Hypervelocity Stars
Tidal disruption of binaries by a massive BH

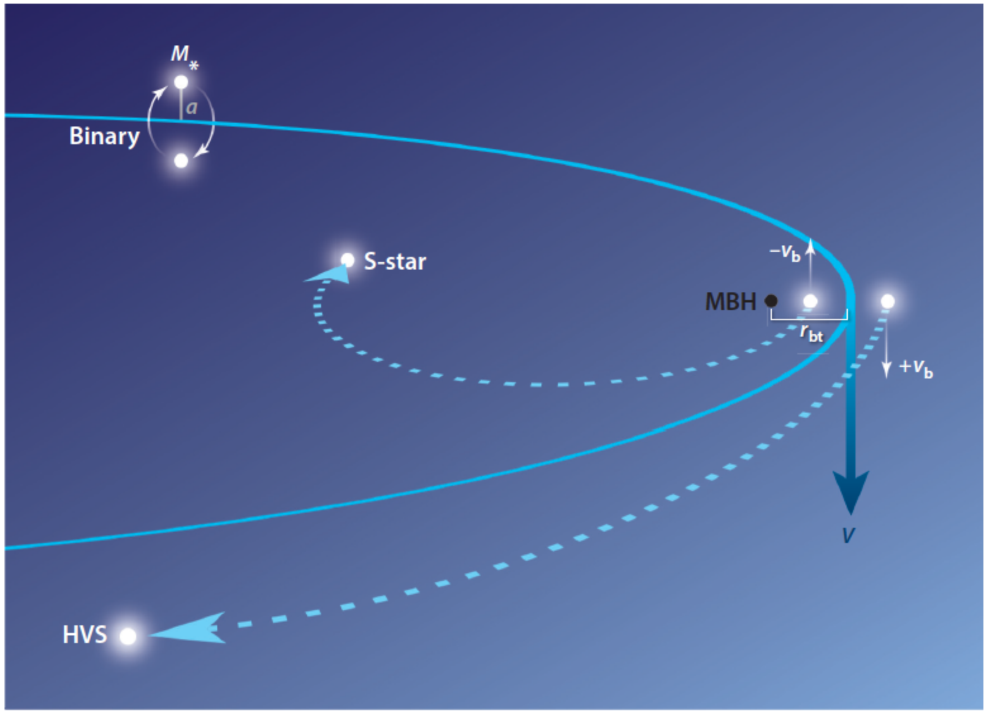
Shiho Kobayashi (Liverpool John Moores, UK)

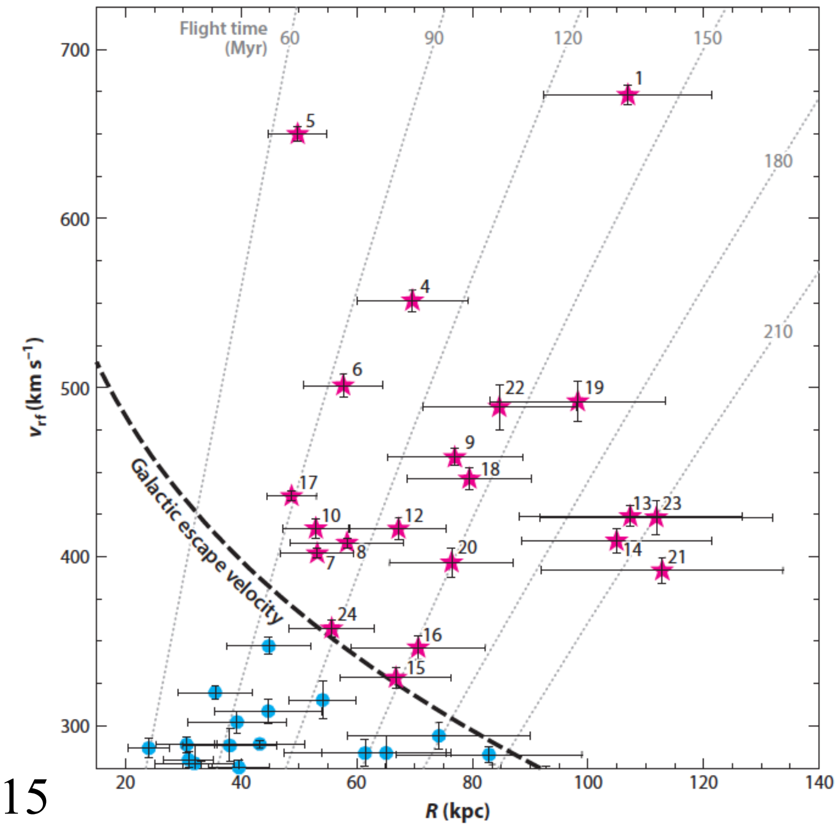
Collaborators
Harry Brown (LJMU) , Elena Rossi (Leiden), Re'em Sari (Hebrew)

Hypervelocity Stars (HVSs)

ejected by the Galaxy's central massive BH at speeds that exceed Galactic escape velocity

Prediction by Hills 1988: Tidal disruption of binaries by the massive BH
Discovery by Brown+ 2005: B-type stars with such high velocities in the halo





Brown 2015

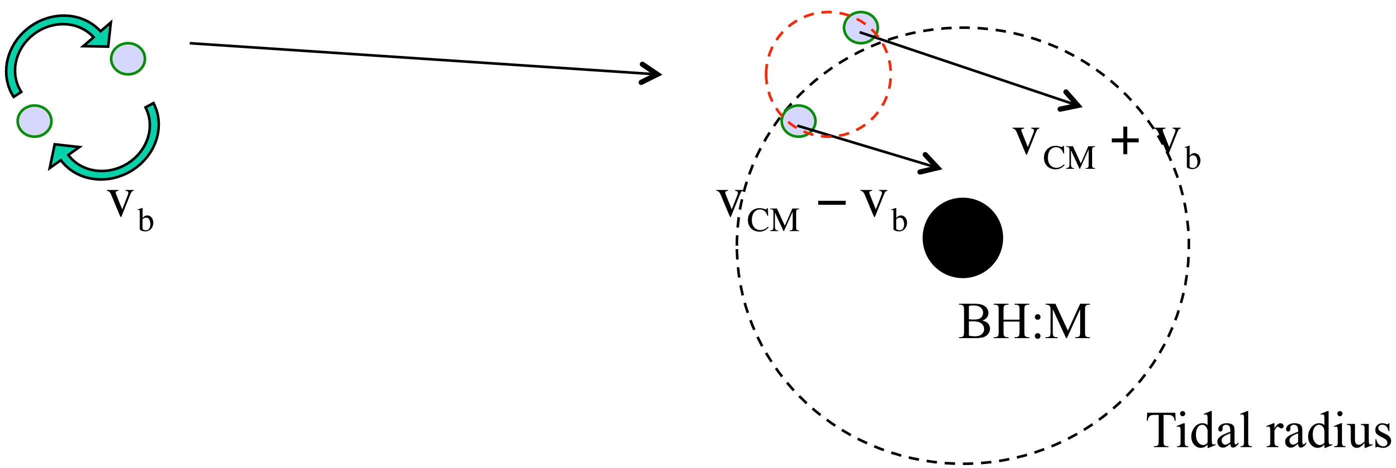
Implications of HVSs

- Important tool to understand the nature and environment of massive BH/BHs
  - Single BH (isotropic ejection) vs BH binary (BH orbital plane)
  - Stellar populations (mass function, binary fraction, ages)

- Tracers of the Galactic Potential (stars & dark matter)
  - Shape and orientation of dark matter halo (Gnedin 2005)
  - Triaxiality of dark halo (Yu&Madau 2007)

- Links to TDEs and massive BH Growth
  - HVS ejection rate: 10^-5 – 10^-4 per year
  - Every HVS leaves its companion behind (S-stars).
  - Central BH may have grown owing to binary disruption and subsequent TDEs
    - a factor of 2-4 in past 5-10Gyr (Bromley+ 2012).

Ejection velocity estimate



Binary rotation velocity : $v_b \sim \sqrt{Gm/a}$.

Binary CM centre moves at r_t with $v_{CM} \sim \sqrt{GM/r_t} \sim v_b (M/m)^{1/3}$.

Additional kinetic enegy $\Delta\varepsilon \sim v_b v_{CM}$

$$v \sim \sqrt{\Delta\varepsilon} \sim \left(M/m\right)^{1/6} v_b$$

$v_b \leq$ (escape velocity from a star) $\sim 600\text{km/s} \Rightarrow v \leq 6000\text{km/s}$

A restricted parabolic three-body problem

Sari, SK & Rossi 2010; SK, Rossi & Sari2012

Binary on parabolic orbit around massive BH

For a large mass ratio: BH / binary >> 1, we can formulate the problem as the motion of a single particle under influence of time-dependent forces.

- Energy gain/loss can be simply rescaled in terms of masses and binary separation

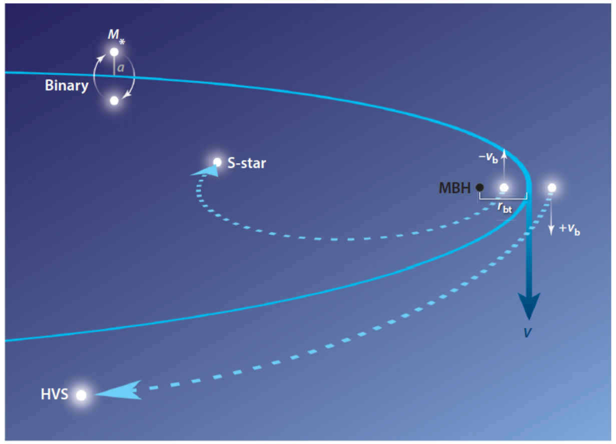
$$\Delta E_1 = -\Delta E_2 = \frac{Gm_1 m_2}{a}\left(\frac{M}{m}\right)^{1/3} f(D,\vec{\ell},\phi)$$

where $D = R_p/R_t$, $\vec{\ell}$: binary orientation, ϕ: binary phase, f is about unit.

$D = \beta^{-1}$: penetration factor

- Analytic solutions for deep penetration $D << 1$

- Even for an unequal-mass binary, each member is ejected in exactly 50% of the cases.



Parabolic orbits : zero energy

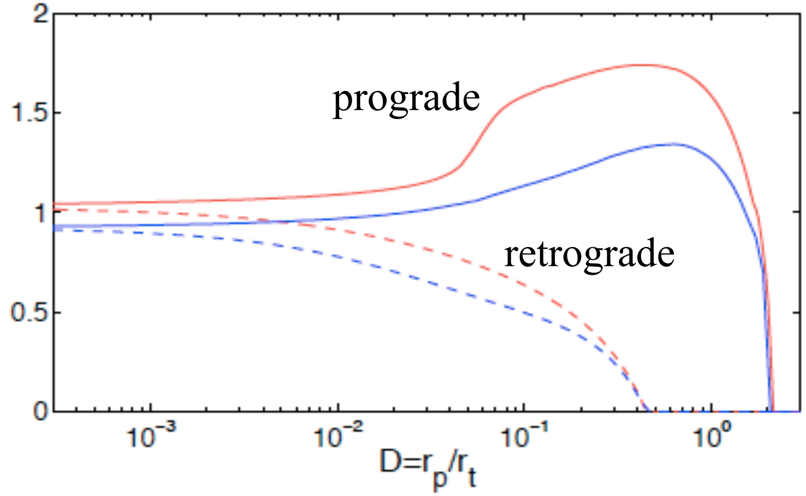
$$\Delta E_1 = -\Delta E_2$$

$$\Delta E_1(\phi + \pi) = -\Delta E_1(\phi)$$

- The radius of gravitational influence of the BH ~ pc ~10^5R_tidal for a ~ several solar radii.
  - equal ejection chance up to $m_1 / m_2 \sim 10^2$.

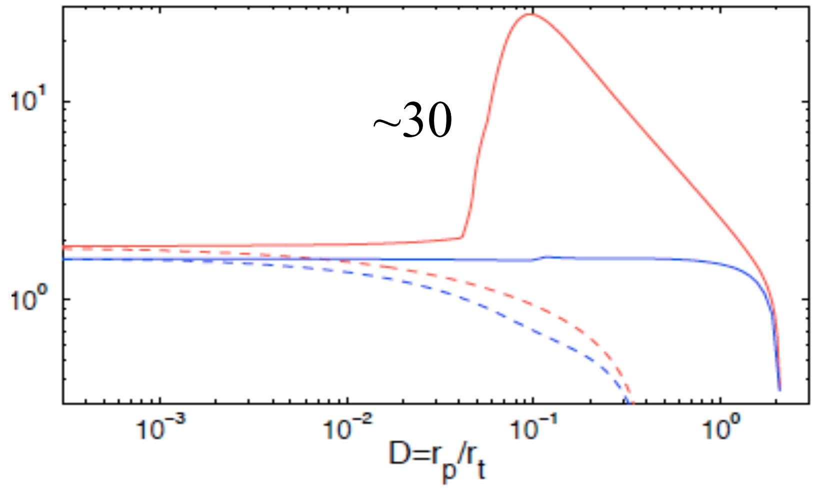
$$\Delta E = \frac{G m_1 m_2}{a}\left(\frac{M}{m}\right)^{1/3} f(D, \vec{\ell}, \phi)$$

$\langle |f| \rangle$



When binaries penetrate the tidal radius deeply, they experience very strong tide. However, ejection energy (ejection velocity) does not become large.

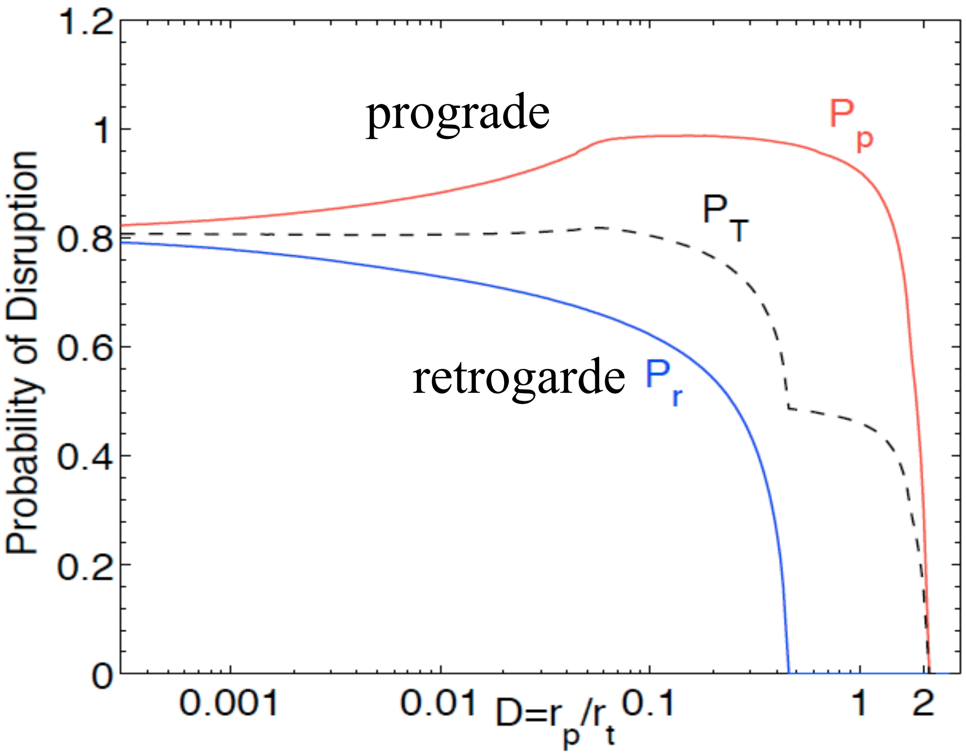
$f_{\max}$

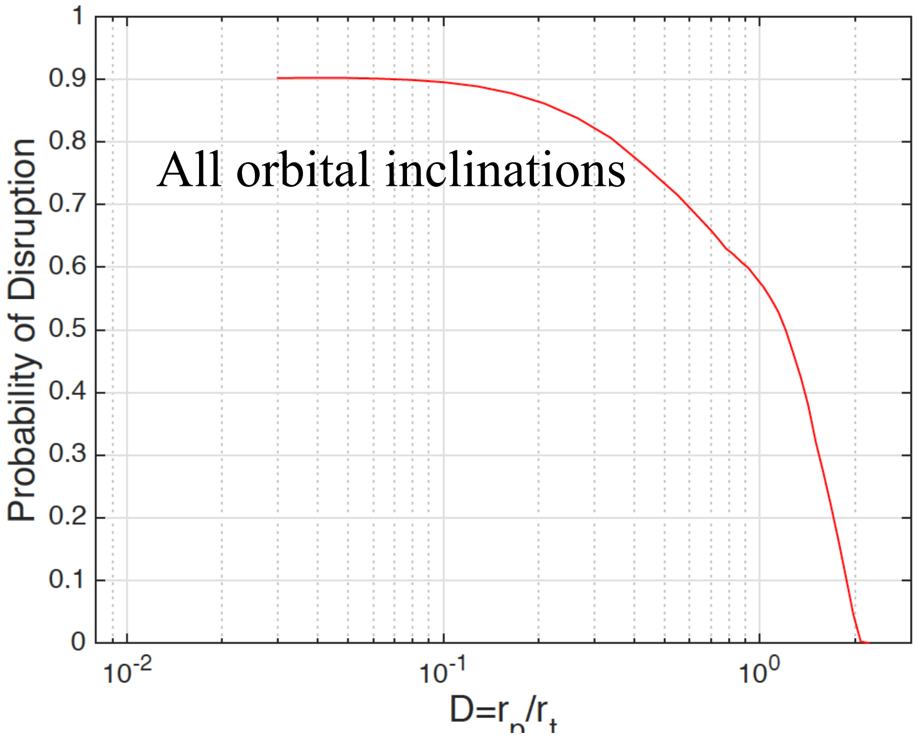


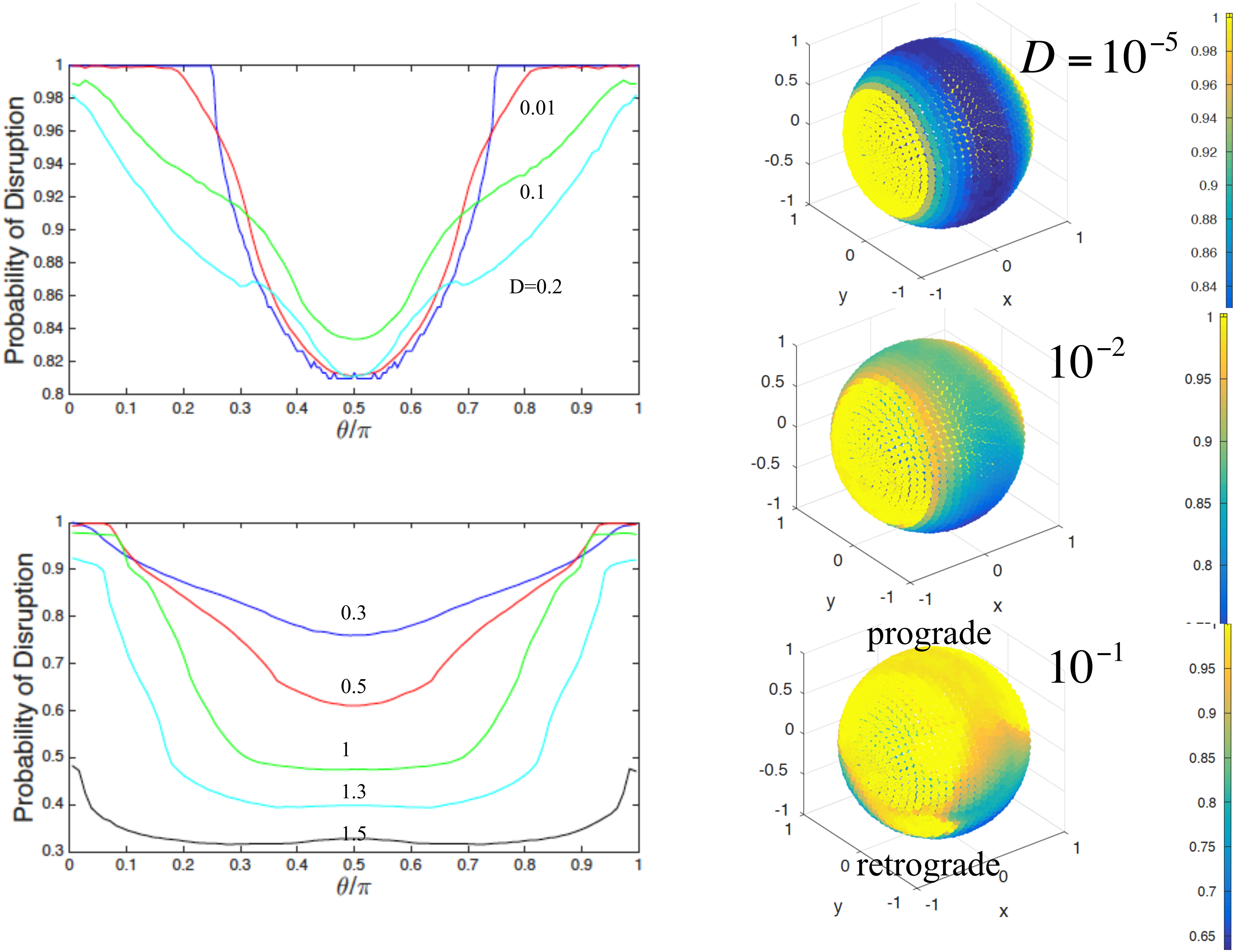
In TDE study, the orbital energy spread of tidal debris is often estimated as $\Delta\varepsilon \sim \frac{GMR_*}{R_p^3}$

but it should be $\sim \frac{GMR_*}{R_t^3}$

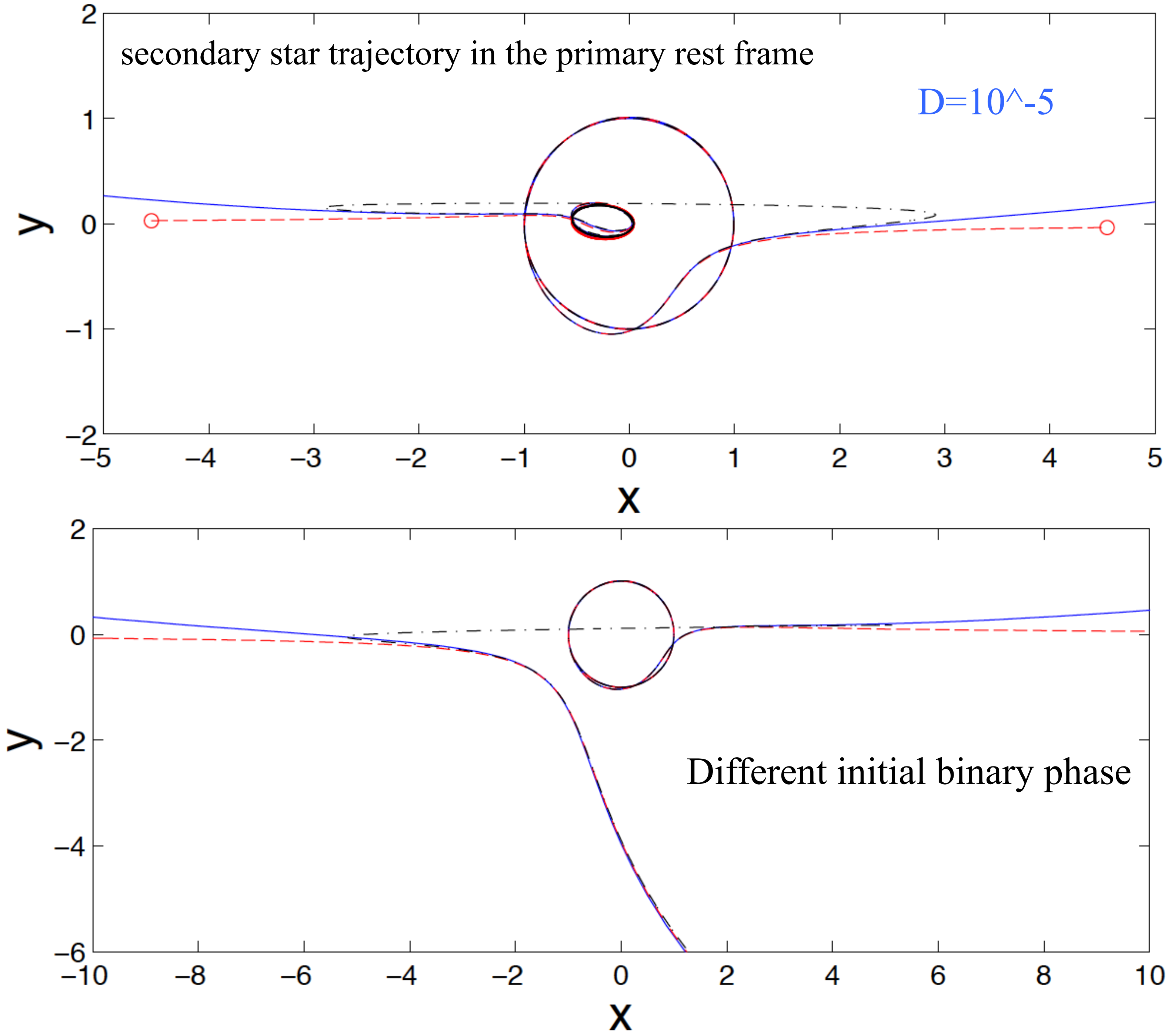
• Even if binaries deeply penetrate the tidal radius, they survive in 10% of the cases, and they become compact binaries.



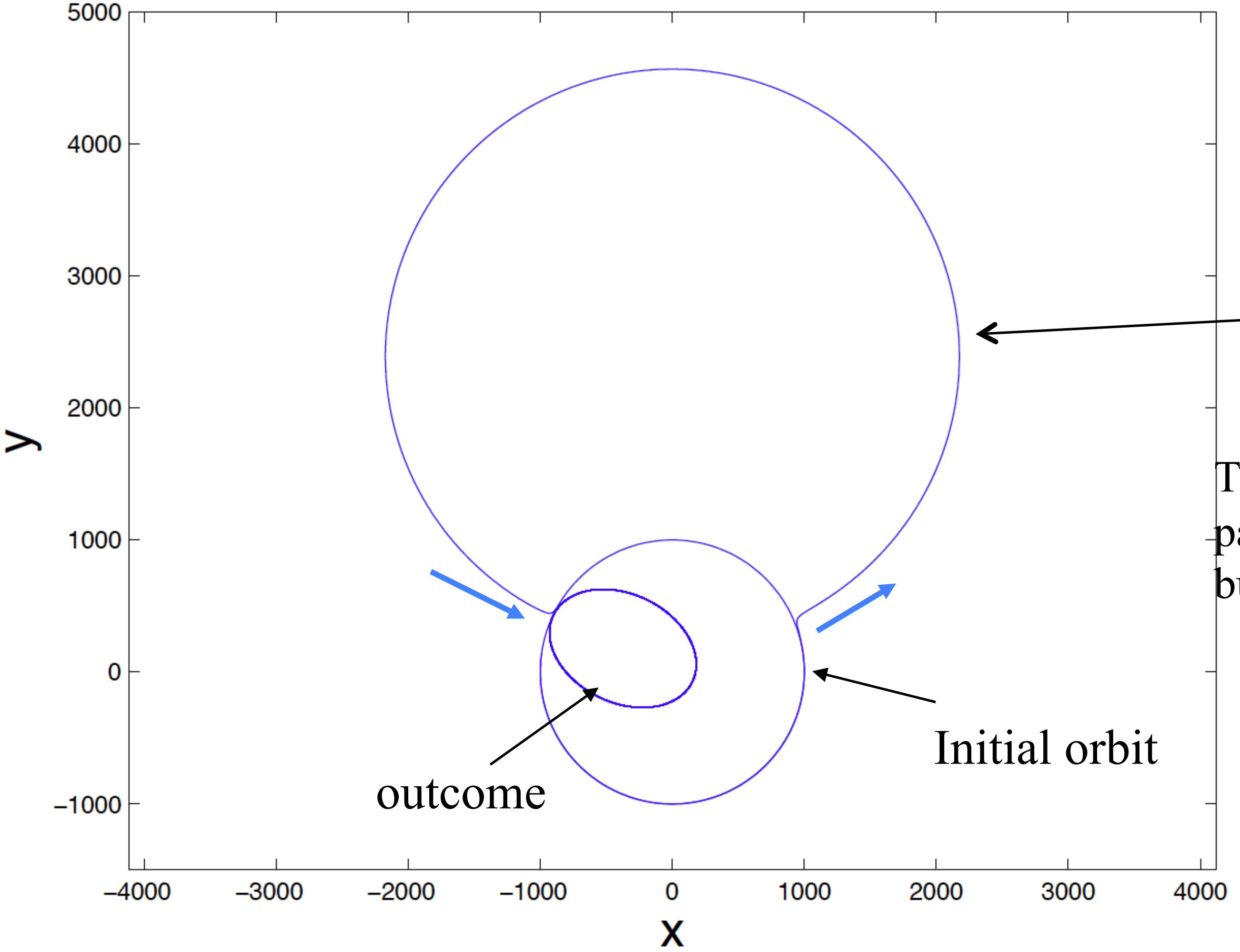




Probability of Disruption
θ/π
0.01
0.1
D=0.2
Probability of Disruption
θ/π
0.3
0.5
1
1.3
1.5
D = 10^−5
10^−2
prograde
10^−1
retrograde
x
y


secondary star trajectory in the primary rest frame
D=10^-5
Different initial binary phase

In deep encounters, one of the free solutions dominates around the periapsis passage.
Binary dissolves, but after the periapsis passage, they come close to each other.

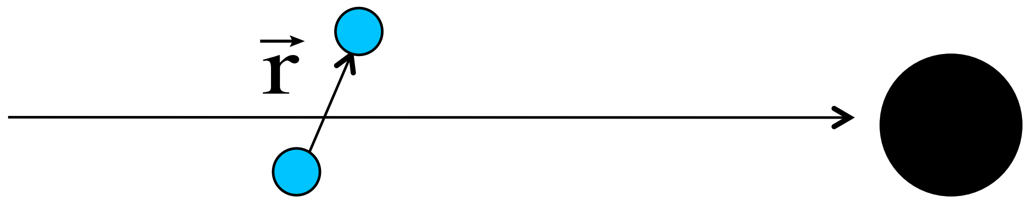


$x = -\sin\chi$

$y = 1 + \cos\chi$

The binary members are in the same parabolic orbit in the BH frame but slightly separated in time.

Radial case



$$\ddot{x} = \frac{4}{9t^2}x - \frac{x}{(x^2+y^2+z^2)^{3/2}},$$

$$\ddot{y} = -\frac{2}{9t^2}y - \frac{y}{(x^2+y^2+z^2)^{3/2}},$$

$$\ddot{z} = -\frac{2}{9t^2}z - \frac{z}{(x^2+y^2+z^2)^{3/2}}.$$

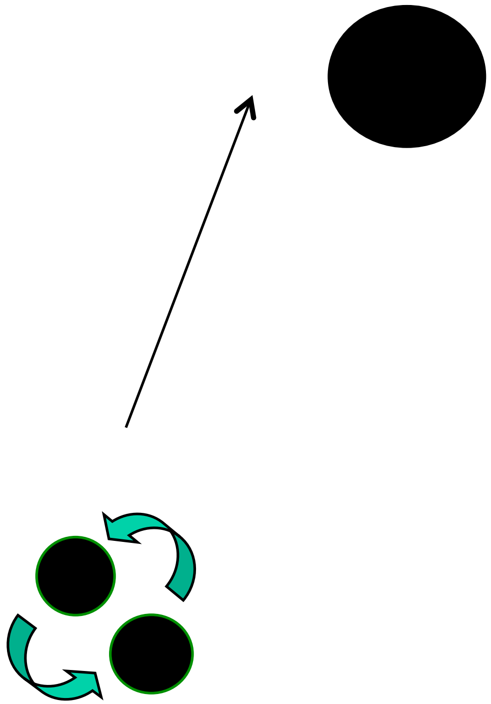
$$x(t) = A_x|t|^{-1/3} + B_x|t|^{4/3},$$

$$y(t) = A_y|t|^{1/3} + B_y|t|^{2/3},$$

$$z(t) = A_z|t|^{1/3} + B_z|t|^{2/3}.$$

Ax solution describes two particles that have the same trajectory, but are slightly separated in time.

Tidal disruption of BH-BH binaries by massive BH



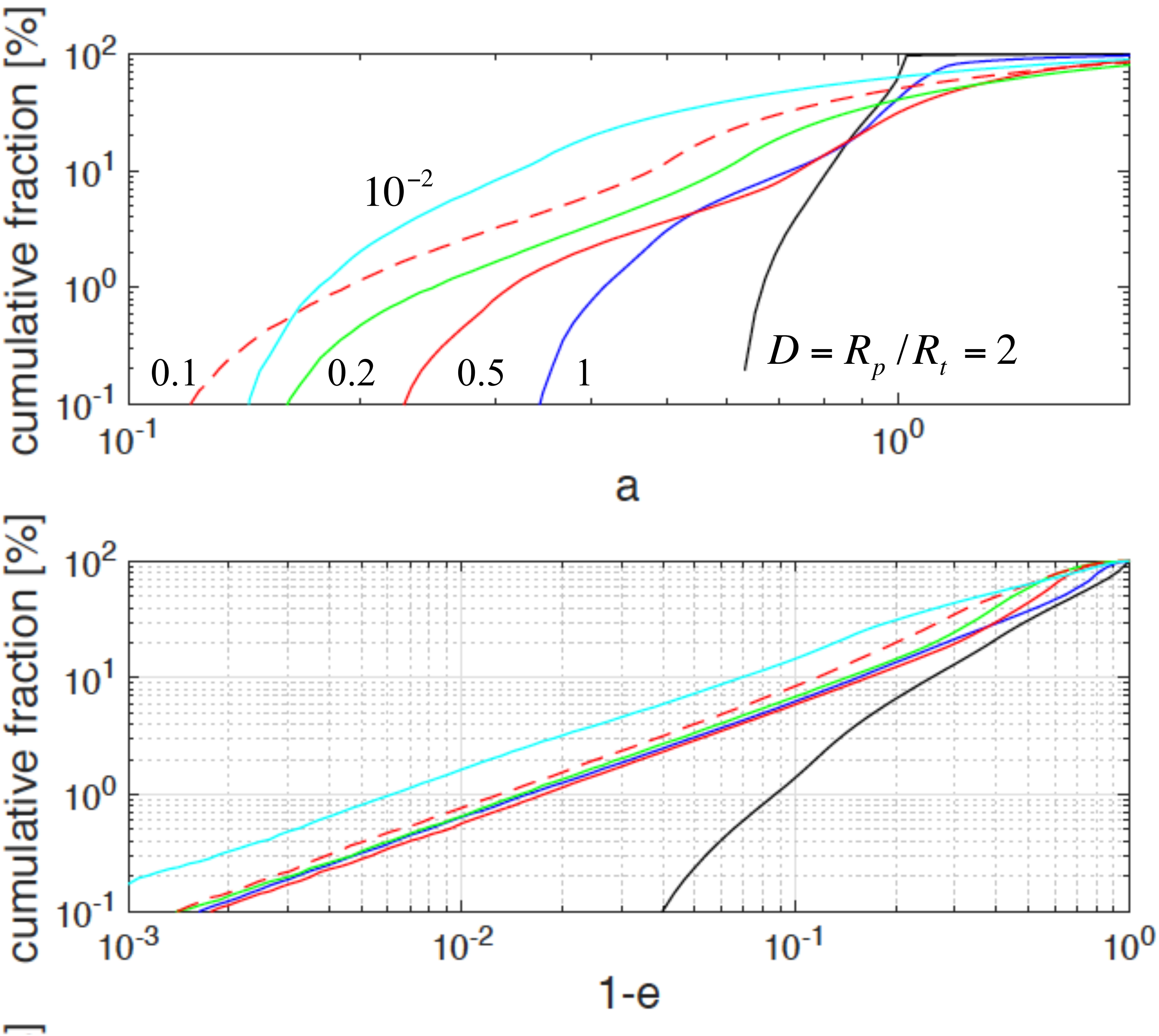
Hypervelocity BHs
Bound ones: EMRI GW

Survivors
Eccentric, Compact BH binaries

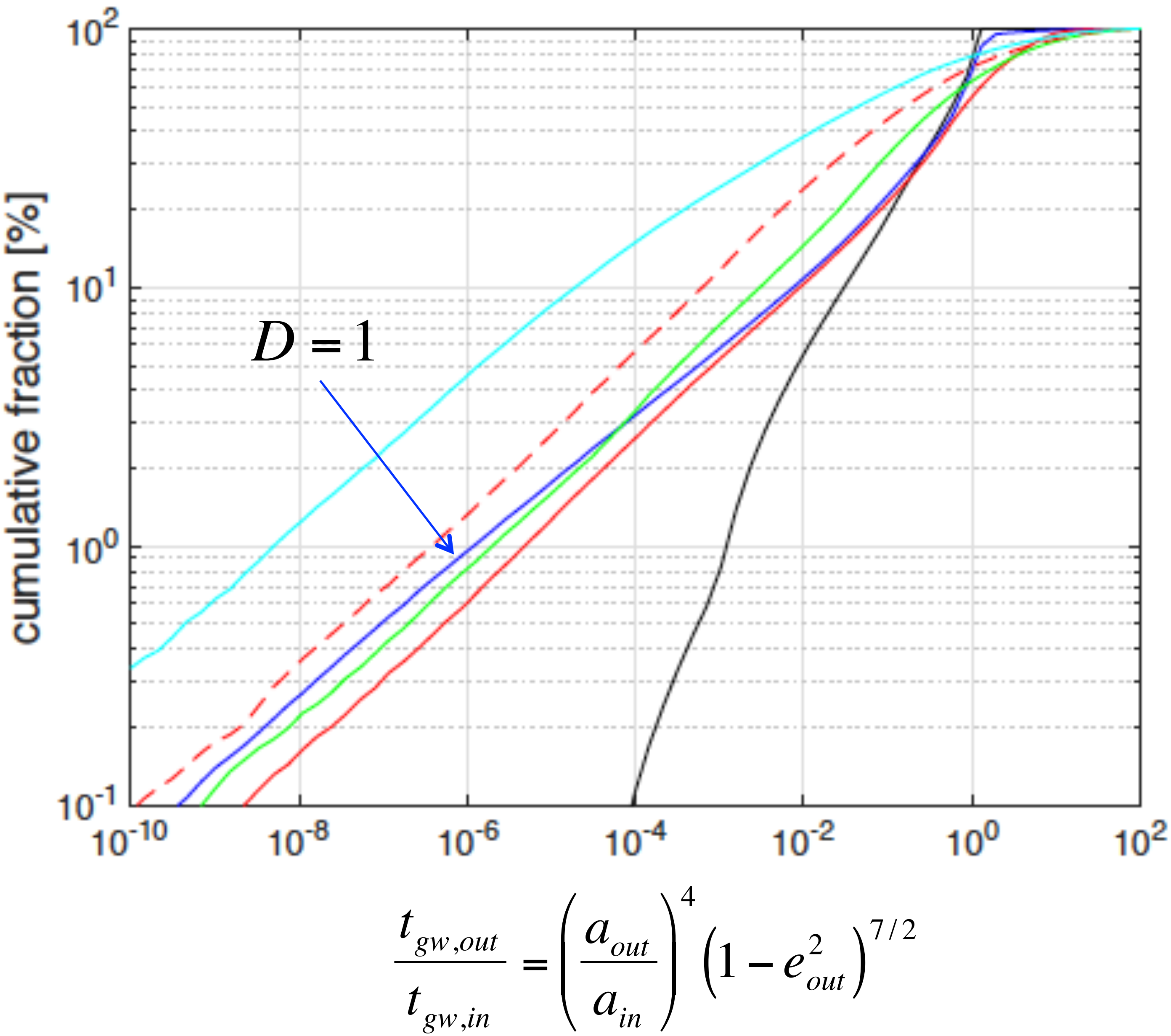
Gravitational wave merger time scale (Peters 1964)

$$T_{GW} = \frac{3}{85}\left(\frac{c^5 a_0^4}{G^3 m_1 m_2 m}\right)\left(1-e_0^2\right)^{7/2}$$

$$= 1.2\times 10^{14}\, yrs\left(\frac{m}{20M_{sun}}\right)^{-3}\left(\frac{a_0}{1AU}\right)^{4}\left(1-e_0^2\right)^{7/2}$$



cumulative fraction [%]
10^{-2}
0.1
0.2
0.5
1
$D = R_p / R_t = 2$
a
cumulative fraction [%]
1-e



cumulative fraction [%]
10^{2}
10^{1}
10^{0}
10^{-1}
$D = 1$
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
$$\frac{t_{gw,out}}{t_{gw,in}} = \left(\frac{a_{out}}{a_{in}}\right)^{4}\left(1 - e_{out}^{2}\right)^{7/2}$$

Summary

- HVSs: tidal disruption of binaries by a massive BH
- Restricted three-body formula (M>>m)
  - Equal ejection chance even for unequal-mass binaries
  - Deep penetration cases do not provide highest ejection velocity. D ~0.1
  - Even very deep penetration cases: 10% survive
  - Survivors: smaller semi-major axis, significant eccentricity
- Tidal disruption of BH-BH binaries
  - survivors have much shorter GW merger times.
    - Kozai mechanism: Antonini and Perets 2012; VanLandingham et al. 2016

- GAIA Data Release 1 on 14 Sep 2016.
  - Positions, proper motions and parallaxes for 1 billion stars; nearby (10kpc) HVSs
  - Accurate proper motion: key for constraining the Galactic potential.