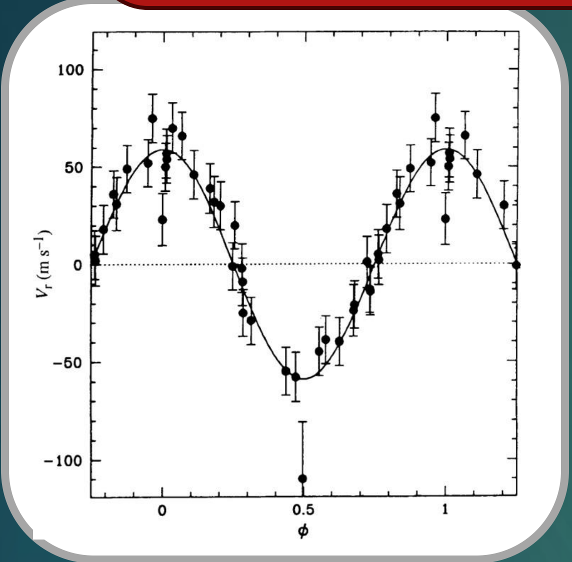
Atmospheric Characterisation (part I)

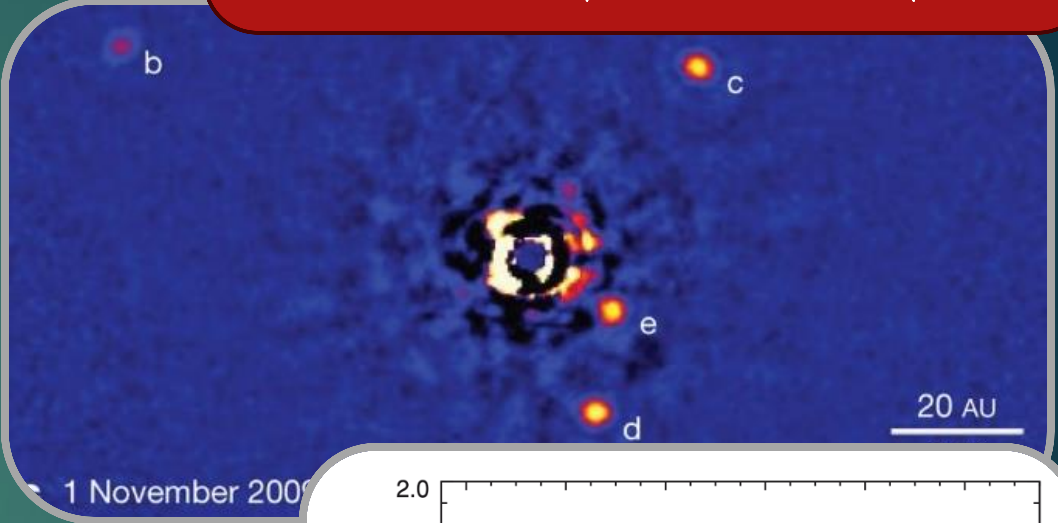
Elisabeth Matthews
matthews@mpia.de
Max Planck Institute for Astronomy | Planet & Star Formation

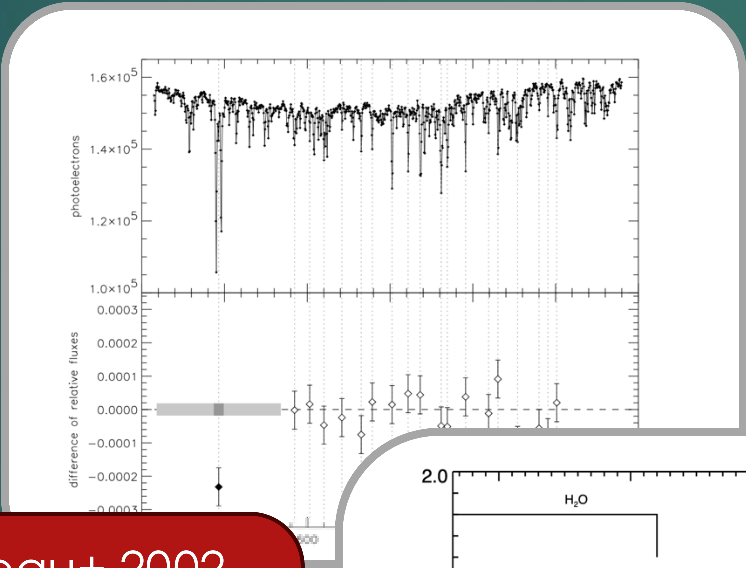
Let's start at the very beginning

51 Peg b, Mayor & Queloz 1995

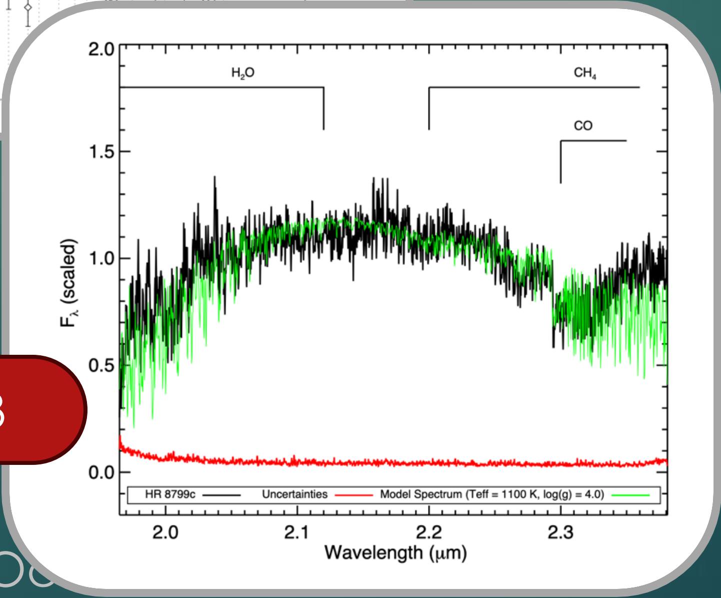


HR 8799 bcde, Marois+ 2008, 2010

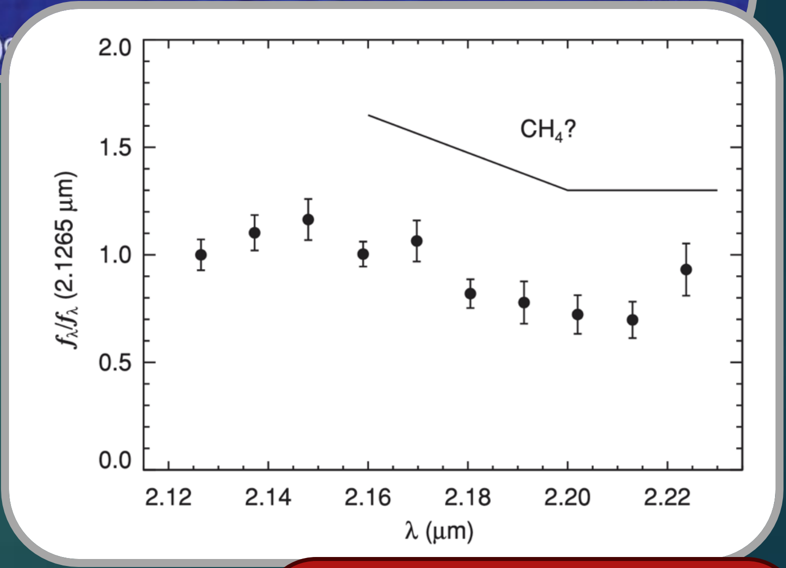




HD 209458 b, Charbonneau+ 2002

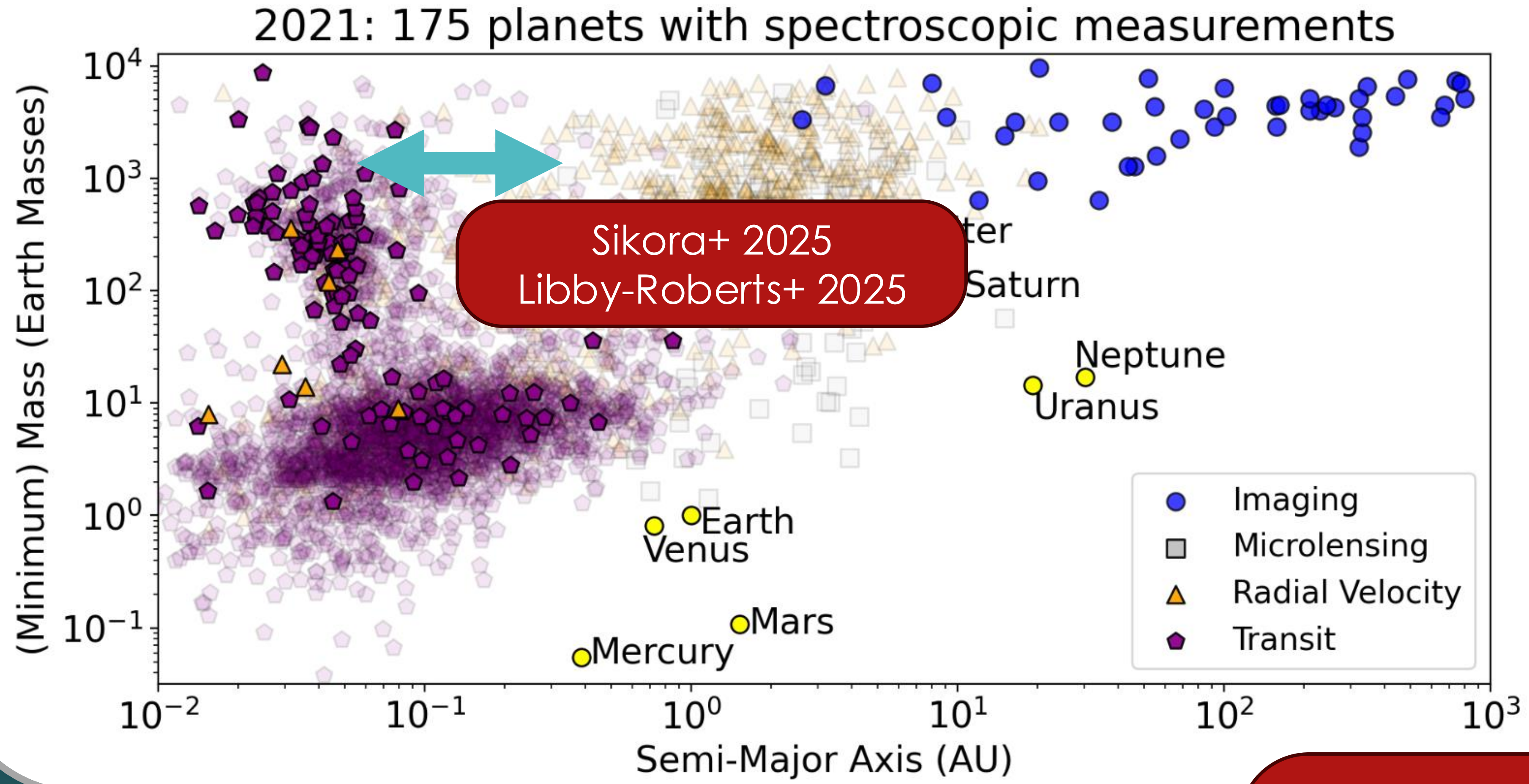


Konopacky+ 2013



Bowler+ 2010

Exoplanets with spectra



Bold = spectroscopy

Currie+ 2022
Figure: Savransky
Data: NASA Exoplanet Archive

Why do we even study atmospheres?

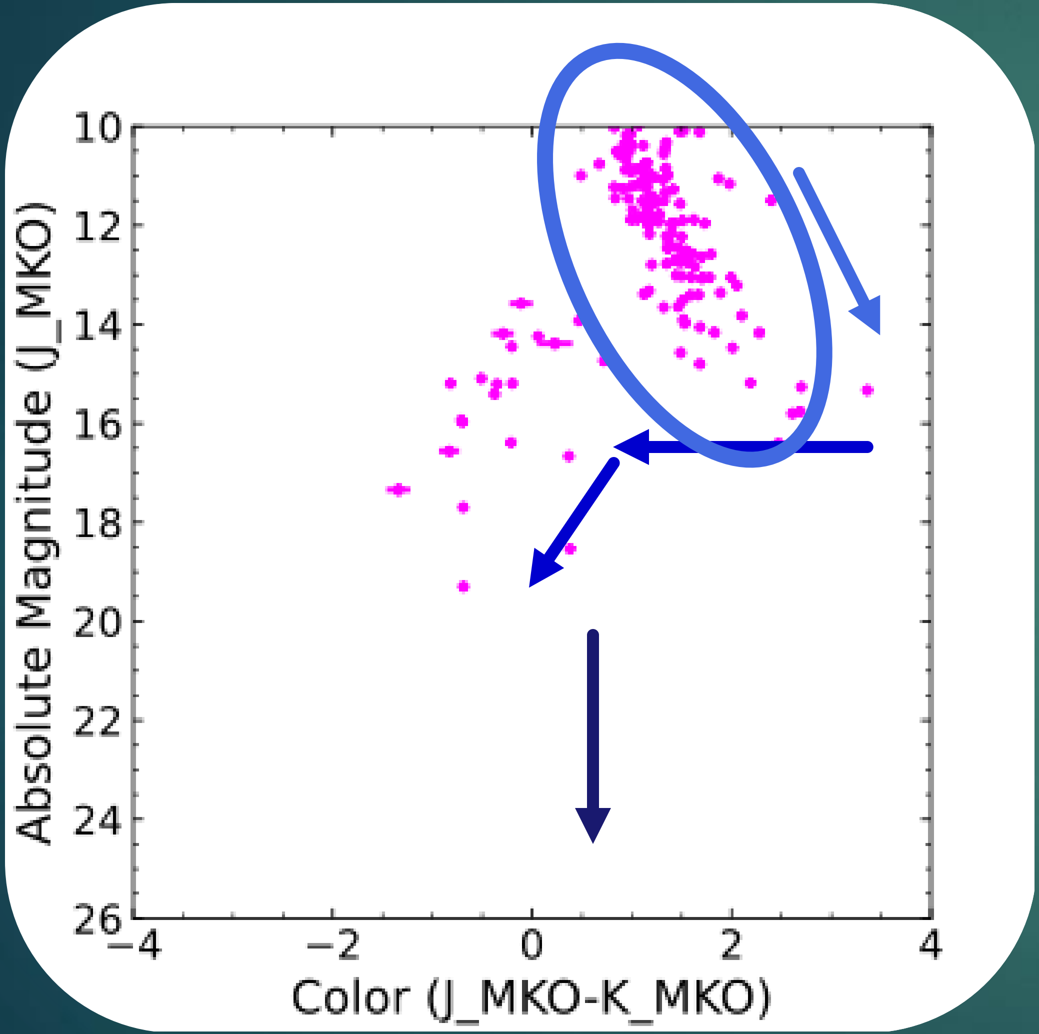
Tracers of formation: metallicity, C/O, isotopes, etc.

Exoplanet dynamics: spins, winds, jets, magnetic fields

Long future: searches for life?

Fundamental physics: cloud condensation, mixing, reaction rates, equation of state

Putting everything on a CMD



data: UltraCool Sheet

L dwarfs: 2200 - 1300K

Warm atmospheres
Silicate clouds, alkali metals & metal hydrides

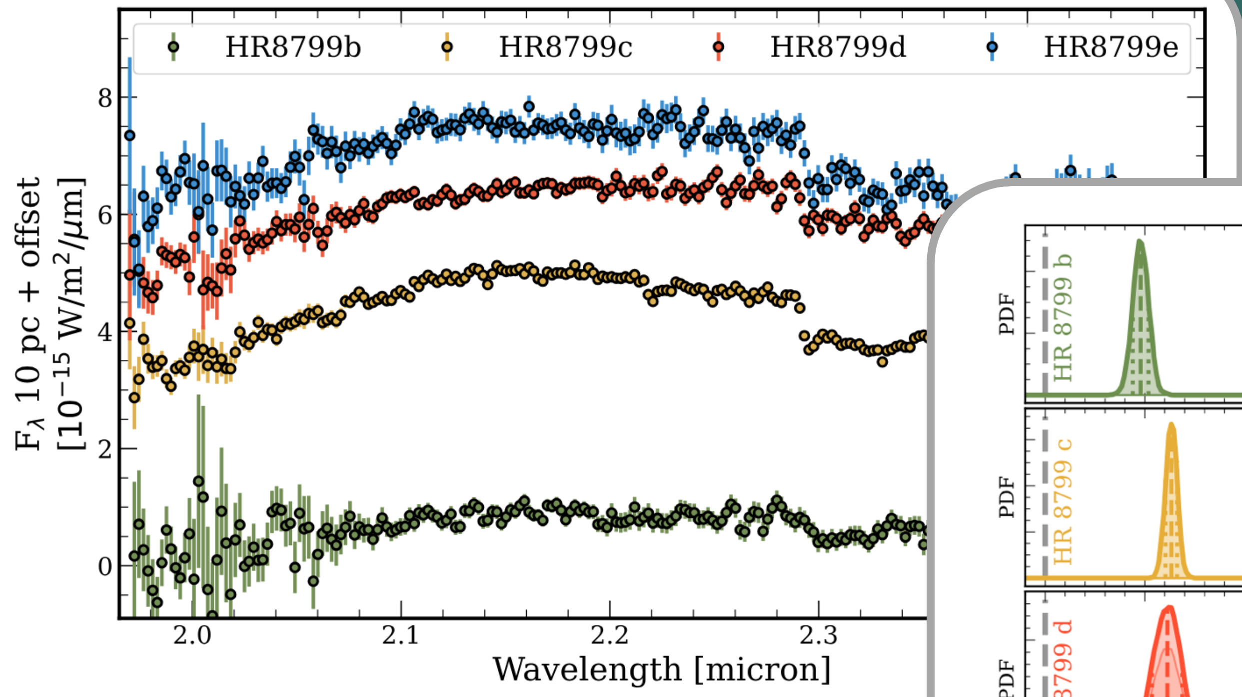
T dwarfs: 1300K – 500K

Silicate clouds disperse
Deep H_2O + CH_4 features

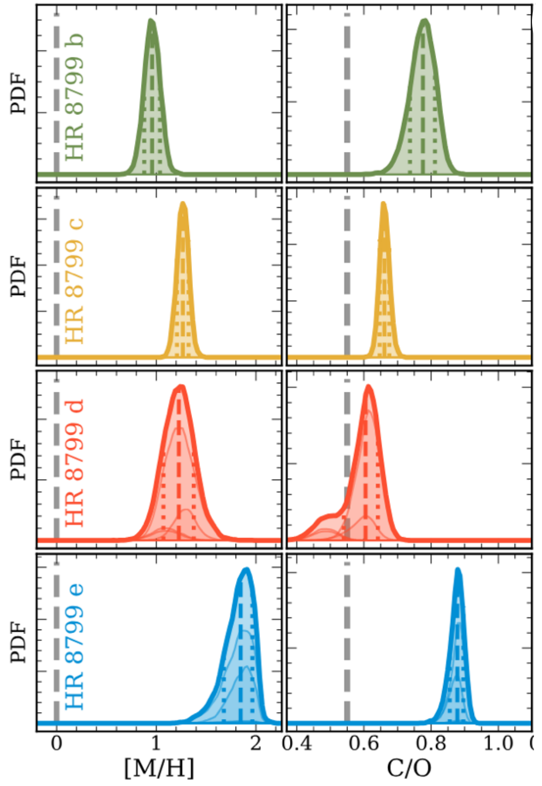
Y dwarfs: <500K

Few near-IR photons remaining
NH_3 emerging, water clouds?, ammonia clouds?

high quality spectra of L dwarfs



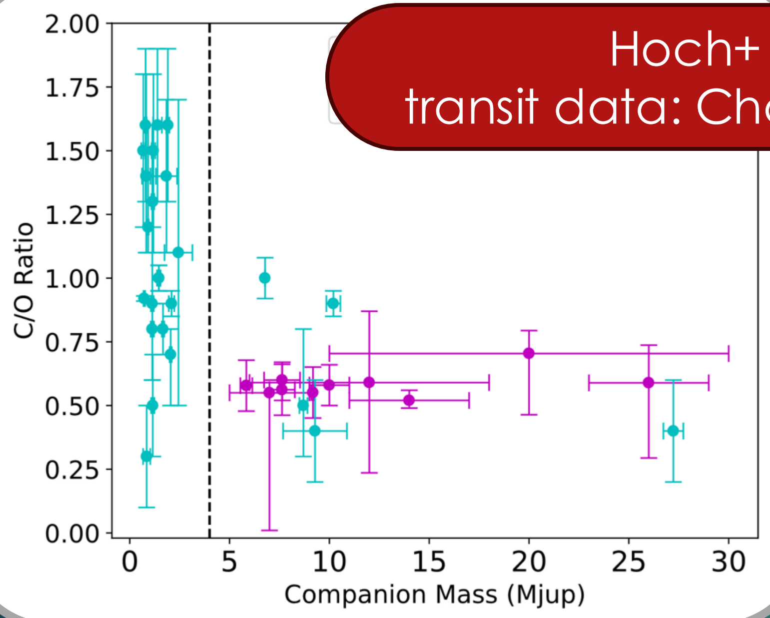
Nasedkin+ 2024



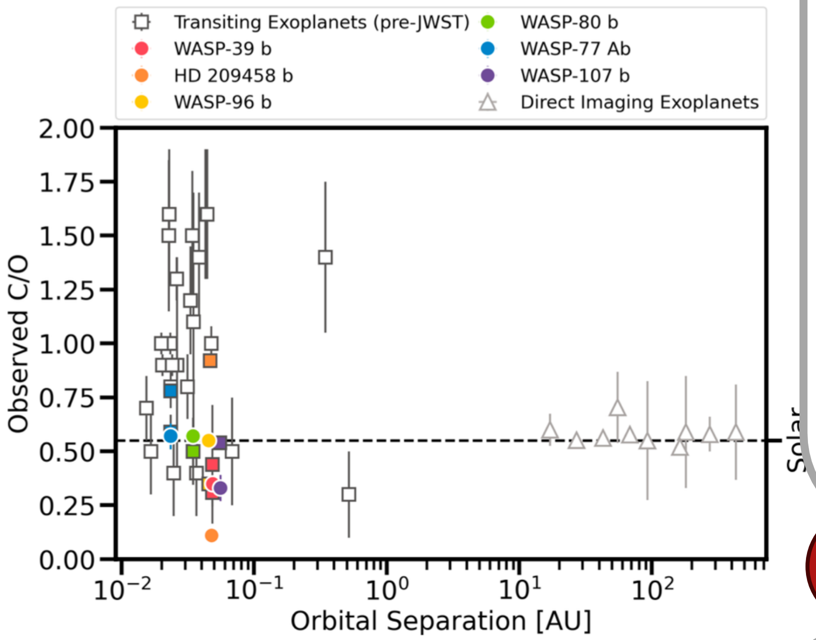
Balmer+ 2025

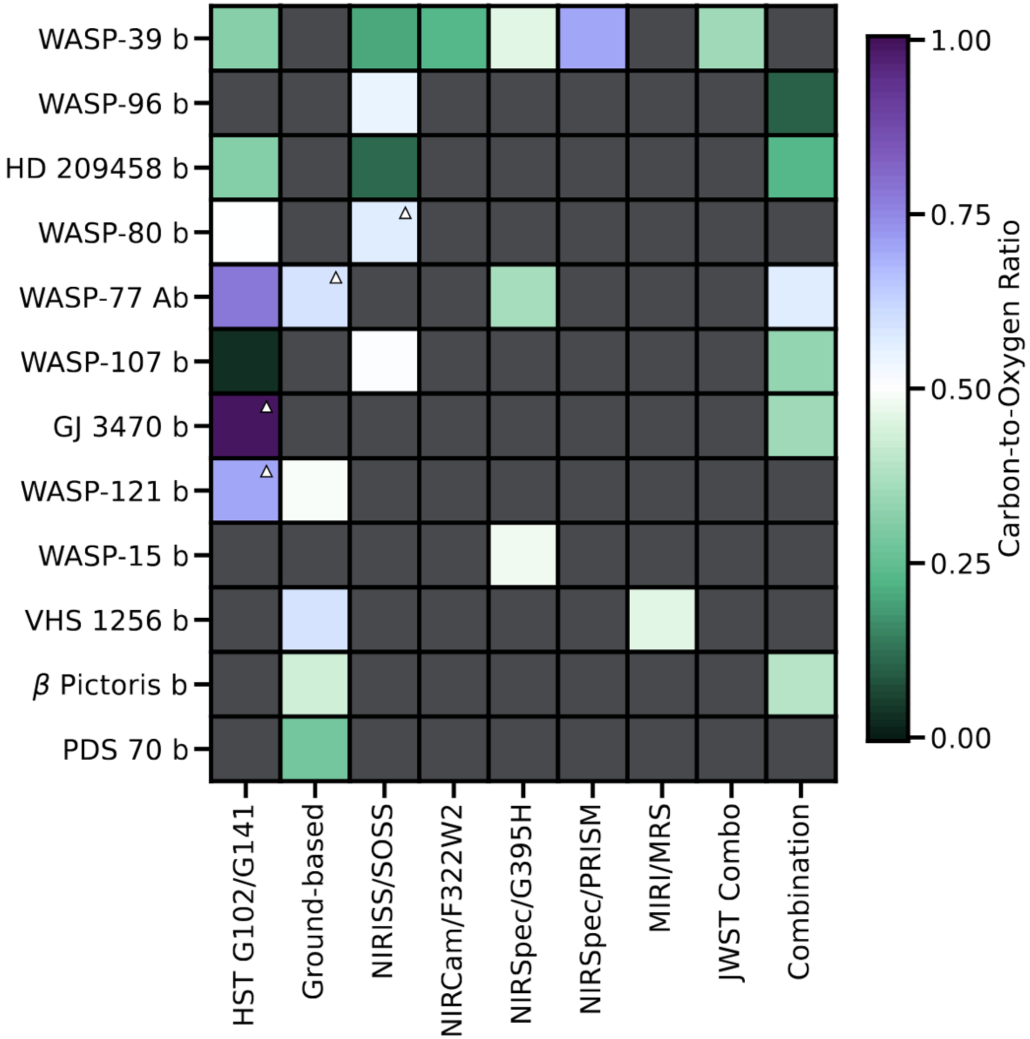
measuring C/O trends

Hoch+ 2023
transit data: Changeat+ 2022



Talk: D

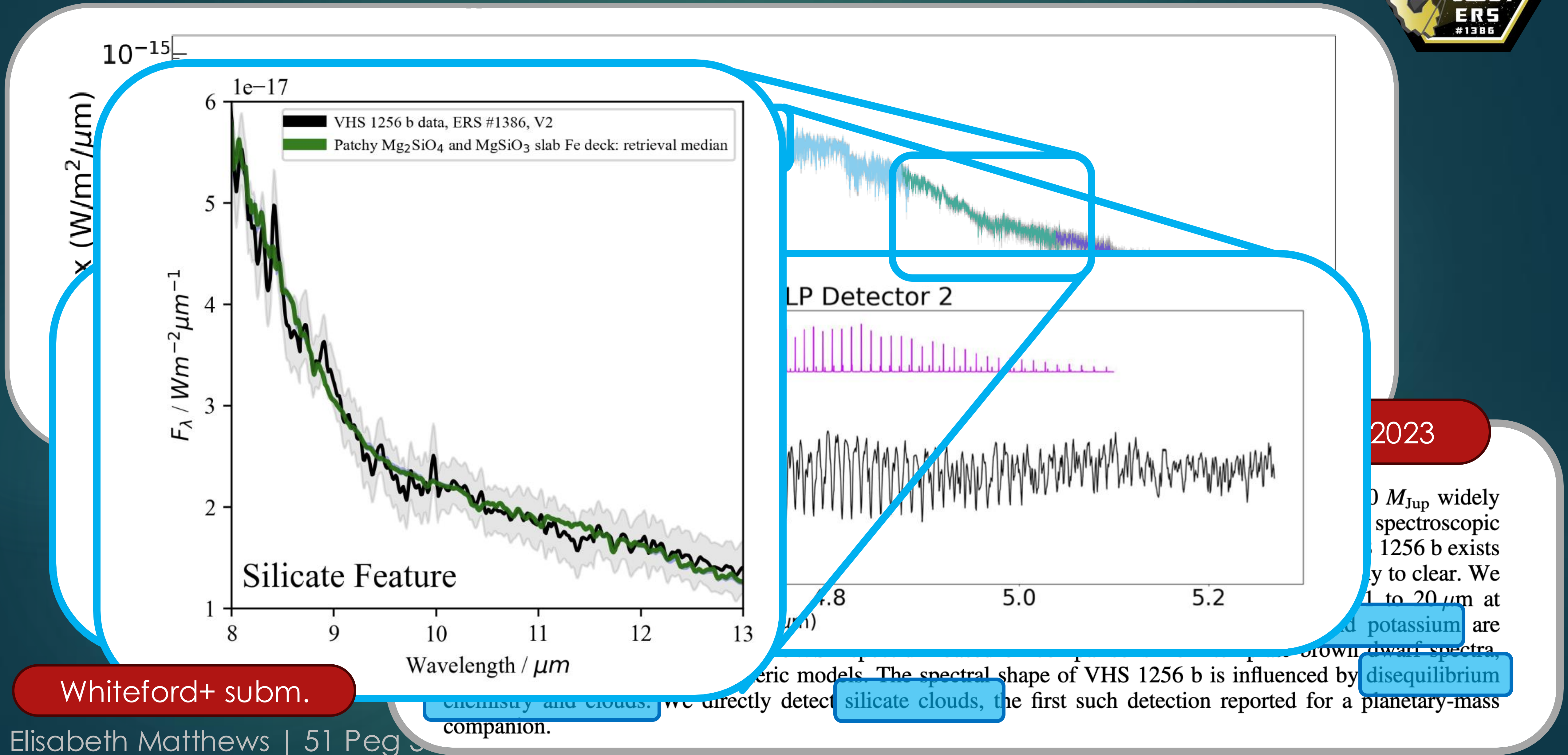




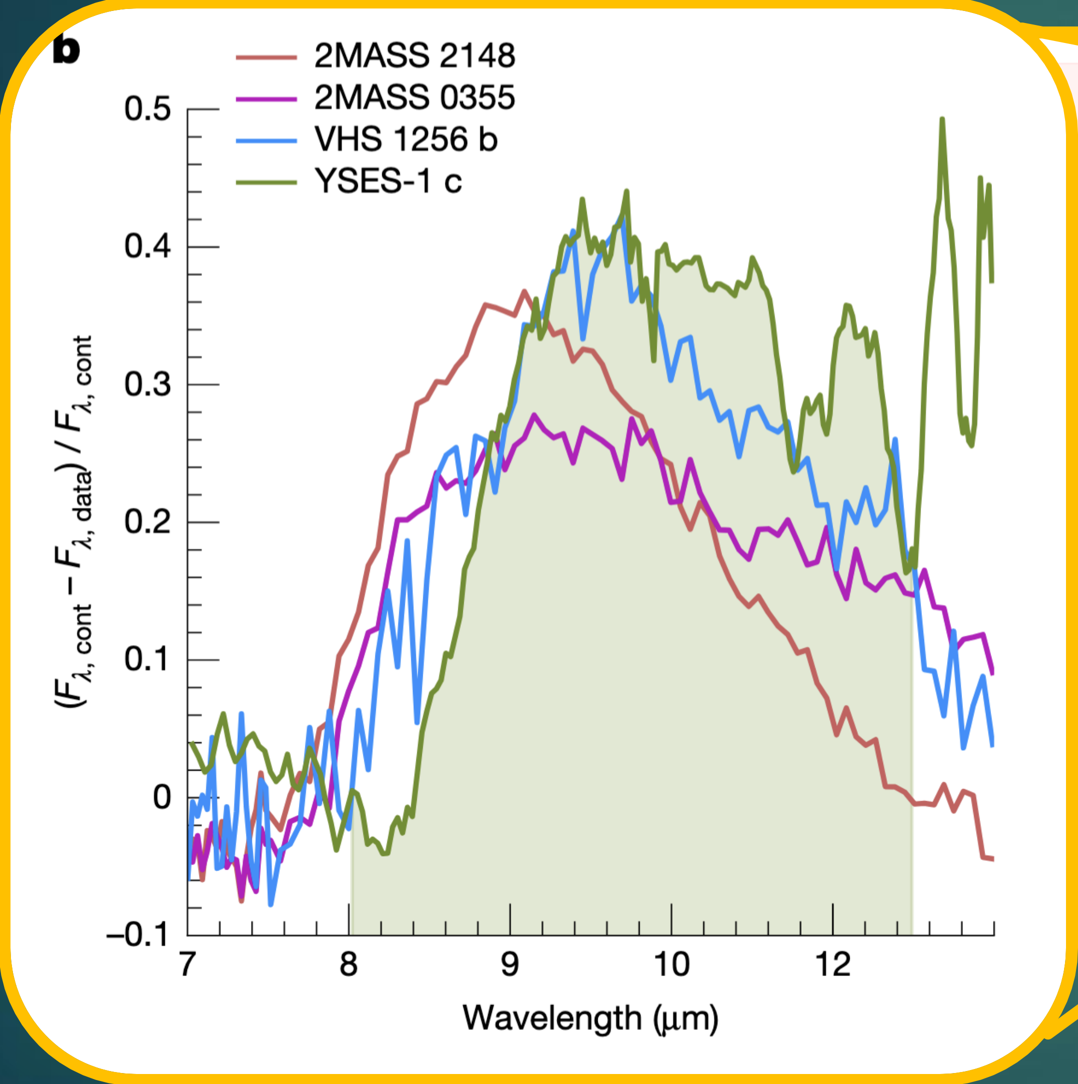
Feinstein+ 2025

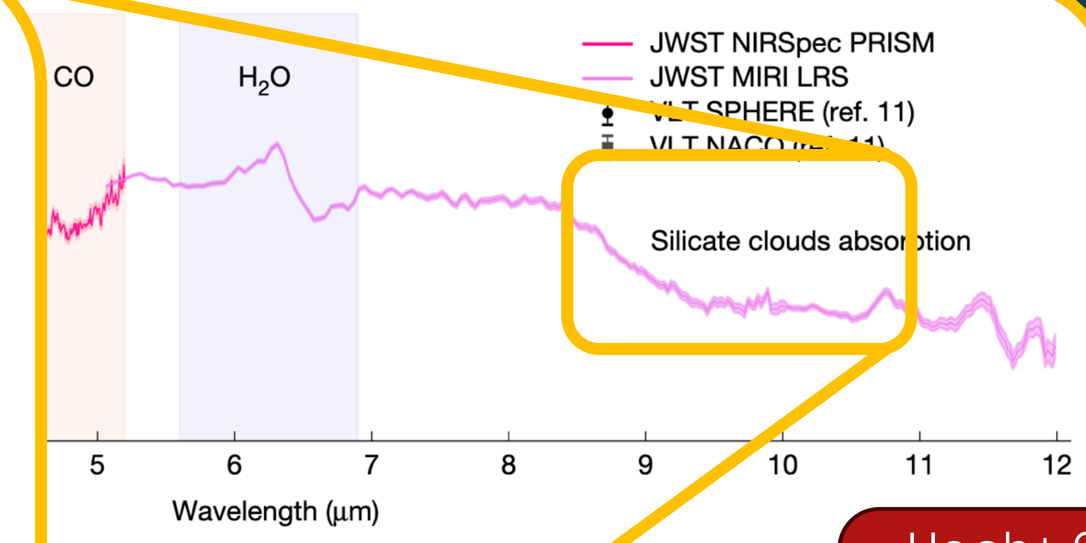
Elisabeth Matthews ... 2025

State-of-the-art in atmosphere studies



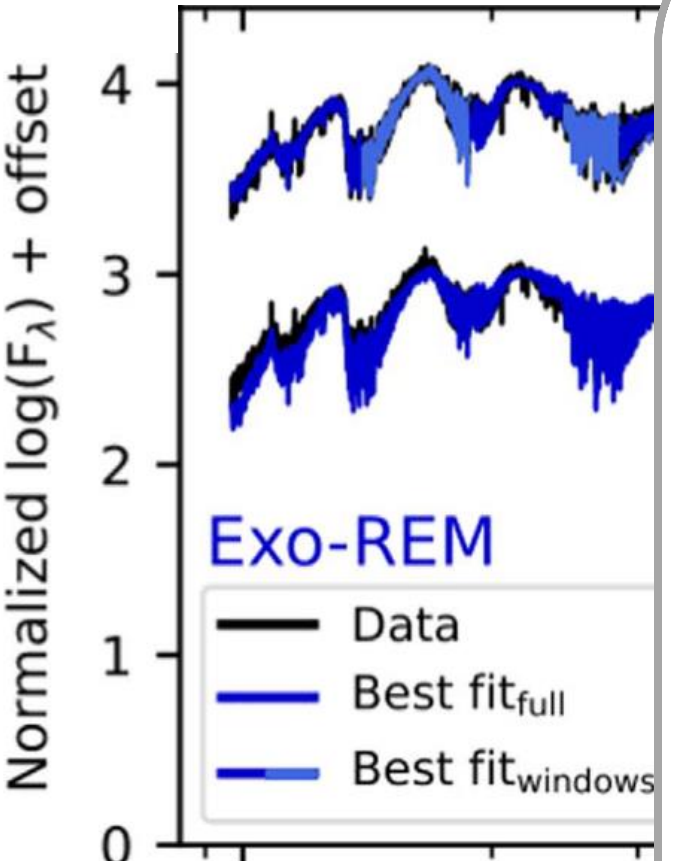
Comparison of silicate cloud properties

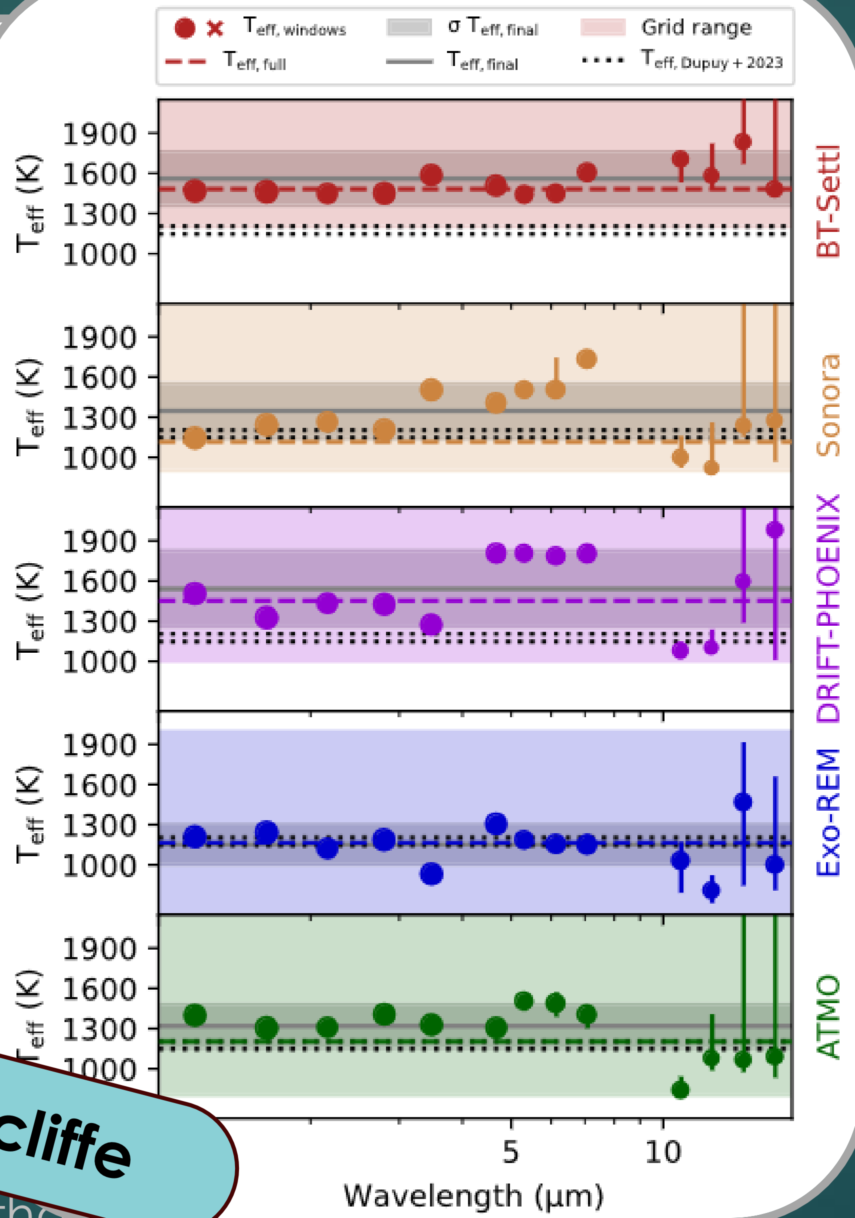


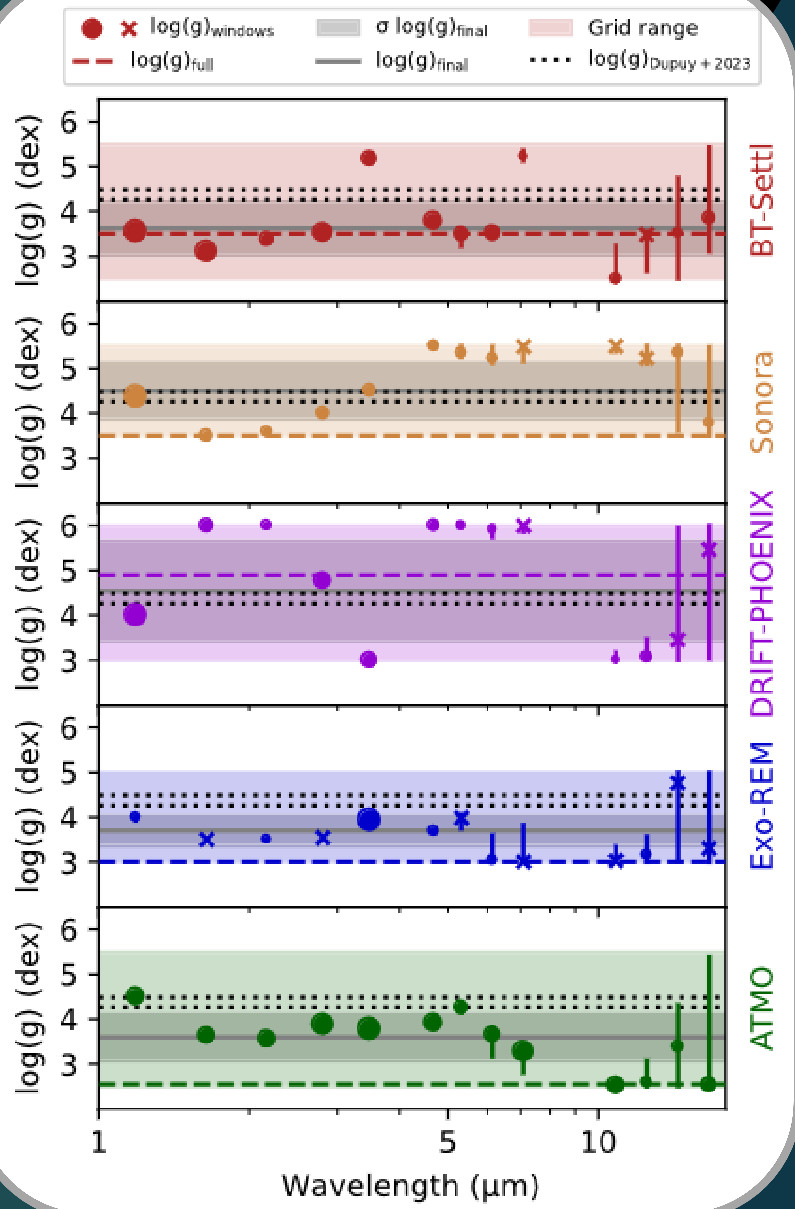


Hoch+ 2025

VHS1256: challenges for models



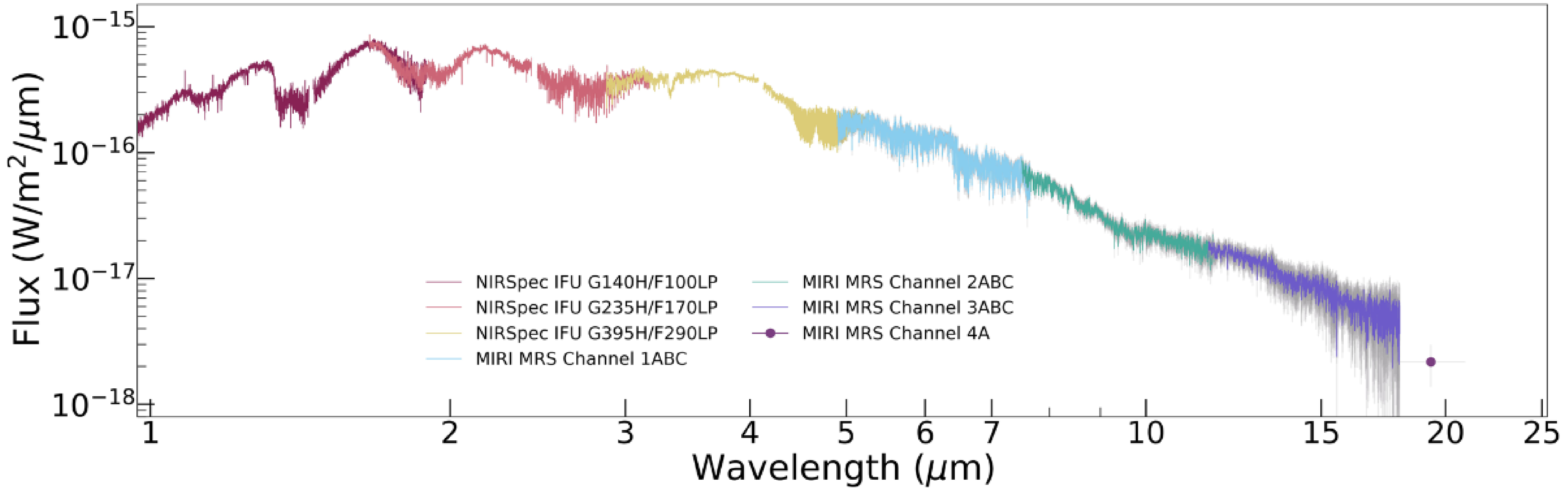




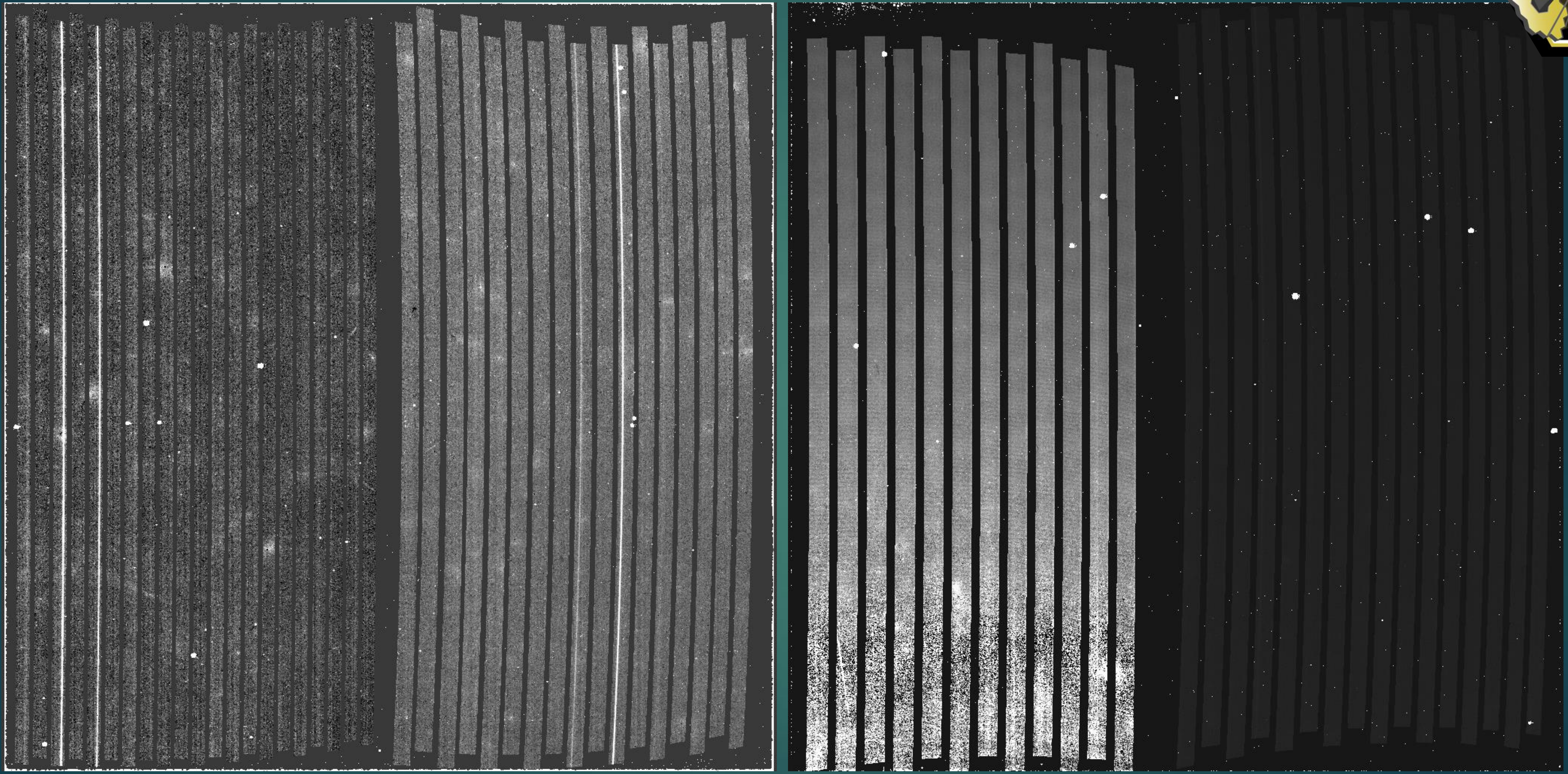
Talk: Alice Radcliffe

Petrus+ 2024

we do our science based on this:



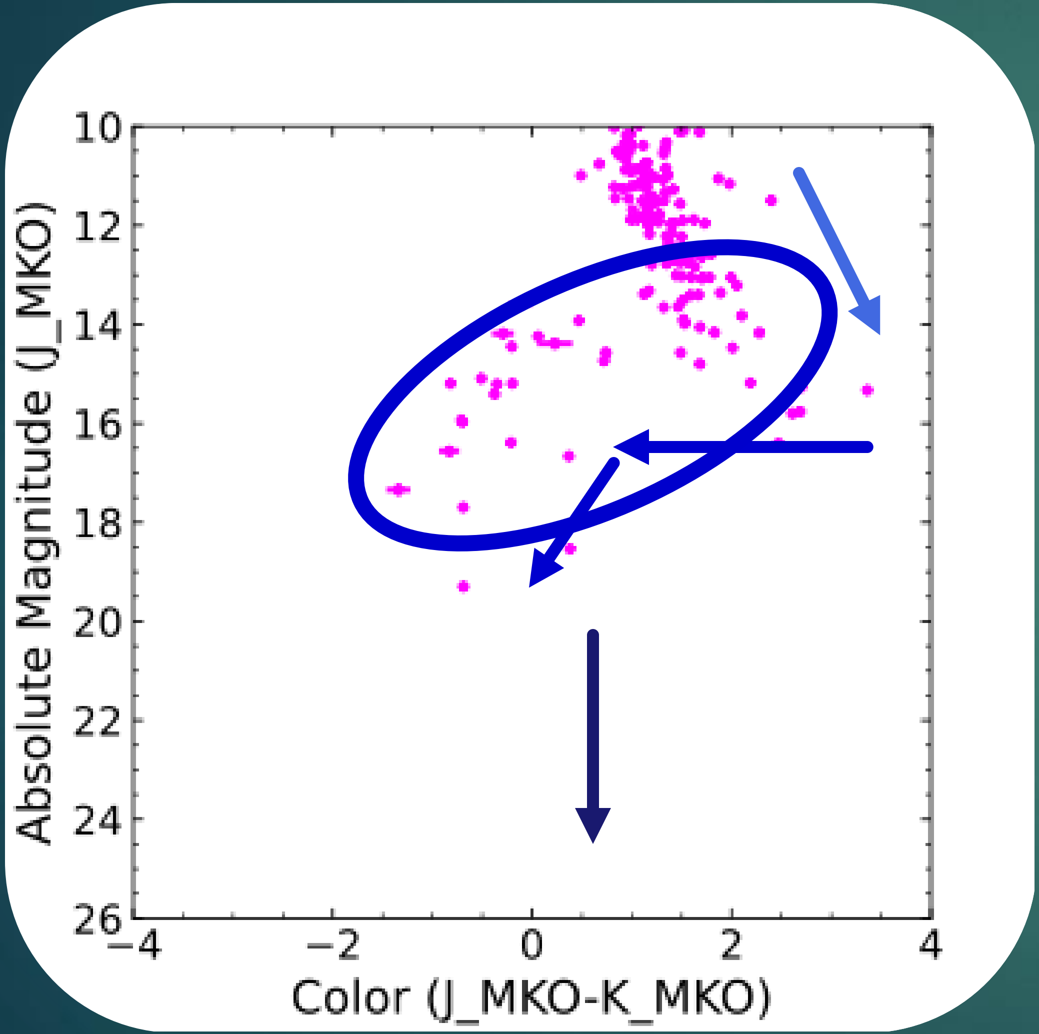
we ***actually observe*** this:



vhs1256 MRS *`cal.fits` files from MAST

Takeaway: with JWST, our data is better than our models - need to keep working!

Putting everything on a CMD



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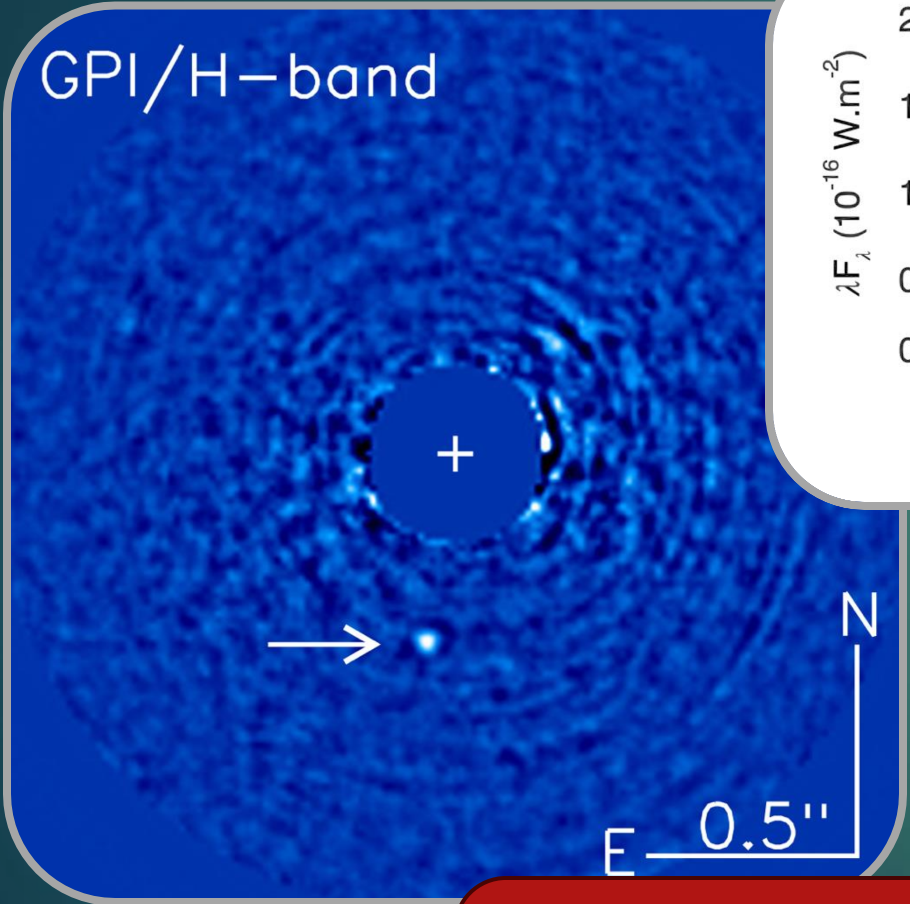
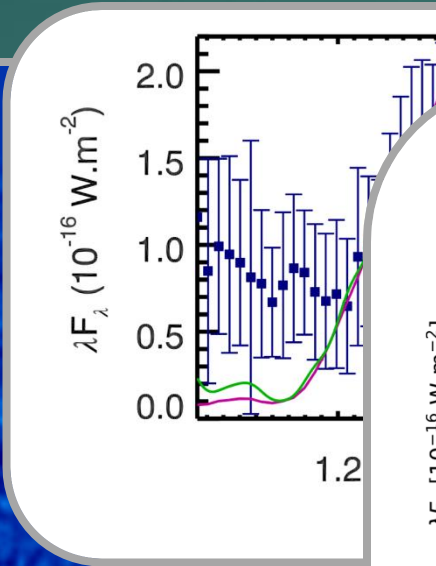
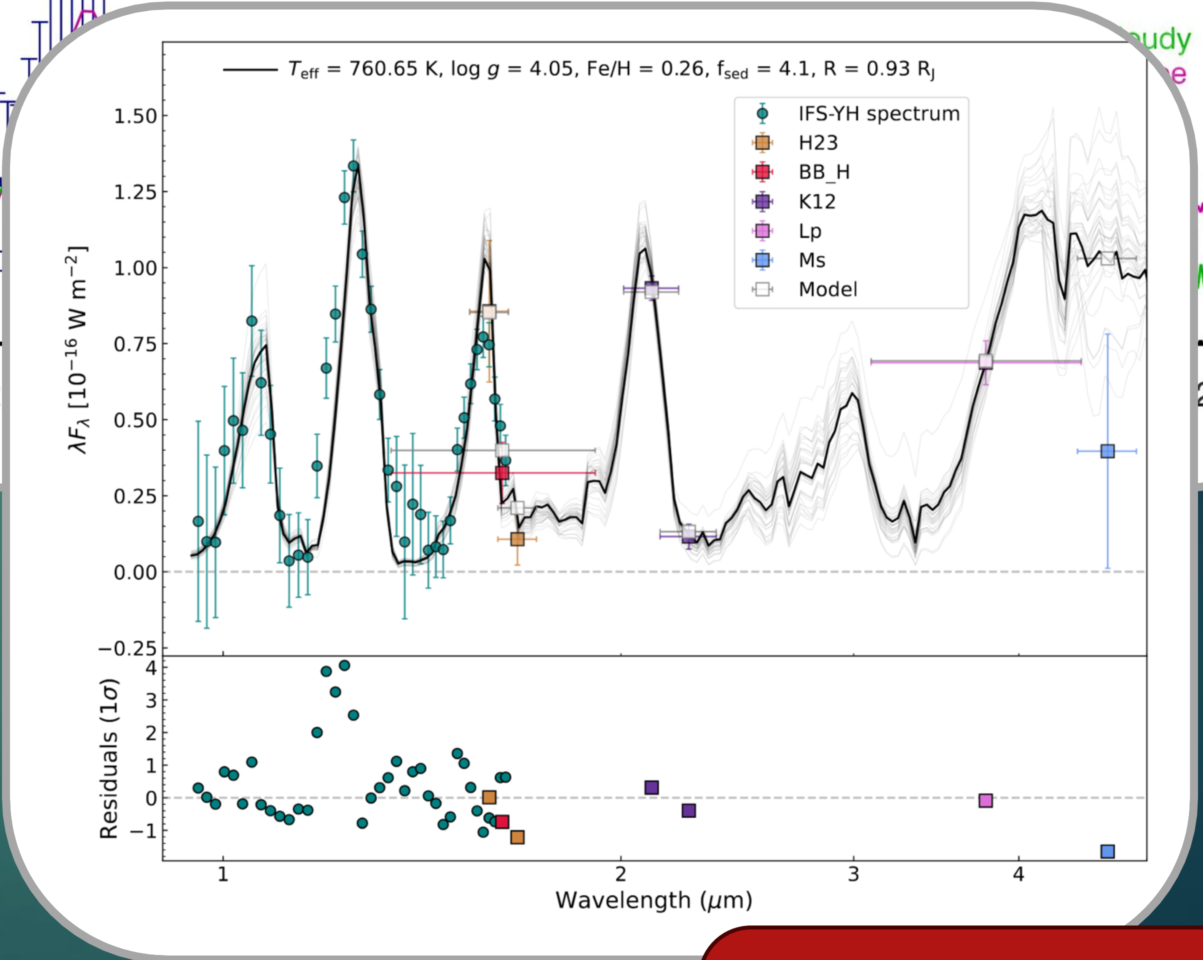
NH_3 emerging, water clouds?, ammonia clouds?

Cool, methane-rich atmospheres with SPHERE and GPI



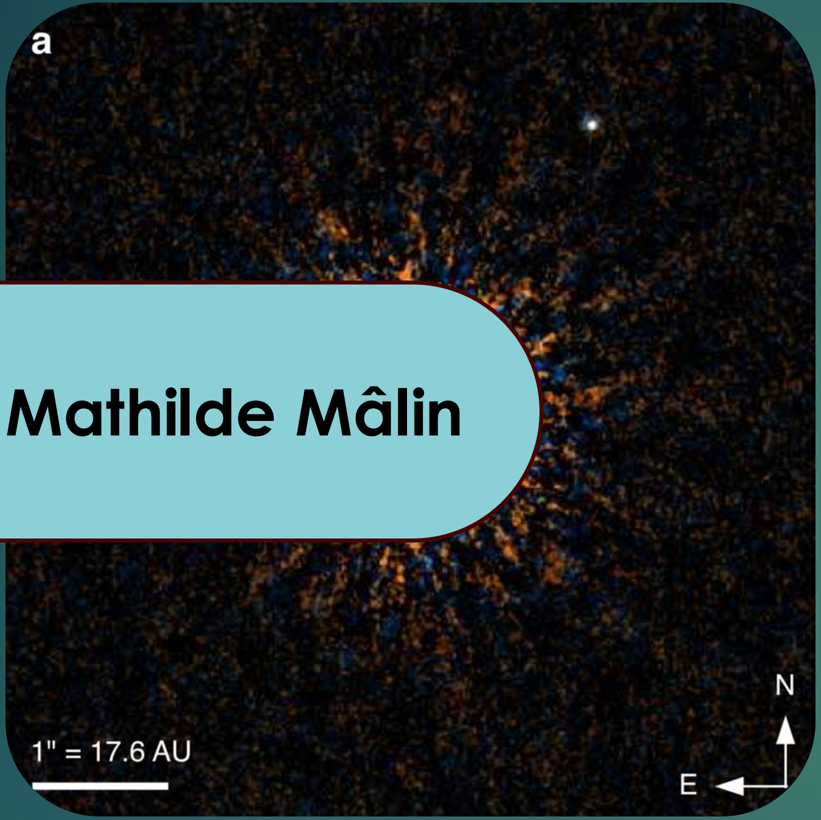
Macintosh+ 2015



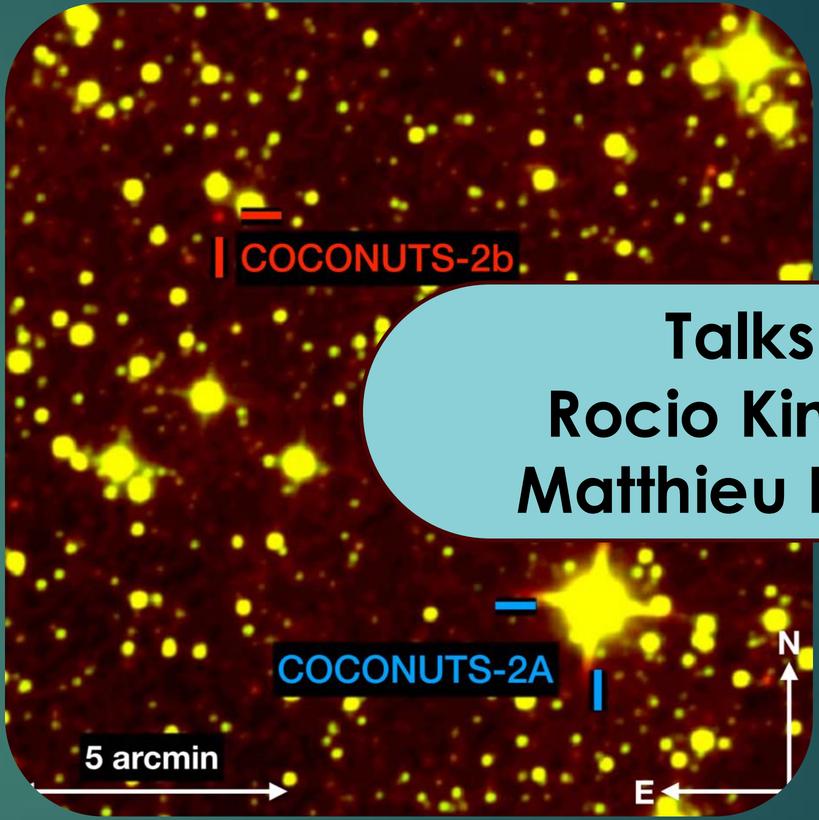


Brown Sevilla+ 2023

even colder T dwarf atmospheres



Talk: Mathilde Mâlin



**Talks:
Rocio Kiman,
Matthieu Ravet**

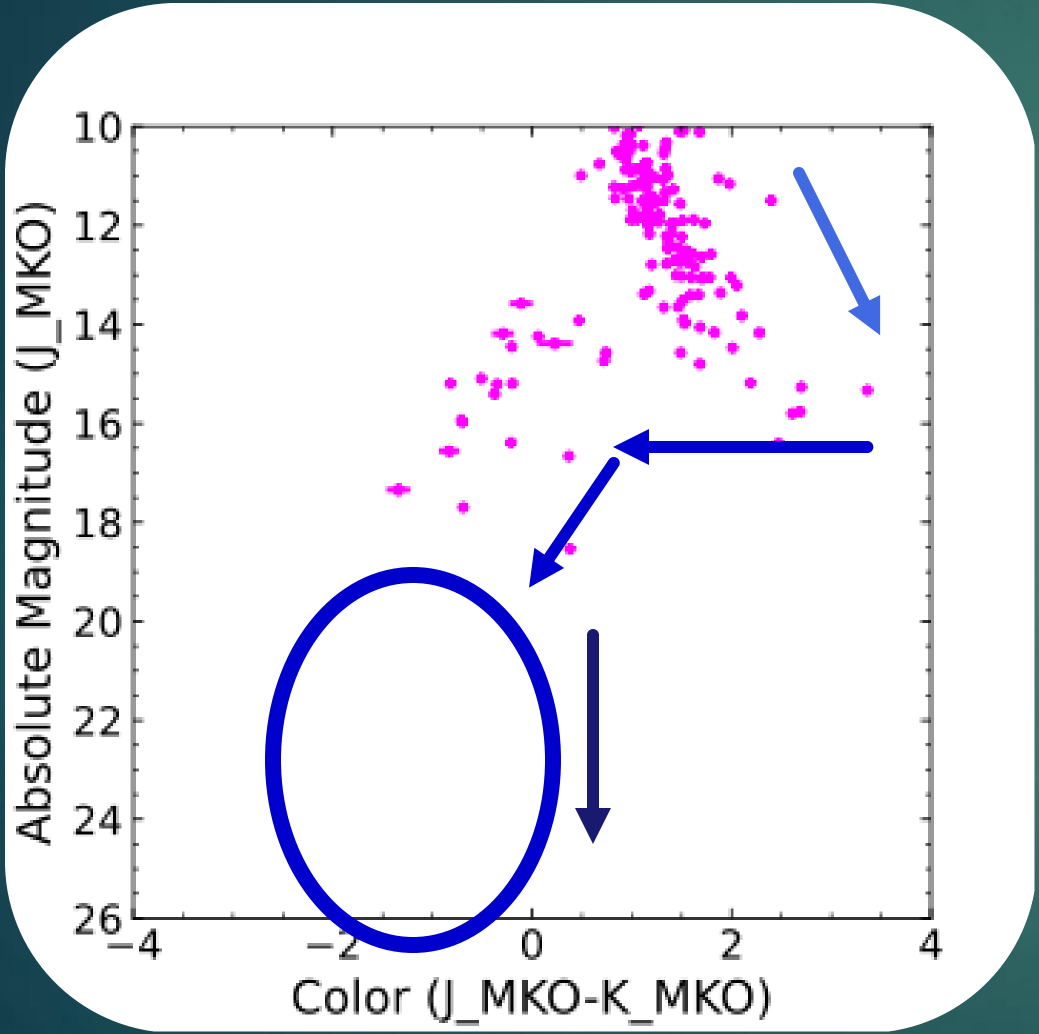
GJ 504 b

Kuzuhara+ 2013

COCONUTS 2 b

Zhang+ 2021

Putting everything on a CMD



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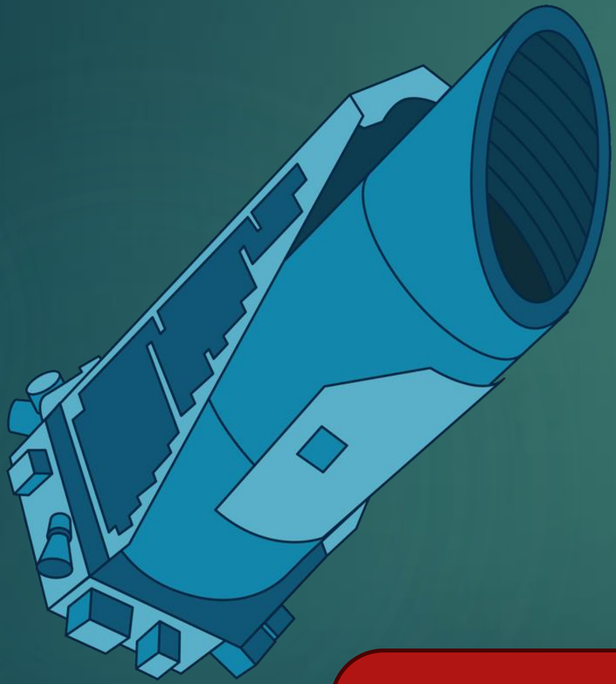
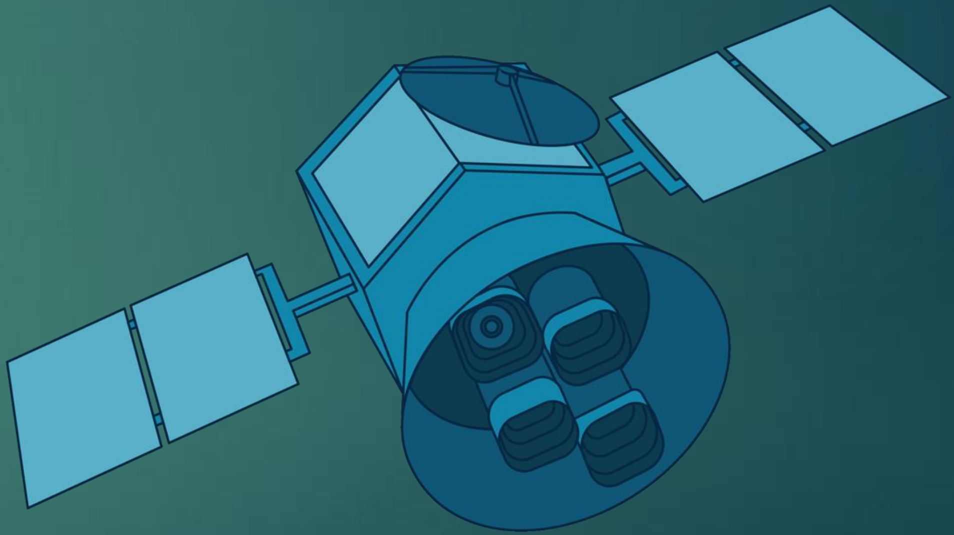
A note on detection strategies

Blind Surveys:
occurrence rates



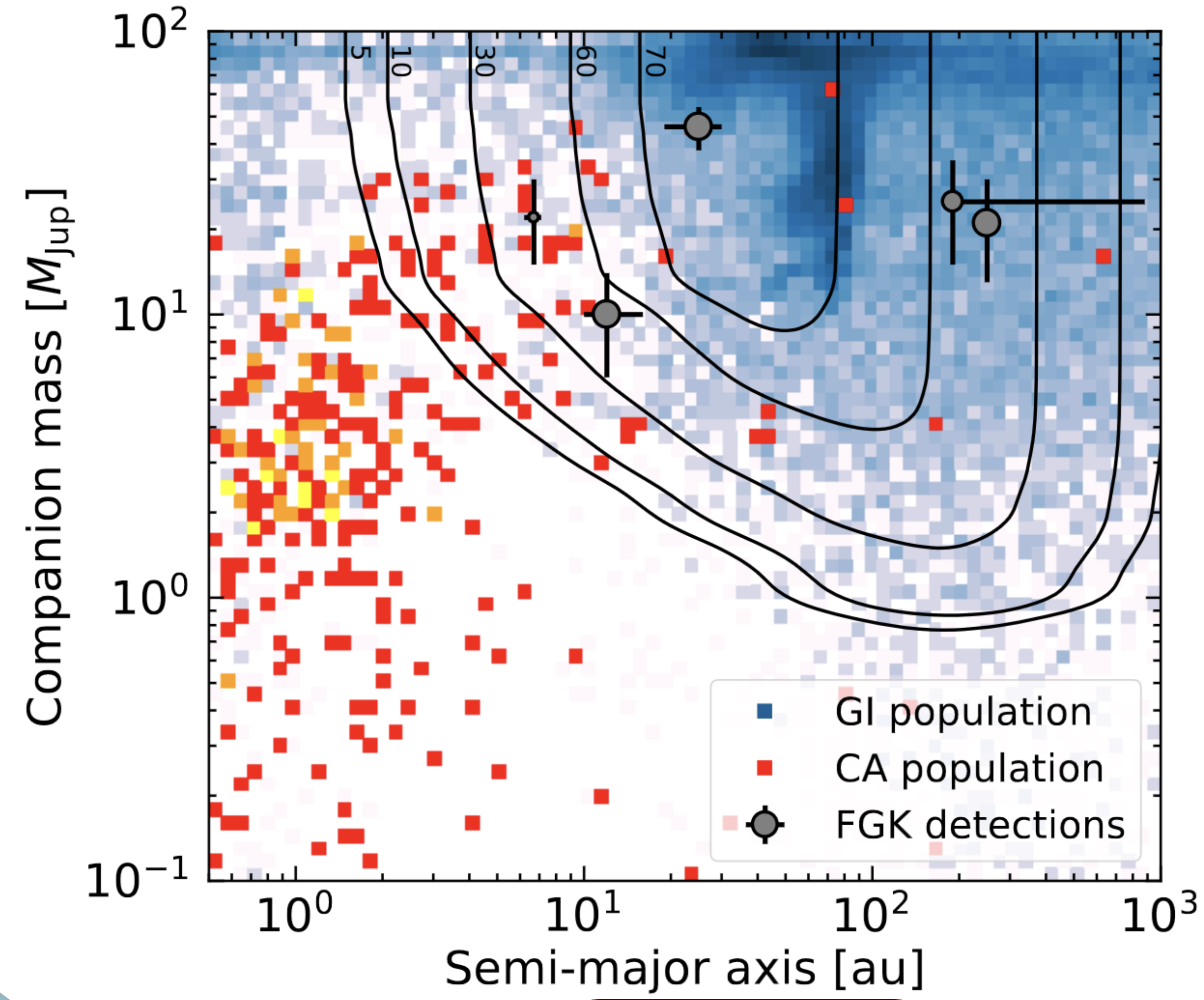
e.g. Kepler

Targeted Surveys:
"prime" targets



e.g. TESS

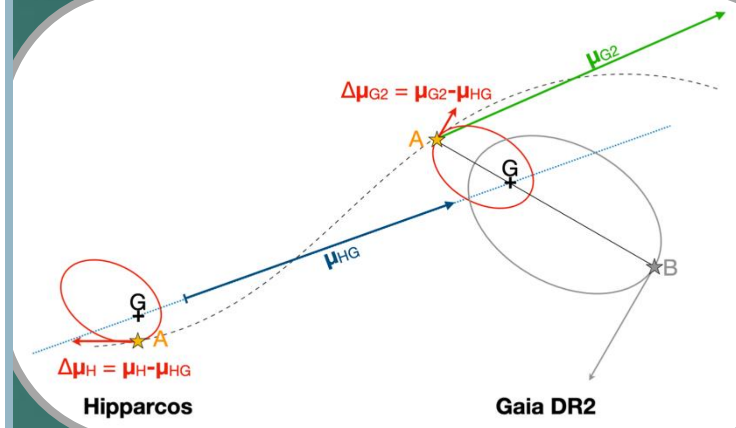
A note on detection strategies



GPI/GPIES

Vigan+ 2021

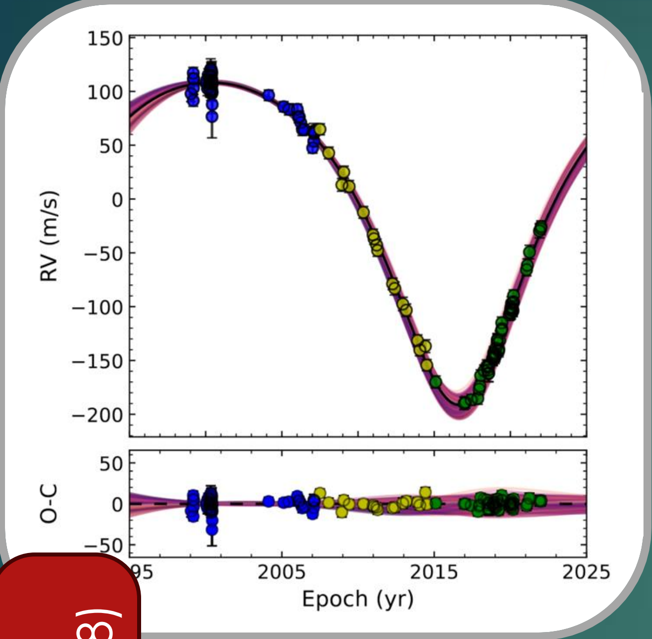
Targeted Surveys:
"prime" targets



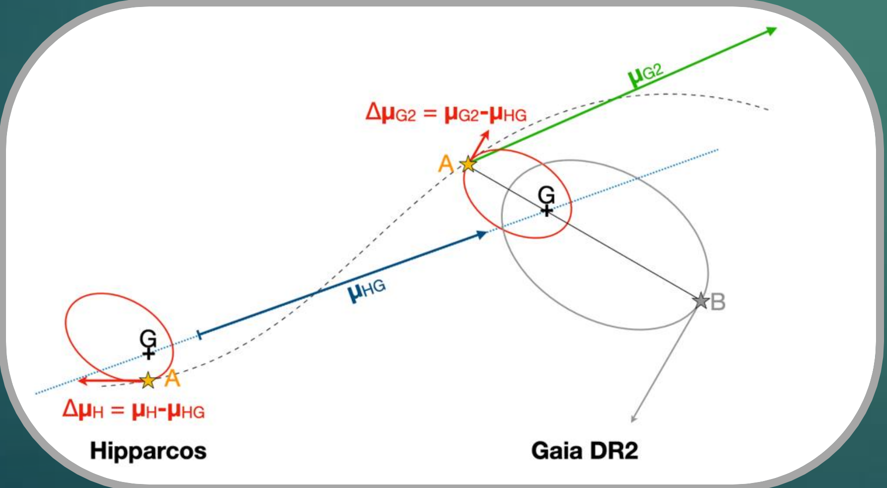
RV & astrometric acceleration as guides

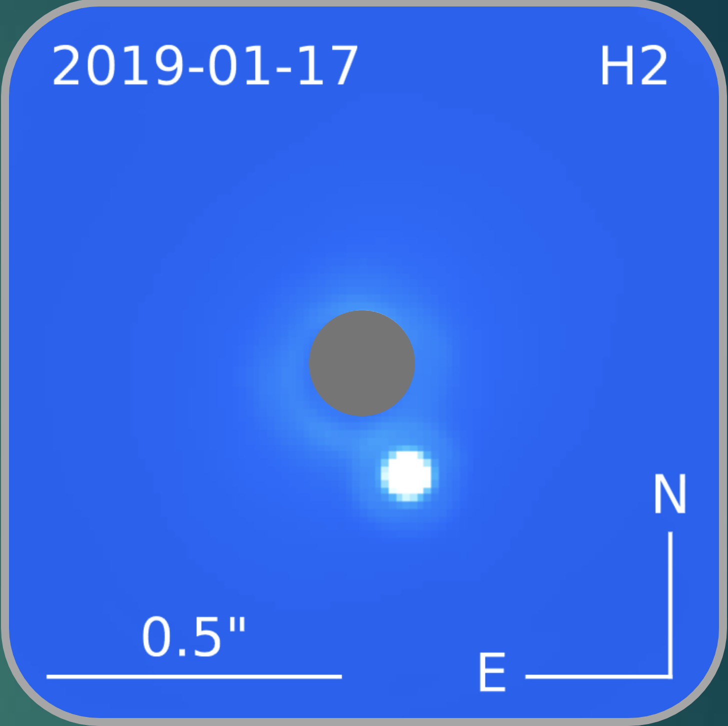
Indirect pointers: targeted imaging surveys

CORALIE RVs
(Rickman, Matthews+ 2022)



Kervella+ 2019
(see also Brandt+ 2018)



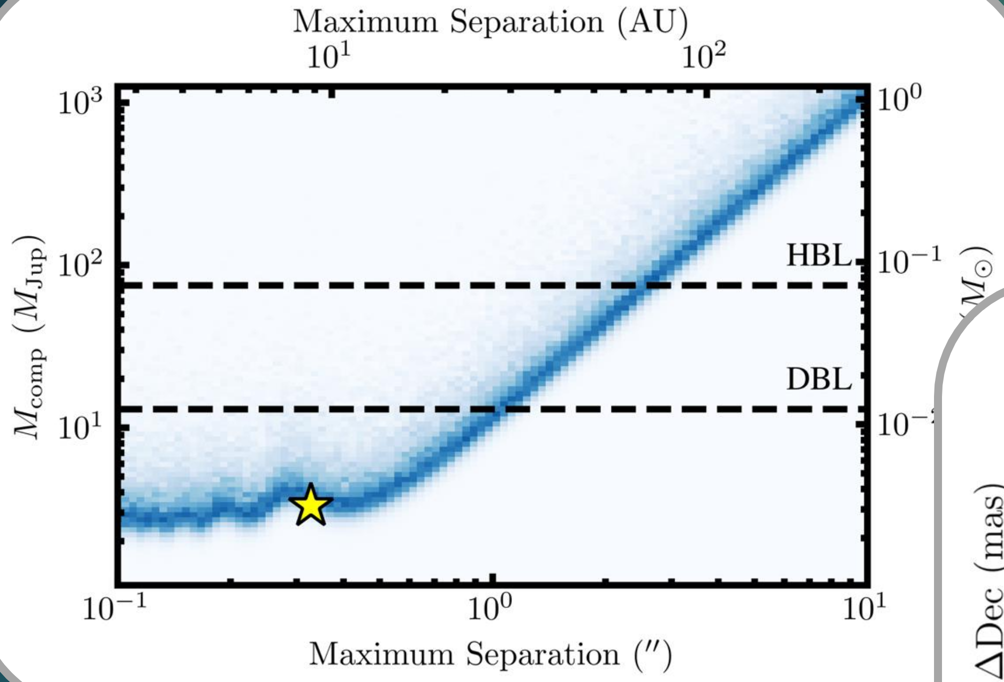


SPHERE imaging
Rickman, Matthews+ 2022

also Crepp+ 2012, 2013ab, 2014ab, PhD thesis Montagnier, PhD thesis Hagelberg, Cheetham+ 2018, Rickman+2020, 2024, Franson+2023, Matthews+ in prep, and many others

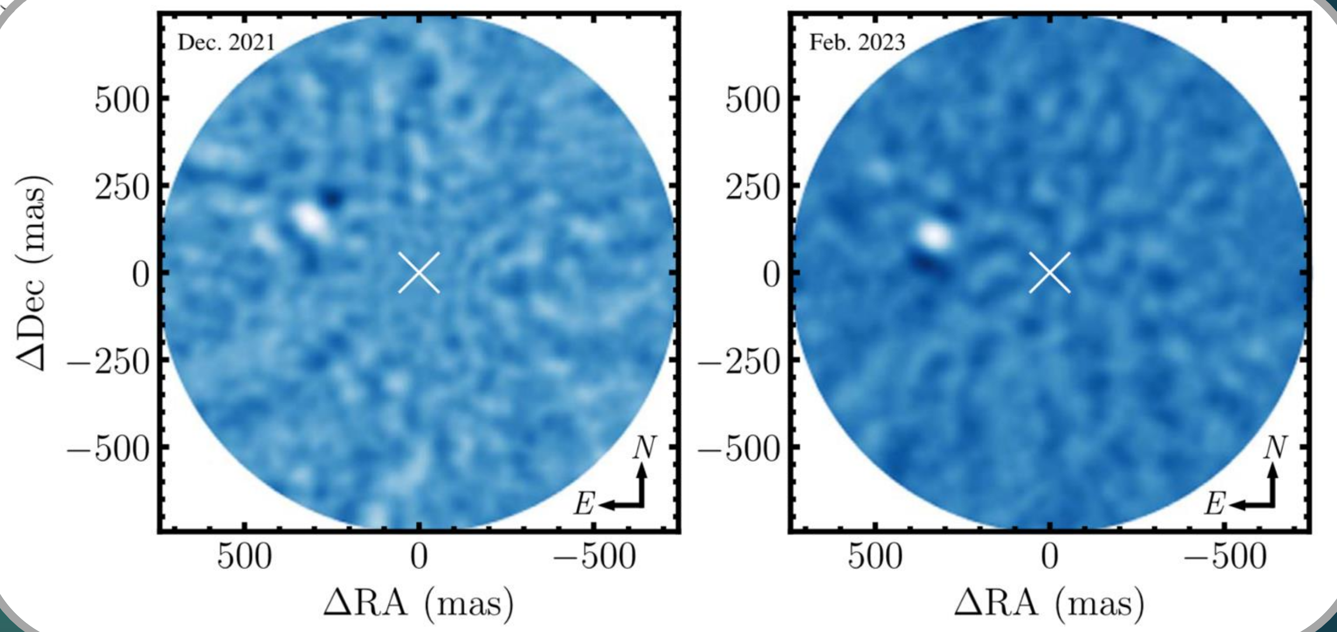
Talks: Kiefer, Destriez
Poster: Ceva

New planets from astrometric accelerations



Franson+ 2023

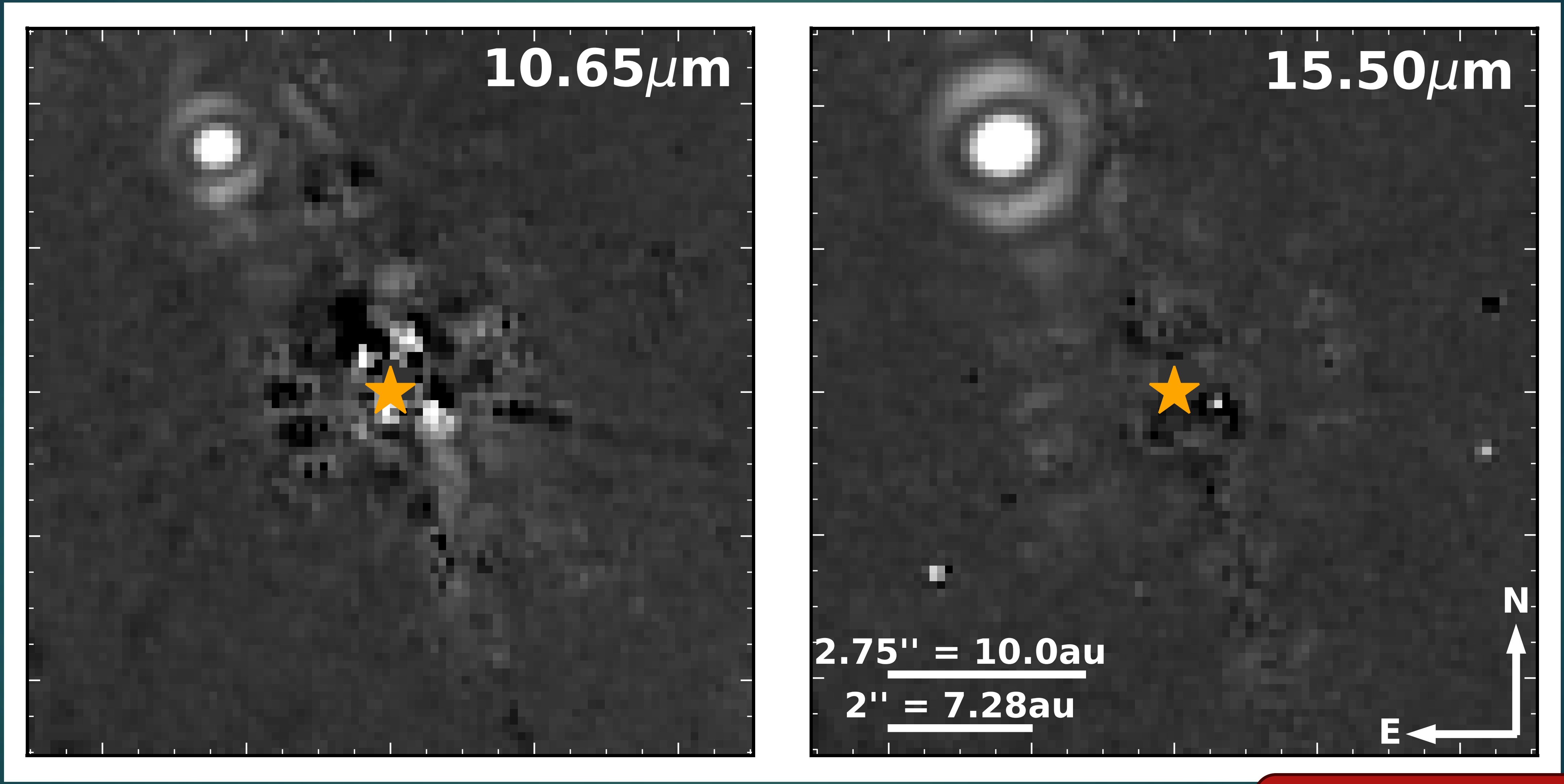
Talk: Kyle Franson



AF Lep b: Franson+ 2023
(also discovered by: de Rosa+ 2023; Mesa+ 2023)

Takeaway: there is an interplay between demographic studies & atmosphere studies

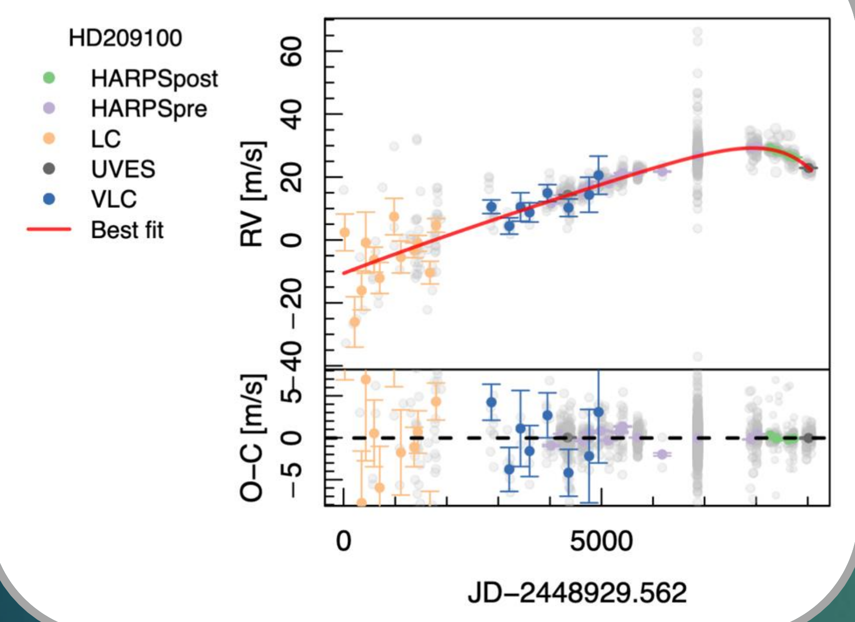
Indirect+direct+JWST: cold, old planets!



Matthews+ 2024

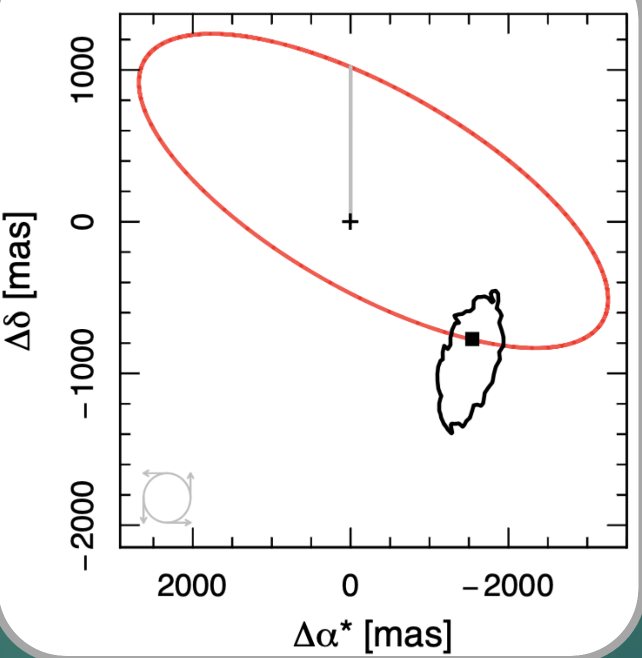
Indirect+direct+JWST: cold, old planets!

RV data since 1992



Feng+ 2023
See also Feng+ 2019, Philipot+ 2023

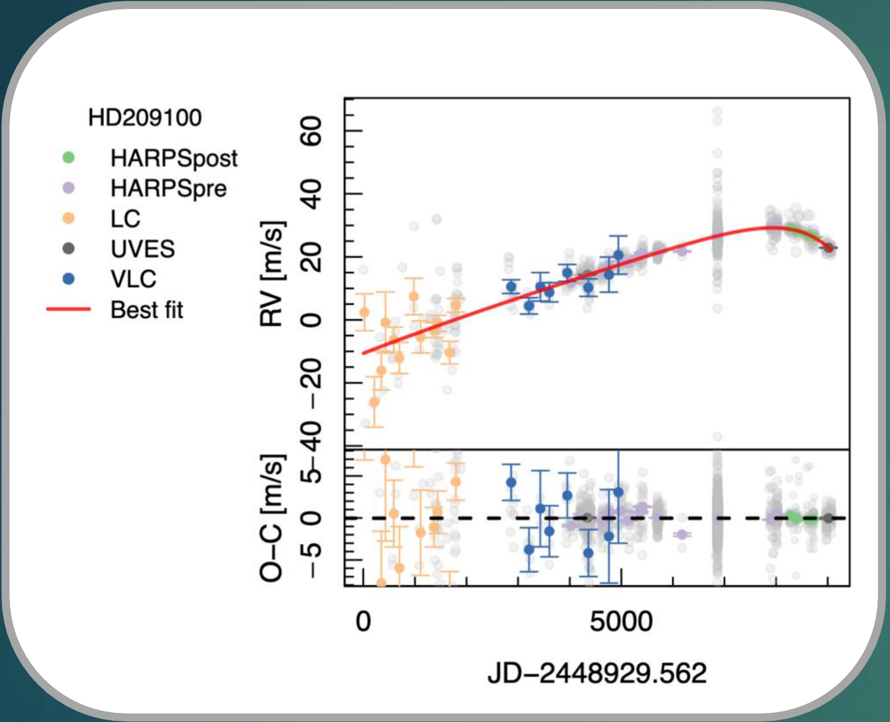
3D orbit (RV & astrometry)



~3M$_J$
~8au

Indirect+direct+JWST: cold, old planets!

RV data since 1992



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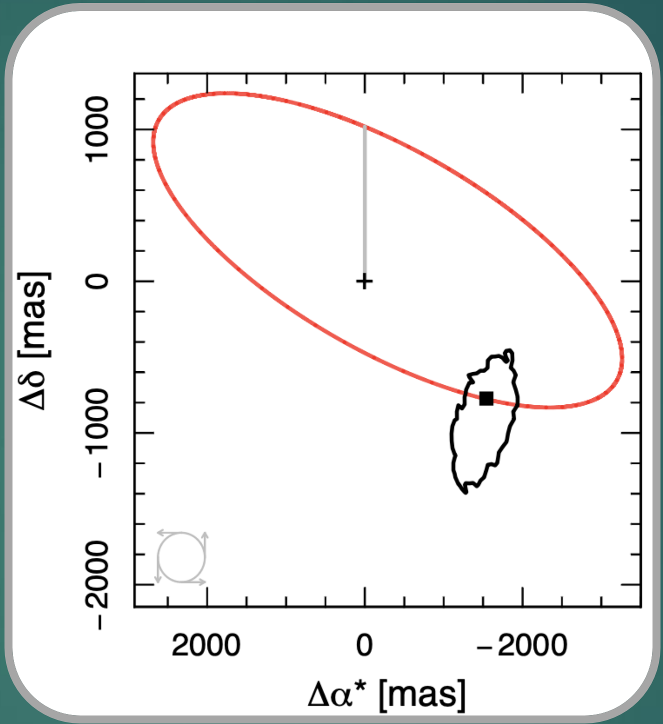
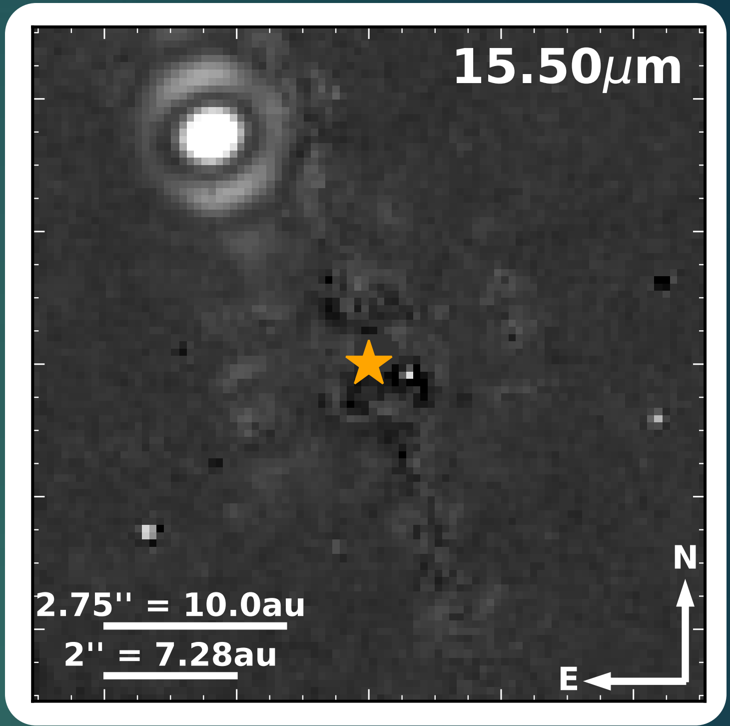


JWST/MIRI detection



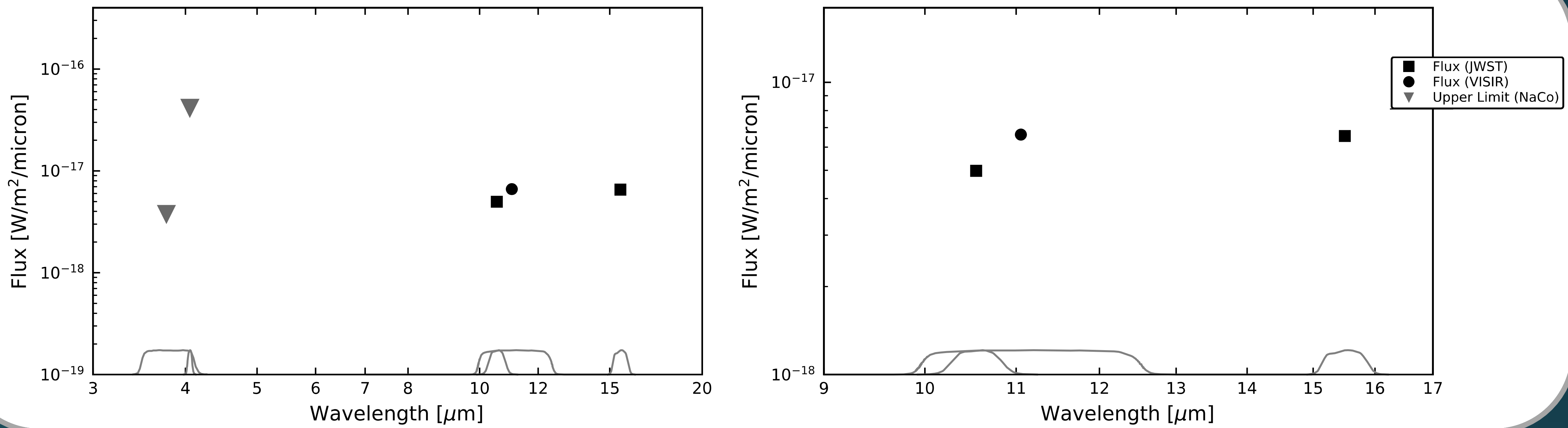
Feng+ 2023
See also Feng+ 2019, Philipot+ 2023

~3M$_J$
~8au

6.3±0.6M$_J$
15au projected

Poster: Bhavesh Rajpoot

Atmosphere of the coldest imaged planet



Photometric measurements: JWST/MIRI, VISIR/NEAR (Matthews+ 2024 subm.)

Photometric upper limits: VLT/NaCo (Janson+ 2009, Viswanath+ 2021)

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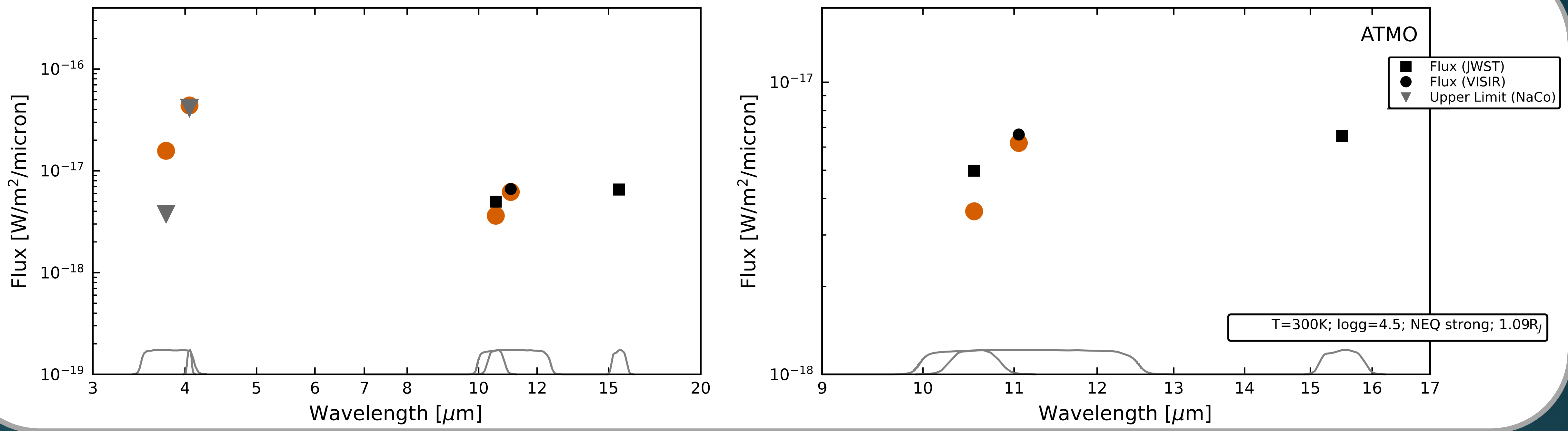

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models:

ATMO (Phillips+ 2020): 300K

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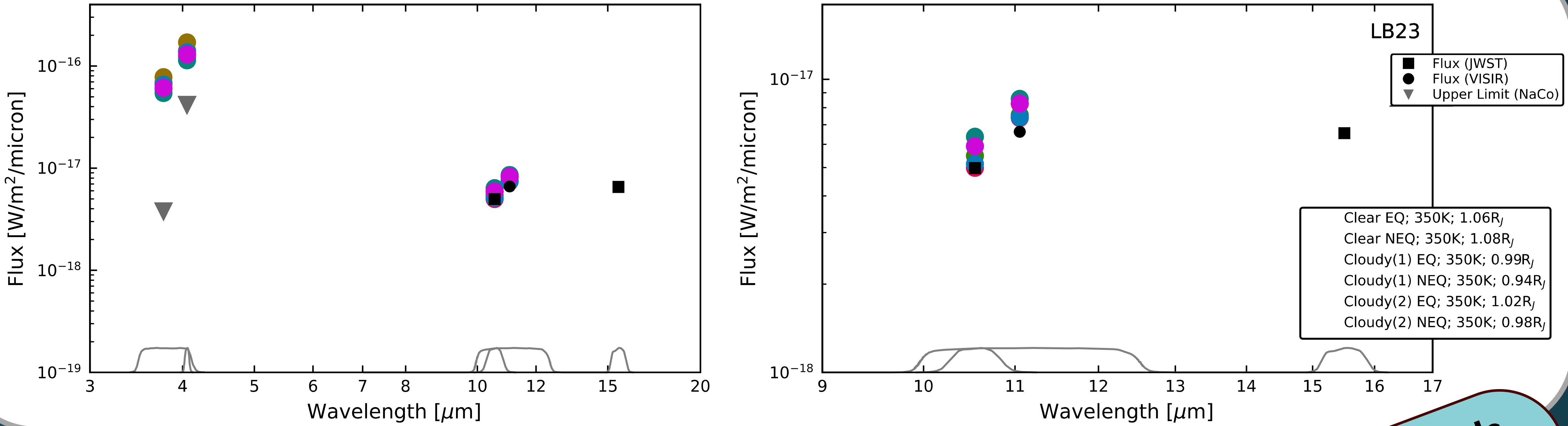

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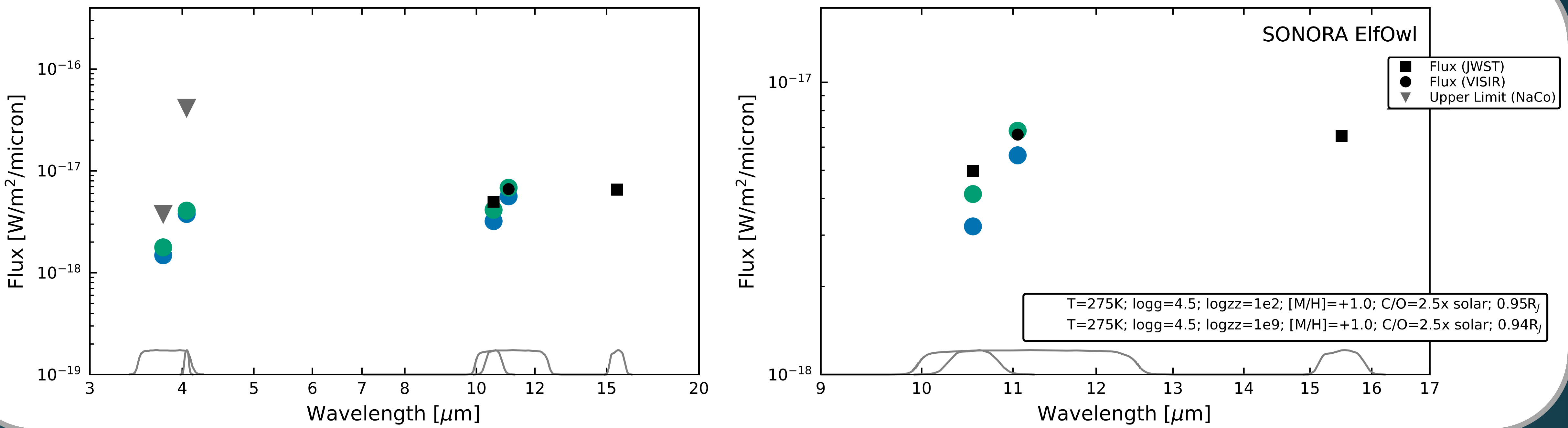
ATMO (P

Lacy &

ater clouds

more water cloud models coming – Mang, Morley

Atmosphere of the coldest imaged planet



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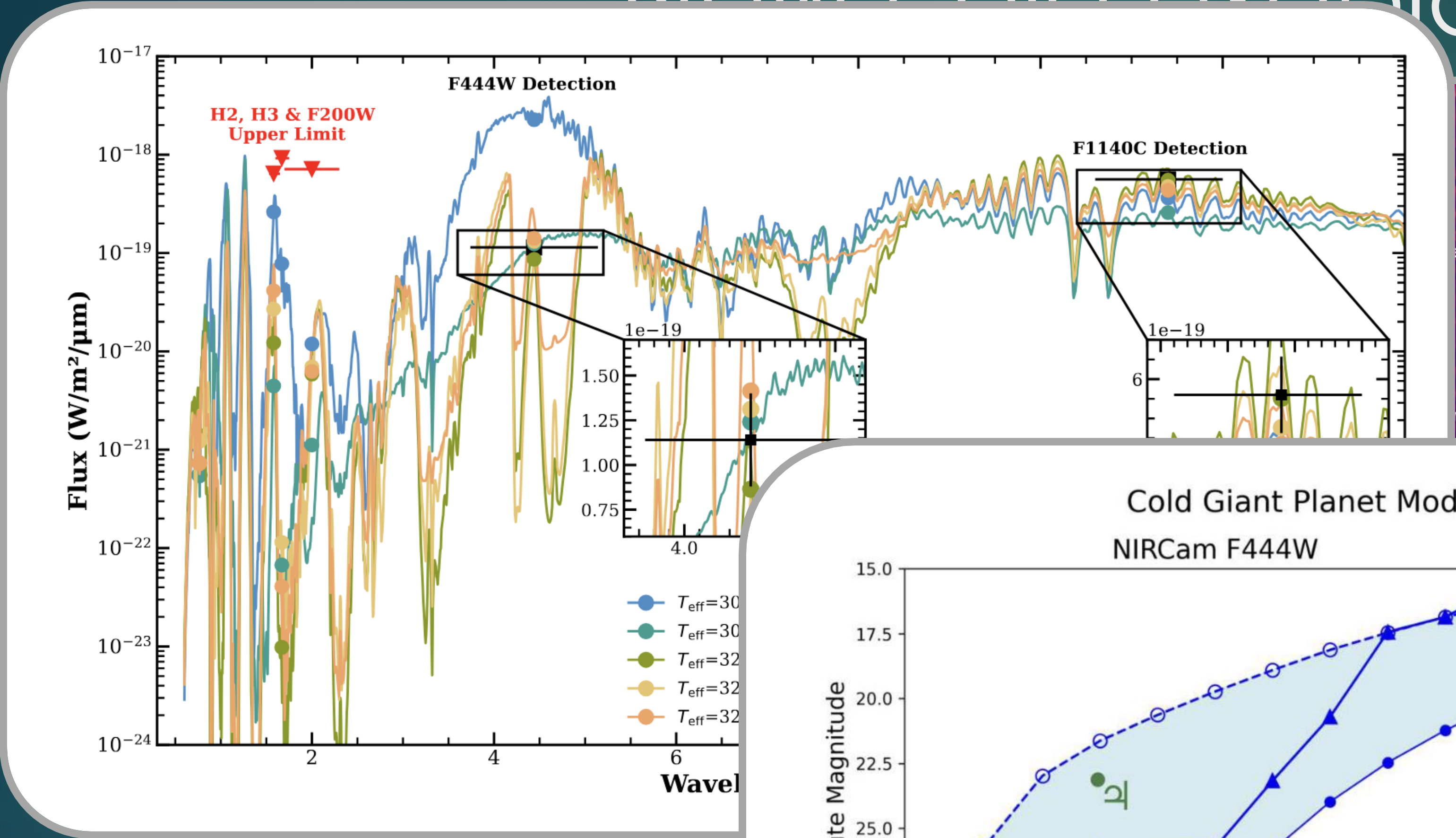
models:

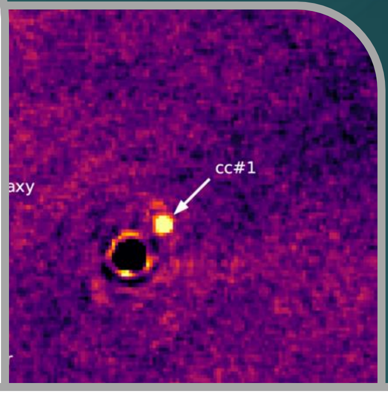
ATMO (Phillips+ 2020): 300K

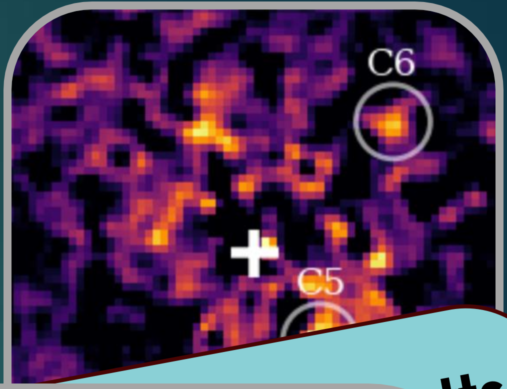
Lacy & Burrows 2023: 350K, water clouds

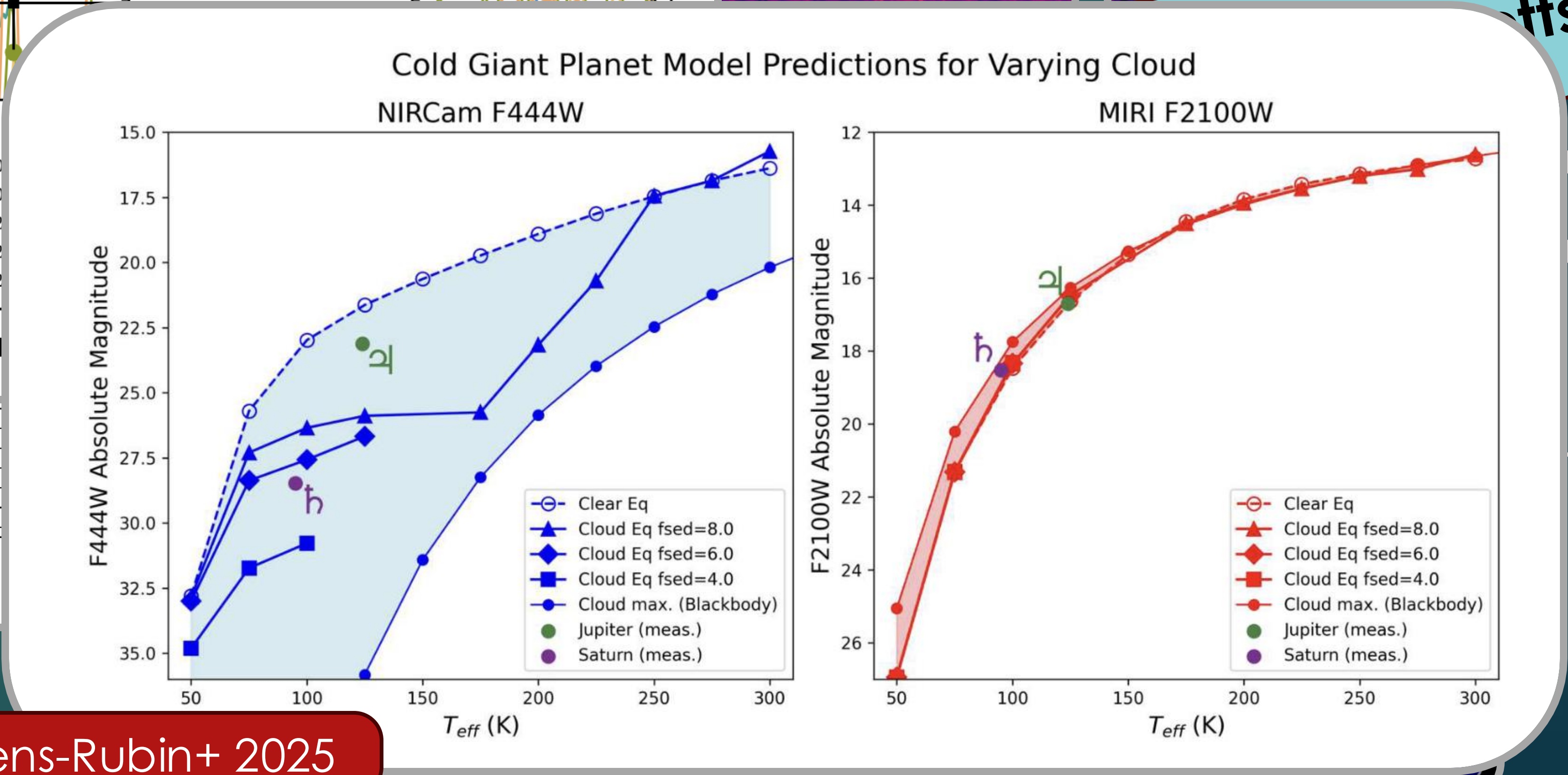
ElfOwl (Mukherjee+ 2024): 275K, [M/H]=1; C/O=2.5x solar

New cold exoplanets with JWST









14 Her c

Bardalez-Gagliuffi & Balmer et al. 2025

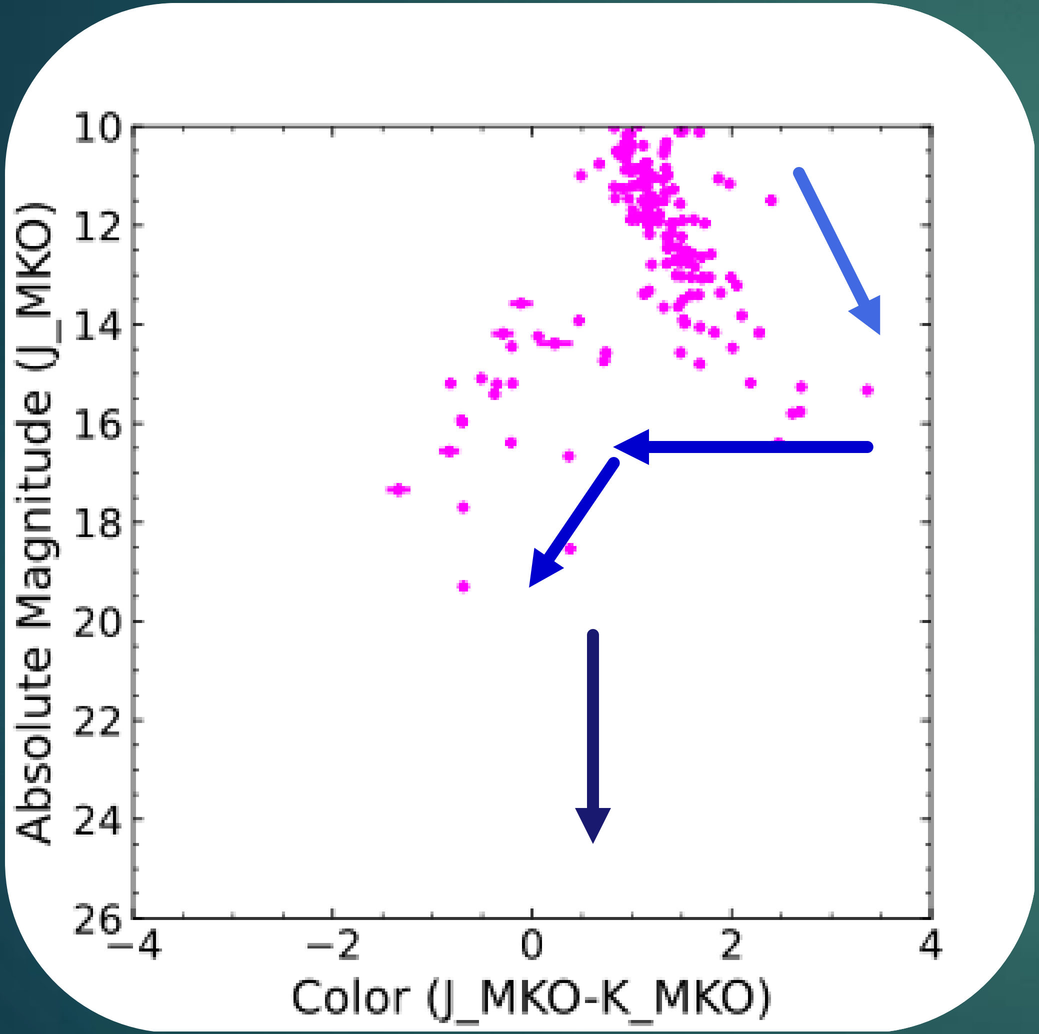
Talk: William Balmer

Bowens-Rubin+ 2025

Sanghi et al. 2025

Takeaway: we can image cold giant exoplanets, including RV planets, and we are starting to study their atmospheres

How can we flesh out this picture?



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Another 30th anniversary

LETTERS TO NATURE

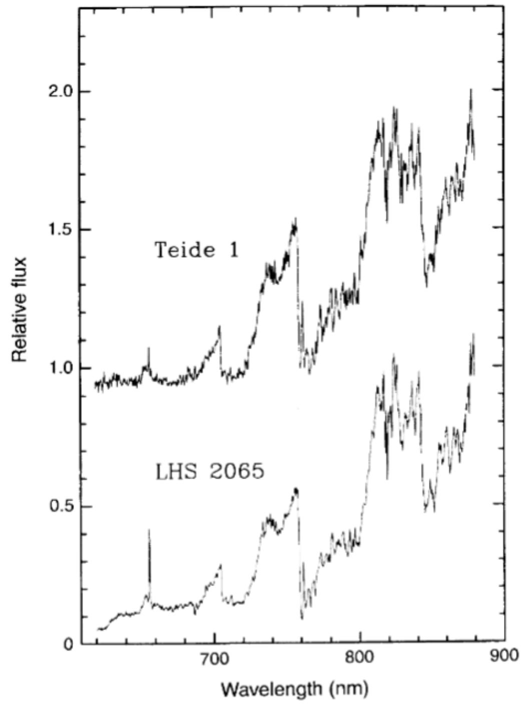
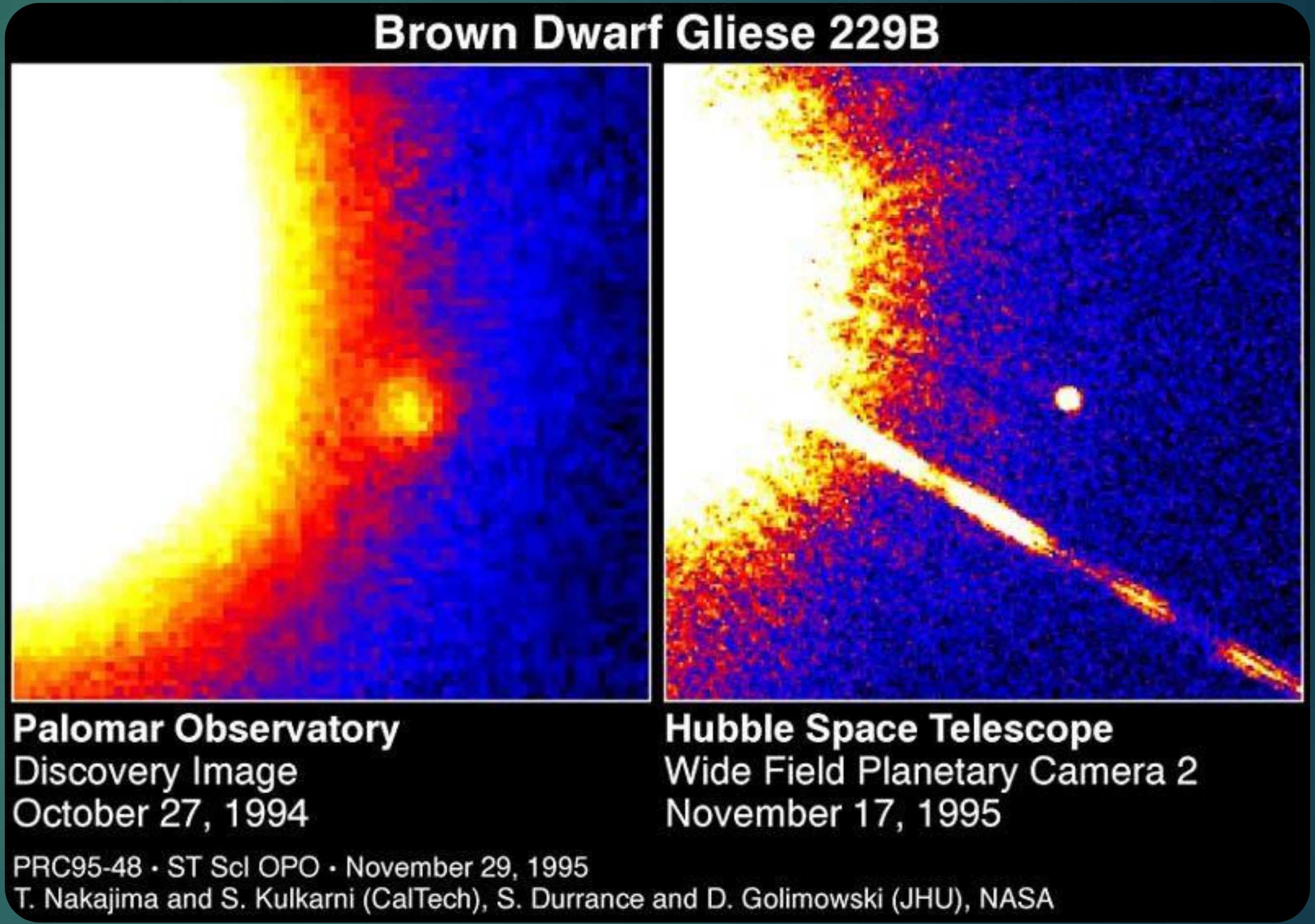


FIG. 1 The optical spectrum of Teide 1 (upper trace) and of the M9 dwarf LHS 2065 (lower trace). The flux scale of both spectra is normalized to unity at 825 nm. An offset has been added to the spectrum of Teide 1 for clarity.



Rebolo+ 1995

Nakajima+ 1995

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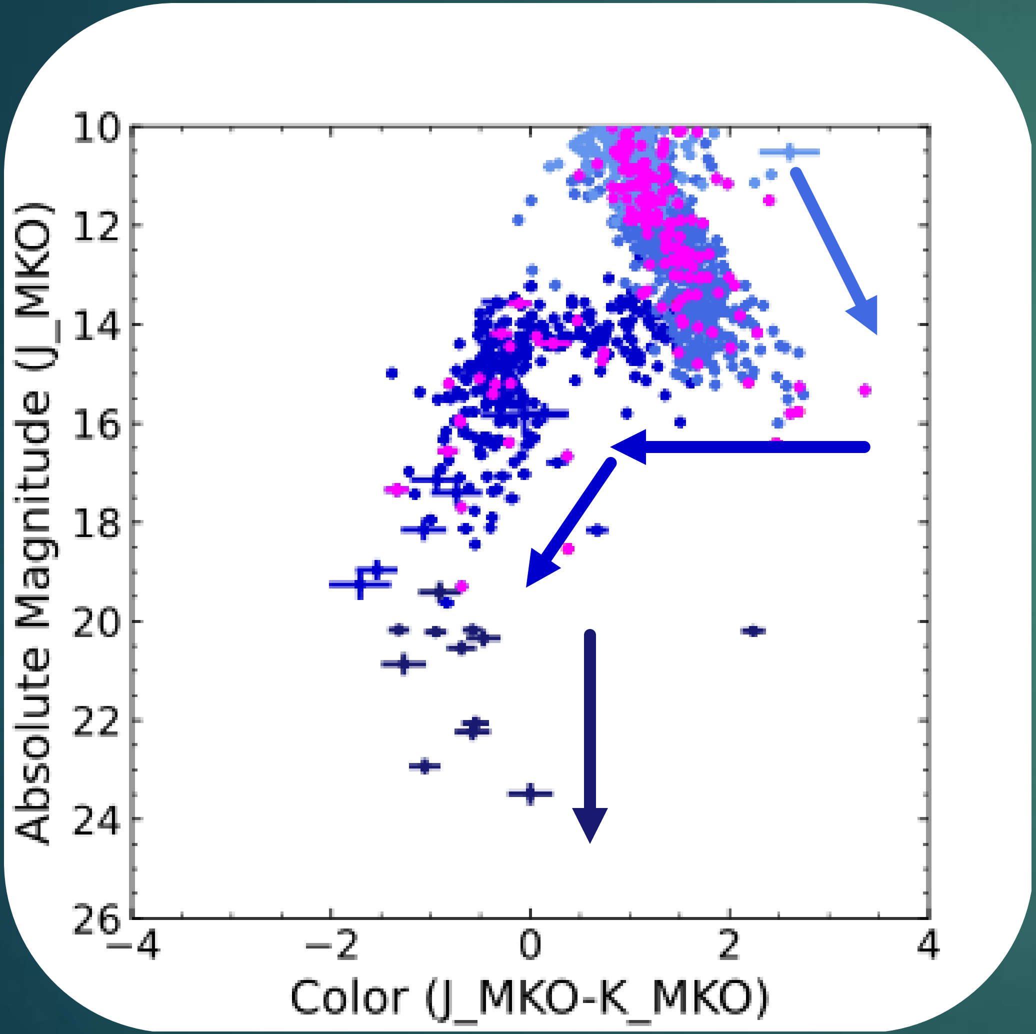

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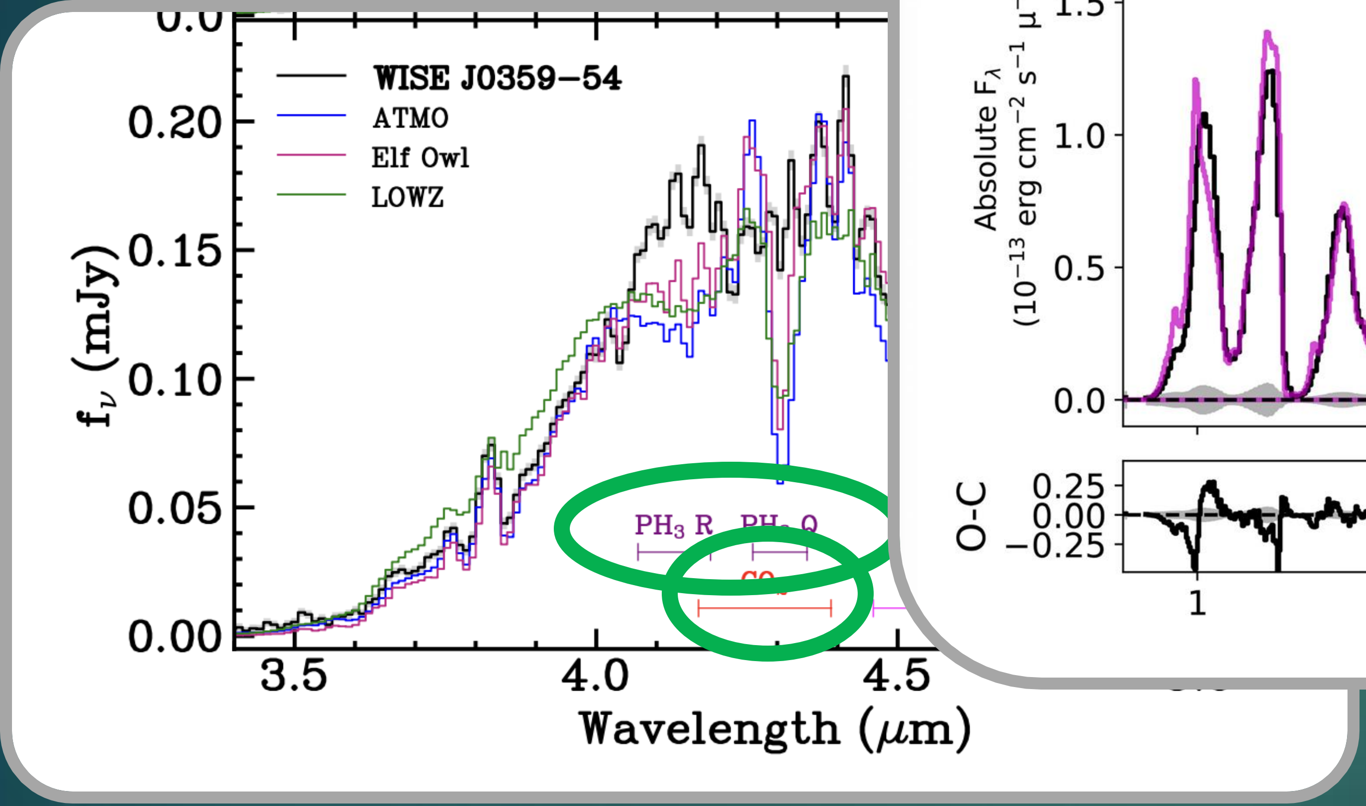
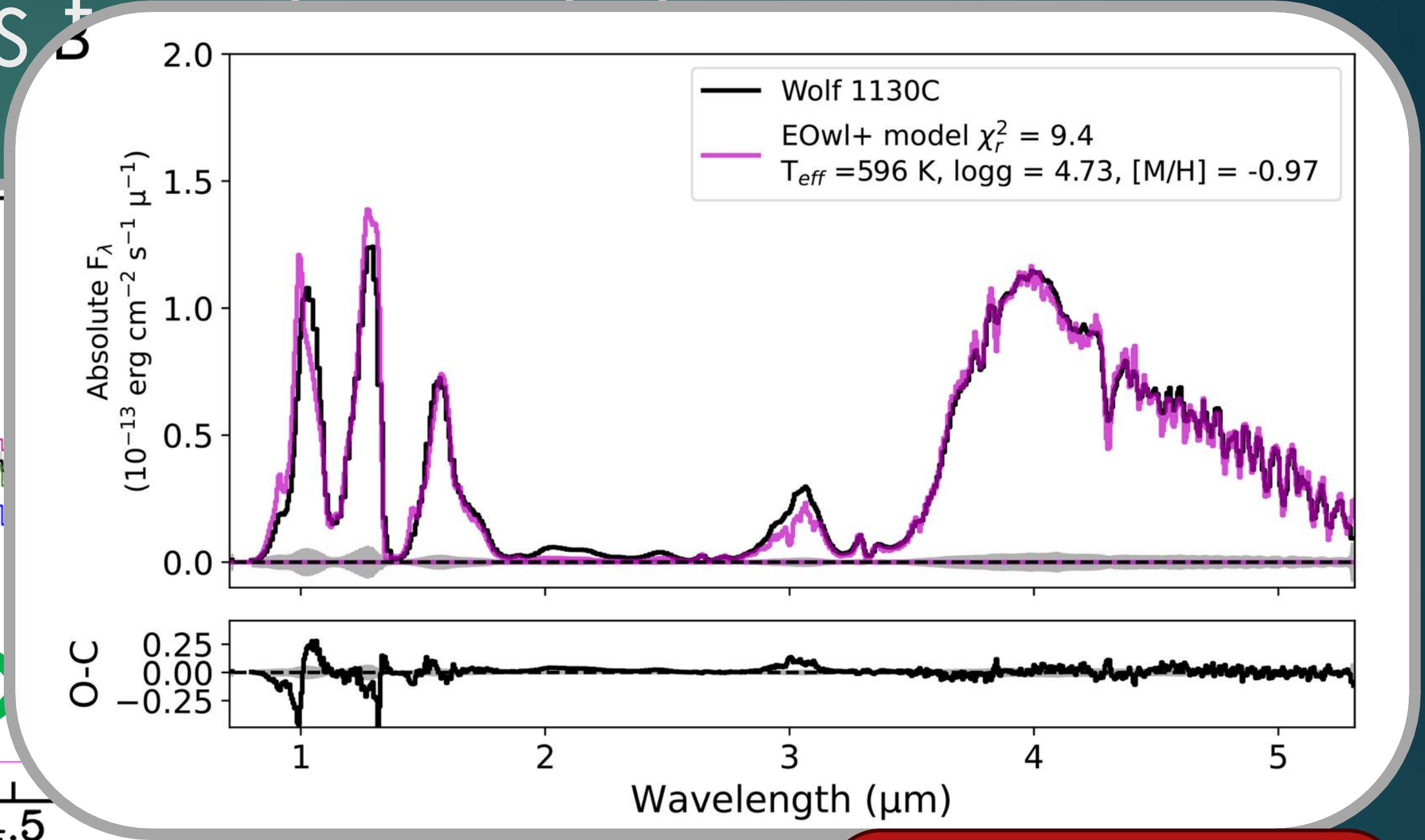
Over/Under-prediction of molecular abundances helps f

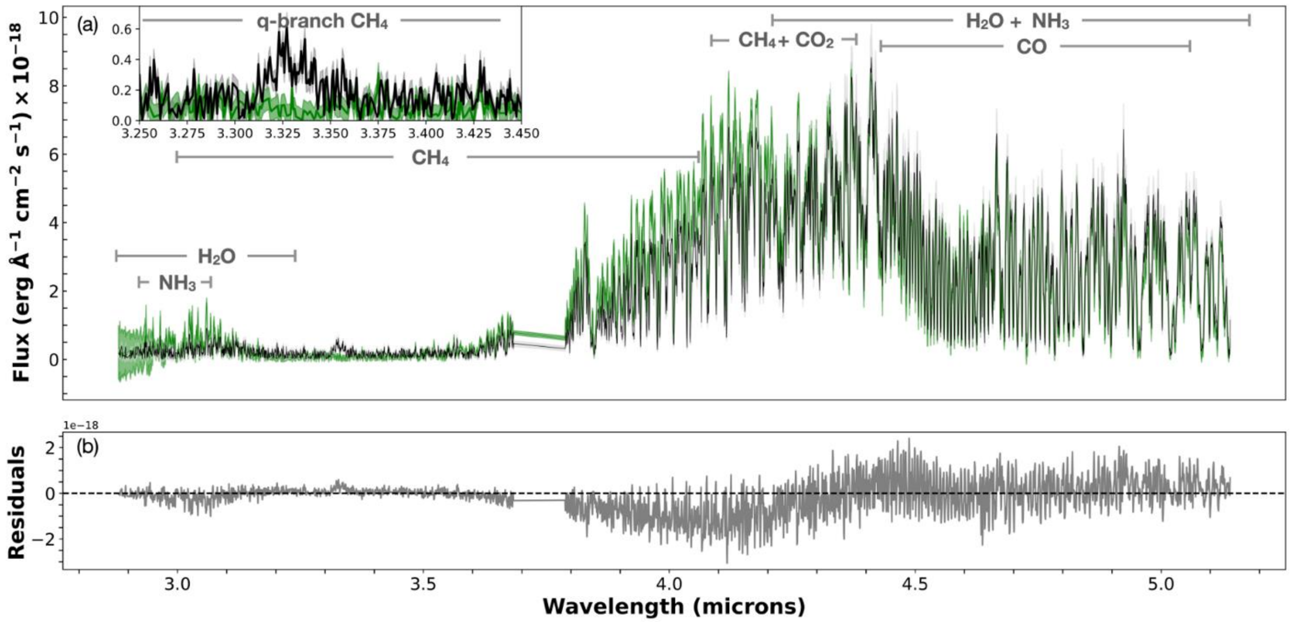




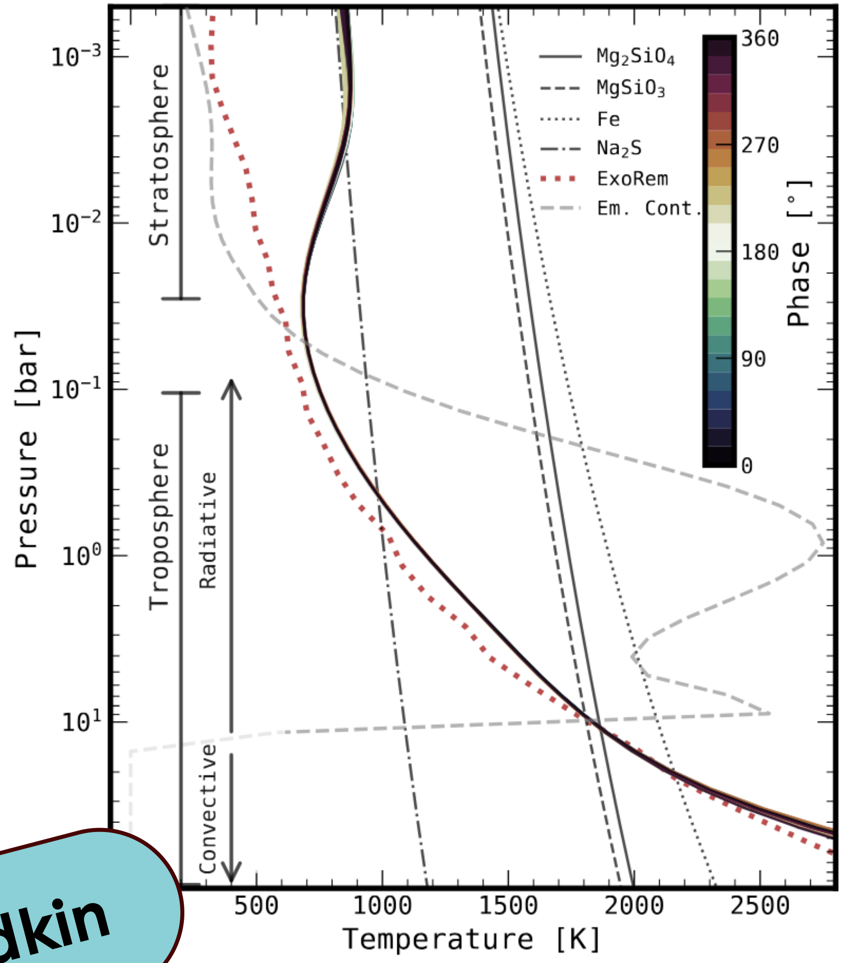
Beiler et al. 2024

but ... ?
Burgasser et al. 2025

Energy processes in cold atmospheres



Faherty et al. 2024

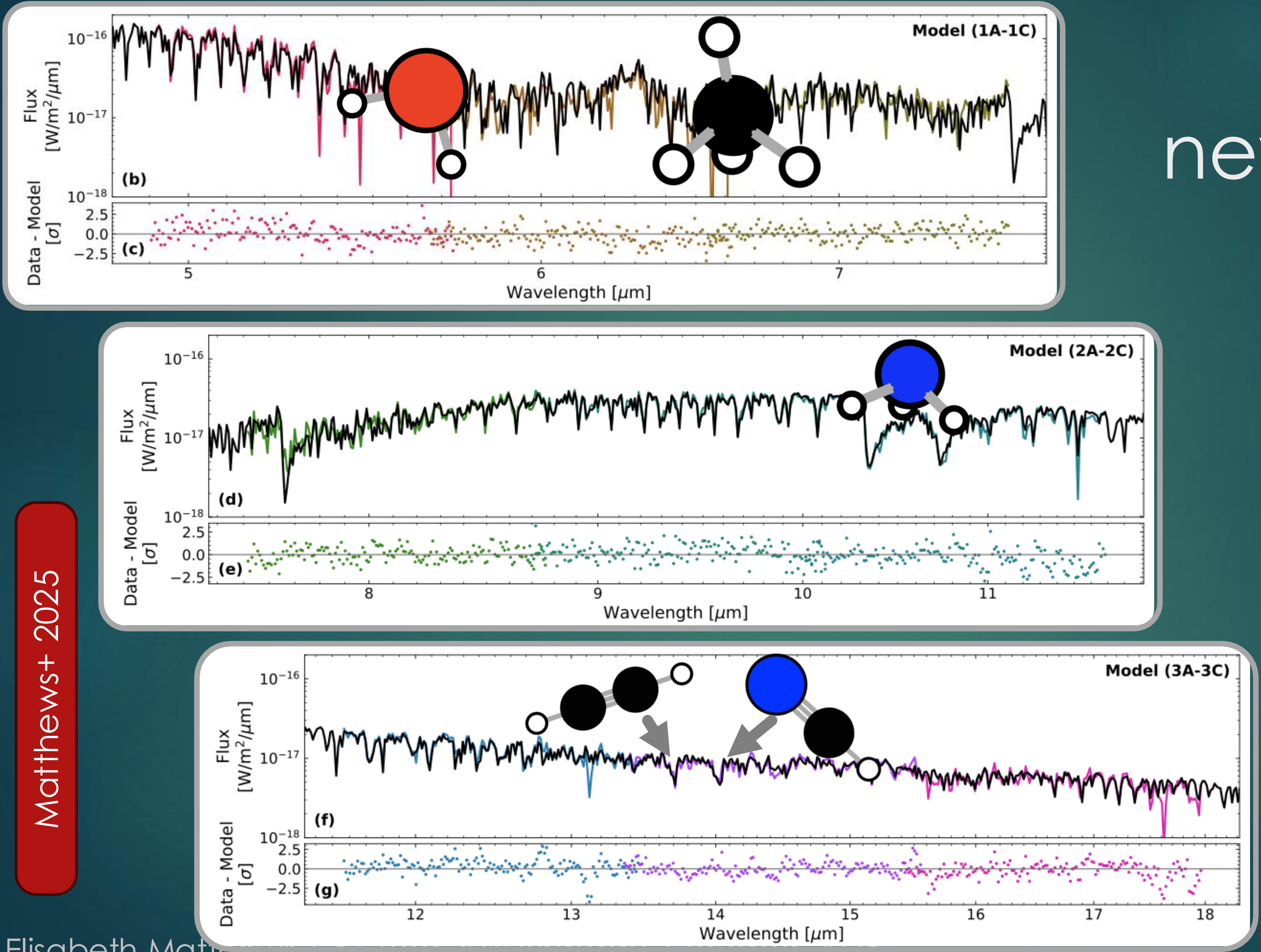


Talk: Evert Nasedkin

Nasedkin et al. 2025

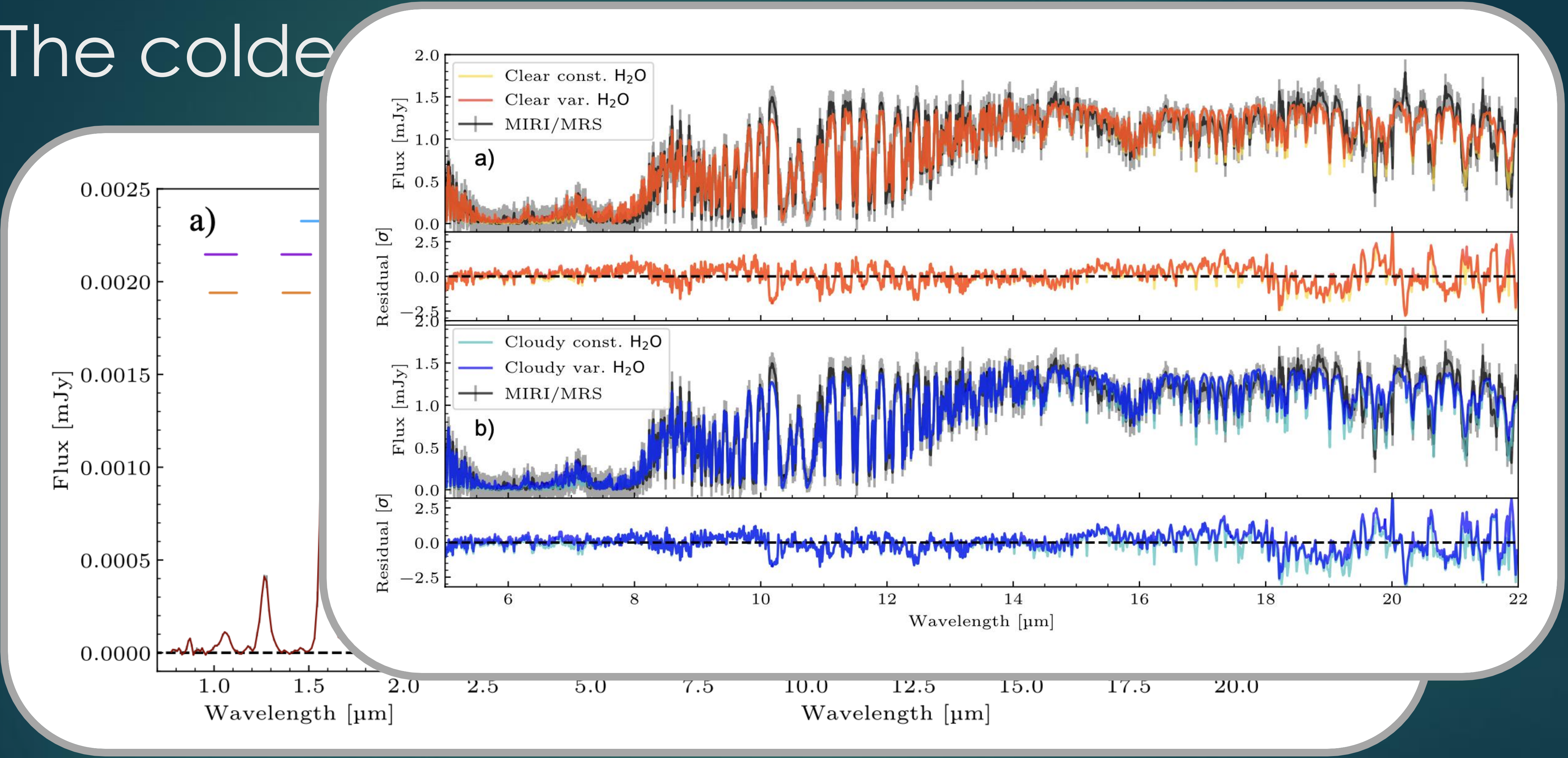
Unexpected new molecules

Matthews+ 2025



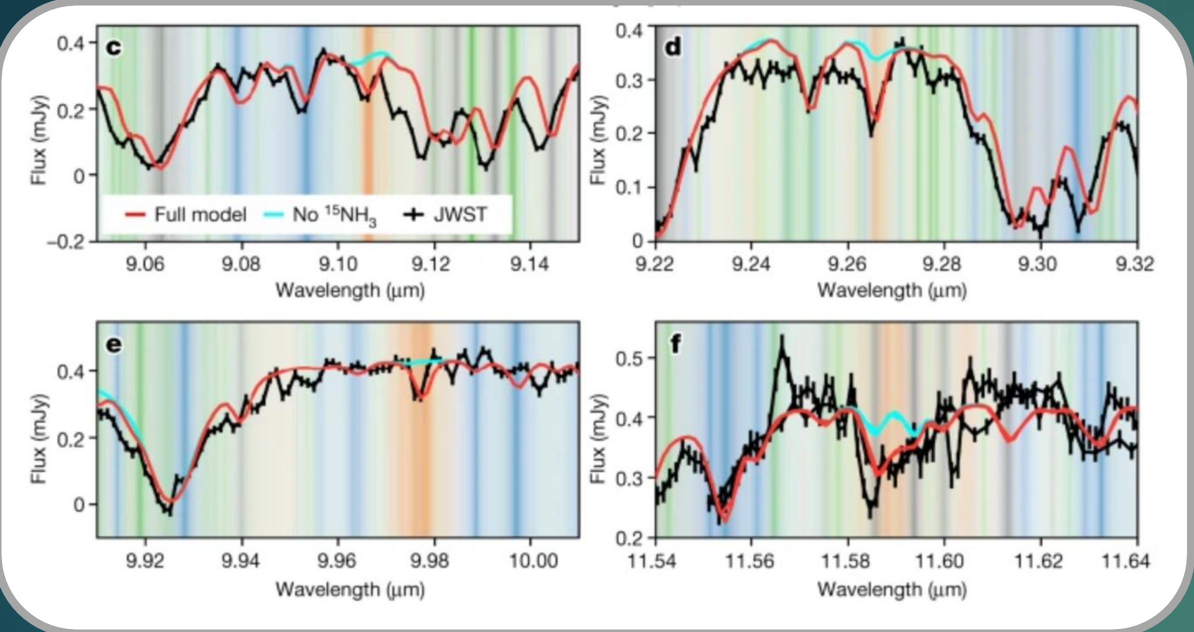
Retrieval with **petitRADTRANS** (Mollière+ 2019, Nasedkin+ 2024)

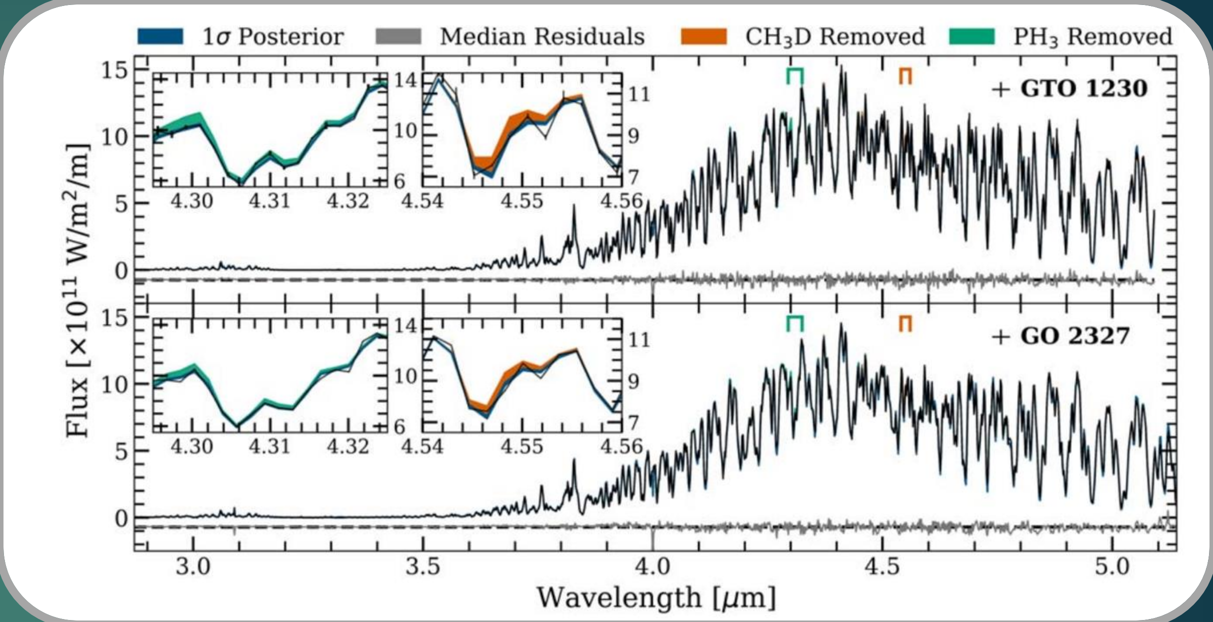
The colde



Kühnle+ 2025 (see also Luhman+ 2024; Rowland+ 2025)

Isotope detections





$^{15}NH_3$ in WISE1828
Barrado & Mollière & Patapis et al. 2023

CH_3D in WISE0855
Barrado & Mollière & Patapis et al. 2023

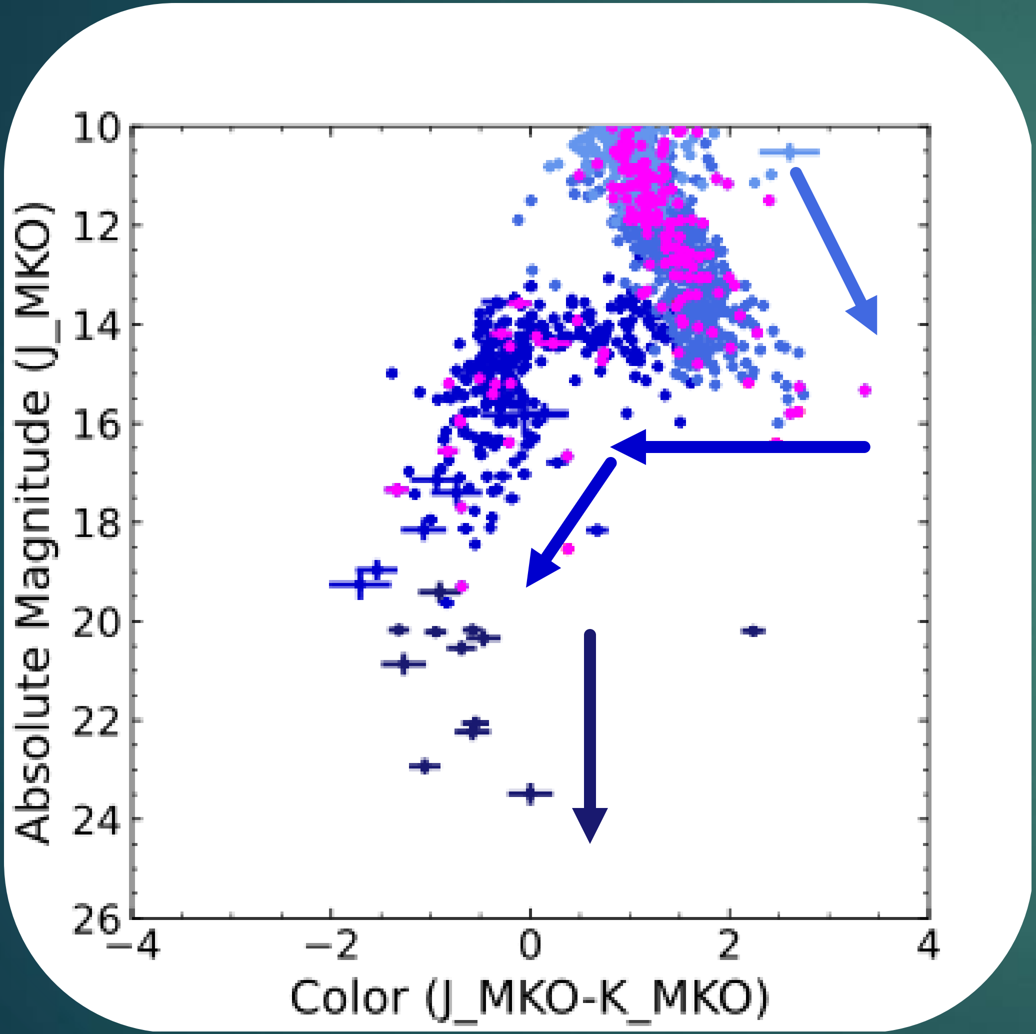
Isotopes are much easier to detect in colder atmospheres (e.g. Mollière & Snellen 2019, Morley+ 2019, Matthews+ 2025)

Takeaway: free-floating objects are an excellent laboratory to test atmosphere models

Conclusions

- We are characterizing “warm” atmospheres in detail, and using these to test formation models
- New atmospheric data is high quality, and is challenging atmosphere models
- We are just beginning to study the atmospheres of <500K planets, mostly with JWST
- Brown dwarfs provide an ideal laboratory to test our understanding of atmospheric physics

Putting everything on a CMD



L dwarfs: 22

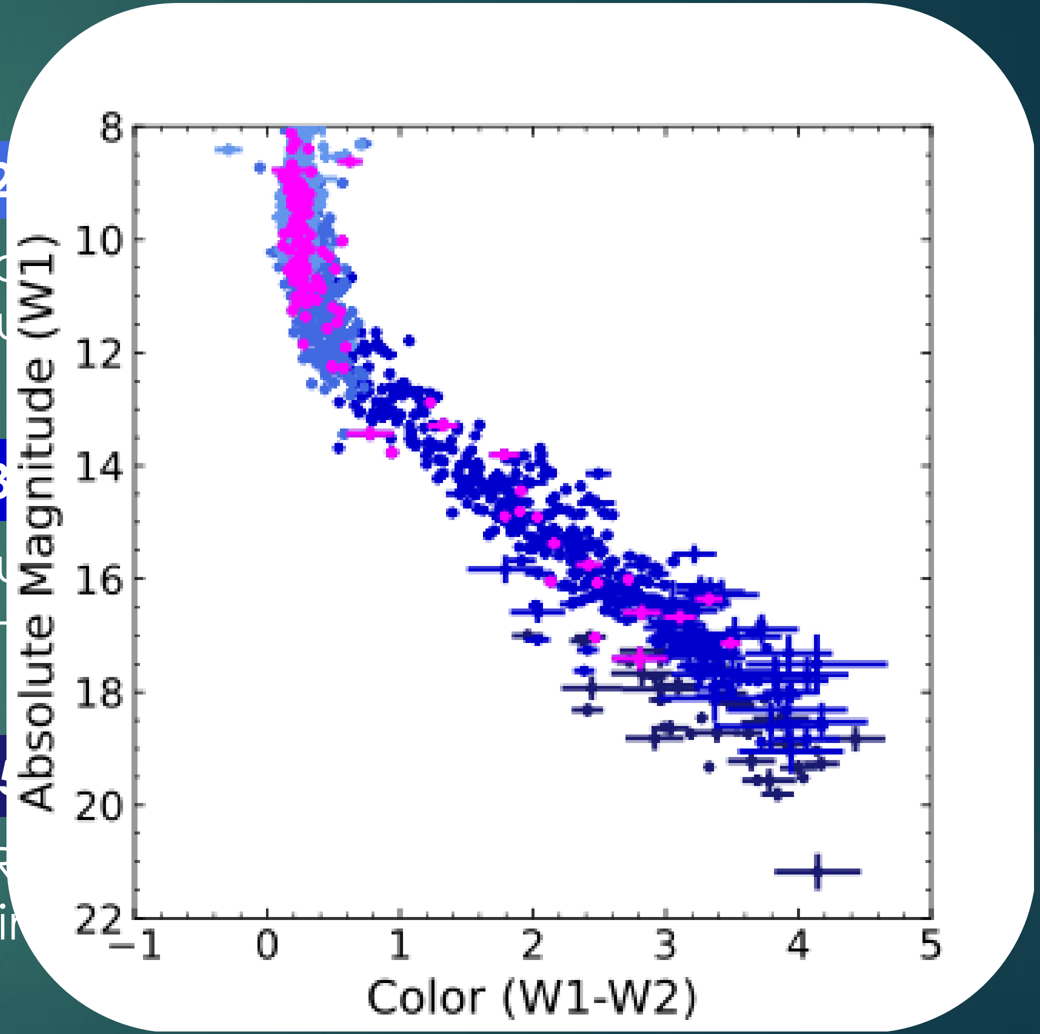
Warm atmo
Silicate clou

T dwarfs: 13

Silicate clou
Deep H_2O -

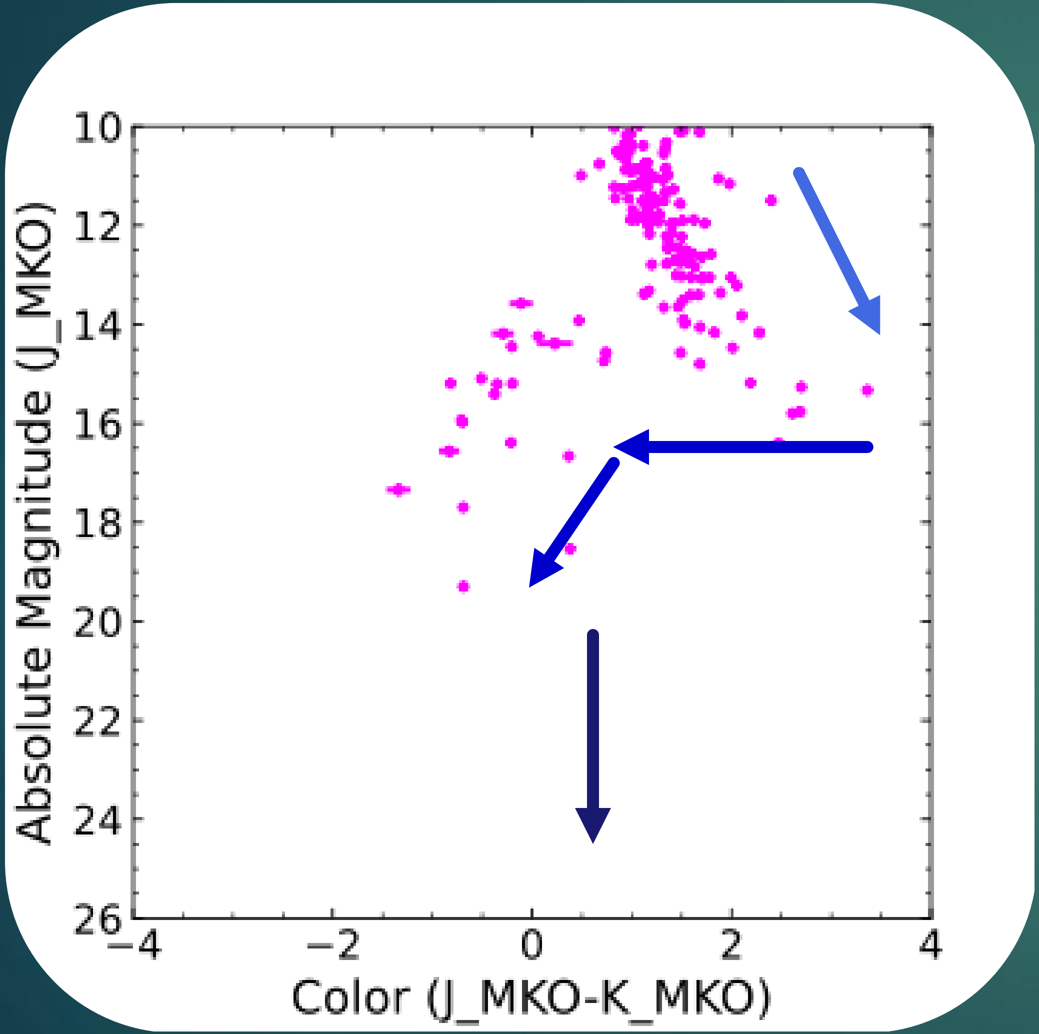
Y dwarfs: <

Few near-IR
NH_3 emergi



data: UltraCool Sheet

Putting everything on a CMD



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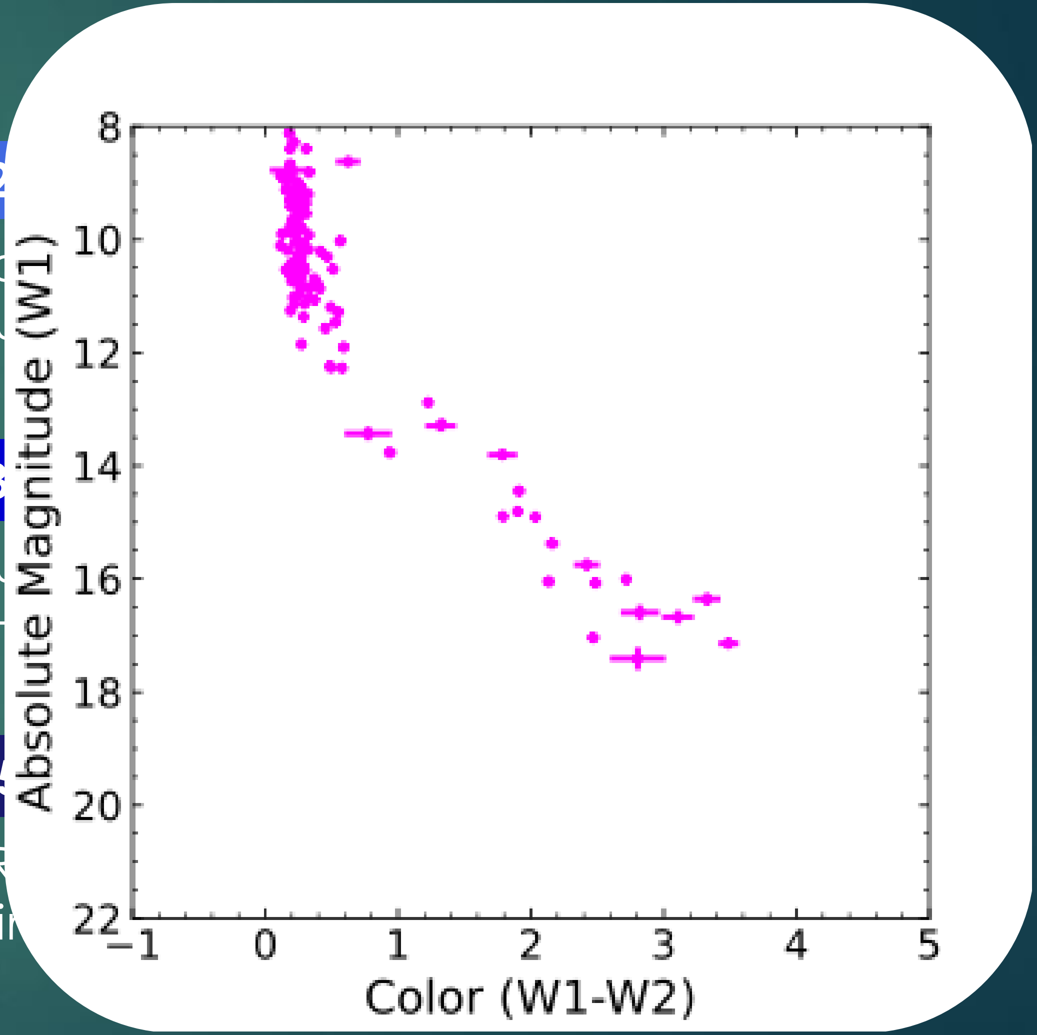
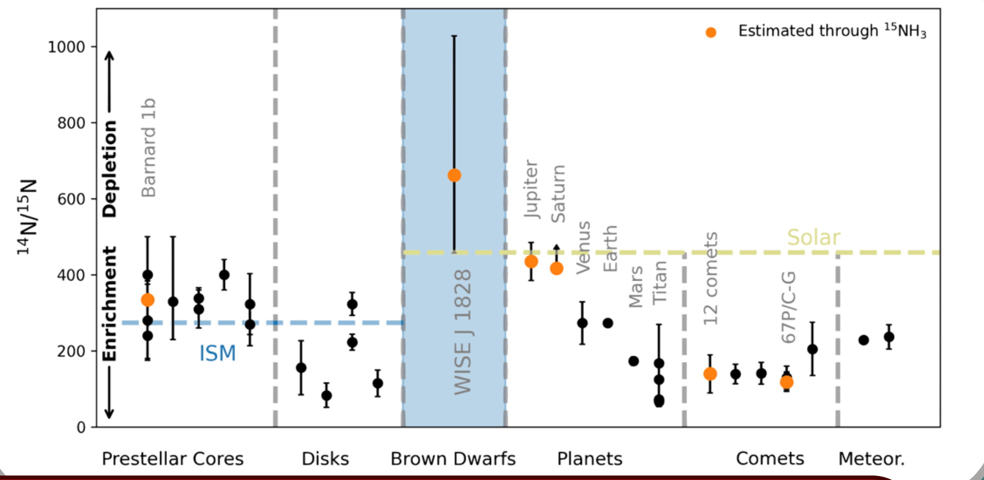


data: UltraCool Sheet

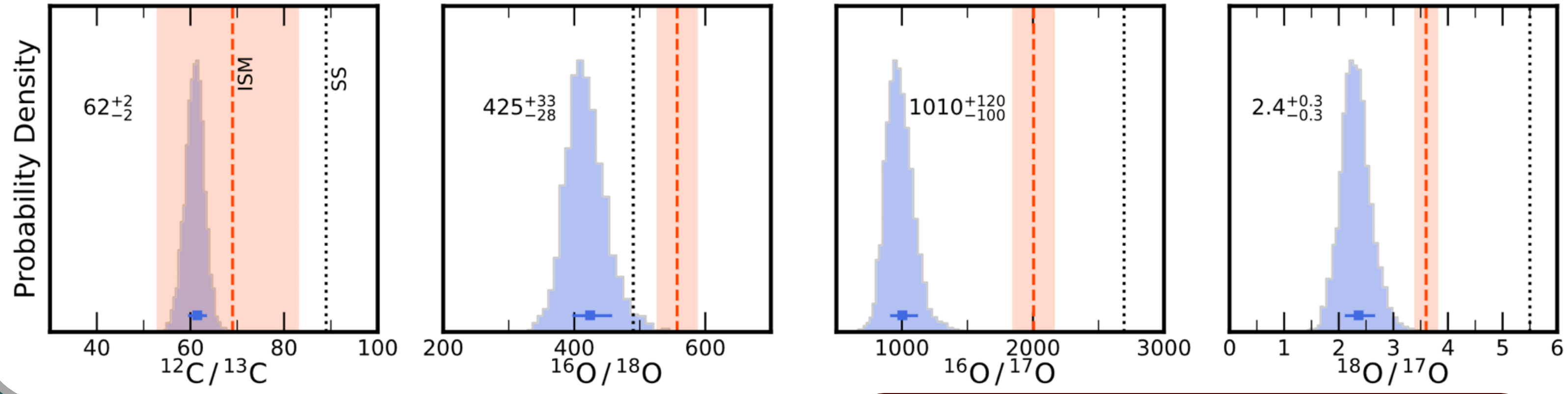
Exoplanet observations in the JWST era

Elisabeth Matthews
matthews@mpia.de

Early JWST isotope ratio measurements



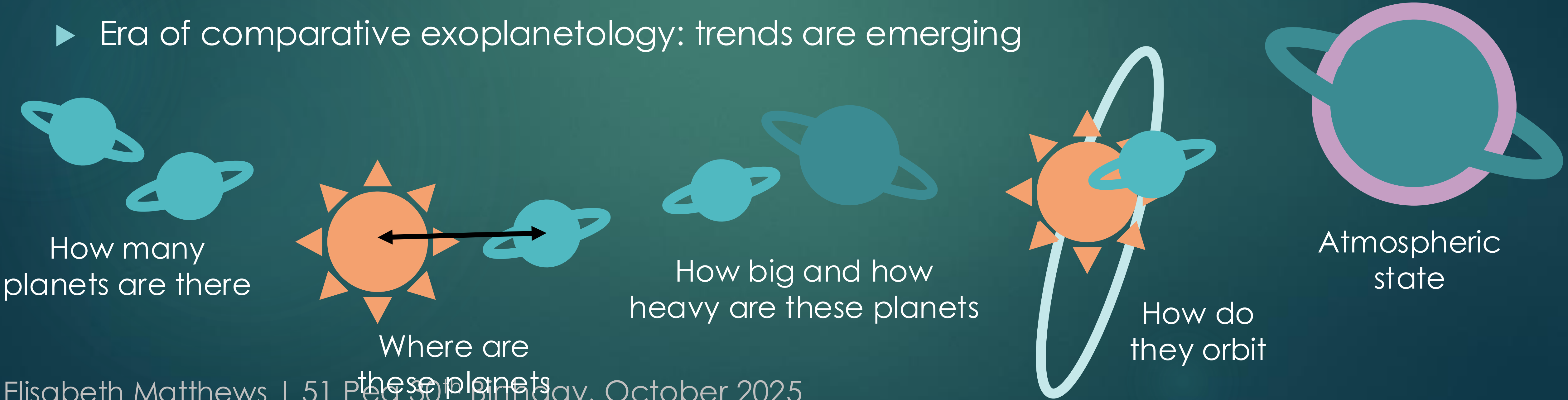
$^{15}NH_3$: Barrado & Mollière & Patapis et al. 2023



^{13}C, ^{17}O, ^{18}O: Gandhi+ 2024

Conclusions

- Only some types of planets have accessible atmospheres
- Exoplanets systems are complex, and changing
  - Want to build a multidimensional picture to relate formation & present day
- JWST is transformative
  - better spectra (SNR, wavelength coverage)
  - different types of planets
- But data is hard, and models are hard: be careful!
- Era of comparative exoplanetology: trends are emerging



CMD backup slide