



Orbit of S4716

SEMINARIUM ASTROFIZYCZNE// Jagiellonian University

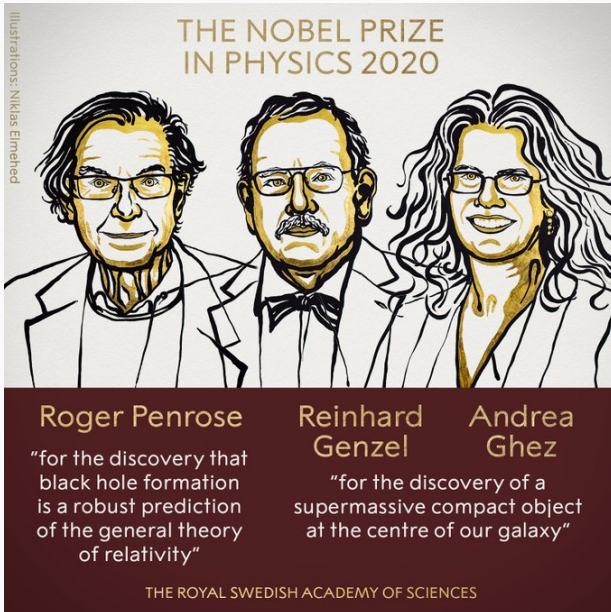
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Masaryk University

Previously CFT PAN (Warsaw), University of Cologne & MPIfR

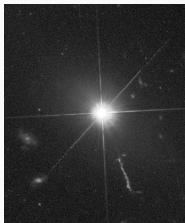
May 24, 2023

Nobel Prize in Physics 2020



What is at the center of galaxies?

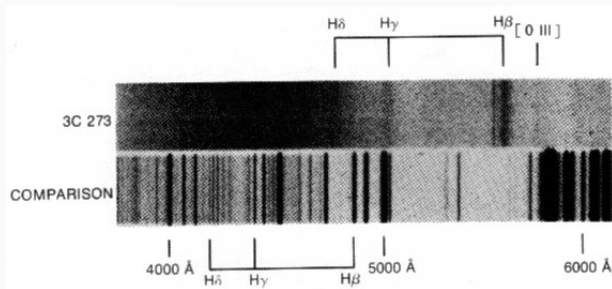
- 1950s: discovery of many radio sources on the sky (WWII radar technique)
- Thomas Matthews and Allan Sandage in 1960 found an optical counterpart with broad lines to the radio source 3C48 → “The thing was exceedingly weird”
- another source 3C273 showed similar spectrum
- point-like, star-like sources: **quasi-stellar radio sources or quasars**



Courtesy of NASA HST and J. Bahcall

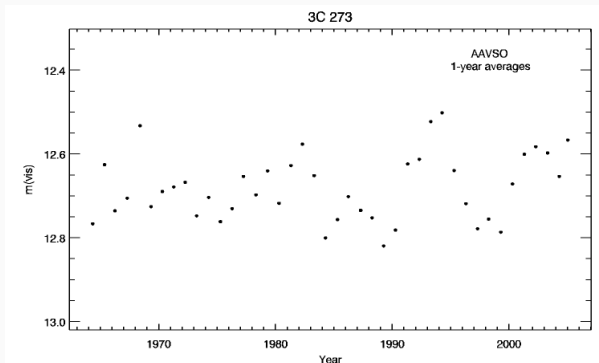
What is at the center of galaxies?

- in 1963 Maarten Schmidt identified redshifted Balmer hydrogen lines in the spectrum of 3C273
- distant source at the distance of $\sim 760 \text{ Mpc} \simeq 2.3 \times 10^{27} \text{ cm}$
- total electromagnetic (bolometric) output of $10^{46} \text{ erg s}^{-1} \sim 10^2 \times 10^{11} L_{\odot}$



Optical spectrum of 3C273 with redshifted Balmer lines of hydrogen

What is at the center of galaxies?



- total electromagnetic (bolometric) output of $10^{46} \text{ erg s}^{-1} \sim 10^{13} L_{\odot}$
- short variability within a month $\rightarrow$ compact size on a scale of a light month, $R \lesssim c\delta t \approx 10^{17} \text{ cm} \sim 0.1 \text{ pc}$ (Sharov & Efremov 1963; Smith & Hoffleit 1963)

Black holes on the scene

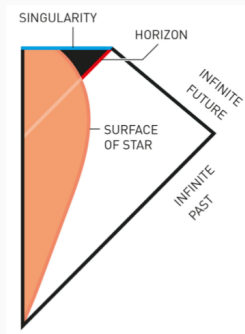
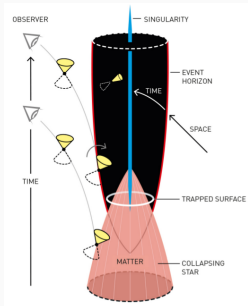
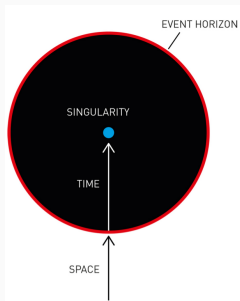
- **1st Texas Symposium on Relativistic Astrophysics** in December 1963 in Dallas
- “black holes” proposed as an explanation for quasar huge luminosity and compactness
- other theoretical advances: Roy Kerr presents the solution of EFEs for a rotating black hole in 1963, in 1965 Kerr-Newman solution is presented as the most general, asymptotically-flat stationary solution to Einstein-Maxwell equations



Black holes on the scene – gravitational collapse

Contribution of **Roger Penrose**

- Oppenheimer & Snyder (1939) studied spherical collapse into a singularity
- Can asymmetry prevent a collapse into a singularity? Or quantum effects? **Einstein** himself disputed about it; Einstein (1939)
- **Roger Penrose (1963, 1965, 1969): Universality of a collapse into a singularity** once a **trapped surface** is formed - no symmetry is needed!!!



Black hole in quasars

- 3C273 as an extragalactic source → accretion of matter onto supermassive black holes (Salpeter 1964; Zeldovich & Novikov 1965)
- objects at the centers must be very **compact** and **massive**; observed luminosities of 10^{46} – 10^{47} erg s⁻¹
- Eddington limit
$$L_{\text{Edd}} = 4\pi GM_{\bullet} m_p c / \sigma_T = 1.3 \times 10^{38} (M_{\bullet} / M_{\odot}) \text{ erg s}^{-1},$$
 $M_{\bullet}$ for quasars must be of the order $10^7 M_{\odot}$ – $10^9 M_{\odot}$ to achieve balance between radiative force and gravitational pull
- **Donald Lynden-Bell** (1935-2018) proposed in 1969 that most galaxies host a supermassive black hole **“Galactic Nuclei as Collapsed Old Quasars”**

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NATURE, VOL. 223, AUGUST 16, 1969

Galactic Nuclei as Collapsed Old Quasars

by

D. LYNDEN-BELL

Royal Greenwich Observatory,
Herstmonceux Castle, Sussex

Powerful emissions from the centres of nearby galaxies may represent dead quasars.

Black hole in the Galactic Center

Donald Lynden-Bell (1935-2018) and **Martin Rees** (1942-) made fundamental theoretical predictions for the existence of the supermassive black hole in the Galactic Center in 1971



Black hole in the Galactic Center

Donald Lynden-Bell (1935-2018) and **Martin Rees** (1942-) made fundamental theoretical predictions for the existence of the supermassive black hole in the Galactic Center in 1971

Proposed observational tests:

- broad emission lines
- very long baseline interferometry
- infrared observations/variability

A “proof” of the black hole existence in the Galactic center involves the determination of the gravitational field/space-time metric components $g_{\mu\nu}$ down to the scale of the event horizon.

ON QUASARS, DUST AND THE GALACTIC CENTRE

D. Lynden-Bell and M. J. Rees

(Received 1971 January 5)

Observations of the Galactic center



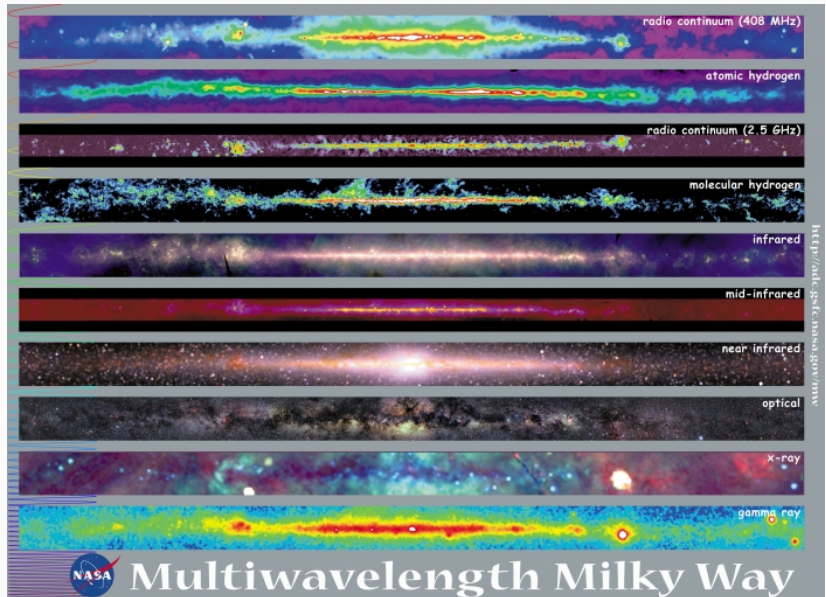
Courtesy of Yuri Beletsky (Paranal, Chile, 2007)

Observations of the Galactic center - minimizing extinction

- Intense scattering and absorption by dust (=extinction) at visible and UV wavelengths (1-700 nm)
- at visible wavelengths the absorption reaches $A_V \sim 30$ magnitudes (12 orders of magnitude drop in visible flux)
- It is necessary to observe at **longer (infrared, radio)** or **shorter wavelengths (X-ray)**



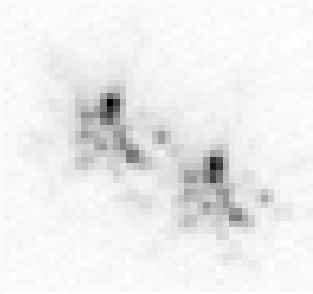
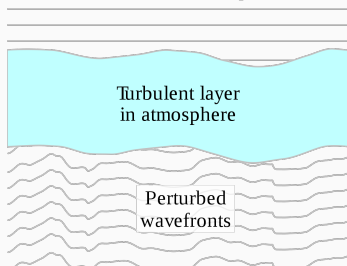
Observations of the Galactic center - minimizing extinction



Observations of the Galactic center - high angular resolution

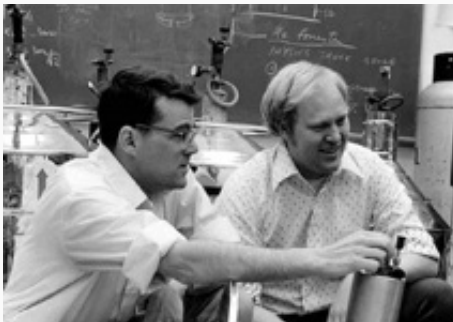
- to resolve objects on the scale of the Solar System (100 AU), angular resolution of $\theta \sim 100\text{AU}/26000\text{ly} \sim 0.01''$ is needed
- event horizon scales $R_s = 2GM_\bullet/c^2 \rightarrow \theta \sim 2R_s/D \sim 20\mu\text{as}$
- standard telescope resolution limited to 1-2 arcseconds because of atmospheric turbulence (seeing) – best seeing disc diameter of $0.4''$ (Maunua Kea, Atacama, La Palma)
- **Goal:** Achieve the diffraction limit (Airy disc size):
 $\theta_{\text{diff}} \sim \lambda/D_{\text{mirror}} \approx 2.2\mu\text{m}/10\text{m} \sim 0.05''$

Plane waves from distant point source



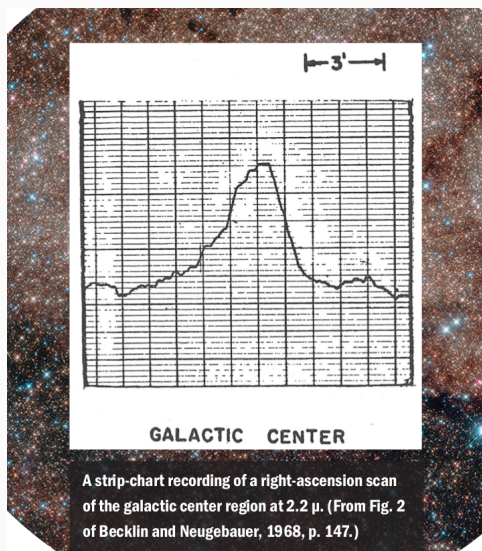
First infrared observations of the Galactic center

- PhD student Eric Becklin and Professor Gerry Neugebauer (1968) at Caltech
- before: vague understanding of the Galactic Center (dynamical center of the Milky Way) in the Sagittarius constellation
- strong radio emission from Sagittarius A complex (first radio observation by Karl Jansky in August 1931)
- Becklin & Neugebauer used a military infrared photometer mounted at 24-inch Mt. Wilson telescope



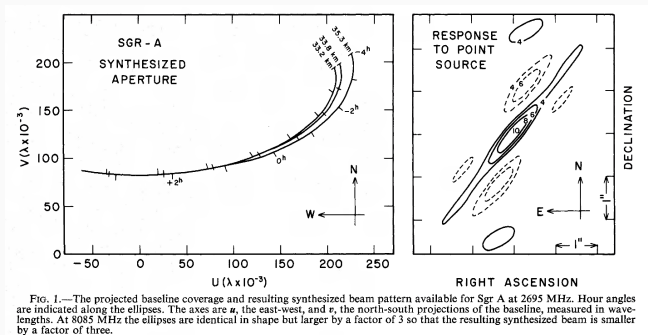
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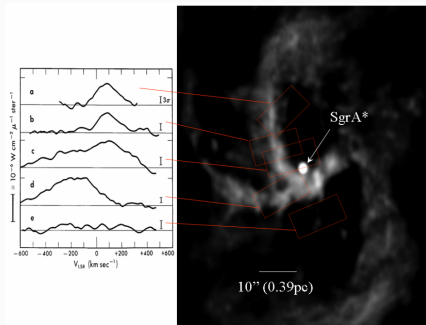
First detection of compact source Sgr A*

- Bruce Balick and Robert L. Brown discovered compact radio emission in Sgr A complex in February 1974
- baseline interferometer Green Bank – Huntersville, WV (35-km baseline)
- bright source of $\sim 0.5 Jy$ ($1 Jy = 10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$) with the high brightness temperature of $\gtrsim 10^7 \text{ K}$ (unresolved $\theta \lesssim 0.1''$)



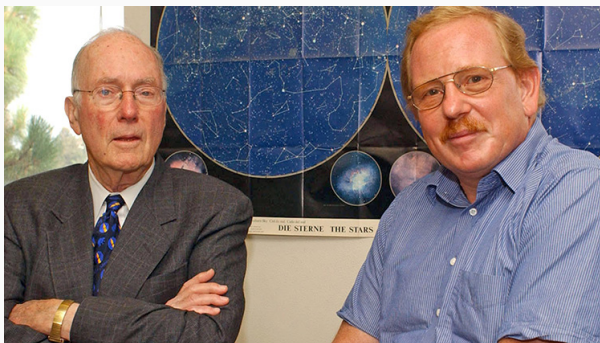
Motion of bodies around Sgr A* – Gas clouds

- a group led by **Charles H. Townes** (Nobel Prize in 1964 shared with Basov and Prokhorov) at the University of California, Berkeley
- Doppler shift of $12.8\ \mu\text{m}$ line of [NeII] $\rightarrow$ central mass of 2-4 million Solar masses in the central parsec
- potential association with compact radio source Sgr A* $\rightarrow$ supermassive black hole (Wollman et al. 1977; Lacy et al. 1980; Lacy, Townes & Hollenbach 1982)

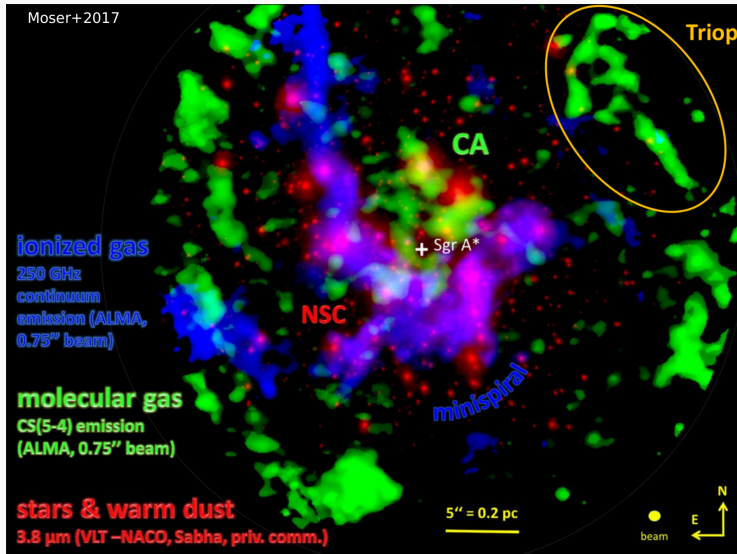


Motion of bodies around Sgr A* – Gas clouds

- a group led by **Charles H. Townes** (Nobel Prize in 1964 for the invention of laser shared with Basov and Prokhorov) at the University of California, Berkeley
- Reinhard Genzel joined the group of Charlie Townes as a post-doc



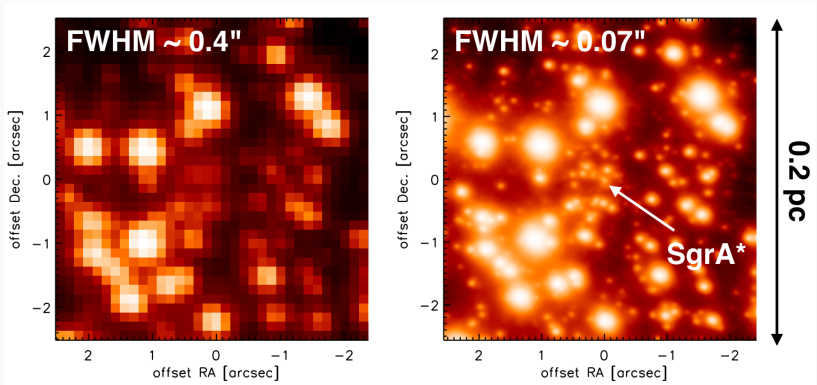
The Galactic center – a unique laboratory



- the inner 1 pc: unique laboratory – a mutual interaction of stars, gas and dust in the potential of the SMBH

Motion of bodies around Sgr A* – stars

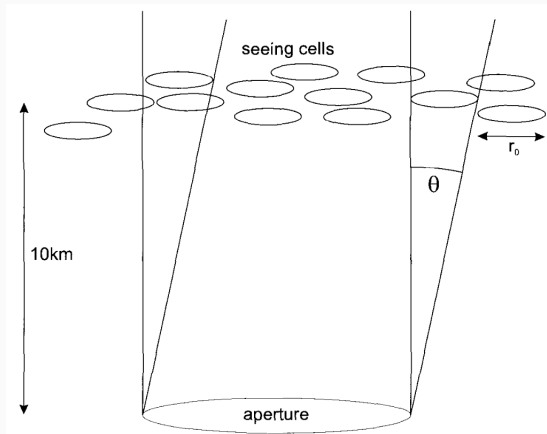
- gas is susceptible to non-gravitational forces → stars are much better and safer probes
- two basic techniques were applied to reach the diffraction-limited images of stars: **speckle interferometry** and **adaptive optics**



Motion of bodies around Sgr A* – stars

Speckle Interferometry

Towards diffraction-limited images: $A = 1.22\lambda/D$, $A_{\text{FWHM}} = 1.02\lambda/D$

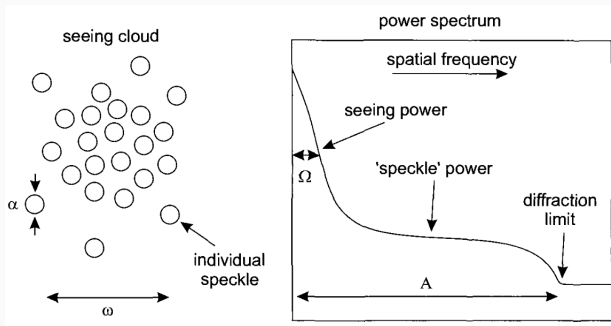


- r_0 diameter of seeing cells, Fried diameter

Motion of bodies around Sgr A* – stars

Speckle Interferometry

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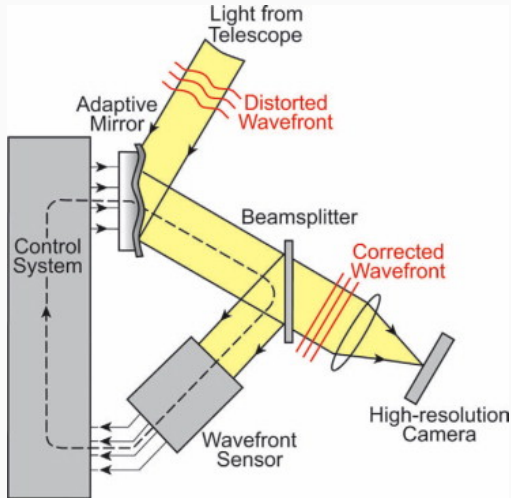


- $\omega \sim \lambda/r_0$
- $\alpha \sim \lambda/D$

Motion of bodies around Sgr A* – stars

Adaptive optics

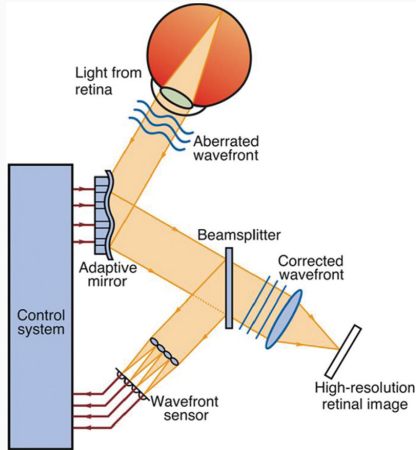
Real-time correction of atmospheric turbulence



Motion of bodies around Sgr A* – stars

Adaptive optics

Also used in the eye retina imaging



Motion of bodies around Sgr A* – stars

Very Large Telescope Interferometry – GRAVITY instrument

Resolution of $10\ \mu\text{as}$ in the interferometer mode by combining the signal from four 8-m class telescopes

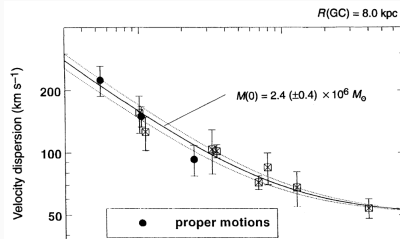
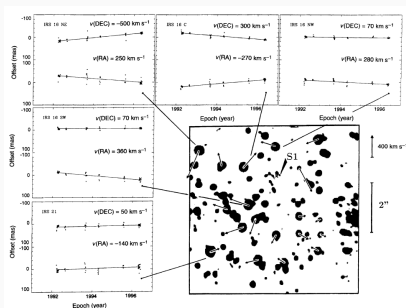


Two main Galactic center teams in competition

- one **European team led by Reinhard Genzel** in Garching/Munich (with a significant contribution by Andreas Eckart, Rainer Schoedel, Stefan Gillessen, Frank Eisenhauer and others)
- one **US team led by Andrea Ghez** at the UCLA (Mark Morris, Eric Becklin, Tuan Do...)
- later on: groups led by **Andreas Eckart (University of Cologne)** and **Rainer Schoedel (Granada)** work independently now
- **European teams** use mostly **ESO/VLT data from Chile**
- **US team** uses **Keck Telescopes on Hawaii**

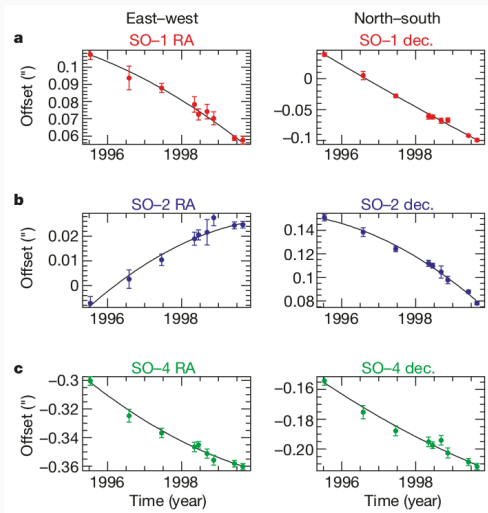
Motion of bodies around Sgr A* – stars

Stellar proper motions by Andreas Eckart and Reinhard Genzel, 1996: increasing stellar velocity dispersion



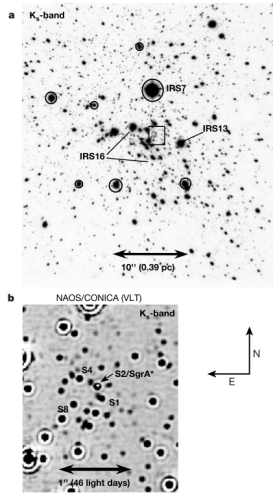
Motion of bodies around Sgr A* – stars

Measurements of accelerations of stars around Sgr A* by Andrea Ghez et al., 2000



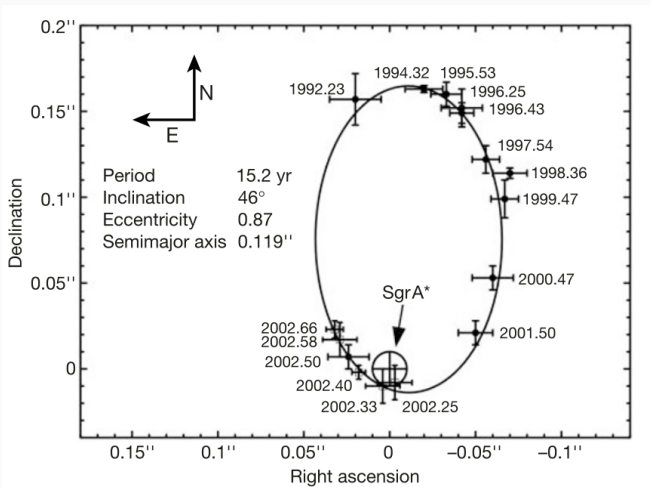
Motion of bodies around Sgr A* – stars

An S2 star in a 15.2-orbit around the supermassive black hole by
Rainer Schoedel et al., 2002



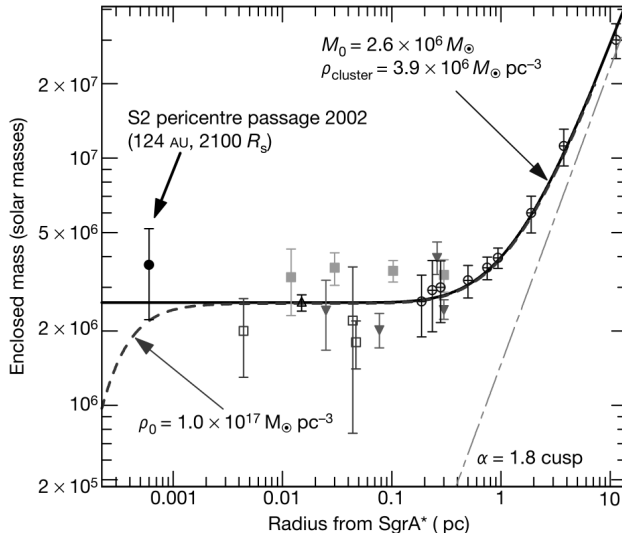
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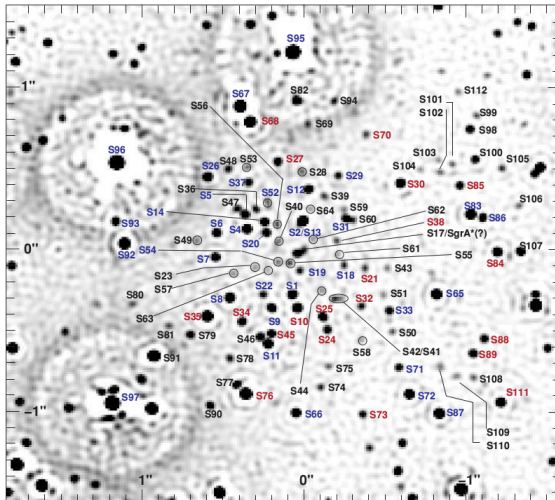
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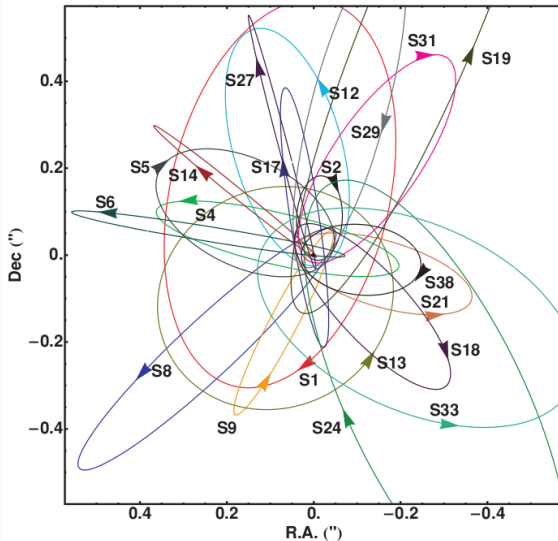
Motion of bodies around Sgr A* – stars

Determination of more orbits (28) in the inner 0.04 pc by Stefan Gillessen, 2009



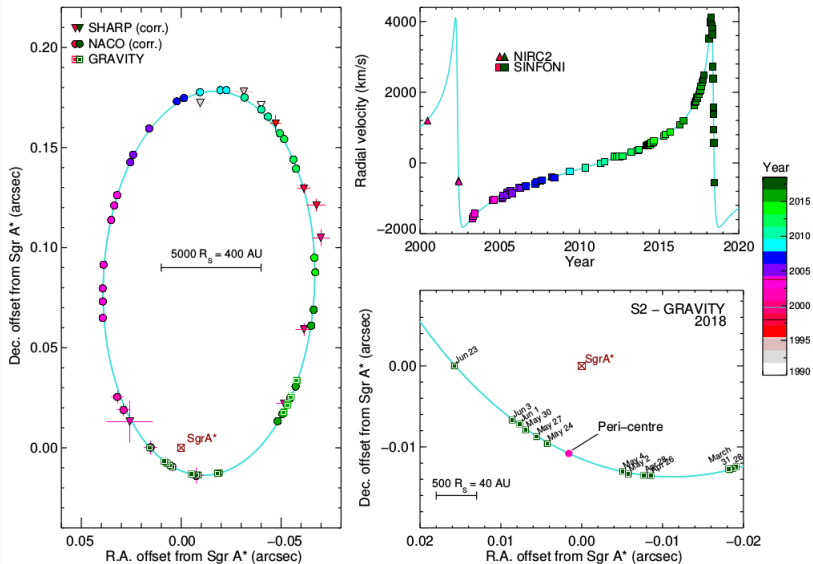
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S2 star: successful measurements by GRAVITY

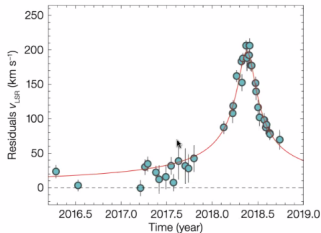
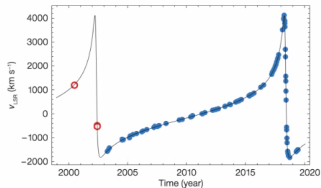
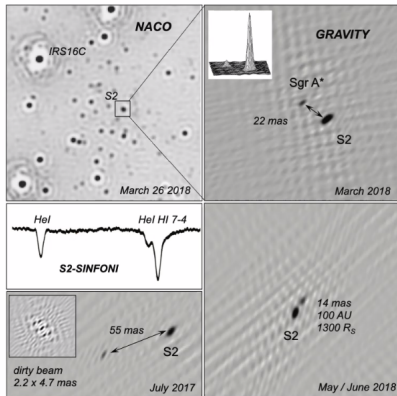
S2 orbit with the period of 16.05 years (Gravity Collaboration, 2018)



S2 star: successful measurements by GRAVITY

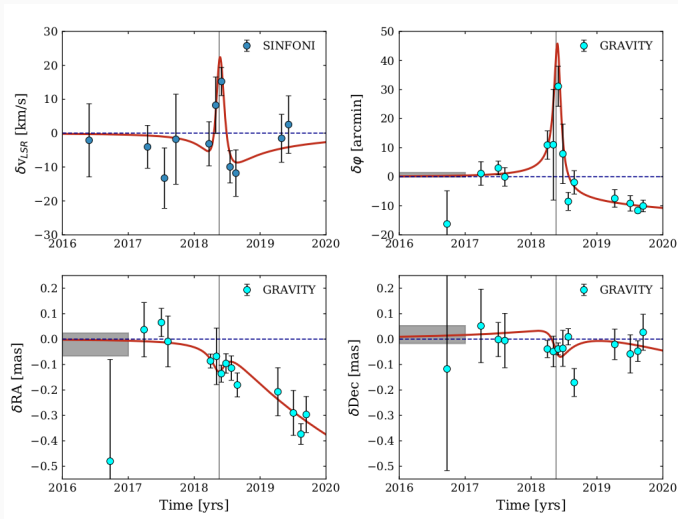
Detection of gravitational redshift (Gravity Collaboration, 2018)

Detection of gravitational redshift of spectrum of S2 A&A 615, L15



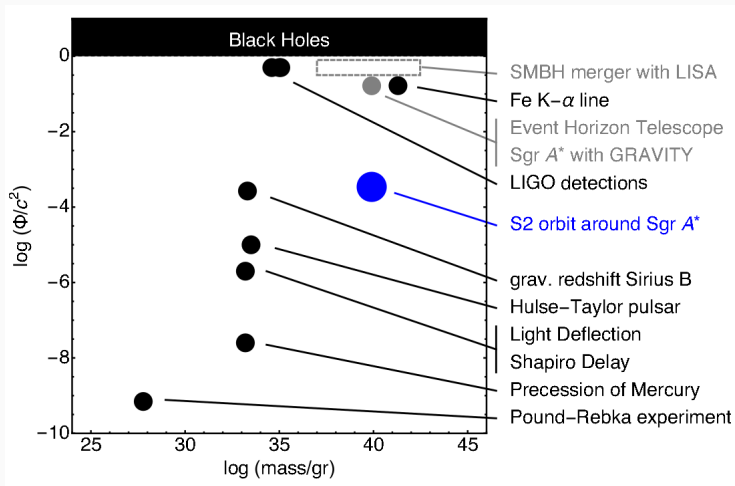
S2 star: successful measurements by GRAVITY

Detection of Schwarzschild precession (Gravity Collaboration, 2020)



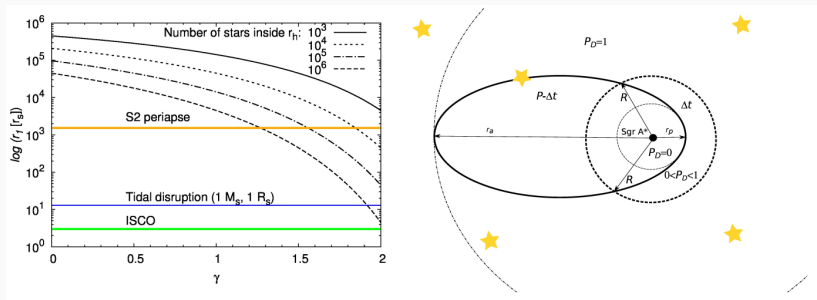
S2 star: successful measurements by GRAVITY

Comparison with other measurements (Psaltis 2004; Gravity Collaboration 2018)



Stars closer to Sgr A*

Can we find closer stars?

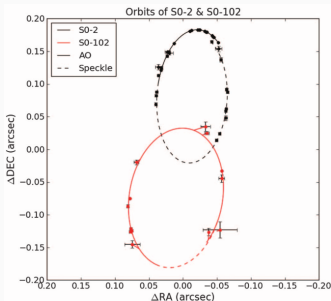
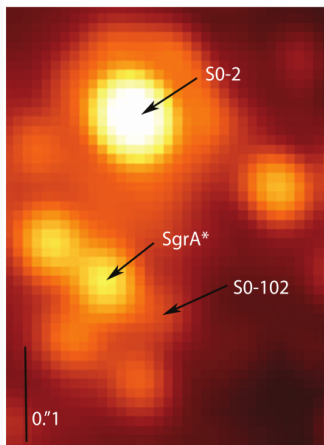


$$r_1 = r_h N_h^{-\frac{1}{3-\gamma}}.$$

Population T	C_T	γ_T	$r_{1,T}$ [pc]	$r_{1,T}$ [r_s]
MS	1	1.4	2×10^{-4}	523
WD	10^{-1}	1.4	7×10^{-4}	1831
NS	10^{-2}	1.5	2×10^{-3}	5231
BH	10^{-3}	2	6×10^{-4}	1569

More compact orbits

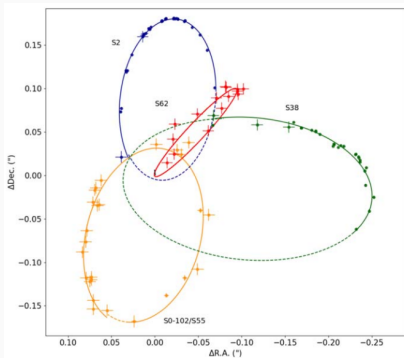
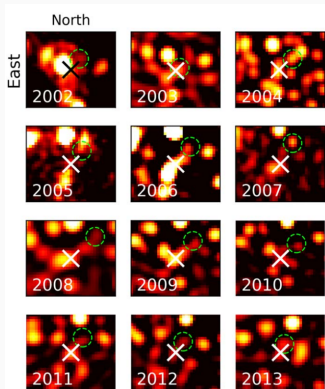
S0-102/S55 - period of 11.5 years; Meyer et al. 2012



Meyer et al. (2012)

More compact orbits - below 10 years

Below 10 years – S62 star

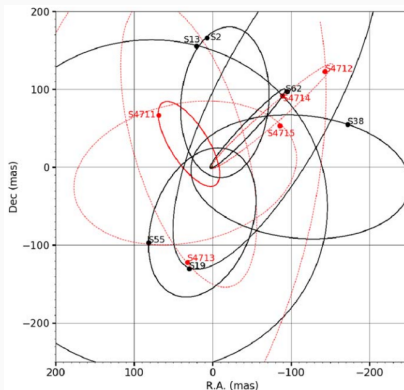
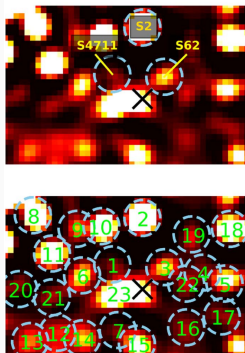


Source	a (mpc)	e	i ($^{\circ}$)	ω ($^{\circ}$)	Ω ($^{\circ}$)	t_{closest} (yr)	t_{period} (yr)
S62	3.588 ± 0.002	0.976 ± 0.002	72.76 ± 4.58	42.62 ± 0.4	122.61 ± 0.57	2003.33 ± 0.01	9.9 ± 0.02

See Peissker, Eckart, Parsa 2020

More compact orbits - below 10 years

Faint stars - S4711 - S4715 (Peisker, Eckart, Zajaček et al. 2020)



Source	a (mpc)	e	i ($^\circ$)	ω ($^\circ$)	Ω ($^\circ$)	t_{closest} (yr)	t_{period} (yr)
S62	3.588 ± 0.02	0.976 ± 0.01	72.76 ± 5.15	42.62 ± 2.29	122.61 ± 4.01	2003.33 ± 0.02	9.9 ± 0.3
S4711	3.002 ± 0.06	0.768 ± 0.030	114.71 ± 2.92	131.59 ± 3.09	20.10 ± 3.72	2010.85 ± 0.06	7.6 ± 0.3
S4712	18.038 ± 0.099	0.364 ± 0.032	117.28 ± 1.31	238.08 ± 3.43	166.38 ± 3.20	2007.12 ± 0.08	112.0 ± 2.9
S4713	8.016 ± 0.379	0.351 ± 0.059	111.07 ± 1.66	301.97 ± 8.02	195.06 ± 5.15	2000.03 ± 0.22	33.2 ± 2.5
S4714	4.079 ± 0.012	0.985 ± 0.011	127.70 ± 0.28	357.25 ± 0.80	129.28 ± 0.63	2017.29 ± 0.02	12.0 ± 0.3
S4715	5.756 ± 0.439	0.247 ± 0.040	129.80 ± 3.72	359.99 ± 5.38	282.15 ± 2.92	2008.05 ± 0.30	20.2 ± 2.4

More compact orbits - below 10 years

Faint stars - S4711 - S4715 (Peissker, Eckart, Zajaček et al. 2020)

Star	r_p (au)	r_a (au)	v_p (km s ⁻¹) (% of c)	Γ (10 ⁻⁴)	$z_{gr}c$ (km s ⁻¹)	$\delta\phi$ (arcmin)	$\dot{\Omega}_{LT}$ (arcsec yr ⁻¹)
S62	17.8 ± 7.4	1462.4 ± 11.0	20124 ± 4244 (6.7 ± 1.4)	46	685.5 ± 288.6	74.7 ± 31.0	5.1 ± 3.2
S4711	143.7 ± 18.8	1094.7 ± 28.7	6693 ± 494 (2.2 ± 0.2)	5.6	84.5 ± 11.8	10.3 ± 1.3	0.34 ± 0.07
S4712	2366 ± 120	5075 ± 122	1449 ± 54 (0.48 ± 0.02)	0.34	5.1 ± 0.4	0.81 ± 0.05	(5.1 ± 0.5) × 10 ⁻⁴
S4713	1073 ± 110	2234 ± 144	2141 ± 153 (0.71 ± 0.05)	0.75	11.3 ± 1.3	1.8 ± 0.1	(5.8 ± 1.1) × 10 ⁻³
S4714	12.6 ± 9.3	1670 ± 10	23928 ± 8840 (8 ± 3)	64	966.1 ± 713.5	104.6 ± 76.3	7.0 ± 7.6
S4715	894 ± 83	1480 ± 122	2253 ± 129 (0.75 ± 0.04)	0.90	13.6 ± 1.4	2.4 ± 0.2	(1.4 ± 0.4) × 10 ⁻²
S2	119.3 ± 0.3	1949.9 ± 2.8	7582 ± 8 (2.527 ± 0.003)	6.8	101.7 ± 5.0	11.7 ± 0.6	0.19 ± 0.02

Relativistic parameter: $\Gamma = \frac{2GM_{\bullet}}{c^2 r_p}$

Schwarzschild precession: $\delta\phi = \frac{6\pi GM_{\bullet}}{c^2 a(1-e^2)}$

Lense-Thirring precession: $\dot{\Omega}_{LT} = \frac{2G^2 M_{\bullet}^2 \chi}{c^3 a^3 (1-e^2)^{3/2}}$

Gravitational redshift: $z_c = c \left[\left(1 - \frac{r_s}{r}\right)^{-1/2} - 1 \right]$

More compact orbits - below 10 years

Faint stars - S4711 - S4715 (Peissker, Eckart, Zajaček et al. 2020)

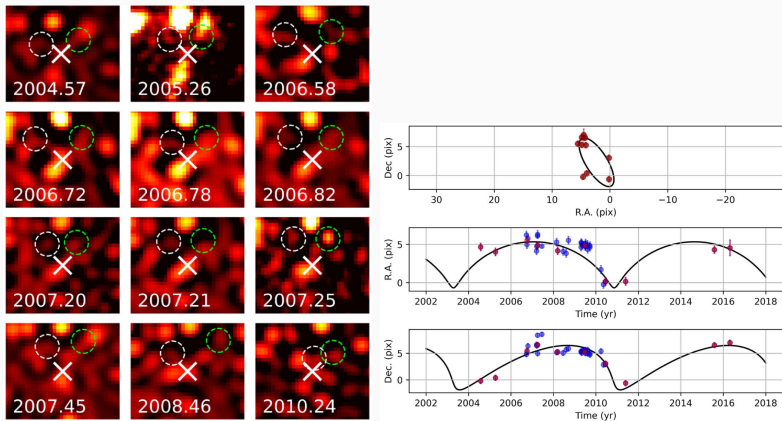
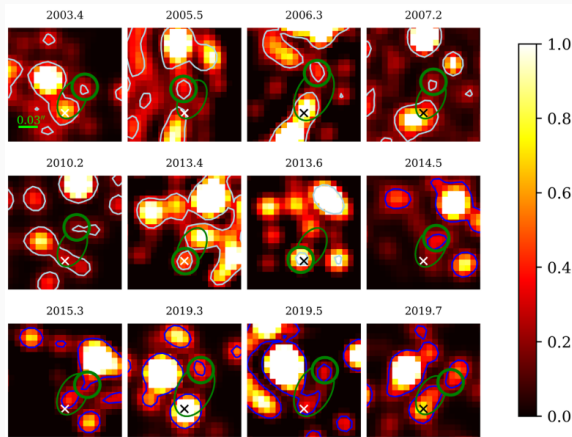


Figure 1: S62-green and S4711 - white

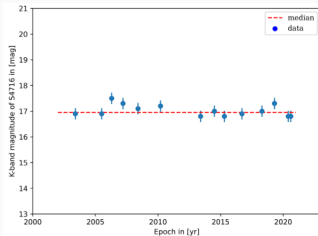
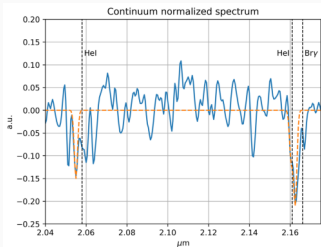
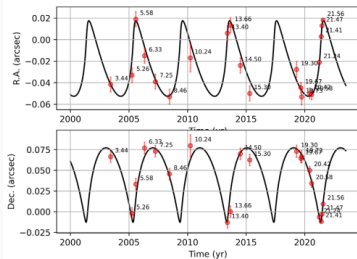
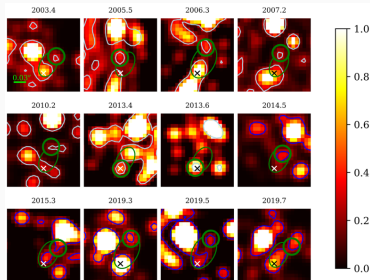
More compact orbits - below 5 years

S4716 (Peissker, Eckart, Zajaček et al. 2022)



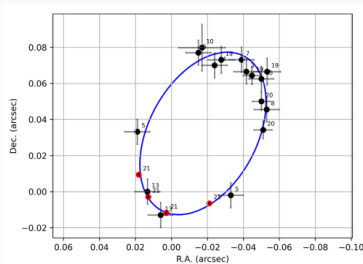
More compact orbits - below 5 years

S4716 (Peissker, Eckart, Zajaček et al. 2022)



More compact orbits - below 5 years

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Orbital Elements of S2 and S4716

Source	a (Mpc)	e	i (deg)	ω (deg)	Ω (deg)	t_{closest} (yr)
S2	5.09 ± 0.01	0.886 ± 0.002	133.49 ± 0.40	65.89 ± 0.75	227.46 ± 1.03	2018.37 ± 0.02
S4716 (estimated)	1.93 ± 0.02	0.756 ± 0.02	161.24 ± 2.80	0.073 ± 0.02	151.54 ± 1.54	2017.41 ± 0.004
S4716 (max. likelihood)	1.94 ± 0.02	0.756 ± 0.02	161.13 ± 2.80	2.25 ± 0.02	153.55 ± 1.54	2017.41 ± 0.004

Summary of Relativistic Parameters of S4716

Parameter	Value
Relativistic parameter Γ^*	$(8.02 \pm 0.68) \times 10^{-4}$
Schwarzschild precession $\delta\phi$ (arcmin)	14.8 ± 1.3
Max. gravitational redshift (km s^{-1})	120 ± 10
Max. transverse Doppler shift (km s^{-1})	106 ± 10
Max. combined redshift (km s^{-1})	226 ± 20
LT precession rate ($\chi = 0.5, \text{arcsec yr}^{-1}$)	1.11 ± 0.13

Summary

- with the identification of S0-102 (S55), S62 (9.9 years), S4711 (7.6 years), and S4716 (3.9 years), there are good prospects of finding shorter-period stars with periods of the order of one year and less
- these stars are rather faint, much fainter than S2 (otherwise, there would always be a bright emission at the position of Sgr A*)
- with future telescopes (ELT) and longer baselines, orbital elements will be better constrained and post-Newtonian effects confirmed
- determination of spin of Sgr A* is one of the prime goals (final confirmation of the Kerr black hole at the Galactic center)

