Spectral Classification of Brown Dwarfs Across the Full Metallicity Range

Zenghua Zhang
Nanjing University
zz@nju.edu.cn

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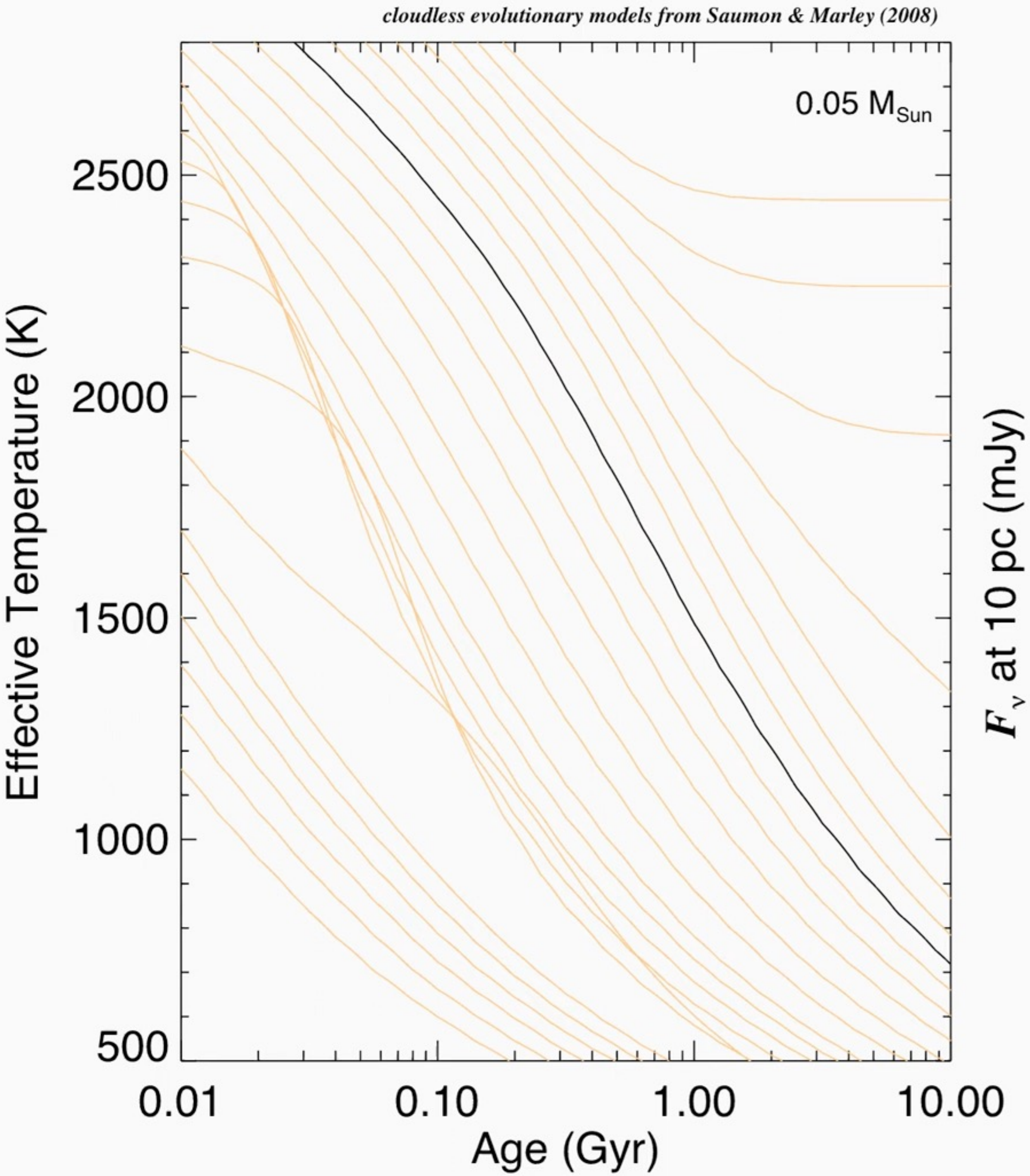
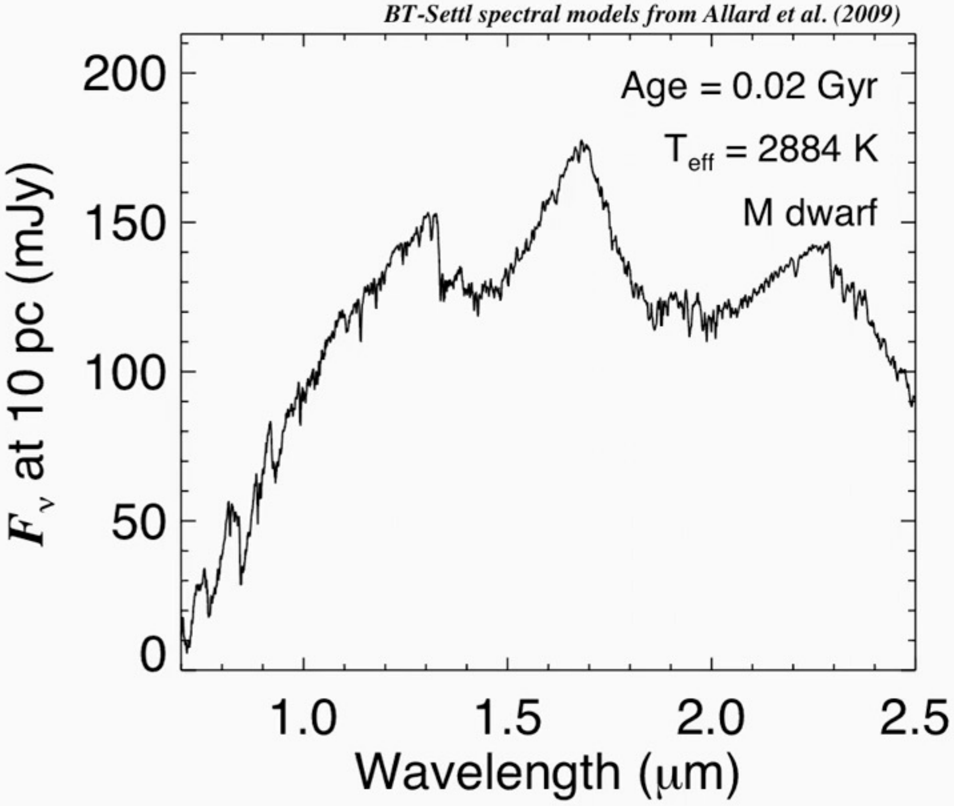
Outline

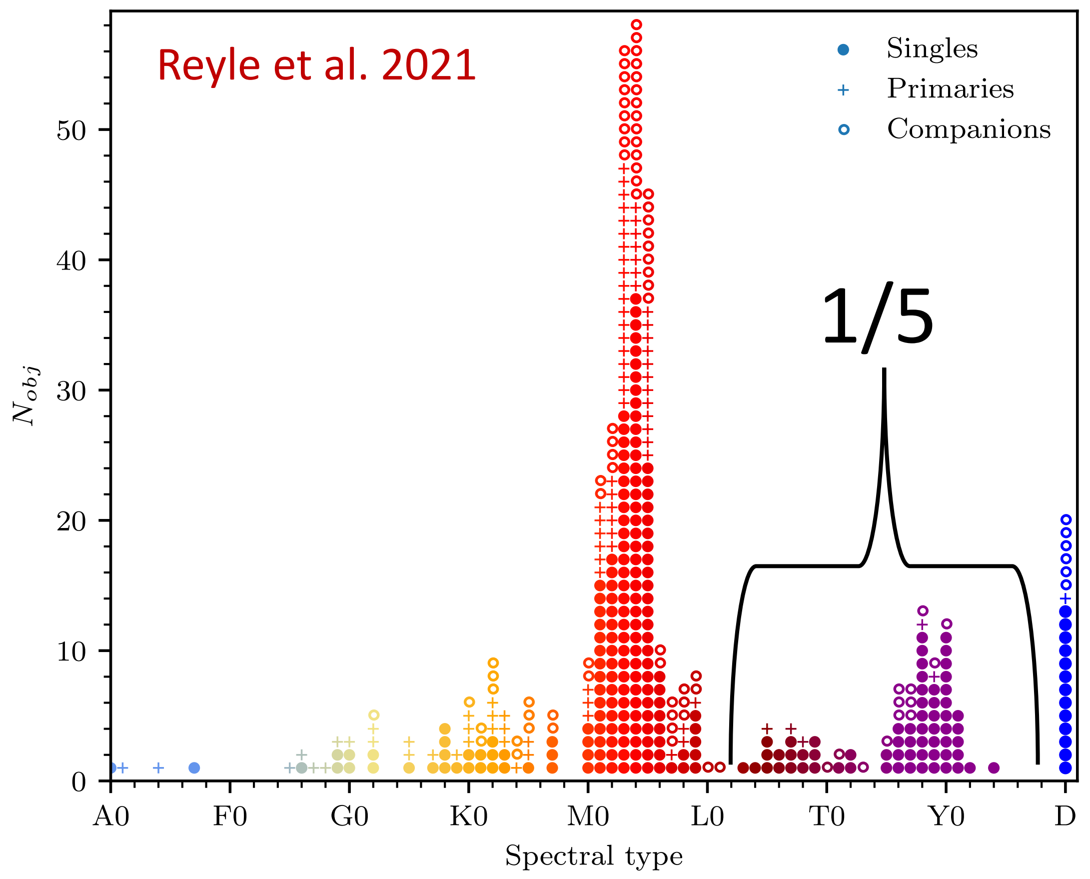
- Spectral classes of brown dwarfs
- Lessions from M subdwarf classification
- L (sub)dwarf classification and physical properties
- T (sub)dwarf observation and classification


cloudless evolutionary models from Saumon & Marley (2008)
0.05 M_Sun
Effective Temperature (K)
2500
2000
1500
1000
500
0.01
0.10
1.00
10.00
Age (Gyr)


BT-Settl spectral models from Allard et al. (2009)
Age = 0.02 Gyr
T_eff = 2884 K
M dwarf
F_ν at 10 pc (mJy)
200
150
100
50
0
1.0
1.5
2.0
2.5
Wavelength (μm)

Spectral classes of brown dwarfs

M: CaH, TiO.
(Bessell 1991; Kirkpatrick et al. 1991)
L: Alkali lines, Oxide, Hydride (FeH).
(Kirkpatrick et al. 1999; Martin et al. 1999)
T: Methane (CH4), Water, broad potassium (KI).
(Burgasser+2002,2003)
Y: Ammonia (NH3).
(Cushing et al. 2011; Kirkpatrick et al. 2012)



Oh, Be A Fine Girl/Guy Kiss My Lips Tonight, Yahoo!

Star (4/5)

BD (1/5)

M subdwarf classification

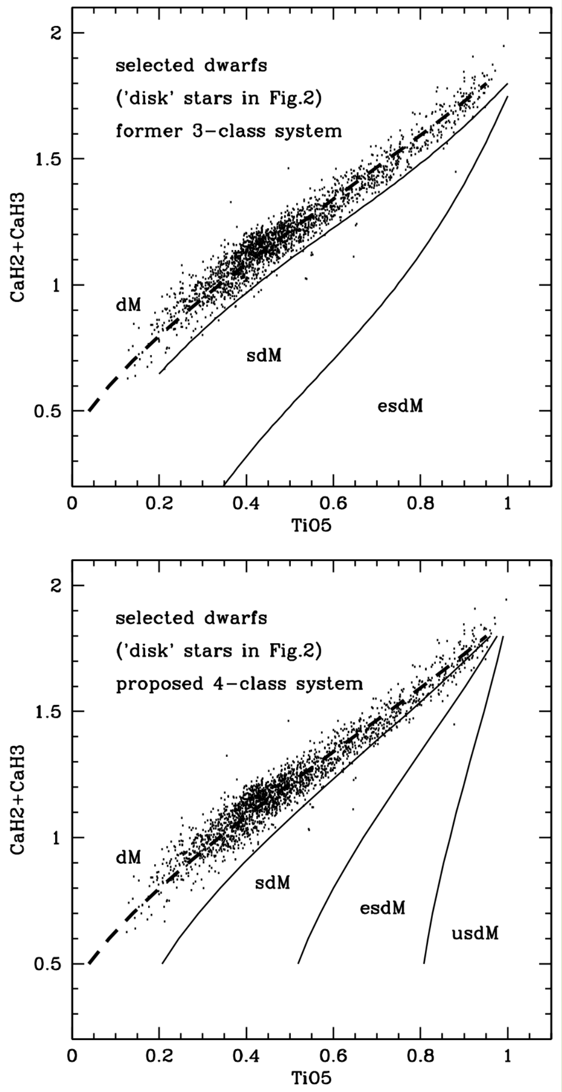
Gizis 1997;
Lepine et al. 2007, 2013
Dhital et al. 2012
Zhang, S. et al. 1019

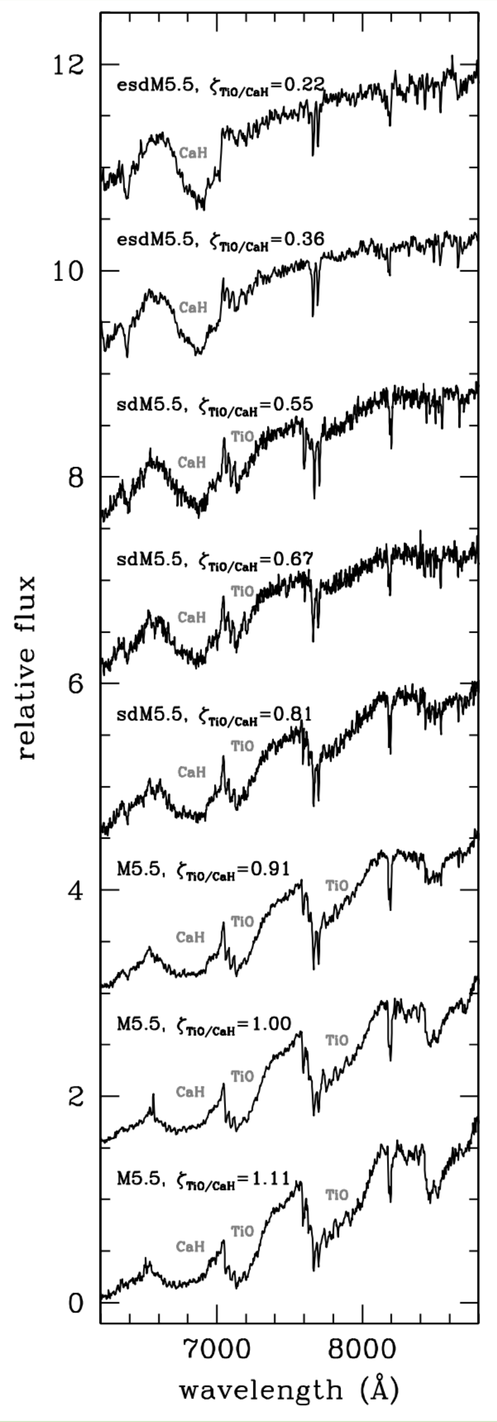
Metalicity subclasses:

1. Dwarf (dM)
2. Subdwarf (sdM)
3. Extreme subdwarf (esdM)
4. Ultra subdwarf (usdM)

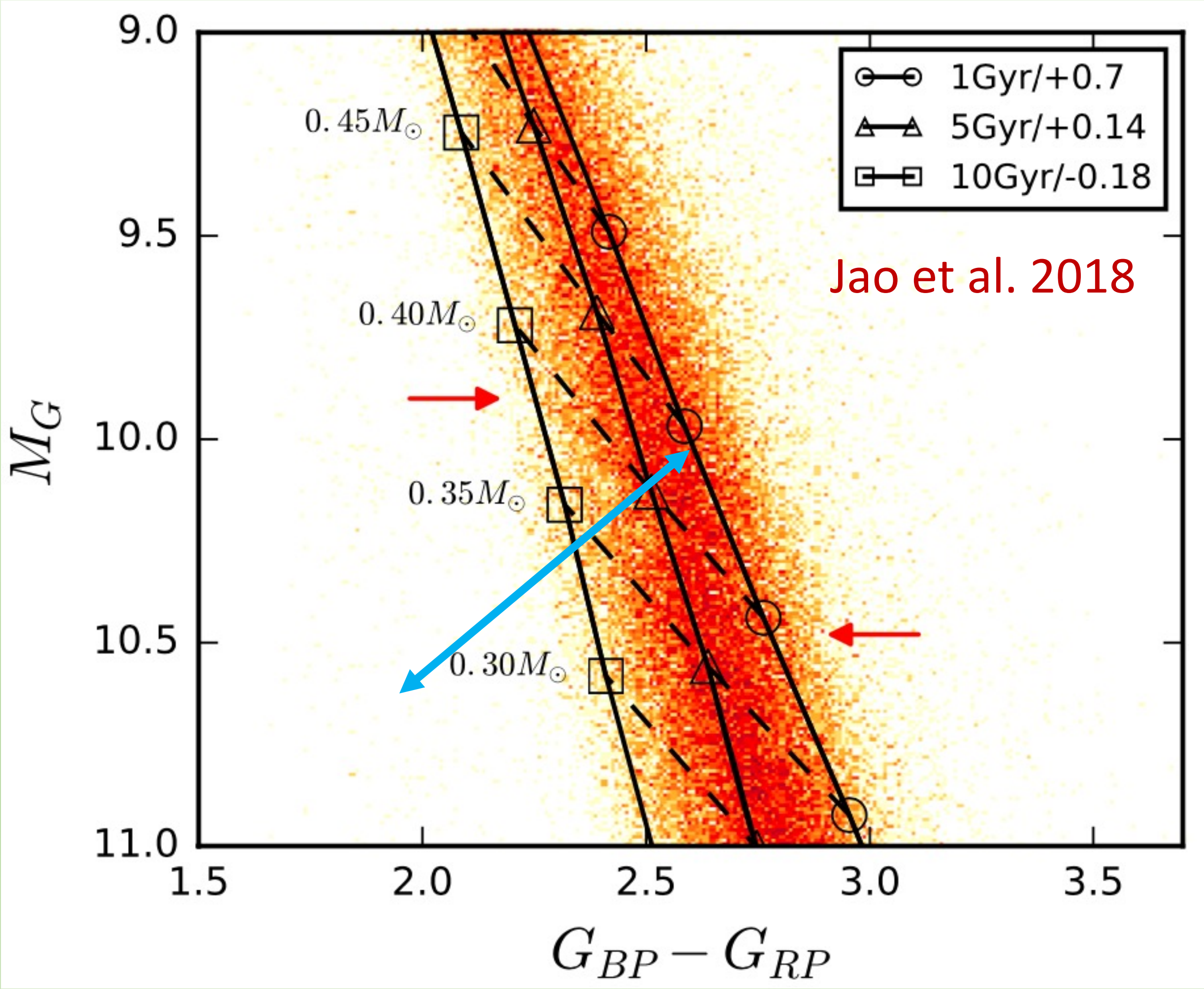
M1.0VI, m------, g++++

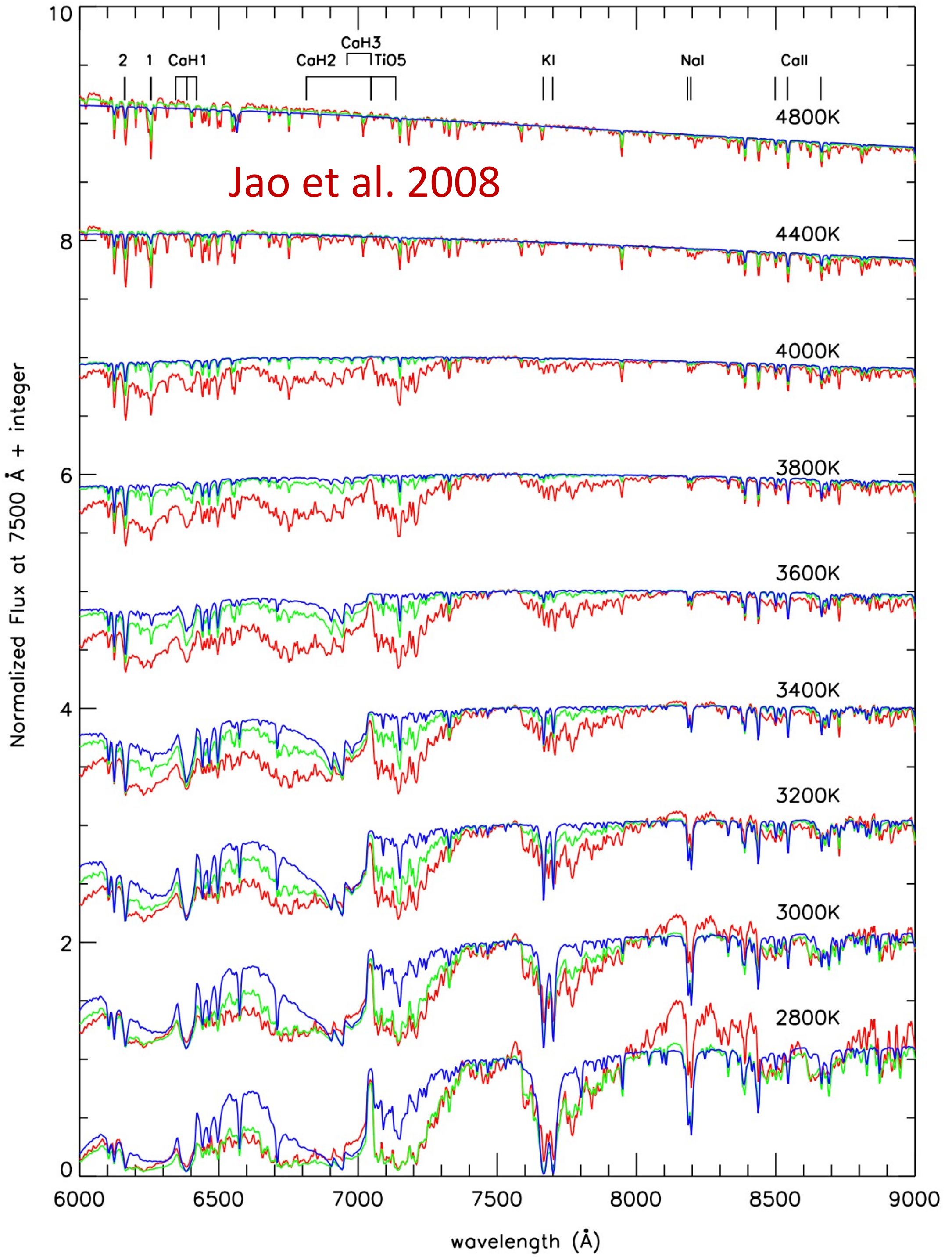
Jao et al. 2008



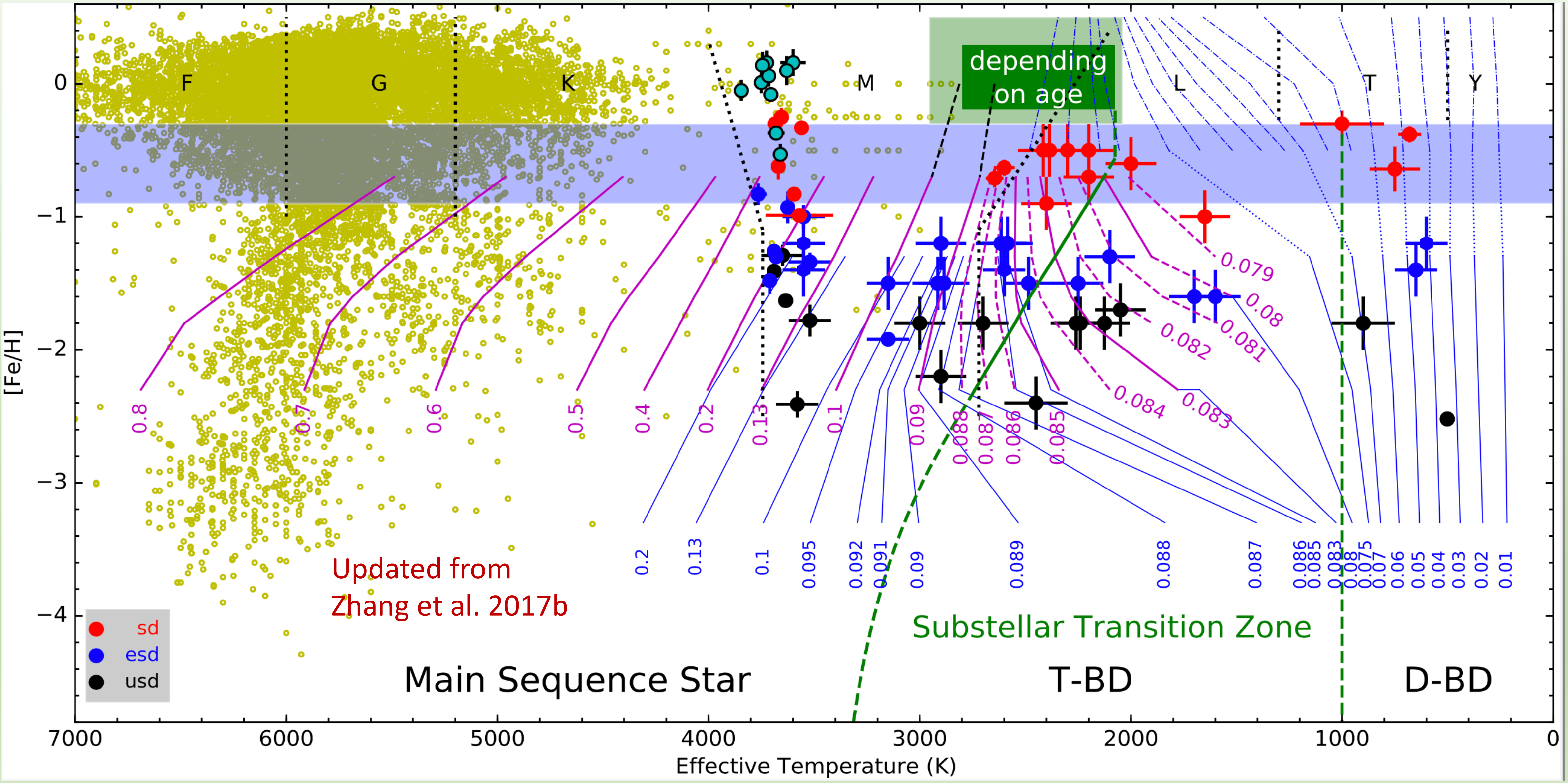


CaH and TiO in M dwarfs affected by [Fe/H] and T_{eff}

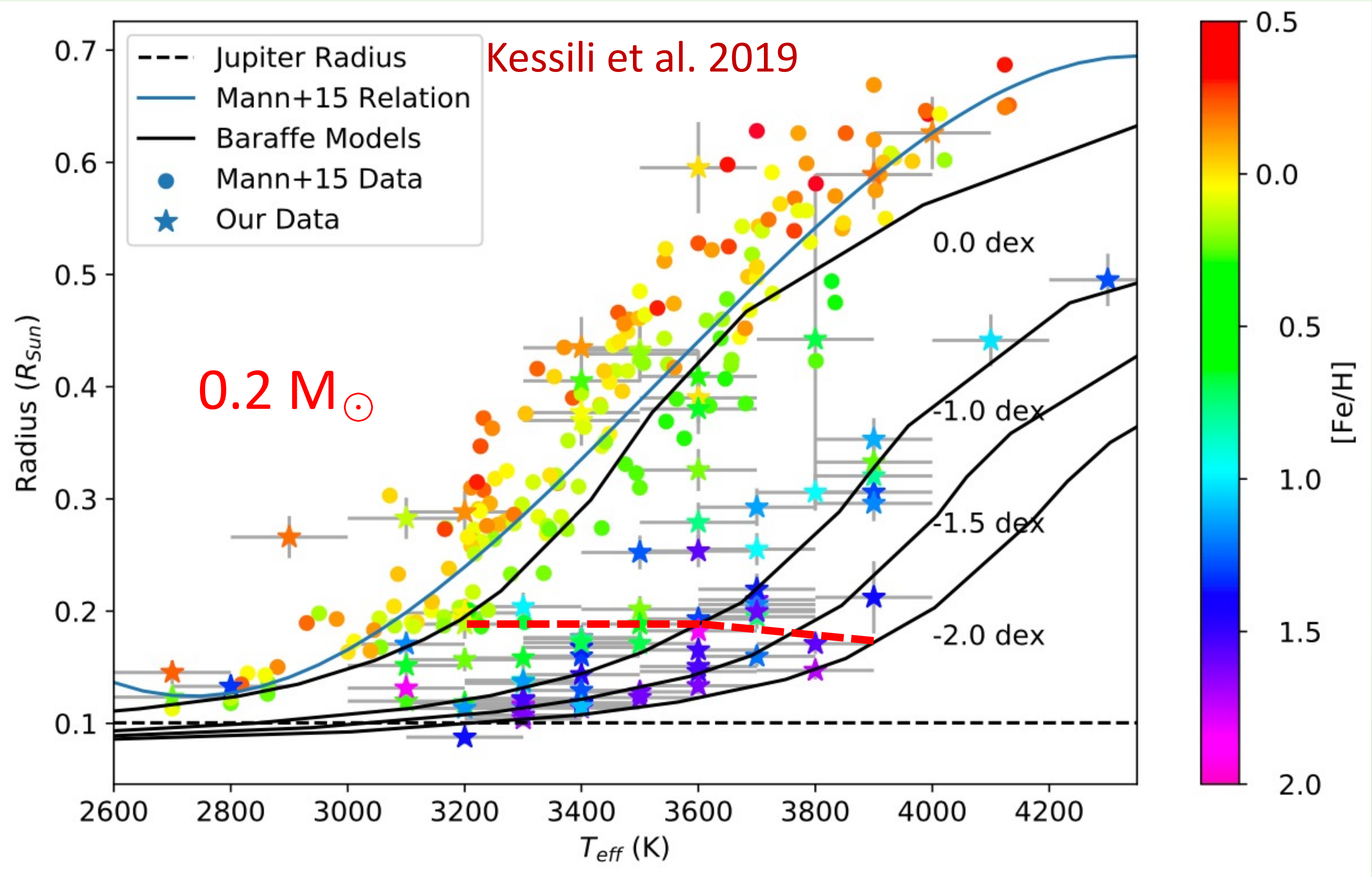


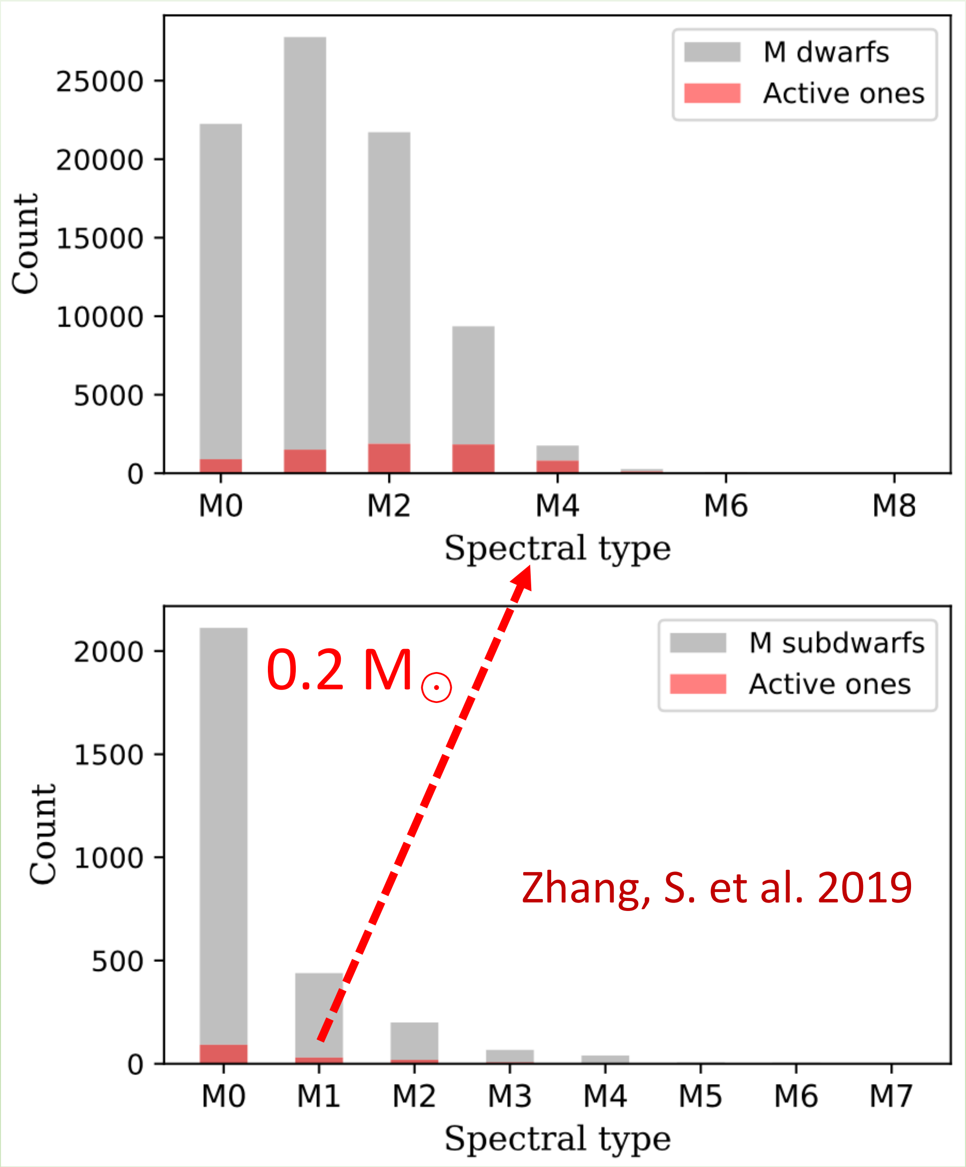


Challenges from M subdwarfs: Misaligned Mass

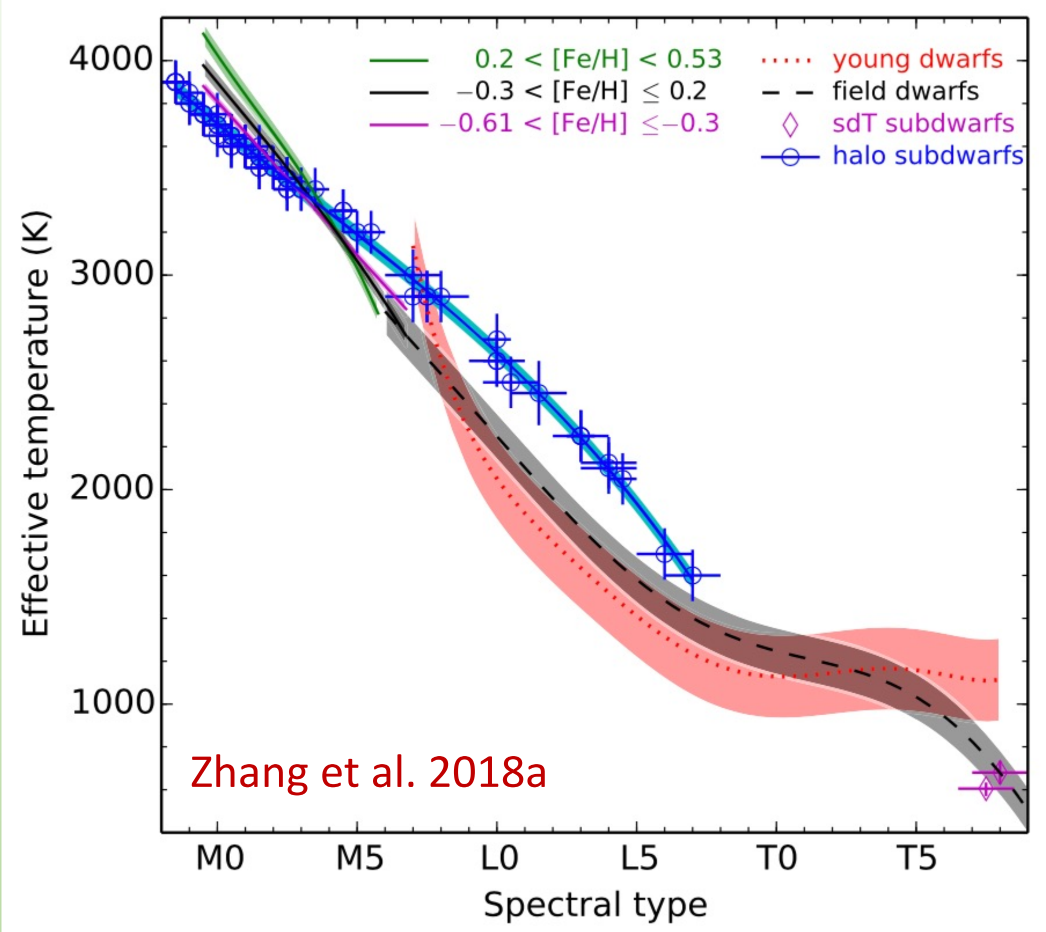


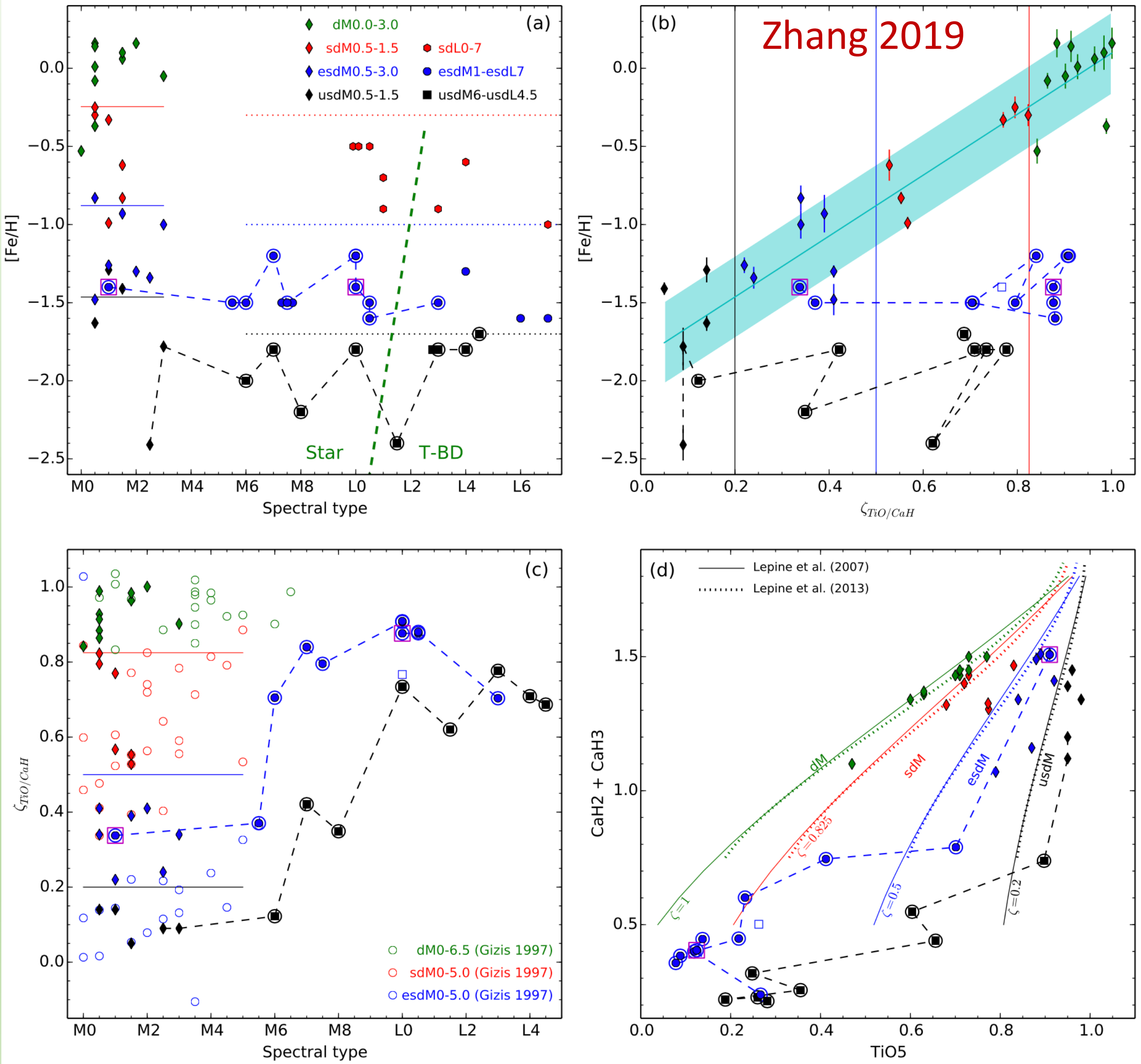
Missunderstanding for radius and activeity





Challenges from M subdwarfs: Inconsistent Metallicity





The zeta index ($\zeta_{TiO/CaH}$) is valid until esdM5.5/usdM6

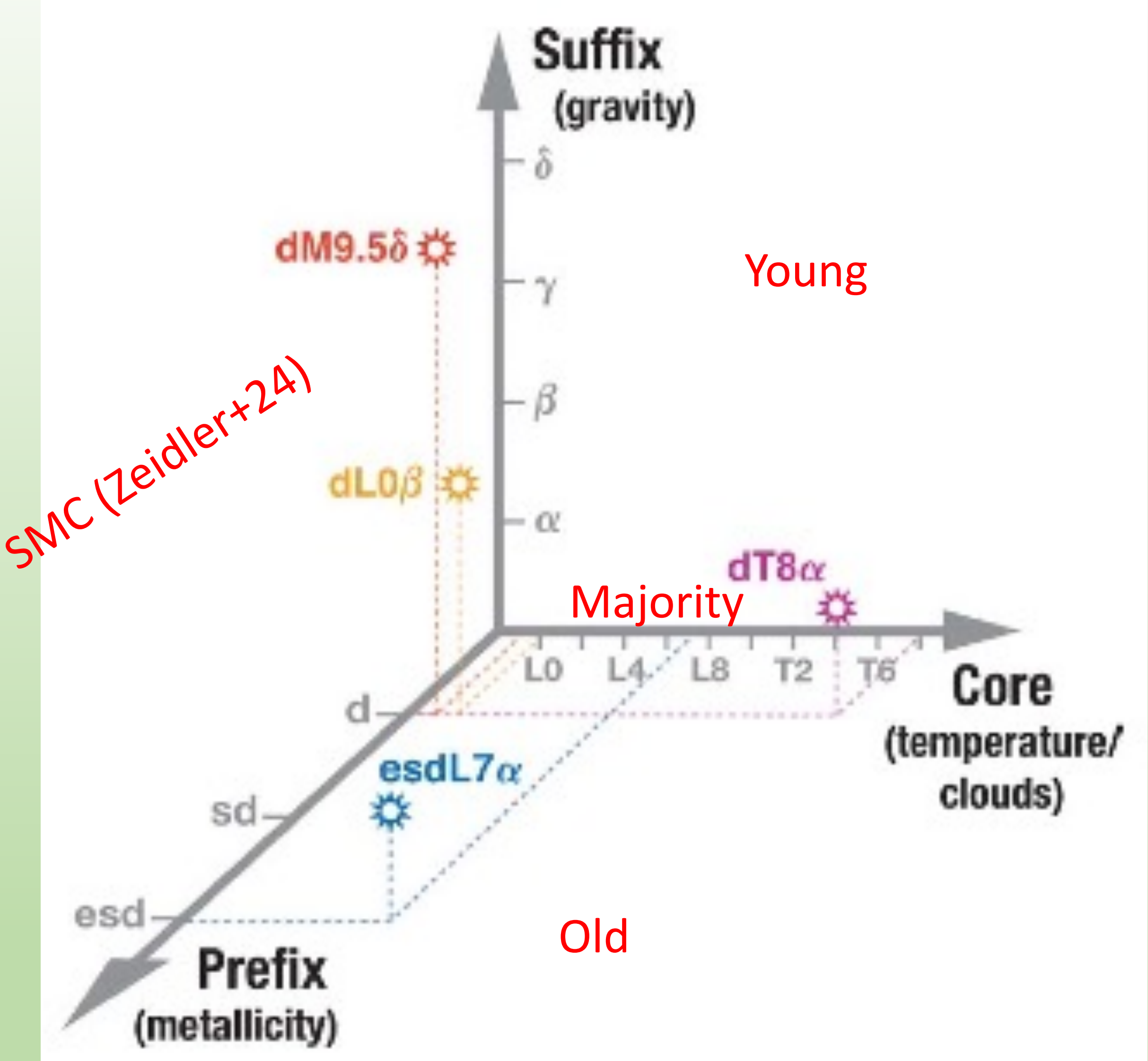
L (sub)dwarf observation and classification

- L dwarf spectrum (GD 165 B; Kirkpatrick et al. 1993)
- L type brown dwarf (Kelu-1 AB, Ruiz et al. 1997)
- L dwarf classification scheme (Kirkpatrick et al. 1999; Martin et al. 1999)
- L subdwarf (2MASS J05325346+8246465, Burgasser et al. 2003)
- L subdwarf classification (Burgasser et al. 2007; Kirkpatrick et al. 2010; Zhang et al. 2017a)

Spectral classification

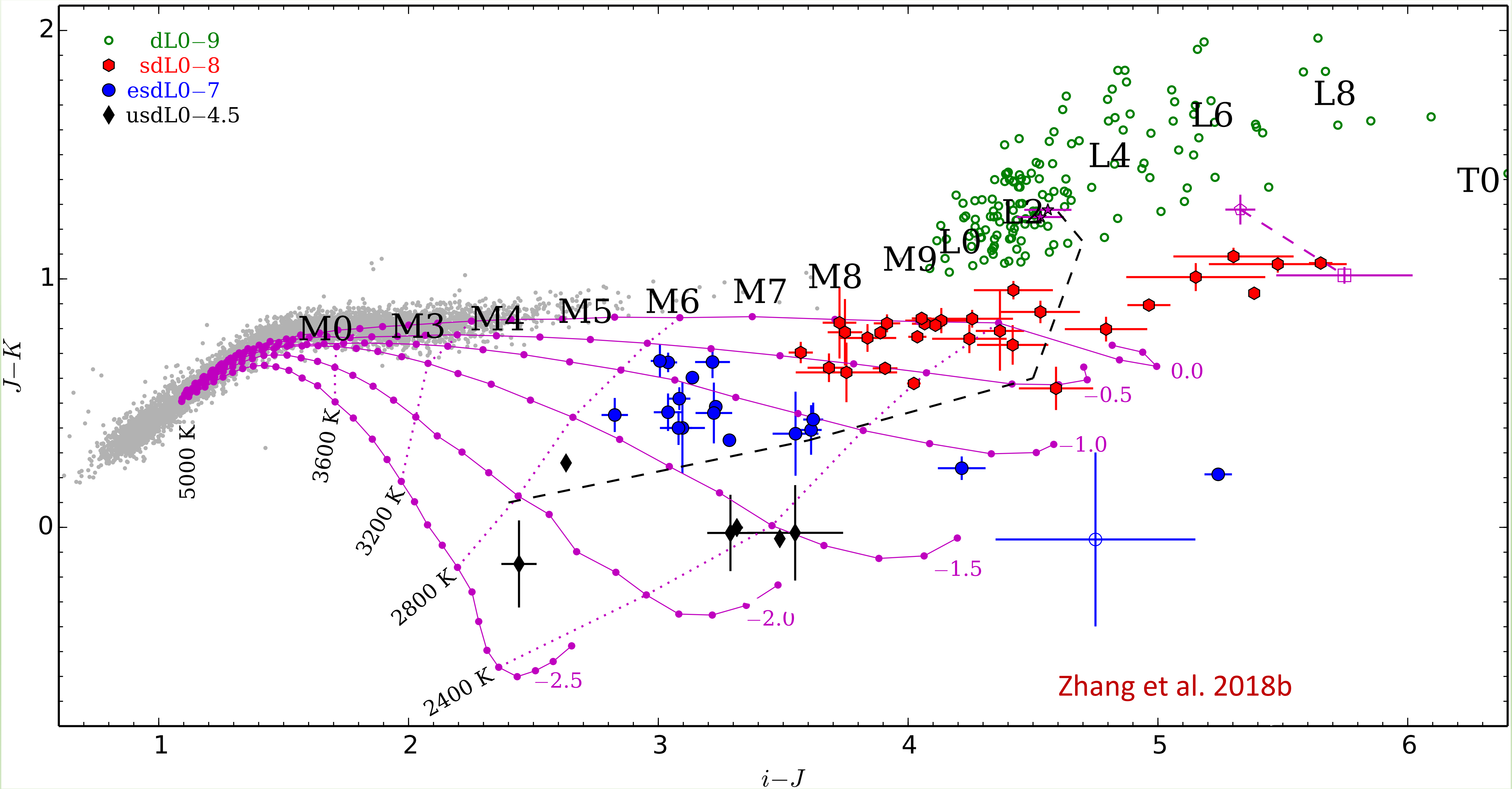
- Prefix + Core + Suffix for Metallicity + Temperature and clouds + Gravity. (Kirkpatrick 2005)

- Burgasser et la. 2007
- Kirkpatrick et al. 2010



Kirkpatrick 2005

Optical-NIR colours of L subdwarfs



Spectral classification of L subdwarfs

Zhang et al. 2017a

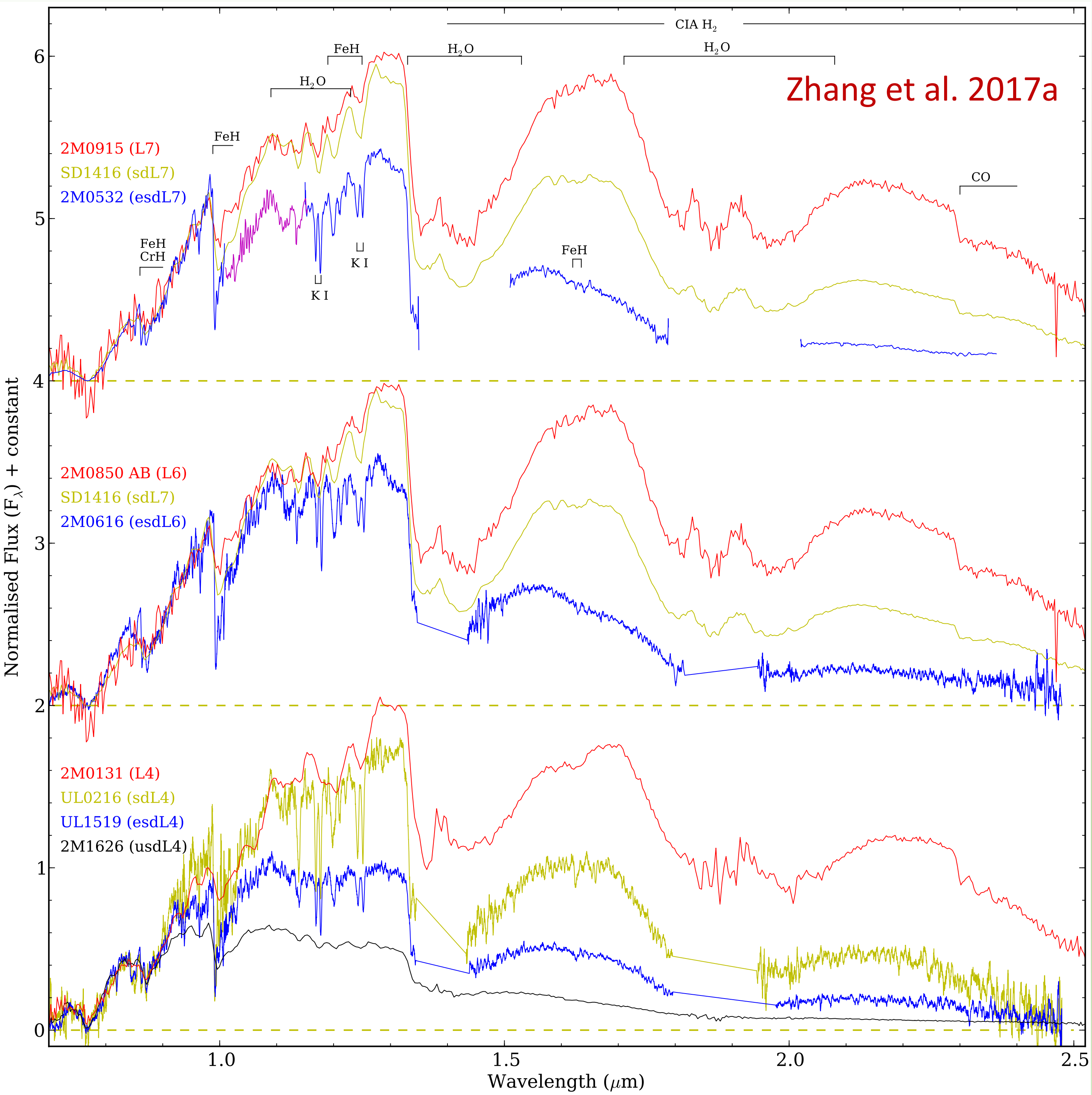
[a]Subclass	[Fe/H]	Kinematics	Subclass	[Fe/H]
dM0–3	>-0.24	Thin disc	dL	>-0.3
sdM0–3	$(-0.9, -0.24]$	Thick disc	sdL	$(-1.0, -0.3]$
esdM0–3	$(-1.5, -0.9]$	Halo	esdL	$(-1.7, -1.0]$
usdM0–3	$\leqq -1.5$	Halo	usdL	$\leqq -1.7$

Subclass	Spectral characteristics	Examples
sdL	*H* and *K* bands are more suppressed than in L dwarfs (normalizing in optical)	SD1416, UL0216 (Fig. 9)
	CaH and TiO at around 0.7 μm are slightly deeper than in L dwarfs	2M1756 (Kirkpatrick et al. 2010)
	VO band at 0.8 μm in early-type sdL is weaker than in L dwarfs	2M1756 (Kirkpatrick et al. 2010)
	0.77–0.81 μm spectral profile of early-type esdL dips below a straight line	SD1333 (Fig. 3)
	FeH at 0.99 μm in mid–late-type sdL is stronger than in L dwarfs	SD1416 (Fig. 9)
	CO band at 2.3 μm is weaker than in dL	2M1756, SD1416 (Fig. 9)
	TiO at 0.85 μm stronger than for same spectral type L dwarfs	SD1347 (Fig. 3)
esdL	*J*, *H*, and *K* bands are strongly suppressed compared to L dwarfs (normalizing in optical).	2M0616, UL1519 (Fig. 9)
	CaH and TiO at around 0.7 μm are deeper than in L dwarfs	UL1244 (Fig. 4)
	VO band at 0.8 μm in early-type esdL disappears	WI0014, UL1244 (Fig. 4)
	0.77–0.81 μm spectral profile of early-type esdL well approximated by a straight slope	UL1244 (Fig. 4)
	FeH at 0.99 μm in mid–late-type esdL is much stronger than in L dwarfs	2M0616, 2M0532 (Fig. 9)
	CO band at 2.3 μm disappears, *K* band is almost flat	2M0616, 2M0532 (Fig. 9)
	TiO at 0.85 μm weaker than same spectral type sdL	UL1244, 2M0616 (Fig. 8)
usdL	*J*, *H*, and *K* bands are significantly suppressed compared to L dwarfs (normalizing in optical).	2M1626 (Fig. 9)
	CaH and TiO at around 0.7 μm are deeper than in dL	SSS1013 (Fig. 10)
	VO band at 0.8 μm in early-type usdL disappears	SSS1013 (Fig. 10)
	0.77–0.81 μm spectral profile of early-type usdL appears well above a straight line	SSS1013 (Fig. 10)
	FeH at 0.99 μm in mid–late-type usdL is much stronger than in L dwarfs	2M1626 (Fig. 9)
	CO band at 2.3 μm disappears, *K* band is somewhat flat	2M1626 (Fig. 9)
	TiO at 0.85 μm weaker than same spectral type esdL	2M1626 (Fig. 8)

L7
sdL7
esdL7

L6
sdL7
esdL6

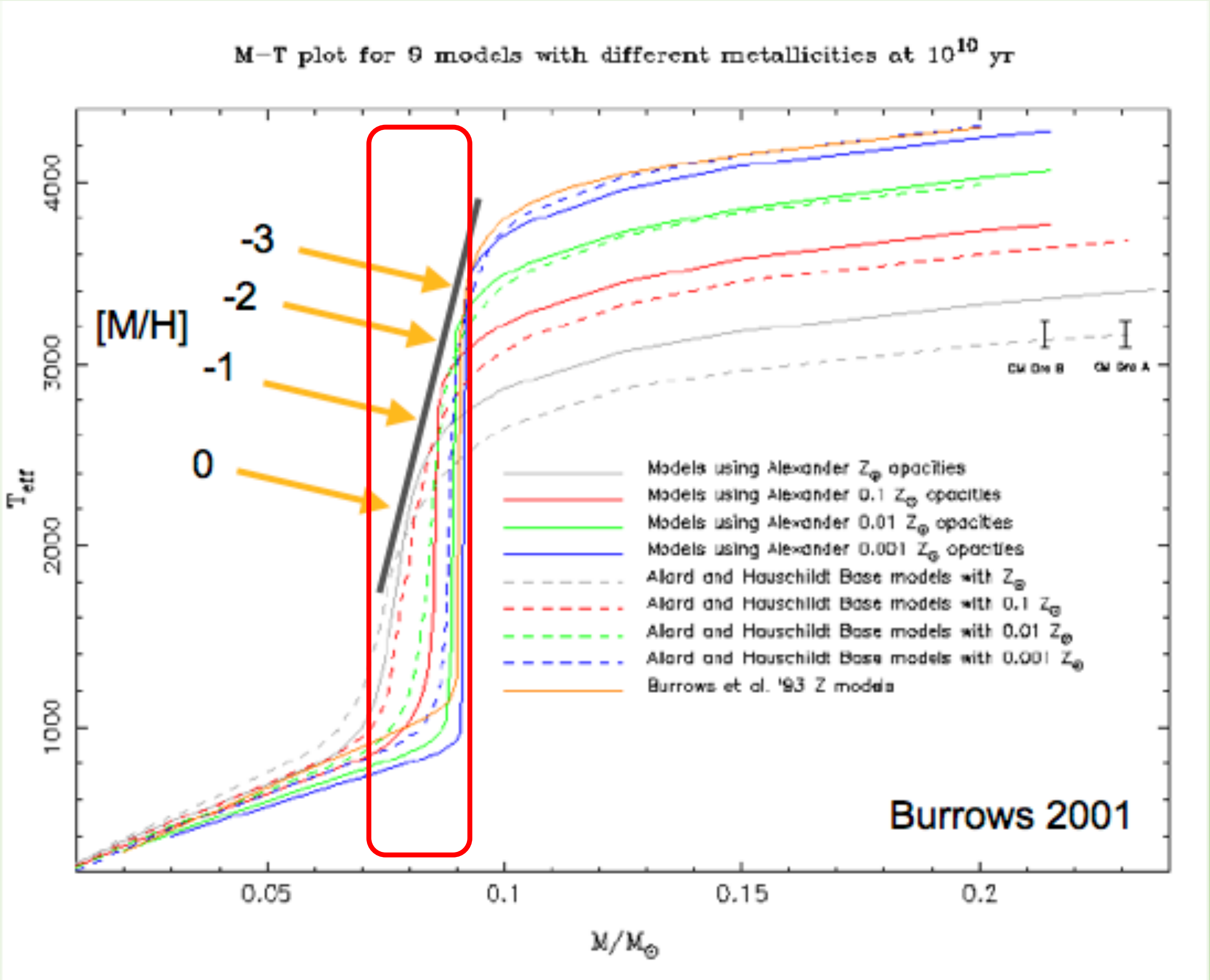
L4
sdL4
esdL4
usdL4

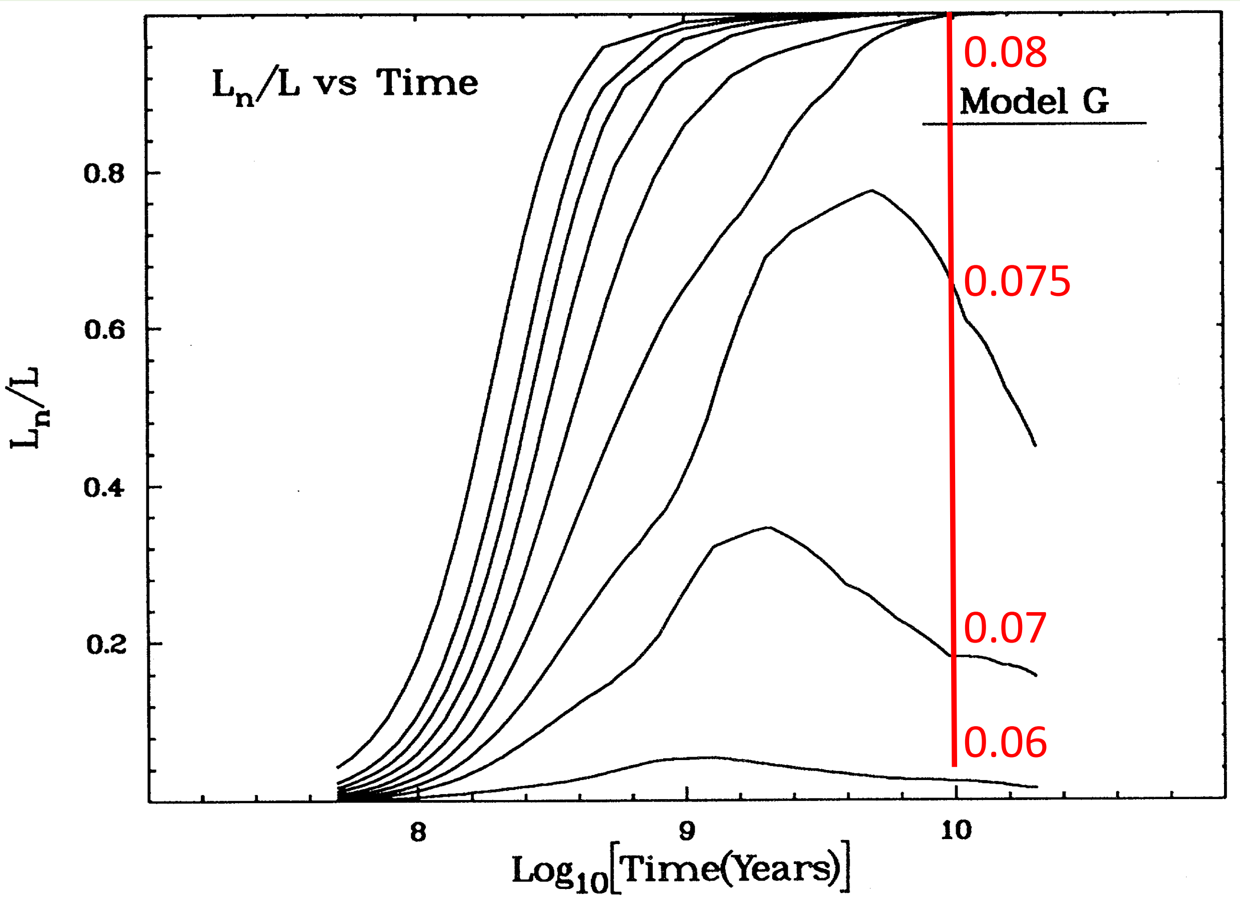


Are they BDs?

10 Gyr Teff isochrones at different metallicity

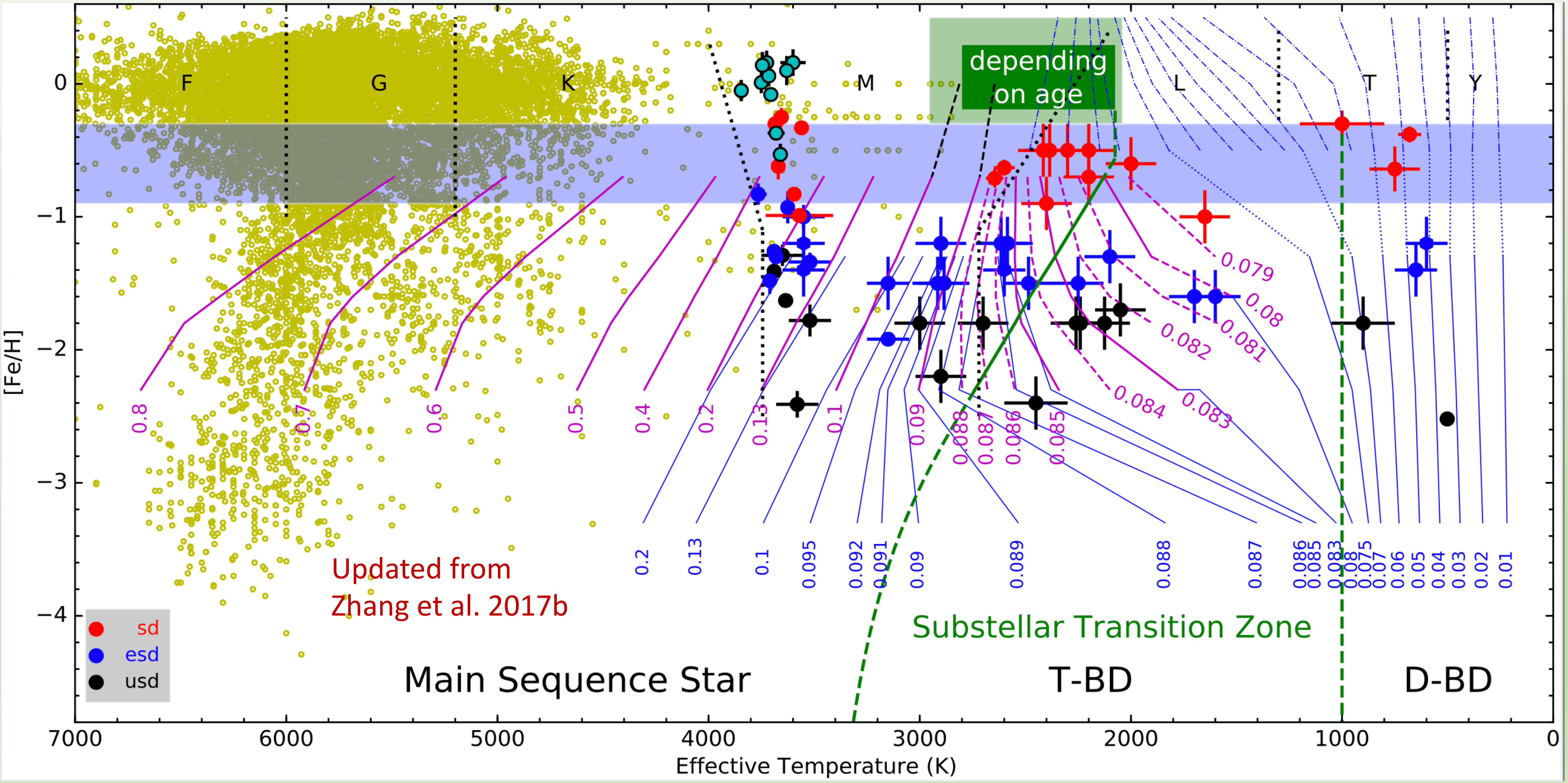
Luminosity contributed by nuclear fusion





Burrows et al. 1993

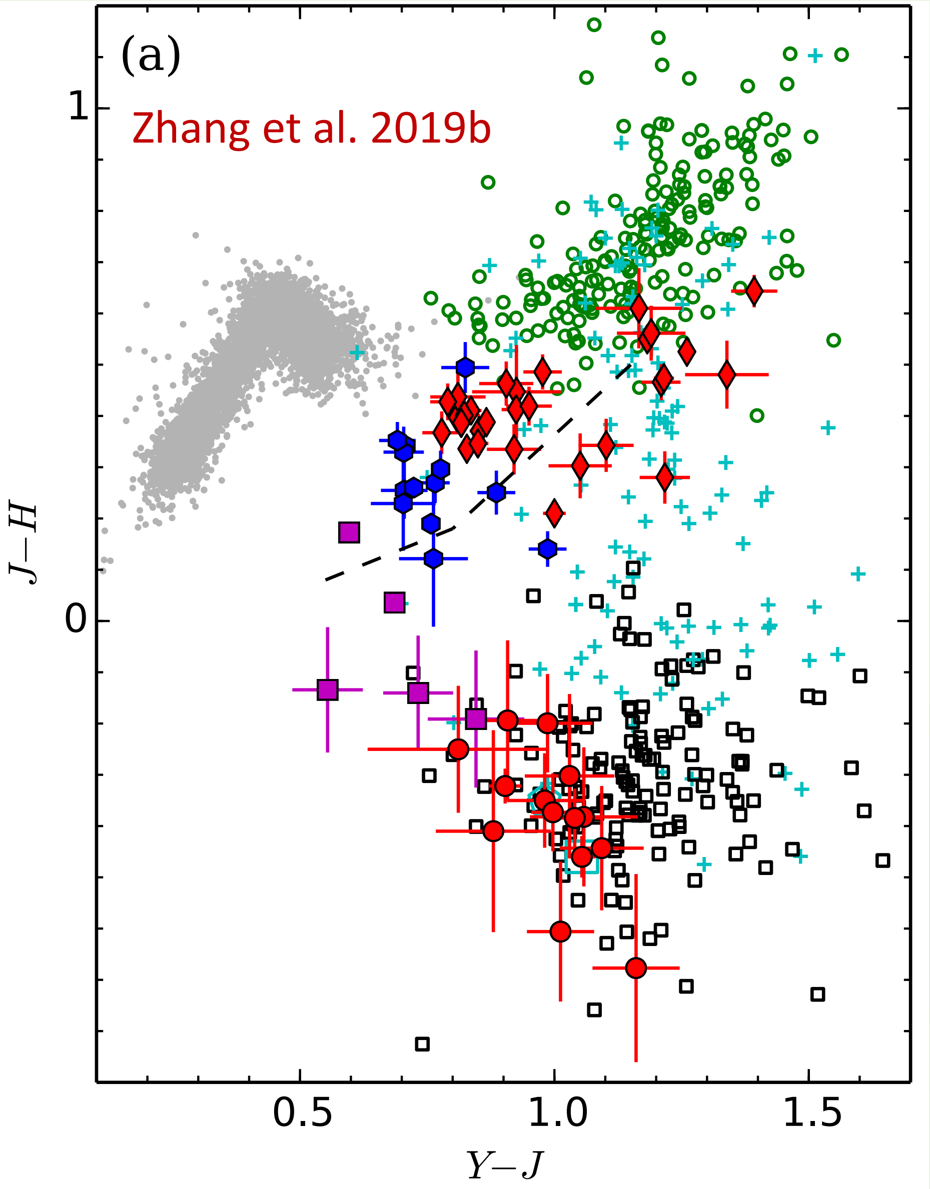
Challenges from M subdwarfs: Misaligned Mass

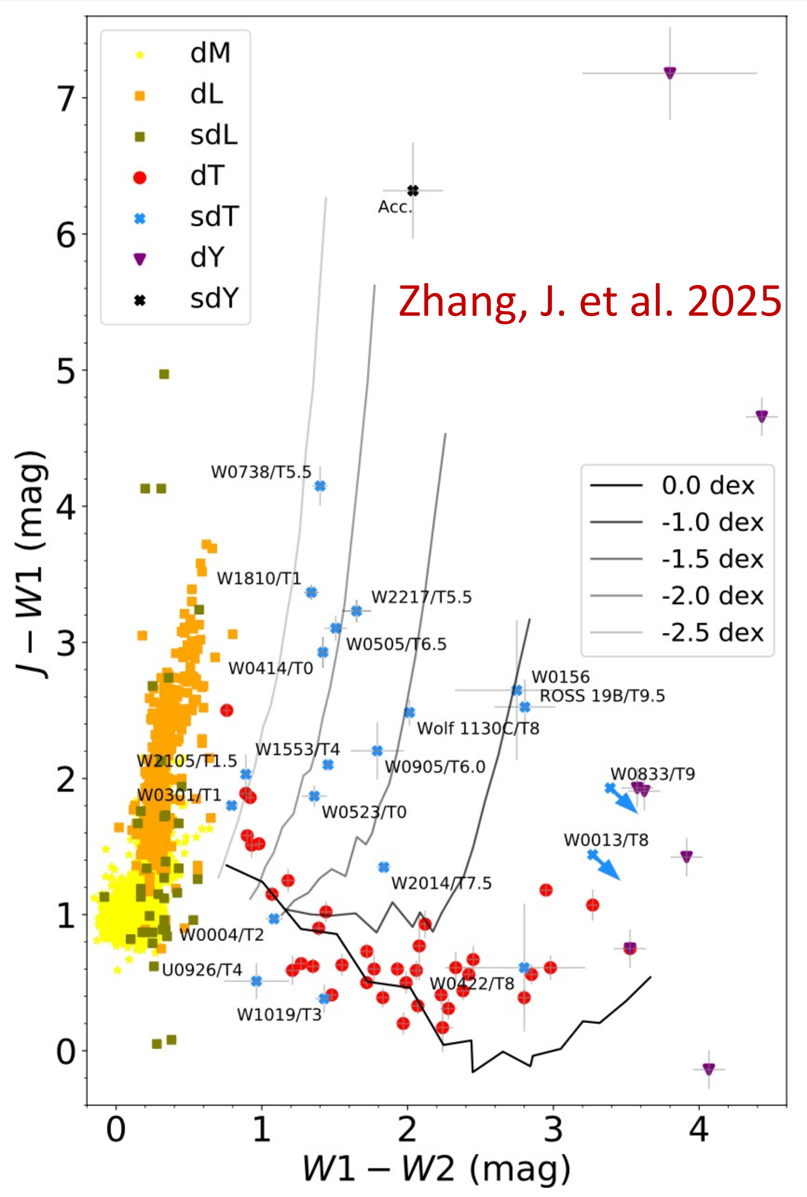


T (sub)dwarf observation and classification

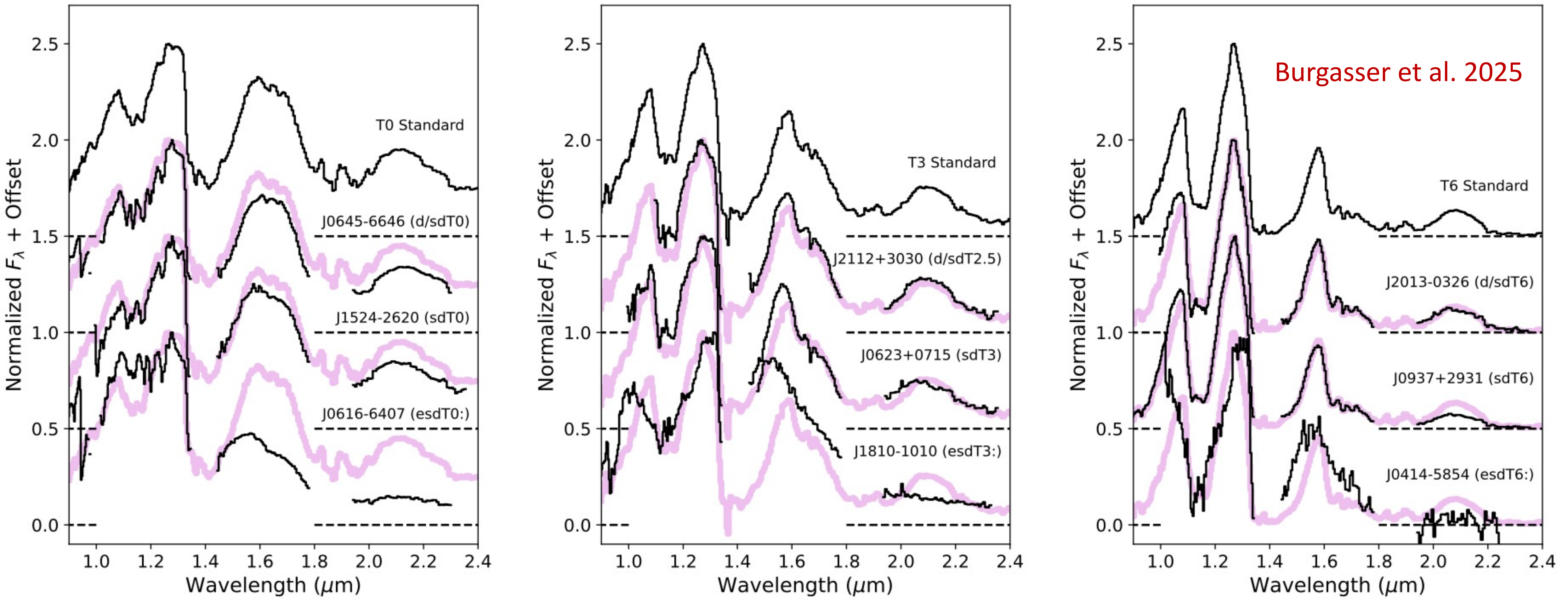
- T dwarf spectrum (GL 229 Bab; Oppenheimer et al. 1995)
- T dwarf classification scheme (Burgasser et al. 2002, 2003)
- T subdwarf (2MASS J09373487+2931409, Burgasser et al. 2002)
- T subdwarf classification (Zhang et al. 2019b; Burgasser et al. 2025)

Colours of T subdwarfs





T subdwarf classification



The zeta index (ζ_T) for T subdwarfs

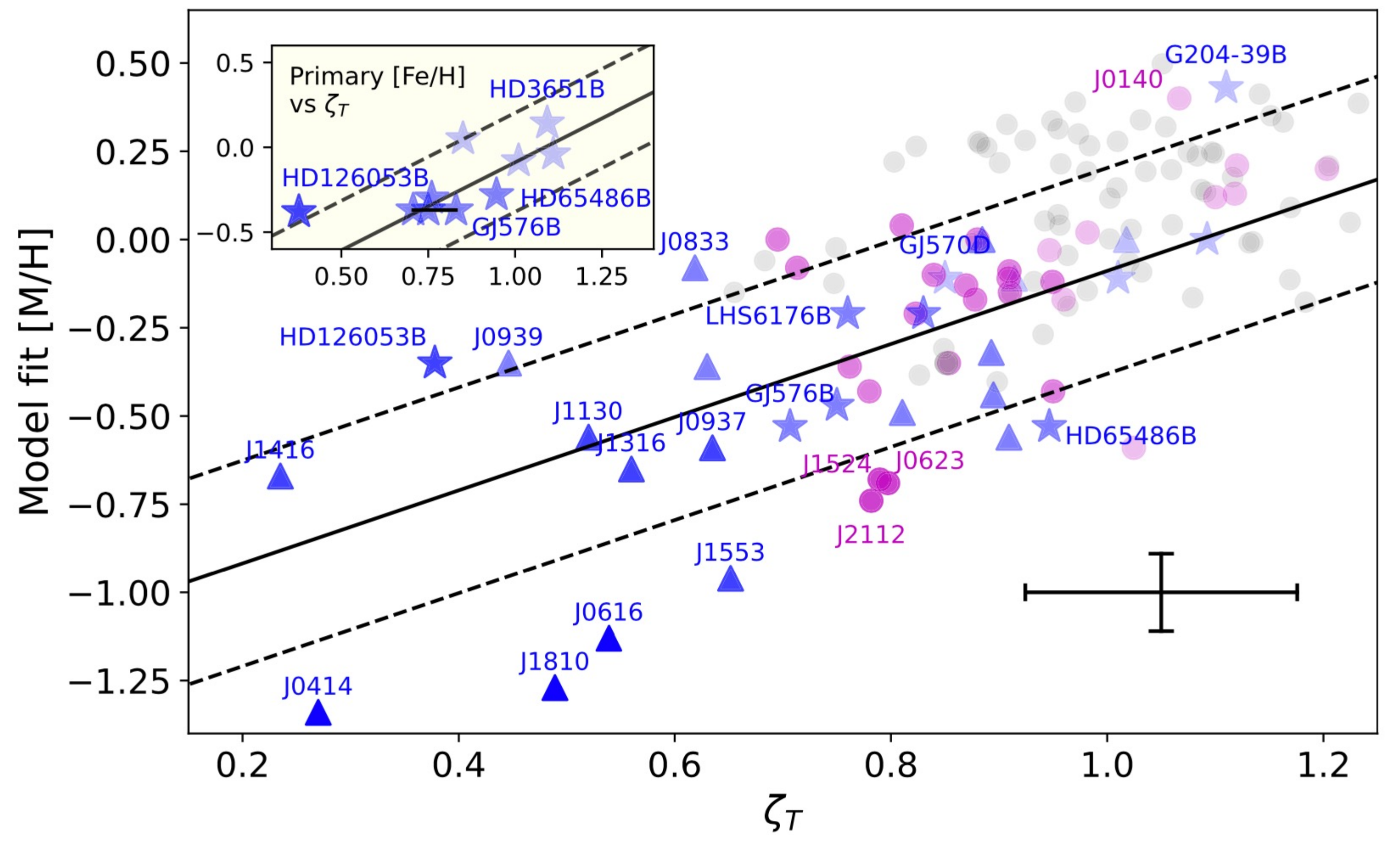
$$\zeta_{T,1} \equiv \frac{[\mathrm{H2O-H}]_\odot([\mathrm{CH4-H}])}{[\mathrm{H2O-H}]}$$

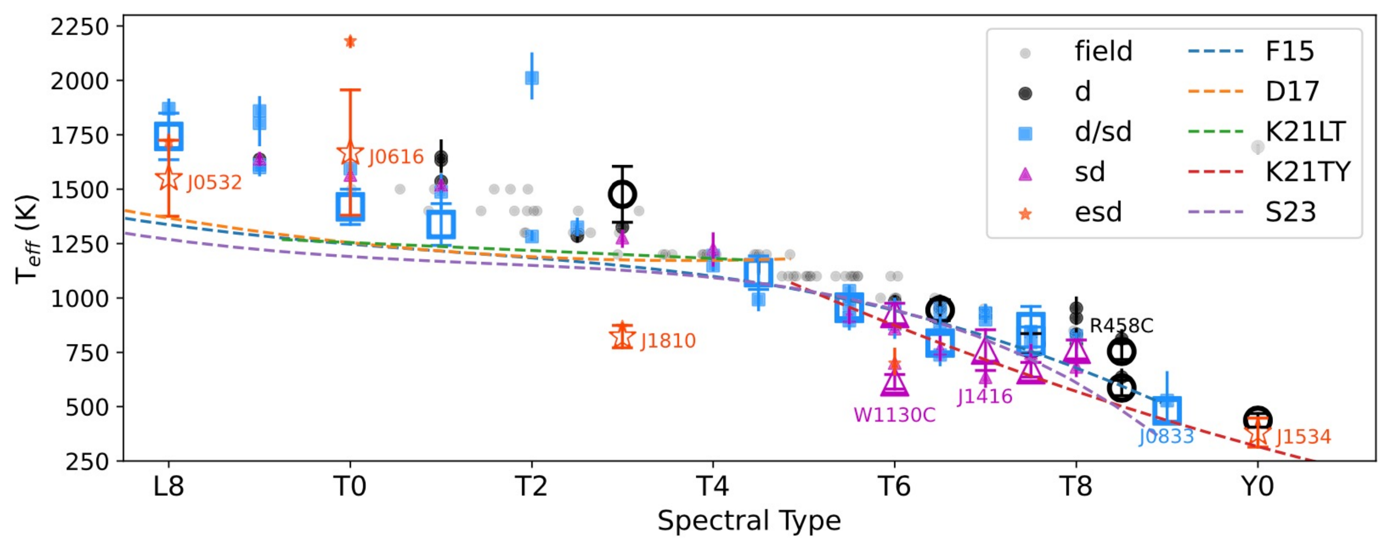
$$\zeta_{T,2} \equiv \frac{[\mathrm{H2O-H}]_\odot([\mathrm{H2O-J}])}{[\mathrm{H2O-H}]}$$

$$\zeta_{T,3} \equiv \frac{[\mathrm{K/H}]}{[\mathrm{K/H}]_\odot([\mathrm{H2O-J}])}$$

$$\zeta_{T,4} \equiv \frac{[\mathrm{K/H}]}{[\mathrm{K/H}]_\odot([\mathrm{H-dip}])}.$$

Burgasser et al. 2025





Summary

- **M subdwarfs**
  - All are stars, but spectral subtype ≠ mass → misinterpreted activity & radii
  - Metallicity classification breaks down beyond esdM5.5/usdM6
- **L subdwarfs**
  - Three classes: usdL (∞,-1.7], esdL (-1.7, -1.0], sdL (-1.0, -0.3]
  - Mix of lowest-mass stars (early L) and transitional brown dwarfs (mid-late L)
- **T subdwarfs**
  - T0-T4: transitional brown dwarfs
  - T5+: degenerate brown dwarfs (majority)
  - Hydride-dominated atmospheres
  - Classification scheme still evolving

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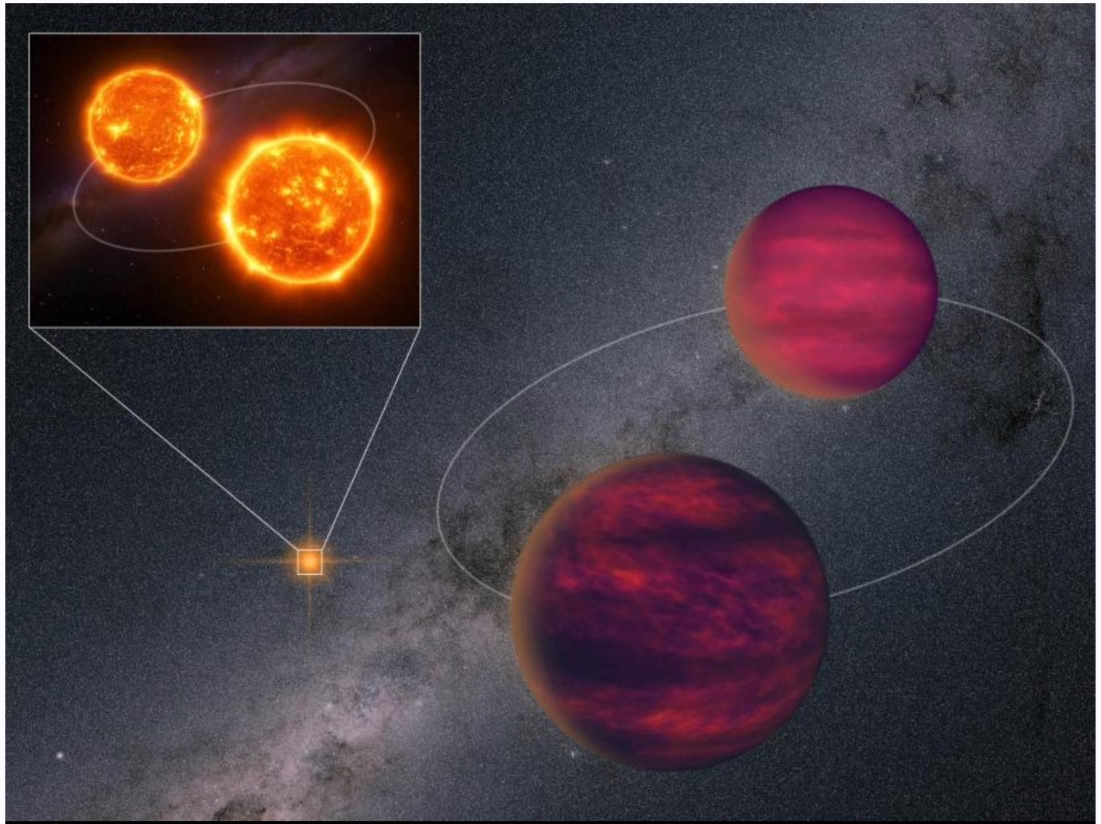
Rare quadruple star system could unlock mystery of brown dwarfs



An artist's impression of the UPM J1040−3551 system against the backdrop of the Milky Way as observed by Gaia. On the left, UPM J1040−3551 Aa & Ab appears as a distant bright orange dot, with an inset revealing these two M-type stars in orbit. On the right, in the foreground, a pair of cold brown dwarfs – UPM J1040−3551 Ba & Bb – orbit each other for a period of decades while collectively circling UPM J1040−3551 Aab in a vast orbit that takes over 100,000 years to complete.

Credit: Jiaxin Zhong/Zenghua Zhang

The New York Times

Scientists Find a Quadruple Star System in Our Cosmic Backyard

Two of the objects in the arrangement are cold brown dwarfs, which will serve as a benchmark for others throughout the Milky Way.

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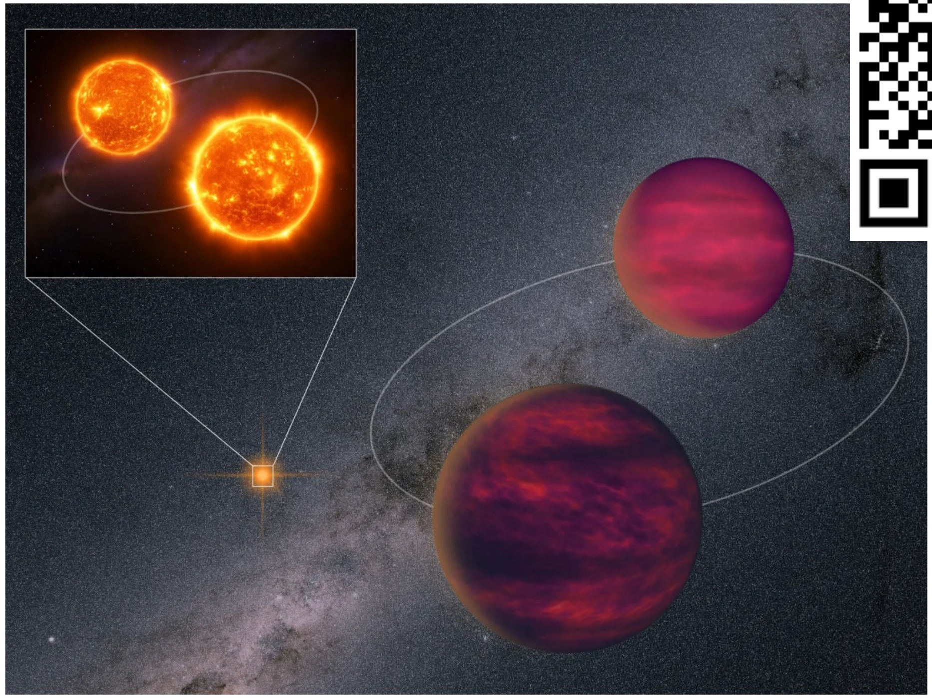

An artist's impression of a star system, UPM J1040−3551, against the backdrop of the Milky Way as observed by Gaia. The two brighter stars appear as a distant orange dot, left, and the cold brown dwarfs are in the foreground. Jiaxin Zhong/Zenghua Zhang