# Radial Velocity of directly imaged planets

*Jean-Baptiste Ruffio,*
*OSIRIS*: Quinn M. Konopacky, Travis Barman, Bruce Macintosh, Kielan K. Wilcomb, Robert J. De Rosa, Jason J. Wang, Ian Czekala, Christian Marois,
*KPIC*: KPIC collaboration, Jason Wang, Evan Morris, Jacques Delorme, Dimitri Mawet, Andrew Skemer, Travis Barman.

jruffio@caltech.edu

## Youtube introduction link

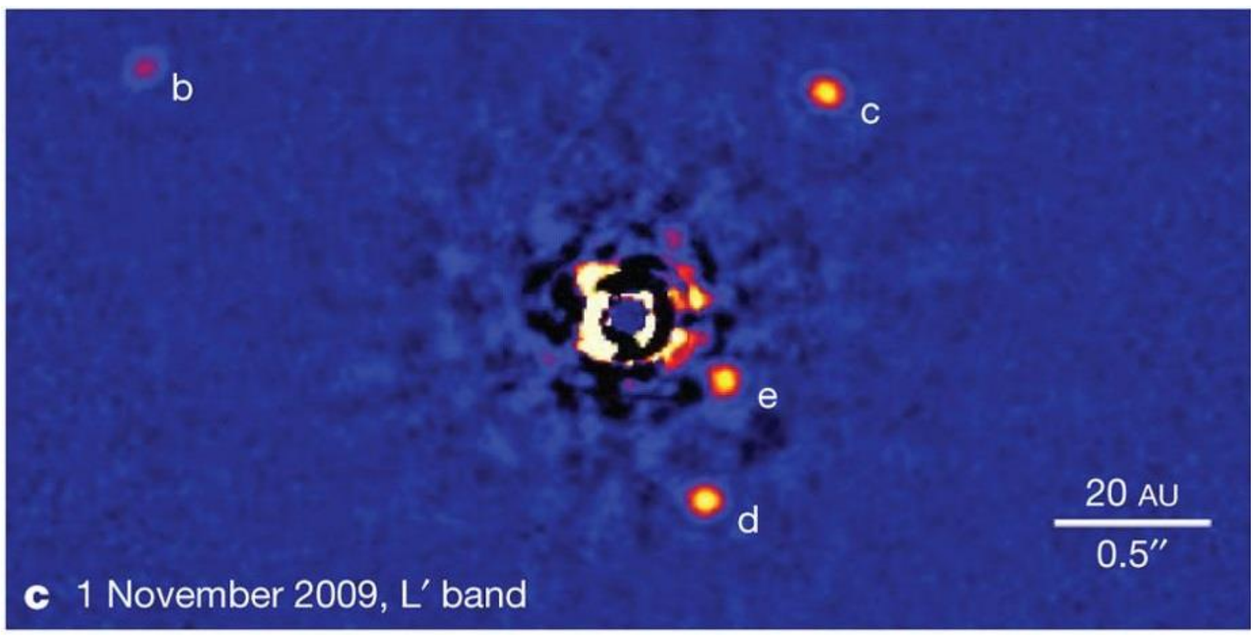


*Fig. 1: HR 8799 four-planet system from Marois et al. (2010) [1]. The orbital motion of the planets can be visualized here.*

Planetary radial velocity (RV) is one of the science drivers for high resolution spectroscopy of exoplanets. It can be used to better constrain the orbital architecture of stellar systems (e.g. eccentricity or obliquity), which can be related to the formation history of exoplanets. Ultimately, planetary RV will even allow the detection of exo-moons. Such measurements are however challenging due to the overwhelming starlight at the small separations corresponding to directly imaged planets.
We present RV measurements of the four large gas giant planets orbiting the star HR 8799 (Fig. 1) using OSIRIS and the new KPIC instruments at Keck.

### Moderate resolution spectroscopy (R≈4,000) with OSIRIS/Keck

The OSIRIS instrument at Keck has been used to detect molecules (CO and $H_2O$) and characterize the atmosphere of HR 8799 b and c for more than a decade [2,3]. Despite the moderate resolution of the instrument (R≈4,000, K band), we showed that we could measure the RV of HR 8799 b and c with a combined precision of 0.5 km/s using a forward modeling approach. These measurements resolve the degeneracy in the 3D orientation of the system [4]. It also provides the first detection of HR 8799 d at higher spectral resolution.
Fig. 2 shows the barycentric corrected RV measurements of HR 8799 b, c, and d with OSIRIS: (top panel) nightly RVs, (middle panel) combined RV posteriors, (bottom panel) RVs relative to HR 8799 c and compared to predictions from astrometry (hatched) assuming stable and coplanar orbits [5] .

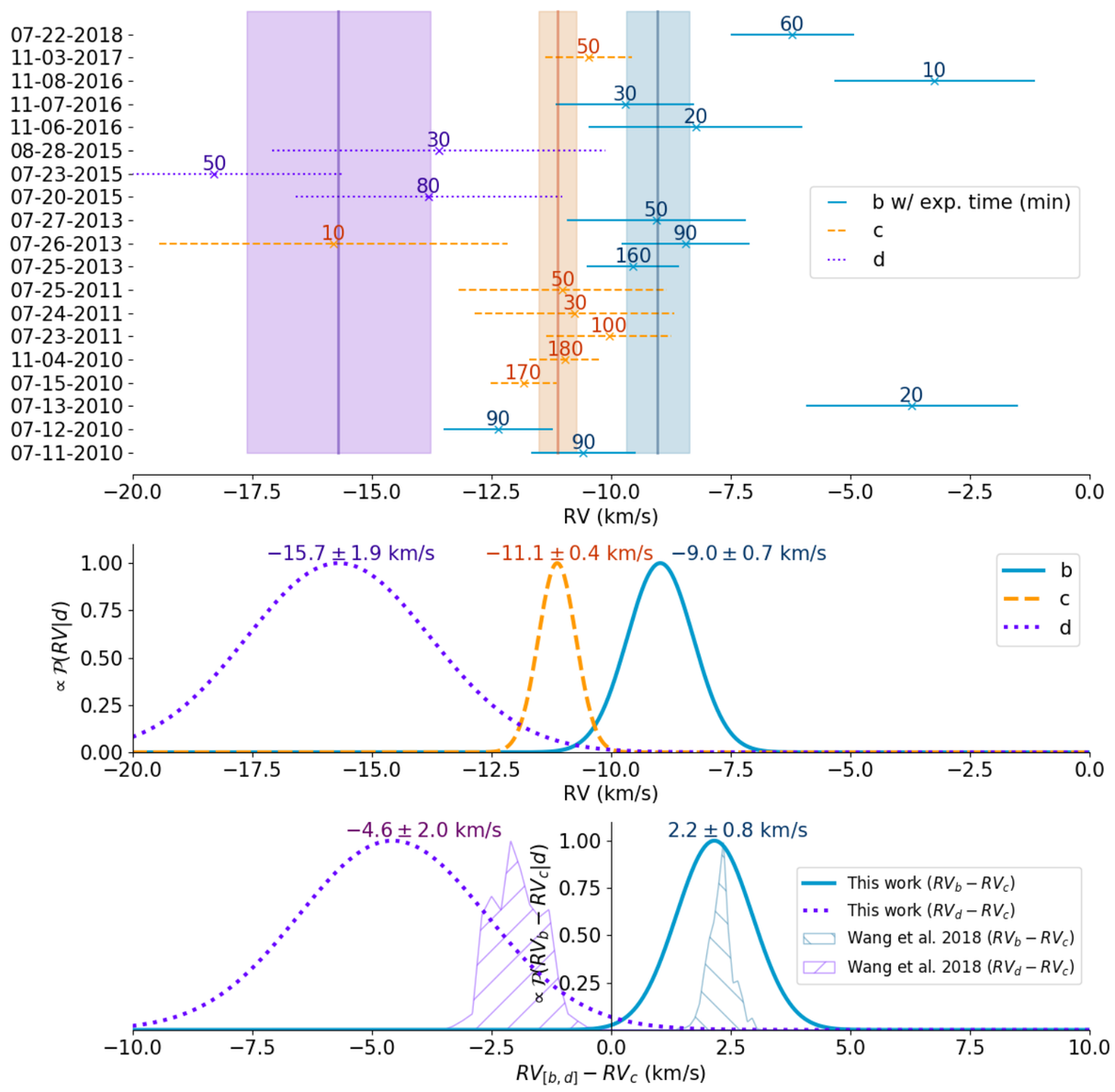


*Fig. 2: RV measurements of HR 8799 bcd with OSIRIS/Keck.*

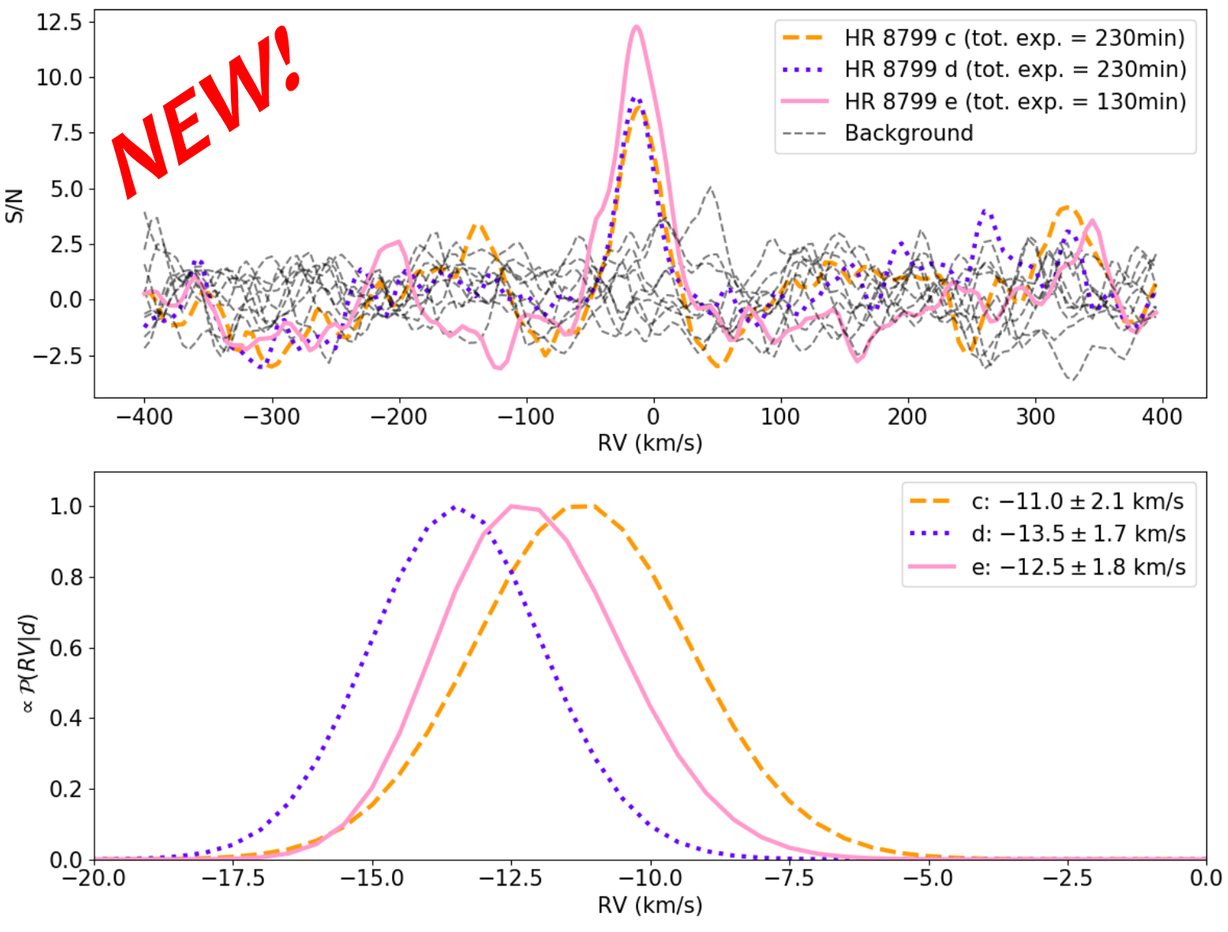


*Fig. 3: Preliminary detections and RV measurements of HR 8799 cde with KPIC/Keck.*

### *NEW!* High resolution spectroscopy (R≈40,000) with KPIC/Keck

The Keck Planet Imager and Characterizer (KPIC) [6] is opening infrared high resolution spectroscopy to directly imaged exoplanets. As a recent milestone, the innermost planet of the HR 8799 system (0.4'' separation, and ~$5.10^{-5}$ flux ratio in K band w.r.t the star ) was detected at high signal to noise in only two hours (Wang et al., in prep.).
Fig. 3 includes preliminary results and shows (top panel) the signal to noise ratio of HR 8799 c, d, and e as a function of the RV of the spectral template as well as (bottom panel) their RV posteriors.
KPIC is the first instrument of its kind to be deployed on sky. Its performance comes from the combined power of an infrared pyramid wavefront sensor, a vortex coronagraph, and an optical fiber injection unit paired to the Keck/NIRSPEC high resolution spectrograph (R~40,000). KPIC will open a wide range of science; from RV and spin measurements to comprehensive atmospheric characterization.

**References:** [1] Marois et al, 2010, Nature, 468, 1080 [2] Konopacky et al., 2013, Science, 339, 1398 [3] Barman et al., 2015, ApJ,804, 61 [4] Ruffio et al., 2019, AJ, 158, 200 [5] Wang et al., 2018b, AJ, 156, 192 [6] Mawet et al., SPIE Conference Series, Vol. 10400, 1040029

**Acknowledgements**: J.-B.R. is supported by a David & Ellen Lee postdoctoral fellowship. The research was supported by grants from NSF, including AST-1411868 (J.-B.R., B.M.), 1614492 and 1614492 (T.S.B.).Support was provided by grants from the National Aeronautics and Space Administration (NASA) NNX15AD95G (J.-B.R., R.J.D.R.). This work benefited from NASA's Nexus for Exoplanet System Science (NExSS) research coordination network sponsored by NASA's Science Mission Directorate.Q.M.K., T.S.B., and K.K.W. were supported by NASA under Grant No. NNX17AB63G issued through the Astrophysics Division of the Science Mission Directorate. Any opinions, findings, and conclusions or recommendations expressed in this work are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration. The KPIC collaboration would like to acknowledge the financial support of the Heising-Simons foundation. The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and NASA. The Keck Observatory was made possible by the generous financial support of the W. M. Keck Foundation. We also wish to recognize the very important cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.