OSU THETA

Observatoire des sciences de l'univers
Terre, homme, environnement, temps, astronomie
Franche-Comté • Bourgogne

UBFC
Université
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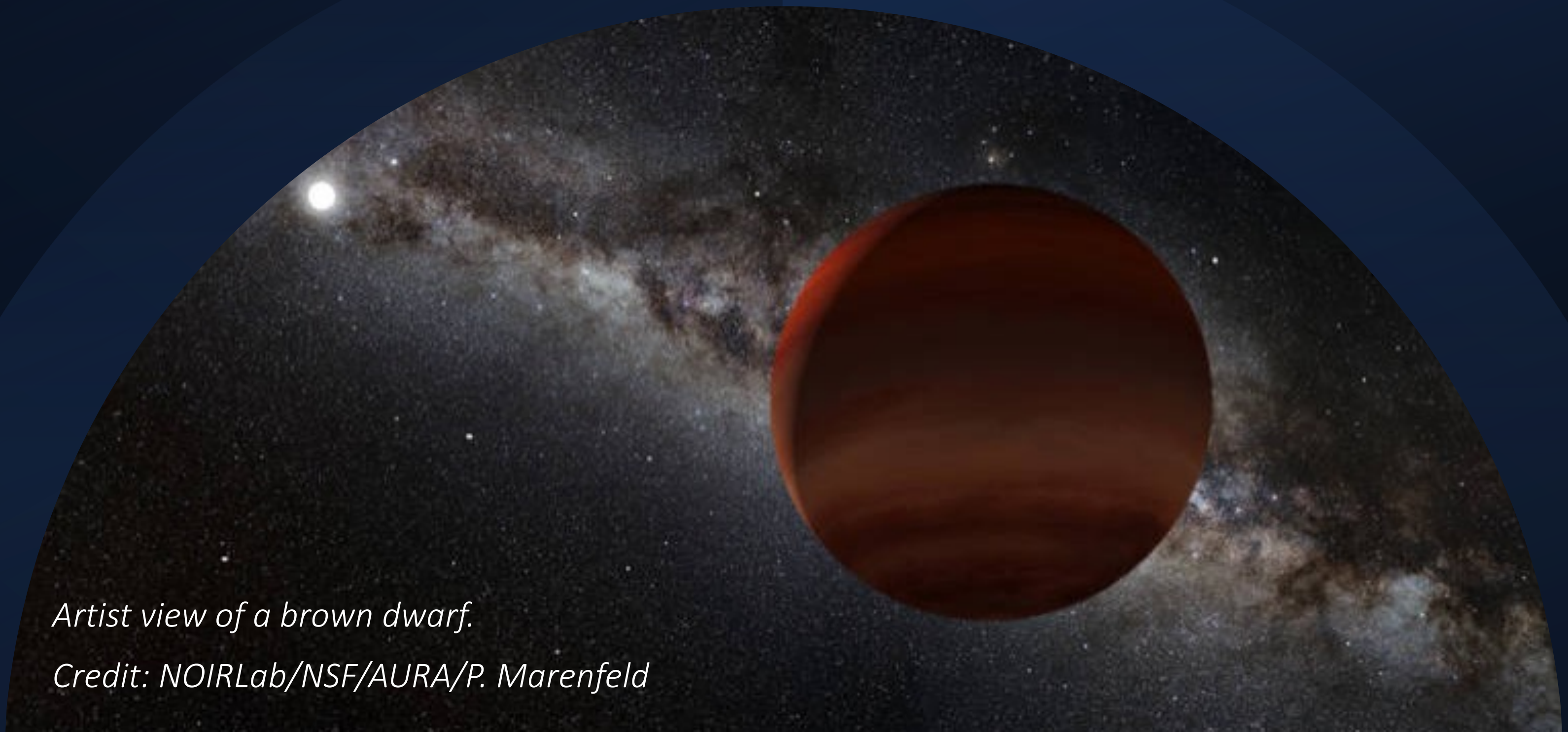
Low mass stars and brown dwarfs and their atmospheres

Céline Reylé

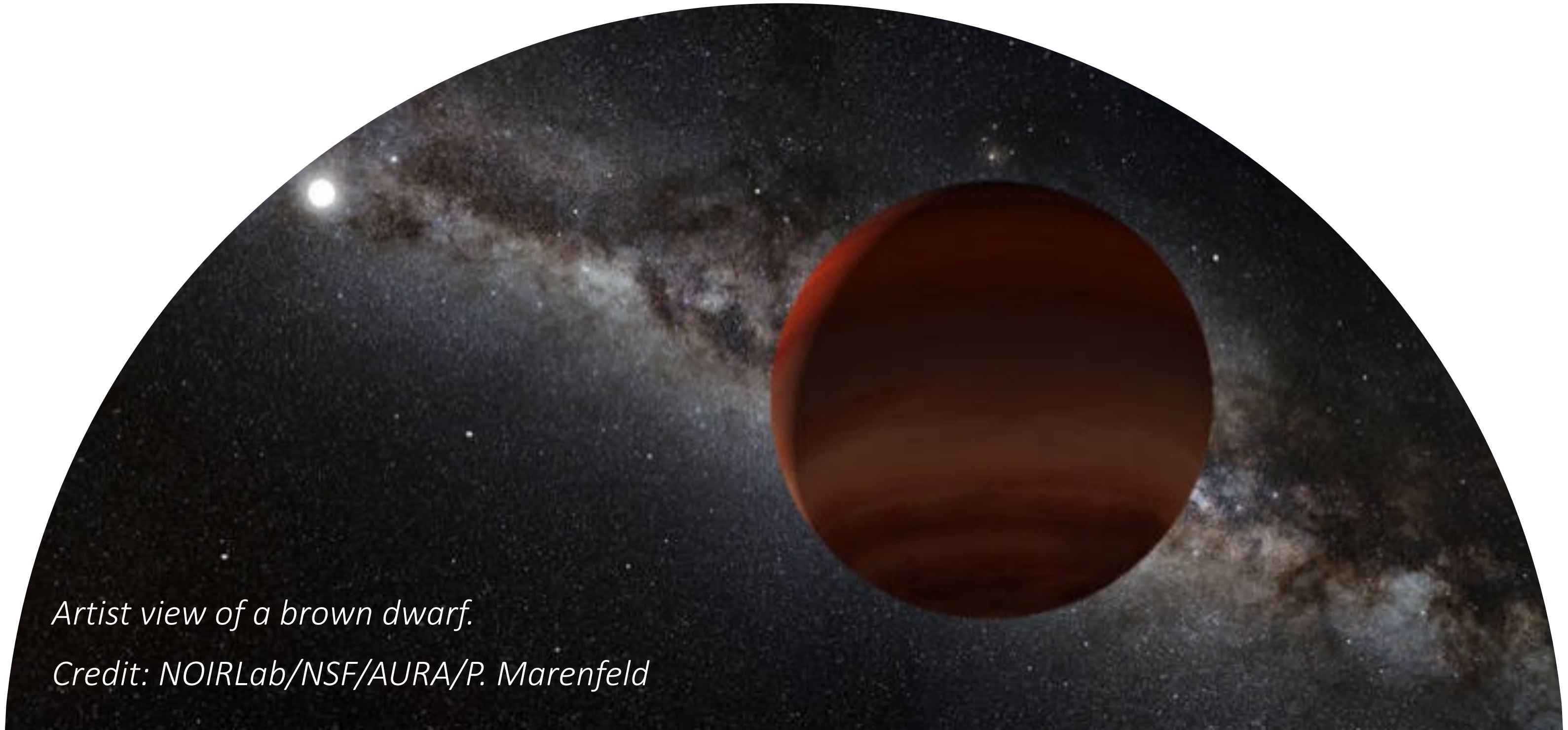


Artist view of a brown dwarf.

Credit: NOIRLab/NSF/AURA/P. Marenfeld

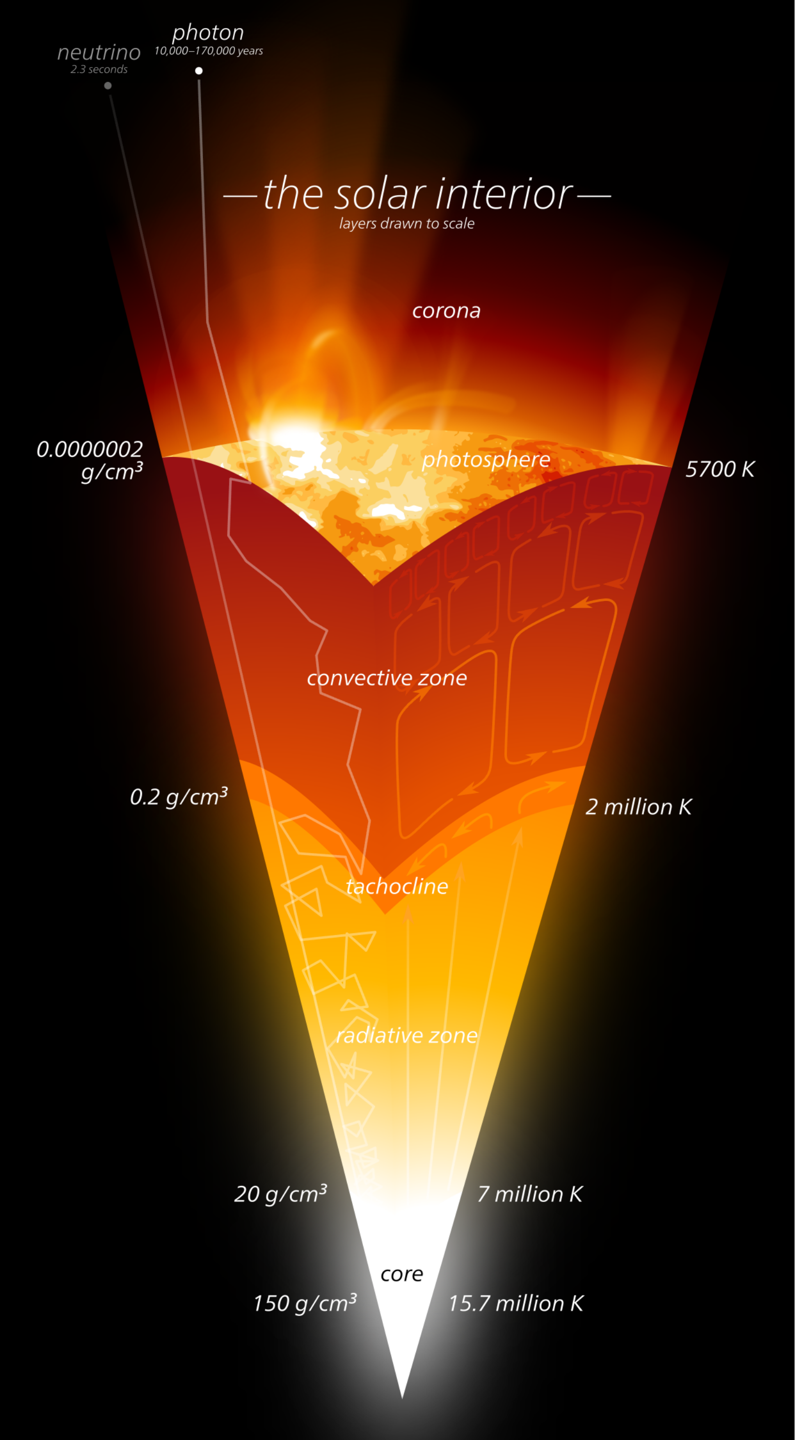
Topics for this lecture

- Stars, low-mass stars, and brown dwarfs
- The stellar/substellar limit
- Spectral classification and atmospheres of low mass stars and brown dwarfs
- Clouds and variability



Artist view of a brown dwarf.

Credit: NOIRLab/NSF/AURA/P. Marenfeld



Stars, low-mass stars, and brown dwarfs

A vast amount of energy is released via nuclear fusion occuring in the core of a star.

$$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He + 2\,{}^{0}_{1}\bar{e} + 2\nu_e$$

$4 \times 938\ MeV = 3752\ MeV$; $3728\ MeV$

net mass loss
⇒ energy release

To fuse hydrogen, the core must have temperatures > $3\text{x}10^6$ K.

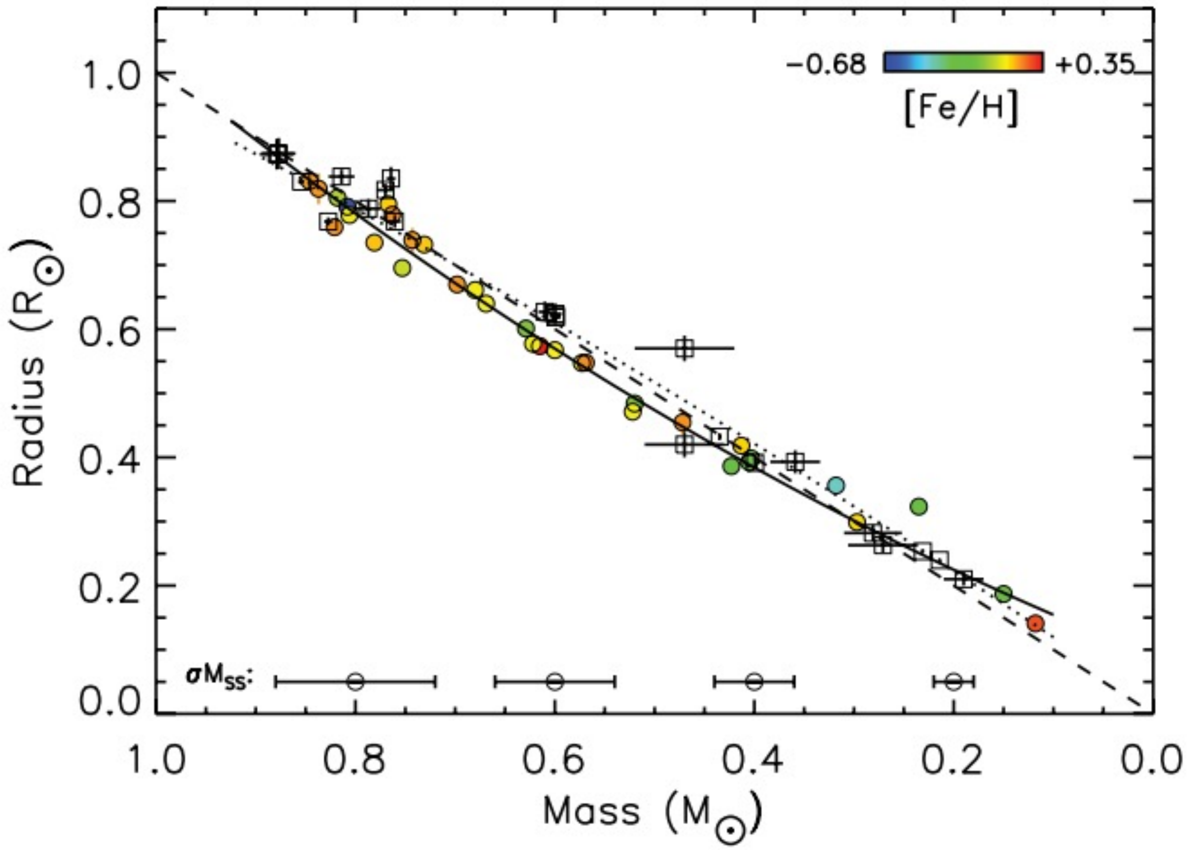
On the Main Sequence, the thermal pressure from fusion keeps a star from gravitational collapse.
The star is in thermal and hydrostatic equilibrium.

Credit: https://commons.wikimedia.org/wiki/File:The_solar_interior.svg

Stars, low-mass stars, and brown dwarfs

The stellar matter follows classical statistical physics: classical nearly perfect gas equation of state and quasistatic equilibrium condition
→ radius ∝ mass

The less mass a star has, the more it needs to contract to heat the core, and the smaller it will be on the Main Sequence.



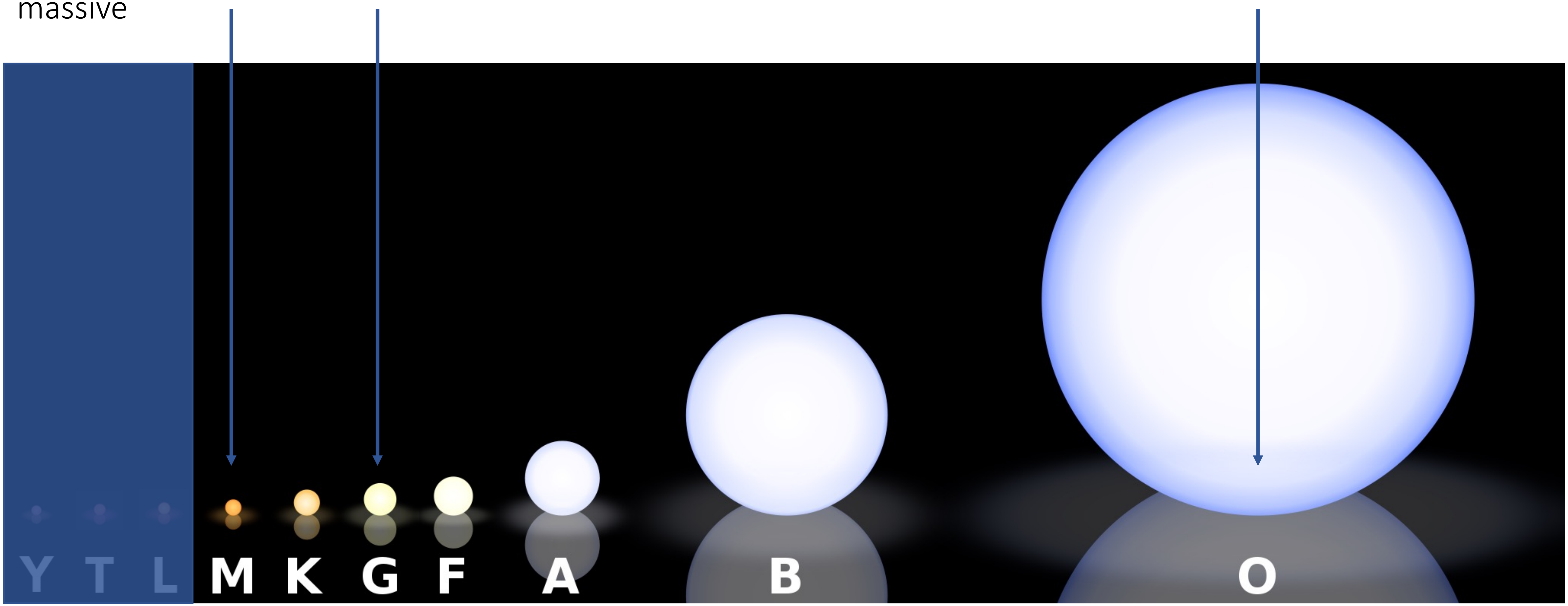
Stellar empirical mass-radius relationship for main sequence K and M stars.
Boyajian et al, 2012

Stars, low-mass stars, and brown dwarfs

Lowest mass stars, tens smaller and less massive

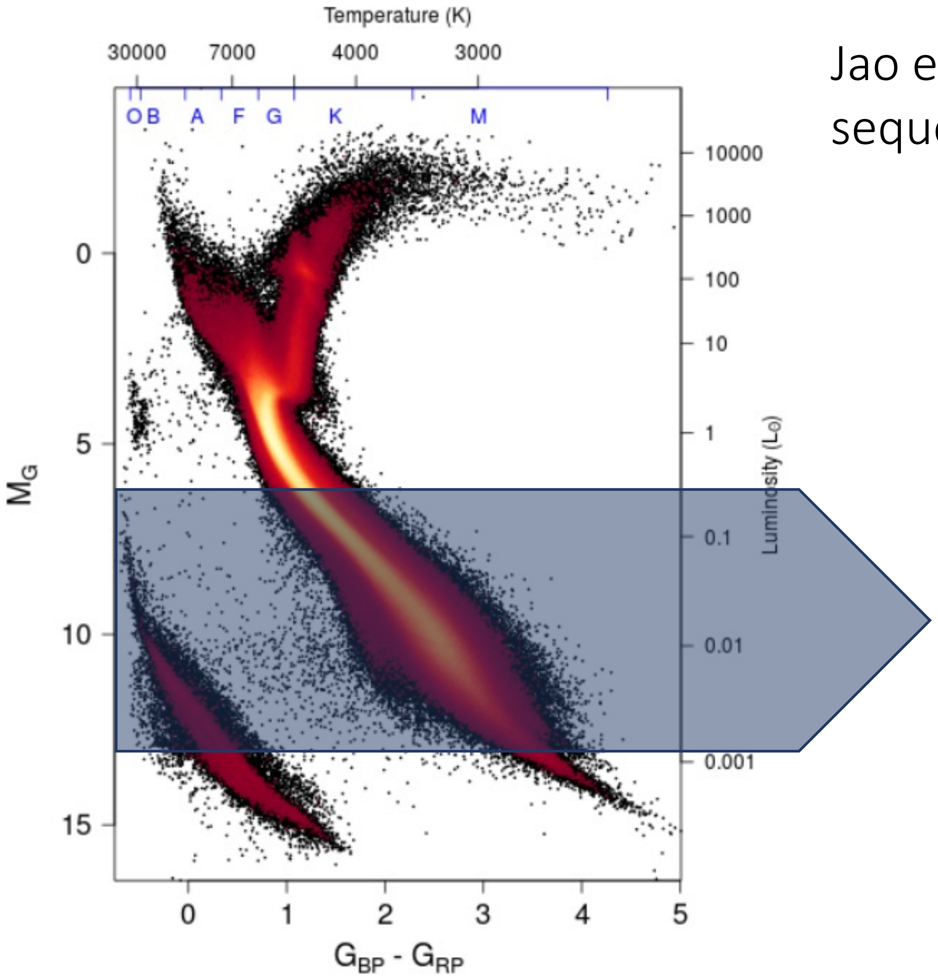
Sun-like

Highest mass stars, several tens larger and more massive



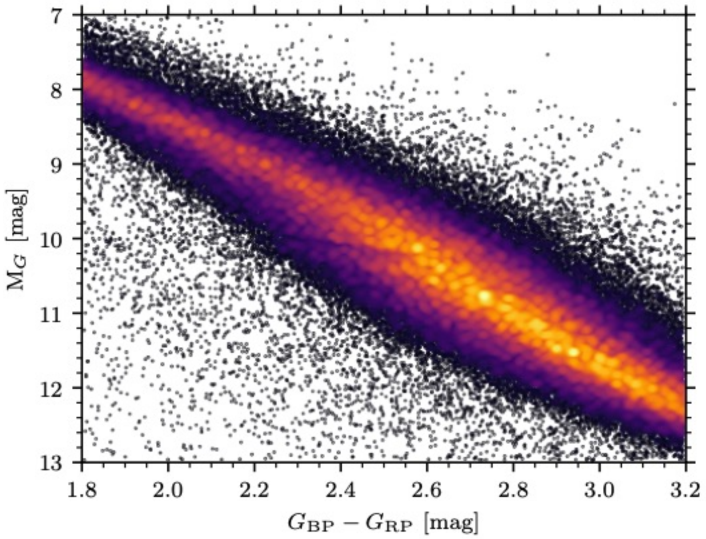
Credit: L. Reylé, adapted from http://en.wikipedia.org/wiki/File:Morgan-Keenan_spectral_classification.png

Stars, low-mass stars, and brown dwarfs



Colour absolute magnitude diagram from *Gaia* DR2, *Gaia Coll., Babusiaux et al 2018*

Jao et al. (2018) discovered a narrow gap (~0.05 mag) in the lower main sequence: M3, M~0.35 $M_\odot$, transition from partly to fully convective stars

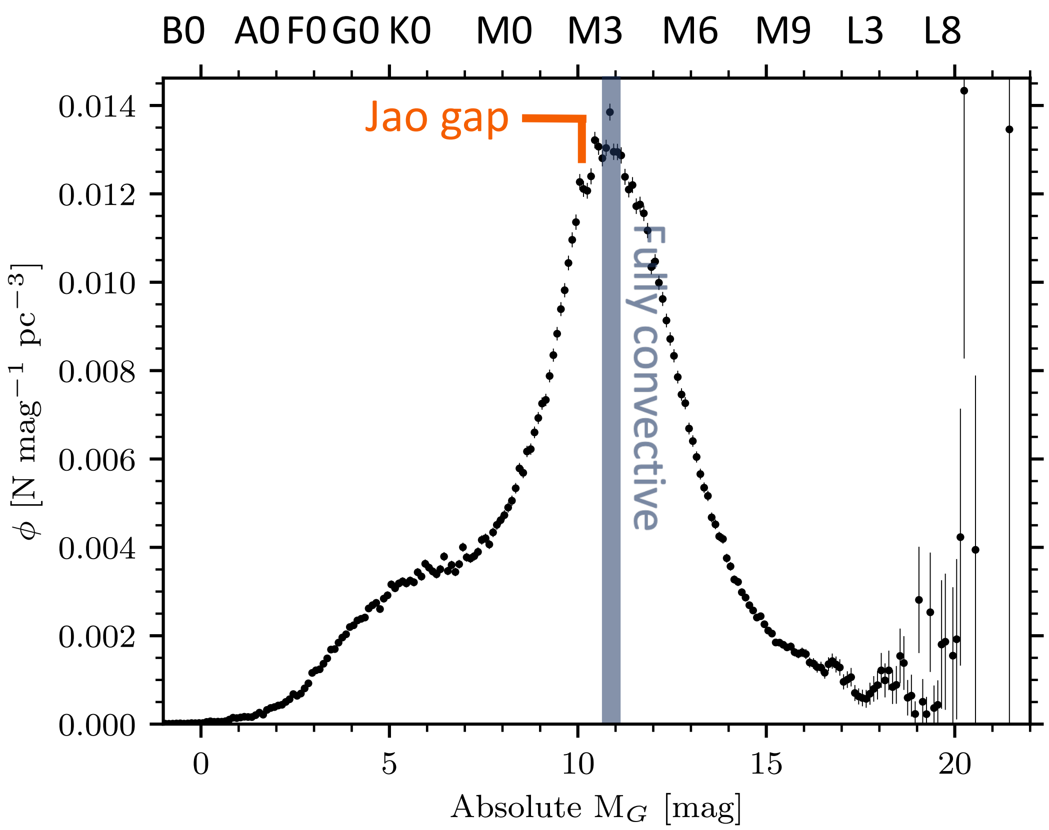


Related to structural instabilities caused by non-equilibrium ^{3}He fusion reactions (MacDonald & Gizis 2018; Baraffe & Chabrier 2018; Feiden, Skidmore & Jao 2021)

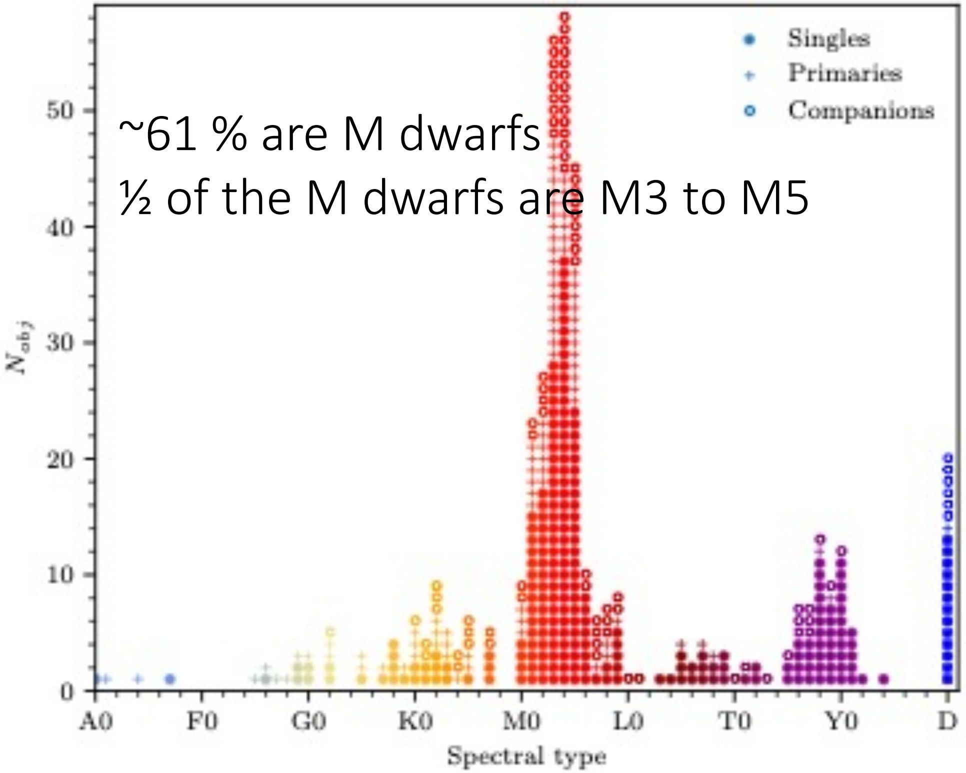
Stars, low-mass stars, and brown dwarfs

Why low-mass stars and (brown dwarfs) are interesting to study?

- They are the most numerous in the Galaxy, they span all ages and are in all populations



Luminosity function of the *Gaia* Catalogue of Nearby Stars (within 100 pc) *Gaia Coll., Smart et al 2021*



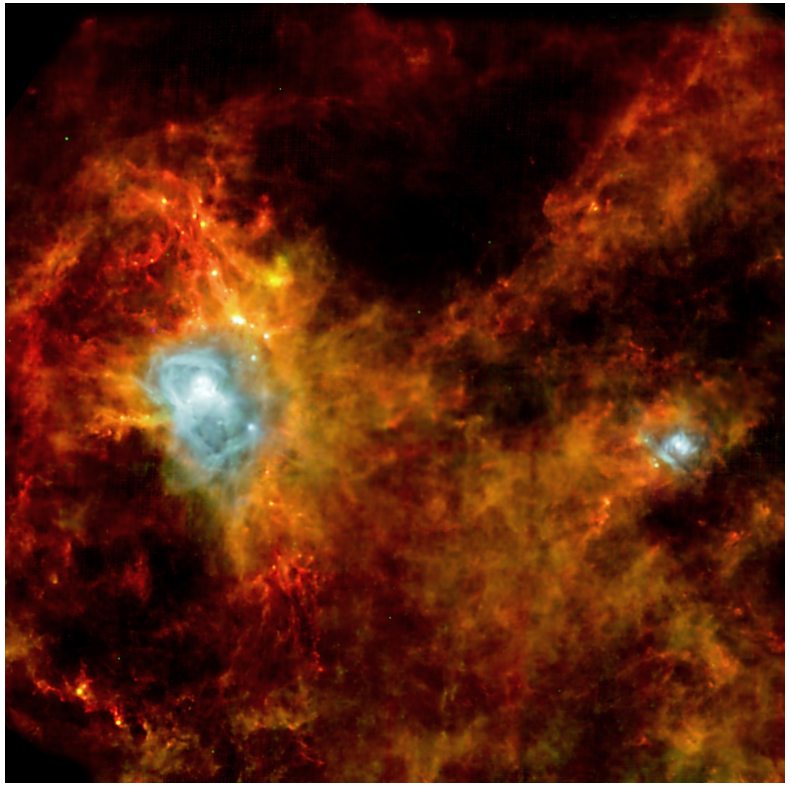
Spectral type distribution of the 10 pc sample *Reylé et al 2021*

Stars, low-mass stars, and brown dwarfs

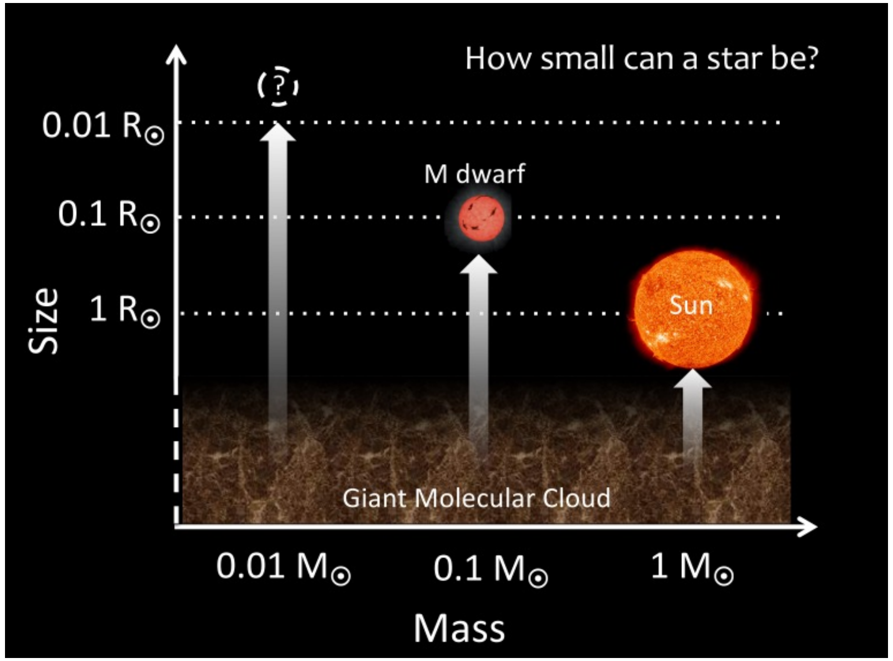
Why low-mass stars and (brown dwarfs) are interesting to study?

- They are the most numerous in the Galaxy, they span all ages and are in all populations
- They give clues on the formation at the low-mass end, still not well understood

From filamentary clouds to prestellar cores to stars

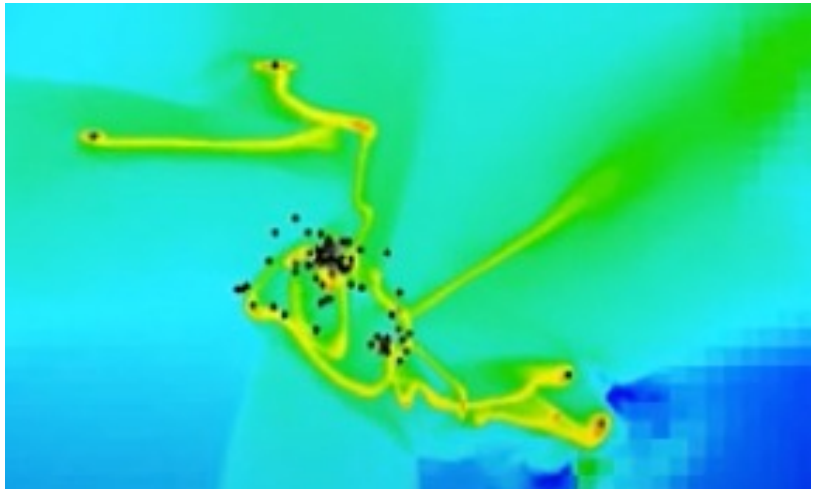


André et al 2010
Credit:
ESA/Herschel/SPIRE/PACS
« Gould Belt survey »
Key Programme

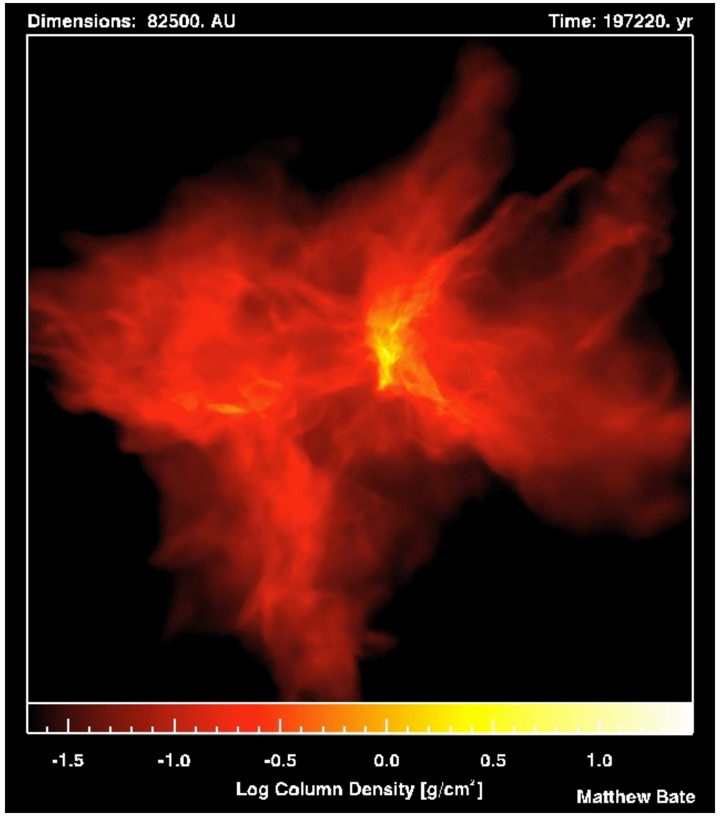


Courtesy of A. Burgasser

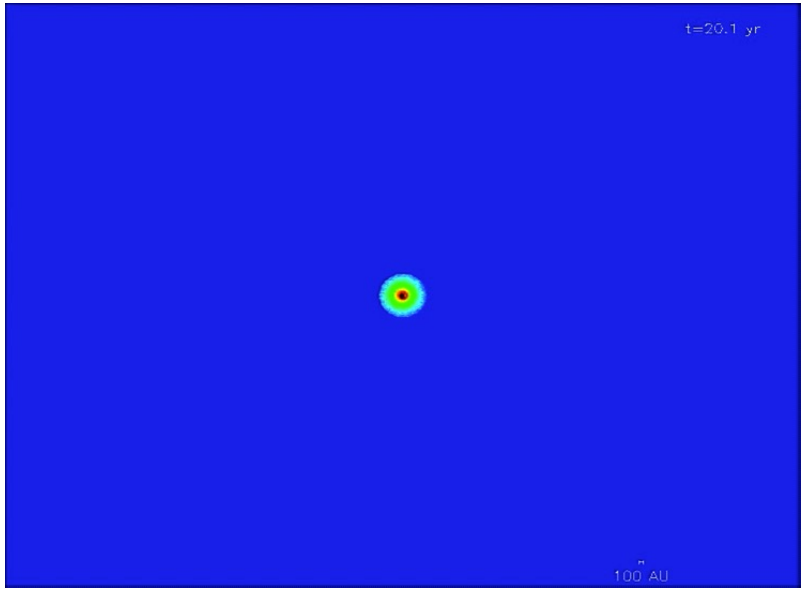
M_{Jeans}: need density of 10^7 cm^{-3} to form $M<0.07\ M_{\odot}$.
Barnard Bok globule has 1000 cm^{-3} (Alves et al 2011)



Grovoturbulent fragmentation
e.g. Padoan & Nordlund 2004; Hennebelle & Chabrier 2008, 2009; Bonnell et al 2008; Lomax et al 2016



Embryo ejection
e.g. Reipurth & Clarke 2001; Bate et al 2002; Goodwin et al 2004, Reipurth & Mikkola 2015



Disc fragmentation
e.g. Vorobyov & Basu 2006, 2010, 2012; Stamatellos et al 2007; Attwood et al 2009, Stamatellos et Herzceg 2015

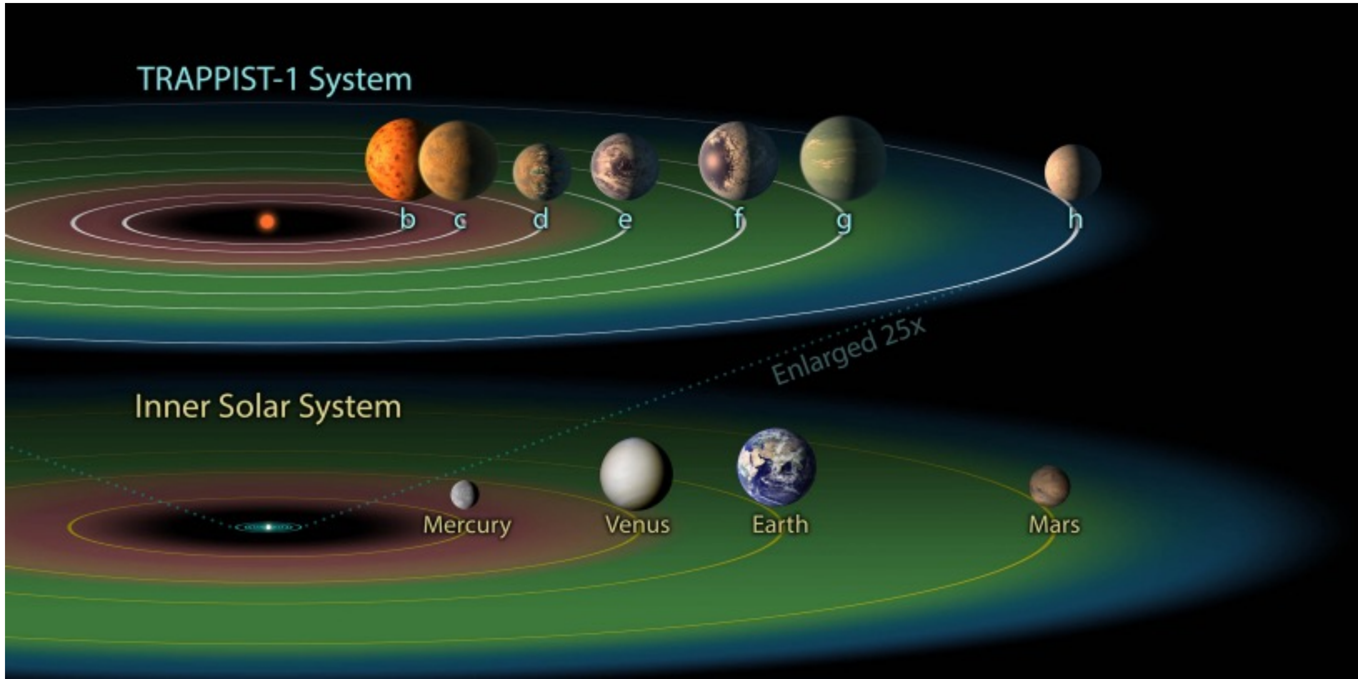
Photoerosion
e.g. Whitworth & Zinnecker 2004; Green et al 2015

Stars, low-mass stars, and brown dwarfs

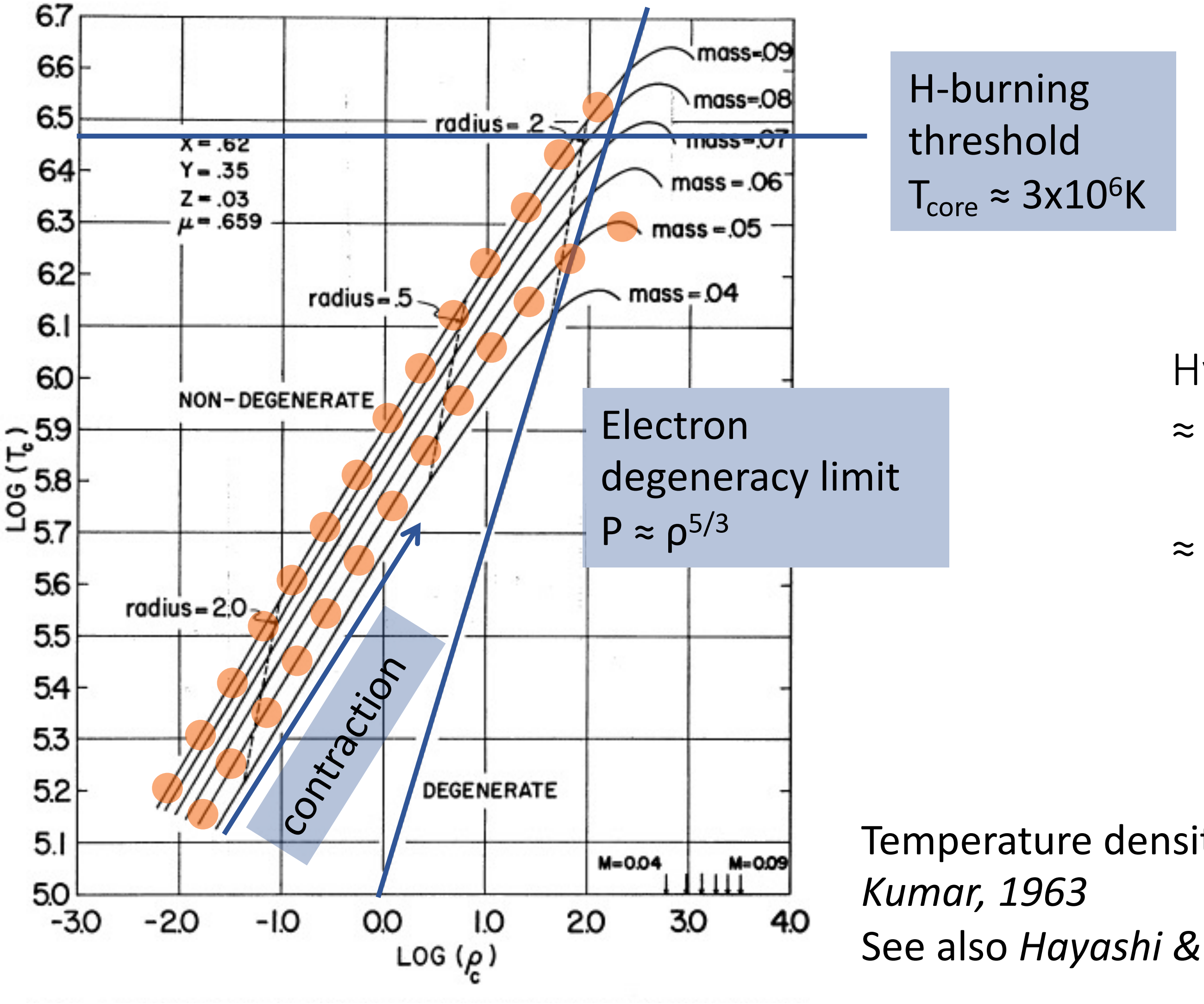
Why low-mass stars and (brown dwarfs) are interesting to study?

- They are the most numerous in the Galaxy, they span all ages and are in all populations
- They give clues on the formation at the low-mass end, still not well understood
- Modeling their complex, cool, atmosphere is still a challenge
- The lowest-mass brown dwarfs more closely resemble the gas giant planets than stars and therefore provide insight into the physical properties of extrasolar giant planets
- They host exoplanets, and are ideal targets for searches for potentially habitable terrestrial planets (e.g. TRAPPIST-1, Gillon et al 2016, 2017; Proxima Cen, Anglada-Escude et al 2016; Ross 128, Bonfils et al 2018)

→ galactic studies, stellar physics, exoplanetary studies



Stars, low-mass stars, and brown dwarfs



Hydrogen burning minimum mass
≈ 0.07 $M_\odot$ (73 M_{jup}) at solar metallicity

≈ 0.09 $M_\odot$ at low metallicity

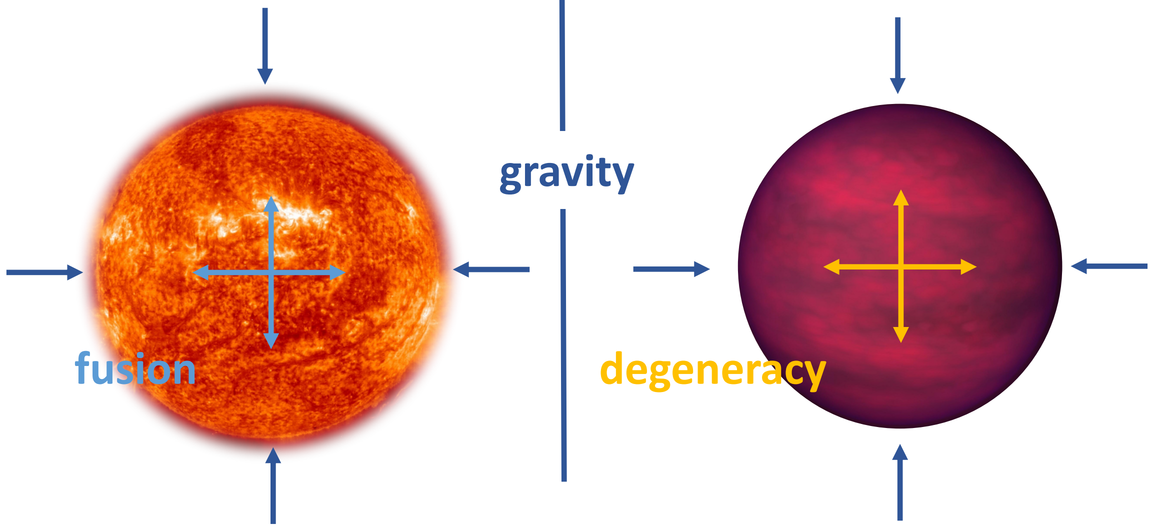
Temperature density diagram for completly convective model
Kumar, 1963
See also *Hayashi & Nakano (1963)*

Stars, low-mass stars, and brown dwarfs

The object’s collapse is stopped by electron degeneracy pressure. The macroscopic properties of the matter are then ruled by different physics and follow a different equation of state (e.g. Saumon et al 1995, Chabrier et al 2019).

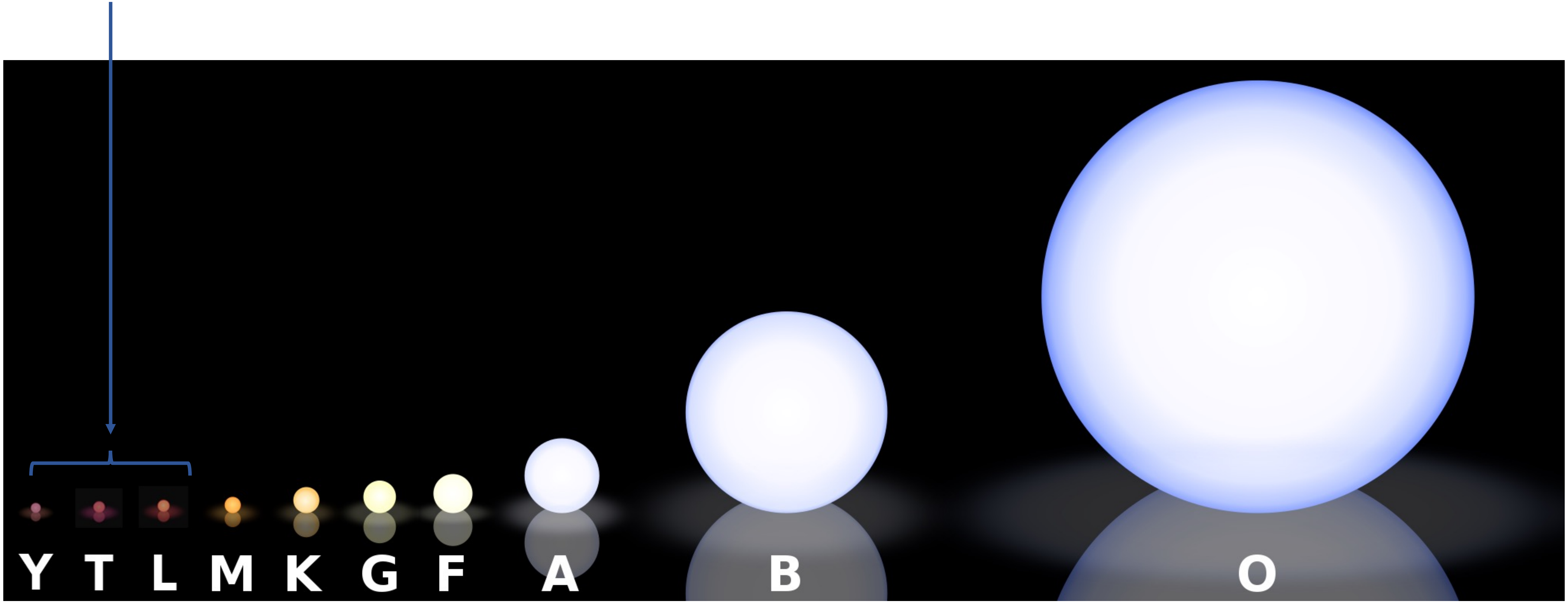
Main Sequence Star supported by thermal pressure from fusion

Degenerate Brown Dwarf supported by electron degeneracy pressure



Stars, low-mass stars, and brown dwarfs

Brown dwarfs do not undergo stable hydrogen fusion → they cool down over time, progressively passing through later spectral types as they age.



Credit: L. Reylé, adapted from http://en.wikipedia.org/wiki/File:Morgan-Keenan_spectral_classification.png

Stars, low-mass stars, and brown dwarfs

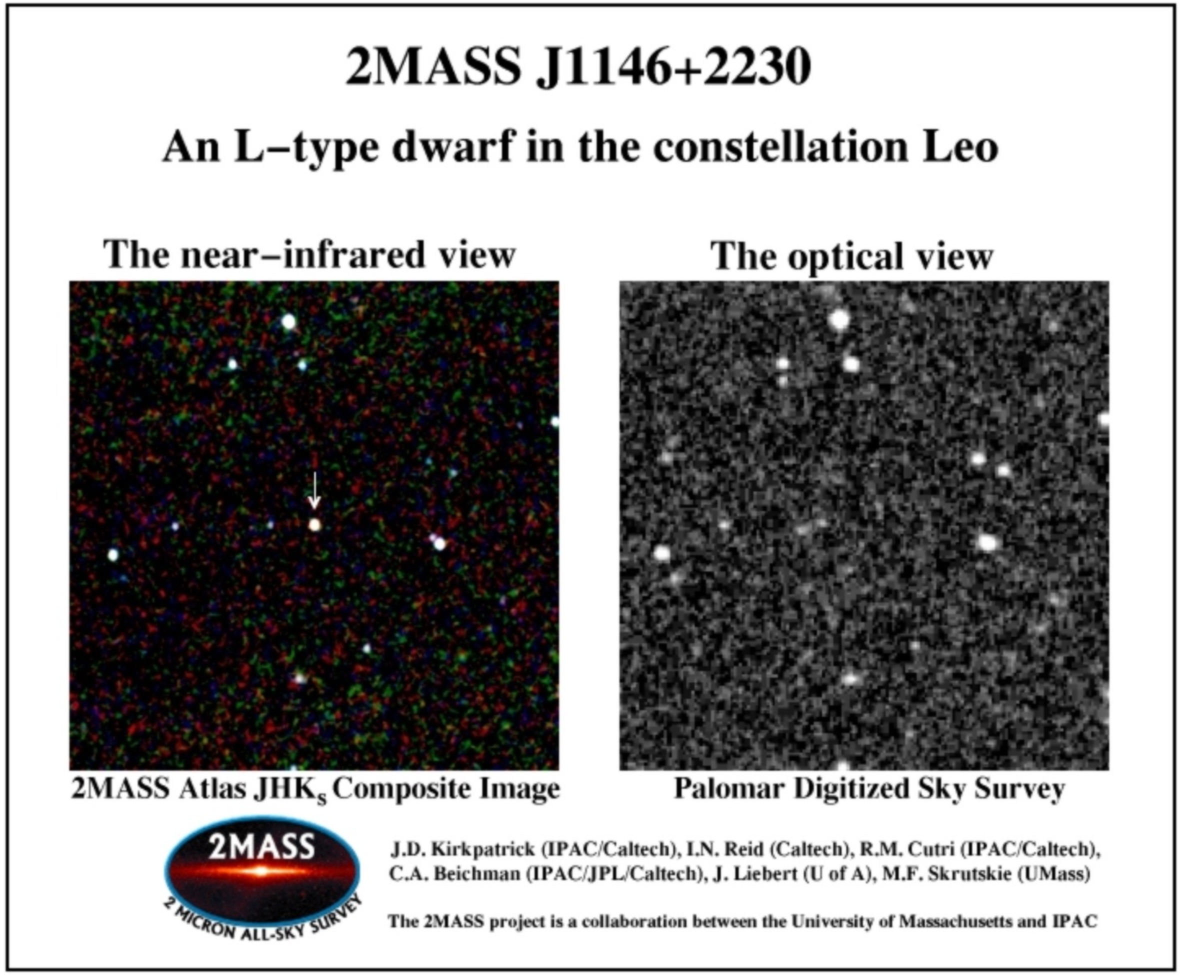
Brown dwarfs are low-luminosity, very red objects, difficult to detect.

Strategies for finding the coolest objects are

- to search for them in young clusters
- to search for them as companions to other objects
- to search for red objects in large scale surveys, eventually large proper motion objects

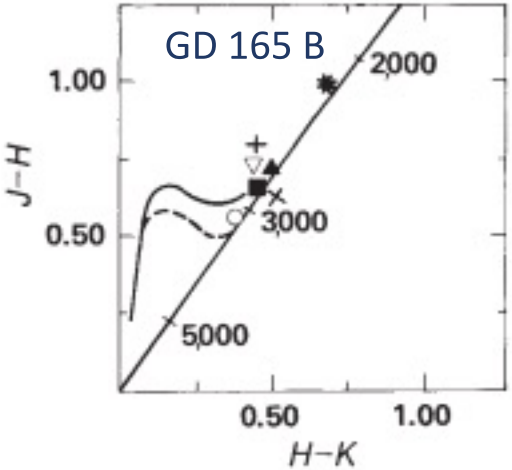
First discoveries late 90s, thanks to the advance of the near-infrared technology

And many discoveries from DENIS, 2MASS, CFHTLS, SDSS, SIMP, UKIDSS, WISE, PanSTARRS, …

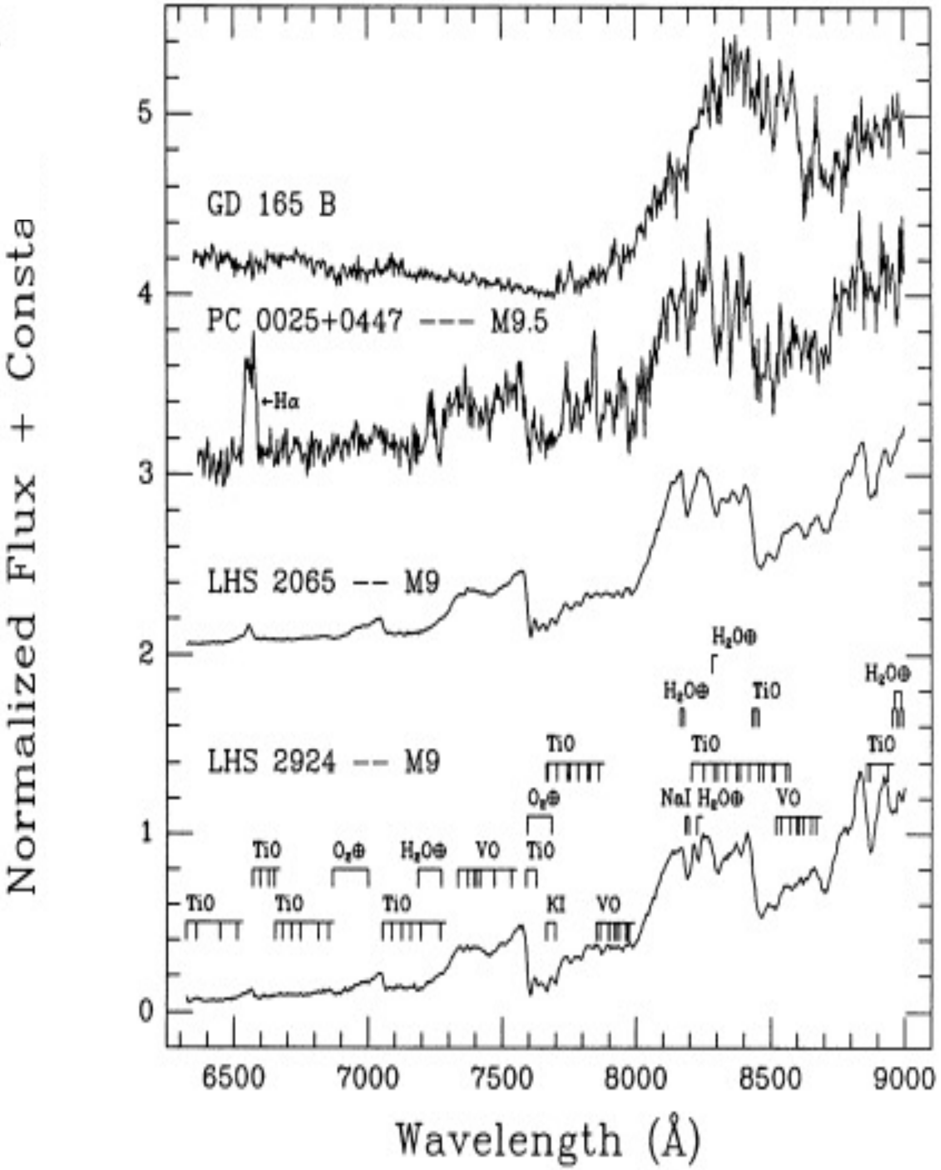


A low-temperature companion to a white dwarf star

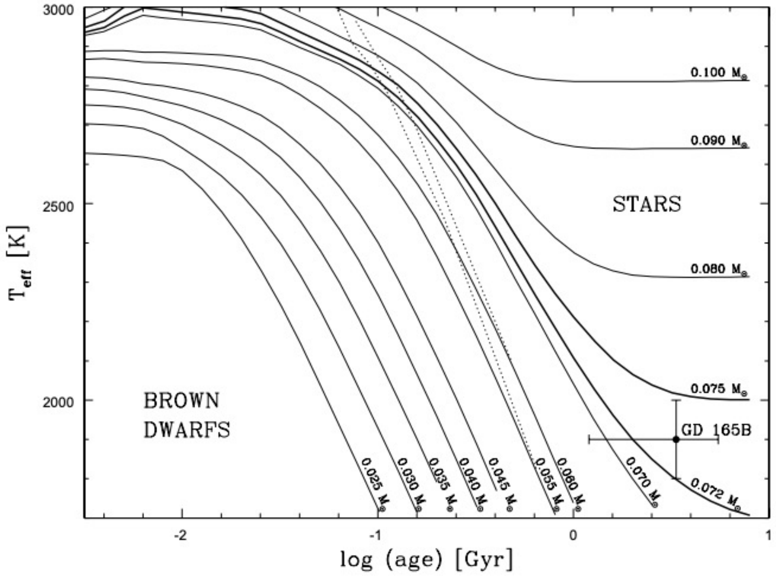
E. E. Becklin* & B. Zuckerman†



Becklin & Zuckerman 1988



Lack of dominant TiO bands seen in M dwarfs
Kirkpatrick et al 1993

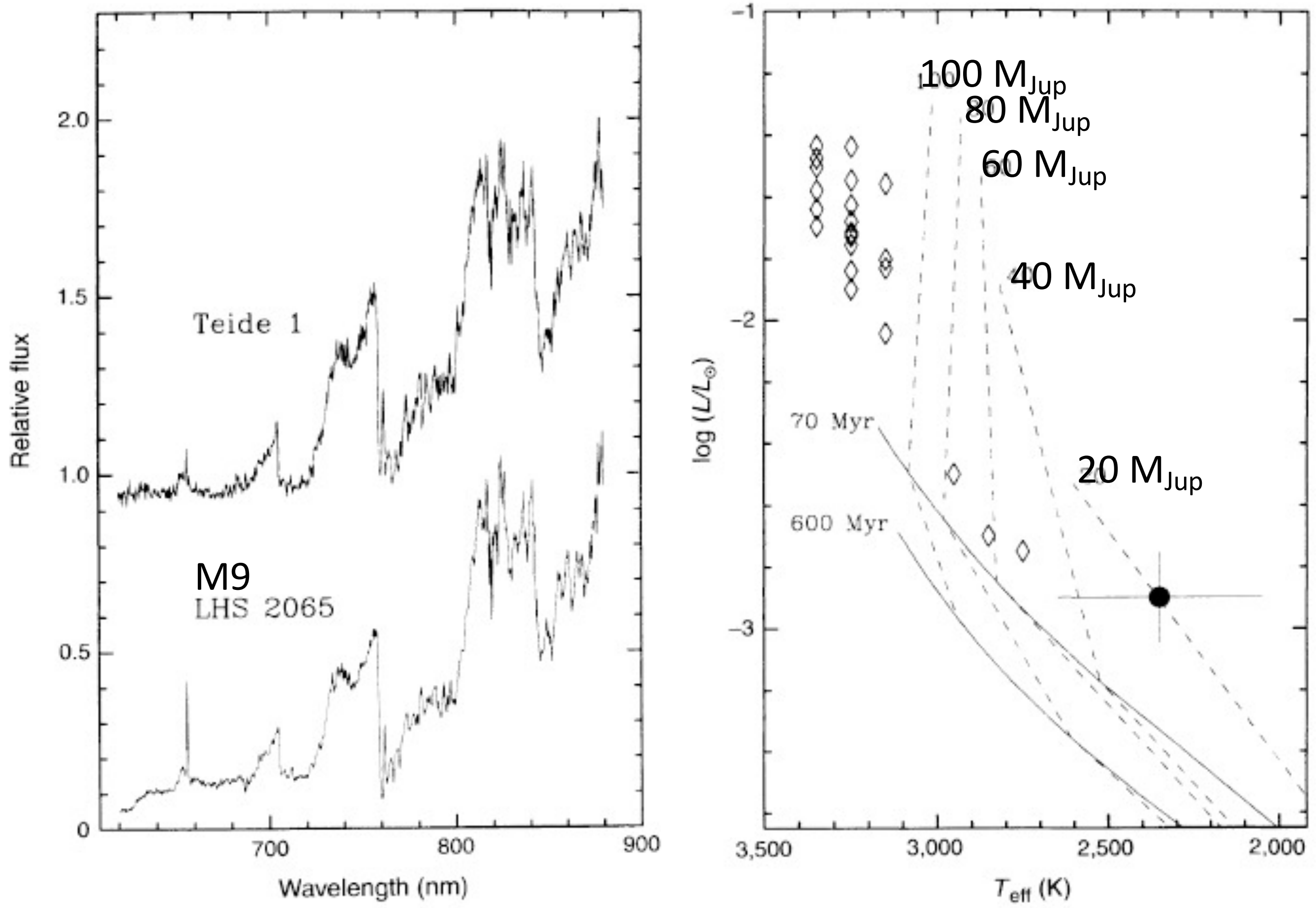


Lies at the stellar/substellar transition
$T_{eff} \simeq 1900$ K
Kirkpatrick et al 1999

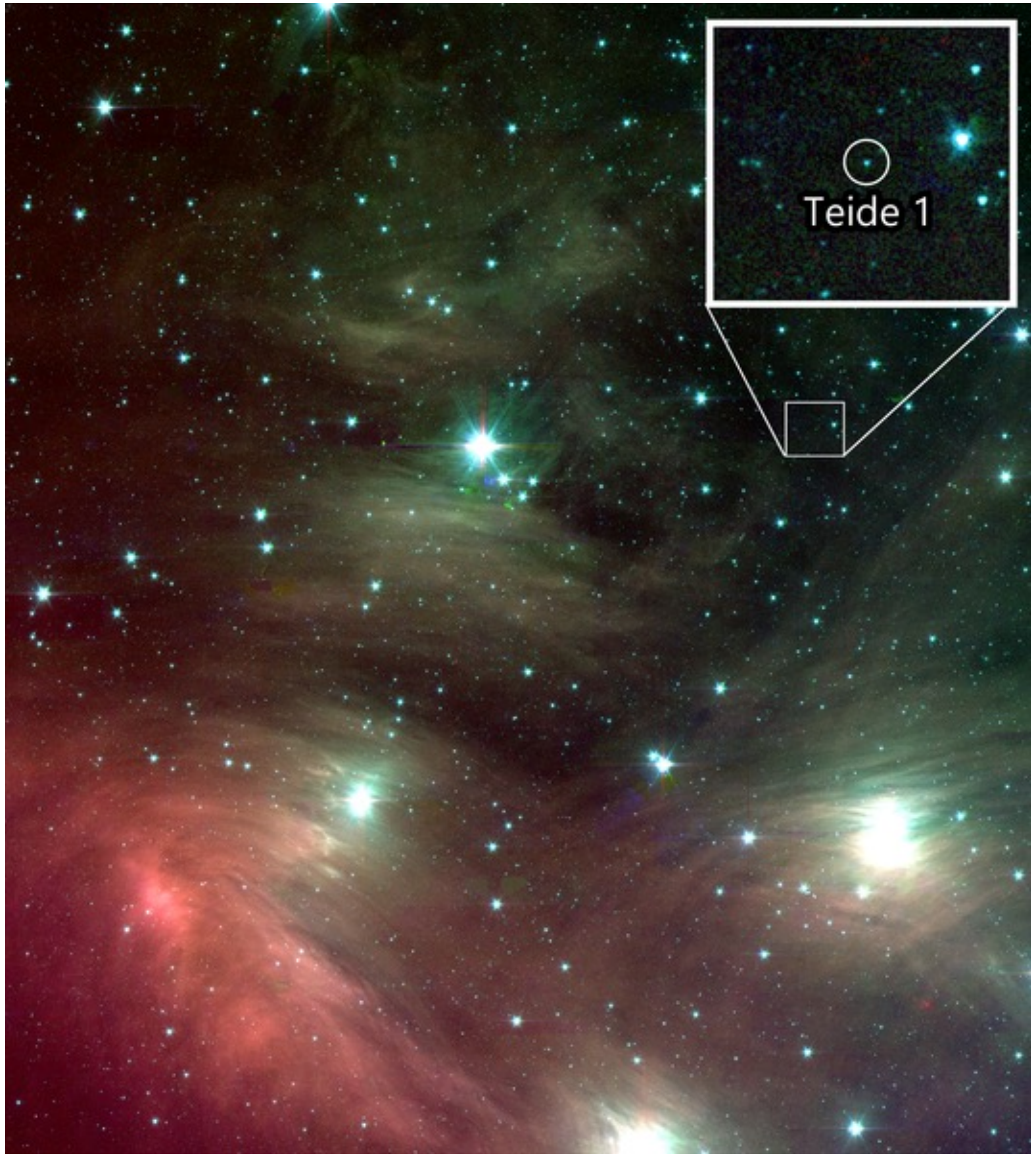
First example of a L dwarf

Discovery of a brown dwarf in the Pleiades star cluster

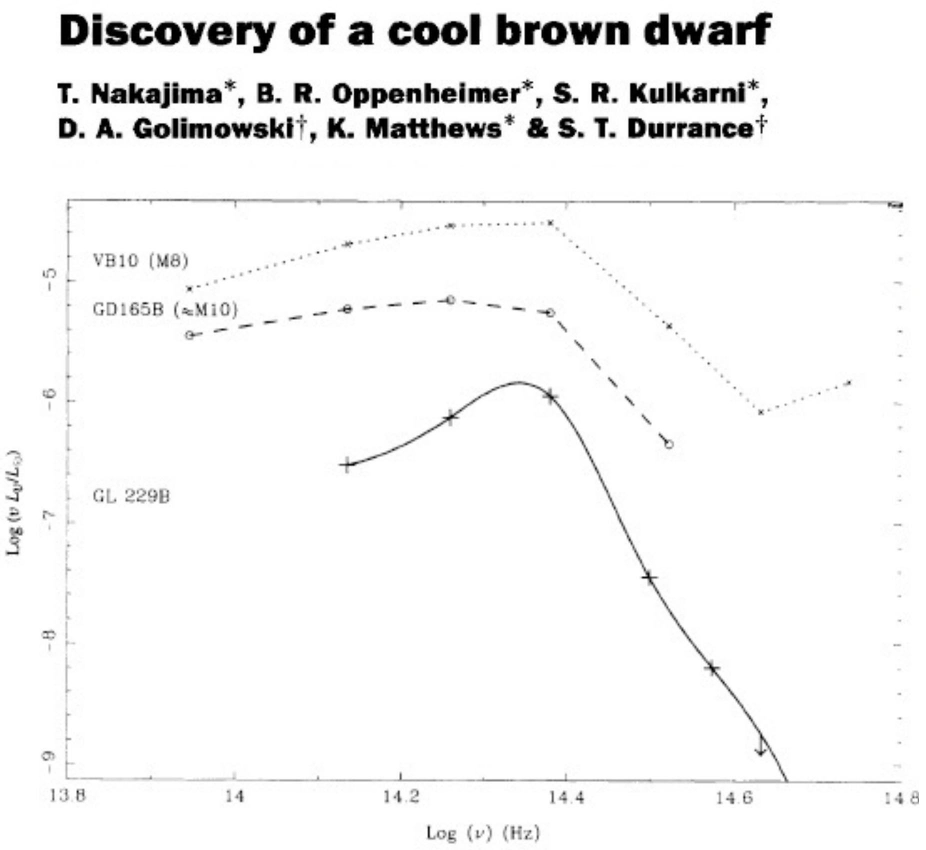
R. Rebolo, M. R. Zapatero Osorio & E. L. Martín



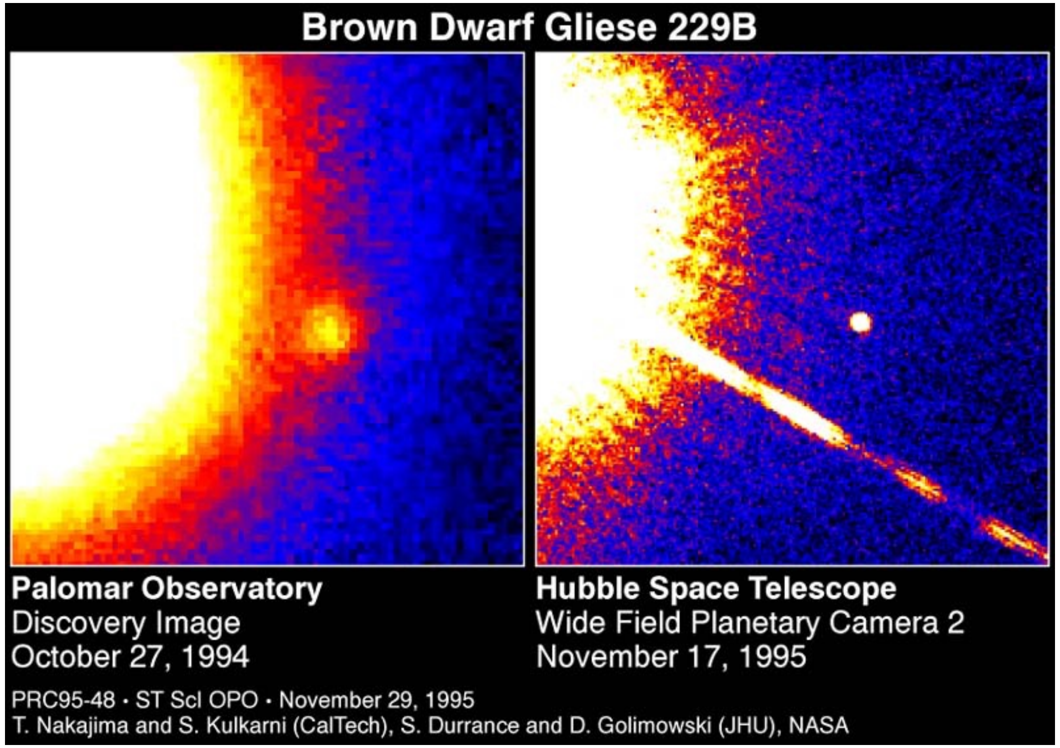
Rebolo, Zapaterio Osario & Martín, 1995



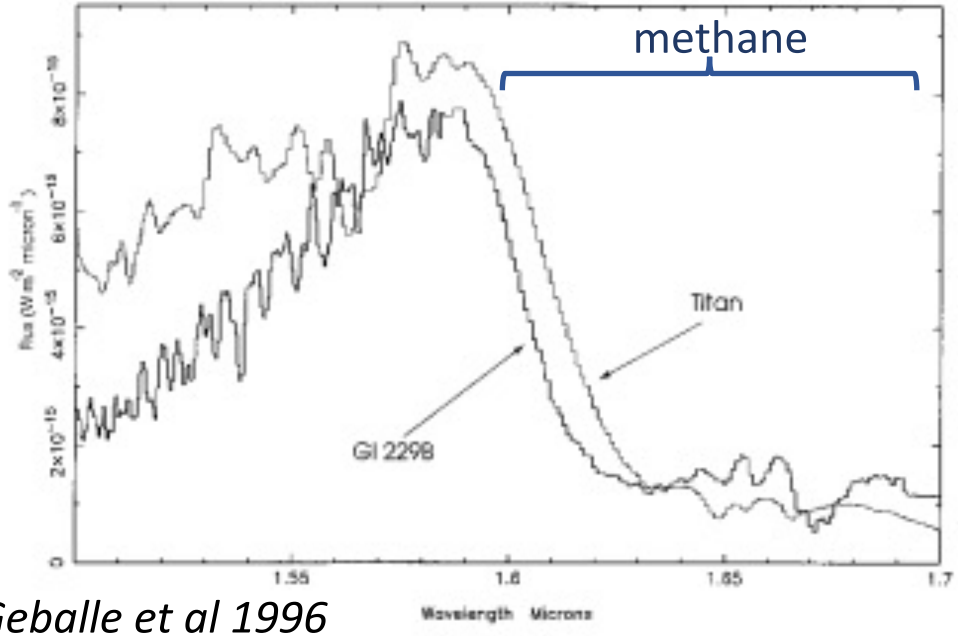
Pleiades and Teide 1 as seen by the Spitzer Space Telescope (IRAC)
Crédit: Meli Thev,
https://commons.wikimedia.org/wiki/File:Pleiades_and_Teide_1.png



Spectral energy distribution
Nakajima et al 1995



First example of a T dwarf



Geballe et al 1996

The detection of strong methane absorption in the NIR spectrum of this object provides further evidence that Gl 229B is a cool object with $T_{eff} \simeq 1000$ K (Oppenheimer et al 1995, Geballe et al 1996)


KELU-1 : A FREE-FLOATING BROWN DWARF IN THE SOLAR NEIGHBORHOOD

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Joint Astronomy Centre, University Park, Hilo, HI 96720
AND
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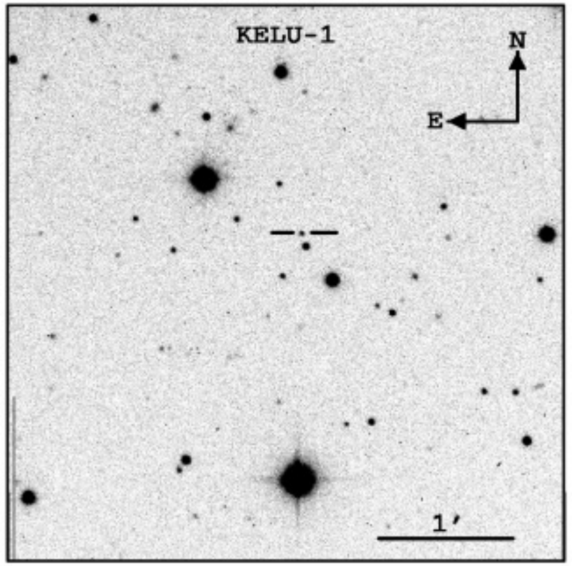
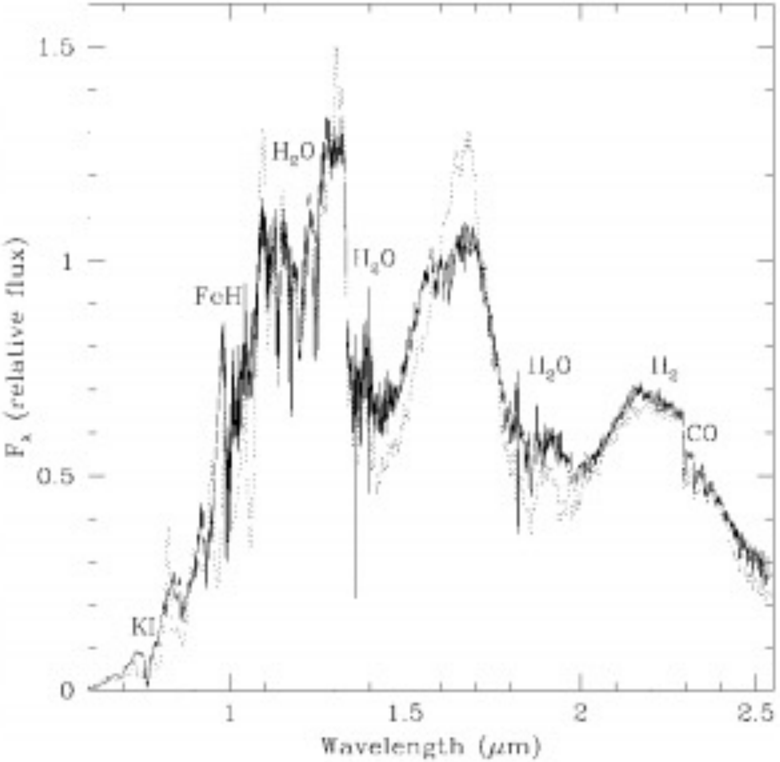
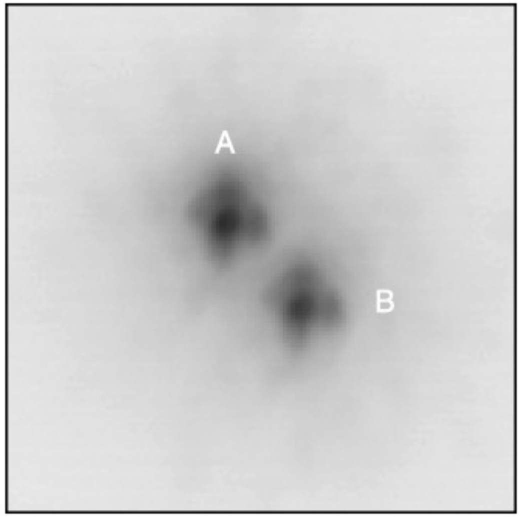
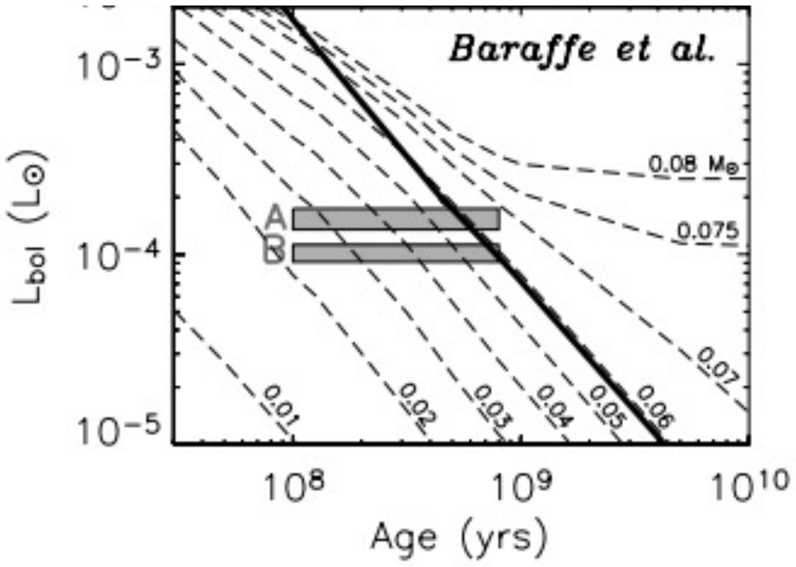
Department of Physics, Wichita State University, 1845 Fairmount, Wichita, KS 67260-0032





Best fit model: $T_{eff} \simeq 1900$ K
Ruiz, Leggett & Allard 1997





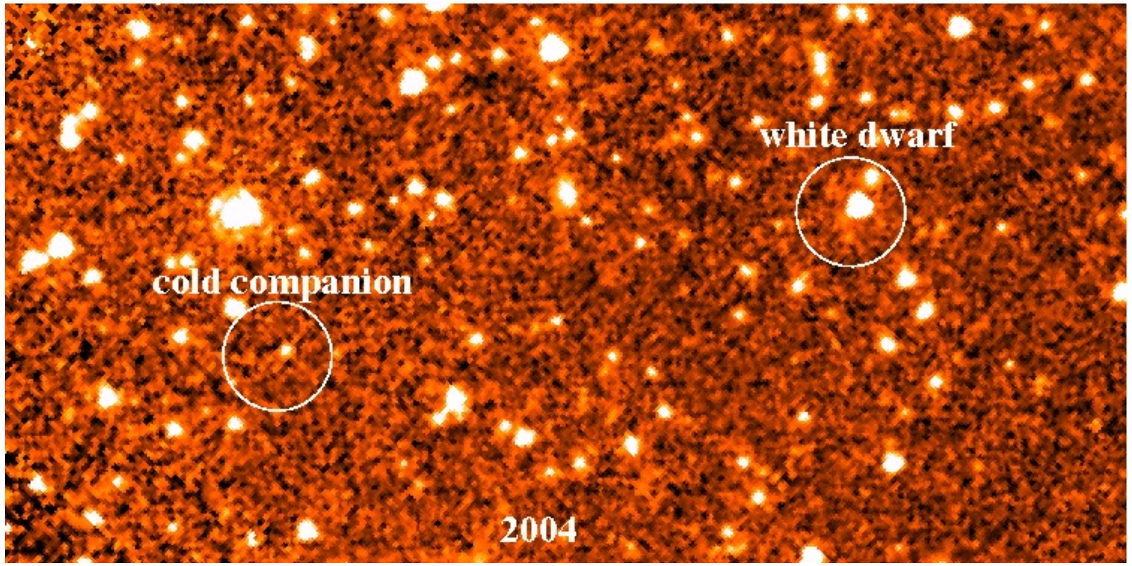
First field brown dwarf

See also 3 field brown dwarfs from DENIS (Delfosse et al 1997)

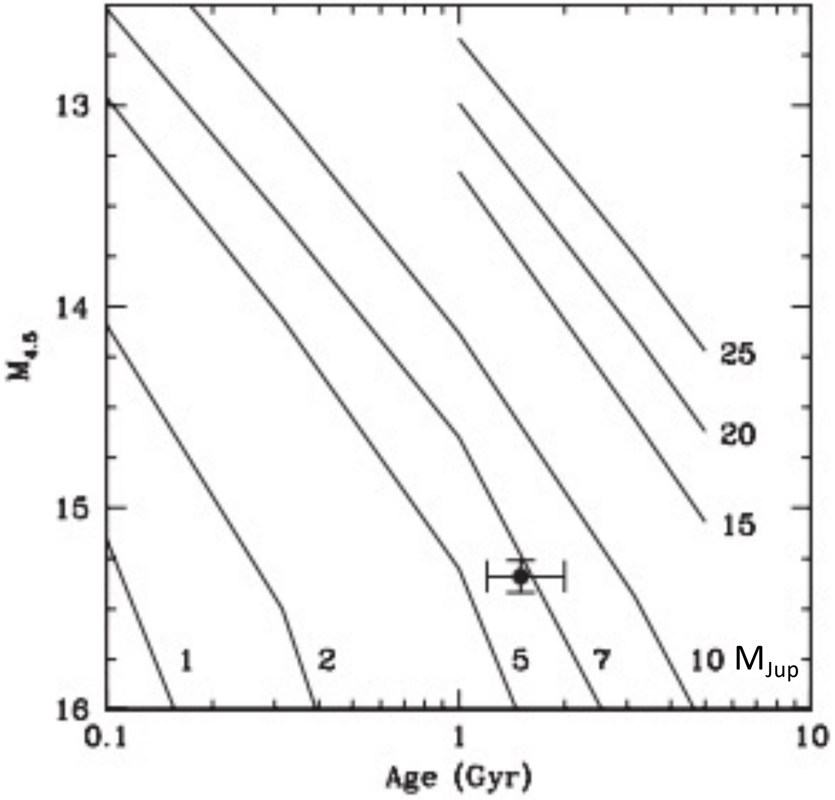
Kelu-1 AB resolved with adaptive optics at Keck: L2+L3.5
Gelino, Kulkarni & Stephens 2006
Liu & Leggett 2005

DISCOVERY OF A CANDIDATE FOR THE COOLEST KNOWN BROWN DWARF*

K. L. Luhman[1,2], A. J. Burgasser[3,4], and J. J. Bochanski[1]



WD 0806-661 AB from Spitzer in 2004 and 2009
Credit: Kevin Luhman Penn State University

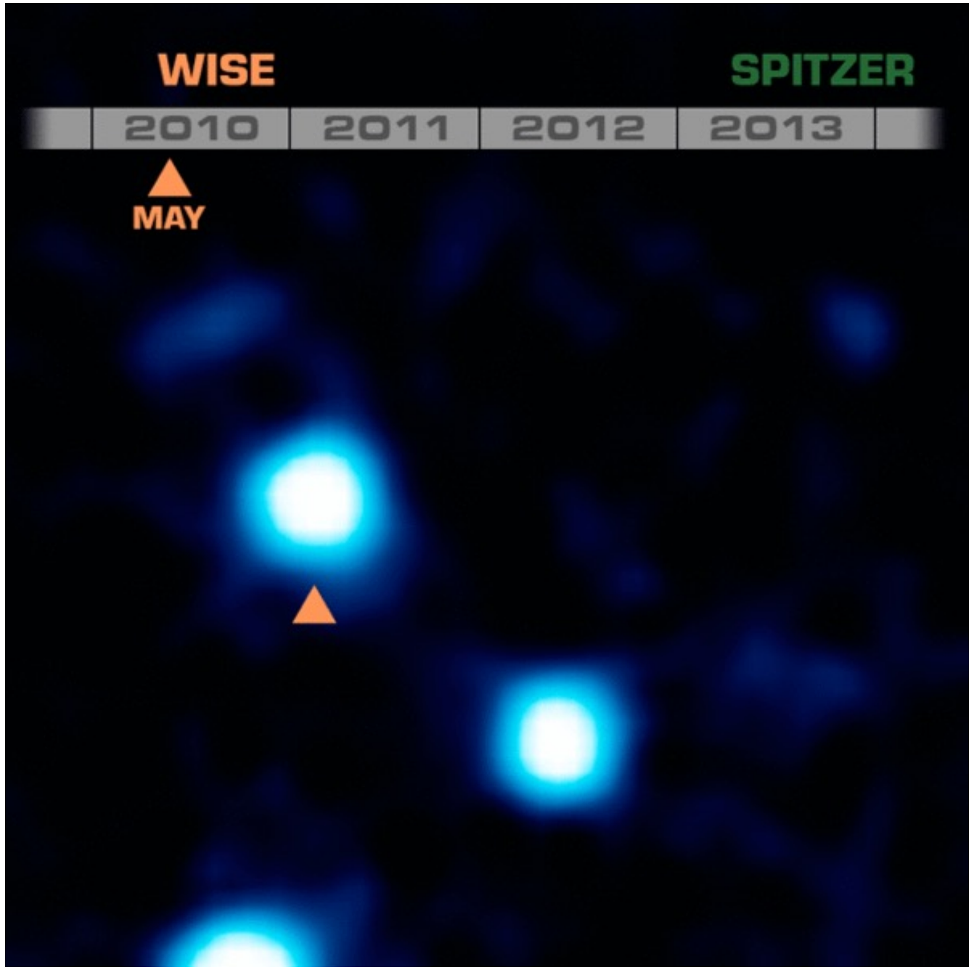


Magnitude predicted by Burrows et al 20.03 evolutionary models
$T_{eff} \simeq 300$ K *and* M $\simeq 7\ M_{Jup}$
Luhman, Burgasser & Bochanski 2011

First example of a Y dwarf

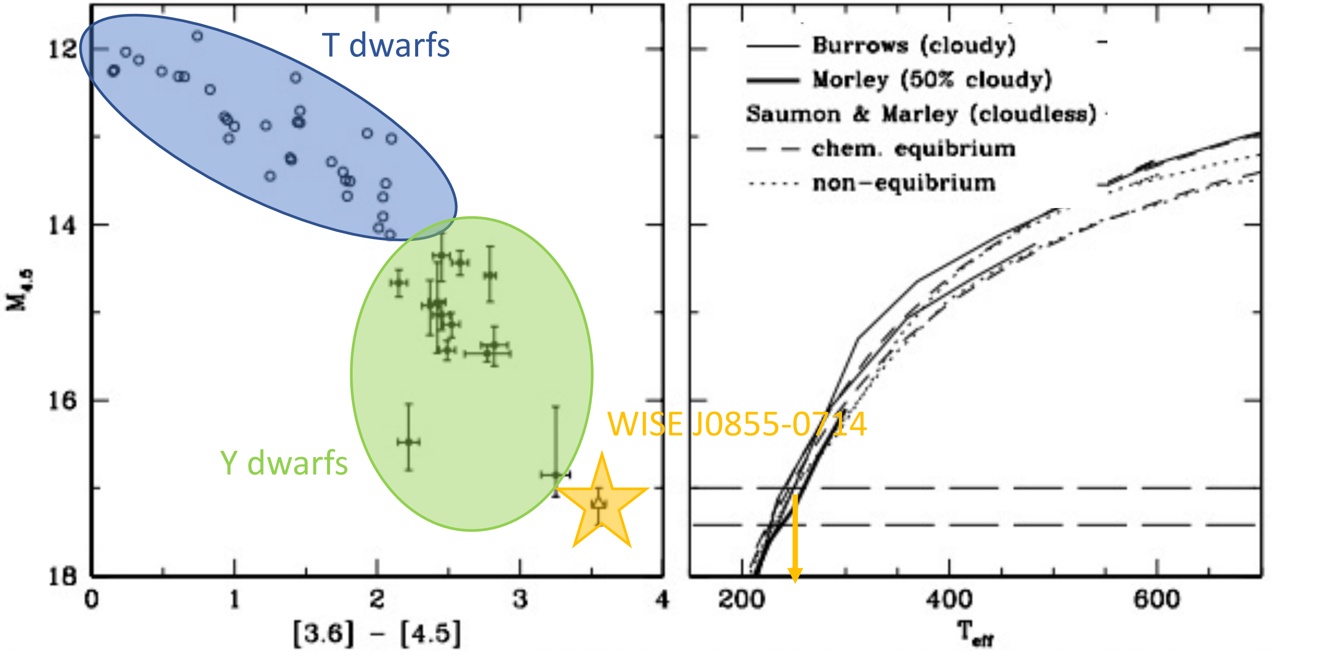
DISCOVERY OF A ~250 K BROWN DWARF AT 2 pc FROM THE SUN*

K. L. Luhman[1,2]



WISE J085510.83-071442.5 seen by WISE and Spitzer

Credit: NASA/JPL-Caltech/Penn State University



3^d highest proper motion, 4^{th} highest parallax

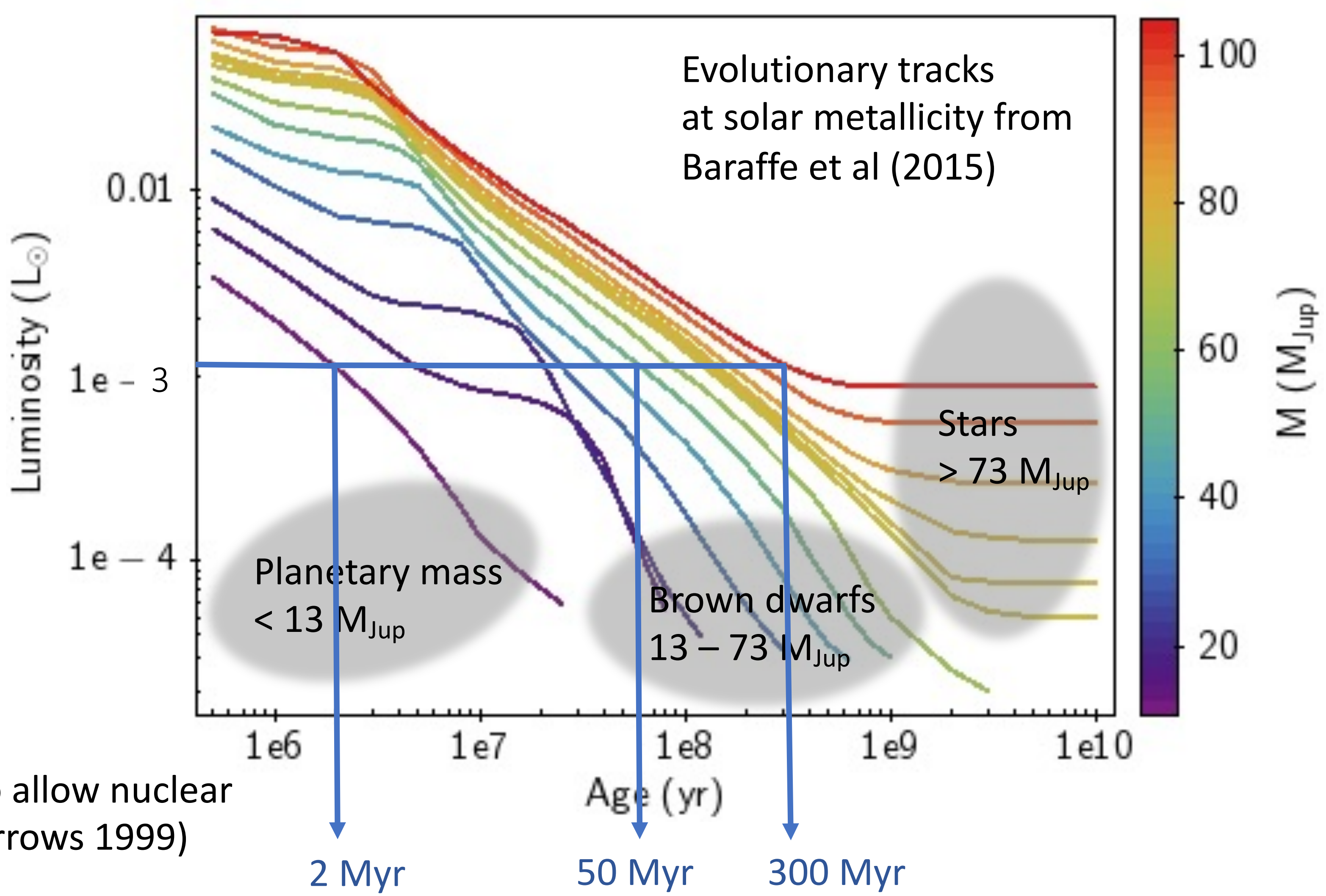
$T_{eff} \simeq 225–260$ K (as cold as the North Pole) and $M \simeq 3–10\ M_{Jup}$

Y4

Luhman 2014

The stellar/substellar limit

Mass

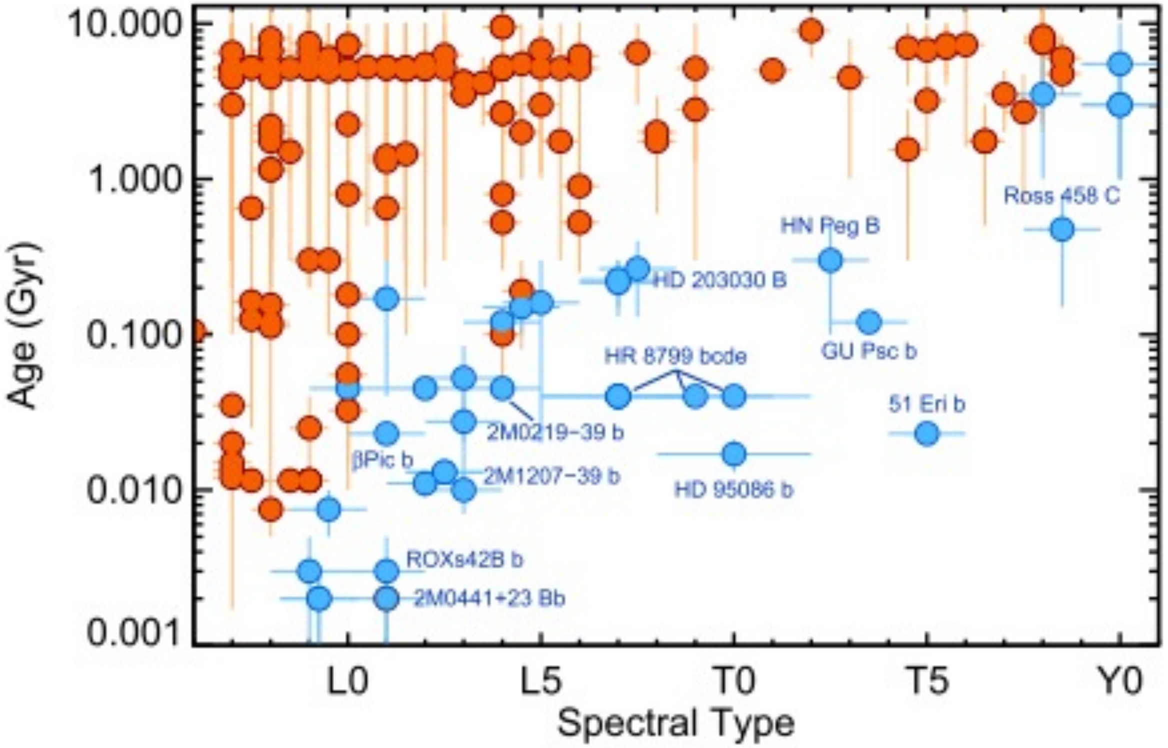


13 M_{Jup} is the mass limit to allow nuclear fusion (deuterium, e.g. Burrows 1999)

The stellar/substellar limit

Very low-mass stars, brown dwarfs, and planetary mass objects can have the same brightness.

Mass



Brown dwarfs and stars >$13M_{Jup}$
Planetary mass objects <$13M_{Jup}$

Ultracool substellar companions with well-constrained ages and spectroscopically derived classifications
Bowler 2016

The stellar/substellar limit

Mass

Theoretical mass limit of hydrogen fusion

- Chabrier & Baraffe (2000) review

0.070–0.072 $M_{\odot}$ (73–75 M_{Jup}) depending on cloud opacities

- Burrows et al. (2001) review

0.070–0.075 $M_{\odot}$ (73–79 M_{Jup}) for solar metallicity

0.092 $M_{\odot}$ (96 M_{Jup}) for zero metallicity

- Cloudy models from Saumon & Marley (2008)

0.070 $M_{\odot}$ (73 M_{Jup})

- Models from Burrows et al. (2011)

0.070–0.075 $M_{\odot}$ (73–79 M_{Jup}) assuming different helium fractions

- Models from Baraffe et al. (2015)

0.067–0.072 $M_{\odot}$ (70–75 M_{jup})

- Models from Marley et al. (2021)

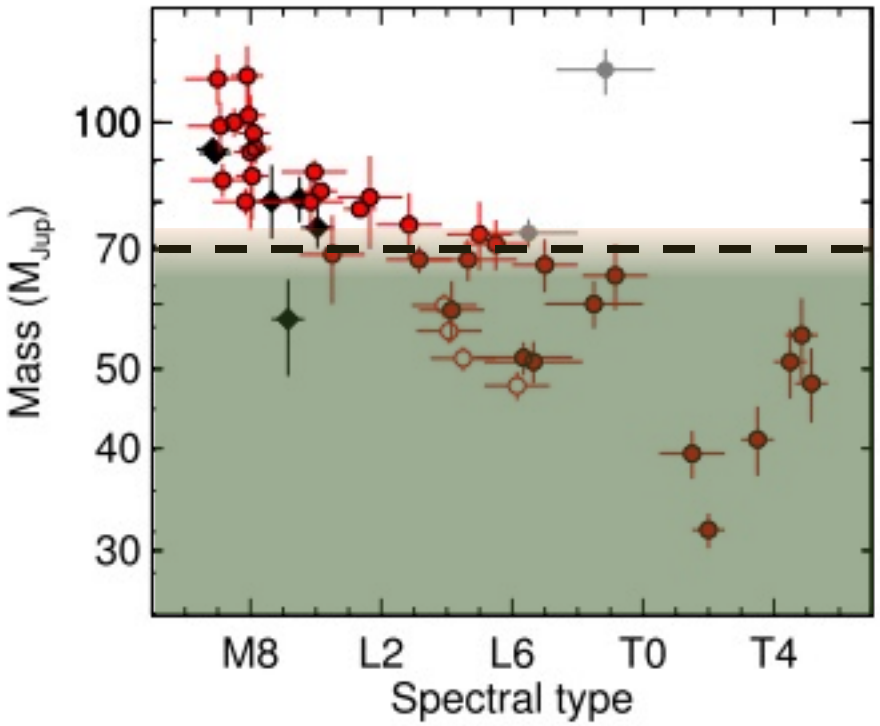
0.070 $M_{\odot}$ (73 M_{Jup})

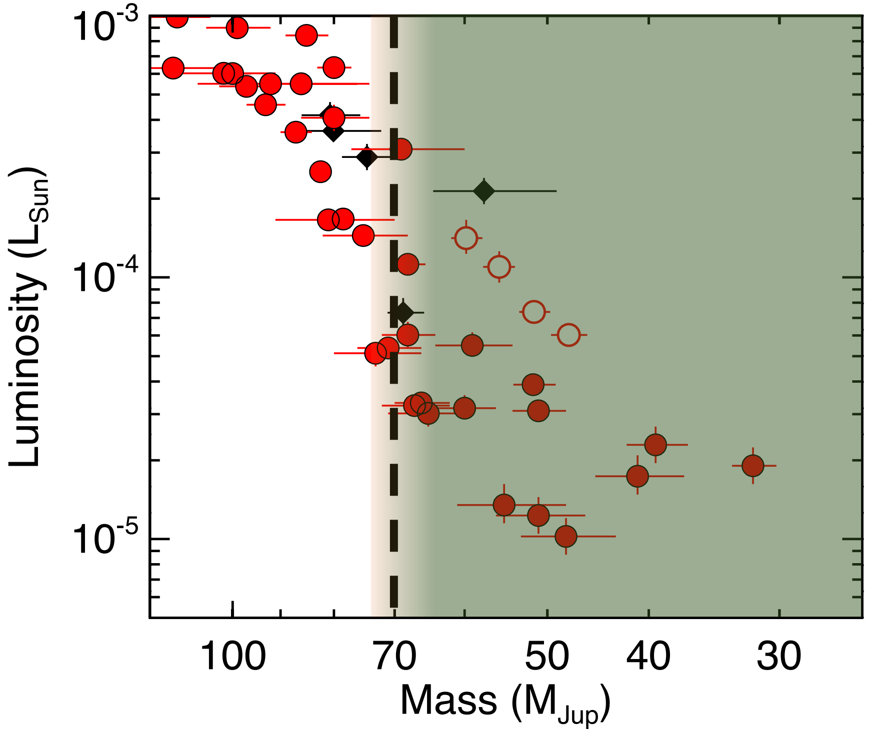
The stellar/substellar limit

Mass

Empirical mass limit of hydrogen fusion

Dupuy & Liu (2017) determined dynamical mass of 31 ultracool dwarfs binaries (M7-T5). Boundary defined by the maximum mass of the latest-type (or lowest luminosity) objects: **70±4 M_{Jup}**





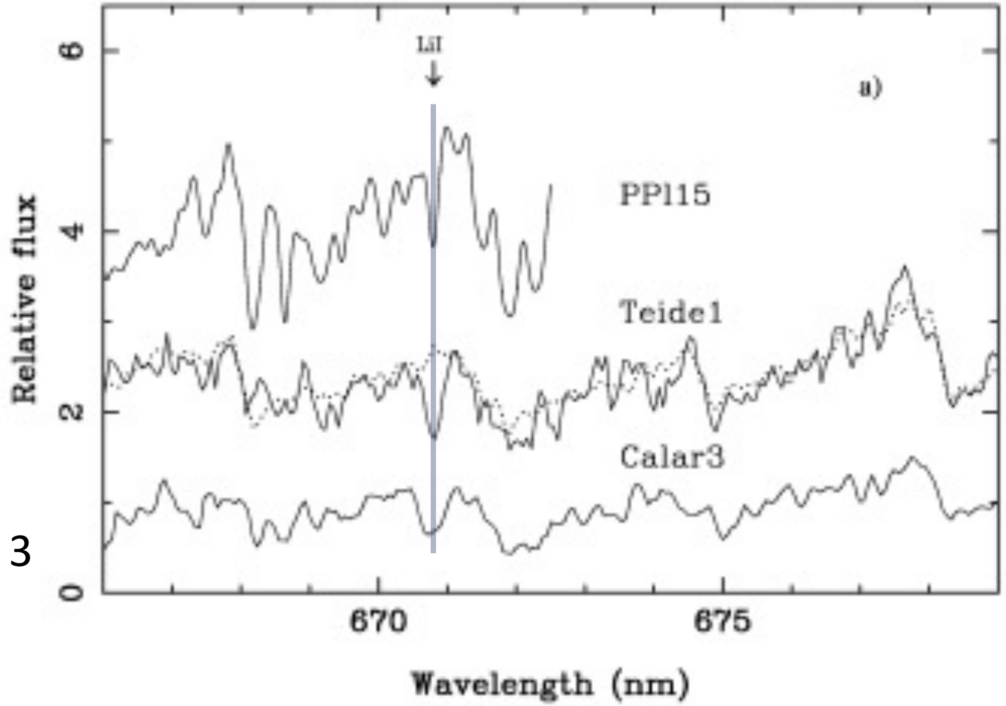
The stellar/substellar limit

Lithium test

« observations of the Li I resonance doublet at 670.8 nm can be used successfully as a powerful spectroscopic test for discriminating between low-mass stars and brown dwarfs » Rebolo et al 1992

Li converted to He through fusion at central temperatures of ~ 2.5×10^6 K.
Li is rapidly destroyed even in very low mass stars. Li I doublet has been observed only in very young T Tauri stars.
Objects not massive enough to reach such temperatures in their interior do not burn Li.

Li first detected in the Pleiades member PPl15 (Basri, Marcy & Graham, 1996), assessing its substellar nature.



Detection of Li in Teide 1 and Calar 3
Rebolo et al, 1996

The stellar/substellar limit

Lithium test

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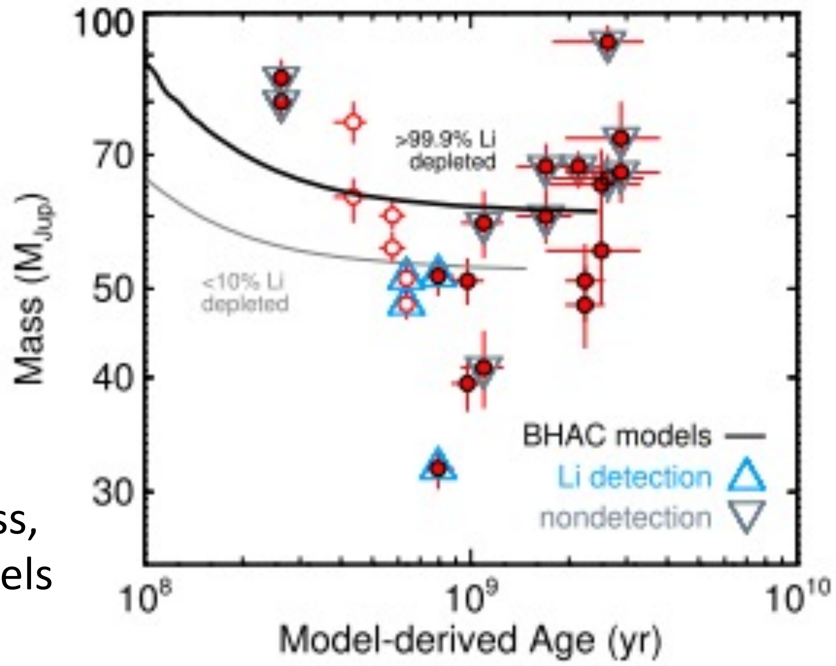
Transition mass $M \approx 0.06\ M_\odot$
$62 - 65\ M_{jup}$

D'Antona & Mazzitelli 1985; Burrows et al 1989 Pozio el al 1991; Magazzu et al 1993; Nelson et al 1993; Chabrier et al 1996; Bildsten et al 1997; …



Li test in 13 binaries with dynamical mass, compared with Baraffe et al (2015) models
Dupuy & Liu, 2017

The stellar/substellar limit

Lithium test

😕 Challenging to apply to all brown dwarfs

- needs quite large telescopes (L- and T-type brown dwarfs are quite faint at 670 nm), medium resolution and good signal-to-noise ratio (see e.g. Martín et al. 1999, Kirkpatrick et al. 2008)
- confusion between the most massive brown dwarfs with depleted Li and the lowest mass stars
- Li I atomic feature disappears in cool objects where Li is rather found in molecular species (LiH, LiCl, LiF , Li2S; Lodders 1999; Weck et al 2004; Gharib-Nezhad et al 2021)

The latest-type object known to display Li I absorption is Luhman16B (T0.5; Faherty et al. 2014; Lodieu et al. 2015)

🙂 Li test is still relevant, even for the cool brown dwarfs showing evident substellar atmosphere (e.g. methane in T-dwarfs)

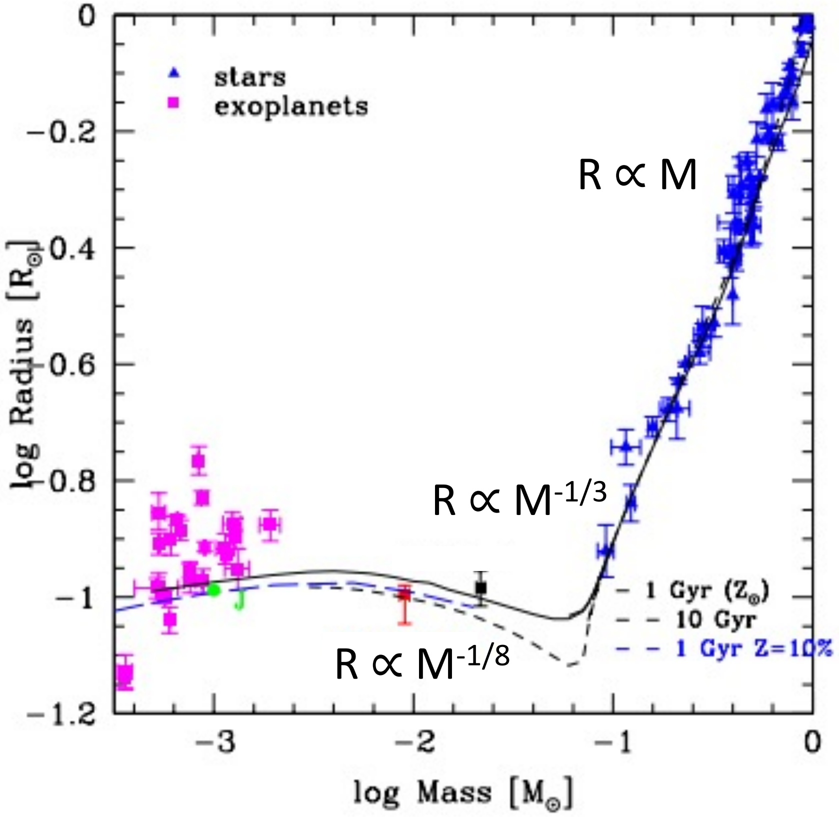
- the Li test brings an independent age and mass indicator.

The stellar/substellar limit

Radius

Models predict a reversal of the mass–radius relation at the hydrogen burning limit

In a more massive brown dwarf, **gravitational force is higher** and causes a **larger fraction** of the brown dwarf **to become degenerate**, causing it to have a smaller radius
→ The mass–radius relation shows a local minimum at the most massive brown dwarfs



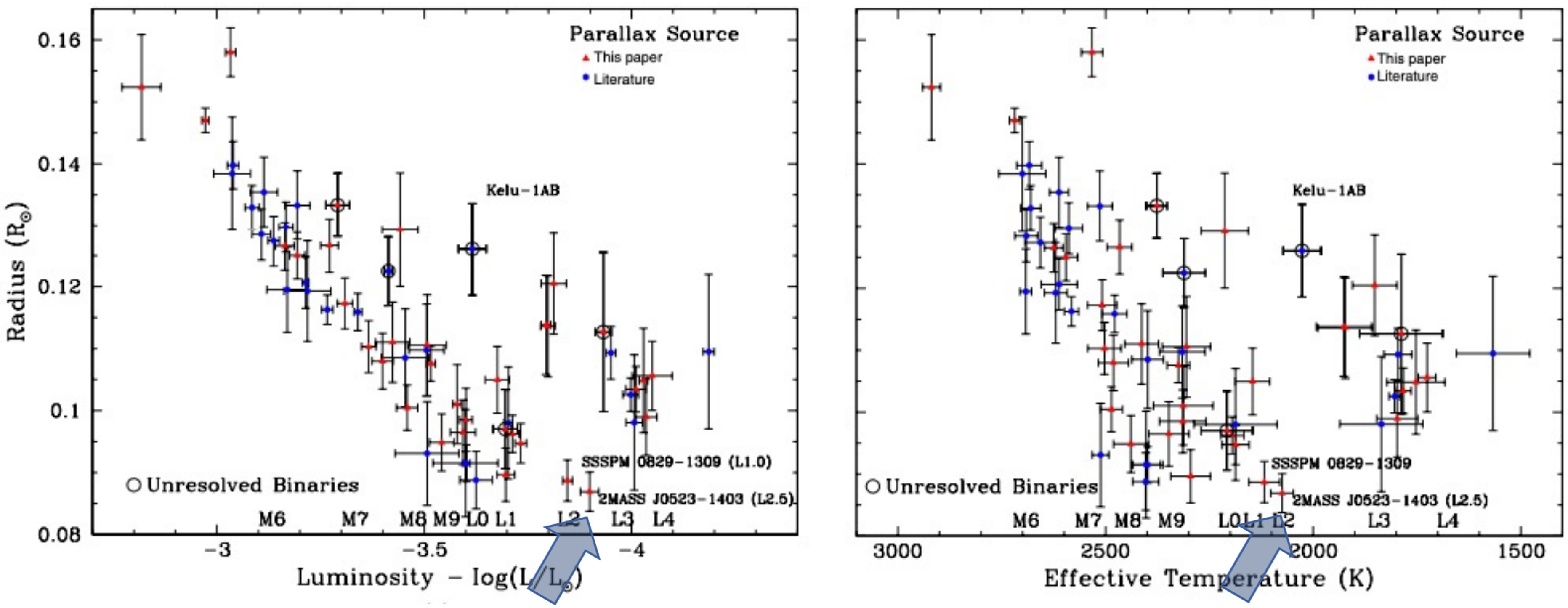
The minimum size is about the size of Jupiter

Mass-radius relation
Chabrier et al 2009

The stellar/substellar limit

Sample of 63 M6 to L4 dwarfs with parallaxes
Radius from Stefan-Boltzman law: $L_{bol} = 4\pi R^2 \sigma T_{eff}^4$

Radius



L_{bol} -R and T_{eff}-R relations
Dieterich et al 2014

2MASS J0523−1403 the lowest-mass star or highest-mass brown dwarf

The stellar/substellar limit

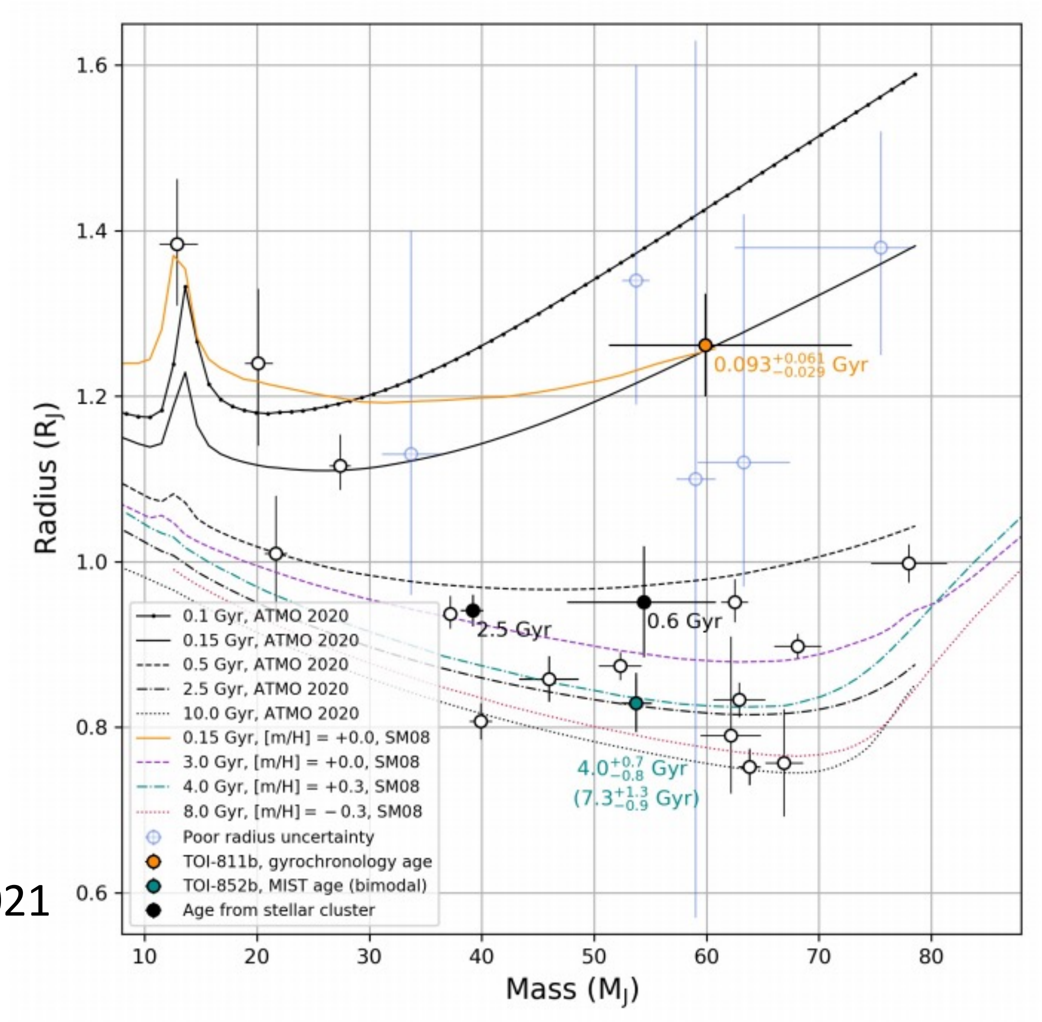
At given mass, theoretical isochrones predict that older objects have smaller radii

Radius

Transiting brown dwarfs and low mass stars with age estimate from the primary star → test of the age-radius effect

Transiting brown dwarfs generally validate model radii

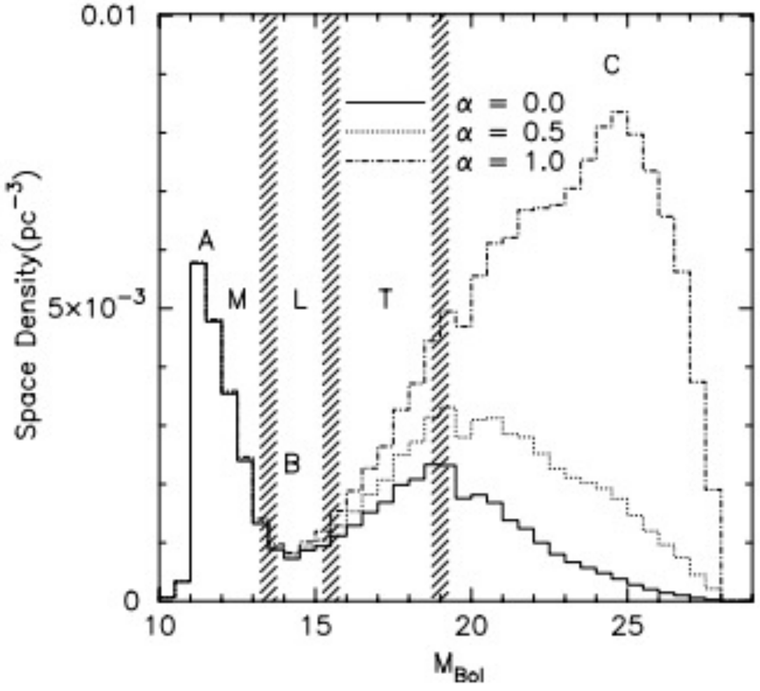
Carmichael et al 2021
see also Grieves et al. 2021



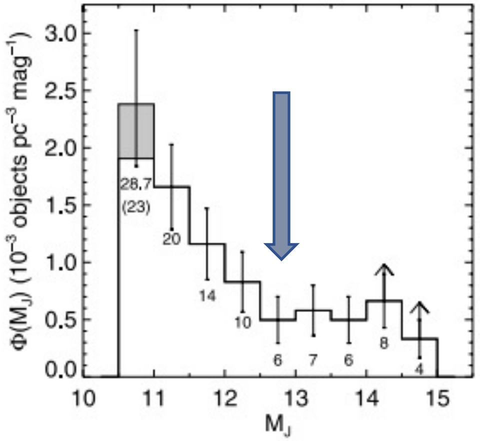
The stellar/substellar limit

Spectral type

Field stars and brown dwarfs are several Gyr in average. Brown dwarfs depopulate rapidly earlier spectral types to go to later ones
→ Expected minimum in the density at the stellar/substellar boundary (as shown in simulations, e.g. Burgasser et al 2004, Allen et al 2005)

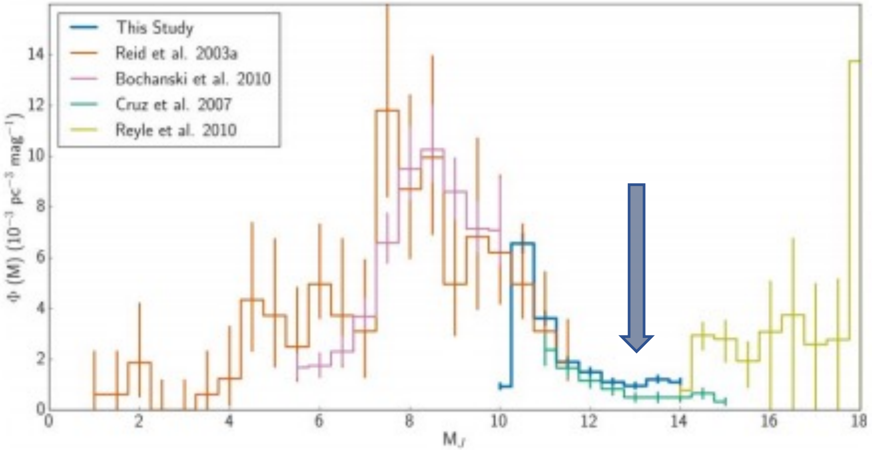


Simulated luminosity function assuming different initial mass functions *Allen et al (2005)*



Cruz et al 2007

Bardalez-Gagliuffi et al 2019



The stellar/substellar limit

Field stars and brown dwarfs are several Gyr in average. Brown dwarfs depopulate rapidly earlier spectral types to go to later ones
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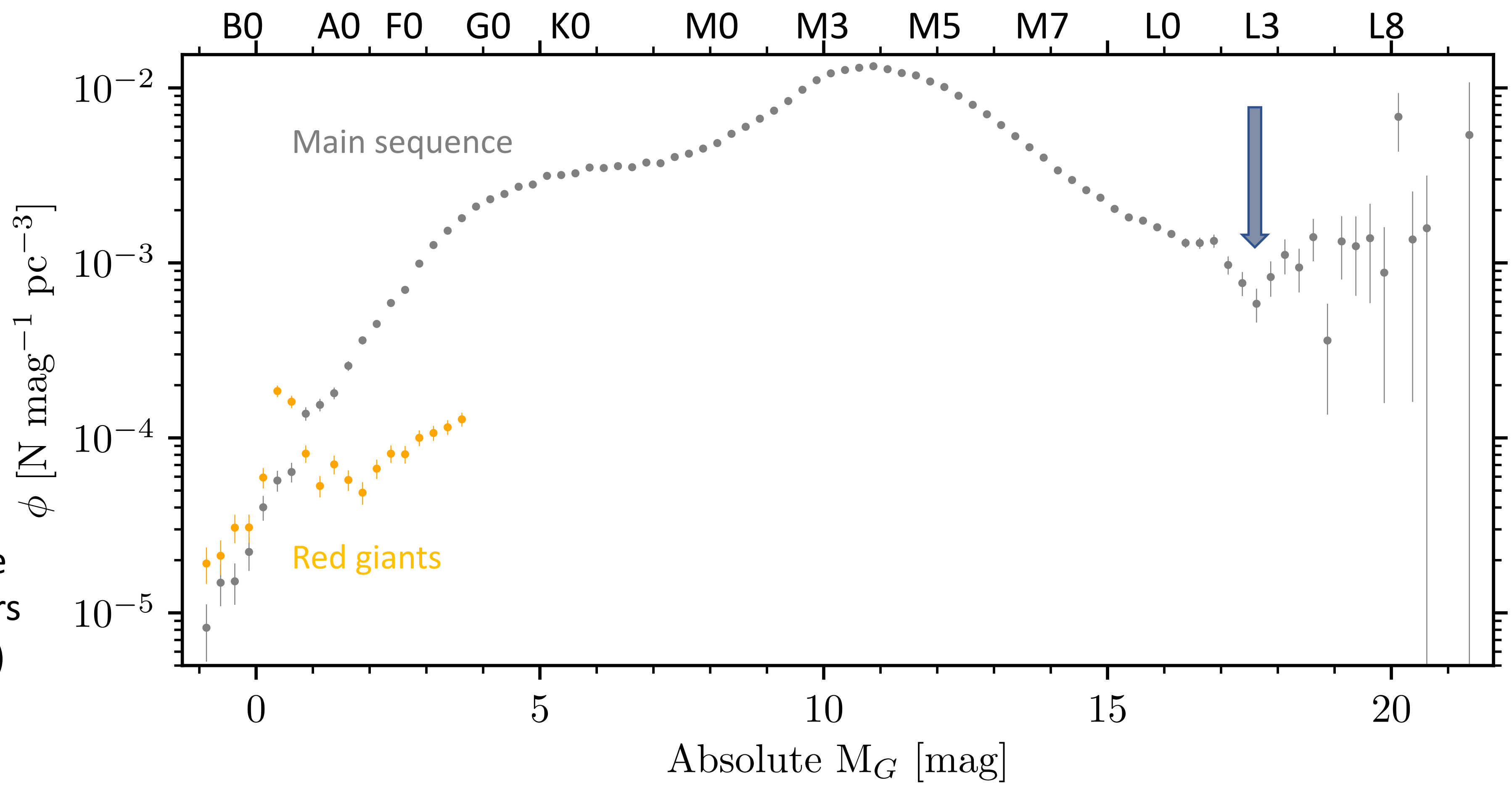
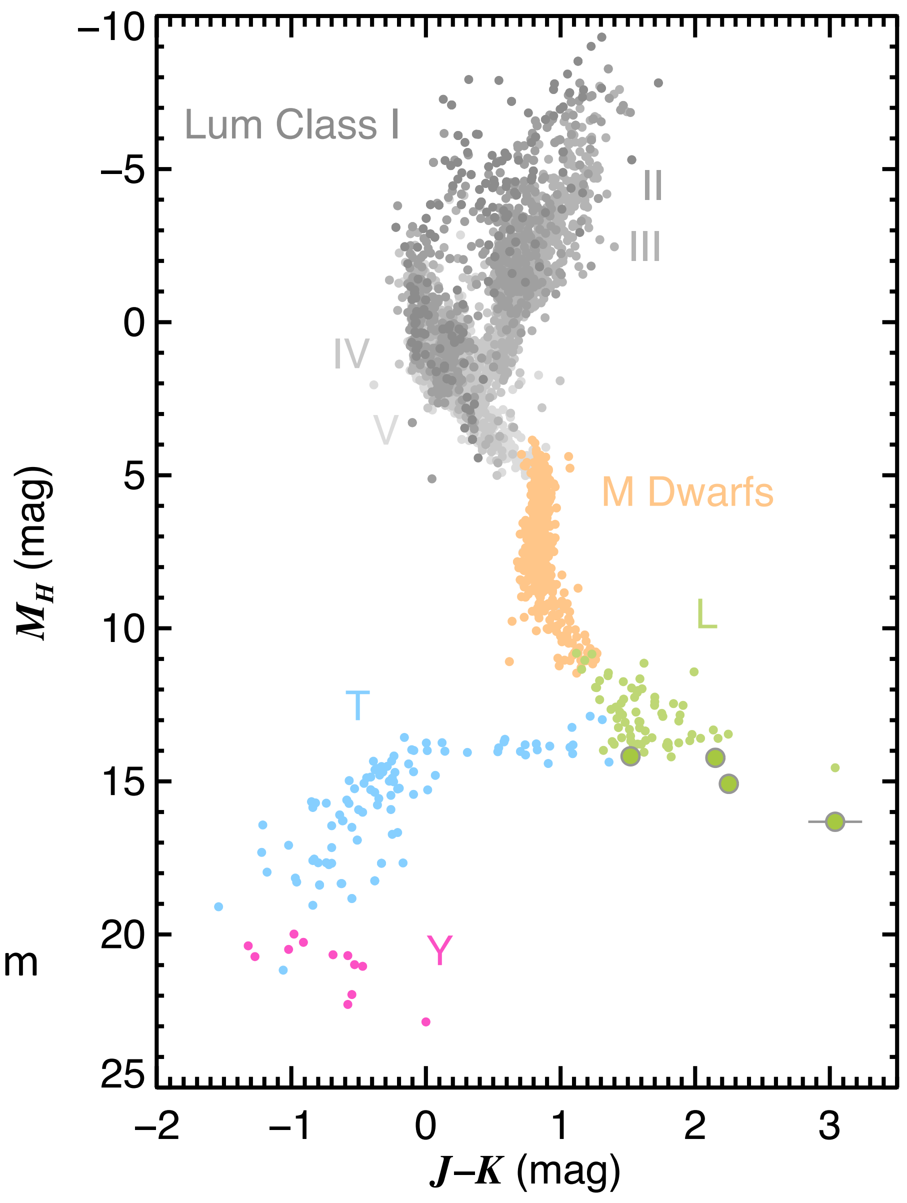
Spectral type



The luminosity function of the *Gaia* Catalogue of Nearby Stars (~330 000 stars within 100 pc)
Gaia Coll., Smart et al 2021

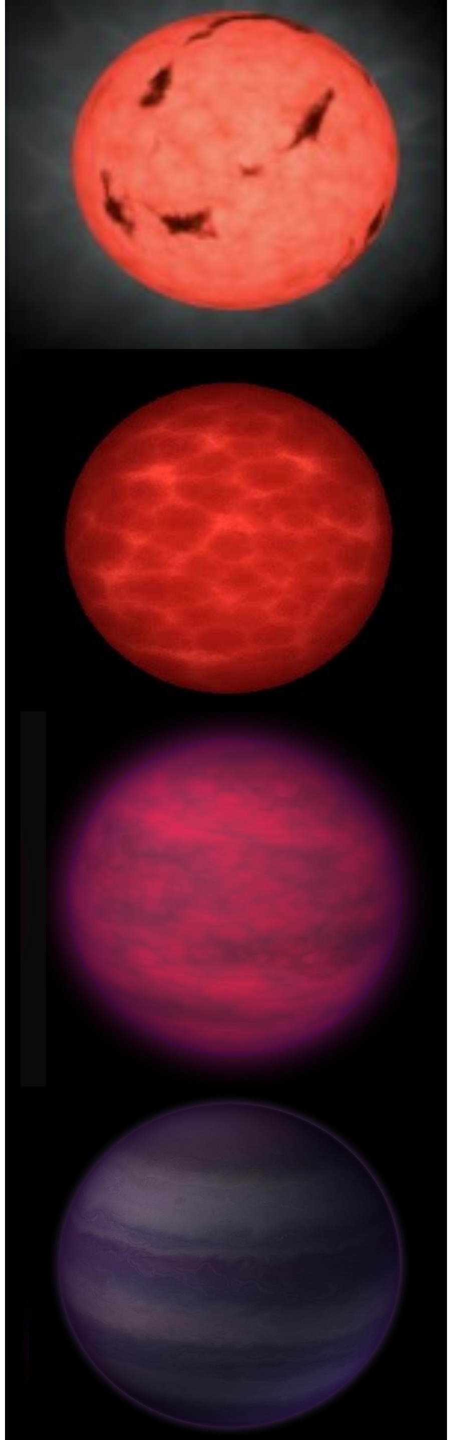
Ultracool dwarfs have a huge range of astrophysical properties!

Large variety of characteristics
→ complex physical processes acting in their atmospheres.



Colour absolute magnitude diagram in 2MASS bands
Bowler 2016

Temperature sequence



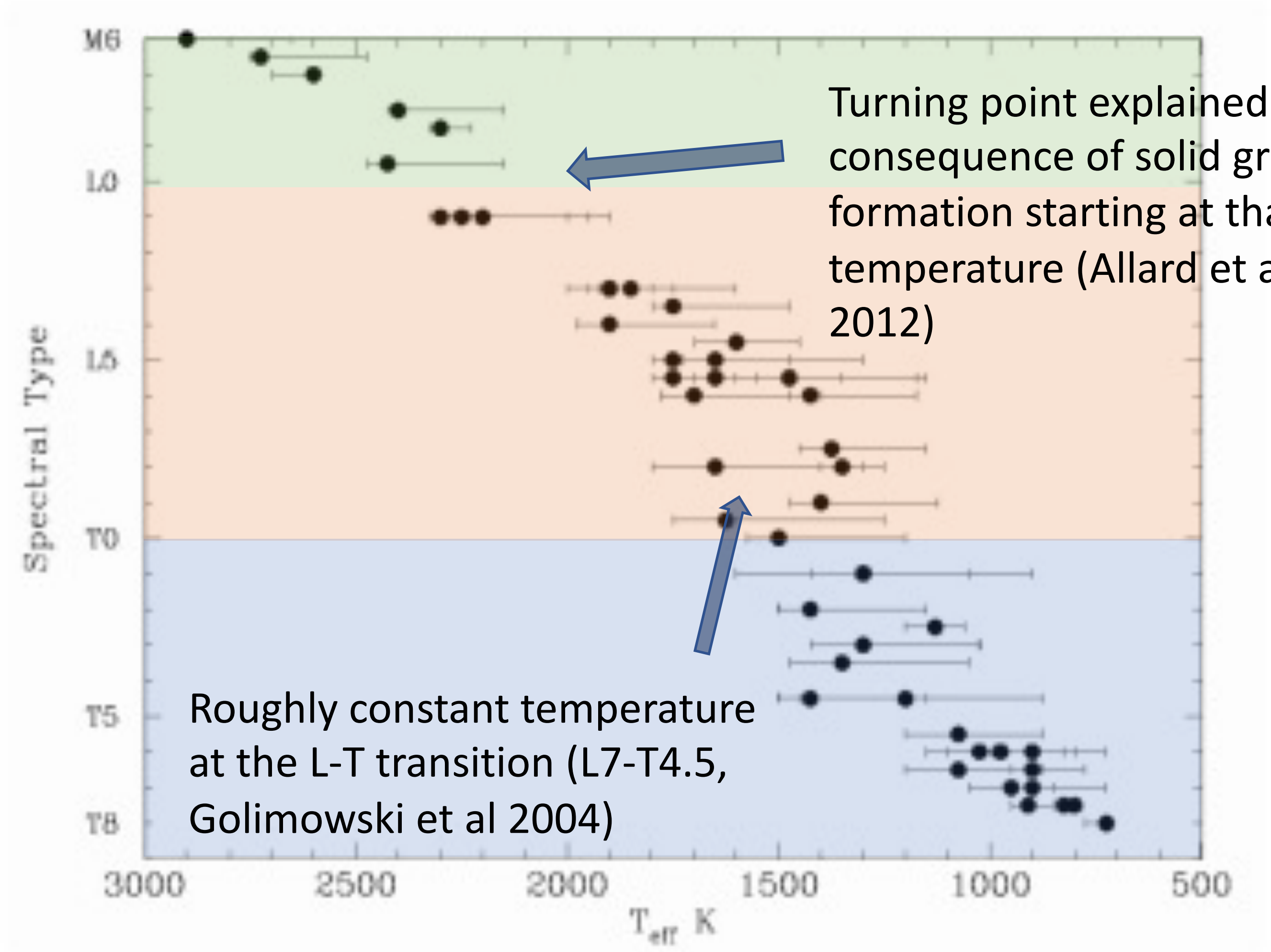
M-dwarfs
~3500-2100 K

L-dwarfs
~2100-1300 K

T-dwarfs
~1300-550 K

Y-dwarfs
~550-<250 K
“room-temperature”

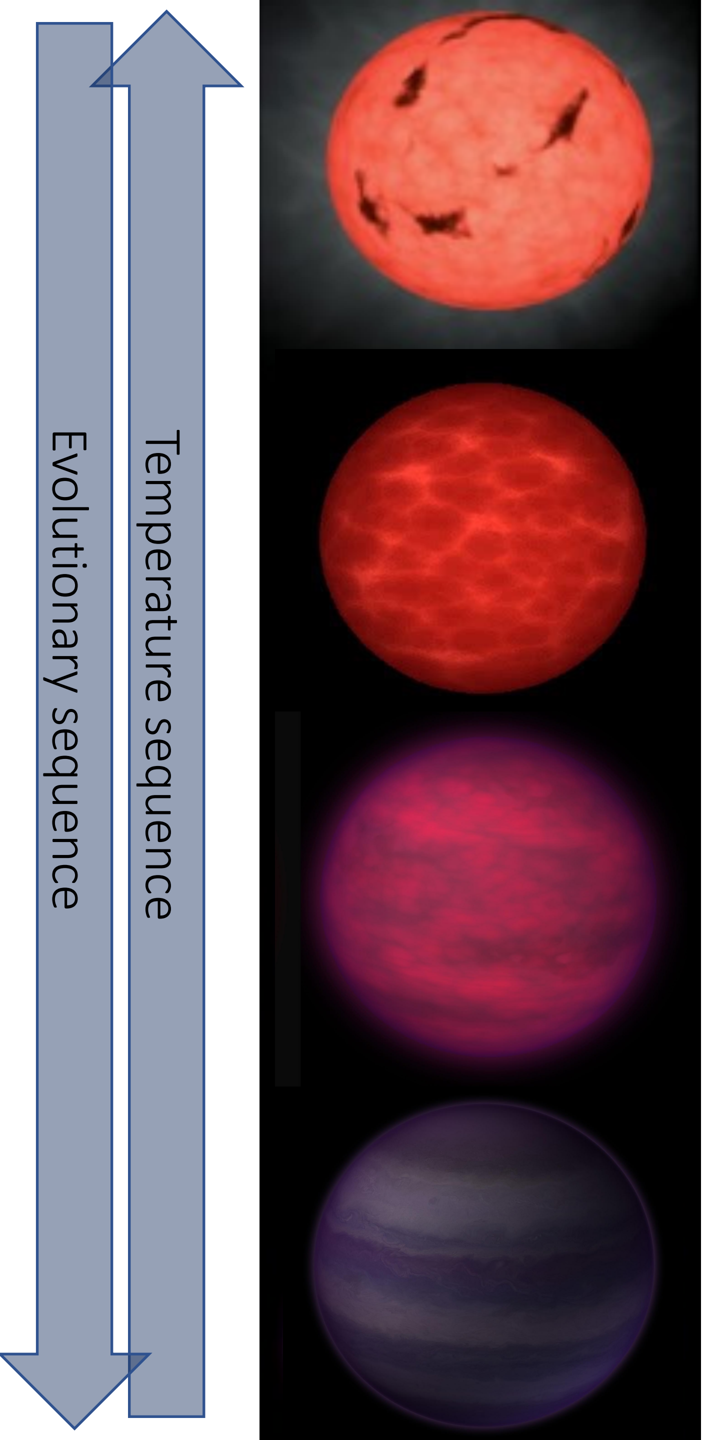
Effective temperature



Turning point explained as consequence of solid grain formation starting at that temperature (Allard et al 2012)

Roughly constant temperature at the L-T transition (L7-T4.5, Golimowski et al 2004)

Marley & Leggett 2008



M-dwarfs

youngest brown dwarfs

L-dwarfs

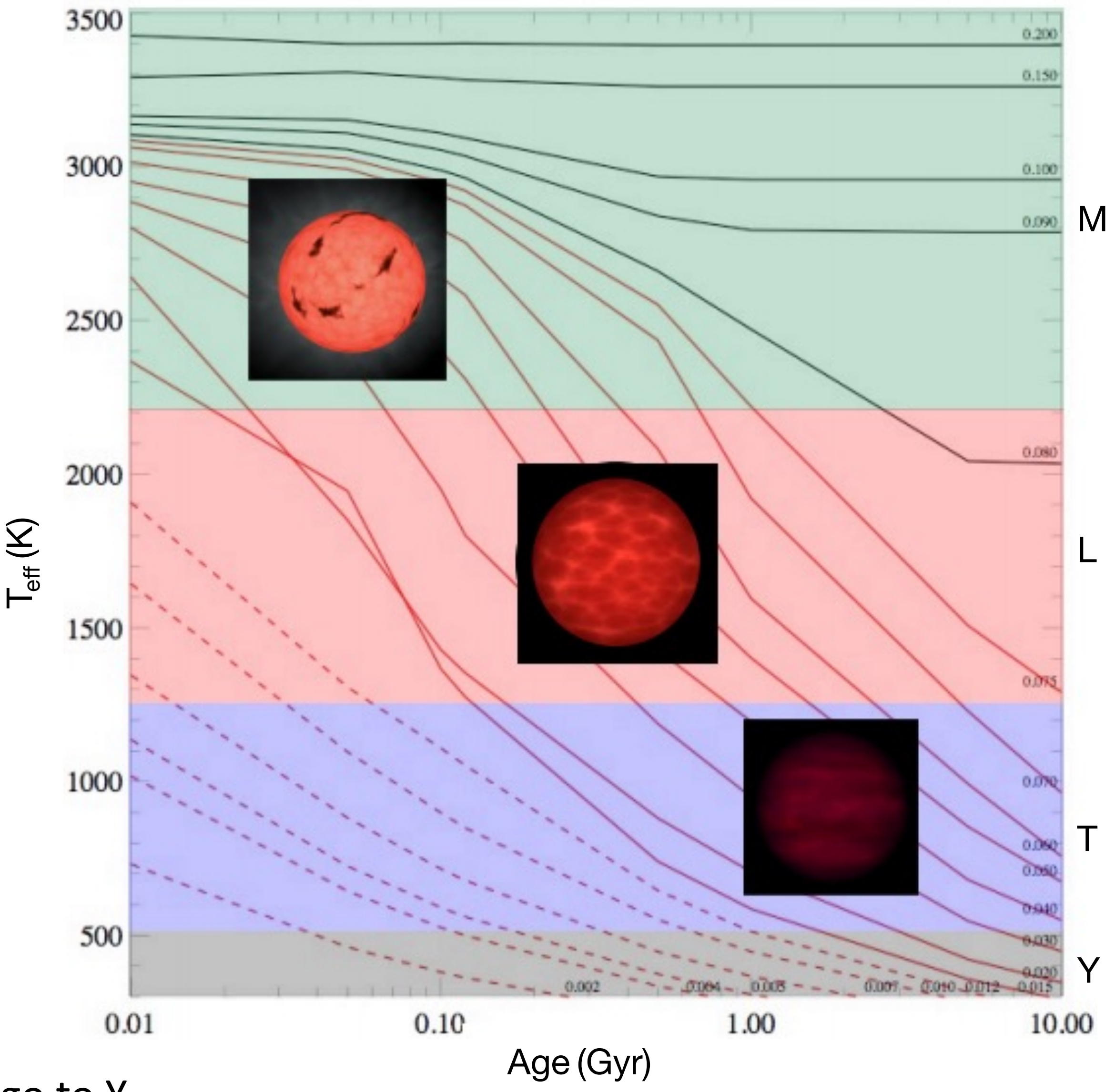
the edge of the H-burning main sequence is an L-dwarf

T-dwarfs

almost all brown dwarfs evolve from M to L to T spectral types

Y-dwarfs

the smallest brown dwarfs go to Y spectral type

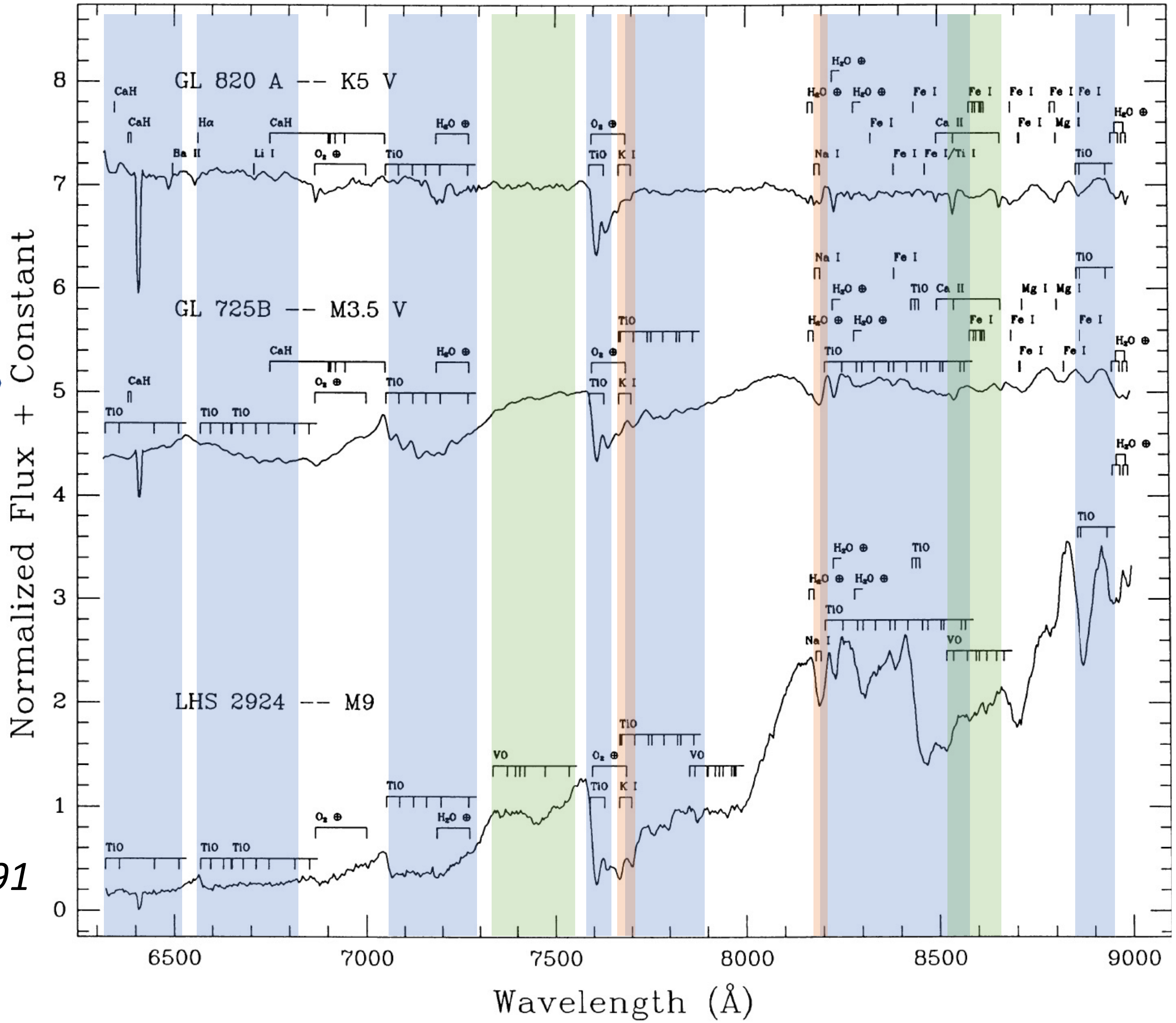


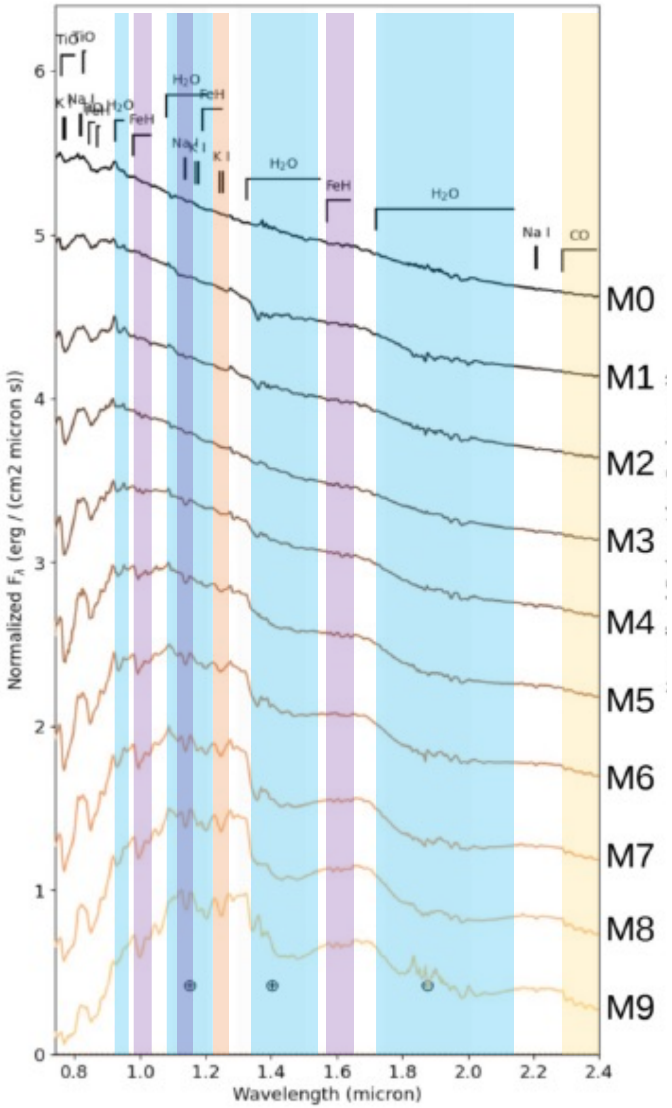
Evolutionary Models from Burrows et al 2001

Spectral classification and atmospheres

TiO | VO | Na I, K I | H_2O | FeH | CO → pseudo-continuum

M-type





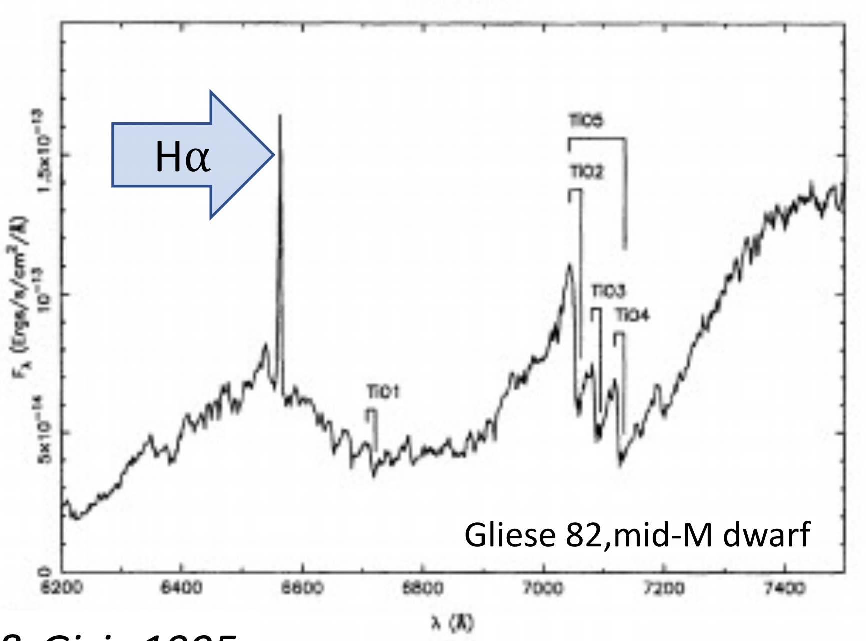
Kirkpatrick et al. 1991

Spectral classification and atmospheres

M-type

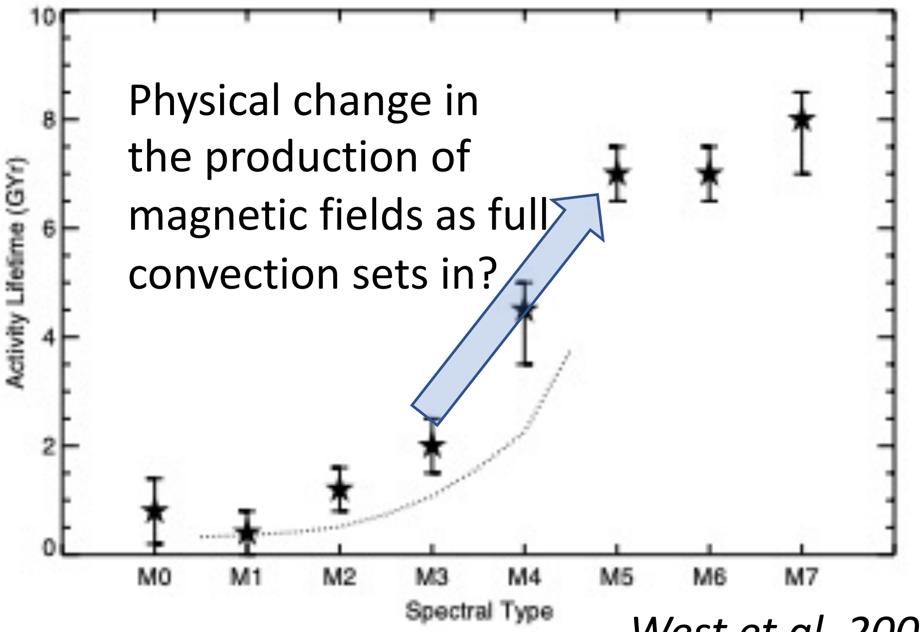
Classification schemes:

- Comparison with standard template + slope of the spectrum (e.g. Kirkpatrick et al. 1991; Henry et al. 2002)
- Spectral indices: ratio of the flux within a given spectral feature (TiO, VO, CaH, CaOH) and the flux in a nearby pseudo-continuum region (Reid, Hawley & Gizis, 1995; Kirkpatrick, Henry & Simons 1995; Kirkpatrick et al. 1999; Martín et al 1999)



Reid, Hawley & Gizis 1995

Activity lifetime of M-dwarfs



West et al. 2008

Spectral classification and atmospheres

M-type

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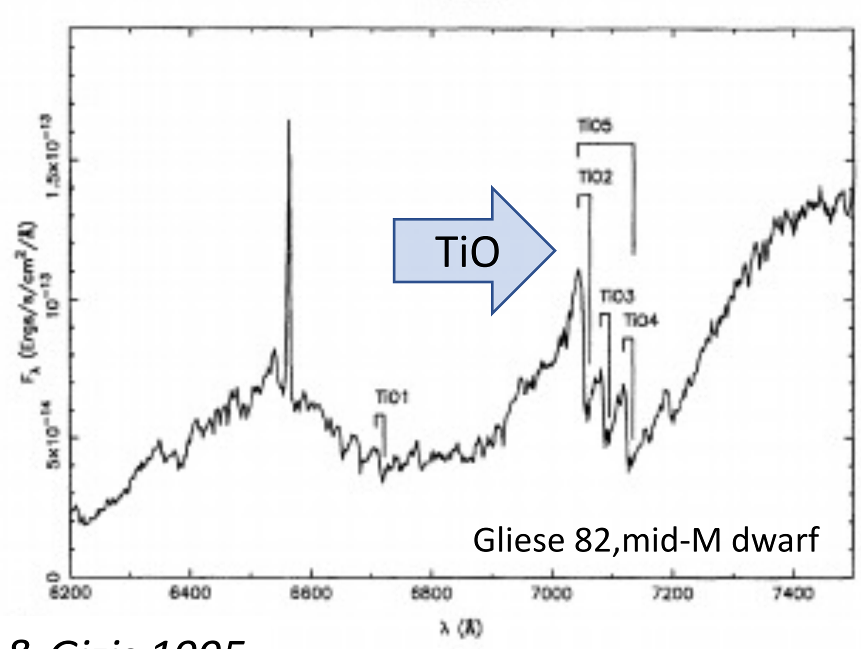
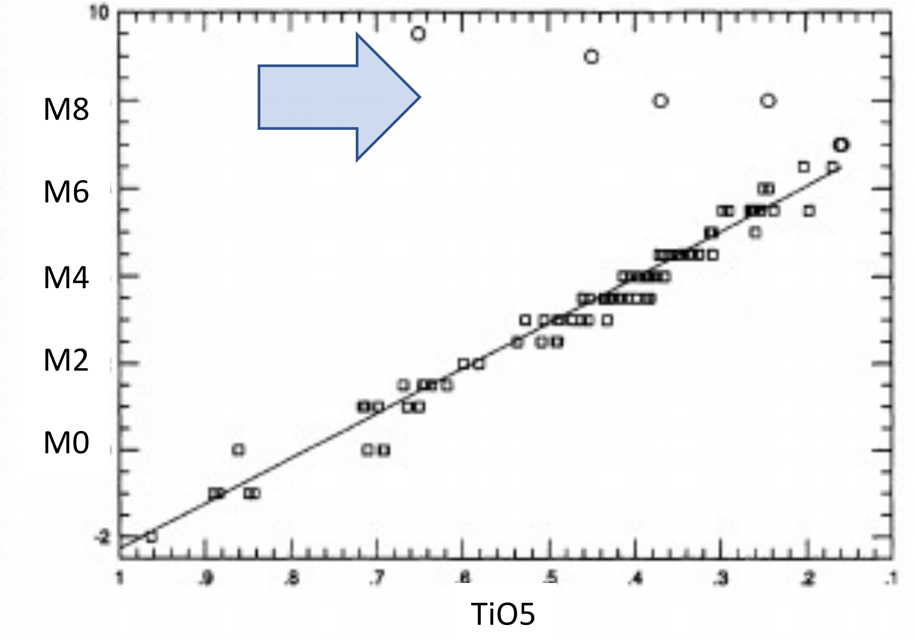
TiO bandstrength is primarily temperature dependent





Reid, Hawley & Gizis 1995

Spectral classification and atmospheres

M-type

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- Comparison with standard template (e.g. Henry et al. 2002) + slope of the spectrum (Kirkpatrick et al. 1991)
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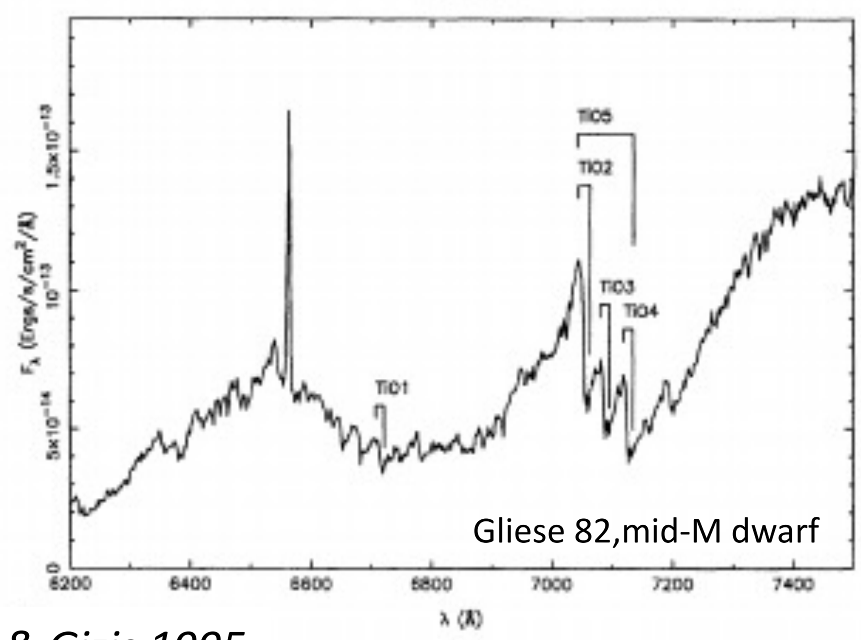
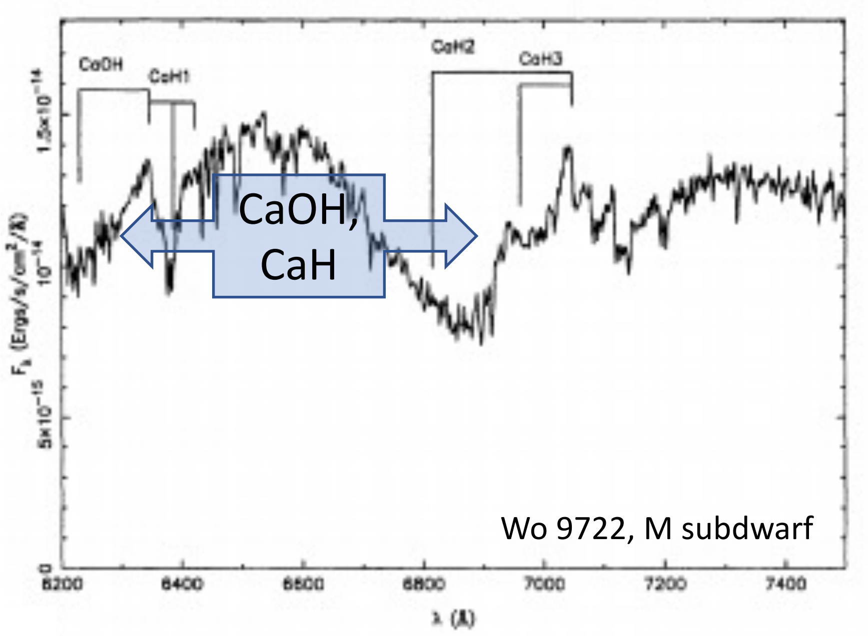
CaH, CaOH become more prominent with decreasing metallicity





Reid, Hawley & Gizis 1995

Spectral classification and atmospheres

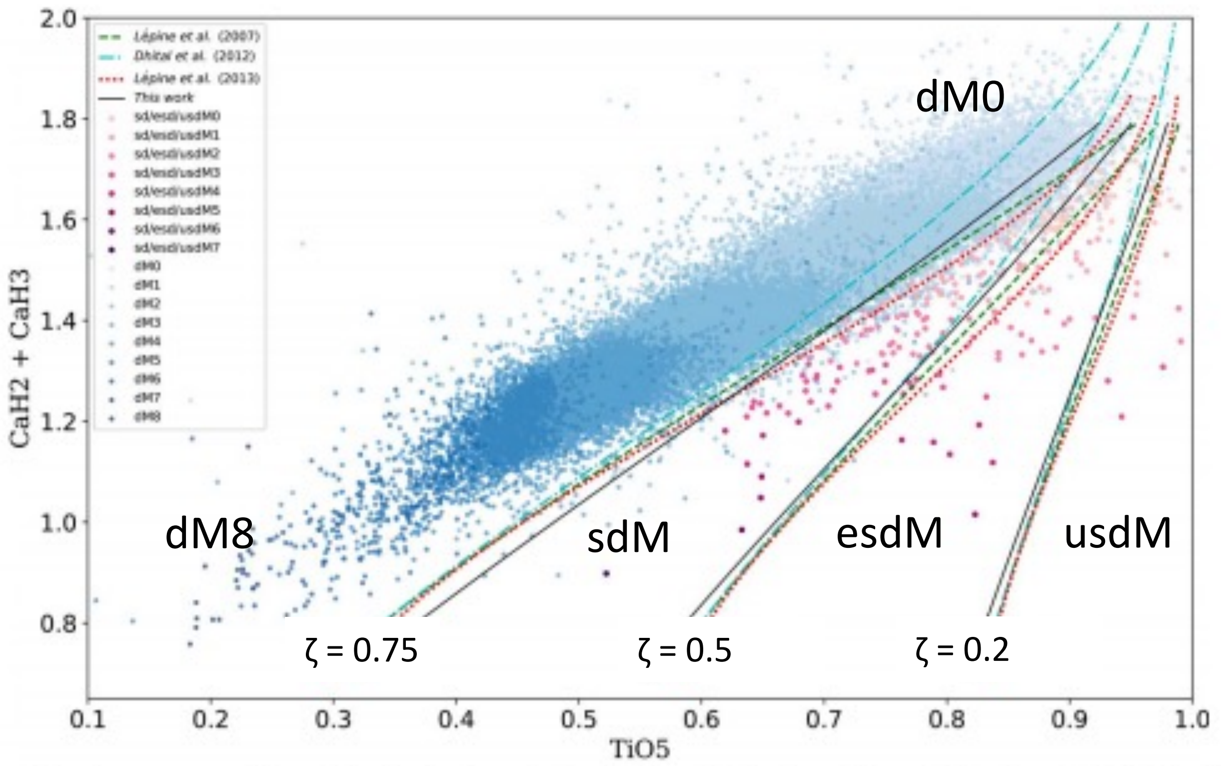
M-type

Classification schemes for subdwarfs (sdM, esdM, usdM) from TiO and CaH spectral indices (Gizis 1997; Lépine, Rich & Shara 2003)
ζ-index introduced by Lépine et al. 2007 (revised by Dithal et al. 2012; Lépine et al. 2013; Zhang et al. 2019)

$$\zeta = \frac{1 - \mathrm{TiO5}}{1 - [\mathrm{TiO5}]_{Z_\odot}}, \qquad (1)$$

where $[\mathrm{TiO5}]_{Z_\odot}$ is a third-order polynomial of (CaH2+CaH3)

$$[\mathrm{TiO5}]_{Z_\odot} = \sum_N a_N (\mathrm{CaH2} + \mathrm{CaH3})^N, \qquad (2)$$



Adapted from Zhang et al. 2019

Spectral classification and atmospheres

M-type

Classification schemes for subdwarfs (sdM, esdM, usdM) from TiO and CaH spectral indices (Gizis 1997; Lépine, Rich & Shara 2003)
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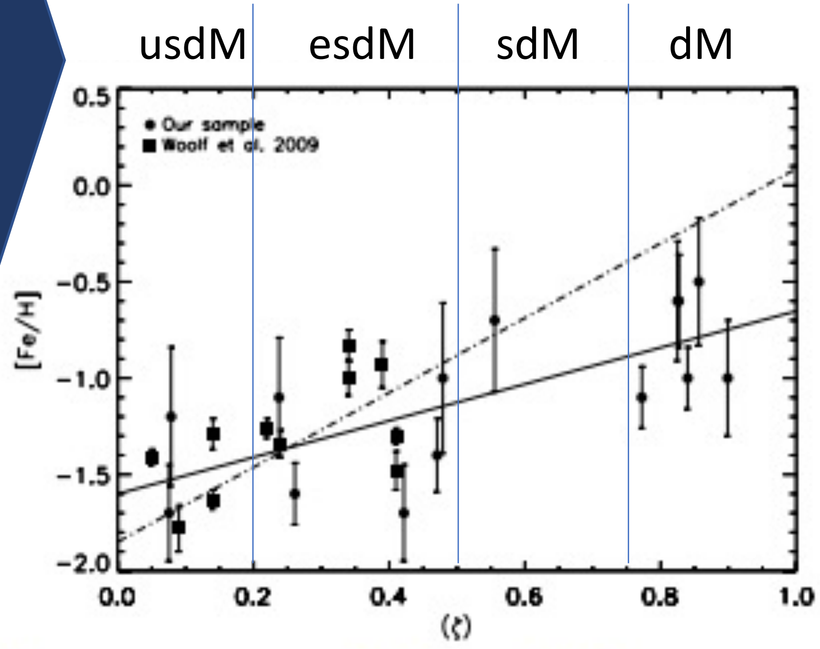
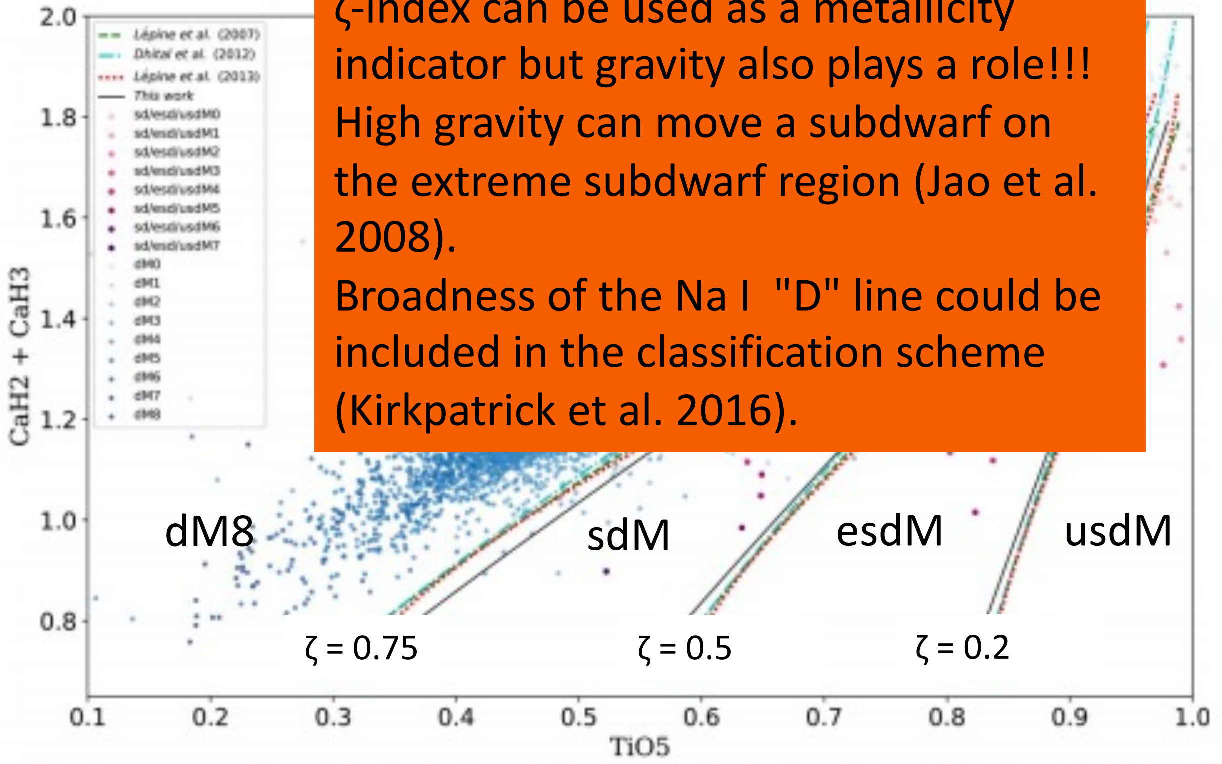


Rajpurohit et al. 2014



ζ-index can be used as a metallicity indicator but gravity also plays a role!!! High gravity can move a subdwarf on the extreme subdwarf region (Jao et al. 2008).
Broadness of the Na I "D" line could be included in the classification scheme (Kirkpatrick et al. 2016).

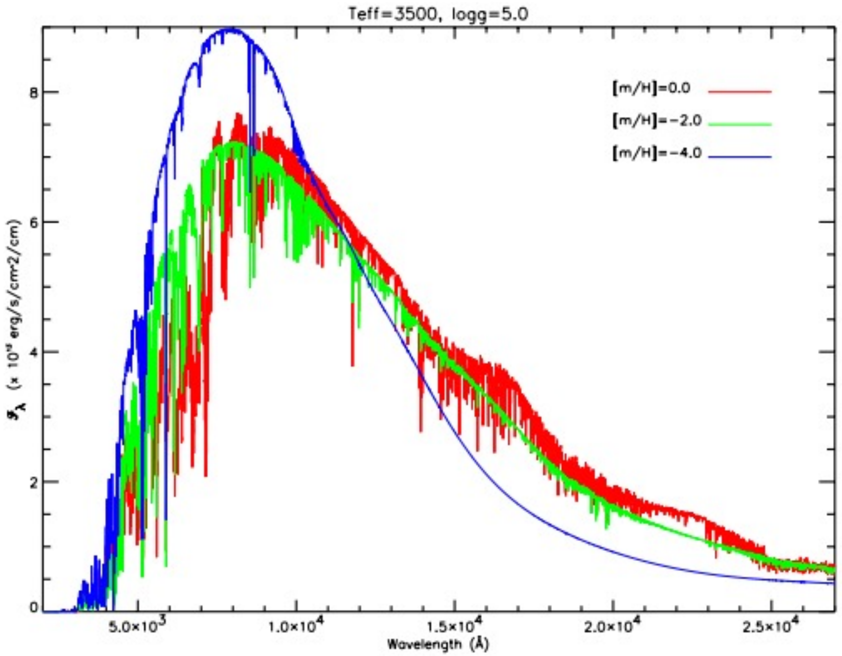
Adapted from Zhang et al. 2019

Spectral classification and atmospheres

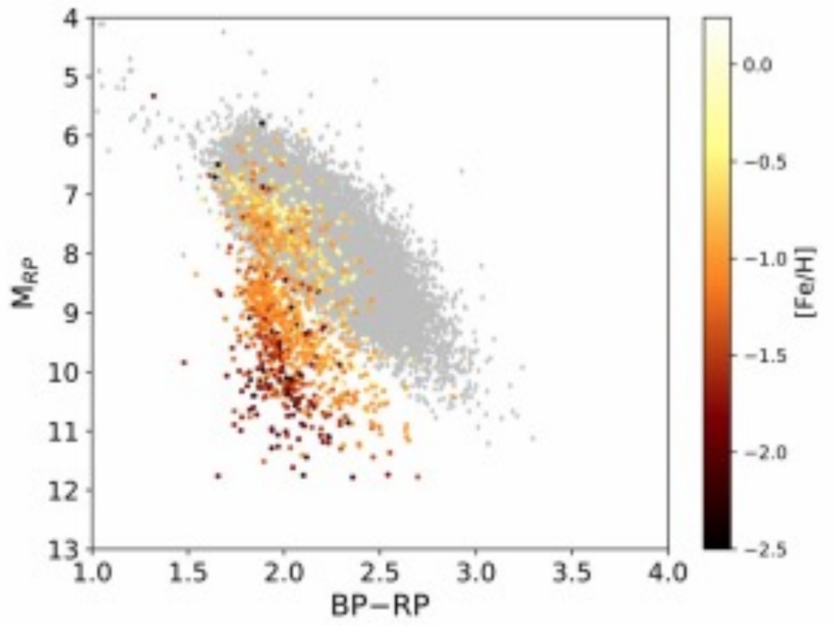
Because of a decreasing metallicity for subdwarfs, TiO opacity decreases.
Less blanketing from TiO bands means more continuum flux radiated from hotter and deeper layers of the atmosphere.
The subdwarf spectrum is closer to that of a blackbody, and subdwarfs appear bluer.

M-type

Synthetic spectra from *Gaia* model grid (Brott & Hauschildt 2005)



Jao et al. 2008



Zhang et al. 2021

Spectral classification and atmospheres

L-type

TiO and VO bands, prominent in late Ms, fade due to the **condensation of Ti and V to dust**
→ New spectral type defined by Martín et al. 1997
"L would be an appropriate new class, suggestive of Low-temperature", Kirkpatrick et al. 1999

- Gradual disappearance of **metallic oxydes** TiO and VO bands;
- Increase of **metallic hydrides** (CrH, FeH) and **neutral alkali metals** (Na I, KI, Rb I, Cs I), with a braodening of Na I and K I lines;
- Increase of **H_2O, CO, FeH** absorptions
- Increasing **steepness** of the 0.6-1 μm spectrum

see Martín et al 1999; Delfosse et al. 1999; Kirckpatrick et al; 1999, 2000; McLean et al. 2000; Leggett et al. 2000, 2001

TABLE 5

Summary of Letters to Guide Choice of New Spectral Type

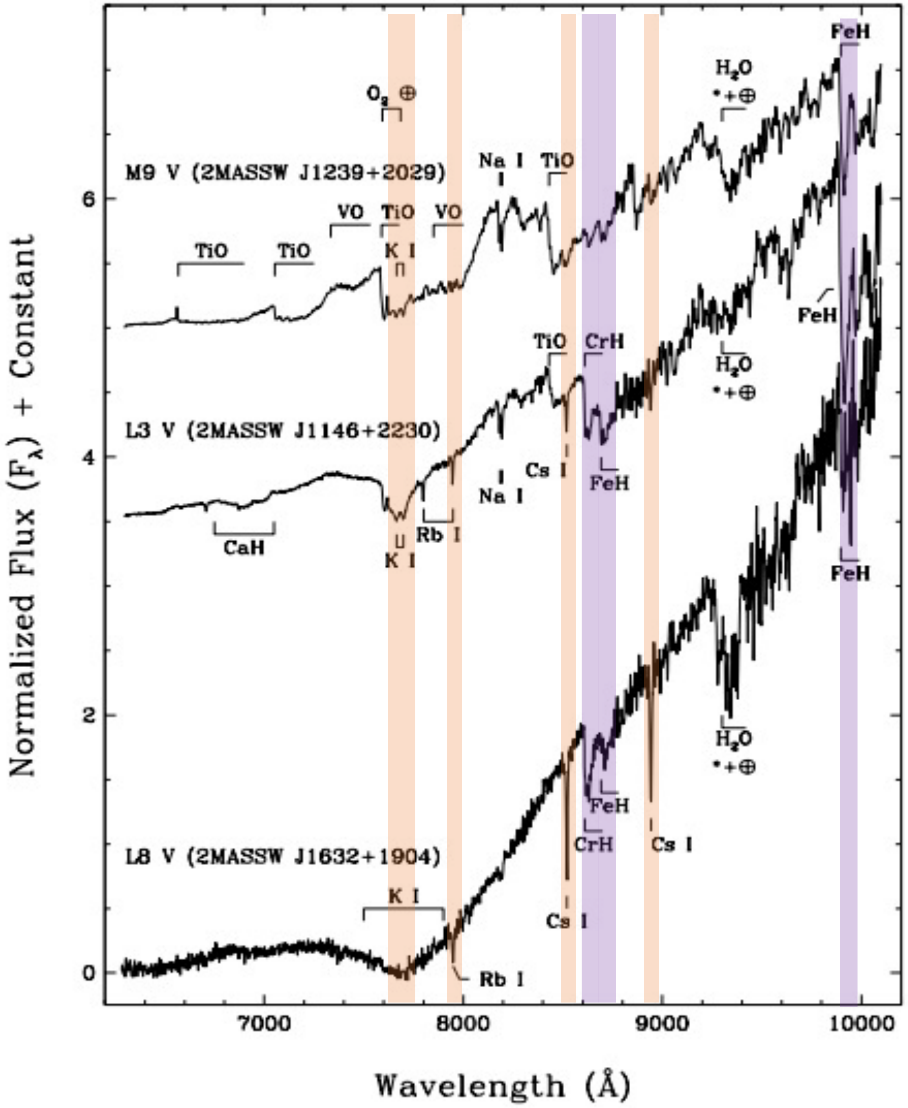
Letter (1)	Status (2)	Notes (3)
A	In use	Standard spectral class
B	In use	Standard spectral class
C	In use	Standard carbon-star class
D	Ambiguous	Confusion with white dwarf classes DA, DB, DC, etc.
E	Ambiguous	Confusion with elliptical galaxy morphological types E0–E7
F	In use	Standard spectral class
G	In use	Standard spectral class
H	OK	
I	Problematic	Transcription problems with I0 (10, Io) and I1 (11, II, Il)
J	In use	Standard carbon-star class
K	In use	Standard spectral class
L	OK	
M......	In use	Standard spectral class
N	In use	Standard carbon-star class
O	In use	Standard spectral class
P	Problematic?	Incorrect association with planets?
Q	Problematic?	Incorrect association with QSOs?
R	In use	Standard carbon-star class
S.......	In use	Standard spectral class for ZrO-rich stars
T	OK	
U	Problematic?	Incorrect association with ultraviolet sources?
V	Problematic	Confusion with vanadium oxide (V0 vs. VO)
W......	Ambiguous	Confusion with Wolf-Rayet WN and WR classes
X	Problematic	Incorrect association with X-ray sources
Y	OK	
Z	Problematic?	Incorrect implication that we have reached "the end"?

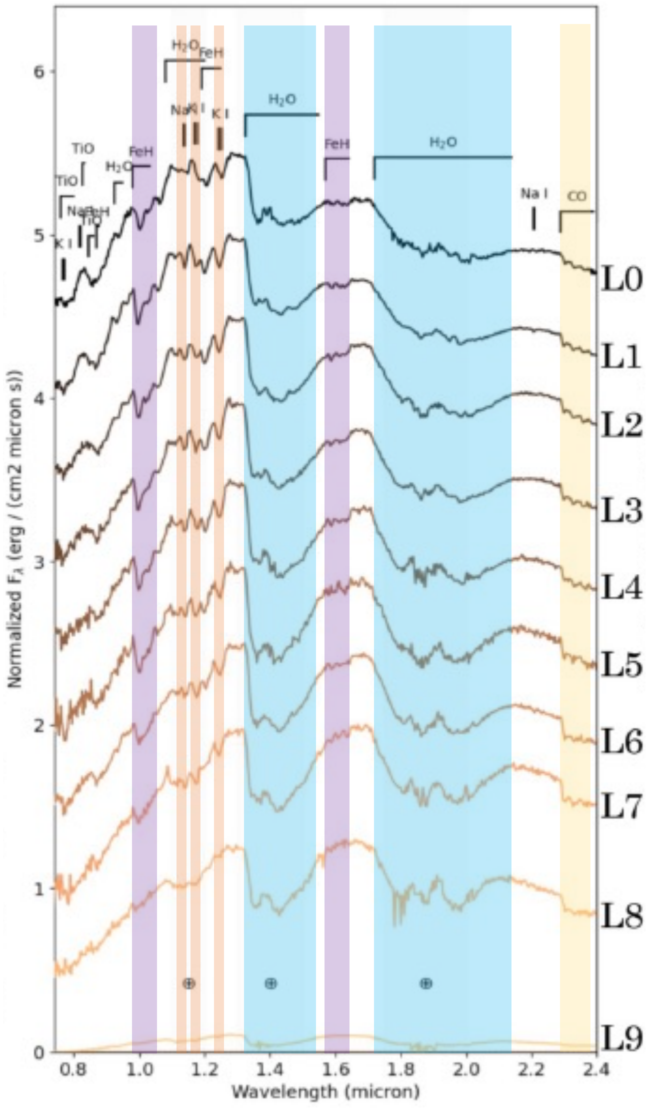
Kirkpatrick et al. 1999

Spectral classification and atmospheres

Na I, K I, Rb I, Cs I | FeH, CrH | H_2O | CO

L-type





Kirkpatrick et al. 1999

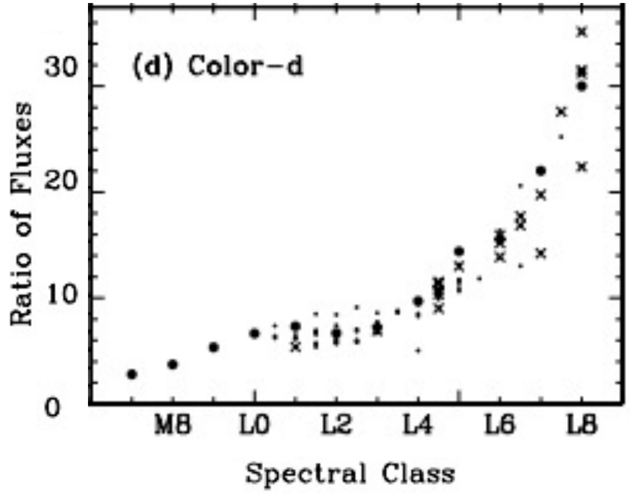
Spectral classification and atmospheres

L-type

Classification schemes: Spectral indices

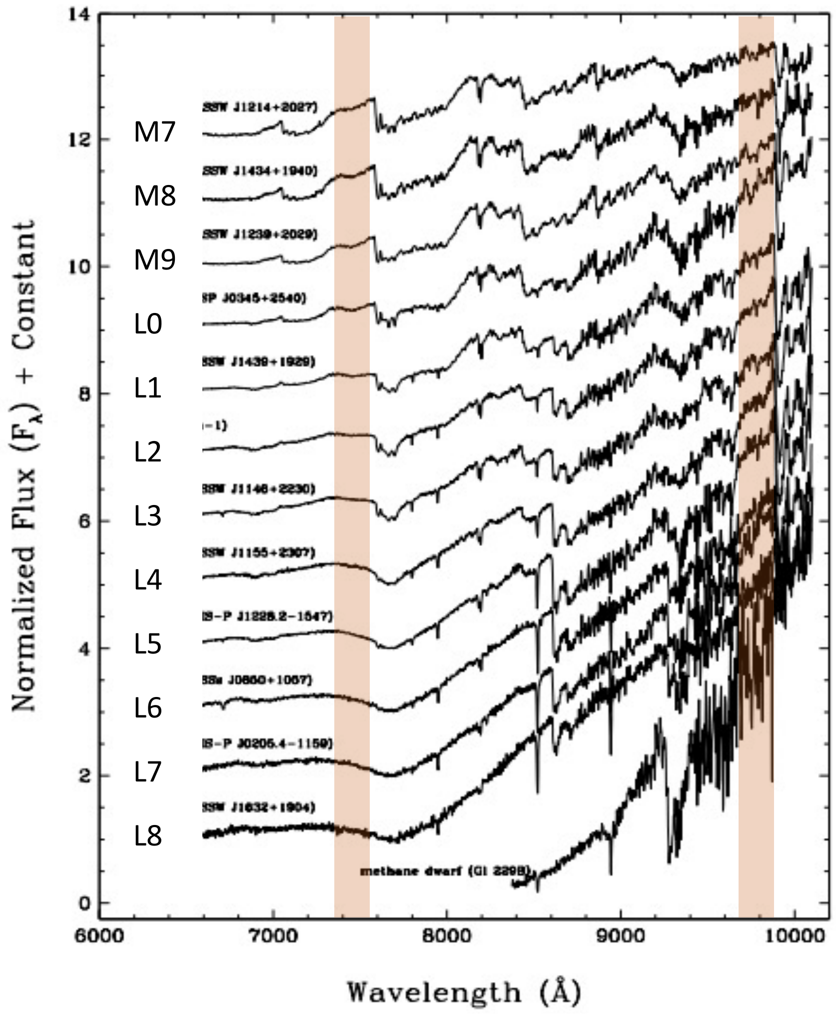
$$\text{index} = \frac{\int_{\lambda_1}^{\lambda_2} f_\lambda \, d\lambda}{\int_{\lambda_3}^{\lambda_4} f_\lambda \, d\lambda}$$

- in the red optical: based on TiO, VO, CrH, Rb, Cs features, and red color terms (Kirkpatrick et al. 1999), or on pseudocontinuum slope (Martín et al. 1999)
- in the NIR: based on H_2O features (e.g. Geballe et al. 2002, pinned to the Kirkpatrick et al. 1999 types)



Kirkpatrick et al. 2000

Color-d index F(9675-9875)/F(7350-7550)



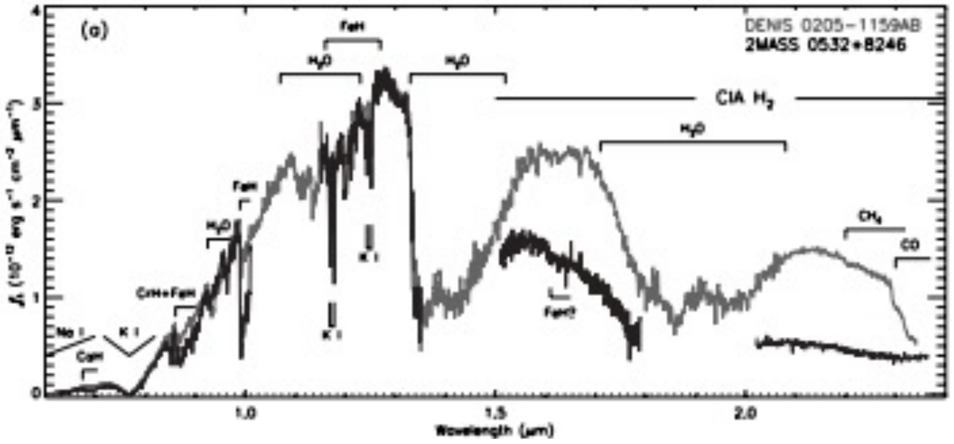
Kirkpatrick et al. 1999

Spectral classification and atmospheres

L-type

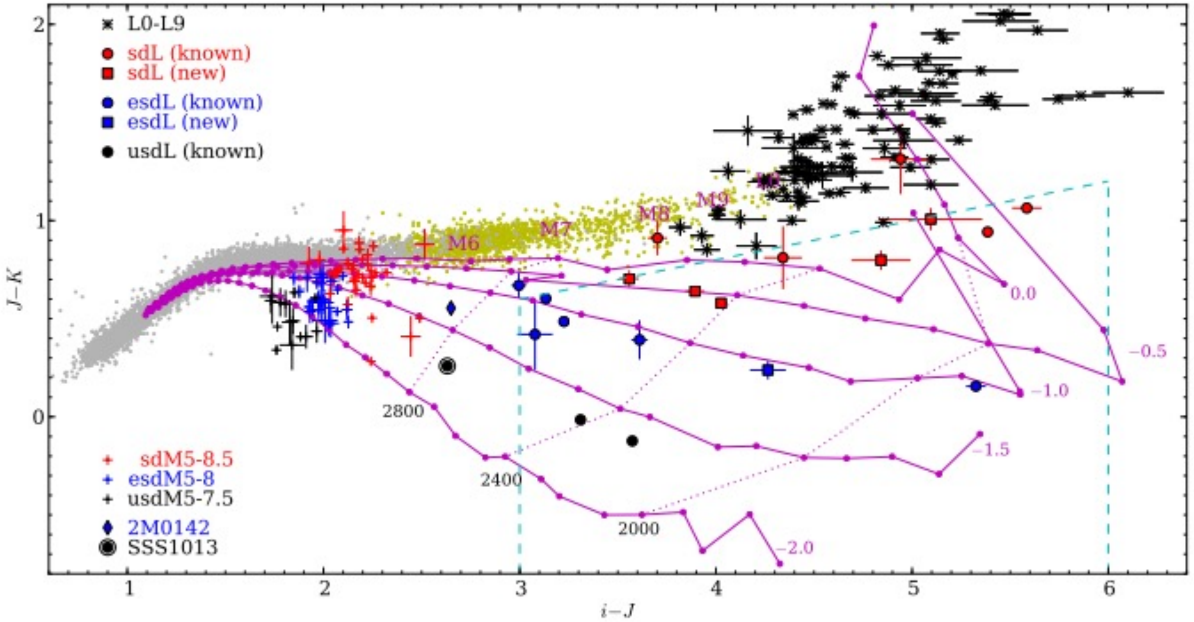
The first L-type subdwarf 2MASS 05325346 (Burgasser et al. 2003), kinematics consistent with halo membership.

Strong metal hydrides (e.g. FeH), weak or absent metal oxides (e.g. VO and CO), and enhanced collision-induced H_2 absorption (suppressed K and K-bands).



Burgasser et al. 2003

See Zhang et al. 2017 and the series of paper "Primeval very low mass stars and brown dwarfs"



Zhang et al. 2017

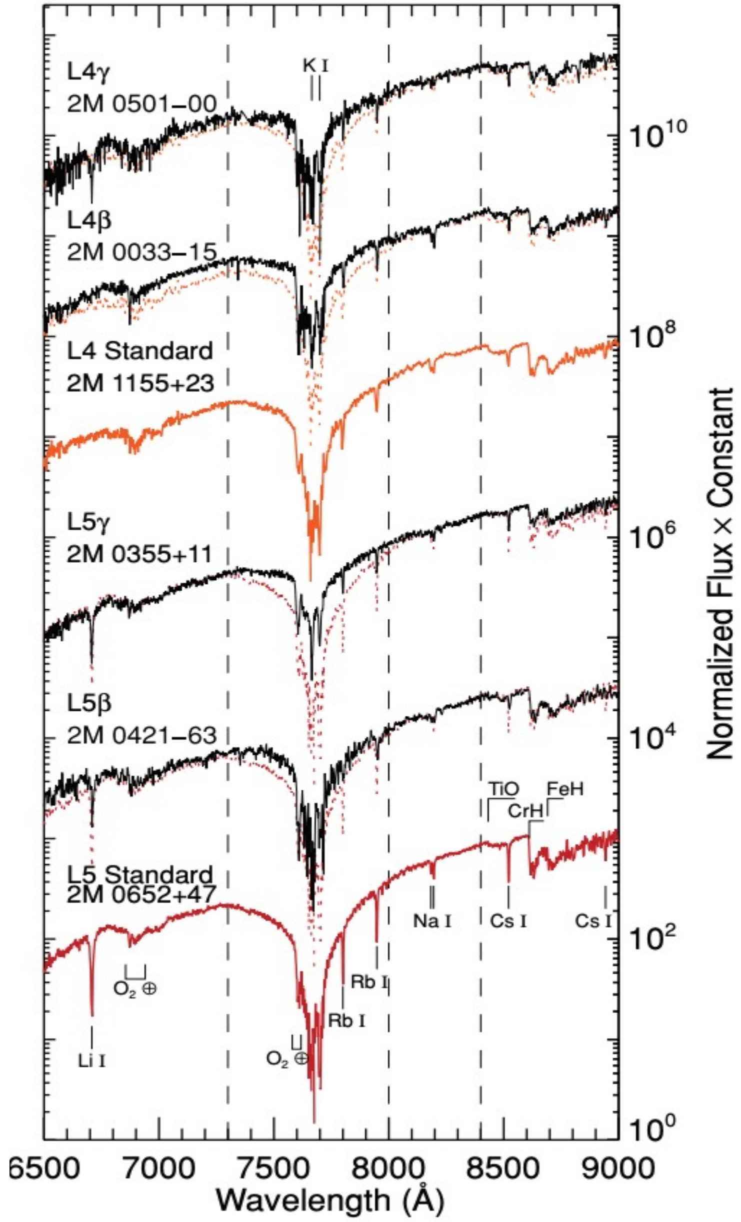
Spectral classification and atmospheres

L-type

Cruz et al. 2009 expanded the classification scheme to include three gravity classes:
α normal gravity
β intermediate gravity
γ very low gravity

Peculiar features are of low-gravity L dwarfs are:
weak alkili lines (Na I, K I, Rb I, Cs I)
sharp K I wings
weak FeH, CrH, TiO absorption

Low-gravity L dwarfs have red colours compared to normal dwarfs with the same spectral type



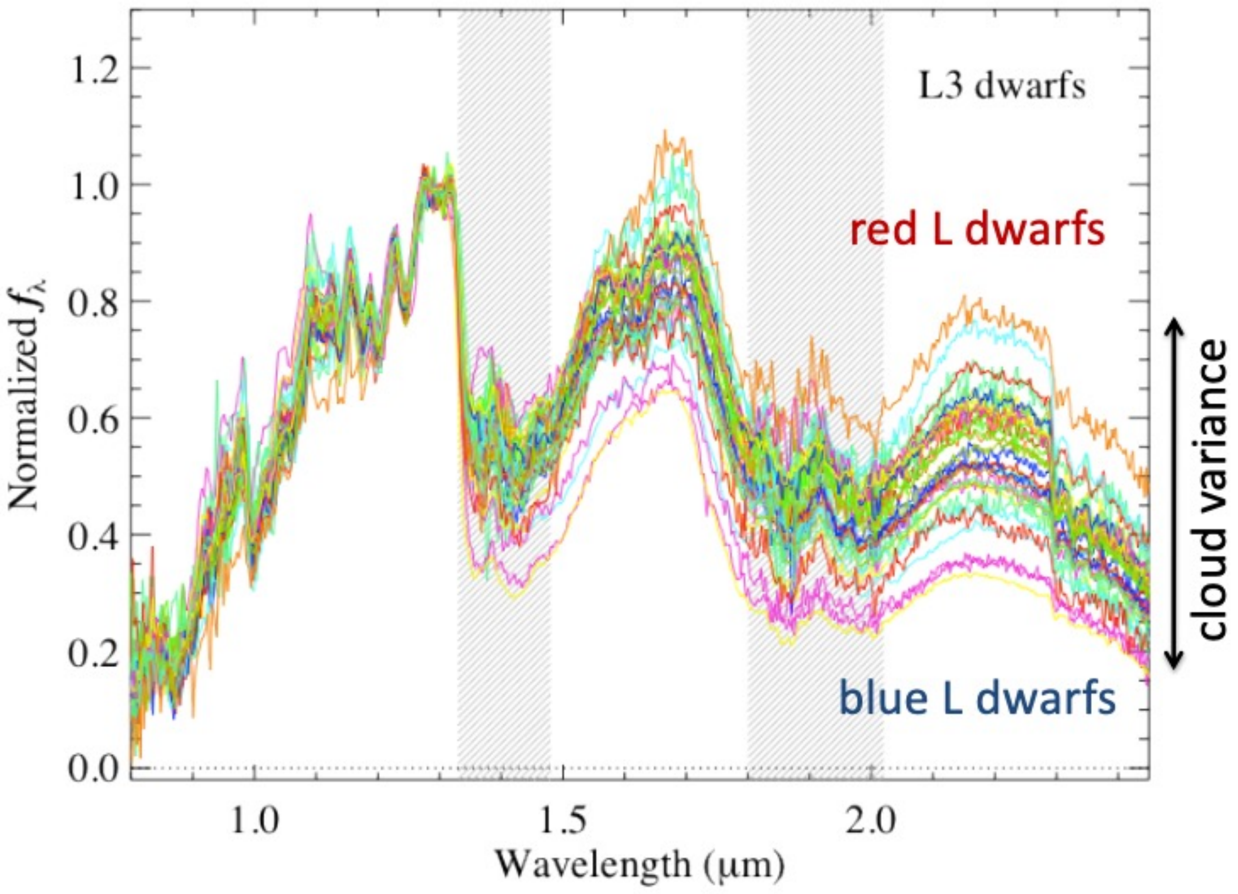
Cruz et al. 2009

Spectral classification and atmospheres

L-type

Condensates modify the shape of the spectrum

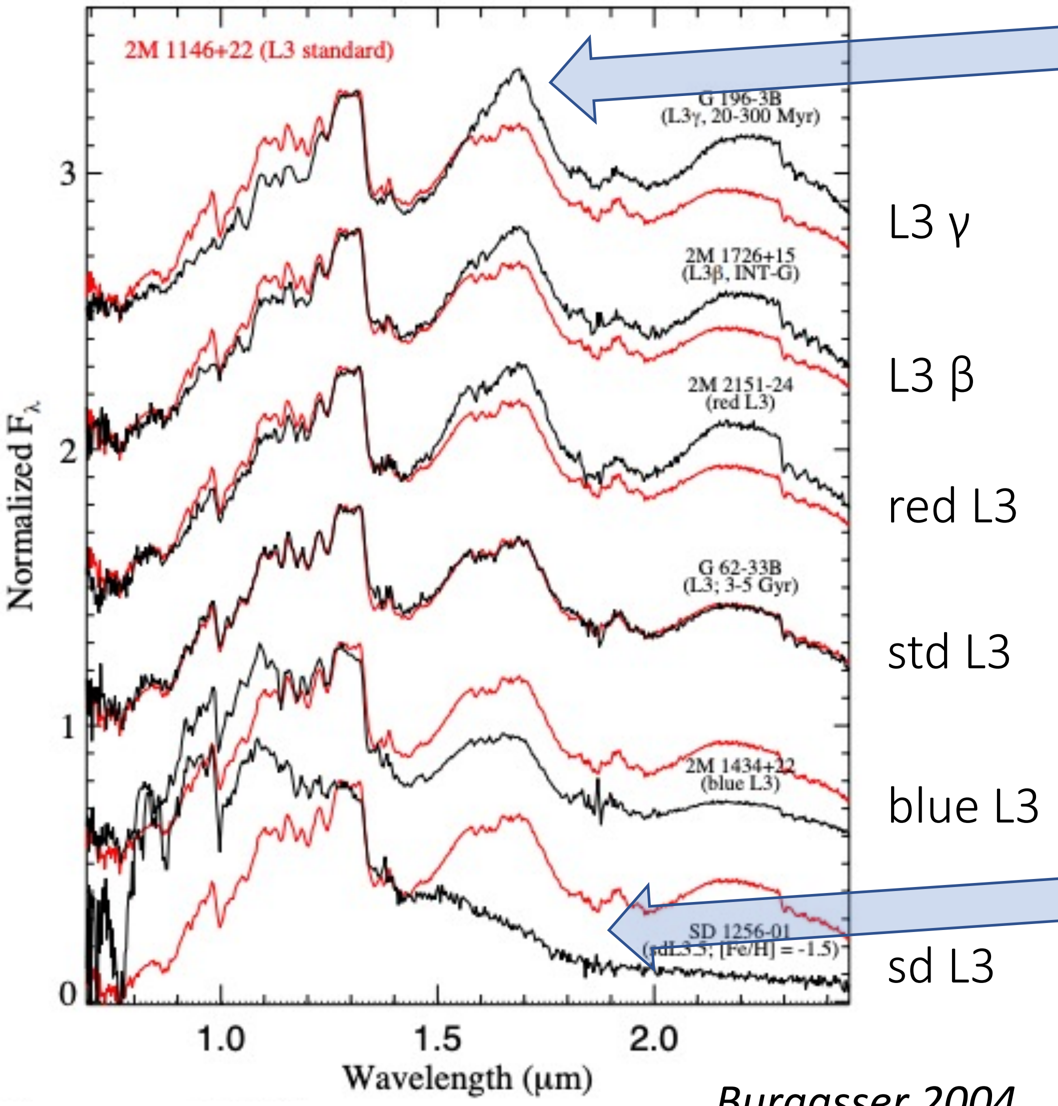
In the NIR, dust can lead to backwarming of the atmosphere, and alters the amount of H_2O and H_2. Slight variations in the H_2O and H_2 opacities can lead to large differences.



Courtesy of A. Burgasser

Spectral classification and atmospheres

L-type



Burgasser 2004

Low-gravity: triangular shaped H-band (Kirkpatrick et al. 2008)

→ The full description of the atmosphere depends on effective temperature, gravity, metallicity, cloud properties, and mixing in the atmosphere

Low-metallicity: higher flux in J, suppressed H and K-bands

Spectral classification and atmospheres

CH_4

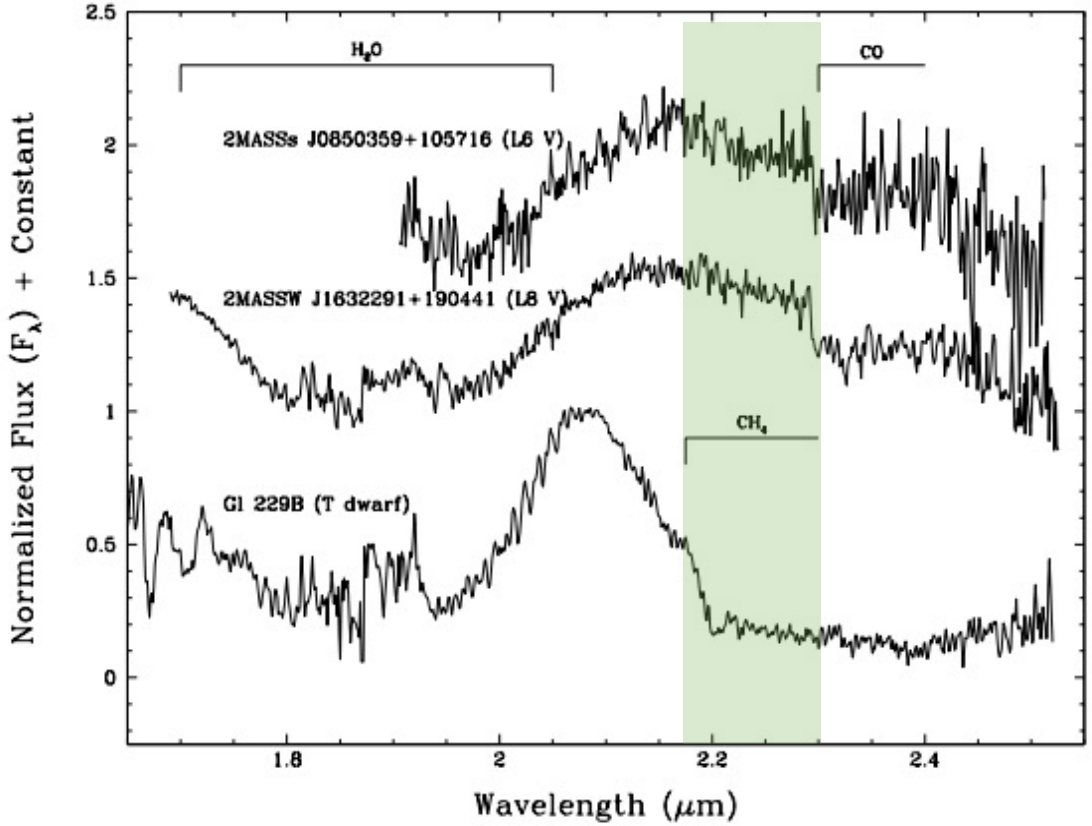
T-type

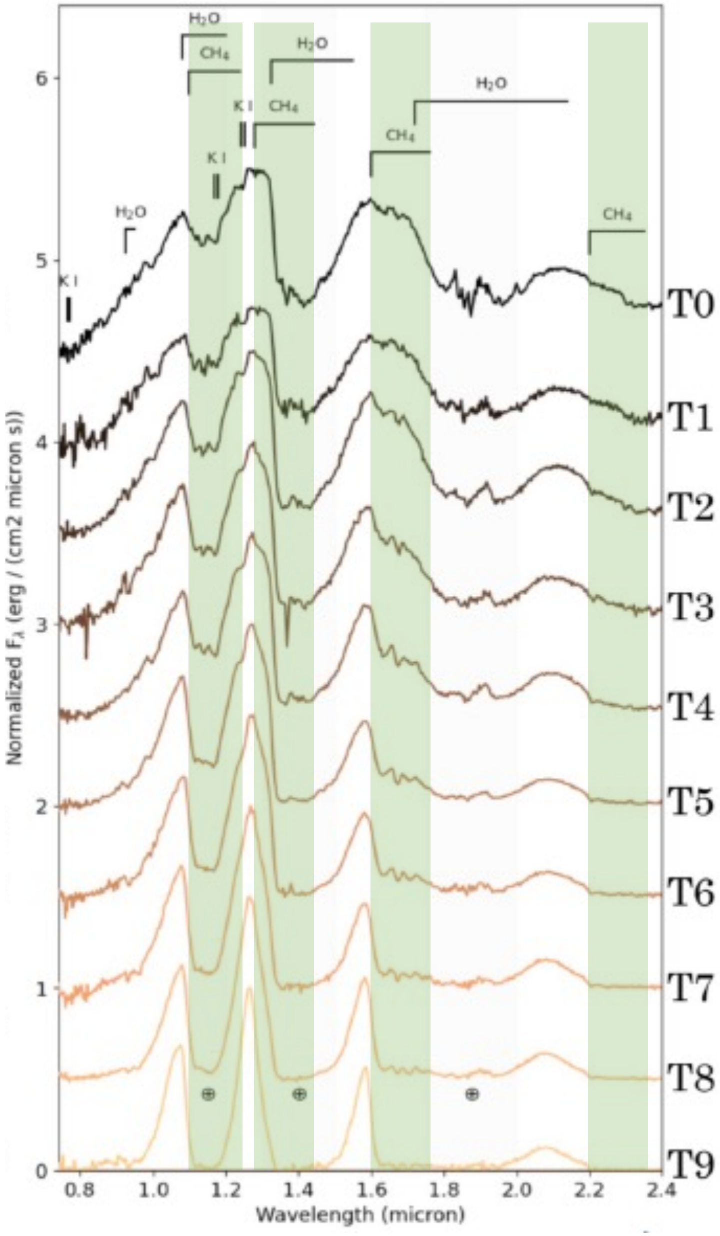
Used by Kirkpatrick et al. 1999 to define a type for Gl 229B, which have a very different spectrum

Deep, pressure-broadened K I and Na I optical lines

→ **all flux emitted in NIR**

Strong **CH_4** absorption (J-H and J-K turn to blue)



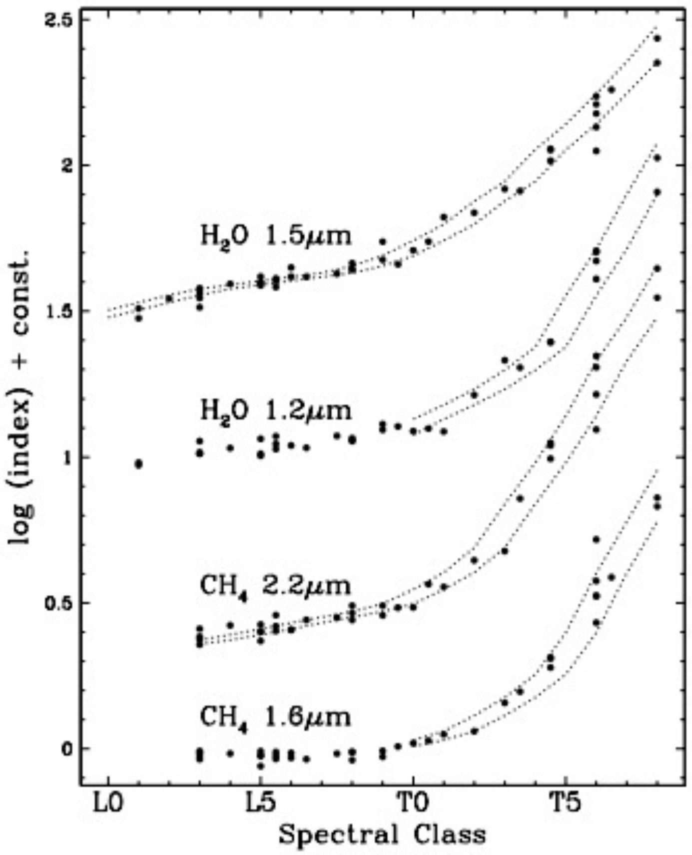


Kirkpatrick et al. 1999

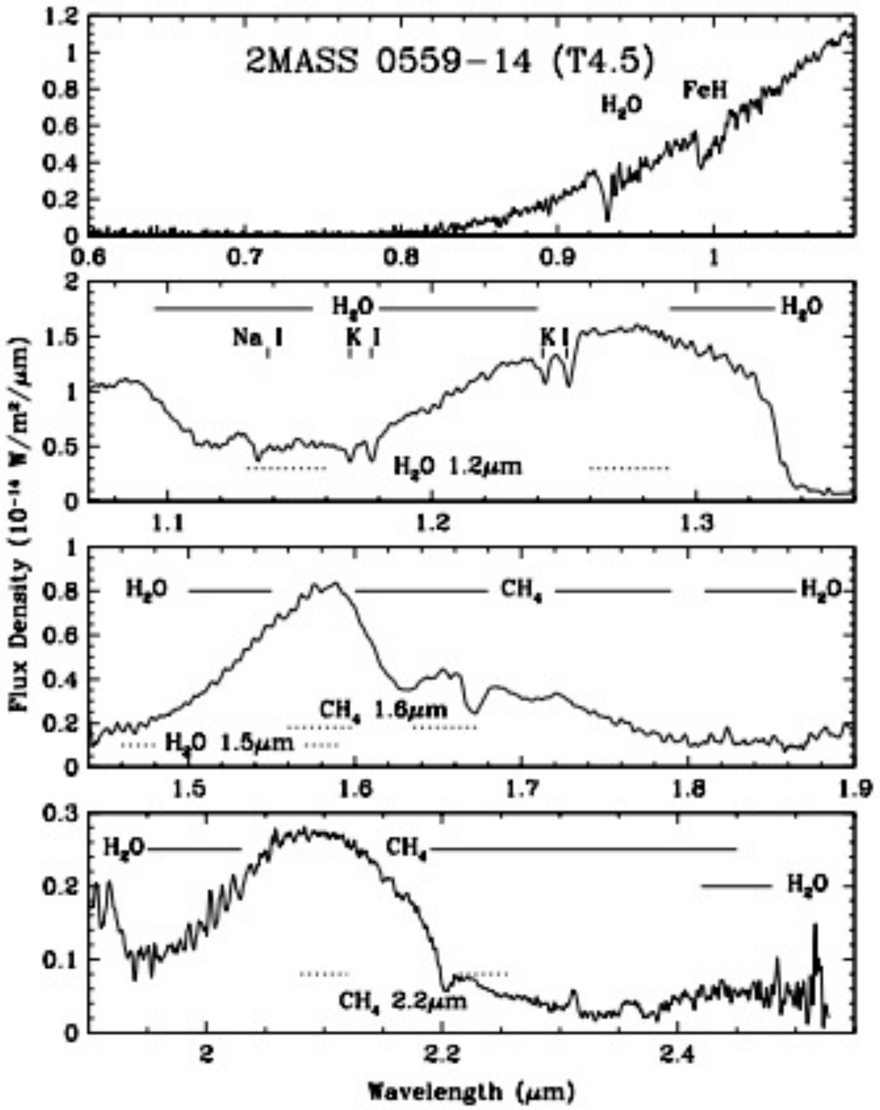
Spectral classification and atmospheres

T-type

Classification schemes:
Spectral indices based on CH_4 and H_2O features (Geba
et al. 2002; Burgasser et al. 2002; 2006)



Geballe et al. 2002



Spectral classification and atmospheres

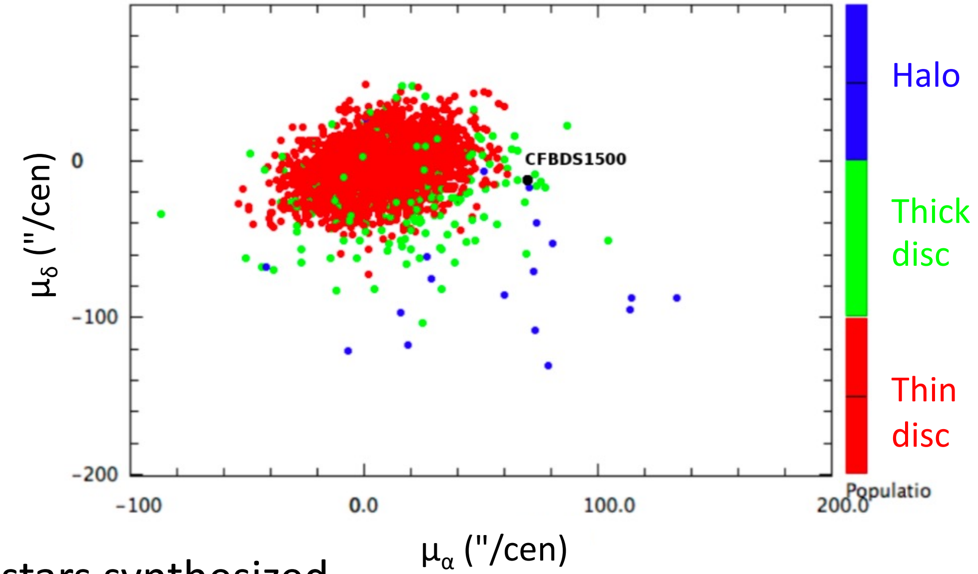
T-type

The first T-subdwarf: 2MASS 0937+2931 (Burgasser et al. 2002; 2006)

- **bluer** than similarly classified T dwarfs,
- **suppressed K-band** peak caused by enhanced collision-induced absorption,
- **enhanced FeH** absorption, **absence of K I** doublet lines,
- kinematics of an old thin disc star.

CFBDS 1500-1824, a thick disc T-subdwarf?

- sub-solar metallicity with H and K-bands underluminous, absent K I doublet
- kinematics more consistent with a thick disc membership (80%)



Few more discoveries of unusual blue, high tangential velocity objects (Murray et al. 2011; Burningham et al. 2014; Zhang et al. 2019)

Proper motions of stars synthesized with the Besançon Galaxy model *http://model.obs-besancon.fr*

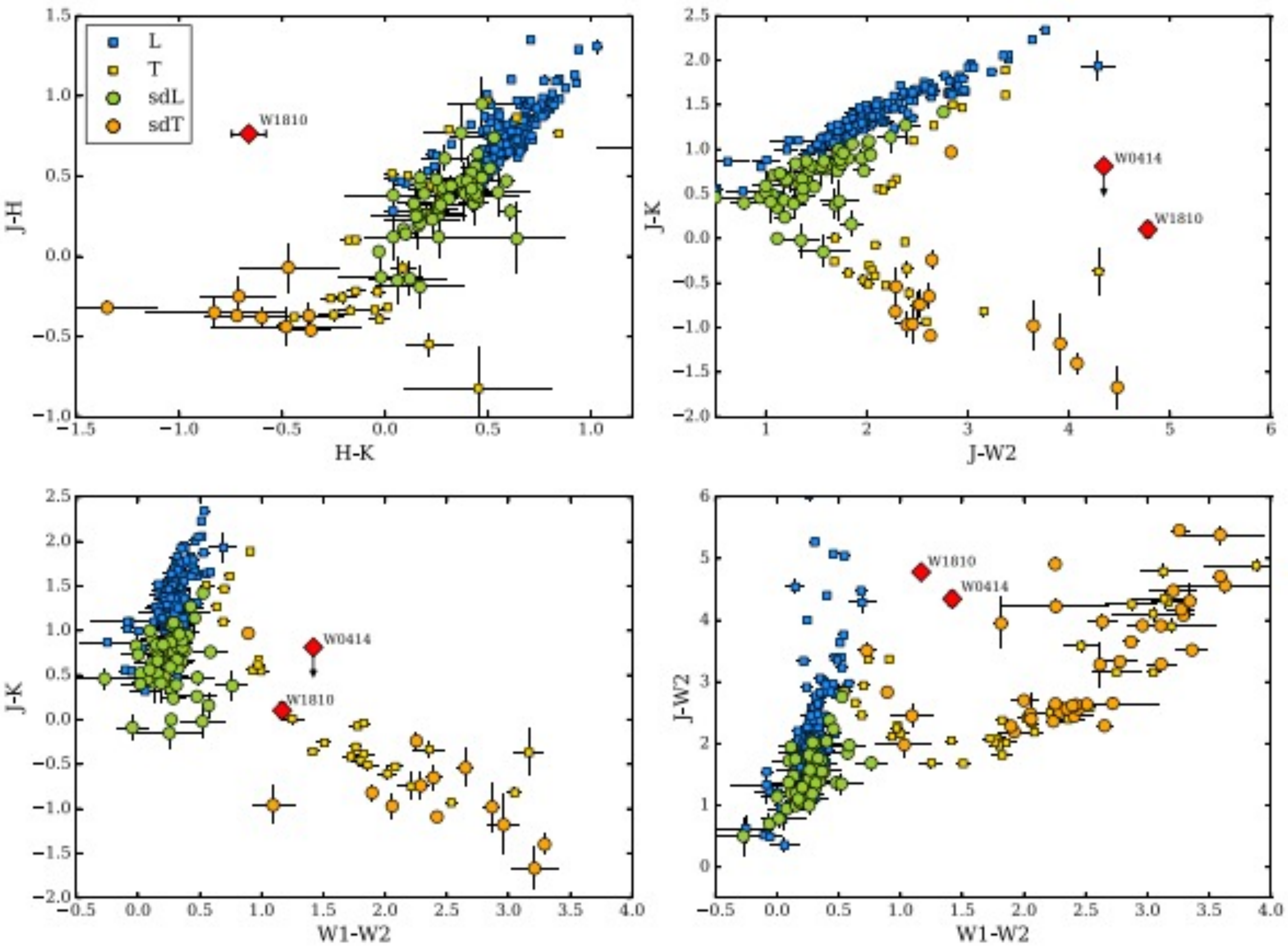
Spectral classification and atmospheres

T-type

First extreme T-type subdwarfs?
WISEA J0414-5854, WISEA J1810-1010 (Schneider et al. 2020), WISEA J0523-0153 (Goodman 2021)

Very atypical colors:

- J-H consistent with Ls, but blue H-K consistent with sdTs
- W1-W2 of typical mid-Ts, but J-W2 consistent with either latest Ls or latest Ts



Schneider et al. 2020

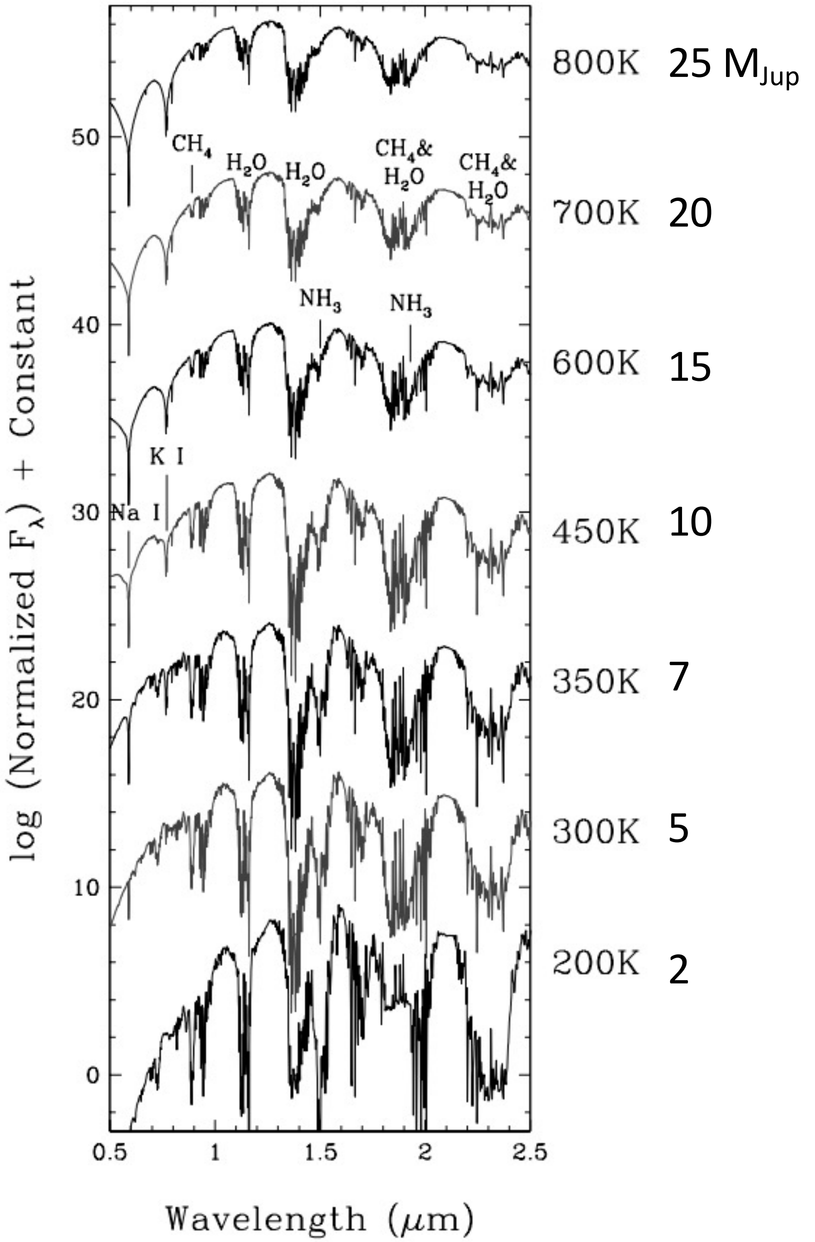
Spectral classification and atmospheres

Y-type

Suggested by Kirkpatrick 2000

What could be the trigger at the T/Y boundary defined from theoretical models?

- appearance of ammonia NH_3 at T_{eff} ≈ 600K
- disappearance of alkali lines at T_{eff} ≈ 400K
- end of the blueward trend of NIR color at Teff ≈ 300K
- The onset of water clouds at T_{eff} ≈ 400-500 K has little impact on the spectra.



Sequence of model spectra from Burrows et al. (2003).
Kirkpatrick et al. 2007

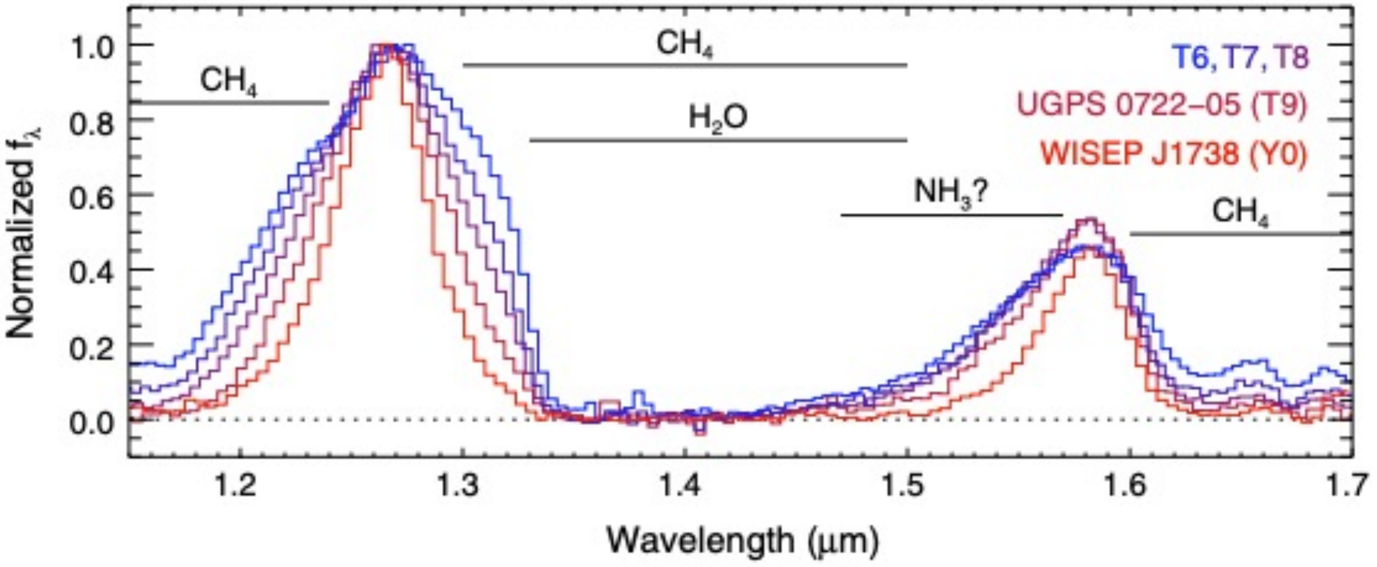
Spectral classification and atmospheres

Y-type

Discoveries of brown dwarfs with estimated T_{eff} of 300–400 K: WD 0806−661B (Luhman et al. 2011) and CFBDSIR J145829 + 101343B (Liu et al. 2011)

Cushing et al. 2011: NIR spectroscopy of 6 brown dwarfs classified as Y0 or later:

- narrow J and H bands
- possible NH_3 absorption



Cushing et al. 2011

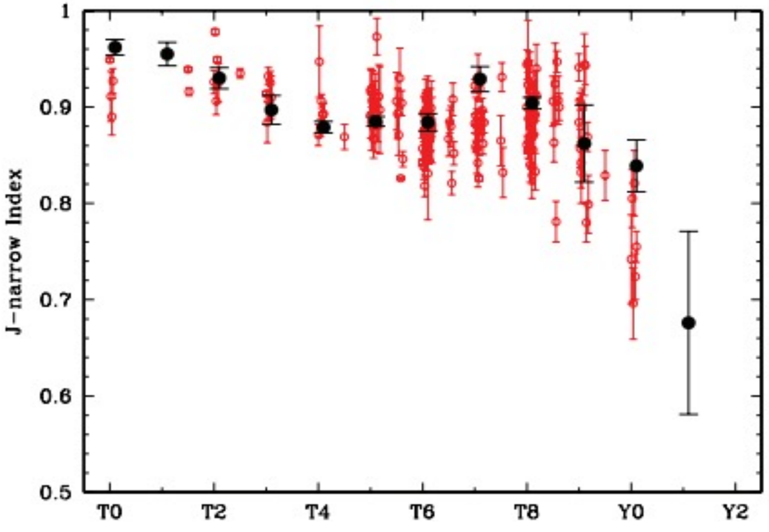
Spectral classification and atmc

Y-type

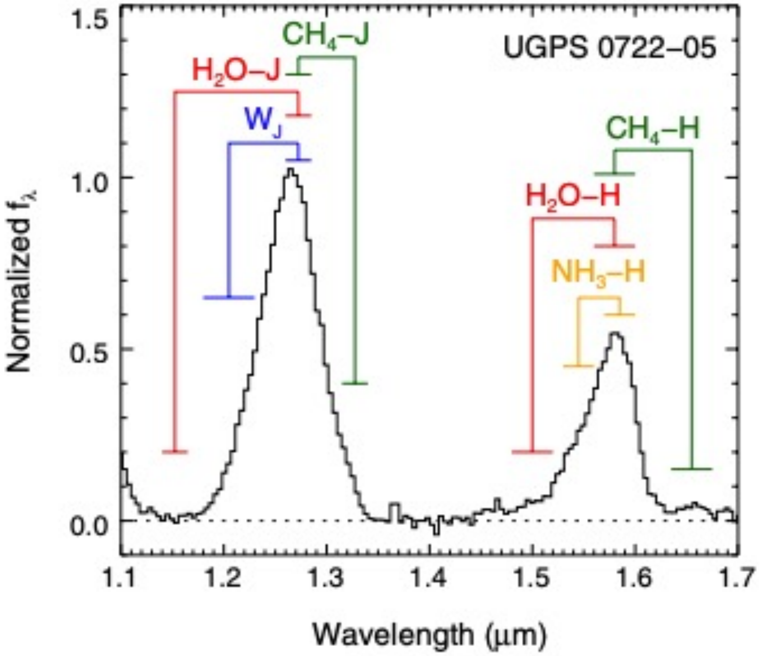
Classification scheme

Indices defined in the NIR to classify the T/Y:

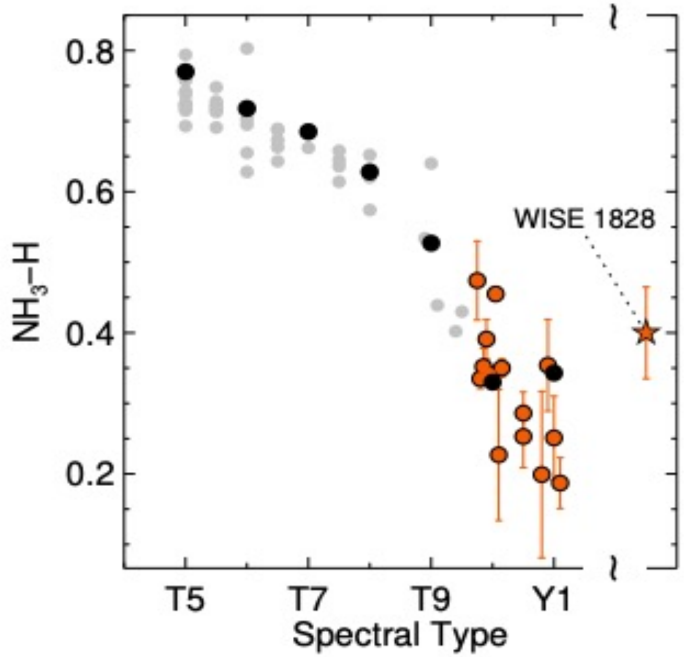
- **H_2O** and **CH_4** features in J- and H-bands (Burgasser et 2006)
- **width** of the J-band (Warren et al. 2007)
- **NH_3** features in H-band (Delorme et al. 2008)



Kirkpatrick et al. 2012



Cushing et al. 2007



Cushing et al. 2021

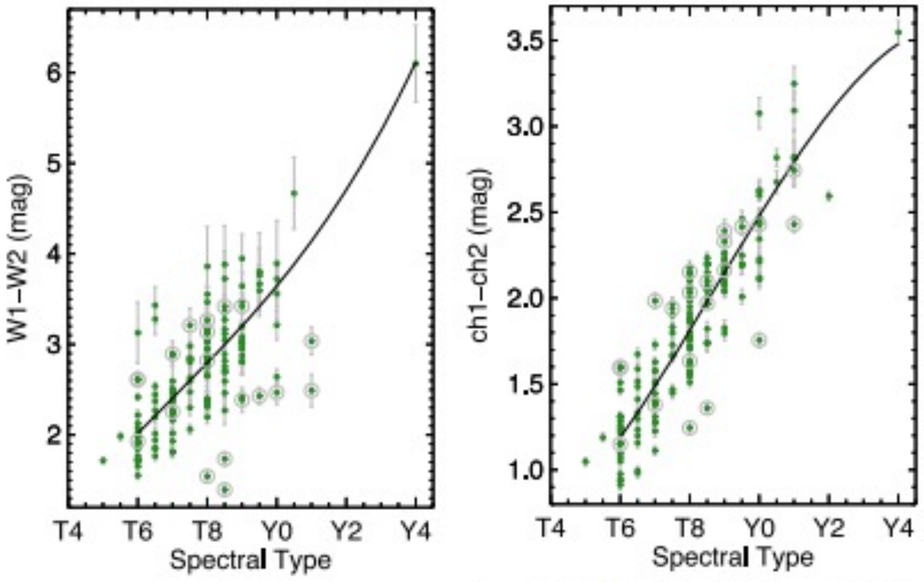
Spectral classification and atmospheres

Y-type

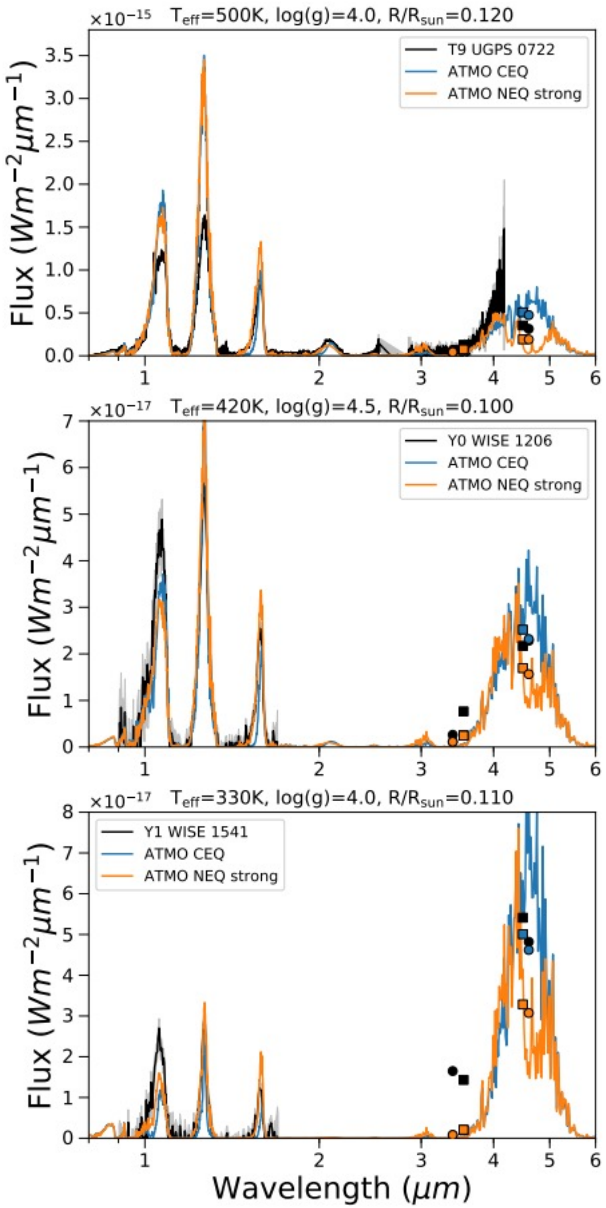
Classification scheme

Y dwarfs emit the majority of their flux in the mid-IR

3.6 – 4.5 µm colors vs spectral type relation from WISE (W1-W2) and Spitzer (ch1-ch2)



Kirkpatrick et al. 2019



Phillips et al. 2020

Spectral classification and atmospheres

Y-type

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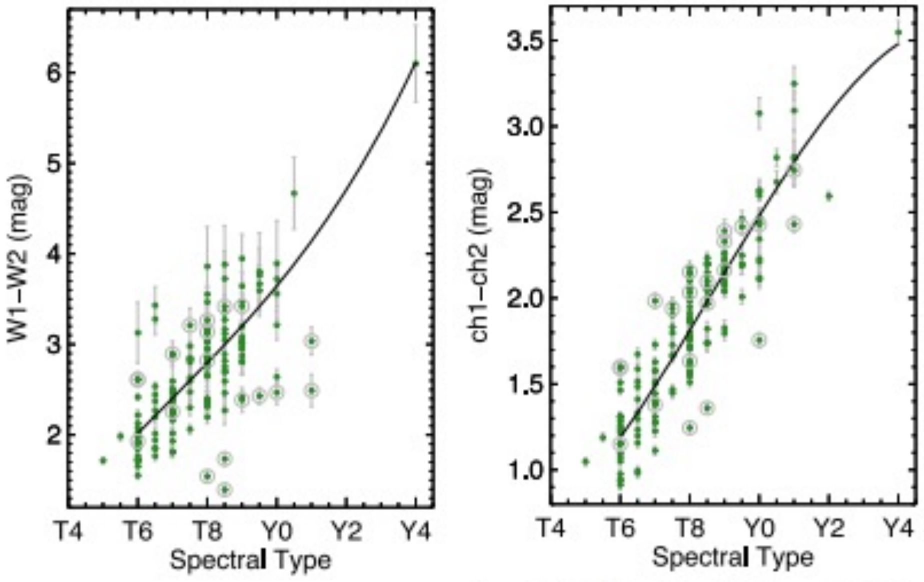
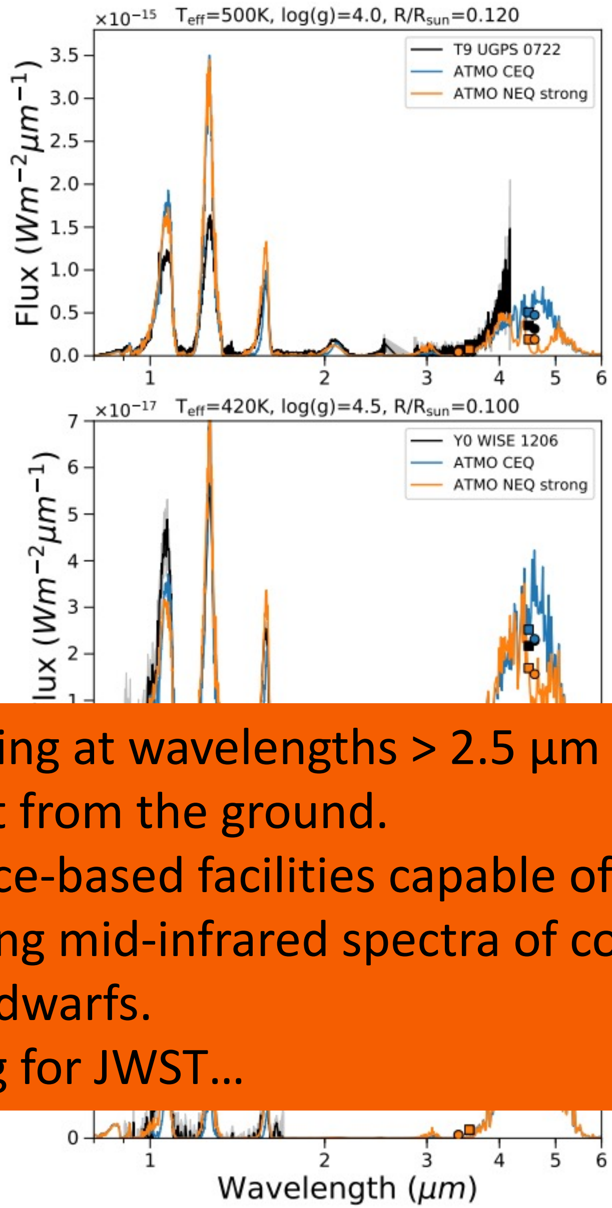


Kirkpatrick et al. 2019



Observing at wavelengths > 2.5 µm difficult from the ground.
No space-based facilities capable of obtaining mid-infrared spectra of cold brown dwarfs.
Waiting for JWST…

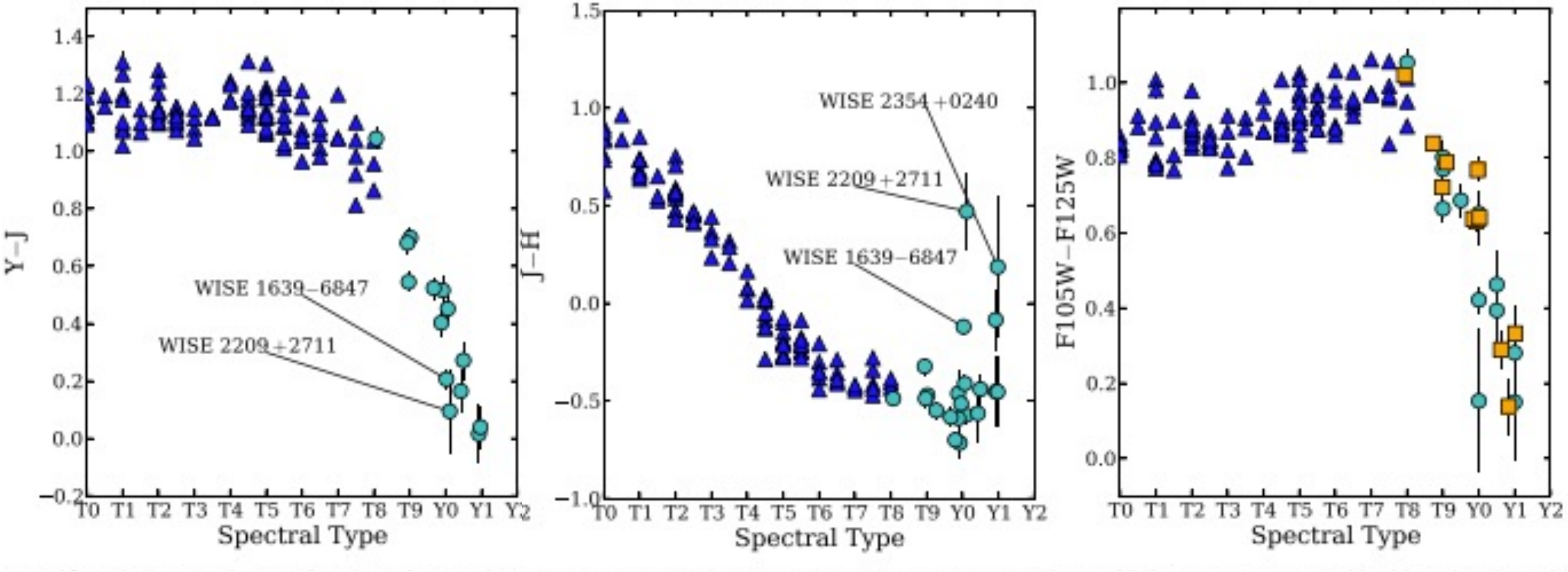
Phillips et al. 2020

Spectral classification and atmospheres

Y-type

The T/Y boundary coincides with the point where the J – H colors turn back to red, as predicted by models (the J-band peak continues to narrow, not the H-band peak).

The blueward trend in the Y – J colors may be due to K I condensing into KCl. The broad 0.77 µm K I doublet weakens, resulting in a brighter Y band.



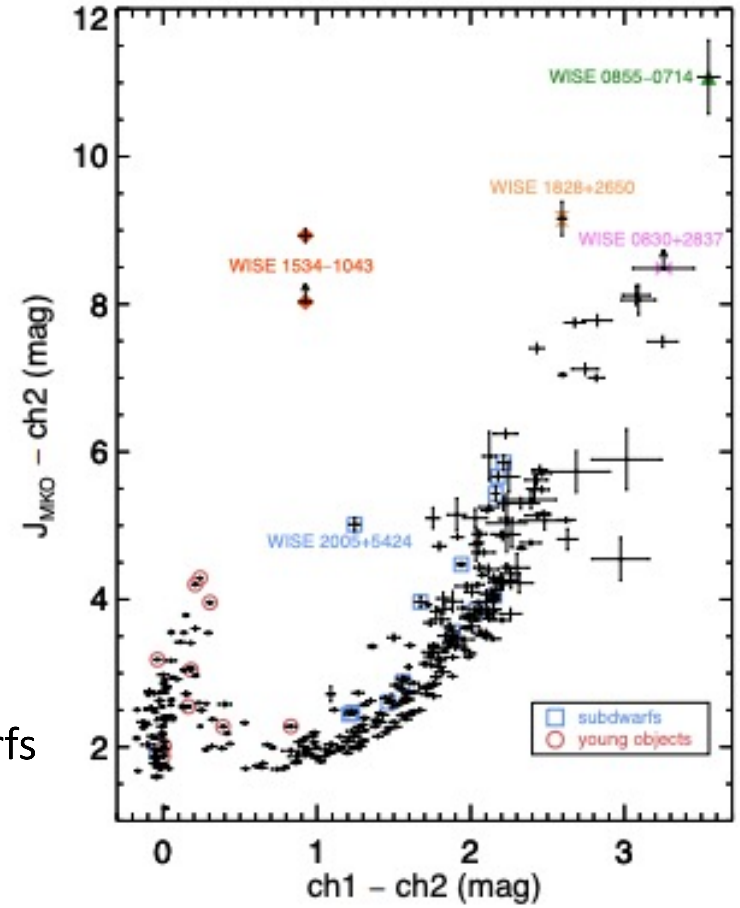
Schneider et al. 2015

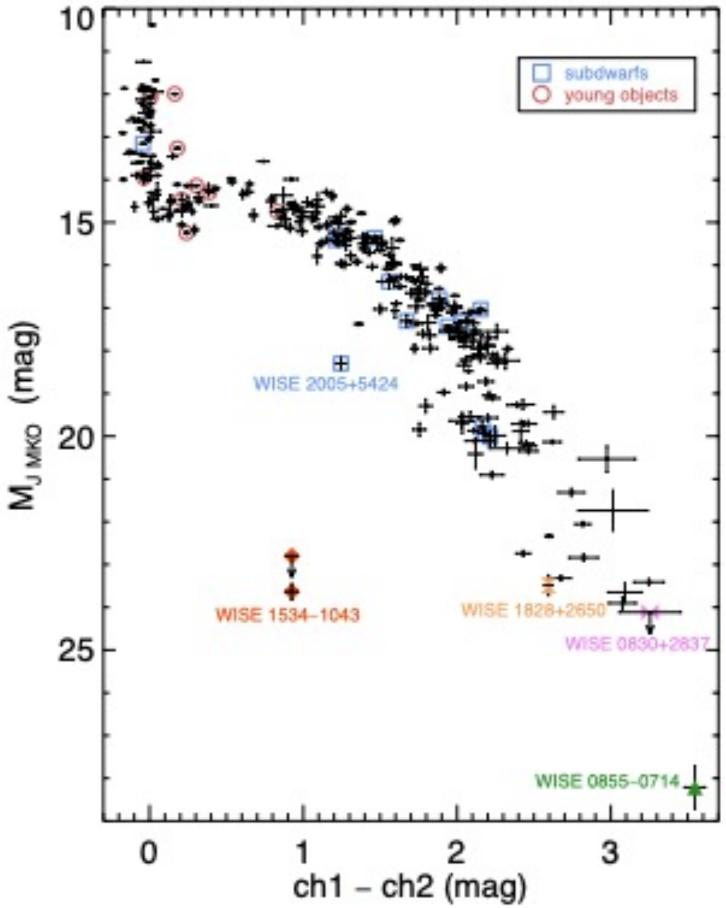
Spectral classification and atmospheres

Y-type

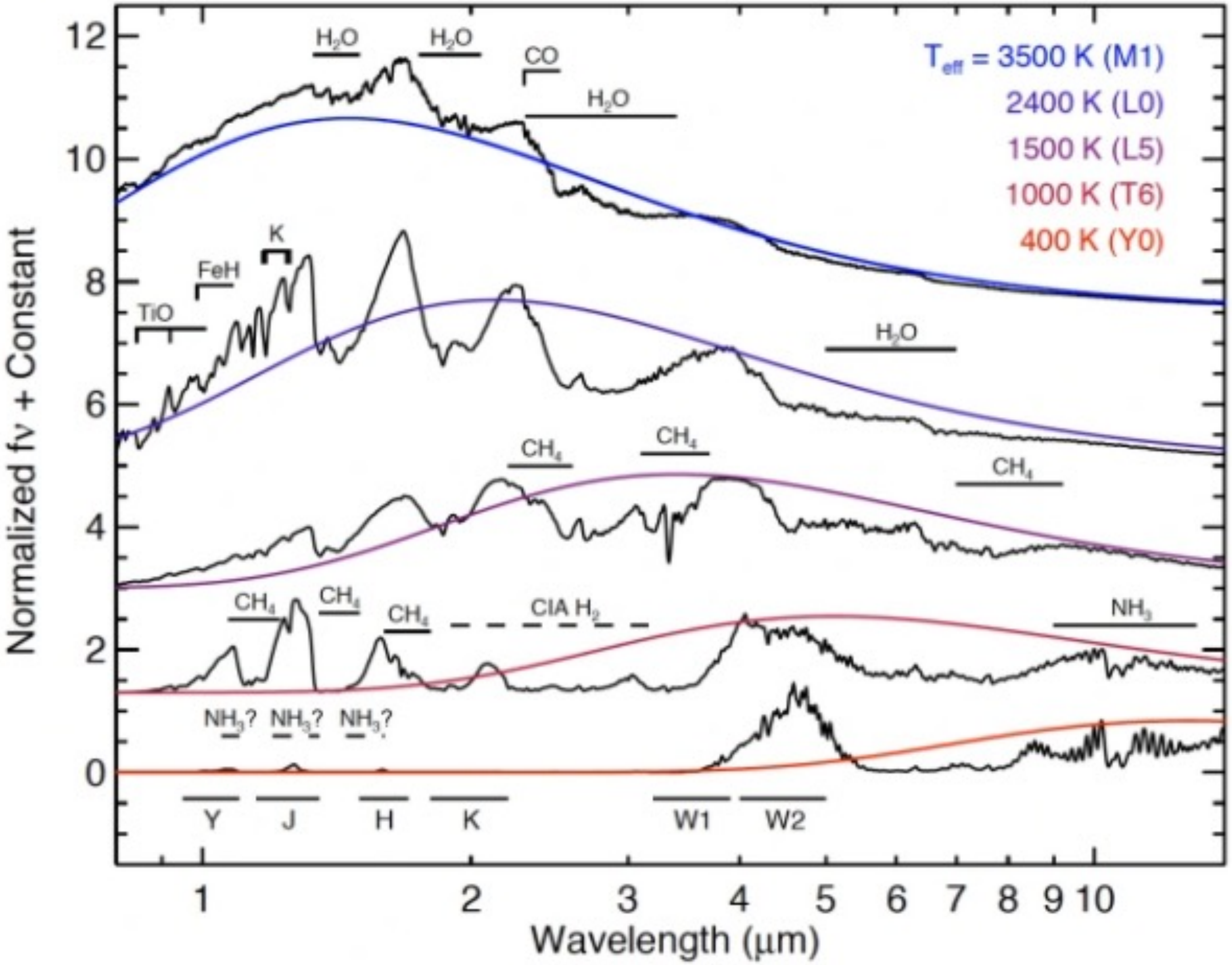
WISEA J153429.75−104303.3 (aka "The Accident")
J−ch2 > 8 mag indicates a very low temperature but ch1-ch2 bluer than typical Y-dwarfs

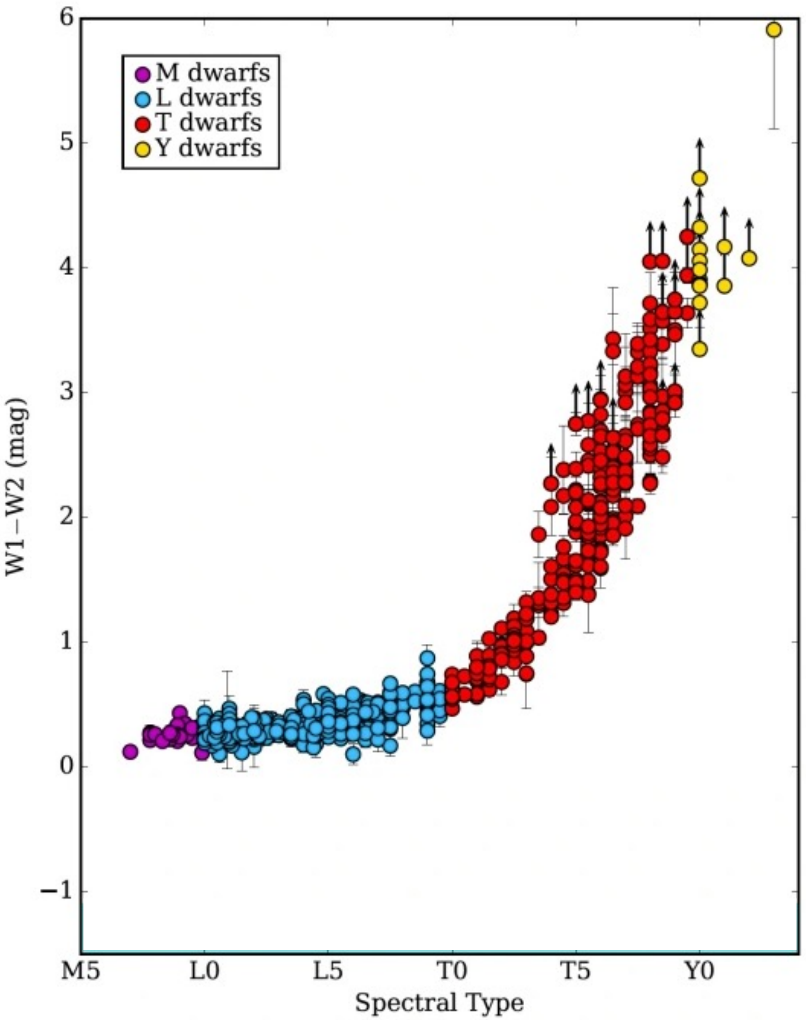
Most likely an old, metal-poor
→ first Y subdwarf?





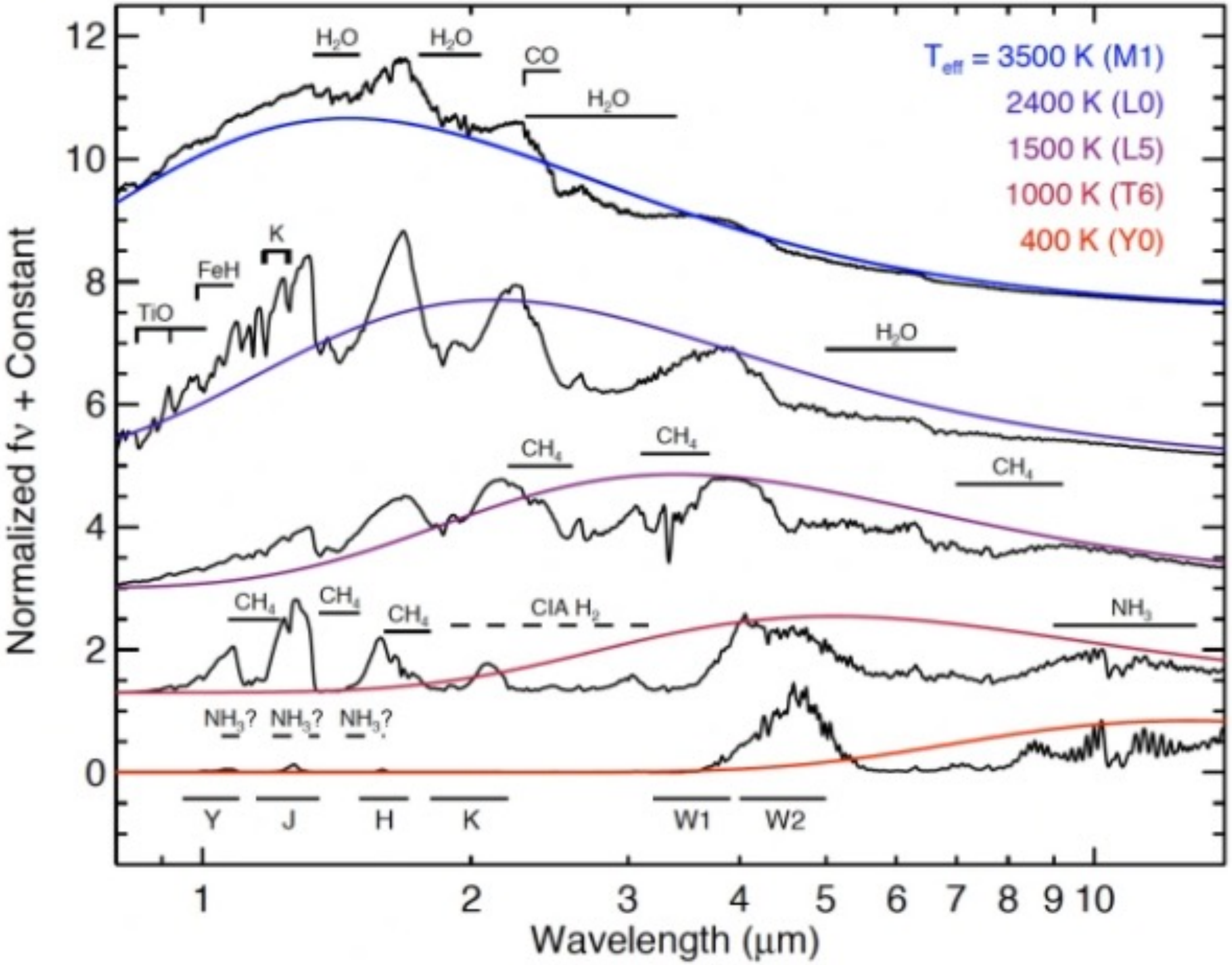
The 20 pc census of L, T, Y dwarfs
Kirkpatrick et al. 2021
See also Meisner et al. 2020

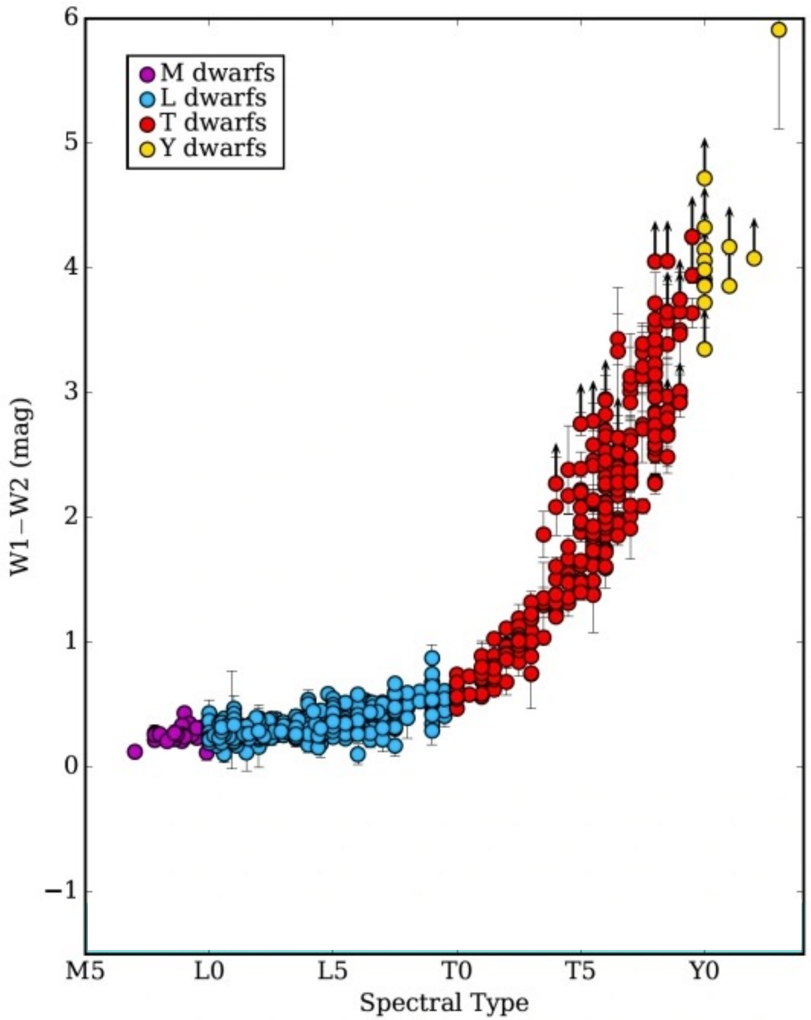




The WISE 3.6 μm (W1) and 4.5 μm (W2) bands were designed for optimal sensitivity to the coldest brown dwarfs (Mainzer et al. 2011). The additional use of motion criteria can help to eliminate stationary extragalactic contaminants.

https://blog.backyardworlds.org/2017/03/22/the-colors-of-cold-brown-dwarfs/





The coolest brown dwarfs revealed by WISE overlap in mass and temperature with extrasolar giant planets. They provide simplified laboratories for modeling planetary atmospheres because they do not undergo the irradiation and light contamination from a host star.

Clouds and variability

As brown dwarfs cool, a variety of species condense in their atmospheres, forming clouds.

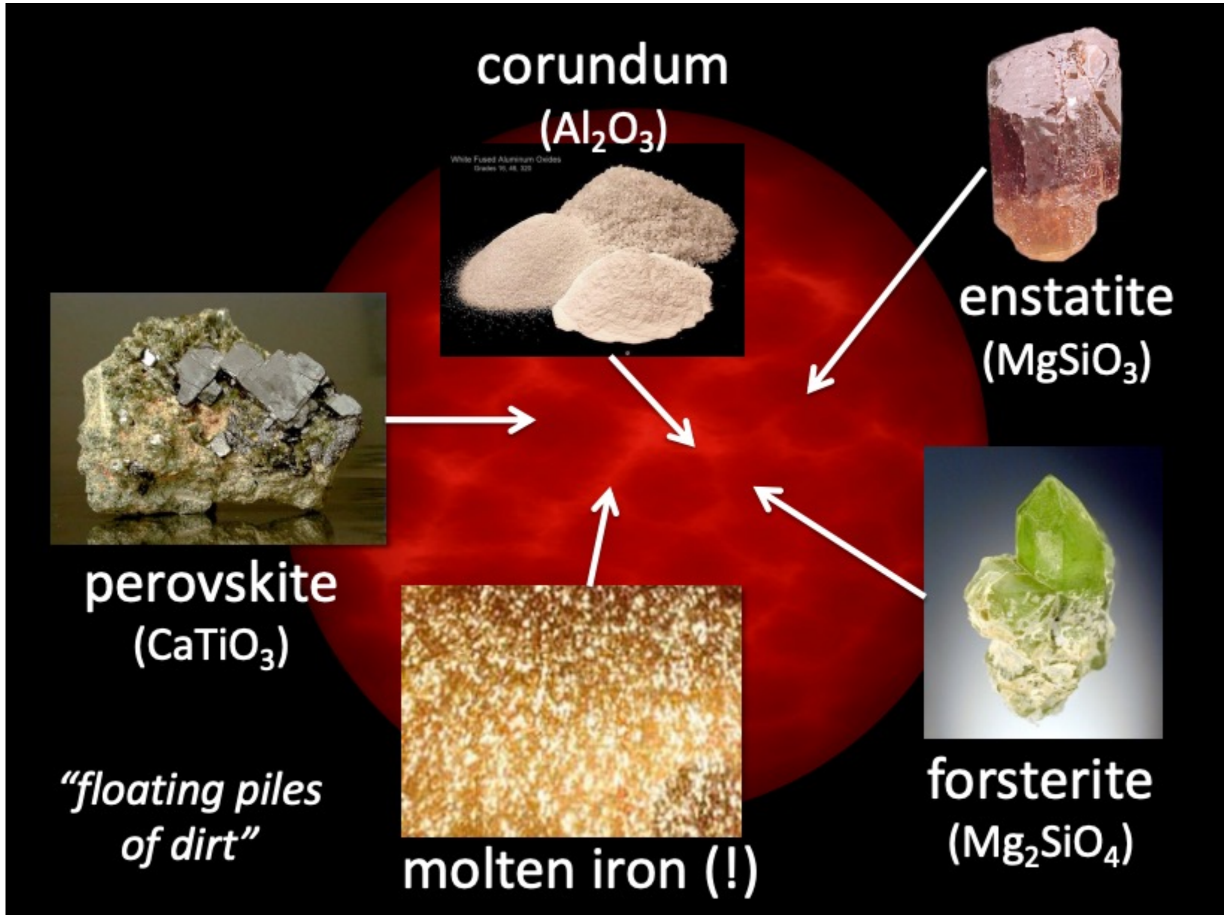
A thick cloud layer:

- alters the temperature profile of the atmosphere
- provides a continuum opacity source
- limits the depth from which the brown dwarf can radiate

Within windows between major molecular absorption bands, there is little gas opacity.
Cloud opacity tends to suppress the flux within these windows

Clouds and variability

As brown dwarfs cool, a variety of species condense in their atmospheres, forming clouds.



Courtesy of A. Burgasser

Iron and silicate clouds shape the emergent spectra of mid L dwarfs. Observed colors and spectra of L dwarfs cannot be well matched without a significant cloud layer (Burrows et al. 2006).

Clouds and variability

At the L/T transition the clouds become dramatically less important within a small range of T_{eff}.

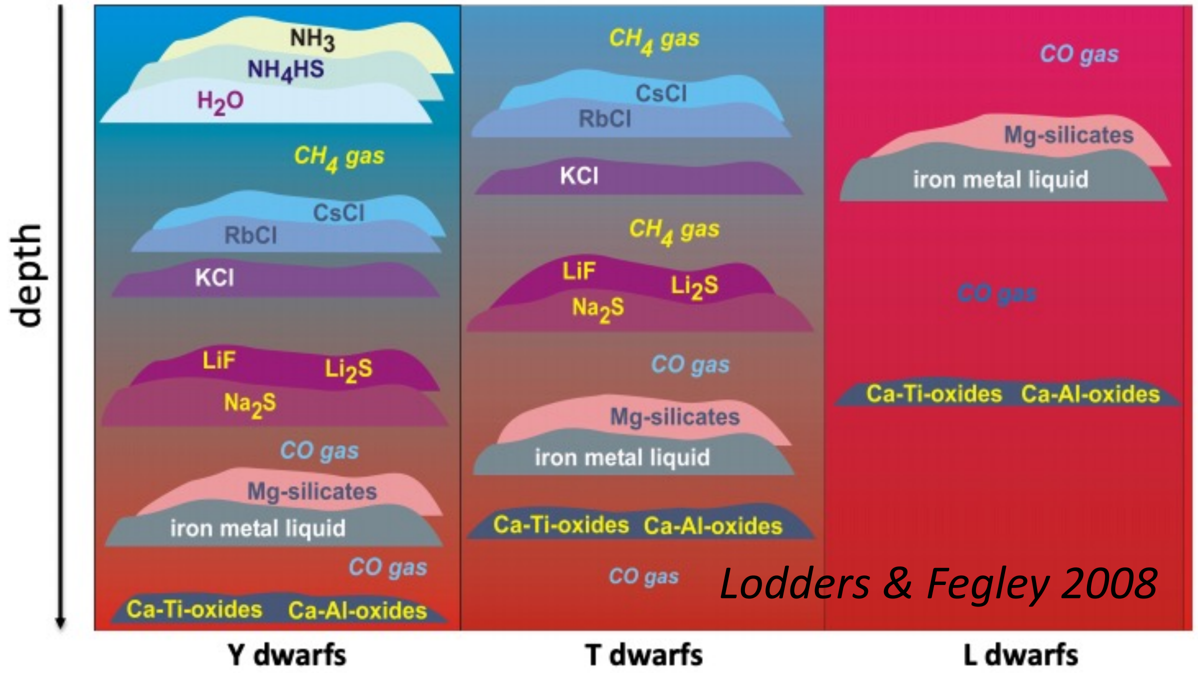
Dust dispersal due to:

- an abrupt sinking of the entire cloud deck into the deep unobservable atmosphere (Stephens et al. 2009, Tsuji et al. 2005)
- breakup of the cloud into scattered patches (Burgasser et al. 2002, Marley et al. 2010)

CO/CH4 “thermohaline or fingering convection“ could also reduce the temperature profile (Trembin et al. 2015)

As the clouds dissipate, the atmospheric windows clear. Flux emerges from deeper, hotter atmospheric layers (above the cloud level), and the brown dwarf becomes much bluer in NIR color.

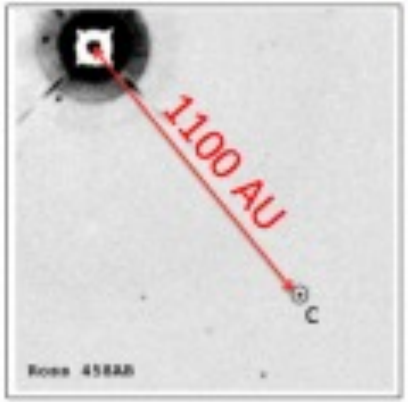
A variety of other condensates (Cr, MnS,Na_2S, ZnS, KCl) are expected to form optically thinner clouds in cooler T dwarfs (Marley et al. 2012, Charnay et al. 2018). At < 350 K, water and ammonia expected to form.



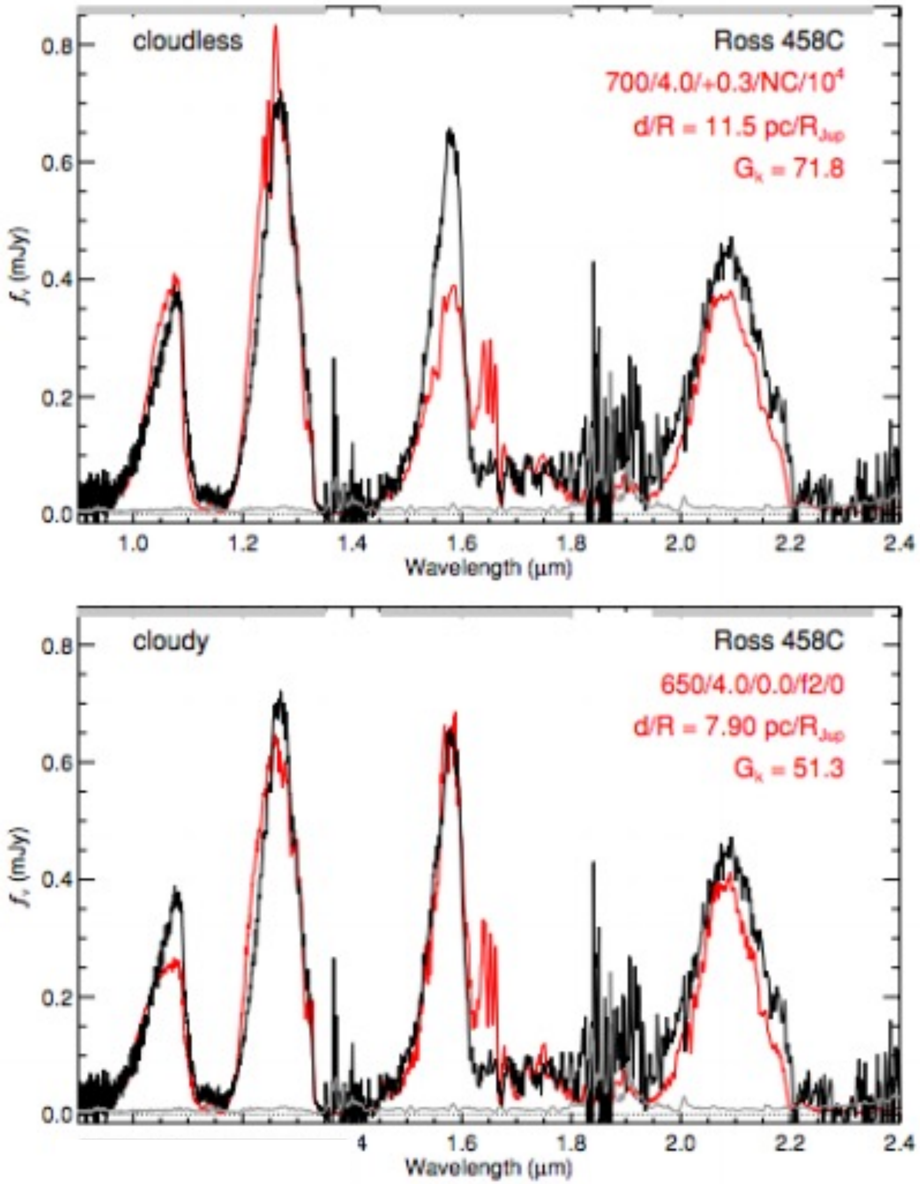
Clouds and variability

Sulfite and salt clouds in cold brown dwarfs significantly change the shape of the spectrum

Ross 458C
A 700 K, 7 Mjup
''planet'' with clouds

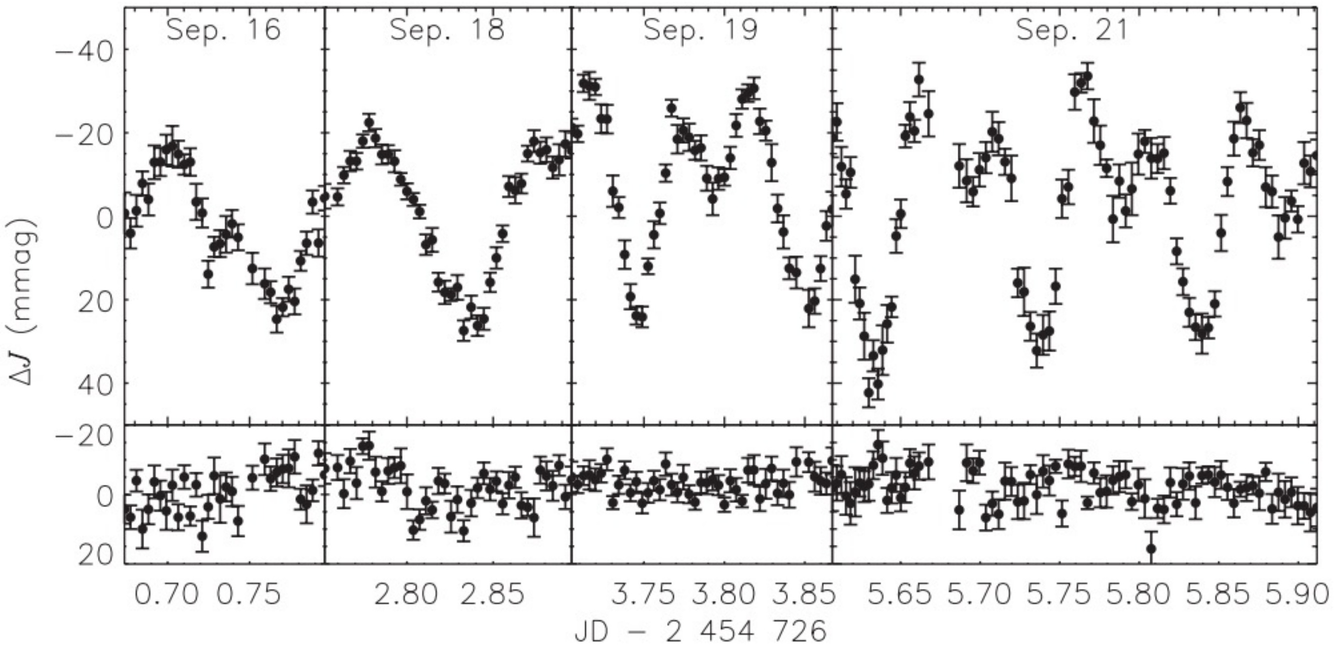


Burgasser et al. 2010



Clouds and variability

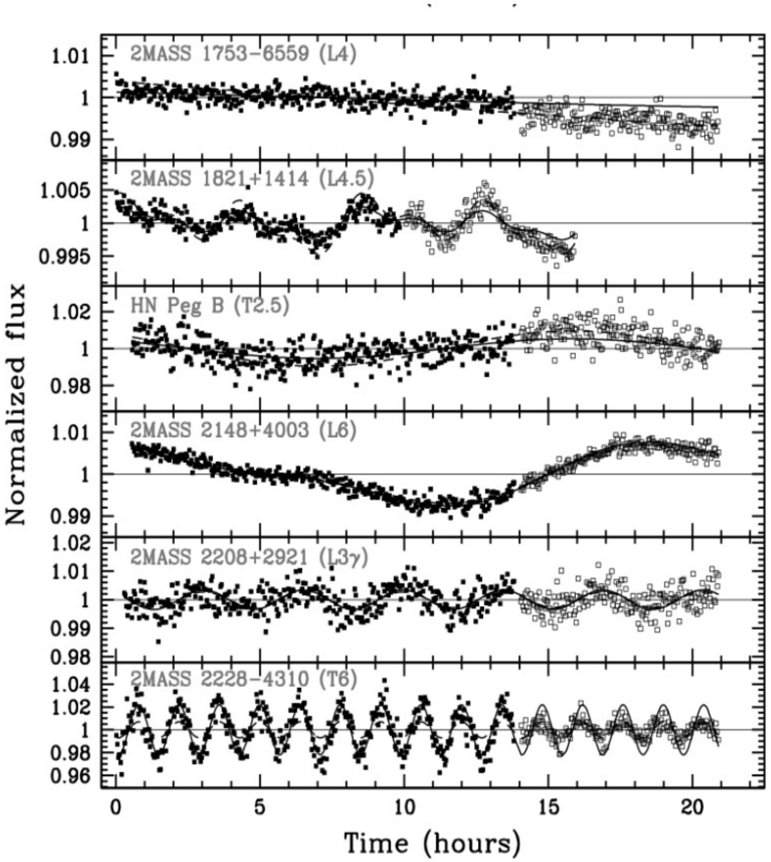
Discoveries of highly photometrically variable early T dwarfs suggest that cloud patchiness may indeed play a role (e.g. Radigan et al. 2012; Artigau et al. 2009).



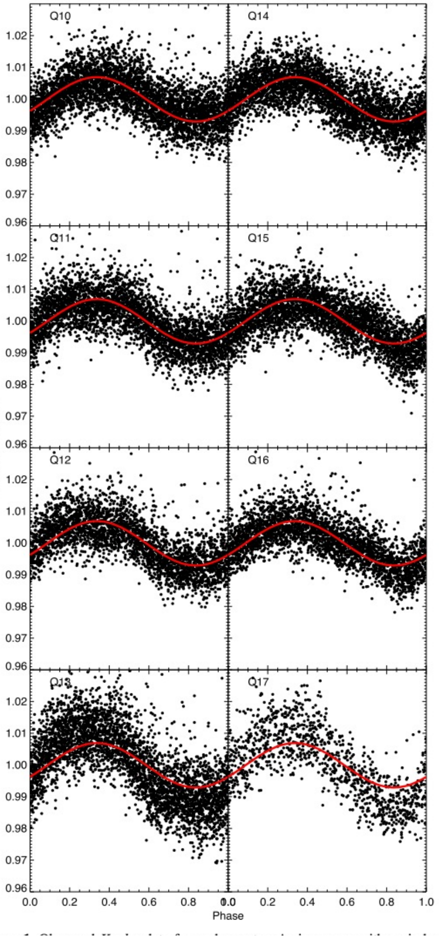
Light curve binned over 5 min time bins of SIMP0136
Artigau et al. 2009

Clouds and variability

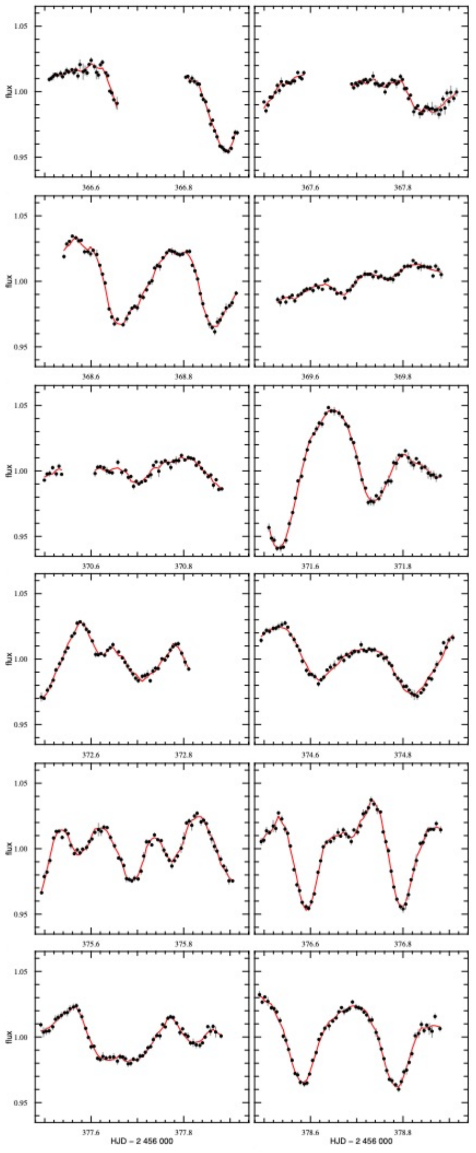
Light curves are quite complexe and diverse!



Weather on Other Worlds Spitzer Exploration
Metchev et al. 2015



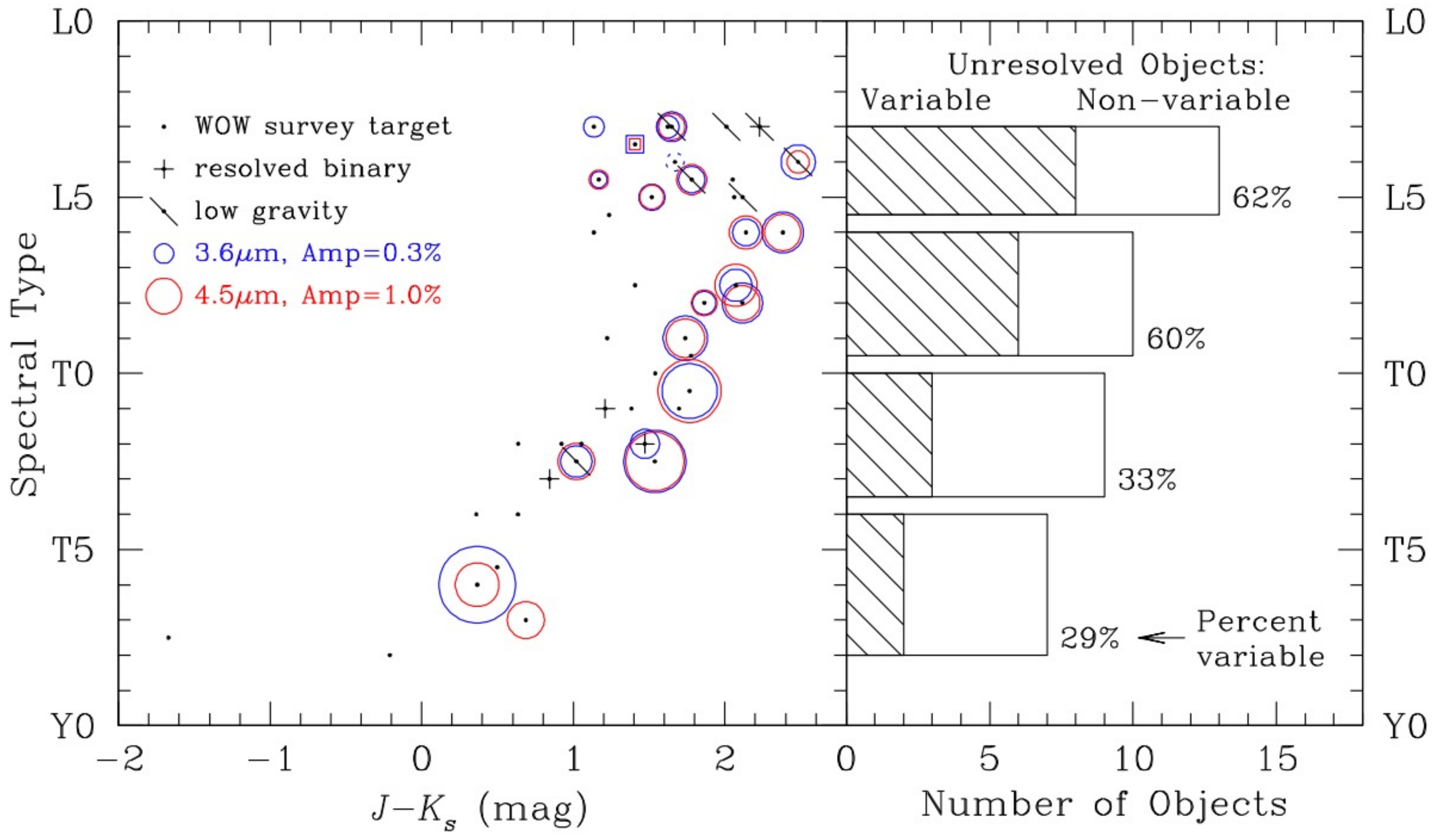
2 yr of Kepler observation, L1
Gizis et al. 2015



12 nights ground-based observation of Luhman 16 AB (L7.5+T0.5, 2pc)
Gillon et al. 2013

Clouds and variability

Variability is common among brown dwarfs



Metchev et al. 2015

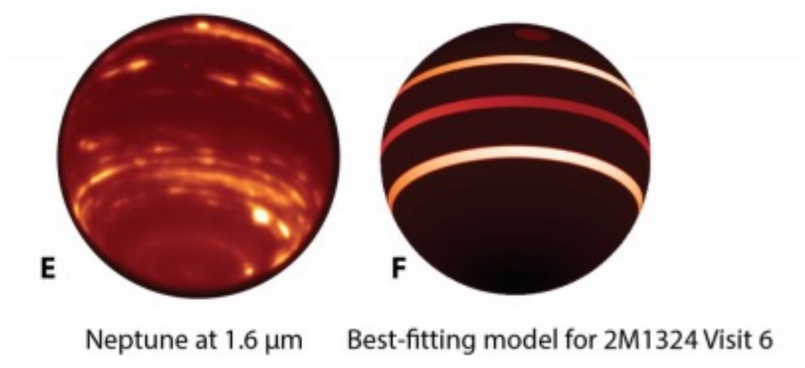
Photospheric heterogeneities are present on most T and L dwarfs

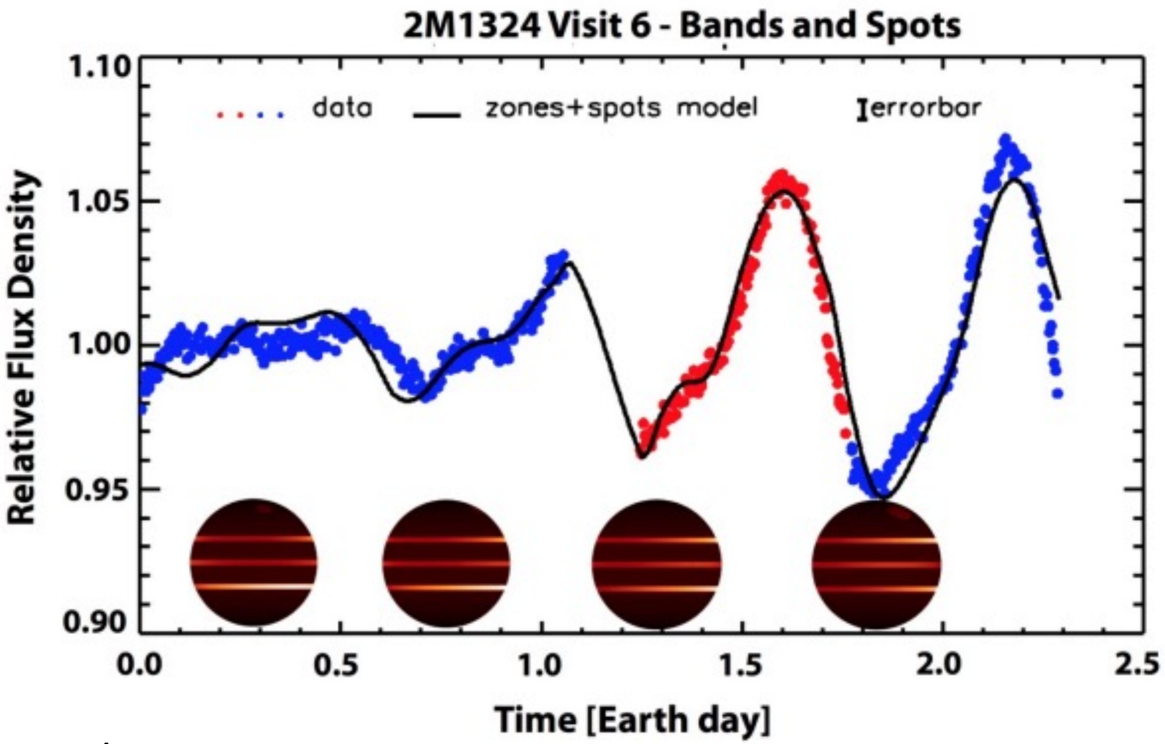
⅓ of L dwarf variables show irregular light curves, indicating multiple spots evolving over a single rotation

Clouds and variability

Variations in time allow us to map the horizontal cloud distributions of brown dwarfs and their evolution

Long-term Spitzer monitoring of the IR brightness of brown dwarfs.
Variations explained by beat patterns caused by bands of clouds and a small number of bright spots rotating within the atmosphere. Such bands are seen in IR images of Neptune.

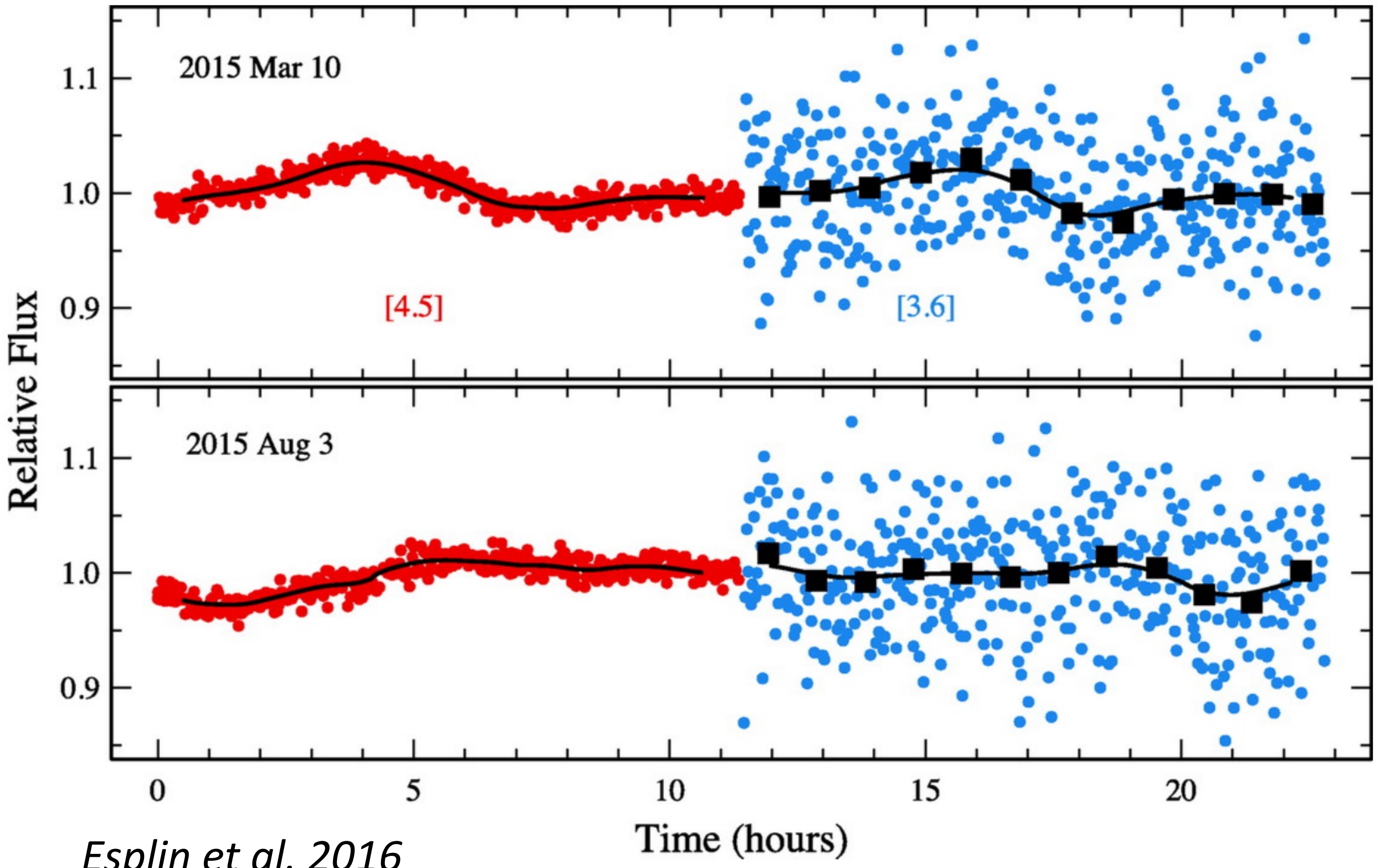




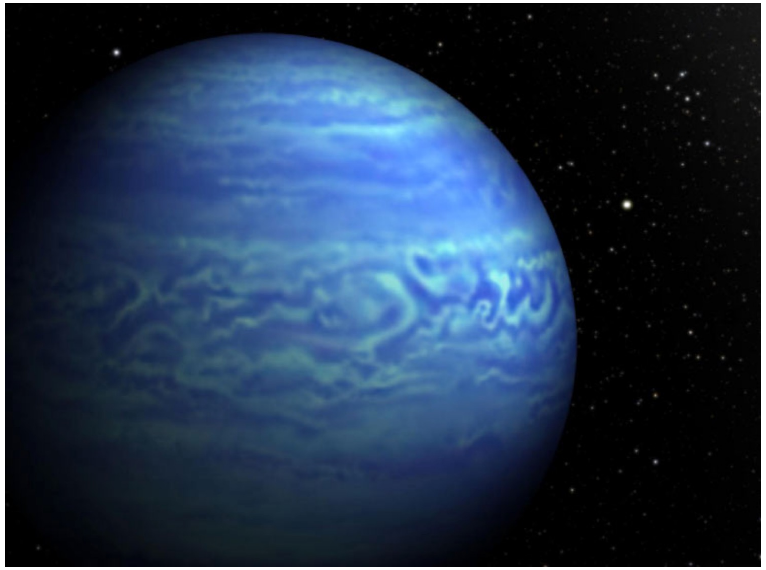
Apai et al. 2017

Clouds and variability

The coldest known brown dwarf, WISE 0855-0714, is also variable. Water ice clouds (Faherty et al. 2014, Schneider et al. (2016), Luhman & Esplin (2016), Esplin et al. 2016)?



Esplin et al. 2016



Clouds and variability

By measuring how the shapes of absorption lines change as a star rotates, we can map dark or bright spots on its surface.

Doppler imaging of Luhman 16B (T0.5) shows a global spotiness.

Weather in brown dwarfs represent a simplified case where atmospheric dynamics is free of external forcing due to irradiation from a host star.

Crossfield et al. 2014