Searching for an inner binary black-hole in a triple system

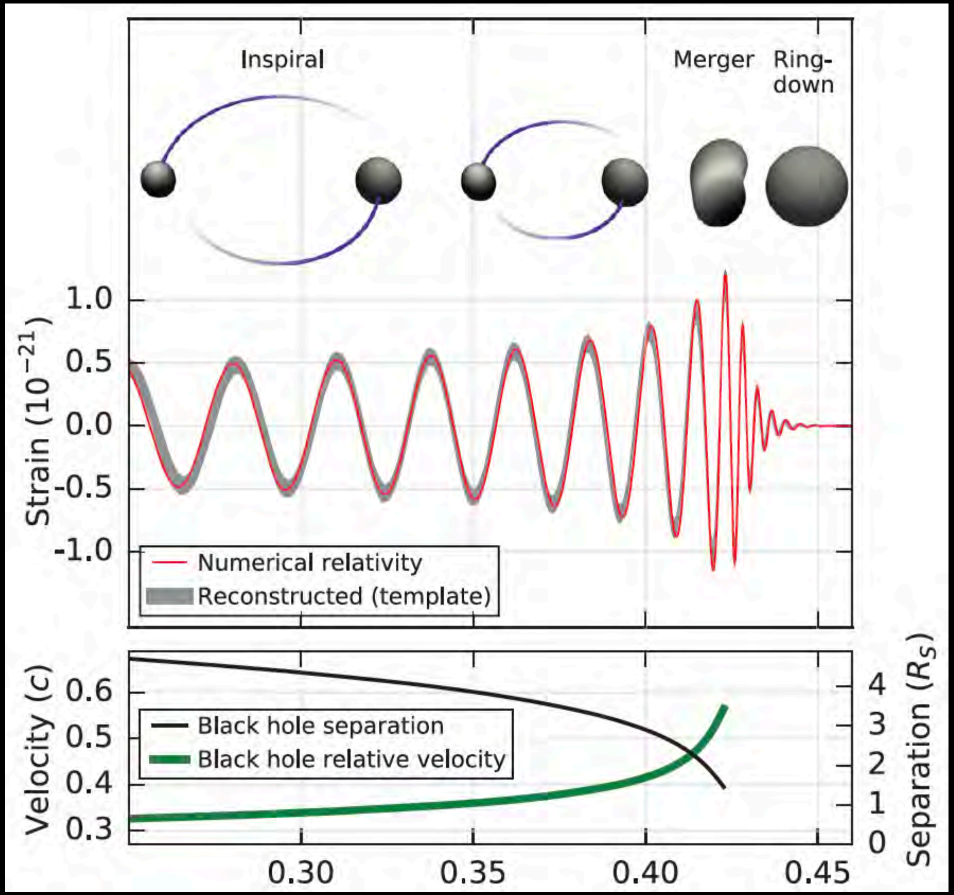
Alpha Centauri was a triple system, two suns tightly orbiting one another, and a third, more remote, circling them both. What would it be like to live on a world with three suns in the sky?

— Carl Sagan, "Contact"

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

Colloquium at Physics Department, Kyoto University
@16:00-17:30, October 29, 2020

Binary black-holes in the universe



First detection of BBHs
via gravitational wave (GW)
Abbot+(LIGO team) 2016

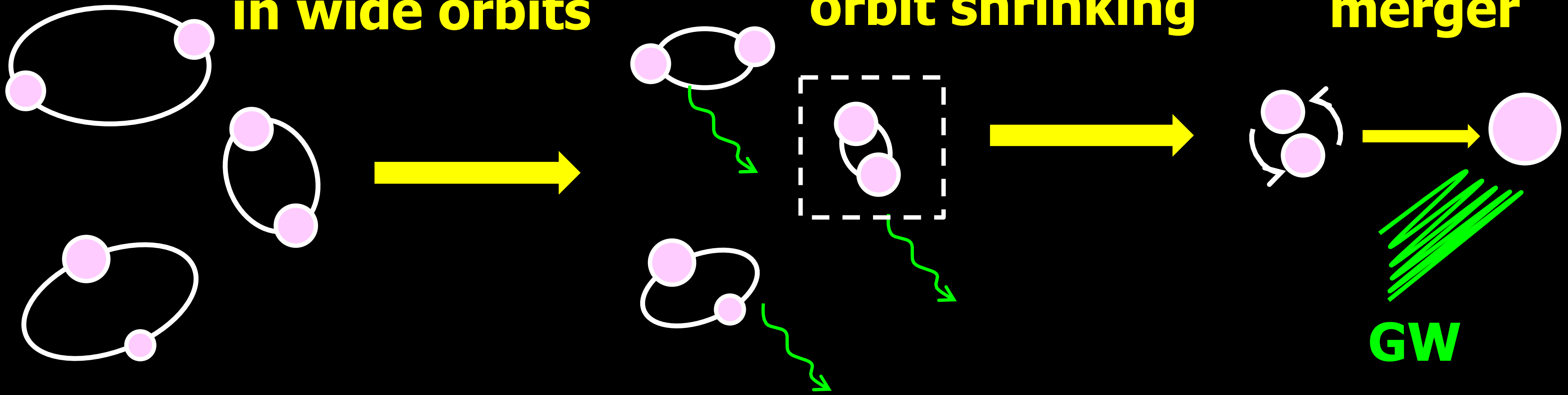
- **Origin of BBHs ?**
  - isolated binary (e.g., Kinugawa+2014)
  - dynamical capture (e.g., Rodriguez+2016)
  - primordial BHs (e.g., Sasaki+2016)
- **Where are their progenitors, probably with much longer orbital periods ?**

Generic picture of binary BH evolution

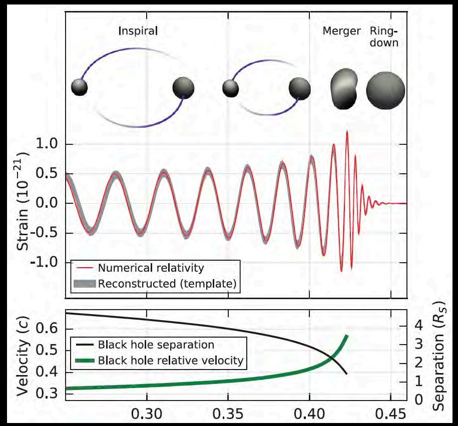
binary black holes form in wide orbits

orbit shrinking

merger



GW



LIGO/Virgo

weak GW(low-frequency)

BBHs would spend longer time in wide orbits before merging

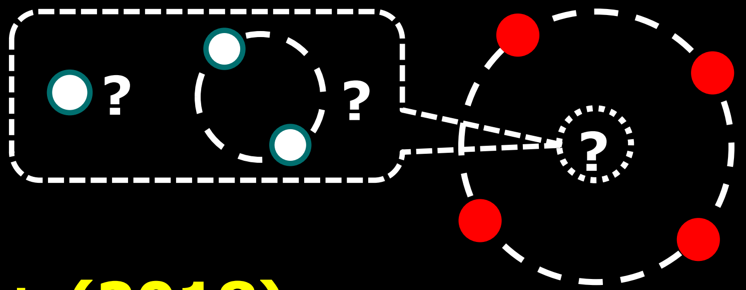
Abundant longer orbital-period BBHs may remain undetected (e.g. ~10day orbital period~10^{-6}Hz).

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)

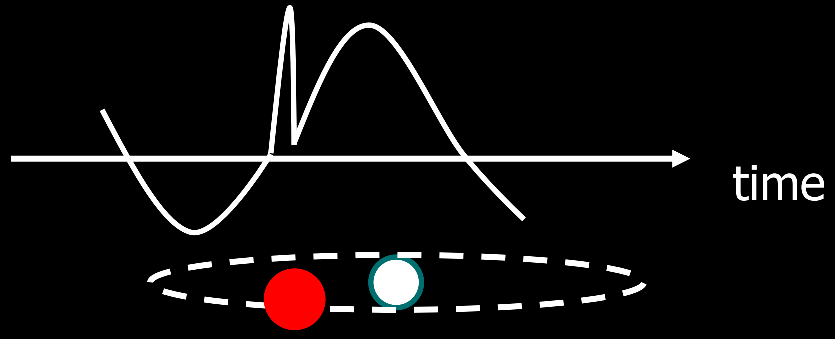
5-year mission may detect
200-1000 star-BH binaries

TESS mission (2018-)

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

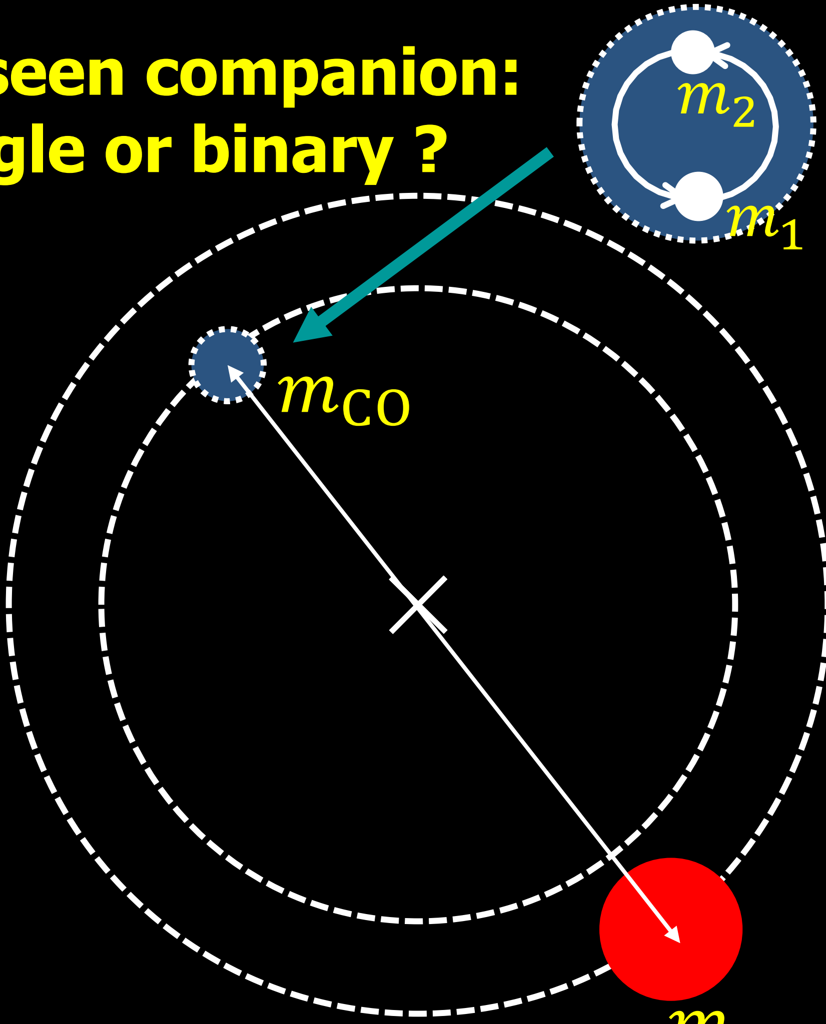
Masuda & Hotokezaka (2019)

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?

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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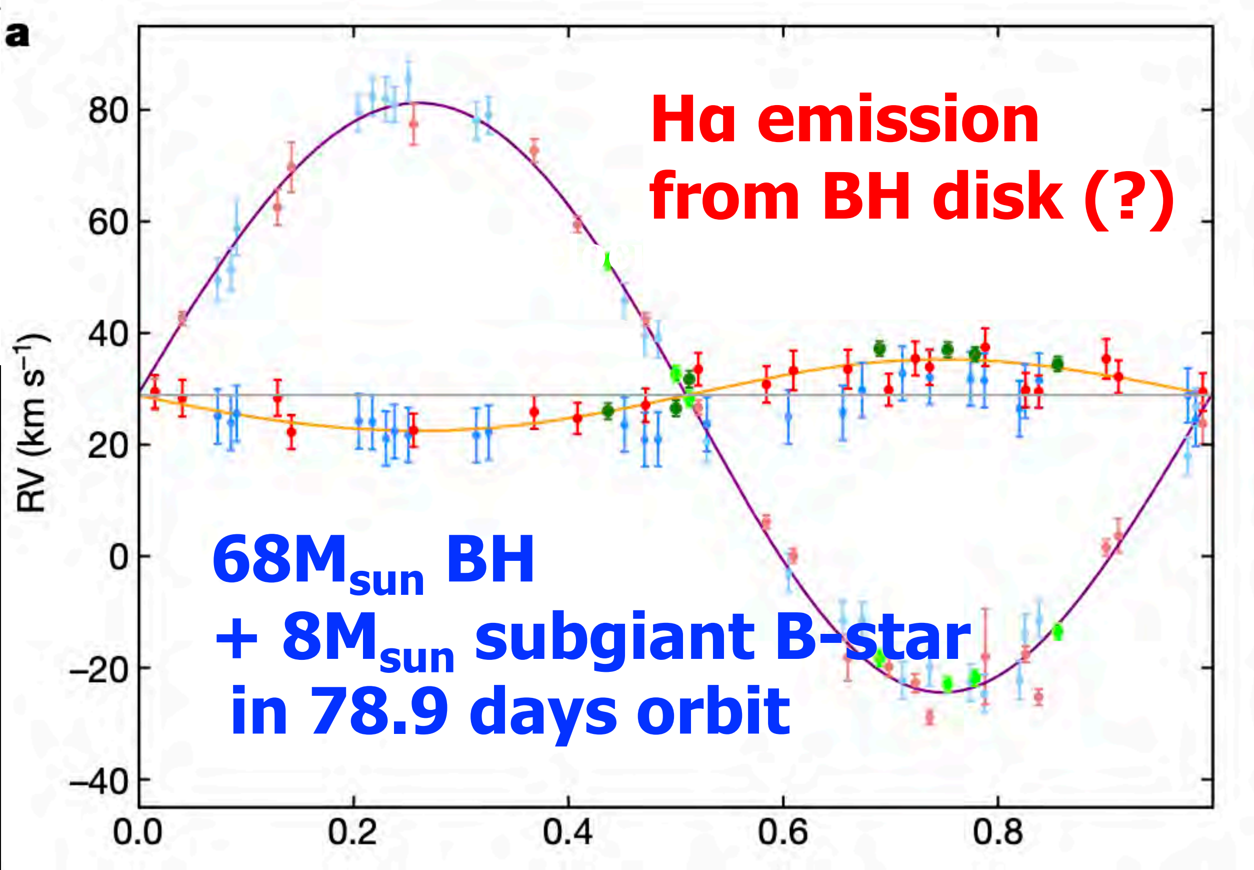
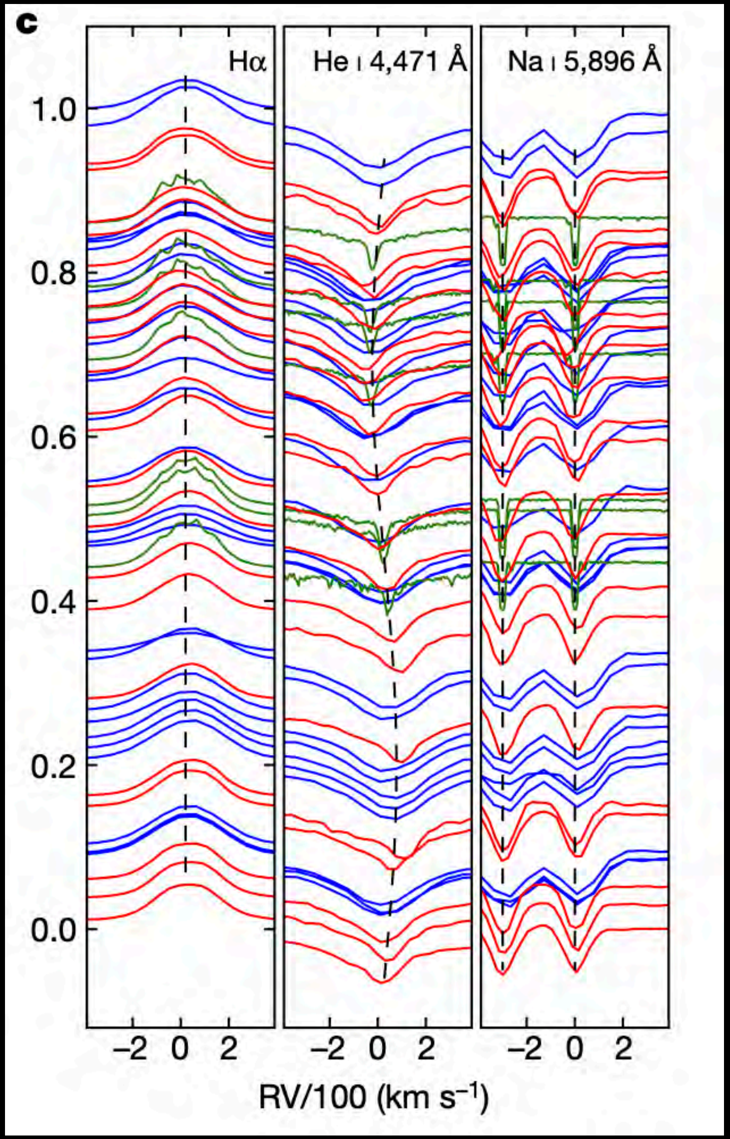
Published online: 27 November 2019





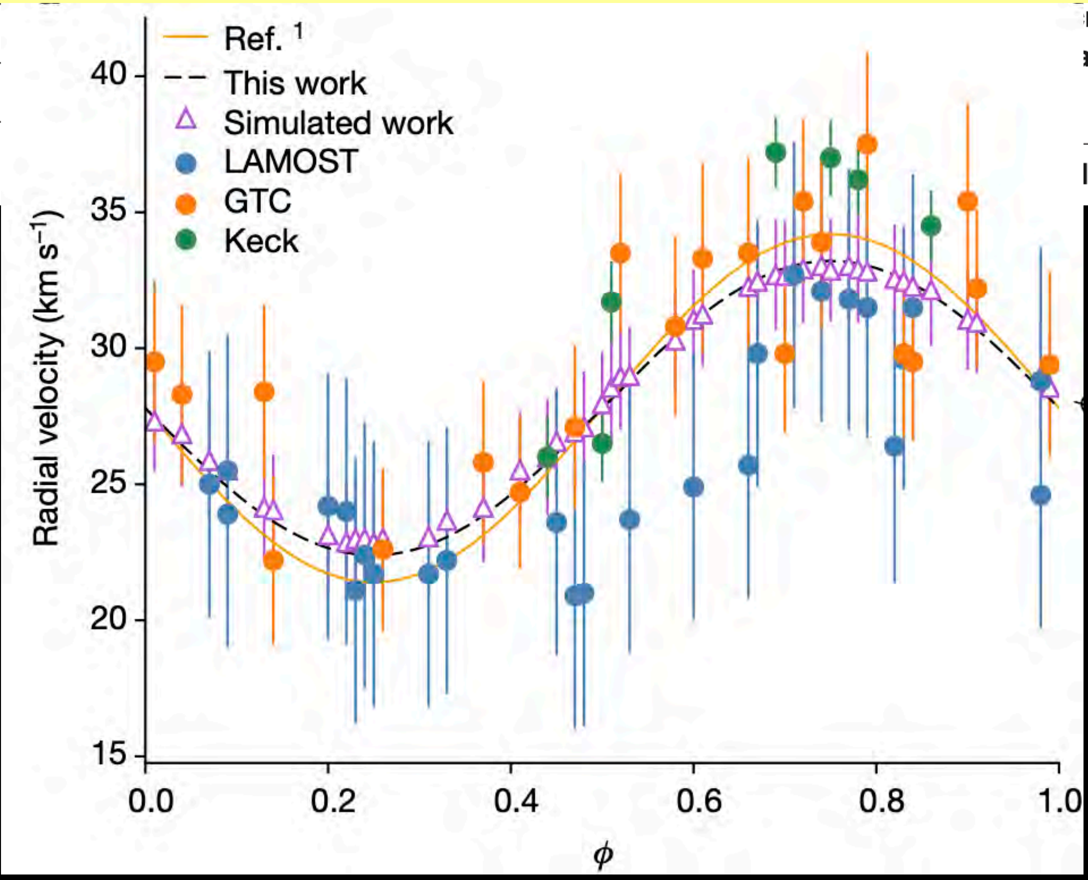
Matters arising

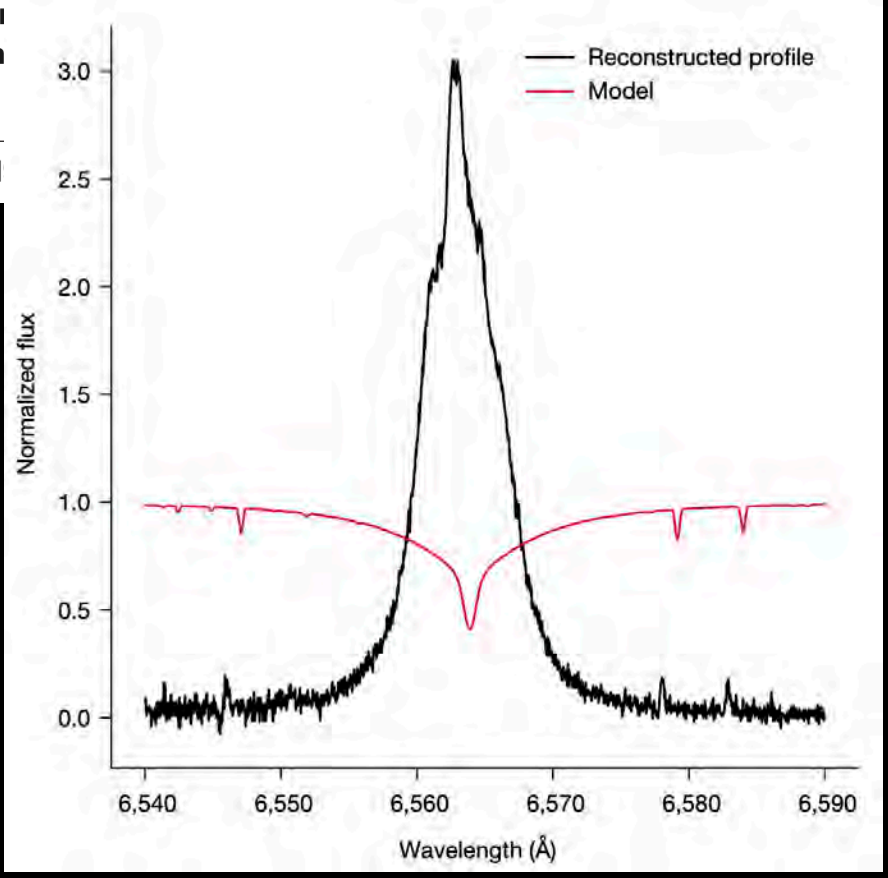
On the signature of a 70-solar-mass black hole in LB-1

Abdul-Masih et al. Nature 580(2020) E11

Hα emission is not from BH disk, but a static Hα + B-star absorption
The unseen companion should be much less massive ($<10M_{sun}$)

Received: 6 December 2019
Accepted: 27 February 2020
Published online: 29 April 2020





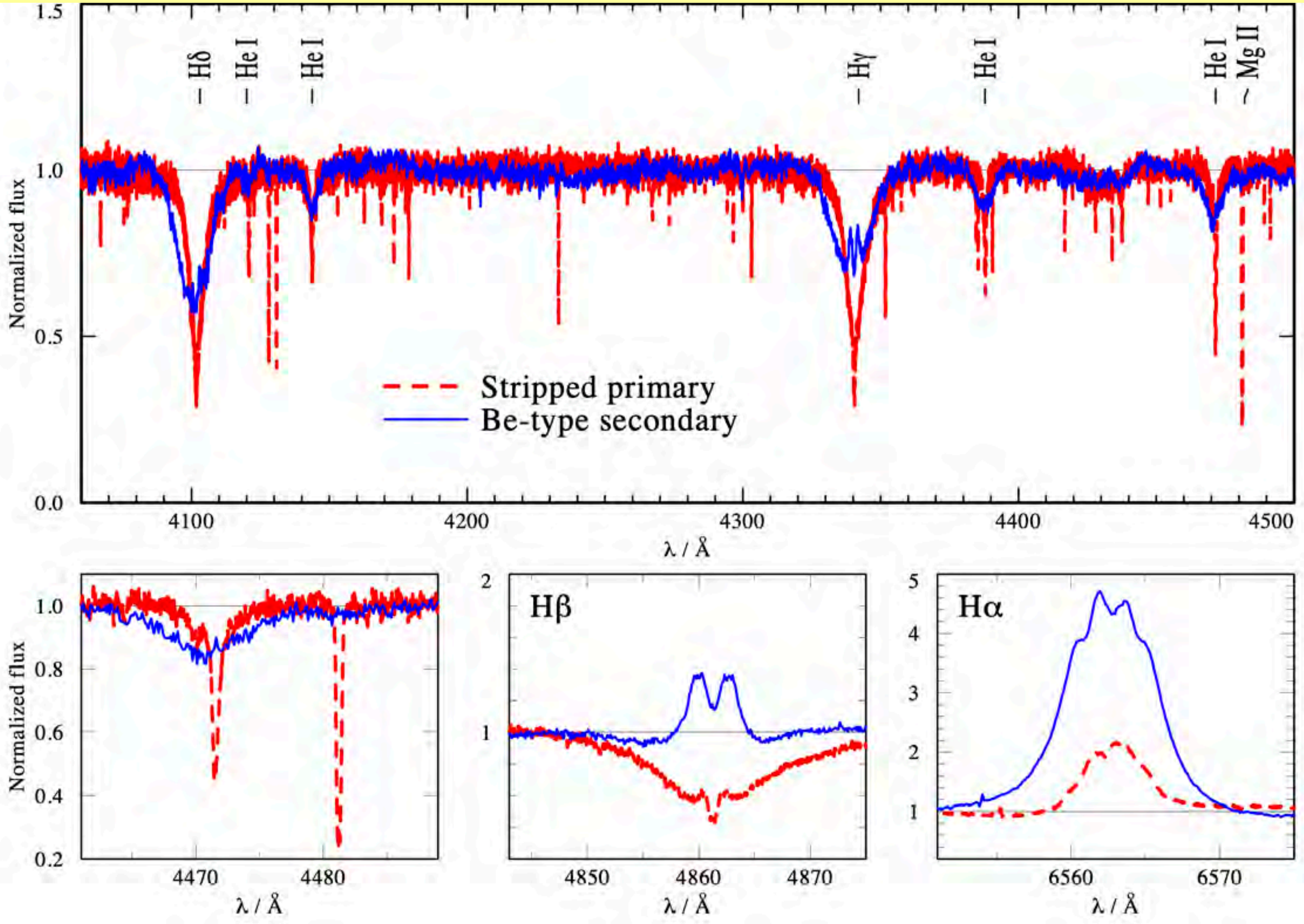
The hidden companion in LB-1 unveiled by spectral disentangling

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

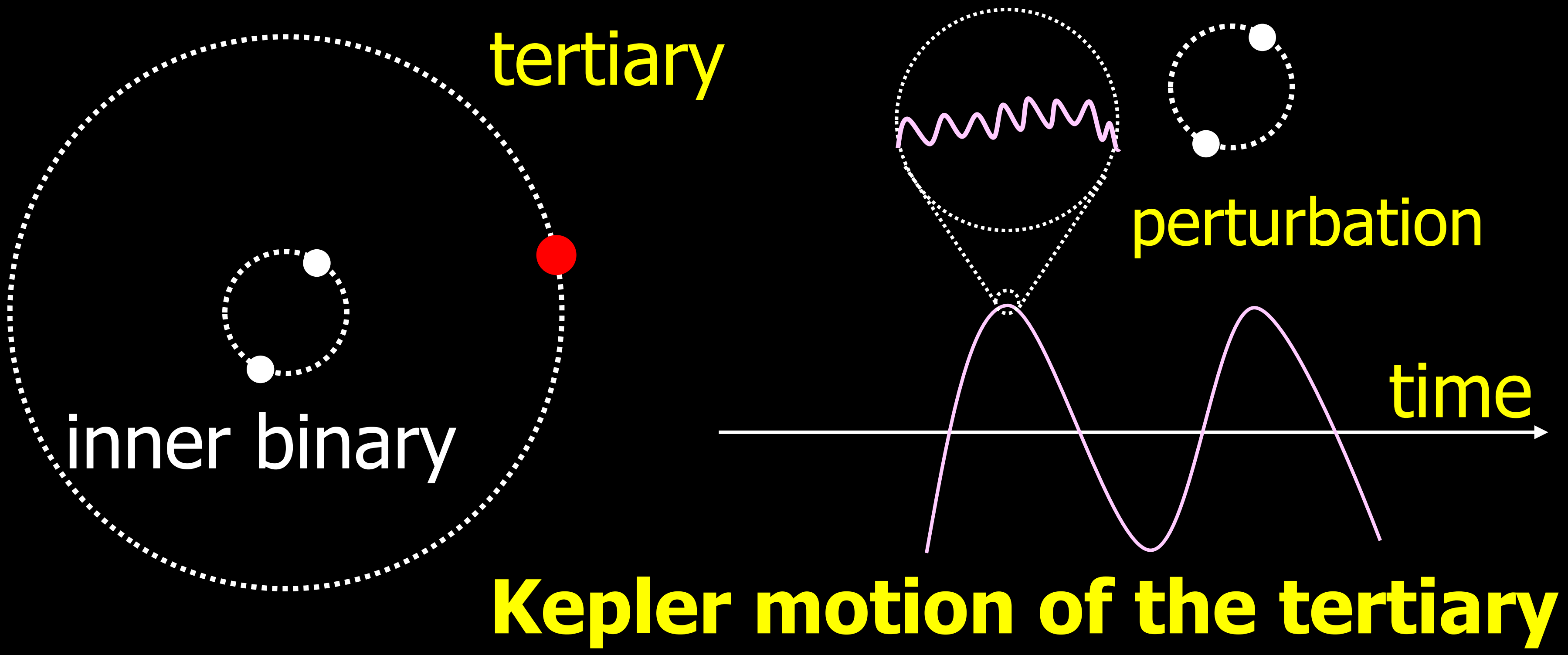
Disentangled the spectra of LB-1 and found that LB-1 comprises a stripped He-rich star (1.5±0.4 M_{sun}) + a Be-type secondary star (7±2 M_{sun}) , not a BH

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 !



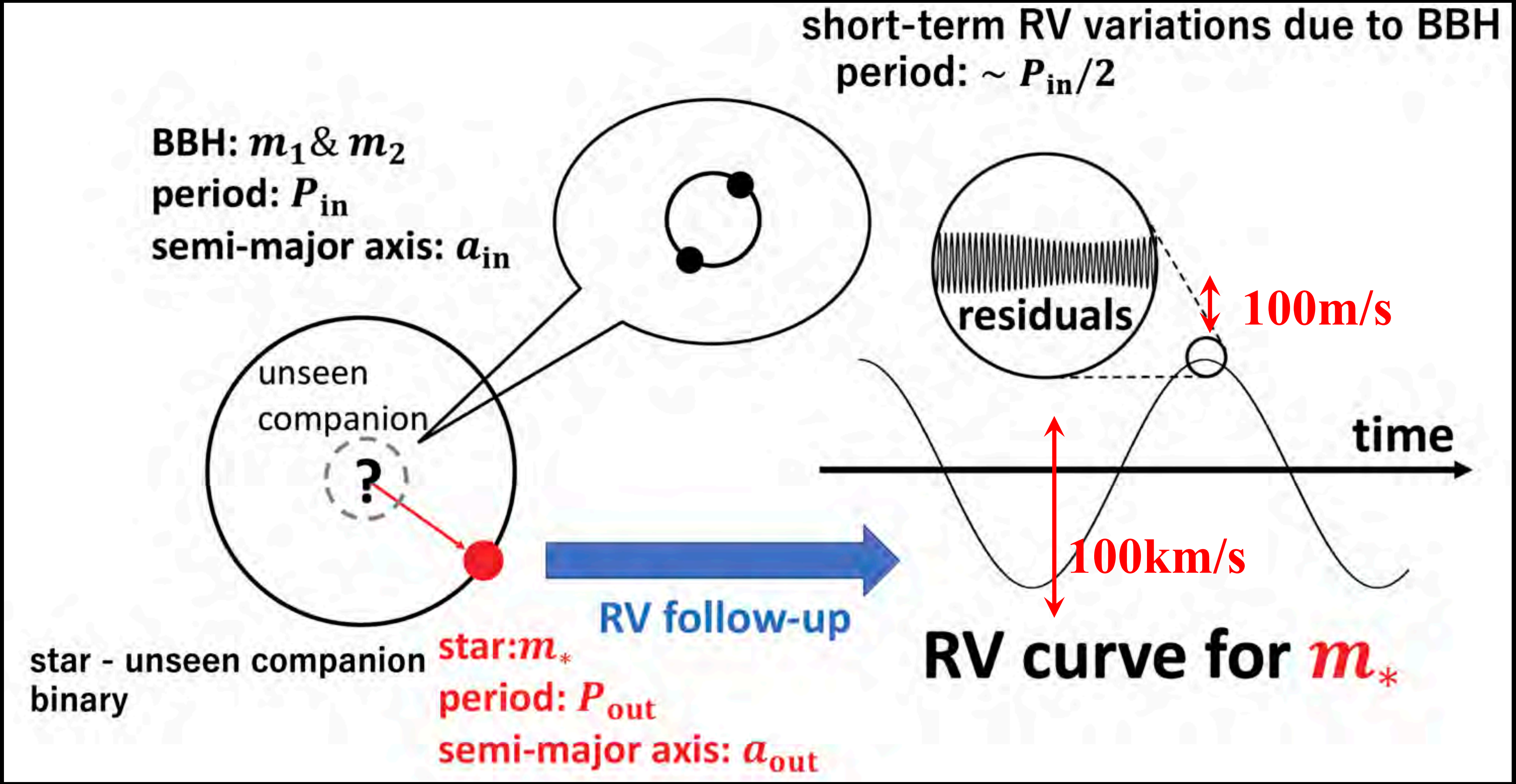
Radial velocity modulation of a tertiary star due to an inner binary



Toshinori Hayashi
林利憲

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

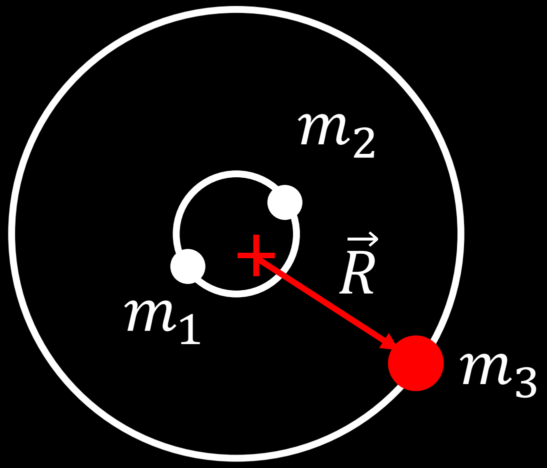
Triple=black hole binary + outer tertiary star



Coplanar systems: Hayashi, Wang & YS 2020, ApJ 890, 112

Non-coplanar systems: Hayashi & YS 2020, ApJ, 897, 29

RV modulations for coplanar triples

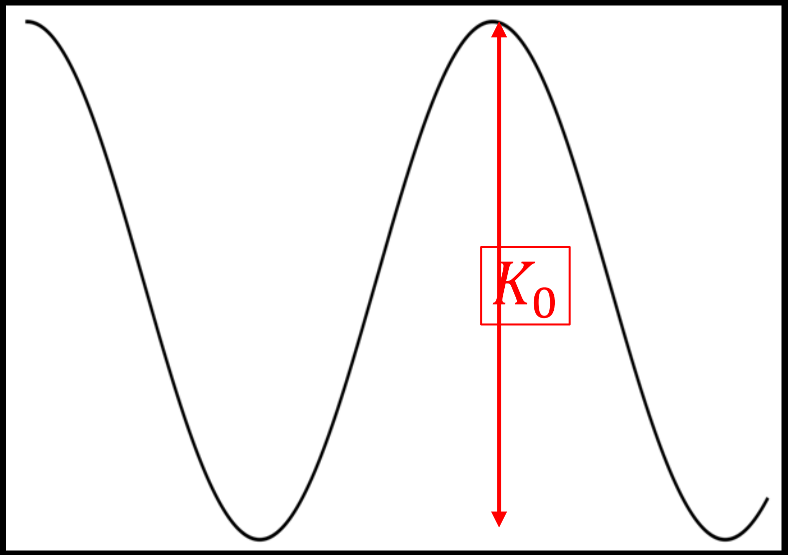


$$\mathcal{H} = \mathcal{H}_{\mathrm{Kep}} - \mathcal{R}$$

Perturbation theory

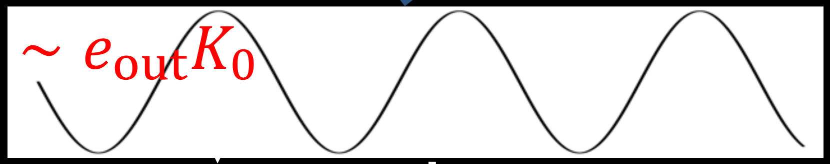
$$\left(\sqrt{\frac{m_1}{m_2}}+\sqrt{\frac{m_2}{m_1}}\right)^{-2}\left(\frac{a_{\mathrm{in}}}{a_{\mathrm{out}}}\right)^{3.5} K_0$$

$\mathrm{RV} =$



period: P_{out}

$+$



period: $P_{out}/2$

first order in e_{out}

$+$

period: $P_{in}/2$

inner binary

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

$$\delta V_{\rm Kep}(t) = K_1 \sin I_{\rm out} \cos[\nu_{\rm out} t + f_{\rm out,0} + \omega_{\rm out}],$$

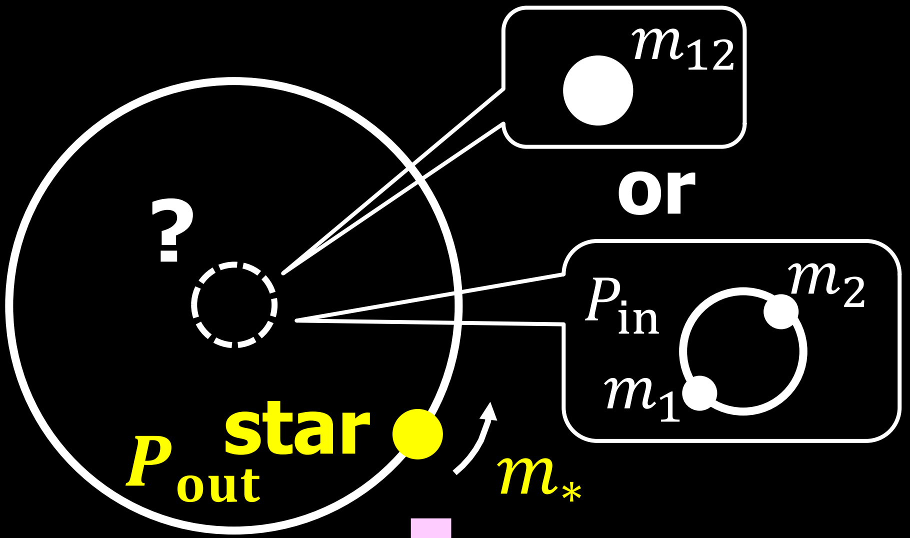
$$K_1 \equiv \frac{3}{4} K_0 \left(\frac{a_{\rm in}}{a_{\rm out}}\right)^2 \frac{m_1 m_2}{(m_1 + m_2)^2}.$$

(iii) Modulation by the inner binary

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

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

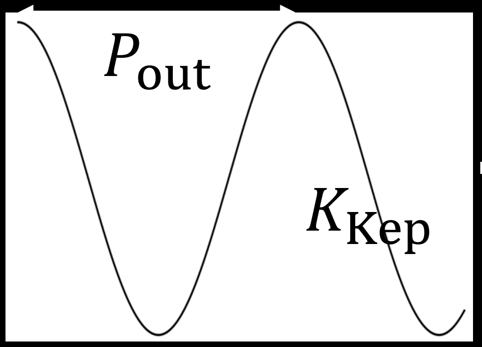
RV modulations for non-coplanar triples



high-precision RV follow-up

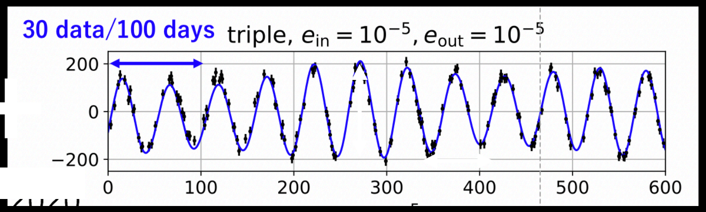
Keplerian motion RV
+ RV variations by inner binary

(i) Coplanar triple



Kepler motion

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



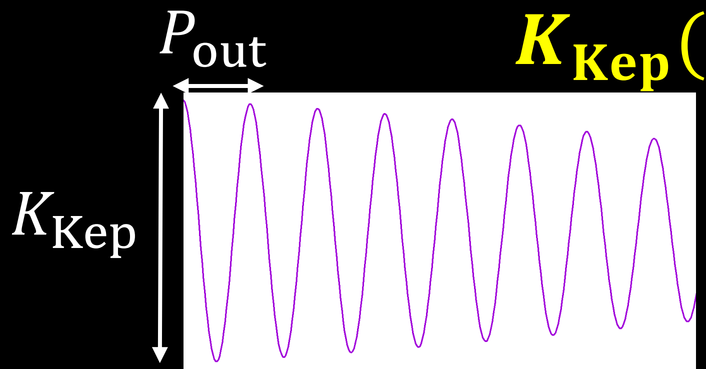
$$\mathrm{Period} \sim P_{\mathrm{in}}/2$$

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

(ii) Non-coplanar triple

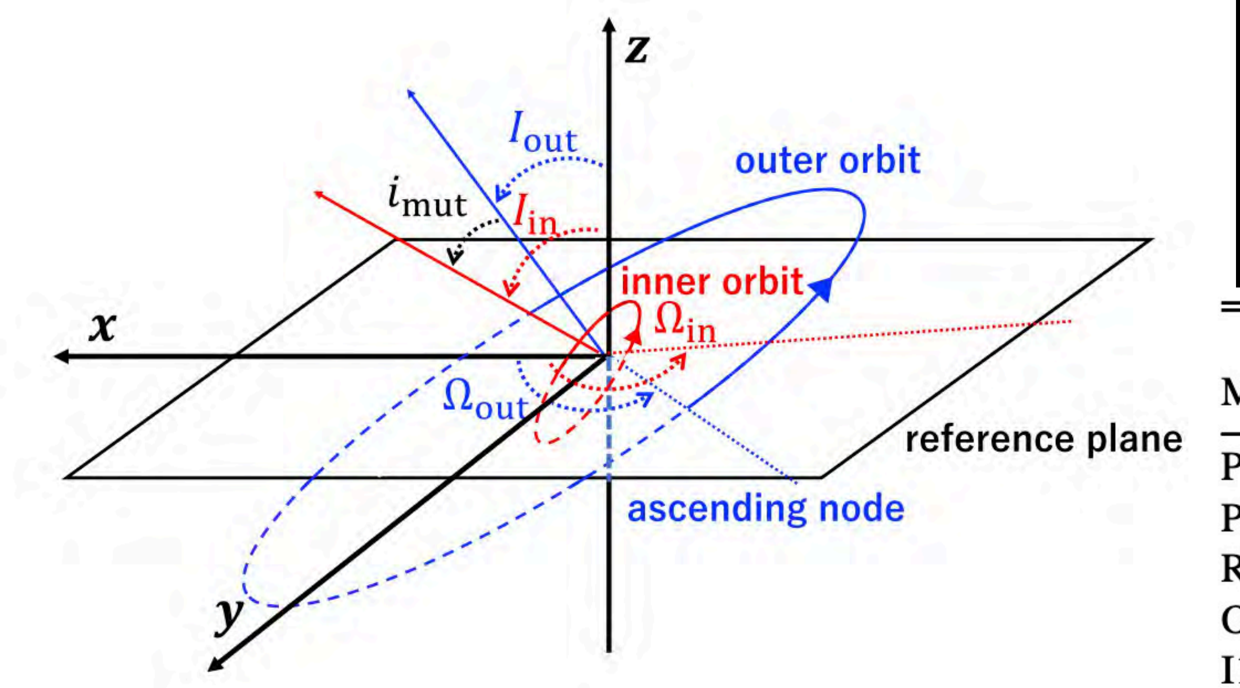
Inclination $I_{out}(t)$ modulated in the Kozai-Lidov timescale

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



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

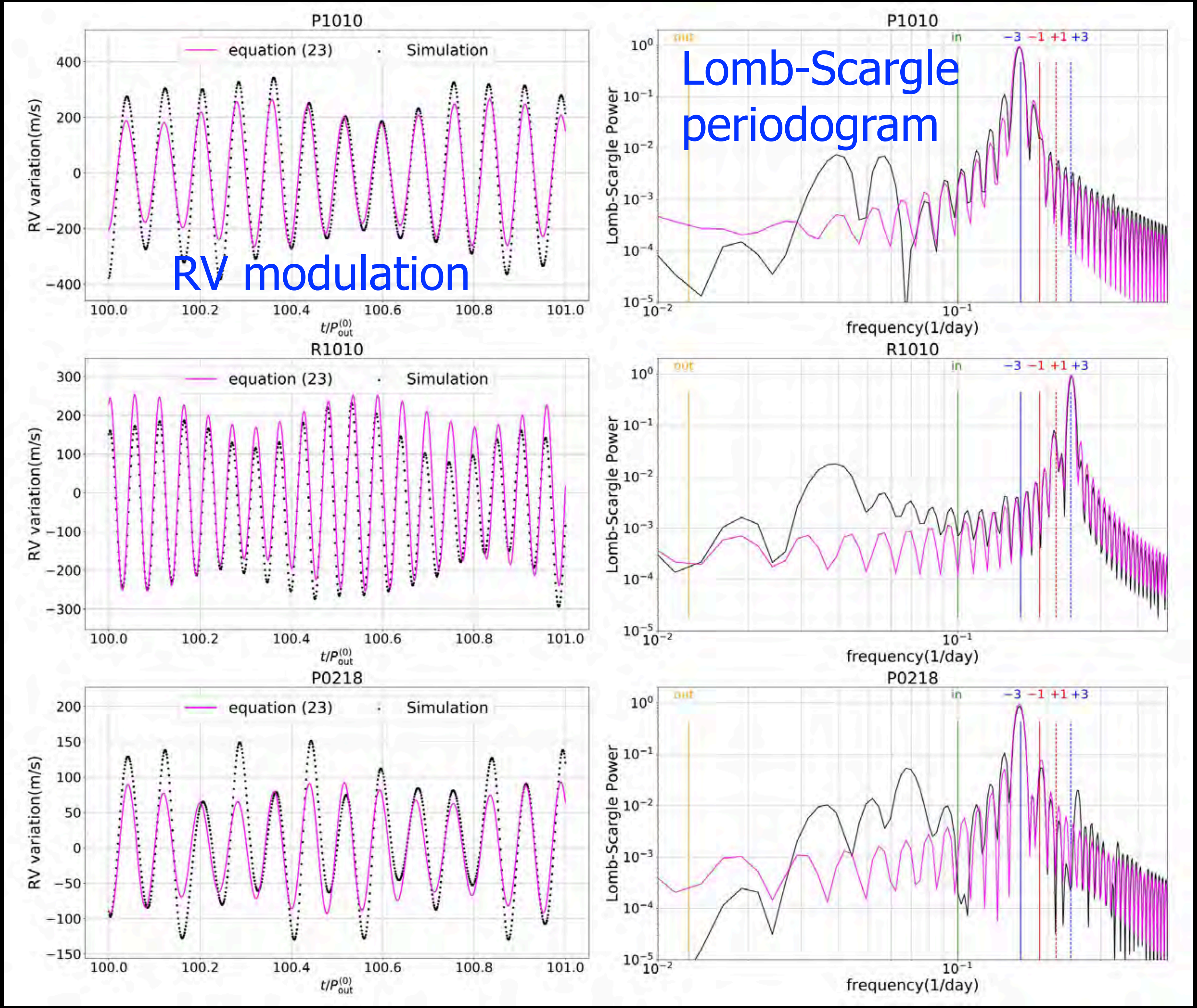
Prograde equal-mass

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

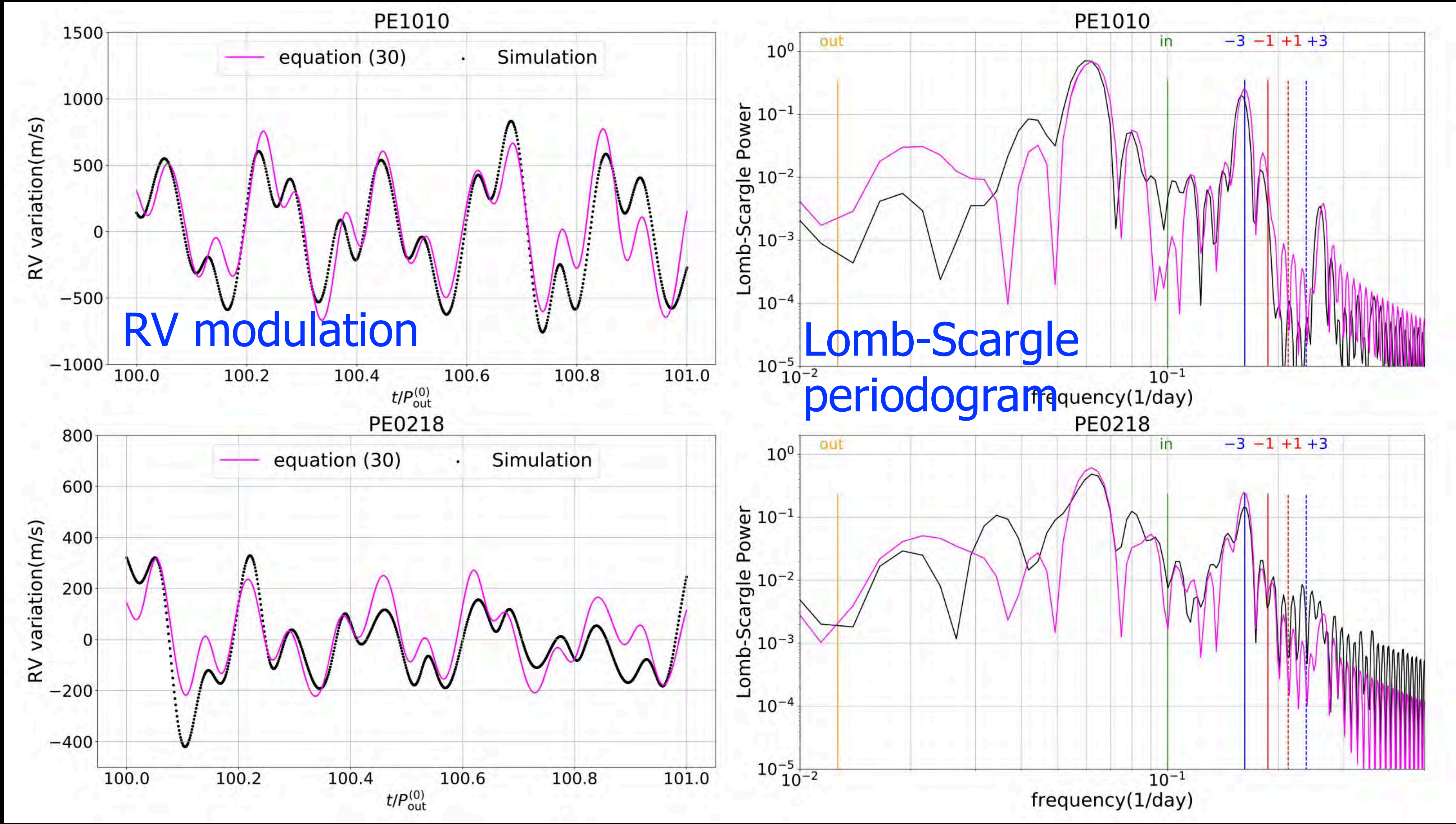


Coplanar eccentric triples

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

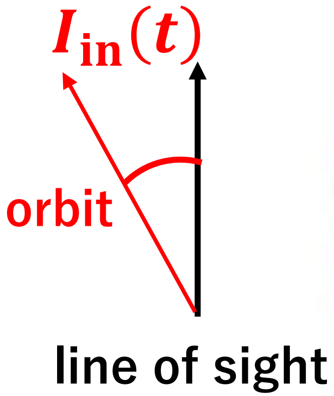
Prograde
equal-mass

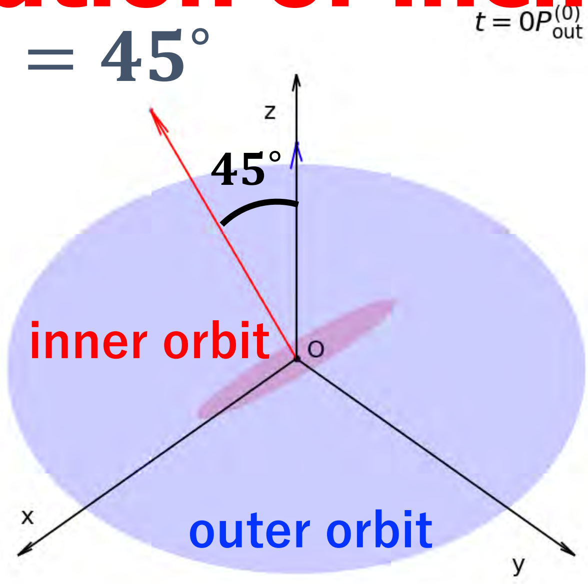
Prograde
unequal-mass



Evolution of inclination for non-coplanar triples

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



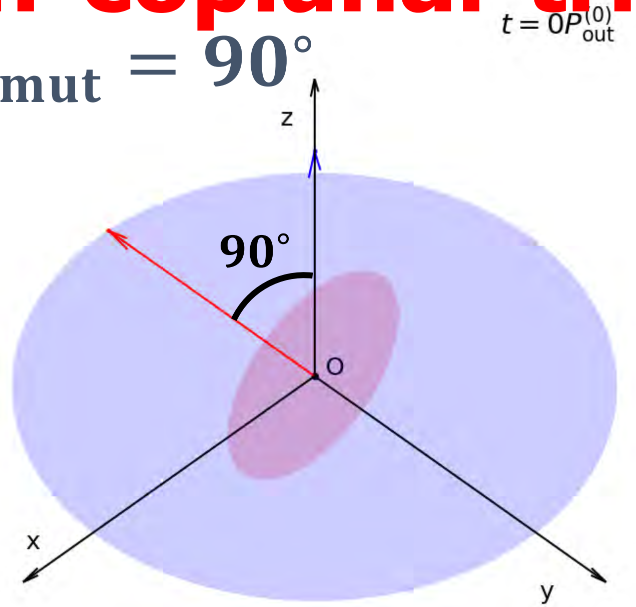


$P_{\rm out} = 78.9$ days
$P_{\rm in} = 10$ days

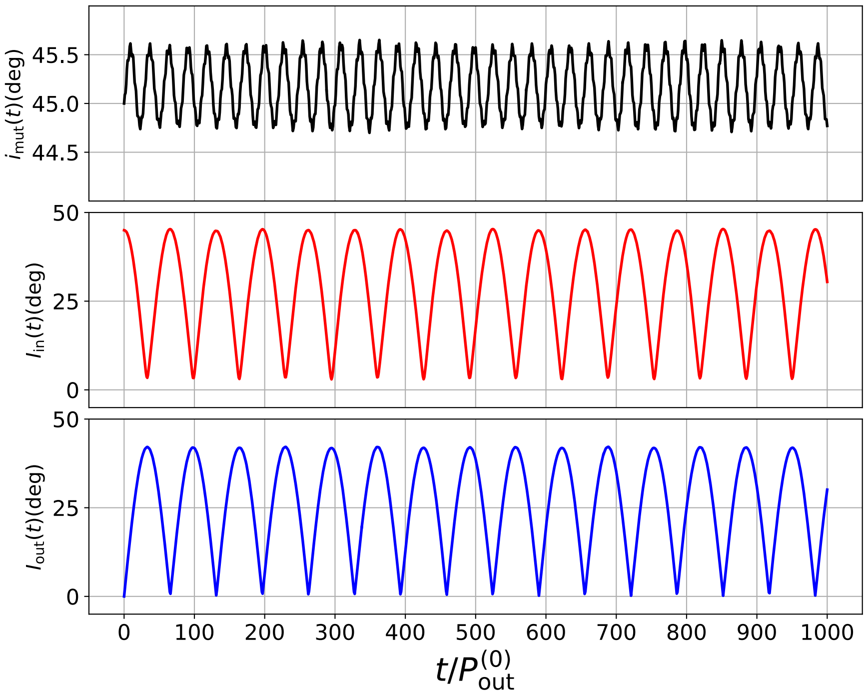
$m_1 = m_2 = 10M_\odot$
$m_* = 3M_\odot$

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

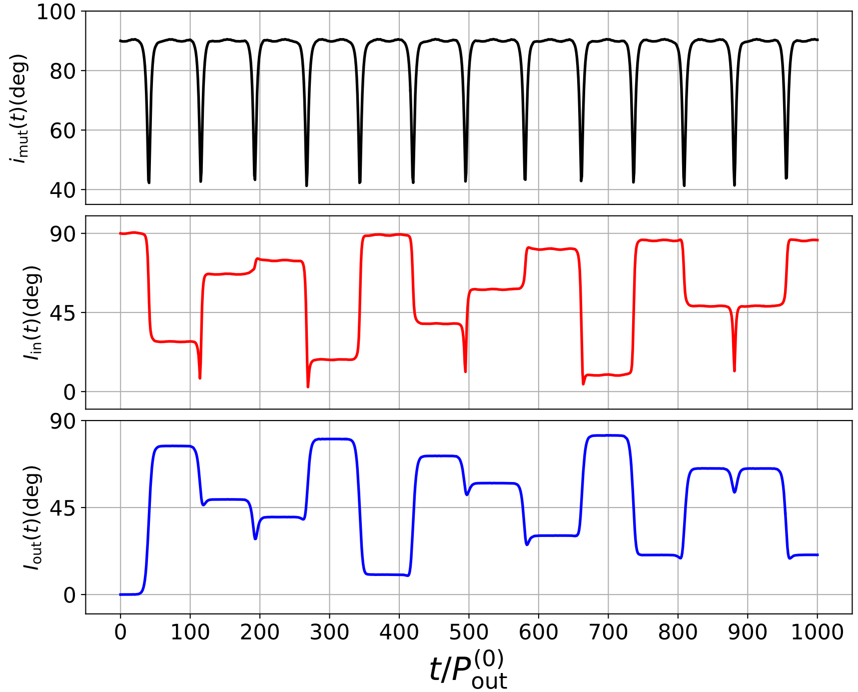
$i_{\rm mut} = 90^\circ$



$i_{\rm mut}(t)$
$I_{\rm in}(t)$
$I_{\rm out}(t)$



$i_{\rm mut}(t)$
$I_{\rm in}(t)$
$I_{\rm out}(t)$

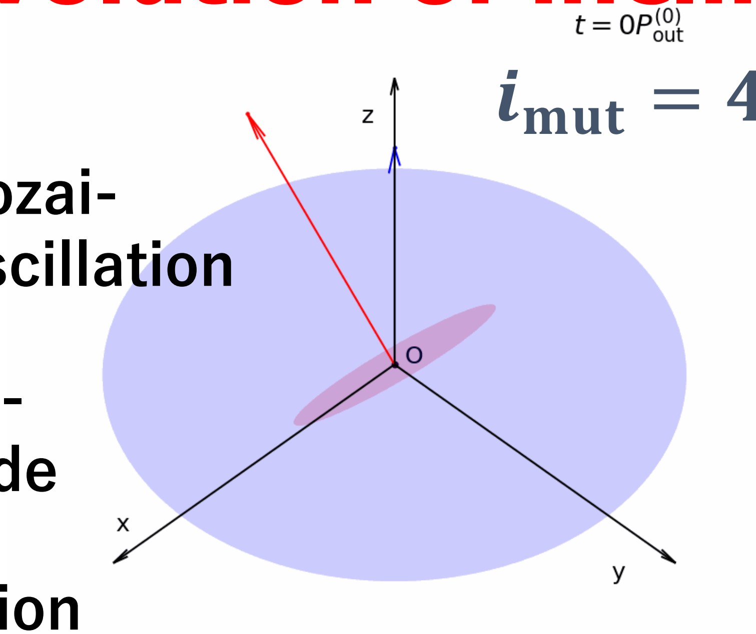


Evolution of inclination for non-coplanar triples

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

weak Kozai-Lidov oscillation

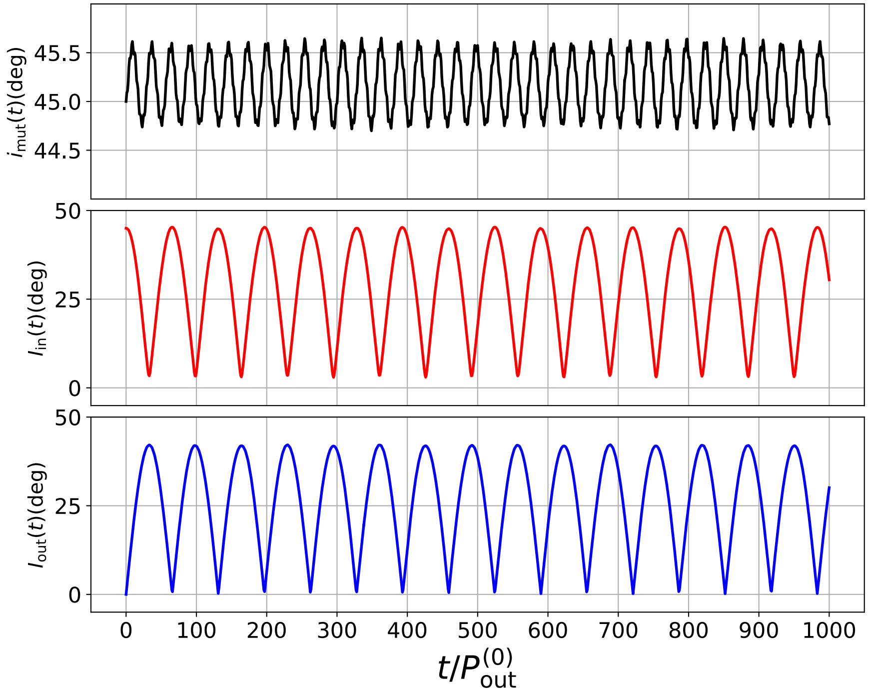
⇒ small-amplitude regular precession



$i_{\rm mut}(t)$

$I_{\rm in}(t)$

$I_{\rm out}(t)$

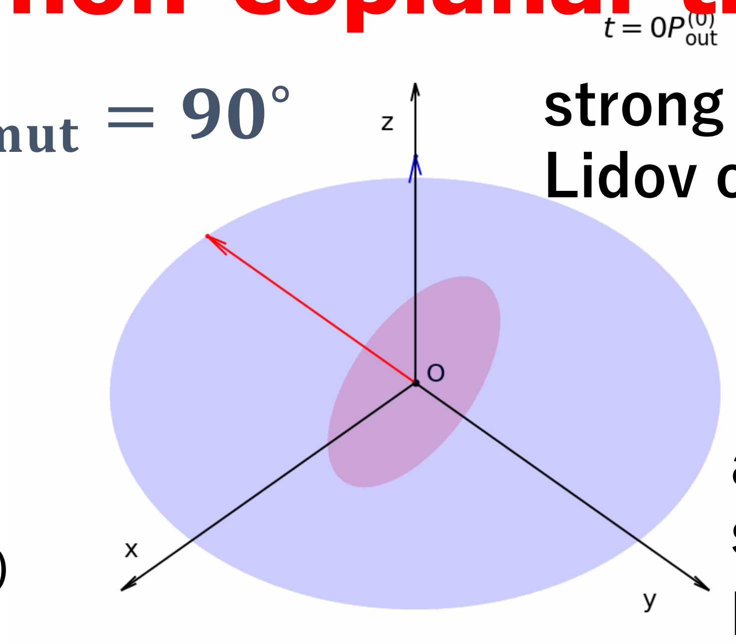


$$K_{\rm Kep} = K_0 \sin I_{\rm out}(t)$$

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

strong Kozai-Lidov oscillation

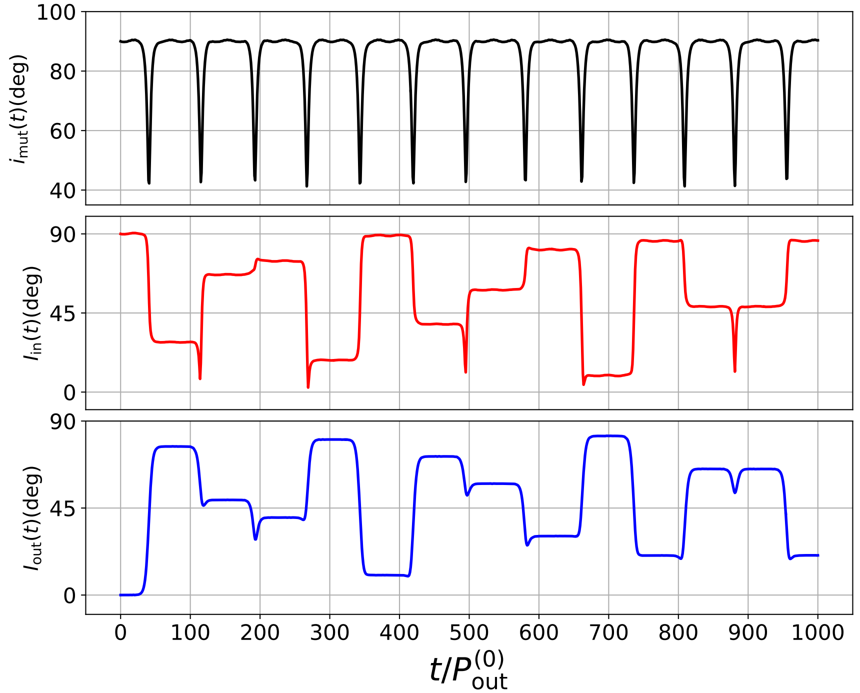
⇒ large-amplitude sporadic precession



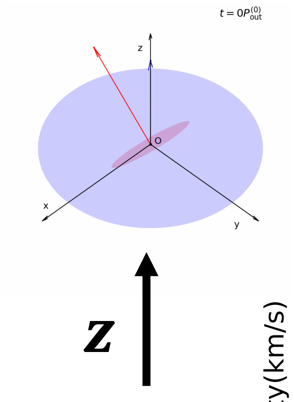
$i_{\rm mut}(t)$

$I_{\rm in}(t)$

$I_{\rm out}(t)$

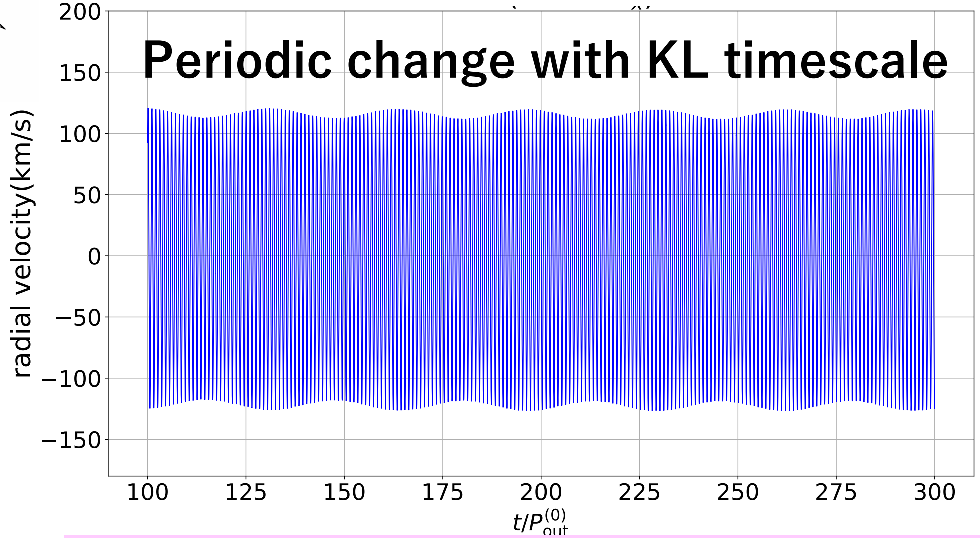


Evolution of radial velocity for non-coplanar triples

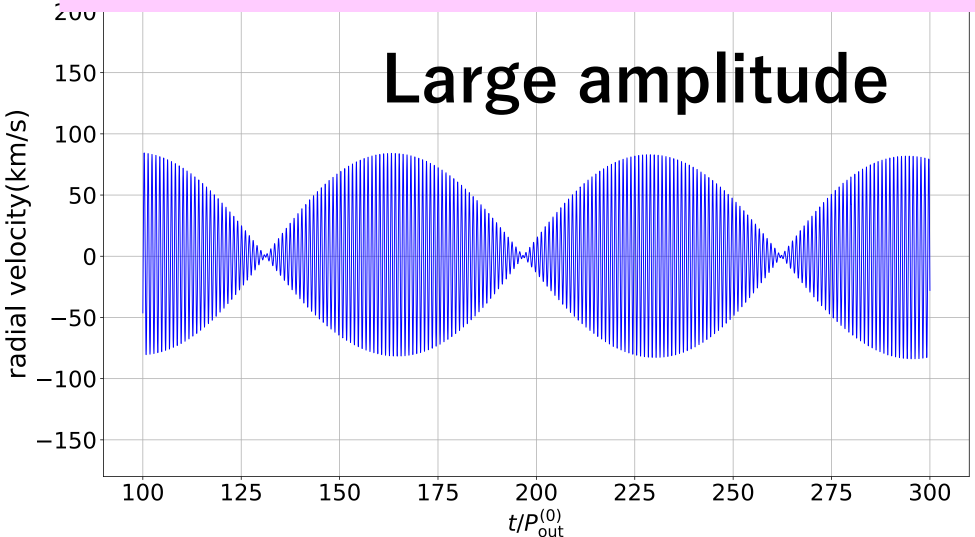


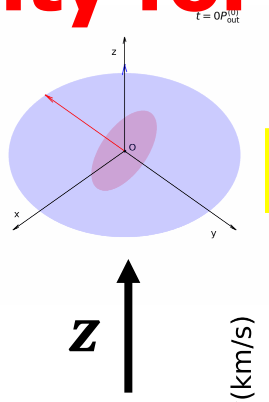
$i_{\mathrm{mut}} = 45^\circ$ $\quad K_{\mathrm{Kep}} = K_0 \sin I_{\mathrm{out}}(t)$

x-direction (near edge-on) total RV



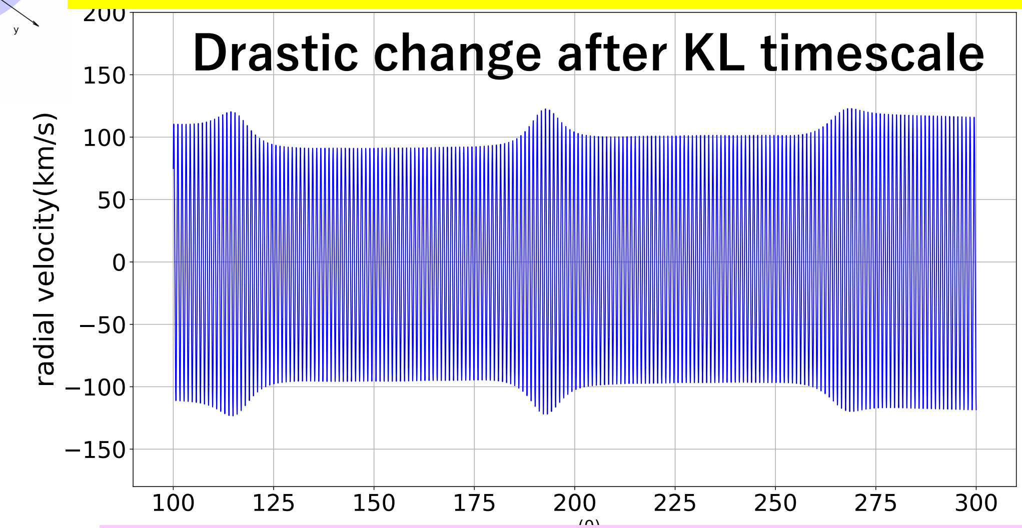
z-direction (near face-on) total RV



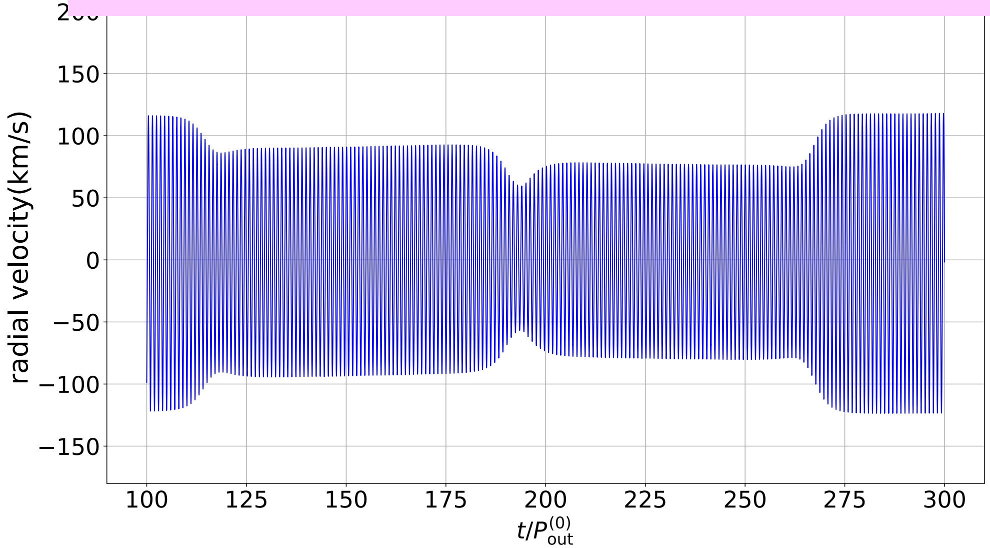


$i_{\mathrm{mut}} = 90^\circ$

x-direction (near edge-on) total RV



z-direction (near face-on) total RV



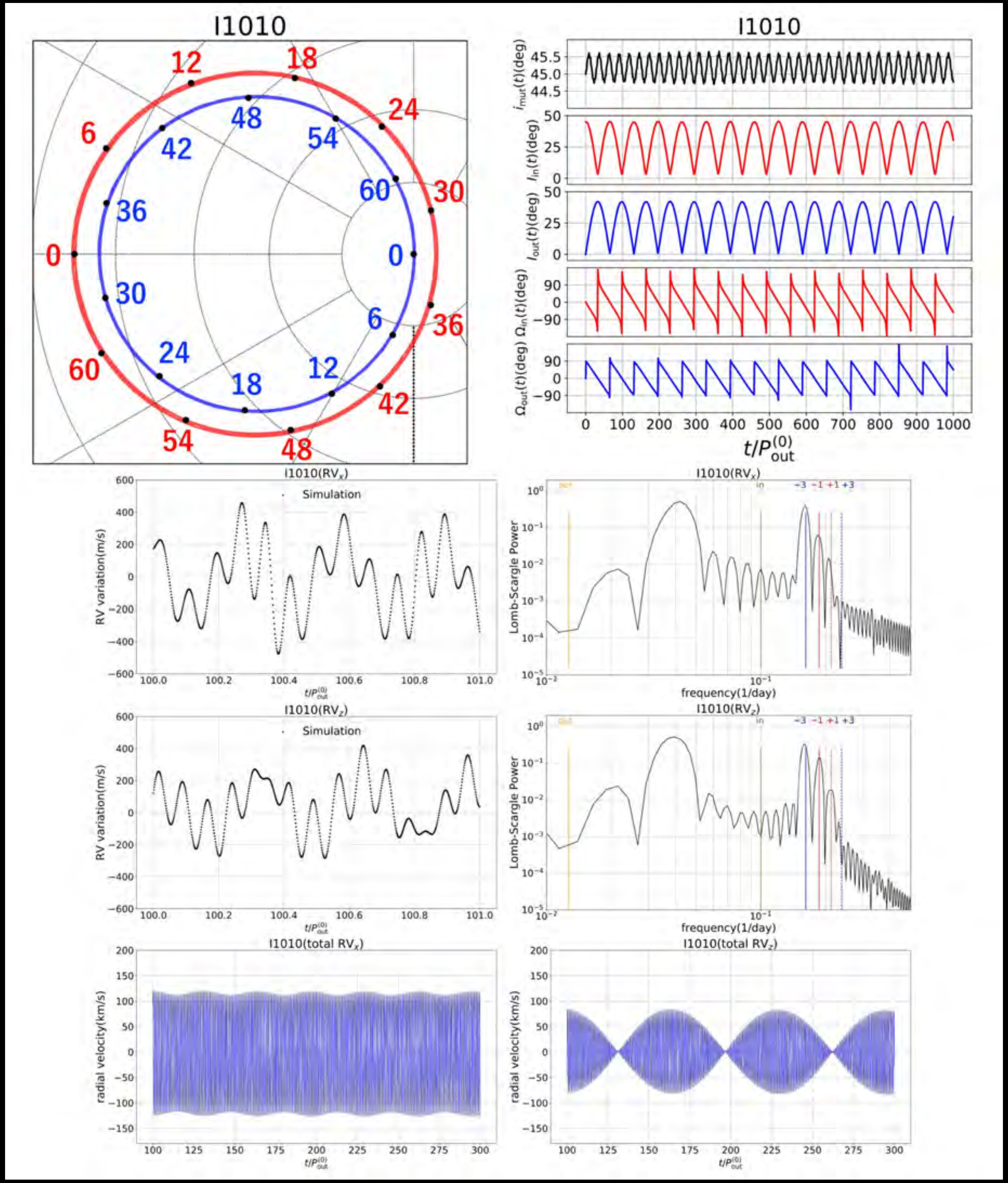
Inclined equal-mass binary

Precession timescale

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

Kozai-Lidov timescale

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



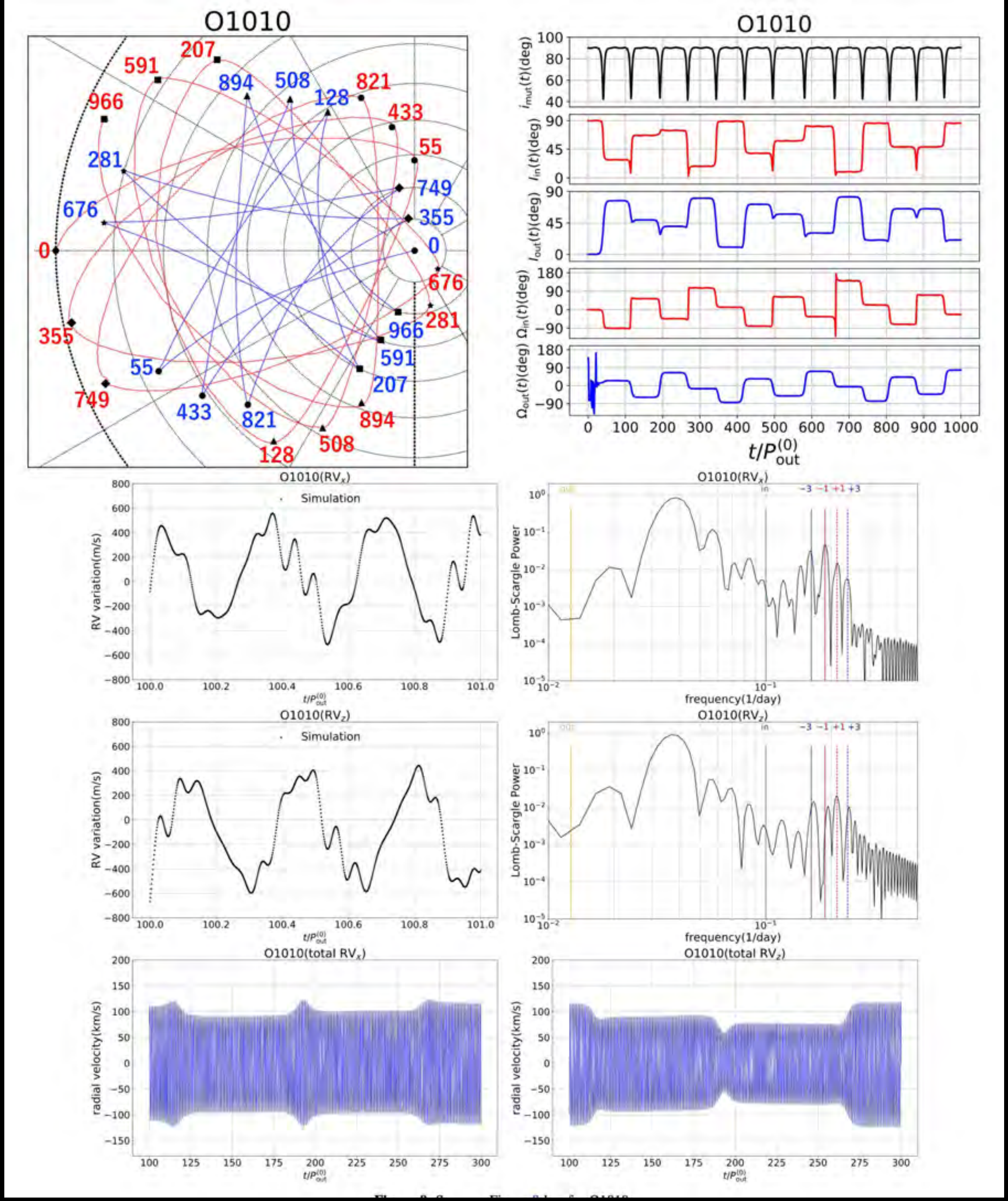
Orthogonal equal-mass binary

Precession timescale

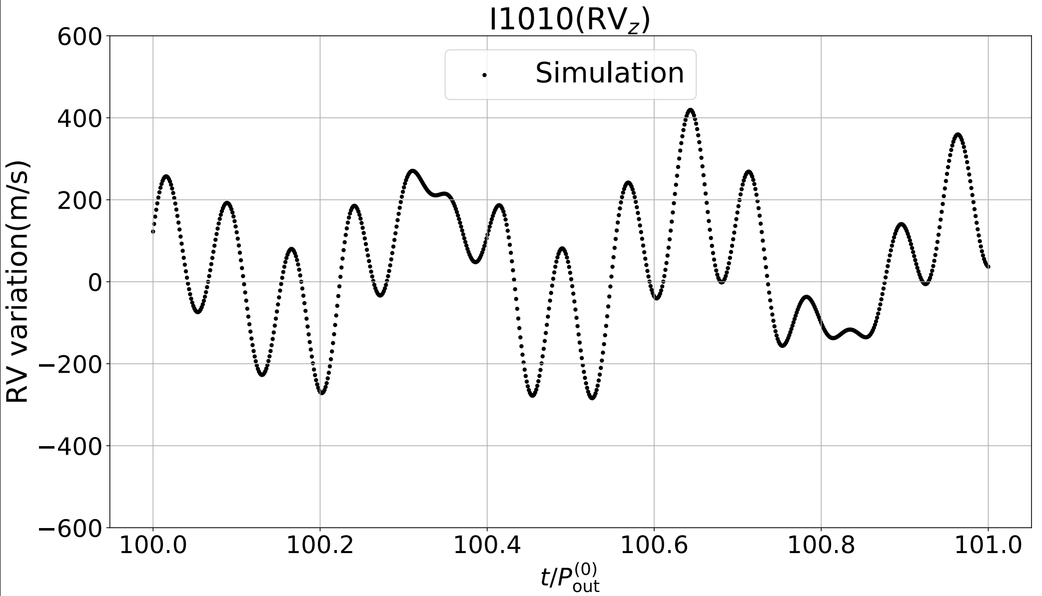
$$\frac{P_\Omega}{P_{\rm out}} \approx \frac{80.7}{\cos i_{\rm mut}} \left(\frac{m_1 + m_2 + m_*}{23\, M_\odot}\right) \left(\frac{m_*}{3\, M_\odot}\right)^{-1} \times \left(\frac{P_{\rm out}}{78.9 \text{ days}}\right) \left(\frac{P_{\rm in}}{10.0 \text{ days}}\right)^{-1}$$

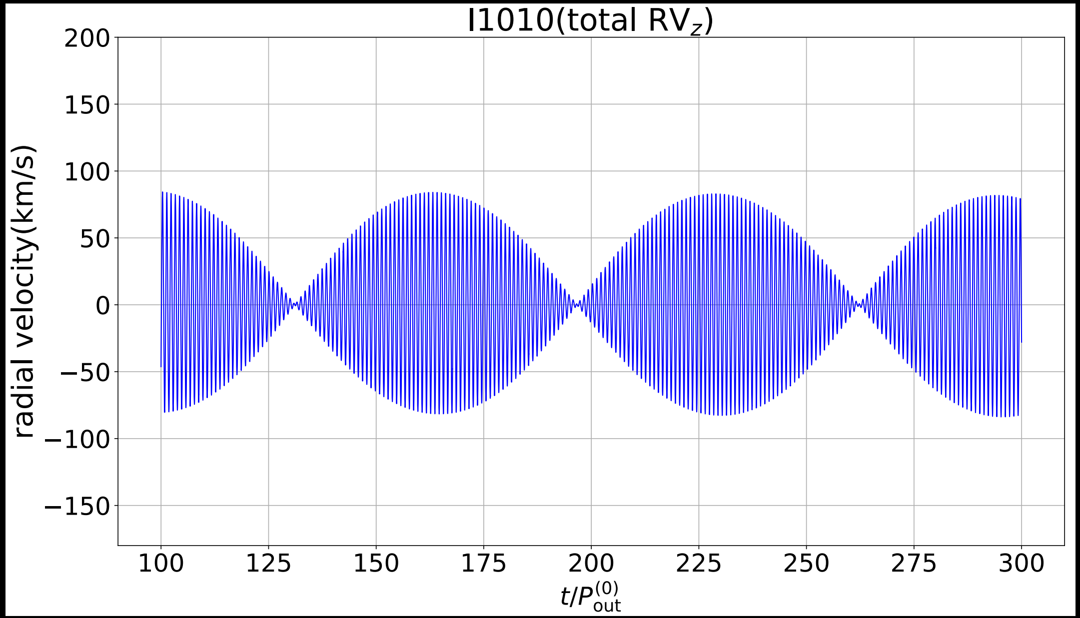
Kozai-Lidov timescale

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



Non-coplanar effect (precession+Kozai-Lidov)





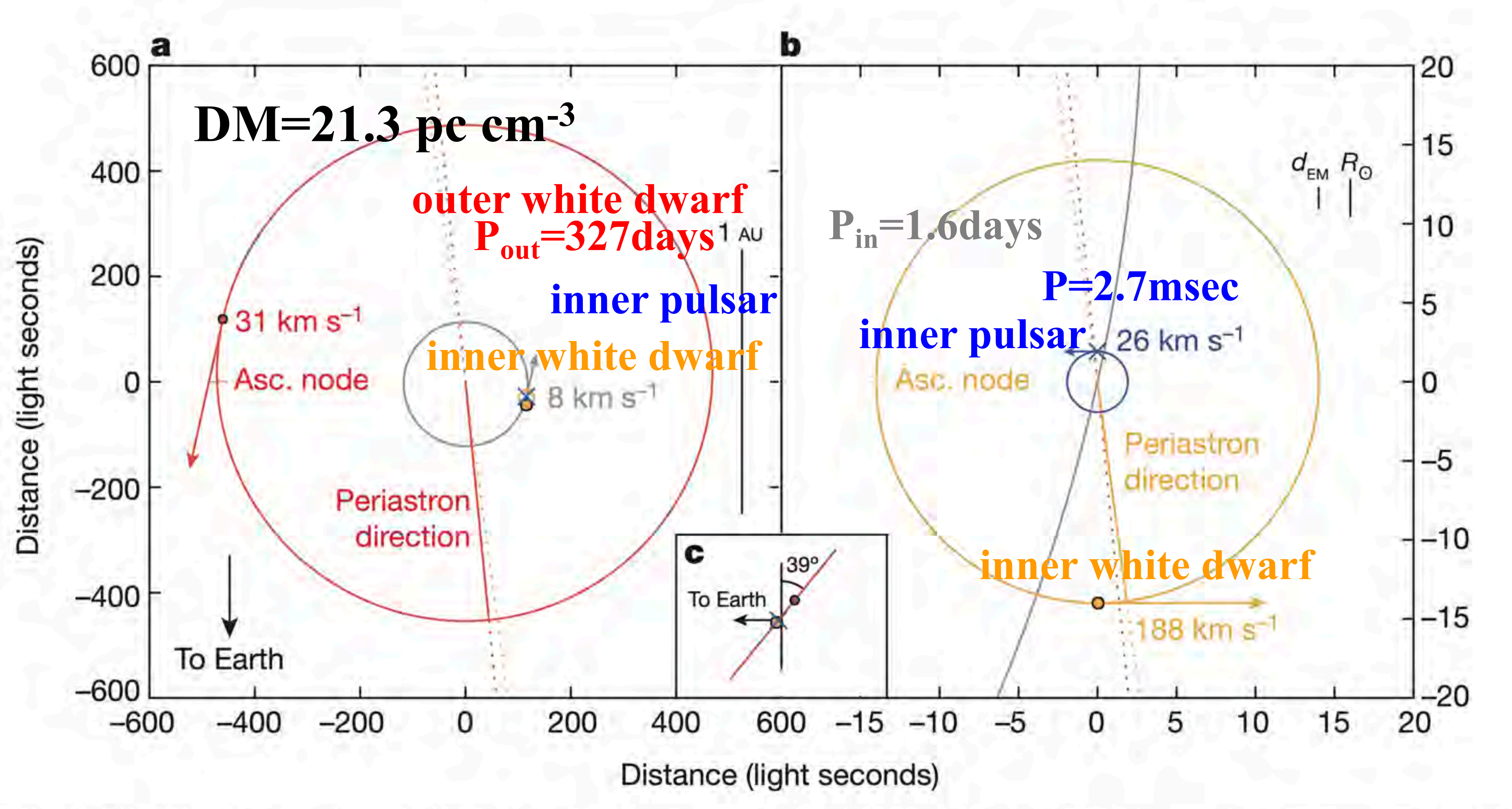
Inner BH binary
$10M_\odot + 10M_\odot$
Initial orbital inclination 45 deg.

short-period modulation
(inner binary orbital period/2)
of O(100m/s)

long-period modulation
(orbital precession + Kozai-Lidov
effect over the KL time-scale)
of O(100km/s)

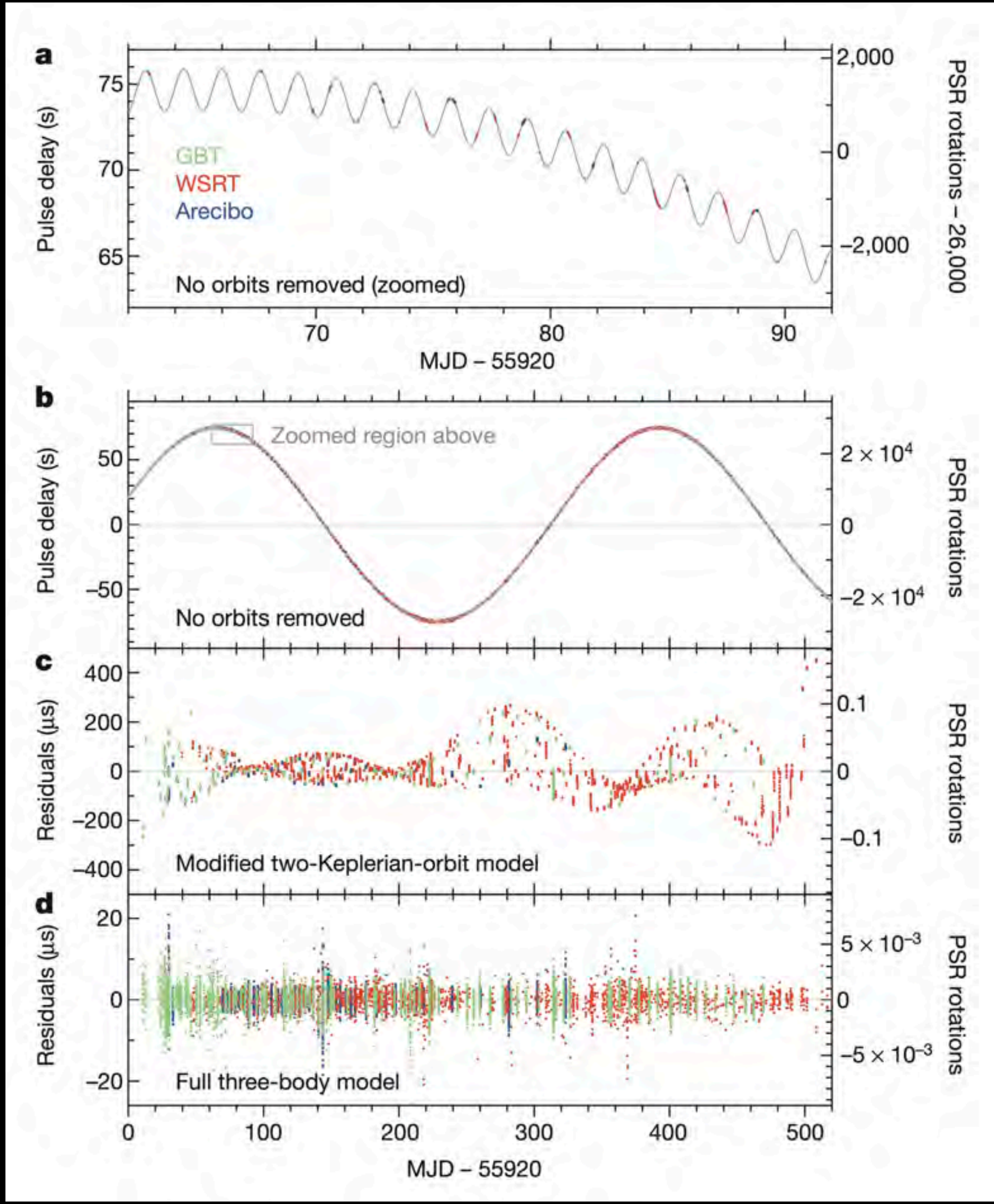
Hayashi & YS (2020)

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 !

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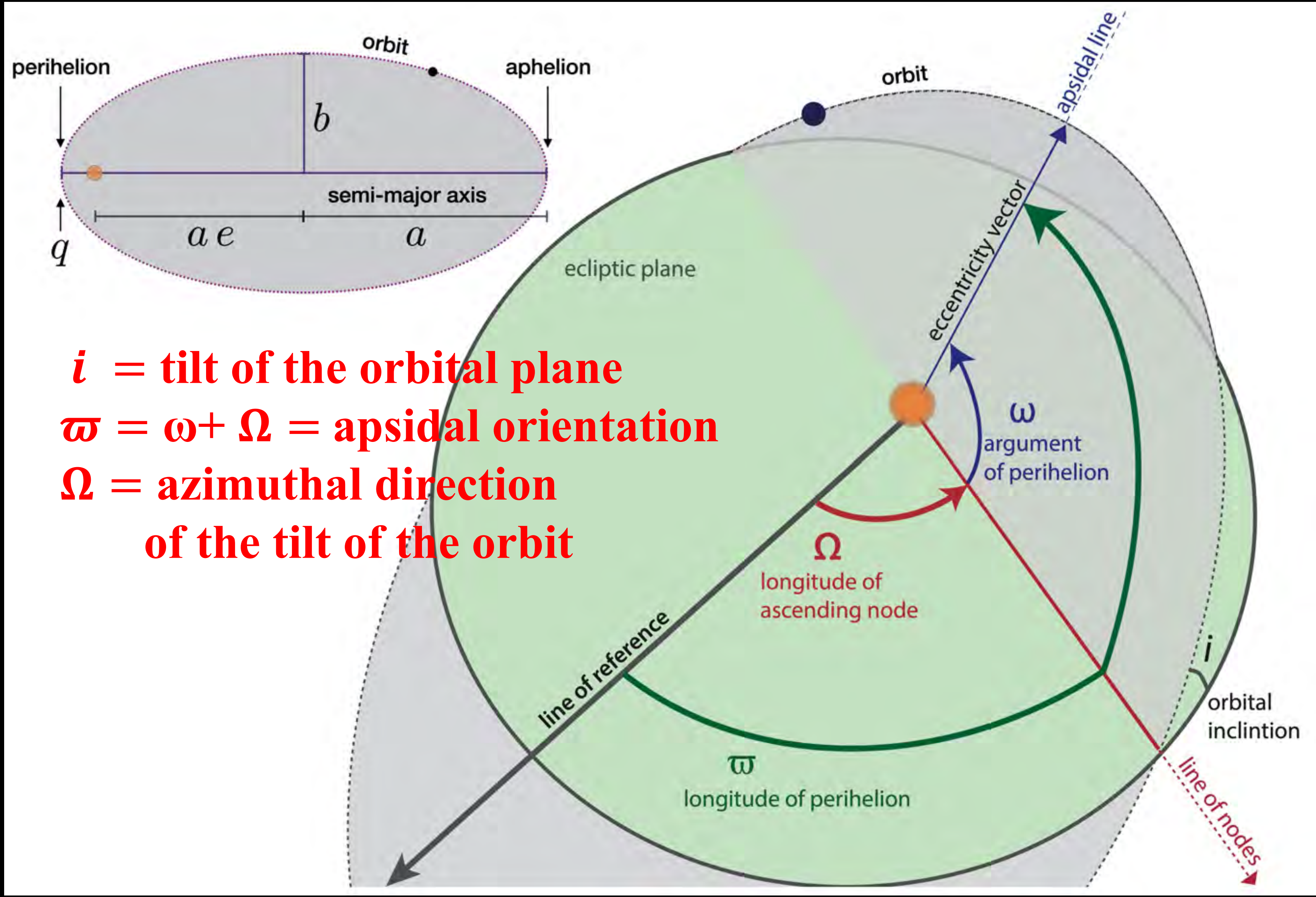
Radial velocity vs. Pulsar arrival timing

- 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

Keplerian orbital elements



i = tilt of the orbital plane

$\varpi = \omega + \Omega$ = apsidal orientation

Ω = azimuthal direction of the tilt of the orbit

Unperturbed Rømer delay

- **Rømer delay** (corresponding to the Keplerian motion around the central binary of total mass m_{12})

$$\Delta_{\rm R,Kep}(t) = x[\sin\omega_{\rm out}(\cos E_{\rm out} - e_{\rm out}) + \sqrt{1-e_{\rm out}^2}\cos\omega_{\rm out}\sin E_{\rm out}]$$

Eccentric anomaly $E_{out}=E_{out}(t)$ via the Kepler equation

$$2\pi t = P_{\rm out}(E_{\rm out} - e_{\rm out}\sin E_{\rm out})$$

Semi-amplitude of the Romer delay

$$x \equiv \frac{m_{12}}{m_{123}}\frac{a_{\rm out}\sin I_{\rm out}}{c} \approx 570\ {\rm sec}\left(\frac{m_{12}}{m_{123}}\right)\left(\frac{m_{123}}{20\ M_\odot}\right)^{1/3}\left(\frac{P_{\rm out}}{100\ {\rm days}}\right)^{2/3}\sin I_{\rm out}$$

Relativistic delays

- **Einstein delay**

$$\Delta_E(t) = \gamma_E \sin E_{out}$$

Gravitational redshift due to the eccentric orbital motion of the tertiary pulsar around m_{12}

Semi-amplitude of the Einstein delay

$$\gamma_E \equiv \left(\frac{\mathcal{G}}{c^3}\right)^{2/3} \left(\frac{P_{out}}{2\pi}\right)^{1/3} e_{out} \frac{m_{12}(m_3 + 2m_{12})}{m_{123}^{4/3}}$$
$$\approx 2.4 \text{ msec} \left(\frac{P_{out}}{100 \text{ days}}\right)^{1/3} \left(\frac{m_{12}}{20\ M_\odot}\right) \left(\frac{m_{123}}{20\ M_\odot}\right)^{-1/3} \left(1 + \frac{m_{12}}{m_{123}}\right) \left(\frac{e_{out}}{0.01}\right)$$

- **Shapiro delay**

Photon travel time change due to the curvature of the space-time

$$\Delta_S(t) = -2r \ln \Big[1 - e_{out} \cos E_{out} - s\left(\sin \omega_{out}(\cos E_{out} - e_{out}) + \sqrt{1 - e_{out}^2} \cos \omega_{out} \sin E_{out}\right)\Big]$$

range parameter

shape parameter

$$r \equiv \frac{\mathcal{G} m_{12}}{c^3} \approx 98\ \mu\text{sec} \left(\frac{m_{12}}{20\ M_\odot}\right)$$
$$s \equiv \sin I_{out}.$$

Significantly large for s=1 (edge-on) systems

Perturbed Rømer delay modulation

Modulation due to the inner binary motion in a coplanar circular orbit

$$\Delta_{\mathrm{R,BBH}}(t) \equiv \frac{z_{\mathrm{BBH}}(t)}{c} = \frac{15}{16}\frac{K_{\mathrm{BBH}}P_{\mathrm{in}}}{4\pi c}\sin I_{\mathrm{out}}\frac{2\nu_{\mathrm{in}}}{2\nu_{\mathrm{in}}-3\nu_{\mathrm{out}}}\sin(\nu_{-3}t+\theta_{0,-3}) + \frac{3}{16}\frac{K_{\mathrm{BBH}}P_{\mathrm{in}}}{4\pi c}\sin I_{\mathrm{out}}\frac{2\nu_{\mathrm{in}}}{2\nu_{\mathrm{in}}-\nu_{\mathrm{out}}}\sin(\nu_{-1}t+\theta_{0,-1}).$$

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

Semi-amplitude of the perturbed Romer delay modulation

$$\frac{K_{\mathrm{BBH}}P_{\mathrm{in}}}{4\pi c}\sin I_{\mathrm{out}} = \frac{1}{2}\frac{m_1 m_2}{m_{12}^2}\left(\frac{m_{12}}{m_{123}}\right)^{2/3}\left(\frac{P_{\mathrm{in}}}{P_{\mathrm{out}}}\right)^{7/3} x \approx 23\ \mathrm{msec}\left(\frac{K_{\mathrm{BBH}}}{100\ \mathrm{m/s}}\right)\left(\frac{P_{\mathrm{in}}}{10\ \mathrm{days}}\right)\sin I_{\mathrm{out}},$$

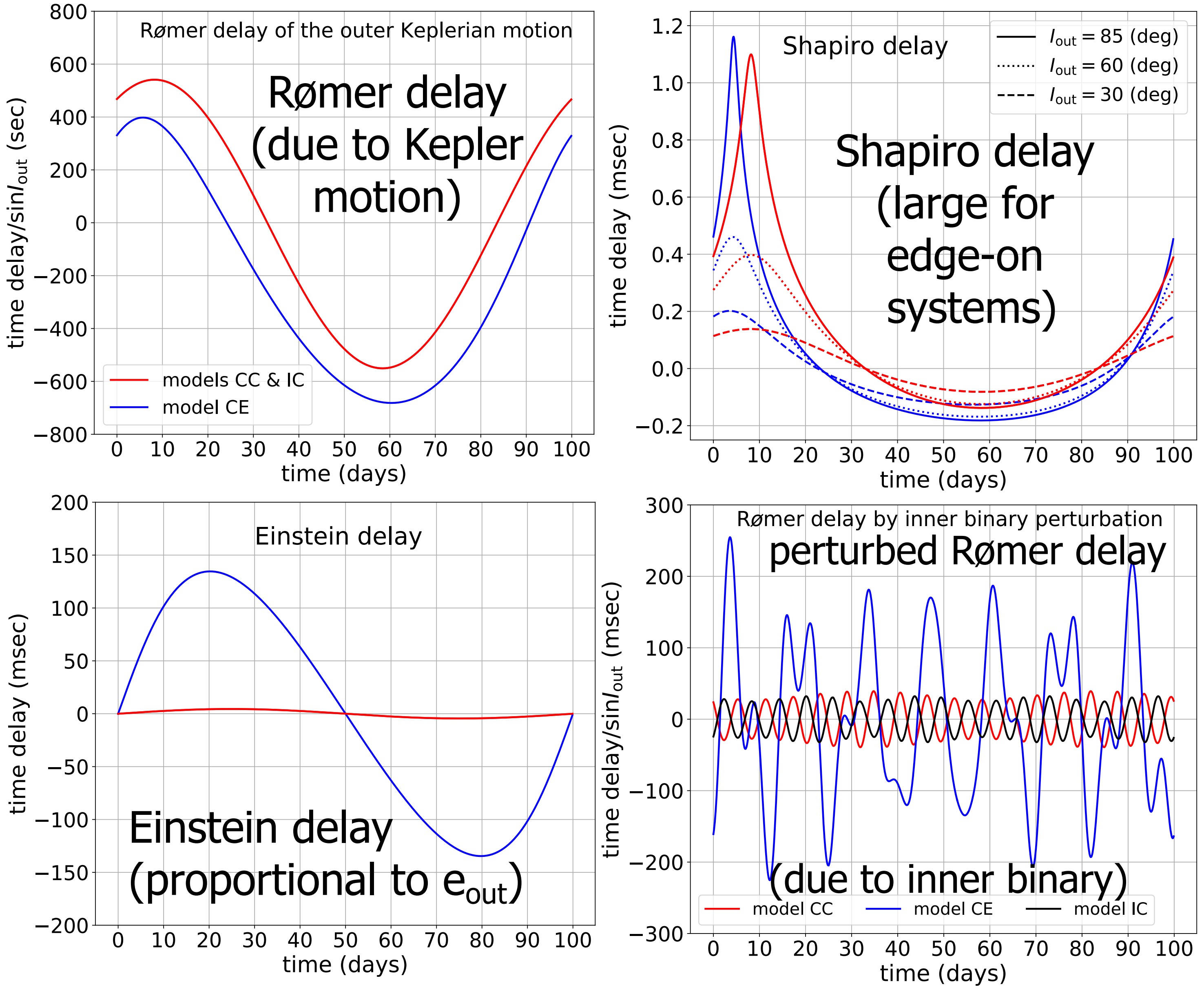
Examples of pulsar arrival timing curves for triples

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

Hayashi & YS (2020, submitted)



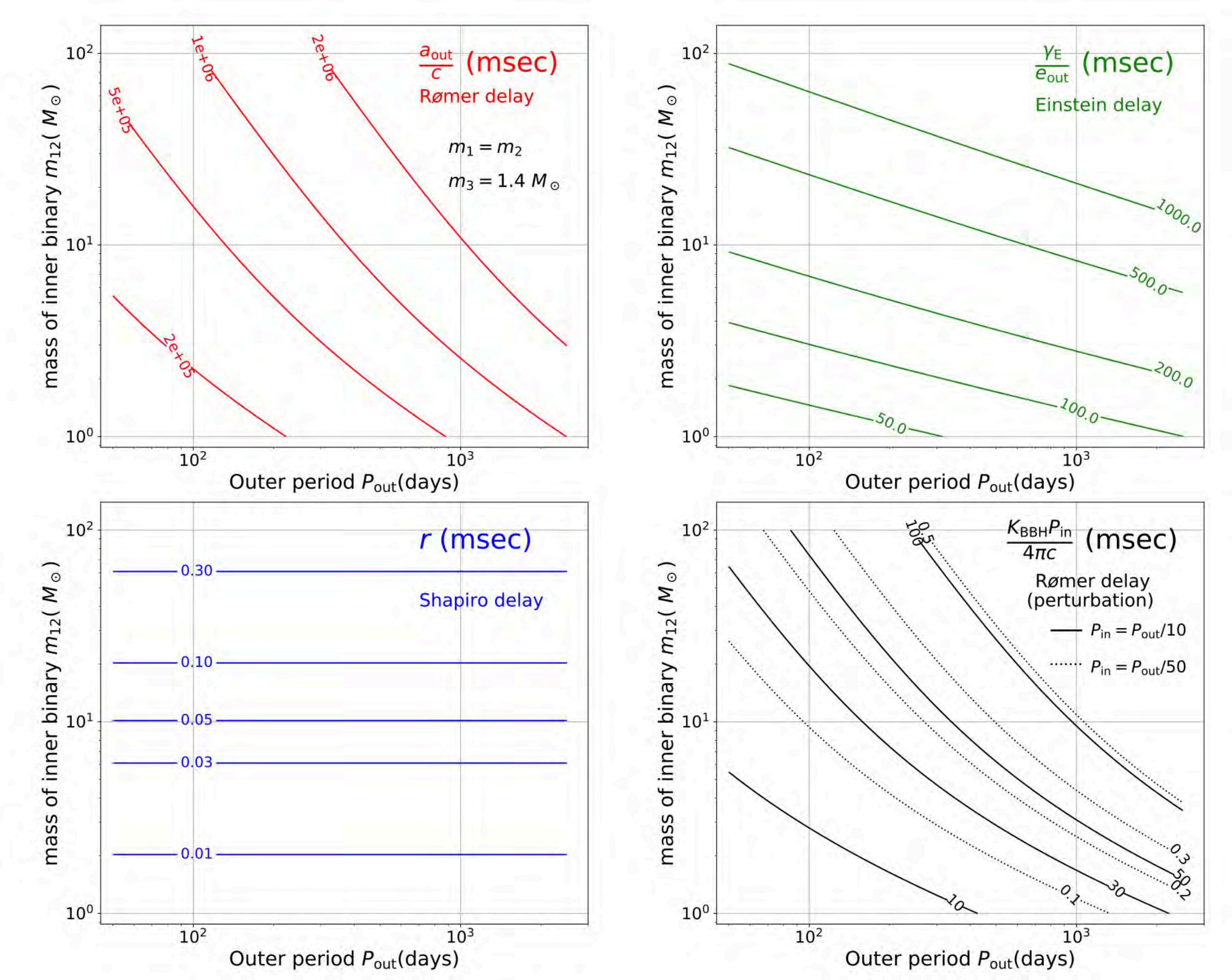
Comparison of arrival time delays

$m_{12}=m_1+m_2$

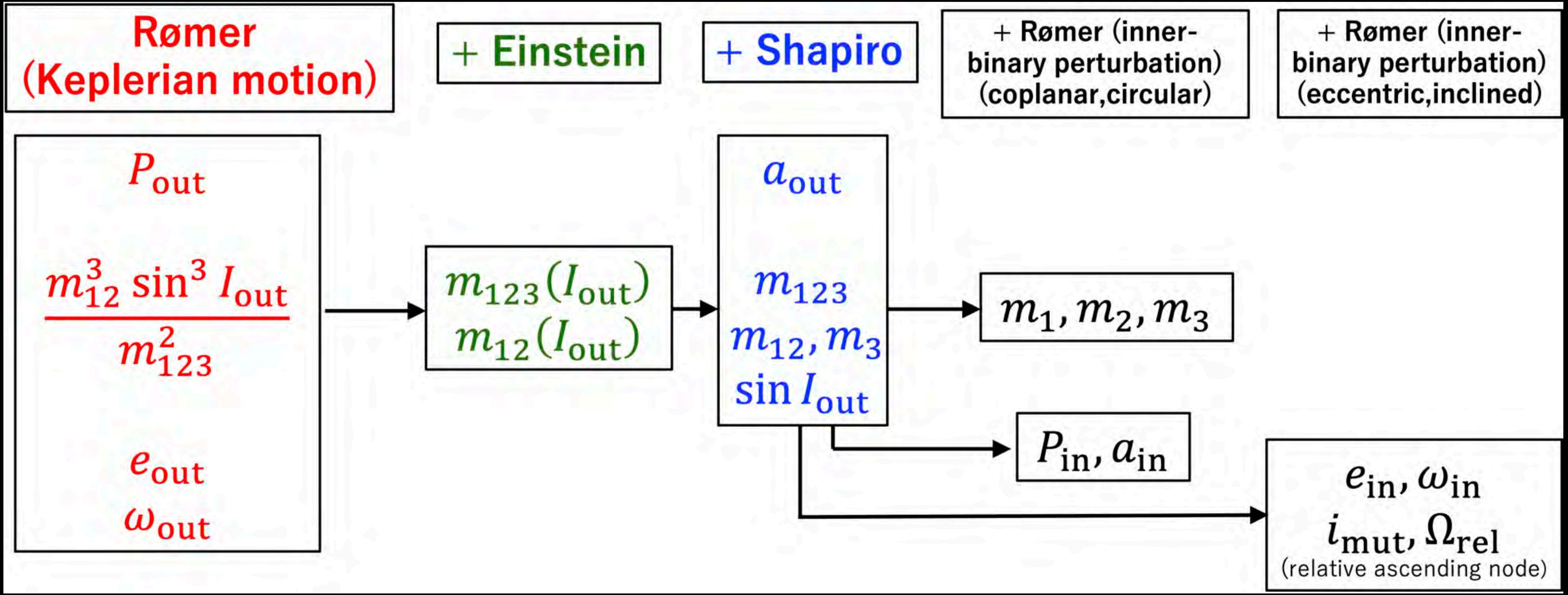
$m_1=m_2$

$m_3=1.4M_\odot$

- Those time-delay measurements break the degeneracy of the system parameters



Unveiling the triple system parameters from the pulsar arrival timing analysis

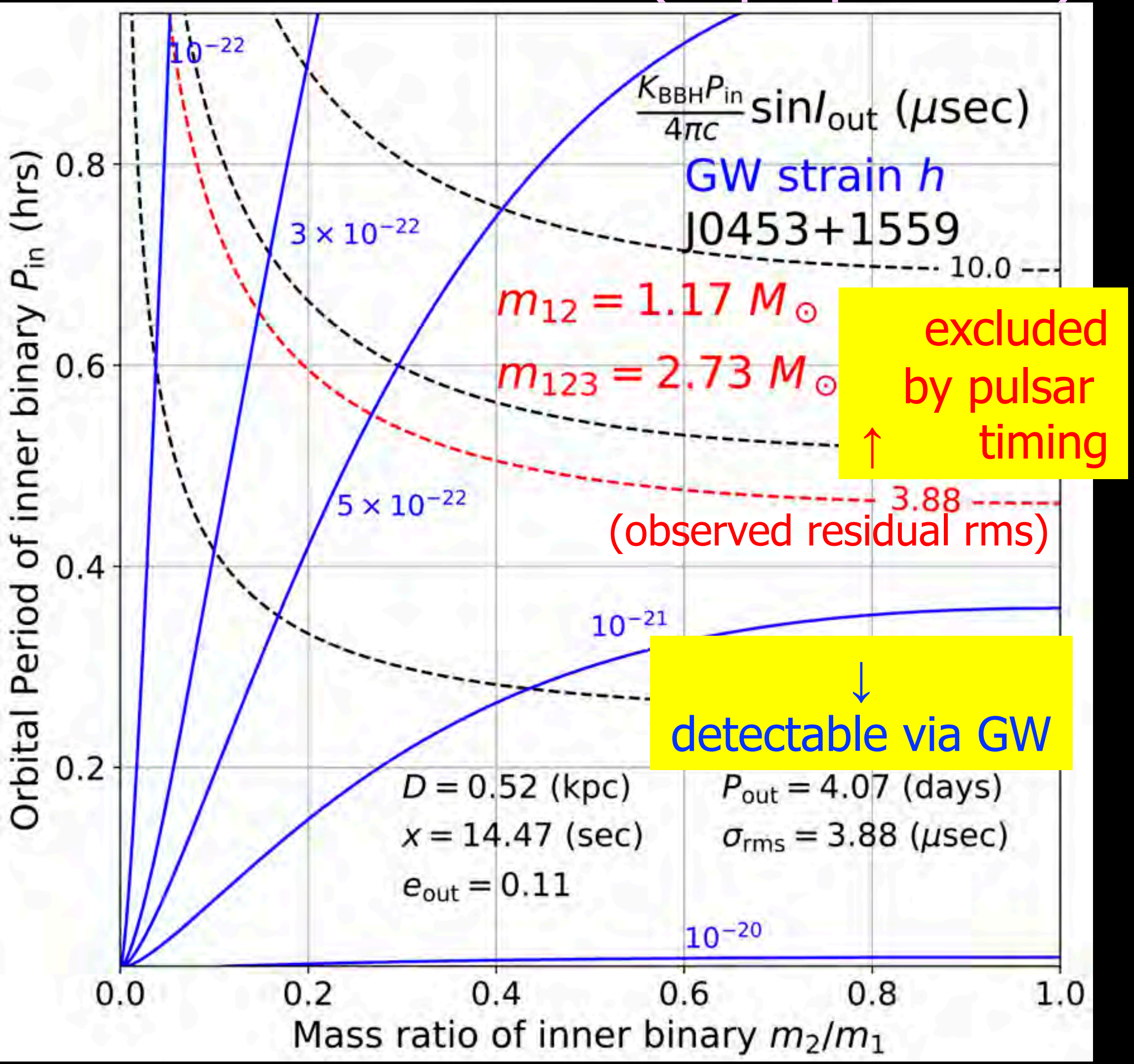


Hayashi & YS (2020, submitted)

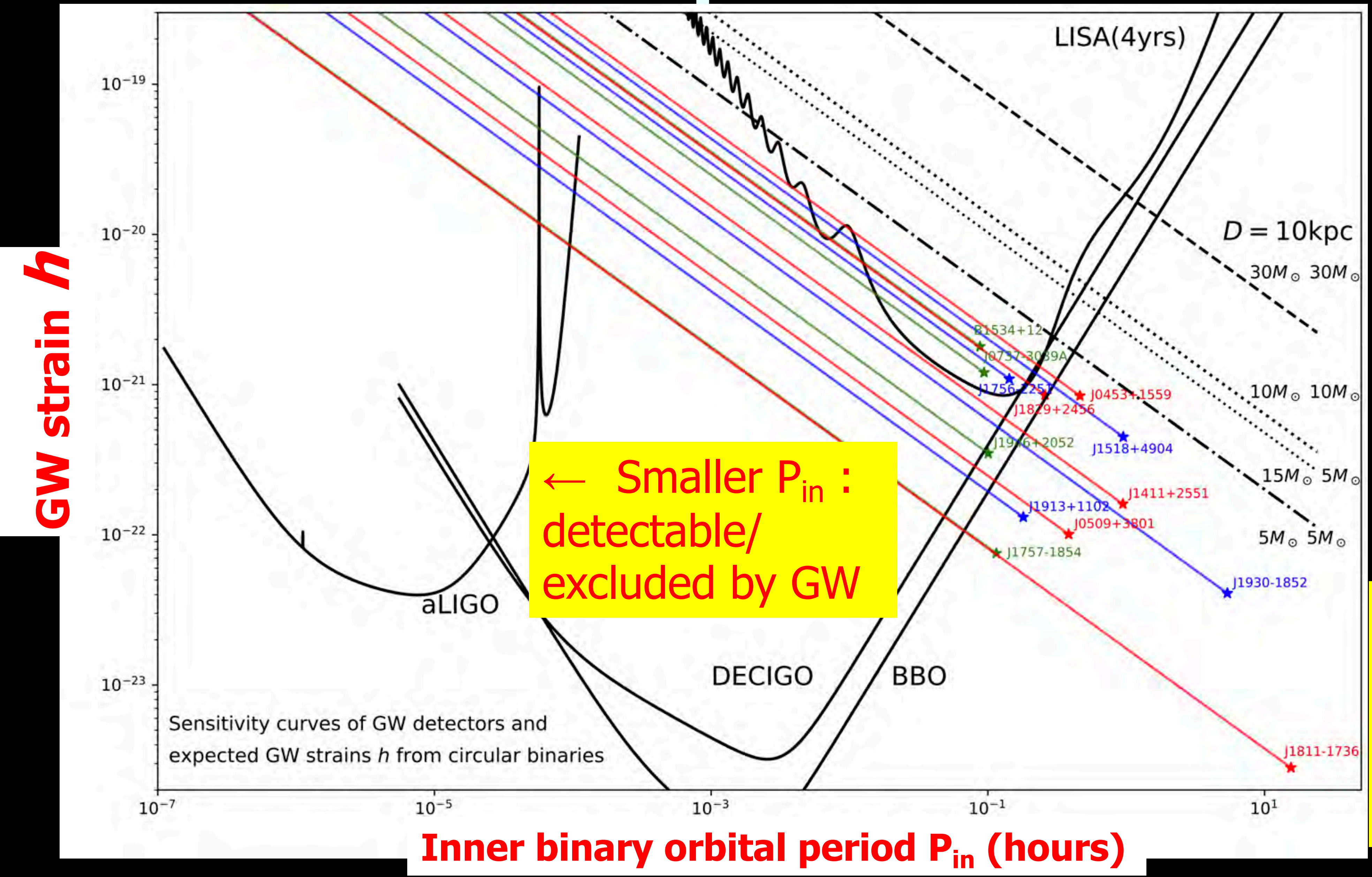
Proof-of-concept using known NS binaries

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