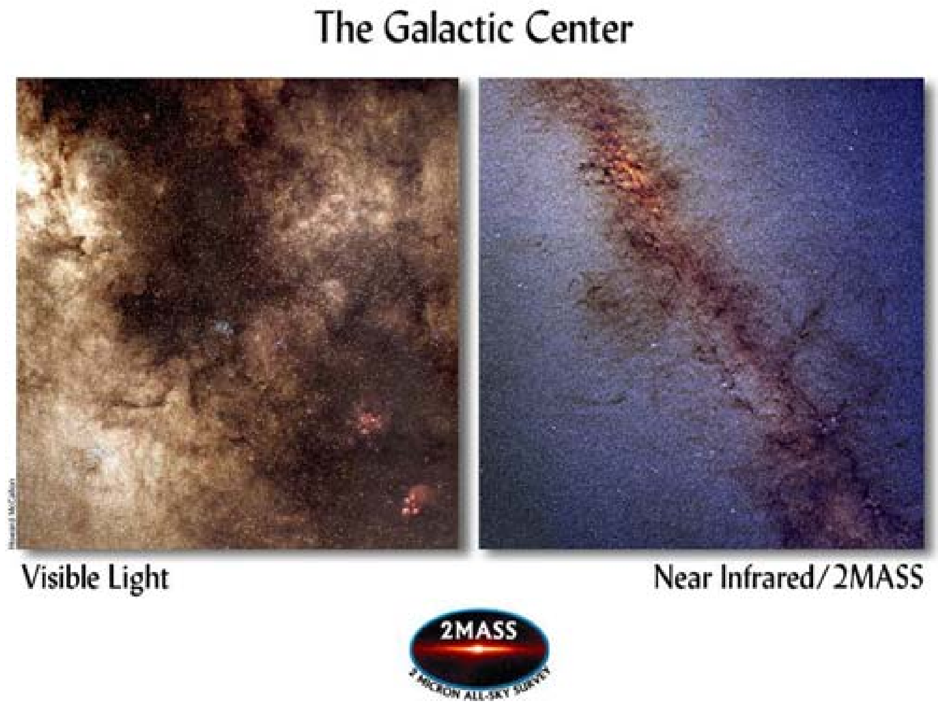
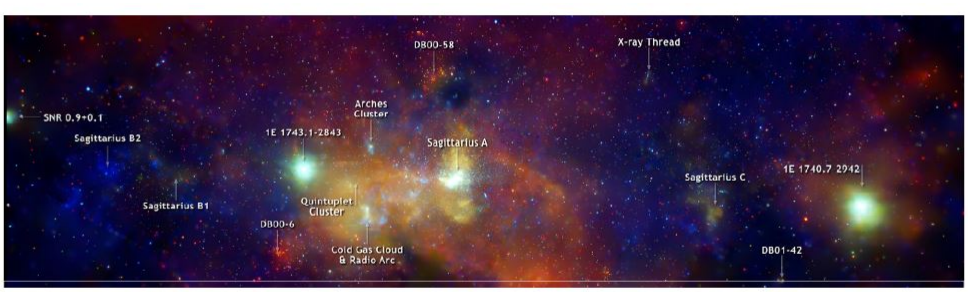
Observations of Galactic Center Evidence for SMBH

- Galactic Center: Galactic center lies in the constellation of Sagittarius. High extinction makes it impossible to observe galactic center in visible band. Observations are thus made in Radio, X-ray and IR.



NASA/2MASS/IPAC

- SMBH at the center: Quintuplet star cluster and Arches star cluster are two of very densely populated star clusters very near to center of the Galaxy. Star formation occurs in cold dense regions of the galaxy, but these star clusters are found very near to Galactic center which is known to have a violent vicinity.They are located 30 pc in projection from the black hole, and formed in one of the most extreme environments in the Galaxy. These clusters experience strong tidal shear forces from the supermassive black hole. X-ray images of the region shows the thermal emissions taking place at the center.These images reveal that the center is very active.



X-ray view of galactic center

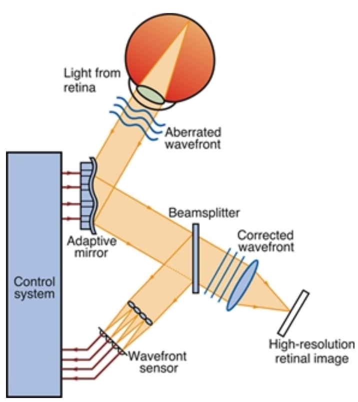
- X-ray can be originated in many sources (WDs, NS,BHs,in binary systems). These are point sources of X-ray. The more diffused sources in the image is due to heating of gas to million Kelvin due to multiple supernova explosions and collisional heating from strong stellar winds from massive stars. One of the sources could emission due to Bremmstrahlung.

- Sagittarius star lies within Sgr A* region. It's position coincides with that of dynamical center of the Galaxy. Although it is not SMBH, but is as near to SMBH as is required to send electromagnetic signals.

- Astrometry: Turbulence in earth's atmosphere makes imaging seeing limited, thus giving a very poor image. As a resort, we use adaptive optics to account for turbulence of the atmosphere.

- Active Optics: Active Optics was developed in 1980s. It actively shapes a telescope's mirror to prevent deformation due to external influences like temperature, wind, mechanical stress.

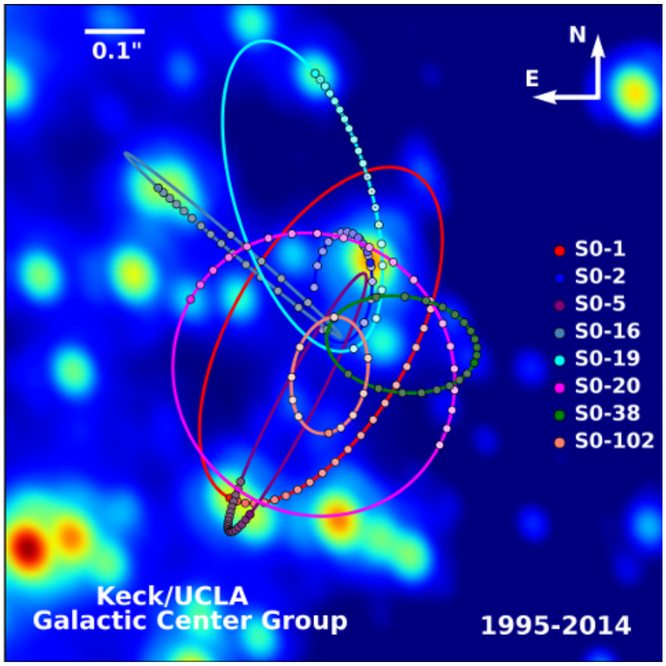
Adaptive Optics: Adaptive optics (AO) operates on a shorter time scale and is a technology used to improve the performance of optical systems by reducing the effect of wavefront distortions: it aims at correcting the deformations of an incoming wave front by deforming a mirror in order to compensate for the distortion.



Adaptive Optics: Schematic

UCLA group has been measuring the positions of several stars in the vicinity of center of the Galaxy for more than 20 years.In particular, a full phase coverage has been measured for two stars: S0-2 with an orbital period of 15.56 years, and S0-102 with 11.5 years.From these orbital data, we can determine the mass of the central black hole in our own Galaxy.

Hyper-velocity stars: SMBH is believed to be orbited by stars that have extraordinary speeds of the order of 5000kmps. These stars are called hyper-velocity stars.



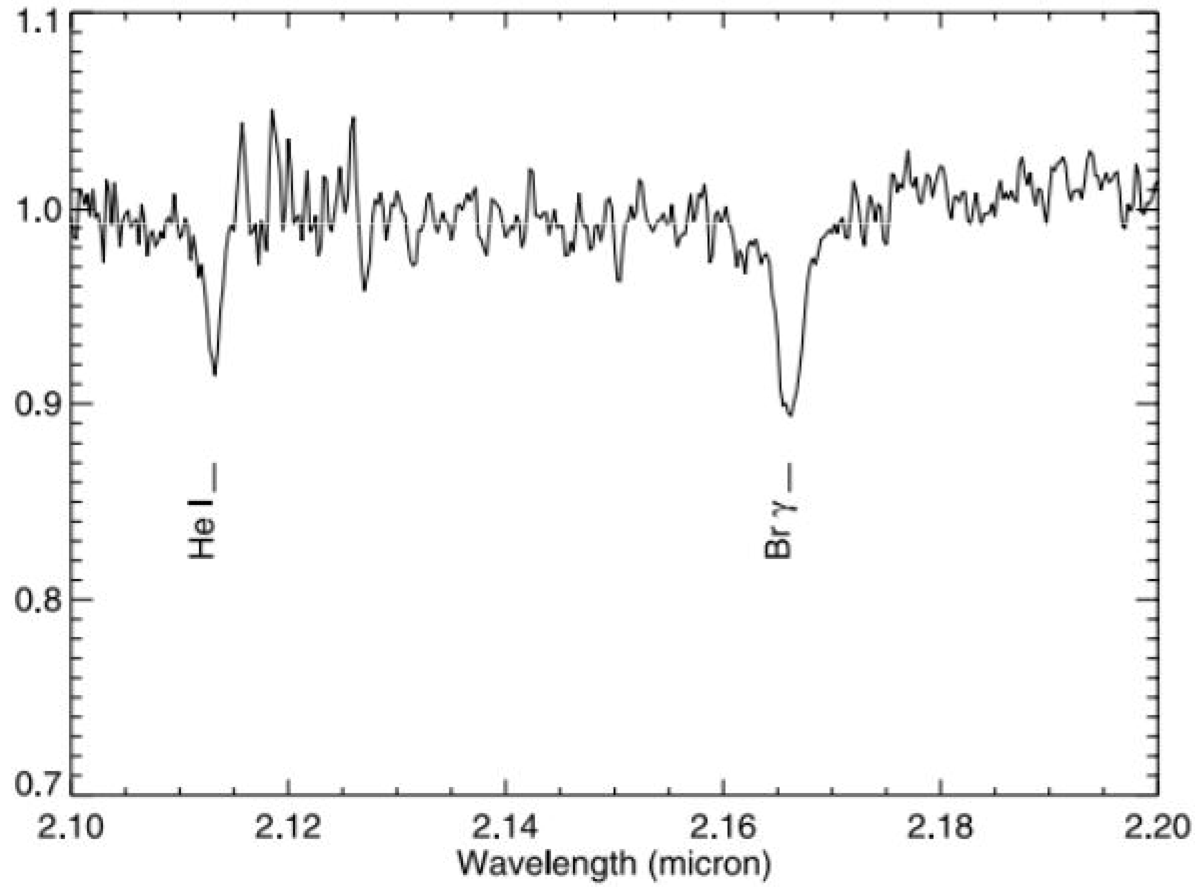
Observations of stars within the central 1.0 X 1.0 arcseconds of our Galaxy. While every star in this image has been observed to move since 1998, estimates of orbital parameters are best constrained for stars that have been observed through at least one turning point of their orbits (S0-2, and S0-102). Ghez et al. 2008

The space velocities of these stars near the galactic center are estimated from:

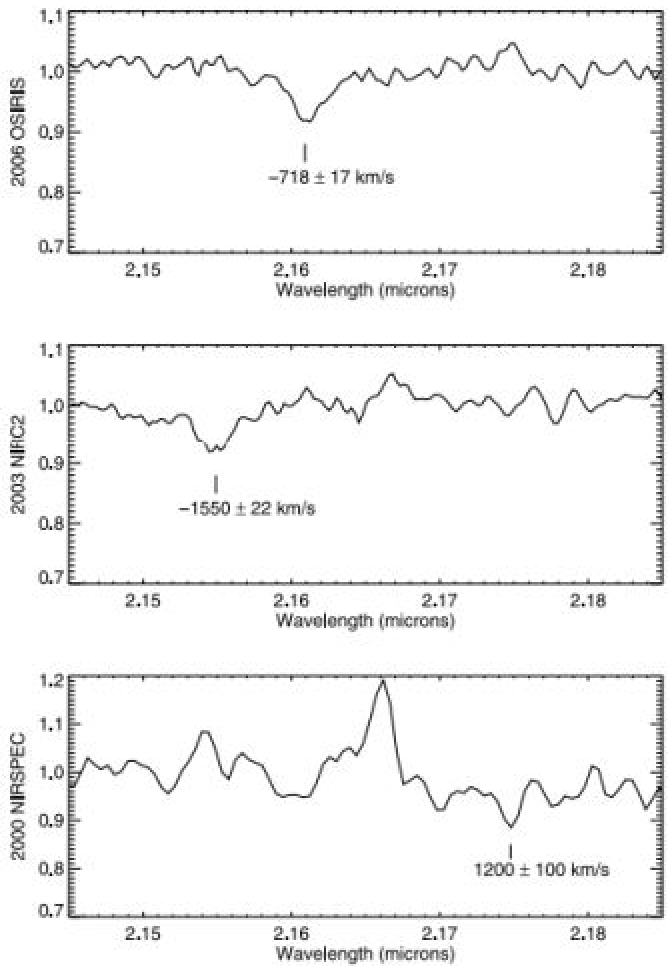
1. Proper motion measurement
2. Radial Velocity measurement

Proper motion measurement is done through astrometry through near diffraction limited high angular resolution imaging using adaptive optics.

Radial Motion:Radial velocity measurement is done through high angular resolution spectroscopic observations with adaptive optics.



IR spectra of hypervelocity star S-02 obtainedwith Keck II telescope. Ghez et al.2008



Measurements of S0-2s Brackett-line at three different epochs (2000,2003,and 2006).These three measurements show that, over time, S0-2s radial velocity has changed by more than 2600 km/s.

Hypervelocity Star : Orbital Parameters

Orbital Elements for S0-2 and the Implied Black Hole Properties

Parameter	$V_z = 0$ Case[a]
Distance (R_0) (kpc)[b]	$8.36\pm^{0.30}_{0.44}$
Period (P) (yr)	15.78 ± 0.35
Semimajor axis (a) (mas)	$124.4\pm^{2.4}_{3.3}$
Eccentricity (e)	0.8866 ± 0.0059
Time of closest approach (T_0) (yr)	$2002.3358\pm^{0.0065}_{0.0093}$
Inclination (I) (deg)	135.3 ± 1.3
Position angle of the ascending node (Ω) (deg)	225.9 ± 1.3
Angle to periapse (ω) (deg)	65.18 ± 1.2
X dynamical center (X_0-$X_{\mathrm{Sgr\ A^*-radio}}$) (mas)[b, c]	$0.95\pm^{0.46}_{1.4}$
Y dynamical center (Y_0-$Y_{\mathrm{Sgr\ A^*-radio}}$) (mas)[b, c]	$-4.8\pm^{2.2}_{1.6}$
X velocity (V_x) (mas yr^{-1})	-0.40 ± 0.25
Y velocity (V_y) (mas yr^{-1})	$0.39\pm^{0.09}_{0.18}$
Z velocity (V_z) (km s^{-1})	...
Mass (M_{bh}) (10^6 $M_\odot$)	$4.53\pm^{0.34}_{0.55}$
Density (ρ) (10^{15} $M_\odot$ pc^{-3})	$5.83\pm^{0.28}_{0.97}$
Periapse distance (R_{min}) (mpc)	0.570 ± 0.037

Ghez et al. 2008

Super massive Black Hole at the galactic center

The hyper-velocity stars have helped the astronomers to determine the mass of the central object.The star S-02 follows an elliptical orbit with a period of 15.2 years. From the motion of S-02 the mass of central object is estimated to be 4.1 Million M_{sun}. At the center, is detected a bright radio source whose emission seems to be coming from a very compact region (3-5 Light minutes), only a black hole can old such a huge mass in such a compact space. Sgr A^* is the most likely candidate for central Black Hole.

- Keplerian fits to the orbits gives the mass enclosed within the orbital radius

$$M = (3.6 \pm 0.4) \ \times \ 10^6 \ M_\odot$$

- *M(r)* is constant over the range $0.01 \lesssim r \lesssim 1 \text{ pc}$

- Central mass concentrated within a region *r* < 0.01 pc

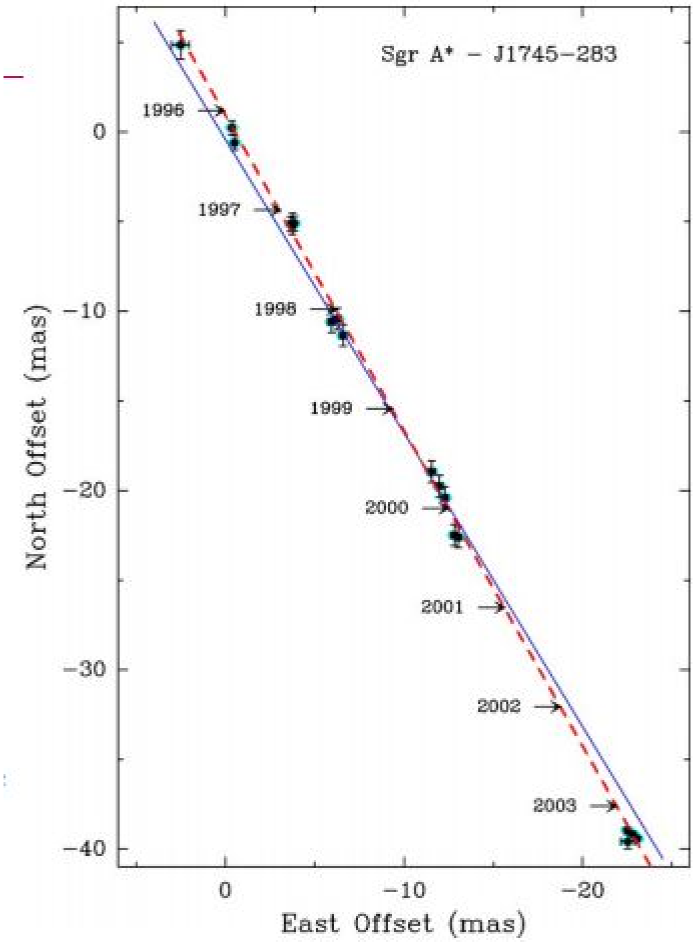
Estimating the Mass of SMBH

$$M_{BH} = \frac{V^2\ R}{G} = \frac{v_r(max)^2\ R}{\sin^2 i\ G}$$

$$\bar{r} = r\cos i \Rightarrow M_{BH} = \frac{v_r(max)^2\ \bar{r}}{\sin^2 i\ \cos i\ G}$$

$$P = \frac{2\pi r}{V} \Rightarrow M_{\rm BH} = \frac{4\pi^2}{G}\left(\frac{\bar{r}}{\cos i}\right)^3 \frac{1}{P^2}$$

Proper Motion of Sgr A^* : If Sgr A_* lies near the gravitational source that is responsible for hyper velocity of stars nearby, then Sgr A^* itself should be nearly at rest at the dynamical center of the Galaxy.



The solid blue line gives the orientation of the Galactic midplane.The dashed line is the variance-weighted best-fit to the proper motion

It is clear from Figure 10 that the apparent motion of Sgr A* is almost entirely in the Galactic plane.Any peculiar motion of Sgr A* perpendicular to the plane of the Galaxy is less than 1.8 kmps.This result is complementary to infrared observations of stellar orbits at the Galactic center, which require 4 million M_{sun} within arcradius of 100 AU of Sgr A*.