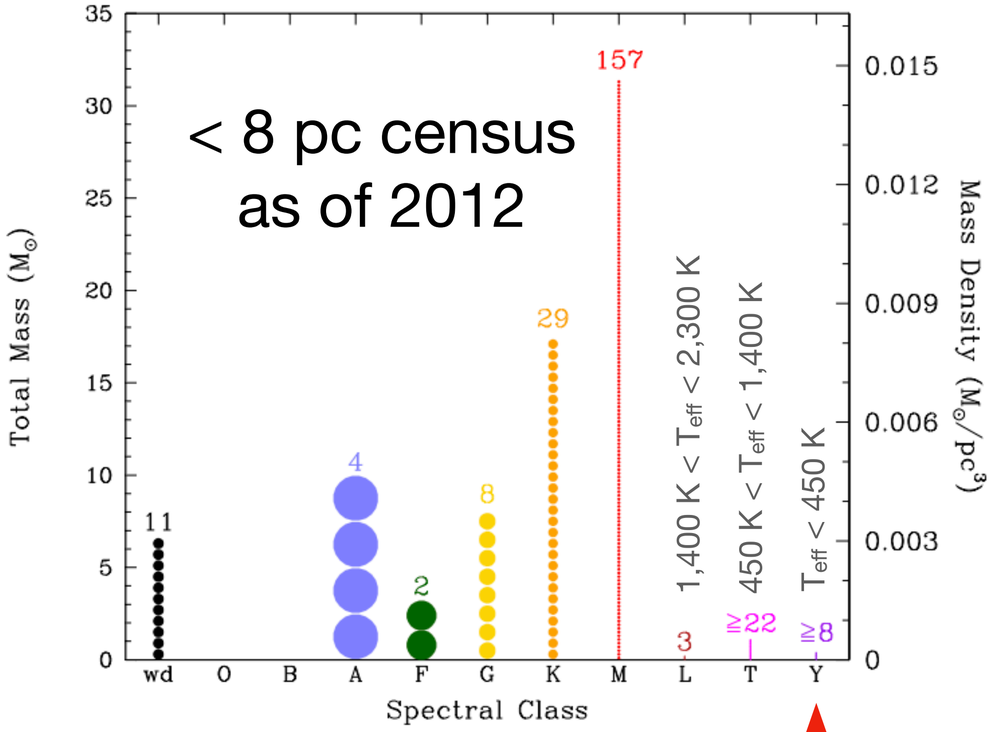
Exploring the Extremes: a New Population of Old and Cold Brown Dwarfs

Aaron Meisner (NOIRLab/CSDC), 3/14/2023
collaborators: Sandy Leggett, Dan Caselden, Sarah Logsdon, Adam Schneider, Pascal Tremblin, Mark Phillips

why study cold brown dwarfs?

- there are lots of brown dwarfs! ~1 brown dwarf per 6 main sequence stars
- exoplanet atmosphere analogs, but without the glare of a primary star
  - brown dwarfs and giant exoplanets overlap in temperature
  - some brown dwarfs can also be of planetary mass
- (initial) mass function, bridging between red dwarf stars and giant planets
- process of star formation at low mass (e.g., multiplicity as a function of masses and separation)



Kirkpatrick et al. 2012

Y dwarfs (Teff < 450 K) are the coldest known class of brown dwarfs

superlative needles (potentially) in the archival survey data haystack

probable

- ✓ Y dwarfs: doubling the known sample
- ✗ discover brown dwarf(s) colder than any currently known
- ✗ find new widest known planetary mass companion
- ✗ find object with higher proper motion than Barnard's Star
- ✗ discover substellar neighbor closer than Proxima Cen
- ✗ Jupiter/Saturn mass companion to the Sun ("Planet X")

unlikely

^my list from 2018 Steward Symposium — still haven't found much/most of what we were hoping to, 4.5 years later…

why haven't we discovered any Jupiter-temperature brown dwarfs yet? …and what have we discovered in the meantime?

- maybe we need to understand the oldest brown dwarfs in order to know how to properly search for the coldest brown dwarfs
- perhaps the coldest brown dwarfs are diverse, like giant exoplanets and the giant planets in our own solar system
- WISE (and perhaps JWST) are currently the primary ways forward for *discovery* with available data/facilities

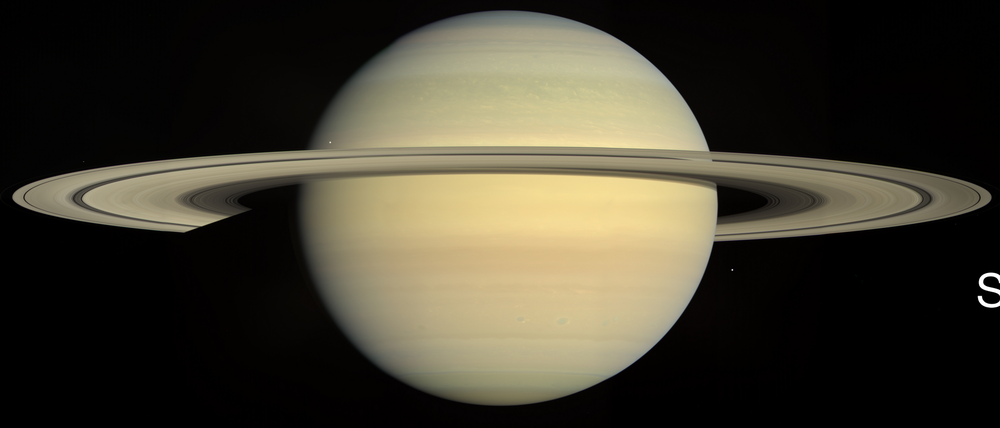
Discovery of Cold Brown Dwarfs or Free-Floating Giant Planets Close to the Sun

Sandy K. Leggett, Daniel Apai, Adam Burgasser, Michael Cushing, Trent Dupuy, Jackie Faherty, John Gizis, J. Davy Kirkpatrick, Mark Marley, Caroline Morley, Adam Schneider, Clara Sousa-Silva

This White Paper describes the opportunities for discovery of Jupiter-mass objects with 300K atmospheres. The discovery and characterization of such cold objects is vital for understanding the low-mass terminus of the initial mass function and for optimizing the study of exoplanets by the next generation of large telescopes, space probes and space missions.

Comments: White Paper submitted for Astro2020 Science

Jupiter (true color)

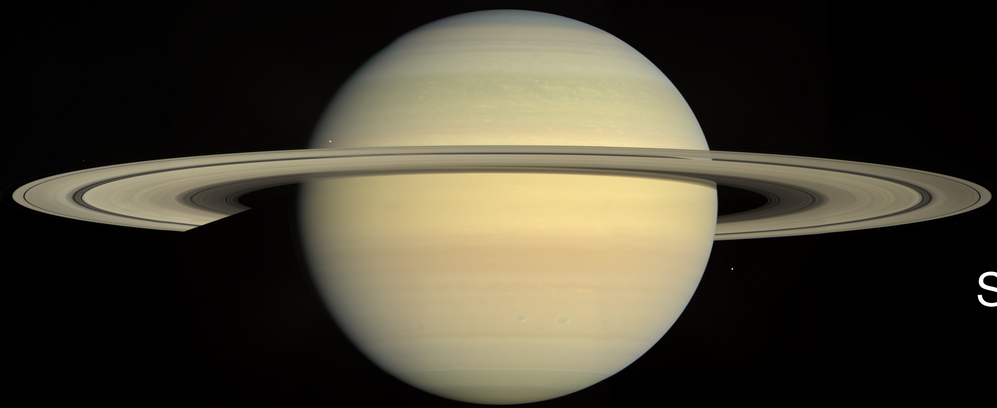


Saturn (true color)

why haven’t we discovered any Jupiter-temperature brown dwarfs yet?
…and what have we discovered in the meantime?

this talk: using WISE as a discovery engine for the oldest/coldest brown dwarfs
+ Gemini Observatory for crucial follow-up of candidates

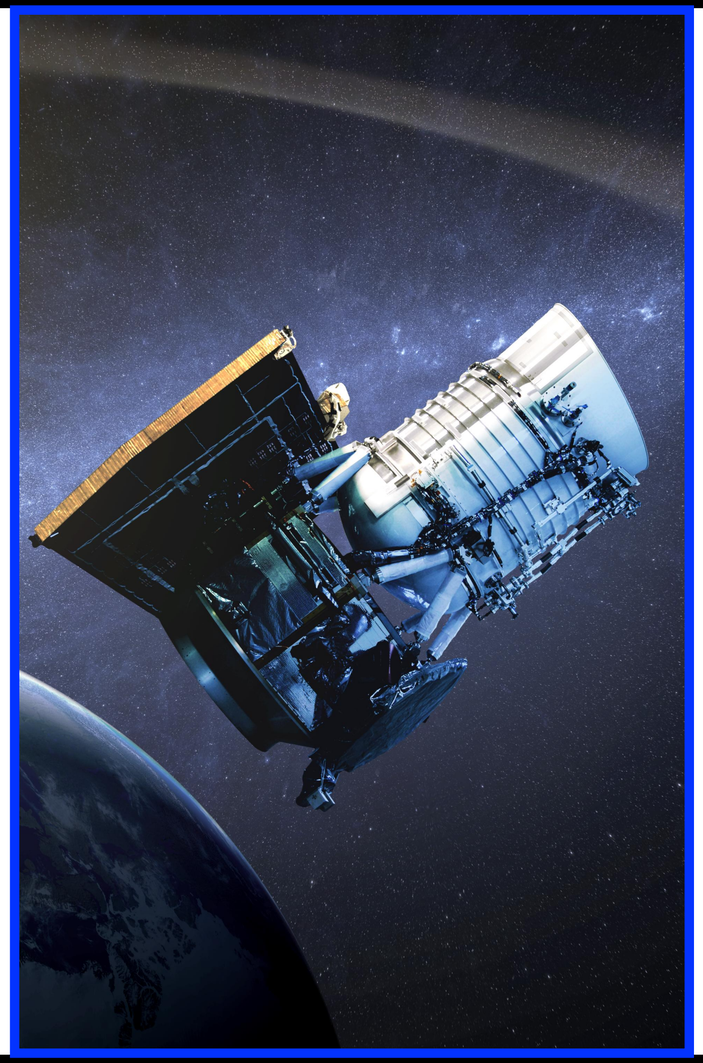
Jupiter (true color)



Saturn (true color)

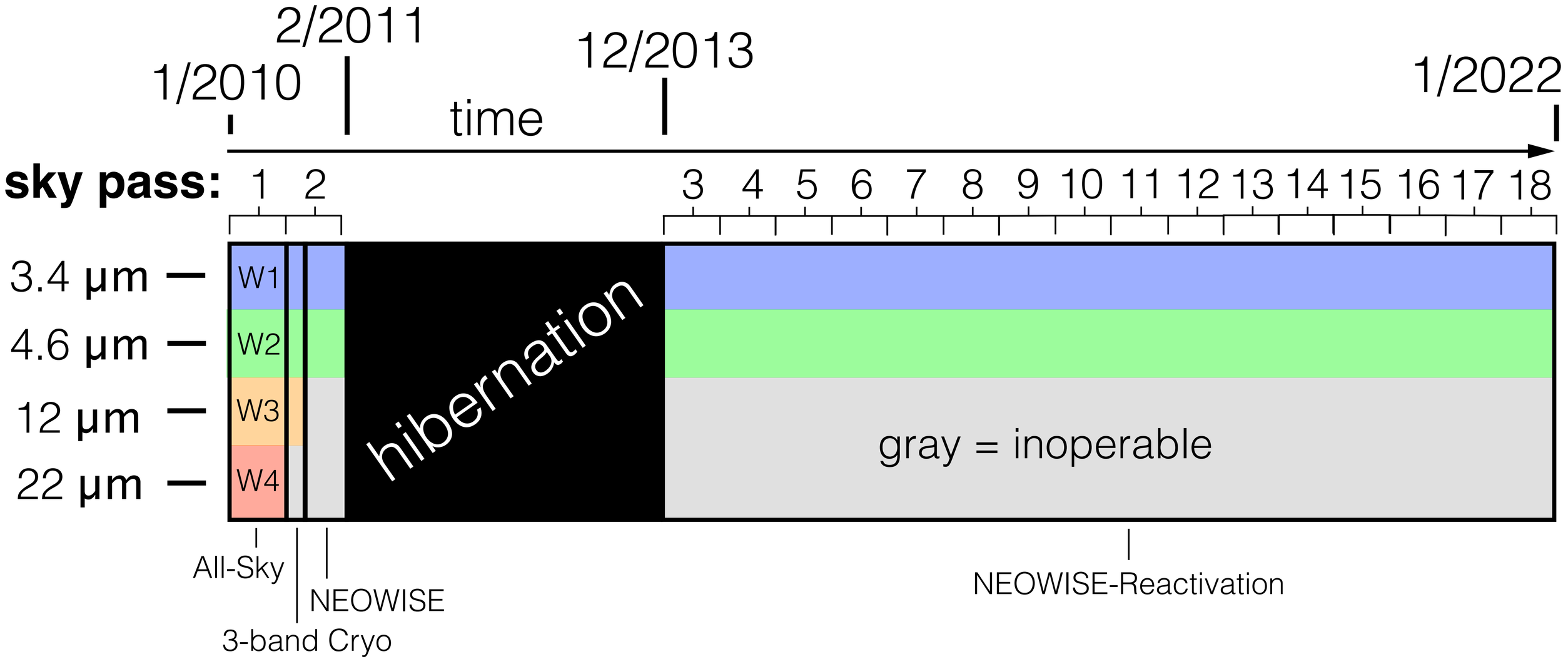
WISE overview

- **W**ide-field **I**nfrared **S**urvey **E**xplorer
- 40 cm telescope
- 0.8° x 0.8° FOV
- one full-sky mapping every 6 months
- FWHM: ~6” (W1-W3) , 12” (W4)

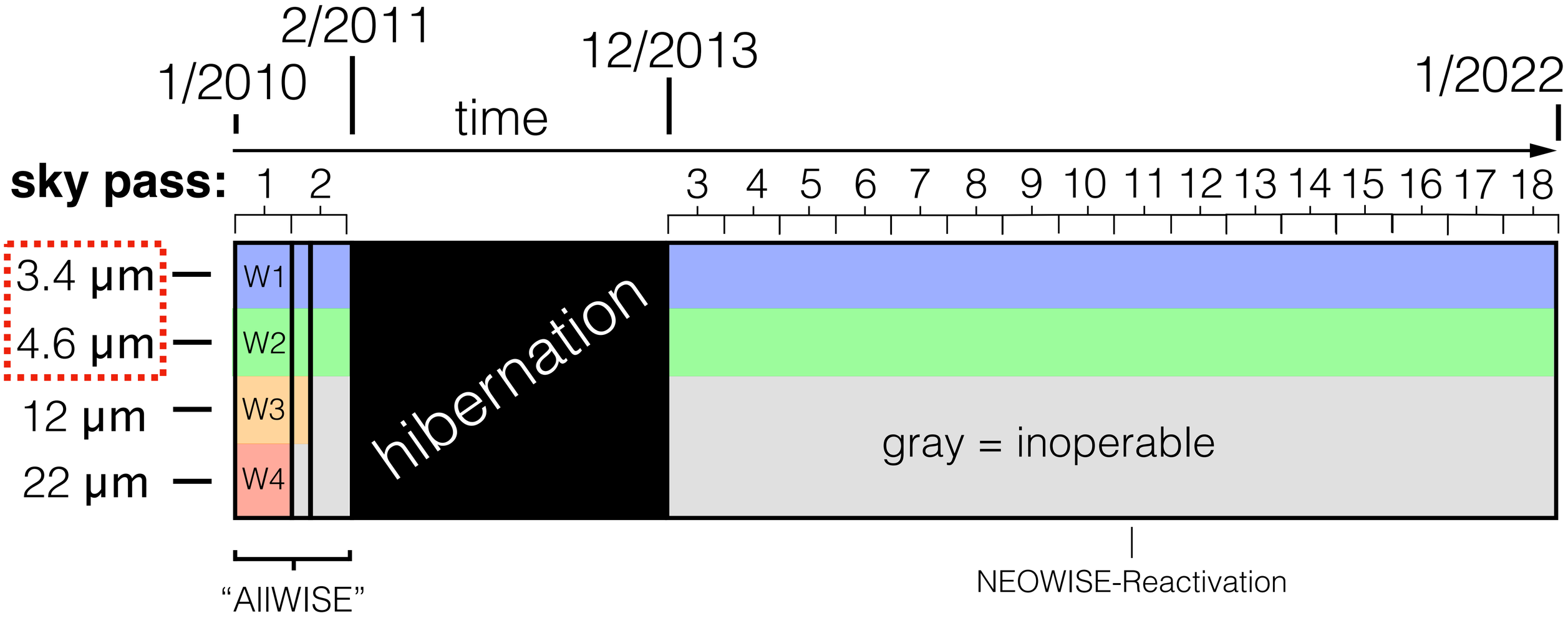


W1: 3.4 μm, W2: 4.6 μm, W3: 12 μm, W4: 22 μm

NEOWISE is good for much more than asteroids

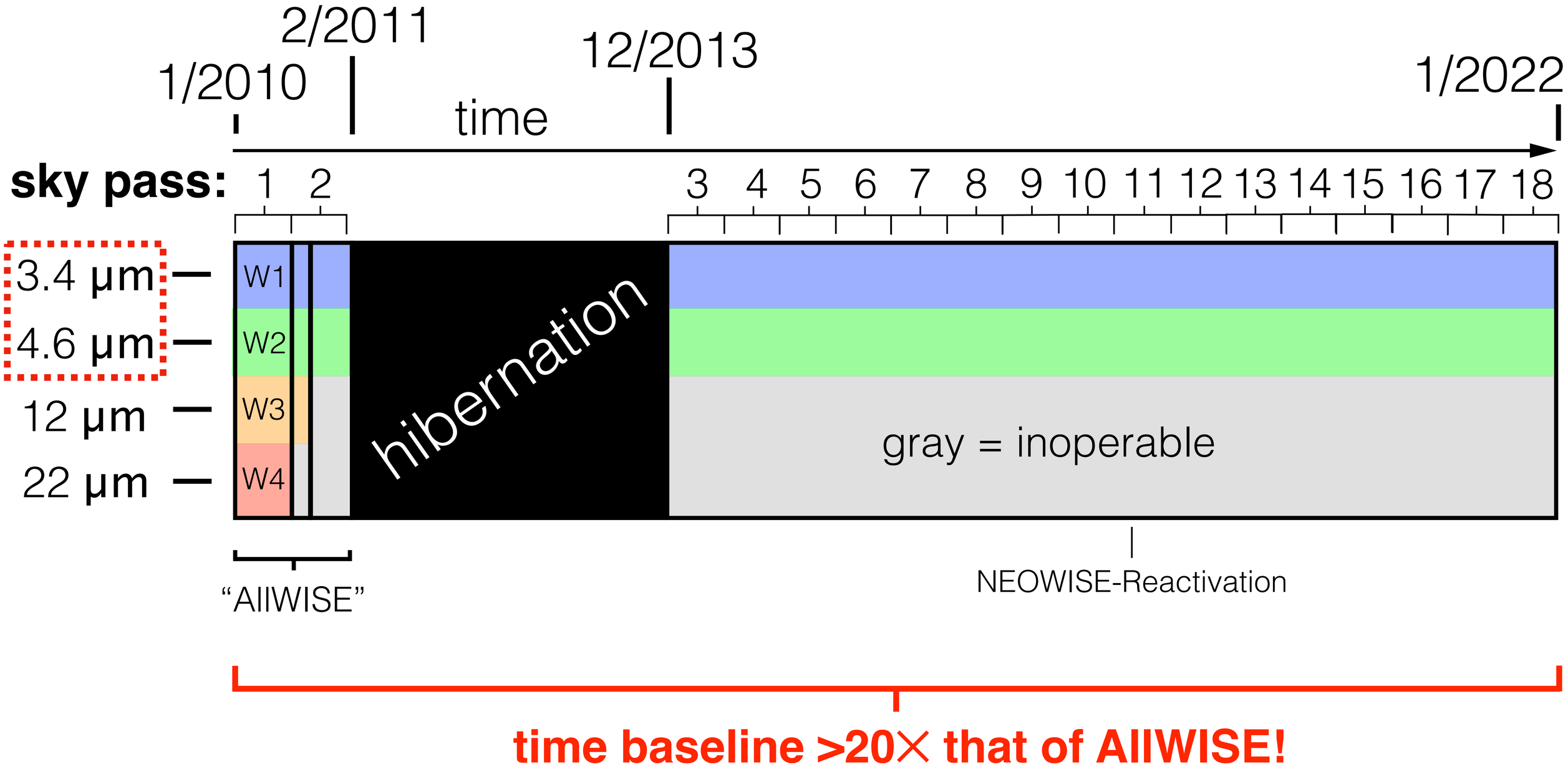


NEOWISE is good for much more than asteroids

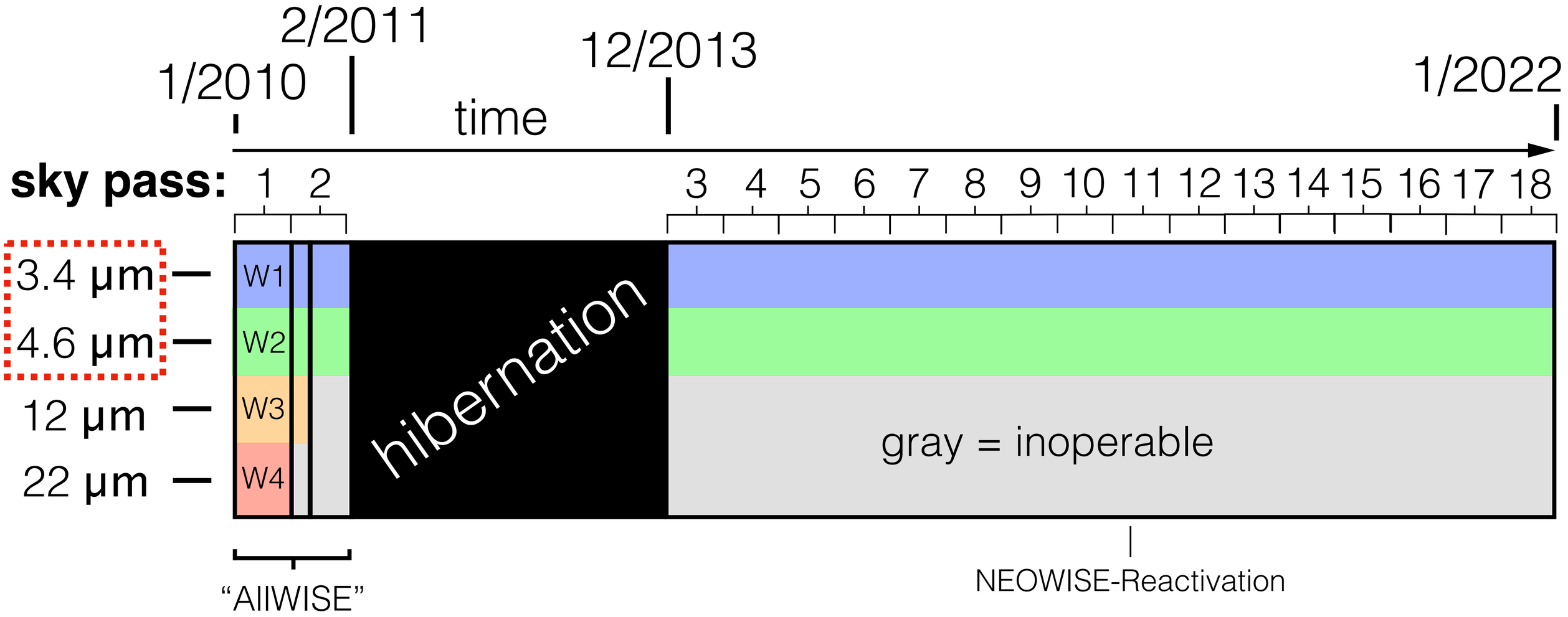


9× greater exposure time than AllWISE!

NEOWISE is good for much more than asteroids

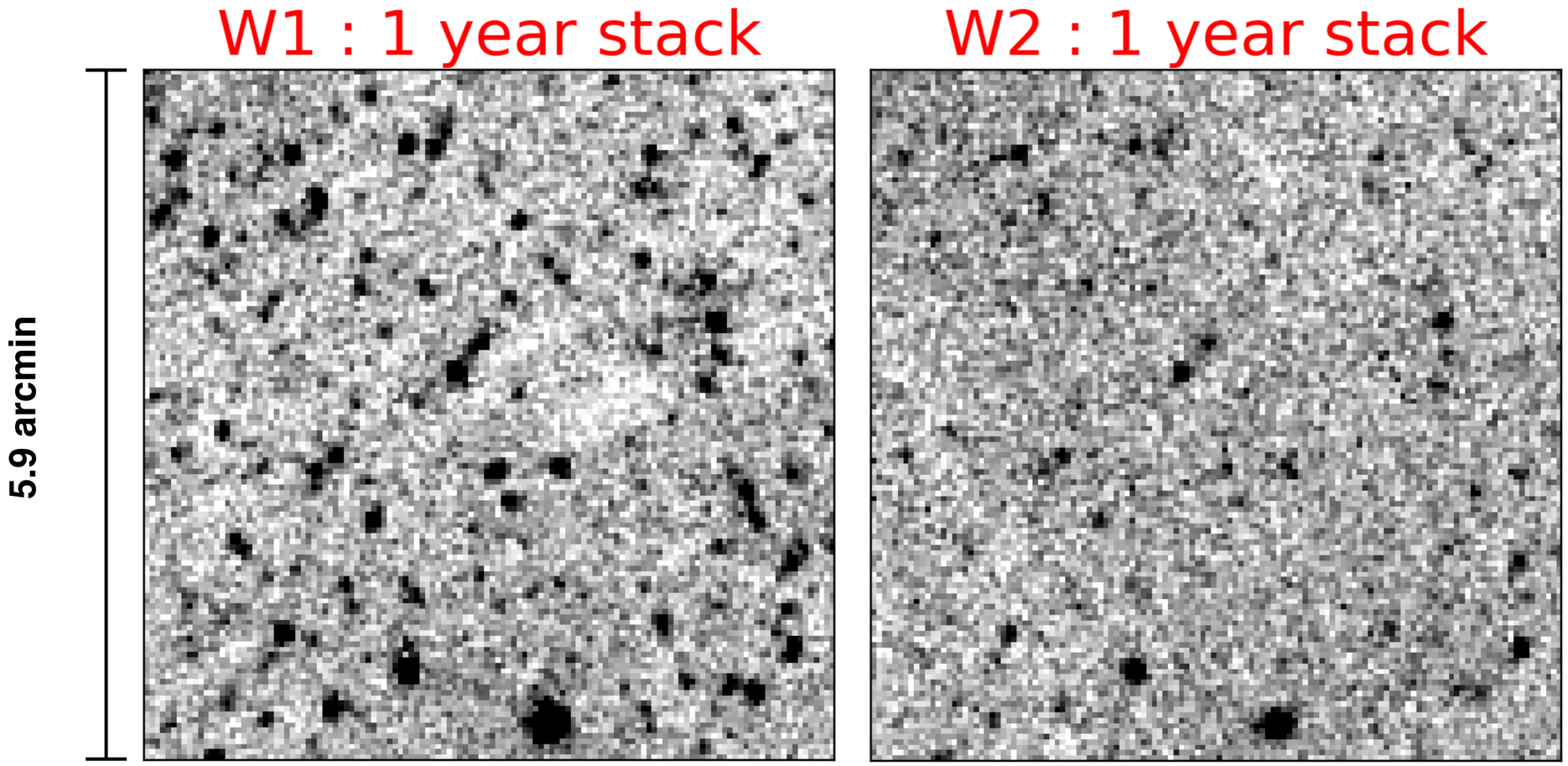


…what's the catch?



~45 million single exposures, ~315 TB total

deepest ever 3-5 micron full-sky maps



unWISE is the "branding" for our WISE/NEOWISE data products

"full-depth unWISE coadds"

>2× deeper static sky photometry enabled!

Meisner+ 2017a,b ; Meisner+2018a ; Meisner+ 2019

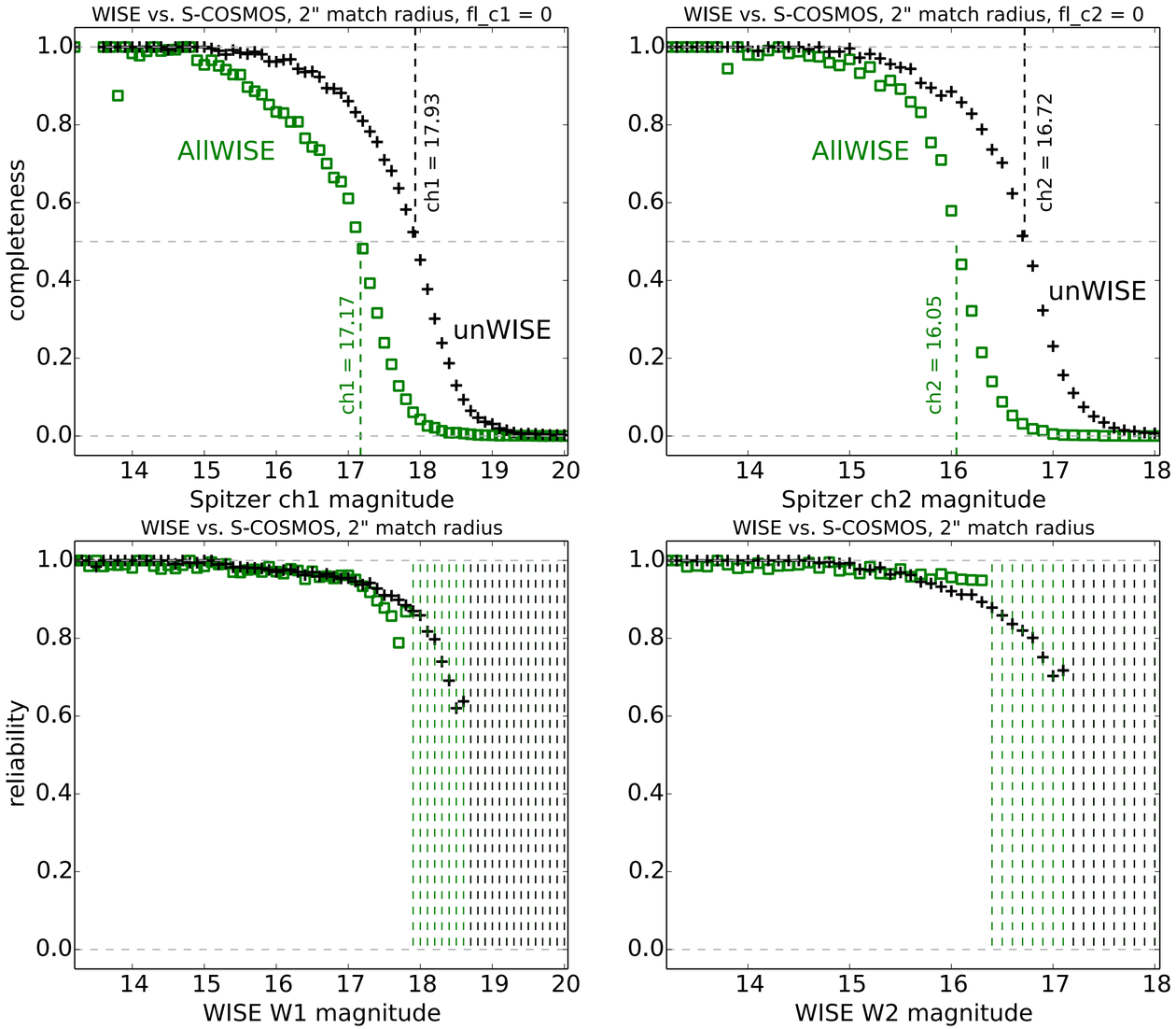
unWISE Catalog

- W1, W2 only
- covers entire sky
- “crowdsource” code models thousands of sources simultaneously
  → excellent deblending

Schlafly, Meisner & Green (2019)

unWISE Catalog is ~2× deeper than AllWISE

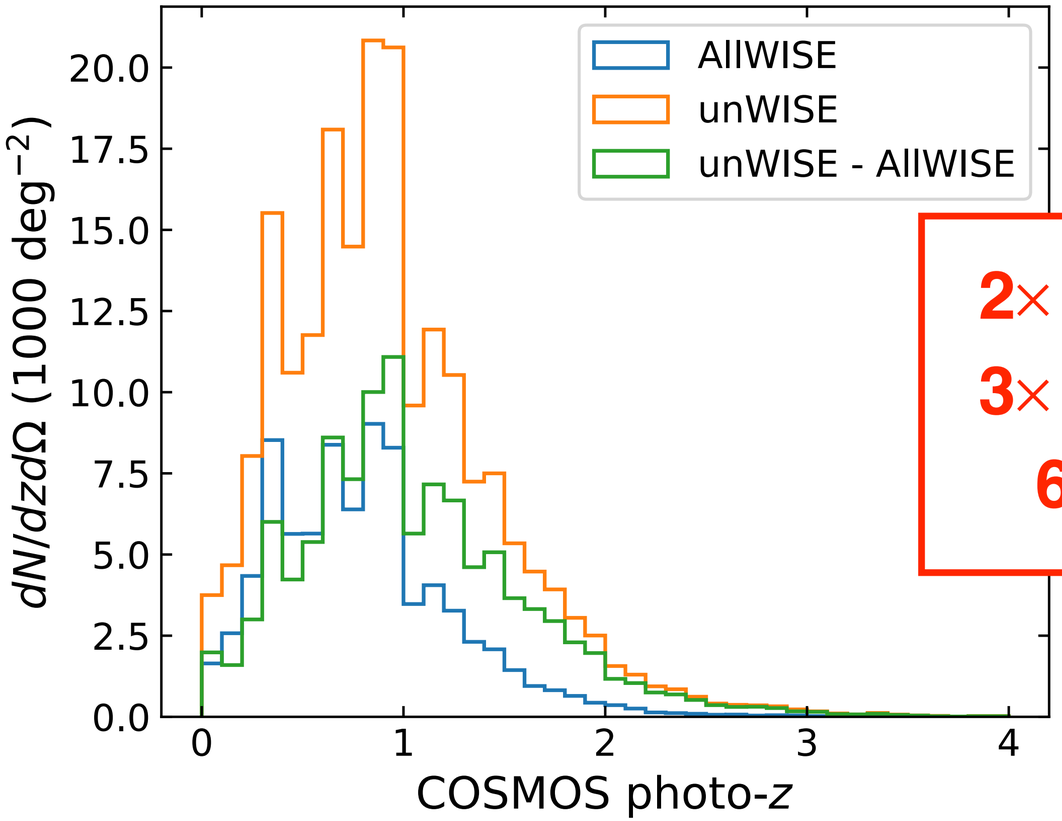
Schlafly, Meisner & Green (2019)



0.76 (0.67) mag deeper than AllWISE in W1 (W2)

unWISE Catalog AB depths: 20.72 (19.97) in W1 (W2)

COSMOS redshift distributions



2× more galaxies at 0 < z < 1

3× more galaxies at 1 < z < 2

6× more galaxies at z > 2

Schlafly, Meisner & Green (2019)

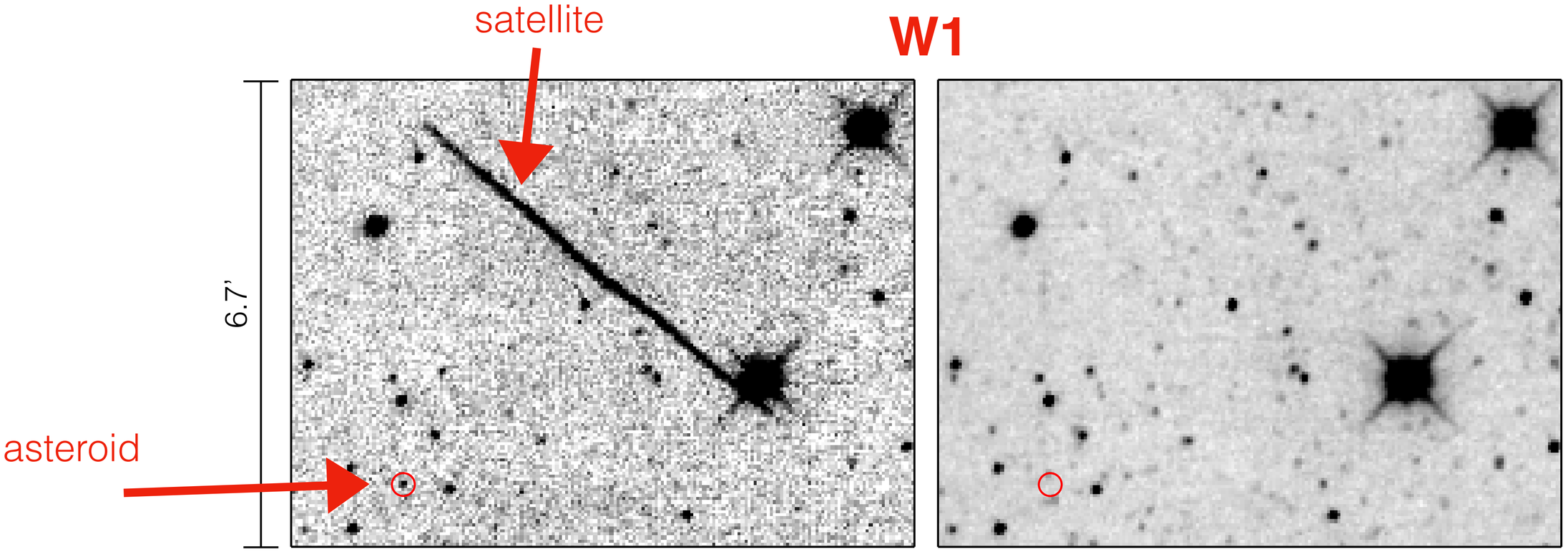
full-sky unWISE Catalog data release:

> **500 million** galaxies

> **2 billion** unique sources

catalog.unwise.me

time-resolved unWISE coadds: deeper and cleaner than single exposures



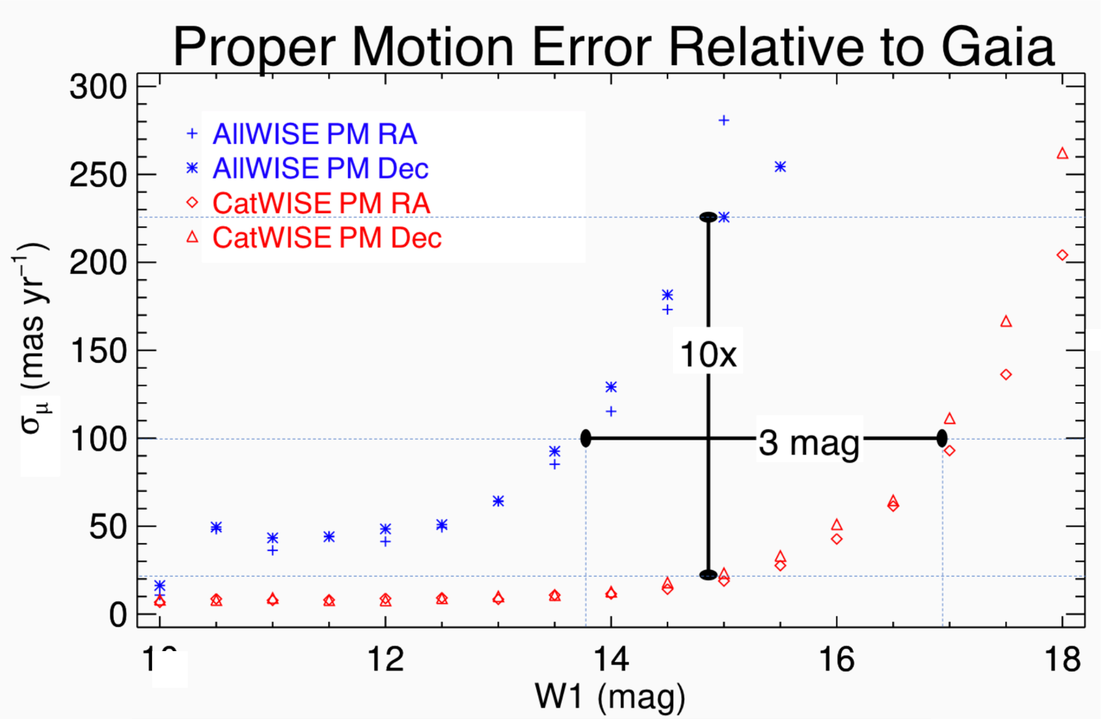
single-exposure image

epochal coadd,
~1 day time interval, ~12 exposures

Meisner+ 2018b

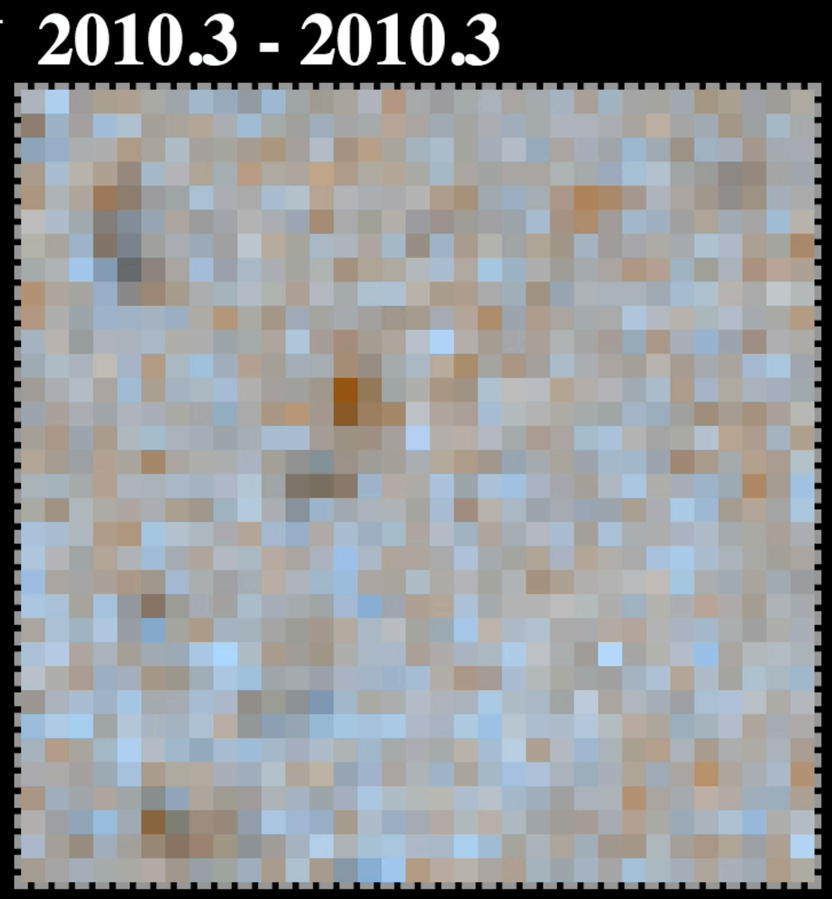
deepest ever mid-infrared proper motions: CatWISE2020

- unWISE Catalog provides the detection step, more than doubling the number of sources in CatWISE2020 relative AllWISE
- Applies AllWISE photometry + motion fitting software to 6 years of time-resolved unWISE coadds (spanning an 8.5 year baseline)

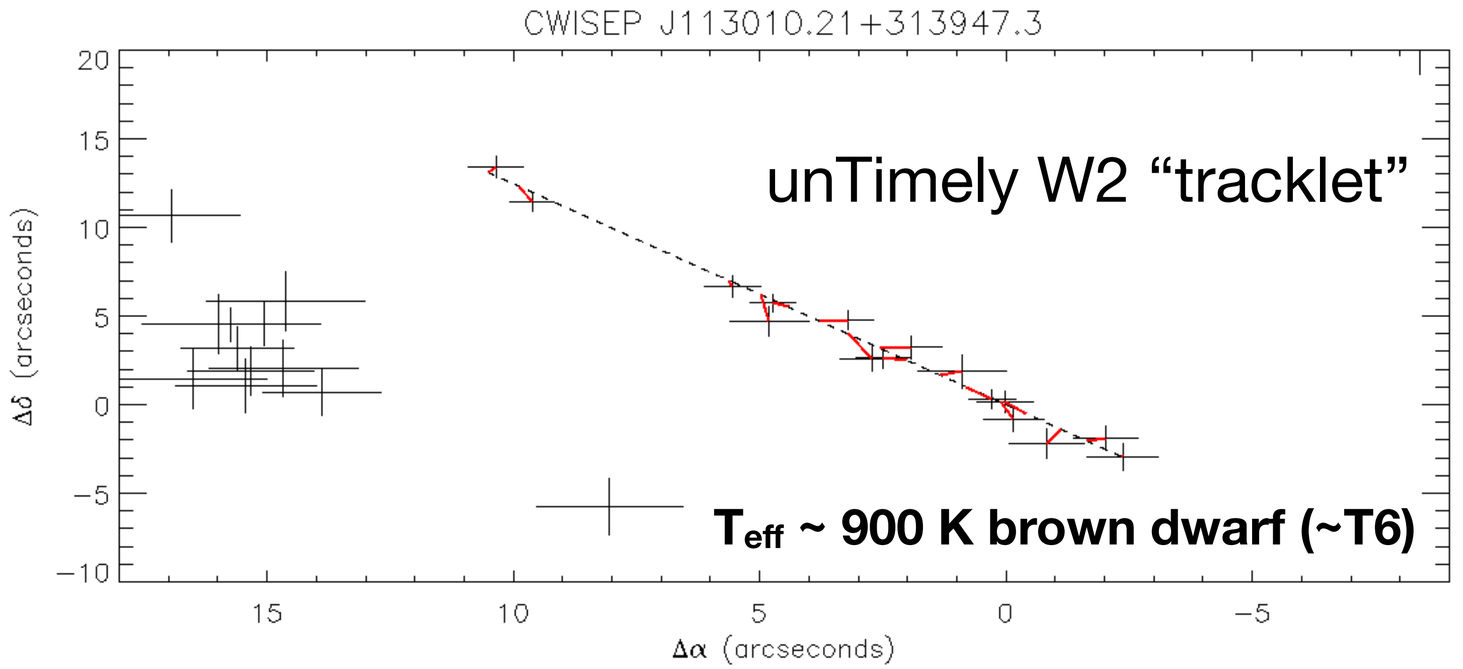


Eisenhardt, Marocco, Fowler, Meisner et al. (2020)

unTimely: an unWISE Catalog for every WISE sky pass



WiseView image blinker
built by citizen scientist Dan Caselden
http://byw.tools/wiseview



- Source detection run independently on each unWISE epochal coadd
- Low detection thresholds: S/N = 4.0 (2.5) in W1 (W2)
- Effectively ~32 all-sky catalogs: (W1, W2) x 16 sky passes
- Total of 23.5 billion (19.9 billion) detections in W1 (W2)
- Roughly 225k CPU hours total (NERSC/Cori)

summary of unWISE coadded data products

deepest 3-5 micron full-sky maps
- ‘full-depth’ unWISE coadds

Meisner+ 2017a, Meisner+ 2017b, Meisner+ 2018a, Meisner+ 2019

new class of all-sky time-domain maps at 3-5 microns
- ‘time-resolved’ unWISE coadds

Meisner+ 2018b, Meisner+ 2018c, Meisner+ 2019

deepest full-sky catalog at 3-5 microns
- the unWISE Catalog

Schlafly, Meisner & Green (2019)

deepest full-sky mid-infrared proper motion catalog
- CatWISE2020

Eisenhardt, Marocco, Fowler, Meisner, Kirkpatrick et al. (2020)

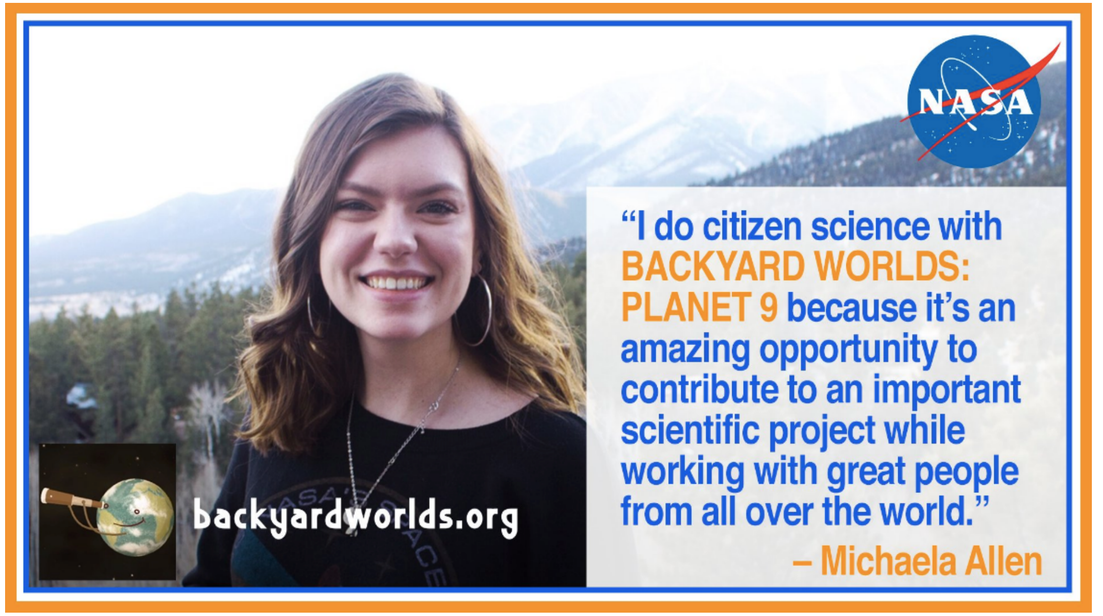
deepest all-sky mid-infrared tracklets & light curves
- the unTimely Catalog

Meisner+ 2023

all of these have been publicly released

Backyard Worlds: crowdsourcing the visual search for cold brown dwarfs

- launched in 2017 February via Zooniverse, NASA & NSF funded
- volunteers look at unWISE time-series blinks
- over 8 million “classifications”
  - equivalent to staring at the entire sky ~6x
- more than 77,000 registered users
- participants from all 50 US states plus DC, Puerto Rico and 167 countries
- ~200,000 unique volunteer contributors



- ~3,900 motion-confirmed LTY dwarf candidates discovered so far
  - Roughly 1.75 LTY discoveries (on average) per day!

who are the Backyard Worlds citizen scientists?

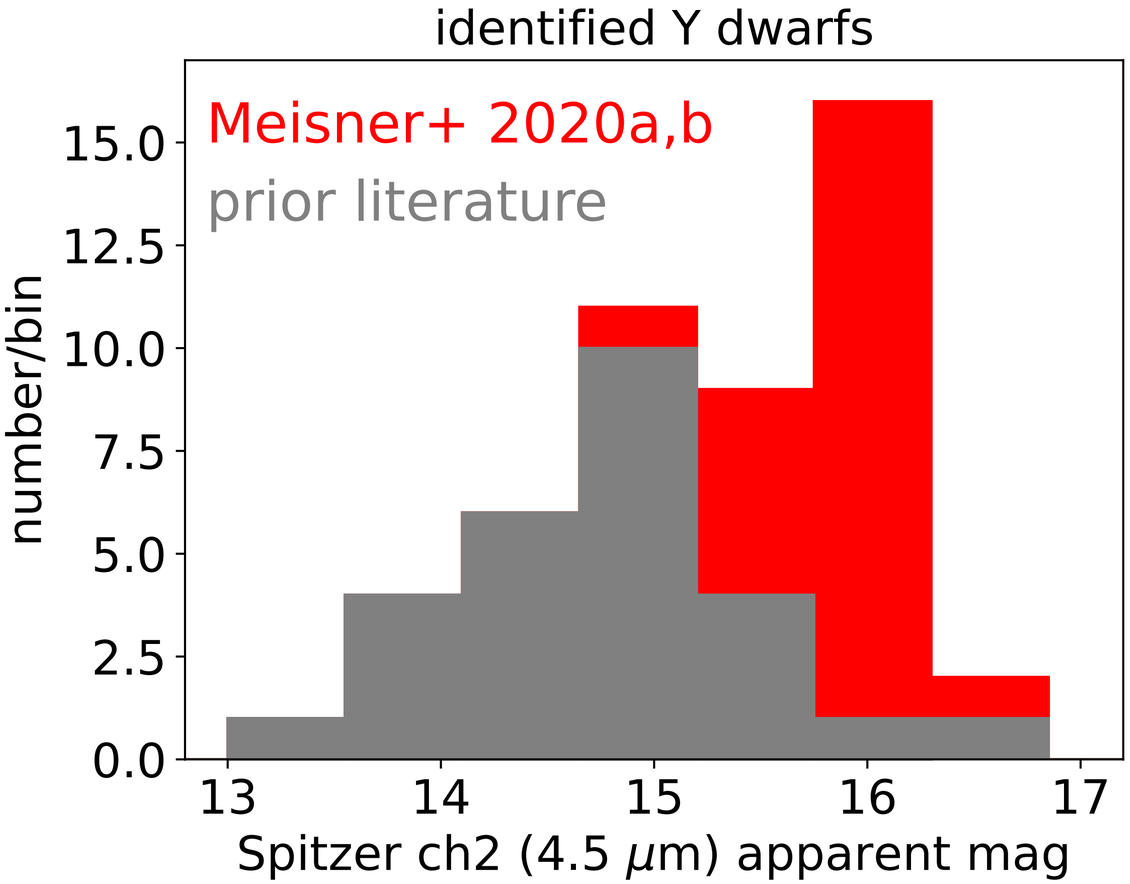
who are the Backyard Worlds citizen scientists?

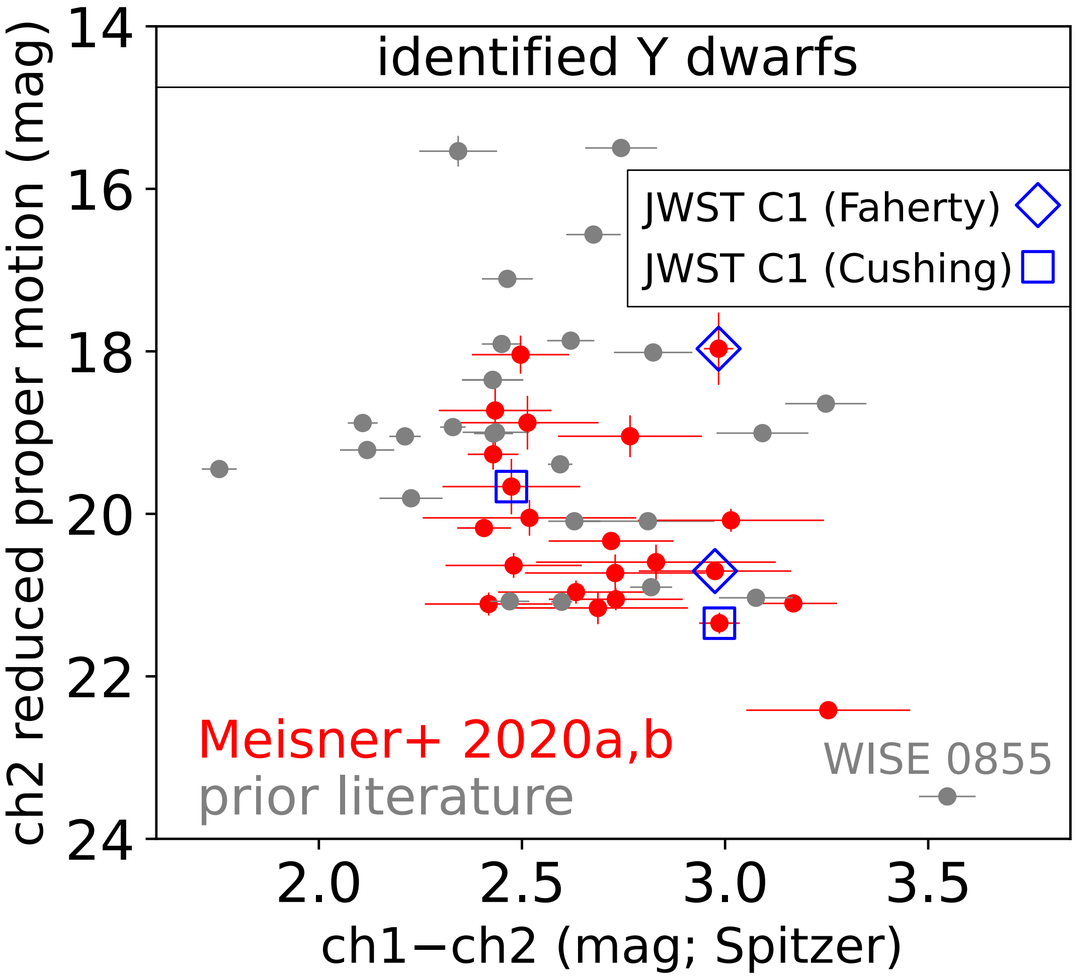
Backyard Worlds: crowdsourcing the visual search for cold brown dwarfs

- Backyard Worlds: Cool Neighbors (PI: Meisner) is a NOIRLab-led, NASA-funded spinoff of the original Backyard Worlds: Planet 9 project
- Launching soon on Zooniverse!
- Project built by NOIRLab summer ’22 undergrad interns Noah Schapera (Emory U.) and Austin Humphreys (UMD)
- Cool Neighbors uses machine learning to preselect extreme (cold, old) brown dwarf candidates, whereas Backyard Worlds: Planet 9 shows random sky patches

COOL NEIGHBORS
CITIZEN SCIENCE PROJECT

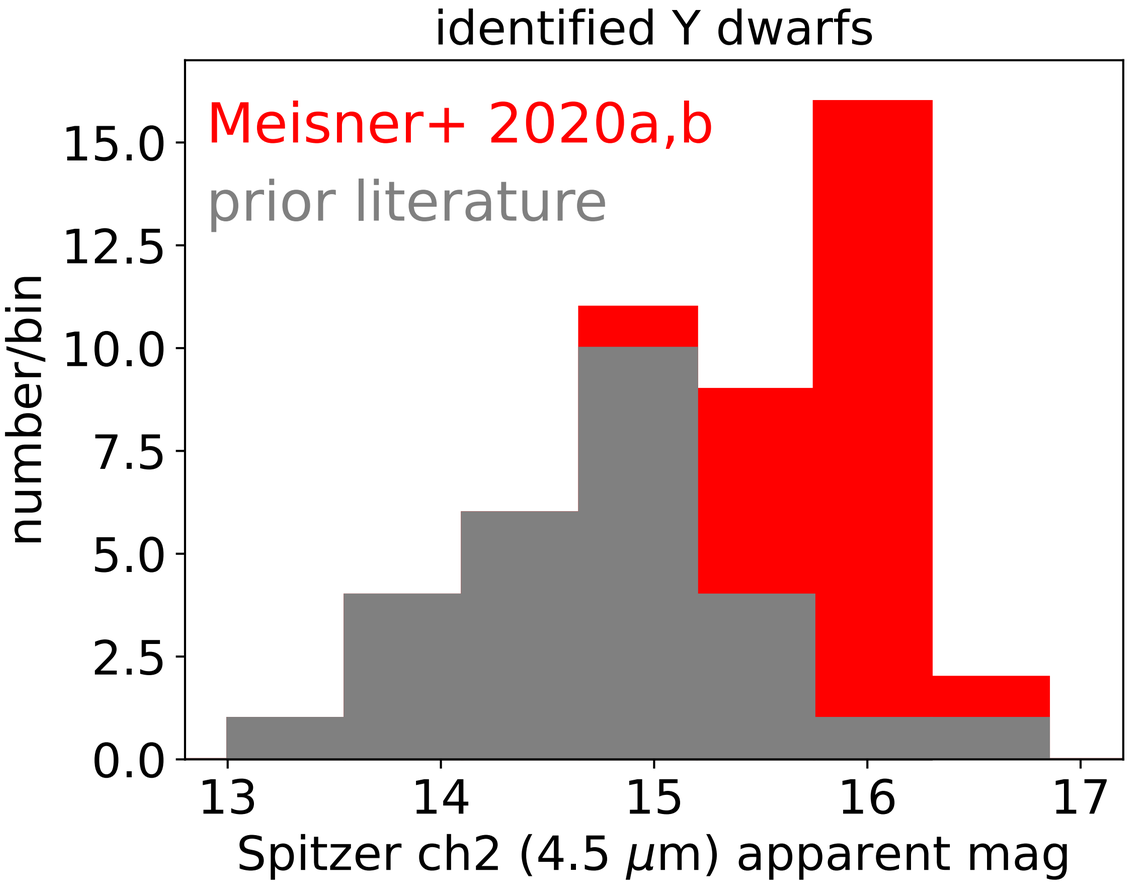
filling in the Y dwarf census

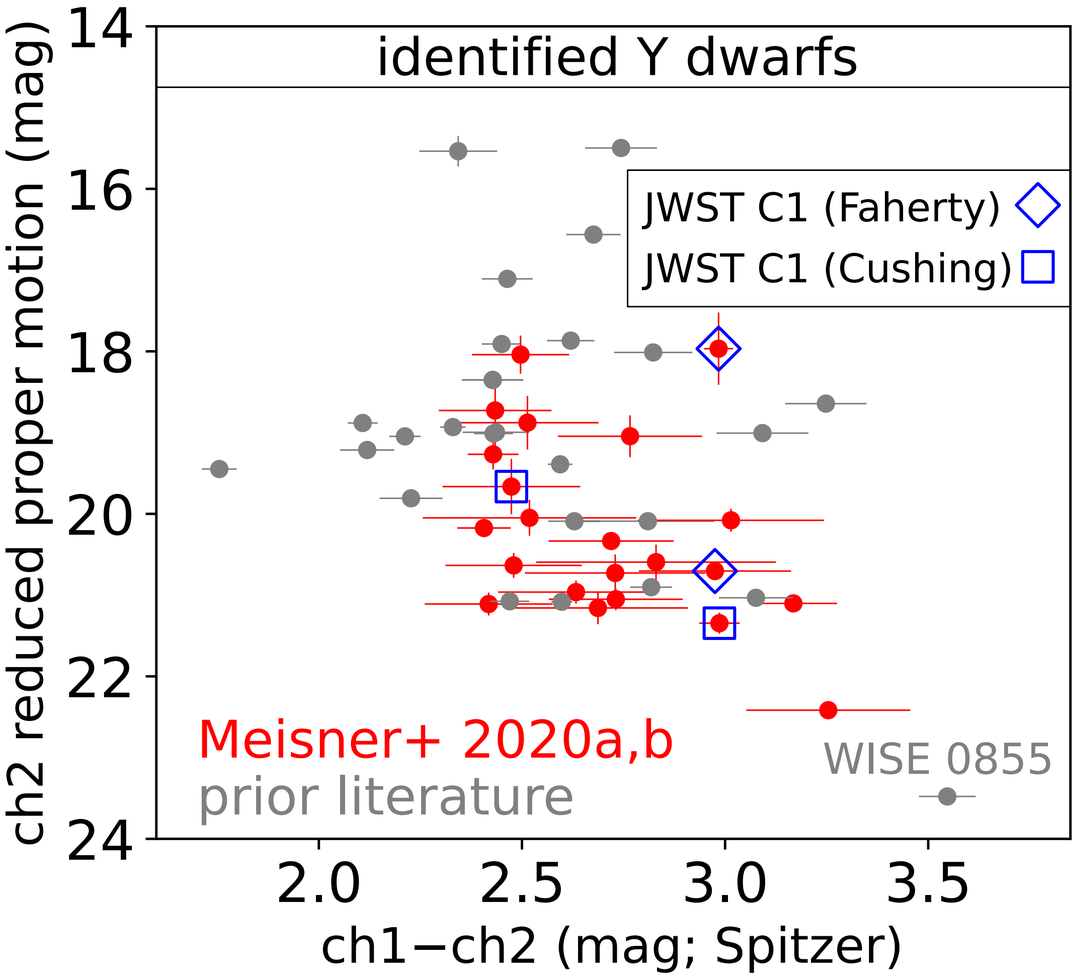




CatWISE & Backyard worlds have begun bridging the gap to WISE 0855, which still stands apart

filling in the Y dwarf census

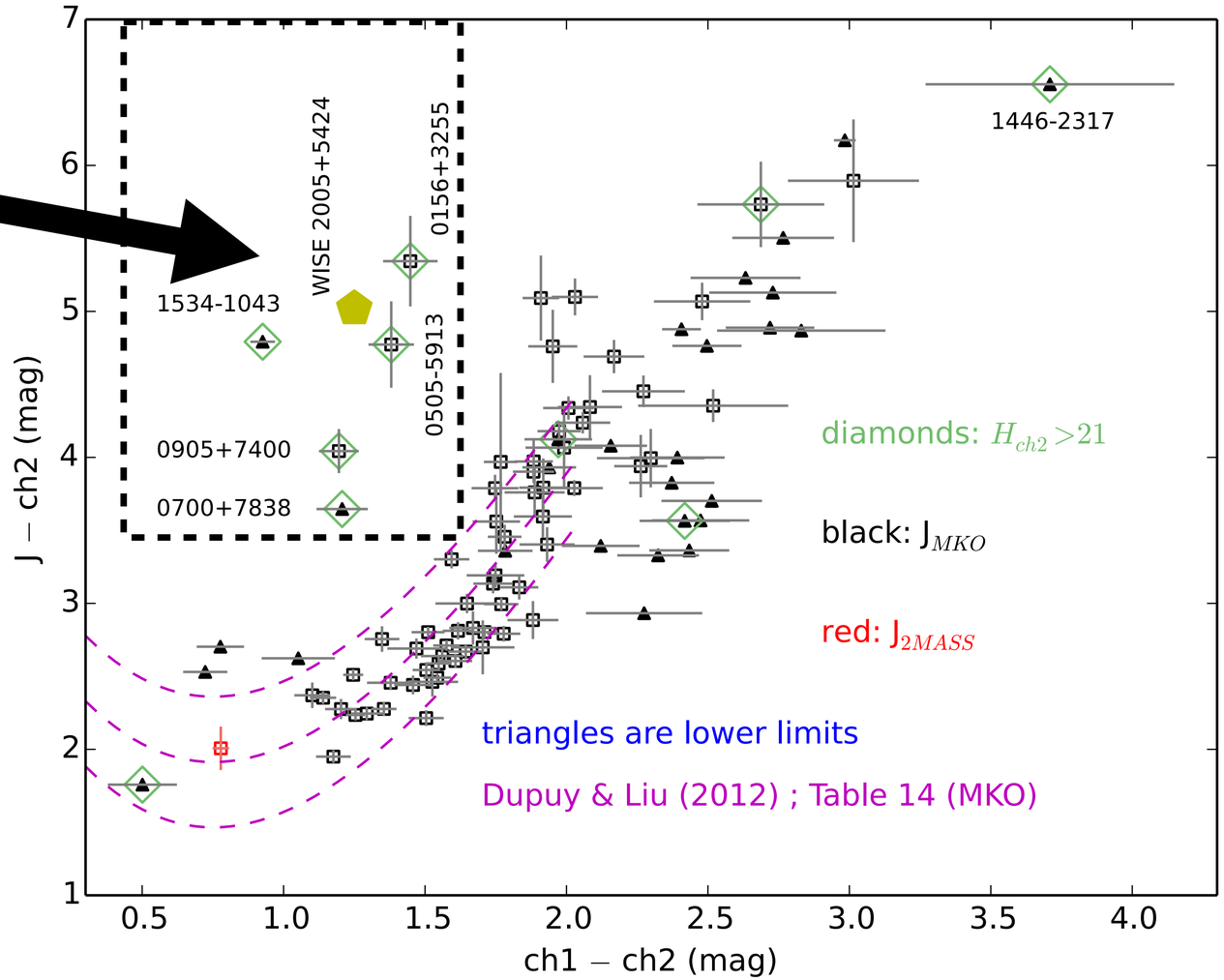




CatWISE & Backyard worlds combined have ~doubled the sample of identified Y dwarfs

Spitzer follow-up of CatWISE-selected Y dwarf candidates (PI: Meisner)

old & cold

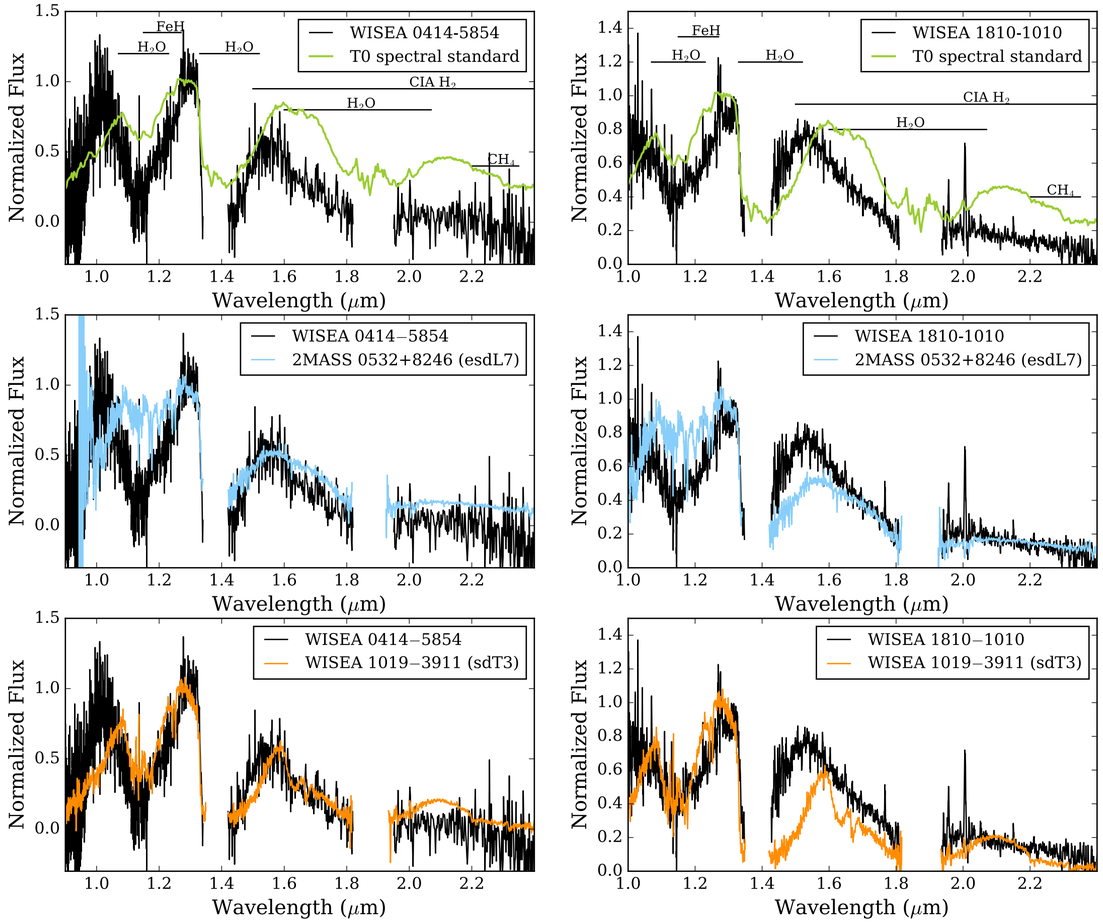


Meisner+ 2020a

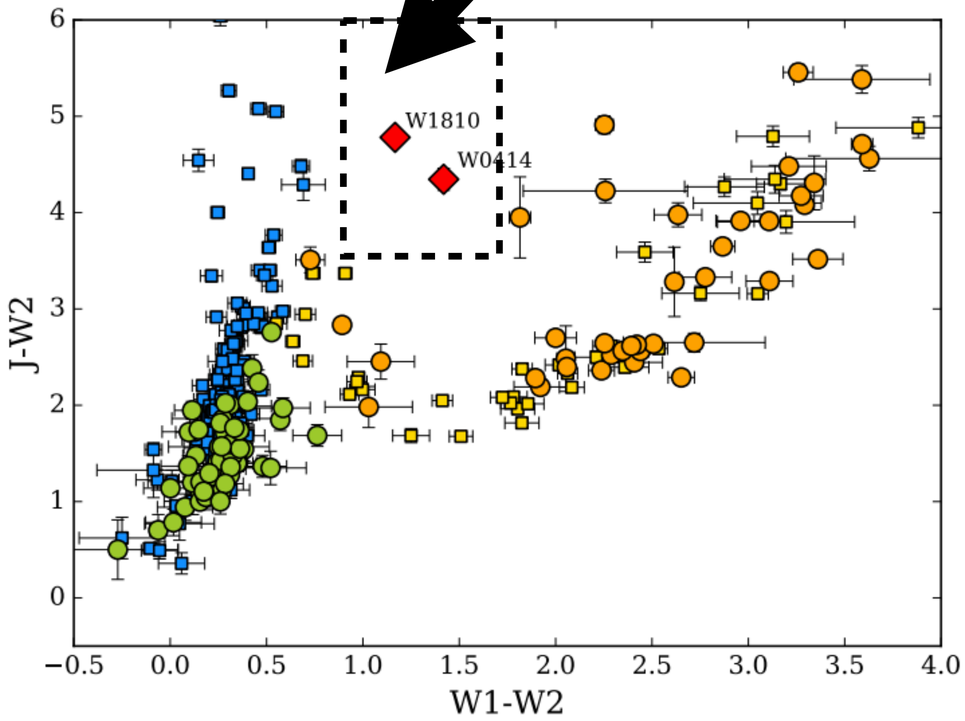
we initially thought that we were targeting the upper right portion of this plot, but it turns out the upper left has been more interesting

the first extreme T-type subdwarfs?

“esdTs”: T_{eff} < 1400 K, [m/H] <= -1



old & cold



(candidate) esdTs don’t match any standards

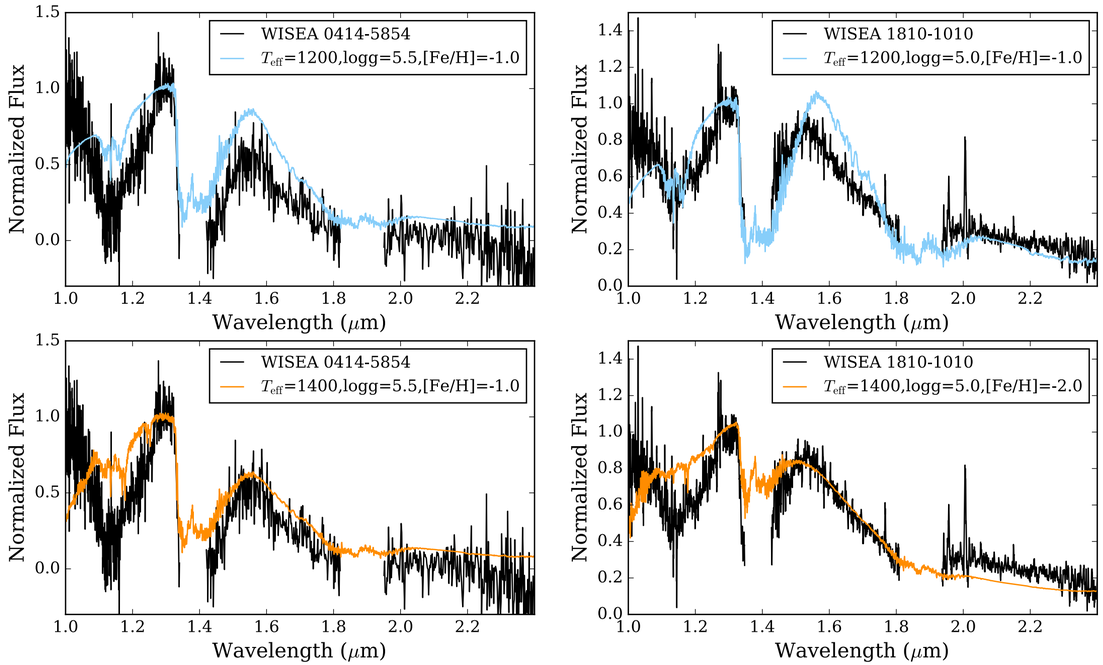
sd : [m/H] ~ -0.5 dex, esd: [m/H] ~ -1 dex, usd: [m/H] ~ -1.5 dex

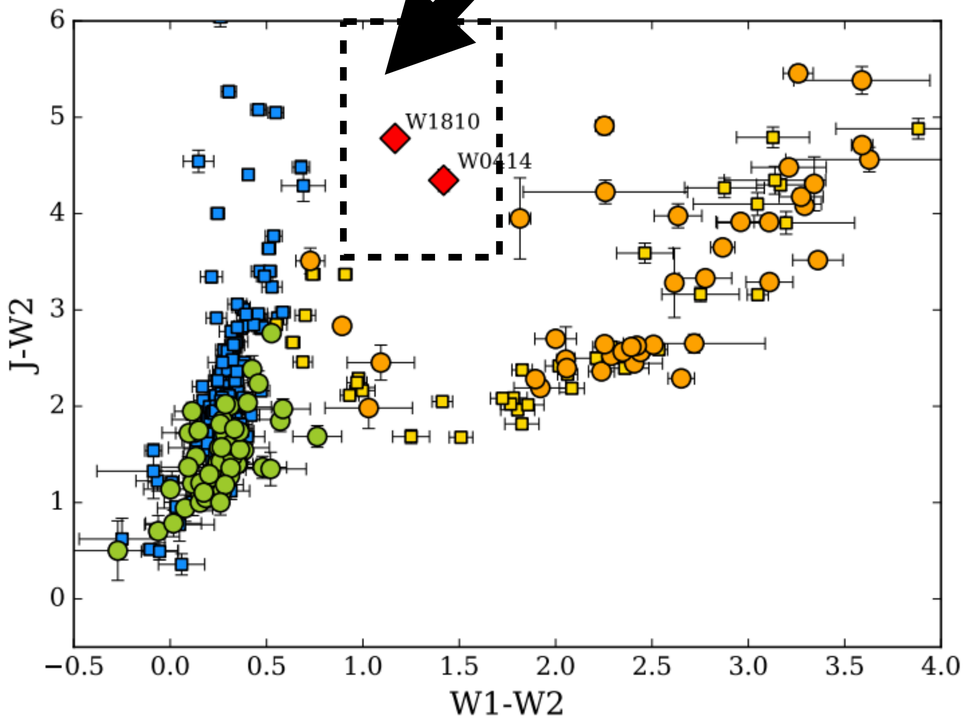
Schneider+ 2020

the first extreme T-type subdwarfs?

“esdTs”: T_{eff} < 1400 K, [m/H] <= -1

old & cold



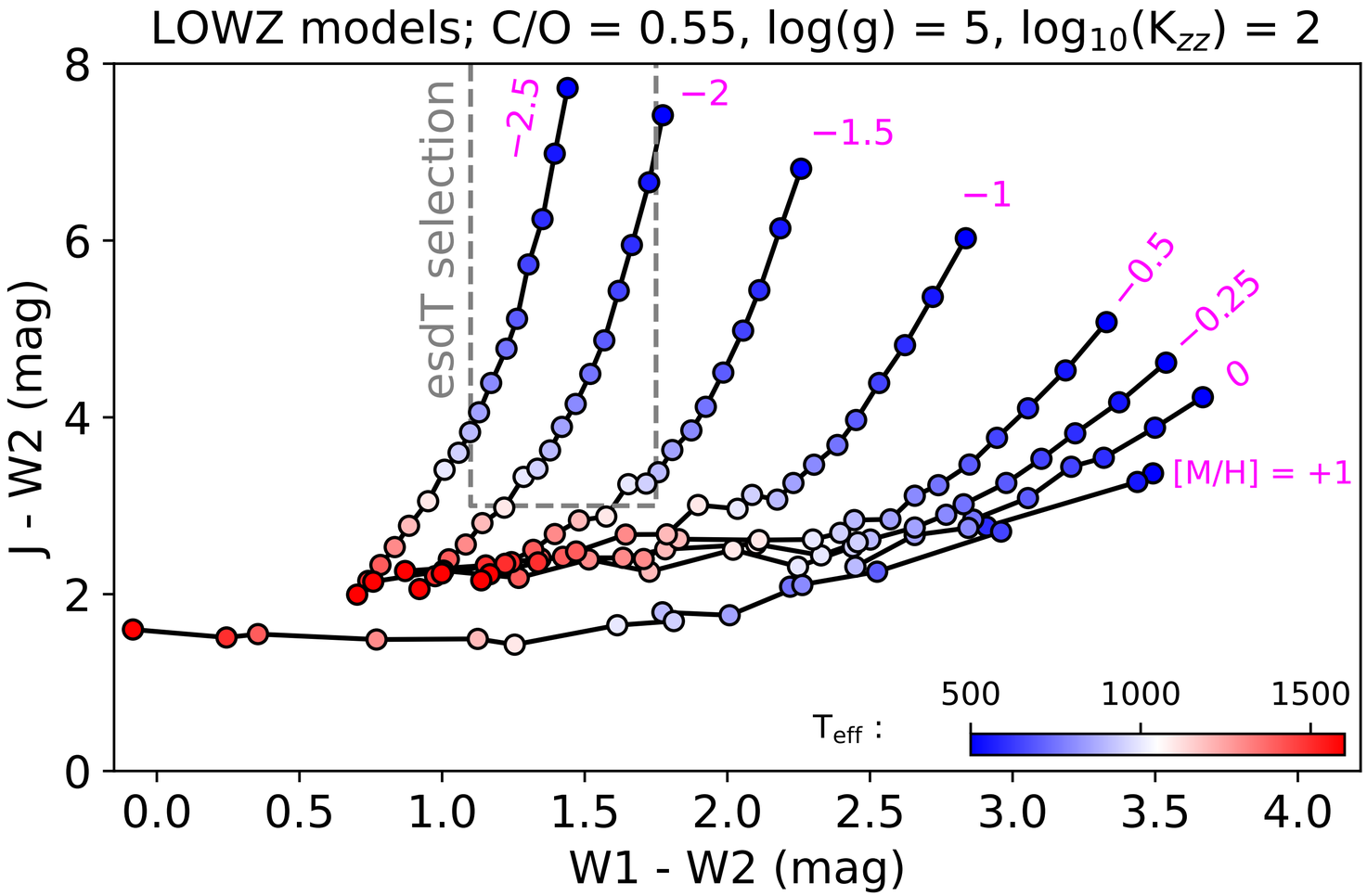


(candidate) esdTs also don’t match any models

sd : [m/H] ~ -0.5 dex, esd: [m/H] ~ -1 dex, usd: [m/H] ~ -1.5 dex

Schneider+ 2020

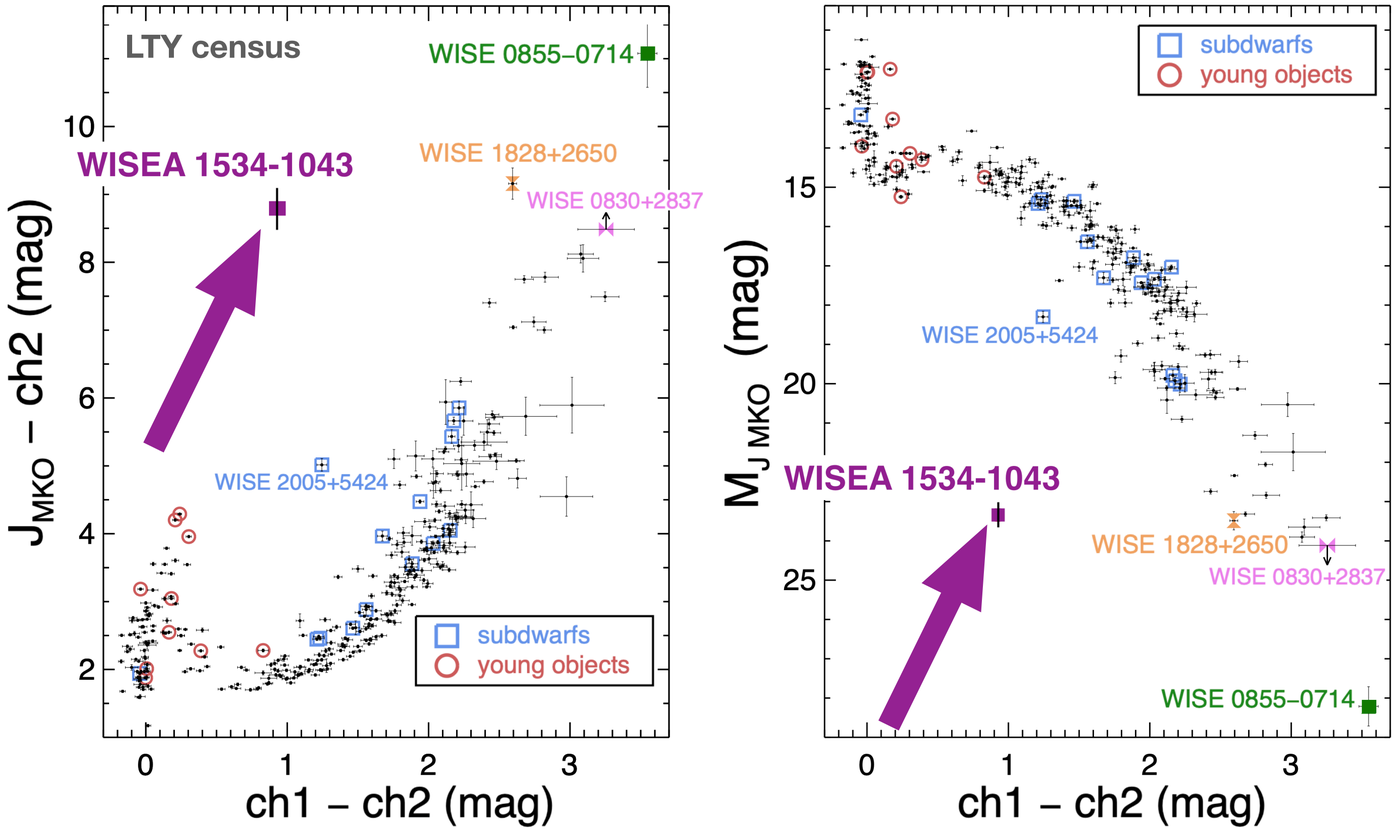
models agree that such color outliers could be cold, low-metallicity objects

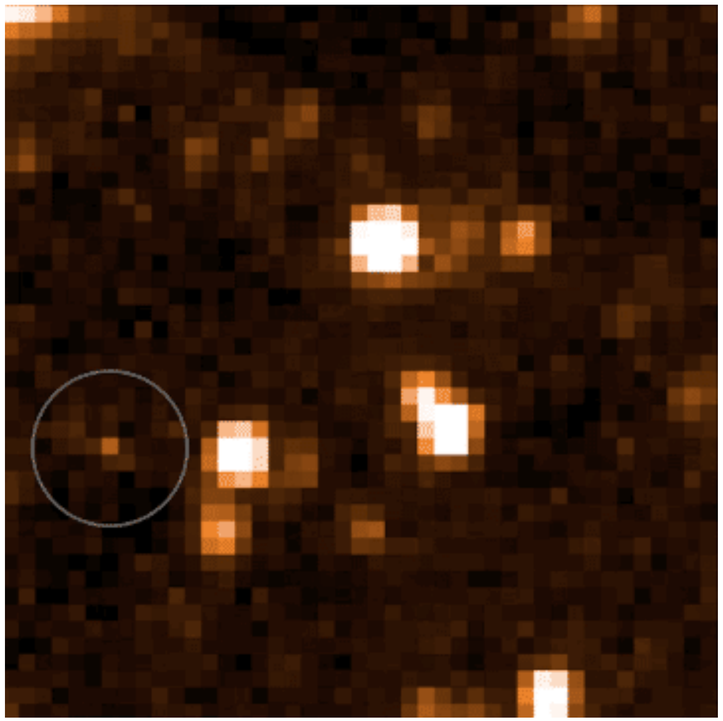


Meisner+ 2021

WISE 1534-1043 a.k.a. “The Accident”

- Discovered accidentally by Backyard Worlds citizen scientist Dan Caselden — in a quadrant all its own!



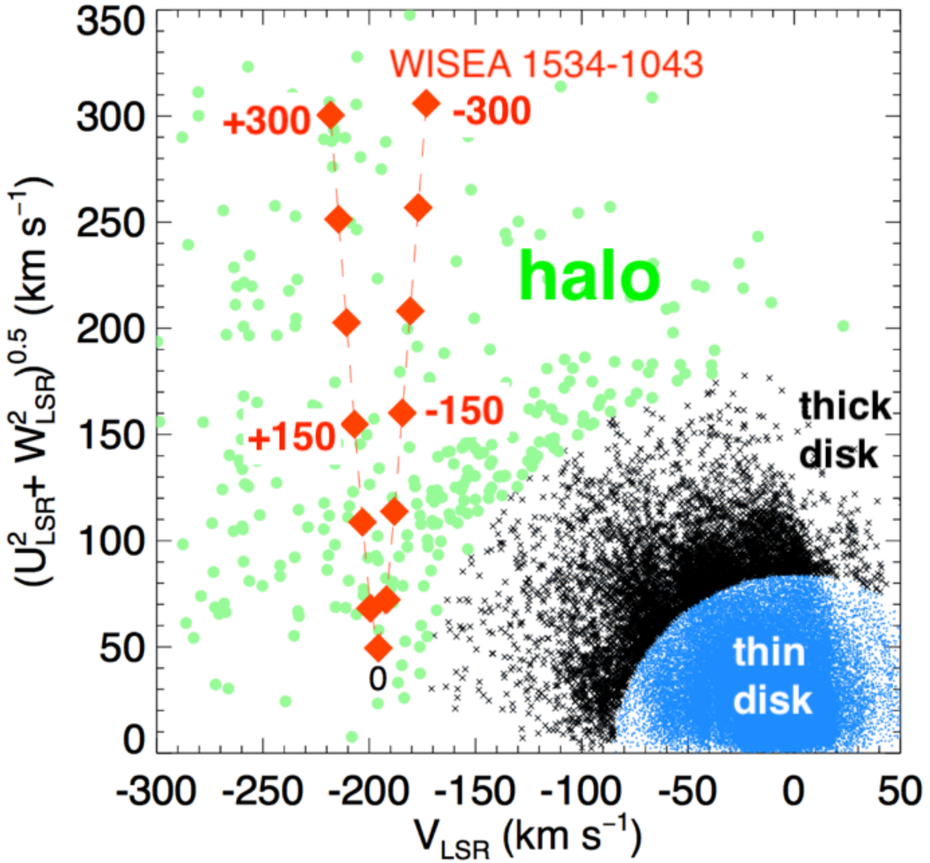


the first Y-type subdwarf? (sdY)

Dan Caselden was up late on November 3, 2018, playing the video game Counter-Strike, when he made astronomy history. Every time he died, he would jump on his laptop to check in on an automated search he was running of NASA space telescope images... *-Quanta Magazine*

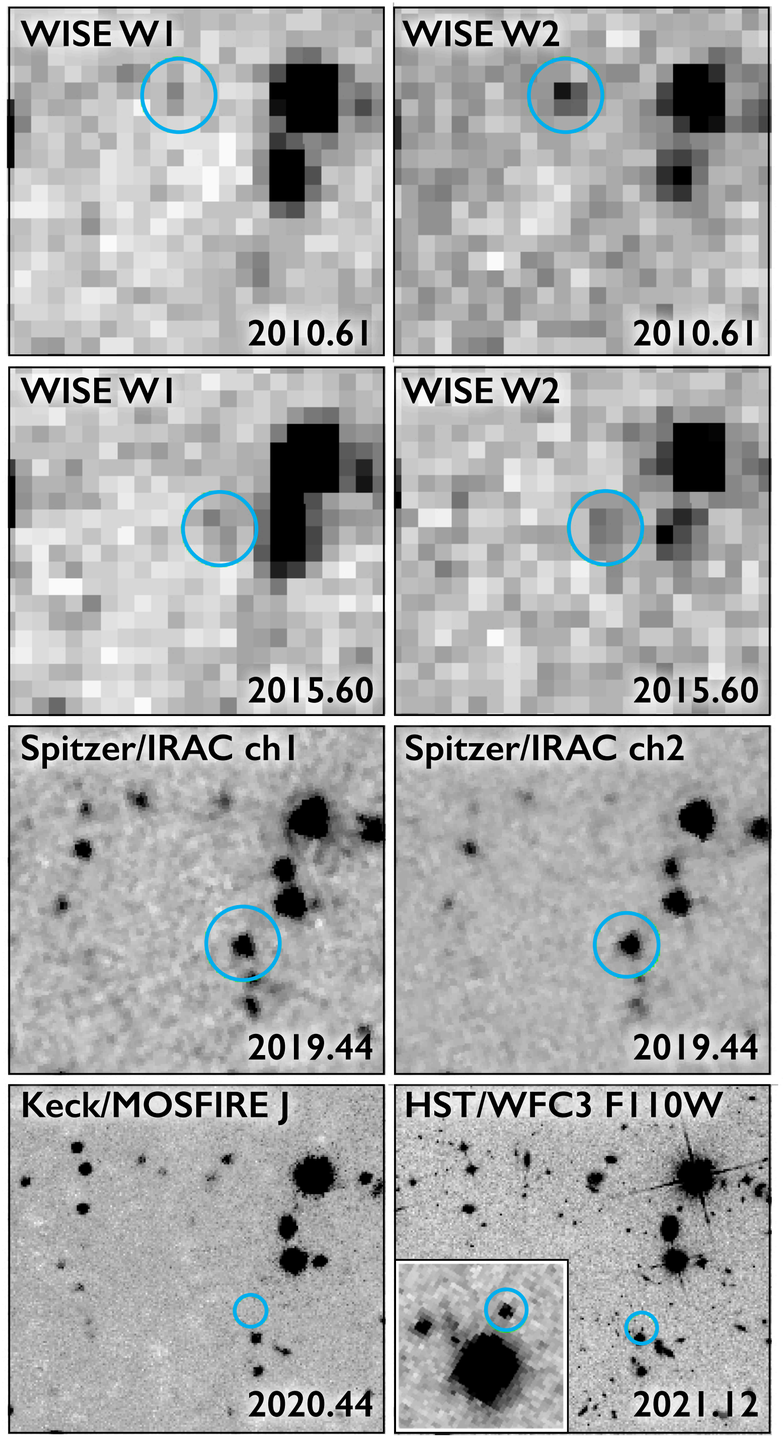
Meisner+ 2020; Kirkpatrick+ 2021

The Accident: definitely a halo brown dwarf



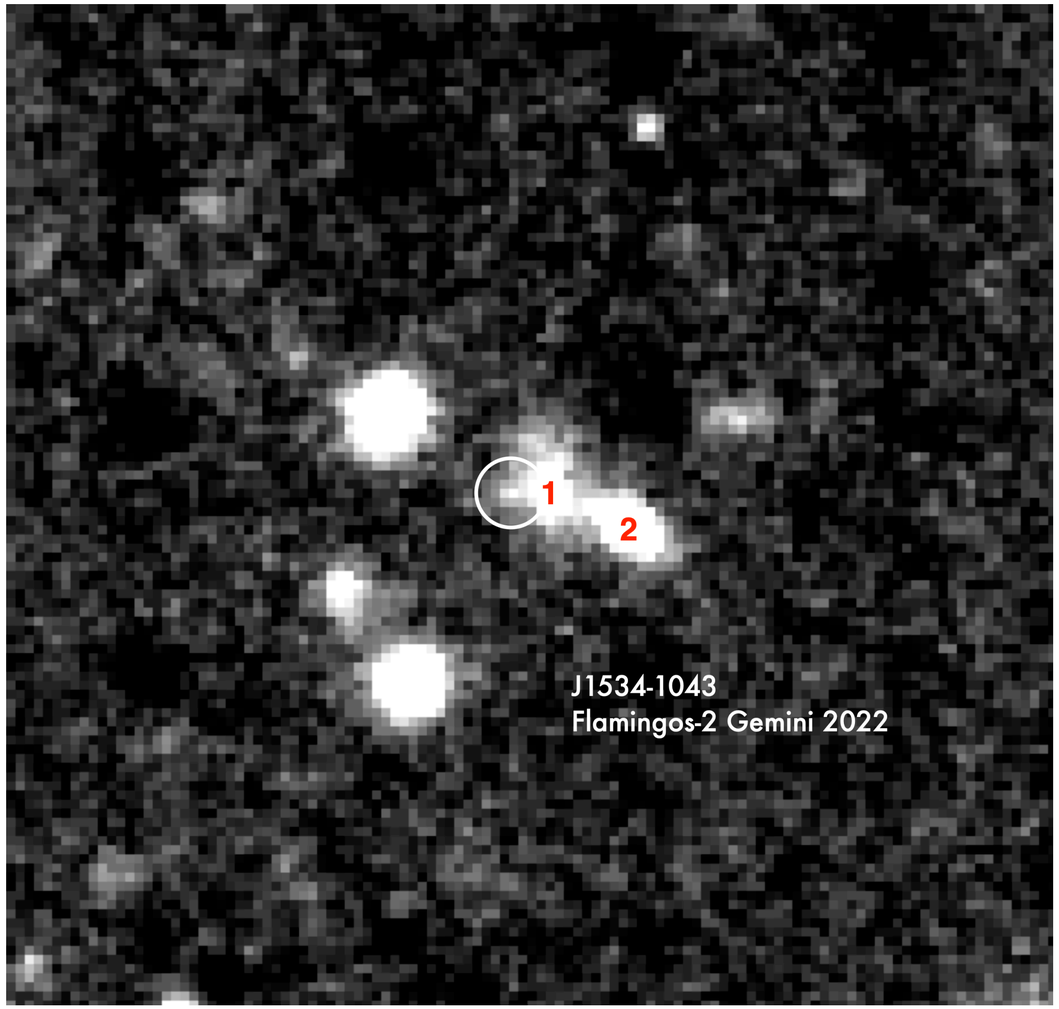
Toomre diagram
red numbers are possible tangential velocities in km/s

- WISE+Spitzer+HST parallax gives distance of 16 pc
- tangential velocity > 200 km/s !
- only two of the esdT candidates have parallaxes —other is WISE 1810-10 at ~9 pc

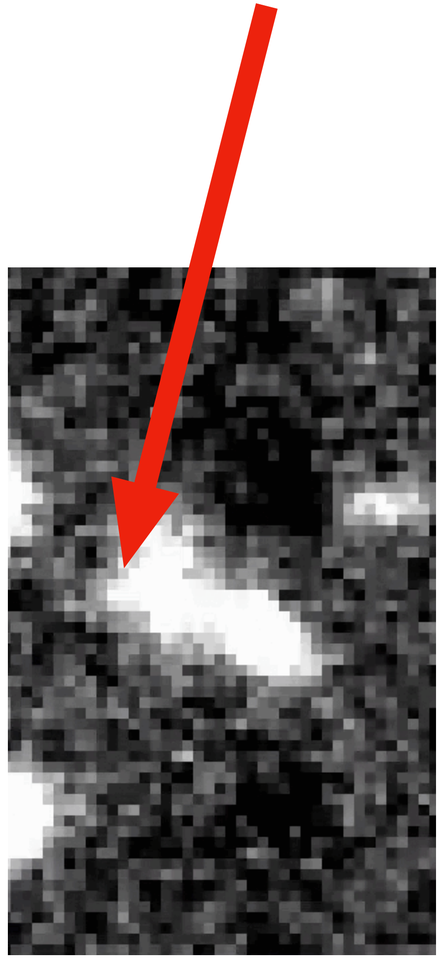


The Accident: Gemini/Flamingos-2

PI: Leggett, 6.43 hours on-source



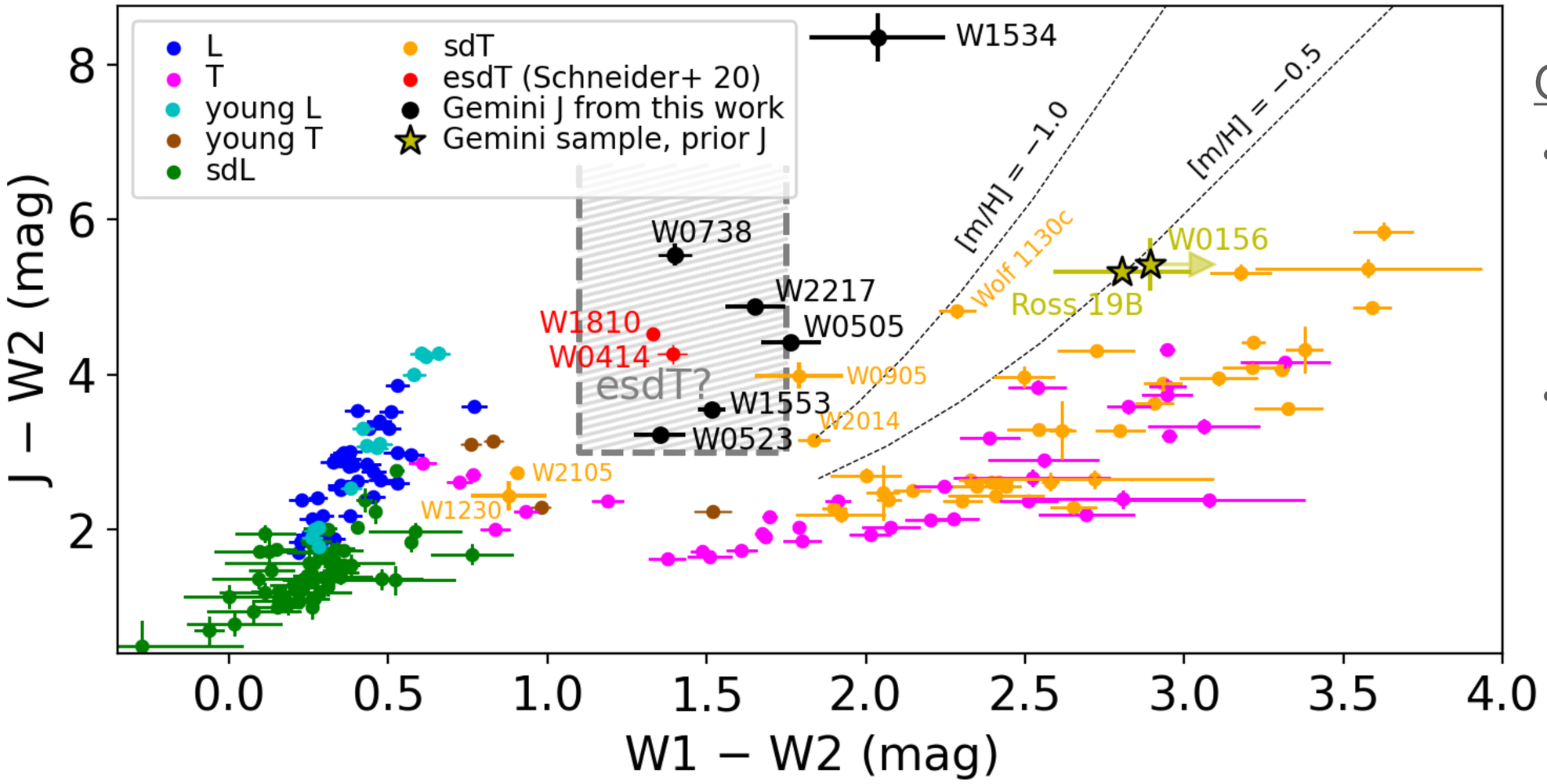
J = 24.5 Vega !!



galaxy subtraction with 2-D Gaussian models

“1” and “2” are resolved background galaxies

latest/greatest color-color plot
all black points thanks to Gemini! (PI: Leggett)



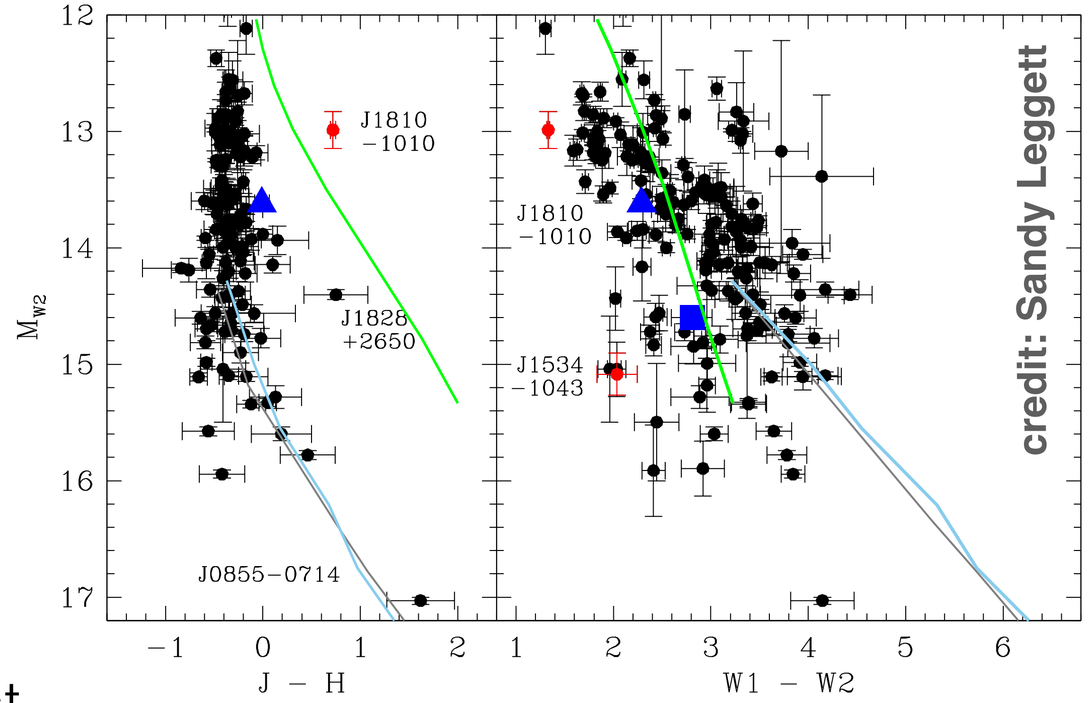
Gemini Observations

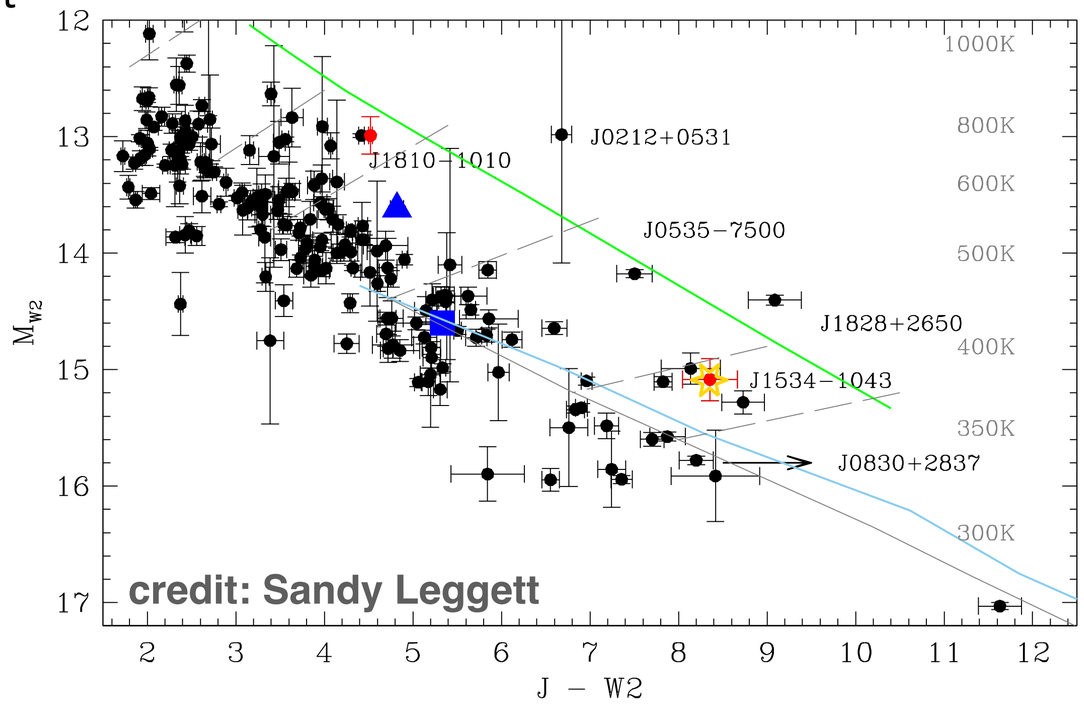
- Gemini-N/GNIRS
  - YJHK
  - 1.9 hr on-source
  - GN-2022A-Q-326
  - PI: Leggett
- Gemini-S/Flamingos-2
  - JHKs
  - 7.2 hr on-source
  - GS-2022A-Q-246
  - PI: Leggett

Meisner, Leggett et al. (2023)

The Accident: temperature & metallicity

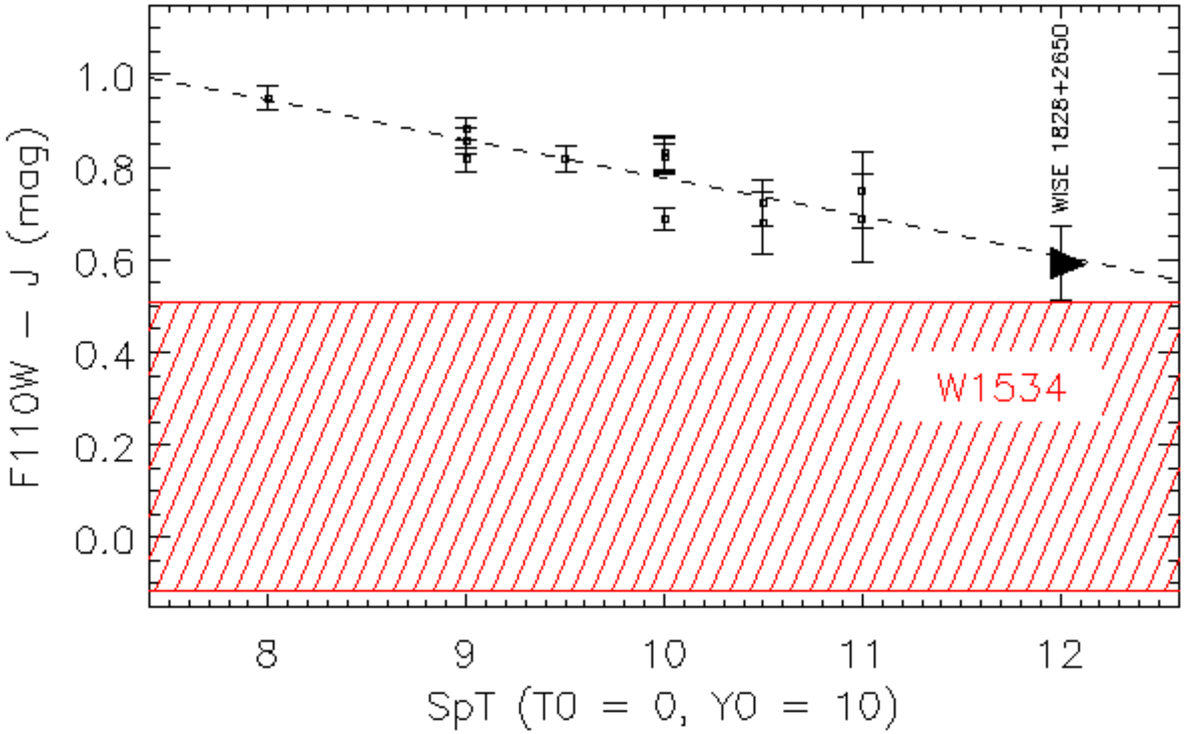
- color versus absolute mag (bottom panel) suggests Teff ~ 400 K
- our Gemini-based color-color plots suggest Teff could be as high as ~550 K
- color versus absolute mag and color-color diagnostics incorporating our Gemini J-band detection all suggest a subsolar metallicity ≤ -0.5 dex.

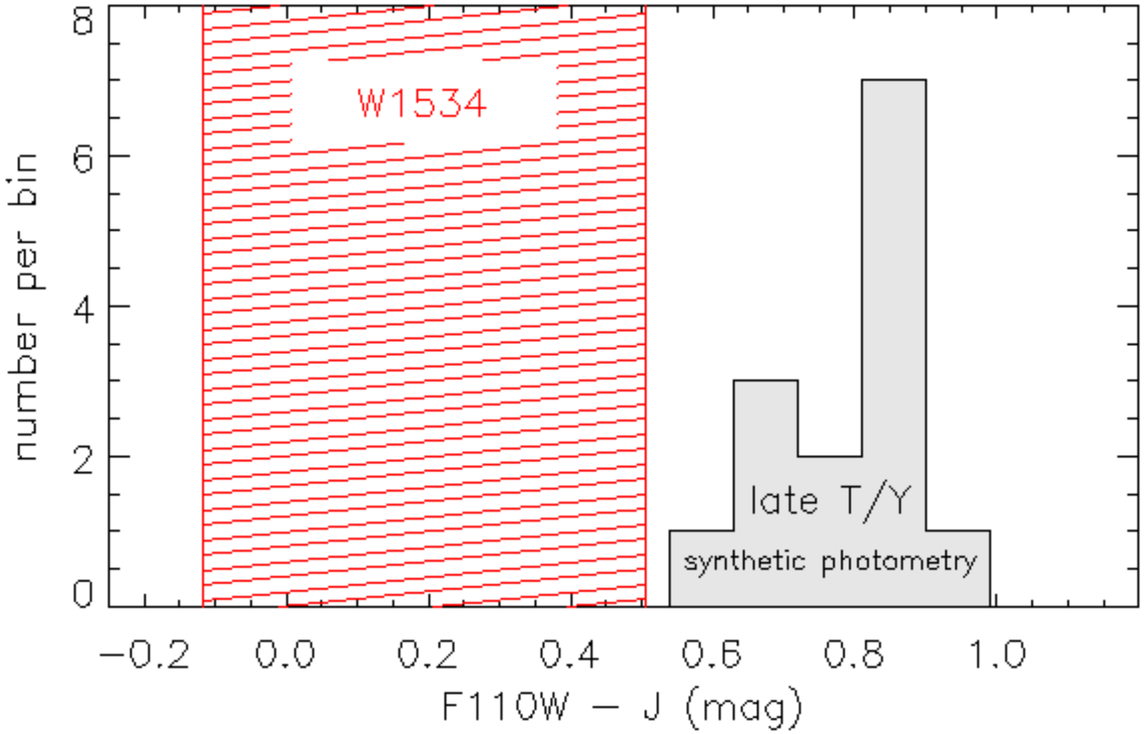




Meisner, Leggett et al. (2023)

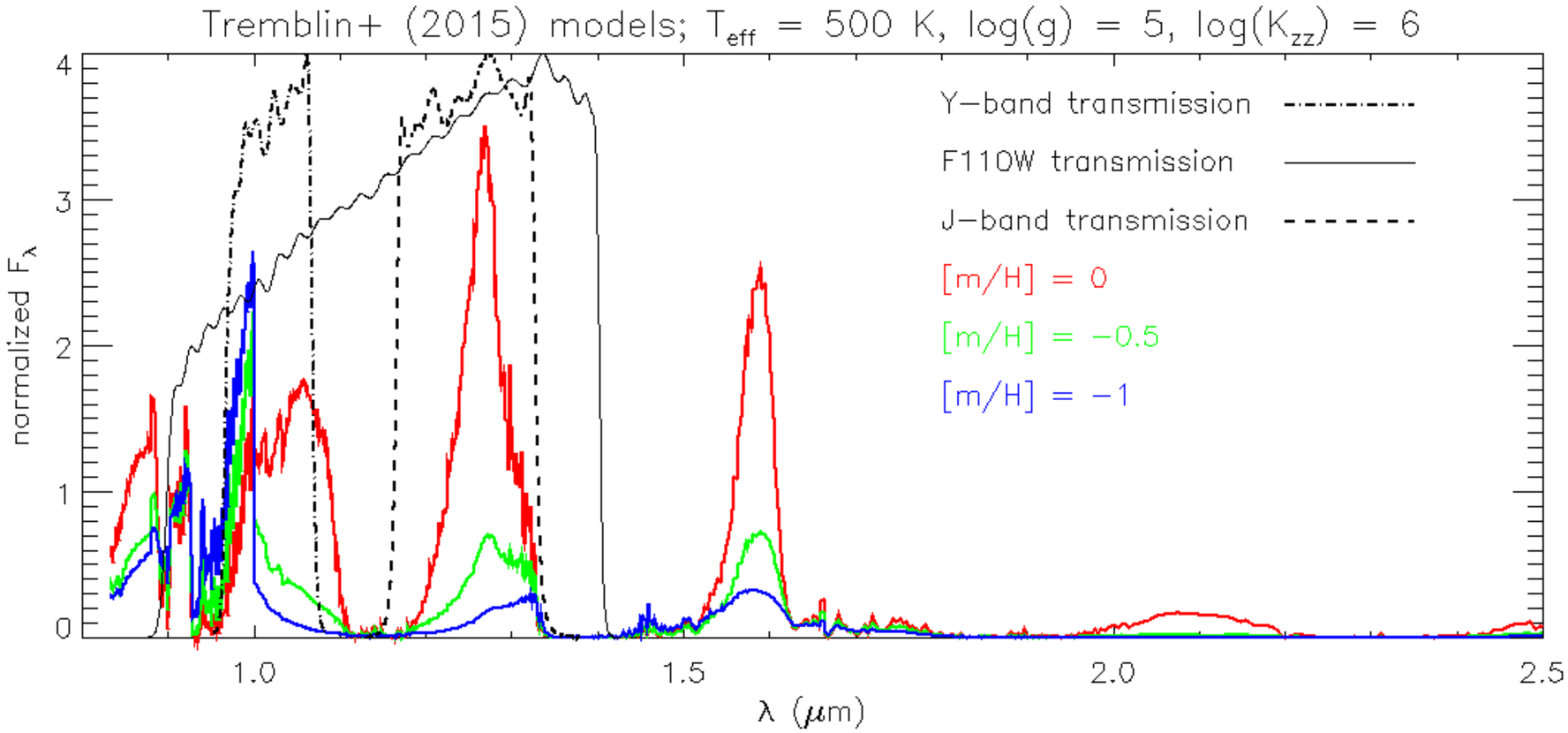
The Accident has a highly anomalous F110W-J color





Meisner, Leggett et al. (2023)

atmospheric models agree that low metallicity can produce blue F110W-J color

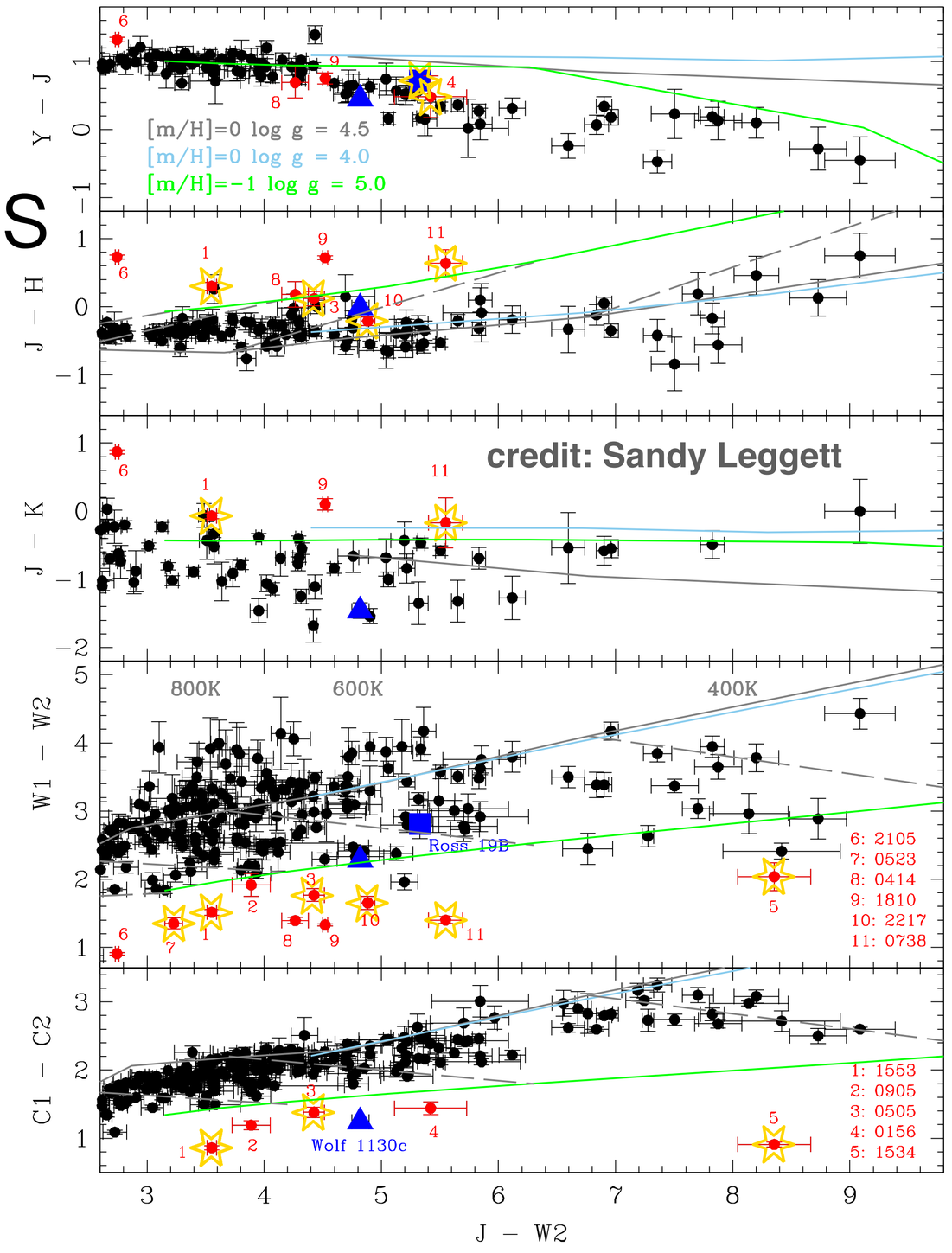


Tremblin+ 2015 low-temperature, low-metallicity atmospheric models

Meisner, Leggett et al. (2023)

color-color diagrams illustrating our Gemini results

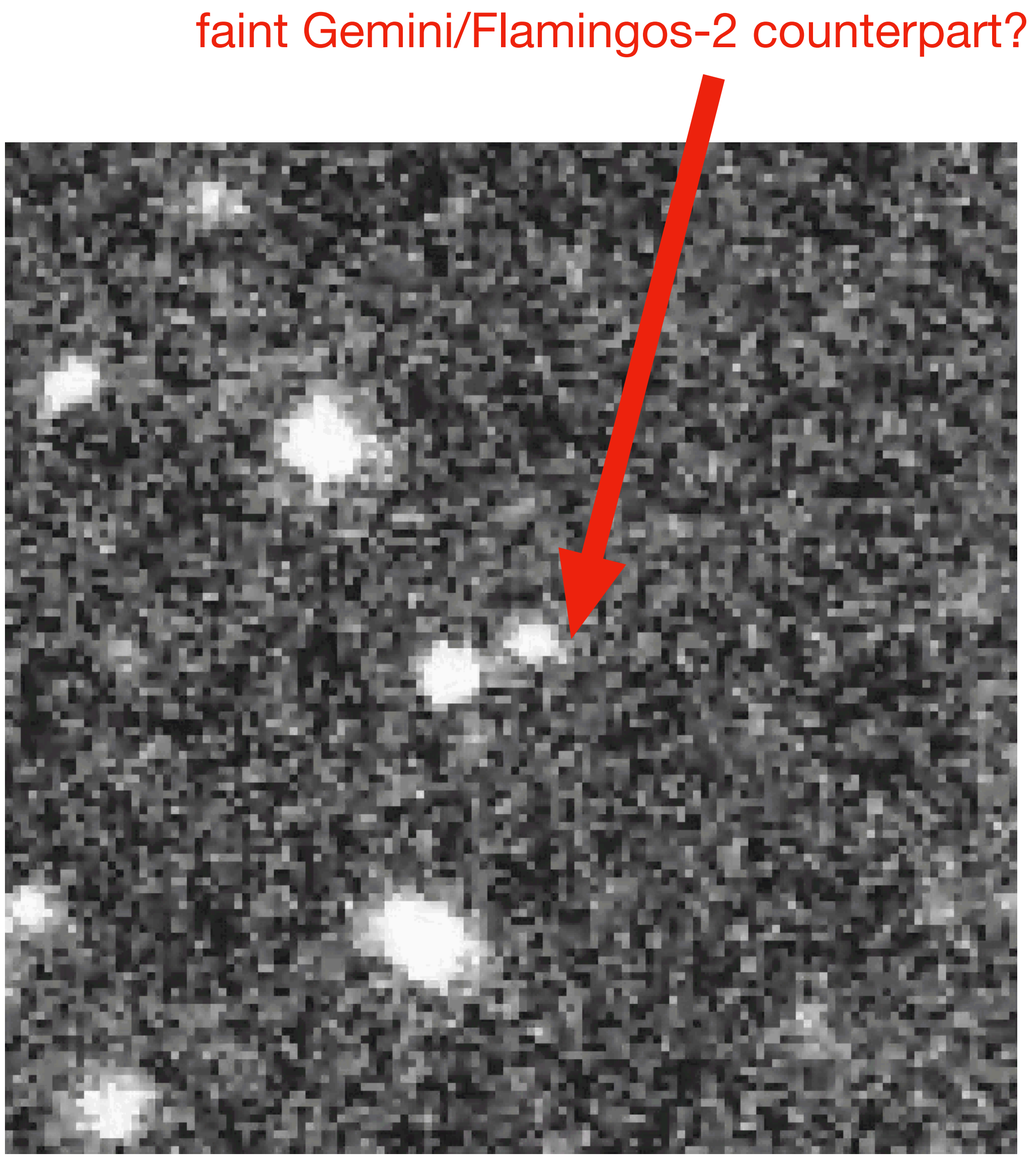
- Y-J does not appear to separate old/cold objects (red and blue points) from the bulk of the brown dwarf population (black), except perhaps at the very coolest temperatures where we currently lack data.
- J-H excess appears to be a relatively consistent and robust indicator of low metallicity.
- J-K is perhaps a mixed bag — not clear whether there is consistently a J-K excess for cold, metal-poor objects



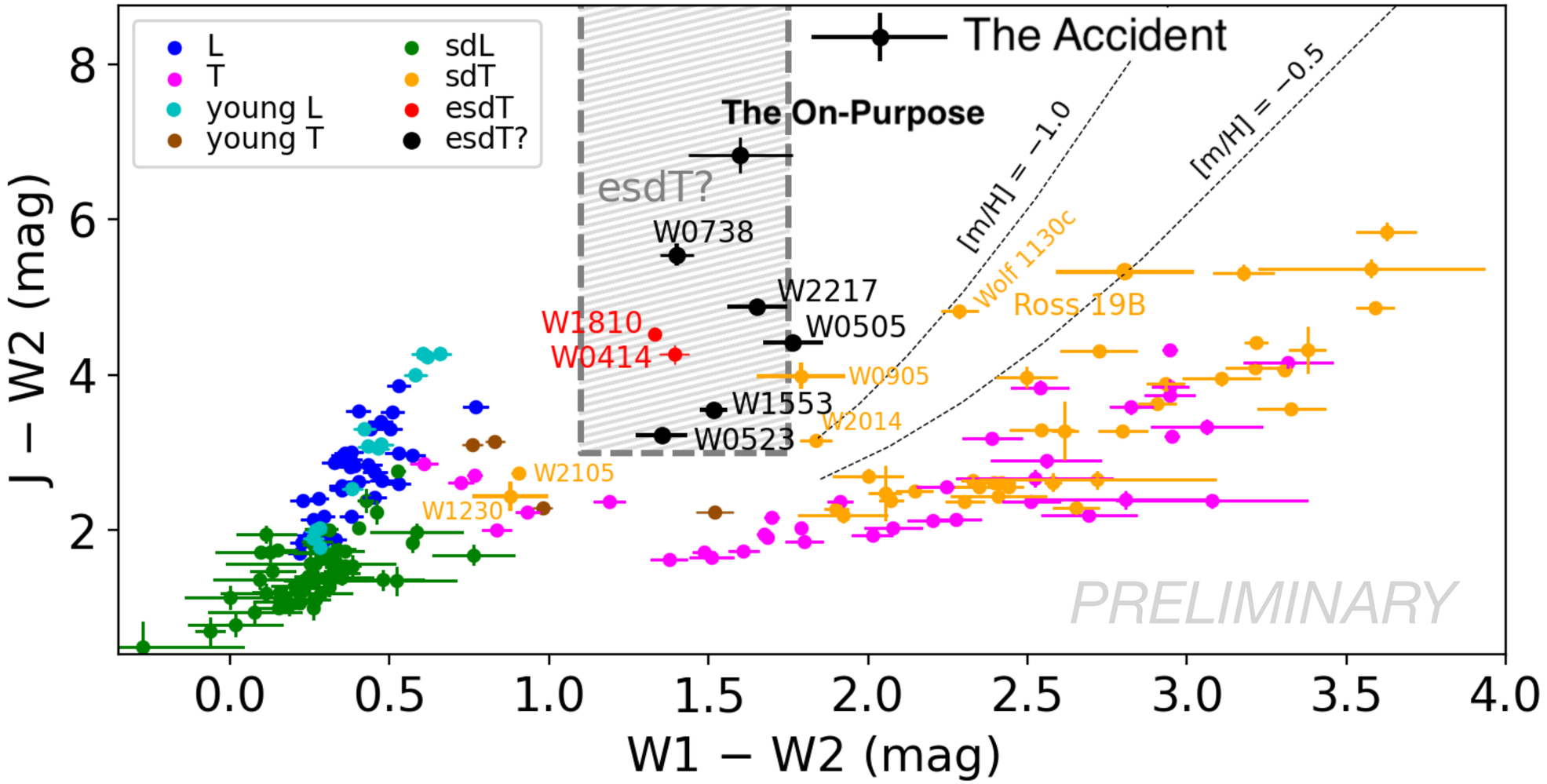
Meisner, Leggett et al. (2023)

“The On-Purpose”

- Discovered (and named) by citizen scientist Dan Caselden circa 2022 November, using pixel-level deep learning as applied to the time-resolved unWISE coadds.
- Single best analog to The Accident discovered via Dan’s dedicated full-sky search.
- Initial deep J-band imaging follow-up performed with Gemini/Flamingos-2 Fast Turnaround observations — awesome experience as an FT PI!
- Likely need another Gemini/Flamingos-2 J-band epoch to confirm (via motion) that we’ve identified the correct counterpart.



“The On-Purpose”



deep Gemini/Flamingos-2 follow-up imaging made it possible to place both The Accident and The On-Purpose on this plot!

perhaps we’re making progress toward a robust sequence of halo brown dwarfs?

next steps

- Of course we'd very much like to get JWST spectroscopy for some old/cold brown dwarfs.
- NEO Surveyor — WISE-like successor that will be deeper in the mid-infrared but same resolution.
- Continued Gemini imaging follow-up of old/cold sample e.g., filling in H and K band.
- Gemini spectroscopy of old/cold brown dwarfs prioritized based on our Gemini photometry.
- Calendar 2022 NEOWISE data release expected next week — another year, another 35 TB !
- Interested in forming more collaborations with Gemini/NOIRLab staff.
- More/different unWISE all-sky data products — let me know if any feedback.

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