Resolving the Motion of the Accretion Flow and Jet in M87*

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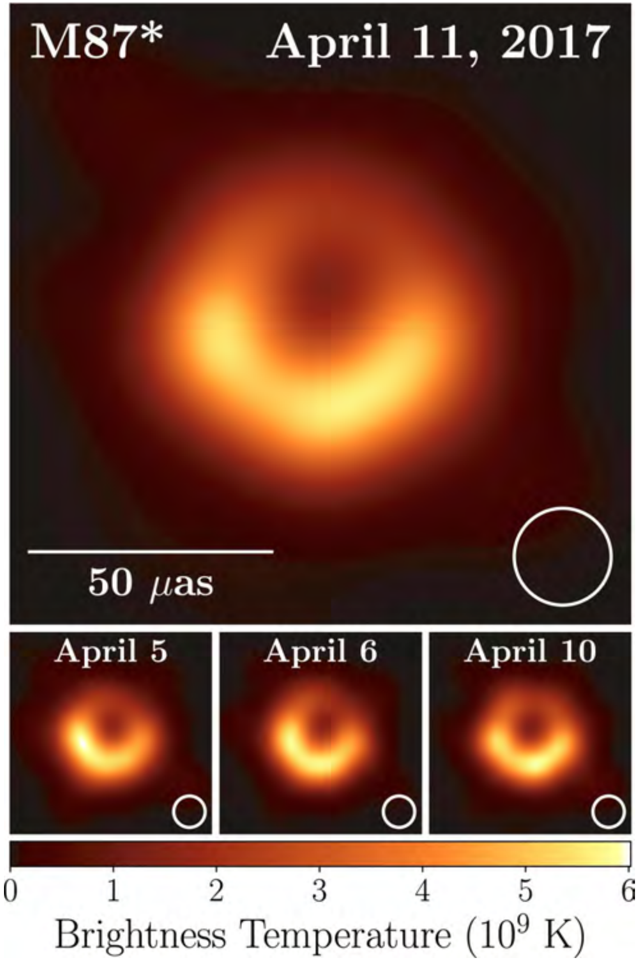
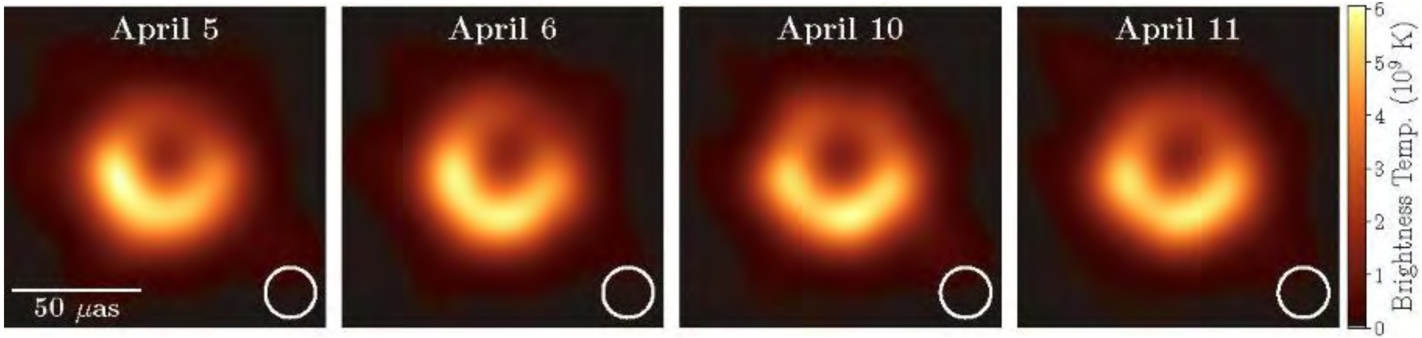


EHT Collaboration et al. 2019a, ApJL (Paper I)

Introduction to the Event Horizon Telescope



EHT Collaboration et al. 2019d, ApJL (Paper IV)

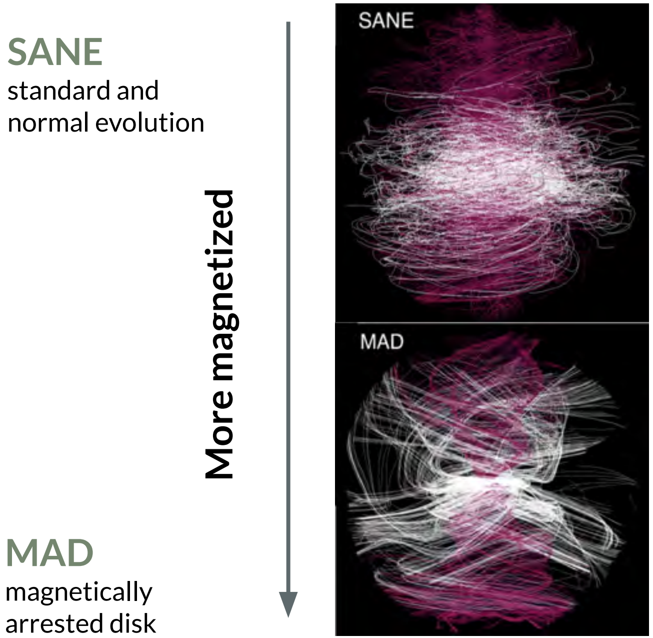
★ EHT observations are a few days at a time - M87* rotates on a scale of weeks

★ a goal of the EHT is to generate a video of the motion of a supermassive black hole from observation in the next several years

★ motion is expected to follow general relativistic magnetohydrodynamics (GRMHD)

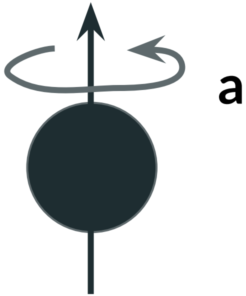
Three Key GRMHD Parameters

MAD or SANE?:
how strongly the black hole is magnetized



Foucart et al. 2018

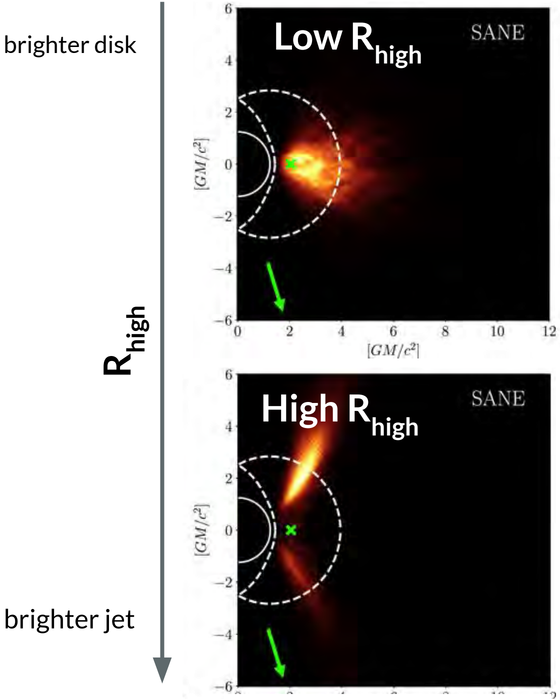
Spin (a):
how fast the black hole rotates



positive spin = **prograde spin**
accretion flow is same direction as black hole rotation

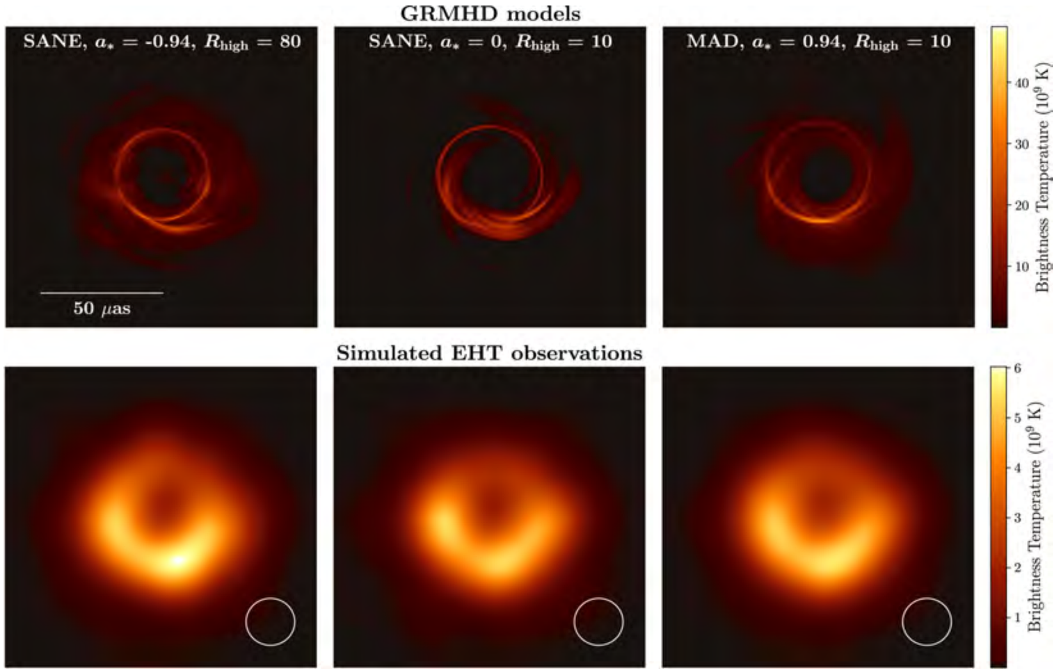
negative spin = **retrograde spin**
accretion flow is opposite direction to black hole rotation

R_{high}:
how hot electrons in the jet are



EHTC+2019e (Paper V)

EHT Images and GRMHD Parameters

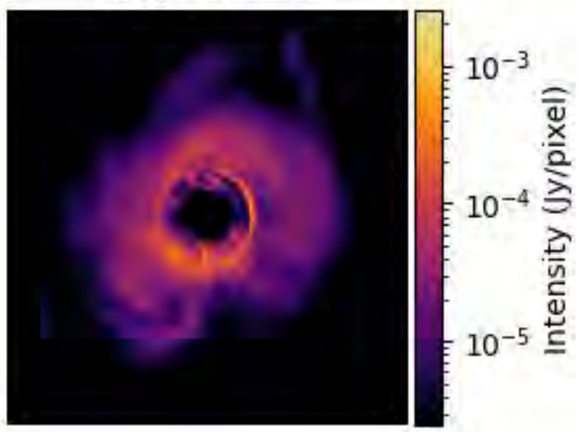


EHT Collaboration et al. 2019a, ApJL (Paper I)

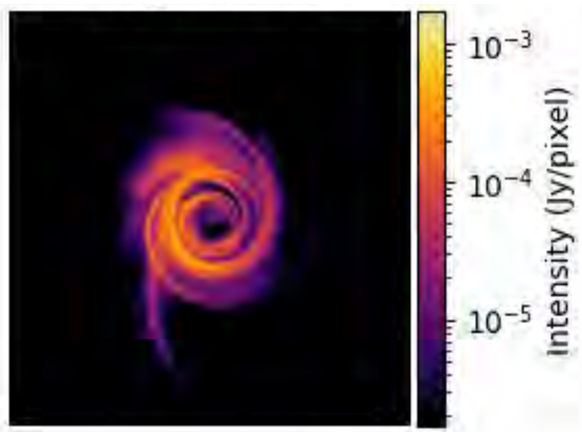
a single snapshot is not enough to determine the different factors involved

Motivation: Using Dynamics to Explore the Flow

MAD, a = -0.5, R_{high} = 10



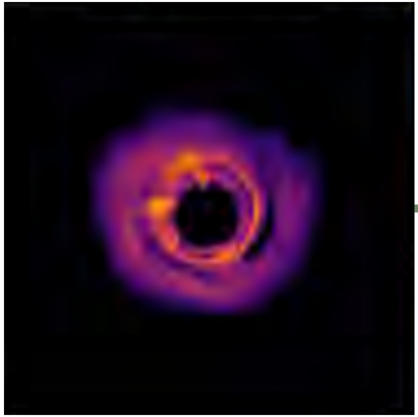
SANE, a =0.94, R_{high} = 160



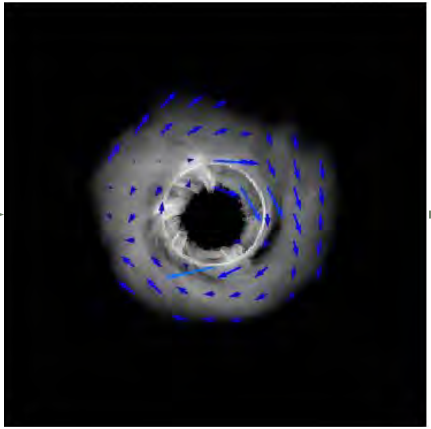
- ★ dynamics may more easily highlight differences in GRMHD parameters
- ★ resolve the complex dynamics of the accretion flow and the jet
- ★ extract and characterize the motions of general relativistic magnetohydrodynamic (GRMHD) simulations

This Project: Characterization of the Flow Dynamics

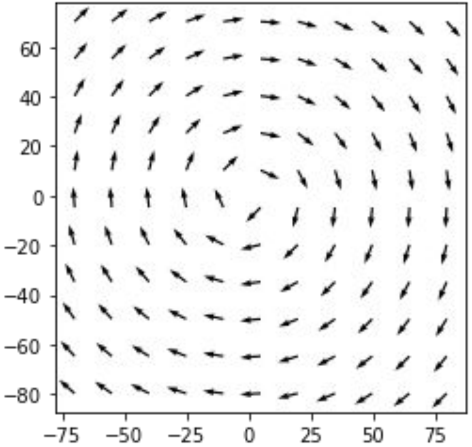
Input GRMHD Video



Optical Flow Video



Flow Characterization

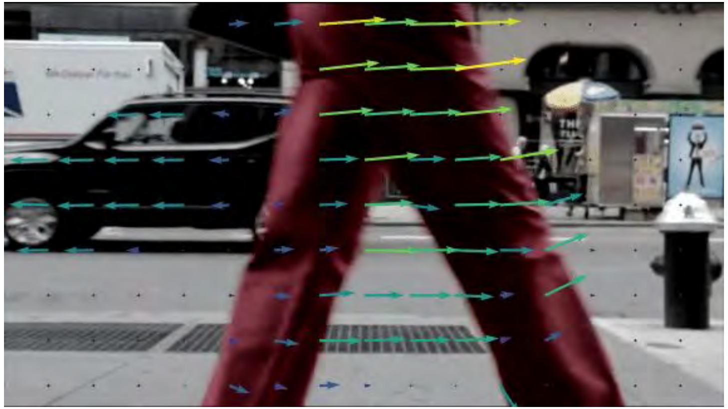


developing a python-based tool and pipeline for:

★ extracting the optical flow from GRMHD videos
★ characterizing the extracted velocity field using polar Fourier analysis

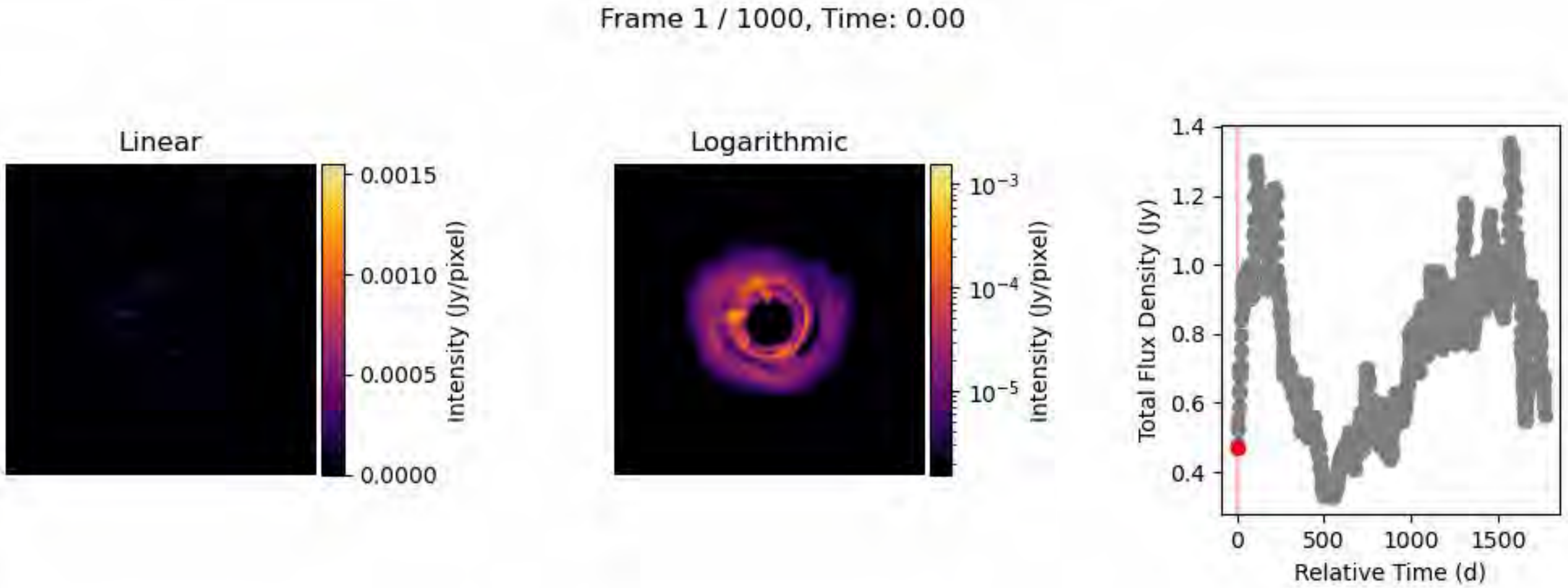
Method: Optical Flow

- ★ optical flow estimates per pixel motion between two frames
- ★ used to estimate an object's **displacement vector** as the camera or object moves
  - ☆ works under the assumption that a pixel's intensity doesn't change
- ★ method used is **dense optical flow** (Lucas-Kanade algorithm)
  - ☆ works under the assumption that nearby pixels have the same displacement vector



from an opencv tutorial

Example Simulation

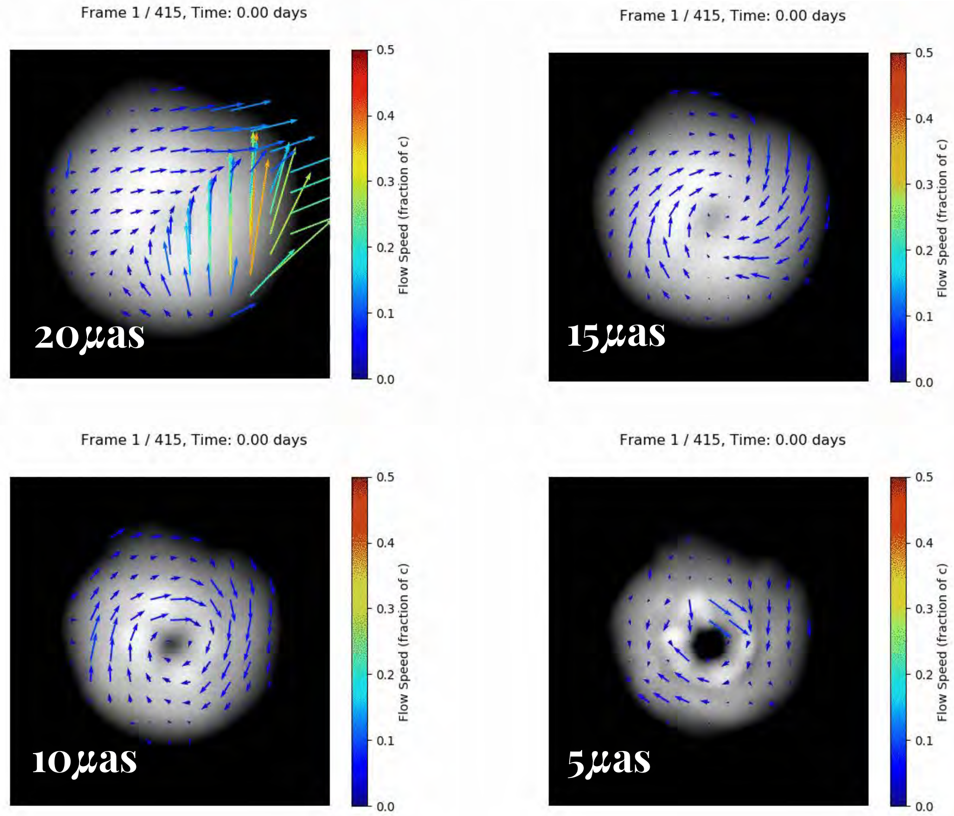


The video for MAD, a=0, and R_{high} = 40. This is the example chosen to demonstrate concepts throughout this presentation.

Expectations vs Reality

- ★ right now the angular resolution of the EHT is **17 microarcseconds**

- ★ with the earth covered in telescopes at 345 GHz, the angular resolution would be **10 microarcseconds**

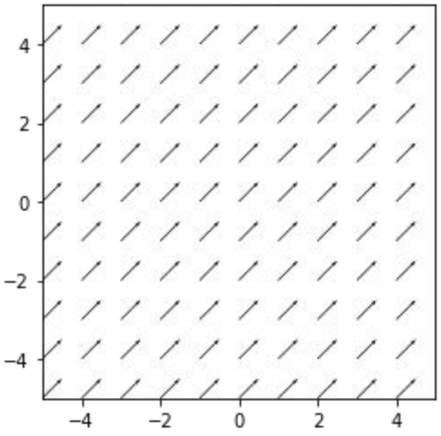


Characterization of the Motion Field

extracted Optical Flow

$$\beta_m(r_{\min}, r_{\max}) = \frac{\int_{r_{\min}}^{r_{\max}} \int_{-\pi}^{\pi} v(r,\theta) e^{-im\theta} r dr d\theta}{\int_{r_{\min}}^{r_{\max}} \int_{-\pi}^{\pi} r dr d\theta}$$

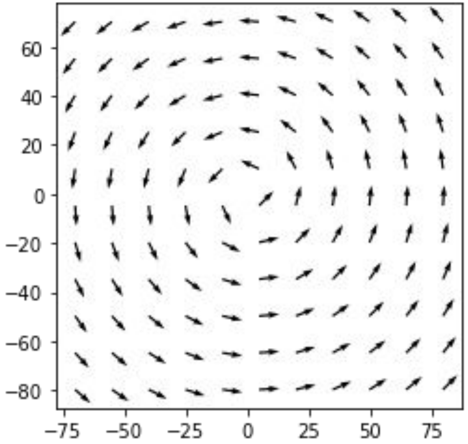
m=0 mode: a mode without a rotation (uniform field)



$|\beta_0|$: velocity

$\arg\beta_0$: position angle

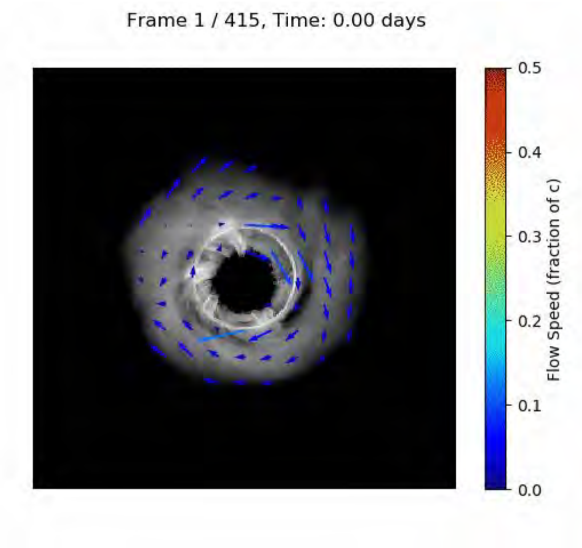
m=1 mode: a mode with a single rotation (spiral pattern)



$|\beta_1|$: spiral velocity

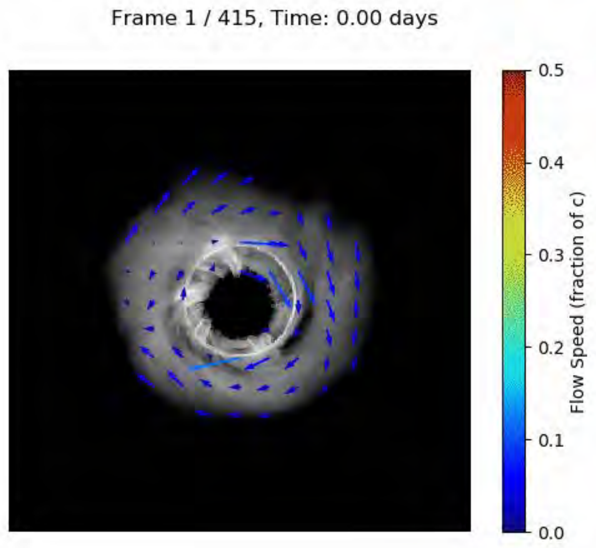
$\arg\beta_1$: spiral pitch angle

Results of Beta Extraction & Spin Dependency



Conclusion & Acknowledgements

- ★ videos are needed to resolve the factors involved in the motion of the accretion disk and jet
- ★ in the future, dense optical flow can be used to extract the motion
- ★ future work:
  - ☆ examining the R_{high} dependency
  - ☆ beta extraction at different resolutions



Thank you to Kazu and Vincent for mentoring me since January; to Charles Gammie for the use of the GRMHD models; to all of the people at Haystack for the seminars throughout the REU program; to Kate for listening to me try to explain what I did each day; to Katy for having random questions for me to humor; and to Northeastern, MIT, and the NSF for this opportunity.

Extracting the Motion of M87*

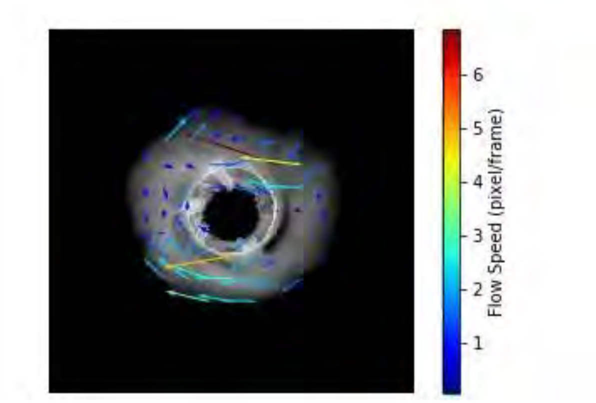
Audrija Sarkar
Northeastern University

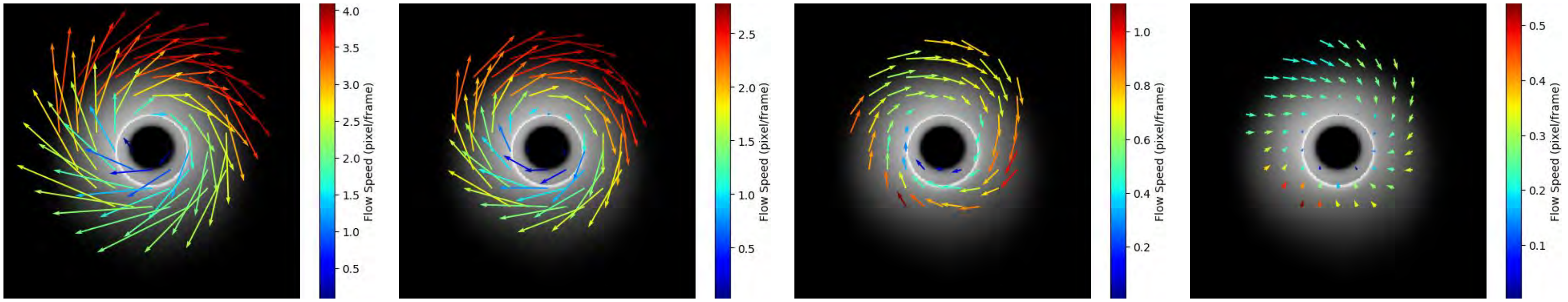
Research Experiences
for Undergraduates
National Science Foundation

MIT
HAYSTACK
OBSERVATORY

Time average plots

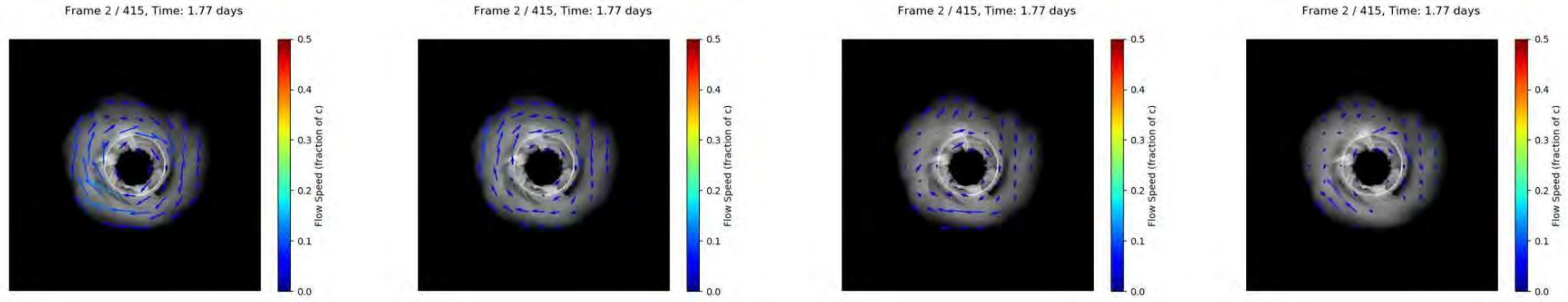
- ★ These are the time averaged vectors of MAD a=0 R_{high}=40
- ★ The video takes the flow over 4 frames
- ★ The plot below are 2 frames, 4 frames, 8 frames, and 16 frames





Time average plots

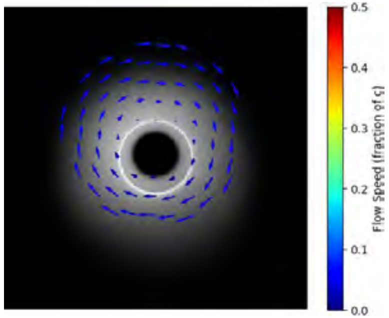
★ These are the vectors of MAD a=0 R_{high}=40
★ These are using the speed as a fraction of c
★ The plot below are 1 frame, 2 frames, 3 frame, 4 frames



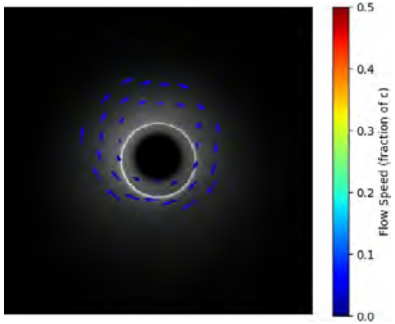
Time average plots (different scaling)

★ This is the ground truth simulation (of MAD +0 40) but at different scales

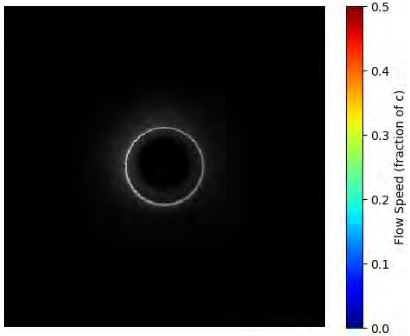
★ Flow speed is as a fraction of c



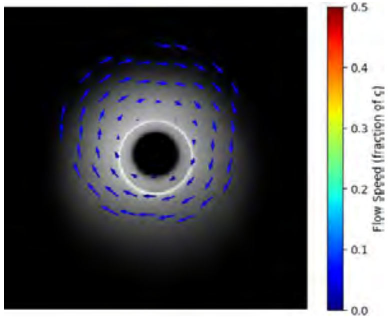
Log scale, peakscale



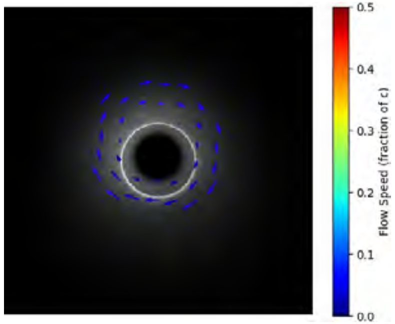
Gamma scale, peakscale



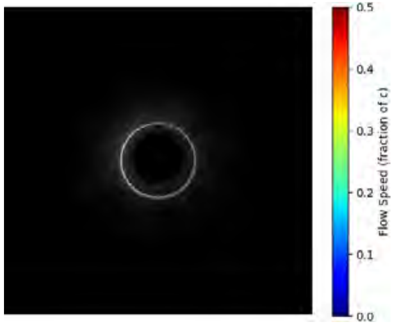
Linear scale, peakscale



Log scale, fluxscale



Gamma scale, fluxscale

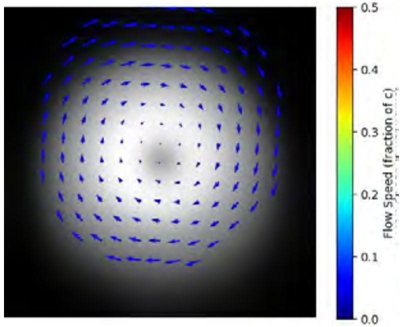


Linear scale, fluxscale

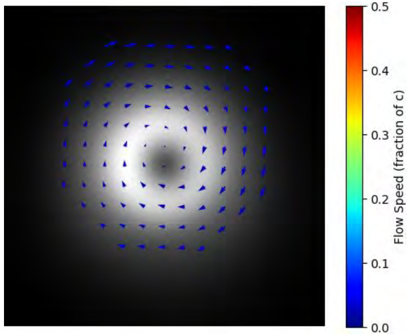
Time average plots (15 microarcseconds)

★ This is the 15 microarcseconds simulation (of MAD +0 40) but at different scales

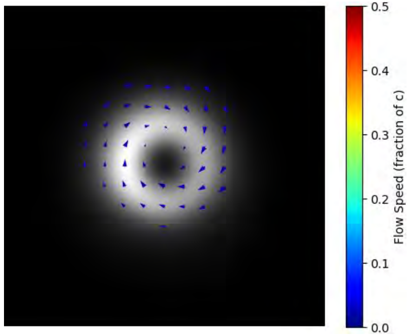
★ Flow speed is as a fraction of c



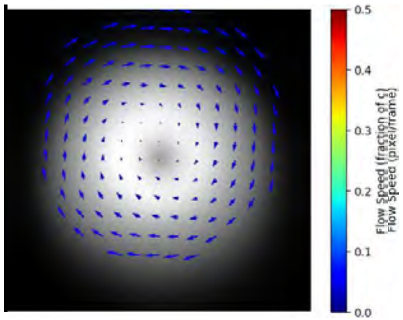
Log scale, peakscale



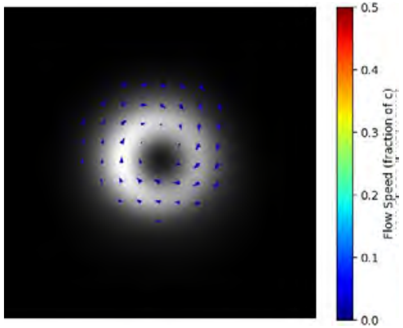
Gamma scale, peakscale



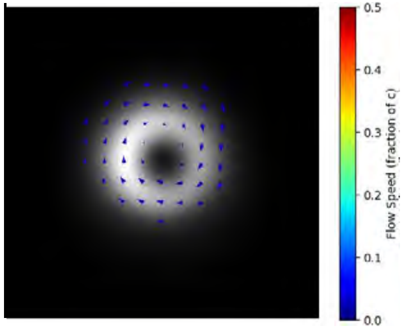
Linear scale, peakscale



Log scale, fluxscale

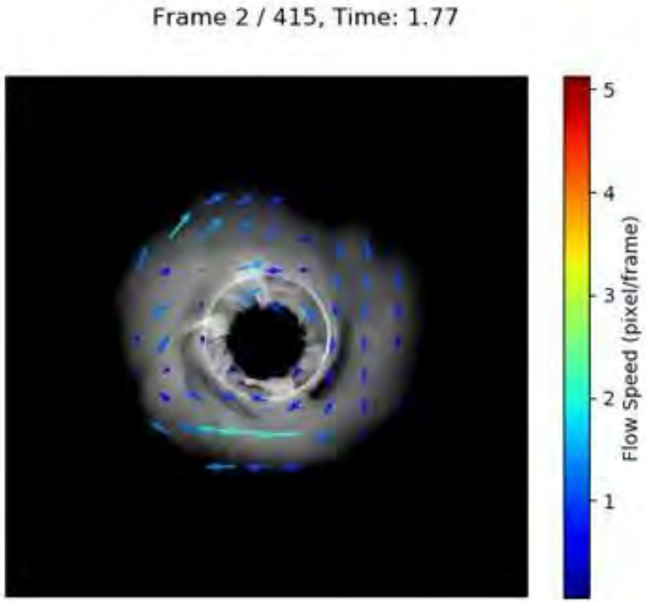


Gamma scale, fluxscale

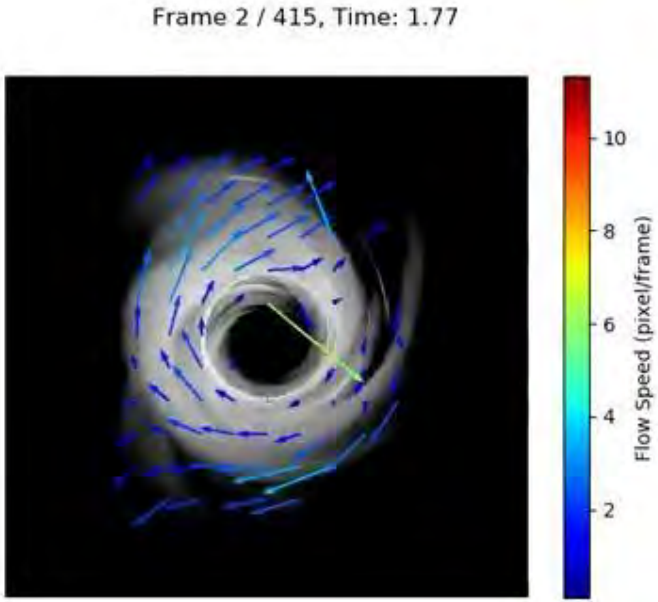


Linear scale, fluxscale

Mad vs sane



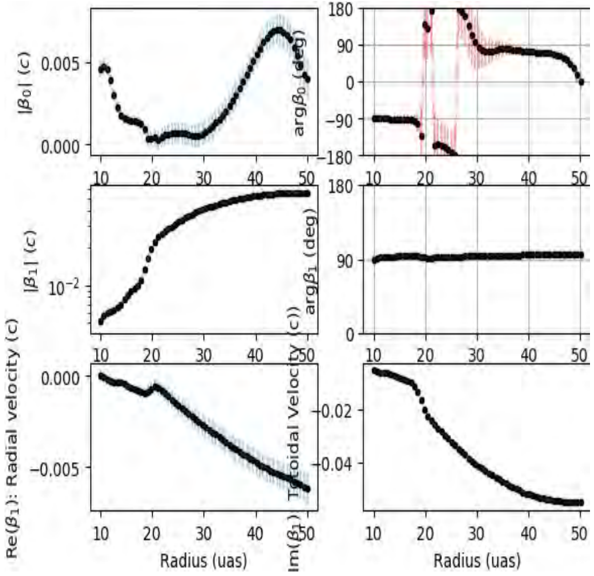
Frame 2 / 415, Time: 1.77
5
4
3
2
1
Flow Speed (pixel/frame)

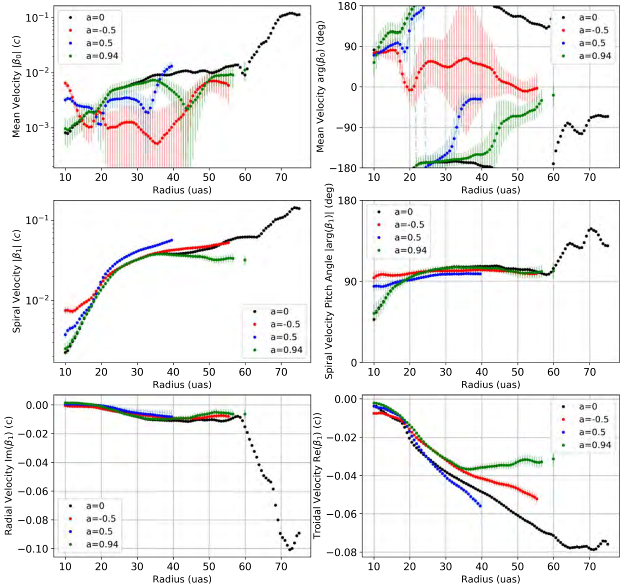


Frame 2 / 415, Time: 1.77
10
8
6
4
2
Flow Speed (pixel/frame)

Beta extraction

6plot of just a=0 compared to 6plot of all spins compared to 6plot of all rhigh





abstract

The Event Horizon Telescope (EHT) currently produces static images of the emission surrounding supermassive black holes. A key goal over the next few years is to lengthen the observing window in order to produce movies of the supermassive black hole at the center of Messier 87, M87*. An important purpose of such a movie would be to resolve the complex dynamics of material in the accretion flow and jet. In this project, we have developed a tool to extract and characterize motions in videos generated from general relativistic magnetohydrodynamic (GRMHD) simulations. For the motion extractions, two methods were examined: voxelmorph, a neural network used in medical imaging, and Lucas-Kanade method in opencv, a classical technique to measure the dense optical flow. We find that the Lucas-Kanade method is more effective at detecting spiral motion than voxelmorph. We further characterized the extracted angles of rotation and velocity field with polar Fourier analysis. These results demonstrate that optical flow methods may be used to characterize the dynamics of the accretion disk from EHT observation.