



Roasting Marshmallows: A Campaign to Disentangle
Composition & Climate in Hot Jupiter Atmospheres with Near
Infrared High Resolution Cross-Correlation Spectroscopy

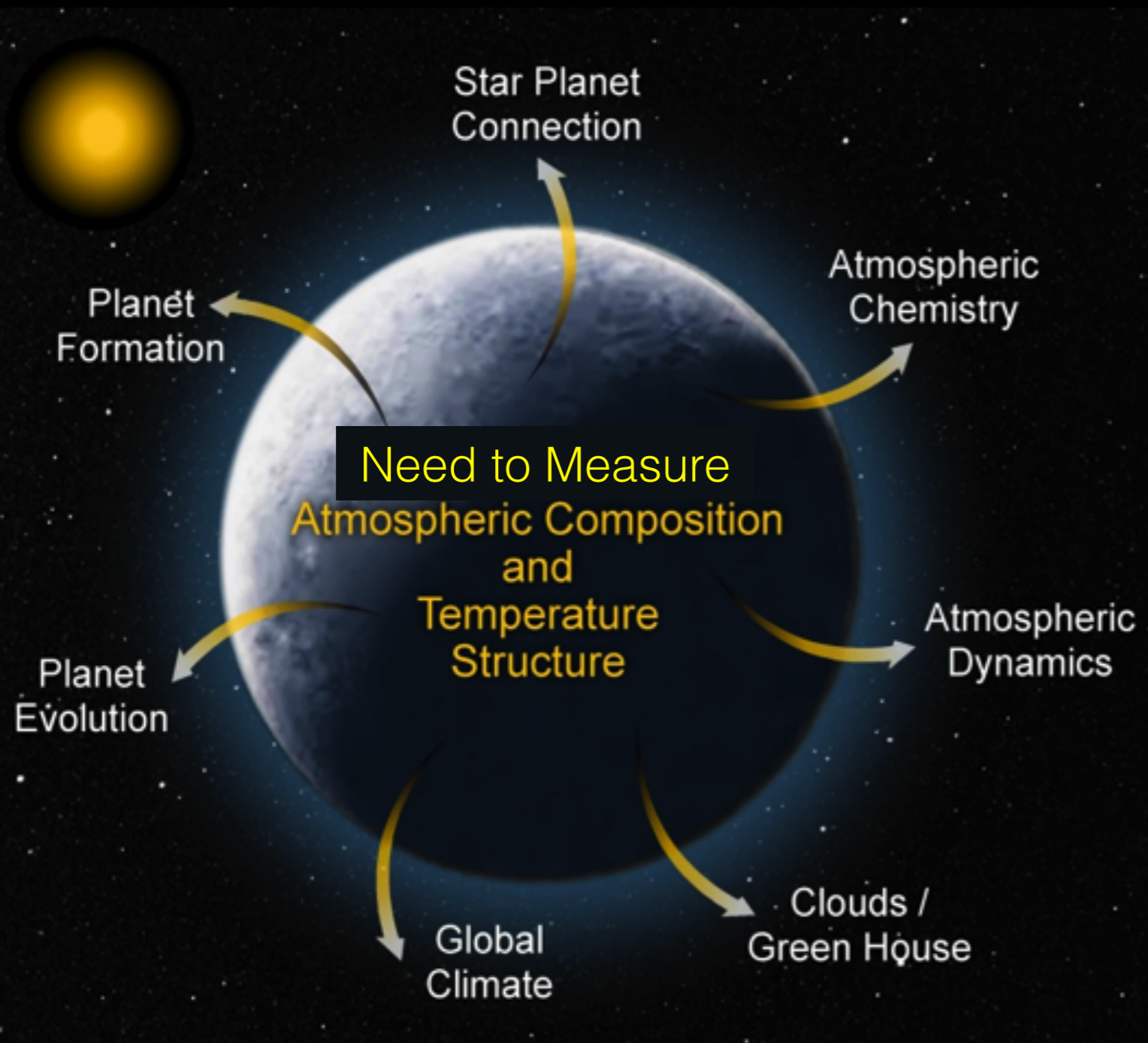
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Jorge Sanchez, Peter Smith, Matteo Brogi, Jacob L.
Bean, Megan Mansfield, Siddharth Gandhi, Joseph
Zalesky, Vivien Parmentier, Gregory N. Mace,
Eliza M.-R. Kempton, Jonathan J. Fortney,
Evgenya Shkolnik, Jennifer Patience, Emily
Rauscher, Jean-Michel De'sert, & Joost P.
Wardenier

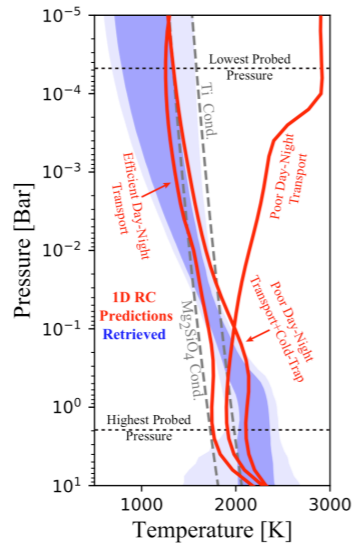
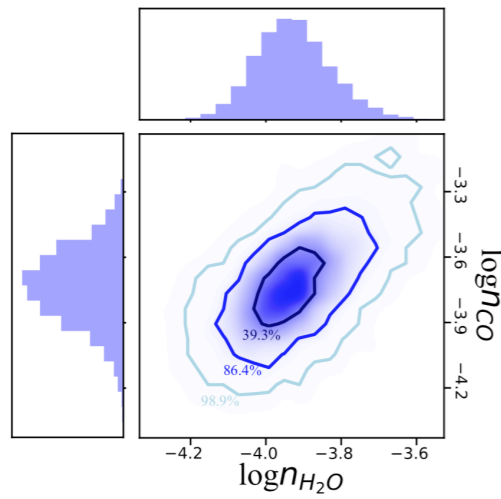
The Astrophysics of Exoplanets: Origins and Processes



- How do atmospheres form and evolve?
- Does atmospheric composition reflect formation conditions?
- What is the range of planetary climates?
- What are the driving atmospheric chemical processes?
- What is the prevalence of biosignatures?

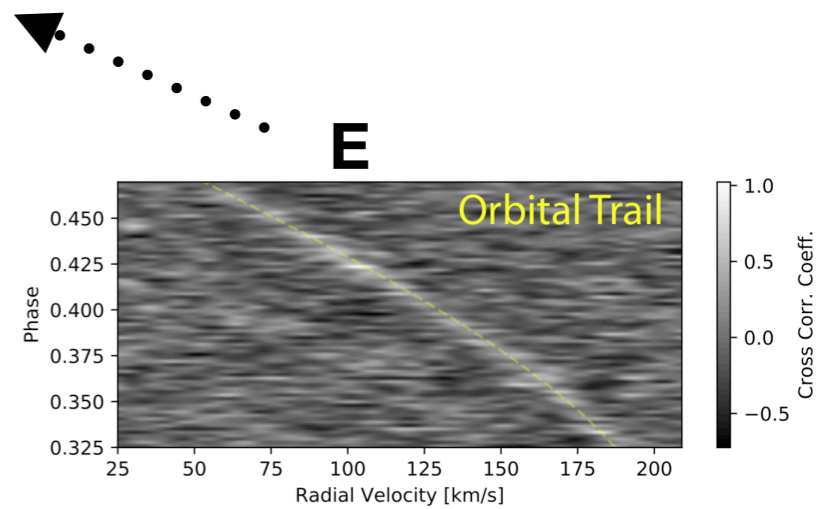
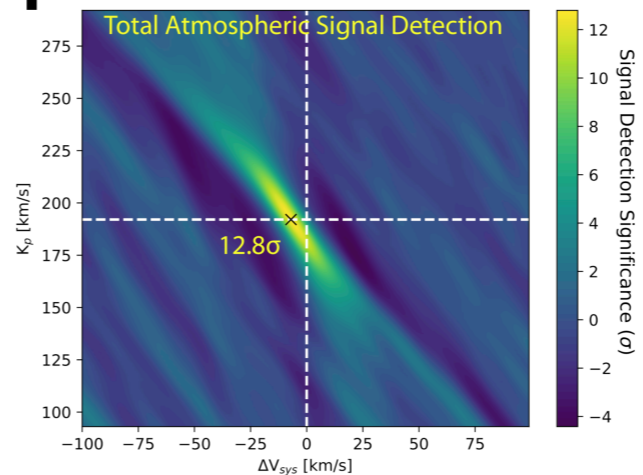
Characterization at High Resolution

Atmospheric Constraints

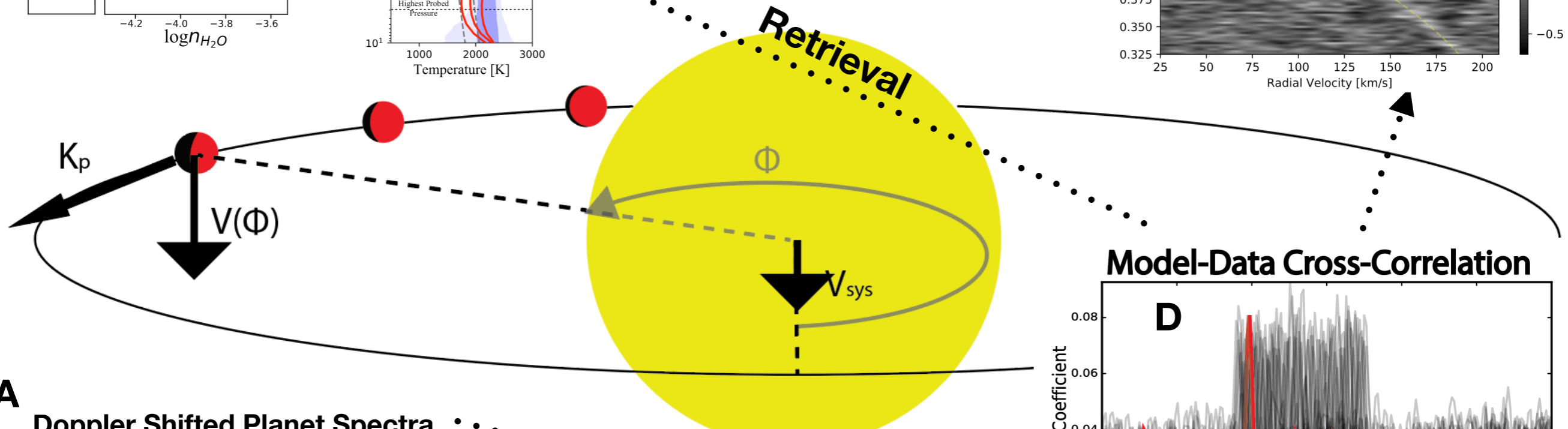


G

F

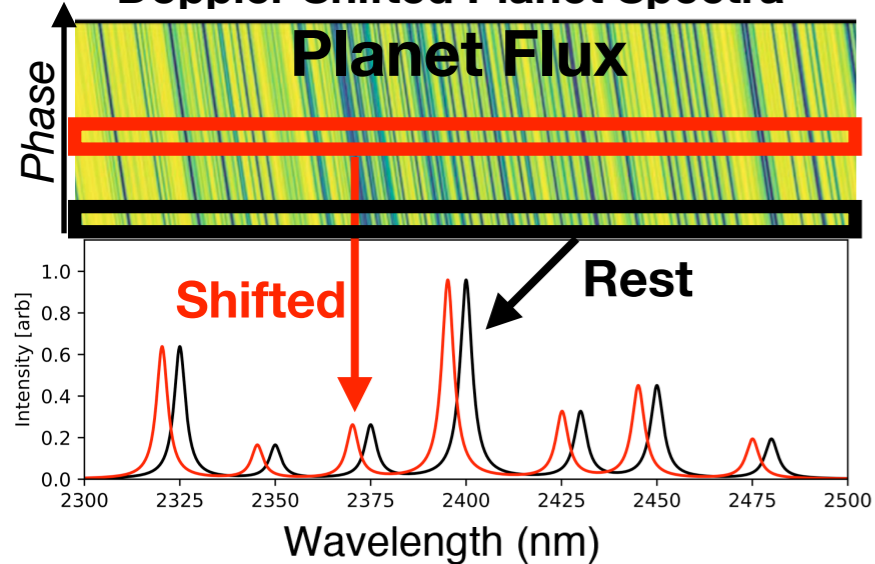


E

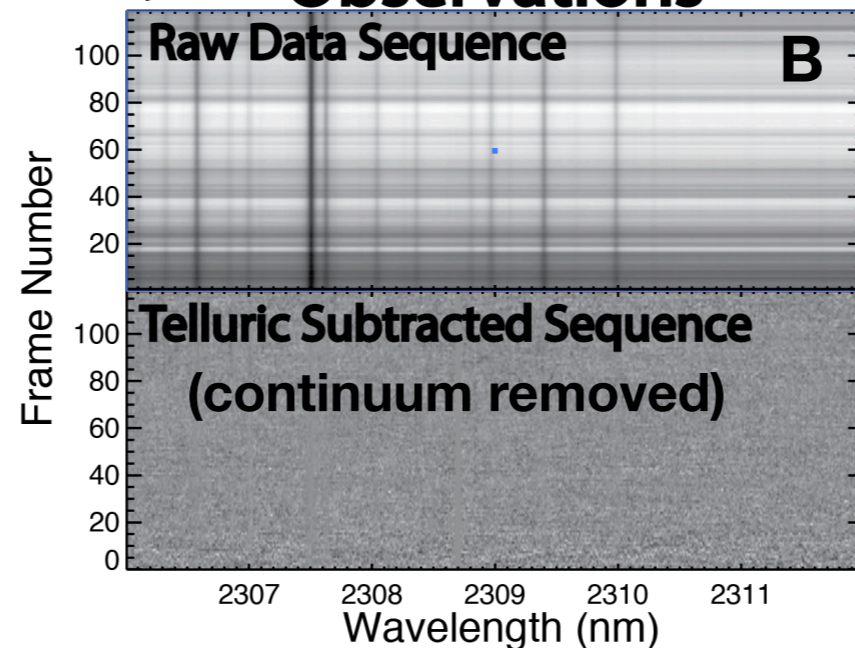


A

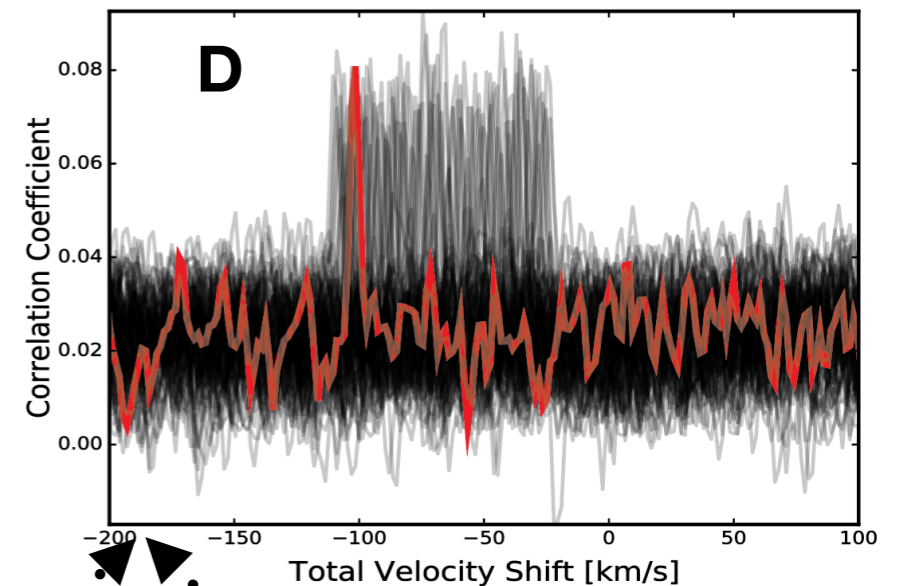
Doppler Shifted Planet Spectra



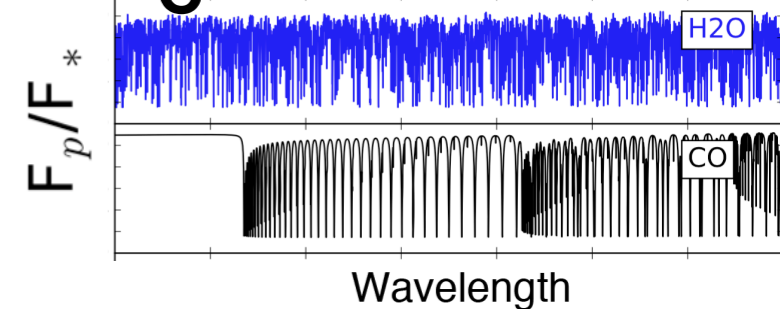
Observations



Model-Data Cross-Correlation



Model Template



Pilot Study: What can IGRINS on GS do?



Immersion GRating INfrared Spectrometer—Gemini South

$R \sim 45,000$,

$D_{\text{tel}} = 8.1 \text{ m}$

$\Delta\lambda = 1.45 - 2.5 \text{ }\mu\text{m}$

$\text{SNR}_p \sim 5x \text{ CRIRES K-band}$

WASP-77Ab

$M_K = 8.4$

$K_p \sim 190 \text{ km/s}$

$V_{\text{sys}} \sim 1.7 \text{ km/s}$

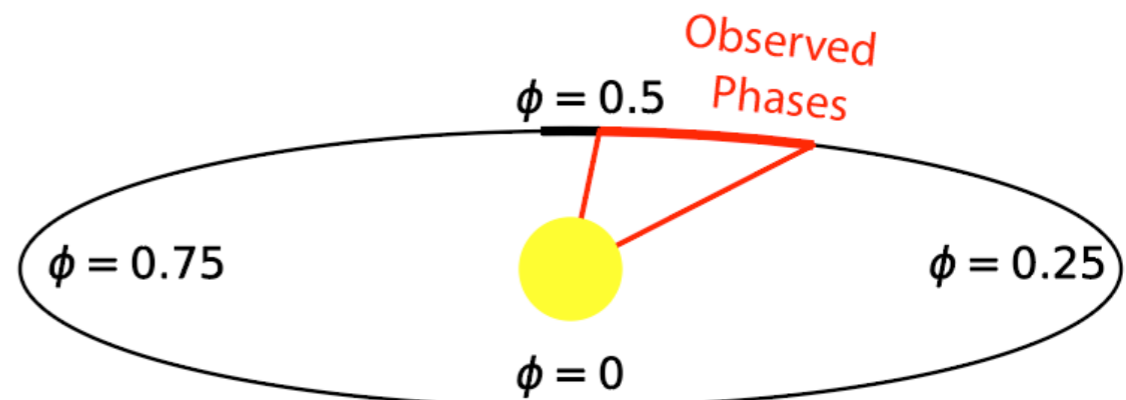
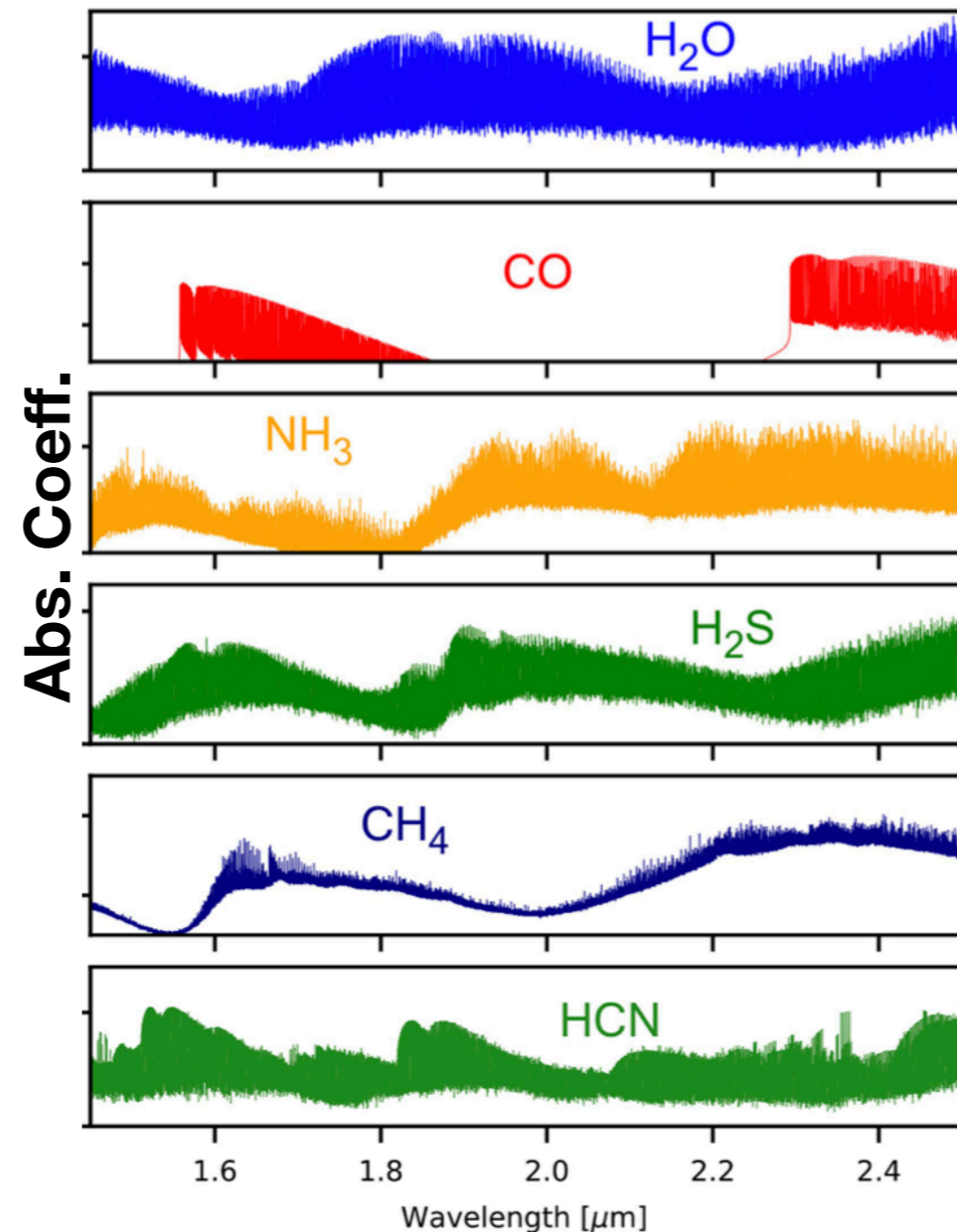
$T_{\text{eq}} \sim 1750 \text{ K}$

79 140s Frames (A+B)

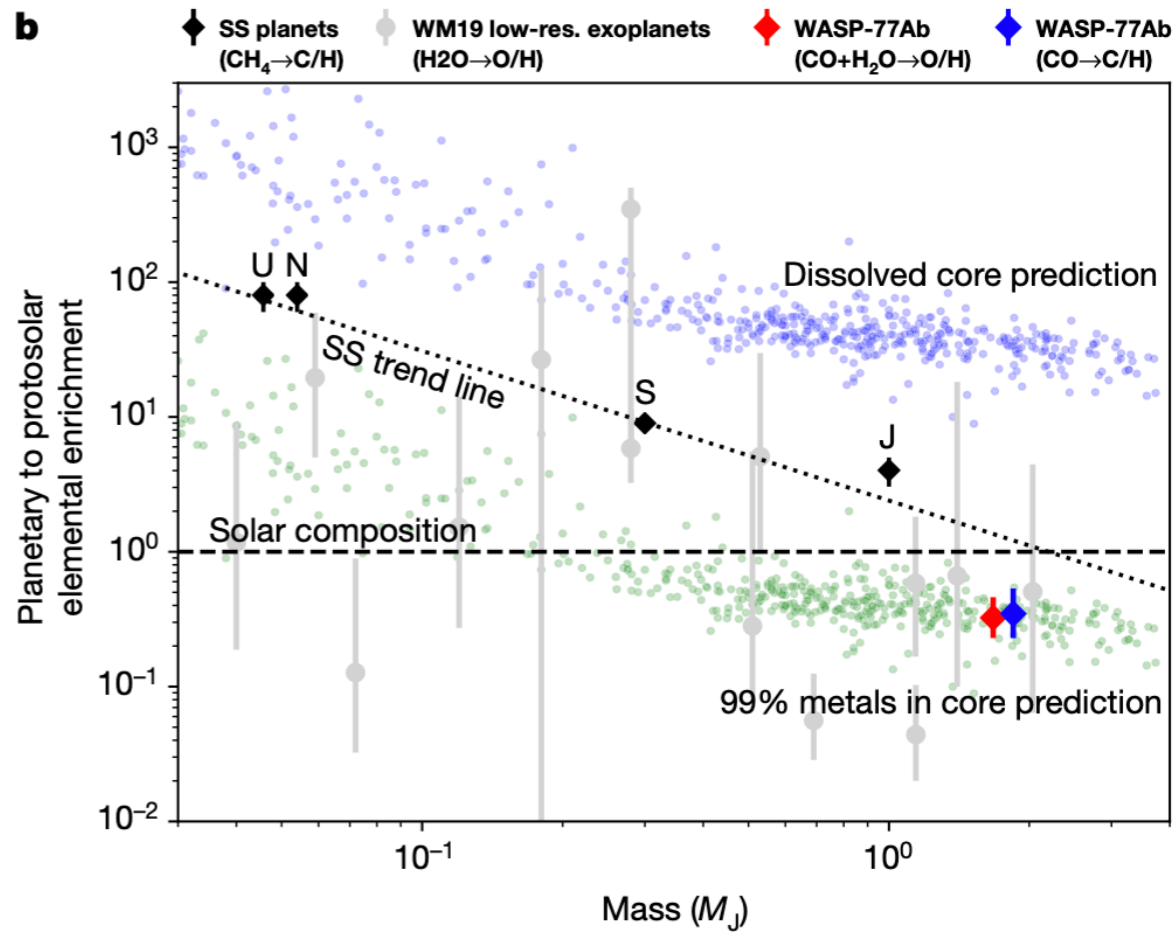
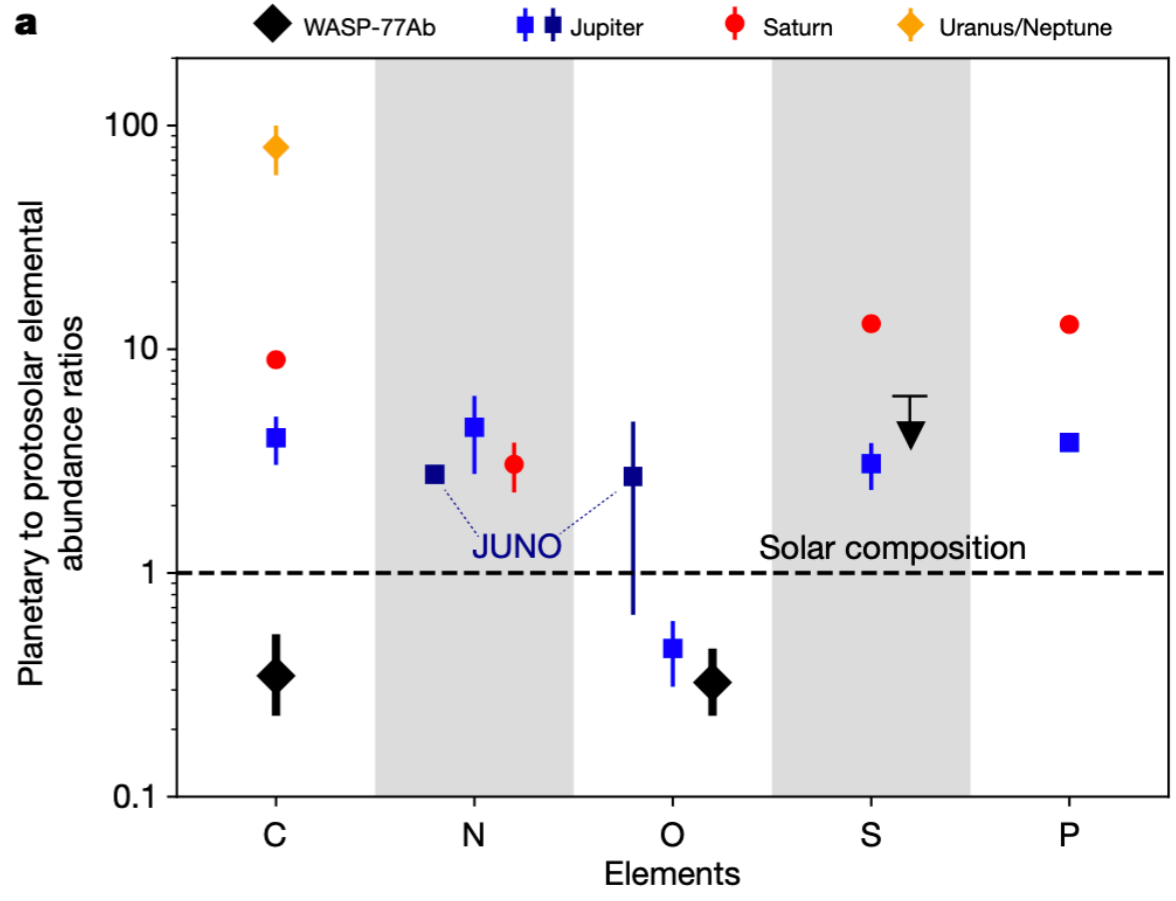
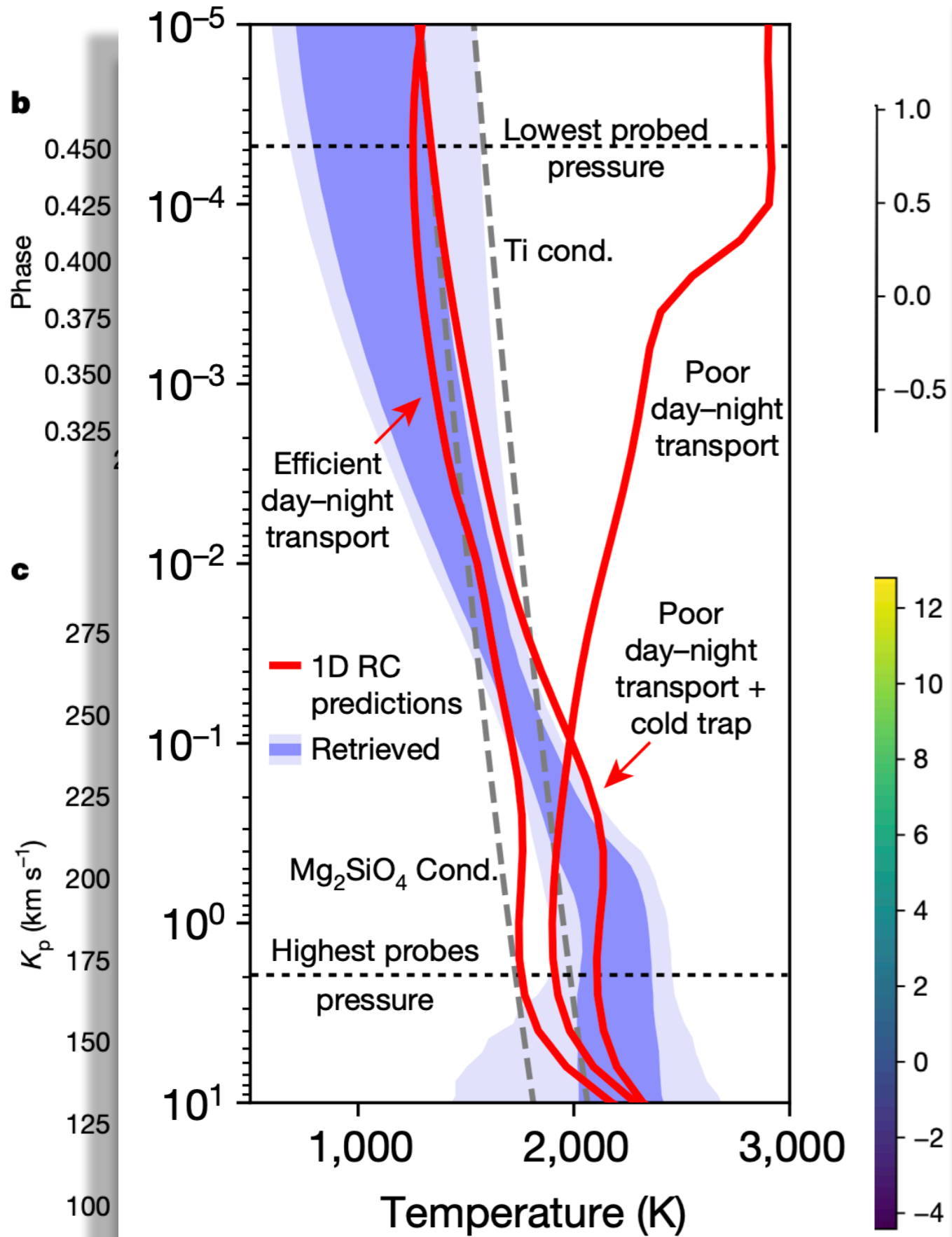
Total of 4.7 hr

Dec. 2020

$\text{SNR} \sim 200\text{-}300/\text{res}$



Strong Signal Detection and “ultra-precise” Abundance/TP Constraints!

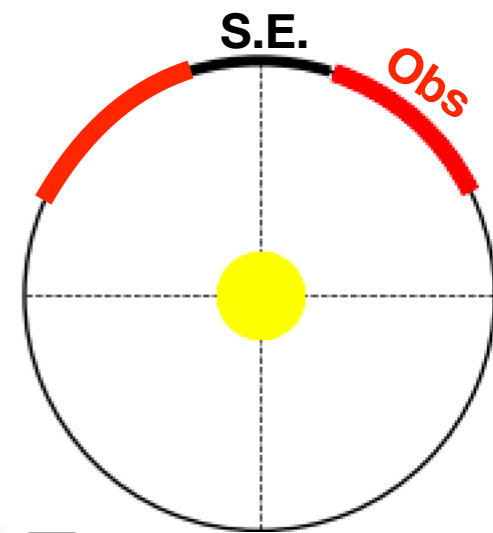
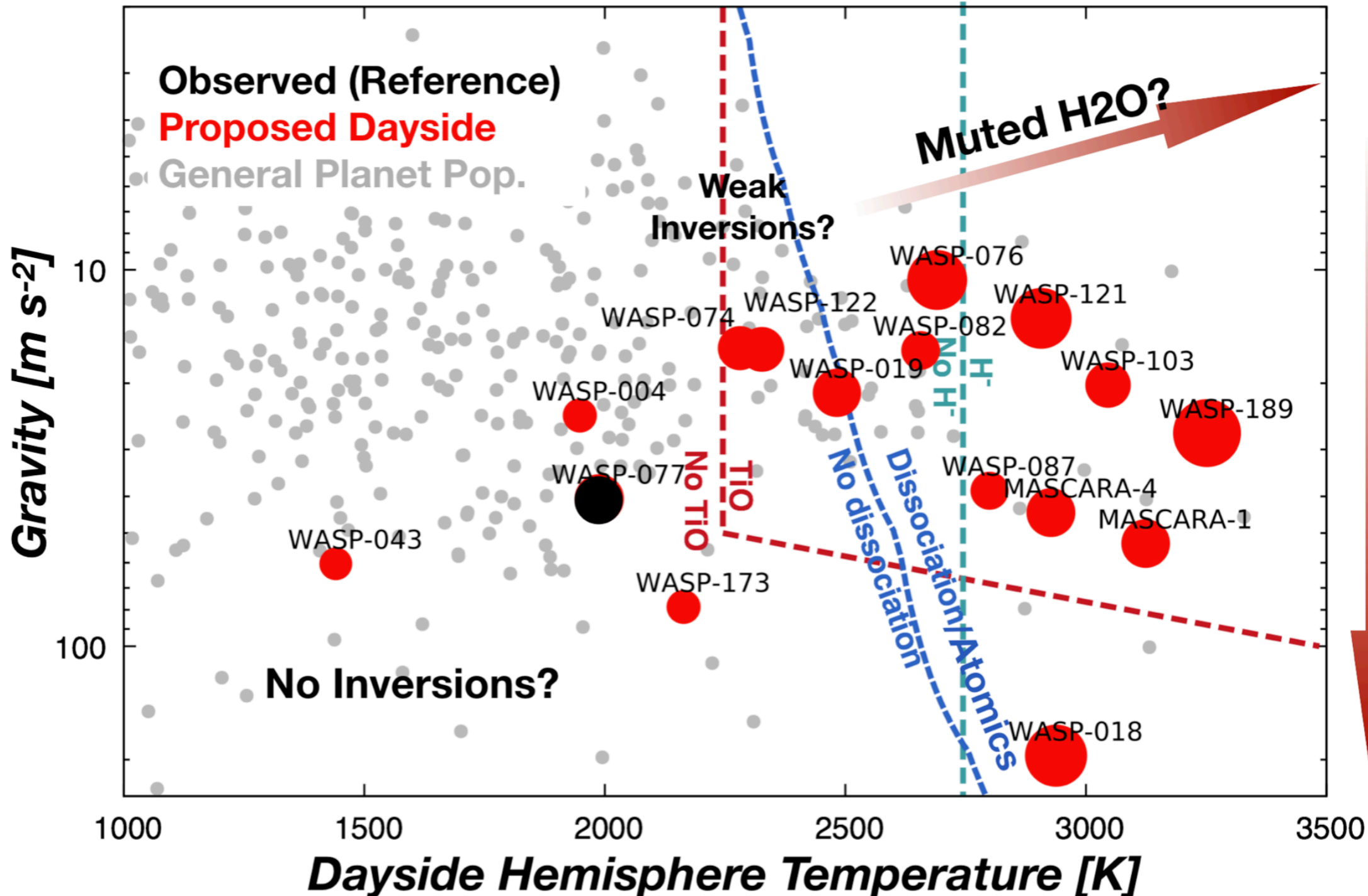


Roasting Marshmallows: Disentangling Composition & Climate in Hot Jupiter Atmospheres through High-Resolution Thermal Emission Cross-Correlation Spectroscopy

117 hrs IGRINS/G-South LLP (2021B-2024A),
15 planets, “pre+/-or post eclipse” phases

Efficient Heat Transport?

Stronger inversions?

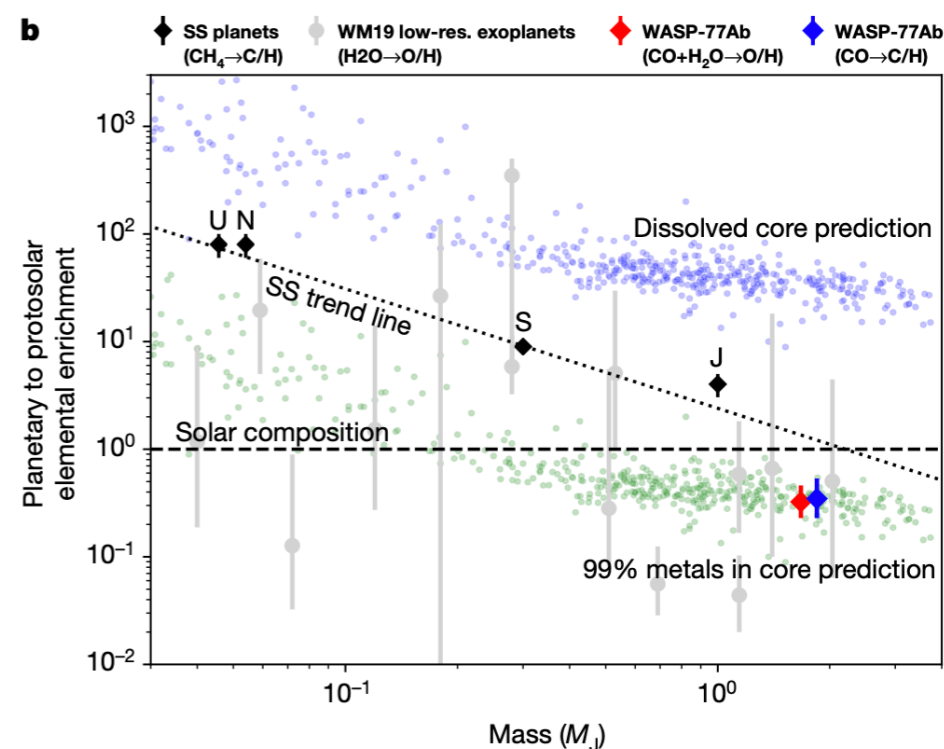
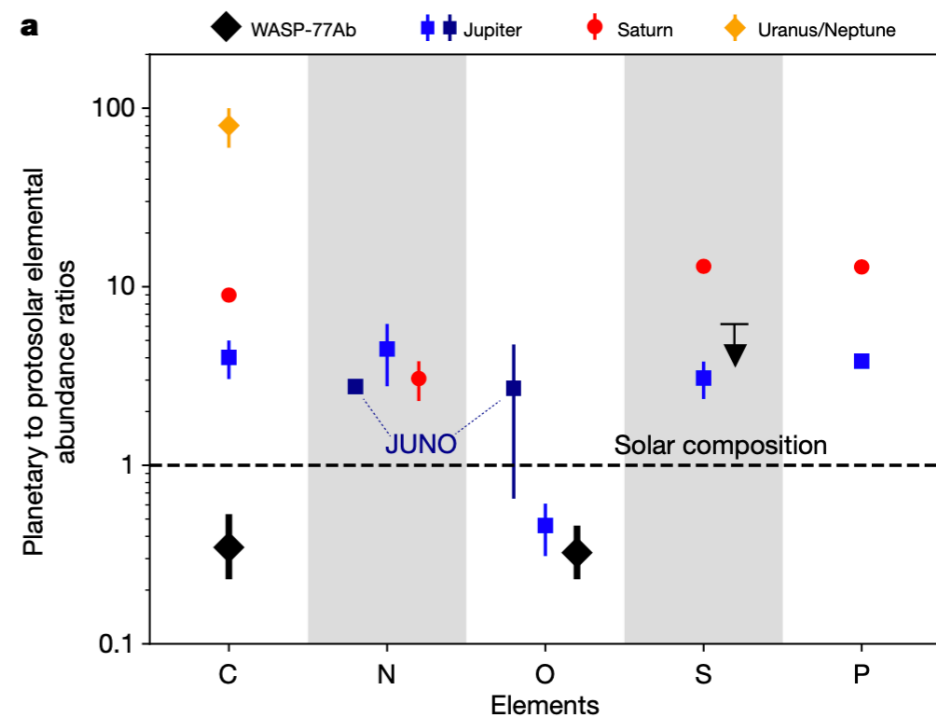
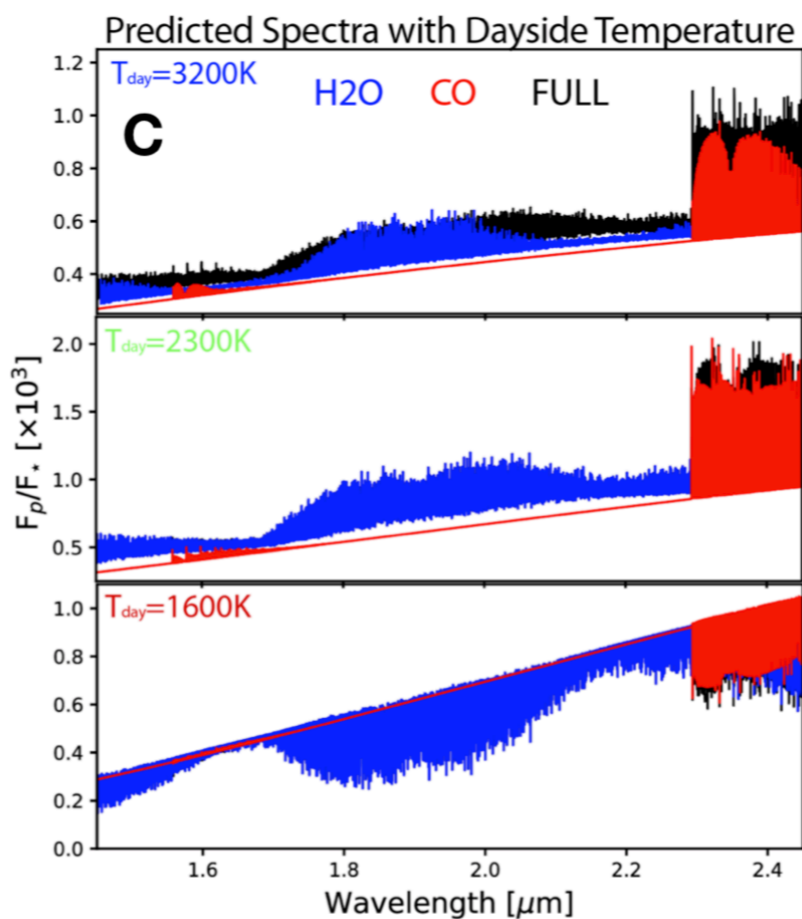
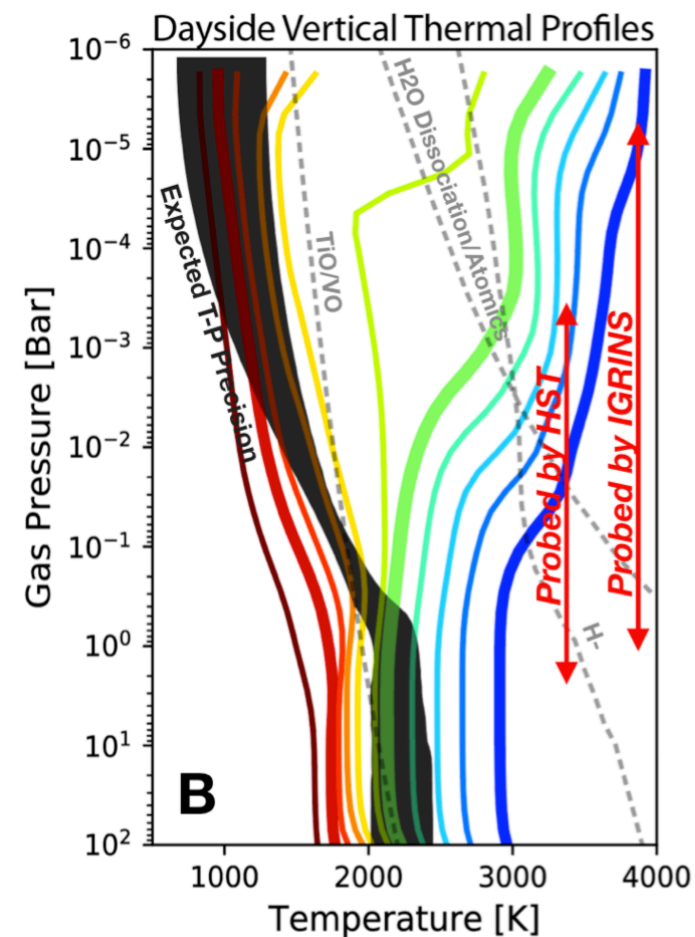
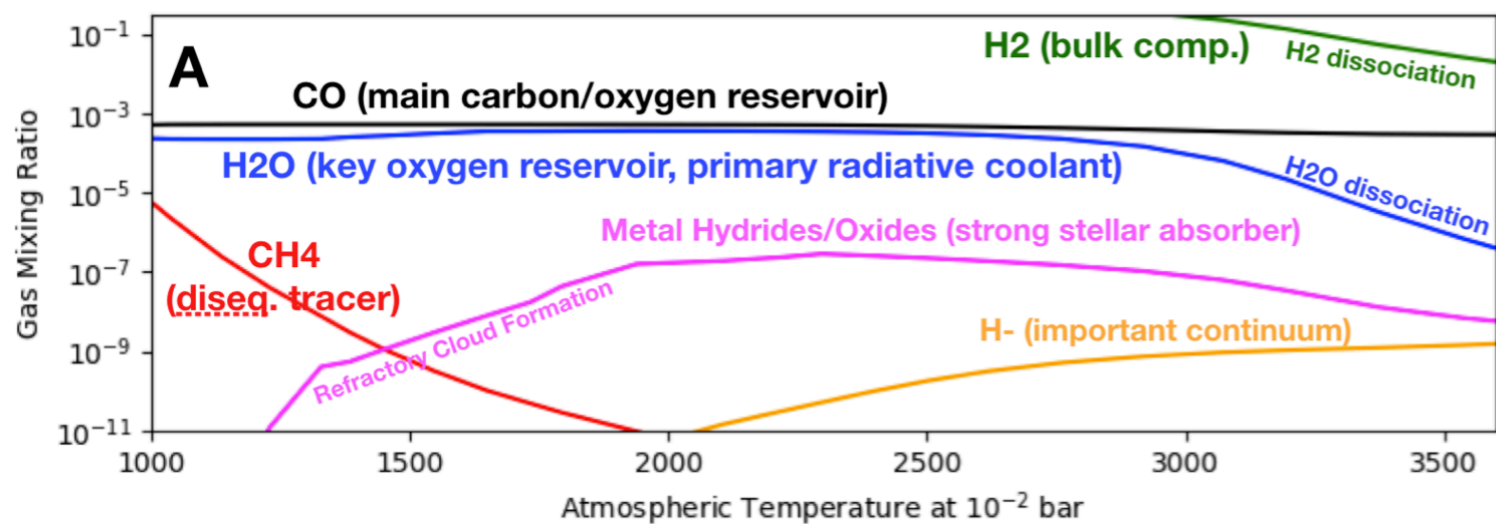


To Obs

Efficient Heat Transport?

Key Questions: What/where are major chemical/thermal transitions?

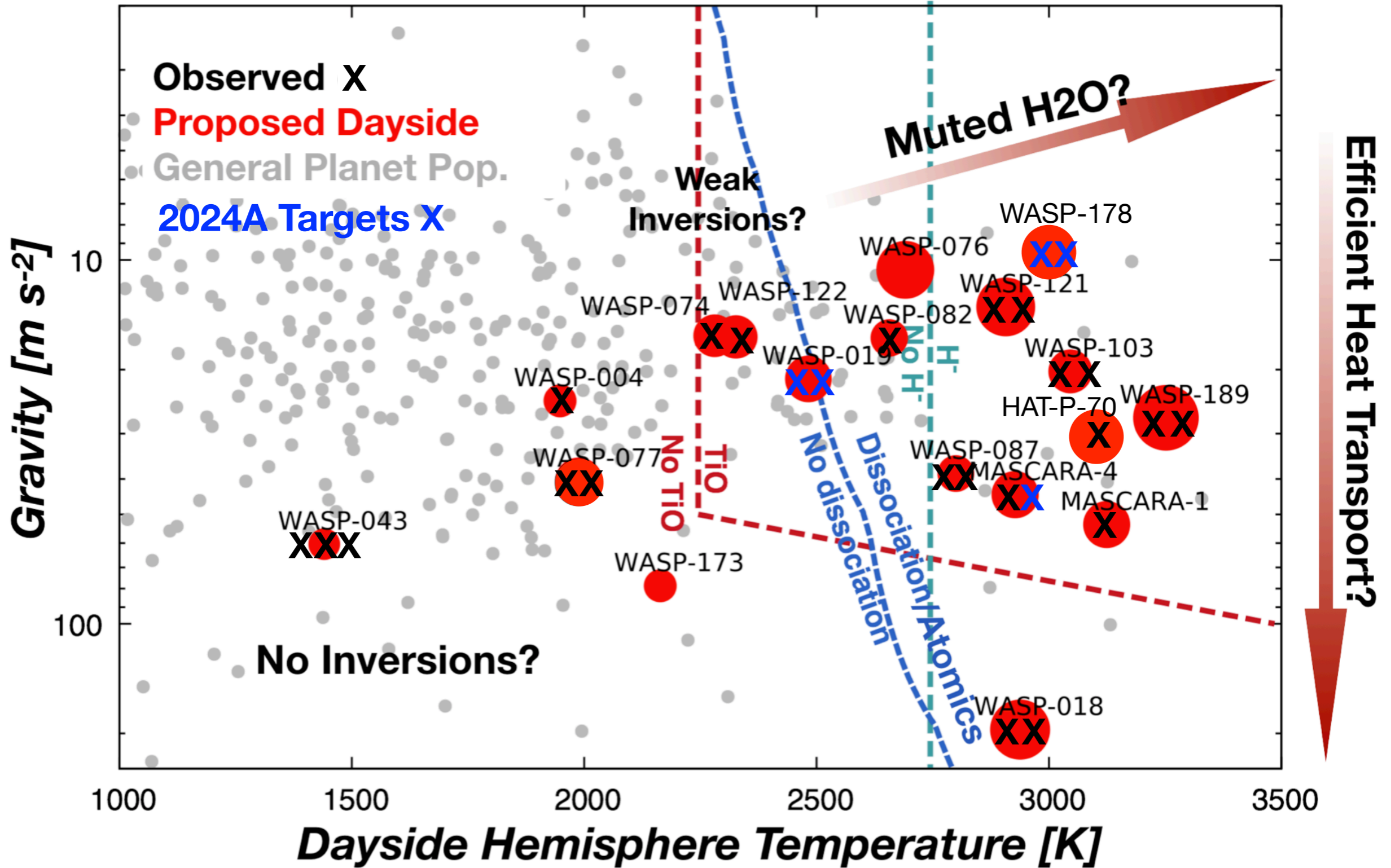
What are intrinsic elemental C and O abundances?



Current Status (LLP+FT's+Queue's)

Efficient Heat Transport?

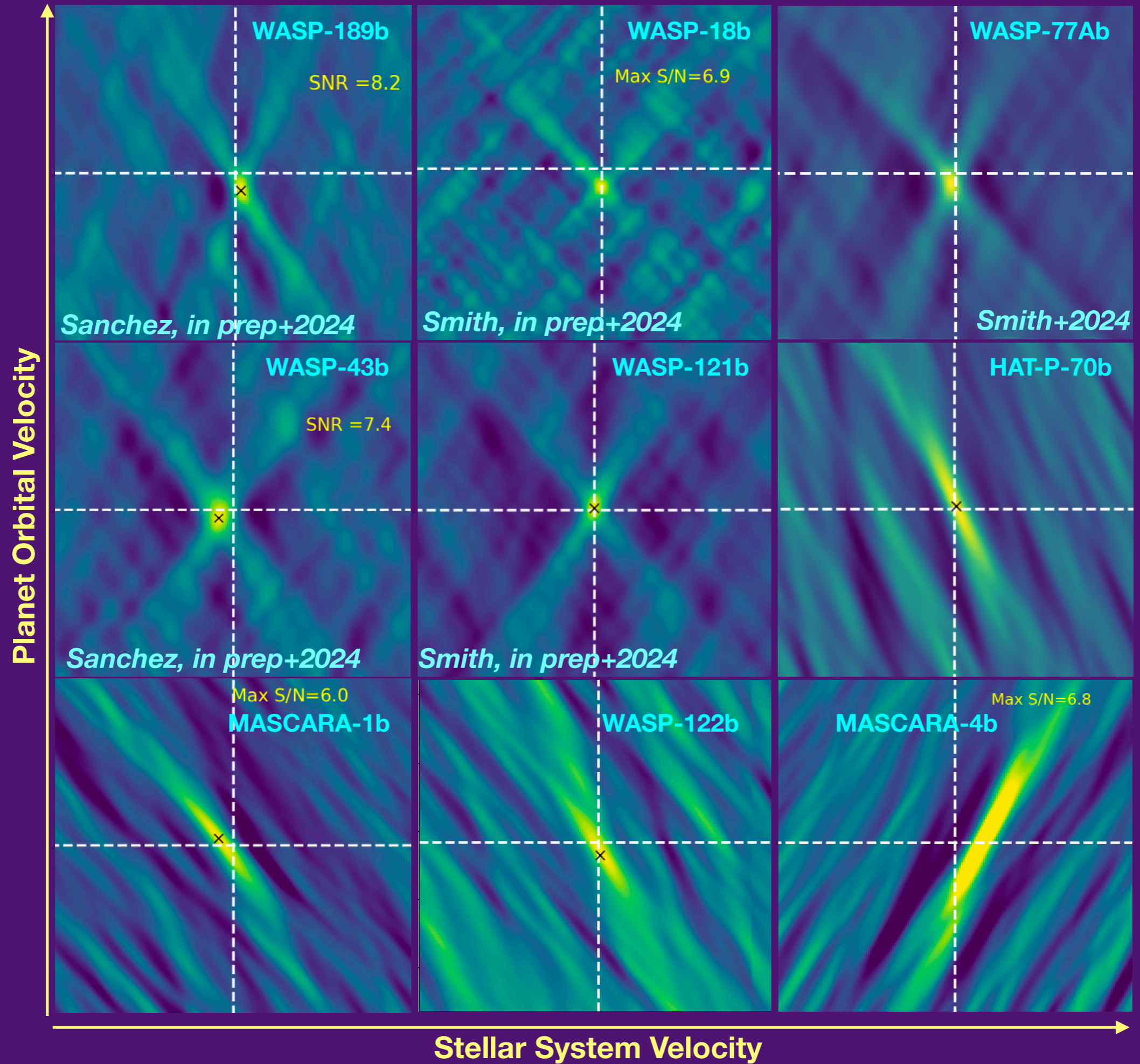
Stronger inversions?



WASP-18 post eclipse: 2022B-FT-203, Line WASP-43 another post/pre-eclipse: 2023A-FT-106, Sanchez

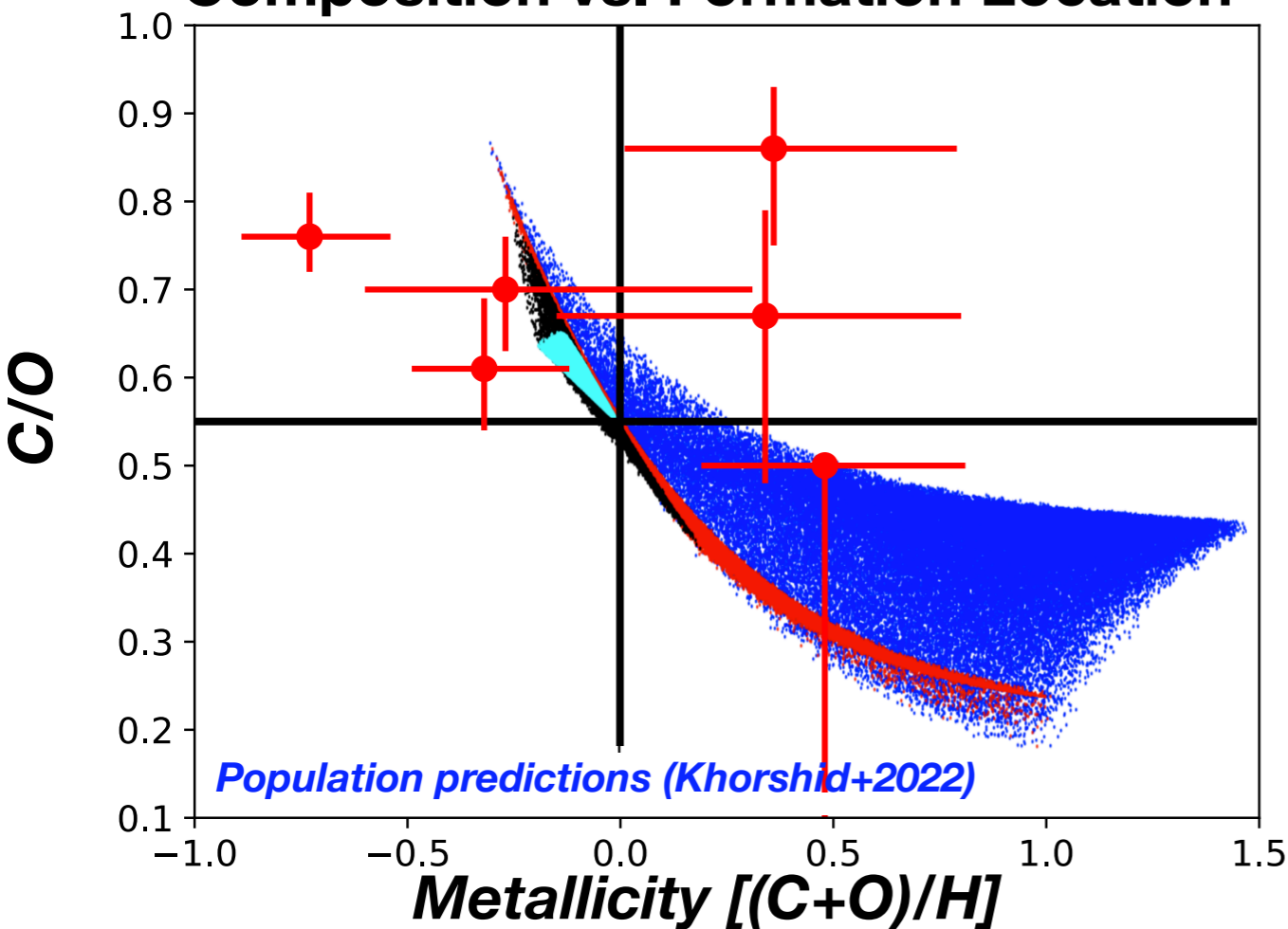
WASP-121 post-eclipse: 2023A-Q-222, Rauscher WASP-189 post-eclipse: 2023A-Q-231, Sanchez

Signal Detection with Model Templates (H₂O+CO+OH)

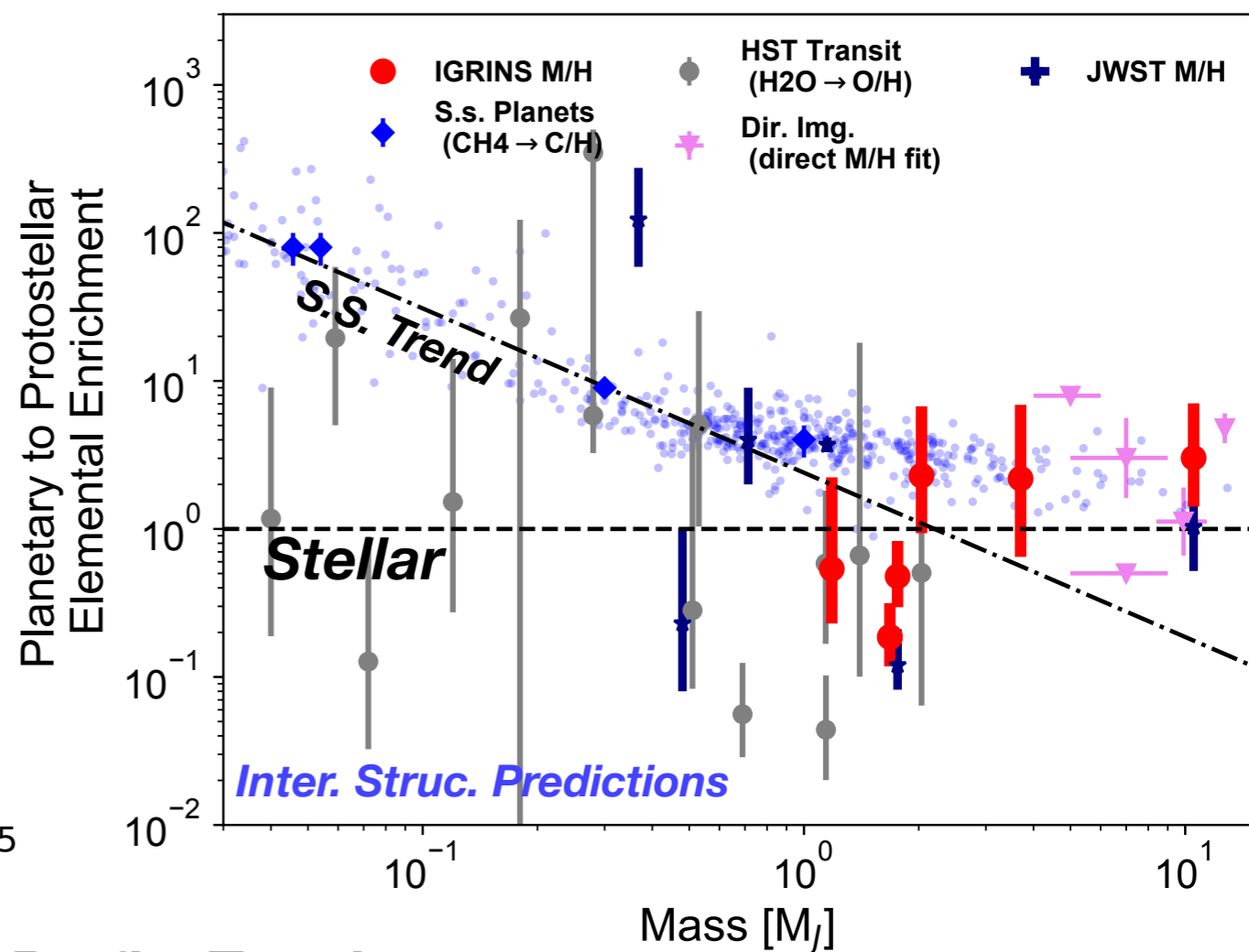


Population Level Constraints (from ~half the planets)

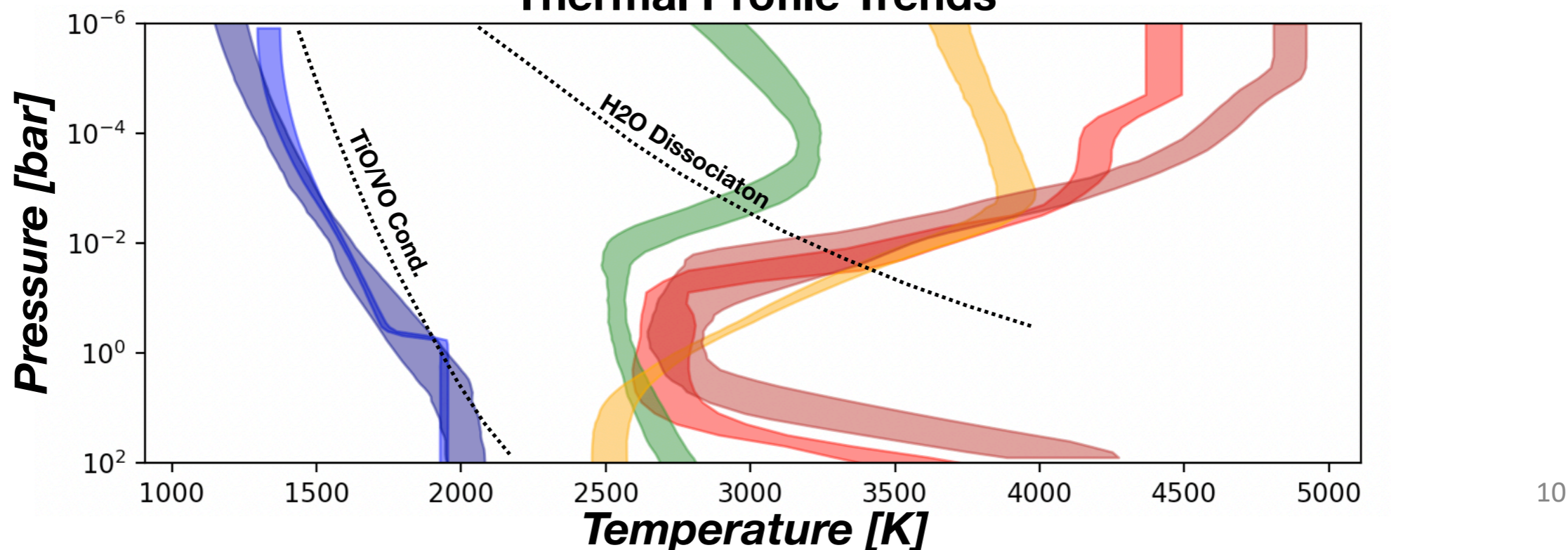
Composition vs. Formation Location



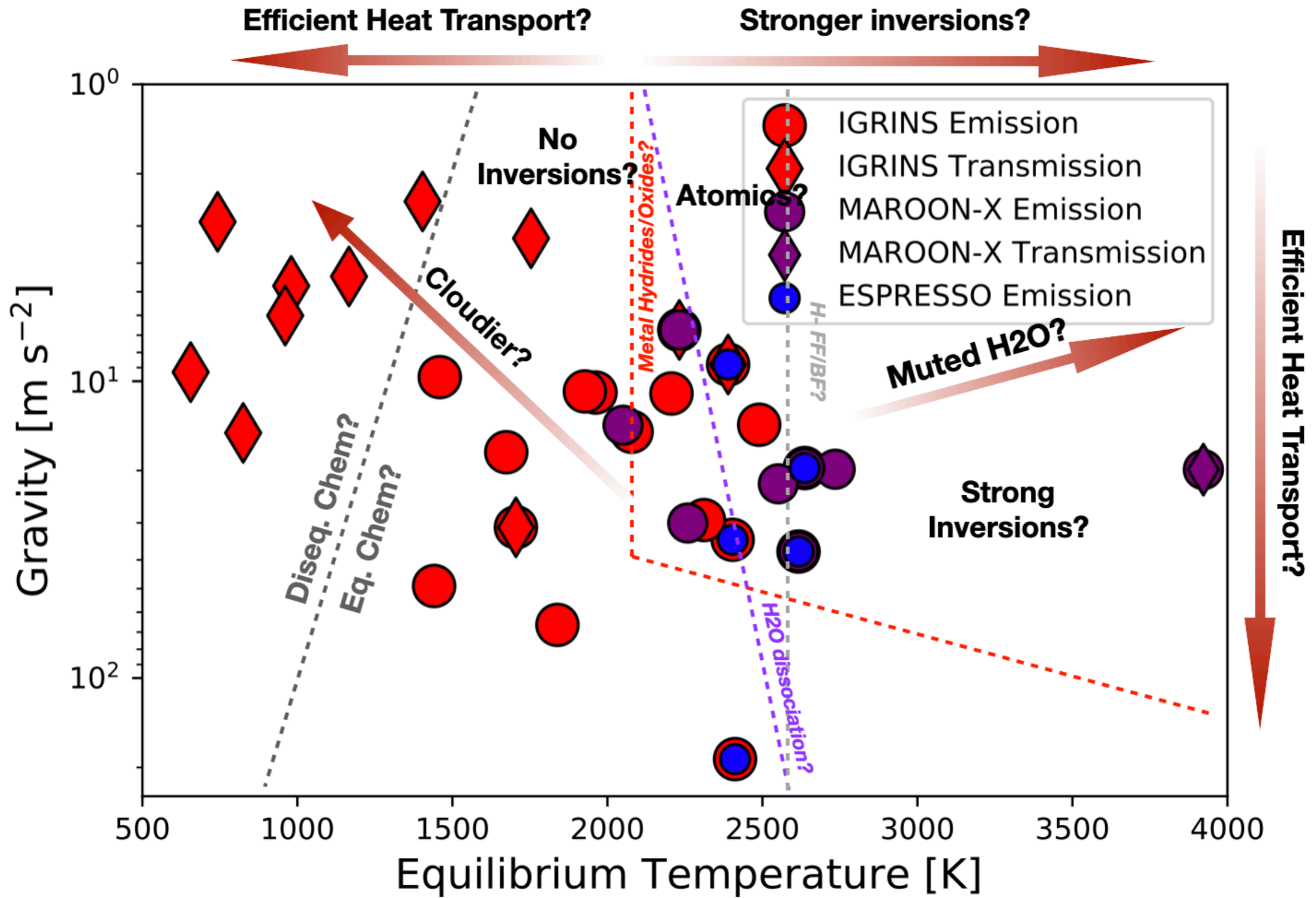
Metal Enrichment vs. Planet Mass



Thermal Profile Trends

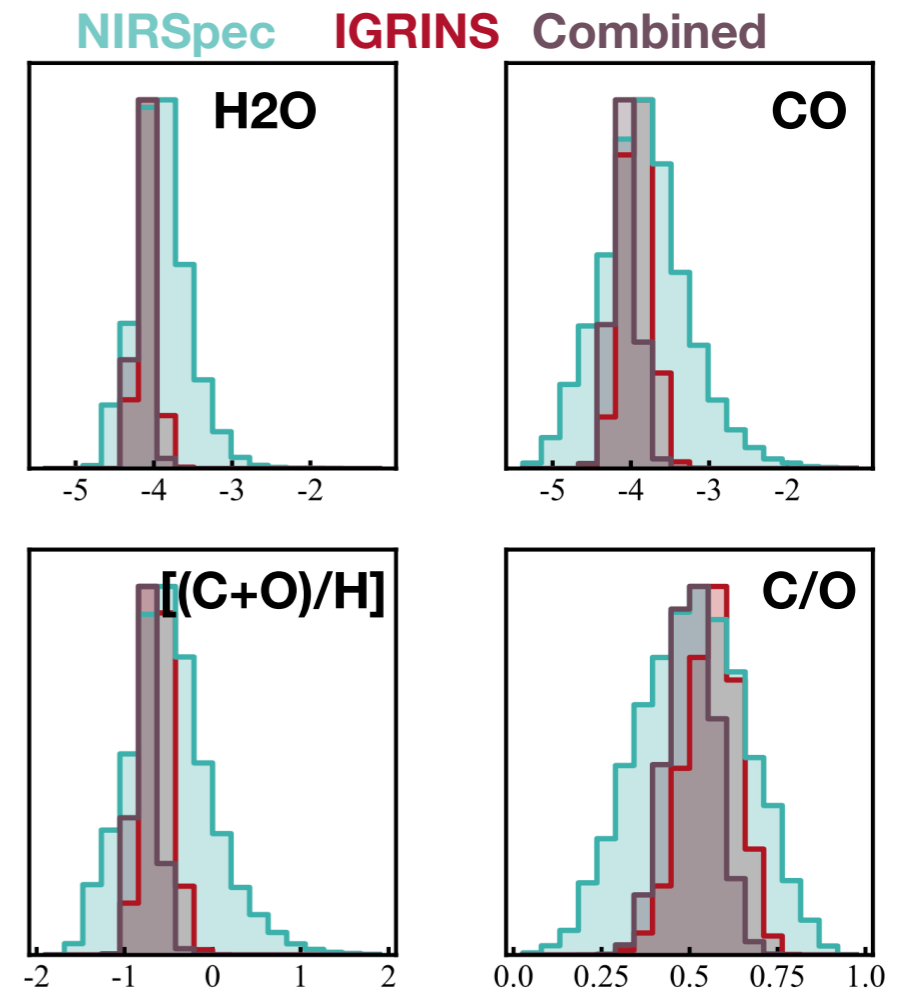
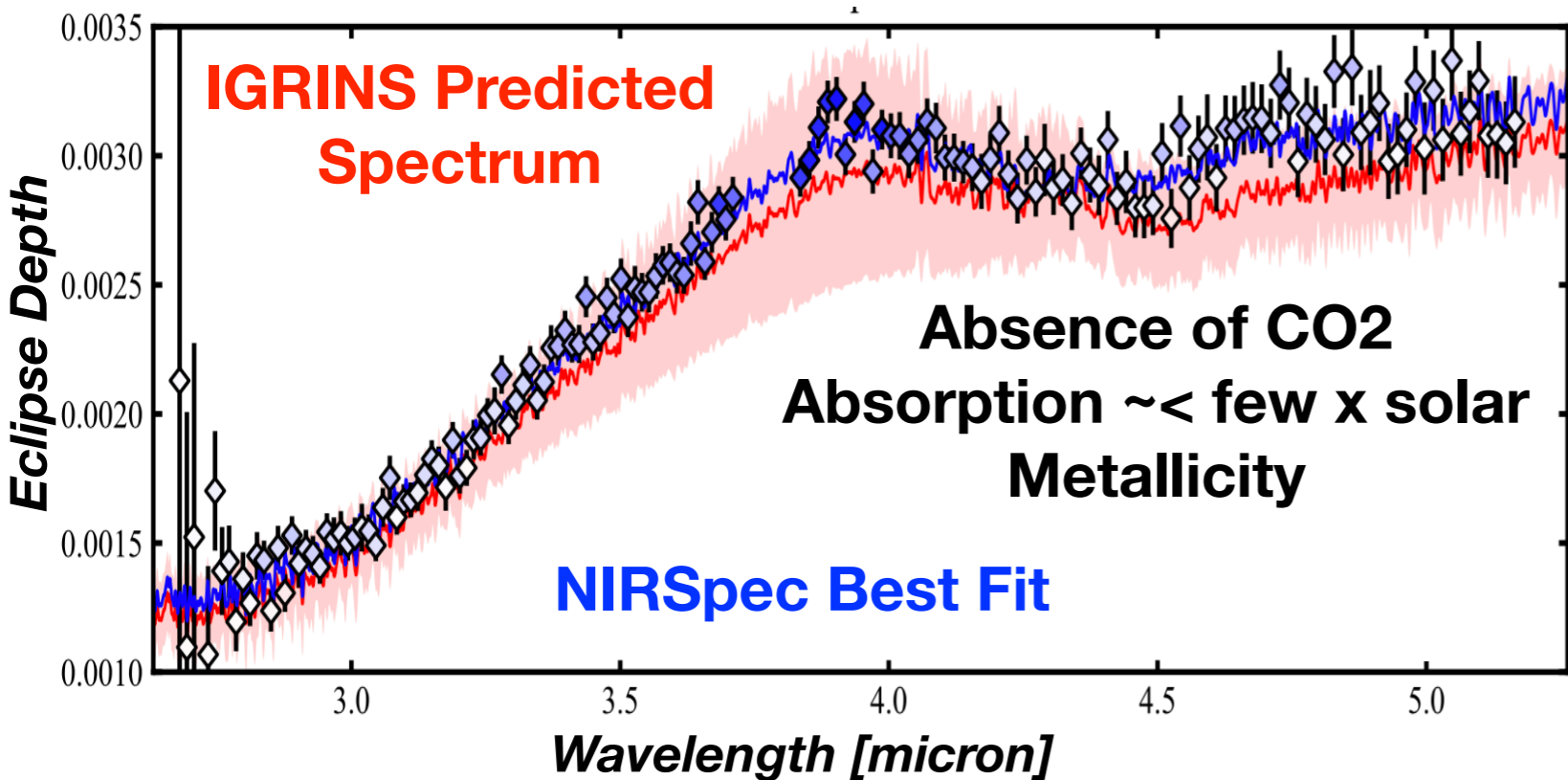
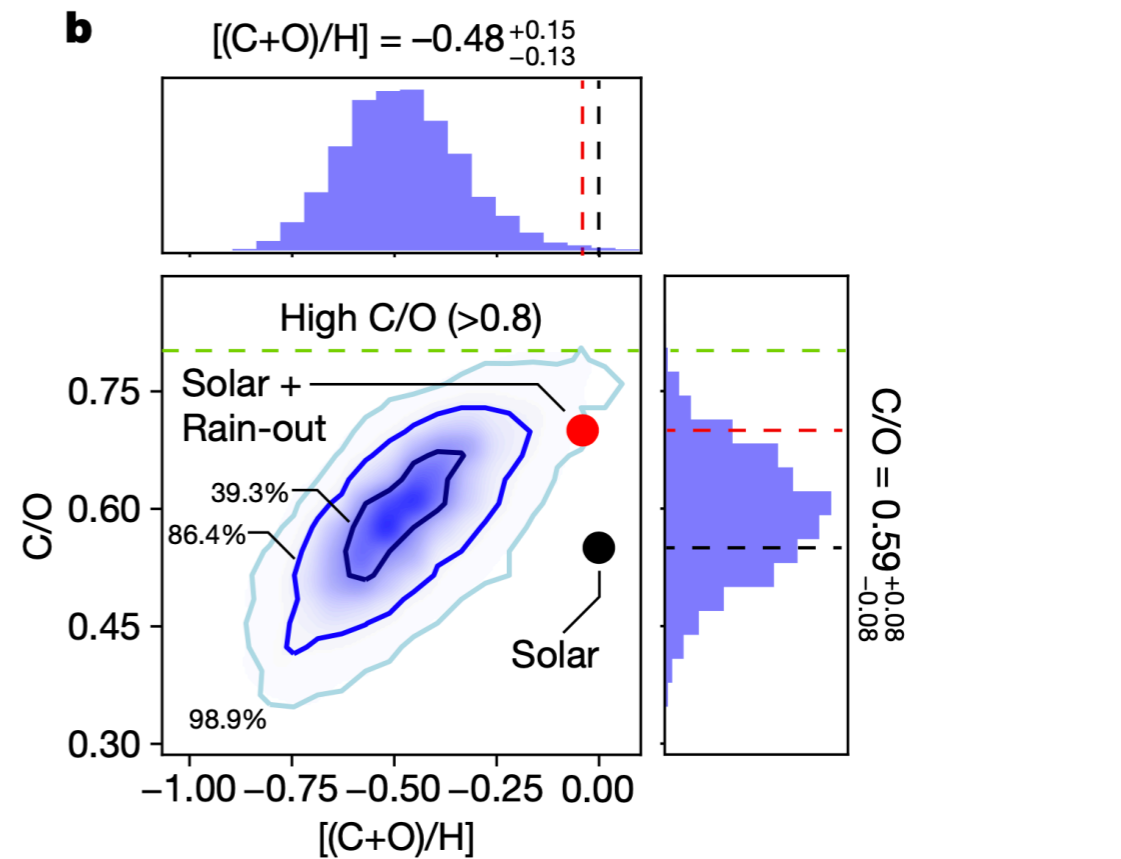
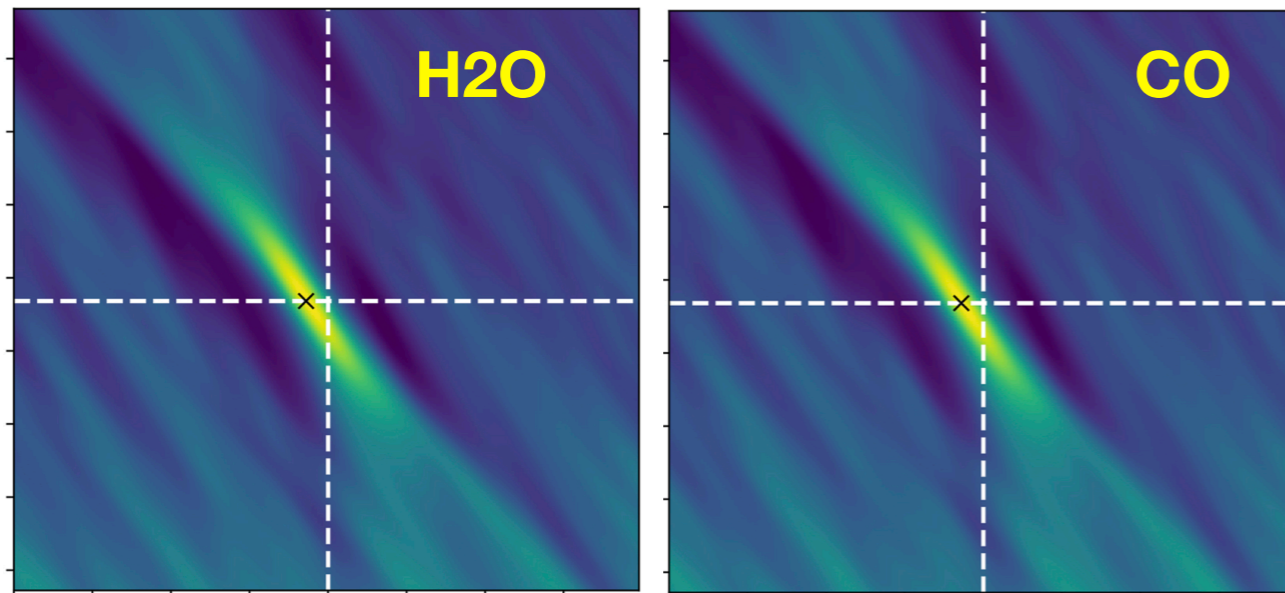


Complimentary Programs



IGRINS Transmission Survey (GS-LP-107): M. Mansfield,
 MAROON-X Emission Survey (GN-2022B-Q-218, 2023A-Q-219 2023B-Q-227, 2024A-Q-220/2020A-Q-234, 2021A-Q-119): L. Pino/J. Bean
 MAROON-X Transmission Survey (GN-2023A-Q-224, 2023B-Q-127, 2024A-Q-130): V. Parmentier
 ESPRESSO: L. Pino

Synergies with JWST: WASP-77Ab

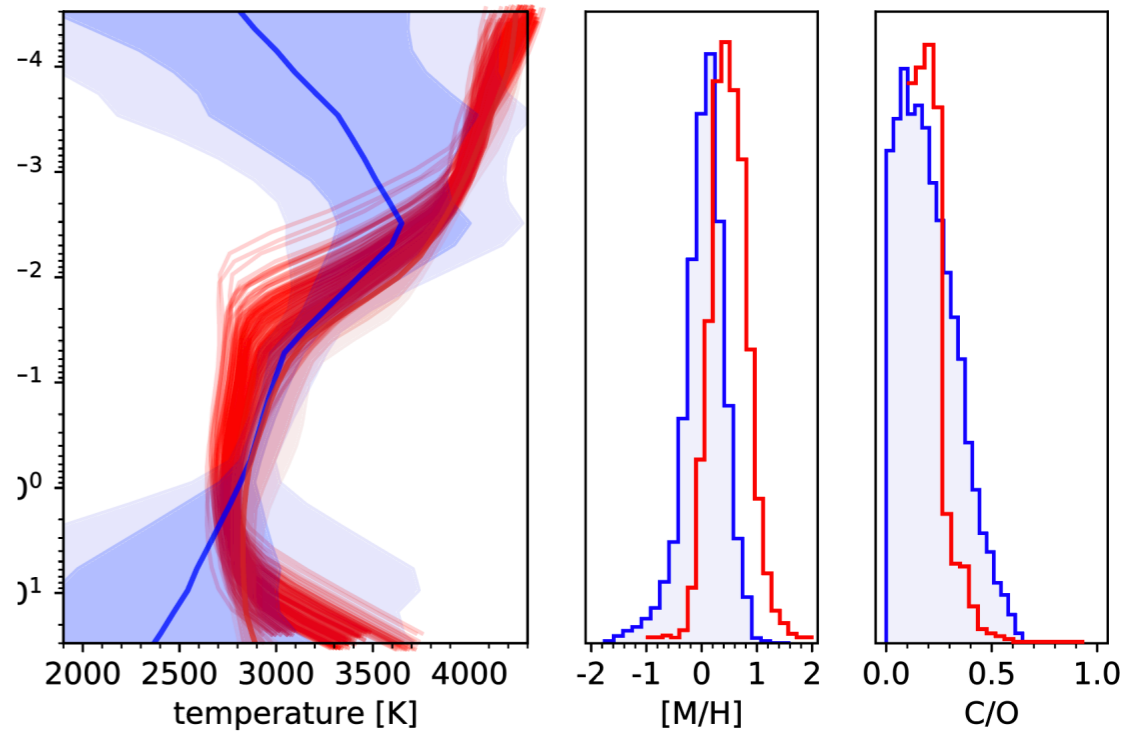
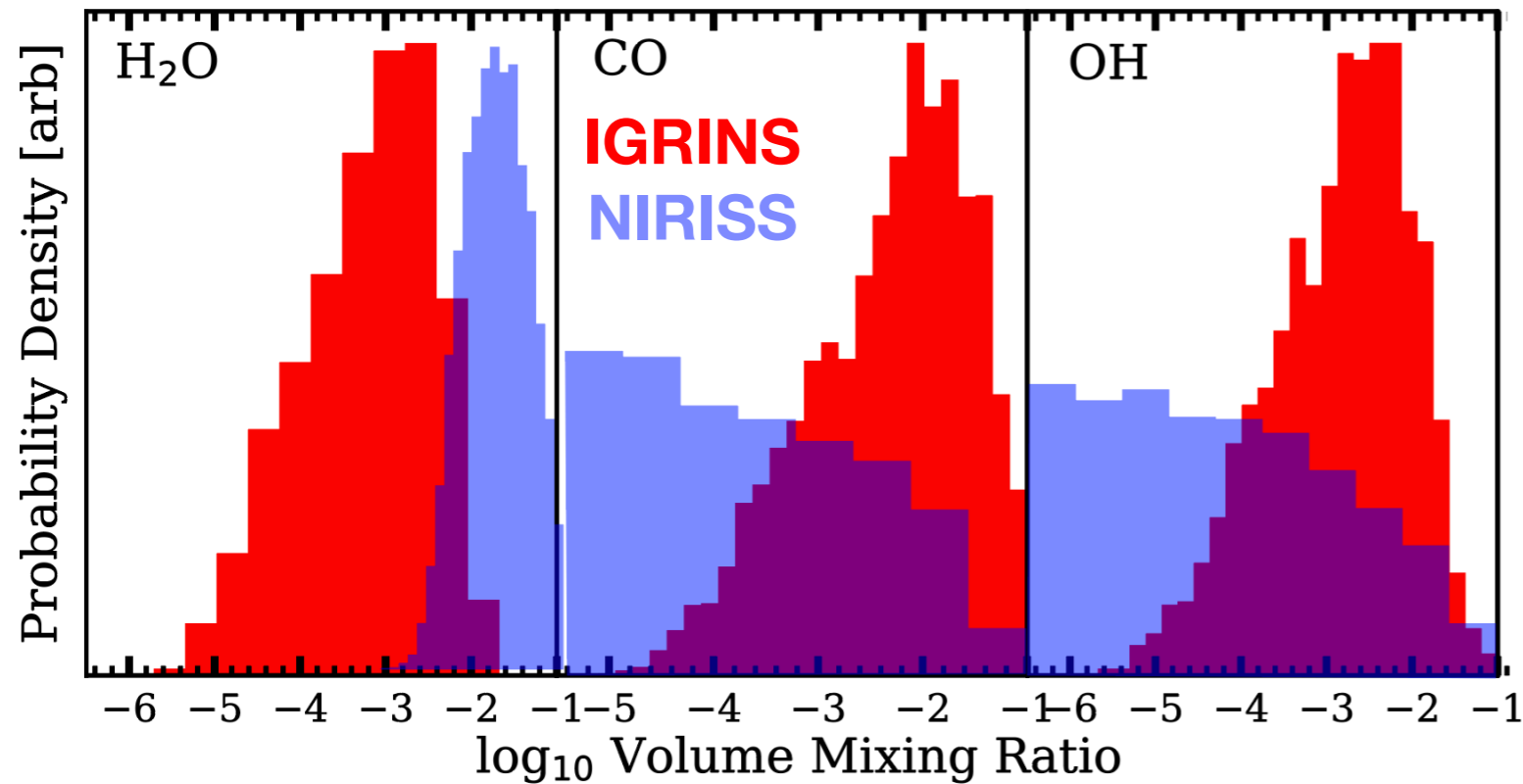
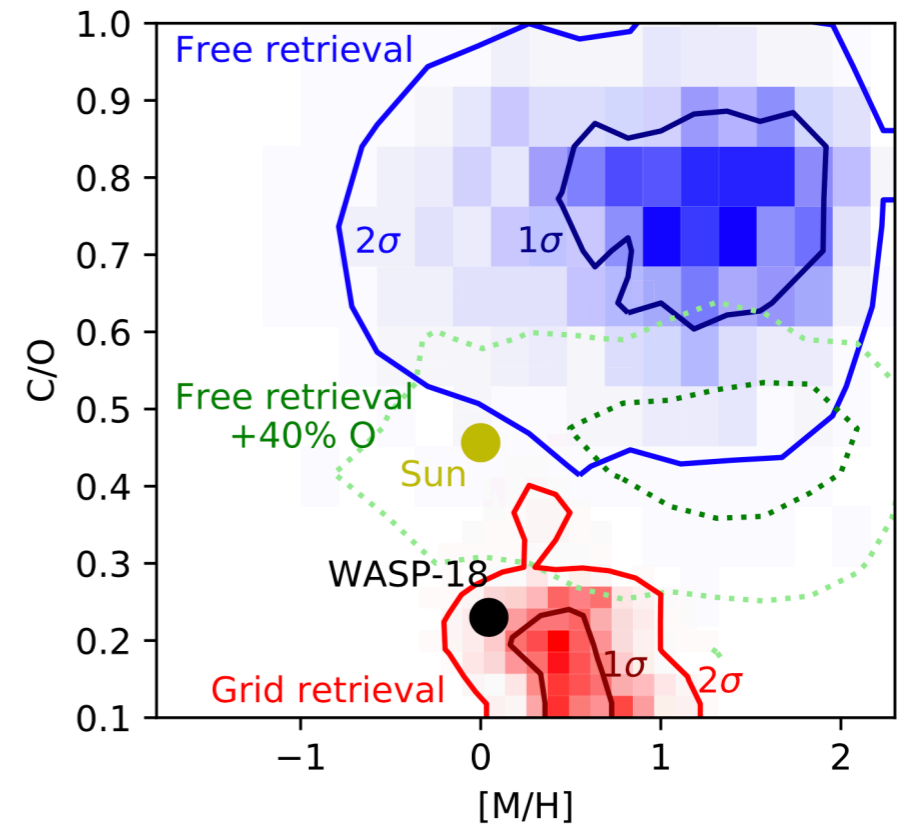
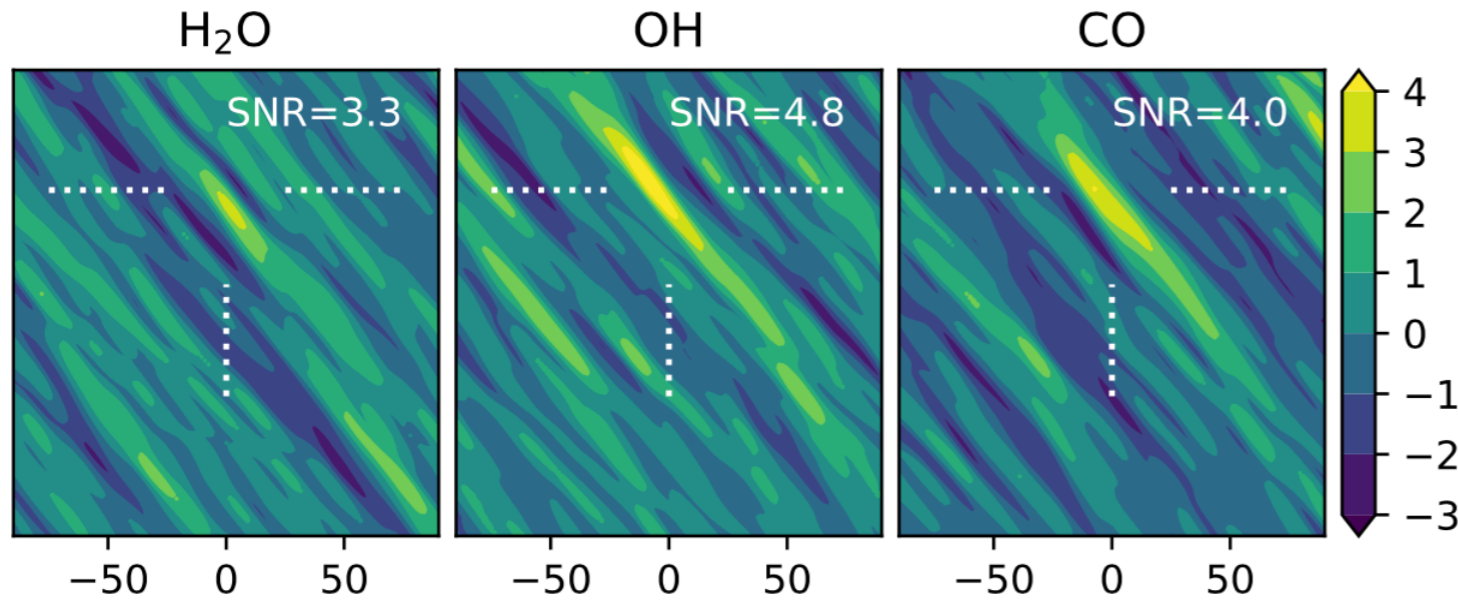


NIRSpec G395H (August+2023)

Smith+2024

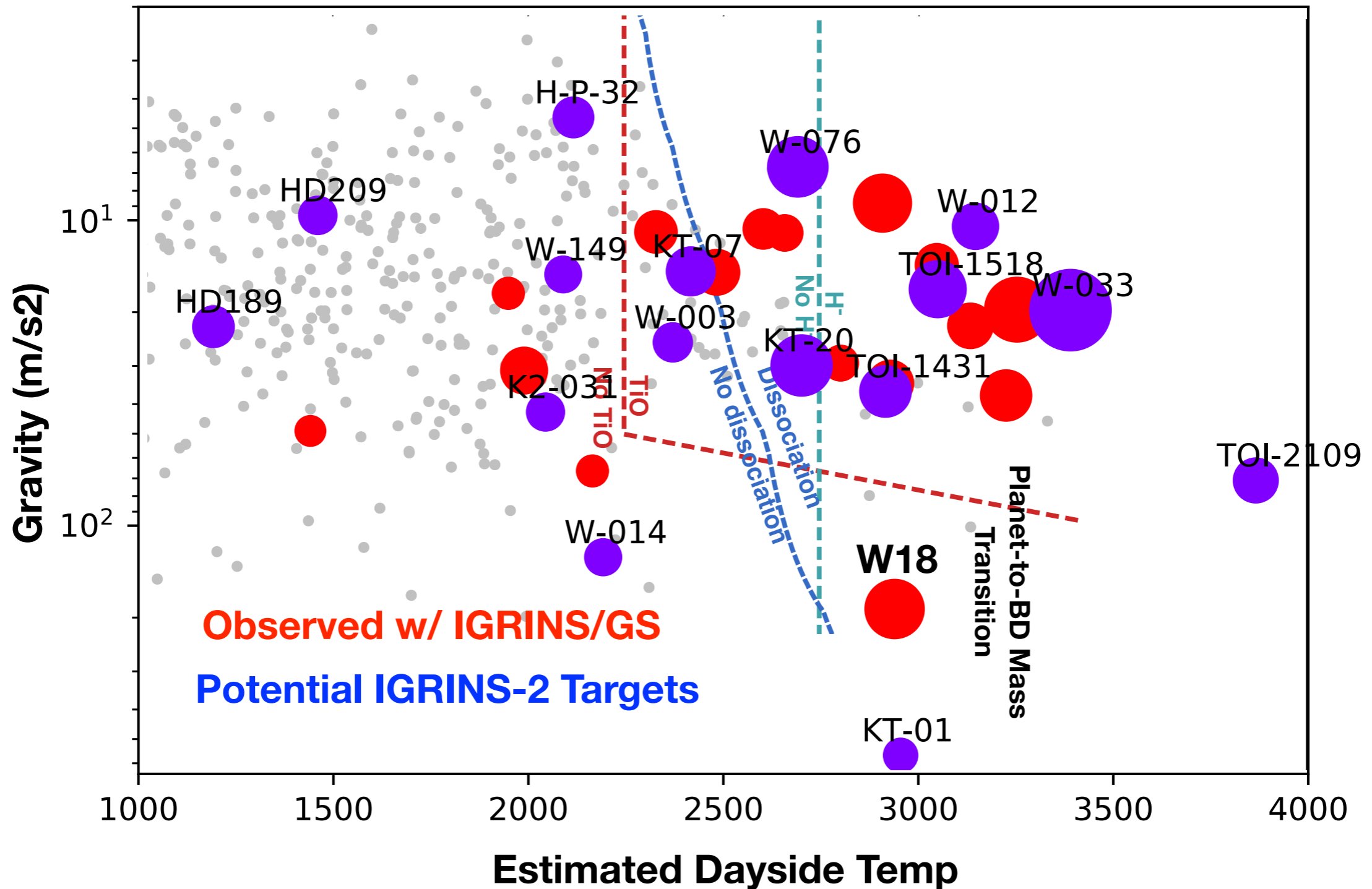
Synergies with JWST: WASP-18

IGRINS ~3 hr pre-eclipse obs (Brogi, Line+2023)

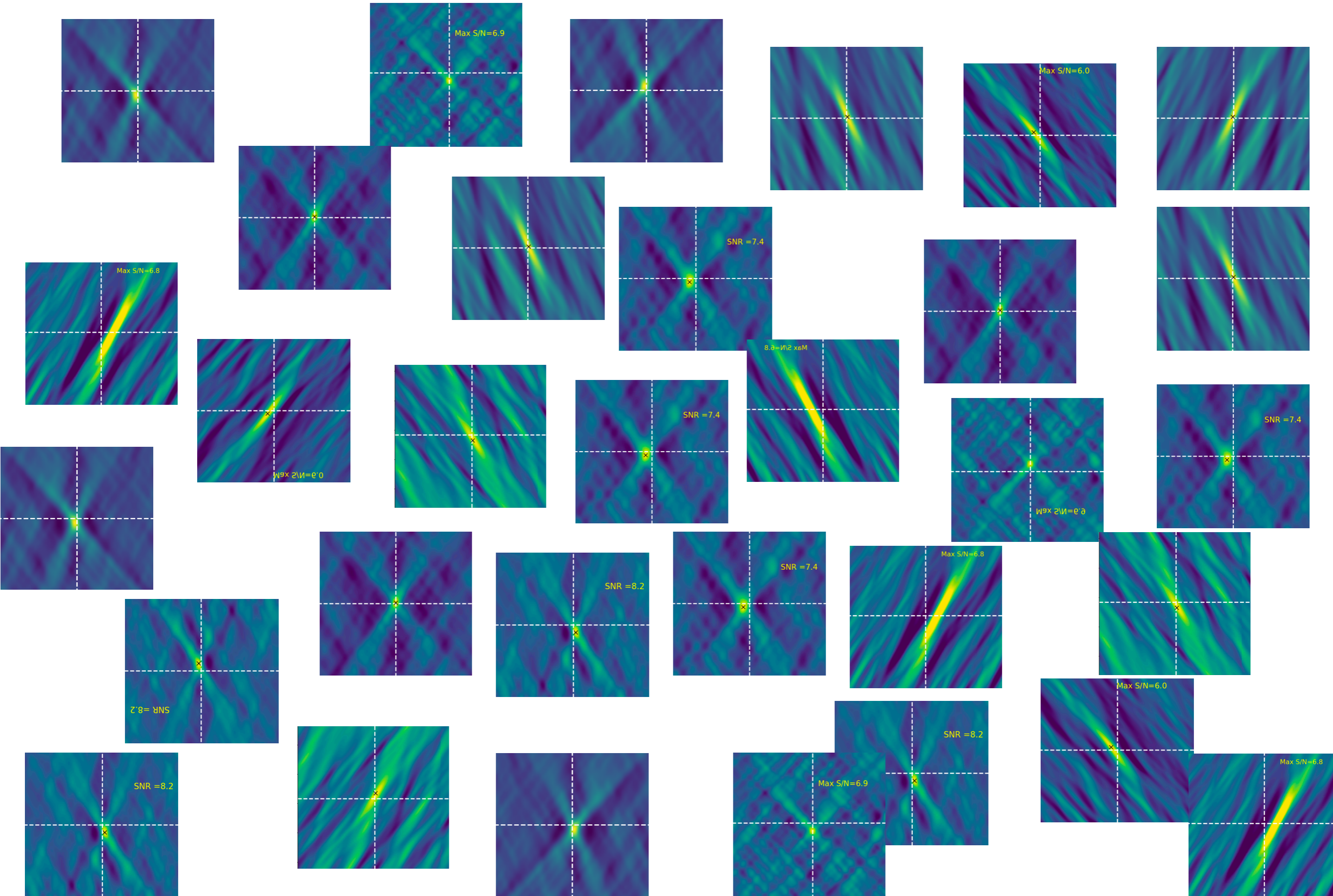


NIRISS SOSS 6.7 hrs (Coulombe+2023)

Lets Extend Survey in the North with *IGRINS-2!*



IGRINS-2: What we could have by 2027



Summary

- **IGRINS+GS can detect major C and O bearing molecules in planets from ~1400 - 3000 K across major transitions**
- **Metallicity, C/O constraints comparable to JWST for some planets**
- **Increasing sample size enables population level hypothesis tests**
 - **Scatter in Mass-Metallicity trend at ~high mass**
 - **Elevated C/O ratios beyond predictions**
 - **Temperature structures show clear transition from “non-inverted” to “inverted”, consistent with TiO/VO transition hypothesis**
- **Agreement with JWST observations for overlapping targets**
 - **Combination can boost constraints; complimentary information**
- **Demonstrate that Ground based HRCCS can “keep up with” space based—> opportunity for bigger surveys—>great potential with GSMT’s**