Imaging Black Holes and AGNs with the Event Horizon Telescope

Kazu Akiyama
NRAO Jansky Fellow / MIT Haystack Observatory

The Event Horizon Telescope Consortium

[Logos and affiliations]
The Shadow of the Black Hole

Black Holes cast shadows (Bardeen 1973; Falcke et al. 2000) with a radius that changes only by 4% with the spin (Johannsen & Psaltis 2010)

Non-spinning Black Hole

Maximumly spinning BH

~5.2 Rs

~4.8 Rs

(Courtesy of Hung-Yi Pu)
# Black Holes with the Largest Angular Sizes

<table>
<thead>
<tr>
<th>Source</th>
<th>BH Mass ($M_{\odot}$)</th>
<th>Distance (Mpc)</th>
<th>Angular radius of $R_s$ (μas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sgr A* Galactic Center</td>
<td>$4 \times 10^6$</td>
<td>0.008</td>
<td>10</td>
</tr>
<tr>
<td>M87 Virgo A</td>
<td>$3 - 6 \times 10^9$</td>
<td>17.8</td>
<td>$3.6 - 7.3$</td>
</tr>
<tr>
<td>M104 Sombrero Galaxy</td>
<td>$1 \times 10^9$</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Cen A</td>
<td>$5 \times 10^7$</td>
<td>4</td>
<td>0.25</td>
</tr>
</tbody>
</table>
The best frequency to see black holes

Flux (Jy)

(Broderick et al. 2009)

T~1 at several x 100 GHz

Optically Thick (Not Transparent)
Optically Thin (Too Faint)

Frequency (GHz)


Moscibrodzka et al. 2014, A&A

Accretion Disk
Disk+Jet

Event Horizon Telescope

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Sgr A*

Shiokawa+

EHT 50μas

M87

Moscibrodzka, Dexter+17

EHT 35μas

1.3 mm (230 GHz) Full Polarization ~ 20 μas
‘Early’ Event Horizon Telescope

[Haystack Observatory]

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Early Sgr A* observations

1. 1.3 mm emission is very compact (2007)
   The emission is offset from the black hole

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Correlated flux density (Jy)

Baseline ($10^6 \lambda$)

unresolved

gaussian

resolved

Ring

$\sim 4 R_{sch}$

(Doeleman et al. 2008, Nature)

Broderick & Loeb 2006
Early Sgr A* observations

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   The emission is offset from the black hole
2. Variability occurs on small (ISCO) scales (2009)

Fish et al. 2011, ApJL
Early Sgr A* observations

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Figure 10.

Figure 11.


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Early Sgr A* observations

1. 1.3 mm emission is very compact (2007)  
   The emission is offset from the black hole
2. Variability occurs on small (ISCO) scales (2009)
3. Discovery of the non-Gaussianity in the structure (2013)
5. Analytic RIAF models/GRMHD models disfavor face-on disk
Early M87 observations

1. 1.3 mm emission is very compact (2009)

(Doeleman et al. 2012, Science)
Early M87 observations

1. 1.3 mm emission is very compact (2009)

Consistent with the parabolic collimation profile of the jet

- 1.3 mm emission is very compact (2009)
- Consistent with the parabolic collimation profile of the jet

Parabolic stream ($z \propto \text{width}^{1.7}$)

Conical Stream ($z \propto \text{width}^{1.0}$)

Asada & Nakamura 2012
Doeleman et al. 2012
Nakamura & Asada 2013
Hada et al. 2013, 2016
Asada et al. 2016
Early M87 observations

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The jet base is magnetically dominated

Early M87 observations

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   The jet base is magnetically dominated

2. Event Horizon Scale structure is stable
during an enhanced TeV gamma-ray state (2012)


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Rs-scale Polarization of Sgr A* 

Johnson et al. 2015, Science
Ordered Fields at the Event Horizon

Johnson et al. 2015, Science

More Compact \rightarrow \text{Larger Scale}
New VLBI Imaging Techniques

Maximum Entropy Method (MEM)

Sparse Modeling
Akiyama et al. 2017a, 2017b

CHIRP (Machine-learning)
Bouman et al. 2016

- All techniques can reconstruct images from closure quantities (closure phase, closure amplitude, …,)
- All techniques outperform CLEAN even when using closure phases particularly in super-resolution regimes

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Event Horizon Telescope
Mitigation of Scattering / Variation

Unscattered

Scattered

Stochastic Optics Reconstructions

50 μas


Simulation

EHT 2017+

00:00:00

1.3mm VLBI confirms ~few Rsch sizes for SgrA* & M87

Imaging an Event Horizon and observing BH orbits are within reach in < 2 years.

Event Horizon Telescope has been fully on-line since 2017.

**Conclusion**

**EHT Postdoc Fellow position at MIT Haystack Observatory**
(To be posted in MIT/AAS websites tonight)

**Team and Support**
Another issue for Sgr A*: Scattering

Johnson & Narayan 2016

Johnson & Gwinn 2015

Doeleman et al. 2008, Nature

\[ \lambda = 0.75 \text{ mm} \]
\[ \nu = 400 \text{ GHz} \]

Wavelength (cm)

FWHM Size (mas)

Scattering Dominated

3 mm 86 GHz

7 mm 43 GHz

1.3 mm 22 GHz

1.3 mm 230 GHz

3.5 cm 8 GHz

\( \lambda = 0.75 \text{ mm} \)
\( \nu = 400 \text{ GHz} \)

Johnson & Narayan 2016
Johnson & Gwinn 2015

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**Early M87 observations**

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3. Closure Phase is consistent with zero (2012)
   Consistent with the compact emission models

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**Akiyama et al. 2015, ApJ**