A New Dynamical Mass Measurement of the Directly Imaged Substellar Companion HD 984 B

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Dynamical Masses Test Substellar Cooling Models

- Masses of imaged planets/brown dwarfs usually inferred through cooling models.
- Dynamical masses anchor models and their underlying assumptions about GP/BD atmospheres and formation.
- **Only 12** model-independent masses with well-constrained luminosities and ages have been measured (Fig. 1), leaving our picture of GP/BD luminosity evolution incomplete.

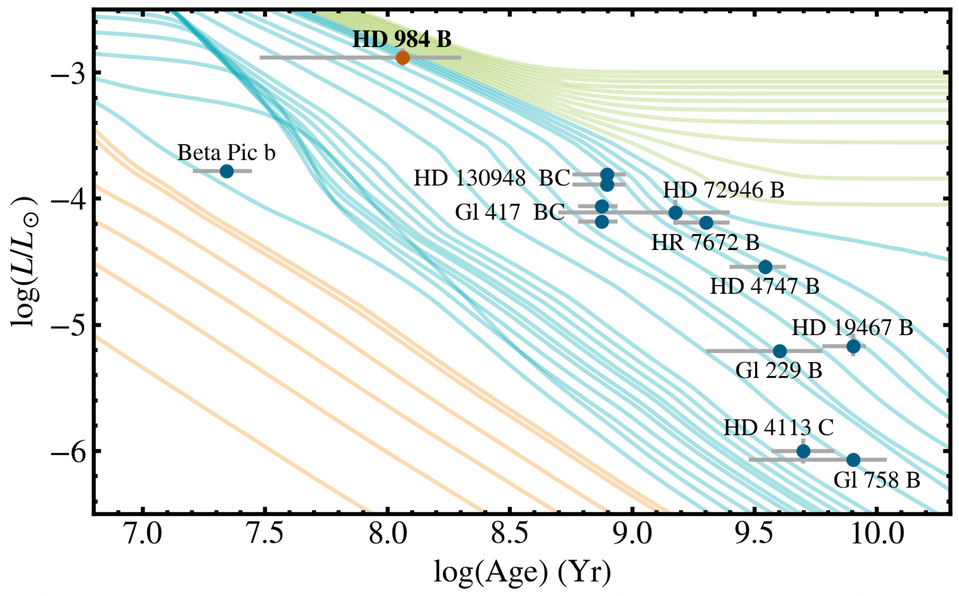

Fig 1: Luminosity-age plot of substellar companions with dynamical masses. The curves show cooling tracks[1] for planets (orange), brown dwarfs (blue), and stars (green).

The HD 984 System

- Measuring a dynamical mass requires fitting the orbital motion of the companion and the acceleration it induces on its host star.
- The young, nearby F7 star HD 984 hosts a substellar companion HD 984 B[3].
- The star's proper motion changes between *Hipparcos* and *Gaia*, creating an opportunity to directly measure the companion's mass.

Observations

Our measurement combines NIRC2 high-contrast imaging, HPF RVs, and the HGCA astrometric acceleration

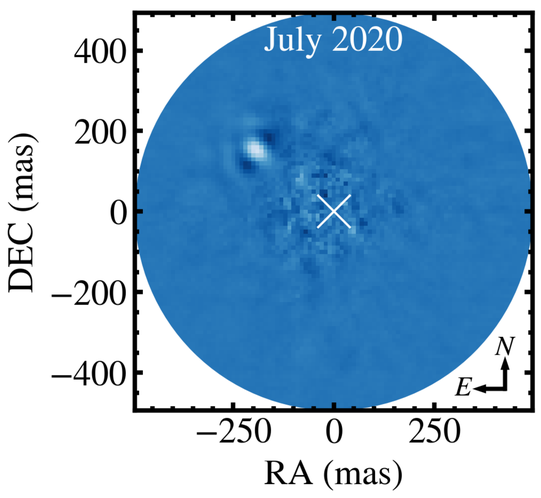

Fig 2: PSF-subtracted image of HD 984 B with NIRC2.

- We obtained new high-contrast imaging (ADI) sequences with NIRC2.
- PSF subtraction was done via PCA in the `VIP` package[2]. We used negative companion injection to measure astrometry.
- Our new astrometry adds to previous imaging with NaCo, SINFONI, and GPI[3,4].

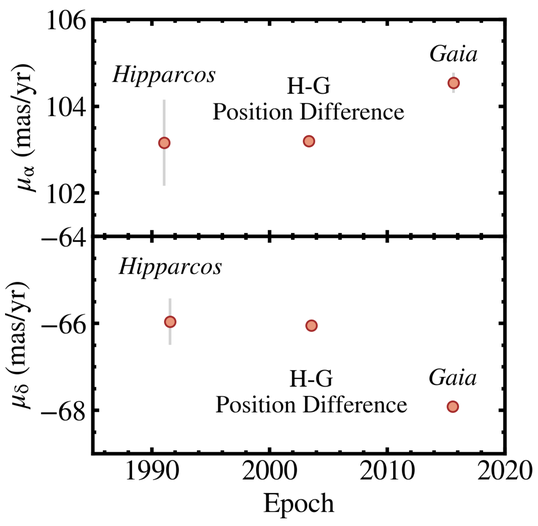

Fig 3: HGCA proper motions of HD 984 B.

- HD 984's proper motion change between *Hipparcos* and *Gaia* DR2 reveals its tangential acceleration.
- We use the *Hipparcos-Gaia* Catalog of Accelerations[5] (HGCA), a recent cross-calibration of the two datasets.
- 3 proper motions in the HGCA: the proper motions in *Hipparcos* and *Gaia* and an average proper motion from the difference in position between the two missions.

New 3D Orbit Fit and Dynamical Mass

- We use the `orvara` package[6] to jointly fit the relative astrometry, radial velocities, and the *Hipparcos-Gaia* proper motions.
- **The orbit fit constrains the mass of HD 984 B to between 50-70 M_{jup} at 95% confidence**, a substantial improvement over previous model-dependent masses of 33-94 M_{jup}[4].
- We can confidently determine that HD 984 B is a brown dwarf (<75 M_{jup}).
- These new data have refined the companion's orbital elements and, in particular, increased the eccentricity from the previous fit[4]:

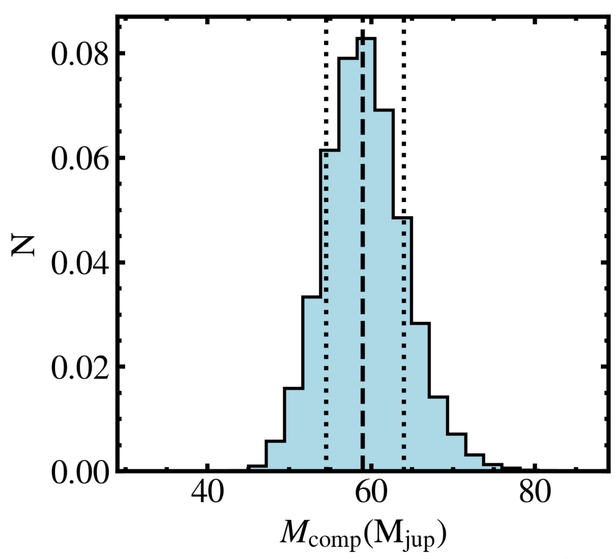

Fig 4: Companion mass posterior for our orbit fit.

	Previous Orbit Fit[4]	New Orbit Fit
a (AU)	18^{+10}_{-4}	$24.1^{+8.1}_{-4.4}$
e	$0.18^{+0.29}_{-0.13}$	0.73 ± 0.06
i (°)	119^{+6}_{-5}	$121.3^{+2.3}_{-2.1}$

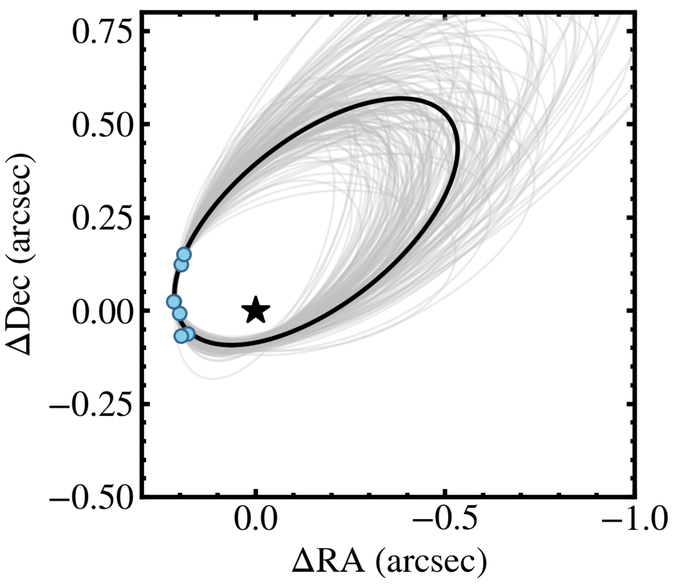

Fig 5: Projected orbit for our orbit fit with the best fit orbit (black) and a randomly drawn sample (grey).

Model Comparison

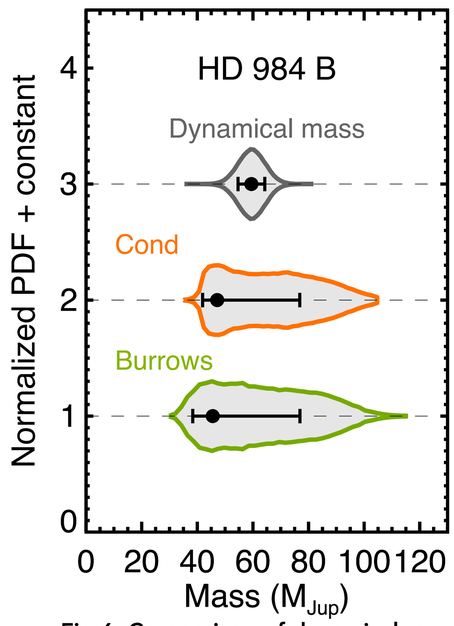

Fig 6: Comparison of dynamical mass with model-inferred masses.

- We compare our dynamical mass to the predicted masses from two models[7,1].
- Our mass is consistent with both models.
- The large age range of the host star (30-200 Myr)[4] causes wide mass distributions for each cooling model that prevent comparative tests.
- Improving HD 984's age constraint is challenging, as rotational age indicators break down around its spectral type (F7).

Looking Forward

- We have measured the dynamical mass of the brown dwarf companion HD 984 B.
- This new benchmark system joins the 12 other dynamical masses of substellar companions.
- Testing substellar cooling models with this system is currently limited by the age range of the host star. Tightening the age constraint would enable a better model test.
- Continued RV monitoring of the system and upcoming *Gaia* data releases are expected to improve the dynamical mass of HD 984 B in the future.

References

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