Imaging with The Event Horizon Telescope

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Dataset Website: vlbiimaging.csail.mit.edu

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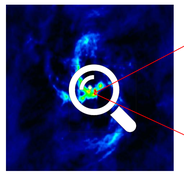
Problem and Motivation

GOAL: Reconstruct an image from sparse frequency measurements obtained using radio telescopes observing at mm/sub-mm wavelengths distributed across the Earth

PROBLEM: Diffraction places a fundamental limit on the maximum resolution we are able to image. The maximum resolution depends on the wavelength of light and the diameter of the aperture.

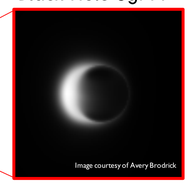
MOTIVATION: The Event Horizon Telescope (EHT) is a collection of telescopes that are capable of imaging the plasma surrounding a black hole's event horizon

Galactic Center



0.0283 Degrees
or
102 Arcseconds

Prediction for Black Hole Sgr A*



4.46×10^{-8} Degrees
or
0.0001605 Arcseconds

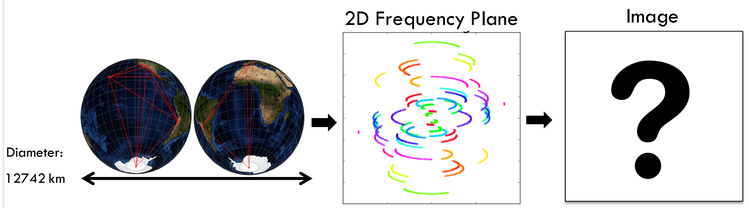
Maximum Resolution

$$\theta \approx \frac{\lambda}{d}$$

1.3×10^{-3} m wavelength

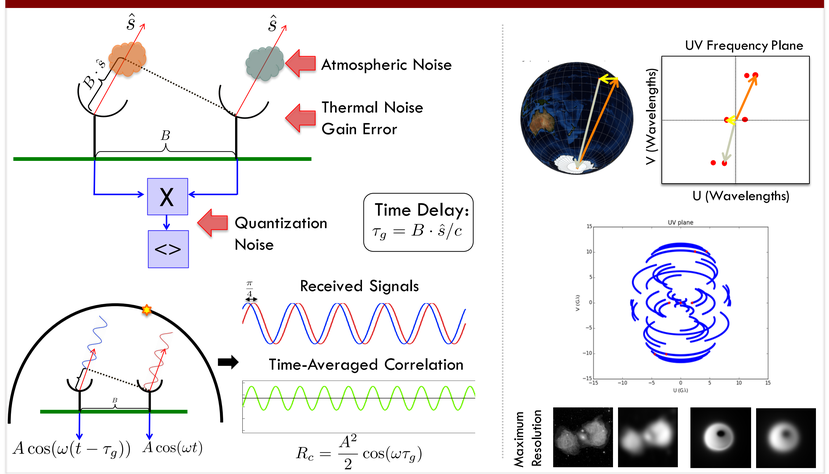
$(7.78 \times 10^{-10}) / 6$ radians

We would need a telescope with ~ 10,000 km Diameter!



Very Long Baseline Interferometry - VLBI

Very Long Baseline Interferometry



Our Algorithm - CHIRP

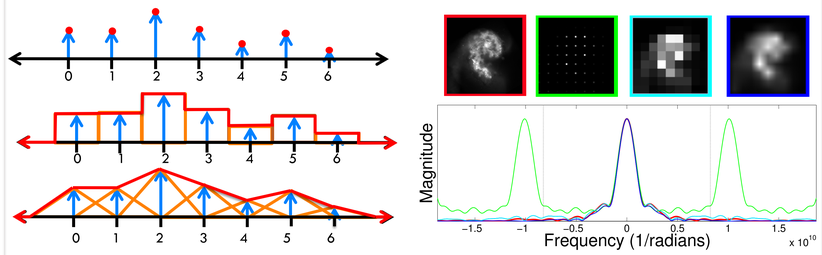
CHIRP – Continuous High Resolution Imaging using Patch priors

Visibility
Time Averaged Cross Correlation

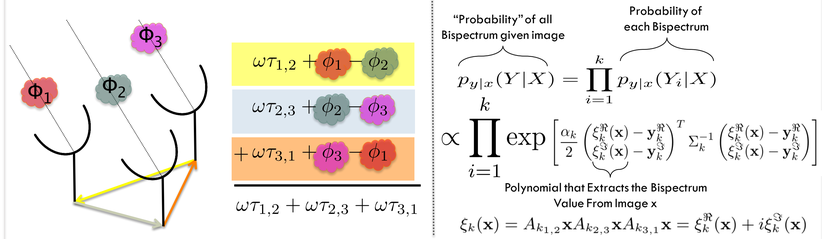
2D Fourier Transform of Continuous Image

$$\Gamma(u,v) = \int_l \int_m e^{-i2\pi(ul+vm)} I_\lambda(l,m) dl dm$$

1) IMPROVED FORWARD MODEL



2) HANDLING OF ATMOSPHERIC NOISE



"Likelihood" Energy:

"Probability" of all Bispectrum given image — Probability of each Bispectrum

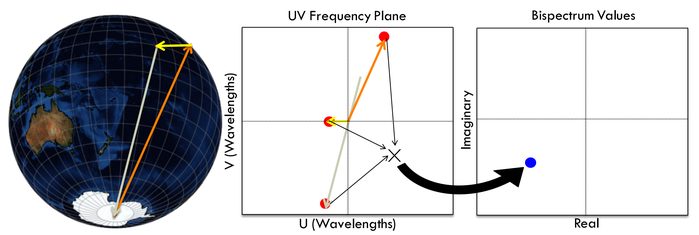
$$p_{y|x}(Y|X) = \prod_{i=1}^{k} p_{y|x}(Y_i|X)$$

$$\propto \prod_{i=1}^{k} \exp\left[\frac{\alpha_k}{2}\left(\xi_k^{\Re}(\mathbf{x}) - \mathbf{y}_k^{\Re}\right)^T \Sigma_k^{-1}\left(\xi_k^{\Re}(\mathbf{x}) - \mathbf{y}_k^{\Re}\right)\right]$$

Polynomial that Extracts the Bispectrum Value From Image x

$$\xi_k(\mathbf{x}) = A_{k_{1,2}}\mathbf{x}A_{k_{2,3}}\mathbf{x}A_{k_{3,1}}\mathbf{x} = \xi_k^{\Re}(\mathbf{x}) + i\xi_k^{\Im}(\mathbf{x})$$

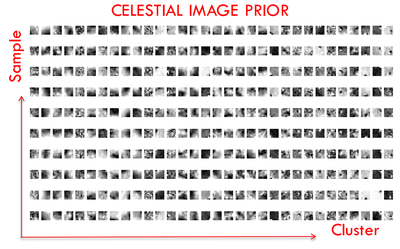
Multiply Closed-Loop Visibility Measurements for Invariance to Atmospheric Noise



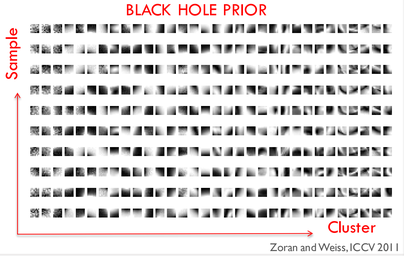
3) GAUSSIAN MIXTURE PATCH "PRIOR"

P() vs P( )

CELESTIAL IMAGE PRIOR



BLACK HOLE PRIOR



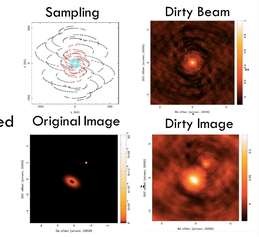
Zoran and Weiss, ICCV 2011

Previous Method

CLEAN: The de-facto standard method for VLBI Imaging

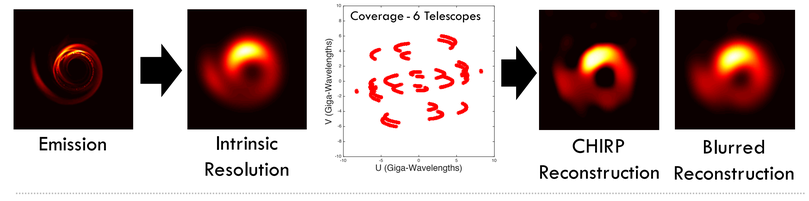
Initialize Residual Map to Dirty Image
LOOP OVER
1. Identify the highest peak in the residual map as a point source
2. Subtract a fraction of this peak from the residual map using the scaled dirty beam
3. Add this point source to the CLEAN component list

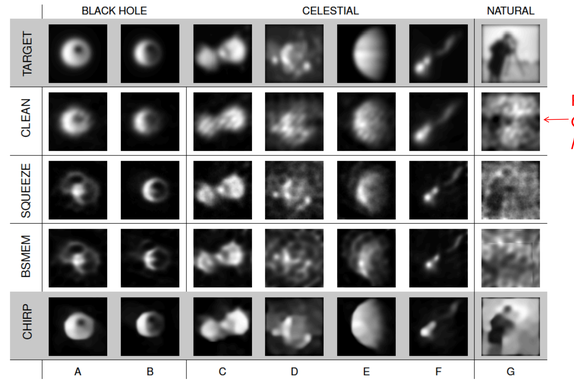
Cannot Handle Atmospheric Noise without Calibration



Figures Taken from Slides by David J. Wilner

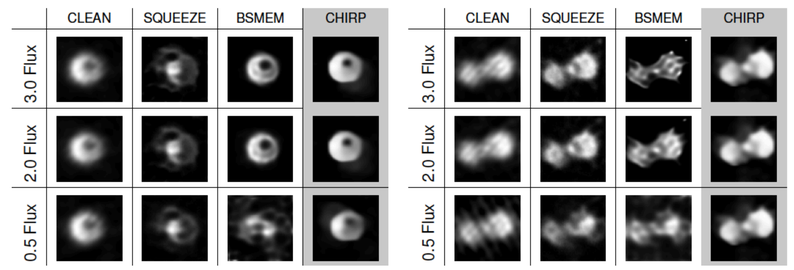
Results



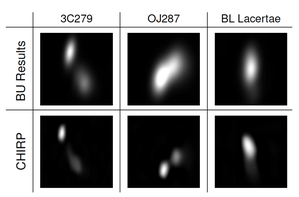


Perfectly Calibrated Measurements

Sensitivity to Noise



Real Measurements



Effect of the "Prior"