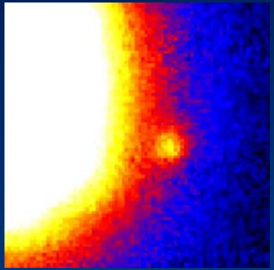
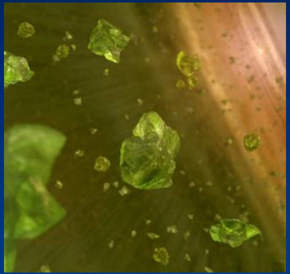
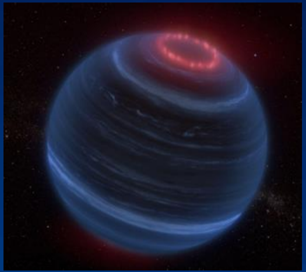
LOOKING BACK AT THE LAST 30 YEARS OF BROWN DWARF RESEARCH AND LOOKING FORWARD TO OPPORTUNITIES AHEAD


1995-2000


2001-2006


2007-2012


2013-2018


2019-2024

J. Davy Kirkpatrick
(IPAC/Caltech)

Retrospective of brown dwarf discoveries

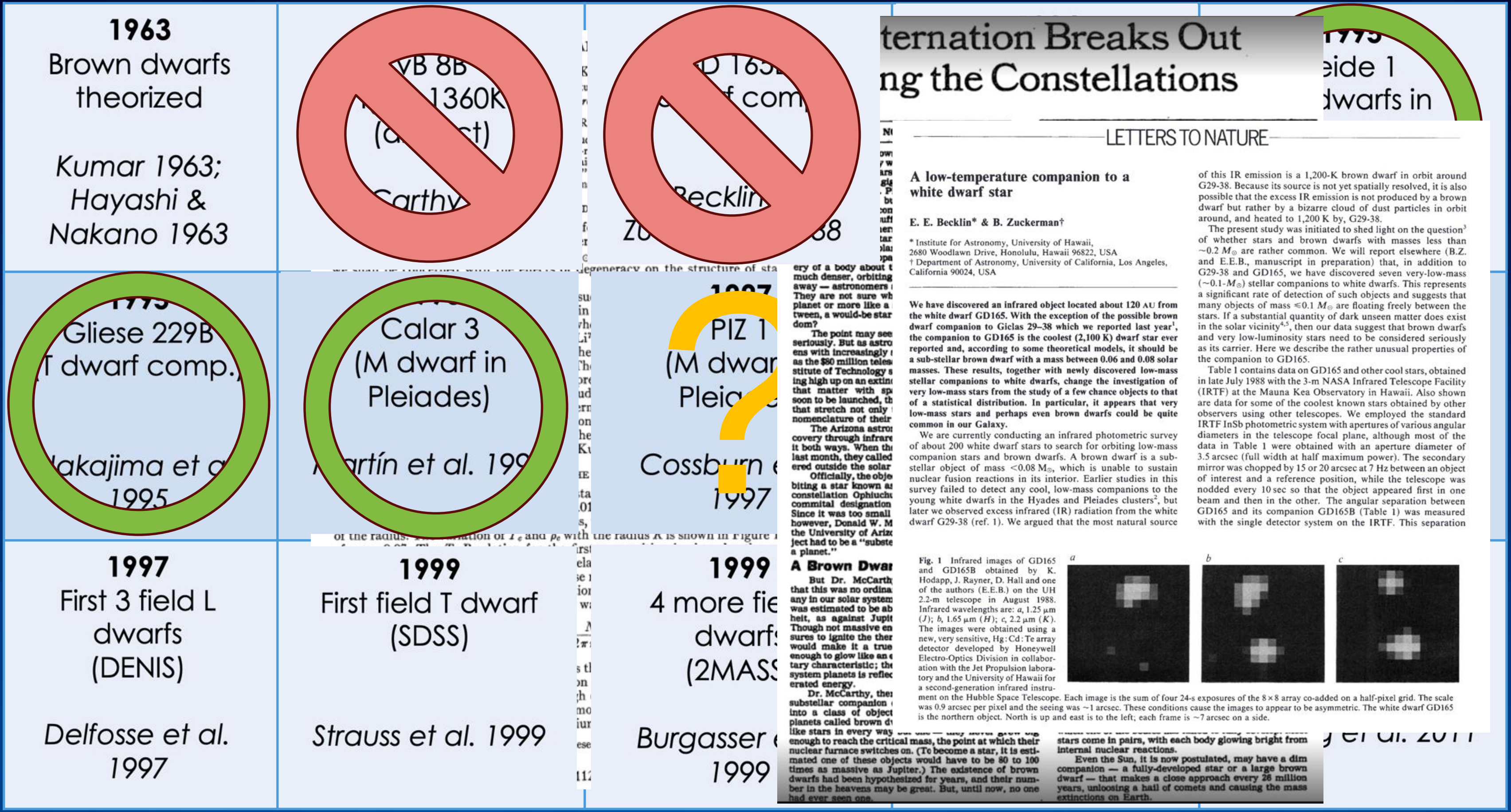
Recent surveys

Current understanding of properties/formation

Major outstanding questions

#8

Do brown dwarfs exist?



LETTERS TO NATURE

A low-temperature companion to a white dwarf star

E. E. Becklin* & B. Zuckerman†

* Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, Hawaii 96822, USA
† Department of Astronomy, University of California, Los Angeles, California 90024, USA

We have discovered an infrared object located about 120 AU from the white dwarf GD165. With the exception of the possible brown dwarf companion to Giclas 29–38 which we reported last year[1], the companion to GD165 is the coolest (2,100 K) dwarf star ever reported and, according to some theoretical models, it should be a sub-stellar brown dwarf with a mass between 0.06 and 0.08 solar masses. These results, together with newly discovered low-mass stellar companions to white dwarfs, change the investigation of very low-mass stars from the study of a few chance objects to that of a statistical distribution. In particular, it appears that very low-mass stars and perhaps even brown dwarfs could be quite common in our Galaxy.

We are currently conducting an infrared photometric survey of about 200 white dwarf stars to search for orbiting low-mass companion stars and brown dwarfs. A brown dwarf is a sub-stellar object of mass $<0.08\ M_{\odot}$, which is unable to sustain nuclear fusion reactions in its interior. Earlier studies in this survey failed to detect any cool, low-mass companions to the young white dwarfs in the Hyades and Pleiades clusters[2], but later we observed excess infrared (IR) radiation from the white dwarf G29-38 (ref. 1). We argued that the most natural source of this IR emission is a 1,200-K brown dwarf in orbit around G29-38. Because its source is not yet spatially resolved, it is also possible that the excess IR emission is not produced by a brown dwarf but rather by a bizarre cloud of dust particles in orbit around, and heated to 1,200 K by, G29-38.

The present study was initiated to shed light on the question[3] of whether stars and brown dwarfs with masses less than $\sim 0.2\ M_{\odot}$ are rather common. We will report elsewhere (B.Z. and E.E.B., manuscript in preparation) that, in addition to G29-38 and GD165, we have discovered seven very-low-mass ($\sim 0.1\text{-}M_{\odot}$) stellar companions to white dwarfs. This represents a significant rate of detection of such objects and suggests that many objects of mass $\leq 0.1\ M_{\odot}$ are floating freely between the stars. If a substantial quantity of dark unseen matter does exist in the solar vicinity[4,5], then our data suggest that brown dwarfs and very low-luminosity stars need to be considered seriously as its carrier. Here we describe the rather unusual properties of the companion to GD165.

Table 1 contains data on GD165 and other cool stars, obtained in late July 1988 with the 3-m NASA Infrared Telescope Facility (IRTF) at the Mauna Kea Observatory in Hawaii. Also shown are data for some of the coolest known stars obtained by other observers using other telescopes. We employed the standard IRTF InSb photometric system with apertures of various angular diameters in the telescope focal plane, although most of the data in Table 1 were obtained with an aperture diameter of 3.5 arcsec (full width at half maximum power). The secondary mirror was chopped by 15 or 20 arcsec at 7 Hz between an object of interest and a reference position, while the telescope was nodded every 10 sec so that the object appeared first in one beam and then in the other. The angular separation between GD165 and its companion GD165B (Table 1) was measured with the single detector system on the IRTF. This separation

Fig. 1 Infrared images of GD165 and GD165B obtained by K. Hodapp, J. Rayner, D. Hall and one of the authors (E.E.B.) on the UH 2.2-m telescope in August 1988. Infrared wavelengths are: *a*, 1.25 μm (*J*); *b*, 1.65 μm (*H*); *c*, 2.2 μm (*K*). The images were obtained using a new, very sensitive, Hg:Cd:Te array detector developed by Honeywell Electro-Optics Division in collaboration with the Jet Propulsion laboratory and the University of Hawaii for a second-generation infrared instrument on the Hubble Space Telescope. Each image is the sum of four 24-s exposures of the 8×8 array co-added on a half-pixel grid. The scale was 0.9 arcsec per pixel and the seeing was ~1 arcsec. These conditions cause the images to appear to be asymmetric. The white dwarf GD165 is the northern object. North is up and east is to the left; each frame is ~7 arcsec on a side.

#7

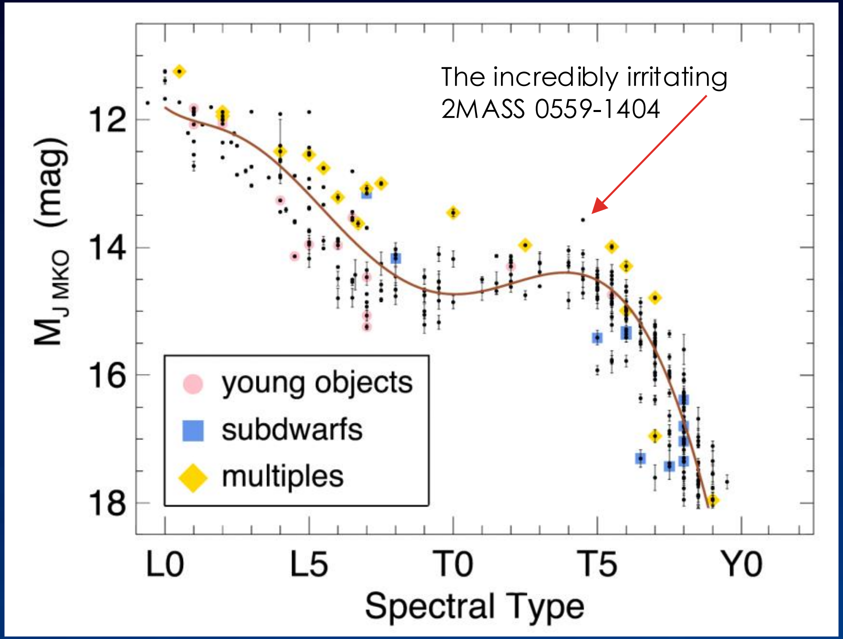
How do we explain the L/T transition?

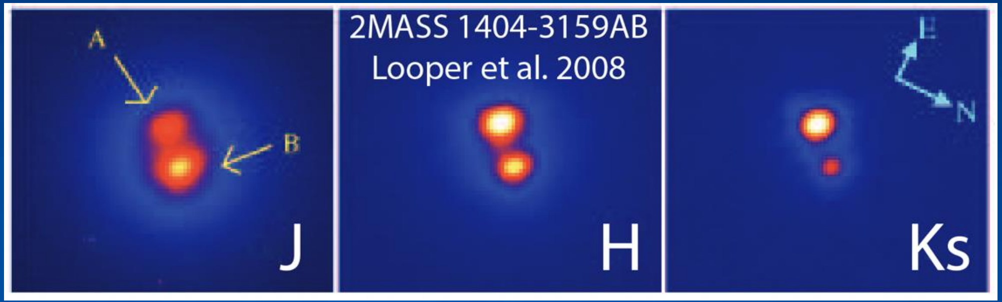
The L/T transition

Grains rain out of the photosphere

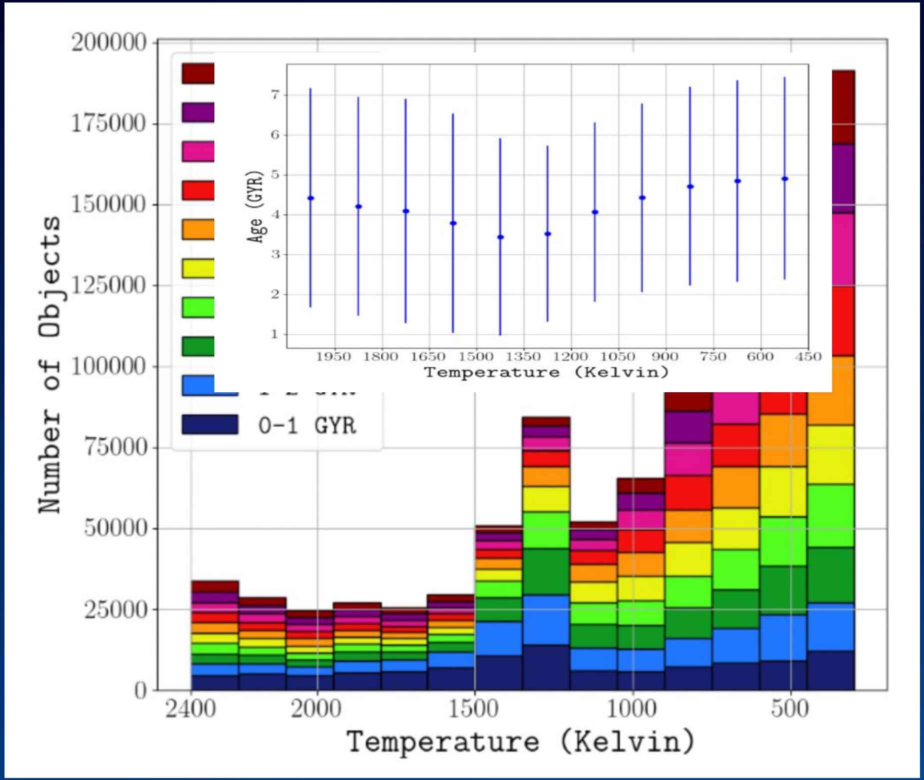
Photosphere transitions from dusty to cloud-free

Why does J-band brighten so much?





M_A = 65±6 M_{jup}
M_B = 55±6 M_{Jup}
(Dupuy & Liu 2017)



The L/T transition

Models based on the observed IMF suggest a sluggish transition.

Saumon & Marley 2008 state --

"Qualitatively, this effect is an inevitable consequence of the disappearance of clouds at the L/T transition and is not dependent on any particular mechanism or model of the 'cloud collapse' responsible for the transition".

#6

Where is the bottom of the IMF?

How low does star formation go?

Young moving groups

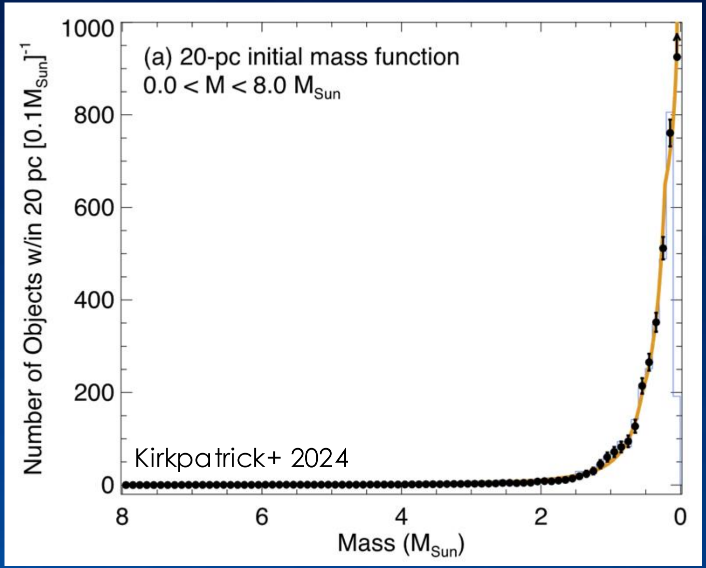
β Pictoris	6.5 M_{Jup}	Liu et al. 2013
TW Hydrae	4-5 M_{Jup}	Kellogg+ 2016, Best+ 2017

Nearby star forming regions

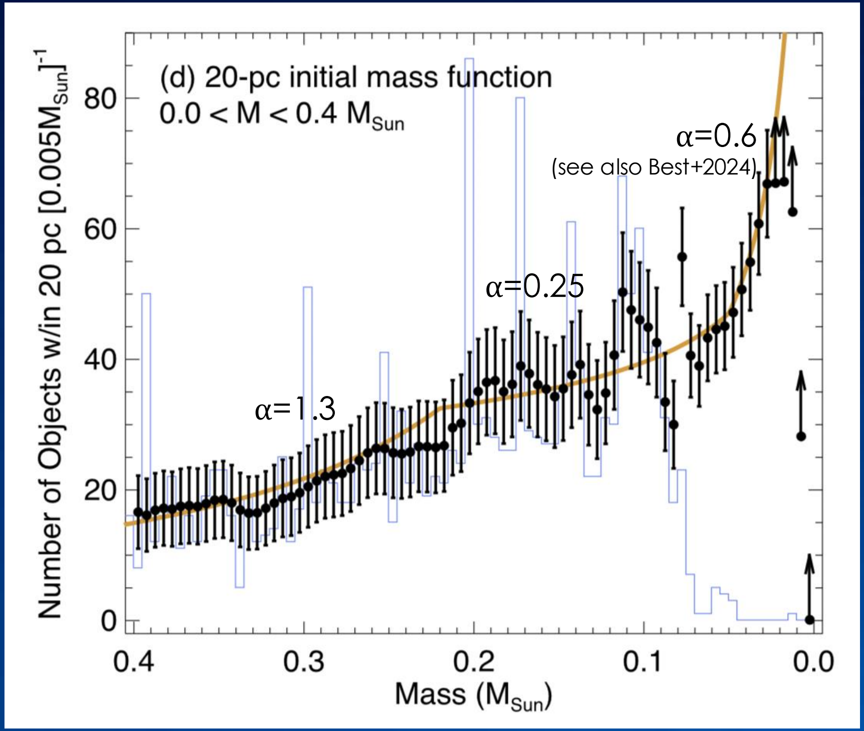
Taurus	5 M_{Jup}	Luhman+ 2009
σ Orionis	4 M_{Jup}	Damian+2023

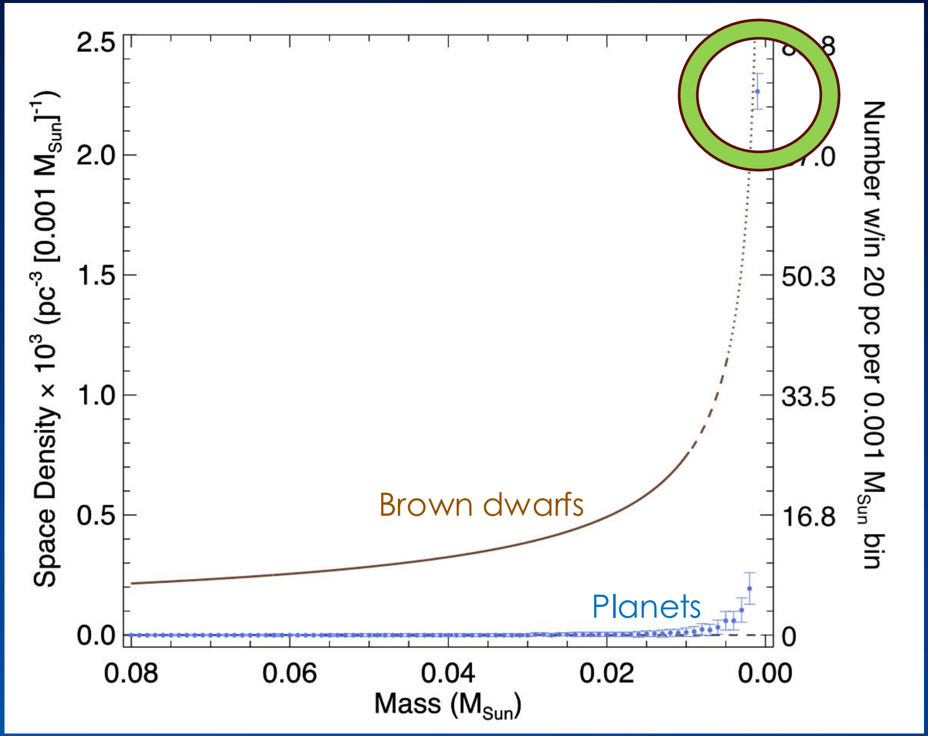
Old populations

20-pc census	<10 M_{Jup}	Kirkpatrick+ 2021
Globular clusters	<80 M_{Jup}	Gerasimov+ 2024, Marino+ 2024



How low does star formation go?



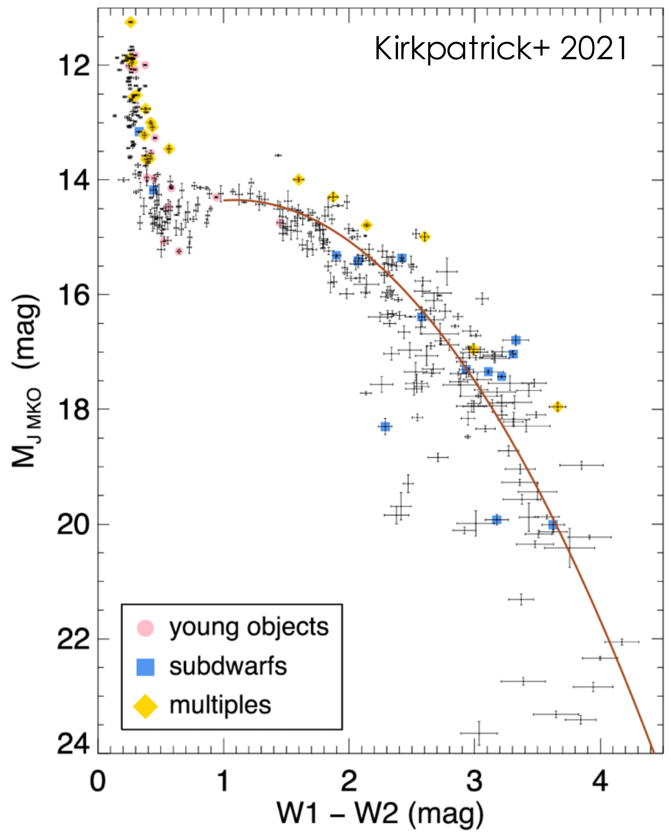


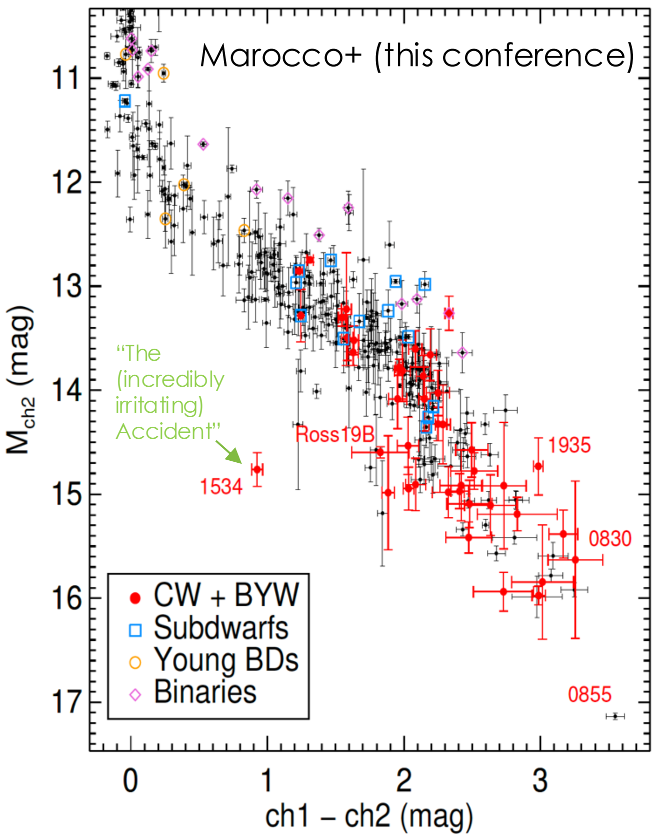
Kirkpatrick+ 2024

#5

How do we explain the diversity of Y dwarfs?

L, T, and Y dwarfs within 20 pc of the Sun





Neutral → Molecule → Solid/liquid Condensate

Exact sequence depends on gas pressure, mixing, metallicity, etc.

↓ Temperature

Formation of --
- Corundum Al_2O_3
- Hibonite $CaAl_{12}O_{19}$
- Grossite $CaAl_4O_7$
- Gehlenite $Ca_2Al_2SiO_7$

→ rob atmosphere of Ca

TiO forms TiO_2 or condenses into --
- Perovskite $CaTiO_3$
- (or other Ti-bearing molecules) $Ca_4T_{13}O_{10}$ $Ca_3Ti_2O_7$ Ti_2O_3 Ti_3O_5 Ti_4O_7

→ locks up some Ti

VO forms VO_2 or condenses into --
Solid VO or solid solutions w/ Ti condensates

Formation of –
- Forsterite Mg_2SiO_4
- Enstatite $MgSiO_3$

→ rob atmosphere of additional O

Time →

4

How has theory advanced?

Forward Modeling

(the traditional approach)

N-dimensional grid of model atmospheres calculated with complete theoretical description.

A few vital physical parameters are varied to simulate those likely to be encountered in real atmospheres.

Real spectra are then compared to the grid to find best-fit model.

Mukherjee+2024
Kothari+2024 Balmer+2024
Morley+2024
Tobin+2024 Luhman+2024 Manjavacas+2024
Burgasser+2024
Hurt+2024
Hsu+2024 Lew+2024 McCarthy+2024
Phillips+2024
Ravinet+2024

Inverse Modeling

(aka "retrieval analysis")

Strives to deduce physical parameters directly from data.

Uses fewer assumptions than forward modeling.

Can discern physical processes missing from the forward models (e.g., non-equilibrium chemistry),

… Or reveal poor assumptions made in those models (e.g., solar elemental abundances).

deRegt+2024 Xuan+2024
Faherty+2024
Lothringer+2024
Costes+2024
Kothari+2024
Lew+2024
Hsu+2024

Kothari+2024: Use 1-12 μm JWST spectrum to show vigorous vertical mixing in a Y0.

mixing

Xuan+2024: Use spectra of 8 companions (10-30 M_{Jup}) to find solar C/O and metallicities, matching their hosts, indicating (likely) star-like formation.

formation

deRegt+2024: Find depleted ^{13}C abundance in an isolated late-L dwarf, lending credence to using this isotope to distinguish formation.

formation

Hsu+2024: Find solar C/O for benchmark brown dwarf companion, matching host.

formation

Lew+2024: Use JWST spectrum of the weird Y dwarf 1828+26 to measure C/O, metallicity, and $^{12}CO/^{13}CO$ and compare these to forward-model results.

technique comparison

Lothringer+2024: Study highly irradiated brown dwarfs around white dwarf hosts to probe dayside/nightside differences.

thermal transport

Costes+2024: Measure C/O and $^{12}CO/^{13}CO$ in brown dwarf companion, favoring a gravitational collapse formation scenario.

formation

Faherty+2024: See discussion on later slide!

aurorae

#3

Where have we been surprised?

Cold objects have magnetic fields and aurorae!

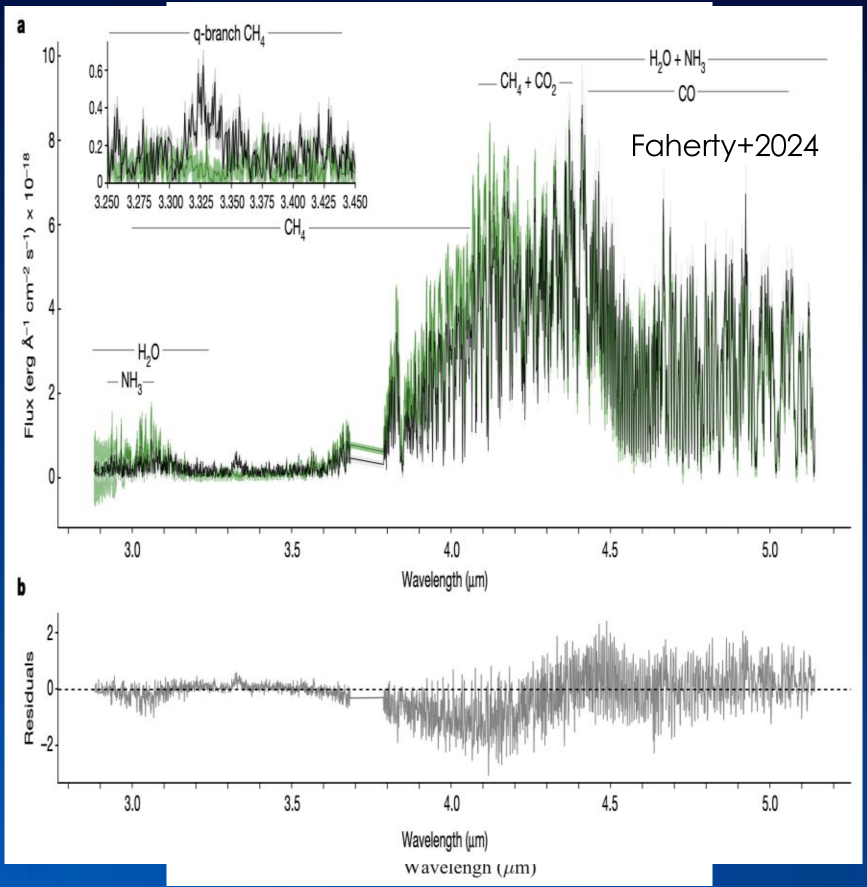
Cool, neutral atmospheres have magnetic fields.

Kilogauss fields inferred from GHz radio emission (electron-cyclotron maser instability).

Hα emission shown to be periodic at the period measured by radio emission.

Brown dwarfs could have aurorae with measurable H_3^+.

Methane emission (aurora) has been observed in one Y dwarfs.



Faherty+2024

Observations depend on viewing angle!

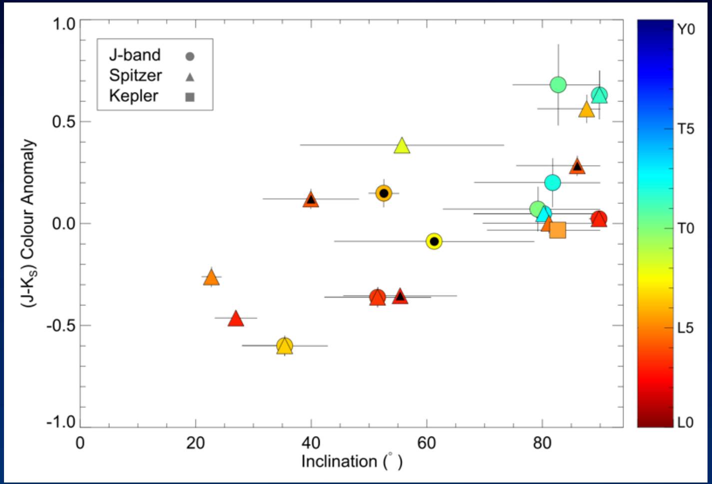
Vos+2017 measured the v sin(i) for ~20 variable L, T dwarfs with measured periods.

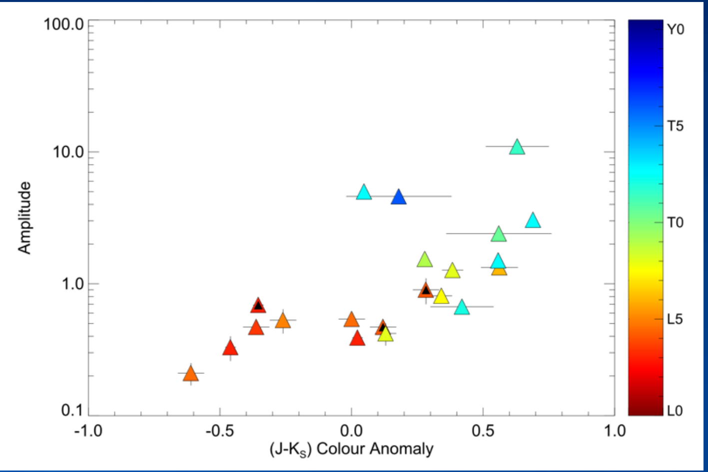
$v = 2\pi R/P \rightarrow i$

Redder objects (for their type) tend to be equator-on.

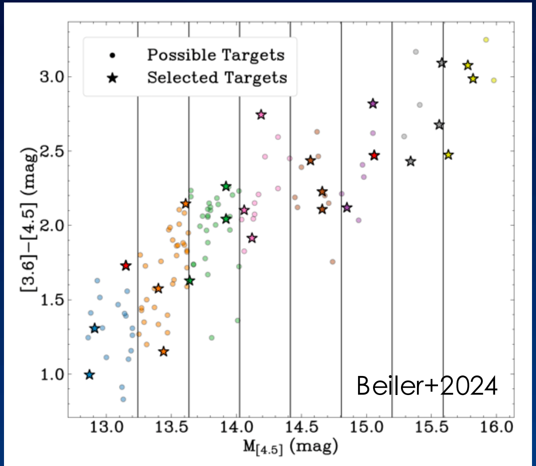
Equator = cloudier (or larger grains)
Poles = clearer (or smaller grains)

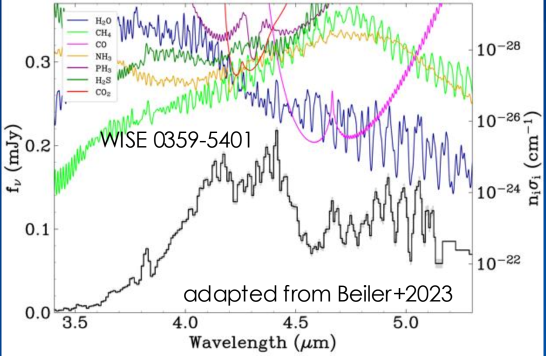
→ Viewing angle affects colors and spectra observed.

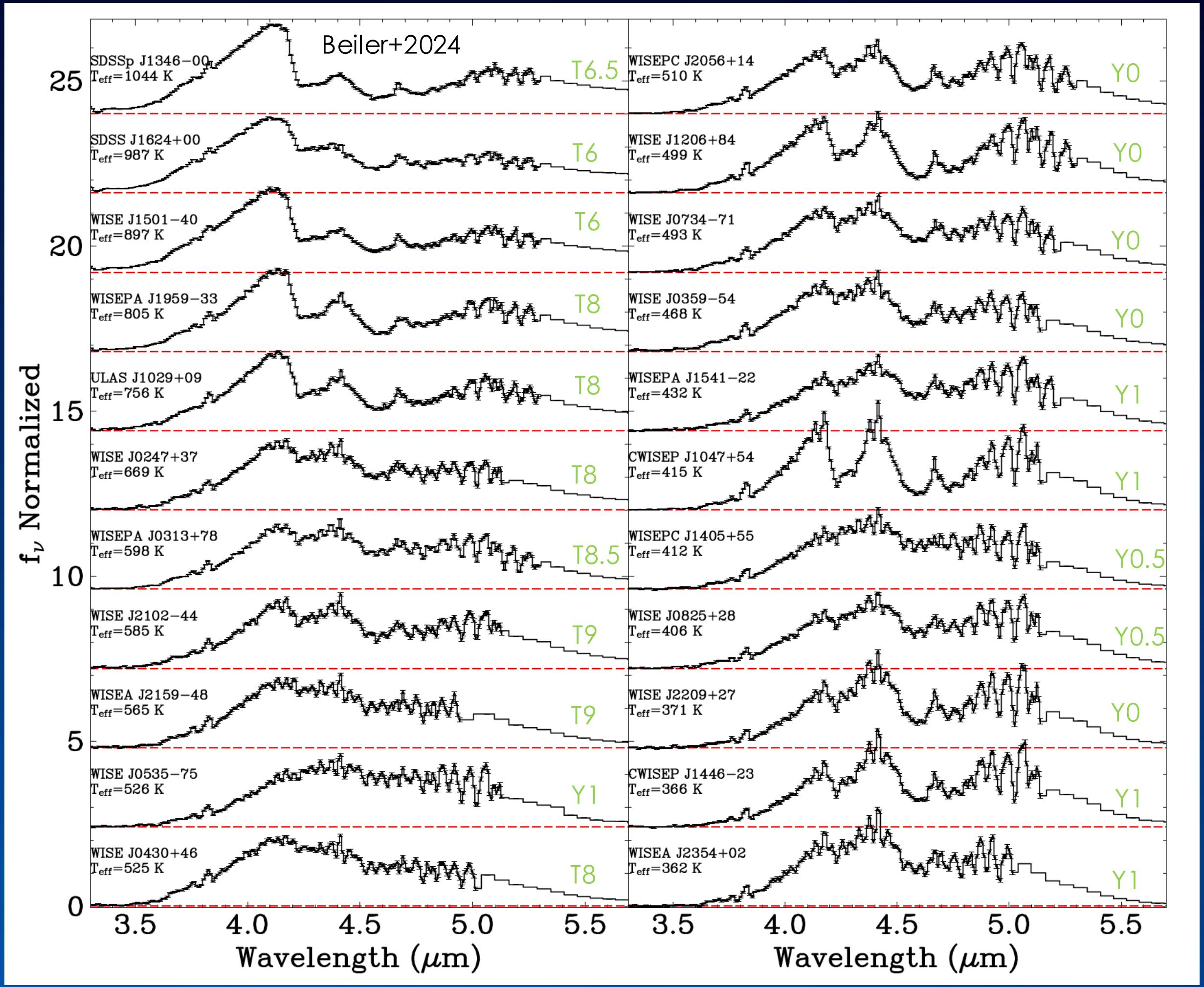




There is no late-T/Y spectral sequence at 5 μm!







#2

How do we tackle the impending onslaught of data?

IRSA’s largest dataset

NEOWISE Single Exposure Source Table
(~200 billion rows)

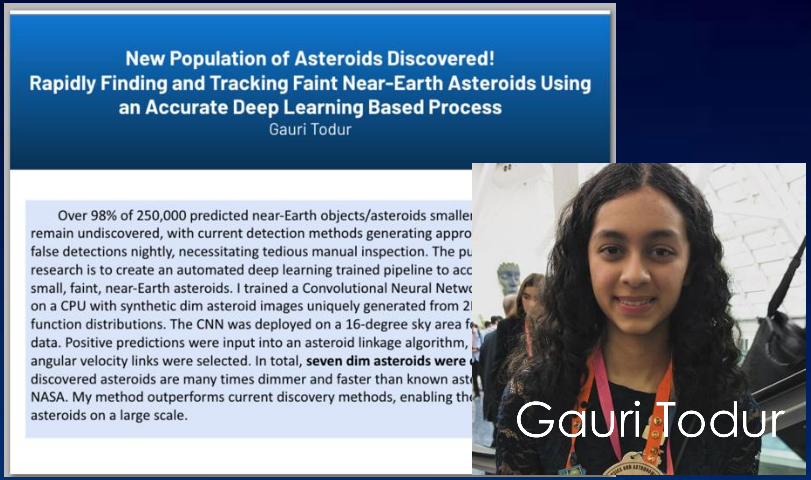
Future data sets will be much larger

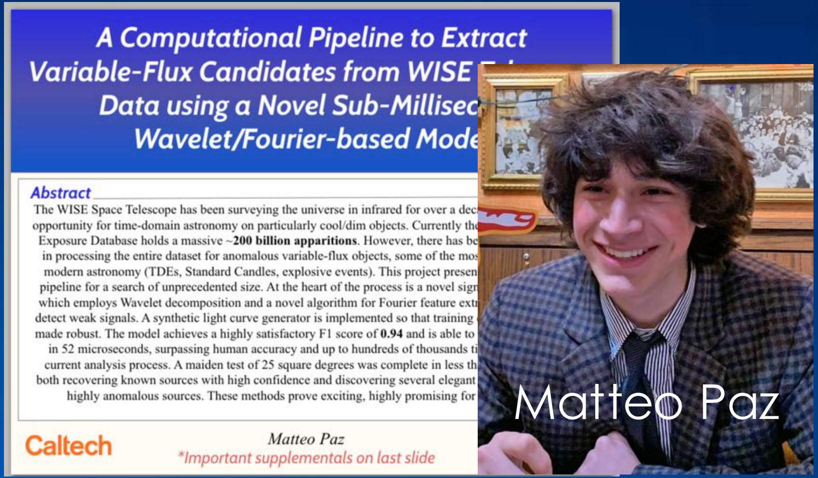
e.g., Rubin/LSST

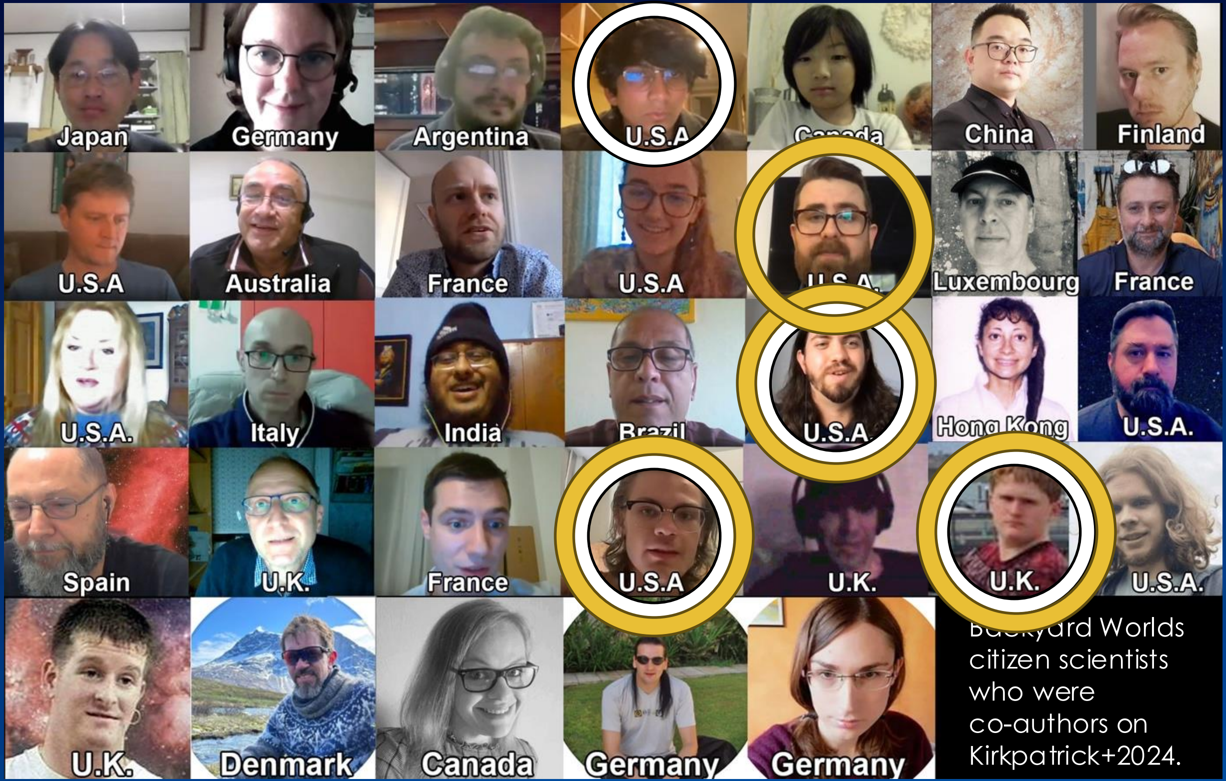
AI (and ML specifically) can

- Characterize data
- Narrow # of objects needing human scrutiny

Many young researchers are eager to test their programming and AI chops on these gigantic data sets.







Backyard Worlds citizen scientists who were co-authors on Kirkpatrick+2024.

Citizen science:

- Share your love of astronomy with like-minded folks.
- Help educate on current cutting-edge research.
- Receive fast results on large data sets scrutinized in diverse ways.

#1

Do we sometimes hamper our own field?

'Failed star' is the coldest radio wave source ever discovered

"FAILED STARS" ARE BEING USED TO UNDERSTAND EXOPLANETS

Ask Ethan: Can Failed Stars Eventually Succeed?

Weird 'failed star' seen blasting off its outer layers for first time

Rogue Failed Star Is One of Smallest Ever Seen

Unique 'Failed Star' Is Like Nothing Else in the Milky Way, Study Finds

Alien Lifeforms Could Exist in the Clouds of Brown Dwarfs, Cold "Failed" Stars

Hubble Space Telescope discovers 'failed stars' are bad at relationships too

Argument:

We need to educate the public what a brown dwarf is – hence, the term "failed star".

Complaint 1:

This term is too terse and too inaccurate.

Use a longer, more accurate definition (see slide to come!).

Complaint 2:

Using the term "failed" isn't doing our field any favors.

Who works on failed stars?
Failed researchers?

Is this field a failure?

Avoid the word "failed".

We have no control on what the press at large does, but we can (largely) control the wording of our press releases.

Rare failed star found circling sun-like star

The Milky Way is home to 100 billion 'failed stars'

James Webb's Astonishing Discovery - 'A Failed Star' That Shouldn't Exist

'Failed Stars Of Universe'

New Kind of Planet or a Failed Star?

Astronomers Discover Clouds of Sand In The Atmosphere of A Failed Star

Weird 'failed star' seen blasting off its outer layers for first time

"Brown dwarfs"

Original: Kumar 1963

The lowest mass products of star formation

Modern:

Objects w/ masses 13 - 75 M_{Jup}

"Planets"

Original: Kant 1755, Laplace 1796

Products formed from a circumstellar disk around a young star

Modern:

Objects w/ masses below 13 M_{Jup}

A

18 M_{Jup}

B

11 M_{Jup}

"This system is challenging our understanding of the planetary formation process."

Thank you!