New Light on Dark Stars

Brown dwarf astrophysics in the 2020s

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image: NASA/IPAC/R.Hurt

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https://sites.nationalacademies.org/DEPS/Astro2020/

573 Science White Papers
were submitted in March 2019 and
are available on the BAAS site:
https://baas.aas.org/community/astro2020-science-white-papers/

330 State of the Profession White Papers
were submitted in June 2019 and
can be found on the NAS site
https://sites.nationalacademies.org/DEPS/Astro2020/DEPS_192906

Astro2020 White Papers on Brown Dwarfs

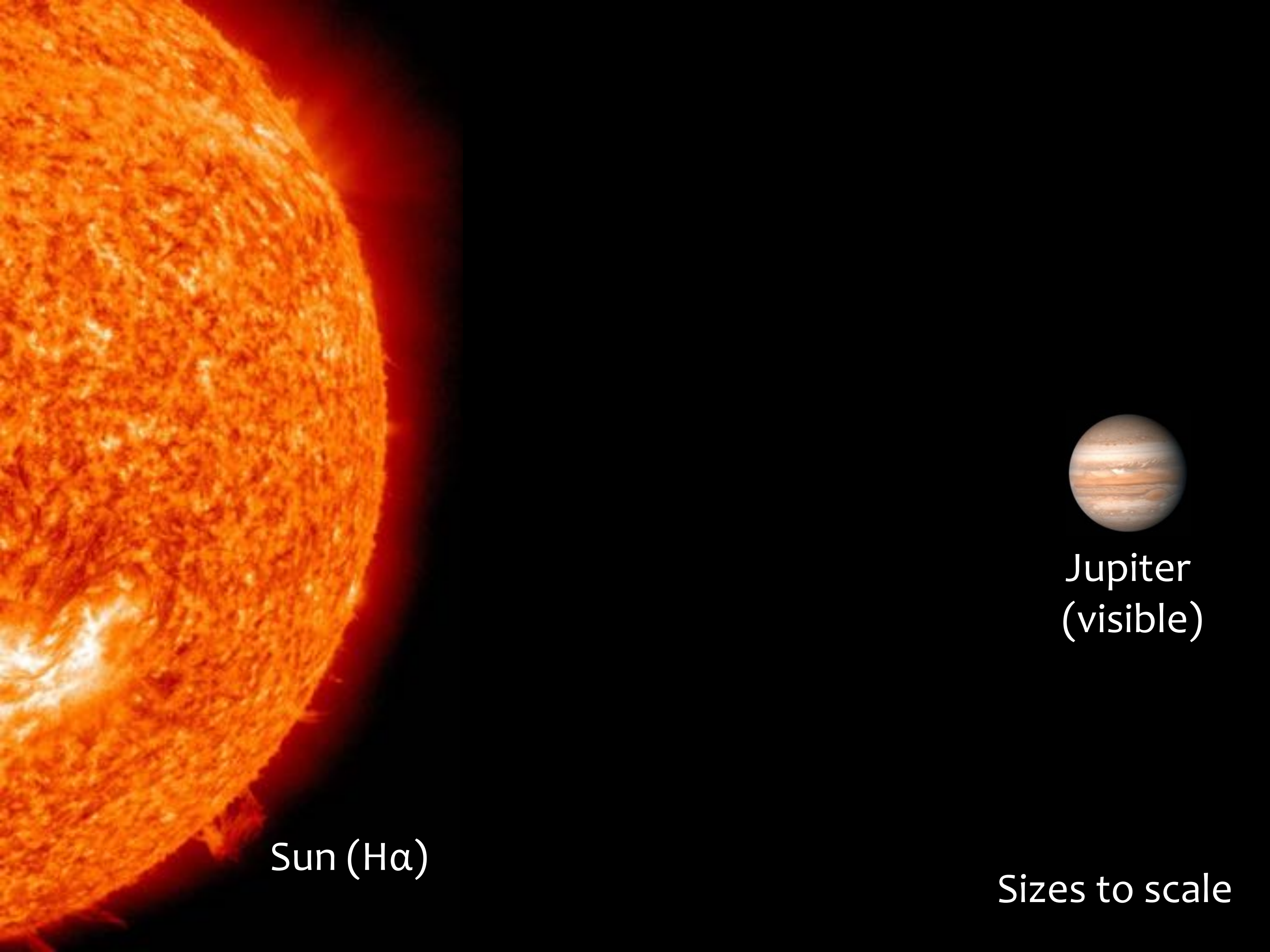
1. Apai et al.: Mapping Ultracool Atmospheres: Time-domain Observations of Brown Dwarfs and Exoplanets
2. Bardalez et al.: Substellar Multiplicity Throughout the Ages
3. Burgasser et al.: Fundamental Physics with Brown Dwarfs: The Mass-Radius Relation
4. Burgasser et al.: High-Resolution Spectroscopic Surveys of Ultracool Dwarf Stars & Brown Dwarfs
5. Caiazzo et al.: Hunting for ancient brown dwarfs: the developing field of brown dwarfs in globular clusters
6. Dupuy et al.: Establishing an Empirical Substellar Sequence to Planetary Masses
7. Faherty et al.: Brown Dwarfs and Directly Imaged Exoplanets in Young Associations
8. Kao et al.: Magnetism in the Brown Dwarf Regime
9. Kirkpatrick et al.: The Need for Infrared Astrometry of Brown Dwarfs in the Post-Gaia Era
10. Leggett et al.: Discovery of Cold Brown Dwarfs or Free-Floating Giant Planets Close to the Sun
11. Muirhead et al.: Searching for Exosatellites Orbiting L and T Dwarfs: Connecting Planet Formation to Moon Formation and Finding New Temperate Worlds
12. Stauffer et al.: The IMF at Very Low Mass Using Near-IR Surveys from Space: The Need for Deep K-band Imaging
13. Vos et al.: The L/T Transition
14. Youngblood et al.: EUV observations of cool dwarf stars

https://baas.aas.org/community/astro2020-science-white-papers/

Outline

- What are brown dwarfs?
- Outstanding problems & opportunities over the next decade:
  - BD formation
  - BD demographics
  - BDs & fundamental physics
  - BD weather & atmospheric dynamics
  - BD magnetism
  - BD Galactic archaeology
- If I had $1B*

** I'd be rich!*


Jupiter
(visible)
Sun (Hα)
Sizes to scale

≈10 light-years

M16 (Eagle Nebula)
Image credit: NASA, ESA and the Hubble Heritage Team (STScI/AURA)

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

$T_{core} \sim M/R$

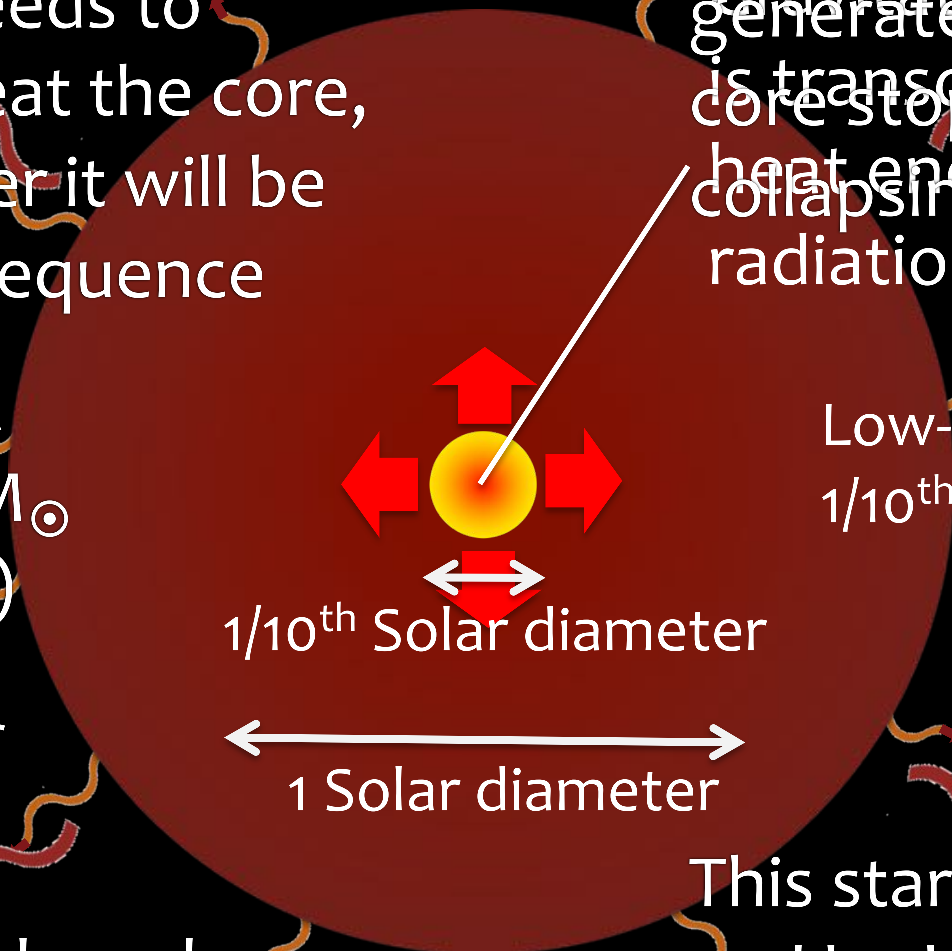
$\Rightarrow R/R_{\odot} \approx M/M_{\odot}$

$(M < 1\ M_{\odot})$

The fusion reactions generated in the star's core stop the star from collapsing further

Gravitational energy is transduced into heat energy in core & radiation at surface

(≈ 50/50)



Low-mass star

1/10th the Sun's mass

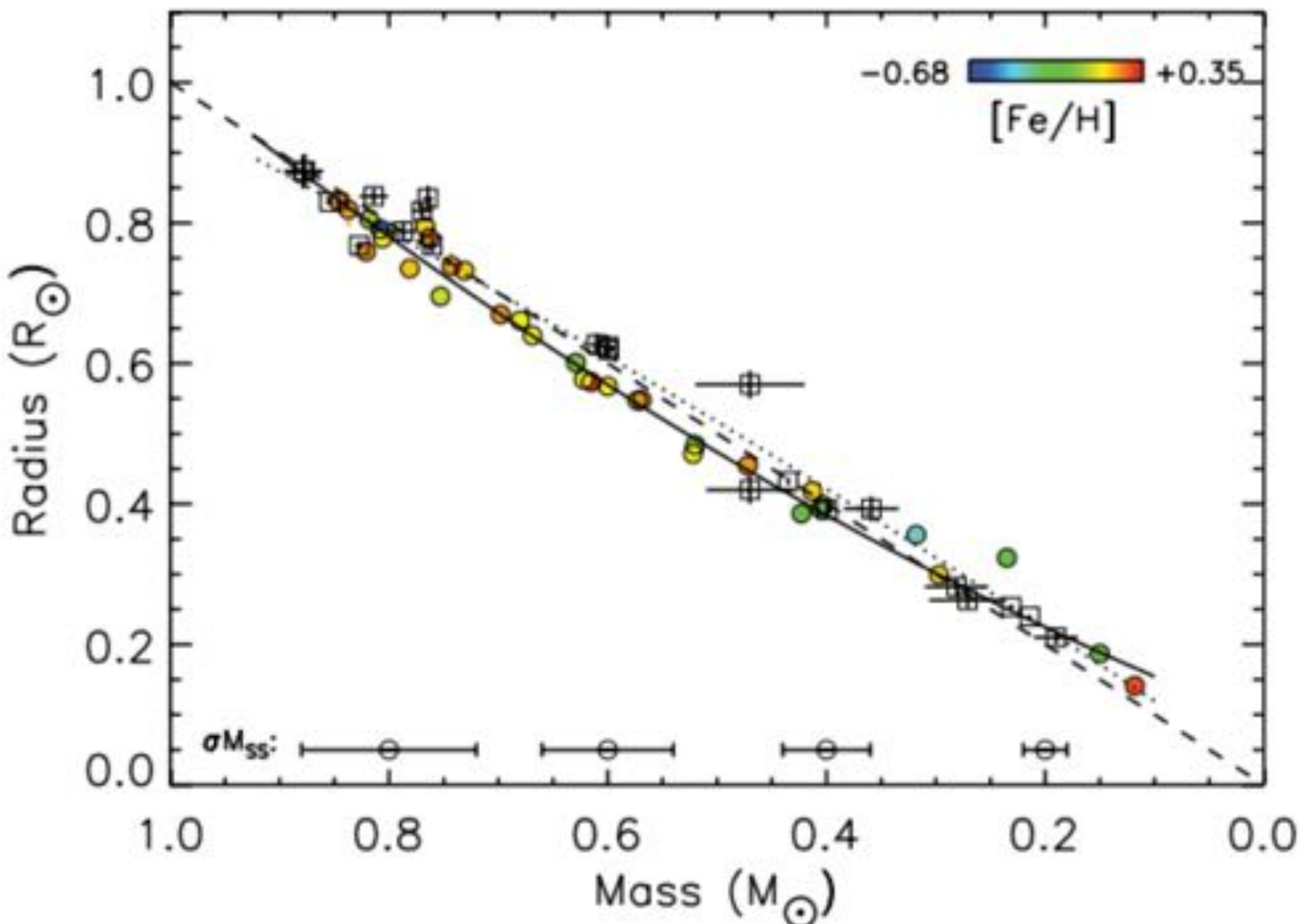
Sun-like star

Radiation cools and gravity compresses the cloud

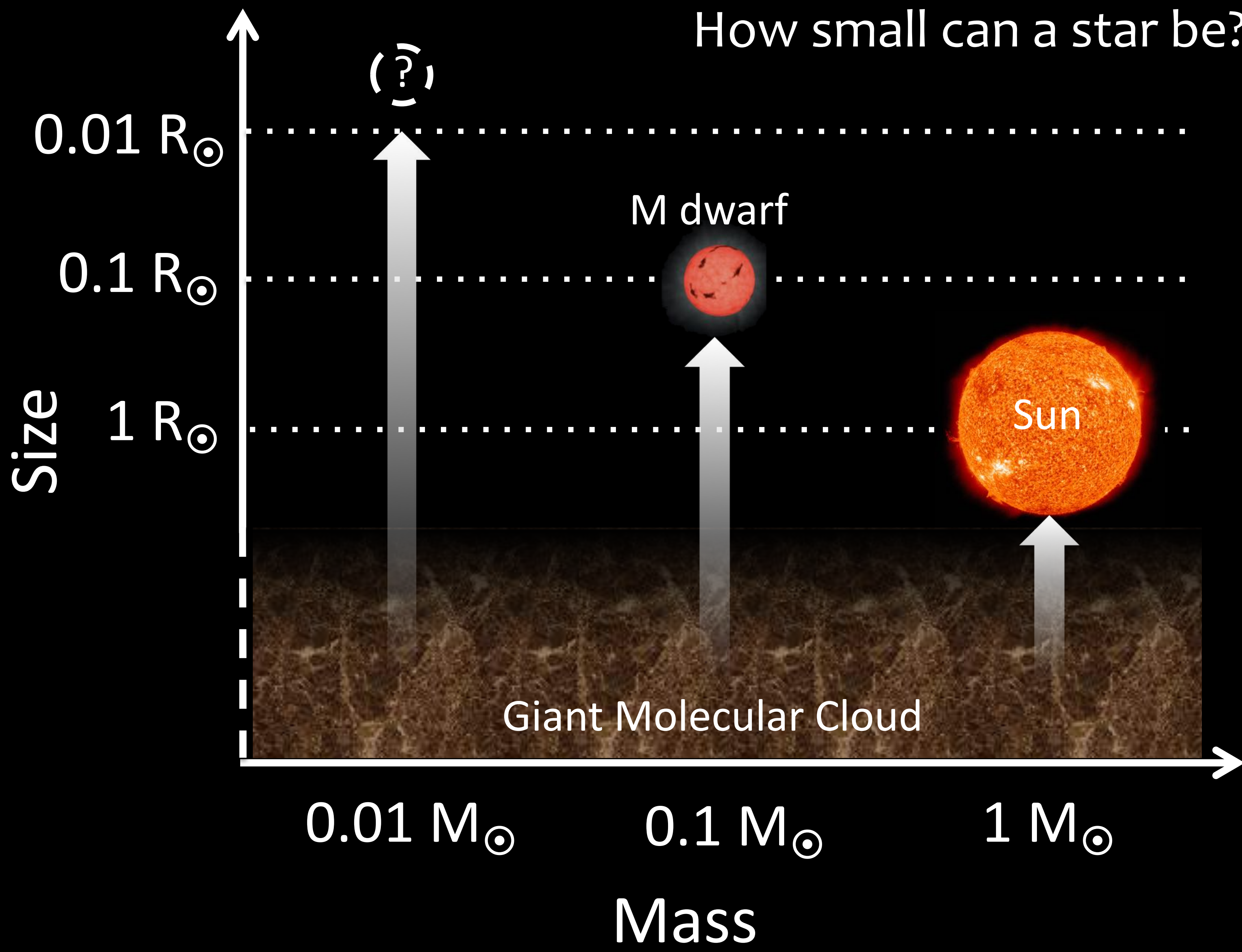
≈0.1 light-year across

This star is in thermal and hydrostatic equilibrium (aka Main Sequence)

Stellar Empirical Mass-radius Relationship



Boyajian et al. (2012)



How small can a star be?
?
0.01 $R_\odot$
0.1 $R_\odot$
1 $R_\odot$
Size
M dwarf
Sun
Giant Molecular Cloud
0.01 $M_\odot$
0.1 $M_\odot$
1 $M_\odot$
Mass

subway degeneracy pressure

degenerate parking

degenerate electron gas

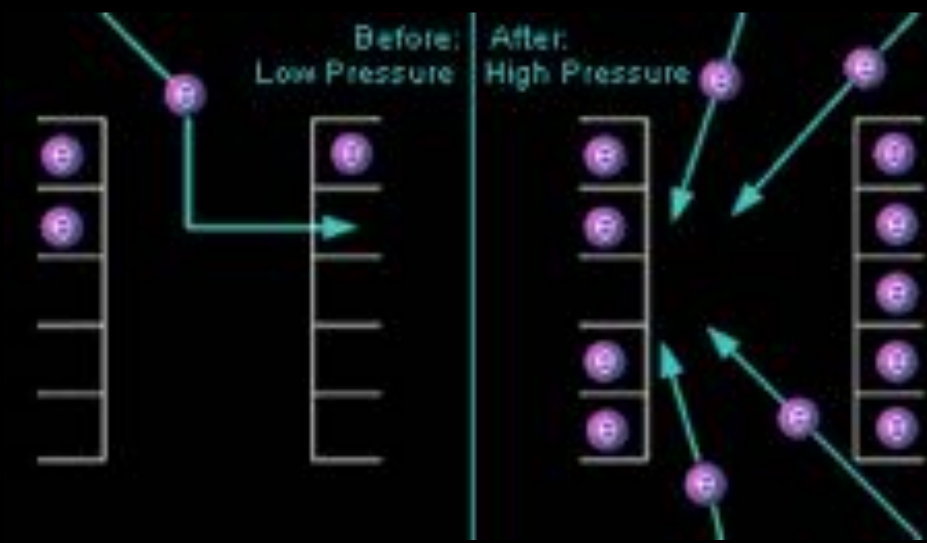
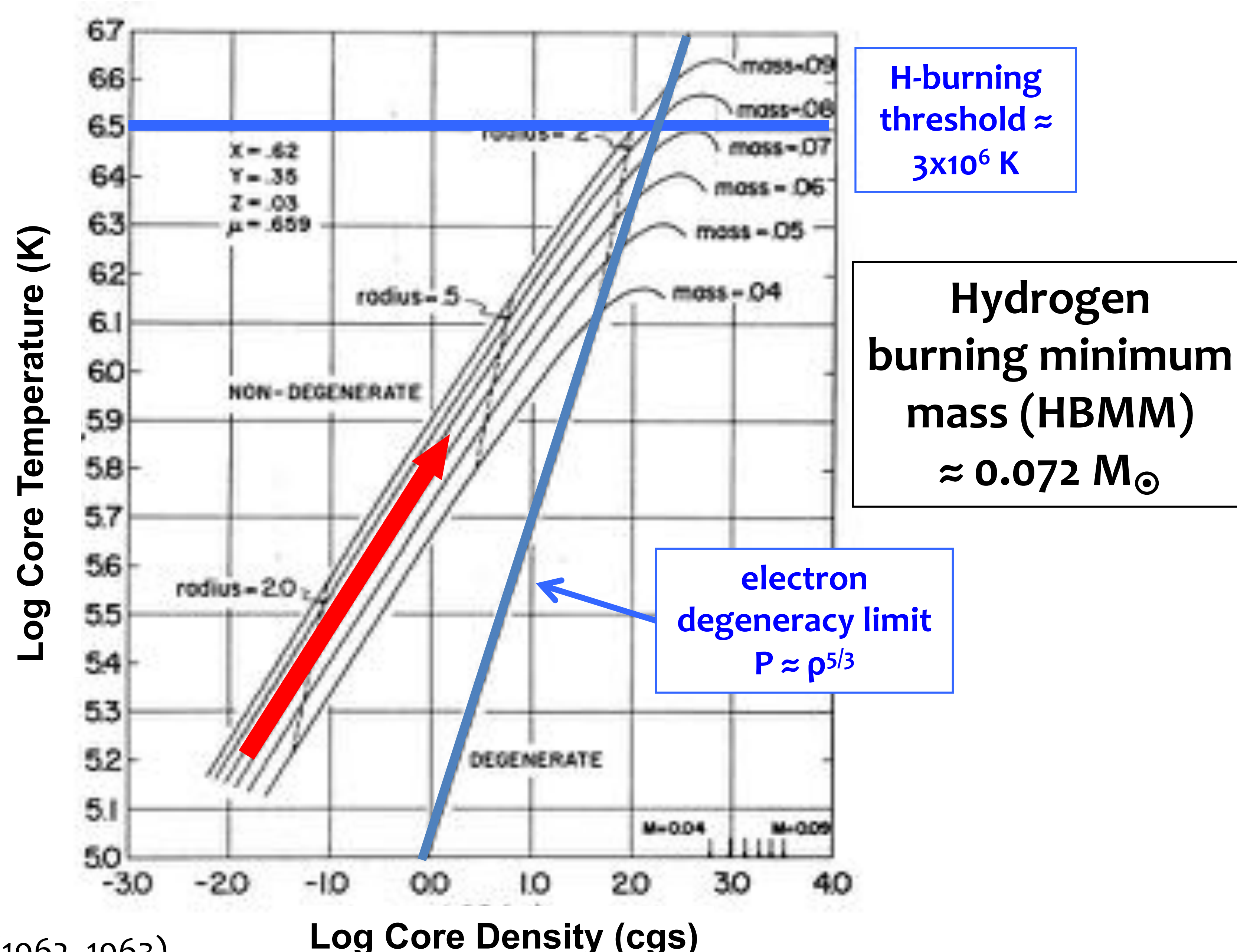
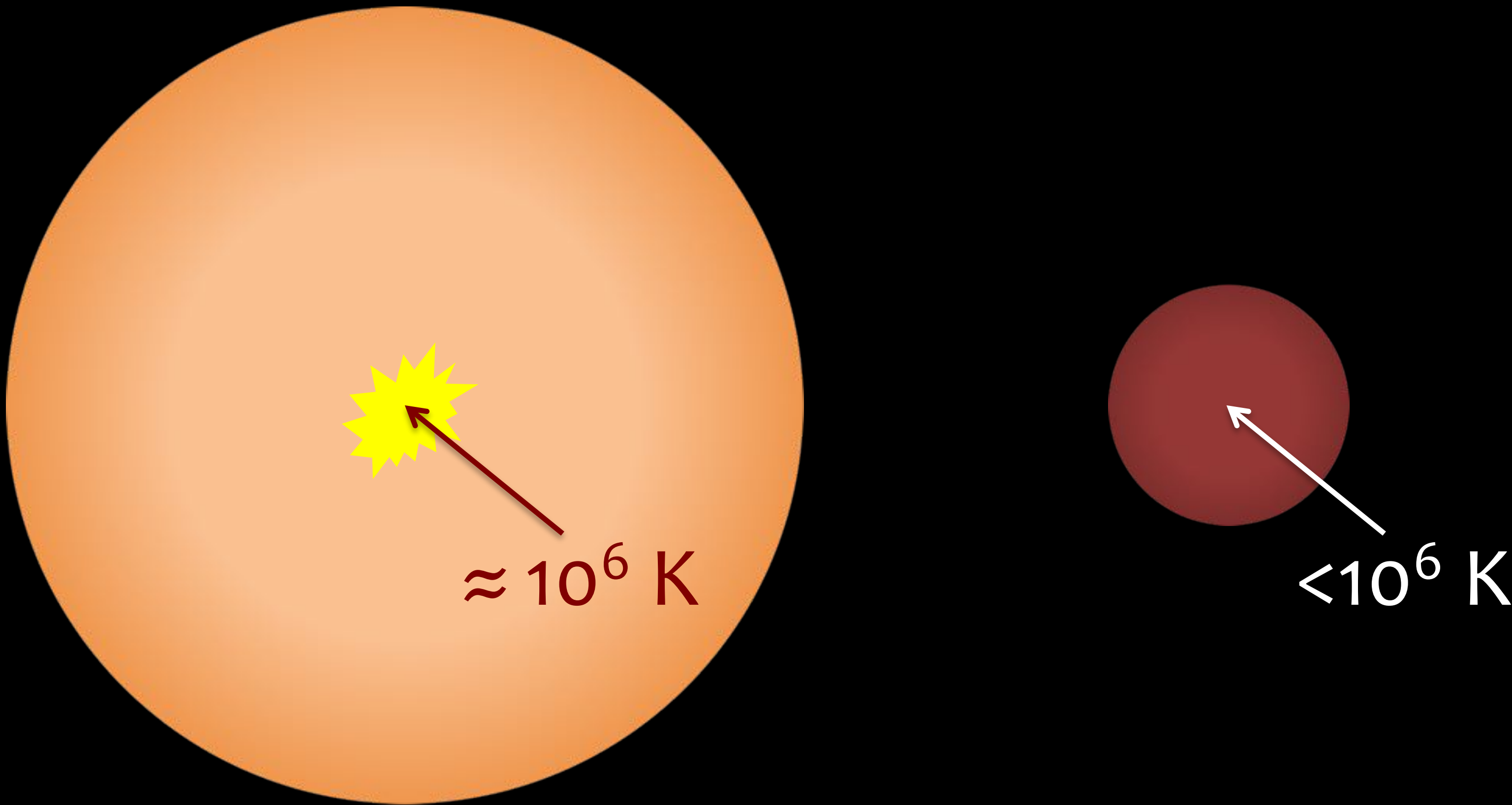


Image credit:
Harvard Chandra X-ray Center



Kumar (1962, 1963)
also Hayashi & Nakano (1963)



Main Sequence:

Thermal pressure support

Strong->Thermal->Radiation

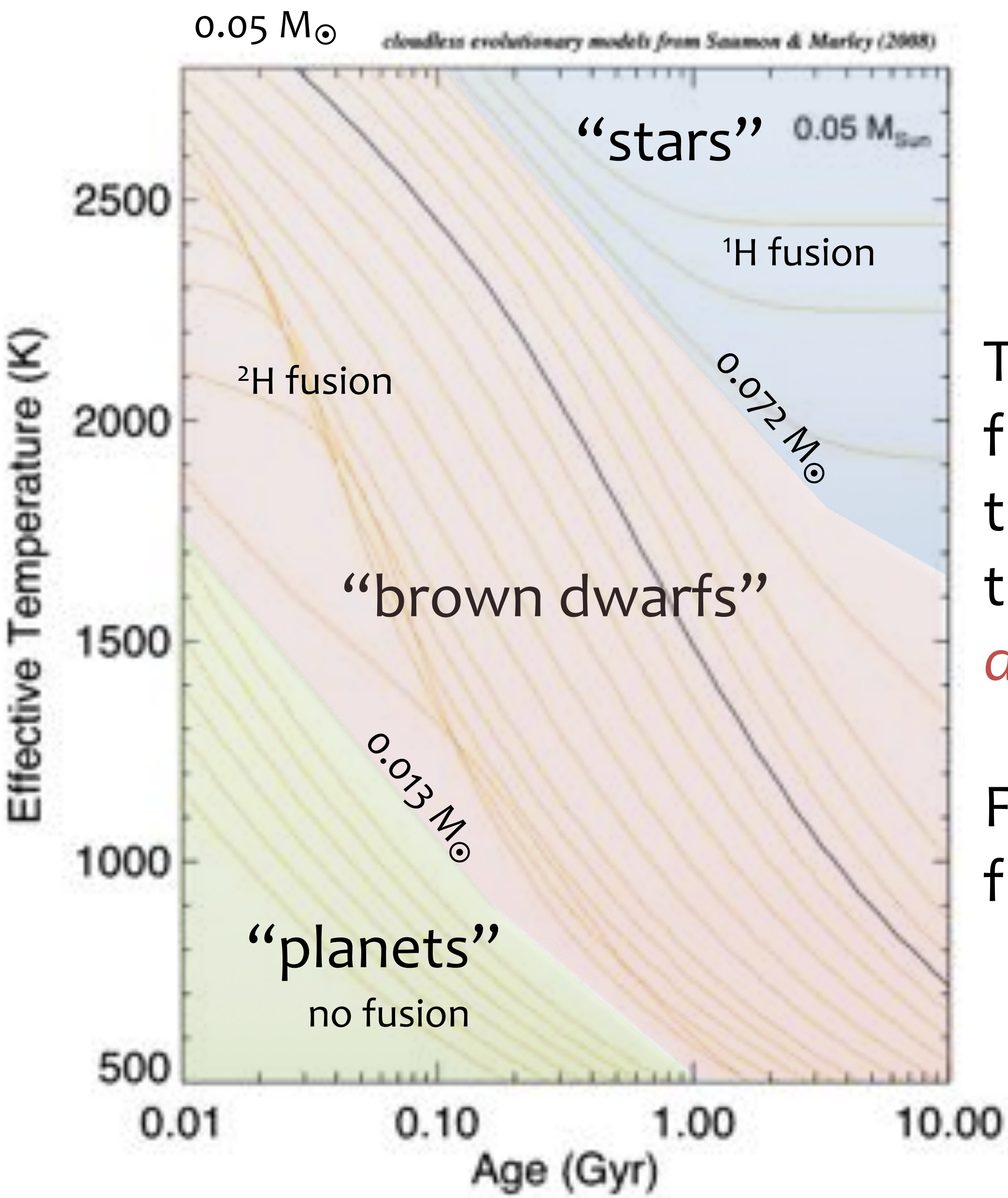
$L_{bol} \approx L_{nuclear}$, $T_{core} \approx$ constant

Degenerate Sequence:

Degeneracy pressure support

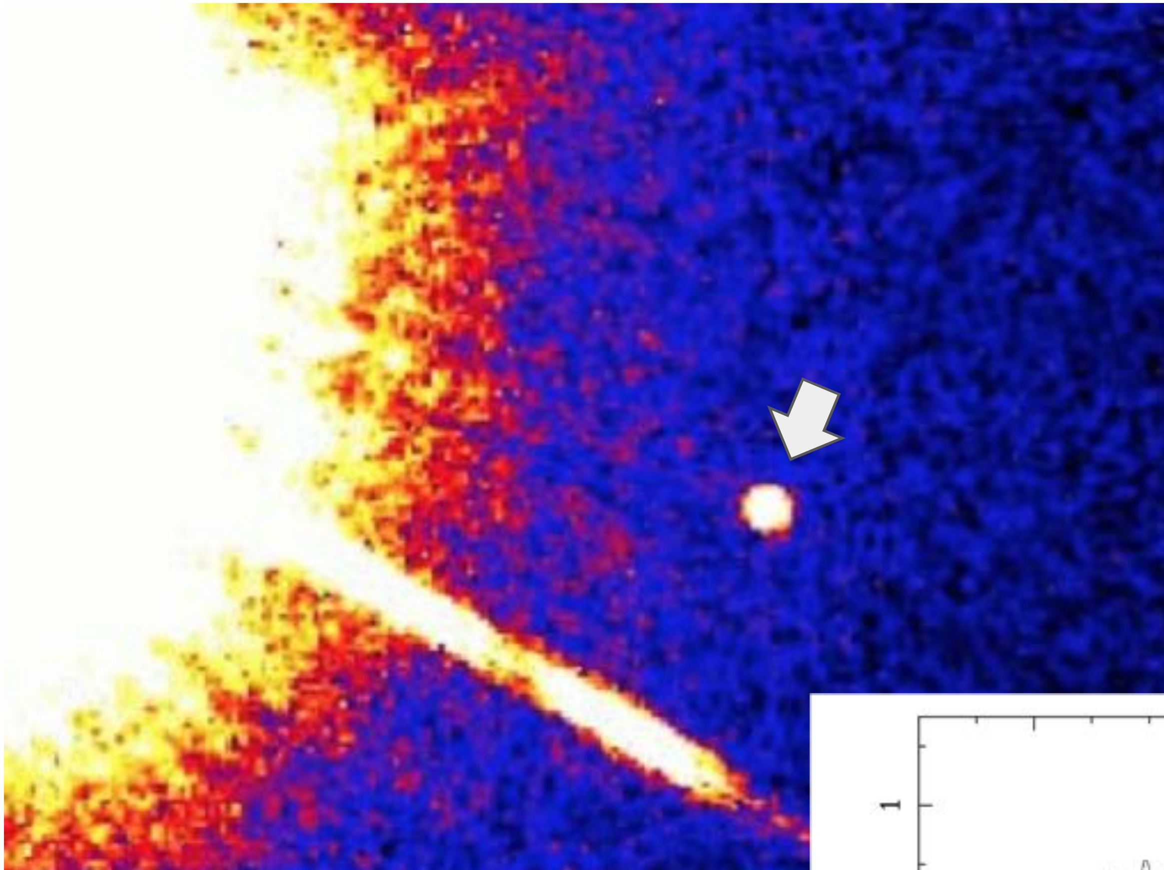
Thermal->Radiation

=> net heat loss

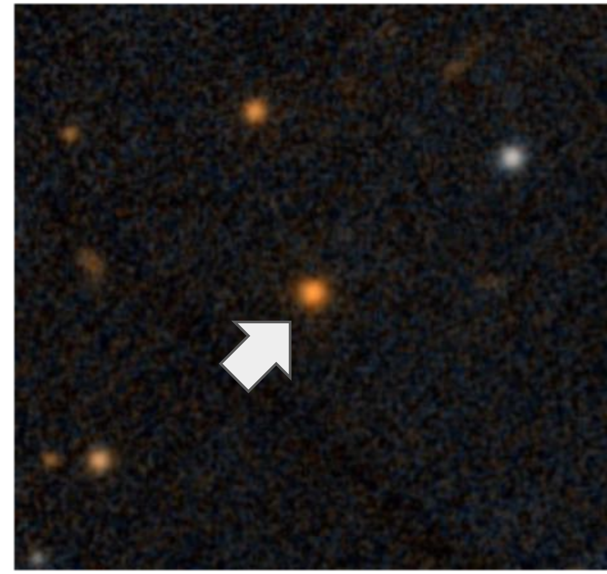


The lack of sustained core H fusion for M < 0.072 $M_\odot$ means that brown dwarfs cool over time – *this is a fundamental distinction compared to stars*

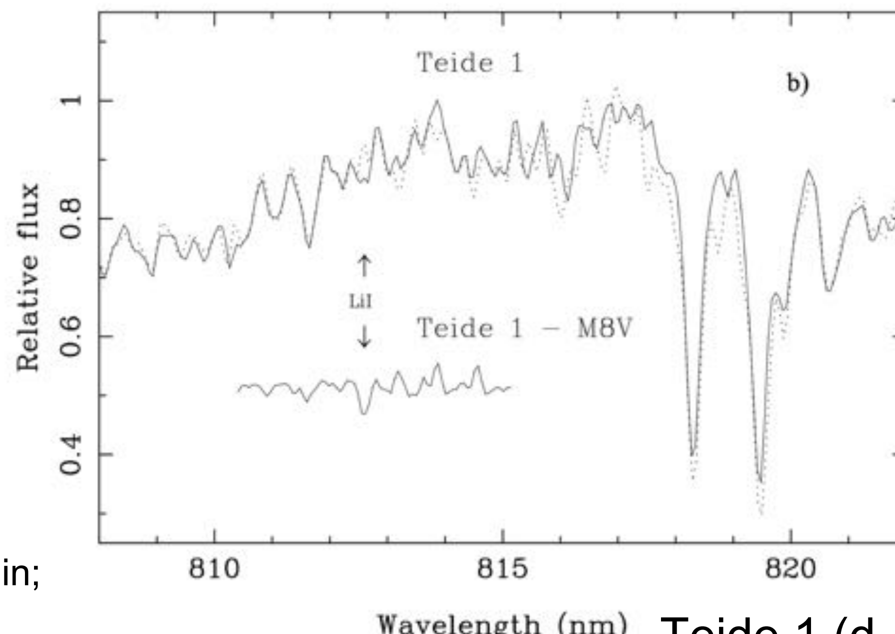
For M < 0.013 $M_\odot$, nothing fuses => "planets" (?)



Gliese 229B (d. 1995)



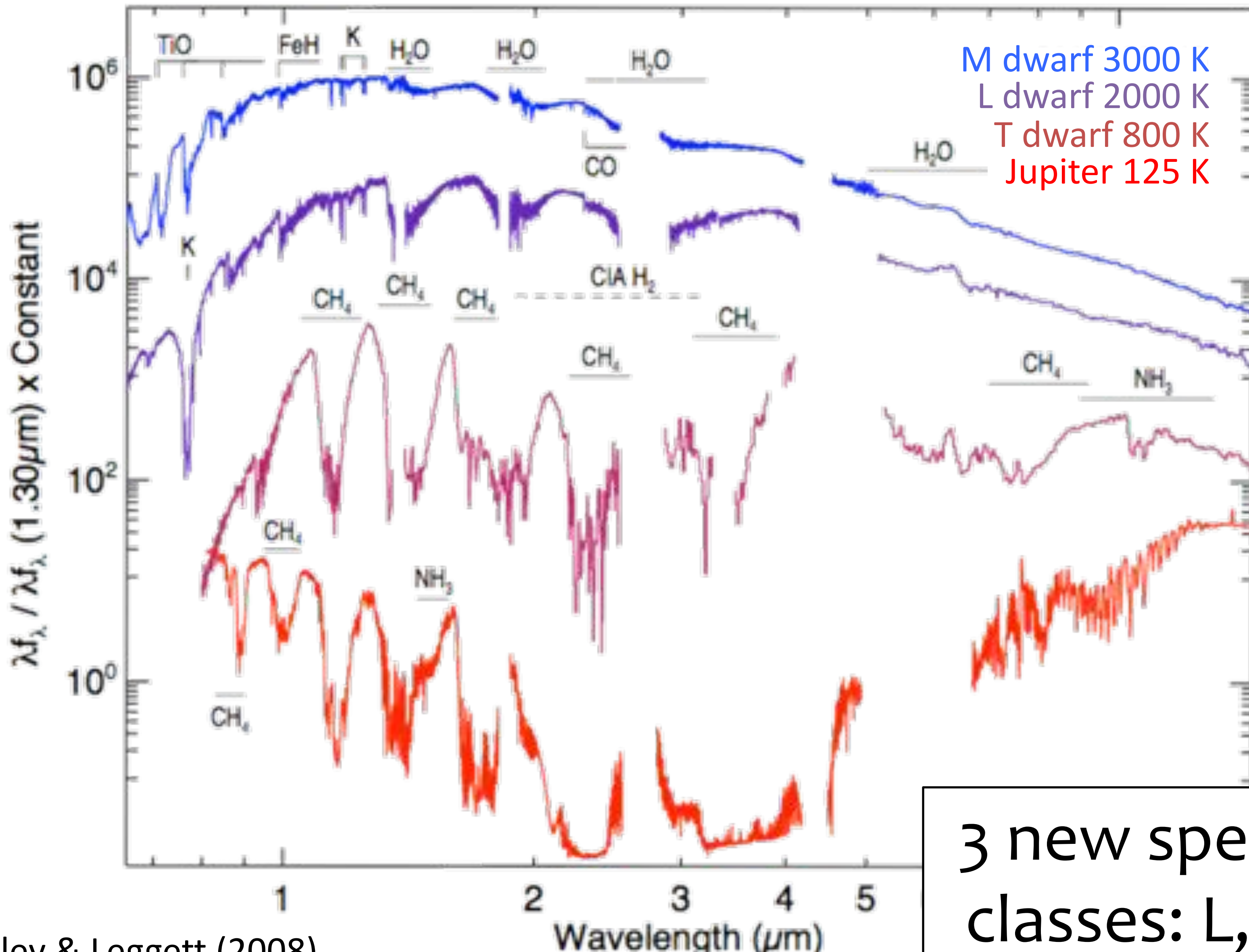
PPL 15 (d. 1994)



Teide 1 (d. 1995)

First Brown Dwarfs

Sources: NASA/ESA/STScI; PanSTARRS/Aladdin; Rebolo et al. (1996, ApJ Letters, 469, L53)



3 new spectral classes: L, T, Y

Marley & Leggett (2008)
data compiled by M. Cushing

The Astrophysical Journal Letters, 786:L18 (6pp), 2014 May 10
doi:10.1088/2041-8205/786/2/L18

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

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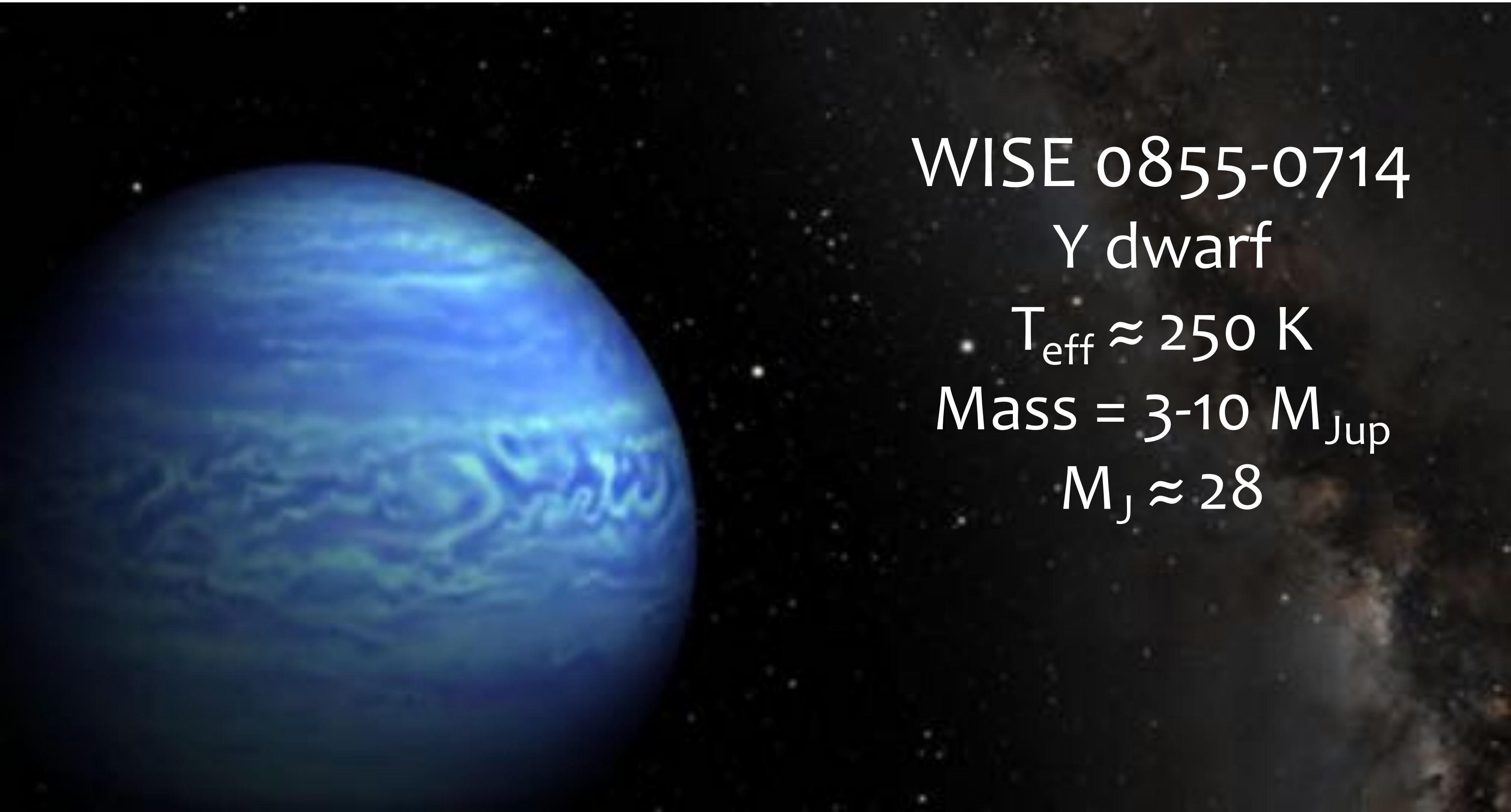
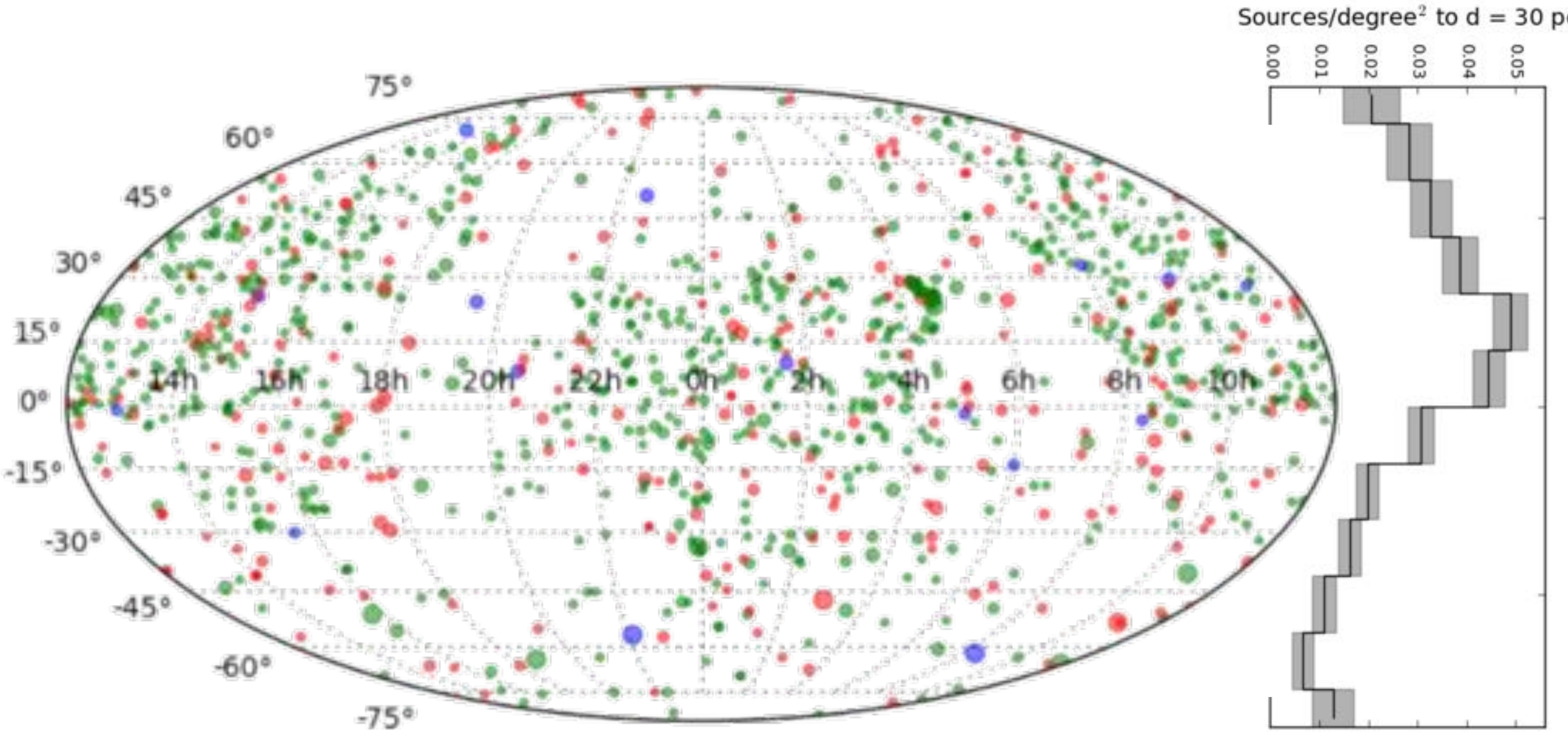
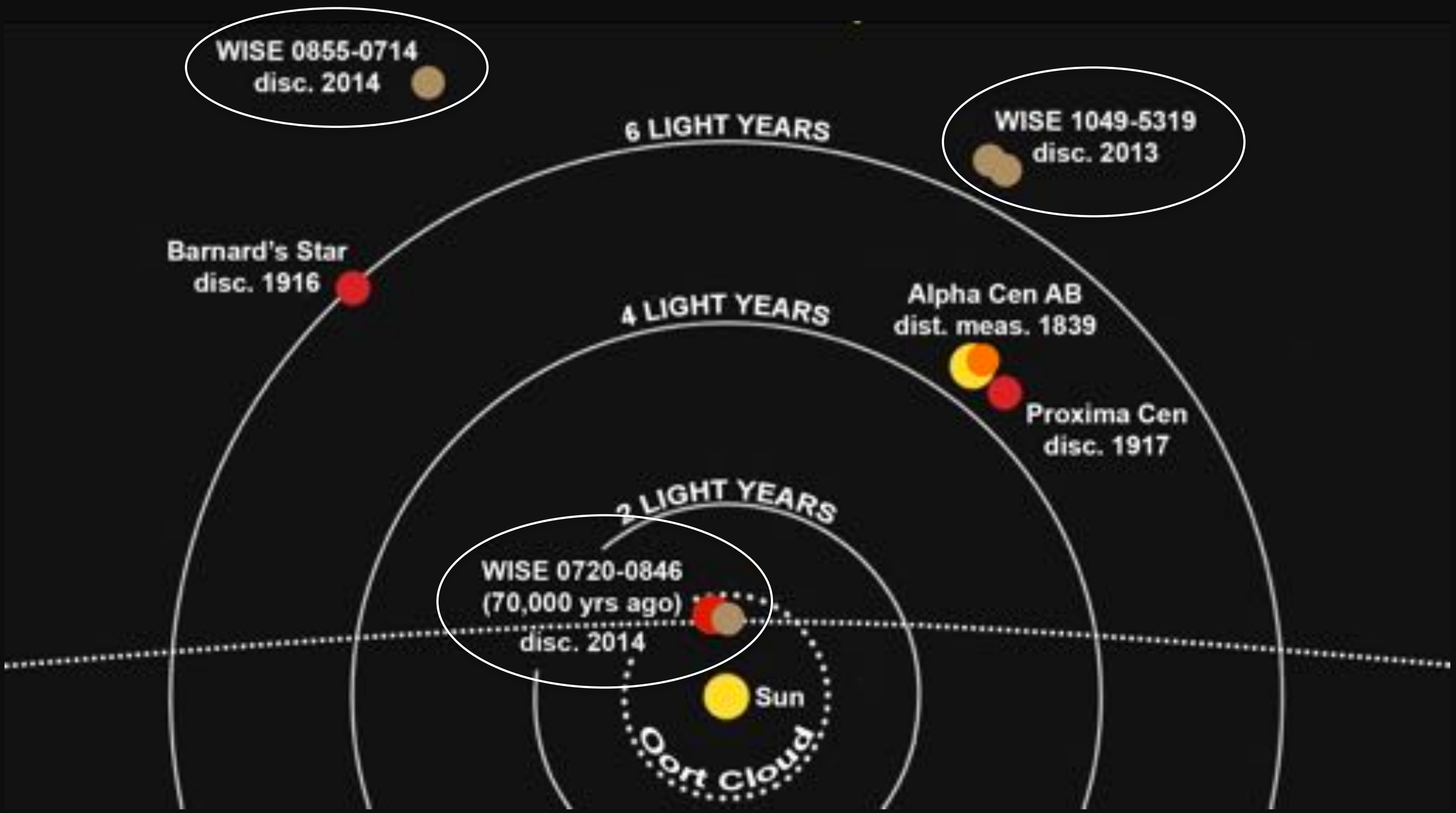
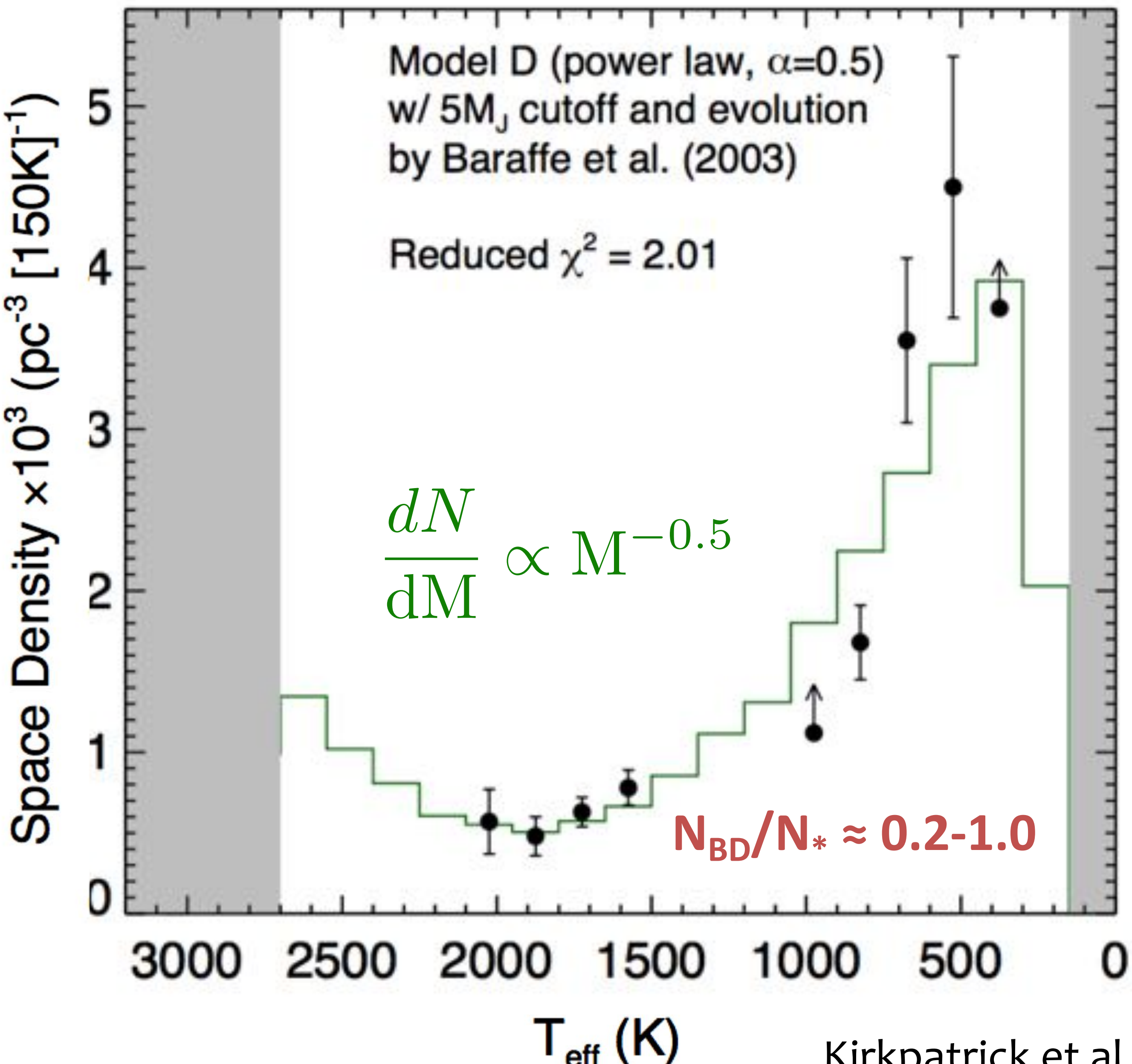




1084 late-M, L and T dwarfs within 30 pc of the Sun
(symbol size indicates proximity)

Our Nearest Neighbors

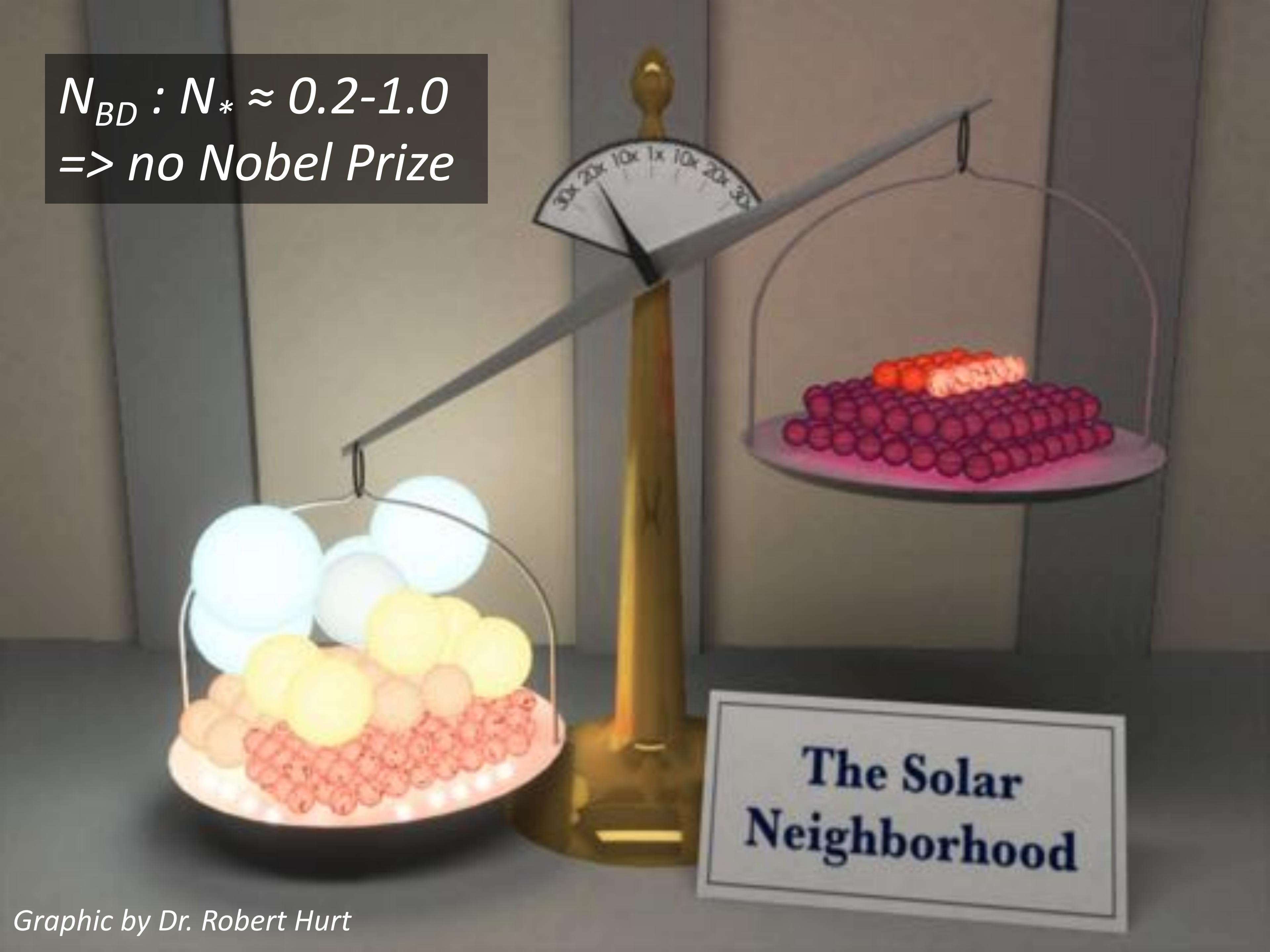




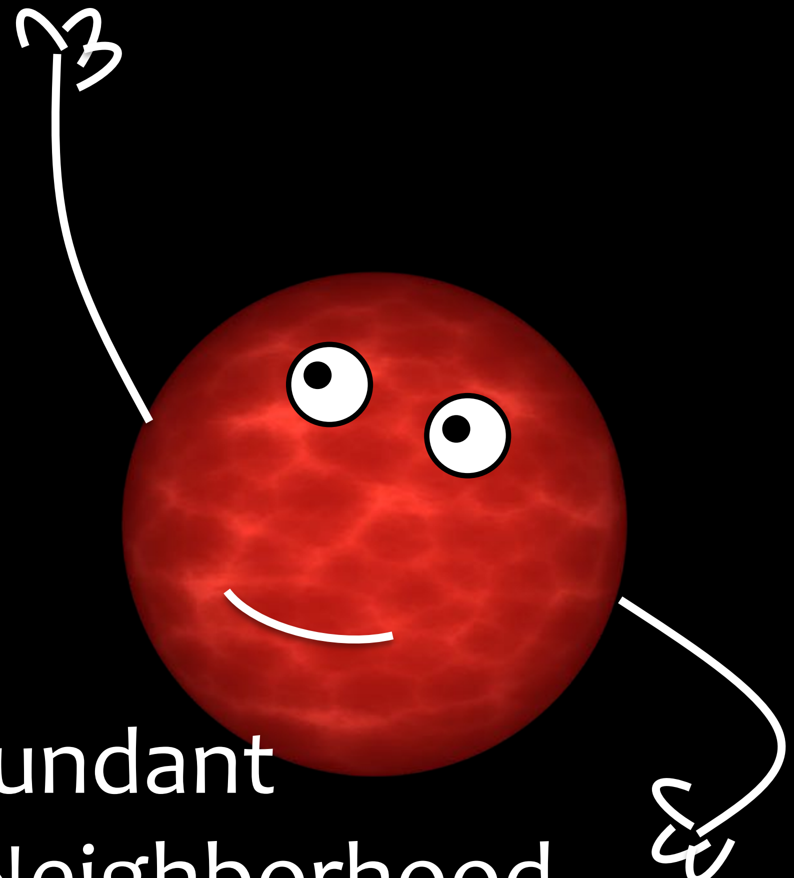
Kirkpatrick et al. (2019)

$N_{BD} : N_{*} \approx 0.2\text{-}1.0$

=> no Nobel Prize



Graphic by Dr. Robert Hurt

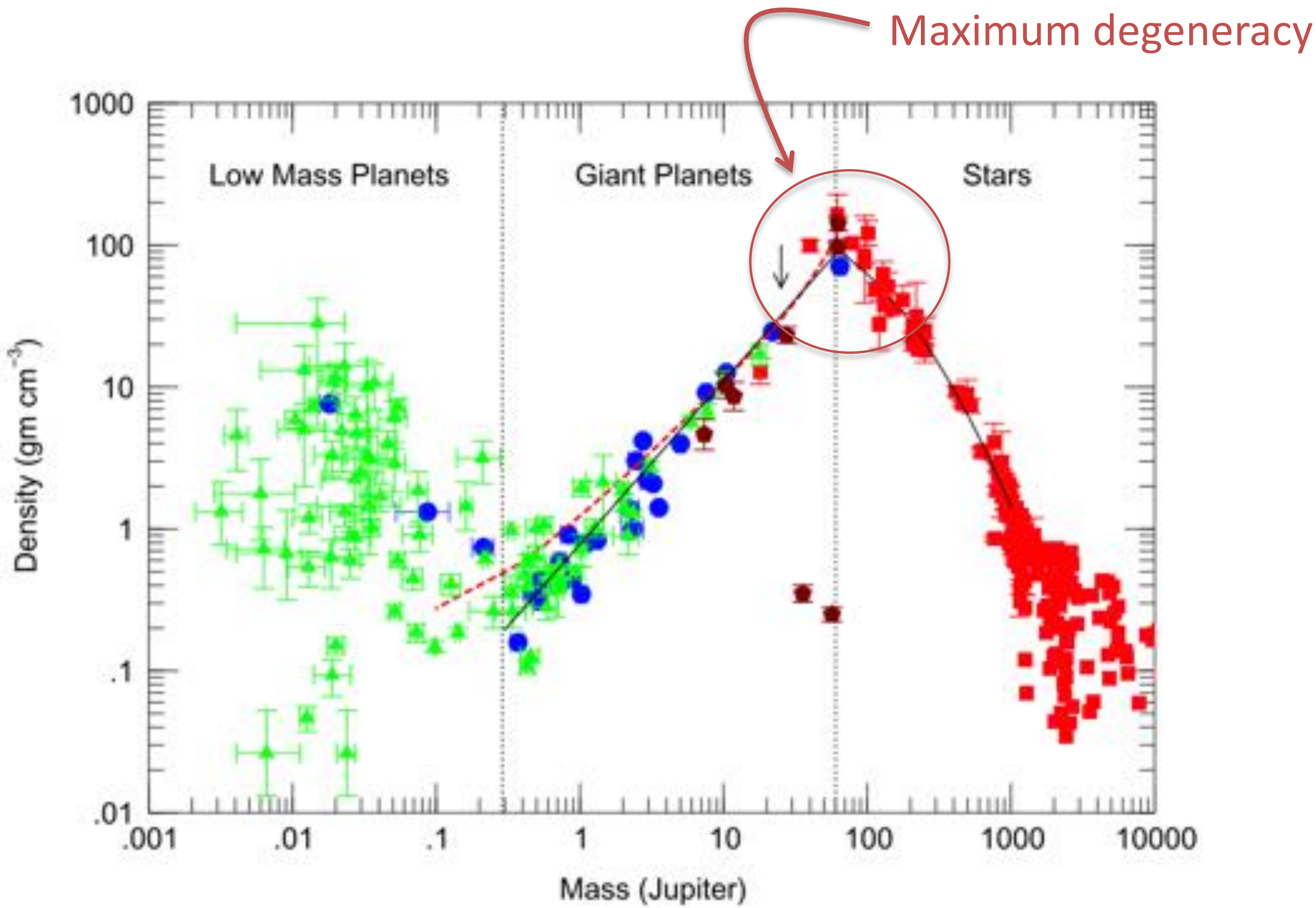


Brown dwarfs are an abundant population in the Solar Neighborhood & Milky Way at large. So what are the interesting problems & opportunities with these sources?

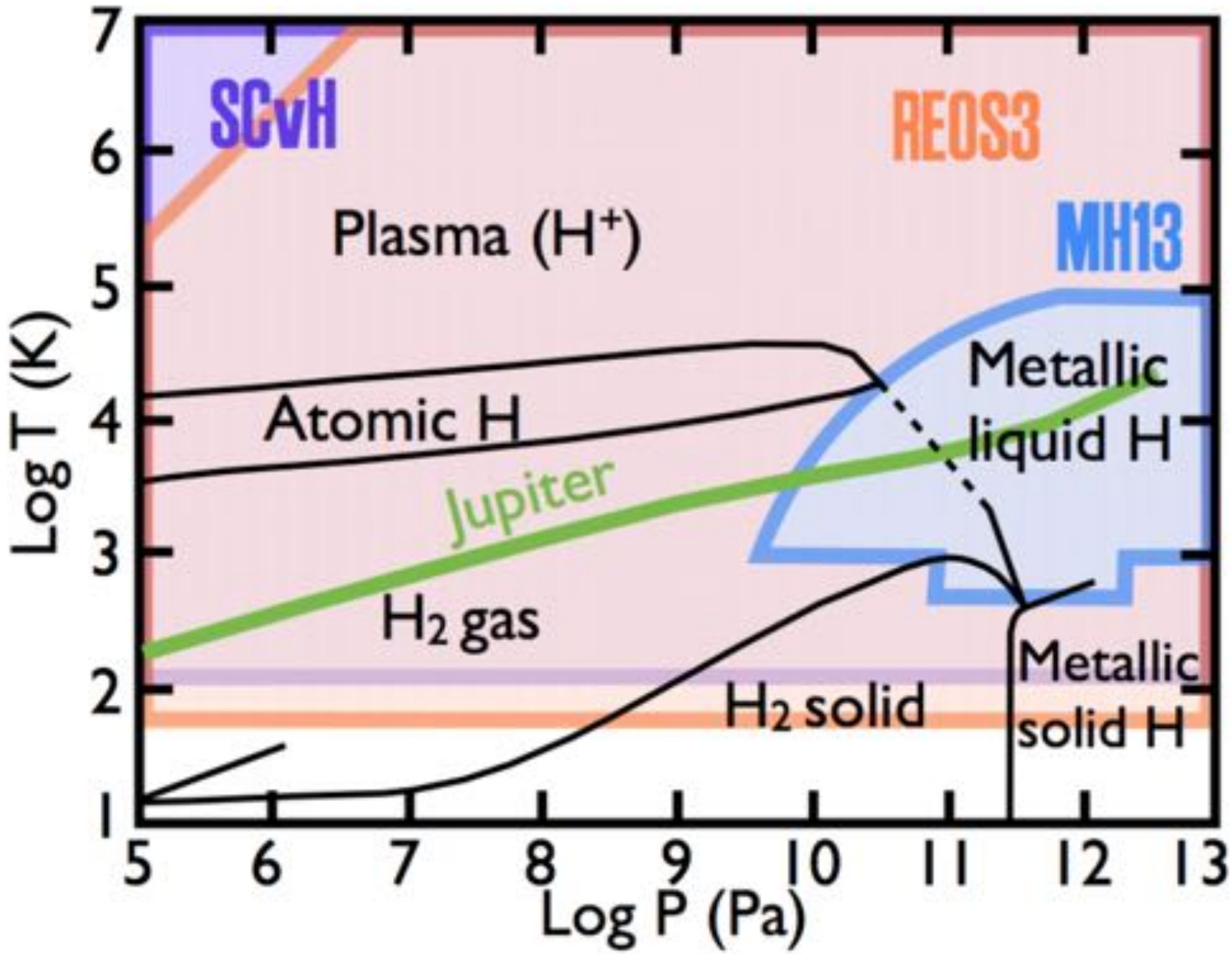
Fundamental Physics with Brown Dwarfs

1. Bardalez et al.: Substellar Multiplicity Throughout the Ages
2. Burgasser et al.: Fundamental Physics with Brown Dwarfs: The Mass-Radius Relation
3. Dupuy et al.: Establishing an Empirical Substellar Sequence to Planetary Masses

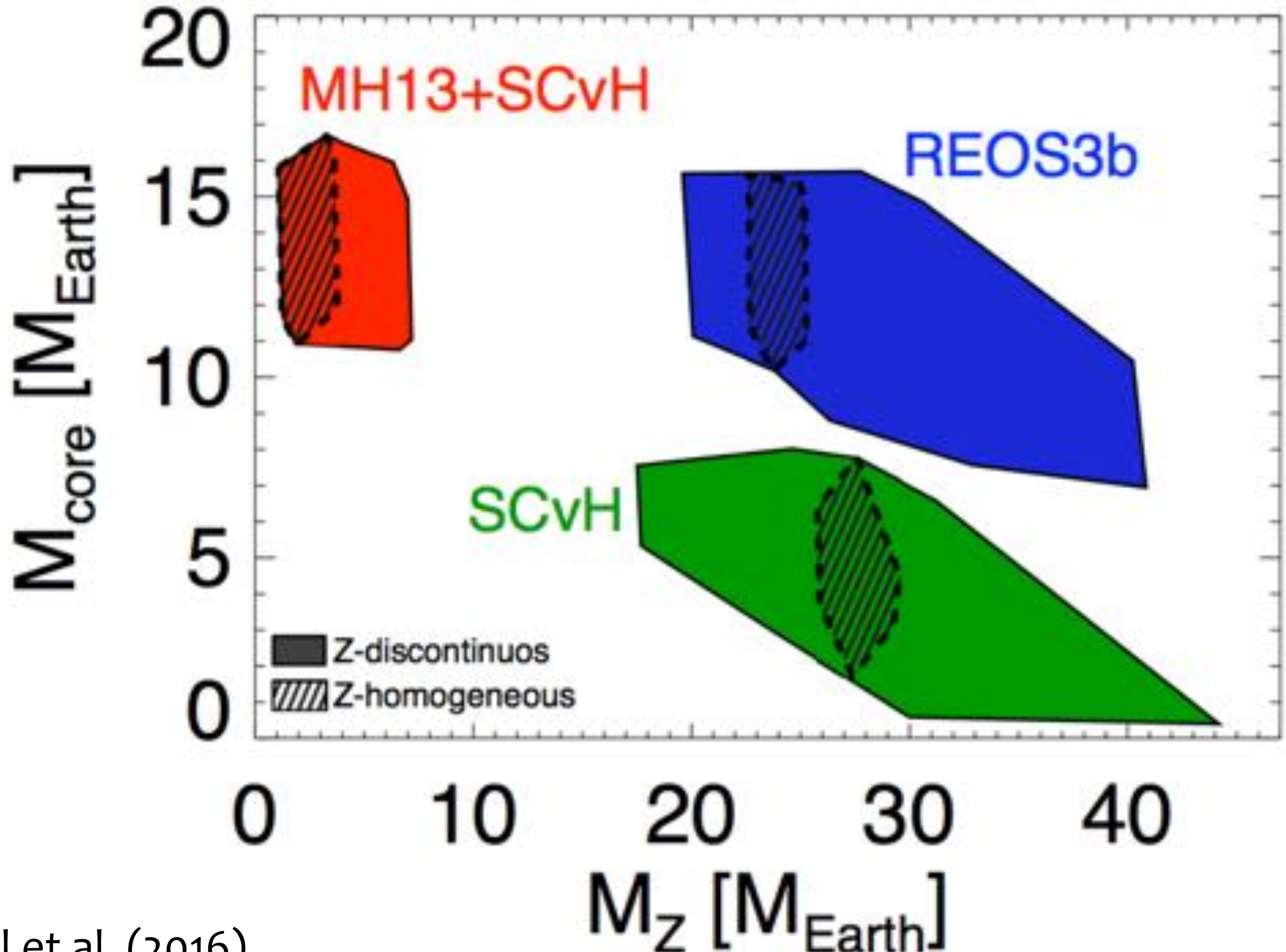
How do we study the physics of degenerate matter?



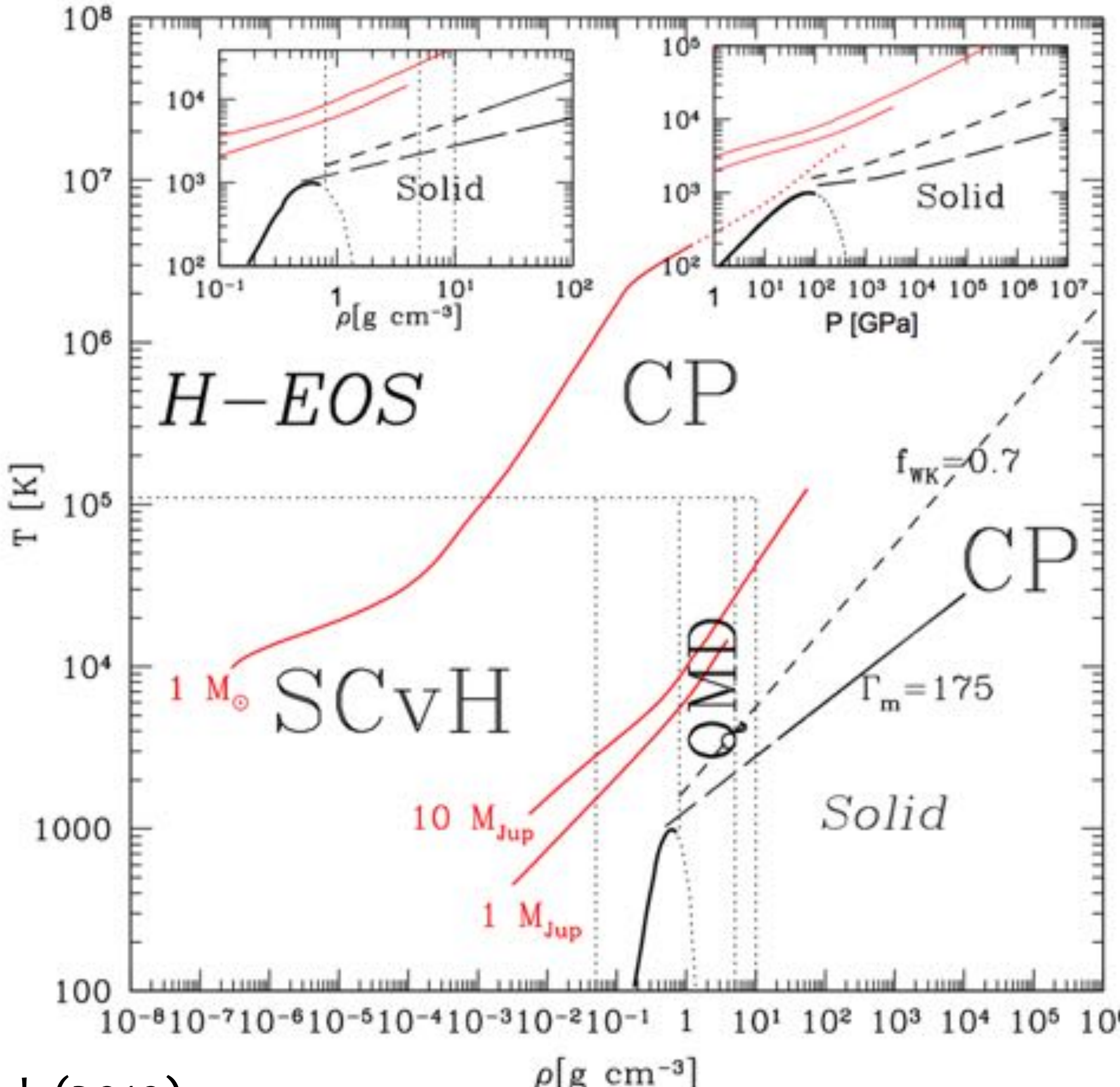
Hatzes & Rauer (2015)



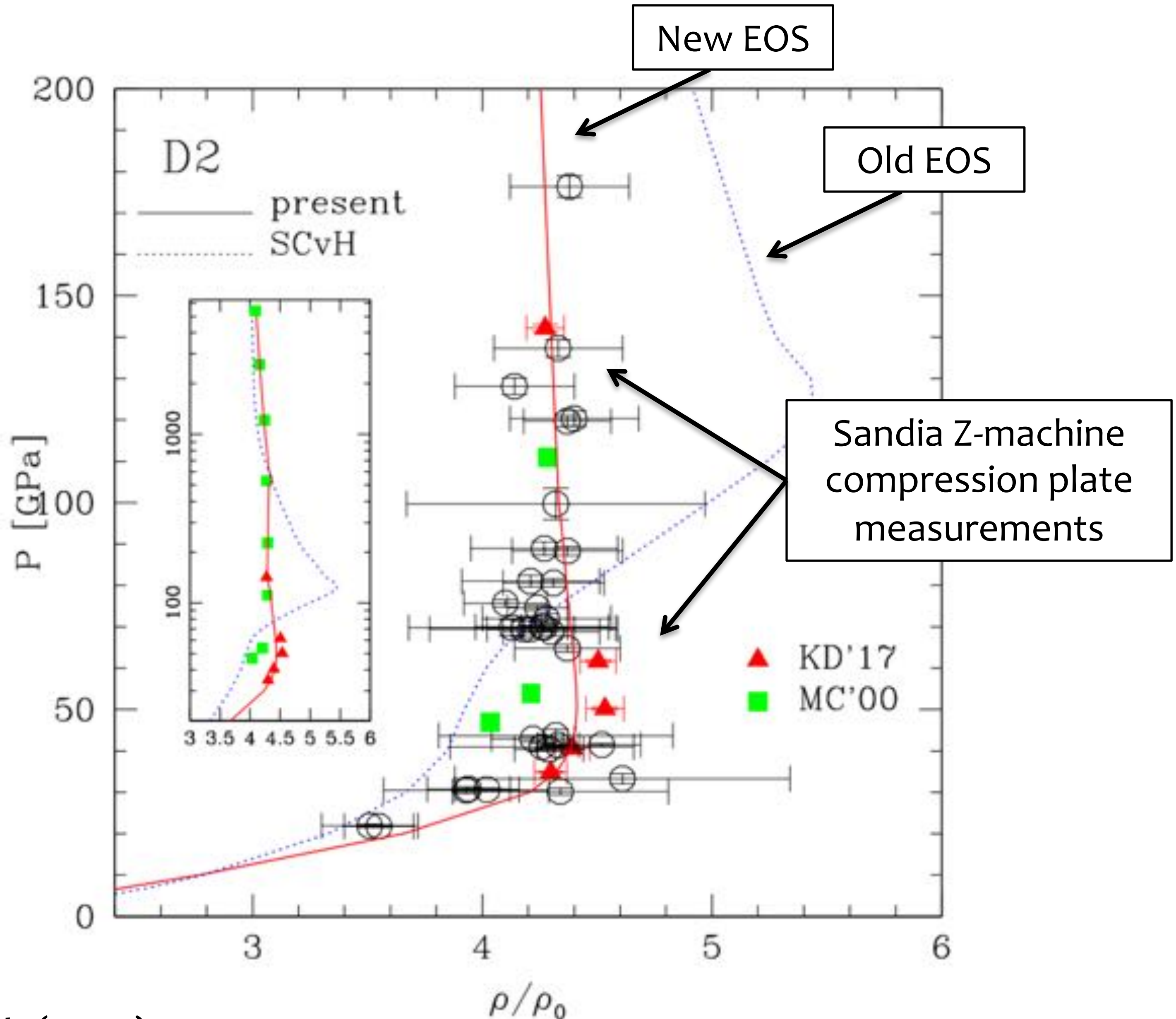
Miguel et al. (2016)



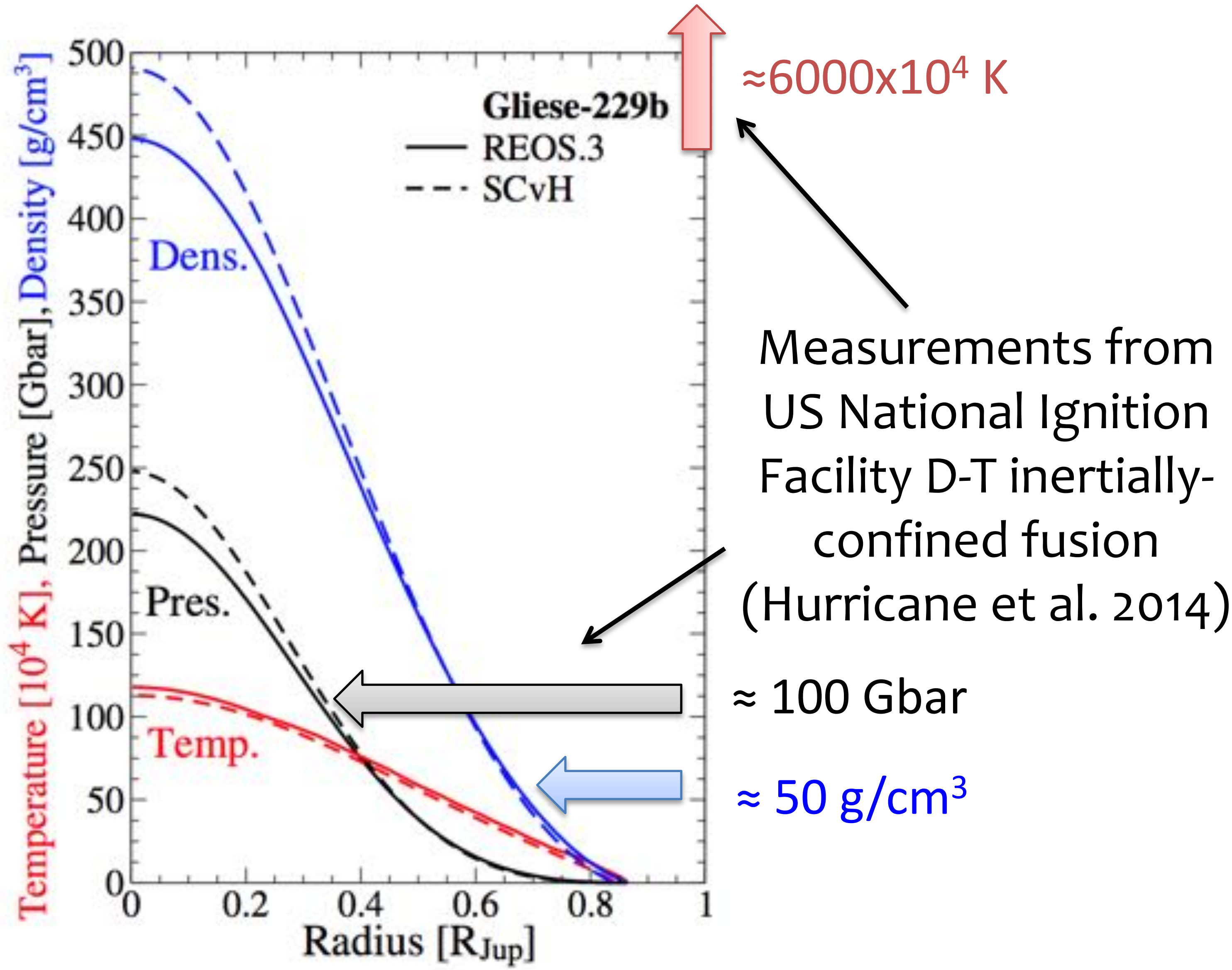
Miguel et al. (2016)



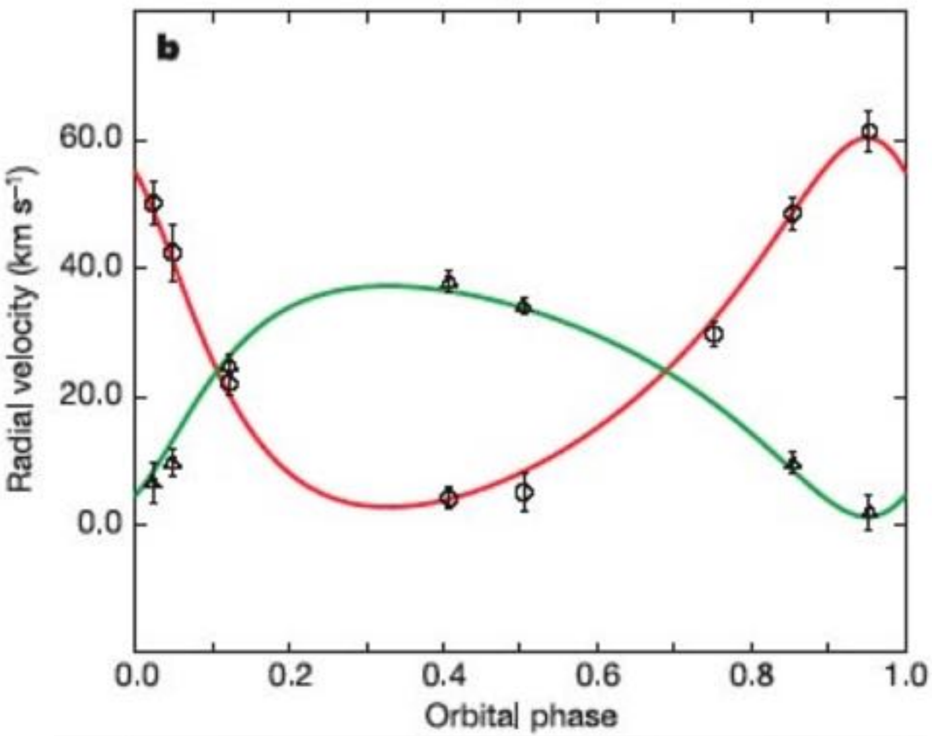
Chabrier et al. (2019)

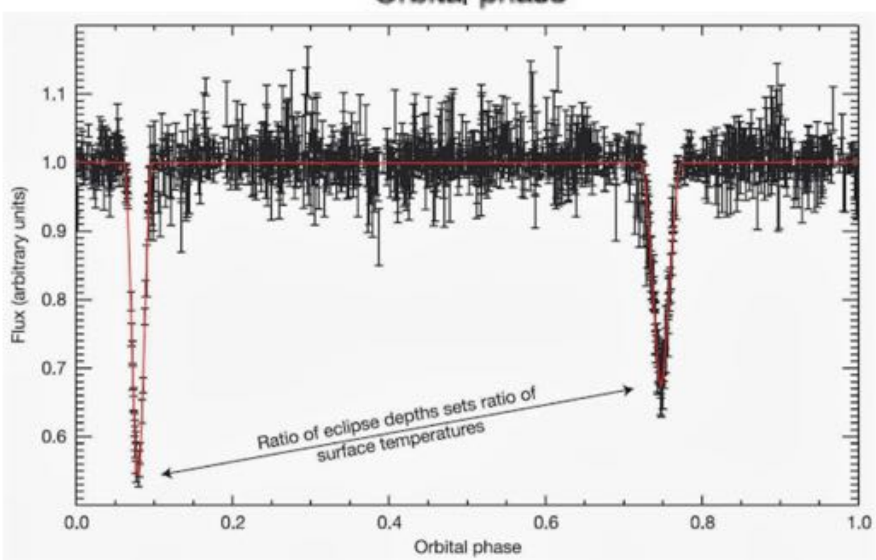


Chabrier et al. (2019)



Becker et al. (2014)
EOS ab initio calculations





Eclipsing BD-BD binaries

There is one currently known: J0535-0546AB

age: ≈ 1 Myr (ONC)

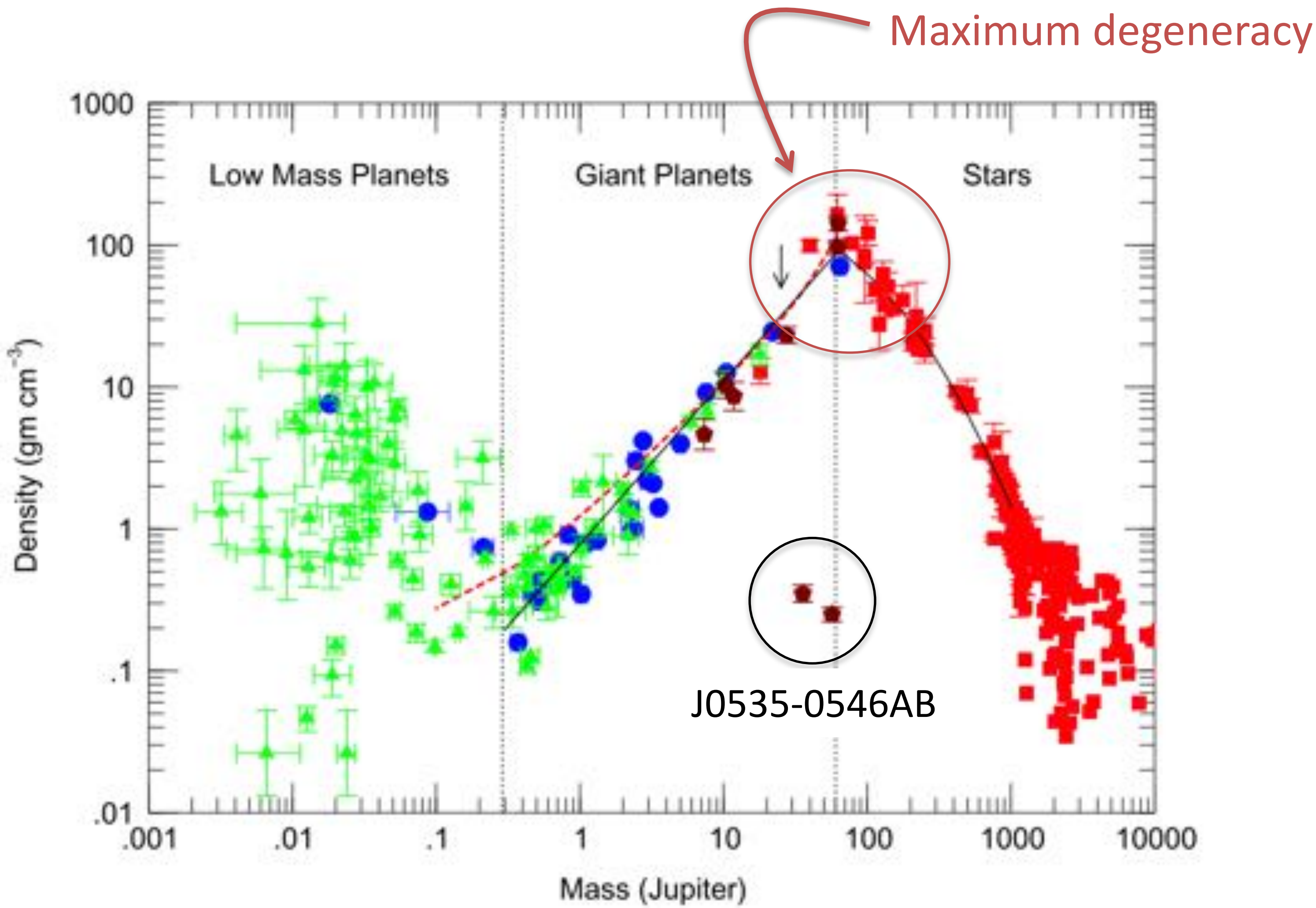
masses: 0.057±0.003 $M_{\odot}$
0.037±0.002 $M_{\odot}$

radii: 0.690±0.011 $R_{\odot}$
0.540±0.009 $R_{\odot}$

$T_{eff,B}/T_{eff,A}$ = 1.050±0.004

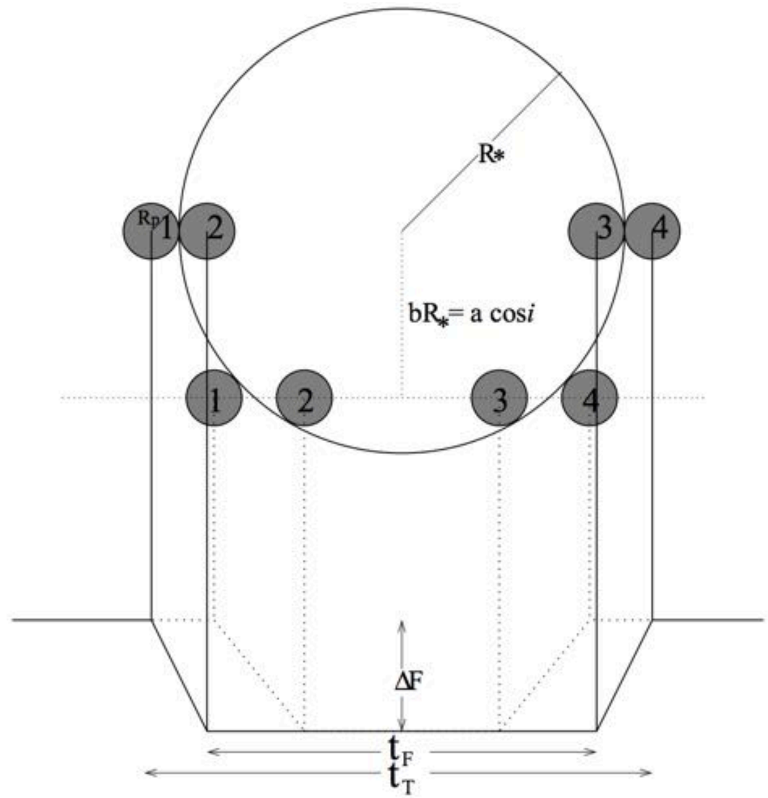
Staussun et al. (2006, 2007);
Gómez Maqueo Chew et al. (2009)

How do we study the physics of degenerate matter?



Hatzes & Rauer (2015)

Stellar density measurements from transits

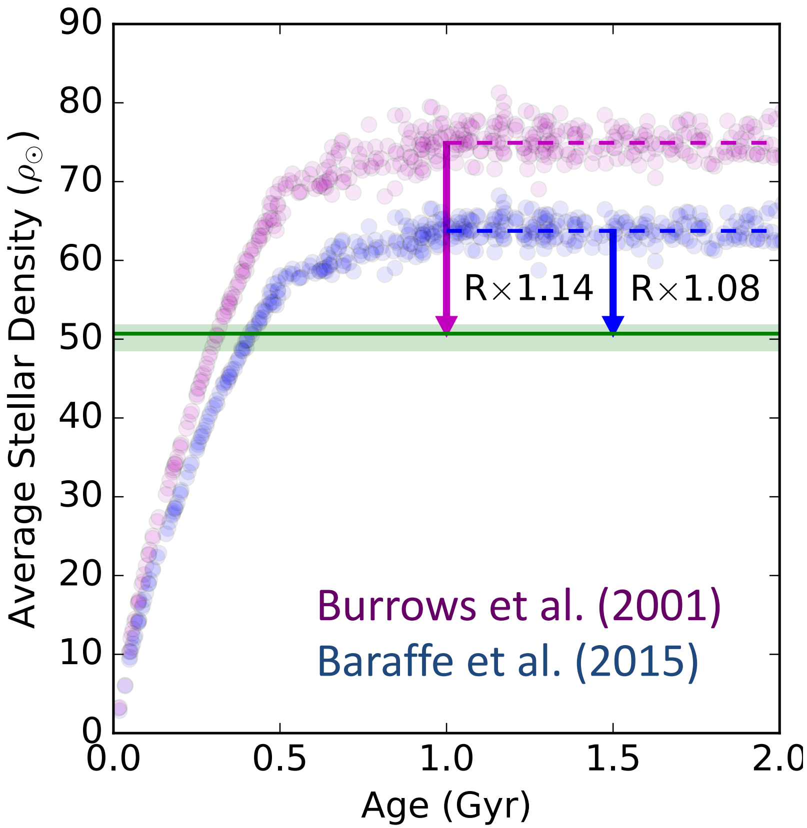


$$\rho_* \equiv \frac{M_*}{R_*^3} = \left(\frac{4\pi^2}{P^2 G}\right)\left\{\frac{\left(1+\sqrt{\Delta F}\right)^2 - b^2\left[1-\sin^2(t_T\pi/P)\right]}{\sin^2(t_T\pi/P)}\right\}^{3/2}$$

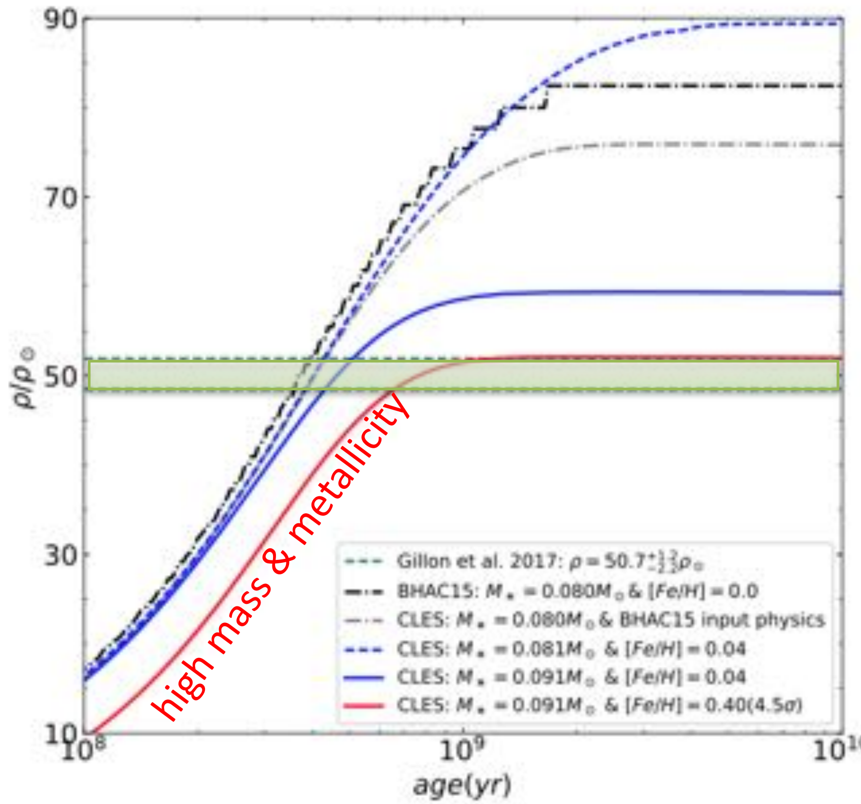
Seager & Mallen-Ornelas (2003)

Trappist-1

Substellar exoplanet hosts test the mass-radius relationship

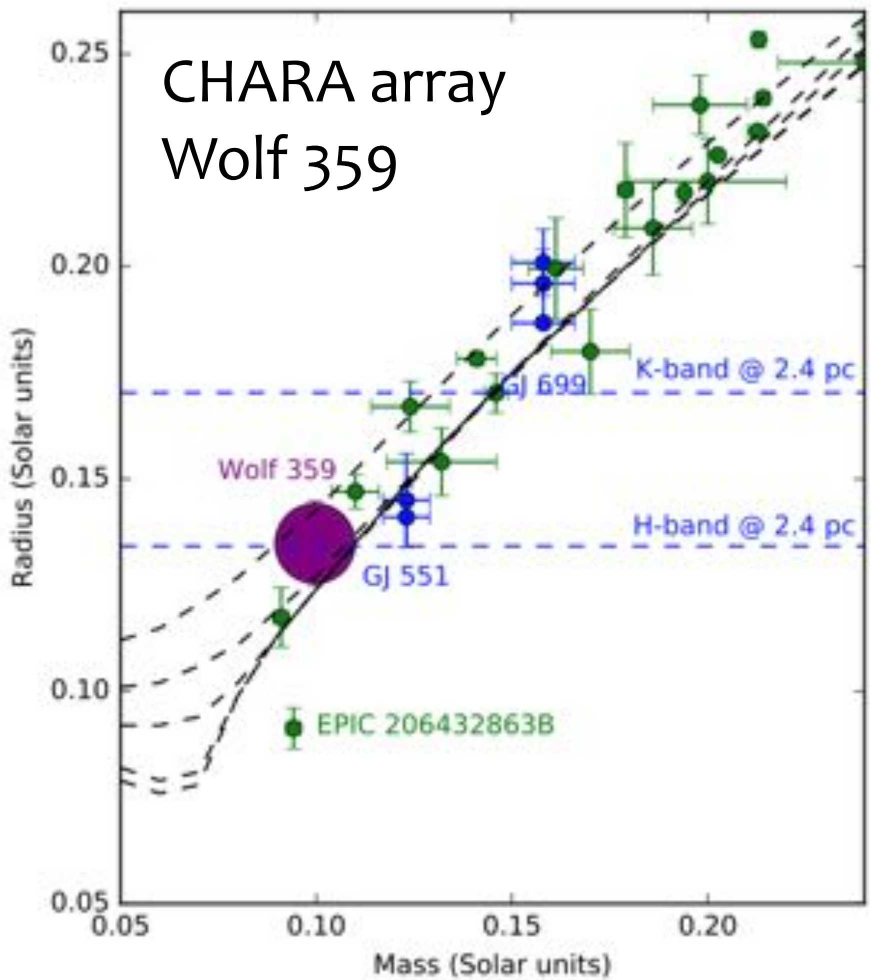


Burgasser & Mamajek (2017)

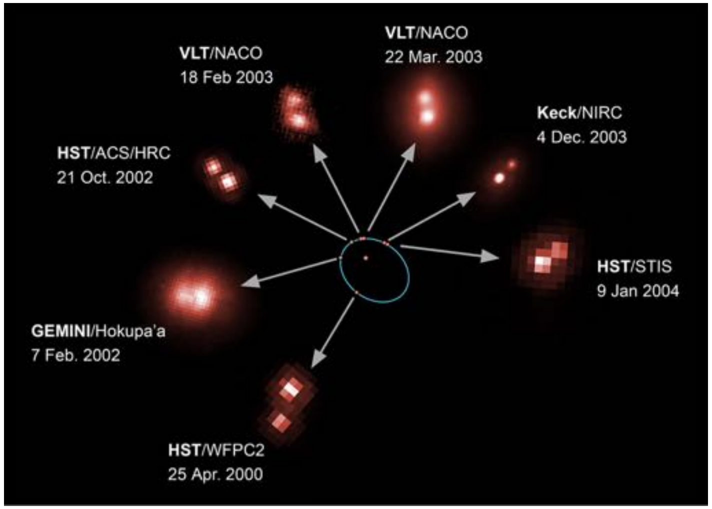


van Grootel et al. (2018)

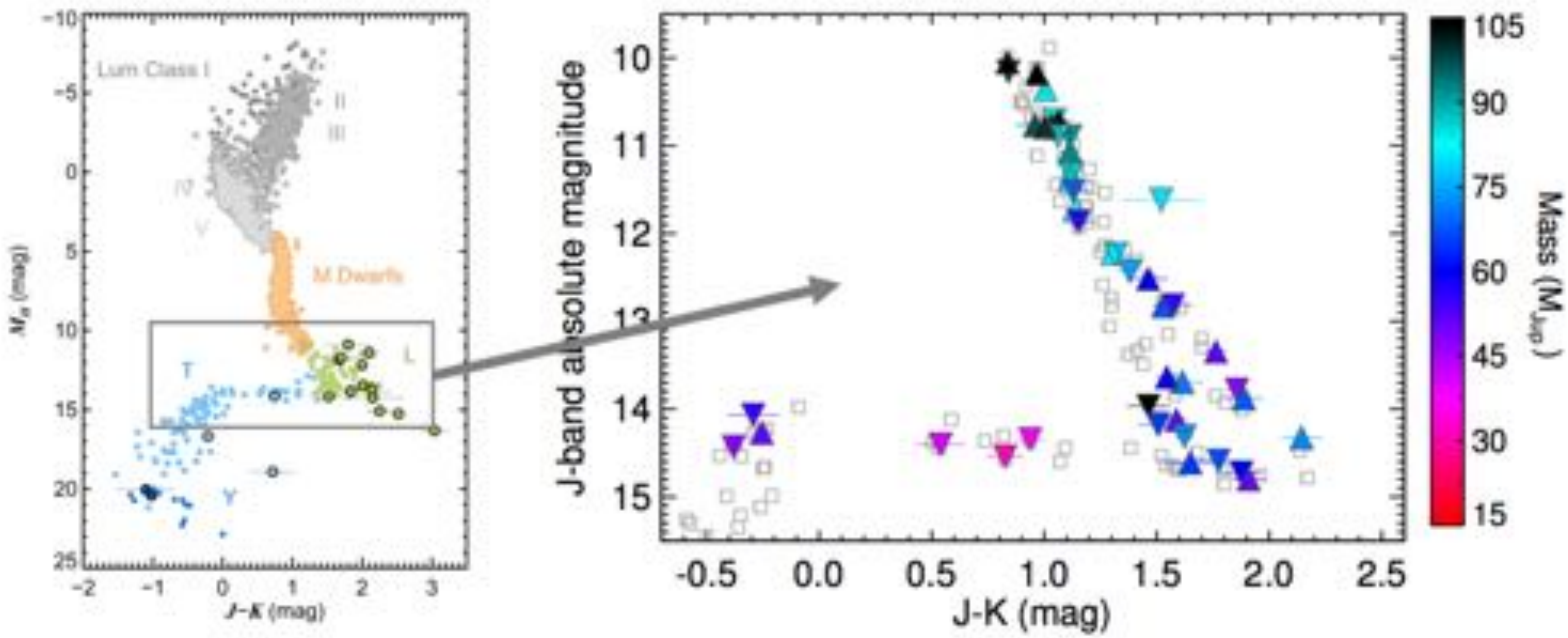
Can we measure BD radii directly? Not yet.



Burgasser et al. (in prep)

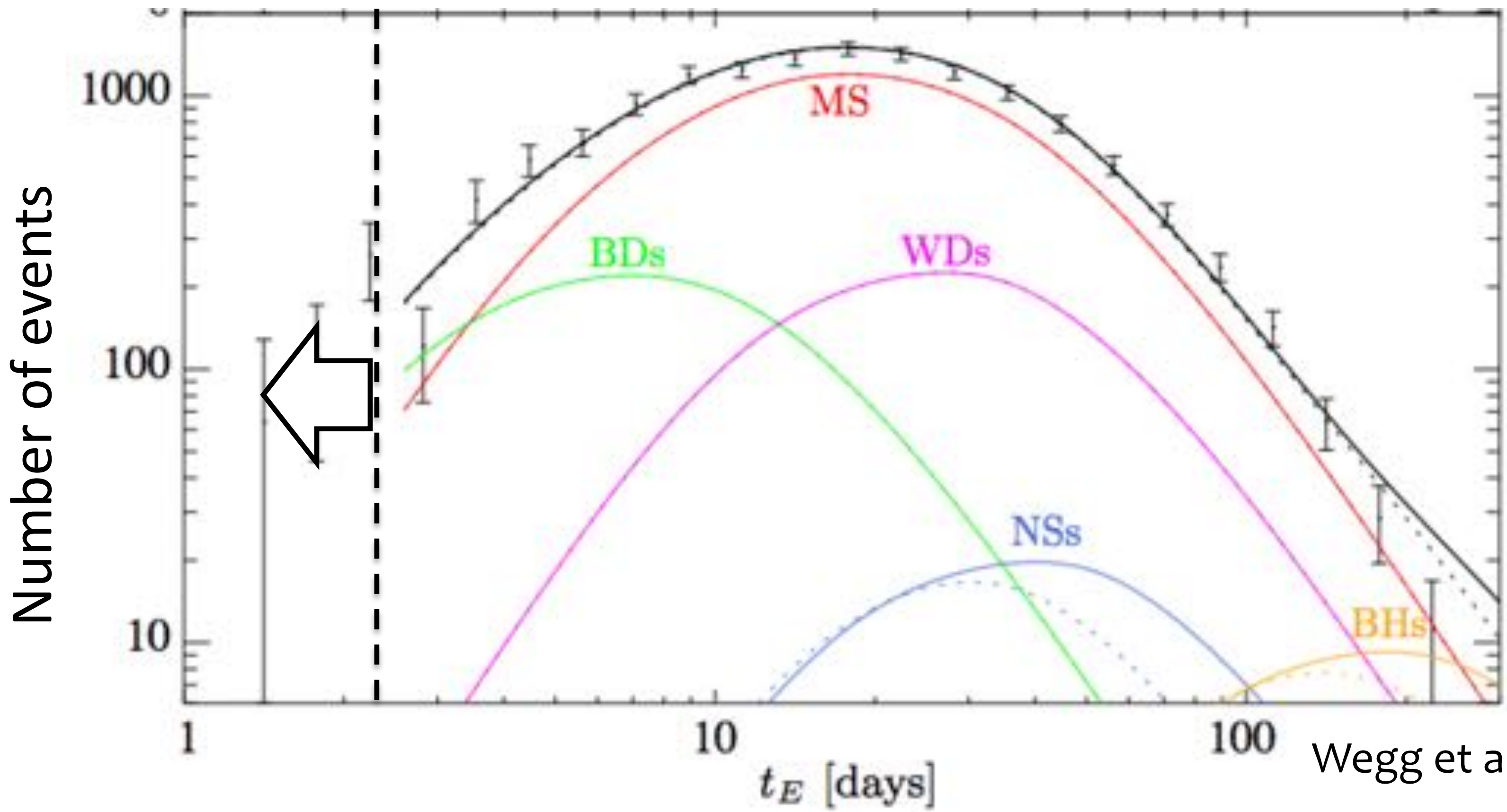


Measuring brown dwarf masses with multiples



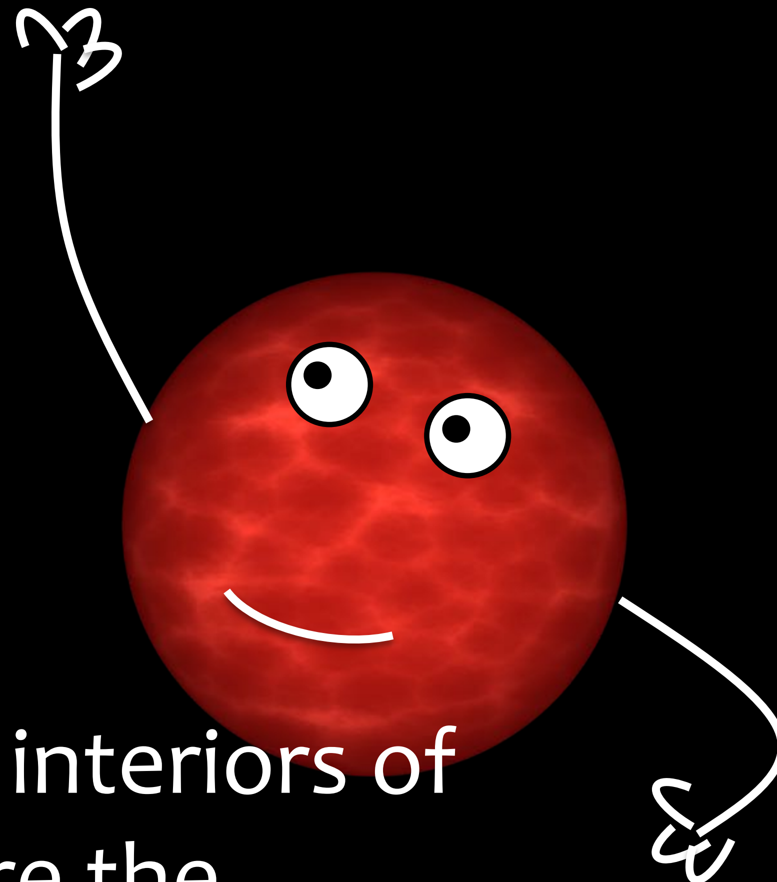
Dupuy et al. (2019)

Don’t forget microlensing!



Wegg et al. (2018)

Brown dwarfs will dominate microlens events with t_E < few days => WFIRST will make a major contribution here



Probing the degenerate interiors of brown dwarfs will require the discovery of new eclipsing binaries, monitoring of multiples, advances in O/IR interferometry, and rapid μ-lenses

Brown Dwarfs & Galactic Archeaology

1. Burgasser et al.: High-Resolution Spectroscopic Surveys of Ultracool Dwarf Stars & Brown Dwarfs
2. Caiazzo et al.: Hunting for ancient brown dwarfs: the developing field of brown dwarfs in globular clusters
3. Faherty et al.: Brown Dwarfs and Directly Imaged Exoplanets in Young Associations
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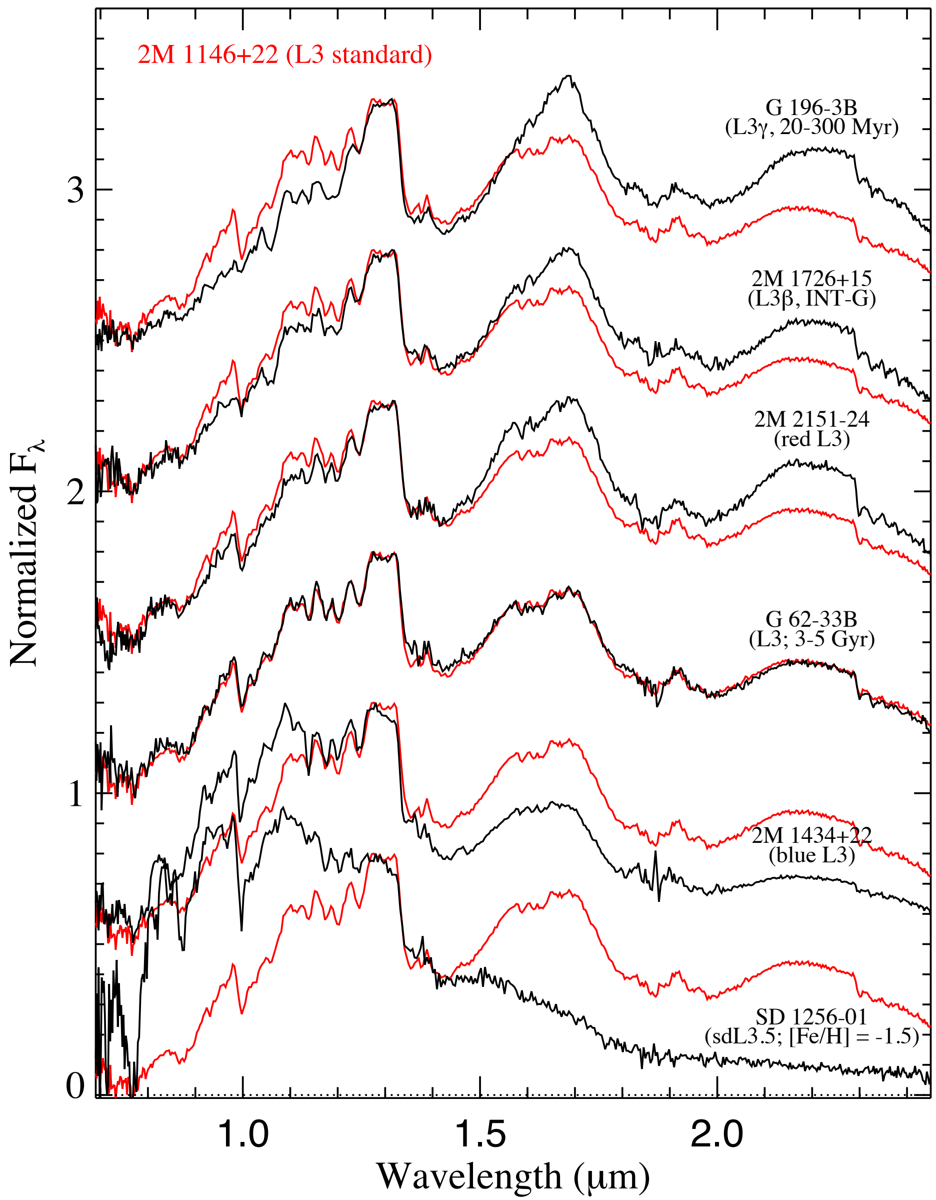
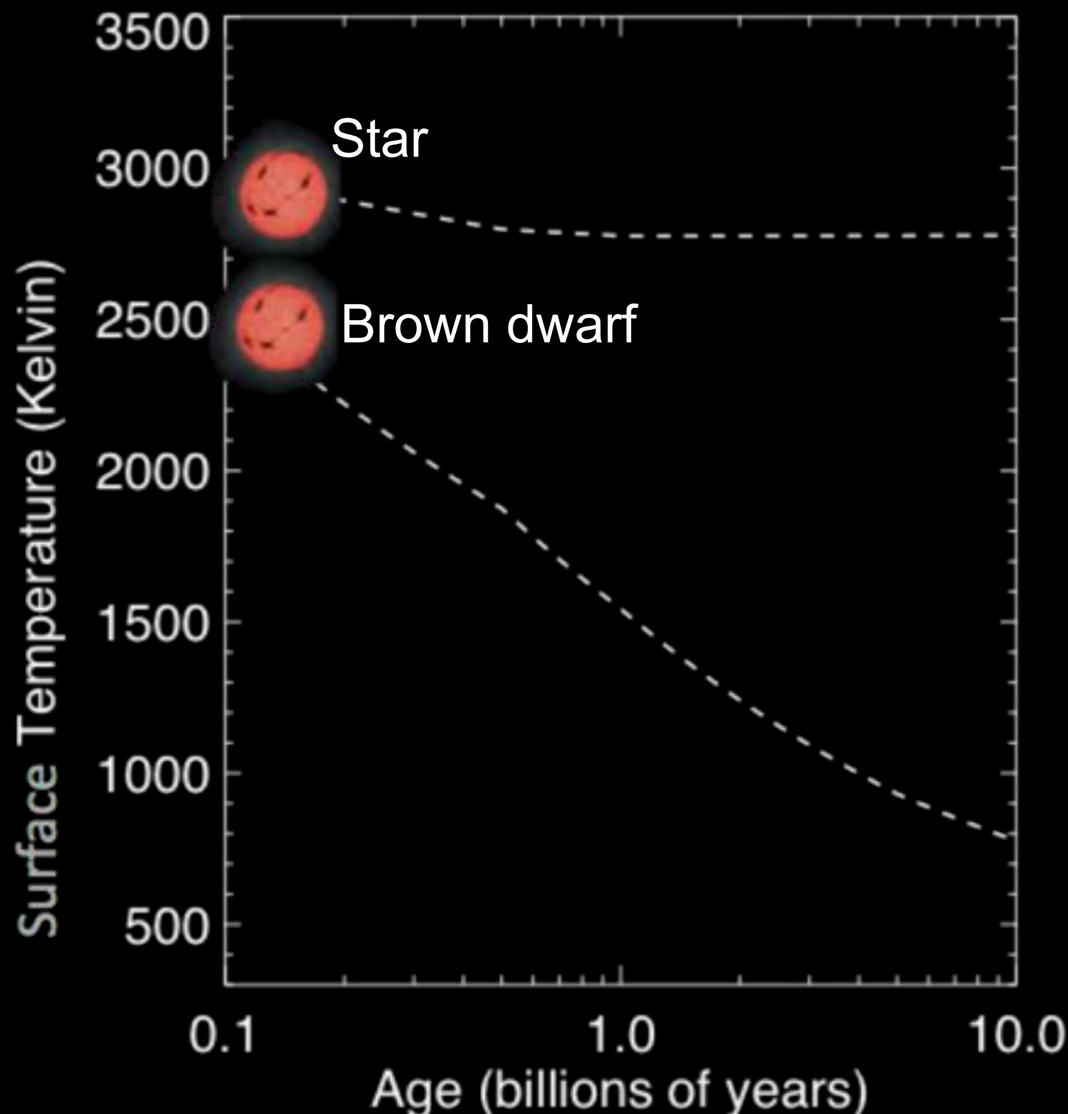


Burgasser (2014)

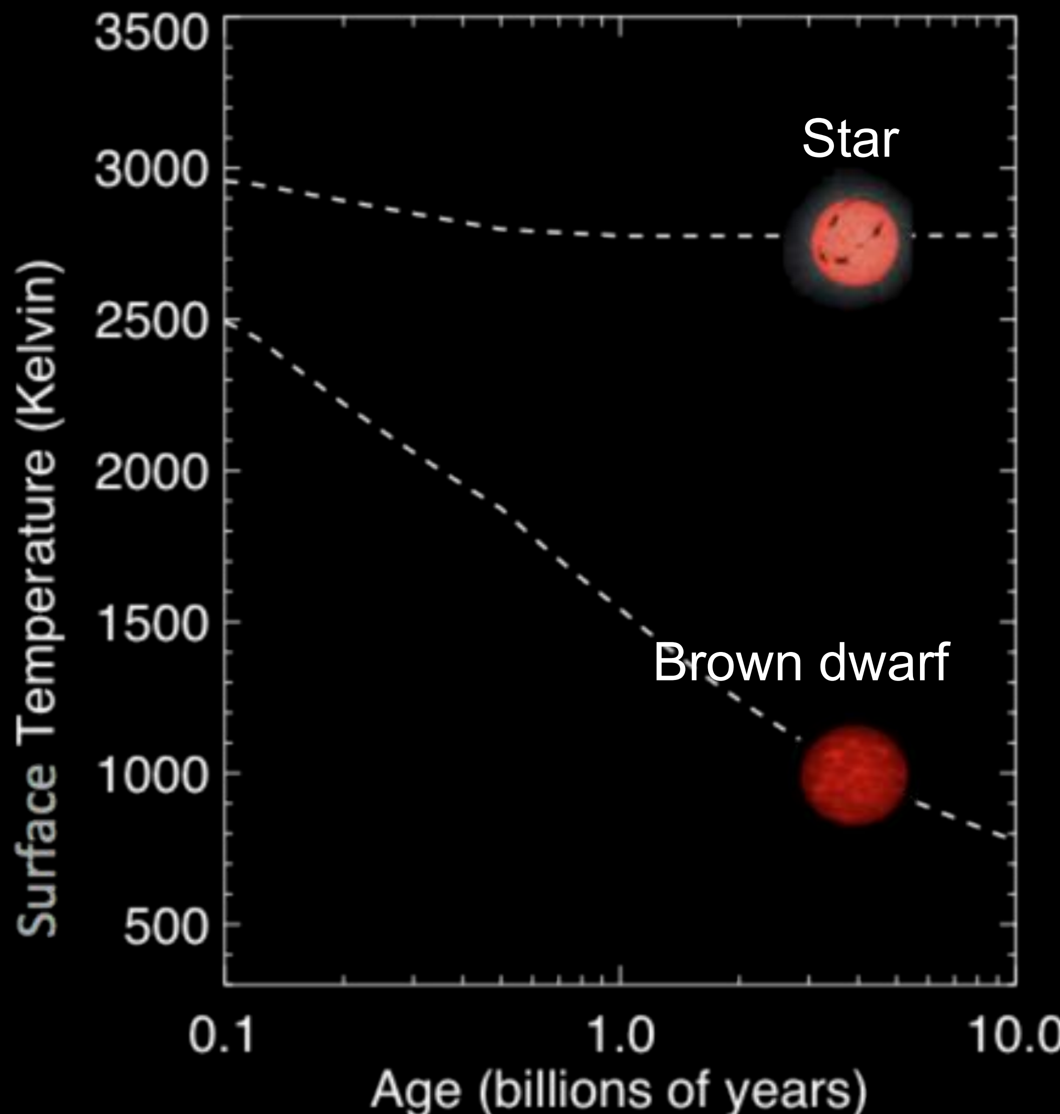
There is a lot of information contained even in low-resolution BD spectra

Temperature, surface gravity, metallicity/elemental composition, cloud properties, multiplicity, etc.



The Brown Dwarf Clock

Image sources: NASA/AMES

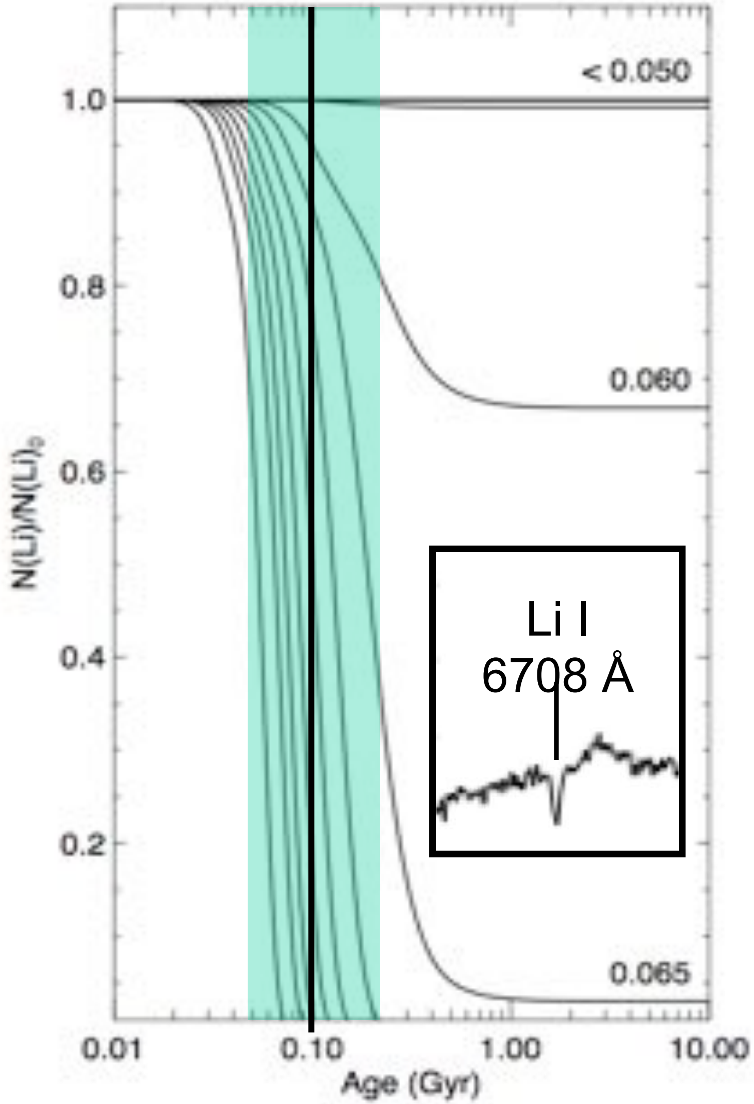


The Brown Dwarf Clock

Image sources: NASA/AMES

The Lithium Clock

models from Burrows et al. (2001)



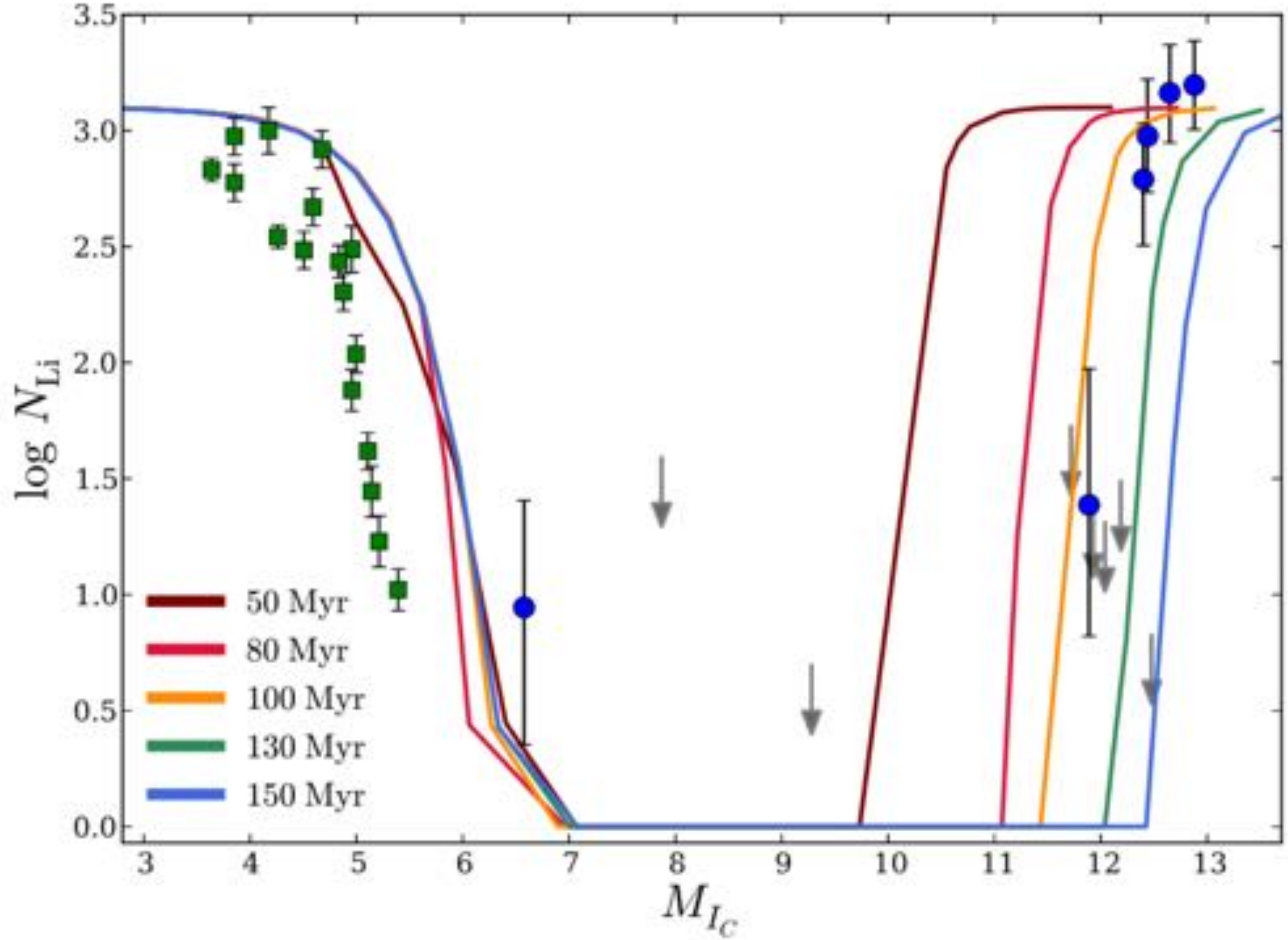
^{6}Li and ^{7}Li are depleted in the cores of stars hotter than 2.5x10^6 K (mass > 0.06 $M_\odot$) in 50-200 Myr.

This can be used to age-date young clusters

$$^1_1\mathrm{H} + ^6_3\mathrm{Li} \rightarrow \; ^7_4\mathrm{Be} + e^- \; \rightarrow \; ^7_3\mathrm{Li} + \nu$$

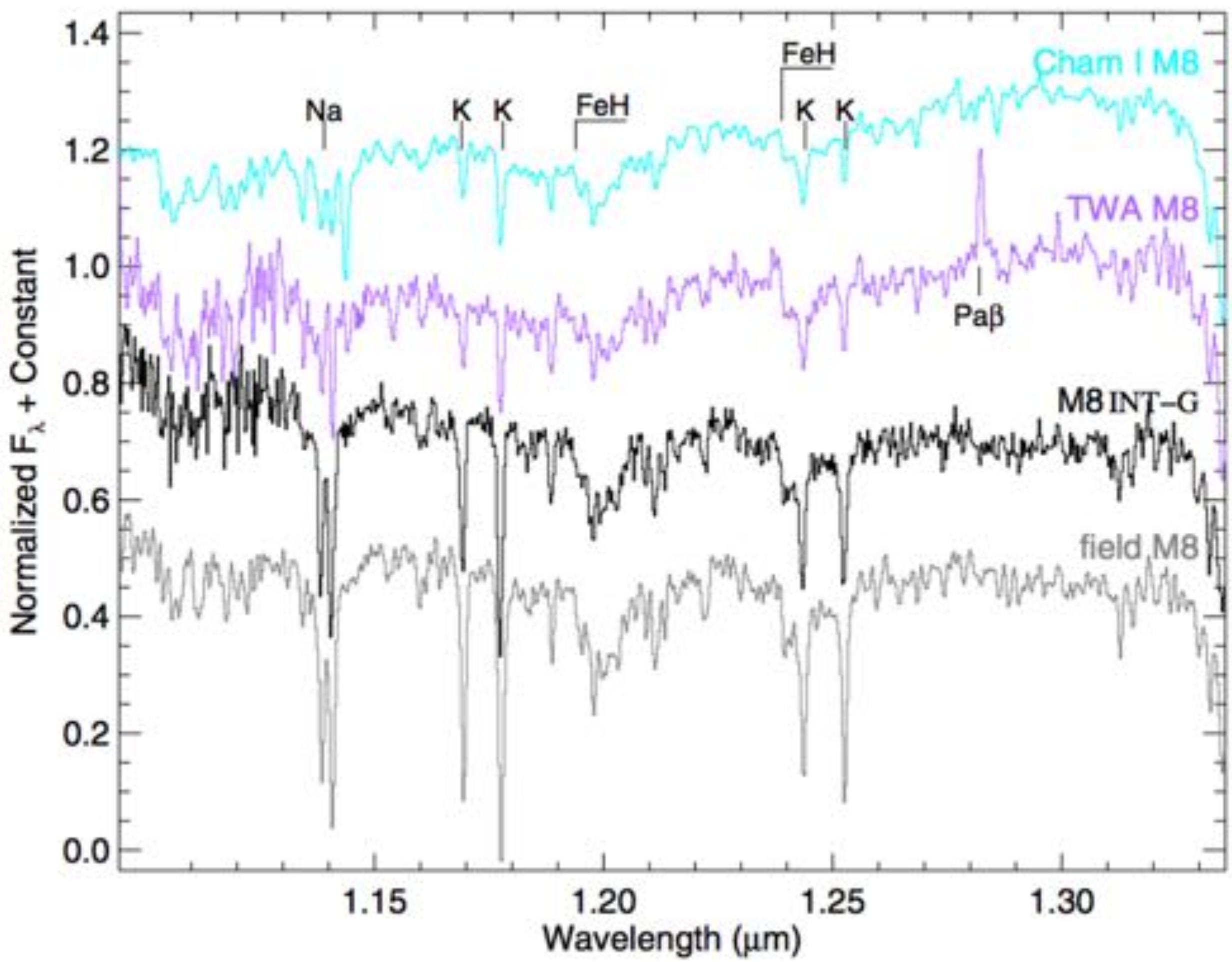
$$^1_1\mathrm{H} + ^7_3\mathrm{Li} \rightarrow \; ^8_4\mathrm{Be} \rightarrow 2 \; ^4_2\mathrm{He} + \gamma$$

Li clock in clusters



Blanco I Li-depletion age 114±10 Myr (incl. B-field effects)
Juarez et al. (2014)

Surface Gravity Features



3 Myr

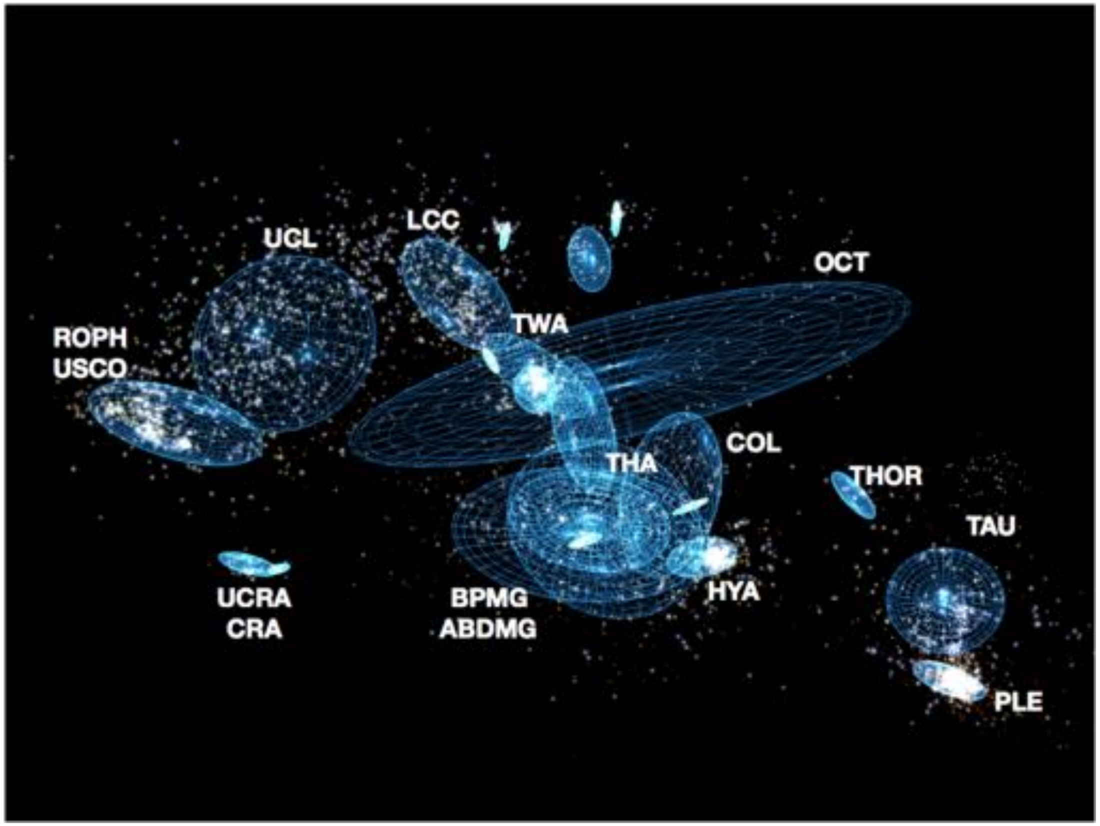
10 Myr

~100 Myr

~1 Gyr

Allers & Liu (2013)

The Young Association Hunting Grounds

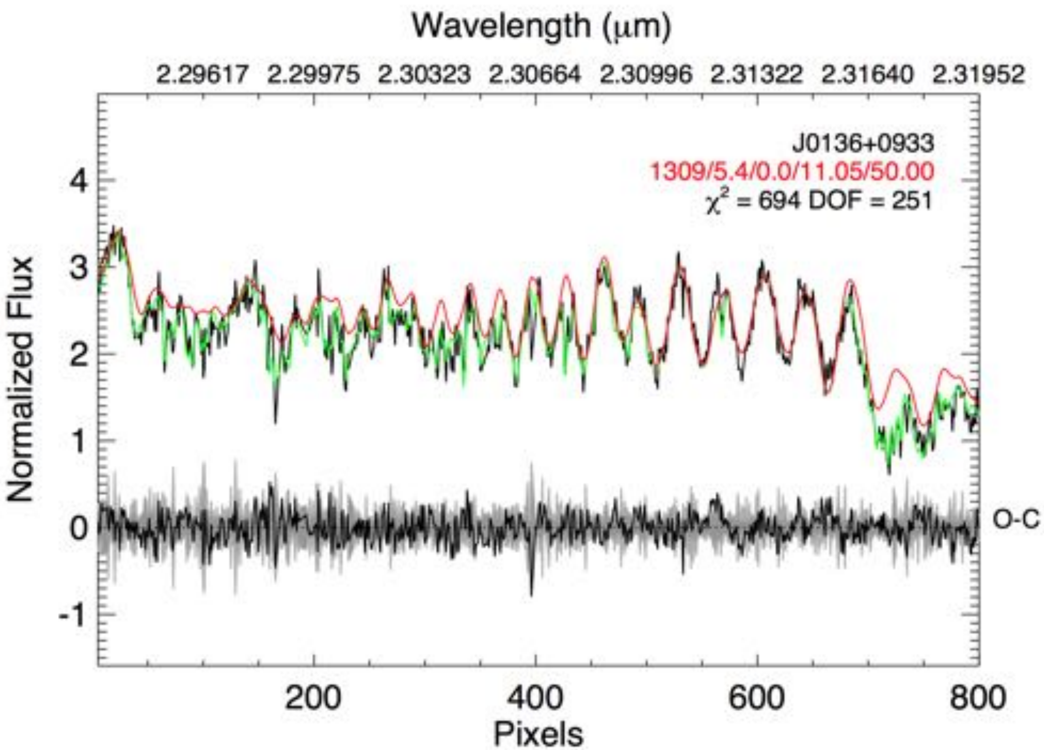


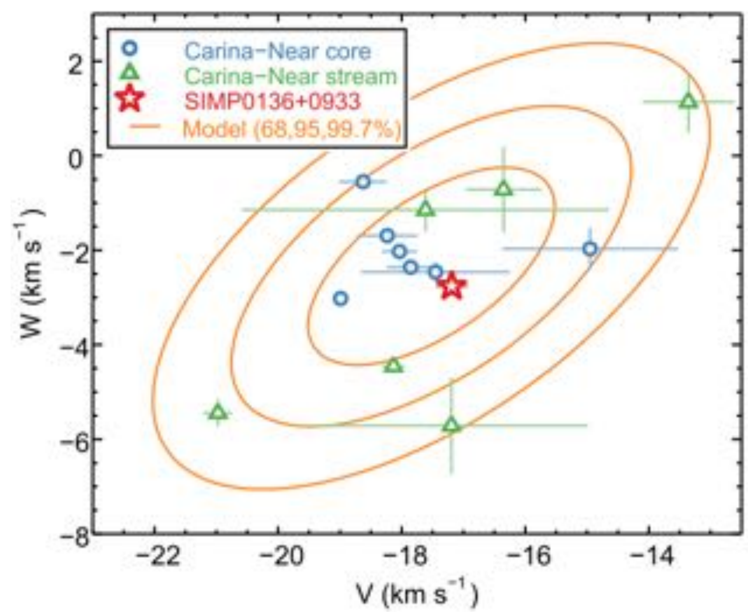
Faherty et al. (2019)

Table 1: **Young Groups Found within 150pc of the Sun defined by BANYAN Σ**

Banyan Name	Full Name	Age (Myr)
ABDMG	AB Doradus	149^{+51}_{-19}
BPMG	β Pictoris	24 ± 3
CAR	Carina	45^{+11}_{-7}
CARN	Carina-Near	~ 200
CBER	Coma Berenices	562^{+98}_{-84}
COL	Columba	42^{+6}_{-4}
EPSC	ϵ Chamaeleontis	$3.7^{+4.6}_{-1.4}$
ETAC	η Chamaeleontis	11 ± 3
HYA	the Hyades cluster	750 ± 100
IC2602	IC 2602	46^{+6}_{-5}
LCC	Lower Centaurus Crux	15 ± 3
OCT	Octans	35 ± 5
PL8	Platais 8	~ 60
PLE	the Pleiades cluster	112 ± 5
THA	Tucana-Horologium	45 ± 4
THOR	32 Orionis	22^{+4}_{-3}
TWA	TW Hydra	10 ± 3
UCL	Upper Centaurus Lupus	16 ± 2
UMA	Ursa Major cluster	414 ± 23
USCO	Upper Scorpius	10 ± 3
XFOR	χ Fornax	~ 500

Planetary-Mass Members of Young Moving Groups





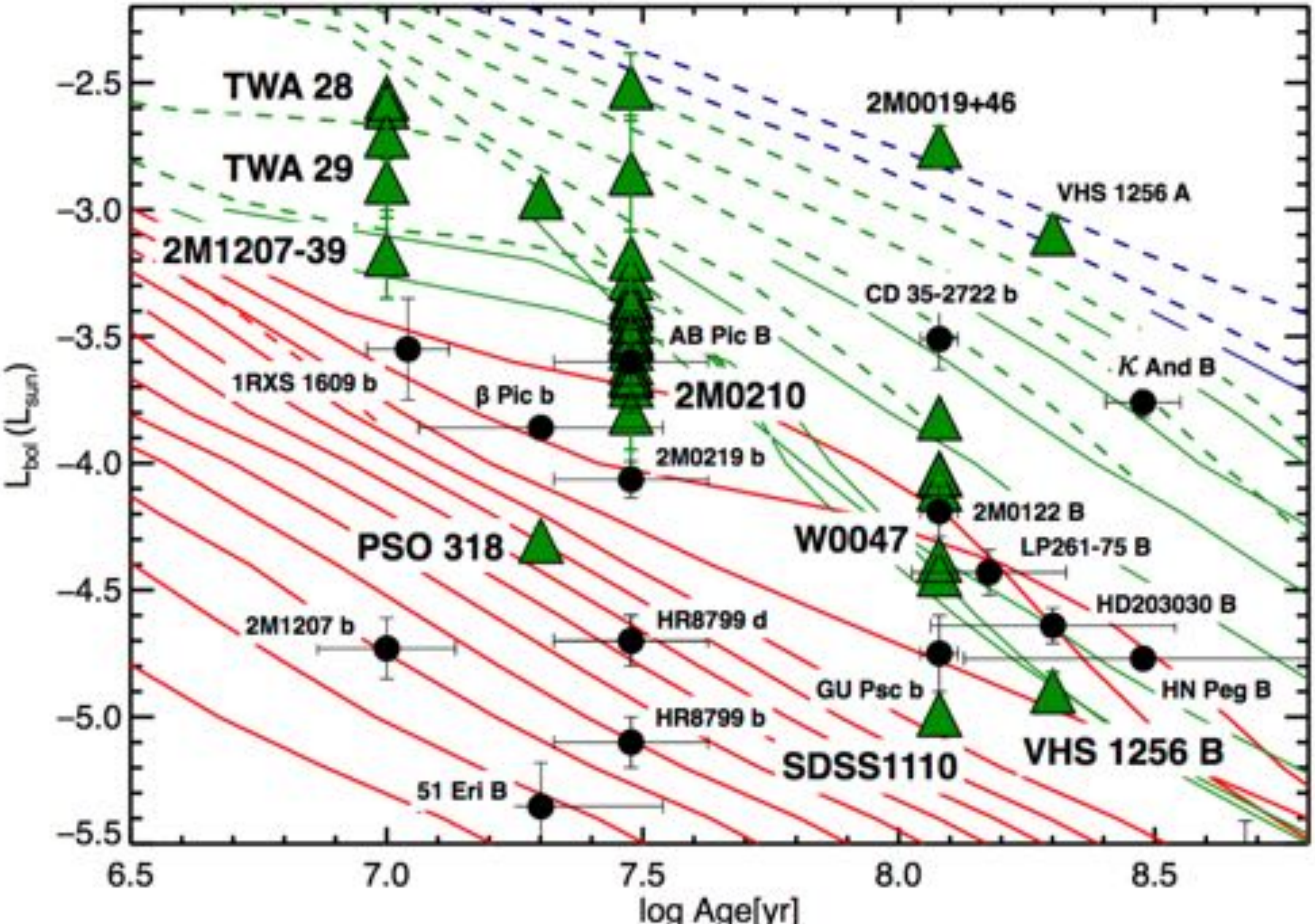
Gagne et al. (2017, 2018)

T2.5, $T_{eff} \approx 1100$ K @ 6 pc

member of 200 Myr Carina-Near

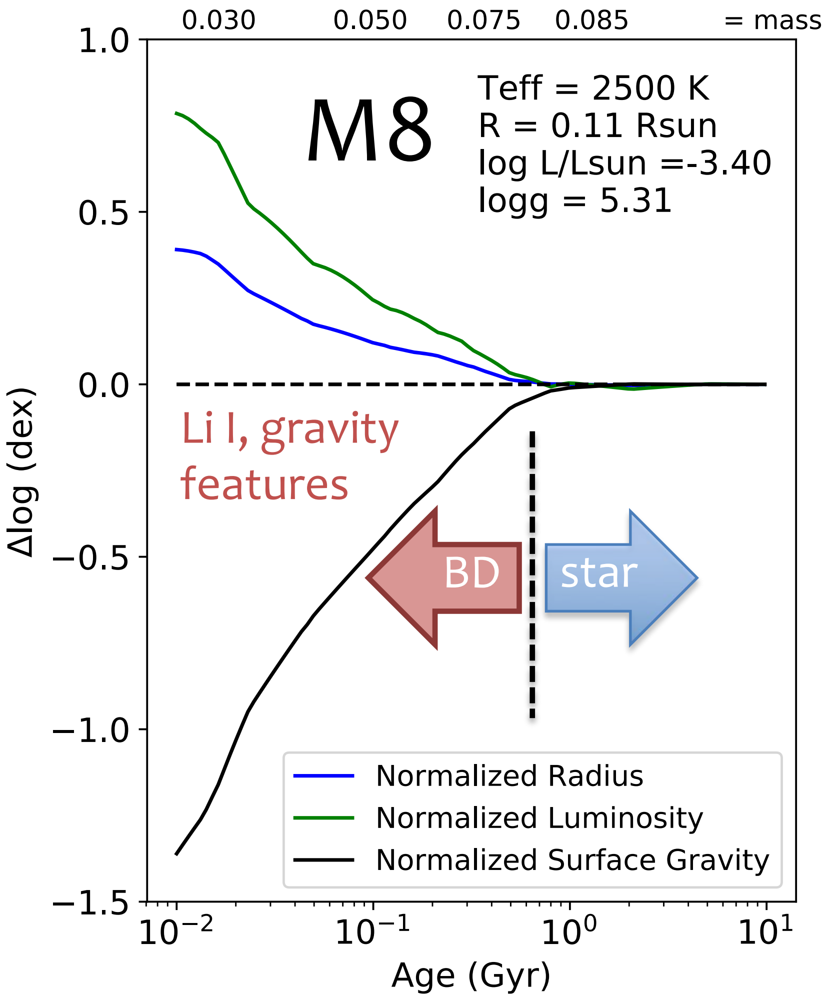
Mass ≈ 13 Jupiter masses

Young Benchmarks



Faherty et al. (2019)

warm BDs are good clocks only at young ages…



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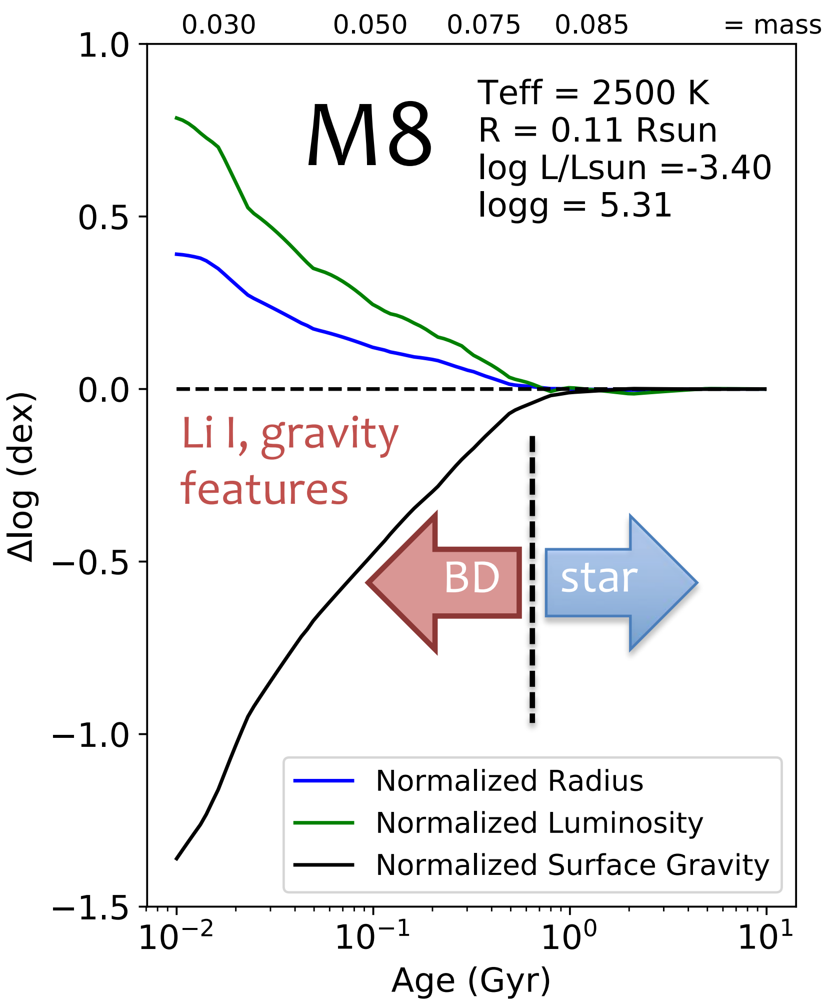
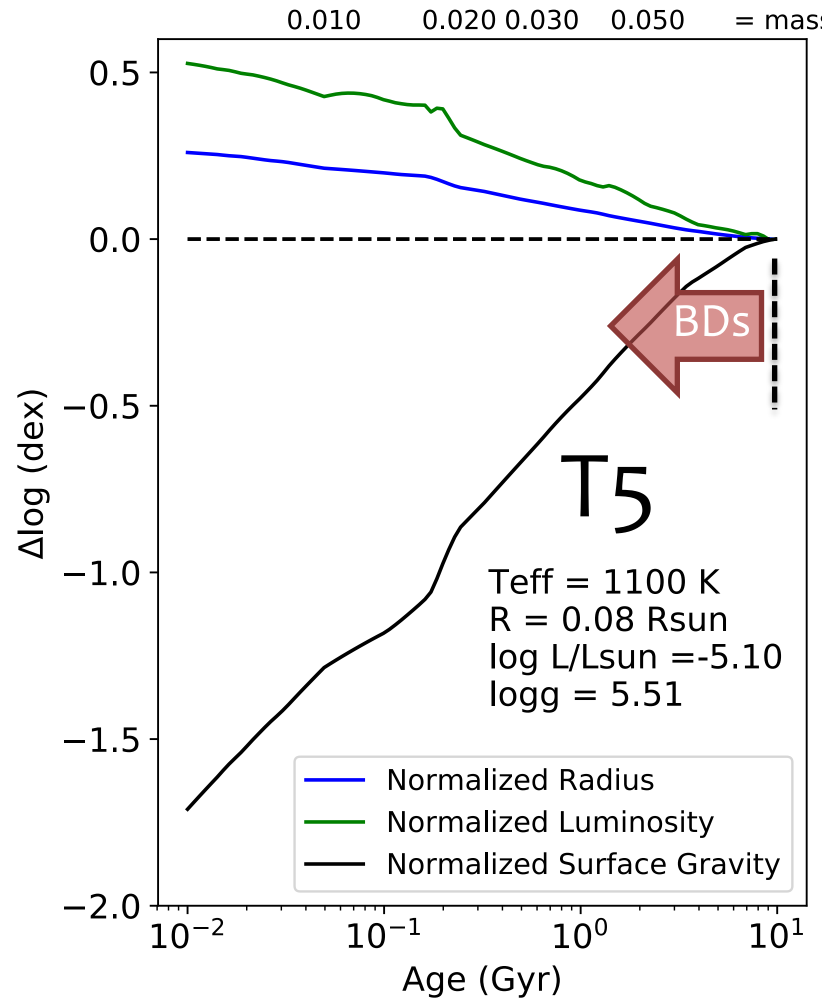
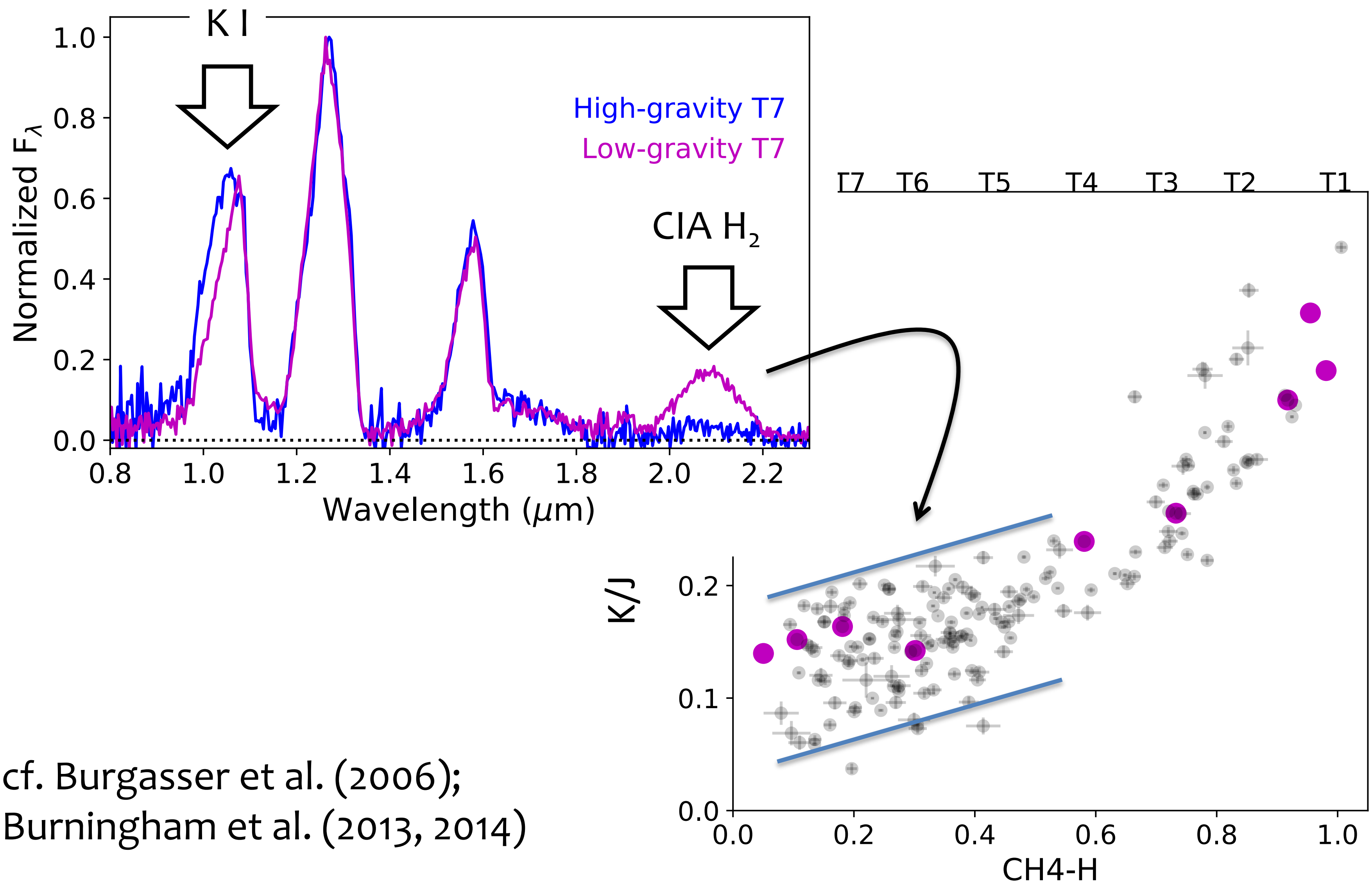




…but cold brown dwarfs are excellent clocks at all ages!

Gravity features in T dwarf NIR spectra can provide an independent measure of the BD formation history

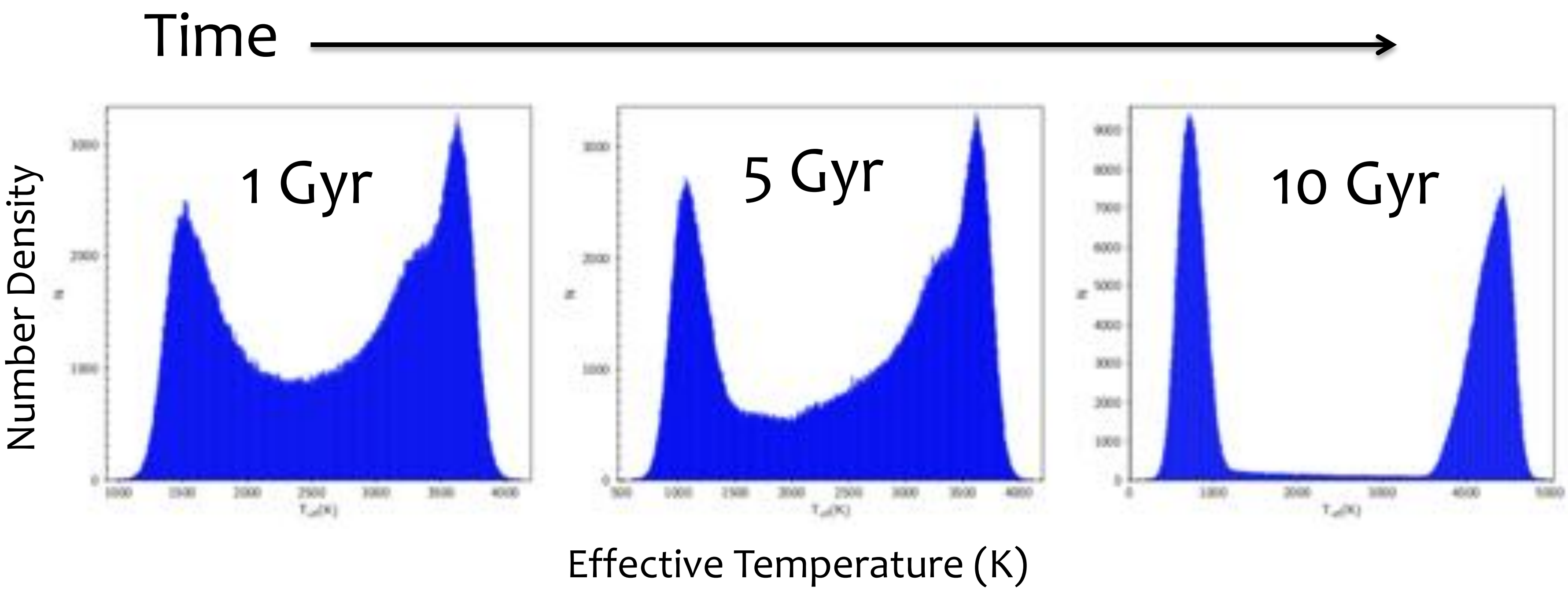


cf. Burgasser et al. (2006);
Burningham et al. (2013, 2014)

Stars ($M > 0.072\ M_\odot$)
BDs ($M > 0.014\ M_\odot$)
FFPs ($M < 0.014\ M_\odot$)

SPLAT Population Simulation Code
IMF: Chabrier et al. (2005) $0.005 < M < 0.2\ M_{sol}$
20% binaries, $\sigma(T) = 10$, % $\sigma(L) = 10\%$
Evolutionary models: Burrows et al. (2000)

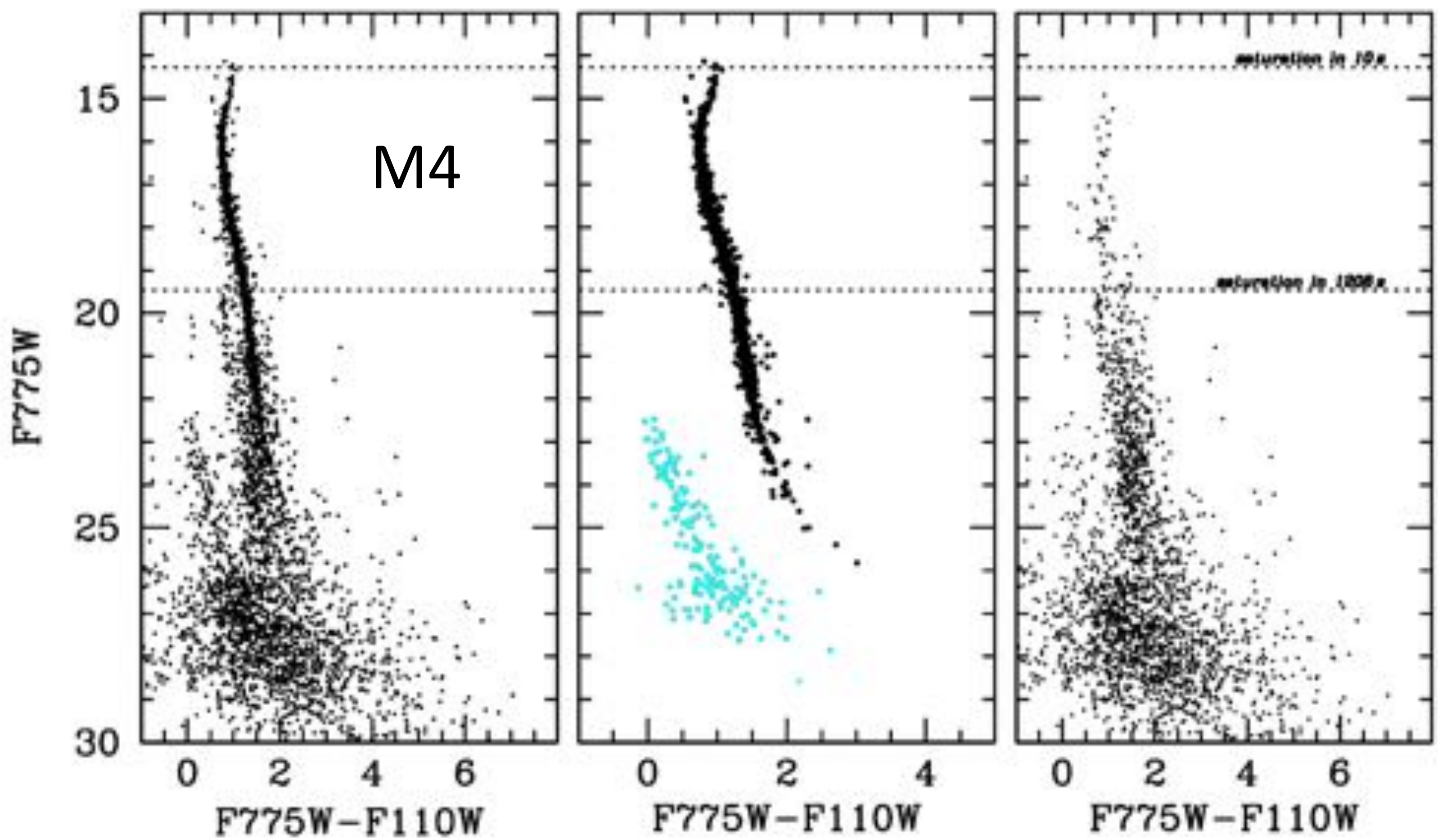
The BD Cluster Gap



Rees et al. (in prep.)

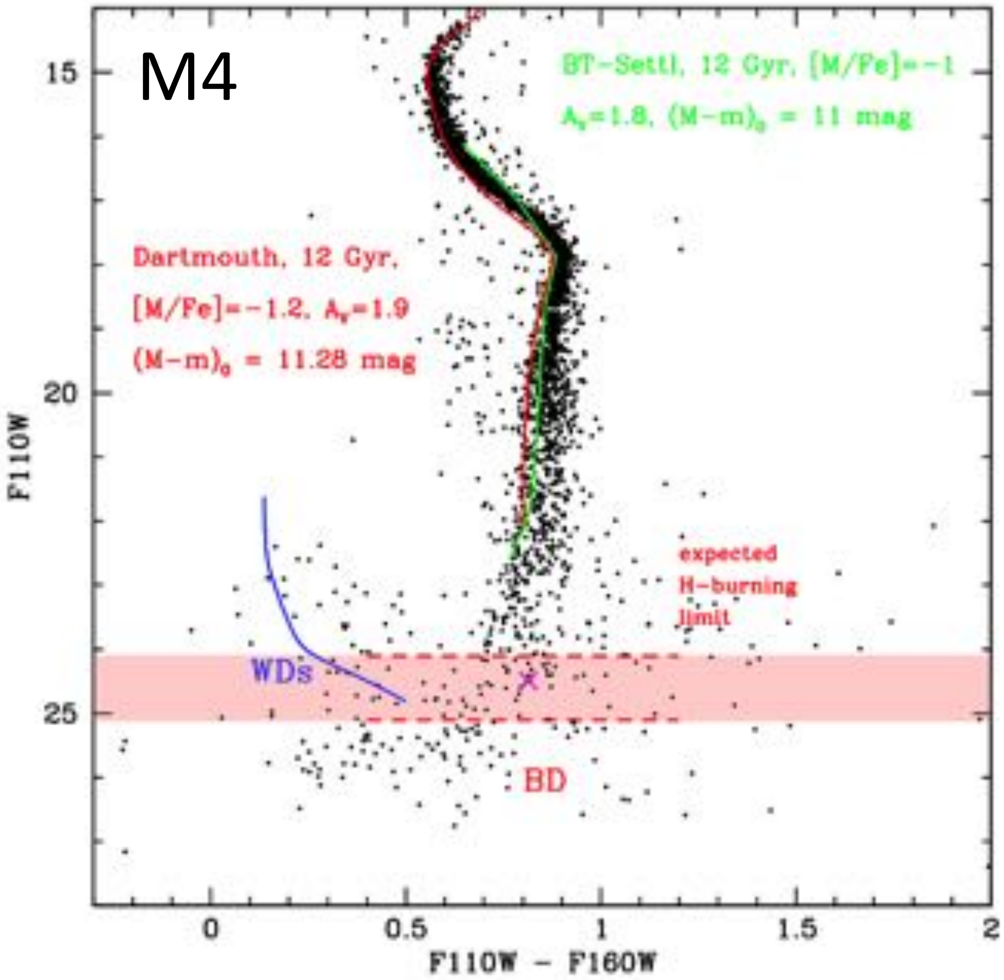
see also Burgasser (2004); Caiazzo et al. (2017)

The BD Gap in Globular Clusters



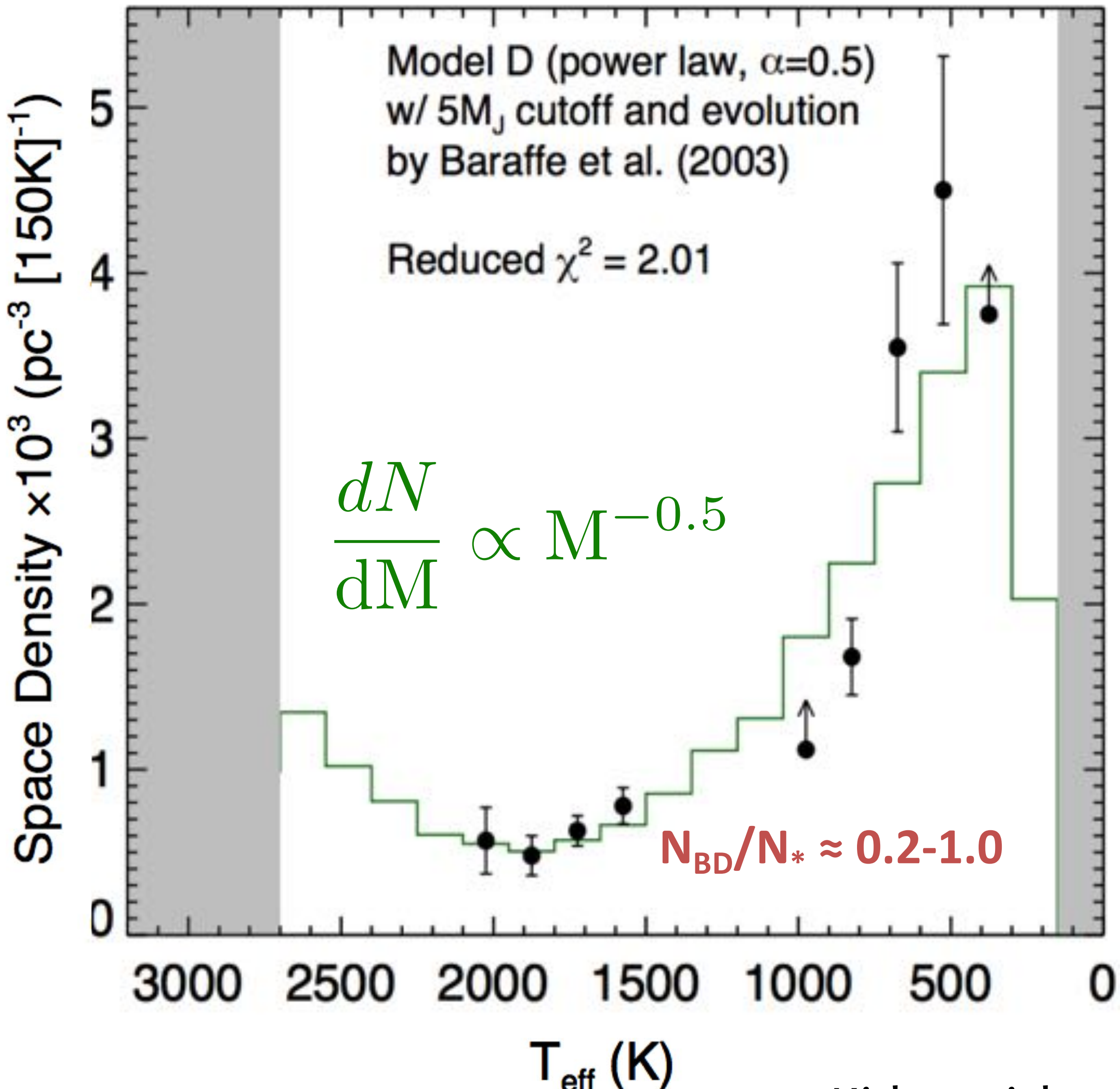
Dieball et al. (2016)

The Gap in Globular Clusters

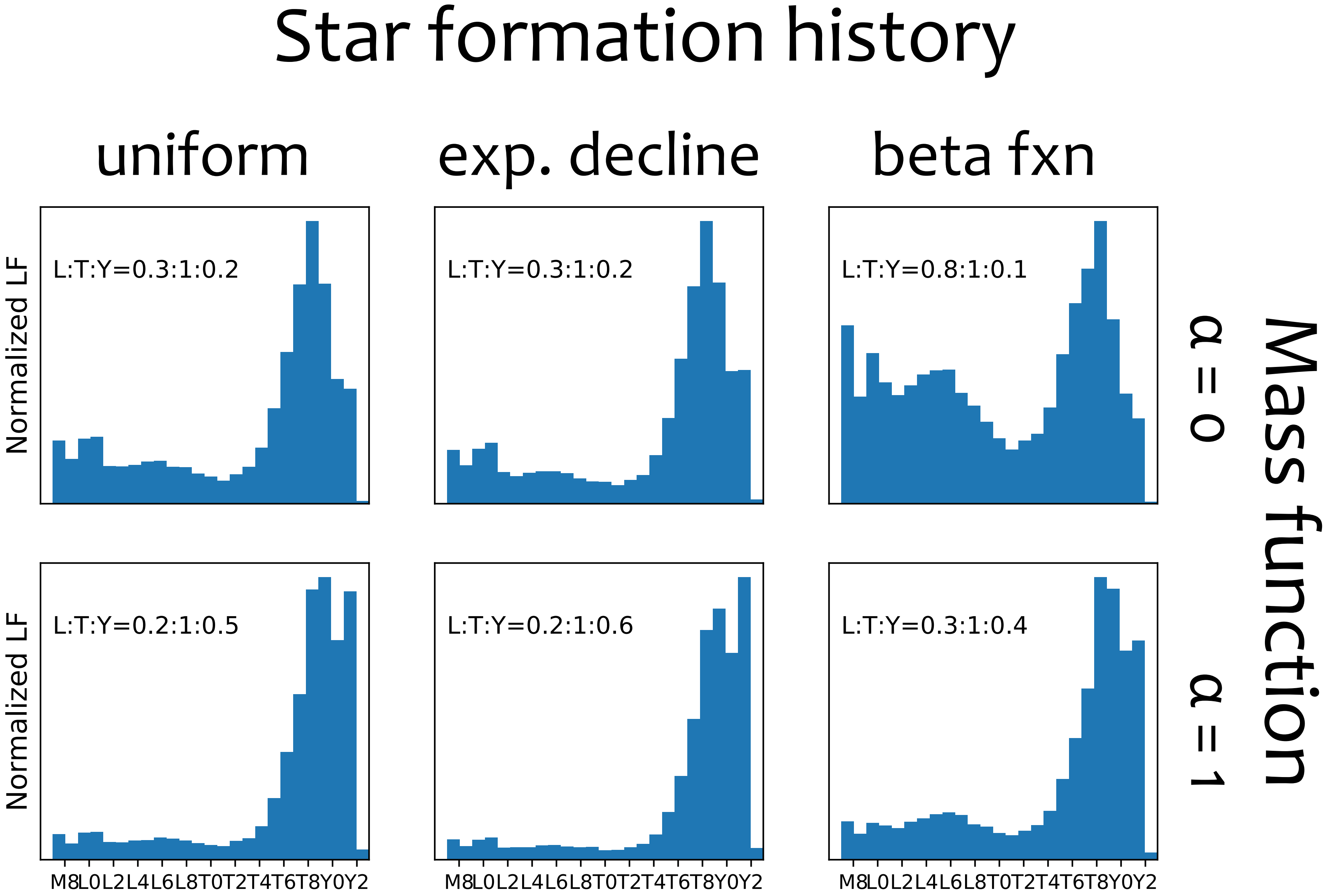


Dieball et al. (2016)

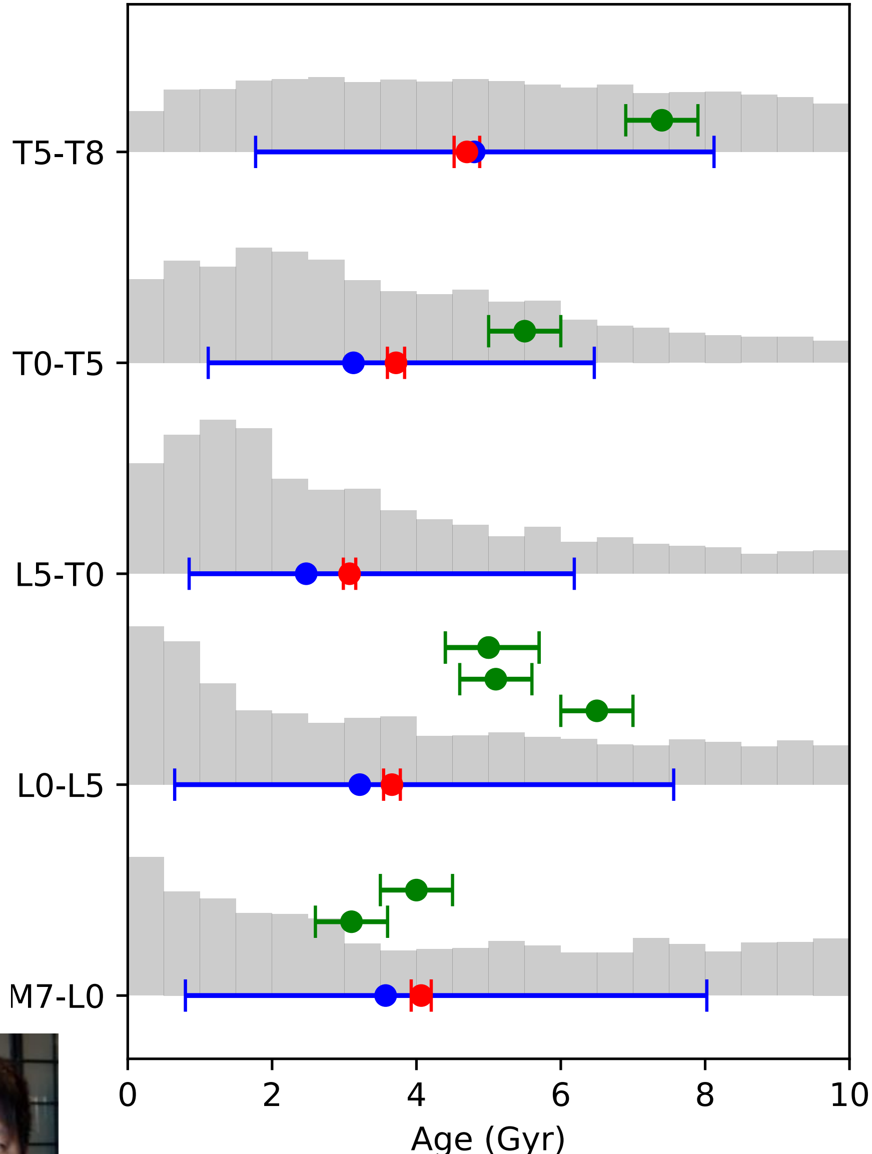
Field Substellar IMF (T & Y dwarfs)



Kirkpatrick et al. (2019)

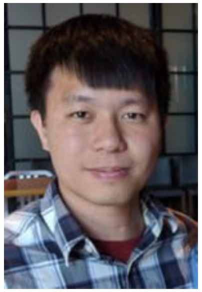


Star formation history
uniform
exp. decline
beta fxn
Normalized LF
L:T:Y=0.3:1:0.2
L:T:Y=0.3:1:0.2
L:T:Y=0.8:1:0.1
α = 0
Mass function
Normalized LF
L:T:Y=0.2:1:0.5
L:T:Y=0.2:1:0.6
L:T:Y=0.3:1:0.4
α = 1
M8L0L2L4L6L8T0T2T4T6T8Y0Y2
M8L0L2L4L6L8T0T2T4T6T8Y0Y2
M8L0L2L4L6L8T0T2T4T6T8Y0Y2



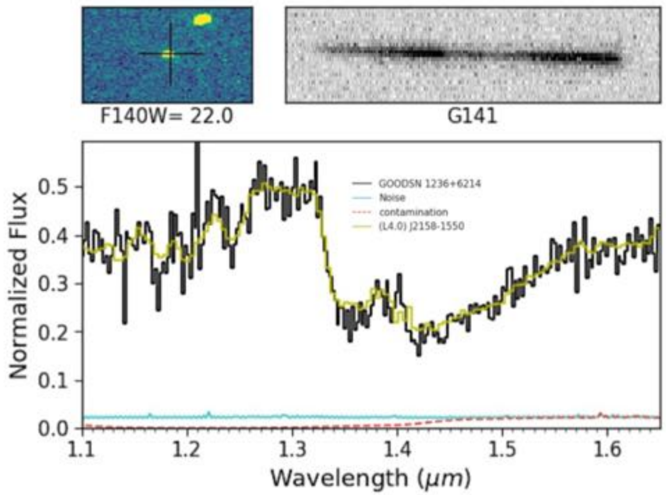
BD Formation history is imprinted on velocity dispersions, which are significantly discrepant from population simulations

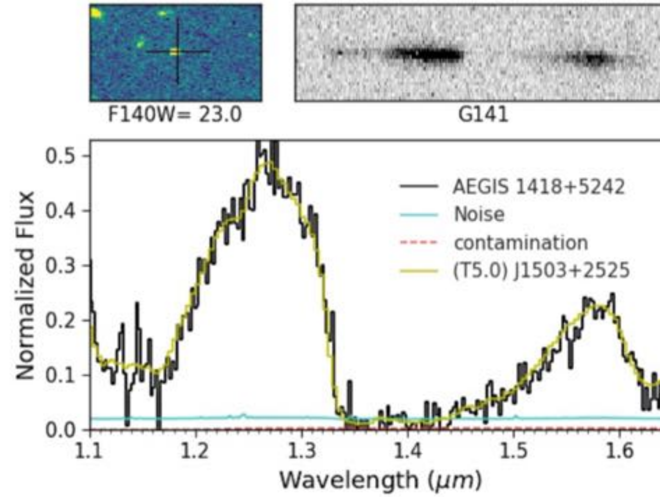
Simulated age distributions
Predicted age quartiles
Predicted velocity distributions
Observed velocity distributions



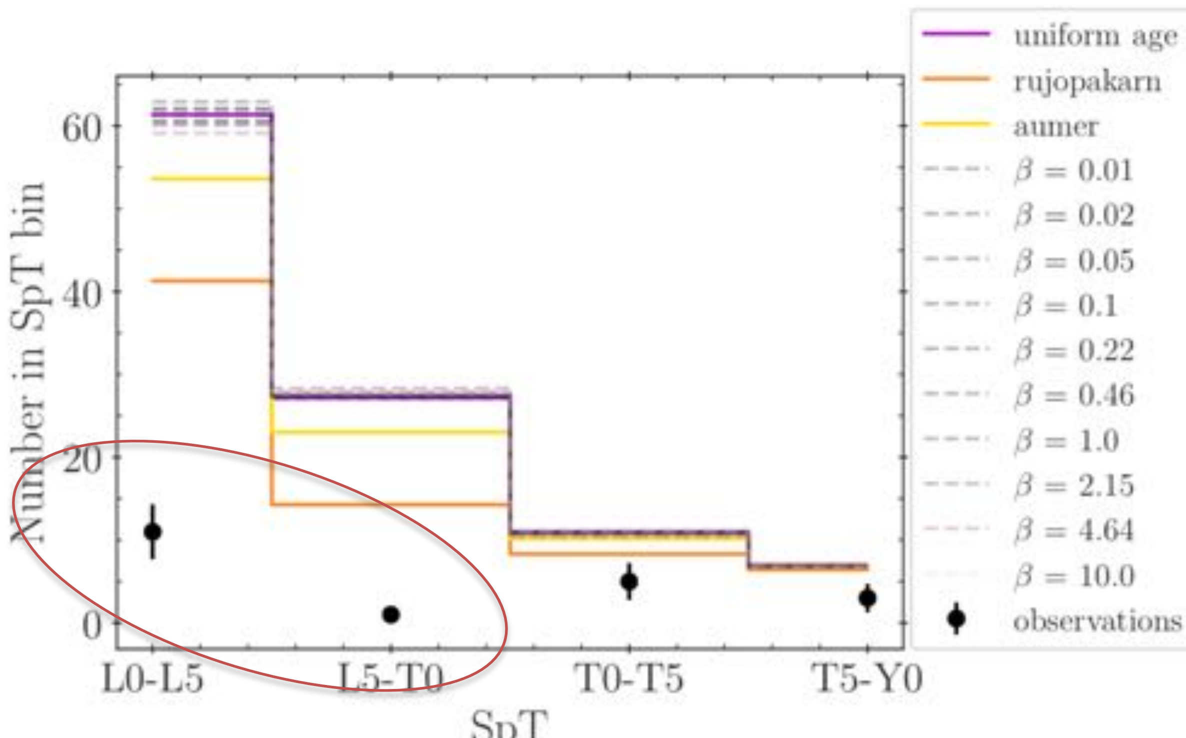
Burgasser et al. (2015); **Hsu et al. (in prep)**

Aganze et al.
(in prep)

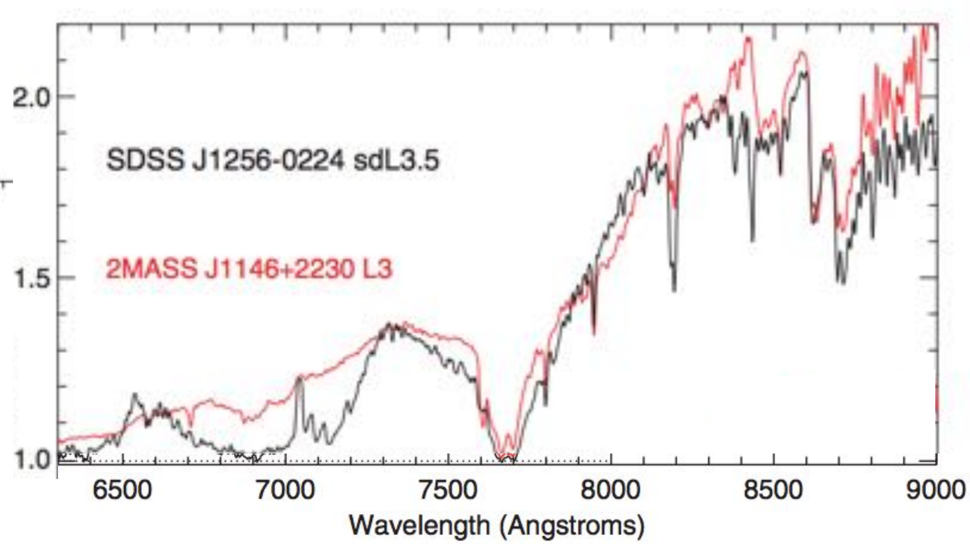


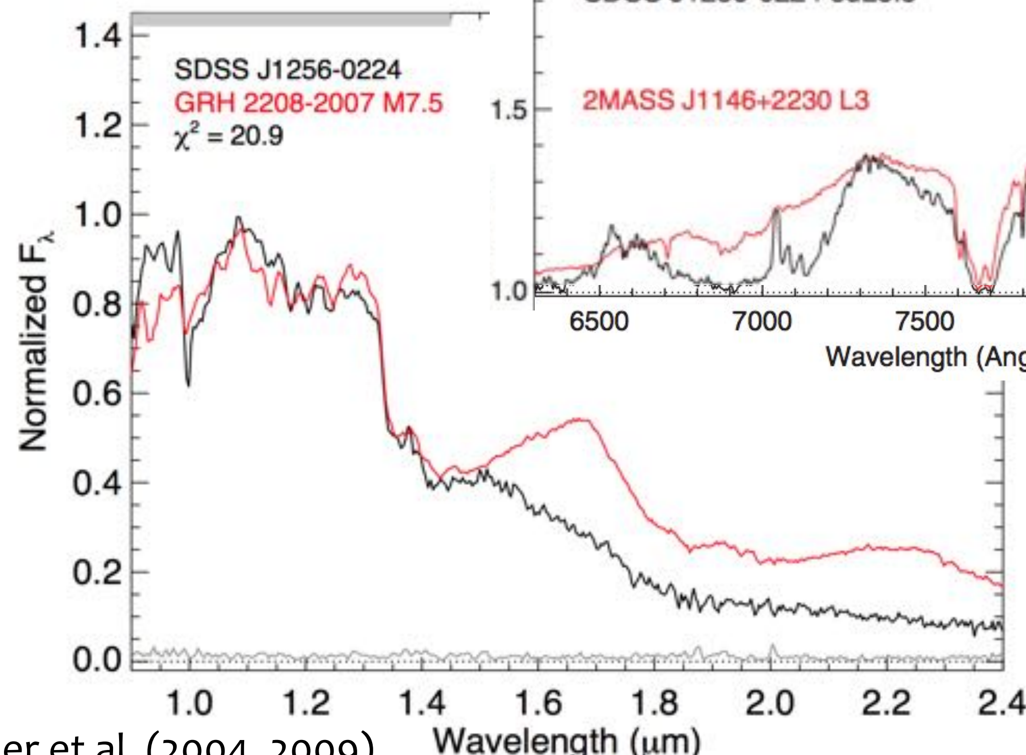


HST WFC3 deep spectral sample is **depleted in L dwarfs**
Is this selection bias?
Evolution? Kinematic scatter?
A feature of star formation history?

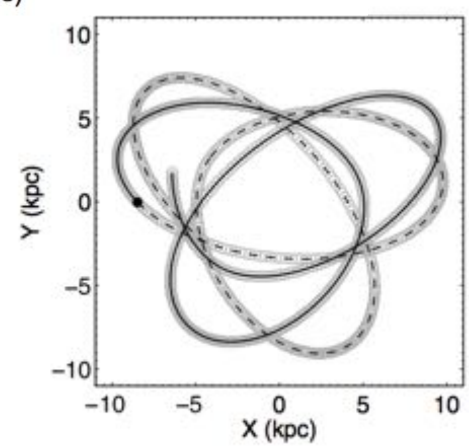


What about the Halo Population?

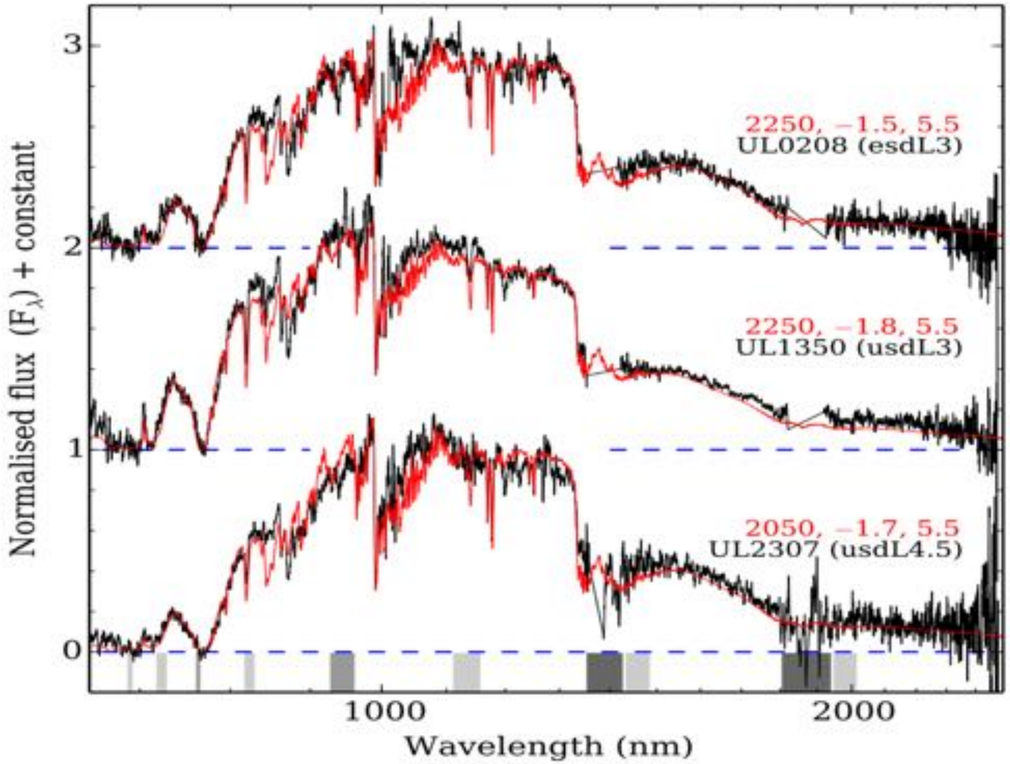




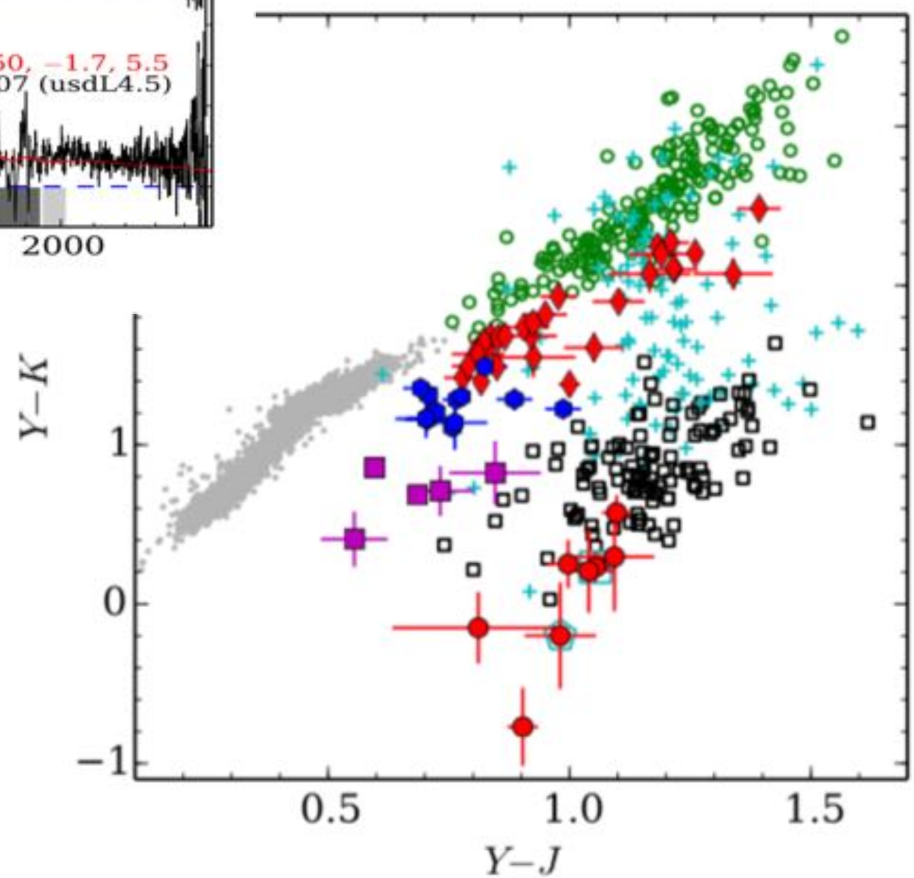
Burgasser et al. (2004, 2009)



≈ dozen metal-poor L dwarfs with halo kinematics are now known

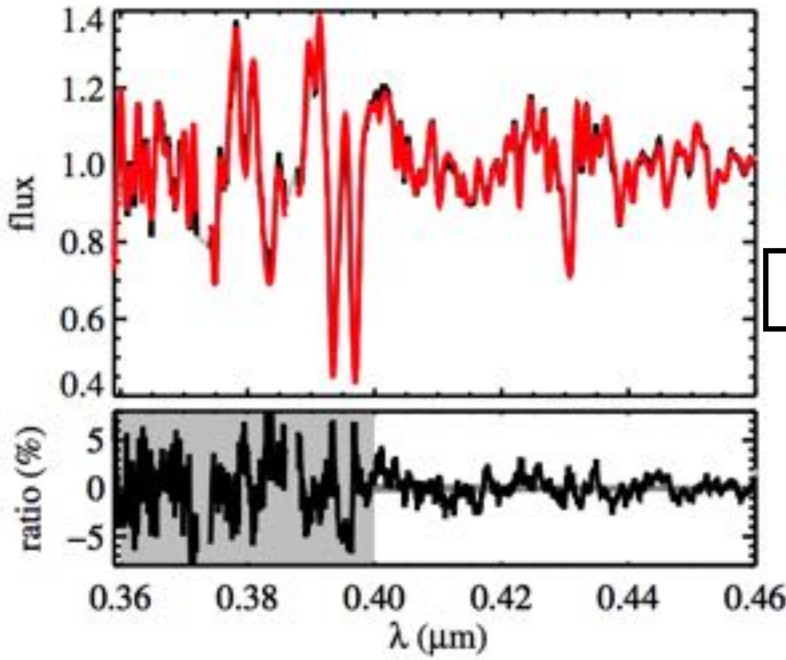


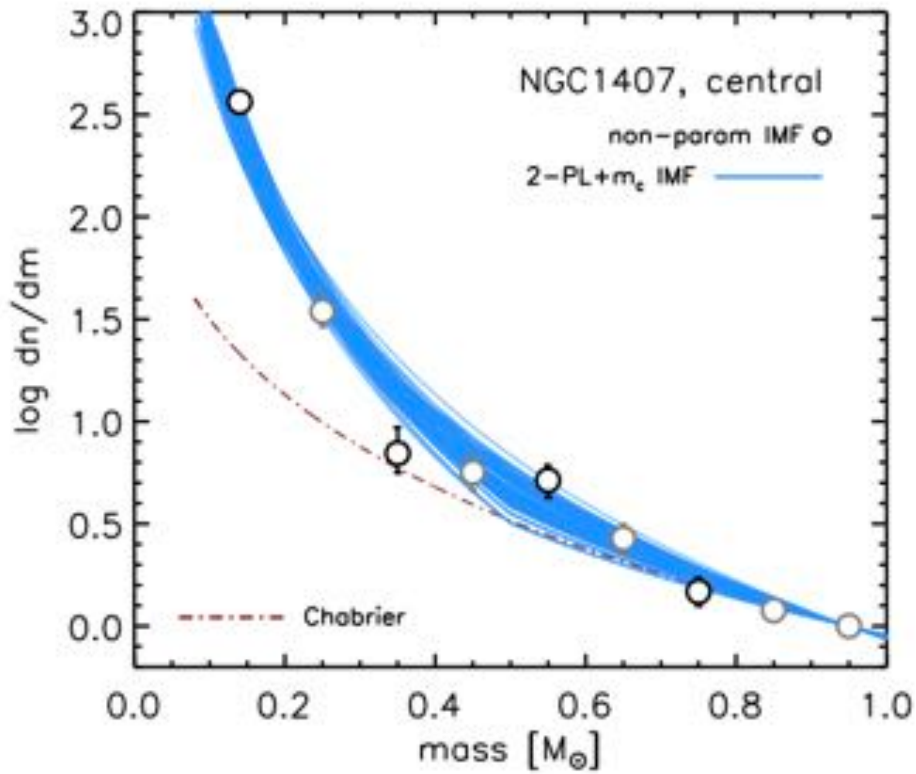
Zhang et al. (2019)



Metallicity signatures are pronounced in L & T subdwarfs, but measurement of individual abundances is limited by the quality of atmosphere model fits

Beyond the MW: Are BDs dominant in Early-type Galaxies?

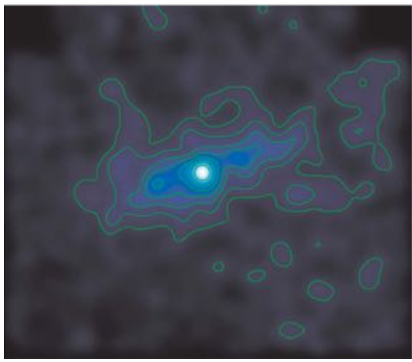




Conroy & van Dokkum (2012)
Conroy et al. (2017)

The era of Extragalactic Brown Dwarfs is nigh (repent!)

JWST/NIRCAM F200W AB 29 S/N = 10 in 10 ks gets you…



Herc dSph

LMC

M5 @ 130 kpc

L0 @ 50 kpc

L5 @ 26 kpc

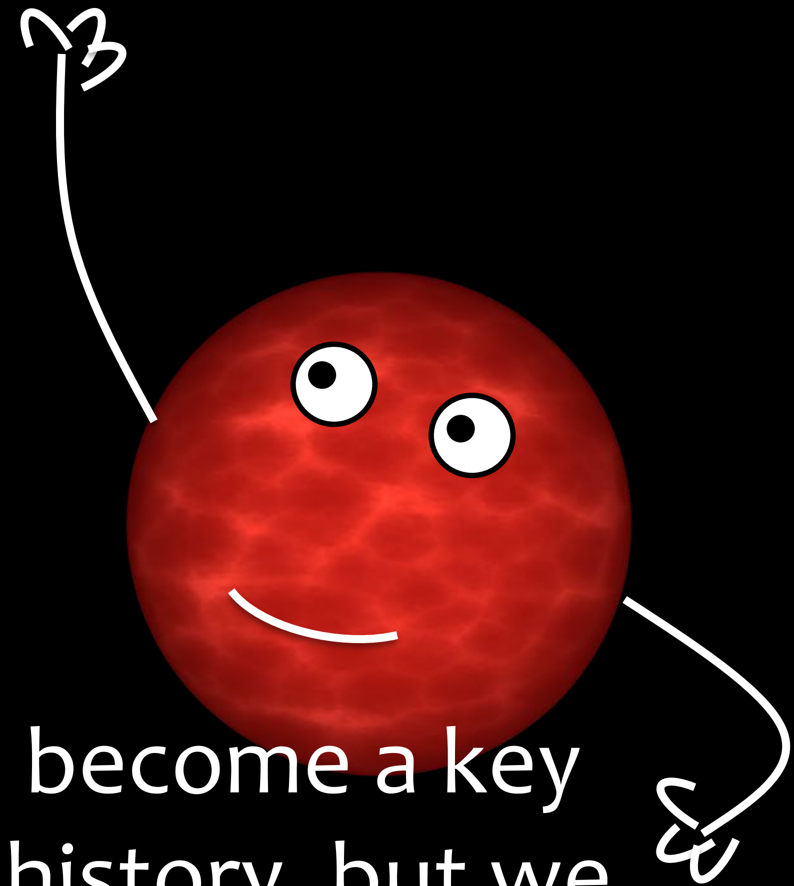
T0 @ 16 kpc

T5 @ 8 kpc

Y0 @ 2 kpc

Sag dSph

MW Center

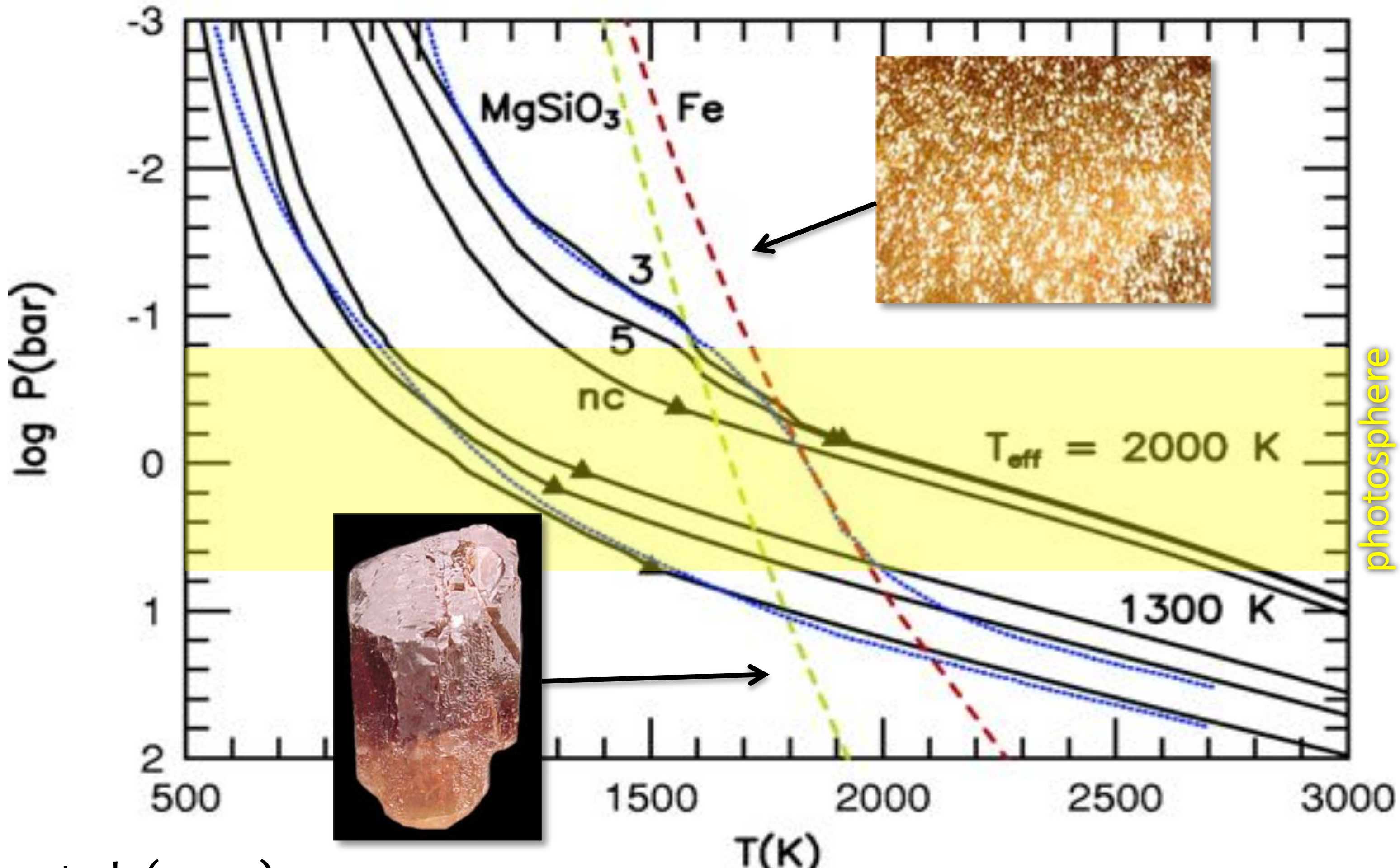


Brown dwarfs are set to become a key probe of star formation history, but we need to better understand spectral signatures of physical parameters and expand the census in multiple populations

Weather & Atmospheric Dynamics

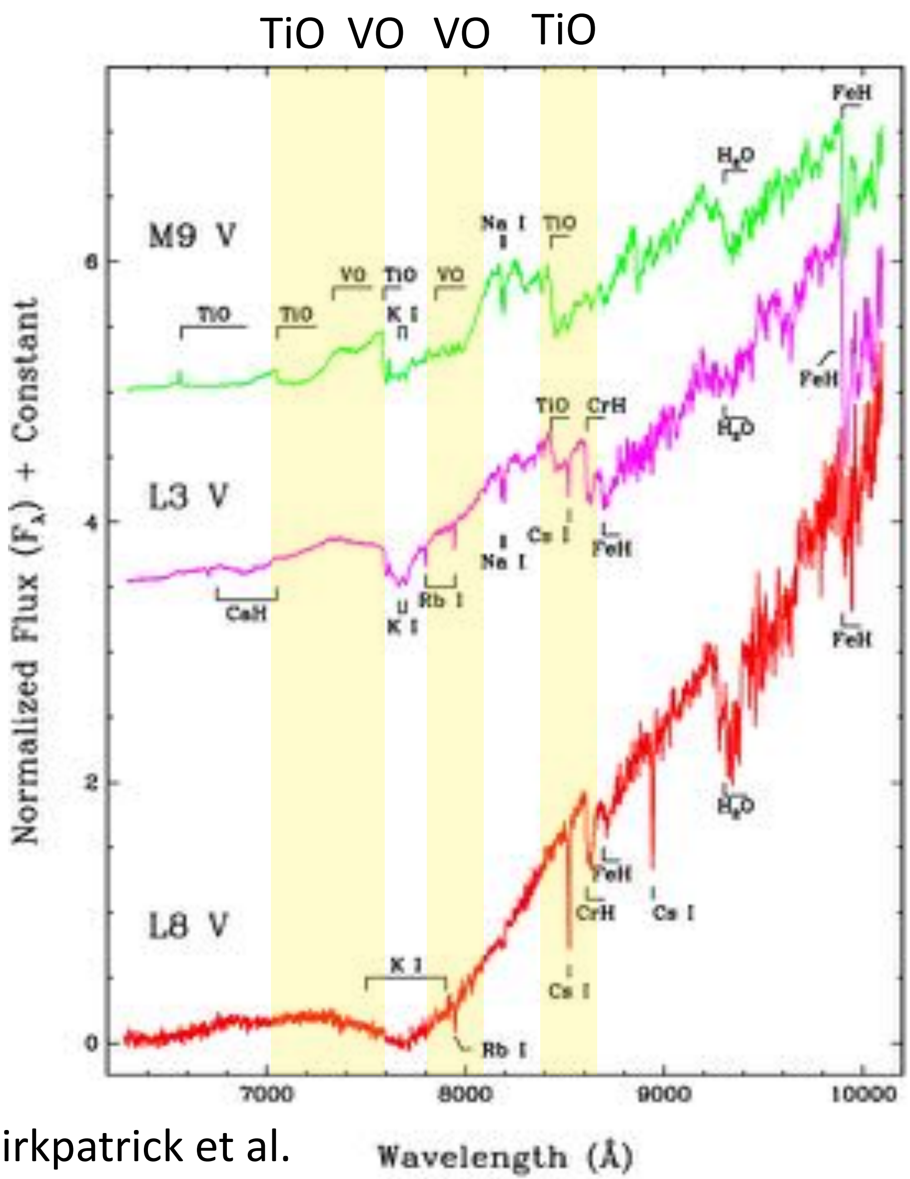
1. Apai et al.: Mapping Ultracool Atmospheres: Time-domain Observations of Brown Dwarfs and Exoplanets
2. Vos et al.: The L/T Transition

Condensation in BD Atmospheres: Theory

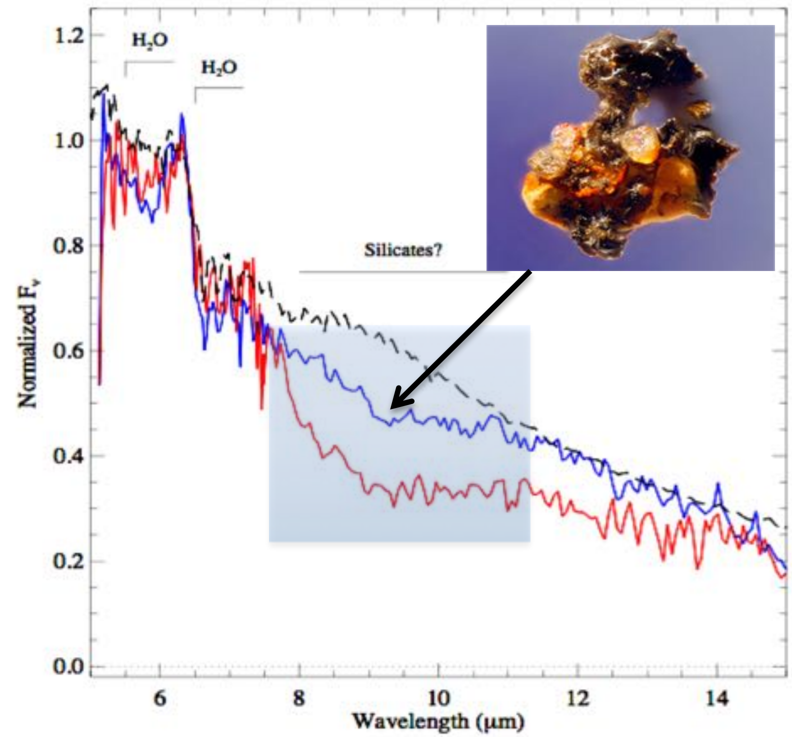


Marley et al. (2002)
also Burrows & Sharp (1999); Allard et al. (2001);
Lodders (2002)

Condensation in BD Atmospheres: Observations



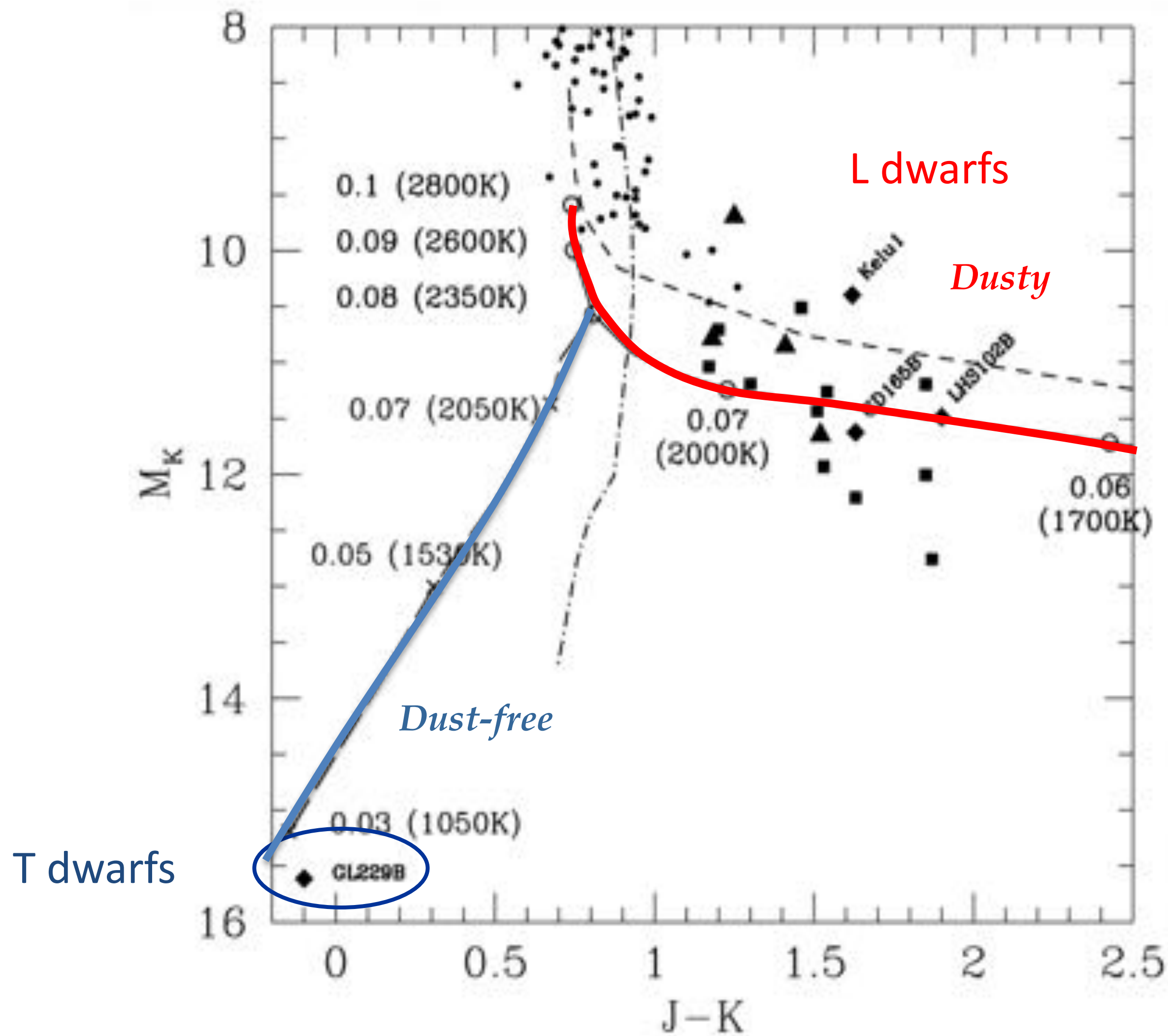
Kirkpatrick et al. (1999)



Burgasser et al. (2008);
data from Cushing et al. (2006)

We detect condensates in brown dwarfs by their impact on gas chemistry, reddening, and presence of silicate absorption bands

Condensation in BD Atmospheres: Observations



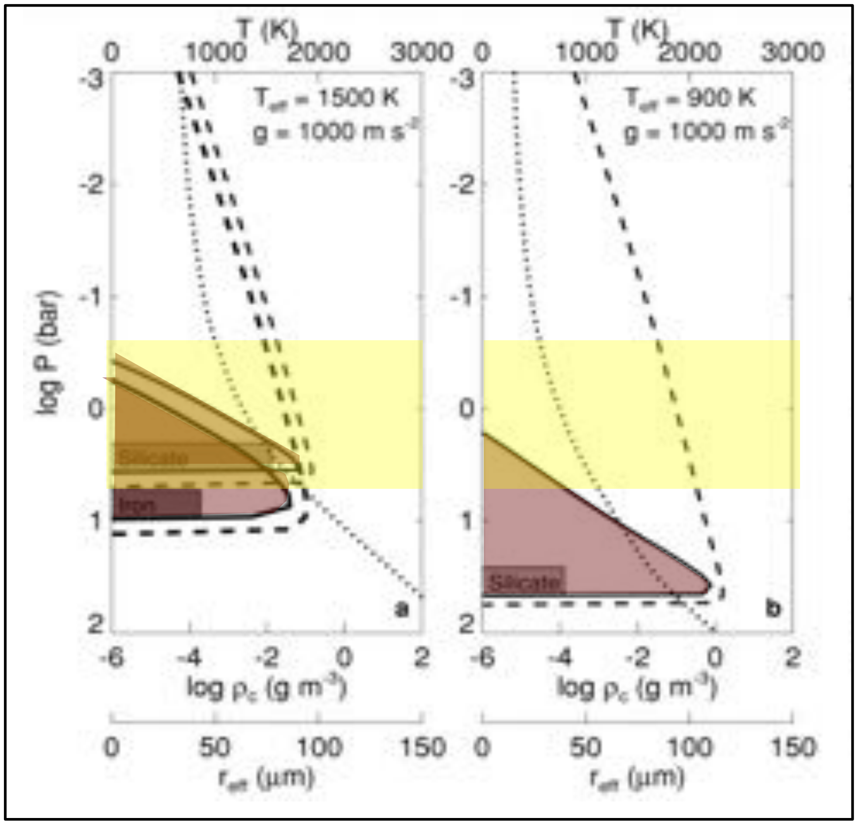
Tsuji et al. (1996); Chabrier et al. (1997, 2000);
Ackerman & Marley (2001); Allard et al. (2001)


fog

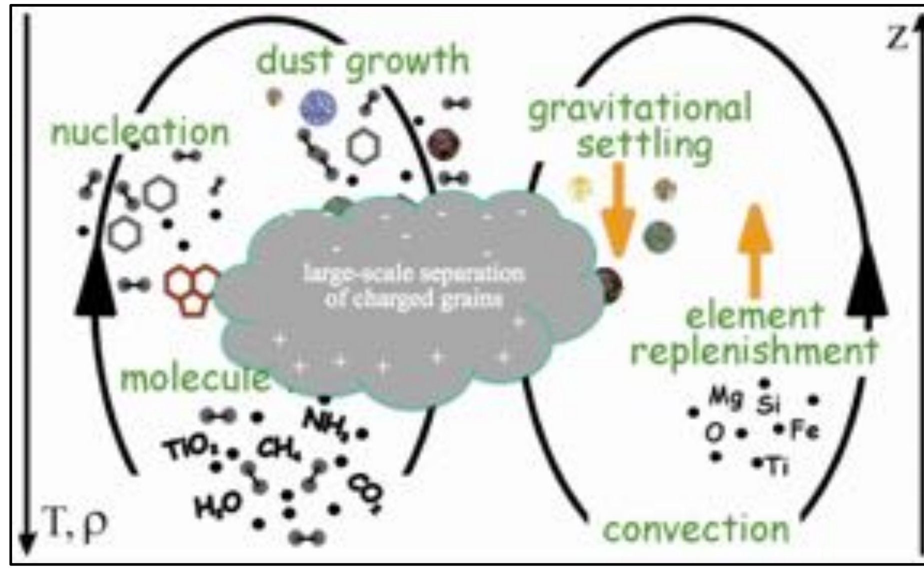

rainout


clouds

Layers of condensation



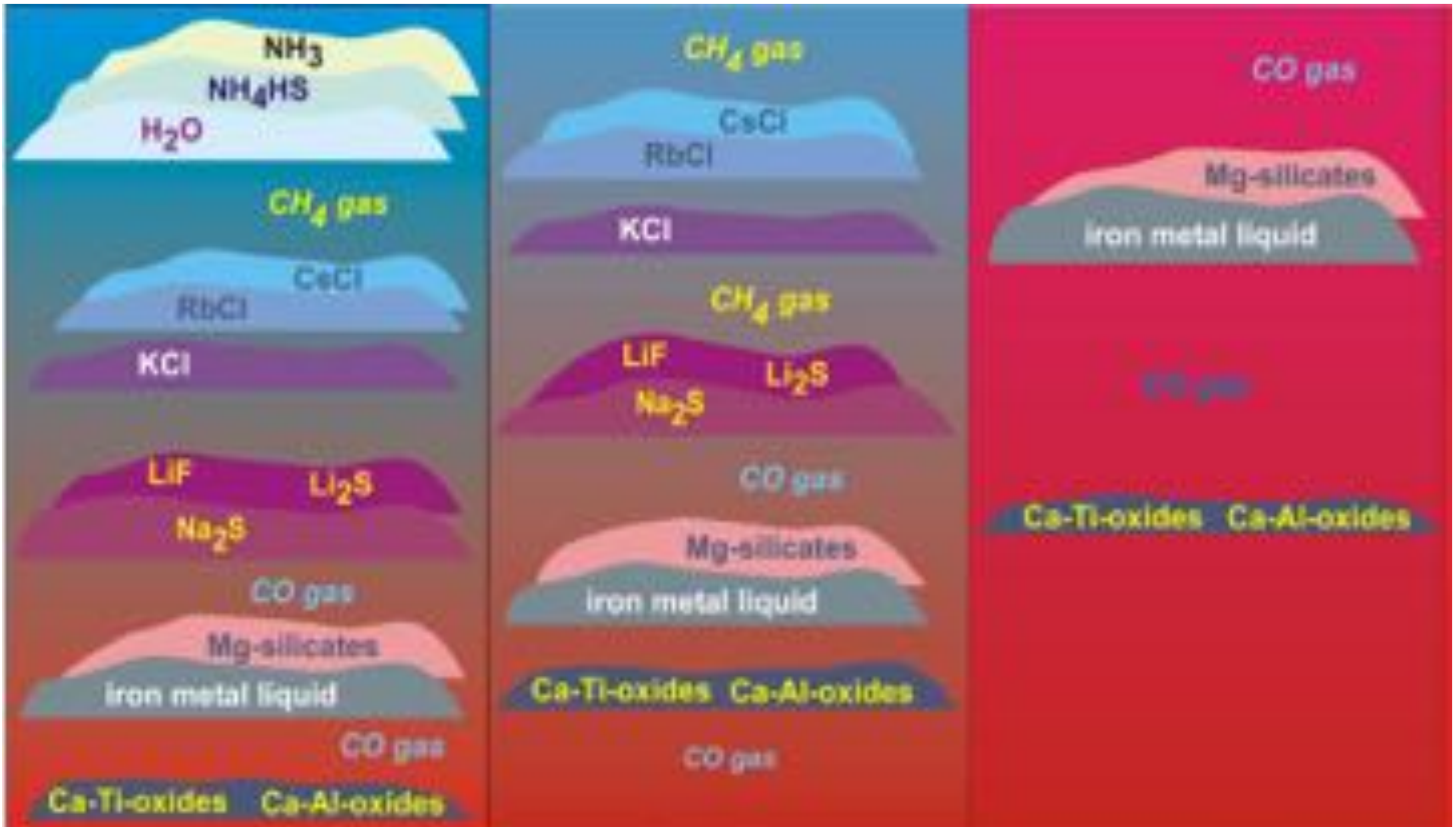
Ackerman & Marley (2001)
also Cooper et al. (2003); Tsuji (2004,2005); Helling et al. (2001,2006,2008)



Helling (2008)

Condensate cloud formation is modeled as a balance of grain growth, "rainout" and convection

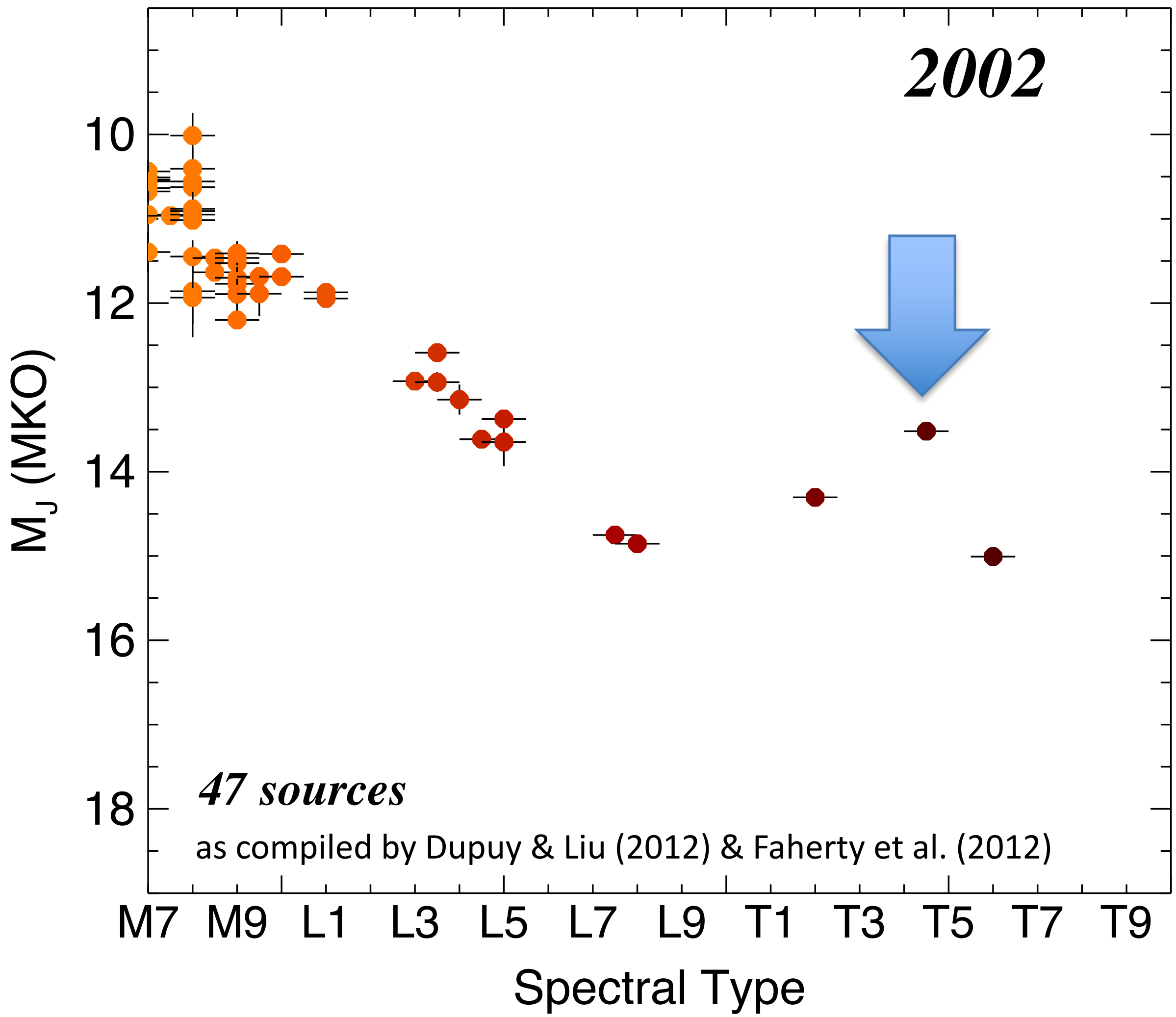
Layers of Condensation



Y dwarfs? **T dwarfs** **L dwarfs**

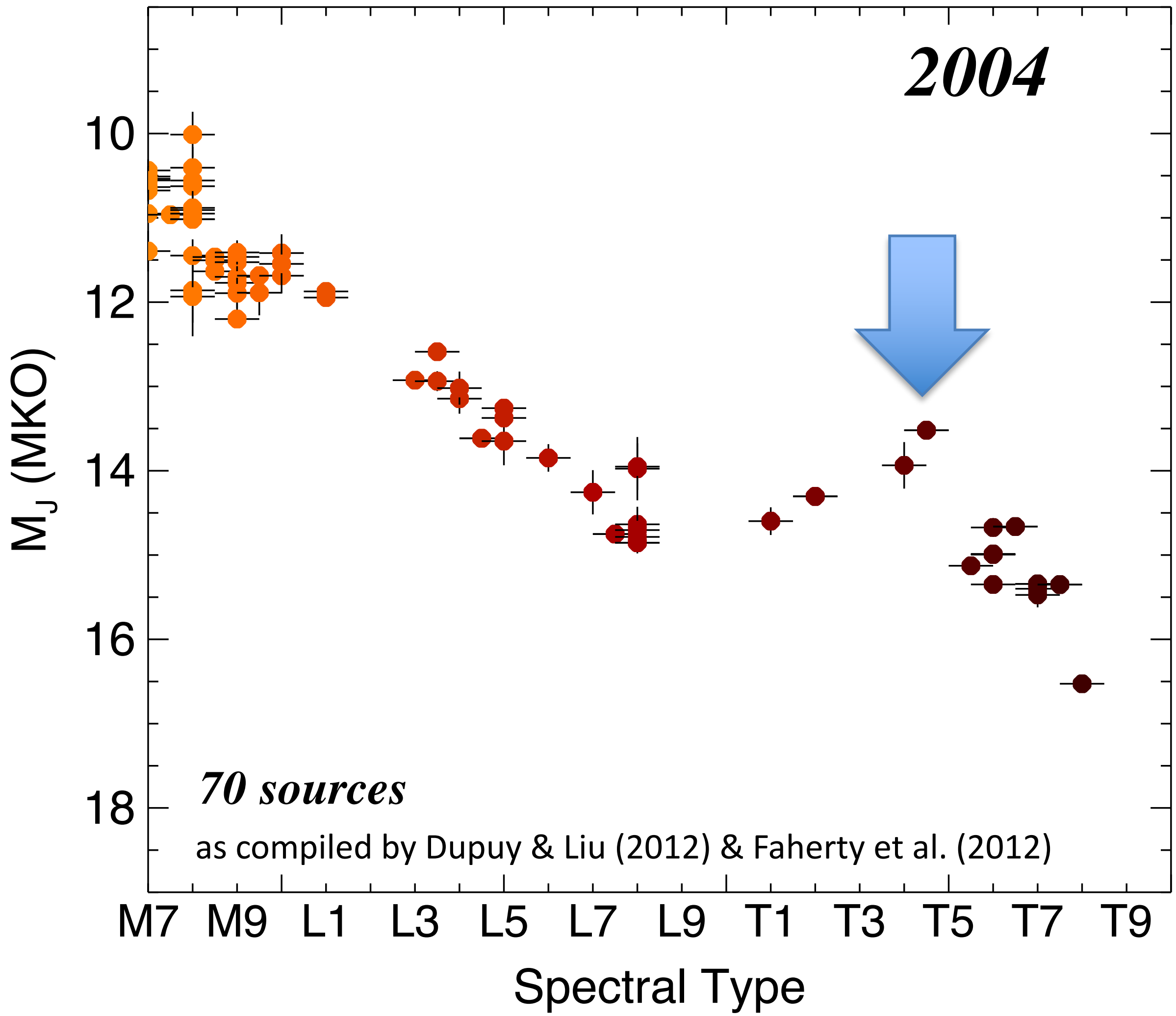
Lodders & Fegley (2008)

The J-band Bump...



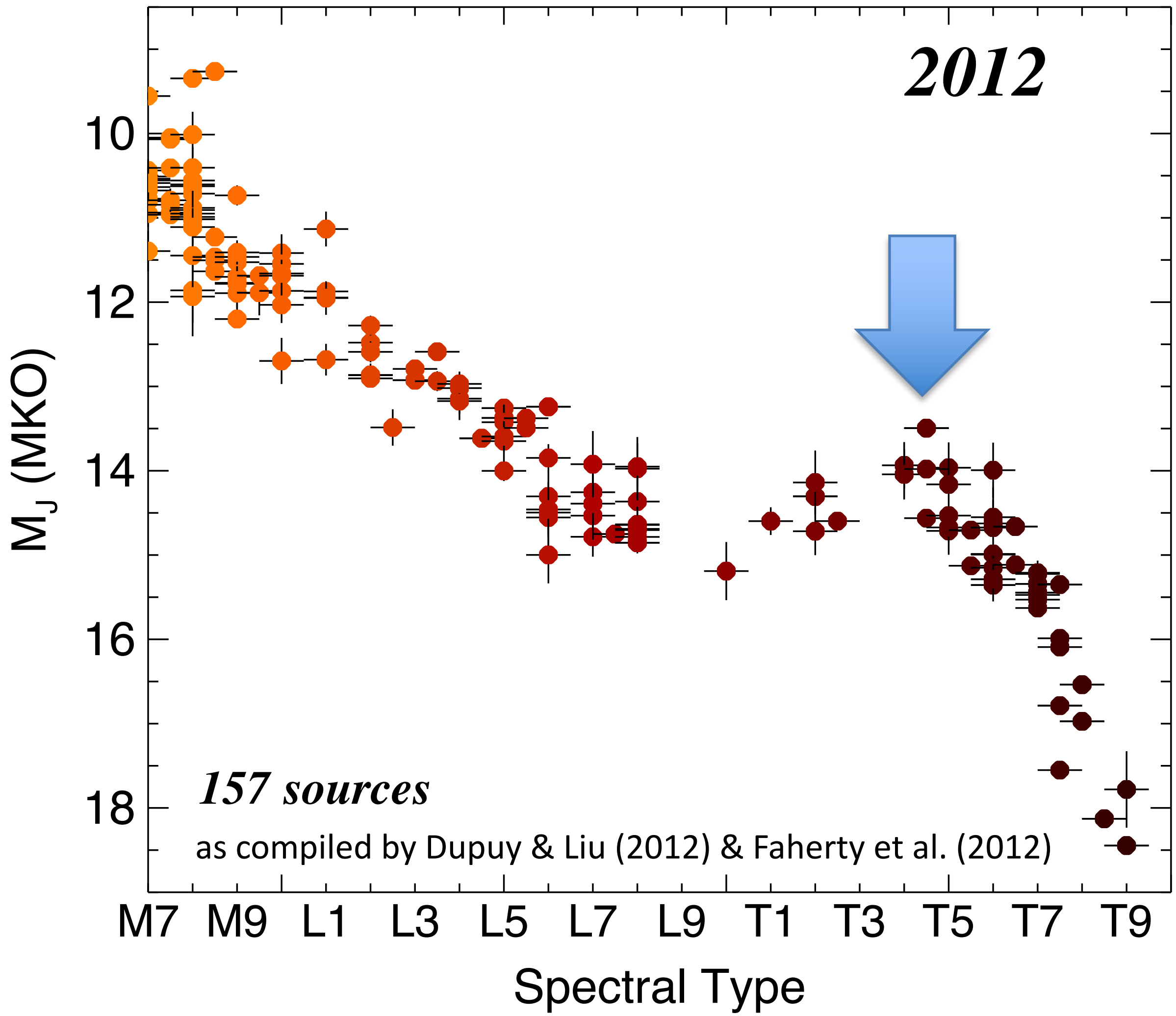
Monet et al. (1992);
Tinney et al. (1995,1996);
van Altena et al. (1995);
Dahn et al. (2002)

The J-band Bump...



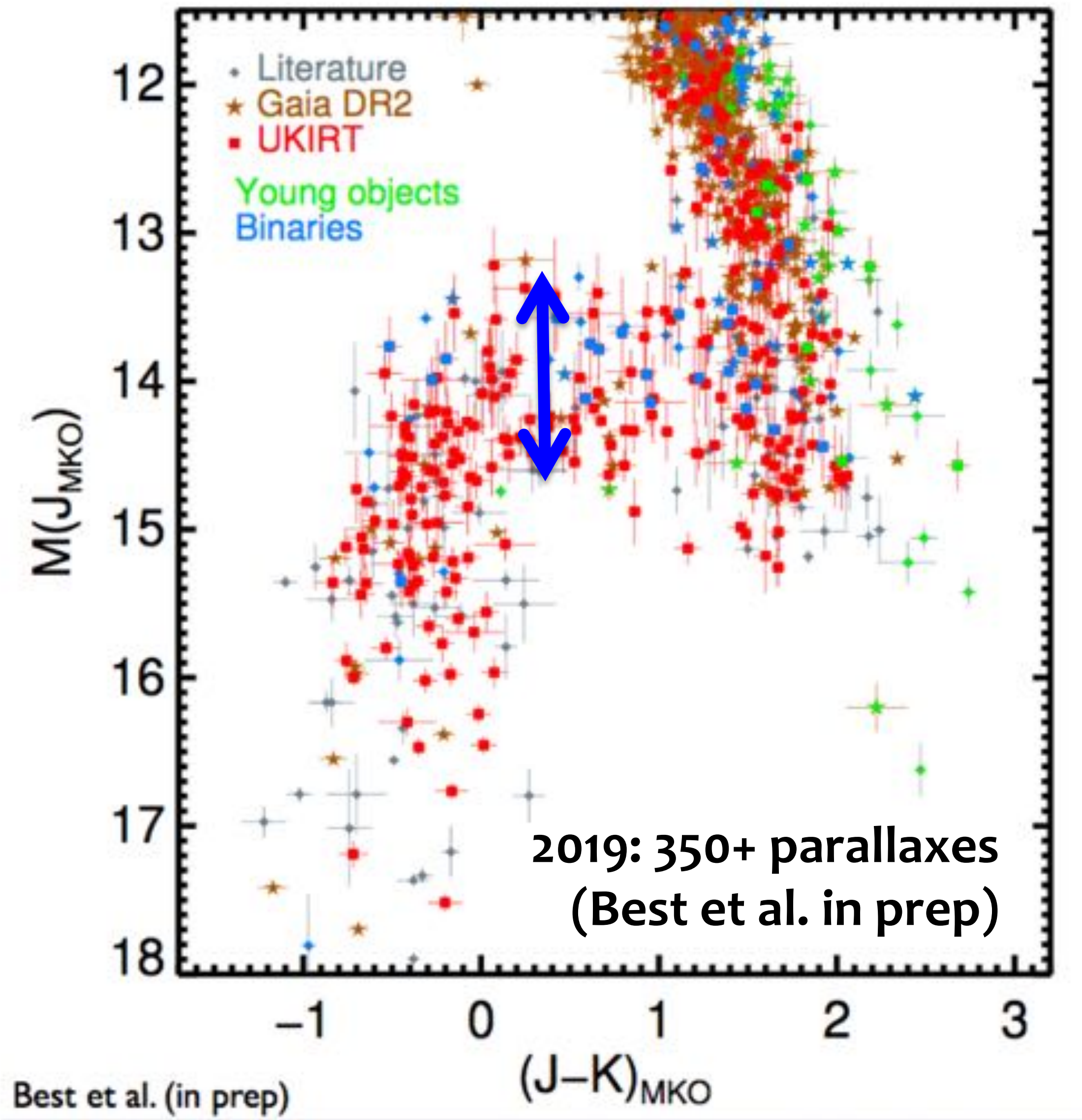
Monet et al. (1992);
Tinney et al. (1995,1996);
van Altena et al. (1995);
Dahn et al. (2002);
Tinney et al. (2003);
Vrba et al. (2004)

The J-band Bump...



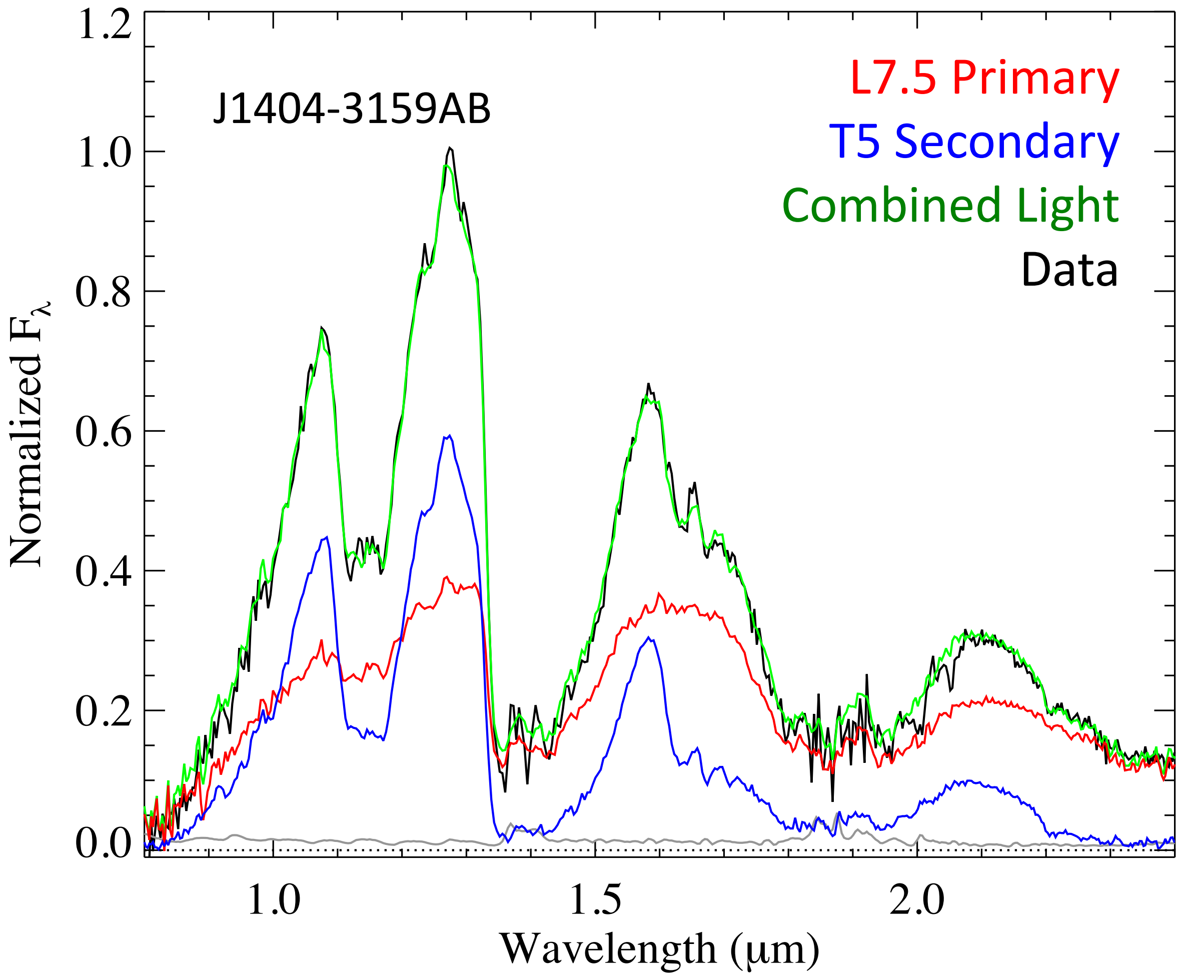
Monet et al. (1992);
Tinney et al. (1995,1996);
van Altena et al. (1995);
Dahn et al. (2002);
Tinney et al. (2003);
Vrba et al. (2004);
Costa et al. (2006);
Schilbach et al. (2009);
Marocco et al. (2010);
Riedel et al. (2010);
Andrei et al. (2011);
Dupuy & Liu (2012);
Faherty et al. (2012)

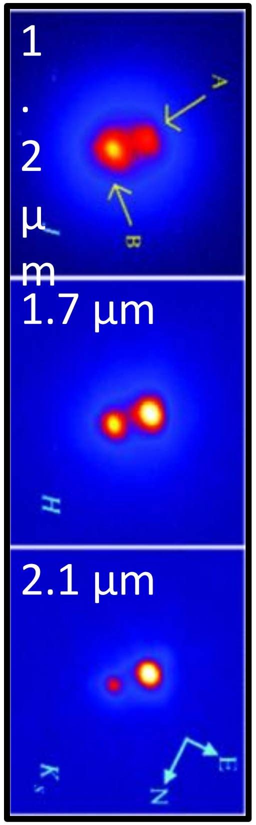
The J-band Bump…



≈1 mag scatter

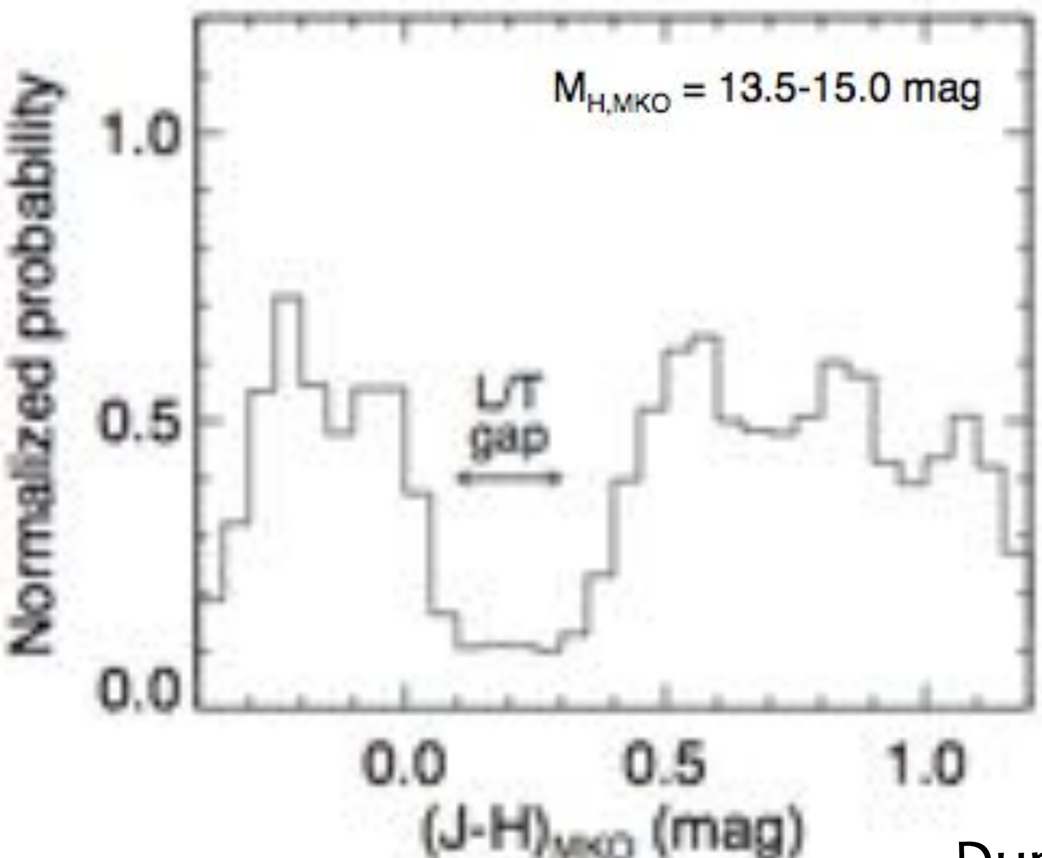
L/T transition binaries





Dupuy & Liu (2012); Looper et al. (2008);
Burgasser et al. (2010)

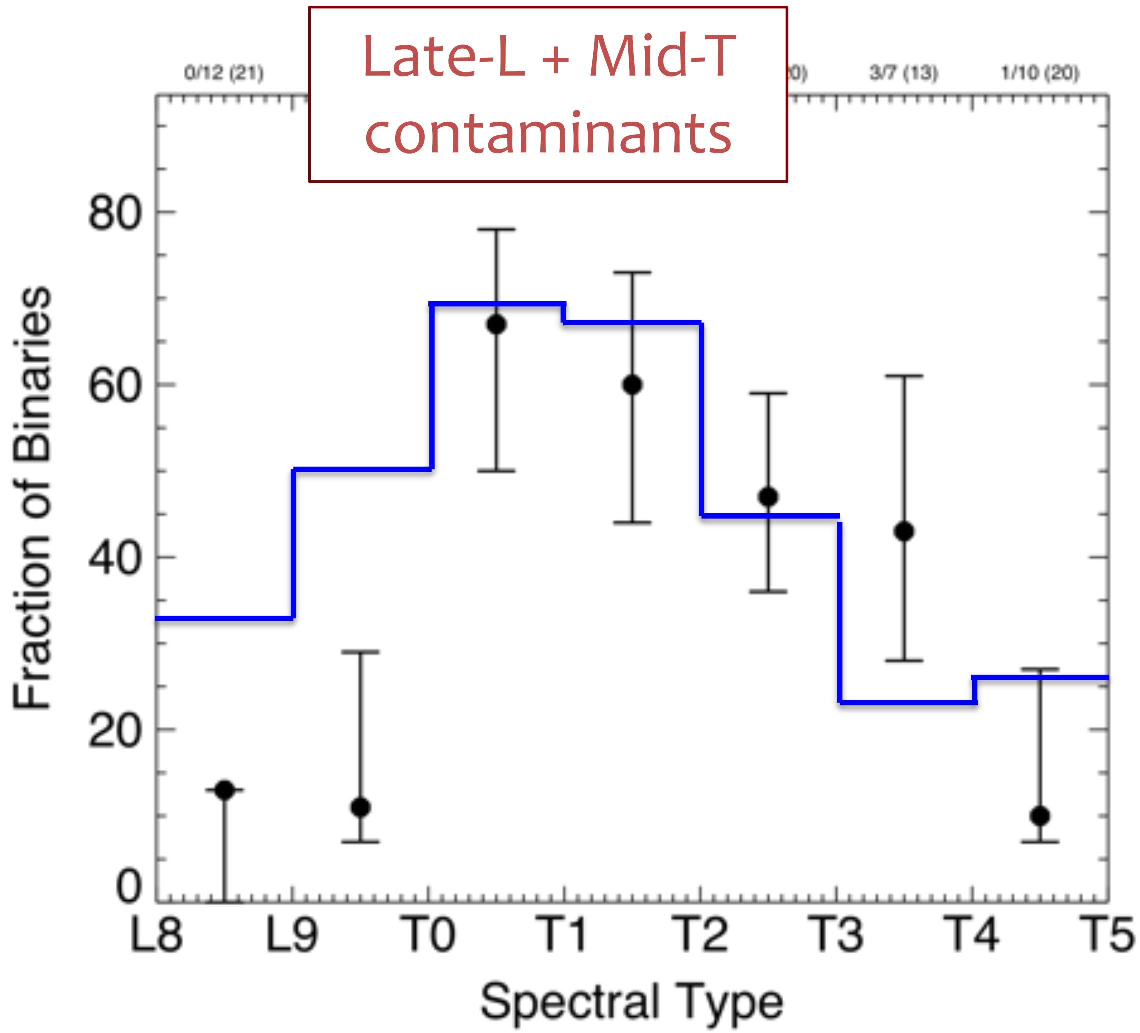
Evidence of rapid evolution



In both magnitude-limited and volume-limited surveys, early- to mid-T dwarfs appear to be rare

Dupuy & Liu (2012)

Evidence of rapid evolution

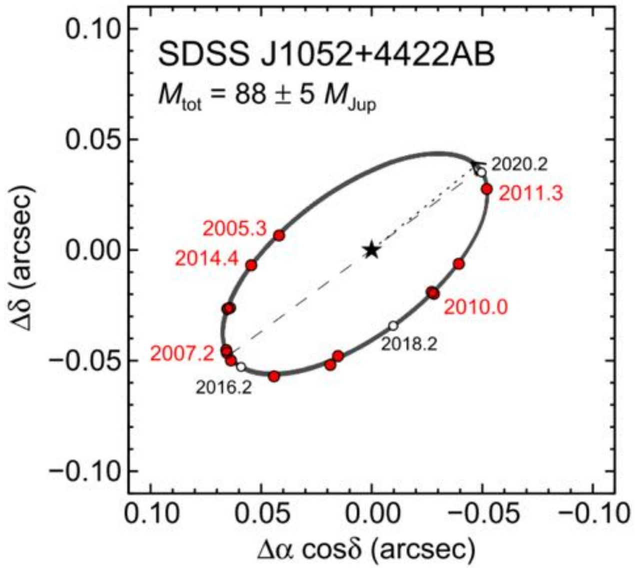


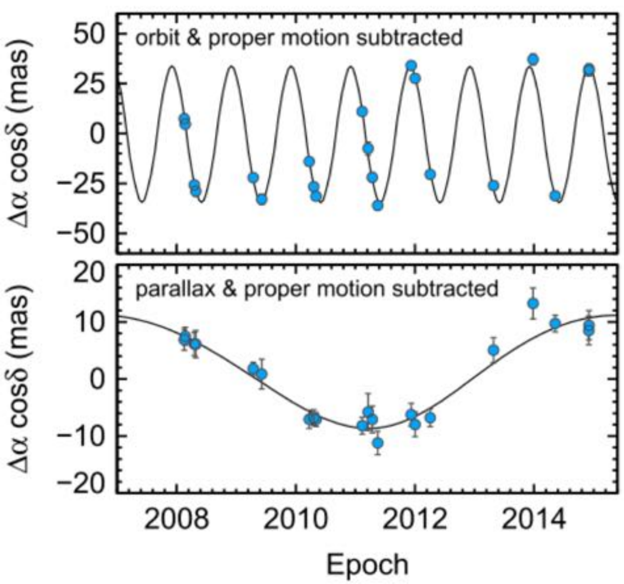
Observed binary fractions

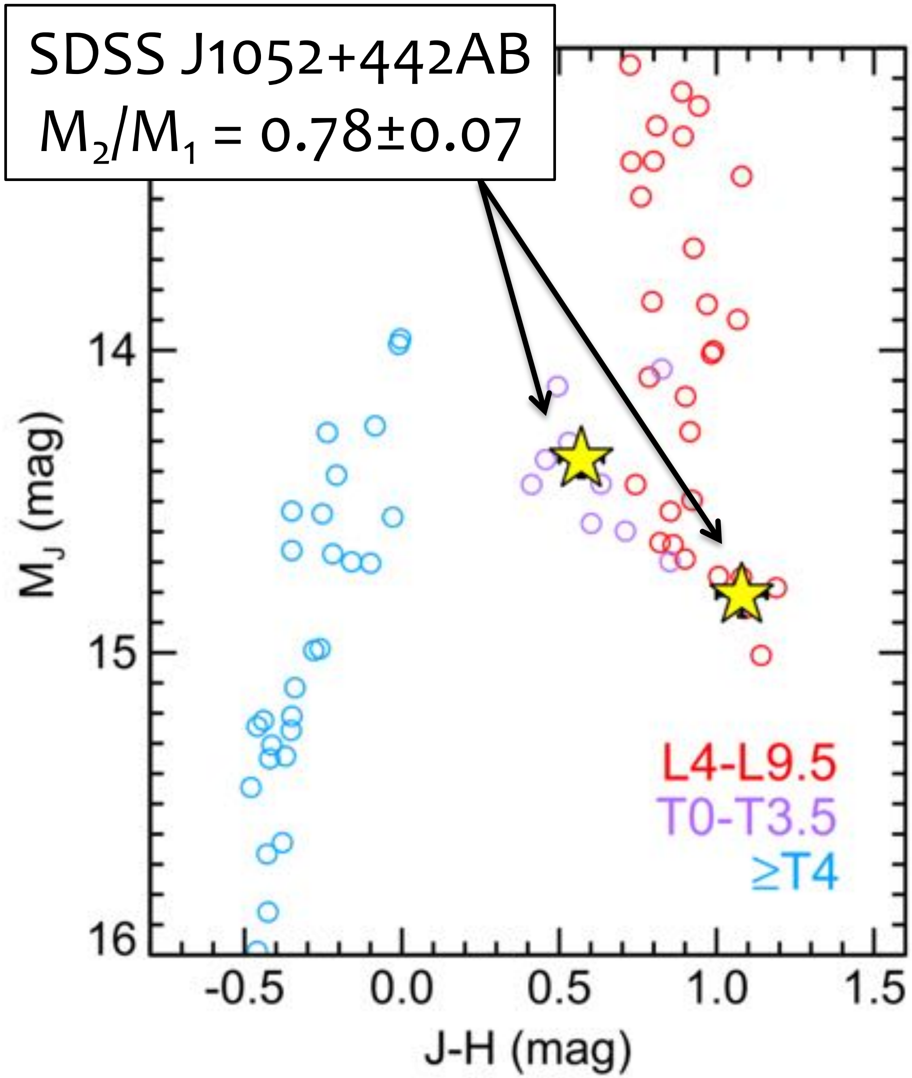
Simulation assuming BF = 15%

Burgasser (2007); Burgasser et al. (2010)

Evidence of rapid evolution

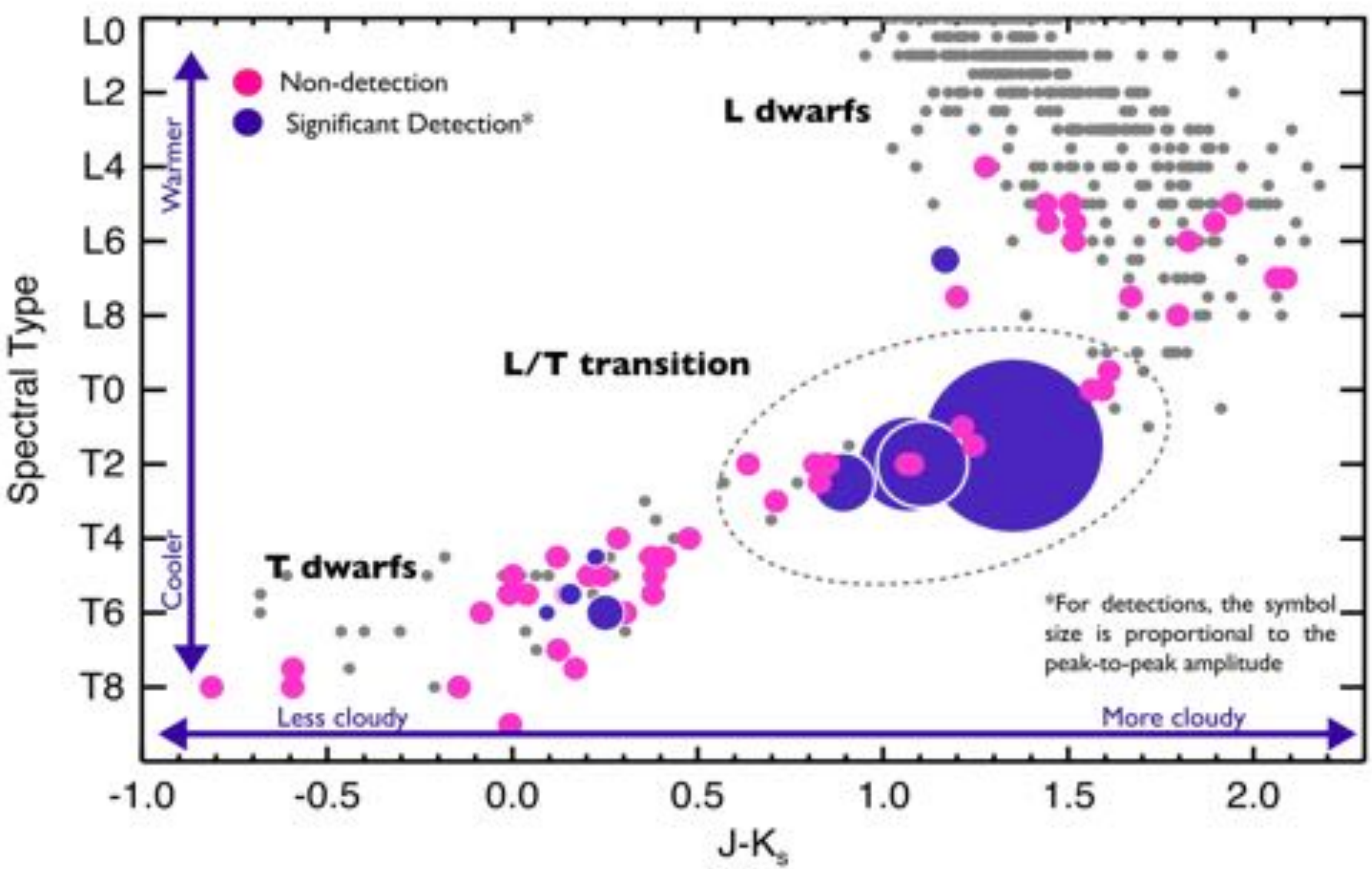






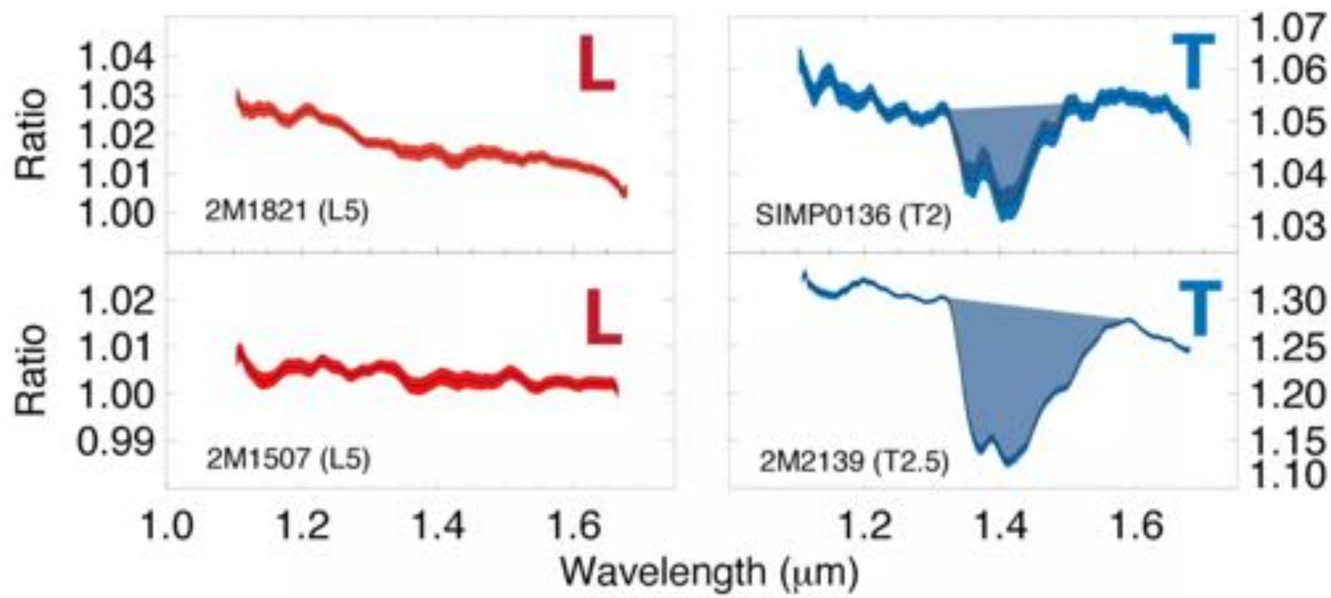
Dupuy et al. (2015)

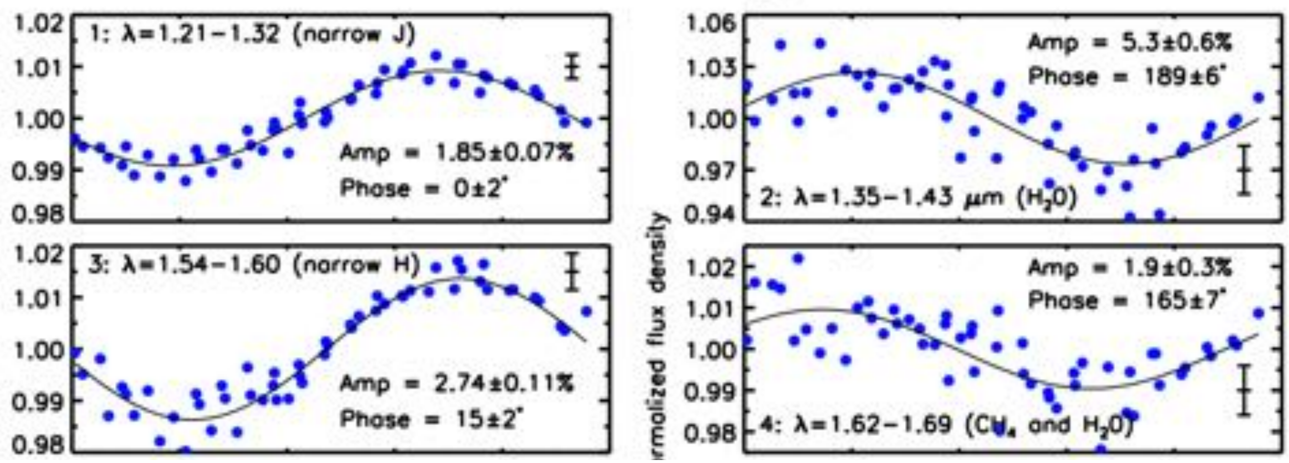
BD Variability is Common



Radigan et al. (2014)

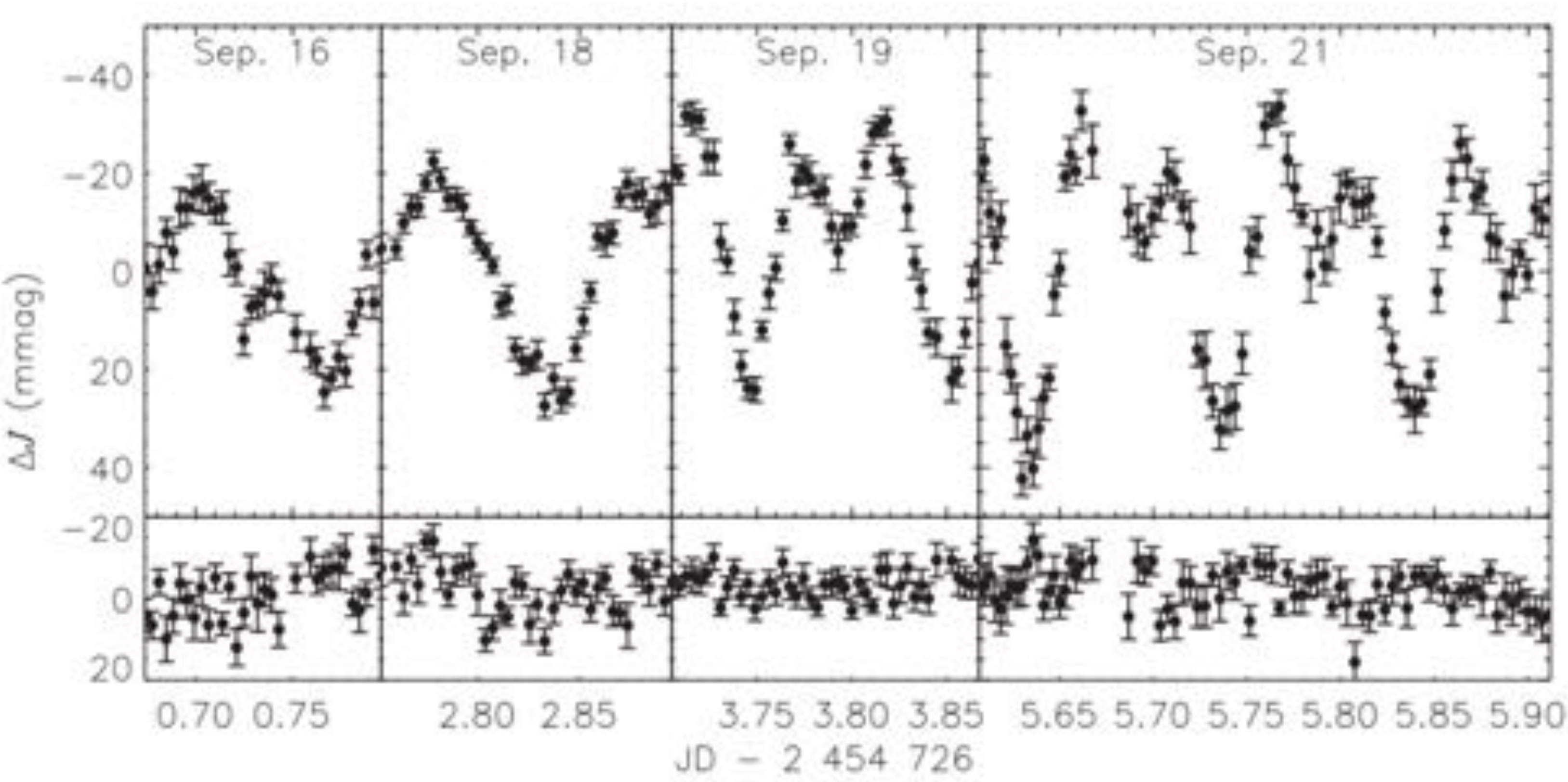
Variability amplitude & phase are wavelength dependent





Yang et al. (2015), Buenzli et al. (2013)

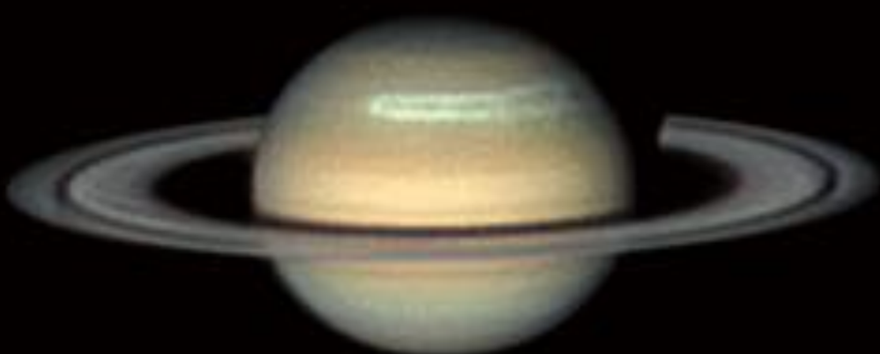
Variability can be very complex



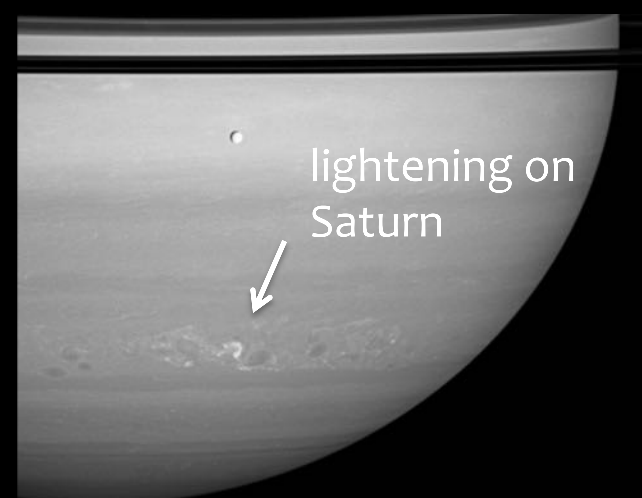
Artigau et al. (2009)

June 2009

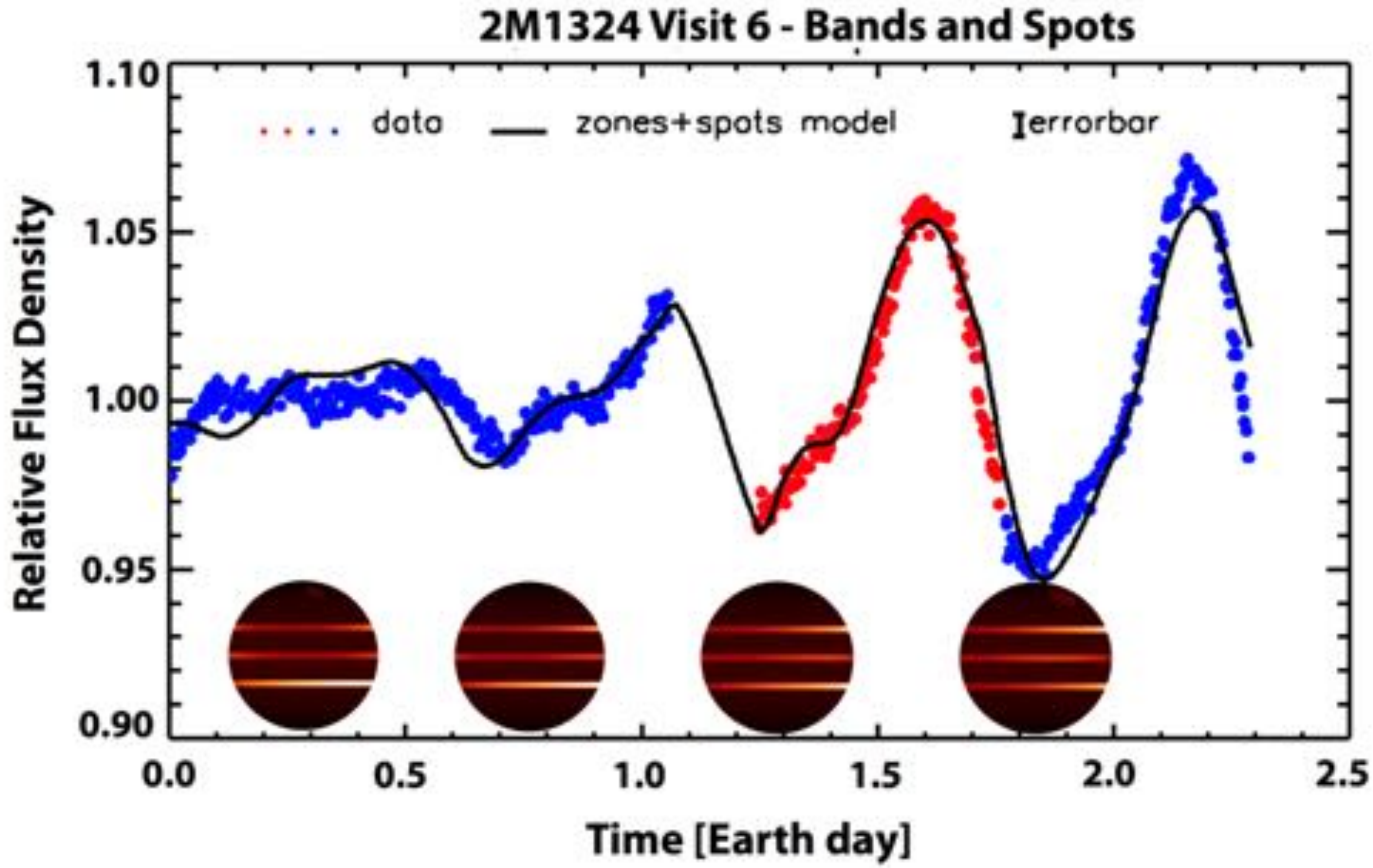
May 9, 2010

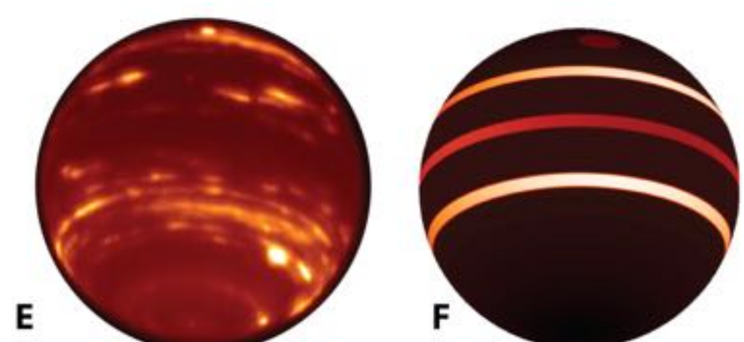


Saturn: NED
February 6, 2011
© Christopher Go (Cebu, Philippines)



images courtesy NASA



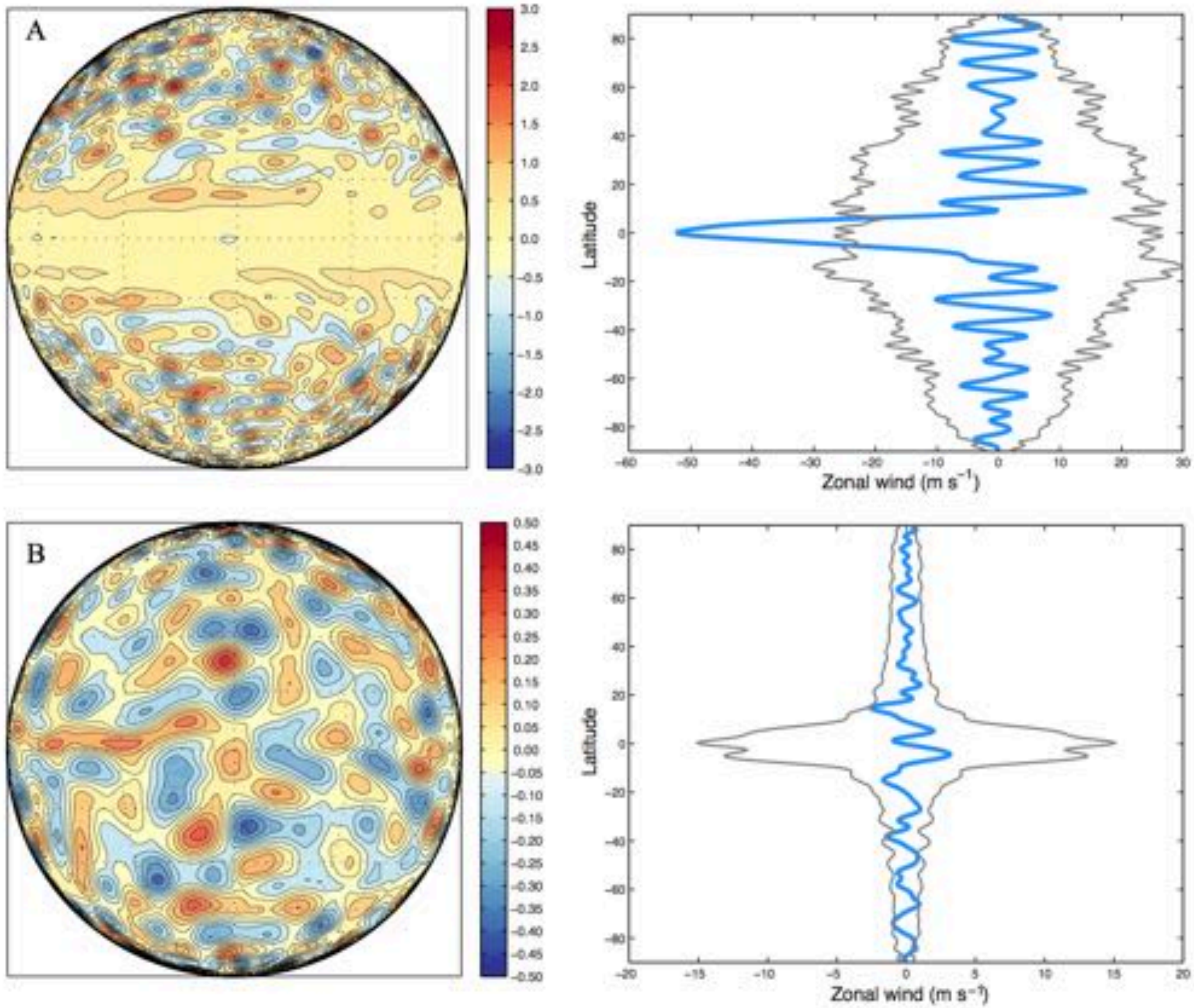


Neptune at 1.6 μm   Best-fitting model for 2M1324 Visit 6

Apai et al. (2017)

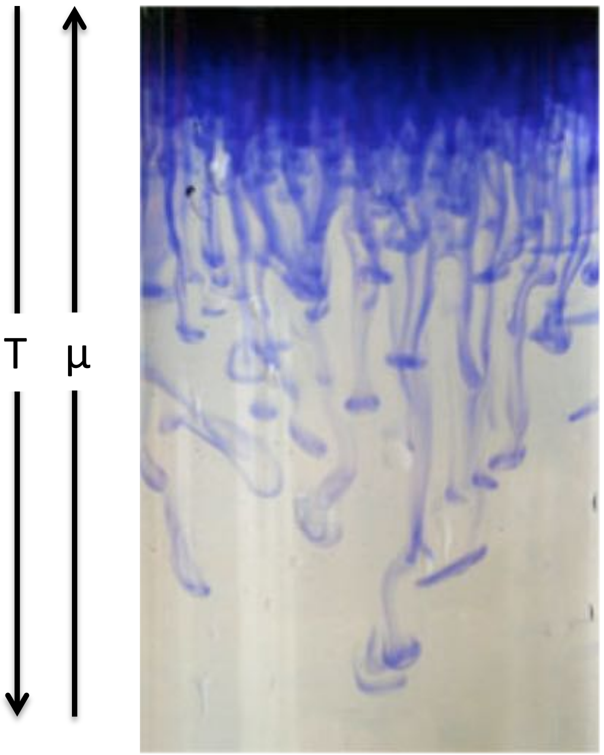
strong injection
weak dissipation

weak injection
strong dissipation



Zhang & Showman (2014)
Brown dwarf circulation models

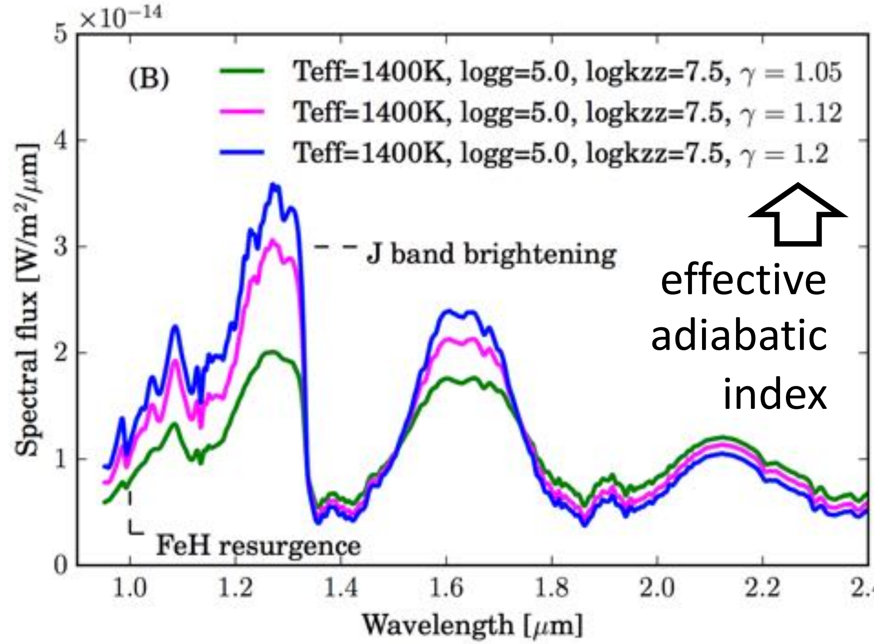
Fingering convection: no need for cloud opacity?

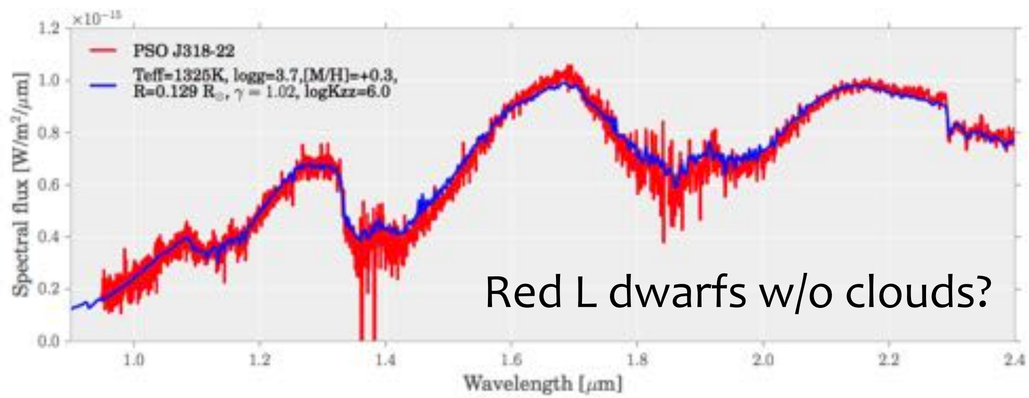


CH_4-rich
cool gas
high μ

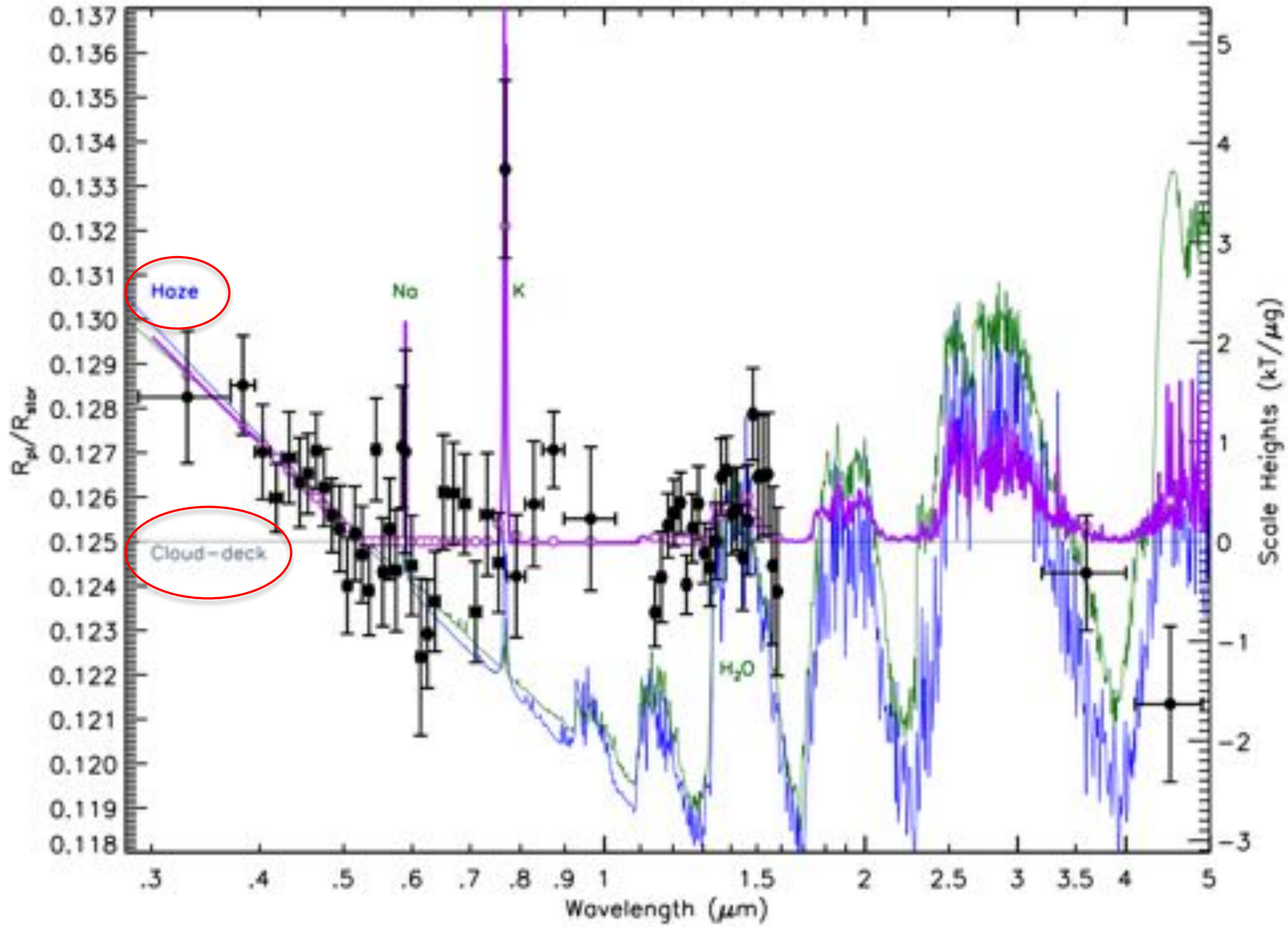
CO -rich
warm gas
low μ

Thermohaline instability
L->T: $CO + 3H_2 \rightarrow CH_4 + H_2O$



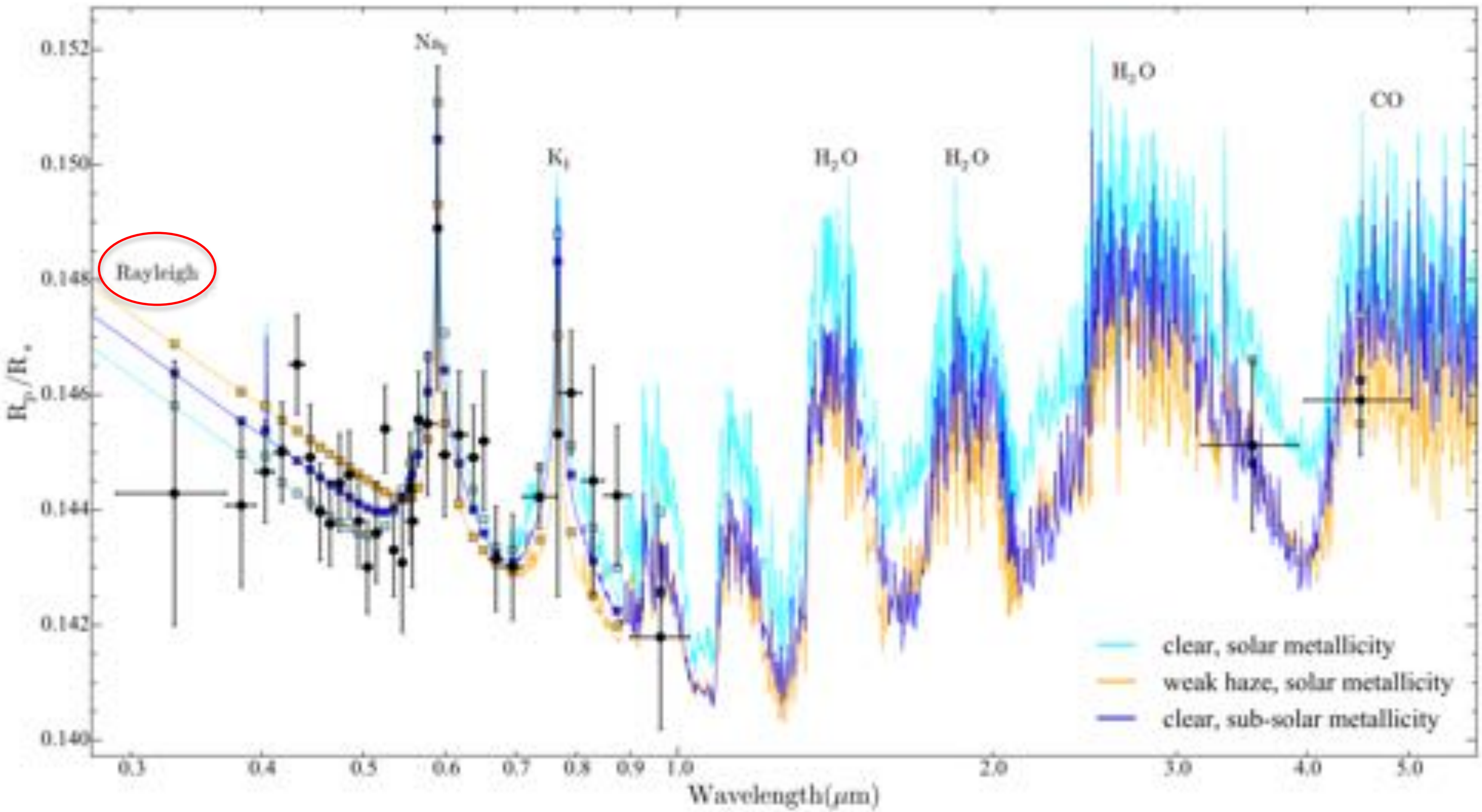


Tremblin et al.
(2015, 2016, 2017, 2019)



Sing et al. (2015)
Transmission spectra of WASP-31b ($T_{eq} \approx 1600$ K)

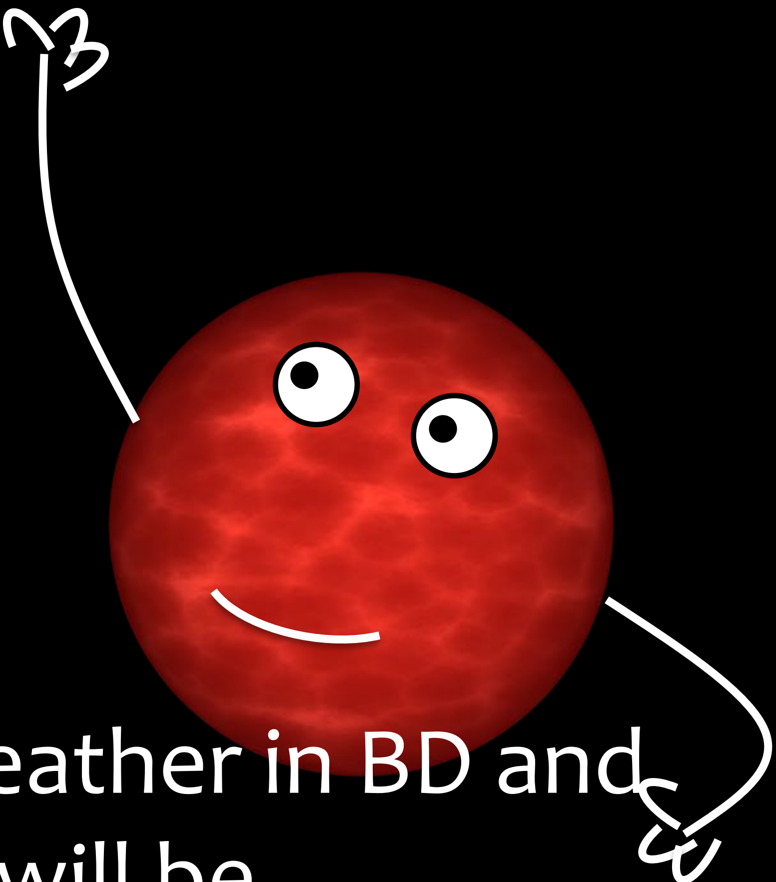
Haze & clouds



Fischer et al. (2016)

Transmission spectra of WASP-39b ($T_{eq} \approx 1100$ K)

Haze, but no clouds



Our understanding of weather in BD and exoplanet atmospheres will be dramatically improved with time domain data, but we need to resolve the issue of clouds vs. fluid instabilities.


$1B*
*0.18 US-Mexico border walls

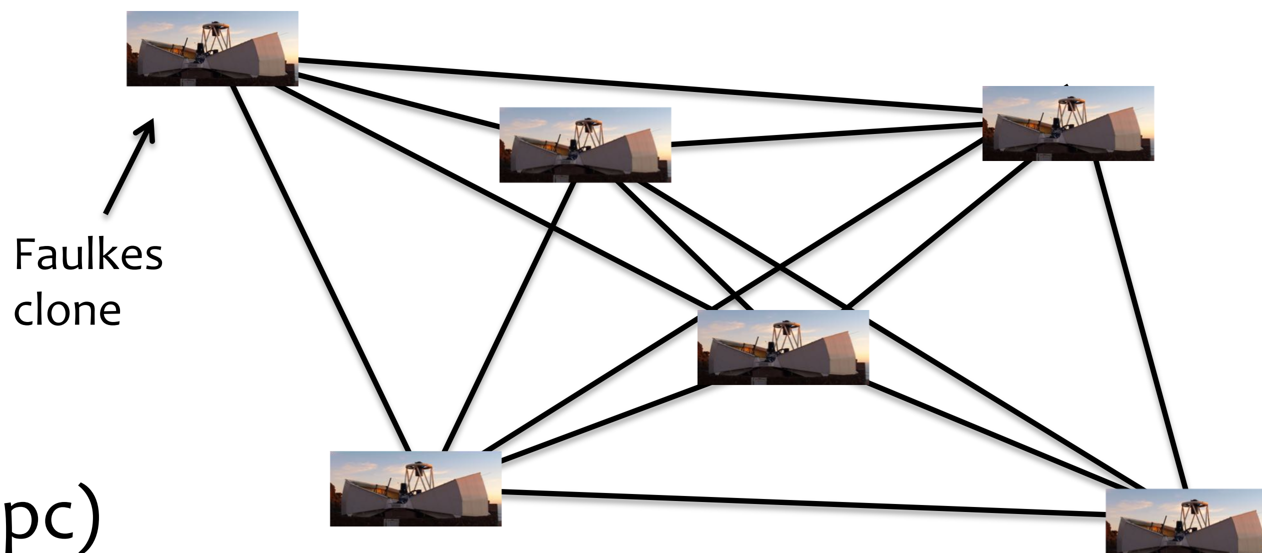
$1B*

$400M: Super CHARA Array

*0.18 US-Mexico border walls

CHARA
1m telescopes
max d = 330 m
H,K ≈ 9
θ(H) ≈ 500 μarc
(R = 0.1$R_\odot$ @ 2 pc)

Super-CHARA
2m telescopes
max d = 3 km
J,H,K ≈ 11-12
θ(J) ≈ 40 μarc
(R = 0.1$R_\odot$ @ 25 pc)



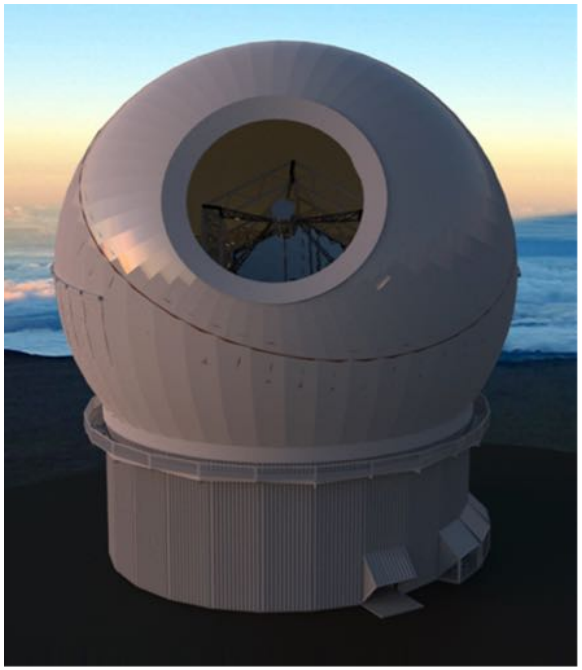
$1B*

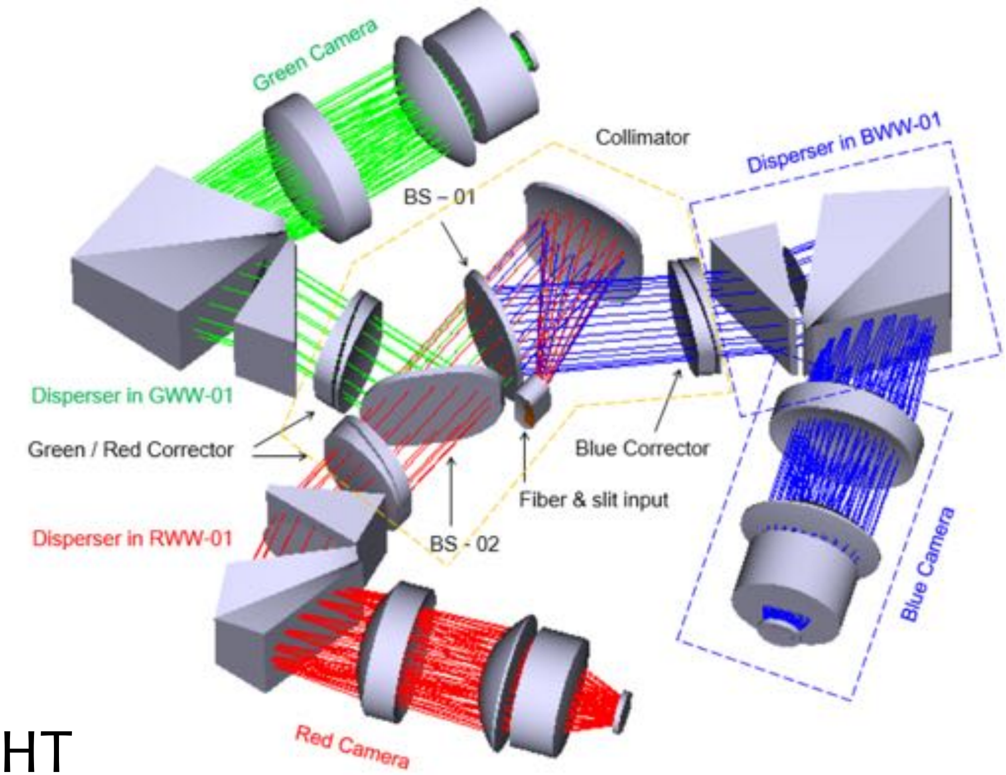
$400M: Super CHARA Array

$400M: Mauna Kea Spectroscopic Explorer

*0.18 US-Mexico border walls

Mauna Kea Spectroscopic Explorer





10.2m Replacement for CFHT
Dedicated multi-fiber, multi-wavelength, multi-resolution spectrograph
0.36 μm ≤ λ ≤ 1.85 μm, 3000 < R < 40,000
7500 simultaneous spectra over 1.52 sq deg FOV

$1B*

$400M: Super CHARA Array

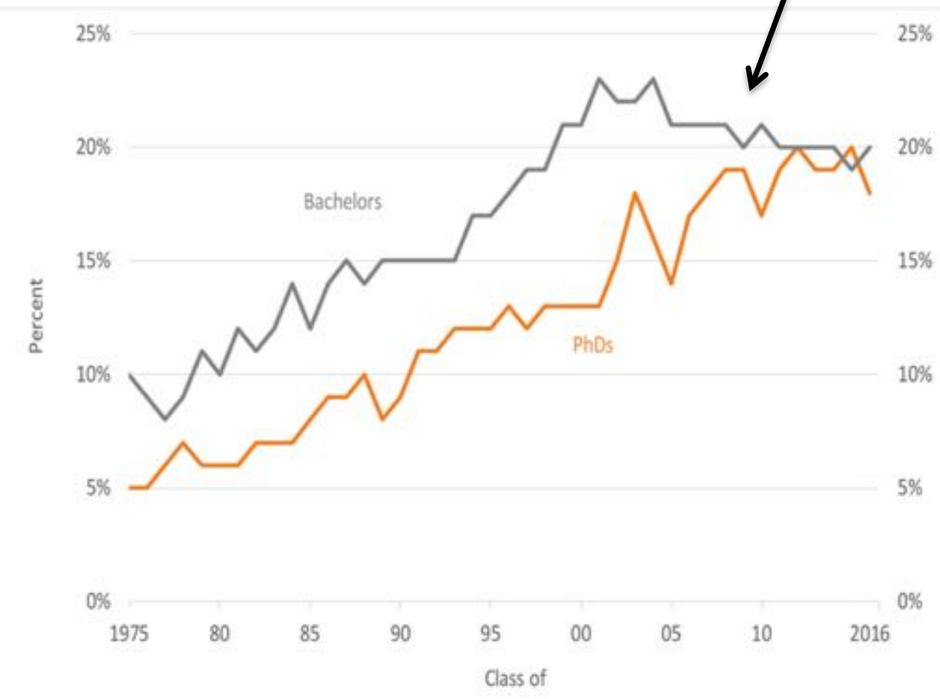
$400M: Mauna Kea Spectroscopic Explorer

$100M: Build/expand/sustain programs that support minorities/women in Ast/Phys

*0.18 US-Mexico border walls

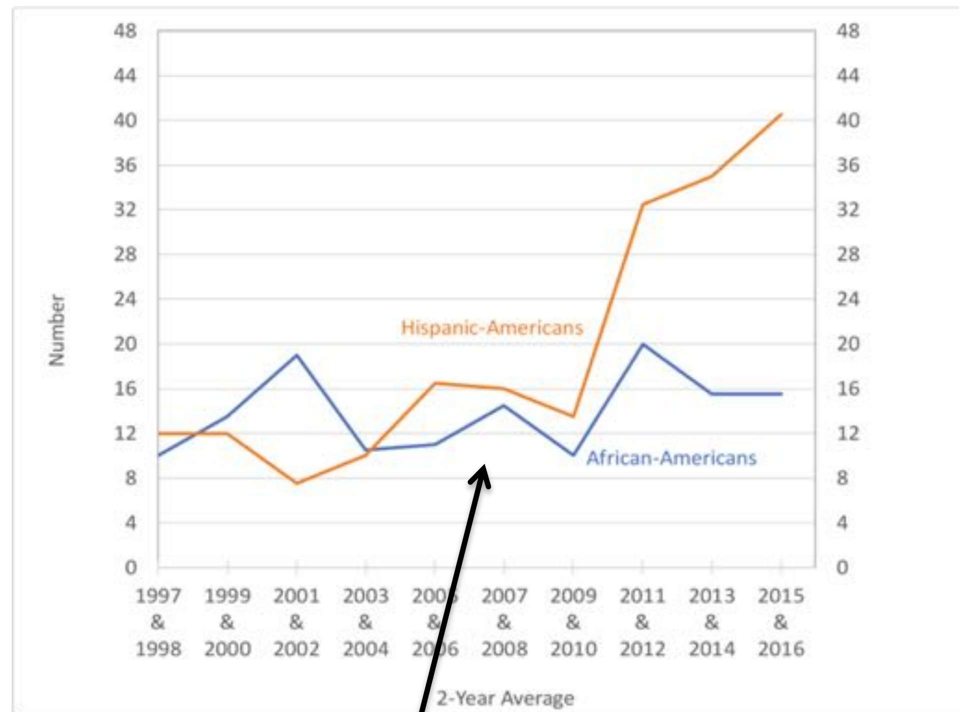
20 year decline in fraction of US women's Physics Bachelors

Percent of Physics Bachelors and PhDs Earned by Women, Classes of 1975 through 2016.



AIP | Statistics aip.org/statistics

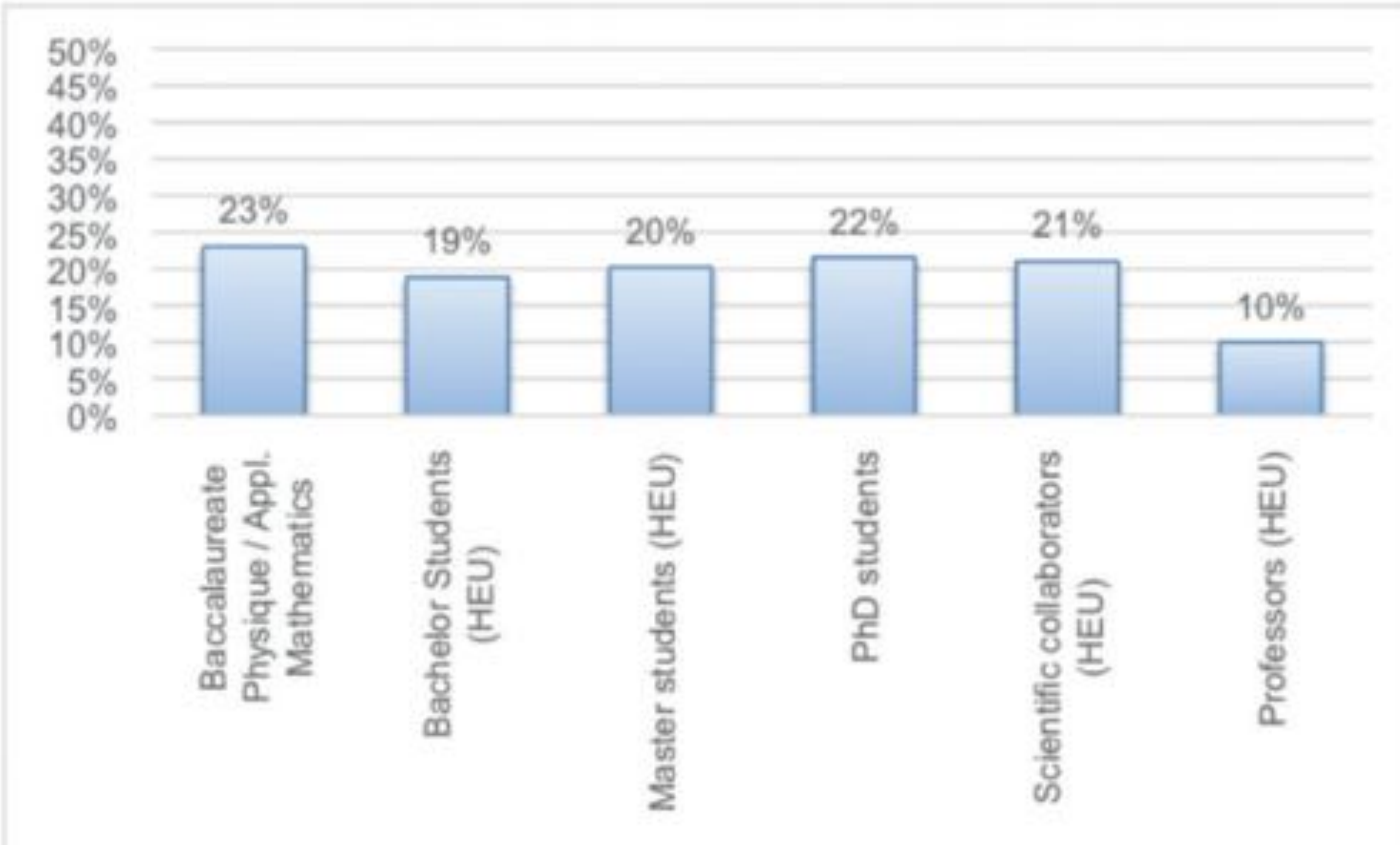
Number of Physics Doctorates Earned by African-Americans and Hispanic-Americans, Classes 1997 through 2016.



AIP | Statistics aip.org/statistics

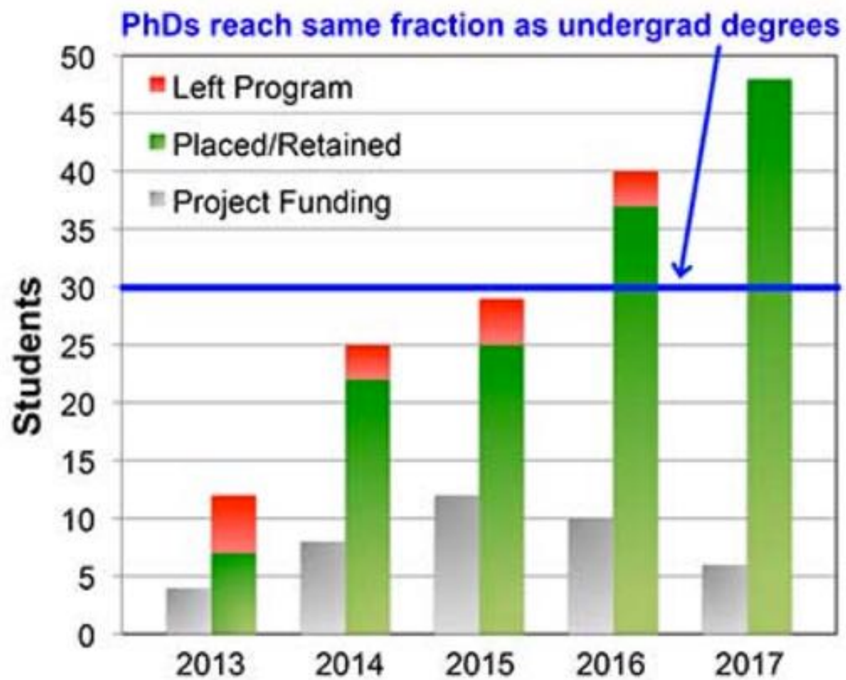
20-year stagnation in number of African American PhDs in Physics

Not much different in Switzerland



Fuger et al. (2017)

Programs that Work



APS Bridge Program

Cal-Bridge

A CSU-UC bridge program in Physics and Astronomy

BANNEKER • AZTLÁN INSTITUTE

$1B*

$400M: Super CHARA Array

$400M: Mauna Kea Spectroscopic Explorer

$100M: Build/expand/sustain programs that support minorities/women in Ast/Phys

$100M: astropy

*0.18 US-Mexico border walls


Thank you!