Towards the Event Horizon

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Black Hole Cam
„Discovery“ of the First Active Black Hole ...

- Heber Curtis (1913) finds an extended structure in the „nebula“ M87.
  - Nobody knows that M87 is a galaxy ...
  - Nobody knows that the structure is a relativistic plasma jet emerging from a black hole ...
  - Neither the concept of black holes nor cosmology existed at that time ...
Singularities in the universe: Beginning and end of spacetime

- **1915**: Einstein develops General Relativity
- **1916**: Schwarzschild metric, Basics for black holes
- Black holes were a purely theoretical concept – nobody knew that black holes had already been spotted!
**Discovery of First Quasars**

- Hazard et al. (1963) detected strong radio emission from a “stellar object”.
- This source, 3C273, had very strange optical emission lines.
- Maarten Schmidt realized this was redshifted hydrogen (z=0.158).
- Inferred luminosity and sizes exceeding an entire Galaxy squeezed into a $10^{-12}$th fraction of its volume!
The Quasar Problem

- Distance: $z=0.156 \Rightarrow D=2 \cdot 10^9$ light years
- Luminosity: $m_B=13.1 \Rightarrow 2.6 \cdot 10^{-25}$ erg/sec/Hz/cm$^2$
  $L=2 \cdot 10^{46}$ erg/sec $= 5 \cdot 10^{12} \times$ luminosity of sun.
- Size: variability within a year $\Rightarrow R < $ light year
- Luminosity is exceeding an entire Galaxy squeezed into a $10^{-12}$th fraction of its volume!
  $\Rightarrow$ Supermassive Black Holes survived as major paradigm to explain this.
Black Holes - Luminosities

• Accretion Rate $\dot{M}$ due to mass inflow:

$$L = \dot{U} = \frac{GM \bullet}{R} \frac{\Delta m}{\Delta t} = \frac{GM \bullet}{R} \dot{M}$$

$$L = \eta \frac{GM}{R_g} \dot{M} = \eta \dot{M} c^2$$

$$L \approx 10^{46} \frac{\text{erg}}{\text{sec}} \left( \frac{\eta}{0.1} \right) \left( \frac{\dot{M}}{M_{\text{sun}} \text{yr}^{-1}} \right)$$

Very efficient: 10 buckets of water poured into a black hole provides enough energy for the entire Netherlands for one year!

40 times the water content of the Earth in one Second!
Search for Supermassive Black Holes

- Black Holes were used to explain luminous emission
- Black-Hole-like activity is found in many normal galaxies also nearby
- Quasar-phase is just a short fraction of life time

⇒ Prediction of massive dark objects at the center of galaxies
⇒ Search for dynamical evidence in nearby galaxies
High-Resolution Spectroscopy of Gas

- HST resolves dynamics of stars and gas
- M87 contains a hot rotating disk in the center
- Spectroscopy yields velocity $v(r)$
- Assumption of Keplerian motions yields
  \[ M_* \approx 6 \cdot 10^9 M_\odot \]

Ford et al. (1994), Harms et al. (1994), Gebhardt et al. (2009)
The Supermassive Black Hole and Jet in M87

LOFAR Imaging: Virgo A at 140 MHz

240,000 lightyears

de Gasperin, Orru, Merloni, Falcke, et al.

VLBA 43 GHz (higher sensitivity)

Walker et al. 2008
Galactic Center
Galactic Center

- The Galactic Center is a bright radio source in the plane of the Milky Way.
- It contains the small radio source Sgr A*, which is suspected to be THE central black hole in the Milky Way.
Sgr A* Spectrum: The submm-bump synchrotron from quasi-thermal electrons

Sgr A*: Radio-submm-NIR Spectrum

\[ S_{\nu} \approx 1.5 \times 10^{12} \text{ cm} k^{-1/17} \left( \frac{S_{\nu_{\text{max}}}}{3.5 \text{ Jy}} \right)^{8/17} \times \left( \frac{\nu_{\text{max}}}{10^{12} \text{ Hz}} \right)^{-16/51} \left( \frac{\nu_{\text{ssa}}}{100 \text{ GHz}} \right)^{-35/51} \approx R_s \]

Zylka, Mezger, Lesch (1992)
Falcke, Goss, Matsuo et al. (1998)
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THE SIMULTANEOUS SPECTRUM OF SAGITTARIUS A* FROM 20 CENTIMETER TO 1 MILLIMETER
AND THE NATURE OF THE MILLIMETER EXCESS

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Received 1997 November 6; accepted 1998 January 12

ABSTRACT

We report results of a multiwavelength campaign to measure the simultaneous spectrum of the supermassive black hole candidate Sgr A* in the Galactic center from centimeter to millimeter wavelengths using the Very Large Array, the Berkeley-Illinois-Maryland Array (BIMA), the Nobeyama 45 m, and the Institut de Radioastronomie Millimetrique (IRAM) 30 m telescopes. The observations confirm that the previously detected millimeter excess is an intrinsic feature of the spectrum of Sgr A*. The excess can be interpreted as and effect of the presence of an ultracompact component of relativistic plasma with a size of a few Schwarzschild radii near the black hole. If so, Sgr A* might offer a unique possibility to image the putative black hole against the background of this component with future millimeter VLBI experiments.
Ray-Tracing in the Kerr Metric

- In Sgr A* there is optically thin emission on event horizon scales!
- What does this mean for an observer?
- Photon orbits are bent due to the black hole.
- At $R \sim 4-5R_g$ orbits can become circular.
- Closer orbits end in the event horizon.
- This produces a “shadow” in the emitting region around the black hole.

(Bardeen 1973, Falcke et al. 2000)
The Shadow of a Black Hole

GR Model

$\lambda 0.6\text{mm VLBI}$

$\lambda 1.3\text{mm VLBI}$

$a=0.998$

$I=r^{-2}$

$a=0$

$I=\text{const}$

(Falcke, Melia, Agol 2000, ApJL)
Dark Mass in the Galactic Center

- Stellar proper motions have revealed a dark mass in the Galactic Center of 4 Million solar masses within the size of the solar system.
- The center of gravity coincides with Sgr A* within 215 Rs (15 AU).

Genzel, Ghez, Eckart ..... (MPE, UCLA, Cologne...)
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Gillessen 2013, priv. comm.
**Fringe Tracking:**
- UTs: K~10 mag
- ATs: K~7 mag

**Milestones:**
- Final design in 2011/12
- Installation at the telescope in 2014

**Astrometry:**
- Few 10 μas in 5 minutes

**Interferometric Imaging:**
- UTs: K~16, ATs: K~13 in 100s
- SNR(V) = 10 for visibility
- σ(φ) = 0.1 rad for referenced phase

Eisenhauer et al. 2011
Stellar orbits for precision astrophysics

Expected in central 100 mas:
~5 stars (K = 17..19 mag)
Orbital Period: 1 year
GR Precession: a few ° per year

S2 - The showcase Star:
Period: 15.9 years
Semi major axis: 125 mas
Eccentricity 0.88
Distance: 8.28 ± 0.15 ± 0.30 kpc
M_{bh} = (4.30 ± 0.06 ± 0.35) \times 10^6 M_{\odot}

see also: Rubilar & Eckart (2001)
A Gas Cloud Disrupted by the Black Hole

Radio Interferometry - VLBI

- The resolution can be increased by a factor of 1000.
Radio Interferometry - VLBI

- This technique is called “Very Long Baseline Interferometry” (VLBI).
- One obtains a virtual telescope the size of the earth.
- The largest resolution is achieved at the highest frequencies (shortest wavelengths).
VLBI – the sharpest view in astronomy

• A pea in New York (radiating one milli-Watt) could be resolved by VLBI from Frankfurt.

• If someone moves the pea by one millimeter, we would see this too.
Dark Mass in the Galactic Center

- High-resolution radio astrometry (VLBI): Sgr A* apparently moves along the Galactic Plane.
- Reflects motion of sun around Galactic Center!
- Unlike stars, Sgr A* does not move relative to the Galactic Center.
- $V_{\text{Sgr A*}} < 1 \text{ km/s}$
- Mass limit: $M > 4 \cdot 10^5 M_\odot$
- Most likely: all the mass is concentrated in the radio source – but, what is it?

(Reid, Brunthaler et al. 2003, 2004)
What is Sgr A*?
Size and Structure

- The radio structure of Sgr A* is blurred by interstellar scattering.
- The apparent size scales with $\lambda^2$.
- The intrinsic size is hidden at most frequencies.
- Deviations from $\lambda^2$ are difficult to detect.
- Bower et al. (2004) found the first deviation from the scattering size at 43 GHz (7mm)

![Graph showing the size/\lambda^2 vs. wavelength (cm)](image)

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0.1 mpc (300 R_s)

Lo et al. (1998)

Bower et al. (2008)
**Sgr A*: Size of radio source**

Size in Schwarzschild radii

- 300 Rs
- 30 Rs
- 3 Rs

Updated from Falcke, Markoff, Bower (2009)

Doeleman et al. (2008)

Shen et al. (2006)

Bower et al. (2008)

30 light minutes

lag = 20 minutes

⇒ Relativistic outflow

Shadow of event horizon

updated from Falcke, Markoff, Bower (2009)
BlackHoleCam Project

European Research Council (ERC) “Synergy Grant” 14 M€ for 6 years
European partners

Robert Laing
• European Instrument Scientist of ALMA (ESO)

Huib-Jan van Langevelde
• Director Joint Institute for VLBI in Europe

Frank Eisenhauer
• Project Scientist “Gravity” - stellar orbits MPE Garching
Create a virtual radio telescope the size of the earth, using the shortest wavelength.
The Black Hole Camera

Digital revolution: 128 Mbit/s → 2 Gbit/s → 64 Gbit/s
more bandwidth = more sensitivity.

IRAM Plateau de Bure Interferometer – France
VLBI with Africa mm-telescope?

Needs ~7 M€ (HW). But: significantly improves image quality for event horizon, better links in European telescopes, establishes EU-African partnership in top science.
Shadow Industry

Bardeen (1973); Dexter & Agol (2009)

Broderick & Loeb (2009)

Falcke, Mella & Agol (2000)

Dexter et al. (2009, 2010)

Time in hours: 0.000

Dolence
Testing the No-Hair Theorem Observationally

- Uncharged (Kerr) BHs should be fully described by two parameters. You can expand spacetime in multipole moments depending only on mass $M$, and spin $a$
- Parameterize quadrupole moment: $q=-(a^2+\varepsilon)$
- Obtain a new metric:

$$ds^2 = -\left(1 - \frac{2Mr}{\Sigma}\right)(1 + h(r, \theta))dt^2 - \frac{4amr \sin \theta}{\Sigma}(1 + h(r, \theta))dtd\phi$$

$$+ \frac{\Sigma(1 + h(r, \theta))}{\Delta + a^2 h(r, \theta) \sin^2 \theta}dr^2 + \Sigma d\theta^2$$

$$+ \left[ \sin^2 \theta \left( r^2 + a^2 + \frac{2a^2 Mr \sin^2 \theta}{\Sigma} \right) + h(r, \theta) \frac{a^2 (\Sigma + 2Mr) \sin^4 \theta}{\Sigma} \right] d\phi^2$$

$h(r, \theta) \equiv \varepsilon_3 \frac{M^3}{r^3}$

Johannsen & Psaltis 2011, PRD

- Use observations to measure (at least) 3 moments
- Check whether indeed $q = -a^2$ (i.e., $\varepsilon=0$)

Gair et al. 2008  
Li & Lovelace 2008  
Will 2008  
Vigeland & Hughes 2010

Johannsen & Psaltis 2010, 2011  
Vigeland et al. 2011  
Ryan 1995, 1997a,b

Collins & Hughes 2004  
Glampedakis & Babak 2006  
Brink 2008, 2009

Barack & Cutler 2004, 2007
Quadropole Effects on Black Hole Shadow

Pseudo-Complex Gravity

Shadow industry; Different spacetimes

Falcke & Markoff, Class. & Quant. Gravity (2013, review)
Advancing the Astrophysical Model

- General Relativity
- 3D Magneto-Hydrodynamics
  - Inflow: Accretion
  - Outflow: Jets
  - BH – MHD interface (ISCO)
- Microphysics:
  - Heating & cooling of particles
- Radiation Transport

⇒ Need to understand basic parameters, spectrum, size, and variability of Sgr A*
Problem: Simulations only give proton temperature and everyone assumes that electron heating in jet and disk work exactly the same.

⇒ You cannot see jets in simulations as there are always fewer particles flowing out than in!

⇒ Physical regions are very different:
  • Jet is highly magnetized and tenuous
  • Disk is low magnetization and dense!
  • Likely different heating mechanisms at work!

⇒ Allow for different proton-ion coupling in disk & jet!

Jet: $T_p/T_e=1$
Disk: two-temperature ADAF ($T_p/T_e>>1$)

Moscibrodzka & Falcke (2013, A&AL)
Moscibrodzka et al. (in prep.)
Variations ...

Te/Tp(jet)

edge-on

BlackHoleCam

face-on

Moscibrodzka et al. (2014)
The broad band spectrum and size

Jet: $T_p/T_e = 1$
Disk: two-temperature ADAF ($T_p/T_e >> 1$)

GRMHD simulations recover basic Blandford & Königl jets and flat-spectrum radio cores ....!

Moscibrodzka et al. (in prep.)
Effect of scatter broadening

- \( \lambda \): 7 mm
- \( \lambda \): 3.5 mm
- \( \lambda \): 1.3 mm

Scales changing!

Scatter broadened

Event horizon even better visible than disk-only fits!
Measuring masses with pulsars

- Binary pulsars test predictions of theories of gravity.
- We can gauge and weigh companion, e.g.,

Pulsar A = 1.3381\pm0.0007 Solar Mass,
Pulsar B = 1.2489\pm0.0007 Solar Mass.

The Double Pulsar

Orbit shrinking by 7.152 \pm 0.003 mm/day.

Kramer et al. (2006, 2014)
Measuring masses with pulsars

• Binary pulsars test predictions of theories of gravity.
• We can gauge and weigh companion, e.g.,

Pulsar A = 1.3381±0.0007 Solar Mass,
Pulsar B = 1.2489±0.0007 Solar Mass.

• Also possible with BHs!
• Ability to measure BH properties scales with mass.
• For few-million solar mass BH:

Mass with precision of 1:1,000,000
Spin with precision of 1:1,000.
Using Pulsars to Measure Spacetime Around Sgr A*  

Black Hole shadow  

Pulsar orbits and timing residuals  

face-on  

edge-on  

GRMHD simulations from Moscibrodzka et al. (2009)  

Synergy-project: Falcke, Kramer, Rezzolla  

Image credit: N. Wex
First Galactic Center Pulsar

Radio proper motions: Bower et al. (2014, to be subm.)

Radio detection: pulse phase
Eatough et al. (2013, Nature)
Conclusions

- Black holes used to be purely theoretical concepts.
- They were introduced to explain distant quasars.
  Now we find them in our back yard.
- The radio source Sgr A* is currently the best candidate for a supermassive black hole:
  - Mass and distance are accurately determined
  - Radio emission comes from event horizon scale and peaks at submm-wavelengths
- If an event horizon exists, it will cast a shadow on the emission region.
- The black hole shadow can be detected with mm-VLBI
- Pulsars would give extreme precision in parameters (10^{-6} in mass, 0.1% spin)
- This will
  - demonstrate that black holes and event horizons exist
  - test GR and also modified GR
  - allow comparison with 3D GRMHD simulations and probe accretion & jet physics
  ⇒ black hole astrophysics becomes testable science!