Harvard John A. Paulson School of Engineering and Applied Sciences

Imaging the Blackhole with VLBI Data

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Final Project for 6.819 Advances in Computer Vision

Background

Angular resolution of a telescope is limited by its **diameter** and the incident wavelength

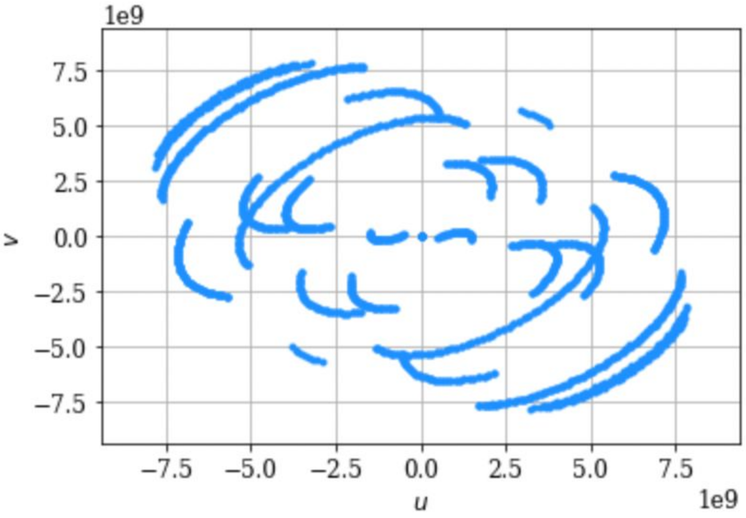
$$\Theta = K\frac{\lambda}{D}$$

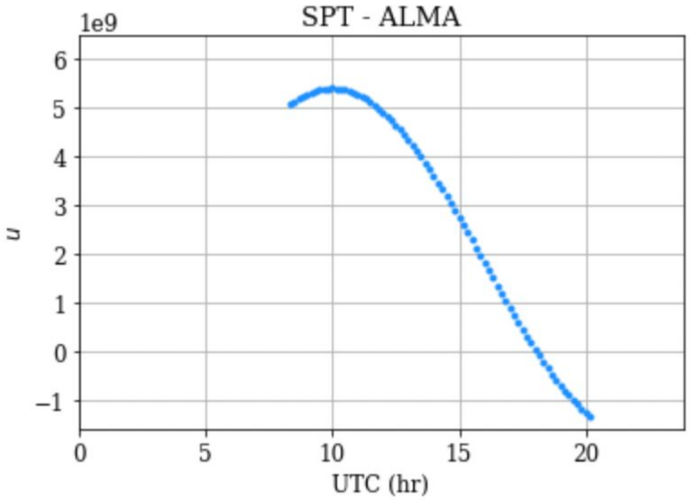
- To achieve higher resolving power for observing events around blackhole, we need an extremely large telescope (e.g. earth sized)
- **Very long baseline interferometry (VLBI):** Using multiple telescopes to emulate samples from a single large telescope (earth sized).
- **Event Horizon Telescope**: International effort to capture image of blackhole by linking telescopes around the world (K choose 2 observations, given K telescopes).

Problem

what problem did you address?

Reconstruct the image of a blackhole Sgr A* with very **sparse measurements** in Fourier Domain from these K choose 2 pairs of observations. Evaluate different reconstruction algorithms' performance.





Motivation & Challenge

- ***Why is it interesting?***
  - Reconstructions are not unique
  - It requires priors knowledge and assumptions (e.g. ring shape? disk shape? image positivity, smoothness, compactness)

- ***Why is it hard?***
  - No one has ever seen a blackhole before, what prior assumption to make about this image?
  - The dangers of false confidence and collective confirmation bias

Approach

Leverage on synthetic data from VLBI image challenge, experiment several Regularized Maximum Likelihood Imaging **(RML) algorithms** and evaluate the performance of these different **imaging algorithms** on Event Horizon Telescope (EHT) data.

$$J(I) = \sum \alpha_D \underbrace{\boxed{\chi^2_D(I,d)}}_{\text{data term}} - \sum \beta_R \underbrace{\boxed{S_R(I)}}_{\text{regularizer}}$$

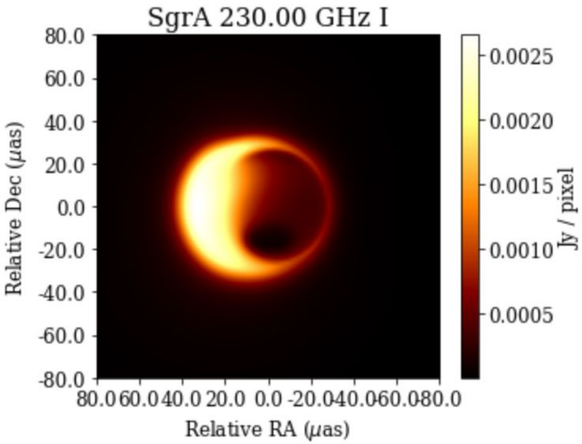
Based on *eht-imaging* (software package), I conducted my experiment to reconstruct the synthesized SgrA* image by using different combinations of available parameters included and compare their performance.

- **Data term:** ['vis', 'bs', 'amp', 'cphase', 'cphase_diag', 'camp', 'logcamp', 'logcamp_diag']
- **Regularizer:** ['simple', 'gs', 'tv', 'tv2', 'l1w', 'lA','patch','compact','compact2', 'rgauss']

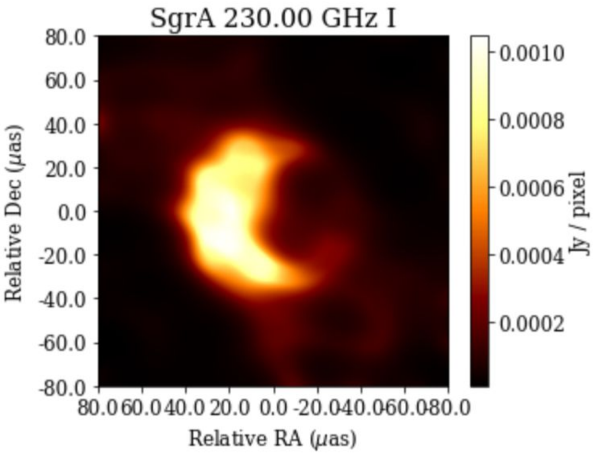
BSMEM - Bispectrum Maximum Entropy Method

Result

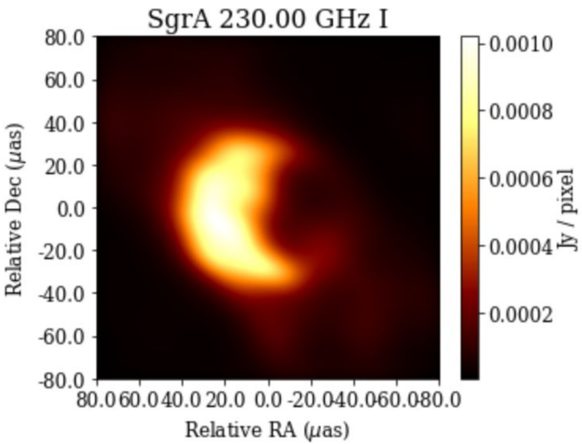
Reconstructed Black Hole Image Sgr A with Best Sets of Params in experiment*



Ground Truth (synthetic data)



Middle (Maximum Entropy Reconstruction)



Right (MEM blurred with fitted beam)

Evaluation

Fidelity metrics from **nxcorr, nrmse, rssd**

*Compare reconstructed image with different regularizer to **ground truth** image by measuring their*

- ***(nxcorr):*** *normalized cross correlation*
- ***(nrmse)****: normalized root mean squared error*
- ***(rssd):*** *square root of the sum of squared differences*

We can see Bispectrum + **Maximum Entropy Method (BSMEM)** gives superior performance.

Top 10 Performance Regularizer and Data Term

Same result sort by nxcorr DESC, nrmse and rssd ASC

	nxcorr	nrmse	rssd
(bs, simple)	0.897626	0.466008	1.277258e-13
(bs, lA)	0.895150	0.469276	1.286215e-13
(bs, gs)	0.894336	0.470849	1.290527e-13
(bs, tv2)	0.892311	0.472694	1.295582e-13
(bs, patch)	0.892311	0.472695	1.295585e-13
(bs, rgauss)	0.892301	0.472718	1.295650e-13
(bs, compact2)	0.892301	0.472718	1.295650e-13
(bs, compact)	0.892301	0.472718	1.295650e-13
(amp, l1w)	0.815637	0.569099	1.559816e-13
(amp, patch)	0.803764	0.590276	1.617859e-13

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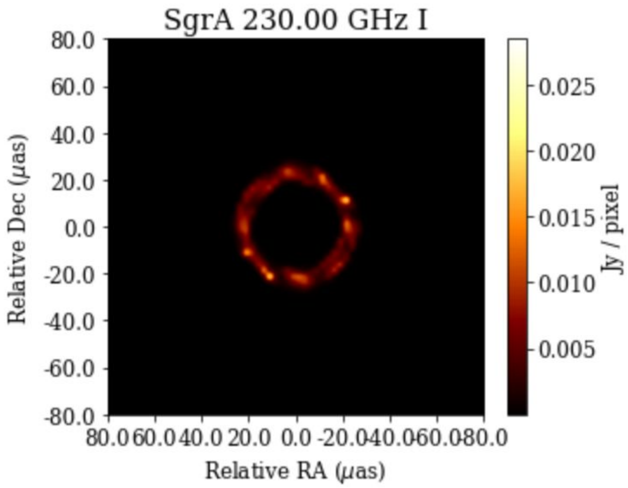
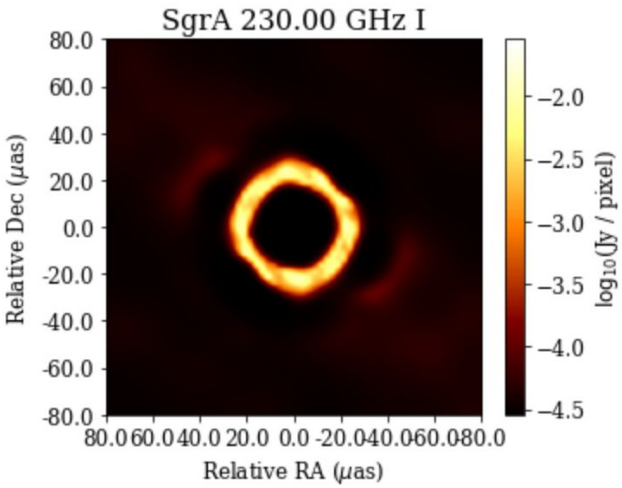
WHERE SCIENCE AND ENGINEERING CONVERGE

Other Interesting Explorations

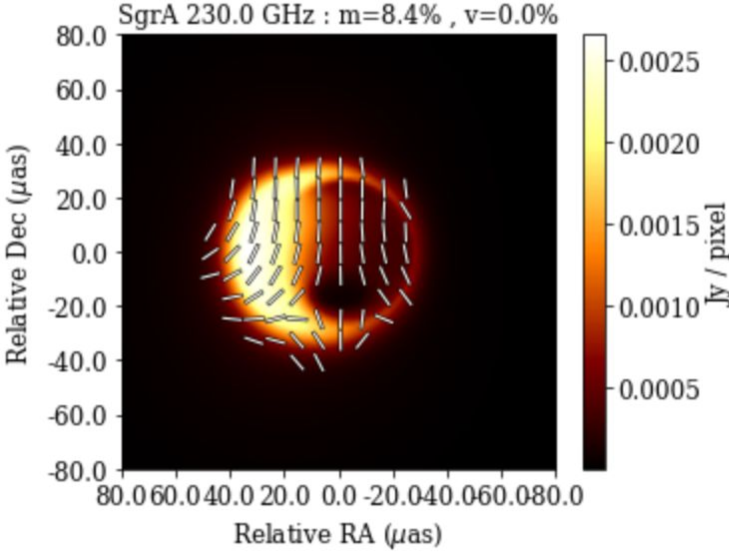
with different assumptions and prior

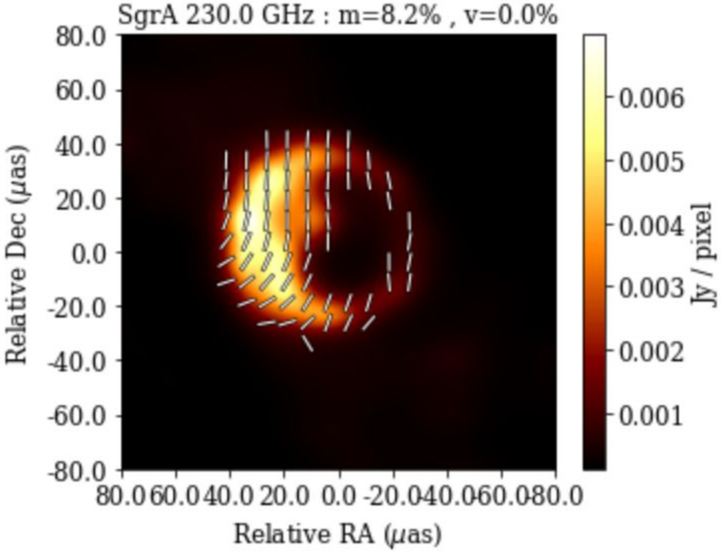
Ring Structure instead of Disk



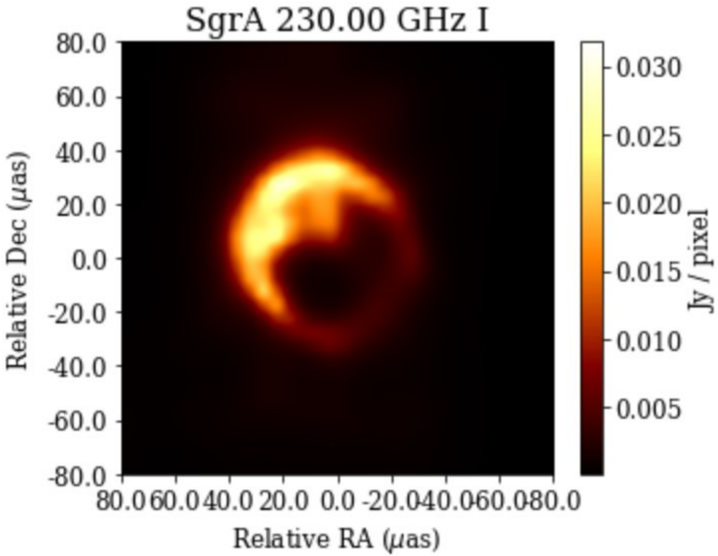


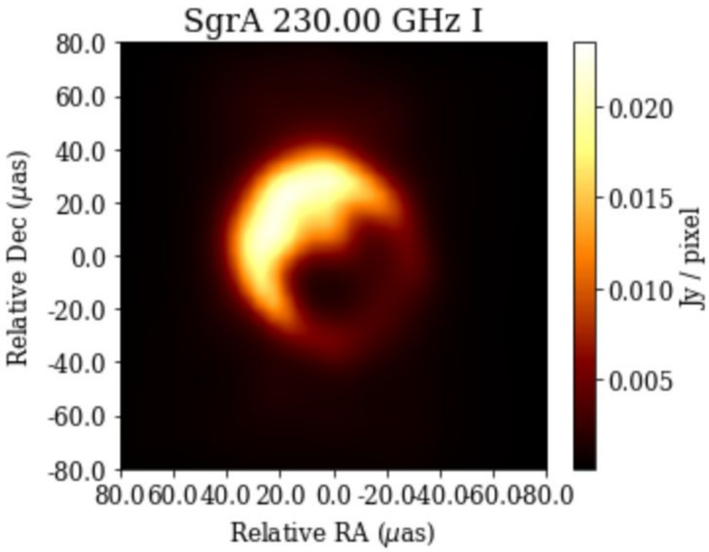
Imaging with Polarization *with the polarimetric ratio*



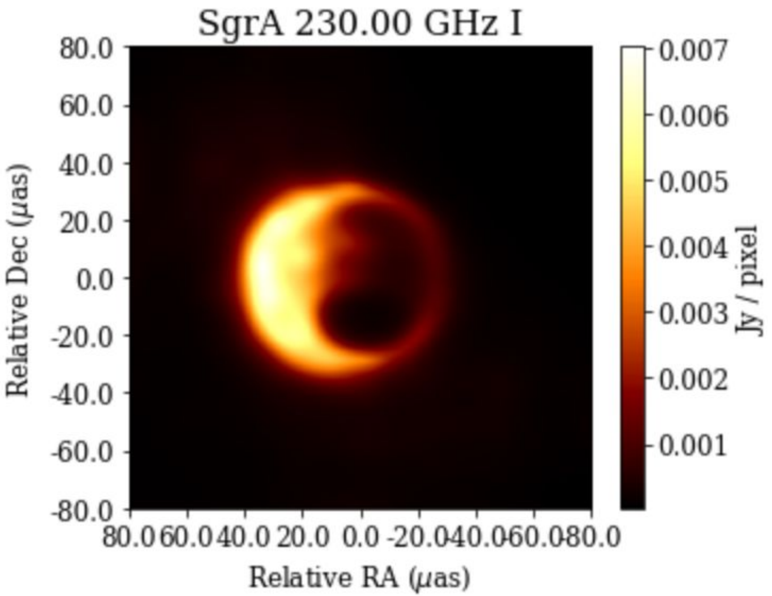


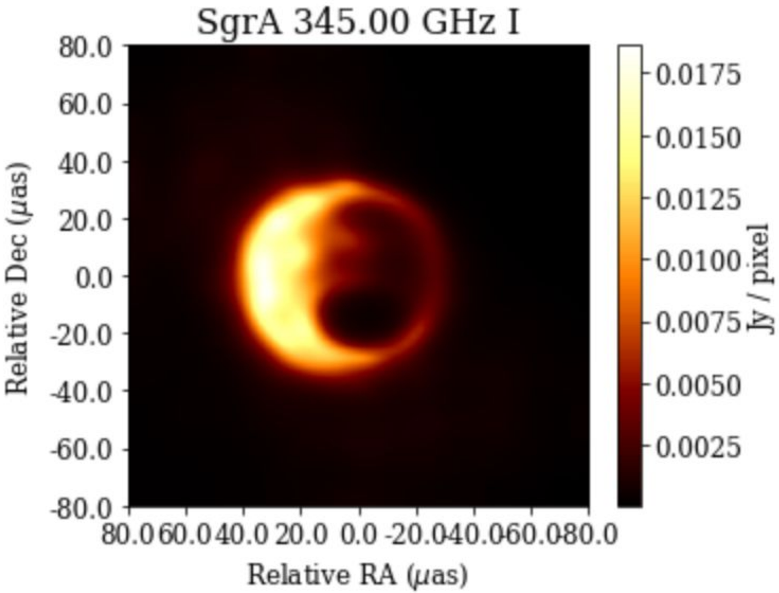
Imaging with Rotated u,v Coordinates





Imaging with Multi Frequency





Conclusion

- **Challenging Task:** No previous comparable VLBI image of blackhole, different assumptions leads to different reconstructed photos
- **Even with Synthetic Data:** carefully designed metrics for evaluation
    - Other possible metrics: Structural Similarity Index Measure - SSIM (not supported in *eht-imaging*)
- In experiment, **BSMEM** algorithm shows superior performance
- **Sgr A* real data**: much smaller than M87 and faster dynamics

Thank you!

The End.