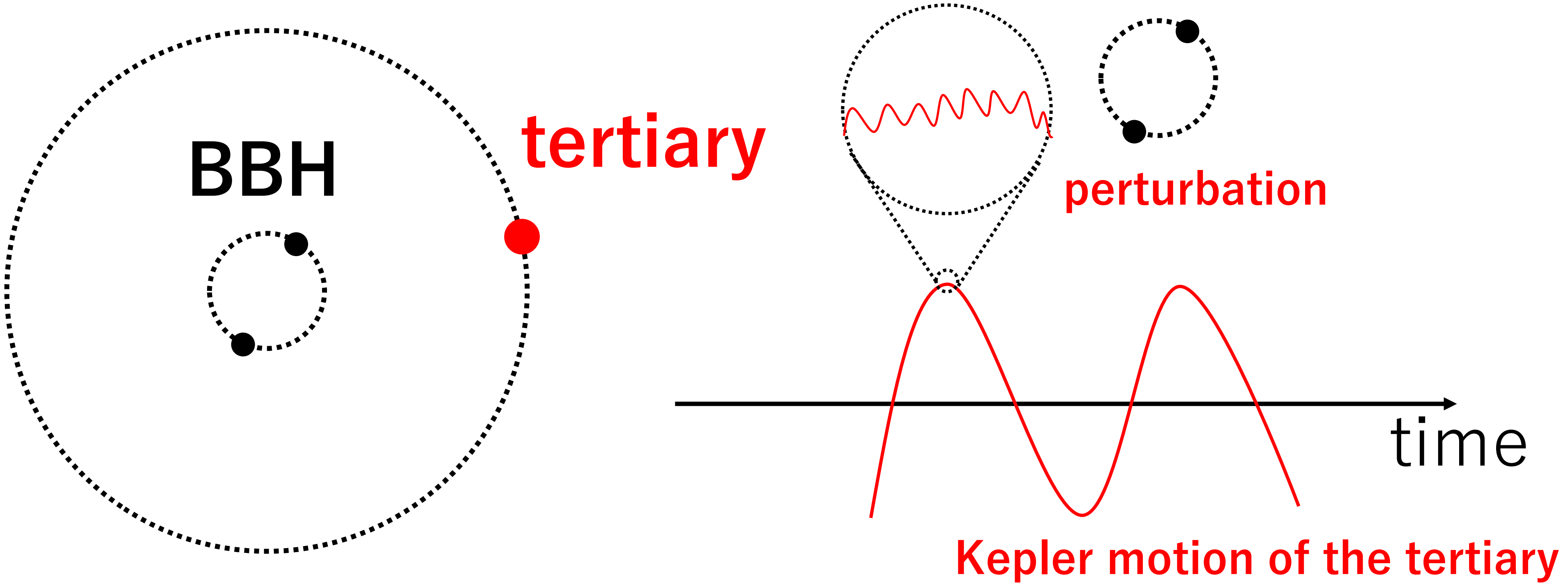
Online RESCEU Summer School 2020

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

radial-velocity modulation of a star and time-delay effect of a pulsar



Toshinori Hayashi
University of Tokyo

11:10-11:25 18 Aug. 2020 @ Zoom meeting

Binary black holes (BBHs)

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

Binary black holes

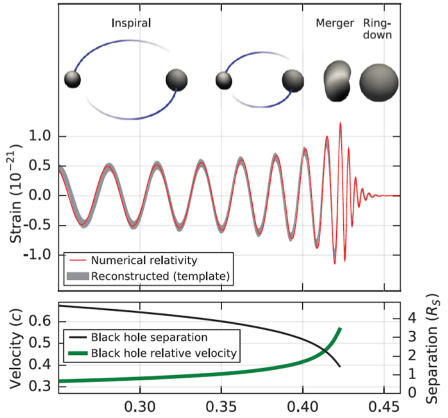
Formation

orbit shrink

Merger

GW

LIGO team 2016



GW detector

weak GW(low-frequency)

~Gyr scale orbital evolution(GW emission)

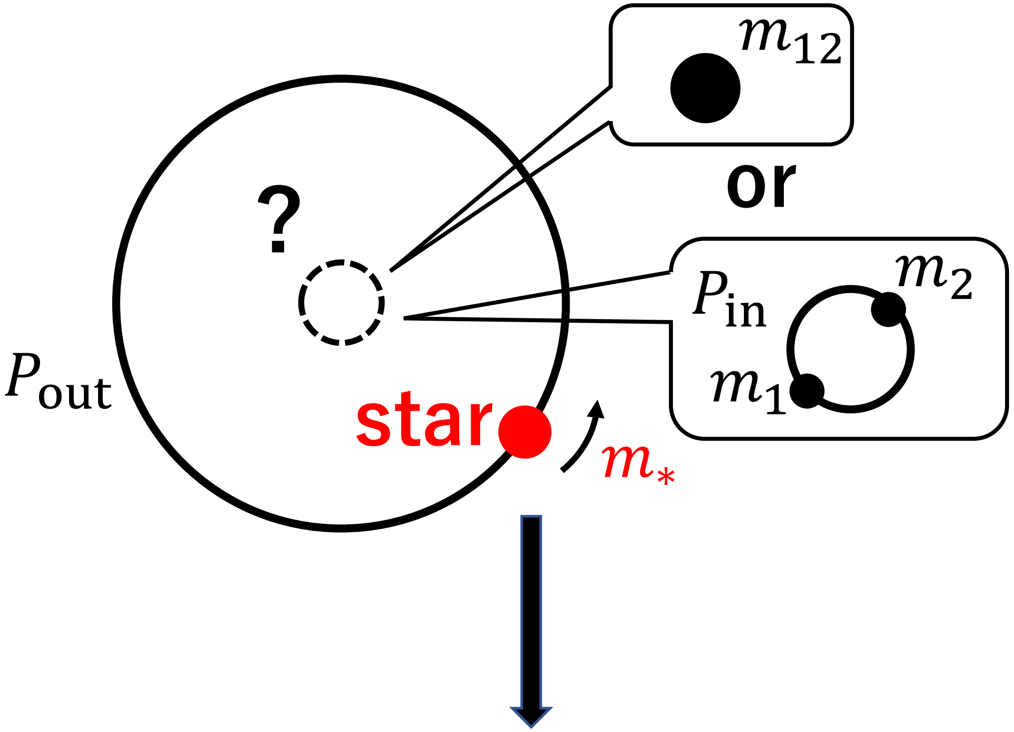
Long orbital-period BBHs
(e.g. ~10day orbital period→~10^{-6}Hz)

Abundant progenitors ??

Except for GW, how to search for ?

RV variations induced by the inner-binary perturbation

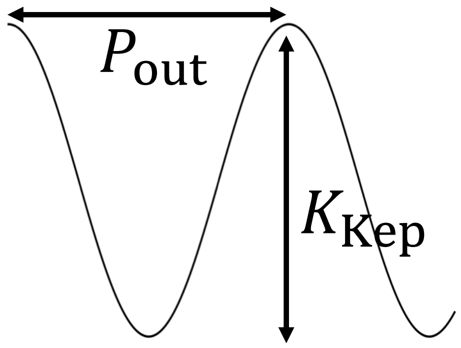
unseen object = single or **inner binary**



high-precision RV follow-up

Keplerian motion RV
\+ **RV variations by inner binary**

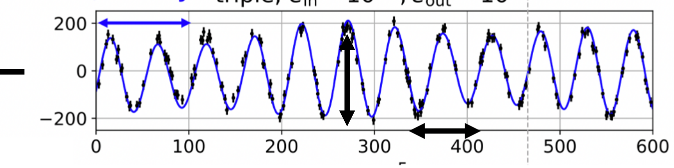
(i) Coplanar triple



Kepler motion

\+

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



$$\mathrm{Per} \sim P_{\mathrm{in}}/2$$

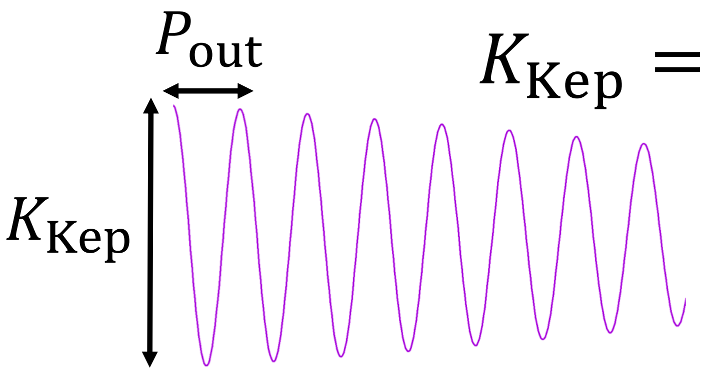
Hayashi, Wang, Suto 2020

Short-term RV variations
(inner-binary perturbation)

(ii) Inclined triple

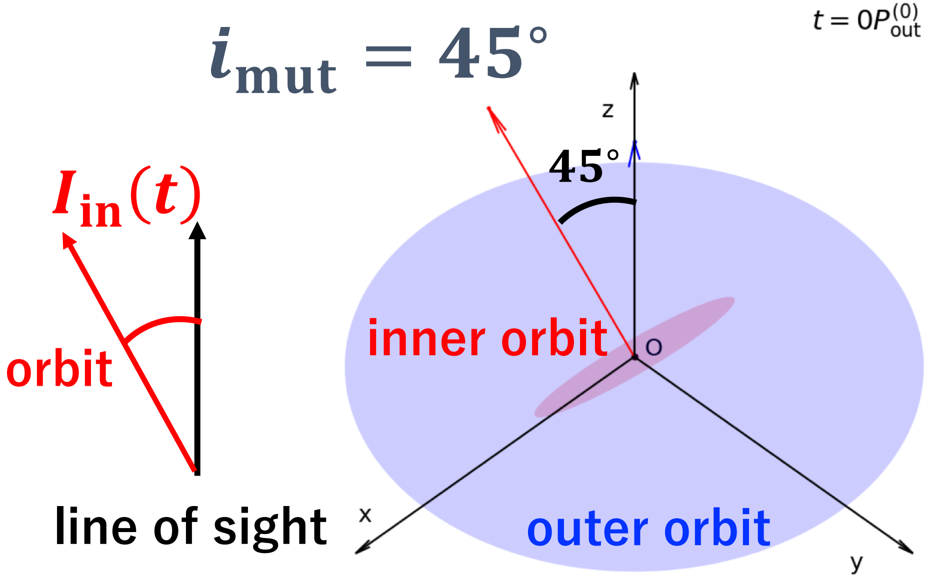
Inclination $I_{out}(t)$ evolves with Kozai-Lidov timescale

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

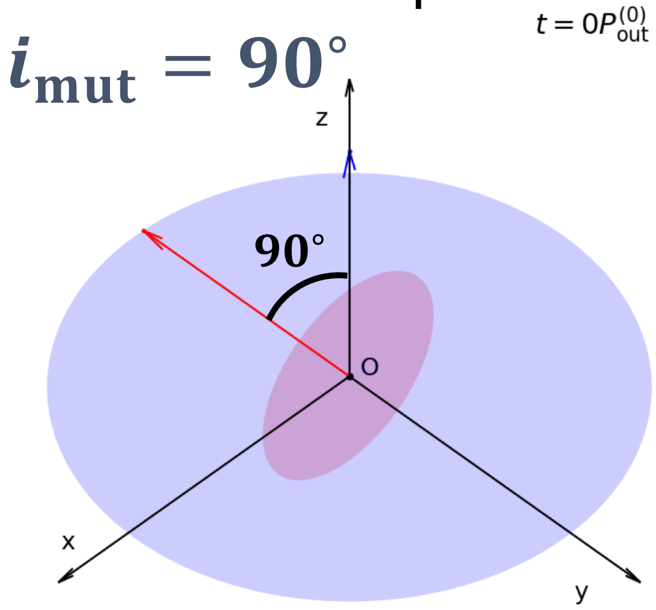


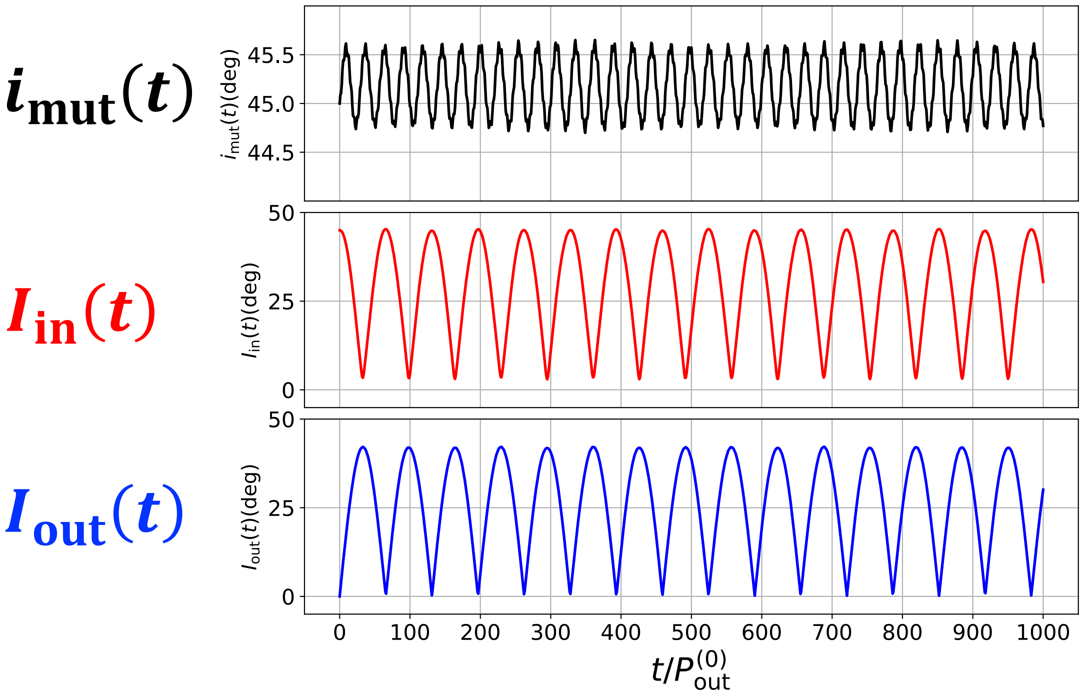
Amplitude of Kepler RV
varies with long-time scale

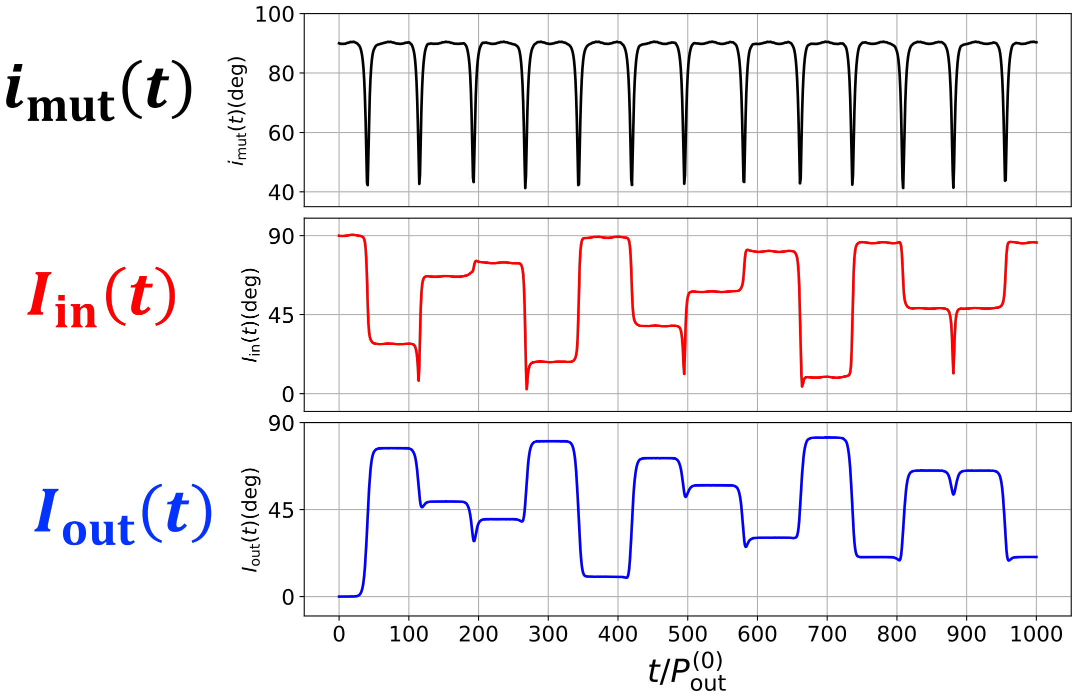
Time evolution of inclination for inclined triples



$$P_{\rm out} = 78.9 \text{ days}$$
$$P_{\rm in} = 10 \text{ days}$$
$$m_1 = m_2 = 10M_\odot$$
$$m_* = 3M_\odot$$
$$e_{\rm out} = 0.03$$
$$e_{\rm in} = 10^{-5}$$

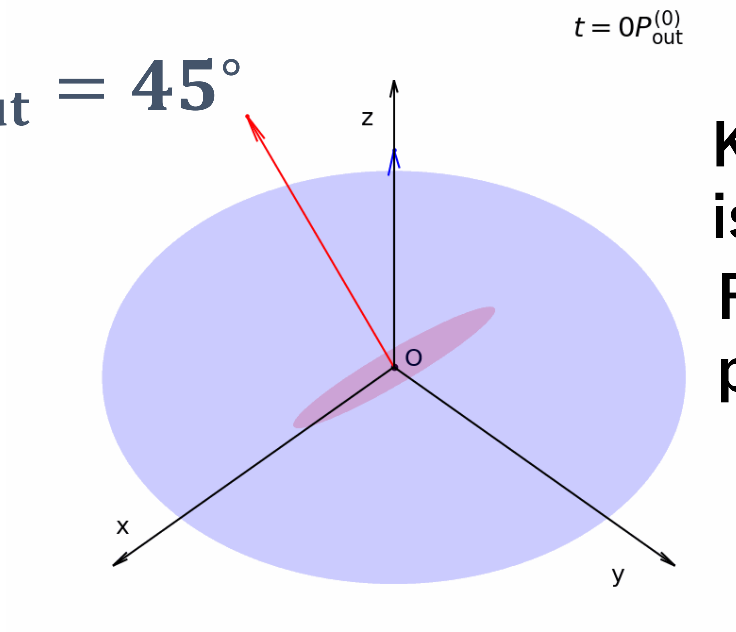






Time evolution of inclination for inclined triples

$i_{\mathrm{mut}} = 45°$

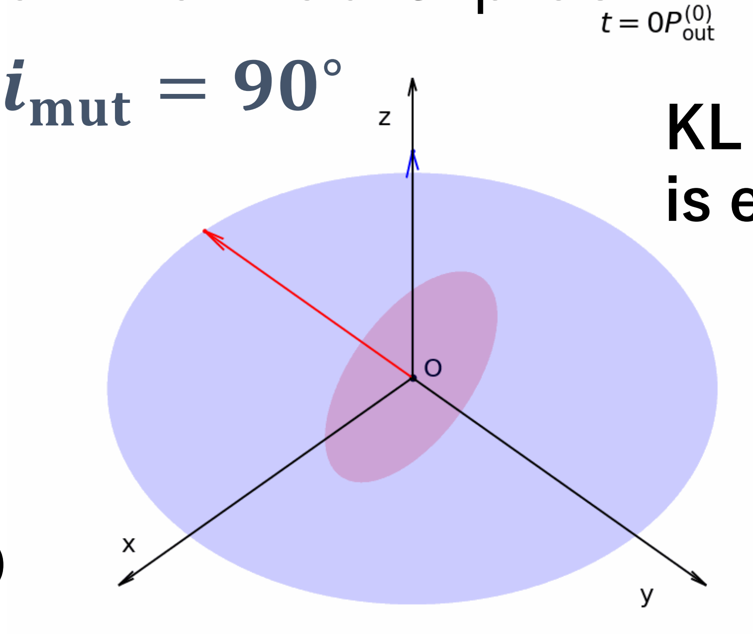


KL oscillation is not effective

Regular precession

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

$i_{\mathrm{mut}} = 90°$



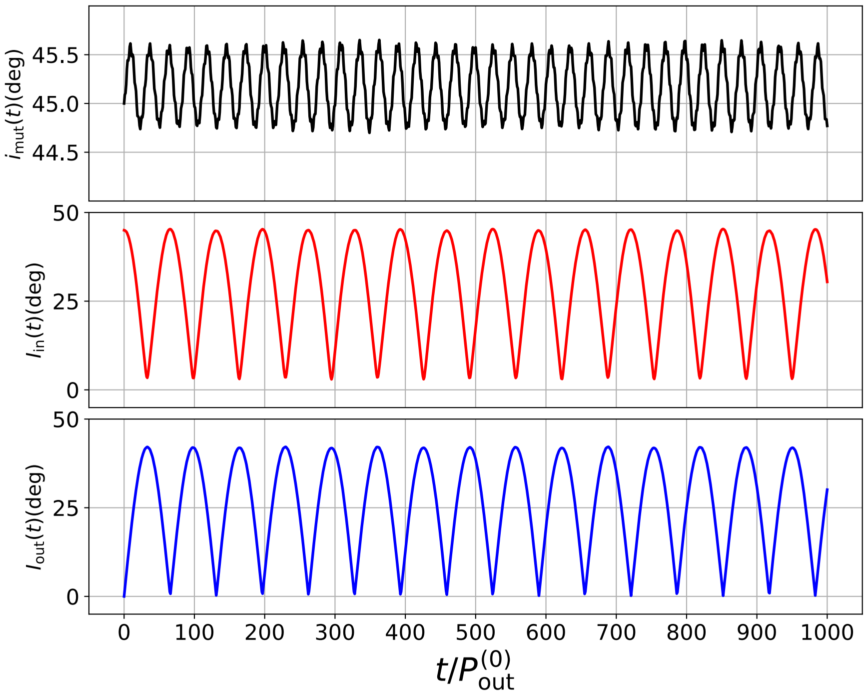
KL oscillation is effective

Drastic change

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

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

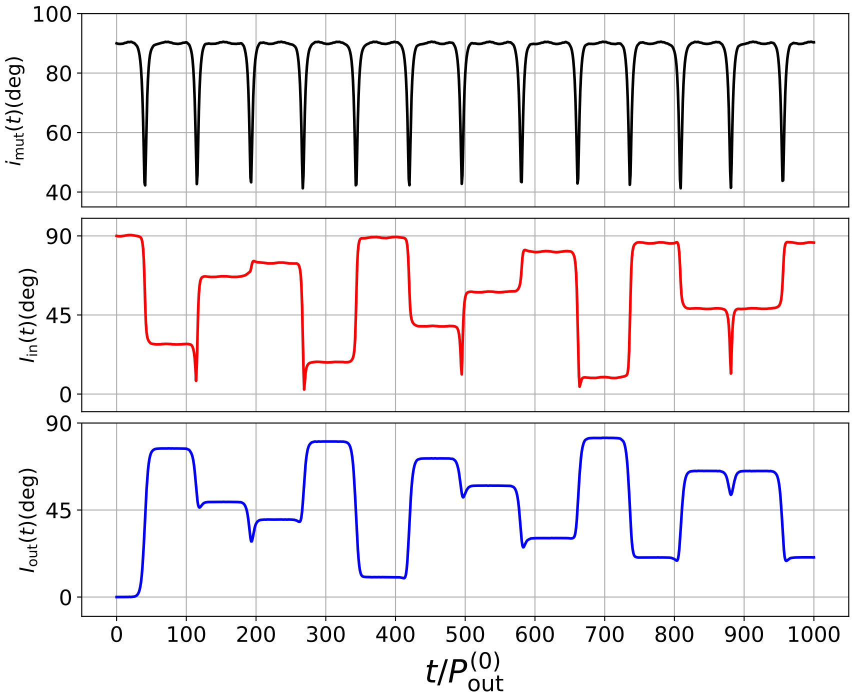
$I_{\mathrm{out}}(t)$



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

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

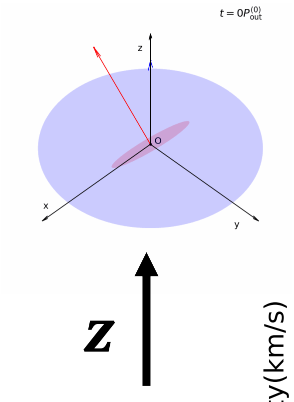
$I_{\mathrm{out}}(t)$



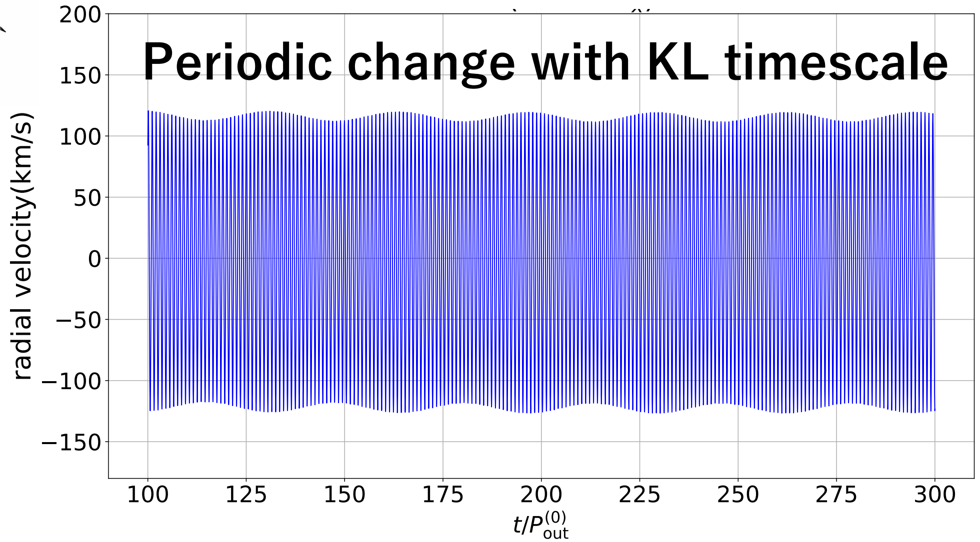
Long-term RV variations for inclined triples (ii)

$i_{\mathrm{mut}} = 45°$

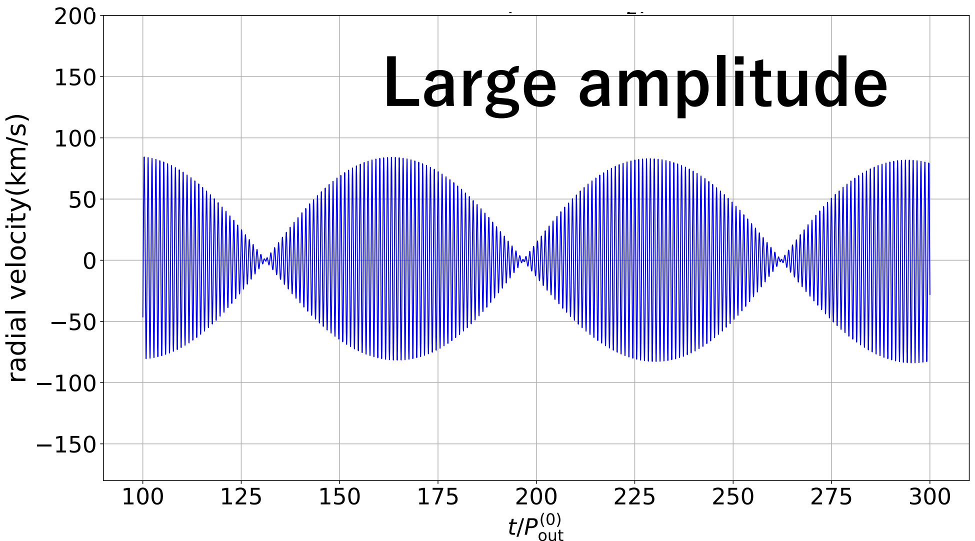
$K_{\mathrm{Kep}} = K_0 \sin I_{\mathrm{out}}(t)$



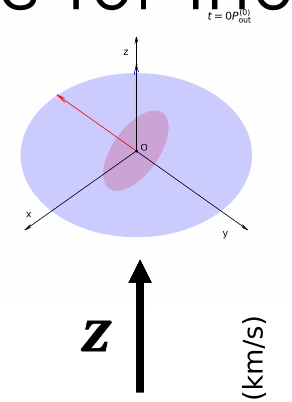
x-direction (near edge-on) total RV



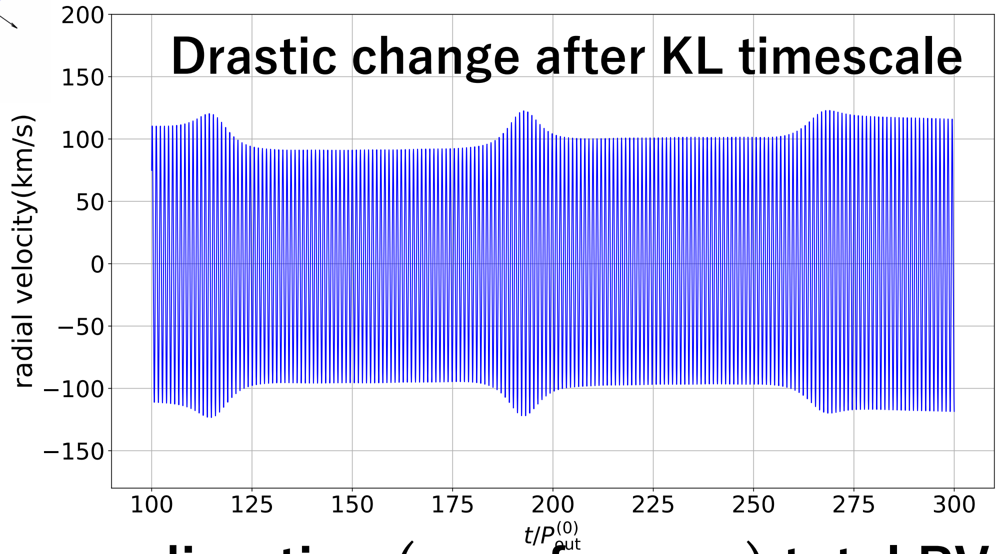
z-direction (near face-on) total RV



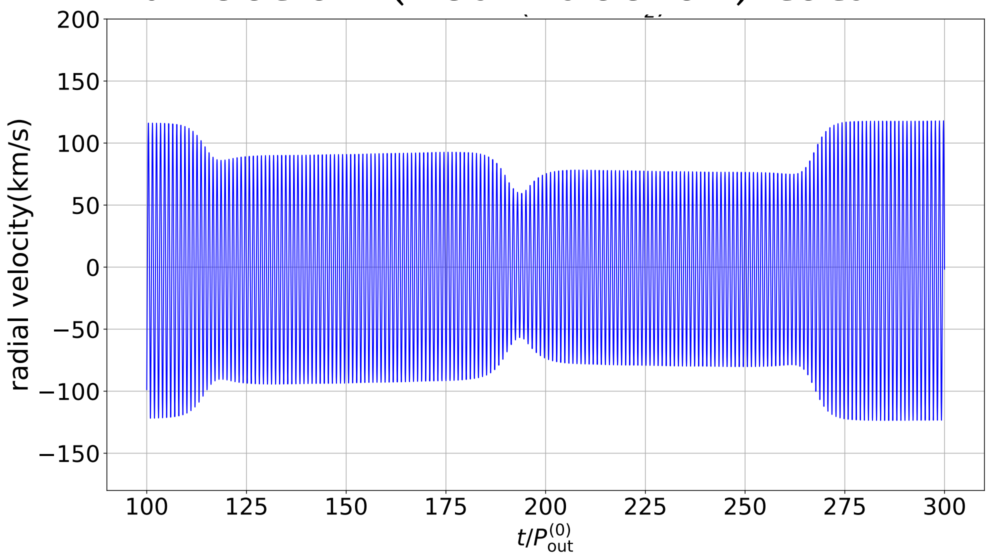
$i_{\mathrm{mut}} = 90°$



x-direction (near edge-on) total RV



z-direction (near face-on) total RV



Pulsar time delay by the inner-binary perturbation

(Radial Velocity)

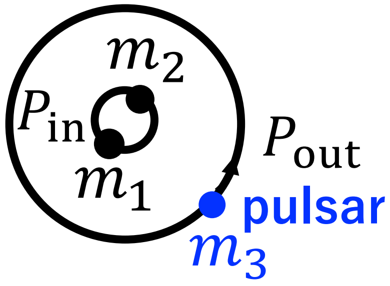
Plavchan+2015

(1) **Short distance (<kpc) for $O(10)$ m/s precision**

(2) **Bright stars (<15mag) for $O(10)$ m/s precision**

(3) **High-precision spectroscopy required**

→



(Pulsar timing)

(1) **High precision (~ $O(10)$ μsec)**

(2) **Long distance (~ 10 kpc or farther)**

(3) **Continuous observations (Pulsar Timing Array)**

Pulsar time delays

(1) **Rømer delay (Keplerian motion)**

Change of the radial distance of pulsar

(2) **Rømer delay (perturbation)**

Gravitational perturbation by inner binary

(3) **Relativistic delays**

Redshift (Einstein delay)

Spacetime curvature (Shapiro delay)

(1)+(2)+(3)
→ **All orbital parameters estimated**

Expected amplitude of each time delay

Equal-mass inner binary

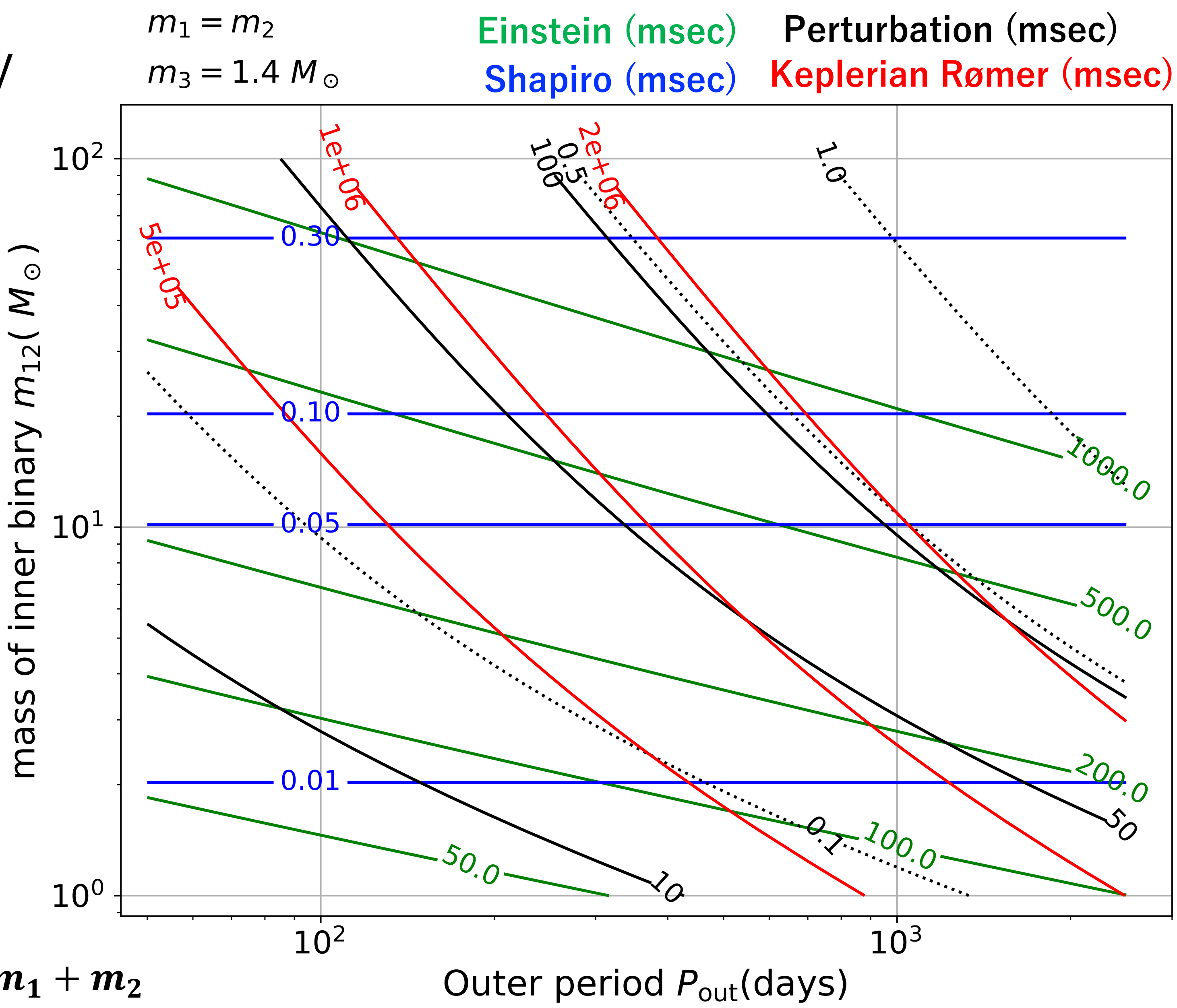
$P_{in} = P_{out}/10$ (solid black)

$P_{in} = P_{out}/50$ (dotted black)

$m_{12} \gtrsim 10 M_\odot$
$P_{out} \lesssim 1000$ days
$P_{in} \gtrsim 1/50\ P_{out}$

target

$m_{12} \equiv m_1 + m_2$



Examples of time delay curves

Analytic expressions (Backer&Hellings 1986, Morais&Correia 2008,2011)

$$m_1 = m_2 = 10M_\odot$$

$$m_3 = 1.4M_\odot$$

$$P_{\rm out} = 100 \text{ days}$$

$$P_{\rm in} = 10 \text{ days}$$

Model CC (Coplanar Circular)

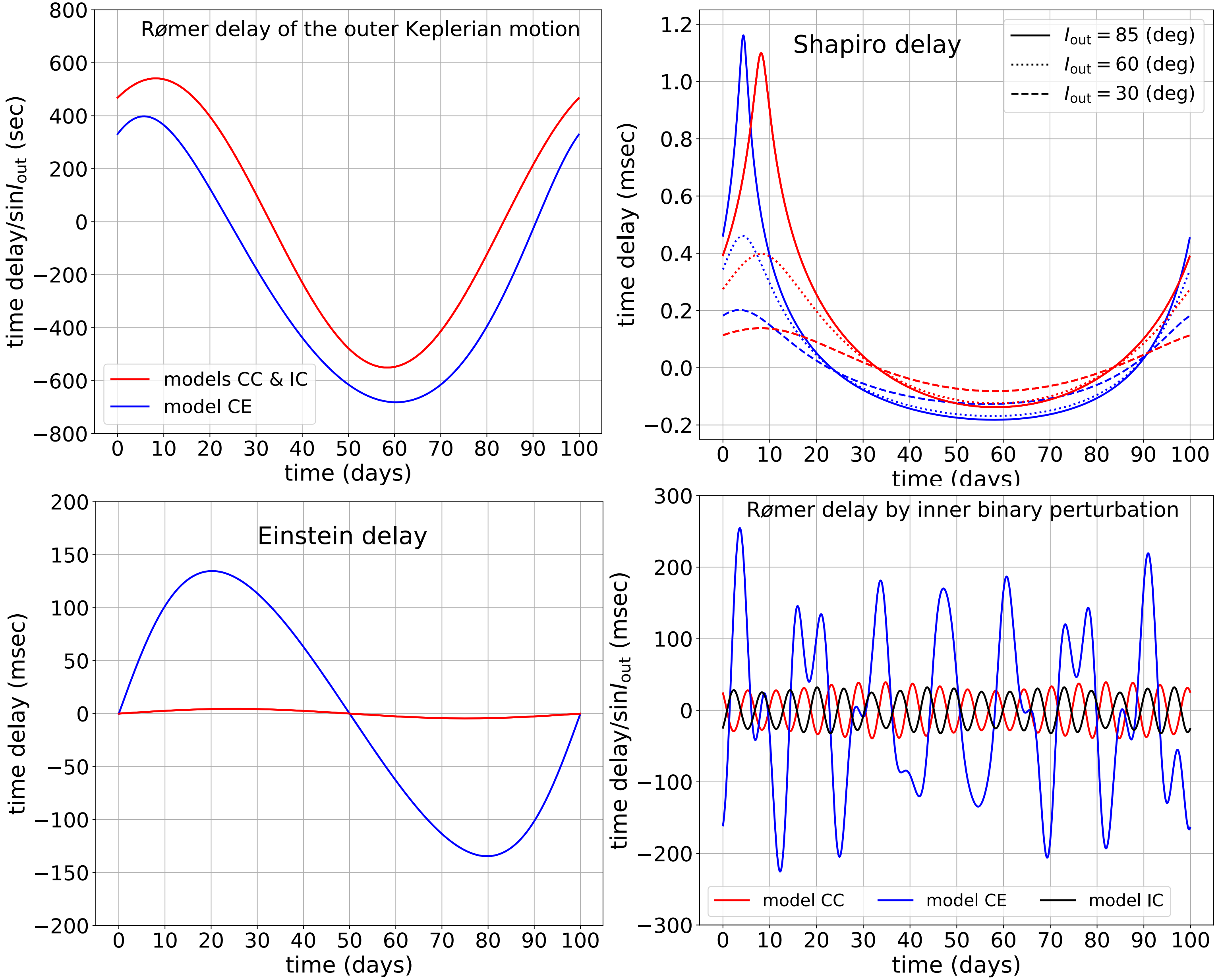
$$e_{\rm out} = 0.01 \quad e_{\rm in} = 0.0 \quad i_{\rm mut} = 0^\circ$$

Model CE (Coplanar Eccentric)

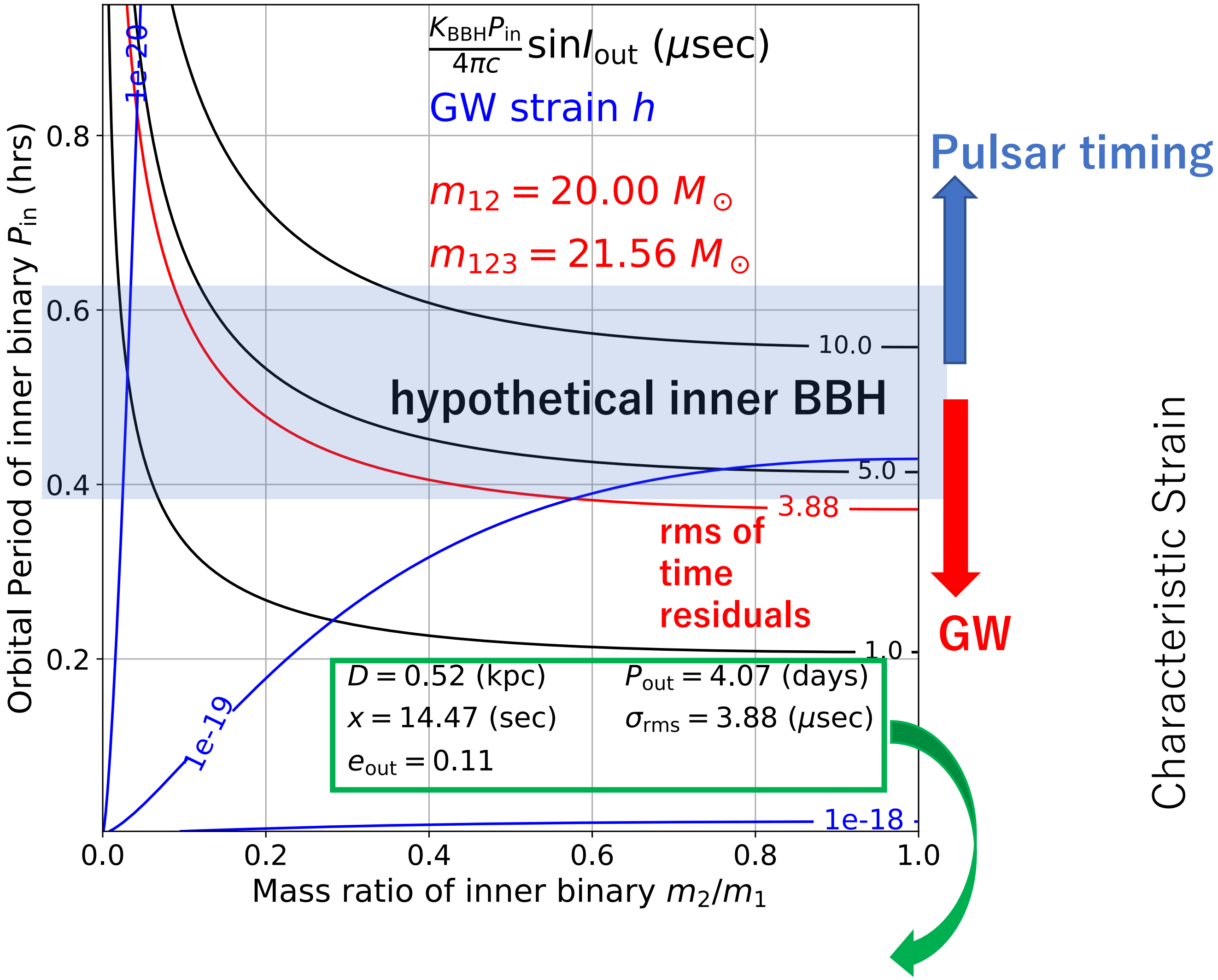
$$e_{\rm out} = 0.3 \quad e_{\rm in} = 0.2 \quad i_{\rm mut} = 0^\circ$$

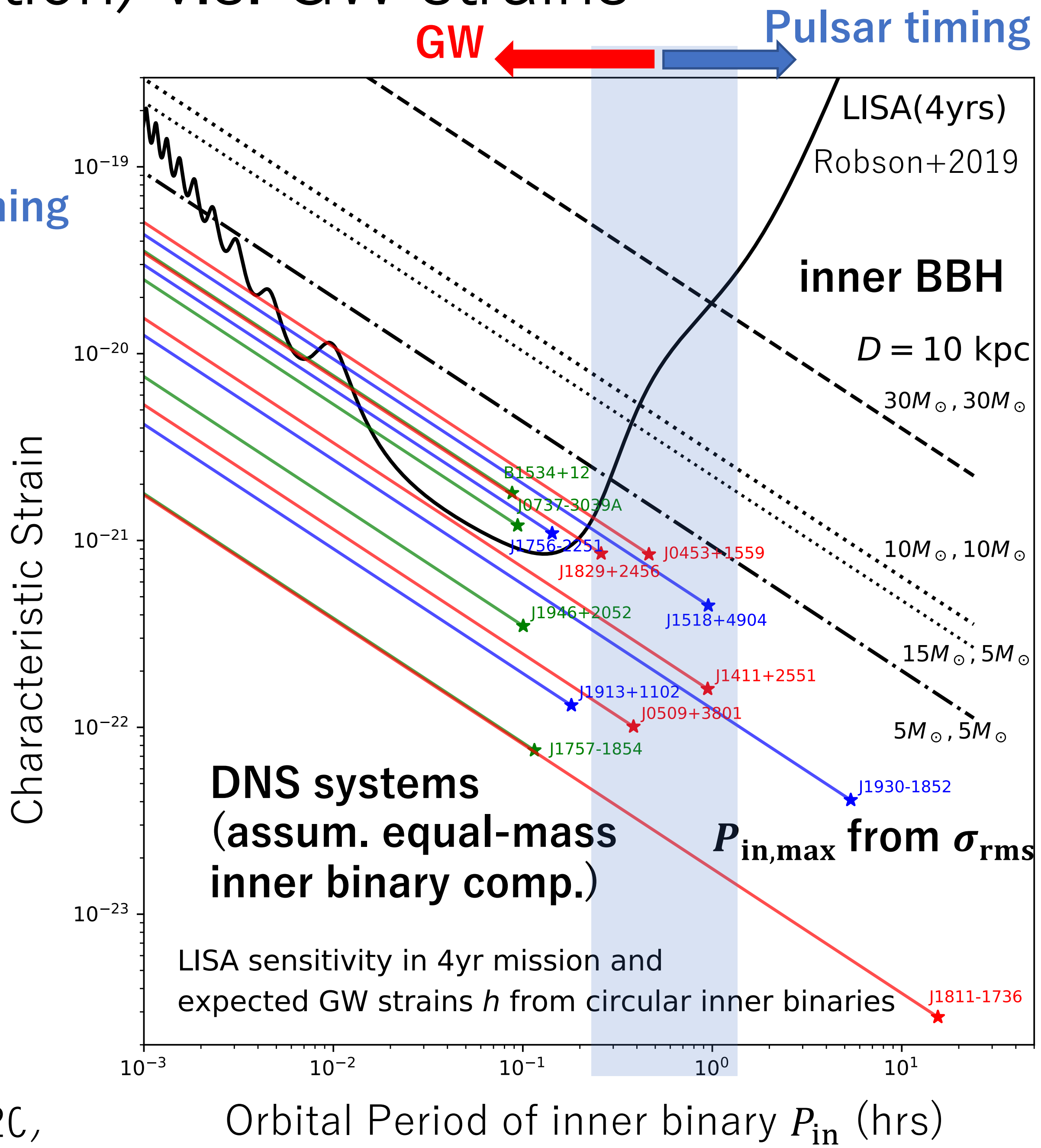
Model IC (Inclined Circular)

$$e_{\rm out} = 0.01 \quad e_{\rm in} = 0.0 \quad i_{\rm mut} = 45^\circ$$



Rømer delay (perturbation) v.s. GW strains





Inner BBH could be constrained effectively by pulsar timing and GW

From double NS binary (DNS) J0453+1559 (Martinez+2015,Haniewicz+2020)

Summary and Future prospects

(Radial velocity)

Short-term RV variations due to an inner binary

Long-term RV amplitude variation with KL timescale for an inclined triple

Future surveys (Gaia; Yamaguchi+2018, TESS; Masuda&Hotokezaka 2019)

(Pulsar timing)

Rømer delays (Kepler, perturbation)+relativistic delays (Einstein, Shapiro)
→ Precise orbital parameter determination

A complementary method to future low-frequency GW surveys (e.g. LISA)