Inference of Black Hole Fluid-Dynamics from Sparse Interferometric Measurements

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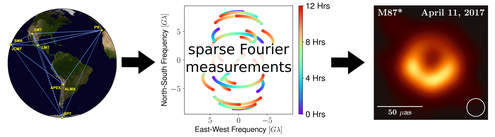
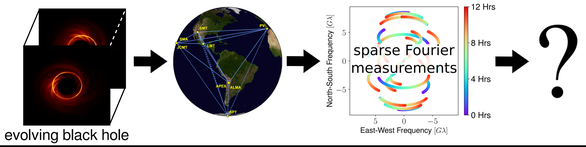
Introduction

In 2019 the Event Horizon Telescope produced the first ever black-hole image (M87*). The image was computationally constructed from measurement of synchronized radio telecopes across the globe. Measurements were collected over the course of an entire night with the underlying assumption is that M87* is **static** throughout acquisition.

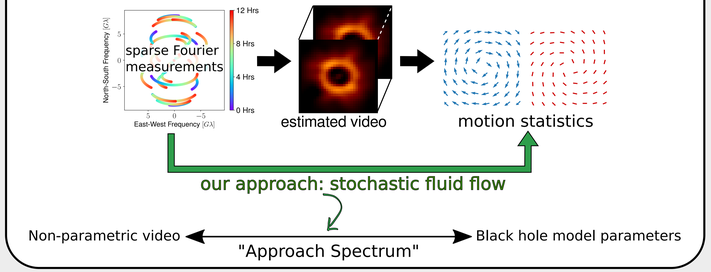


In this work we seek to recover the dynamic properties of an **evolving** black hole, such as SgrA*, at the center of the Milky Way.



Approach

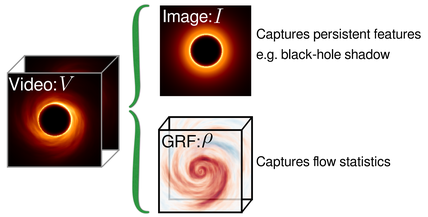
A possible approach to recover the source dynamics is by trying to estimate a whole video sequence. However, strong temporal regularization is required to recover a movie due to the extremely sparse measurements at each frame. Our approach **directly** estimates the parameters of a fluid dynamical model.



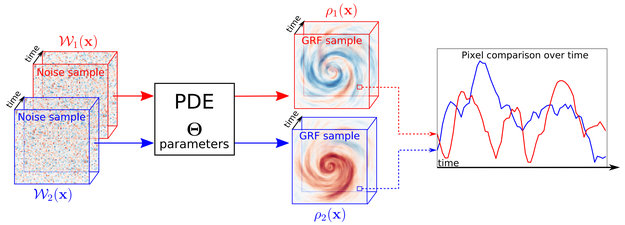
Methodology

We model a video as a static image modulated by a dynamic Gaussian Random Field (GRF):

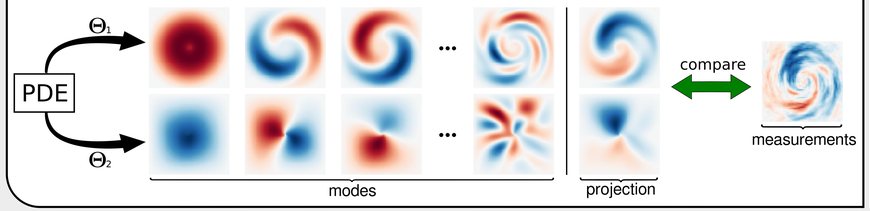
$$V(t,x,y) = I(x,y)e^{\rho(t,x,y)}$$



GRFs are sampled as solution to a Stochastic Partial Differential Equation (SPDE), namely, an anisotropic diffusion equation (parameterized by a diffusion tensor). GRFs sampled from identical PDE parameters with different random noise source, $\mathcal{W}$, have very different pixel values over time.

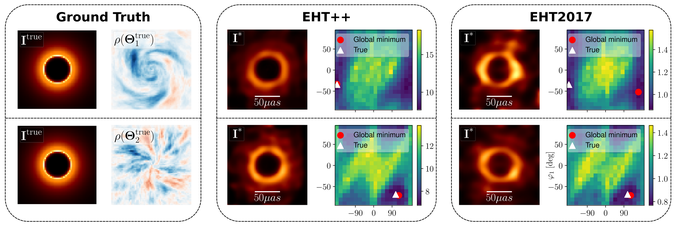


We formulate an inverse problem to jointly estimate the unknown static image and PDE parameters: $\{\mathbf{I}, \Theta\}$. A key point is that we do not have access to the unknown random noise $\mathcal{W}$, therefore, we cannot compare a hypothesis to the measurements on a pixel-by-pixel basis. We define a projection loss metric using the top modes of the SPDE. This metric is robust to the unknown random noise

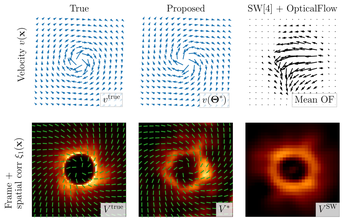


Results

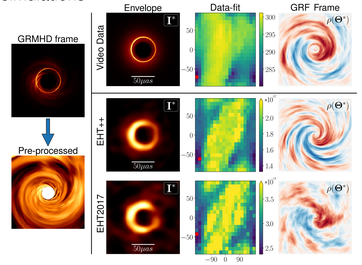
We show recovery results jointly estimating the unknown static image and dynamic parameters for different underlying fluid flows. Measurements are synthetically generated according to the EHT2017 exisiting telescope array and an augmented array with additional prospected telescopes (EHT++)

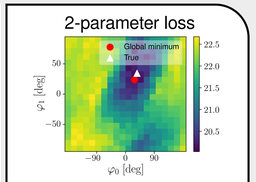


We comapre our approach to OpticalFlow evaluated on a video reconstruction using state-of-the-art imaging (StarWarps) and show that our model is crucial when the measurements are sparse



We show applicablity to complex, physically realistic, black hole simulations





For each parameter set we compute the projection residual

$$\min_{\mathbf{c}} \|\mathbf{y} - \mathbf{U}_\Theta \mathbf{\Sigma}_\Theta \mathbf{c}\|^2_{\mathbf{\Sigma}_\mathbf{y}} + \|\mathbf{c}\|^2$$

$\mathbf{y}$ - measurement augmented by the estimated image (details in paper)

$\mathbf{U}_\Theta$ - top singular vectors (PDE modes)

$\mathbf{\Sigma}_\Theta$ - top singular values

$\mathbf{c}$ - projection coefficients

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