Exoplanetary Atmospheres with the ELTs

Mercedes López-Morales

Image Credit: M. Weiss / CfA

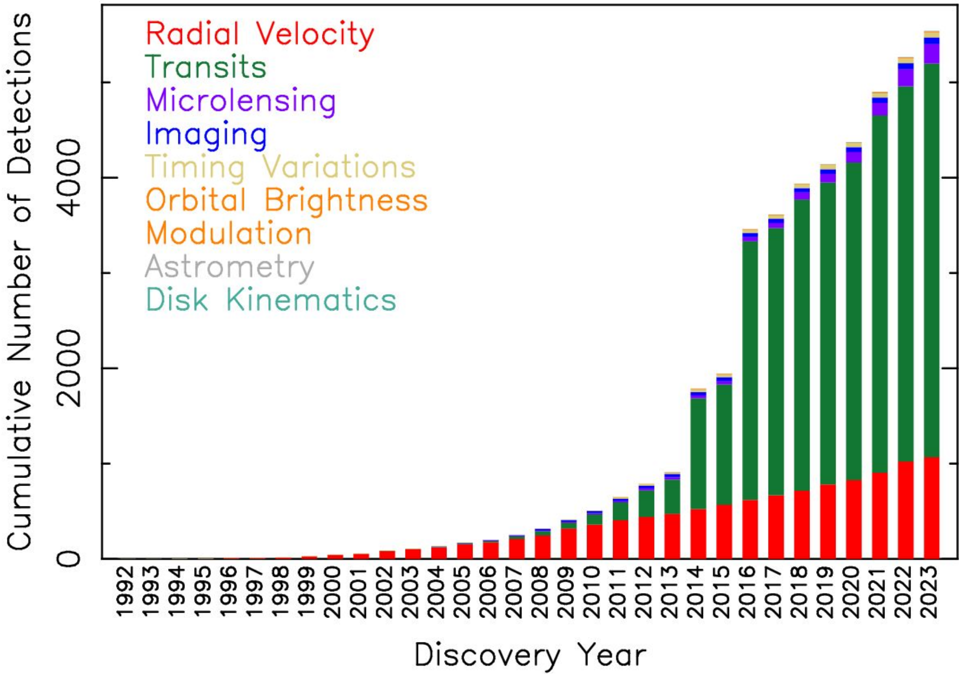
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

<u>As of Today</u>:

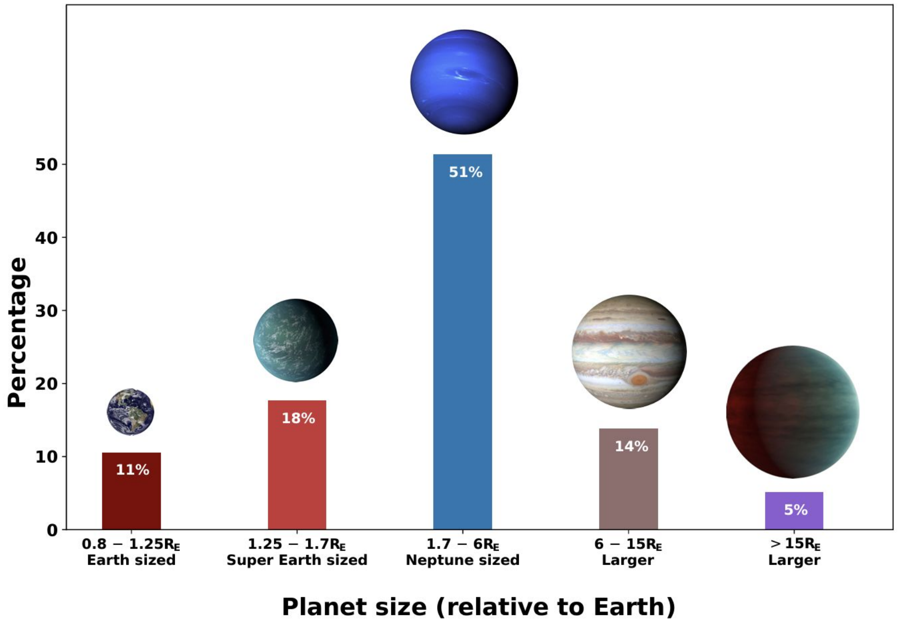
Over 5,500 exoplanets confirmed around other stars
About 1605 of them are rocky
About 610 are Earth-sized

The majority of them a bit too hot.

Cumulative confirmed exoplanets per year

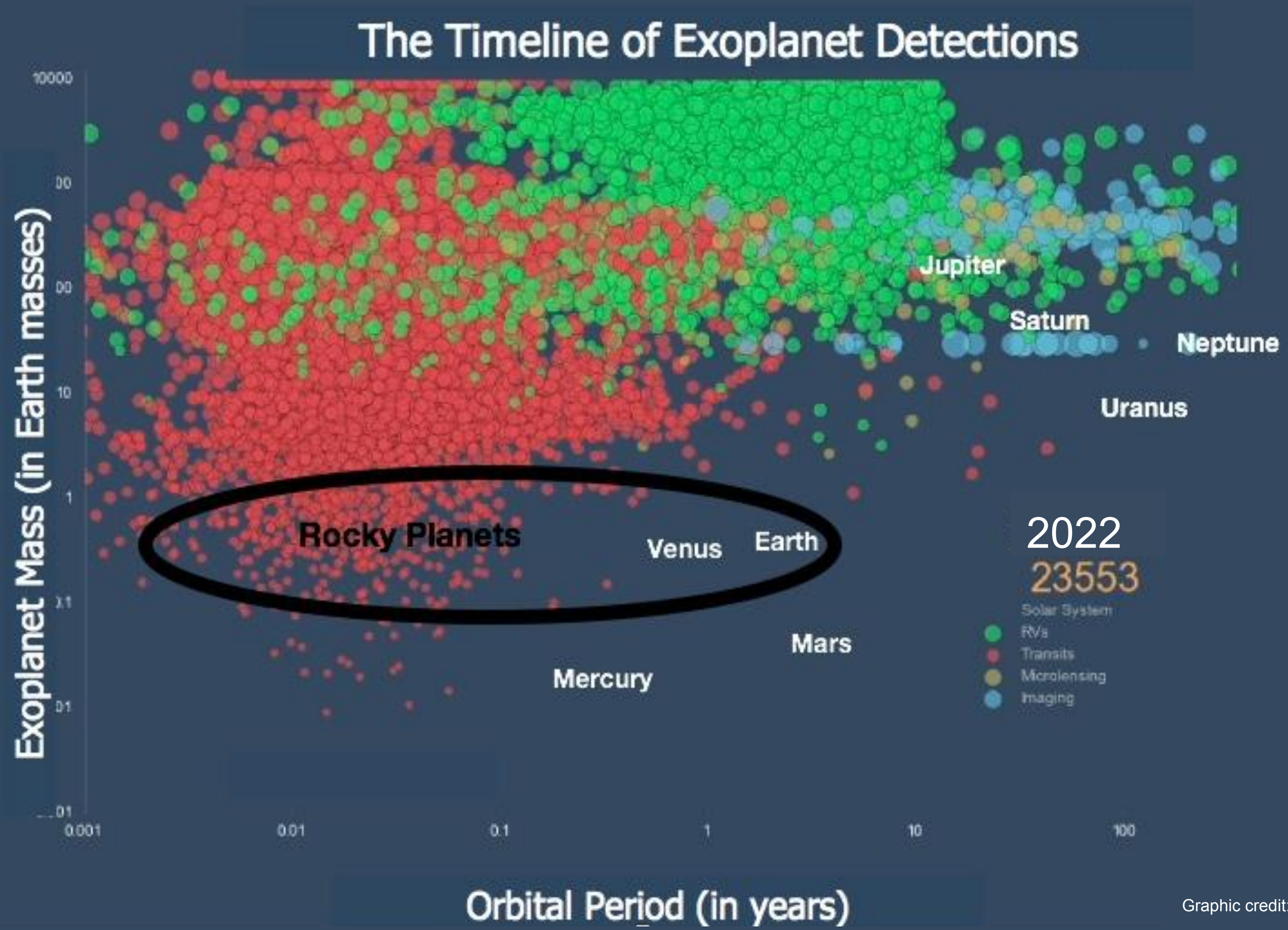


Confirmed exoplanets per size

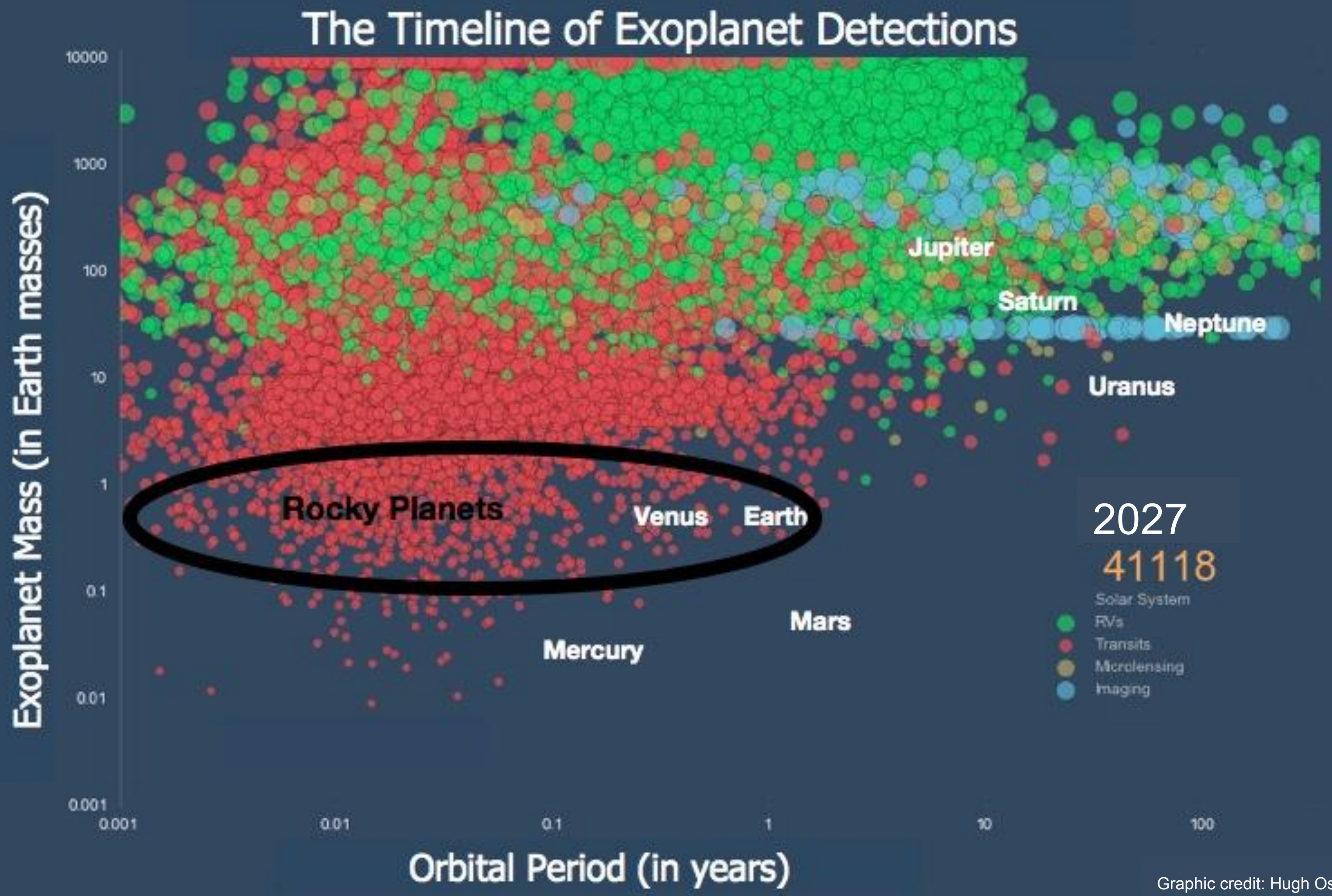


exoplanetarchive.ipac.caltech.edu

Atreya+2020



Graphic credit: Hugh Osborn



Graphic credit: Hugh Osborn

Dedicated Exoplanet Missions

Exoplanet Sensitive Missions

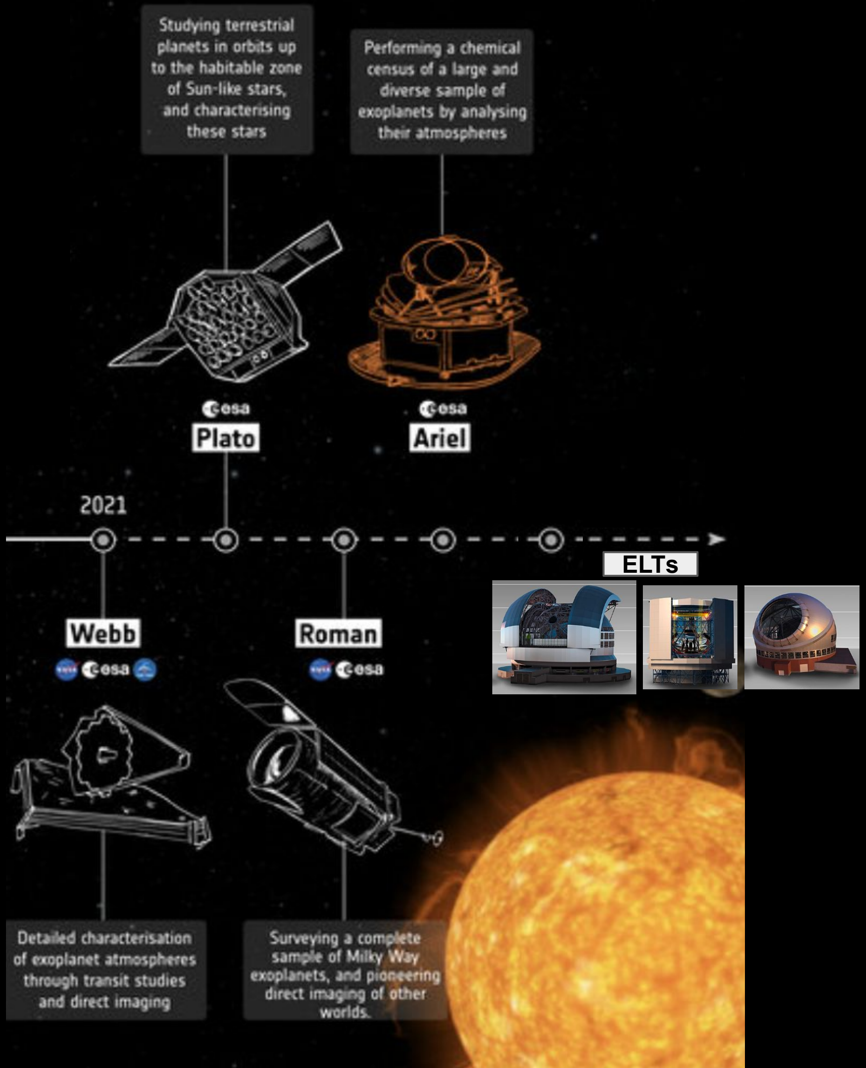
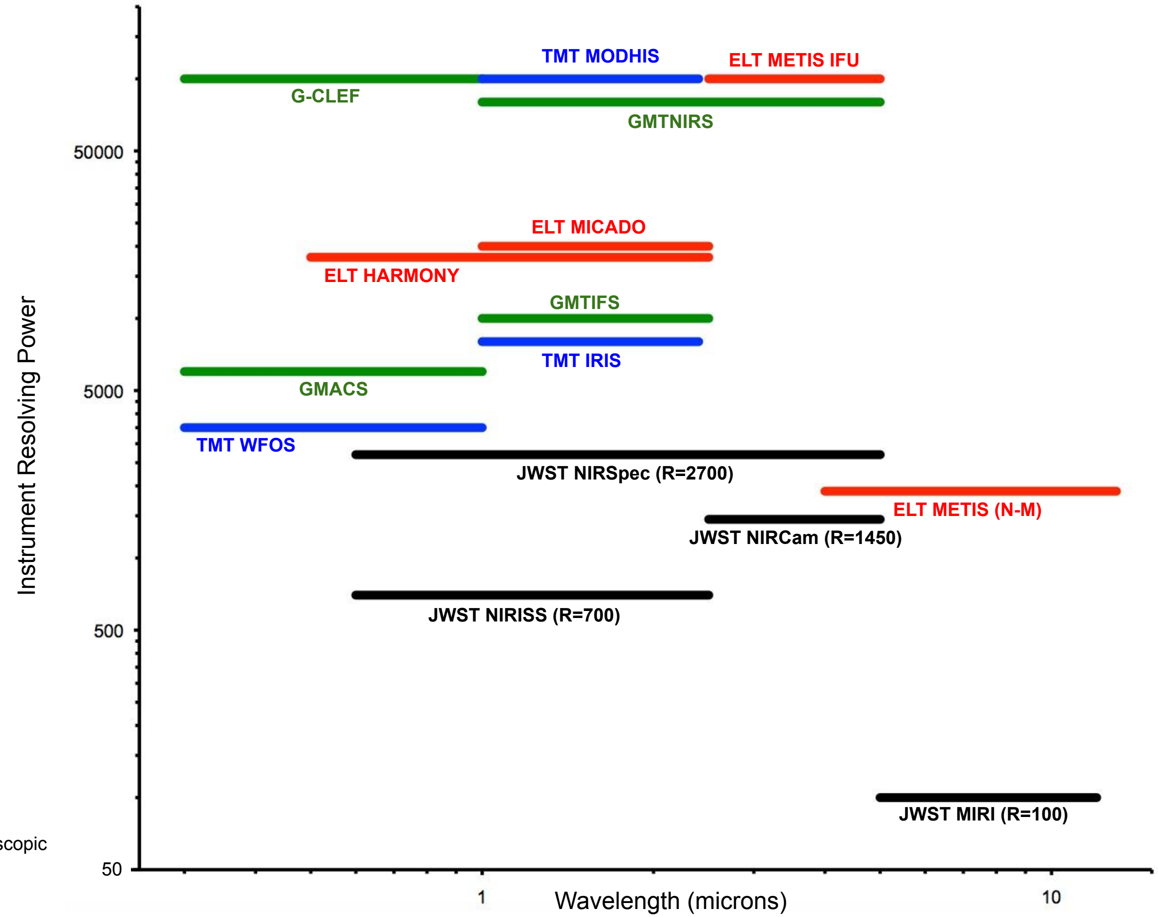


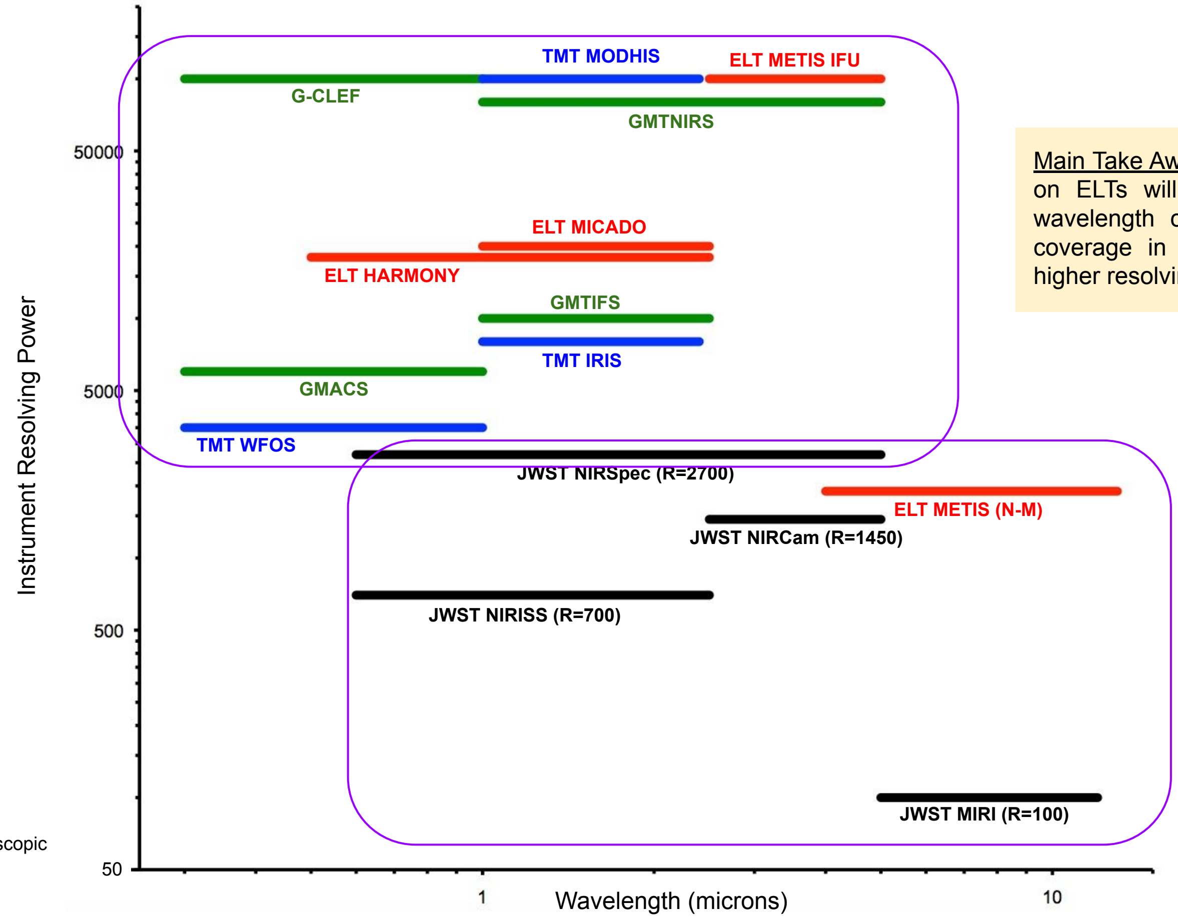
Image Credit: ESA

Expected 1st Generation ELTs Instrument Capabilities vs JWST*



*Only showing JWST spectroscopic modes used for exoplanets

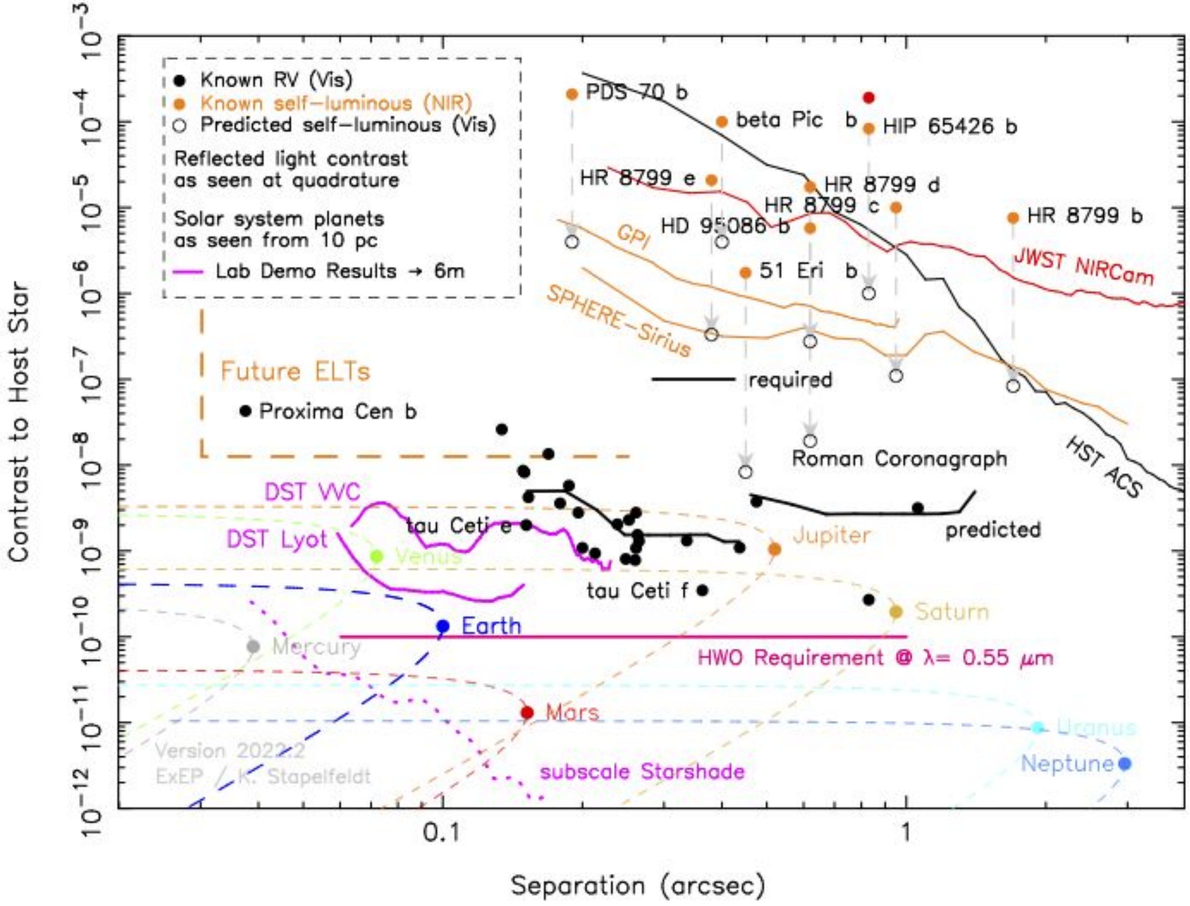
Expected 1st Generation ELTs Instrument Capabilities vs JWST*



Main Take Away: For exoplanets, instrumentation on ELTs will provide similar IR spectroscopic wavelength coverage as JWST, but additional coverage in the optical and up to 30+ times higher resolving power.

*Only showing JWST spectroscopic modes used for exoplanets

Expected 1st Generation ELTs Instrument Capabilities vs JWST



<u>Main Take Away 2</u>: For exoplanets, instrumentation on ELTs will also provide imaging contrast 100 mines better than JWST, and image resolution 10+ times larger than JWST.

Figure Credit: https://exoplanets.nasa.gov/exep/technology/technology-overview/

Approved exoplanet programs on JWST[1]:

Transiting Planets: 3218.66 hours

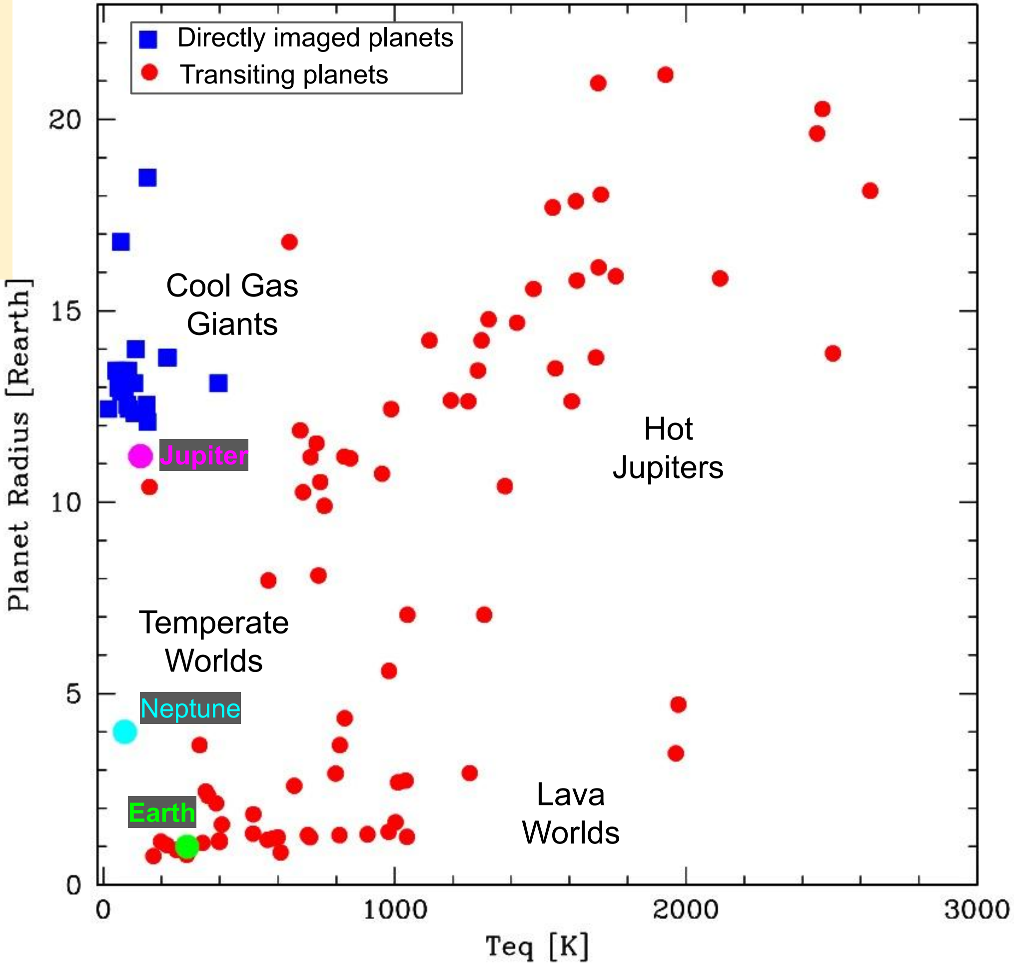
Direct Imaging Planets: 858.08 hours

Source: TrExoLiSTS:JWST and DIExoLISTS:JWST by N. Nikolov (nnikolov@stsci.edu)

[1] **Includes approved ERS, GTO, and Cycle 1 and 2 GO programs**. Time includes overheads

- About 120 transiting and 20 directly imaged exoplanets allocated observations between ERS, GTO, and Cycle 1 and 2 GO programs.
- 25% of GO time currently being allocated to exoplanets.

For reference: The atmospheres of about 60 planets had been studied before the launch of JWST, between 2002 and 2021

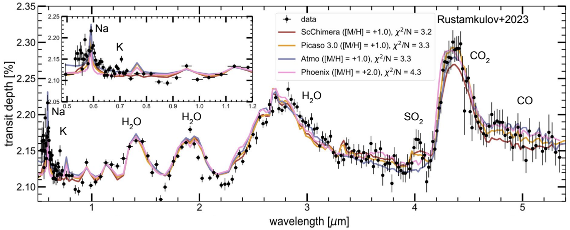


JWST results from transiting planets so far

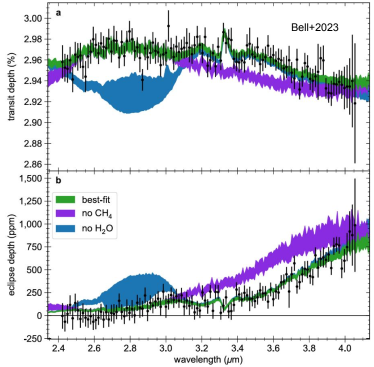
Gas Giants

Esparza-Borges+2023 recently reported evidence of ^{13+}C

Detection of CO_2, H_2O, CO, SO_2, Na, K in WASP-39b (R_p = 1.3 R_j ; T_{eq}=1120K)

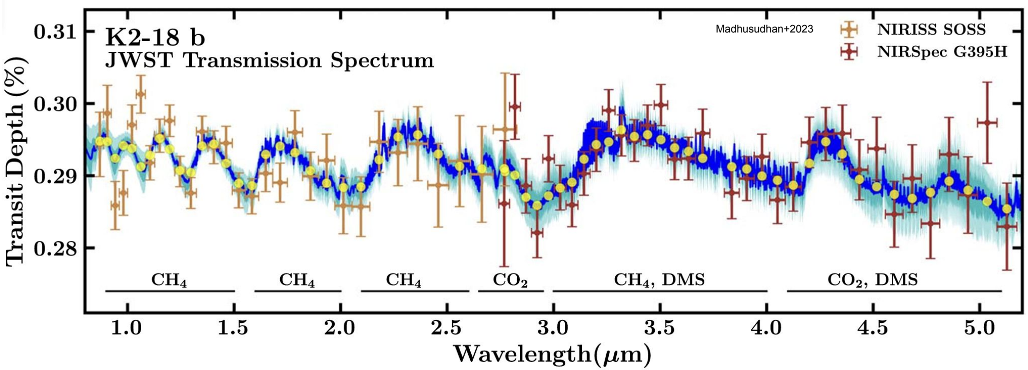


Detection of H_2O, CH_4 in WASP-80b (R_p = 1.0 R_j ; T_{eq}=827K)



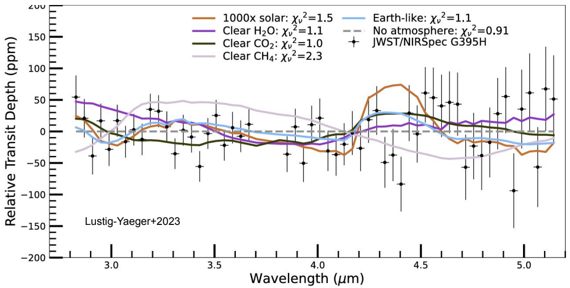
Sub-Neptunes to Super-Earths

Detection of CH_4, CO_2 in K2-18b (R_p = 2.4 R_e; T_{eq}= 282K)

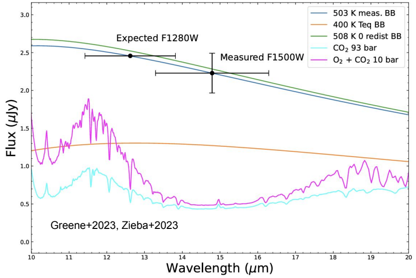


Rocky Planets

Strong constraints on LHS-475b (R_p = 1.0 R_e; T_{eq}= 586K)

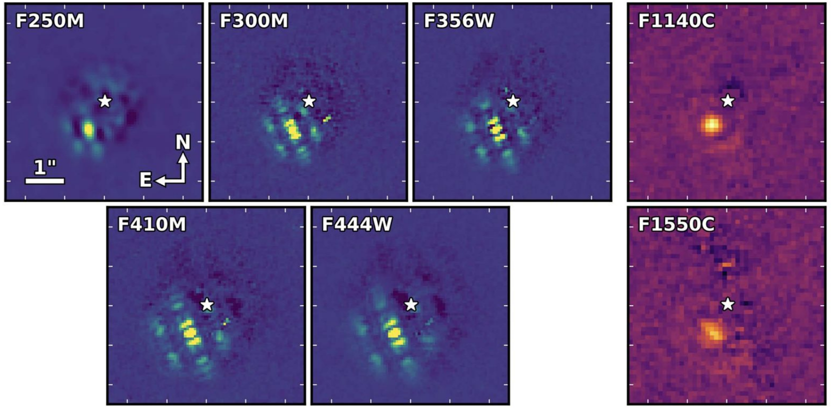


Trappist-1b/1c have no atmospheres (R_p = 1.1 R_e; T_{eq}= 400k, 340K)



JWST results from directly imaged planets so far

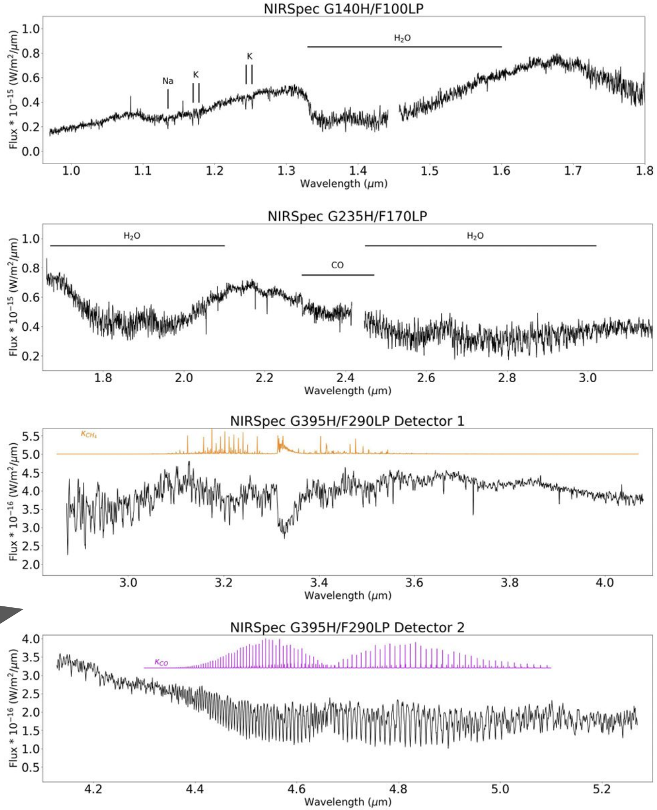
Direct detection of HIP65426b
(R_p = 1.5R_j ; T_{eq}= 60K ; a = 92 AU)
with NIRCam and MIRI



Carter+2023

Sensitive to 0.3M_J beyond ~100au

Spectrum of VHS 1256 b
(M_p < 20M_j ; a = 150 AU)
with NIRSPEC and MIRI



Gandhi+2023 recently detected ^{13}C, ^{18}O, and ^{17}O

Miles+2023

Where will JWST exoplanet studies be when the ELTs go online?

Assuming exoplanets continue to receive 25% of the GO time (75% for transits; 25% for directly imaged planets) and 6000h per GO Cycle, **by 2029 JWST will have observed**:

- **About 330 transiting planets**
- **About 60 directly imaged planets**

Current open questions that will likely be answered by then:

- Exoplanet atmospheric metallicity distribution (like the Solar System's or not?)
- Is atmospheric C/O a good tracer of planet migration or not?
- Where is the methane?
- Do terrestrial planets around M-dwarfs have atmospheres?

Still open questions: Atmospheric properties of small planets and Isotope ratios

ELTs and Isotope Ratios in Exoplanets

JWST:

- CO isotopologues in transit observation of WASP-39b (Esparza-Borges+2023)
- ^{13}C, ^{18}O, and ^{17}O in direct imaging observation of VHS-1256b (Gandhi+2023)

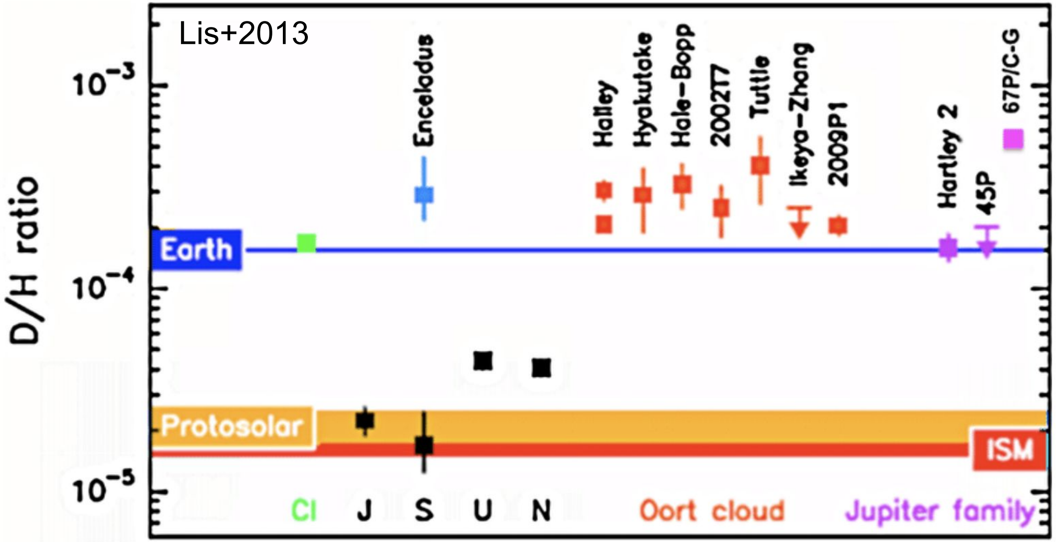
Ground-based:

- $^{12}C/^{13}C$ constraint in high-resolution emission observations of WASP-77b with IGRINS (Line+2021)
- $^{12}C/^{13}C$ constraint in direct imaging observations of TYC 8998-760-1 b with SINFONI (Zhang+2021)

Why Isotope Ratios?

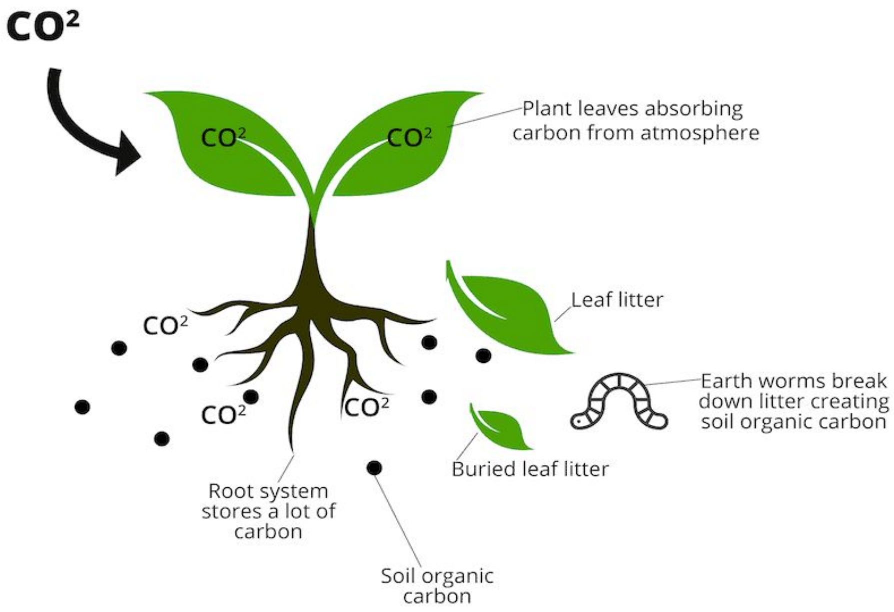
D/H isotope ratios are informative tracers of planet formation conditions and their evolution history.

We know that Earth was H-rich because of D/H enrichment



Carbon Isotope Ratios as a Potential Biosignature

Photosynthesis

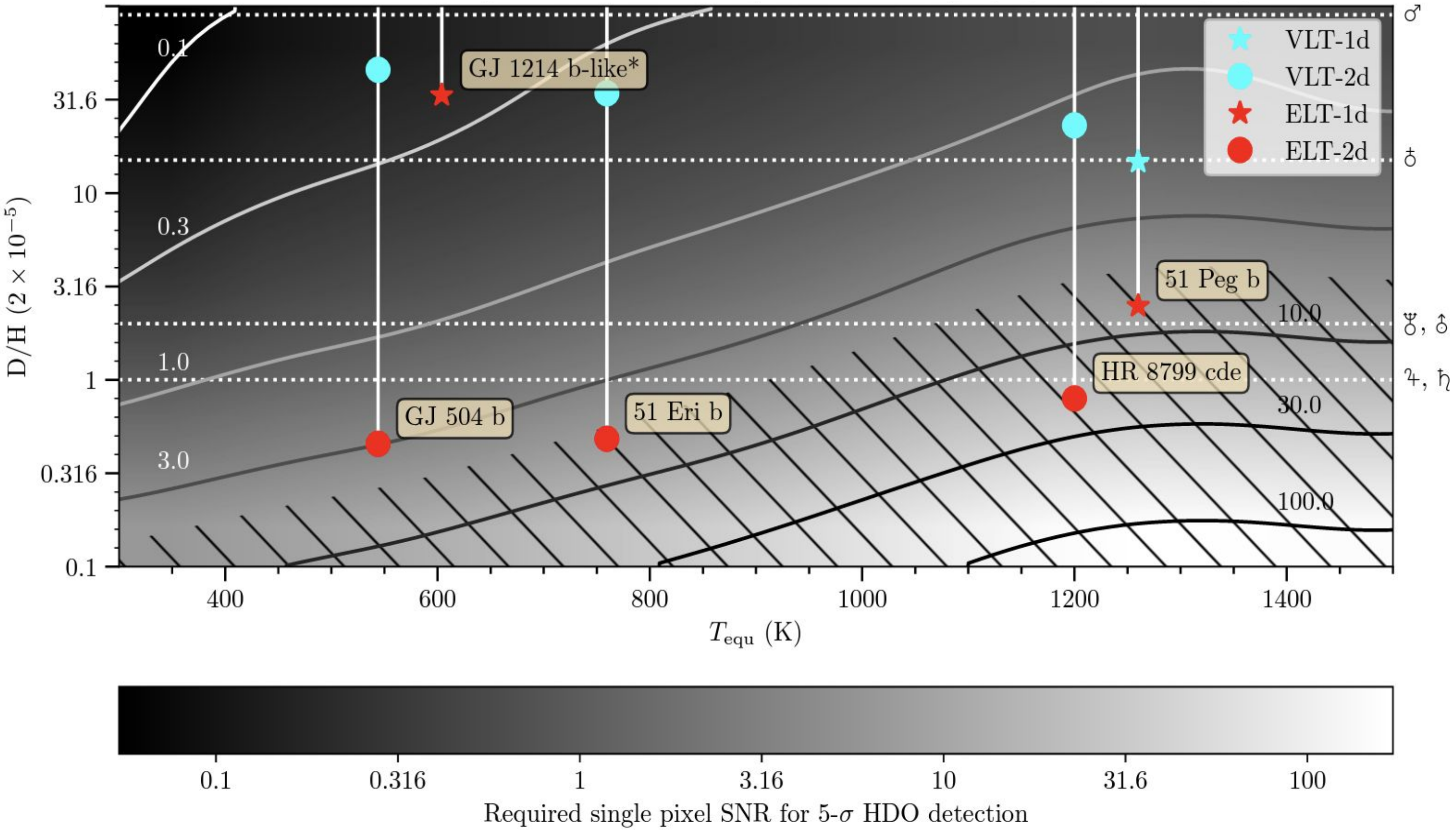


Plants preferentially absorb ^{12}C because is lighter, altering the carbon isotopologue ratios, i.e. $^{12}C/^{12+n}C$, in the atmosphere.

C isotope ratios are already detectable in giant exoplanets with existing large ground-based telescopes (e.g. Line+2021), and JWST (Esparza-Borges+2023), **but we will need ELTs for smaller planets**.

Figure Credit: GreenElement.co.uk

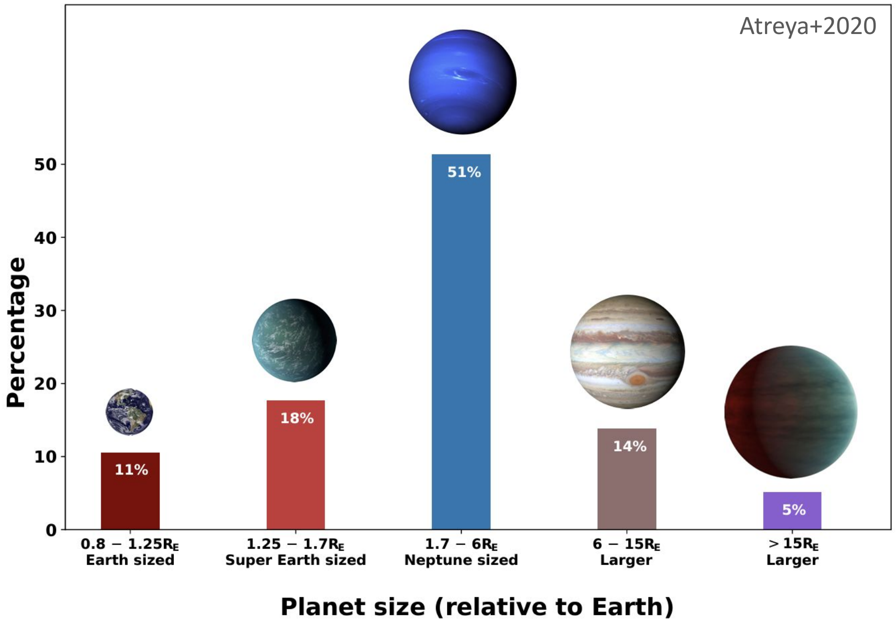
D/H ratio detectability for self-luminous gas giants with ELTs



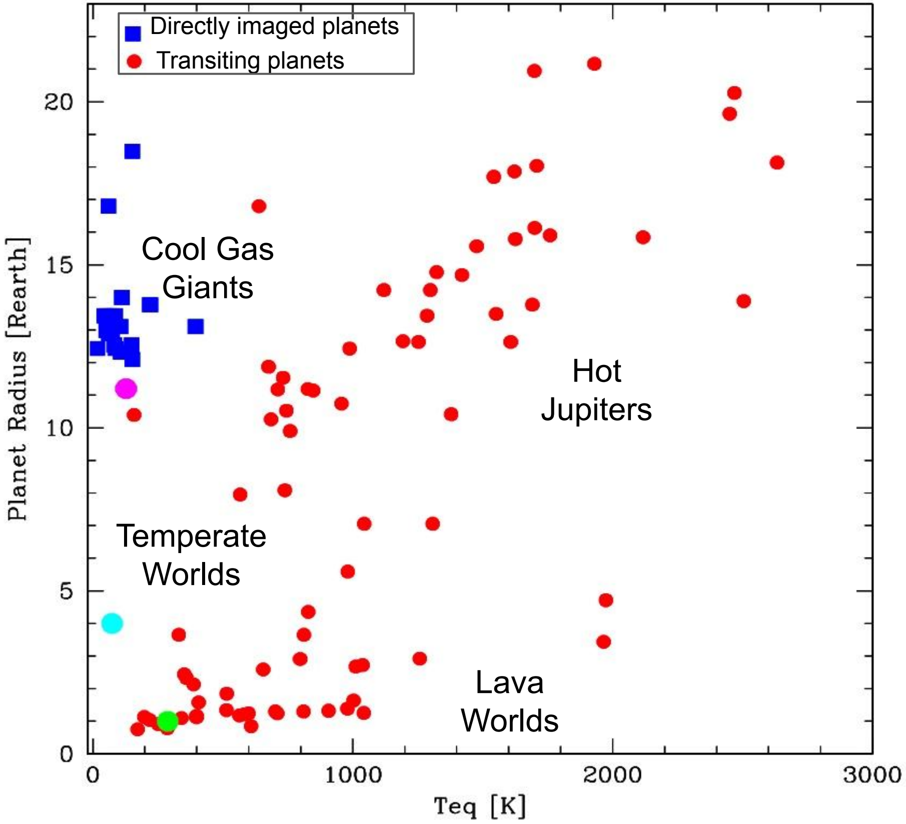
Molliere & Snellen 2019

ELTs and Atmospheres of Small Temperate Planets

Confirmed Exoplanets per Size



Planets Observed with JWST



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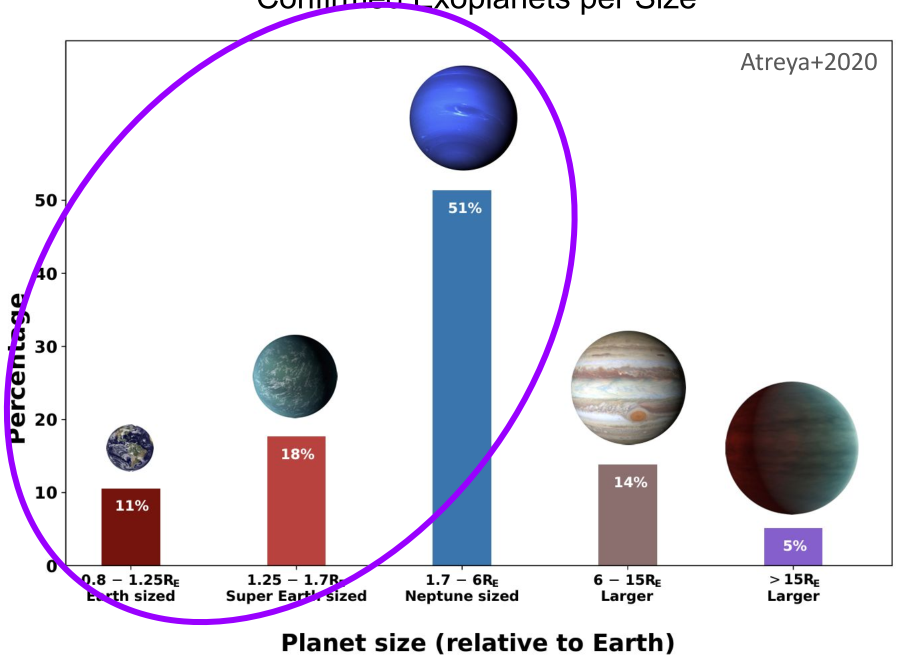

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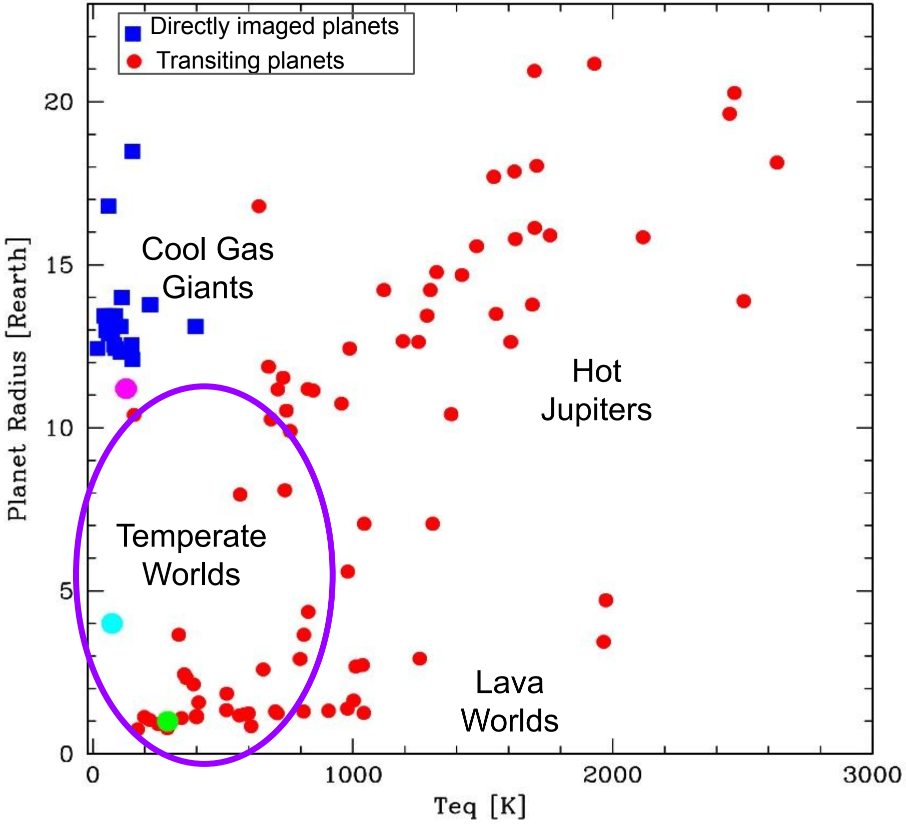
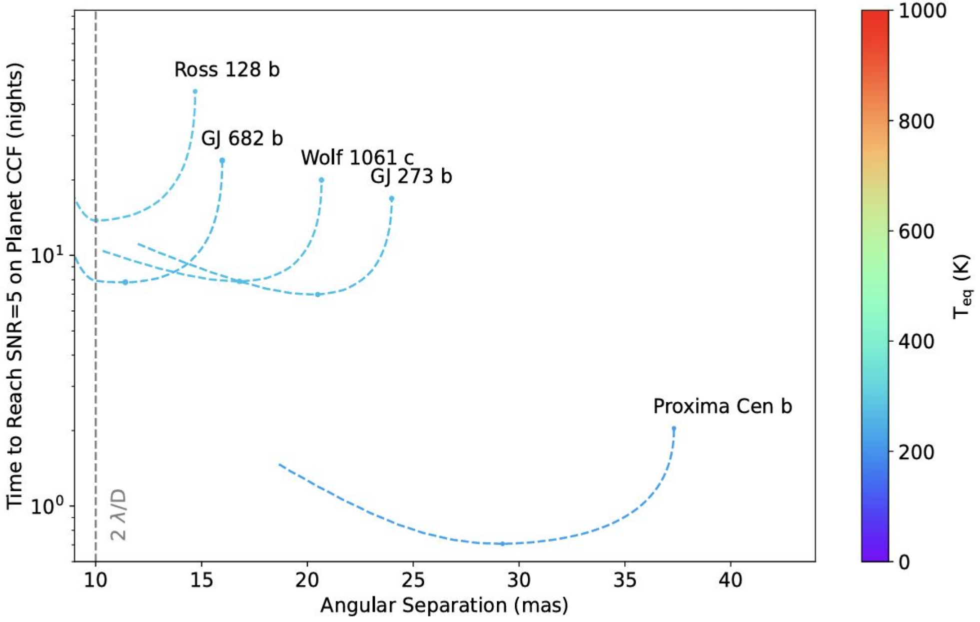
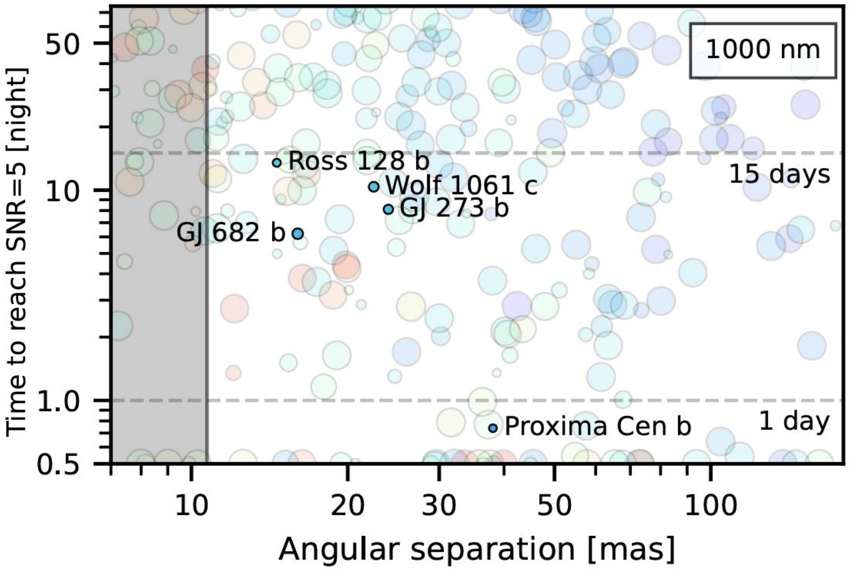


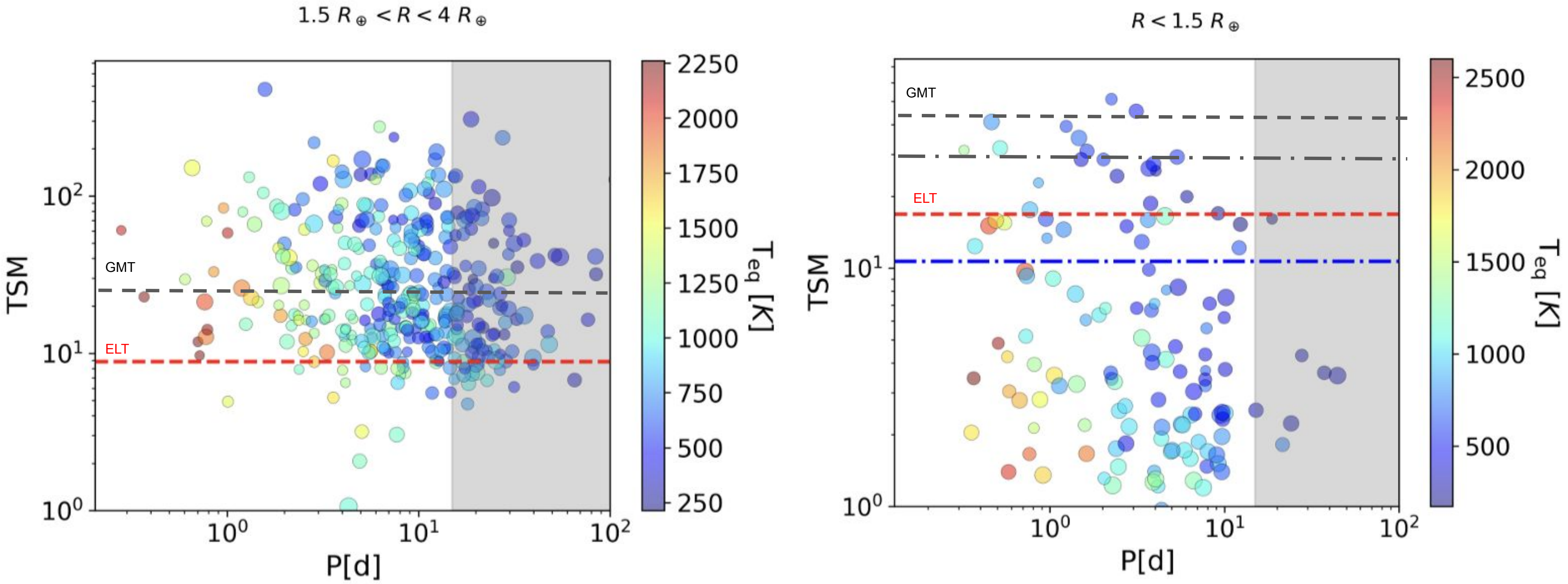
Earth size temperate planets observable at SNR=5 with ANDES/ELT in direct imaging





Palle+2023

Rp < 4Re transiting planets observable at SNR=5 with ANDES/ELT



Palle+2023

Summary

- JWST will have observed **over 330 transiting planets and about 60 direct imaging planets** when ELTs see first light.

- Current open questions like the *What is that gas giant exoplanets metallicity distributions? Is C/O a good planet migration tracer? Where is the methane?* and *Do terrestrial planets around M-dwarfs have atmospheres?* will have been solved.

- But questions such as **atmospheric properties of small planets, and isotope ratios** will still be unanswered.

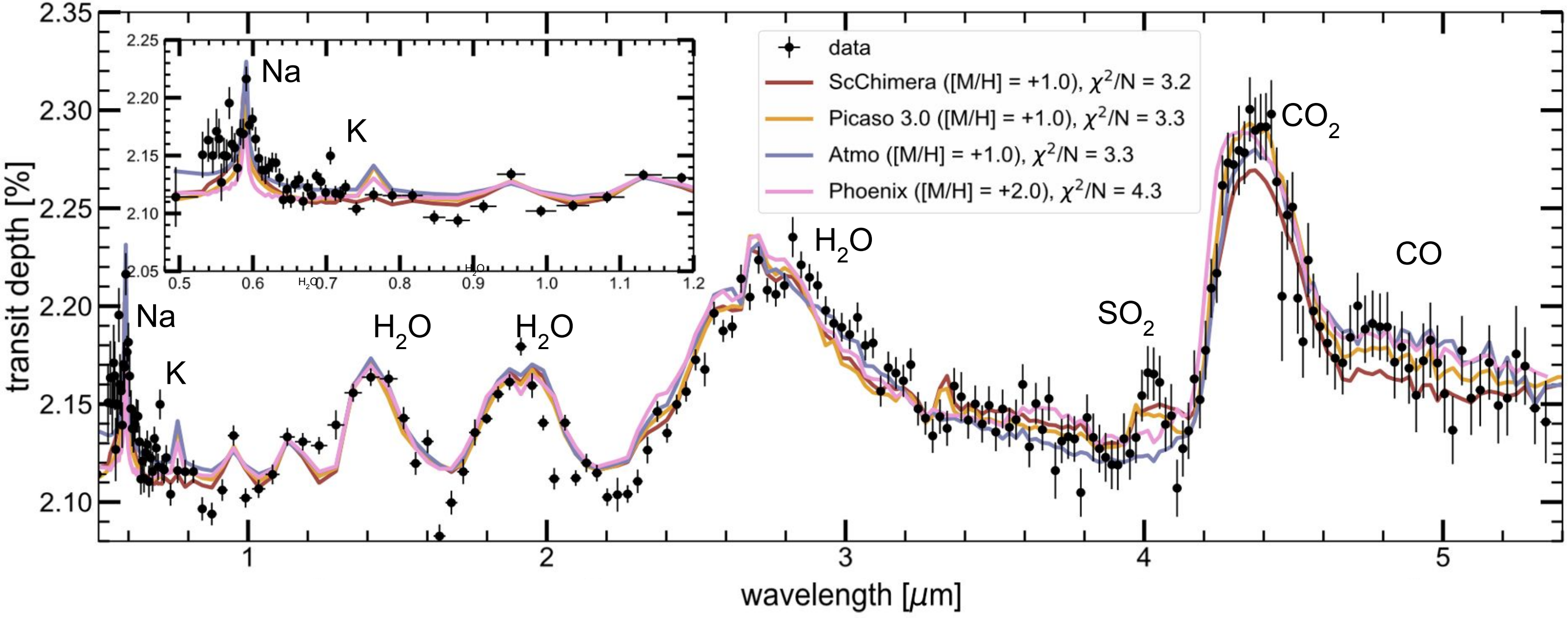
- The **ELTs will provide insights about isotope ratios of Jupiter to super-Earth size planets, detailed atmospheric characterization of planets > 1.5 Re, and a number of hot, earth size planets**.

- ELTs will be able to observe the atmospheres of a small mumber of earth analogs. Proxima b is by far the best target.

Backup Slides

Gas Giants

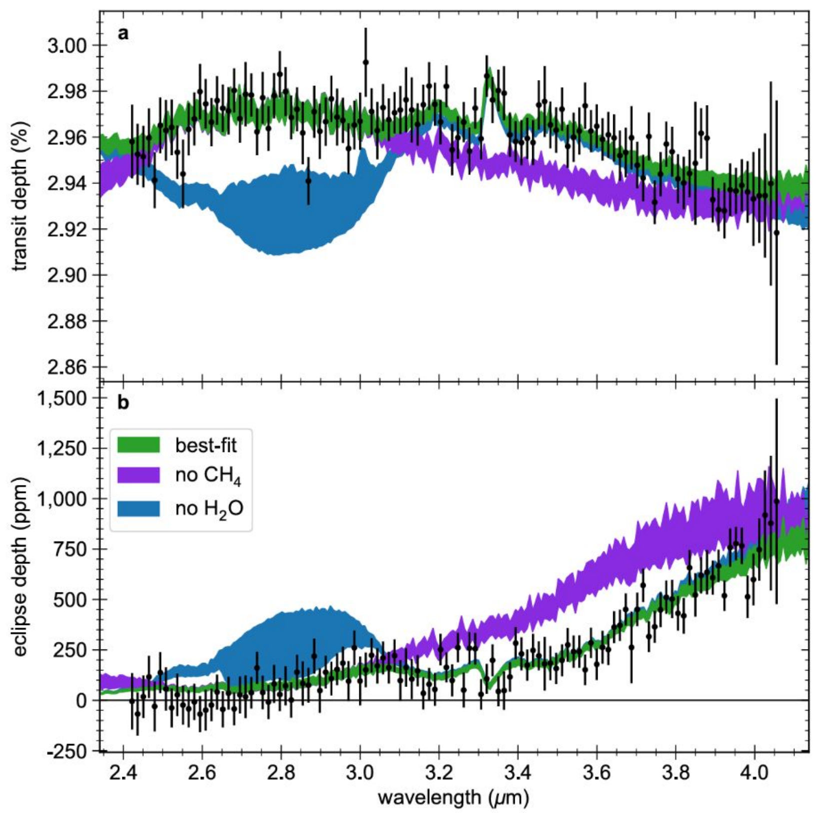
Detection of CO_2, H_2O, CO, SO_2, Na, K in WASP-39b (T_{eq}= 1120K)



Rustamkulov+2023

Sub-Neptunes and Super-Earths

Detection of CO_2, H_2O and CH_4 in WASP-80b (T_{eq}=827K)



Bell+2023

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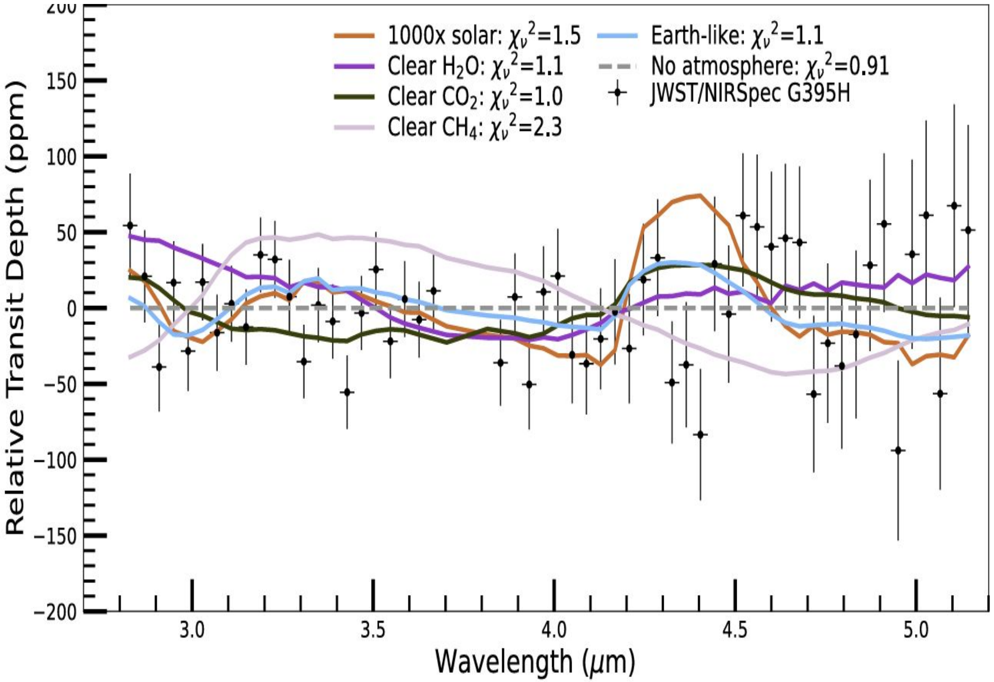
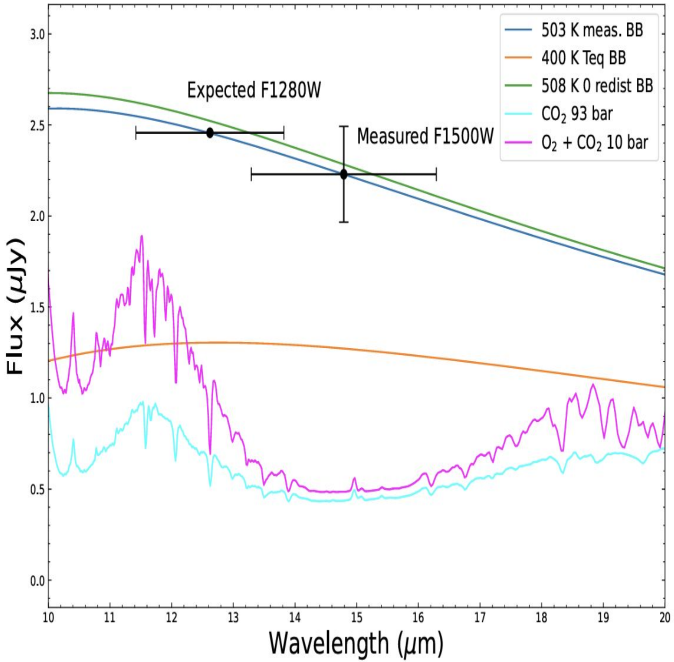


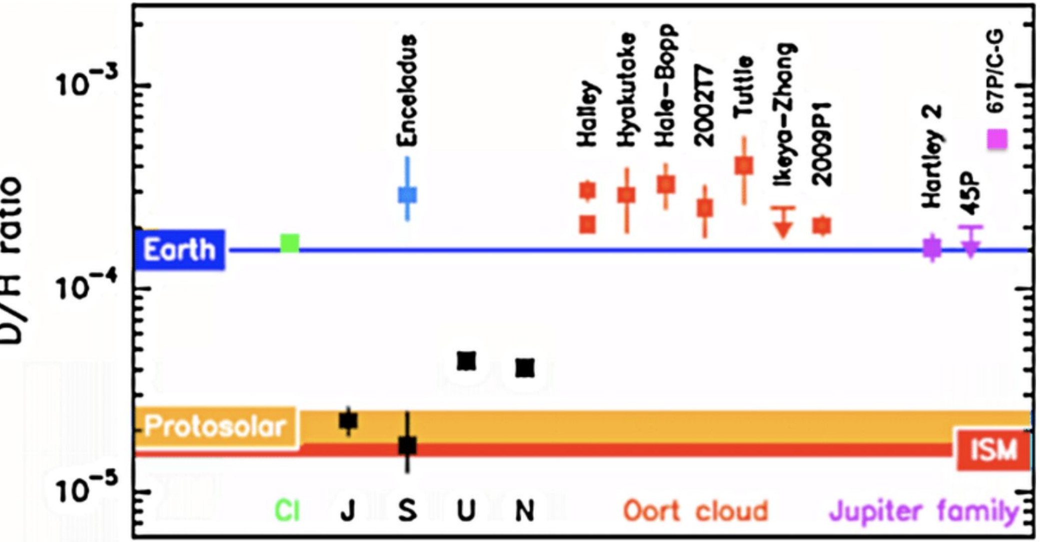
Lustig-Yaeger+2023

Trappist-1b/1c have no atmospheres (R_p = 1.1 R_e; T_{eq}= 400k, 340K)

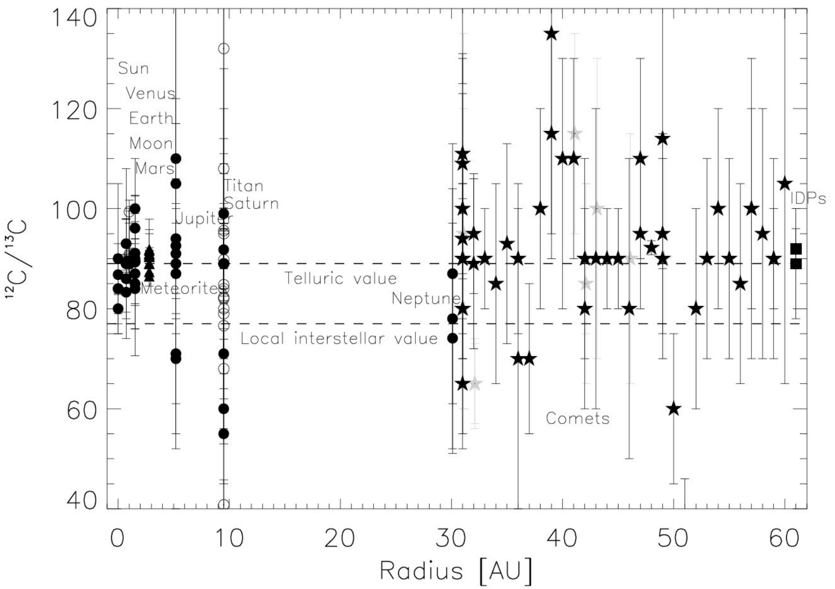


Greene+2023, Zieba+2023

D/H vary in the solar system, while $^{12}C/^{13}C$ are uniform



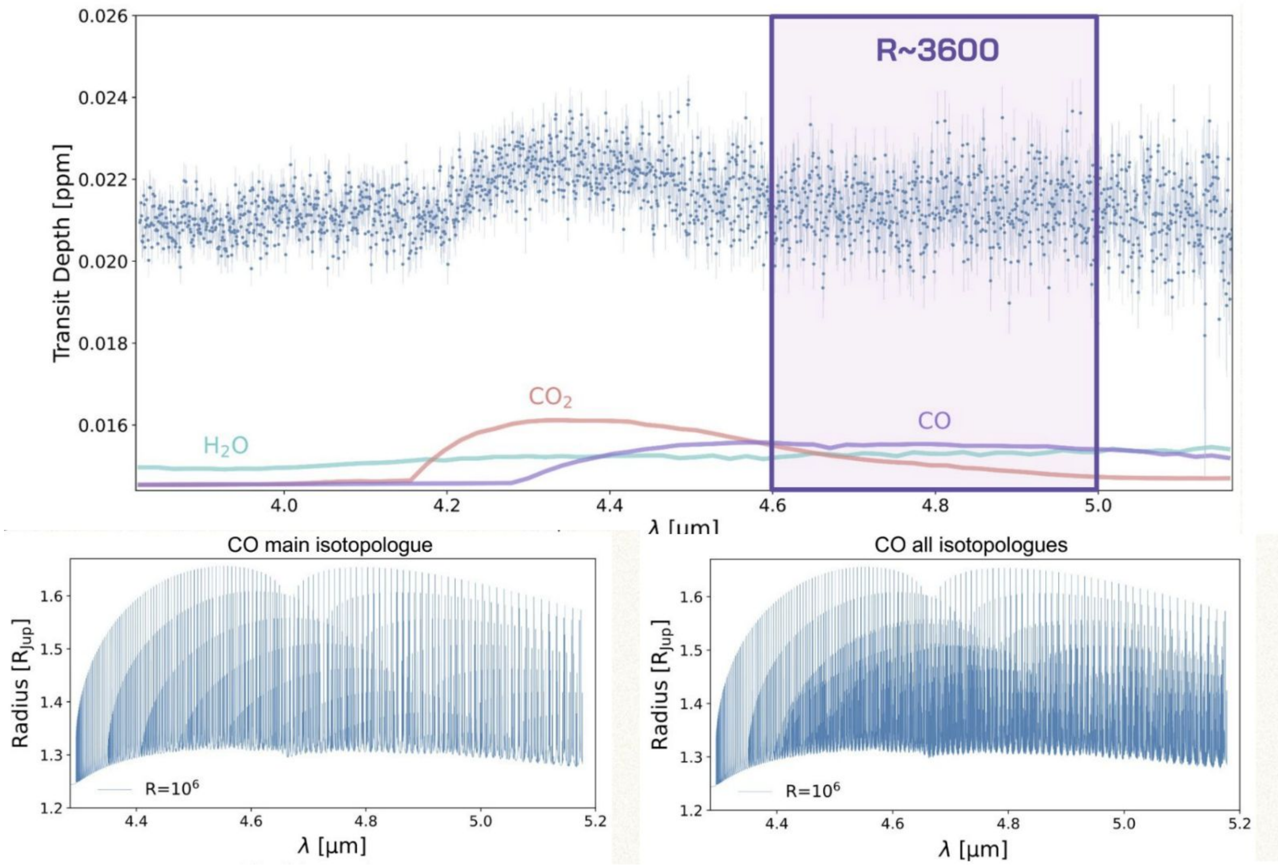
Lis+2013



Wood 2009

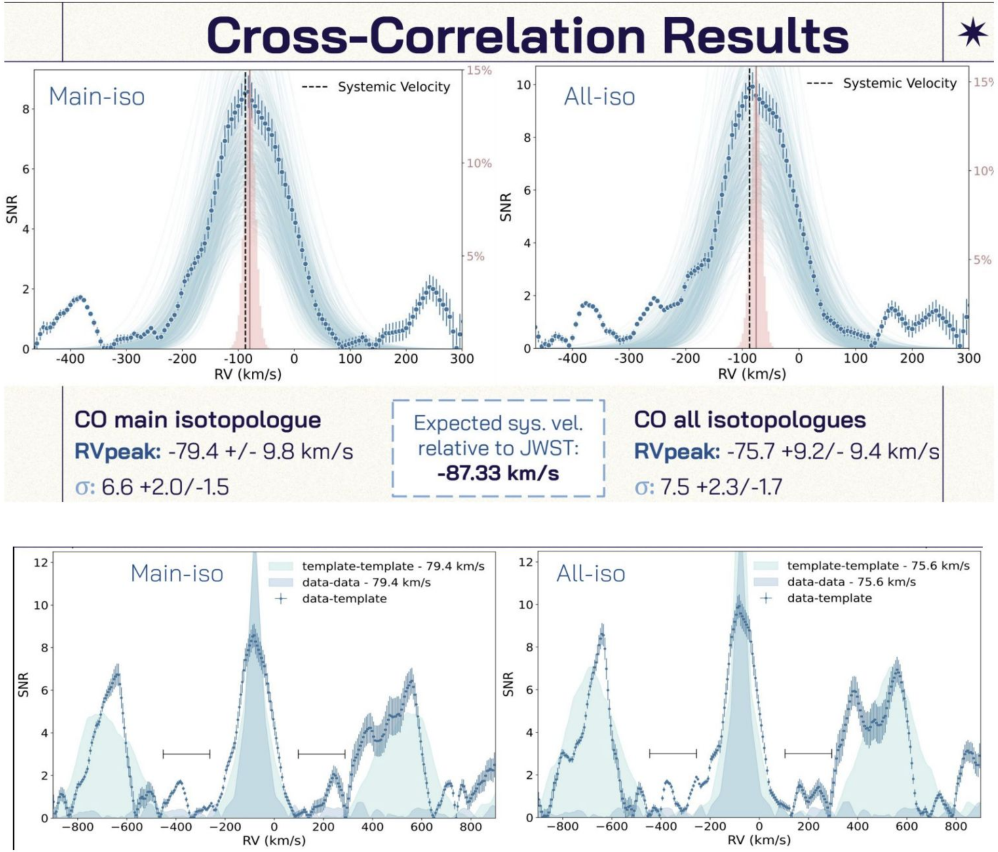
… however $^{12}C/^{13}C$ might be an indicator of biological processes (e.g Glidden+2022)

CO isotopologue detection with JWST

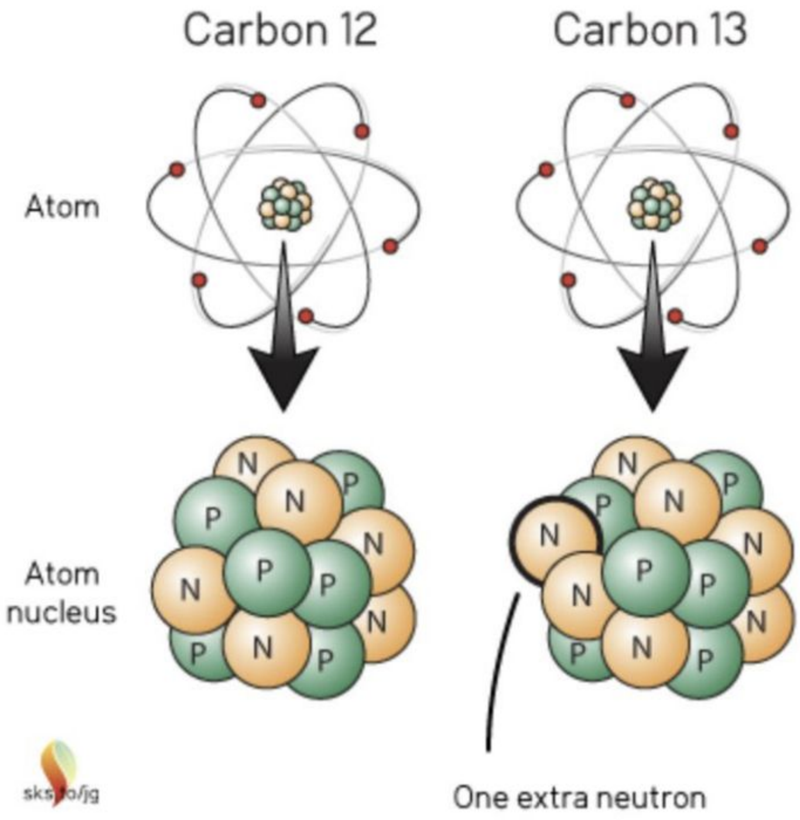


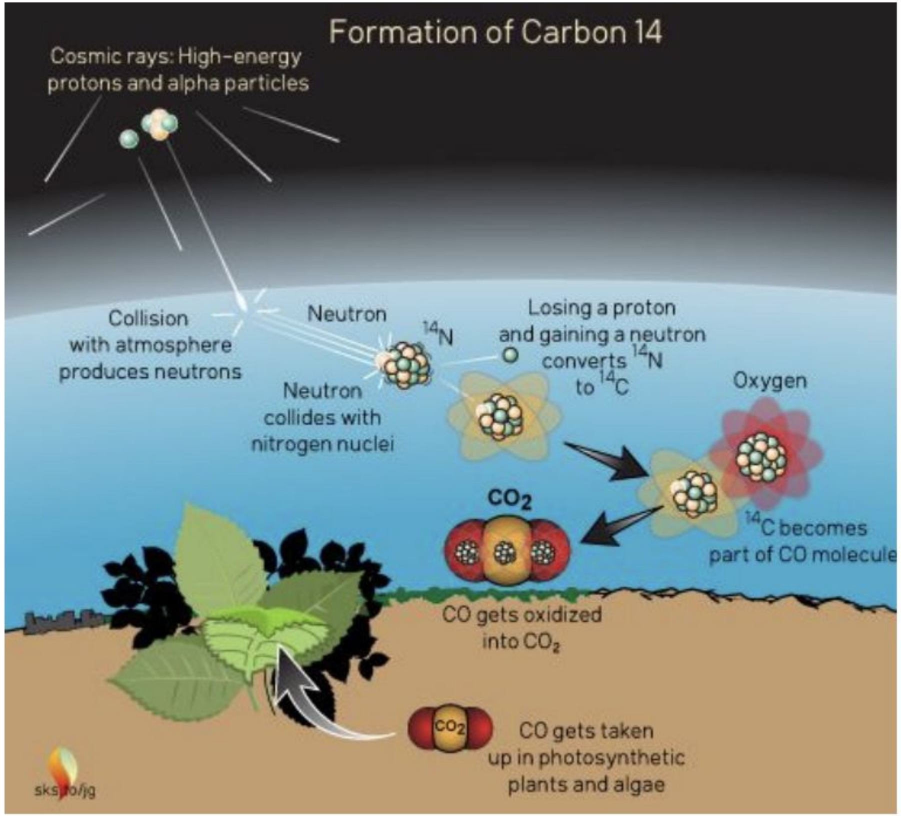
Esparza-Borges+2023

CO isotopologue detection with JWST



Esparza-Borges+2023


Carbon 12
Carbon 13
Atom
Atom nucleus
N
P
One extra neutron
sks/jg


Formation of Carbon 14
Cosmic rays: High-energy protons and alpha particles
Collision with atmosphere produces neutrons
Neutron
^{14}N
Neutron collides with nitrogen nuclei
Losing a proton and gaining a neutron converts ^{14}N to ^{14}C
Oxygen
CO_2
^{14}C becomes part of CO molecule
CO gets oxidized into CO_2
CO gets taken up in photosynthetic plants and algae
sks/jg