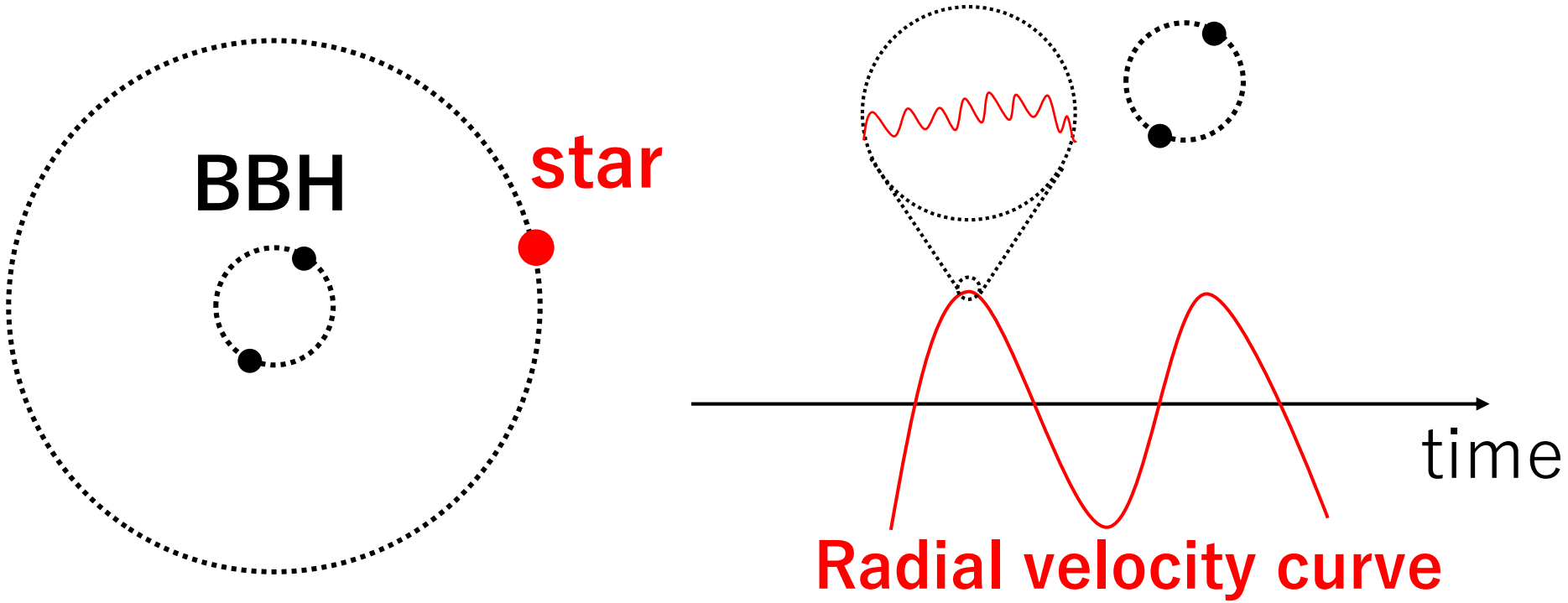
“The Evolution of Massive Stars and Formation of Compact Stars: from the Cradle to the Grave”

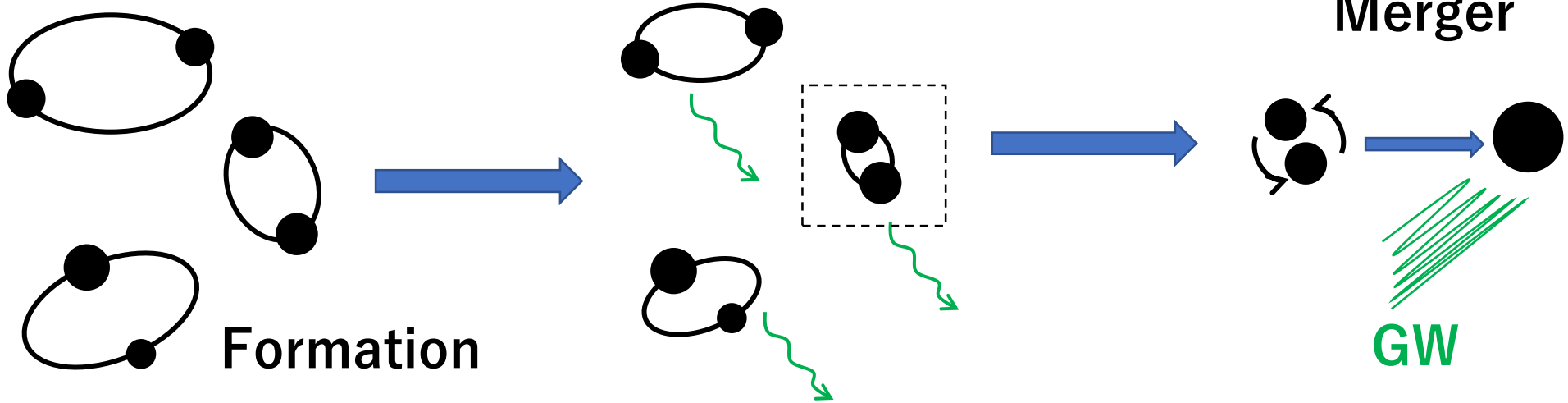
A strategy to search for an inner binary black hole from the motion of the tertiary star



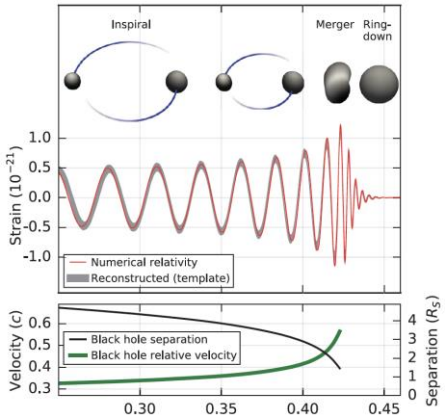
Toshinori Hayashi, Shijie Wang, Yasushi Suto
University of Tokyo
17:05- 27 Feb. 2020 @ Waseda University

Background： Binary black holes (BBHs)

The discovery of BBH merger with GW
(2015, LIGO)



LIGO team 2016



GW detector

weak GW(low-frequency)

~Gyr scale orbital evolution(GW emission)

Long orbital-period BBHs
(e.g. ~10day period→~10^{-6}Hz)

Abundant progenitors ??

Except for GW, how to search for ?

Background： star-BH binary

Surveys

Gaia(2013-) Astrometry for $\sim 10^9$ stars

Yamaguchi+2018 proposal

TESS(2018-) Photometry for near-by stars

Masuda+2018 proposal

LB-1 system

B-type star – unseen companion binary

RV by LAMOST (Liu+2019)

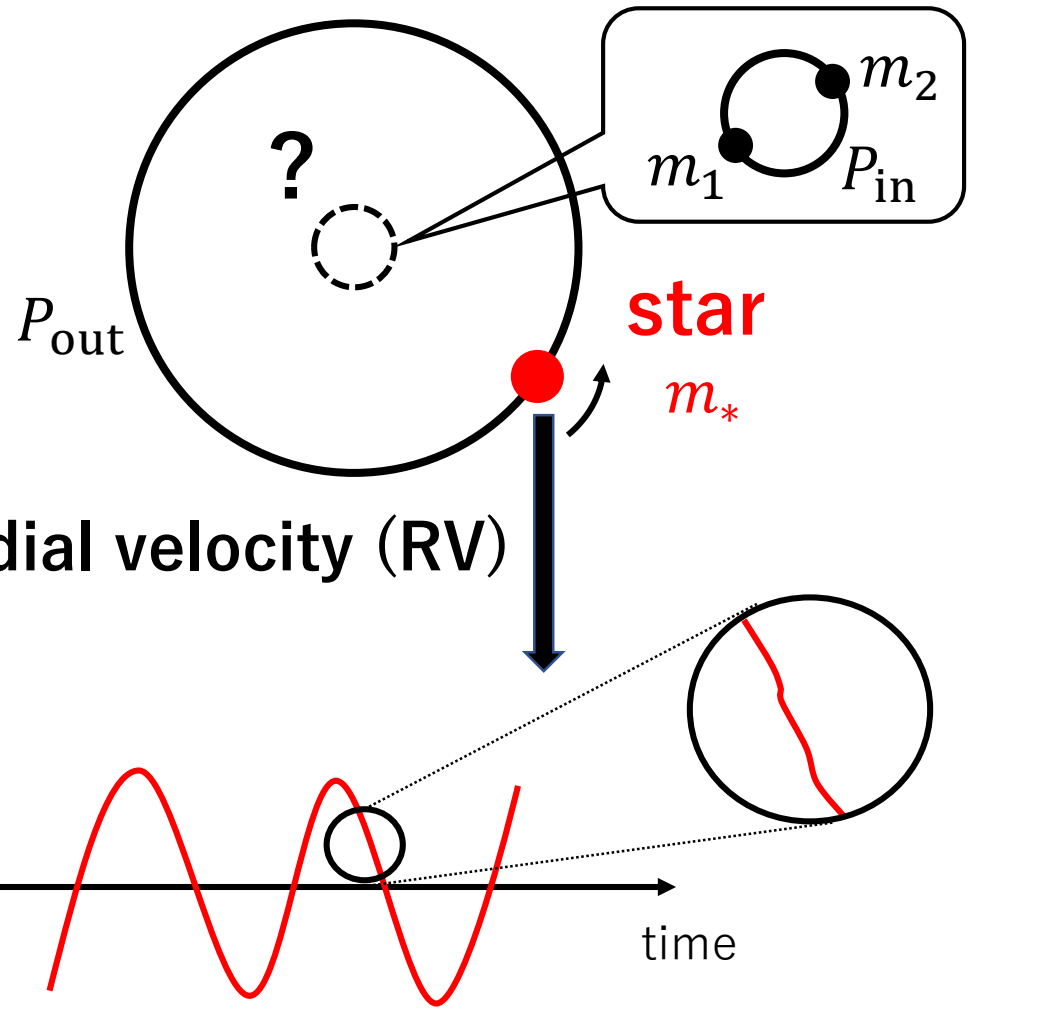
$P_{\rm out} \sim 78.9$ days $\quad e_{\rm out} \sim 0.03$

$m_* \sim 8M_\odot \quad m_{\rm CO} \sim 70M_\odot \quad I_{\rm out} \sim 15$ deg

inner binary is strongly constrained (Shen+2019)

$m_* \sim 3-5M_\odot$ **Abdul-Masih+ 2019**

$5M_\odot \lesssim m_{\rm CO} \lesssim 20M_\odot$ **El-Badry+ 2019**



Keplerian motion + RV variations by inner binary

high-precision RV follow-up

Research: numerical setups

Our fiducial numerical setup

parameter	input value
outer orbital period $P_{\rm out}$	78.9 days
inner orbital period $P_{\rm in}$	10.0 days
inner binary mass $m_1 + m_2$	$20\ M_\odot$
star mass m_*	$3\ M_\odot$
outer eccentricity $e_{\rm out}$	0.03
true anomalies $(f_{\rm in}, f_{\rm out})$	$(30°, 120°)$
arguments of pericenter $(\omega_{\rm in}, \omega_{\rm out})$	$(0°, 0°)$
longitudes of ascending node $(\Omega_{\rm in}, \Omega_{\rm out})$	$(0°, 0°)$

N-body simulation (REBOUND)
RV outputs every 0.1 day

coplanar setup

set	m_2/m_1	$e_{\rm in}$	$i_{\rm mut}$
P1010	1	10^{-5}	$0°$
PE1010	1	0.2	$0°$
R1010	1	10^{-5}	$180°$
P0218	0.2	10^{-5}	$0°$

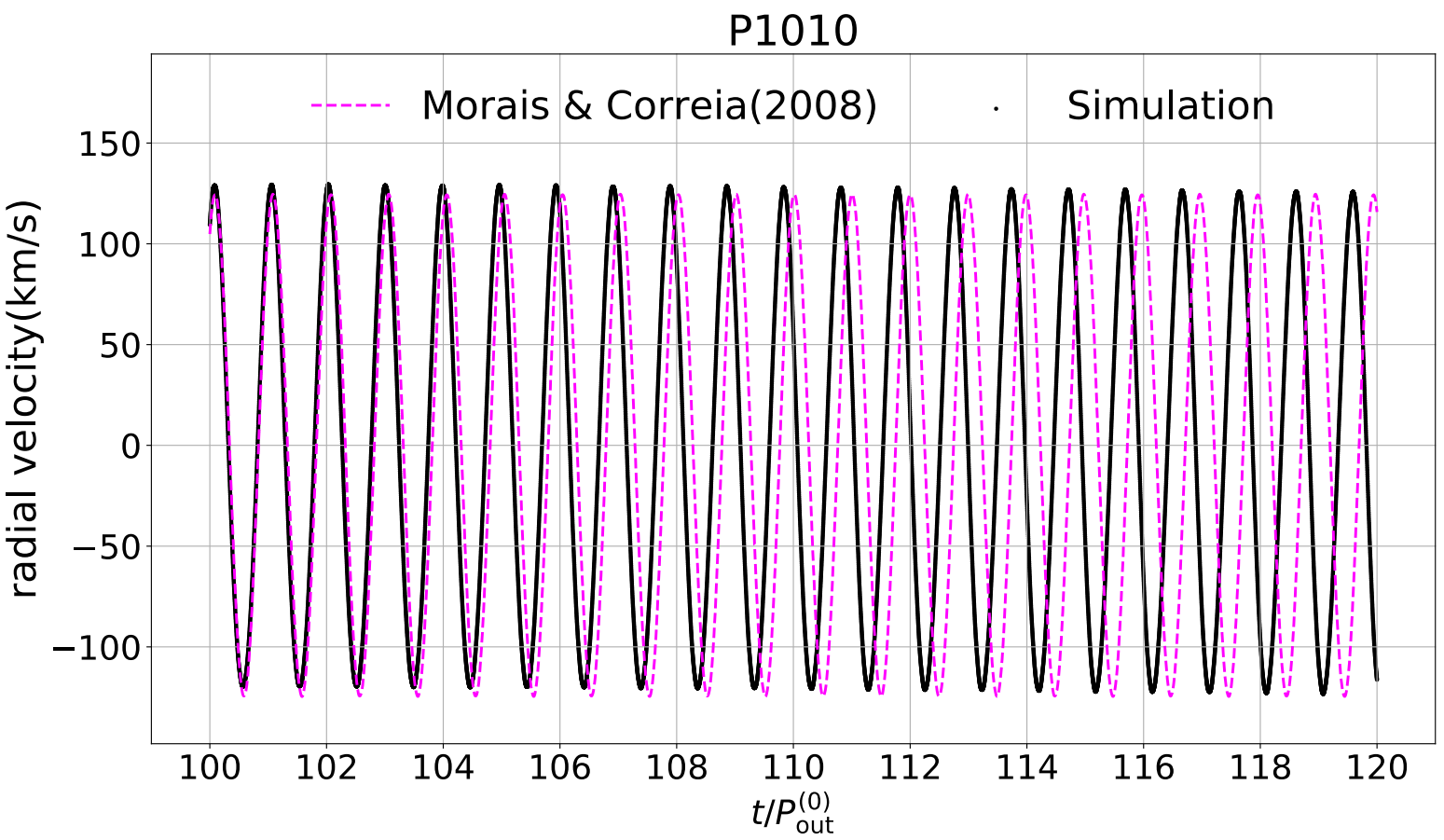
inclined setup

set	m_2/m_1	$e_{\rm in}$	$i_{\rm mut}$
I1010	1	10^{-5}	$45°$
O1010	1	10^{-5}	$90°$

Research: Determination of base-line Keplerian

The orbital period varies from its input value $P_{\mathrm{out}}^{(0)} = 78.9$ days

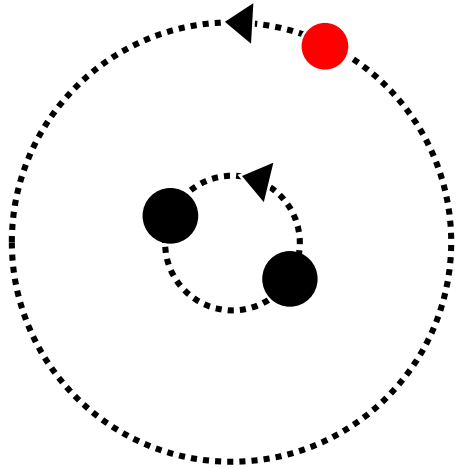
Not rigorous Kepler motion due to inner-binary perturbation



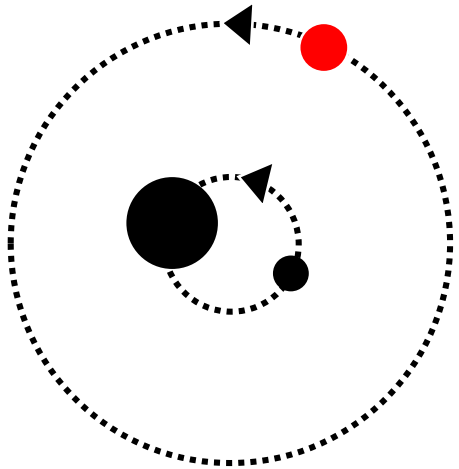
RV Fitting code RadVel

Determined the best-fit base-line quasi-Kepler motion for one period

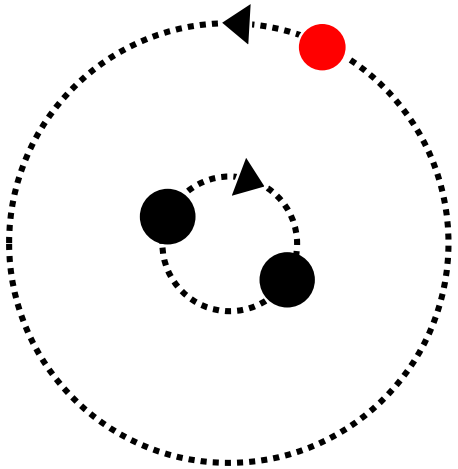
RV variations are extracted as the residuals



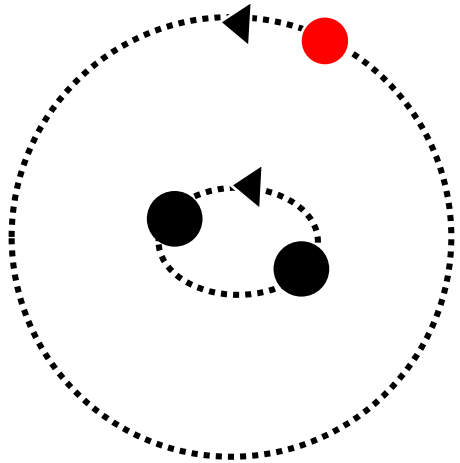
P1010



P0218



R1010



PE1010

Coplanar triples

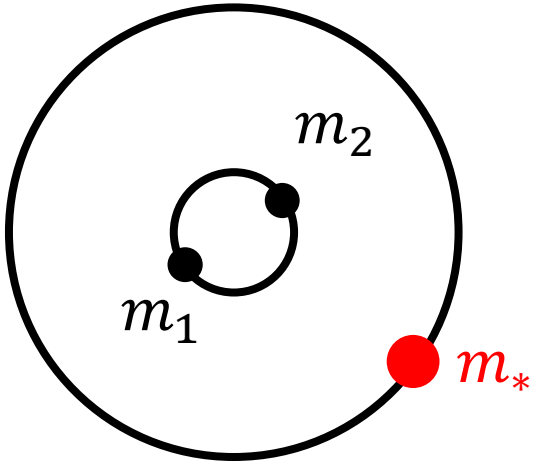
P1010 (circular, prograde, equal-mass inner binary)

P0218 (circular, prograde, 5:1 mass inner binary)

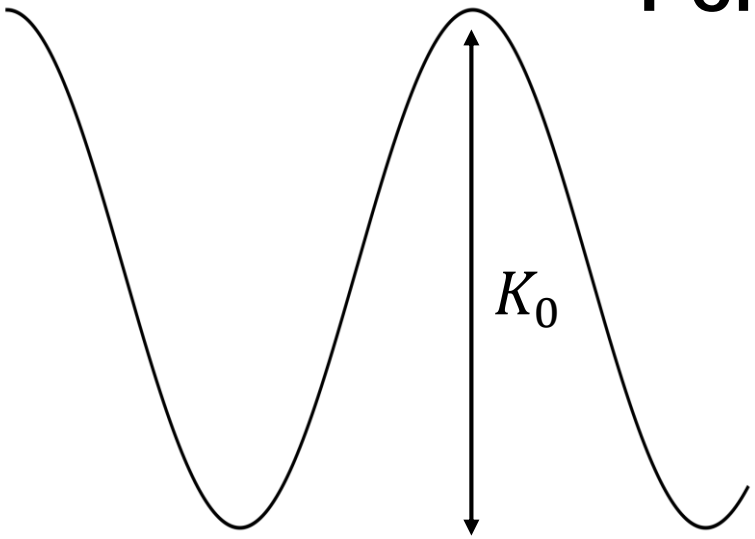
R1010 (circular, retrograde, equal-mass inner binary)

PE1010 (inner eccentricity 0.2, prograde, equal-mass inner binary)

Research: RV variations for a coplanar circular case



RV =



+

Perturbative solution

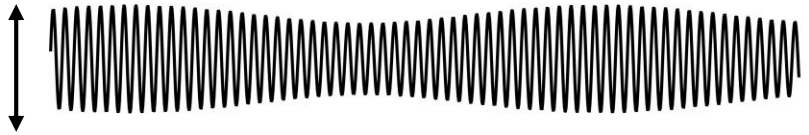
$\sim \nu_{\rm out}$

~Keplerian

$$K_{\rm BBH} \sim \left(\sqrt{\frac{m_1}{m_2}}+\sqrt{\frac{m_2}{m_1}}\right)^{-2}\left(\frac{a_{\rm in}}{a_{\rm out}}\right)^{3.5} K_0$$

(Morais+2008)

$\sim K_{\rm BBH}$



$\frac{15}{16}K_{\rm BBH}$ $\nu_{-3} = 2\nu_{\rm in} - 3\nu_{\rm out}$

$\frac{3}{16}K_{\rm BBH}$ $\nu_{-1} = 2\nu_{\rm in} - \nu_{\rm out}$

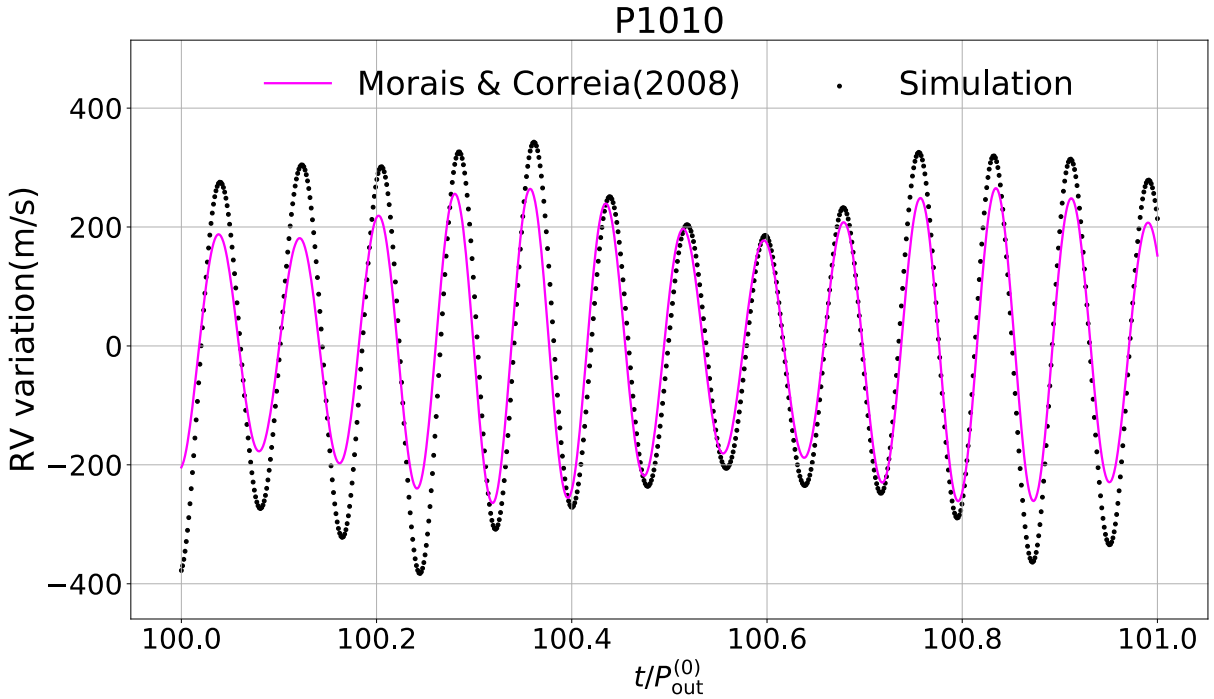
inner binary

Research: RV variations for a coplanar circular case (1)

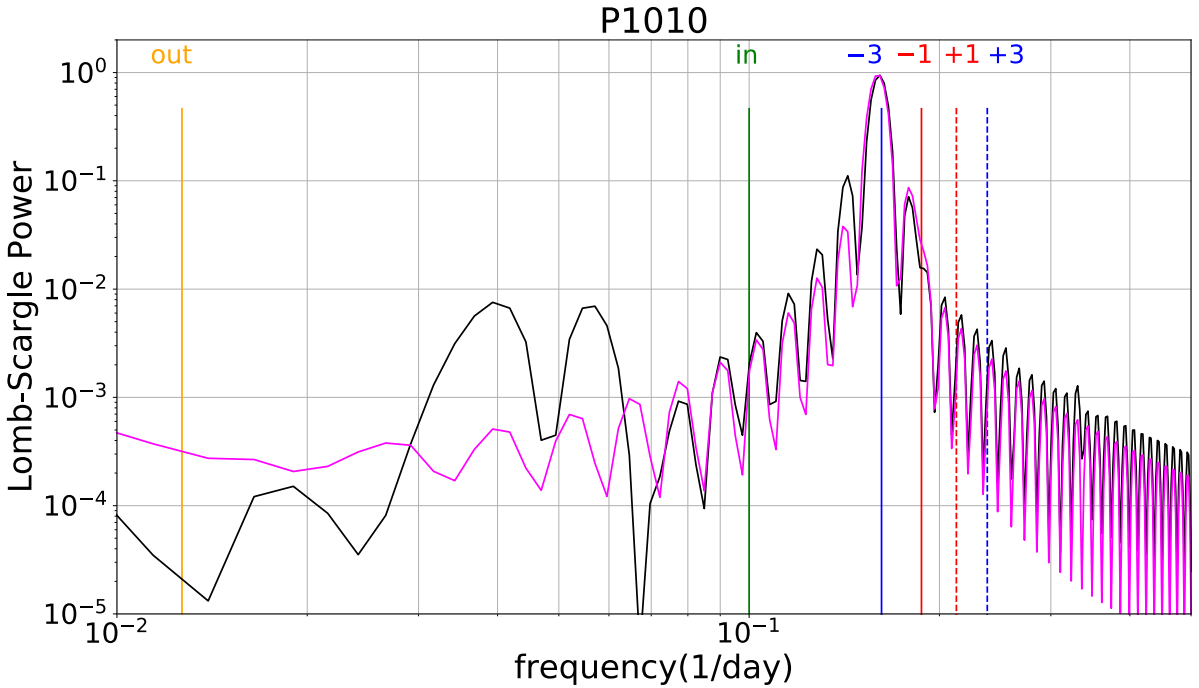
P1010 (coplanar, circular, prograde, equal-mass inner binary)

RV variations agree well with the expected variations from approximation (Morais+2008)

$$\nu_{-3} = 2\nu_{\rm in} - 3\nu_{\rm out}$$
$$\nu_{-1} = 2\nu_{\rm in} - \nu_{\rm out}$$



time series



LS periodogram

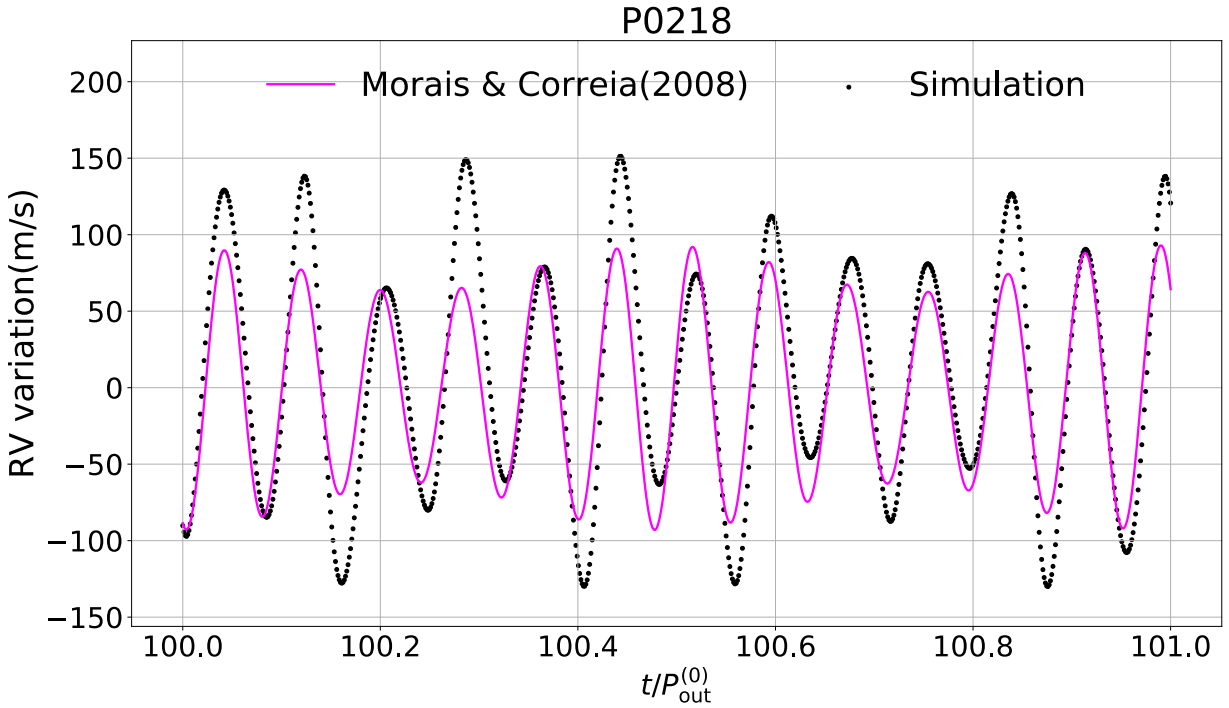
Research: RV variations for a coplanar circular case (2)

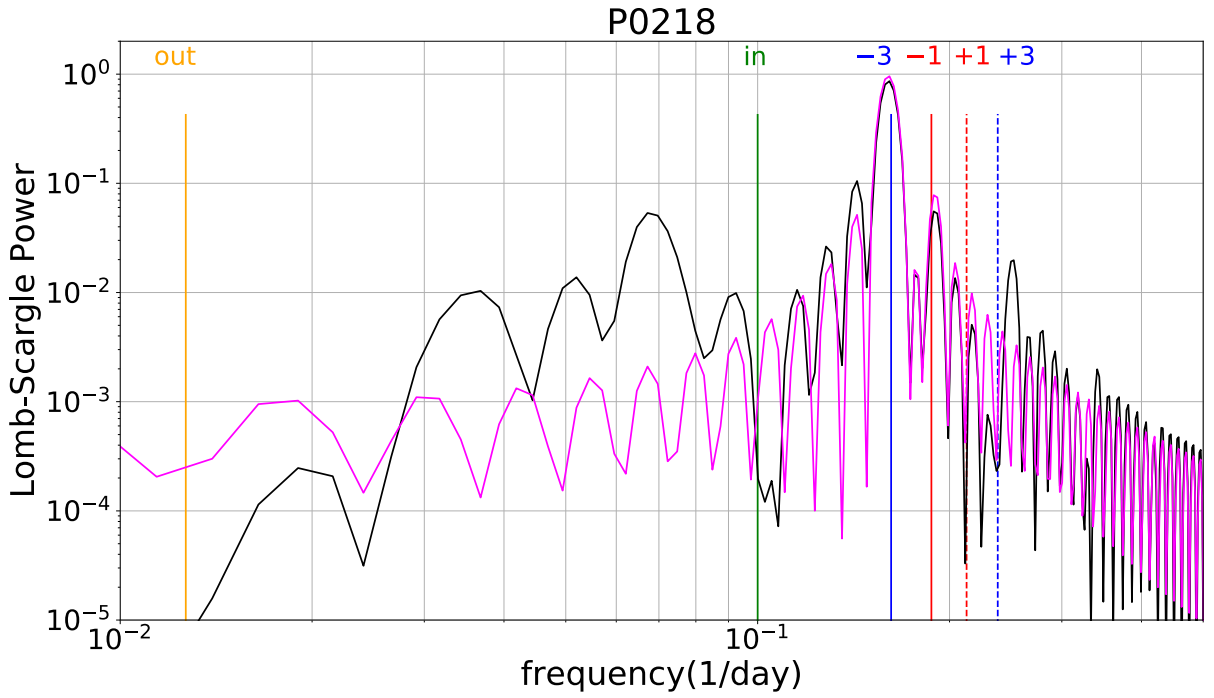
P0218 (coplanar, circular, prograde, 5:1 mass inner binary)

Large mass ratio reduces the amplitude
Basically well agree with Morais+2008

Large mass ratio enhances the higher-order effect (octupole) and causes some discrepancy

ν_{-3}-mode still outstanding





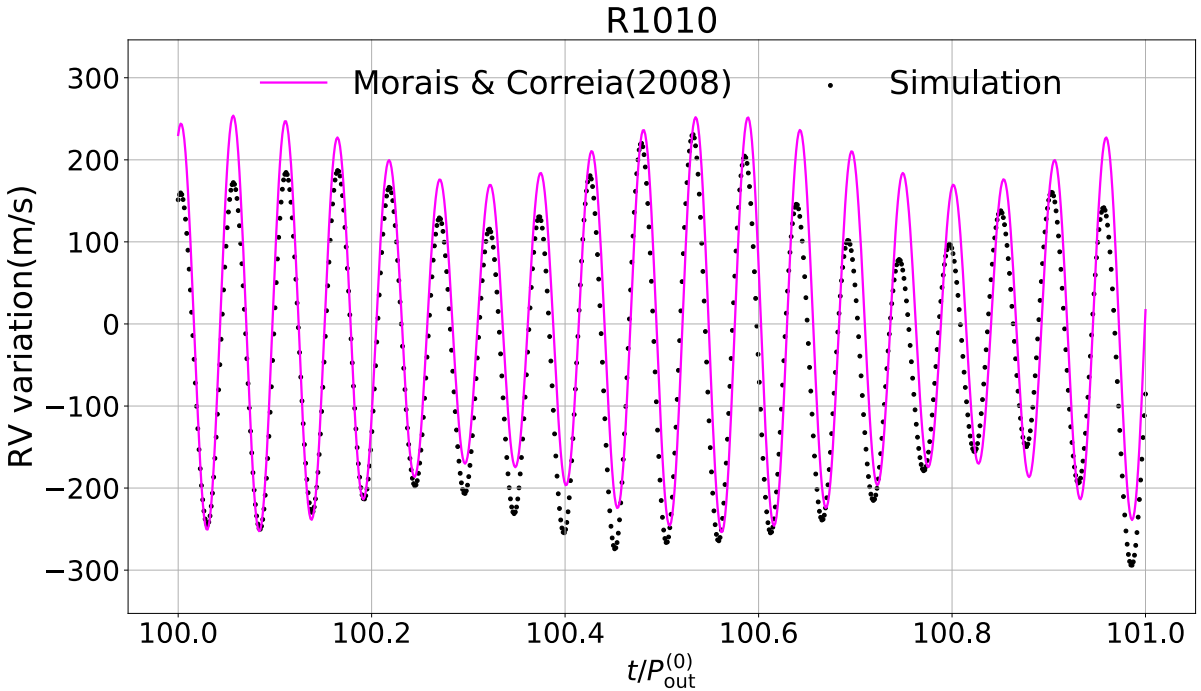
Research: RV variations for a coplanar circular case (3)

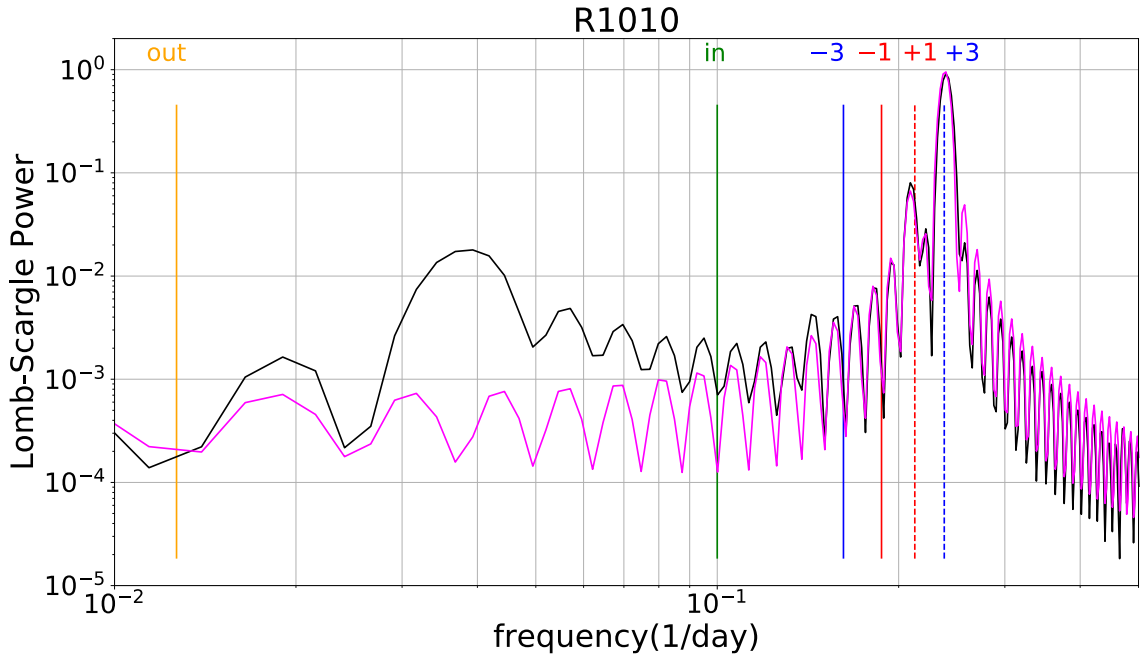
R1010 (coplanar, circular, retrograde, equal-mass inner binary)

cf. prograde $\begin{cases} \nu_{-3} = 2\nu_{\rm in} - 3\nu_{\rm out} \\ \nu_{-1} = 2\nu_{\rm in} - \nu_{\rm out} \end{cases}$

$\begin{cases} \nu_{+3} = 2\nu_{\rm in} + 3\nu_{\rm out} \\ \nu_{+1} = 2\nu_{\rm in} + \nu_{\rm out} \end{cases}$ **mode**

is detected for a retrograde case





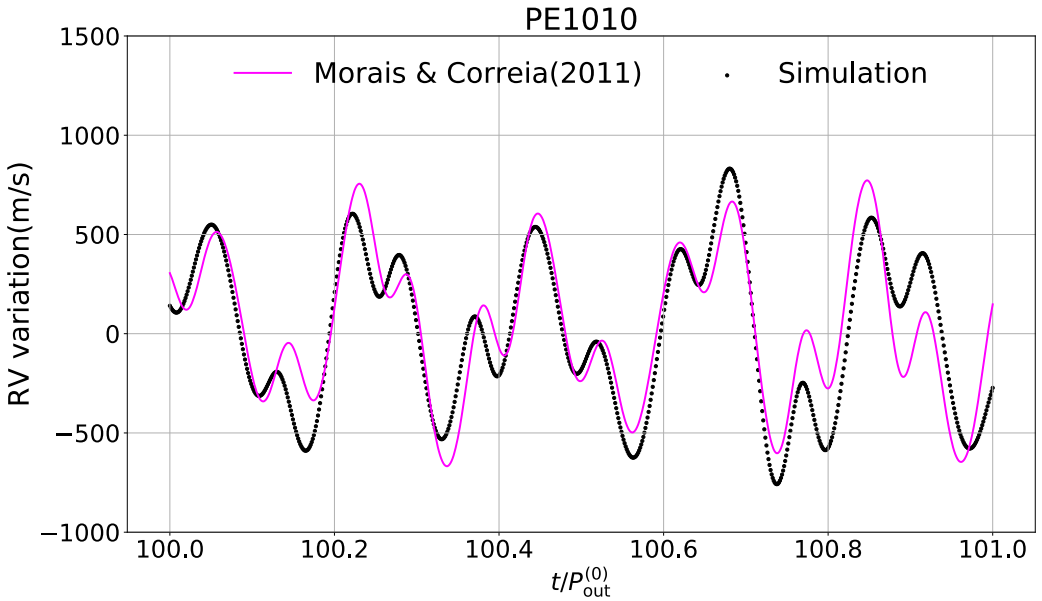
Research: RV variations for a coplanar eccentric case (4)

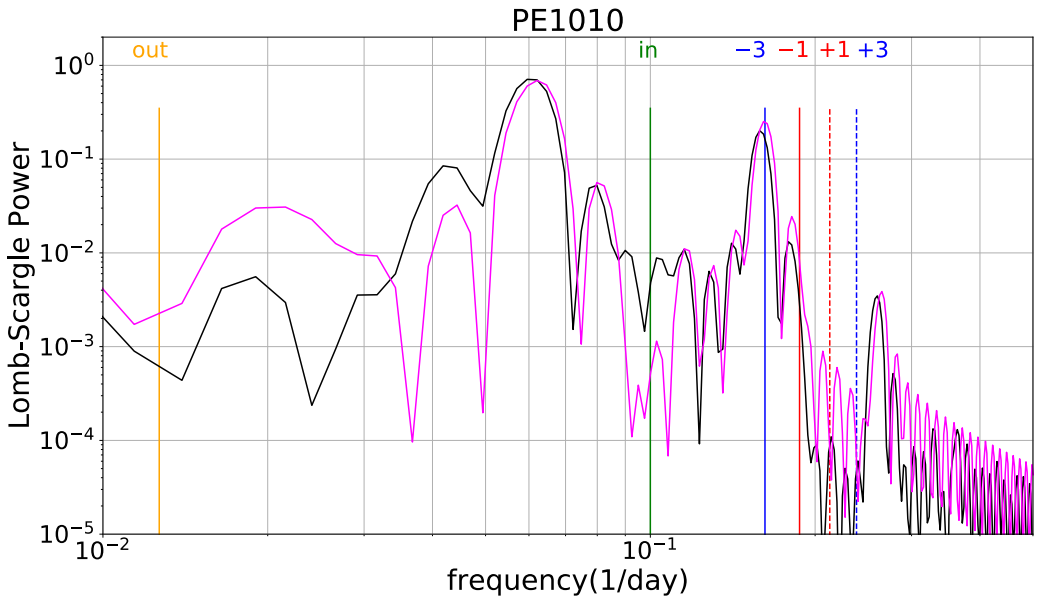
PE1010 (coplanar, eccentric, prograde, equal-mass inner binary)

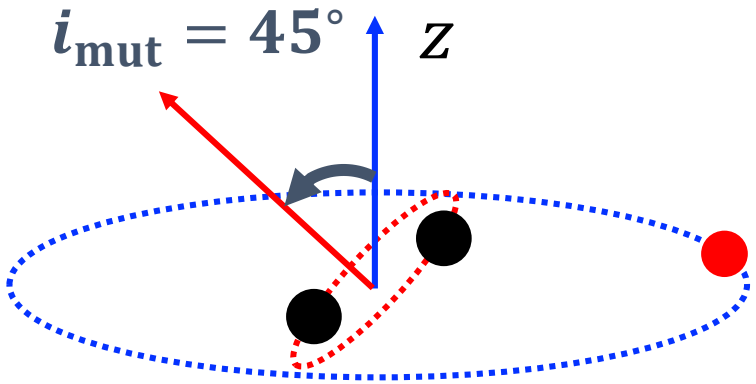
Inner eccentric binary induces other-mode variations (e.g. $\nu_{\mathrm{in}} - 3\nu_{\mathrm{out}}$)

include the information on eccentricity

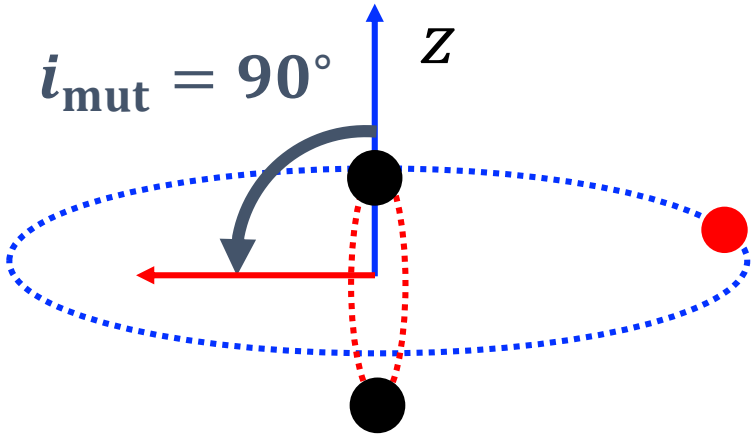
Morais+2011 approximate formula agrees well after phase and offset corrections







I1010



O1010

Inclined triples

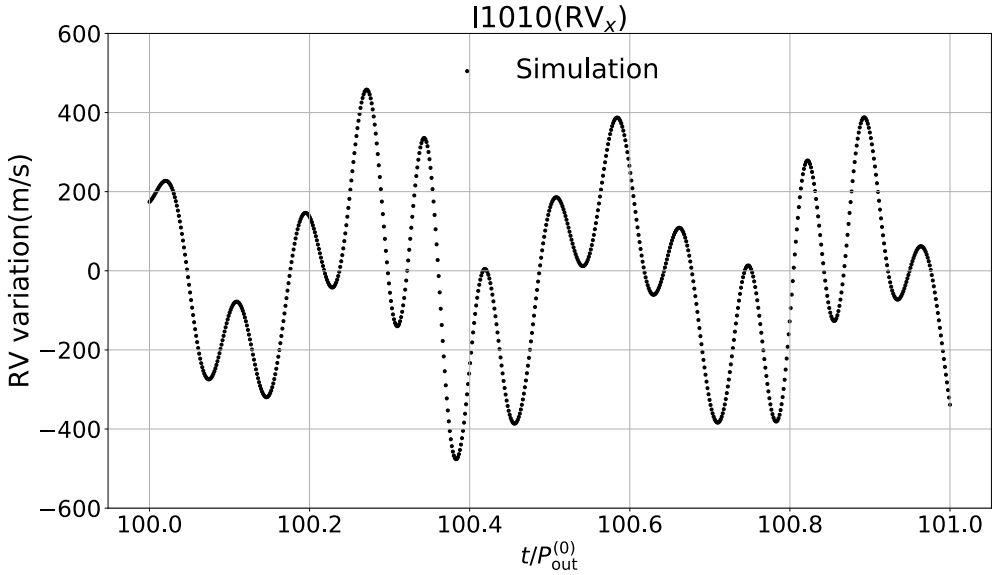
I1010 (circular, equal-mass inner binary, $i_{\mathrm{mut}} = 45^\circ$)

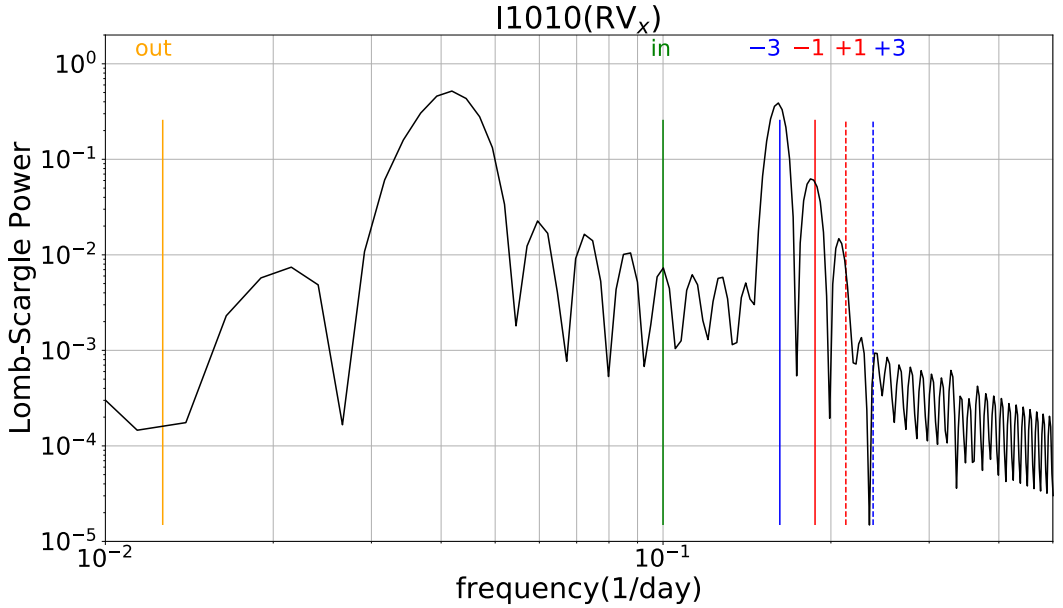
O1010 (circular, equal-mass inner binary, $i_{\mathrm{mut}} = 90^\circ$)

Research: RV variations for a inclined case ($i_{mut} = 45°$)

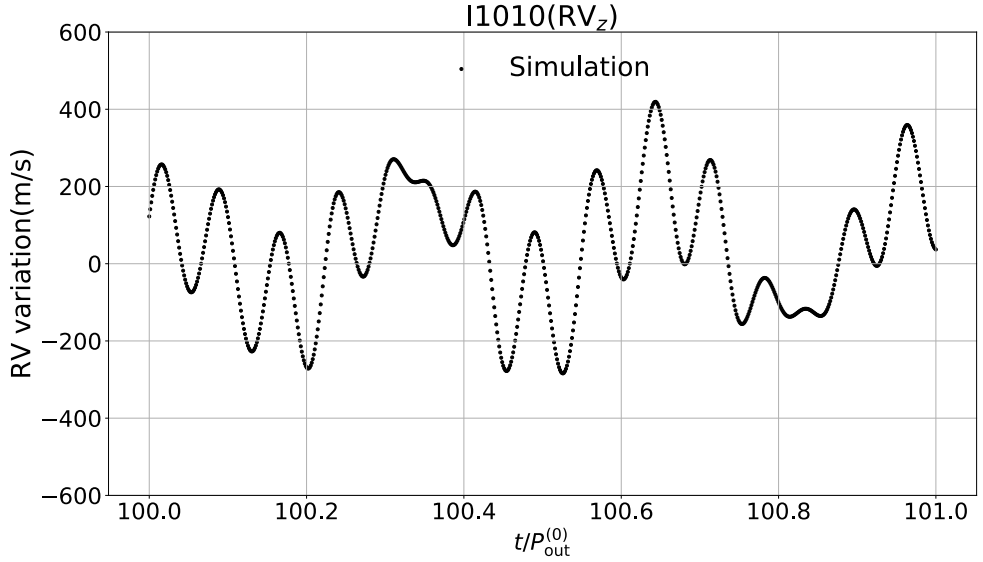
I1010

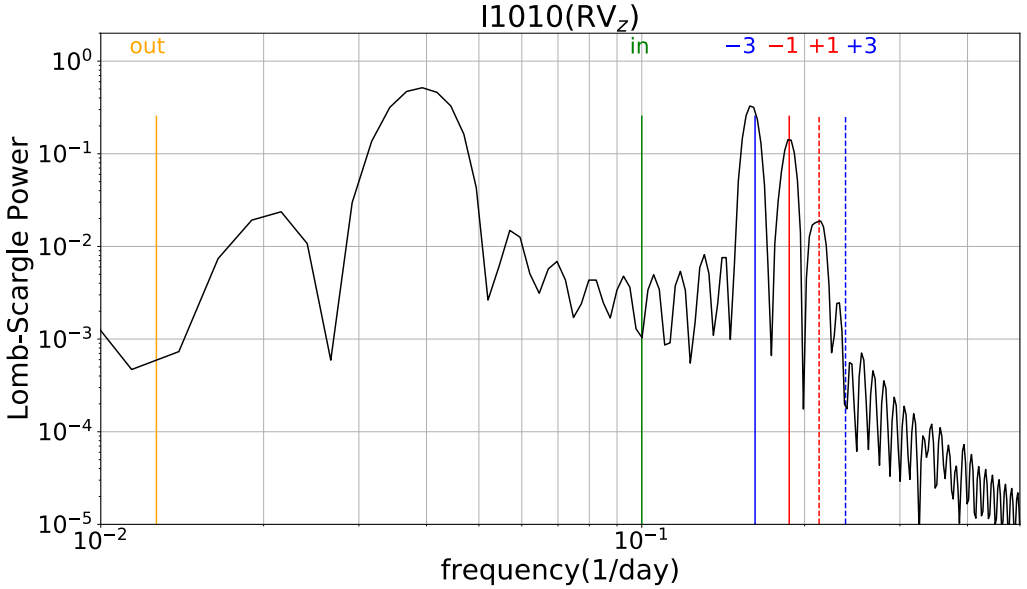
x-direction



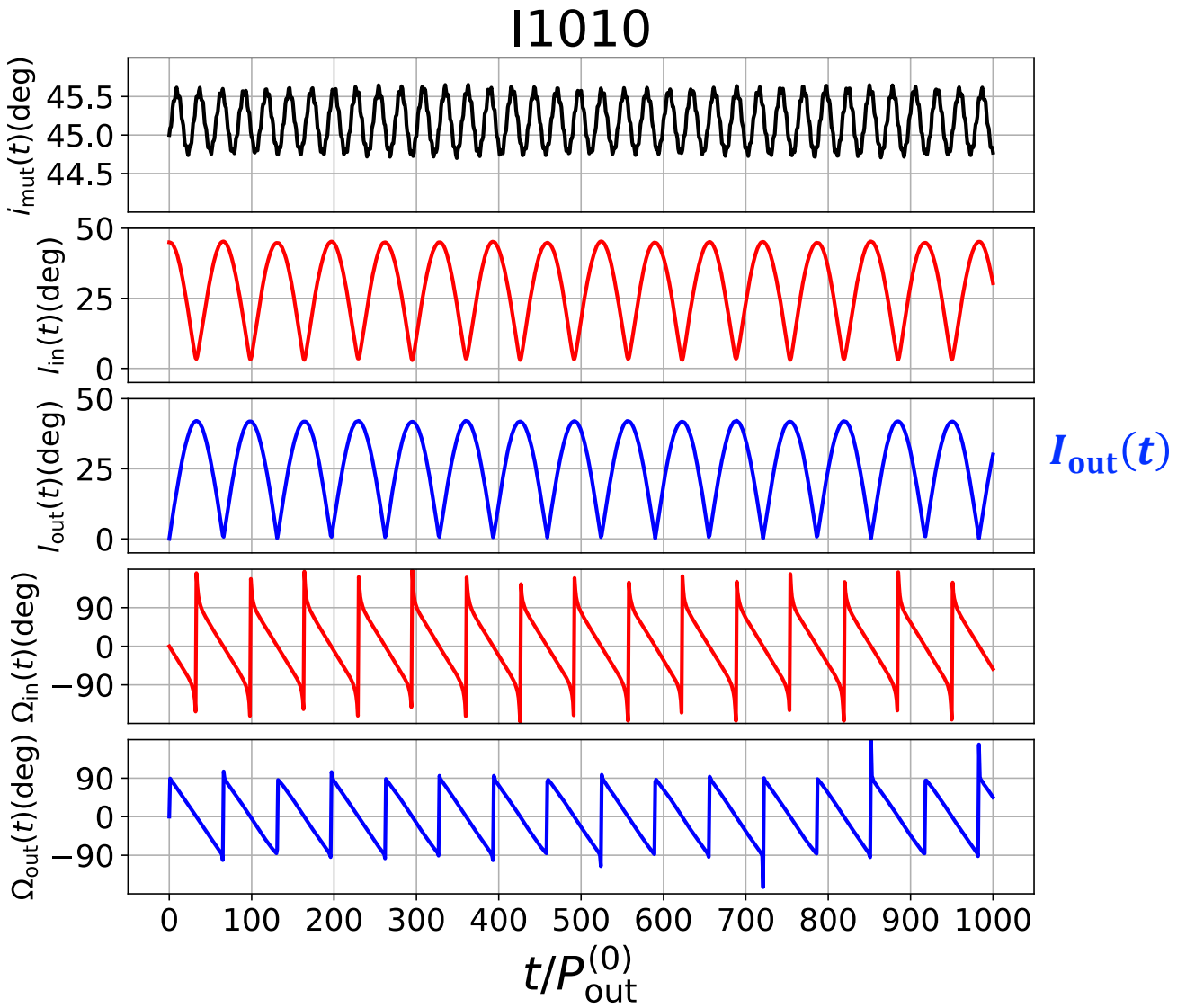


z-direction

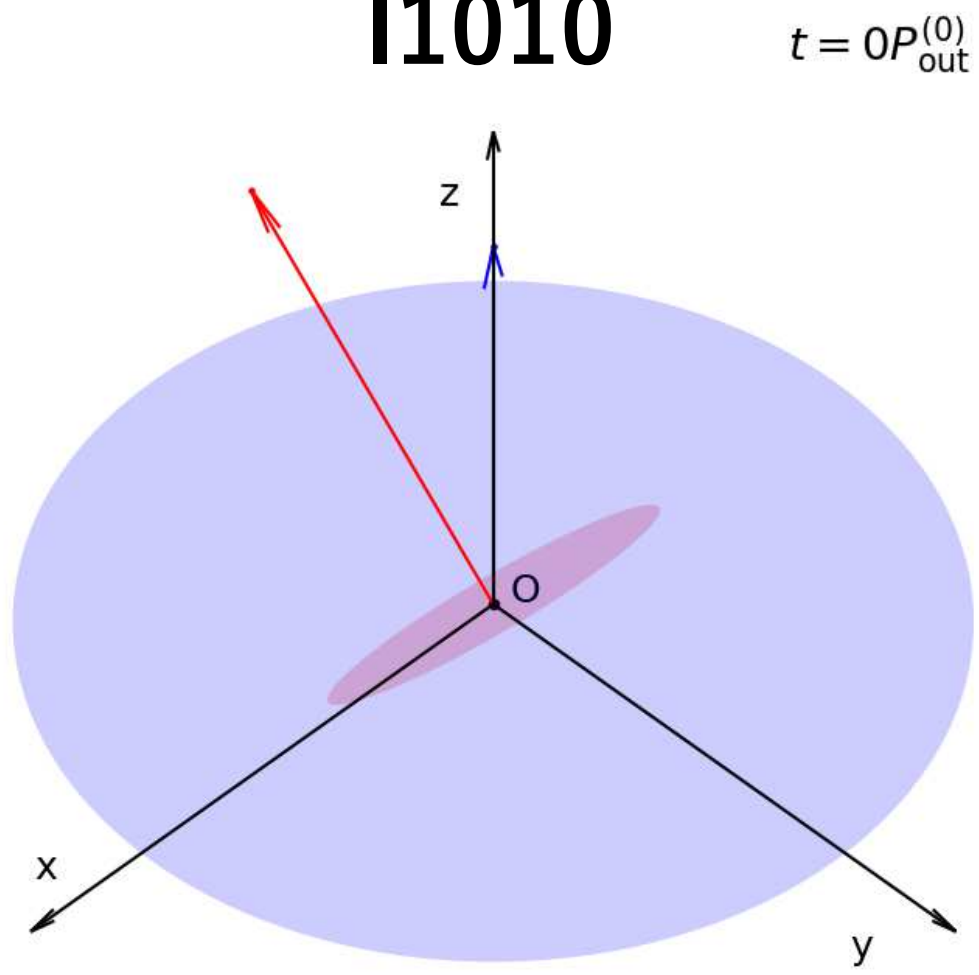




Research: RV variations for a inclined case ($i_{mut} = 45°$)



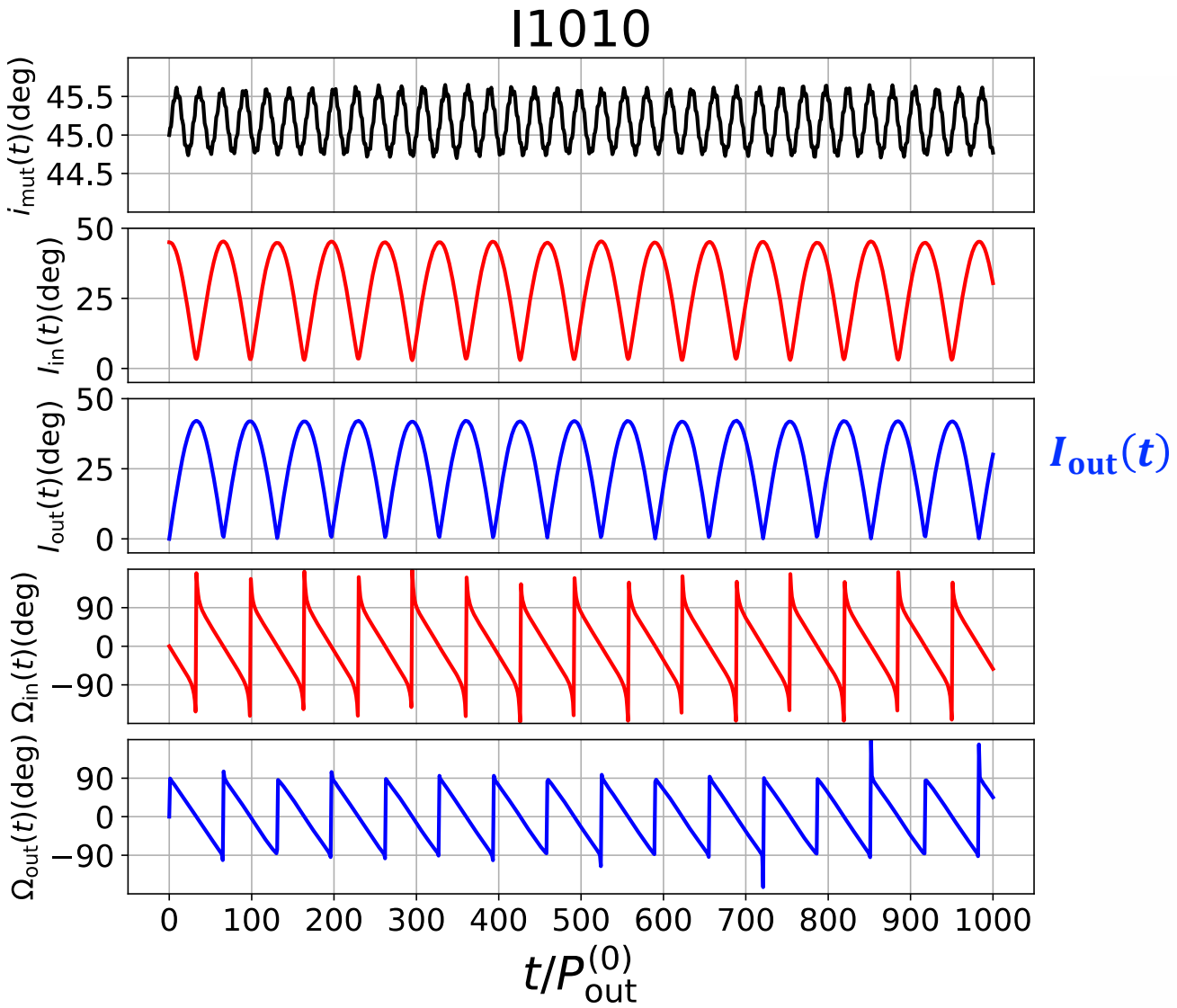
$I_{out}(t)$



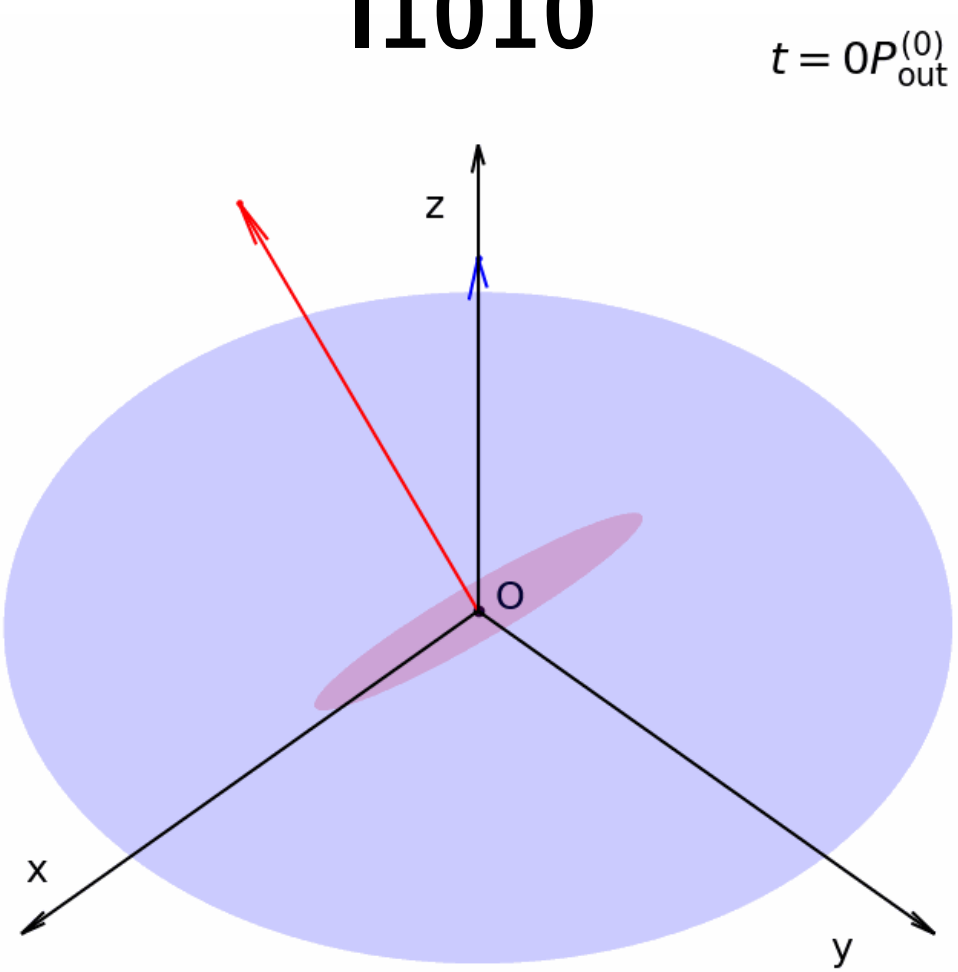
Kozai-Lidov oscillation is not effective

Regular precession induces the inclination variation

Research: RV variations for a inclined case ($i_{mut} = 45°$)



$I_{out}(t)$



Kozai-Lidov oscillation is not effective

Regular precession induces the inclination variation

Research: orbital evolution for a inclined case ($\boldsymbol{i_{\mathrm{mut}} = 45°}$)

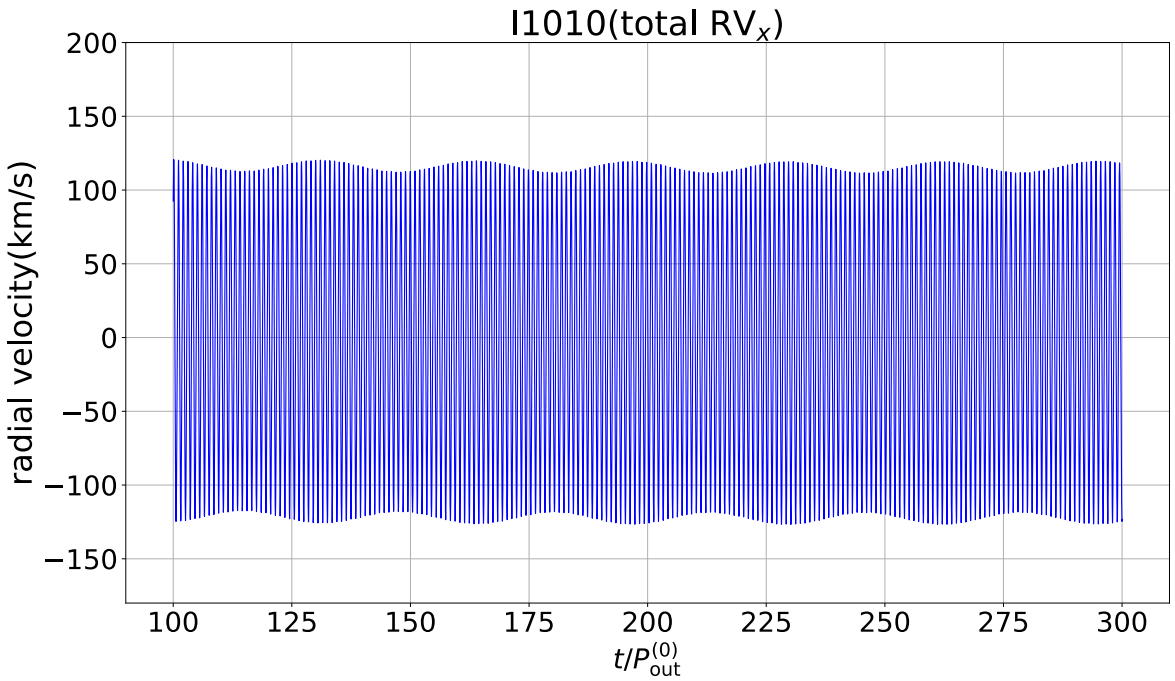
Periodic change of semi-amplitude of total RV

The variation is more visible for a nearly face-on system

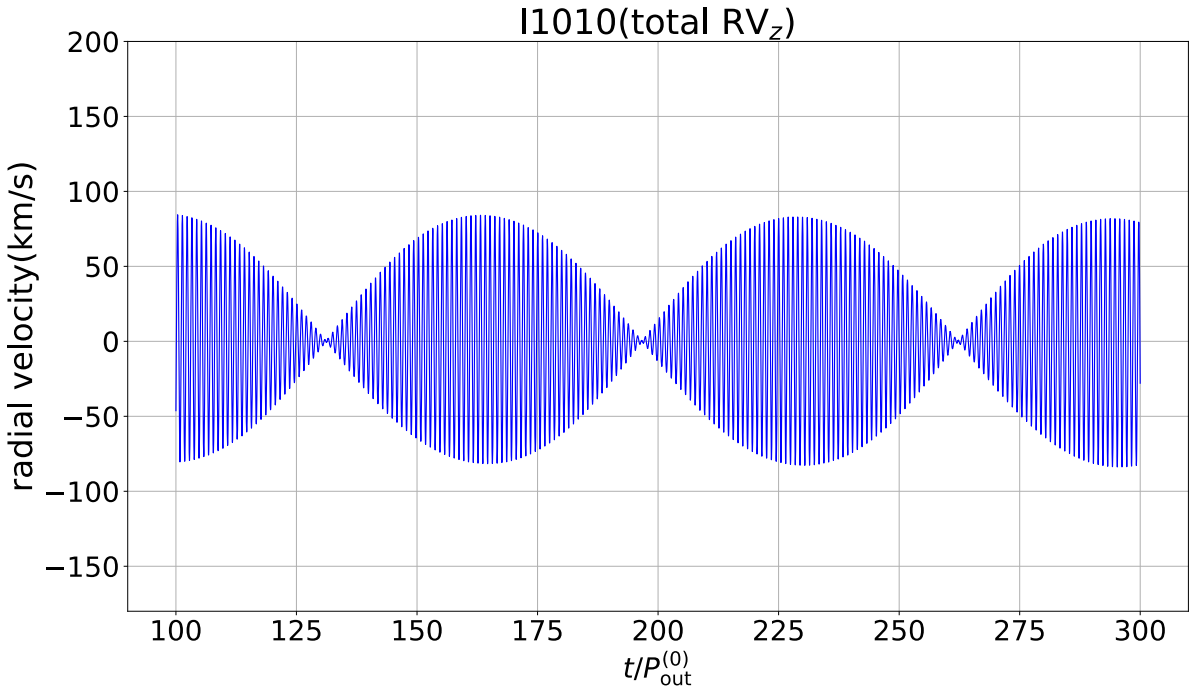
$$K_{\mathrm{Kep}} = K_0 \sin I(t) \sim K_0 \sin I(0) + K_0 \cos I(0) \times \dot{I}(0)\, t$$

Period ~ Kozai-Lidov timescale

x-direction (near edge-on) total RV



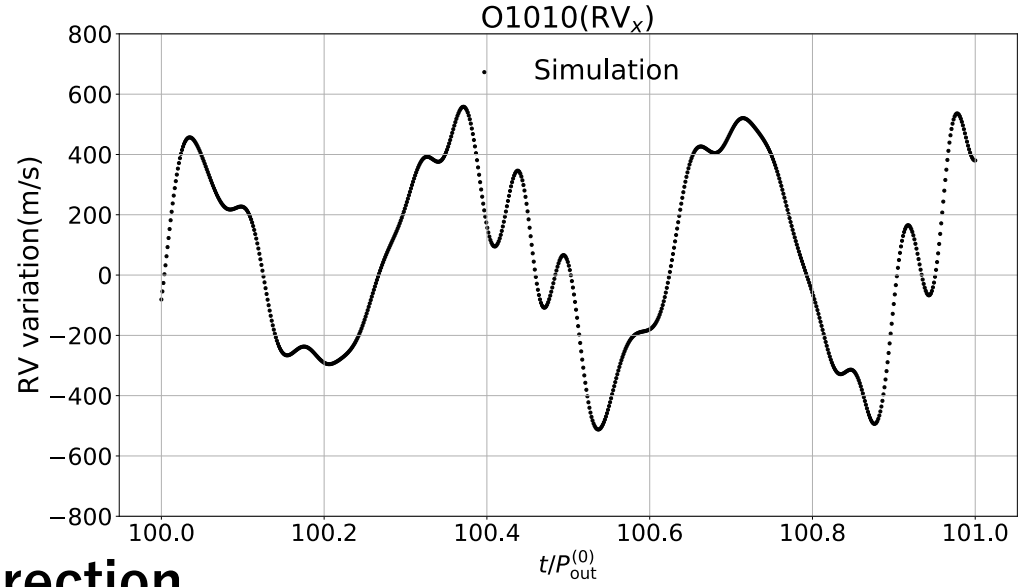
z-direction (near face-on) total RV

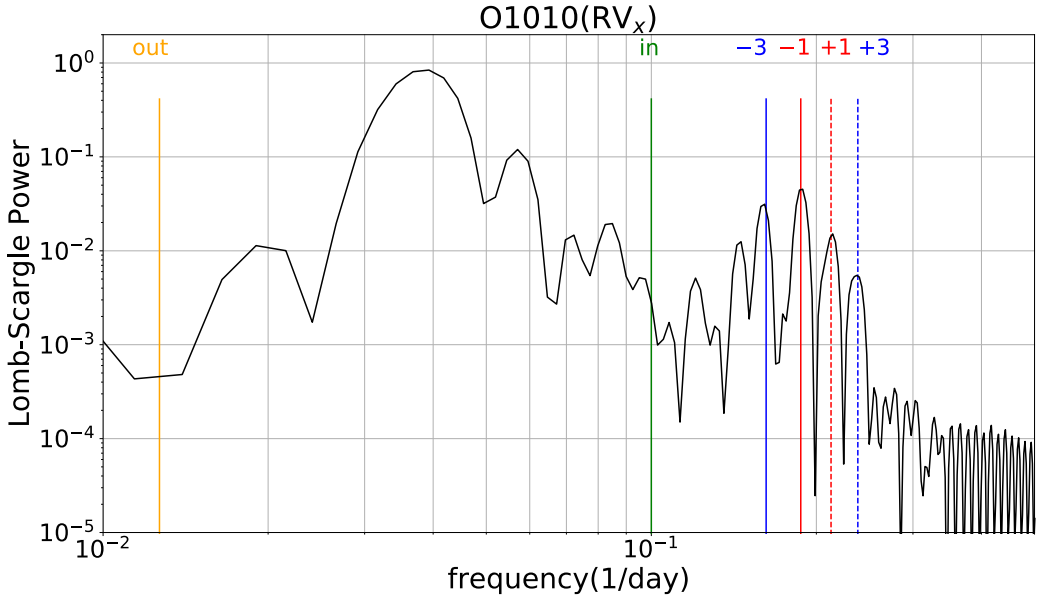


Research: orbital evolution for a inclined case ($i_{mut} = 90°$)

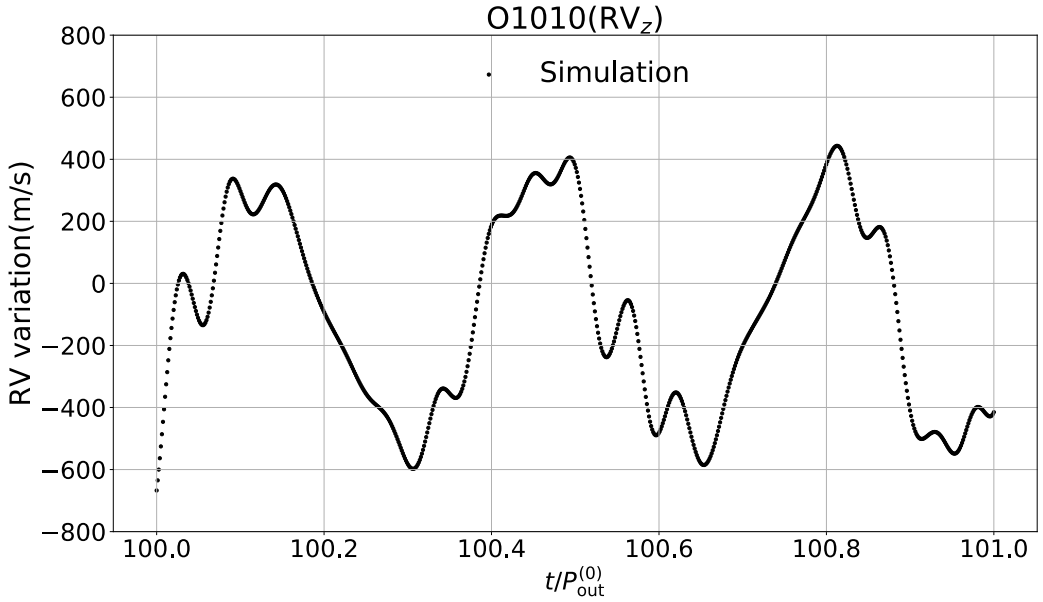
O1010

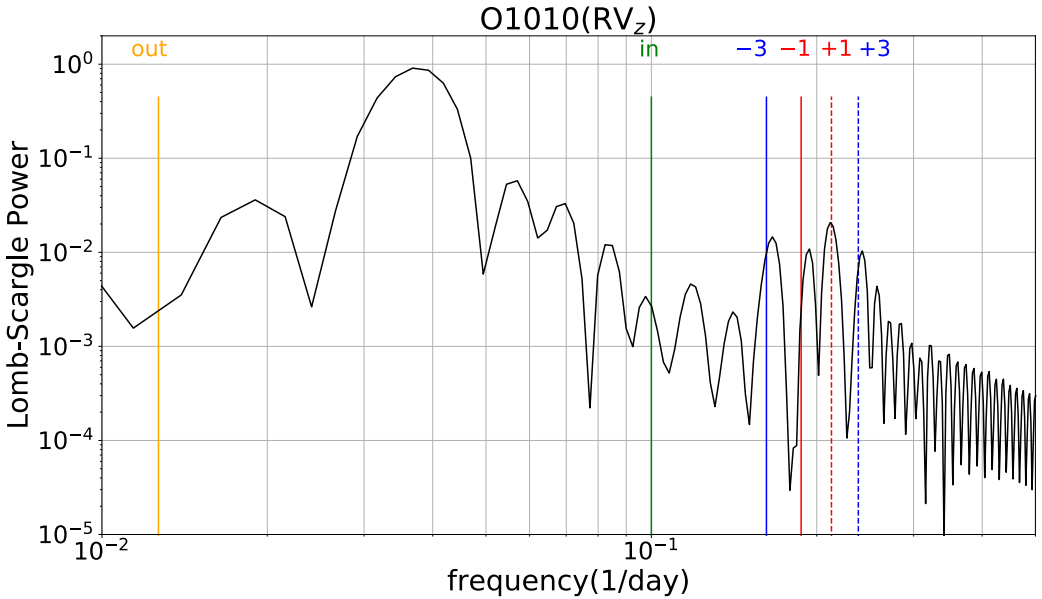
x-direction



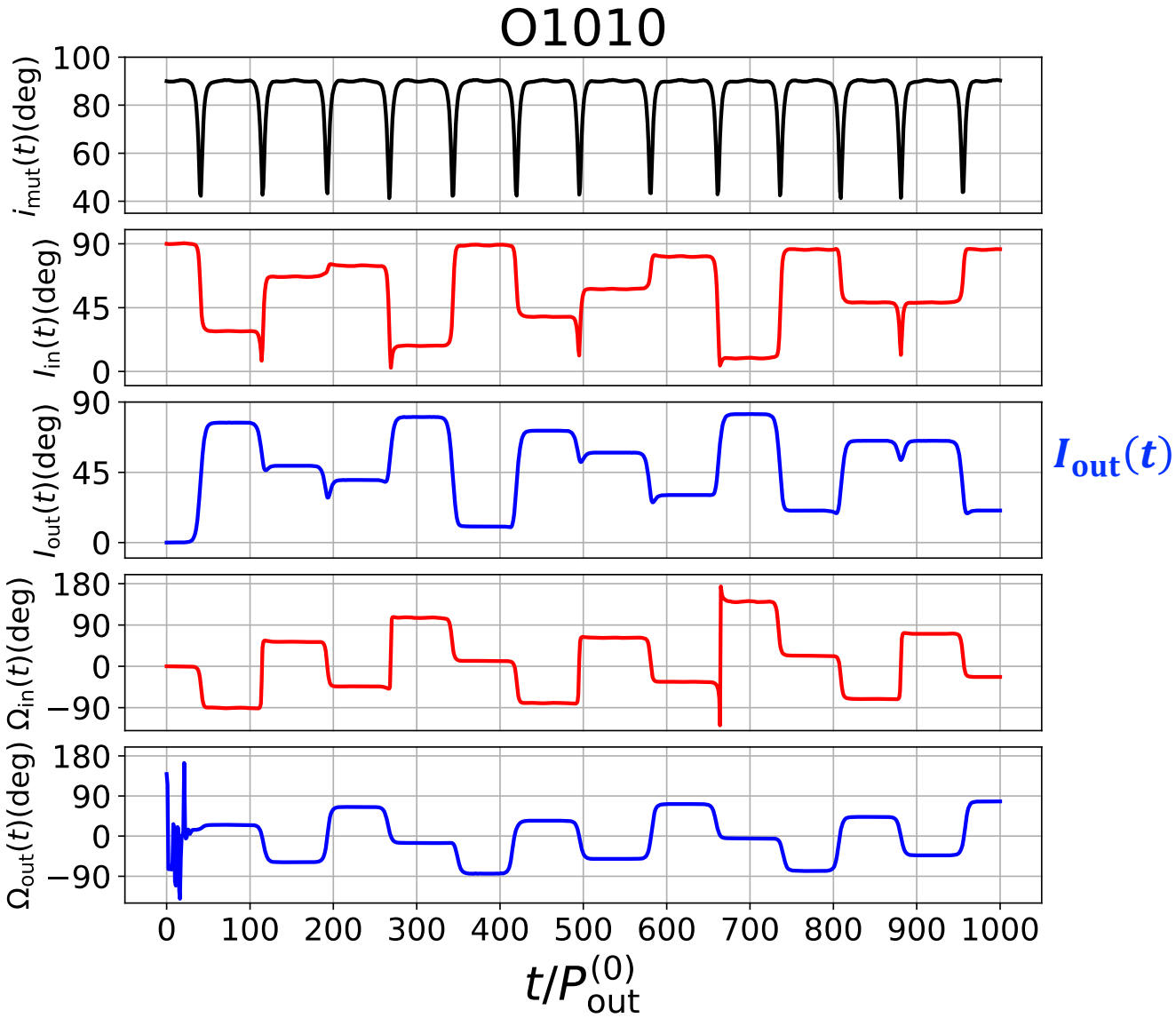


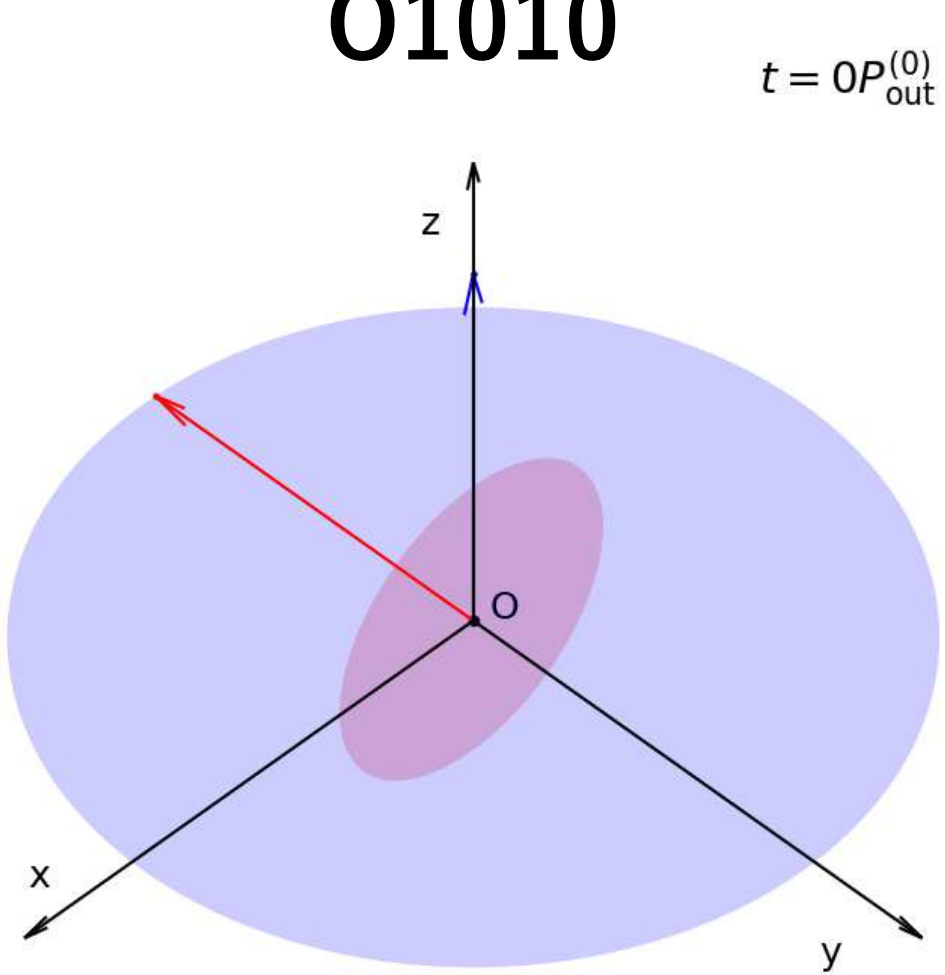
z-direction





Research: RV variations for a inclined case ($i_{mut} = 90°$)

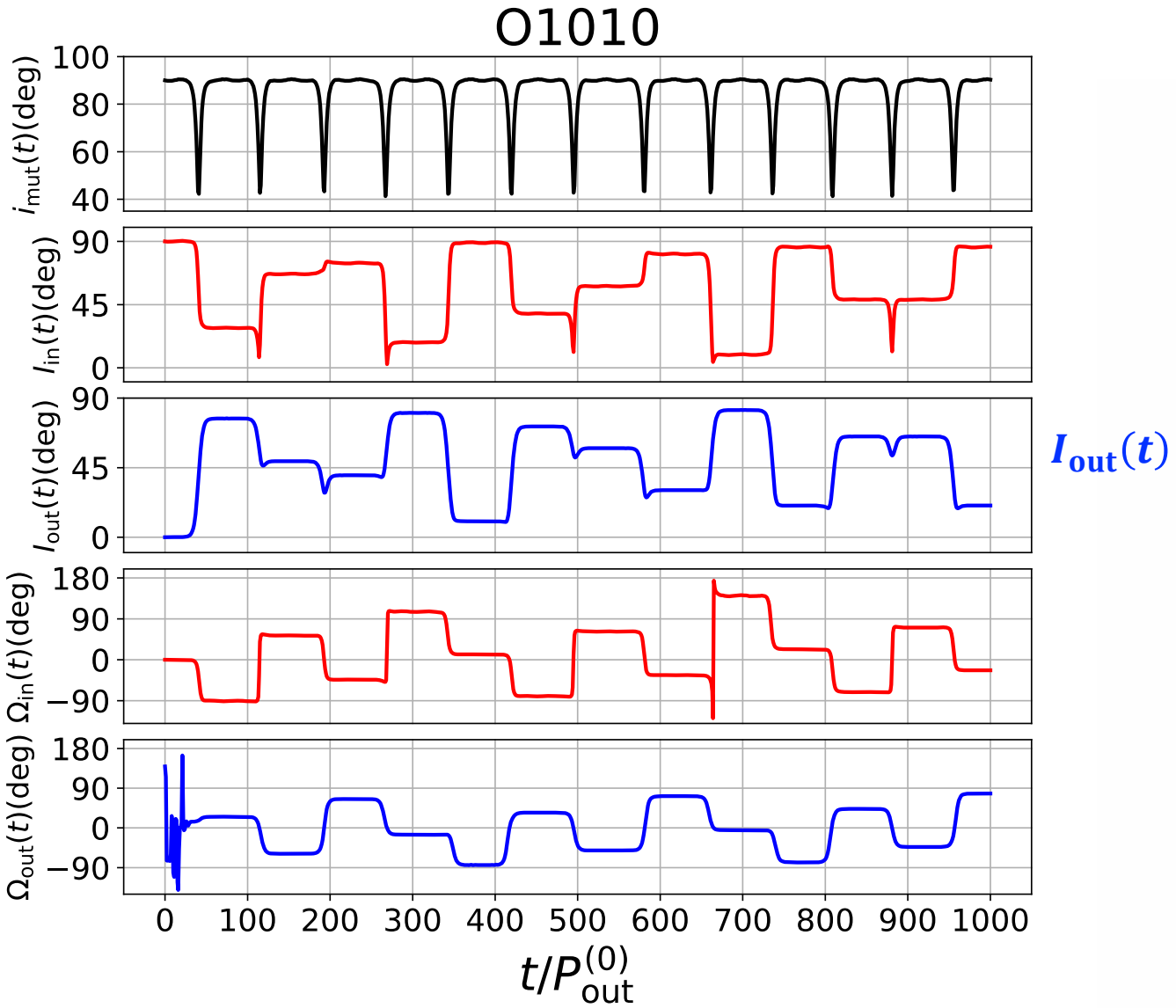




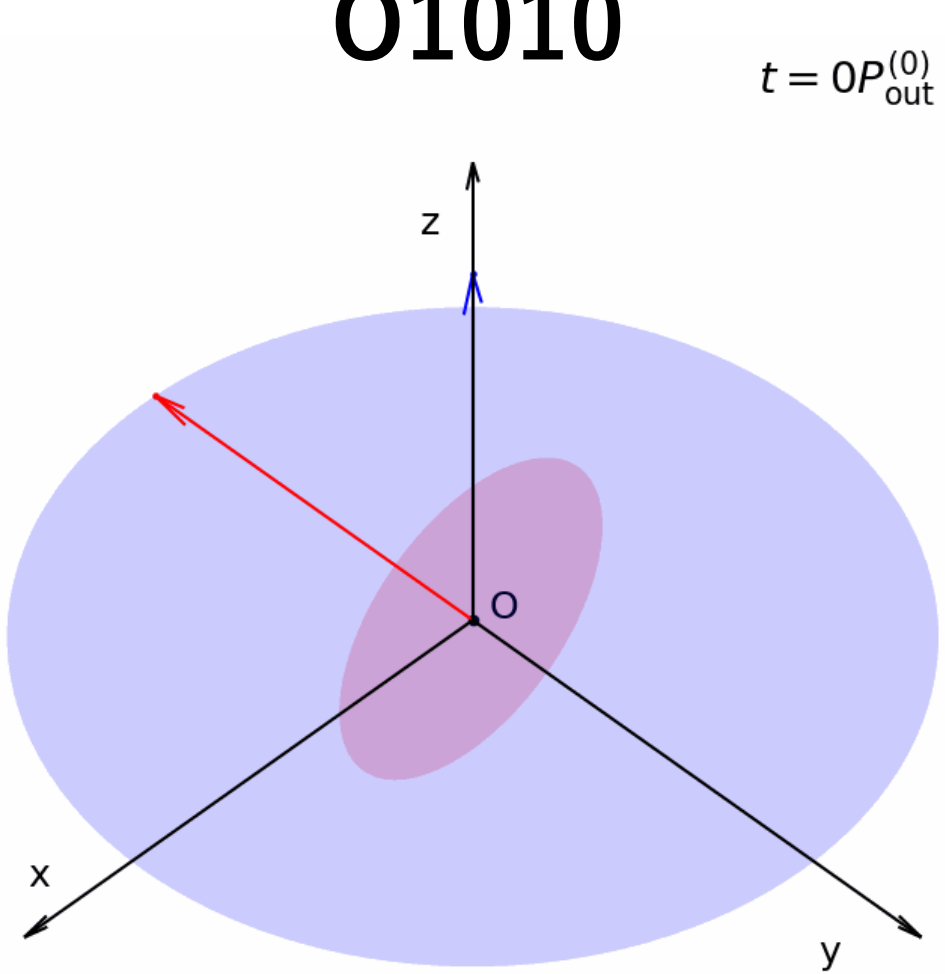
For some time, constant inclination

-> Drastic change due to Kozai-Lidov oscillation

Research: RV variations for a inclined case ($i_{mut} = 90°$)



$I_{out}(t)$



For some moment, constant inclination

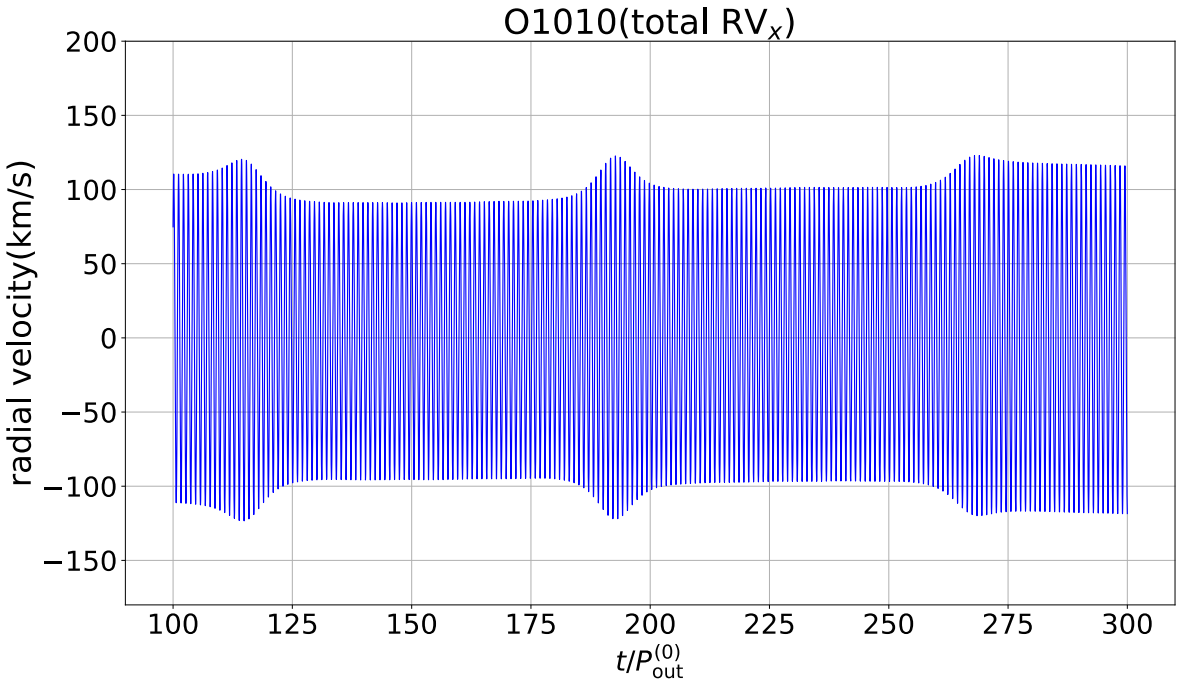
-> Drastic change due to Kozai-Lidov oscillation

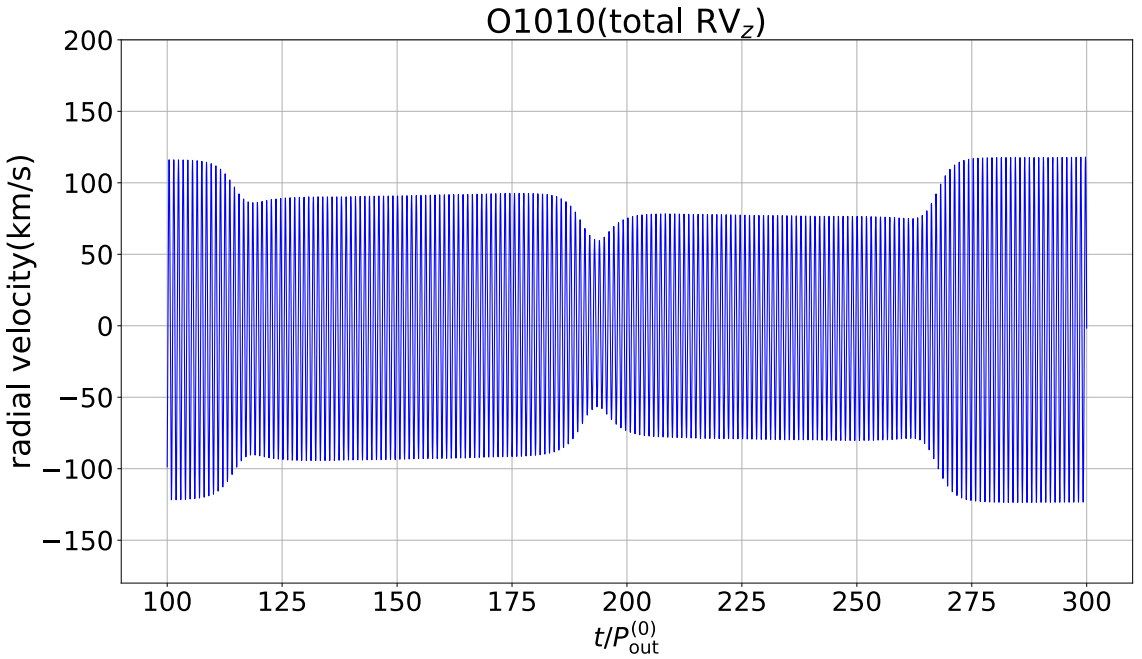
Research: RV variations for a inclined case ($i_{mut} = 90°$)

Semi-amplitude keeps constant for some time

Drastic change of semi-amplitude after static phase

Kozai-Lidov oscillation triggers the sudden change





Summary and future prospect

Simulation for expected RV variations assuming triples inspired by LB-1

RV variations with half inner orbital period could indicate the inner binary for a variety of orbital configuration (incl. eccentric, inclined, etc.)

Precise detection of each mode could determine the orbital configuration

Long-term RV semi-amplitude variation could also detect inclined inner binary

future prospect

Fraction and formation channels of triples including inner compact binary

Extending this methodology for unbound systems, binary-planet surveys etc.

Observational feasibility
RV followup for candidate systems

Yamaguchi+2018 Gaia proposal
200-1000 star-BH binaries

Masuda+2018 TESS proposal
~O(10) star-BH