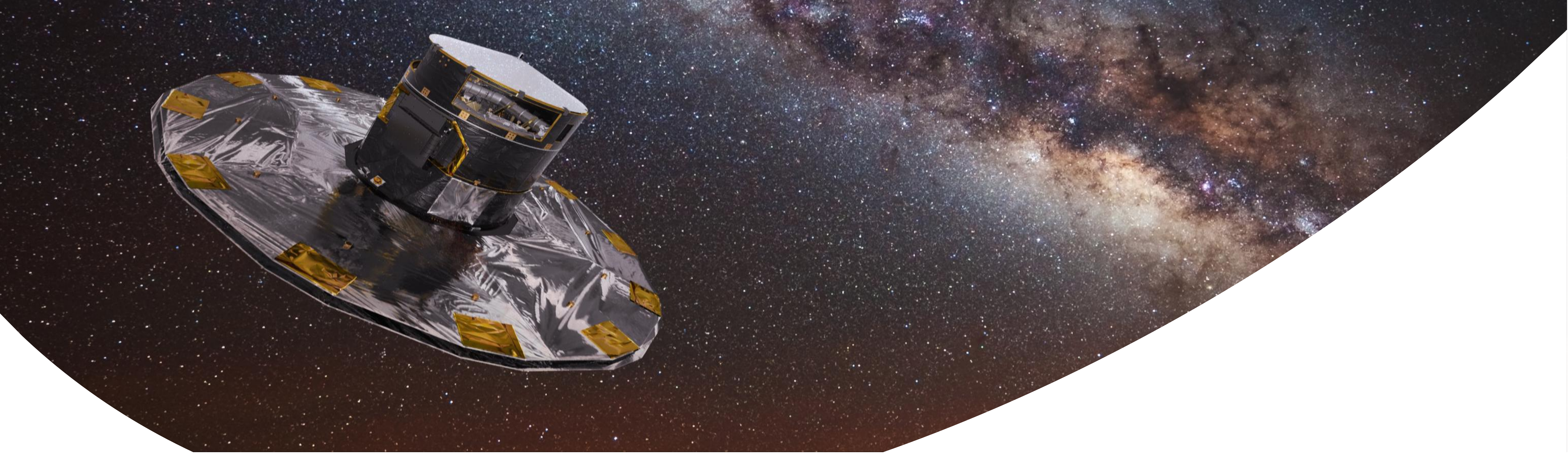
Exoplanet detection limits of Gaia DR4 astrometry



NGUYEN Tung Lam

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LIRA – Observatoire de Paris

31 March 2026 – ExoSystèmes V

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Gaia Data Release 4

- Gaia Data Release 4 (DR4):

Expected December 2026

- Epoch astrometry now available:

> 2 billion sources spanning 66 months

- Pre-release result:

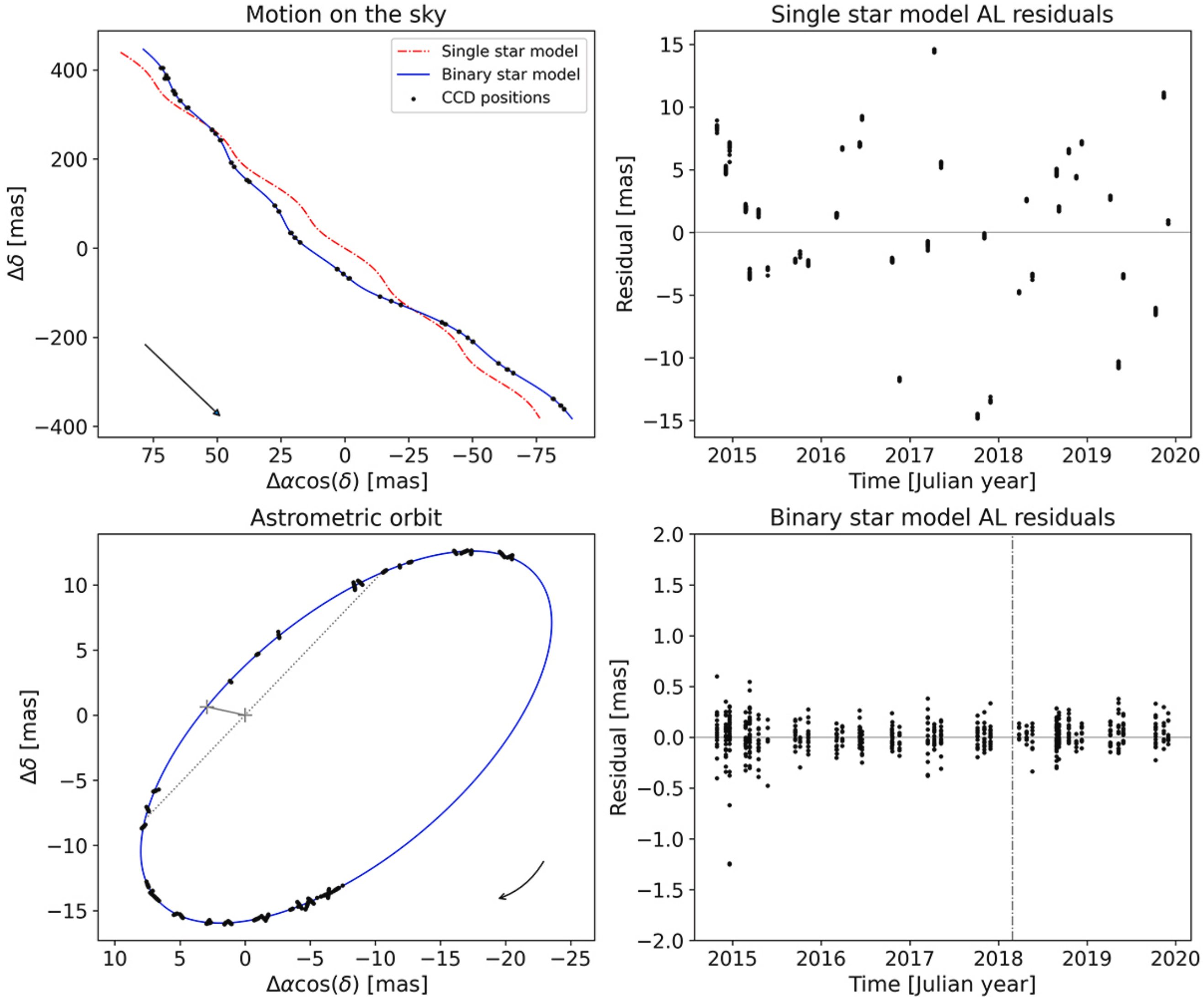
Discovery of Gaia BH3 – a 33 $M_\odot$ black hole

(Gaia Collaboration+2024)

- Great potential:

~ 7500 ± 2100 planets (Lammers & Winn 2025)

⇒ Limitations of Gaia DR4 epoch astrometry?



Modeling of Gaia astrometry

Recipes from GaiaPMEX (Kiefer+2021):

- Photocenter orbit: semi-major axis a_{phot} and period P
  - Primary star mass $M_\star$ at parallax ϖ
  - Dark companion mass M_B

$\Rightarrow$ Mean astrometric signature projected onto along-scan (AL):

$$\frac{a_{\mathrm{phot}}}{\mathrm{mas}} = \left(\frac{\varpi}{\mathrm{mas}}\right)\left(\frac{M_B}{\mathrm{M}_\odot}\right)\left[\frac{P/(\mathrm{yr})}{(M_\star + M_B)/\mathrm{M}_\odot}\right]^{2/3}$$

$$s = \frac{2}{\pi} a_{\mathrm{phot}}$$

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$$s = \frac{2}{\pi} a_{\rm phot}$$

- Noise and error: estimated from G-mag and B_P - R_P color
  - Calibration noise σ_{calib}
  - AL angle measurement error σ_{AL}
  - N_{AL} ~ 9 AL angle measurements per transit
  - ~ 70 transits/target
  - For a solar analogue at 10 pc:

  G-mag ~ 9.61 and B_P - R_P ~ 0.82 (Gaia Collaboration+2023)

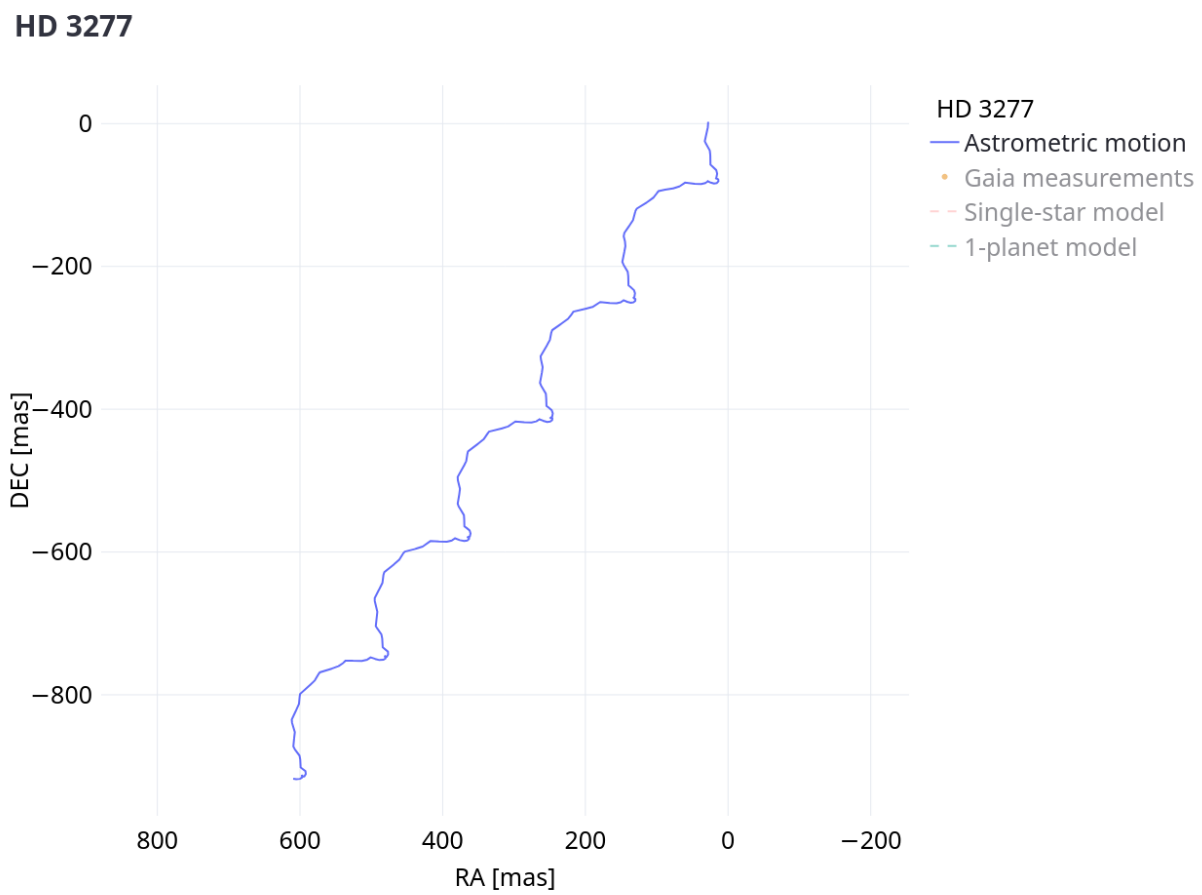
  $\Rightarrow$ σ_{Gaia} ~ 0.117 mas

$$\sigma_{\rm Gaia} = \sqrt{\sigma^2_{\rm calib} + \sigma^2_{\rm AL}/N_{\rm AL}}$$

$${\rm SNR} = \frac{s}{\sigma_{\rm Gaia}}$$

Orbit fitting

Periodogram analysis (Delisle & Ségransan 2022 – same approach for Gaia BH3 detection)



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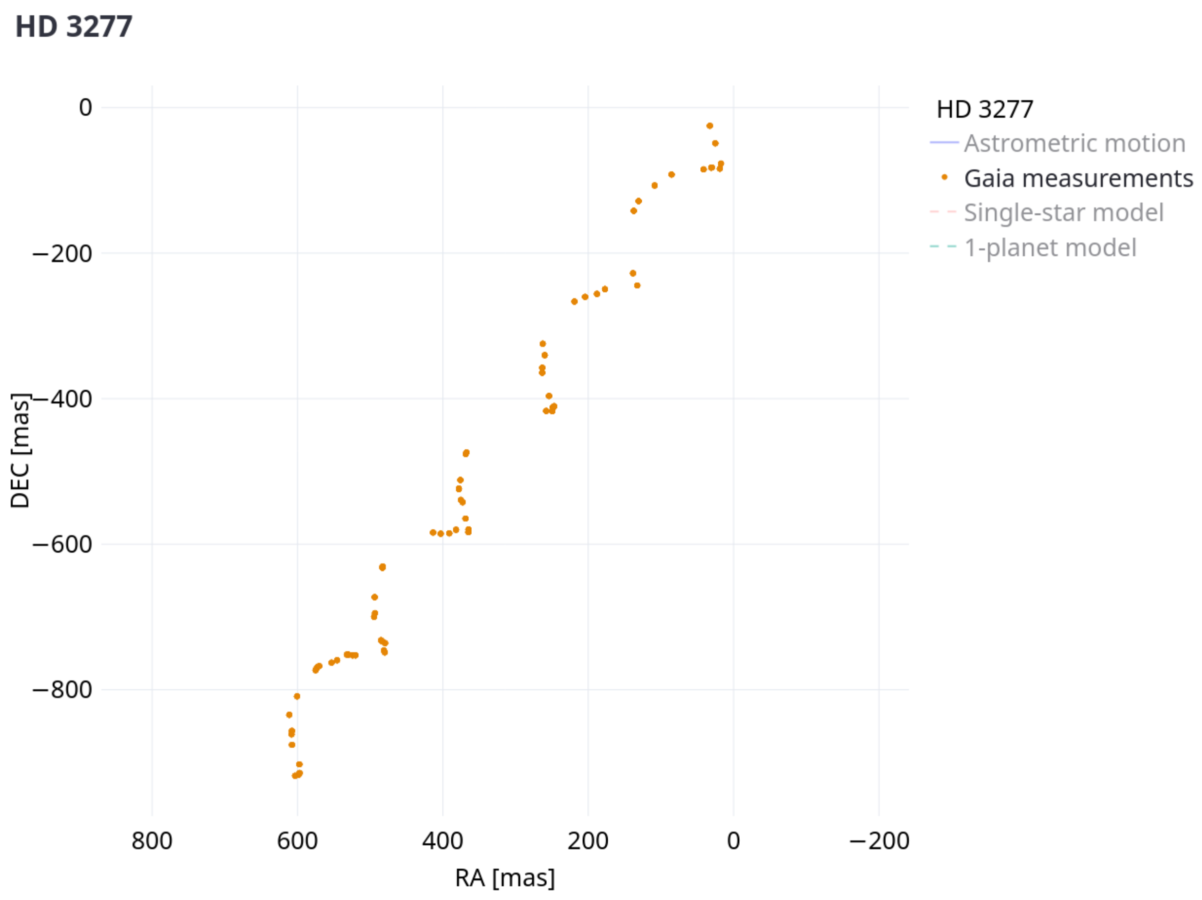


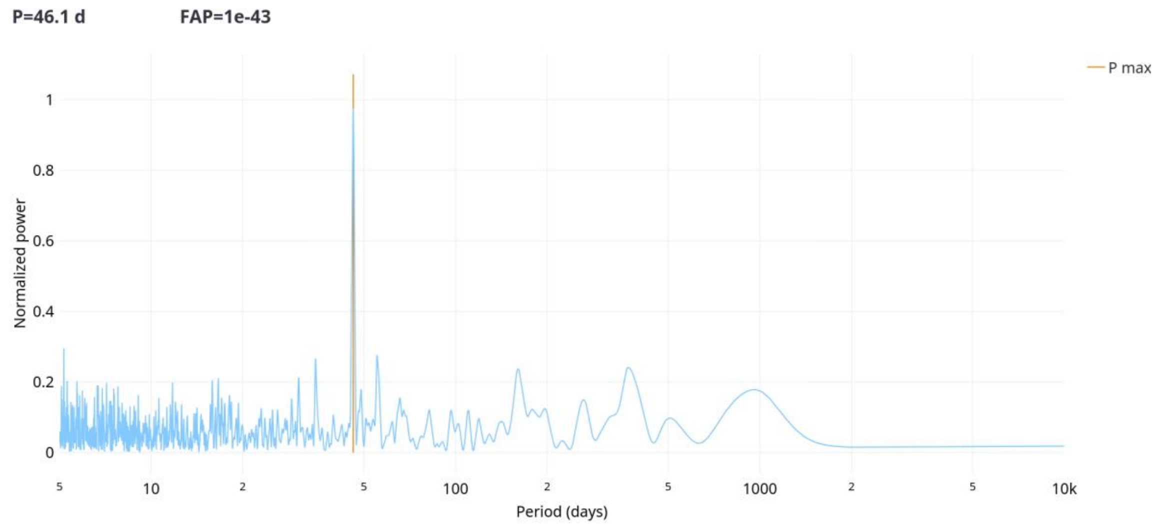
Orbit fitting

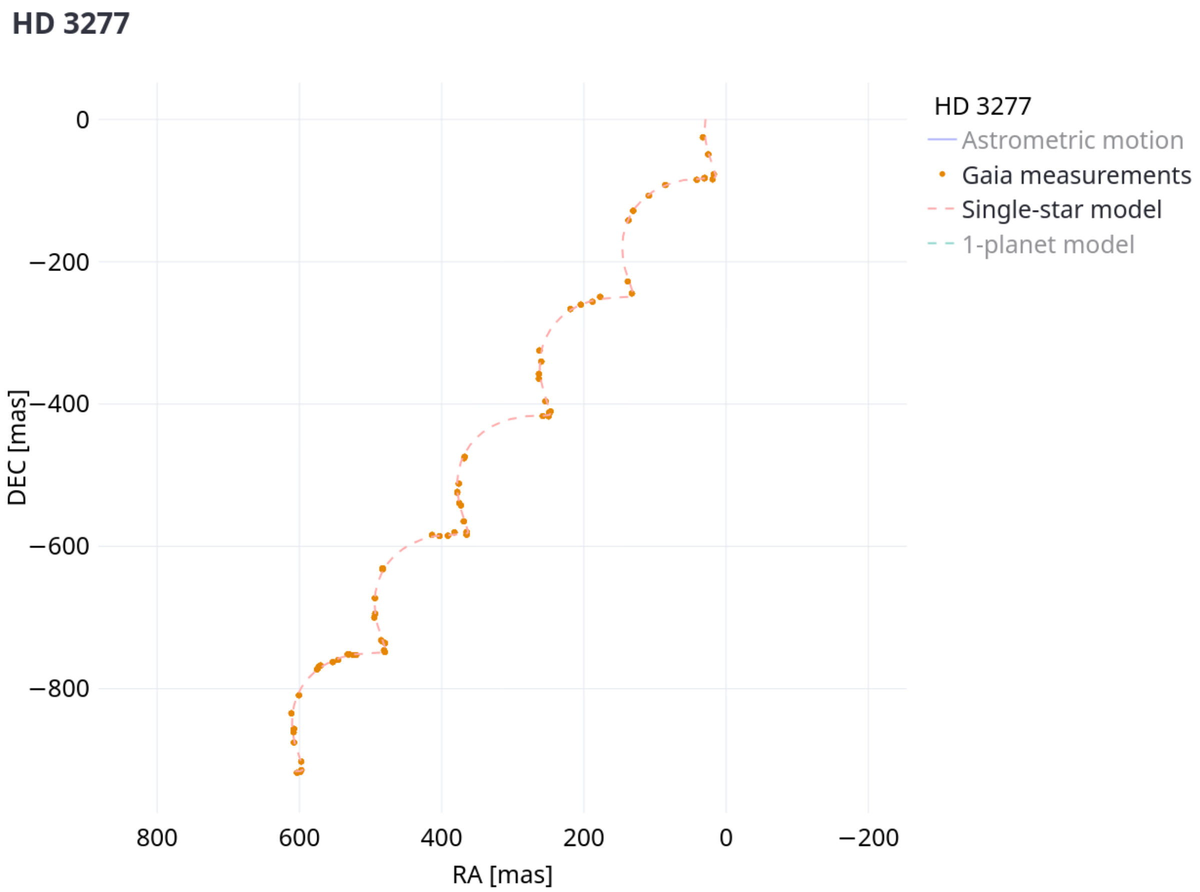
Periodogram analysis (Delisle & Ségransan 2022 – same approach for Gaia BH3 detection)

1. Fit standard astrometric model and calculate periodogram of residuals

⇒ Period P with False Alarm Probability (FAP)

⇒ Proper motion ($\mu_{\alpha*}$, μ_δ) and parallax ϖ





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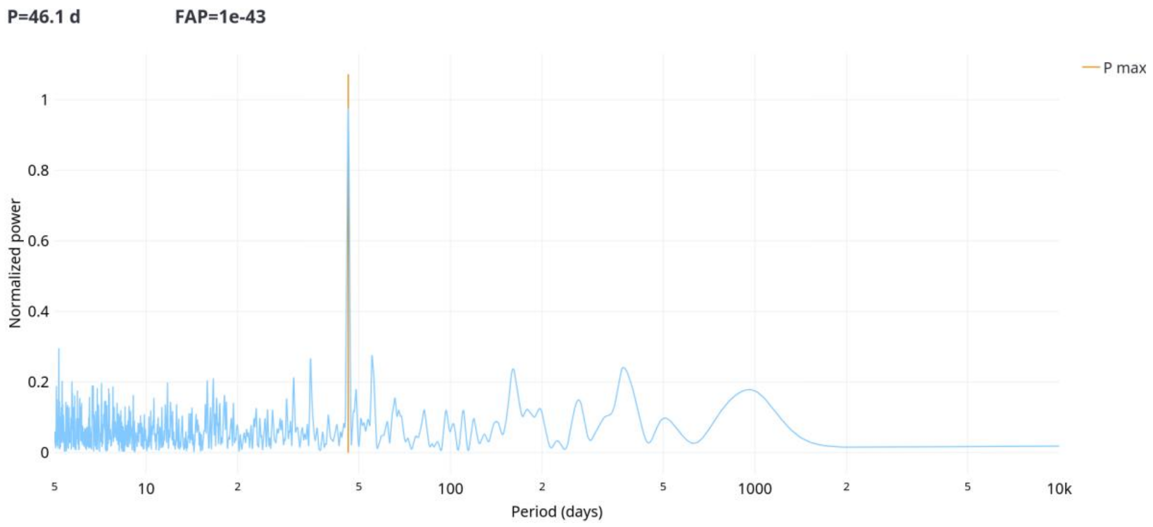
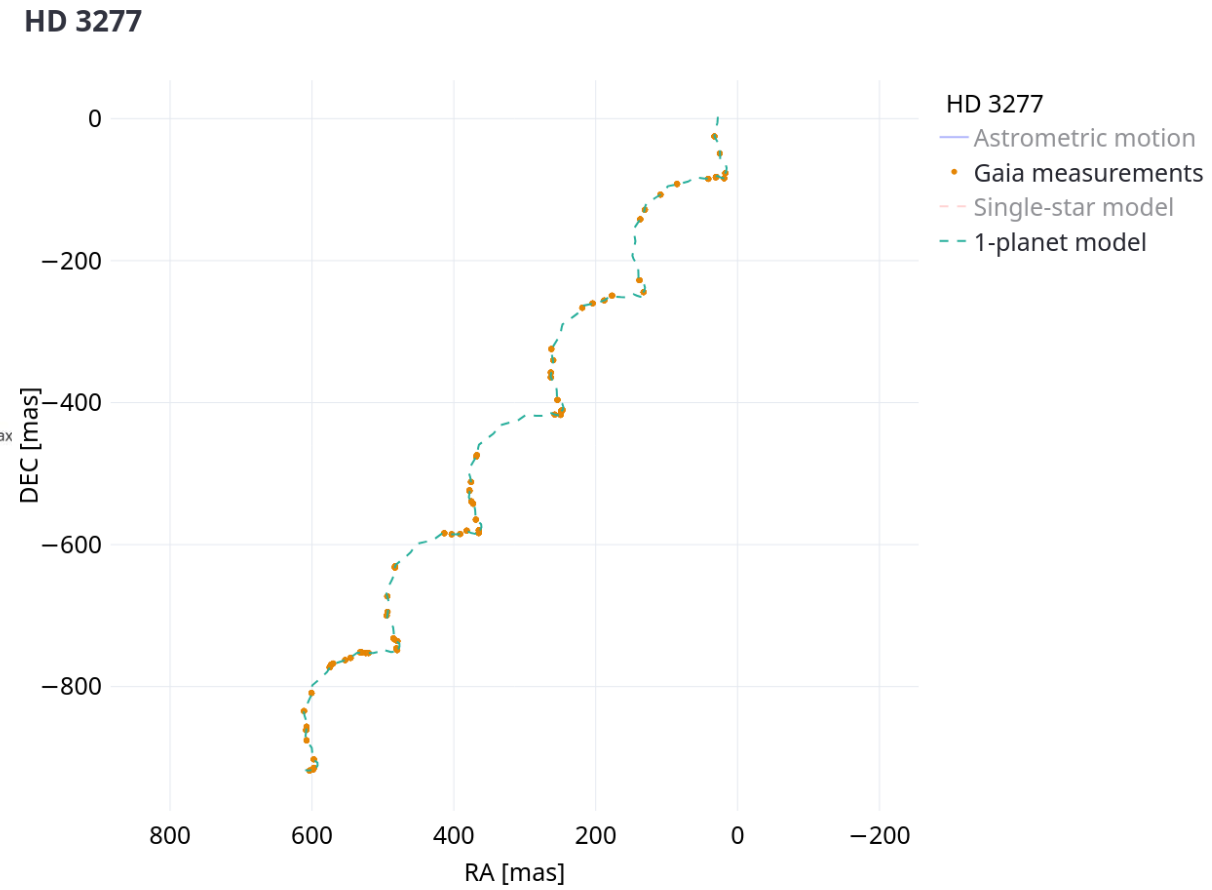
2. Fit the Keplerian model

⇒ Orbital parameters

⇒ Photocentric semi-major axis a_{phot}





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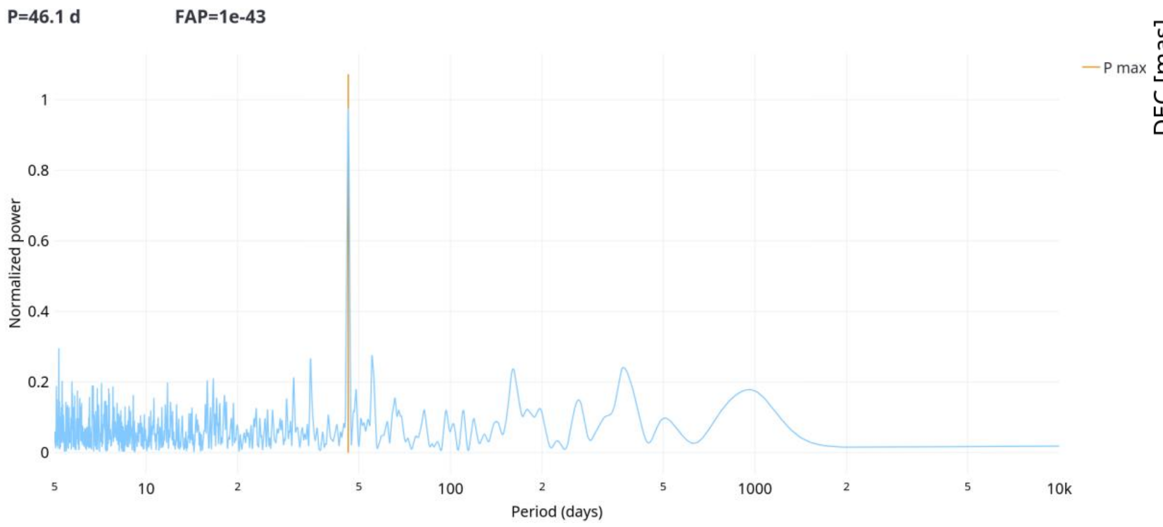
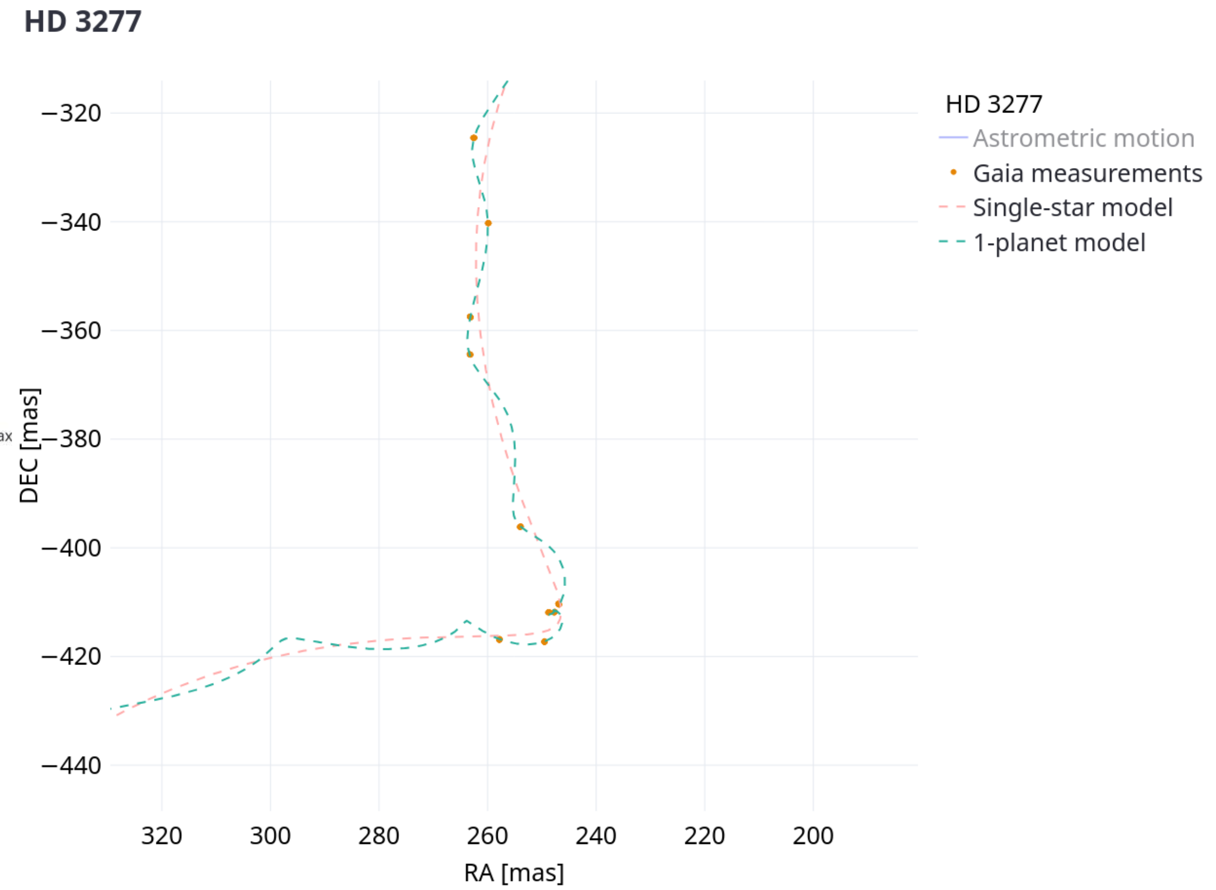


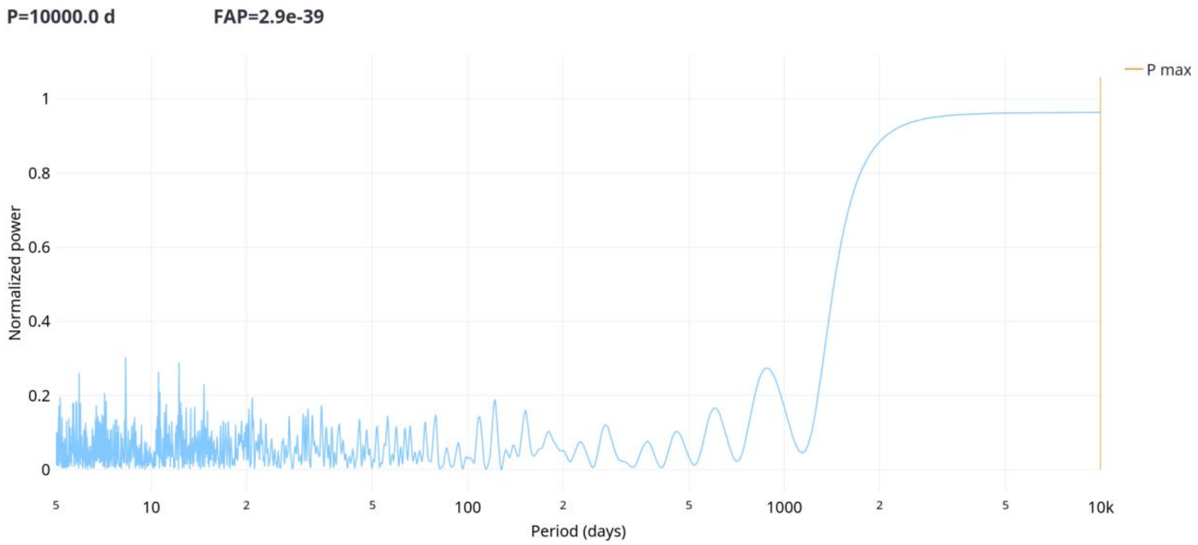


Degeneracy at long periods

- Long orbital periods ≳ 5.5 yr Gaia DR4 baseline cannot be recovered from periodograms

Example:

- $M_\star = 1\ M_\odot$ & $M_B = 10\ M_{Jup}$
- $\varpi = 100$ mas, $\mu_{\alpha\star} = \mu_\delta = 1$ mas/yr
- P = 20 yr



Degeneracy at long periods

- Long orbital periods $\gtrsim$ 5.5 yr Gaia DR4 baseline cannot be recovered from periodograms

$\Rightarrow$ Arbitrary initial guess of period for orbit fitting

$\Rightarrow$ Multiple solutions exist for the same Gaia astrometric timeseries

Example:

- $M_\star = 1\ M_\odot$ & $M_B = 10\ M_{Jup}$
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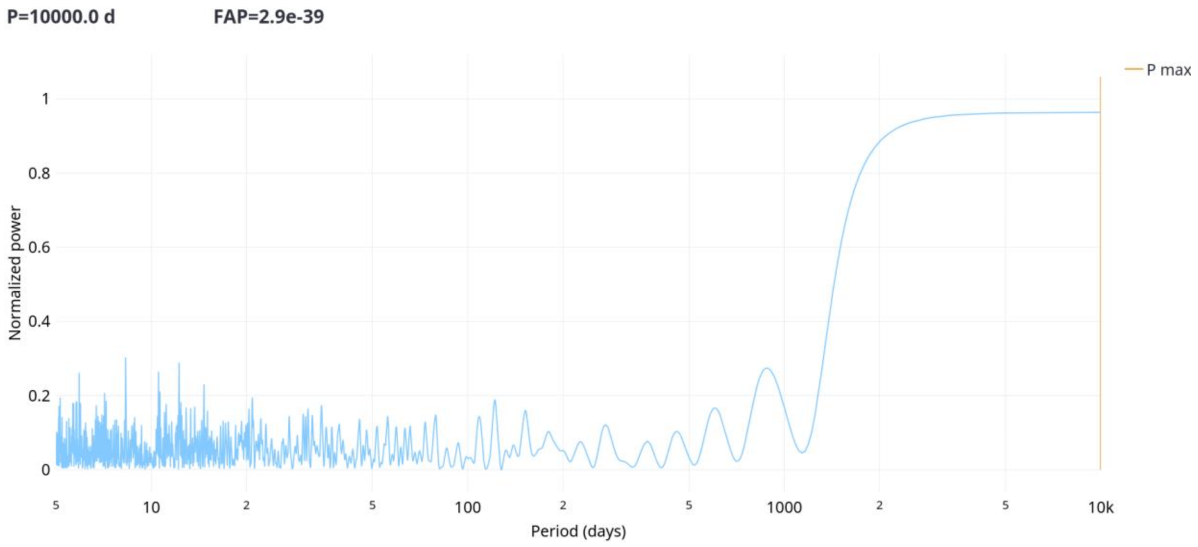
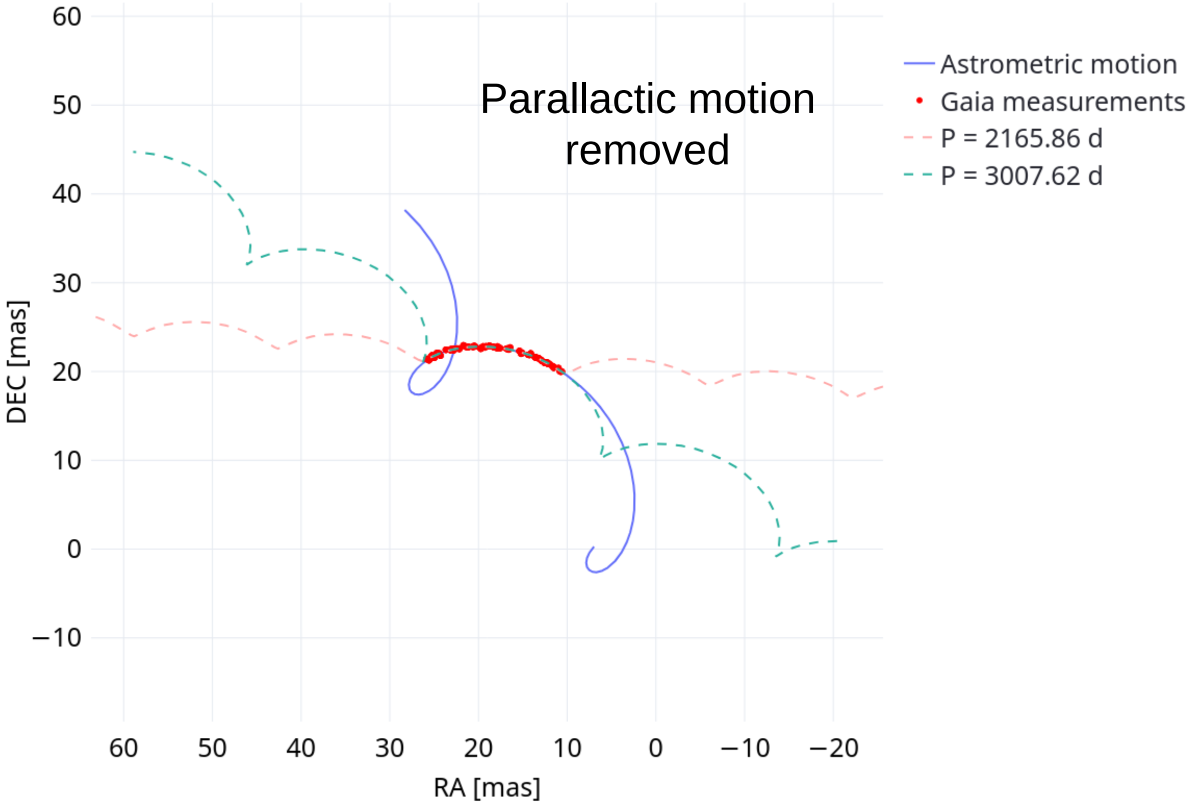
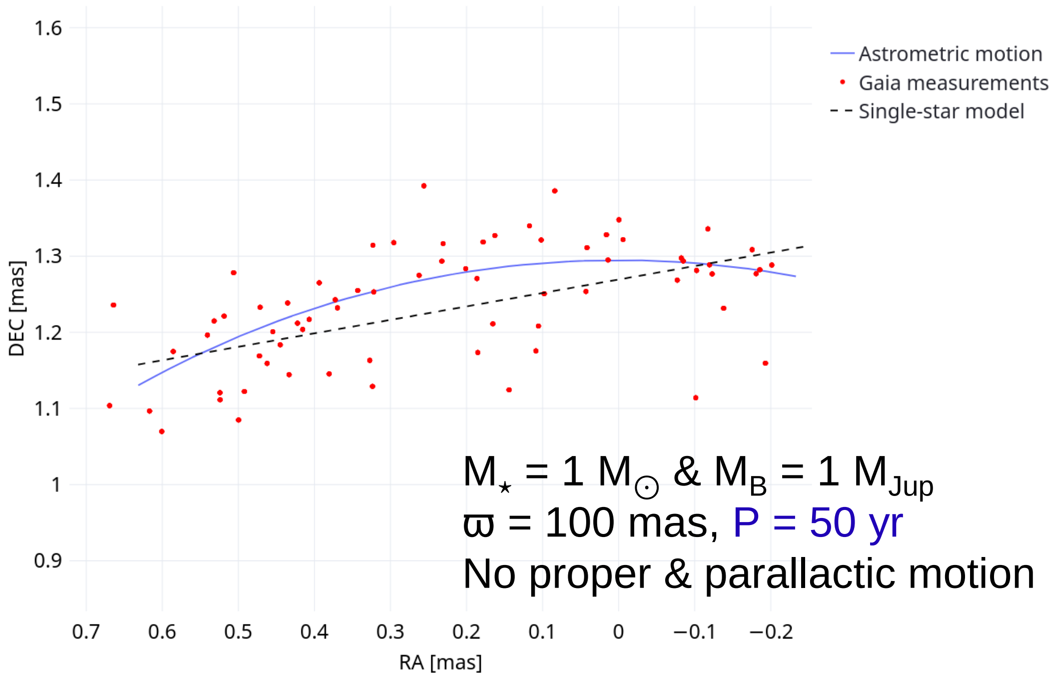




Detection limit at long periods

- Orbital motion & proper motion become indistinguishable at long orbital periods ≳ 5.5 yr



Detection limit at long periods

- Orbital motion & proper motion become indistinguishable at long orbital periods ≳ 5.5 yr
- Astrometric acceleration (face-on circular orbit):

$$\frac{\gamma}{\mathrm{mas\,yr^{-2}}} = 4\pi^2 \left(\frac{a_{\mathrm{phot}}}{mas}\right)\left(\frac{P}{yr}\right)^{-2}$$

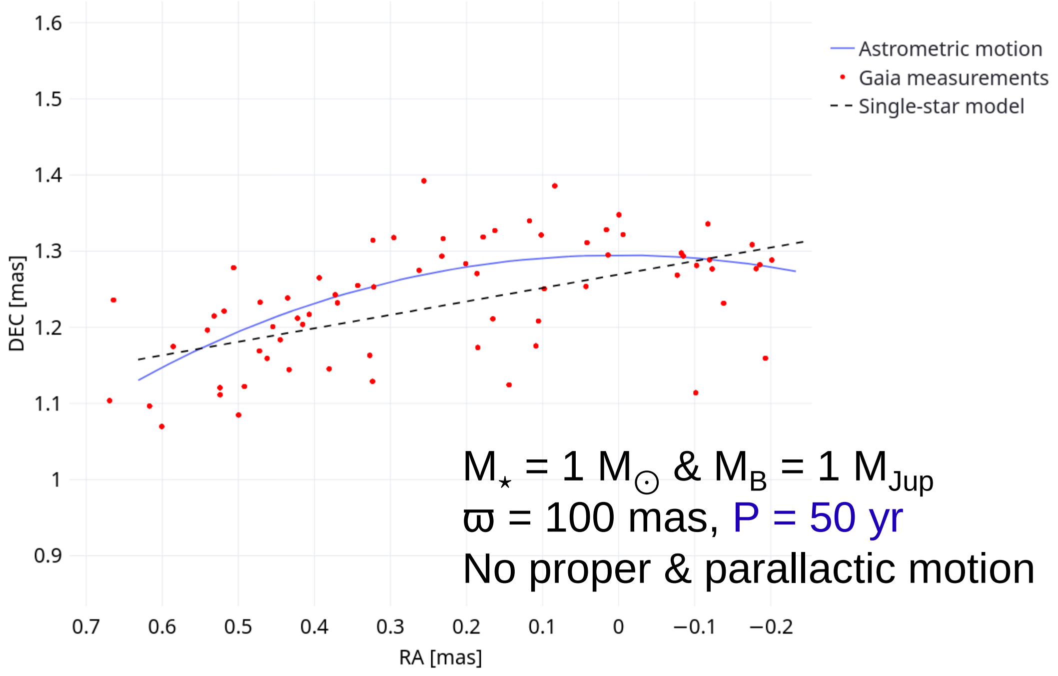
⇒ Amplitude of astrometric accelerated motion during observation baseline Δt:

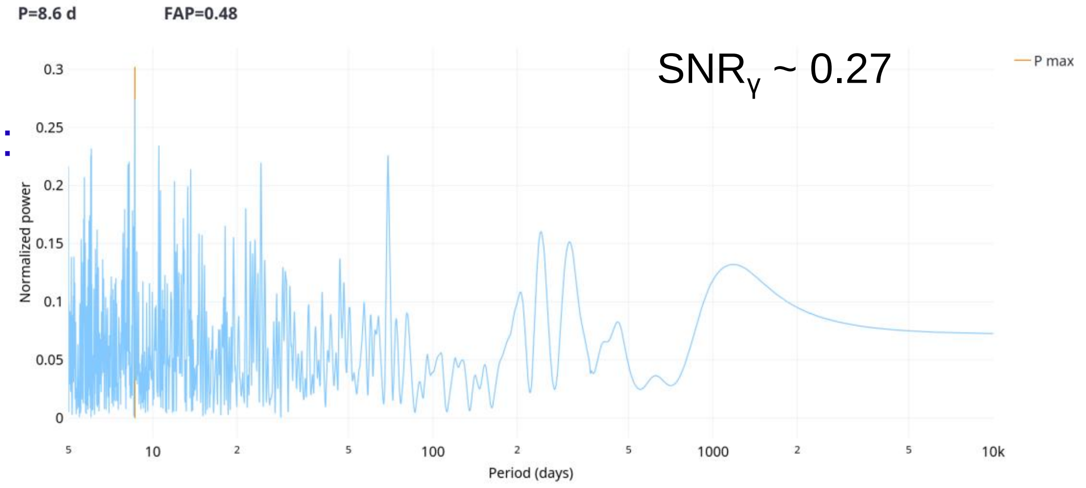
$$\frac{\Delta_\gamma}{\mathrm{mas}} = \frac{1}{2}\left(\frac{\gamma}{\mathrm{mas\,yr^{-2}}}\right)\left(\frac{\Delta t/2}{\mathrm{yr}}\right)^2$$

⇒ Standard deviation of sampled positions on AL direction:

$$\frac{\sigma_\gamma}{\mathrm{mas}} = \frac{1}{\sqrt{6}}\left(\frac{\Delta_\gamma}{\mathrm{mas}}\right)$$

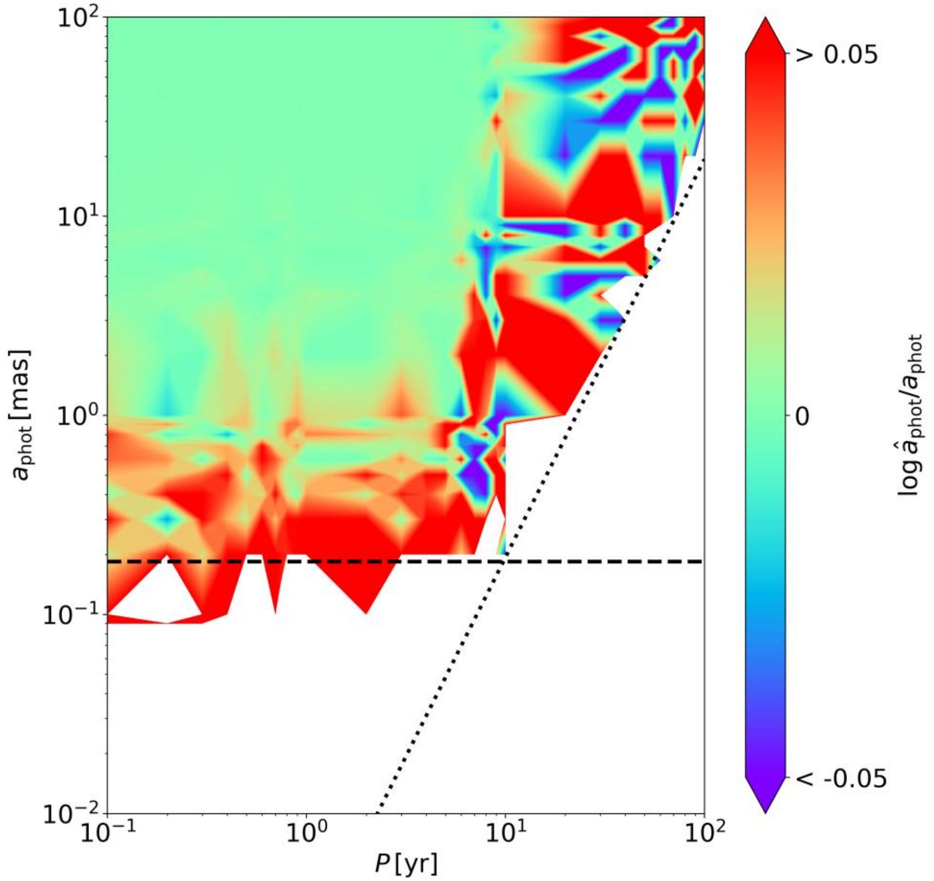
$$\mathrm{SNR}_\gamma = \frac{\sigma_\gamma}{\sigma_{\mathrm{Gaia}}}$$

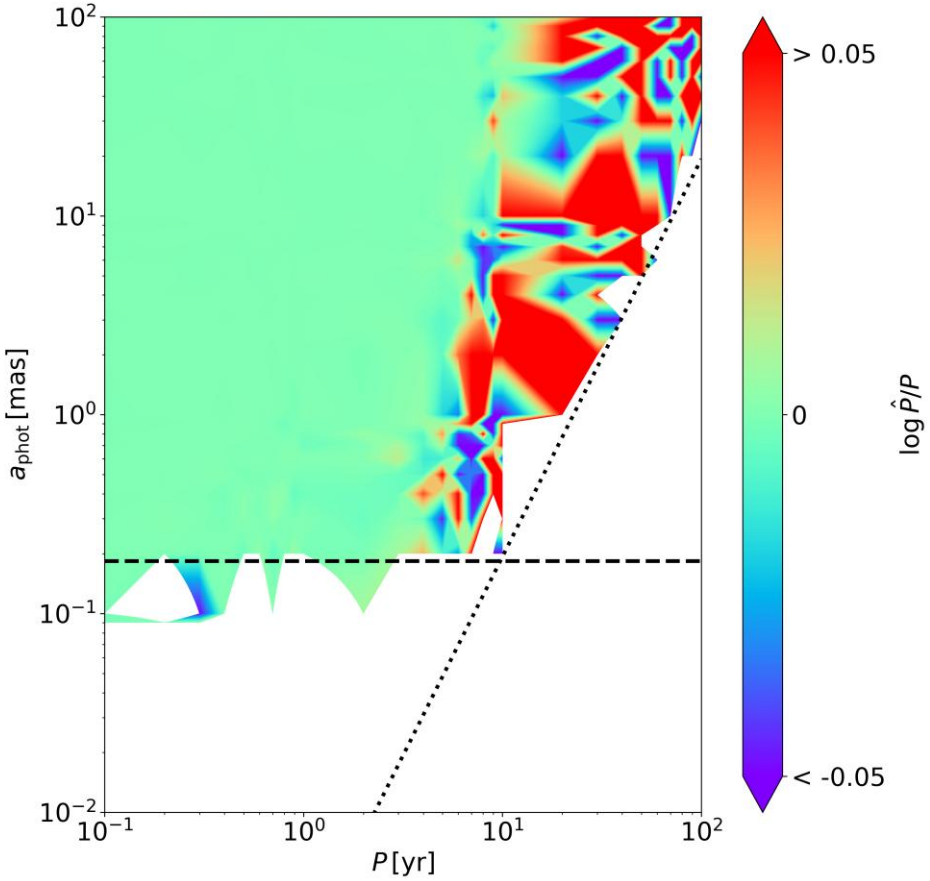




Photocentric semimajor axis – period grid

Grid of Keplerian models: a_{phot} = 0.01 – 100 mas vs P = 0.1 – 100 yr

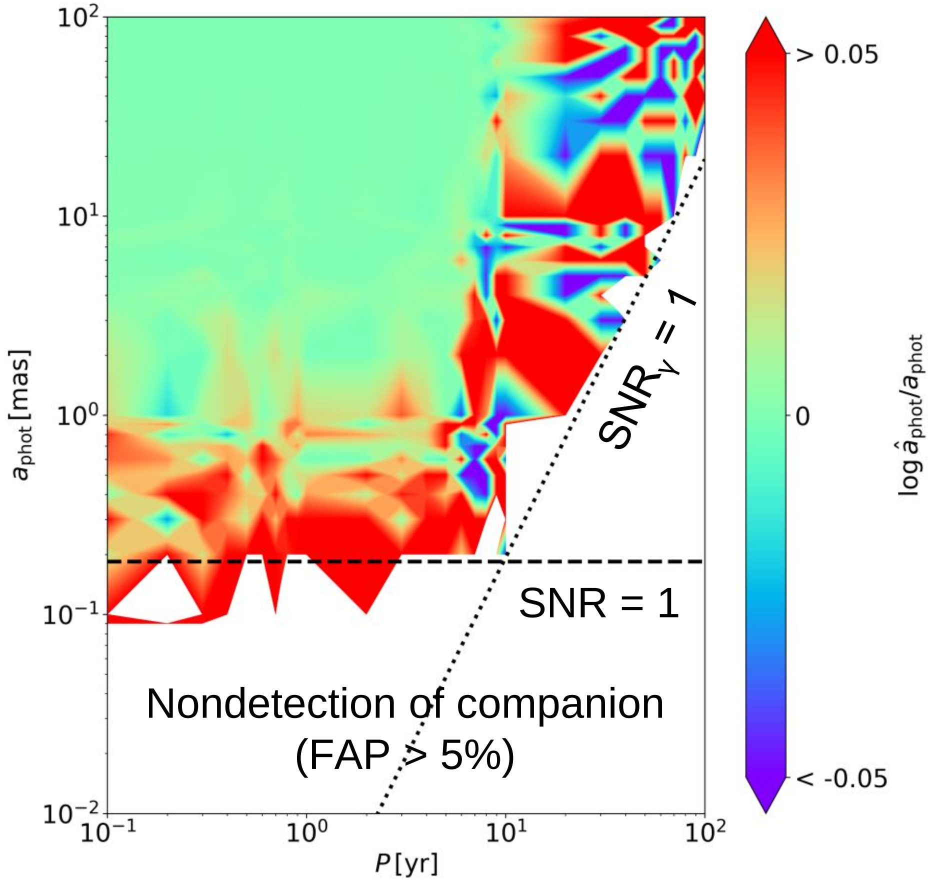


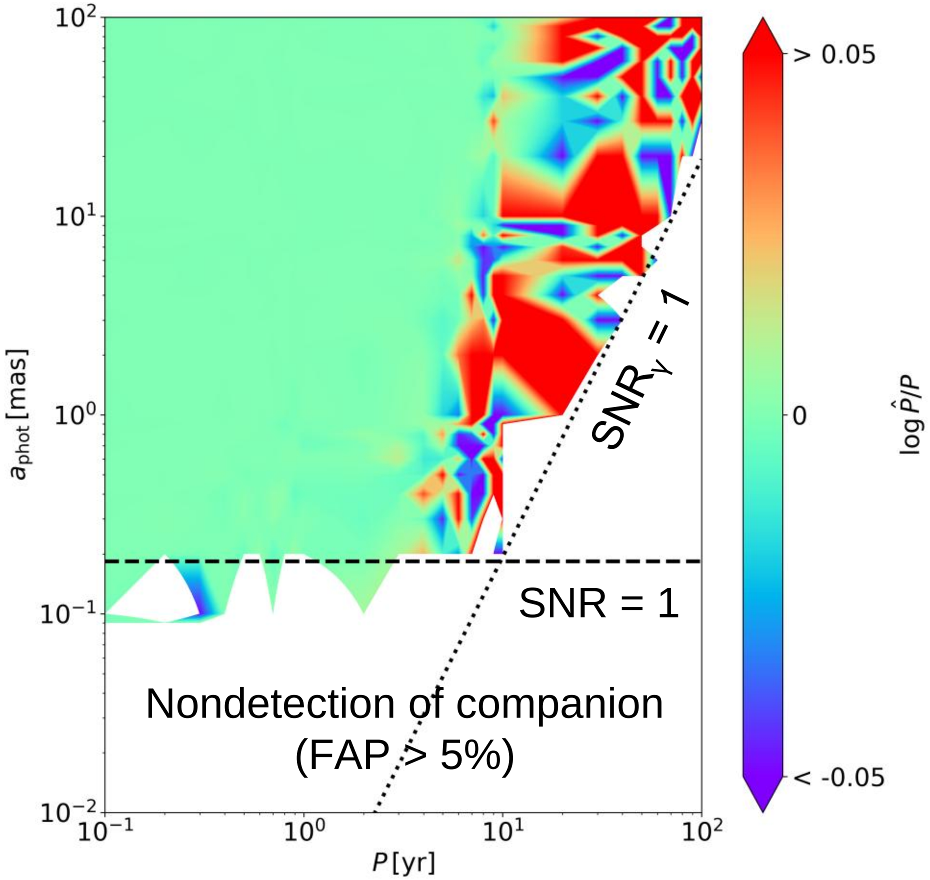


Photocentric semimajor axis – period grid

Grid of Keplerian models: a_{phot} = 0.01 – 100 mas vs P = 0.1 – 100 yr

⇒ Companion detected at SNR ≳ 1 and SNR_γ ≳ 1





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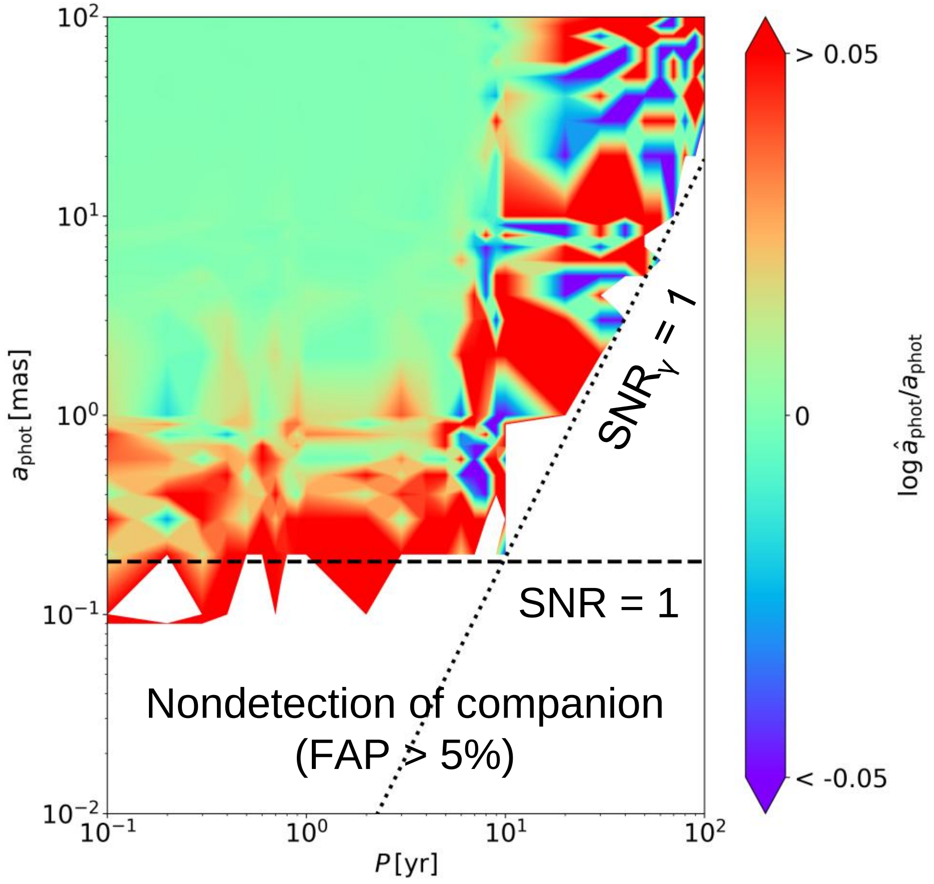
Grid of Keplerian models: a_{phot} = 0.01 – 100 mas vs P = 0.1 – 100 yr

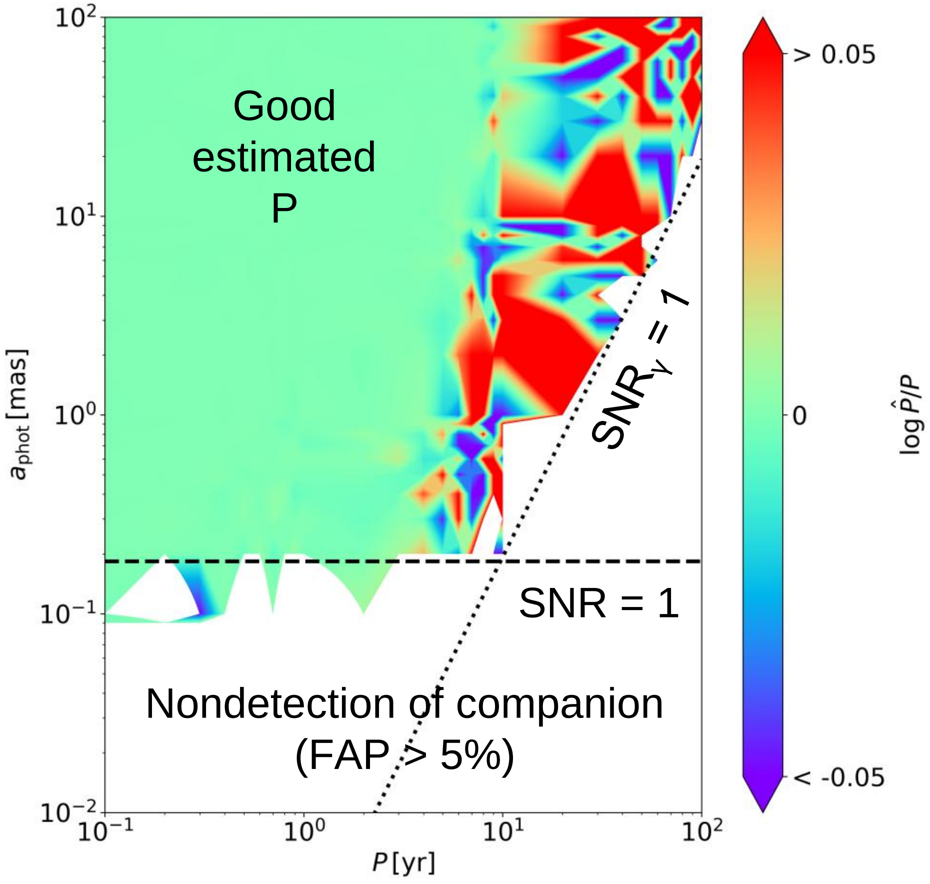
⇒ Companion detected at SNR ≳ 1 and SNR_γ ≳ 1

⇒ Period P recovered at SNR ≳ 1 and P ≲ 5.5 yr



Overestimation > 10 %

Underestimation > 10%



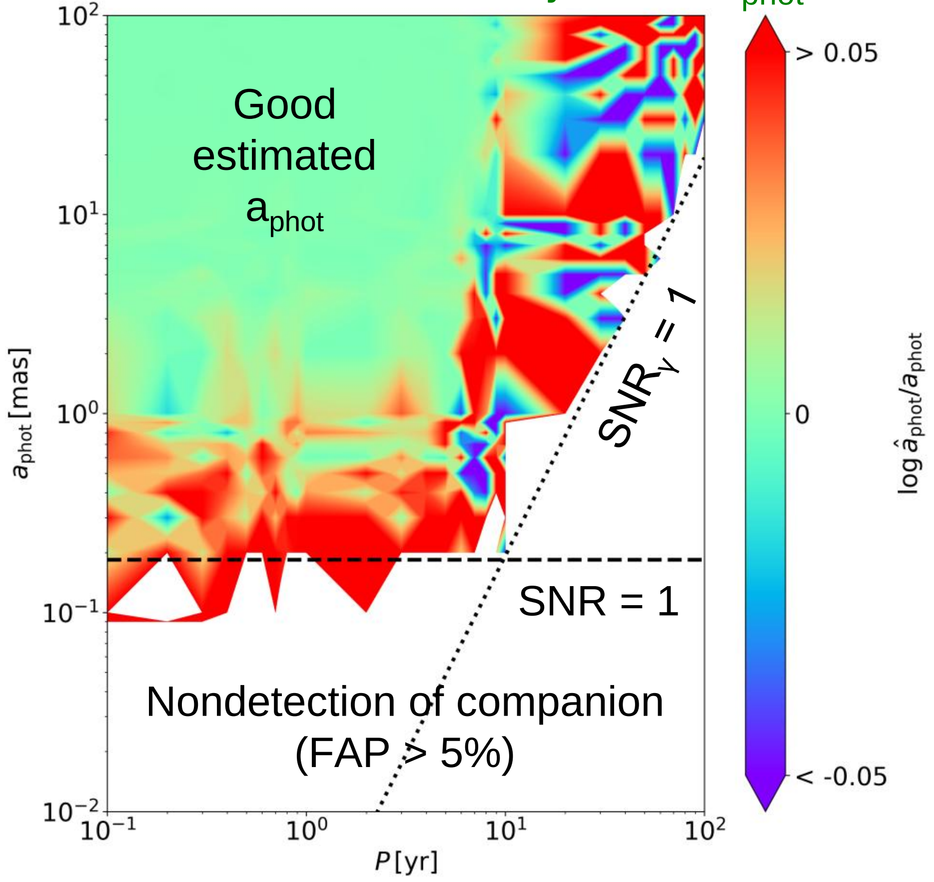
Photocentric semimajor axis – period grid

Grid of Keplerian models: a_{phot} = 0.01 – 100 mas vs P = 0.1 – 100 yr

⇒ Companion detected at SNR ≳ 1 and $SNR_γ$ ≳ 1

⇒ Period P recovered at SNR ≳ 1 and P ≲ 5.5 yr

⇒ Photocentric semimajor axis a_{phot} recovered at SNR ≳ 10 and P ≲ 5.5 yr



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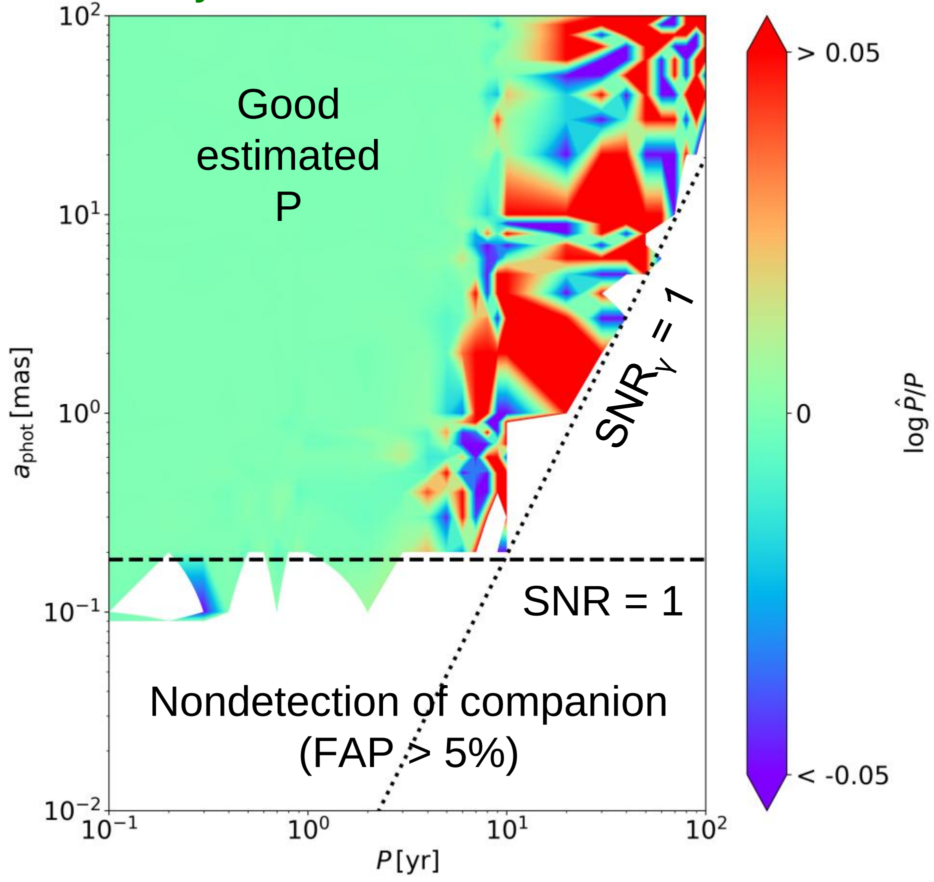

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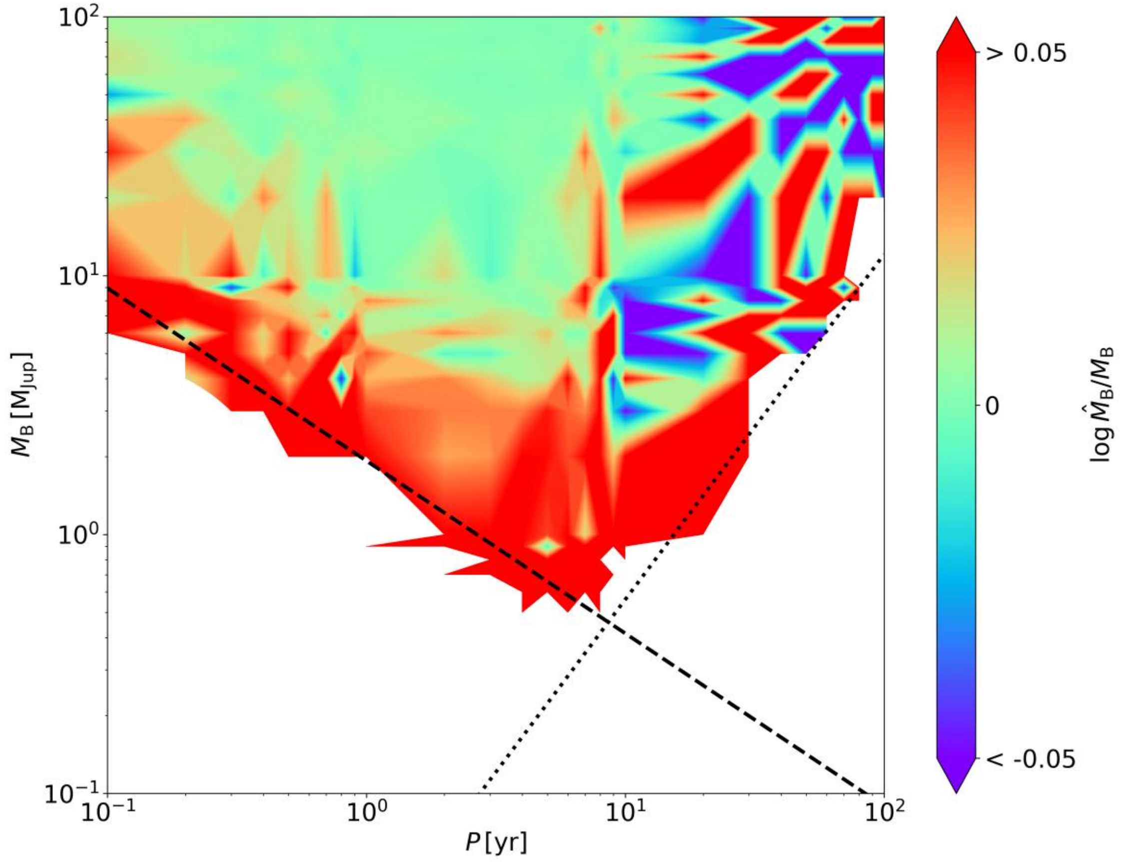
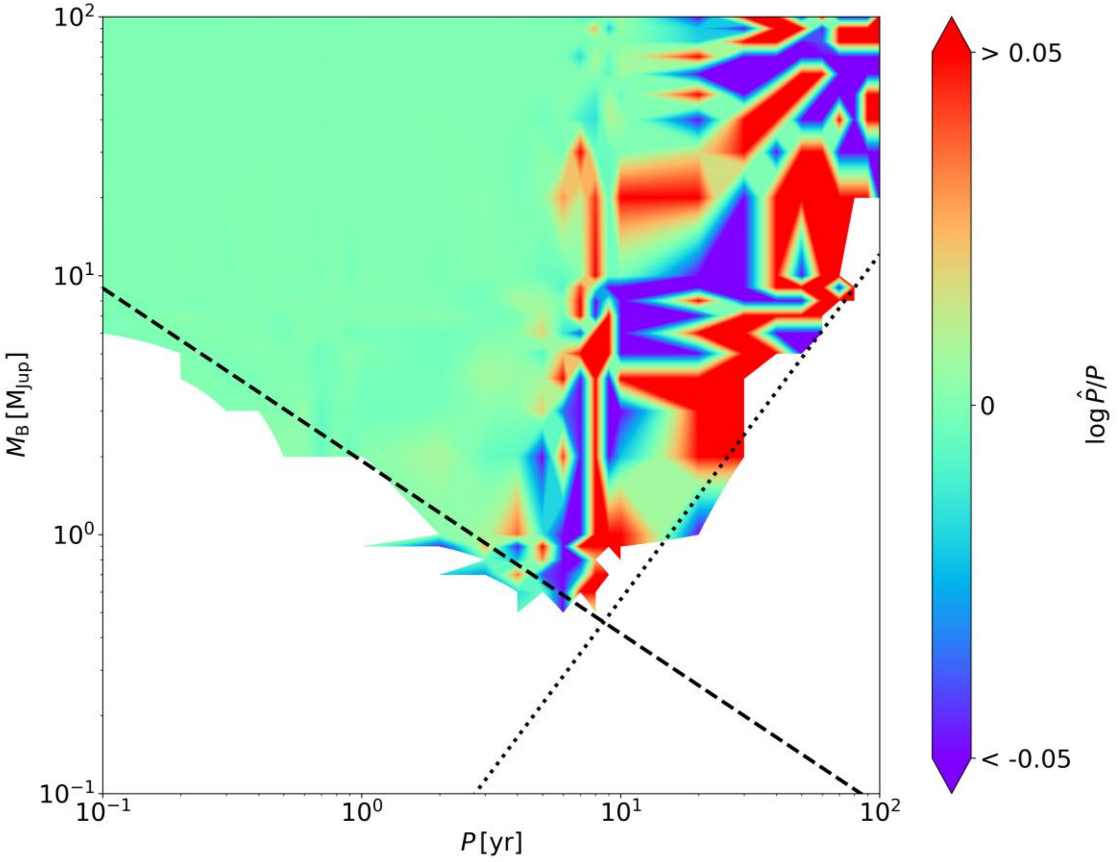
Companion mass – period grid

Grid of Keplerian models: M_B = 0.01 – 100 M_{Jup} vs P = 0.1 – 100 yr, assuming $M_* = 1.0\ M_\odot$ and ϖ = 10 pc





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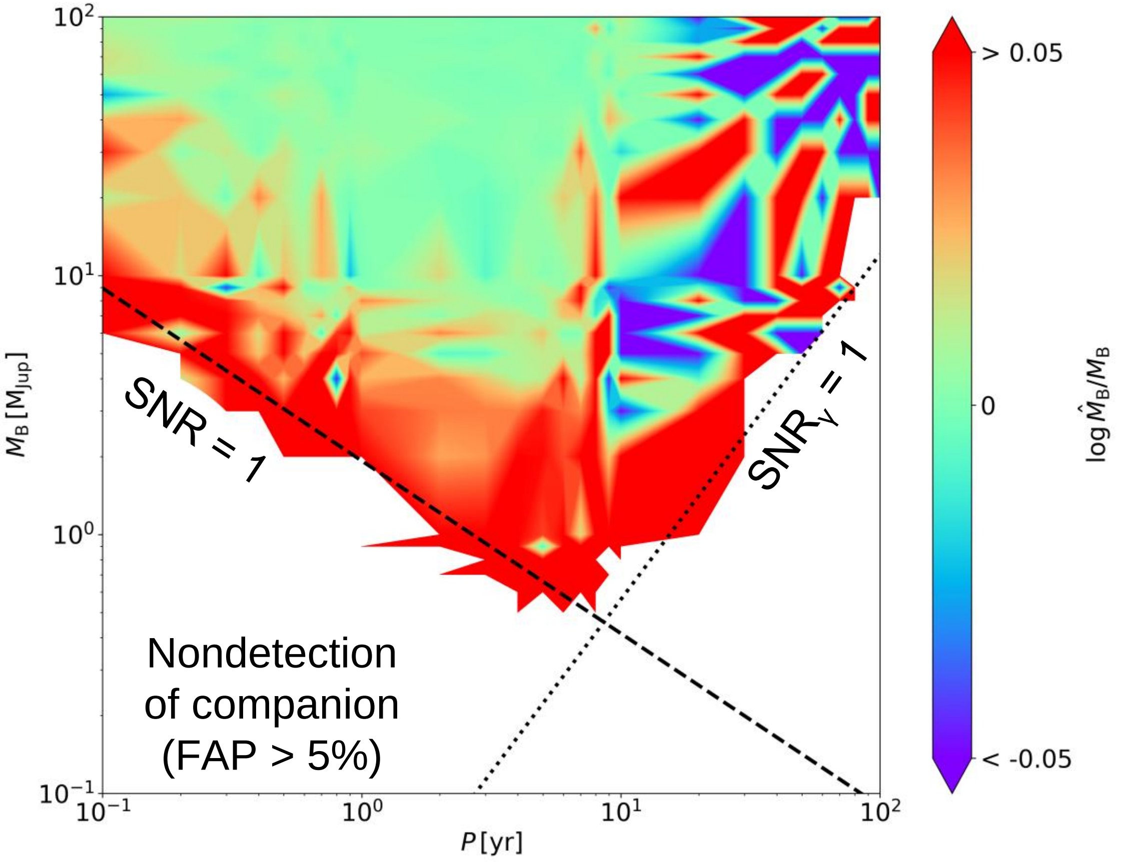
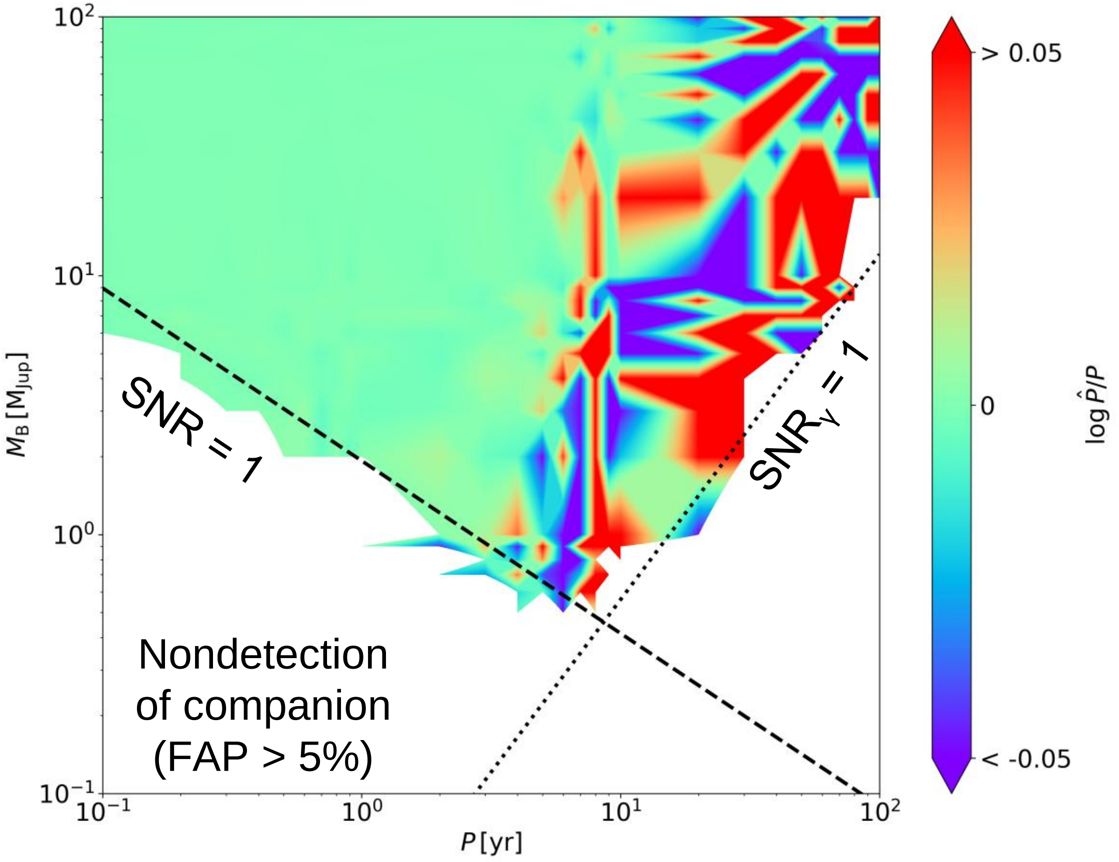
Grid of Keplerian models: M_B = 0.01 – 100 M_{Jup} vs P = 0.1 – 100 yr, assuming M_* = 1.0 $M_\odot$ and ϖ = 10 pc

$\Rightarrow$ Companion detected at SNR $\gtrsim$ 1 and $SNR_\gamma \gtrsim$ 1





Companion mass – period grid

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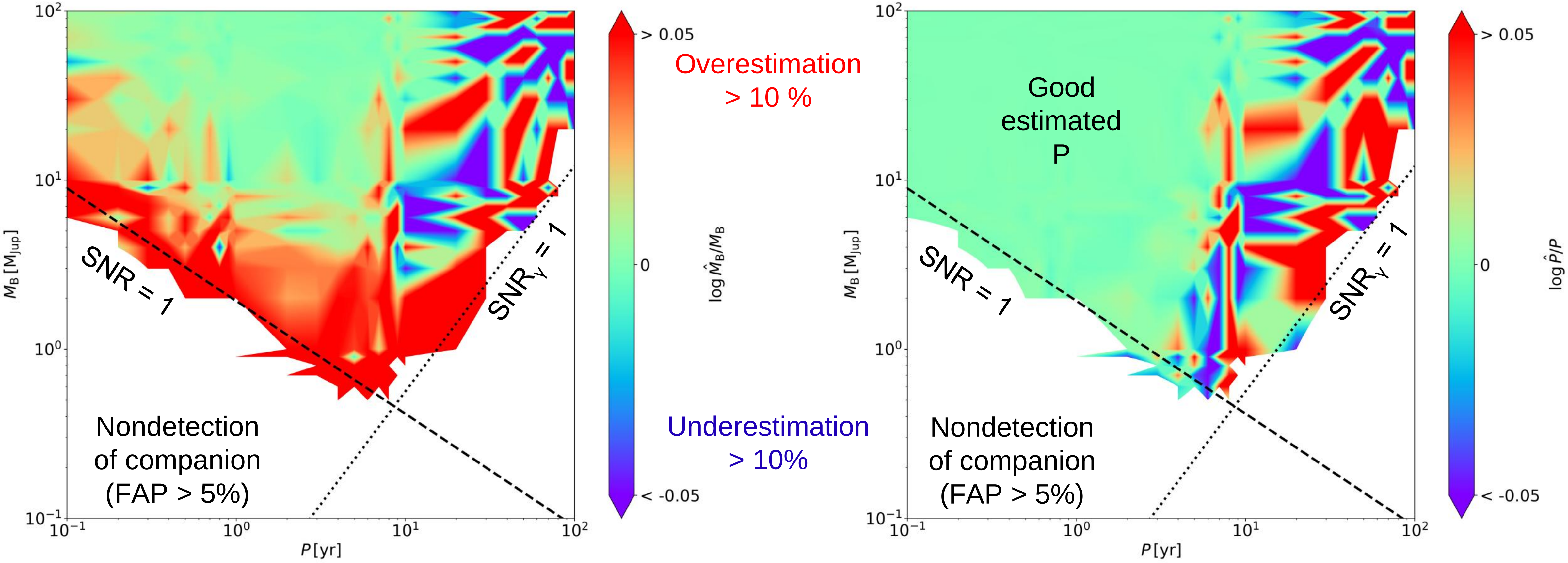
$\Rightarrow$ Companion detected at SNR $\gtrsim$ 1 and $SNR_\gamma \gtrsim$ 1

$\Rightarrow$ Period P recovered at SNR $\gtrsim$ 1 and P $\lesssim$ 5.5 yr



Companion mass – period grid

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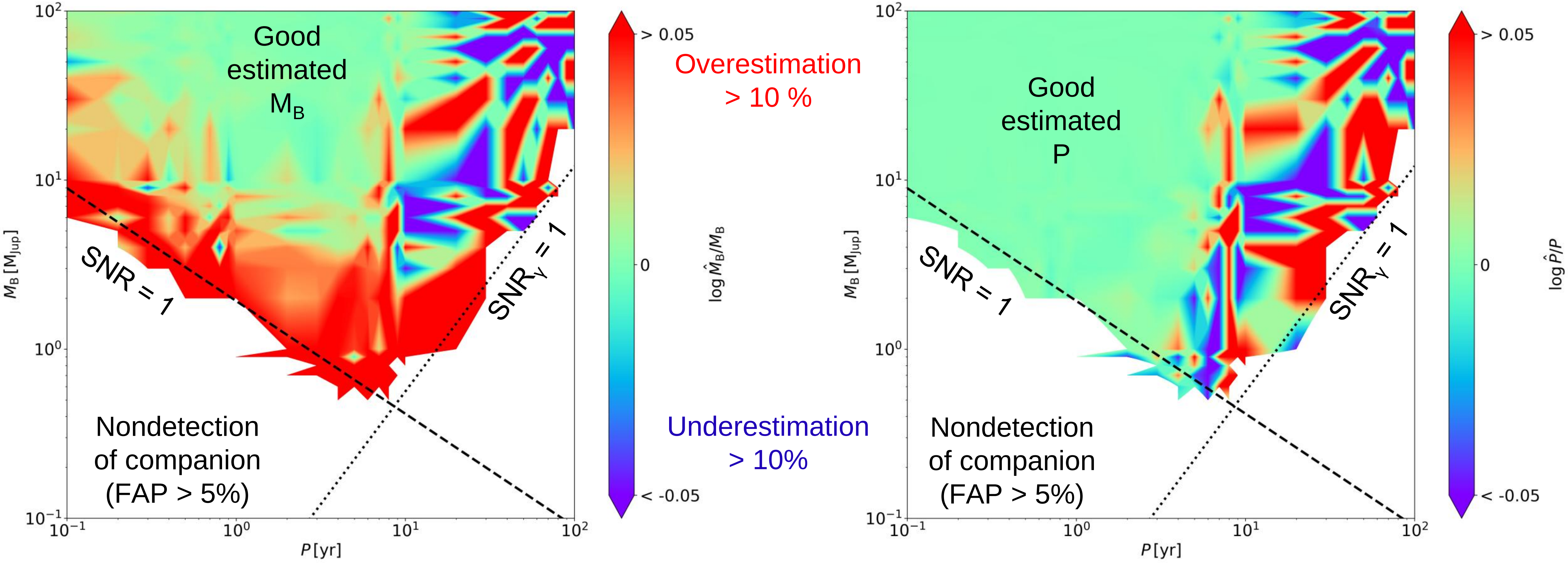
⇒ Companion detected at SNR ≳ 1 and SNR_γ ≳ 1

⇒ Period P recovered at SNR ≳ 1 and P ≲ 5.5 yr

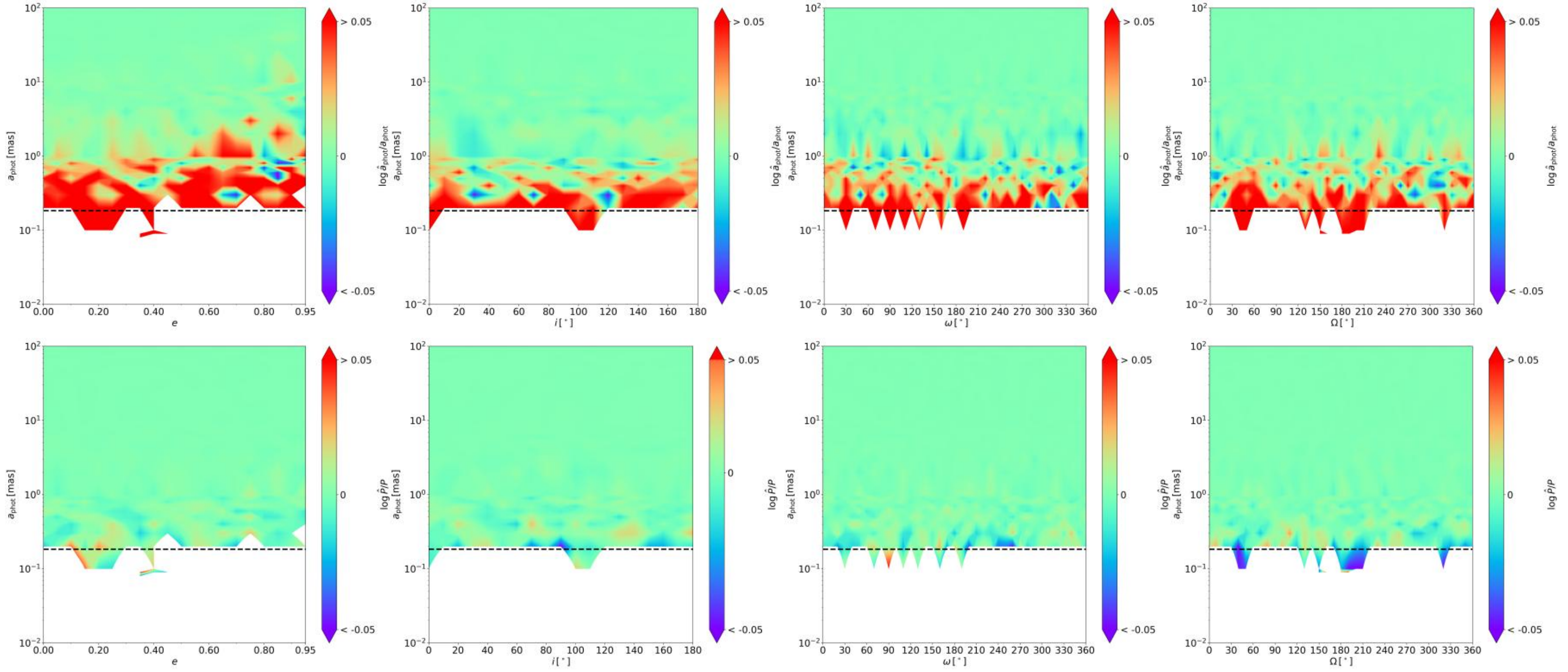
⇒ Companion mass M_B recovered at SNR ≳ 10 and P ≲ 5.5 yr



Effects of eccentricity and orbital angles

Grids of Keplerian models: a_{phot} = 0.01 – 100 mas vs

- Eccentricity e = 0.1 – 0.95 assuming P = 1000 d
- Inclination i = 0° – 180° assuming P = 1000 d
- Argument of periastron ω = 0° – 360° assuming P = 1000 d, e = 0.2 and i = 30°
- Longitude of ascending node Ω = 0° – 360° assuming P = 1000 d and i = 30°



Eccentricity | Inclination | Argument of periastron | Longitude of ascending node

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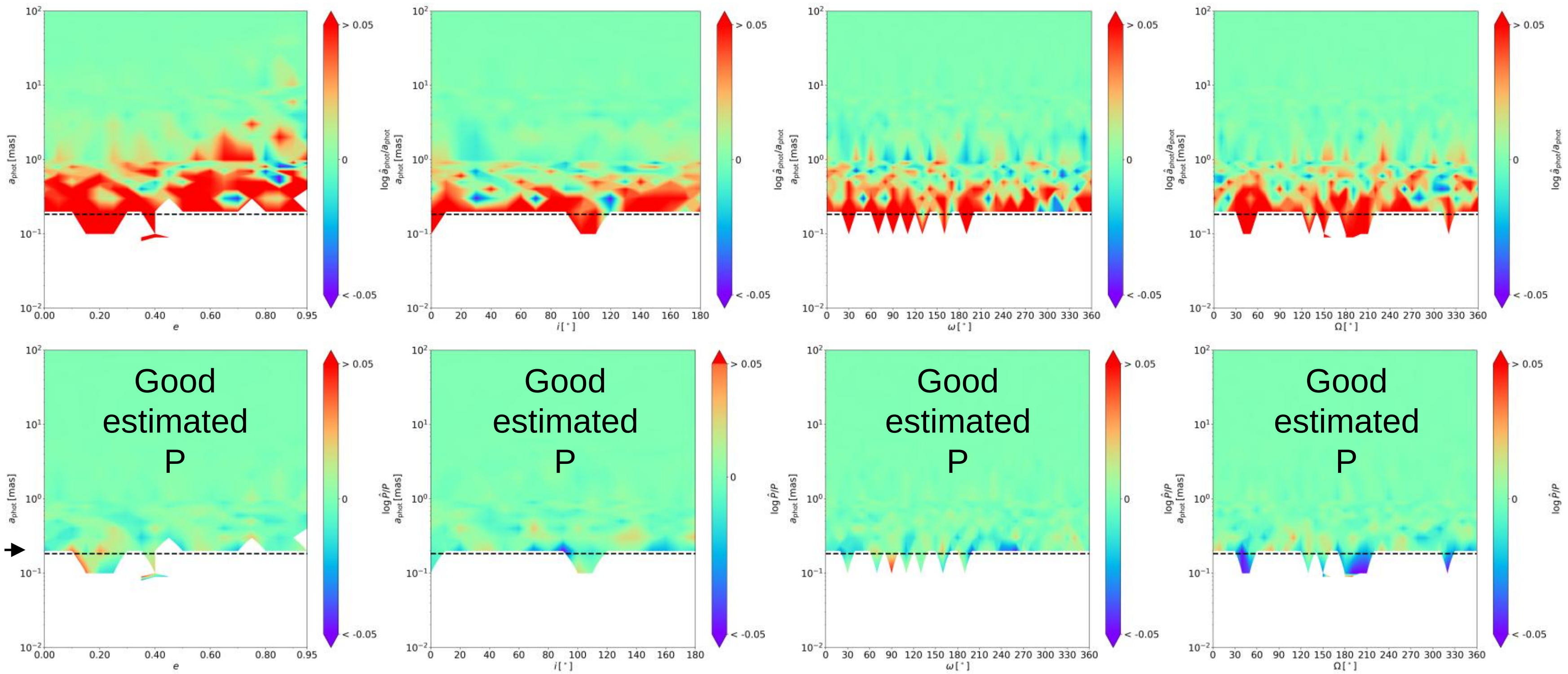
Companion detected
Period recovered at
SNR ≳ 1



Eccentricity

Inclination

Argument of periastron

Longitude of ascending node

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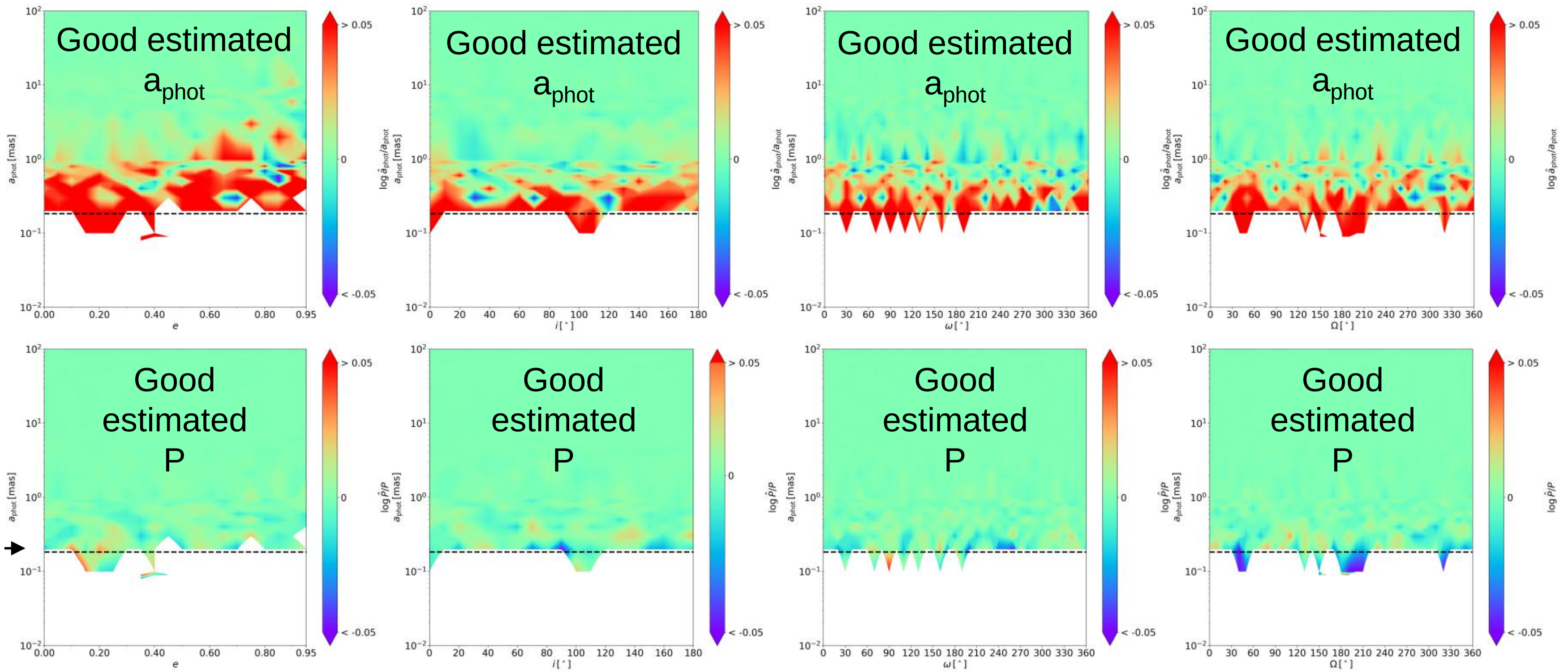
a_{phot} recovered at SNR ≳ 10
Higher SNR required at high eccentricity

Companion detected
Period recovered at SNR ≳ 1



Eccentricity | Inclination | Argument of periastron | Longitude of ascending node

Conclusions and Perspectives

- Gaia DR4 epoch astrometry allows robust detection of orbital periods up to 5.5 yr baseline

$\Rightarrow$ Longer periods require supplementary data

- SNR can be derived from the system's photocentric semimajor axis, G-mag and B_P - R_P color

$\Rightarrow$ SNR $\gtrsim$ 1 required for good period estimates

$\Rightarrow$ SNR $\gtrsim$ 10 required for good photocentric semimajor axis (and companion mass) estimates

- June 2026: Pre-release of Gaia DR4 astrometric timeseries for several sources

$\Rightarrow$ Test noise models and detection limits

- Statistics of potential exoplanet detections can be estimated (cf. Lammers & Winn 2025)

Thank you for your attention!

Q&A

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (COBREX; grant agreement n° 885593).

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Established by the European Commission