COMBINING RADIAL-VELOCITIES AND ASTROMETRY: LONG-PERIOD PLANET DISCOVERIES

EMPEROR II – Jupiter analogues around CHEPS stars

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ABSTRACT

Cold Jupiters on multi-AU orbits are key to understanding planetary system architectures, but they remain poorly sampled: radial-velocity (RV) surveys lose sensitivity at long periods and only measure minimum masses, while transits are intrinsically rare for such orbits. Combining decades of precise RVs with Hipparcos–Gaia absolute astrometry allows us to break the inclination degeneracy, recover true planetary masses, and increase detection confidence. With four additional years of observations, we extend the Chile–Hertfordshire ExoPlanet Survey (**CHEPS**) to a ~16-year baseline. We jointly model **RVs** and **astrometry** with the **EMPEROR** framework, perform **Bayesian model comparison**, and derive **full orbital posteriors**. In this first long-baseline CHEPS sample we confirm two known planets and uncover **four new Jupiter analogues** plus a **warm Jupiter**, with astrometry tightening period and mass uncertainties by factors of ≳3–10 and Bayes' factors by up to ~60.
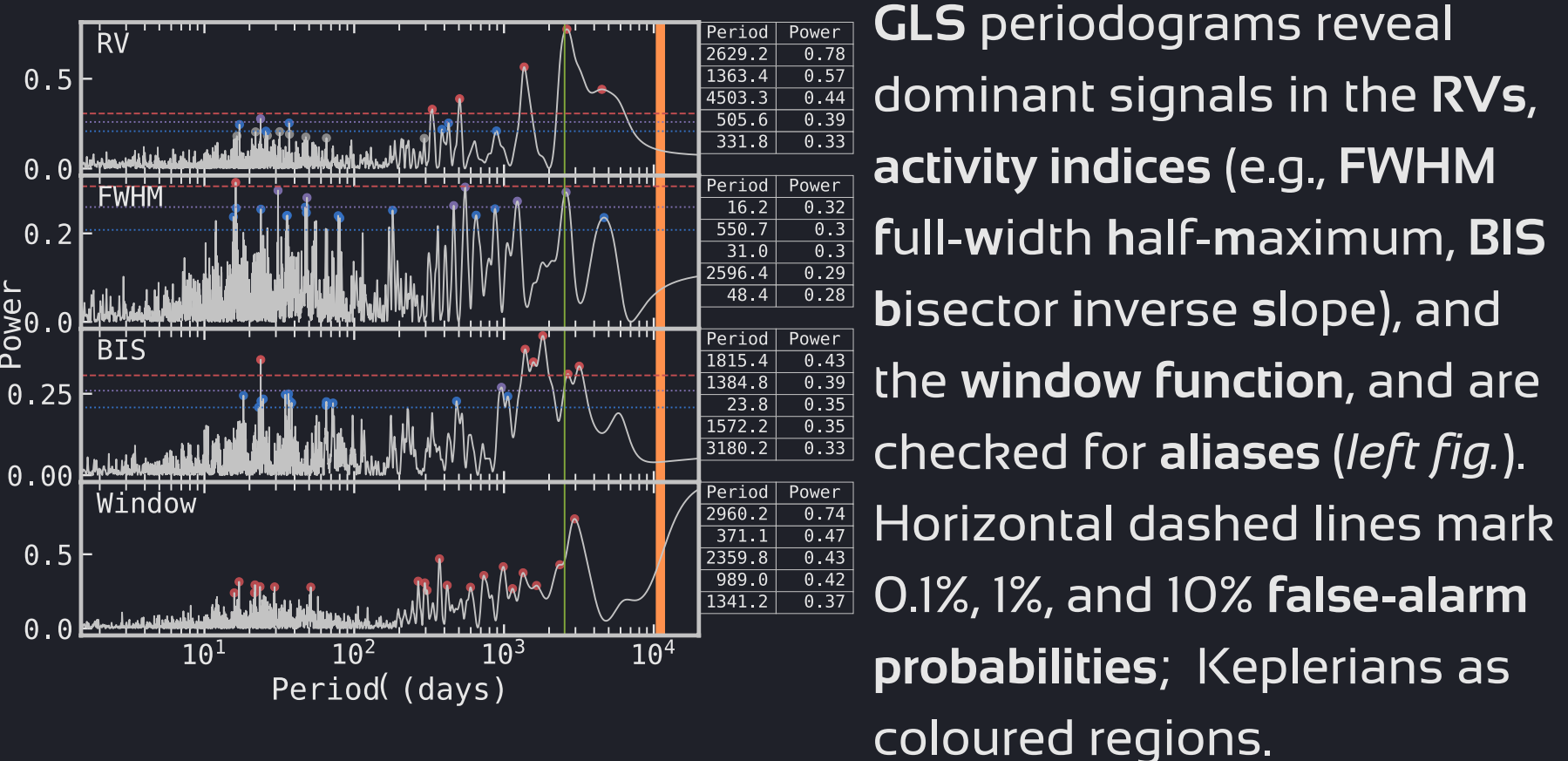
MOTIVATION

Cold, outer giants regulate the assembly and long-term stability of inner planetary systems and set boundary conditions for **planet-formation models** and **migration.** Establishing how common true Jupiter analogues are is crucial to assess how typical the Solar System is. Metal-rich CHEPS targets, monitored over decades and now anchored by Hipparcos–Gaia astrometry, provide an ideal testbed to **build a homogeneous census of cold giants.**

The **advent of Gaia DR4**, with intermediate astrometry and improved non-single-star solutions, will massively increase the number of stars with detectable astrometric accelerations. Having a robust, automated joint RV+astrometry toolkit in place *now* means we can scale from this CHEPS pilot sample to the much larger DR4 regime: reanalyse **long-baseline RV archives**, homogeneously **identify cold giants**, and deliver **catalogues of dynamical masses** ready for **direct imaging** and **atmospheric characterisation.**

WOULD YOU LIKE TO KNOW MORE?

We adopt the term **Jupiter**, to refer to planets with mass in the range 0.3-$13\,M_J$. **Cold Jupiter**, for those with a semi-major axis $\in [1, 10]\,AU$. And **Jupiter analogue** for those $\in [3, 7]\,AU$.

The **CHEPS** (**C**hile–**H**ertfordshire **E**xo**P**lanet **S**urvey) was initiated in **2009** to target **inactive, metal-rich FGK stars** with high-precision RVs from both **HARPS** and **CORALIE**, to find gas giants. By extending the CHEPS observations through **2022-2025**, a **16-year** time baseline is assembled, ideally suited to unveil **long-period signals**.
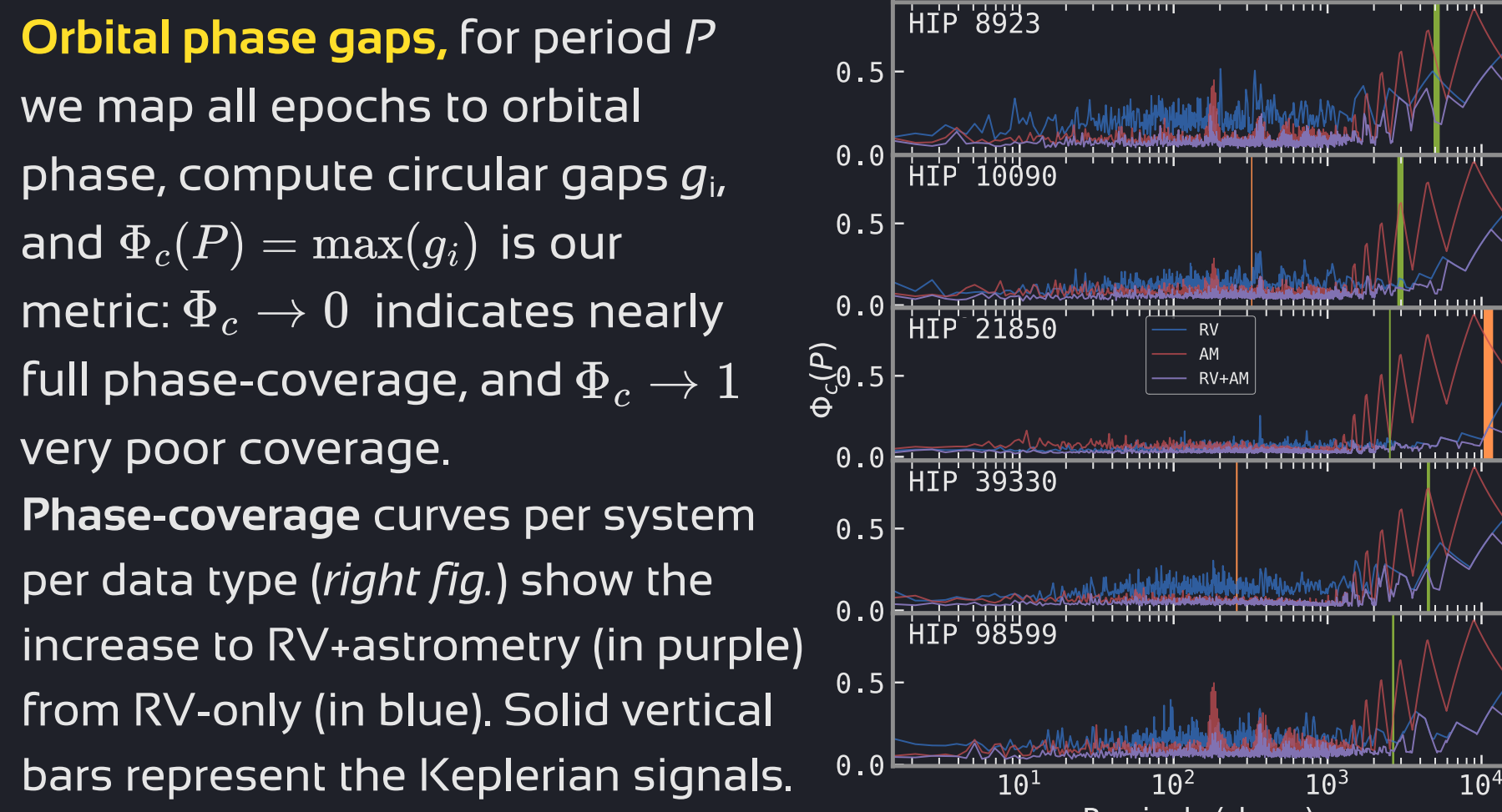
We validate our **joint RV+astrometry framework** on the known system HIP 21850. For each target we inspect RV **G**eneralised **L**omb-**S**cargle (**GLS**) periodograms and Pearson-correlation ϱ **correlograms,** then fit progressively complex Keplerian models with **EMPEROR**, selecting between them via **Bayesian evidence.** Summary analysis for HIP 21850:

GLS periodograms reveal dominant signals in the **RVs**, **activity indices** (e.g., FWHM full-width half-maximum, BIS **b**isector **i**nverse **s**lope), and the **window function**, and are checked for **aliases** (*left fig.*). Horizontal dashed lines mark 0.1%, 1%, and 10% **false-alarm probabilities**; Keplerians as coloured regions.

Correlograms (*right fig.*) show **Pearson coefficient** ϱ between RVs and activity indices; we find no evidence of stellar-activity contamination. Residuals' GLS and correlogram are flat.
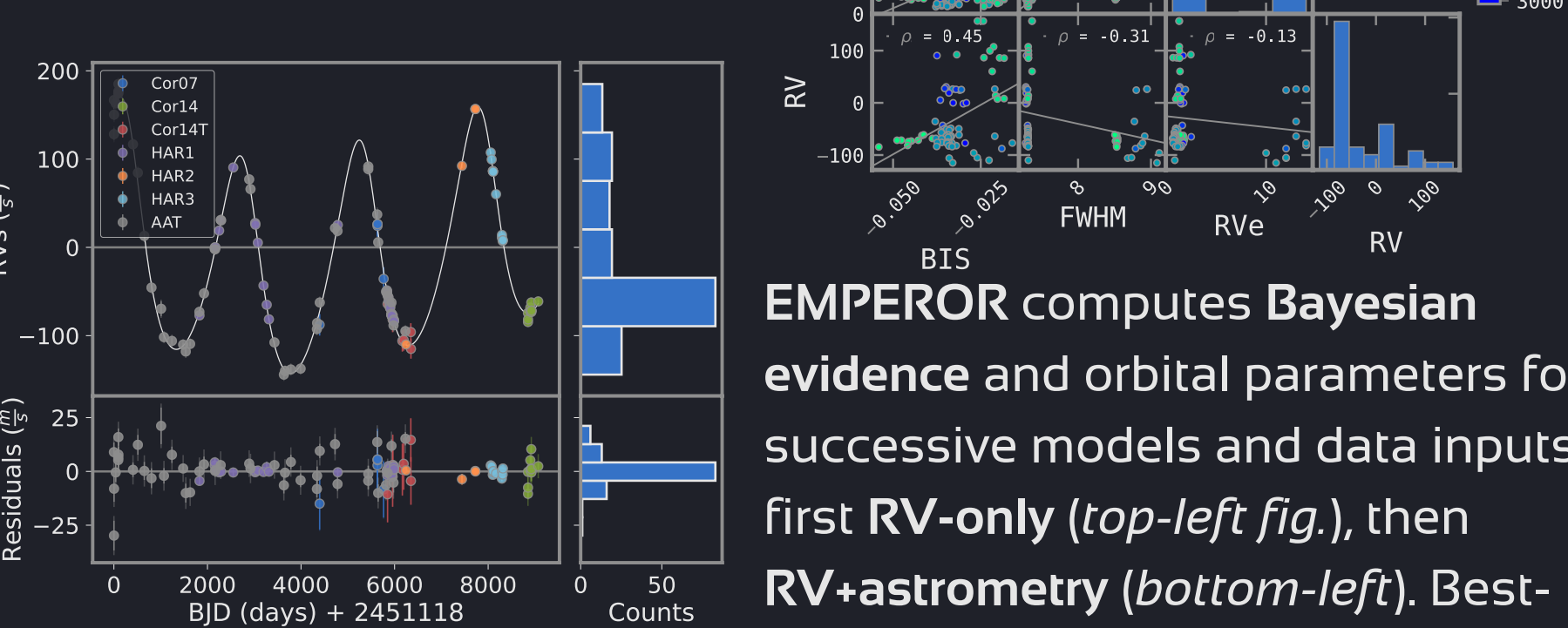
EMPEROR computes **Bayesian evidence** and orbital parameters for successive models and data inputs: first **RV-only** (*top-left fig.*), then **RV+astrometry** (*bottom-left*). Best-fit orbits are solid curves; data as circles coloured per instrument. Then, we compare metrics, such as the **Bayes' factor difference** (gain in BF when adding astrometry):
$$\Delta\mathrm{BF} = \Delta \ln \hat{\mathcal{Z}}_{\mathrm{RV+AM}} - \Delta \ln \hat{\mathcal{Z}}_{\mathrm{RV}}$$
I.e., the extra support for the planet model over the null in RV+ astrometry relative to RV-only.

Orbital phase gaps, for period P we map all epochs to orbital phase, compute circular gaps g_i, and $\Phi_c(P) = \max(g_i)$ is our metric: $\Phi_c \to 0$ indicates nearly full phase-coverage, and $\Phi_c \to 1$ very poor coverage. **Phase-coverage** curves per system per data type (*right fig.*) show the increase to RV+astrometry (in purple) from RV-only (in blue). Solid vertical bars represent the Keplerian signals.
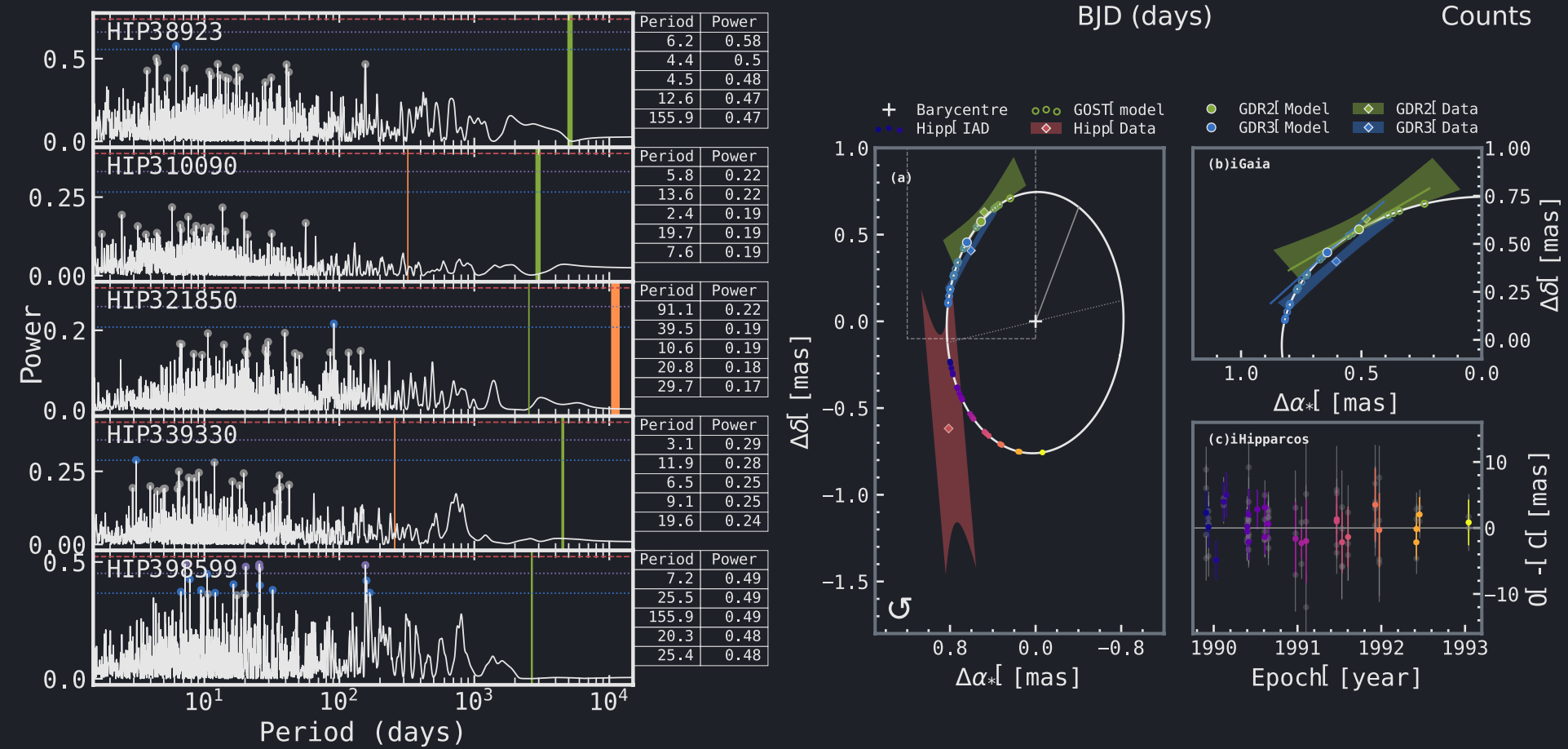

RESULTS

Our joint RV+astrometry analysis revealed five new long-period giant planets in the CHEPS sample.

HIP 8923

HIP 8923b, a **Jupiter analogue** with an orbital period of ~14.1 yr. A massive ~10 M_J planet on a ~5 AU orbit. RVs almost capture a single orbit, with joint astrometry we confirm its mass and orbit. **Residuals' GLS** below.


HIP 10900

In this two-planet system lies a Jupiter analogue, HIP 10090b, $P\approx8.1\,yr$, $M\approx3.9\,M_J$, and its warm Jupiter brethren, HIP 10090c, with $P\approx322\,d$ and $M\approx0.85\,M_J$. We perform **RV sufficiency** tests on this system by removing individual datasets. Our results show that **not all RV subsets contribute equally**. While some high-precision but phase-redundant datasets have low impact, others with few observations (e.g., Cor14T in red below) can substantially influence the BF when sampling unique orbital phases.
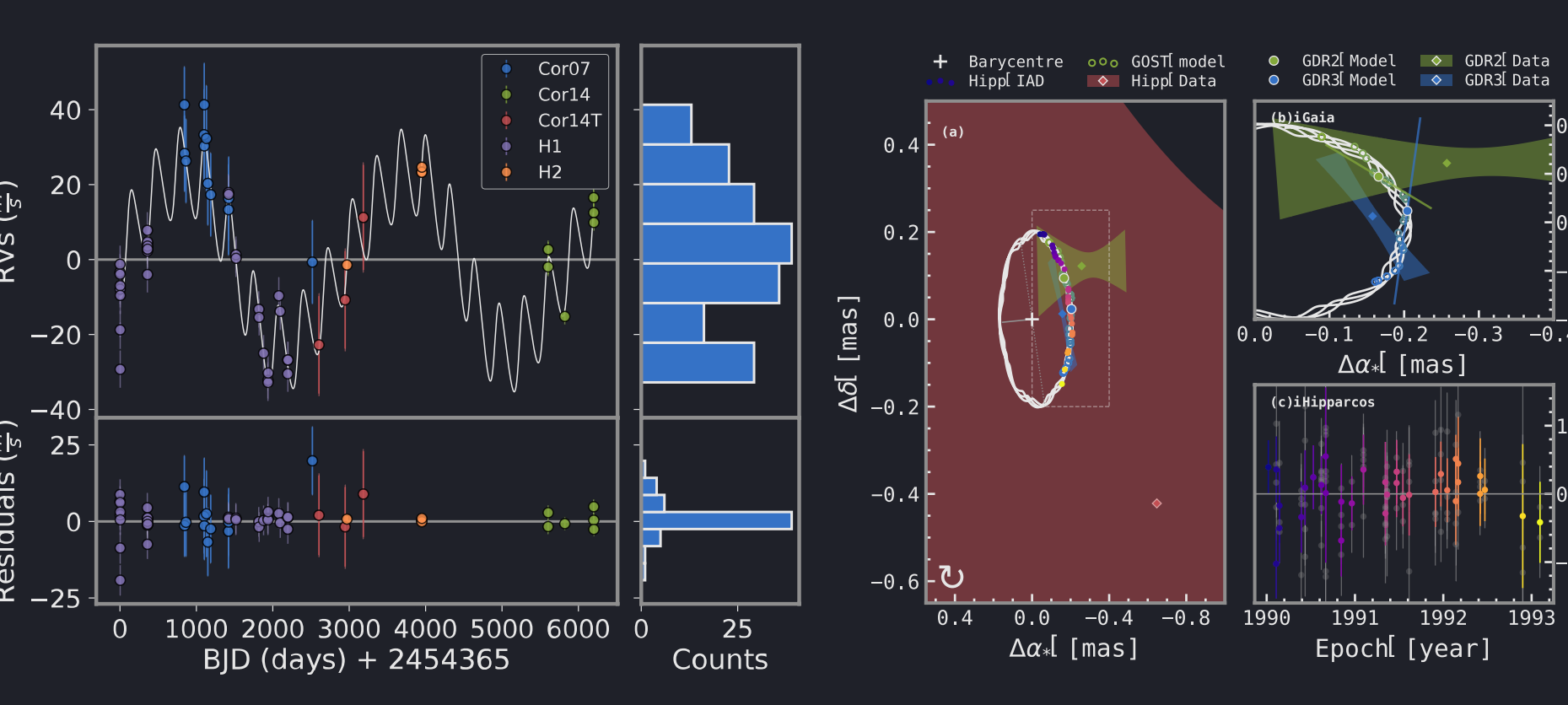

HIP 39330

HIP 39330b is a **Jupiter analogue** $P\approx12.7\,yr$, $M\approx1.7\,M_J$. Notably, in this system a second signal is found ($P\approx266\,d$), but remains unconfirmed. This is an interesting case of the **astrometry limitations**: due to **insufficient astrometric coverage** we have a bimodal posterior. With equivalent periods, but not angular parameters ($I_1\approx55°$ and $I_2\approx125°$). This underscores the need for strategically timed RV observations to complement the astrometric data. As our solution, we adopted the more conservative model with a **single planet**.
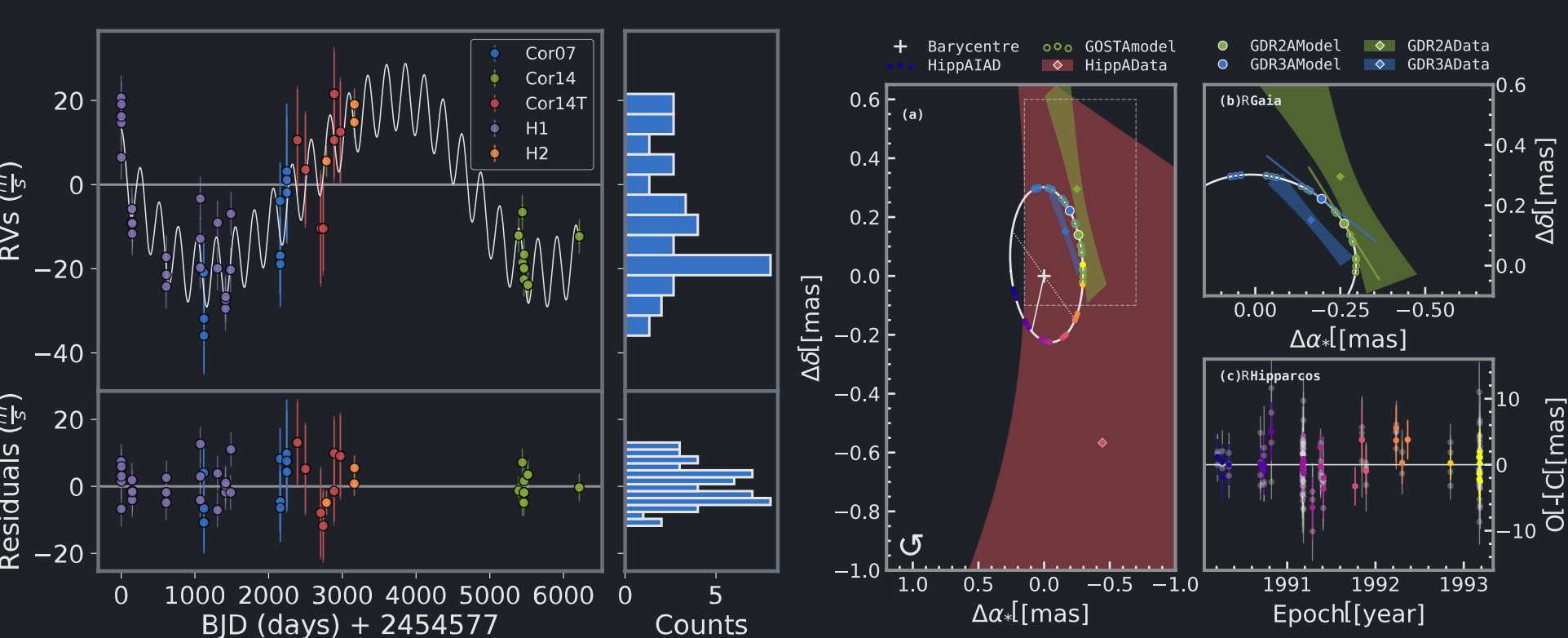
HIP 98599

HIP 98599b is a **Jupiter analogue** $P\approx7.3\,yr$, $M\approx6.9\,M_J$. A multi-year giant orbiting a metal-rich star. These CHEPS discoveries show that with the RV+astrometry synergy we can start filling the demographic gap in the cold Jupiter regime (see *below*). By establishing a sample of **Jupiter analogues**, we will improve constraints for **population-level inferences** and refine predictions for **DI yields**. Combining CHEPS targets with **coronagraphic imaging** from ELTs or Roman could provide **direct detections** and **atmospheric characterisation** of these cold worlds.
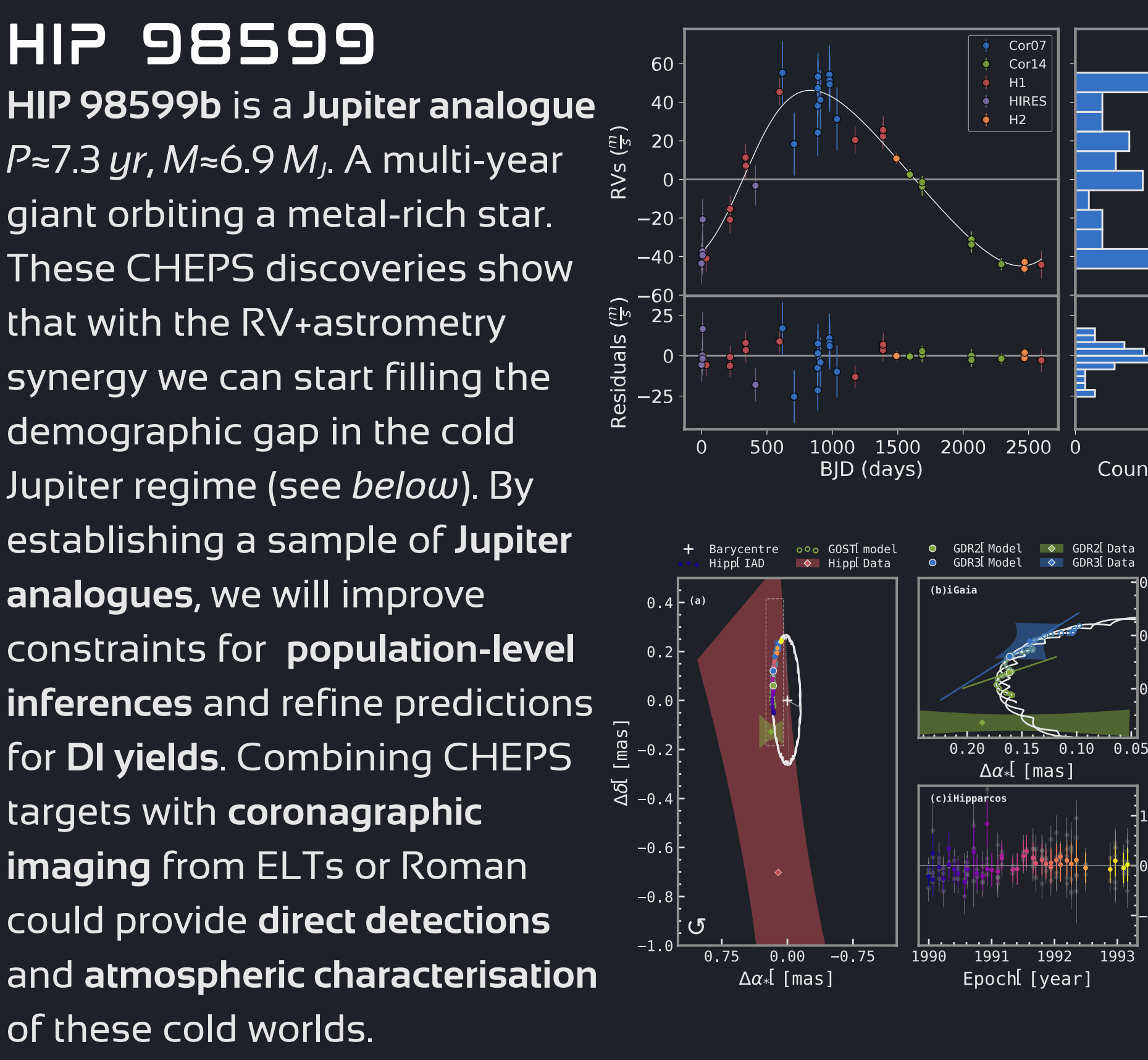
IMPROVED DETECTION

We quantify how adding astrometry boosts confidence and constrains orbital parameters. The **Bayes' factor differences** $\Delta\mathrm{BF}$ range between ~2 to ~60. Astrometry significantly reduces **gaps in orbital phase** Φ_a and more than doubles the **temporal baseline** B_c for some systems, leading to reductions in period and mass constraints up to an order of magnitude. *Table summary below.*

| Planet	Period (days)	$\Delta\mathrm{BF}$	$\Delta\Phi_c$	B_c
HIP 8923b	5162^{+153}_{-238}	57.71	0.274	2.372
HIP 10090b	2958^{+102}_{-102}	16.30	0.062	2.068
HIP 21850c	11320^{+494}_{-939}	1.70	0.016	1.414
HIP 39330b	4654^{+513}_{-228}	3.04	0.108	2.064
HIP 98599b	2656^{+40}_{-16}	11.94	0.056	1.687

IMPROVED ESTIMATES

All systems present improved parameter estimates: all **mass** and **period** constraints where reduced by factors between **3** and **10**. E.g., **HIP 10090c** turns from an ambiguous Saturn with $Msin\,i=0.39\,M_J$ to a bona-fide Jupiter-mass planet $M\approx0.85\,M_J$. **HIP 21850c** presents tighter period constraints with $P= \sim15903\pm3655 \rightarrow \sim11320\pm717\,d$. We derive true masses for all systems with the inclination constraints, yielding masses $\in \sim[1, 10]\,M_J$ on orbits $\in \sim[1, 7]\,AU$. Orbital estimates below.

Planet	Period (days)	Mass (M_J)	a (AU)	e	I (°)
HIP 8923b	5162^{+153}_{-238}	$9.98^{+0.78}_{-0.75}$	$5.90^{+0.10}_{-0.10}$	$0.011^{+0.022}_{-0.008}$	$24.82^{+1.24}_{-1.12}$
HIP 10090b	2958^{+102}_{-105}	$3.87^{+0.60}_{-0.40}$	$3.87^{+0.20}_{-0.19}$	$0.115^{+0.035}_{-0.031}$	$156.46^{+1.72}_{-1.15}$
HIP 10090c	$321.8^{+0.3}_{-0.3}$	$0.85^{+0.10}_{-0.08}$	$0.90^{+0.01}_{-0.01}$	$0.188^{+0.053}_{-0.043}$	$153.81^{+1.27}_{-2.22}$
HIP 21850c	2539^{+1}_{-1}	$8.25^{+3.15}_{-1.45}$	$3.49^{+0.13}_{-0.15}$	$0.186^{+0.048}_{-0.046}$	$65.49^{+3.27}_{-2.77}$
HIP 21850c	11320^{+494}_{-939}	$4.67^{+0.65}_{-0.45}$	$9.90^{+0.46}_{-0.45}$	$0.210^{+0.04}_{-0.06}$	$72.71^{+4.77}_{-3.52}$
HIP 39330b	4654^{+513}_{-228}	$1.67^{+0.09}_{-0.10}$	$5.05^{+0.53}_{-0.26}$	$0.078^{+0.035}_{-0.025}$	$55.01^{+1.81}_{-1.85}$
HIP 98599b	$2655.6^{+40.3}_{-16.4}$	$6.85^{+0.13}_{-0.22}$	$3.96^{+0.01}_{-0.01}$	$0.169^{+0.016}_{-0.055}$	$29.69^{+4.48}_{-6.18}$

JUPITER ANALOGUES

Our **CHEPS** analysis places four systems in the **Jupiter analogue regime** $M\in[0.3, 13]\,M_J$, and $a\in [3, 7]\,AU$, see *Figure bellow*. The RV+astrometry frame-work presented here enables a timely opportunity for cold giant demographics, to make the most out of the upcoming **Gaia DR4**.
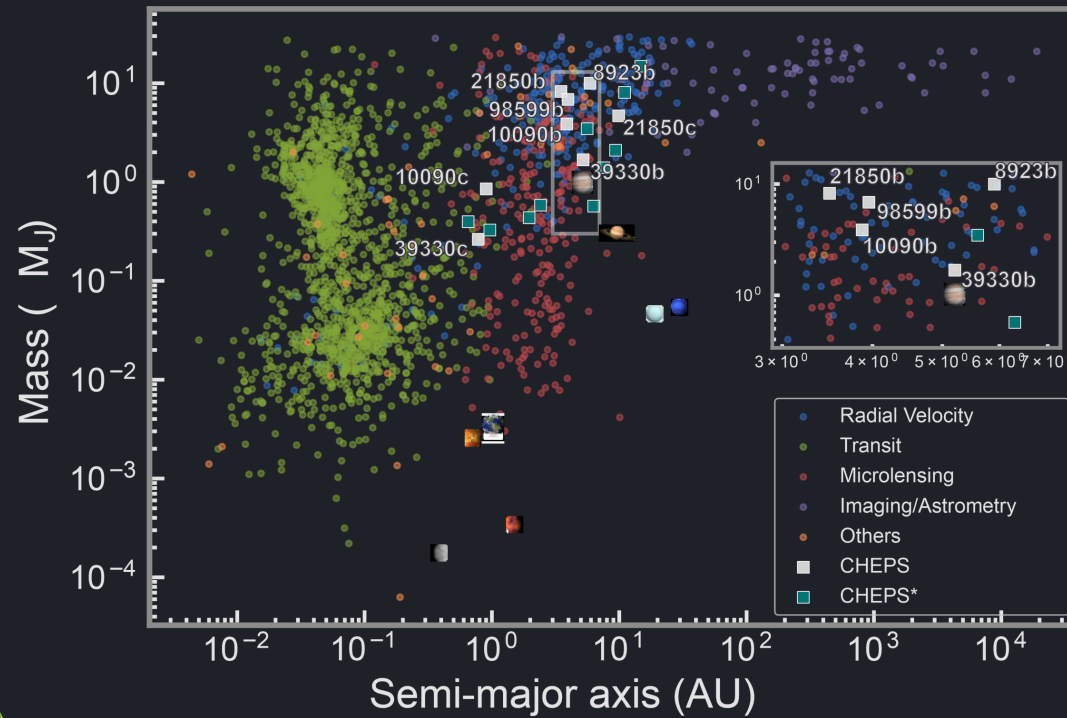
EMPEROR

EMPEROR (**E**xoplanet **M**CMC **P**arallel t**E**mpering for **R**V **O**rbit **R**etrieval) is a Python-based framework for detecting and characterising exoplanets in RV and astrometry data. Including, but not limited to:

- **Multi-instrument, multi-planet capability.**
- **Advanced noise modelling**: supports trends, stellar activity correlations, moving averages, and Gaussian processes to model stellar jitter, stellar rotation, and magnetic cycles.
- **Model comparison**: computation of Bayesian evidence.
- **Astrometry Integration**: incorporate Hipparcos–Gaia data with the astrometric differencing technique.
- **Publication-ready plots**: As all you can see here.

The EMPEROR pipeline (Peña & Jenkins 2025) served as the workhorse for this analysis. It automates everything from identifying planetary signals via periodograms to performing full joint RV+astrometry MCMC fits. **A step-by-step tutorial is available online.**

WOULD YOU LIKE TO KNOW MORE?