Galactic Archeology With Ultracool Dwarfs

Christian Aganze (UCSD)

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1. UCSD
2. Amherst College
3. Princeton
4. Northwestern
5. Space Telescope Institute
6. U of Louisville
7. U of Delaware

UC San Diego

Credit: R. Hurt (Caltech/IPAC)

Outline

Introduction: UCDs and Galactic Archeology

Finding UCDs in Deep Parallel WFC3 Surveys (Aganze+ 2022a)

Measuring Galactic Structure with UCDs (Aganze+ 2022b)

Looking Ahead: JWST, Rubin Observatory, Euclid and The Nancy Grace Roman Telescope (Aganze+ 2023 in prep.)

Guiding Science Questions

*(1) Are the **chemical compositions and kinematics** **of halo UCDs** consistent with main-sequence FGK stars ?*

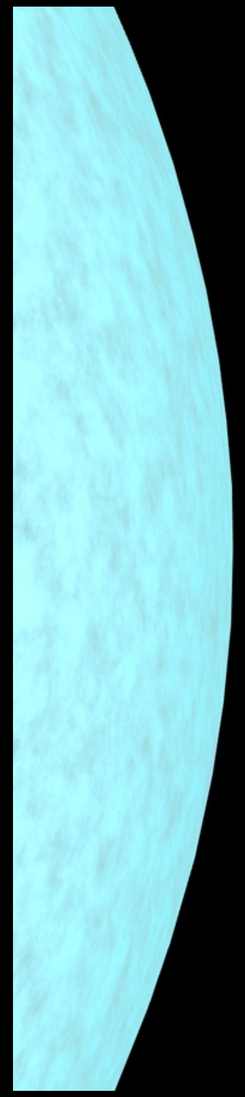
*(2) Is the **number fraction of halo/disk for UCDs** similar to main-sequence FGK stars ?*

*(3) What drives **kinematic heating in the disk,** does this process change with lowest-mass stars and brown dwarfs?*

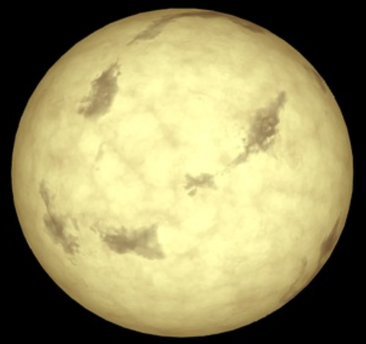
*(4) Does metallicity affect th**e** **hydrogen-burning minimum mass?***

*(5) Are low-mass stars in the **solar neighborhood (<100 pc)** unusual?*

What are Ultracool Dwarfs?



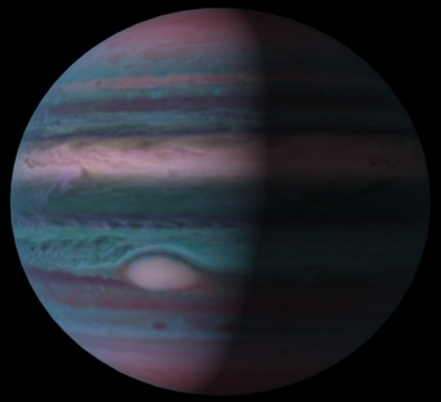
M dwarfs
< 3500 K



L dwarfs
< 2200 K

T & Y dwarfs
< 1200 K

Jupiter
125 K

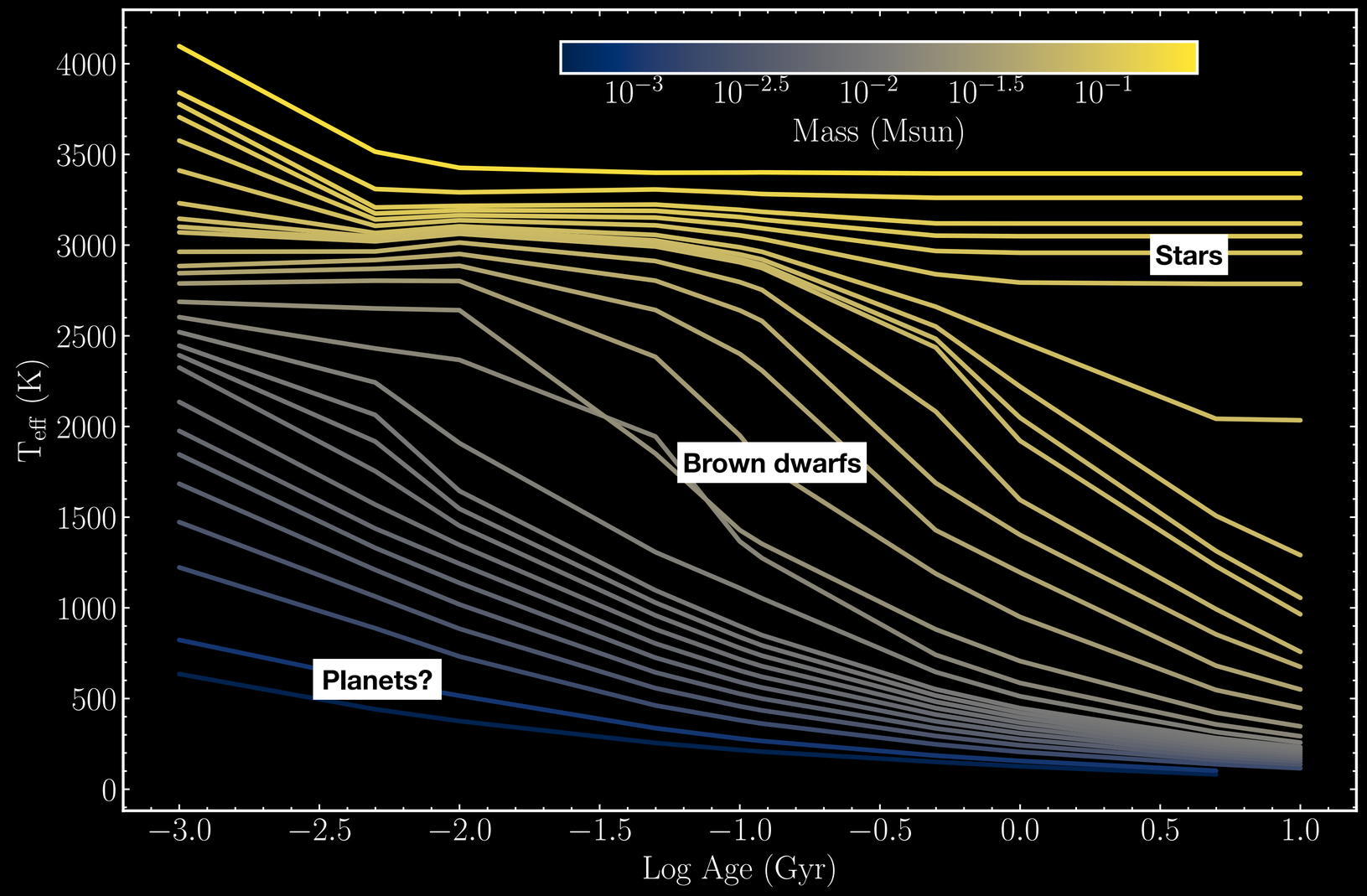


Low-mass stars and brown dwarfs (< **0.1 Msun**)

The bottom end of the initial mass function (>20 **%** of all “stars”, Reyle+ 2021)

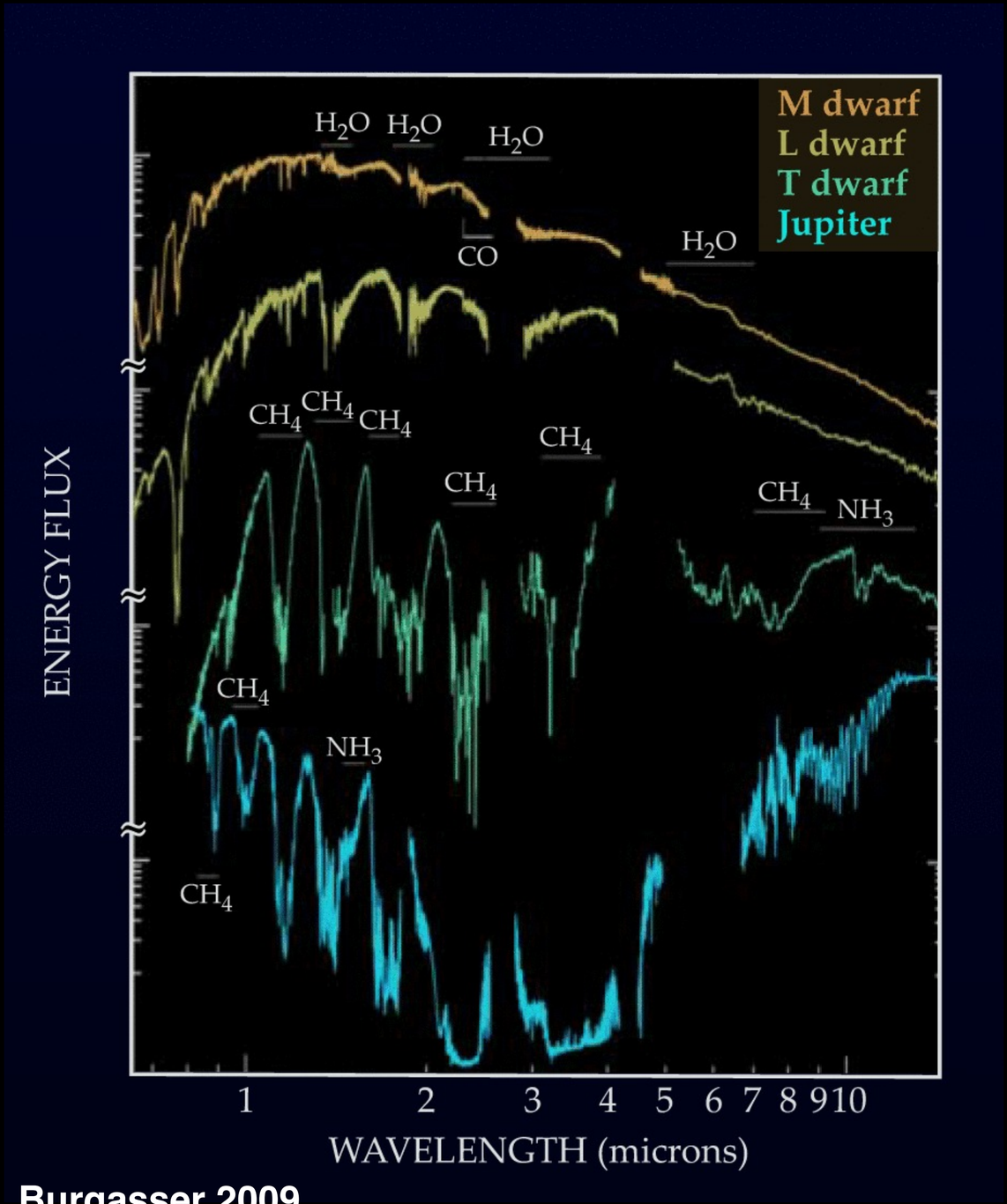
Image credit: Robert Hurt

What are Ultracool Dwarfs?



Burrows+ 2001

Spectra of UCDs Show Rich Chemistry

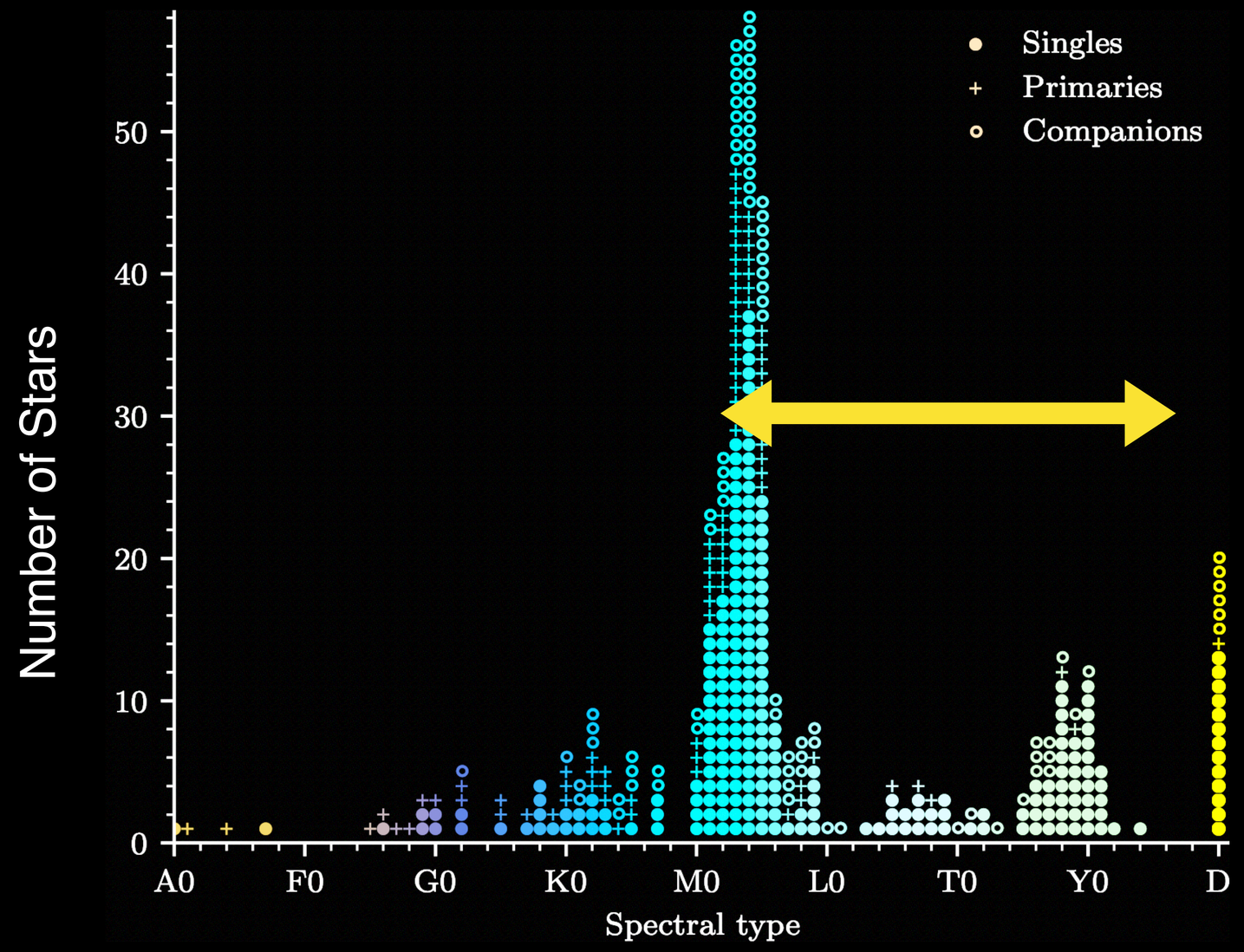


Colder objects

Burgasser 2009

UCDs are Extremely Common

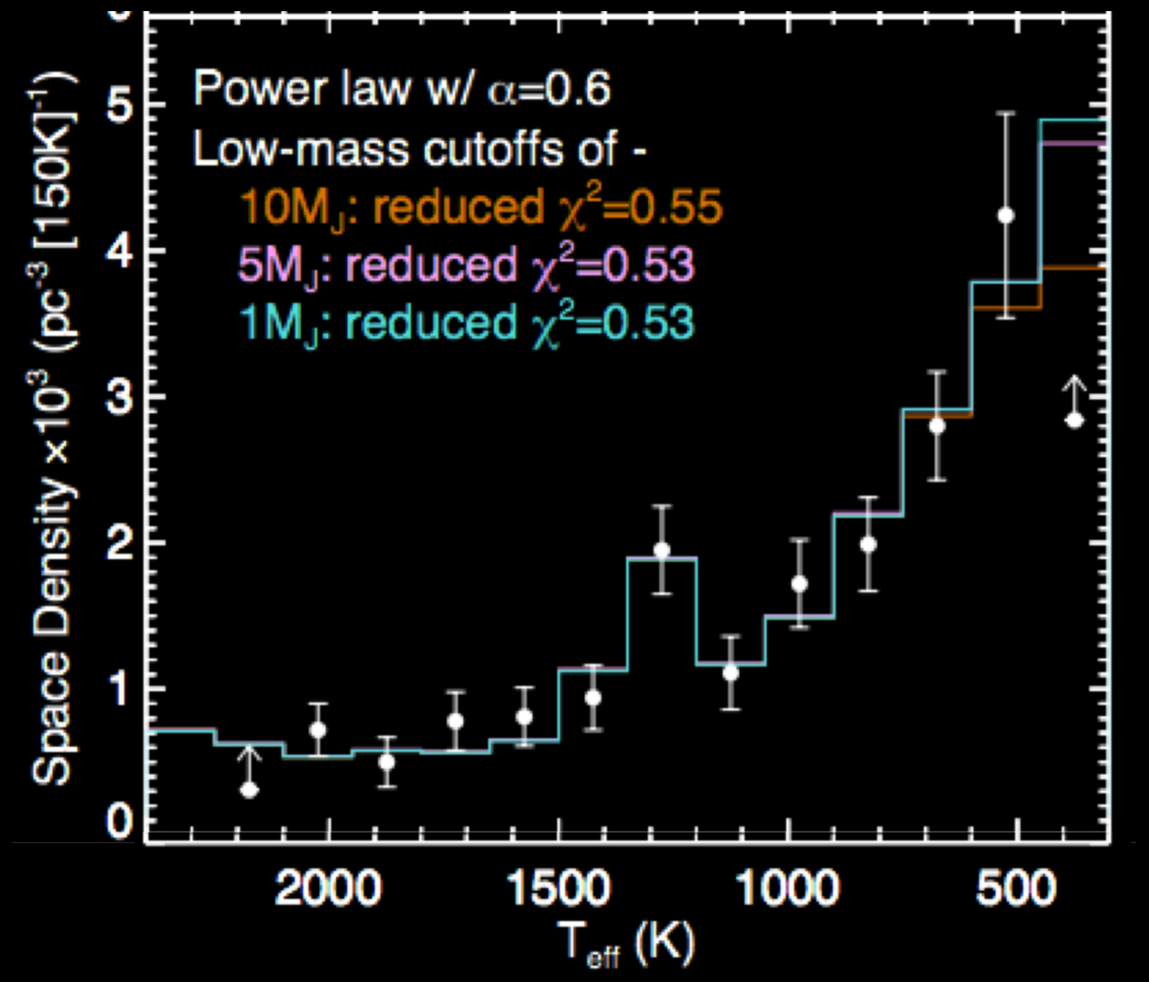
Distribution of objects within **10 pc**



Reyle+ 2021

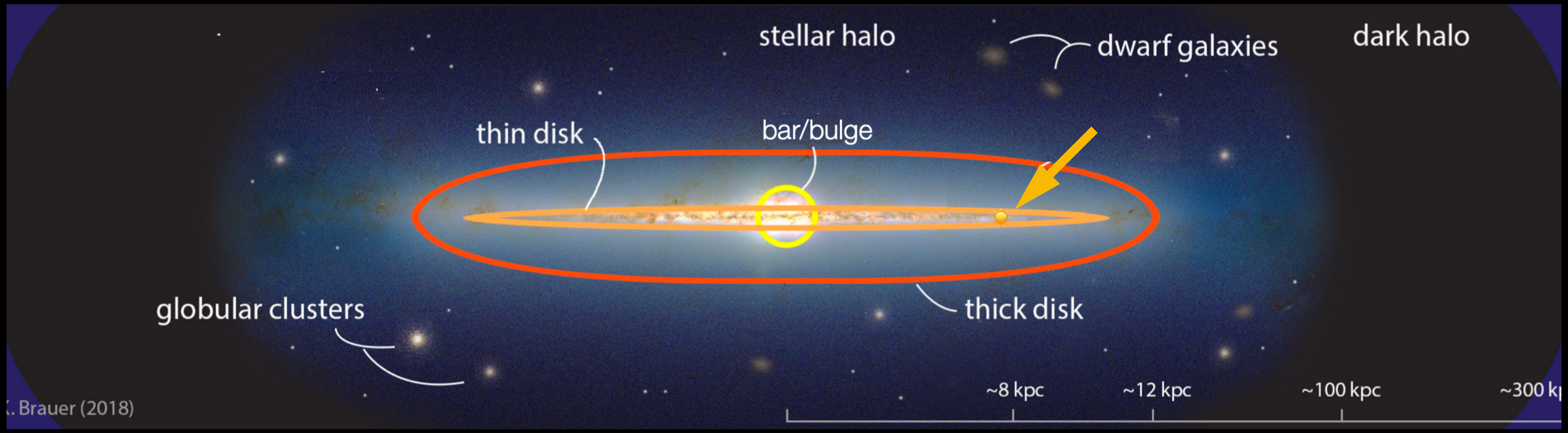
UCD Discoveries are Local (<100 pc)

Volume-limited sample
within **< 20 pc**



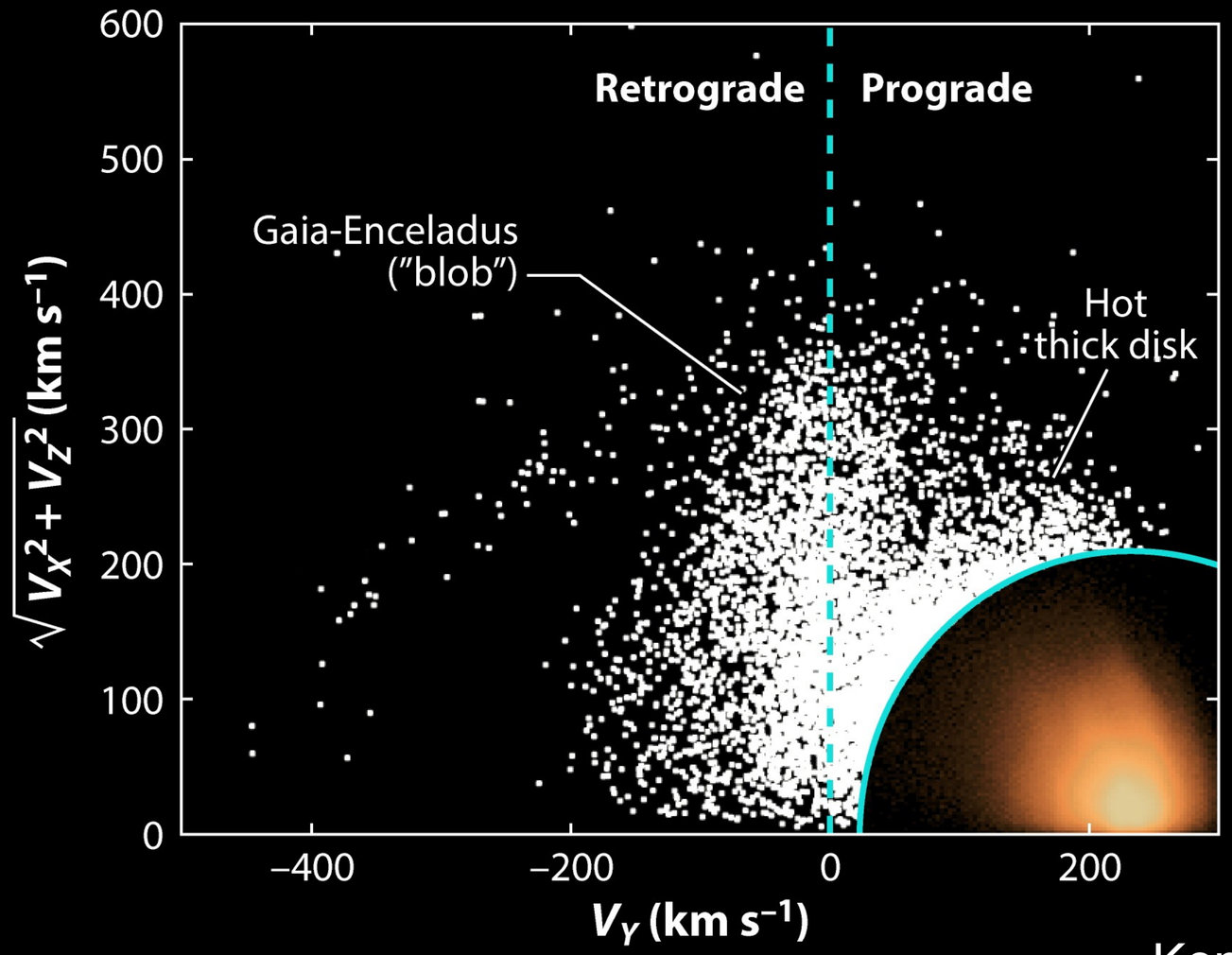
Cruz+ 2007, Kirkpatrick+ 2012, 2019, 2021, Bardalez-Gagliuffi+2019, Best+2020

UCD Discoveries are Local (<100 pc)



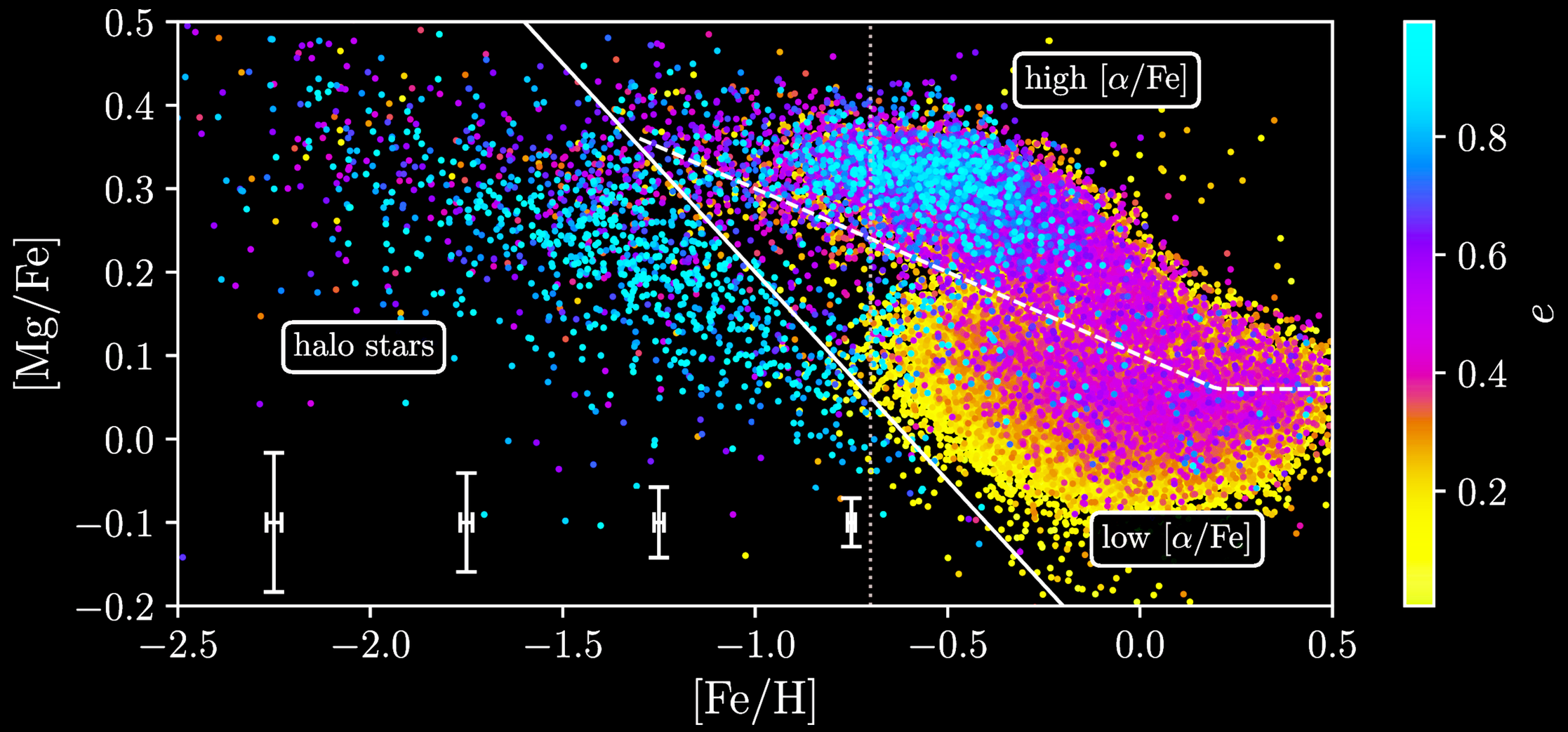
Credit: Adrian Price-Whelan, https://adrian.pw/aas237/

The Halo is Dominated by Accreted Populations



Koppelman+ 2018, Helmi 2020

Halo Stars Are Chemically Distinct from Disk Stars



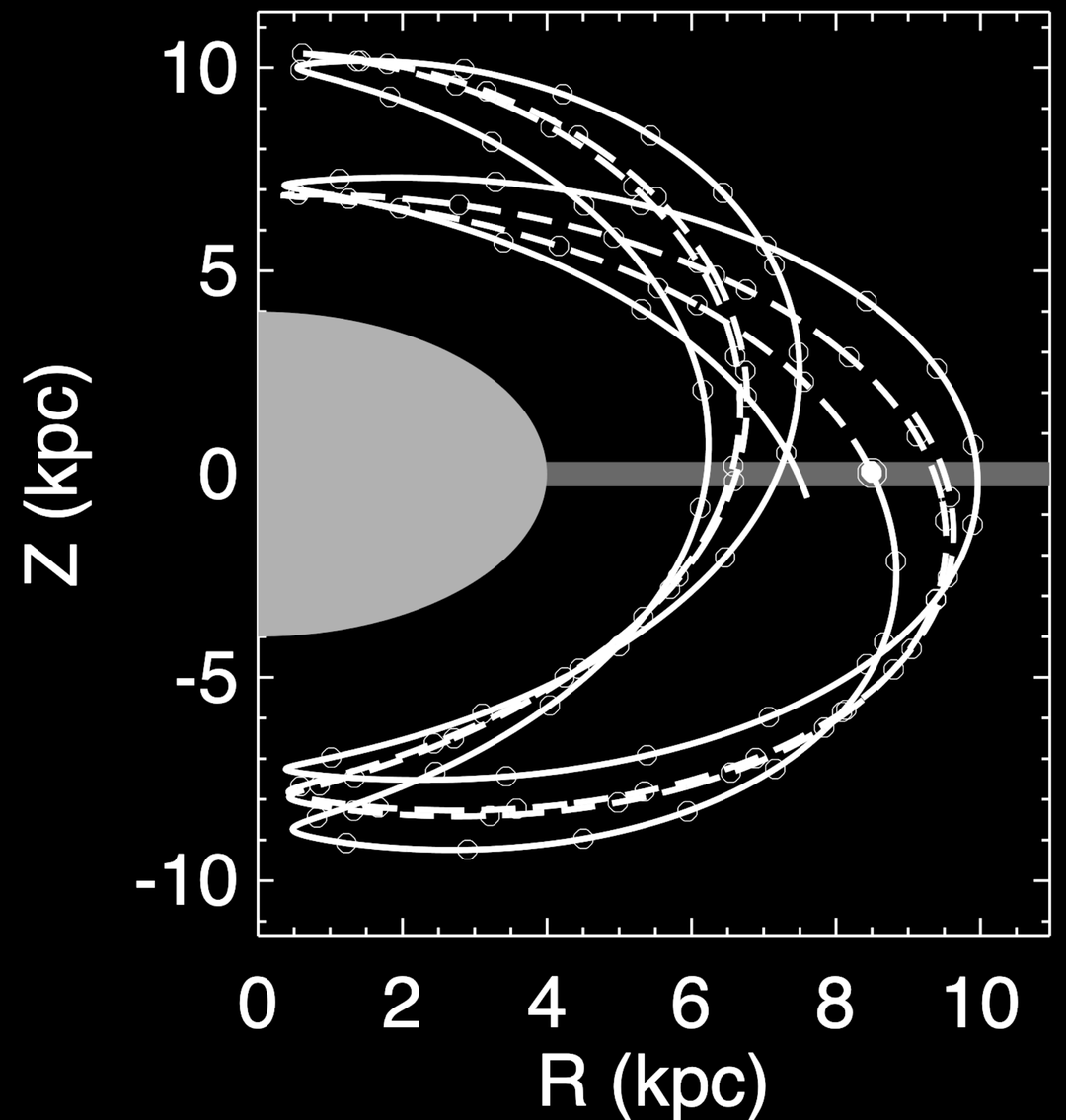
Mackereth+ 2019

Halo UCDs Are Rare

SDSS J1256-0224 (sdL3.5)

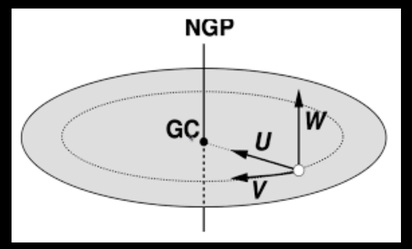
[Fe/H] = -1.8 +/0.2 (Gonzales + 2021)

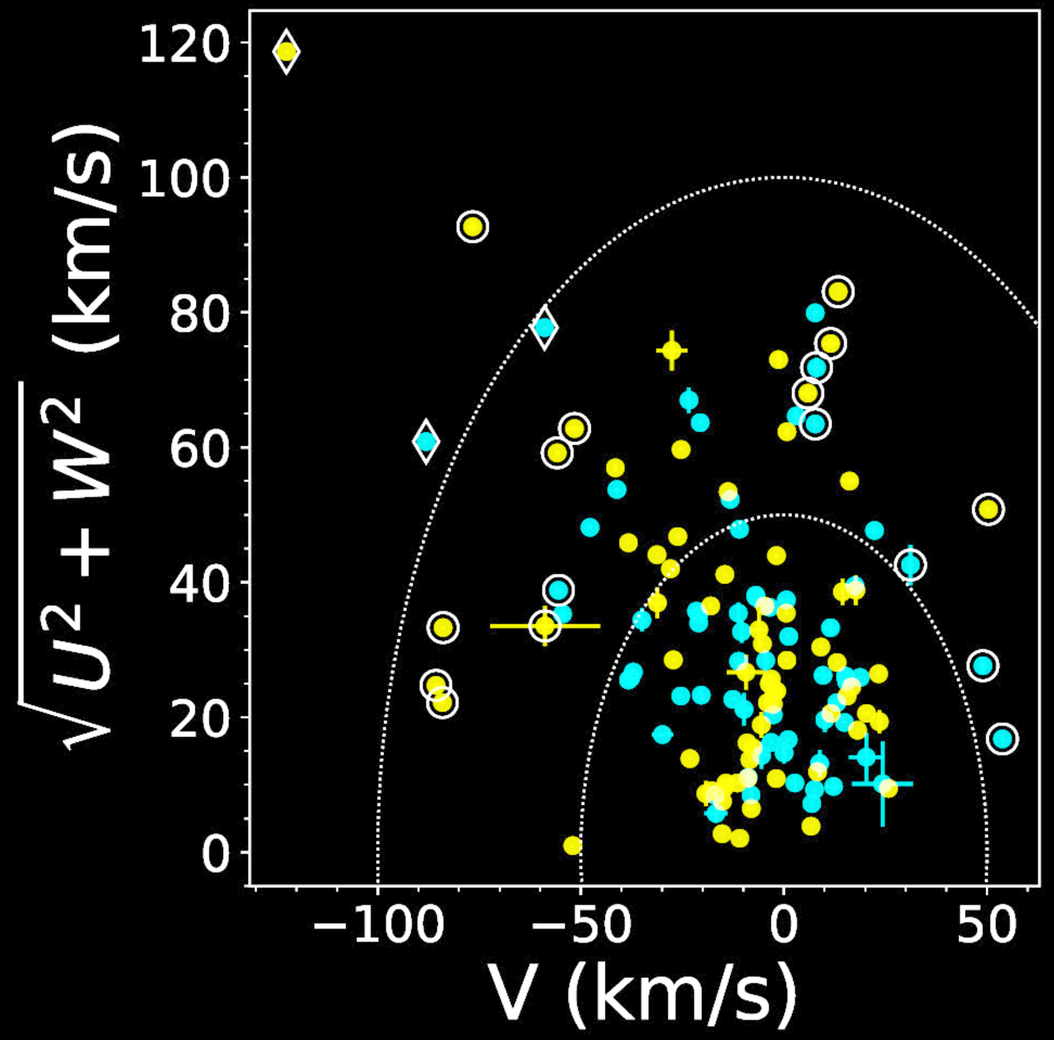
Radial velocity: -130 km/s



Lodieu+ 2015

Local L Dwarfs Are Highly-Dispersed





Faherty+ 2012, Burgasser+ 2015

Hsu+2021

Why Study the Galaxy with UCDs?

Guiding Science Questions

*(1) Are the **chemical compositions and kinematics** **of halo UCDs** consistent with main-sequence FGK stars ?*

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Part1: Finding Distant UCDs with HST/WFC3

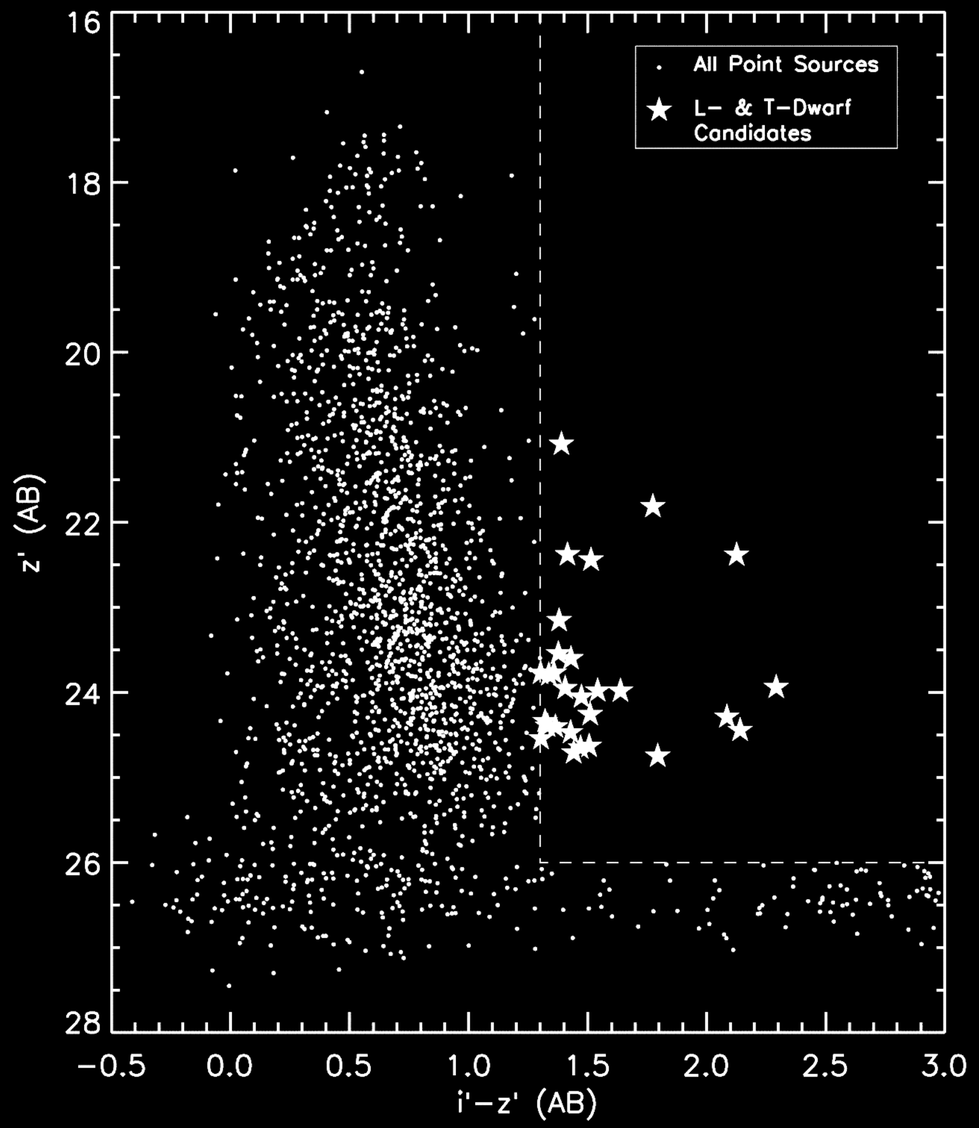
Distant Color-Selected Samples

HST/ACS

15 fields

28 L & T dwarfs candidates

Identification by z mag and i-z color

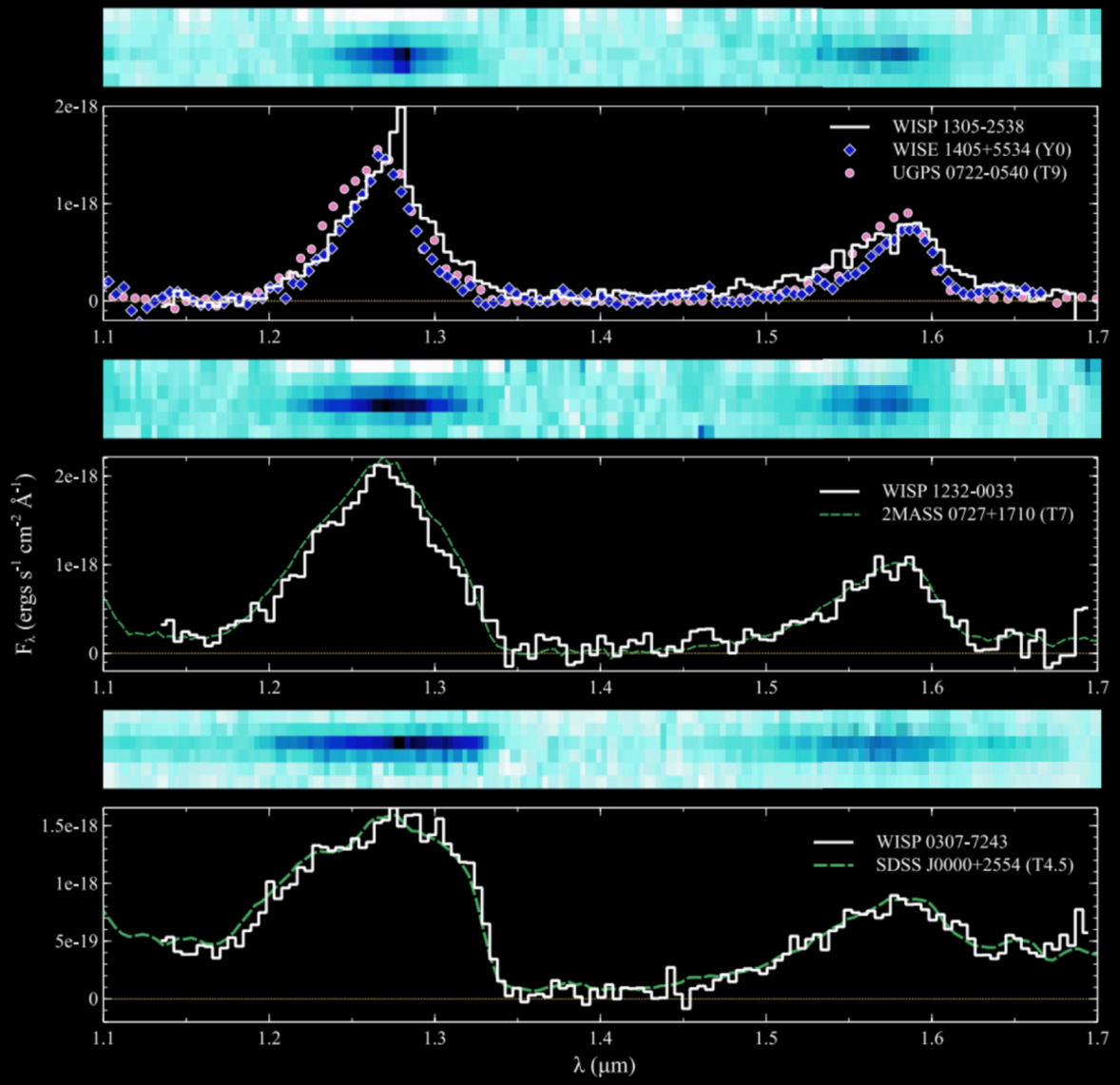


Ryan Jr. + 2005

Deep HST/WFC3 Spectroscopic Samples are Small

HST/WFC3

3 T dwarfs
(identified by eye)



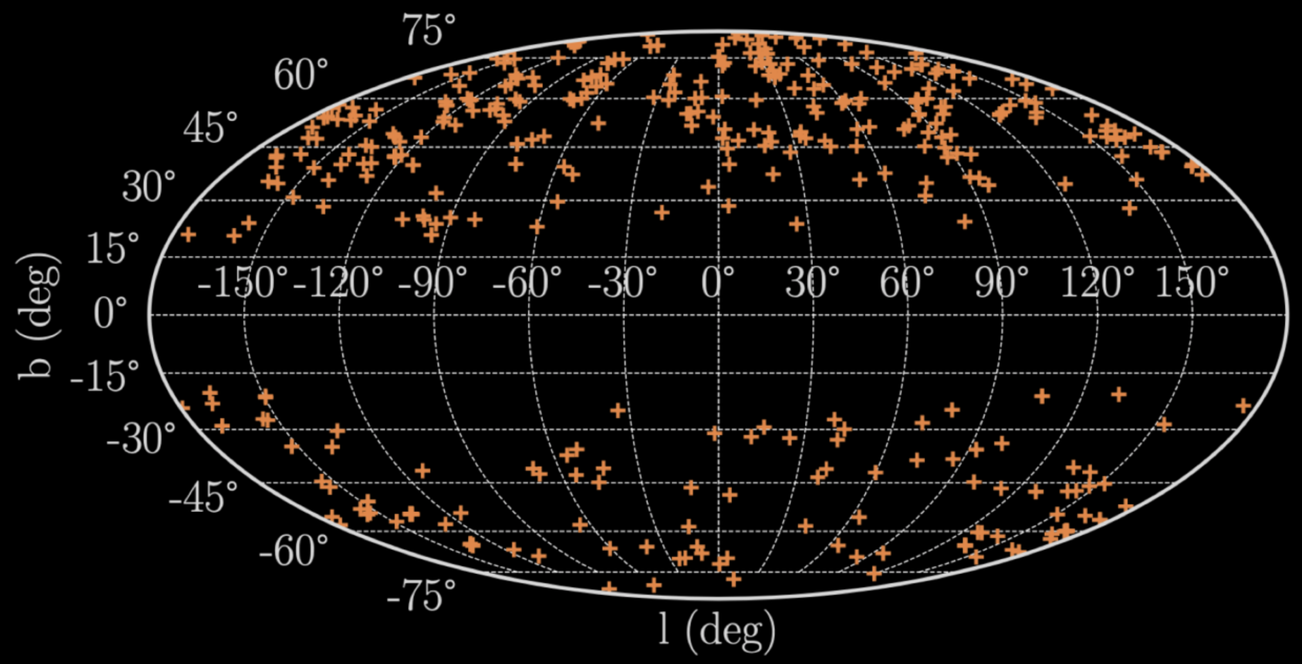
Masters + 2012

Distant UCDs in Deep Surveys

2 Surveys (WISPS & 3D-HST) conducted using parallel observations with the Hubble Space Telescpe WFC3 Instrument with an area ~ **0.5 sq deg**

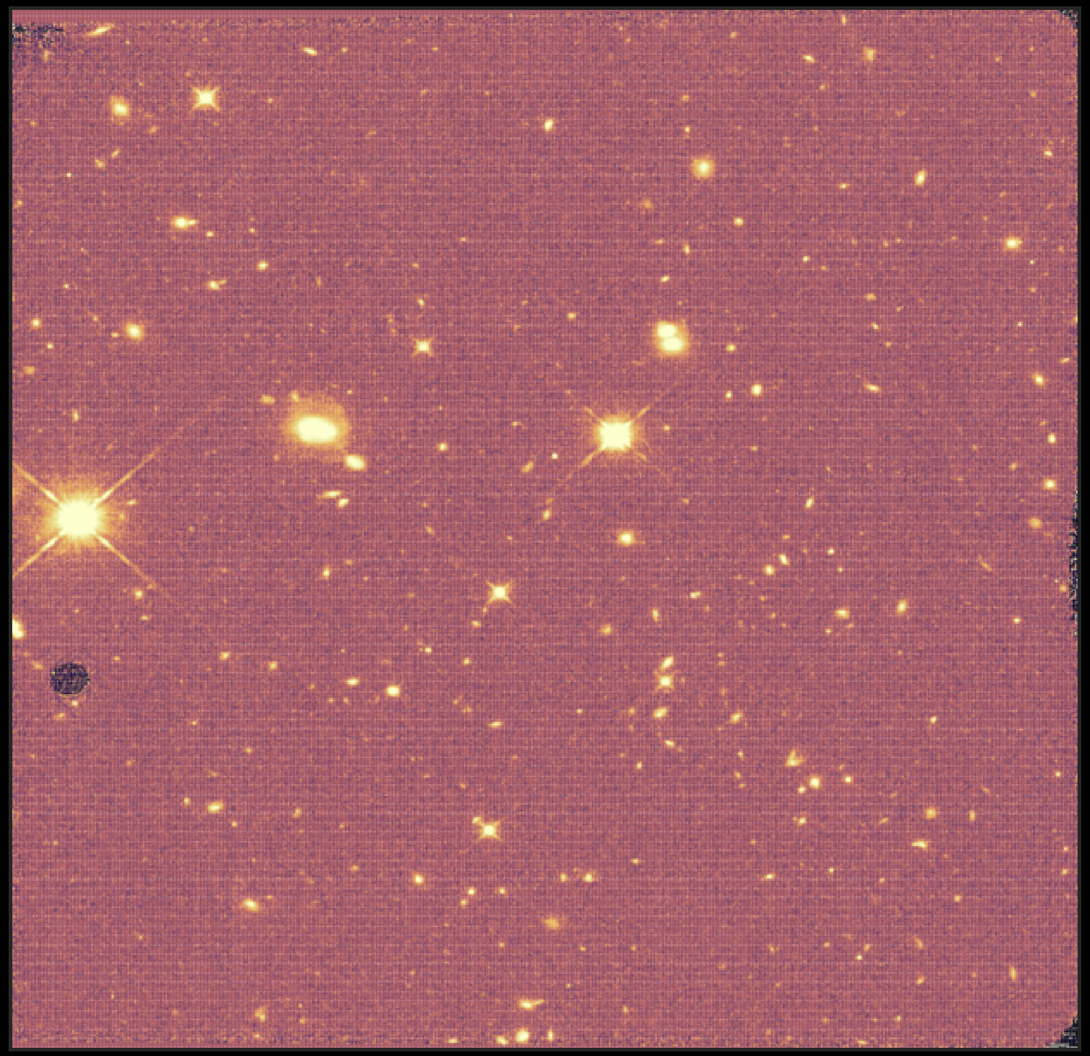
Both surveys provide spectra of > **250,000 objects**

Galactic Distribution of all the pointings

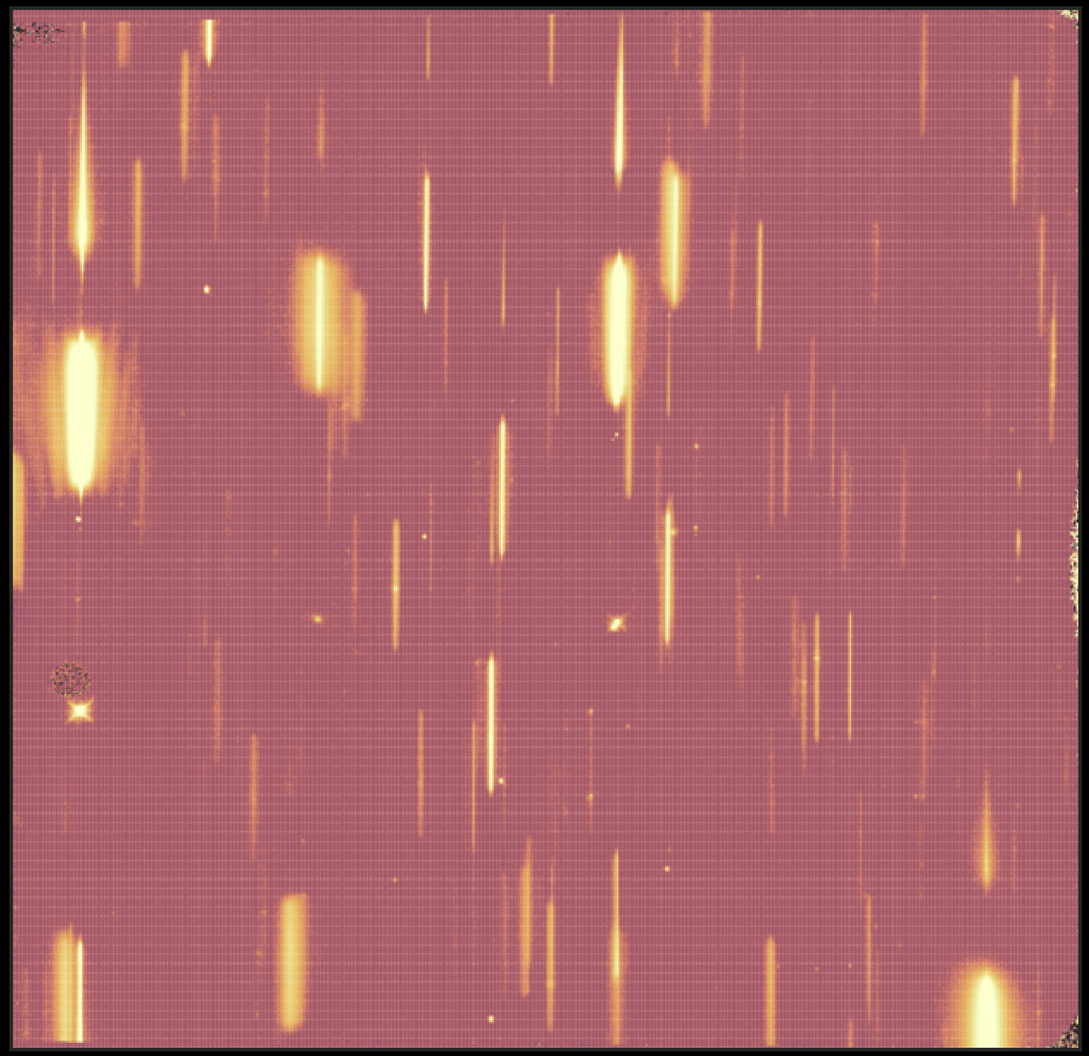


Atek+ 2011, Momcheva+ 2015

Data

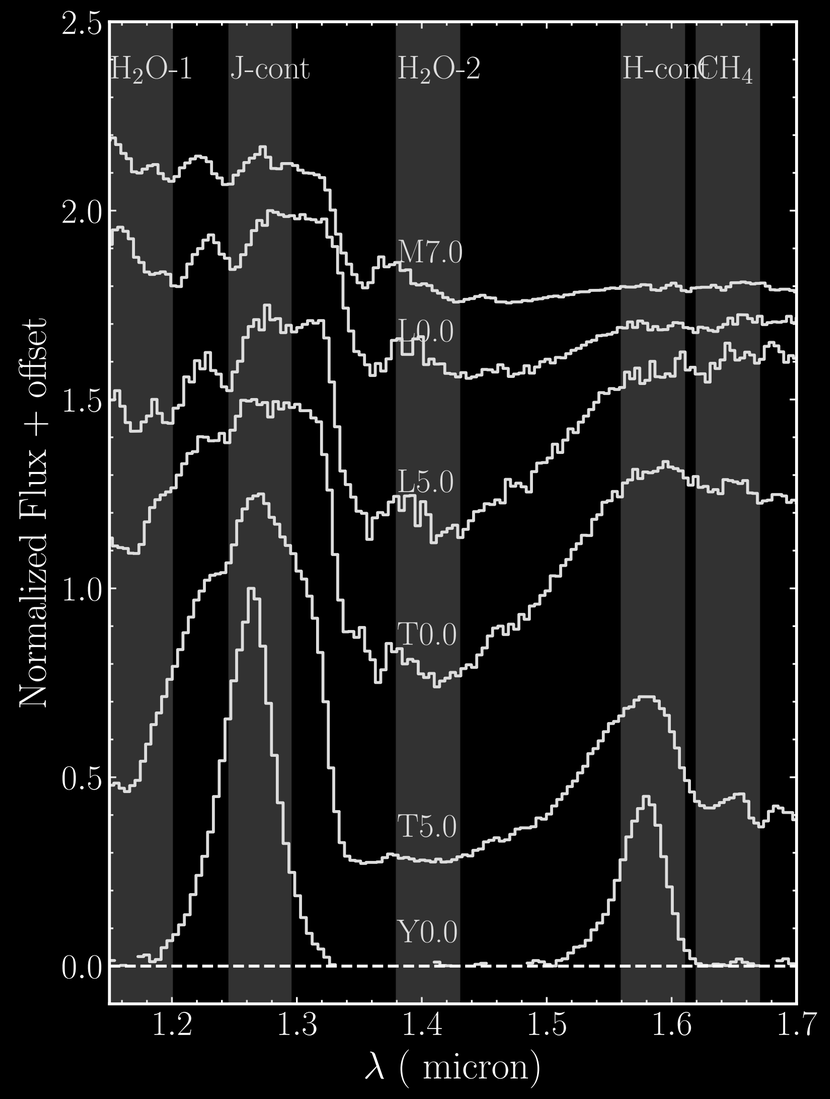


F160W Image



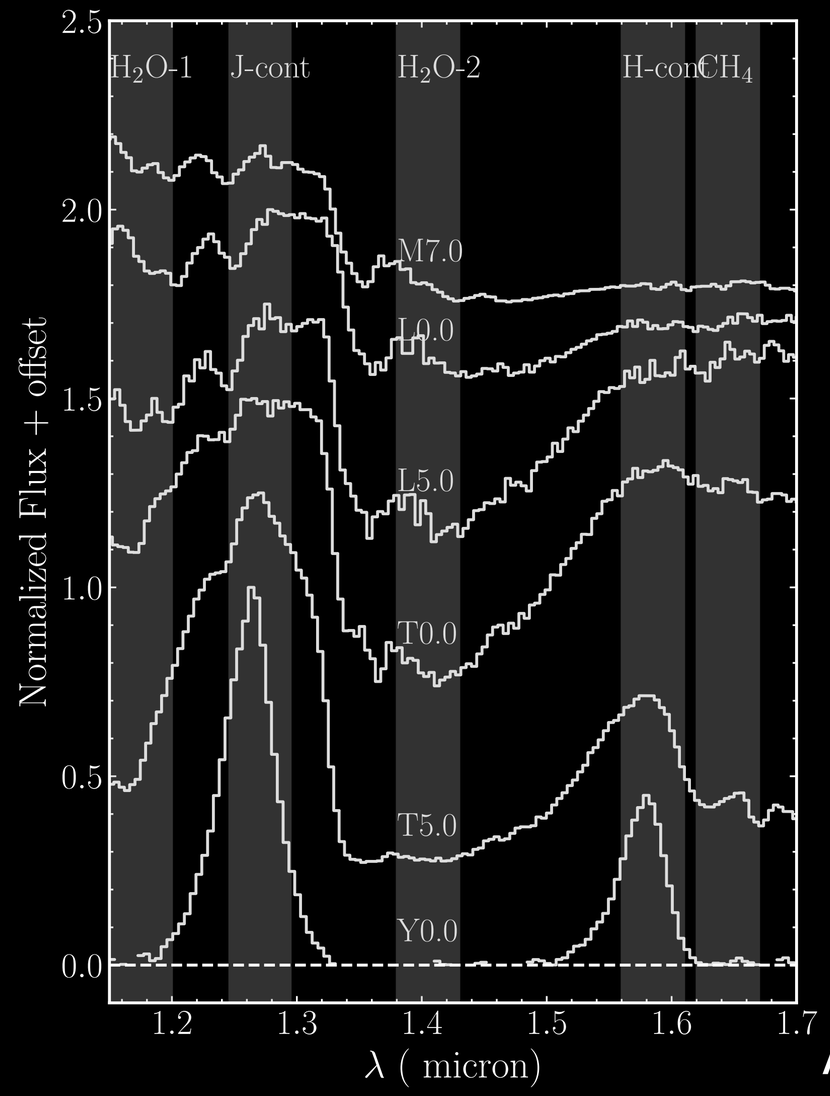
G141 Spectrum

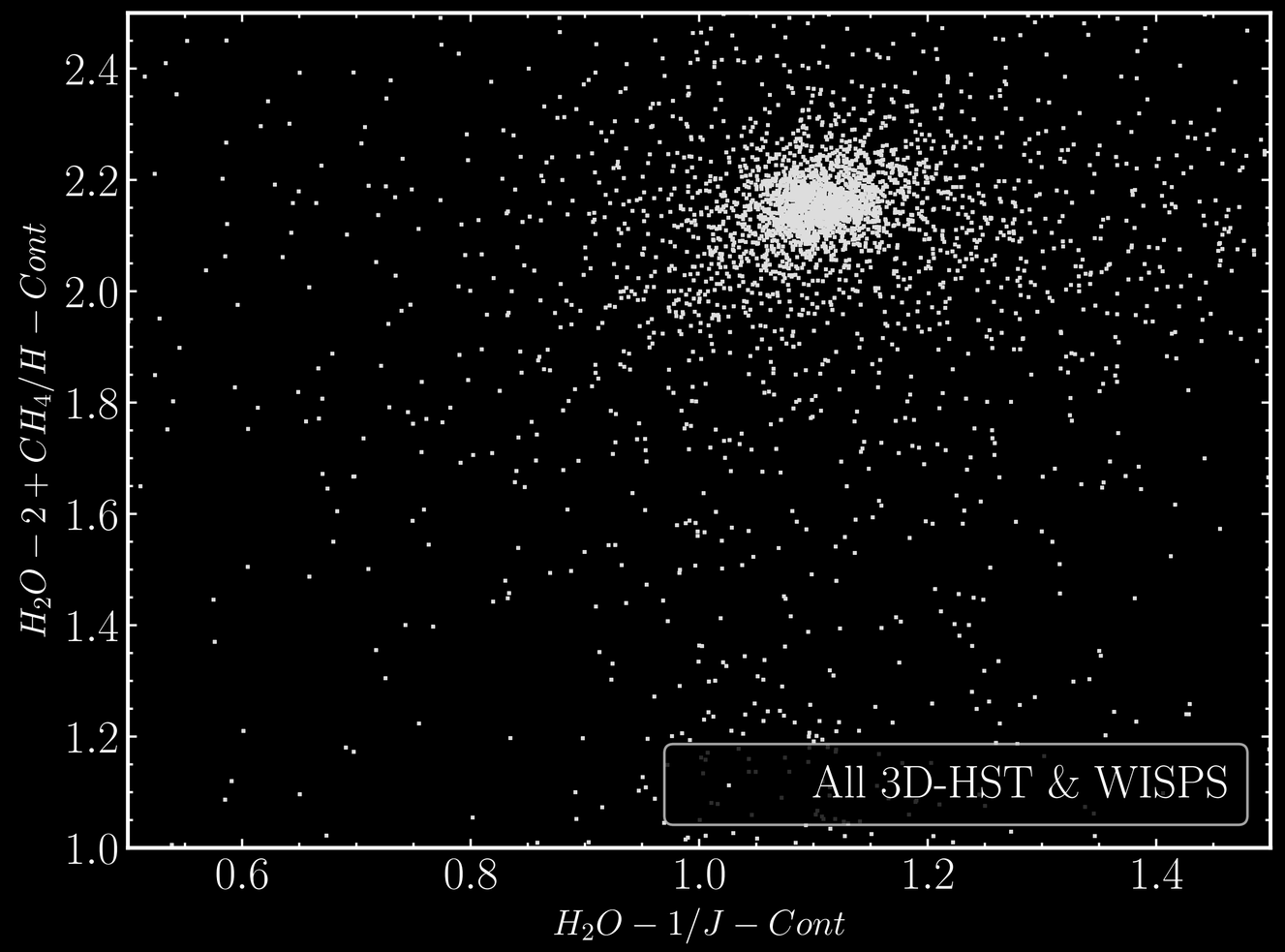
Selection by Spectral Indices



Aganze + 2022a

Selection by Spectral Indices





Aganze + 2022a

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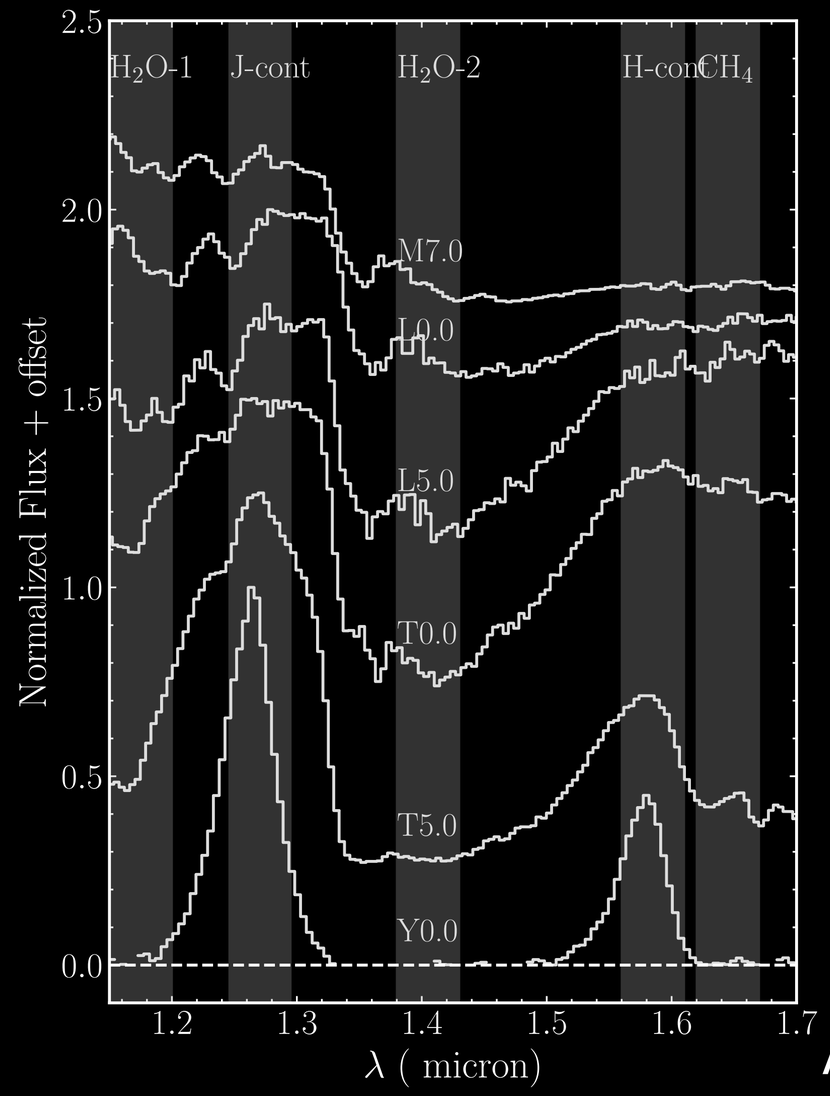

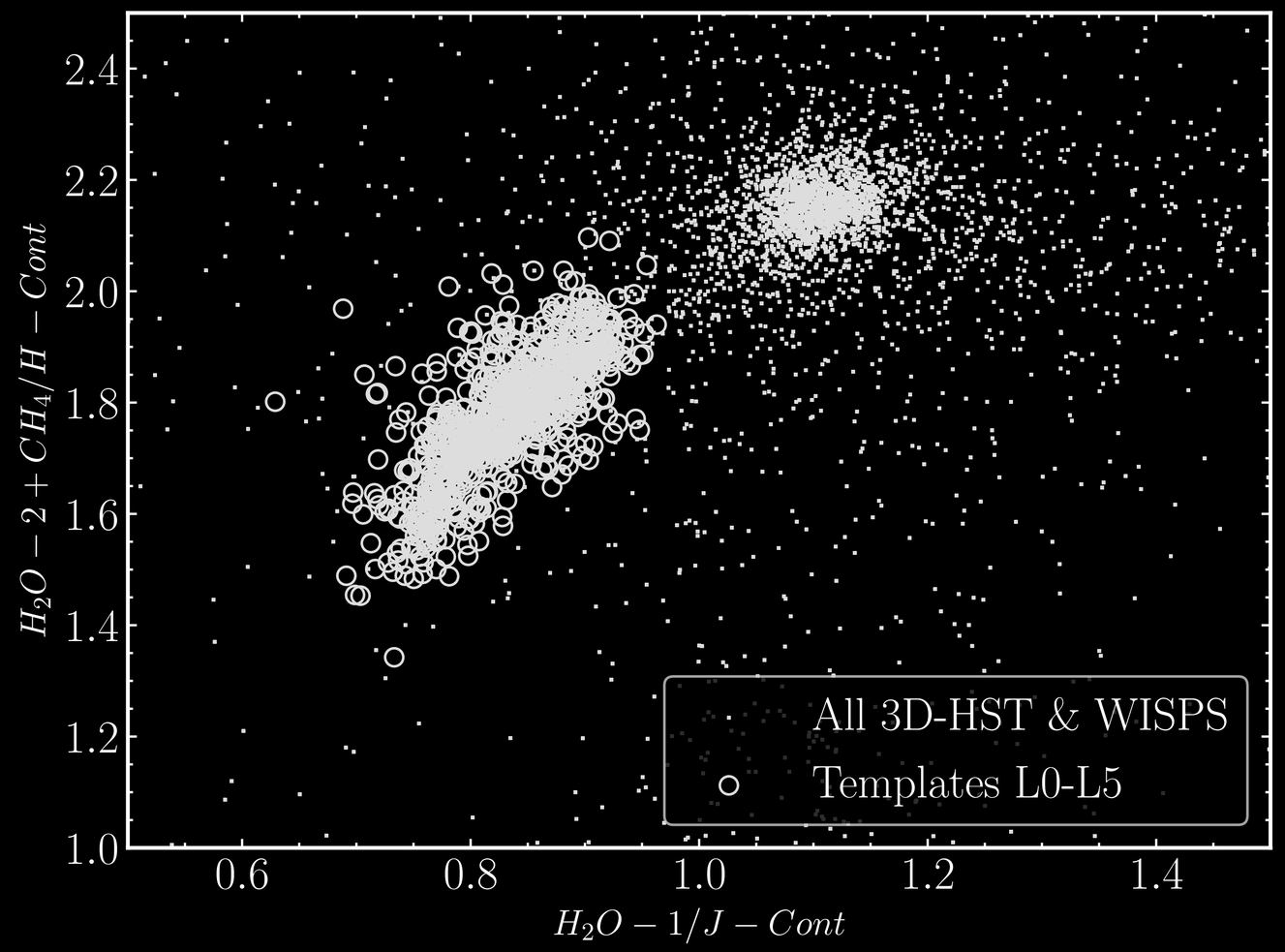

Aganze + 2022a

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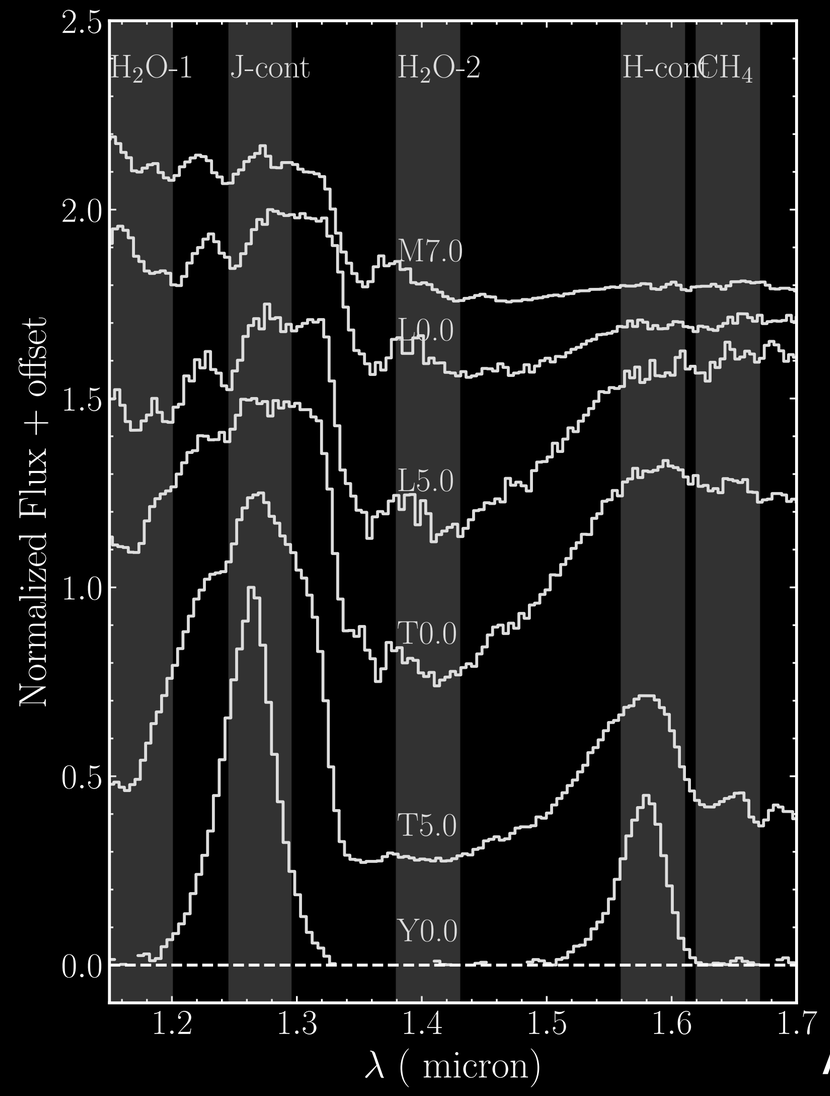
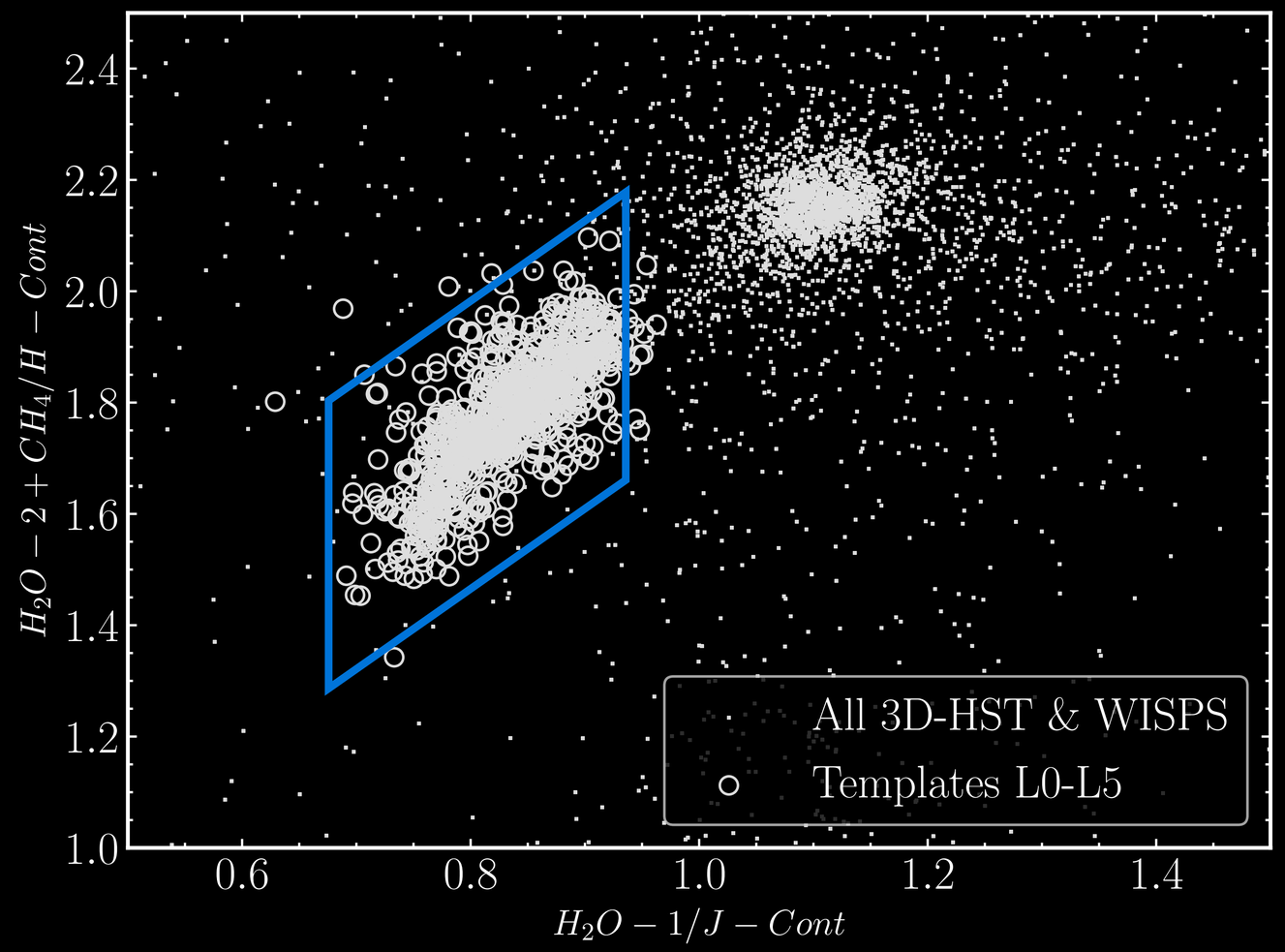
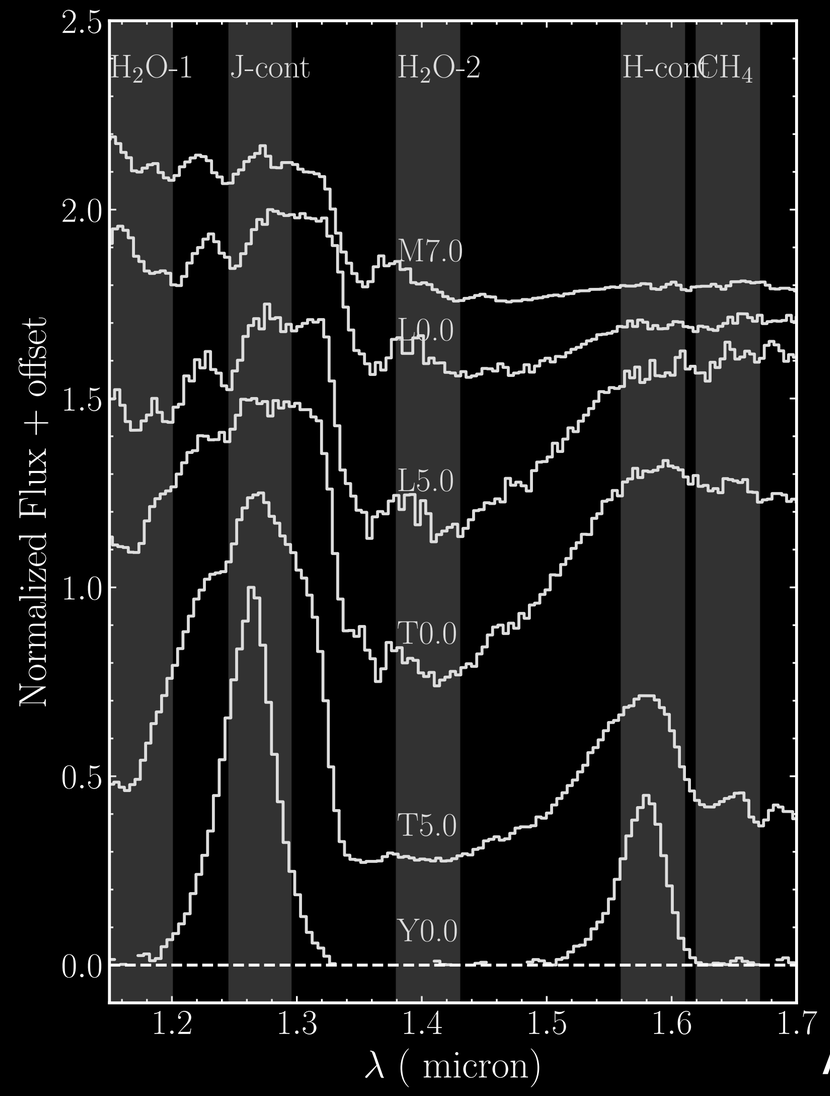
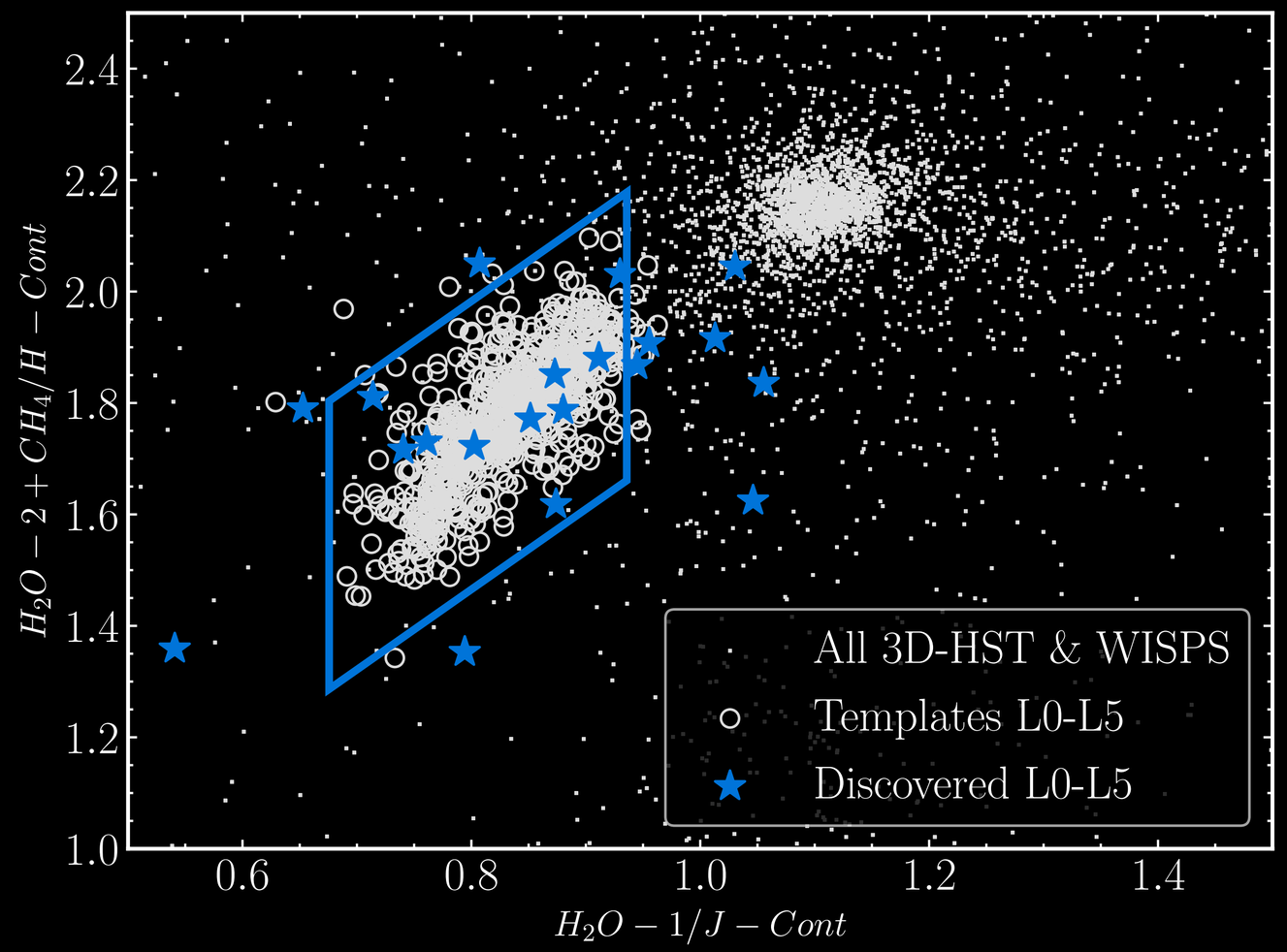




Aganze + 2022a

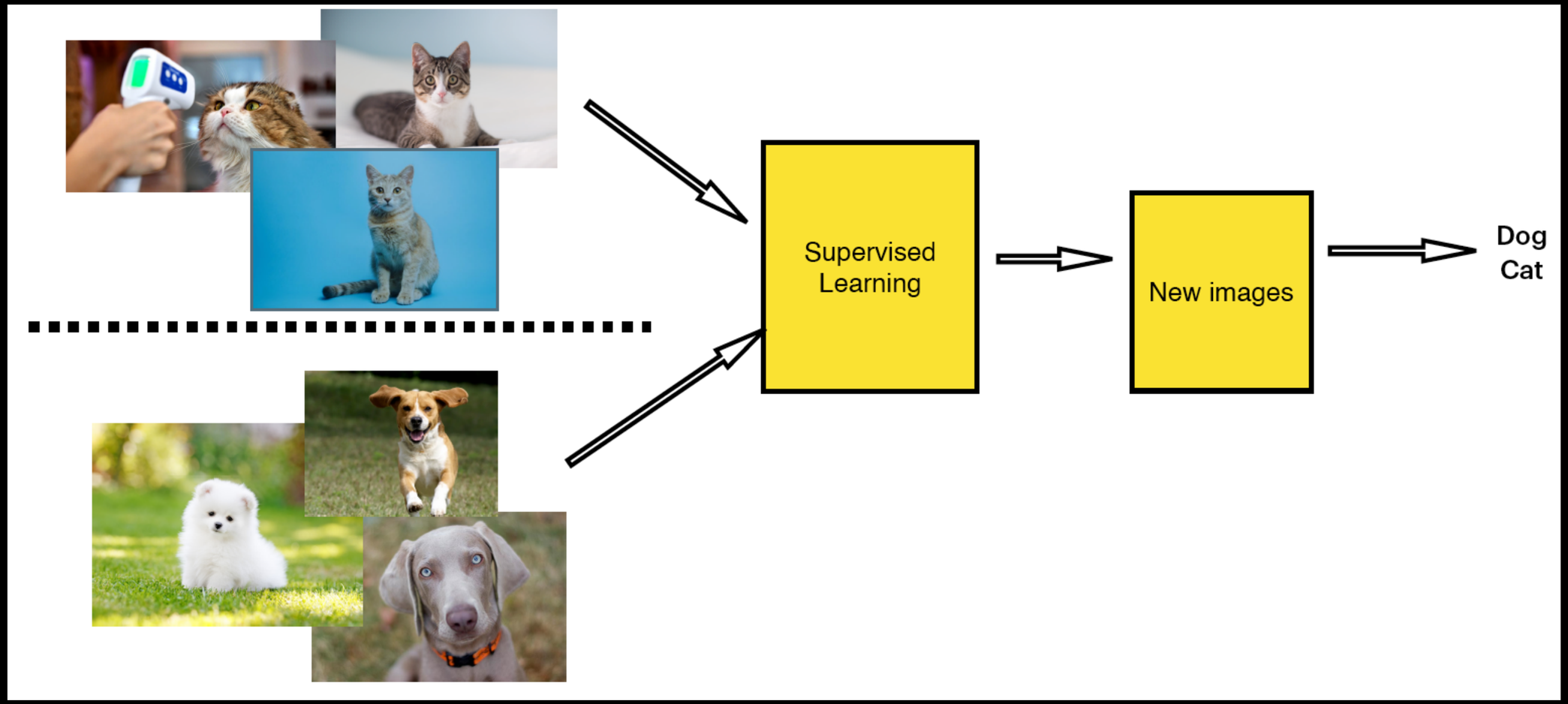
Selection by Spectral Indices



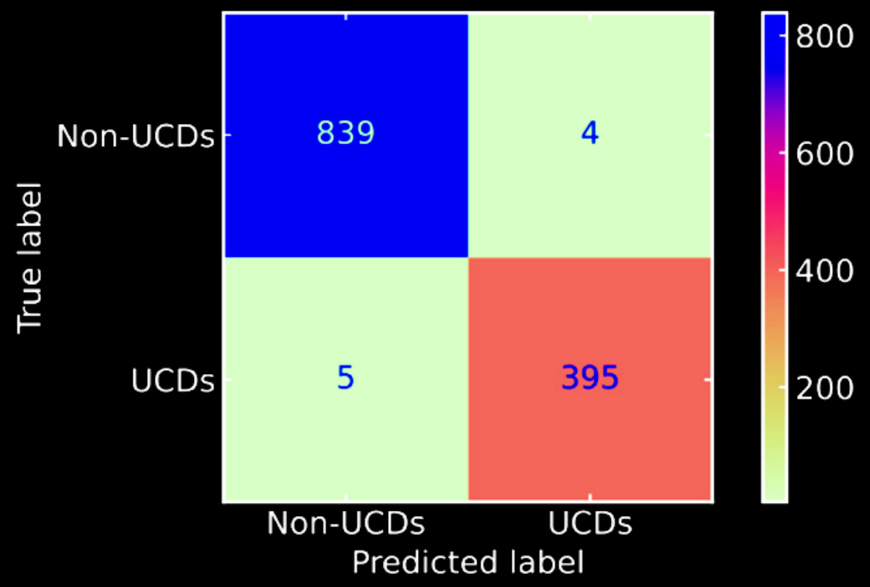


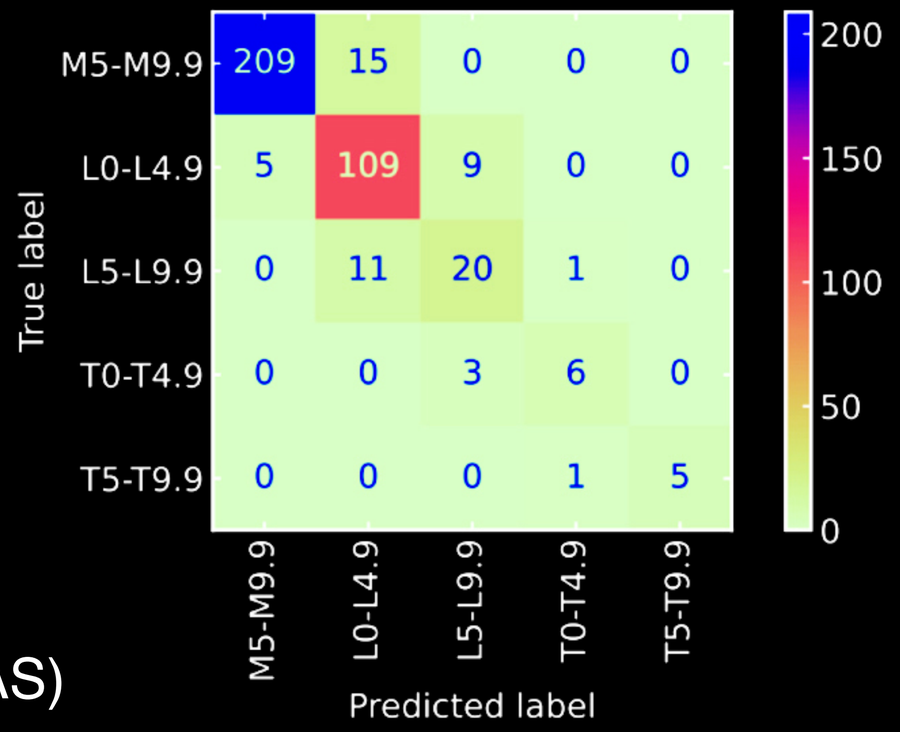
Aganze + 2022a

Alternative: Supervised Machine Learning



Training Students to Use Machine Learning Methods





Photometric classification

Gutierezz+ 2021 (RNAS), Gong + 2021 (RNAS)

Finding spectral binaries

Desai+ 2022 (in prep)

10+ students from UCSD + local high schools

Training Sets & Features

Training set

~ 3,000 known ultracool dwarfs spectra (SpexPrism Library, Burgasser 2014)

~150,000 objects flagged as galaxies

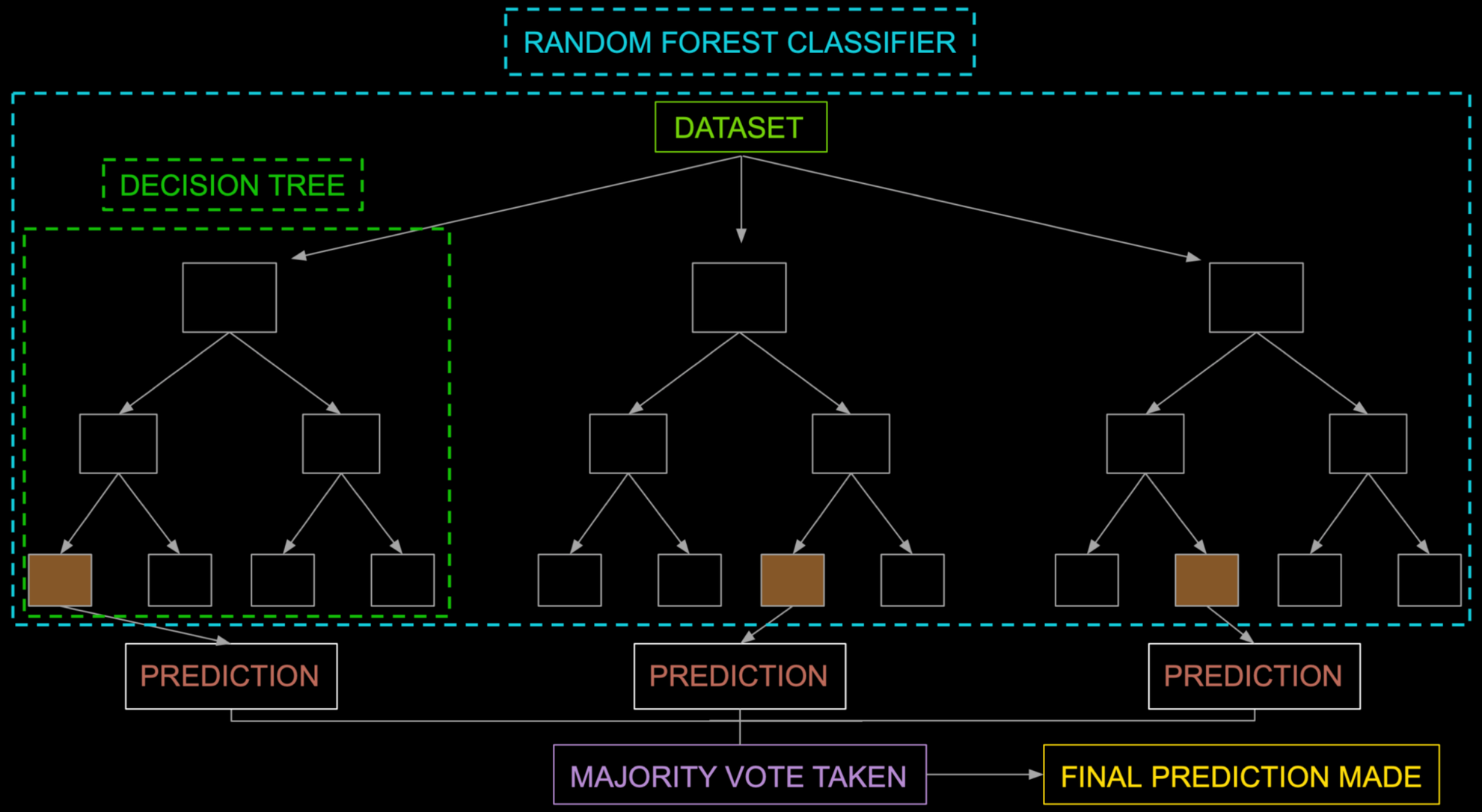
Prediction set

104,346 objects flagged as point sources

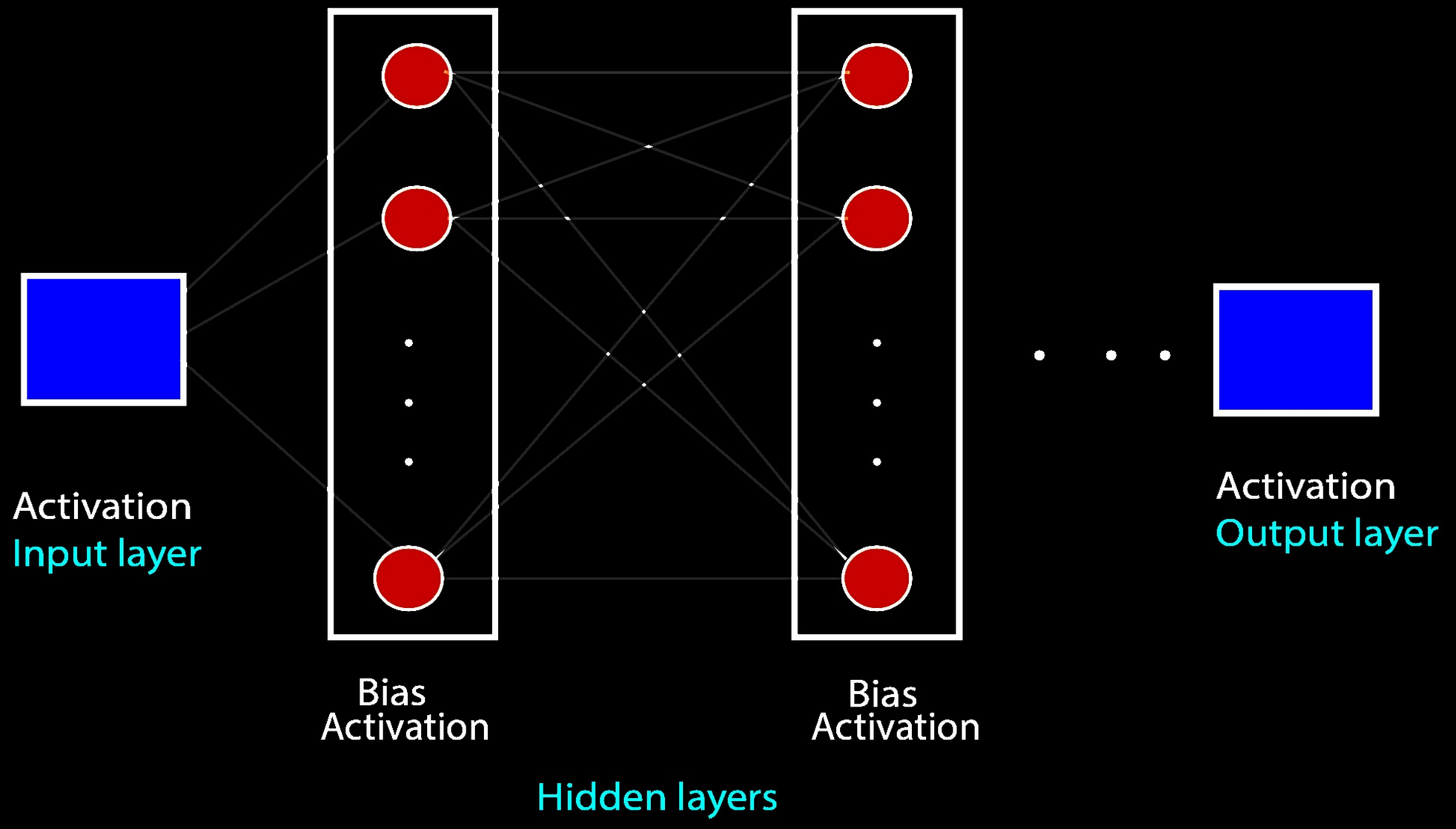
Measurements: spectral indices, S/N ratio and other comparison statistics

Classes: Galaxies, early M, late M, L & T dwarfs

Random Forest



Selection by Artificial Neural Network



Comparing Methods

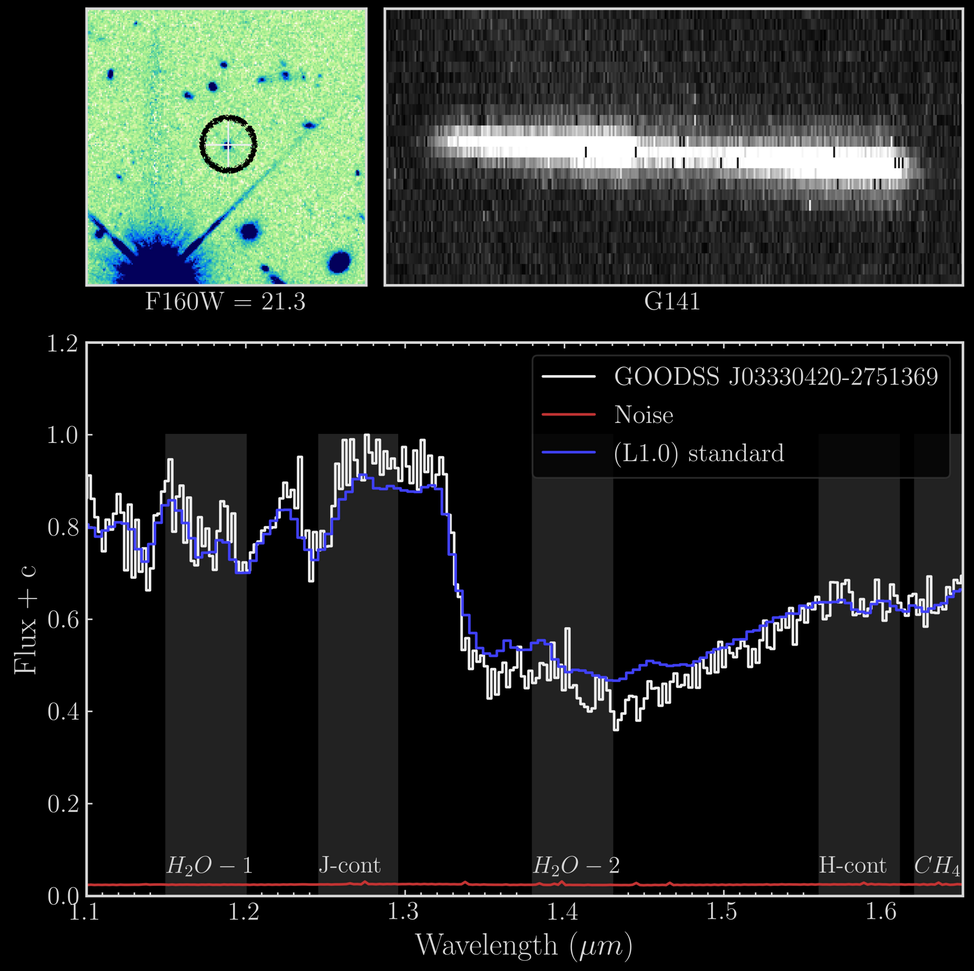
	M7-M9	L0—L4	L5-L9	T0-T4	T5-Y0	Contaminants
Indices	125	21	5	7	3	3400
Random Forest	120	21	5	7	3	120
Neural Network	124	19	5	7	3	124

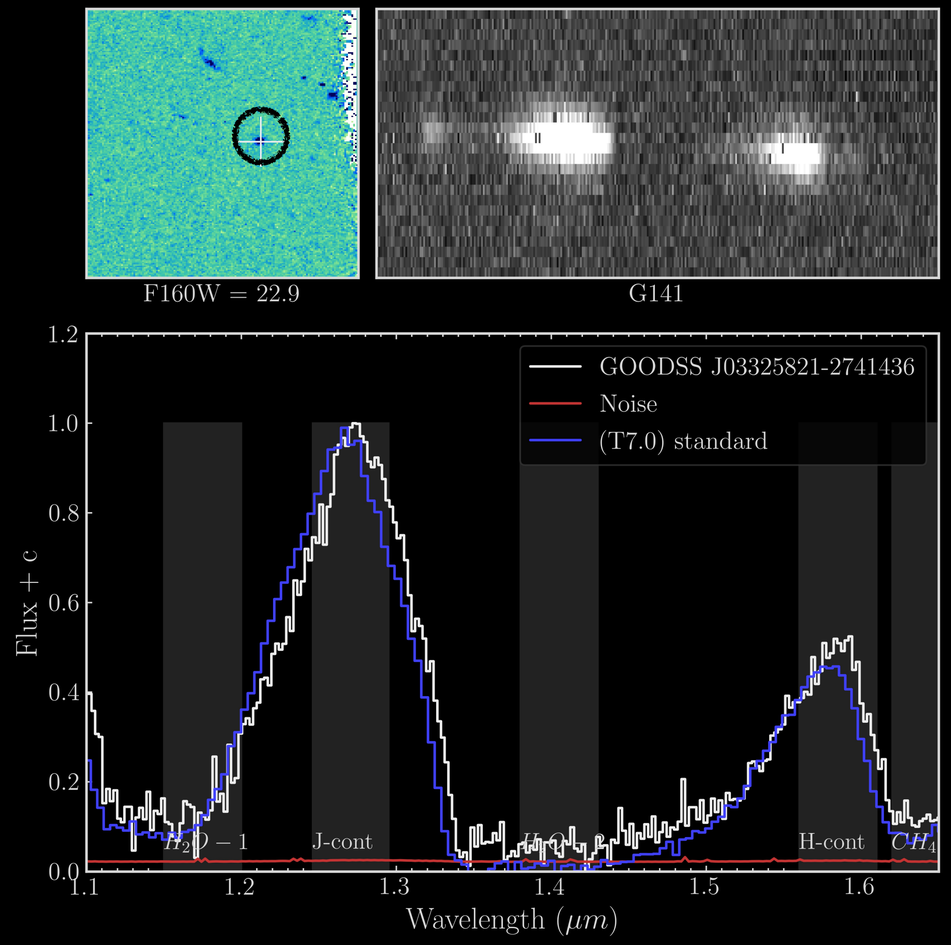
Example of Discovered UCDs

164 M7-M9 dwarfs up to **~2 kpc**

26 L dwarfs up to **~2 kpc**

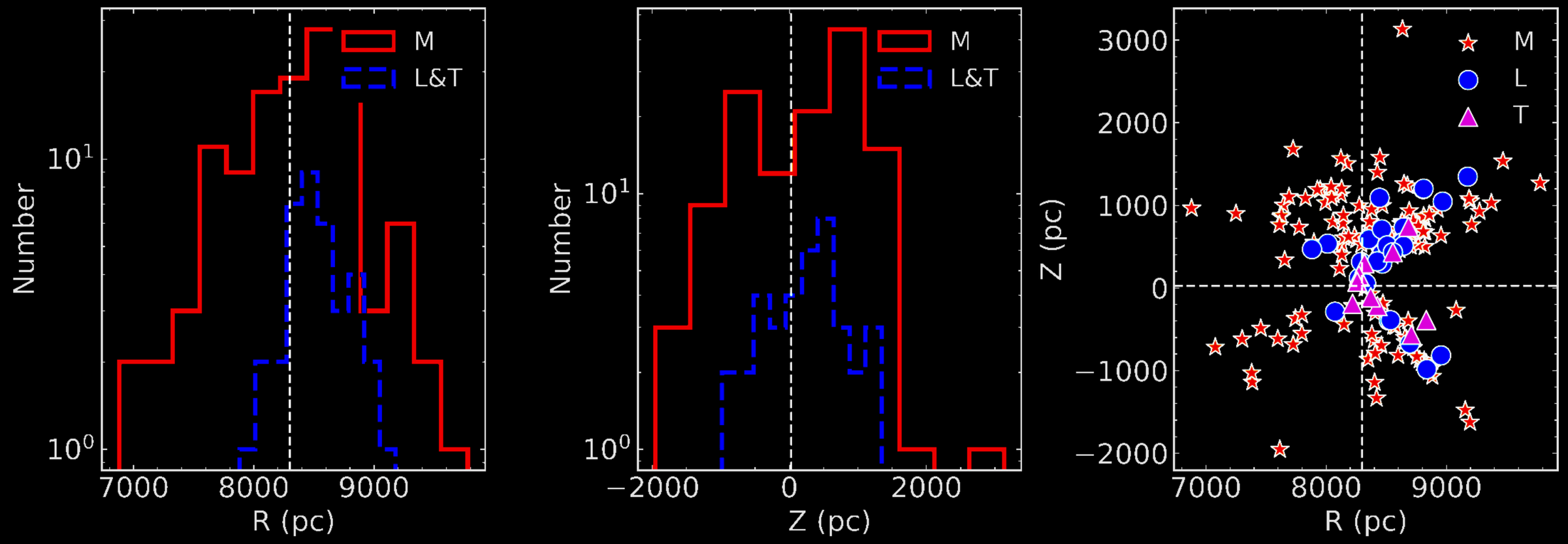
10 T dwarfs up to **~500 pc**





Aganze + 2022a

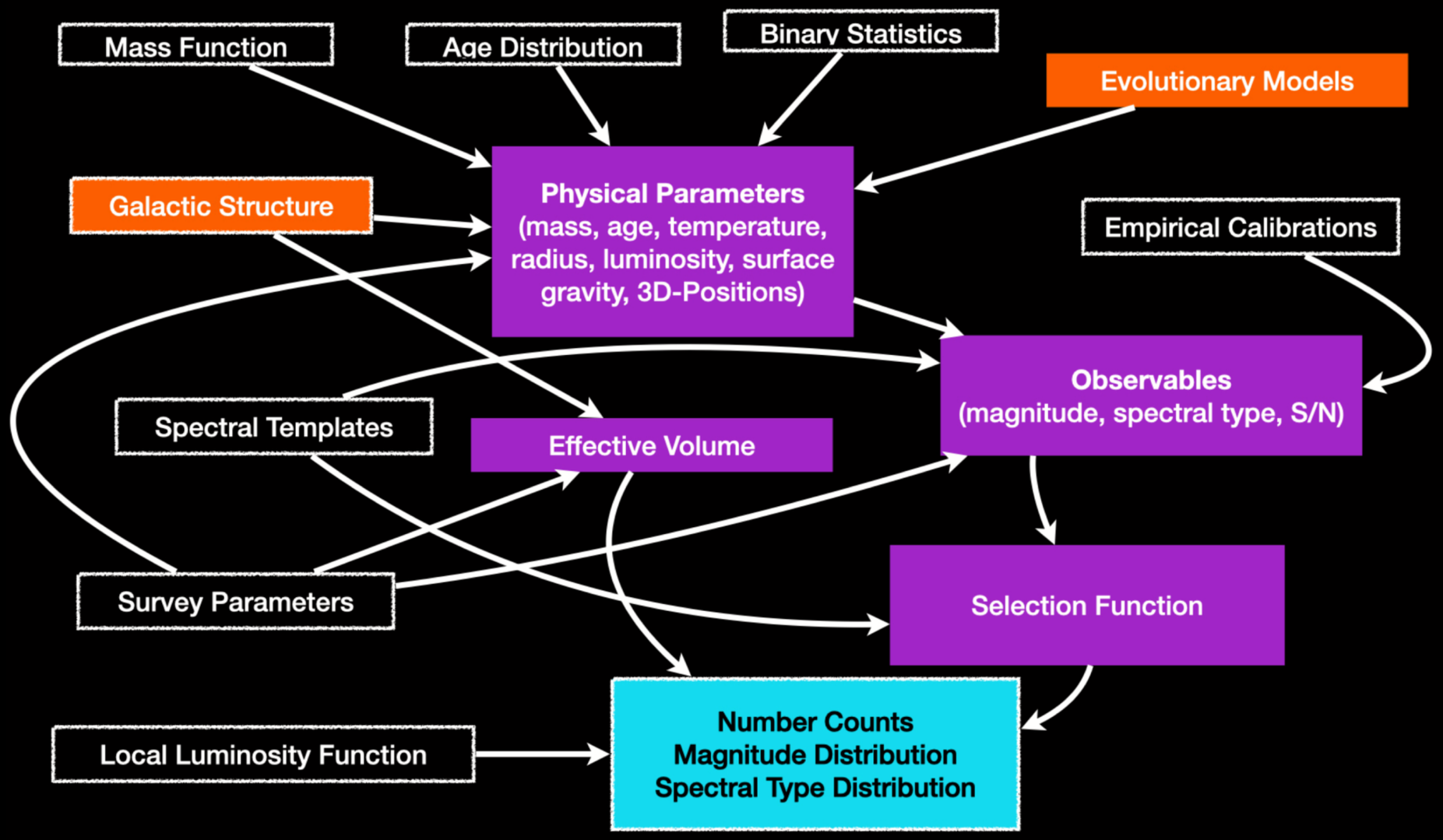
Galactic Distribution of the Sample



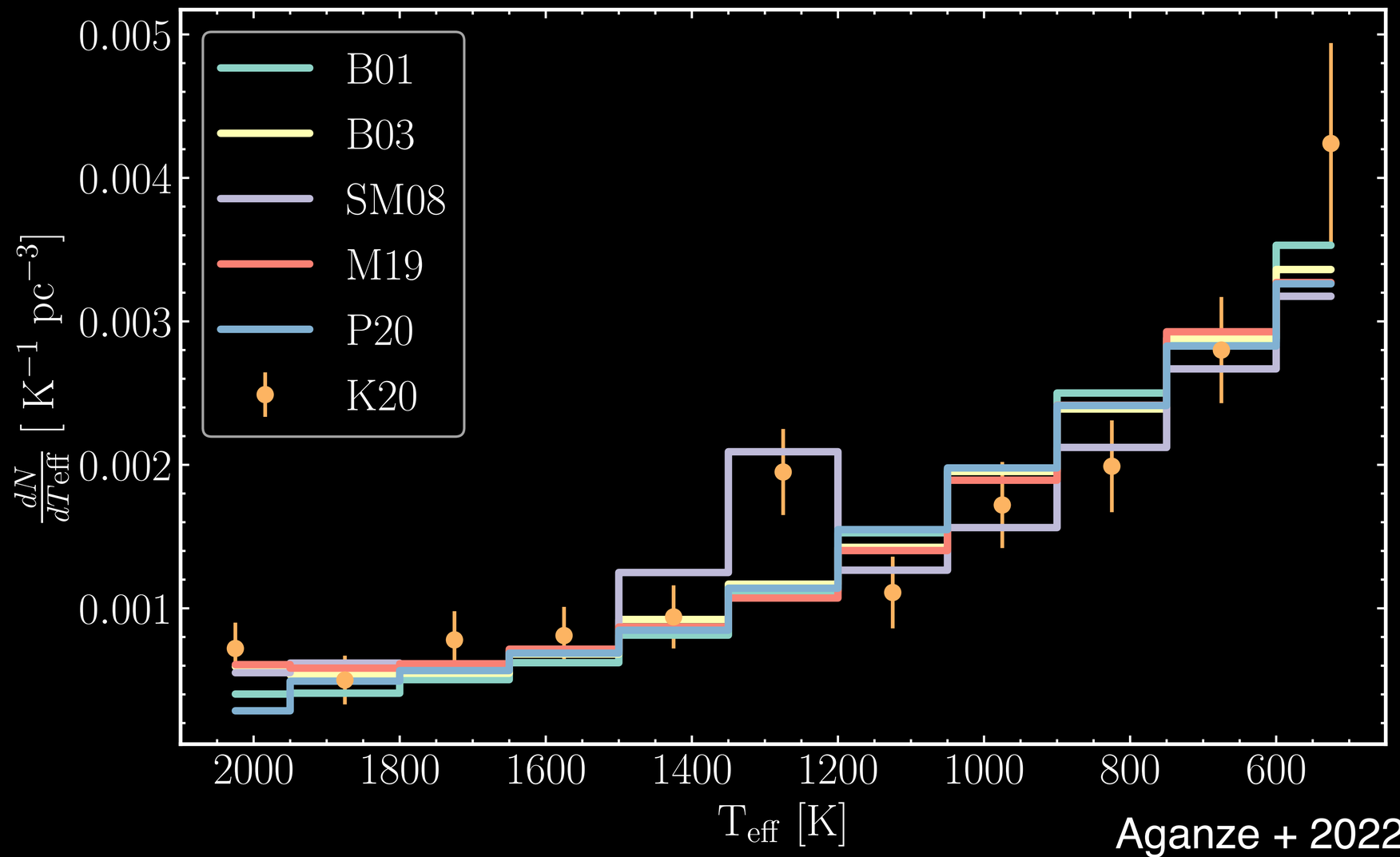
Aganze + 2022a

Part 2: Measuring Galactic Structure

Measuring Structure: Monte-Carlo Simulations

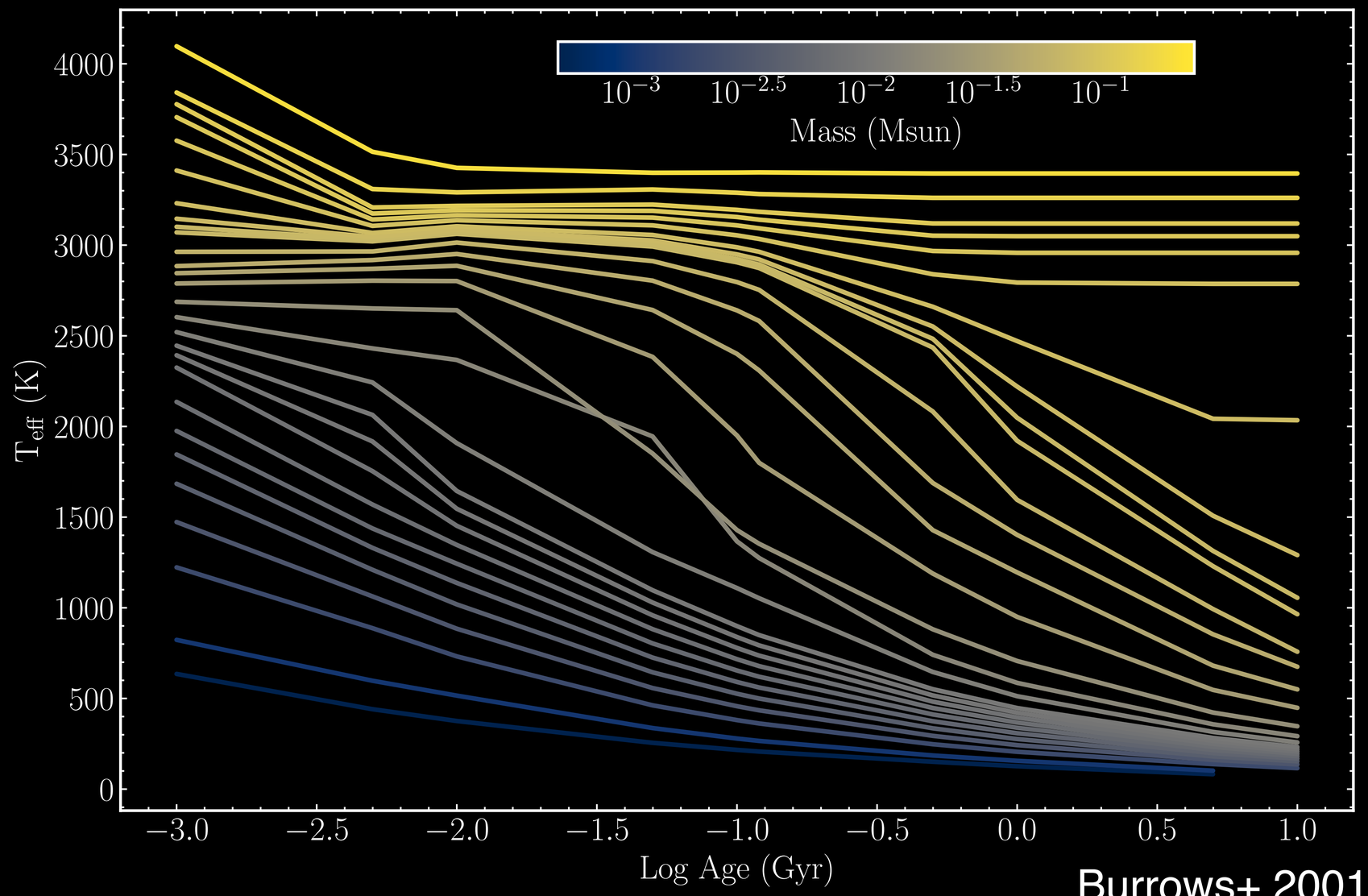


Comparison with the Local Luminosity Function



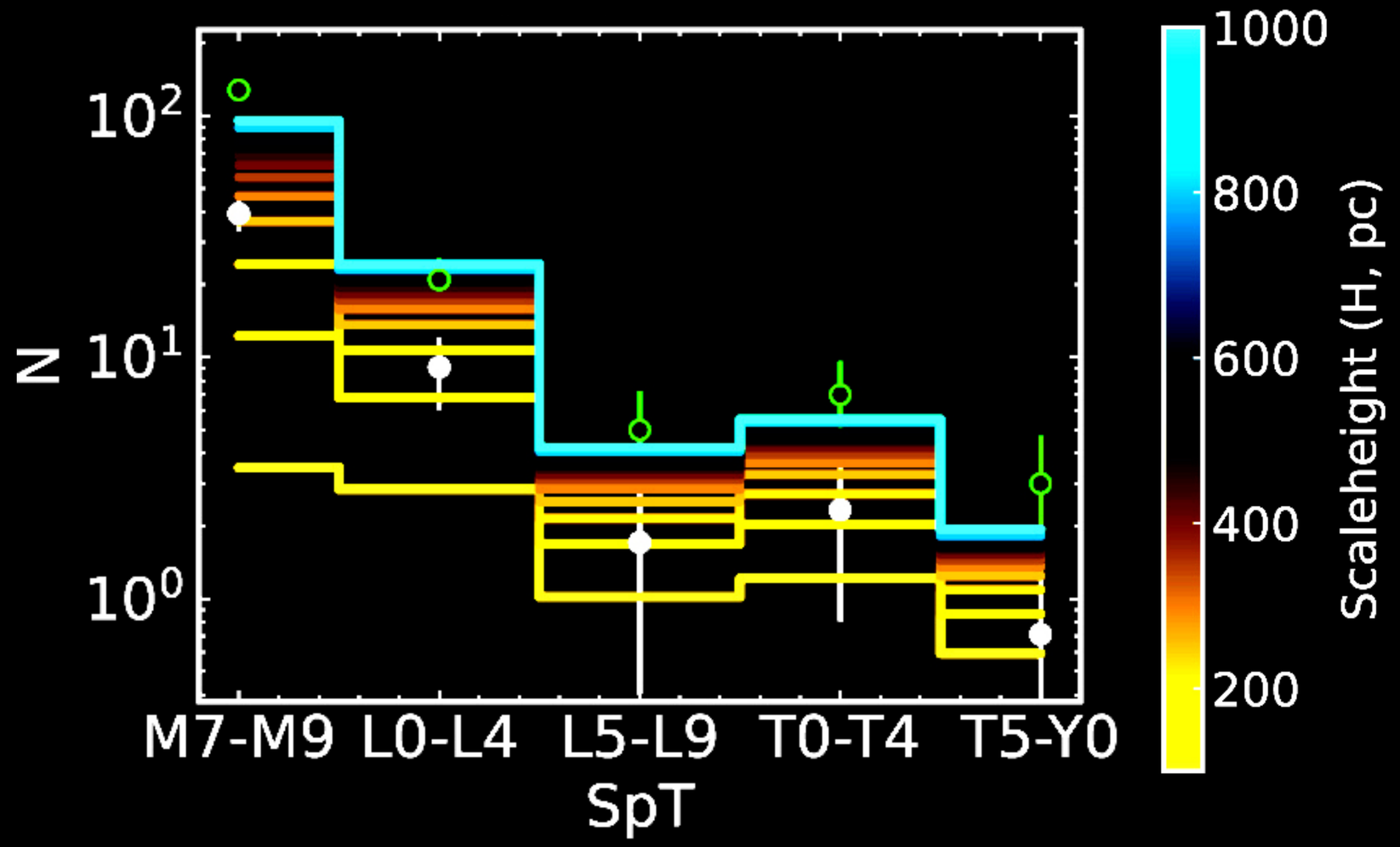
Aganze + 2022b

UCDs Pile up to Low Temperatures Due to Cooling



Burrows+ 2001

Inferring Scaleheight from Counts



Vertical distance (pc)

Density in (pc^{-3})

$$\rho \propto \exp\left(\frac{-|Z - Z_0|}{H}\right)$$

Scaleheight (pc)

Aganze + 2022b

Constraints on Population Ages

Velocity dispersion in units [20 km/s]

Scaleheight [pc]

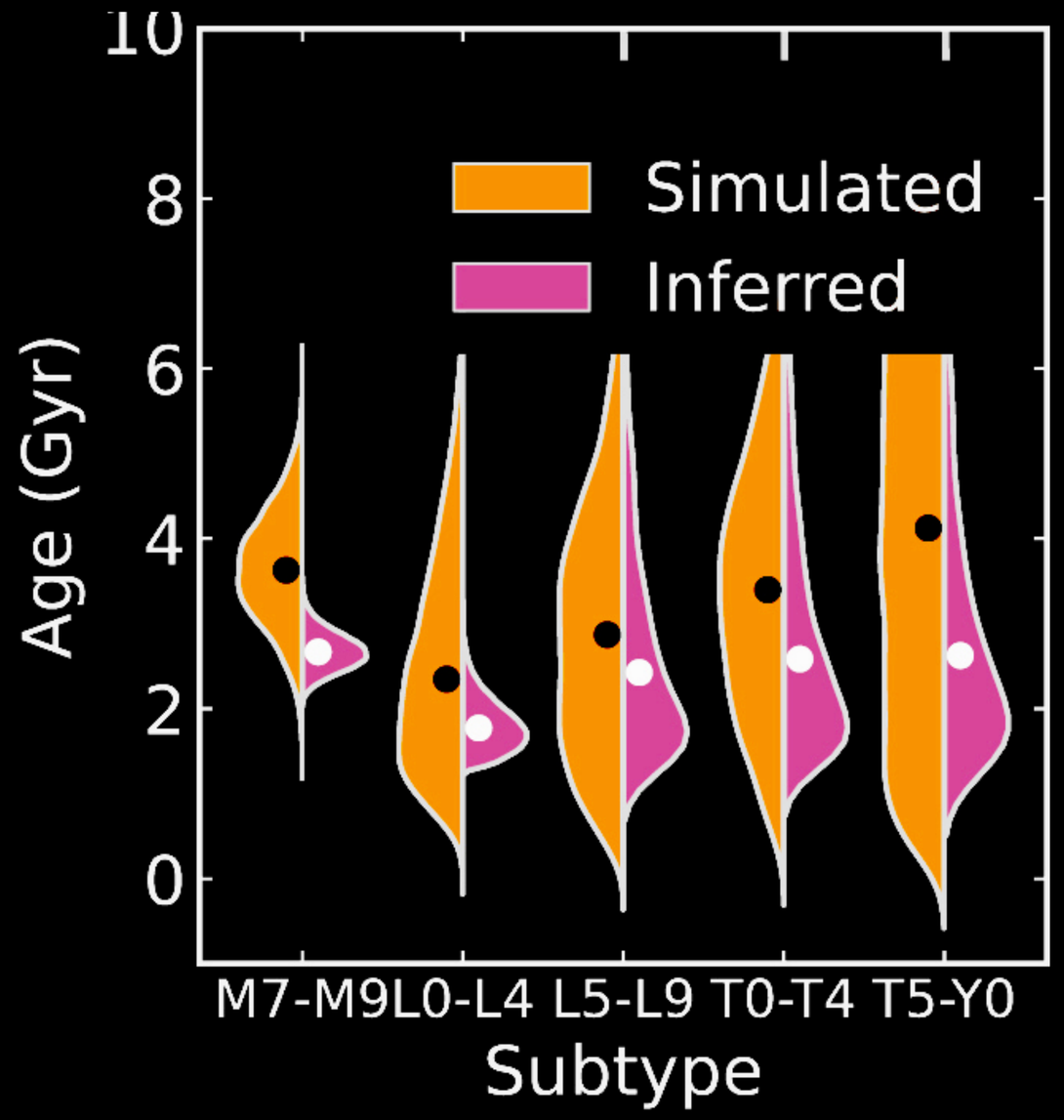
$$H = \zeta_n \frac{\sigma_{20}^2}{\Sigma_{68}}$$

Surface mass density in [68 $M_\odot$ pc^{-2}]

Age (Gyr)

$$\sigma(\tau) = \nu_{10}\left(\frac{\tau + \tau_1}{10\text{Gyr} + \tau_1}\right)^\beta$$

Velocity dispersion in units [km/s]



Van der Kruit 1988, Aumer & Binney 2009, Sharma+ 2021

Aganze + 2022b

Summary of the WFC3 Parallel Surveys

We discovered a sample of **164 distant UCDs** in deep spectroscopic HST surveys

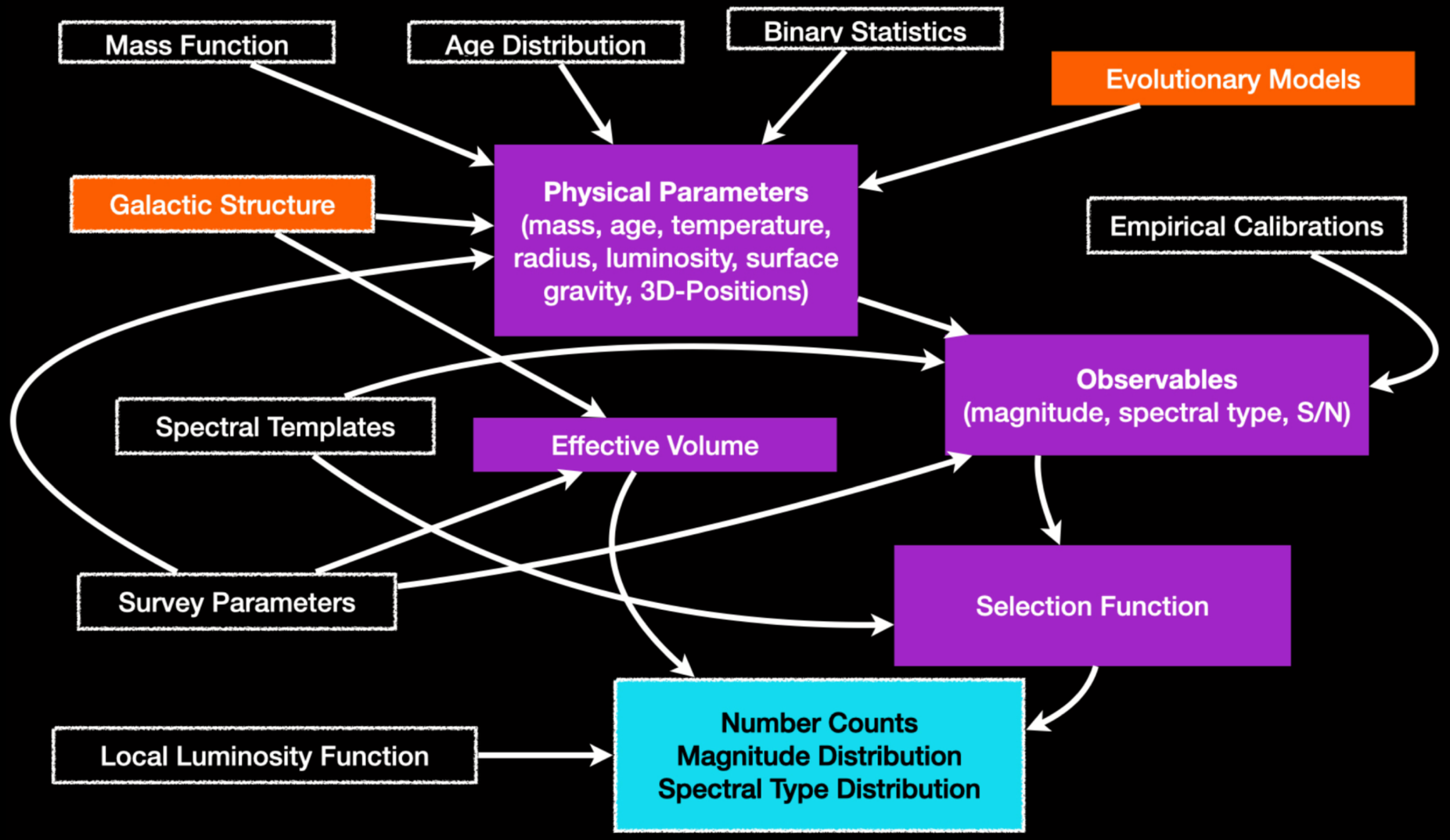
We estimate scale heights of **~250 pc** for late Ms, **~150 pc** for L dwarfs and **~180 pc** for T dwarfs

We estimate median population ages of **~3.6 Gyr** for late Ms, **~2.1 Gyr** for L dwarfs and **~2.4 Gyr** for T dwarfs with additional 1-2 Gyr systematics from AVRs

Our estimates of scaleheights and ages are consistent with predictions from evolutionary models and reveal complex age structure of UCDs in the Galactic thin disk

Part 3: Predictions for the Next Generation of Surveys

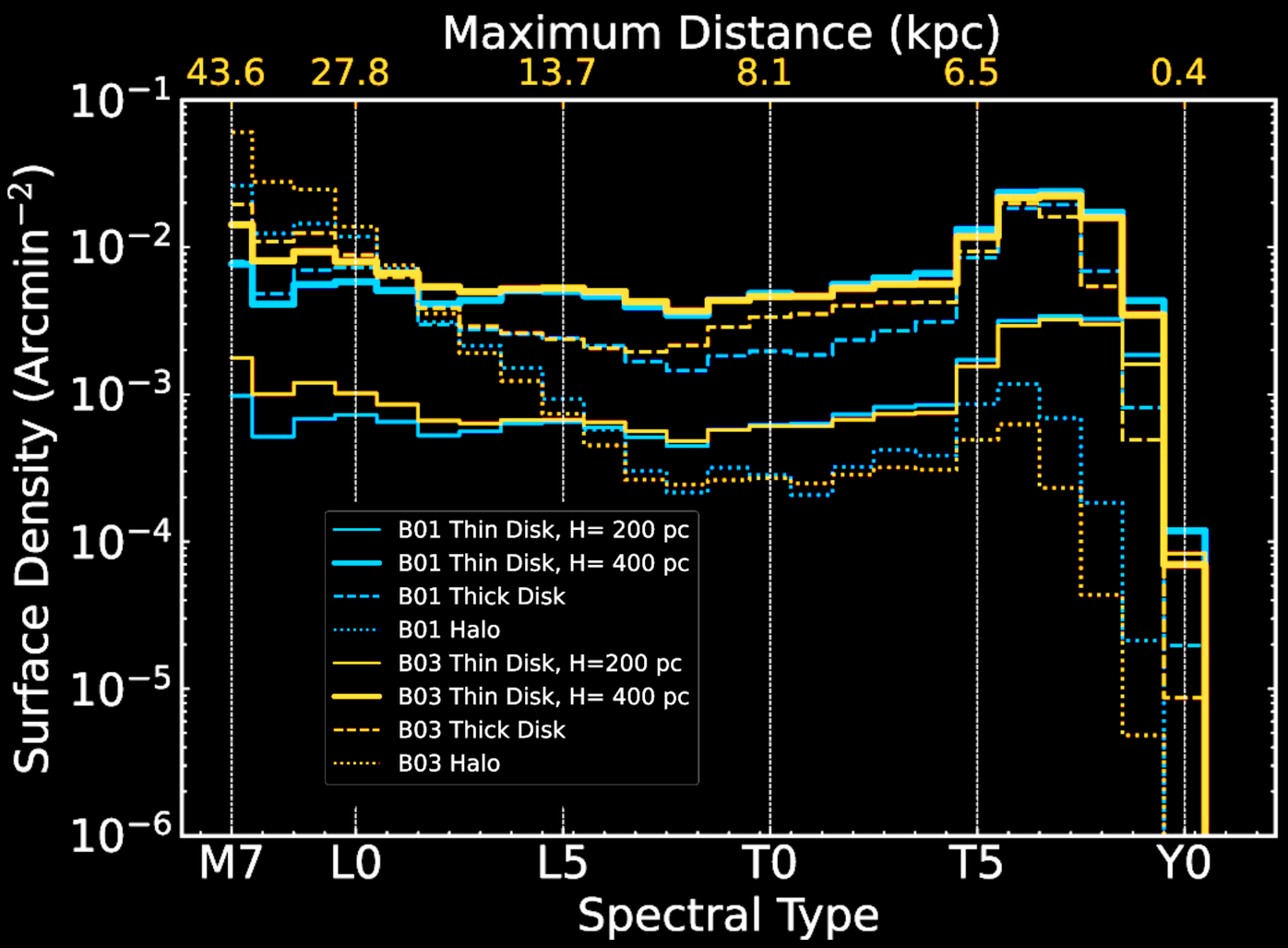
Simulation Inputs



Looking Ahead: the JWST PASSAGE Survey

124 parallel fields
Area: 500 arcmin ^{2} (0.14 deg ^{2})
F115W & F200W = 27

Expect > 100 halo dwarfs (late-M& L)

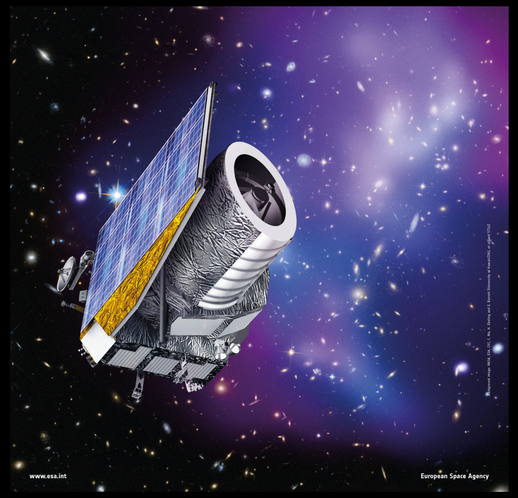


Aganze + 2022b

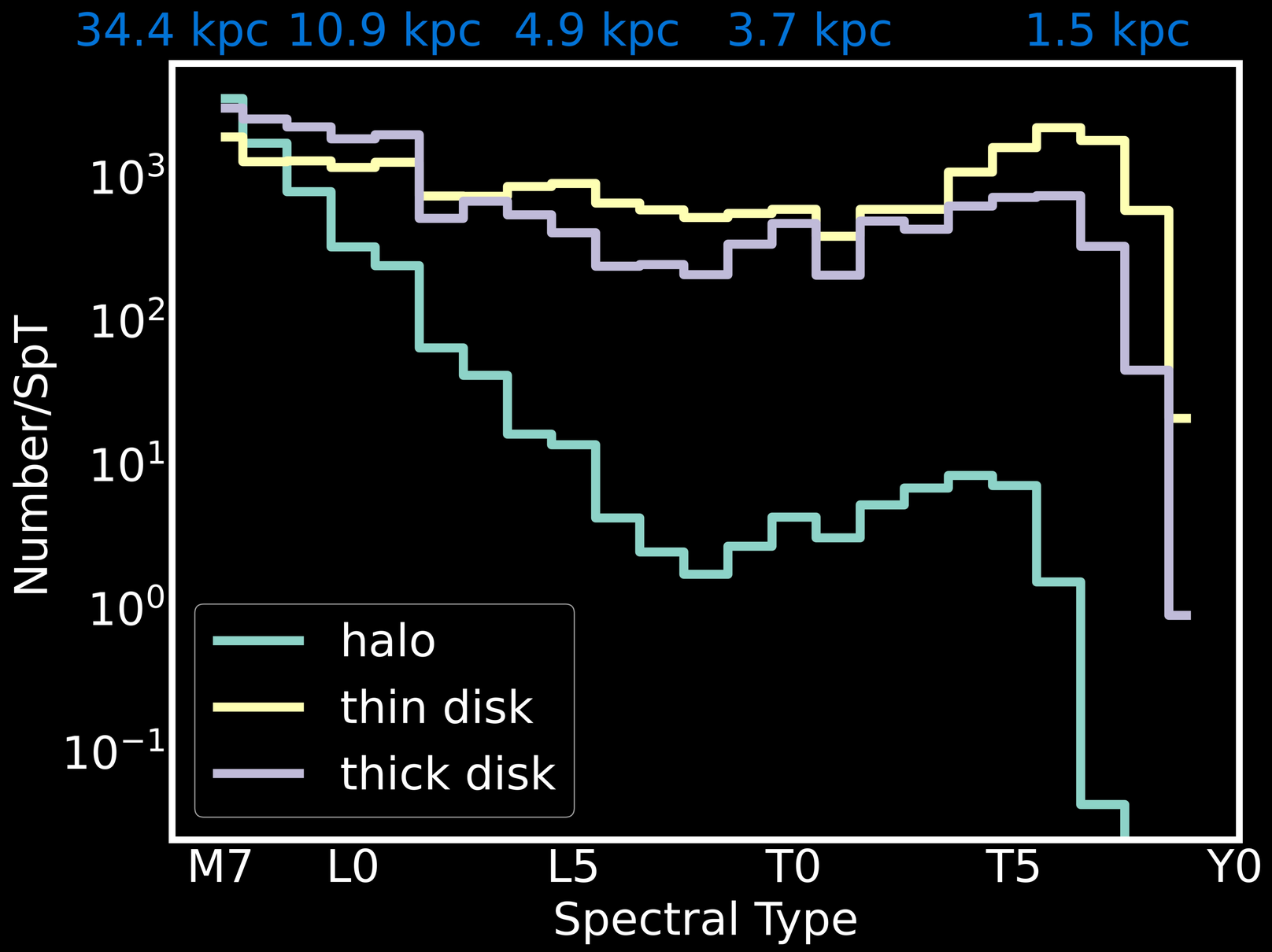
Euclid

Euclid J=27
Area/field=40 deg^2, deep fields

Expect ~7000 halo, 10^4 thick disk



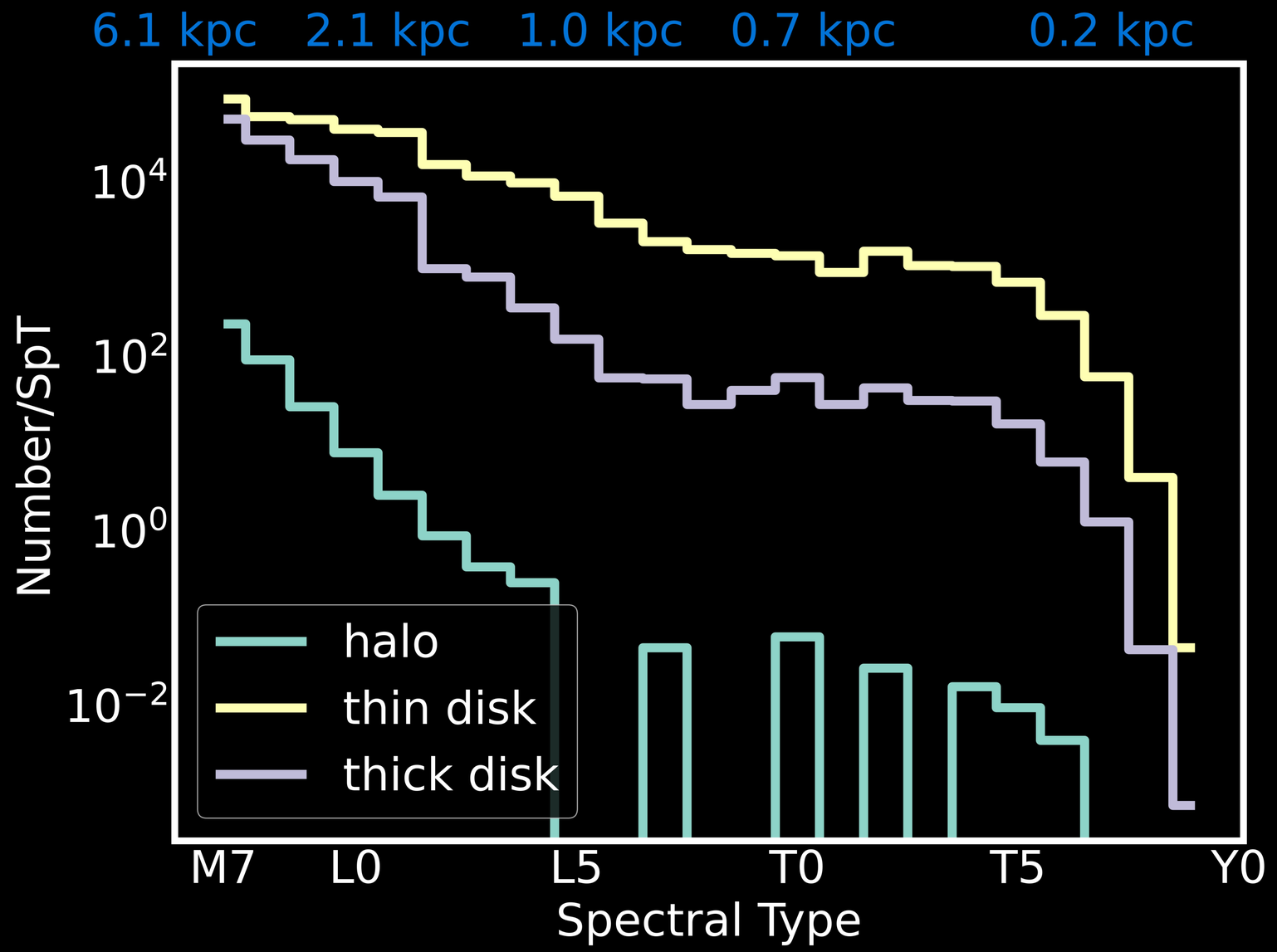
Aganze + 2023 (in prep)



The Nancy Grace Roman Telescope

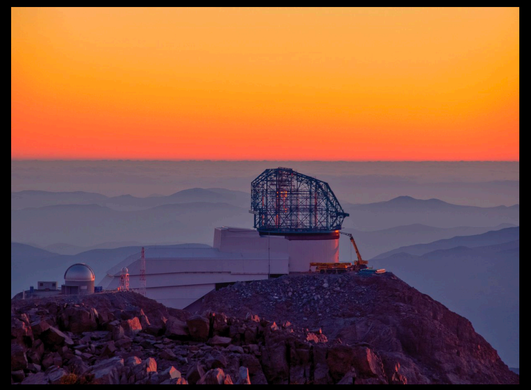
The High Latitude survey
Area= 2000 deg^2
J=24

Expect ~1000 halo,
> 10^4 thick disk



Aganze + 2023 (in prep)

The Vera Rubin Observatory

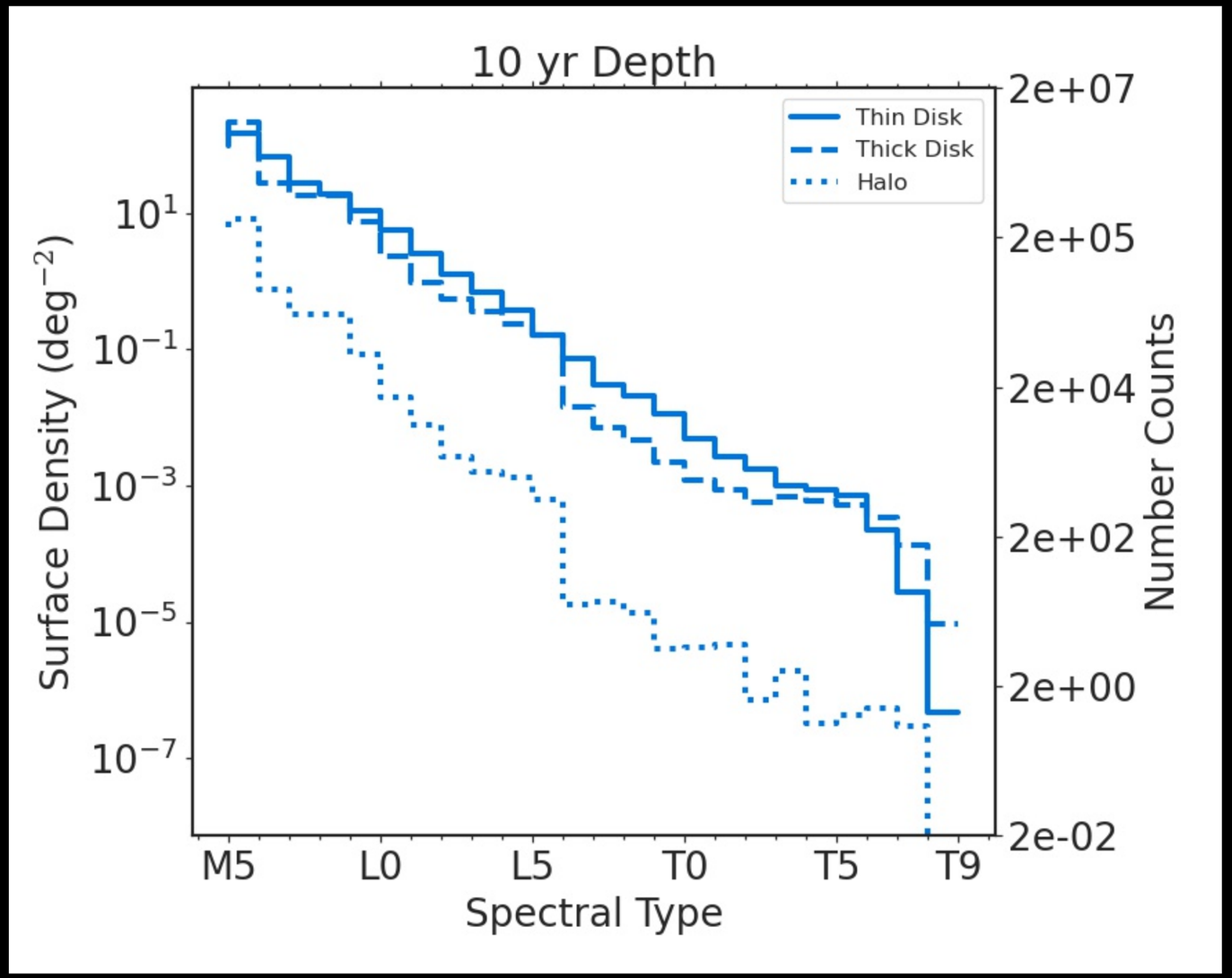


Depths:
z= 23 (single epoch)
z= 26 (10 years)
Area/field=18,000 deg^2

~ 1 mas astrometric precision

Expect >1000 halo, > 10^4 thick disk

Aganze + 2023 (in prep)



Comparing Surveys

Survey/Facility	Advantage
JWST	Spectra in multiple bands (**IR and Mid-IR**) **First unambiguous samples of halo UCDs**
Euclid	Depth (**> 5-10 kpc for L dwarfs** in deep fields) Large survey area (**>15,000 deg^2)**
Roman	Large field of view for a single pointing (**0.28 deg^2)** Large survey area (**>2,000 deg^2)**
Rubin	Large survey area (**>18,000 deg^2**) Optical imaging and 1 mas arcsec precision

Summary

We found **164 distant UCDs** in deep spectroscopic HST/WFC3 surveys

We confirmed that **late-M dwarfs are older** than L dwarfs

The next generation of upcoming surveys will provide **thousands of halo UCDs**, **tens of thousands of thick disk UCDs**, opening up a new era in galactic archeology with UCDs

Additional Slides

Limitations of our Simulations

Lack of metal-poor templates to simulate halo and thick disk populations

Lack of metal-poor models to simulate evolution/cooling of metal-poor UCDs

Smooth models of the density structure of the MW, no consideration of asymmetries and disequilibrium

Ultracool Dwarfs as Tracers of Galactic Structure

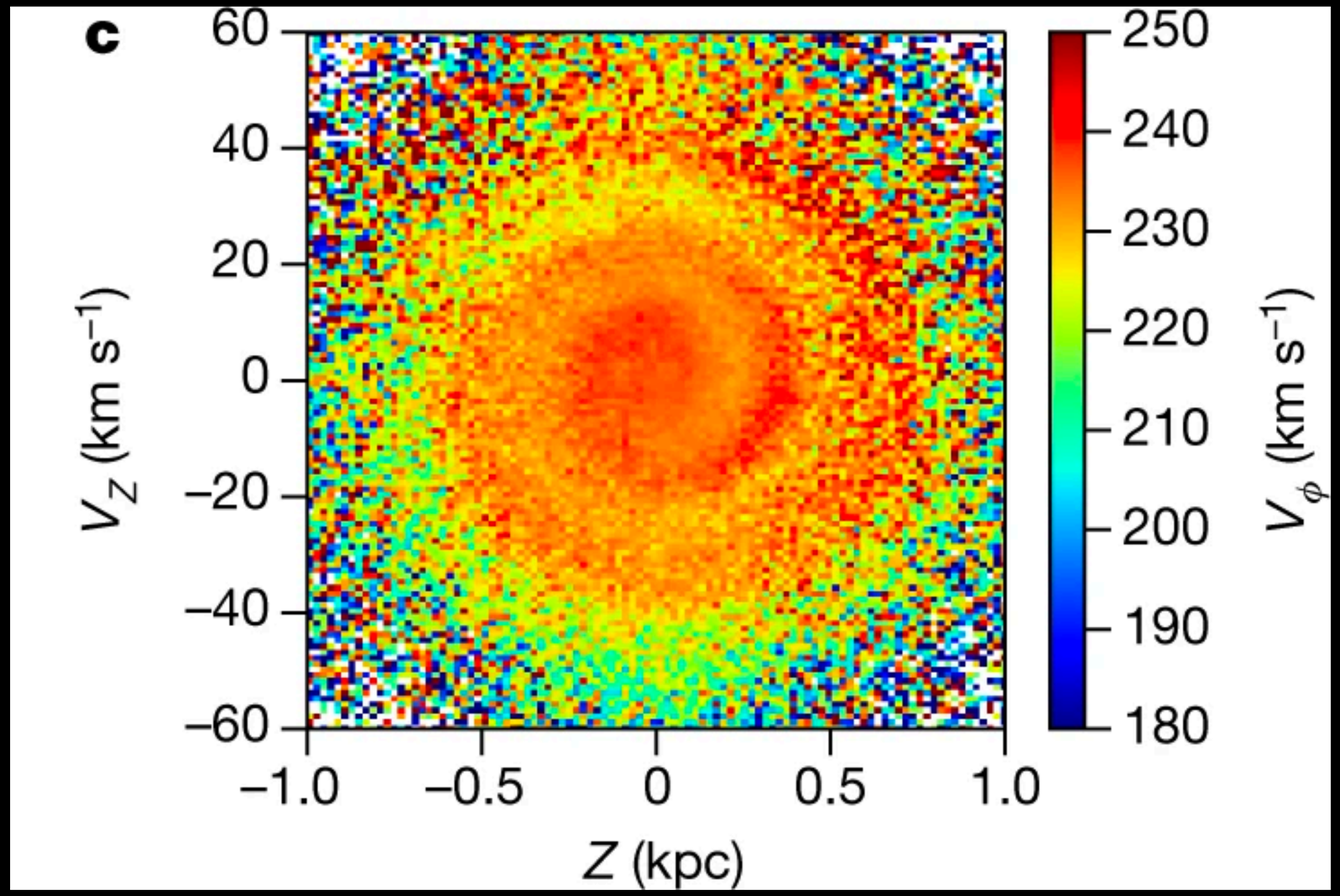
Pros

- They are ubiquitous in the Galaxy (> 20% of all stars)
- They have long lifetimes (> 1 trillion years)
- Their cooling curve directly traces their age
- Fully convective, brown dwarfs probe elemental abundances from progenitor molecular clouds

Cons

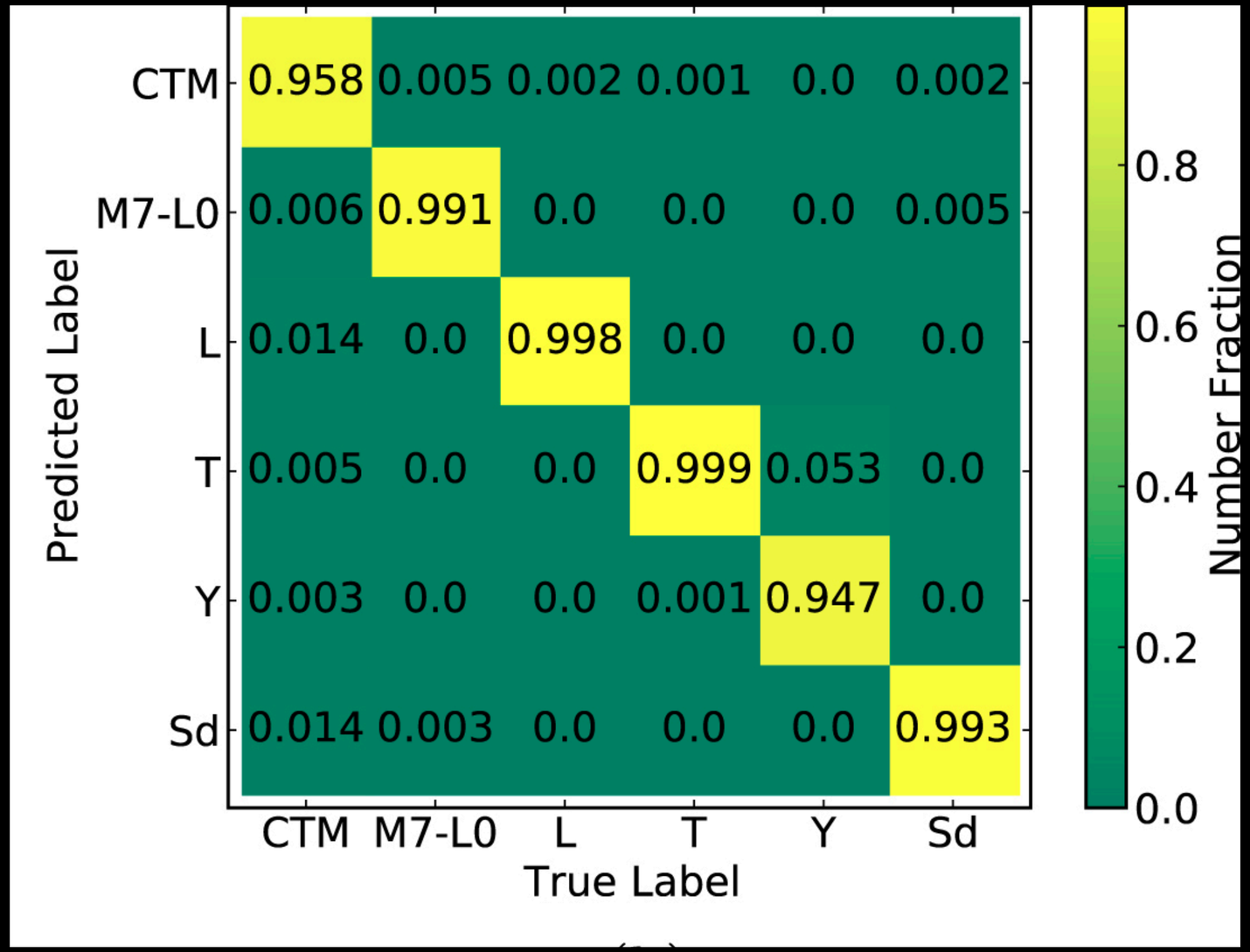
- Intrinsically faint and cold (10^{-4} solar luminosity for the coldest dwarfs)
  - *Solution: big telescopes in the infrared*
- Degeneracy between ages and masses
  - *Solution: model populations with Monte-Carlo simulations*
- Their cooling and evolution changes their observable properties (spectra)
  - *Solution: employ empirical calibrations based on local samples*

Disequilibrium in the Disk



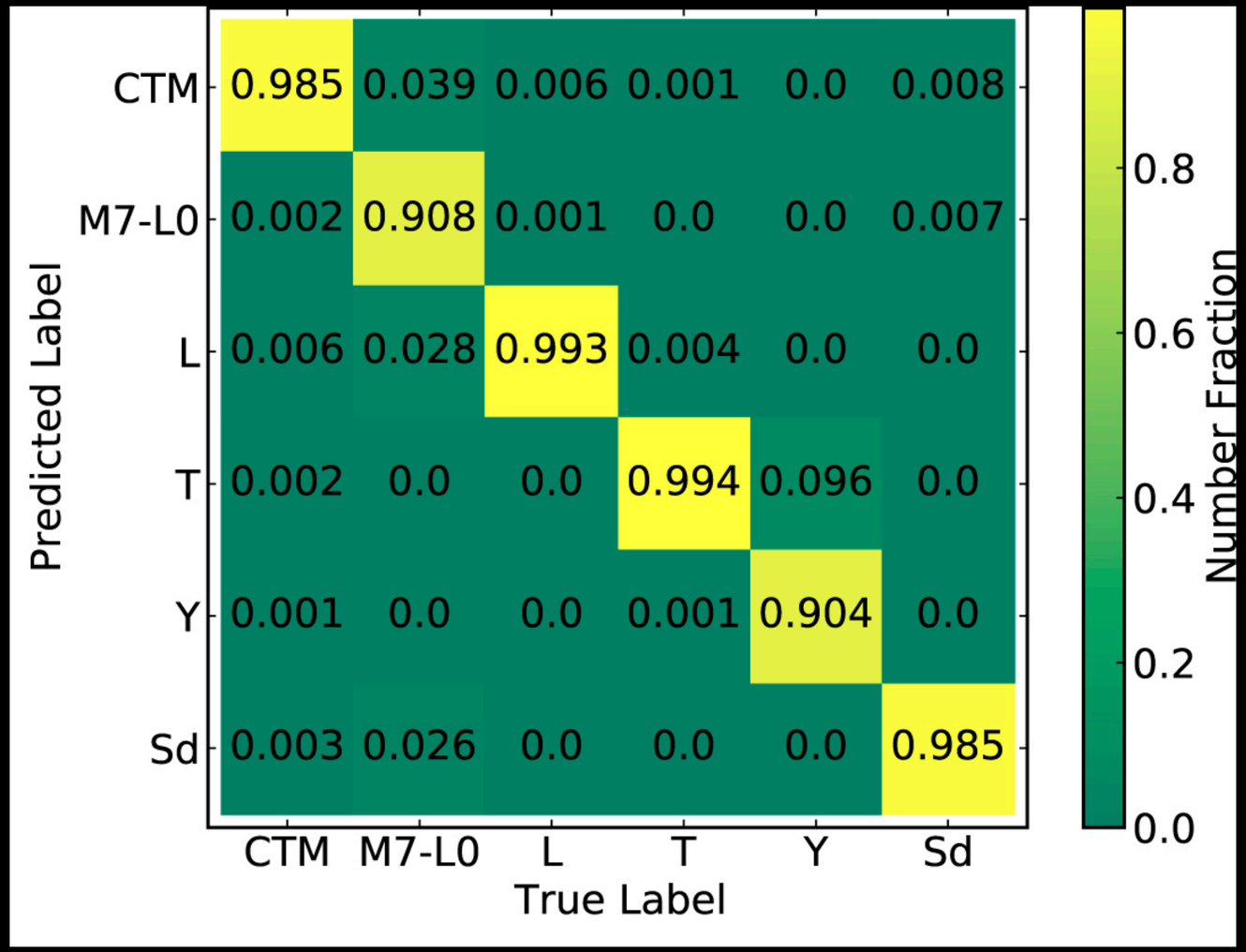
Antoja+ 2018, Hunt+ 2021, Banik+ 2022

RF Parameters & Metrics on Test Set



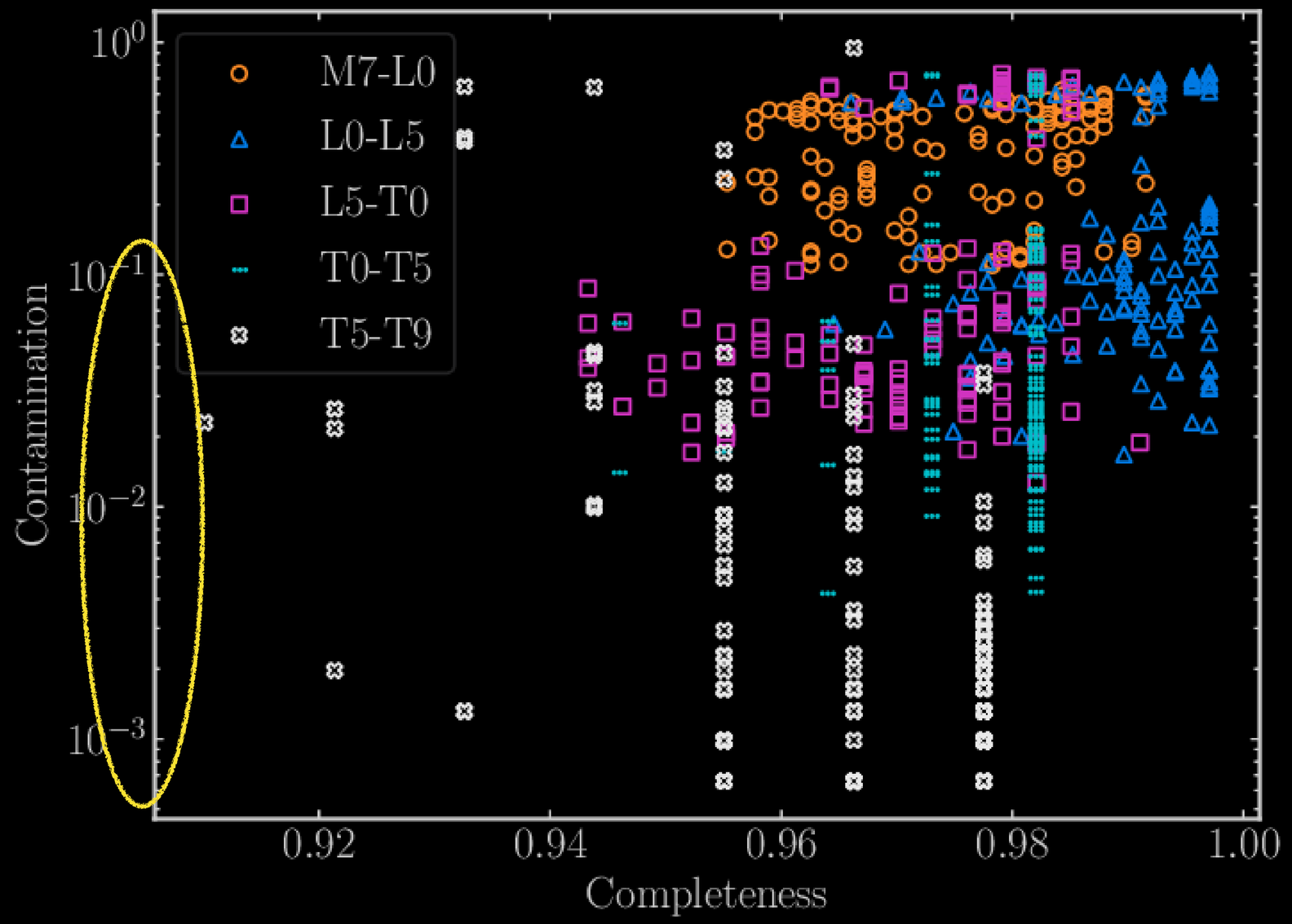
Aganze + 2022a

Deep Neural Net metrics (Test Set)

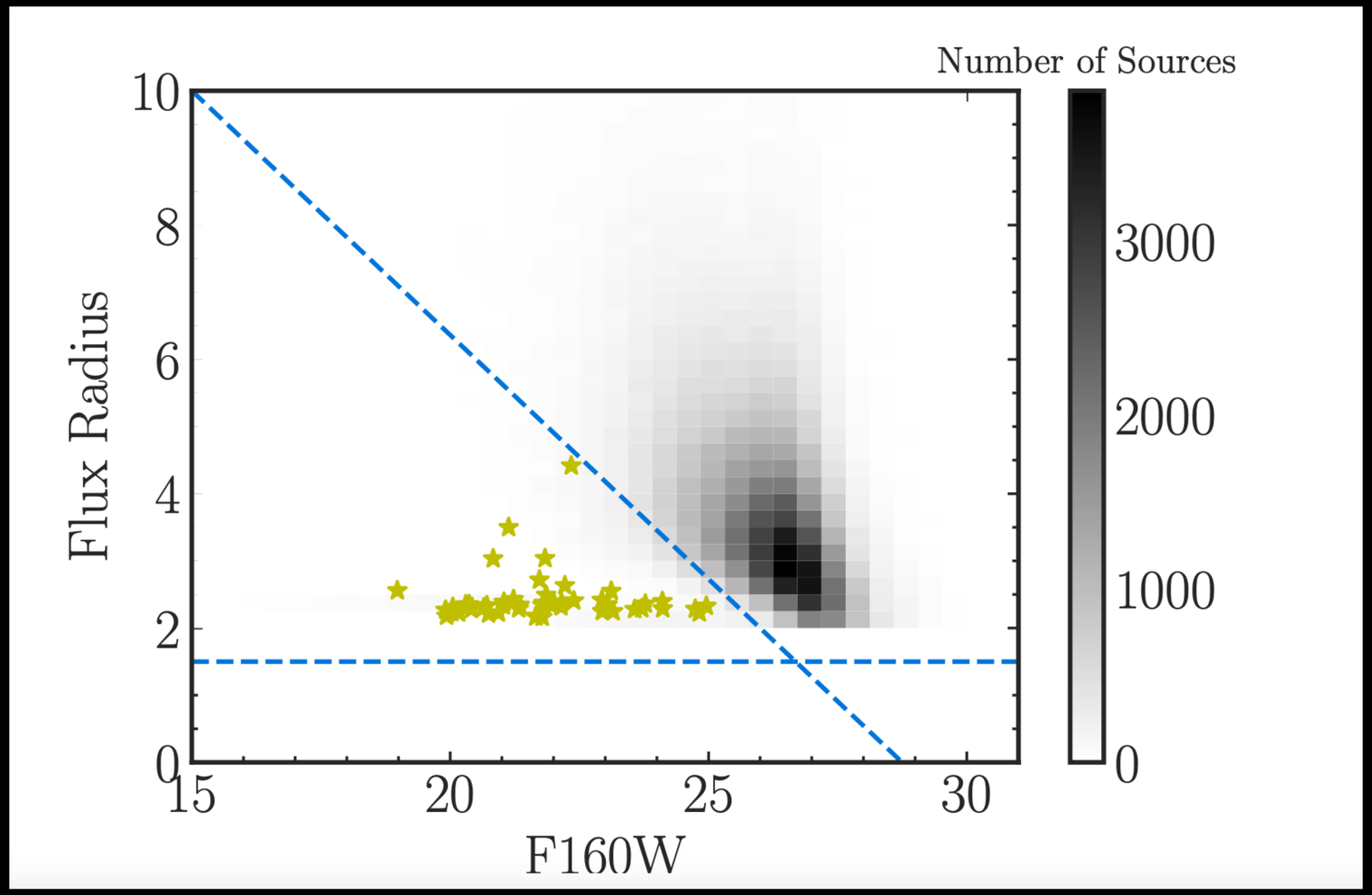


Aganze + 2022a

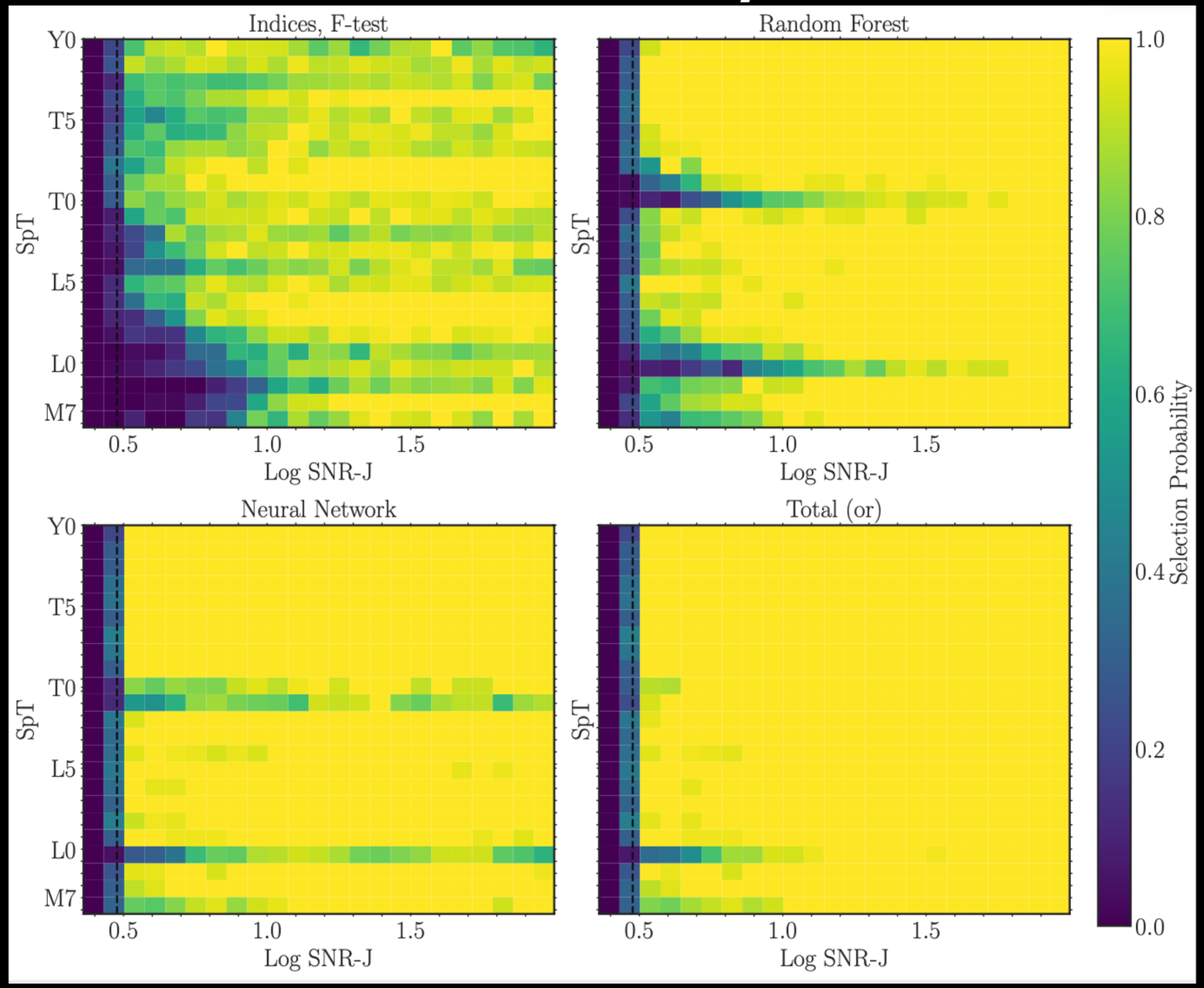
Evaluating Completeness and Contamination



Point Sources vs Galaxies

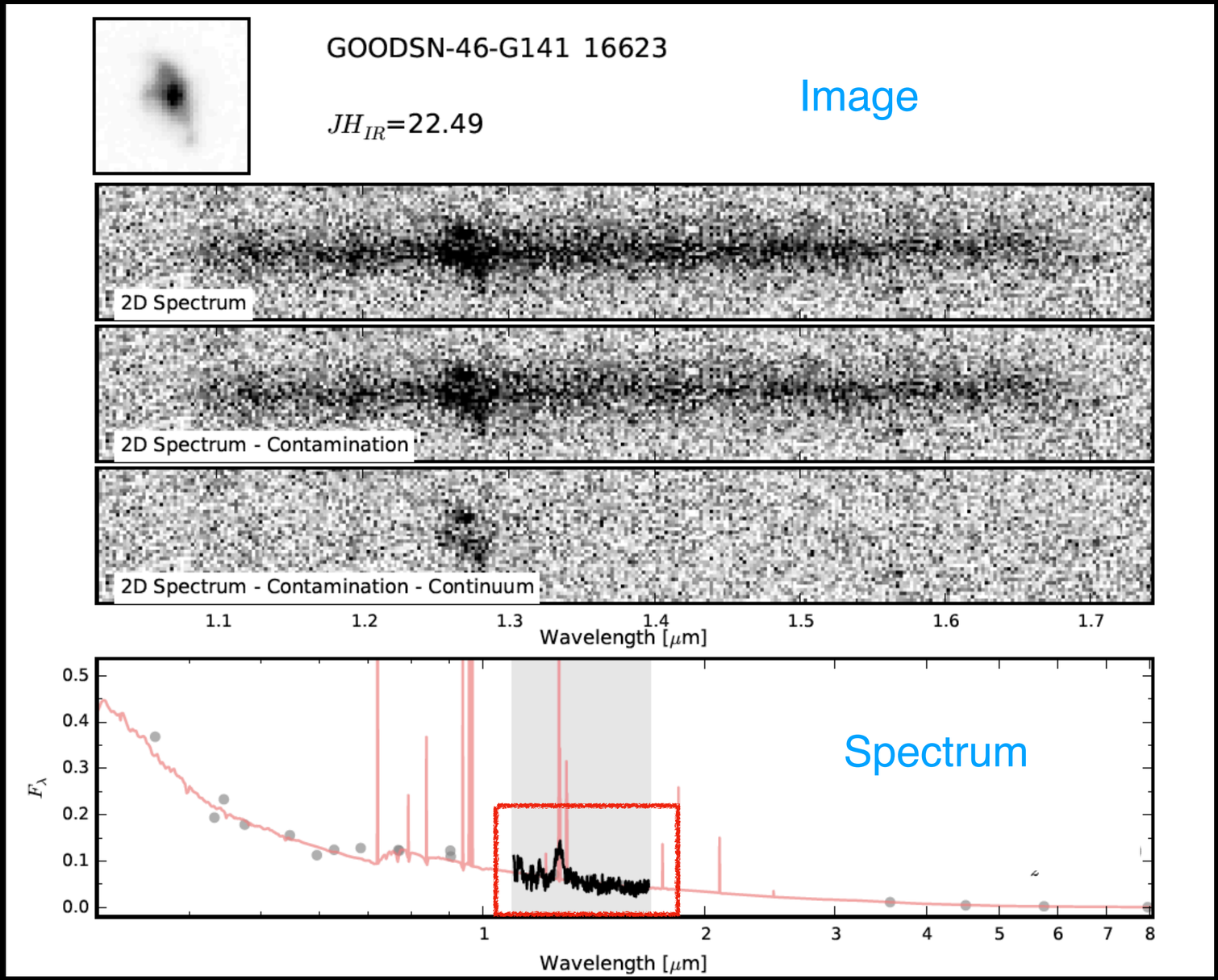


Selection as Function of S/N

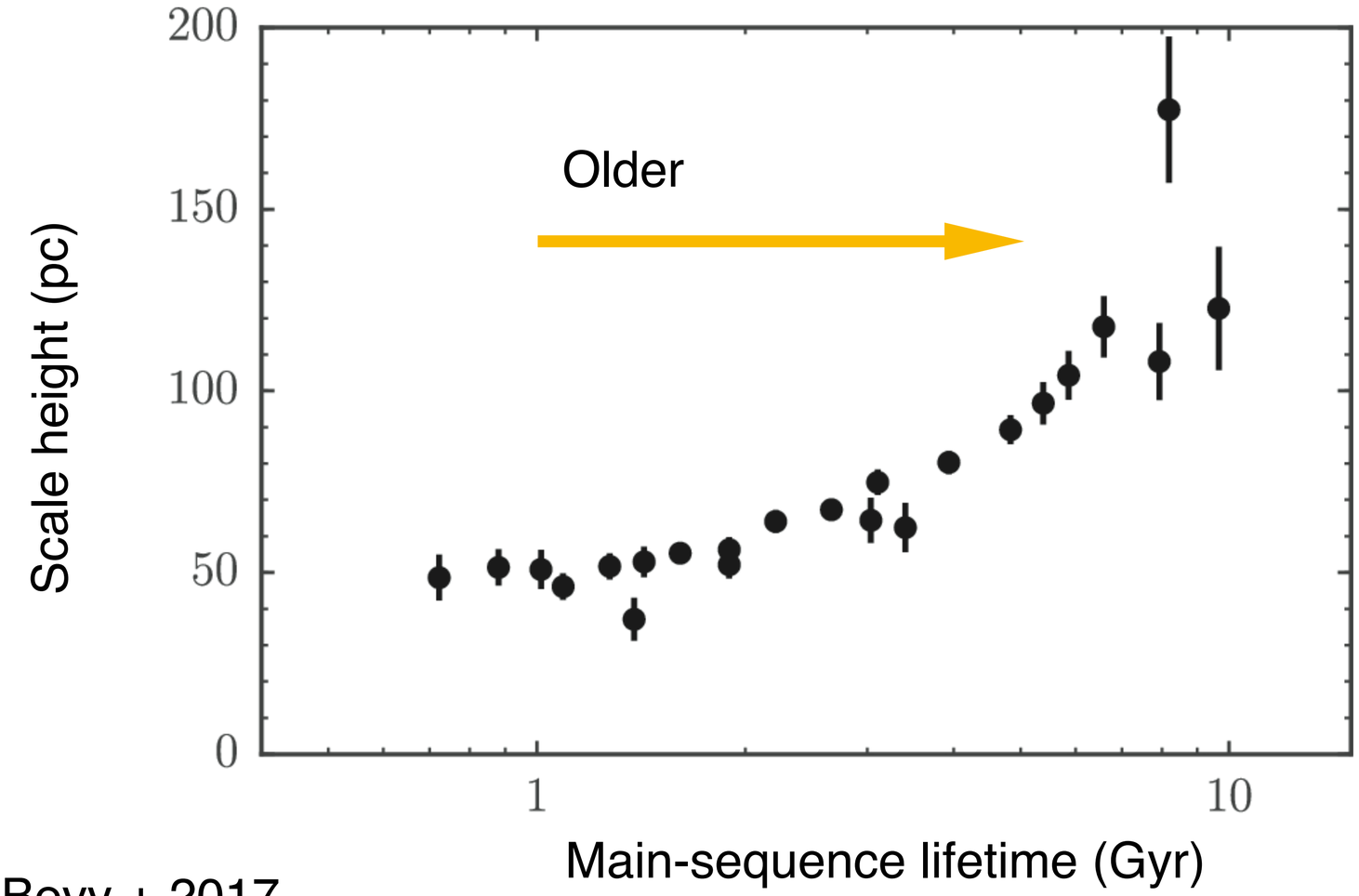


Example Spectra

Momcheva et al. 2016



Scale height, Velocity Dispersion and Age



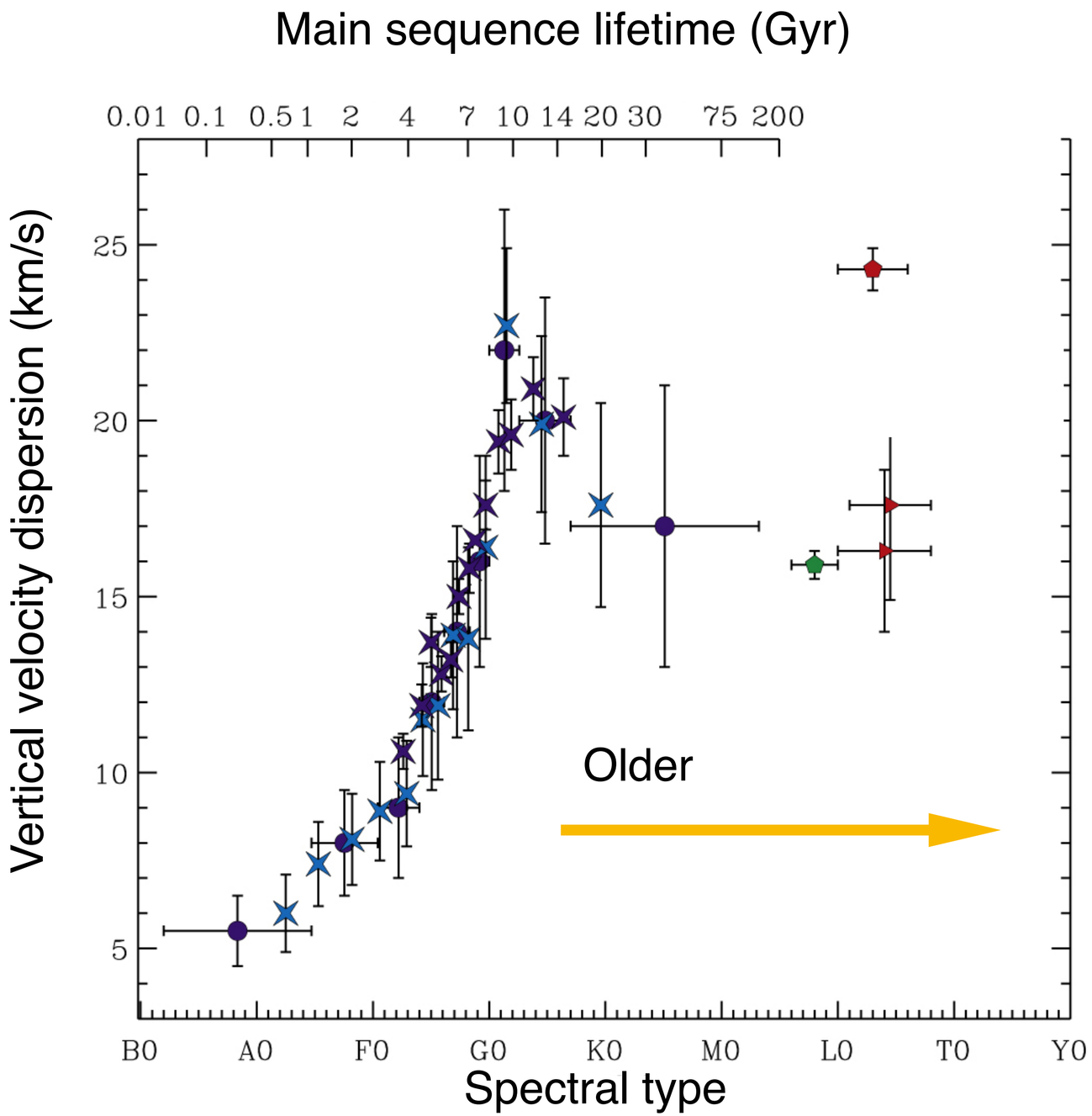
Bovy + 2017

Vertical height above the plane (pc)

$$\rho \propto sech^2\left(\frac{-|Z - Z_0|}{2H}\right)$$

Density in (pc^{-3})

Scaleheight (pc)


Main sequence lifetime (Gyr)
0.01 0.1 0.5 1 2 4 7 10 14 20 30 75 200
Vertical velocity dispersion (km/s)
25
20
15
10
5
Older
B0 A0 F0 G0 K0 M0 L0 T0 Y0
Spectral type

Ryan Jr + 2017