Mind the Gap: Crunching the Atmospheres of the Coldest Free-Floating Brown Dwarfs

Thematic Areas (Check all that apply):

☒ (Theme A) Key science themes that should be prioritized for future JWST and HST observations
☐ (Theme B) Advice on optimal timing for substantive follow-up observations and mechanisms for enabling exoplanet science with HST and/or JWST
☐ (Theme C) The appropriate scale of resources likely required to support exoplanet science with HST and/or JWST
☒ (Theme D) A specific concept for a large-scale (∼500 hours) Director's Discretionary exoplanet program to start implementation by JWST Cycle 3.

Summary: Y-dwarfs are the coldest ($\mathrm{T_{eff}}$ <500 K), and least-massive brown dwarfs (M<20 $\mathrm{M_{Jup}}$), filling the gap in $\mathrm{T_{eff}}$ and mass between the very-well characterized T dwarfs, and Jupiter-like gas giant planets (∼128 K). Nevertheless, due to their faintness (M_J >19), only ∼40 Y-dwarfs have been discovered in the last decade [1]. From those, about half could be spectroscopically studied [2], and only three have time-resolved photometry or spectroscopy [3, 4, 5]. In summary, the characterization of the atmospheres of Y-dwarfs has been highly limited by the sensitivity of the instrumentation available prior to JWST. Thus, we propose to conduct a comprehensive time-resolved near- and mid-infrared spectroscopic campaign with NIRSpec and MIRI, to characterize in deep detail the atmospheres of the currently known Y-dwarfs. This survey will allow us to: 1/ Obtain high signal-to-noise high-resolution spectroscopy of all the known Y-dwarfs up-to-date, allowing us to test the atmospheric models for the coldest brown dwarfs at a wide wavelength range. 2/ Time-resolved spectroscopy will allow us to characterize the types and composition of clouds that condense at each atmospheric depth in Y-dwarfs, allowing us to study the 3D structure of these cold giants free-floating objects. In conclusion, a comprehensive time-resolved spectroscopic study of Y-dwarfs will allow us to bridge the gap between the free-floating brown dwarfs and exoplanets, and to improve the existing atmospheric models in this temperature regime.

Anticipated Science Objectives: 1/ *Testing (forward and retrieval) Atmospheric Models for Y-dwarfs*. Since many of these objects are too faint to be characterized with instrumentation other than that onboard JWST, few high SNR spectroscopic data set was available to test these models with a wide near- and mid-infrared wavelength coverage (Fig. 1 middle and bottom panel [2], [6]). In addition, Y-dwarfs surveys with ground-based photometric and spectroscopic data suggest that Y-dwarfs colors and spectra are quite sensitive to metallicity ([2], Fig. 1 upper panel). Thus, having a survey monitoring all Y-dwarfs known up to date is vital to characterize all Y-dwarf parameter space. 2/ *Characterizing the atmospheric cloud structure and evolution*. Time-resolved spectroscopic studies require stability and high SNR spectra. Due to instrumental limitations, this type of monitoring campaign cannot be accomplished other than with JWST. Time-resolved spectroscopy will allow us to measure the variability amplitudes at the different molecule bands and atomic lines, each of them probing different depths in the atmospheres of these objects. By analyzing the differences in variability amplitude at the different spectral characteristics, we will characterize the types of clouds that condense at each atmospheric depth, allowing us to study the 3D structure of these cold giants. This studies were successfully performed in L- and T-dwarfs (i.e. [7], [8], [9], [10]).

Urgency: The $\mathrm{T_{eff}}$ and masses of most of the Y-dwarfs are similar to those of the *coldest* exoplanets detected by direct-imaging and transiting methods. Given the isolated nature of Y-dwarfs, they offer a unique opportunity to characterize the atmospheres similar to those of many planets for which these studies are more challenging. Y-dwarfs offer a unique opportunity to improve atmospheric models in the cold regime, including retrievals, which are commonly used for deriving the properties of transiting exoplanets.

Risk/Feasibility: The three Y-dwarfs that were monitored for time-resolved photometry showed significant variability [3, 4, 5]. Thus, likely most Y-dwarfs will show some level of spectral variability. For those Y-dwarfs which do not show spectroscopic variability, we still will obtain a high signal-to-noise spectra allowing us to test atmospheric models/retrievals.

Timeliness: Our proposal is well aligned with the recommendations of the Astro2020 Decadal Survey.

Cannot be accomplished in the normal GO cycle: We need to cover at least one rotational period of each object. Most brown dwarfs have rotational periods <20 hr [11], thus, we propose to monitor each Y-dwarf for 10 hr with NIRSpec/BOTS and 10 hrs with MIRI/LRS.

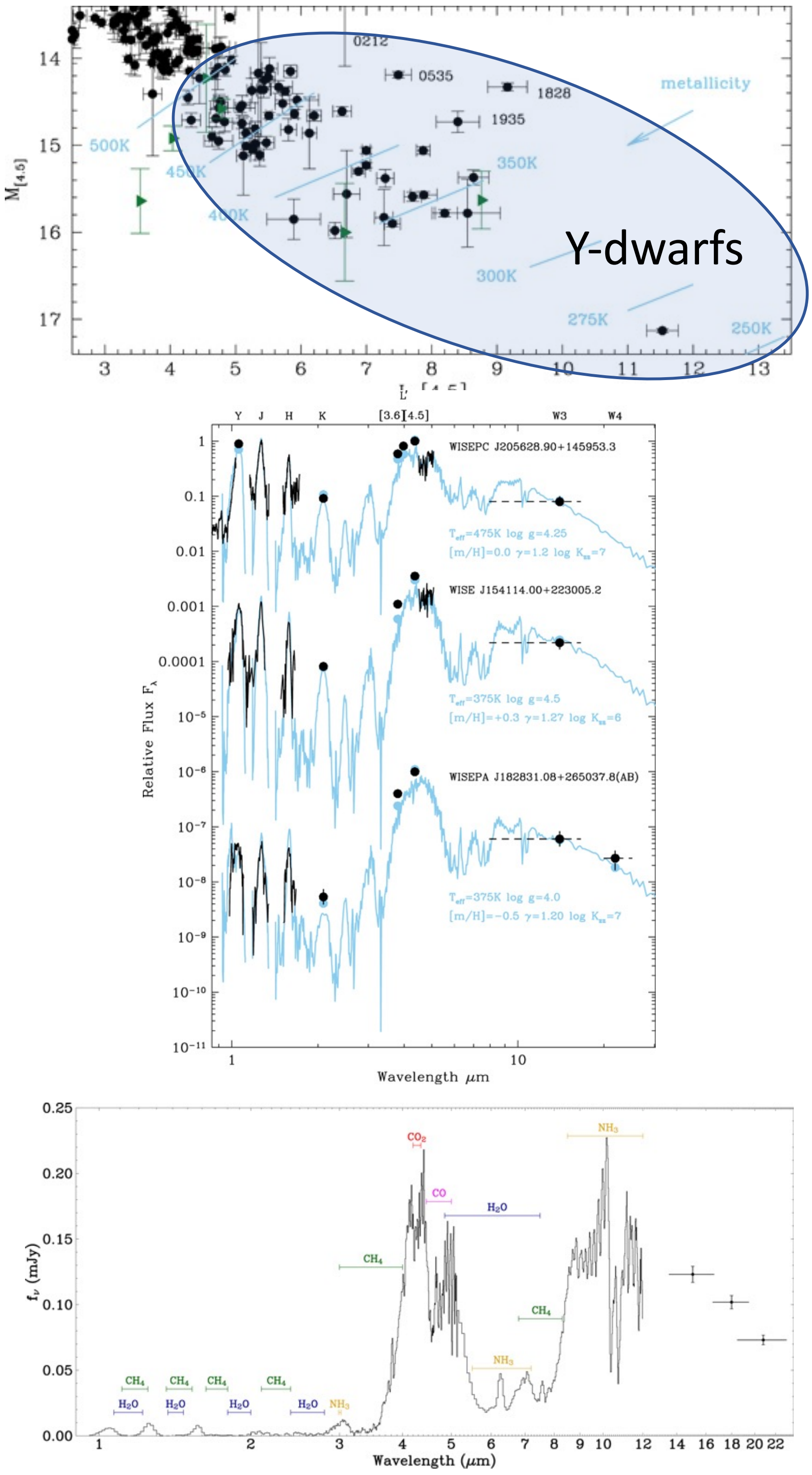

Figure 1: **Upper panel**: Color-magnitude diagram for the Y-dwarfs known up to date (those with $T_{\rm eff}$ <500 K. The spread in colors in this diagram for Y-dwarfs is most likely due to differences in metallicity [2]. **Middle panel**: Example of ∼400 K Y-dwarf spectra obtained with pre-JWST instrumentation (in black, blue are the best fit models) [2]. **Bottom panel**: JWST/NIRSpec and MIRI spectrum from [6].

References

[1] J. Davy Kirkpatrick et al. "The Field Substellar Mass Function Based on the Full-sky 20 pc Census of 525 L, T, and Y Dwarfs". In: 253.1, 7 (Mar. 2021), p. 7. DOI: `10.3847/1538-4365/abd107`. arXiv: `2011.11616 [astro-ph.SR]`.

[2] S. K. Leggett et al. "Measuring and Replicating the 1-20 μm Energy Distributions of the Coldest Brown Dwarfs: Rotating, Turbulent, and Nonadiabatic Atmospheres". In: 918.1, 11 (Sept. 2021), p. 11. DOI: `10.3847/1538-4357/ac0cfe`.

[3] T. L. Esplin et al. "Photometric Monitoring of the Coldest Known Brown Dwarf with the Spitzer Space Telescope". In: 832.1, 58 (Nov. 2016), p. 58. DOI: `10.3847/0004-637X/832/1/58`. arXiv: `1609.05850 [astro-ph.SR]`.

[4] S. K. Leggett et al. "Observed Variability at 1 and 4 μm in the Y0 Brown Dwarf WISEP J173835.52+273258.9". In: 830.2, 141 (Oct. 2016), p. 141. DOI: `10.3847/0004-637X/830/2/141`. arXiv: `1607.07888 [astro-ph.SR]`.

[5] Michael C. Cushing et al. "The First Detection of Photometric Variability in a Y Dwarf: WISE J140518.39+553421.3". In: 823.2, 152 (June 2016), p. 152. DOI: `10.3847/0004-637X/823/2/152`. arXiv: `1602.06321 [astro-ph.SR]`.

[6] Samuel A. Beiler et al. "The First JWST Spectral Energy Distribution of a Y Dwarf". In: 951.2, L48 (July 2023), p. L48. DOI: `10.3847/2041-8213/ace32c`. arXiv: `2306.11807 [astro-ph.SR]`.

[7] Hao Yang et al. "Extrasolar Storms: Pressure-dependent Changes in Light-curve Phase in Brown Dwarfs from Simultaneous HST and Spitzer Observations". In: 826.1, 8 (July 2016), p. 8. DOI: `10.3847/0004-637X/826/1/8`. arXiv: `1605.02708 [astro-ph.EP]`.

[8] Beth A. Biller et al. "Simultaneous Multiwavelength Variability Characterization of the Free-floating Planetary-mass Object PSO J318.5-22". In: 155.2, 95 (Feb. 2018), p. 95. DOI: `10.3847/1538-3881/aaa5a6`. arXiv: `1712.03746 [astro-ph.EP]`.

[9] Elena Manjavacas et al. "Revealing the Vertical Cloud Structure of a Young Low-mass Brown Dwarf, an Analog to the β-Pictoris b Directly Imaged Exoplanet, through Keck I/MOSFIRE Spectrophotometric Variability". In: 162.5, 179 (Nov. 2021), p. 179. DOI: `10.3847/1538-3881/ac174c`. arXiv: `2107.12368 [astro-ph.EP]`.

[10] Dániel Apai, Domenico Nardiello, and Luigi R. Bedin. "TESS Observations of the Luhman 16 AB Brown Dwarf System: Rotational Periods, Lightcurve Evolution, and Zonal Circulation". In: 906.1, 64 (Jan. 2021), p. 64. DOI: `10.3847/1538-4357/abcb97`. arXiv: `2101.02253 [astro-ph.EP]`.

[11] M. R. Zapatero Osorio et al. "Spectroscopic Rotational Velocities of Brown Dwarfs". In: 647.2 (Aug. 2006), pp. 1405–1412. DOI: `10.1086/505484`. arXiv: `astro-ph/0603194 [astro-ph]`.