Testing General Relativity with the Event Horizon Telescope

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Outline

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What is Event Horizon Telescope?

- EHT is an array of global network of radio telescopes.
- Currently (2018) operating at 1.3 mm wavelength.
- Aim is to observe surroundings of Black Holes of Milky way and Messier 87 galaxies.
- Main project scientist is Dimitrios Psaltis.

Radio Telescope

Figure: Large Millimeter Telescope(left) and Greenland Telescope (right). (Source: eventhorizontelescope.org)

EHT Radio Telescope Locations

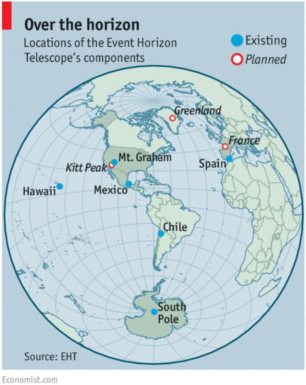

Figure: EHT Radio Telescope Locations (Source: www.economist.com)

Collaboration of Radio Telescopes

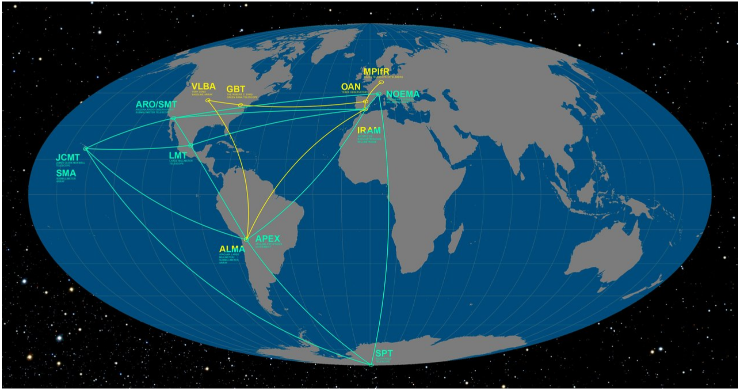

Figure: Collaboration of Radio Telescopes (Source: wikipedia)

Names of Participating Telescopes

- 1. JCMT/SMA (James Clerk Maxwell Telescope) (Summillimeter Array) Hawaii.
- 2. ARO/SMT (Arizona Radio Observatory)(Submillimeter Telescope) Kitt Peak, Arizona
- 3. VLBA (Very Long Baseline Array) USA many places
- 4. GBT (Green Bank Telescope) West Virginia
- 5. LMT (Large Millimeter Telescope) Mexico
- 6. OAN (National Astronomical Observatory) (Baja California Mexico)

Names of Participating Telescopes Contd.

- 7. IRAM (Institut de Radioastronomie Millimétrique) Spain
- 8. MPIfR (Max Planck Institute for Radio Astronomy) (Germany)
- 9. NOEMA (Northern Extended Millimeter Array) French Alps
- 10. ALMA/APEX (Atacama Large Millimeter Array) (Atacama Pathfinder Experiment telescope) Chile
- 11. SPT (South Pole Telescope)

What can be done with Event Horizon Telescope?

- Test the [1] cosmic censorship conjecture.
- Test the [2] no-hair theorem.
- Find evidence for classical effects of the quantum structure of black holes.
- Find more accurate measurements of the spins of the black holes.
- Find more accurate measurements of the precession of stellar orbits and timing of black hole.

[1] Cosmic censorship: All singularities are clothed behind horizons.

[2] no-hair theorem: All black hole solutions can be completely characterized by only three externally observable classical parameters: mass, electric charge, and angular momentum.

Event Horizon Telescope Animated Movie

From the official website of Event Horizon Telescope, we can view the animated video about the telescope.

EHT Introduction

- Very small size of BH makes imaging very challenging.
- MW BH requires $\sim 10\mu ac$ angular resolution.
- At optical wavelength we need 200 m telescope.
- That's why we need global combination of telescopes.

Largest Radio Telescopes in the World

Figure: FAST Telescope 500m China (left) and Arecibo Telescope Puerto Rico 305m (right). (Source: wired.com and wikipedia)

Outline

Observation Requirements

- Building high-res antennae is not sufficient.
- The Earth atmosphere, the Galaxy, and the accretion flow around the black hole needs to be transparent.
- The mm-wavelength satisfy all three conditions.
  - The transparency of Sgr A* was proved in 1970.
  - The transparency of accretion flow was proved mid of 1990s.

Outline

Early observations with a subset of the array

Early observations with a subset of the array have shown following:

1. Horizon-scale structures at 1.3 mm for Sgr A*.
2. Horizon-scale structures at 1.3 mm for BH of M87.
3. Source substructure and variability.
4. Highly polarized emission at horizon scales.

Prime Targets of EHT

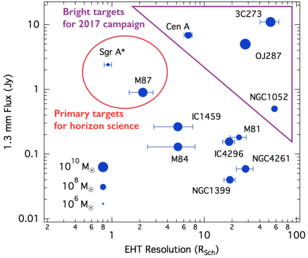

Fig. 2 Prime targets for observations with the Event Horizon Telescope. The 1.3mm flux and nominal EHT resolution in units of the Schwarzschild radius is shown for a number of known black-hole targets. The two primary targets for horizon-scale science, Sgr A* and M87, as well as four additional bright targets that were observed during the April 2017 campaign are indicated. The source 3C279, which is also a science target for the array, lies outside the boundaries of this plot.

Figure: Prime targets

Outline

Why Test General Relativity with the EHT?

- Many GR test have been done only within the Solar System.
- All the GR test have passed with flying colors.
- In earth, LIGO detected gravitational waves.
- However, it has not been tested with black hole.

Why Test GR with EHT?

- BH space-time are different than other astronomical objects.
- Observation of BH at horizon scale will allow us to :
  - test the cosmic censorship hypothesis.
  - measure the properties of their spacetimes.
  - look for the signatures of quantum structures.

Gravitational potential and curvature

- The gravitational fields around BH are different than other objects.
- Gravitational potential: $\epsilon = \frac{GM}{rc^2}$
- Gravitational curvature: $\xi = \frac{GM}{r^3c^2}$

Note: These formulae are first order approximations and more precise definitions that are based on invariant quantities and are more broadly applicable.

Gravitational potential and curvature Observation

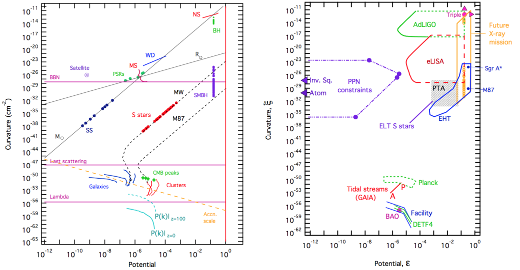

Fig. 3 The gravitational potential and curvature probed *(left)* in different astrophysical settings and *(right)* with different types of observations. The Event Horizon Telescope (EHT) offers the possibility of gravitational tests that are complementary to those of other current and planned experiments, such as those with LIGO/VIRGO, LISA, Pulsar Timing Arrays (PTA), and with optical observations of S-Stars around Sgr A*. (After Ref. [75].)

Figure: Gravitational potentials and curvatures

Outline

Tests with Black-Hole Shadows

- EHT plans to get the first image of shadows of Sgr A* and M87 BH.
- The figure below shows the simulated images of shadows.
- In the figure the detailed emission structures depends on:
  - Initial conditions in the simulation.
  - Heating of the electrons in the plasma.
  - Spin and orientation of the black hole with respect to the observer.

Predicted Images of Black-Holes Shadows

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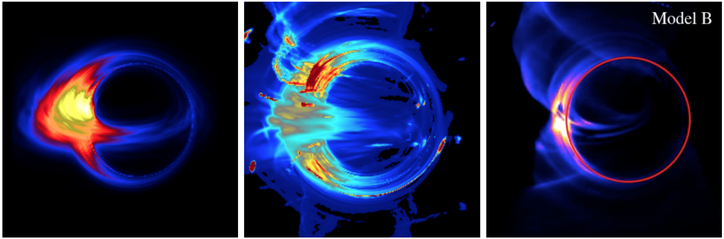

Fig. 4 Predicted 1.3mm images for Sgr A* from three different GRMHD simulations [57, 56, 63]. Even though the simulations employ different algorithms and different prescriptions for the sub-grid plasma physics, they all show prominent features at the outline of the black-hole shadow (marked by a red circle in the rightmost panel). The size of the black-hole shadow is $\sim 10GM/c^2$.

Figure: Predicted Images of Black Holes Shadows

Proposed Tests

1. Cosmic Censorship Tests.

   - Use observations of black-hole shadows to differentiate between Kerr metrics that are surrounded by horizons ($a \leq 1$) or not ($a > 1$)

2. Null Hypothesis Test of Kerr Spacetime.

   - Measure and check the radii of Shadows of Kerr black holes For Sgr A*,

$$\frac{GM}{D_{BH}c^2} = 5.09 \pm 0.17\mu as$$

Footnote: a is the specific angular momentum of the black hole per unit mass.

Proposed Tests Contd.

1. Tests of the No-Hair Theorem and of non-Kerr metrics.

   - Based on the fact that the shadow of a black hole is nearly circular only if its spacetime obeys the particular relation between the quadrupole moment and its spin that is dictated by the no-hair theorem

2. Tests of Quantum Structure.

   - It is plausable that the spacetimes of black holes appear to have classical dynamics because of quantum fluctuations at horizon scales. The characteristic timescale of fluctuations would be ~ 1 hr for Sgr A* and 60 d for $M87$.

Time Dependent Black Hole Shadow

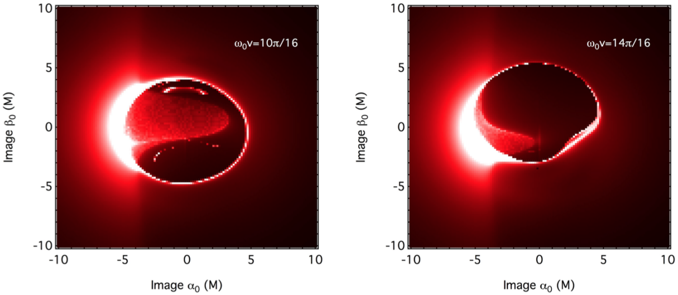

Fig. 9 Two snapshots of the time-dependent black-hole shadow calculated in Ref. [95] for a spacetime that is characterized by quantum fluctuations at horizon scales.

Figure: Time Dependent Black Hole Shadow

Implementation and Challenges

- Shape and size of shadow of BH only depend on BH spacetime.
- As a result, property of BH is free from astrophysical complications.
- However, intricacies of thermodynamics of plasma of accretion flow affect the results.
- The main complication introduced by the accretion flow is the fact that it may be obscuring, partially or fully, the shadow.
- This does not affect Sgr A* and M87 since accretion flow is not optically thick.

Outline

Timescale Variation of Accretion Flow

- Flux of radiation of accreting black holes is highly variable.
- Timescales varies with the mass of the black holes.
- Sgr A* has potential turn-over timescale variation of few hours.
- M87 has potential turn-over timescale variation of tens of days.

Timescale Variation and Black Hole Spin

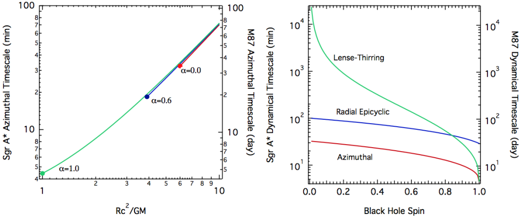

Fig. 10 *(Left)* The dynamical timescale for azimuthal (orbital) motions of test particles around a black hole, as a function of the location of the orbit, for three different values of the black-hole spin. The filled circles mark the location of the ISCO. *(Right)* The characteristic dynamical timescales for the azimuthal motion of a test particle at the ISCO, for the radial epicyclic motion at the location of the peak radial frequency, and for the Lense-Thirring precession at the location of the ISCO, as a function of the black-hole spin. The latter two timescales are expected to be comparable to the periods of $g-$ and $c-$modes excited in the inner accretion flows. In both panels, the left axes show the timescales in minutes for the mass of Sgr A* and the right axes show the timescales in days for the mass of M87.

Figure: Timescale Variation and Black Hole Spin

Black Hole Spin and Quadrupole Moment

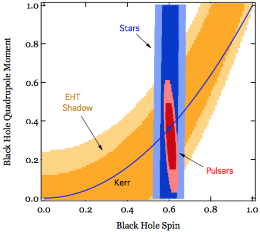

Fig. 13 Combined constraints on the spin a and spacetime quadrupole q of Sgr A* based on hypothetical measurements of the shape and size of its shadow (orange), of the orbital precession of orbiting stars (blue), and of the timing properties of an orbiting pulsar (red). If the black hole is described by the Kerr metric, the measurements should lie on the thin blue line for which $q = -a^2$. Each of these measurements faces different challenges and potential systematic effects. Statistical agreement between the three measurements will increase substantially their credibility [50].

Figure: Black Hole Spin and Quadrupole Moment

Outline

Combining Tests with the EHT, Stars, and Pulsars

- EHT offers more than one ways of testing gravity (Imaging and Timing).
- In the case of Sgr A* there are also additional avenues of testing gravity using stars and pulsars.
- Measuring the precessions of stars we can test the no-hair theorem.