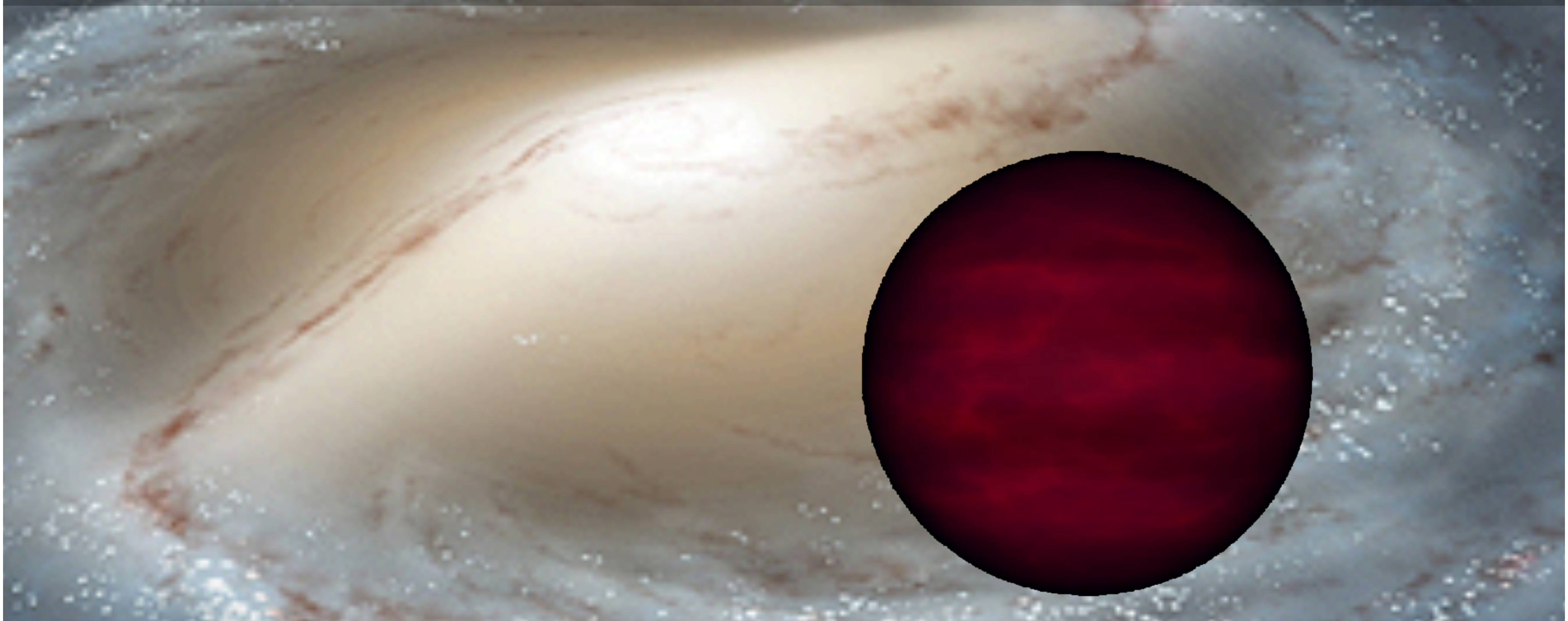
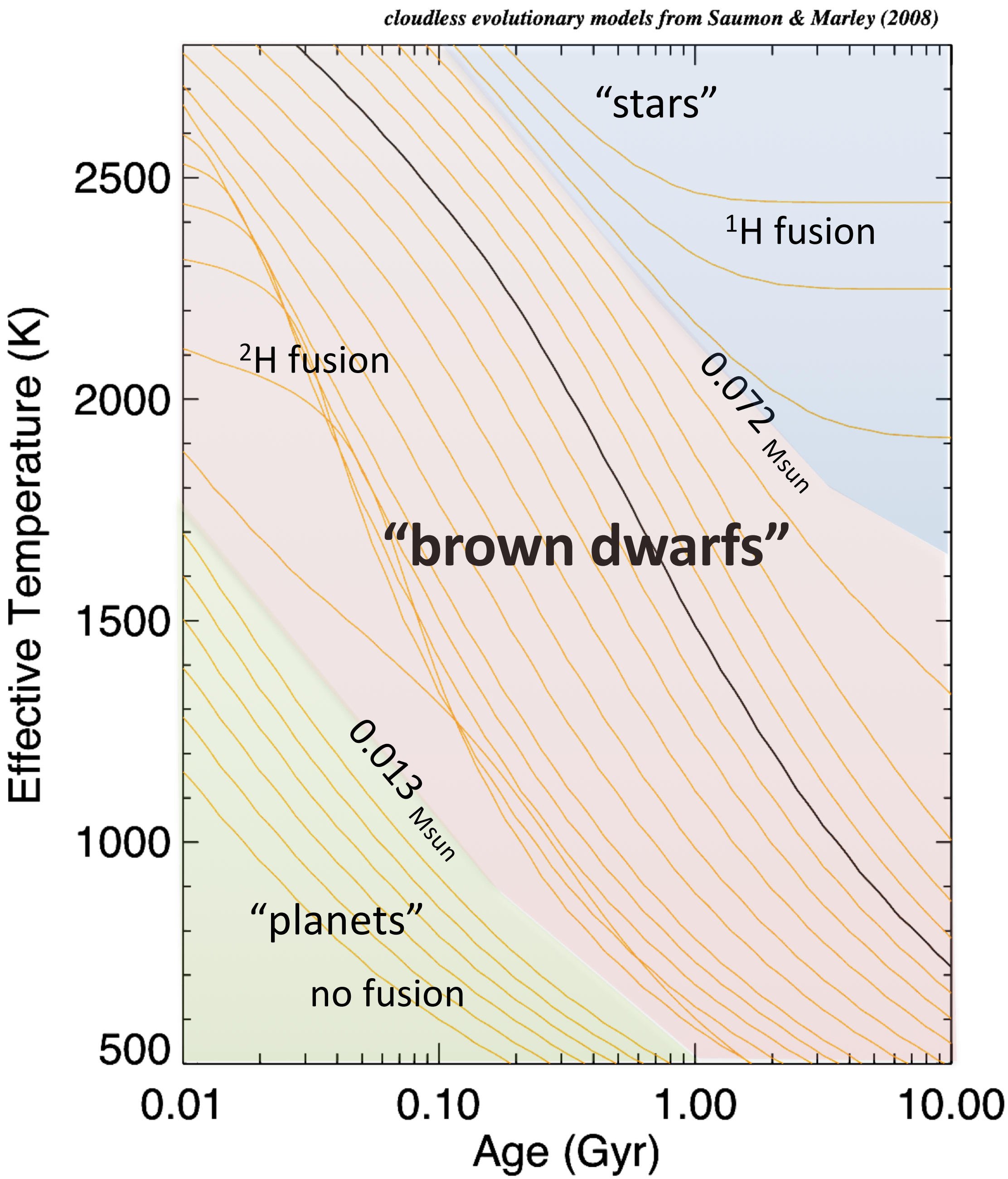
# Cold Candles & Clocks:

## Galactic Star Formation and Chemical Enrichment History Traced by WFIRST Brown Dwarfs

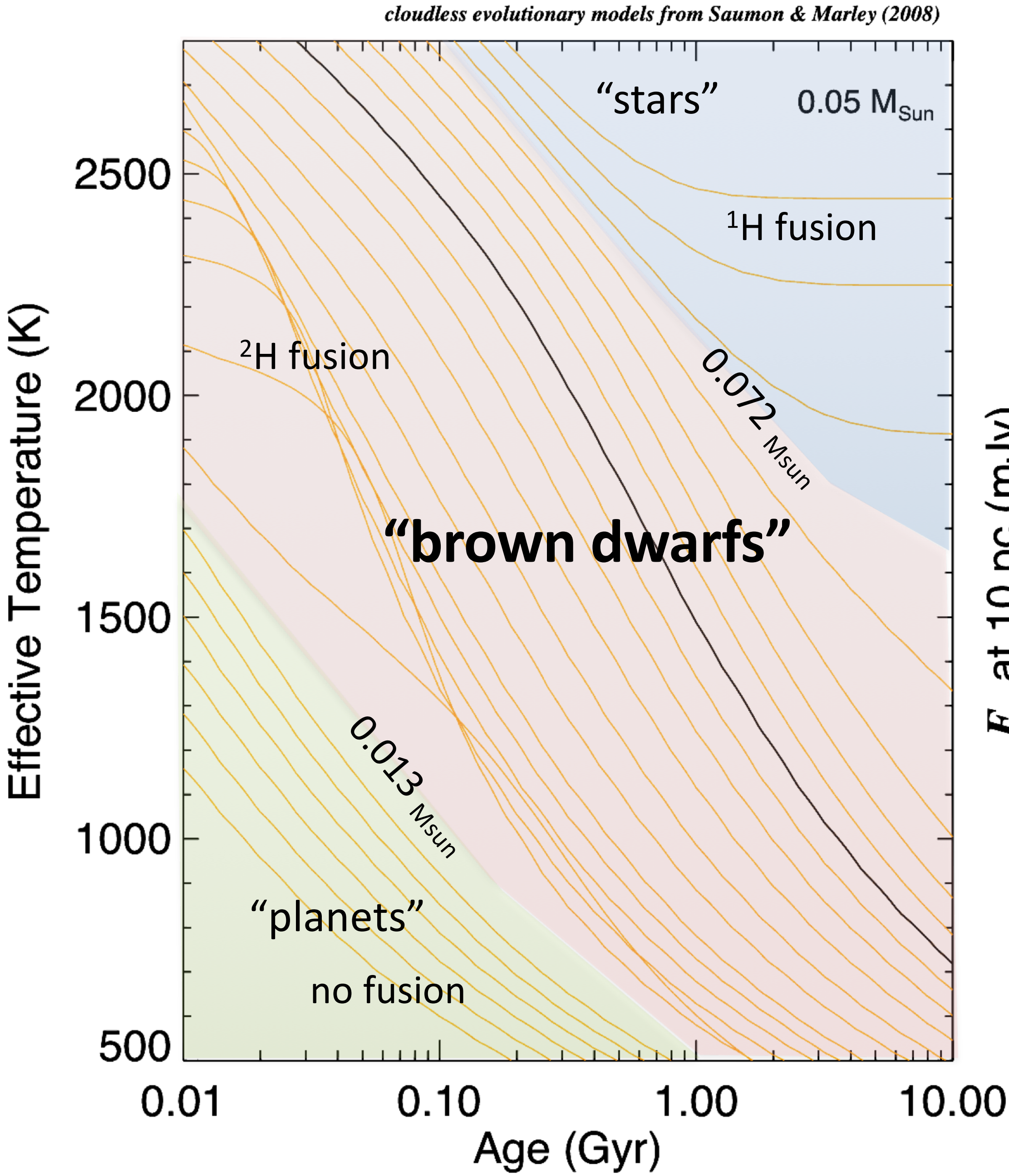


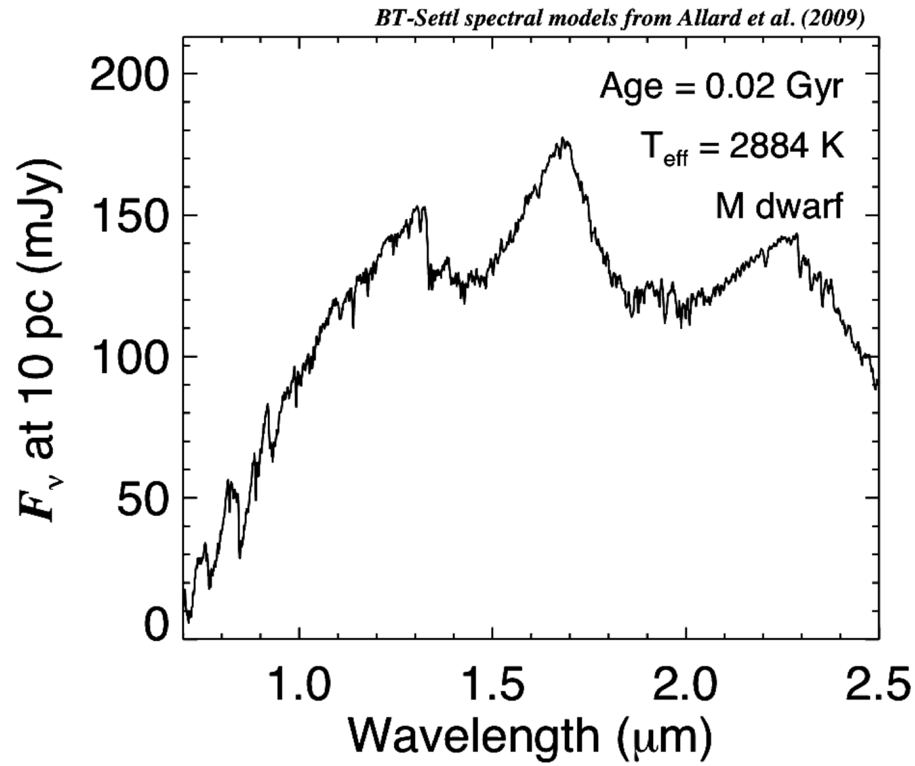
Adam Burgasser (UC San Diego)

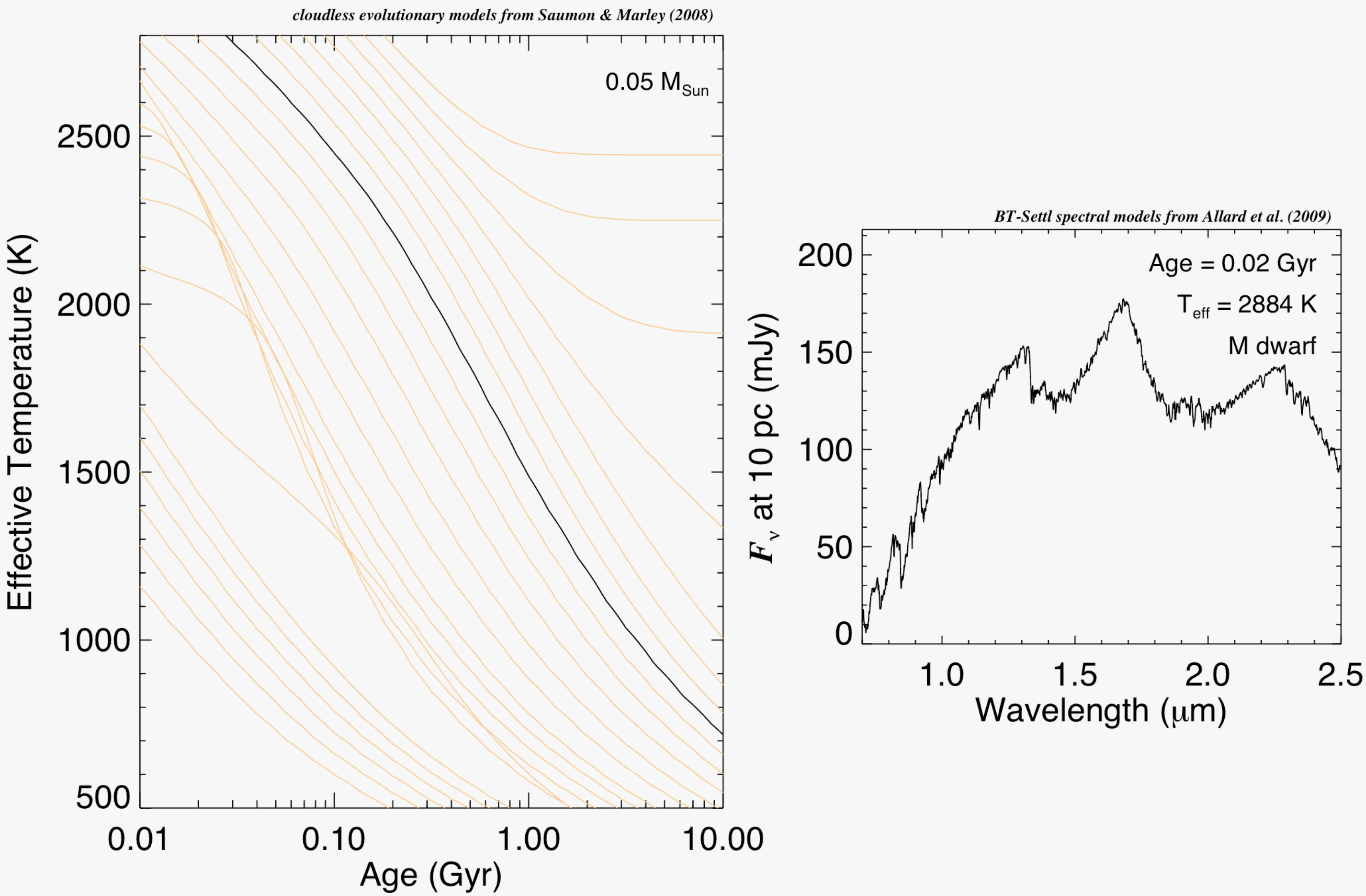
Christian Aganze (UCSD), Jon Rees (UCSD/UNM)




Brown dwarfs are incapable of sustained core hydrogen fusion, making them perpetually evolving objects


cloudless evolutionary models from Saumon & Marley (2008)
"stars"
0.05 $M_{Sun}$
$^1$H fusion
$^2$H fusion
0.072 Msun
"brown dwarfs"
0.013 Msun
"planets"
no fusion
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
$F_\nu$ at 10 pc (mJy)
200
150
100
50
0
1.0
1.5
2.0
2.5
Wavelength (μm)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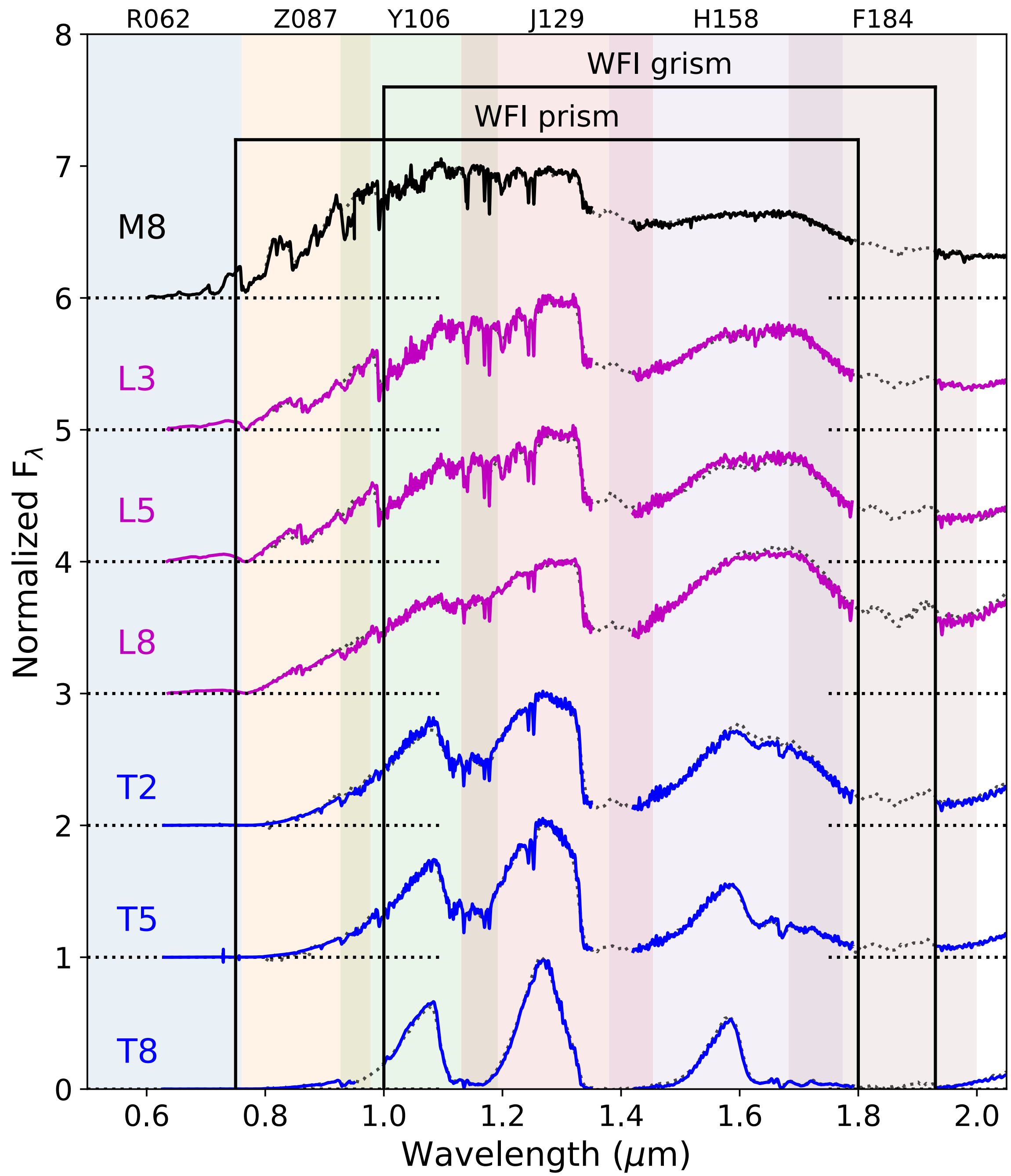
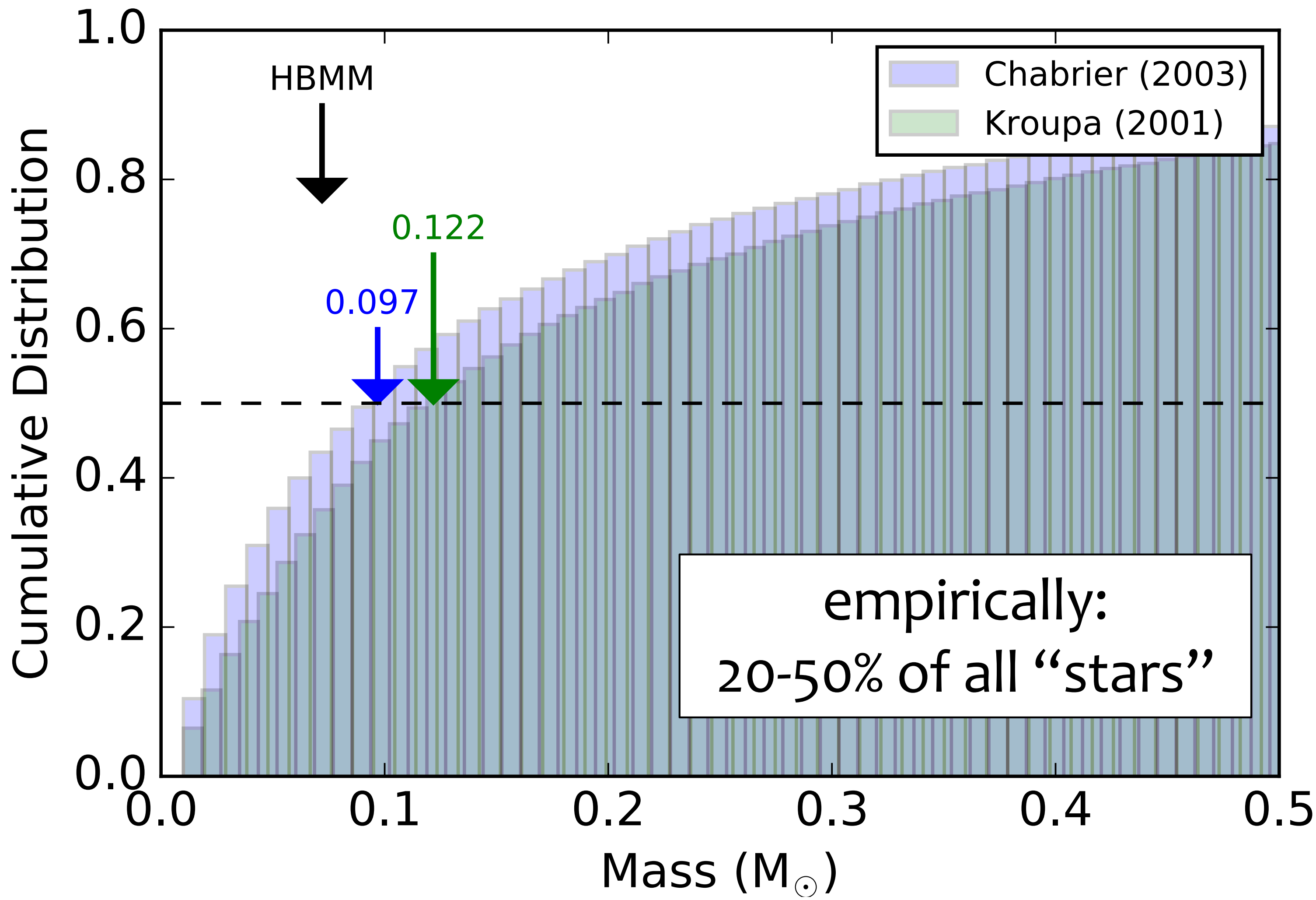


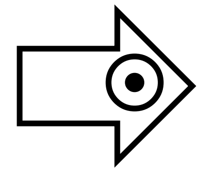

spectra from Kirkpatrick et al. (1999,2000),
Burgasser et al. (2003,2019); Cushing et al. (2005); SPLAT

# 1

# Measuring the IMF of the field brown dwarf population

# There are a lot of brown dwarfs in the Galaxy, and they're all still around

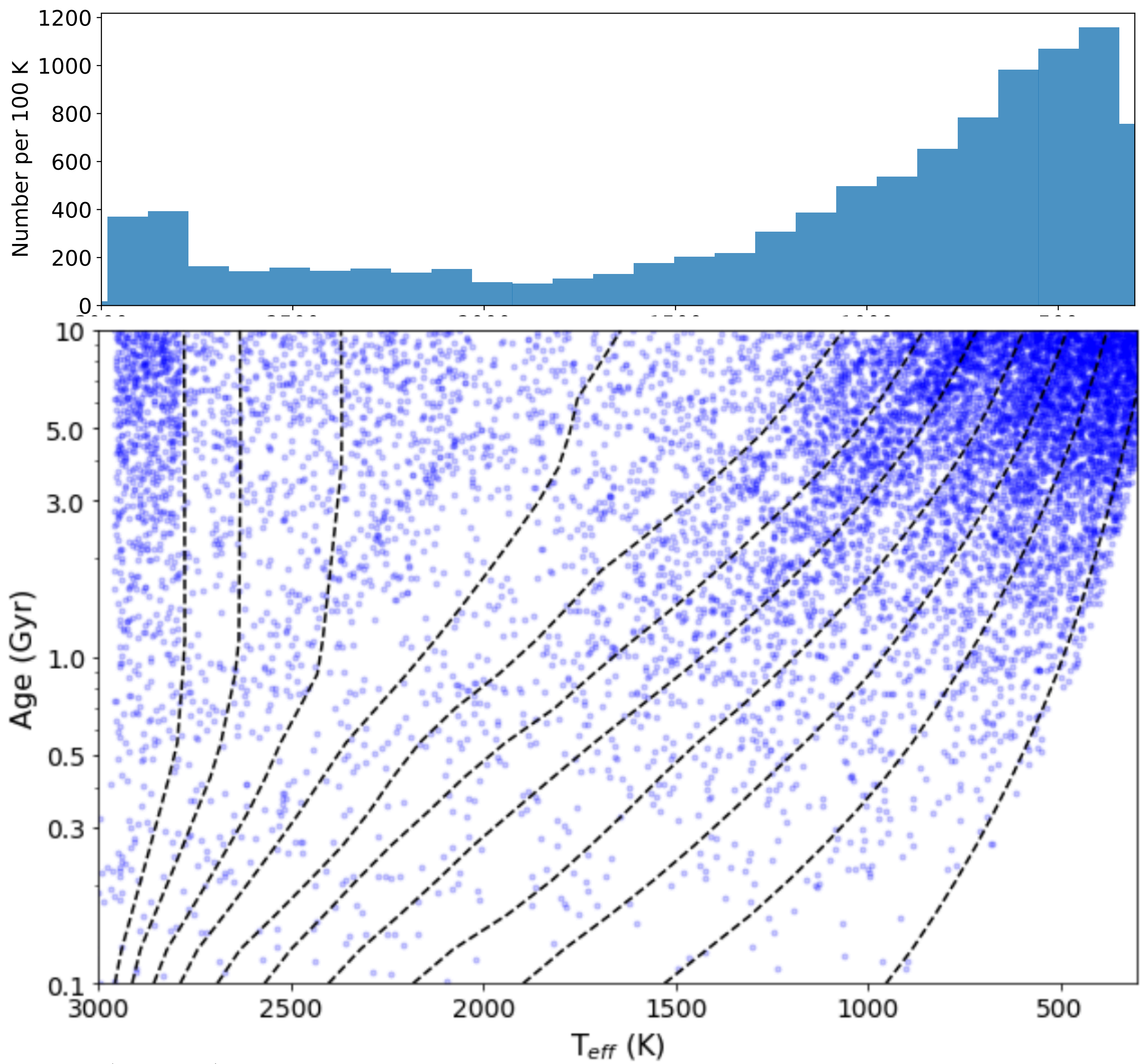


*assuming a mass range 0.01-10 $M_\odot$

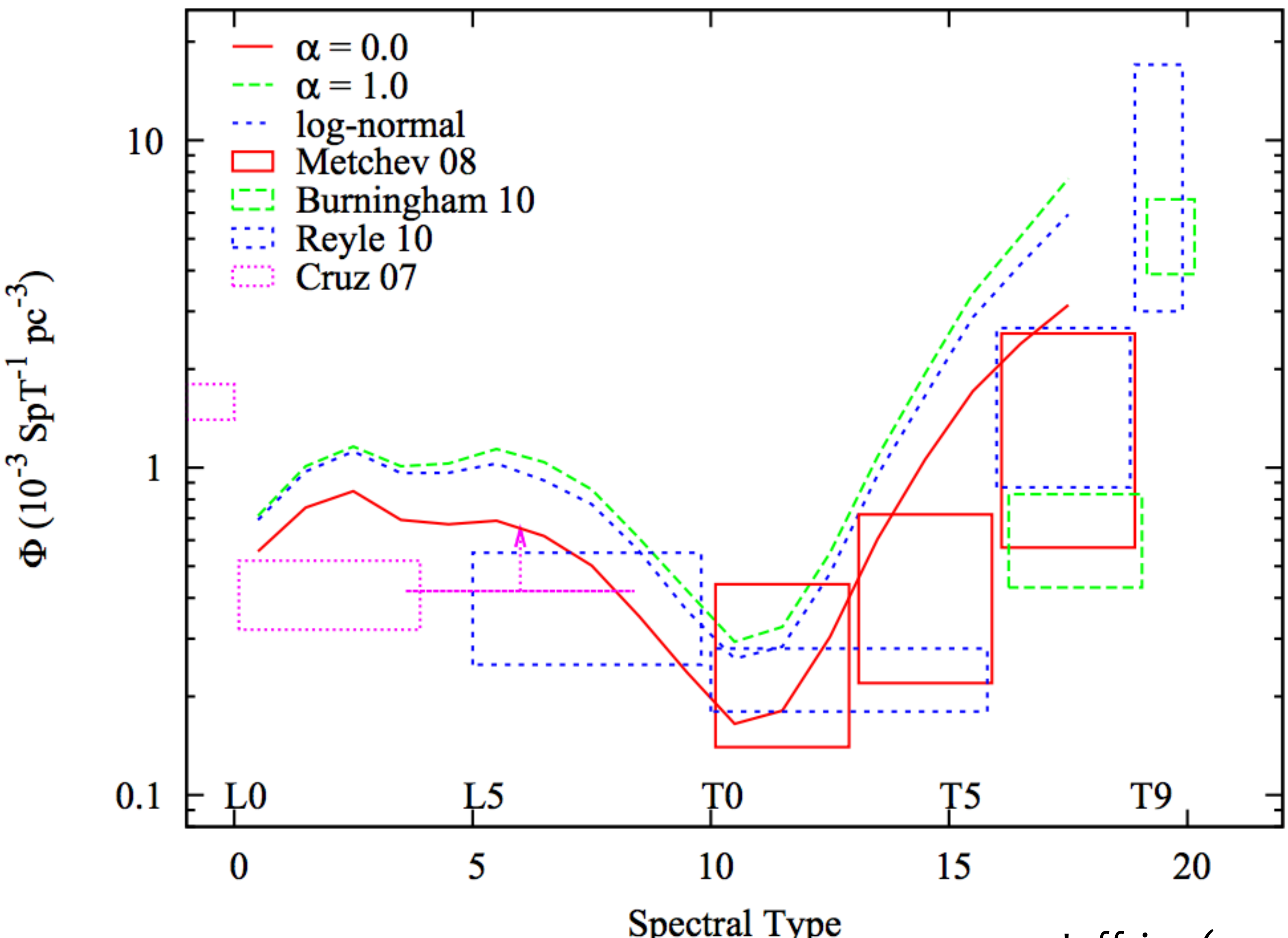
MF: Kroupa (2001); Chabrier (2003)
LF: Mužic+ (2017); Kirkpatrick et al. (2019)

# Most brown dwarfs are very cool & faint

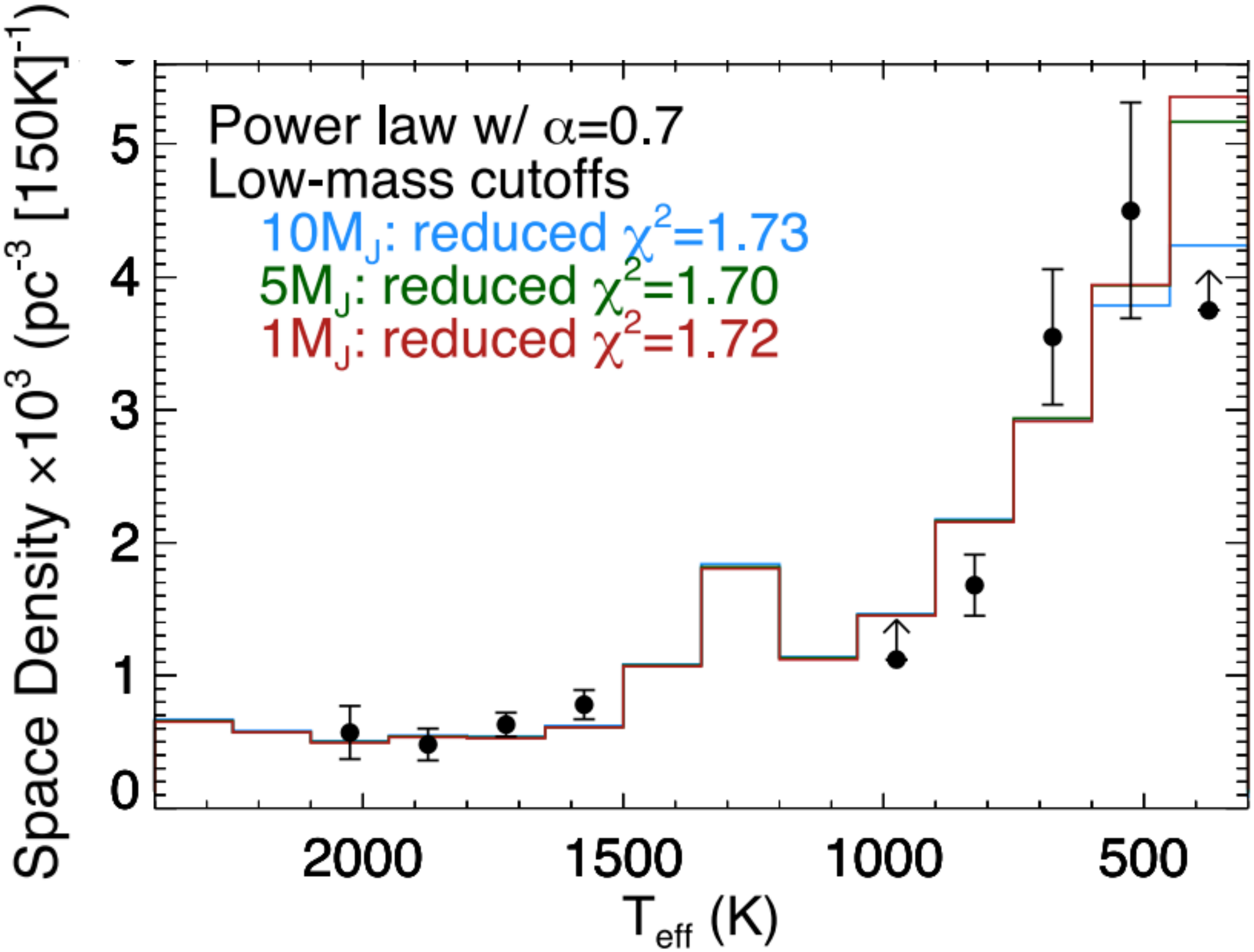



>75% of brown dwarfs are T & Y dwarfs

IMF: Chabrier (2005); uniform SFR; evolutionary models: Baraffe et al. (2003) simulation with SPLAT (Burgasser 2017)

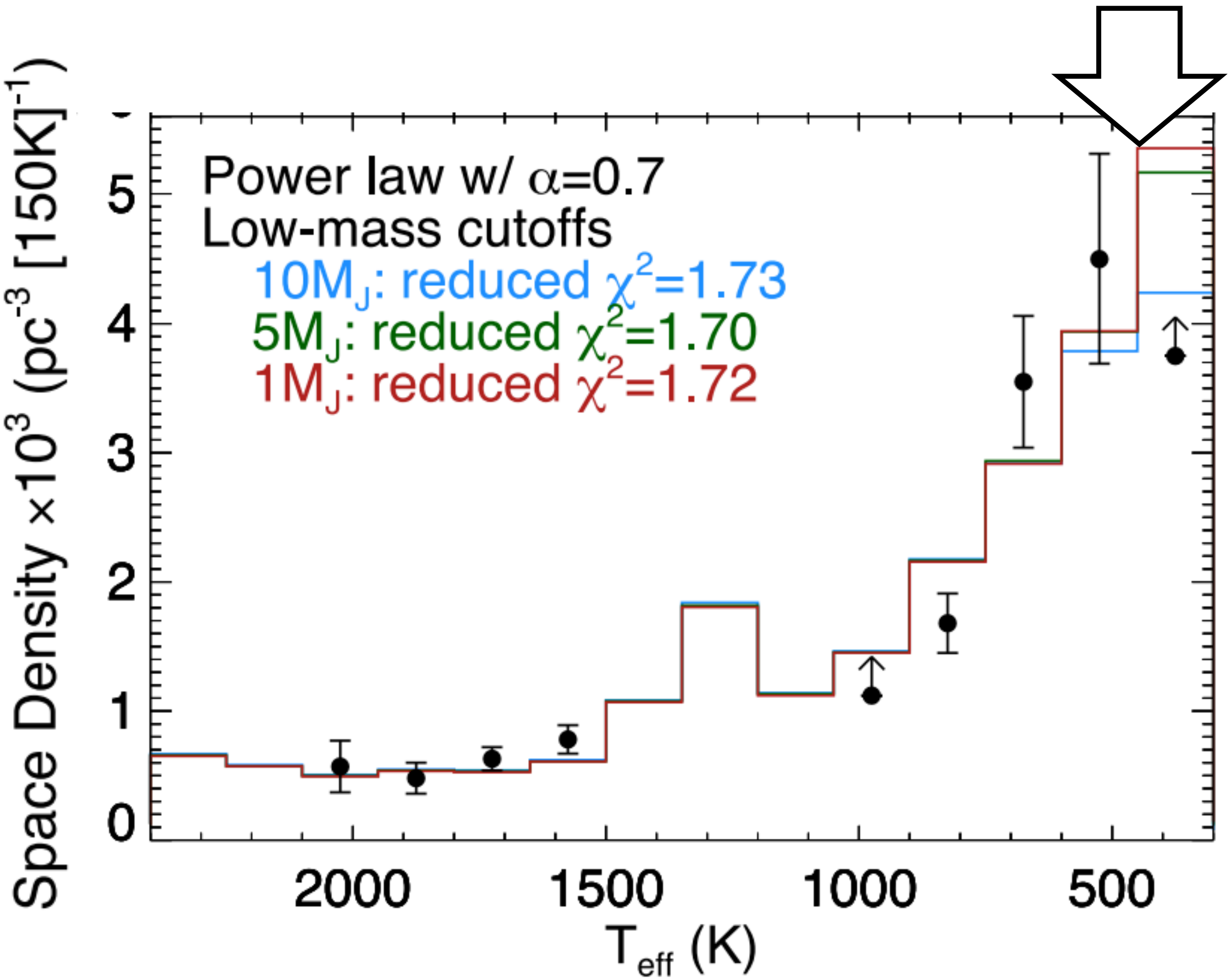



Jeffries (2012)

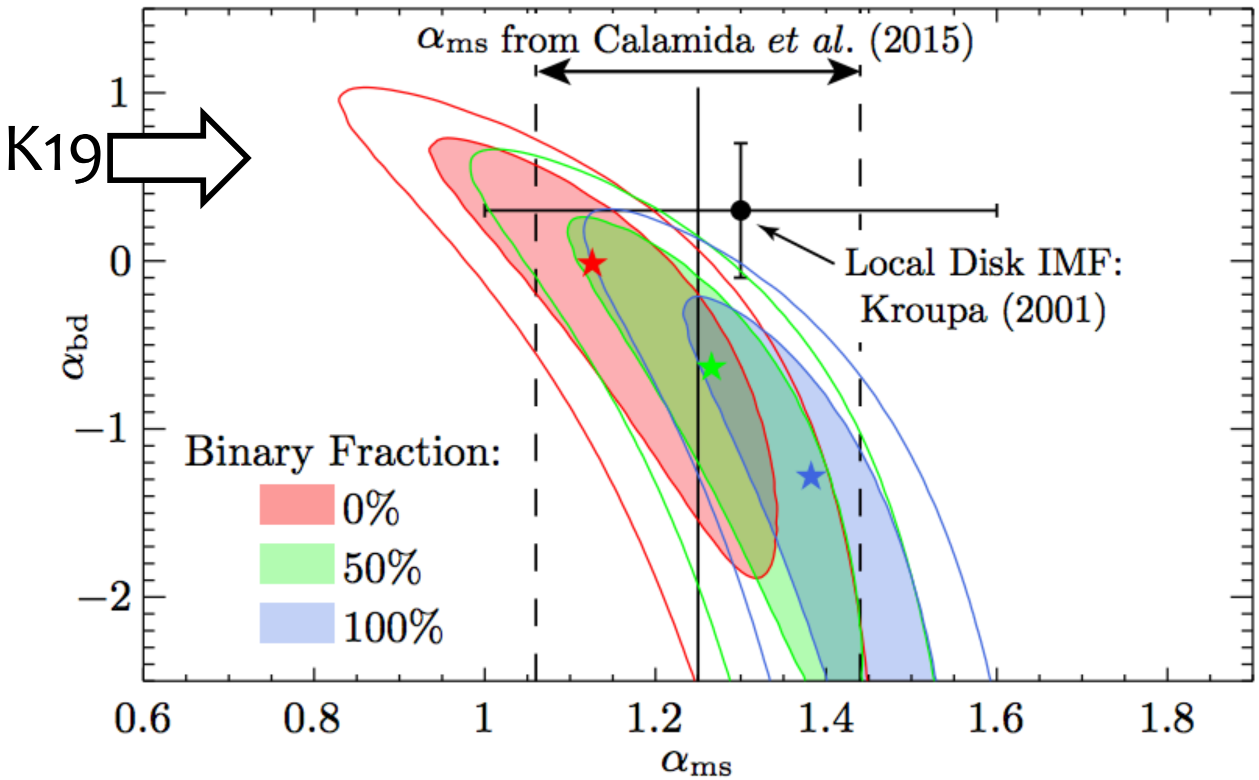



Kirkpatrick et al. (2019)

What is the minimum BD mass?

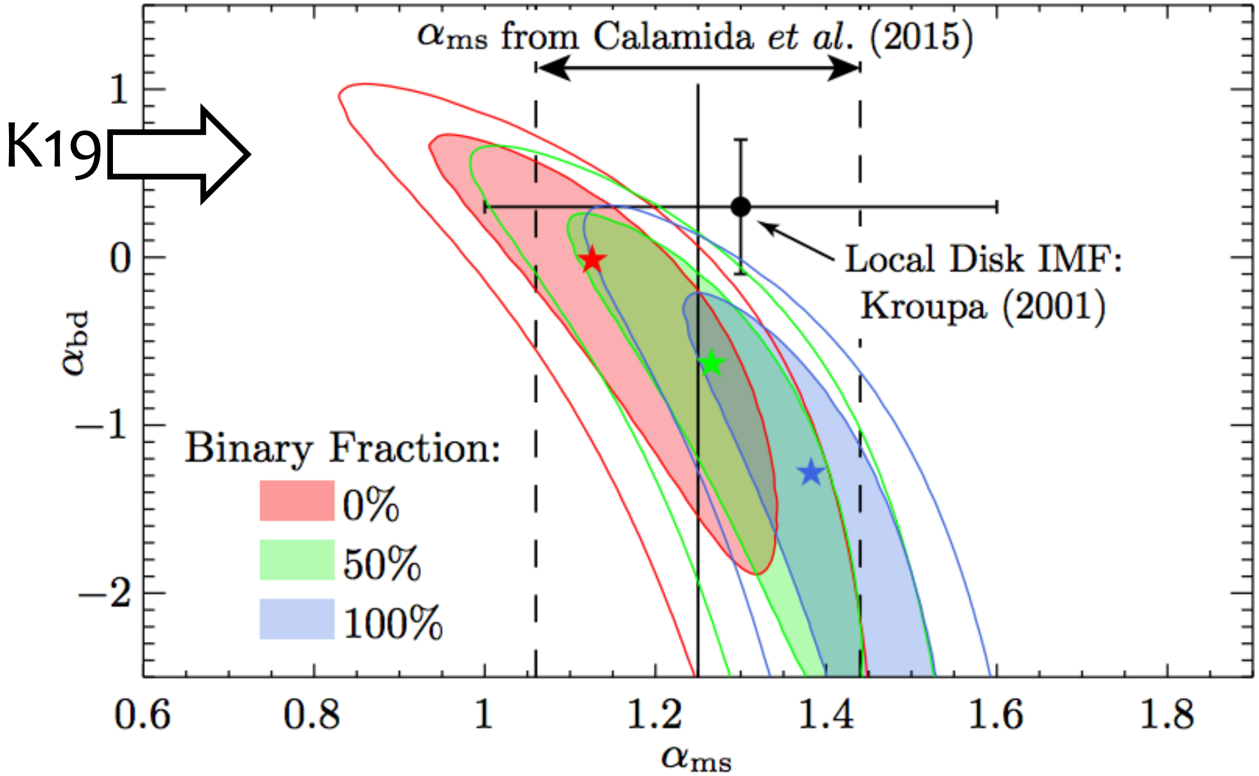


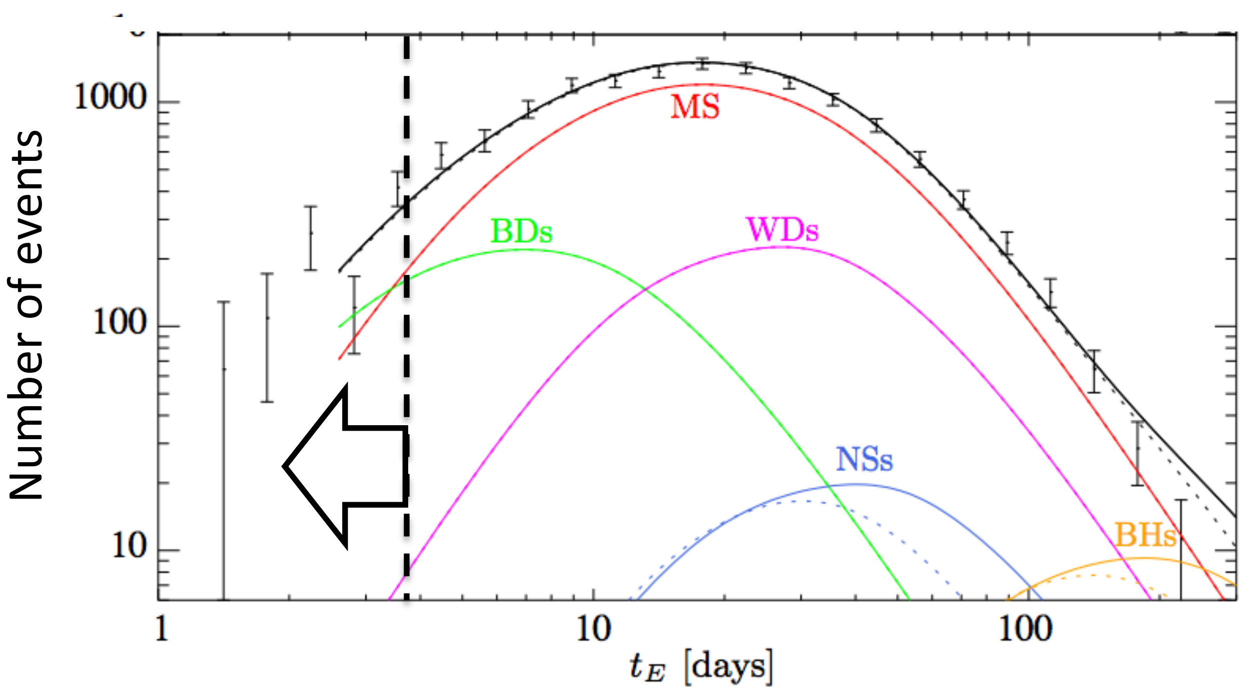

Kirkpatrick et al. (2019)




There is some tension between LF and microlens IMF measures

Wegg et al. (2018)



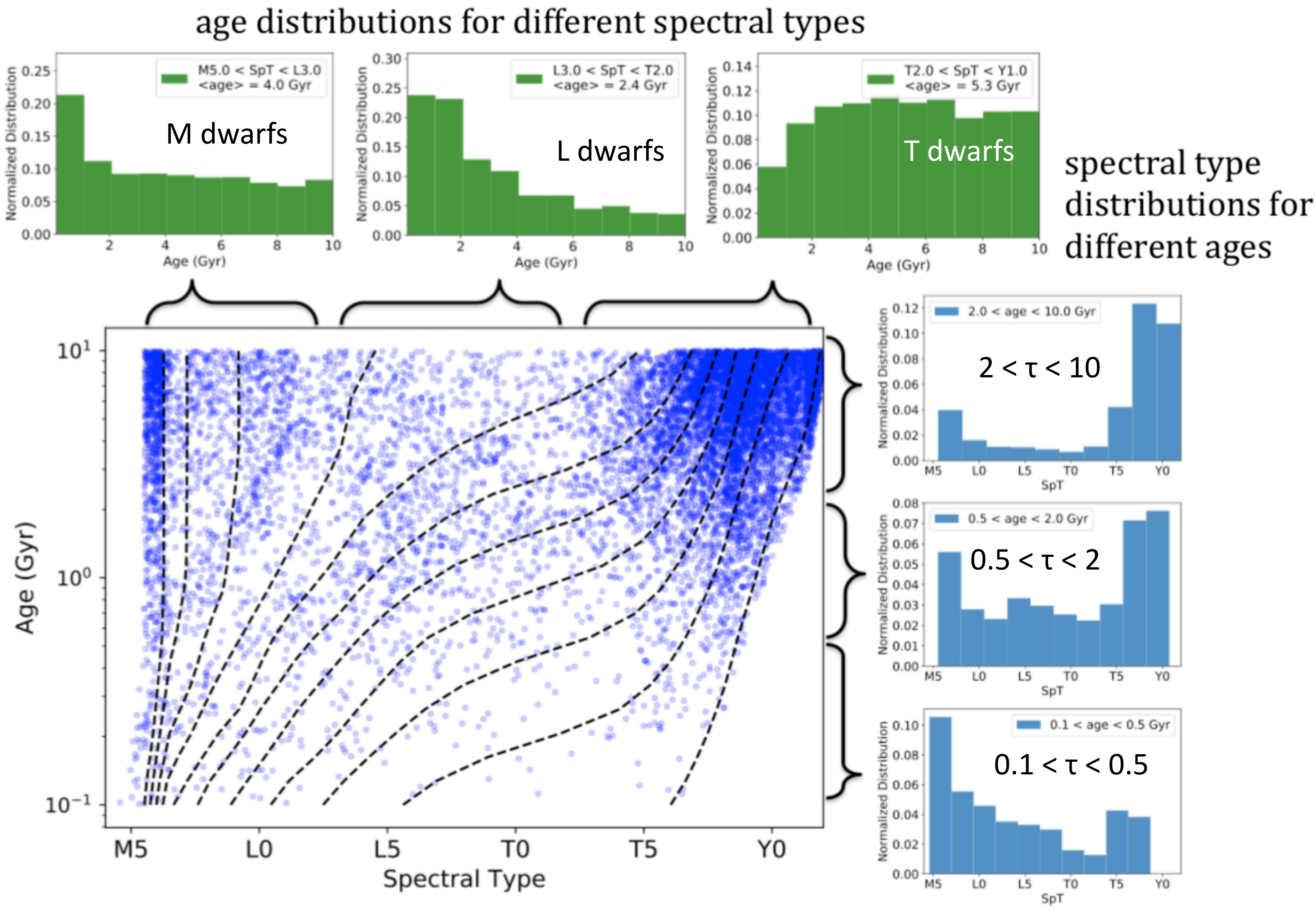

There is some tension between LF and microlens IMF measures

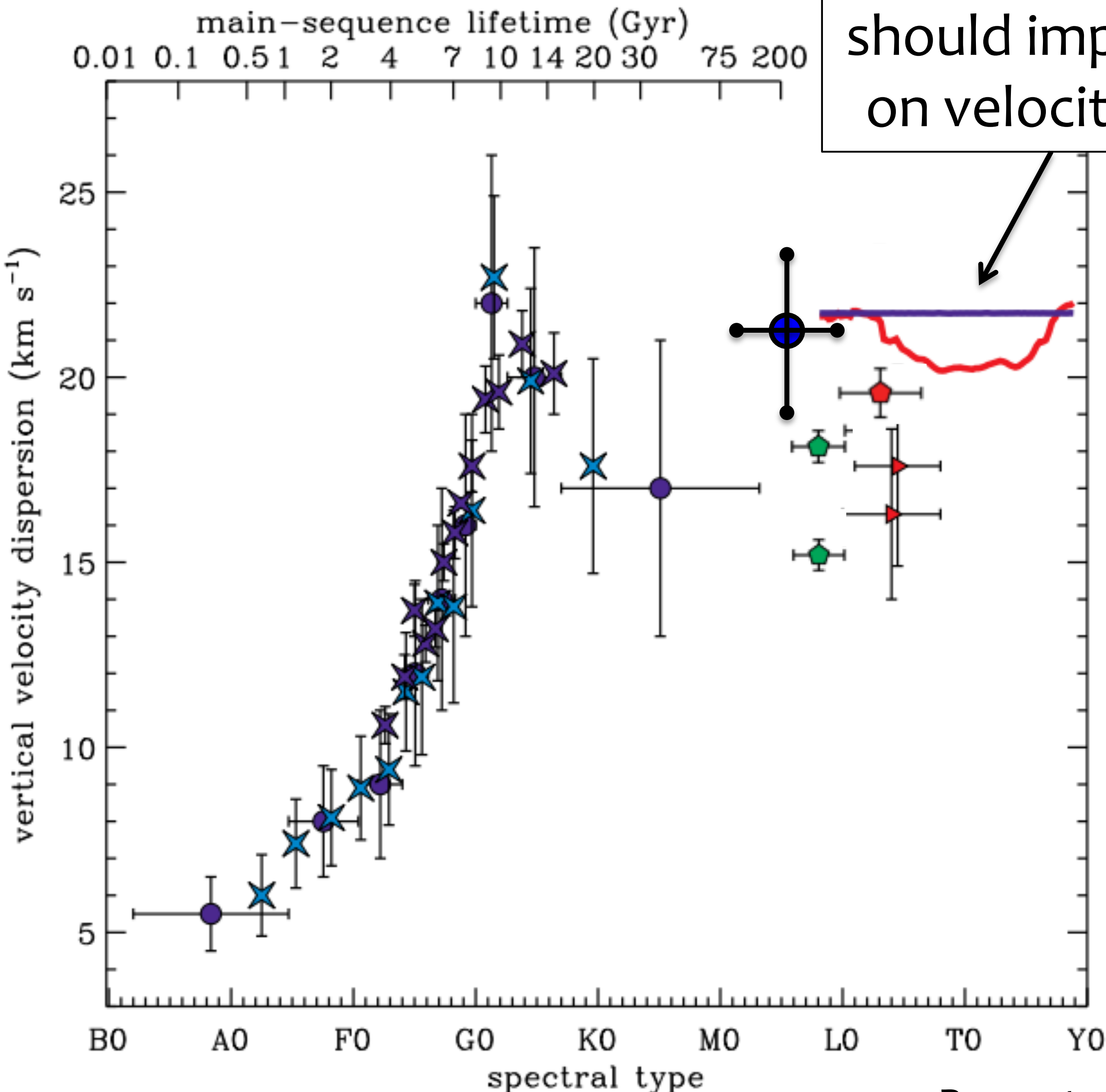
Brown dwarfs will dominate microlens events with $t_E$ < few days => WFIRST will make a major contribution here

Wegg et al. (2018)

# 2

# Exploiting brown dwarf evolution to probe star formation history

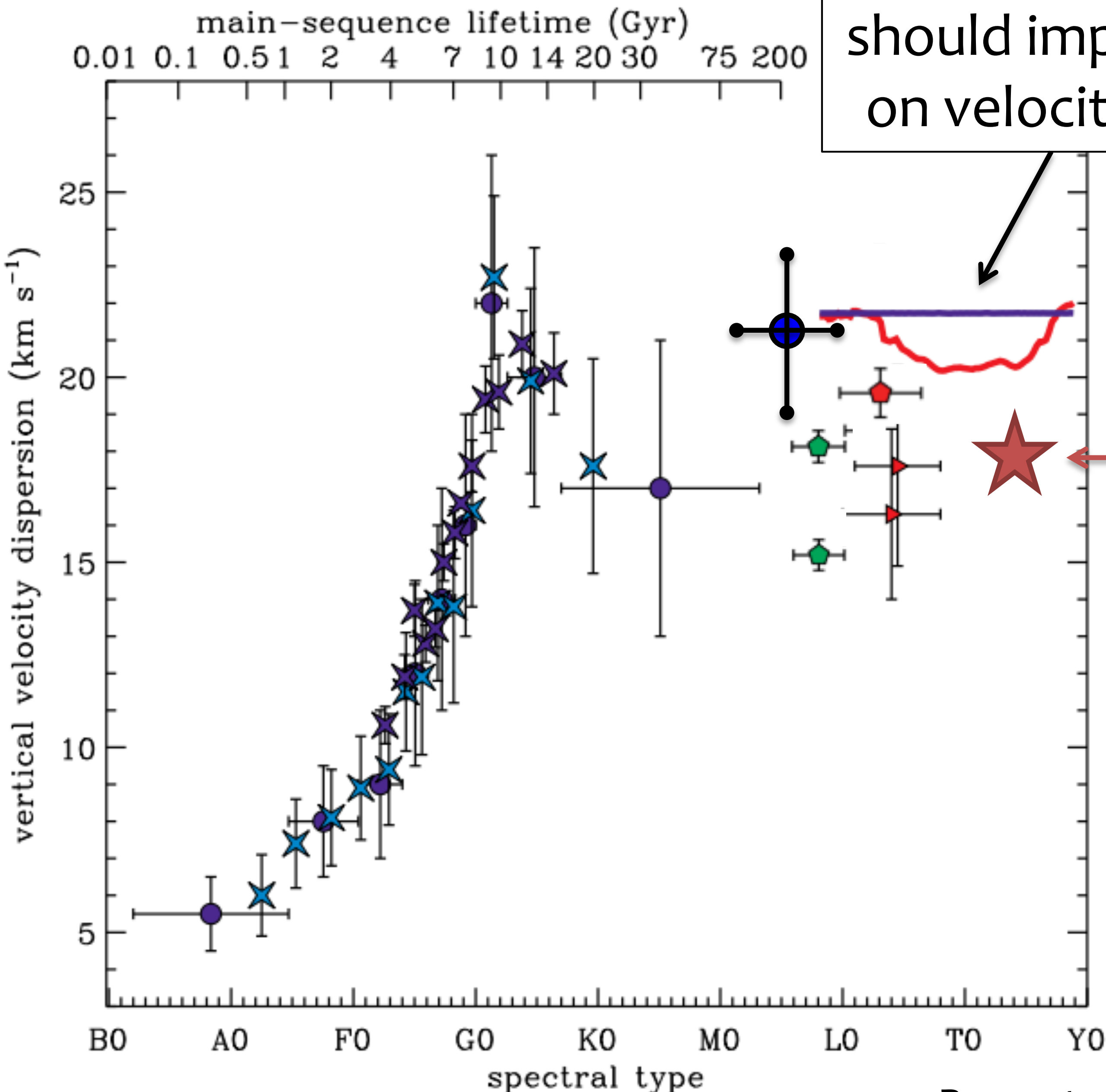

age distributions for different spectral types
M5.0 < SpT < L3.0
<age> = 4.0 Gyr
M dwarfs
L3.0 < SpT < T2.0
<age> = 2.4 Gyr
L dwarfs
T2.0 < SpT < Y1.0
<age> = 5.3 Gyr
T dwarfs
Normalized Distribution
Age (Gyr)
spectral type distributions for different ages
2.0 < age < 10.0 Gyr
2 < τ < 10
0.5 < age < 2.0 Gyr
0.5 < τ < 2
0.1 < age < 0.5 Gyr
0.1 < τ < 0.5
SpT
M5
L0
L5
T0
T5
Y0
Spectral Type



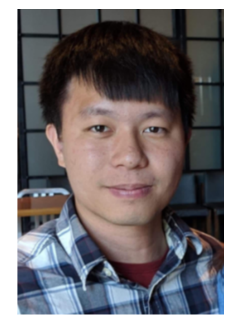

Brown dwarf evolution should impose structure on velocity dispersions

Ryan et al. (2017)
see Russell's poster!

Brown dwarf evolution should impose structure on velocity dispersions




Hsu et al. (in prep)



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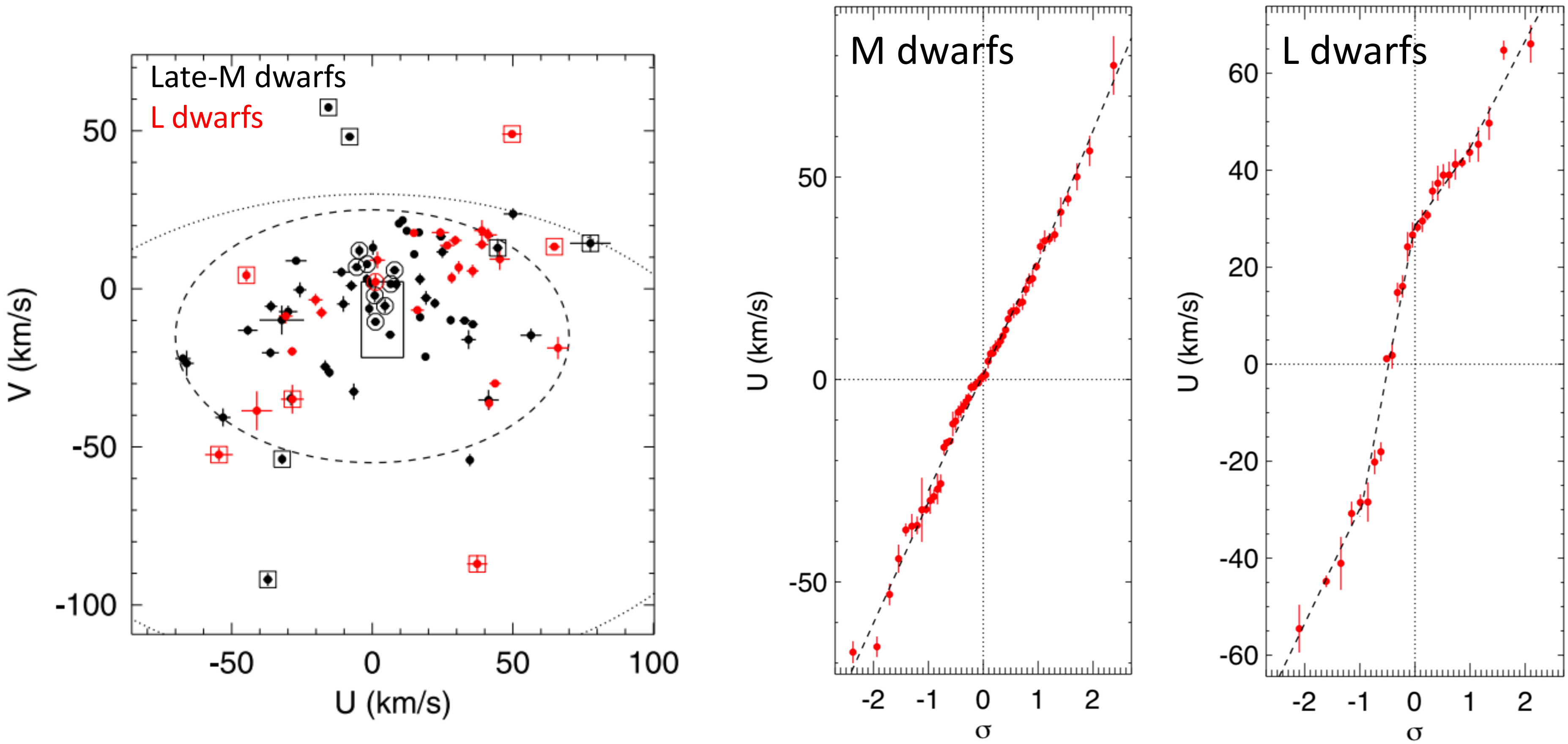
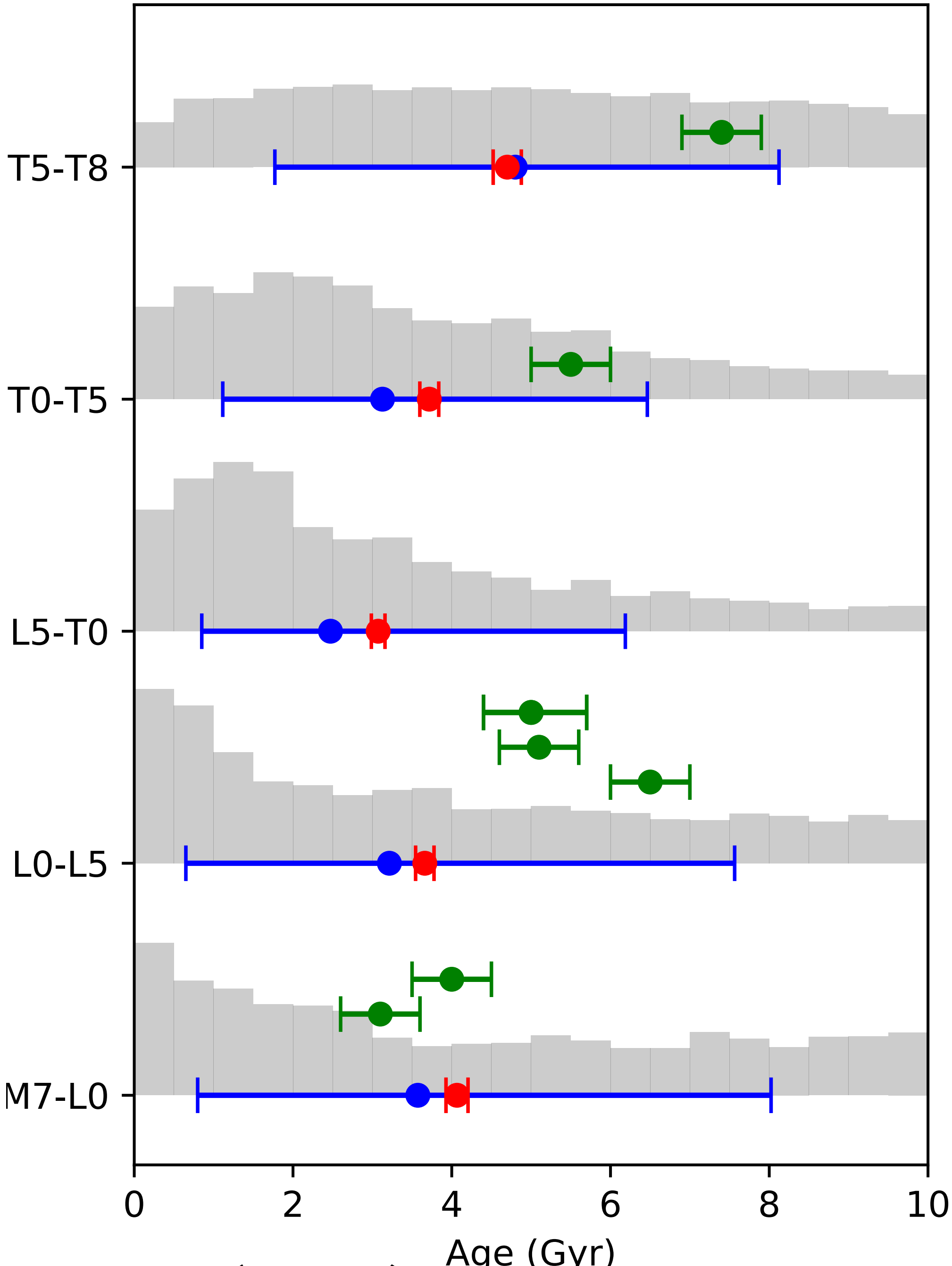



Kinematic analyses suggest that nearby late-M dwarfs are *younger* (less dispersed) than L dwarfs

(Reiners & Basri 2009; Seifahrt et al. 2010; Blake et al. 2012; Burgasser et al. 2015)

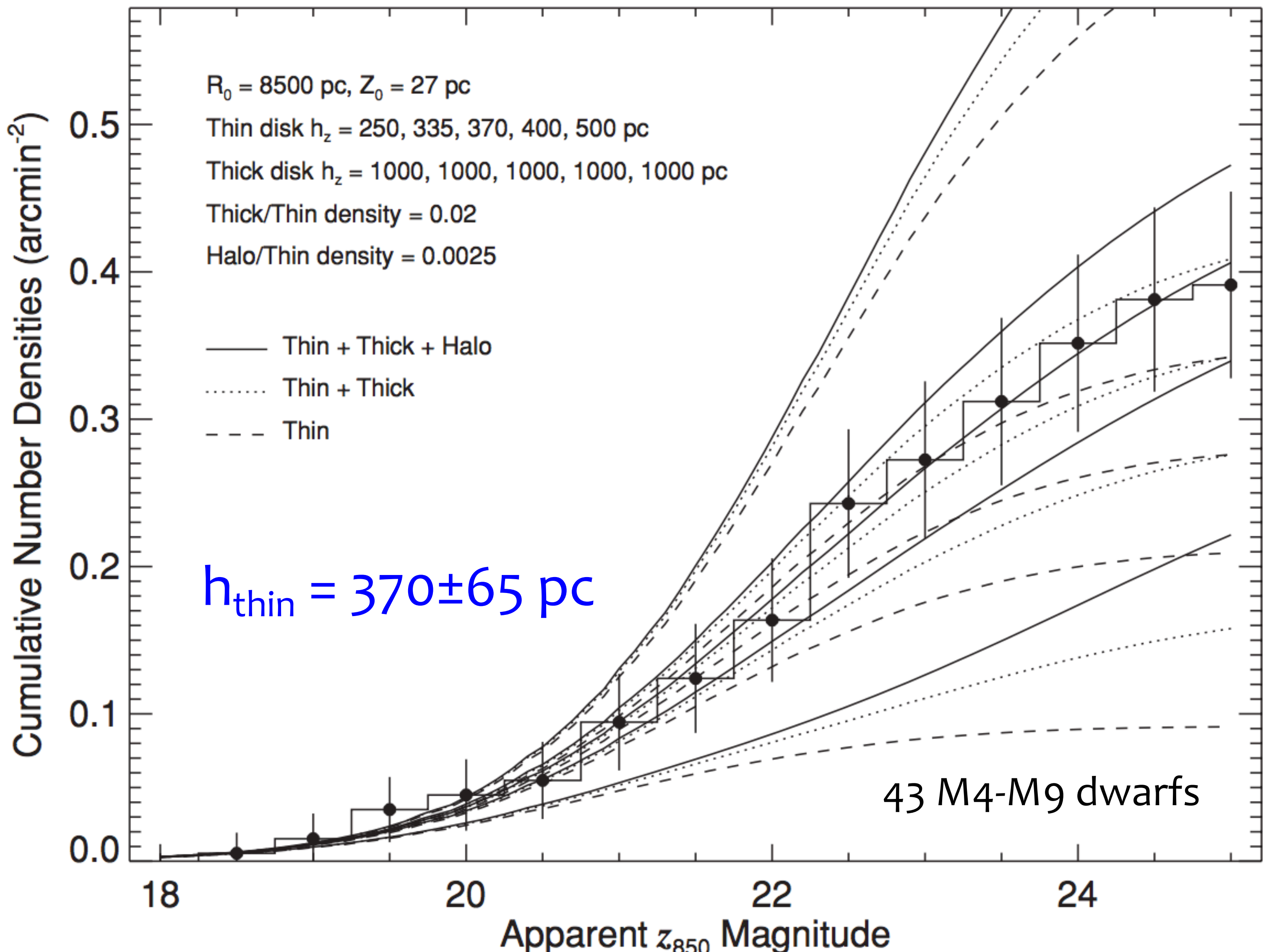



Velocity dispersions are significantly discrepant from the same simulations that correctly reproduce the local luminosity function

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

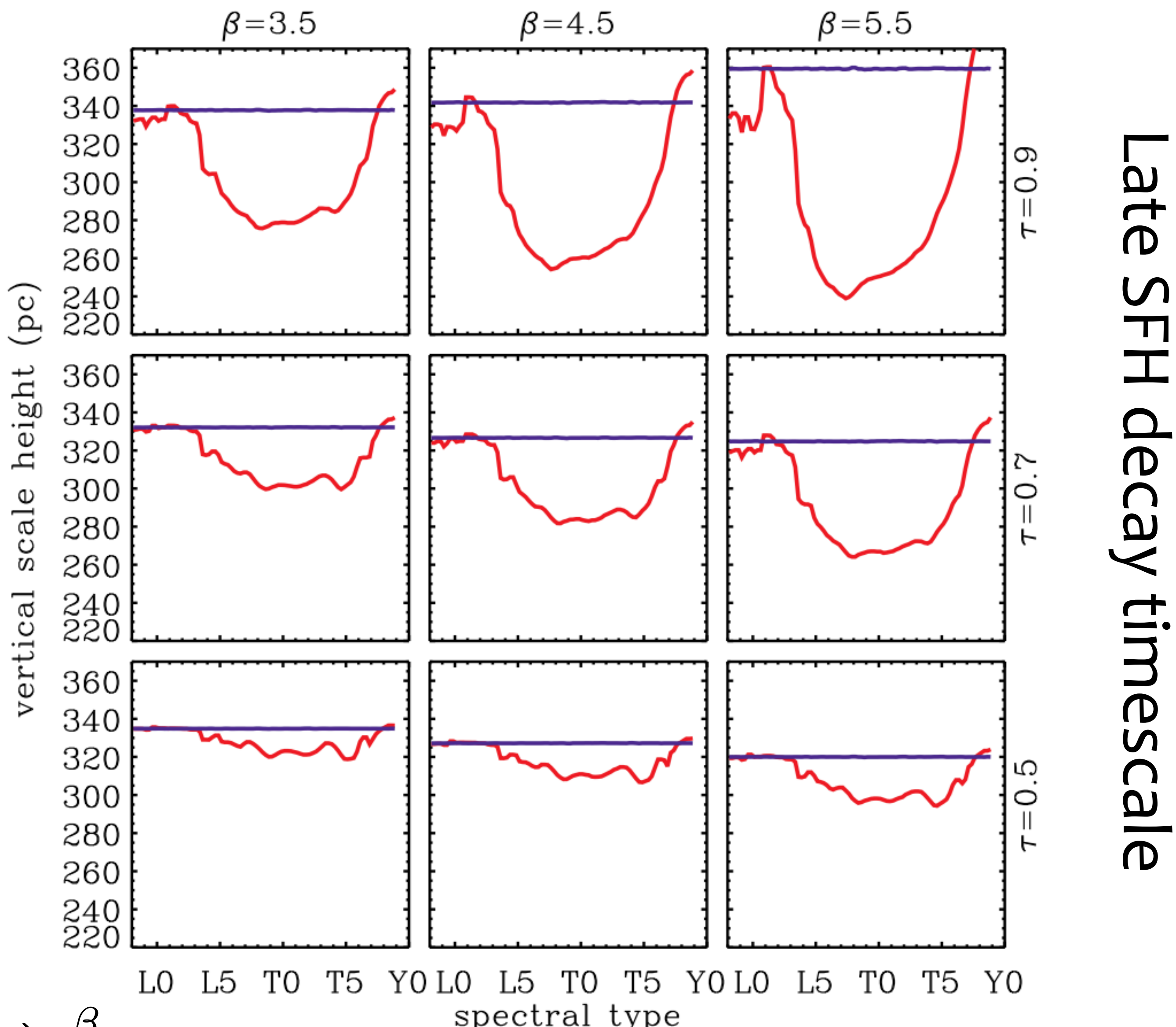
Burgasser et al. (in prep)

# A WFIRST approach: brown dwarf Galactic scale heights




Pirzkal et al. (2009)
HST-PEARS

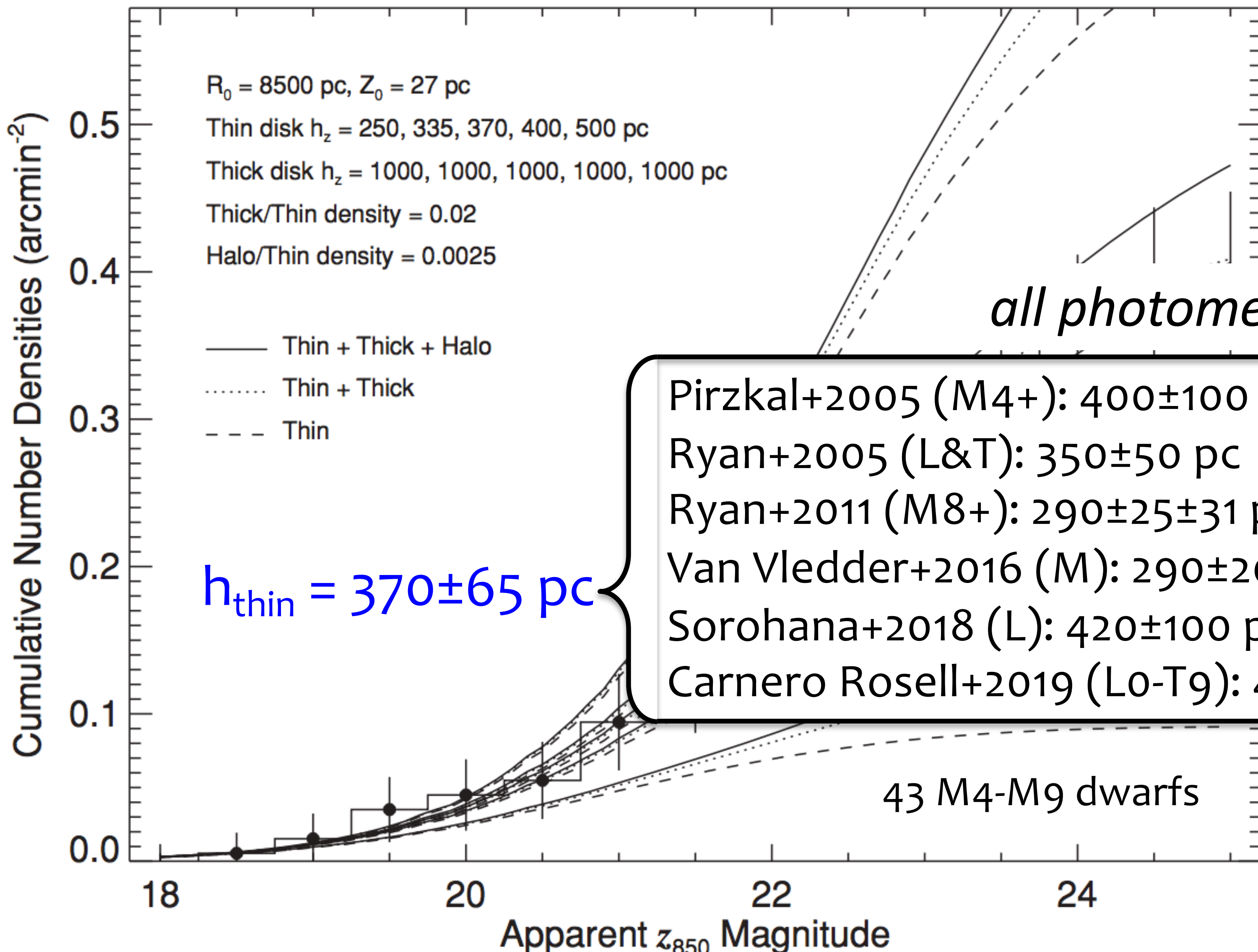
# Early SFH ramp-up




$$SFH \propto \left(\frac{t}{\tau}\right)^{\beta} e^{-t/\tau}$$

Ryan et al. (2017)
see Russell's poster!

# A WFIRST approach: brown dwarf Galactic scale heights




*all photometric!*

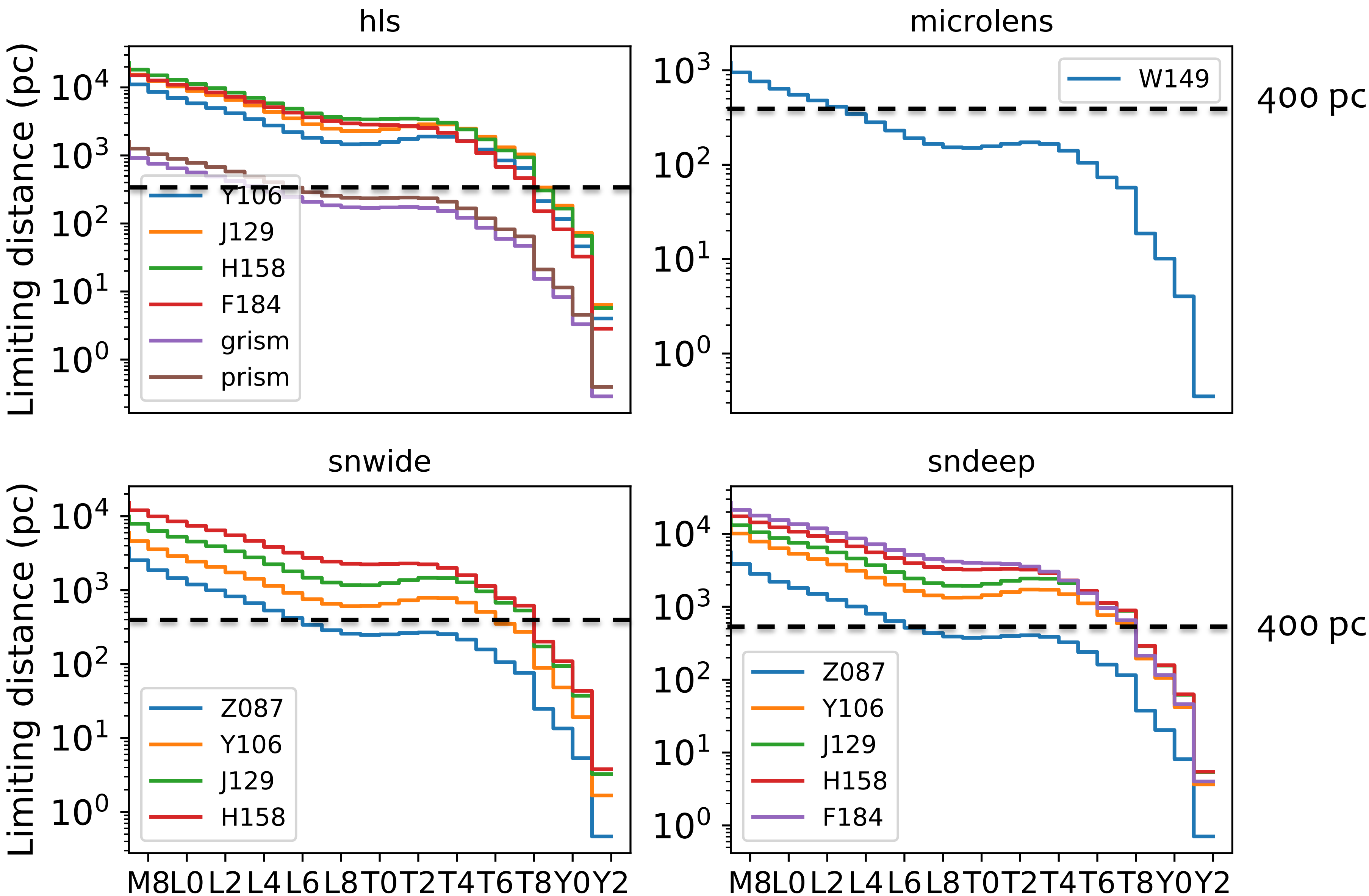
$h_{thin}$ = 370±65 pc

Pirzkal+2005 (M4+): 400±100 pc
Ryan+2005 (L&T): 350±50 pc
Ryan+2011 (M8+): 290±25±31 pc
Van Vledder+2016 (M): 290±20 pc
Sorohana+2018 (L): 420±100 pc
Carnero Rosell+2019 (L0-T9): 450 pc

43 M4-M9 dwarfs

Pirzkal et al. (2009)
HST-PEARS

# WFIRST will reach L & T brown dwarfs at distances & numbers sufficient to measure Galactic scale heights



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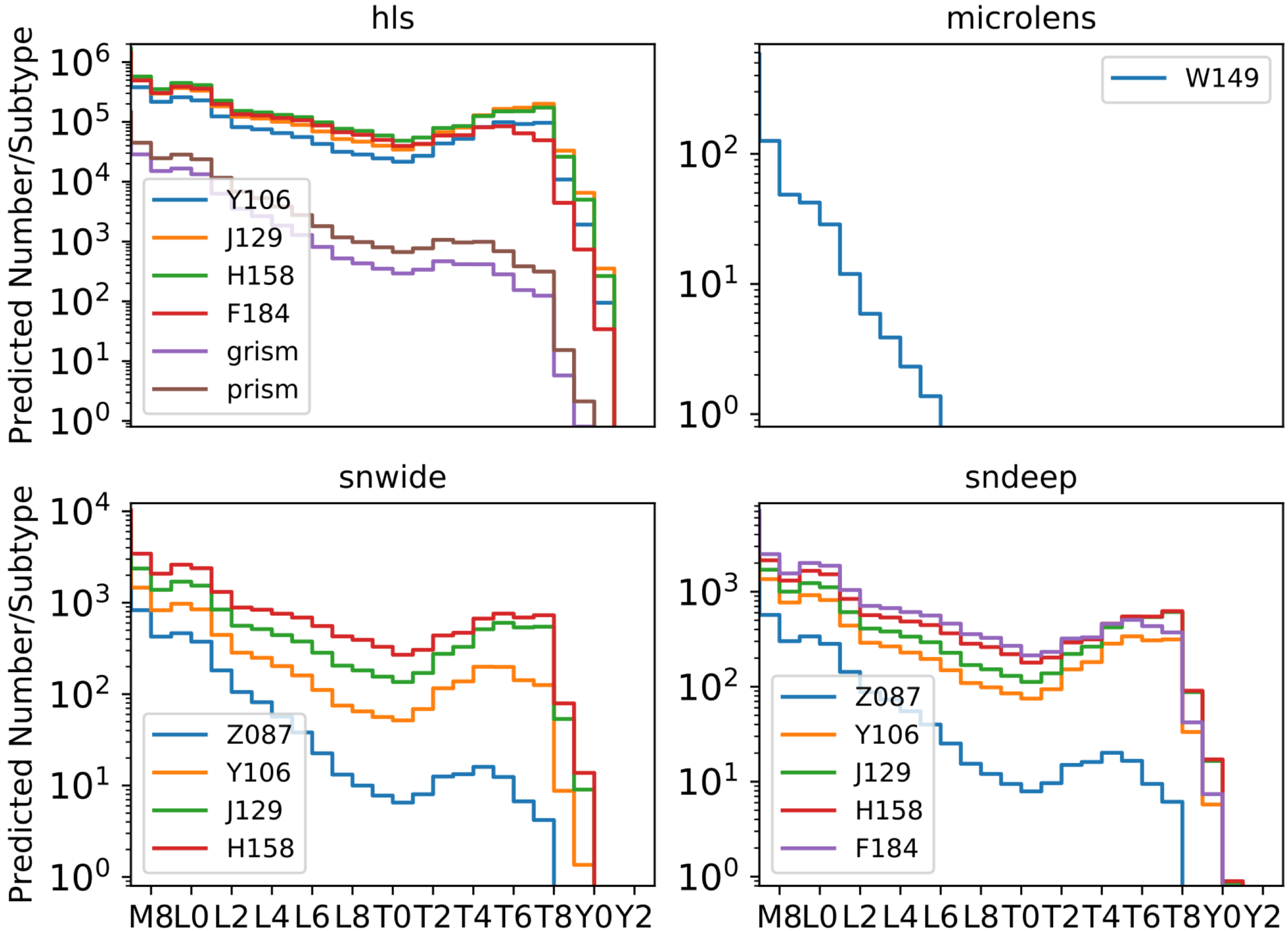

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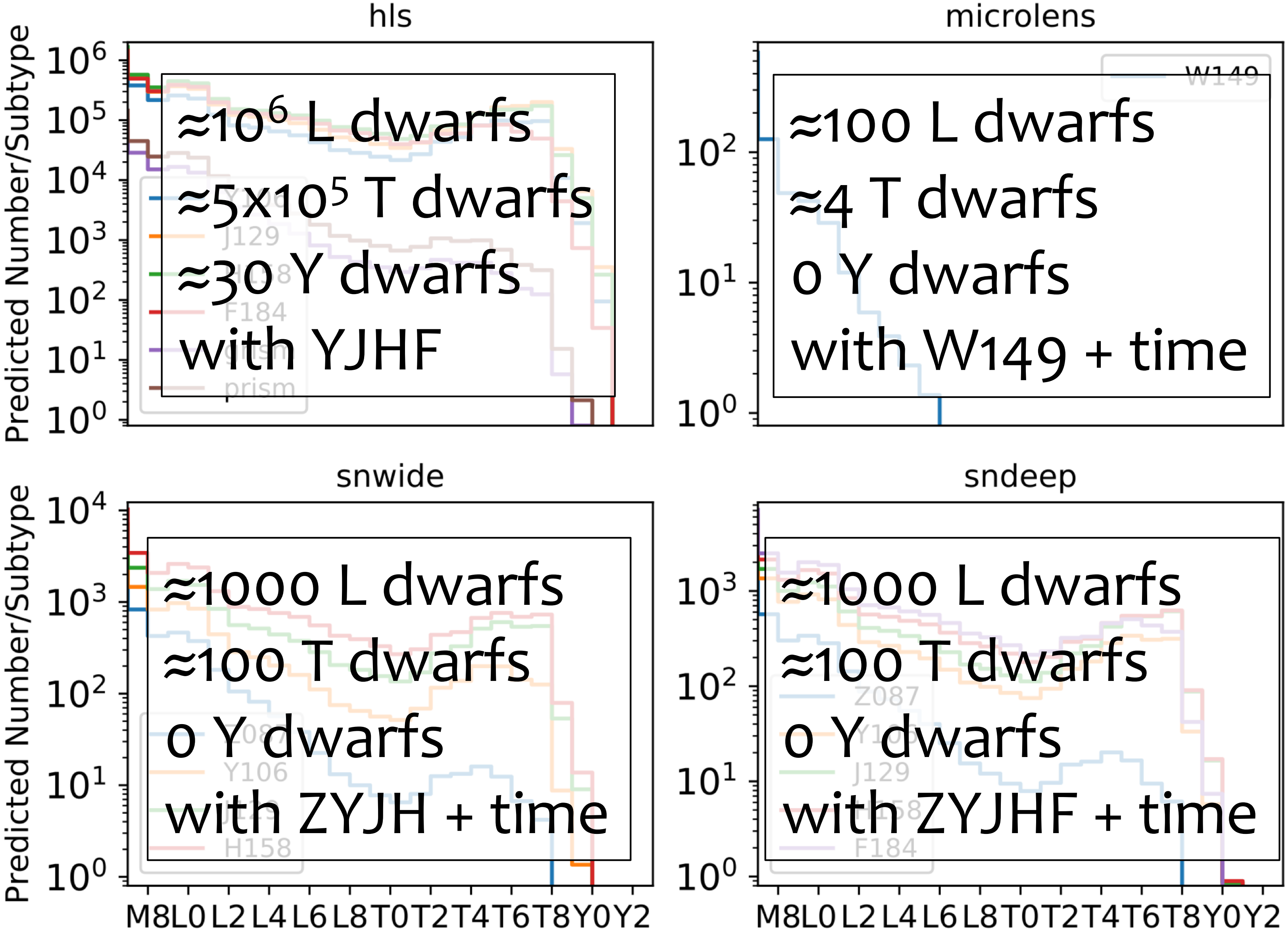
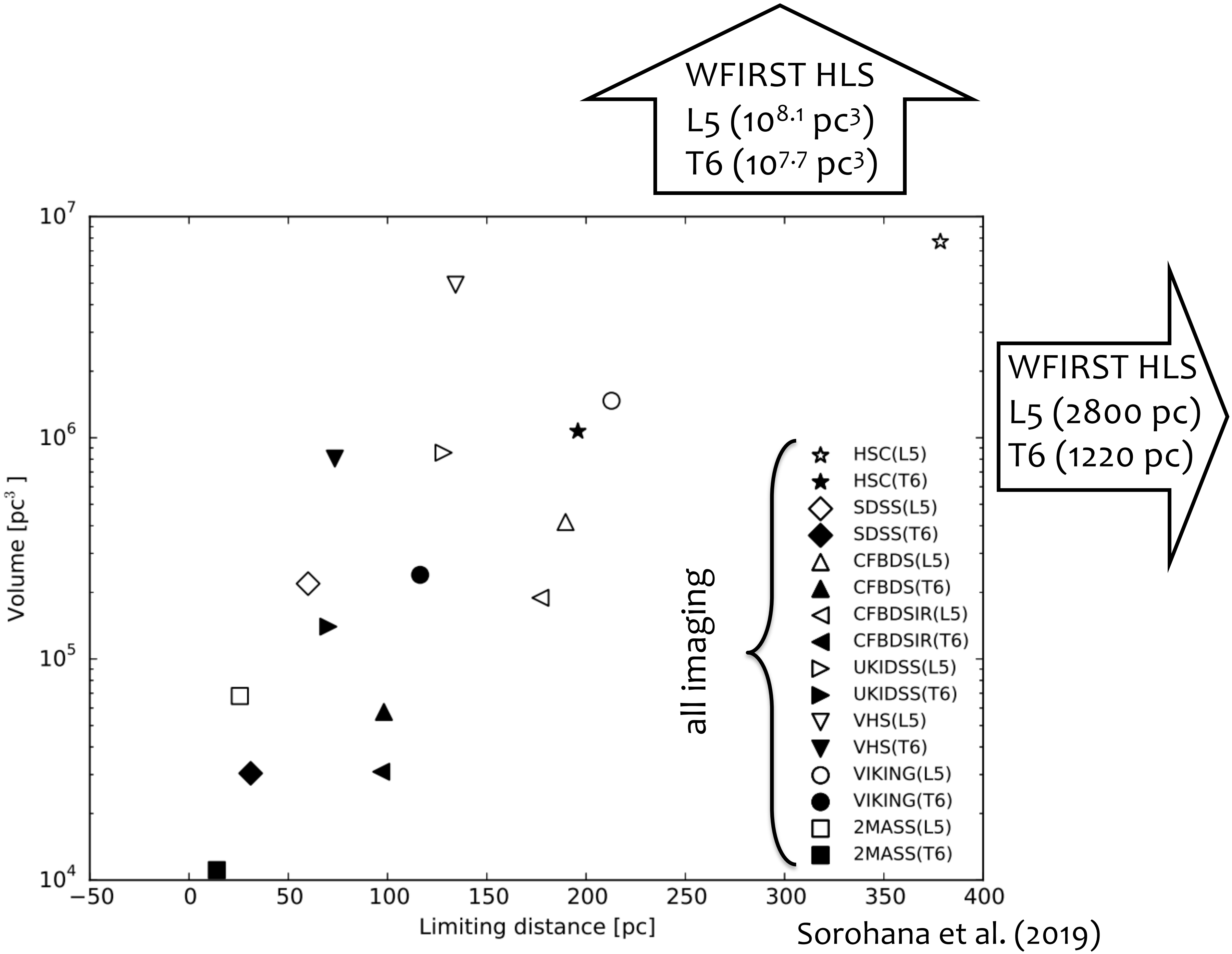
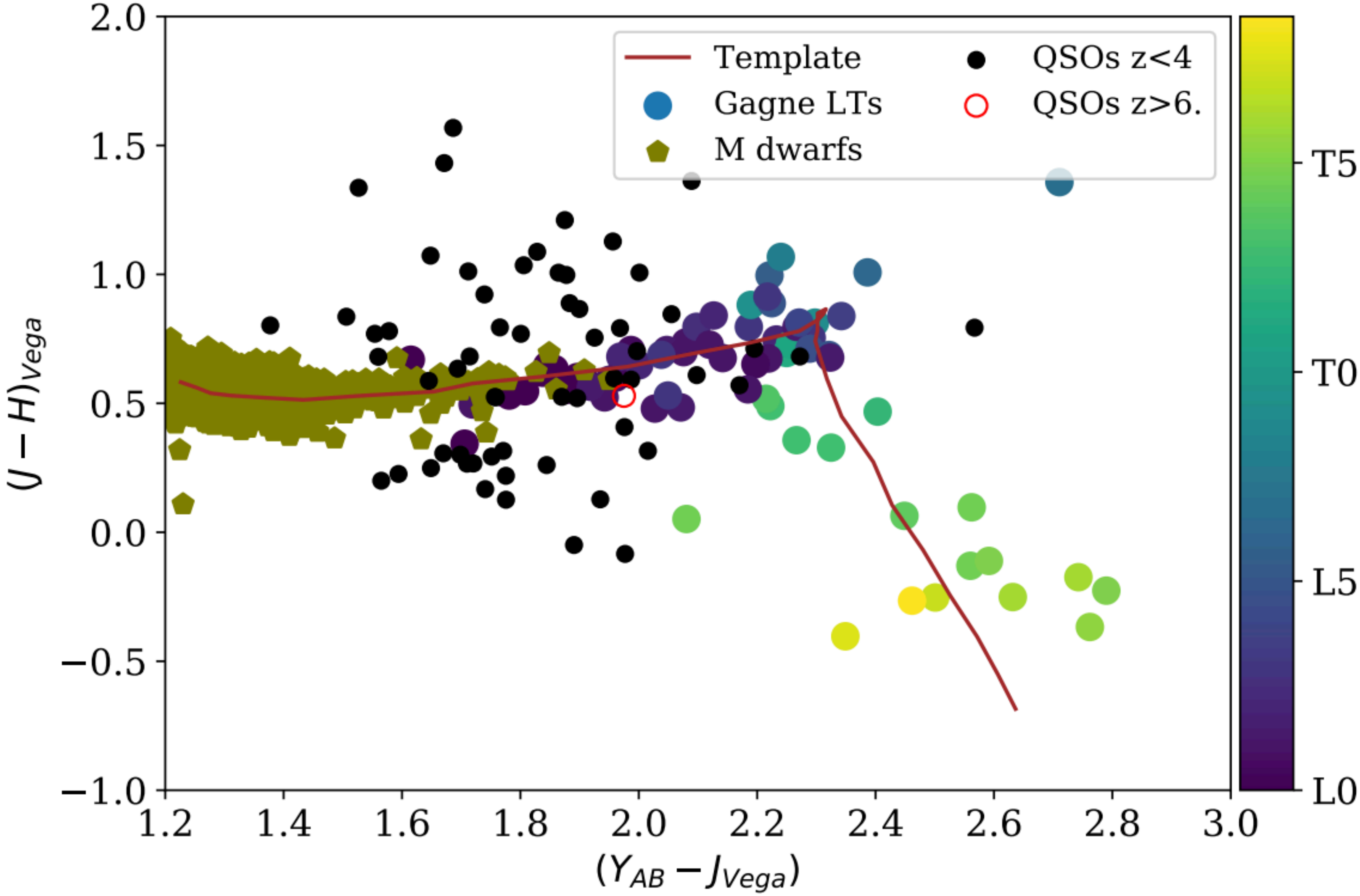
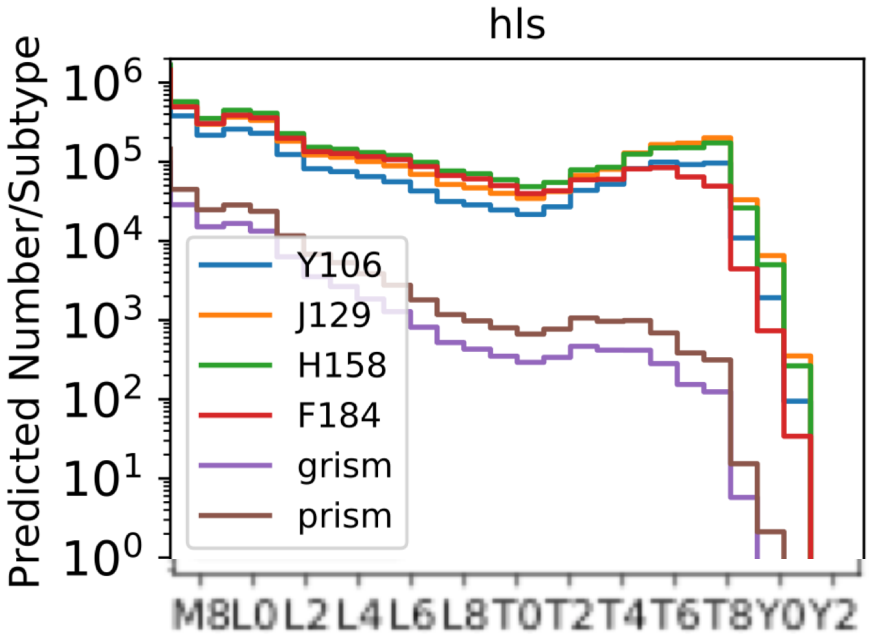




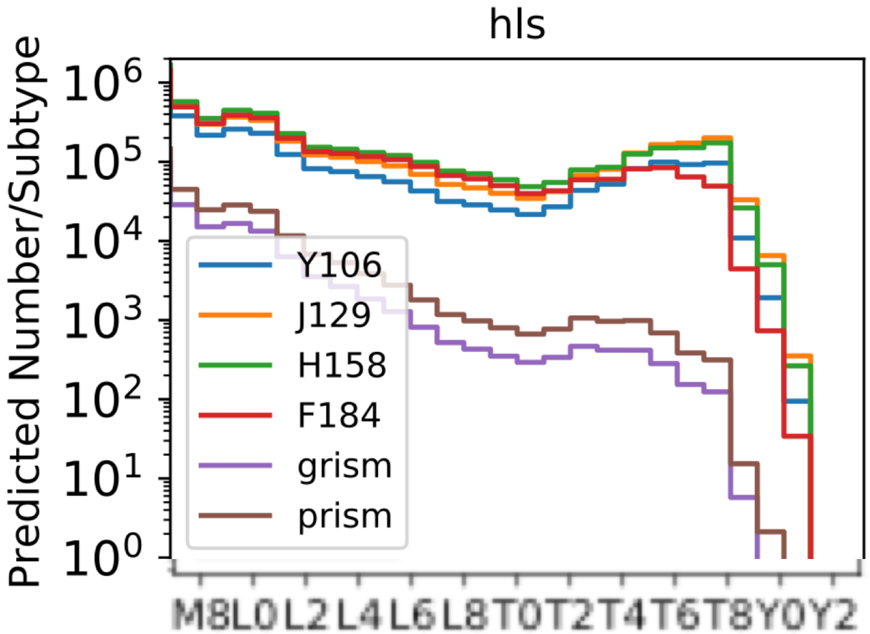
WFIRST HLS
L5 ($10^{8.1}$ pc$^3$)
T6 ($10^{7.7}$ pc$^3$)
WFIRST HLS
L5 (2800 pc)
T6 (1220 pc)
Volume [pc$^3$]
Limiting distance [pc]
all imaging
HSC(L5)
HSC(T6)
SDSS(L5)
SDSS(T6)
CFBDS(L5)
CFBDS(T6)
CFBDSIR(L5)
CFBDSIR(T6)
UKIDSS(L5)
UKIDSS(T6)
VHS(L5)
VHS(T6)
VIKING(L5)
VIKING(T6)
2MASS(L5)
2MASS(T6)
Sorohana et al. (2019)




Carnero Rosell et al. (2019)




≈40,000 L dwarfs
≈3,000 T dwarfs
0 Y dwarfs
**with spectra**

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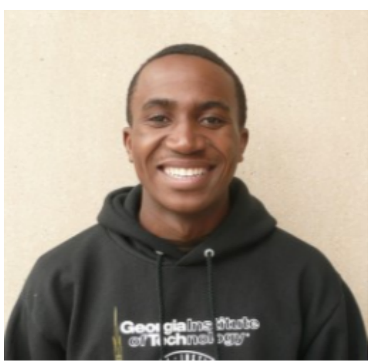
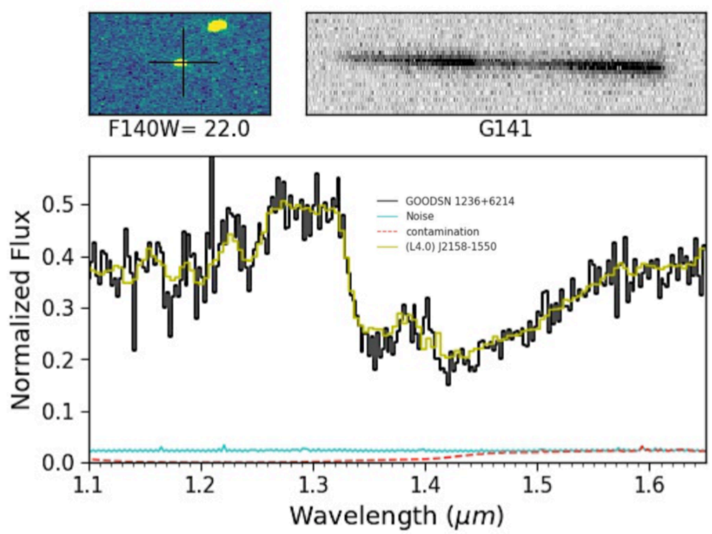
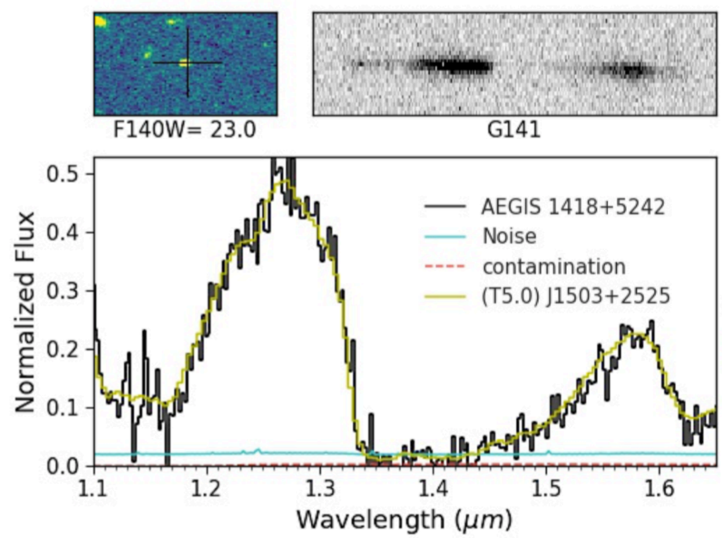
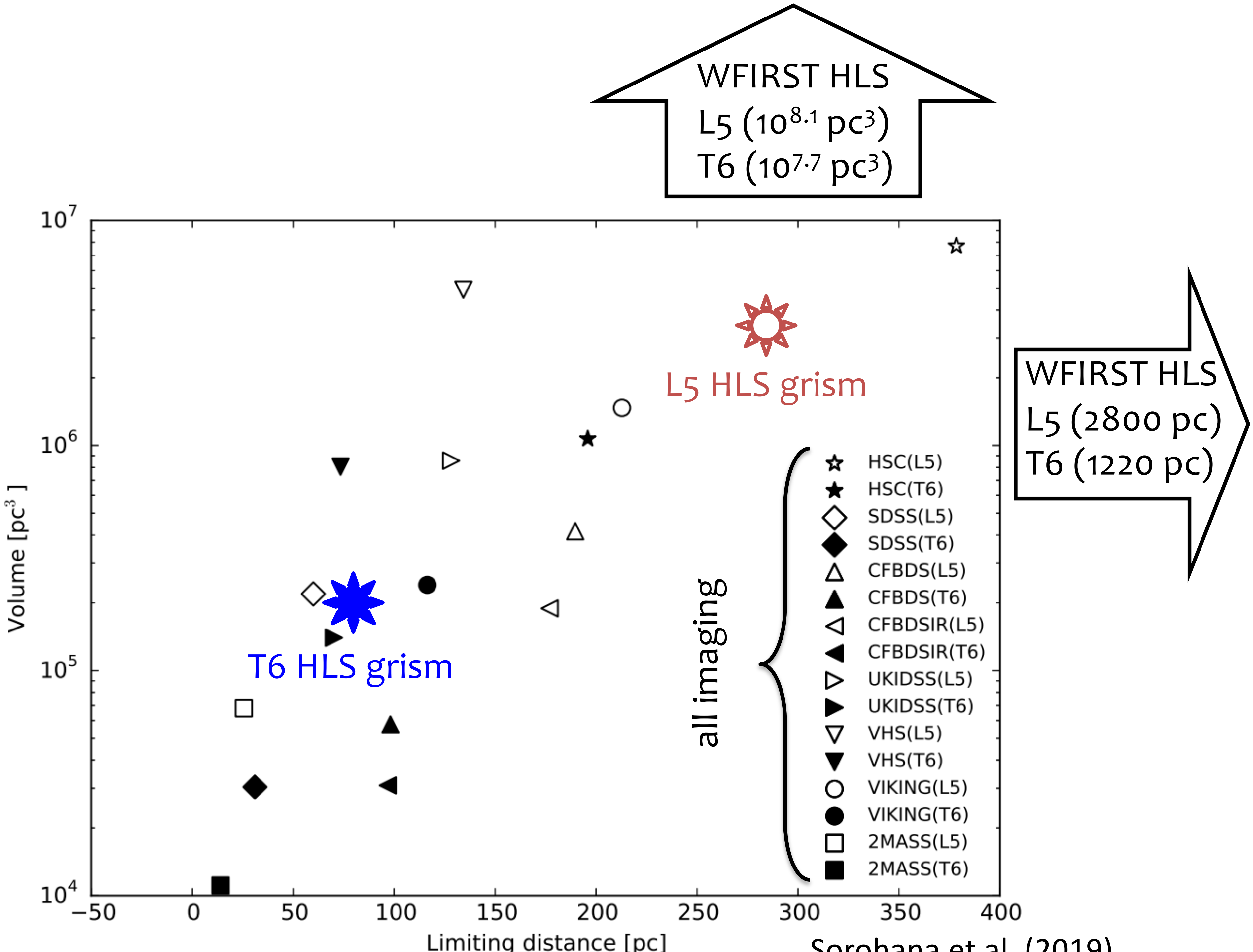


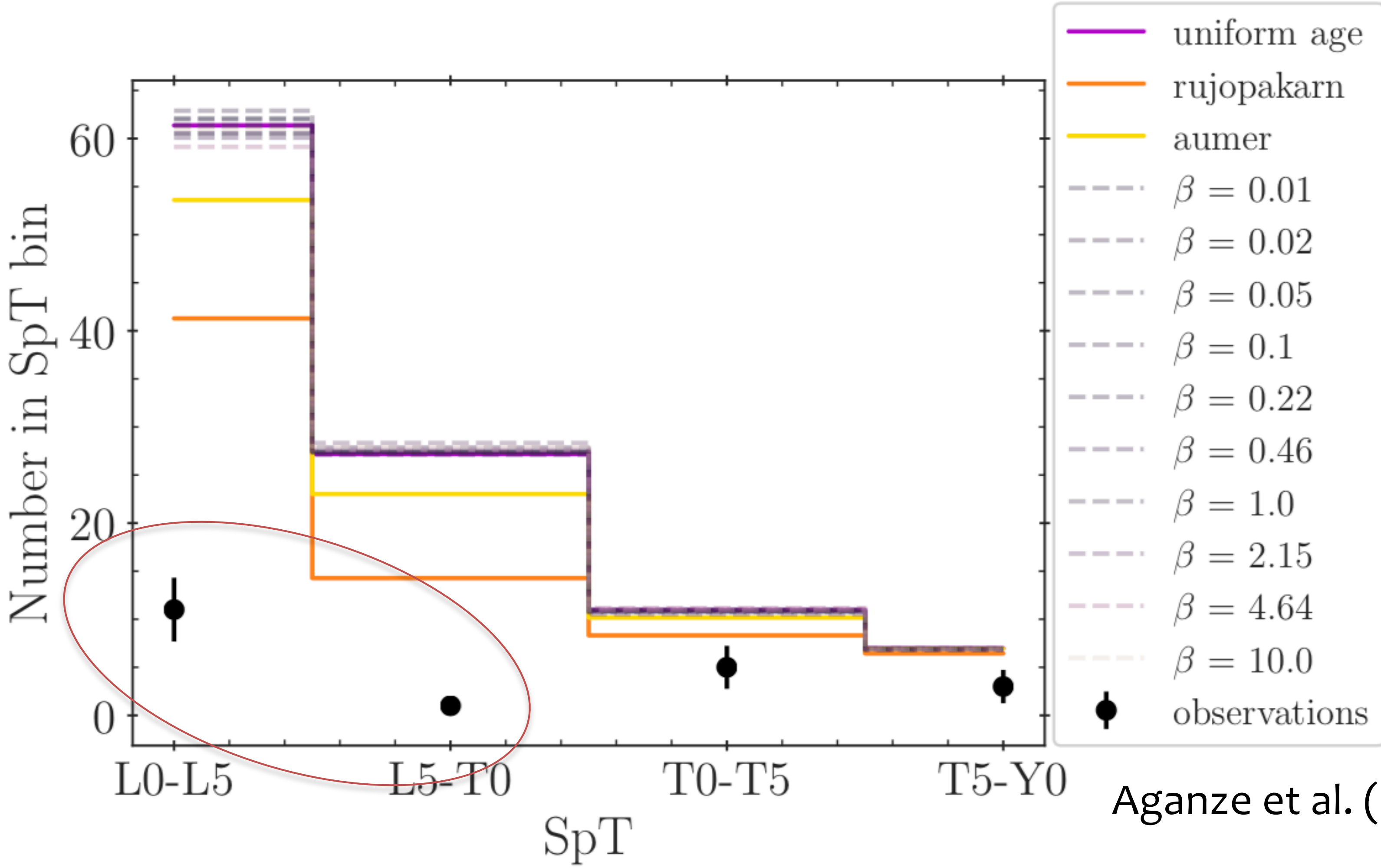
Aganze et al.
(in prep)






Sorohana et al. (2019)

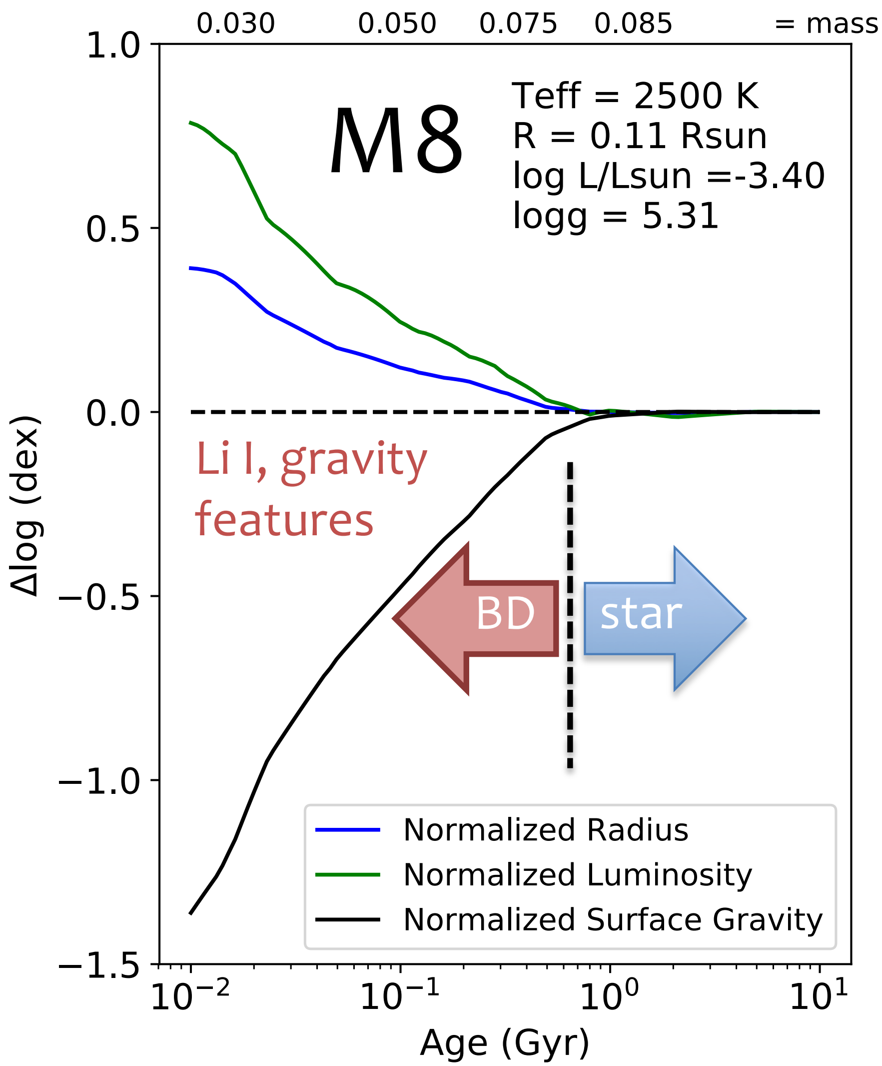



Aganze et al. (in prep)

HST WFC3 Parallels sample is severely below predicted yield
Is this a scaleheight signature? Additional evolutionary effects? A feature of star formation history? Selection effect?

# 3

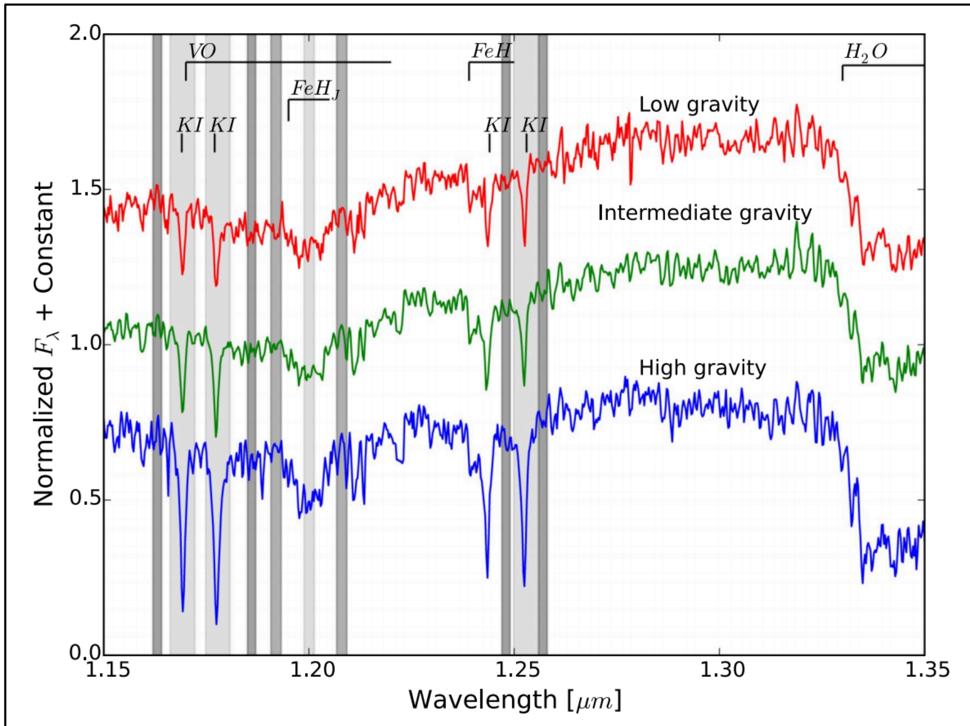
Better constraints on ages and compositions from spectroscopy



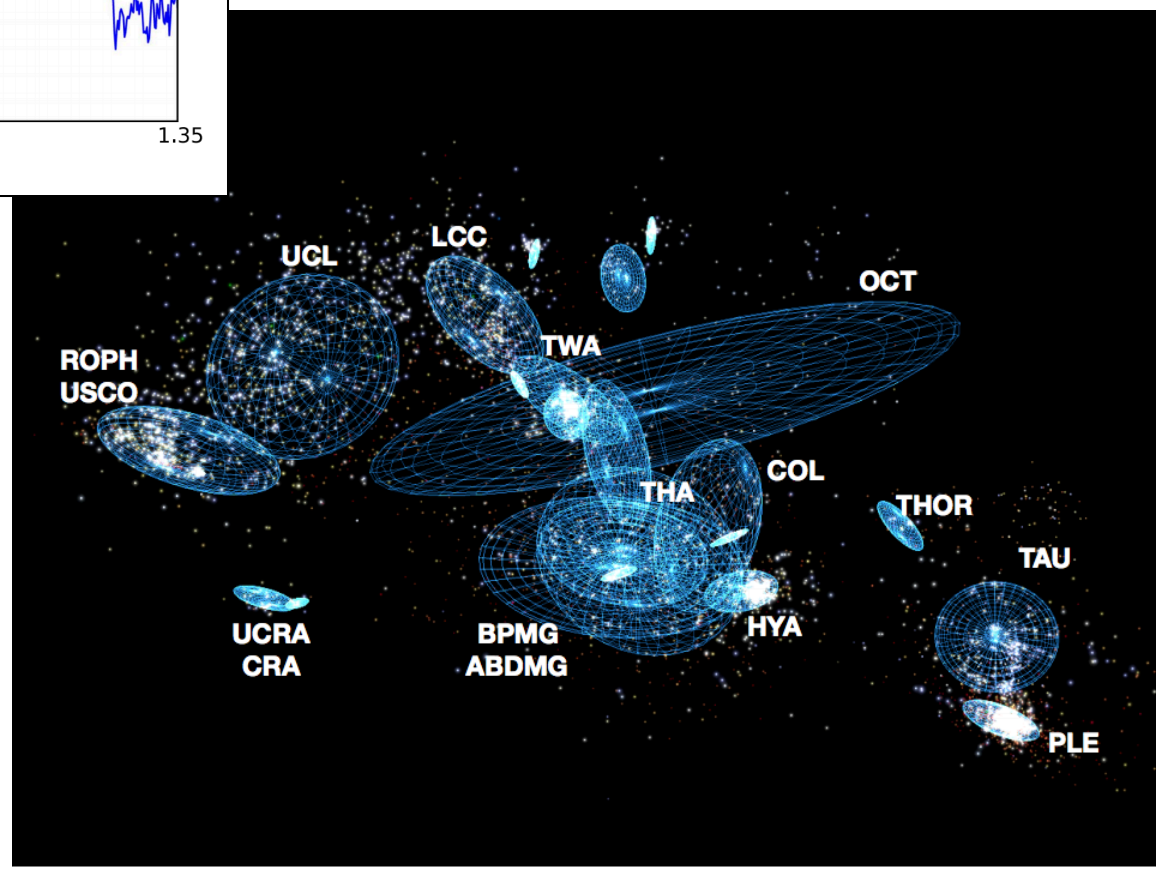

# Also not working:

- CMDs (too little evolution along MS, no post-MS)
- Gyrochronology (spindown times ≈ several Gyr)
- Magnetic activity (lack of spindown + neutral photospheres)

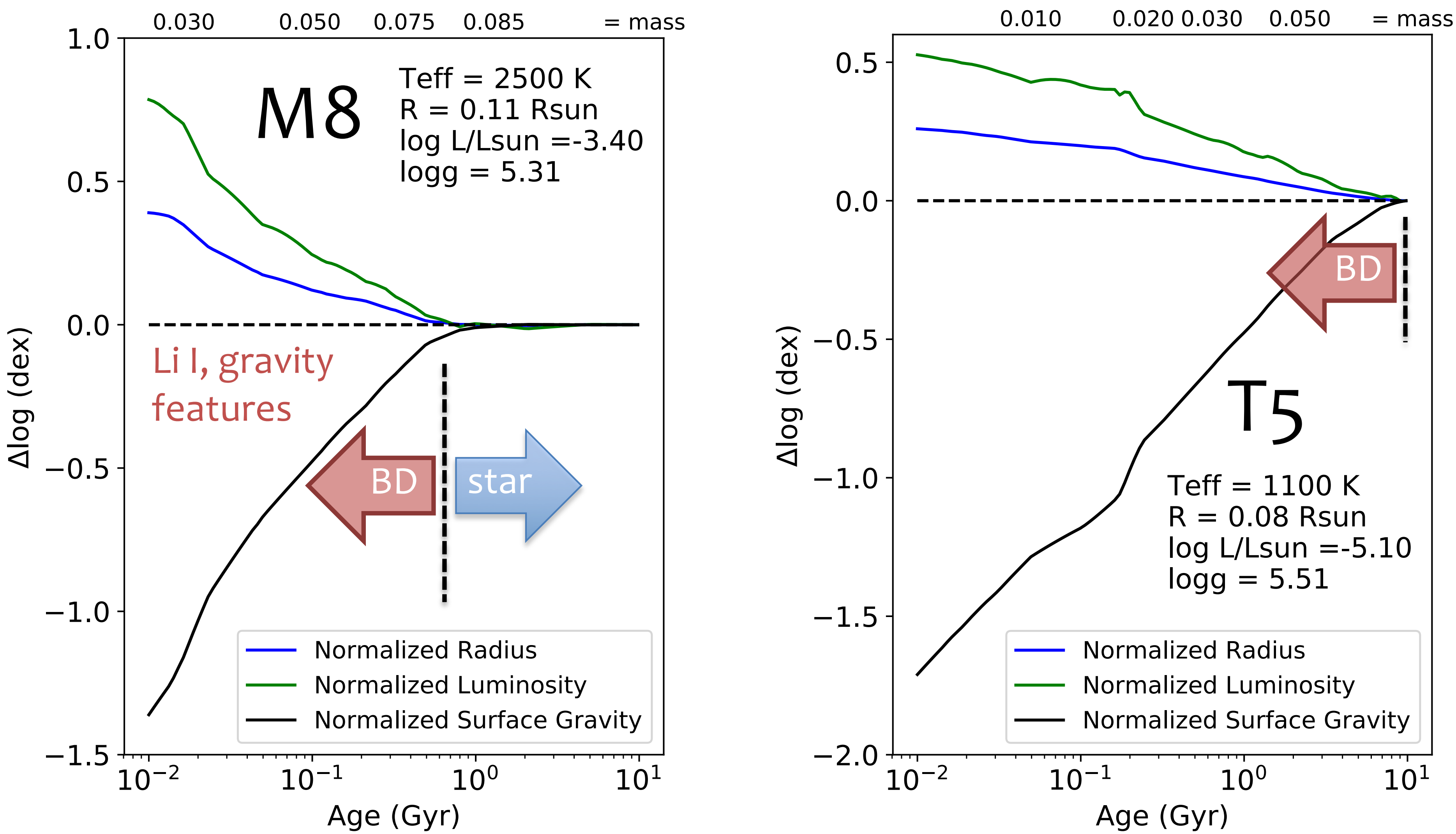
warm BDs are good clocks only at young ages



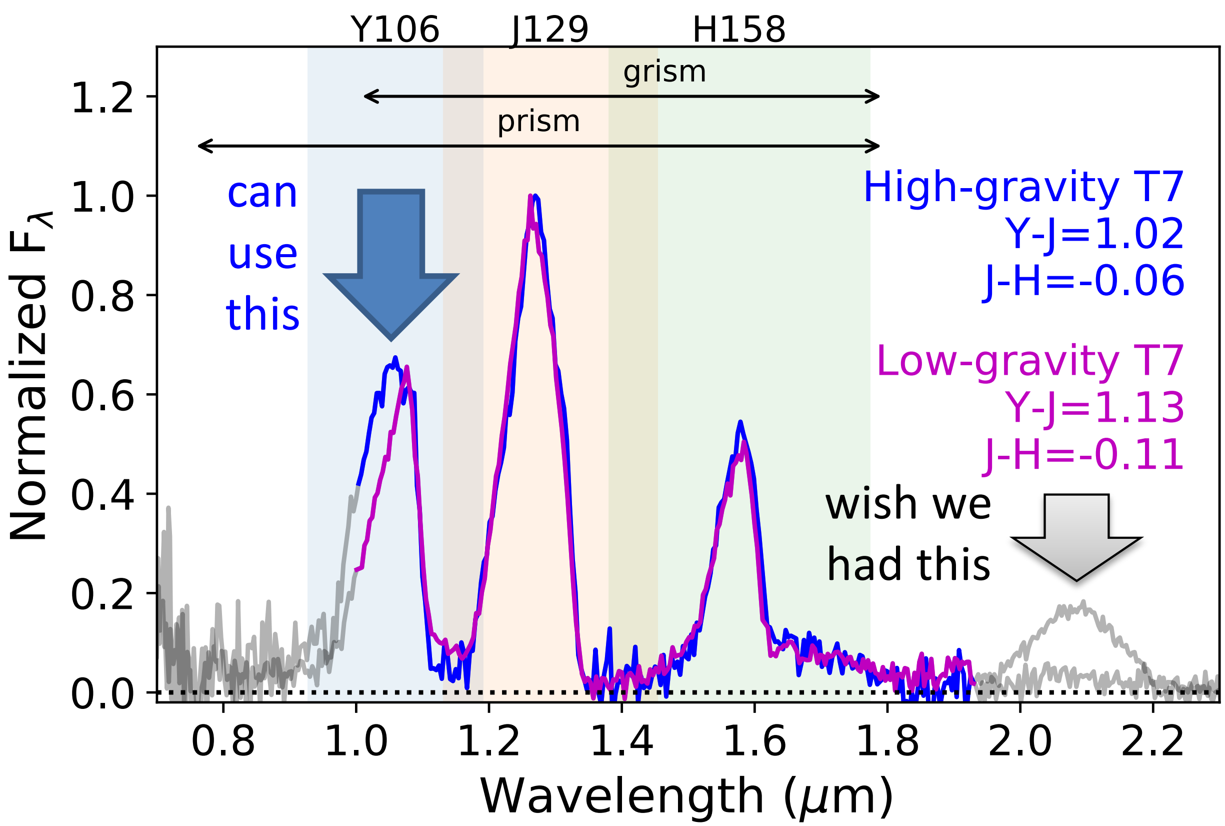

spectra: Martin et al. (2017; R = 2000)
Illustration: Faherty et al. Astro2020



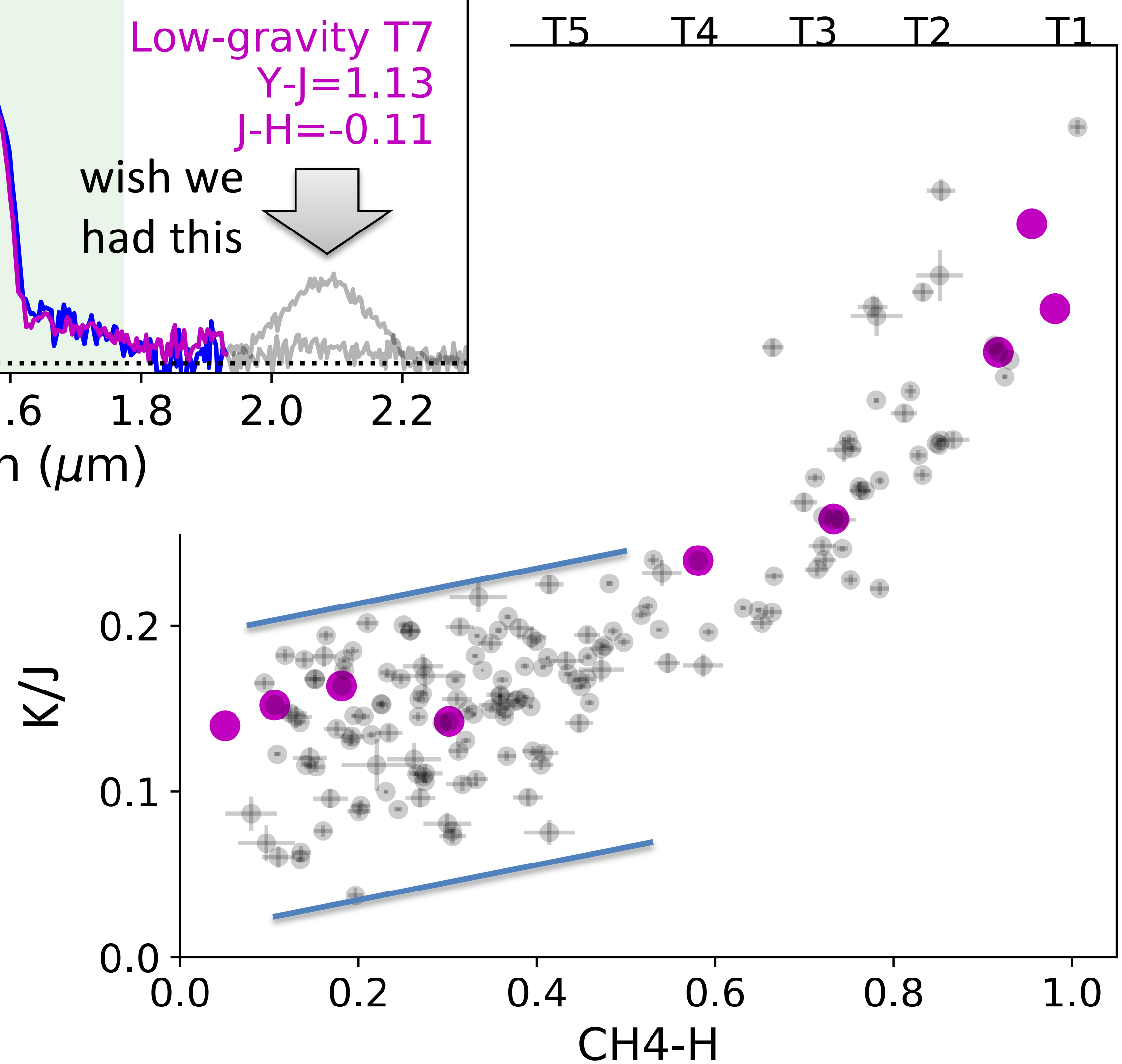

WFIRST prism/grism data will enable accurate classification of brown dwarfs and characterization of gravity/age & metallicity




cold brown dwarfs are excellent clocks!




cf. Burgasser et al. (2006)

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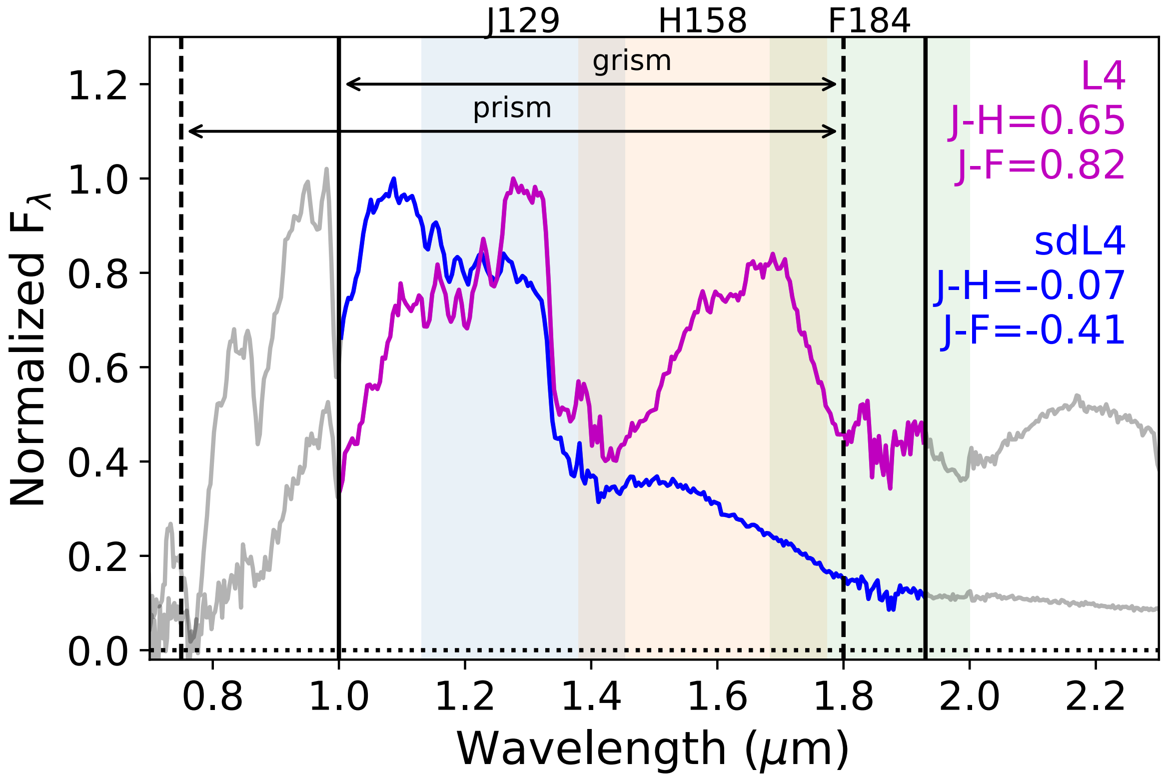
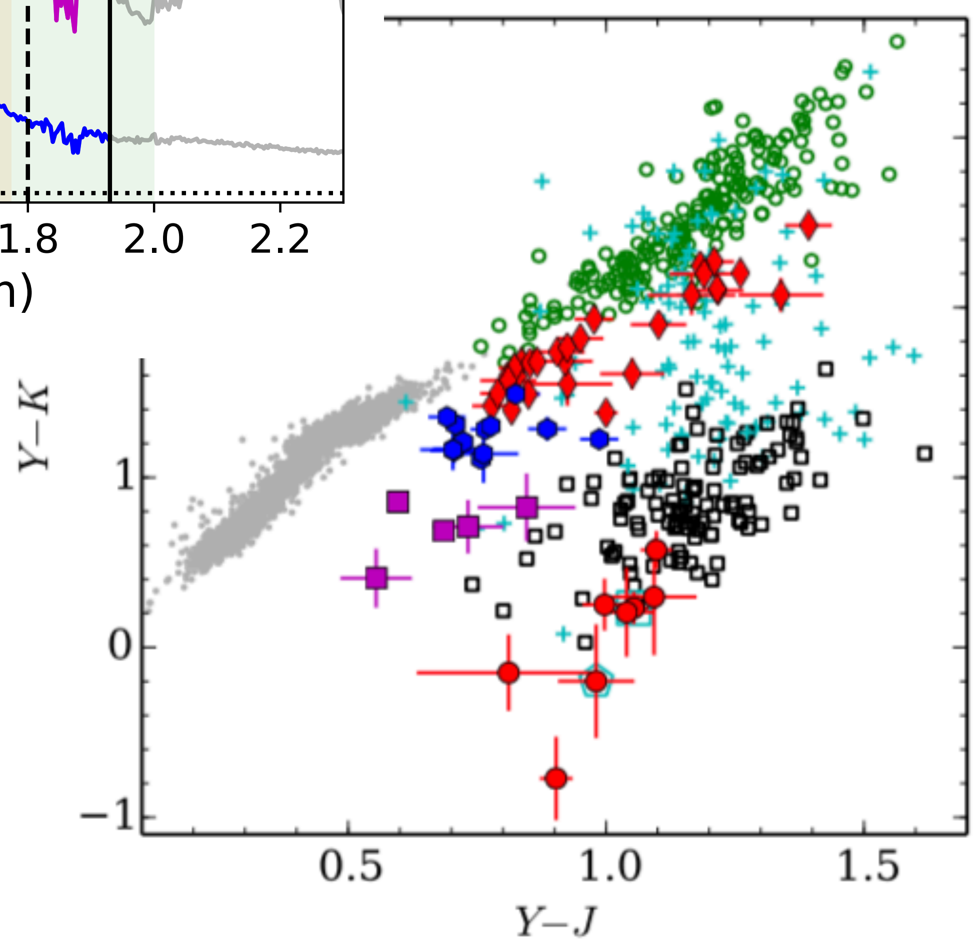



Zhang et al. (2019)




WFIRST prism/grism data will enable accurate classification of brown dwarfs and characterization of gravity/age & metallicity

# 4

…and much more

# Auxiliary Brown Dwarf Science

- Complete young cluster/association surveys down to planetary mass objects
- H-burning gap in old & globular clusters (GO)
- Halo brown dwarfs: 1000s L subdwarfs & 100s of T subdwarfs
- M/L dwarf IR variability for weather, flaring & rotation studies
- Brown dwarf multiples (resolved, μlens & astrometric) & companions (benchmarks)
- Astrometric sample that surpasses *GAIA* (for brown dwarfs)

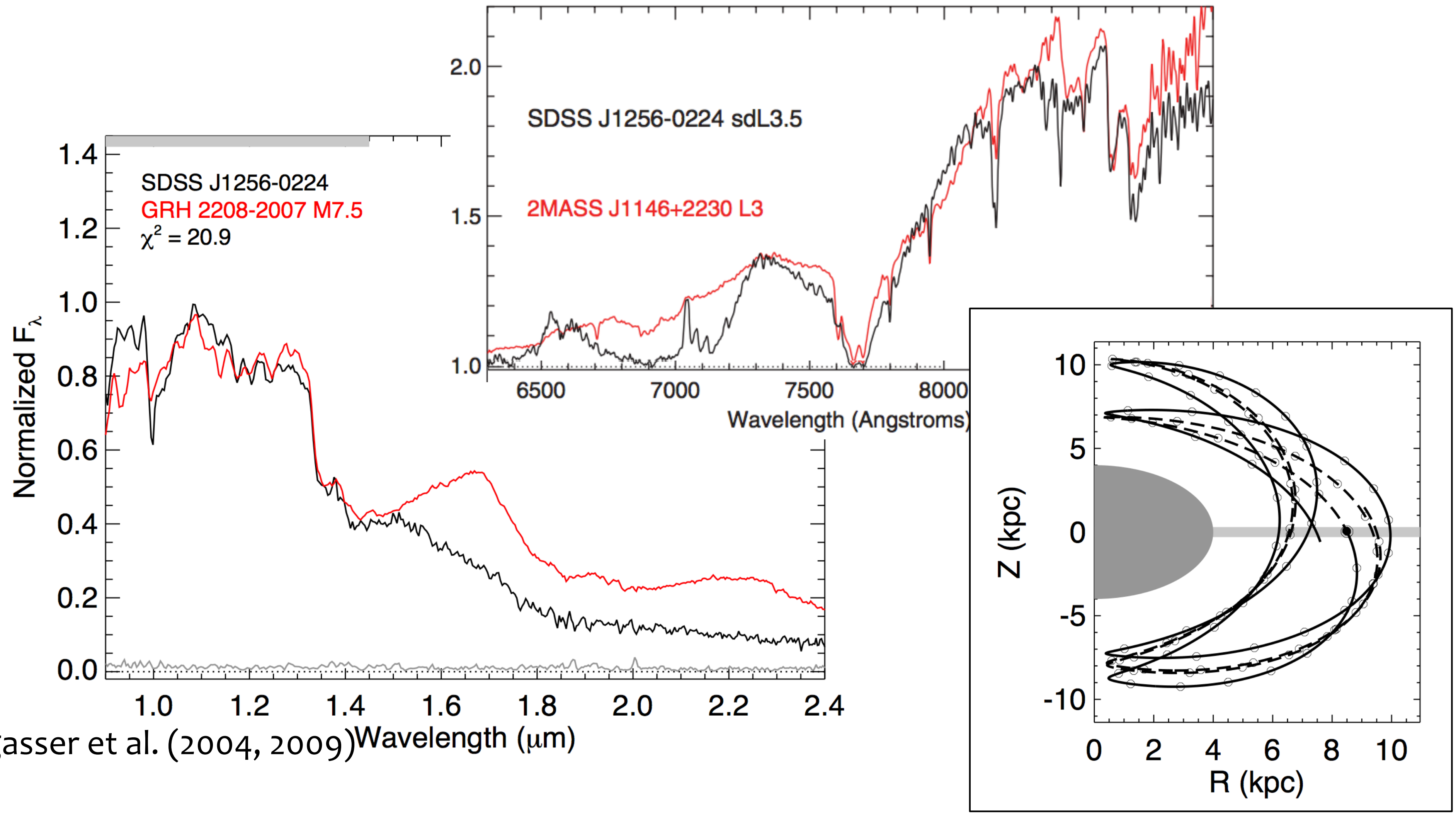
# WFIRST WILL DO:

- Nail down the BD field IMF and enable investigation of secondary effects (SFH, minimum mass)
- Constrain SFH and evolutionary models through scaleheight measurements and proper motions for $>10^6$ BDs
- Grism/prism spectra sufficient to classify & constrain gravity/age & metallicity for $>10^4$ BDs
- Plenty of ancillary science in survey data alone

# Please consider

- HLS multi-epoch imaging synched to provide proper motions/parallaxes
- Shift the prism to sample K-band
- Provide the community with basic, easy-to find survey-based information for planning
  - A single place to find current instrument characteristics & survey designs
  - Pre-generated mock data for various imaging & spectroscopic modes
  - A broader set of spectral templates sampled to prism/grism modes

# What about halo brown dwarfs?




Burgasser et al. (2004, 2009)

≈ 10 metal-poor L & T dwarfs with halo kinematics are known in the immediate Solar Neighborhood

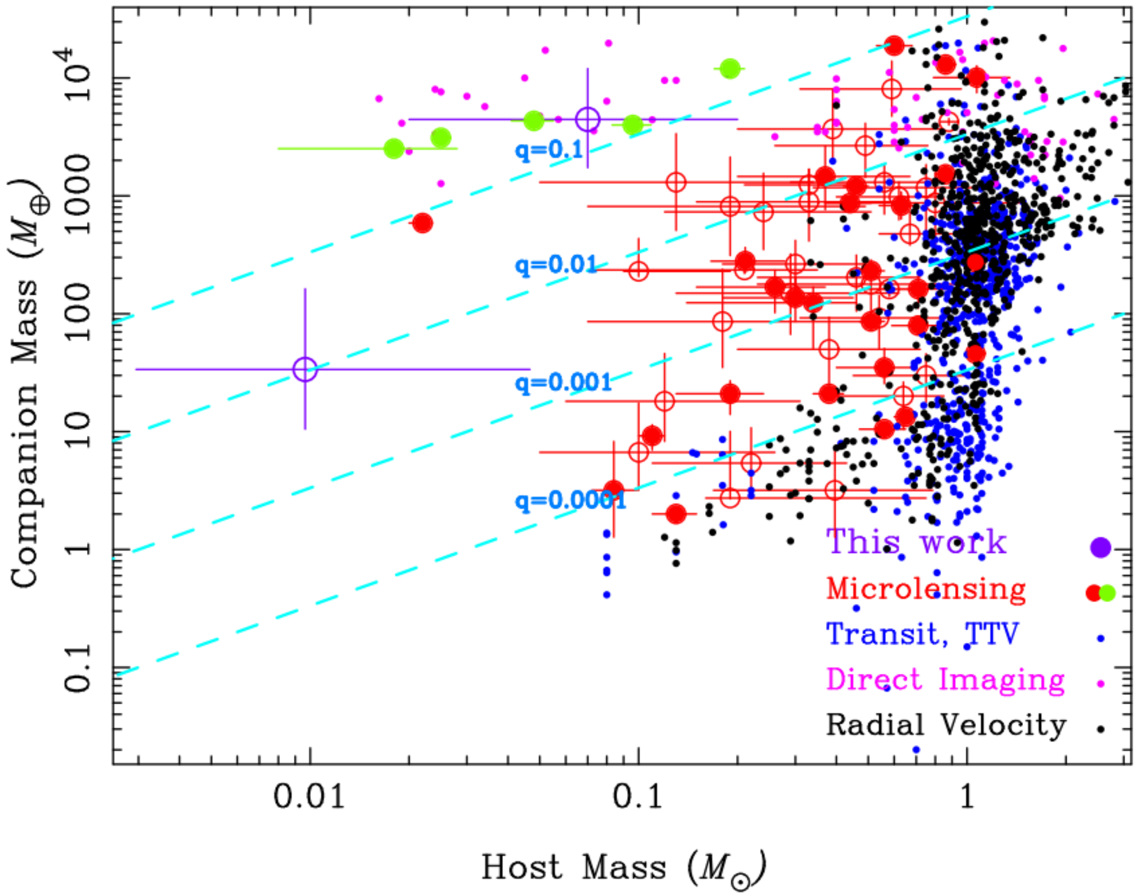
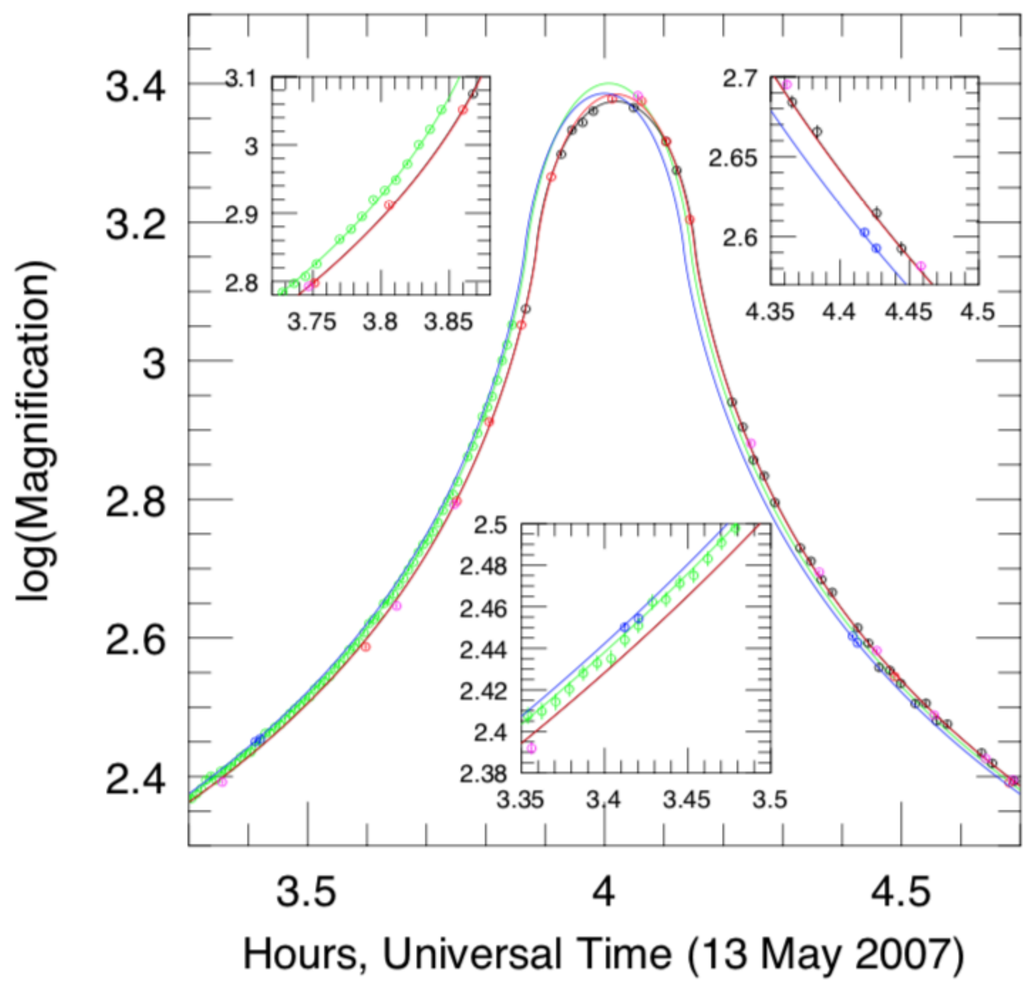
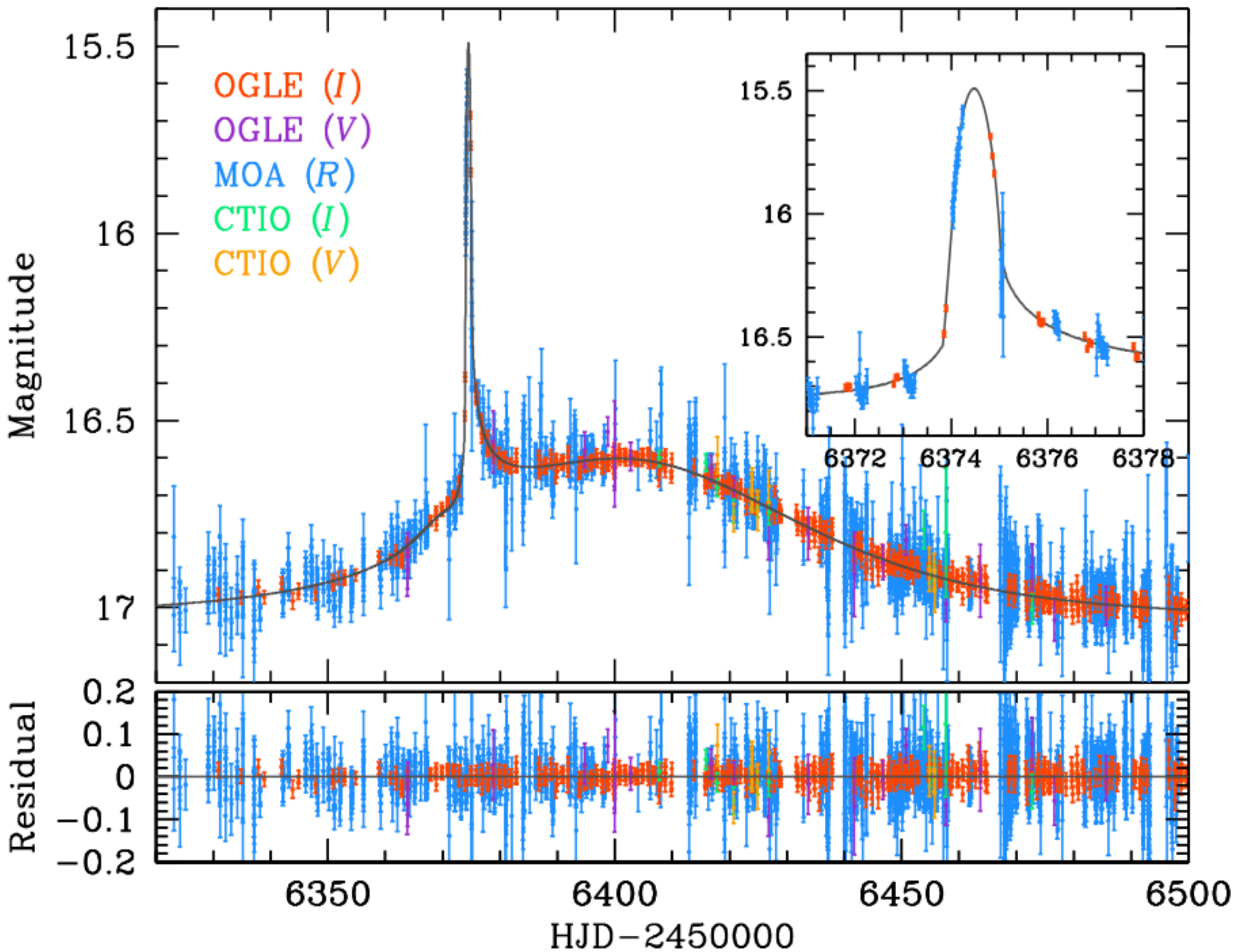



**Figure 7.** Distribution of bound exoplanets and very low mass companions in which the vertical axis shows the companion masses and the horizontal axis shows the host masses. The two purple points indicates the results of the Bayesian analysis for MOA-2015-BLG-337. The red, green, blue, magenta and black points indicate the planetary systems found by Microlensing (with a mass ratio of planet/host of $q < 0.1$), Microlensing ($q > 0.1$), Transit & TTV, Direct Imaging, and Radial Velocity, respectively. For the microlensing planets, filled circles indicate that their masses are measured and open circles indicate that their masses are estimated by a Bayesian analysis. The values of microlensing planets are from each discovery paper, while those of the others are from http://exoplanet.eu.

Miyazaki et al. (2018)




Gould et al. (2009); Gould & Yee (2013)




OGLE-2013-BLG-0102.

Jung et al. (2018)

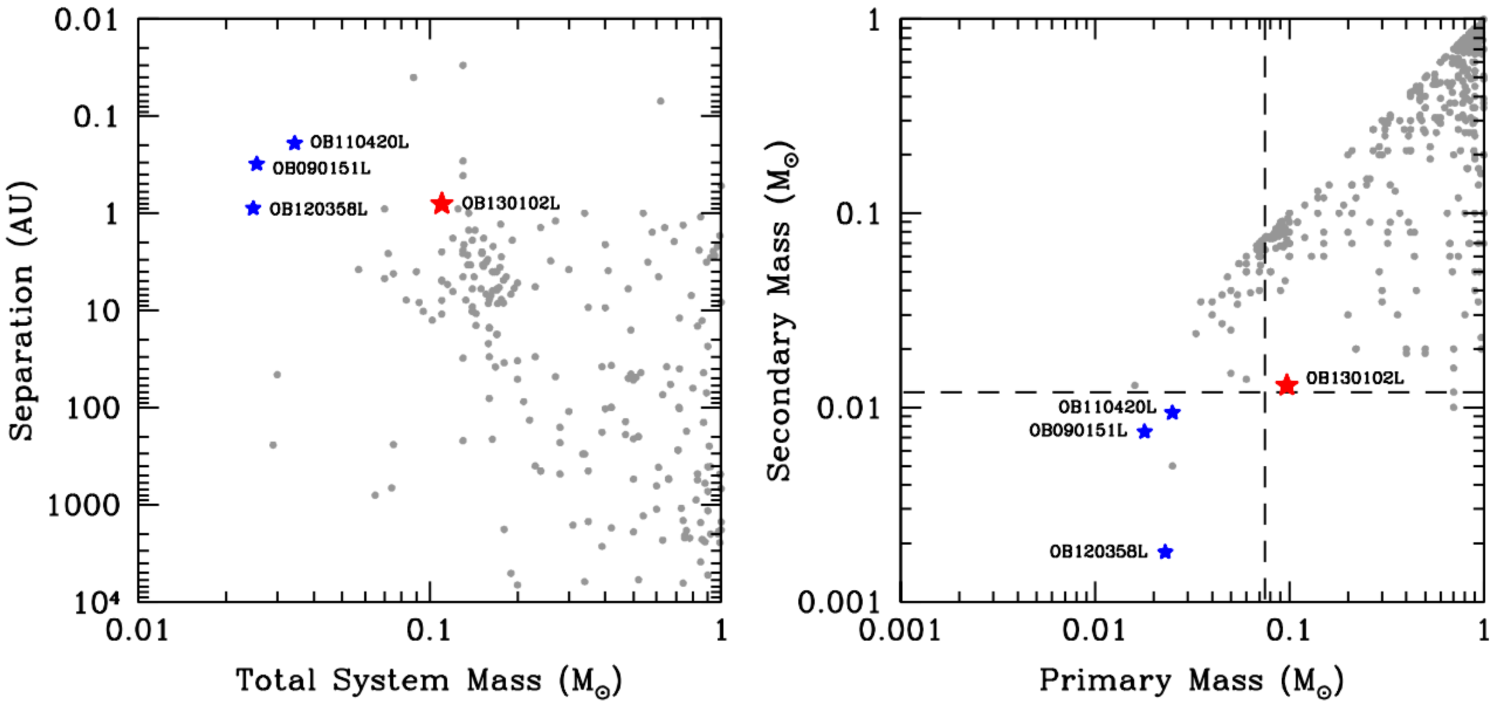



FIG. 5.— Total mass vs. separation (left panel) and primary vs. secondary masses (right panel) for a compilation of low-mass binaries. Microlensing binaries are denoted in 'star' marks while those discovered by other methods are marked by dots. The red star is the microlensing binary reported in this work and the three blue stars are the binaries reported by Choi et al. (2013) and Han et al. (2013). The vertical and horizontal dashed lines represent the star/brown-dwarf and brown-dwarf/planet boundaries, respectively.

Jung et al. (2018)

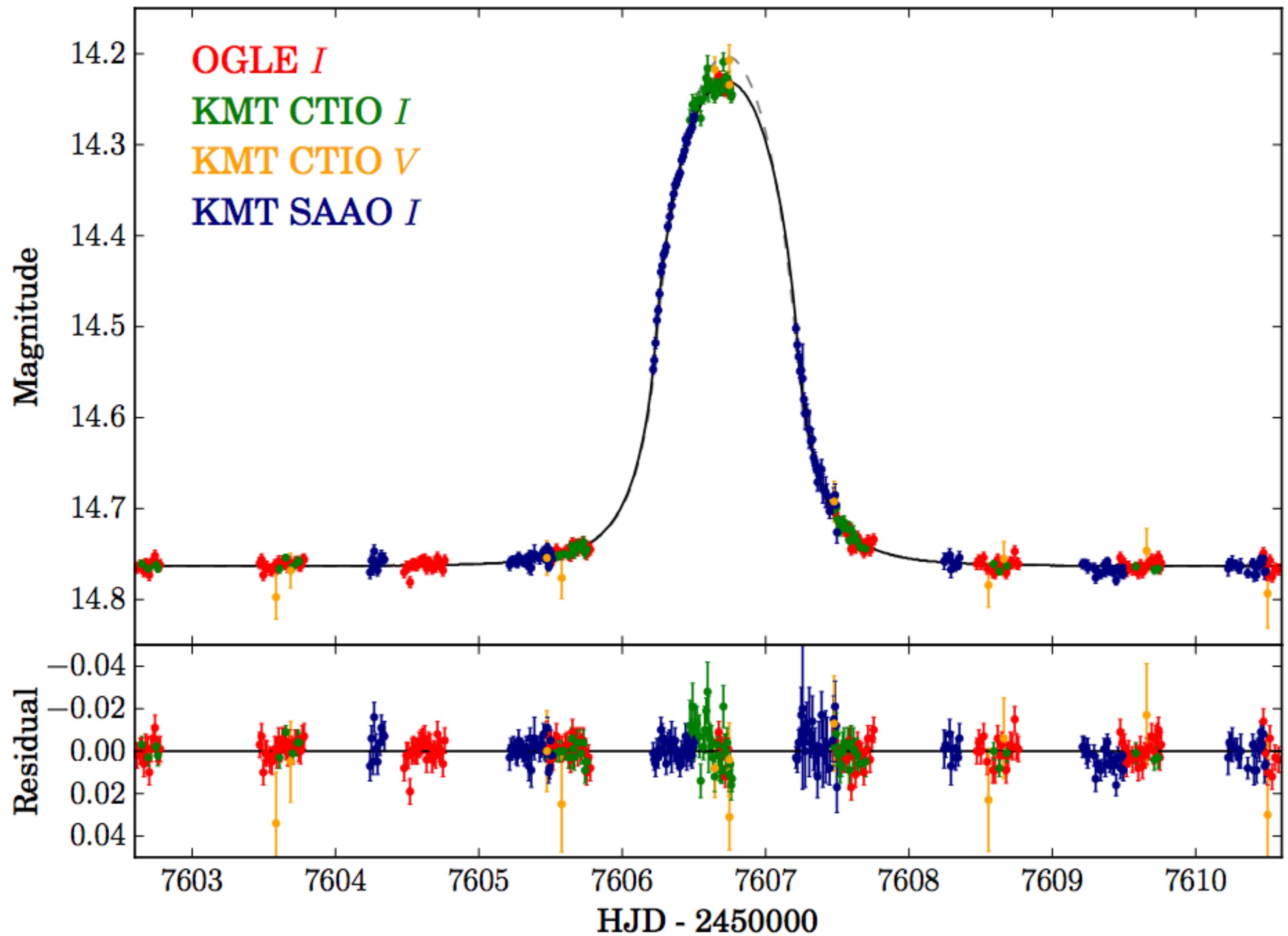
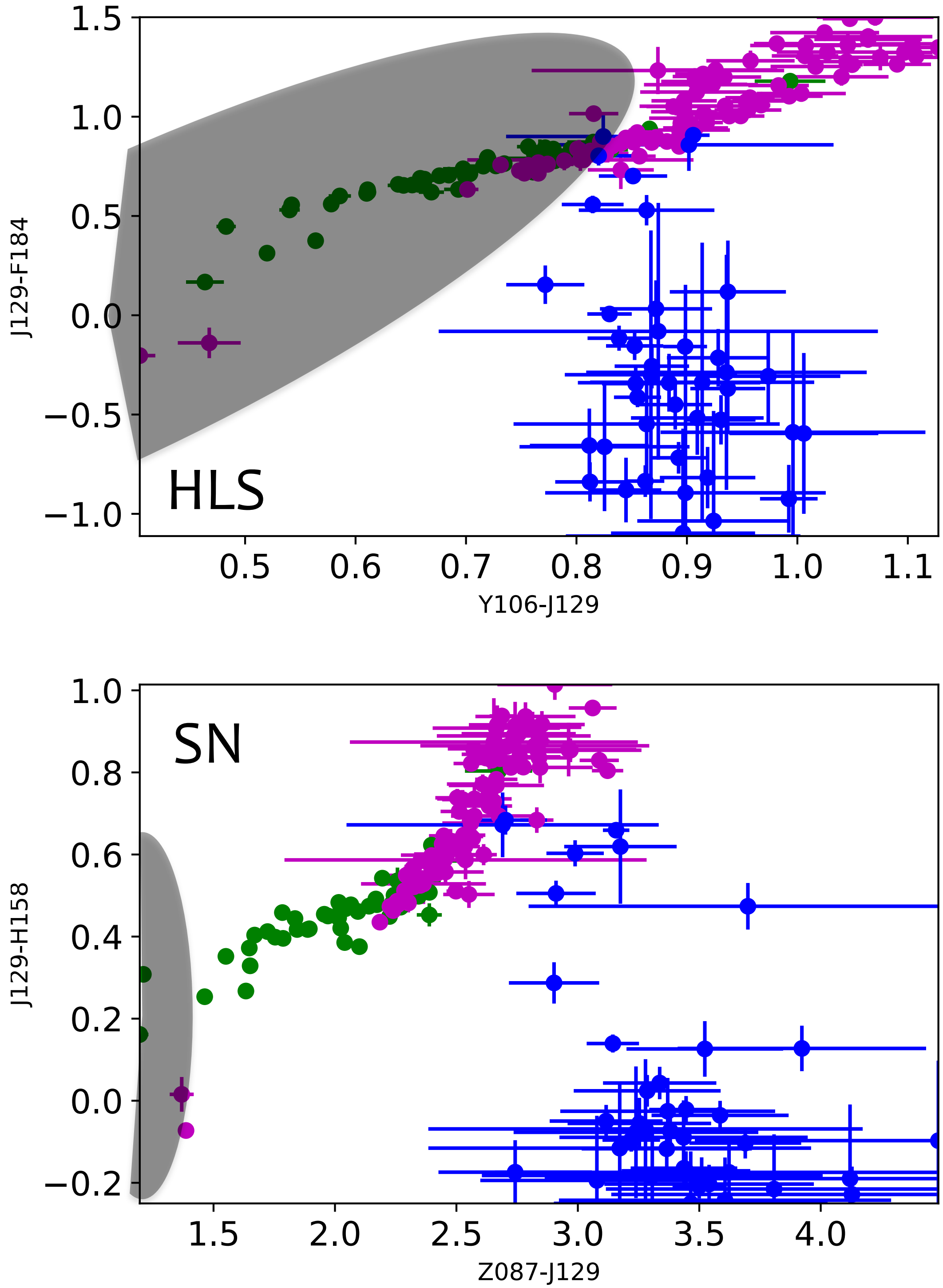


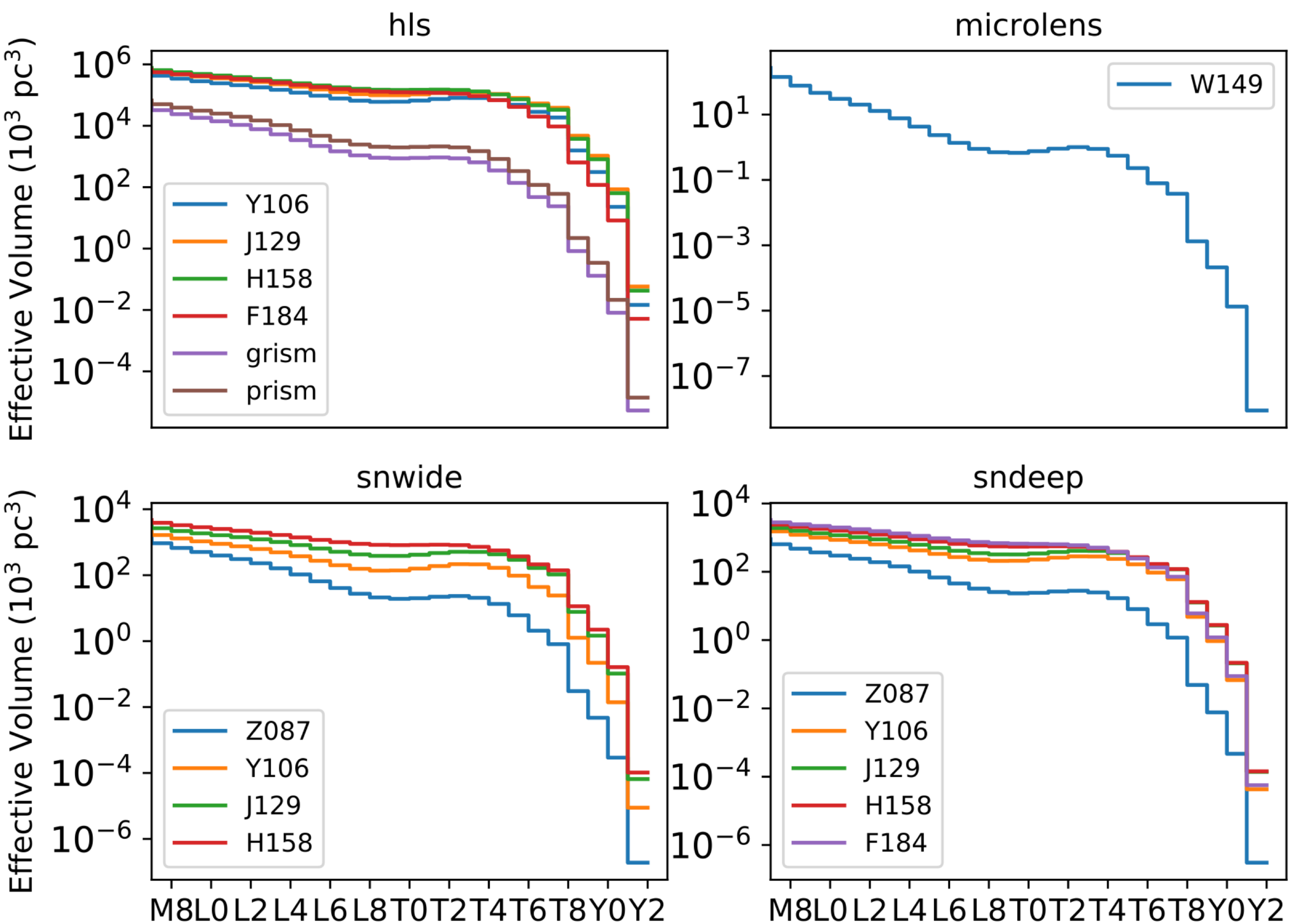

FIG. 1.— Microlensing event OGLE-2016-BLG-1540 exhibits prominent finite-source effect, because the source is larger than the angular Einstein ring. The light curve can be accurately described using the finite-source point-lens model (black solid line in the $I$-band, gray dashed line in the $V$-band). $I$- and $V$-band models differ because of different limb-darkening profiles of the source star in two filters. $V$-band data were not used in the modeling. All measurements were transformed to the OGLE magnitude scale.

Mroz et al. (2018)




LTY dwarfs should be separable from contaminant background *point sources* in ZYJF color-color plots

Reduced proper-motion selection with improve fidelity



hls
microlens
snwide
sndeep
Effective Volume ($10^3$ pc$^3$)
Effective Volume ($10^3$ pc$^3$)
$10^6$
$10^4$
$10^2$
$10^0$
$10^{-2}$
$10^{-4}$
Y106
J129
H158
F184
grism
prism
$10^1$
$10^{-1}$
$10^{-3}$
$10^{-5}$
$10^{-7}$
W149
$10^4$
$10^2$
$10^0$
$10^{-2}$
$10^{-4}$
$10^{-6}$
Z087
Y106
J129
H158
Z087
Y106
J129
H158
F184
M8 L0 L2 L4 L6 L8 T0 T2 T4 T6 T8 Y0 Y2
M8 L0 L2 L4 L6 L8 T0 T2 T4 T6 T8 Y0 Y2