Galactic Bulge and Galactic center are best observed in IR, sub-mm, radio and X-ray where attenuation by dust is less

The Galactic Center

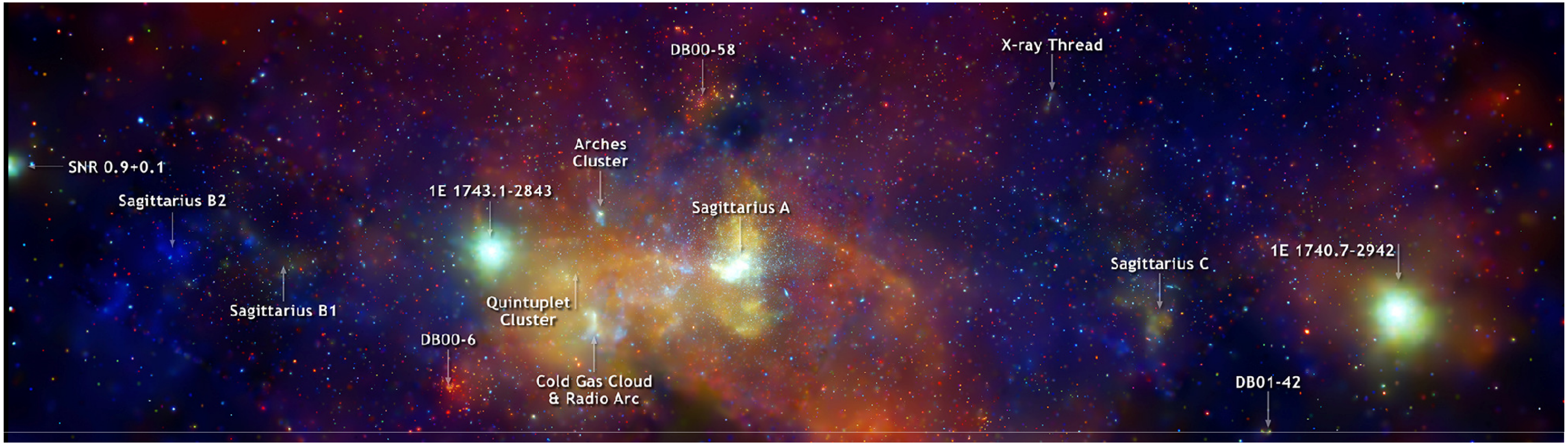
- **Lies in the direction of the constellation Sagittarius**

  $\alpha \sim 19^h$, $\delta \sim -25^o$

High levels of dust extinction make optical observations impossible.

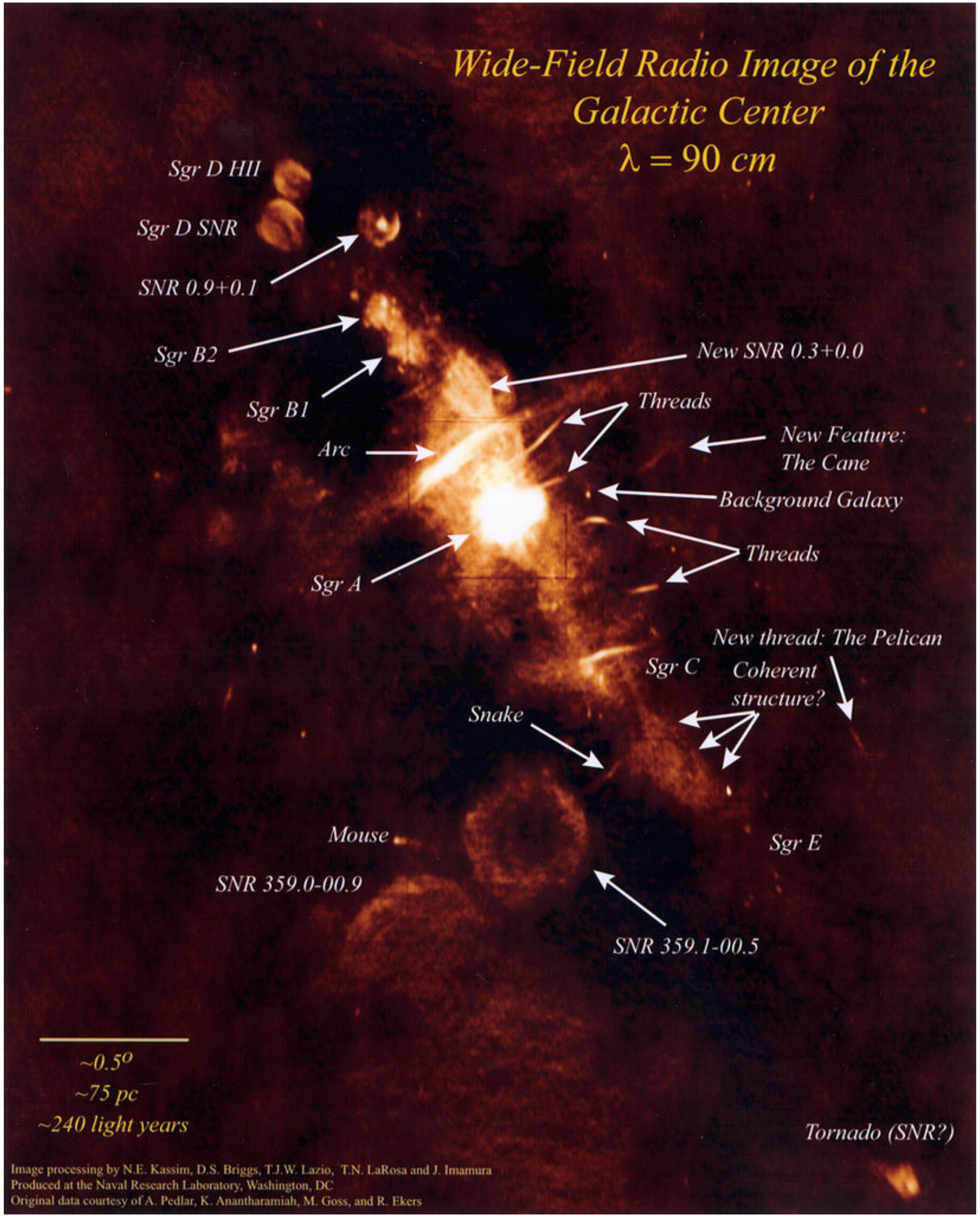
- **Radio, sub-mm, infrared and X-ray observations**

An X-ray View of the Galactic Center

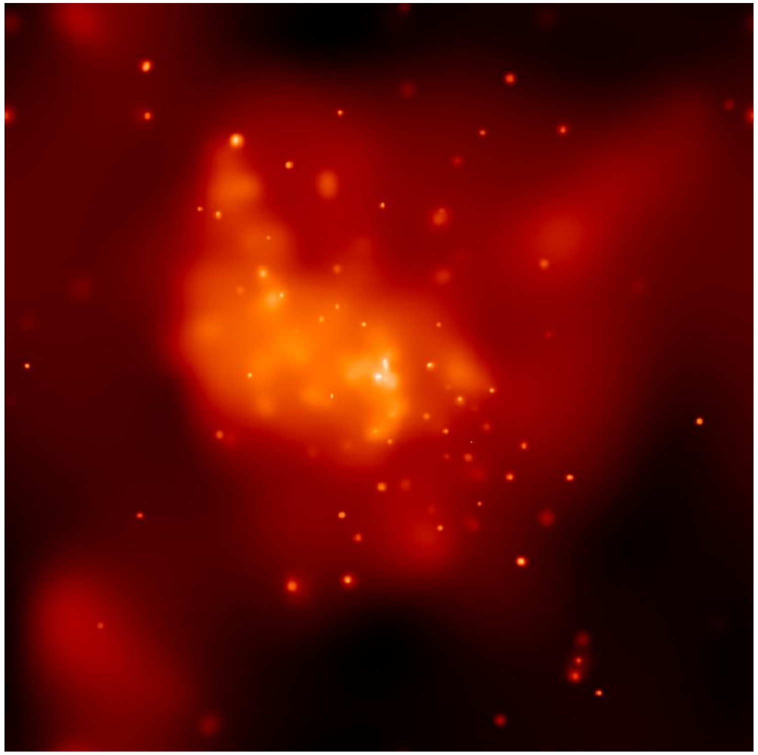


- The more diffuse X-ray brightness is due to gas heated to million Kelvin due to multiple supernova explosions and collisional heating from strong stellar winds from massive stars.

- There are also many stellar X-ray binaries (WDs, NS, BHs, in binary systems). These are the X-ray point sources.



The Galactic Center



CHANDRA X-RAY IMAGE

The Galactic Center

- **The central few tens of parsecs of the Galaxy contain a few dense and luminous star clusters (Arches, Quintuplet, Central Cluster)**
- **The central parsecs also contains neutral gas, ionized H II regions, and million K plasma**
- **Near the center are orbiting ionized gas, further surrounded by molecular cloud filaments.**
- **Several SNRs, bright in radio, X-rays**
- **At the center is a strong radio source whose emission seems to come from a very compact region (3 – 10 light minutes across) – *Sgr A* (faint in all bands except radio and mm)***

Sgr A* is the most likely candidate for the dynamical center of the Galaxy

The Galactic Center

- **The most compelling evidence for the presence of a massive object at the center comes from the measurement of dynamics of objects close to the center.**

- **Stars within 1 arcsecond of Sgr A* show large proper motions corresponding to transverse velocities of v_t ~ 1000 km s^{-1} :** ***hypervelocity stars***

Hypervelocity Stars

- The space velocities of stars near the Galactic center are estimated from

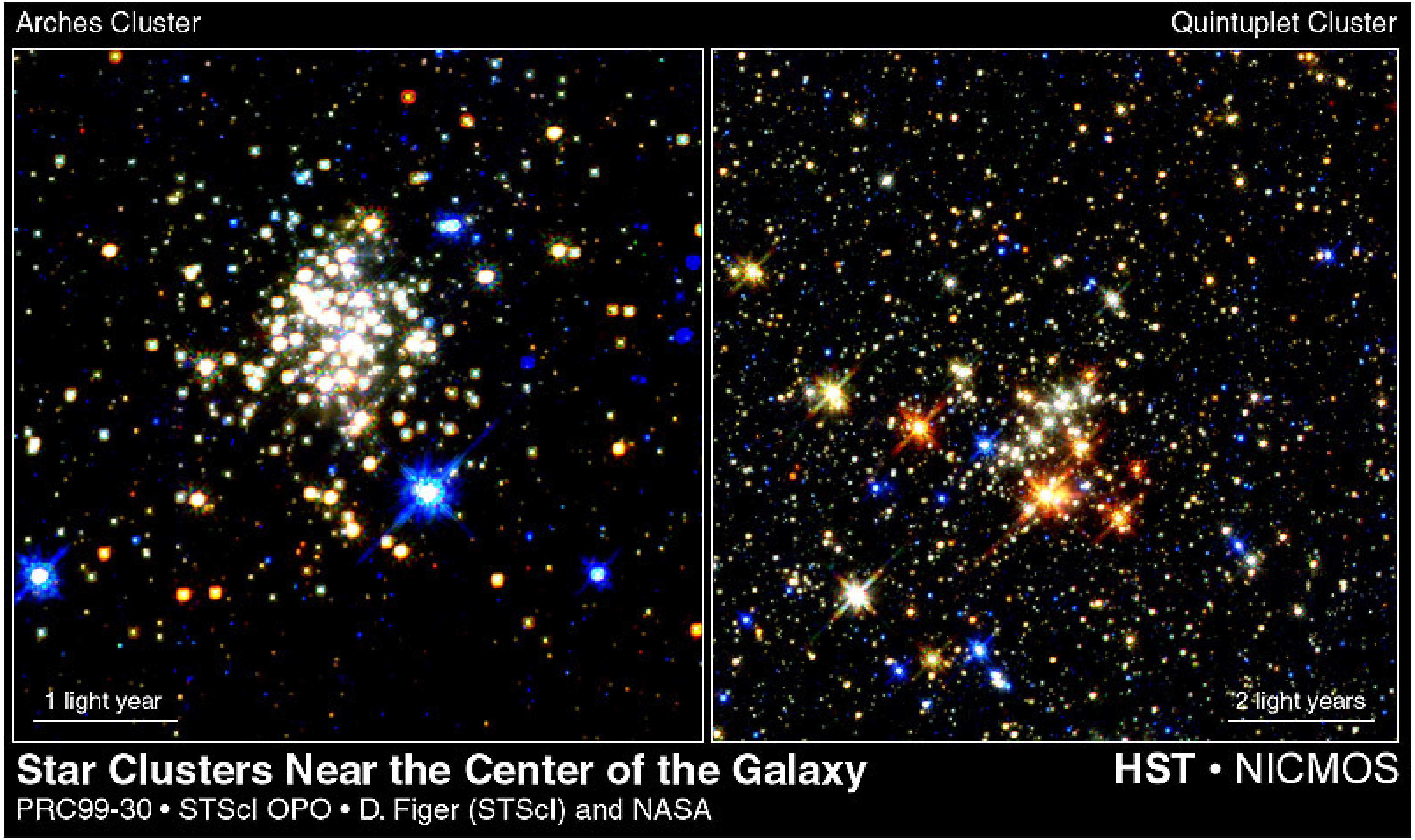
  (a) proper motion measurements

  (b) radial velocity measurements

- Proper motion measurements (*astrometry*) through near diffraction limited high angular resolution imaging using adaptive optics

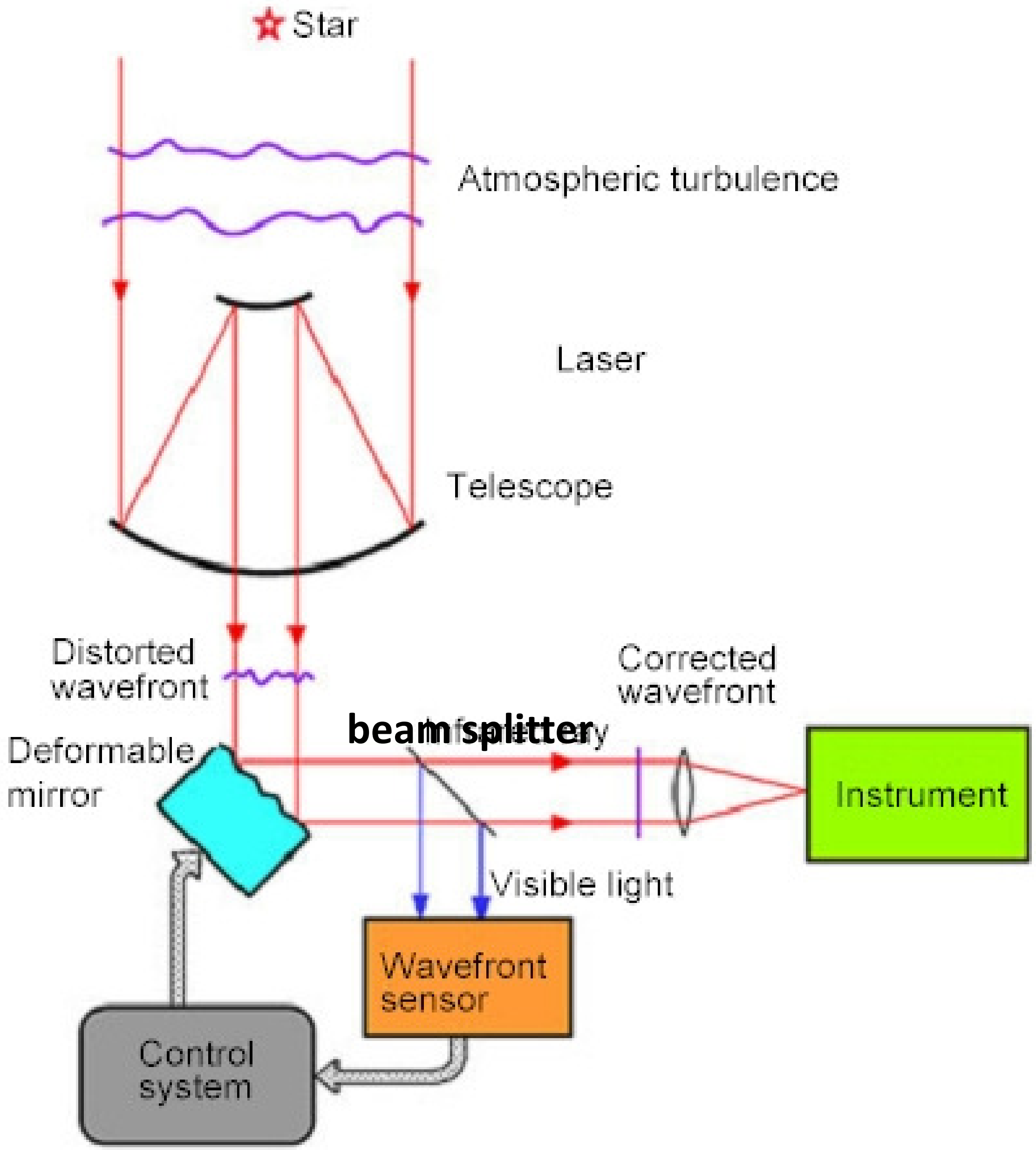
  e.g. Keck 10 m telescope near-IR camera coupled with laser guide-star adaptive optics (LGSAO) can give angular resolutions of 60 milliarcseconds.

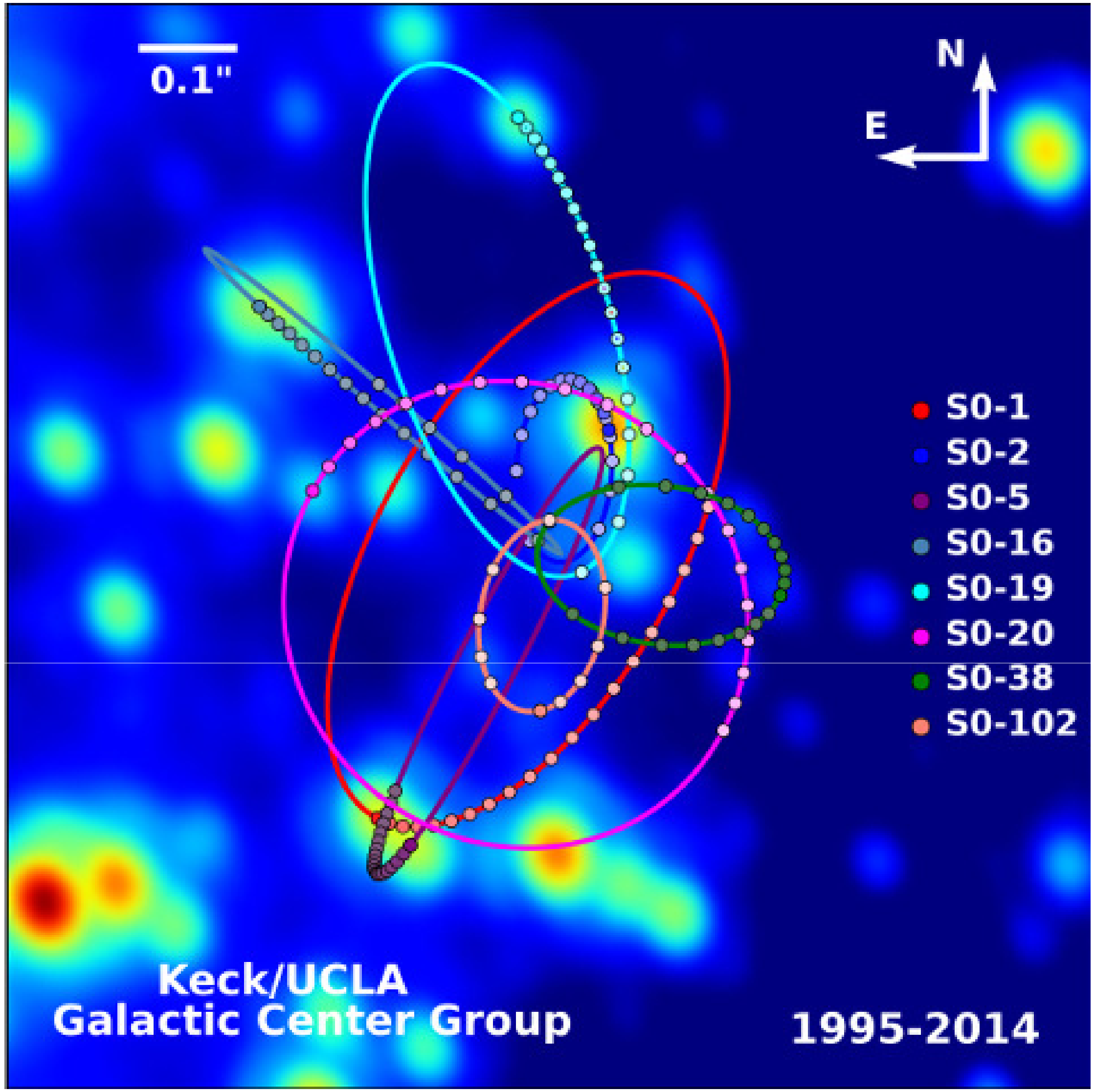
The Galactic Center



The previous slide shows HST images of the Arches and Quintuplet clusters. Both star clusters are located a distance of about 30 pc from Sgr A*. The Arches is a surprisingly densely packed cluster considering its proximity to a supermassive black hole which should cause the cluster to be torn apart. This suggests it is a fairly young cluster. These clusters experience strong tidal shear forces from the supermassive black hole. Along with the young star clusters in the immediate vicinity of the Galactic Center, these clusters provide an ideal opportunity to study how stars and clusters form under extreme initial conditions.

Adaptive Optics





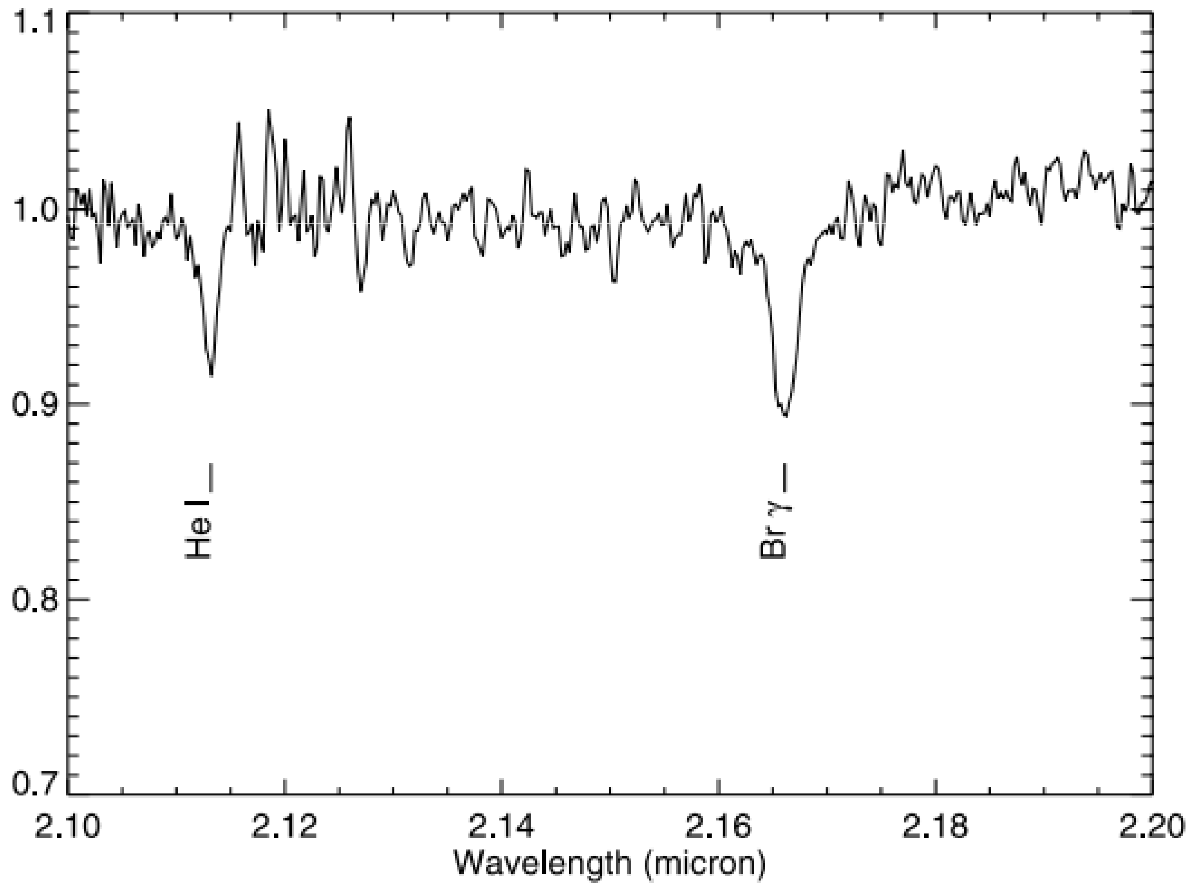
Observations of stars within the central 1.0 X 1.0 arcseconds of our Galaxy. While every star in this image has been observed to move since 1998, estimates of orbital parameters are best constrained for stars that have been observed through at least one turning point of their orbits (S0-2, and S0-102).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

Hypervelocity Stars : Radial Motion

- **Radial velocity measurements of hypervelocity stars through high angular resolution spectroscopic observations with adaptive optics.**

IR spectra of hypervelocity star S0-2 obtained with Keck II telescope.

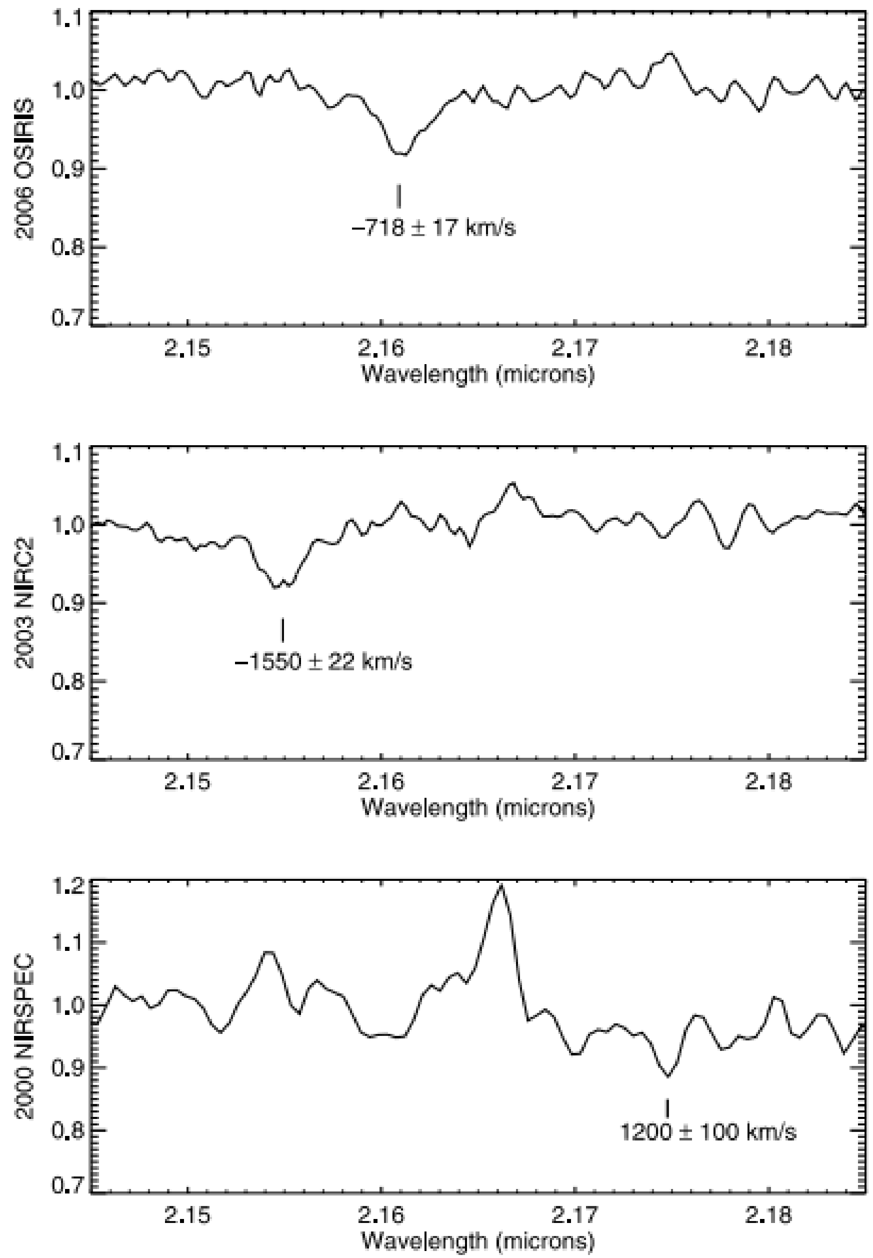
Ghez et al. 2008



Hypervelocity Stars : Radial Motion

Measurements of S0-2's Brackett-γ line at three different epochs (2000, 2003, and 2006).

These three measurements show that, over time, S0-2's radial velocity has changed by more than 2600 km/s



Ghez et al. 2008

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]	$8.36^{+0.30}_{-0.44}$
Period (P) (yr)	15.78 ± 0.35
Semimajor axis (a) (mas)	$124.4^{+2.4}_{-3.3}$
Eccentricity (e)	0.8866 ± 0.0059
Time of closest approach (T_0) (yr)	$2002.3358^{+0.0065}_{-0.0093}$
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-$X_{\mathrm{Sgr\ A^*\text{-}radio}}$) (mas)[b, c]	$0.95^{+0.46}_{-1.4}$
Y dynamical center (Y_0-$Y_{\mathrm{Sgr\ A^*\text{-}radio}}$) (mas)[b, c]	$-4.8^{+2.2}_{-1.6}$
X velocity (V_x) (mas yr^{-1})	−0.40 ± 0.25
Y velocity (V_y) (mas yr^{-1})	$0.39^{+0.09}_{-0.18}$
Z velocity (V_z) (km s^{-1})	...
Mass (M_{bh}) (10^6 $M_\odot$)	$4.53^{+0.34}_{-0.55}$
Density (ρ) (10^{15} $M_\odot$ pc^{-3})	$5.83^{+0.28}_{-0.97}$
Periapse distance (R_{min}) (mpc)	0.570 ± 0.037

Ghez et al. 2008

Super Massive Black Hole at the Galactic Center

- 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

SUPER-MASSIVE BLACK HOLE (SMBH)

Estimating the Mass of SMBH

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

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

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

If the compact radio source, Sgr A is close to the gravitational source responsible for the hypervelocity of its nearby stars, then Sgr A* itself should be nearly at rest at the dynamical centre of the Galaxy*

Proper Motion of Sgr A*

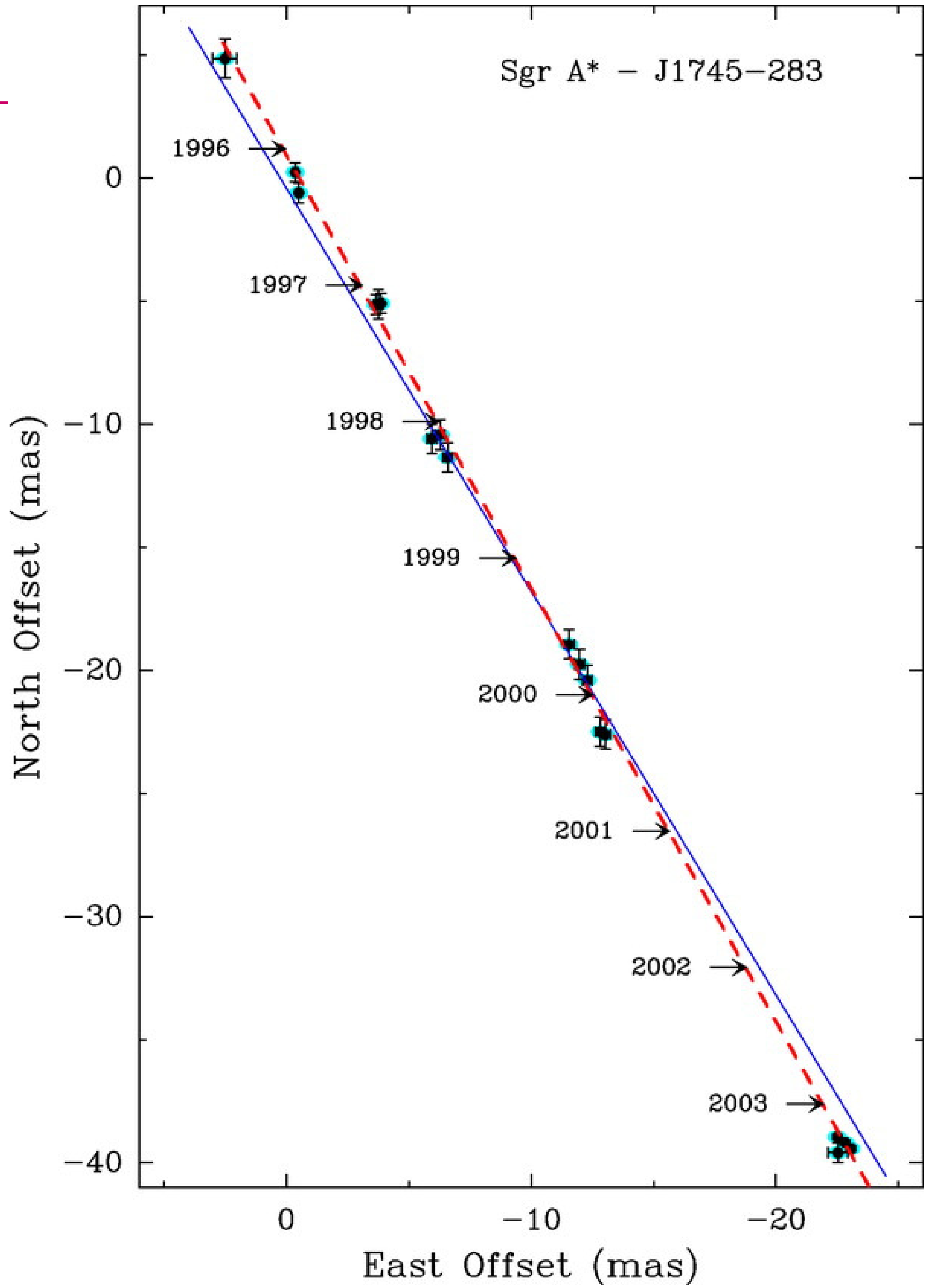
Position residuals of Sgr A* relative to J1745-283 in the plane of the sky.

J1745-283 is an extragalactic radio source

8 years of VLBI observations done at 43 GHz.

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

Reid & Brunthaler, 2004, ApJ, 616, 872



Proper Motion of Sgr A*

3.1. *Motion of Sgr A* in the Plane of the Galaxy*

It is clear from Figure 1 that the apparent motion of Sgr A* is almost entirely in the Galactic plane. Thus, we convert the positions from equatorial to Galactic coordinates and determine motions in Galactic coordinates. (Because of the high accuracy of our observations, some pitfalls in the implementation of the equatorial to Galactic coordinate conversion (Lane 1979), and the need to transfer the IAU-defined plane from B1950.0 to J2000.0 coordinates, we document the procedures involved in the Appendix.) Figure 4 plots the position of Sgr A* relative to J1745−283 in Galactic coordinates. Variance-weighted least-squares fits of straight lines to these data are indicated by dashed lines. The apparent motion of Sgr A* is -6.379 ± 0.026 and -0.202 ± 0.019 mas yr^{-1} in Galactic longitude and latitude, respectively.

Assuming a distance to the Galactic center (R_0) of 8.0 ± 0.5 kpc (Reid 1993), the apparent angular motion of Sgr A* in the plane of the Galaxy translates to -241 ± 15 km s^{-1}. The uncertainty from measurement error alone is only 1 km s^{-1}, and the quoted value is dominated by the 0.5 kpc uncertainty in

Reid & Brunthaler, 2004, ApJ, 616, 872