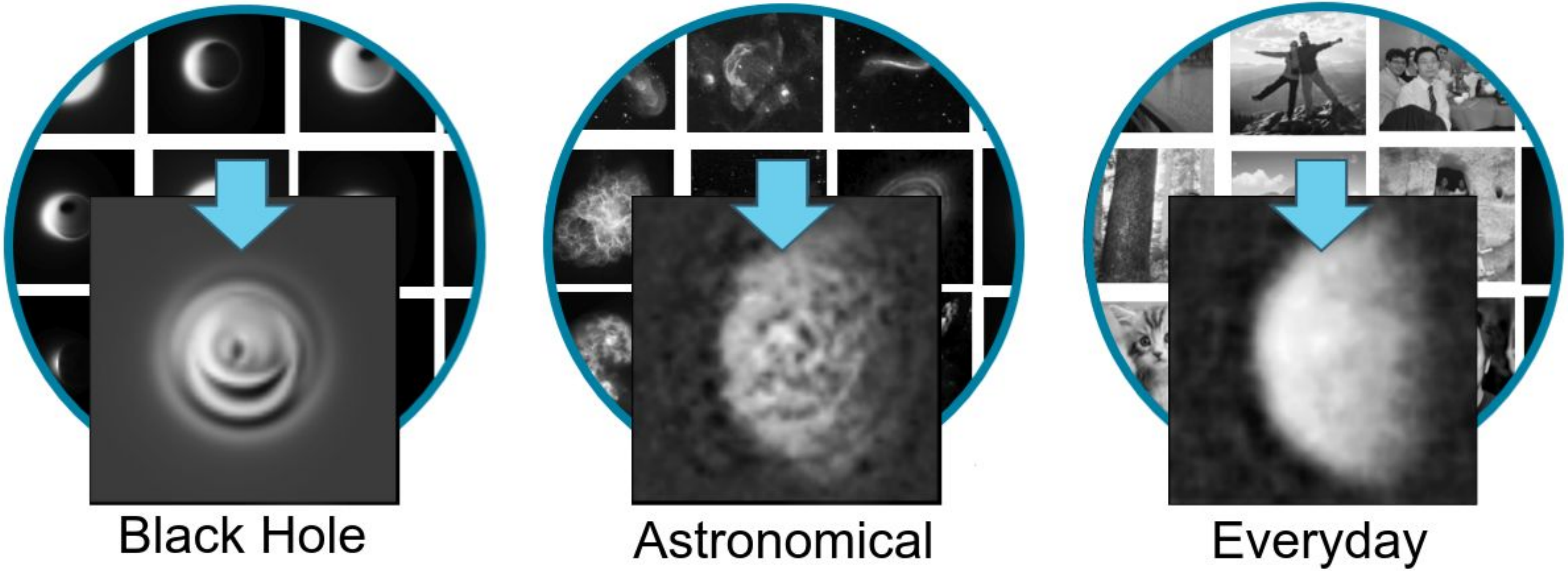
Unlikely



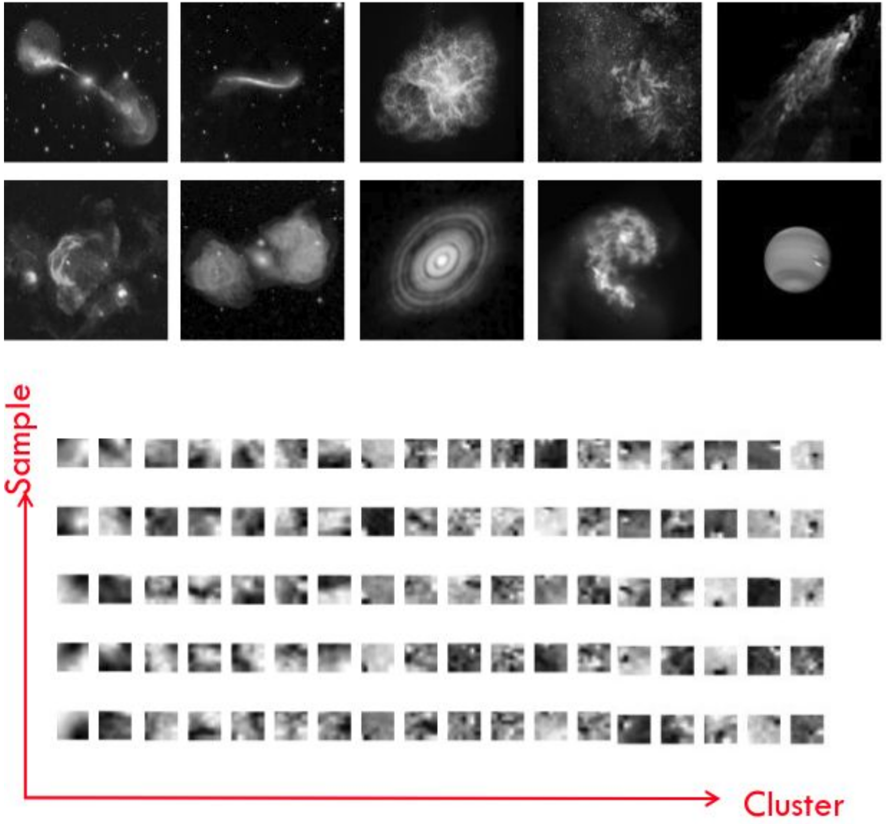
More likely

Very likely

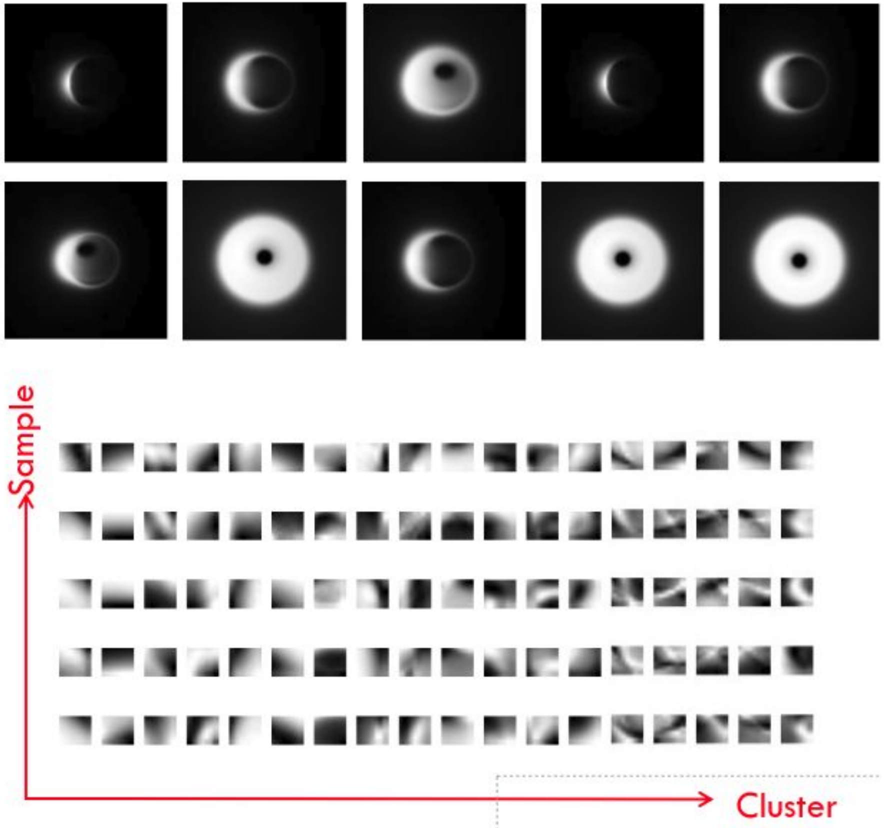
Data-driven Image Priors



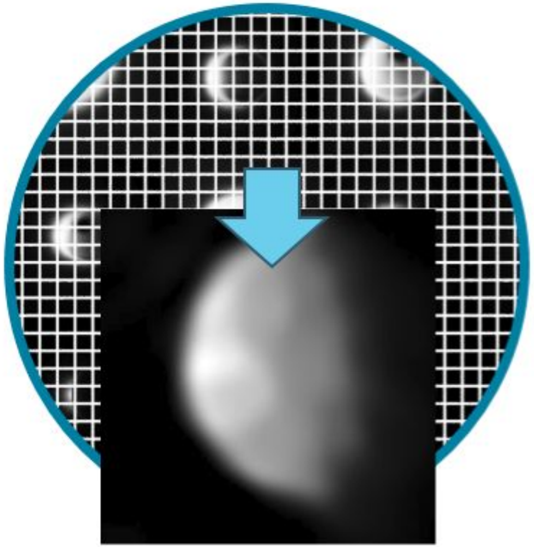
Astronomical Images



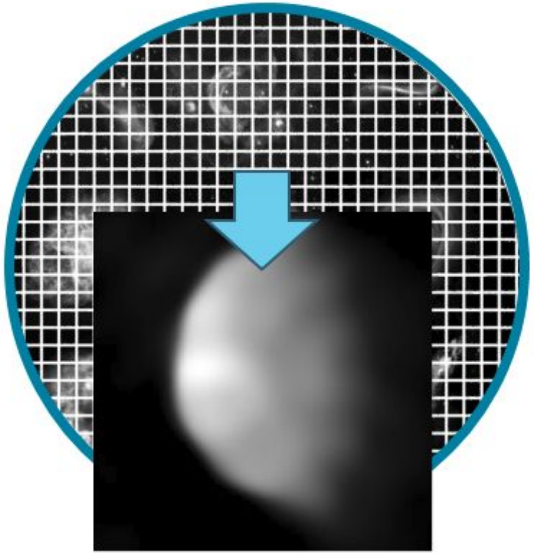
Synthetic Black Hole Images



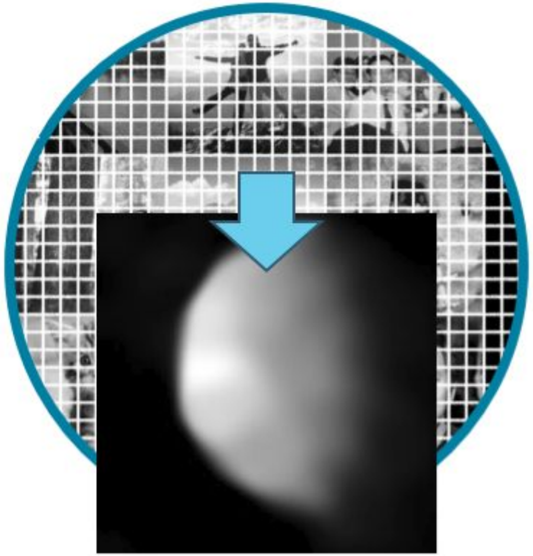
Results from Different Patch Models



Black Hole



Astronomical



Everyday

Section 2: CHIRP (Continuous High-resolution Image Reconstruction using Patch priors)

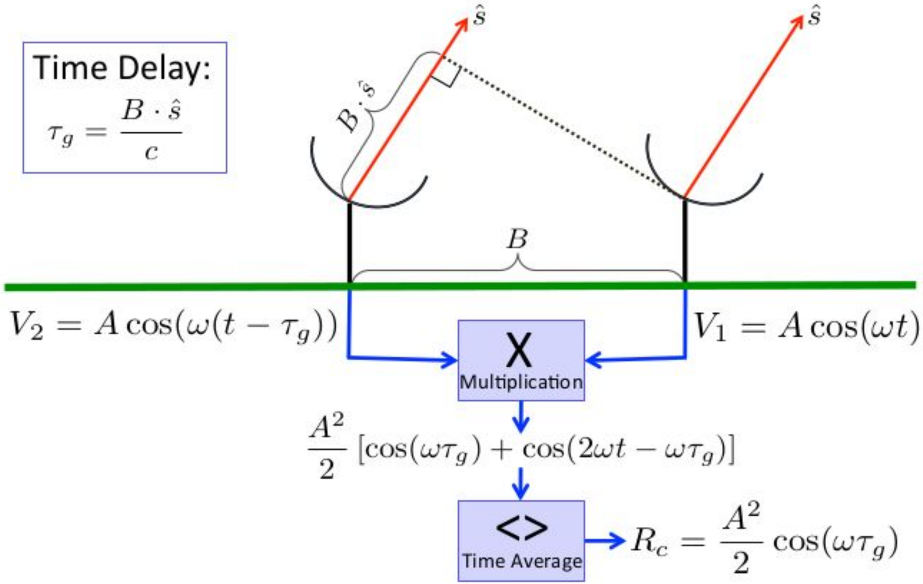
- Calibration phase
  - This process attempts to relate the pairwise correlation coefficients r_ij , which are in units of thermal noise of the detector, to correlated flux density in units of Jansky (equivalent to 10−26 watts per square metre per hertz).

$$r_{ij} = \gamma_i \gamma_j^* V_{ij}.$$

- The time-averaged correlation of the received signals is equivalent to the sinusoidal variation on the emission’s intensity distribution. - **Van Cittert–Zernike theorem**

$$\Gamma_{i,j}(u,v) \approx \int_{\ell} \int_{m} e^{-i2\pi(u\ell+vm)} I_{\lambda}(\ell,m) dldm$$

Section 2: CHIRP



Section 2: CHIRP

- Previous algorithms assume a discretized image of point sources during reconstruction
- Instead, CHIRP parameterize a continuous image using a discrete number of terms/parameters.
- Each measured complex visibility is approximated as the Fourier transform of $I_{\lambda}(l, m)$
- **Assume that image is to represent it as a discrete number of scaled and shifted continuous pulse functions, such as triangular pulses.**
- Those pulses in $N_l \times N_m$ space are h(l, m) defined as:

$$l = i\Delta_\ell + \frac{\Delta_\ell}{2} - \frac{F_\ell}{2} \quad \text{for} \quad i = 0, ..., N_\ell - 1$$

$$m = j\Delta_m + \frac{\Delta_m}{2} - \frac{F_m}{2} \quad \text{for} \quad j = 0, ..., N_m - 1$$

Section 2: CHIRP

- we can represent a continuous image as a discrete sum of shifted pulse functions scaled by x[i, j]. We refer to this image as $(I_\lambda(x))_{reconstructed}$ for vectorized coefficients x.

$$\Gamma_{i,j}(u,v) \approx \int_\ell \int_m e^{-i2\pi(u\ell+vm)} I_\lambda(\ell,m)dldm$$

$$\Gamma(u,v) \approx \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{-i2\pi(u\ell+vm)} \sum_{i=0}^{N_\ell-1}\sum_{j=0}^{N_m-1} x[i,j]h\left(\ell-\left(\Delta_\ell i+\frac{\Delta_\ell}{2}-\frac{FOV_\ell}{2}\right), m-\left(\Delta_m j+\frac{\Delta_m}{2}-\frac{FOV_m}{2}\right)\right) d\ell dm$$

$$= \sum_{i=0}^{N_\ell-1}\sum_{j=0}^{N_m-1} x[i,j]e^{-i2\pi\left(u\left(\Delta_\ell i+\frac{\Delta_\ell}{2}+a_\ell\right)+v\left(\Delta_m j+\frac{\Delta_m}{2}+a_m\right)\right)} H(u,v) = A\mathbf{x} = \left(A^{\Re}+iA^{\Im}\right)\mathbf{x}$$

Section 2: CHIRP

- Model optimization:
  - We seek a maximum a posteriori (MAP) estimate of the image coefficients, x, given complex bispectrum measurements, y.

$$f_r(\mathbf{x}|\mathbf{y}) = -D(\mathbf{y}|\mathbf{x}) - \mathrm{EPLL}_r(\mathbf{x})$$

$$\overbrace{\hat{\mathbf{x}}_{\mathrm{MAP}}}^{\text{Best Image}} = \operatorname{argmax}_{\mathbf{x}} \left[\underbrace{\log p(\mathbf{y}|\mathbf{x})}_{\text{Likelihood}} + \underbrace{\log p(\mathbf{x})}_{\text{Prior}}\right]$$

- Expected patch log likelihood (EPLL): GMM is used as a patch prior to regularize our solution

$$\mathrm{EPLL}_r(\mathbf{x}) = \sum_{n=1}^{N} \log p(P_n \mathbf{x}).$$

Section 4: Validation pipeline

Section 4: Validation pipeline

- Synthetic data tests:
    - Software(true images) = measurements
    - Use different methods (CLEAN, CHIRP) and show it to experts
- Blind imaging procedure for M87 and AGN
    - The EHT submission portal
- Objectively choosing parameters in imaging methods, ie automating these methods.
    - Refer to the notebook
- More validation
    - Variation in parameters
    - Same image every day

References

- Bouman, Katherine L., et al. "Computational imaging for vlbi image reconstruction." *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*. 2016.
- Akiyama, Kazunori, et al. "First M87 Event Horizon Telescope Results. III. Data Processing and Calibration." *The Astrophysical Journal Letters* 875.1 (2019): L3.
- Akiyama, Kazunori, et al. "First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole." *The Astrophysical Journal Letters* 875.1 (2019): L4.
- https://www.youtube.com/watch?v=UGL_OL3OrCE&t=1128s
- https://www.youtube.com/watch?v=YgB6o_d4tL8

Thank you.