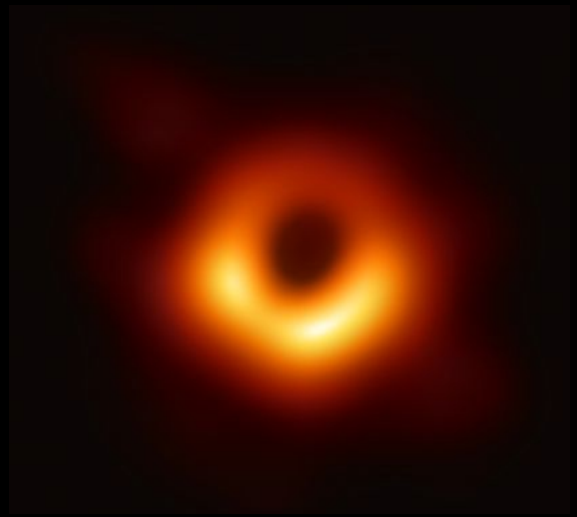


Imaging M87's Inner Ring

Katy Hunter

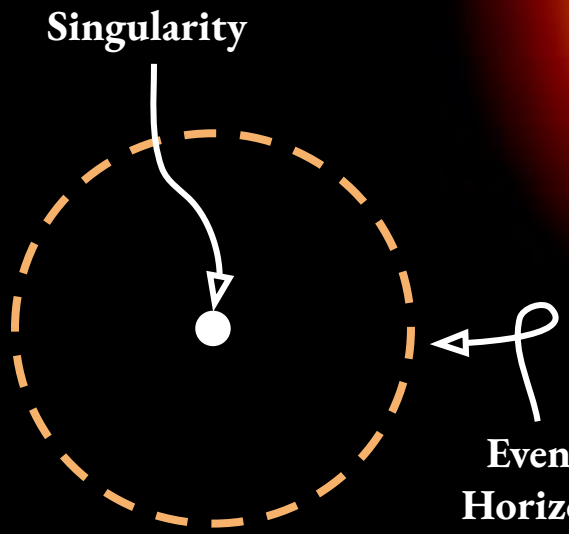
Mentors: Vincent Fish and Kazu Akiyama

Research **E**xperience for **U**ndergraduates

Black Hole Structure

Observer Angle: 20°

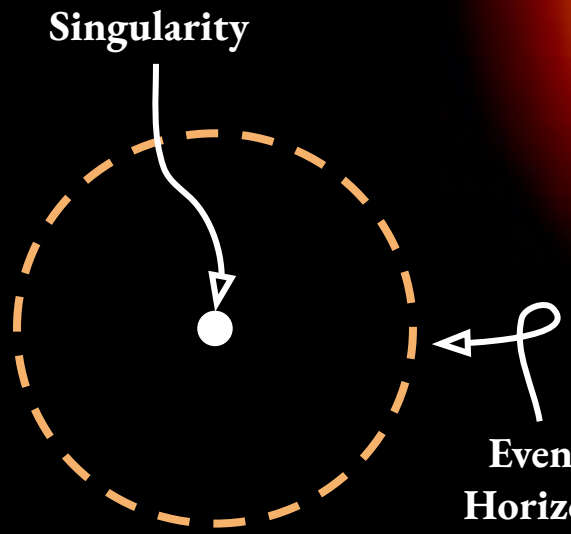
Models from Charles Gammie

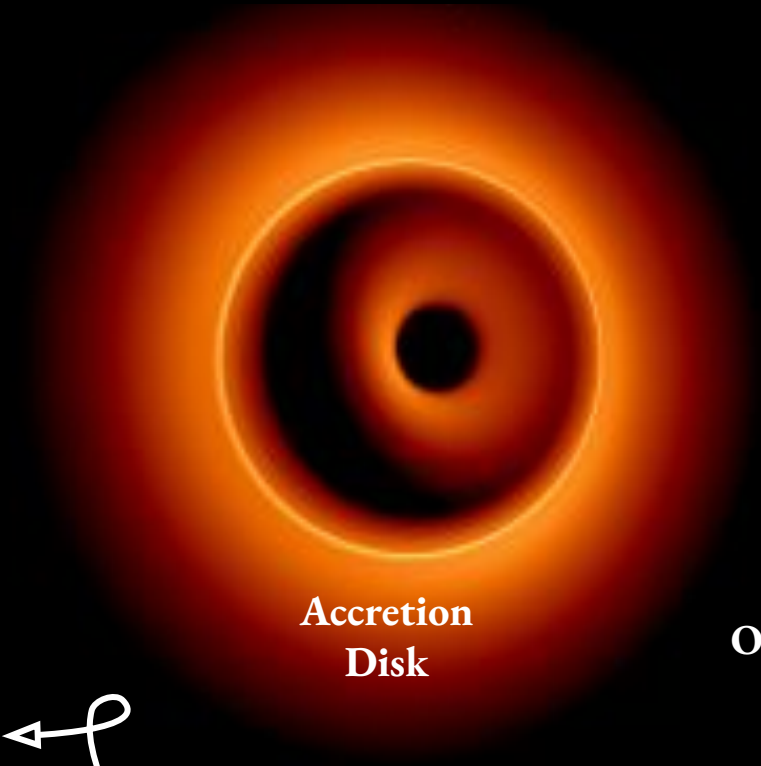


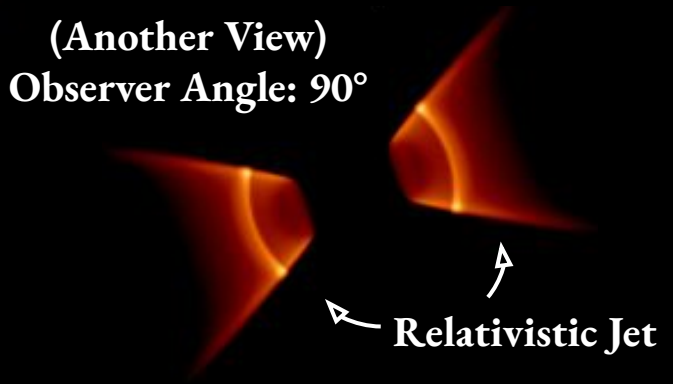
(Another View)
Observer Angle: 90°

Models from Charles Gammie

Black Hole Structure

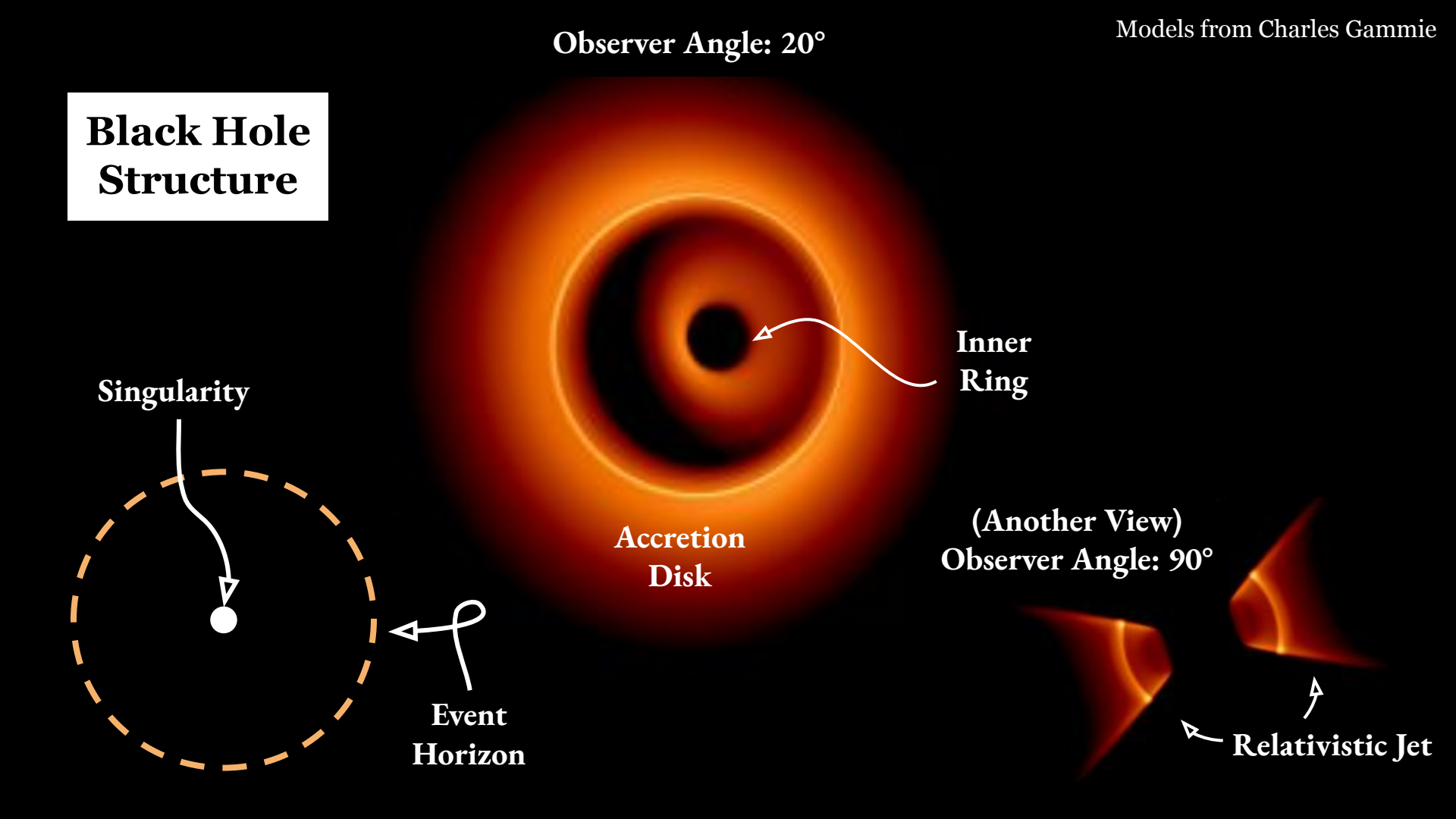






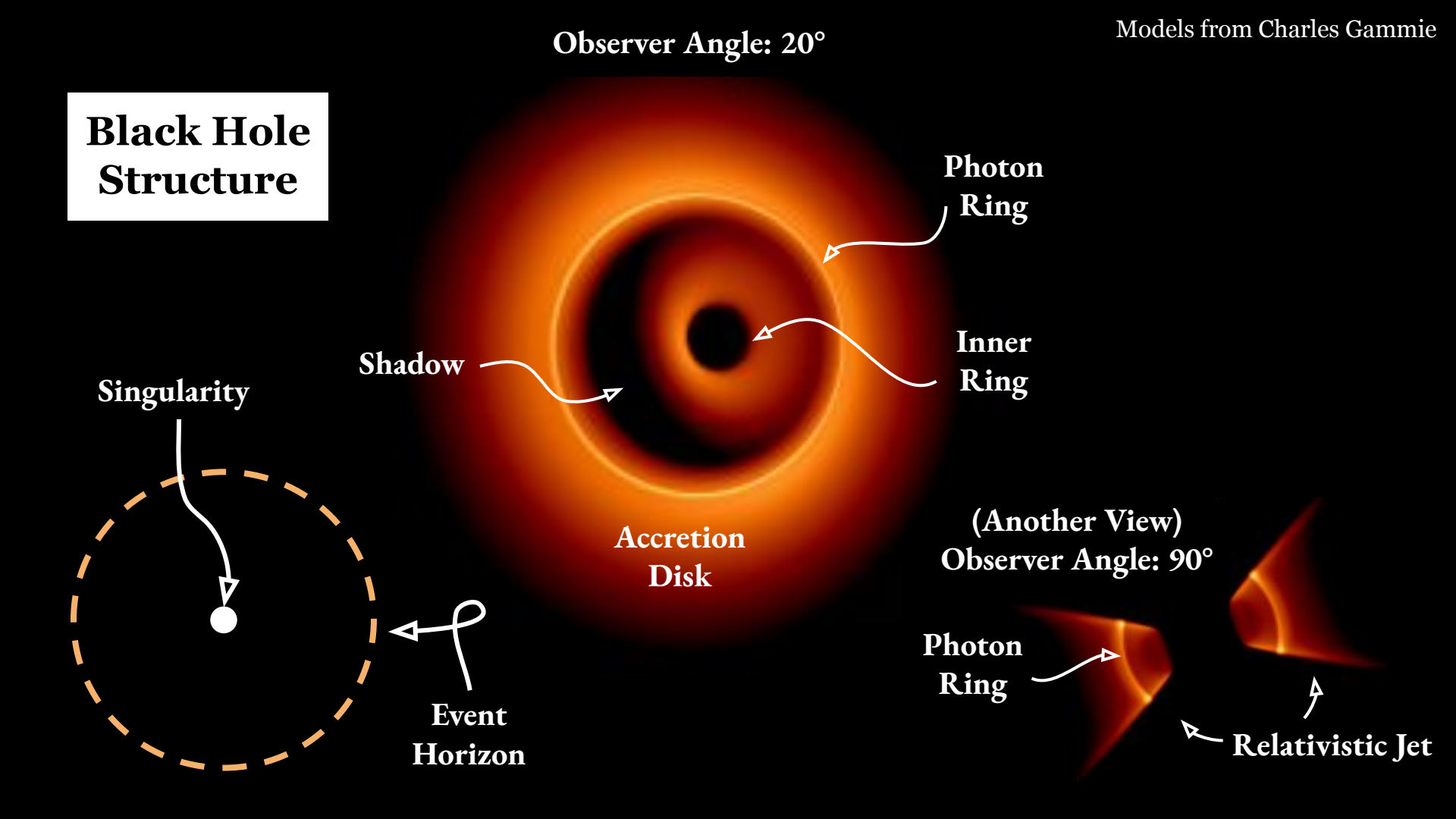
Black Hole Structure

Models from Charles Gammie



Black Hole Structure

Models from Charles Gammie



Black Hole Structure

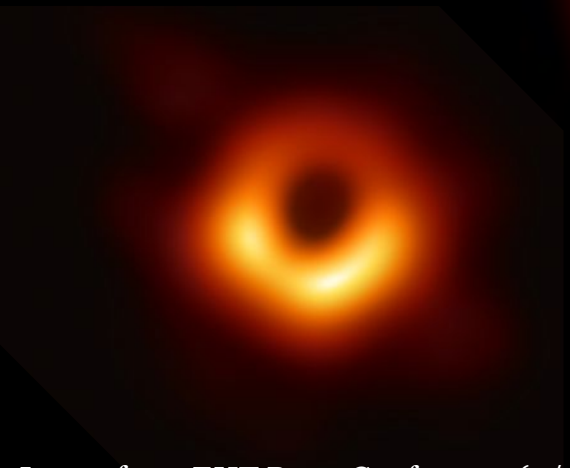


Image from EHT Press Conference (4/10/2019)

Observer Angle: 20°

Photon Ring

Inner Ring

Shadow

Accretion Disk

Models from Charles Gammie

(Another View)
Observer Angle: 90°

Photon Ring

Relativistic Jet

Black Hole Structure

Black holes have mass, spin, and charge

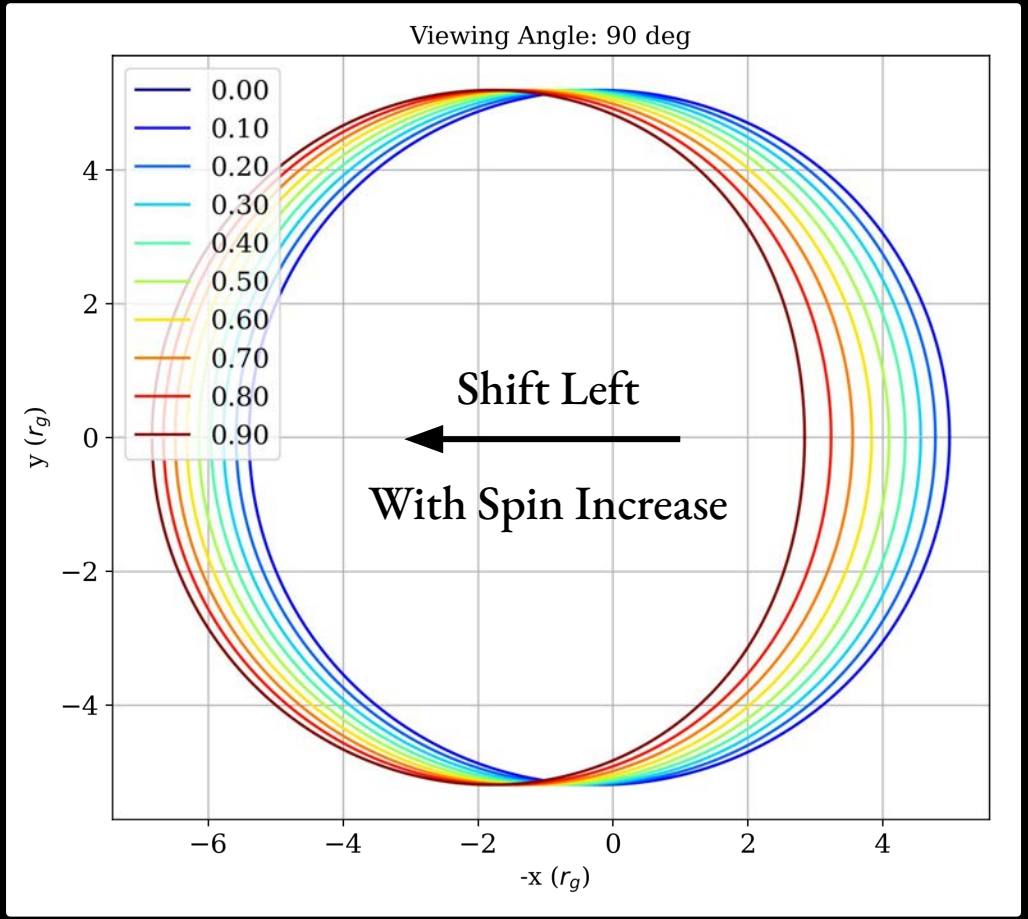
a = spin

Photon ring **size** varies by

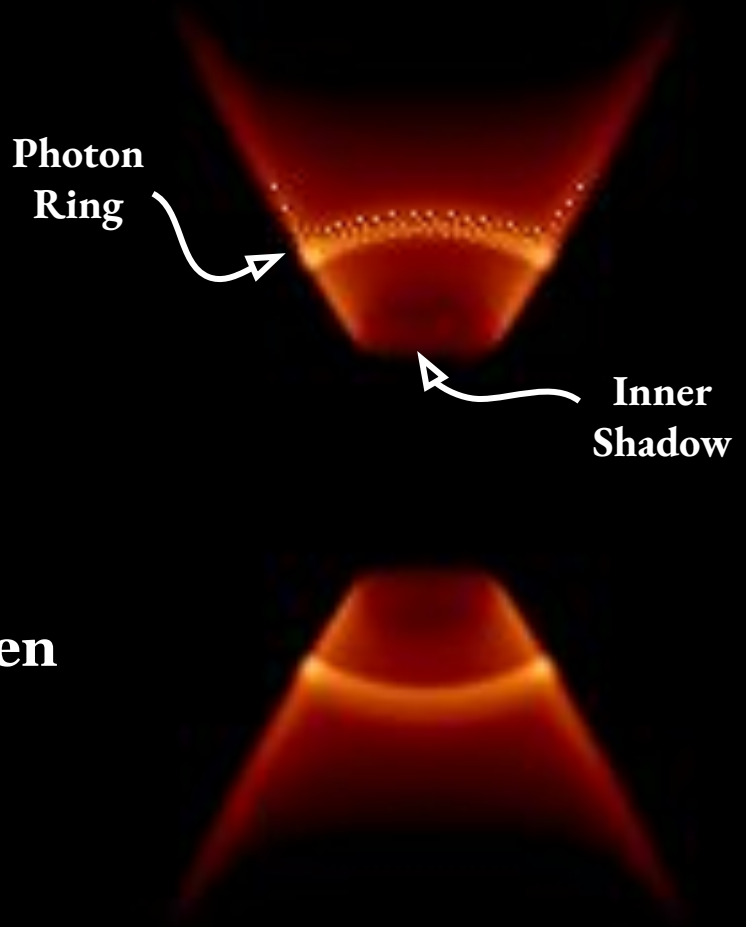
1 - (constants) a^2 = (~4%)

Photon ring **position** varies as

2a



Black Hole Structure



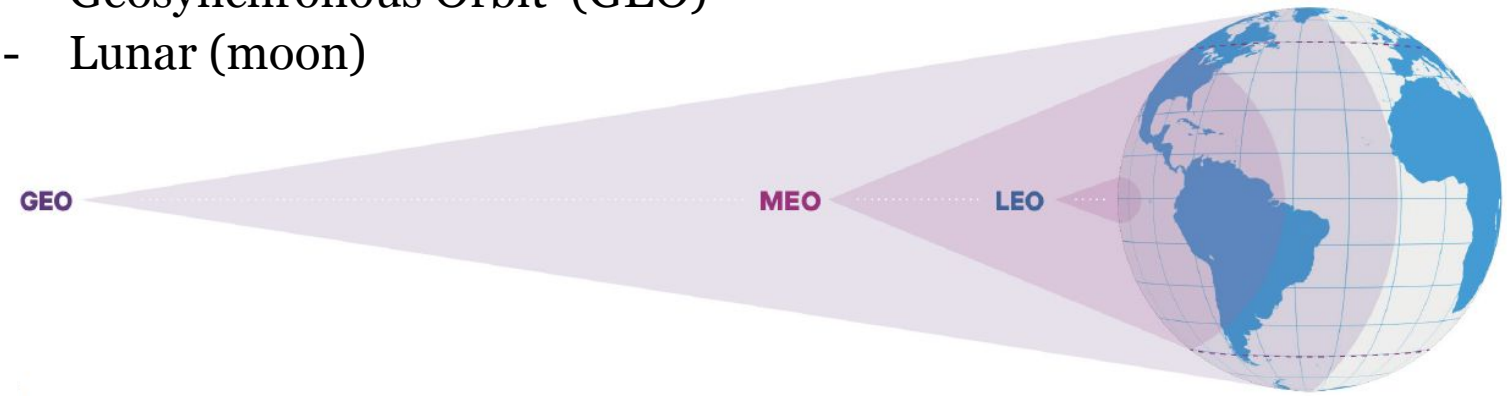
For different spins:

- **Inner ring remains stationary**
- **Outer ring shifts**

By measuring the offset between outer ring and inner ring, we can find the black hole spin

Very-Long Baseline Interferometry (VLBI)

- Angular resolution for 2019 M87 image was not enough to resolve the inner ring
- More coverage and/or longer baseline = better angular resolution
- Some types of orbits:
  - Low-Earth Orbit (LEO)
  - Medium-Earth Orbit (MEO)
  - Geosynchronous Orbit (GEO)
  - Lunar (moon)



Goals for the Project

1. Test our ability to resolve the inner ring with ideal coverage **ground VLBI**
2. Simulate observations with **space VLBI** using telescope arrays with various LEO, MEO, GEO, and GEO/Lunar satellites
3. **Extract the offset** of the outer and inner ring positions and compare to the predicted offset in order to determine whether this process can be used to find the spin of a black hole

1. **Limits of Ground VLBI**
2. **Space VLBI**
3. **Modeling & Feature Extraction**

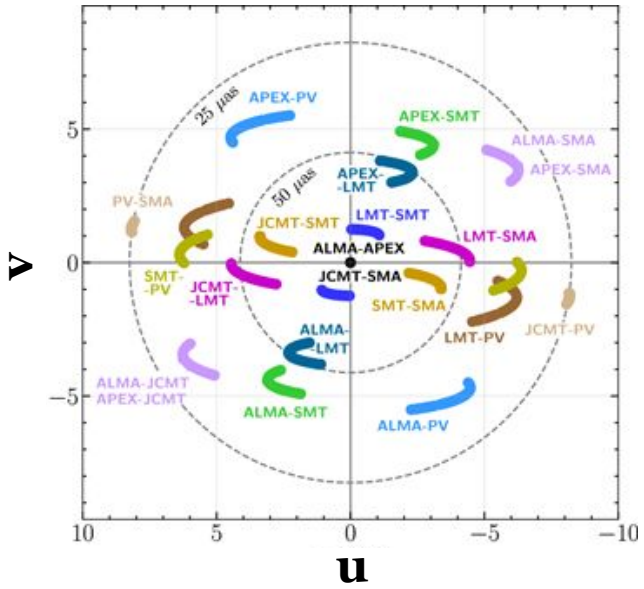
Ideal Coverage

Max Baseline ~ 1.1 x 10^6 m

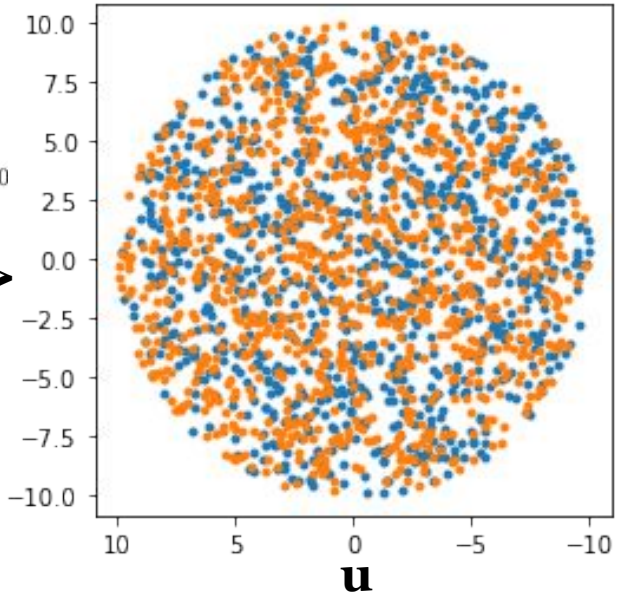
~ 12 G λ at 345 GHz

(based on Earth's diameter)

Coverage for EHT 2019 M87 image



Ideal coverage



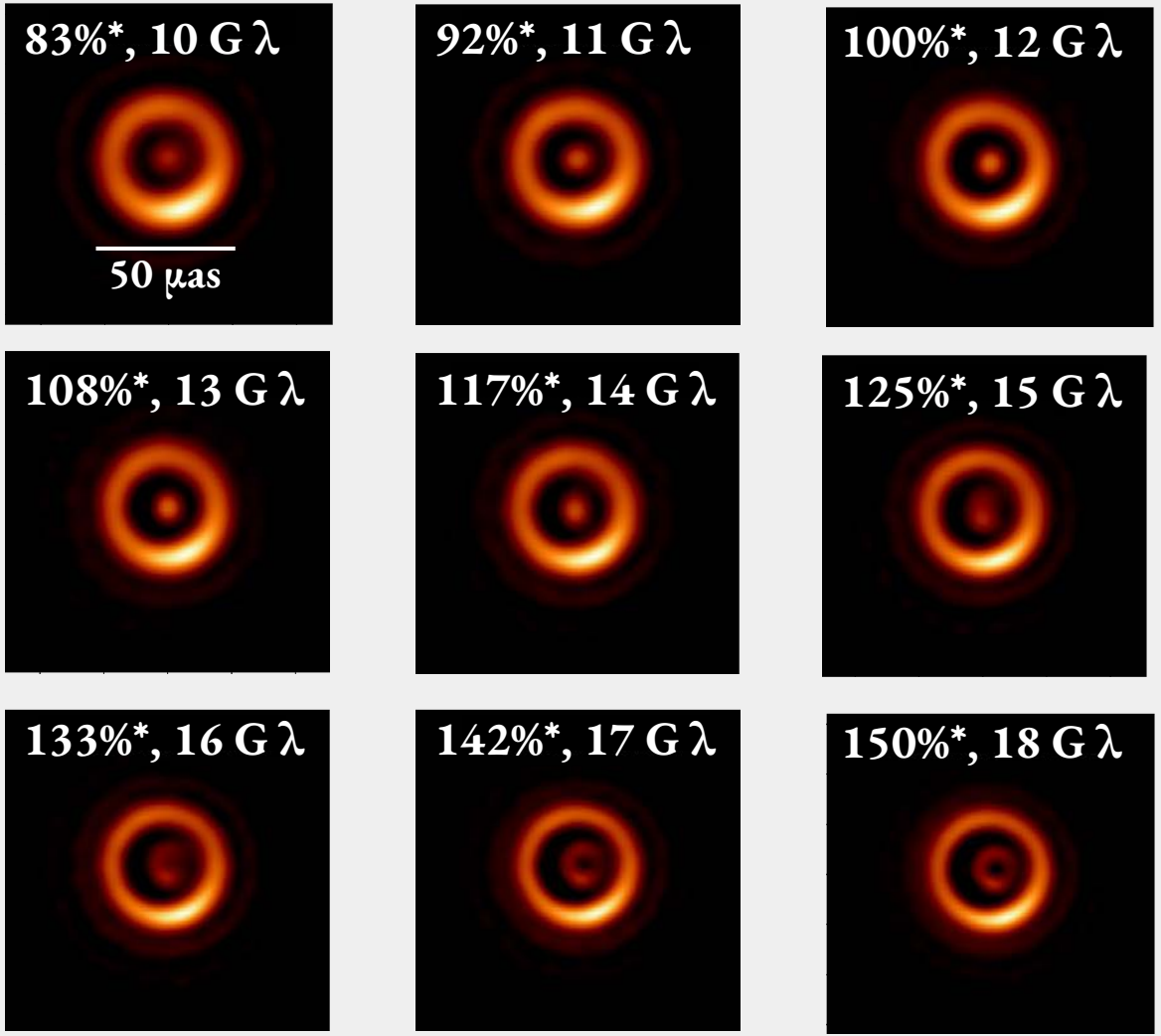
*of Earth's diameter

Ideal Coverage

Max Baseline ~ 1.1 x 10^6 m

~ 12 G λ at 345 GHz

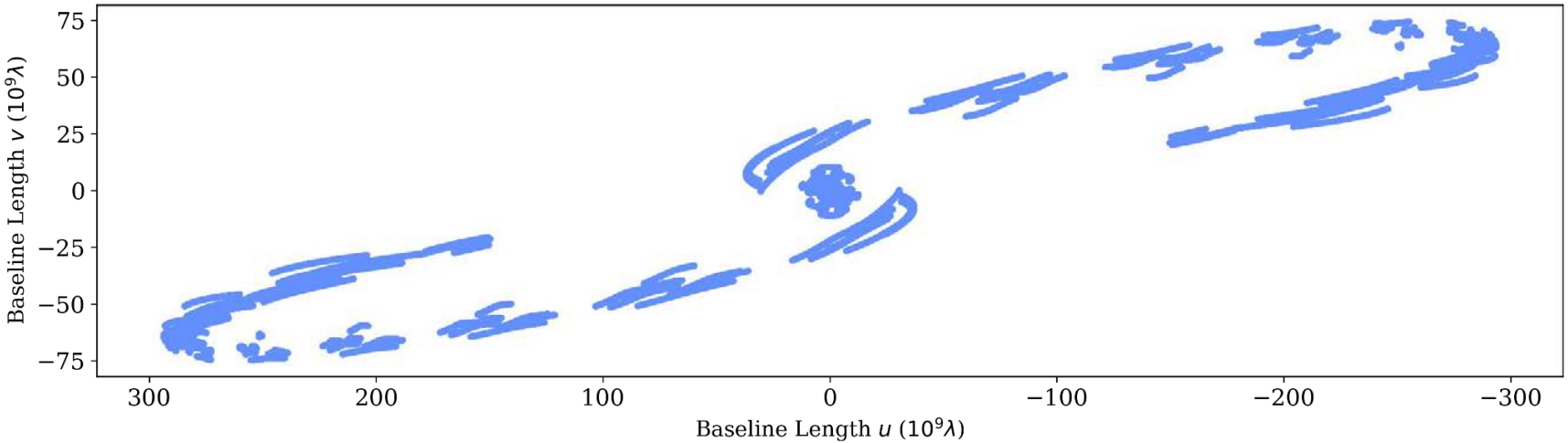
(based on Earth's diameter)



1. Limits of Ground VLBI
2. Space VLBI
3. Modeling & Feature Extraction

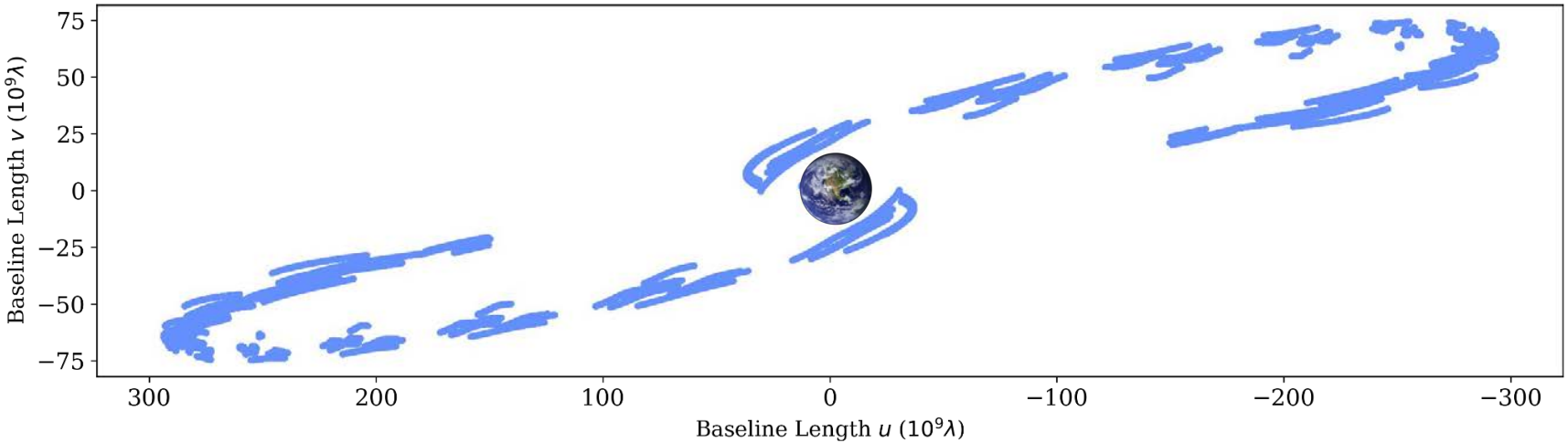
SALTUS Orbit

- GEO/Lunar
- For mid/far infrared
- Very elliptical



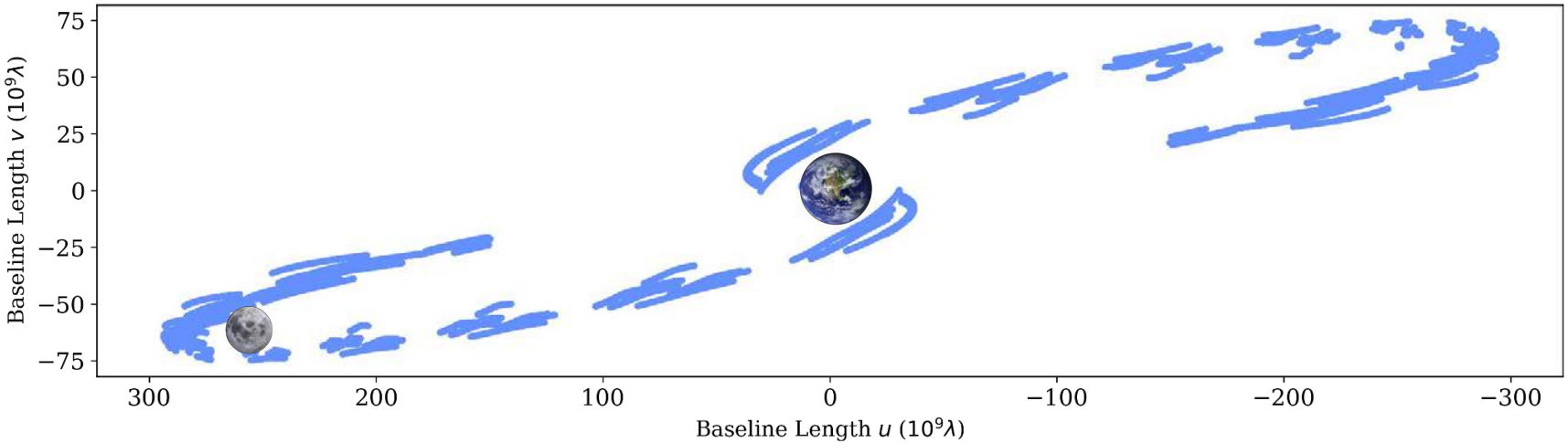
SALTUS Orbit

- GEO/Lunar
- For mid/far infrared
- Very elliptical



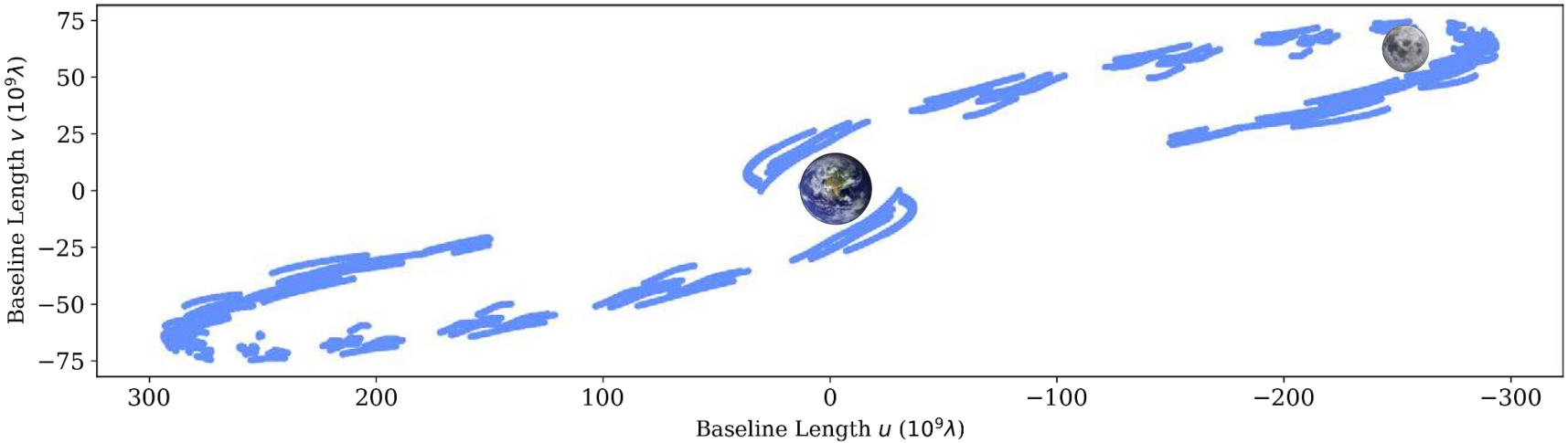
SALTUS Orbit

- GEO/Lunar
- For mid/far infrared
- Very elliptical

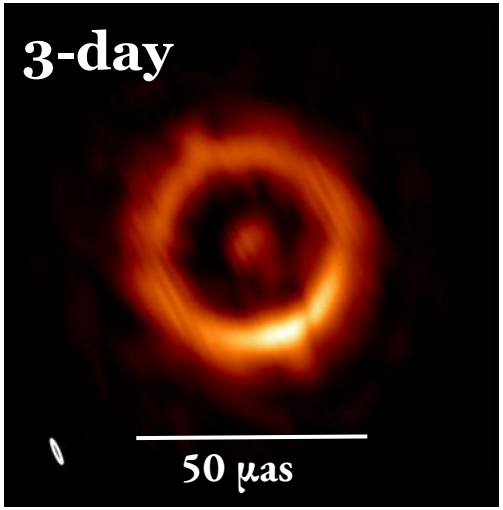


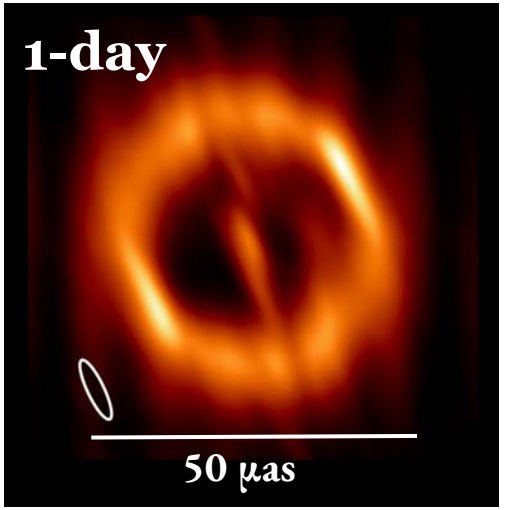
SALTUS Orbit

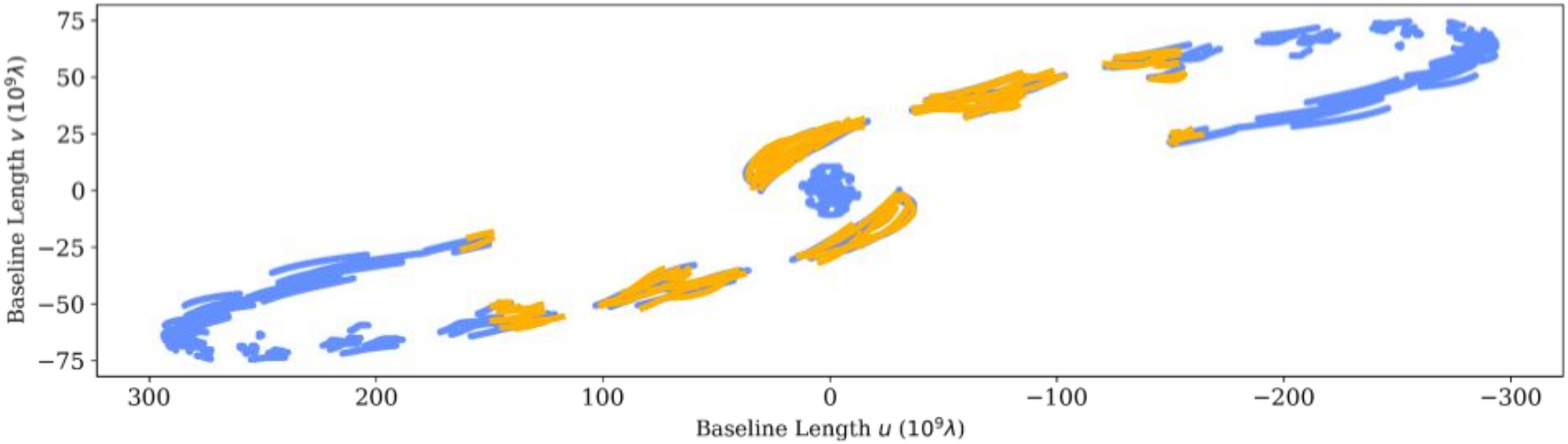
- GEO/Lunar
- For mid/far infrared
- Very elliptical



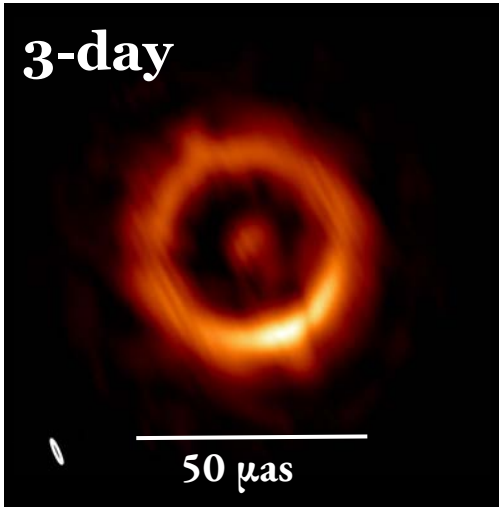
SALTUS Orbit

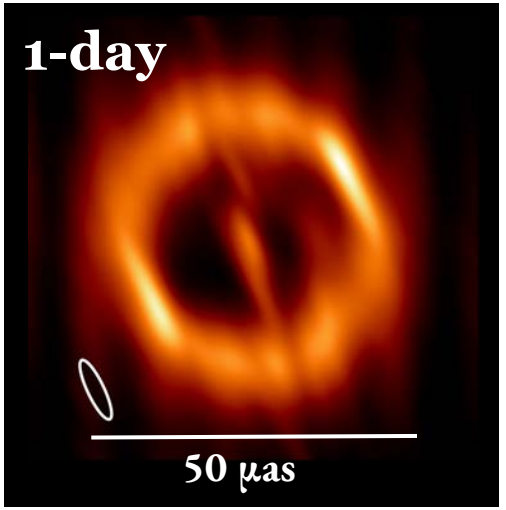


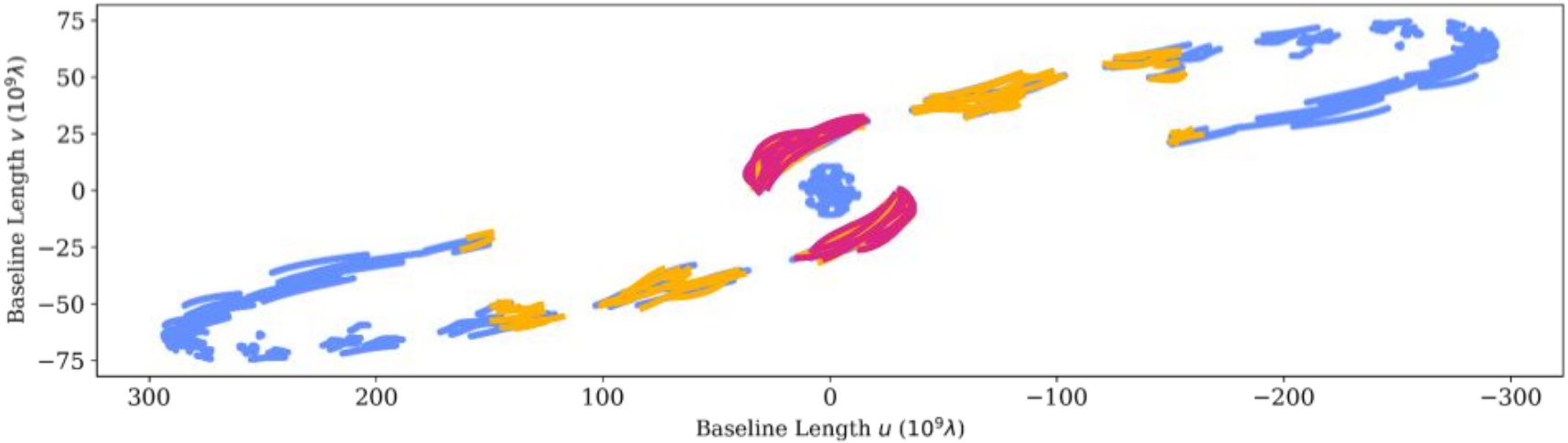




SALTUS Orbit





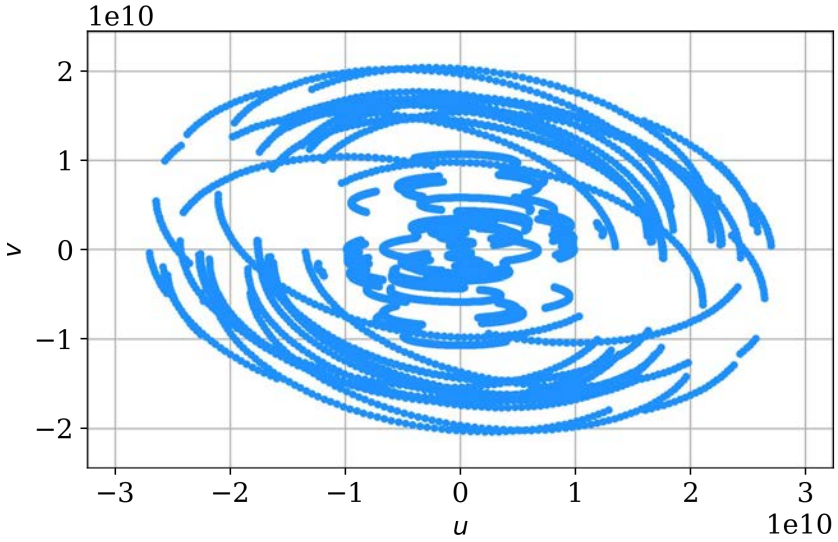


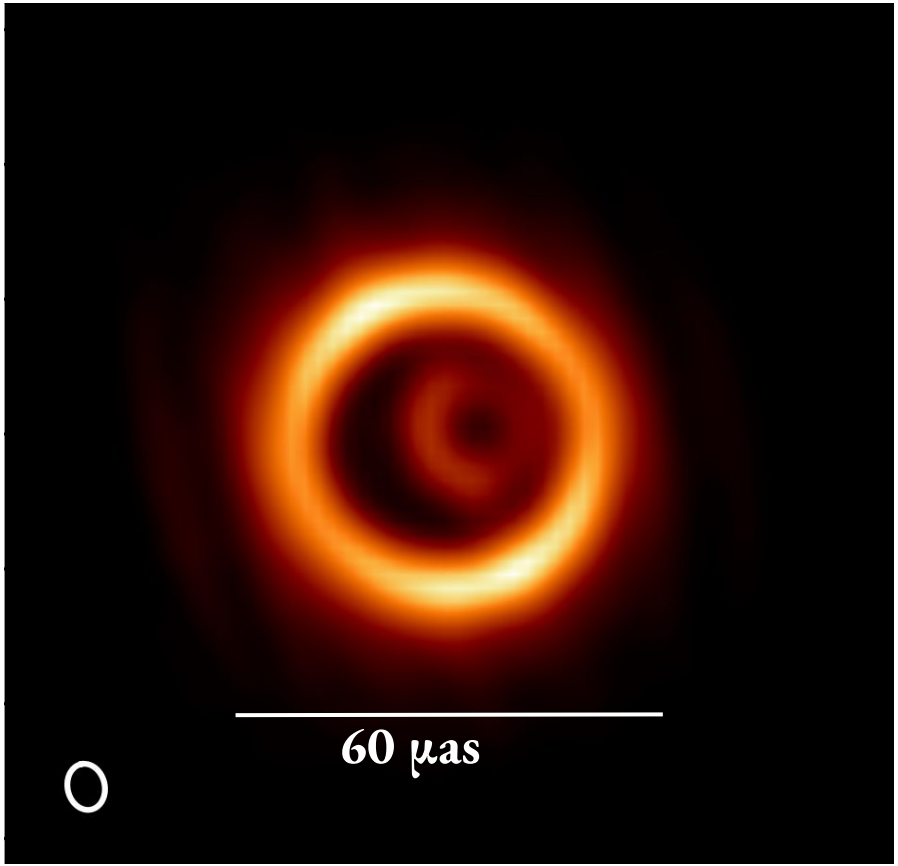
Emulating Event Horizon Explorer Orbit (MEO)

Inclination: 30°

Right Ascension: 300°

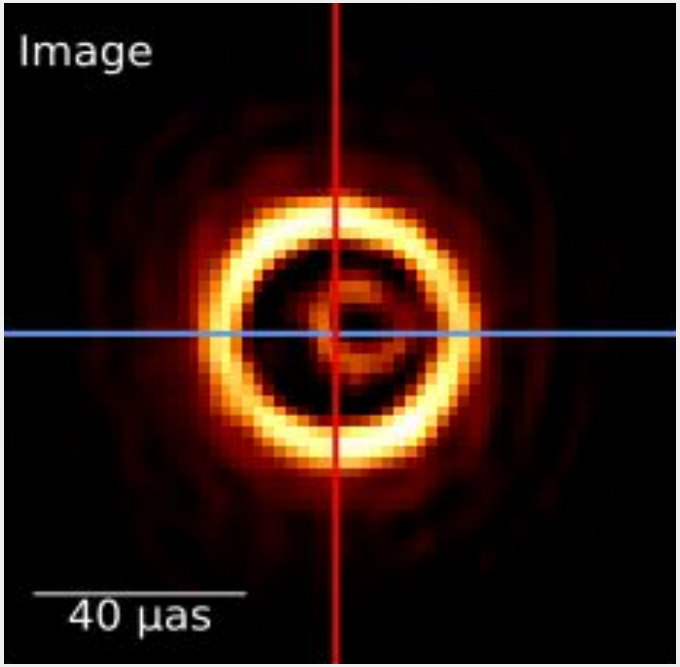
Eccentricity: 0.0002

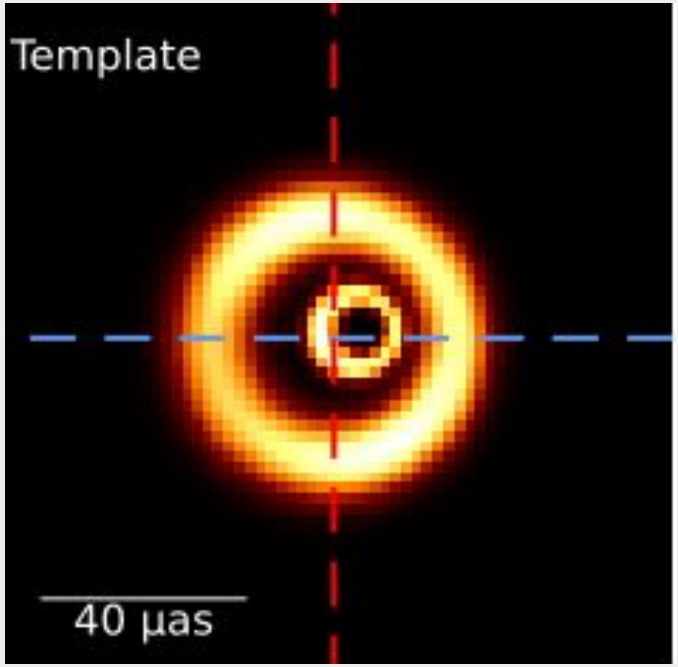




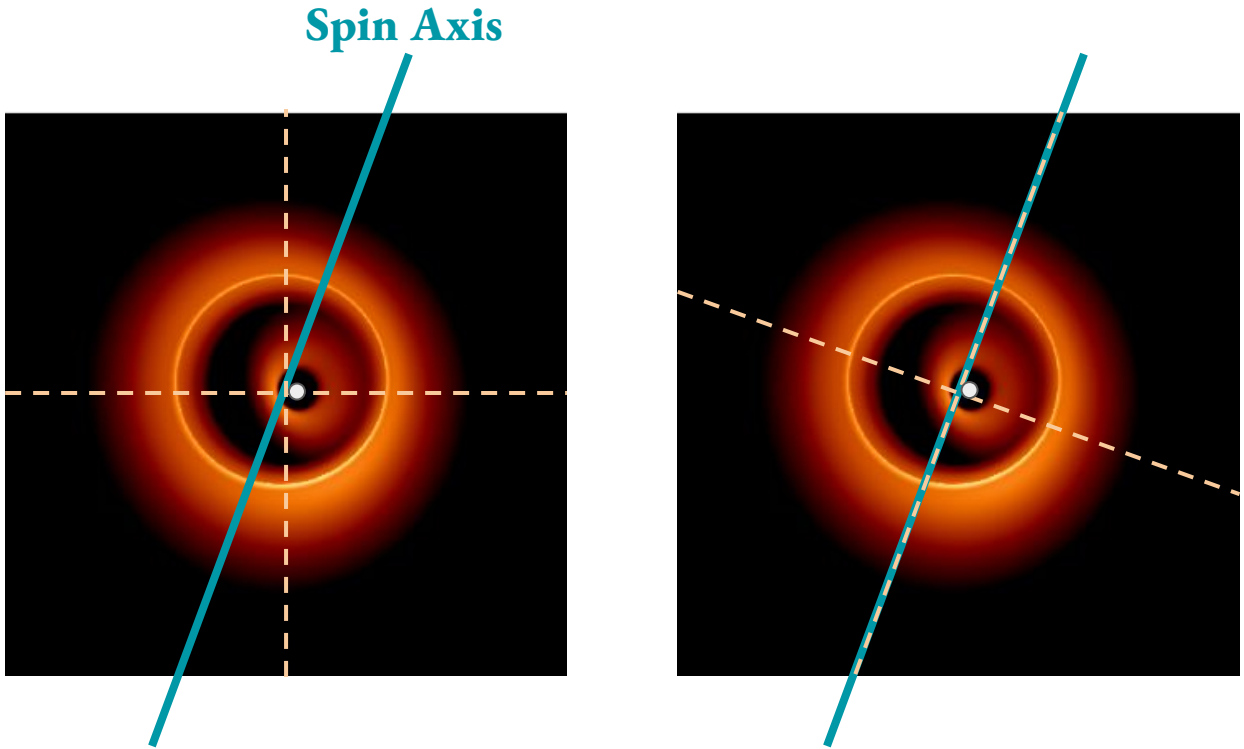
1. **Limits of Ground VLBI**
2. **Space VLBI**
3. **Modeling & Feature Extraction**

VIDA
(Variational Image Domain Analysis)

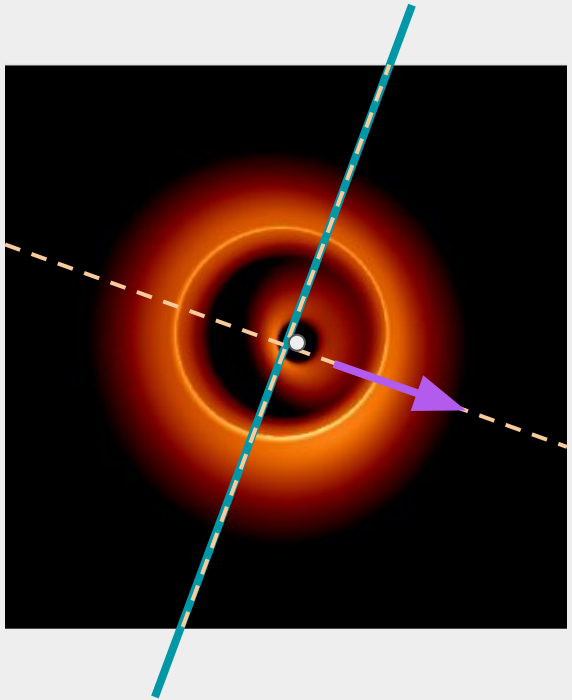


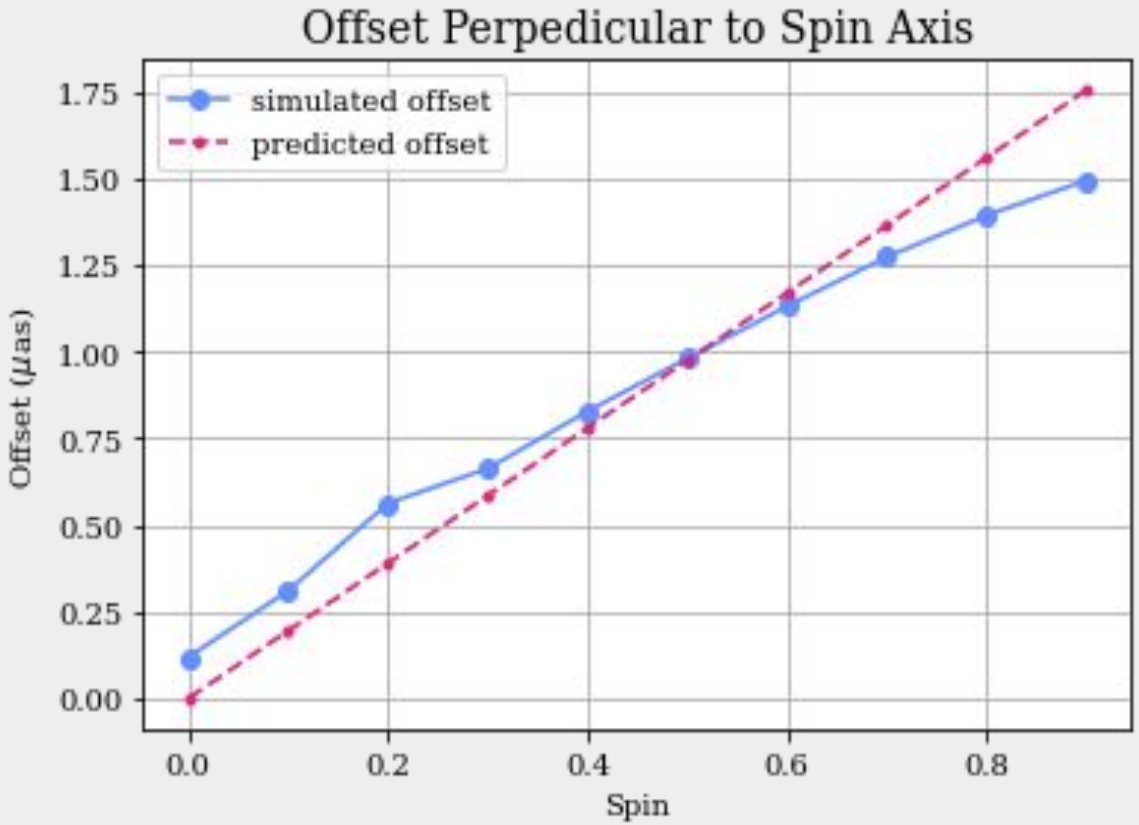


VIDA
(Variational Image Domain Analysis)

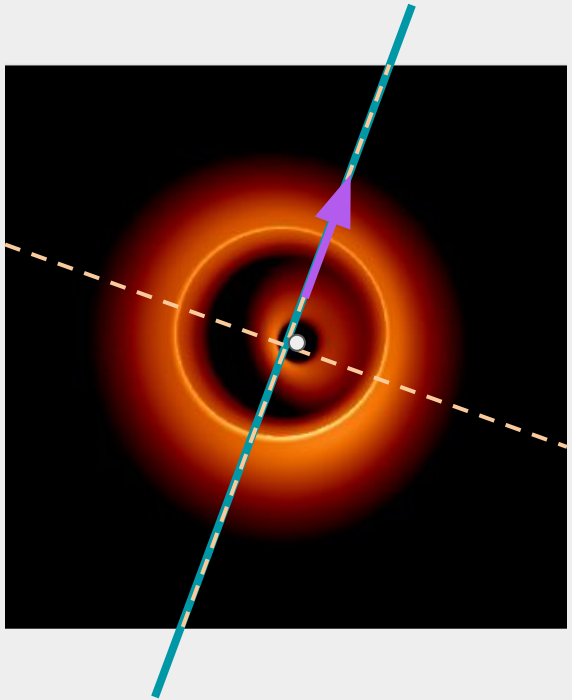


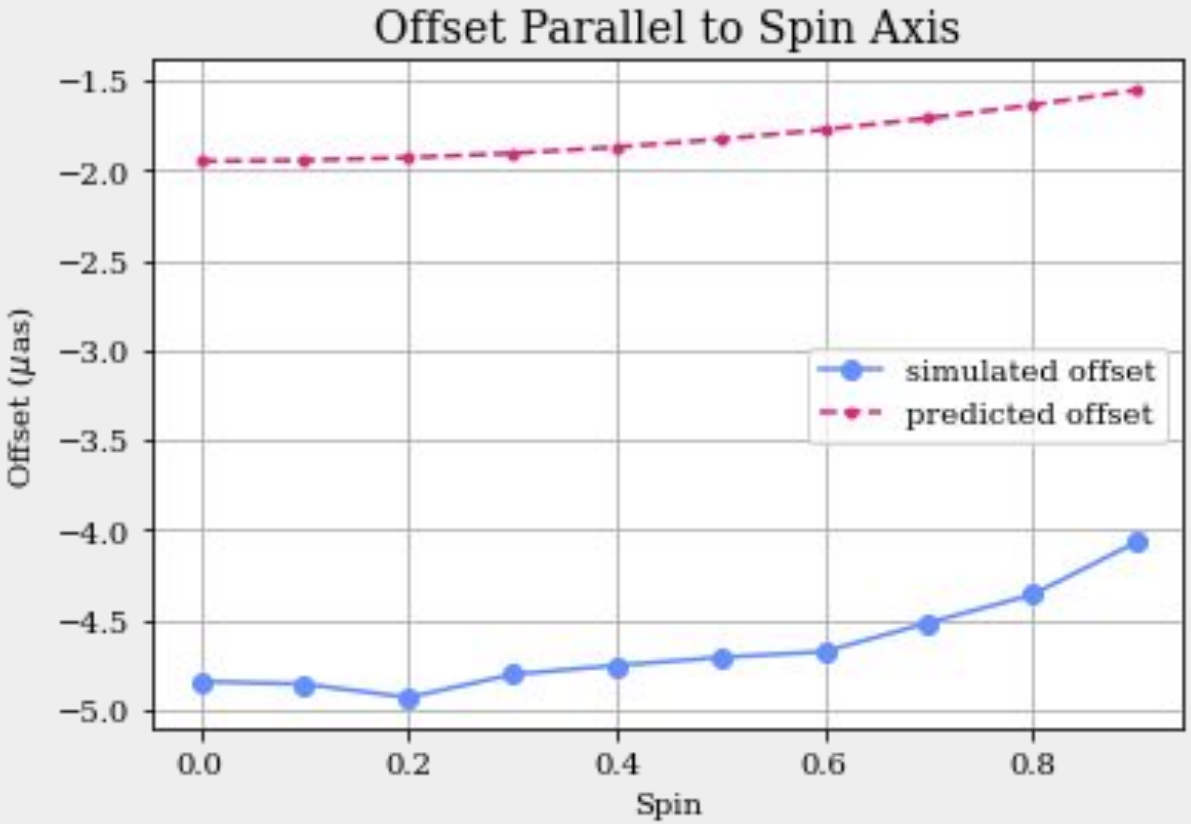
VIDA
(Variational Image Domain Analysis)





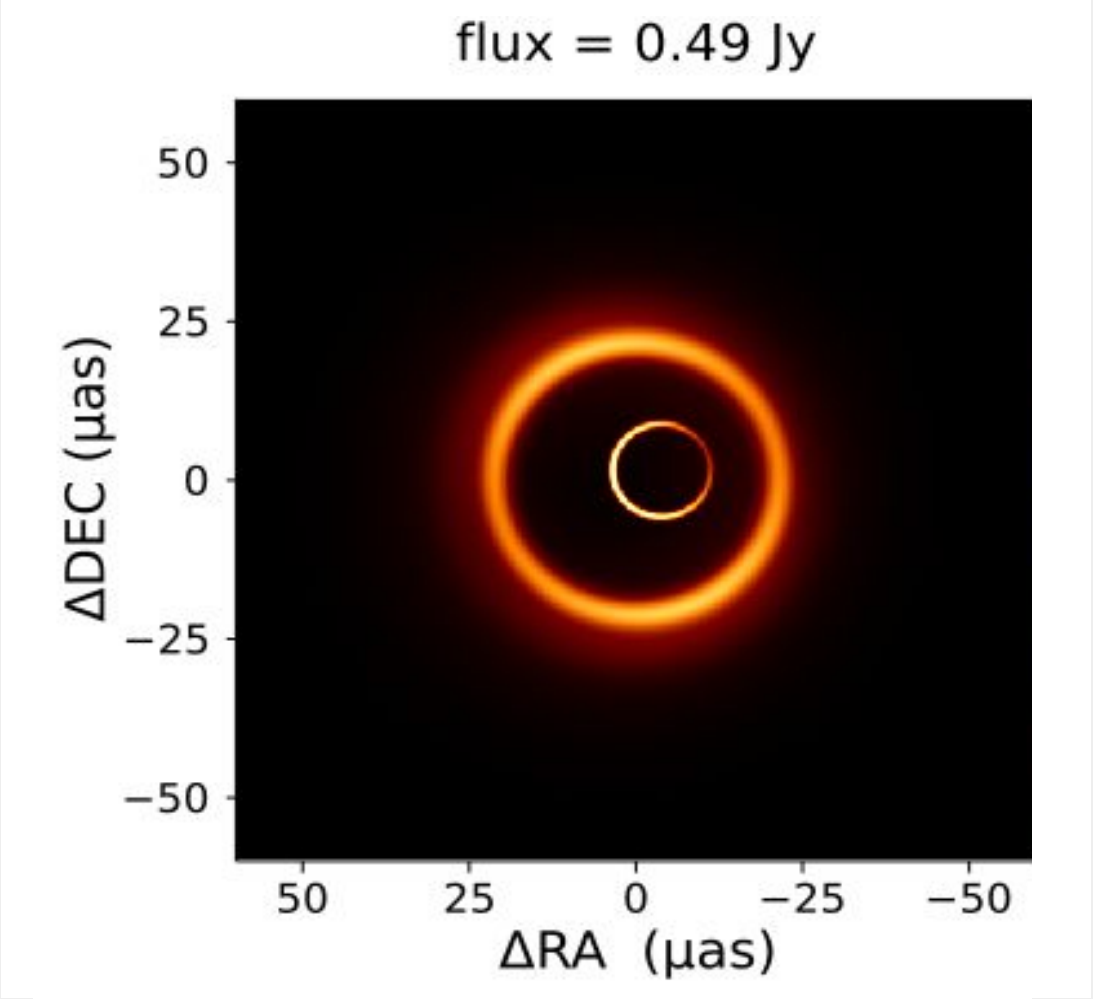
VIDA
(Variational Image Domain Analysis)

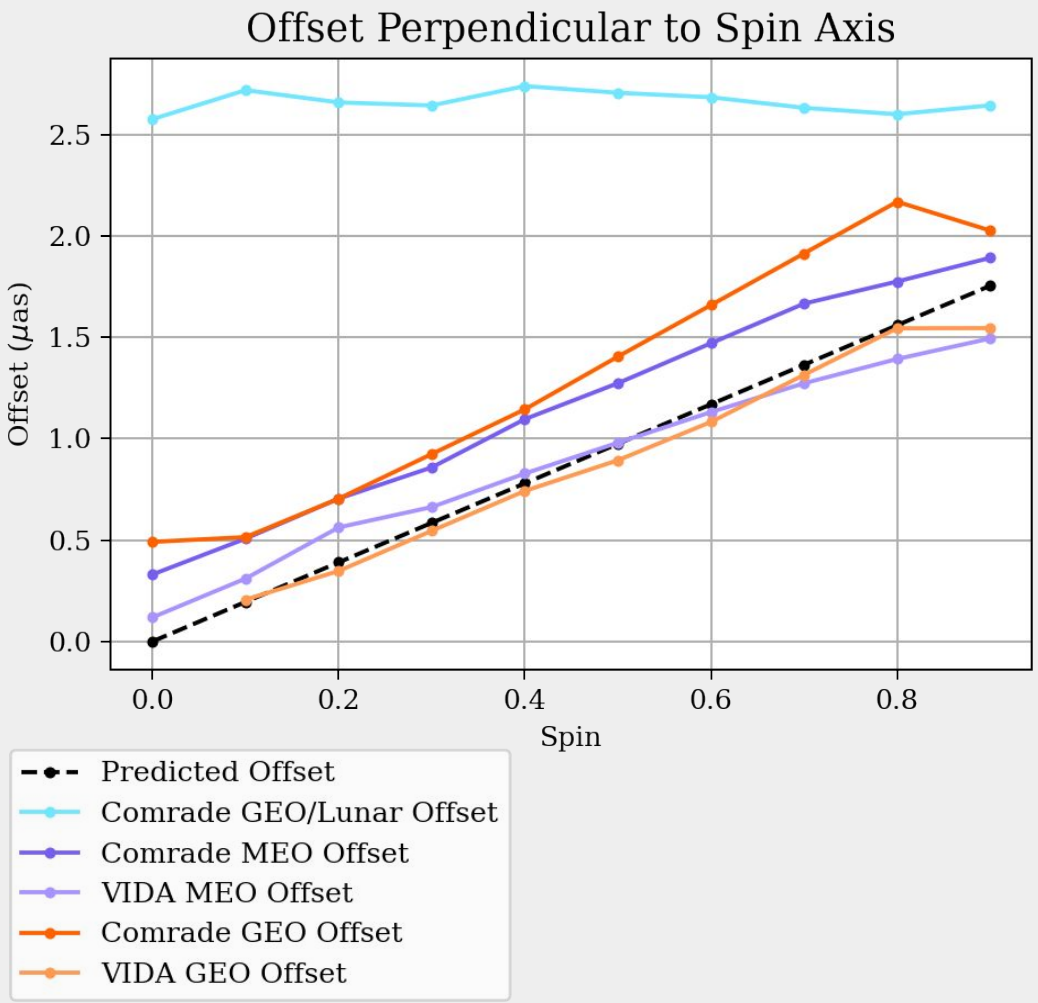




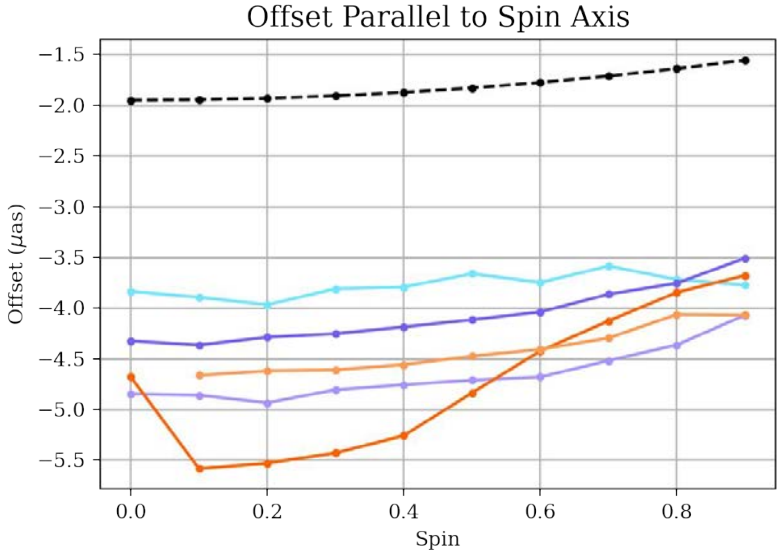
Comrade Modeling

Fits geometric ring models directly to observation data



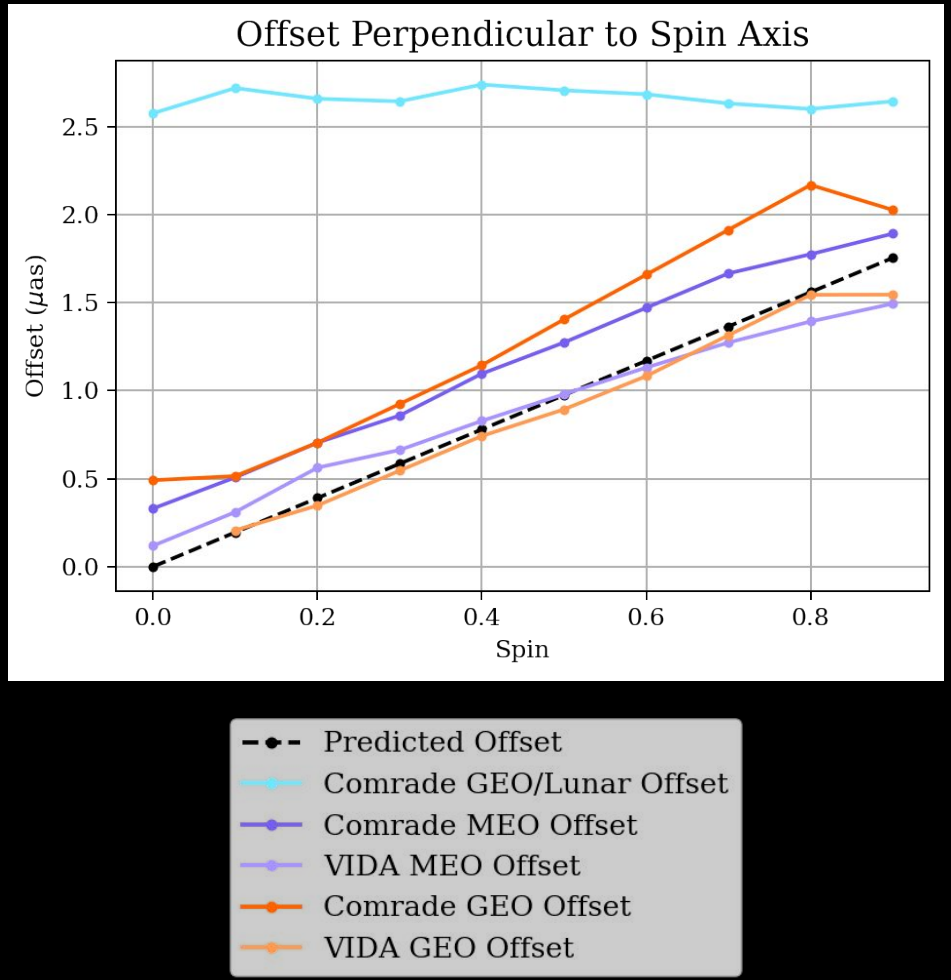


Comrade Modeling



Conclusions

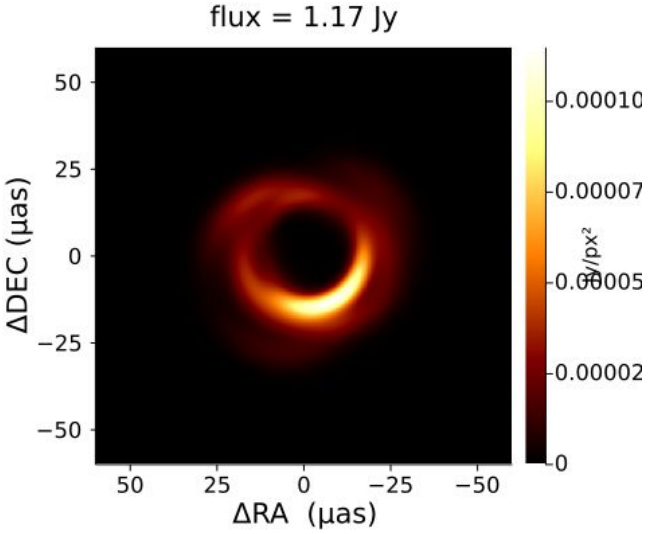
1. One MEO Satellite works well
2. LEO and GEO/Lunar satellites do not produce great results
3. The outer and inner ring offset can likely be used to determine M87 spin



Future Areas of Interest

-Image general relativistic magnetohydrodynamic (GRMHD) models that have an inner ring feature

-Further test our ability to resolve the inner ring



email: katyhunt@umich.edu
github: katyhunt

Questions?

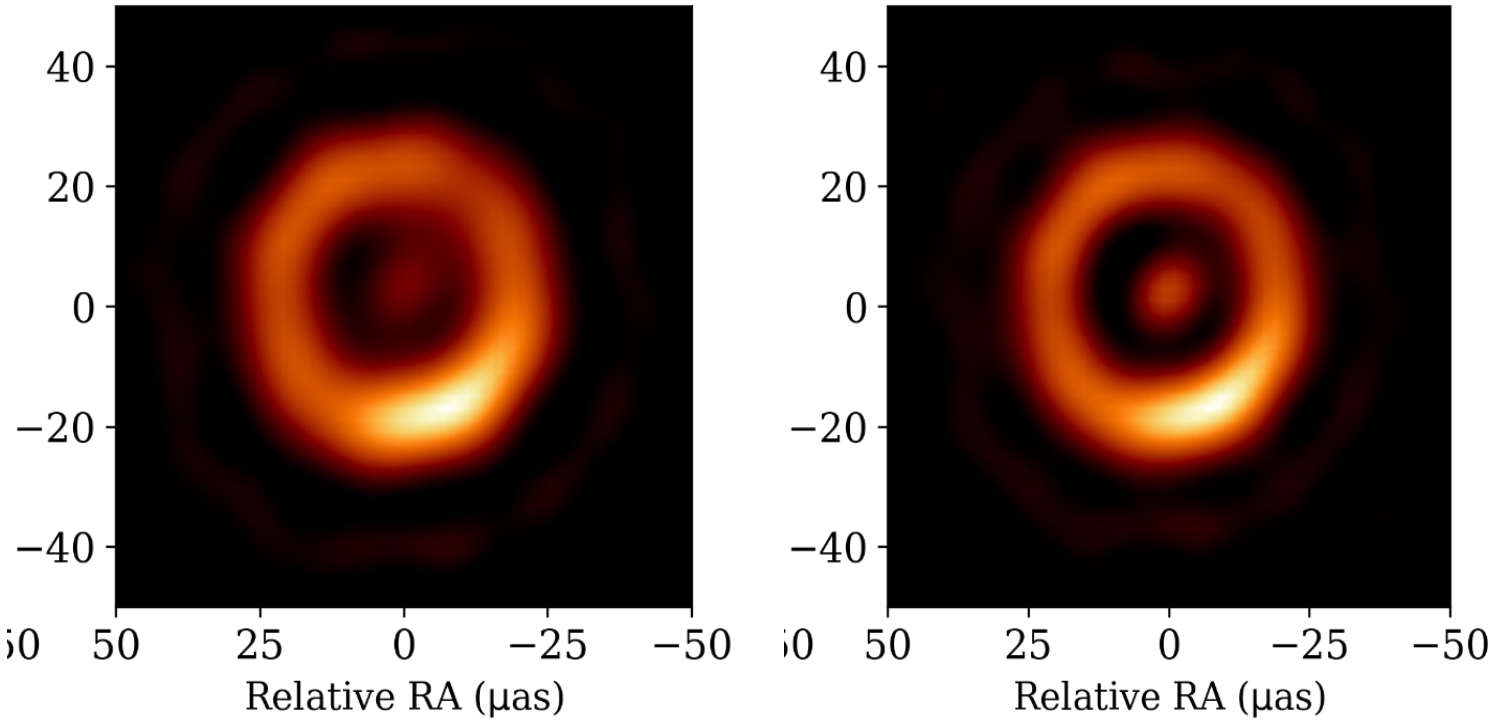
Thank you to Kazu and Vincent for mentoring me through this process; to Paul Tiede for sharing VIDA and Comrade; to Charles Gammie for providing the models, to Nancy, Phil, and Dianne for helping run this program; to IT for all their help, to Audrija for humoring my random questions; and to the whole Haystack community for welcoming us.

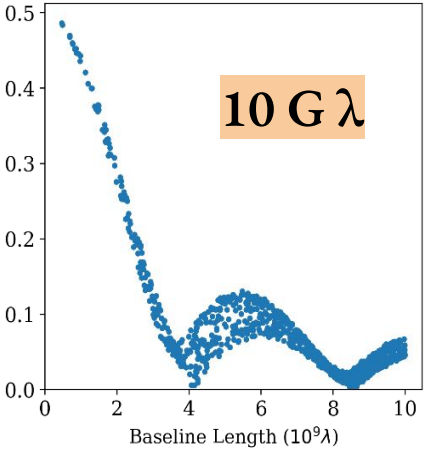
Telescope Array:

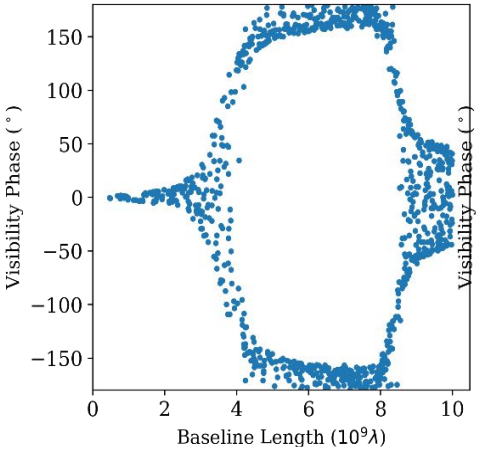
PDB 4523998.40 468045.240 4460309.760 1500
PV 5088967.9000 -301681.6000 3825015.8000 1400
SMT -1828796.200 -5054406.800 3427865.200 5000
SMA -5464523.400 -2493147.080 2150611.750 4900
LMT -768713.9637 -5988541.7982 2063275.9472 600
ALMA 2225061.164 -5440057.37 -2481681.15 90
SPT 0.01 0.01 -6359609.7 5000
APEX 2225039.53 -5441197.63 -2479303.36 3500
JCMT -5464584.68 -2493001.17 2150653.98 6000
KP -1995678.840 -5037317.697 3357328.025 10000
GLT 1500692.0 -1191735.0 6066409.0 10000
OVRO -2409598.8669 -4478350.4481 3838603.7849 10000 **#Owens Valley Radio Obs, Caltech**
HAY 1492420.4965 -4457272.10037 4296891.72893 10000 **#Haystack**
GAM 5627251.83789 1632172.52014 2517405.60946 10000 **#Gamsberg, Namibia**

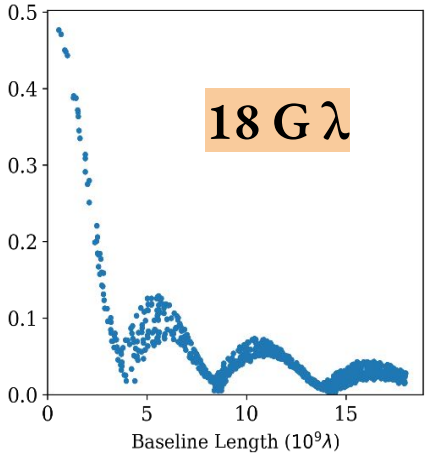
Radio Frequency

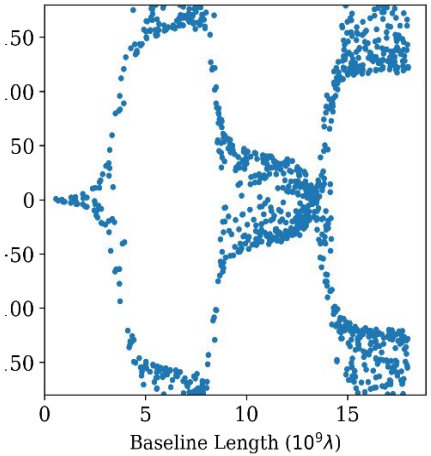
290 GHz vs 345 GHz



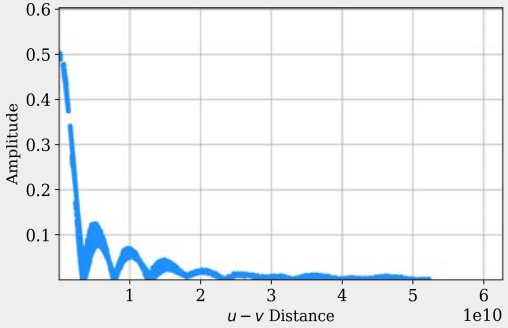


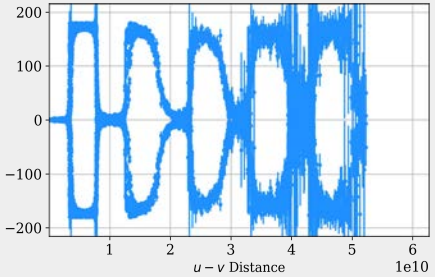




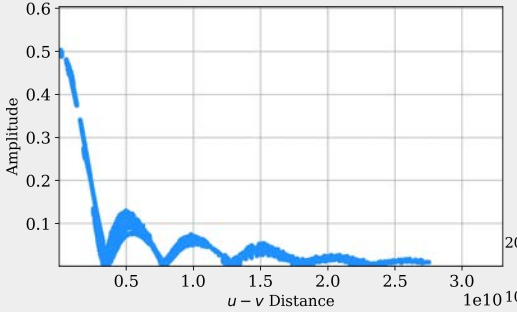


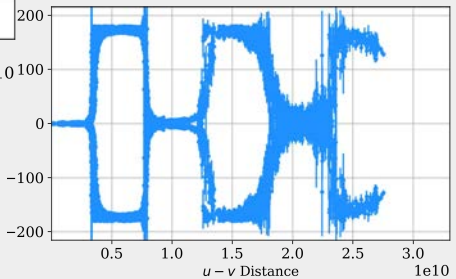
SALTUS



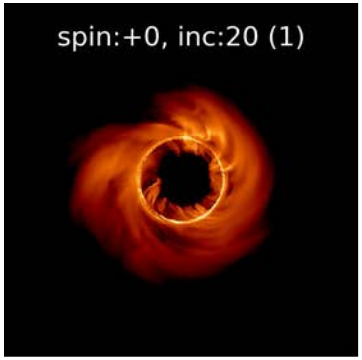


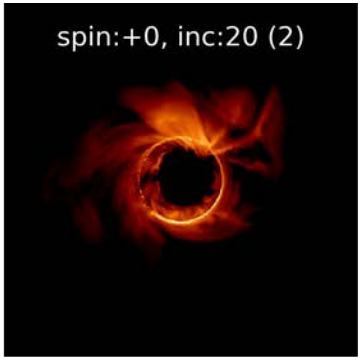
EHT Explorer

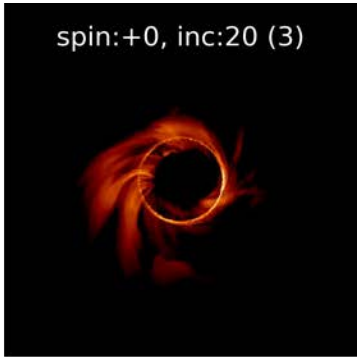


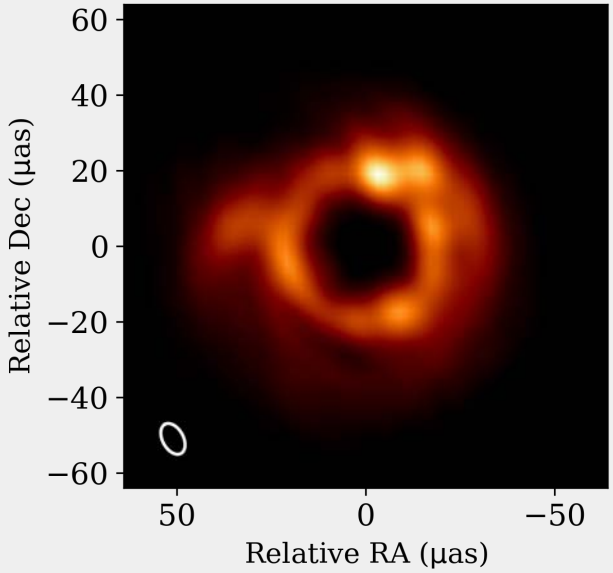


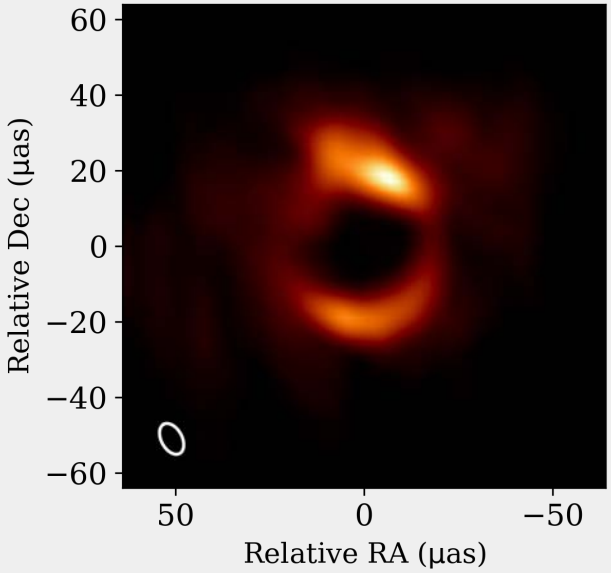
Spin 0
Inclination 20

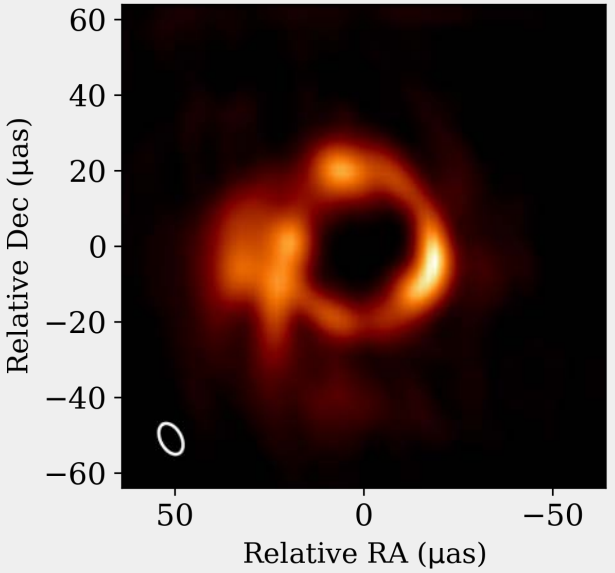




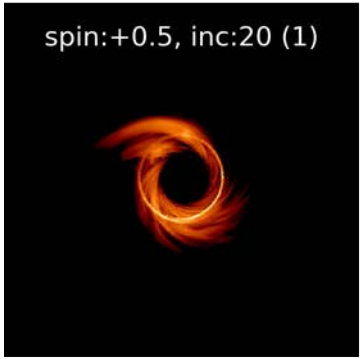


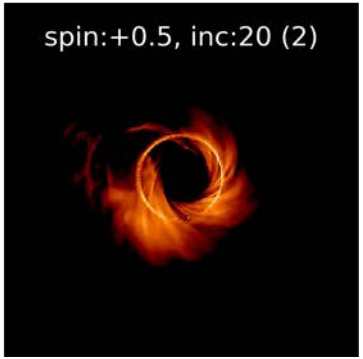


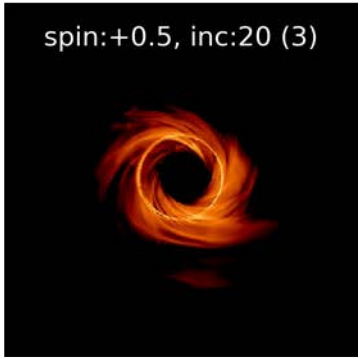


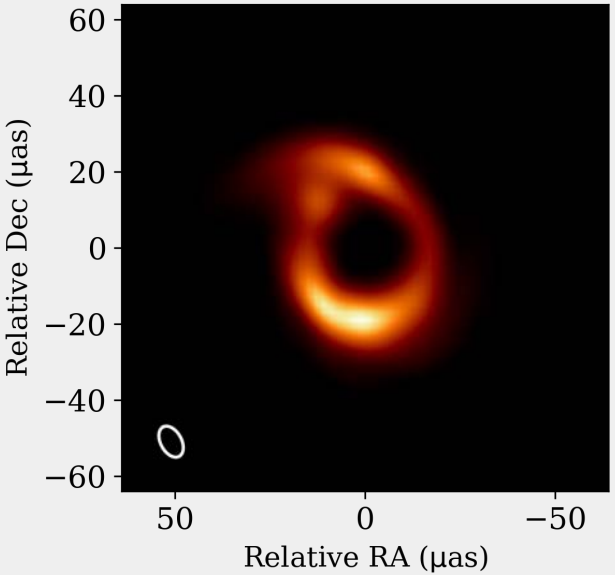


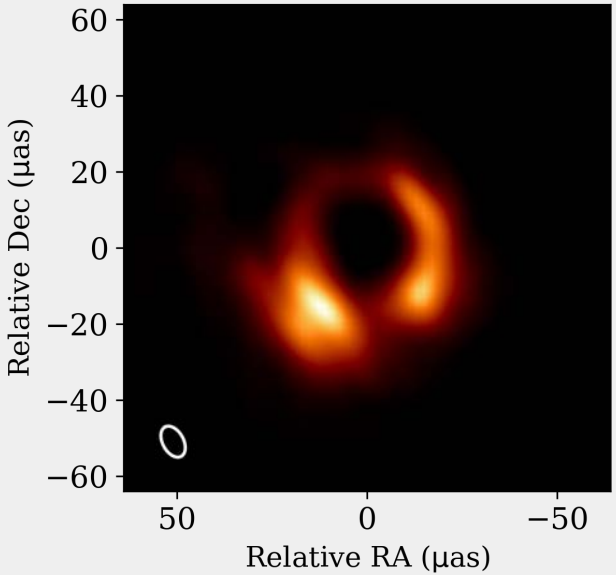
Spin 0.5
Inclination 20

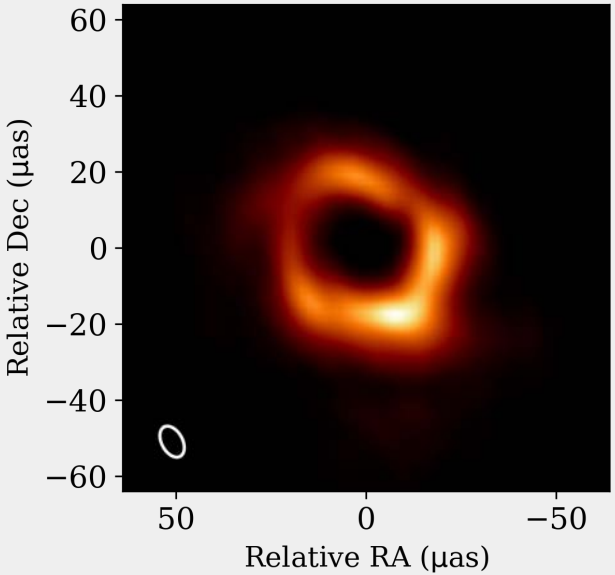




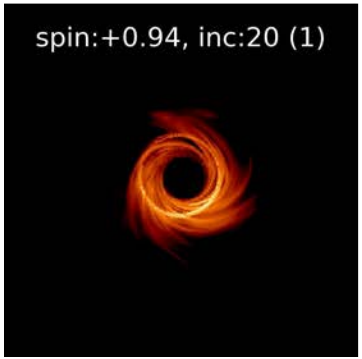


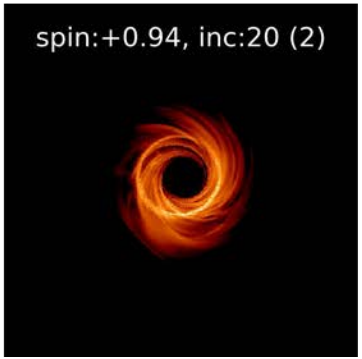


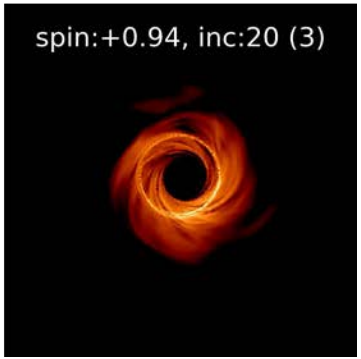


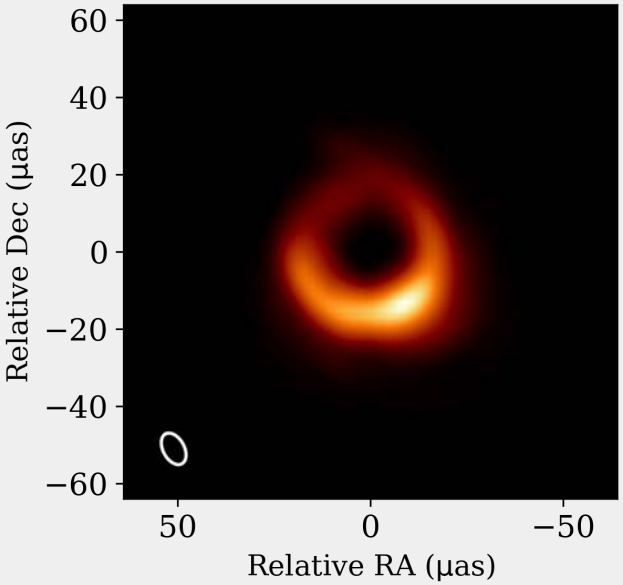


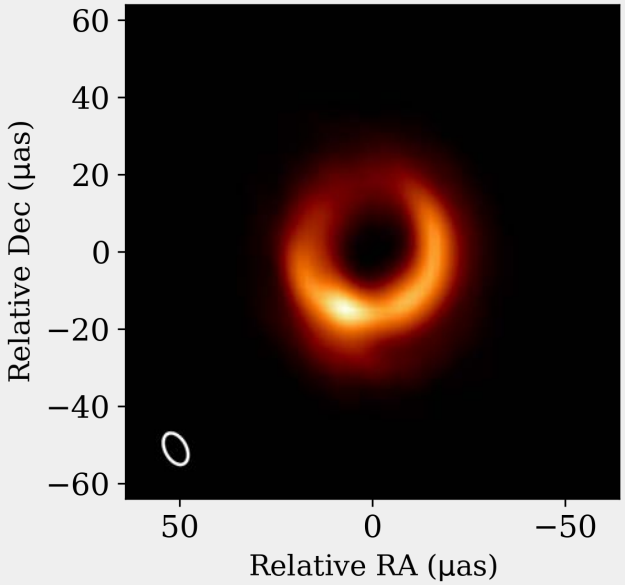
Spin 0.94
Inclination 20

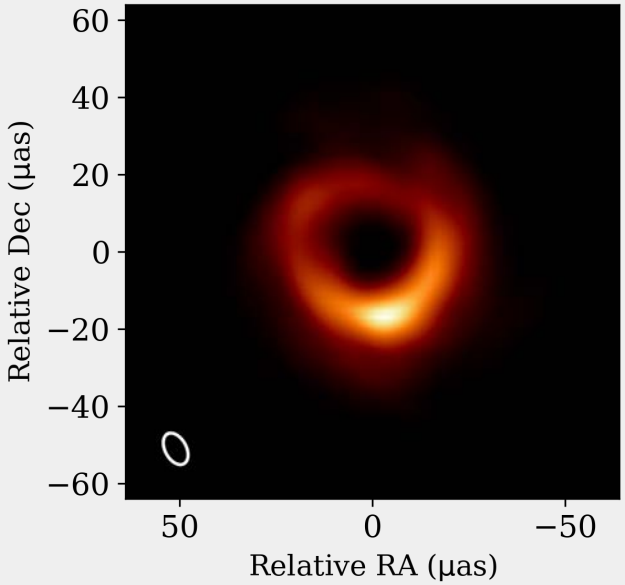


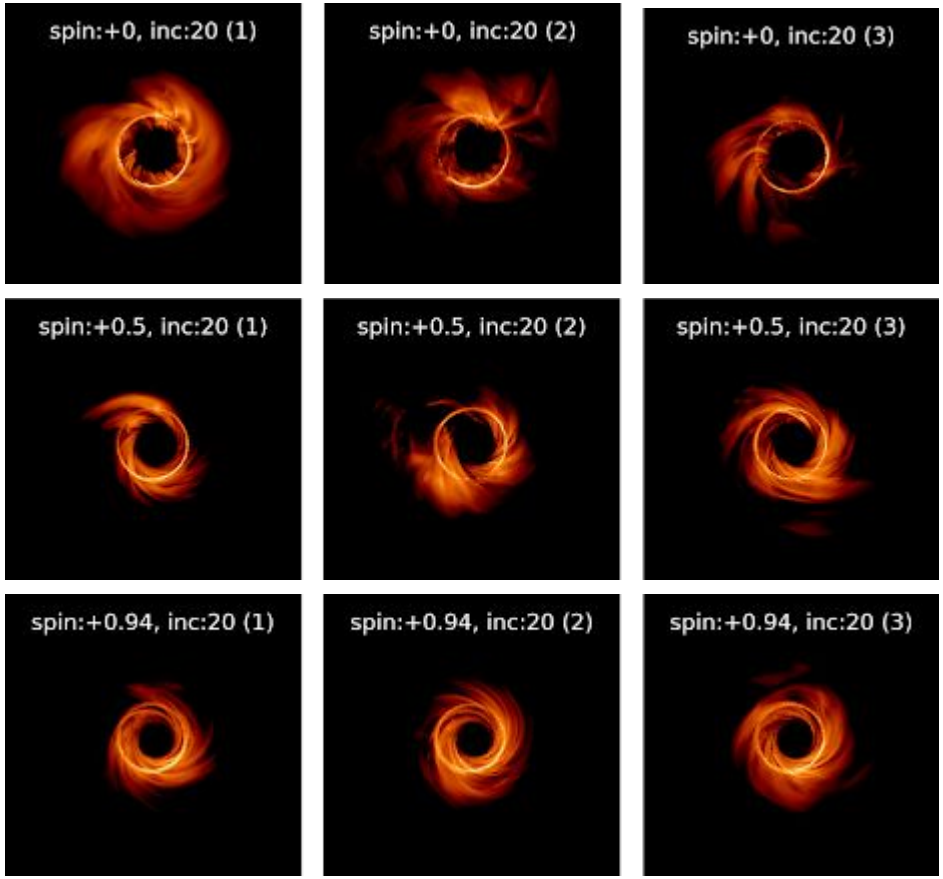











spin:+0, inc:20 (1)
spin:+0, inc:20 (2)
spin:+0, inc:20 (3)
spin:+0.5, inc:20 (1)
spin:+0.5, inc:20 (2)
spin:+0.5, inc:20 (3)
spin:+0.94, inc:20 (1)
spin:+0.94, inc:20 (2)
spin:+0.94, inc:20 (3)