Imaging & modeling
Super-Massive Black Holes

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Event Horizon Telescope
http://blackholecam.org
http://www.eventhorizontelescope.org
Outline

I. Introduction: General Relativity & Black Holes
II. Simulations of Black Holes
III. Event Horizon Telescope (EHT)
IV. Apr 2017 Observing Campaign
V. More than an image: stars/pulsars
VI. Outlook
I. General Relativity and Black Holes

- Gravity is successfully described by Einstein’s General Theory of Relativity (GR).

- Black holes (BHs) are one of the most fundamental predictions of GR.

- Theoretically well studied - theory more advanced than observations (changing with GWs astronomy).

- The event horizon is the defining feature of a BH – and yet, we have never seen the event horizon.

- Are Black Holes observable astrophysical objects?
- Does GR hold in its most extreme limit or are alternatives needed?
II. Simulations of Black Holes

1. Theoretical modeling of the accretion onto SMBH
   - GRMHD Simulations

2. Modeling the corresponding EM emission
   - Radiative transfer models (ray tracing)

3. Tests of theories of gravity
   - GR and alternatives
Modeling the accretion onto SMBHs
1. GRMHD Simulations

BHAC (Black Hole Accretion Code)

Porth, Rezzolla, et al., 2017
Relativistic jets and BHs


Boccardi et al. 2017
The Shadow of a Black Hole

Bardeen 1973, Luminet 1979
Falcke, Melia, Agol (2000)
Bronzwaer et al. 2018
The Shadow of a Black Hole

2. Radiative transfer models (ray tracing) to link to observations

**BH OSS** (Black Hole Observations in Stationary Spacetimes)

Younsi, Bronzwaer, Davelaar
The Shadow of a Black Hole
Constraining BH spin and inclination

More face-on

More edge-on

Younsi et al., Bronzwaer et al., Davelaar, et al.
The Shadow of a Black Hole

3. Testing theories of Gravity

Goddi et al. 2017, Younsi et al. 2017
The Shadow of a Black Hole
Astrophysical Targets

\[ R_{\text{Sch}} = 2 \frac{GM_{\text{BH}}}{c^2} \]
\[ \theta_{\text{Sch}} = \frac{R_{\text{Sch}}}{D} \approx 0.02 \text{ nano-arcsec} \left( \frac{M_{\text{BH}}}{M_\odot} \right) / (\text{kpc} / D) \]

Stellar mass BHs (D\sim 1 \text{ kpc}, M_{\text{BH}} \sim 10 M_\odot)
Super-massive BHs (D\sim 1 \text{ Mpc}-1 \text{ Gpc}, M_{\text{BH}} \sim 10^6-10^9 M_\odot)
=> Both generally too small

Two notable exceptions:

**Sgr A^*** : D\sim 8 \text{ kpc}, M_{\text{BH}} \sim 4 \times 10^6 M_\odot => \theta_{\text{Sch}} \sim 10 \text{ micro-arcseconds}

**M87** : D\sim 17 \text{ Mpc}, M_{\text{BH}} \sim 7 \times 10^9 M_\odot => \theta_{\text{Sch}} \sim 8 \text{ micro-arcseconds}

=> Gravitationally-lensed size \sim 50 \text{ micro-arcseconds}
The Galactic Center contains the best and closest SMBH: Sagittarius A* (4 \times 10^6 \text{ solar masses})
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Stellar proper motions around Sgr A*: 4.3 × 10^6 M_{\text{sol}}  
Gillessen et al. 2017
The SMBH and relativistic jet in M87

GRMHD Simulation

VLBI Observations


(Using Harm3D - Gammie et al.)
III. Event Horizon Telescope (EHT)
VLBI – Very Long Baseline Interferometry
Resolution: smallest angular scale: $\sim\lambda/D$

Create a virtual radio telescope the size of the earth at mm-waves

10000 km @43 GHz $\Rightarrow \theta \sim 200 \, \mu\text{as}$
10000 km @230 GHz $\Rightarrow \theta \sim 30 \, \mu\text{as}$
The importance of high frequencies

3D GRMHD simulations

Jet

43 GHz / 7mm

86 GHz / 3mm

230 GHz / 1.3mm

Disk

Moscibrodzka et al.
Very Long Baseline Interferometry at mm-waves (mmVLBI)

- VLBI is “routine” at cm-wavelengths

- VLBI at <3mm is still in an experimental phase, due to challenges of high frequencies:
  - stability of receiver chains
  - distortion effect of the wave fronts by the troposphere
  - small number of telescopes operating in this short wavelength range

=> Till recently, mm-VLBI experiments have been conducted with a limited number of stations (3) which provided to few baselines and thus visibilities to make an image
The Event Horizon Telescope (EHT)

Very Long Baseline Interferometry at mm-waves (mmVLBI)

Create a virtual radio telescope the size of the earth, using the shortest wavelength.
Event Horizon Telescope Consortium

interim board

A. Zensus (chair)
C. Lonsdale (vice-chair)

EHTC Board
Executive Group

Director
S. Doeleman

Chair: H. Falcke
Science Council
Secretary: C. Goddi

13 EHT Stakeholders

- Harvard/SAO (USA)
- MIT Haystack Obs. (USA)
- Univ. Arizona (USA)
- Univ. Chicago (USA)
- Perimeter (Canada)
- INAOE (Mexico)
- MPIFR Bonn (Germany)
- IRAM (D/F/E)
- Radboud Uni. (Netherlands)
- Univ. Frankfurt (Germany)
- EACOA (East Asia)
- NOAJ (Japan)
- ASIAA (Taiwan)

Interim Board since Jan 2015.

50 telecons ... 

Finally consortium agreement signed July 2017.

About 200 individual EHT members ...
14 M€ ERC Synergy Grant BlackHoleCam

**Pis:** H. Falcke (Radboud), M. Kramer (MPIfR), L. Rezzolla (Frankfurt)

**Project Scientist:**
Ciriaco Goddi (Radboud/Leiden)

**Project Manager:**
Remo Tilanus (Radboud/Leiden)

**EU Players & Partners**
Amsterdam: Multi-wavelength observ.
Bonn VLBI: Data correlation, APEX tel.
ESO: ALMA telescope
IRAM: Pico Veleta & NOEMA telescopes
JIVE: VLBI analysis software
Rhodes Univ.: VLBI Simulations
Sweden: Polarisation calibration
Bologna: VLBI Software
IV. April 2017 Observing Campaign
mmVLBI Networks with ALMA in 2017

**GMVA**: Effelsberg, IRAM-PV, Ys, GBT, 8 x VLBA + ALMA

**EHT**: SPT, APEX, LMT, SMT, SMA/JCMT, PV + ALMA

- GMVA @3mm (128 MHz BW, dual pol., 2 Gbps recording)
- EHT @1.3mm (~4 GHz BW, dual pol., 32 Gbps recording)
ALMA VLBI projects in Cycle 4

• **GMVA (B3):** fixed dates (Apr 2-4)
  1. 2016.1.01116.V // OJ287- April 02
  2. 2016.1.00413.V // **Sgr A**- April 03
  3. 2016.1.01216.V // 3C273- April 04

• **EHT (B6):** trigger 5 nights in 10 days (Apr 5-14)
  1. 2016.1.01404.V // **Sgr A**
  2. 2016.1.01114.V // OJ287
  3. 2016.1.01154.V // **M87**
  4. 2016.1.01176.V // 3C279
  5. 2016.1.01198.V // cen A
  6. 2016.1.01290.V // ngc1052
**Go/NoGo Decision (Each day, a few hours ahead of time)**

- Each station reports that it is **Ready** or **Not Ready**, based on weather and technical considerations.
- VLBI Monitor developed at Radboud very useful
- For first 5 days, all stations (except APEX & JCMT) were required
2017 EHT Observations
Projects observed in “Tracks”

10 days (Apr 5-14) during which trigger 4 “tracks”: A,B,C,D
- SgrA* = Tracks B, C ; M87 = Tracks B, D

April 5th (UT) : TRACK D

5 nights observing (April 5th, 6th, 7th, 9th, 10th)
2017 EHT Campaign

- April 5-11 2017
- 8 telescopes, 6 sites (Largest 1mm VLBI experiment ever tried)
- 3 new stations, one dropped
- 5 observing nights in 10 day period
- ~4 PB raw data
- Overall excellent weather!
- Only minor technical hiccups (fraction of lost data small)
- "Fringes" to all stations! ⇒ Imaging is technically possible!
MWL Campaign during EHT run

April 2017 campaign

SgrA*

M87
So \textbf{when} are we gonna see the image of Sgr A*?
First (preliminary!) image of a black hole

Theory:
Black Hole @ Interstellar

Observations:
Black Hole @ IRAM 30 m Telescope
What we **might** actually see

Challenges: troposphere (10 sec), sparse array (max 8 stations, 6 sites), refractive scattering substructures (days), source variability (hours)

- Includes source **variability**
- 8 epochs
- Averaging, smoothing, scaling of visibilities
- De-blurring of scattering
- **EHT imaging** library

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*Shiokawa (2013)*
V. Outlook
Event Horizon Telescope Upgrades

Planned Upgrades:
- **2018**: Double BW 4 x 4 GHz (64 Gbps)
- **New Telescopes**:
  - **2018**: Greenland Telescope (ASIAA) (will not see Sgr A*)
  - **2019**:
    - Kit Peak (Arizona)
    - phased-NOEMA
  - **2020**: LLAMA (Brazil/Argentina)
  - After 2020: African mm Telescope?
VLBI with Africa mm-telescope?

A dedicated African mm-VLBI telescope for EHT, GMVA & EVN (Investment cost: ~8 M€ + ops ...)

Earth seen from Sgr A*
Not only VLBI and shadow image.....

The image itself might not be able to identify deviations from a Kerr spacetime due to correlations with mass and spin magnitude and orientation

⇒ key to determine the BH parameters (mass, spin, inclination) independently from the imaging
Stellar orbits with GRAVITY @ ESO VLTI

Milestones:
• First science light in 2017
• Measuring S2 periastron in May 2018

Astrometry:
• few 10 µas in 5 minutes

Interferometric Imaging:
• Few mas resolution

Improved astrometry will allow to measure mass and spin using S2 orbit and may allow to detect even tighter stars

Eisenhauer et al. 2011
Even better a pulsar!

Why do we want to find a pulsar orbiting the SMBH in the centre of our Galaxy?

- Gauge and weigh companion to test predictions of theories of gravity. E.g.:
  - Hulse-Taylor binary (Hulse & Taylor 1975)
  - Double Pulsar (Lyne et al. 2004)

- Ability to measure BH properties scales with mass
- For few-million solar mass BH:
  - Mass with precision of $1:1,000,000!$
Pulsar orbiting Sgr A*

Pulsar in a 0.3 yr eccentric (e = 0.5) orbit
- Semi-major axis: 72 AU = 860 $R_{\text{Schwarzschild}}$
- Pericentre distance: 36 AU = 430 $R_{\text{Schwarzschild}}$
- Pericentre velocity: 0.042 c

Liu & Eatough, Nature Astronomy, 1, 812-813, 2017

- Highly precise measurement of the black hole mass: $\sim 0.001\%$
- Precise measurement of the Lense-Thirring effect / spin: $\sim 0.1 \ldots 1\% + \text{spin orientation}$
- Testing GR with a pulsar-black holes system and the Kerr-hypothesis (no-hair theorem test)
Complementarity to imaging

1. Pulsars and stars probe the far-field (100-1,000s Rg), the shadow image probes the near-field (< 10s Rg)

2. The 3 different techniques are affected by very different systematics which can be characterized by cross-comparison.

3. Uncertainties in measurements of BH spin and quadrupole moment using orbits of stars and pulsars are nearly orthogonal to those obtained from the image.
Conclusions & Remarks

- Imaging the event horizon is possible for at least two SMBHs.

- First **EHT** campaign with ALMA conducted in April 2017
  - Data looks excellent so far, **imaging** is technically possible

- Images will look crappy at first, but they will become sharper with time: EHT, 345 GHz, Africa, Space ...

- We have a powerful set of **theoretical tools** to compare data with and **test theories of gravity**

- **Stellar orbits** will constrain spin and mass better with **GRAVITY @VLT**

- **Pulsars** searches in the GC being conducted with radio and mm telescopes (Effelsberg, Pico-Veleta, LMT, **phased-ALMA**)

*The Galactic center will allow precision tests of GR!*