Accessing Schwarzschild Radius Scales with the Event Horizon Telescope

Sheperd Doeleman
MIT Haystack Observatory & SAO
Bardeen 1973
Luminet 1979

Shadow size and shape encodes GR.

Non-spinning (a=0)
Dsh = sqrt(27) * Rsch

Spinning (a=1)
Dsh = 9/2 * Rsch
Models/Simulations of SgrA* 

Spinning (a=1)  Non-spinning (a=0)  

Falcke, Melia, Agol 2000  

Broderick & Loeb 2006  

Noble & Gammie
Strong GR Effects: Matter

- Innermost Stable Circular Orbit Size.

Max. Prograde
ISCO_d = 1 Rsch

No Spin
ISCO_d = 6 Rsch

Max Retrograde
ISCO_d = 9 Rsch
Short Wavelength VLBI

Resolution:
\[ \frac{\lambda}{D} \text{ (cm)} \sim 0.5 \text{ mas} \]
\[ \frac{\lambda}{D} \text{ (1.3mm)} \sim 30 \mu\text{as} \]
\[ \frac{\lambda}{D} \text{ (0.8mm)} \sim 20 \mu\text{as} \]

ISM Scattering:
\[ \Theta_{\text{scat}} \sim \lambda^2 \]
SgrA*: Event Horizon Structure Confirmed

About 4 Schwarzschild radii across.

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

4 million suns within the orbit of Mercury.
SgrA*: Piercing the Scattering Screen

![Graph showing the relationship between FWHM size and wavelength, with data points and trends labeled from various studies.]
M87: BH Origins of a Relativistic Jet

Craig Walker et al. 2008

5.5 Schwarzschild Radii
Doeleman et al 2012

Graphic: Broderick
Strong GR Effects:

- Smaller than the expected ISCO: prograde disk.

Doeleman et al. 2012
EHT Specifications: The Next 2-3 Years

- Increase stations from 3 to 8: baseline number grows from 3 to 28 \((n*(n-1)/2)\).
- Bandwidth increase from 1 GHz to 16 GHz.
- Collecting area increase by x10.
- Impact:
  - Sensitivity increase by x40: Long baselines.
  - Full closure phase information: modeling/imaging.
  - Full polarization information: magnetic fields.
  - Time domain: time resolving BH/jet dynamics.
Assembling the Event Horizon Telescope

CARMA - SMA, JCMT

LMT - GLT - Greenland

SMT - ALMA

IRAM

SPole - SPole

Friday, October 25, 13
3mm VLBI with the LMT

50m diameter. First light at 3mm & 1.3mm.
Phasing ALMA

- An effective 85m aperture.
- Passed PDR (Nov 2012) and CDR (May 2013)
- First ALMA VLBI scheduled 2014/2015.
Next Gen VLBI Technology: Keeping up with Moore

Digital Backend (DBE)

Digital Recorder (Mark6)

Current capability: 4 GHz real time.
Improved physical modeling through closure phases.

Broderick et al 2011
Progression to an Image: M87
Baron & Monnier (U. Michigan)

Broderick et al

Dexter et al

GR Model  |  4 Stations  |  7 Stations
M87: Time Evolution of a Jet

R_{load}: 2.028 (M)

Lu, Broderick et al
Event Horizon Scale Polarization

- CARMA, SMA: D. Marrone et al.
- Magneto Rotational Instability (MRI)
- Circularization in accretion flow
- Blandford-Payne: disk jet launch
- Blandford-Znajek: BH jet launch

Fish, Broderick, et al 2009

\[ \sqrt{Q^2 + U^2} \text{ field: } a_{\ast} = 0.5, \nu = 231 \text{GHz}, \theta = 74^\circ \]

Shcherbakov, Penna & McKinney 2012

Dexter & McKinney (in prep).
Time Resolving BH Orbits

- Full EHT can measure closure phase on 10s intervals (25 times faster than smallest ISCO Period).
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South Pole: Polarization at the Event Horizon:

Orbiting hot-spot

Quiescent Structure

phase = 0

0.33

0.67

Fish et al 2009
Critical New Work

• VLBI Correlator: from 4 Gb/s to 64 Gb/s.
  – Data Challenge: ~10 Petabytes recorded per session.
• Instrumentation for the LMT.
• Data/Modeling/Imaging Pipeline
  – Polarization, more baselines.
• Operations (~3 years post-ALMA phasing).
• Time concerns
  – Some pressure on existing sites.
  – EHT can resolve G2 impact effects.
Increased accretion may hide shadow!

Moscibrodzka + (2012)
Event Horizon Telescope Collaboration

MIT Haystack: Shep Doeleman, Alan Rogers, Vincent Fish, R. Lu et al
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U. Arizona Steward Obs: Lucy Ziurys, Robert Freund, Dan Marrone
CARMA: Dick Plambeck, Mel Wright, David Woody, Geoff Bower
NRAO: John Webber, Ray Escoffier, Rich Lacasse
Caltech Submillimeter Observatory: Richard Chamberlin
UC Berkeley SSL: Dan Werthimer
MPIfR: Thomas Krichbaum, Anton Zensus, Alan Roy, et al
IRAM: Michael Bremer, Karl Schuster
APEX: Karl Menten, Michael Lindqvist
James Clerk Maxwell Telescope: Remo Tilanus, Per Friberg
ASIAA: Paul Ho, Makoto Inoue, Keiichi Asada
U. Concepcion: Neil Nagar

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Summary

• EHT has confirmed targets (SgrA*/M87) with Horizon scale structure.

• Required technical work is low-risk: early results validate all systems.

• Considerable work to do: requires support of community.

• First imaging, modeling and time-resolving BH/Jet emission are within reach in <3 years.

• Event Horizon Telescope fully on-line by 2015.

• www.eventhorizontelescope.org