NAOC 中国科学院国家天文台 NATIONAL ASTRONOMICAL OBSERVATORIES, CAS

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Discovery of CH_4 and metallicity constraint in an ultracool extremely metal-poor atmosphere

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4th year PhD

Supervisors: Nicolas Lodieu & Eduardo Martín

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SUBSTELLAR

Funded by the European Union

European Research Council

My path…



- 2009 eclipse
- Astro. olympiad
- Astro. club



- BSc. in physics
- Astro. club



Research assistant in soft matter lab



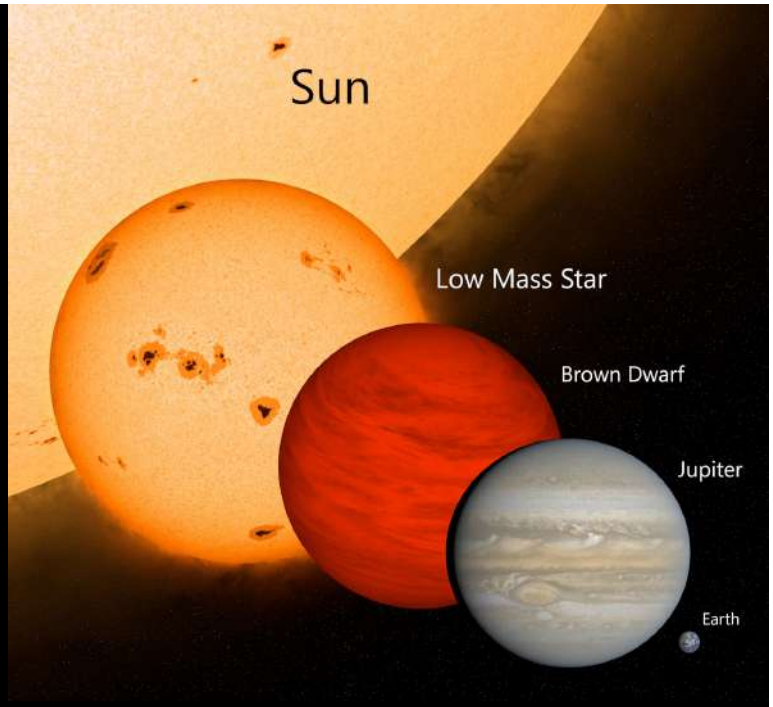
MSc. in cosmology



- PhD in astrophysics
- Supervisors: Nicolas Lodieu & Eduardo Martín

Brown Dwarfs

- Do not reach ^{1}H-burning limit : $M \lesssim 80 M_J$
- Only energy source: gravity!
- Contract and cool down, T < 2700K to room temp.
- SpT depends on age & mass OBAFGK MLTY



- Planetary mass objects: $M \lesssim 13 M_J$ (^{2}H-burning limit)

Metal-poor brown dwarf

- **BD** preserves original element ingredients
- Halo or thick disk population (Pop.II) are as old as our Galaxy.

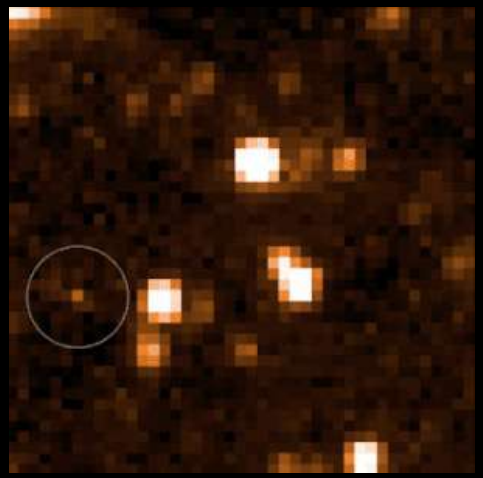
- We want to know the Galaxy evolution, cosmic dawn chemistry
- We want to know the metal-poor substellar evolution model & metal-poor ultracool atmospheric model

- They are **metal-poor, namely subdwarf: sd**
  - **Extreme: esd**
  - **Ultra: usd**

Metal-poor brown dwarfs are few…

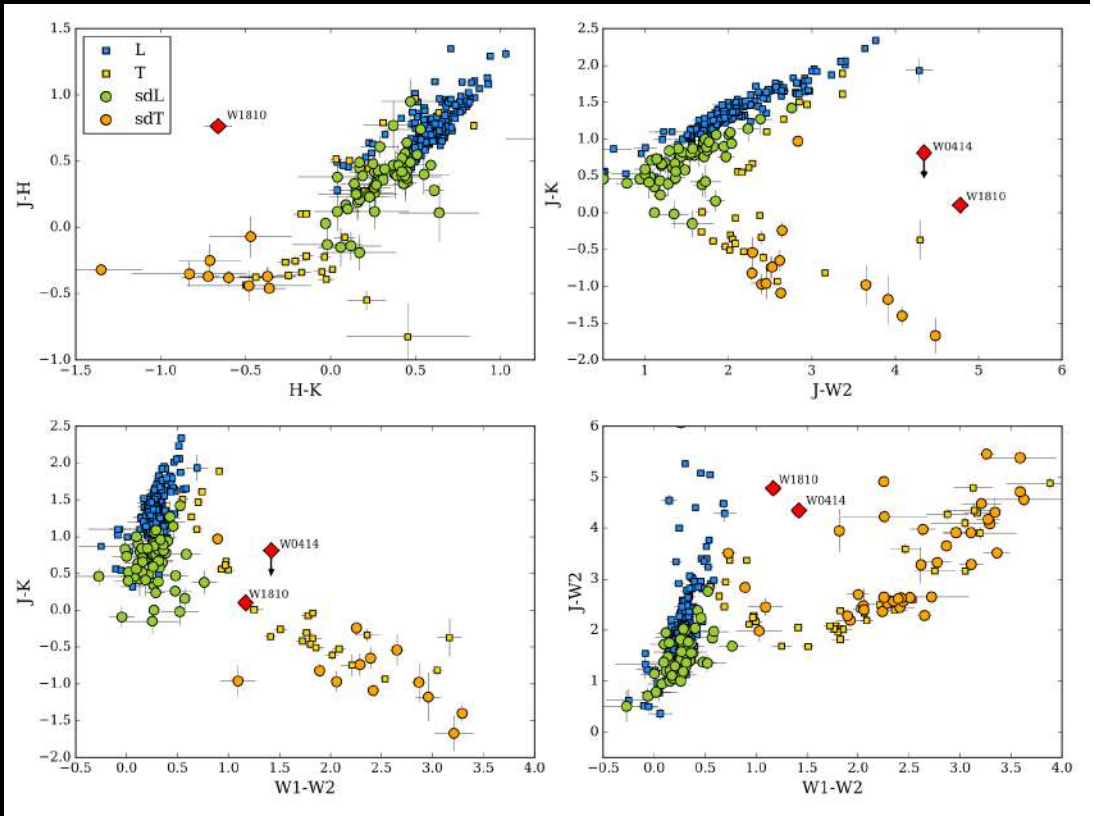
- BDs are small and cold
  → **faint (**spec. type **M, L, T, Y)**
- Metal-poor BDs are **old**, no H-fusion
  → even colder & **fainter (T, Y)**
- Halo members are **rare** (1/5000) & searching radius limited to 100pc
- Halo members **move super fast** (> 1’’/yr)

- Till today
  - ~20 metal-poor sdT candidates
  - 1 metal-poor sdY candidate ?
  - Mainly discovered by WISE



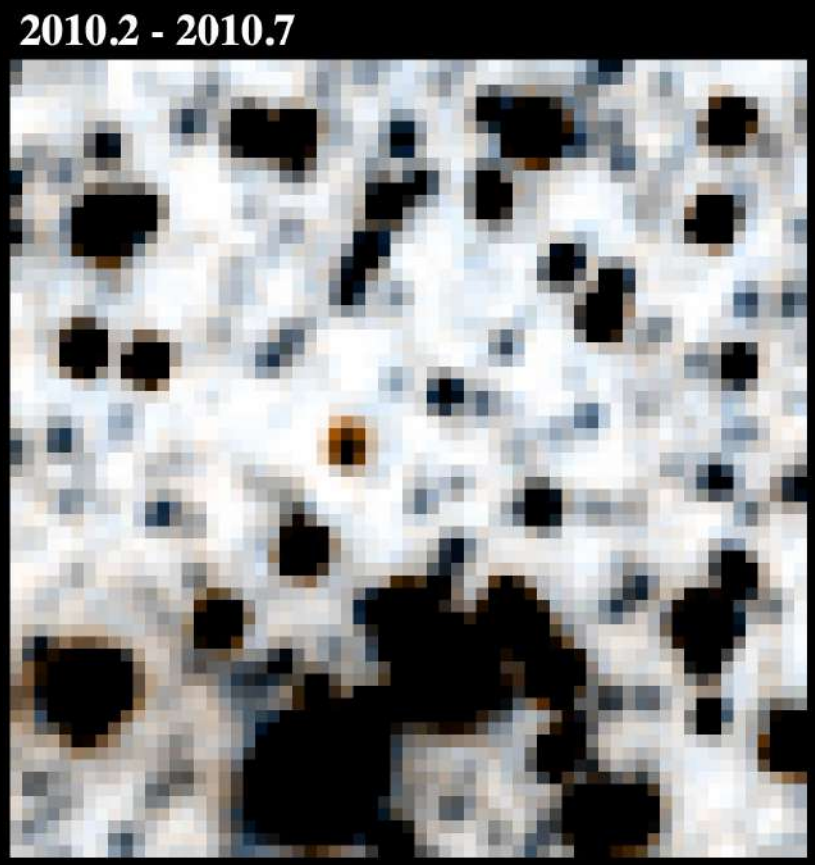
Our target

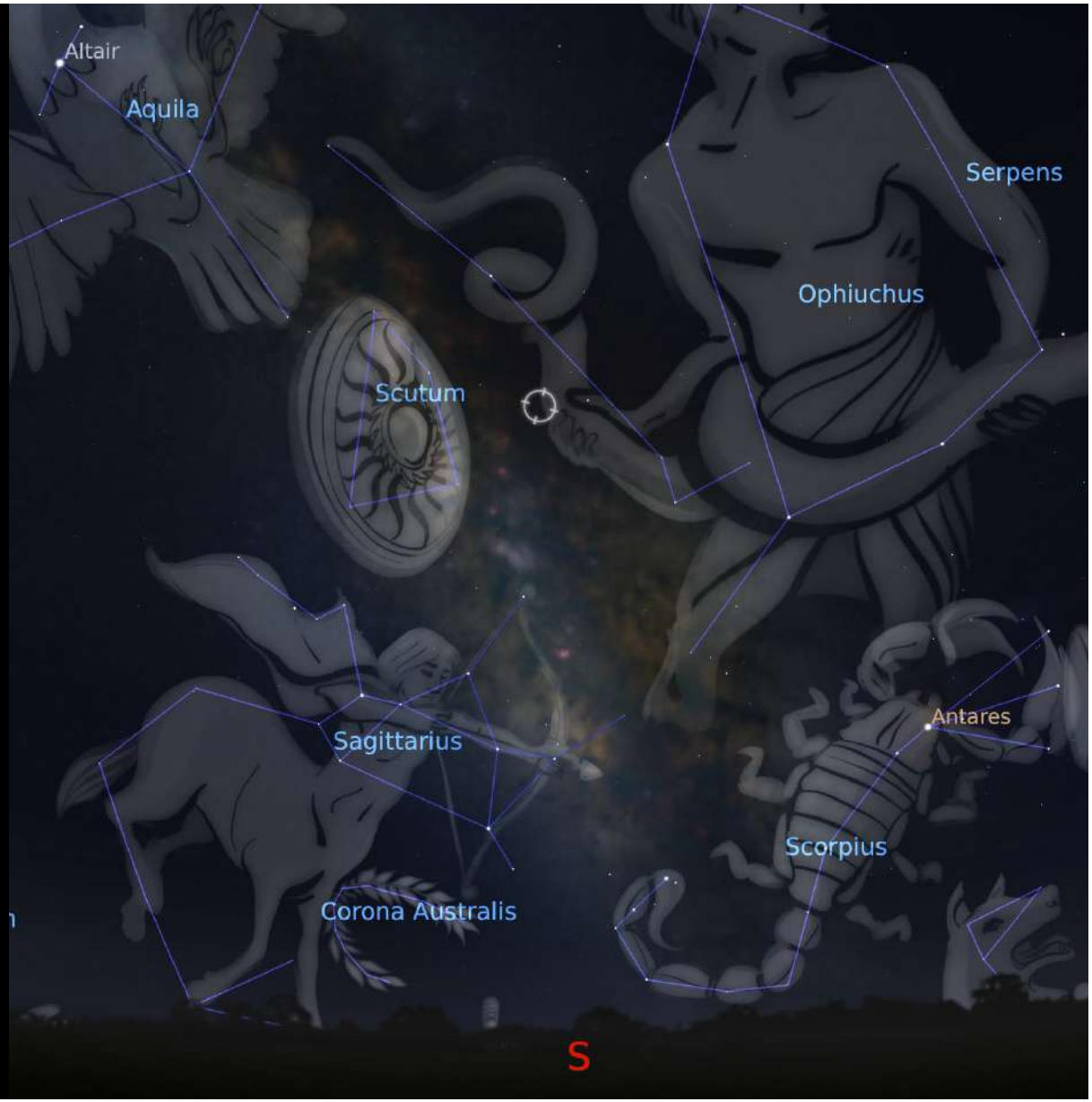
- WISEA J181006.18−101000.5
- Identified as high-proper-motion candidates in NeoWISE survey
- Discovered in the Backyard Worlds
- Peculiar colors



Schneider et al. 2021

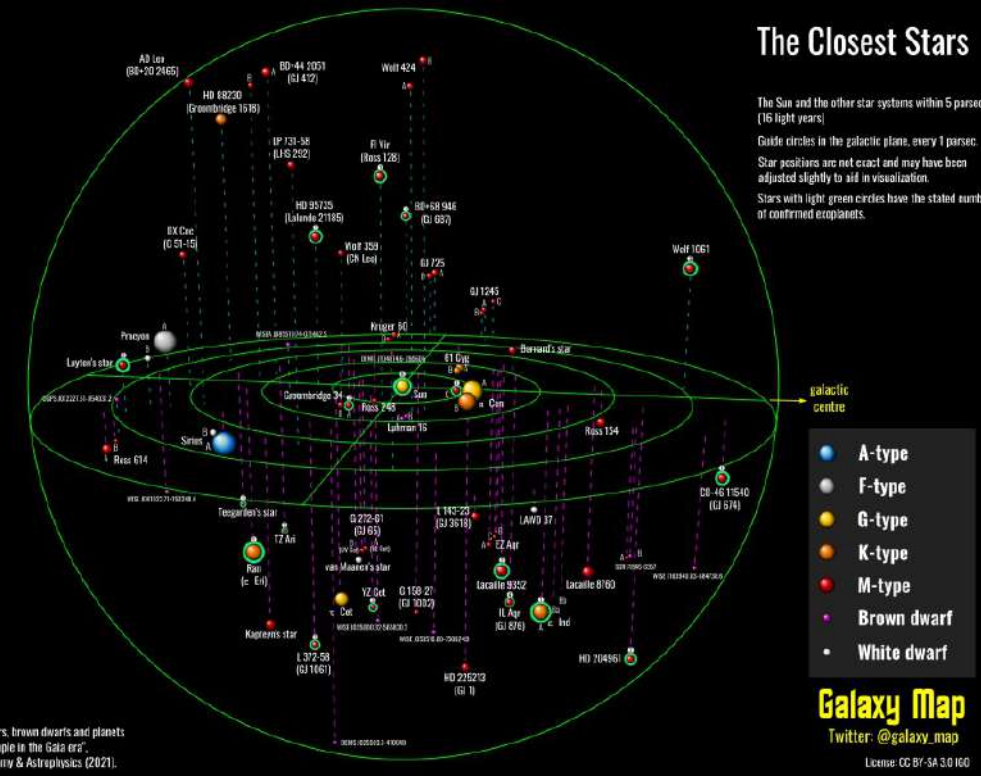
WISE1810

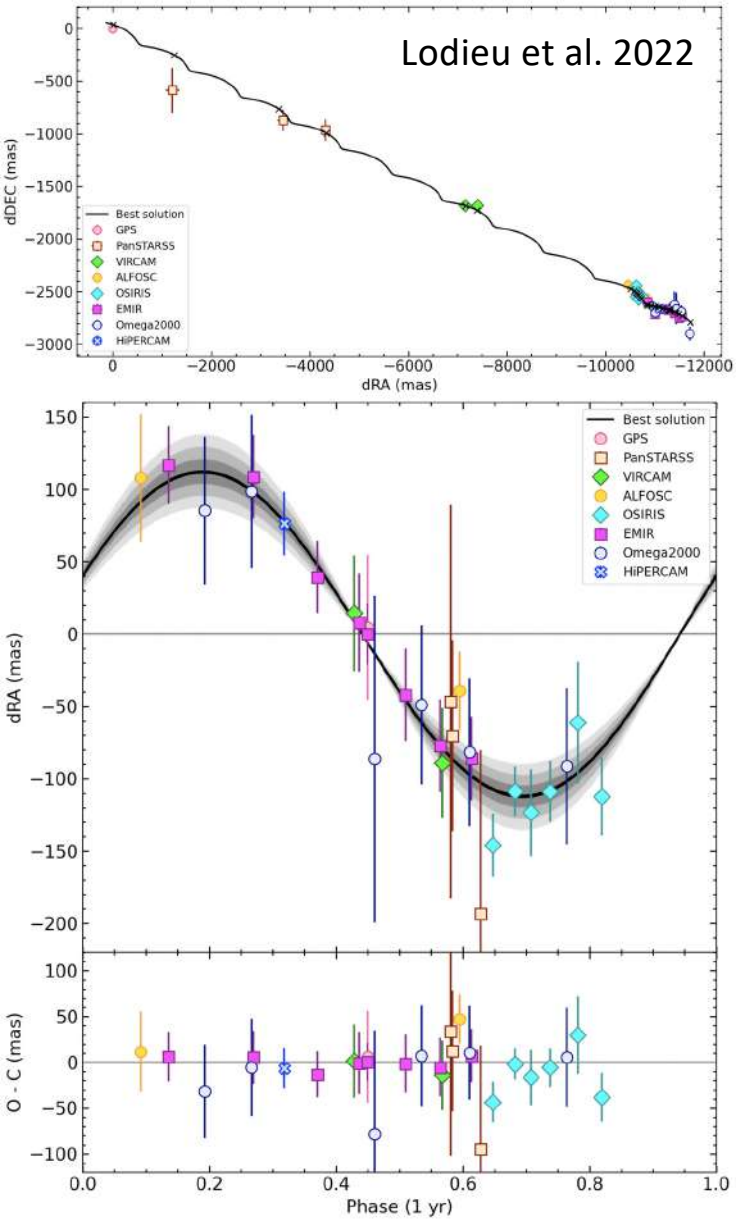

2010.2 - 2010.7


Altair
Aquila
Serpens
Ophiuchus
Scutum
Sagittarius
Antares
Scorpius
Corona Australis
S

Our closest metal-poor neighbor

- **8.9** pc from a robust parallax measurement

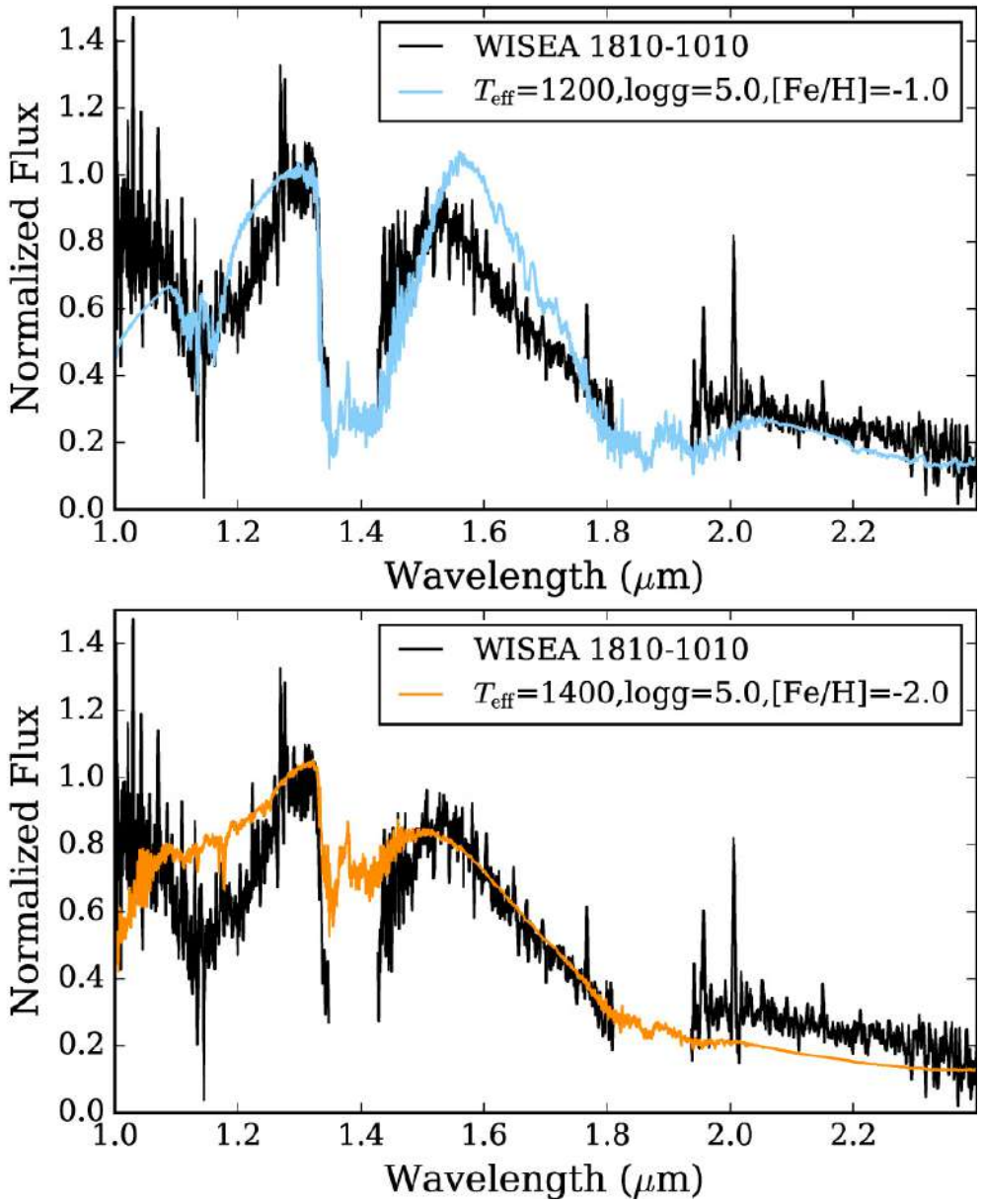


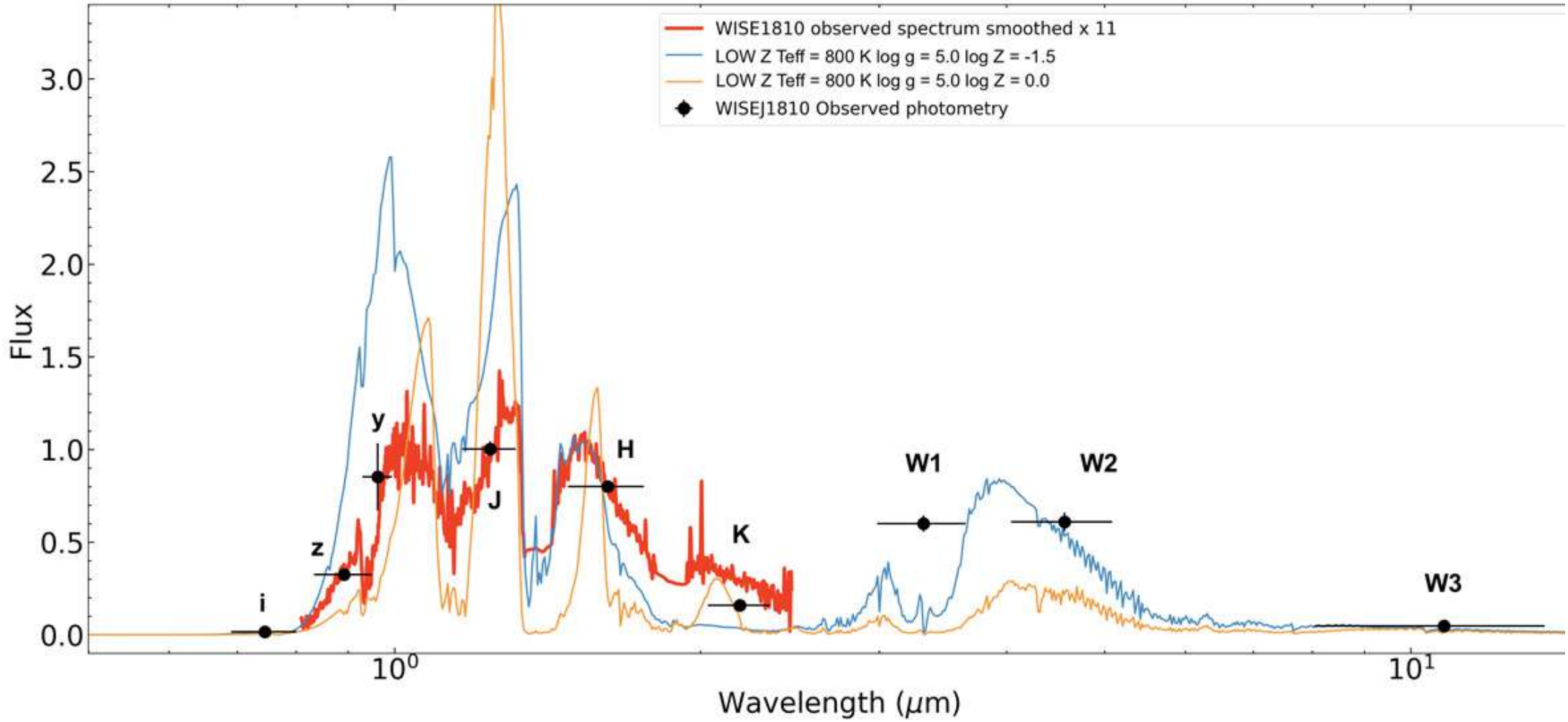


Previous spectroscopy

- No methane
- Strong CIA H_2
- Inferred T = 1300 K - 800 K
- No good template fit
- Nor model fit

Schneider et al. 2021, Burgasser et al. 2024





Lodieu et al. 2022

Lodieu et al. 2022

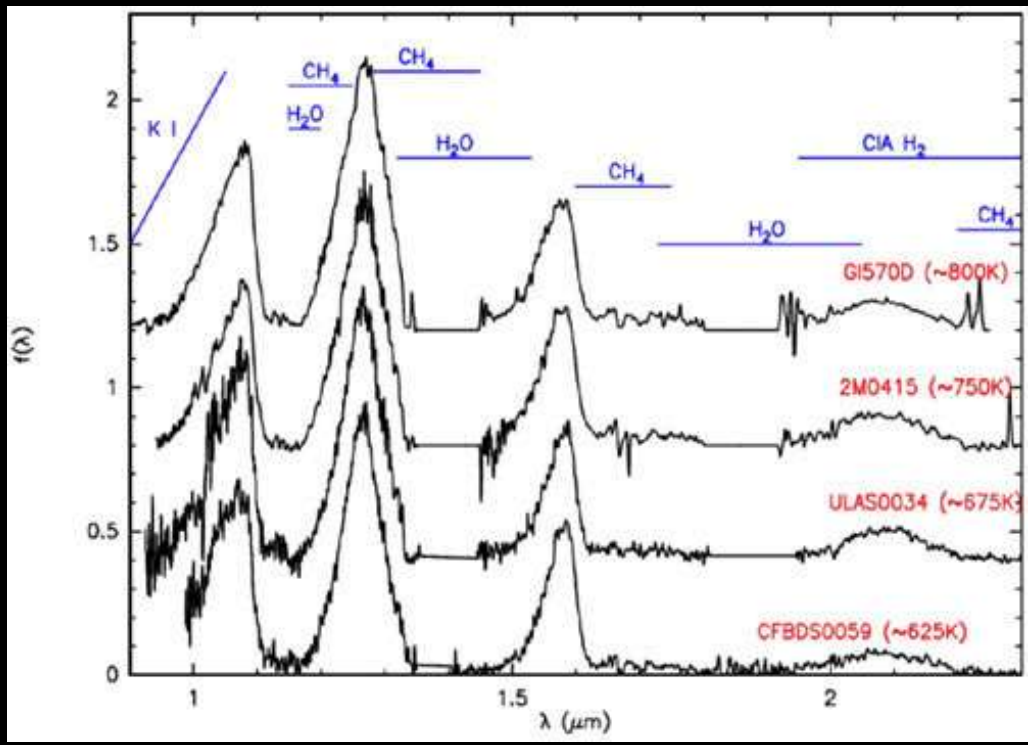
Name	Parameter	Value
Parallax	ω	$112.5^{+8.1}_{-8.0}$ mas
Distance	d	$8.9^{+0.7}_{-0.6}$ pc
Proper motion in RA	$\mu_\alpha \cos\delta$	-1027.0 ± 3.5 mas yr^{-1}
Proper motion in dec	μ_δ	-246.4 ± 3.6 mas yr^{-1}
Heliocentric velocity	$v_{\rm h}$	45.6 ± 3.5 km s^{-1}
Tangential velocity	$v_{\rm t}$	44.5 ± 3.6 km s^{-1}
Galactic velocity	U	-36.9 ± 2.9 km s^{-1}
Galactic velocity	V	-44.5 ± 1.8 km s^{-1}
Galactic velocity	W	-29.1 ± 2.7 km s^{-1}
Luminosity	$\log(L/L_\odot)$	-5.78 ± 0.11 dex
Bolometric magnitude	$M_{\rm bol}$	$19.850^{+0.082}_{-0.074}$ mag
Effective temperature	$T_{\rm eff}$	800 ± 100 K
Gravity	$\log g$	5.0 ± 0.25 dex (cm s^{-2})
Metallicity	[Fe/H]	-1.5 ± 0.5 dex
Radius	R	$0.067^{+0.032}_{-0.020}\,R_\odot$
Mass	M	$17^{+56}_{-12}\,M_{\rm jup}$

Classified as esdT0-3, but T dwarf …



- 500 K < T < 1300 K
- Known as methane dwarf
- Characteristic molecule: CH_4





Burgasser et al. 2003

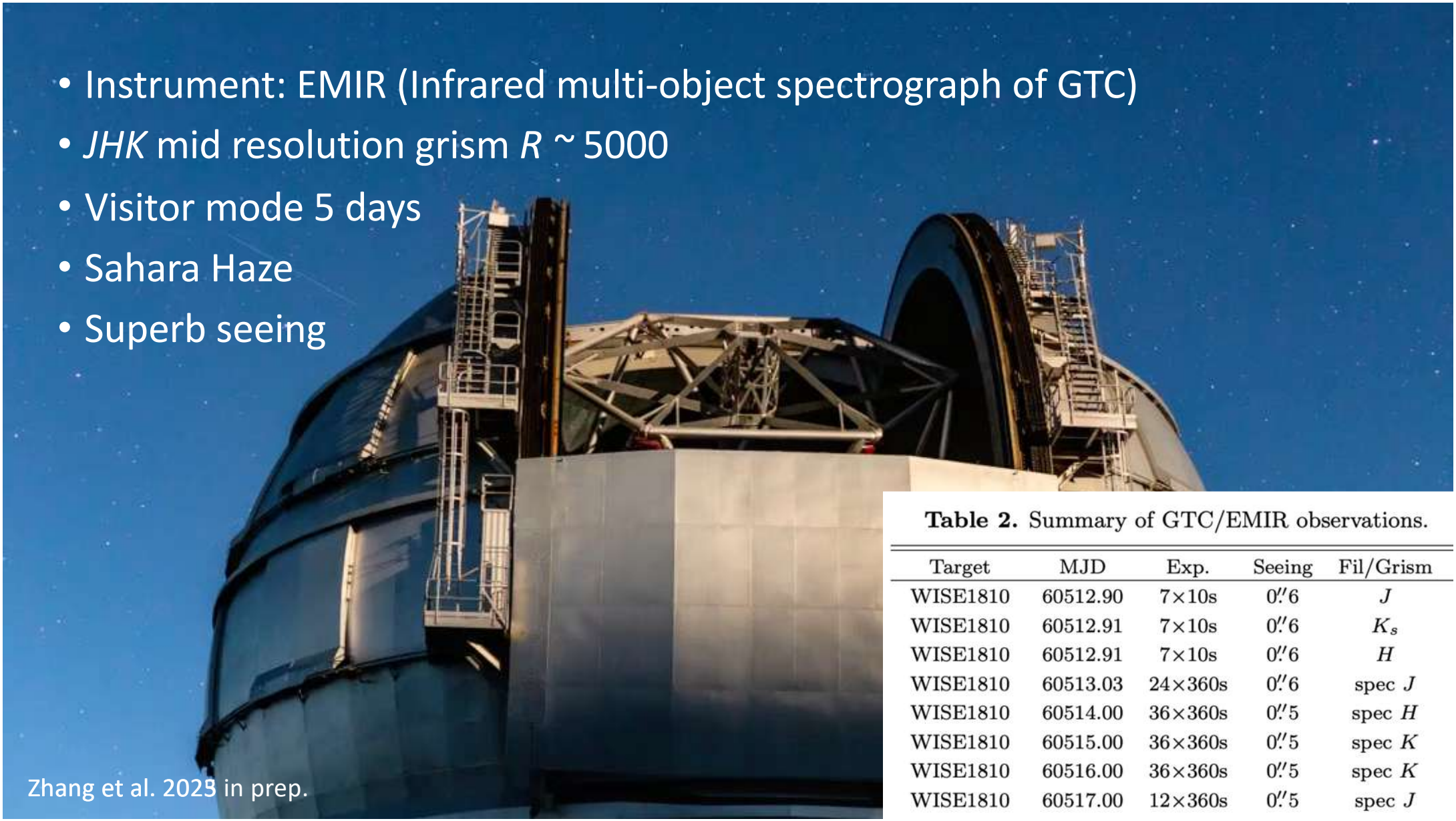
International Gemini Observatory/NOIRLab/NSF/AURA

What is the problem?

- Wrong classification as esdT?
- New spectral classification scheme?
- Physical parameter wrongly measured?
- Binary?
- Strongly modified atmosphere chemistry in metal-poor environment?



GTC observation

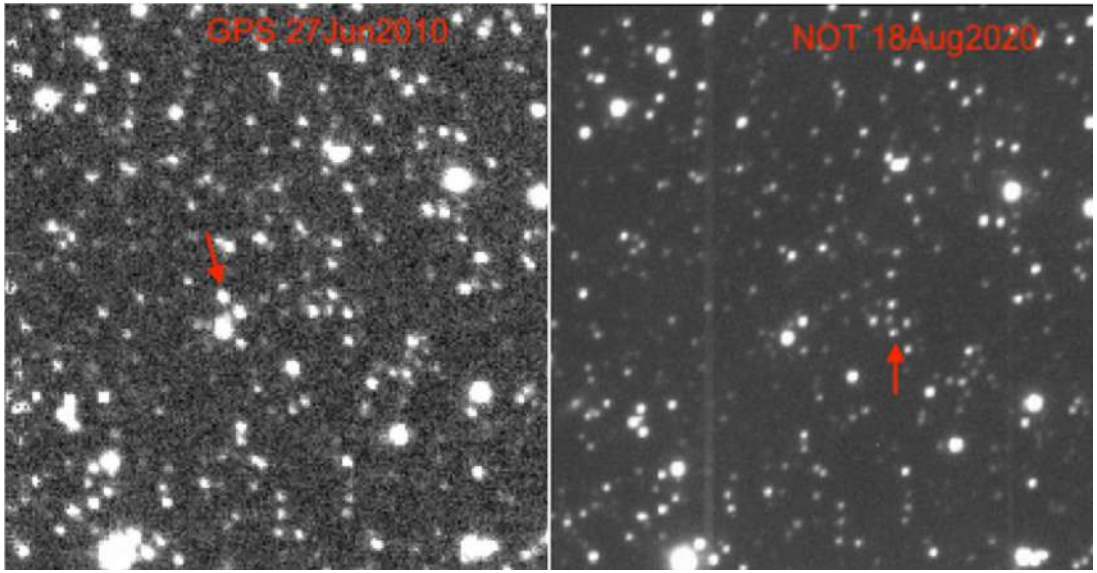


- Instrument: EMIR (Infrared multi-object spectrograph of GTC)
- *JHK* mid resolution grism $R \sim 5000$
- Visitor mode 5 days
- Sahara Haze
- Superb seeing

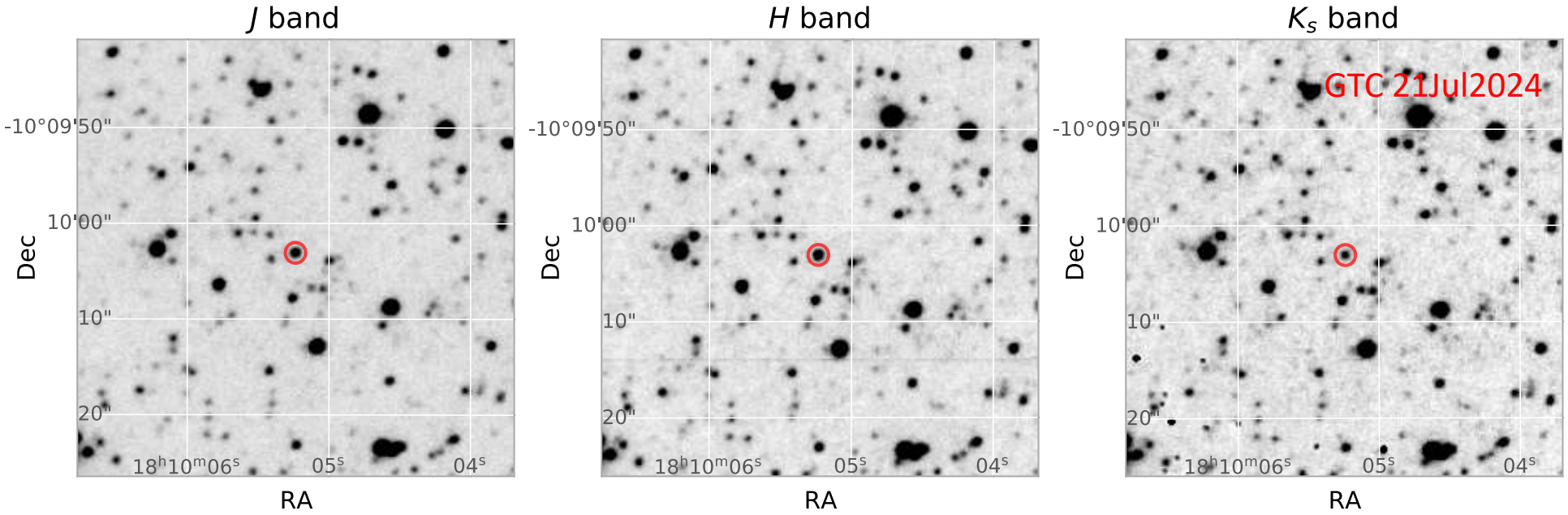
Zhang et al. 2023 in prep.

Table 2. Summary of GTC/EMIR observations.

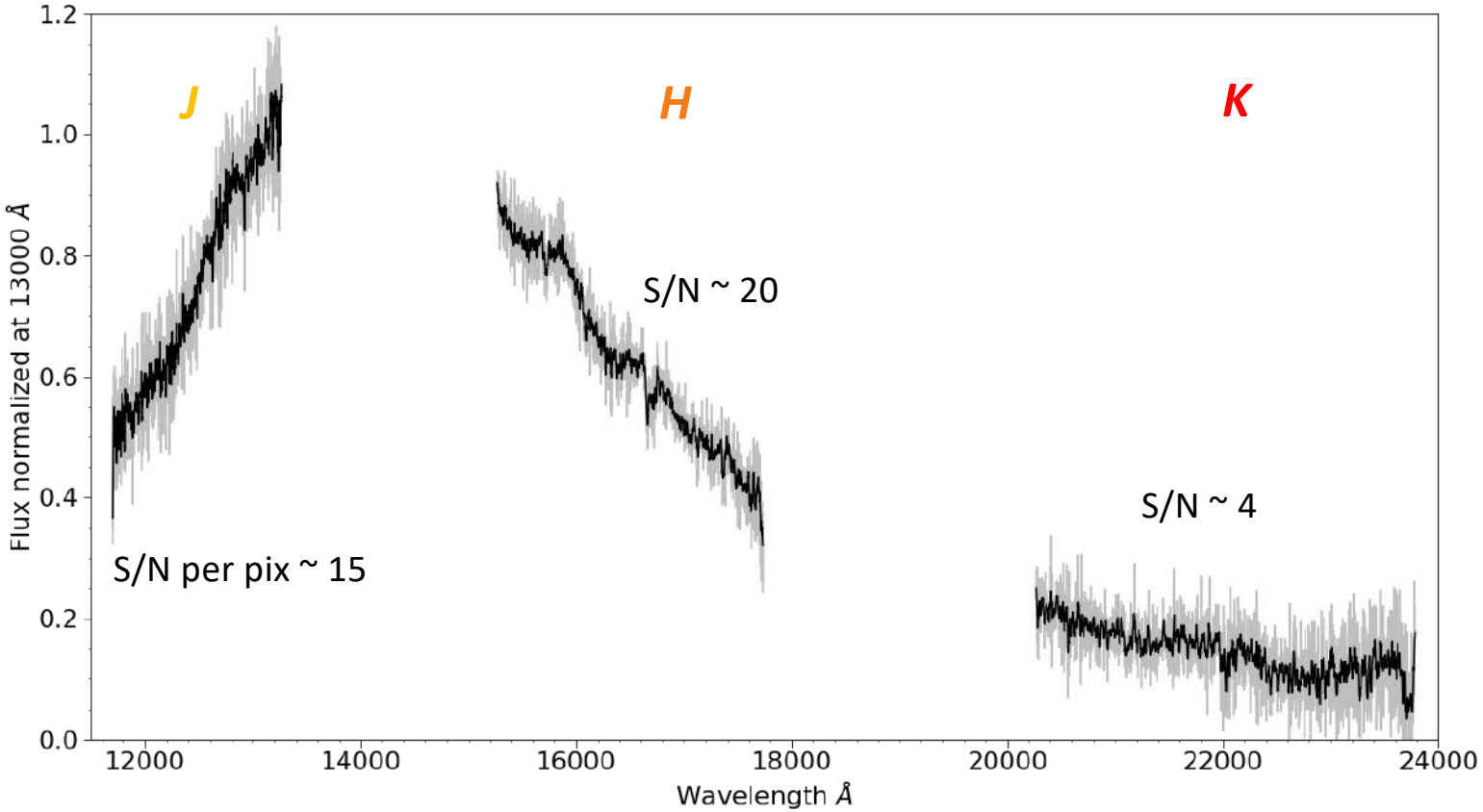
Target	MJD	Exp.	Seeing	Fil/Grism
WISE1810	60512.90	7×10s	0.″6	J
WISE1810	60512.91	7×10s	0.″6	K_s
WISE1810	60512.91	7×10s	0.″6	H
WISE1810	60513.03	24×360s	0.″6	spec J
WISE1810	60514.00	36×360s	0.″5	spec H
WISE1810	60515.00	36×360s	0.″5	spec K
WISE1810	60516.00	36×360s	0.″5	spec K
WISE1810	60517.00	12×360s	0.″5	spec J



- 2024 WISE1810 was on a relatively empty field!

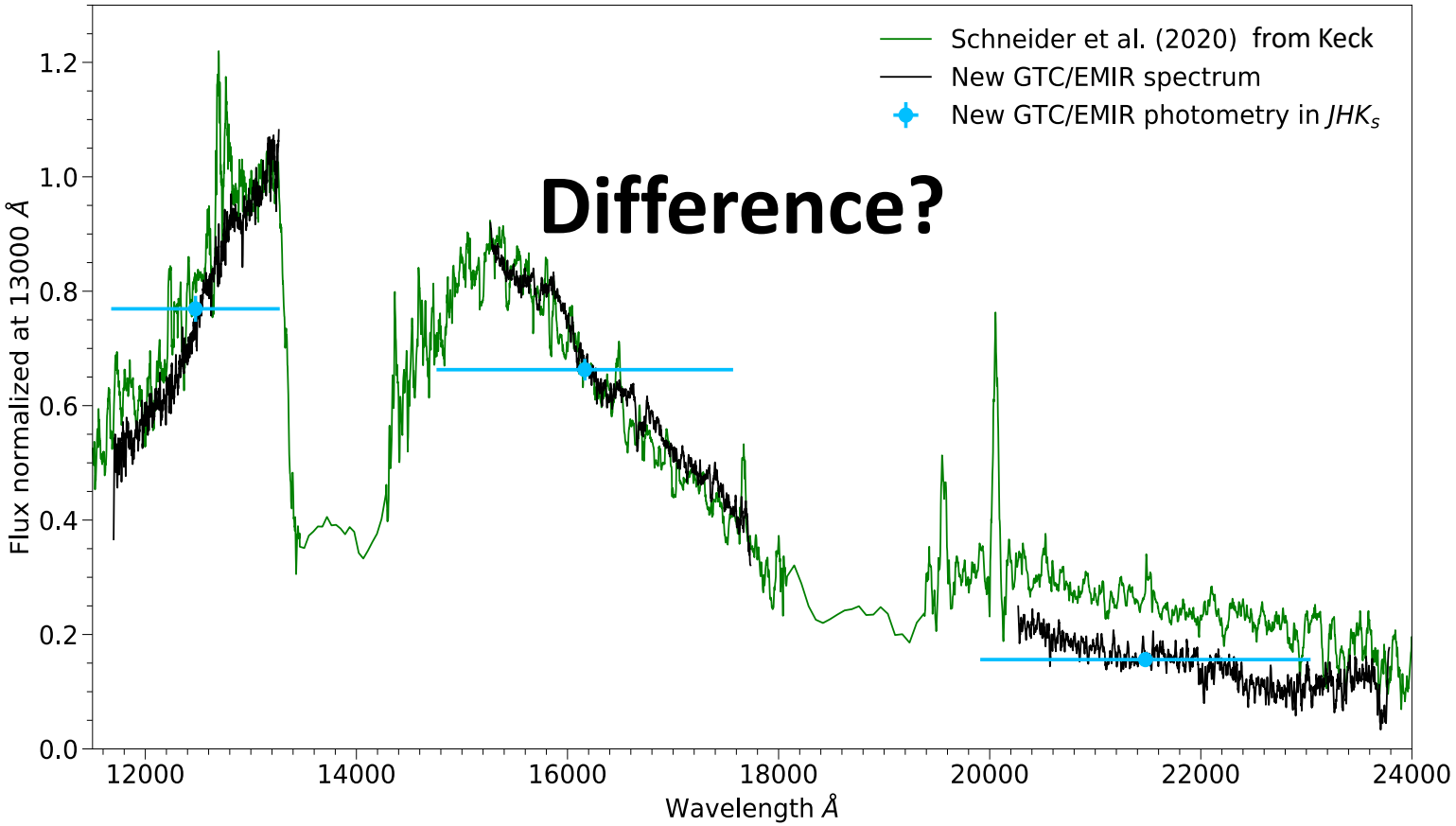


NIR high-Q medium-R Spectroscopy



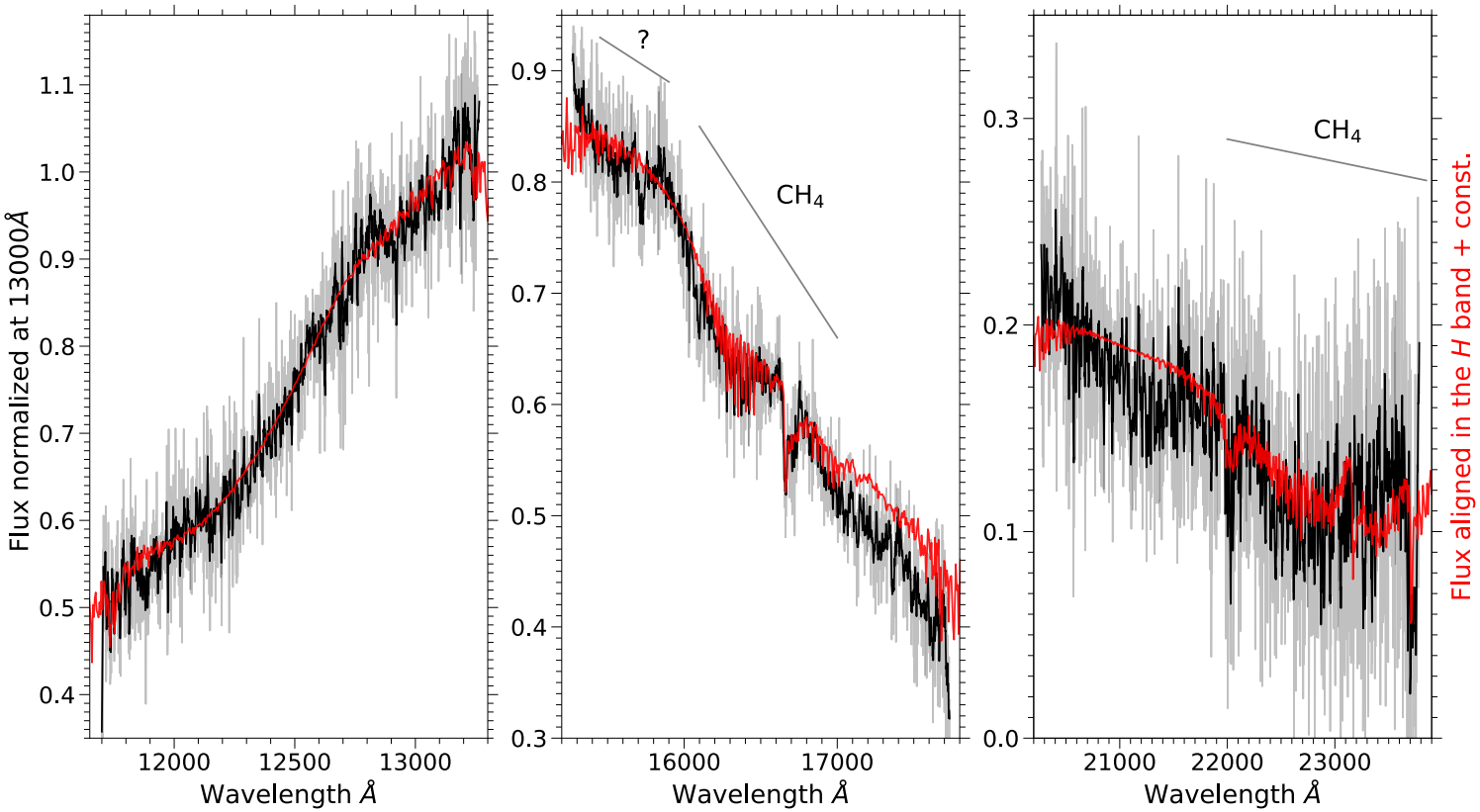
Zhang et al. 2025 in prep.

NIR Spectroscopy comparison



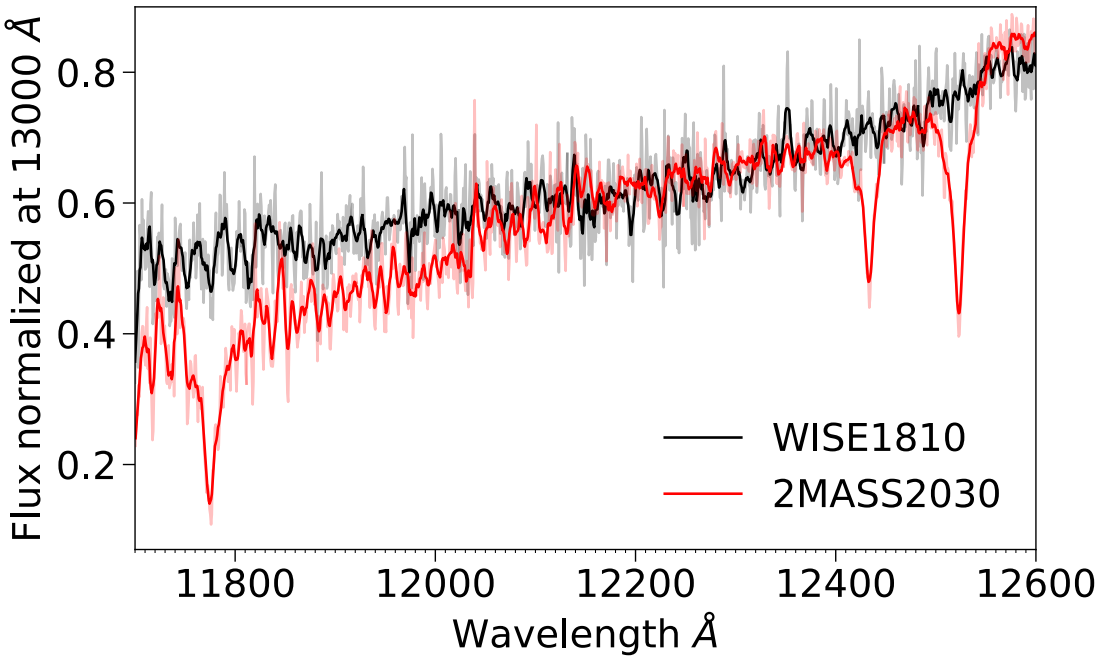
Zhang et al. 2025 in prep.

We undoubtedly detected CH_4 !! But no CO …



Zhang et al. 2025 in prep.

Still no potassium



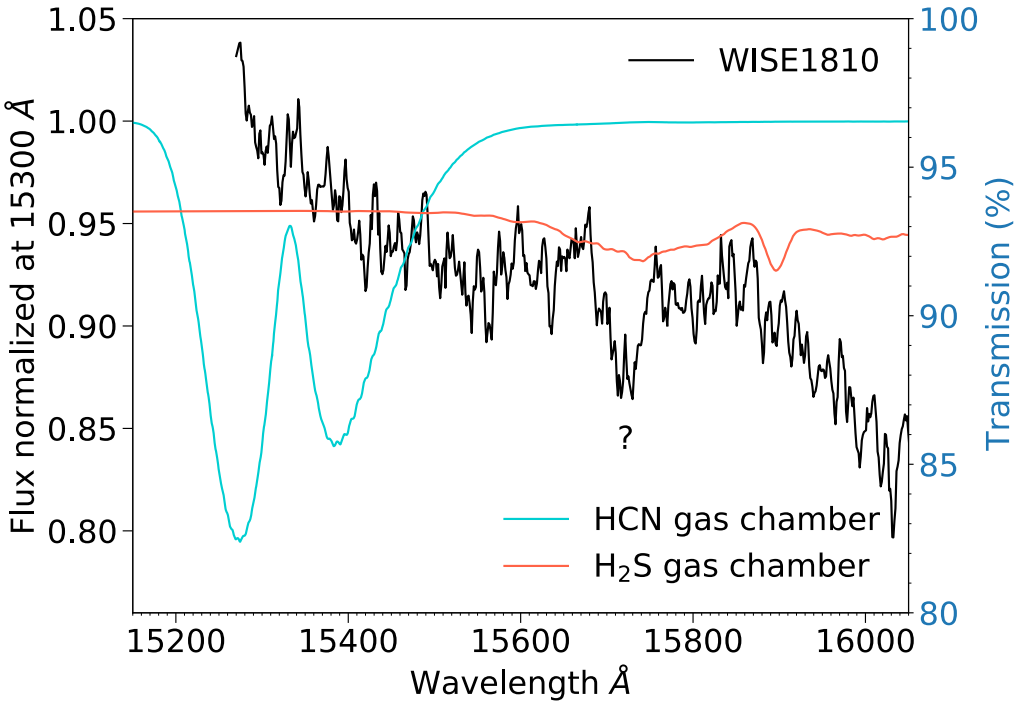
Zhang et al. 2025 in prep.

Observationally:

- Confirms as a T dwarf by definition
- Favors a cooler temperature: < 1200 K
- Favors a low metallicity

A mysterious feature

- Opacity databases ❌
- Lab chamber transmission spec. ❌
- Unlike to be telluric ❌



Zhang et al. 2025 in prep.

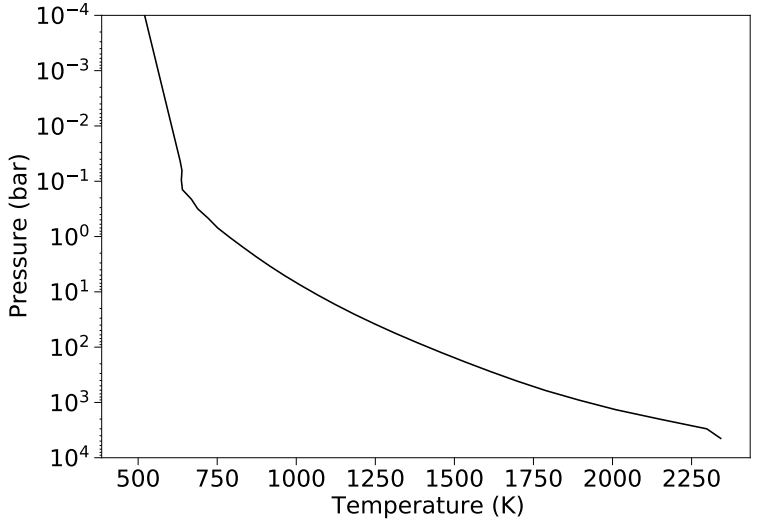

Model fit

Model fit

- ATMO2020++ (Leggett et al. 2021; Meisner wet al. 2023)
- Grid step size
  - 100 K for Temp.
  - 0.5 dex for log g
  - 0.5 dex for [M/H]
- Adjust T-P profile, and adiabatic coefficient..
- Lowering [M/H] to match the CH_4 feature

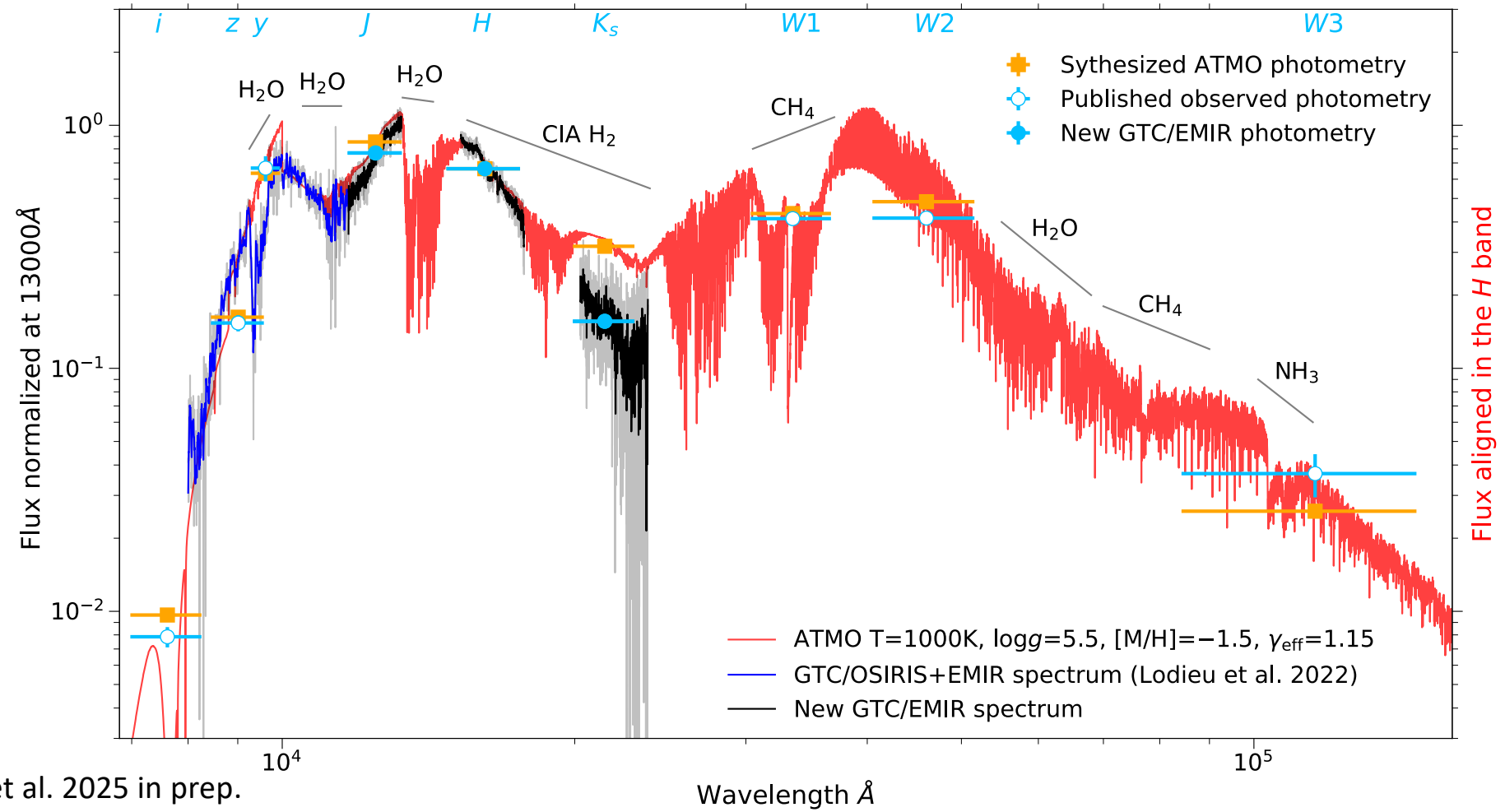
Result:

- T 1000 ± 100 K
- log g 5.5 ± 0.5 dex
- [M/H] -1.5 ± 0.2 dex



Zhang et al. 2025 in prep.

Model fit



Zhang et al. 2025 in prep.

Methane and metallicity?

- CH_4 17 ± 6 ppm
- [M/H] -1.5 ± 0.2 dex

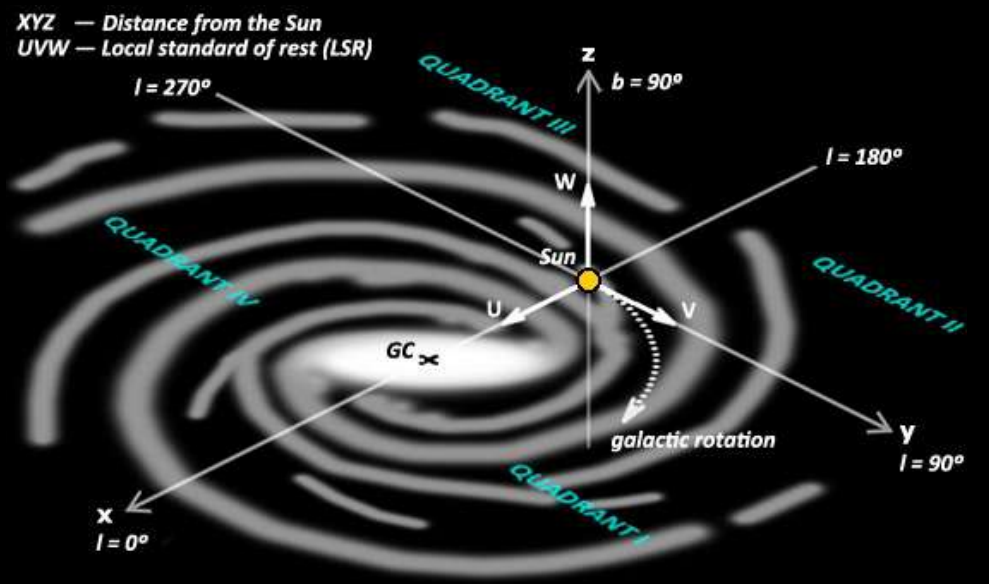
- [C/Fe] 0.2 dex for thick disk stars (Nissen et al. 2014)

- **[Fe/H] -1.7 ± 0.2 dex**

Zhang et al. 2025 in prep.

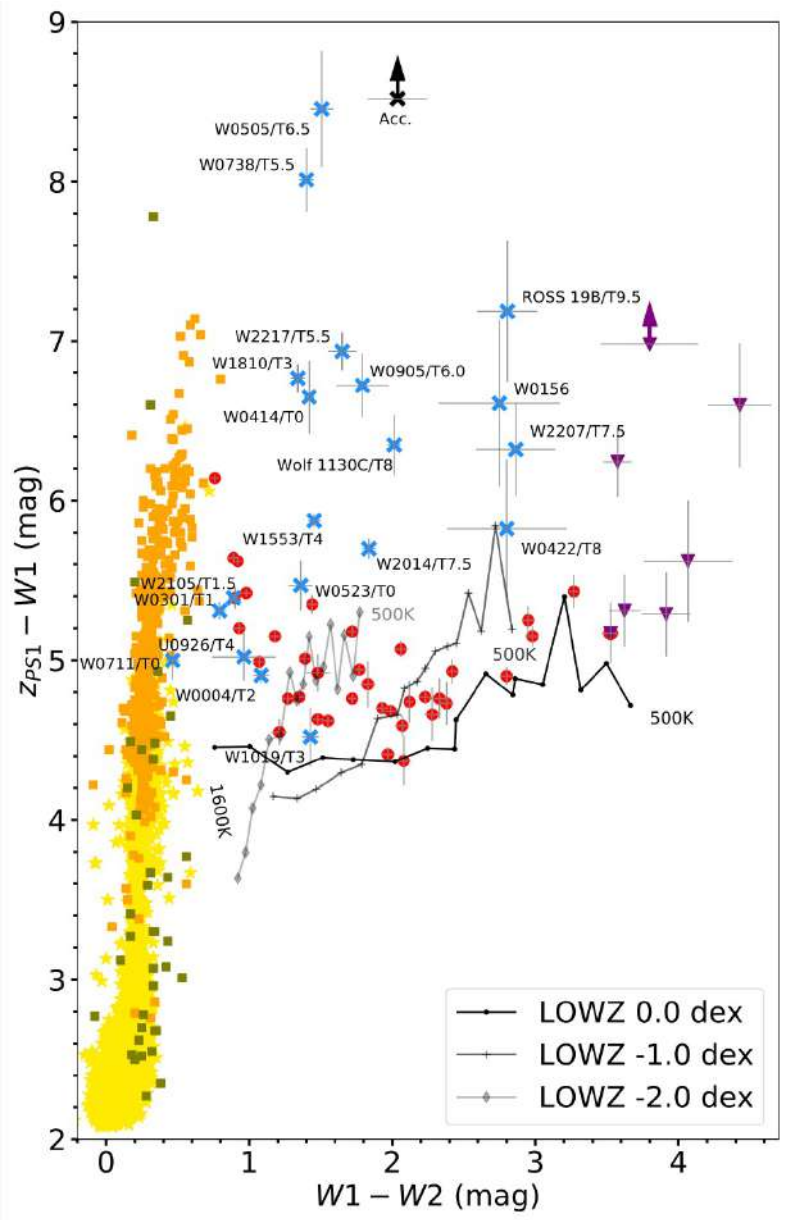
Why **thick disk**? RV measurement.

- Triple-band CCF
- Heliocentric RV -83 ± 13 km/s
- *UVW wrt LSR* (-62 ± 13 , - 43 ± 5, -33 ± 2) km/s



More esdTs?

- We found an indicator of metallicity for objects as cool as T and Y dwarfs.
- Some of them are supposed to be more metal-poor than WISE1810

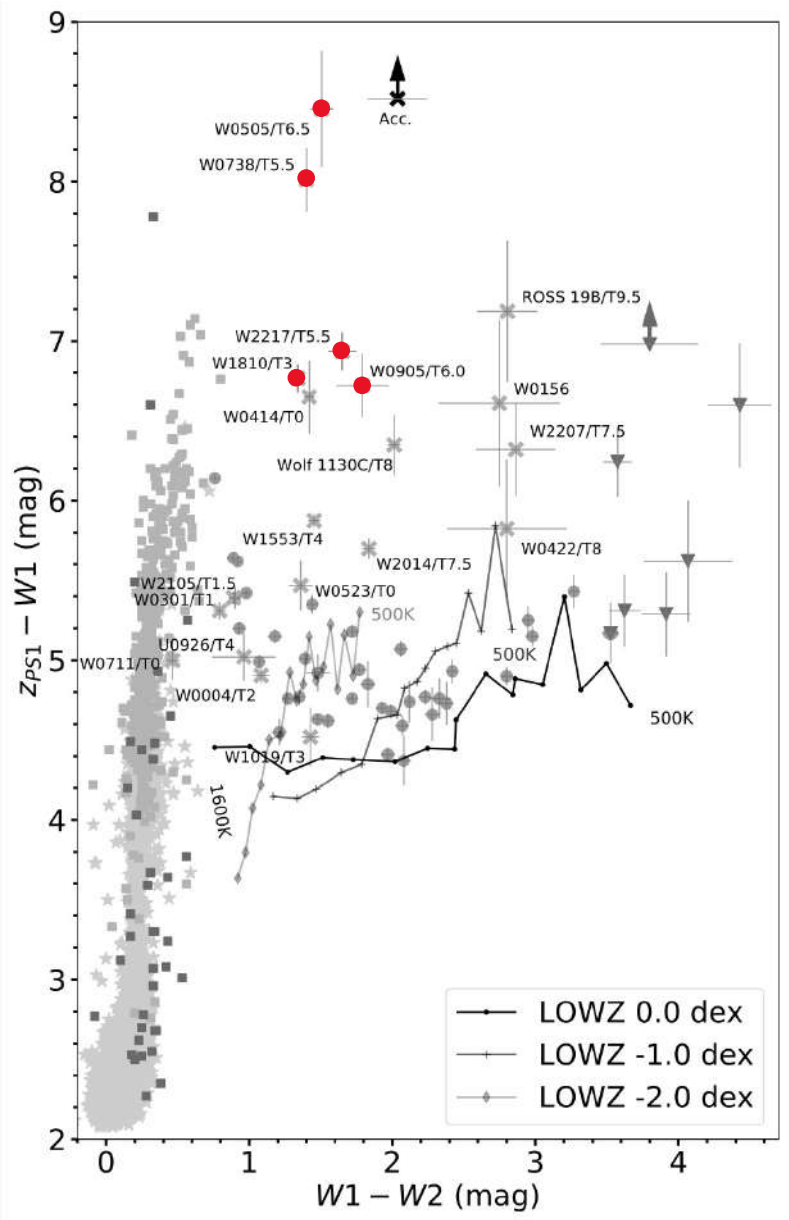


Zhang et al. 2024b in prep.

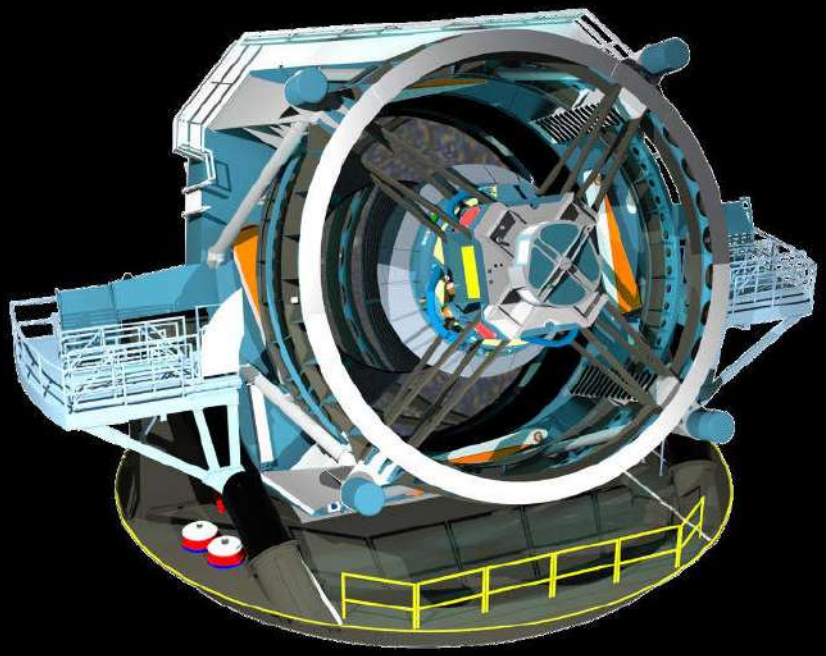
IR Spectroscopy

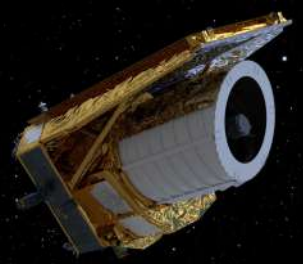
- IR spectra for these esdTs or usdTs
- JWST NIRSpec & MIRI program (Burgasser et al. 2025) is on-going but ground-base observation can provide more information at red optical/NIR
- Still difficult observationally…
- More robust metallicity estimation?

Zhang et al. 2024b in prep.



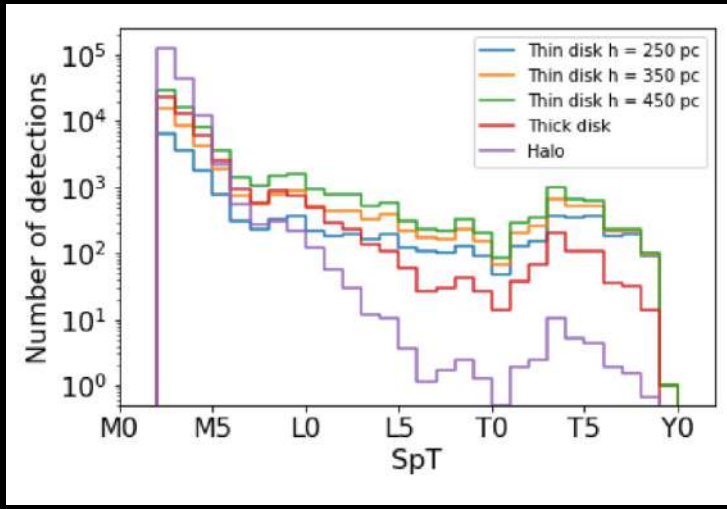
DEEP surveys





- *u g r i z y*
- *z* 22.7 mag
- 18000 deg^2
- ~ 180 visits

- *I 26.2 mag*
- *Y 24.3 mag*
- *J 24.5 mag*
- *H 24.3 mag*
- Wide field *15000* deg^2
- Deep fields 53 deg^2
  - 2 mag deeper
  - 50 visits



Solano et al. 2021


WISE1810, the closest extremely metal-poor neighbor is unique
Our IR spectroscopy constrained its RV, physical properties, and chemical compositions
Take home message
CH_4 feature can precisely constrain the metallicity of metal-poor T dwarf atmosphere
Future surveys & deep observations will help to characterize this population