Production of the Fastest Luminous Stars in the Universe:

Semi-relativistic hypervelocity stars (SHS)

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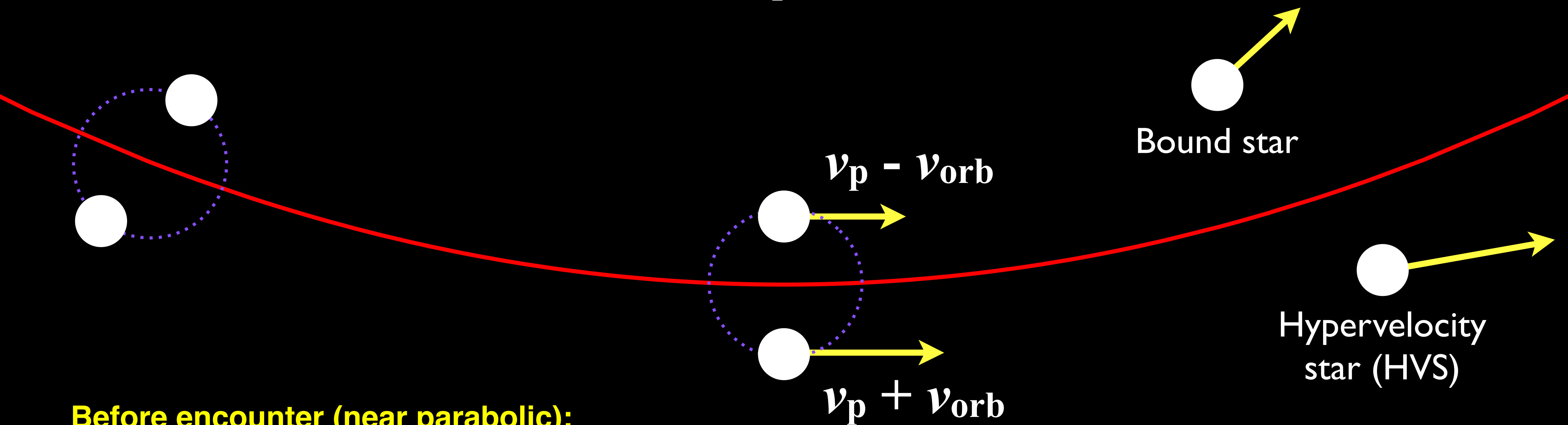
In collaboration with Abraham Loeb

Outline

- The Hills mechanism and a speed-limit for hypervelocity stars (HVS).
- The fastest known luminous stars at present: The S-stars.
- We have to go faster: The Hills mechanism with a SMBH and the production of “semi-relativistic” HVS (SHS).
- Description of three-body experiments: Method and inputs.
- Characteristics of the population.
- Detection.
- Identification?

Hills' Mechanism (production of HVS)



Before encounter (near parabolic):

$$\frac{1}{2}v_{\mathrm{p}}^2 - \frac{GM_{\mathrm{h}}}{r_{\mathrm{p}}} = 0$$

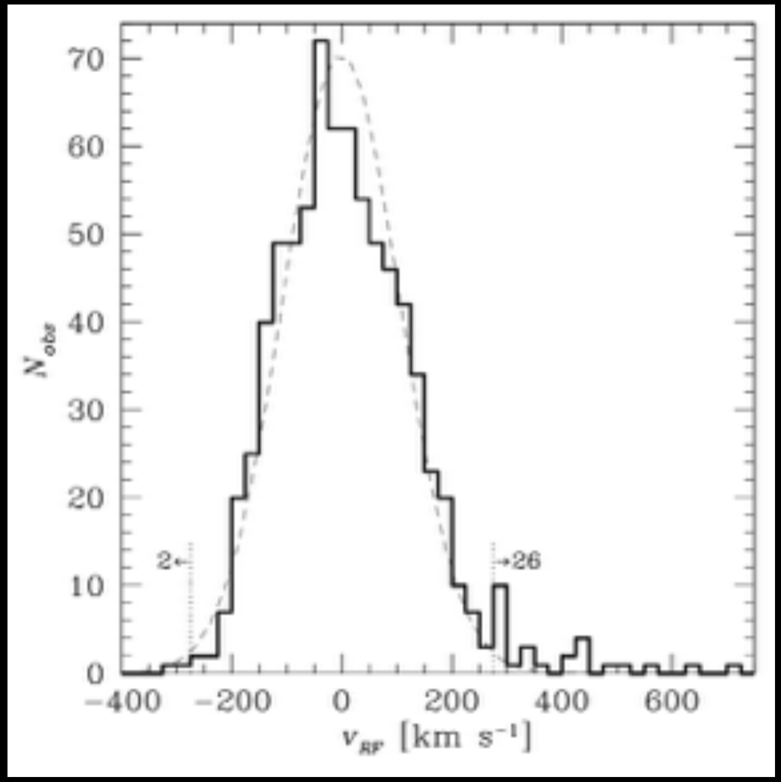
After encounter:

$$\frac{1}{2}v_{\infty}^2 = \frac{1}{2}(v_{\mathrm{p}} + v_{\mathrm{orb}})^2 - \frac{GM_{\mathrm{h}}}{r_{\mathrm{p}}}$$

$$\frac{1}{2}v_{\infty}^2 = \frac{1}{2}(v_{\mathrm{p}}^2 + 2v_{\mathrm{p}}v_{\mathrm{orb}} + v_{\mathrm{orb}}^2) - \frac{GM_{\mathrm{h}}}{r_{\mathrm{p}}}$$

$$v_{\infty} \simeq \sqrt{2v_{\mathrm{p}}v_{\mathrm{orb}}}$$

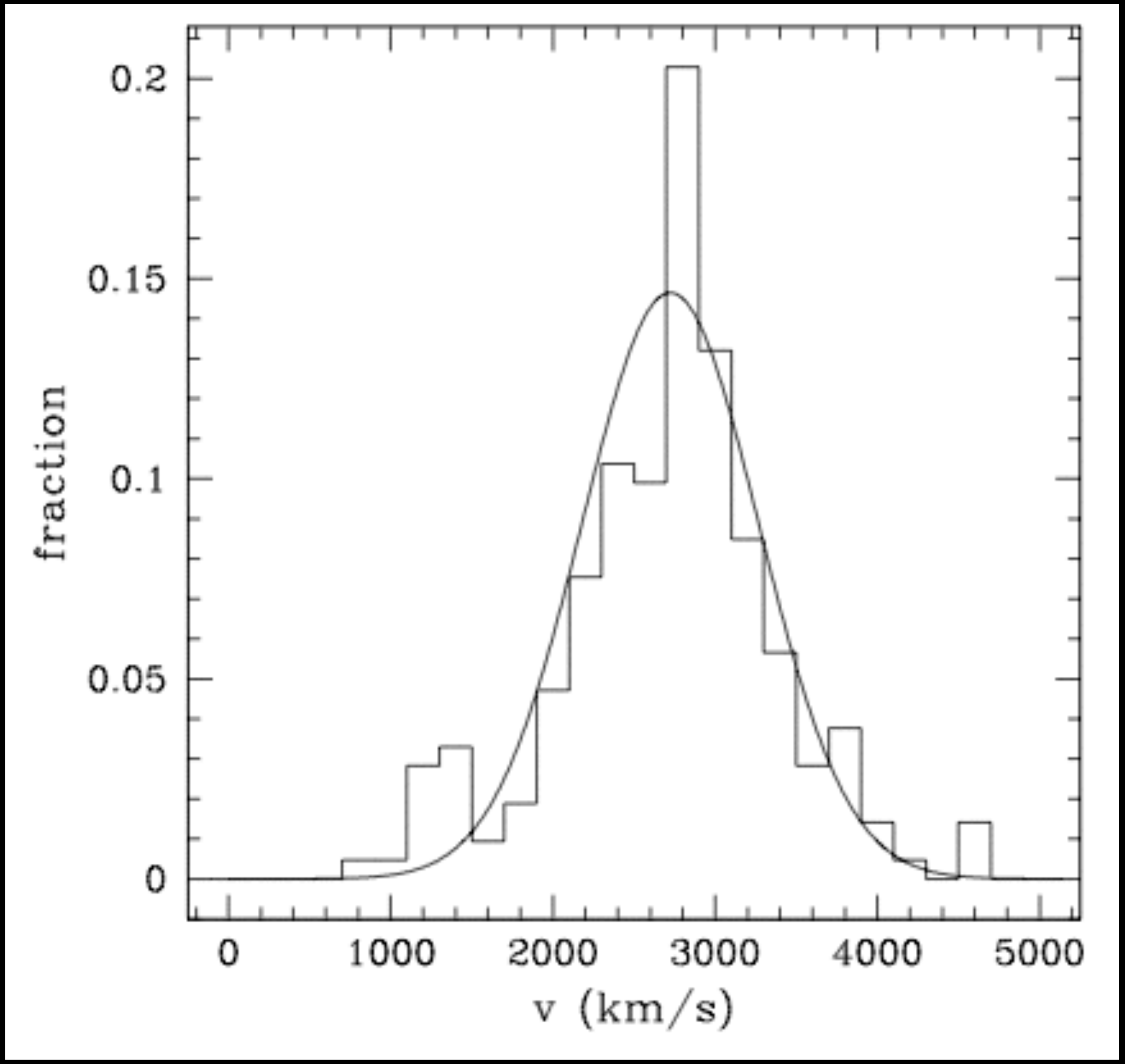
Unbound from galaxy, velocity vector points back to galactic center. Binary disruption is the most plausible.



Brown+ 2011

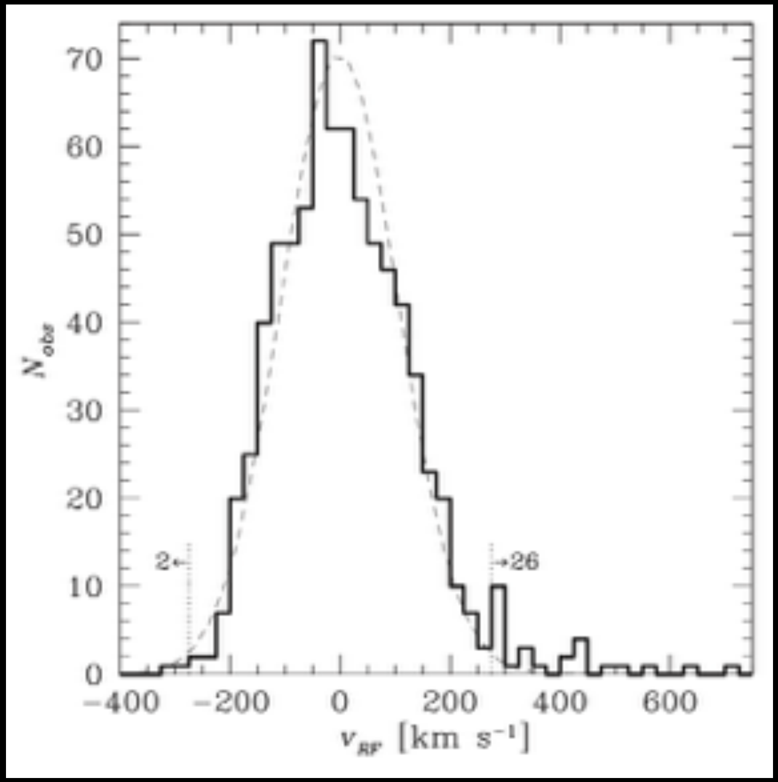
HVS are fast, but the fastest?

Predicted velocity distribution for 4+4 solar mass binaries, 0.1 AU separation



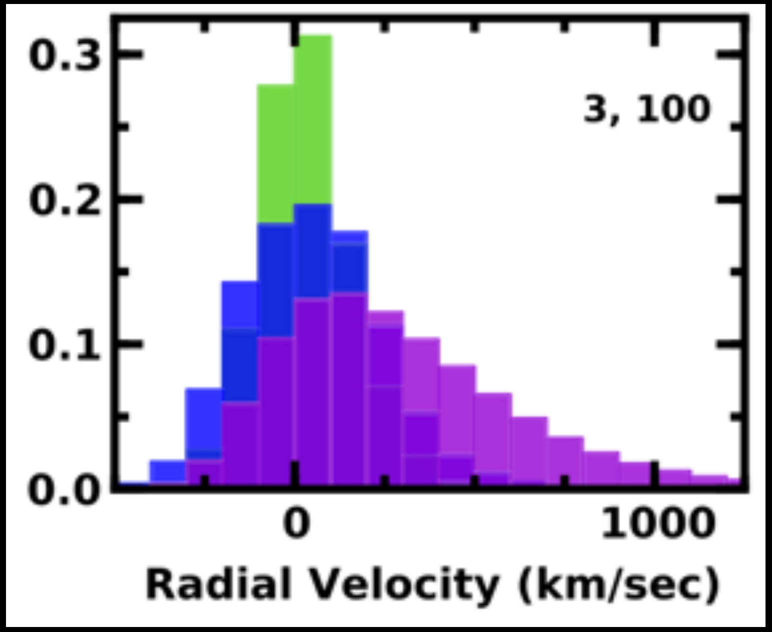
Kenyon+ 2006

Observed distribution, present day



Brown+ 2011

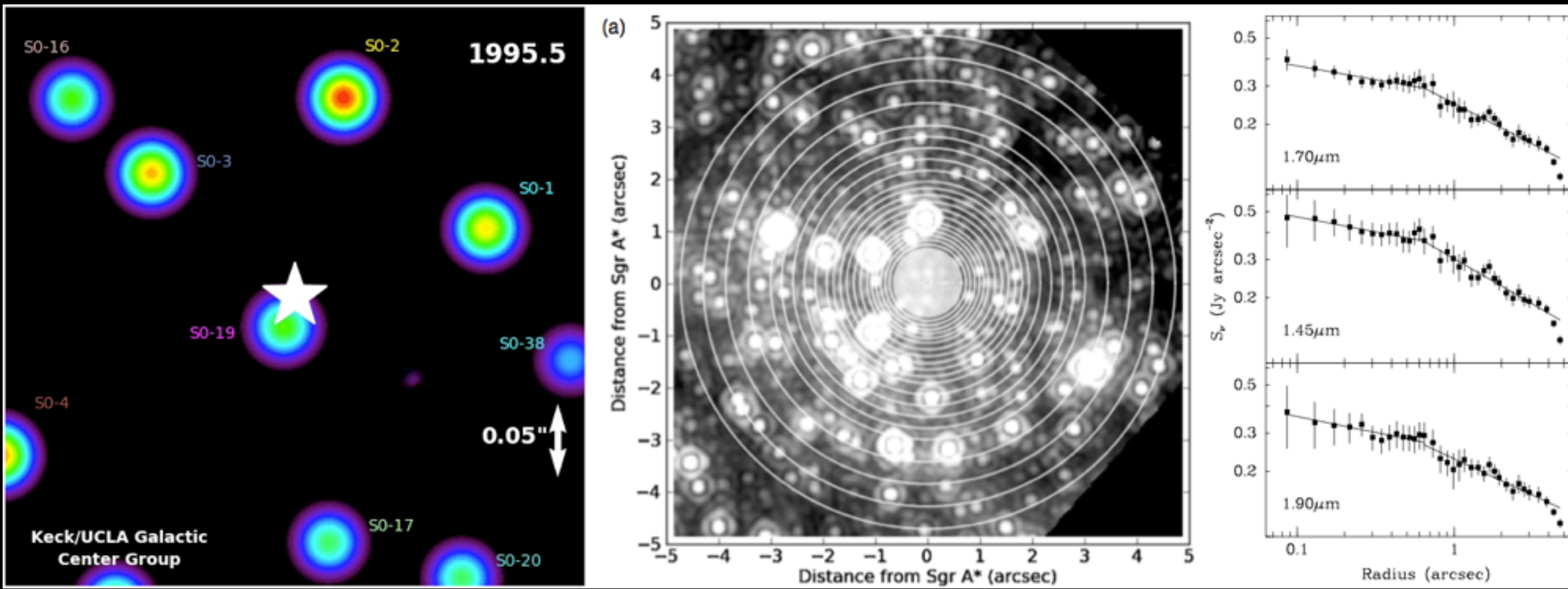
GAIA era



Kenyon+ 2014

Based on Sari+ 2010

Faster stars we know about: The S-stars



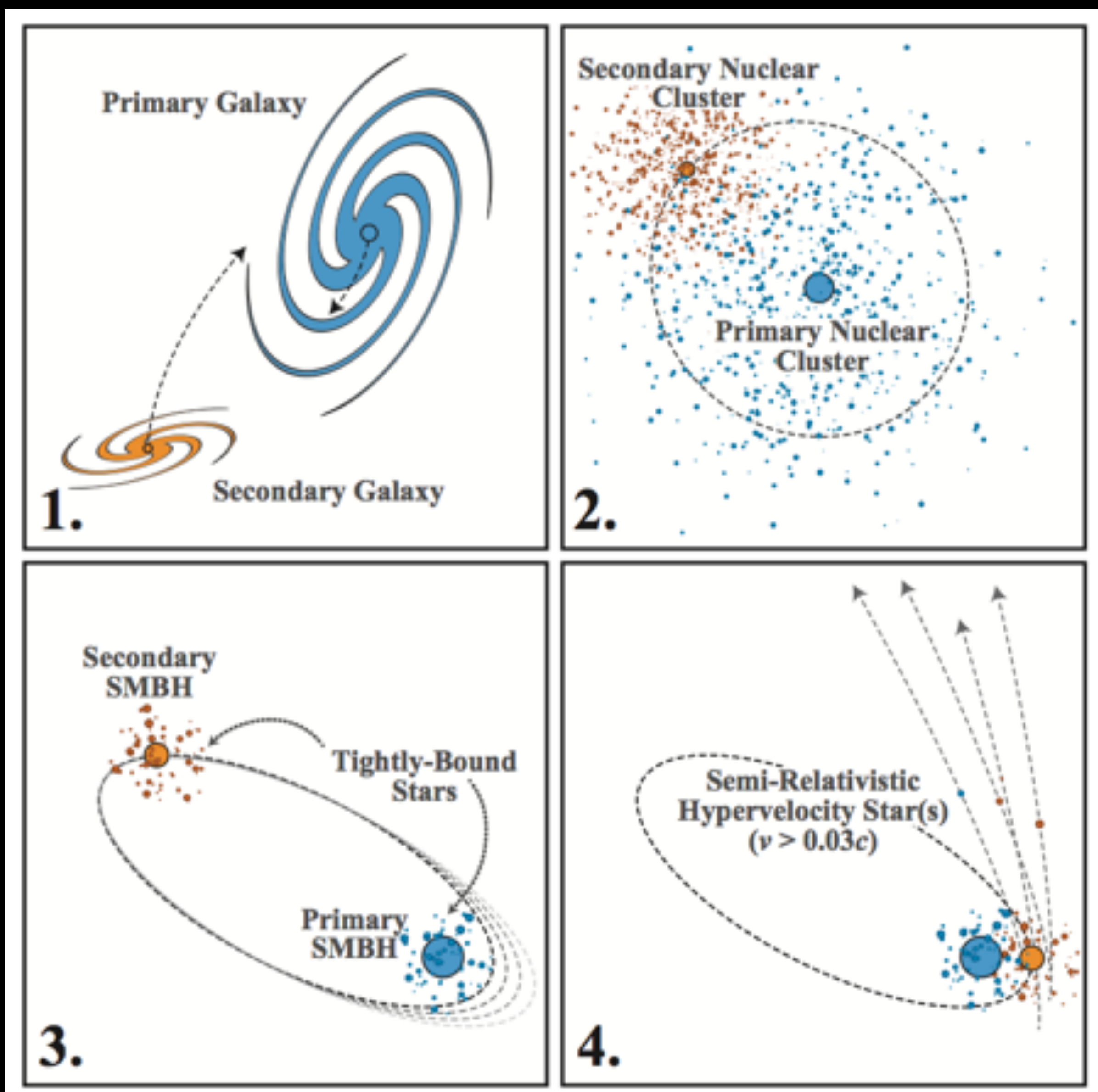
Yusef-Zadeh+ 2012

- Typical velocities are a few thousand km/s (similar to HVS).
- **BUT:** The fastest known, S0-16, 12,000 km/s at periapse!
- Faster stars likely exist that are closer than S0-16, but are too dim to see individually. Density distribution seems to flatten interior to ~1” (at 1”, v = 1,000 km/s).

In principle, stars can be arbitrarily close to

What if we could set the S-Stars free?

Mergers of SMBHs: Liberators of the S-stars.

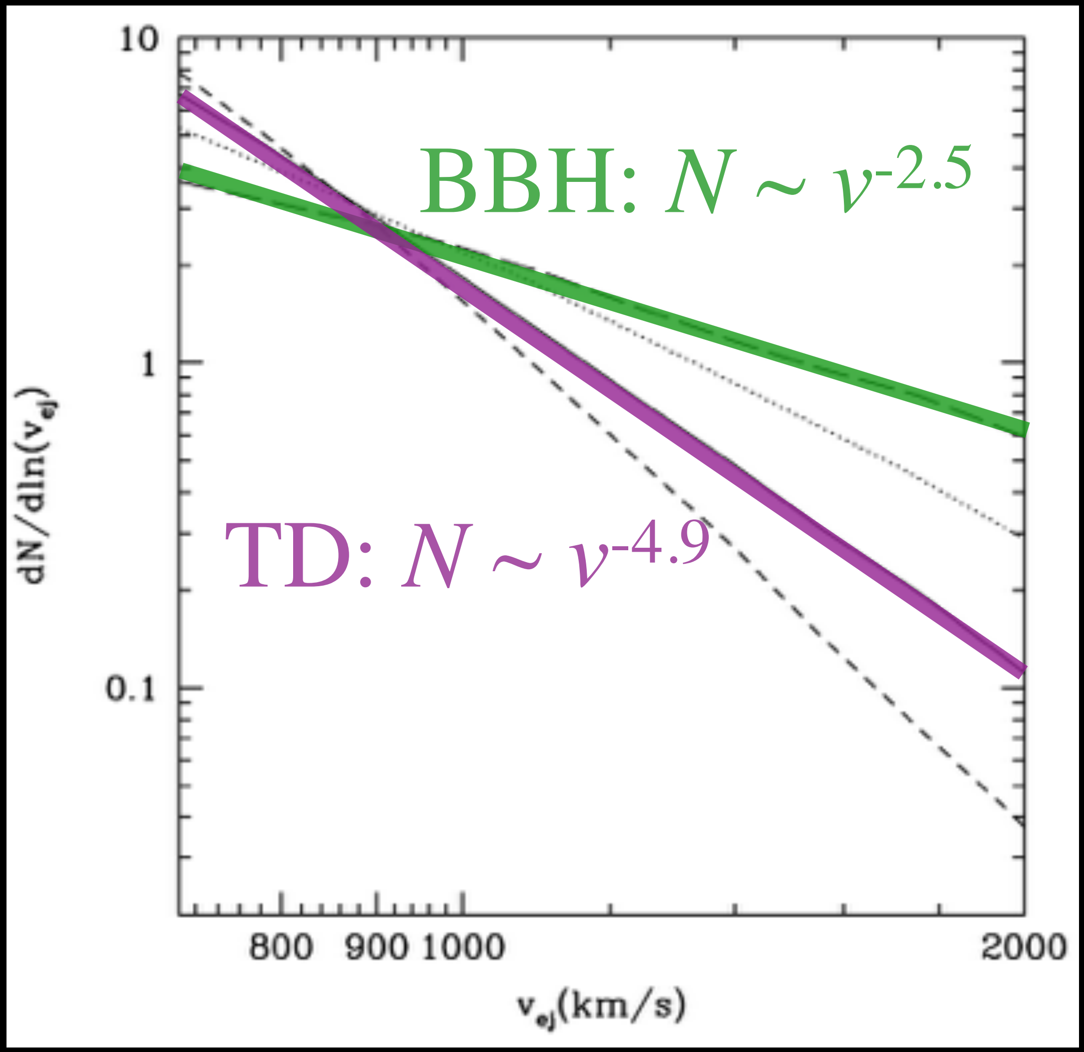


Guillochon & Loeb, in prep.

1. Two galaxies, each hosting a SMBH, merge.
2. The two SMBHs sink into a common core, each still surrounded by its own nuclear cluster.
3. Eccentricity of the secondary is excited by stellar dynamics.
4. Stars both originally bound to the primary and the secondary are ejected. **All stars originally bound to the secondary are eventually removed.**

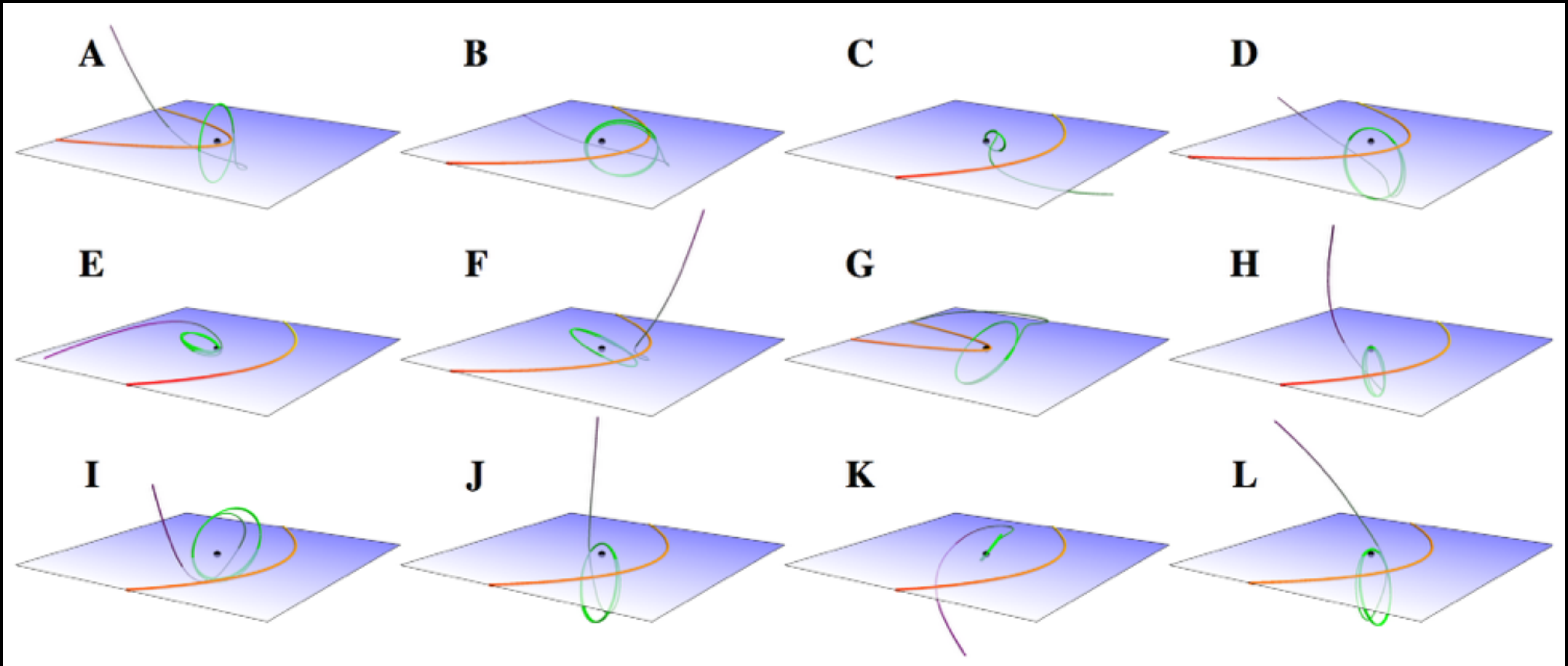
Idea is not entirely original, however most literature has considered only the star originally bound to the *primary.*

- First noted by Quinlan 1996.
- Further refinements by Yu & Tremaine 2003, Sesana 2006, 2007a, 2007b.
- Most only consider the most common ejections from the outer parts of the cluster (where most of the stars reside).
- One thing they did not notice: The relatively shallow power-law for this mechanism *extends to much higher velocities*.
- What we did was consider the stars originally bound to the *secondary,* and stars that are much more tightly bound to begin with (such as the S-stars).



Sesana+ 2007

Setup: Numerical three-body experiments



Guillochon & Loeb, in prep.

- Simulations performed in *Mathematica* using a “projection” differential solver.
- Advantages: Easy data analysis and visualization, guaranteed numerical accuracy to a specified precision (I’ve performed tests where conserved quantities are maintained to octuple precision, ~64 digits of precision).
- Disadvantage: Slooooooow…
- All systems are constrained to have a maximum error of 10^{-14}.

Inputs

- To calculate the total population of HVS in the universe, we need to know the number of SMBH mergers.

    1. Draw dark matter halos (HMFCalc, hmf.icrar.org).

    2. Randomly draw a list of secondary galaxies to merge with based on merger statistics (Fakhouri+ 2010).

    3. Draw galaxies for those halos (Moster+ 2010).

    4. Draw bulge-to-total for each galaxy (Bluck+ 2014).

    5. Use bulge mass-SMBH relation (McConnell & Ma 2013).

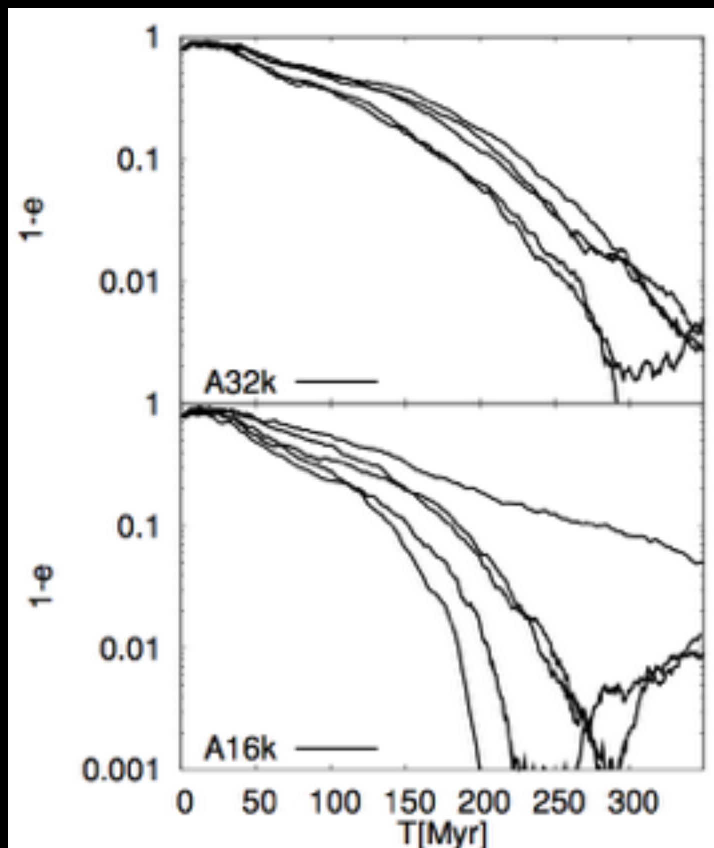
- With our list of black hole mergers, now randomly draw three-body configurations.

    - Configurations where tertiary has large *a* are more likely (density ~ $r^{-7/4}$). Because of this, we split the calculations into bins of *a*. We presume collisions deplete stars interior the two-body relaxation distance.

    - More massive secondaries host more stars, and thus most configurations involve very massive black holes (> 10^8).

    - Eccentricities are presumed to be thermal, orientations random.

Secondary orbits are



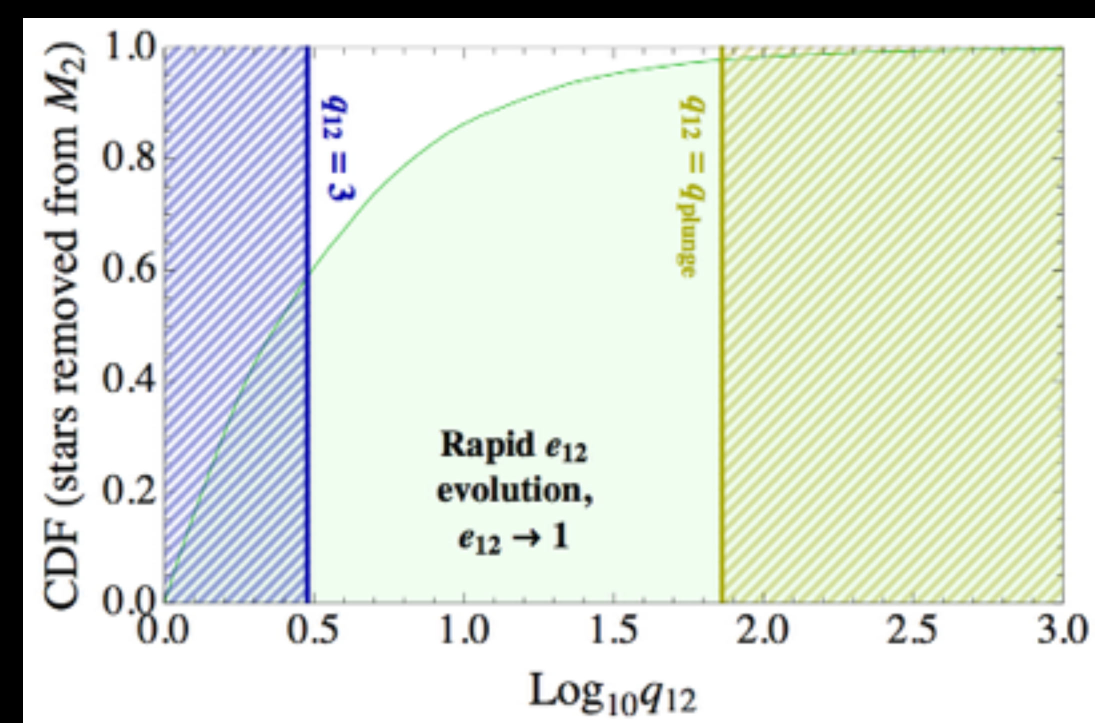
Iwasawa+ 2011

- Motivated by N-body simulation results of Iwasawa+ 2011 where orbits become radial due to interactions with

$$T_e = 2 \times 10^8 \left(\frac{M_1}{10^{10} M_\odot} \right)^{3/2} \left(\frac{M_2}{10^8 M_\odot} \right)^{-2} \left(\frac{a_{\rm stall}}{4 \text{ pc}} \right)^{3/2} \text{ yr}$$

Important constraints:

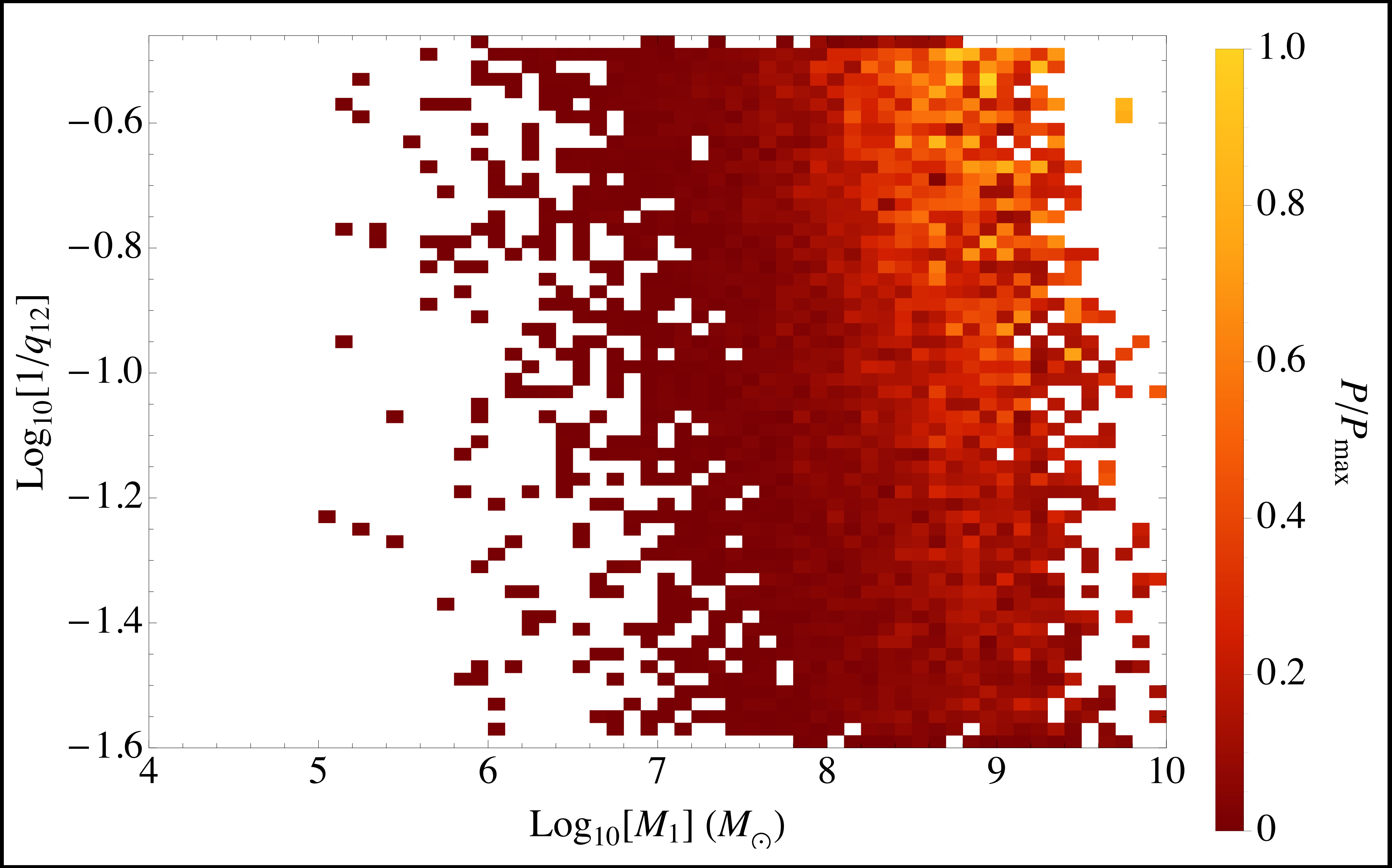
- Near-equal SMBH binaries do not acquire large eccentricities (orbit common barycenter, Sesana 2010).
- Low-mass secondaries also do not acquire large eccentricities.
- Eliminates about 50% of SHS.
- **Note:** Have tested with constant eccentricity of 0.8 for all systems (rather than plunging), get similar results.



Guillochon & Loeb, in prep.

Origin systems for SHS:

The largest SMBH mergers contribute the most

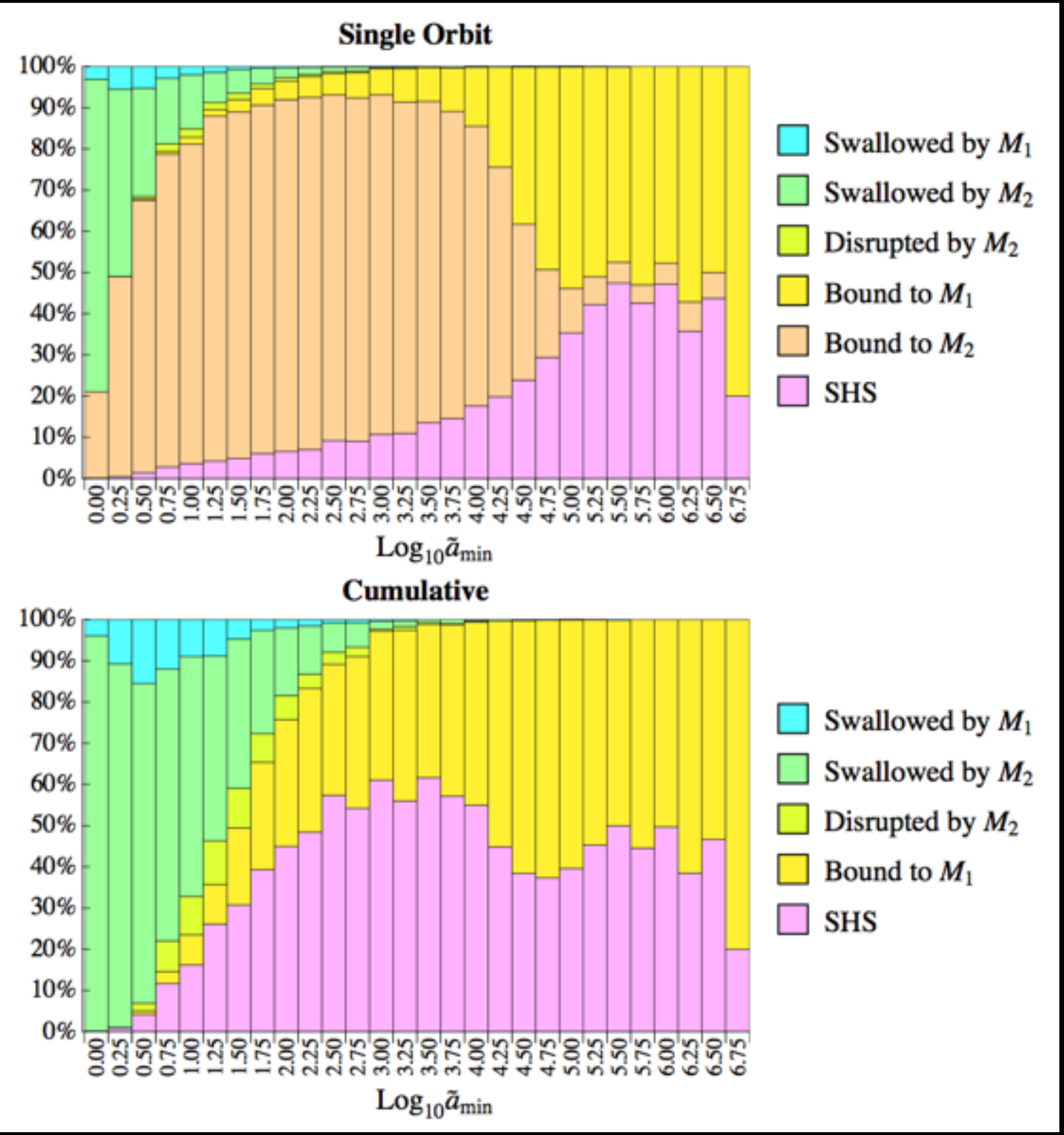


Loeb & Guillochon, in prep.

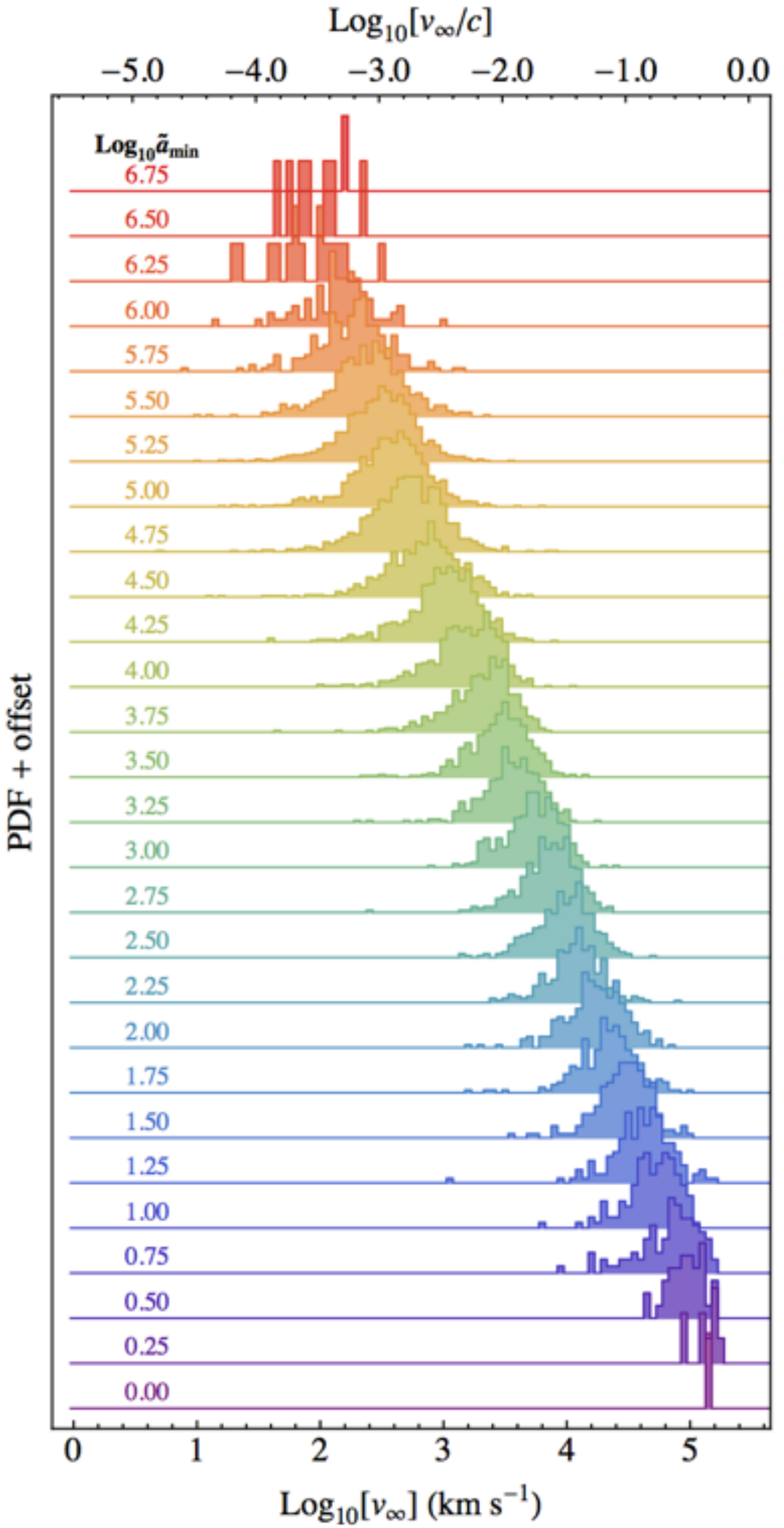
Results:
Fates of removed stars

$$\tilde{a}_{\rm min} \equiv a_{23}/r_{\rm IBCO,2}$$

- Most objects remain bound to the secondary over a single orbit, but eventually, all stars are removed from the secondary.
- When close to the secondary initially, many stars end up being swallowed by the secondary (a few by the primary, or tidally disrupted by the secondary).
- Further away, roughly equal numbers of stars become bound to the primary or SHS.



Guillochon & Loeb, in prep.

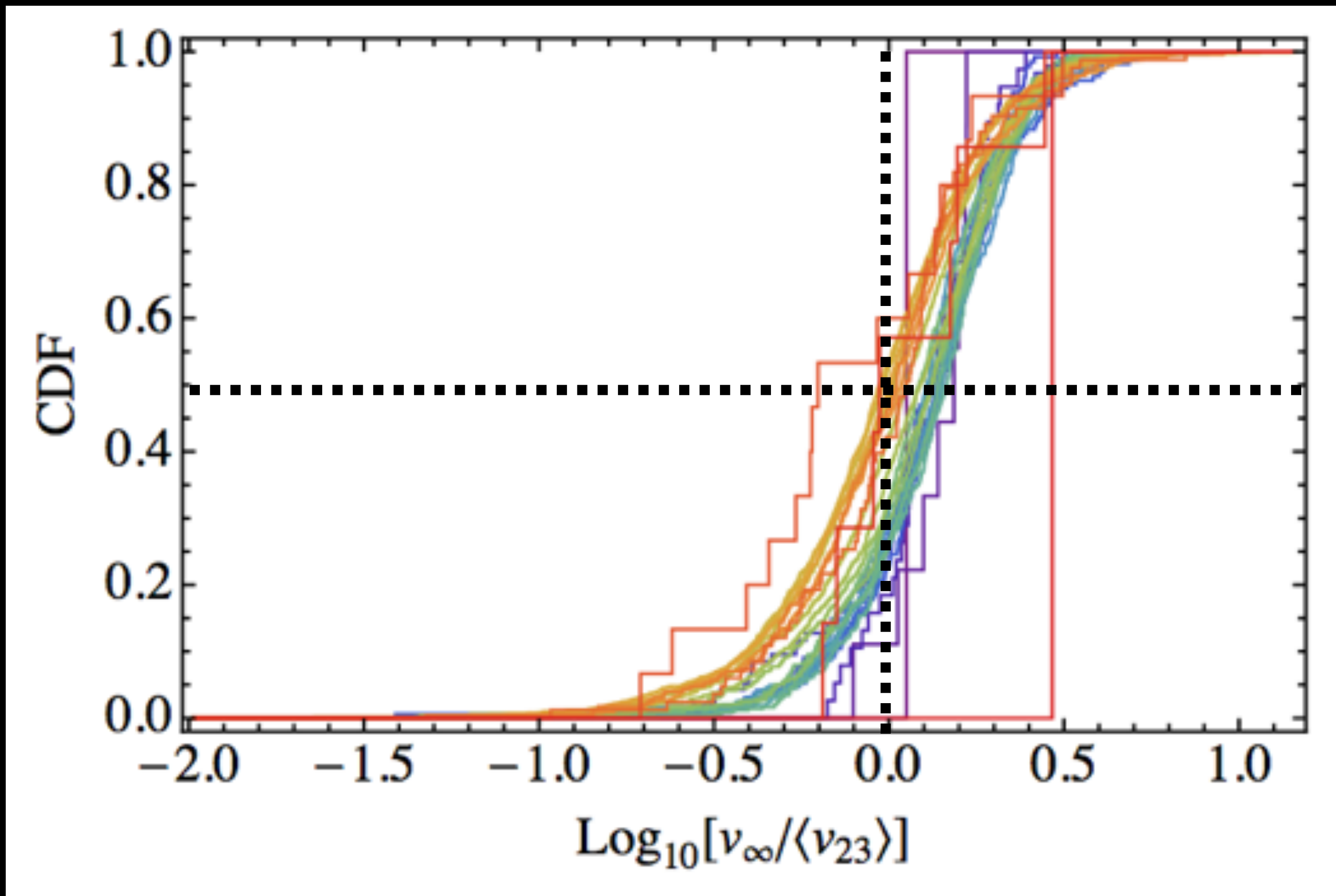


Guillochon & Loeb, in prep.

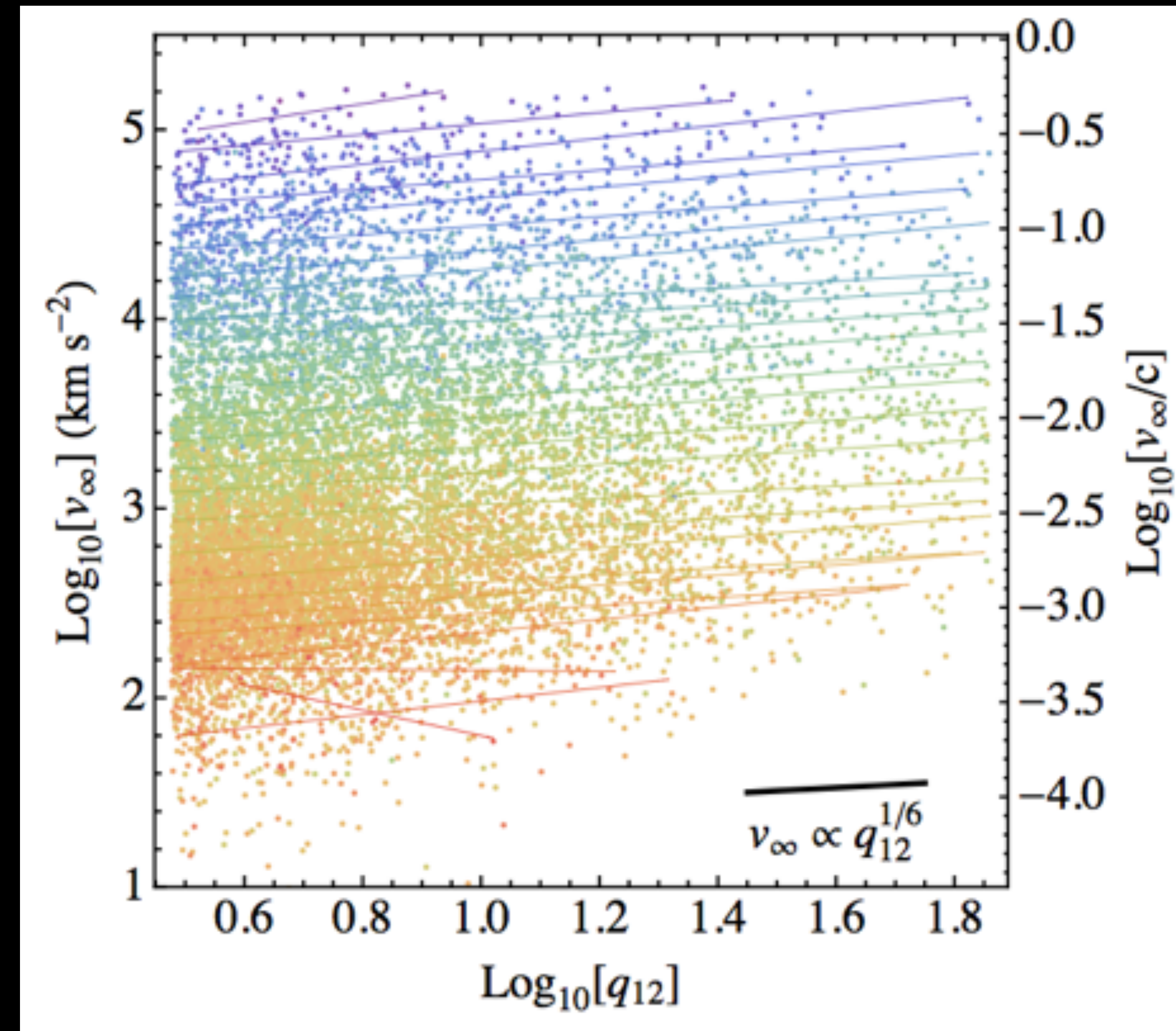
Distributions of velocity

- Each distribution constructed from 4,096 3-body scattering experiments.
- Velocity distributions approximately Gaussian (same as HVS, Bromley+ 2006).
- At small and large separations, number of SHS reduced because they are either destroyed (small a) or because a is larger than the secondary's sphere of influence.

Distributions of velocity, cont.

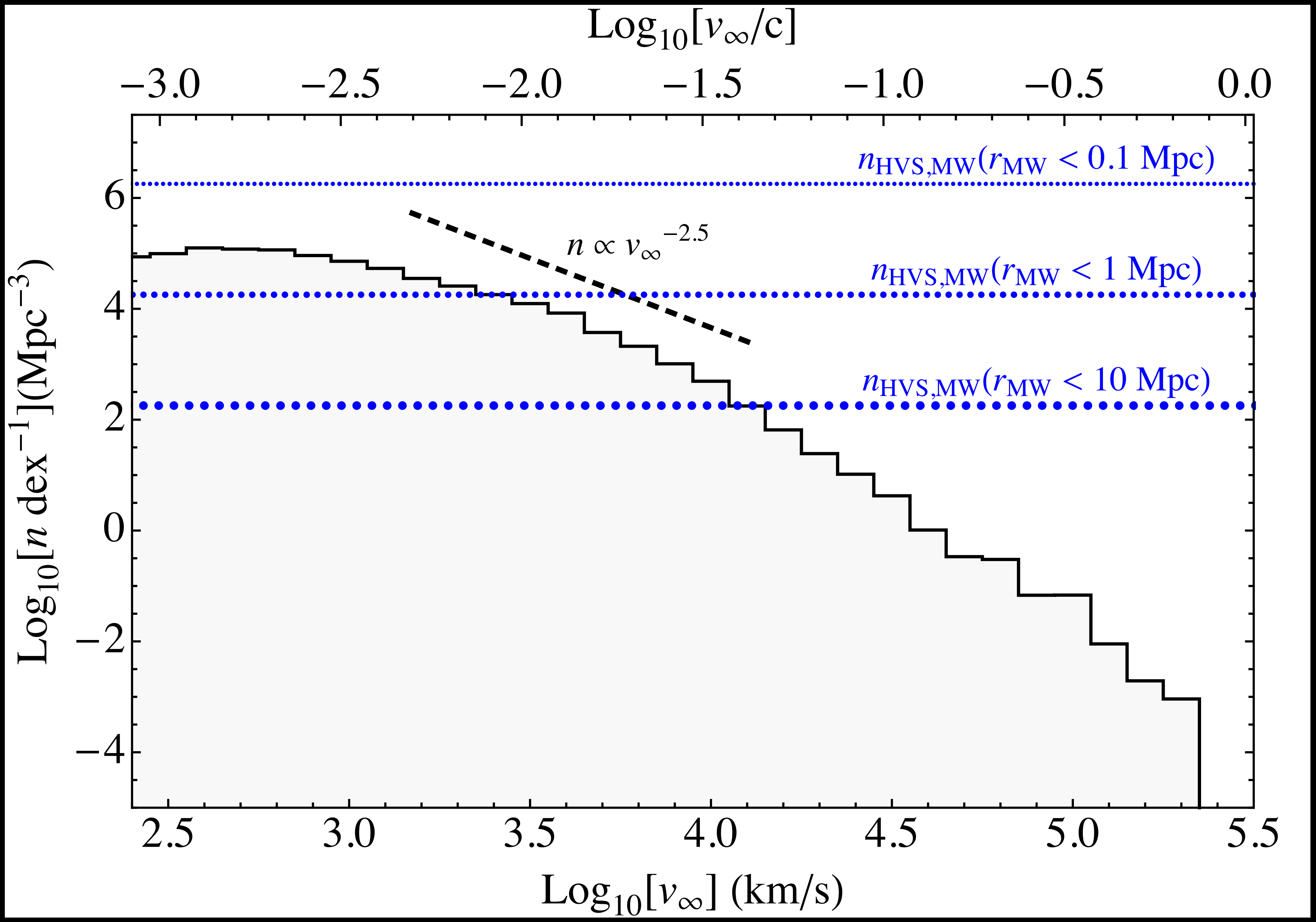


Guillochon & Loeb, in prep.



- Relative to the average velocity the star has about the secondary initially, the ejection velocity is larger to some degree (left panel).
- This shift is entirely explainable by the primary-secondary mass ratio.

Resulting velocity distribution
(properly normalized)



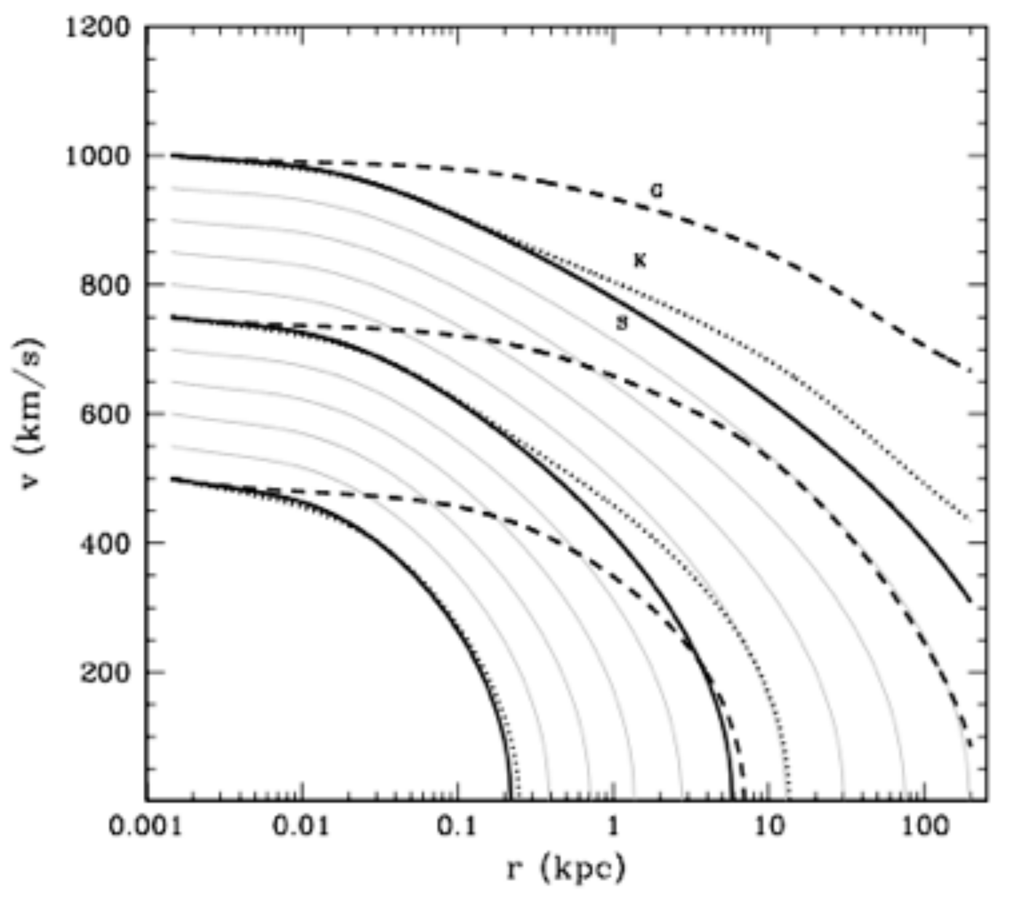
Guillochon & Loeb, in prep.

- Velocity distribution very similar to distributions found when scattering stars originally bound to the secondary.
- SHS outnumber HVS for v ~ 3,000 km/s at distances greater than 1 Mpc from the MW.
- The tail of high velocity objects is small, but non-zero.

Two Important Reductions:

Escaping the host galaxies & velocity decrease from cosmology

- Have to escape your host galaxy! **This removes some low velocity SHS.**

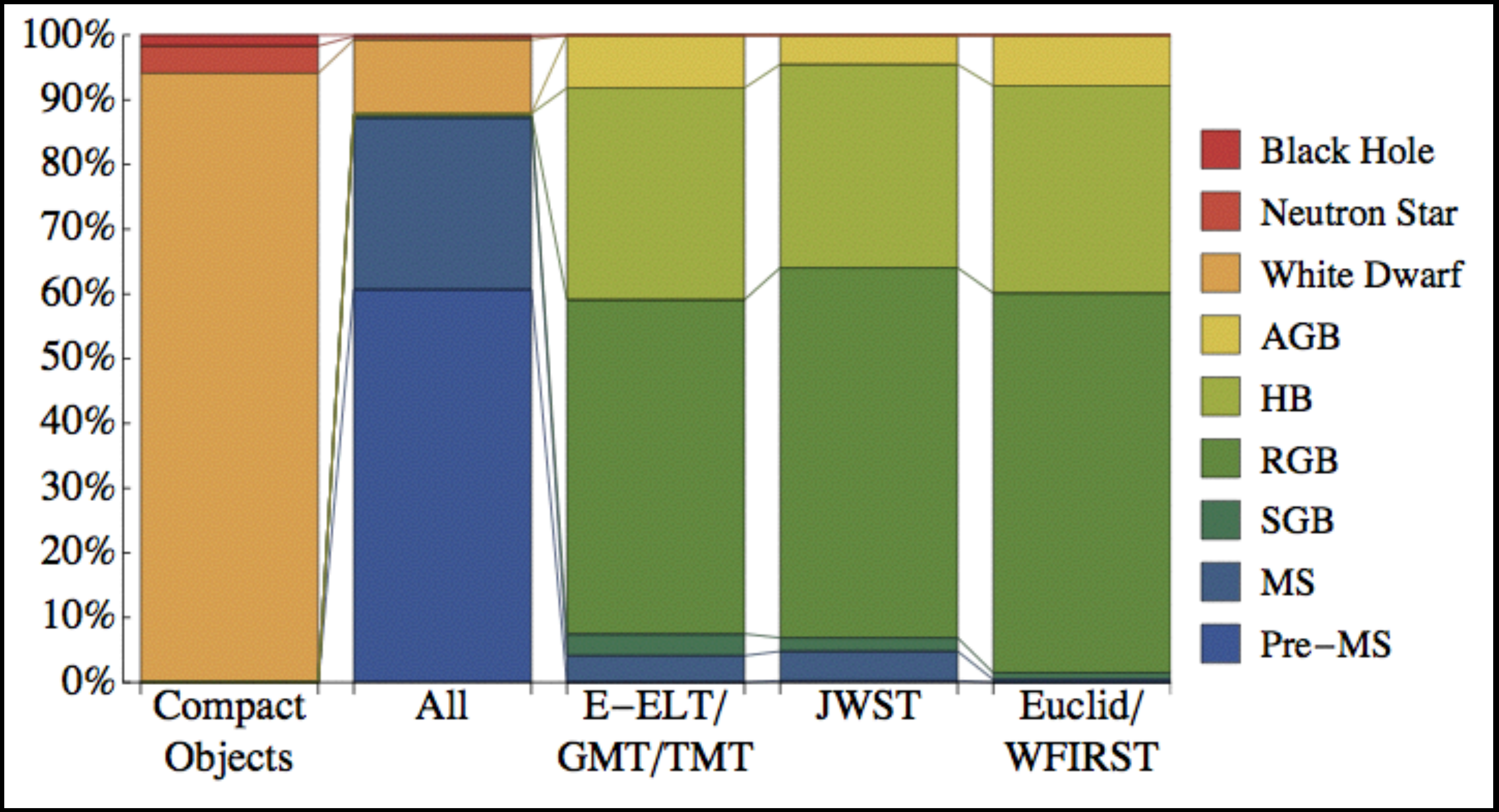


Kenyon+ 2008

- The expansion of the universe reduces the momentum of free particles as the scale factor increases. **This slows down older SHS.**

$$v = v_0 a_0 = v_0 (1 + z)^{-1}$$

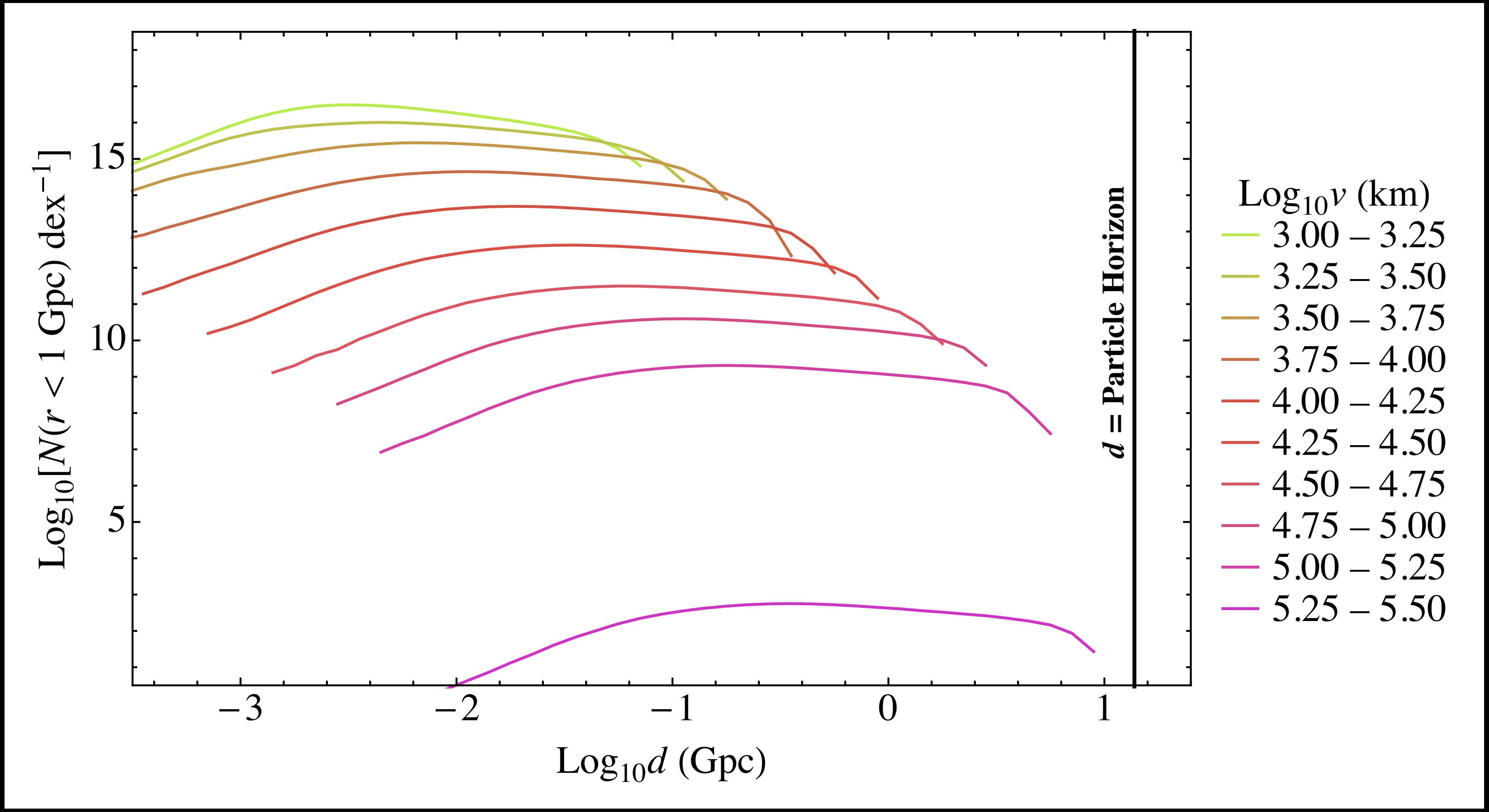
Stellar types of detectable SHS



Guillochon & Loeb, in prep.

- Using star formation history, time of SMBH mergers, and CMD generator (PARSEC), can predict the stellar type of SHS near us.
- When not accounting for detectability, most SHS are 10 Gyr old, and thus few MS stars with masses > 1 are nearby (more massive stars are now compact objects. Most are very dim low-mass dwarfs.
- IR surveys will primarily find the small fraction that happen to be evolving off the MS when they are nearby the MW.

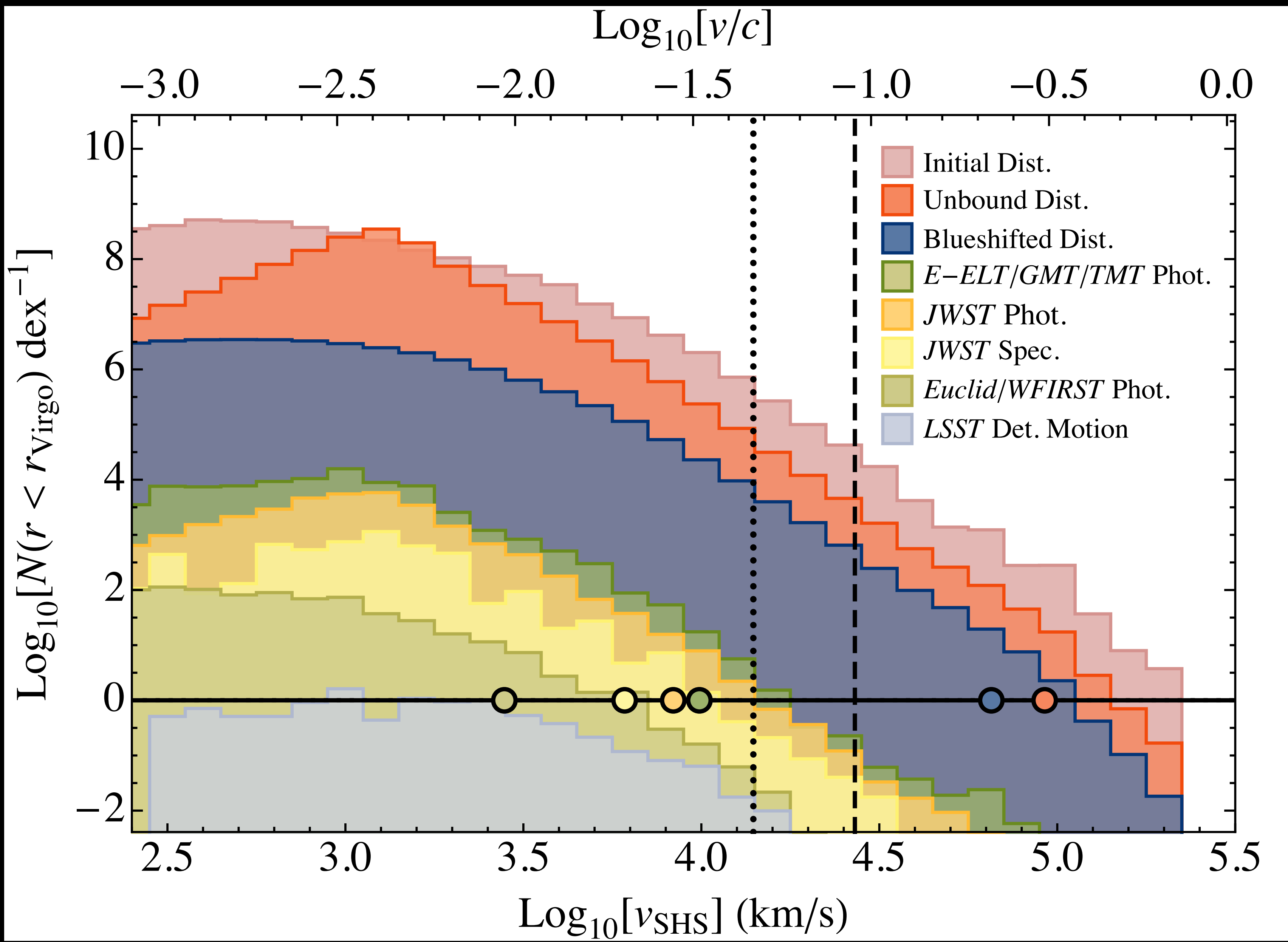
A long time ago *from* a galaxy far, far away…



Loeb & Guillochon, in prep.

- The fastest SHS within 1 Mpc of the MW have typically traveled 1 Gpc.
- The very fastest SHS have crossed a significant fraction of the Universe.
- A "natural" way stars (and planets, and life?) can be exchanged between distant galaxies.

So how many will we find?

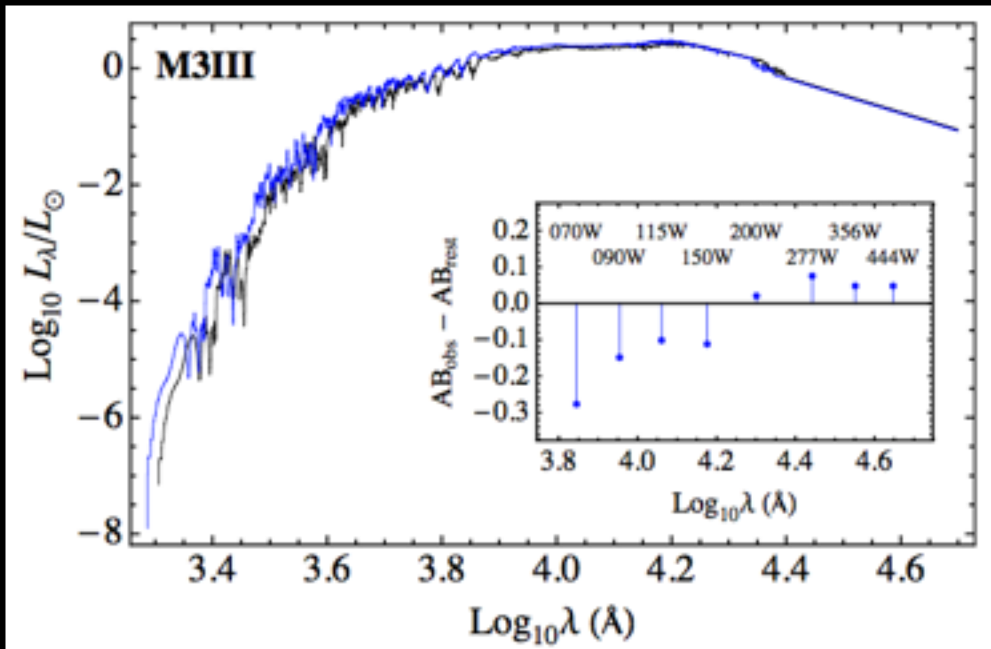


Guillochon & Loeb, in prep.

- All-sky ground based IR surveys (Euclid, WFIRST): **Hundreds**. Fastest will move close to 5,000 km/s.
- Space-based IR observatories, ground-based thirty-meter class facilities (E-ELT, GMT, TMT, JWST): **Thousands**. Fastest will move close to 10,000 km/s.
- **Tens of millions** of SHS total out to the distance of Virgo.
- Fastest object within this distance: 100,000 km/s.
- Counts should likely be multiplied by a factor of ~2 to account for stars originally bound to the primary that are scattered.
- A Kroupa IMF is presumed here, results slightly more favorable with a top-heavy IMF.
- Key here: **Detected**, not identified!

Identification: Challenging!

Guillochon & Loeb, in prep.

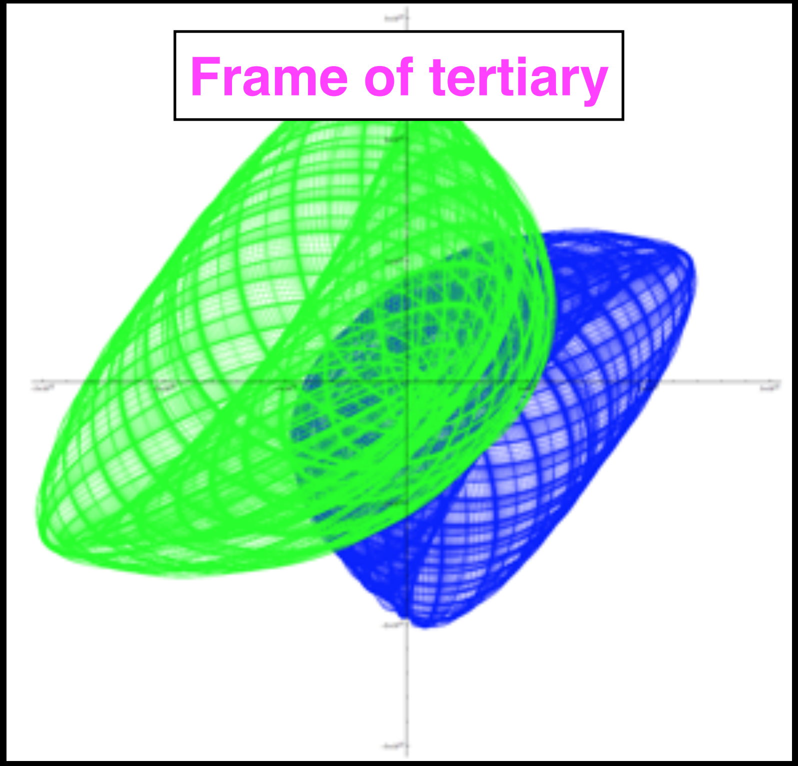


Hubble UDF (NICMOS)

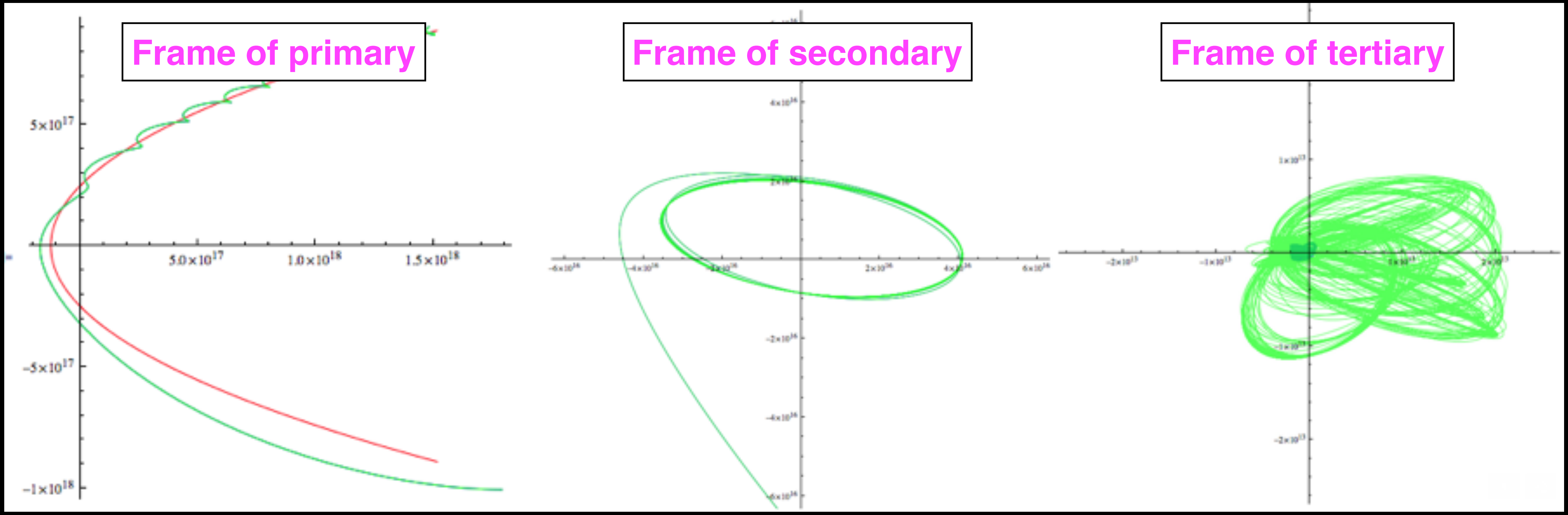
- Unique features:
  - Spectra will often be blueshifted, resulting in color shifts a few tenths of a magnitude. Spectra visibly different from rest-frame spectra.
  - Velocities can be much higher than HVS.
  - Velocity vector will not point back to galactic center, nor M31 (e.g. Sherwin + 2008).
- Problems:
  - Most bright objects that are detectable are red (red giants, AGB stars, etc).
  - There will be a **lot** of unresolved red objects of similar magnitude (K ~ 25-27).
  - Typical distances are large enough that proper motions are not detectable.

Binaries (and planetary systems) can be SHS as well!

- A similar mechanism exists for stellar triples (Perets 2009), and for planetary systems (Ginsburg+ 2012)
- Noted also for scattering of the stars originally orbiting the primary (Sesana+ 2009).
- Survival is difficult given the strong tidal field, and the system is often heavily perturbed.
- High numerical accuracy is very important here, binding energy of stellar binary $\sim 10^{12}$ times smaller than binding energy of SMBH binary.



An example binary system in which the binary remains bound, but experiences eccentric Kozai.



An example binary system that is ejected.

Other means of detection/identification?

- **Accreting binary systems**
  Very small fraction of binaries, but fraction may be higher than field given small separation distances.

- **Merger products**
  Former binaries may be induced to merger, these stars may evolve differently.

- **Pulsars**
  Neutron stars small fraction of total, beaming fraction small, SKA goes ~1 Mpc.

- **Bow shocks**
  Objects with the strongest bow shocks are already intrinsically bright (giants). May make some nearby low-mass stars visible.

- **Microlensing**
  Too little mass in the SHS component to have a chance of a lensing event.

Summary

- The fastest known stars in the Universe are those that orbit our galaxy's central black hole.
- HVS are fast, but have a speed limit of ~1% the speed of light.
- SHS are likely to be produced in significant quantities, with a number of them being detectable in future IR surveys. Speeds top out at one third the speed of light.
- Identification within these surveys will be challenging, but some unique aspects of this population may make SHS identifiable via other means.
- The discovery of a star with velocity greater than ~15,000 km/s would be strong evidence that the most SMBHs merge eccentrically.

Thanks!