Hyper Velocity Stars from the Galactic Centre

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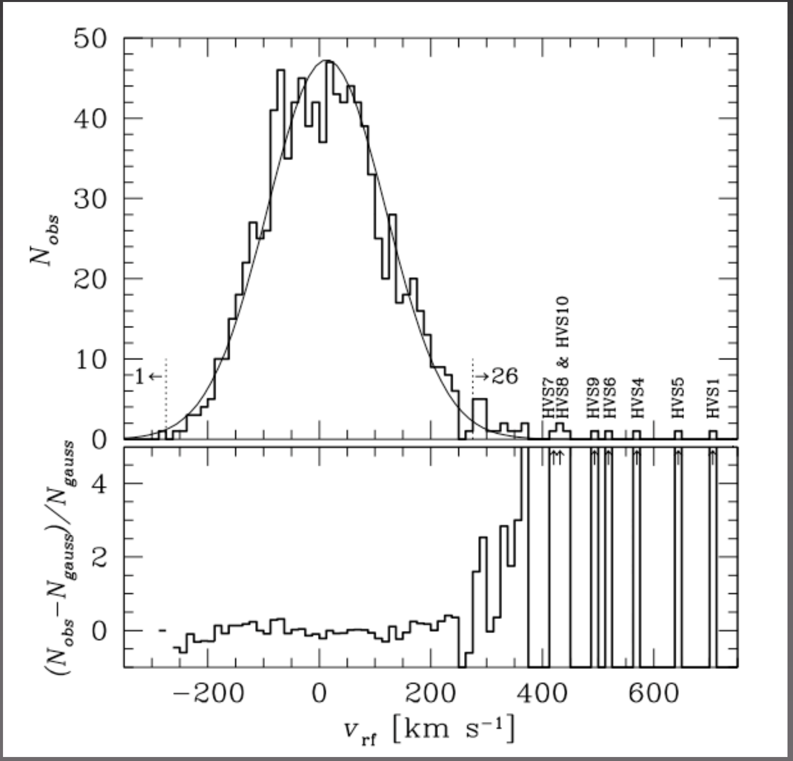
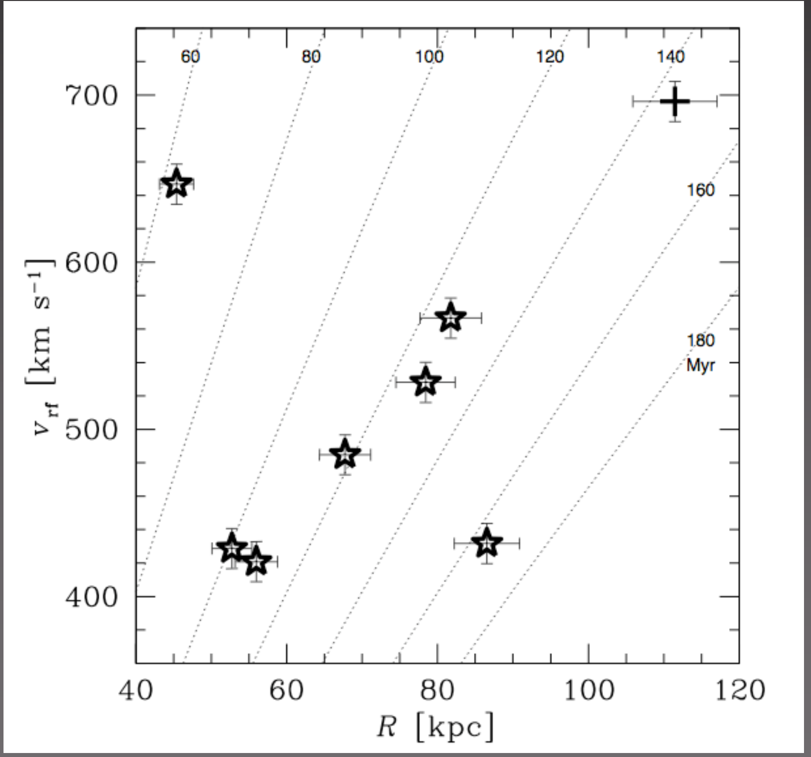
Hypervelocity Stars

Population of ~15 mostly B-type stars in Galactic halo with velocities exceeding Galactic escape velocity

Observational results from Brown et al. (2007)



Distribution of 1000 B-type stars in Galactic rest frame

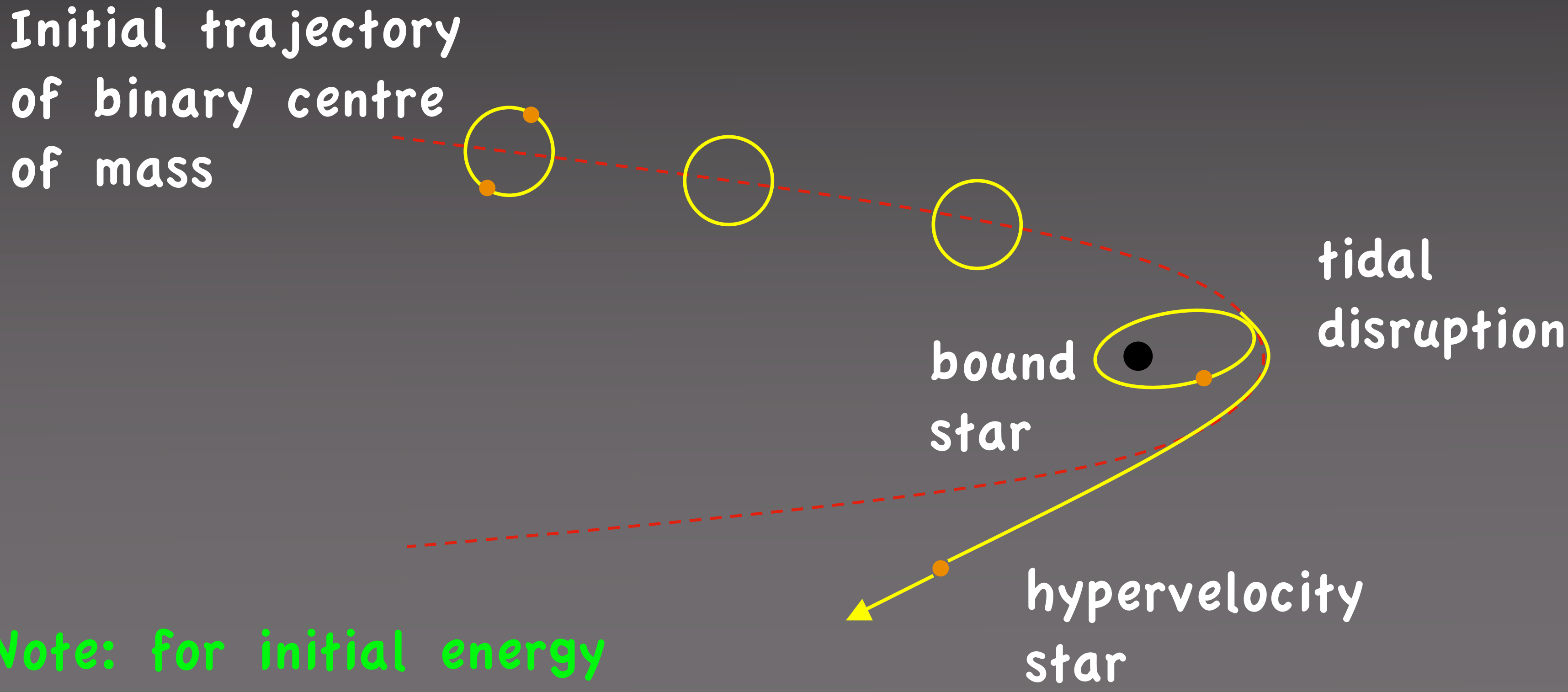


Minimum velocities and Distances for identified HVS

HVS from tidal break-up of binaries by Galactic Centre supermassive black hole?

"A close but Newtonian encounter between a tightly bound binary and a 10^6 Solar mass black hole causes one binary component to become bound to the black hole and the other to be ejected at up to 4,000 km s^{-1}."

Hills (1988)



Note: for initial energy $E \sim 0$, must have $E_{HVS} = -E_{bound}$

Where does the ejection energy come from?

Binary: separation a, total mass m, orbital velocity v_0, is disrupted at distance r_t from black hole mass M

Tidal radius: $$r_t \approx \left(\frac{M}{m}\right)^{1/3} a$$

...where black hole tidal force overcomes binary gravitational attraction

Work done by star-star forces within binary:

$$\frac{Gm}{a^2} \times r_t \approx \frac{GM}{a}\left(\frac{M}{m}\right)^{1/3} \approx v_0^2 \left(\frac{M}{m}\right)^{1/3}$$

force per unit mass

distance over which force acts

$(M/m) \gg 1$, so can eject stars with $v \sim (M/m)^{1/6} v_0$ which is $\sim 10 v_0$ for GC

We wish to know

- Fate of binary upon encounter with BH (probability of disruption)
- Ejection energy distribution

An old approach to an old problem...

Formation of HVS considered by many authors: Hills (1988); Yu & Tremaine ('03); Gould & Quillen ('03); Bromley et al '07, Perets et al 07, Sesana et al. ('07)... using 3-body simulations

"New" approach with ``old method"
(Sari, Kobayashi & Rossi '09):

- analytically simplify equations of motion and Energy, using fact that M >> m

Simplifying the equations of motion

Now define separation between stars $\mathbf{r} = \mathbf{r}_2 - \mathbf{r}_1$ and position of *effective centre of mass* relative to black hole $\mathbf{r}_m$

$$\frac{M}{m} \gg 1 \rightarrow \frac{r_t}{a} \gg 1$$

so separation between stars is small compared to distance to BH

$$\ddot{r}$$

$$\ddot{\mathbf{r}} = -\frac{GM}{r_m^3}\mathbf{r} + \frac{3GM}{r_m^5}(\mathbf{r}\mathbf{r}_m)\,\mathbf{r}_m - \frac{GM}{r^3}\mathbf{r}$$

- easier and faster to integrate numerically
- In limit of no mutual gravity, analytic solutions

Energy: what is the star's final fate?

Calculate energy of star including black hole potential and kinetic energy only :

$$E_1 = -\frac{GMm_1}{r_1} + m_1 \left|\dot{\mathbf{r}}_1\right|^2/2\,.$$

OK to ignore binary binding energy as

$$V_{HVS}^2 \sim v_0^2 \left(\frac{M}{m}\right)^{1/3} \rightarrow v_0^2 \simeq \frac{Gm}{a} \ll V_{HVS}^2$$

Simplifying it using M/m we already obtain important analytical results...

Defining $D=r_p/r_t$ (r_p periapsis of centre of mass orbit, r_t tidal radius)

$$E_1 = -E_2 = -\frac{G m_1 m_2}{a\, D}\left(\frac{M}{m}\right)^{1/3} \times \left[\frac{r_p^2}{r_{\rm m}^2}\vec{r}\hat{r}_{\rm m} + \frac{\dot{\vec{r}}_{\rm m}}{r_p}\dot{\vec{r}}\right]$$

- main dependence in first term analytic, second term in brackets must be computed numerically
- [...] is mass independent, linear in co-ordinates such that

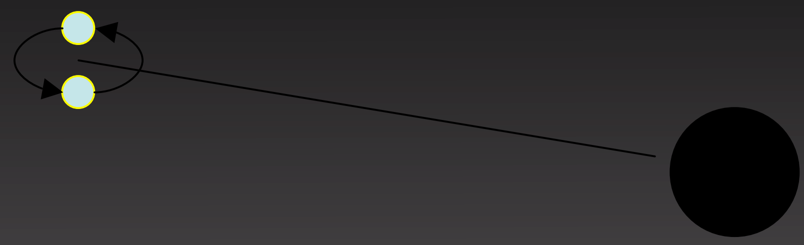
  Implies P(ejection) is equal for the more and less massive stars

  Energy distribution is also independent of mass: hence velocity increases with lower mass

- *numerically we find -27 <[...]< 27*
- *Note* : apparent divergence as 1/D

Radial limit

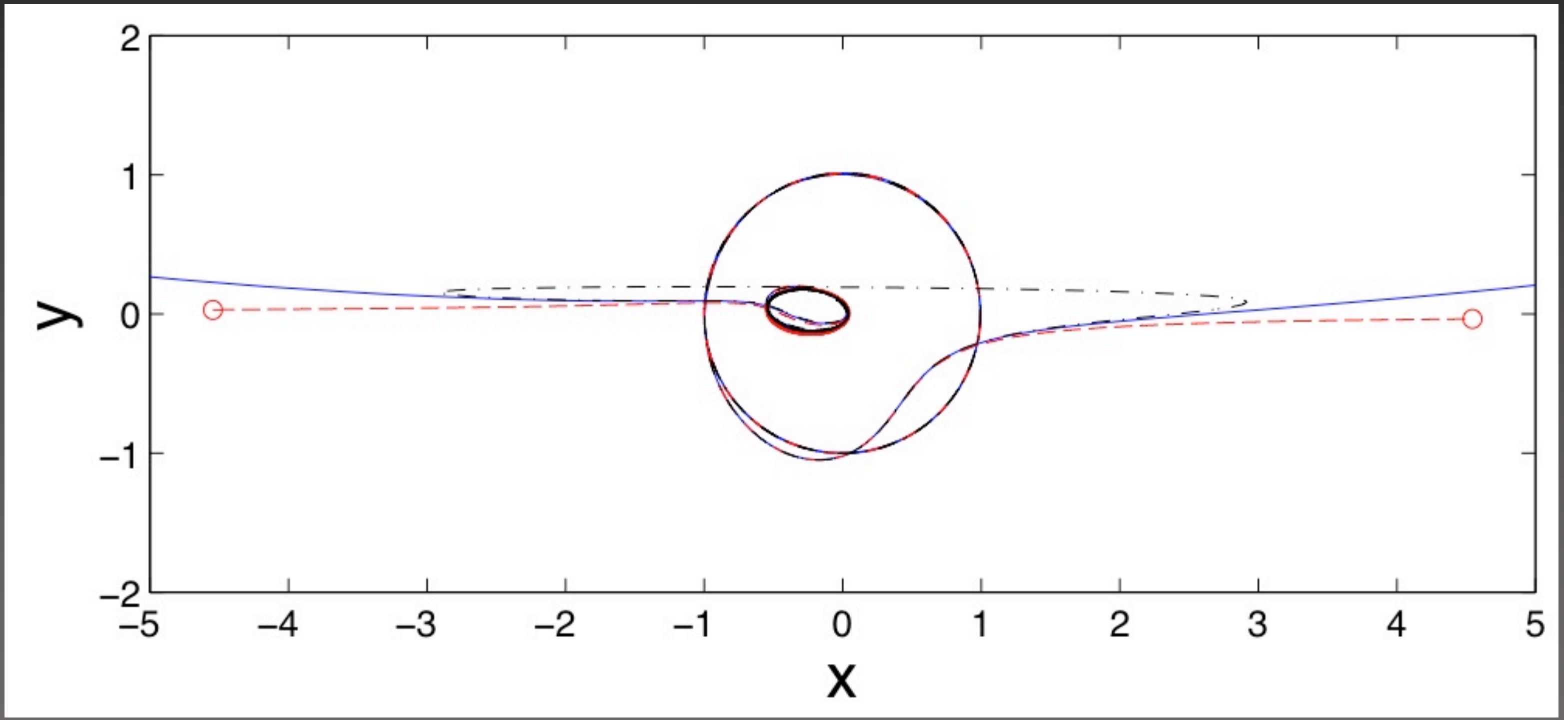
Investigate apparent divergence by studying radial limit (degenerate limit of parabola)



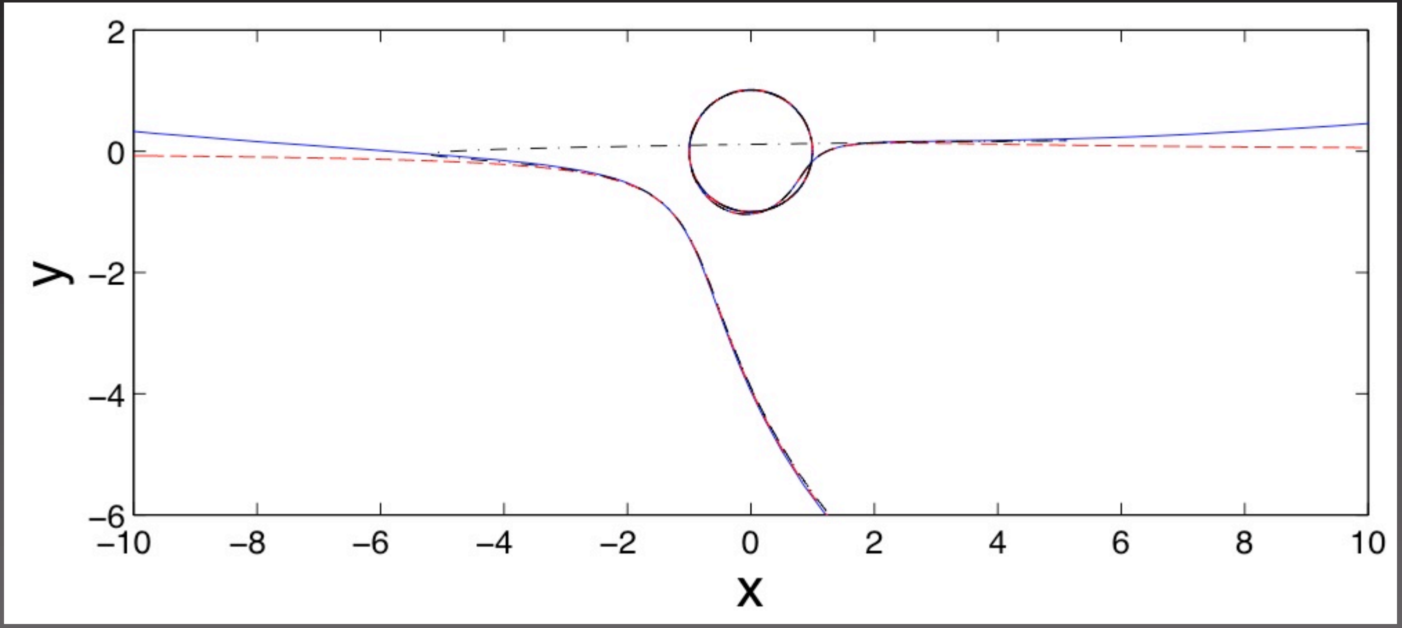
Final energy: $E_1 \propto \frac{Gm_1m_2}{a}\left(\frac{M}{m}\right)^{1/3}$

- divergence is NOT real
- in fact, highest ejection velocities are for non-zero D
- the proportionality constant is bound [-2,2]
- and even for D = 0 fraction (~10%) survives passage
- 90% cases binary gets harder

Behaviour close to the BH of deep penetrating binaries



Frame of the primary, secondary leaves but comes back !



The secondary comes back but they separate again

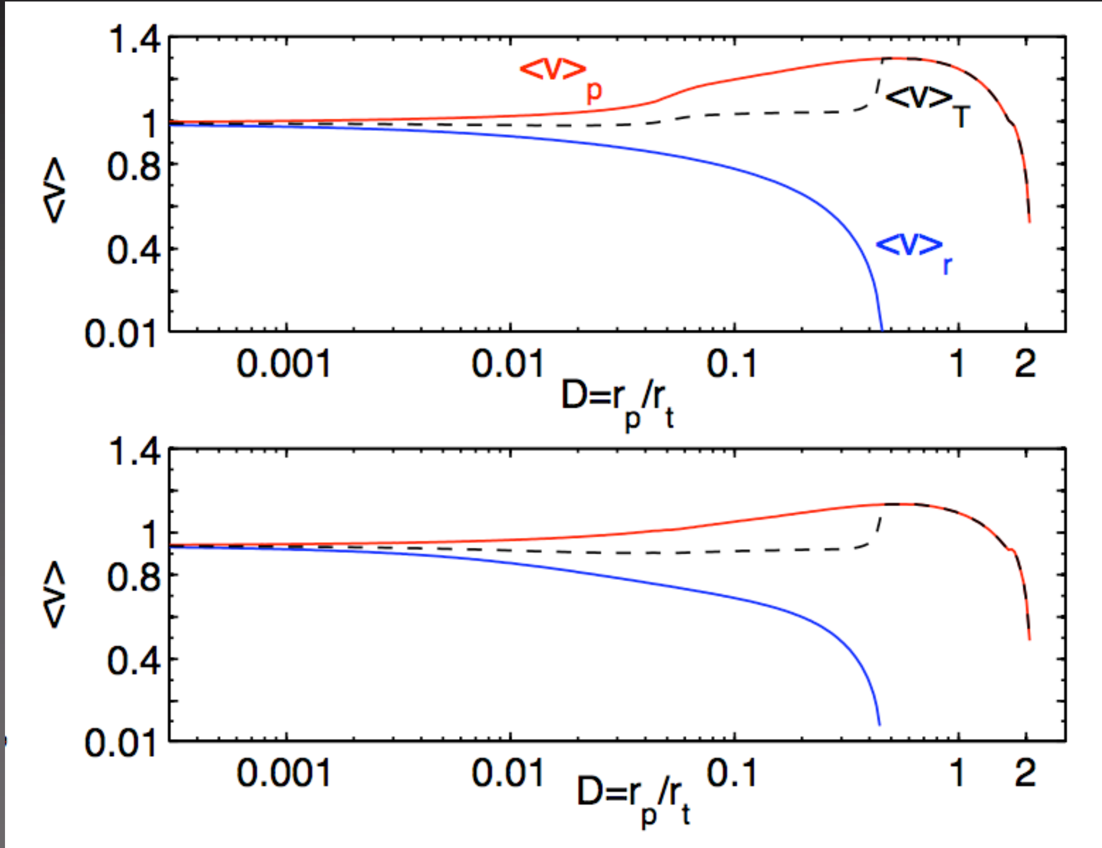
Towards observables:

$$v = \sqrt{\frac{2E_1}{m_1}}$$

Average ejection velocity over phase

$$\sqrt{\frac{2Gm_2}{a}}\left(\frac{M}{m}\right)^{1/6}$$

$$\sqrt{\frac{2Gm_2}{R_{\rm min}}}\left(\frac{M}{m}\right)^{1/6}$$



- mean ejection velocity is ~constant with D
- allowing for finite size of stars (bottom panel) does not change conclusion

Maximum ejection velocities

- $m_1 = m_2$

$$v_{\rm max} = 1.3 \times \sqrt{\frac{2Gm_2}{R_{\rm min}}} \left(\frac{M}{m}\right)^{1/6} = 0.9\, v_{\rm esc} \left(\frac{M}{m}\right)^{1/6}$$
$$= 9 v_{\rm esc} \sim 7000 \text{ Km s}^{-1}$$

- $m_2 << m_1$

$$v_{\rm max} = 1.3 \times v_{\rm esc} \left(\frac{M}{m}\right)^{1/6} \sim 10000 \text{ Km s}^{-1}$$

The velocity distributions of HVSs

$$v = \begin{cases} \sqrt{\frac{2Gm_c}{a}} \left(\frac{M}{m}\right)^{1/6} & \text{for } r_p \le r_t \\ 0 & \text{othewise} \end{cases}$$

Statistical description of approaching binaries

$$f(a) \propto 1/a; \quad f(m_c) \propto m_c^{-\alpha}; \quad f(r_p) = \text{constant}$$

Fixing the HVS mass m_*, $m = m_* + m_c$

Rossi et al in prep.

Results Full loss cone regime

$$v \times f_v \propto \begin{cases} v^{-2} & \text{for } v \le v_{\min}, \\ v^{-2(\alpha-1)} & \text{for } v_{\min} \le v < v_{\max}. \end{cases}$$

$\alpha > 2$

For $\alpha > 2.35$ $v^{-2.7}$

$$v_{\min} = v(R_*, m_c) \sim 700 \text{ Km s}^{-1}$$
$$v_{\max} \simeq v_{\text{esc},*} \left(\frac{M}{2m_*}\right)^{1/6} \simeq 5000 - 7000 \text{ Km s}^{-1}$$

Slope is very steep > 2 for *any* α and also equal mass binaries

Back-up slides

$$E_1 = -E_2 = -\frac{G m_1 m_2}{a\,D}\left(\frac{M}{m}\right)^{1/3} \times \left[\frac{r_p^2}{r_m^2}\vec{r}\hat{r}_m + \frac{\dot{\vec{r}}_m}{r_p}\dot{\vec{r}}\right]$$

compute numerically and plot as f(D,binary phase)

- $E(\phi)=-E(\phi+\pi)$
- non-disrupted cases to D=0
- numerical factor is finite
- easier to disrupt prograde binaries