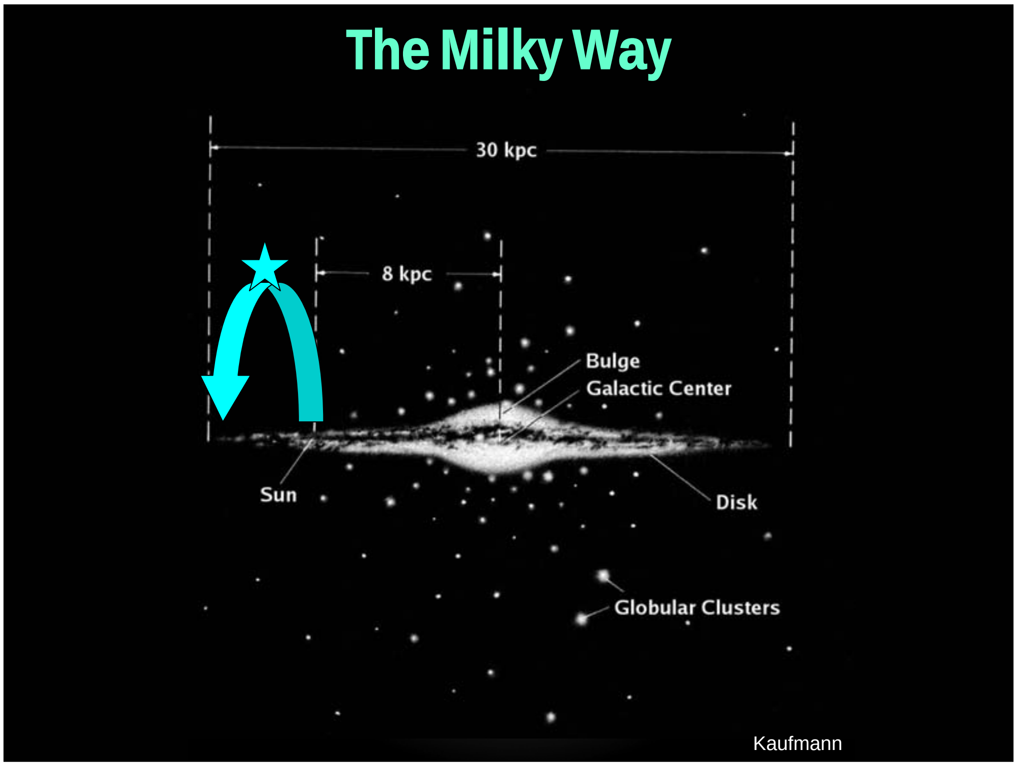
Hypervelocity stars (HVSs) are stars traveling with such extreme speeds that they are no longer bound to the Galaxy. Hypervelocity stars are interesting because they must be ejected by a massive black hole. As a result, hypervelocity stars give us tools to understand the history stellar interactions with the massive black hole and environment of stars around it.



If this is a picture of the Milky Way, the hypervelocity stars we are finding are deep in the halo, at distances of 50 – 100 kpc.

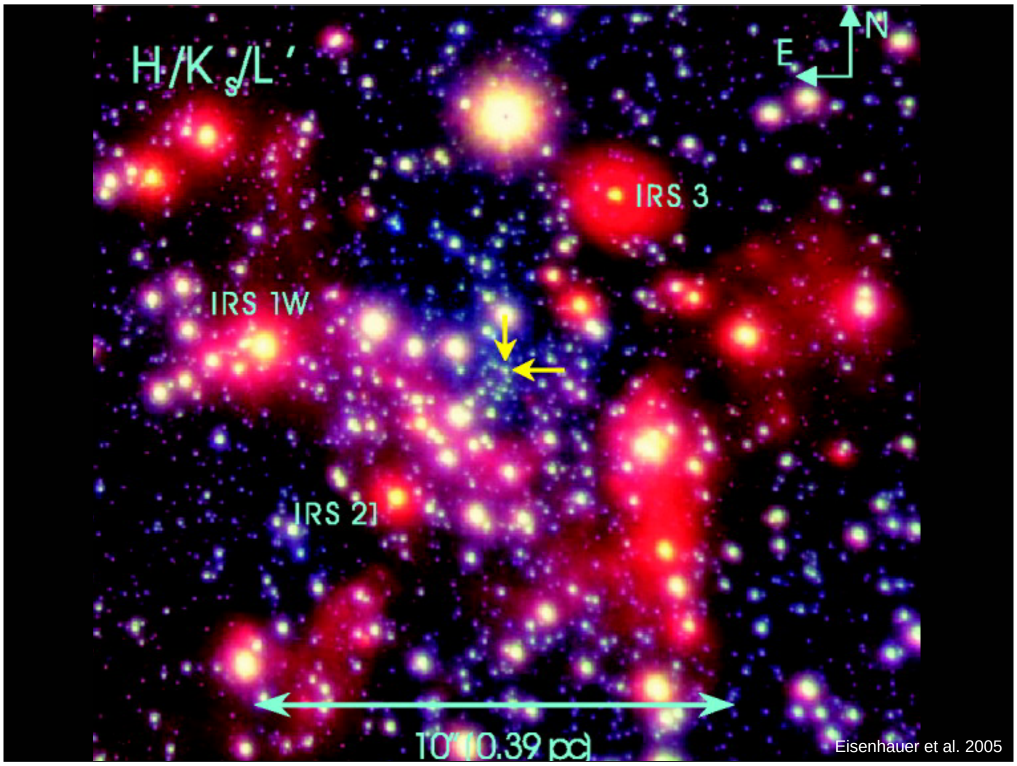
The hypervelocity stars we are finding are also B-type stars. B-type stars are stars that are more massive and much more luminous than the Sun. Because B stars burn their fuel very rapidly, they have relatively short lifetimes of order 100 million years.

In 1947, Humanson and Zwicky first reported B-type stars at high Galactic latitudes. Because B stars are born in the disk and live only a short time, you wouldn't expect to find B stars very deep in the halo. Spectroscopic surveys show that the high-latitude B stars are a mix of evolved (horizontal branch) stars that belong to the halo and some main sequence, so-called "run-away B stars."

These run-away B stars all have travel times constant with a disk origin. Run-away stars are explained by two mechanisms: ejections from stellar binary encounters in young star clusters, or when a former binary companion goes supernova. But getting a large ejection velocity from either of these mechanisms is difficult, and is physically bounded by the escape velocity from the surface of the star. For example, a pair of 3 solar mass stars in a contact binary have an orbital velocity of 240 km/s.

Theoretical simulations (by Leonard 1991, Portegeis-Zwart 2000, and Davies et al. 2002) find that most B-star ejections have velocities below 100 km/s. A few can reach velocities up to 300 km/s. Because these velocities are well below the escape velocity of the Galaxy, run-away B stars travel on bound orbits. Thus they spend most their lives near the apex of their trajectory with small line-of-sight velocities. The point here is that classical "runaway" stars cannot simultaneously have large distance and large velocity.

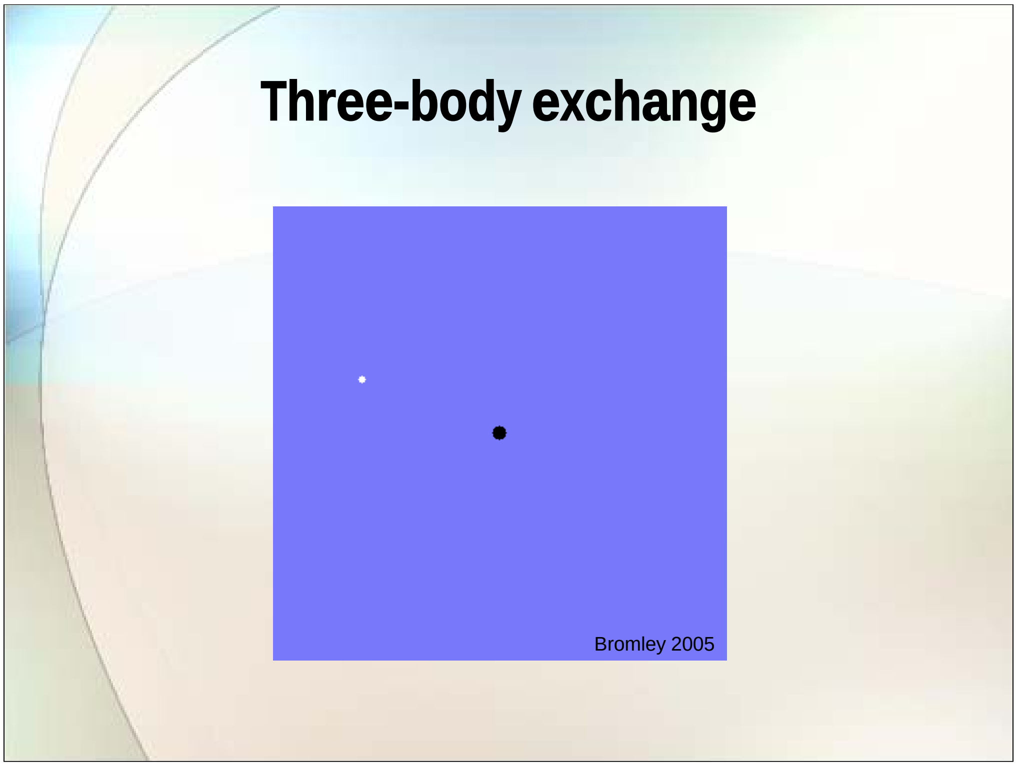
So now let's talk about the very center of our Galaxy.



All galaxies with bulges are thought to harbor supermassive black holes. Some of the best evidence for a supermassive black hole comes from measurements of stellar orbits in our own Galactic Center.

This is a near-infrared image of the central parsec of the Galactic Center. What I want to point out here is that the relative fraction of blue stars to increase towards the center. Spectroscopy shows that these are main sequence B stars, orbiting right near the central black hole. This a puzzle: why are short lived stars found in such a hostile environment, right next to a massive black hole? One class of explanations for these short-lived stars are dynamical mechanisms, such as dynamical friction or 3-body interactions, to bring normal B stars from farther out.

Let’s step back a moment and notice that dynamical processes used to capture stars are just as good at ejecting stars from the Galactic Center. In a prescient Nature paper in 1988, Jack Hills first pointed out that a three-body interaction involving a tight pair of stars and a massive black hole could eject one star at 1000 km/s velocities. He called such objects Hypervelocity Stars. Simply put, hypervelocity stars are a natural consequence of having a massive black hole in a dense stellar environment.

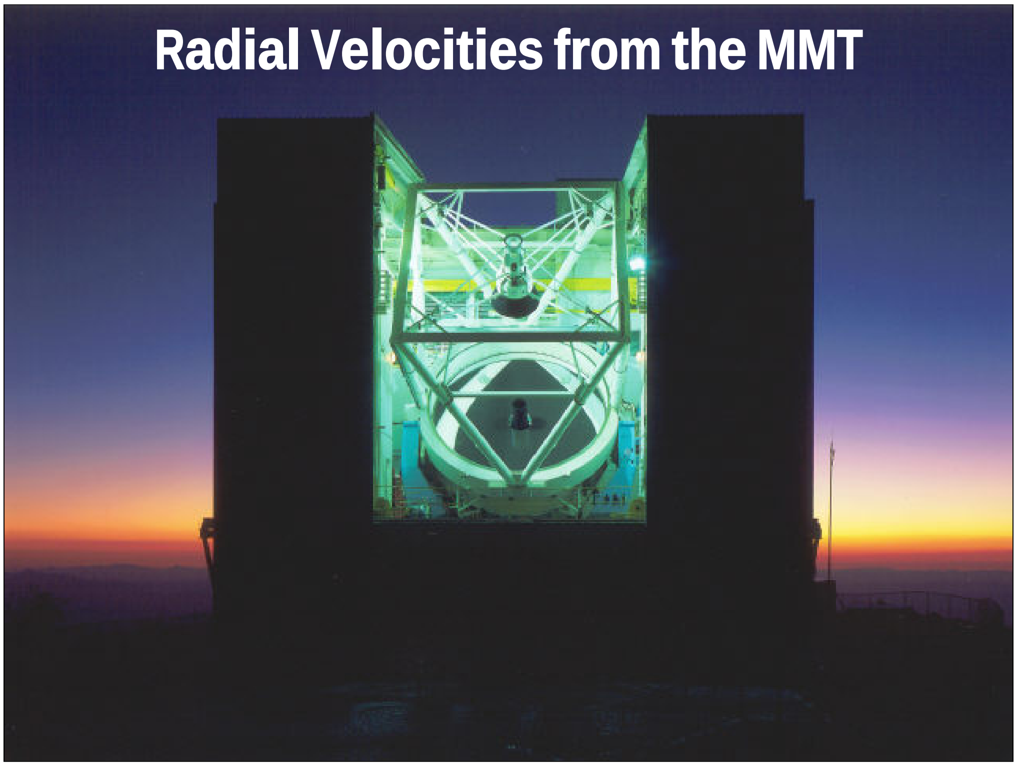


The HVS ejection process is illustrated in this simulation by Ben Bromley.

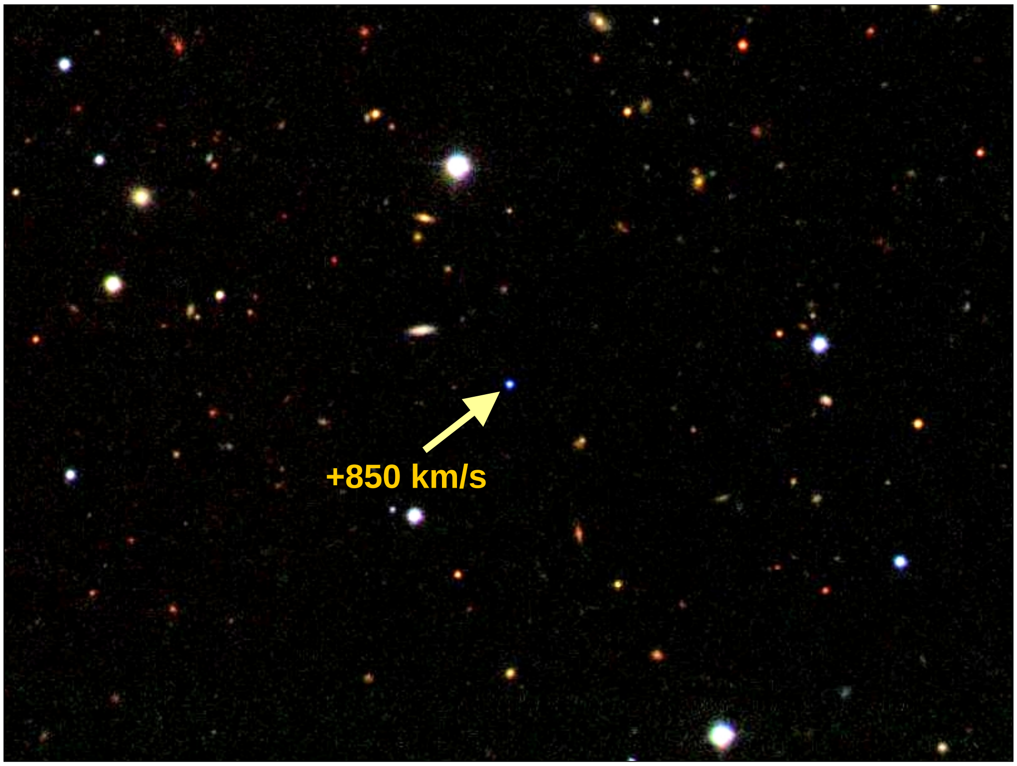
What you see is a tight pair of stars on an orbit approaching the black hole. The moment that the gravitational tidal energy of the black hole exceeds the binding energy of the pair, the pair is broken.

Because the incoming velocity of the pair is much larger than the internal orbital velocity of the pair, the orbital velocity acts as a perturbation on the two stars. The star that is captured by the black hole is bound with a very strong binding energy. And, by conservation of energy, the other star gains a large amount of energy, and so is ejected at a large velocity.

So that’s how you can get a hypervelocity star. The very existence of a hyper-velocity star would provide yet another piece of evidence for a massive black hole at the Galactic Center.

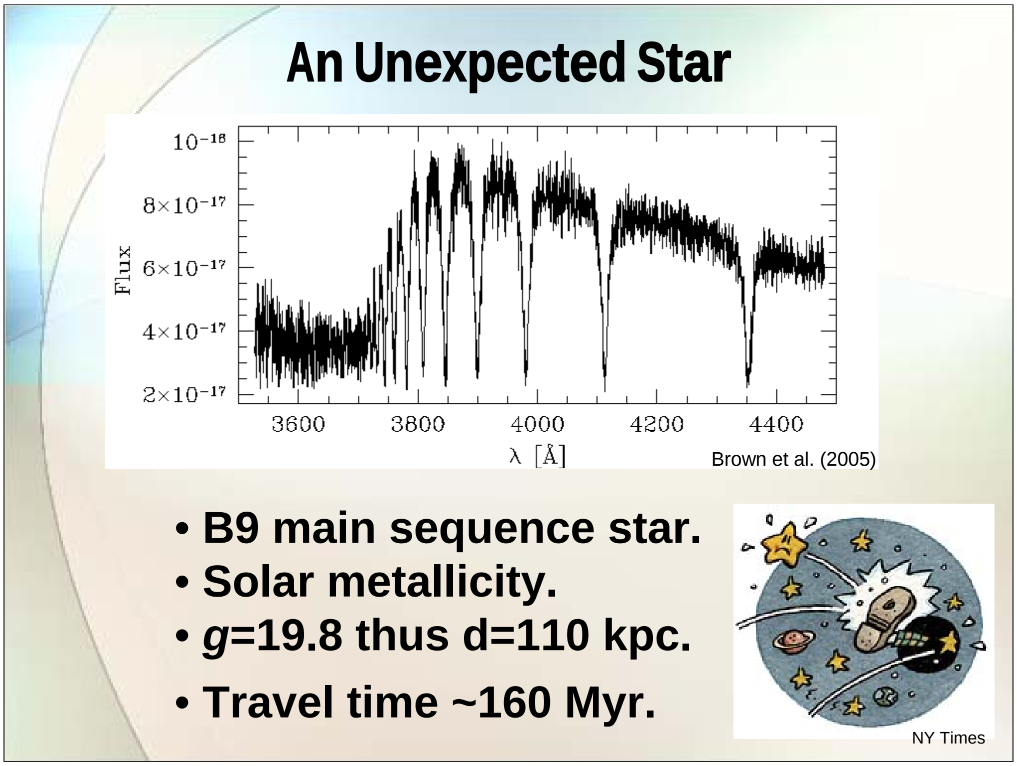


I’ve spent the past few years using the MMT to measure the velocities of distant, blue stars.



As part of this survey, I measured the radial velocity of this star, here. Come to find out, this star is moving away from us at 850 km/s. This is an absurd velocity. Stars near the Sun have relative motions of order 10 km/s. Stars in the halo have different types orbits, with a dispersion around 100 km/s. But 850 km/s makes this star the fastest moving main sequence star in the Galaxy outside the Galactic Center.

This star, though, is 110 kpc away, well beyond the normal confines of the Galaxy. In fact, the star is moving many times the velocity it needs to escape the Galaxy, forever.



This is the discovery spectrum of the first HVS. The lines are the hydrogen Balmer lines; the spectrum is that of a B9 star. We know now it is a main sequence star for two reasons: Uli Heber's work indicates it is a fast rotator, and Fuentes et al (2006) find it is a slowly pulsating B variable. These are both properties of main sequence stars.

We estimate its metallicity from the equivalent width of the Ca K line. As you can see, the Ca line provides poor leverage at the effective temperature of a B9 star. But the fact that we see Ca as strongly as we do suggests that the star's metallicity is approximately solar.

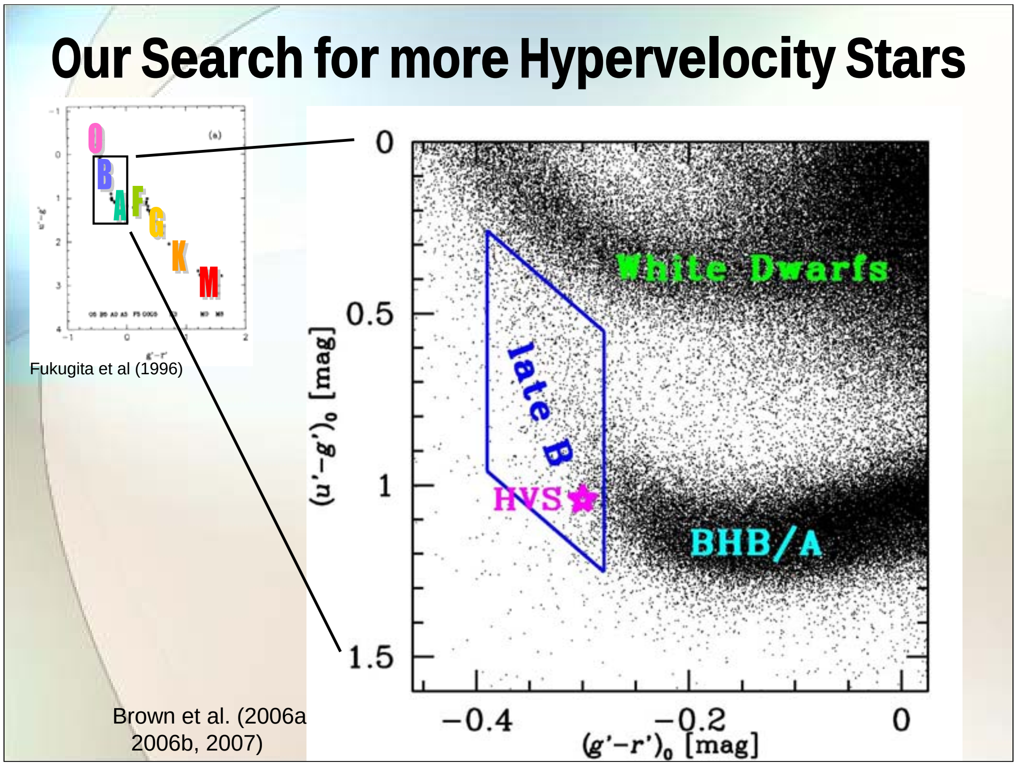
Knowing these two things, we can then estimate its intrinsic luminosity from stellar evolution tracks for a 3 solar mass, solar metallicity star. The difference between the apparent magnitude and absolute magnitude puts the star at a distance of 110 kpc. You might ask, is this star is in another galaxy? No, neither the location, nor the velocity, of the star is consistent with any Local Group galaxy.

If this a main sequence B star from the Milky Way, what could have ejected it at such an extreme velocity? Well, I've already answered that question. Besides explaining the extreme velocity, a hypervelocity star origin is consistent with all the observations:

1. The Galactic Center is full of B-type stars, like the spectral type of our star.
2. The star appears to be metal-rich, consistent with the metal-rich environment of the Galactic Center (and inconsistent with the metal-poor halo).
3. Finally, even if we assume the star's radial velocity is its full space motion, its travel time from the Galactic Center is 160 Myr. This is well within the 350 Myr lifetime of a 3 solar mass star.

This object must certainly be an hypervelocity star.

Finding the first hypervelocity star is exciting, but it would be very interesting to find more. Following our original discovery, two objects, in existing surveys of subdwarf stars, were announced to be HVSs by Edelmann et al (2005) and Hirsch et al (2005). One is a subdwarf O star escaping the Galaxy at 700 km/s and the other is a 8 solar mass B star possibly ejected from the LMC. What I'm going to tell you about now, is a survey we have designed specifically to find new HVSs.



These plots are color-color diagrams of stars in the SDSS. In the upper left plot (for reference) you can see the stellar sequence of different types of stars with different colors, going from red K & M dwarfs up to hot O & B stars.

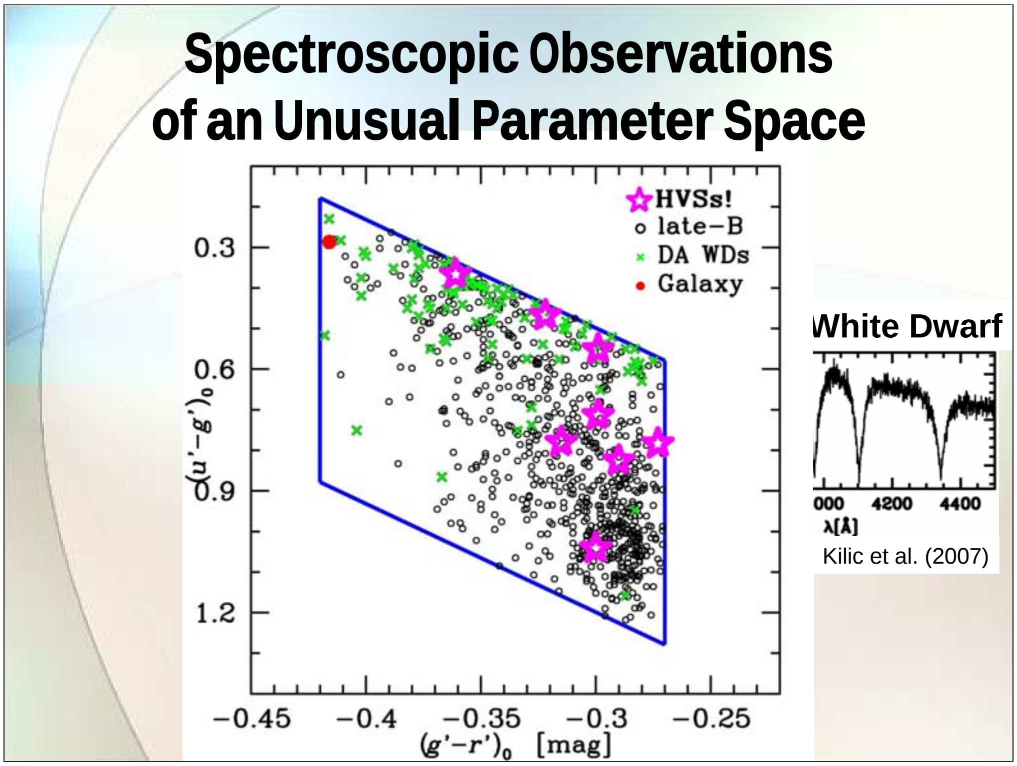
Now the problem with finding new HVSs is that HVSs ought to be extremely rare. Yu & Tremaine (2003) predict that a HVS is ejected once every 100,000 years. This means there are of order 1000 HVSs out to a depth of 100 kpc. So if we want to find more, survey volume is going to be very important.

Surveys of stars in the solar neighborhood have *not* discovered HVSs for this very reason. Even if solar neighborhood surveys were perfectly complete to a depth of 1kpc, there is only a 0.1% chance of finding a HVS in such a small volume.

Our observational strategy is two-fold. Because the density of stars in the halo falls off very steeply, the further out we look, the more we maximize our contrast between hyper-velocity stars and boring, halo stars. Secondly, the stellar halo contains mostly old, low mass stars. Thus we target massive B-type stars, stars with lifetimes consistent with travel times from the Galactic center, but which you don't expect to find in the halo.

The central figure plots every star in SDSS DR5 with these sets of colors. The lower band of objects are stars with A-type colors. A-type stars are relatively luminous, so we can see them far away, but finding a HVS star here will be difficult because you have to contend with vast numbers of blue horizontal branch stars in the halo. Interestingly, there is a faint group of stars with B-type colors, just like the first HVS, that extends up the stellar sequence until it is lost in the mass of white dwarfs. It is this blue parallelogram that defines our survey.

Note that our HVS candidates are not very common. There is only 1 object every 6 square degrees on the sky. But over the past 2 yrs we have obtained spectra for nearly every candidate in our survey. That means we've mapped about 20% of the entire sky available in SDSS DR5. To find rare objects really requires an all-sky survey with good colors, like the Sloan Digital Sky Survey.

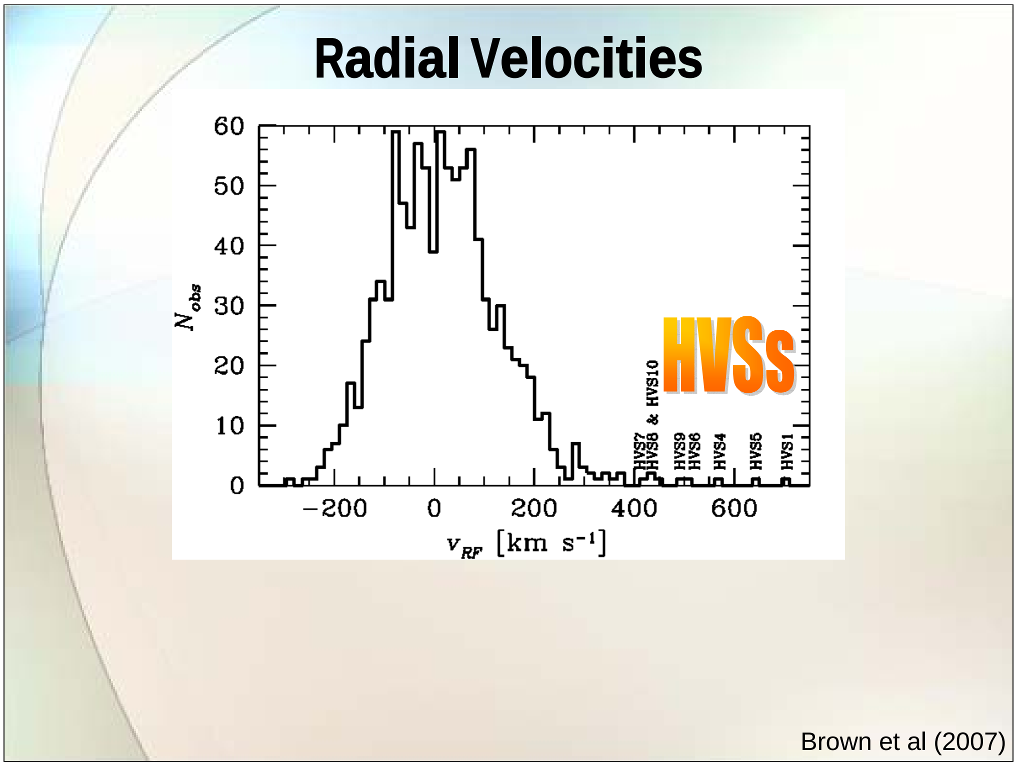


This plot shows the spectroscopic identifications of the targets in our survey, where the blue parallelogram is the same as before. So what are we finding? It turns out that 78% of the objects in our survey are stars of late B-spectral type, just what we're looking for.

21% of the objects are white dwarfs, mostly DA white dwarfs with hydrogen atmospheres. Curiously, these are very unusual colors for DA white dwarfs, colors that suggest they have very low surface gravities. In a collaboration with Mukremin Kilic and Carlos Allende-Prieto, we have analyzed the white dwarf spectra and found that one of the objects has a mass of 0.17 solar masses. This is the lowest mass white dwarf ever found. There are only a handful of such objects known, and they are thought to form in compact binary systems. Indeed, follow-up observations show that this object orbits an invisible companion with an amplitude of 300 km/s every 7.6 hrs (Kilic et al. 2007b).

So is there any hope of us finding another hypervelocity star in all of this?

The answer is Yes! Our survey has discovered not one, but 7 new HVSs. The three from this observing season are so recent that I haven't even published them.

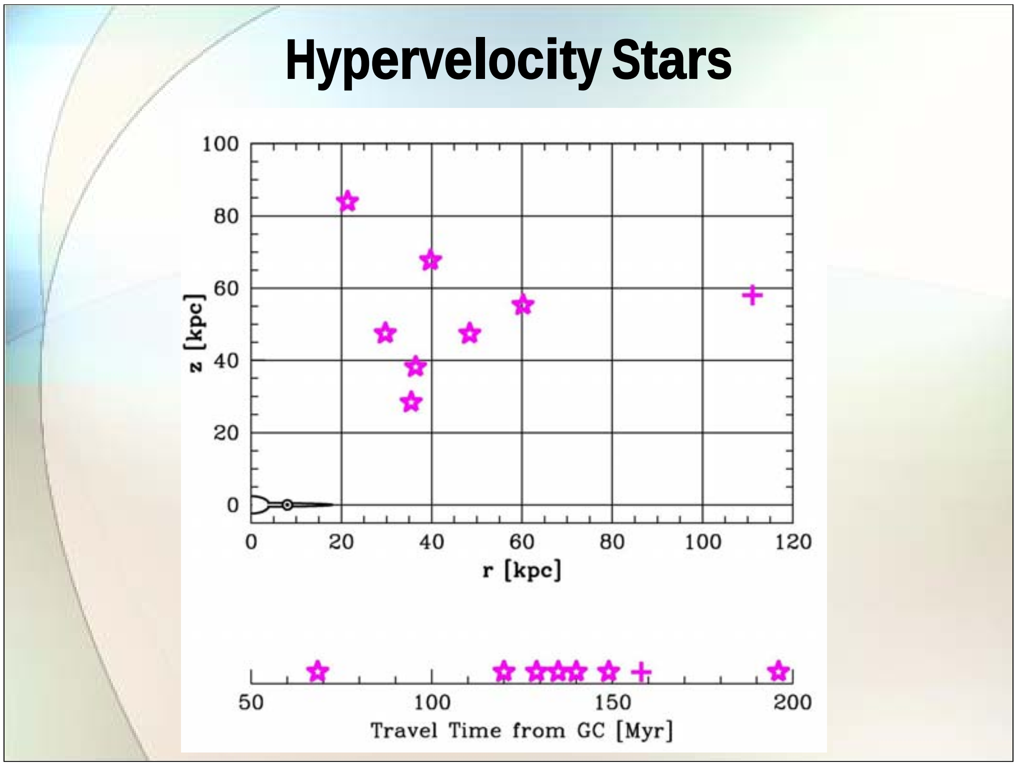


This figure shows the distribution of radial velocities, corrected to the Galactic rest-frame, for the 1018 late B-type stars in our survey.

One interesting result that immediately jumps out at you is that *all* of the HVSs have positive radial velocities. That is they are all moving *away* from us, none are moving towards us. This is consistent with the picture of them coming from the Galactic Center.

If you iteratively clip 3-sigma outliers, the sample has a dispersion of 105 km/s, which means most of these stars are normal halo stars.

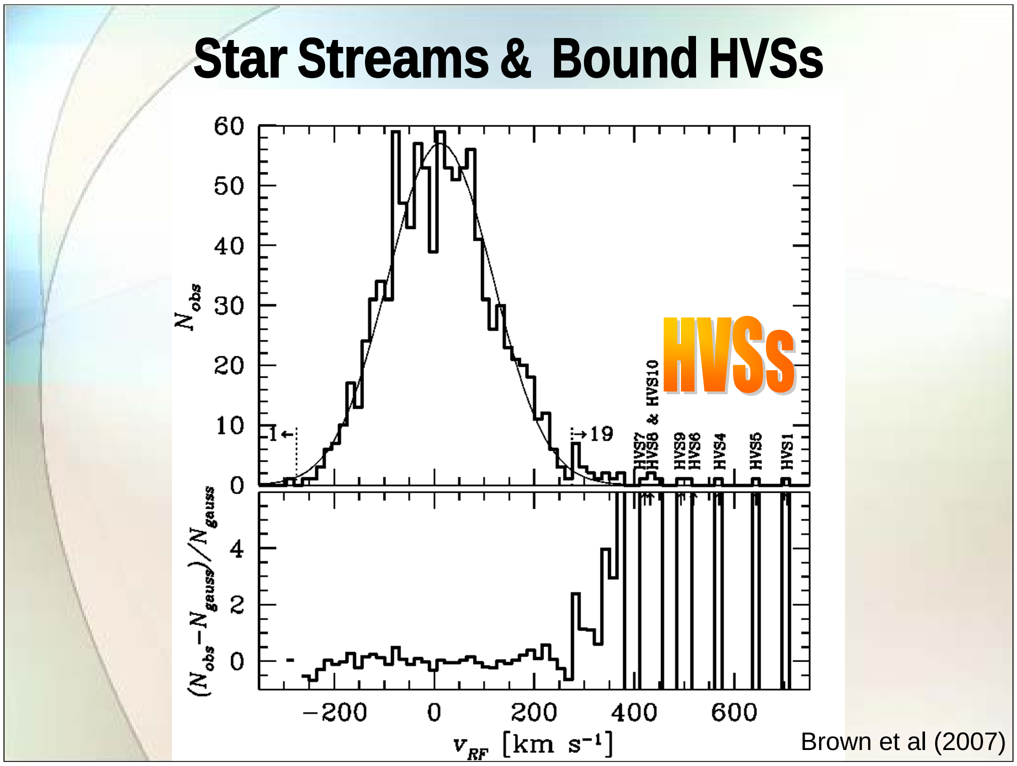
The HVSs, by comparison, are 4-6-sigma outliers from this distribution. The escape velocity of the Galaxy, at the approximate distance of these stars, is 300 - 400 km/s. So the HVSs are never coming back.



Where are the hypervelocity stars? If we assume the new discoveries are main sequence B stars like the first ones, then they are located 50 to 100 kpc from the Galactic Center. This plot shows the stars' distances above the Galactic plane and in the direction along the Galactic plane, where the Galactic Center is at 0. Note that to keep our exposure times short, our survey does not sample stars as faint as the first HVS (marked with a plus sign).

Knowing distance and velocity, we can estimate the stars' travel times from the Galactic Center, plotted below. These travel times are really upper limits, because we assume the radial velocities are the full space motions of the stars. That said, the travel times are all well below the 350 Myr lifetime of a 3 solar mass star, consistent with a Galactic Center origin.

Interestingly, the travel times are spread over 100 Myr. Thus the HVSs we observe do not come from a single ejection event. In other words, it appears that no massive star cluster or dwarf galaxy has fallen in to the Galactic Center in the past couple hundred Myr and produced a coherent burst of HVSs. Rather, the different travel times suggest there is a more continuous ejection process at work. I'll come back to this in a little while.

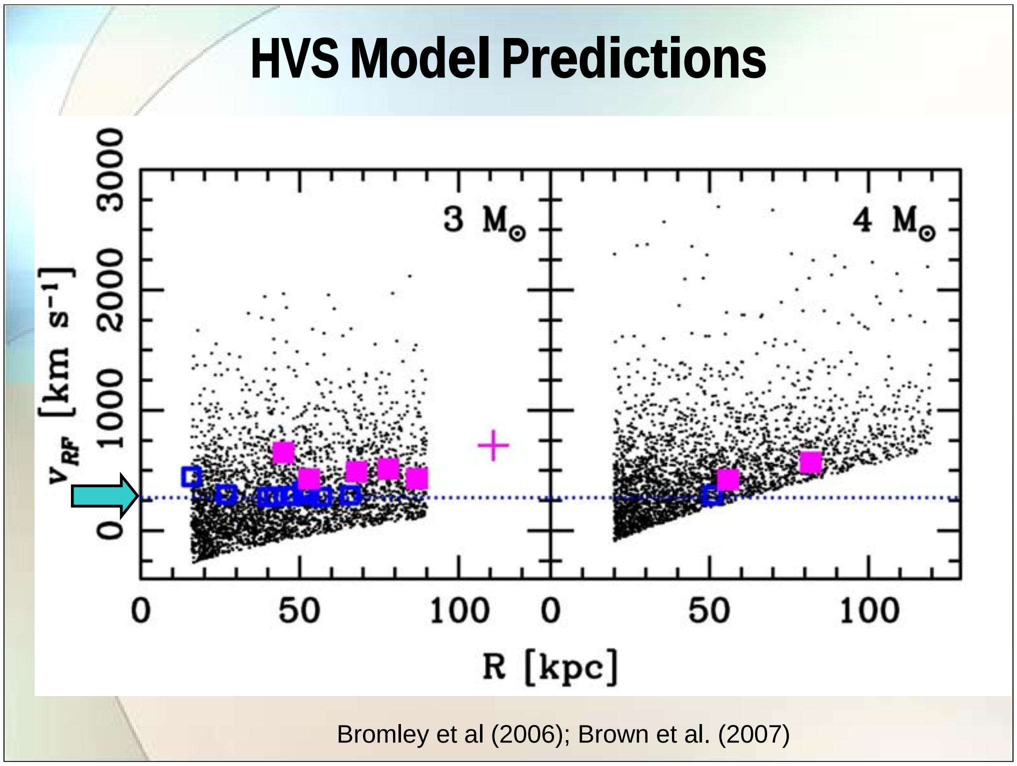


Let me point out two other curious things in the velocity histogram. First, what about the bumps and wiggles in the velocity histogram – is this real velocity structure in the halo? Quite possibly. I've matched the velocities and positions of our stars to Sgr stream models, and it turns out a few dozen stars are likely Sgr Stream members, including part of the clump near -100.

Another curious thing, if you now ignore the unbound HVSs, is a significant excess of stars moving away at ~300 km/s. They are likely bound objects, are so aren't leaving the Galaxy, but the asymmetry is curious. The asymmetry becomes clearer if I show the best-fit Gaussian to this distribution, and then plot below the fractional difference of the data from the Gaussian model. So you see a lot of low significance variation until you suddenly hit the stars above 275 km/s.

Given this Gaussian distribution, we expect to find 3 stars below -275 km/s and 6 stars above 275 km/s. We observe 19 stars, not counting the HVSs, above 275 km/s. The likelihood of randomly drawing such an asymmetry from the observed distribution is 1 in 10,000. Thus this excess of positive velocity outliers appears significant at the 4 sigma level.

What can these stars be? Main sequence run-aways don't make sense, because these stars are both fast and distant. If the outliers are halo stars on radial orbits, we would expect to find equal numbers moving towards and away from us, contrary to observations. Compact binary systems may also produce outliers in the velocity distribution, but they should be distributed symmetrically, again contrary to observation. The most plausible explanation, I argue, is the HVS mechanism.



Before we go any further, we need to know the *distribution* of radial velocities that we'd expect for HVSs ejected by a MBH. In a collaboration with Ben Bromley and Scott Kenyon, we have simulated the disruption of binaries containing 3- and 4-solar mass stars, matched to our survey of B-type stars.

It turns out that the ejection velocity depends not only on the parameters that you would expect, such as the separations and masses of the binary and black hole, but also on the orbital phase of the binary when it encounters the MBH. We use a Monte Carlo code to create catalogs of ejected stars, and then integrate the orbits of ejected stars though a Galactic potential. For these calculations, we assume the stars are ejected at a random time during their main sequence lifetime.

The plots show the resulting distribution of distances and velocities of stars ejected by our model. This envelope here is the lifetime of the stars: only the fastest HVSs can survive to large distance. Interestingly, you can get stars ejected at many thousands of km/s, but such an ejection is very rare. Most of the ejections have lower velocities. In fact, some of the stars are found falling back onto the Galactic Center. Clearly, many HVS are bound, but stars below here are impossible to identify, simply because their radial velocities are indistinguisable from stars in the rest of the Galaxy.

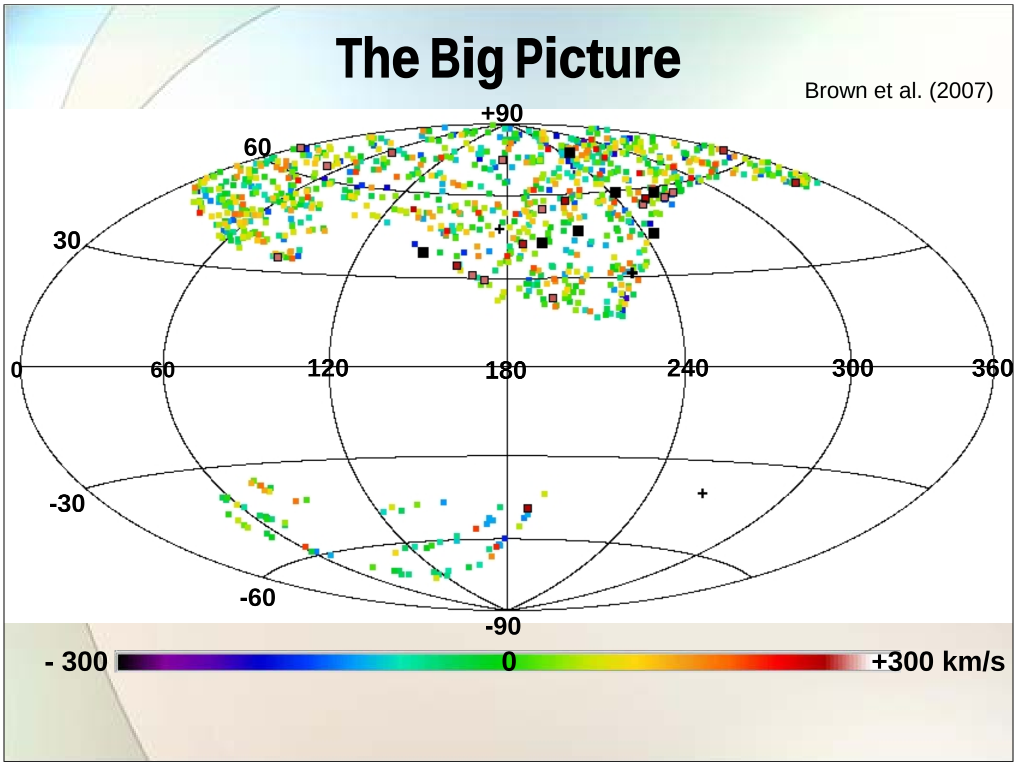
So over the volume sampled by our survey, the simulations predict there should be comparable numbers of HVSs (above that 275 km/s threshold) ejected onto bound and unbound orbits.

Now we observe 7 unbound HVSs in our survey (the plus sign is the first HVS). Seven unbound HVSs suggests that 7 of the excess of 9 3- and 4-solar mass velocity outliers (blue squares) are plausibly bound HVSs. 7 and 9 is pretty good agreement, given the small number statistics. However, it is possible that other HVS mechanisms may be at work. O'Leary and Loeb (2007) predict that single stars will be ejected by encounters with stellar mass black holes orbiting the central MBH. Such HVSs tend to have lower ejection velocities, and thus may account for additional HVSs on bound orbits.

Suffice it to say, stars are certainly being ejected on bound trajectories, and we appear to see them in our survey.

The existence of bound HVSs tells us something about the nature of the stars. Demarque and Virani (2007) argue that the Galactic Center contains a large number of old, low mass stars, and thus our HVSs should mostly be blue horizontal branch stars, evolved stars that are burning helium in their cores. But there is a problem here. Blue horizontal branch progenitors are low mass stars stars that live billions of years. If the Galactic Center has been happily ejecting low mass stars for billions of years (mostly on bound orbits), we'd expect to find blue horizontal branch stars falling back onto the Milky Way with large negative velocities. We don't see that.

And so the absence of stars moving towards us with large negative velocities suggests that our hypervelocity stars are unlikely to be evolved stars, but rather are recently ejected main sequence stars, like the first one. This is interesting, because the types of stars we are finding in principle tells us about the types of stars orbiting near the massive black hole.



The figure here is a sky map, in Galactic coordinates. The dots show the locations of the late B-type stars in our survey, and color indicates their velocity. Our HVSs are completely off this color scale, and indicated by these 7 solid squares. The pluses mark the other HVSs, the first one (here) and the other two found by the Edelman, Hirsch, and collaborators. The possibly bound HVSs are plotted as open squares.

Isn't it striking … all of the unbound HVSs from our survey are grouped together in the Galactic anti-center. The only exception is the HVS associated with the LMC.

Now, statistically, there is a 2-sigma probability of randomly drawing all seven HVSs from our survey in the anti-center hemisphere. So this isn't statistically significant, but is certainly suggestive.

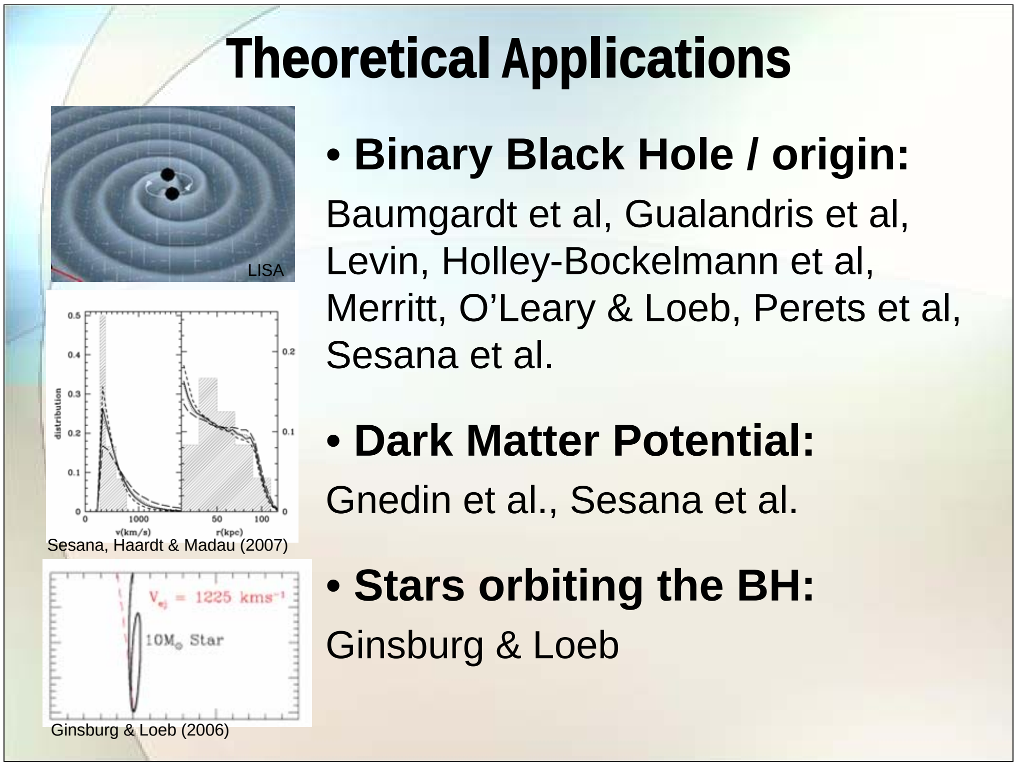
This spatial distribution is interesting because it is linked to the star's origin. Remember that only the fastest (unbound) hypervelocity stars survive to largest distances. Because the Sun is located 8 kpc from the Galactic center, our survey reaches 16 kpc deeper towards the anti-center than towards the center. So perhaps this distribution merely a selection effect, but a selection effect we expect for a Galactic Center origin: a larger fraction of unbound HVSs towards the anti-center.

There is another, much more provocative, explanation for the spatial structure: a binary black hole in the Galactic Center. Theoretical work (by Gualandris et al (2005, 2007), Sesana et al (2006, 2007), Merritt (2006), and others) shows that a binary black hole will preferentially eject HVSs in its orbital plane, and thus produce a band of HVSs on the sky. So perhaps this band of HVSs is telling us our Galaxy hosts a pair of massive black holes in its center.

Radio interferomtery provides observational constraints against the presence of an equal mass black hole binary in the Galactic Center. This has prompted others, including Levin (2005), Baumgardt et al (2006), and Perets et al. (2006, 2007), to focus on the idea of intermediate mass black holes. If IMBHs exist, they are likely formed in massive core-collapse star clusters (like those seen near the Galactic Center). As the IMBH spirals in towards the central black hole, it should eject HVS stars along the way. A circular inspiral will result in an band of hypervelocity stars, while an inspiral on a very eccentric orbit will result in bursts of hypervelocity stars ejected in broad jets.

There are, however, a couple problems with the IMBH picture. The orbital plane of an in-spiraling black hole is constantly perturbed. Baumgardt et al (2006) argues that HVSs may in fact be ejected rather isotropically during an in-spiral event. Furthermore, in-spirals occur on ~1 Myr time scales, whereas we observe HVS travel times we observe are spaced by many 10s of Myr.

What we really need to find is a set of HVSs with common travel times to test the binary black hole hypothesis.

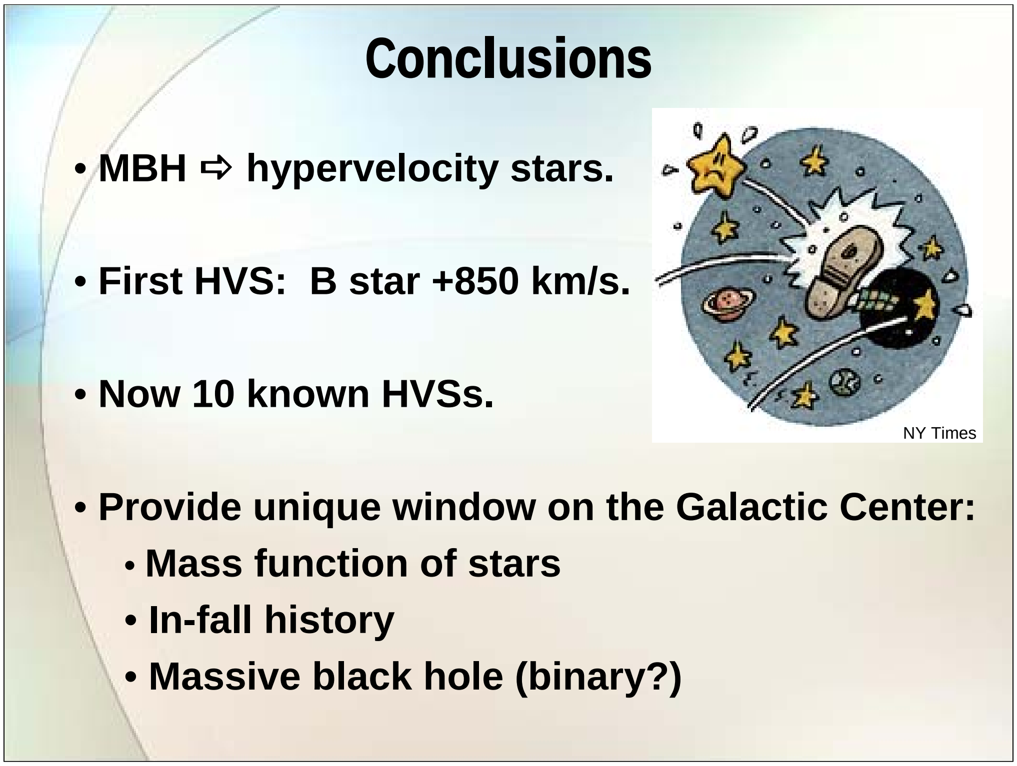


There are a number of interesting applications of HVSs. Besides the spatial signature of a binary black hole, a growing body of theoretical work shows that HVSs will have a different spectrum of ejection velocities and ejection rates from a binary black hole vs. a single massive black hole. As we discover more hypervelocity stars, this is potentially something we can test.

Another application is measuring the gravitational potential of the Galaxy. Gnedin et al (2005) show that any deviation of a HVS's trajectory from the Galactic Center is a great way of measuring the shape of the dark matter potential. In effect, the HVSs integrate up the potential as they travel out of the Galaxy. See also Sesana et al. (2007)

Ginsburg & Loeb (2006, 2007) suggest that the stars on highly eccentric orbits in the Galactic Center hole may be the former companions to HVSs.

Clearly, there are a lot of directions we can go with the HVSs. To make progress on the broader astrophysical questions requires a larger sample of hypervelocity stars, and so we are focusing our efforts on discovering more of these interesting objects.



In conclusion:

1. A massive black hole, in a dense stellar environment like the Galactic Center, will inevitably eject hypervelocity stars.
2. We have discovered the first HVS, traveling 850 km/s. The star is a 3 solar mass main sequence B star, just like the stars seen orbiting very near the massive black hole, but this star is destined to wander alone in the depths of inter Galactic space. In fact, the very existence of such a star is yet another piece of evidence for a super massive black hole at the Galactic Center.
3. In the past 2 years we have discovered seven more HVSs with the MMT, bringing the total sample of HVSs to 10.
4. Our HVSs provide a truly unique window on the types of stars orbiting around massive black holes, the history of these stars interacting with the black hole, and possibly the presence of a massive black hole binary.
5. There is a lot of interesting follow-up work to do. The future of HVSs appears…unbound!