Ultra-High Angular Resolution VLBI

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MIT Haystack Observatory
Ultra-High Angular Resolution VLBI

enabled by mm-VLBI

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The quest for high resolution VLBI

typical resolution (ground-based):
\[ \frac{\lambda}{D} \text{ (cm)} \sim 0.5 \text{ mas} \]

\{ space VLBI
    shorter \( \lambda \) \}

Both are challenging, but feasible

future: space (sub)mm-VLBI
Advantages provided by mm-VLBI

Self-absorption:
look “deeper”

Marscher et al.
Advantages provided by mm-VLBI

Self-absorption: look “deeper”

Scattering in the ISM

$\Theta_{\text{scat}} \propto \lambda^2$

Wavelength

Size

Scattering law

Doeleman et al. 2008

Sgr A*
Advantages provided by mm-VLBI

Faraday rotation:
\[ \chi \propto \lambda^2 \]

Self-absorption:
look “deeper”

Scattering in the ISM
\[ \Theta_{\text{scat}} \propto \lambda^2 \]

Faraday rotation:
\[ \chi \propto \lambda^2 \]
The Event Horizon Telescope:  
(a global (sub)mm-VLBI array)

EHT Sites

- Mauna Kea, Hawaii:
  SMA (~8 x 6-m, single polarization)
  JCMT (15-m, single polarization)

- Mount Graham, Arizona:
  SMT (10-m, dual polarization)

- Inyo Mountains, California:
  CARMA (5 x 10-m + 3 x 6-m, dual polarization; 10-m, dual polarization, reference)

- Sierra Negra, Mexico: LMT (50-m)

- Atacama desert, Chile, APEX, (12-m)
- Atacama desert, ALMA, (85-m)

- Pico Veleta (Sierra Nevada, Spain, 30-m)
- Plateau de Bure (France, 35-m)

- South Pole Telescope (10-m)
- Greenland Telescope (12-m)
(near) Future goal: black hole shadow imaging

Not all black holes are created equal:

- Sgr A*: 4 million $\text{M}_\odot$ BH, $R_{\text{sch}} = 10 \mu\text{as}$
- M87: $\sim 6.6$ billion $\text{M}_\odot$ BH, $R_{\text{sch}} = 7.5 \mu\text{as}$

$\text{size} = \frac{9}{2} * R_{\text{sch}}$

$\text{size} = \sqrt{27} * R_{\text{sch}}$

(Bardeen 1973, Falcke, Agol & Melia 2000)

EHT provides well-matched resolution!

$\sim 30\text{-}20 \mu\text{as}$
Imaging the BH shadow in M87

Varying Loading Radii

Minimum requirements:

1. The counter jet has to be sufficiently bright for the black hole to cast a jet against ($R_{\text{load}} \leq 11 M$)

2. The phased ALMA has to be included in the array with bandwidth $\times$ coherence time $\geq 4\text{GHz} \times 12\text{ s}$ at 230 GHz (more stringent requirement at 345GHz)

Imaging the BH shadow in M87

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Imaging the BH shadow in Sgr A* (overcome scattering broadening)

The effects of scattering can be mitigated by correcting the visibilities before reconstructing the image.

other applications:
low frequency VLBA images of Sgr A*
or, other scatter-broadened sources(?)
**Horizon-scale structure in Sgr A\***

SgrA\* has the largest apparent event horizon of any black hole in the Universe

About 4 Schwarzschild radii across

\[
\rho = 10^{23} M_\odot pc^{-3}
\]

1.3 mm emission offset from the BH

Doeleman et al. 2008, Nature
Resolving jet-launching structure in M87

size of jet base set by ISCO?

M87 measured size = 5.5 Rsch

Doeleman et al. 2012, Science
Resolving structure in Sgr A*

Non-zero closure phase detected

Median closure phase (+6.3 deg) on the California-Hawaii-Arizona triangle

consistent sign (daily average) over many days over the course of multiple years [compare: characteristic timescale GM/c^3 ~ 20s]

sign of day-to-day variability

no point symmetry: elliptical Gaussian, uniform ring, two-sided jet in the sky plane etc.

call for physically motivated models

Fish et al. in prep
EHT polarimetry calibration

Johnson et al.
EHT polarimetry calibration

Fractional Polarization due to instrumentation is removed modest and slow varying polarization in BL Lac

Johnson et al.


**EHT polarimetry: 3C279**

- Low polarization on short baselines (beam depolarization?)
- High polarization on long baselines
- Fine-scale structures are polarized

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Johnson et al.

\[ m = (55 \pm 5)\% \text{ on JCMT - Phased CARMA} \]
\[ m = (41 \pm 4)\% \text{ on SMA_L - Phased CARMA} \]
\[ m = (46 \pm 7)\% \text{ on JCMT - SMT} \]
\[ m = (48 \pm 6)\% \text{ on SMA_R - Phased CARMA} \]
Probing inner structure of AGN jets: an example

multi-epoch data to study jet acceleration & “precession”? (may need to combine low frequency data)
Summary

Horizon-scale structures in Sgr A* and M 87 detected

Imaging black hole shadow in Sgr A* and M87 demonstrated (within reach in next few years)

Polarimetry as a new tool to probe B field structure in the vicinity of nearby black holes

New data point towards “complex” and extremely compact structures in Sgr A*

Study AGN jet formation and propagation on sub-pc scales (horizon scales for M87)