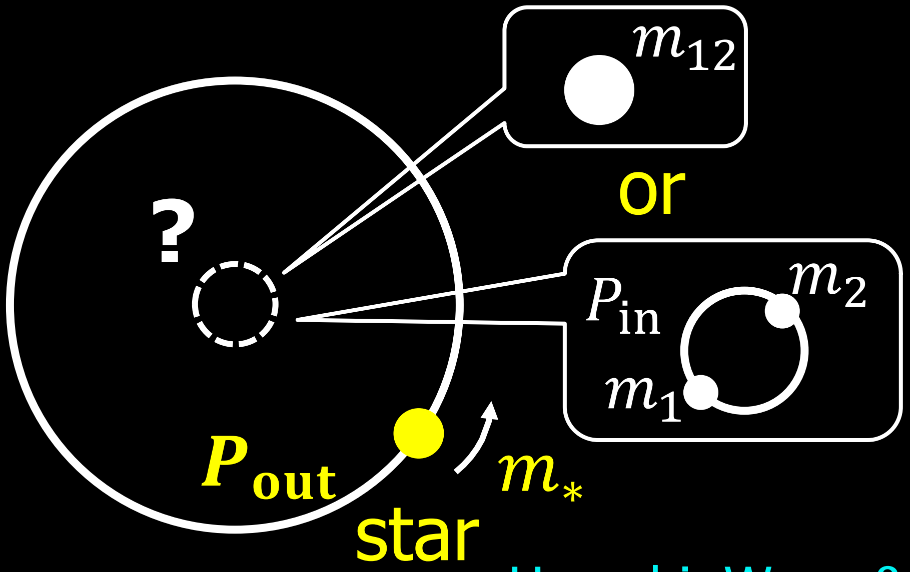
Dynamical signature of triple systems including inner binary black-holes



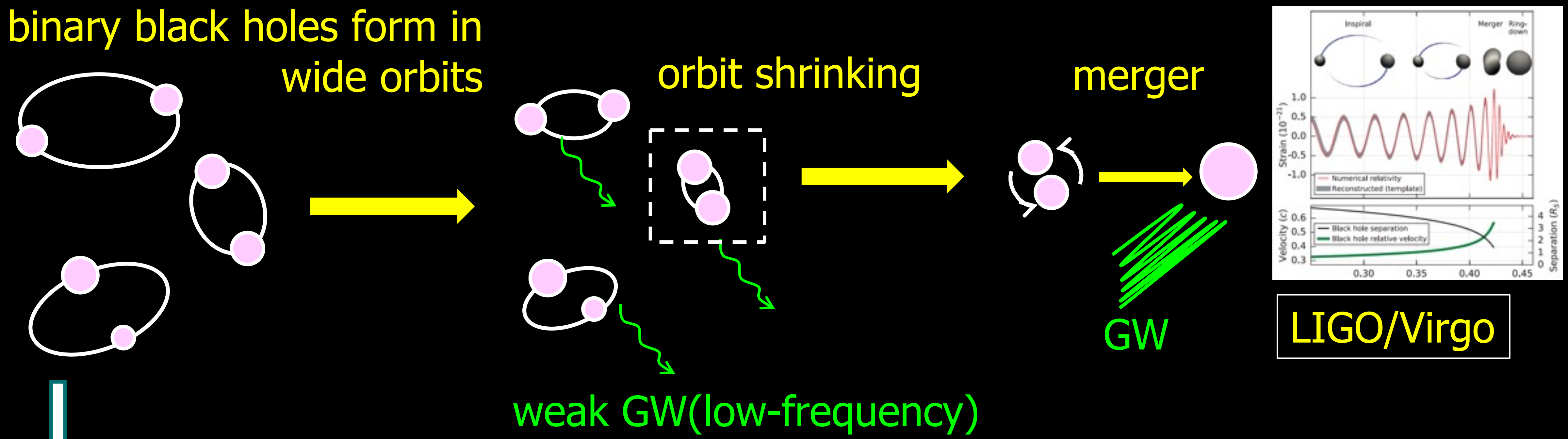
Hayashi, Wang & YS: ApJ 890(2020)112

Hayashi & YS: ApJ 897(2020)29, ApJ 907(2021)48

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

13:00 February 15, 2023 @Niels Bohr Institute

Generic picture of binary BH evolution



BBHs would spend longer time in wide orbits before merging

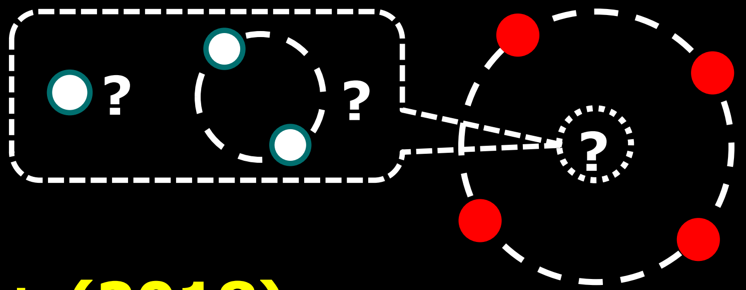
Abundant longer orbital-period BBHs may remain undetected (e.g. ~10day orbital period~10^{-6}Hz).

How to unveil those possible progenitor BBHs without 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)

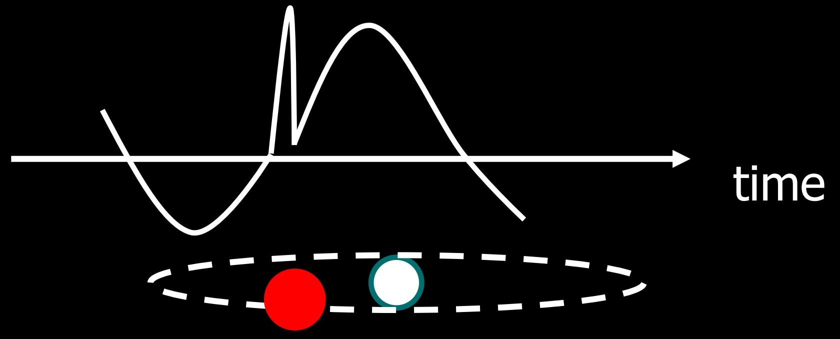
5-year mission may detect
200-1000 star-BH binaries

TESS mission (2018-)

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

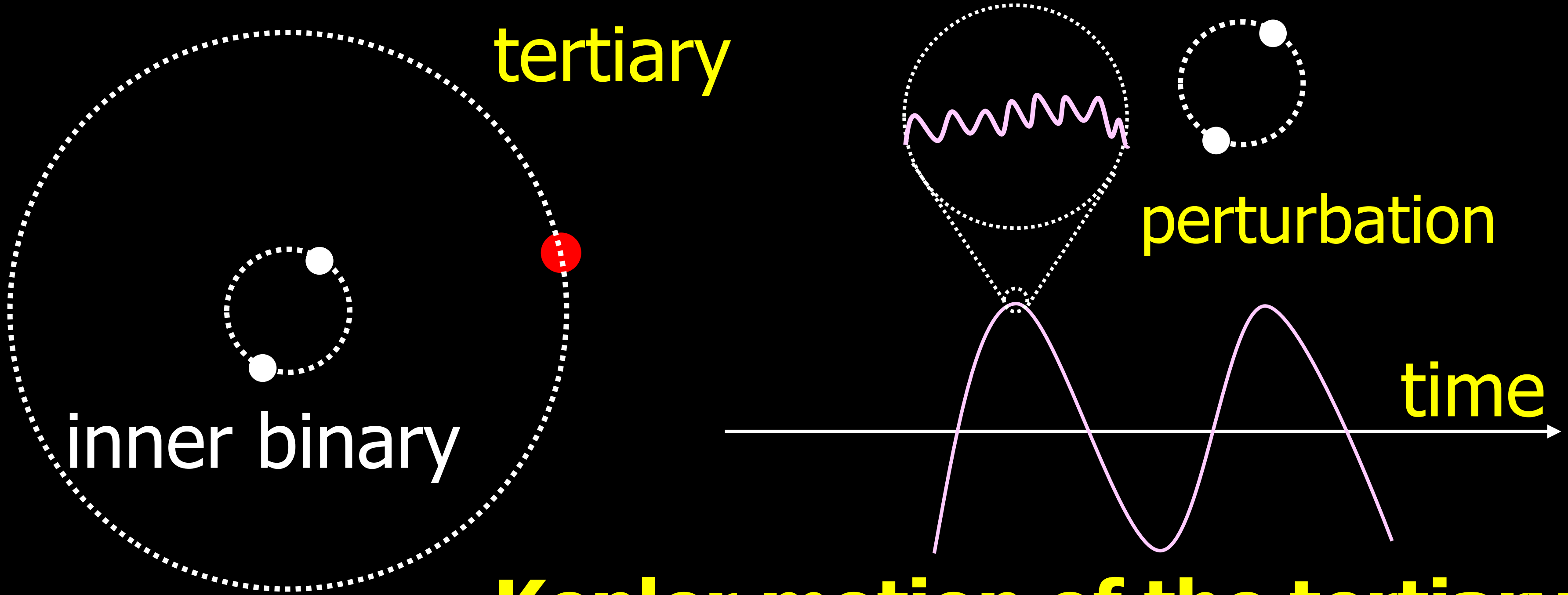
Masuda & Hotokezaka (2019)

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?

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

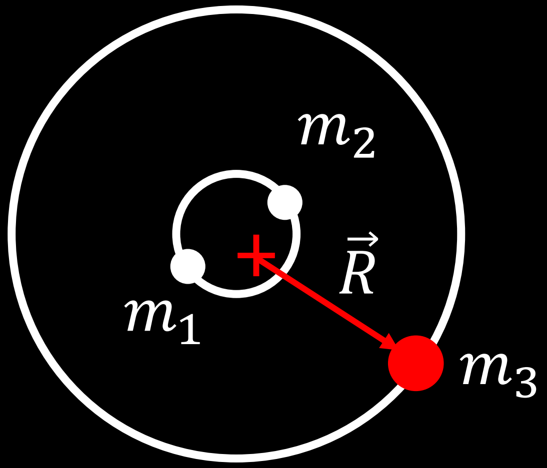


Kepler motion of the tertiary

Toshinori Hayashi

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

RV modulations for coplanar triples

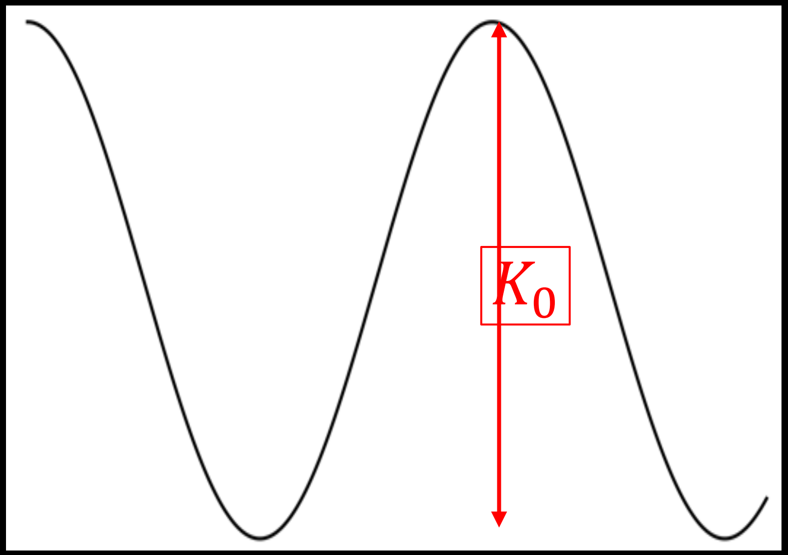


$$\mathcal{H} = \mathcal{H}_{\mathrm{Kep}} - \mathcal{R}$$

Perturbation theory

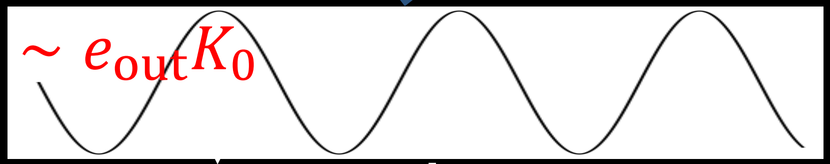
$$\left(\sqrt{\frac{m_1}{m_2}}+\sqrt{\frac{m_2}{m_1}}\right)^{-2}\left(\frac{a_{\mathrm{in}}}{a_{\mathrm{out}}}\right)^{3.5} K_0$$

$\mathrm{RV} =$



period: P_{out}

$+$



period: $P_{out}/2$

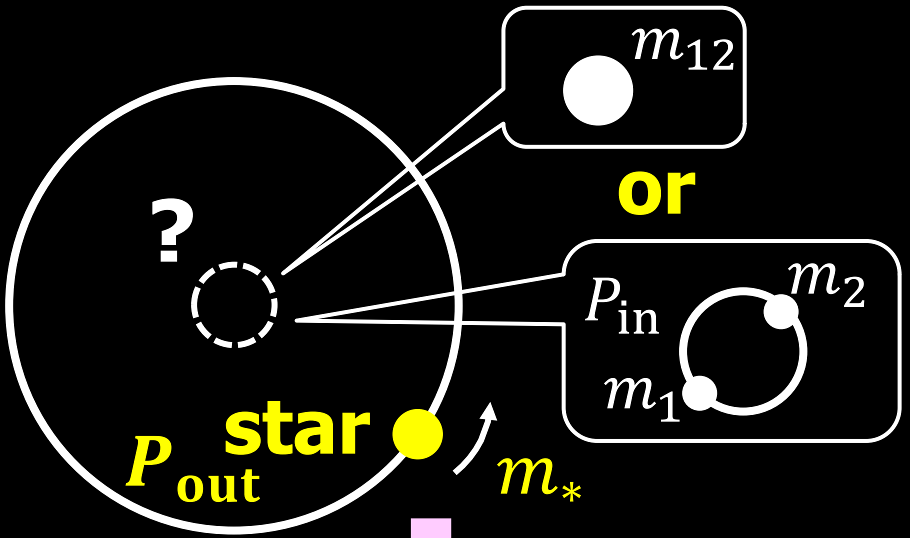
first order in e_{out}

$+$

period: $P_{in}/2$

inner binary

RV modulations for non-coplanar triples

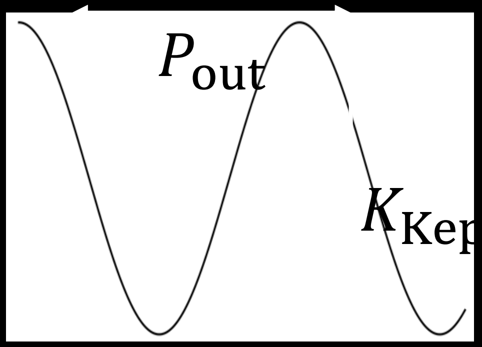


high-precision RV follow-up

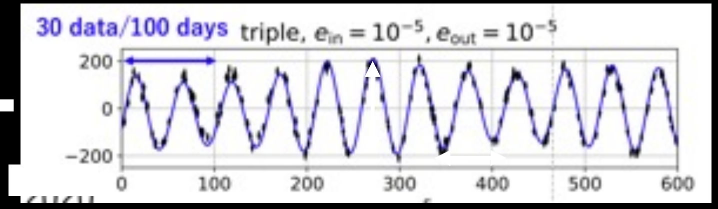
Keplerian motion RV
+ RV variations by inner binary

(i) Coplanar triple

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



+



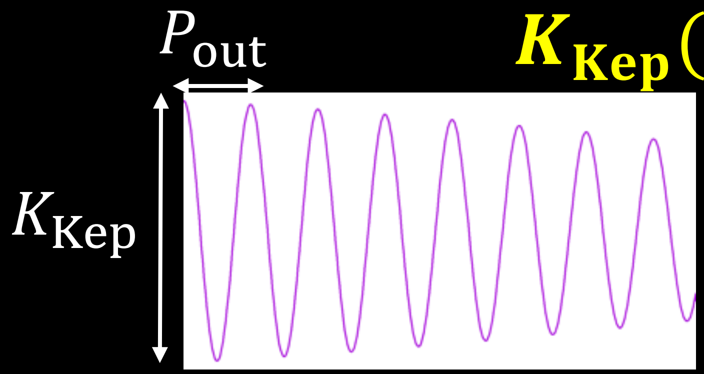
$$\mathrm{period} \sim P_{\rm in}/2$$

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

(ii) Non-coplanar triple

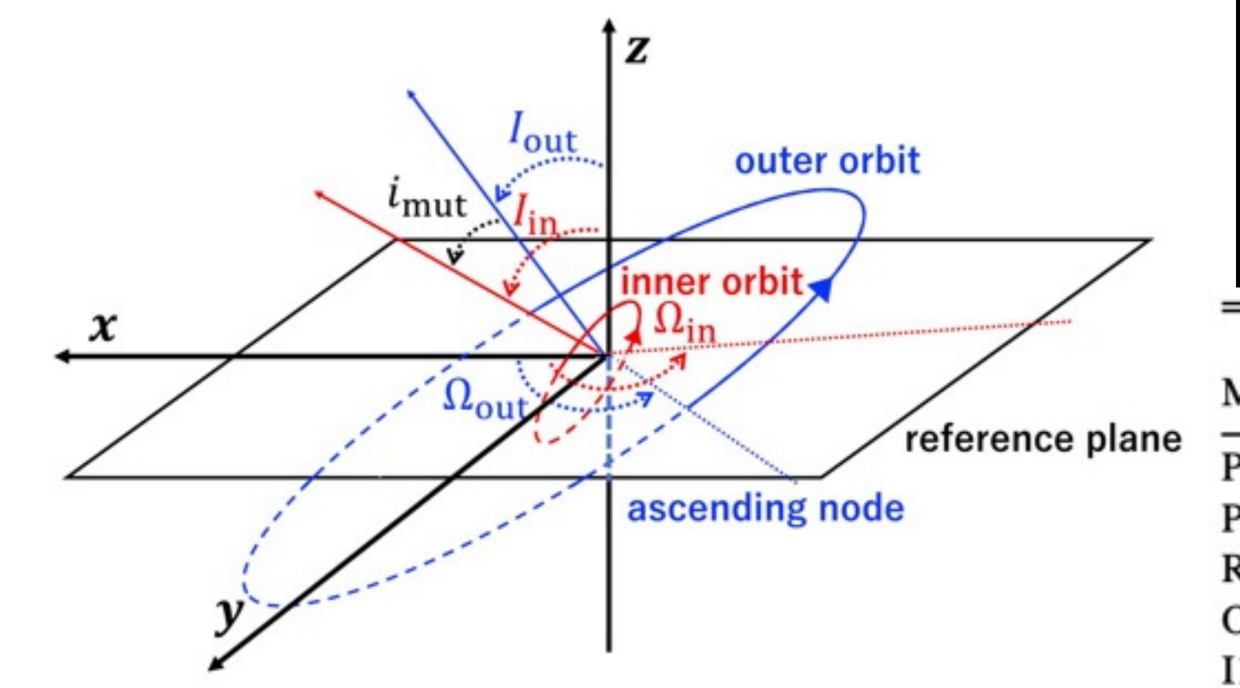
Inclination $I_{\rm out}(t)$ modulated by precession and ZKL effect

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



Amplitude of Kepler RV varies with a longer timescale

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 $2M_\odot + 18M_\odot$

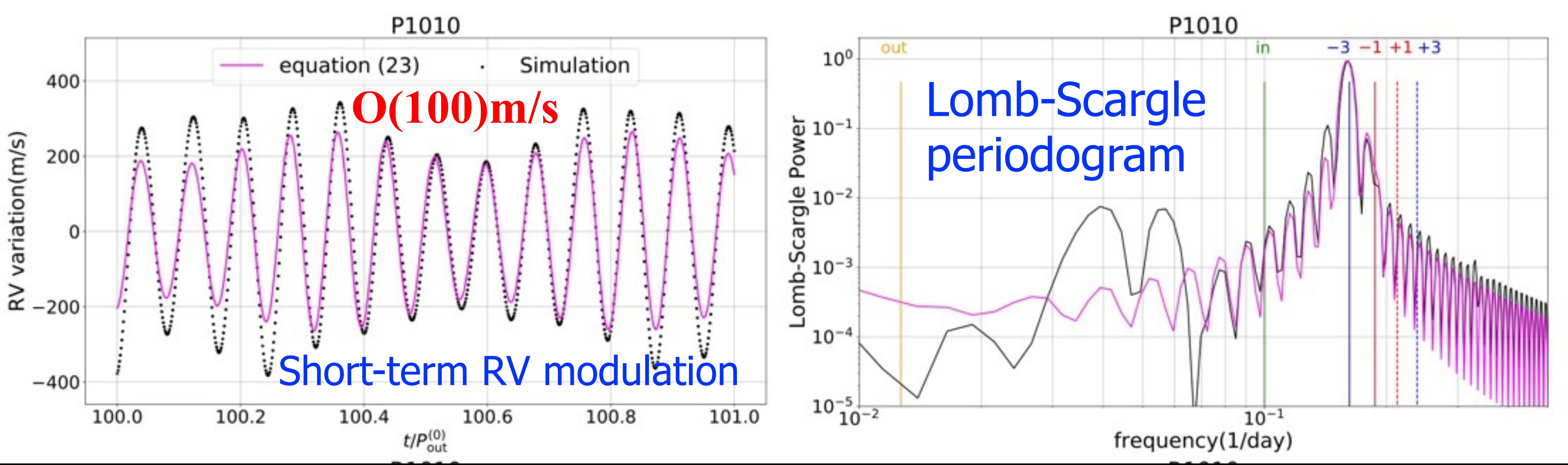
Coplanar prograde circular triples: radial velocity modulation at $\sim 2\nu_{in}$

equal-mass inner binary

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

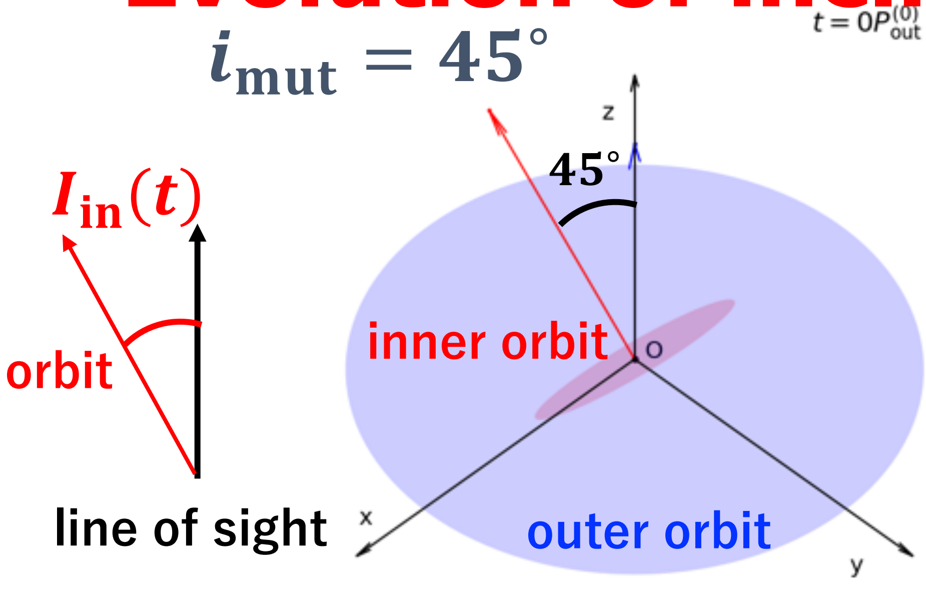
$$\nu_{-3} \equiv 2\nu_{\rm in} - 3\nu_{\rm out},$$
$$\nu_{-1} \equiv 2\nu_{\rm in} - \nu_{\rm out}.$$

ν_{in}: inner orbital frequency



Evolution of inclination for non-coplanar triples

$i_{\mathrm{mut}} = 45°$



$P_{\mathrm{out}} = 78.9$ days

$P_{\mathrm{in}} = 10$ days

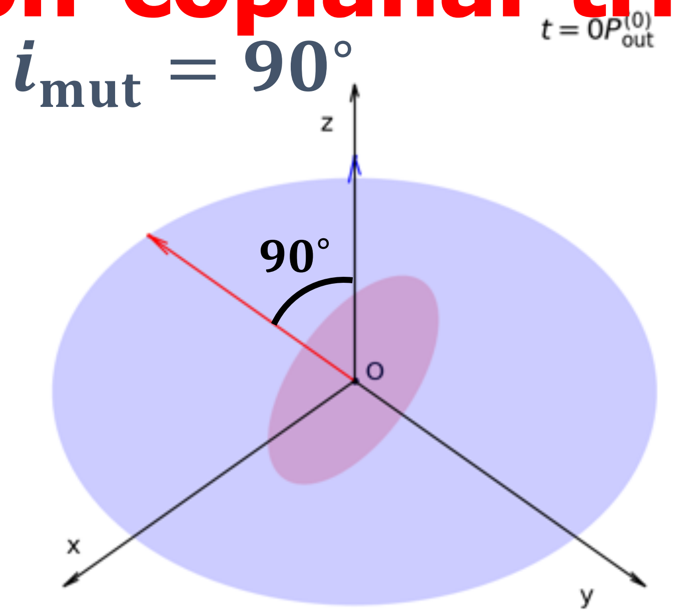
$m_1 = m_2 = 10M_\odot$

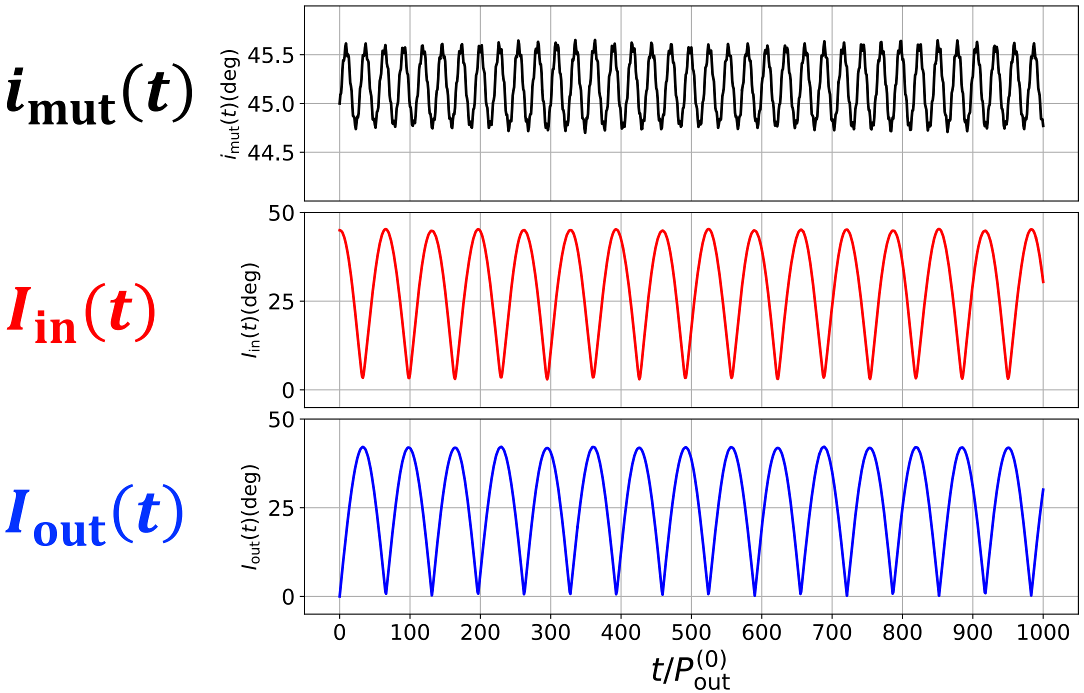
$m_* = 3M_\odot$

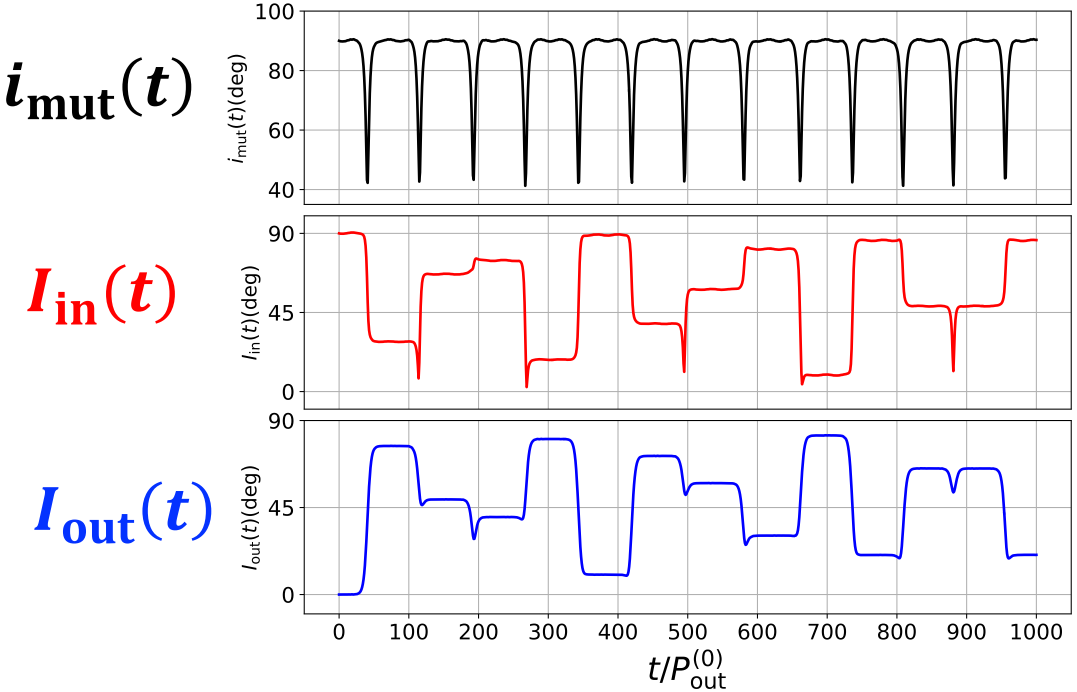
$e_{\mathrm{out}} = 0.03$

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

$i_{\mathrm{mut}} = 90°$





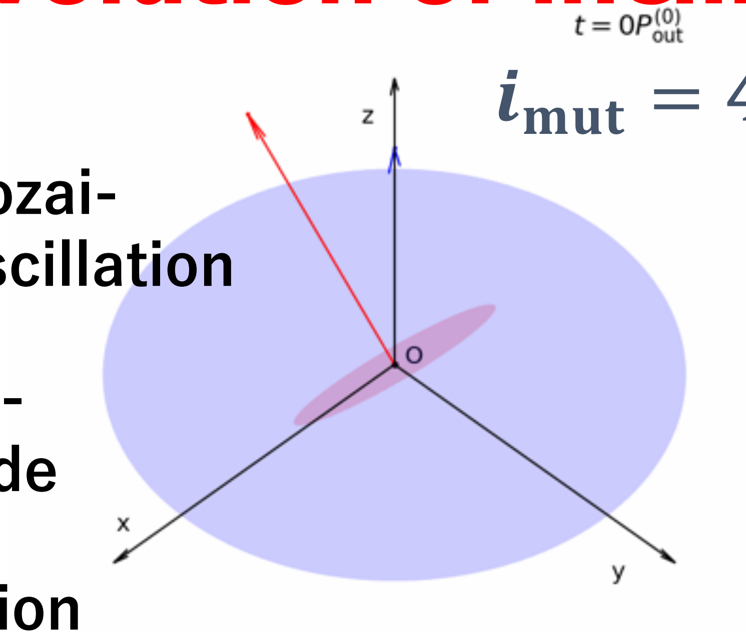


Evolution of inclination for non-coplanar triples

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

weak Kozai-Lidov oscillation

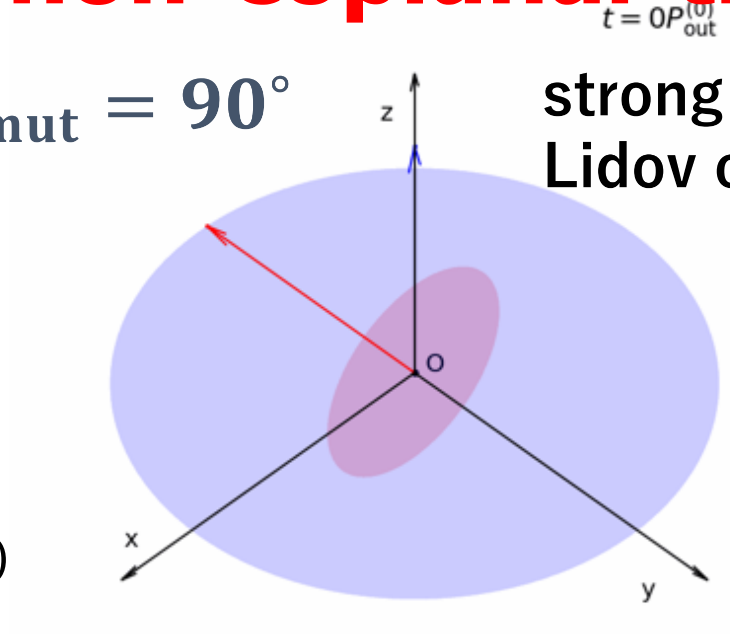
⇒ small-amplitude regular precession



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

strong Kozai-Lidov oscillation

⇒ large-amplitude sporadic precession

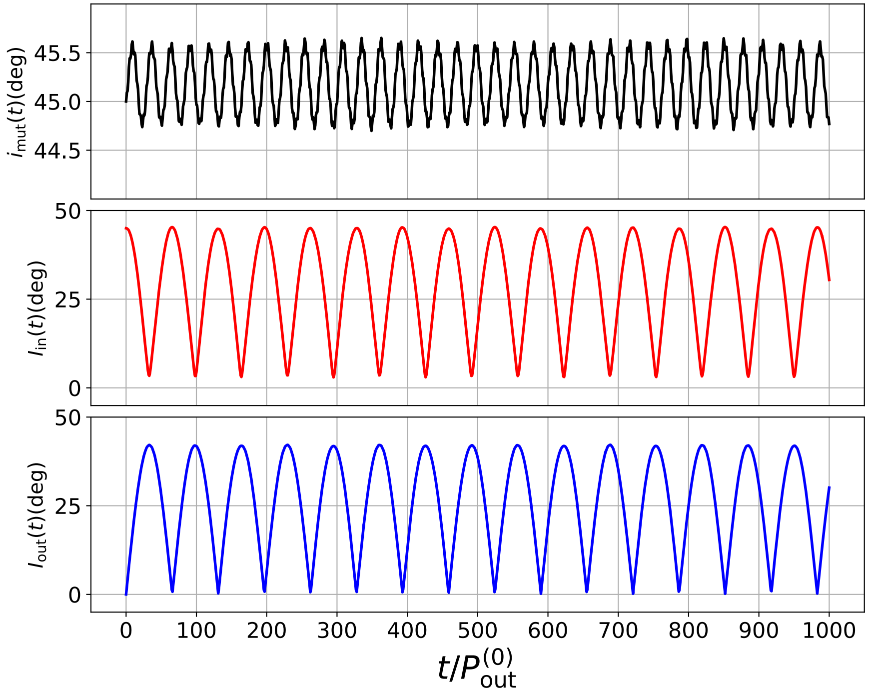


$$K_{\mathrm{Kep}} = K_0 \sin I_{\mathrm{out}}(t)$$

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

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

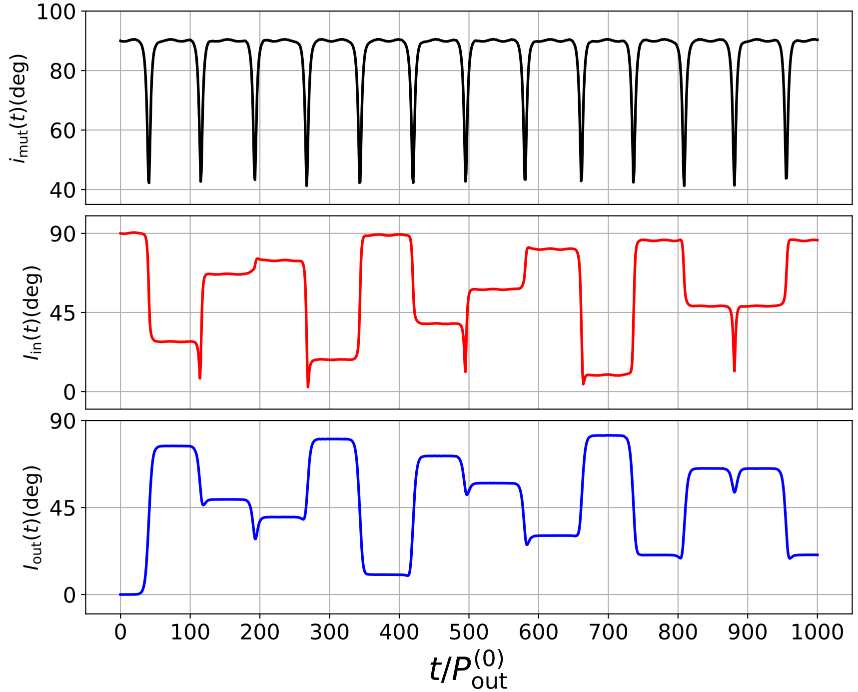
$I_{\mathrm{out}}(t)$



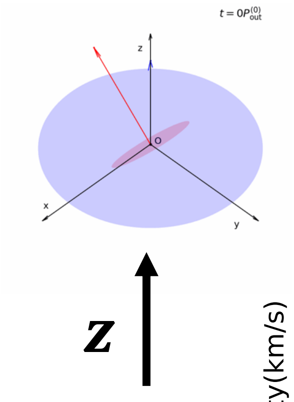
$i_{\mathrm{mut}}(t)$

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

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

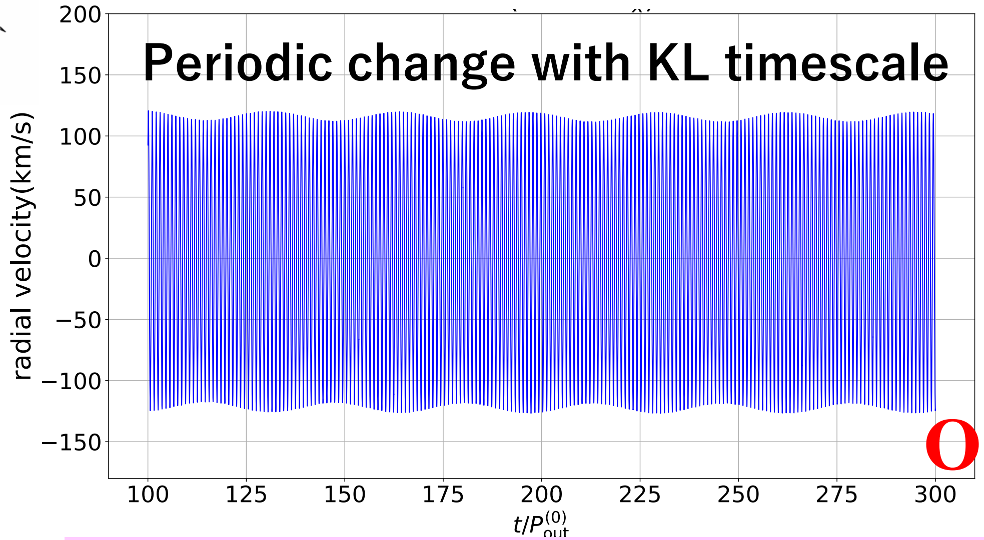


Evolution of radial velocity for non-coplanar triples



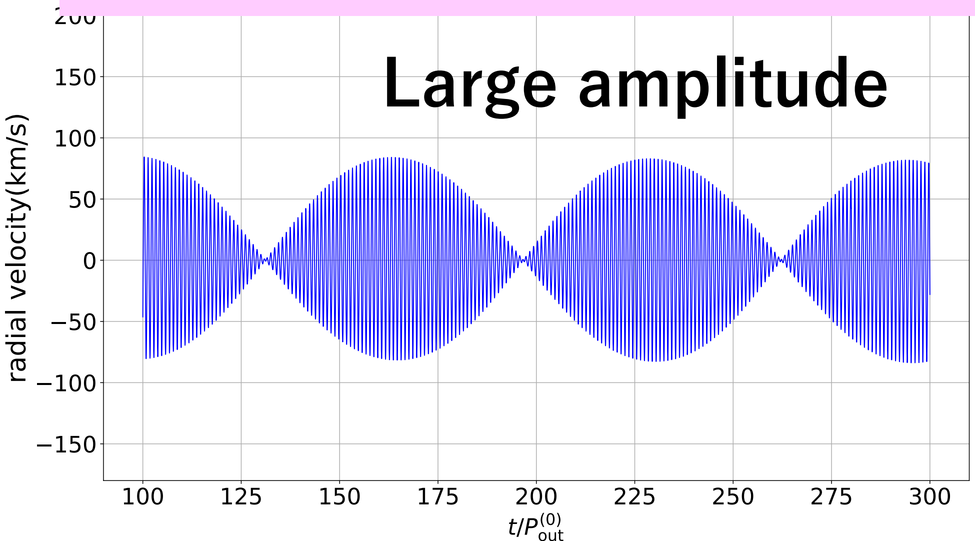
$i_{\mathrm{mut}} = 45°$ $K_{\mathrm{Kep}} = K_0 \sin I_{\mathrm{out}}(t)$

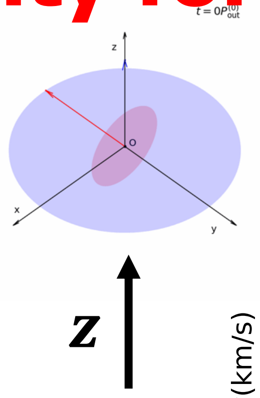
x-direction (near edge-on) total RV



O(100)km/s

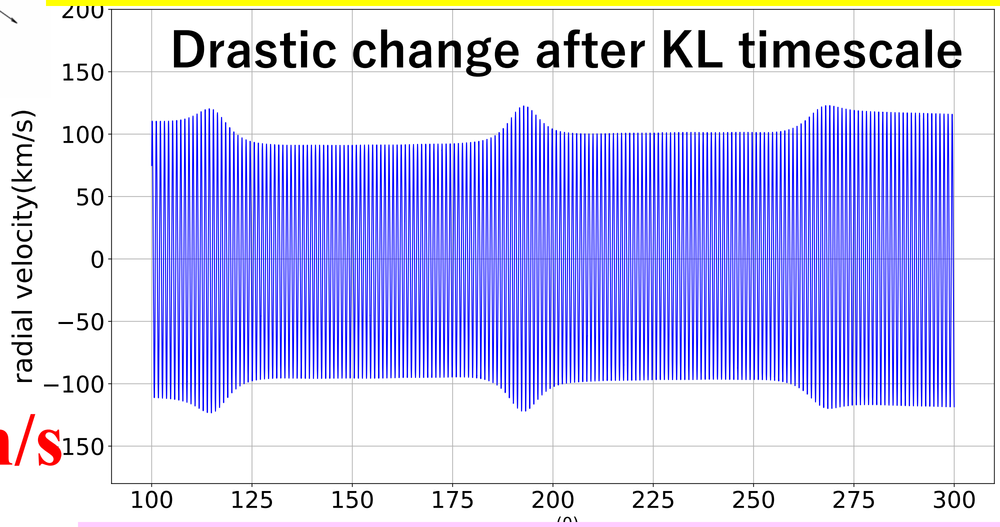
z-direction (near face-on) total RV



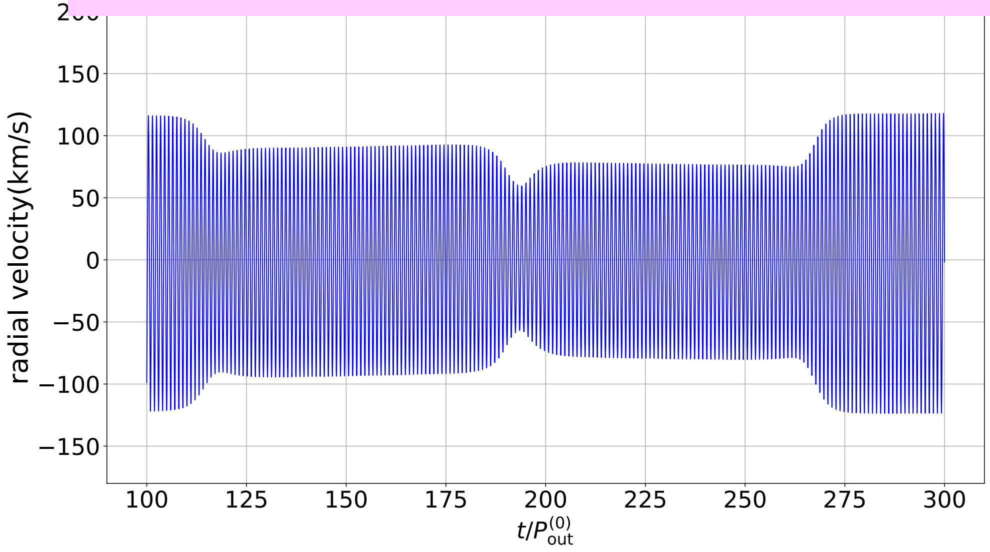


$i_{\mathrm{mut}} = 90°$

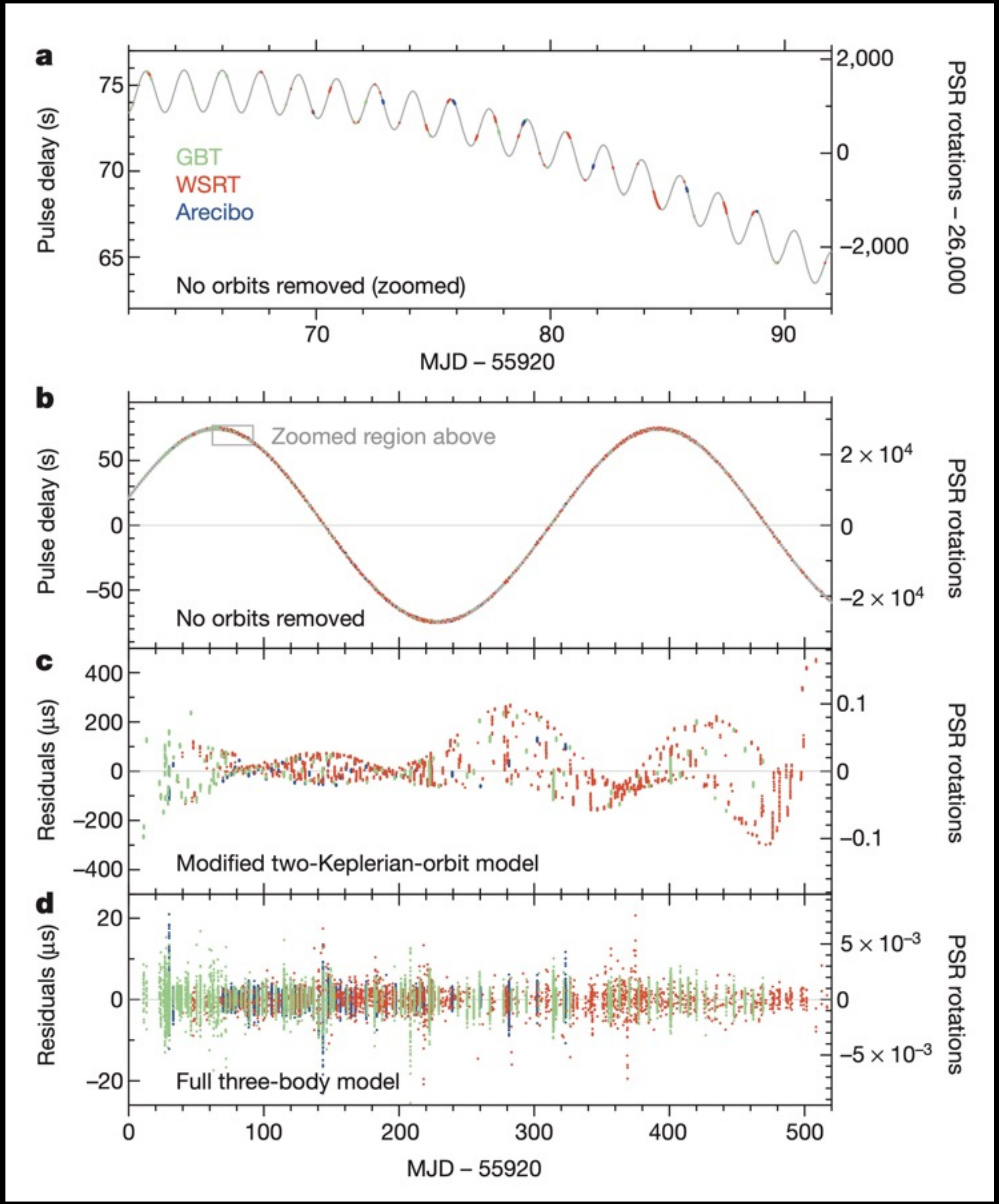
x-direction (near edge-on) total RV



z-direction (near face-on) total RV



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



PSR J0337+1715 @ 1.3kpc	
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 O(10)pc
- Pulsar arrival timing analysis
  - Very precise measurement feasible
  - can survey almost the entire Galaxy O(kpc)
  - Systematic survey (Pulsar Timing Array) already on-going
- 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

A Danish astronomer
Ole Christensen Rømer
(1644-1710)

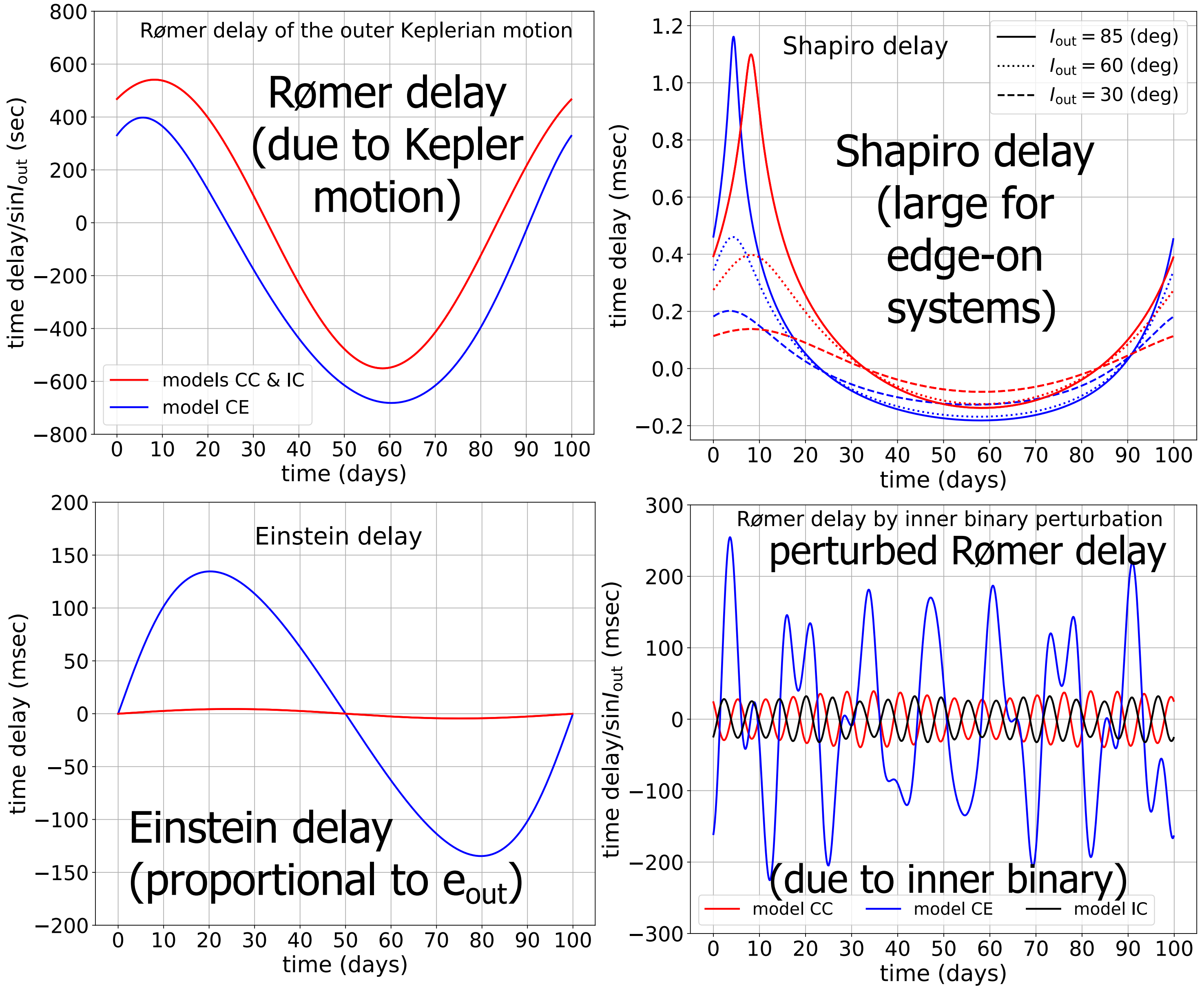
Examples of pulsar arrival timing curves for triples

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

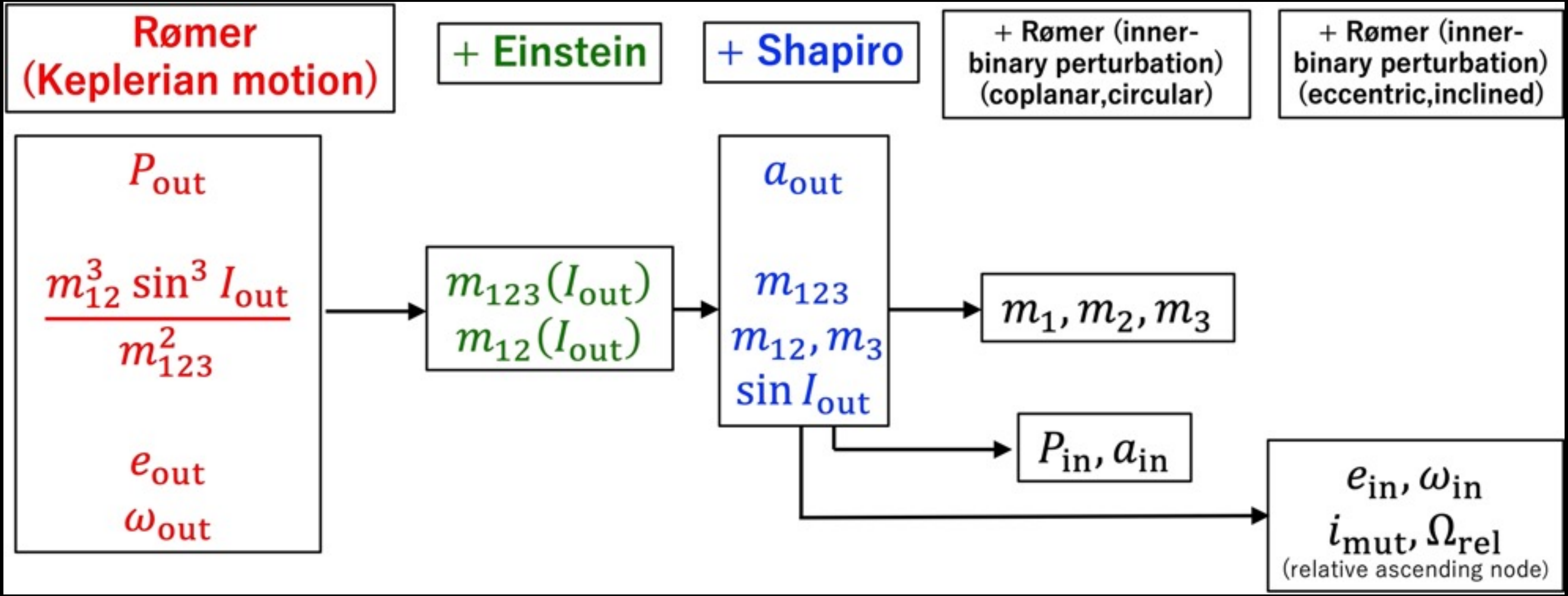
$$m_1 = m_2 = 10M_\odot$$
$$m_3 = 1.4M_\odot$$
$$P_{\rm out} = 100 \text{ days}$$
$$P_{\rm in} = 10 \text{ days}$$

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

Hayashi & YS (2020)

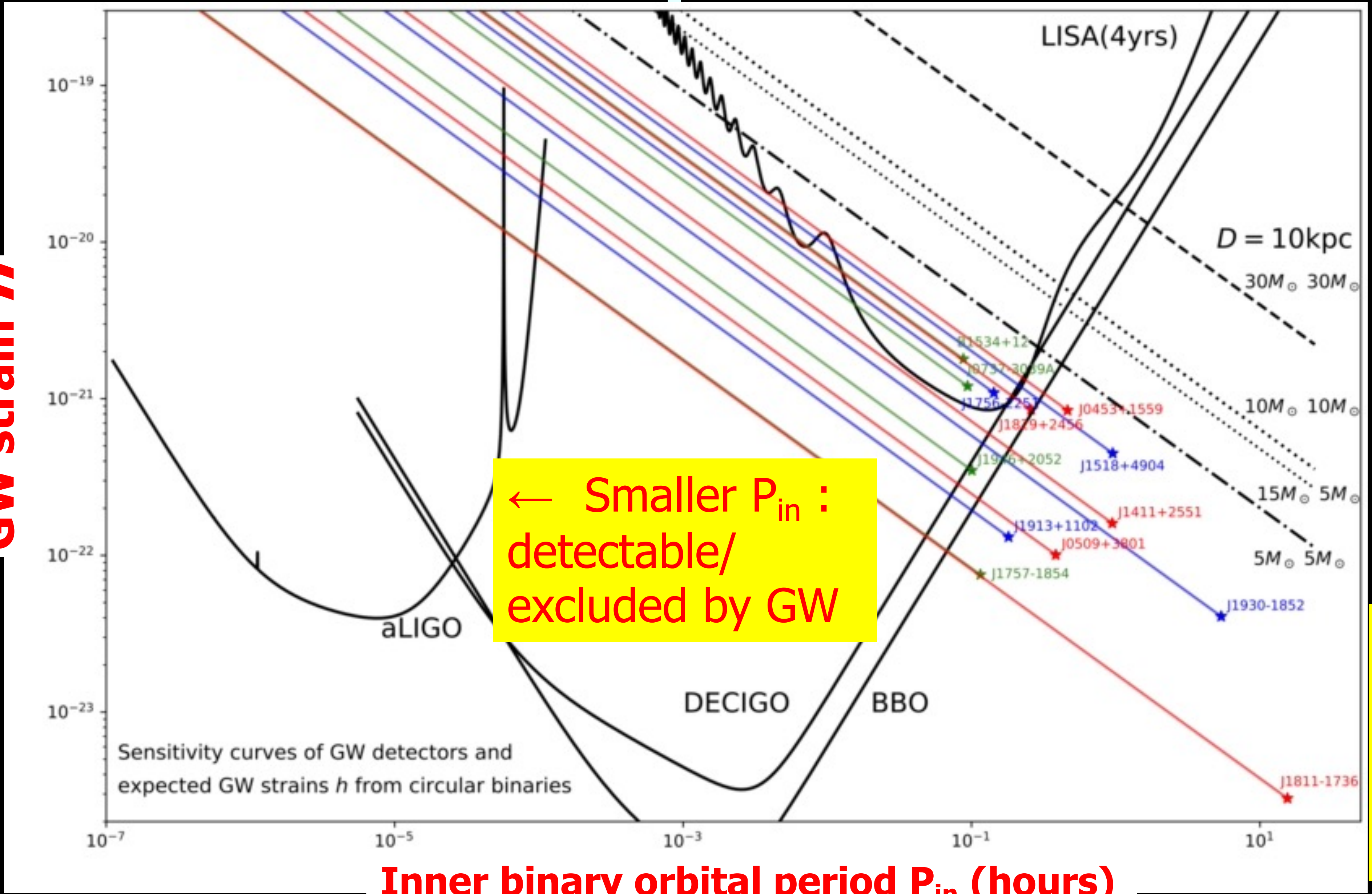


Unveiling the triple system parameters from the pulsar arrival timing analysis



Hayashi & YS (2020)

Constraints and predictions for NS binaries



← Smaller P_{in} : detectable/ excluded by GW

Circular and equal-mass inner binaries assumed

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

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 $(10\text{-}100)(P_{out}/P_{in})P_{out}$

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