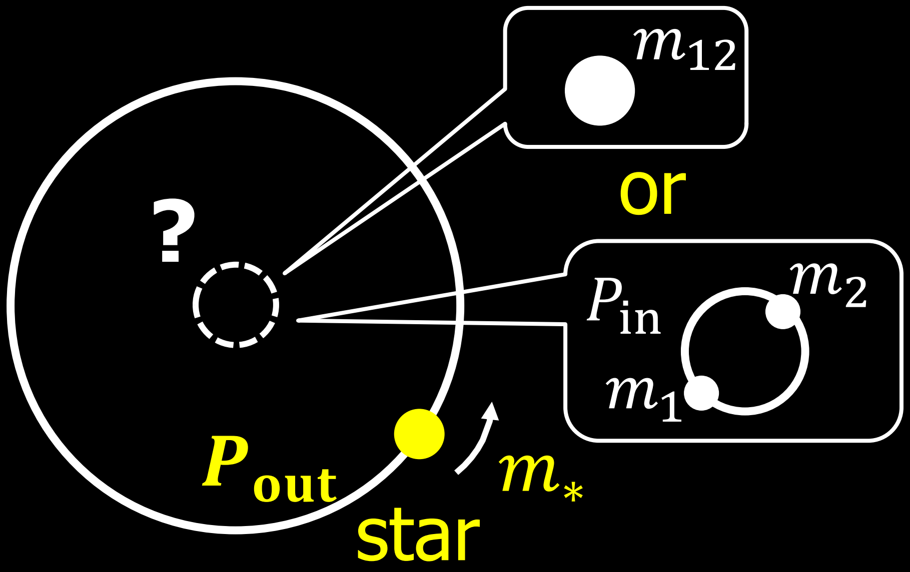
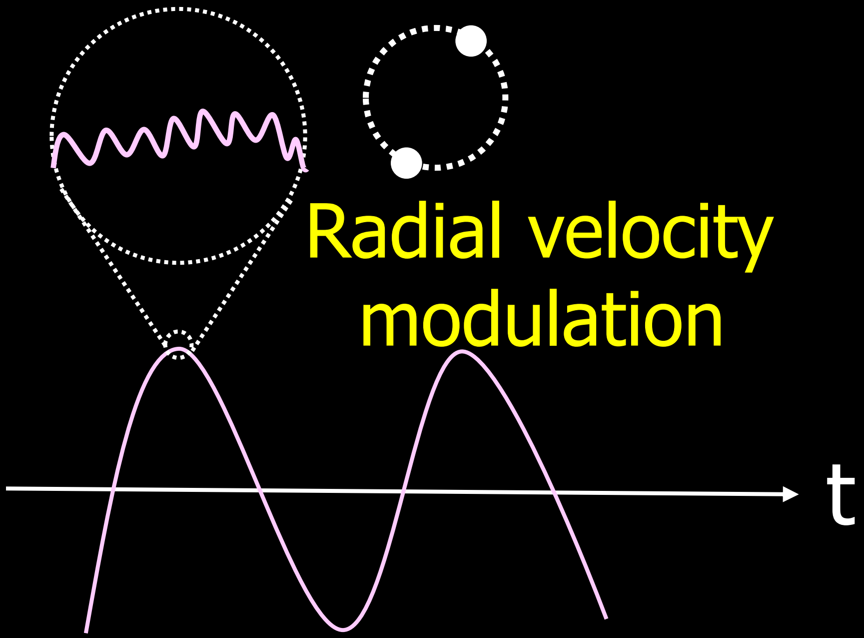
Signatures of an inner binary black hole with a tertiary orbiting star





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The University of Tokyo

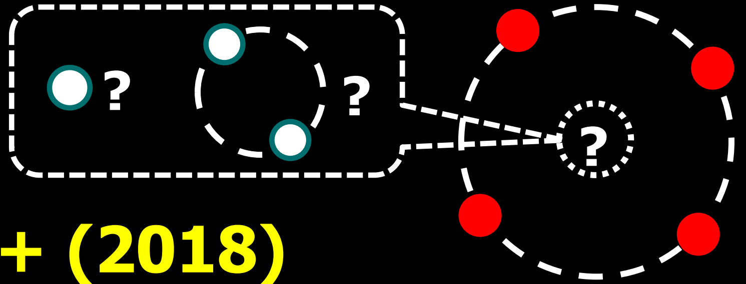
Astronomy session@ Copernicus World Congress, February 20 2023

Search for progenitors of LIGO binary BHs

star-BH binaries = star-BBH triples?

Gaia mission (2013-)

Astrometry of stars in Galaxy
$\sim 10^9$ stars eventually
RV with 200-350m/s precision
for brightest stars (Katz 2018)



Yamaguchi+ (2018)

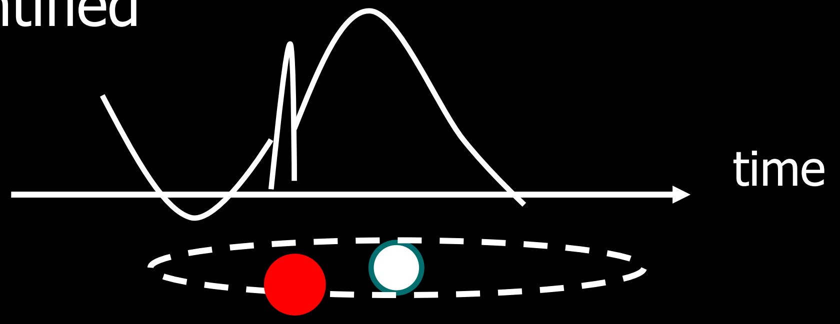
5-year mission may detect
200-1000 star-BH binaries

TESS mission (2018-)

photometry of nearby stars ($\sim$ 12mag)
transit planets

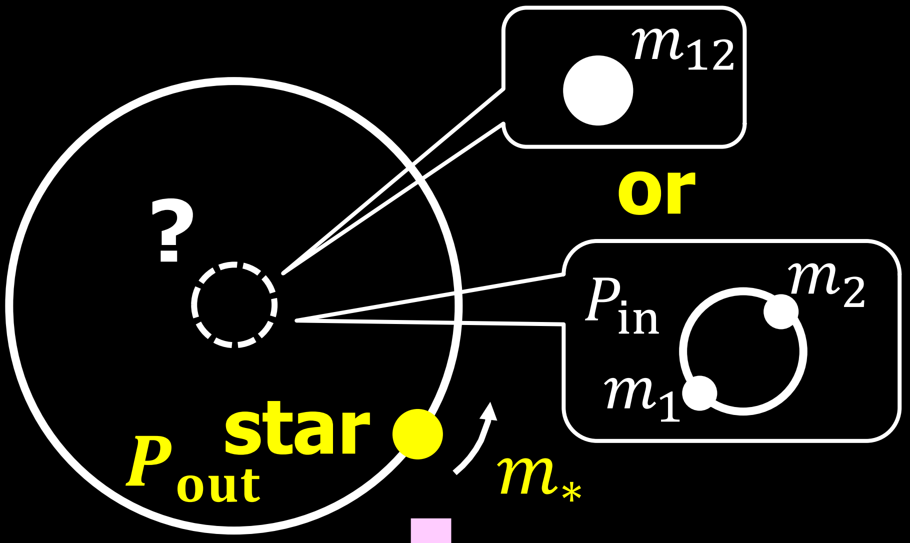
Masuda & Hotokezaka (2019)

Light curve modulation
(relativistic effects, tidal deformation)
$\Rightarrow$ $(10-100)$ star-BH binaries may be identified



Some of them may be indeed a star-binary BH triple!
Can precise radial velocity follow-up unveil the inner BBH?

RV modulations of a tertiary star

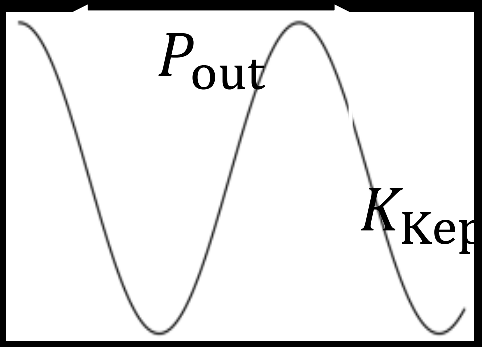


high-precision RV follow-up

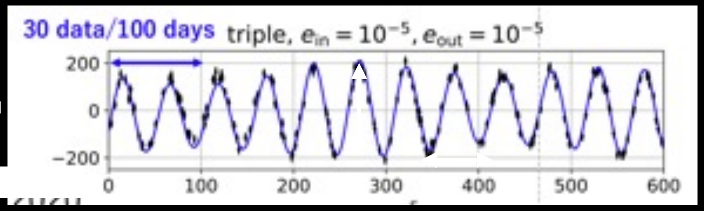
Keplerian motion RV
+ RV variations by inner binary

(i) Coplanar triple

$$\mathrm{Amp} \sim K_{\rm Kep}\left(\frac{P_{\rm in}}{P_{\rm out}}\right)^{\frac{7}{3}}$$



+



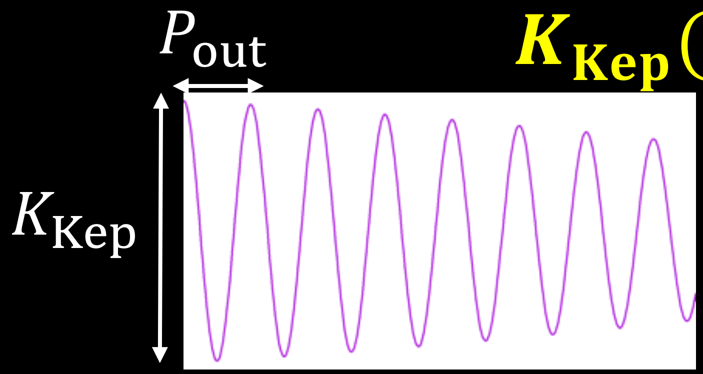
$$\mathrm{period} \sim P_{\rm in}/2$$

Kepler motion + Short-term RV variations (inner-binary perturbation)

(ii) Non-coplanar triple

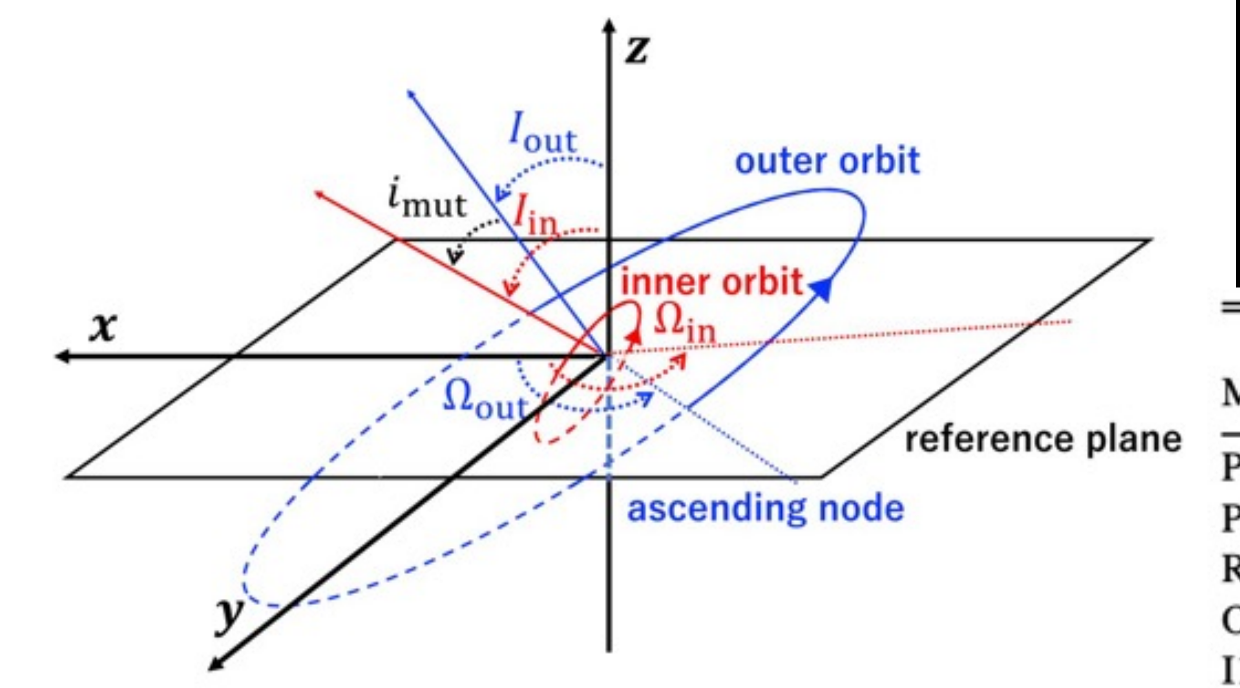
Inclination $I_{\rm out}(t)$ modulated by precession and ZKL effect

$$K_{\rm Kep}(t) = K_0 \sin I_{\rm out}(t)$$



Amplitude of Kepler RV varies with a longer timescale

Examples of simulated triple systems



Hayashi & YS 2020, ApJ, 897, 29

Model	I_{out} (deg)	I_{in} (deg)	i_{mut} (deg)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	e_{in}
P1010	90	90	0	10	10	10^{-5}
PE1010	90	90	0	10	10	0.2
R1010	90	270	180	10	10	10^{-5}
O1010	0	90	90	10	10	10^{-5}
I1010	0	45	45	10	10	10^{-5}
P0218	90	90	0	18	2	10^{-5}
PE0218	90	90	0	18	2	0.2
R0218	90	270	180	18	2	10^{-5}
O0218	0	90	90	18	2	10^{-5}
I0218	0	45	45	18	2	10^{-5}

Note. P, PE, R, O, and I indicate prograde, prograde eccentric, retrograde, orthogonal, and inclined orbits.

P_{out} = 78.9 days
P_{in} = 10 days

equal-mass binary $10M_\odot + 10M_\odot$

unequal-mass binary $2M_\odot + 18M_\odot$

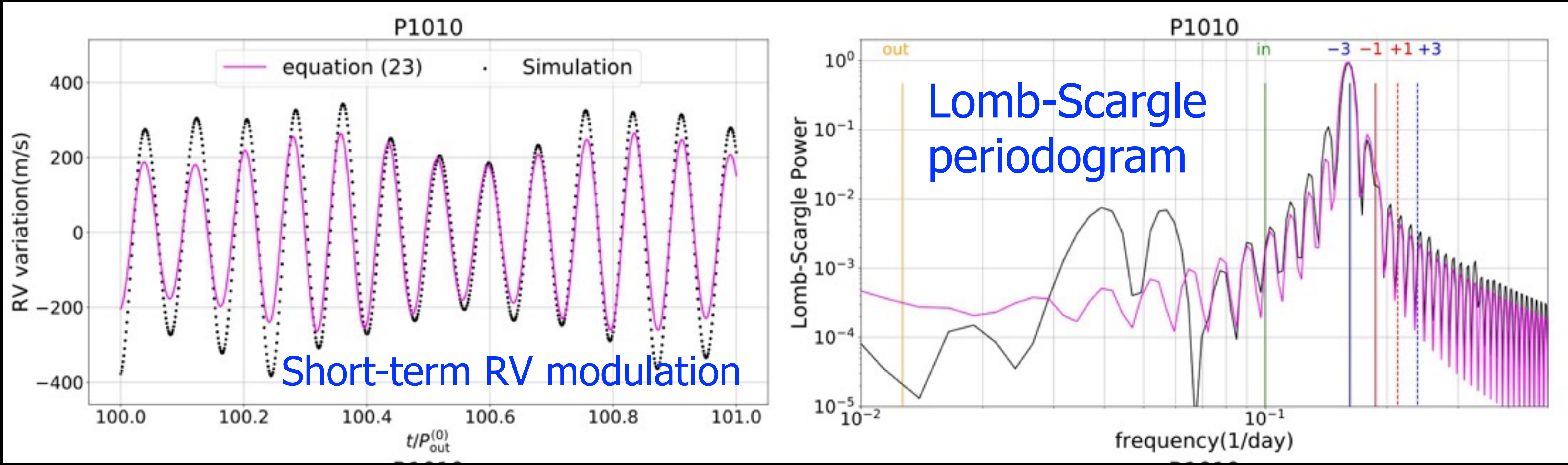
Coplanar prograde circular triples: radial velocity modulation at $\sim 2\nu_{in}$

equal-mass inner binary

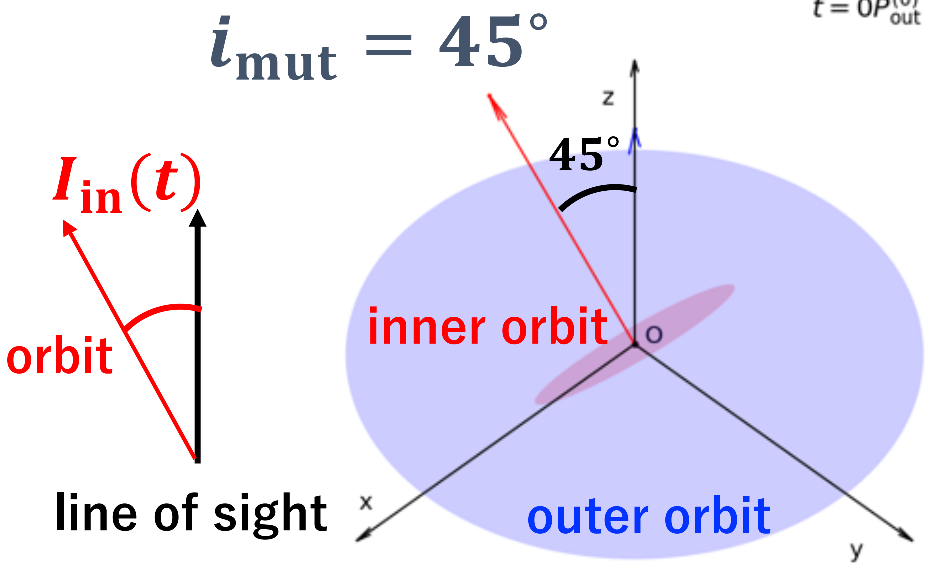
Simulation against
Perturbative model
(Morais & Correia 2008, 2012)

$$\nu_{-3} \equiv 2\nu_{\rm in} - 3\nu_{\rm out},$$
$$\nu_{-1} \equiv 2\nu_{\rm in} - \nu_{\rm out}.$$

ν_{in}: inner orbital frequency



Evolution of inclination for non-coplanar triples



$P_{\rm out} = 78.9$ days

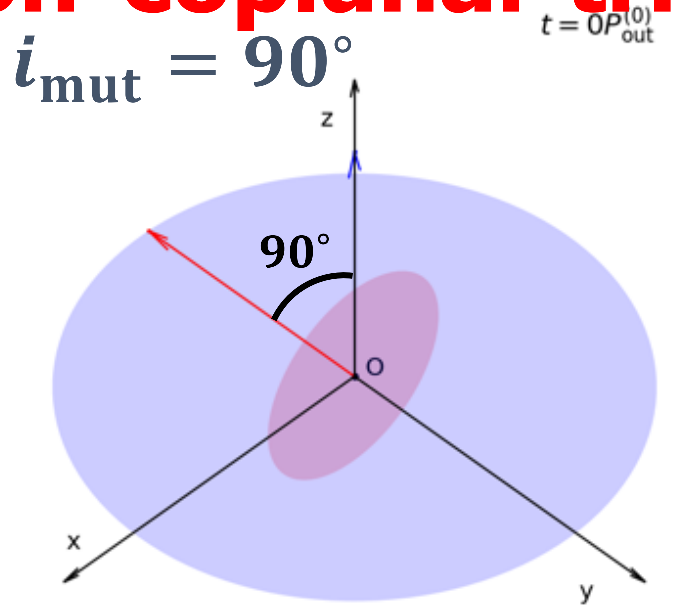
$P_{\rm in} = 10$ days

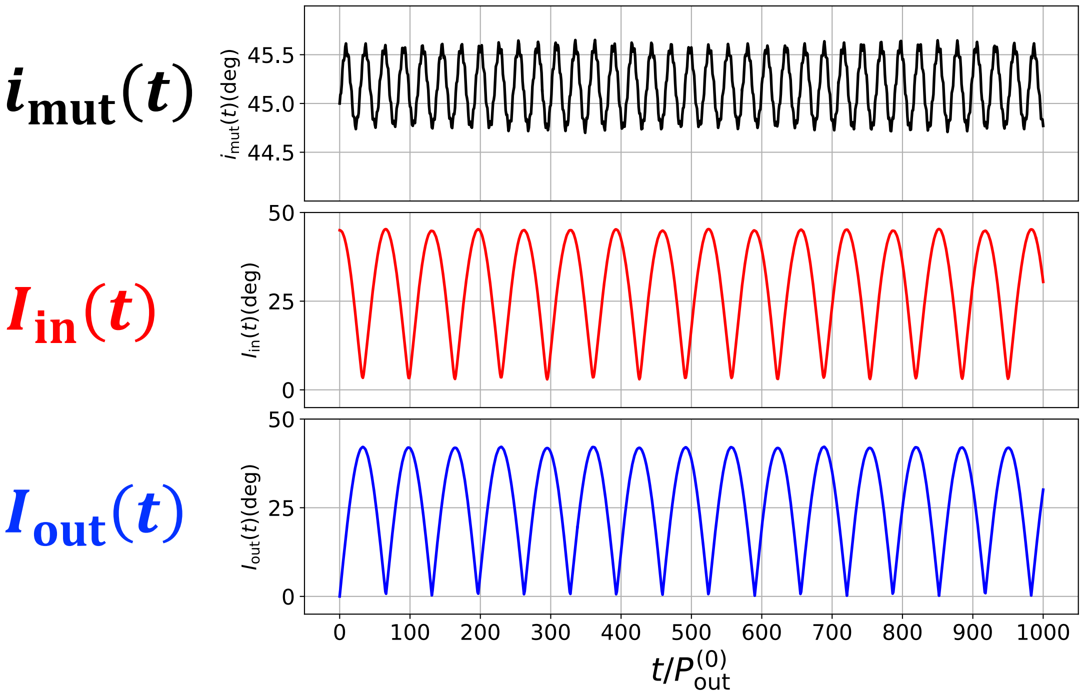
$m_1 = m_2 = 10M_\odot$

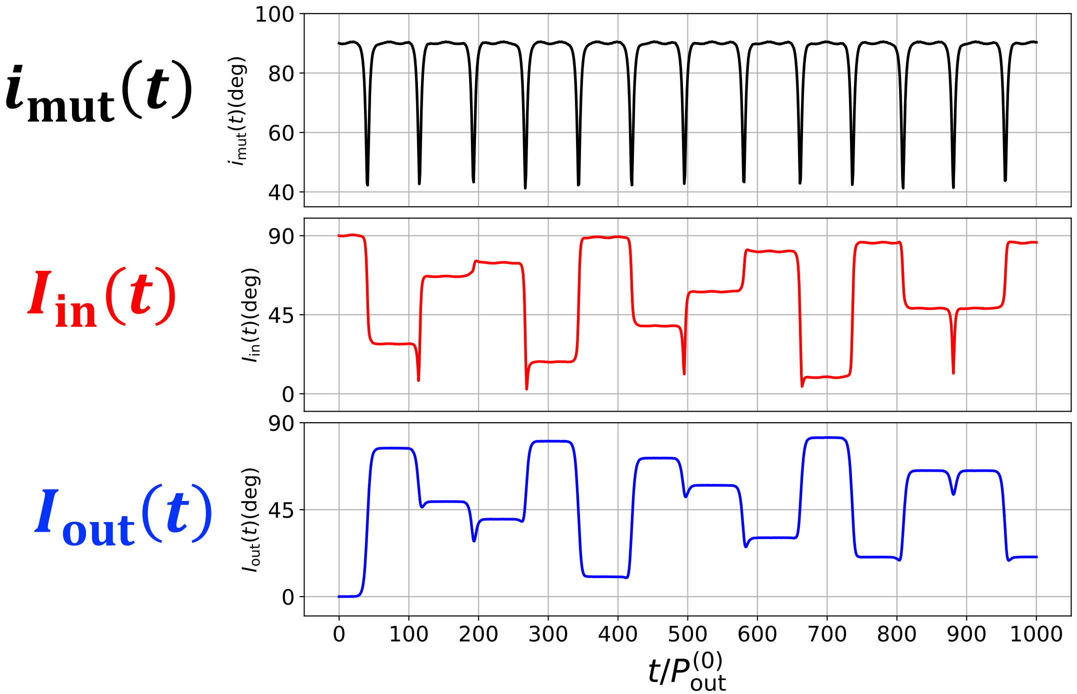
$m_* = 3M_\odot$

$e_{\rm out} = 0.03$

$e_{\rm in} = 10^{-5}$





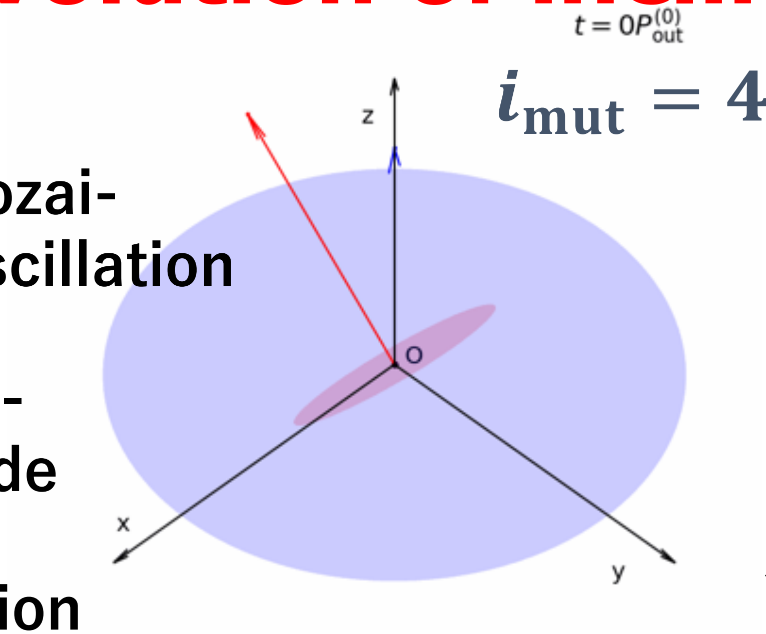


Evolution of inclination for non-coplanar triples

$i_{\mathrm{mut}} = 45^\circ$

weak Kozai-Lidov oscillation

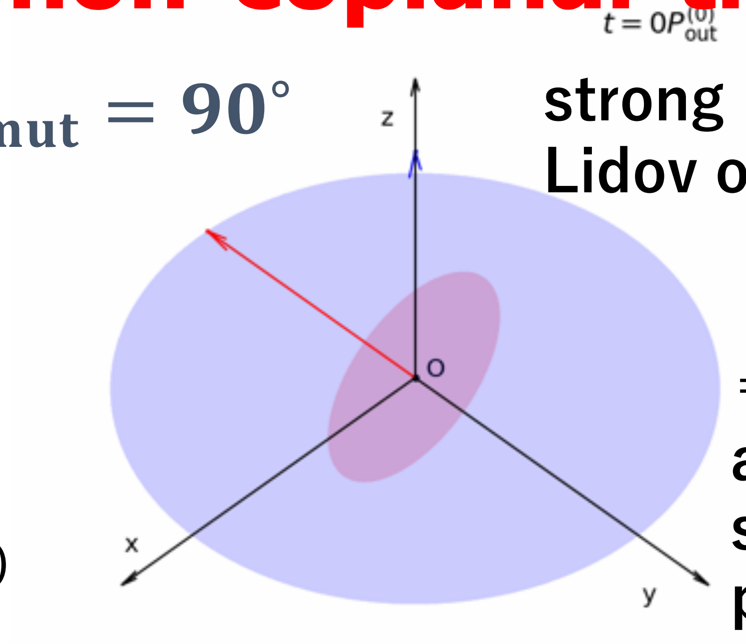
⇒ small-amplitude regular precession



$i_{\mathrm{mut}} = 90^\circ$

strong Kozai-Lidov oscillation

⇒ large-amplitude sporadic precession

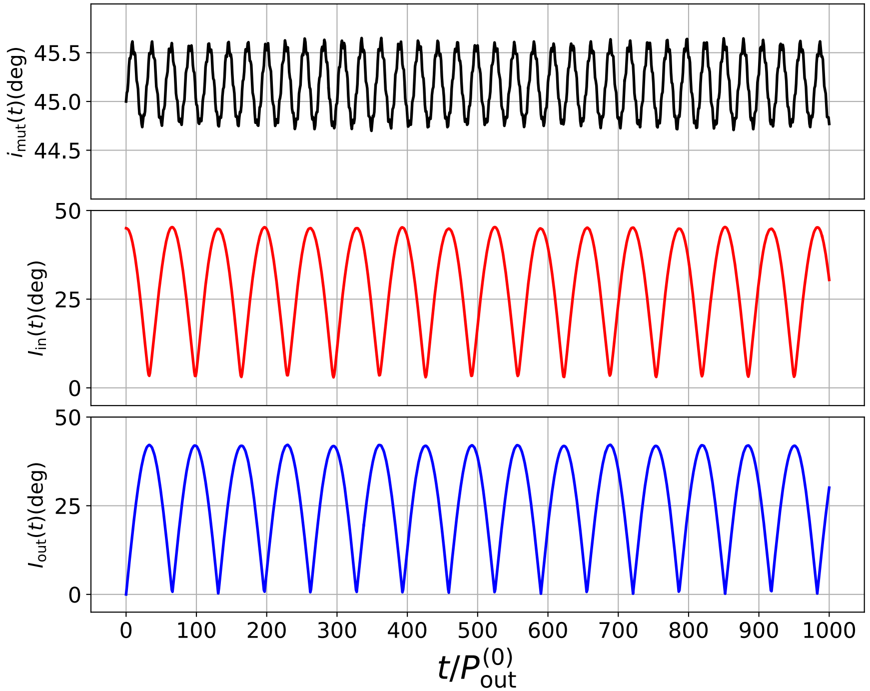


$K_{\mathrm{Kep}} = K_0 \sin I_{\mathrm{out}}(t)$

$i_{\mathrm{mut}}(t)$

$I_{\mathrm{in}}(t)$

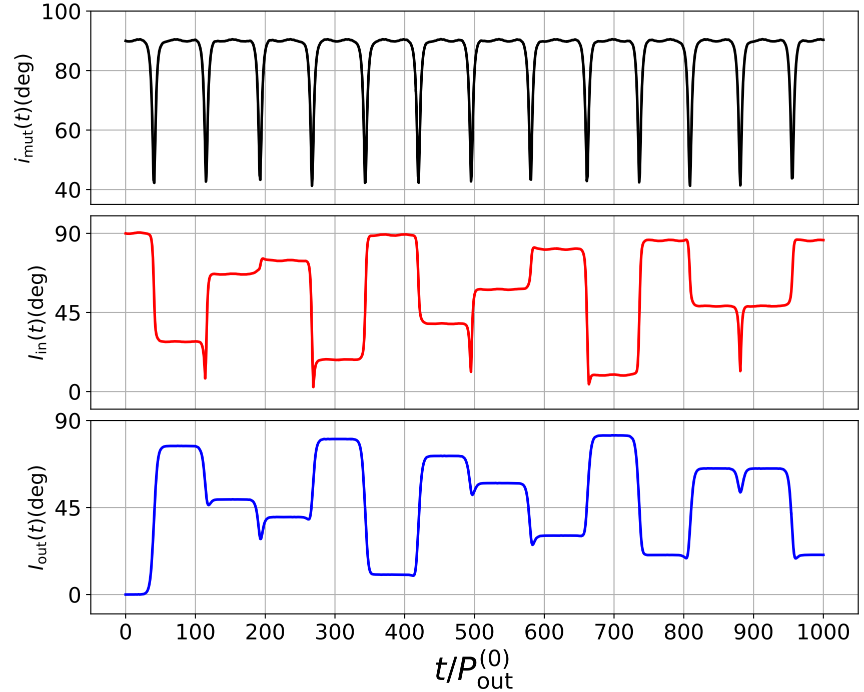
$I_{\mathrm{out}}(t)$



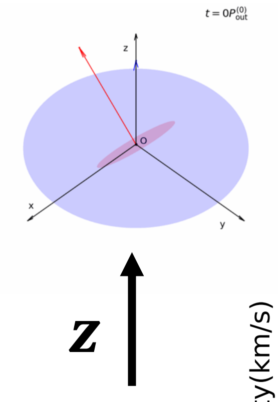
$i_{\mathrm{mut}}(t)$

$I_{\mathrm{in}}(t)$

$I_{\mathrm{out}}(t)$

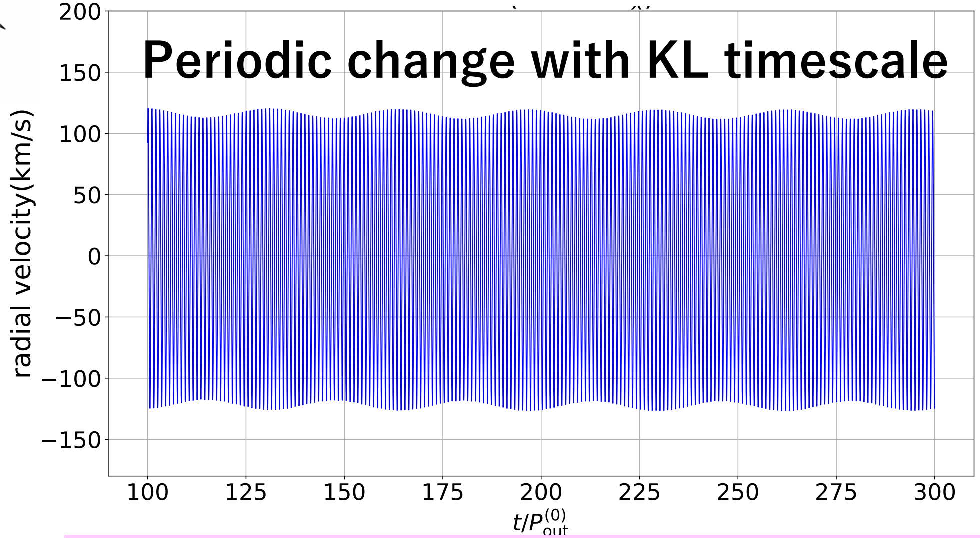


Evolution of radial velocity for non-coplanar triples

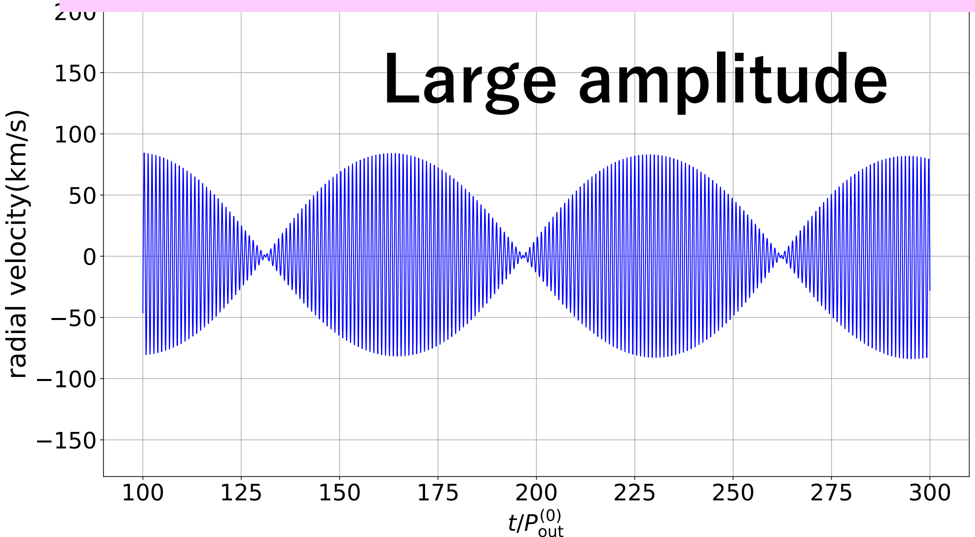


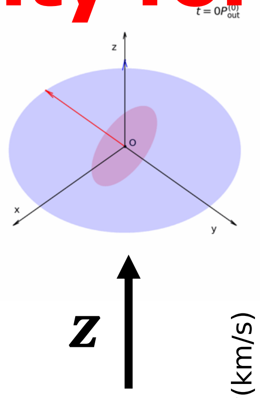
$i_{\mathrm{mut}} = 45^\circ$ $\quad K_{\mathrm{Kep}} = K_0 \sin I_{\mathrm{out}}(t)$

x-direction (near edge-on) total RV



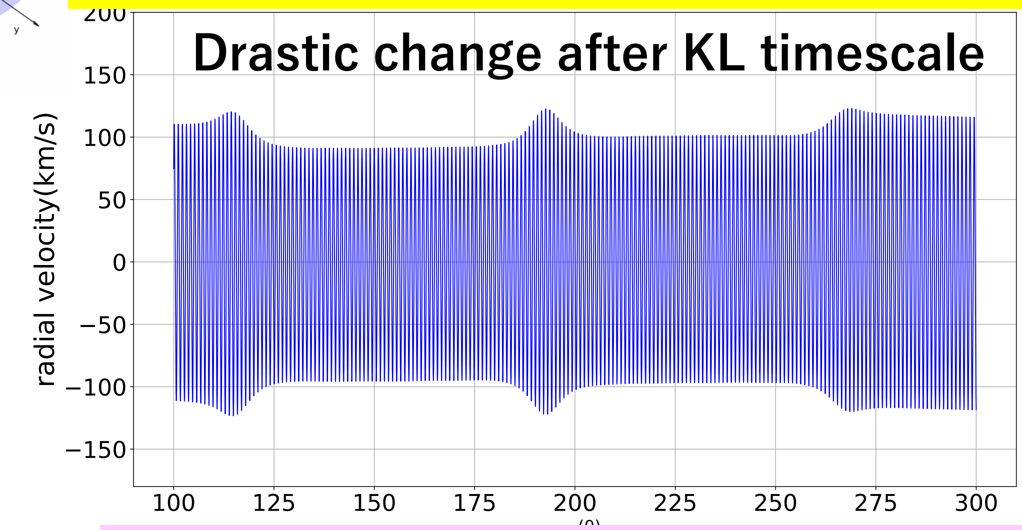
z-direction (near face-on) total RV



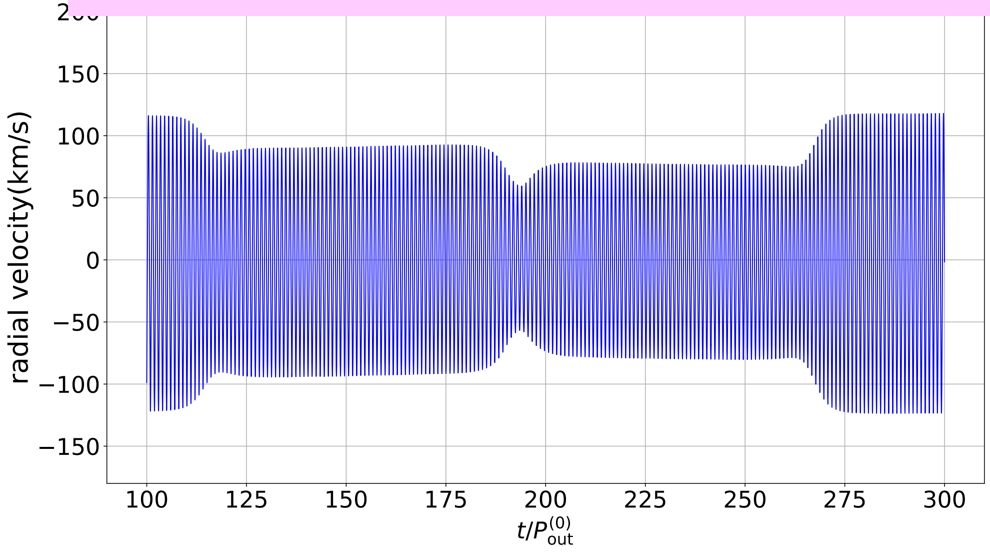


$i_{\mathrm{mut}} = 90^\circ$

x-direction (near edge-on) total RV



z-direction (near face-on) total RV



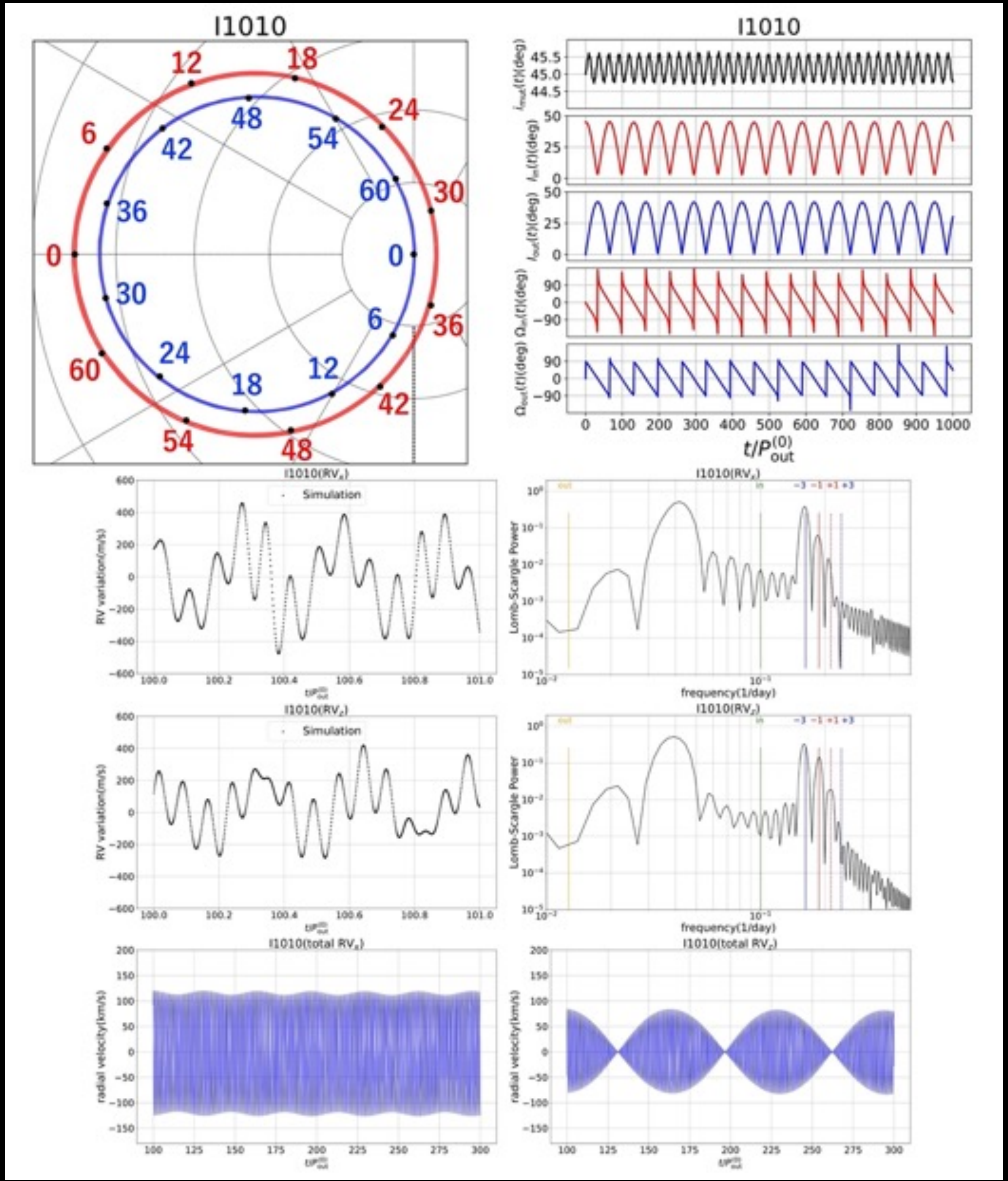
Inclined equal-mass binary

Precession timescale

$$\frac{P_\Omega}{P_{\rm out}} \approx \frac{80.7}{\cos i_{\rm mut}} \left(\frac{m_1+m_2+m_*}{23\ M_\odot}\right)\left(\frac{m_*}{3\ M_\odot}\right)^{-1} \times \left(\frac{P_{\rm out}}{78.9\ {\rm days}}\right)\left(\frac{P_{\rm in}}{10.0\ {\rm days}}\right)^{-1}$$

Kozai-Lidov timescale

$$\frac{T_{\rm KL}}{P_{\rm out}} = \frac{m_1}{m_*}\left(\frac{P_{\rm out}}{P_{\rm in}}\right)(1-e_{\rm out}^2)^{3/2} \approx 26\left(\frac{m_1}{10\ M_\odot}\right)\left(\frac{m_*}{3\ M_\odot}\right)^{-1} \times \left(\frac{P_{\rm out}}{78.9\ {\rm days}}\right)\left(\frac{P_{\rm in}}{10\ {\rm days}}\right)^{-1}$$



Dynamical signature of inner binary black holes in triple systems

- Radial velocity (RD) monitoring of future star-black hole binary candidates may reveal inner binary black holes (instead of single black holes) in those systems
  - short-term RD variations

    Hayashi, Wang + YS: ApJ 890(2020)112
    - periodic modulations of O(1) percent of the Kepler orbital velocity amplitude with a half inner orbital period
  - long-term RD variations in inclined triples

    Hayashi + YS: ApJ 897(2020)29
    - the semi-amplitude of the Kepler orbital velocity modulated periodically by the precession of the inner and outer orbits over $(10\text{-}100)(P_{out}/P_{in})P_{out}$