

The black hole in the Milky Way

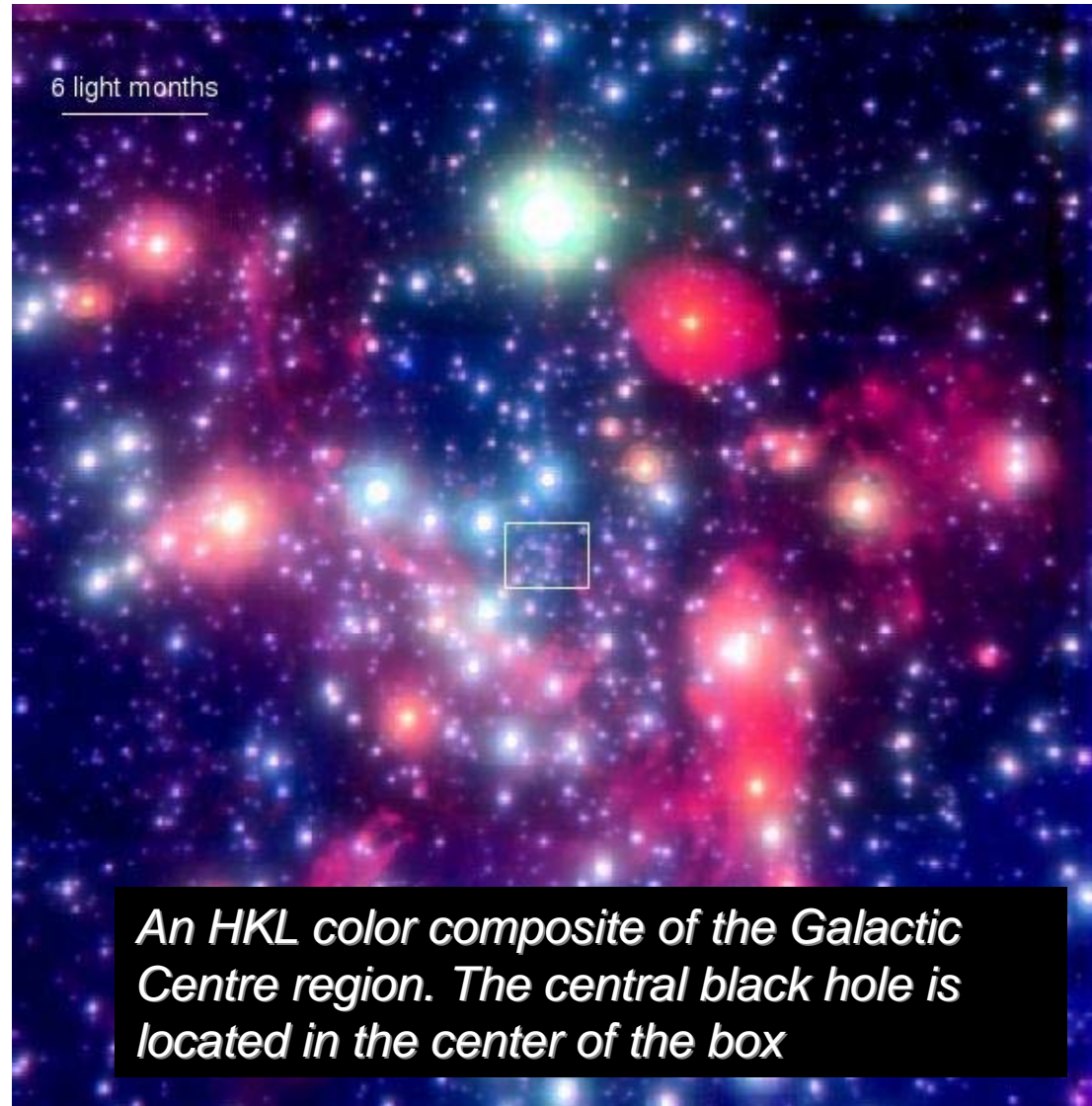
Astronomy 200

16 Feb 2005

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What can we say about *the* black hole in the Milky Way?

- Mmm... this one is probably black, too
- Location, velocity
- Mass, Spin, Charge (“no hair” theorem)
- How do we measure these?



An HKL color composite of the Galactic Centre region. The central black hole is located in the center of the box

Talk Outline

- Is it a black hole or something else there (fermion ball, cluster of stars)?
- History of Galactic BH mass measurement
- Measurement techniques:
 - Kepler orbits fit
 - Observational techniques (speckle imaging vs. adaptive optics)
- Is SgrA* motionless enough to be a supermassive black hole?
- Conclusions

What are Black Hole alternatives?

- Galactic Black Hole (usu. associated with radio source SgrA*)
 - $M = (3 - 4) \times 10^6 M_{\text{sun}}$ (Ghez 2004, Schödel et al. 2003)
- Cluster of dark objects (e.g. neutron stars or stellar mass black holes)
 - Ruled out by observations: matter density of $10^{16} M_{\text{sun}}/\text{pc}^3$ imposes a lifetime of less than $\sim 10^5$ yrs (Maoz 1998)
- Fermion ball
 - Still possible to make it work by tuning the particle mass to $50 \text{ keV } c^{-2}$ but not viable anymore (Viollier 2003)

History of BH mass measurements

- Radial velocity measurements of ionized gas imply central concentration of dark matter (Lacy et al. 1980);
- Radial velocity measurements of stars suggest dark matter mass $M \sim 3 \times 10^6 M_{\text{sun}}$ within $R \sim 0.1 \text{ pc}$ (McGinn et al. 1989, Haller et al. 1996, Genzel et al. 1997), i.e. imply density of $\sim 10^9 M_{\text{sun}}/\text{pc}^3$ – this still allows the case of cluster of stars;
- Proper motion velocities measurements of stars increase dark matter density to $10^{12} M_{\text{sun}}/\text{pc}^3$ (Eckart & Genzel 1997; Ghez et al. 1998); this only leaves the black hole and the fermion ball hypotheses;
- Ghez et al. 1998 show that the position of the black hole candidate – the unusual radio source SgrA* – is consistent with the dynamical center of the Galaxy (within $0''.1 = 0.004 \text{ pc}$).

How can we show it's indeed a Black Hole?

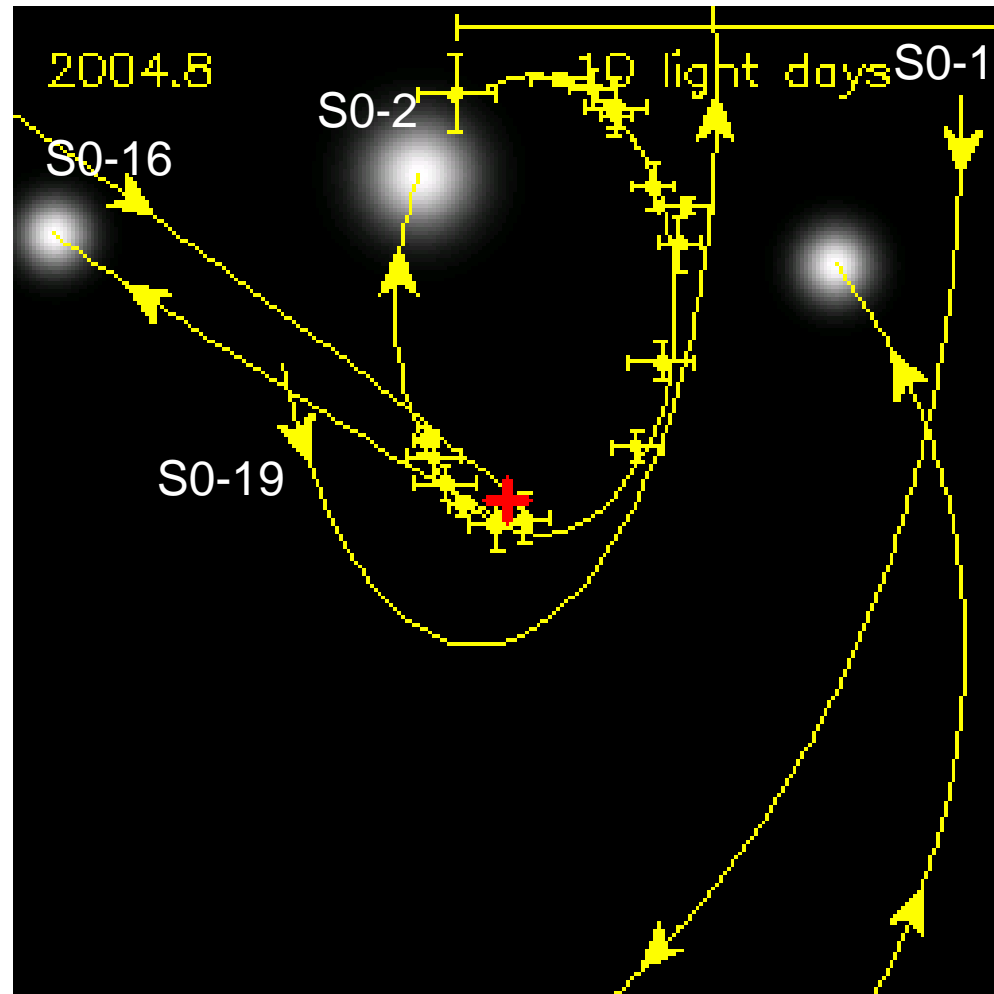
- *Ideally*: find the mass distribution near the gravitational center – and that's it!
- *Realistically*: localize the central mass to within as close to the gravitational center as possible, preferably to within a few Schwarzschild radii (currently, $\sim 1000 r_S$).
 - We can use stars' orbits as our probes into the mass distribution so intimately close to the center and ...

...that's how we do that

This movie shows a model of proper motions of stars near the Galactic Center (based on observations in the infrared).

The size of the red cross is about 10^3 times larger than that of the black hole.

Let's go back and see how it all started...



1st orbital solutions for stars around the central Black Hole

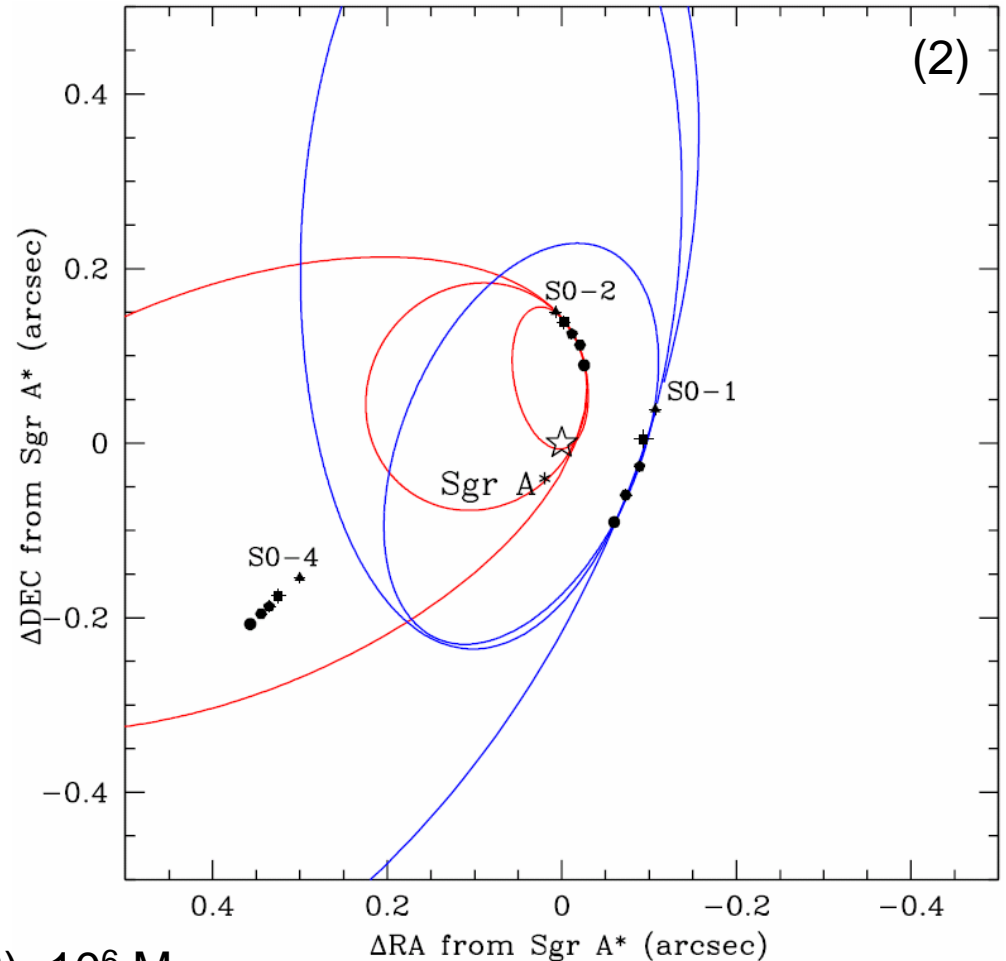
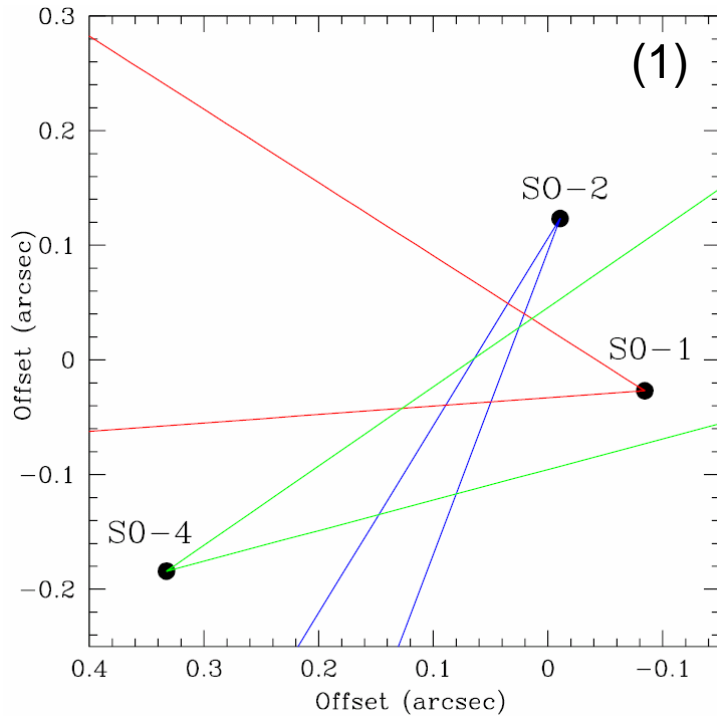
Assumptions about central mass distribution:

- It's a point source
- Distance = 8 kpc (Reid 1993)
- No motion w.r.t. Galaxy (Reid 1999, 2003)
- Its position = position of SgrA*
- $M = 2.6 \times 10^6 M_{\text{sun}}$ (Genzel et al. 1997, Ghez 1998)

Six unknown binary star parameters to fit orbits:

1. Period P
2. Eccentricity e
3. Time of periaapse passage T_0
4. Angle of nodes to periaapse ω
5. Angle of line of nodes Ω
6. Inclination i

1st orbital solutions for stars around the central Black Hole



1. Acceleration directions (common area harbors the gravitational center).
2. Good orbital fits for $M = (2.3 - 3.3) \times 10^6 M_{\text{sun}}$ confirm the association of gravitational center with SgrA* and this value of black hole mass.

Advanced orbital solutions for a 15.2-yr period star, S0-2 (S0)

Assumptions about central mass distribution:

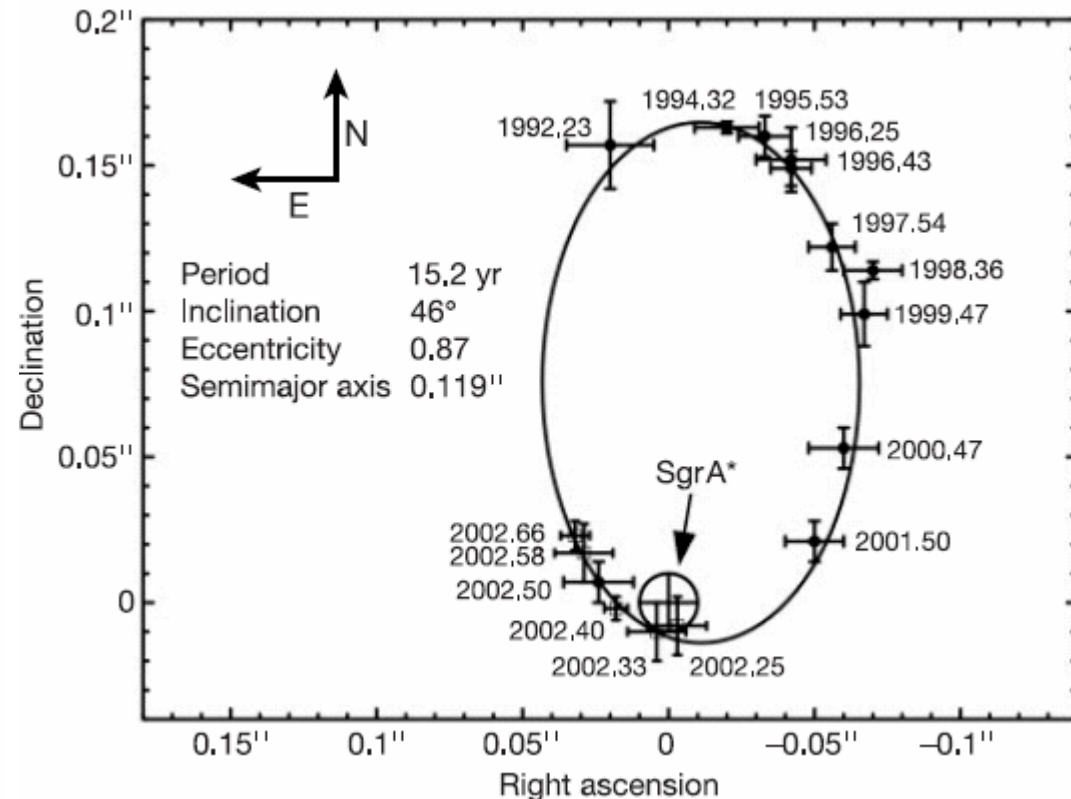
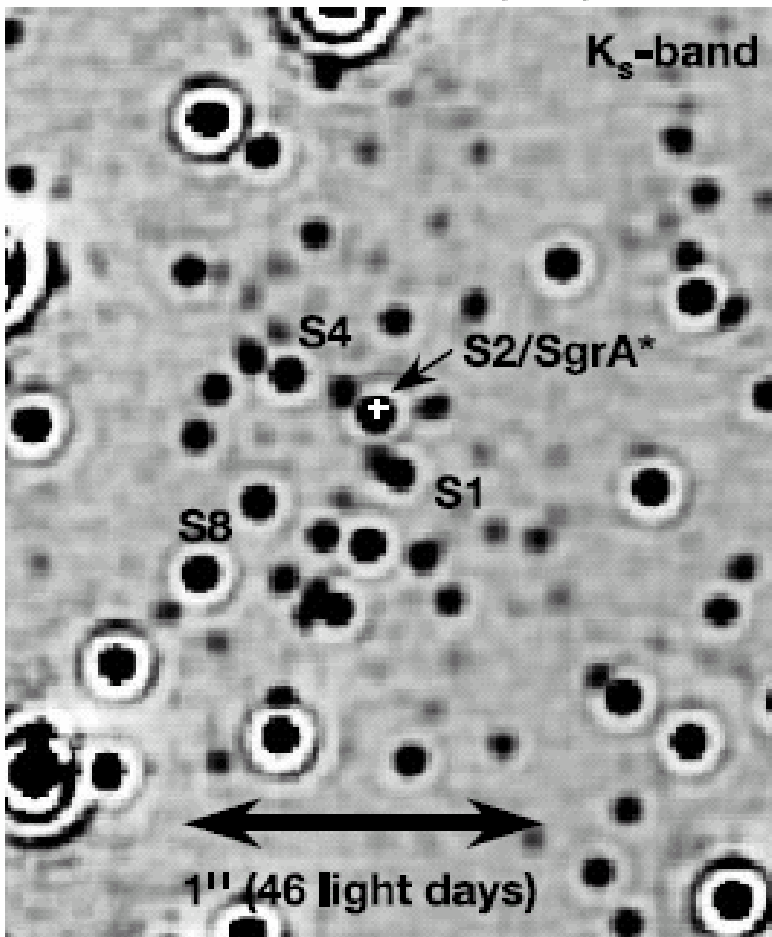
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6. Inclination i
7. Mass M

Advanced orbital solutions for a 15.2-yr period star, S0-2 (S0)

Drop BH mass assumption and derive $M = (3.7 \pm 1.5) \times 10^6 M_{\text{sun}}$



K_s-band image of the centre of the Milky Way.

Advanced orbital solutions for a 15.2-yr period star, S0-2 (S0)

Assumptions about central mass distribution:

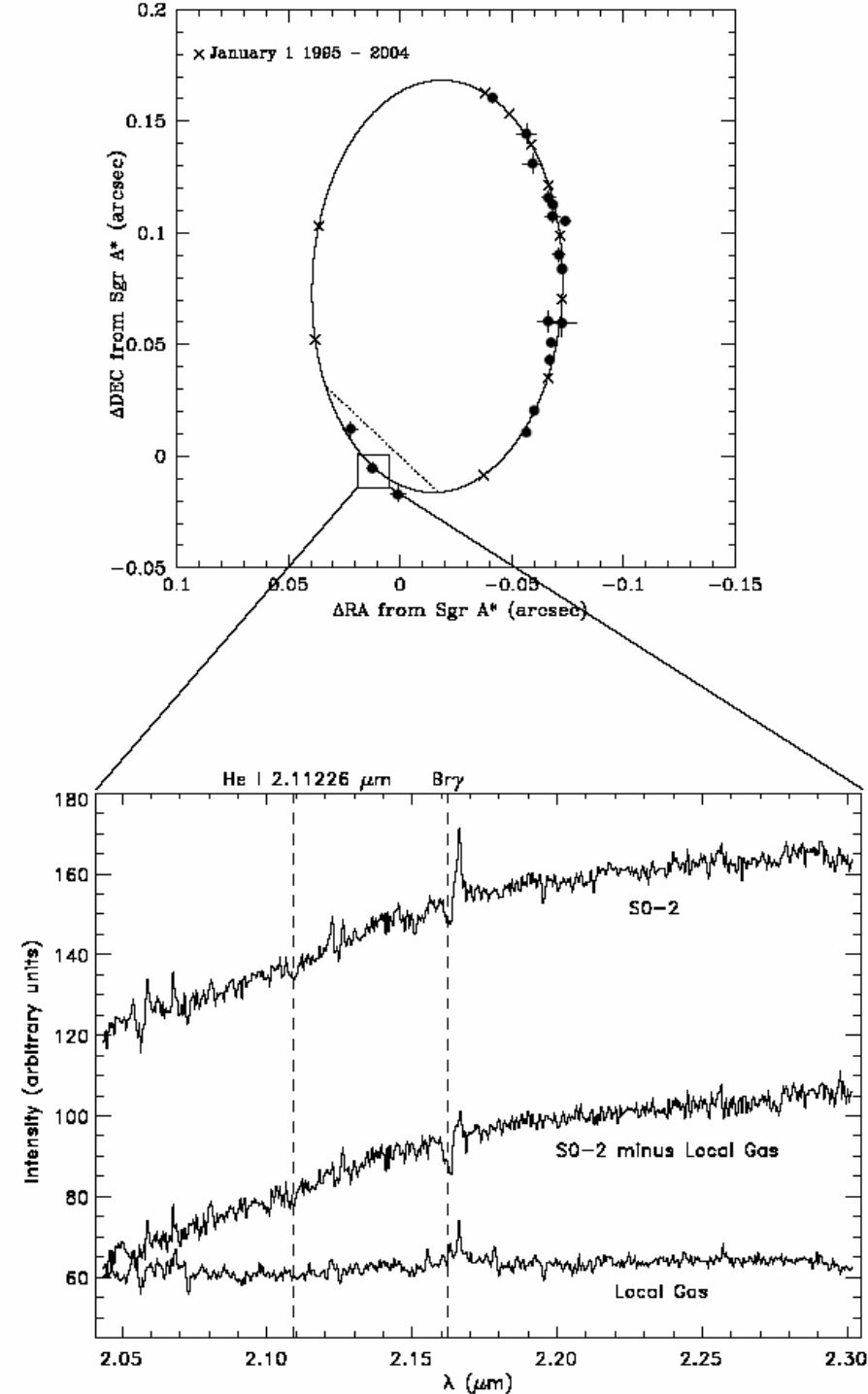
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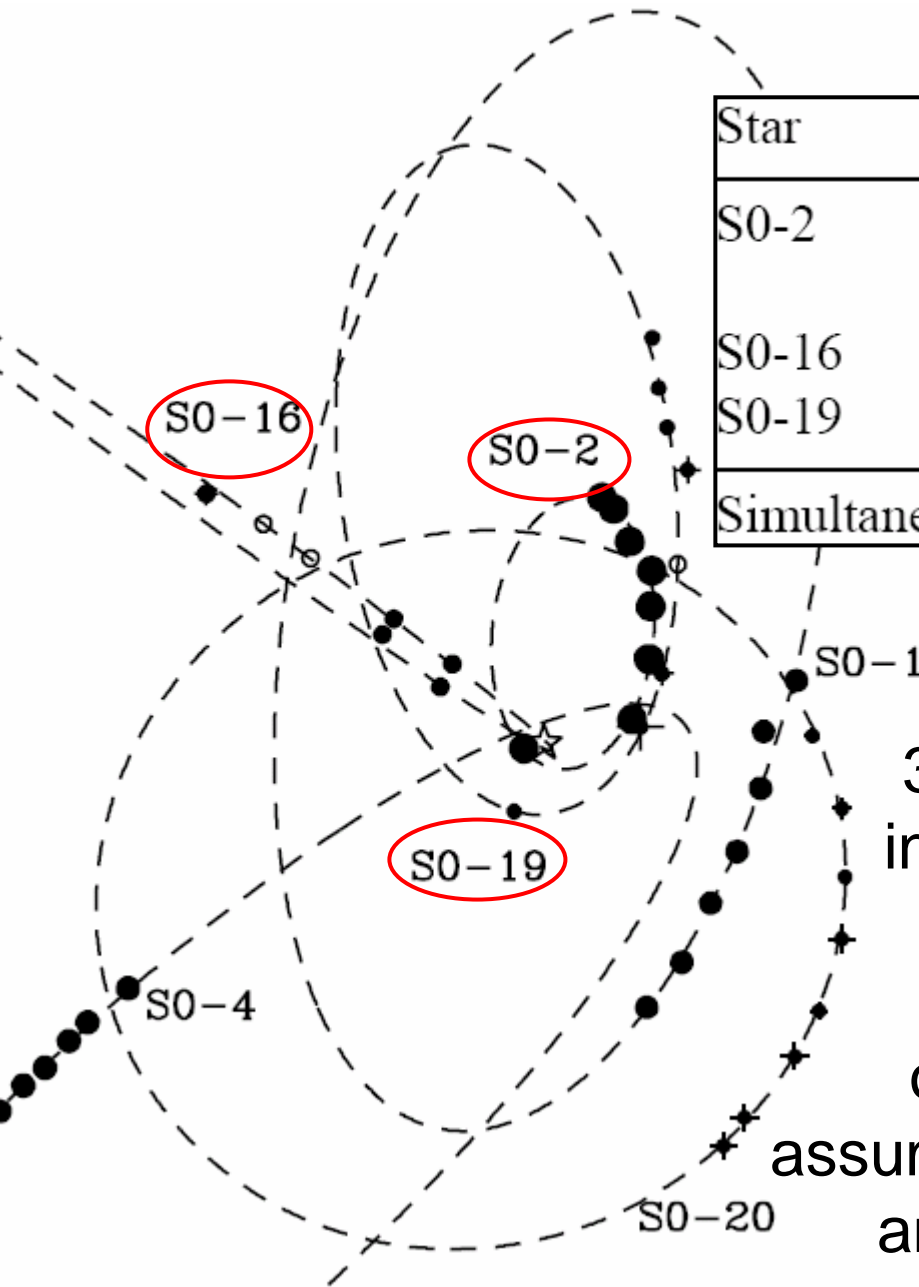
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2. Eccentricity e
3. Time of periaapse passage T_0
4. Angle of nodes to periaapse ω
5. Angle of line of nodes Ω
6. Inclination i
7. Mass M
- 8, 9. Center of mass position

Advanced orbital solutions for S0-2

- Drop mass and center of attraction assumptions and get $M = (4.1 \pm 0.6) \times 10^6 M_{\text{sun}}$, i.e. a similar mass estimate with 2 times lower uncertainties in orbital parameters and localize this mass within 0.0004 pc, i.e. impose $\rho > 3 \times 10^{16} M_{\text{sun}}/\text{pc}^3$ (Ghez et al. 2003a);
- Use radial velocity measurements to break the ambiguity of the inclination angle (Ghez et al. 2003a): at the time of periaapse S0-2 is behind the black hole.



Simultaneous orbital fits



Star	Mass ($10^6 M_{\odot}$)	Reference
S0-2	3.7 ± 1.5	Schödel et al. (2002)
	4.1 ± 0.6	Ghez et al. (2003a)
S0-16	3.0 ± 0.7	Ghez et al. (2004)
S0-19	3.4 ± 0.9	Ghez et al. (2004)
Simultaneous	3.7 ± 0.4	Ghez et al. (2004)

Sufficient curvature of these 3 stars orbits' allows them to be fit independently (Ghez et al. 2003b).

Agreement between individual masses and positions of centers of attraction support the validity of assumption of a common central mass and a common center of attraction.

Adaptive optics (AO) imaging

- An adaptive optics system uses the light from a reference star within the field of view to deduce information about the atmospheric distortion and corrects for it by means of a deformable mirror.

CFHT Adaptive Optics Bonnette & Monica

Double star, separation=0.38"

Magnitude=10.7

H Band, Tinteg=40seconds

Seeing=0.7" @ 0.5 μ

Strehl Ratio=30%

Maximum Likelihood

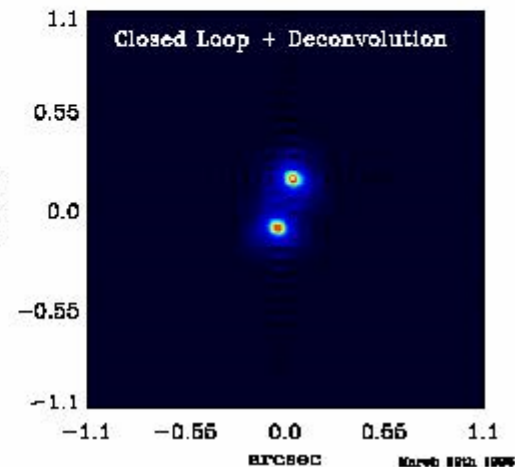
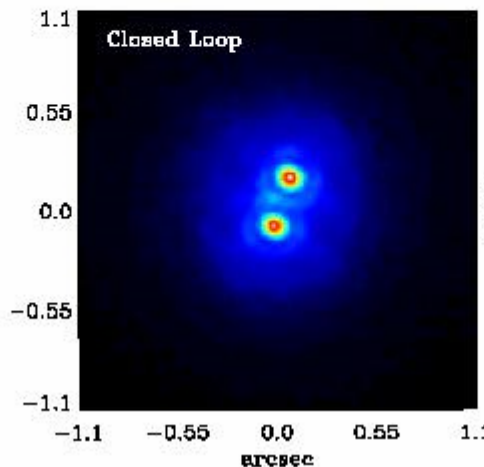
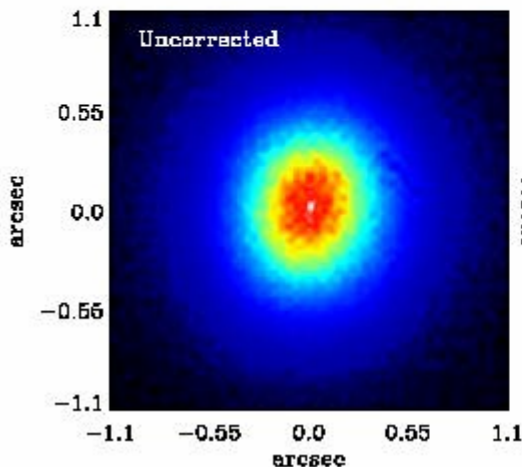


Image source: Sky & Space magazine, p20-24, Dec 1996

Speckle imaging

- Speckle imaging: take very short exposures to “freeze” the atmospheric turbulence and capture the light while it is still forming coherent interference patterns at the detector.
- The coherence patterns in each image contain diffraction-limited information that is used to determine the object’s Fourier amplitudes and phases, which are combined with an inverse Fourier transform to produce a diffraction-limited image (Macintosh et al. 2003).
- Because of shorter exposures, demand is for brighter objects than for AO. However, speckle imaging is easier to implement than AO.

Constraints on motion of SgrA*

If the compact radio source, SgrA*, is indeed the gravitational source, then it should be nearly at rest at the dynamical center of the Galaxy.

VLBI observations (Reid et al. '04) of SgrA* are in agreement with no motion at all and limit *its...*

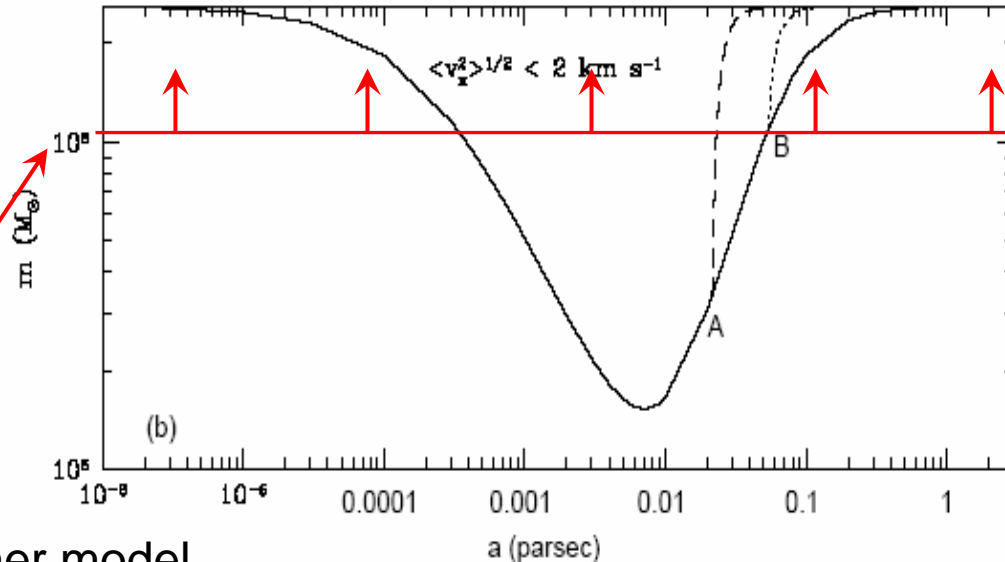
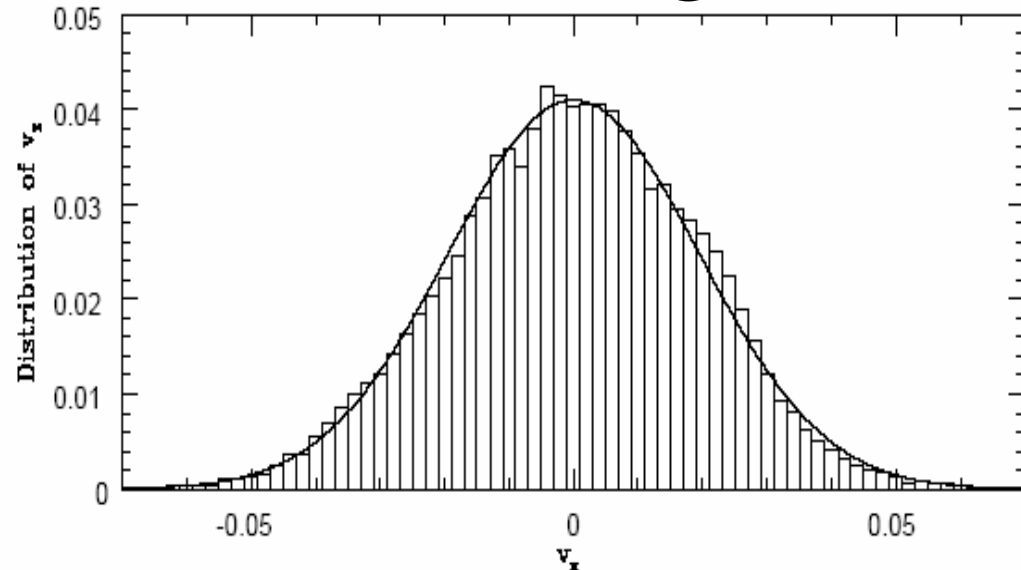
- ...*velocity*
 - in the galactic plane: $-18 \pm 7 \text{ km/s}$
 - \perp to the galactic plane: $-0.4 \pm 0.9 \text{ km/s}$
- ...*short-period position excursions*: $< 4 \text{ AU}$

For $M_{\text{SgrA}^*} = 4 \times 10^6 M_{\text{sun}}$ Reid et al. (2004) expect SgrA* to have rms speed of 0.18–0.30 km/s (depending on the assumed IMF slope).

Constraints on motion of SgrA*

- Chatterjee, Hernquist, & Loeb (2002) showed that SMBH motion in a cluster of stars¹ is well approximated by Brownian motion in a harmonic potential well.

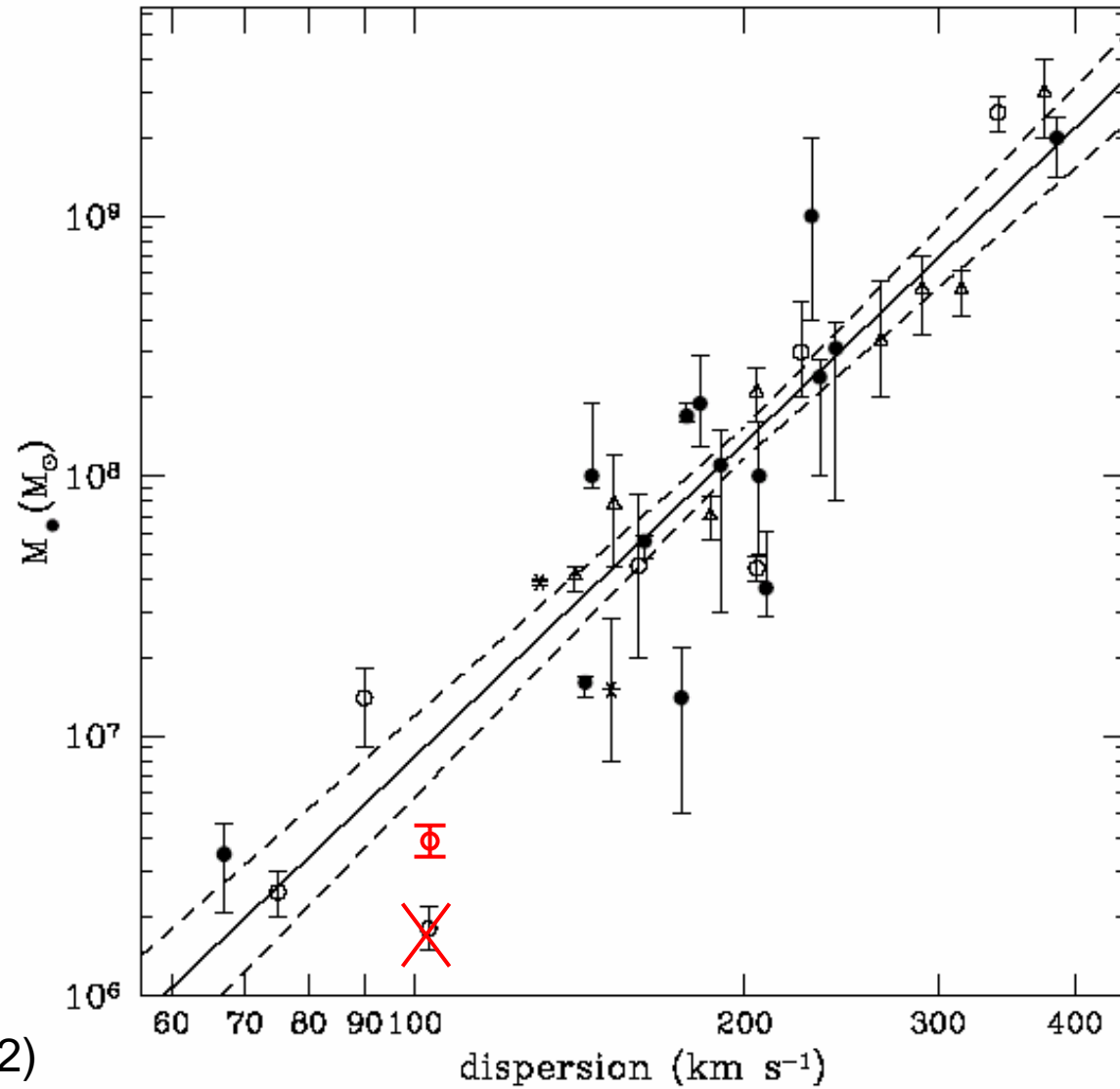
- For $M(r < 0.01 \text{ pc}) = 2.6 \times 10^6 M_{\text{sun}}$ and $\langle v_x^2 \rangle < 2 \text{ km/s}$, they estimate the **minimum limit** for the black hole mass to be $\sim 10^6 M_{\text{sun}}$.



¹ distributed according to the Plummer model

New BH mass estimate falls better on to M- σ relationship

- Old BH mass value (used in Tremaine et al. 2002), crossed out on the plot:
 $(1.85 \pm 0.35) \times 10^6 M_{\text{sun}}$
- New BH mass value (Ghez et al. 2004), falls better on the plot, shown in red.



Tremaine et al. (2002)

Conclusions

- “The new orbital masses increase the central dark mass density by 4 orders of magnitude, dramatically strengthening the case for a central supermassive black hole” (Ghez 2004).
- The motion of SgrA* is consistent with the fact that it is a supermassive black hole.
- The improved mass estimate falls much better on to the M - σ relationship, so that this relationship becomes even sweeter (as was discussed last week by Matt, see Tremaine et al. 2002).

References

- Ghez A.M. 2004, Carnegie Observatories Astrophysics Series, Vol. 1
- Reid & Brunthaler 2004, ApJ, 616, 872
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- Ghez et al. 2003b, Astron. Nachr., 324, S1
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- Chatterjee et al. 2002, ApJ, 572, 371
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- Haller et al., 1996, ApJ, 456, 194
- McGinn et al., 1989, ApJ, 338, 824
- Lacy et al. 1980, ApJ, 241, 132