Stellar & Sub-Stellar CNO Abundances

PALOOZA S24: 4/13/2024

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OVERVIEW

1

CNO Snowline Chemistry

Volatile element (C, N, O) abundances may tell us about where a planet formed relative to different snowlines.

2

Recent Measurements

We will discuss recent exoplanet & brown dwarf isotope measurements from instruments like KPIC and JWST.

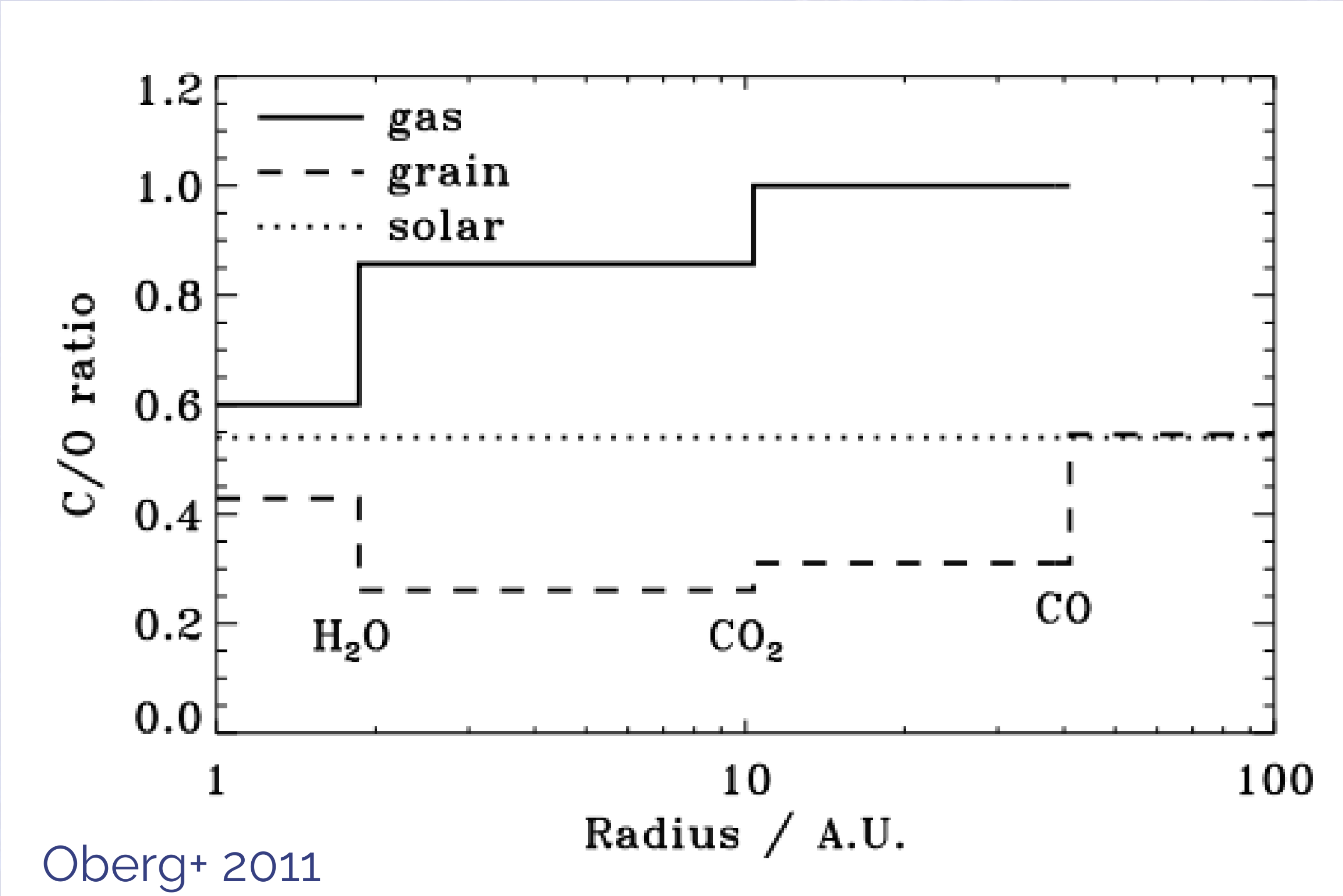
3

Future Work

Finally, we'll discuss the progress and prospects for measuring CNO isotopologues in cool dwarf exoplanet host stars.

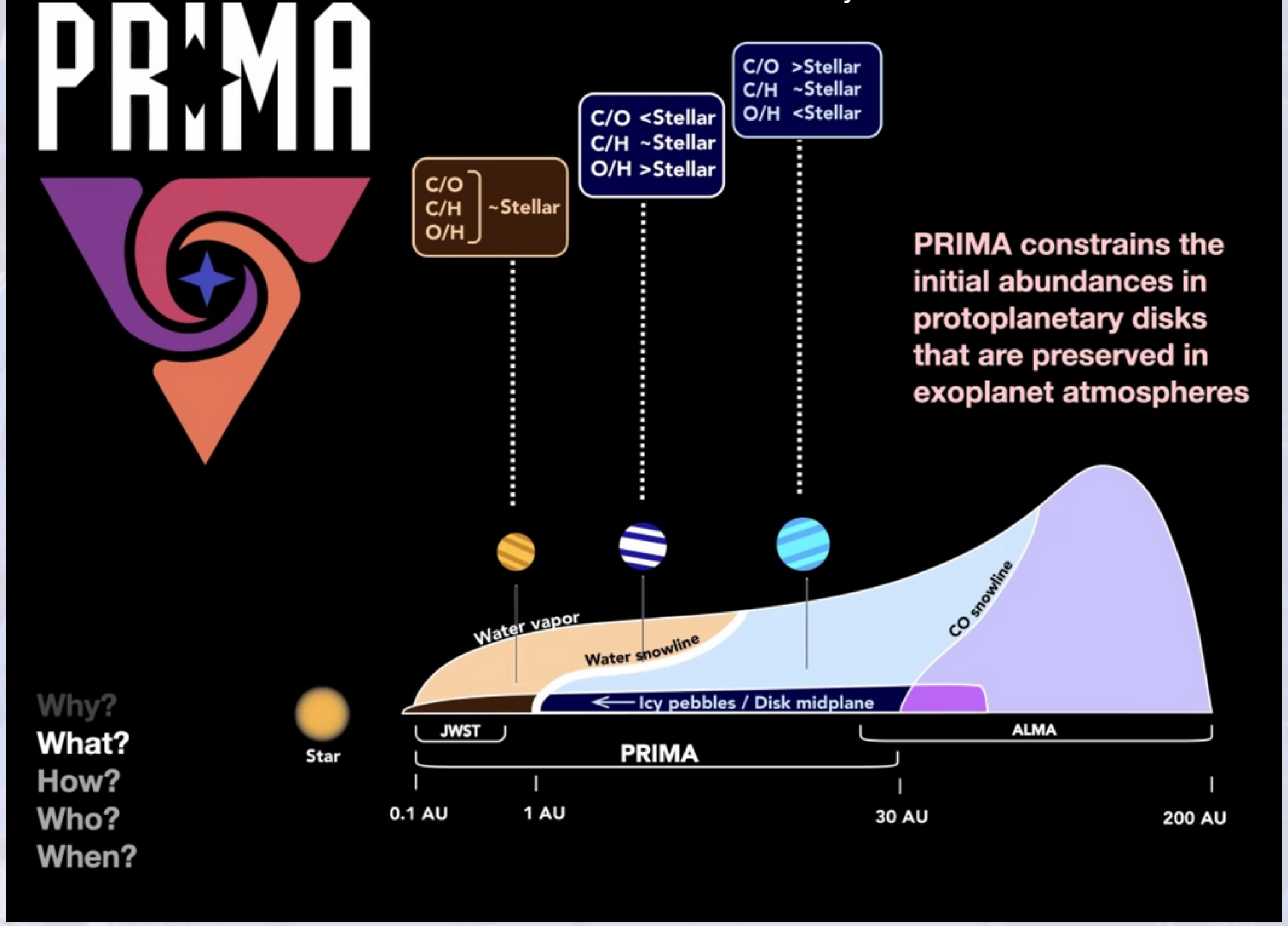

Background

Stellar Abundances: Context for Exoplanet Formation



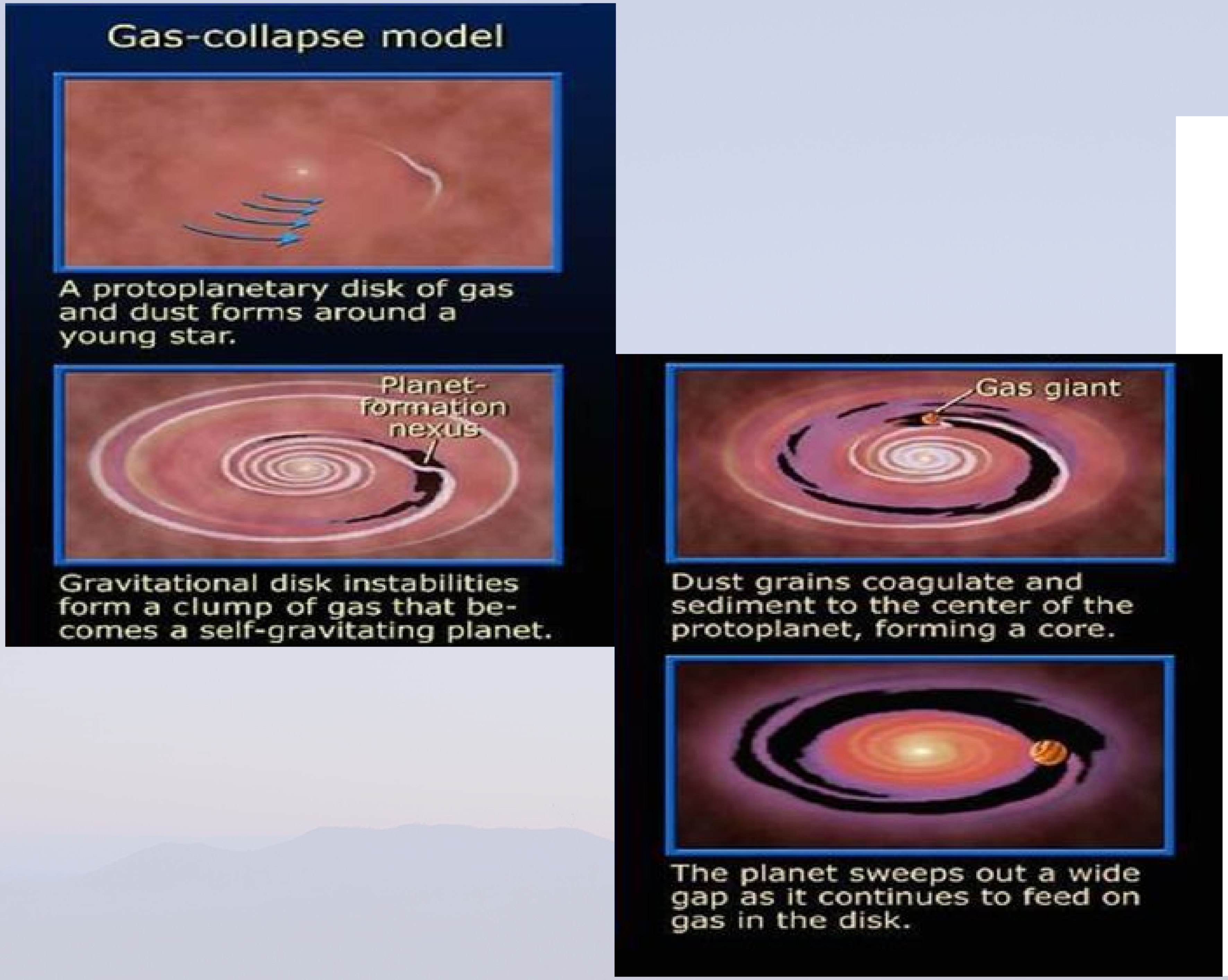
Oberg+ 2011

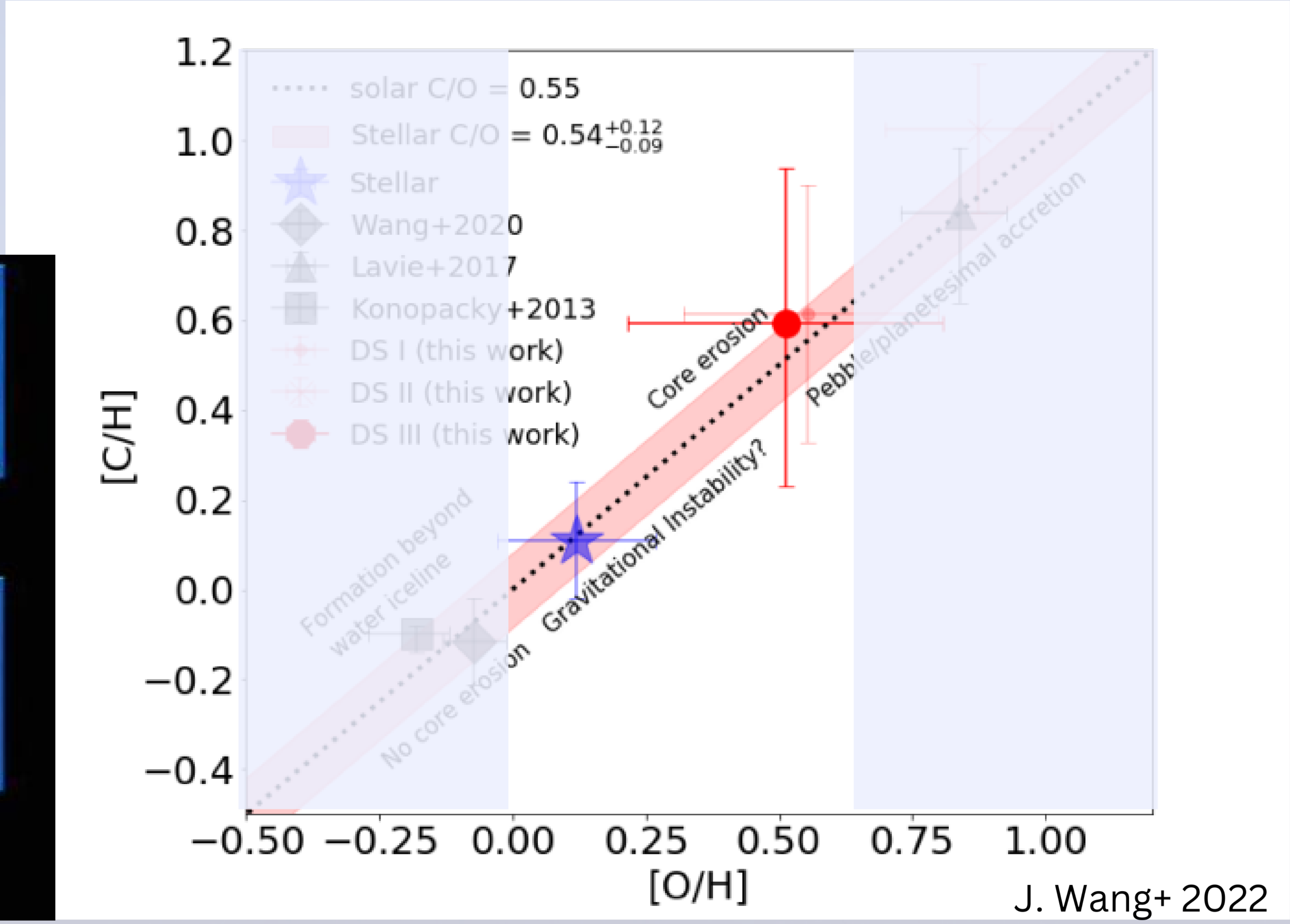
Courtesy of Dr. Elisabeth Mills



Abundances ~should~ trace formation location relative to snowlines

Formation via Gravitational Instability

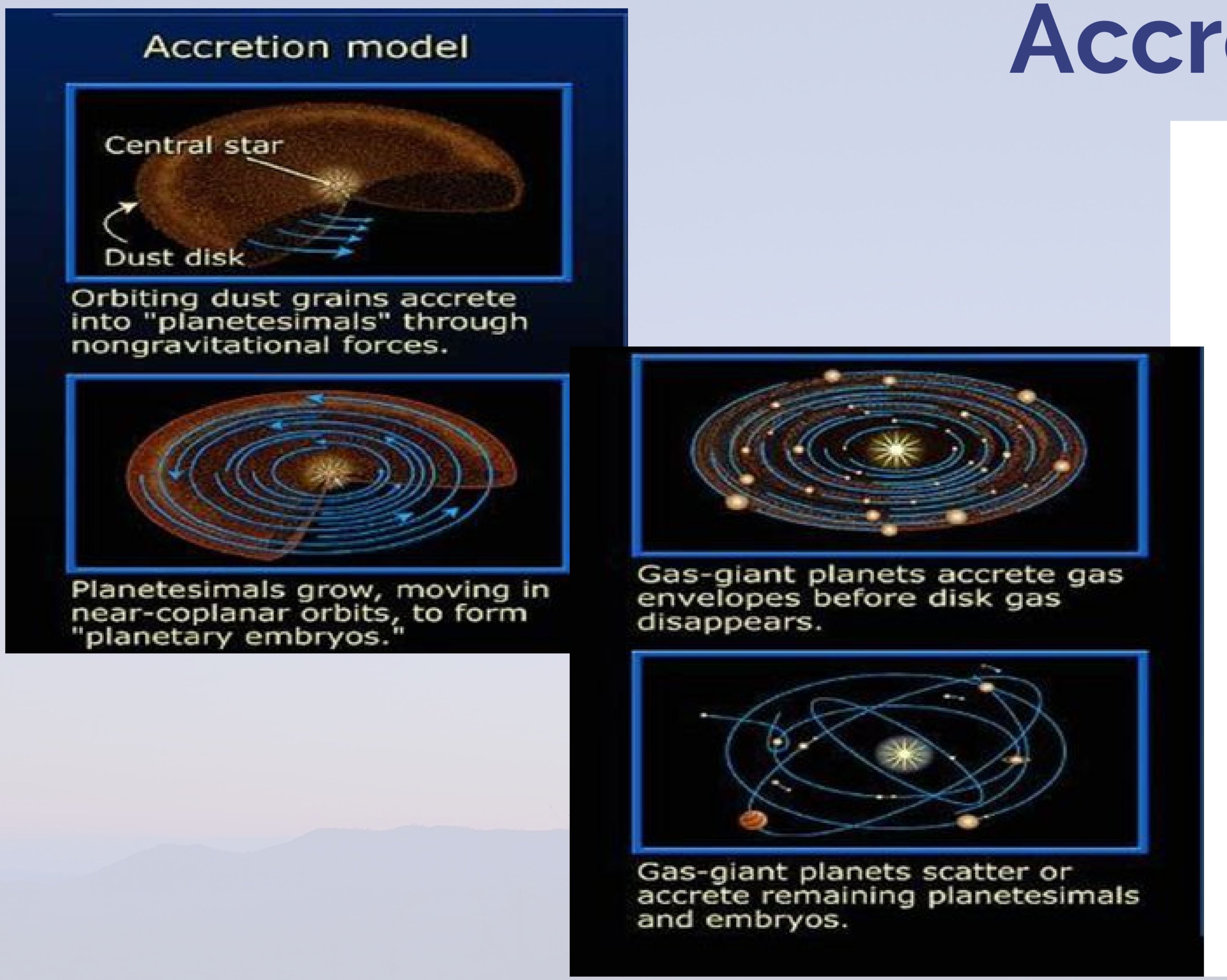


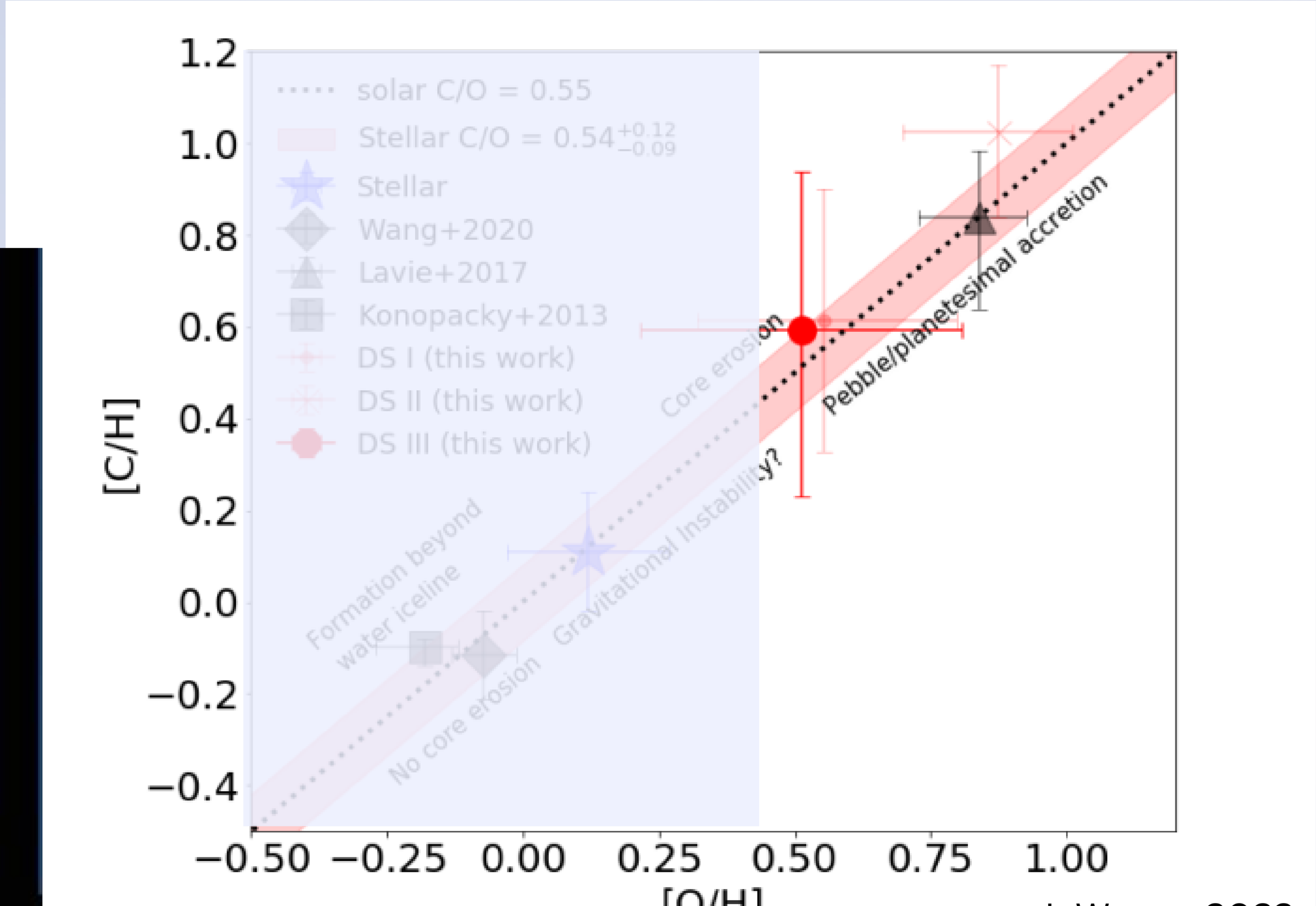


H_2O and CO detections constrain planet formation mechanisms

Ingraham+ 2014, Barman+ 2015, Ruffio+ 2021, J. Wang+ 2022 and many others

Formation via Pebble/Planetesimal Accretion





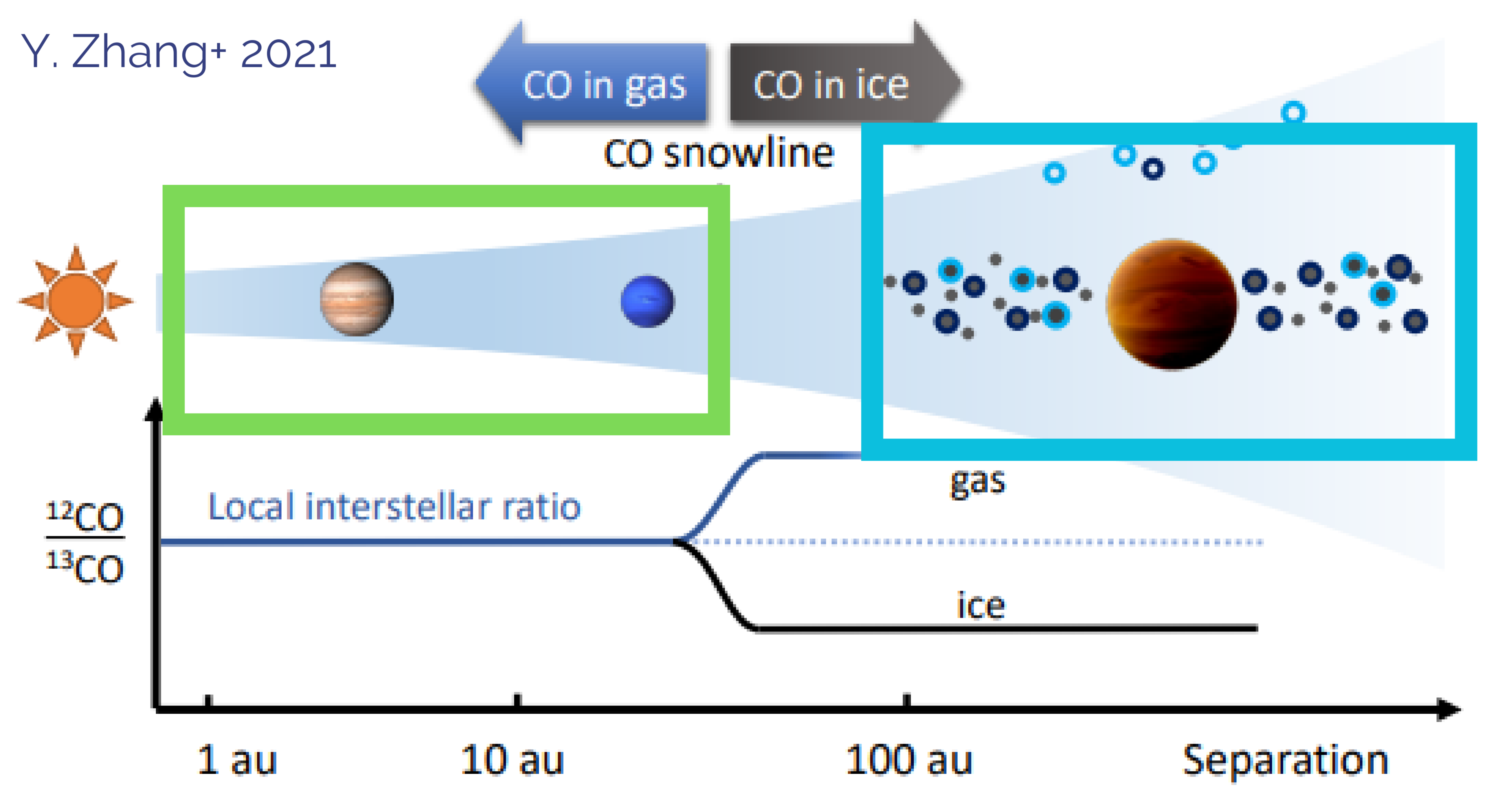
J. Wang+ 2022

H_2O and CO detections constrain planet formation mechanisms

Ingraham+ 2014, Barman+ 2015, Ruffio+ 2021, J. Wang+ 2022 and many others

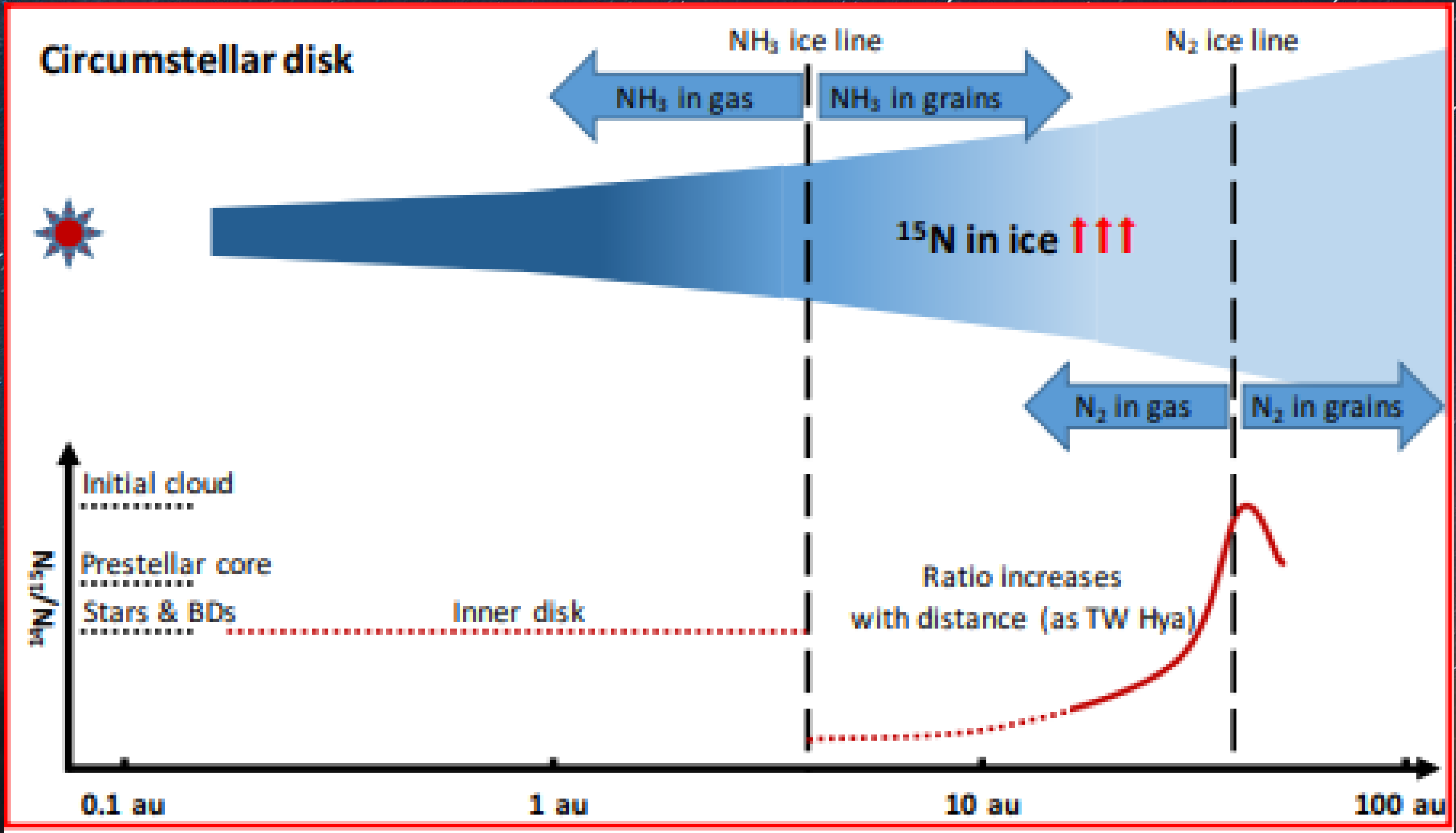
Isotopologue Abundance Ratios

12C/13C Ratio: Fractionation near CO Snowline



Contamination by icy planetesimals rich in minor isotopes can lead to non-stellar isotope ratios in exoplanets

14N/15N Fractionation

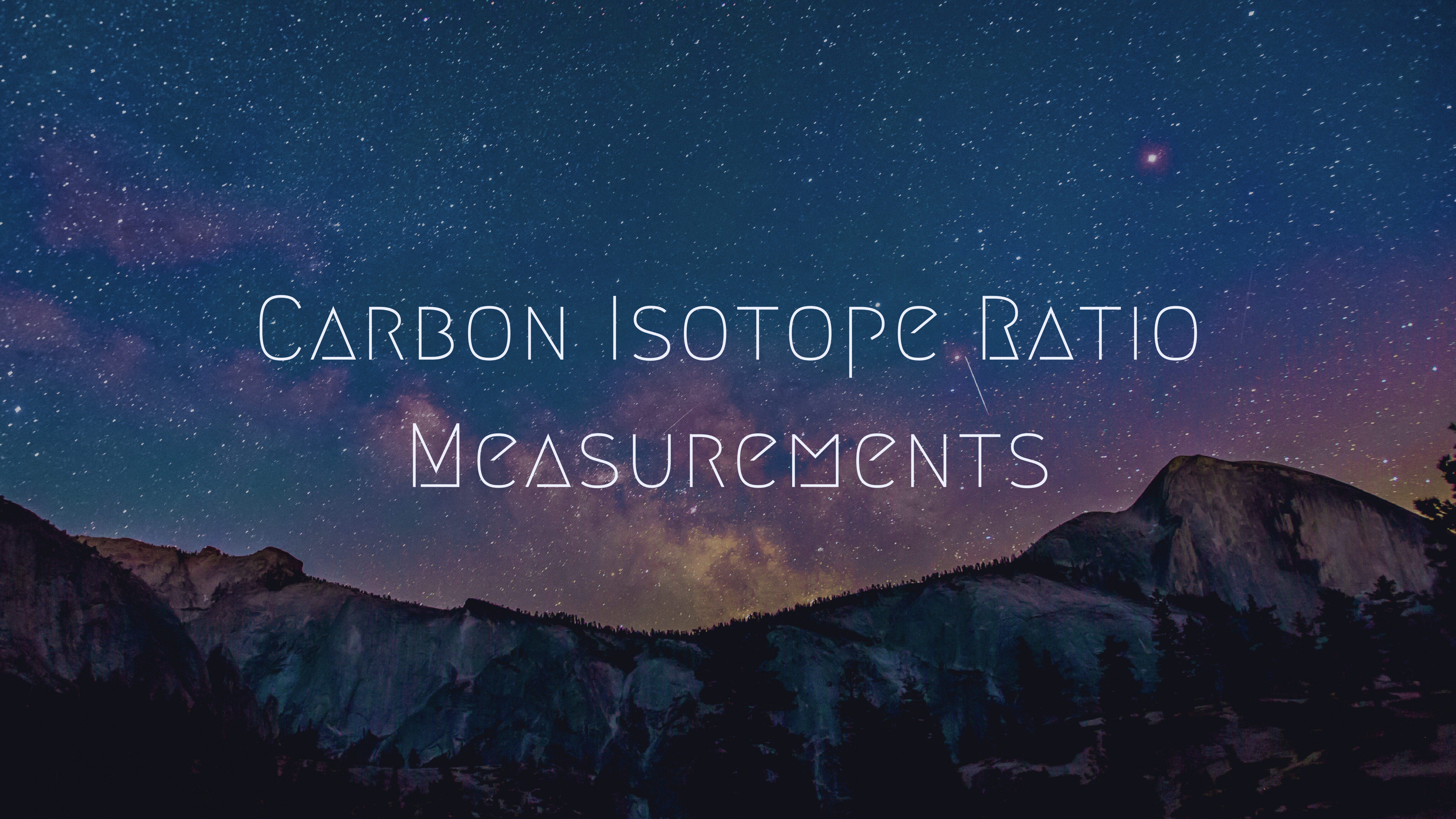


D. Barrado+ 2023

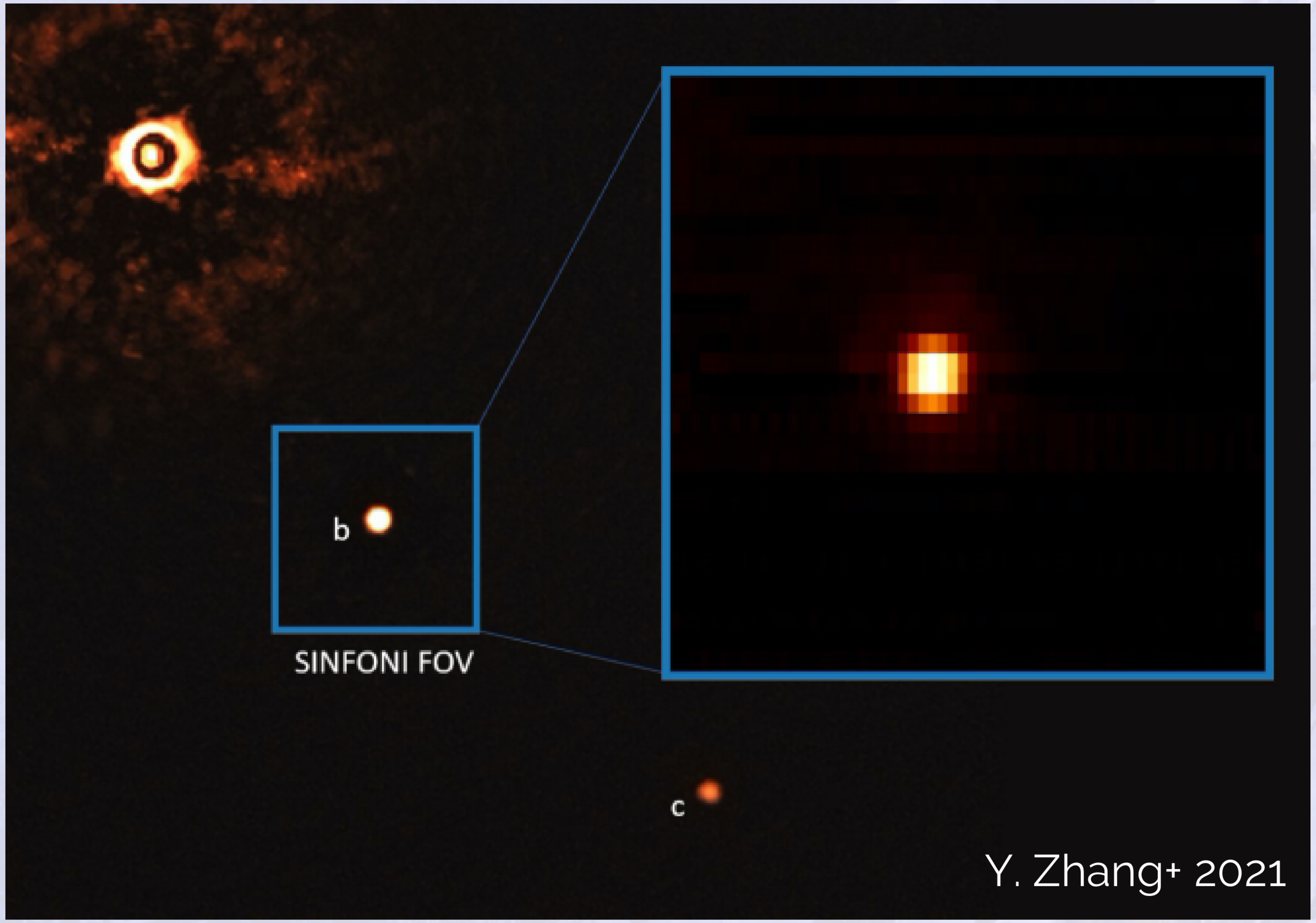
Enrichment from the minor isotope 15N is expected in the mid-disk--closer to the ammonia snowline

16O/18O Ratio: No fractionation throughout the solar system?

No evidence for significant oxygen fractionation in chondritic meteorites: they have 16O/18O values ~solar [M&S 2019]


Carbon Isotope Ratio
Measurements

TYC 8998-760-1: Two Young Super-Jupiters



-Powerful telescopes with high resolution spectrographs can detect MINOR isotopes!

-TYC 8998 b shows abnormal 13C enrichment

-No host star measurement for comparison

TYC 8998 b 12C/13C = 31
<< Solar ~90

WASP-77 A b

Line+ 2021

Gemini/IGRINS
R ~ 45,000
Near-Infrared

12C/13C = 26.4 ± 16.2
T_eq = 1650 K
Mass = 1.67 M_J
Radius = 1.23 R_J
Semi-Major Axis ~ 0.02 AU

Host Stars:
-Orbits the primary of a G/K dwarf binary

VHS 1256 b

Gandhi+ 2023

JWST/NIRSpec
R ~ 2,700
Mid-Infrared

12C/13C = 62 ± 2
T_eq = 1150 K
Mass = 12 M_J
Radius = 1.3 R_J
Semi-Major Axis ~ 350 AU

Host Stars:
-Orbits an M dwarf binary
-Very young system (Myr)

HD 189733 b

Finnerty+ 2024

KPIC/NIRSpec
R ~ 25,000
Near-Infrared

12C/13C < 68 (ISM)
T_eq = 1200 K
Mass = 1.13 M_J
Radius = 1.13 R_J
Semi-Major Axis ~ 0.03 AU

Host Stars:
-Orbits the primary of a K/M dwarf binary

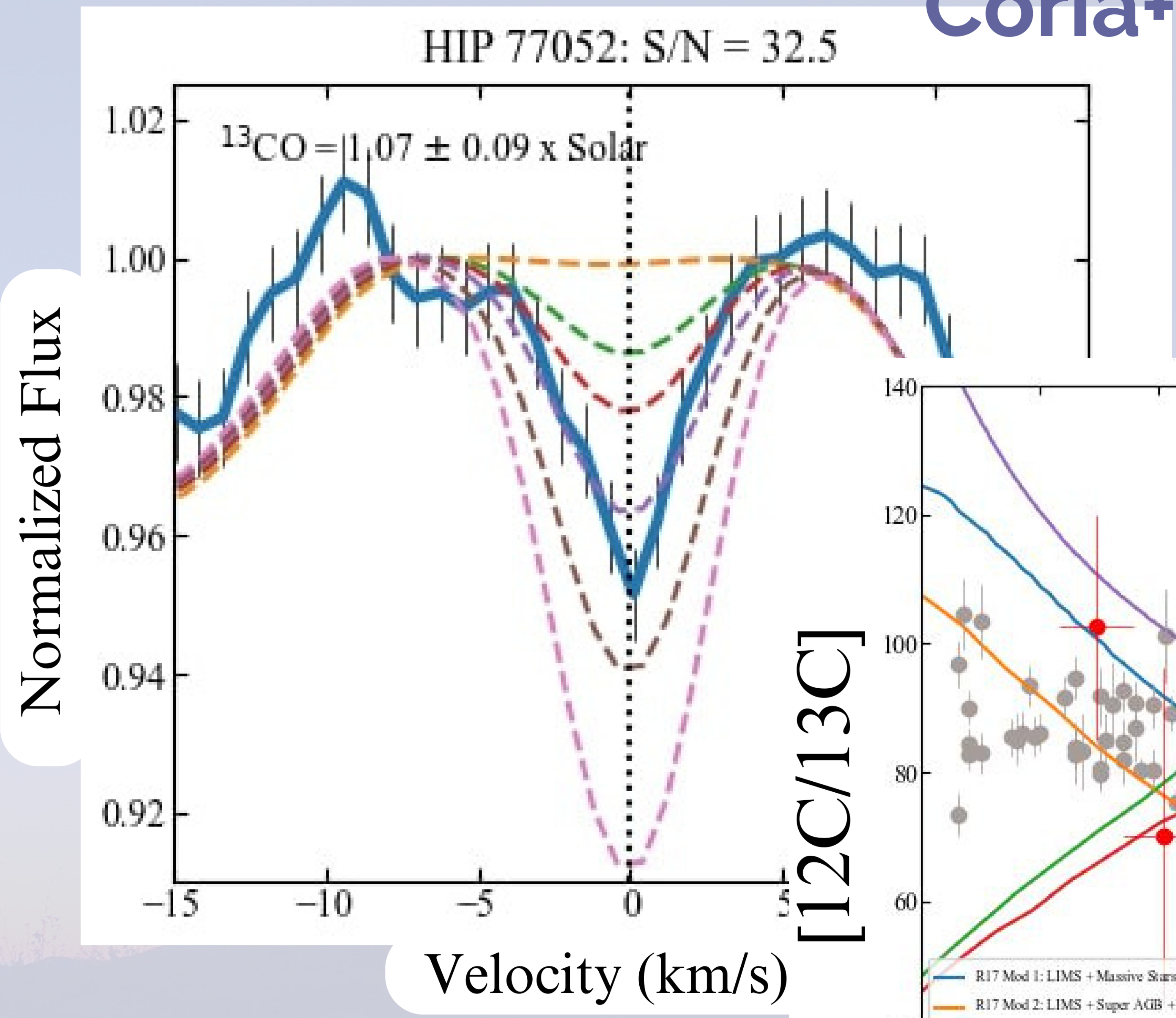
12C/13C In Solar Twin Stars

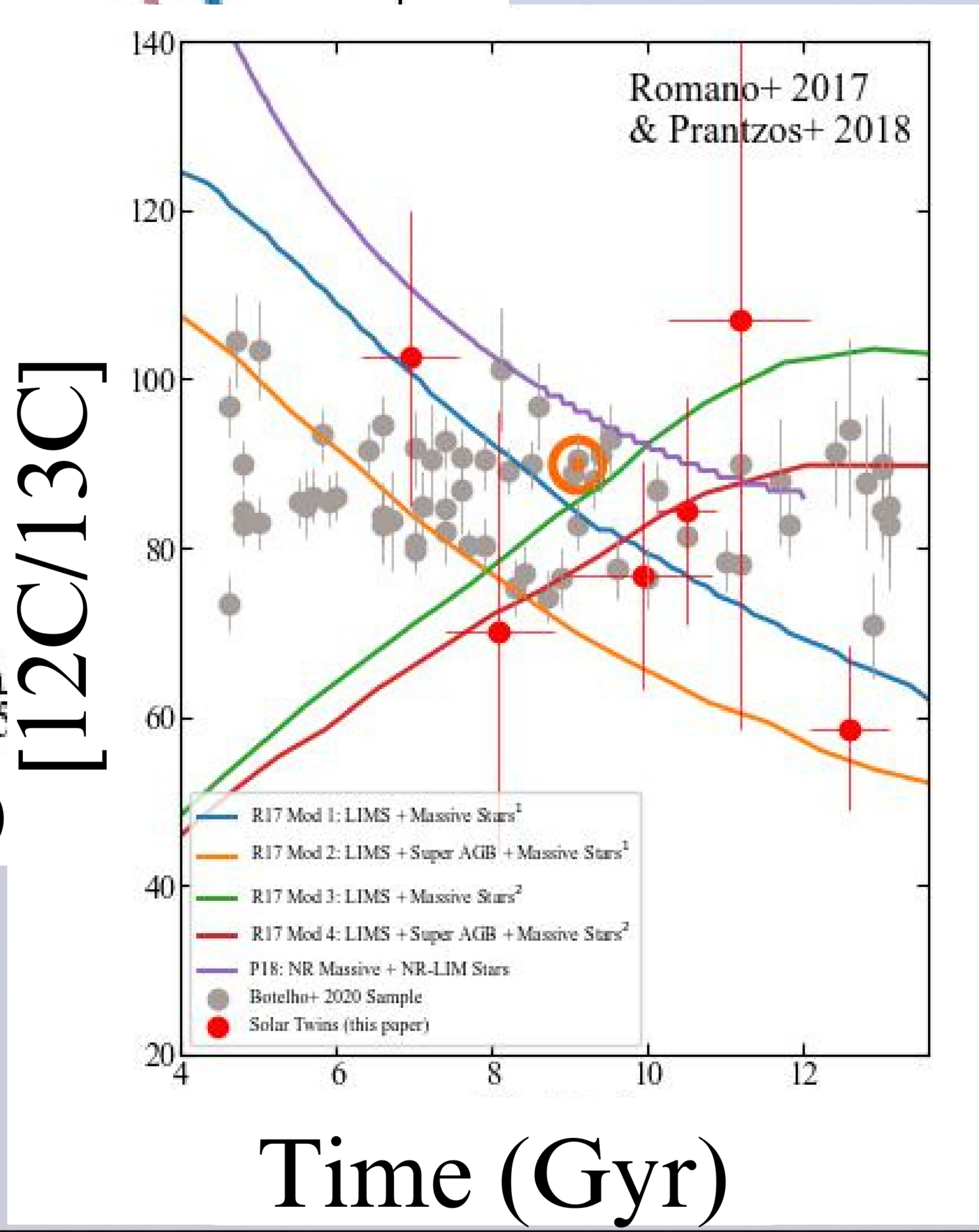
Coria+ 2023

~70 Dwarf Star Measurements in the Literature; fewer exoplanet hosts

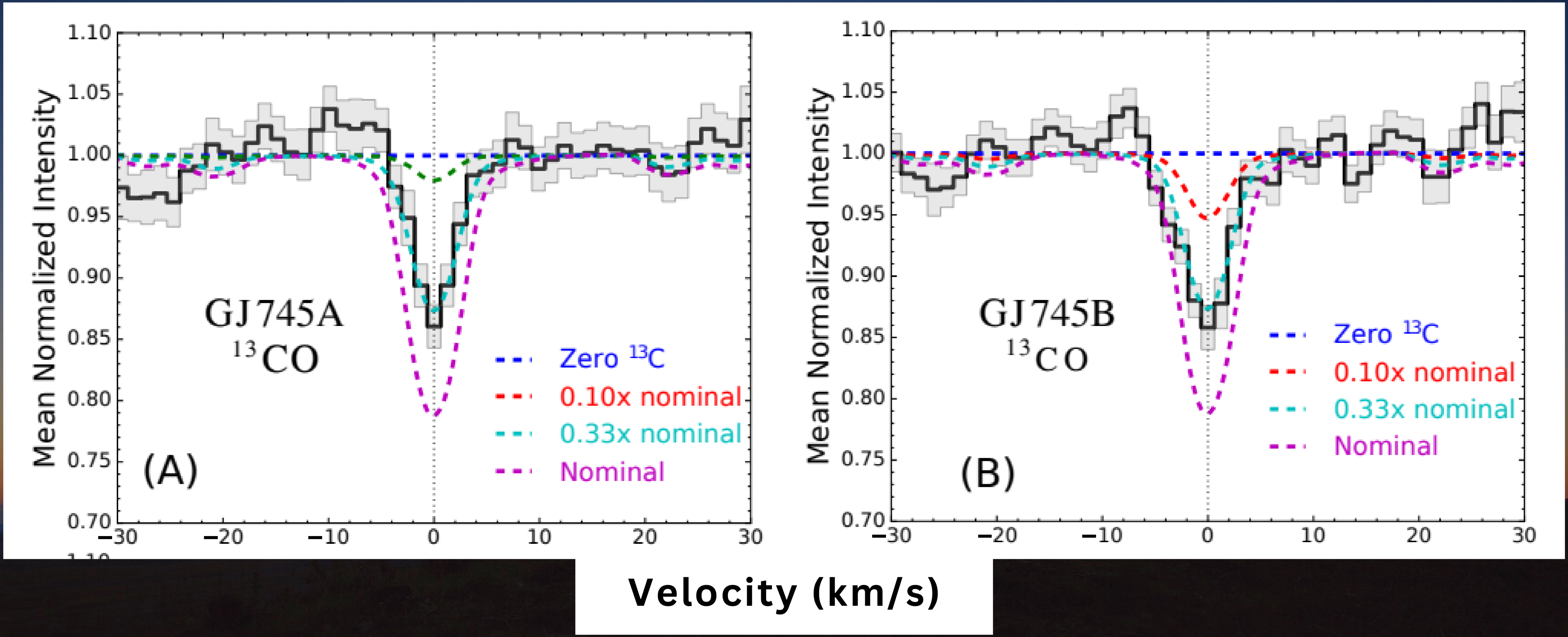
-We observe in the MIR because it gives us access to the CO rovibrational band @ 4.6-4.7 microns

-Lots of lines in this wavelength regime

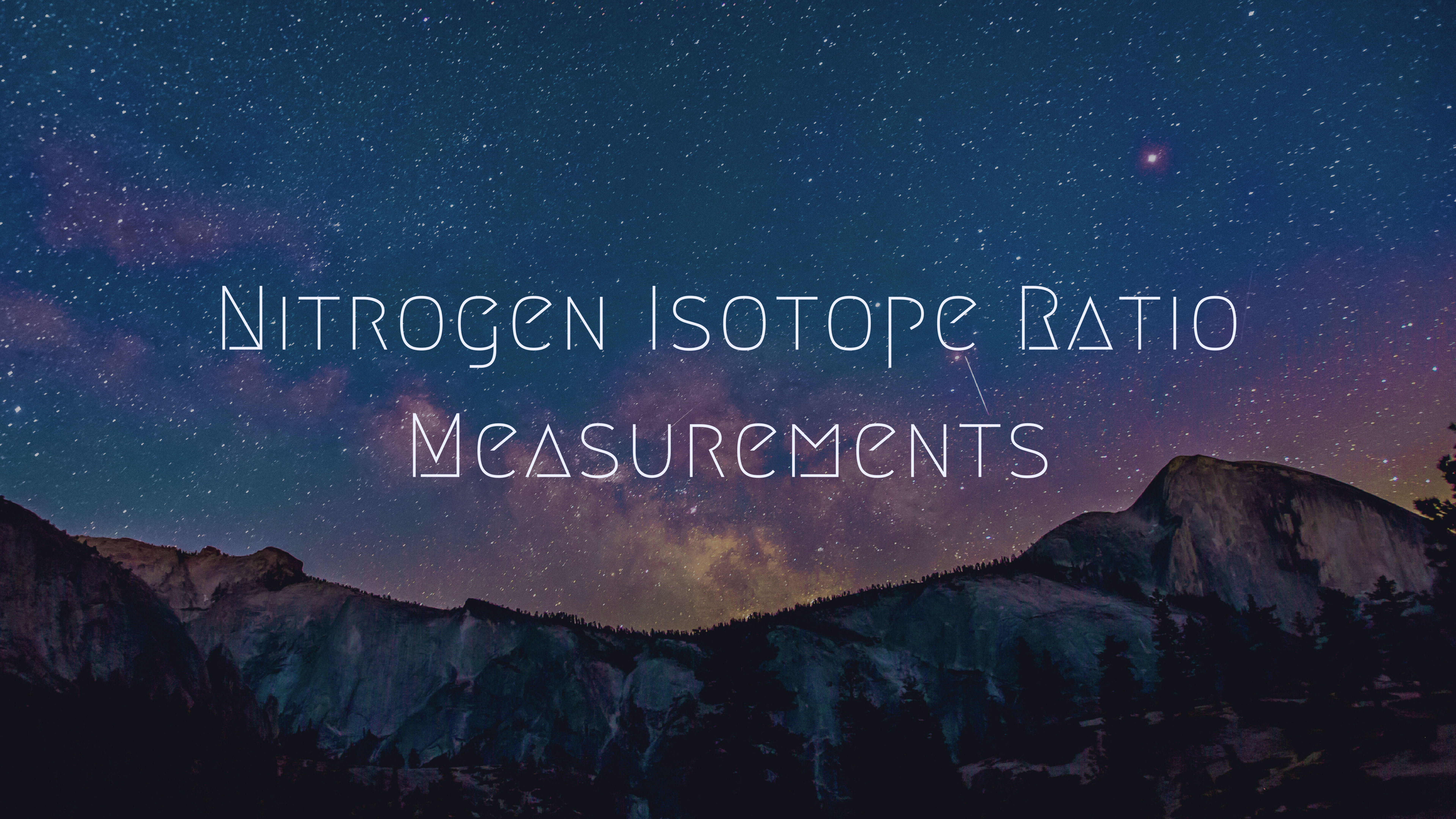




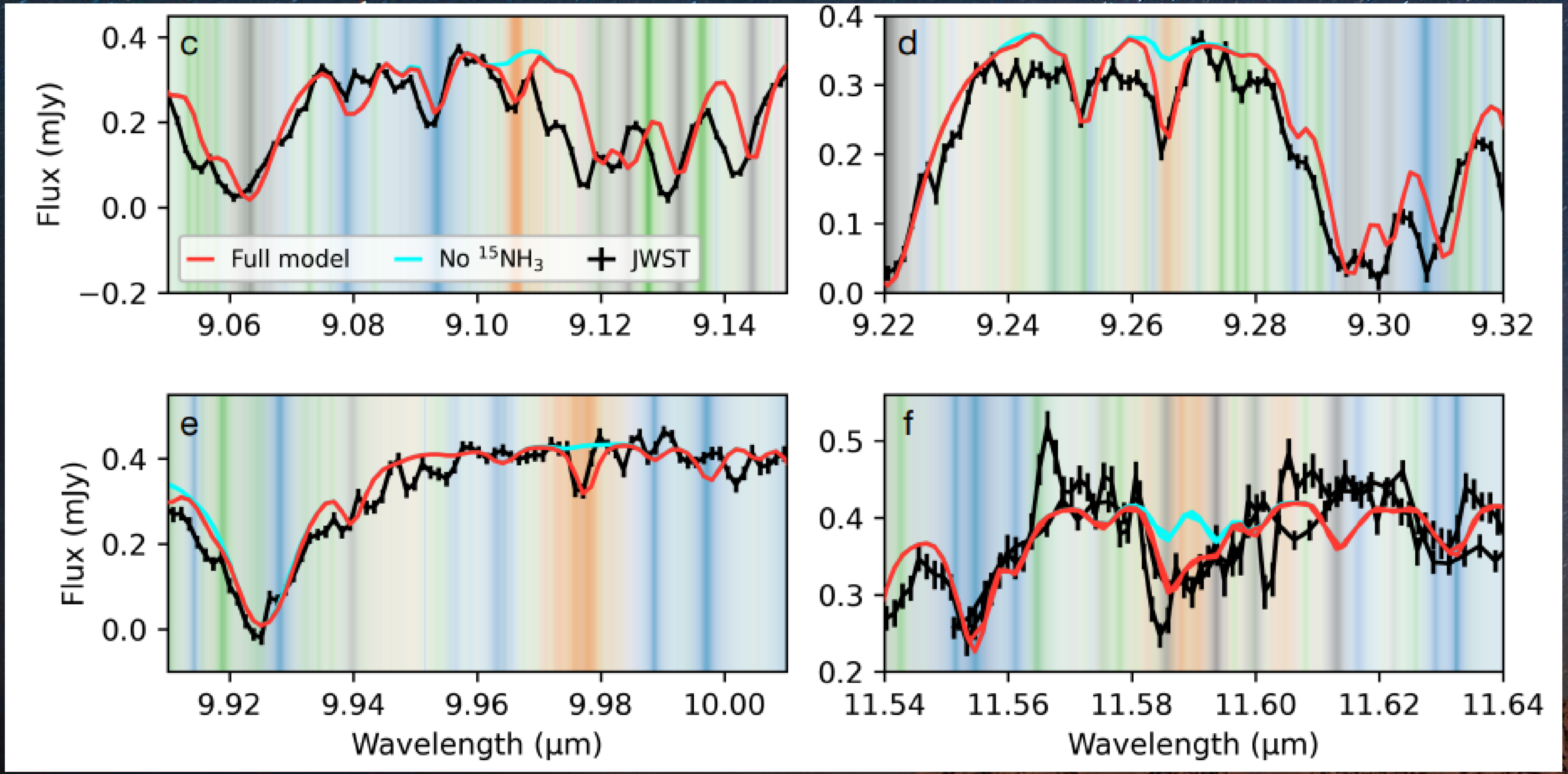
Crossfield+ 2019: 13C Detection in M Dwarf Stars

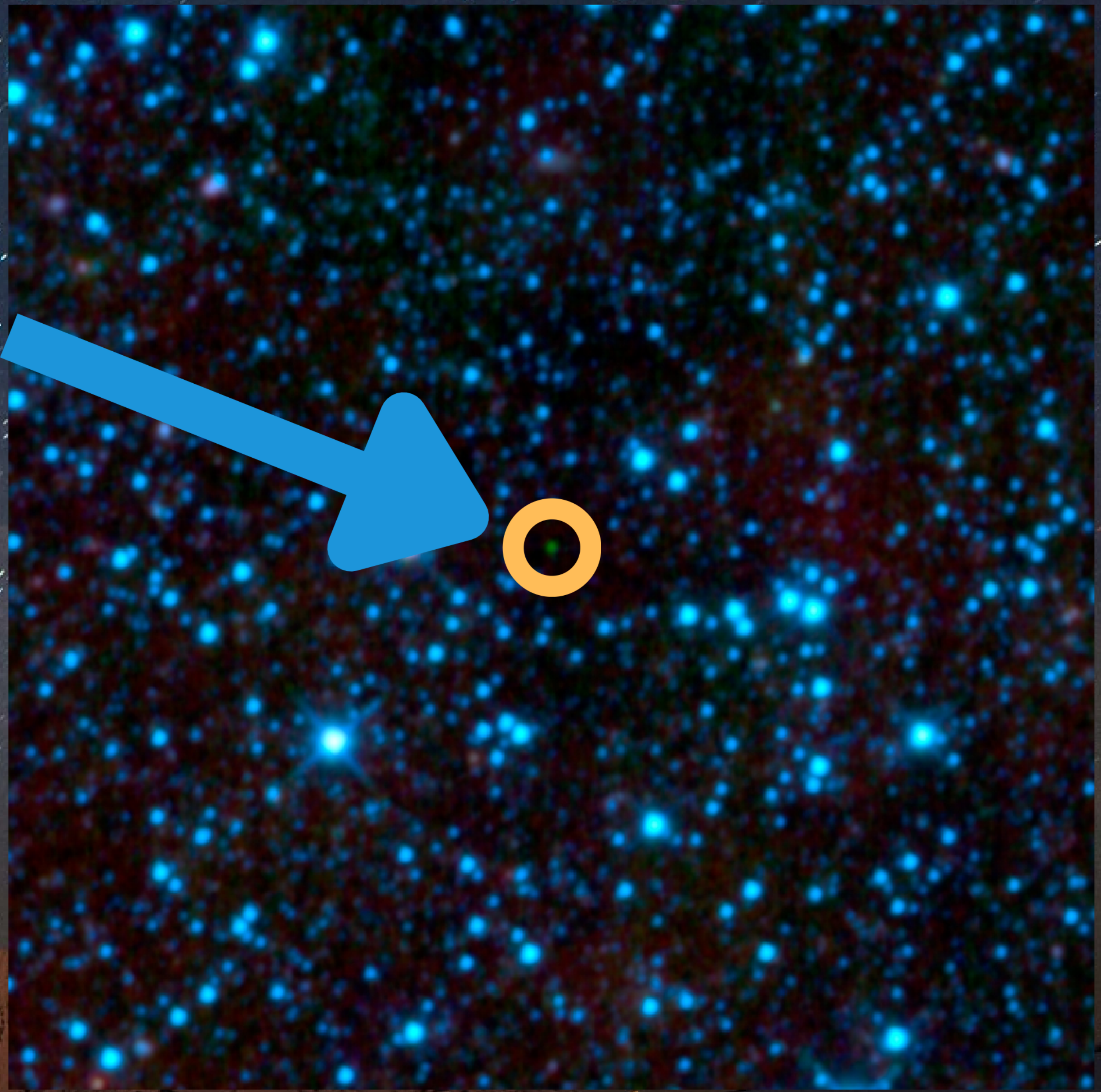


We can now make these measurements in the coolest, faintest stars!


Nitrogen Isotope Ratio
Measurements

WISE J1828: Nitrogen Isotope Detections in a Rogue Brown Dwarf



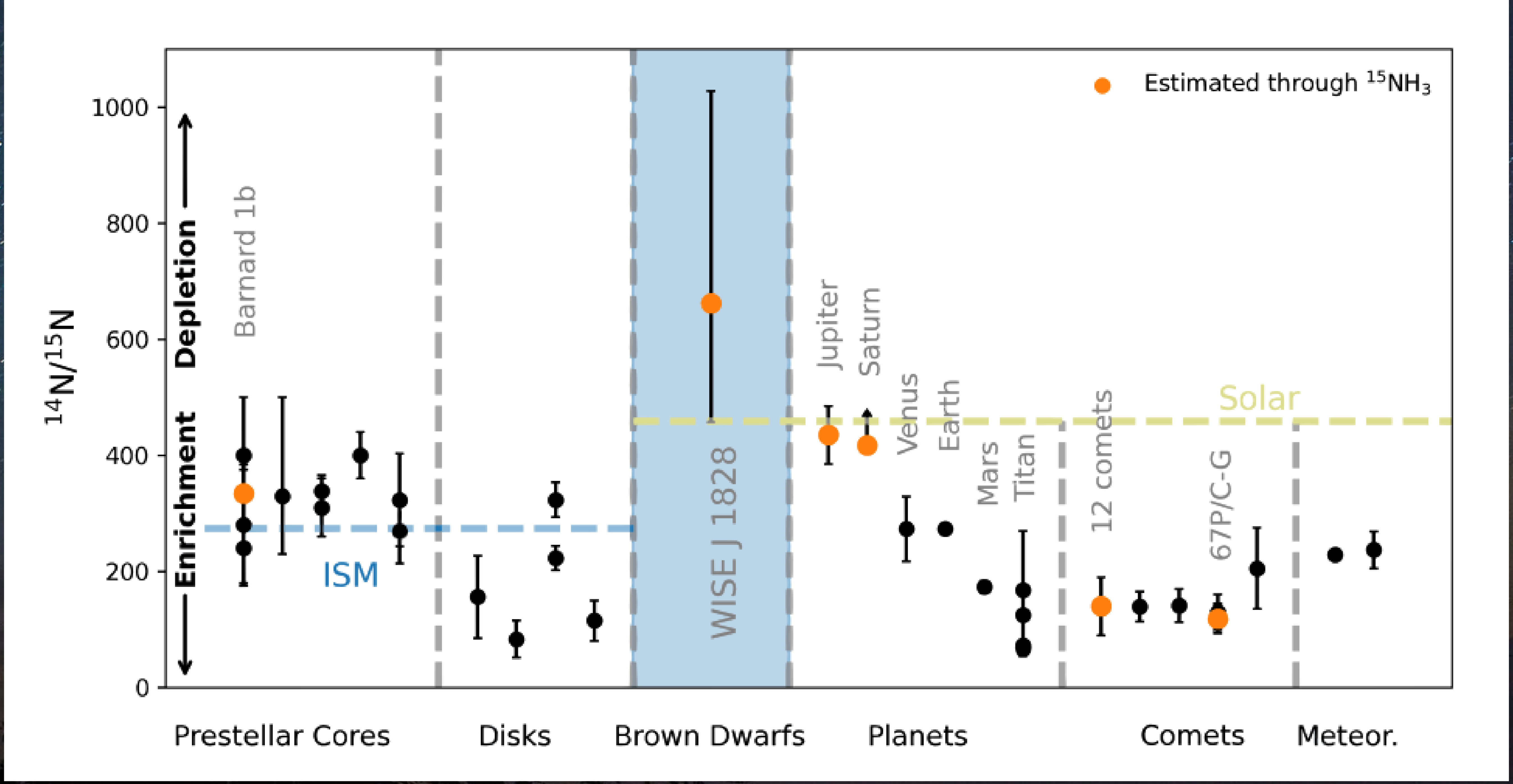


Barrado+ 2023

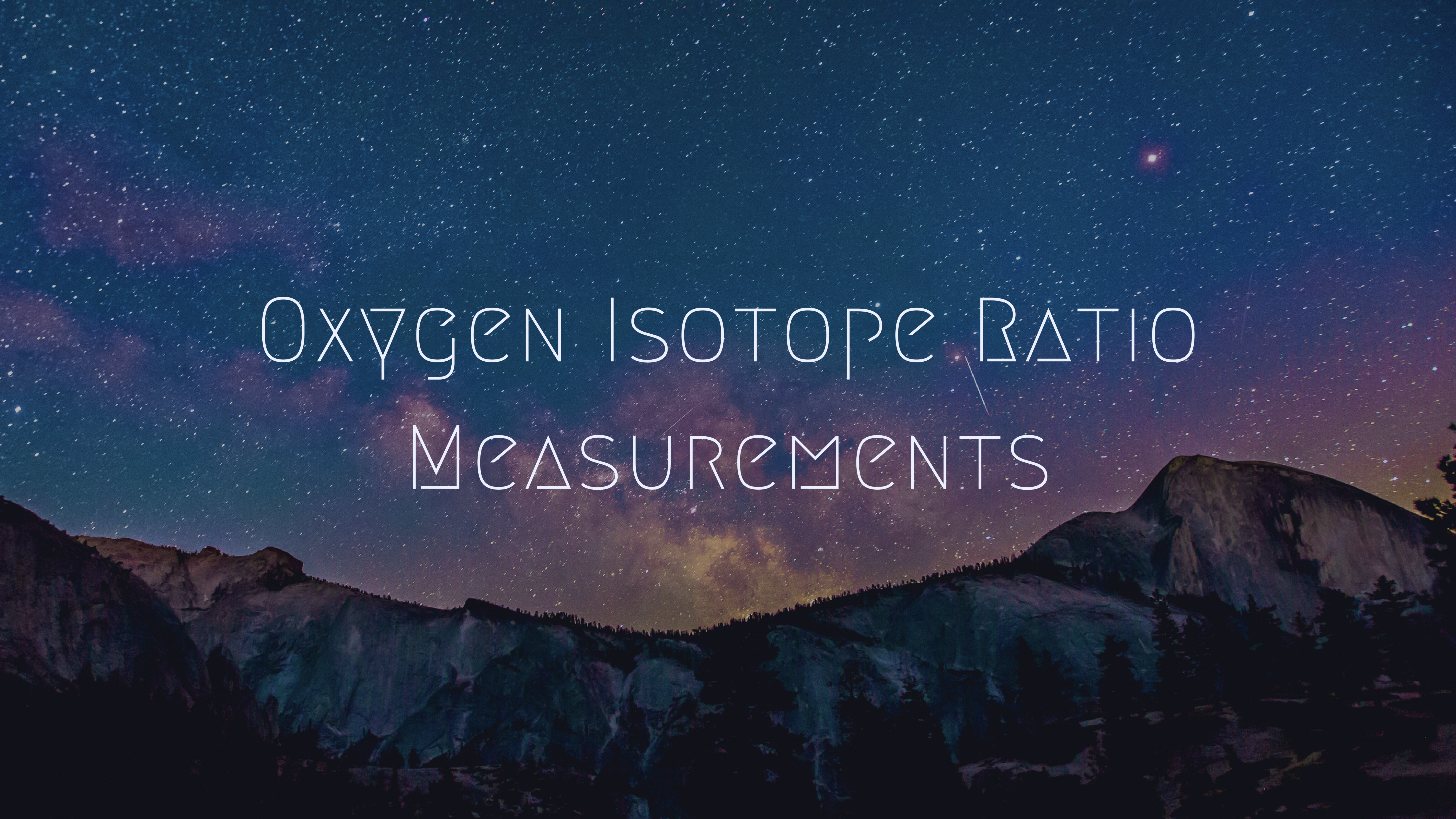
JWST is sensitive to ammonia isotopologues!
Ground-based observatories DO NOT have this wavelength coverage.

14N/15N Ratio: No Measurements in Cool Dwarf Stars!

Sub-stellar nitrogen isotopes are typically detected using ammonia or other isotopologues not suited for stellar abundance determinations



Barrado+ 2023


Oxygen Isotope Ratio
Measurements

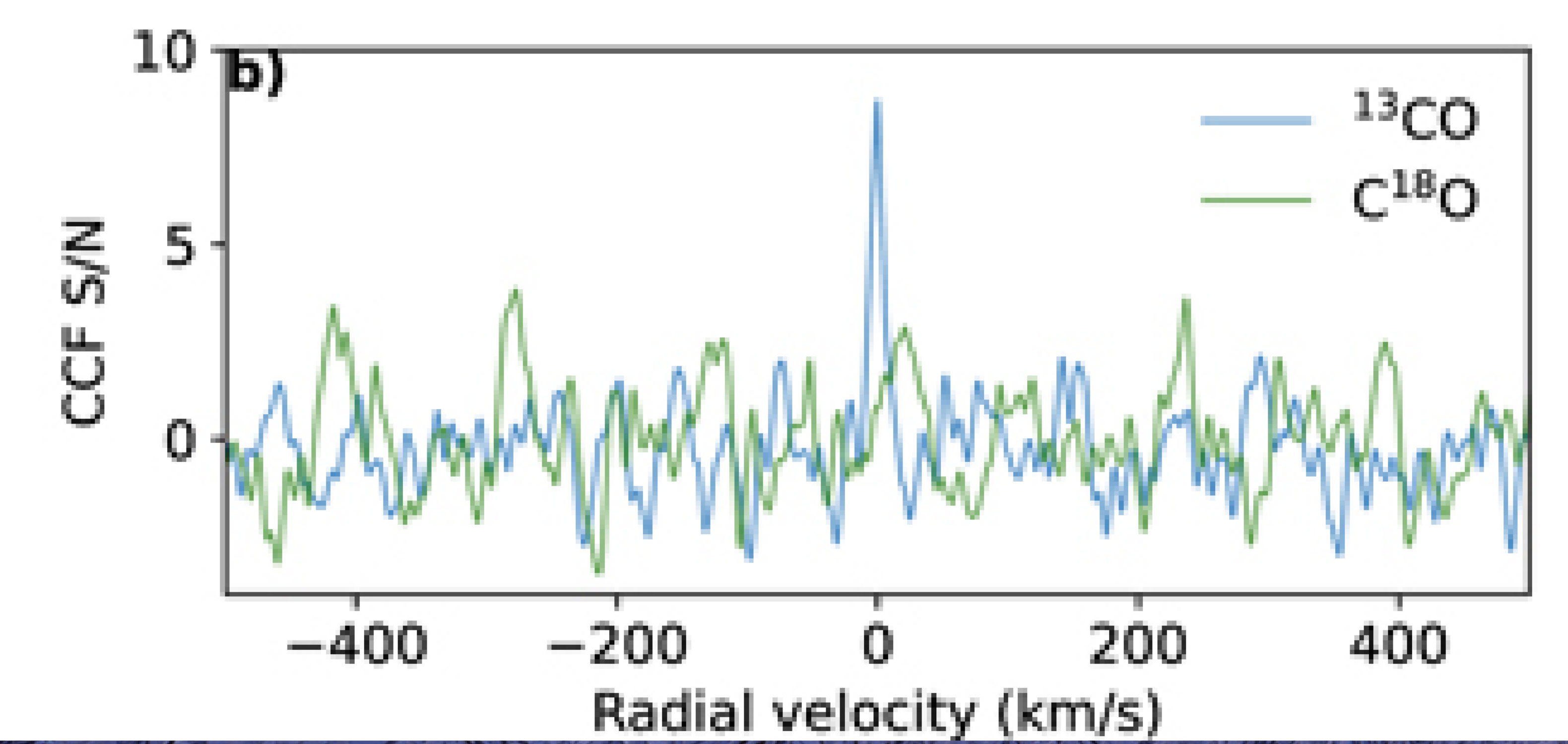
Brown Dwarf: 2M0355

Y. Zhang+ 2022

-0.5 hr on VLT/CRIRES+

-Tentative super-solar constraint $^{16}O/^{18}O$ = 1489 (err: +1027, -426)

- S/N ≲ 2 due to sub-optimal observing conditions



Super-Jupiter: VHS 1256 b

Gandhi+ 2023

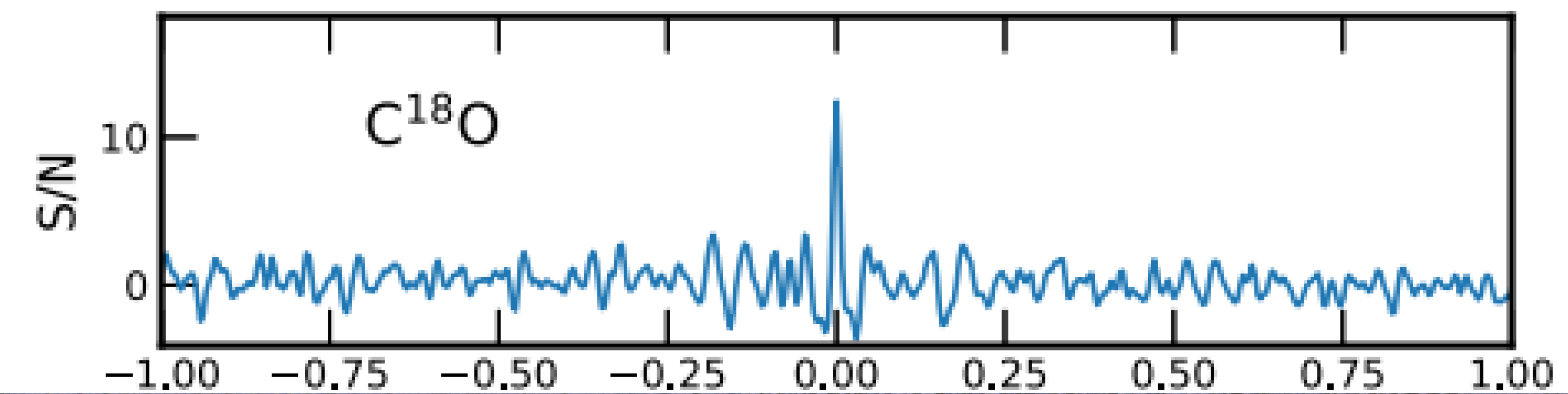
JWST/NIRSpec @ 4.1-5.3 um

-Precise sub-solar constraints

$^{16}O/^{18}O$ = 425± 30

$^{16}O/^{17}O$ = 1010 ± 120

-High S/N data ~ 10



16O/18O In Cool Dwarf Stars

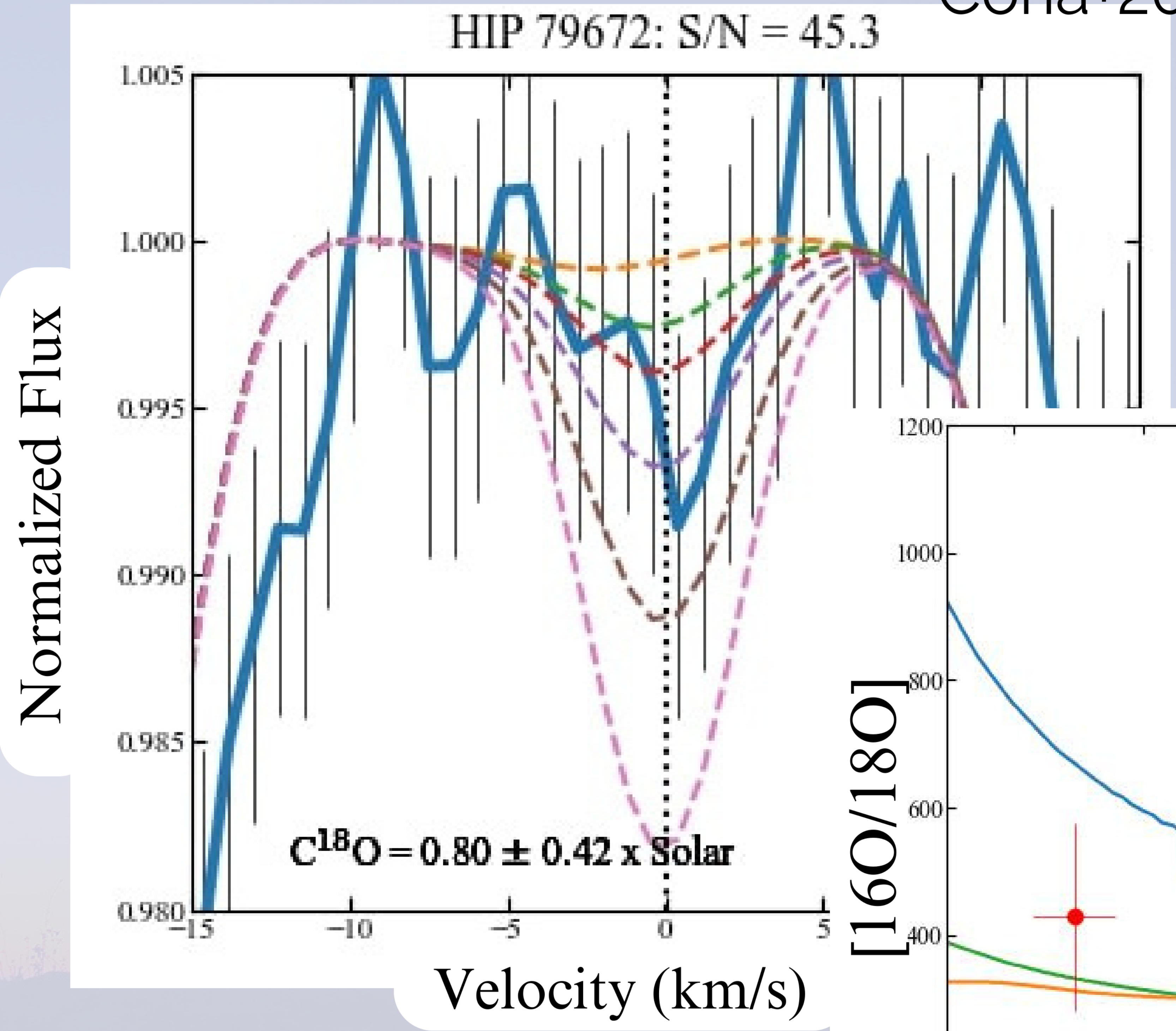
~Only ~8 Dwarf Star Measurements in the Literature; 1 exoplanet Host

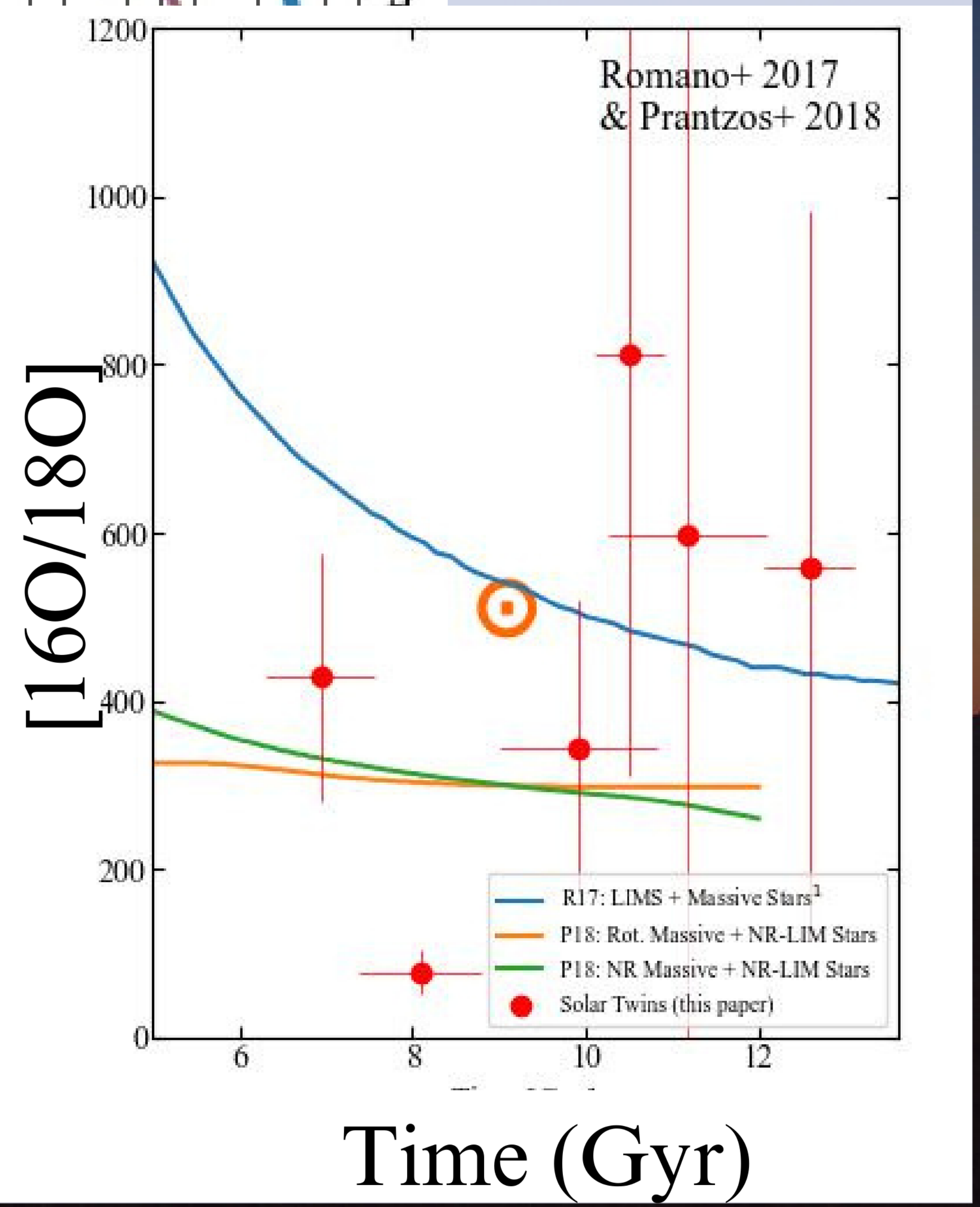
-C18O is a minor isotopologue, less abundant than 13CO

-Lines are WEAK

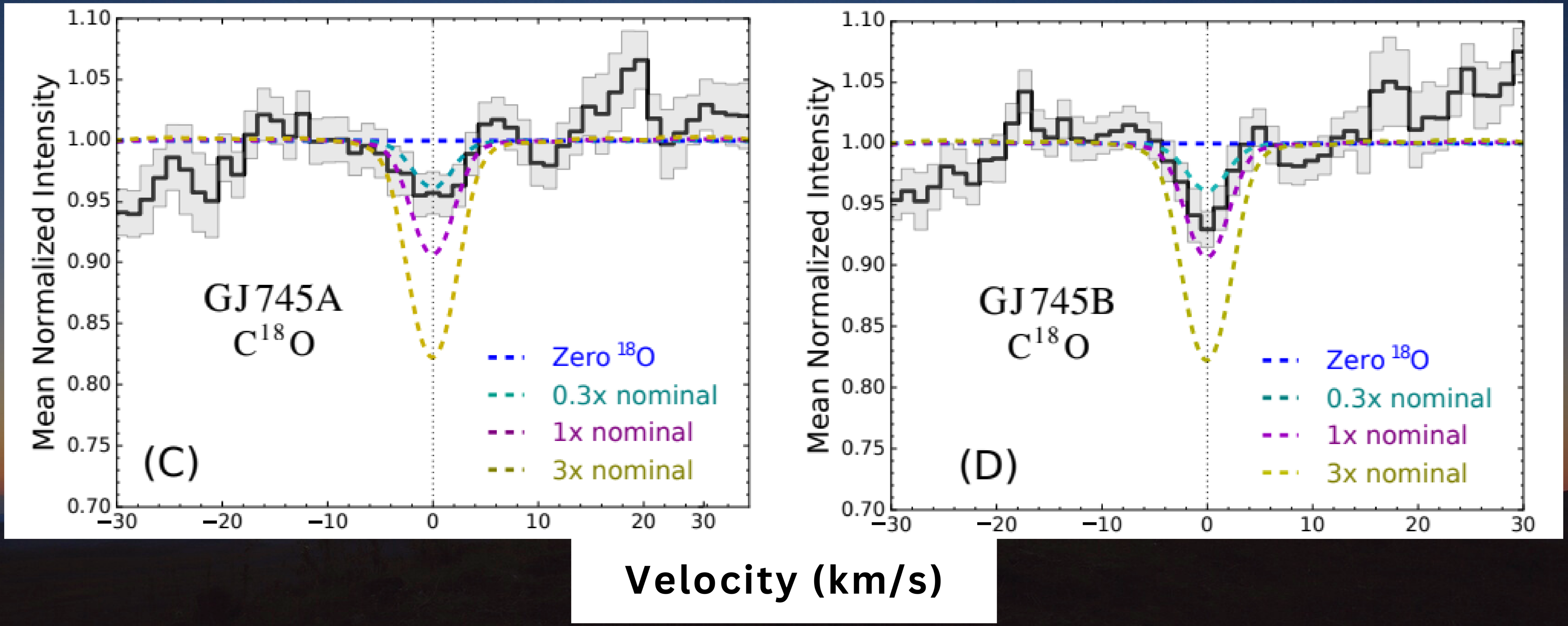
-Analysis requires ~pristine~ spectra; large error bars even in these solar twin stars

Coria+2023





Crossfield+ 2019: 18O Detection in M Dwarf Stars



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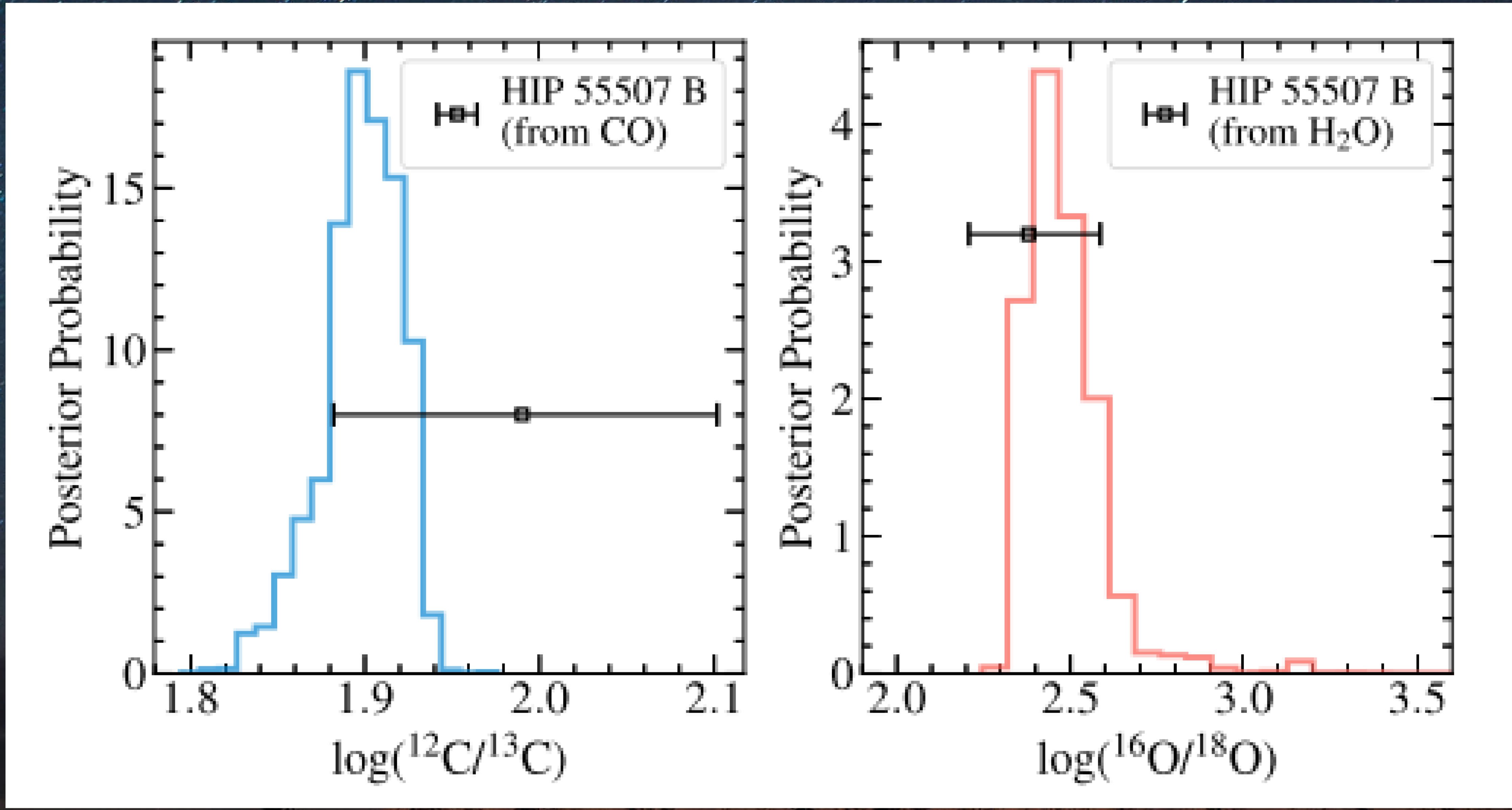
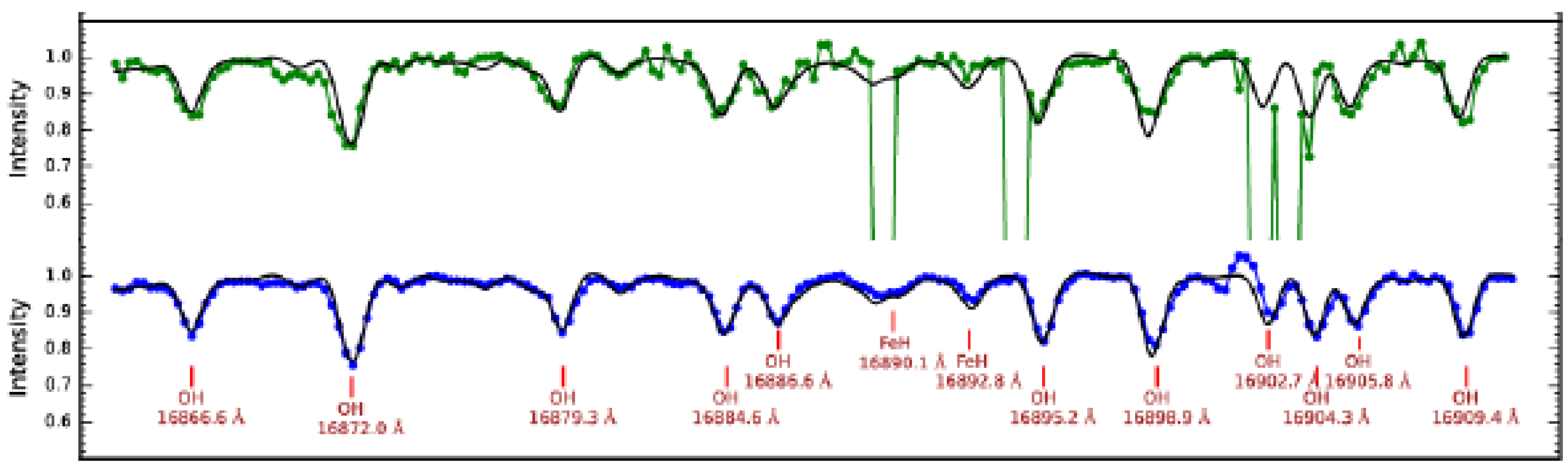
J. Xuan+ 2024: Carbon & Oxygen Isotope Ratios from Retrievals of NIR spectra



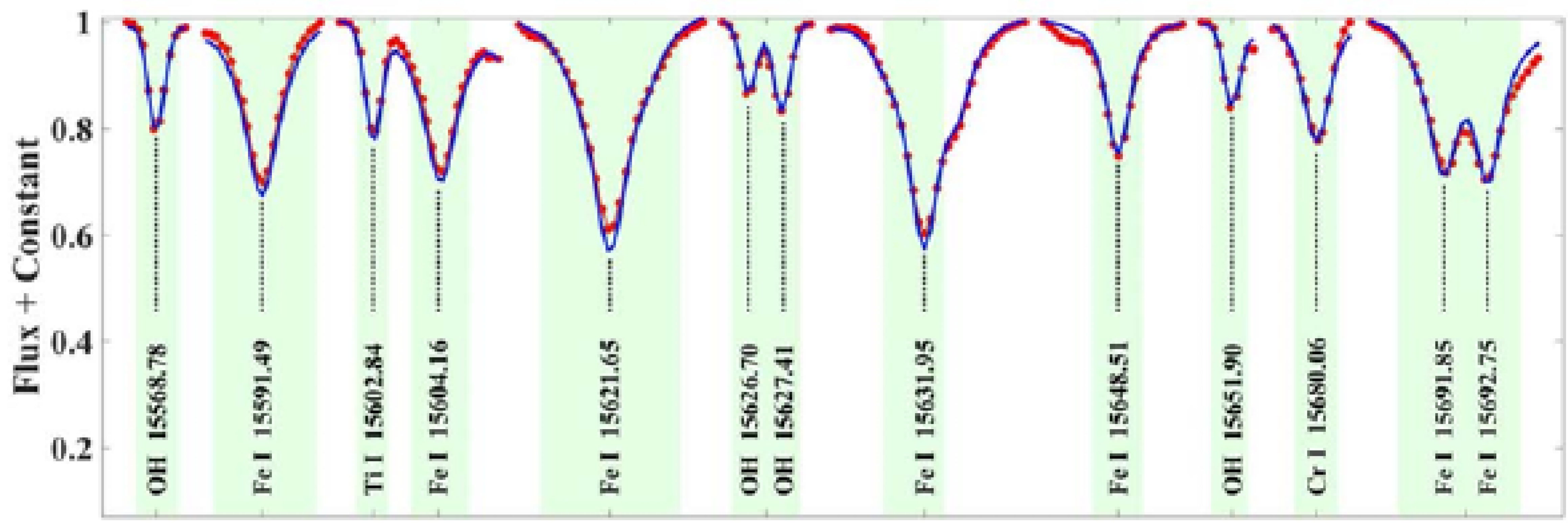
Both CO and H2O isotopologues can be used to derive these ratios from cool dwarf, near-infrared spectra!


Progress In Dwarf Star
Isotope Measurements

Modelling Stellar Spectra & Deriving Abundances



Souto+ 2017, 2018



Hejazi+ 2023

We have the tools necessary to accurately model cool dwarf spectra and measure their abundances precisely!

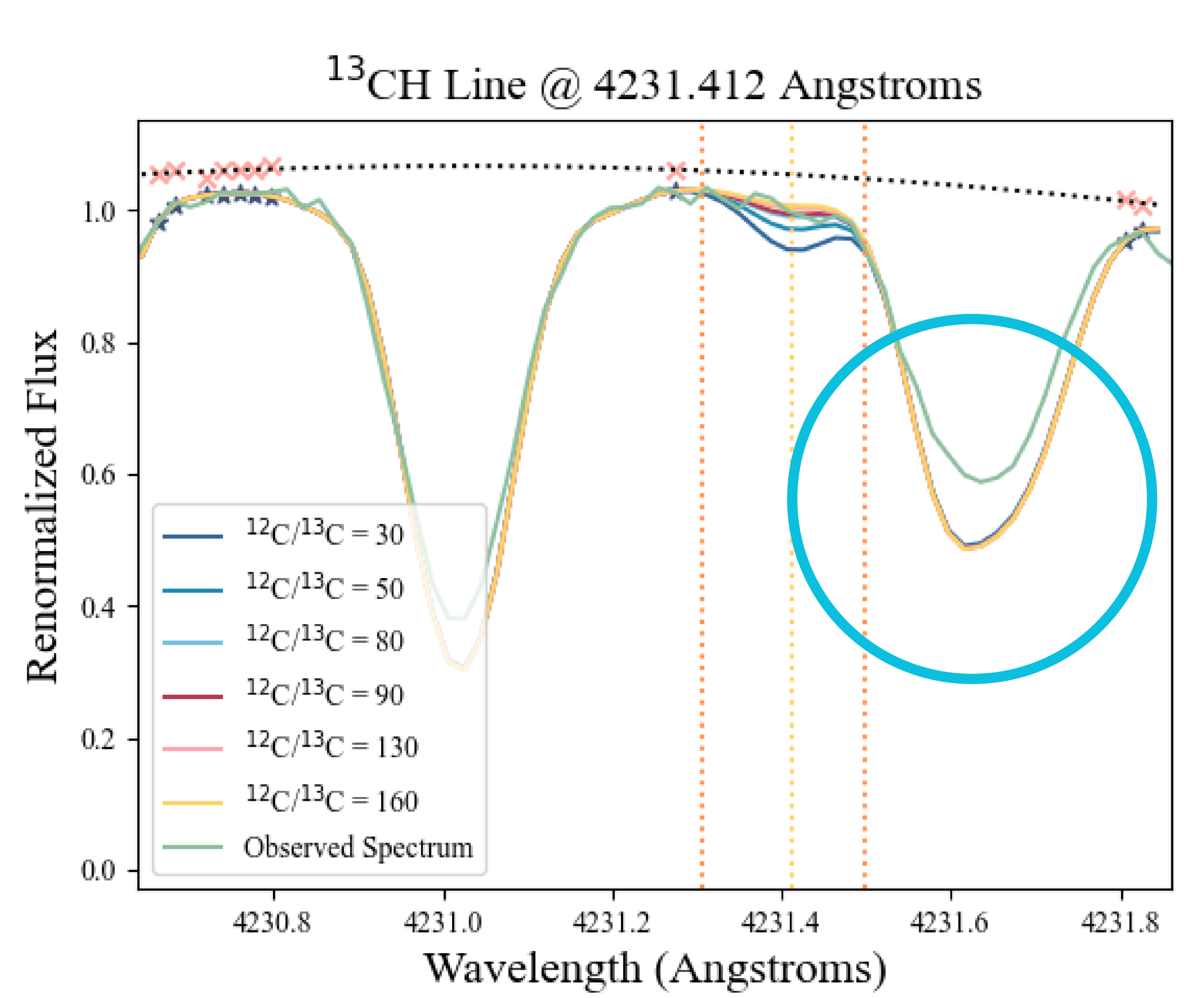
12C/13C in WASP-77A: Keck/HIRES Spectrum

3600 - 4400 Angstroms

-Used MARCS/TurboSpectrum to generate a grid of model spectra with varying 12C/13C

-Analysis requires careful continuum renormalization, and may need elemental abundance fit first

-Weak lines in the optical; CO lines in the NIR are preferable



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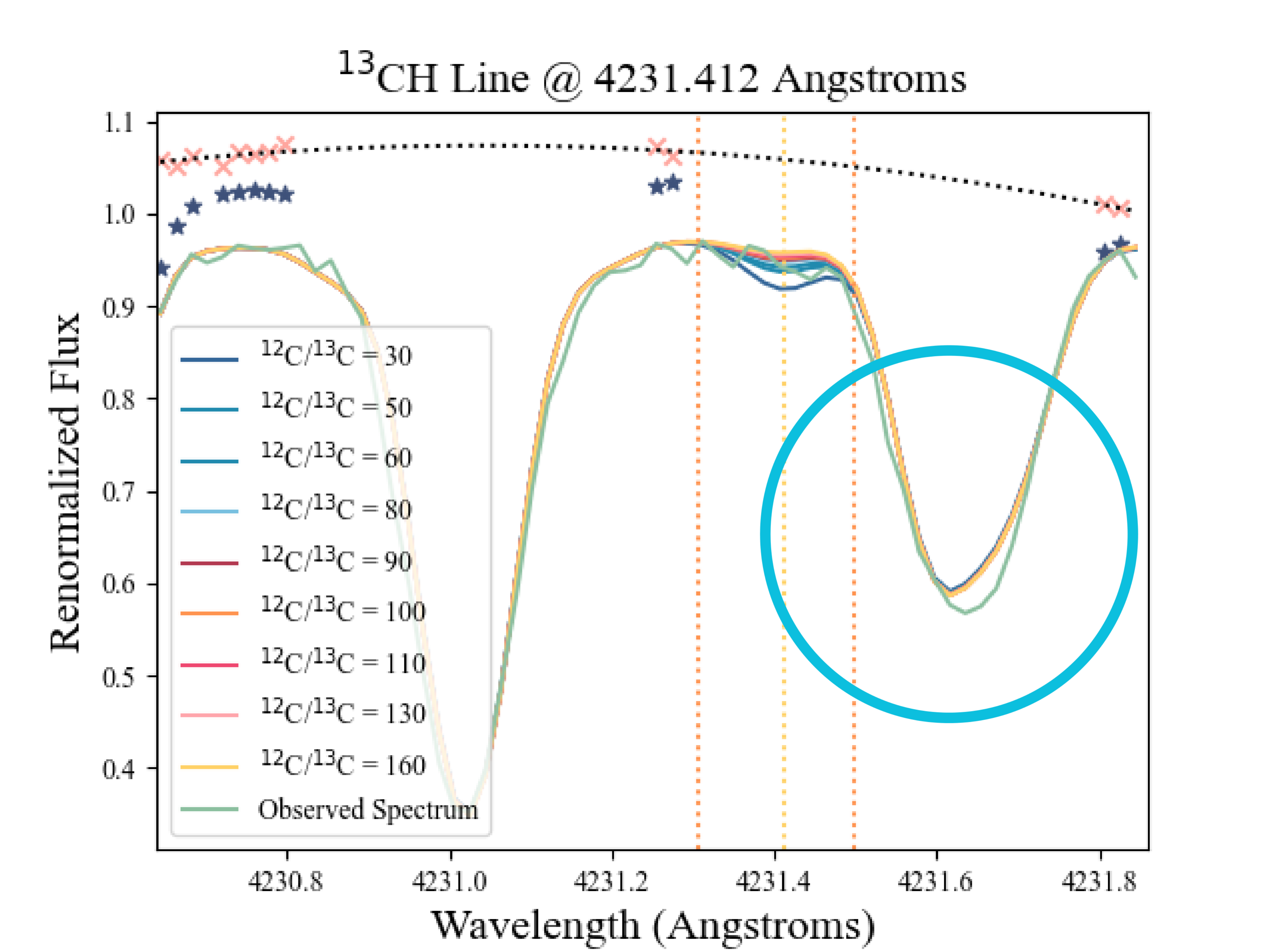

Instrument	Reference	[Fe/H]	[C/H]	[O/H]	C/O
Keck/HIRES	Polanski+ 2022	0.01 ± 0.03	-0.02 ± 0.05	0.06 ± 0.07	0.46 ± 0.09
ARC/ARCES	Reggiani+ 2022	-0.05 ± 0.02	0.10 ± 0.09	0.23 ± 0.02	0.44 ± 0.07
ESO/FEROS	Kolecki & Wang 2022	-0.15 ± 0.06	-0.04 ± 0.04	-0.04 ± 0.04	0.59 ± 0.08

Host Star: WASP-77A

12C/13C: 52 ± 9

Instrument	Reference	[Fe/H]	[C/H]	[O/H]	C/O
Gemini/IGRINS	Line+ 2021	-0.48 ± 0.15	-0.46 ± 0.17	-0.49 ± 0.14	0.59 ± 0.08
JWST/NIRSpec	August+ 2023	-0.91 ± 0.24	X	X	0.36 ± 0.10

Hot Jupiter: WASP-77Ab

12C/13C: 26.4 ± 16.2

KEY TAKEAWAY

1) Embrace the Host Star!

Exoplanet atmosphere constraints are best interpreted in the context of their parent star.

NEXT STEPS

1) ID more "formation tracer abundances"

*****Nitrogen and Sulfur may be useful!**

2) Measure formation tracer abundances in stars hosting Jupiter-class planets where complementary measurements are possible

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