Astronomy 401/Physics 903
Lecture 4
The Galactic Center

- Hard to observe because of dust. 30 magnitudes of extinction in optical, so must observe either at IR wavelengths or longer (radio), or in X-rays or γ-rays.
- Observing in IR shows that number density of stars $n_* \sim 10^7$ pc^{-3}. Compare $n \sim 0.1$ pc^{-3} near the Sun.
- Density of stars rises toward the center as $r^{-1.8}$ to a radius between 0.1 and 1 pc; this is roughly the distribution expected from dynamical consideration of the rapidly rising, "rigid body" portion of the rotation curve. Because the stellar density is so high, encounters between stars are frequent. This is expected to produce a "thermalized" velocity distribution, meaning that the stars have a velocity distribution like the particles in an isothermal gas, i.e. a Maxwellian distribution. For such a distribution we expect a density profile $n \propto r^{-2}$, close to what is observed.
- However, other measurements show that stellar velocities begin to increase closer to the center, meaning that either the stellar density must rise much faster than r^{-2} near the center, or there must be a large mass in a small volume near the center.
- Strong radio source called **Sagittarius A** at the center of the Galaxy
  - About 8 pc across, with more extended structure to ~ 100 pc
  - Synchrotron emission, produced by relativistic electrons accelerated by a magnetic field—relativistic electrons in a magnetic field follow a helical path, and since they are continually accelerating they emit radiation. This radiation is **synchrotron radiation**, and is observed at radio wavelengths.
  - Also emission from molecular and ionized gas
  - Complex structure, evidence for recent violent event
- Within Sagittarius A is a highly compact radio source called **Sagittarius A*** (Sgr A*)
  - Angular size measured from radio interferometry: $d \sim 0.8$ milliarcsec ~ 6 AU.
  - Sagittarius A* is also an X-ray source, and varies on a timescale < 1 hour, which means $d < ct$ where t is 1 hour; so $d \lesssim 1$ light-hour $\simeq 7$ AU.
  - Luminosity (Sgr A* alone) $\sim 3 \times 10^4$ L$_\odot$ (but variable). This is an estimate of the bolometric luminosity (the total luminosity at all wavelengths), which is very difficult to measure because of the high extinction.
- Sagittarius A* is probably an accreting supermassive black hole
  - We can measure the orbits of stars near Sgr A*, observing at near-IR wavelengths to avoid the effects of dust and using *adaptive optics* which correct for the blurring effects of the atmosphere. We measure both radial velocity and proper motion, so the three-dimensional velocities are known. We have also measured acceleration for some of the stars. This has been done by two groups, one in Europe and one based at UCLA. See Figure 1 for a diagram of stellar orbits from the UCLA group. They find that the star S2 has semimajor axis $a = 920$ AU, period $P = 14.5$ yr. From Kepler's 3rd law, using this and other stars near Sgr A*, we calculate the enclosed mass:

$$M_{\rm SgrA*} = 3.7 \pm 0.2 \times 10^6 \ {\rm M}_\odot \tag{1}$$

  - All stars are on Keplerian orbits, therefore mass is highly concentrated at the center
  - One star comes within 45 AU of Sgr A*, so size must be smaller than that
  - Must be a black hole — only way to get that much mass in that small a volume. An ultra-dense cluster of stars would not be stable.

- We can calculate the Schwarzchild radius (radius at which the escape velocity is equal to the speed of light; the event horizon of the black hole):

$$R_{\text{SgrA}*} = r_S = \frac{2GM_{BH}}{c^2} = 0.08 \text{ AU} = 16 \text{ R}_\odot \tag{2}$$

  This is well below the ~ 2 AU resolution limit of current observations.

- Where does all the energetic radiation come from? Accretion onto the black hole? Let's check whether or not this is plausible. The observed IR radiation and degree of ionization seen in gas in the molecular circumnuclear ring of Sgr A, which extends over $2 \lesssim r \lesssim 8$ pc, require a UV luminosity of $\sim 10^7$ L$_\odot$ and an effective blackbody temperature of 35,000 K. Observations of the number density and velocity structure of particles near the center suggest that the accretion rate is $\dot{M} = 10^{-3}$ to 10^{-2} M$_\odot$ yr^{-1}.

  The **virial theorem** tells us that total energy of a system is equal to 1/2 the (time-averaged) potential energy, $E_{\text{tot}} = 1/2\ U$. Consider a particle of mass M spiraling onto a black hole from an initial radius r_i to a final radius r_f. According to the virial theorem, the energy radiated is half the change in potential energy,

$$E = \frac{1}{2}\left(\frac{GM_{\text{BH}}M}{r_f} - \frac{GM_{\text{BH}}M}{r_i}\right). \tag{3}$$

  Assume $r_i \gg r_f$ and $r_f = r_S$, the Schwarzchild radius. Then

$$E = \frac{1}{2}\frac{GM_{\text{BH}}M}{r_S}. \tag{4}$$

  Assuming the luminosity is $L = dE/dt$ and mass accretion rate is $\dot{M} = dM/dt$, and substituting the expression for r_S, we have

$$L = \frac{dE}{dt} = \frac{1}{2}\left(\frac{GM_{\text{BH}}}{r_S}\right)\left(\frac{dM}{dt}\right) = \frac{1}{4}\dot{M}c^2, \tag{5}$$

  which is independent of the mass and radius of the black hole.

  The minimum mass accretion rate required to generate 10^7 L$_\odot$ is

$$\dot{M} = \frac{4L}{c^2} = 1.7 \times 10^{17} \text{ kg s}^{-1} = 2.7 \times 10^{-6} \text{ M}_\odot \text{ yr}^{-1}. \tag{6}$$

  This is much lower than the observed accretion rate of 10^{-3} to 10^{-2} M$_\odot$ yr^{-1}, indicating that the observed accretion is sufficient to produce the luminosity required, and that the energy release from accretion is not perfectly efficient.

- Recall that the mass of the bulge of the Galaxy is $\sim 10^{10}$ M$_\odot$. This means that the supermassive black hole is less than 0.04% of the mass of the bulge. Outside of a central region a few pc in size, the black hole has no effect at all on the dynamics of the Galaxy.

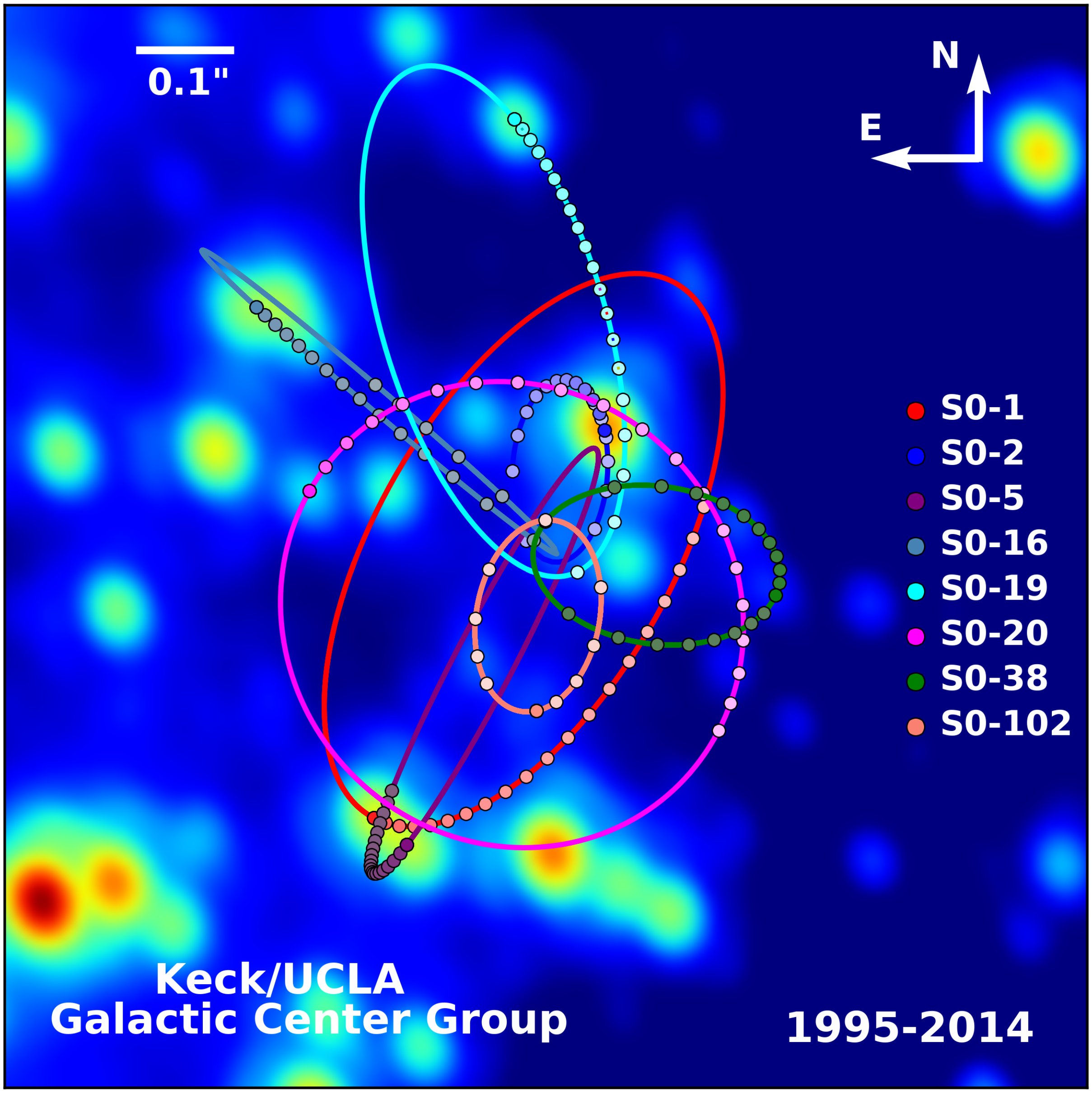

Figure 1: The orbits of stars at the Galactic Center, as mapped using adaptive optics on the Keck telescope by the Galactic Center group at UCLA. The stars follow Keplerian orbits around the supermassive black hole at the center of the Galaxy.