The Centre of the Milky Way

An easy one, for today: stars and star formation, ISM, galaxy evolution, accretion, supermassive black holes, fundamental physics
A difficult one, in general: technically, observationally, theoretically
A highly competitive one, worldwide, but rewarding

- The last decade(s) – an overview
- The basis for success – telescopes and instruments
- The topics for the coming decade(s) – an educated guess
- ESO’s role and how it can best contribute

Frank Eisenhauer (Max-Planck-Institute for extraterrestrial Physics)
The Center of the Milky Way

Courtesy ESO
The Galactic Center harbors a black hole

Massive
Small
The Small is the Heavy
Faint
The Galactic Center harbors a black hole

Massive: $4.3 \times 10^6 \ M_{\odot}$

The Galactic Center harbors a black hole

Massive: $4.3 \times 10^6 \, M_{\odot}$
Small: $3.7 \, R_{\odot}$

The Small is the Heavy
Faint: $10^{-6} \, L_{\text{Edd}}$

The Galactic Center harbors a black hole

Massive: \(4.3 \times 10^6 \, M_{\text{Sun}}\)
Small: \(3.7 \, R_{\odot}\)

The Small is the Heavy
Faint: \(10^{-6} \, L_{\text{Edd}}\)

Fish et al. 2011, Doelman et al. 2008
Bower et al. 2006, 2004, Shen et al. 2005,
Krichbaum et al. 1998
The Galactic Center harbors a black hole

Massive: $4.3 \times 10^6 \, M_\text{Sun}$
Small: $3.7 \, R_\odot$

The Small is the Heavy
Faint: $10^{-6} \, L_{\text{Edd}}$

Reid & Brunthaler et al. 2004
Reid et al. 2008
The Galactic Center harbors a black hole

Massive: $4.3 \times 10^6$ M$_{\text{Sun}}$
Small: $3.7$ R$_S$
The Small is the Heavy
Faint: $10^{-6}$ L$_{\text{Edd}}$

Nagar et al. 2005

The Galactic Center is a rich region with stars ...
And gas on all scales ... 

Down towards the very center

Gas developing tidal shear in front of our eyes

Gillessen et al. 2011, 2013+, Pfuhl et al. 2015
What is it? Where does it come from?

We can’t tell, but we know ...

**Object**
- Ionized gas slightly extended and tidally disrupted
- Not detected at 2 µm
- Point-like 3.5 µm emission, not disrupted

**Orbit**
- Orbital plane coincides with disk plane
- Apocenter in the disk
- Orbit with large eccentricity $e \geq 0.966$

Basis for success I: large optical / IR telescopes
Basis for success II: adaptive optics and integral field spectroscopy

NACO, Keck AO: Astrometry with 300 μas
- Rousset et al. 2003
- Lenzen et al. 2003
- Matthews et al.
- Wizinowich, Max et al.

Laser guide stars
- Bonnaccini et al.
- Rabien et al.
- Wizinowich, Max et al.

SINFONI, OSIRIS: Spectroscopy with 15 km/s
- Eisenhauer et al. 2004
- Bonnet et al. 2003
- Larkin et al. 2006
Basis for success III: radio, VLBA and VLBI

North American

Europe
Topics for the next decade(s) I: relativistic physics

- Bozza & Mancini 2012
- Zucker et al. 2006
- Jaroszynski 1998
- Psaltis 2004
Topics for the next decade(s) I: relativistic physics

Spin

\[ \dot{\Omega}_J \approx 0.847 \chi P^{-4/3} (1 - e^2)^{-3/2}, \]

Quadrupole moment

\[ \dot{\Omega}_{Q_2} \approx 9.68 \times 10^{-3} \chi^2 P^{-5/3} (1 - e^2)^{-2}, \]

Testing the no-hair theorem

Topics for the next decade(s) I: relativistic physics

Angelil et al. 2010, Iorio 2010

Will 2008

Extended mass steep profile
Extended mass shallow profile

Classical velocity
Time dilation
Schwarzschild
Frame dragging
Quadrupole

100 km/s
10 km/s
1 km/s

100 µas/yr
10 µas/yr
What matters: spatial resolution and accuracy

Diffraction limit \( \sim D \)
Pointsource sensitivity \( \sim D^2 \)
Crowding limit \( \sim D^4 \)
With the help of VLT interferometry
And GRAVITY

Eisenhauer et al. 2005, 2010
Timing matters

Precession “ticks” during peri-passage

Angelil & Saha 2014

Gillessen et al.
But this is nothing compared to finding a pulsar

Providing exquisite precision, here “Best examples” for binary pulsar

Table from M.Kramer

<table>
<thead>
<tr>
<th>Masses:</th>
<th>Masses of neutron stars: $m_1 = 1.4398(2) , M_\odot$ and $1.3886(2) , M_\odot$</th>
<th>(Weisberg et al. 2010)</th>
</tr>
</thead>
</table>

**Orbital parameters:**

<table>
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<tr>
<th>Period:</th>
<th>0.102251562479(8) day</th>
<th>(Kramer et al. in prep.)</th>
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<tbody>
<tr>
<td>Eccentricity:</td>
<td>3.5 (1.1) $\times 10^{-7}$</td>
<td>(Freire et al. in 2012)</td>
</tr>
</tbody>
</table>

**Astrometry:**

<table>
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<tr>
<th>Distance:</th>
<th>157(1) pc</th>
<th>(Verbiest et al. 2008)</th>
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<tbody>
<tr>
<td>Proper motion:</td>
<td>140.915(1) mas/yr</td>
<td>(Verbiest et al. 2008)</td>
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</table>

**Tests of general relativity:**

<table>
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<tr>
<th>Periastron advance:</th>
<th>4.226598(5) deg/yr</th>
<th>(Weisberg et al. 2010)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shrinkage due to GW emission:</td>
<td>7.152(8) mm/day</td>
<td>(Kramer et al. in prep)</td>
</tr>
<tr>
<td>GR validity (obs/exp):</td>
<td>1.0000(5)</td>
<td>(Kramer et al. in prep.)</td>
</tr>
<tr>
<td>Constancy of grav. Constant, $dG/dt/G$:</td>
<td>$(9\pm12) \times 10^{-13} , \text{yr}^{-1}$</td>
<td>(Zhu et al. in prep)</td>
</tr>
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</table>
Giving mass, spin, cosmic censorship etc.

Example: For pulsar in a 0.3 yr eccentric (e=0.5) orbit around Sgr A* 

BH mass with precision < 0.1%
BH spin with precision < 1%
Cosmic Censorship: \( S < \frac{GM^2}{c} \)

And maybe even quadrupole from characteristic periodic residuals

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Liu 2012, Wex et al. in prep.

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But finding a Pulsar is not easy

Pulse smearing at low frequencies

Faint at high frequencies

Löhmer et al. (2001)
And requires a large collecting area

Ideally with SKA

But also e.g. ALMA cophased for intensity recording

Braun, this conference

APP Doeleman et al.
Topics for the next decade(s) I: relativistic physics

Broderick & Loeb 2005
Paumard et al. 2005

Dexter, Agol et al., Mościbrodzka, Gammie, Dolence et al., Broderick, Loeb et al., Shcherbakov, Penna, McKinney
Infrared might offer one possibility

Hamaus et al. 2009
Mayer et al. 2010

Paumard et al. 2005
mm-Very Long Baseline Interferometry is another method to create a virtual radio telescope the size of the earth, using the shortest wavelength.

resolution = \frac{\text{wavelength}}{\text{telescope separation}}
Imaging the shadow of the black hole

Maximum spin

No spin

Quadropole effects

Falcke et al. 2000, Broderick et al. 2009/11

Orbiting hot spots

Johannsen, Psaltis 2012

Steeger et al.
Topics for the next decade(s) II: Complex Dynamics

Complex, but not too complex

From Genzel et al. 2010

Kocsis & Tremaine 2010
Large field astrometry and massive spectroscopy

Bartko et al., Pfuhl et al. 2011, Feldmeier et al. 2014, Fritz et al. 2014,

Courtesy: P. Plewa
Topics for the next decade(s) III: Gas dynamics

Feeding the Bondi accretion

Cuadra et al. 2006
Topics for the next decade(s) III: Gas dynamics

Feeding the Black Hole

High resolution imaging and deep spectroscopy

About 30 h of very good seeing on source

Only source removal reveals G2 at peri

Paumard et al. 2004

Pfuhl et al. 2015

Witzel et al. 2014

Paumard et al. 2004
Topics for the next decade IV: Star formation

Forming the stars

Hobbs & Nayakshin 2009
Deep spectroscopy and high resolution imaging

Genzel et al. 2010

Pfuhl et al. 2011
Deep spectroscopy and high resolution imaging

Genzel et al. 2010

Courtesy HST
ESO’s role and how it can best contribute

You have set the right directions for the next decade

VLT(I), GRAVITY

EELT, MICADO, HARMONI

Thatte et al. 2014, Davies et al. 2014

ALMA Phasing Project

Doeleman et al.
ESO’s role and how it can best contribute

But we need to stay on track and in time

VLT(I), GRAVITY
Ready and well performing before the S2 peri passage
Continued support and adequate observing model

And keep enough margin for unexpected problems to come
SKA, CTA etc. at ESO?

Faster than TMT
Competitive adaptive optics
EELT, MICADO, HARMONI

I don’t feel competent to advice
ALMA Phasing Project
In any case – exciting times to come

Thank you very much for your attention