Sgr A* - the galactic center black hole - part 1 A

The COST action “Black Holes in a Violent Universe” (MP-0905) organizes a Summer School on “Black Holes at all scales Ioannina, Greece, September 16 and 18

Andreas Eckart
I. Physikalisches Institut der Universität zu Köln
Max-Planck-Institut für Radioastronomie, Bonn

14:30-16:00 Part I: Observational methods to study the Galactic Center – SgrA* and its environment
CND/mini-spiral/central stellar cluster - dust sources in the central few arcseconds
The Galactic Center

I Observational methods to study galaxy nuclei

II Structure of the Galactic Center

III Variable emission from Sagittarius A*

incomplete and biased
The Center of the Milky Way

Closest galactic center at 8 kpc
High extinction of $A_v = 30$, $A_k = 3$
Stars can only be seen in the NIR

VLA 90cm

Kassim, Briggs, Lasio, LaRosa, Imamura, Hyman
Observational methods to the Galactic Center

- Imaging/daptive optics
- Interferometry in the radio
- Interferometry in the mm-domain
- Interferometry in the NIR
- Imaging spectroscopy
Direct Imaging
Speckle Interferometry
Via short exposures (typically 100 ms) the influence of the atmosphere on the image can be recorded and corrected for.
Image Formation

- Seeing cells
- 10 km
- Aperture

- Seeing cloud
- Individual speckle

- Power spectrum
  - Spatial frequency
  - Seeing power
  - 'Speckle' power
  - Diffraction limit
Image Formation

image plane

\[ I(x, y) = O(x, y) * P(x, y) \]

Fourier plane

\[ i(u, v) = o(u, v) p(u, v) \]

\[ |\langle i(u, v) \rangle|^2 = o^2(u, v) |\langle T(u, v) \rangle|^2 \]

\[ |\langle i \rangle|^2 = |\langle ae^{i\phi} \rangle|^2 \]

\[ \langle |i(u, v)|^2 \rangle = o^2(u, v) \langle |T(u, v)|^2 \rangle \]

\[ \langle |i|^2 \rangle = \langle i^* \times i \rangle = \langle a^2 \rangle \langle e^{-i\phi} e^{i\phi} \rangle = \langle a^2 \rangle \]

image is object convolved with PSF

long exposure power spectrum

short exposure power spectrum

information at high spatial frequencies is preserved!
The seeing is better in the Infrared wavelength domain!!

Also: $\gamma$ should be small!
Go to Chile!!

Telescope transfer function: $T^*$
\( \langle T(u, v) \rangle = T_s(u, v)T^*(u, v) \)

Seeing transfer function: $T_s$

\[ w^2 = u^2 + v^2 \]

\[ T_s(\omega) \approx \exp\left(-3.44 \frac{\lambda|w|^{5/3}}{r_0}\right) \]

\[
\begin{align*}
    r_0 & \propto \lambda^{6/5} \times (\cos(\gamma))^{3/5} \\
    \omega & \approx \frac{\lambda}{r_0} \\
    \omega & \propto \lambda^{-1/5}
\end{align*}
\]
Adaptive Optics
Adaptive Optics

A distorted wavefront is measured online and straightened via a deformable mirror.

Shack–Hartmann wavefront sensor

Delta x Delta y
Image Formation
Adaptive Optics

Keck II AO image of the GC

Galactic Center
Keck Adaptive Optics

Mosaic of 24 images (total integration time: 120 seconds), this image shows the very central area of our own galaxy, the Milky Way. It was obtained on May 26th, 1999. The central arcsecond (Inset) will help to determine the mass of the central black hole Sgr A*.
MPE laser guide star at the ALFA Calar Alto AO-System
Adaptive Optics at ESO Paranal

28 Jan. 2006; 8 W into a fiber
Interferometry in the radio
\[ \tau_g = \frac{b \cdot s}{c} \]

Diagram of a signal processing system with blocks labeled as follows:
- **Local Oscillator**
- **Phase Shifter**
- **Compensating Delay**
- **Correlator**

**Inputs and Outputs:**
- **Input:** \( r(t) \)
- **Output:** \( \nu_{IF} \)

**Signals:**
- **USB:** \( \nu_{RF} - \nu_{LO} \)
- **LSB:** \( \nu_{LO} - \nu_{RF} \)

**Other Symbols:**
- **\( \nu_{RF} \)**
- **\( \nu_{IF} \)**
- **\( \phi_L \)**
- **\( \tau_i \)**
Interferometry in the mm-domain
The Combined Array for Research in Millimeter-wave Astronomy (CARMA) is a university-based interferometer consisting of six 10.4-meter, nine 6.1-meter, and eight 3.5-meter antennas that are used in combination to image the astronomical universe at millimeter wavelengths. Located at a high-altitude site in eastern California,
Atacama Large Millimeter Array

5000m altitude; 50 12m antennas; 70-900 GHz

Linear resolutions of a few parsecs can be reached for nearby active nuclei.
Interferometry in the NIR
Incoming Starlight

Extra pathlength

Astrometric baseline

Physical baseline

Compressor

Siderostat

Beam Splitter (Combiner)

Detector

Adjust Delay to equalize Pathlength for each arm
IF simulates a large aperture telescope in terms of resolution

\[ \approx 2I_{tel}(\theta) \left[ 1 + V_{UD1} \cos(2\pi \theta B/\lambda) \right] \]

\[ V_{UD} = \frac{2J_1(\pi B\theta_{UD}/\lambda)}{\pi B\theta_{UD}/\lambda}. \]
The 8m diameter VLT mirrors combined with high throughput instrumentation and adaptive optics will allow sensitive subarcsecond NIR spectroscopy of active nuclei.
Sgr A* - the galactic center black hole - part 1 B

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CND/mini-spiral/central stellar cluster - dust sources in the central few arcseconds
The Environment of SgrA*  
Orbital motion of high-velocity S-stars  
On the possibility to detect relativistic and Newtonian peri-center shifts  
- Granularity of scatterers  
- Search for stellar probes
The Center of the Milky Way

Closest galactic center at 8 kpc
High extinction of Av=30  Ak=3
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Kassim, Briggs, Lasio, LaRosa, Imamura, Hyman
SgrA* and its Environment

Orbits of High Velocity Stars in the Central Arcsecond

Eckart & Genzel 1996/1997 (first proper motions)
Eckart et al. 2002 (S2 is bound; first elements)
Schödel et al. 2002, 2003 (first detailed elements)
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Eisenhauer 2005, Gillessen et al. 2009 (improved elements on more stars and distance)

~4 million solar masses at a distance of ~8.3+-0.3 kpc
Progress in measuring the orbits

$T_{\text{orbit}} = 15.6 \pm 0.4 \text{ yrs}$
$e = 0.883 \pm 0.003$
$\alpha = 0.125 \pm 0.002$

$R_0 = 8.28 \pm 0.15 |_{\text{stat}} \pm 0.29 |_{\text{sys}} \text{ kpc}$

$M_{\text{MBH}} = 4.30 \pm 0.20 |_{\text{stat}} \pm 0.30 |_{\text{sys}} \times 10^6 \ M_\odot$

Gillessen+ 2009
Shortest known period star with 11.5 years available to resolve degeneracies in the parameters describing the central gravitational potential \((e=0.68)\) (Meyer et al. 2012 Sci 338, 84),
Für S2 ist der etwa 15 jährige Orbit geschlossen. Die Kepler'schen Gesetze ergeben:

\[ M_{S2} = \frac{4\pi^2 a^3}{GT^2} \]

mit der Umlaufzeit \( T \) und der großen Halbachse \( a \).

Für S2 ergibt das:

\[ M_{SgrA^*} \approx (4 \pm 0.3) \times 10^6 M_\odot \]

Man kann gleichzeitig für die Entfernung lösen und erhält: 7.7\(+/-\)0.3 kpc

Eisenhauer et al. 2005
The Environment of SgrA*

Orbital motion of high-velocity S-stars

On the possibility to detect relativistic and Newtonian peri-center shifts
  • Granularity of scatterers
  • Search for stellar probes
Most authors claim a ~10 Msol population of black holes residing at the ‘bottom’ of the central potential well. Chandra observations by Muno, Baganoff + 2008, 2009 and simulations by Freitag et al. 2006 Merritt 2009

The stellar BH density is expected to be largest at a radius of a few 0.1 pc.
The Effect of Resonant Relaxation

\[ \frac{\Delta L}{L_c} \approx K \sqrt{N} \frac{m}{M_*} \frac{\Delta t}{P} \]

calculates the change of torque due to field stars.

Changes in L over \( \Delta t \) imply changes in eccentricity and orbital plane angles:

\[ L_c = \sqrt{GM_* a} \]

Equivalent angular momentum of test star on circular orbit.

\[ \cos(\Delta \theta) = \frac{L_1 \cdot L_2}{L_1 L_2} \]

\[ |\Delta e|_{RR} \approx K_e \sqrt{N} \frac{m}{M_*} \]

\[ (\Delta \theta)_{RR} \approx 2\pi K_t \sqrt{N} \frac{m}{M_*} \]

Resonant relaxation:

Rauch & Tremaine 1996
Hopeman & Alexander 2006
Merritt et al. 2010

Two stellar populations
Species 1 smooth
Species 2 perturbing

\[ (\Delta \theta)_{RR} = K_t \left[ \frac{m_1 \sqrt{N_1} + m_2 \sqrt{N_2}}{M_*} \right] \]

Sabha, Eckart, Merritt et al. 2012
Filled circles are from integrations with \( m = 50 \, M_\odot \) and open circles are for \( m = 10 \, M_\odot \); number of field stars \( N = \{25, 50, 100, 200\} \) for both \( m \). The abscissa is the distributed mass within S2’s apo-apsis, at \( r = 9.4 \, \text{mpc} \). In each frame, the points are median values from the 100 N-body integrations.

(a) Changes in the argument of peri-bothron. The contribution from relativity has been subtracted.

(b) Changes in the eccentricity. Solid and dashed lines are with \( m = 50 \, M_\odot \) and \( m = 10 \, M_\odot \), respectively.

(c) The angle between initial and final values of L i.e. \( \Delta \theta \) for S2.

Sabha et al. 2012
The shift due to relativity (~11′), has been subtracted. What remains is due to Newtonian perturbations (peri-bothron shift and perturbation/scattering) from the field stars.

\[
\frac{|\Delta L|}{L_c} \approx K \sqrt{N} \frac{m}{M_\odot} \frac{\Delta t}{P}
\]

\[
|\Delta e|_{RR} \approx K_e \sqrt{N} \frac{m}{M_\odot},
\]

\[
(\Delta \theta)_{RR} \approx 2\pi K_t \sqrt{N} \frac{m}{M_\odot}
\]

Enclosed mass up to \(2000M_\odot\)

Resonant relaxation:

Rauch & Tremaine 1996
Hopeman & Alexander 2006
Merritt et al. 2010

Sabha, Eckart, Merritt, Shahzamanian et al. 2012
Newtonian and relativistic periastron shift for S2

\[ m_1 = 1 \, M_\odot, \quad m_2 = 10 \, M_\odot, \quad N_1 = 10^4, \quad N_2 = 1500 \]

\[ |\Delta e|_{RR} \approx 1.7 \times 10^{-4} \]

\[ (\Delta \theta)_{RR} \approx 3'.0. \]

\[ m_1 = 1 \, M_\odot, \quad m_2 = 10 \, M_\odot, \quad N_1 = 10^5, \quad N_2 = 15000 \]

\[ |\Delta e|_{RR} \approx 5.4 \times 10^{-4} \]

\[ (\Delta \theta)_{RR} \approx 8'.0. \]

**Significant contributions to periastron shift** \( \Delta \omega \)
from encounters
due to granularity of ‘scattering’ population \( \Delta \theta \):
\[ \propto \sqrt{N_2} \]
and
variation in enclosed mass due to scattering population:
\[ \propto \sqrt{N_2} \]
The variance in for S2 for one orbital period (~16 yr) in the N-body integrations.

Relative variance of peri-center shift as the absolute variance over the shift itself.

The absolute variance is large and of the order of the entire peri-center shift.
The Environment of SgrA*

Orbital motion of high-velocity S-stars

On the possibility to detect relativistic and Newtonian peri-center shifts
  • Granularity of scatterers
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Subtraction of stars within $R < 0.7''$

S<1mJy in the NIR K-band

Sabha et al. 2010
Map of the 51 brightest stars close to SgrA*. The color of each star indicates its K-magnitude. The size of each symbol is proportional to the flux of the corresponding star. The position of Sgr A* is indicated as a cross at the center.
The Central S-star Cluster

luminosity function $\exp(-\Gamma)$

radial distribution $\exp(-\alpha)$

Sabha et al. 2011, 2012
Extrapolation of the KLF power-law fit. The KLF slope of $\alpha = 0.18$ and the upper limit imposed by the uncertainty in the fit ($\alpha = 0.25$) are plotted as dashed and dash-dotted lines, respectively. The black filled circles represent the data while the hollow circles represent new points based on the extrapolated KLF. The location of the detection limit is indicated by the red line. 

Sabha et al. 2012
Apparent stars due to blends

Upper panel: 3 different snapshots of the simulation for the $\alpha = 0.25$ KLF slope, power-law index $\Gamma = -0.3$ and a $\sim 25$ K-magnitude cutoff.
Lower panel: The same as upper but with only the detectable blend stars visible.
Right: Average of all the 104 simulation snapshots for the same setup.

INTERFEROMETRY IS NEEDED to make progress!

Sabha et al. 2012
SgrA* and its Environment

Orbits of High Velocity Stars in the Central Arcsecond

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~4 million solar masses at a distance of ~8.3+-0.3 kpc

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Progress expected in determining relativistic effects

Possible hot spots orbiting SgrA* the detection of strong relativistic effects is complicated by processes in the accretion stream/outflow and relativistic disk effects.

Stars are and remain the preferred (?) probes making use of NIR adaptive optics and interferometric measurements.

It is, however, unclear if there are any perturbing effects that may even further complicate the usage of stars for these high precision measurements.
Newtonian and relativistic periastron shift for S2

Newtonian:
retrograde shift $\Delta \phi$

$\rho = \text{const}$

Relativistic:
prograde shift $\Delta \phi$

\[(\Delta \omega)_M = -2\pi G_M(e, \gamma) \sqrt{1 - e^2} \left[ \frac{M_*(r < a)}{M_*} \right] \]

\[G_M = \left(1 + \sqrt{1 - e^2}\right)^{-1} \approx 0.68 \text{ for S2} \]

\[(\Delta \omega)_M \approx -1.0' \left[ \frac{M_*(r < a)}{10^3 M_\odot} \right] \]

\[(\Delta \omega)_{GR} = \frac{6\pi G M_*}{c^2 a(1 - e^2)} \]

\[a = 5.0 \text{ mpc}, \ e = 0.88 \text{ for S2} \]

\[(\Delta \omega)_{GR} \approx 10.8' \]

Several stars are needed to disentangle the two effects.

Rubilar & Eckart 2002
Zucker + 2006;
Gillessen+ 2009;
Sabha + 2012
The high-velocity Galactic Center Stars are important probes for relativistic effects.

Average orbital distance:

$$\langle d \rangle = a(1 + e^2 / 2)$$

Ratio to gravitational radius:

$$\rho = \frac{\langle d \rangle}{r_g} \quad r_g = \frac{GM}{c^2}$$

$$\frac{\rho_{\text{Mercury}}}{\rho_{S_2}} \approx 1200$$
Observed redshift as a function of the 3 dimensional velocity $\beta$

$z = \Delta \lambda / \lambda = B_0 + B_1 \beta + B_2 \beta^2 + O(\beta^3)$

offset; Doppler; rel. effects

Zucker+ 2006, Gillesen+ 2009
Observed redshift as a function of the 3 dimensional velocity $\beta$

$$z = \Delta \lambda / \lambda = B_0 + B_1 \beta + \boxed{B_2 \beta^2} + O(\beta^3)$$

$$B_2 = B_{2,D} + B_{2,G} = \frac{1}{2} + \frac{1}{2}$$

$B_{2,G}$ : gravitational redshift effect

$$z_G \equiv r_s / 4a + \frac{1}{2} \beta^2 = B_{0,G} + B_{2,G} \beta^2$$

$B_{2,D}$ : special relativistic transverse Doppler effect

$$z_D \equiv (1 + \beta \cos \vartheta)(1 - \beta^2)^{-1/2} - 1$$

$$z_D \equiv z_{\text{Newton}} + z_{\text{transverse}} = \beta \cos \vartheta + \frac{\beta^2}{2} = B_1 \beta + B_{2,D} \beta^2$$

Zucker et al. 2006
$O(\beta^2)$ – effects should be observable with today’s instrumentation:

$$(B_{2,D} + B_{2,G})\beta^2_P \sim 10^{-3} > \frac{\delta \lambda}{\lambda} \sim 10^{-4}$$

$$\beta_P \sim \frac{v_{\text{Peri}}}{c}$$

Contribution of the $O(\beta^2)$ – effects

full relativistic radial velocity of S2 near periaps

S2  e=0.88, r = 1500 rs
S14 e=0.94  r = 1400 rs
Progress expected in determining relativistic effects

For Schwarzschild, Kerr, quadrupol and non-luminous matter contributions see also Iorio 2011, MNRAS
Progress in measuring the orbits

\[ T_{\text{orbit}} = 15.6 \pm 0.4 \text{ yrs} \]
\[ e = 0.883 \pm 0.003 \]
\[ a = 0.125 \pm 0.002 \]

\[ R_0 = 8.28 \pm 0.15_{\text{stat}} \pm 0.29_{\text{sys}} \text{ kpc} \]
\[ M_{\text{MBH}} = 4.30 \pm 0.20_{\text{stat}} \pm 0.30_{\text{sys}} \times 10^6 M_\odot \]

Gillessen+ 2009
Shortest known period star with 11.5 years available to resolve degeneracies in the parameters describing the central gravitational potential (e=0.68) (Meyer et al. 2012 Sci 338, 84),
Relativity and evolution of S-star orbits

\[ T_{\text{orbit}} = 11.5 \pm 0.3 \text{ yrs} \]
\[ e = 0.68 \pm 0.02 \]
\[ a = 0.10 \pm 0.01 \]

\[ T_{\text{orbit}} = 15.6 \pm 0.4 \text{ yrs} \]
\[ e = 0.883 \pm 0.003 \]
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Orbits above (smaller \( e \)) the Schwarzschild line are subject to resonant relaxation and undergo a random walk in \( e \). For stars below that curve the orbital torques of stars with smaller semi-major axis \( a \) compete with the SMBH torque (along dash-dotted curves with different spin \( c \)).

Staubquellen im galaktischen Zentrum

- Der Fall IRS13N
  fortlaufende Sternentstehung im GC?
- Das staubige S-cluster Objekt (DSO)
- Ausfluß und Akkretion
Proper Motions of Dusty Sources within 2” of SgrA*
Zooming in – towards IRS 13N

500mas
23 light days
HKL-colors of sources in the IRS13N complex

Eckart et al. 2003

$L = 10^2 - 10^4 \ L_{\text{sol}}$

$M = 2 - 8 \ M_{\text{sol}}$

Low luminosity bow shock sources.

Are the IRS 13N sources at the GC Herbig Ae/Be stars?
Proper Motions in IRS13N

K-band proper motion from red to blue

Eckart et al. 2003, 2012
Muzic et al. 2009
Proper Motions in IRS13N

K- and L-band positions and proper motions agree. K-band emission likely to be photospheric e.i. from stars rather than from dust.

Eckart et al. 2003, 2012
Muzic et al. 2009
1. Modeling Approach

100 Msun molecular clump, 0.2 pc radius,
Test with 10 & 50 Kelvin, isothermal gas

Timescales:
clump free fall time $\sim 10^5$ yr
CND orbital period $\sim 10^5$ yr

Semi-major axis=1.8 pc $\rightarrow$ orbital period $\sim 10^5$ yr,

two Orbits:
peri-center$\sim 0.1$ pc $\rightarrow$ ecc.= 0.95
peri-center$\sim 0.9$ pc $\rightarrow$ ecc.= 0.5

Jalali+2013 in prep.
The Galactic Center is a unique laboratory in which one can study signatures of strong gravity with GRAVITY.

NL leads Euro-Team
University of Cologne
studies for METIS @ E-ELT

MPE, MPIA, Paris, SIM
University of Cologne
participation
GRAVITY @ VLTI

NIR Beam Combiner:
University of Cologne
MPIA, Heidelberg
Osservatorio Astrofisico di Arcetri
MPIfR Bonn

Cologne
collection to
MIRI on JWST
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Eisenhauer et al. 2005
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The stellar BH density is expected to be largest at a radius of a few 0.1 pc.
The Effect of Resonant Relaxation

\[ \frac{|\Delta L|}{L_c} \approx K \sqrt{N} \frac{m}{M_*} \frac{\Delta t}{P} \]

change of torque due to field stars

Changes in \( L \) over \( \Delta t \) imply changes in \( e \) and orbital plane angles:

\[ L_c = \sqrt{GM_*a} \]

Equivalent angular momentum of test star on circular orbit

\[ \cos(\Delta \theta) = \frac{L_1 \cdot L_2}{L_1 L_2} \]

Resonant relaxation:

Rauch & Tremaine 1996
Hopeman & Alexander 2006
Merritt et al. 2010

\[ |\Delta e|_{RR} \approx K_e \sqrt{N} \frac{m}{M_*}, \]

\[ (\Delta \theta)_{RR} \approx 2\pi K_t \sqrt{N} \frac{m}{M_*} \]

Two stellar populations
Species 1 smooth
Species 2 perturbing

\[ (\Delta \theta)_{RR} = K_t \left[ \frac{m_1 \sqrt{N_1} + m_2 \sqrt{N_2}}{M_*} \right] \]

Sabha, Eckart, Merritt et al. 2012
Average values of the changes in $\Delta \omega$, $\Delta \theta$, $\Delta e$ and for S2 over one orbital period (~16 yr) in the N-body integrations.

Filled circles are from integrations with $m = 50 M_\odot$ and open circles are for $m = 10 M_\odot$; number of field stars $N = \{25, 50, 100, 200\}$ for both $m$. The abscissa is the distributed mass within S2’s apo-apsis, at $r = 9.4$ mpc. In each frame, the points are median values from the 100 N-body integrations.

(a) Changes in the argument of peri-bothron. The contribution from relativity has been subtracted.
(b) Changes in the eccentricity. Solid and dashed lines are with $m = 50 M_\odot$ and $m = 10 M_\odot$, respectively.
(c) The angle between initial and final values of $L$ i.e. $\Delta \theta$ for S2.

Sabha et al. 2012
The shift due to relativity (~11′), has been subtracted. What remains is due to Newtonian perturbations (peri-bothron shift and perturbation/scattering) from the field stars.

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\[ |\Delta e|_{RR} \approx 5.4 \times 10^{-4} \]
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Significant contributions to perisatron shift \( \Delta \omega \) from encounters due to granularity of ‘scattering’ population \( \Delta \theta \):

\[ \propto \sqrt{N_2} \]

and variation in enclosed mass due to scattering population:

\[ \propto \sqrt{N_2} \]
The variance in $S_2$ for one orbital period (~16 yr) in the N-body integrations.

Relative variance of peri-center shift as the absolute variance over the shift itself.

The absolute variance is large and of the order of the entire peri-center shift.
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- Granularity of scatterers
- Search for stellar probes
Subtraction of stars within $R < 0.7''$

S<1mJy in the NIR K-band

Sabha et al. 2010
Map of the 51 brightest stars close to SgrA*. The color of each star indicates its K-magnitude. The size of each symbol is proportional to the flux of the corresponding star. The position of Sgr A* is indicated as a cross at the center.
The Central S-star Cluster

luminosity function $\exp(-\Gamma)$

radial distribution $\exp(-\alpha)$

Sabha et al. 2011, 2012
Extrapolation of the KLF power-law fit. The KLF slope of $\alpha = 0.18$ and the upper limit imposed by the uncertainty in the fit ($\alpha = 0.25$) are plotted as dashed and dash-dotted lines, respectively. The black filled circles represent the data while the hollow circles represent new points based on the extrapolated KLF. The location of the detection limit is indicated by the red line. All stars fainter than the faintest stars detected in the central arcsecond.

Extrapolation of the KLF power-law fit. The KLF slope of $\alpha = 0.18$ and the upper limit imposed by the uncertainty in the fit ($\alpha = 0.25$) are plotted as dashed and dash-dotted lines, respectively. The black filled circles represent the data while the hollow circles represent new points based on the extrapolated KLF. The location of the detection limit is indicated by the red line.

Sabha et al. 2012
Upper panel: 3 different snapshots of the simulation for the $\alpha = 0.25$ KLF slope, power-law index $\Gamma = -0.3$ and a $\sim25$ K-magnitude cutoff.

Lower panel: The same as upper but with only the detectable blend stars visible.

Right: Average of all the 104 simulation snapshots for the same setup.

INTERFEROMETRY IS NEEDED to make progress!

Sabha et al. 2012
SgrA* and its Environment

Orbits of High Velocity Stars in the Central Arcsecond

Eckart & Genzel 1996/1997 (first proper motions)
Eckart et al. 2002 (S2 is bound; first elements)
Schödel et al. 2002, 2003 (first detailed elements)
Ghez et al. 2003 (detailed elements)
Eisenhauer 2005, Gillessen et al. 2009 (improved elements on more stars and distance)

~4 million solar masses at a distance of ~8.3+-0.3 kpc
Progress expected in determining relativistic effects

Possible hot spots orbiting SgrA* the detection of strongly relativistic effects is complicated by processes in the accretion stream/outflow and relativistic disk effects.

Stars are and remain the preferred (?) probes making use of NIR adaptive optics and interferometric measurements.

It is, however, unclear if there are any perturbing effects that may even further complicate the usage of stars for these high precision measurements.
Newtonian and relativistic periastron shift for S2

Newtonian:
retrograde shift $\Delta \phi$

Relativistic:
prograde shift $\Delta \phi$

\[(\Delta \omega)_M = -2\pi G_M(e, \gamma) \sqrt{1 - e^2} \left[ \frac{M_*(r < a)}{M_*} \right] \]

\[G_M = \left(1 + \sqrt{1 - e^2}\right)^{-1} \approx 0.68 \text{ for S2} \]

\[(\Delta \omega)_M \approx -1.0' \left[ \frac{M_*(r < a)}{10^3 M_\odot} \right] \]

\[(\Delta \omega)_{GR} = \frac{6\pi GM_*}{c^2 a(1 - e^2)} \]

\[a = 5.0 \text{ mpc, } e = 0.88 \text{ for S2} \]

Rubilar & Eckart 2002
Zucker + 2006;
Gillessen+ 2009;
Sabha + 2012

Several stars are needed to disantangle the two effects.
The high-velocity Galactic Center Stars are important probes for relativistic effects.

Average orbital distance:

\[ \langle d \rangle = a \left( 1 + \frac{e^2}{2} \right) \]

Ratio to gravitational radius:

\[ \rho = \frac{\langle d \rangle}{r_g} \quad r_g = \frac{GM}{c^2} \]

\[ \frac{\rho_{\text{Mercury}}}{\rho_{S2}} \approx 1200 \]
Observed redshift as a function of the 3 dimensional velocity $\beta$

$z = \Delta\lambda / \lambda = B_0 + B_1 \beta + B_2 \beta^2 + O(\beta^3)$

offset; Doppler; rel. effects
Observed redshift as a function of the 3 dimensional velocity $\beta$

$$z = \Delta \lambda / \lambda = B_0 + B_1 \beta + \boxed{B_2 \beta^2} + O(\beta^3)$$

$$B_2 = B_{2,D} + B_{2,G} = \frac{1}{2} + \frac{1}{2}$$

$B_{2,G}$ : gravitational redshift effect

$$z_G \equiv r_s / 4a + \frac{1}{2} \beta^2 = B_{0,G} + B_{2,G} \beta^2$$

$B_{2,D}$ : special relativistic transverse Doppler effect

$$z_D \equiv (1 + \beta \cos \vartheta)(1 - \beta^2)^{-1/2} - 1$$

$$z_D \equiv z_{\text{Newton}} + z_{\text{transverse}} = \beta \cos \vartheta + \beta^2 / 2 = B_1 \beta + B_{2,D} \beta^2$$

Zucker et al. 2006
$O(\beta^2)$ – effects should be observable with today’s instrumentation:

$$(B_{2,D} + B_{2,G})\beta_P^2 \sim 10^{-3} > \frac{\delta \lambda}{\lambda} \sim 10^{-4}$$

\[ \beta_P \sim \frac{v_{\text{peri}}}{c} \]

Contribution of the $O(\beta^2)$ – effects

full relativistic radial velocity of S2 near periaps

S2  $e=0.88$, $r = 1500$ rs
S14 $e=0.94$  $r = 1400$ rs

Zucker et al. 2006
Progress expected in determining relativistic effects

For Schwarzschild, Kerr, quadrupol and non-luminous matter contributions see also Iorio 2011, MNRAS
Progress in measuring the orbits

$T_{\text{orbit}} = 15.6 \pm 0.4 \text{ yrs}$

$e = 0.883 \pm 0.003$

$a = 0.125 \pm 0.002$

$R_0 = 8.28 \pm 0.15|_{\text{stat}} \pm 0.29|_{\text{sys}} \text{ kpc}$

$M_{\text{MBH}} = 4.30 \pm 0.20|_{\text{stat}} \pm 0.30|_{\text{sys}} \times 10^6 M_\odot$

Gillessen+ 2009
Shortest known period star with 11.5 years available to resolve degeneracies in the parameters describing the central gravitational potential ($e=0.68$) (Meyer et al. 2012 Sci 338, 84),
Orbits above (smaller $e$) the Schwarzschild line are subject to resonant relaxation and undergo a random walk in $e$. For stars below that curve the orbital torques of stars with smaller semi-major axis $a$ compete with the SMBH torque (along dash-dotted curves with different spin $c$).

Staubquellen im galaktischen Zentrum

- Der Fall IRS13N 
  fortlaufende Sternentstehung im GC?
- Das staubige S-cluster Objekt (DSO)
- Ausfluß und Akkretion
Proper Motions of Dusty Sources within 2” of SgrA* 

Eckart et al. 2012
Zooming in – towards IRS 13N

500mas
23 light days
HKL-colors of sources in the IRS13N complex

L = $10^2 - 10^4$ $L_{\text{sol}}$

M = 2-8 $M_{\text{sol}}$

Low luminosity bow shock sources.

Are the IRS 13N sources at the GC Herbig Ae/Be stars?
Proper Motions in IRS13N

K-band proper motion from red to blue

Eckart et al. 2003, 2012
Muzic et al. 2009
Proper Motions in IRS13N

K- and L-band positions and proper motions agree. K-band emission likely to be photospheric e.i. from stars rather than from dust.

Eckart et al. 2003, 2012
Muzic et al. 2009
1. Modeling Approach

100 Msun molecular clump, 0.2 pc radius,

Test with 10 & 50 Kelvin, isothermal gas

Timescales:
- Clump free fall time $\sim 10^5$ yr
- CND orbital period $\sim 10^5$ yr

Semi-major axis=1.8 pc $\rightarrow$ orbital period $\sim 10^5$ yr,

two Orbits:
- Peri-center $\sim 0.1$ pc $\rightarrow$ ecc. = 0.95
- Peri-center $\sim 0.9$ pc $\rightarrow$ ecc. = 0.5

Jalali+2013 in prep.
The Galactic Center is a unique laboratory in which one can study signatures of strong gravity with GRAVITY.