INSTITUTIONAL ID NUMBER:
DESCRIPTIVE TITLE: Diagnosing Ultra-Cool Brown Dwarf Candidates
PI: John Wisniewski
OBSERVER(S): J. Wisniewski, S. Silverberg
UNCERTIFIED/UNTRAINED OBSERVERS:
COLLABORATORS: NASA Backyard Worlds: Planet 9 team
CONTACT INFORMATION: wisniewski@ou.edu 206-427-0184

INSTRUMENT: NICFPS
PRIMARY DIS GRATING:
SECONDARY DIS GRATING (IF REQUIRED):
SLITS/FILTERS/ETC NEEDED:

IS THIS A TARGET OF OPPORTUNITY PROGRAM: NO
IF YES, NUMBER OF PREVIOUS TRIGGERS FROM THIS PI:
IF YES, PUBLICATIONS OF PI FROM APO ToO OBSERVATIONS:

REMOTE OR ONSITE: REMOTE

NUMBER OF HALF-NIGHTS REQUESTED: 1 A half-night
Dark -
Grey -
Bright - 1 A half-night (any moon phase is actually ok)

SCIENTIFIC SCHEDULE CONSTRAINTS: We note that if the Silverberg proposal is awarded time, our program could fill the rest of Silverberg's half-night.
PERSONAL SCHEDULE CONSTRAINTS: None
NEED FOR PROTECTION FROM PRE-EMPTION: No

BRIEF SCIENCE JUSTIFICATION: We propose to use APO/NICFPS to characterize the status of candidate ultra-cool Y dwarfs identified via the Backyard Worlds:Planet 9 citizen science project. These candidate objects have WISE (W1-W2) colors consistent with the sources being Y dwarfs; however, they are too dim to have near-IR (JHK) photometry from 2MASS, Pan-STARRS, or other catalogs. We therefore will establish the status of these candidates with APO's NICFPS, and then plan to obtain follow-up IR spectroscopy on Keck/Gemini.

Photometry of Ultra-Cool Brown Dwarf Candidates

John Wisniewski, Marc Kuchner (NASA Goddard Space Flight Center), Adam Schneider (Arizona State University), Aaron Meisner (University of California, Berkeley)

Ultra-cool brown dwarfs represent the forefront of brown dwarf research. These rare objects reveal the low-mass end of the substellar mass function (Allen et al. 2005; Lodieu et al. 2017) informing theories of star and planet formation. They have become crucial proving grounds for models of exoplanet atmospheres (Marley et al. 2012; Burrows et al. 2001; Tremblin et al. 2016; Currie et al. 2011) since their atmospheres have the same temperatures as giant exoplanets.

Brown dwarfs occupy the M, L, T and Y spectral types, which form a low-temperature extension of the OBFGKM sequence. The coldest of these, the Y type, include WISE 0855, the coldest known brown dwarf, which has allowed us to study the onset of water clouds (Faherty et al. 2014). Y dwarfs colder than WISE 0855 would likely be below the deuterium-burning limit (Bodenheimer et al. 2013; Spiegel et al. 2011), making them planetary-mass worlds. Only 25 Y dwarfs are presently known (compared to ~500 T dwarfs), and these examples show a striking variety of inferred atmospheric properties. So each new one we find represents an opportunity to break new ground: locating benchmark systems and exotic objects, and mapping the distributions of their ages, temperatures, colors and chemistries.

However, discovering new Y dwarfs presents substantial challenges. The first is a big-data analysis problem, often requiring visual inspection of images. For the most recent large mid-infrared survey, Schneider et al. (2016) inspected images of over 1 million sources searching for brown dwarfs. The second challenge arises because objects are typically not considered bona fide brown dwarfs until their spectra have been compared to brown dwarf spectral standards. But spectroscopic follow-up of Y dwarfs generally requires 10m class telescopes or the *Hubble Space Telescope*, which in turn requires reasonably accurate near-infrared photometry to determine observing parameters. Y dwarfs are often so red that they lack near-infrared photometry in the Two-Micron All Sky Survey (2MASS) or any other near-infrared catalog.

To address these challenges and find new Y dwarfs, we propose to use APO to acquire near-IR photometry of 10 new Y dwarf candidates found via the Backyard Worlds: Planet 9 citizen science project. The Backyard Worlds: Planet 9 citizen science project combs through images from NASA's Wide-field Infrared Survey Explorer (WISE) mission to search for new brown dwarfs (Kuchner et al. 2017). More than 100,000 volunteers have been working online at BackyardWorlds.org, visually inspecting 3.5 and 4.6 μm images to find moving objects. So far, the project has identified more than 200 new brown dwarf candidates based on their colors and high proper motions (>275 mas/yr) spanning a range of infrared colors and spectral types. Of these, ~20 have WISE W1-W2 colors consistent with the Y spectral class (W1-W2 > 2.5). However, most of these objects lack adequate near-infrared (JHK) photometry from 2MASS, Pan-STARRS or any other catalog.

We propose to acquire near-infrared photometry for 10 Y dwarf candidates that will be observable at APO in the proposed quarter to refine their spectral types and enable future spectroscopy of these objects with large telescopes. We will model the data using a goodness-of-fit (G_k) statistical test (Cushing et al. 2008) comparing the photometry to a library of spectra from Mace et al. (2013) and Filippazzo et al. (2015) to determine improved spectral type estimates. Then—based on the results—we will apply for time on larger telescopes (IRTF, Keck, and Gemini) proposals for medium resolution spectroscopy, estimating exposure times based on the APO photometry. The new objects we find will lead to an improved understanding of the Y dwarf spectral class and the boundary between brown dwarf and rogue planet. Four citizen scientists were co-authors on the first publication from Backyard Worlds: Planet 9; we will continue to involve citizen scientists in all stages of the follow-up process.

Our sources have RAs between 22hr – 4hr, so A-half time during Q4 will be acceptable. ***Moreover, we note that our program could use a fraction of A or B-half time from Silverberg's partial ½-night request, should that program be awarded time.*** Our sources have WISE W1 magnitudes of 17-19, so we expect total exposure times of 15-30 minutes per source per filter will yield the SNR we need to assess the status of these sources. Our main priority will be obtaining quality J-band photometry for our 10 sources, followed by K-band photometry (if weather conditions and sky background conditions allow).

Allen, P.R. et al., 2005. The Substellar Mass Function: A Bayesian Approach. *The Astrophysical journal*, 625(1), pp.385–397.

Bodenheimer, P. et al., 2013. DEUTERIUM BURNING IN MASSIVE GIANT PLANETS AND LOW-MASS BROWN DWARFS FORMED BY CORE-NUCLEATED ACCRETION. *The Astrophysical Journal*, 770(2), p.120.

Burrows, A. et al., 2001. The theory of brown dwarfs and extrasolar giant planets. *Reviews of modern physics*, 73(3), pp.719–765.

Currie, T. et al., 2011. A COMBINED SUBARU/VLT/MMT 1-5 μm STUDY OF PLANETS ORBITING HR 8799: IMPLICATIONS FOR ATMOSPHERIC PROPERTIES, MASSES, AND FORMATION. *The Astrophysical Journal*, 729(2), p.128.

Faherty, J.K. et al., 2014. Indications of water clouds in the coldest known brown dwarf. *Astrophysical Journal Letters*, 793(1), p.L16.

Filippazzo, J.C. et al., 2015. FUNDAMENTAL PARAMETERS AND SPECTRAL ENERGY DISTRIBUTIONS OF YOUNG AND FIELD AGE OBJECTS WITH MASSES SPANNING THE STELLAR TO PLANETARY REGIME. *The Astrophysical Journal*, 810(2), p.158.

Kuchner, M.J. et al. 2017. The First Brown Dwarf Discovered by the Backyard Worlds: Planet 9 Citizen Science Project. *The Astrophysical Journal Letters,* 841(2), p. L19.

Lodieu, N. et al., 2017. New ultracool subdwarfs identified in large-scale surveys using Virtual Observatory tools (Corrigendum). *Astronomy & astrophysics. Supplement series*, 597, p.C3.

Mace, G.N. et al., 2013. A STUDY OF THE DIVERSE T DWARF POPULATION REVEALED BY WISE. *The Astrophysical journal. Supplement series*, 205(1), p.6.

Marley, M.S. et al., 2012. MASSES, RADII, AND CLOUD PROPERTIES OF THE HR 8799 PLANETS. *The Astrophysical Journal*, 754(2), p.135.

Schneider, A.C. et al., 2016. A PROPER MOTION SURVEY USING THE FIRST SKY PASS OFNEOWISE-REACTIVATION DATA. *The Astrophysical journal*, 817(2), p.112.

Spiegel, D.S., Burrows, A. & Milsom, J.A., 2011. THE DEUTERIUM-BURNING MASS LIMIT FOR BROWN DWARFS AND GIANT PLANETS. *The Astrophysical Journal*, 727(1), p.57.

Tremblin, P. et al., 2016. CLOUDLESS ATMOSPHERES FOR L/T DWARFS AND EXTRASOLAR GIANT PLANETS. *The Astrophysical Journal Letters*, 817(2), p.L19.