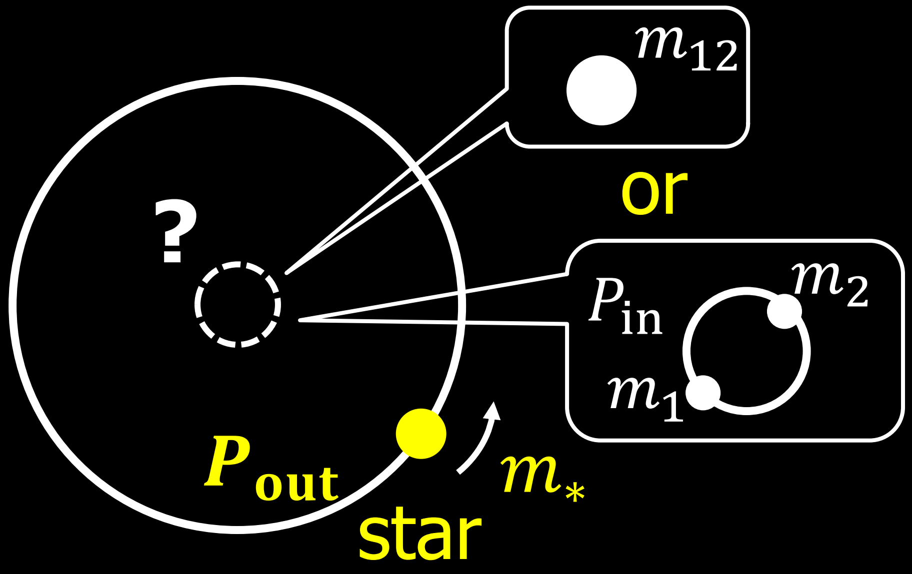
Radial velocity modulation of a tertiary star orbiting an inner binary black hole



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14:20 March 15, 2023 @Academia Sinica Institute of Astronomy and Astrophysics

My past talks at Taiwan

- Talk at the 8th Taipei Astrophysics Workshop AMiBA2001: high-z clusters, missing baryons and CMB polarization@National Taiwan University and Grand Formosa（June11-15, 2001）“Clustering of Dark Matter Halos on the Light-cone”
- Matter and Energy in Clusters of Galaxies@National Central University, Chung-Li, Taiwan (April 23-27, 2002) “Density profiles and clustering of dark halos and clusters of galaxies”
- DENET-Taiwan HSC collaboration meeting@ASIAA, Taipei (March 7-8, 2011) "DENET and Sumire collaboration”
- Seminar@ASIAA (February 2, 2012) "Cosmological implications of inhomogeneities in intra-cluster gas”
- Colloquium@ASIAA (February 3, 2012) "Colors of a second Earth"

Today’s talk

1. Three-body dynamics: old and new problem
2. Hierarchical three-body systems
3. Secular-perturbation theory in the three-body problem and von Zeipel-Lidov-Kozai effect
4. Search for star-blackhole binaries in optical surveys: a star-blackhole binary or a star-binary blackhole triple?
5. Dynamical signature of triple systems with an inner binary black-hole

1 Three-body dynamics: old and new problem

Celestial mechanics and the three-body problem = "superstring theory" before the 20th century

- Great mathematicians had seriously worked on the topic
  - Joseph-Louis Lagrange (1736-1813)
  - Pierre-Simon Laplace (1749-1827)
  - Johann Carl Friedrich Gauß (1777-1855)
  - Carl Gustav Jacob Jacobi (1804-1851)
  - William Rowan Hamilton (1805-1865)
  - Jules-Henri Poincaré (1854-1912)
- If quantum theory and relativity had not been discovered, three-body problem could have been the frontier in mathematical physics at the current epoch that the best scientists would choose to work on
  - what can "we" do then? $\Rightarrow$ amazing three-body systems + accurate numerical simulations that those great people never expected in their epochs

Ubiquity of triple systems in astronomy

- Stellar systems
  - more than 70% of OBA-type stars and 50% of FGK-type stars a belong to binary/multiple systems (e.g., Alpha Centauri)
- (Exo)Planetary systems
  - planets around binary stars, multi-planets, satellites,,,
- Compact objects
  - Possible pathway towards binary BHs detected by GW
  - Binaries (stars, BHs) around a supermassive BH in galaxies
  - Triples of compact objects, e.g., pulsar-WD binary + tertiary WD (Ransom et al. 2014)

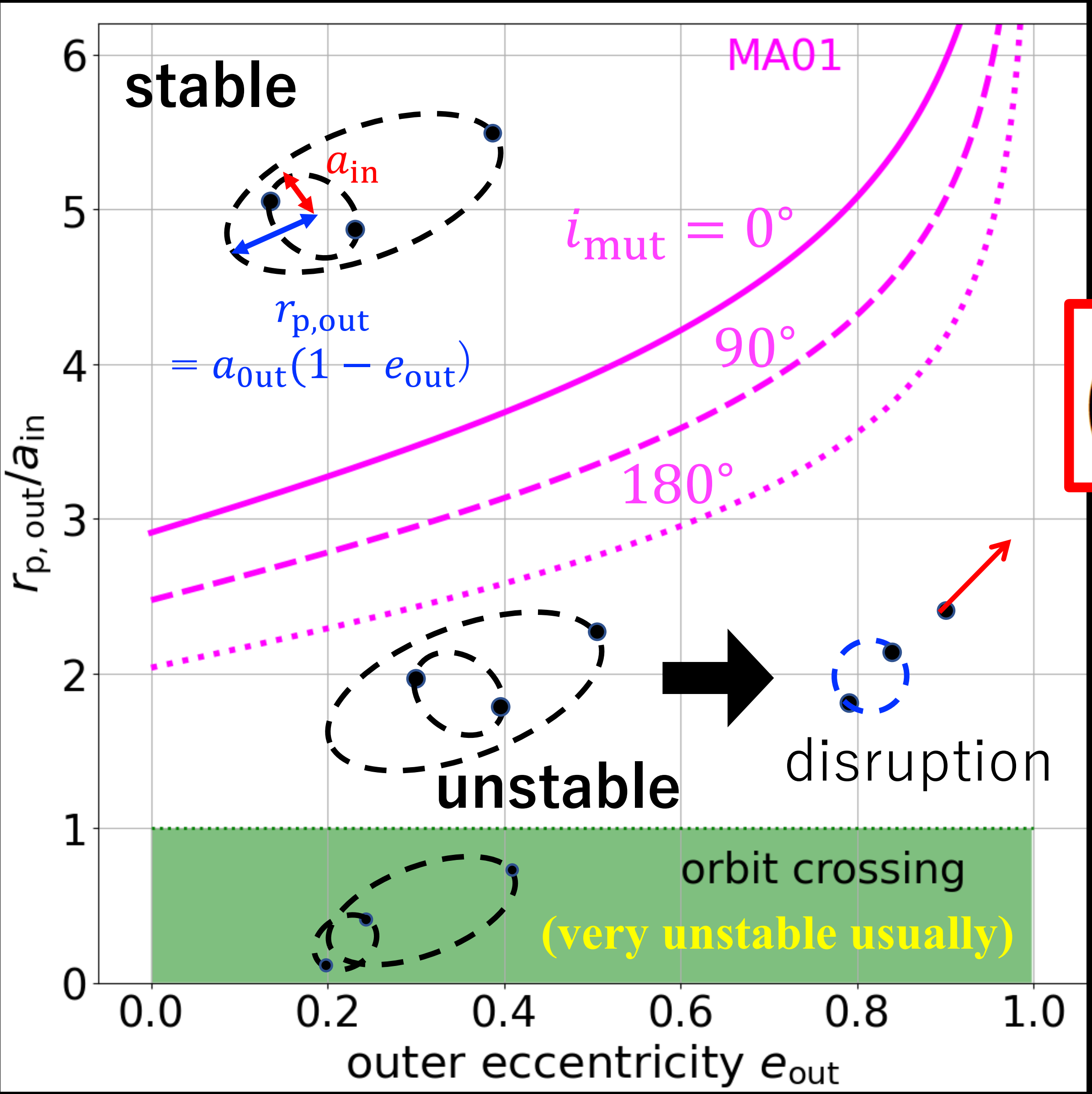
Diversities triggered by triple dynamics

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"

2 Hierarchical three-body systems

Triples are unstable in general ⇔ diversity



- Stability criterion

  (Mardling & Aarseth 2001)

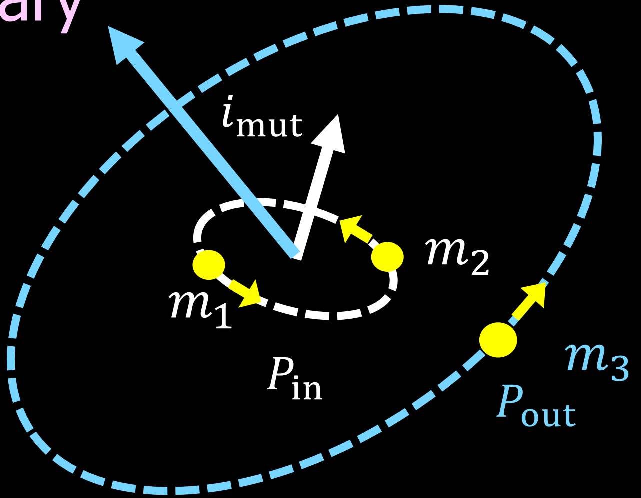
$$\left(\frac{r_{p,out}}{a_{in}}\right)_{MA} \equiv 2.8\left(1 - 0.3\frac{i_{mut}}{\pi}\right)\left[\left(1 + \frac{m_3}{m_{12}}\right)\frac{(1+e_{out})}{\sqrt{1-e_{out}}}\right]^{2/5}$$

  - Well-known and widely used, but its implication is often misinterpreted…
  - Lyapunov (chaoticity of local trajectory) vs. Lagrange (escape of a body from the system) stability
- Hayashi, Trani & YS; ApJ 939(2022)81

  ApJ 943(2023)58

Hierarchical three-body systems

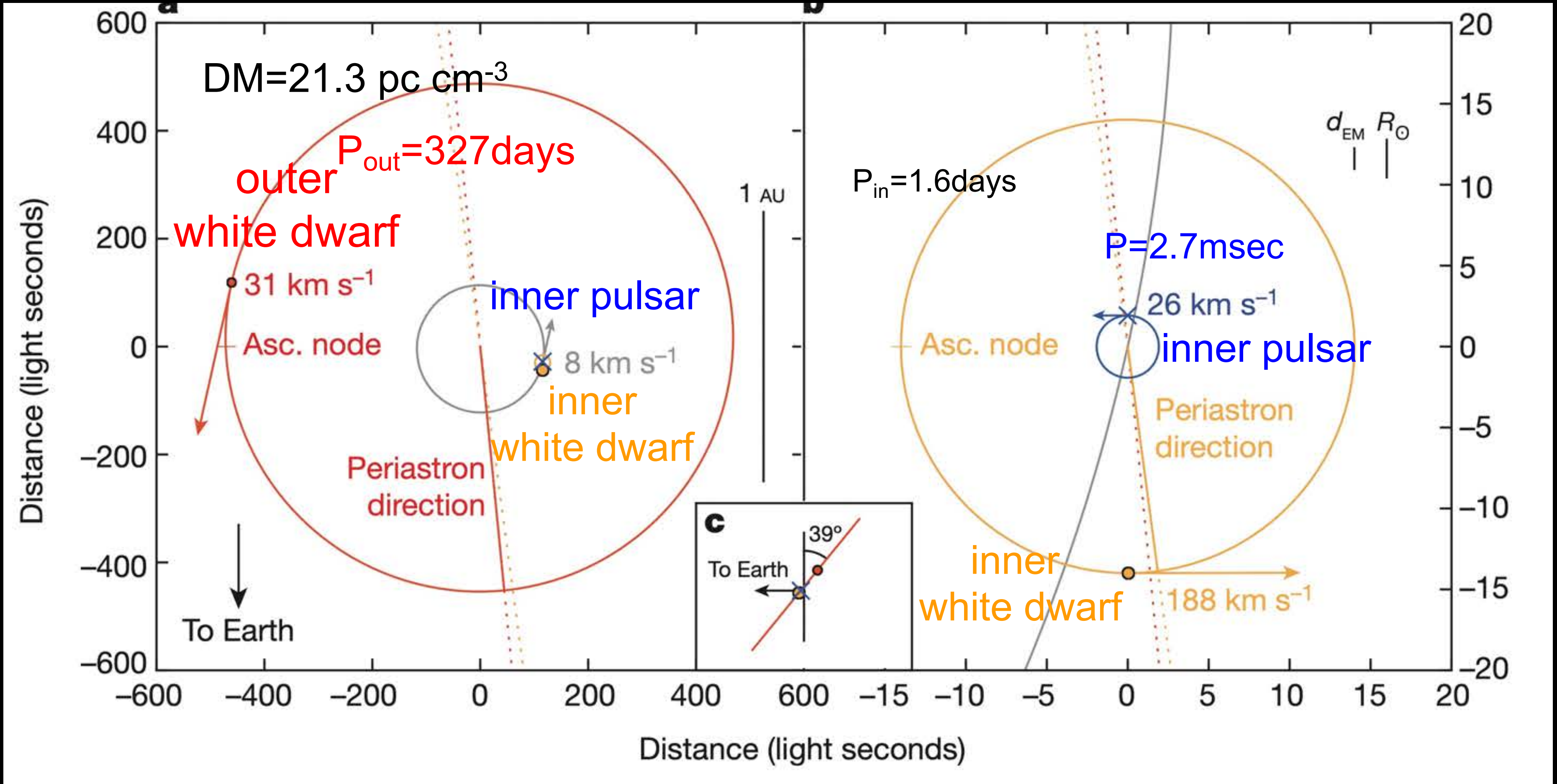
- Gravitational three-body systems are unstable in general
  - stable three-body systems are mostly hierarchical: tight binary + distant tertiary orbiting the center-of-mass of the inner binary
  - observed three-body systems are likely to be hierarchical
- Stable systems are inevitably associated with (undemocratic) hierarchies
  - quite universal in biological, astronomical and social systems
    - quarks and leptons – atoms – molecules – DNAs – cells – organs – animals – villages – cities – nations – planets – stars – star clusters – galaxies – galaxy clusters – universe(s) – multiverse(s)



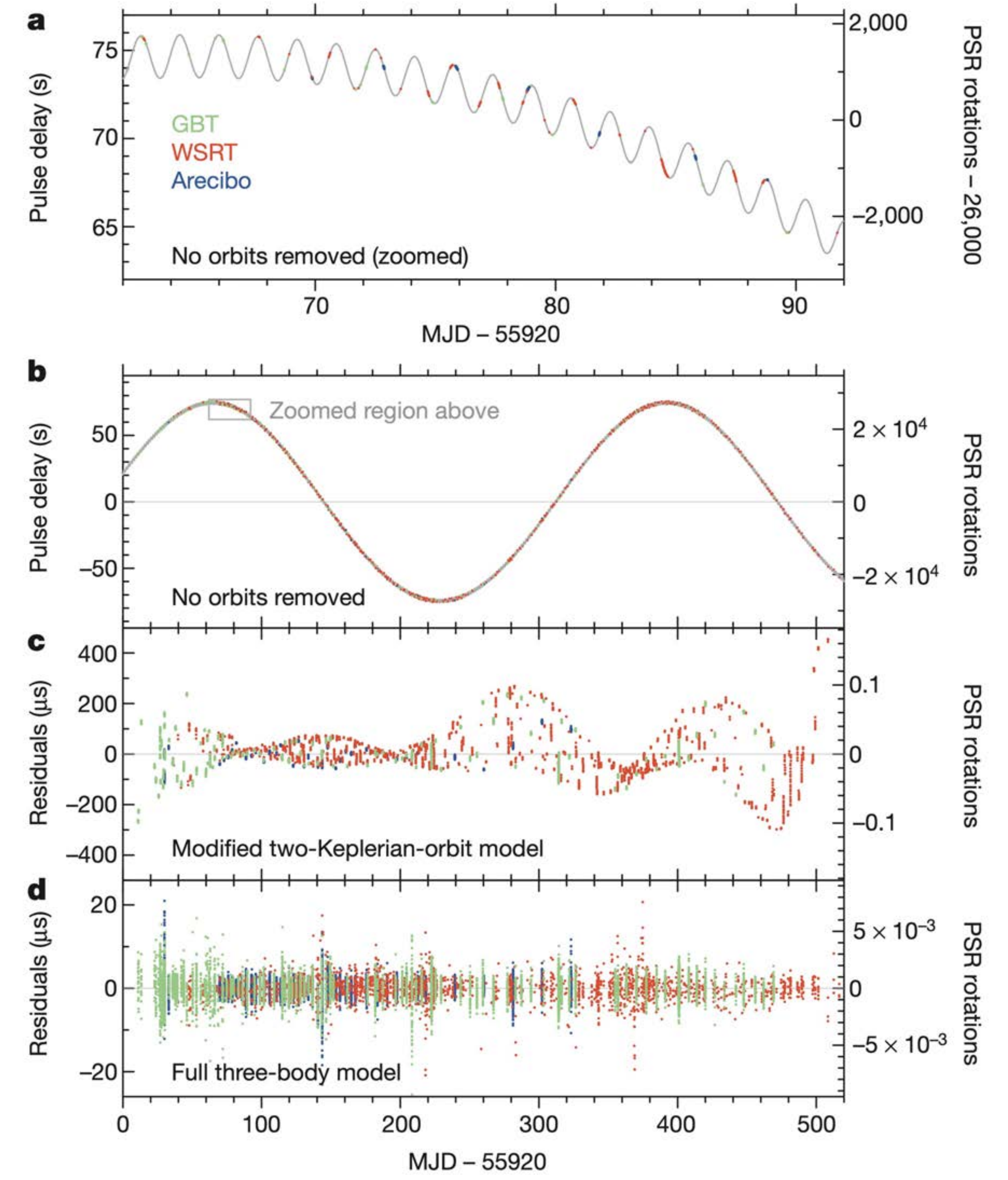
- non-intuitive (counter-intuitive) dynamical behavior of hierarchical triples triggers unexpectedly broad diversities in astronomical phenomena (e.g., ZKL effect)

A millisecond pulsar in a stellar triple system

S. M. Ransom[1], I. H. Stairs[2], A. M. Archibald[3,4], J. W. T. Hessels[3,5], D. L. Kaplan[6,7], M. H. van Kerkwijk[8], J. Boyles[9,10], A. T. Deller[3], S. Chatterjee[11], A. Schechtman-Rook[7], A. Berndsen[2], R. S. Lynch[4], D. R. Lorimer[9], C. Karako-Argaman[4], V. M. Kaspi[4], V. I. Kondratiev[3,12], M. A. McLaughlin[9], J. van Leeuwen[3,5], R. Rosen[1,9], M. S. E. Roberts[13,14] & K. Stovall[15,16]



Ransom et al. Nature 505 (2014) 520



Ransom et al.
Nature 505(2014)520
NS-WD binary + WD

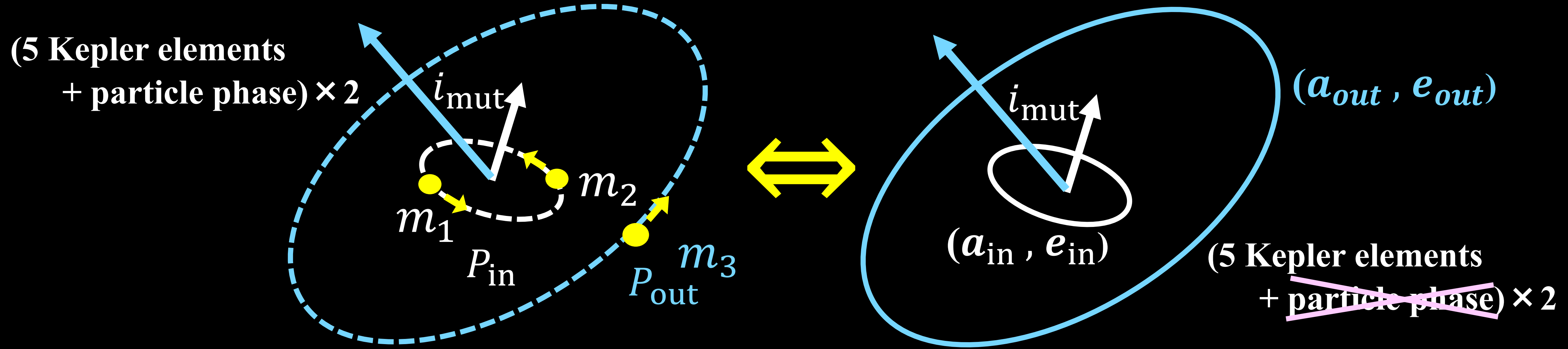
PSR J0337+1715 parameters	
inner orbital period (pulsar+WD)	1.629401788(5) day
outer orbital period (WD)	327.257541(7) day
pulsar spin period	2.73258863244(9) msec
mutual orbital inclination	0.0120(17) deg.
Pulsar mass	1.4378(13) $M_\odot$
Inner WD mass	0.19751(15) $M_\odot$
Outer WD mass	0.4101(3) $M_\odot$

highly circular & coplanar !

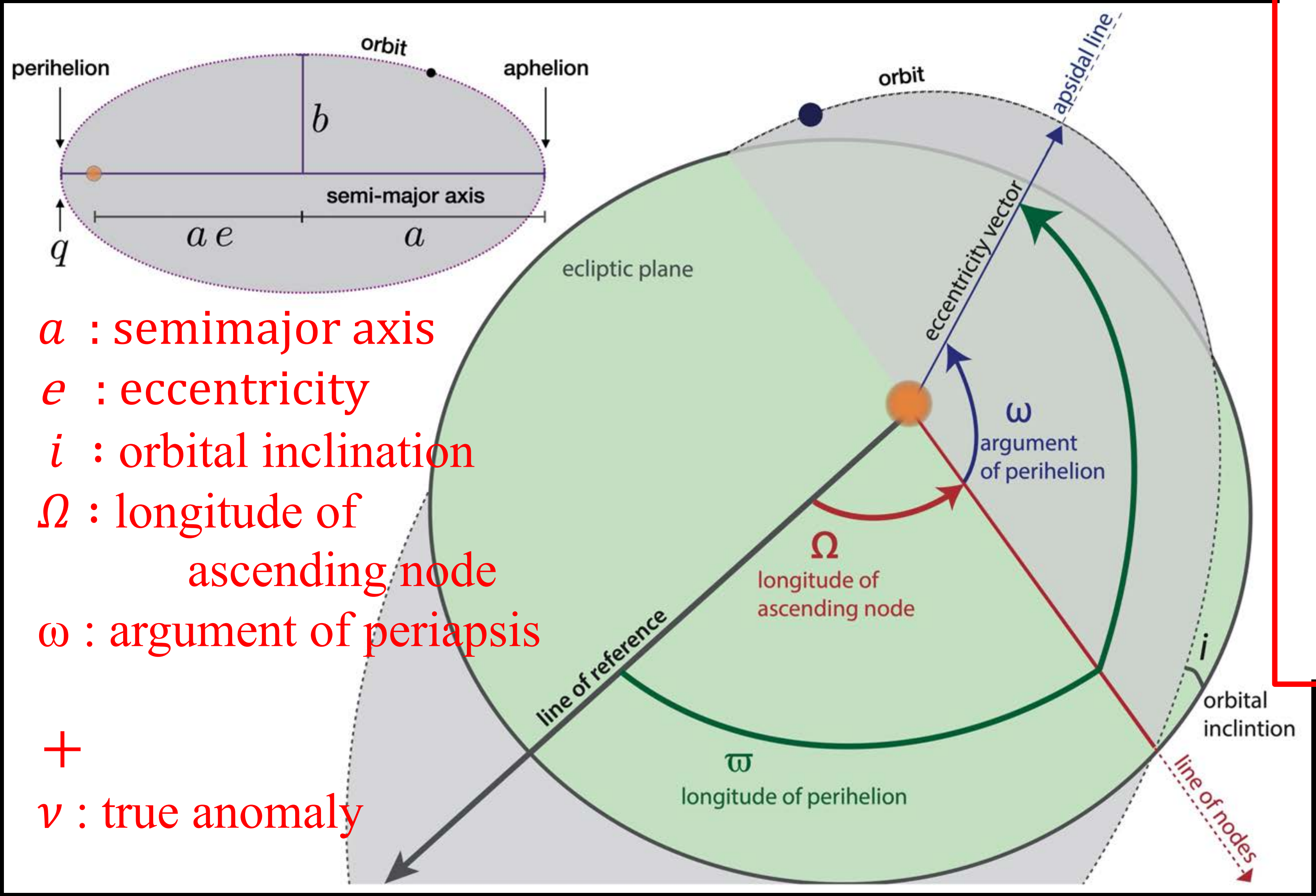
3 Secular-perturbation theory in the three-body problem and von Zeipel-Lidov-Kozai effect

Secular approximation to triple dynamics

- Very different timescales involved: $P_{in} \ll P_{out}$
  - time-consuming for accurate numerical integration
- perturbative expansion in terms of $a_{in}/\ a_{out}$ ($\ll 1$)
  - long-time numerical integration by approximating the particle-particle interaction with the ring-ring interaction over appropriate time-averaging of particles on their orbits



Kepler orbital elements



a : semimajor axis

e : eccentricity

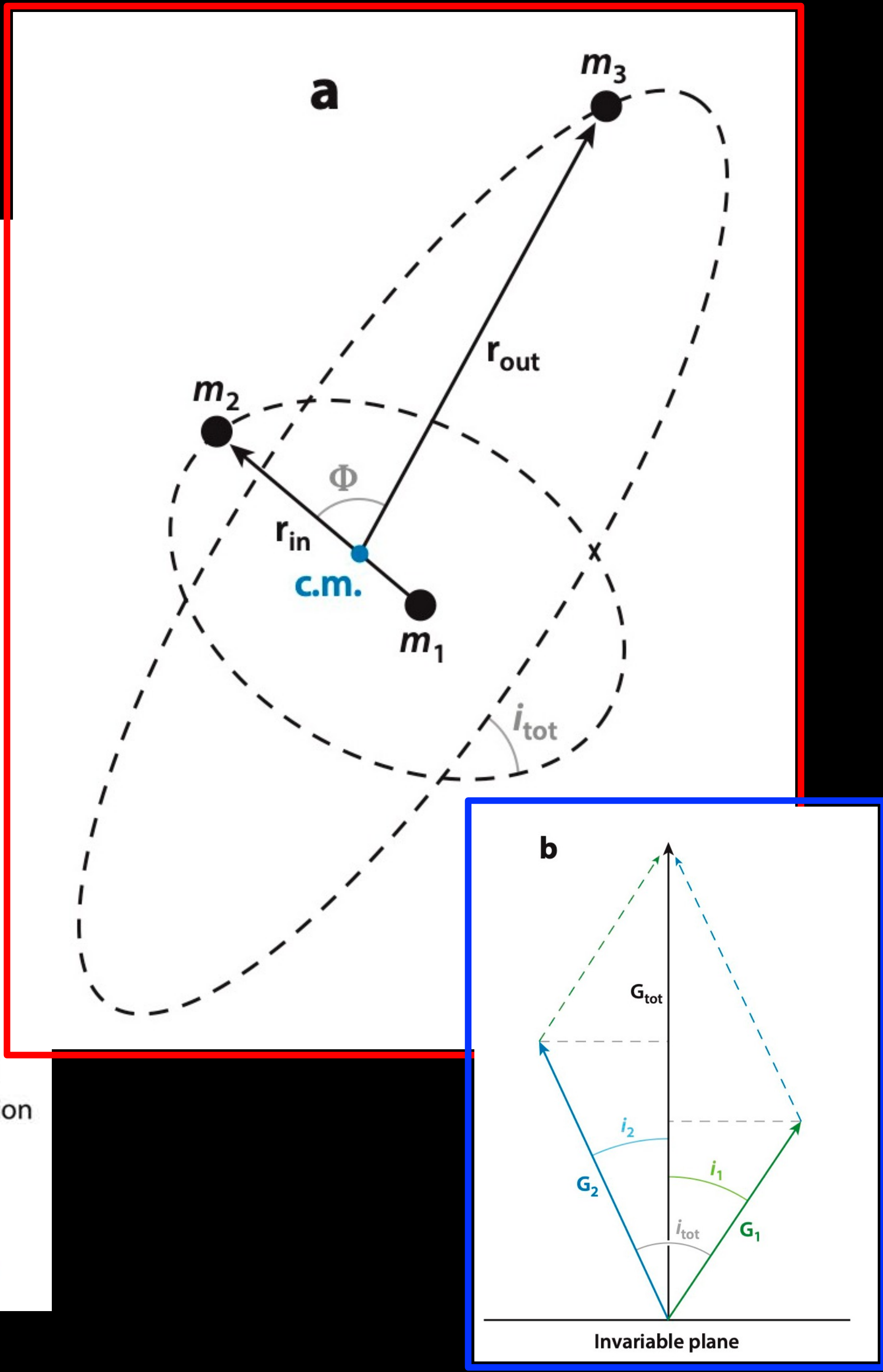
i : orbital inclination

Ω : longitude of ascending node

ω : argument of periapsis

+

ν : true anomaly



Legendre expansion of Hamiltonian

Kepler motion for inner orbit

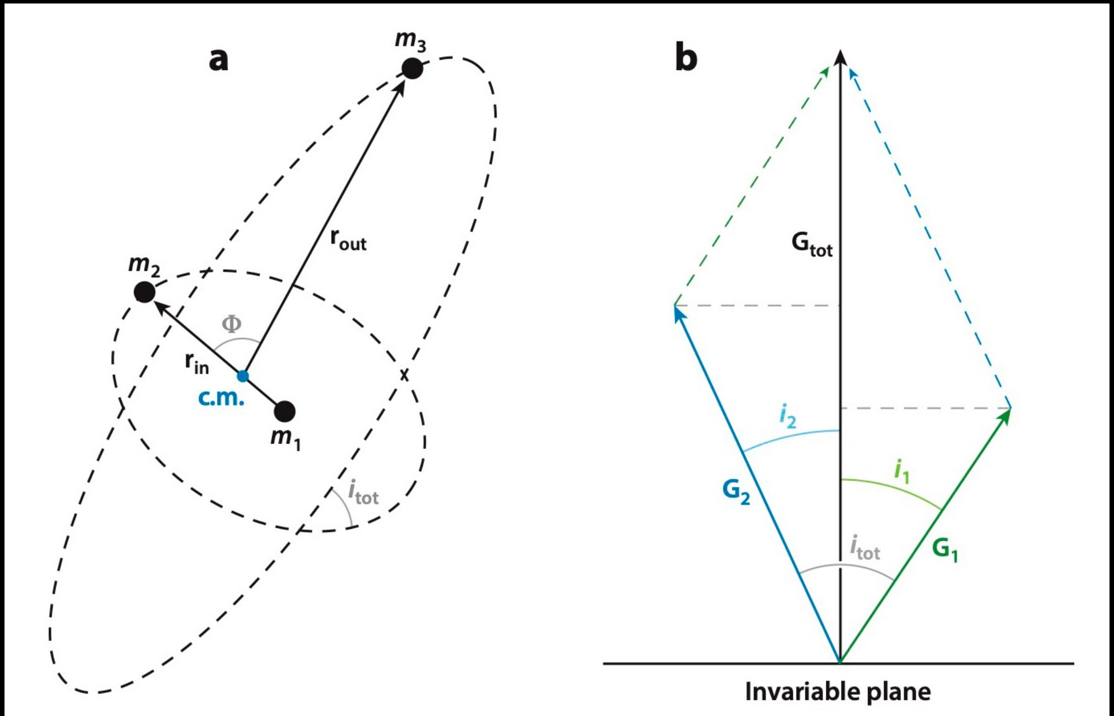
interaction between inner and outer orbits

$$\mathcal{H} = \frac{k^2 m_1 m_2}{2a_1} + \frac{k^2 m_3 (m_1 + m_2)}{2a_2} + \frac{k^2}{a_2} \sum_{n=2}^{\infty} \left(\frac{a_1}{a_2}\right)^n M_n \left(\frac{\mathbf{r}_{\rm in}}{a_1}\right)^n \left(\frac{a_2}{\mathbf{r}_{\rm out}}\right)^{n+1} P_n(\cos\Phi)$$

Kepler motion for outer orbit

coupling constant

$$M_n = m_1 m_2 m_3 \frac{m_1^{n-1} - (-m_2)^{n-1}}{(m_1+m_2)^n}$$



$$\mathcal{H} = \mathcal{H}_{\rm Kep,in} + \mathcal{H}_{\rm Kep,out} + \mathcal{H}_{\rm int}$$

$$\mathcal{H}_{\rm int} = \mathcal{H}_{\rm quad} + \mathcal{H}_{\rm oct} + \cdots$$

⇒ approximation by double-averaging of the Hamiltonian over the inner and outer orbits

double-averaged quadrupole and octupole Hamiltonians

$$\langle \mathcal{H}_{\rm quad} \rangle = \frac{\mu_{12}\Phi_0}{16}\left[(2+3e_1^2)(3\cos^2 i_{\rm tot} - 1) + 15 e_1^2 \sin^2 i_{\rm tot} \cos 2\omega_1\right]$$

$$\langle \mathcal{H}_{\rm oct} \rangle = -\frac{15}{64}\mu_{12}\Phi_0 e_1 \varepsilon_{\rm oct}\left[A\cos\phi + 10\cos i_{\rm tot} \sin^2 i_{\rm oct}(1-e_1^2)\sin\omega_1 \sin\omega_2\right]$$

$$\varepsilon_{\rm oct} = \frac{m_1 - m_2}{m_1 + m_2}\frac{a_1}{a_2}\frac{e_2}{1-e_2^2}$$

$$\mu_{12}\Phi_0 = \frac{m_1 m_2}{m_1 + m_2}\frac{G m_3 a_1^2}{a_2^3 (1-e_2^2)^{3/2}}$$

- octupole term vanishes if $m_1 = m_2$ (equal-mass inner binary) or $e_2 = 0$ (circular outer orbit)
- both a_{in} and a_{out} are conserved in the secular approximation ⇒ no energy exchange between inner and outer orbits (angular momentum exchange alone)

$$A = 4 + 3e_1^2 - \frac{5}{2}\sin^2 i_{\rm tot}(2 + 5e_1^2 - 7e_1^2 \cos 2\omega_1)$$

$$\cos\phi = -\cos\omega_1 \cos\omega_2 - \cos i_{\rm tot} \sin\omega_1 \sin\omega_2$$

von Zeipel-Lidov-Kozai effect

- Takashi Ito and Katsuhito Ohtsuka (2019) “The Lidov–Kozai Oscillation and Hugo von Zeipel” Monogr. Environ. Earth Planets, 7, 1–113
- von Zeipel, H. (1910) “Sur l'application des séries de M. Lindstedt à l'étude du mouvement des comètes périodiques”, Astronomische Nachrichten, 183, 345–418
- M.L. Lidov (1961) “Evolution of the orbits of artificial satellites of planets as affected by gravitational perturbation from external bodies” Artificial Earth Satellite, 8, 5–45
- Kozai, Yoshihide (1962) “Secular perturbations of asteroids with high inclination and eccentricity” The Astronomical Journal, 67, 591–598
- Naoz, S. (2016) “The eccentric Kozai–Lidov effect and its applications”, Annual Reviews of Astronomy and Astrophysics, 54, 441–489

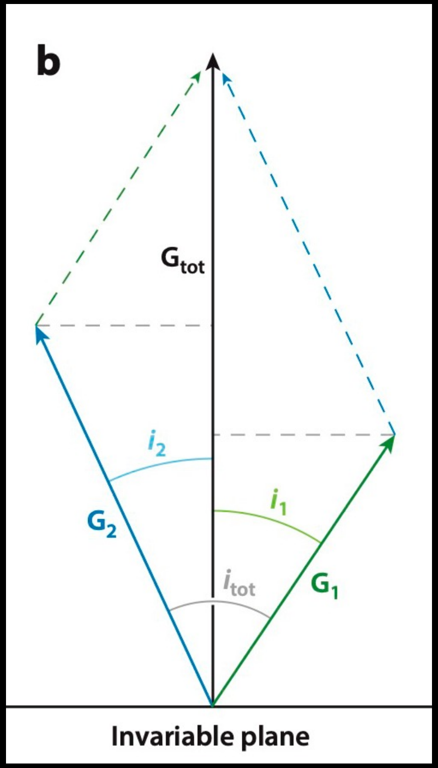
standard and eccentric ZKL effects

- standard ZKL
  - test particle limit (m_2=0) and circular outer orbit (e_{out}=0)
  - angular momentum of the inner orbit along the total (outer) orbital axis is conserved

$$j_{1,z} = \sqrt{1-e_1^2}\cos i_1 = \sqrt{1-e_{1,\mathrm{init}}^2}\cos i_{1,\mathrm{init}}$$

  - inner eccentricity and inclination periodically change with

$$e_{1,\max} = \sqrt{1-\frac{5}{3}\cos^2 i_{1,\mathrm{init}}}$$ if $$39.2^\circ < i_{1,\mathrm{init}} < 140.8^\circ$$



- eccentric ZKL
  - $e_{out}\sim 1 \Rightarrow$ more drastic effect due to the octupole term

examples of ZKL effects in secular approximation

Naoz, S: ARAA 54(2016)441

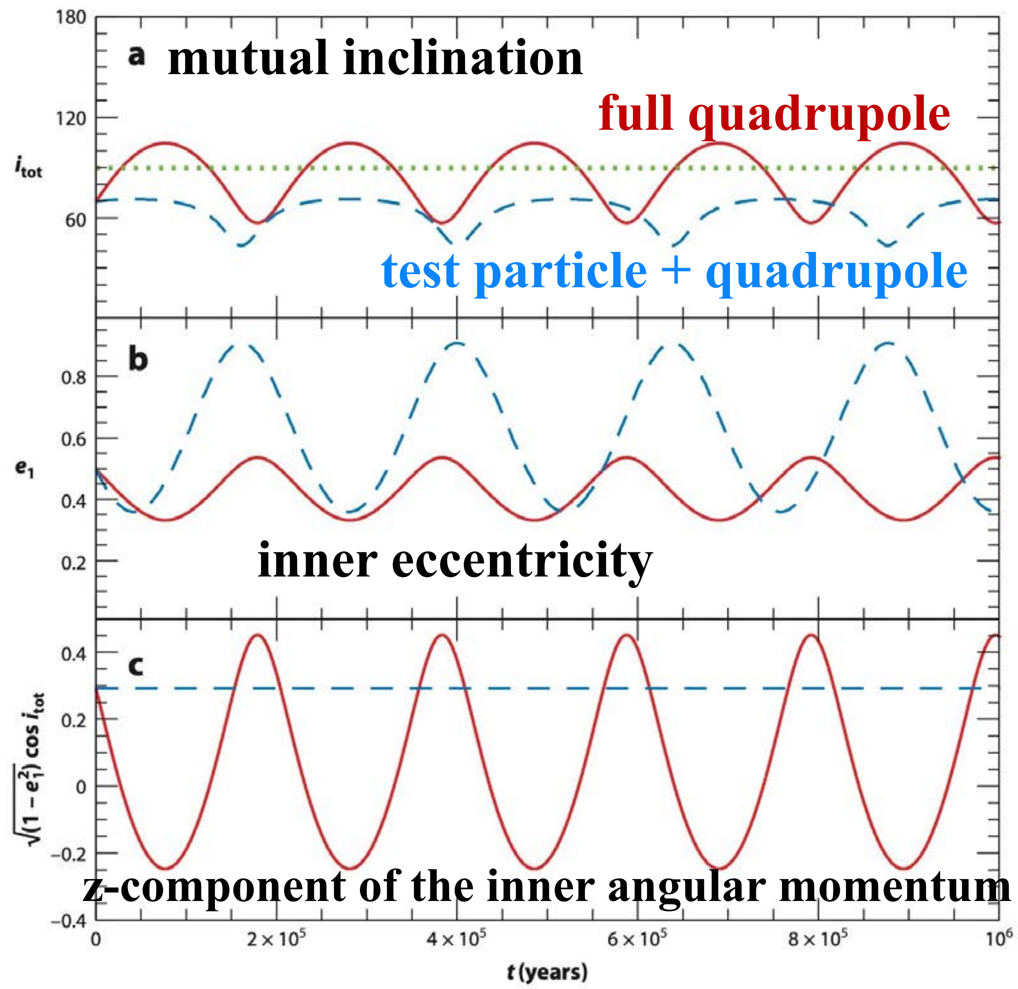


Figure 3

Comparison between the test particle quadrupole (TPQ) formalism (*dashed blue lines*) and the full quadrupole calculation (*solid red lines*). The system has an inner binary with $m_1 = 1.4 M_\odot$ and $m_2 = 0.3 M_\odot$, and the outer body has mass $m_3 = 0.01 M_\odot$. The orbit separations are $a_1 = 5$ AU and $a_2 = 50$ AU. The system was set initially with $e_1 = 0.5$ and $e_2 = 0$, $\omega_1 = 120°$ and $\omega_2 = 0$, and relative inclination $i_{tot} = 70°$. The panels

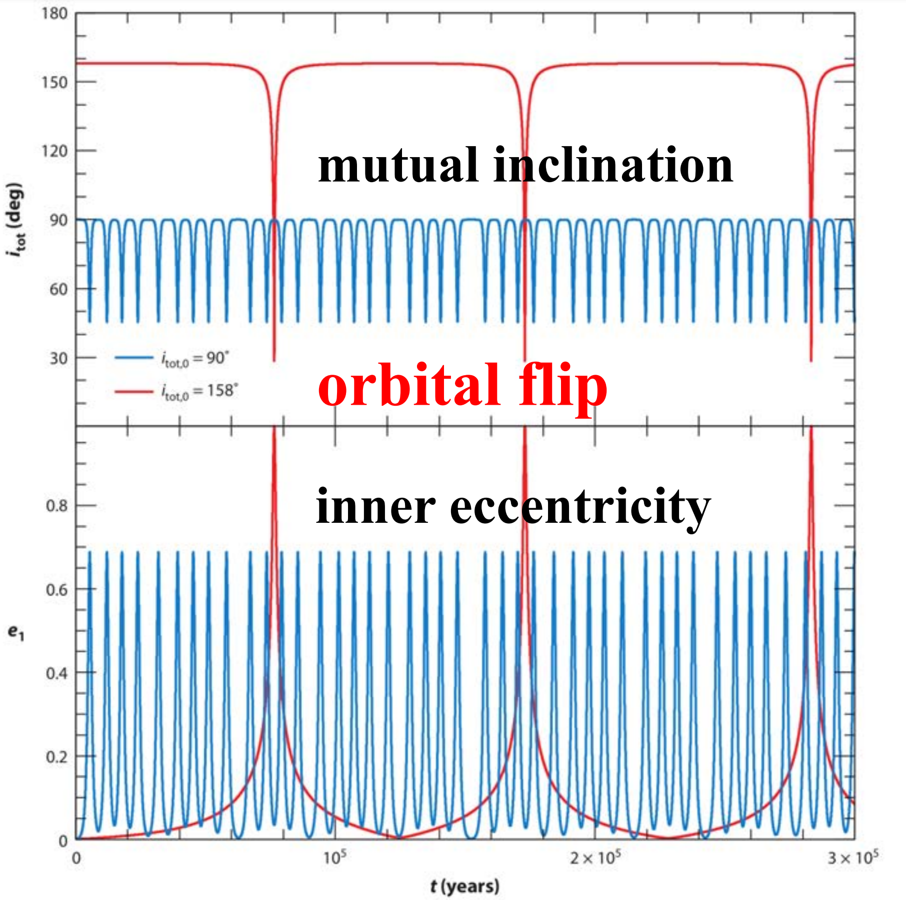
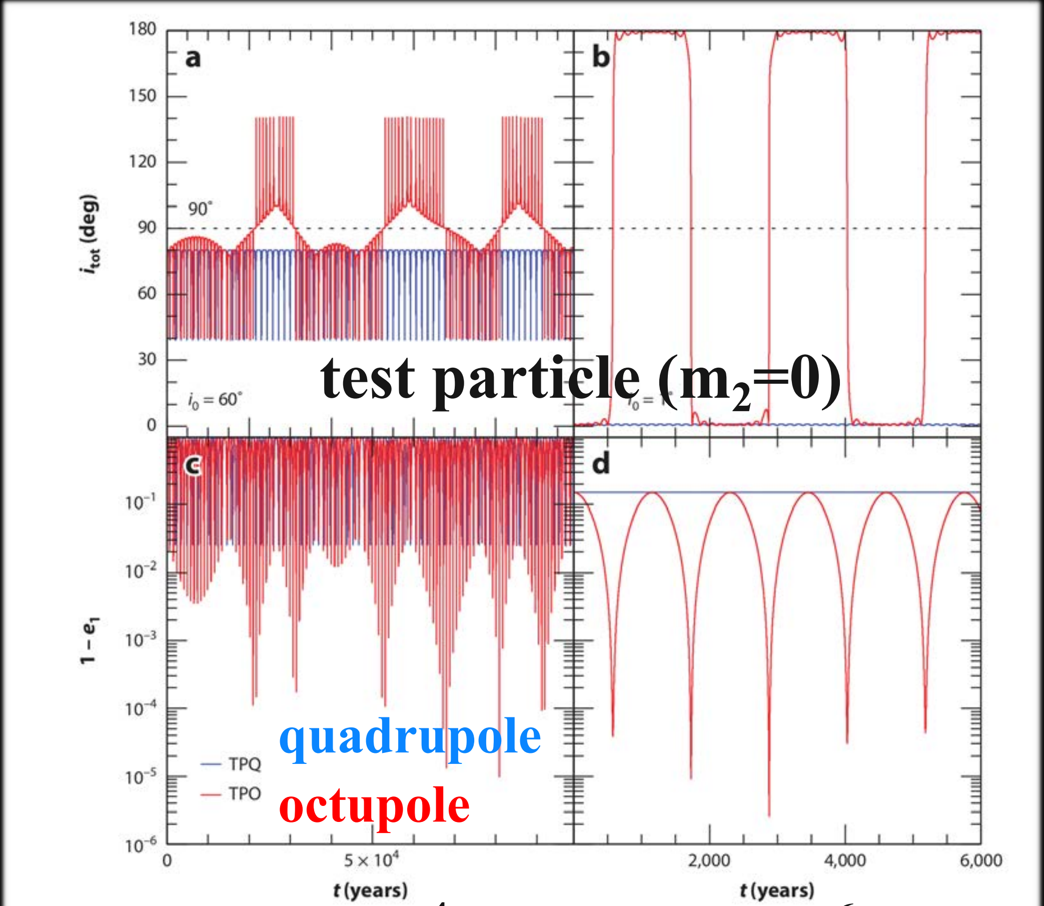


Figure 4

Small-mass outer perturber that induces large eccentricity excitation away from the nominal range of the Kozai angles of 39.2°–140.77°. We consider $m_1 = 1 M_\odot$, $m_2 = 0.5 M_\odot$, $m_3 = 0.05 M_\odot$, $a_1 = 0.5$ AU, and $a_2 = 5$ AU. Both outer and inner eccentricities are set initially to zero, and also set initially are $\omega_1 = 90°$ and $\omega_2 = 0°$. We show two examples: The first shows the eccentricity excitations for as expected initial mutual inclination of $i_{tot} = 90°$, where in this case $i_1 = 25.01°$ and $i_2 = 64.99°$. This produces eccentricity excitation with $e_{1,max} = 0.689$. We also consider an example for which the mutual inclination is set initially to be $i_{tot} = 158°$. In this case $i_1 = 17.12°$ and $i_2 = 140.88°$. The latter parameters are adapted from Martin & Triaud (2015b), which leads to maximum inner eccentricity of $e_{1,max} = 0.99$. Note that in both examples i_2 is close to the nominal Kozai angles range.

effects of octupole and general relativity

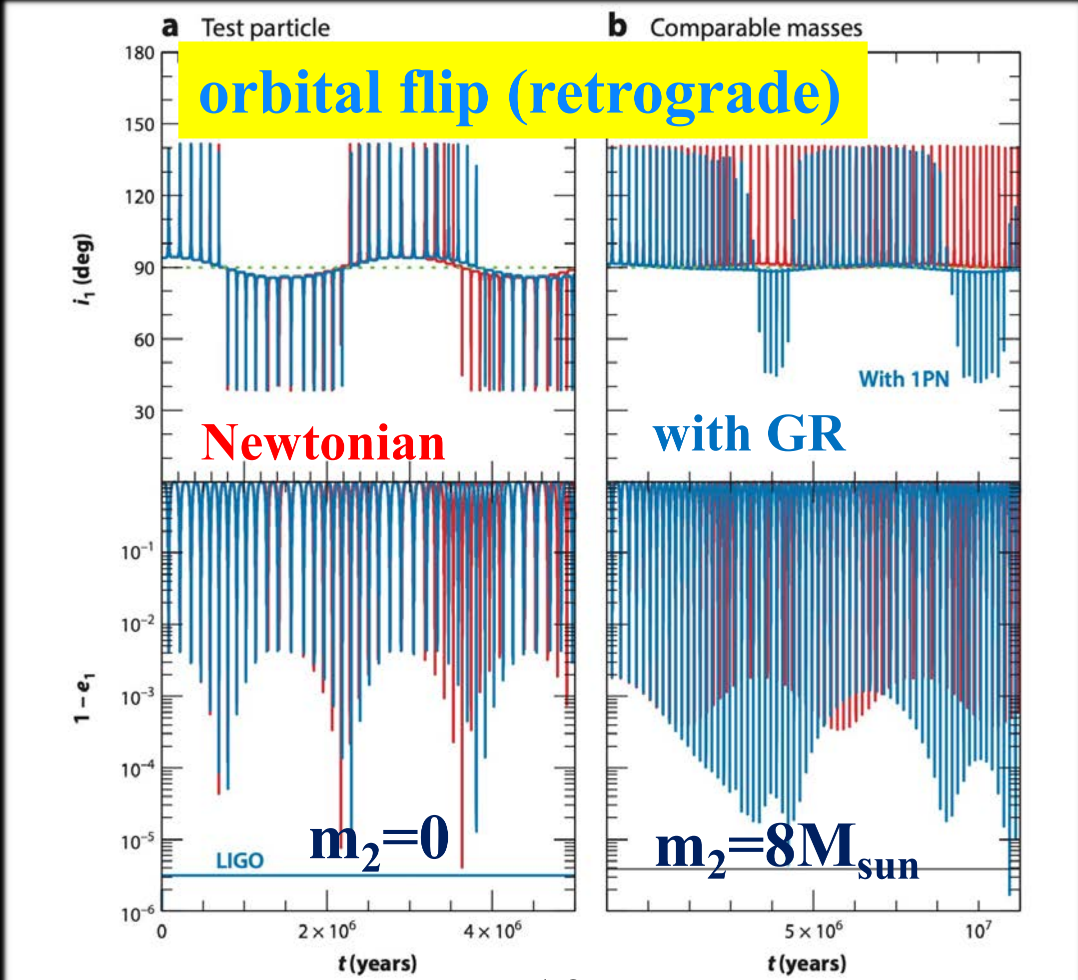
Naoz, S: ARAA 54(2016)441



$m_1=10^4 M_{sun}$ $m_3=4x10^6 M_{sun}$

Figure 5

Time evolution example of the test particle octupole (TPO) approximation (*red lines*) and the test particle quadrupole (TPQ) approximation (*blue lines*). Panels *a* and *c* show high-inclination ($i > 39.2°$) flip, whereas panels *b* and *d* show low-inclination ($i < 39.2°$) flip (high inclination $i > 39.2$, low inclination $i < 39.2$). In this example, we consider the time evolution of a test particle at 135 AU around a 10^4-$M_\odot$ intermediate black hole located 0.03 pc from the massive black hole in the center of our galaxy (4×10^6 $M_\odot$). In panels *a* and *c* the system initially is set with $e_1 = 0.01$, $e_2 = 0.7$, $i = 60°$, $\Omega_1 = 60°$, and $\omega_1 = 0°$. In panels *b* and *d* the system is initially set with $e_1 = 0.85$, $e_2 = 0.85$, $i = 1°$, $\Omega_1 = 180°$, and $\omega_1 = 0°$. In panels *a* and *b*, we show the inclination, and in panels *c* and *d* the inner orbit eccentricity as $1 - e_1$.



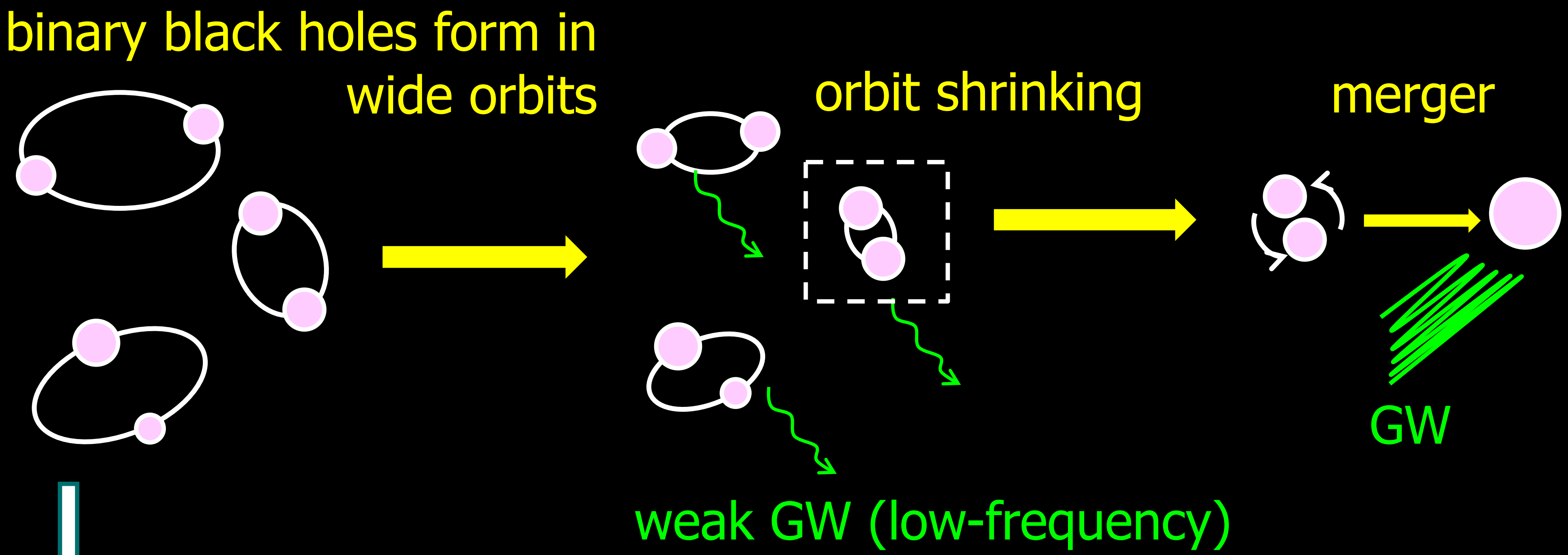
m_1=10M_{sun} m_3=30M_{sun}

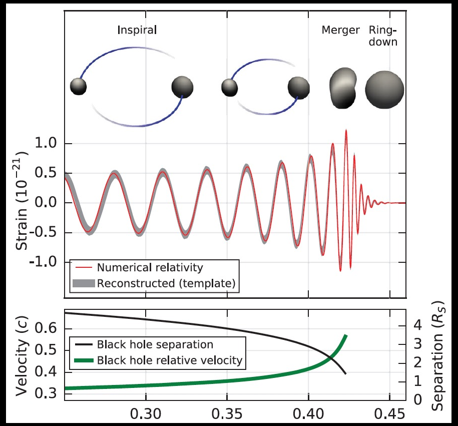
Figure 12

Comparison between the test particle approximation and a comparable-mass system in the presence of general relativity. The systems in the right and left panels have the same parameters and initial conditions apart from m_2, which is set to zero in panel *a* and $m_2 = 8$ $M_\odot$ in panel *b*. The other parameters are: $m_1 = 10$ $M_\odot$, $m_3 = 30$ $M_\odot$, $a_1 = 10$ AU, $a_2 = 502$ AU, $e_1 = 0.001$, $e_2 = 0.7$, $\omega_1 = \omega_2 = 240°$, and $i_{tot} = 94°$. Red lines correspond to pure Newtonian evolution, and blue lines include general relativity (GR)

4 Search for star-blackhole binaries in optical surveys: a star-blackhole binary or a star-binary blackhole triple?

Generic picture of binary BH evolution





LIGO/Virgo

BBHs would spend longer time in wide orbits before merging

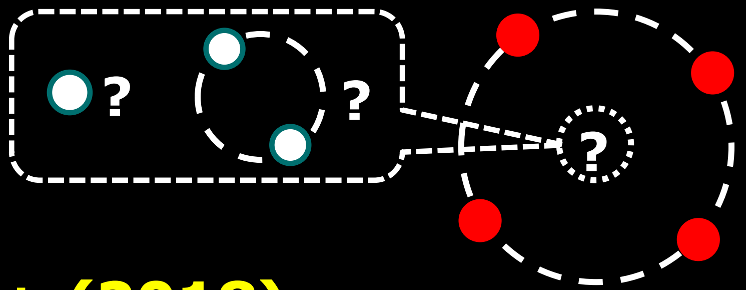
Abundant longer orbital-period BBHs may remain undetected (e.g. ~10day orbital period~10^{-6}Hz).

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)

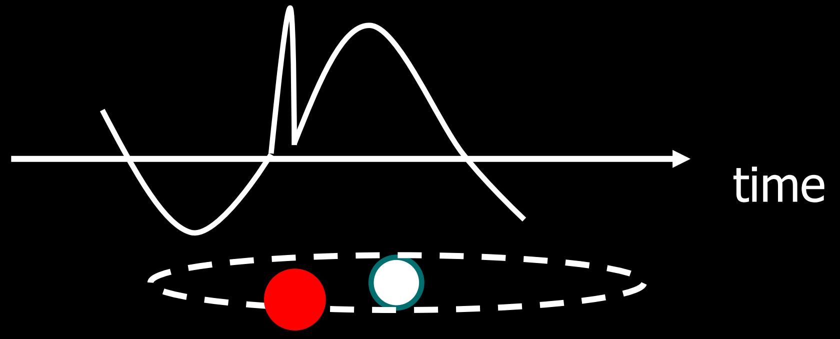
5-year mission may detect
200-1000 star-BH binaries

TESS mission (2018-)

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

Masuda & Hotokezaka (2019)

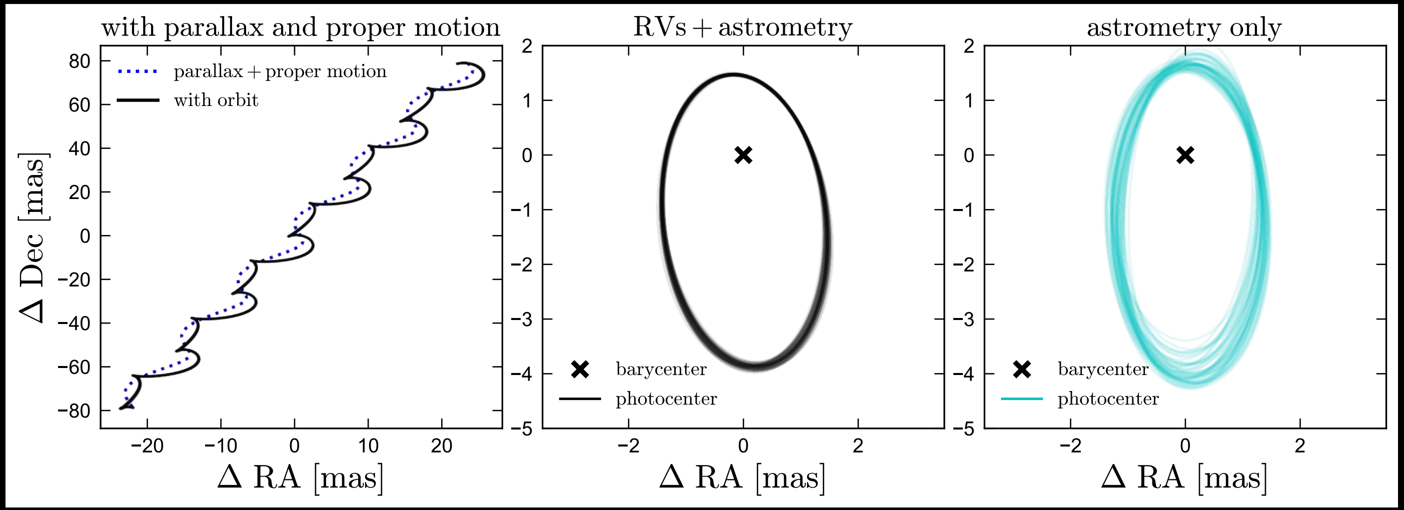
Light curve modulation
(relativistic effects, tidal deformation)
$\Rightarrow$ $(10-100)$ star-BH binaries may be identified

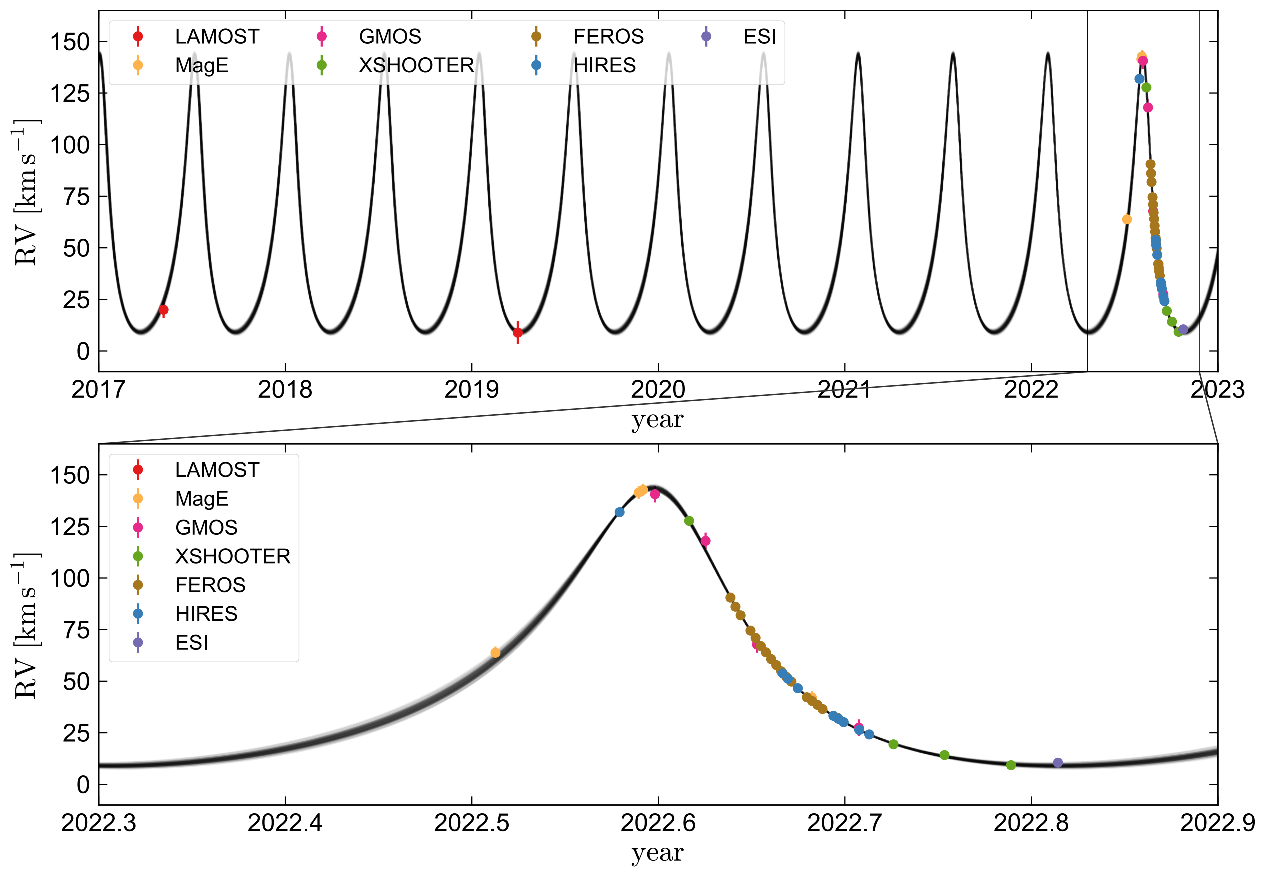


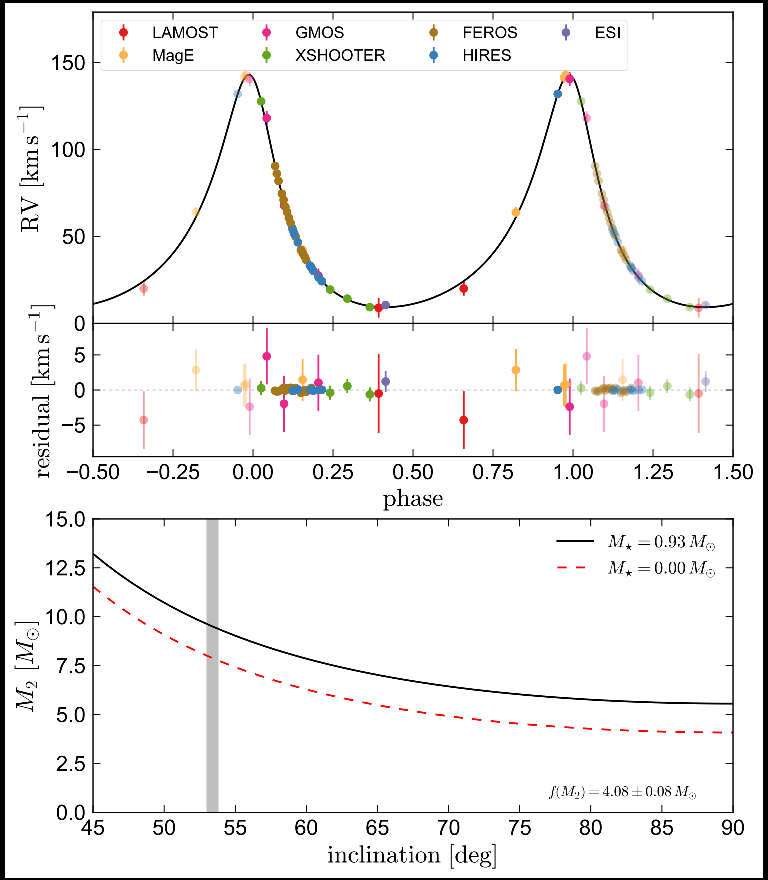
Some of them may be indeed a star-binary BH triple!
Can precise radial velocity follow-up unveil the inner BBH?

Gaia BH-1

$0.93M_{\odot}$ G star + $9.6M_{\odot}$BH
(P_{orb}=186days) at d=477pc
eccentricity ~ 0.45



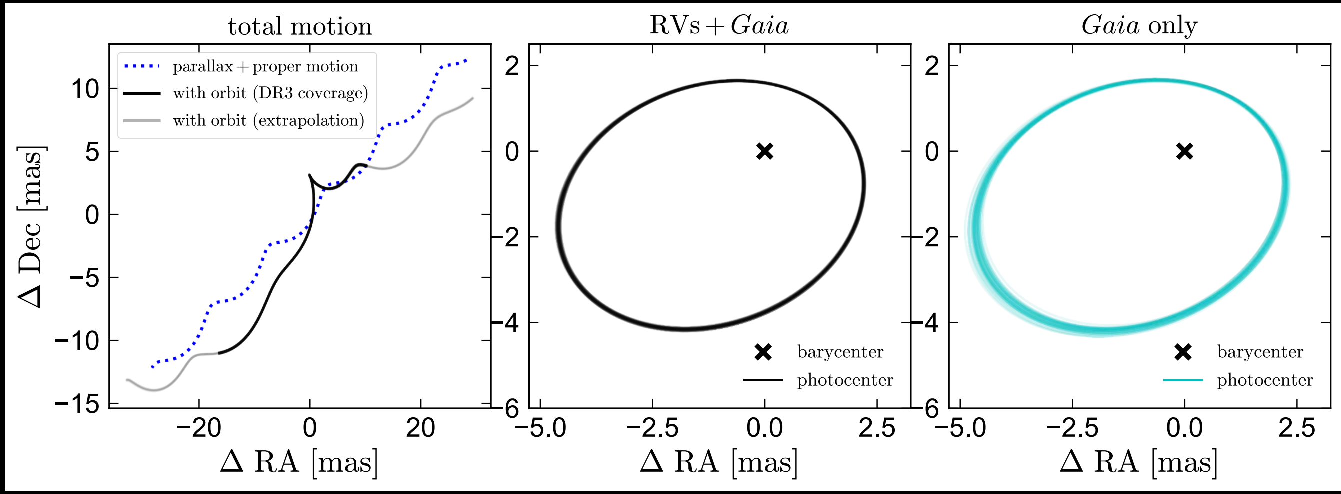


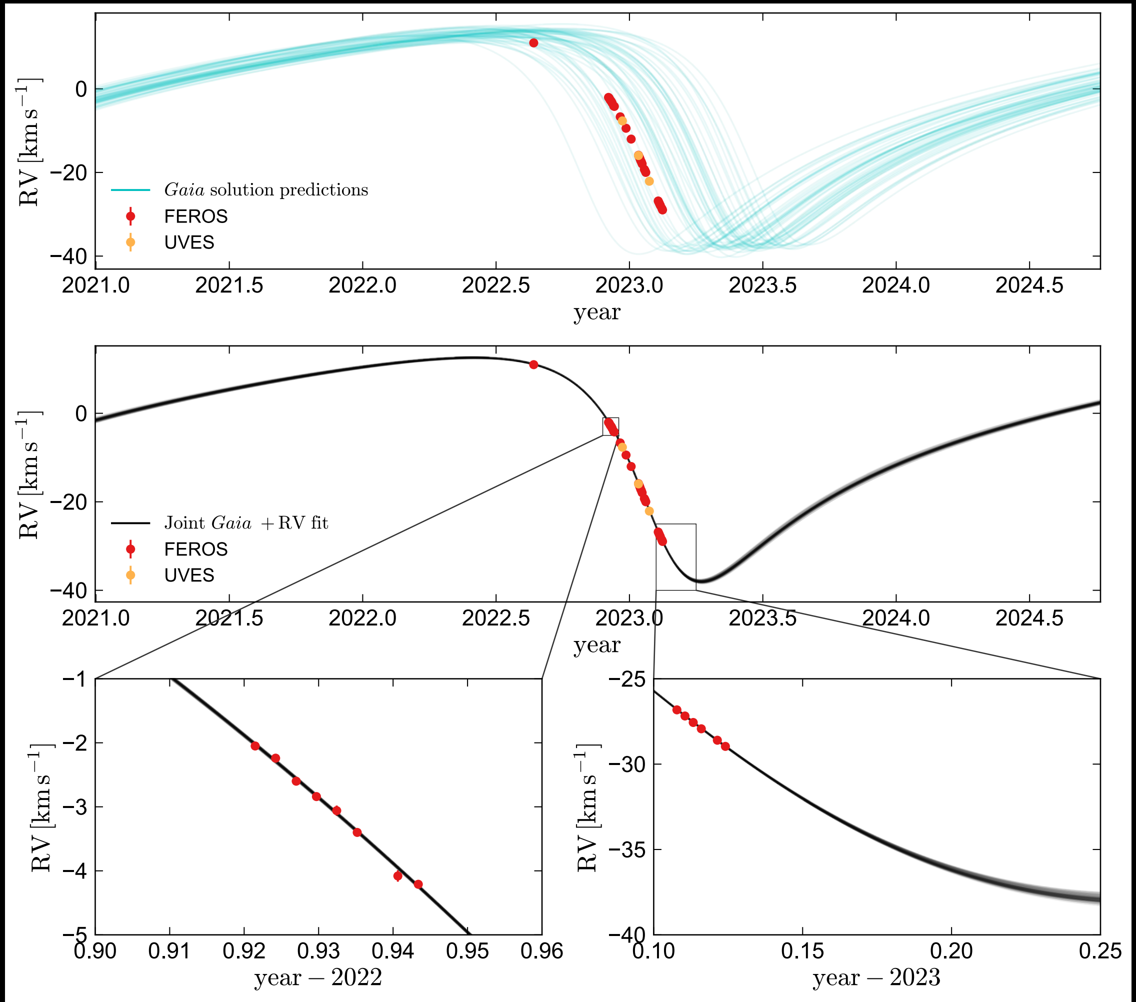


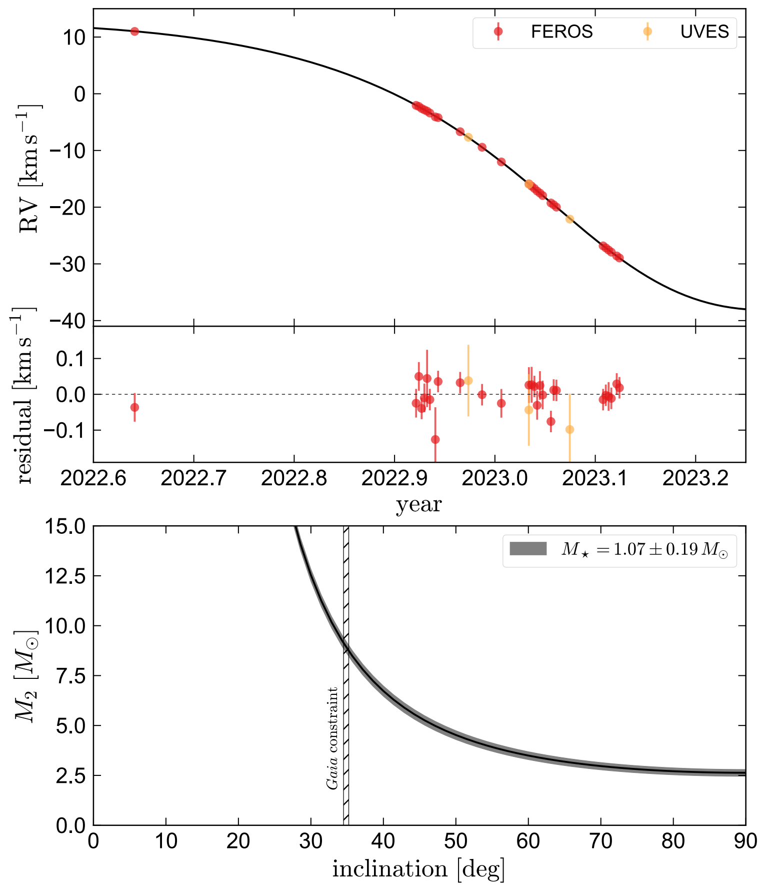
El-Badry et al.
MNRAS
518 (2023)1057

Gaia BH-2

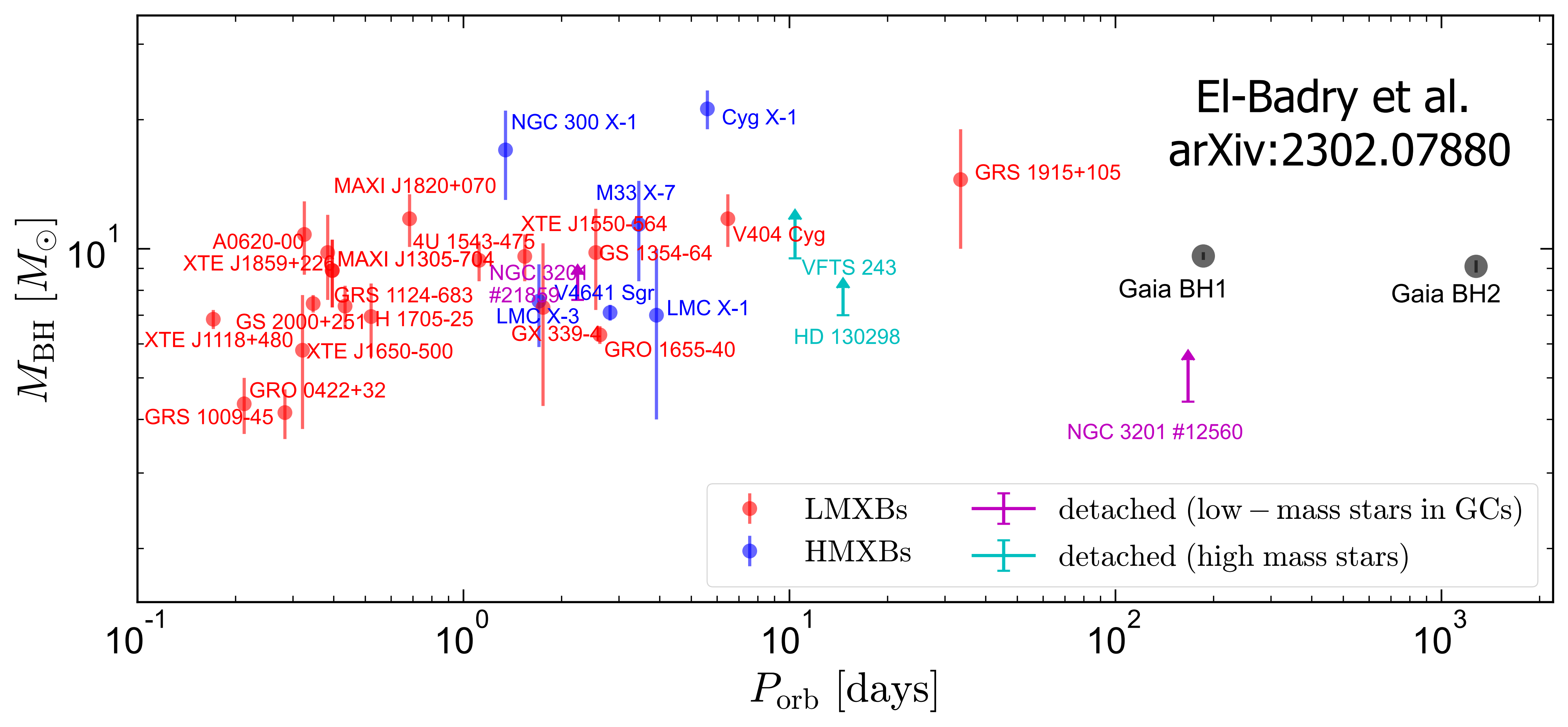
$1M_\odot$ red giant + $9M_\odot$BH
(P_{orb}=1277days) at d=1.16kpc
eccentricity ~ 0.52



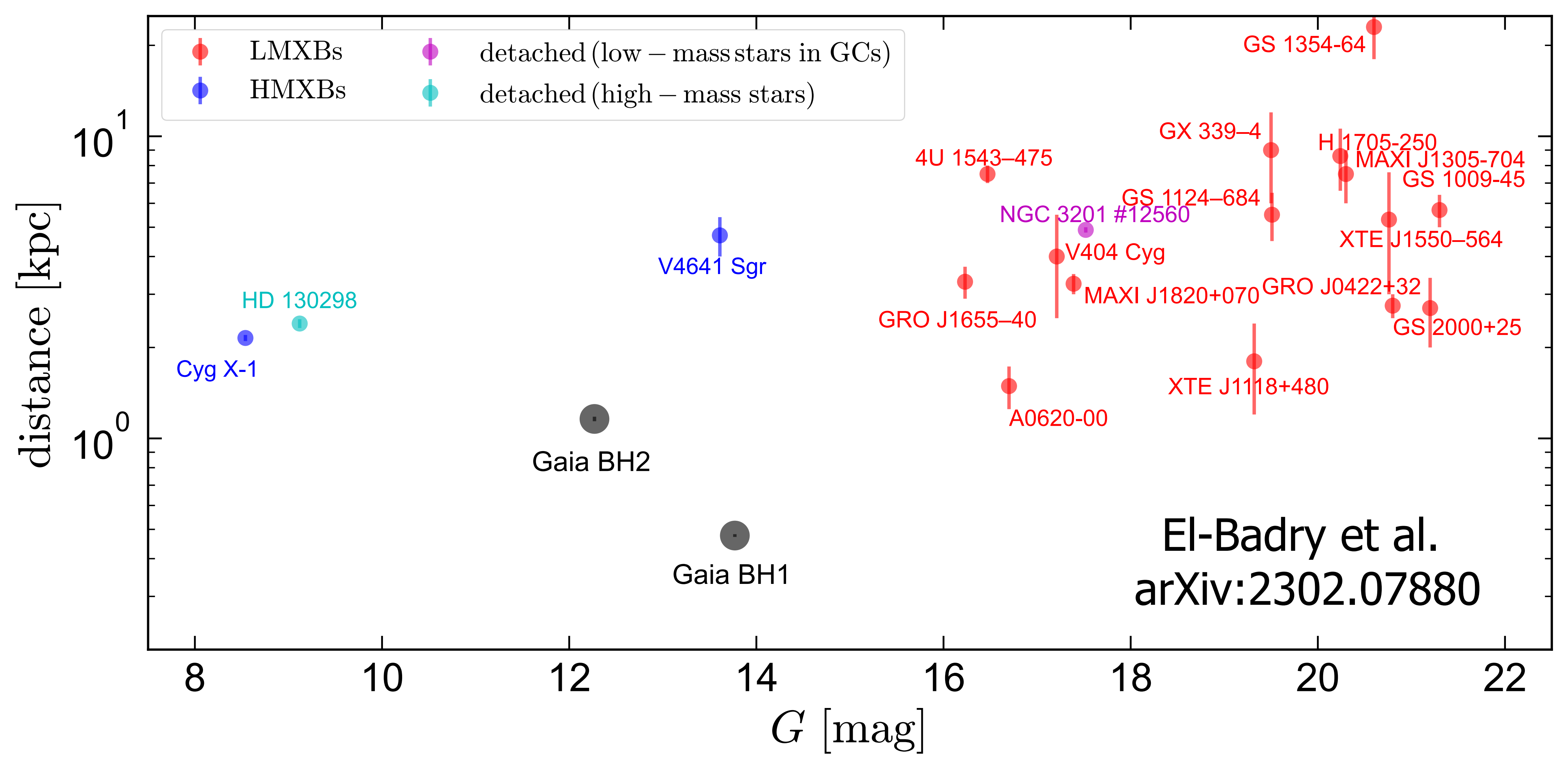




El-Badry et al.
arXiv:2302.07880



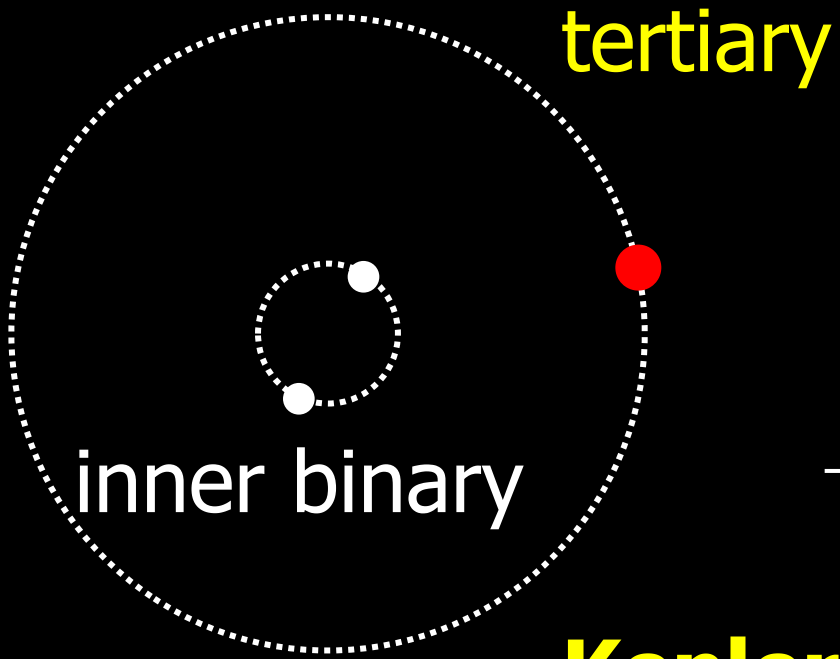
Comparison of Gaia BH1 and BH2 to other known BHs. Red and blue symbols correspond to accreting BHs with low- and high-mass companions. Magenta symbols show detached binaries in the globular cluster NGC 3201, and cyan points show detached binaries in which the luminous star is a high-mass (>20 $M_\odot$) star.

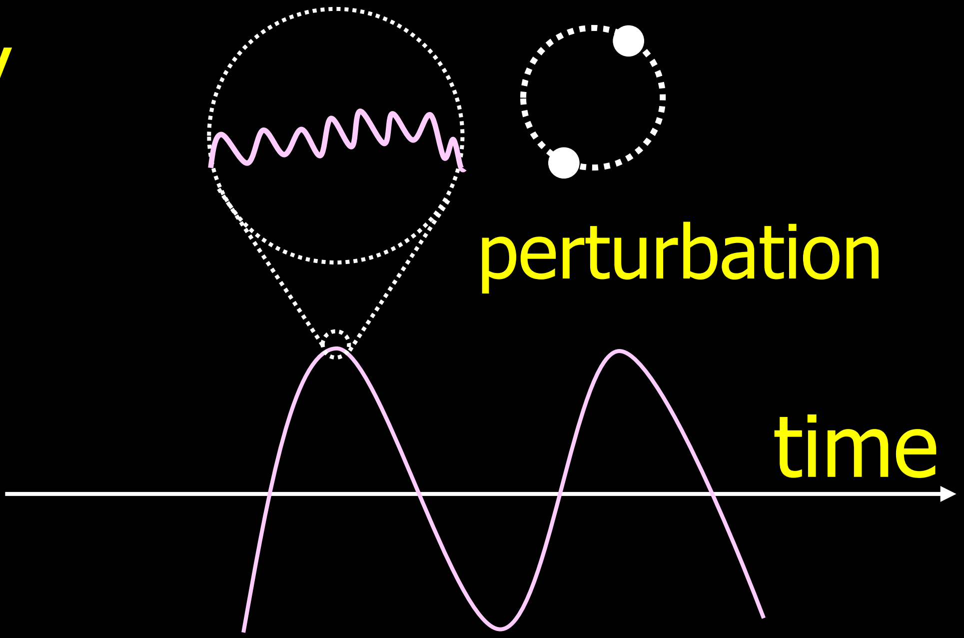


Comparison of Gaia BH1 and BH2 (black points) to known Galactic BHs in the plane of distance and quiescent optical magnitude

5 Dynamical signature of triple systems with an inner binary black-hole

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



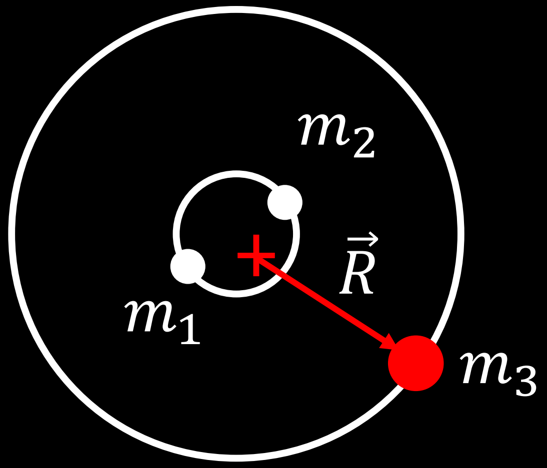


Kepler motion of the tertiary

Toshinori Hayashi
(林 利憲)

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

RV modulations for coplanar triples

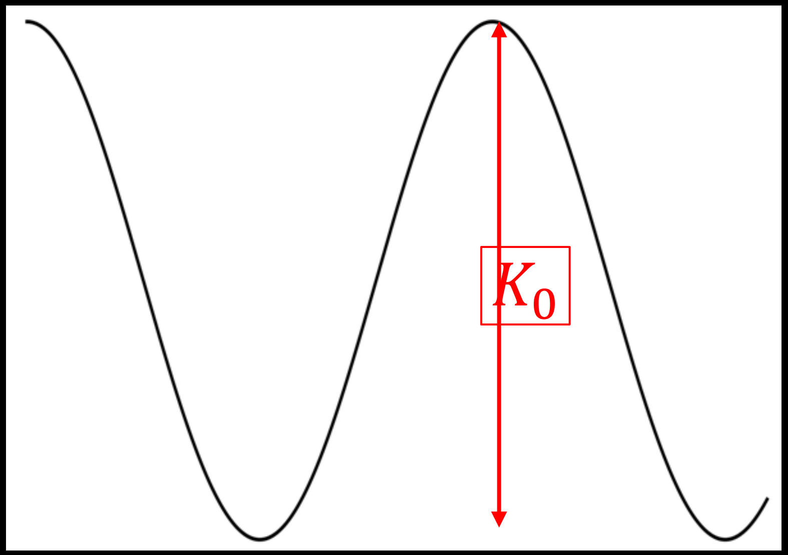


$\mathcal{H} = \mathcal{H}_{\text{Kep}} - \mathcal{R}$

Perturbation theory

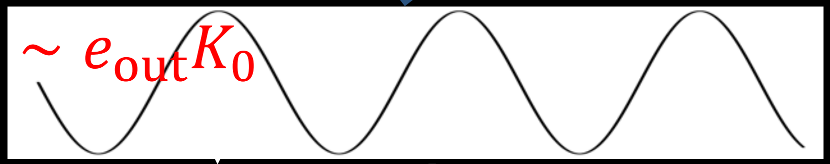
$$\left(\sqrt{\frac{m_1}{m_2}} + \sqrt{\frac{m_2}{m_1}}\right)^{-2} \left(\frac{a_{\text{in}}}{a_{\text{out}}}\right)^{3.5} K_0$$

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

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

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

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

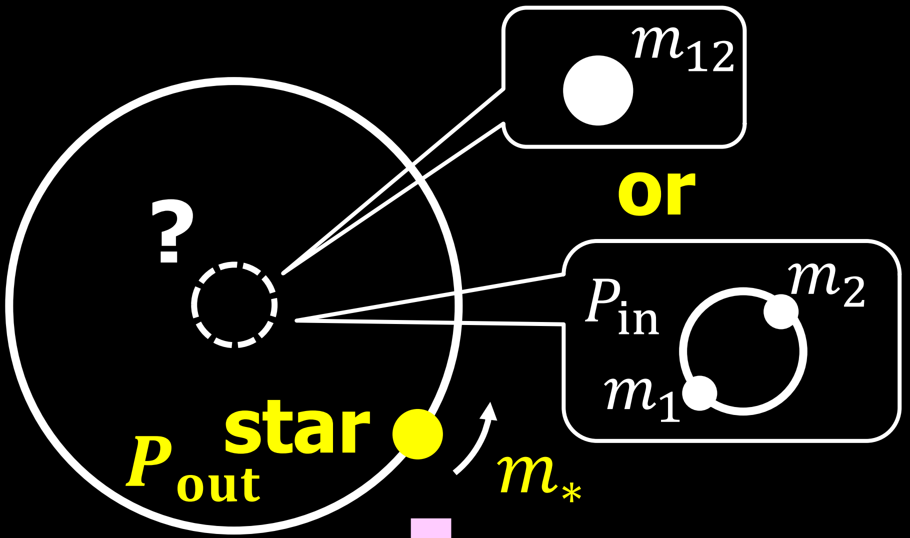
(ii) Perturbation to the Kepler motion

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

(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

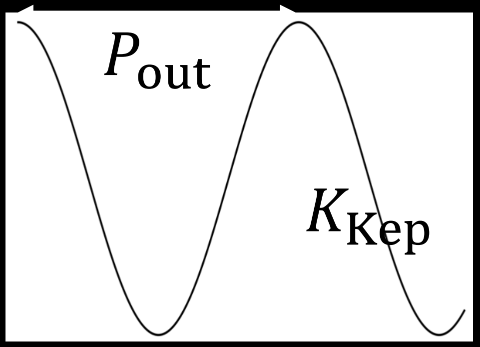


high-precision RV follow-up

Keplerian motion RV

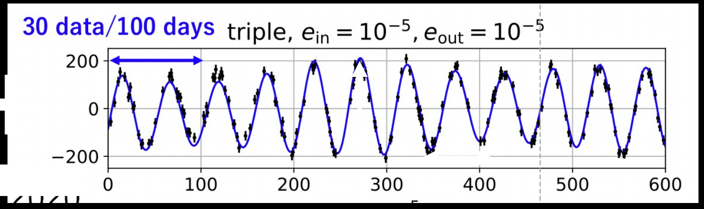
\+ RV variations by inner binary

(i) Coplanar triple



Kepler motion

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



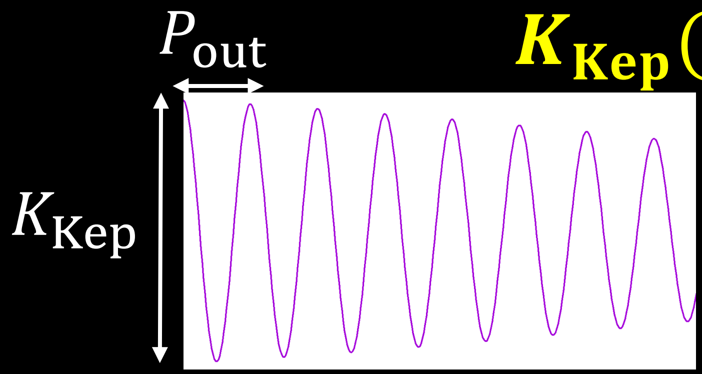
$$\mathrm{period} \sim P_{\rm in}/2$$

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

(ii) Non-coplanar triple

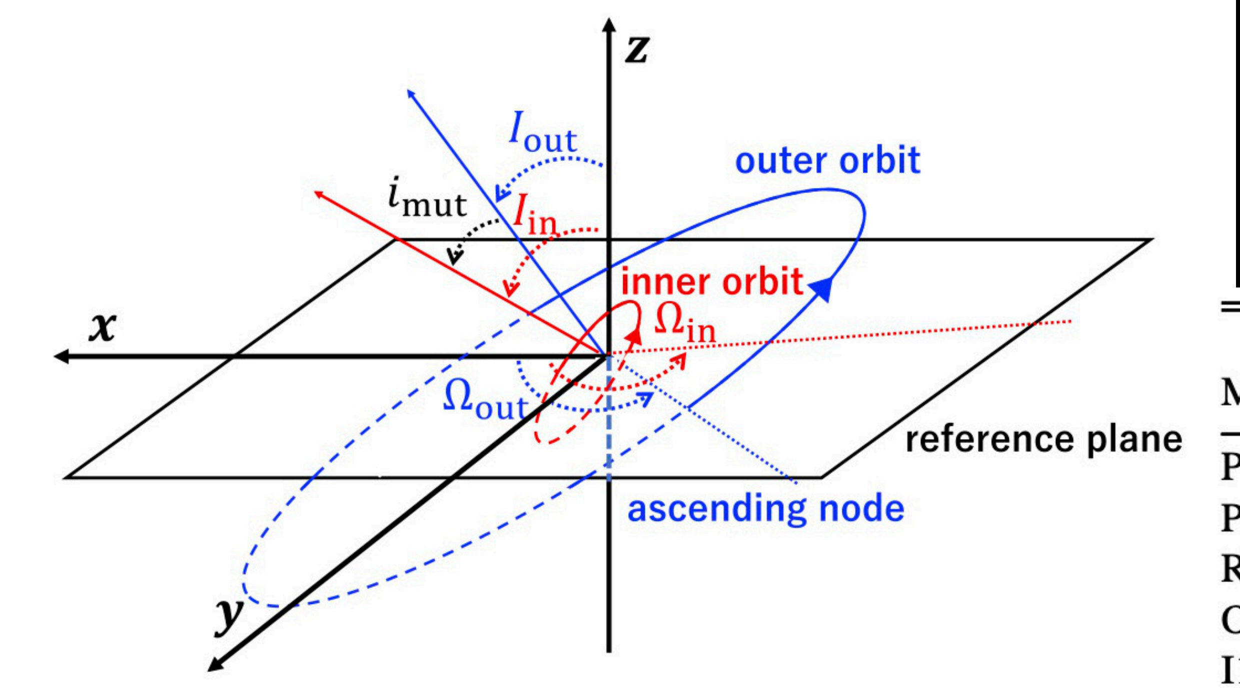
Inclination $I_{\rm out}(t)$ modulated in the Kozai-Lidov timescale

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



Amplitude of Kepler RV varies with the timescale

Parameters for simulated triple systems



direct N-body (N=3) simulation
without secular approximation

Hayashi & YS 2020, ApJ, 897, 29

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

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

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

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.

Coplanar circular triples

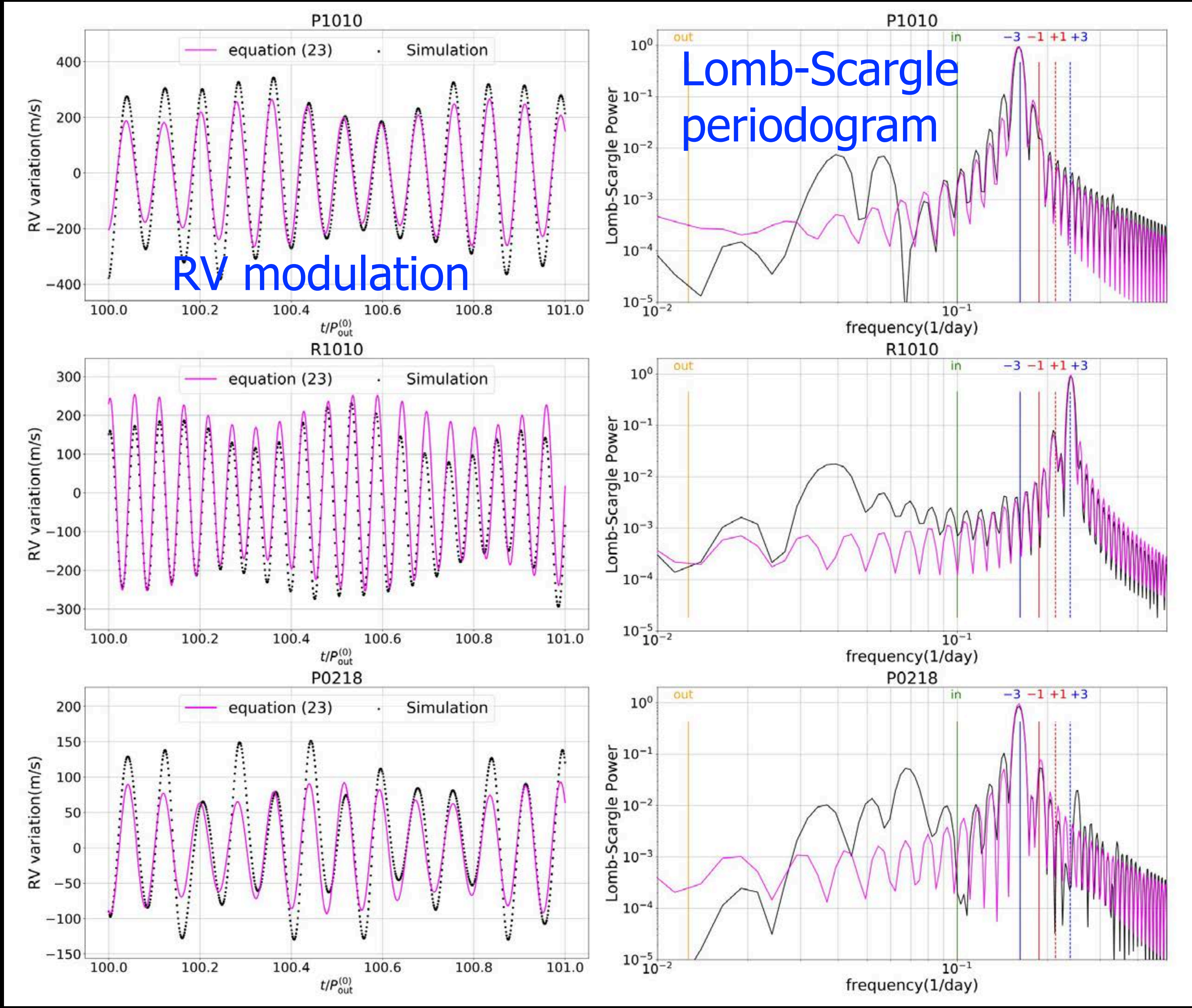
Prograde equal-mass

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

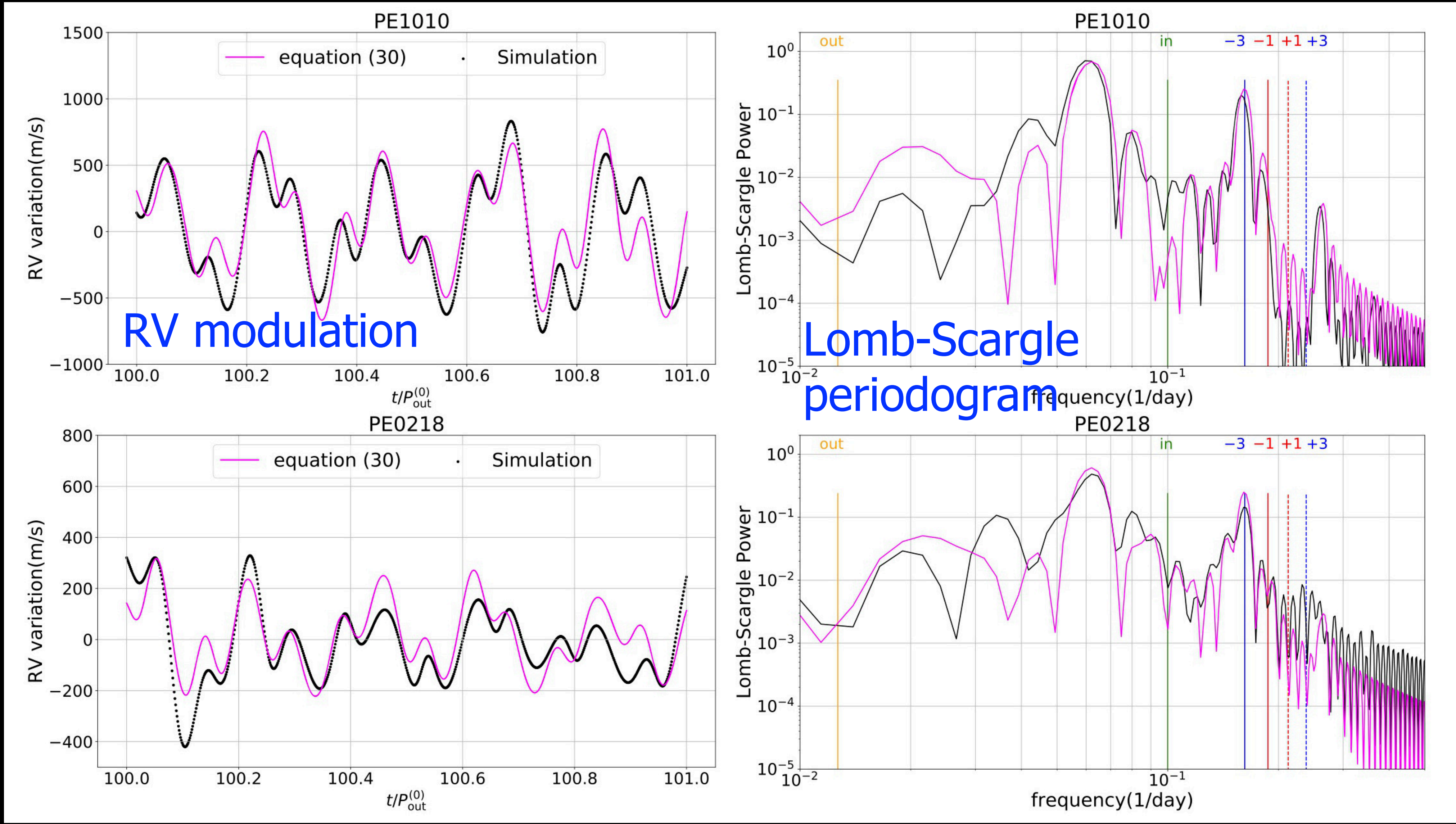


Coplanar eccentric triples

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

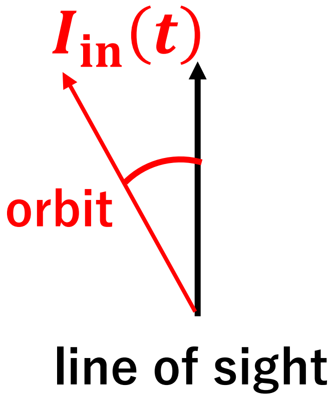
Prograde equal-mass

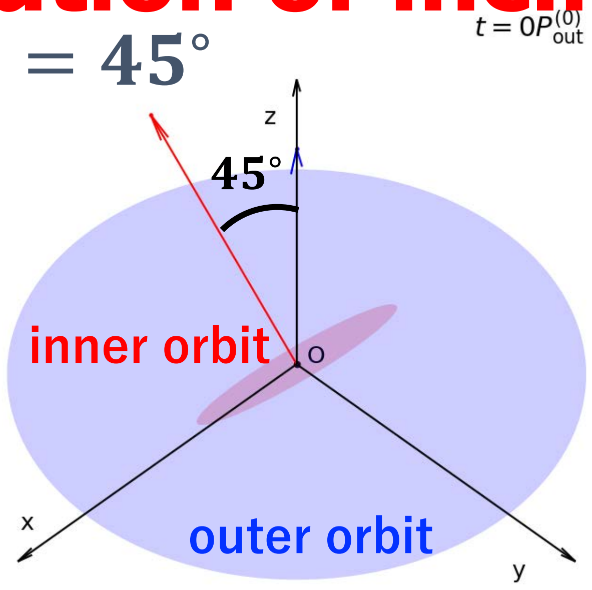
Prograde unequal-mass



Evolution of inclination for non-coplanar triples

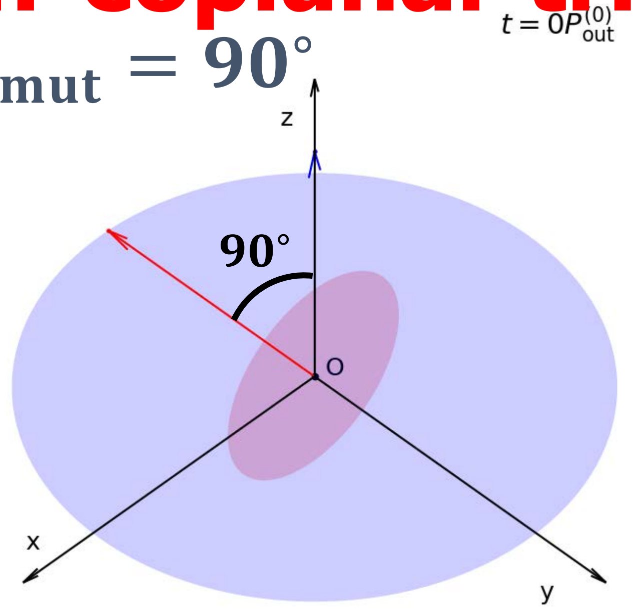
$i_{\mathrm{mut}} = 45^{\circ}$

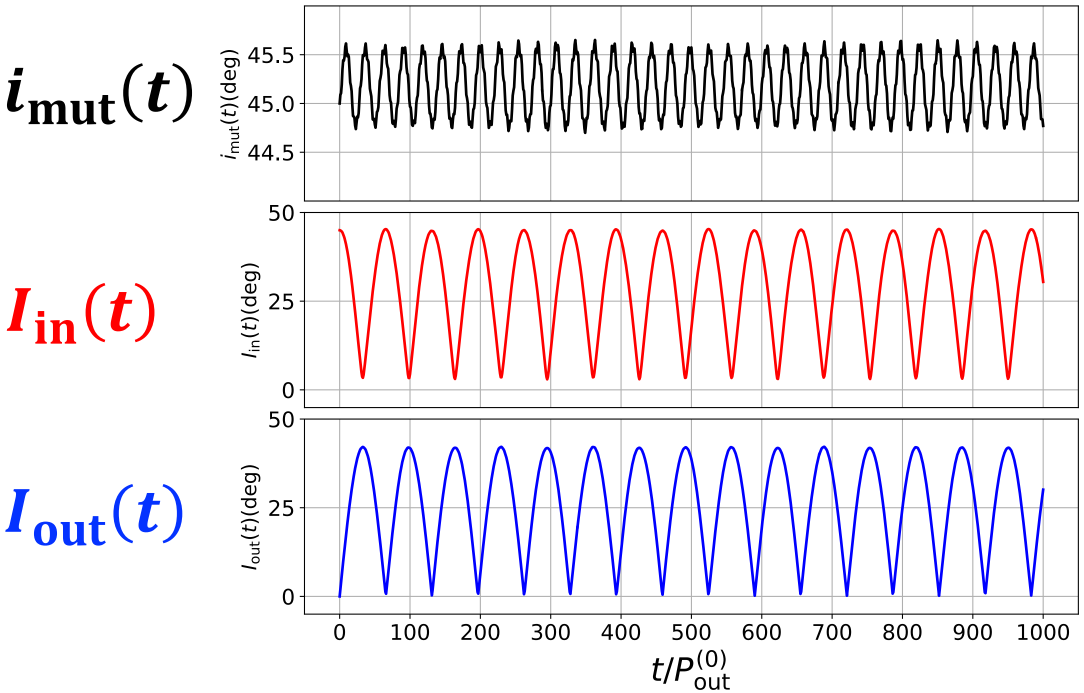


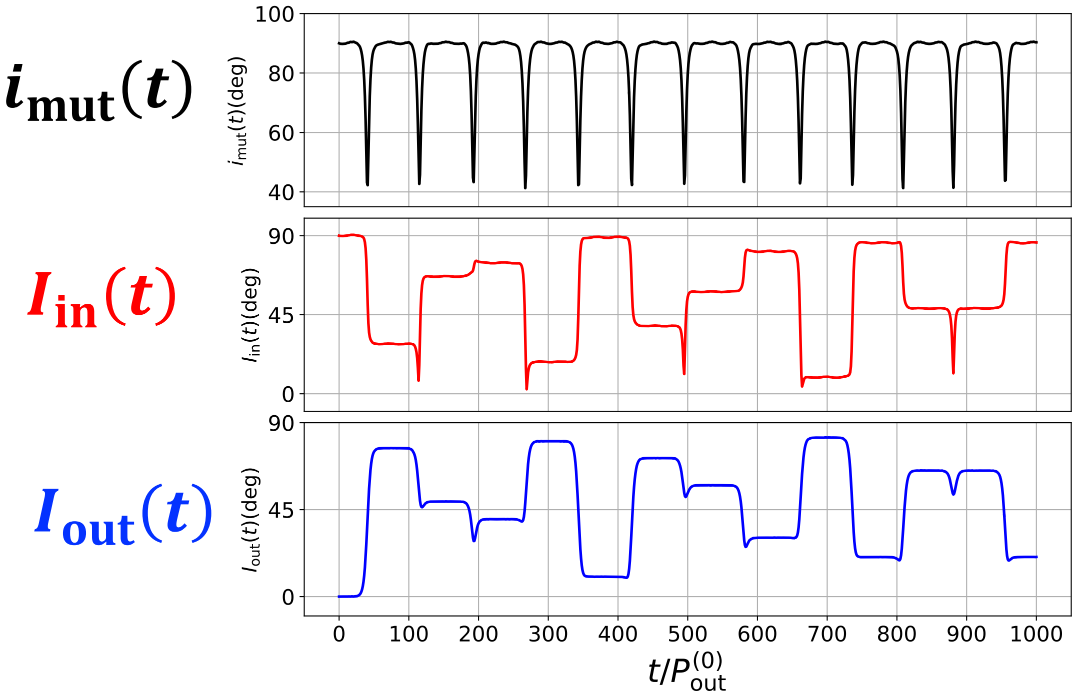


$$P_{\mathrm{out}} = 78.9 \text{ days}$$
$$P_{\mathrm{in}} = 10 \text{ days}$$
$$m_1 = m_2 = 10M_{\odot}$$
$$m_* = 3M_{\odot}$$
$$e_{\mathrm{out}} = 0.03$$
$$e_{\mathrm{in}} = 10^{-5}$$

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





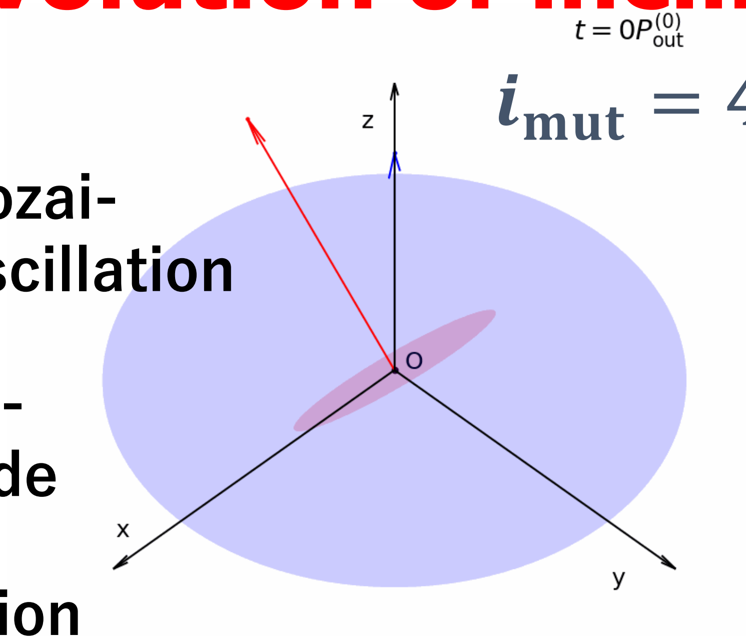


Evolution of inclination for non-coplanar triples

$i_{\rm mut} = 45°$

weak Kozai-Lidov oscillation

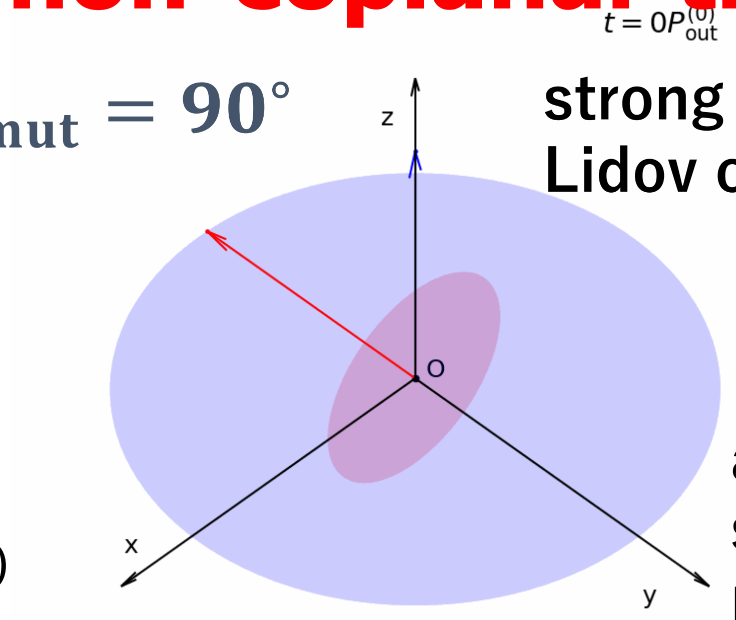
⇒ small-amplitude regular precession



$i_{\rm mut} = 90°$

strong Kozai-Lidov oscillation

⇒ large-amplitude sporadic precession

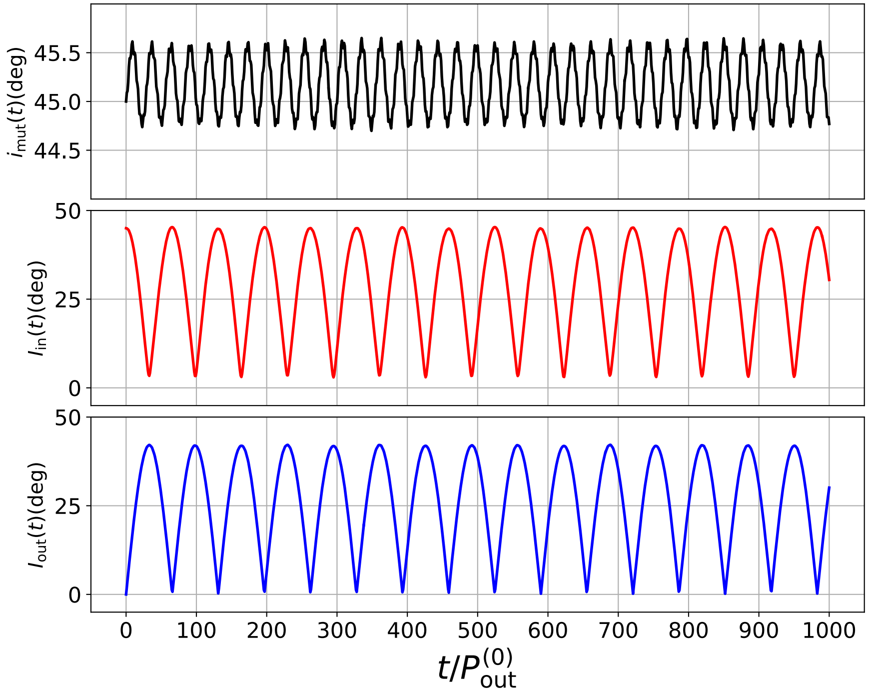


$K_{\rm Kep} = K_0 \sin I_{\rm out}(t)$

$i_{\rm mut}(t)$

$I_{\rm in}(t)$

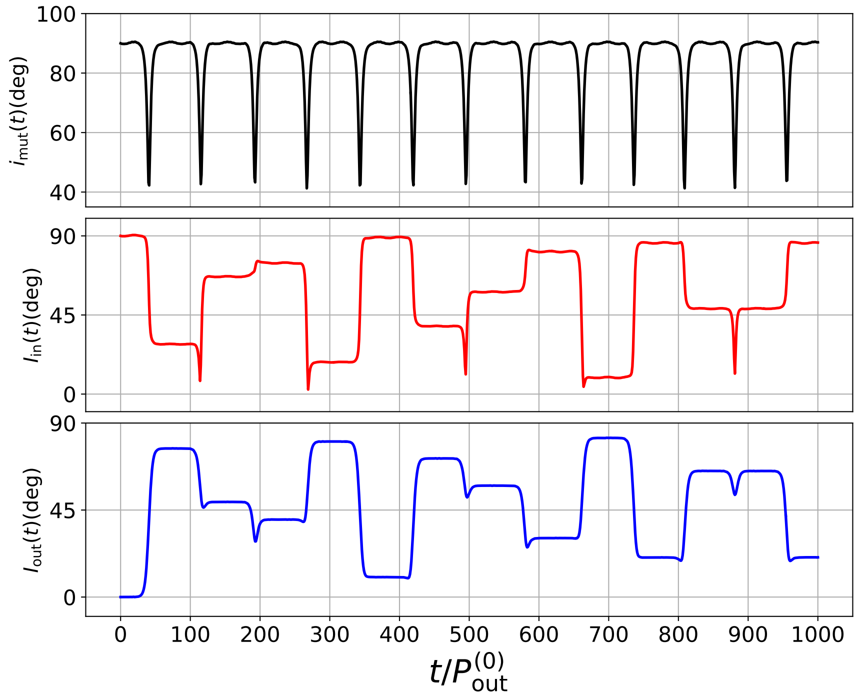
$I_{\rm out}(t)$



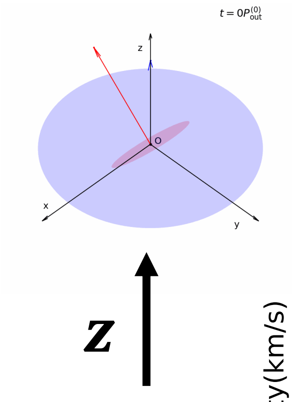
$i_{\rm mut}(t)$

$I_{\rm in}(t)$

$I_{\rm out}(t)$

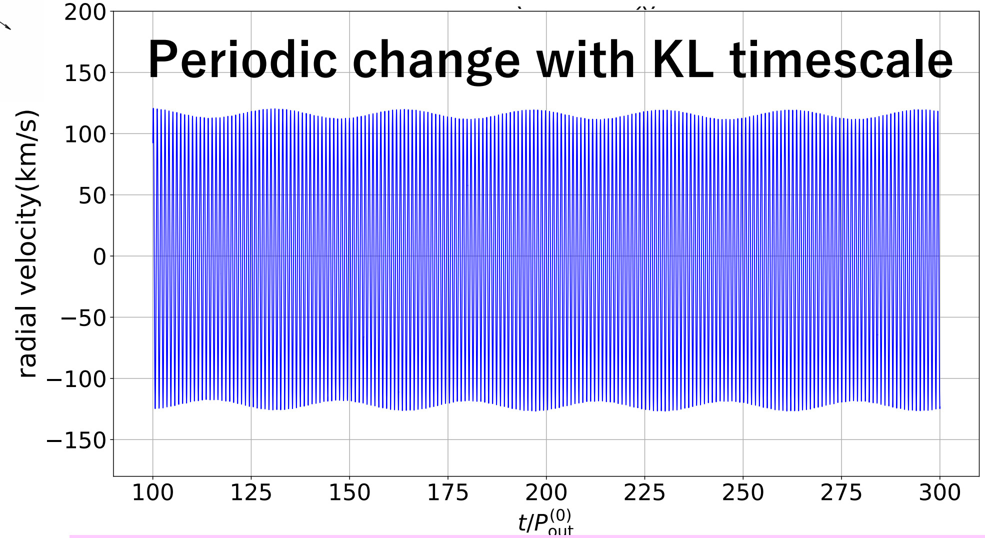


Evolution of radial velocity for non-coplanar triples

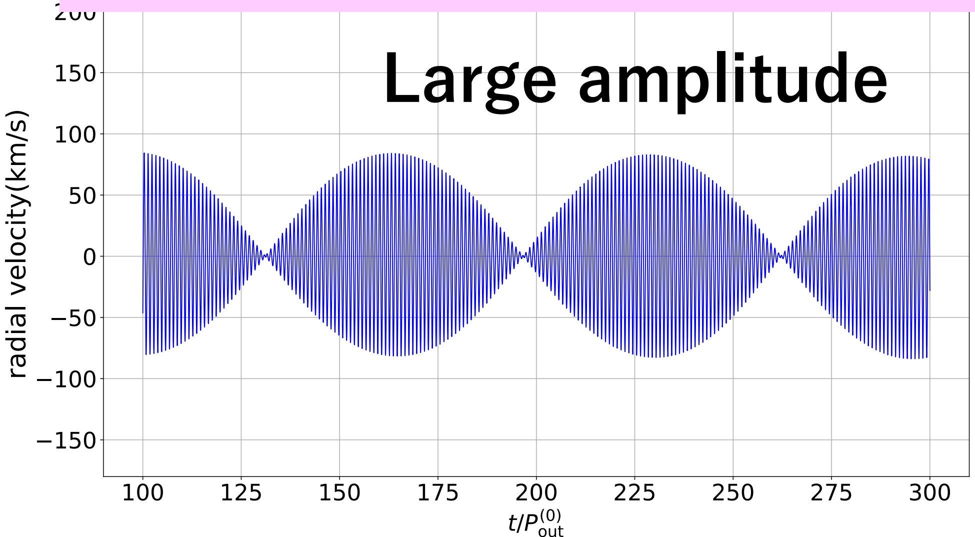


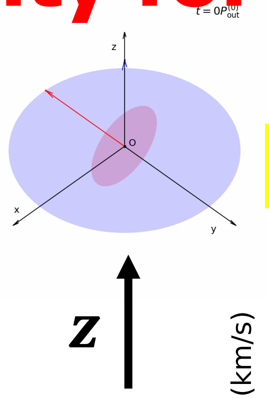
$i_{\mathrm{mut}} = 45°$ $K_{\mathrm{Kep}} = K_0 \sin I_{\mathrm{out}}(t)$

x-direction (near edge-on) total RV



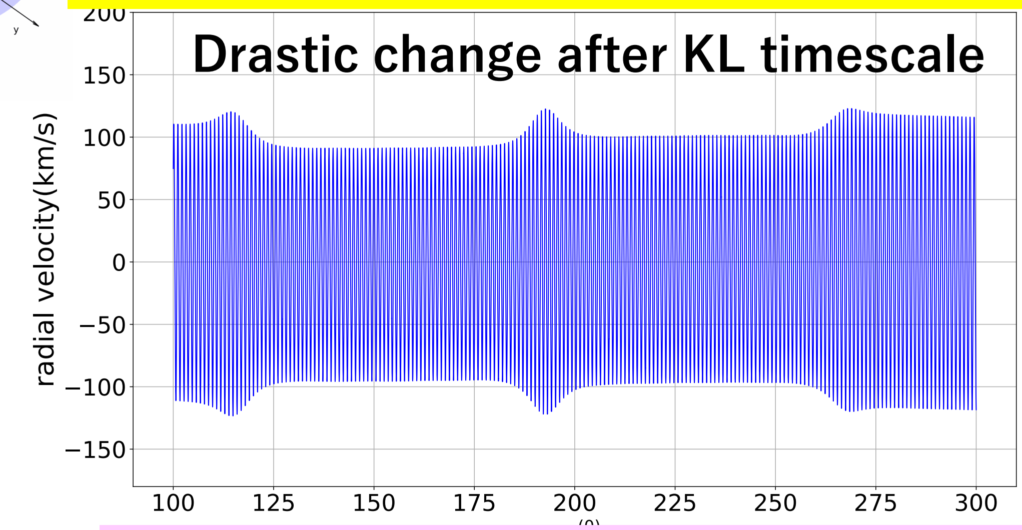
z-direction (near face-on) total RV



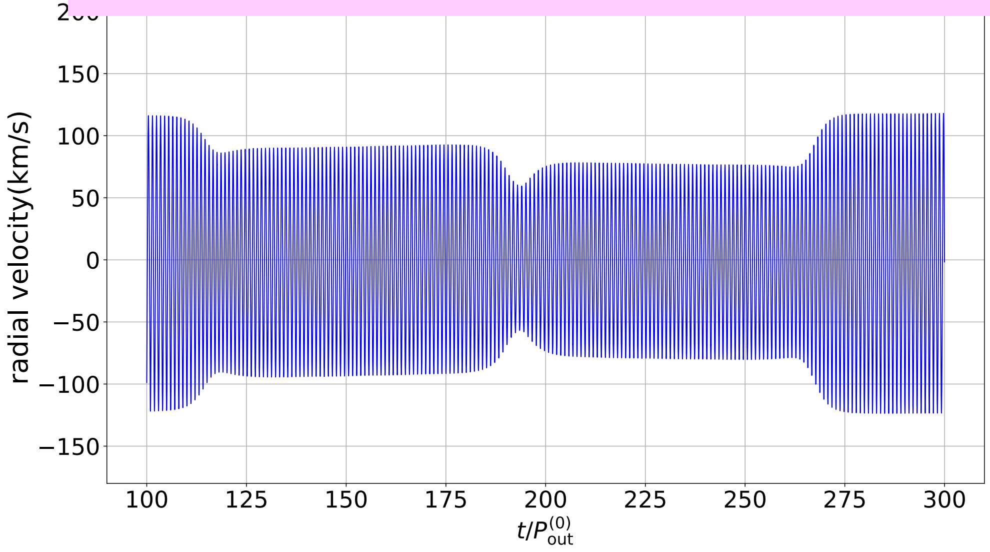


$i_{\mathrm{mut}} = 90°$

x-direction (near edge-on) total RV



z-direction (near face-on) total RV



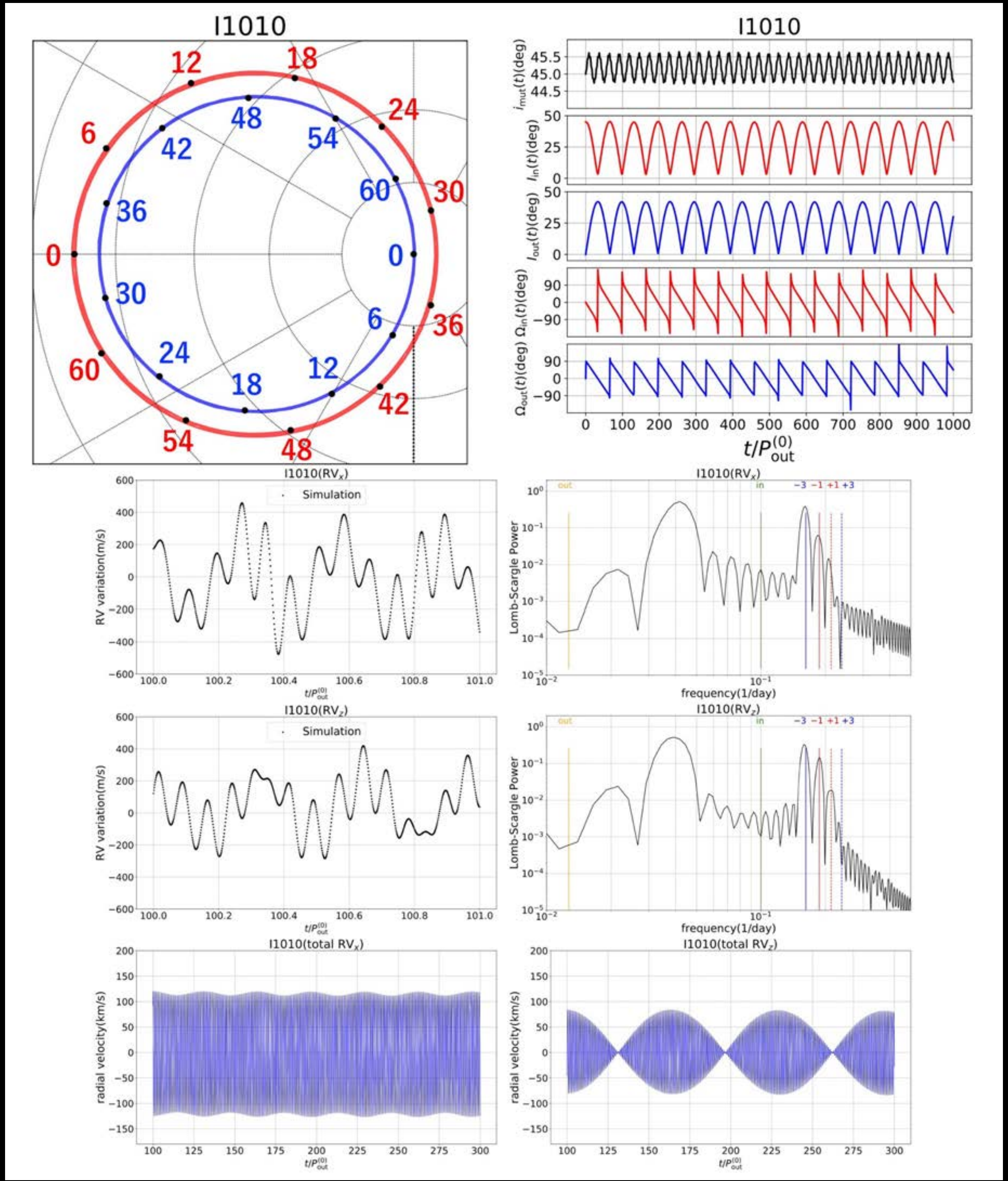
Inclined equal-mass binary

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

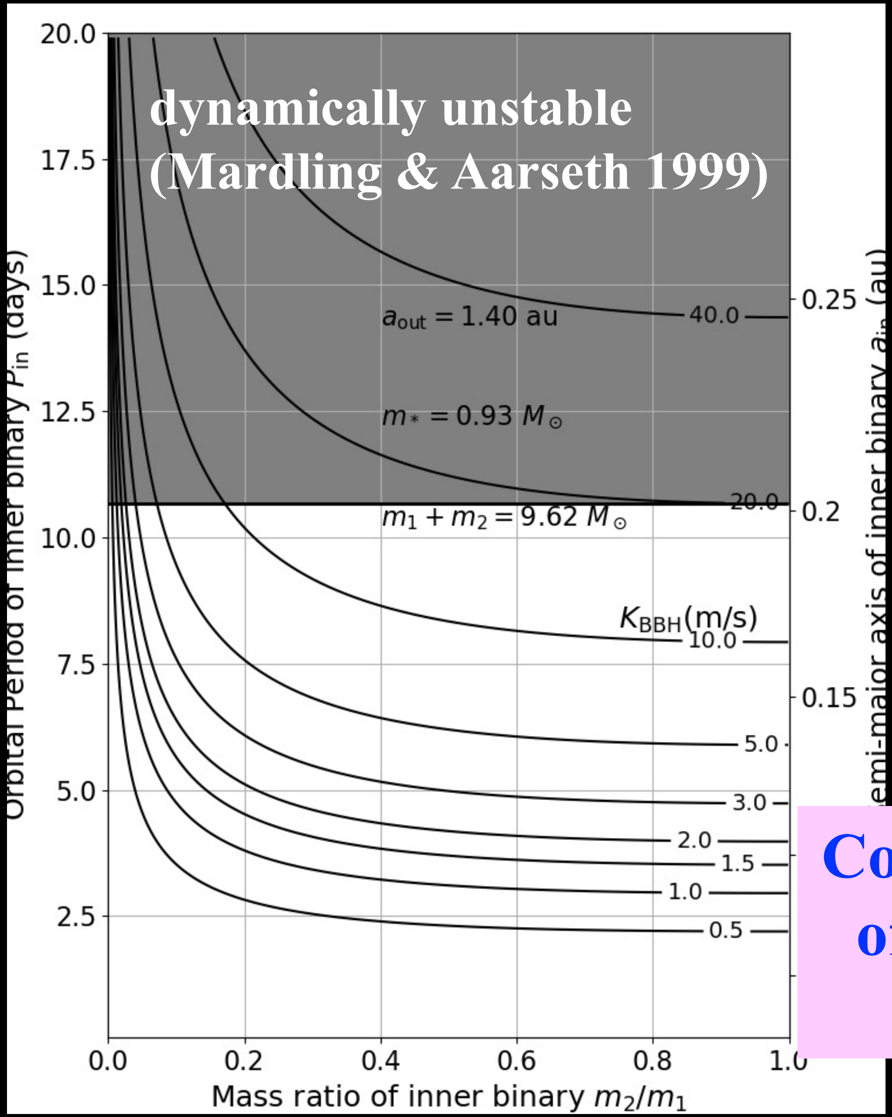
$$\frac{T_{\rm KL}}{P_{\rm out}} = \frac{m_1}{m_*}\left(\frac{P_{\rm out}}{P_{\rm in}}\right)(1-e_{\rm out}^2)^{3/2} \approx 26\left(\frac{m_1}{10\,M_\odot}\right)\left(\frac{m_*}{3\,M_\odot}\right)^{-1} \times \left(\frac{P_{\rm out}}{78.9\ \text{days}}\right)\left(\frac{P_{\rm in}}{10\ \text{days}}\right)^{-1}$$



Constraints on the binarity of Gaia BH1 and BH2 from short-term RD modulations

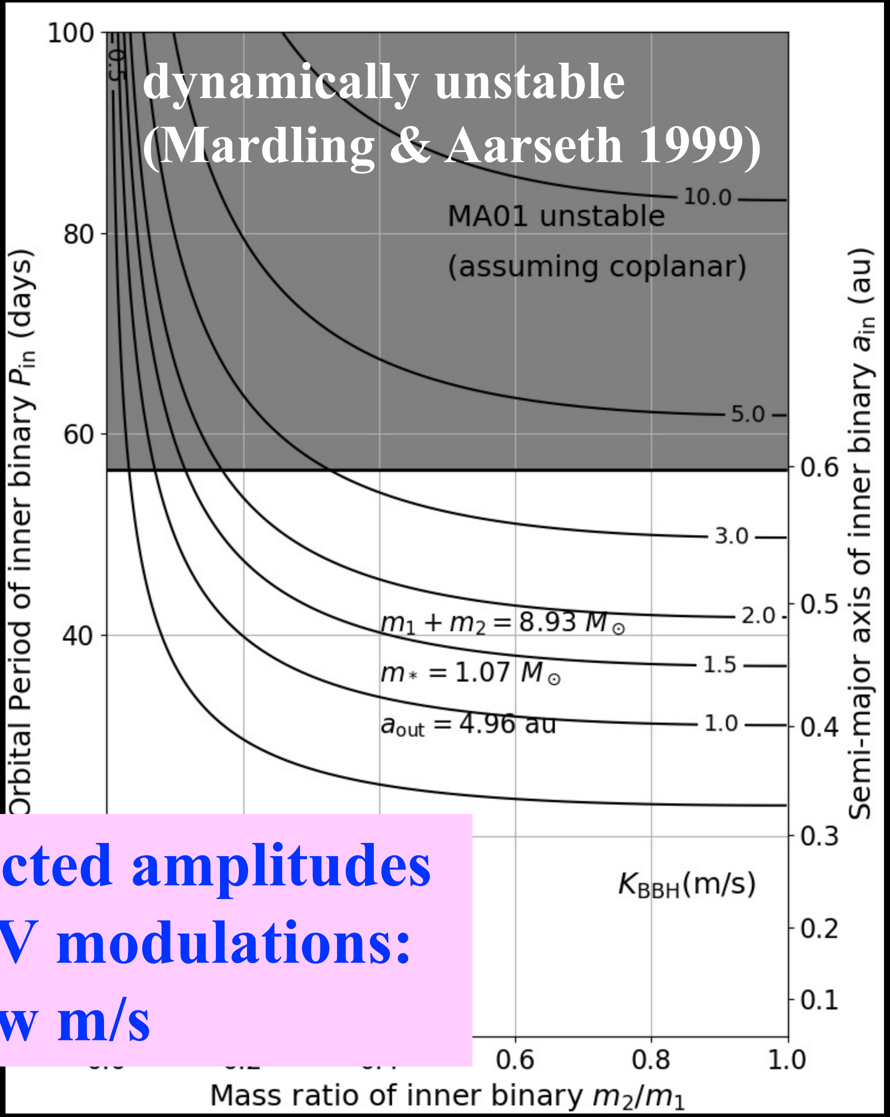
Gaia BH1

P_{in}(days)



Gaia BH2

P_{in}(days)



Contours of expected amplitudes of short-term RV modulations: ~ a few m/s

Conclusions: 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 (and the ZKL oscillation) of the inner and outer orbits over $(10\text{-}100)(P_{out}/P_{in})P_{out}$