Instrumentation prospects for rocky exoplanet atmospheres with high-resolution spectroscopy

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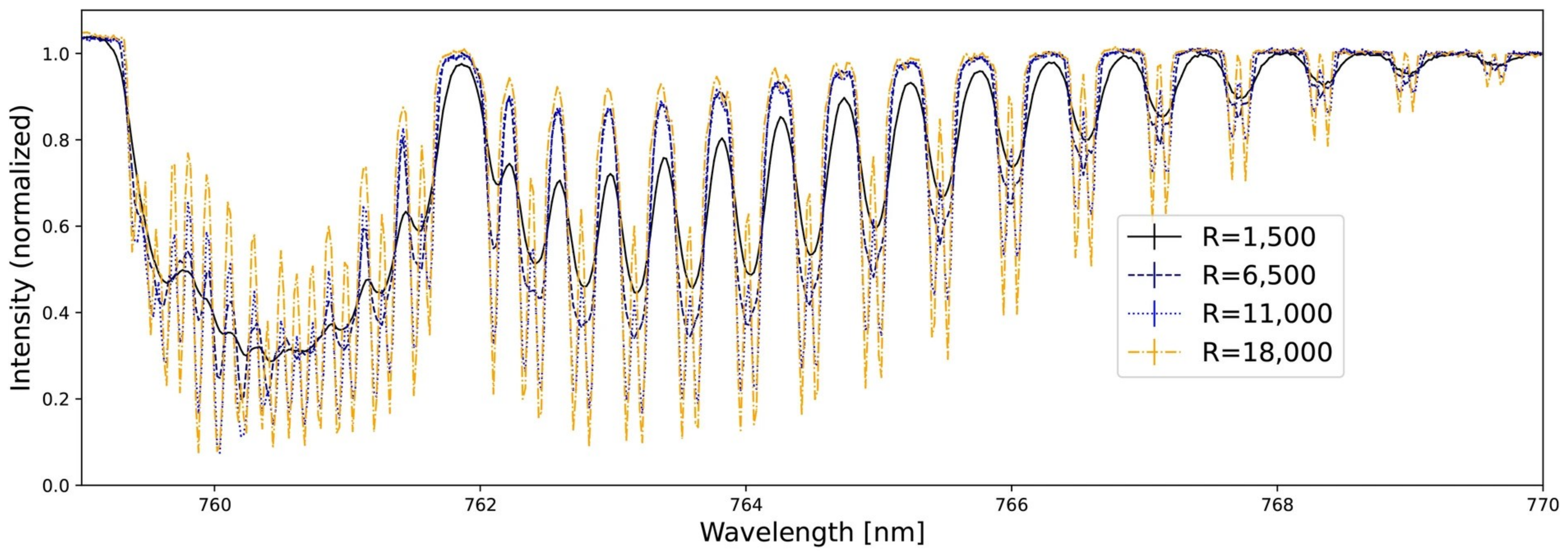
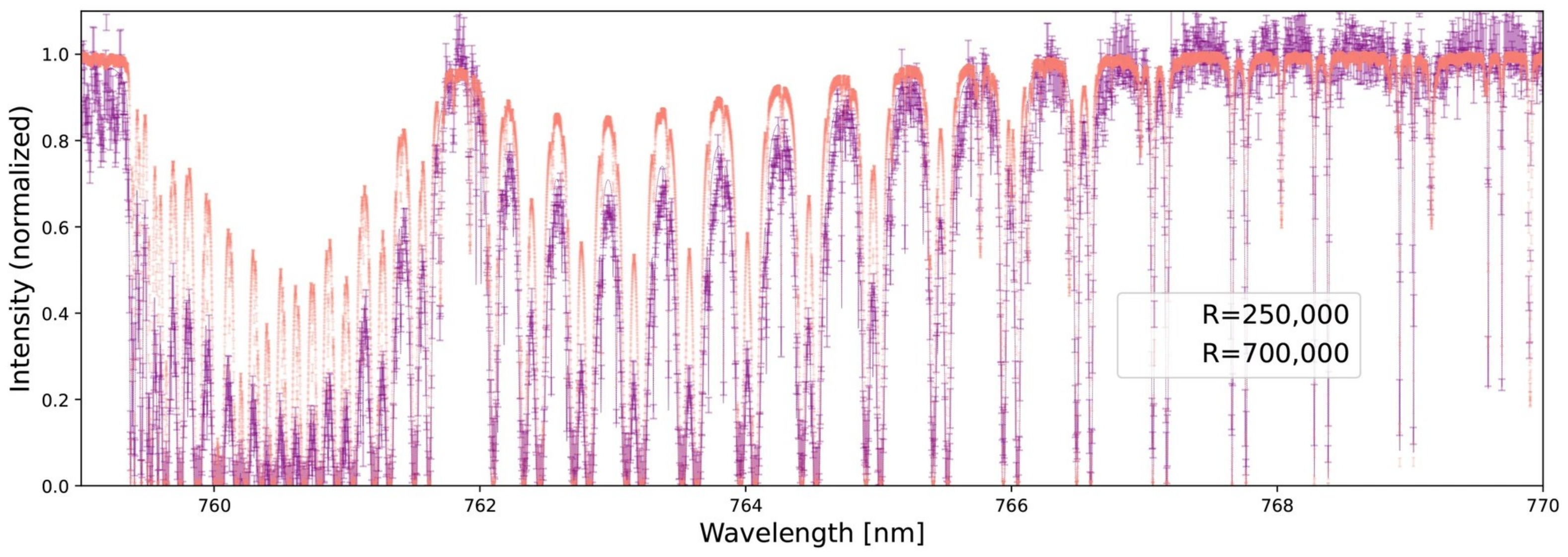
Abstract

Studying the atmospheres of exoplanets is one of the most promising ways to learn about distant worlds beyond our solar system. The composition of an exoplanet's atmosphere can provide critical insights into its geology and potential habitability. For instance, the presence of certain molecules such as water vapor, oxygen, or methane has been proposed to indicate the possibility of life. From an observational point of view, over the past fifteen years, significant progress has been made in characterizing exoplanetary atmospheres. This work reviews recent developments in ground-based high-resolution spectroscopic instruments that make it possible to analyze distant atmospheres in detail. High-resolution transmission spectroscopy, one of the most effective methods used, has examined the atmospheres of Jupiter-like planets and is pushing towards the smaller, sub-Neptunian exoplanets. Numerous molecules have been detected using this technique. We explore the intriguing possibilities that lie ahead for future ground-based instrumentation, particularly in the context of detecting biologically relevant molecules within Earth-analog exoplanetary atmospheres, including molecular oxygen (O_2). With detailed exposure time calculations for detecting, we find that at the same exposure time spectral resolution of 300,000 reaches higher significance compared to 100,000. The exposure time and therefore the needed number of transits is reduced by a factor of 4 in challenging haze and cloud scenarios.

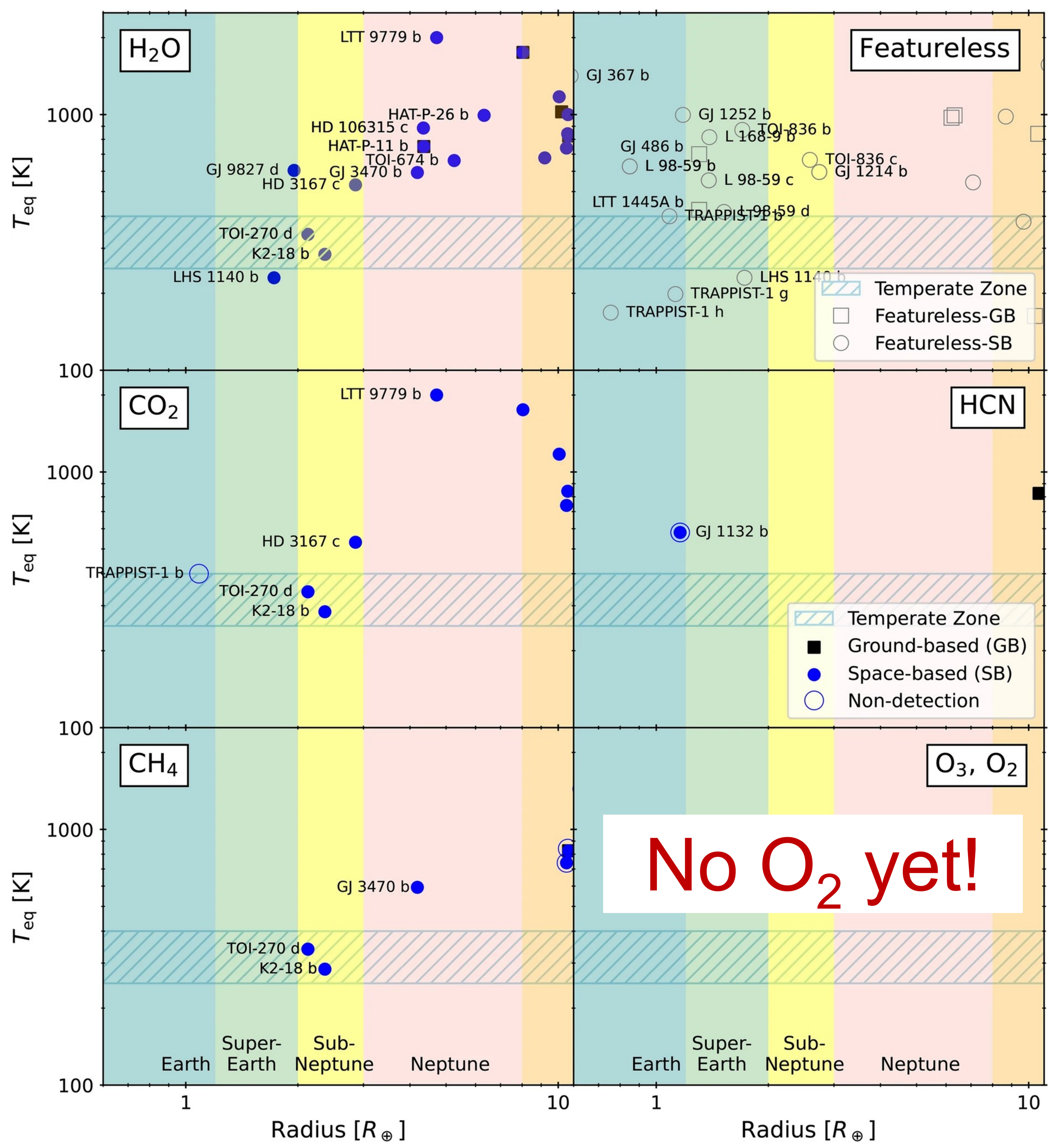
High-Resolution Spectroscopy





- Essential for ground-based exoplanet atmosphere observations:
  - Overcomes telluric lines, exoplanet clouds and hazes
  - Study line shapes e.g. wind in the atmosphere (Seidel+ 2023)
- Typical Echelle spectrographs reach R = 100,000 or R = 200,000 with pupil slicer or single-mode fiber.
- Hazes can suppress up to 50% of the signal (Hood+2020).
- Could help create the line list (Sithajan+2025 under review).
- Increasing R from 100,000 to 300,000 doubles the spectral line depth and shortens observing time by up to 30%. (Lopez-Morales+2019, Currie+2023, Hardegree-Ullman+2023)

Detections of Molecules in ExoAtmospheres



- Various molecules have been detected around gas giants.
- Water can be detected from Super-Earth sized planets.
- Many featureless detection around Super-Earth, Earth-sized planets. Possible reasons are:
  - Instrument limit
    - Not enough resolution/photons
  - Strong stellar activity/radiation
  - Clouds and hazes

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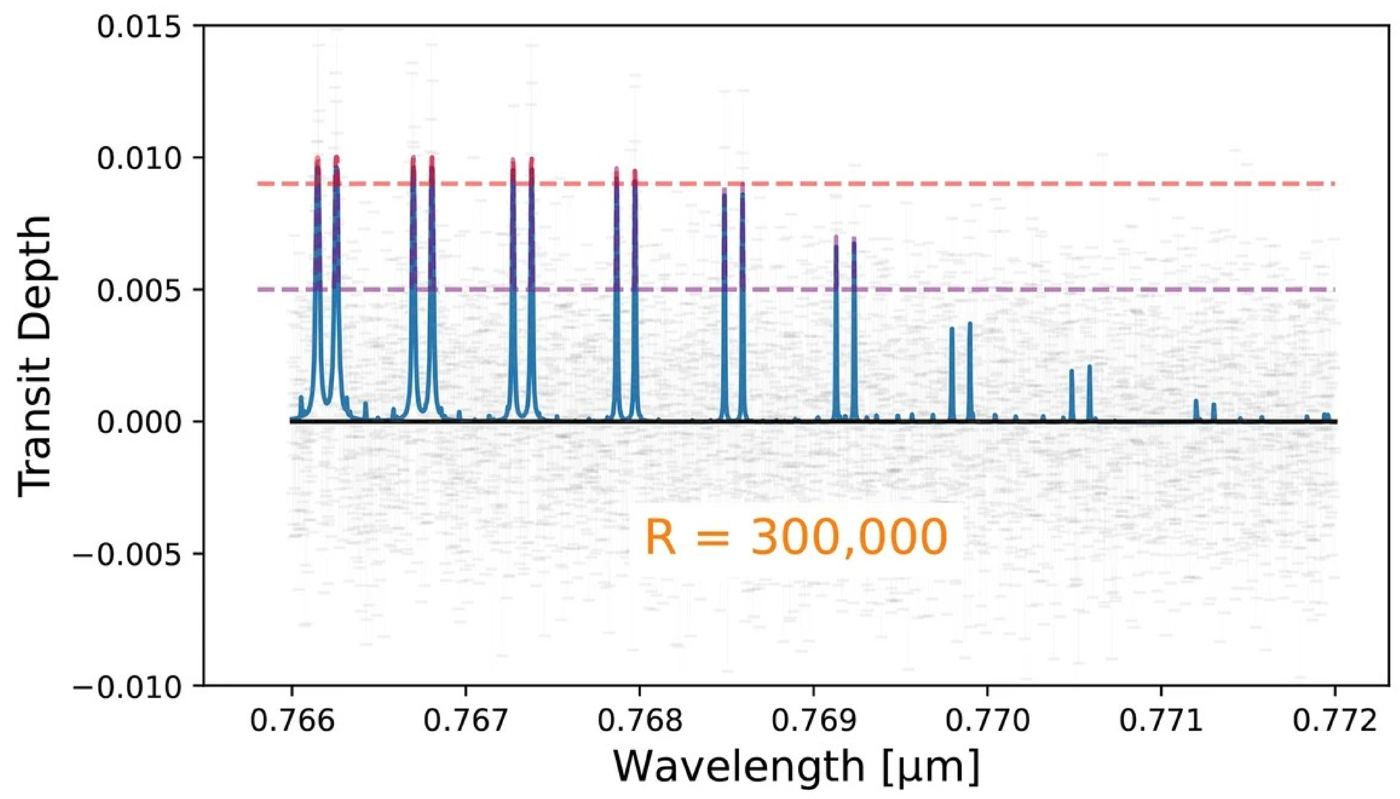
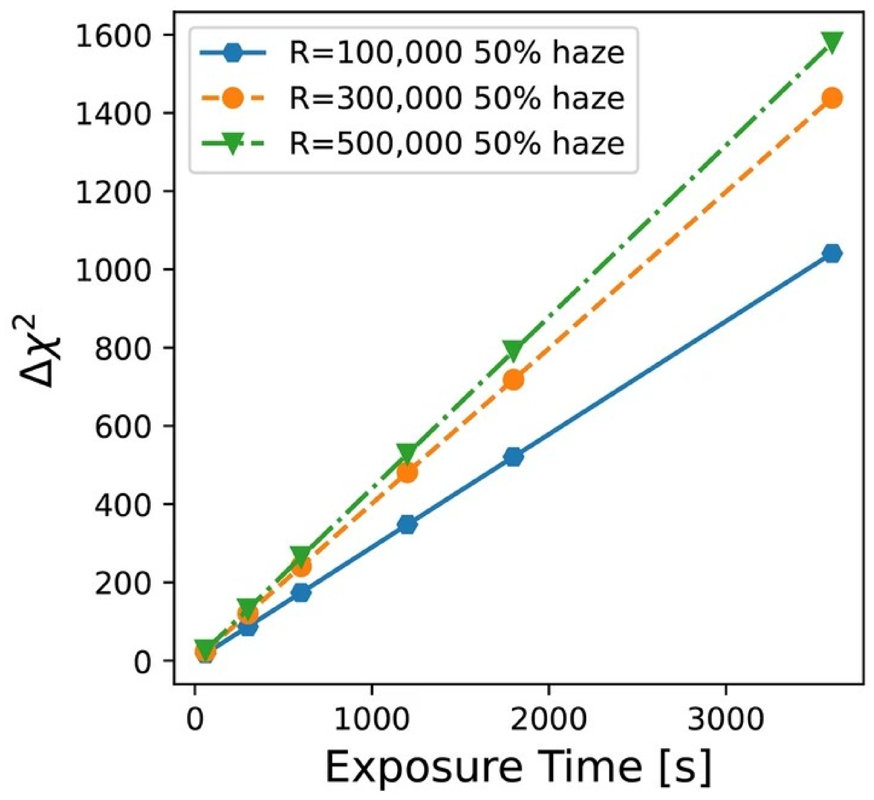
Data retrieved from Exoplanet Atmospheres Database as of Sep. 2024
https://research.iac.es/proyecto/exoatmospheres/index.php

Boosting Spectral Resolution to Look Through Haze and Clouds

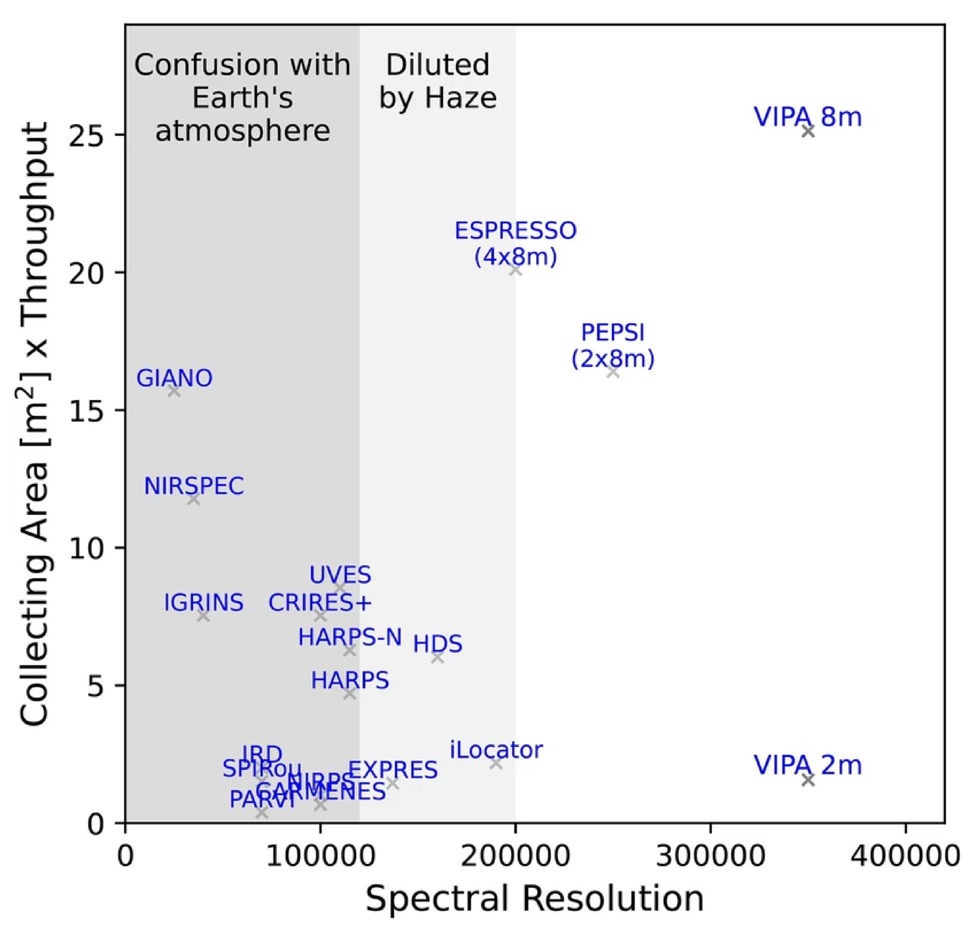




Summary

In challenging cloud and haze scenarios,

- Increasing the resolution from R = 100,000 to R = 300,000 enables significant detection with 4 times shorter exp. time.
- Combining a large telescope aperture, high throughput, and a high-resolution instrument to collect photons in hazy and cloudy scenarios more efficiently.



References

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- Hood, C. et al. AJ (2020)
- Seidel, J. et al. A&A (2023)
- **Rukdee Scientific Report (2024)**