Unveiling the presence of an inner binary black-hole from the tertiary orbiting star

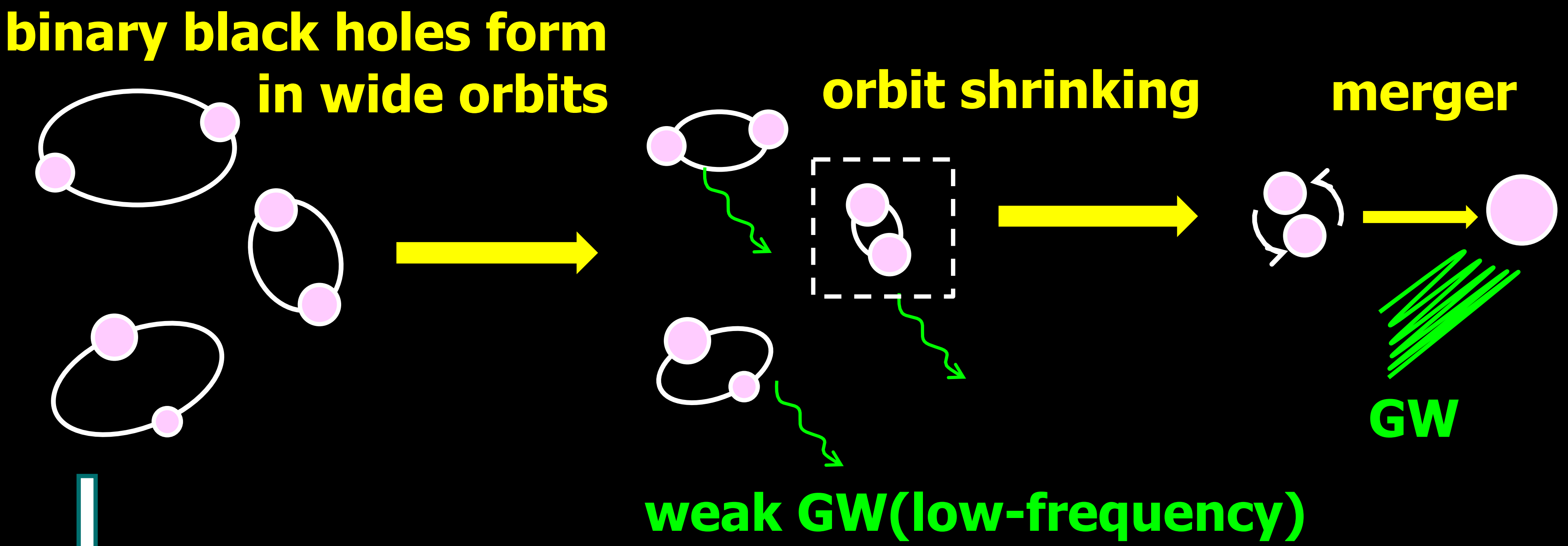
Alpha Centauri was a triple system, two suns tightly orbiting one another, and a third, more remote, circling them both. What would it be like to live on a world with three suns in the sky?

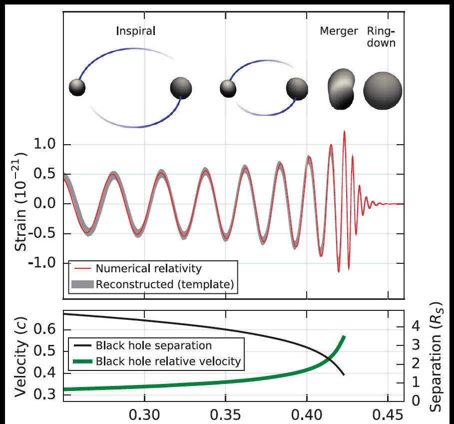
— Carl Sagan, "Contact"

Yasushi Suto Department of Physics, and Research Center for the Early Universe, the University of Tokyo

The 9th KIAS workshop on Cosmology and Structure Formation
@Korean Institute of Advanced Study, 10:10-10:35, November 2, 2020

Generic picture of binary BH evolution





LIGO/Virgo

BBHs would spend longer time in wide orbits before merging

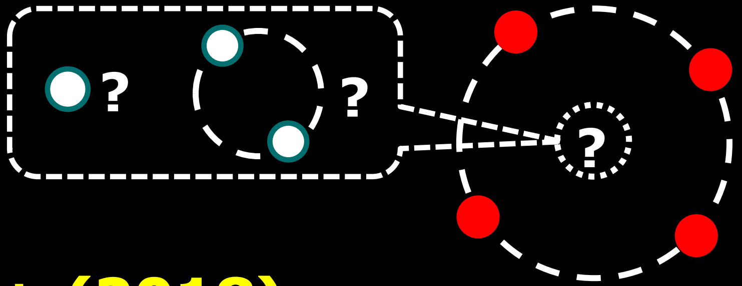
Abundant longer orbital-period BBHs may remain undetected (e.g. ~10day orbital period~10^{-6}Hz).

Detection strategy complementary to GW ?

Proposals to search for star-BH binaries

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)

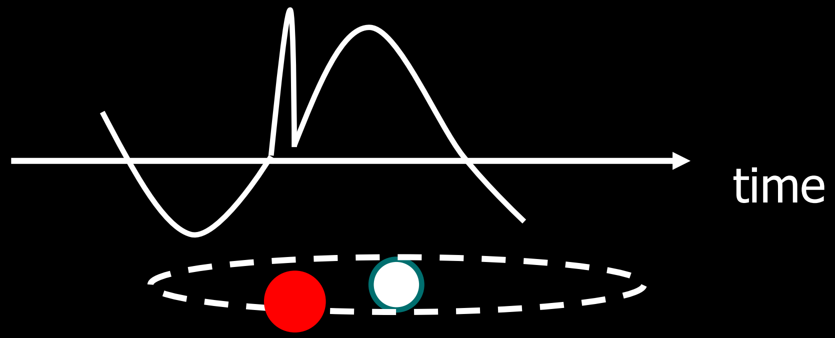
5-year mission may detect
200-1000 star-BH binaries

TESS mission (2018-)

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

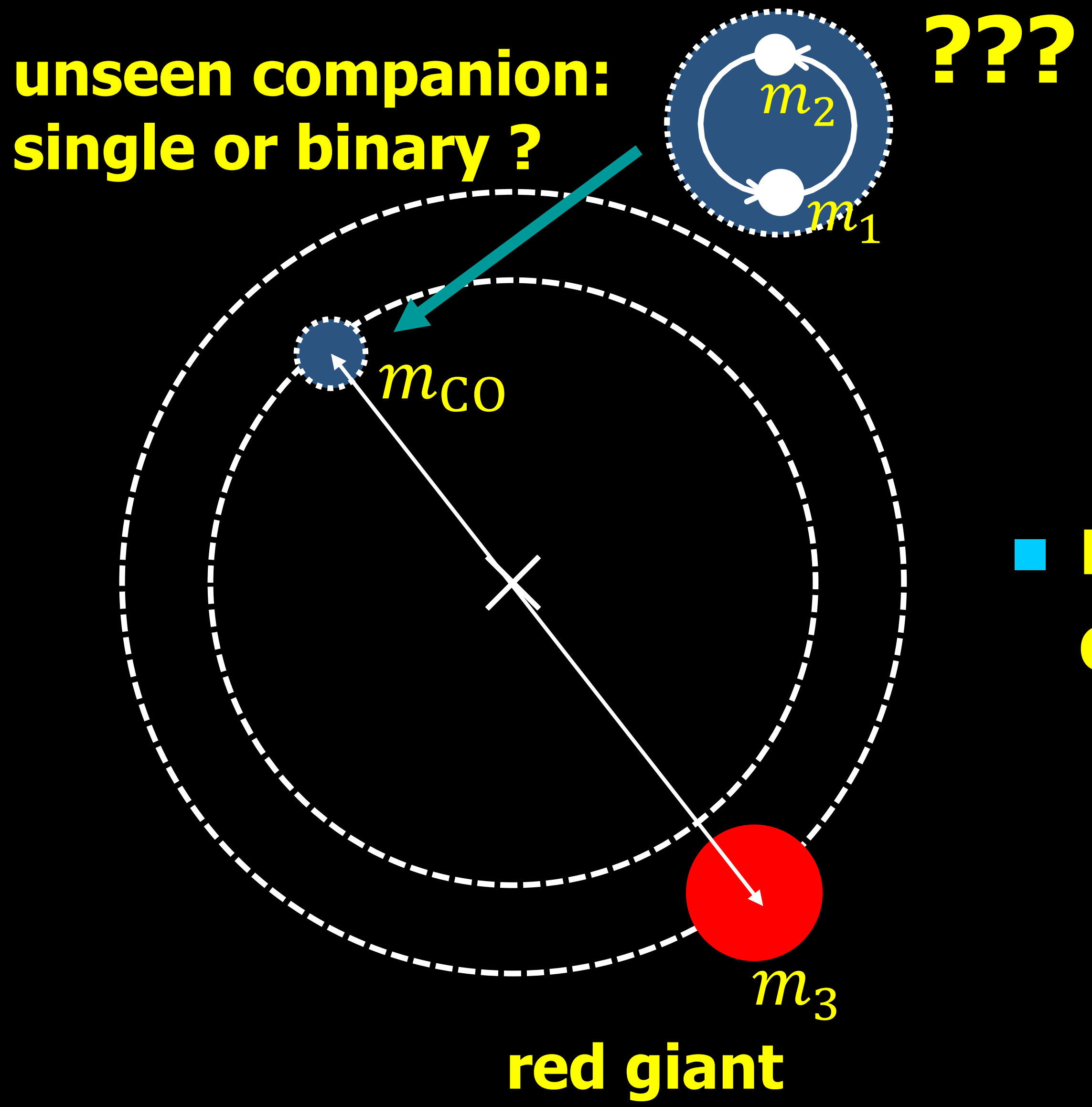
Masuda & Hotokezaka (2019)

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?

A binary system 2M05215658+4359220



Thompson+ (2019)

P_{out}	83.205 ± 0.064 days
$m_{co}(= m_1 + m_2)$	$3.2^{+1.1}_{-0.4}$ $M_\odot$
m_3	$3.0^{+0.6}_{-0.5}$ $M_\odot$
e_{out}	0.0048 ± 0.0026

highly circular !

- **red giant + unseen companion binary ?**
  - Detected by a low-resolution radial velocity change
  - The companion mass is $3.2M_\odot$ ⇒ a single BH or a NS binary ?

Ups and downs of LB-1

Article

A wide star–black-hole binary system from radial-velocity measurements

Liu et al. Nature 575(2019)618

https://doi.org/10.1038/s41586-019-1766-2
Received: 1 March 2019
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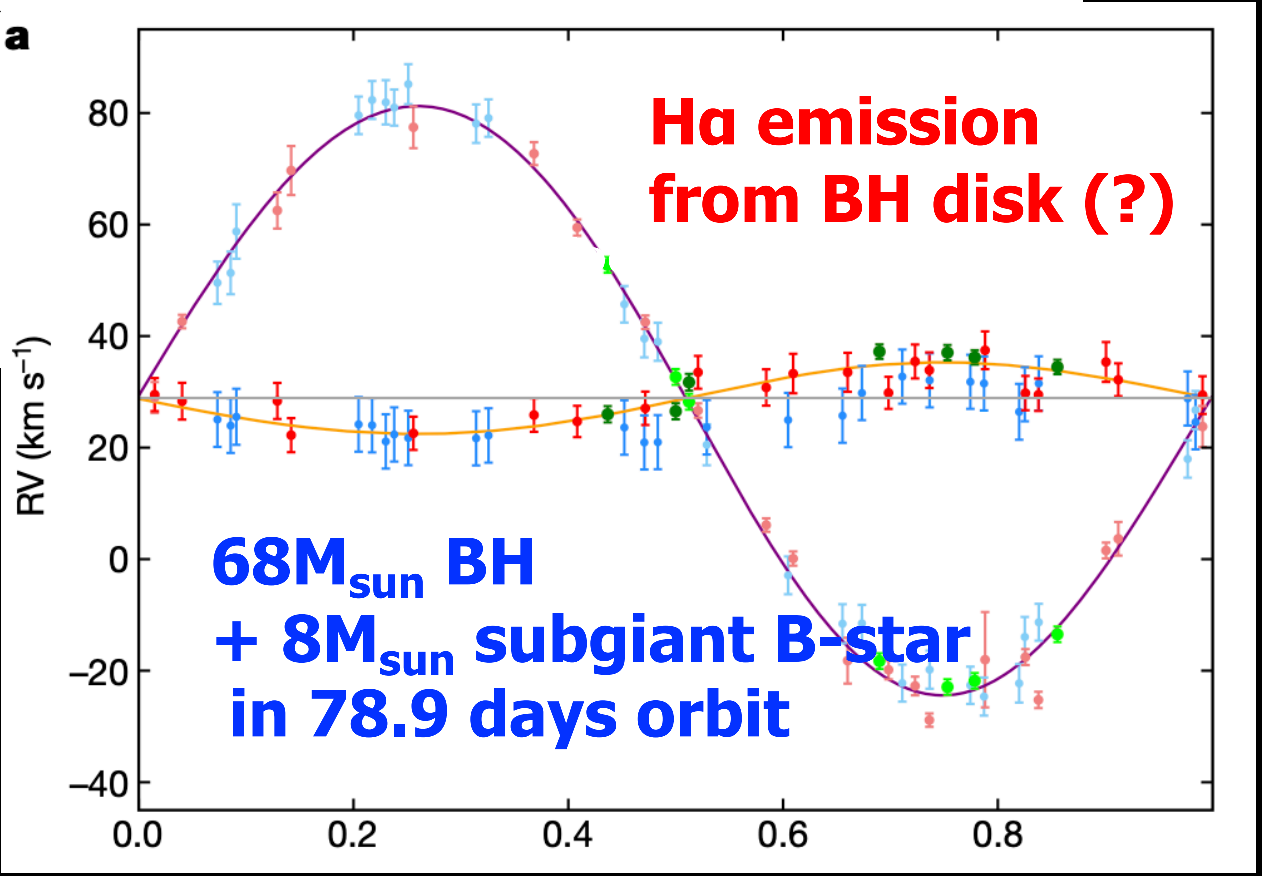
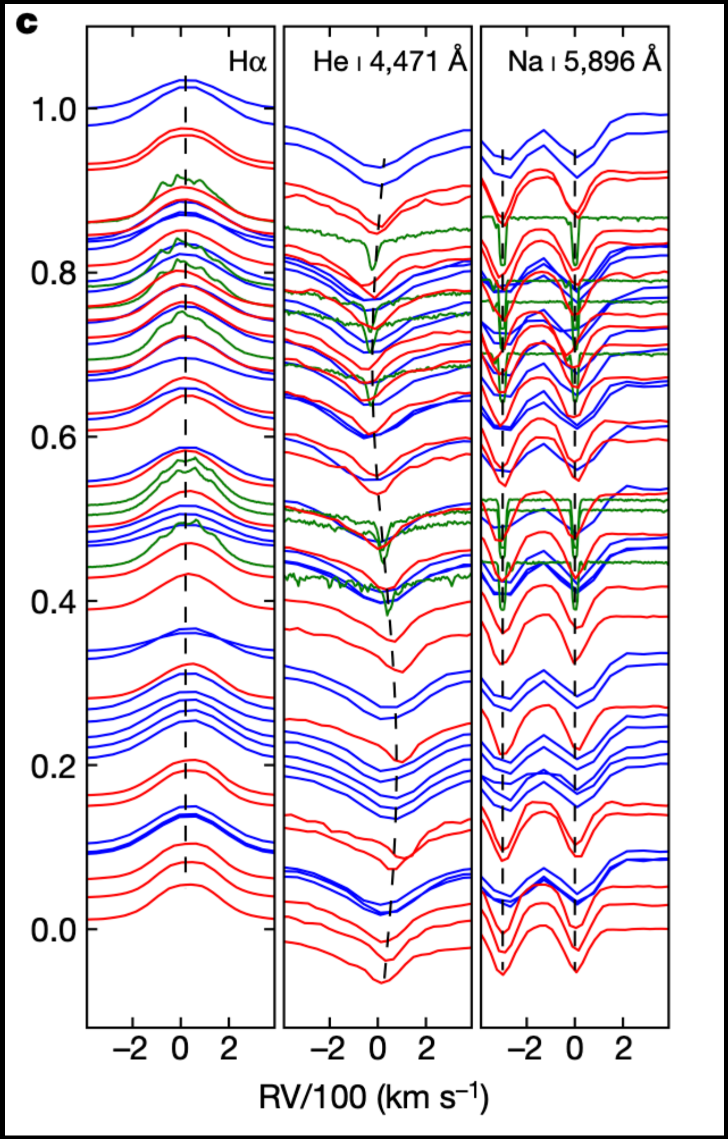
Published online: 27 November 2019





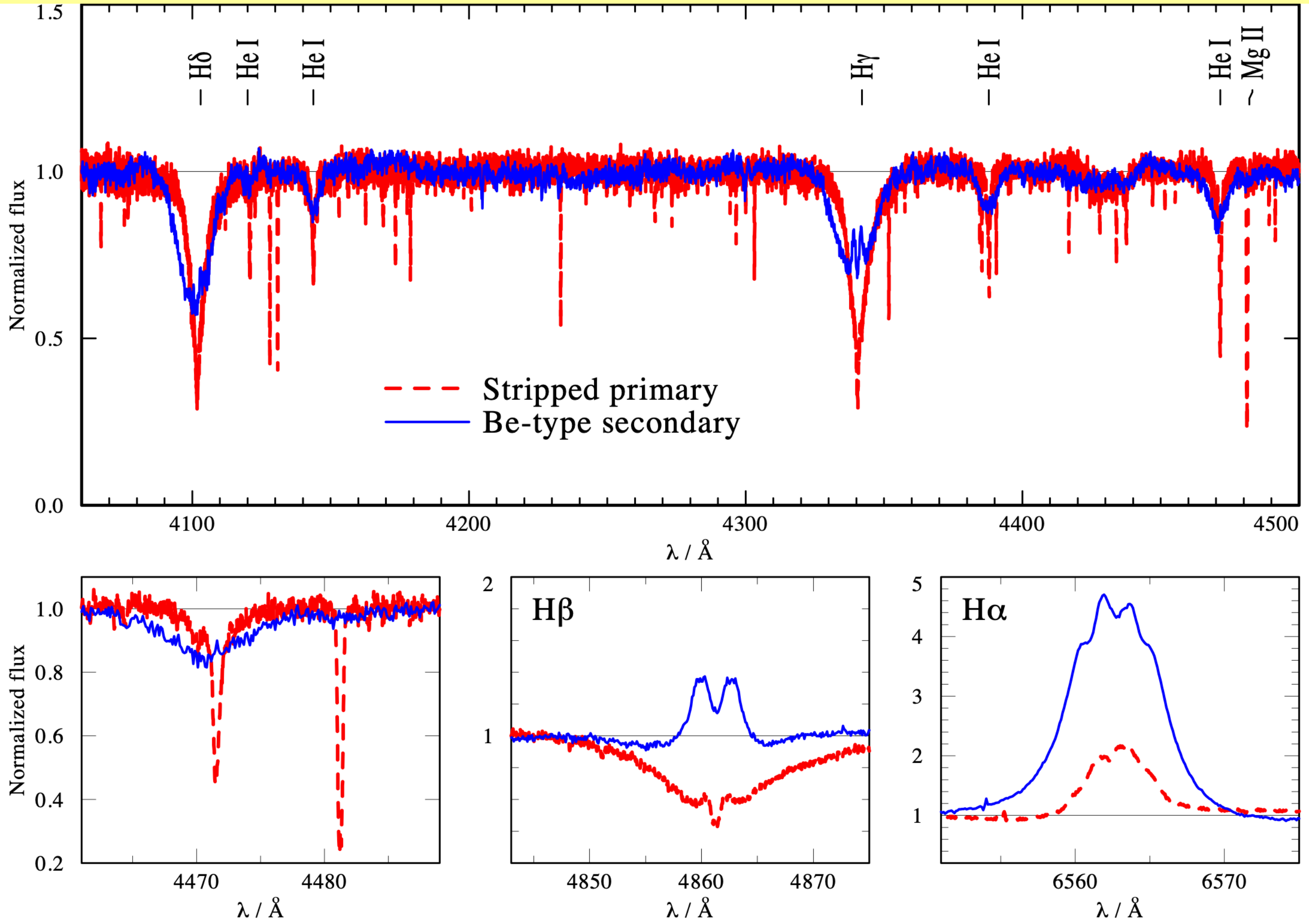
The hidden companion in LB-1 unveiled by spectral disentangling

T. Shenar, J. Bodensteiner, M. Abdul-Masih, M. Fabry, L. Mahy, P. Marchant,

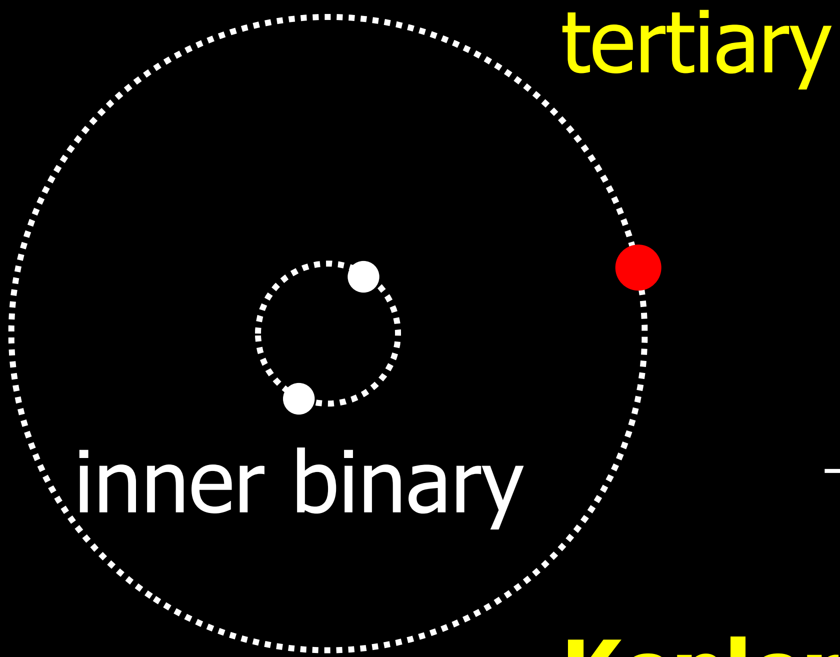
Disentangled the spectra of LB-1 and found that LB-1 comprises a stripped He-rich star (1.5±0.4 M_{sun}) + a Be-type secondary star (7±2 M_{sun}) , not a BH

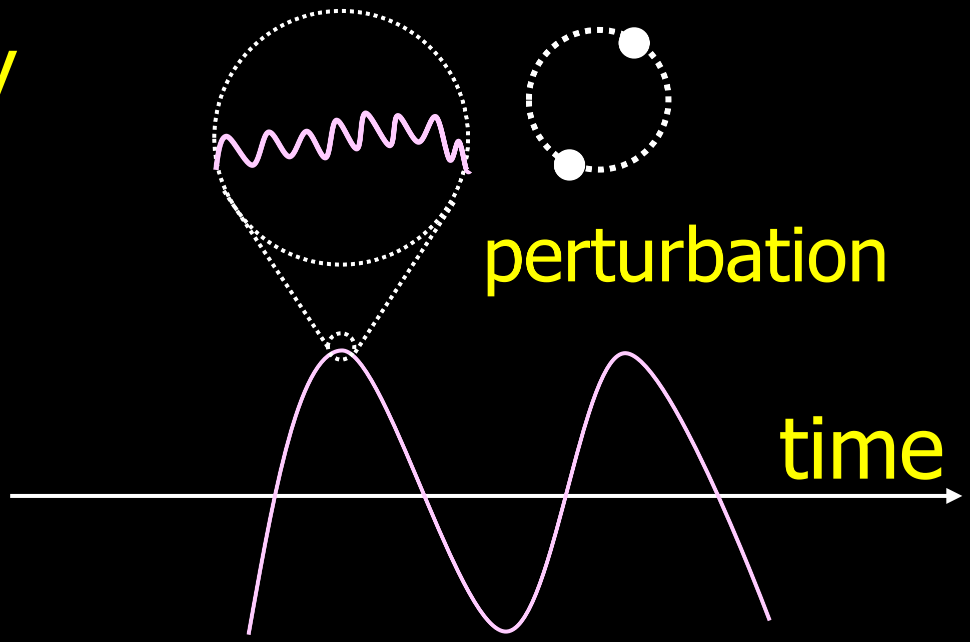
T. Shenar et al. A&A 639(2020)L6

LB-1 turned out to be not a star-BH system that we have been looking for, but such candidates will come in future !

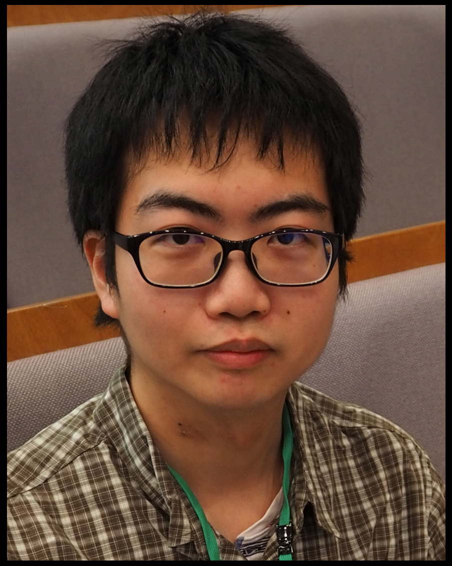


Radial velocity modulation of a tertiary star due to an inner binary





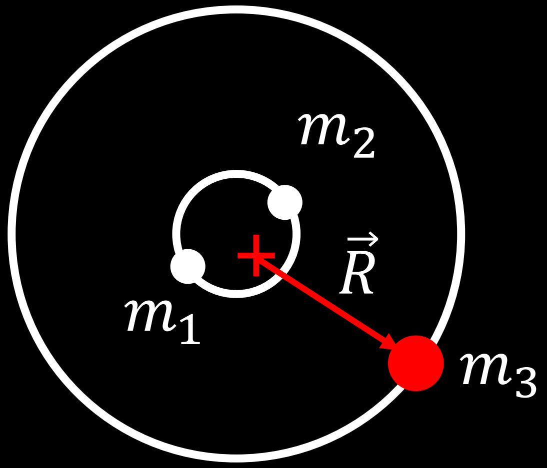
Kepler motion of the tertiary



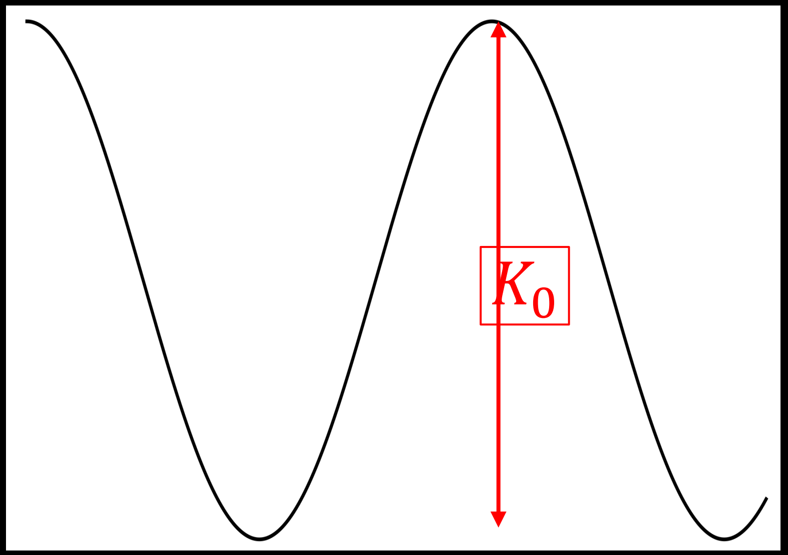
Toshinori Hayashi
林利憲

Hayashi, Wang + YS: ApJ 890(2020)112
Hayashi + YS: ApJ 897(2020)29

RV modulations for coplanar triples

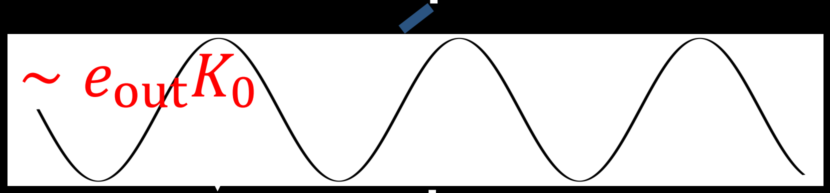


$\mathrm{RV} =$



period: $\boldsymbol{P_{out}}$

$+$



period: $\boldsymbol{P_{out}/2}$

first order in $e_{\rm out}$

$+$

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

period: $\boldsymbol{P_{in}/2}$

inner binary

$$\mathcal{H} = \mathcal{H}_{\rm Kep} - \mathcal{R}$$

Perturbation theory

Approximate expressions for RV of the tertiary star

$$V_{\rm RV}(t) = V^{(0)}_{\rm Kep}(t) + \delta V_{\rm Kep}(t) + V_{\rm bin}(t).$$

Morais & Correia (2008)
Hayashi & YS (2020)

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

(i) Unperturbed Kepler motion

$$V^{(0)}_{\rm Kep}(t) = K_0 \sin I_{\rm out} \cos[\nu_{\rm out} t + f_{\rm out,0} + \omega_{\rm out}]$$
$$K_0 \equiv \frac{m_1 + m_2}{m_1 + m_2 + m_*} a_{\rm out} \nu_{\rm out},$$

(ii) Perturbation to the Kepler motion

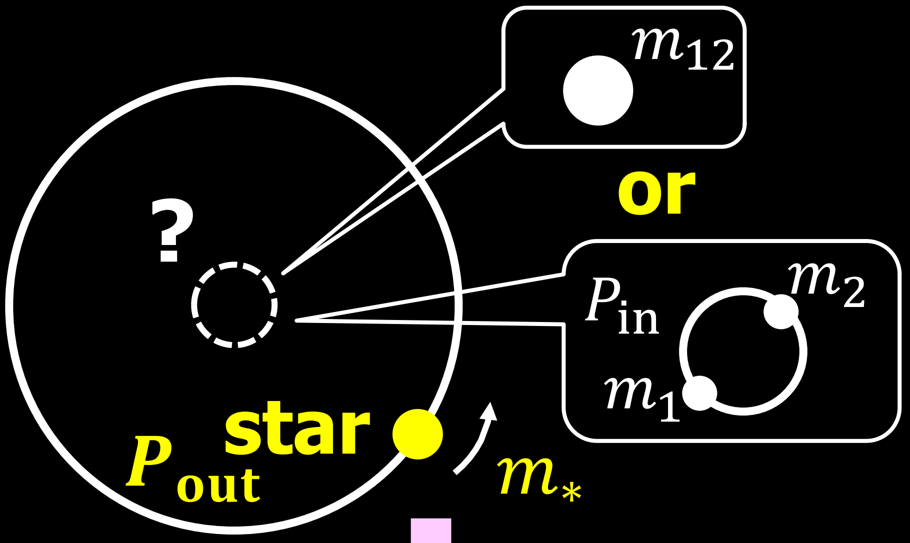
$$\delta V_{\rm Kep}(t) = K_1 \sin I_{\rm out} \cos[\nu_{\rm out} t + f_{\rm out,0} + \omega_{\rm out}],$$
$$K_1 \equiv \frac{3}{4} K_0 \left(\frac{a_{\rm in}}{a_{\rm out}}\right)^2 \frac{m_1 m_2}{(m_1 + m_2)^2}.$$

(iii) Modulation by the inner binary

$$\begin{aligned} V_{\rm bin}(t) = -\frac{15}{16} K_{\rm bin} \sin I_{\rm out} \cos[(2\nu_{\rm in} - 3\nu_{\rm out})t \\ + 2(f_{\rm in,0} + \omega_{\rm in}) - 3(f_{\rm out,0} + \omega_{\rm out})] \\ + \frac{3}{16} K_{\rm bin} \sin I_{\rm out} \cos[(2\nu_{\rm in} - \nu_{\rm out})t \\ + 2(f_{\rm in,0} + \omega_{\rm in}) - (f_{\rm out,0} + \omega_{\rm out})], \end{aligned}$$

$$K_{\rm bin} \equiv \frac{m_1 m_2}{(m_1 + m_2)^2} \sqrt{\frac{m_1 + m_2 + m_*}{m_1 + m_2}} \left(\frac{a_{\rm in}}{a_{\rm out}}\right)^{7/2} K_0,$$

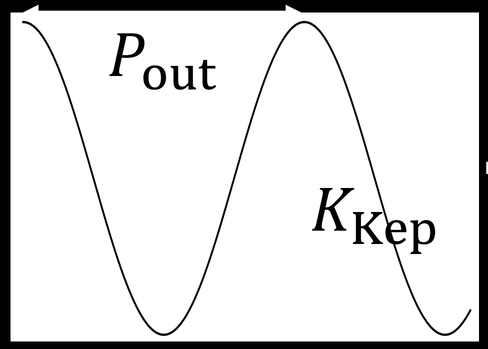
RV modulations for non-coplanar triples



high-precision RV follow-up

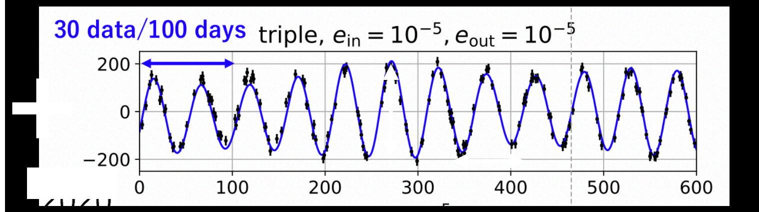
Keplerian motion RV
+ RV variations by inner binary

(i) Coplanar triple



Kepler motion

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

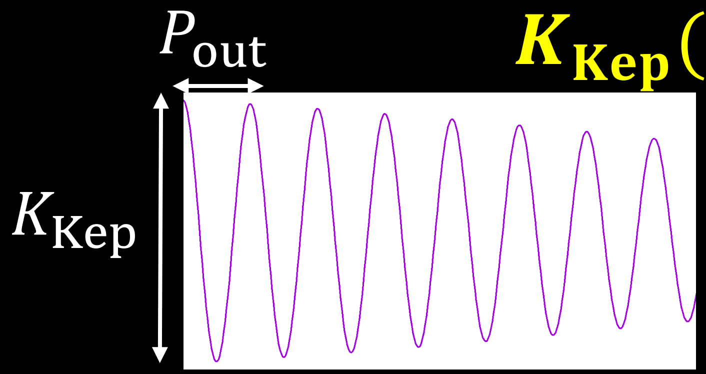


$$\mathrm{period} \sim P_{in}/2$$

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

(ii) Non-coplanar triple

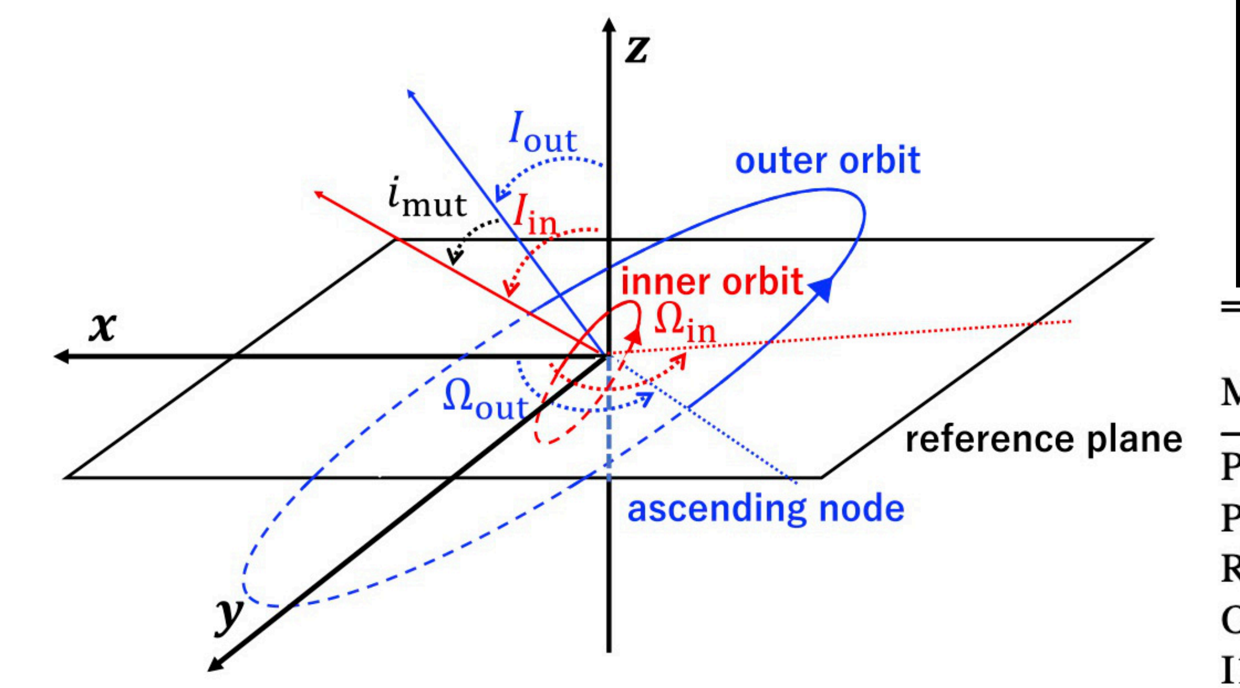
Inclination $I_{out}(t)$ modulated in the Kozai-Lidov timescale



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

Amplitude of Kepler RV varies with the timescale

Parameters for 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 circular triples

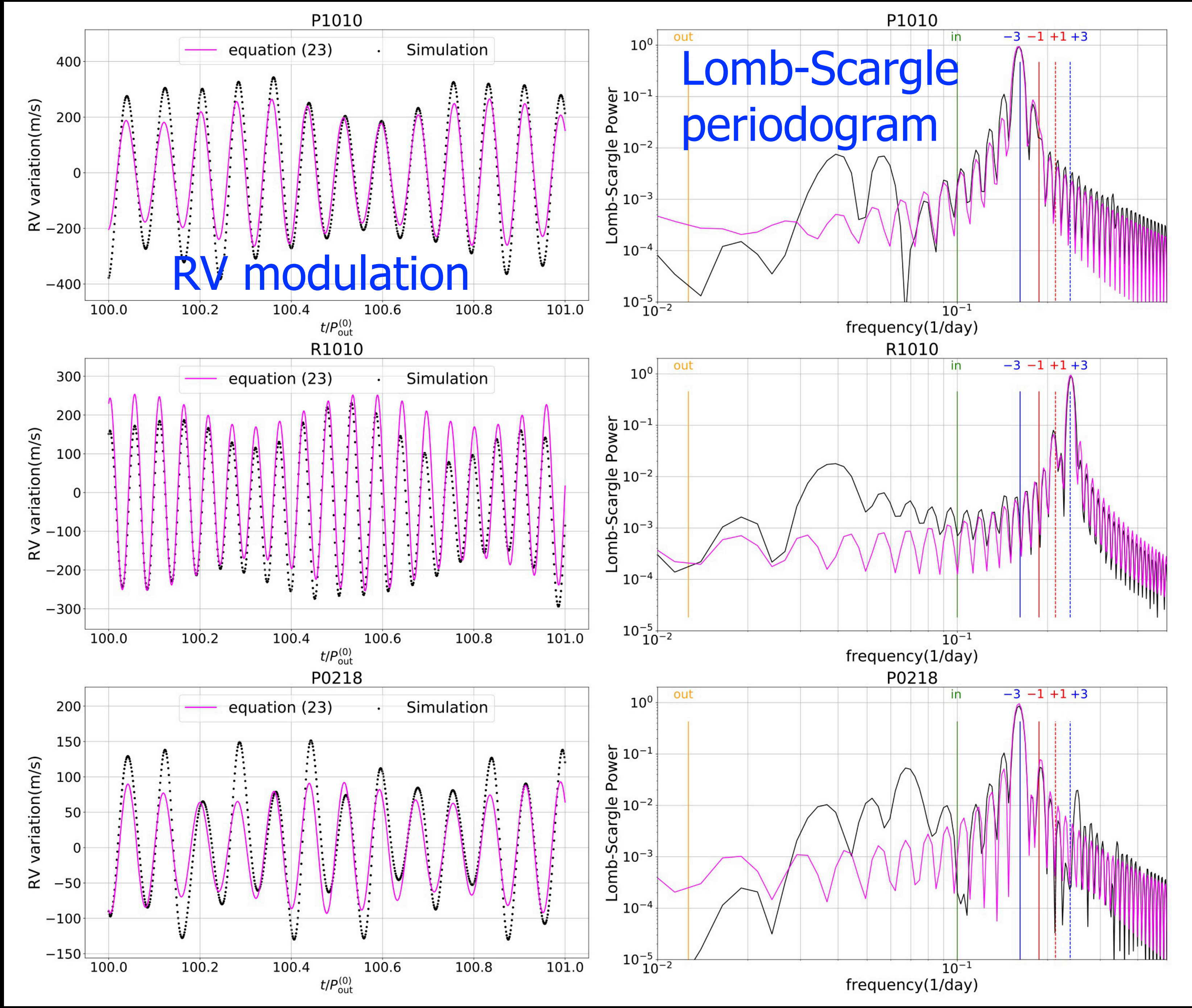
Prograde equal-mass

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

Retrograde equal-mass

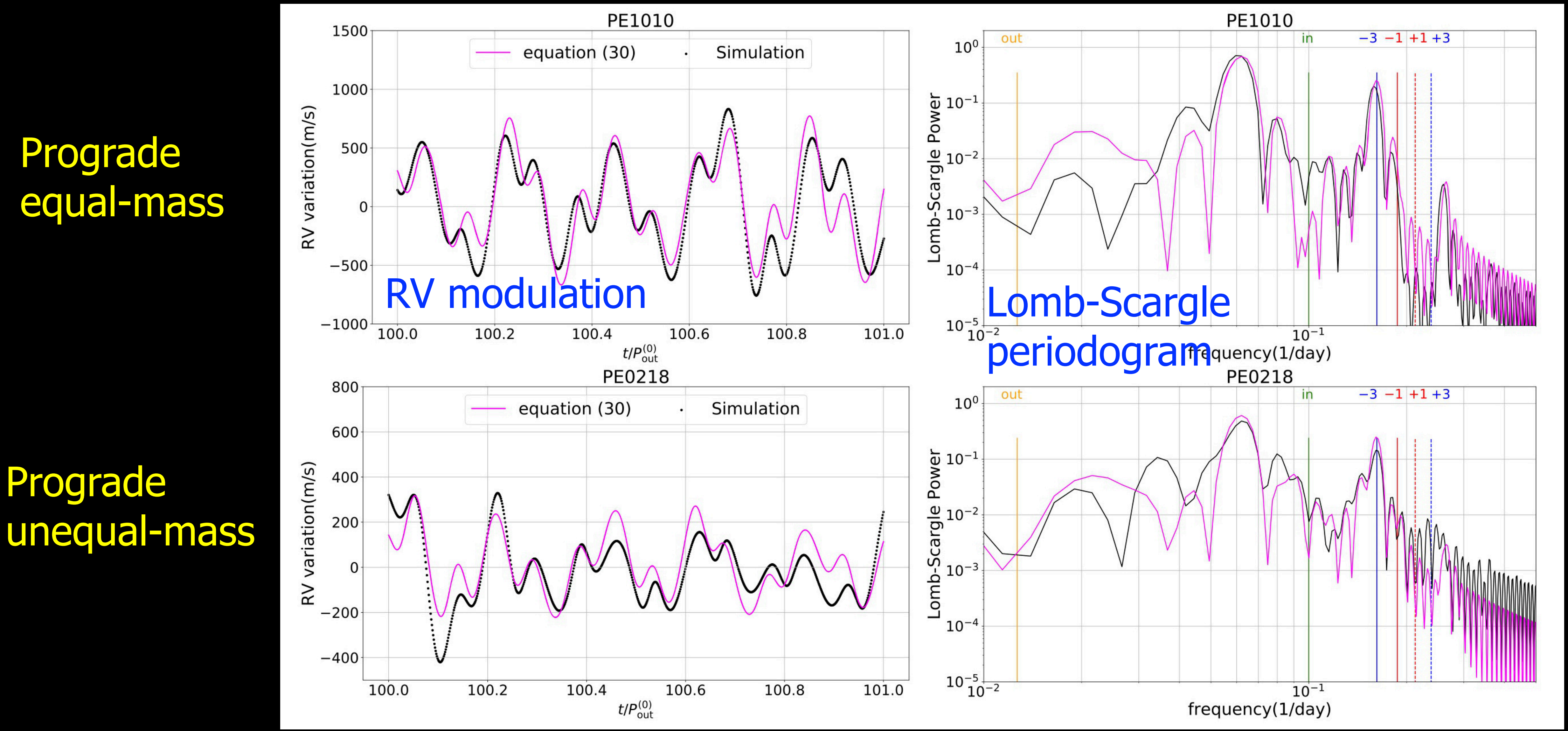
$$\nu_{-3} \equiv 2\nu_{\rm in} - 3\nu_{\rm out},$$
$$\nu_{-1} \equiv 2\nu_{\rm in} - \nu_{\rm out}.$$

Prograde unequal-mass



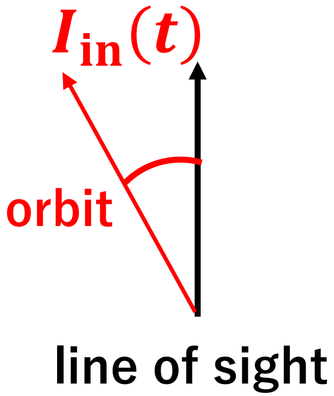
Coplanar eccentric triples

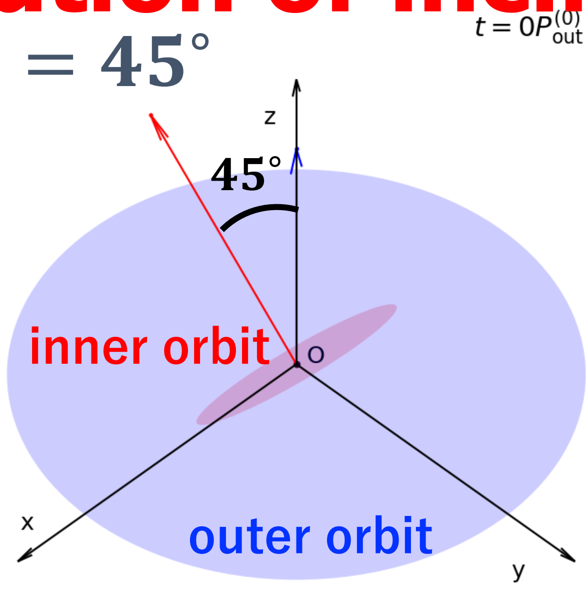
Simulation against Perturbative model (Morais & Correia 2008, 2012)



Evolution of inclination for non-coplanar triples

$i_{\rm mut} = 45°$



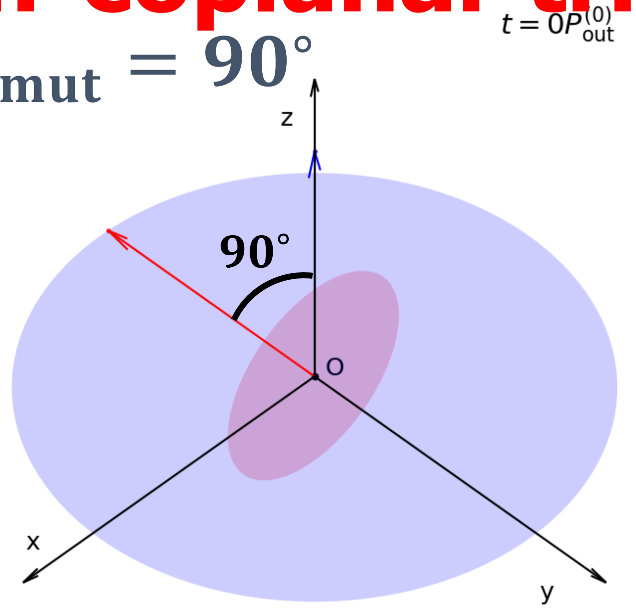


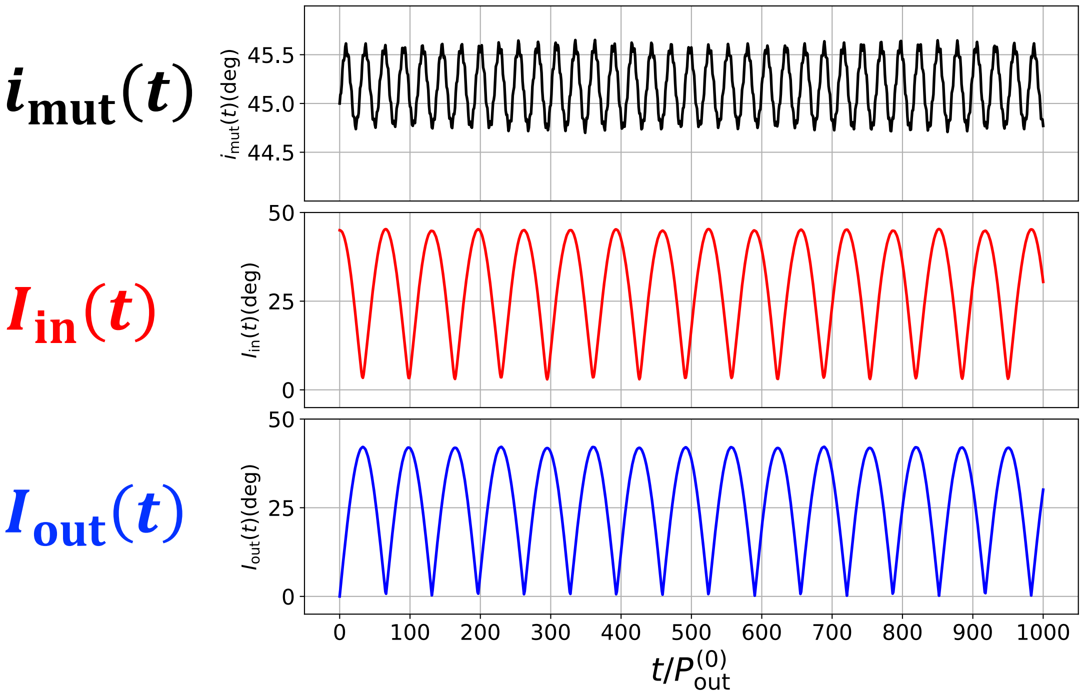
$P_{\rm out} = 78.9$ days
$P_{\rm in} = 10$ days

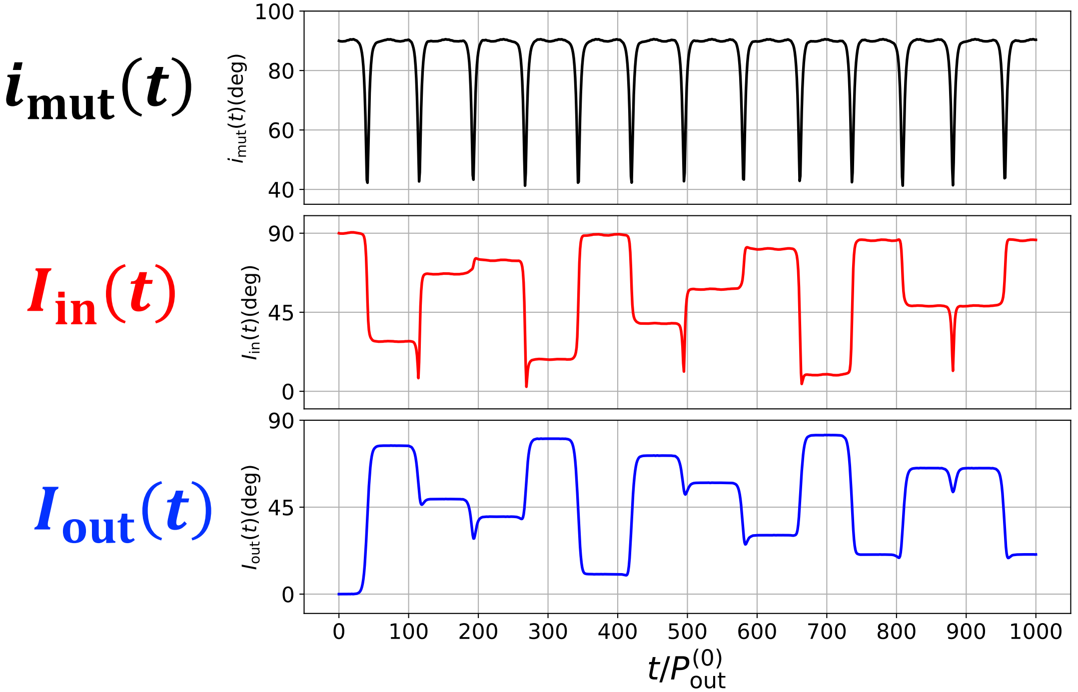
$m_1 = m_2 = 10M_\odot$
$m_* = 3M_\odot$

$e_{\rm out} = 0.03$
$e_{\rm in} = 10^{-5}$

$i_{\rm mut} = 90°$





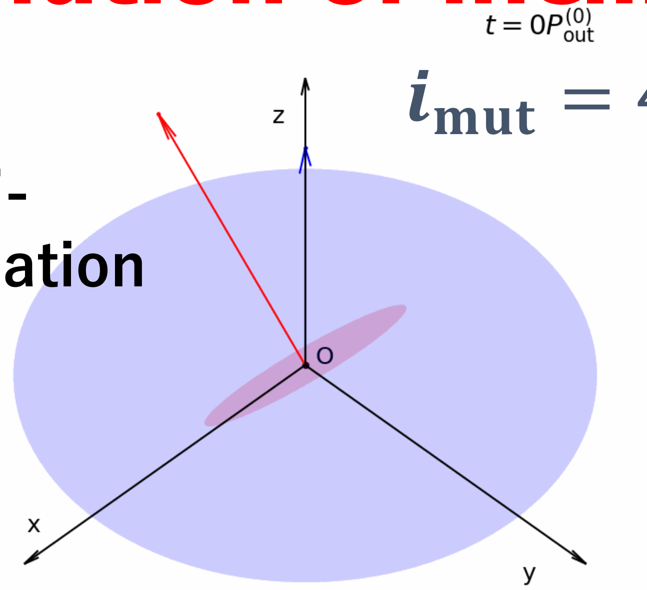


Evolution of inclination for non-coplanar triples

weak Kozai-Lidov oscillation

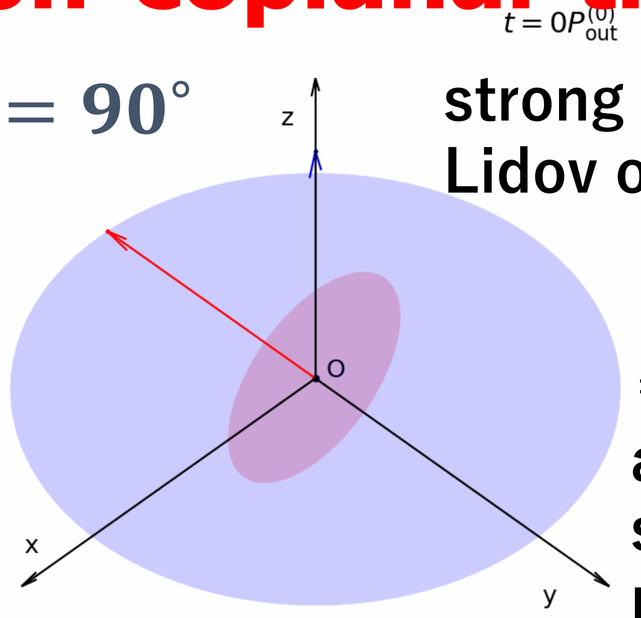
⇒ small-amplitude regular precession

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



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

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



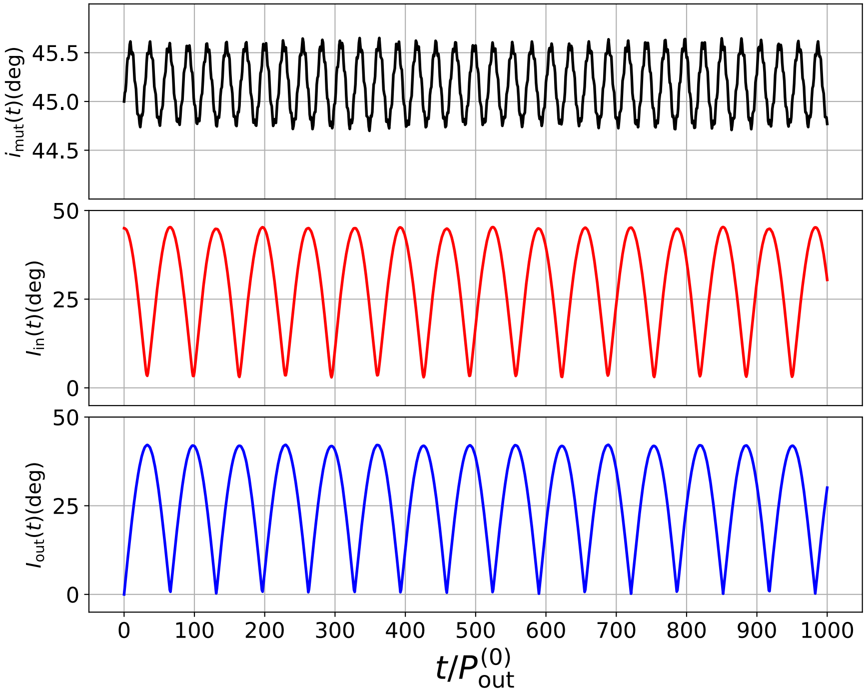
strong Kozai-Lidov oscillation

⇒ large-amplitude sporadic precession

$i_{\rm mut}(t)$

$I_{\rm in}(t)$

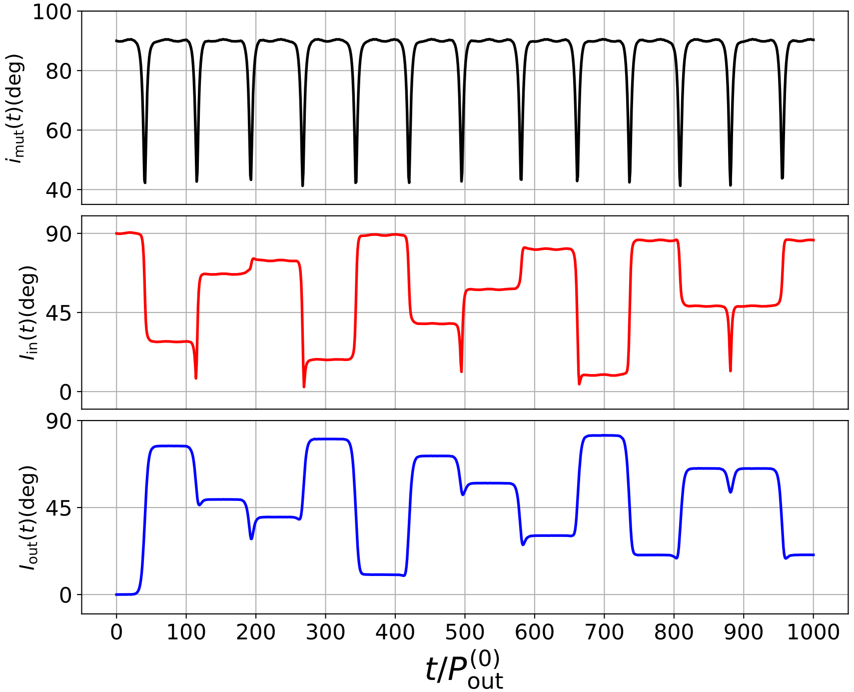
$I_{\rm out}(t)$



$i_{\rm mut}(t)$

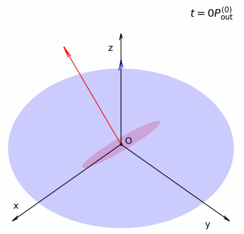
$I_{\rm in}(t)$

$I_{\rm out}(t)$



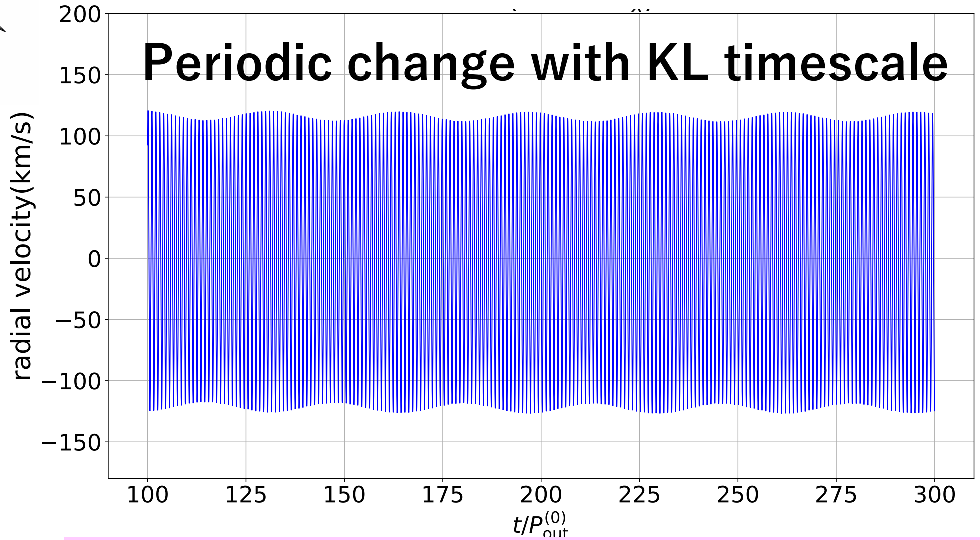
Evolution of radial velocity for non-coplanar triples

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

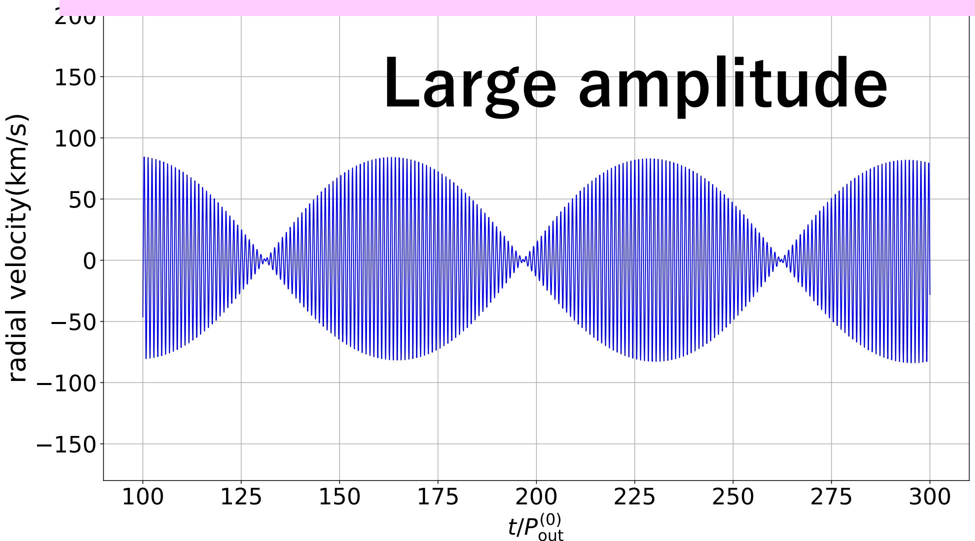


z

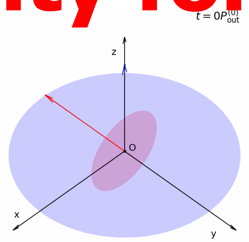
x-direction (near edge-on) total RV



z-direction (near face-on) total RV

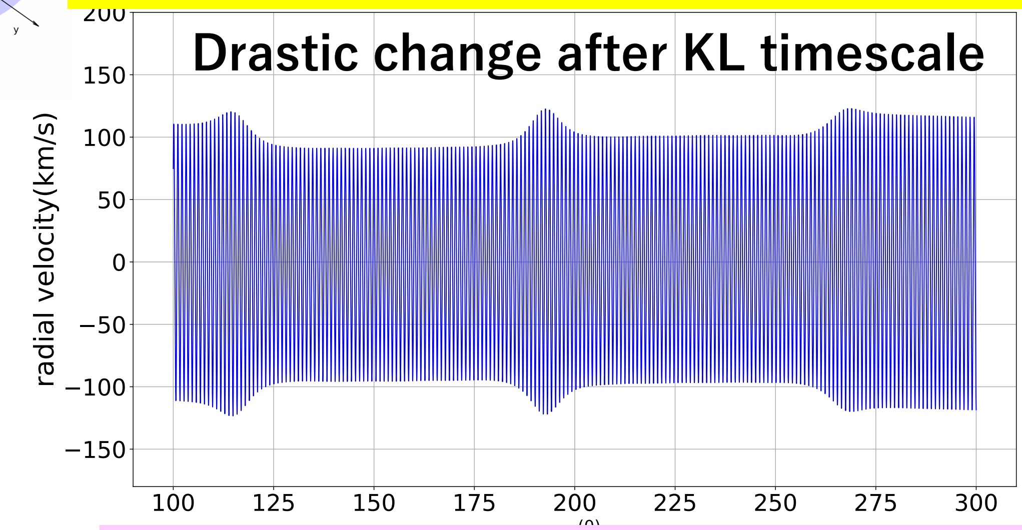


$i_{\mathrm{mut}} = 90°$

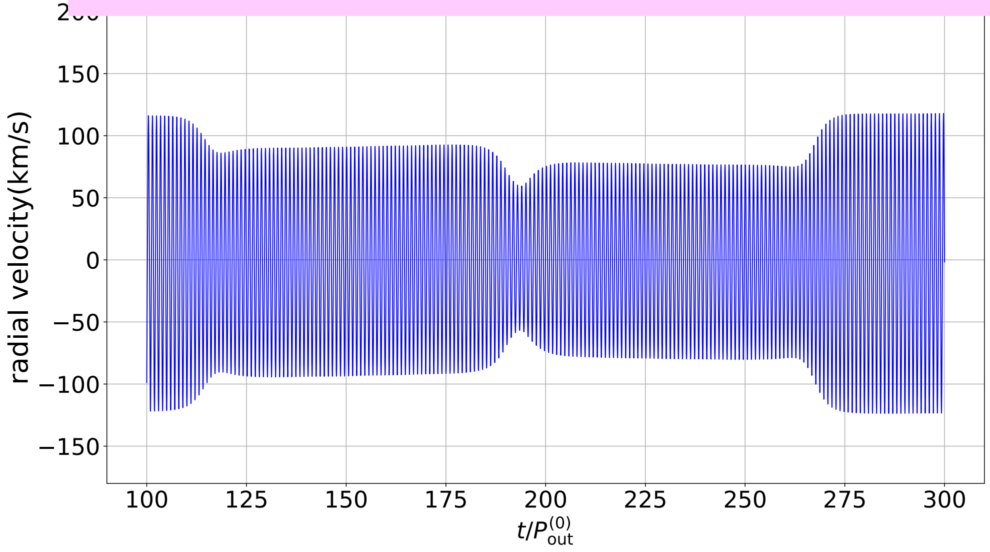


z

x-direction (near edge-on) total RV



z-direction (near face-on) total RV



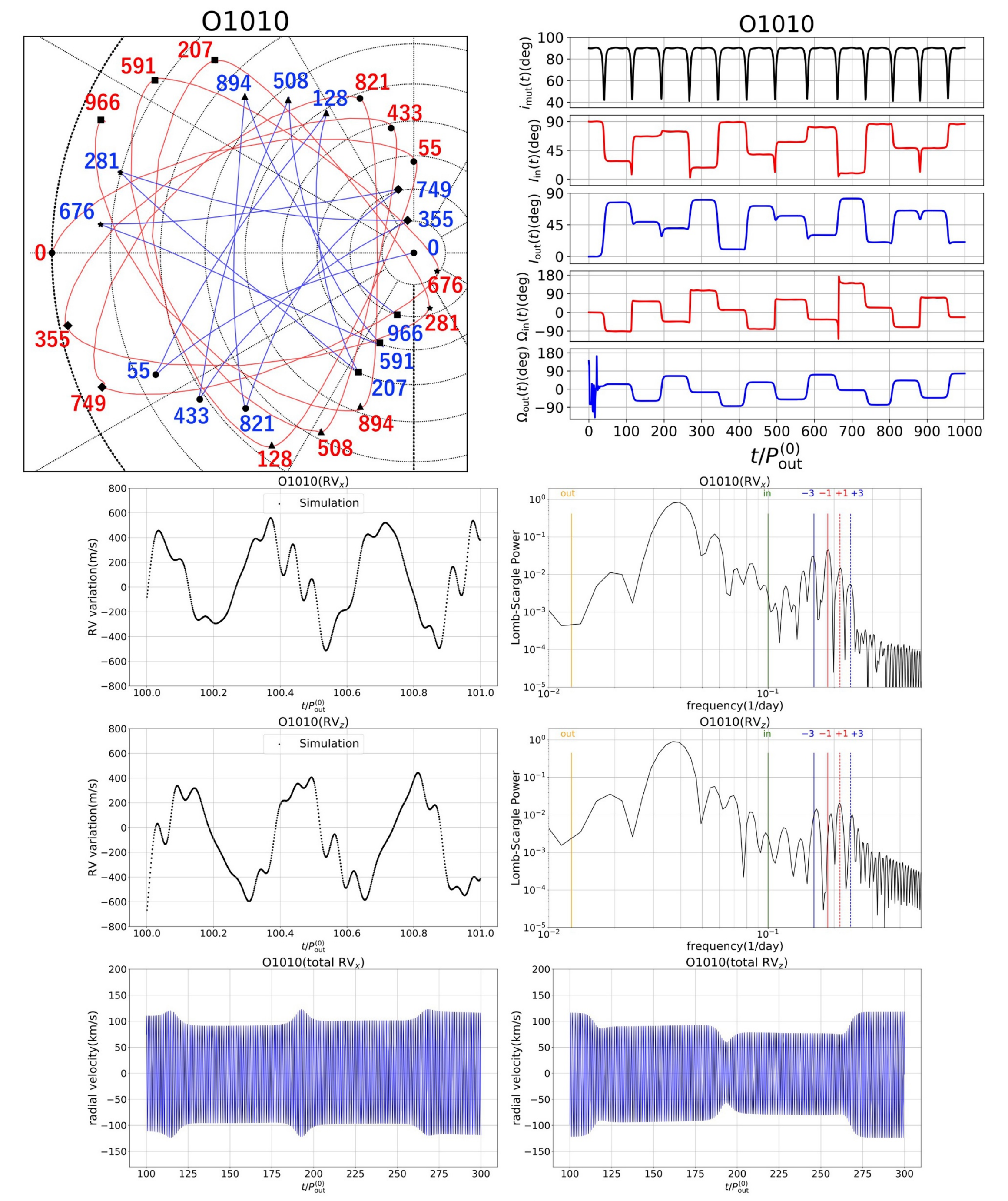
Orthogonal equal-mass binary

Precession timescale

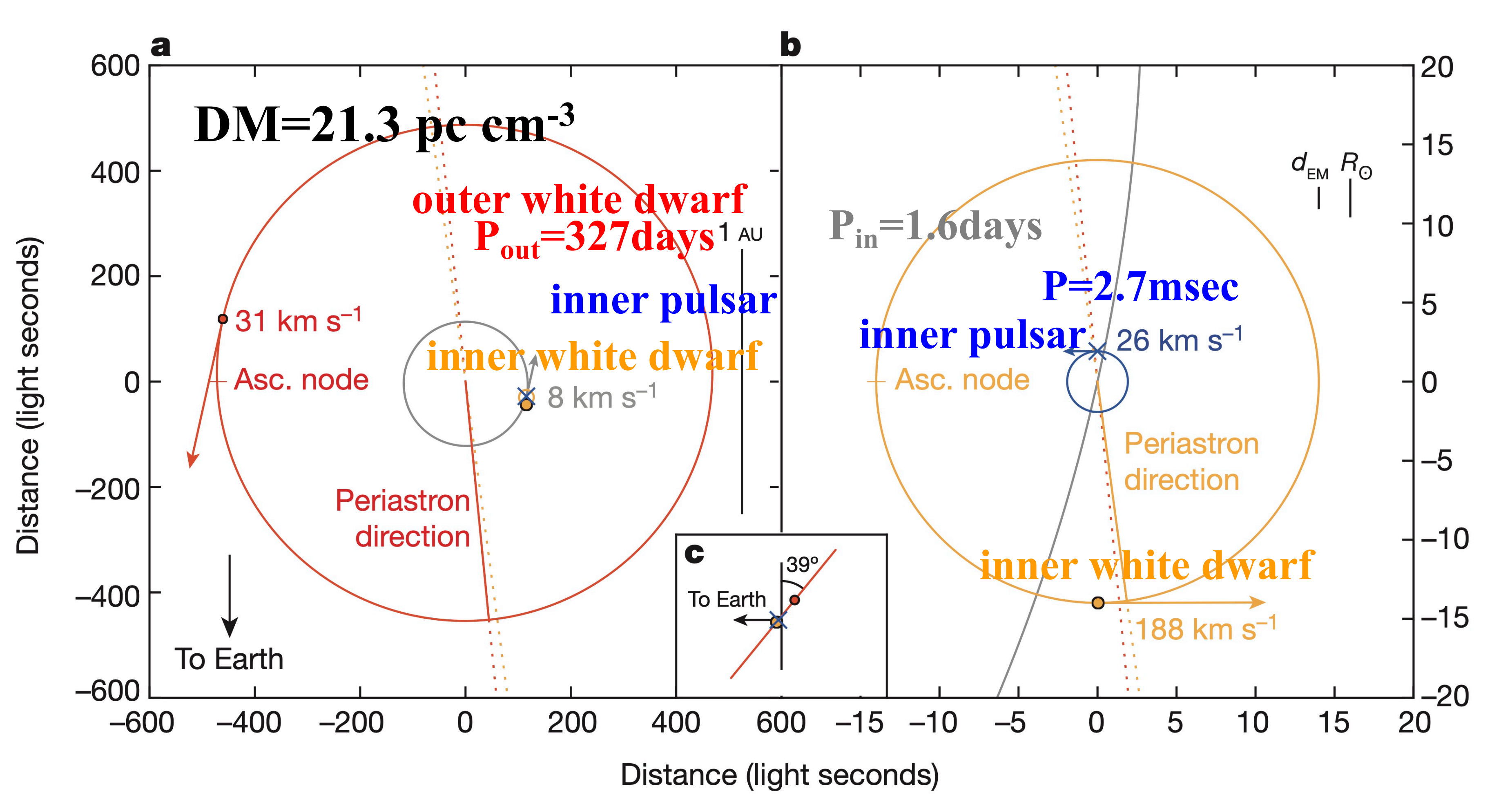
$$\frac{P_\Omega}{P_{\rm out}} \approx \frac{80.7}{\cos i_{\rm mut}}\left(\frac{m_1+m_2+m_*}{23\,M_\odot}\right)\left(\frac{m_*}{3\,M_\odot}\right)^{-1} \times \left(\frac{P_{\rm out}}{78.9\ {\rm days}}\right)\left(\frac{P_{\rm in}}{10.0\ {\rm days}}\right)^{-1}$$

Kozai-Lidov timescale

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

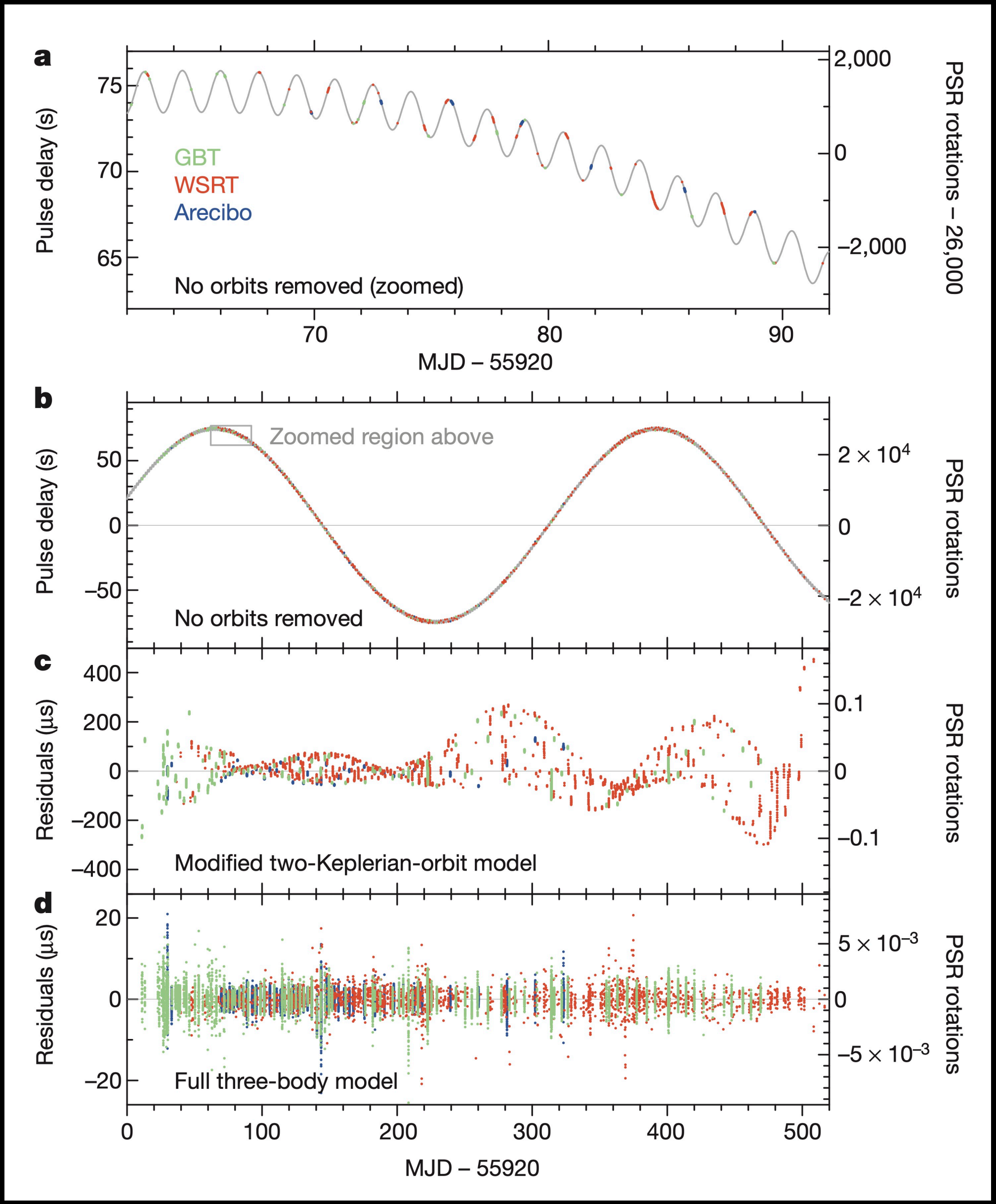


PSR J0337+1715: a hierarchical triple comprising an inner compact WD+pulsar binary



Ransom et al. Nature 505 (2014) 520

PSR J0337+1715: triple architecture revealed by pulsar timing analysis



PSR J0337+1715	
inner orbital period (pulsar+WD)	1.629401788(5) day
outer orbital period (WD)	327.257541(7) day
pulsar spin period	2.73258863244(9) msec
mutual orbital inclination	0.0120(17) deg.
Pulsar mass	1.4378(13) $M_\odot$
Inner WD mass	0.19751(15) $M_\odot$
Outer WD mass	0.4101(3) $M_\odot$

highly circular & coplanar !

Ransom et al. Nature 505 (2014) 520

Radial velocity vs. Pulsar arrival timing

- Radial velocity monitoring
  - High-resolution spectroscopy required for 10 m/s precision
  - Limited to targeted monitoring of nearby & bright stars
- Pulsar arrival timing analysis
  - Very precise measurement feasible
  - can survey almost the entire Galaxy
  - Systematic survey (Pulsar Timing Array) operating
- The fraction of triples with a tertiary star (RV) or a tertiary pulsar is largely unknown, and therefore they are complementary. It is worthwhile to explore simultaneously

Pulsar arrival time delays

- Unperturbed Rømer delay
  - due to the unperturbed Keplerian motion of a tertiary pulsar around the center of mass of the inner binary
- Relativistic delays
  - Einstein delay (gravitational redshift due to the eccentric orbit)
  - Shapiro delay (photon travel time change due to the space curvature)
- Perturbed Rømer delay modulation
  - due to perturbed Keplerian motion of a tertiary pulsar from the inner binary motion

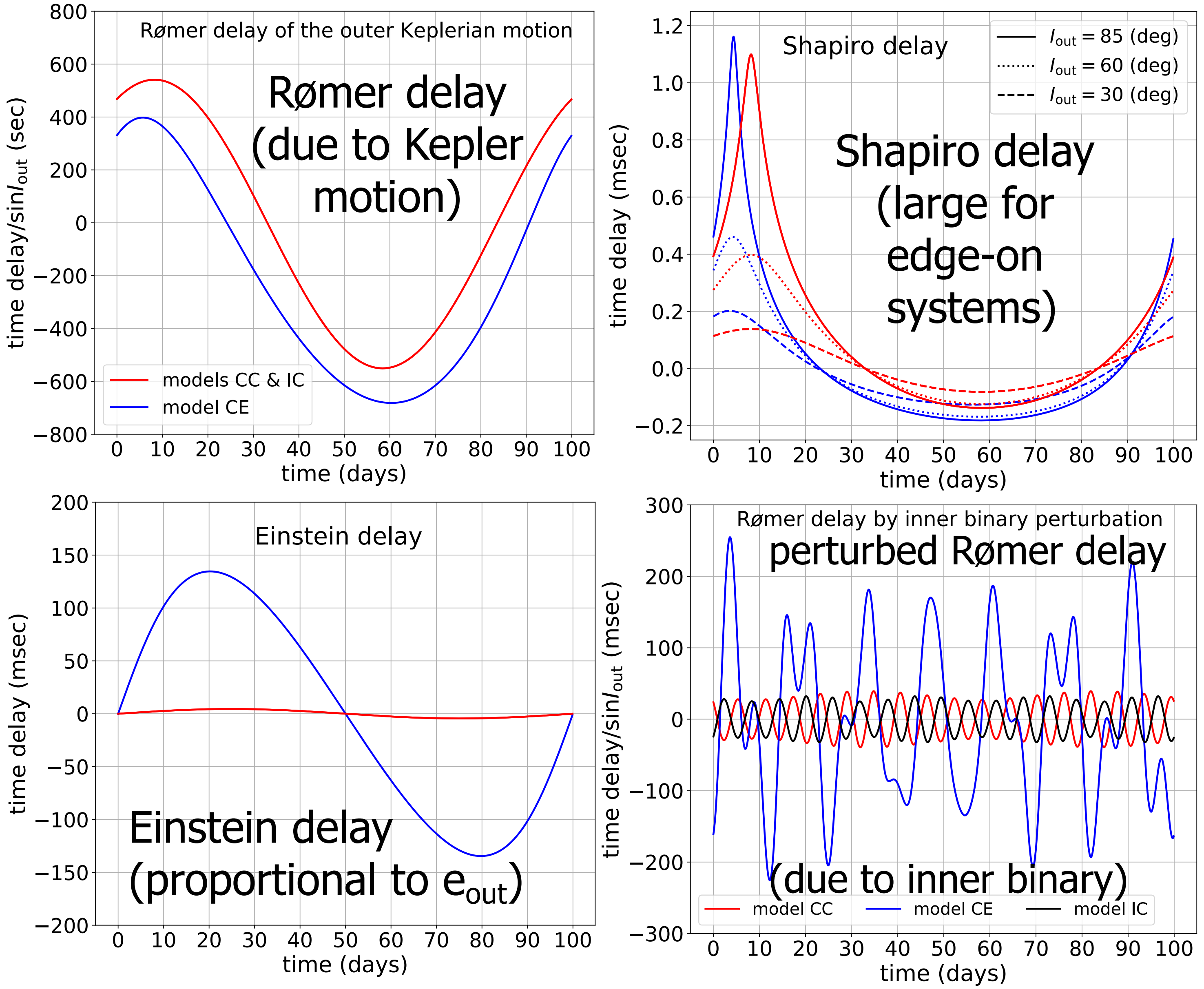
Examples of pulsar arrival timing curves for triples

Based on analytic expressions
by Backer & Hellings (1986)
and Morais & Correia 2008, 2011)

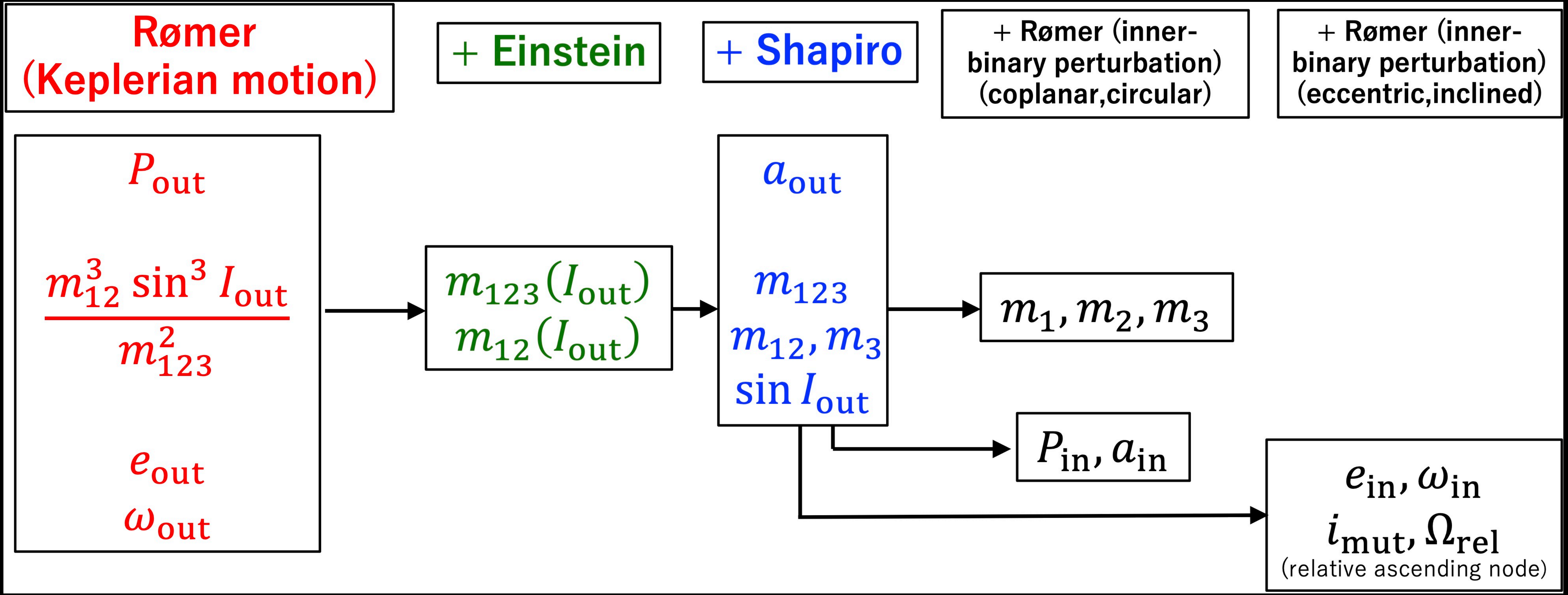
$$m_1 = m_2 = 10M_\odot$$
$$m_3 = 1.4M_\odot$$
$$P_{\rm out} = 100 \text{ days}$$
$$P_{\rm in} = 10 \text{ days}$$

- **Model CC (Coplanar Circular)**
  - $e_{out} = 0.01,\ e_{in} = 0.0,\ i_{mut} = 0°$
- **Model CE (Coplanar Eccentric)**
  - $e_{out} = 0.3,\ e_{in} = 0.02,\ i_{mut} = 0°$
- **Model IC (Inclined Circular)**
  - $e_{out} = 0.01,\ e_{in} = 0.0,\ i_{mut} = 45°$

Hayashi & YS (2020, submitted)



Unveiling the triple system parameters from the pulsar arrival timing analysis

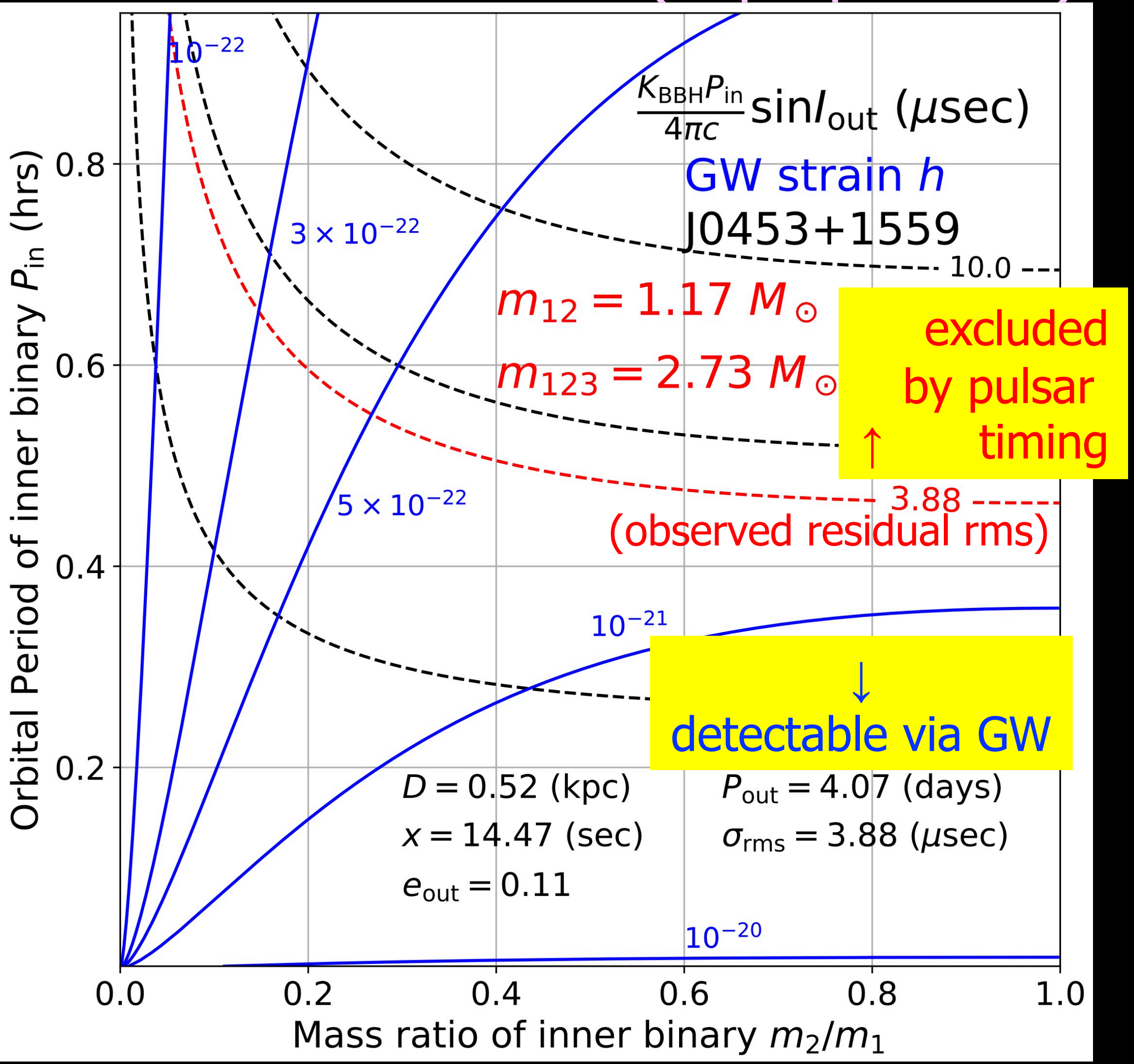


Hayashi & YS (2020, submitted)

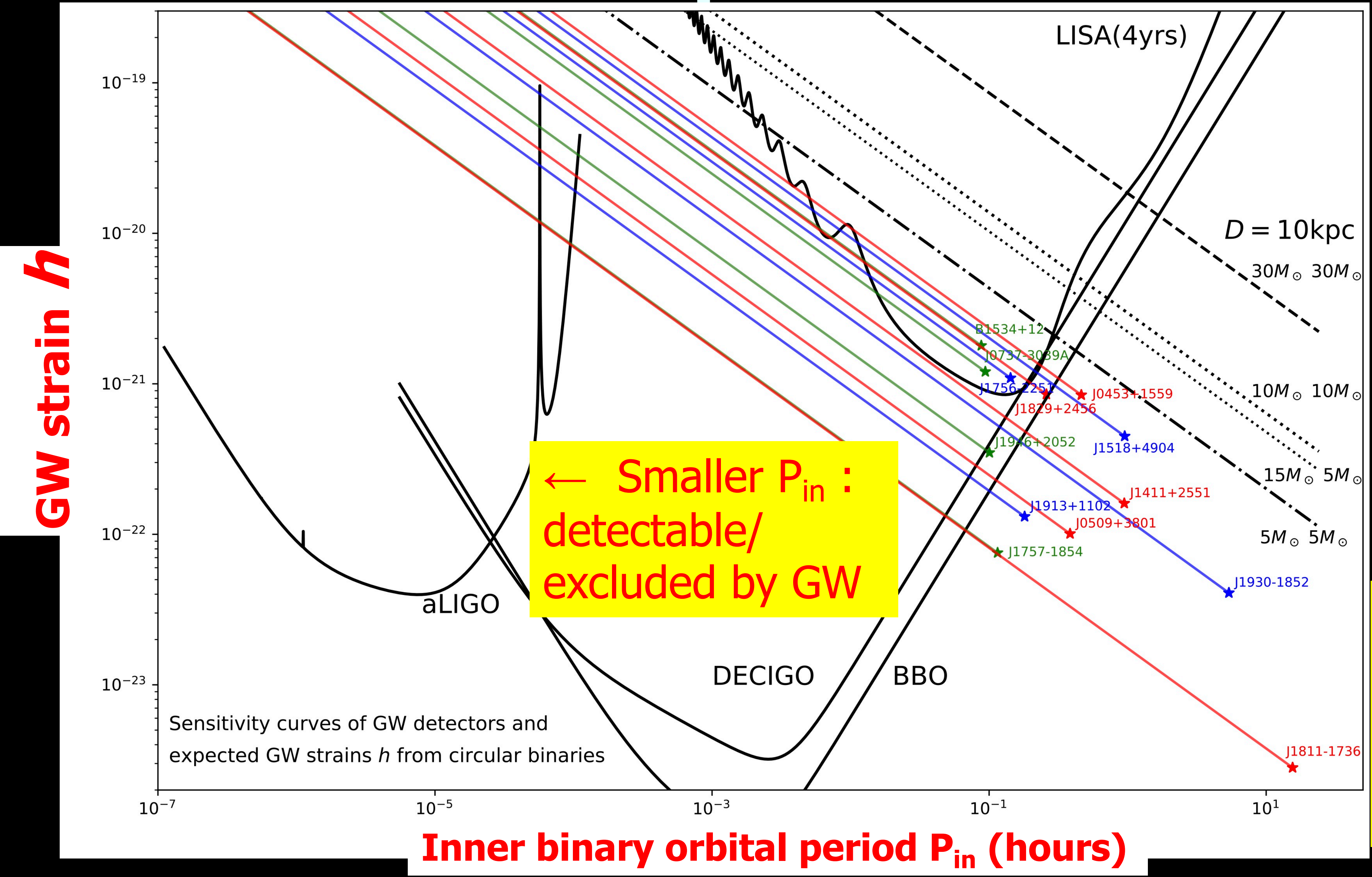
Proof-of-concept using known NS binaries

Kumamoto, Hayashi, Takahashi & YS (in preparation)

- No candidate for a pulsar-BH binary yet
- Consider known NS binaries as a proof-of-concept of our methodology
  - Given P_{out} , a large value of P_{in} is excluded by the dynamical stability of a possible inner binary in a triple system
  - A small value of P_{in} does not generate a detectable Rømer delay modulation (the inner binary is indistinguishable from a single object)
  - Such inner binaries, however, emit gravitational wave that is detectable with future instruments including LISA and DECIGO



Constraints and predictions for NS binaries

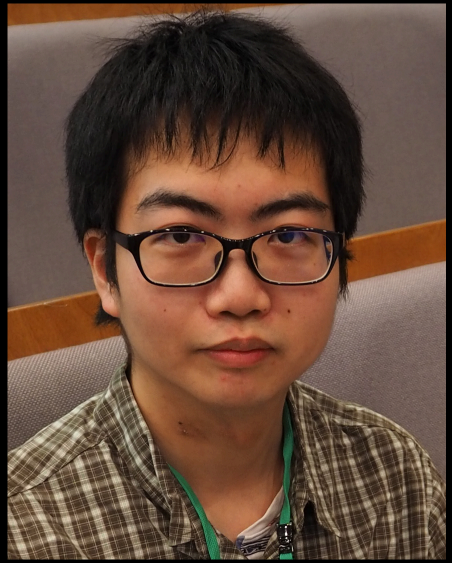


Circular and equal-mass inner binaries assumed

⇒ Larger P_{in} :
detectable/
excluded
by pulsar timing

Conclusions

Everything not forbidden by the laws of nature is mandatory *— Carl Sagan "Contact"*



- **Methodologies to search for wide-separation binary BHs** (likely but hidden progenitors of binary BHs detected by LIGO)
  - **Radial velocity of tertiary stars**: nearby star-BH system if detected from Gaia and/or TESS surveys
  - **Arrival timing of tertiary pulsars**: (even more distant) pulsar—BH systems if detected from future pulsar surveys