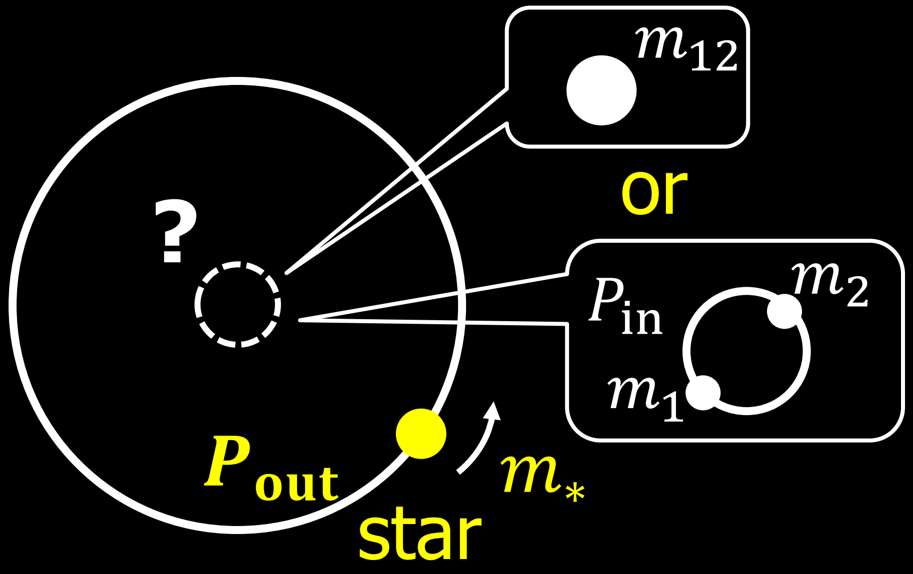
Dynamics of a triple system comprising an inner binary black hole in a mutually inclined orbit



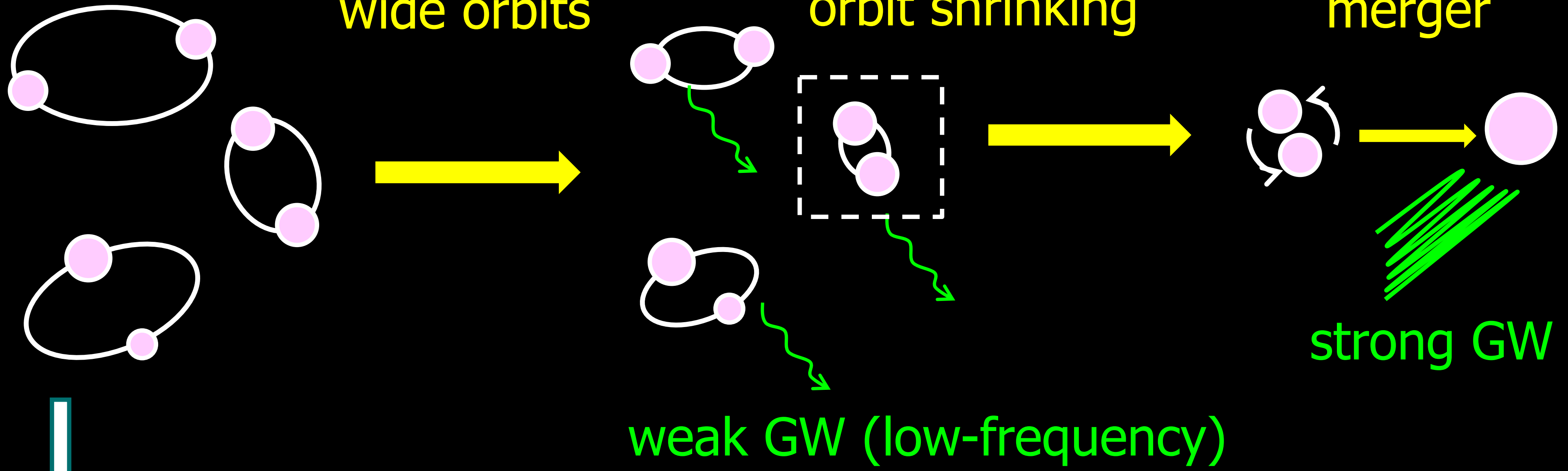
Yasushi Suto

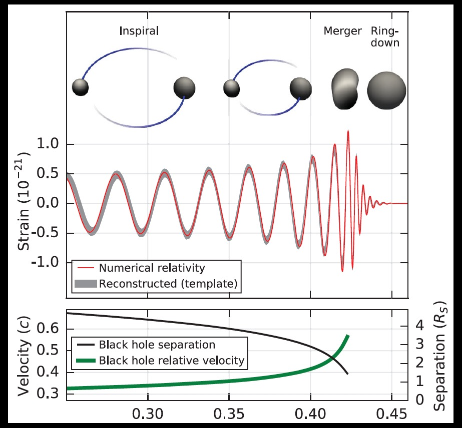
Department of Physics & Research Center for the Early Universe, The University of Tokyo

12:00 July 6, 2023. Kavli-IAU Symposium 382 “Complex Planetary Systems II”
@ University of Namur, Belgium

Generic picture of binary BH evolution

binary blackholes form in wide orbits





LIGO/Virgo

BBHs would spend longer time in wide orbits before merging

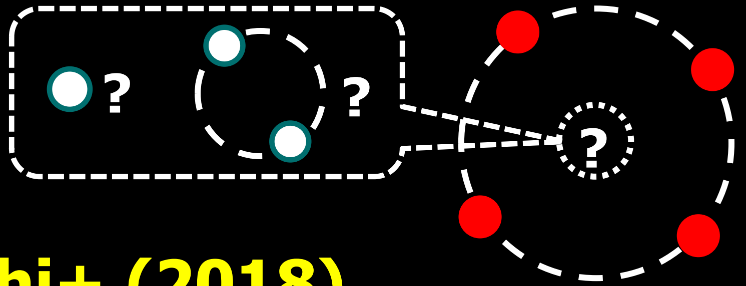
Abundant longer orbital-period BBHs may remain undetected (e.g. ~10day orbital period~10^{-6}Hz).

Other detection strategies 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

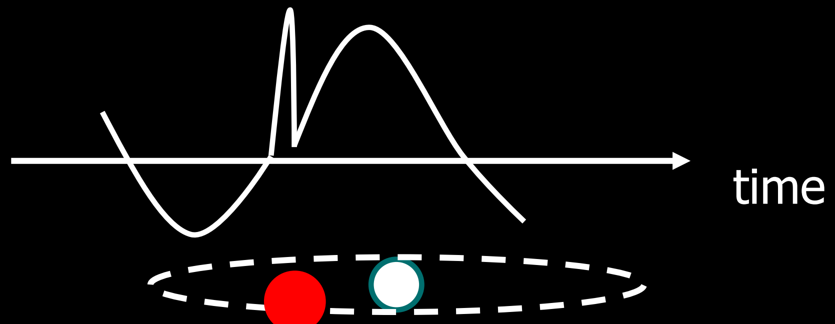
Tanikawa+(2023)

TESS mission (2018-)

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

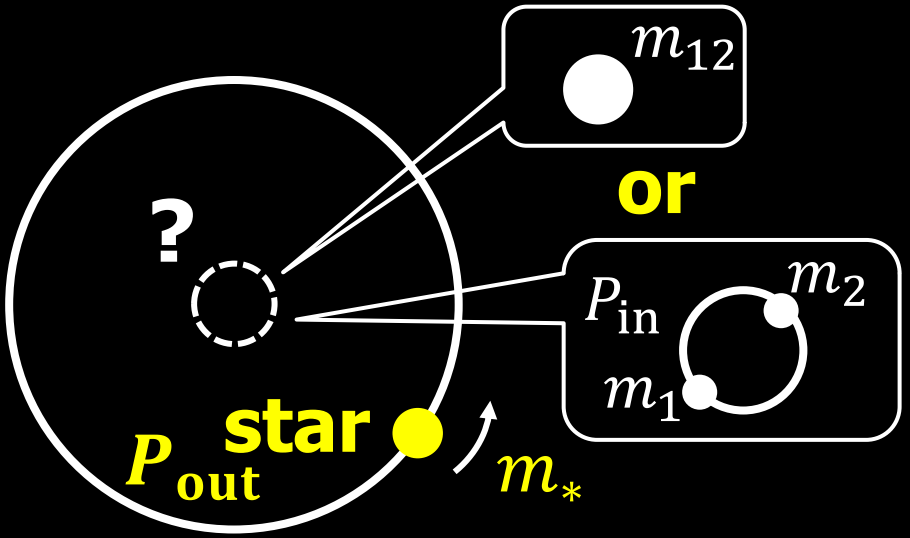
Masuda & Hotokezaka (2019)

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-ups unveil the inner BBH?

RV (radial velocity) modulations of a tertiary star



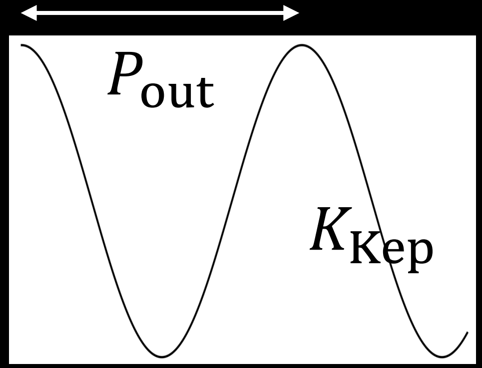
Keplerian motion RV
+ RV modulations of a tertiary star due to a hidden inner binary

Hayashi, Wang + YS: ApJ 890(2020)112
Hayashi + YS: ApJ 897(2020)29
Hayashi, YS + Trani (2023): arXiv:2307.01793

Morais & Correia (2008, 2012)

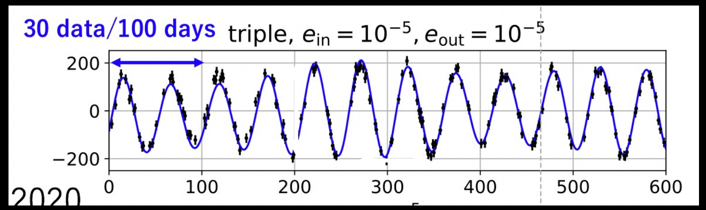
(i) short-term

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



Kepler motion

+



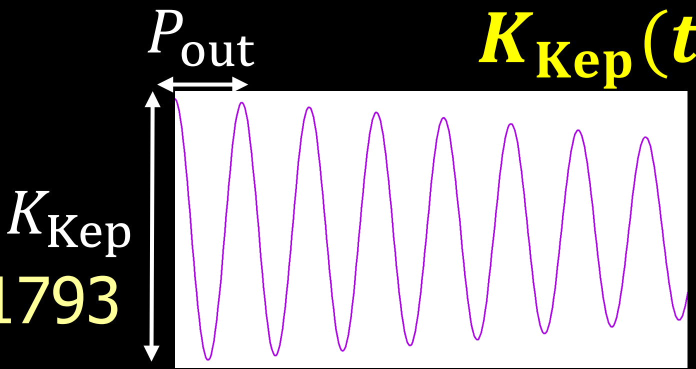
$$\mathrm{period} \sim P_{\rm in}/2$$

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

(ii) long-term for non-coplanar triples

Inclination $I_{\rm out}(t)$ modulated in the ZKL timescale

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

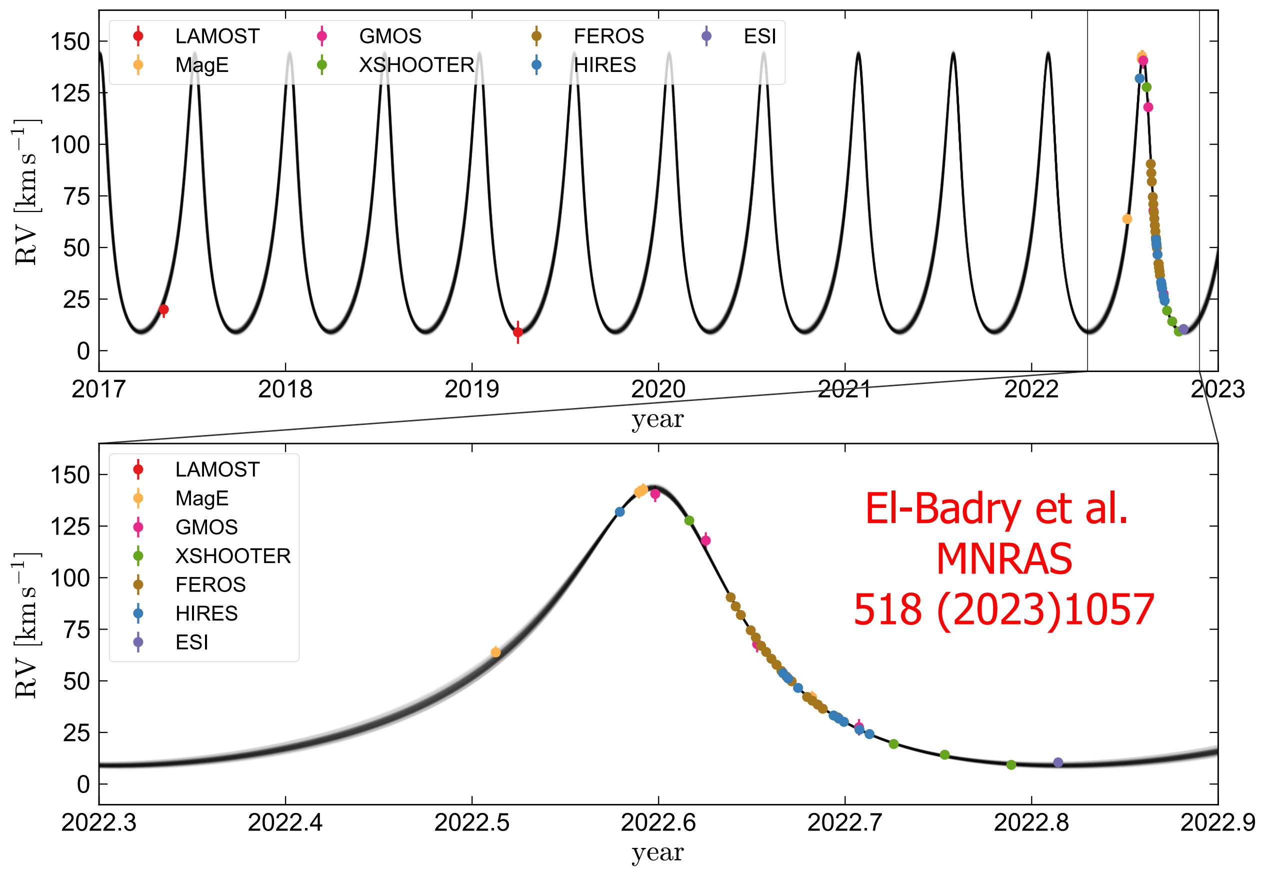


semi-amplitude of Kepler RV varies over longer timescales

A proof-of-concept study with Gaia star-BH candidates

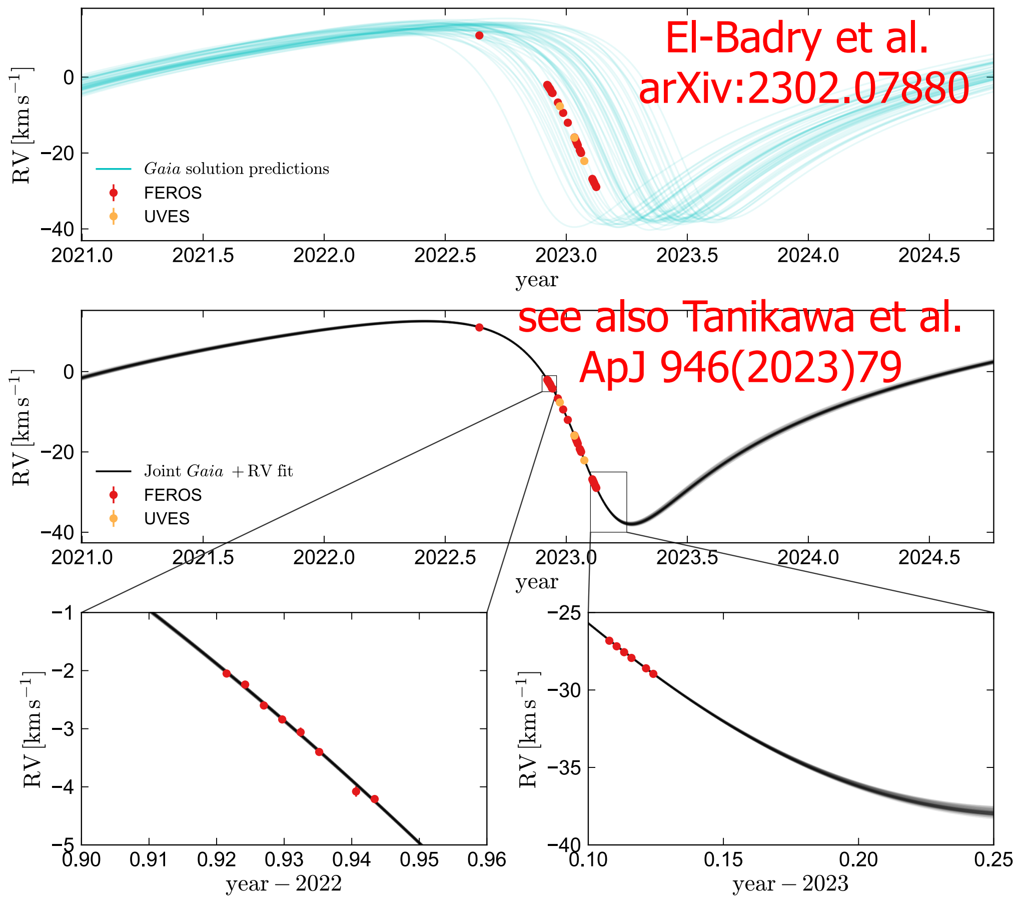
Gaia BH-1

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



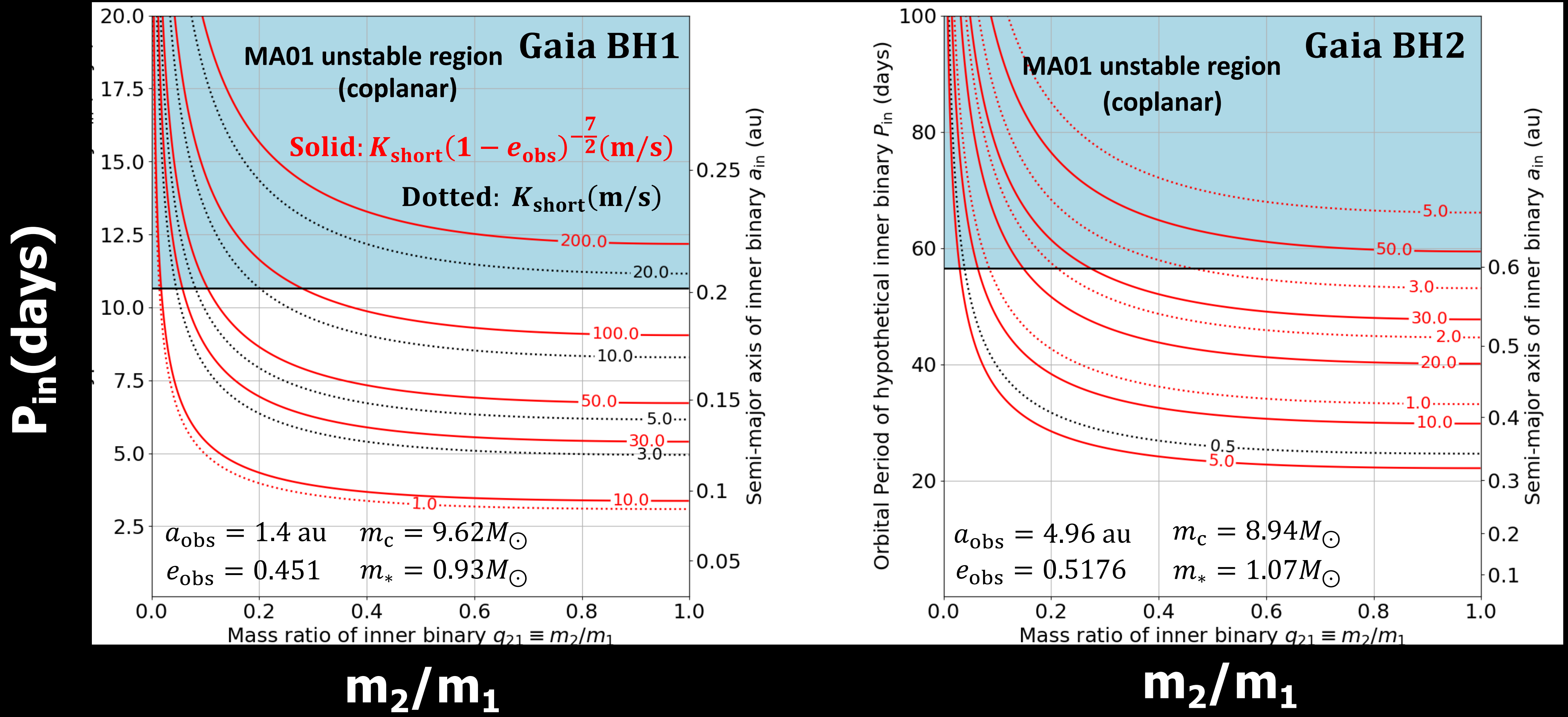
Gaia BH-2

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

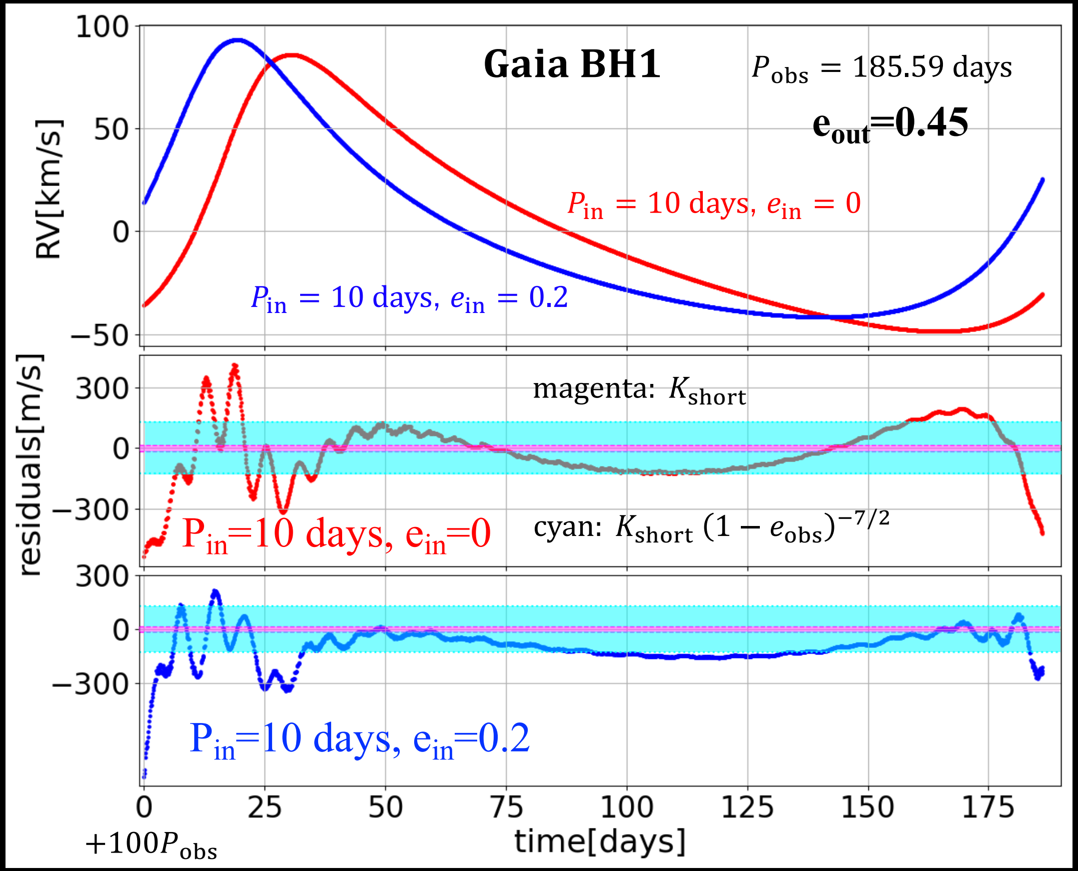


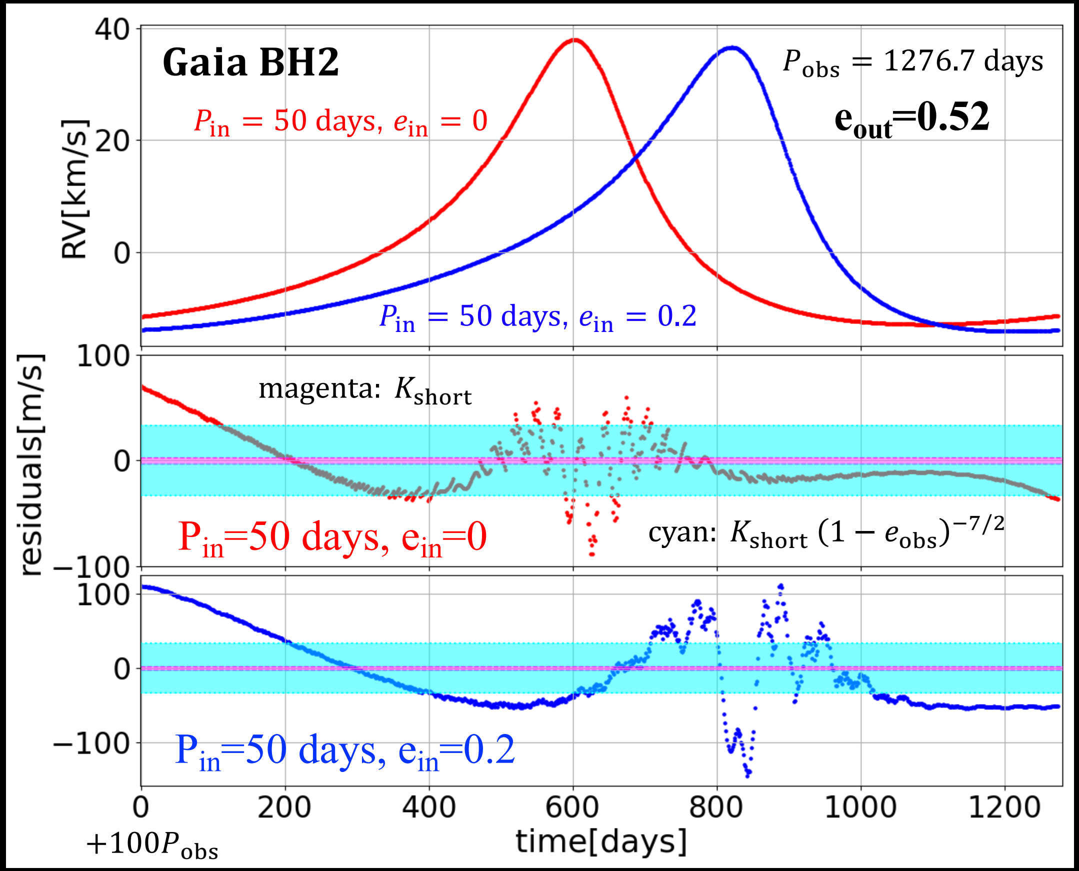
Short-term RV modulations expected from analytic approximation (coplanar + circular tertiary)

Contours of expected semi-amplitudes of short-term RV modulations:
~ (1-100) m/s for coplanar outer orbits (Hayashi, YS + Trani 2023)



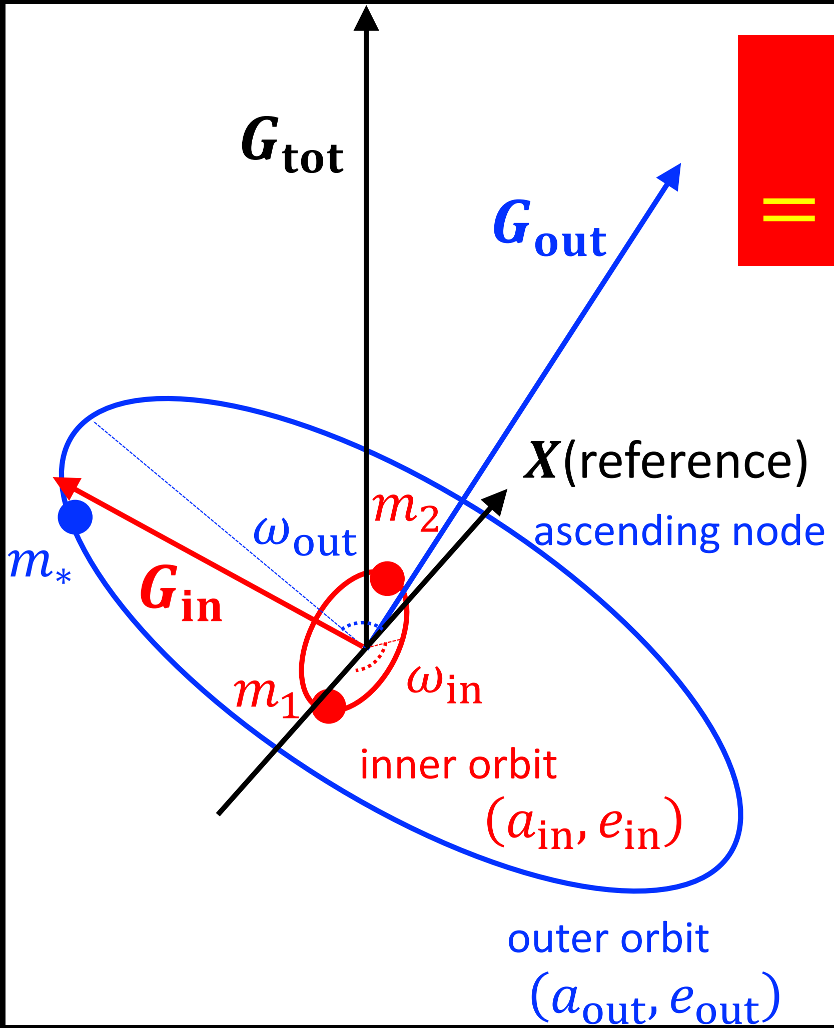
Short-term RV modulations from direct three-body simulation (coplanar + tertiary with observed eccentricity)



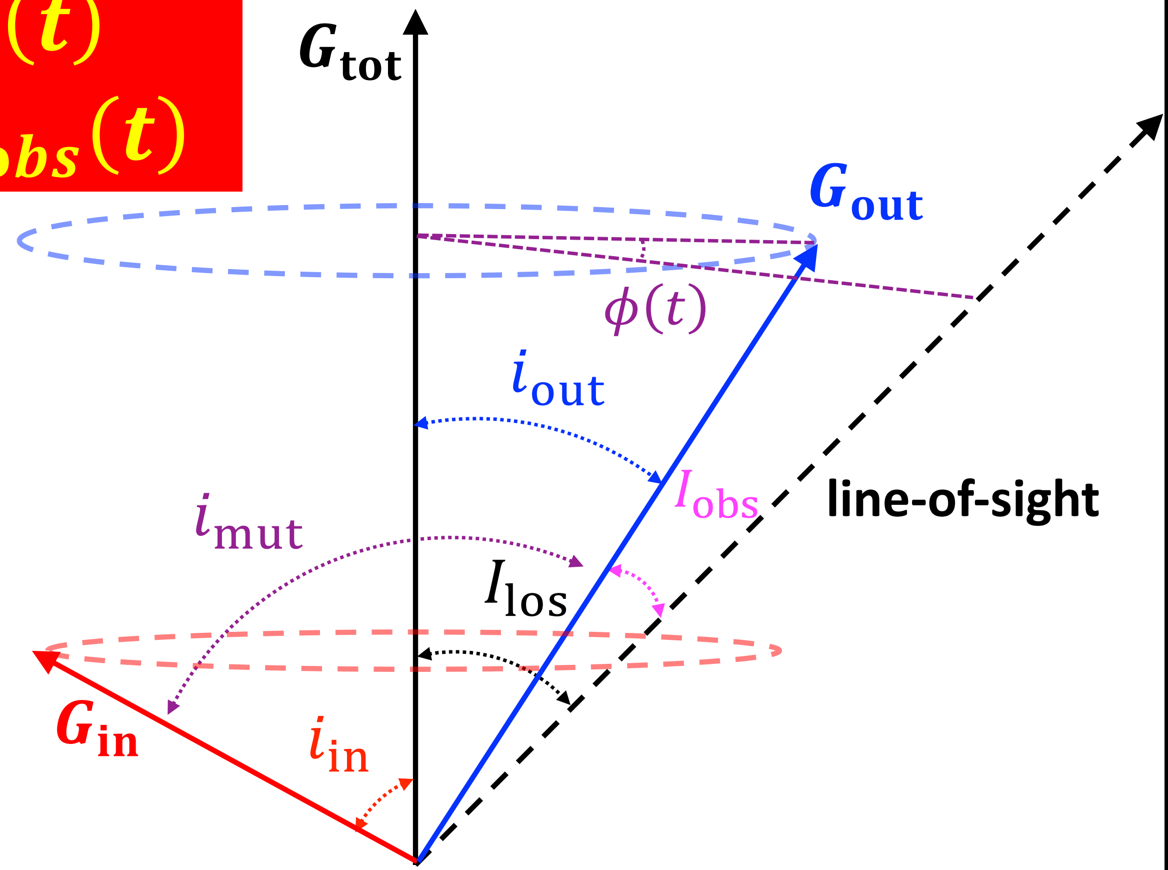


- Due to the outer eccentricity, the amplitude of the short-term RV modulations becomes (10-100) times larger at the pericenter passage than the analytic estimate for circular outer orbits

Long-term RV modulations due to nodal precession and ZKL (von Zeipel-Kozai-Lidov) oscillations for non-coplanar inclined triples



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

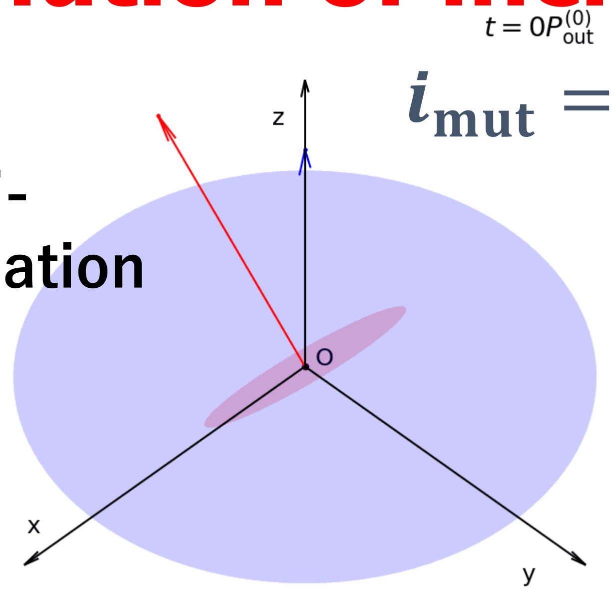


Evolution of inclination for non-coplanar triples

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

weak Kozai-Lidov oscillation

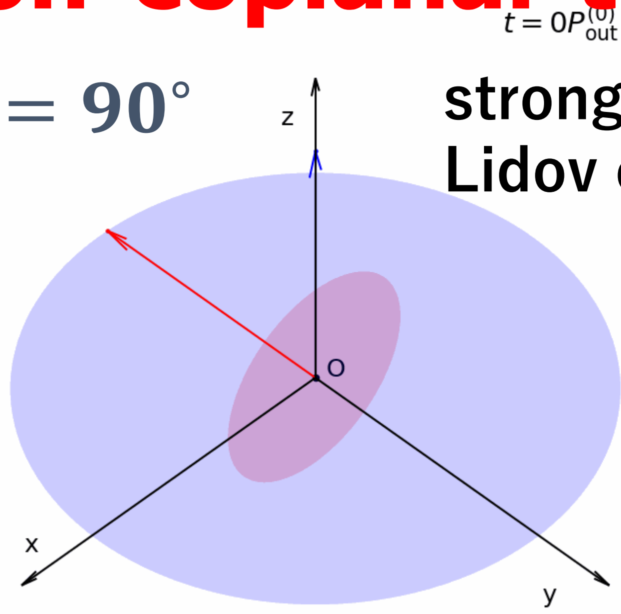
⇒ small-amplitude nodal precession



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

strong Kozai-Lidov oscillation

⇒ large-amplitude sporadic precession



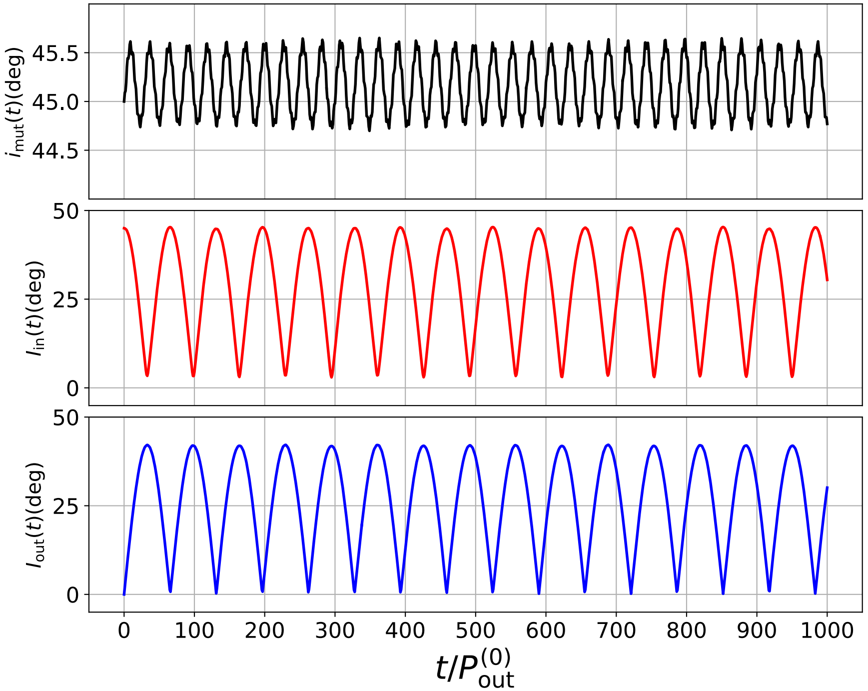
Hayashi + YS: ApJ 897(2020)29

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

$i_{\rm mut}(t)$

$I_{\rm in}(t)$

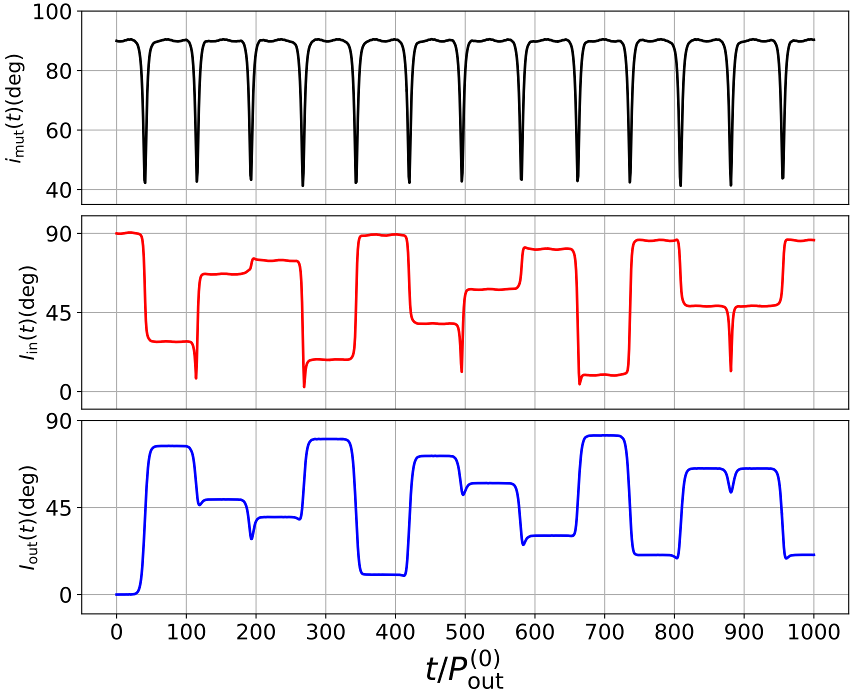
$I_{\rm out}(t)$



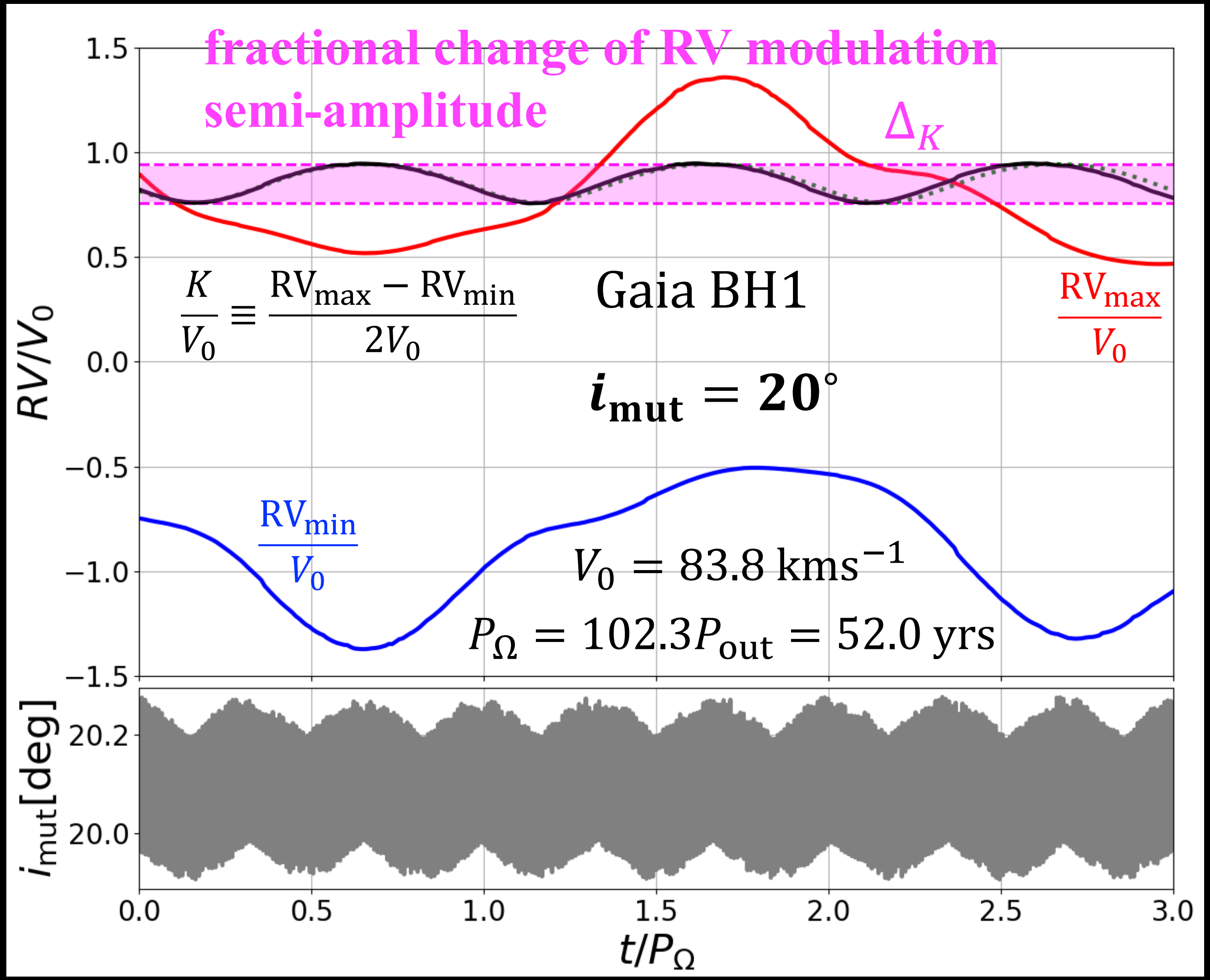
$i_{\rm mut}(t)$

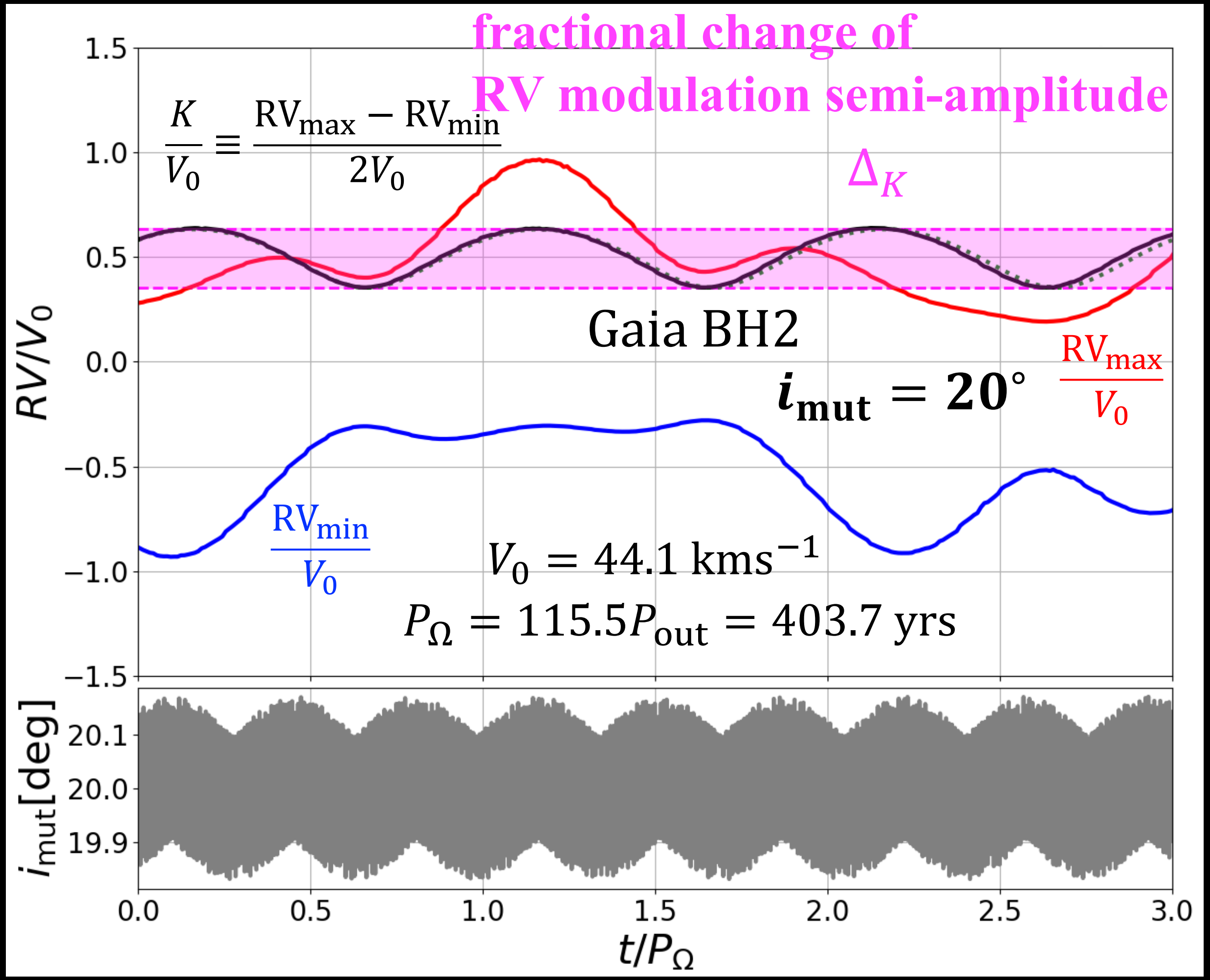
$I_{\rm in}(t)$

$I_{\rm out}(t)$



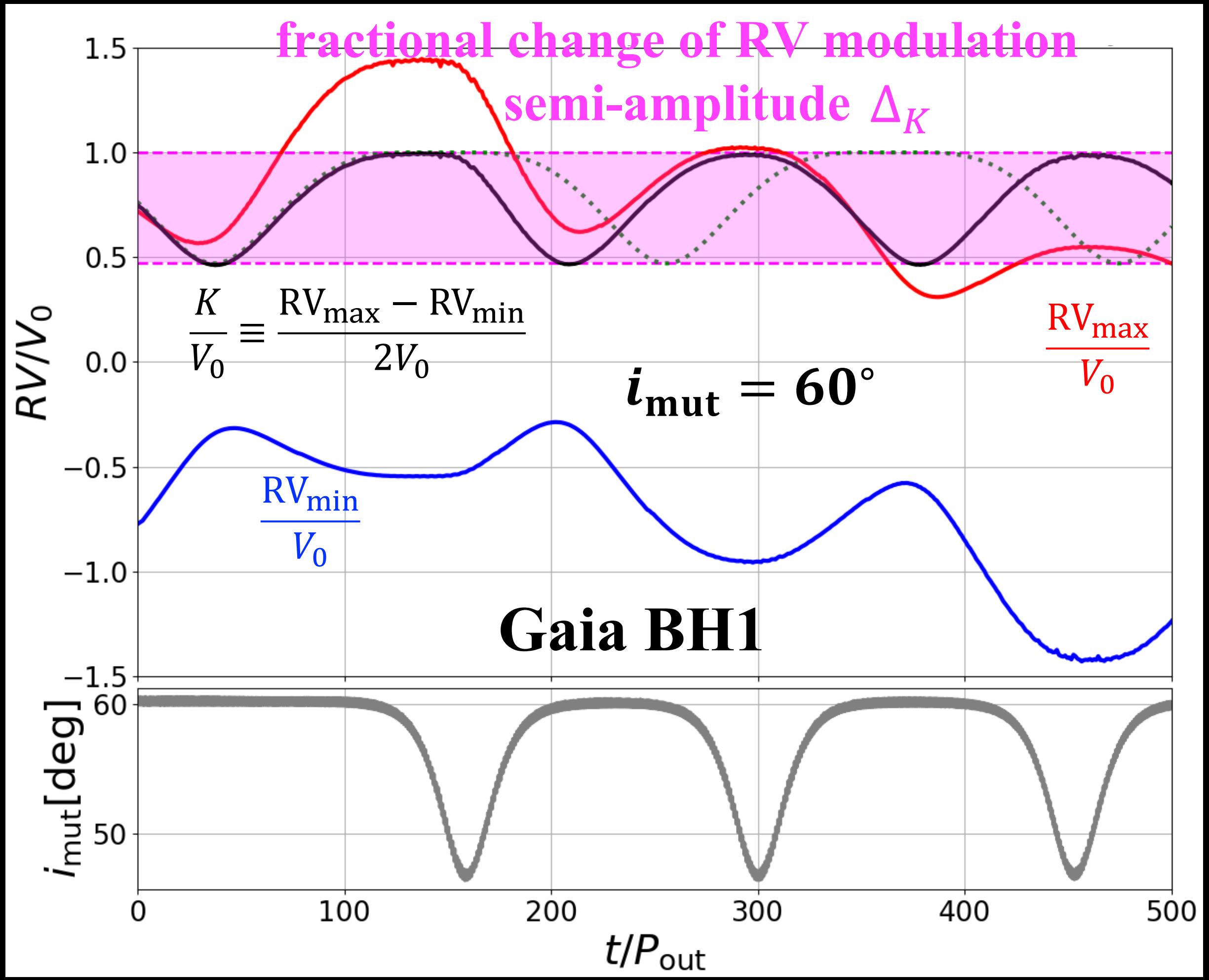
Long-term RV modulations due to nodal precession (i_{mut}=20°)

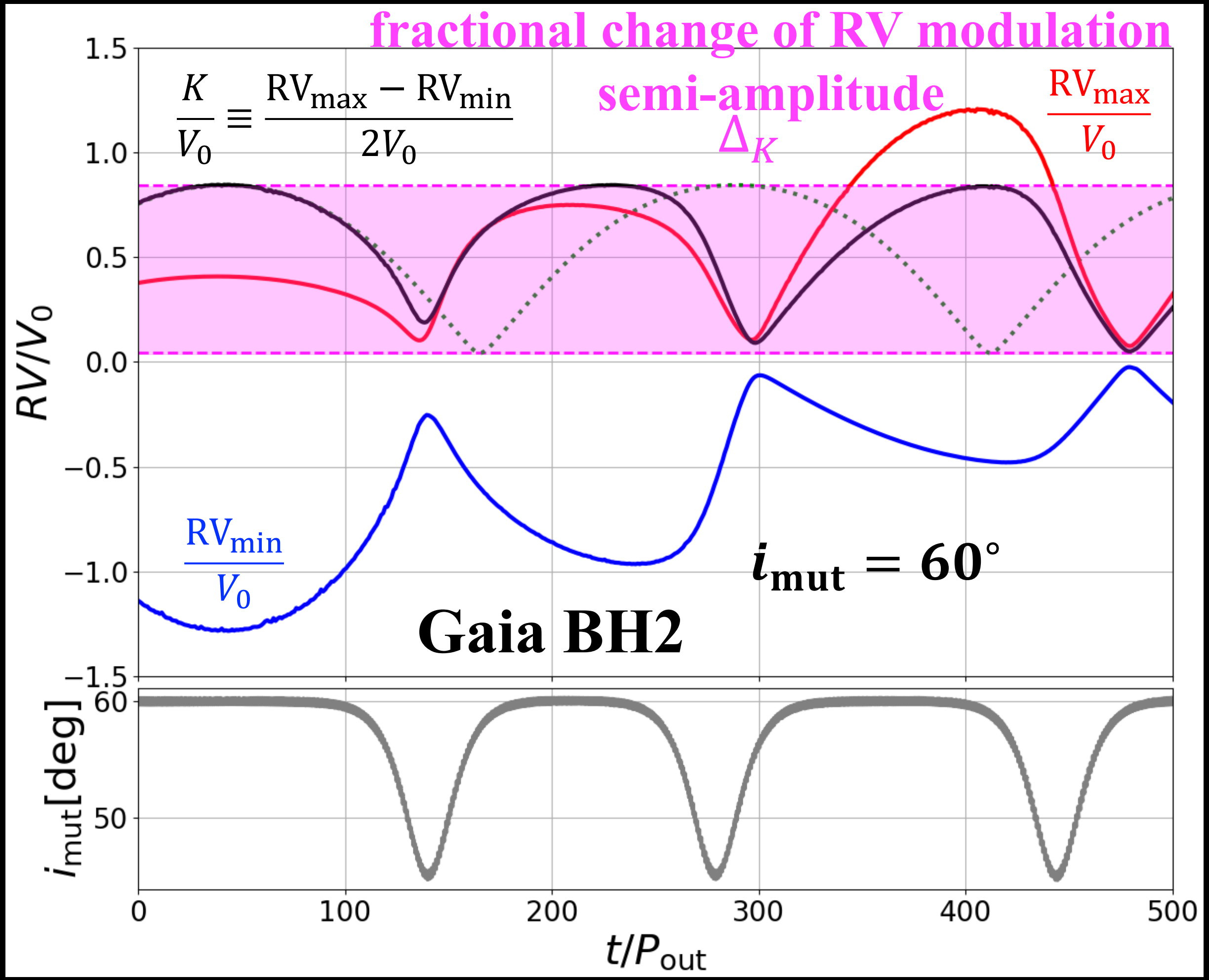




Hayashi, YS + Trani (2023)

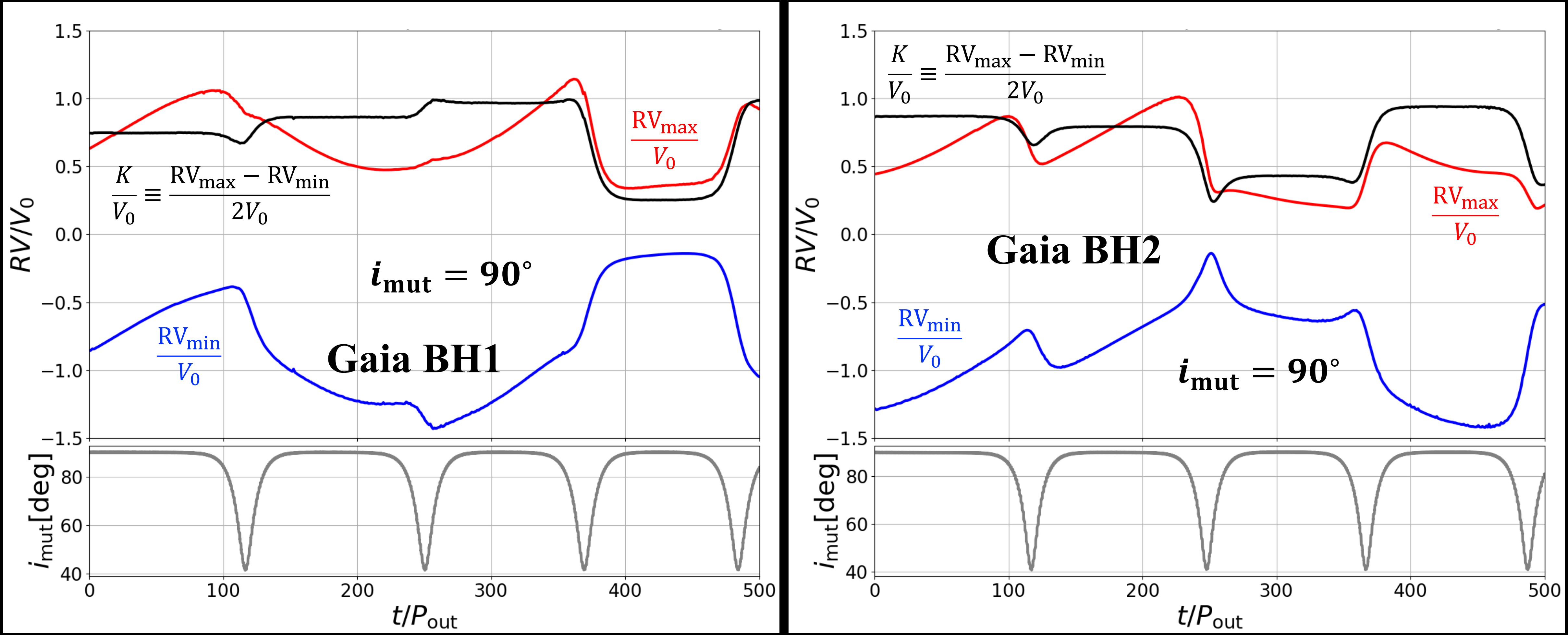
Long-term RV modulations due to moderate ZKL oscillations (i_{mut}=60°)





Hayashi, YS + Trani (2023)

Long-term RV modulations due to strong ZKL oscillations (i_{mut}=90°)



Hayashi, YS + Trani (2023)

Conclusion: RV signatures of inner binary black holes in triple systems may be detectable

- Radial velocity (RD) monitoring of star-black hole binary candidates may reveal inner binary black holes if exist at all
  - short-term RD variations Hayashi, Wang + YS: ApJ 890(2020)112
    - periodic modulations of O(0.1) 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 quasi-periodically by the nodal precession and/or the ZKL oscillations of the inner and outer orbits over O(100) years
  - A proof-of-concept study for Gaia BH1 and BH2 systems
    - may be even detectable for Gaia BH1! Hayashi, YS + Trani: arXiv:2307.01793

False positive: *Tant pis? Non, Tant mieux!*

- ***Suppose that Gaia BH1 exhibits a short-term RV modulation of ~100m/s with period P_{short}***
  - Signal (=false positive for people in this session)
    - the first discovery of a stellar-mass binary blackhole (orbital period of $2P_{short}$) in a triple system
  - False positive (=signal for people in this session)
    - the first discovery of a planetary system (orbital period of P_{short}) orbiting a stellar-mass blackhole

see Morais & Correia (2008, 2012), Hayashi, Wang & YS (2020)