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White dwarf-White dwarf collisions in AGN disk via close encounters

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Outline

1. Background
2. Simulation Models and Initial Set up
3. Results
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Compact objects in AGN disks

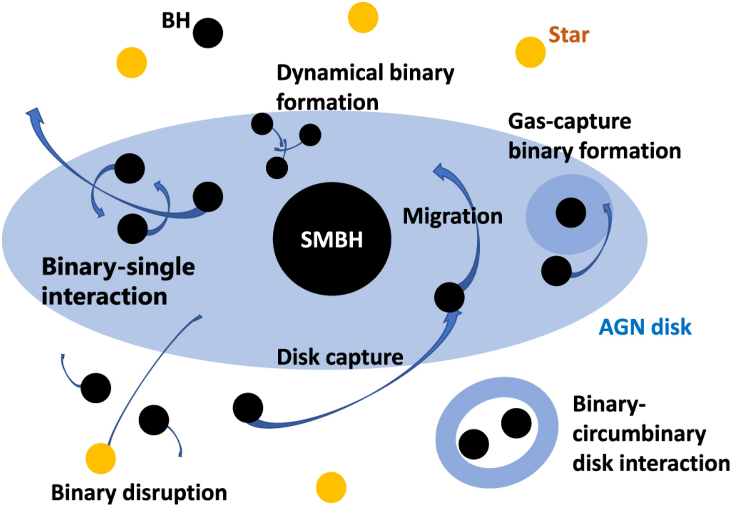
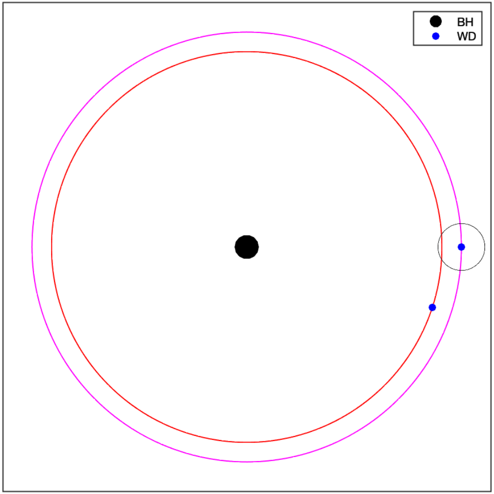


Figure: Compact objects in AGN disks, Tagawa et al. 2020.

Outline

Restricted three-body system

- A large population of WDs in AGNs;
- WDs align into AGN disks;
- WDs migrate in AGN disks and finally form restricted three-body systems;



The orbital separation $p = a_2 - a_1$. If

$$p \leq p_c = 2 \cdot 3^{1/6} \left(\frac{m_1 + m_2}{M} \right)^{1/3} = 2\sqrt{3} R_H, \tag{1}$$

the orbits are unstable and chaotic, leading to close encounters.

- Ejection

$$r_e \sim 2 \frac{G(m_1 + m_2)}{v_{orb}^2}. \tag{2}$$

- Binary formation via GW emission

$$r_b \equiv 3.48 \left(\frac{m_1 m_2}{(m_1 + m_2)^2} \right)^{\frac{2}{7}} \left(\frac{m_1 + m_2}{M} \right)^{\frac{10}{21}} \left(\frac{GM/c^2}{a_1} \right)^{\frac{5}{7}} R_H. \tag{3}$$

- Collision

$$r_c = r_1 + r_2. \tag{4}$$

Assume $M = 10^6 M_\odot$, $m_1 = m_2 = 0.6 M_\odot$, $a_1 = 100 r_\mathrm{g}$

$$\begin{aligned} r_\mathrm{c} &\approx 1.5 \times 10^7 \mathrm{m} \\ r_\mathrm{b} &\approx 1.76 \times 10^5 \mathrm{m} \\ r_\mathrm{e} &\approx 3.6 \times 10^5 \mathrm{m} \end{aligned} \tag{5}$$

$r_\mathrm{c} \gg r_\mathrm{b}, r_\mathrm{e}$

The two WDs will collide together before they form a binary or one of the WD be ejected.

- WD mass $m_1 = m_2 = 0.6M_\odot$, initial orbital separation $p = a_1 - a_2$.
- Initial eccentricities $e_1 = 0$ and $e_2 = 10^{-5}$.
- Initial orbital phase difference uniform distribute in $[0, 2\pi]$.
- N-body units $G = M = a_1 = 1$, $P_1 = 2\pi$.
- REBOUND, $10^5 P_1$.
- Three different initial parameters
  - Initial orbital separation
  - Relative orbital inclination
  - Mass of central SMBH

name	M	m_1, m_2	a_1	p/R_H	i_1, i_2	N
Run1	1	6×10^{-7}	1	1.0	0	1000
Run2	1	6×10^{-7}	1	1.5	0	1000
Run3	1	6×10^{-7}	1	2.0	0	1000
Run4	1	6×10^{-7}	1	2.5	0	1000
Run5	1	6×10^{-7}	1	3.0	0	1000
Run6	1	6×10^{-7}	1	3.5	0	1000
Run7	1	6×10^{-7}	1	[0.8,4]	0	4000
Run8	1	6×10^{-7}	1	3.0	$\lvert i_1-i_2\rvert=10^{-3}\frac{R_H}{a_1}$	1000
Run9	1	6×10^{-7}	1	3.0	$\lvert i_1-i_2\rvert=10^{-2}\frac{R_H}{a_1}$	1000
Run10	1	6×10^{-7}	1	3.0	$\lvert i_1-i_2\rvert=10^{-1}\frac{R_H}{a_1}$	1000
Run11	1	6×10^{-7}	1	3.0	$\lvert i_1-i_2\rvert=\frac{R_H}{a_1}$	1000
Run12	1	6×10^{-8}	1	3.0	0	1000
Run13	1	6×10^{-9}	1	3.0	0	1000

Closest separation of different p

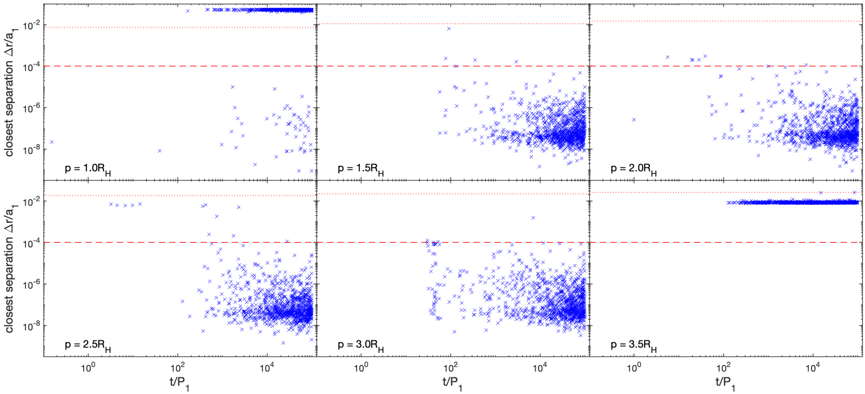
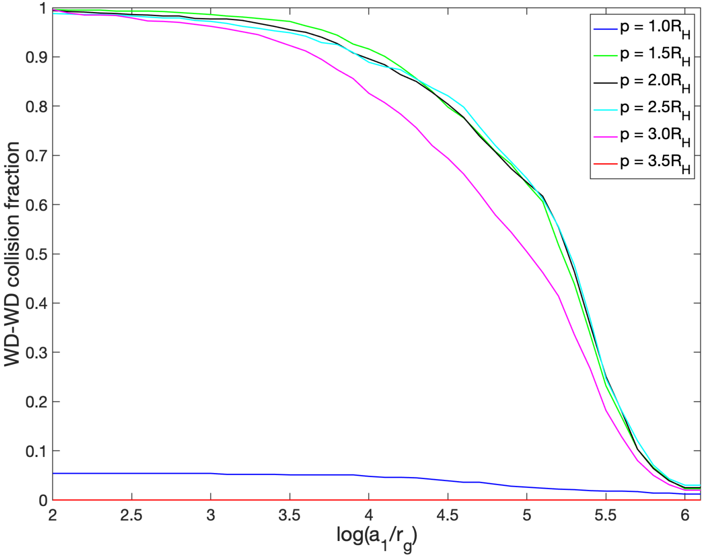
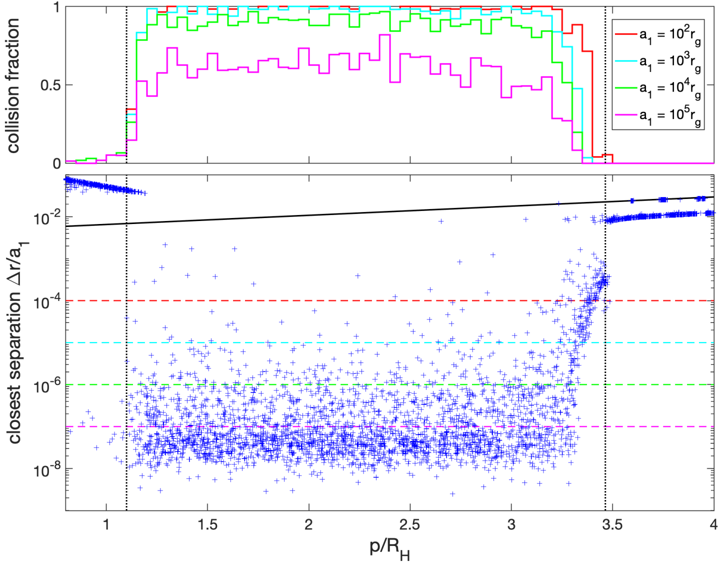


Figure: Closest separation in $10^5 P_1$ as a function of time. The red dot lines correspond to $\Delta r = p$. The red dash lines correspond to the close encounter separation.

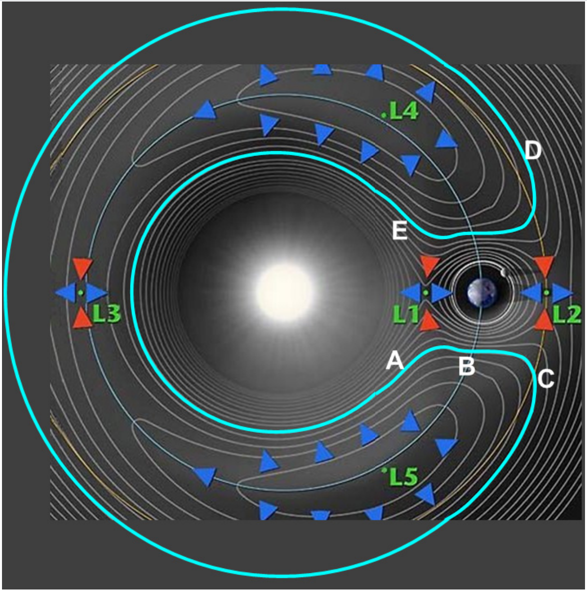
WD-WD collision fraction



Random initial orbital separation (Run7)



Horseshoe orbits and tadpole orbits



orbital radius evolution for $p < 1.1R_{\rm H}$

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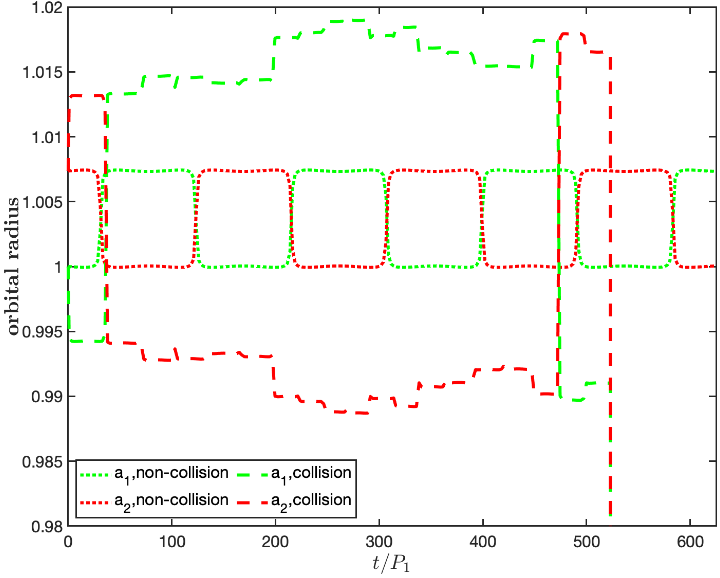

WD-WD collision as a function of time

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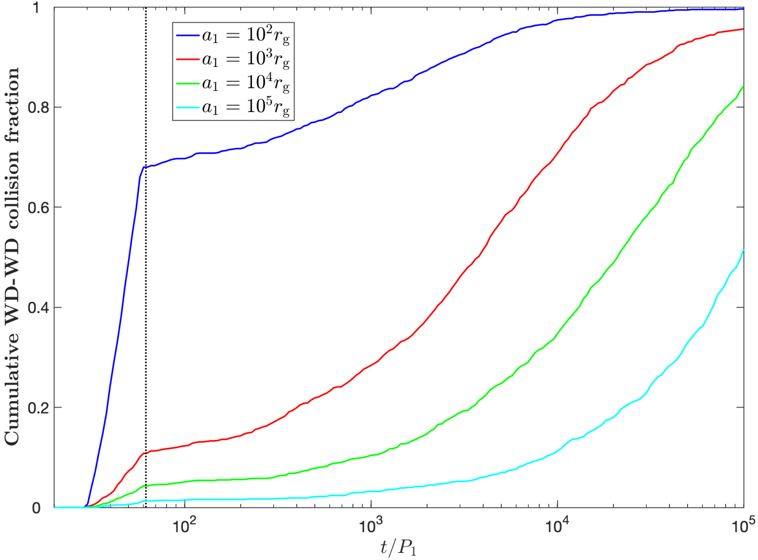
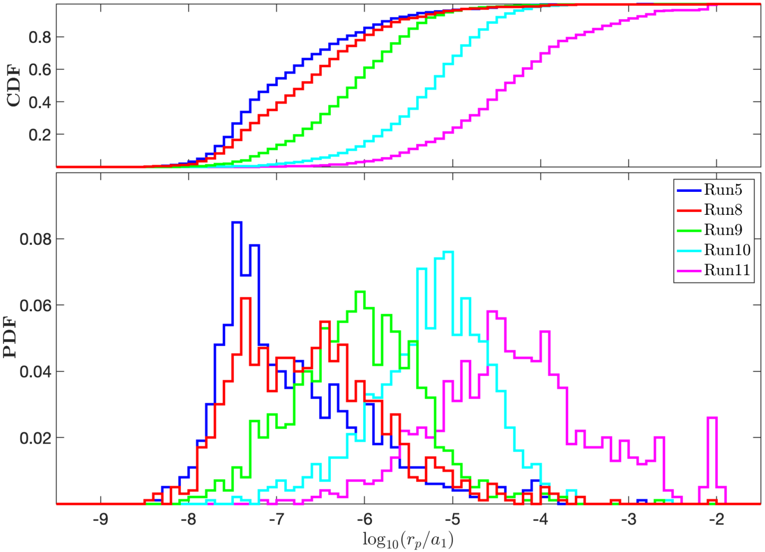
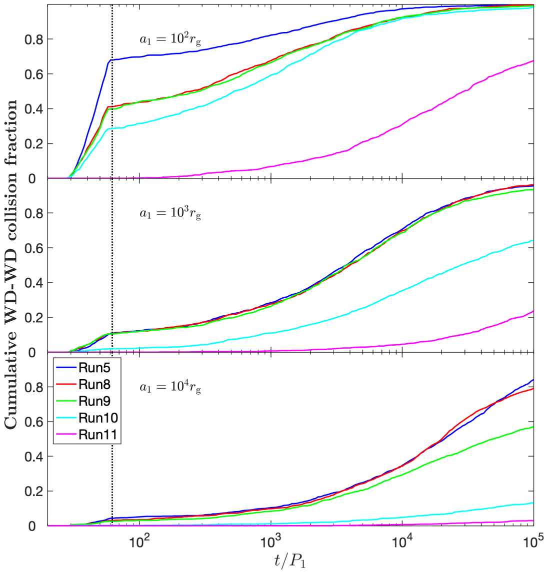



CDF
0.8
0.6
0.4
0.2
PDF
0.08
0.06
0.04
0.02
Run5
Run8
Run9
Run10
Run11
-9
-8
-7
-6
-5
-4
-3
-2
$\log_{10}(r_p/a_1)$

Inclinations



Different central SMBH mass

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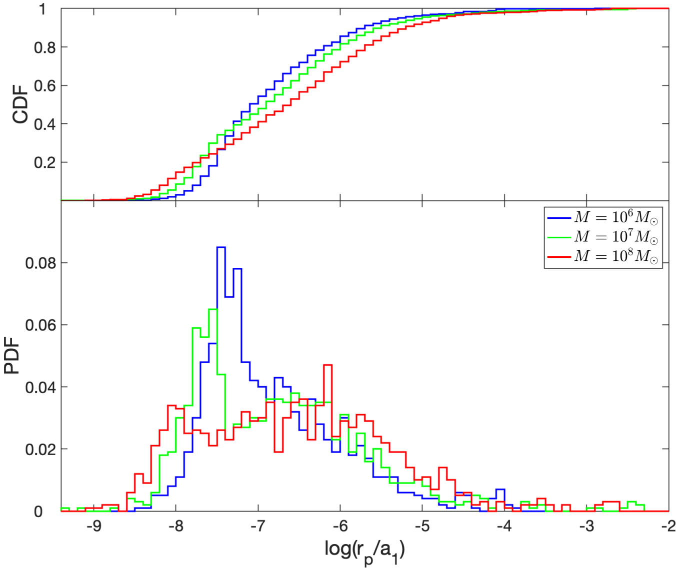
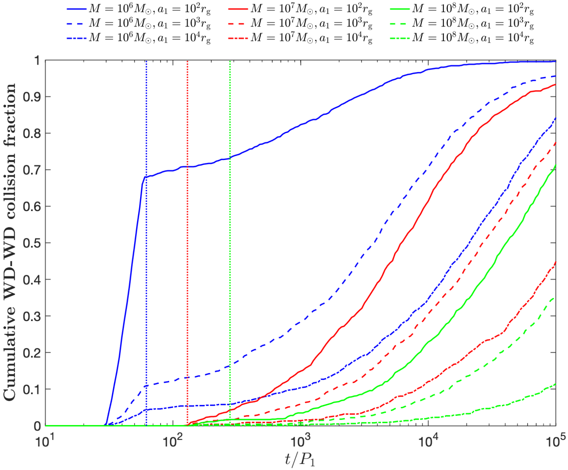


Different central SMBH mass



The red dot line correspond to $62P_1$.

WD-WD collision rates

The number of BHs around the SMBH is $\sim 1 - 4 \times 10^4$.

As a reuslt, there should exist $\sim 2 \times 10^5$ WDs around the SMBH.

the WD-WD collision rate

$$\begin{aligned}\mathcal{R} =& n_{\rm GN} \times f_{\rm AGN} \times \frac{N_{\rm WD} \times f_{\rm d} \times f_{\rm 3b} \times f_{\rm c}}{\tau_{\rm AGN}}, \\ =& 300{\rm Gpc}^{-3}{\rm yr}^{-1} \frac{n_{\rm WD}}{0.006{\rm Mpc}^{-3}} \frac{N_{\rm WD}}{2 \times 10^5} \frac{f_{\rm AGN}}{0.1} \frac{f_{\rm d}}{0.1} \\ & \times \frac{f_{\rm 3b}}{0.25} \frac{f_{\rm c}}{1} \left(\frac{\tau}{10{\rm Myr}}\right)^{-1}.\end{aligned} \tag{6}$$

Around 1% type Ia SNe rate.

- WDs will collide rather than form binary in our restricted three-body system.
- The close encounter occur in most of our system for $1.1R_{\mathrm{H}} < p < 2\sqrt{3}R_{\mathrm{H}}$.
- The WD-WD collision fraction decrease as inclination increase.
- As the mass of central SMBH increase, WD-WD collision will decrease.
- The WD-WD collision rate is $300\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$.