Image credit: John Hook

Unveiling the Atmospheric Composition of Giant Exoplanets

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PlanetS

iREx

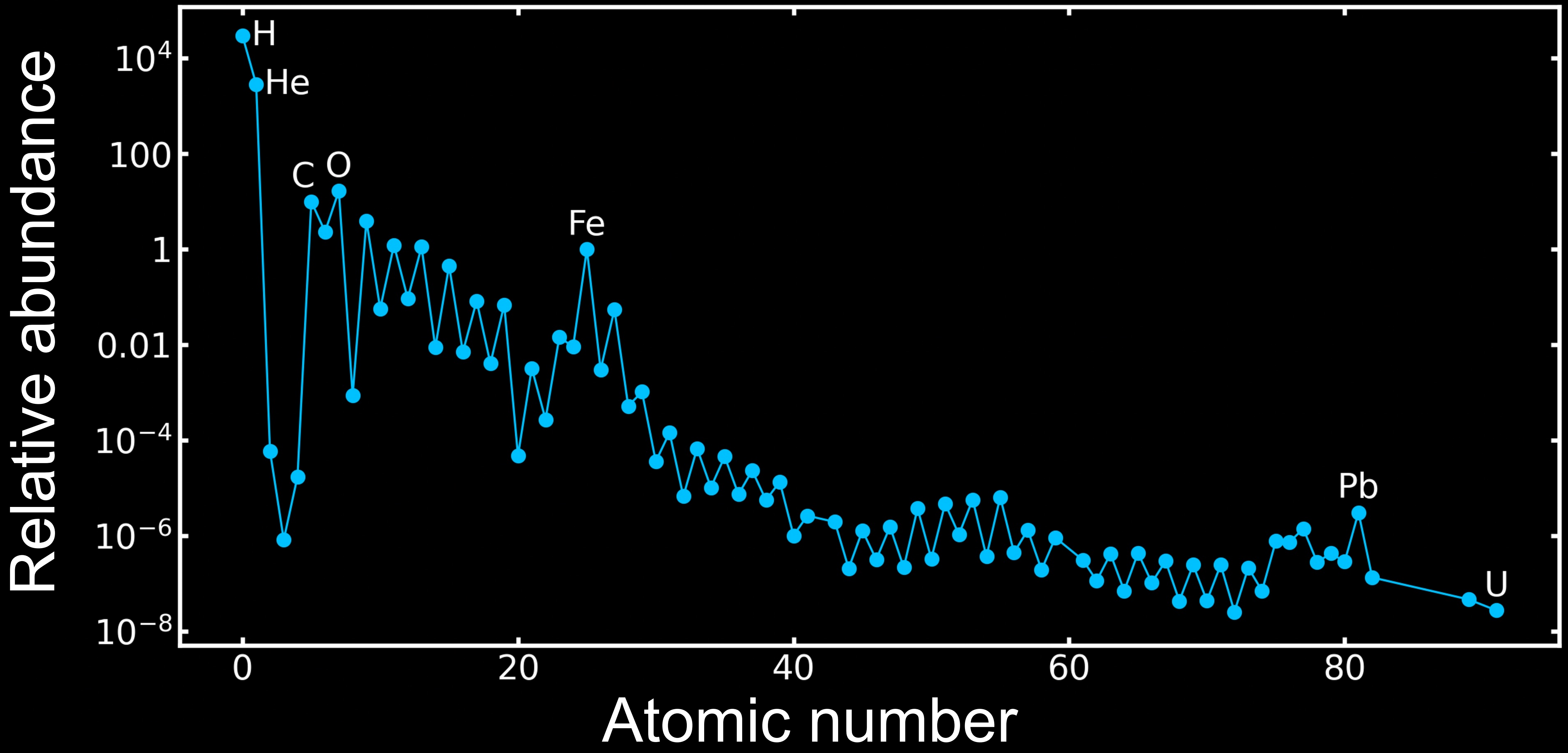
Swiss National Science Foundation

“En ce qui touche les étoiles, nous ne saurons jamais étudier par aucun moyen leur composition chimique.”

– Auguste Comte 1835

Image credit: NASA/Goddard

Abundance of elements in the Sun



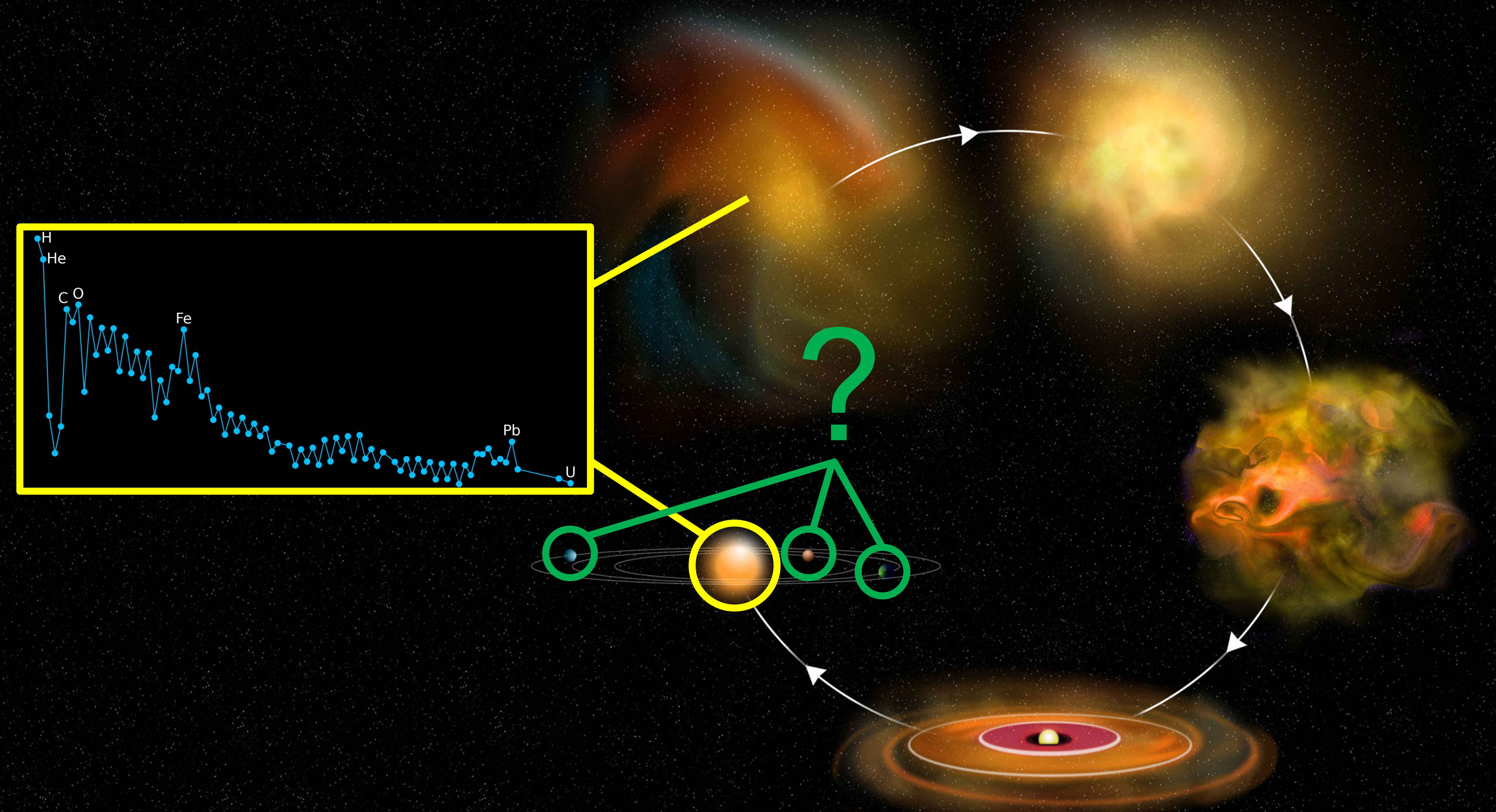
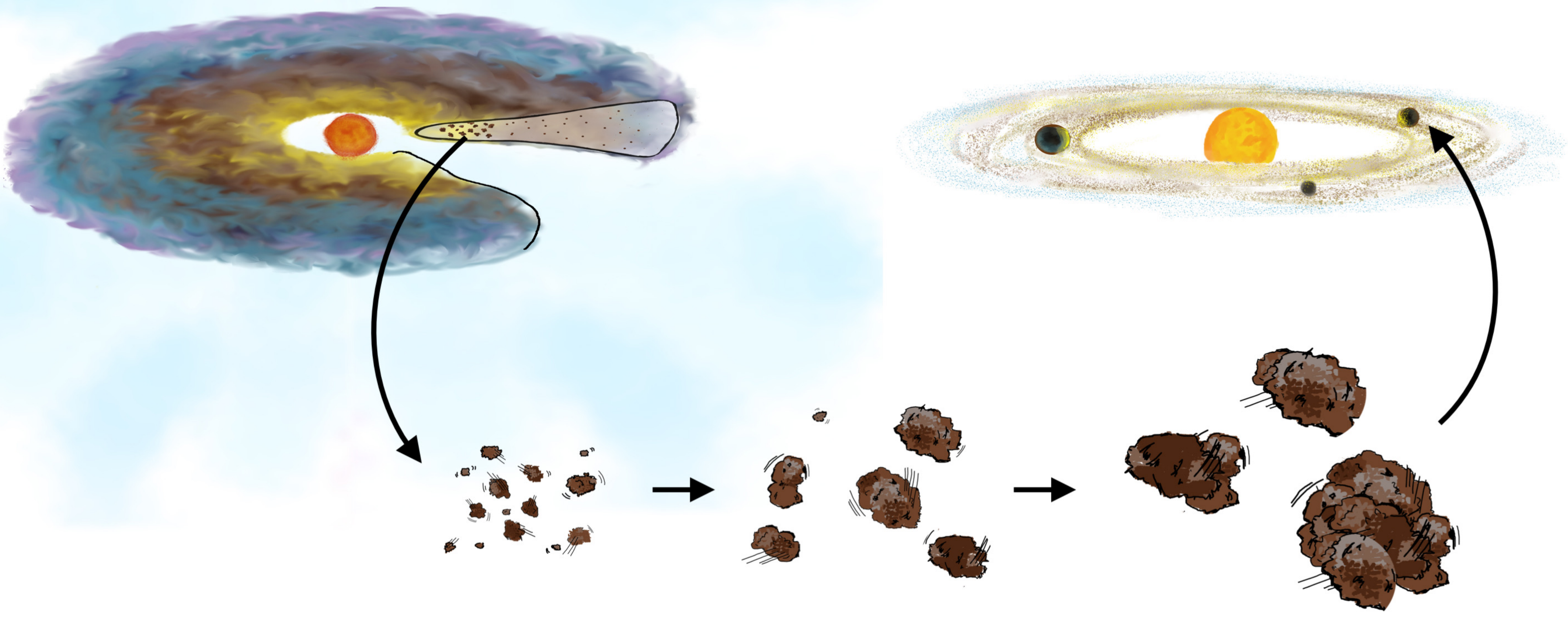


Image credit: Bill Saxton

Forming planets is a multi-step process



➢ End composition will depend on accretion history

Image credit: Daria Dall`Olio

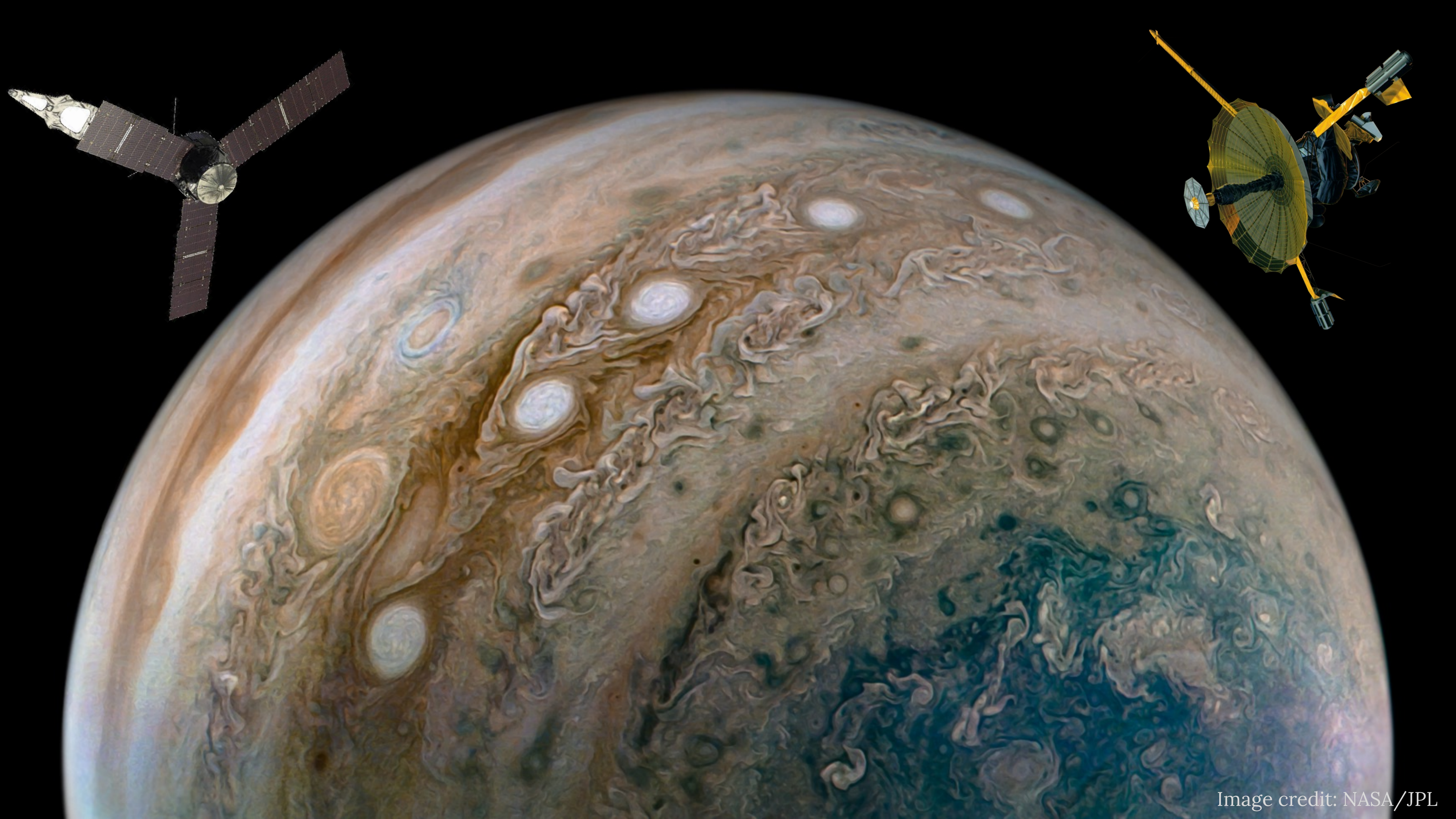
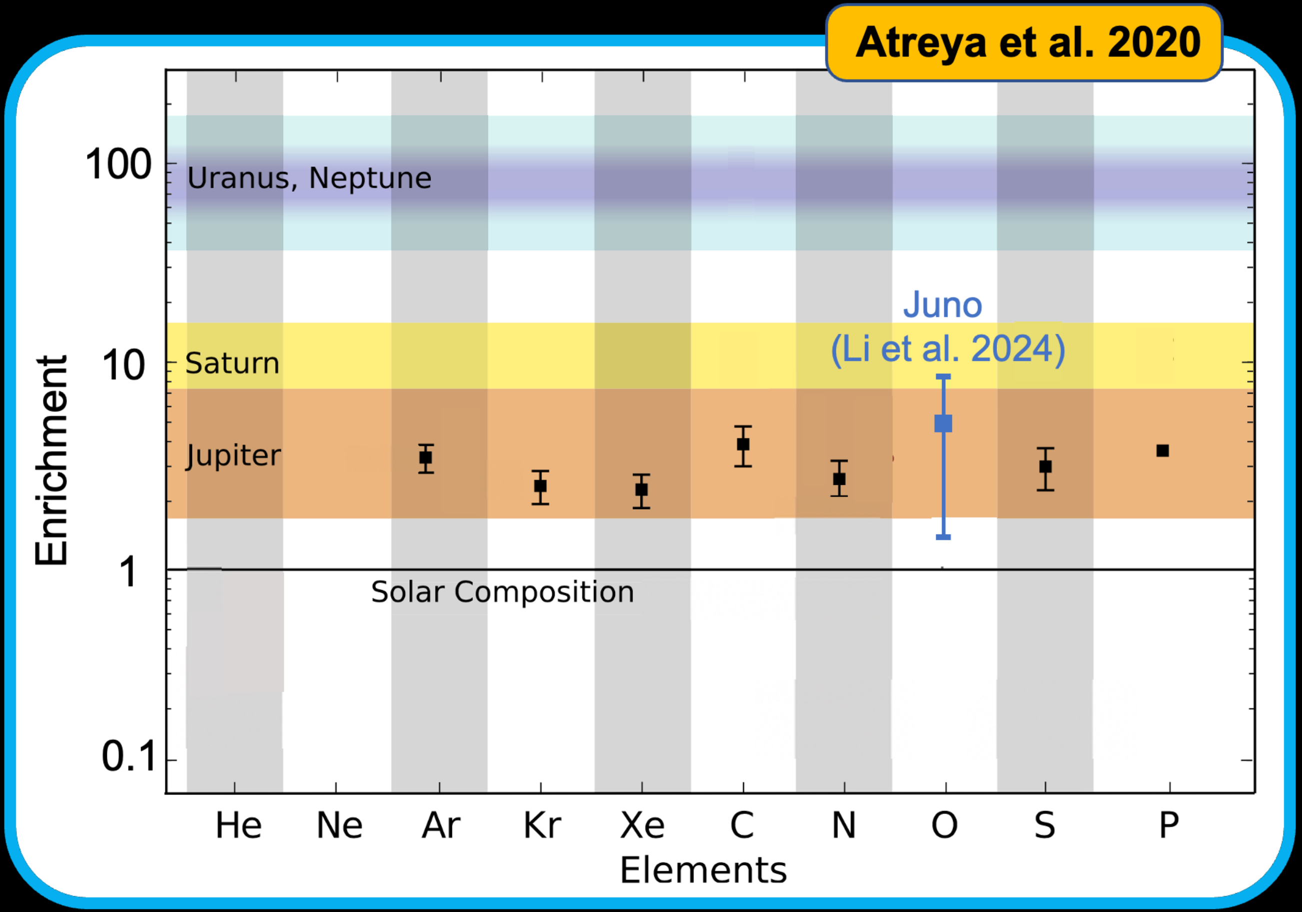


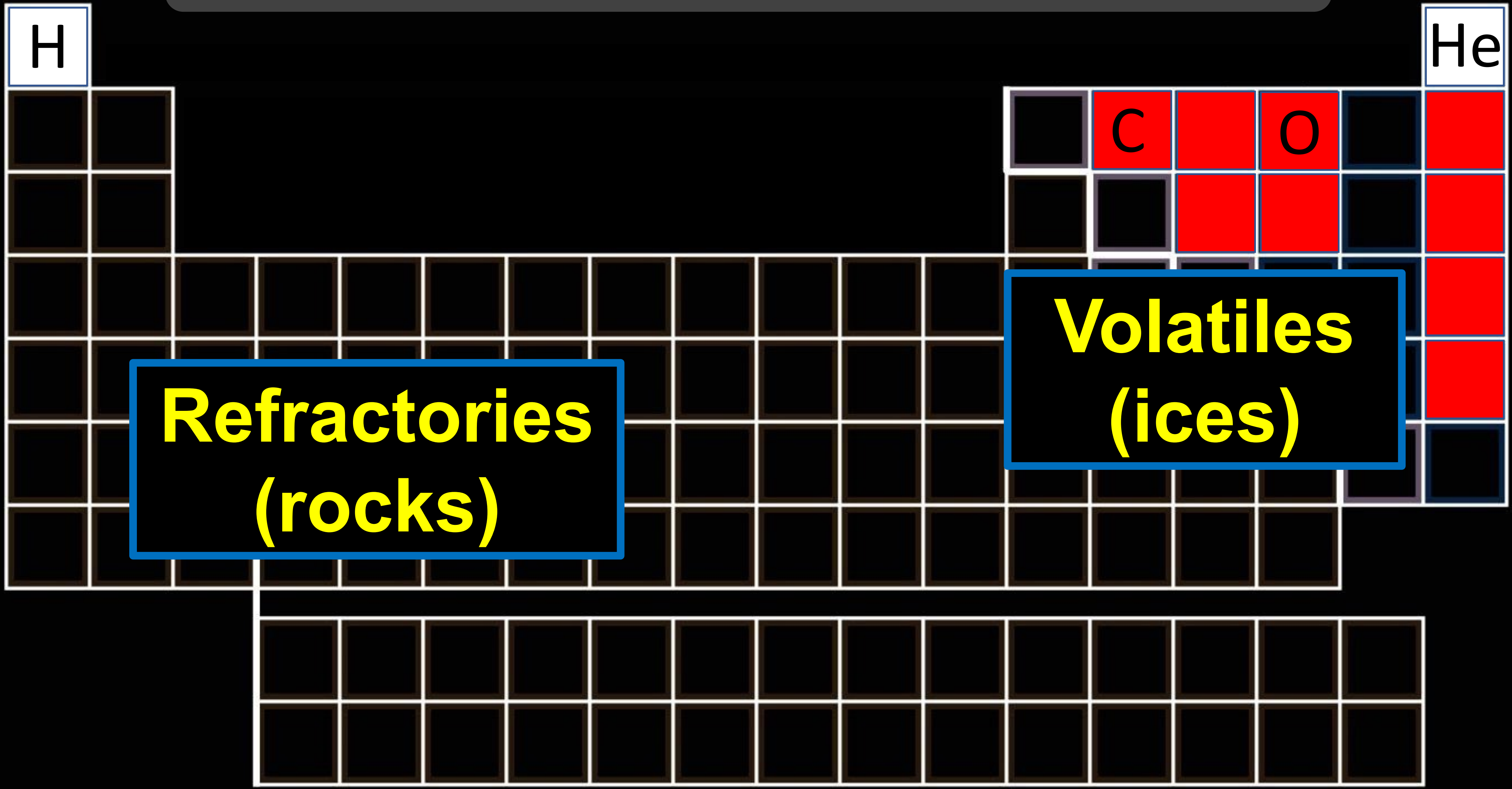
Image credit: NASA/JPL

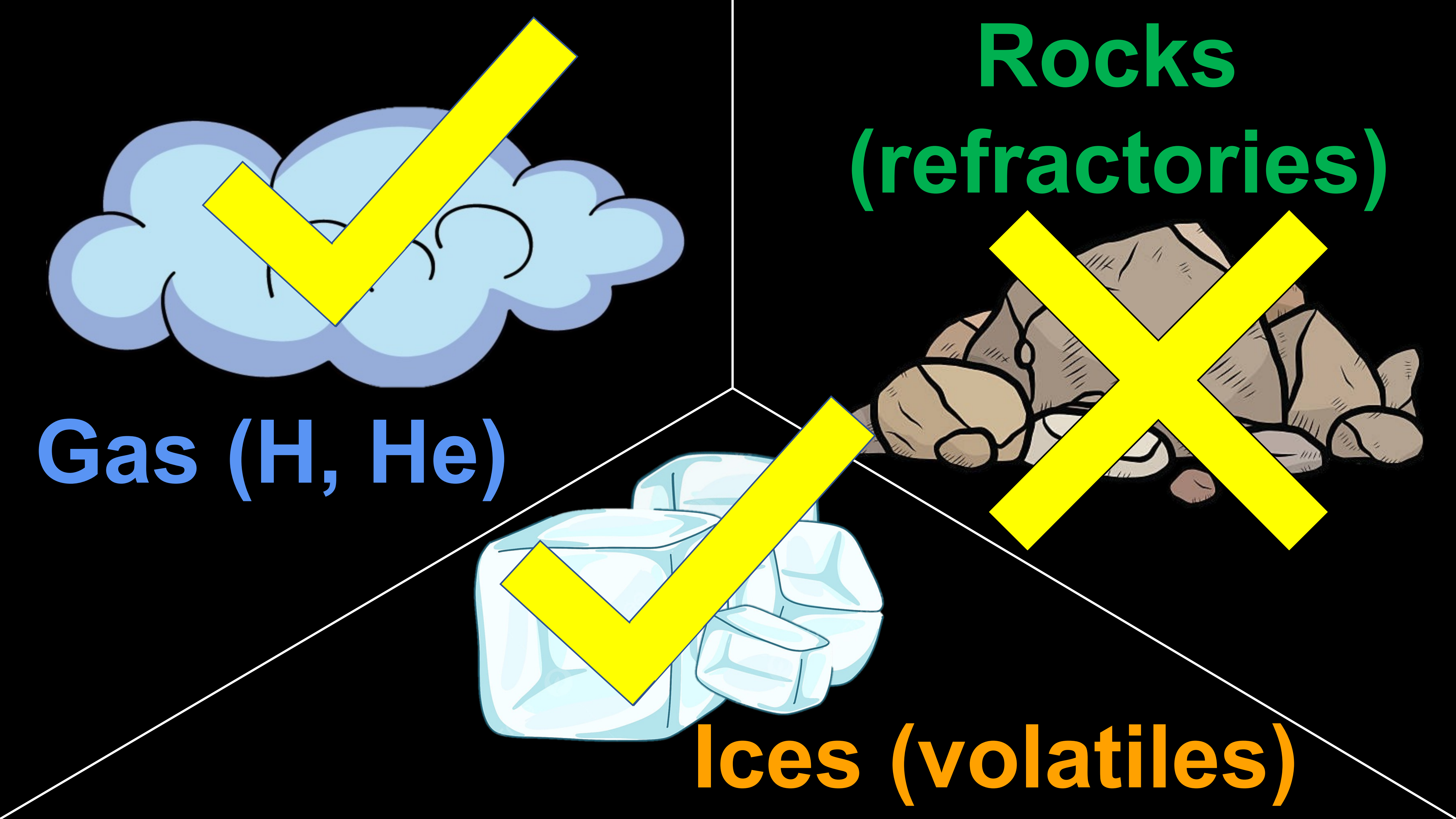
Atmospheric composition of Jupiter



- ➢ Elements on Jupiter are ~3× enriched relative to solar

Elements measured on Jupiter




Rocks (refractories)
Gas (H, He)
Ices (volatiles)

We do not have a direct measurement of the ice-to-rock ratio for any of the Solar System giants.

The ultra-hot Jupiter opportunity

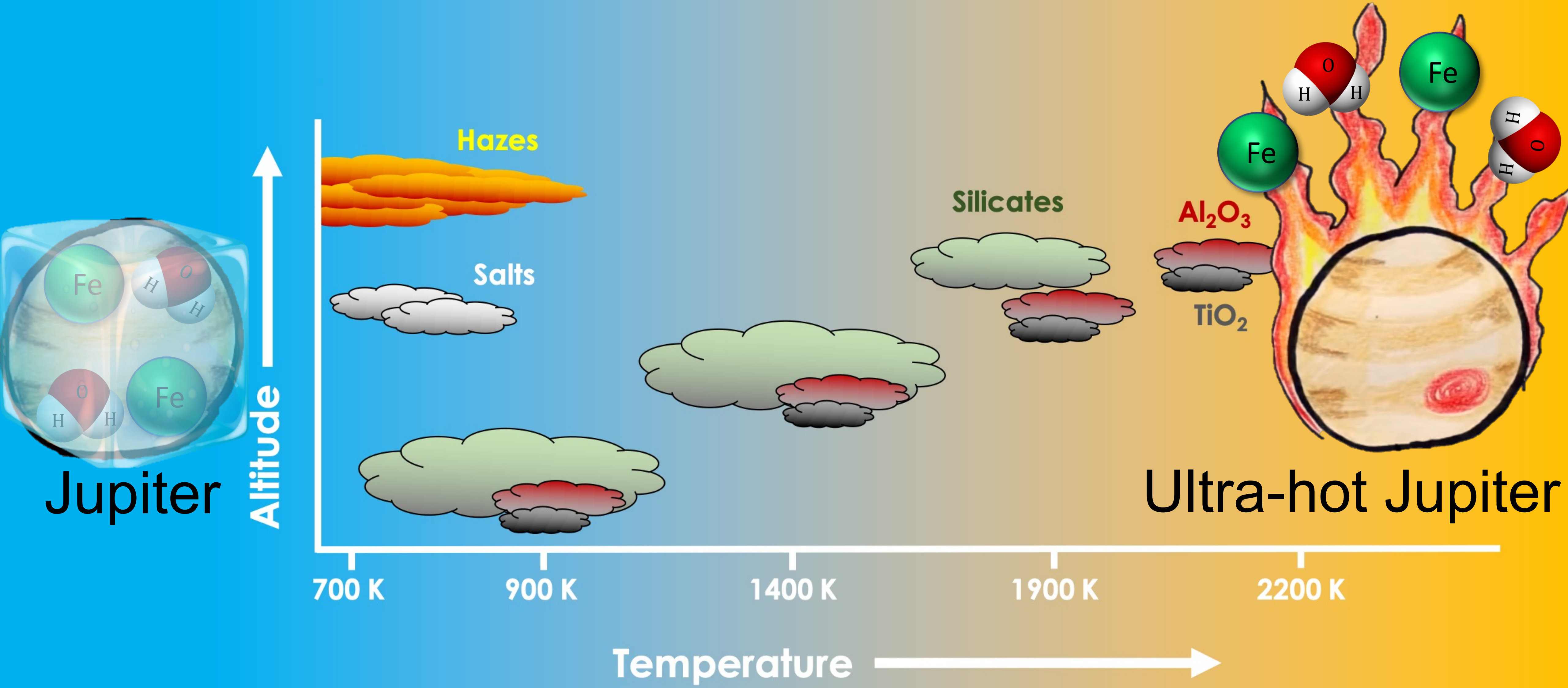
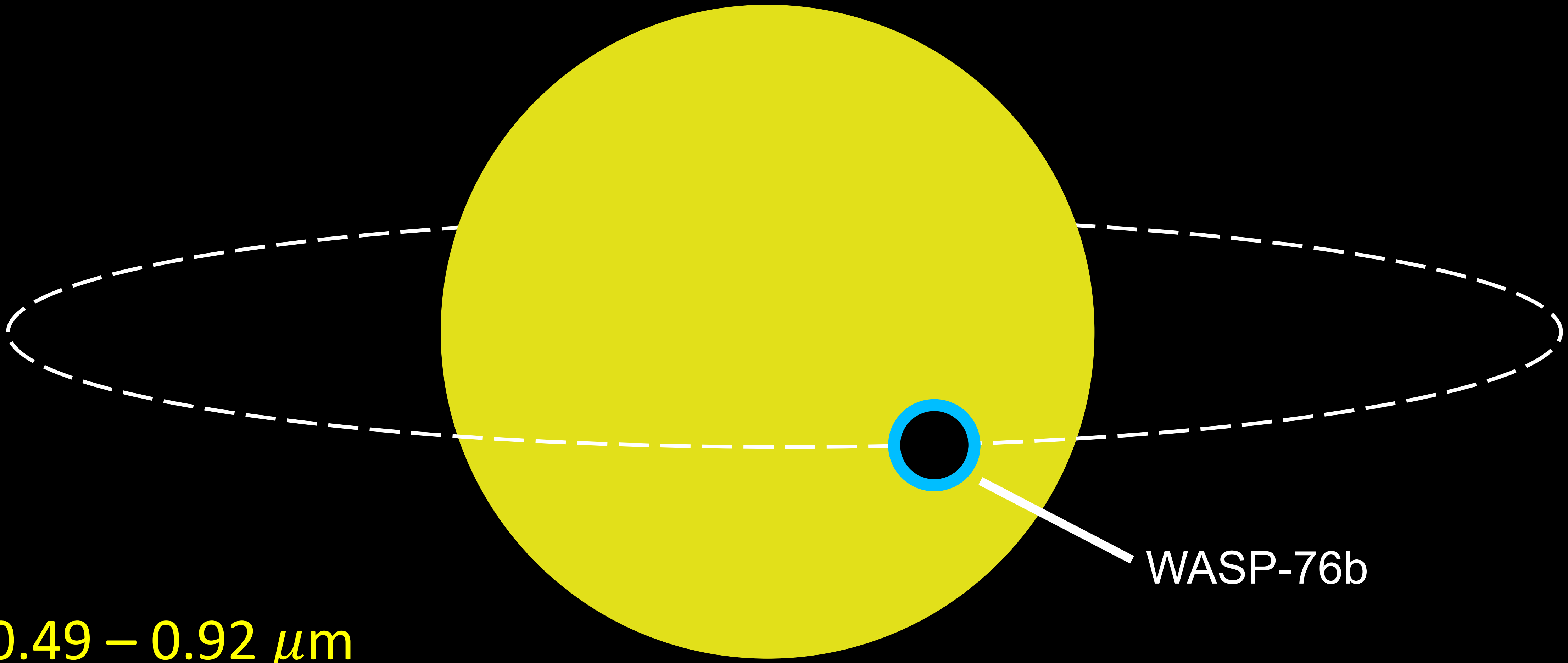


Image credit: Peter Gao

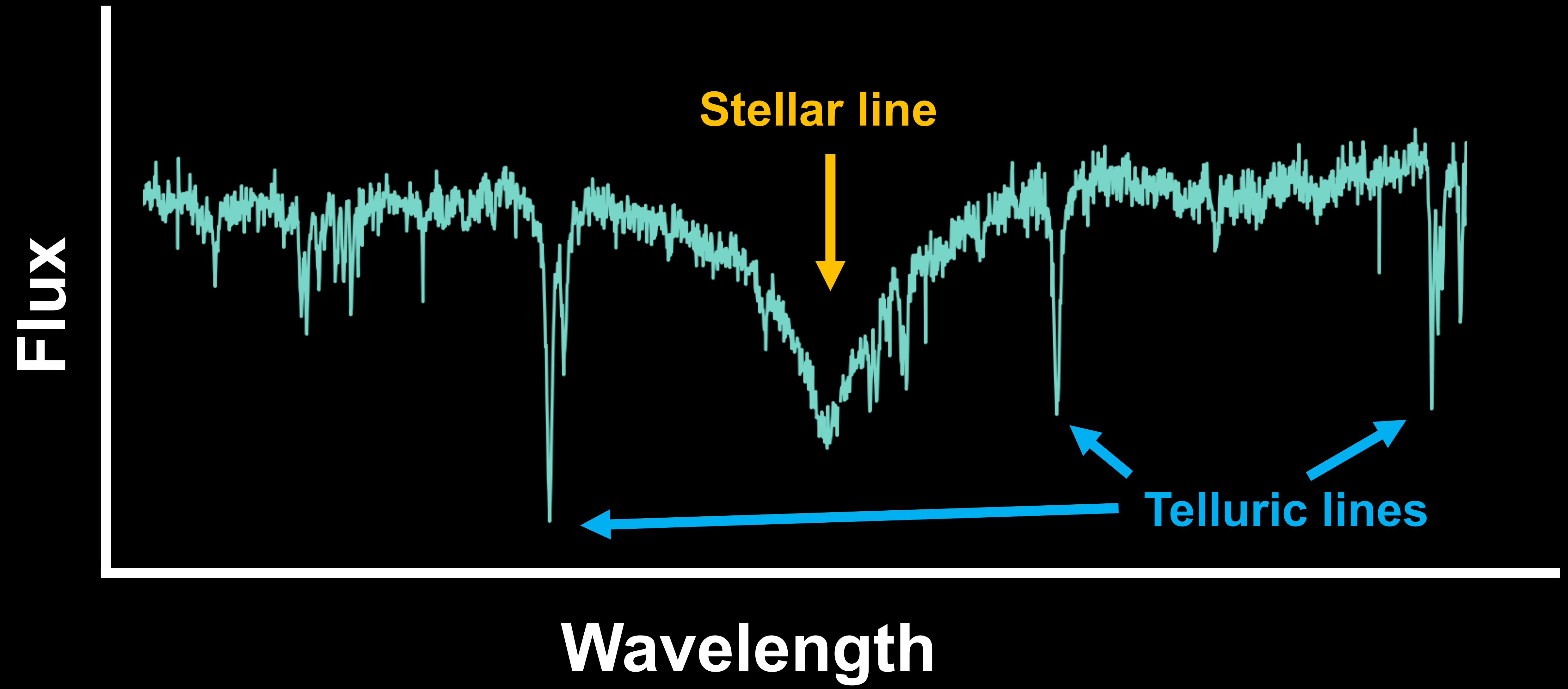
WASP-76b

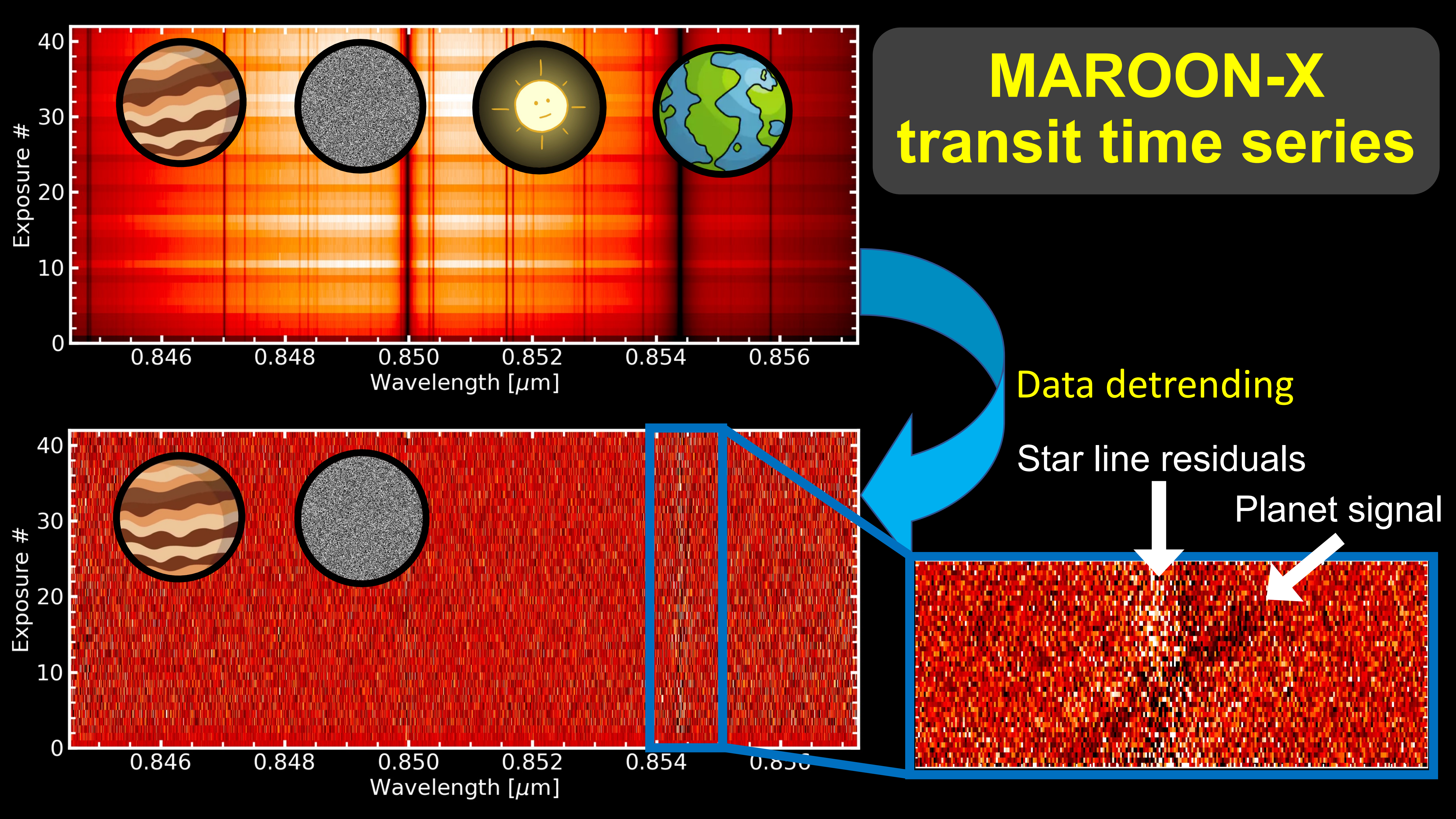
Transit observation of WASP-76b



$0.49 - 0.92\ \mu m$

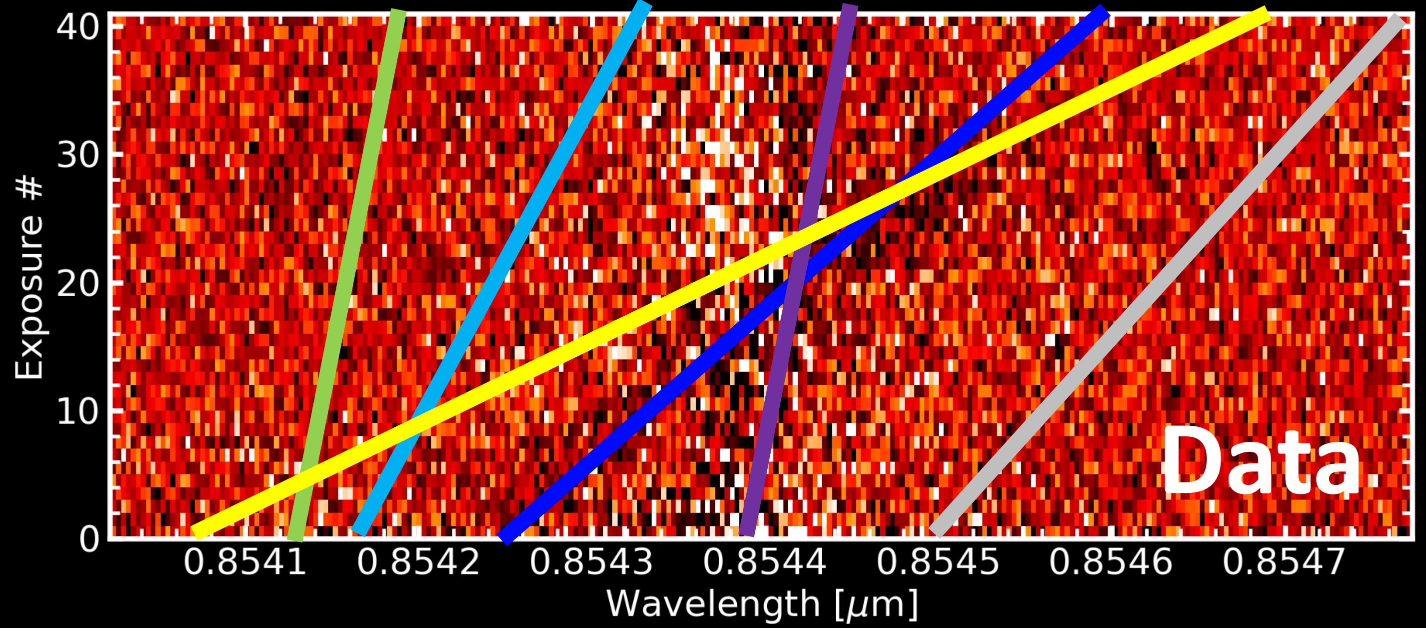
The high-resolution data:

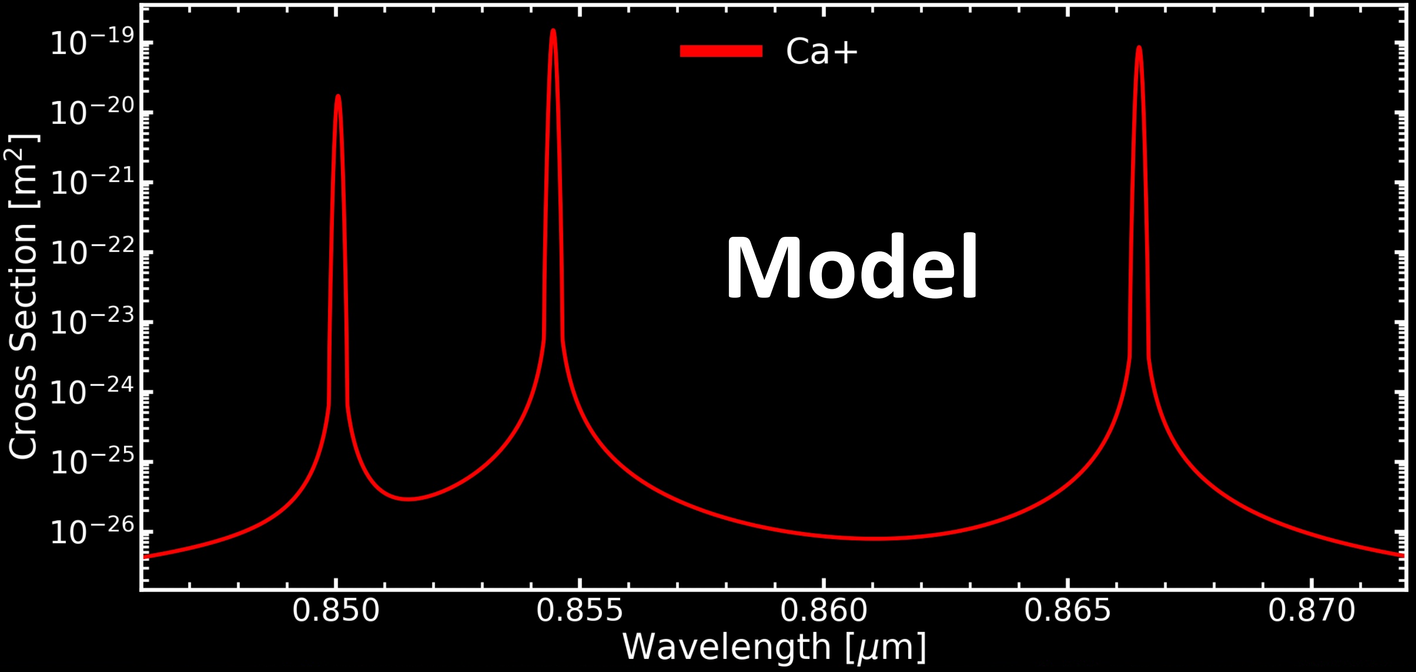



MAROON-X
transit time series
Data detrending
Star line residuals
Planet signal
Exposure #
0
10
20
30
40
Wavelength [μm]
0.846
0.848
0.850
0.852
0.854
0.856

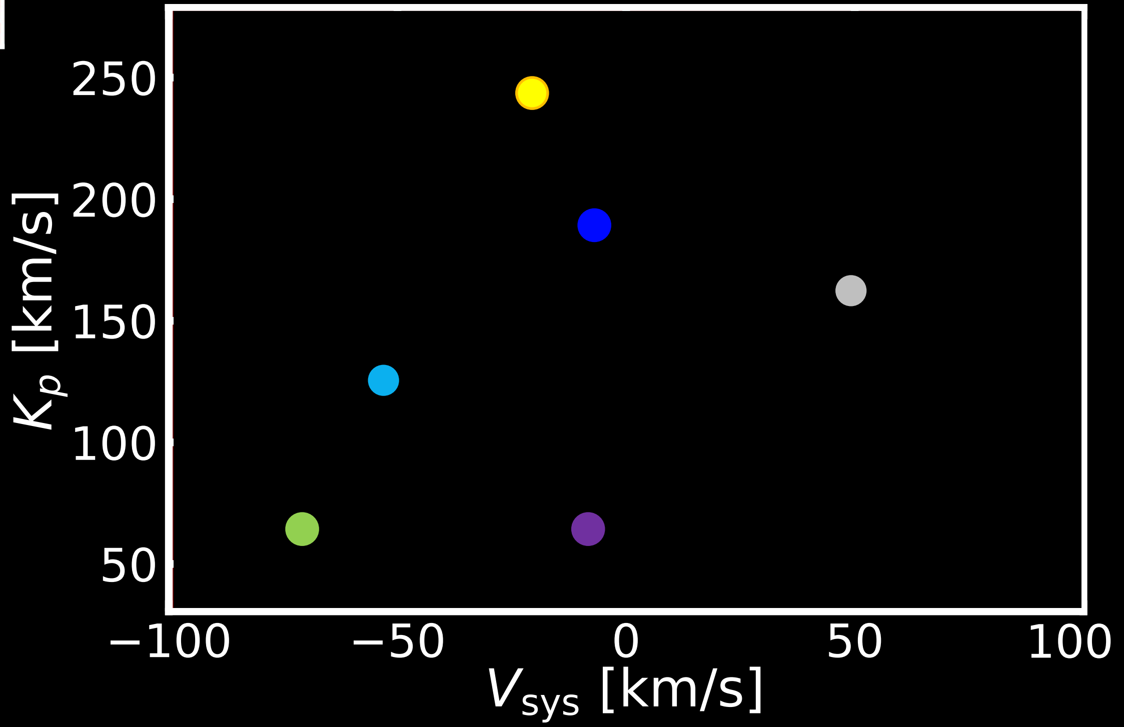
Cross-correlation analysis

Offset = V_{sys}, Slope = K_p

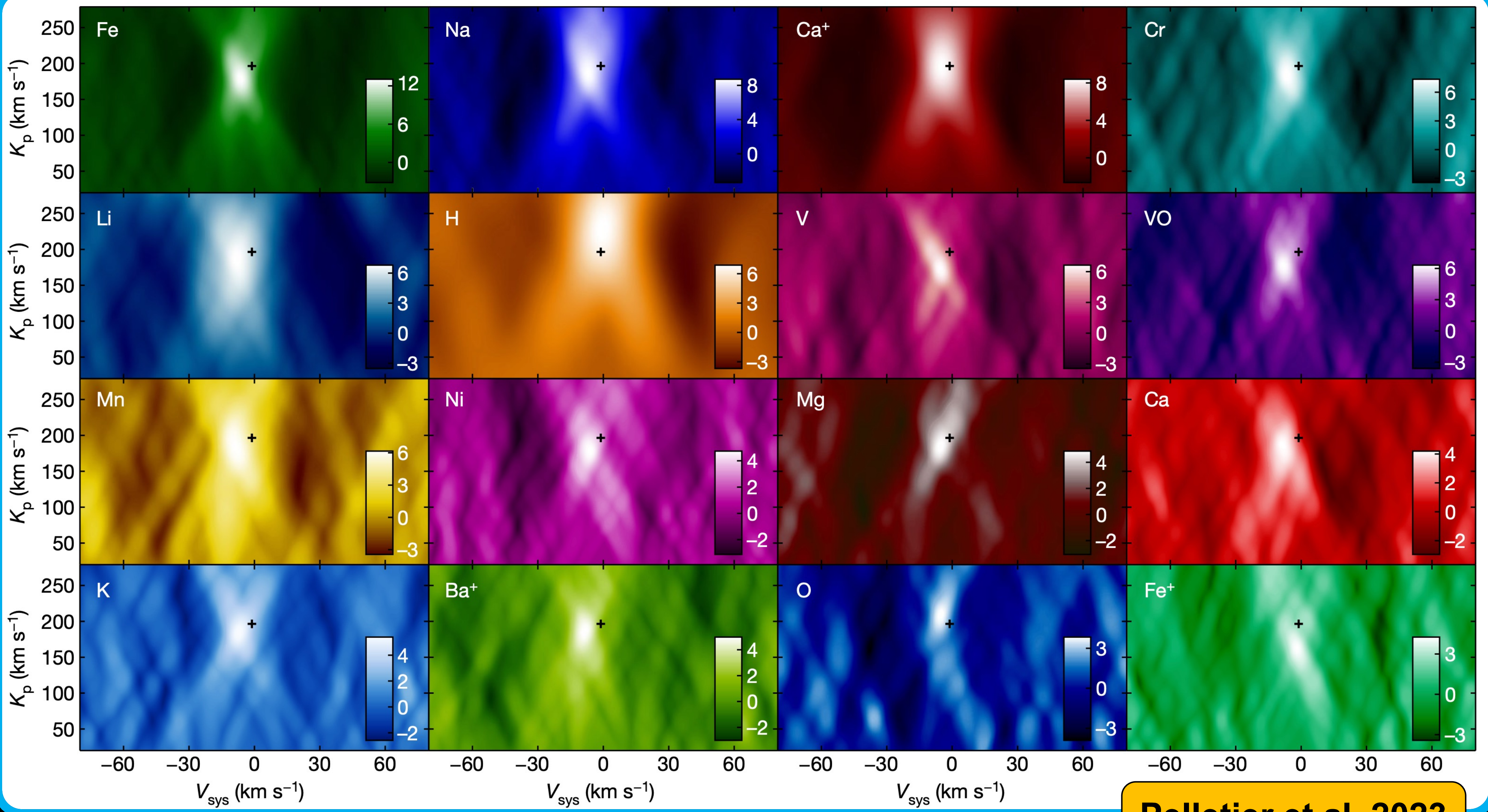




Ca+ detected on WASP-76b!

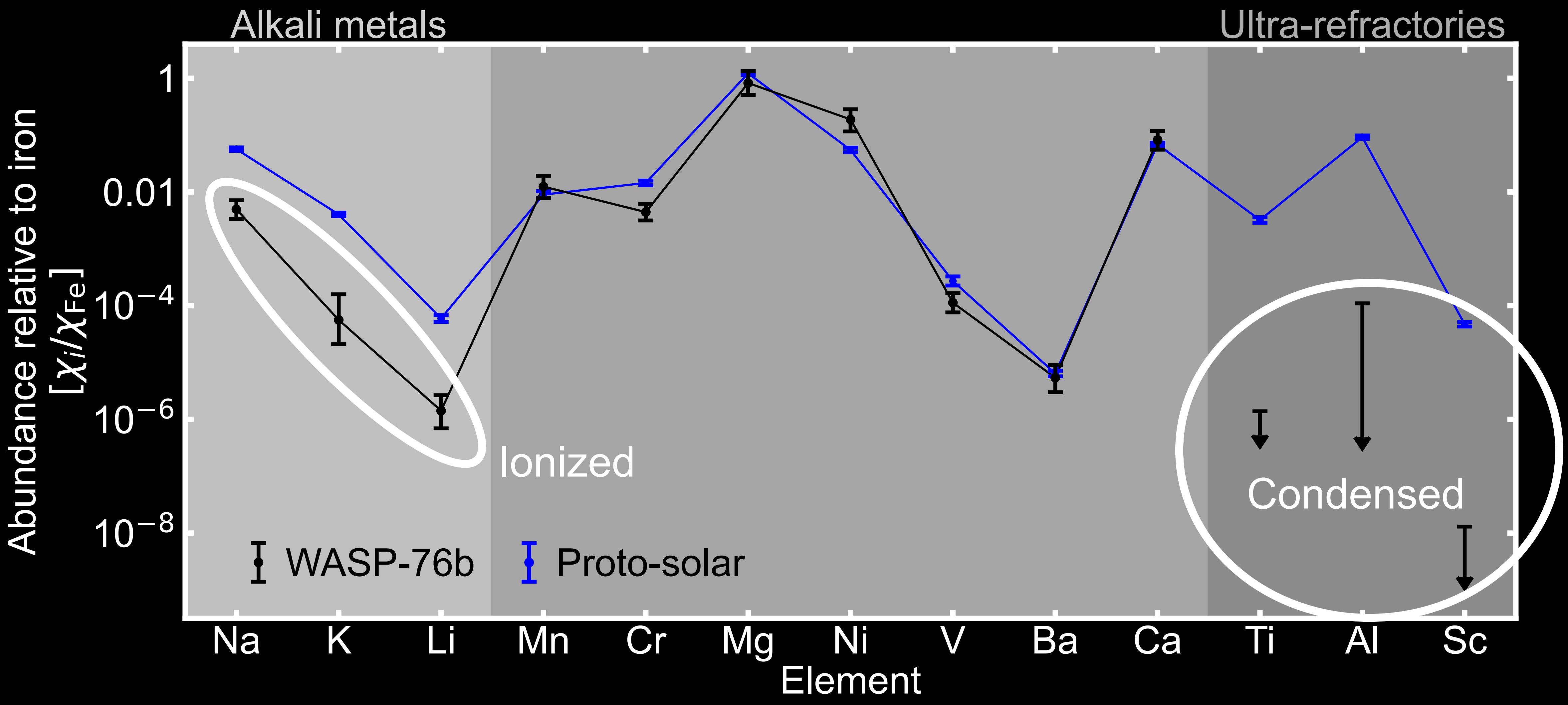


Species detected on WASP-76b



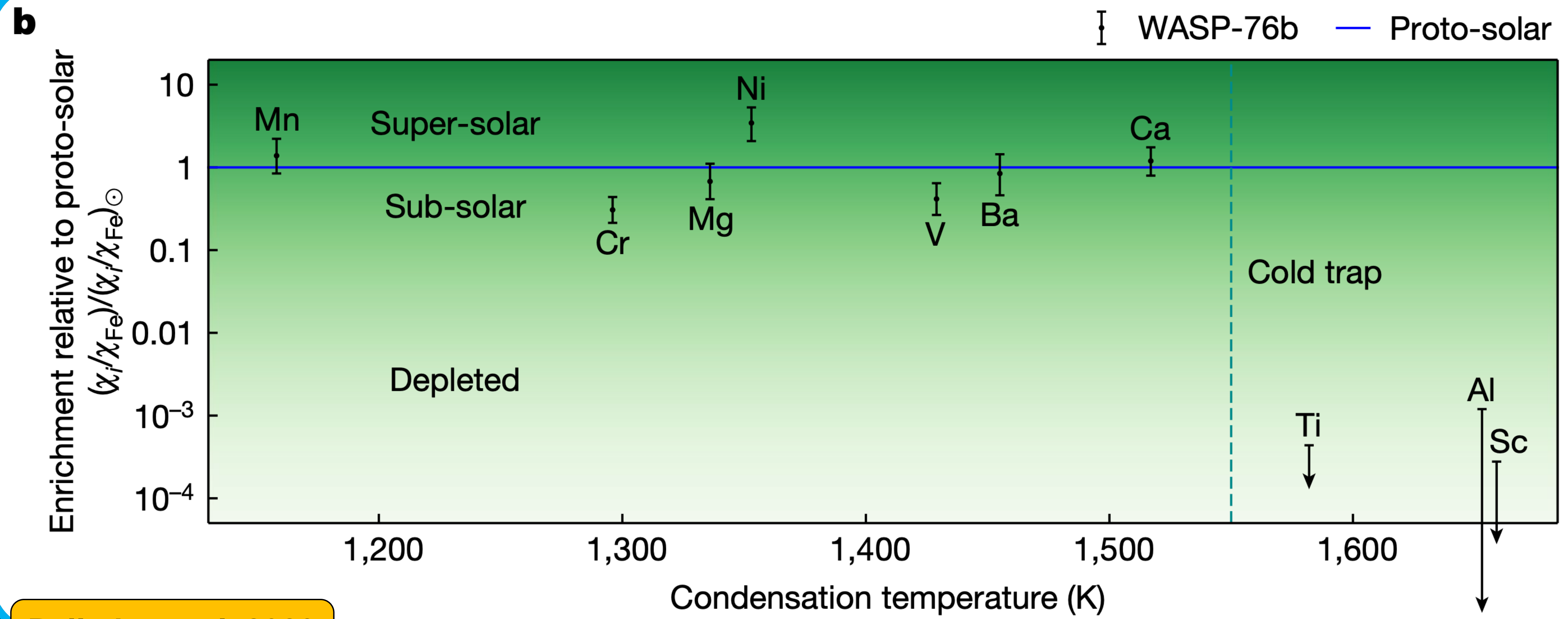
Pelletier et al. 2023

Retrieved abundances for WASP-76b



- ➢ Elements match solar/stellar abundances in most cases

A sharp cold-trapping onset



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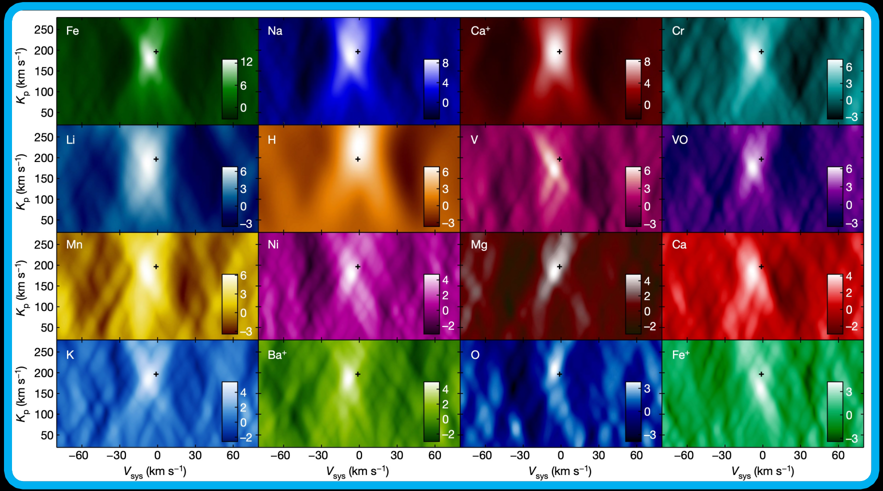
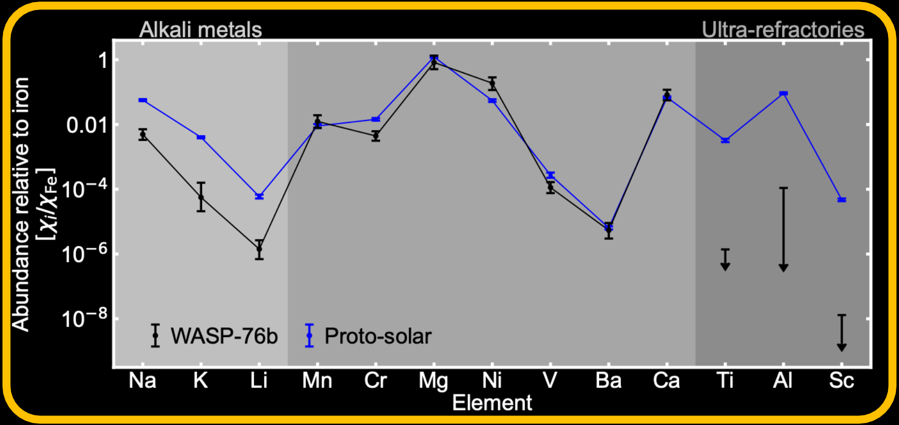
- Solar-like abundances until T_{cond} ~1550K, then strong depletion

Takeaways: WASP-76b

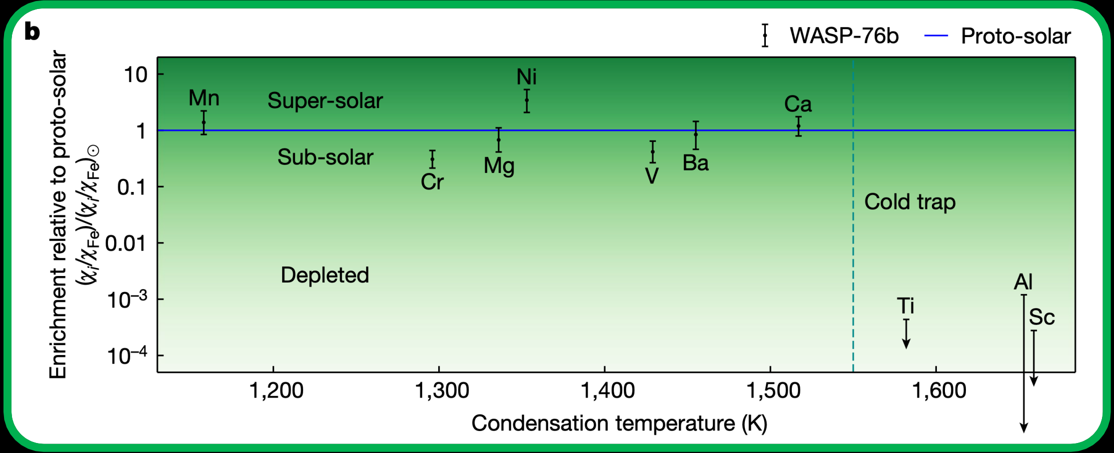
① Many refractory species detected on WASP-76b from MAROON-X transits





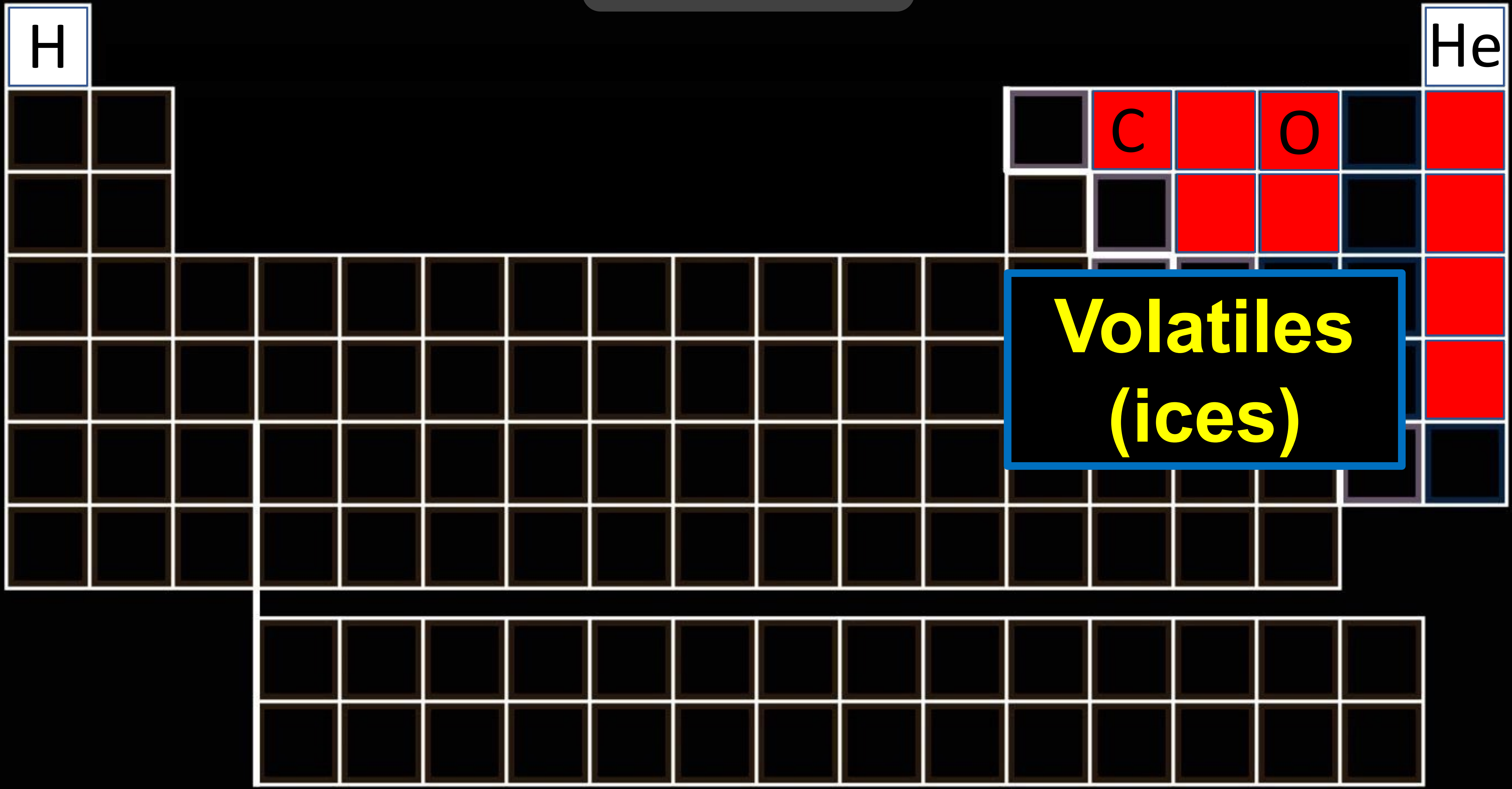
② Most refractory abundance ratios on WASP-76b match those of the host star

③ There exist a sharp onset in condensation temperature for measured abundance ratios

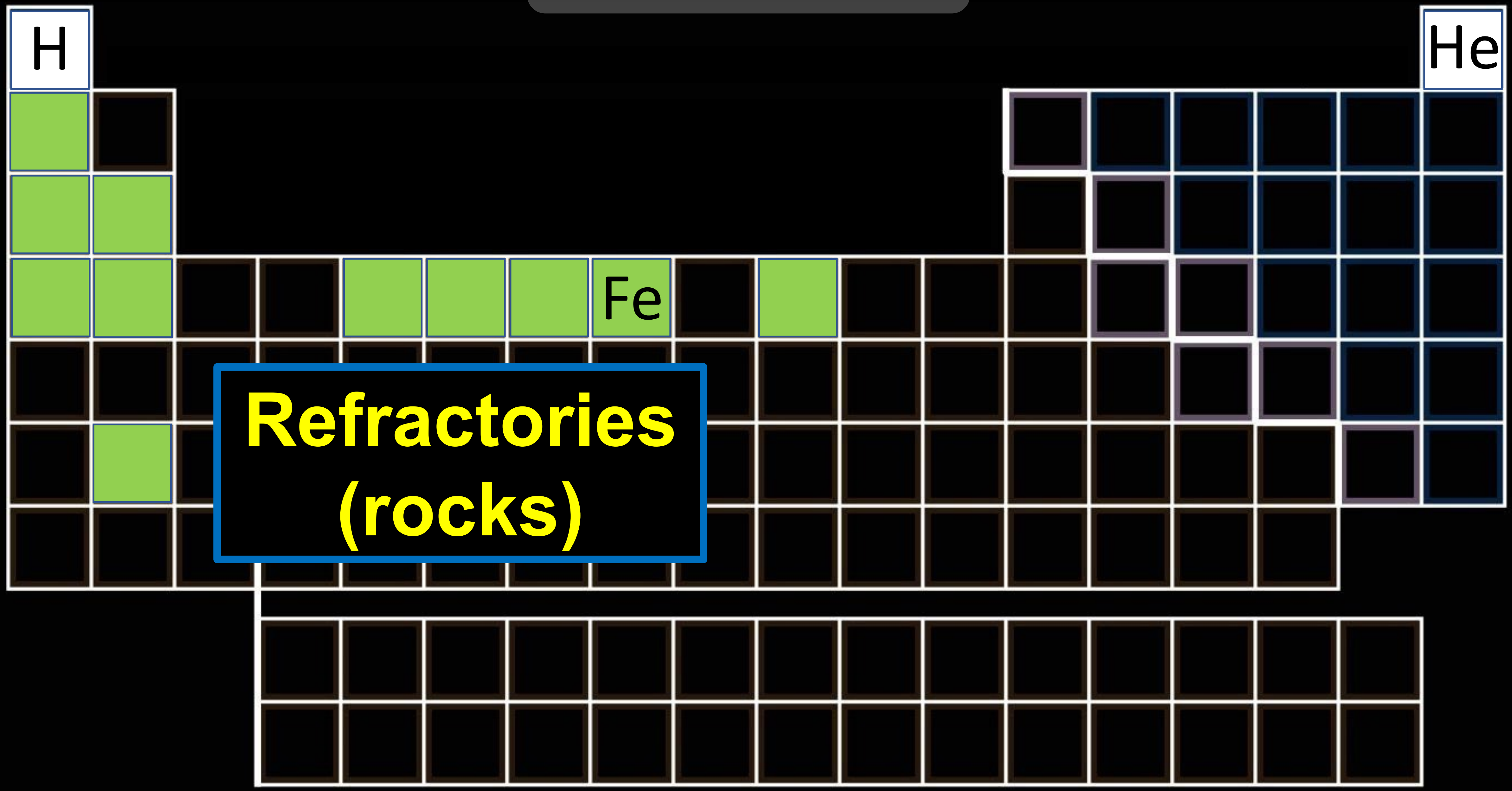


WASP-121b

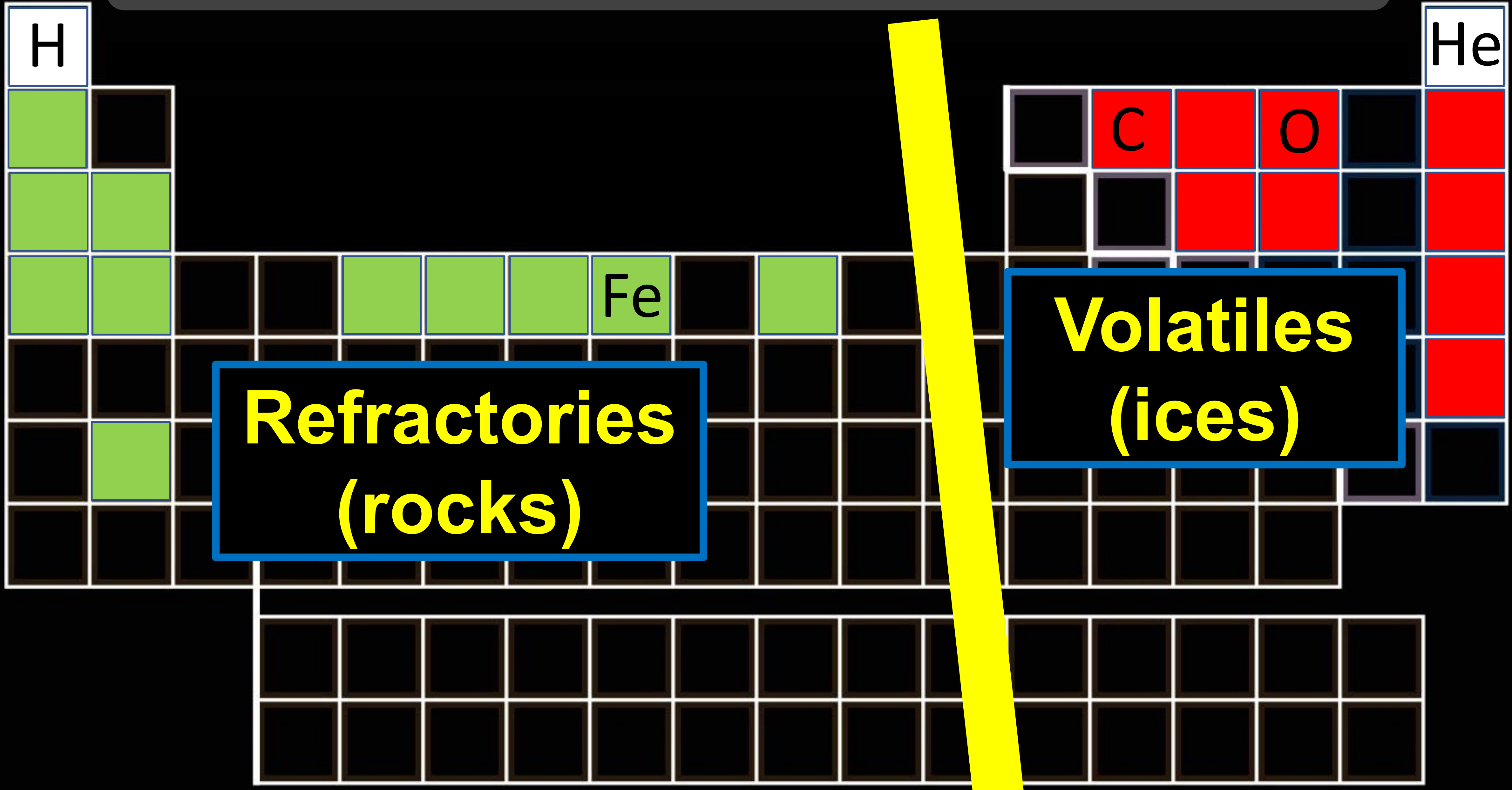
Jupiter



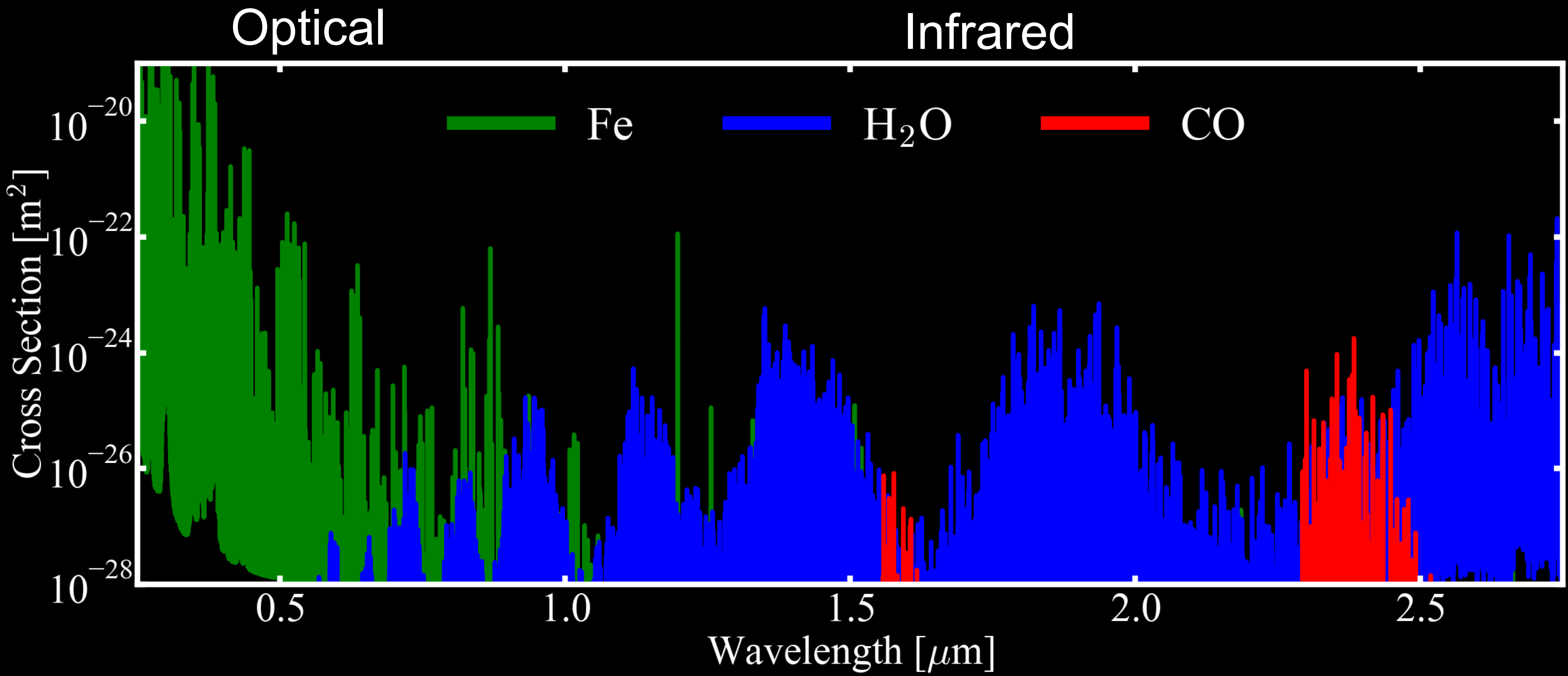
WASP-76b



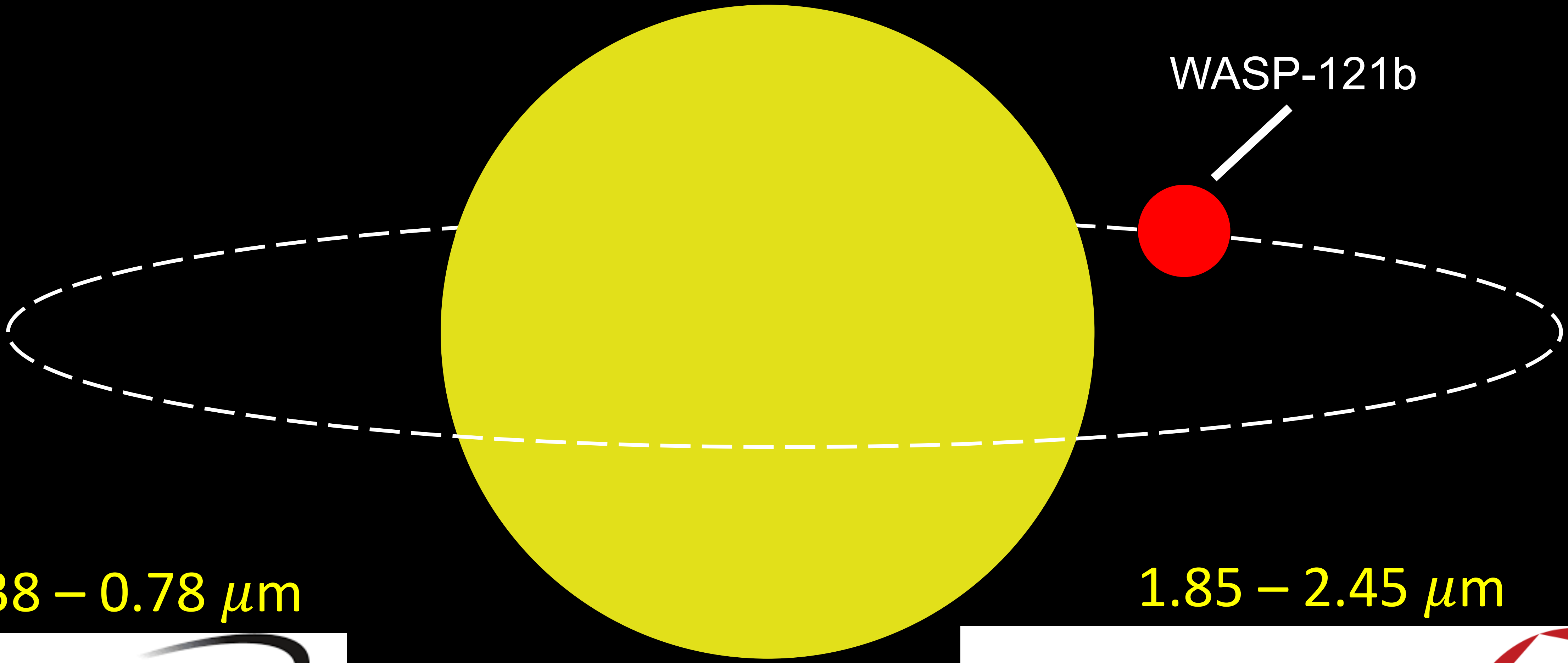
Bridging the volatile/refractory gap



Refractories → Optical
Volatiles → Infrared



Dayside observation of WASP-121b



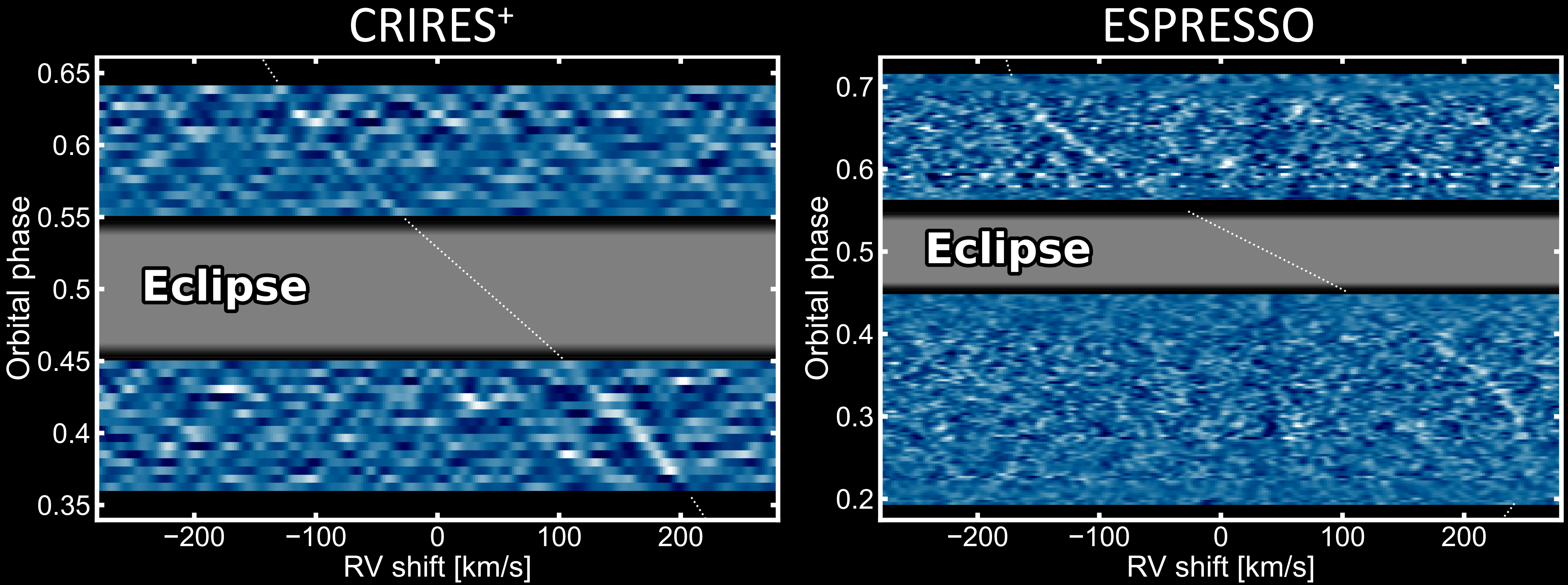
$0.38 – 0.78\ \mu m$

espresso

$1.85 – 2.45\ \mu m$

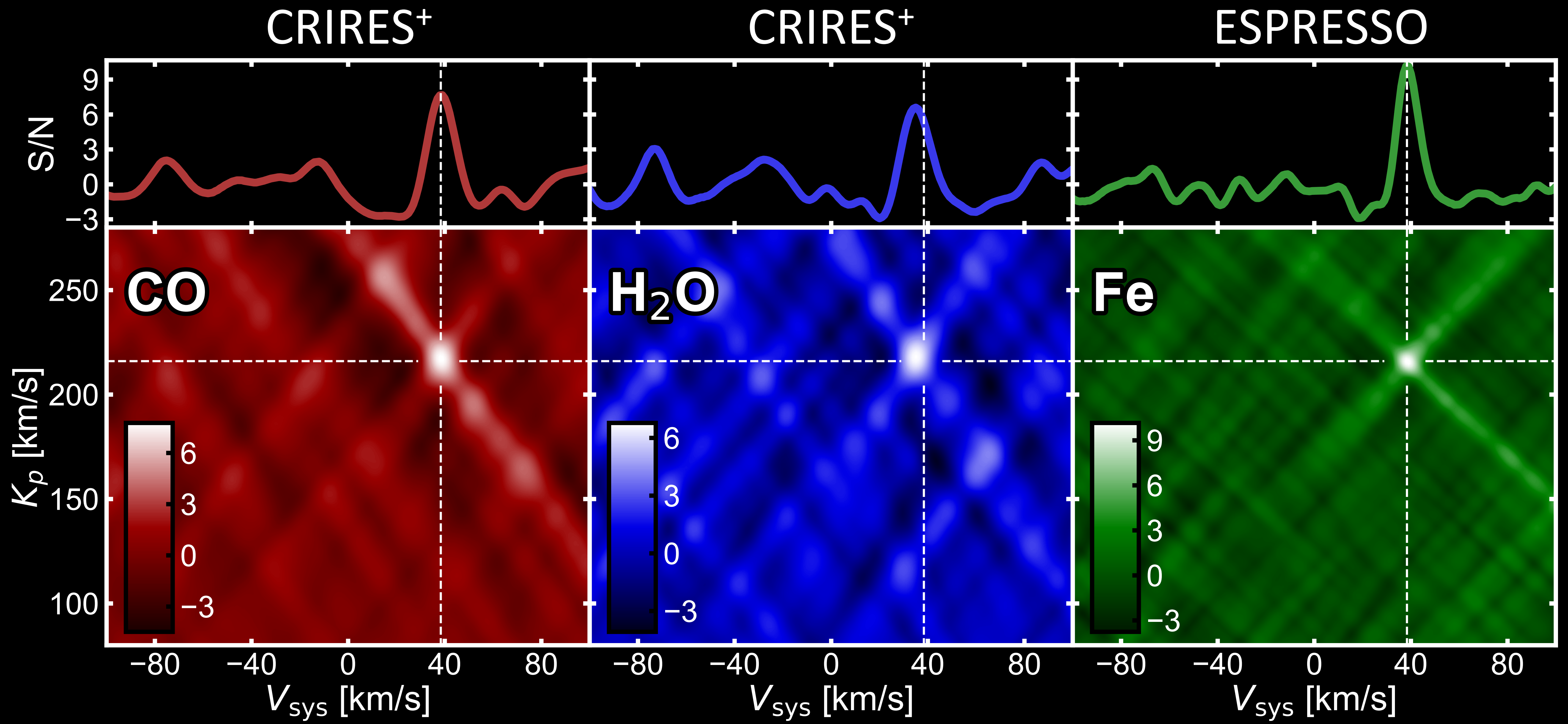
CRIRES+

Orbital trace of WASP-121b's atmosphere



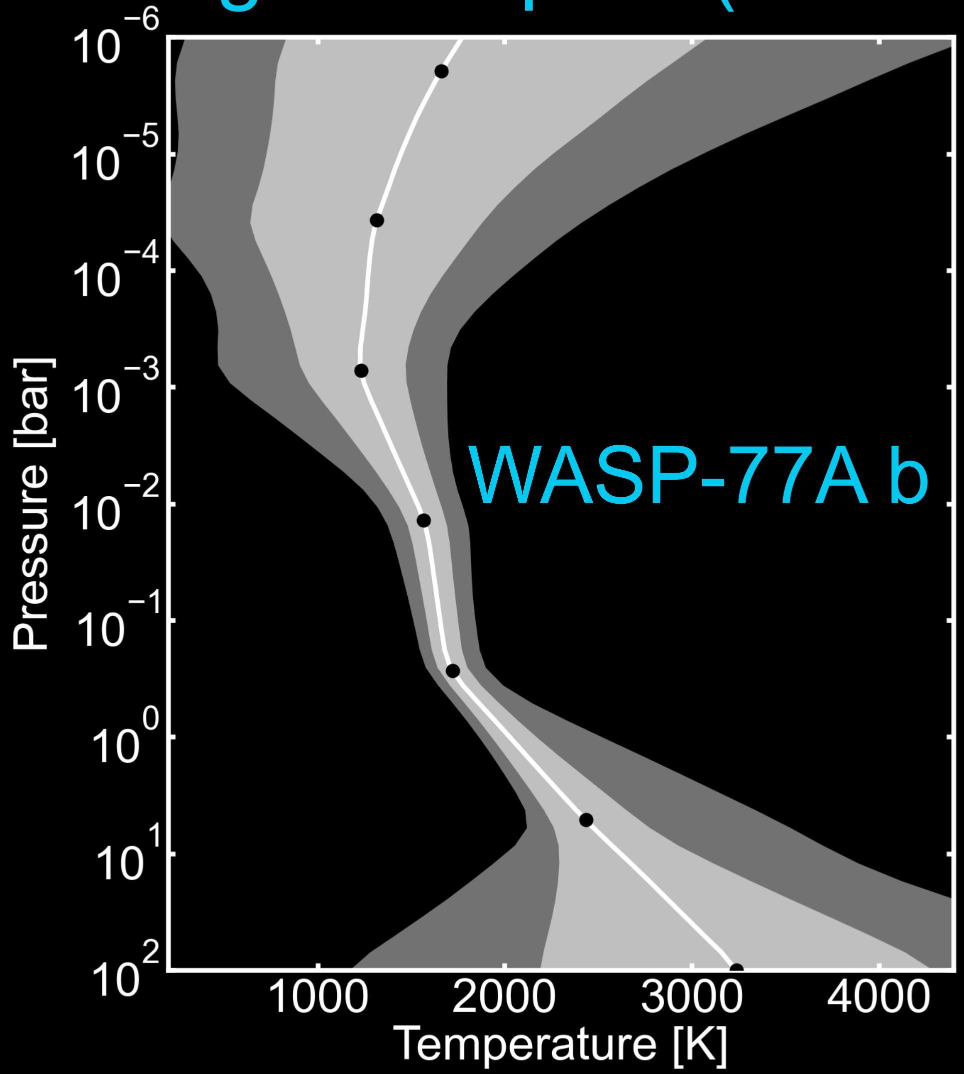
- ➢ Lines seen in emission, indicating a thermally inverted atmosphere

CO, H_2O, and Fe on the dayside of WASP-121b

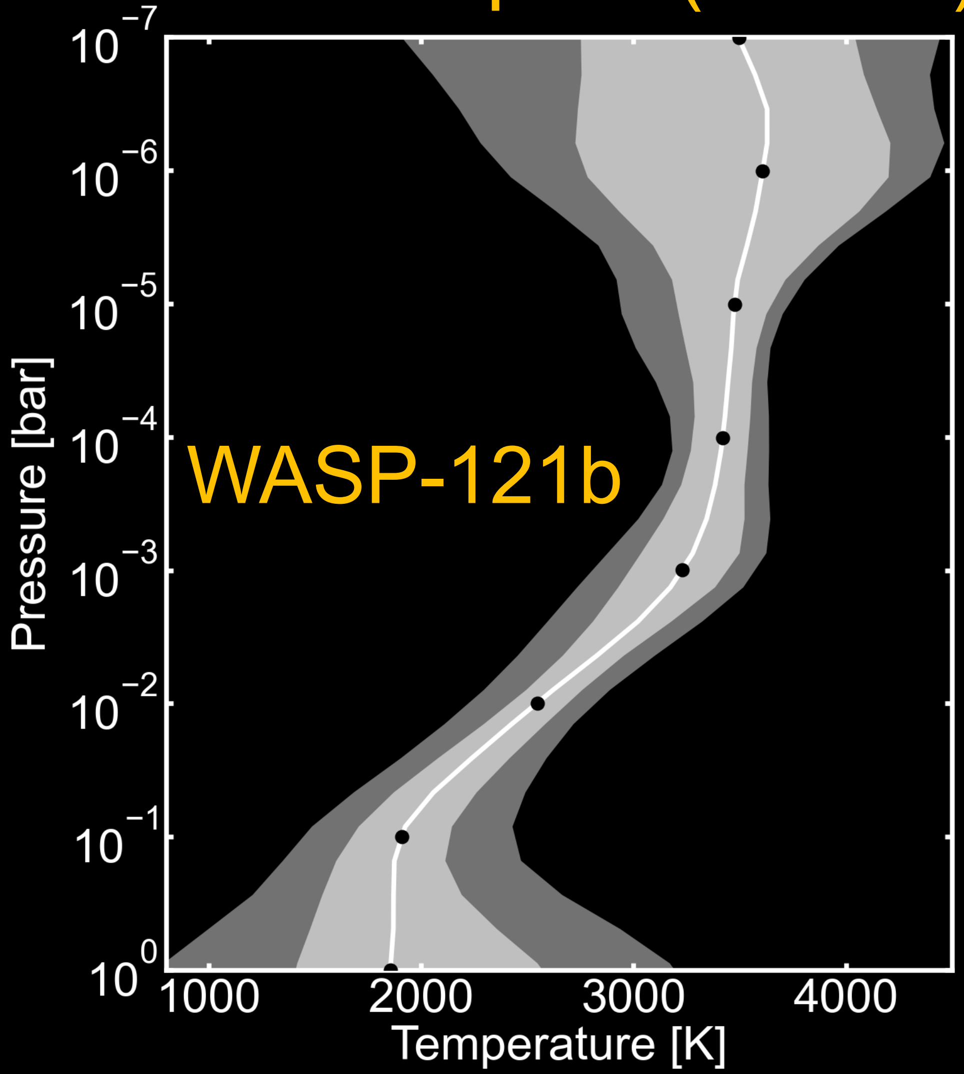


Retrieved dayside temperature structure

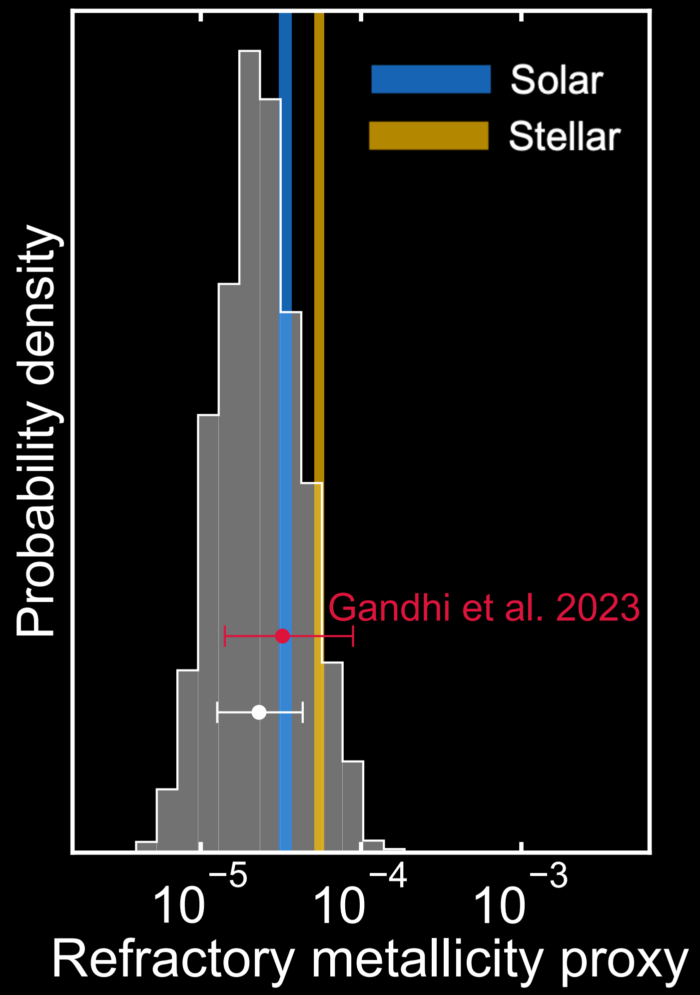
Boring hot Jupiter (1700K)



Ultra-hot Jupiter (2350K)

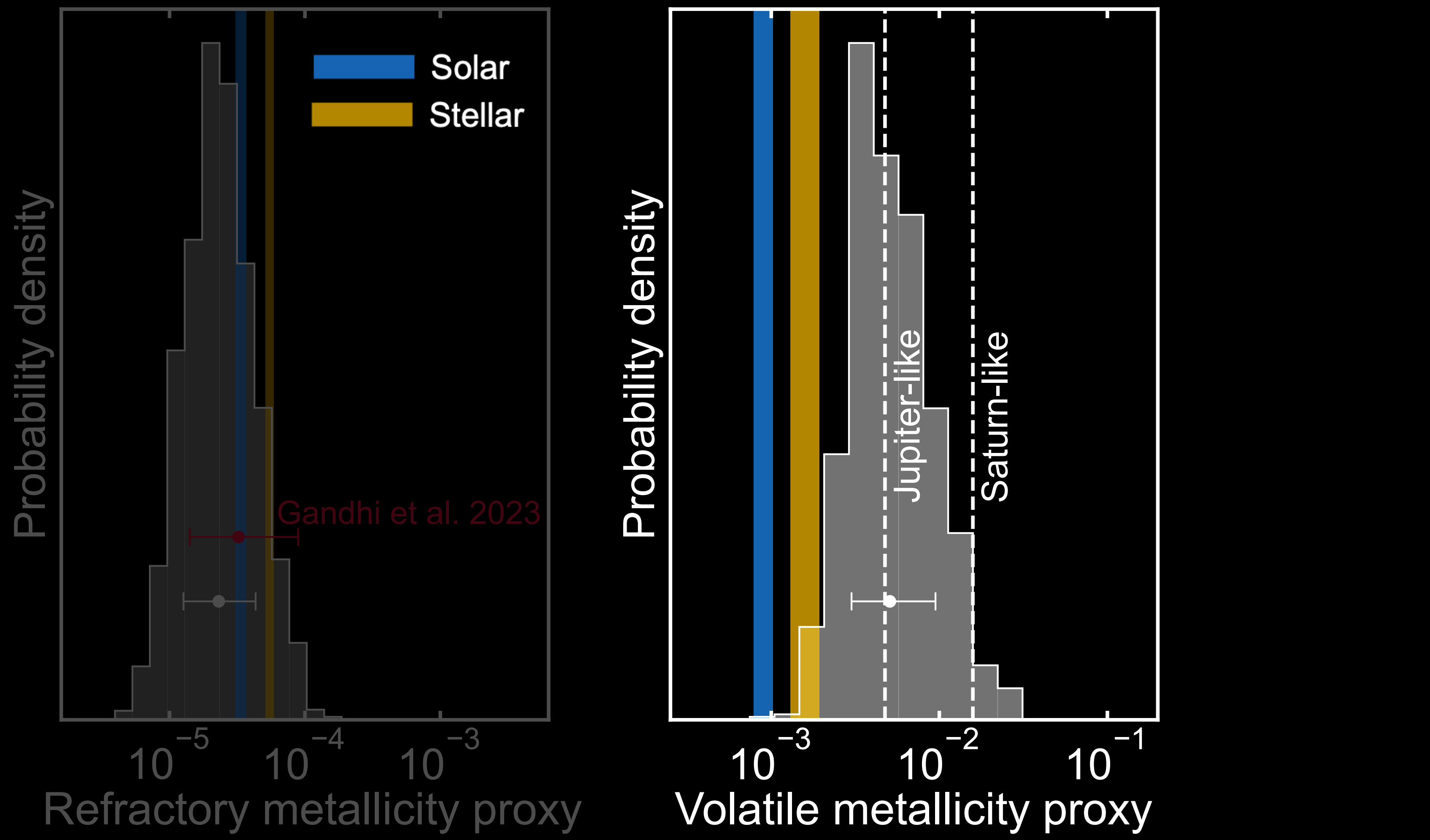


WASP-121b elemental abundance ratios



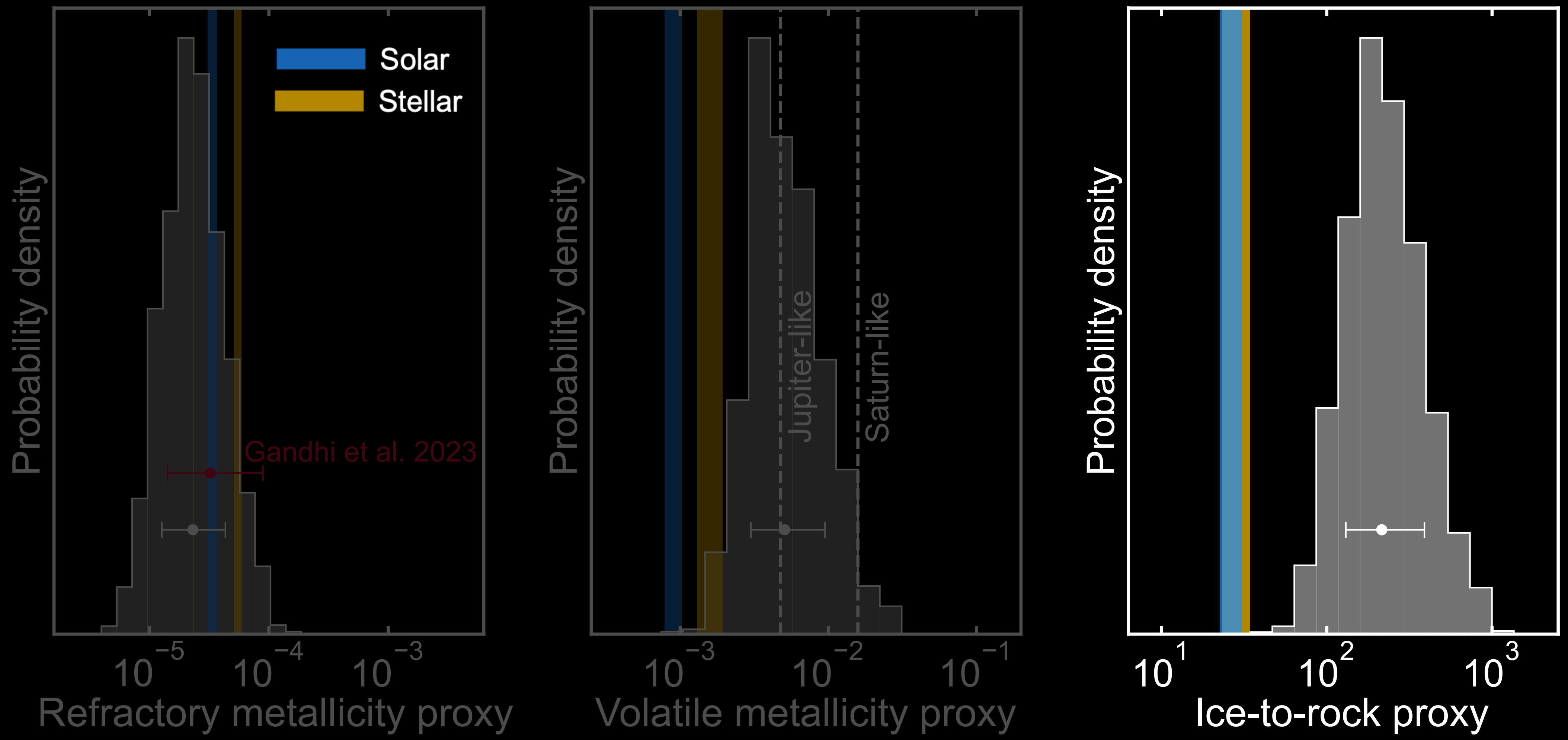
- Fe/H on WASP-121b is consistent with solar/stellar

WASP-121b elemental abundance ratios



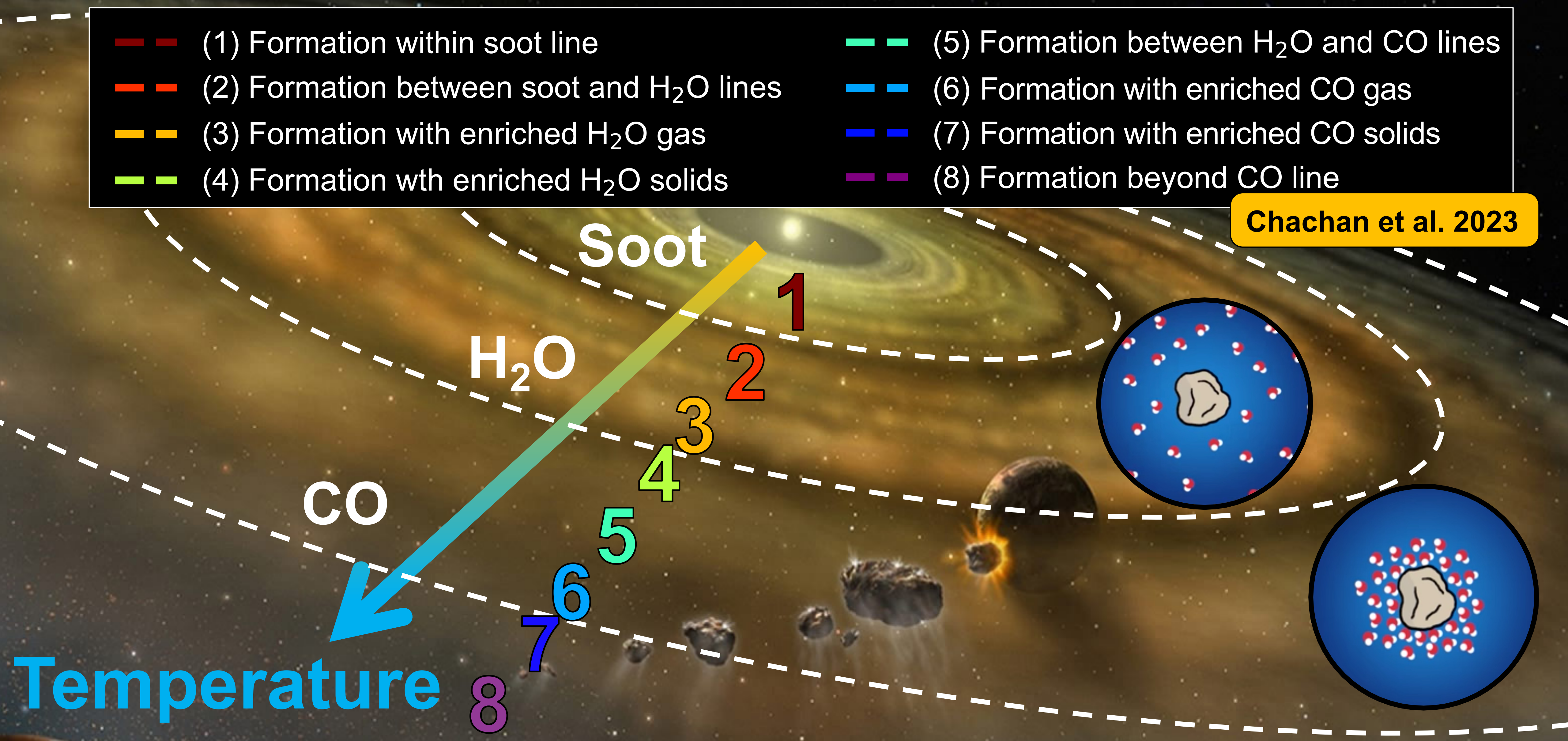
- C/H and O/H on WASP-121b are super-solar/stellar

WASP-121b elemental abundance ratios



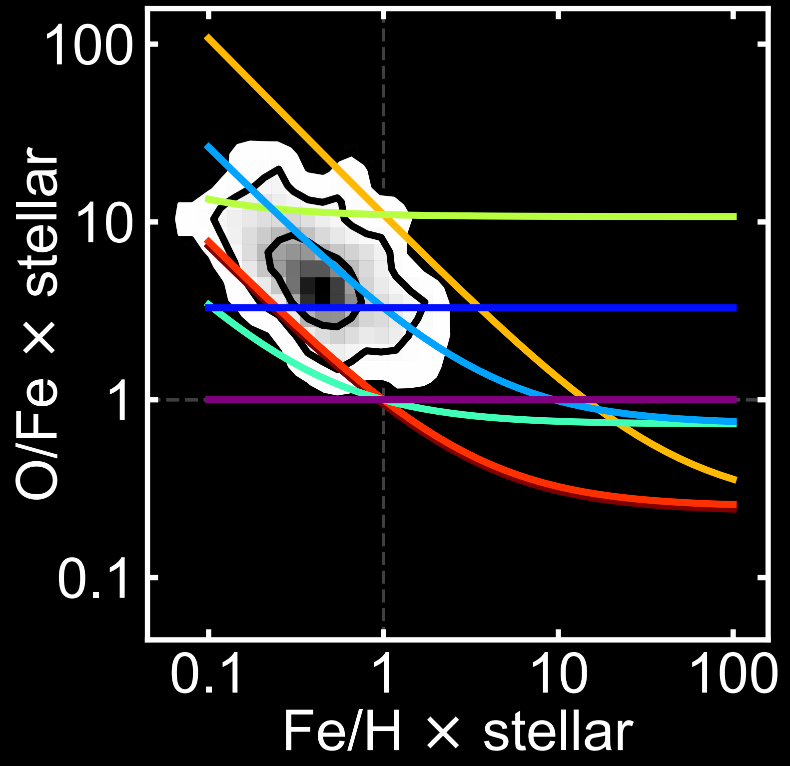
- WASP-121b is enriched in volatiles relative to refractories

Linking composition to formation



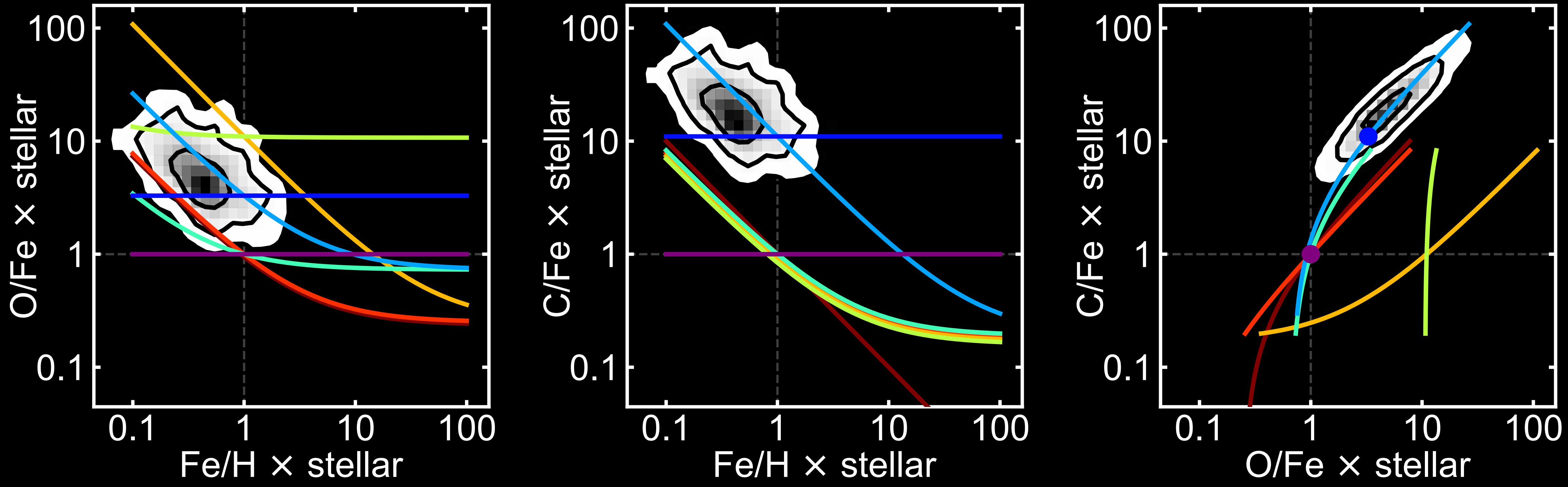
Linking composition to formation

- (1) Formation within soot line
- (2) Formation between soot and H_2O lines
- (3) Formation with enriched H_2O gas
- (4) Formation wth enriched H_2O solids
- (5) Formation between H_2O and CO lines
- (6) Formation with enriched CO gas
- (7) Formation with enriched CO solids
- (8) Formation beyond CO line

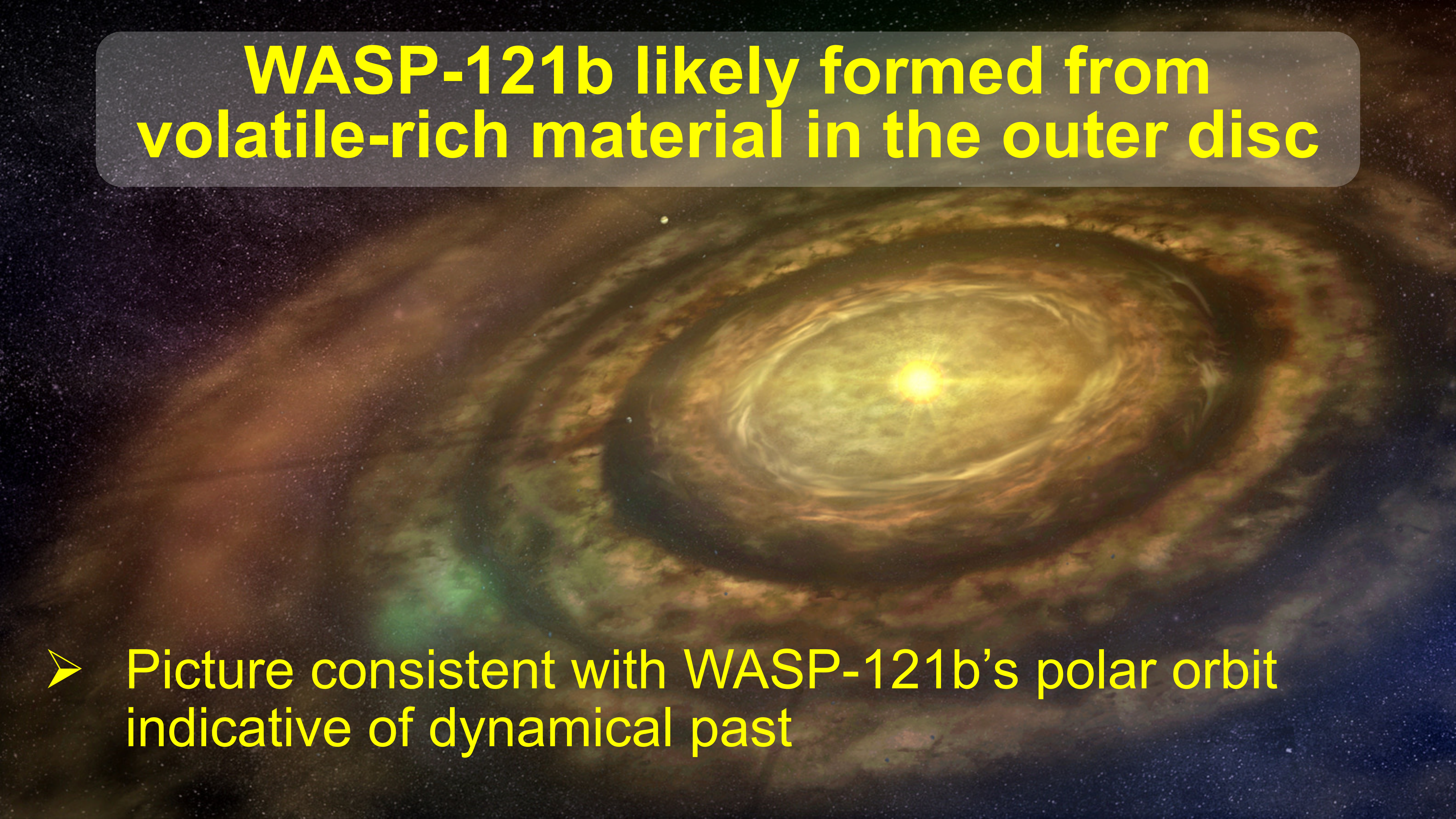


Linking composition to formation

- ~~(1) Formation within soot line~~
- ~~(2) Formation between soot and H_2O lines~~
- ~~(3) Formation with enriched H_2O gas~~
- ~~(4) Formation wth enriched H_2O solids~~
- ~~(5) Formation between H_2O and CO lines~~
- (6) Formation with enriched CO gas
- (7) Formation with enriched CO solids
- ~~(8) Formation beyond CO line~~



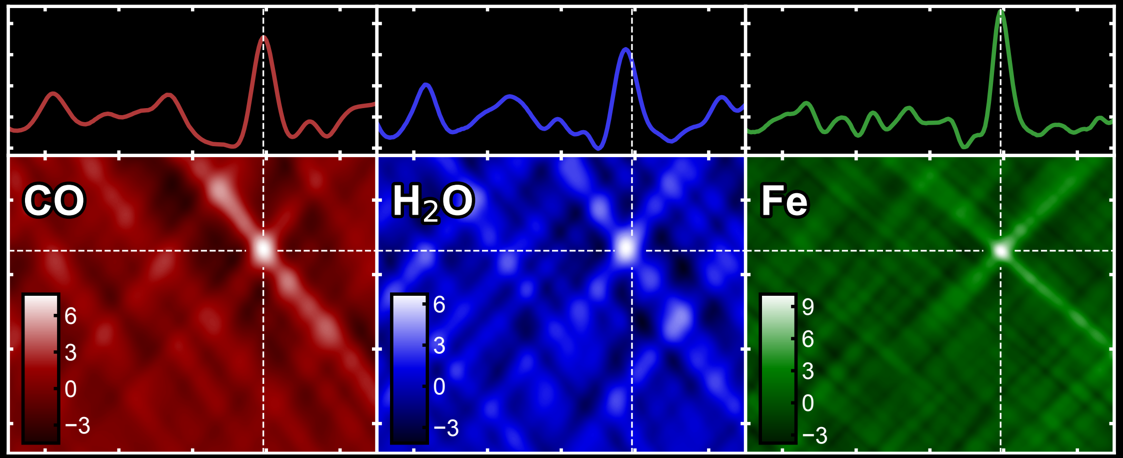
WASP-121b likely formed from volatile-rich material in the outer disc

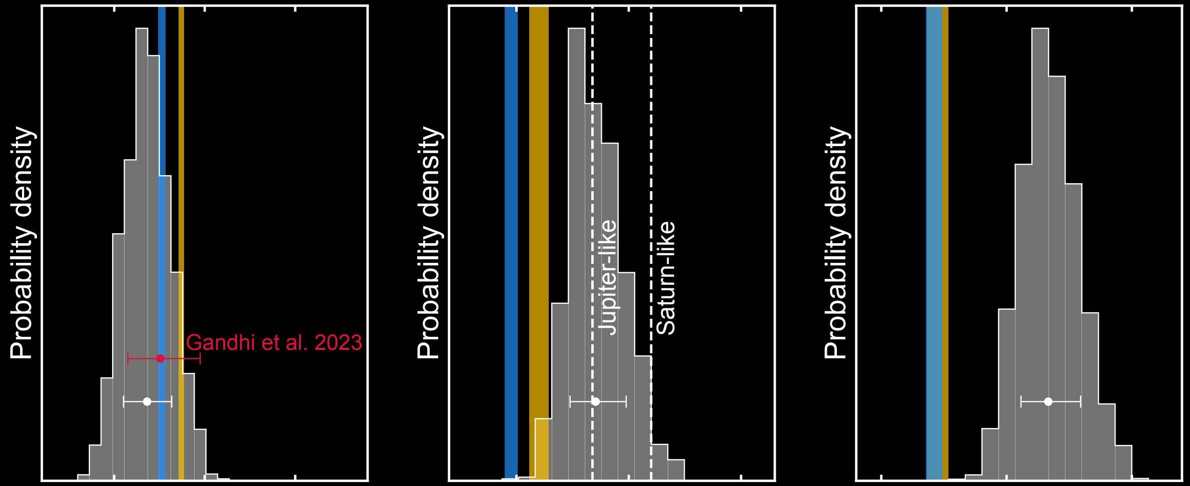


- Picture consistent with WASP-121b's polar orbit indicative of dynamical past

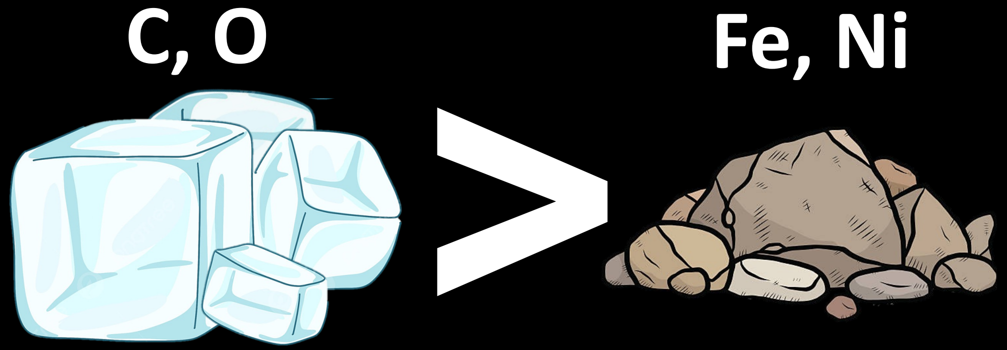
Takeaways: WASP-121b

① Volatile (CO, H_2O) and refractory (Fe) species detected on WASP-121b



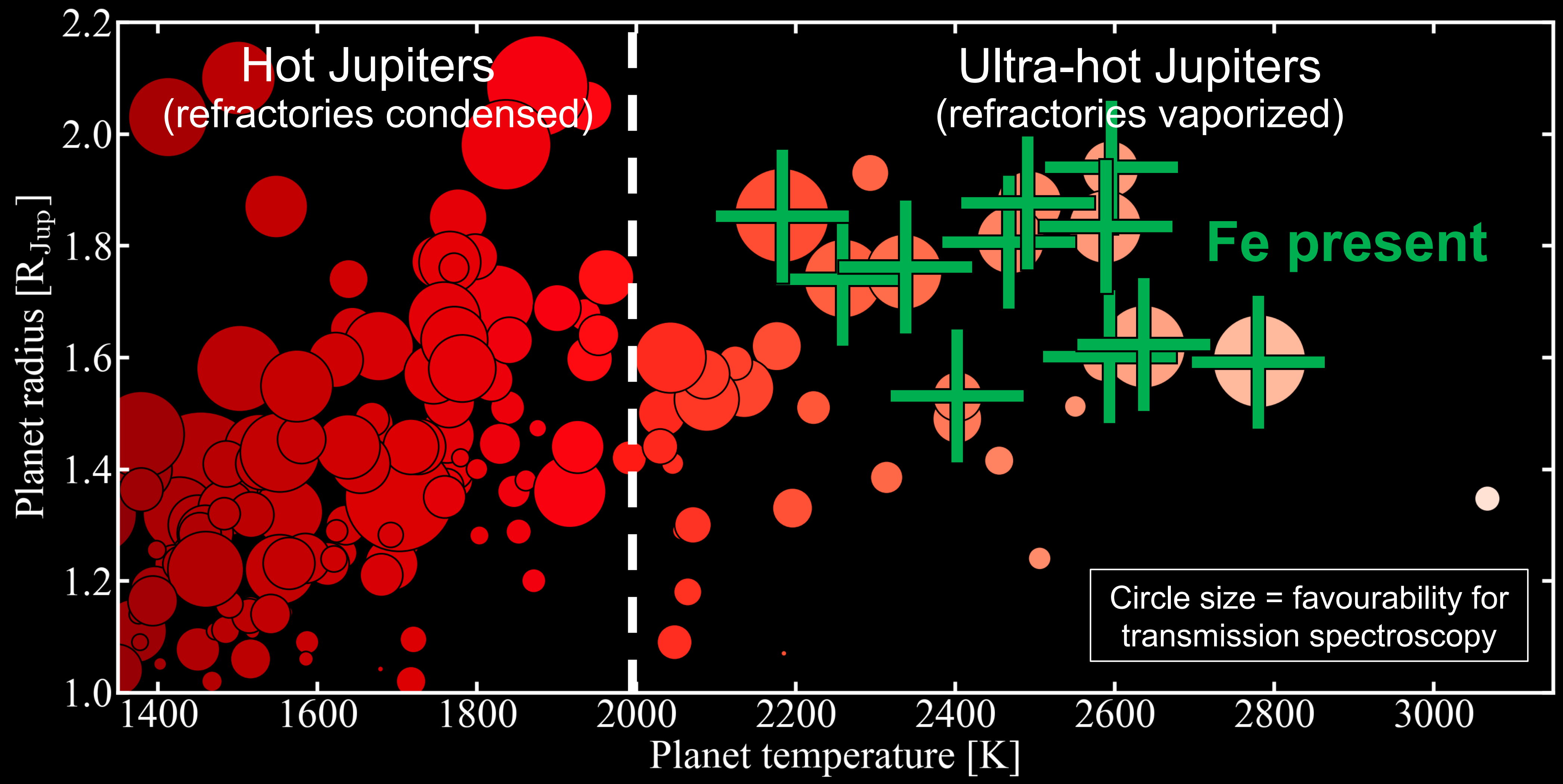


② Refractories abundances are consistent with stellar but volatiles are enriched



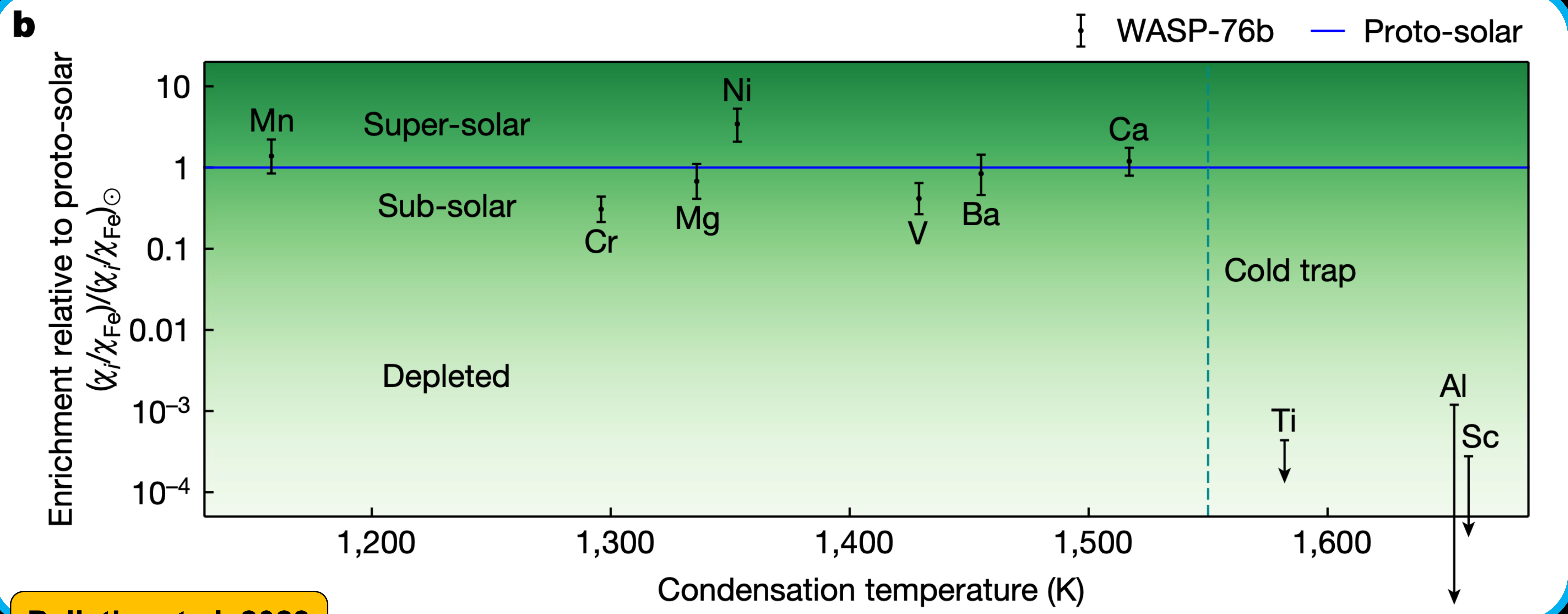
③ WASP-121b has a super-stellar ice-to-rock ratio, and may have formed in a volatile-rich environment

The hot giant exoplanet population



➢ Hot and ultra-hot Jupiter atmospheres are compositionally different

Recall: Ti depletion on WASP-76b



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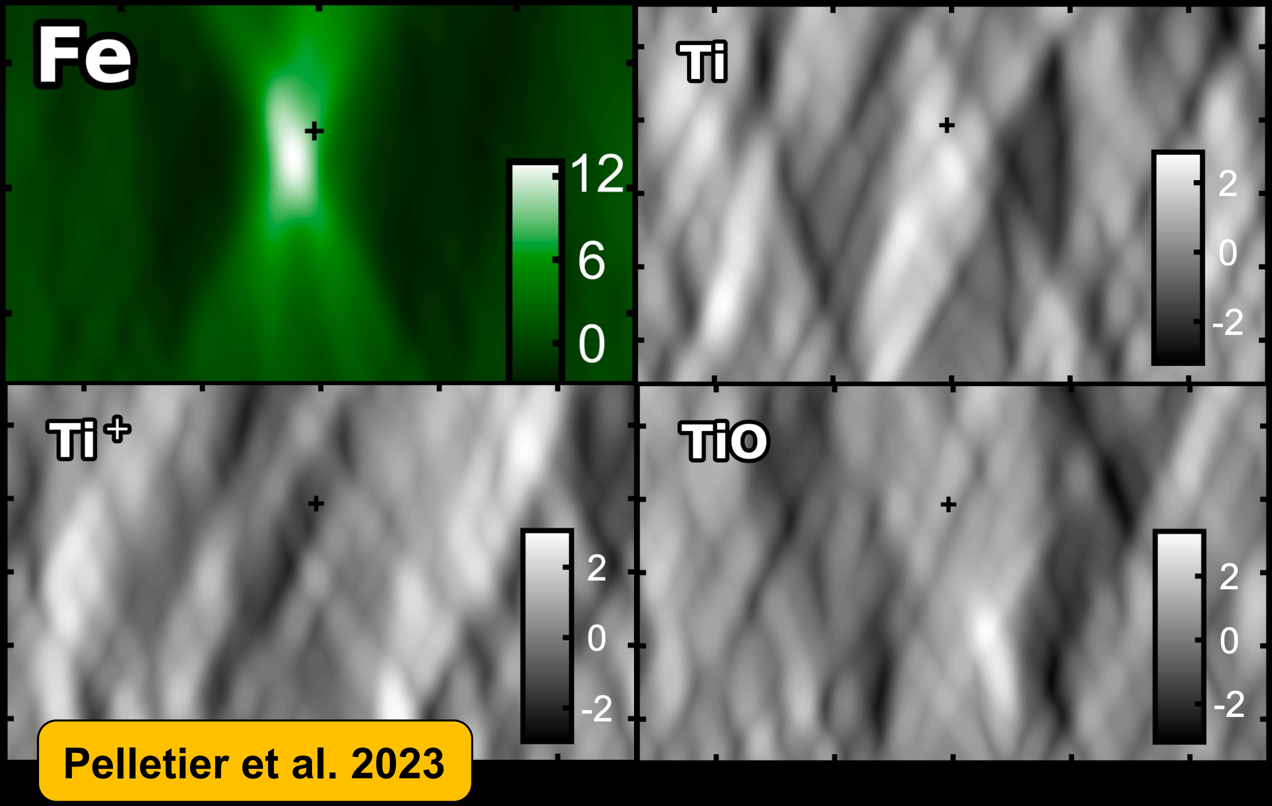
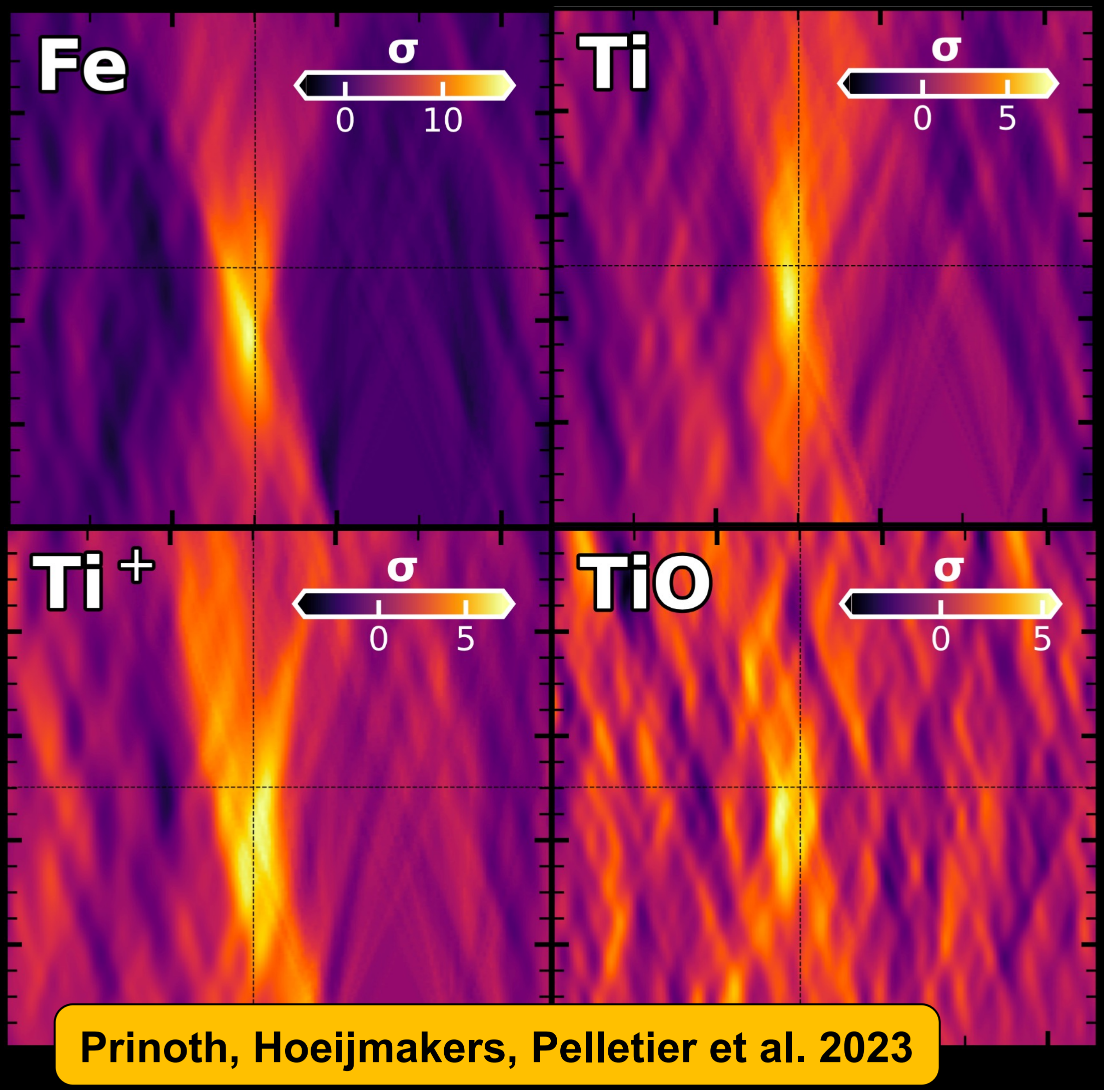
- Not all refractories are the same

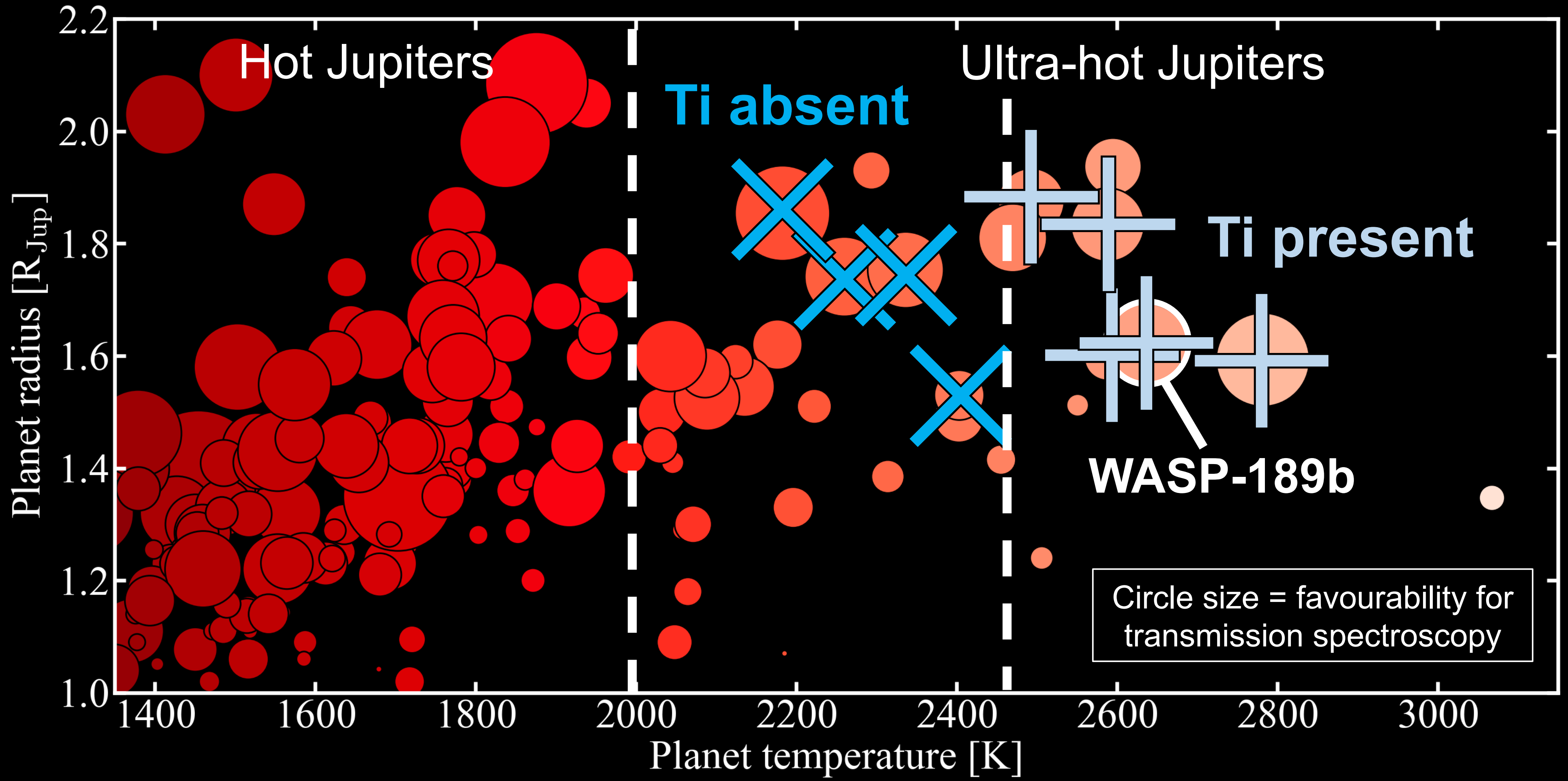
WASP-76b (T_{eq} = 2200K)
Titanium absent



WASP-189b (T_{eq} = 2650K)
Titanium present



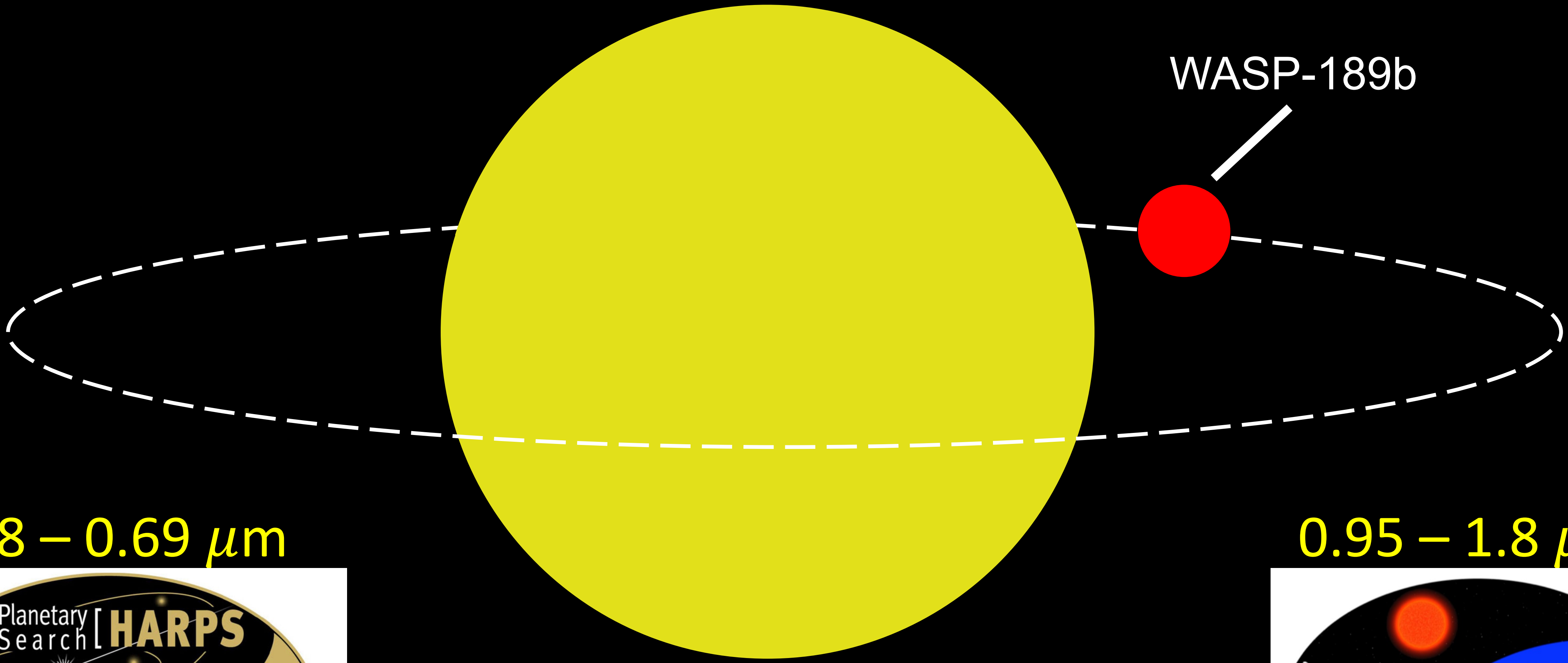
Titanium on ultra-hot Jupiters



➢ When does the titanium transition occur? And how sharp is it?

WASP-189b

Dayside observation of WASP-189b

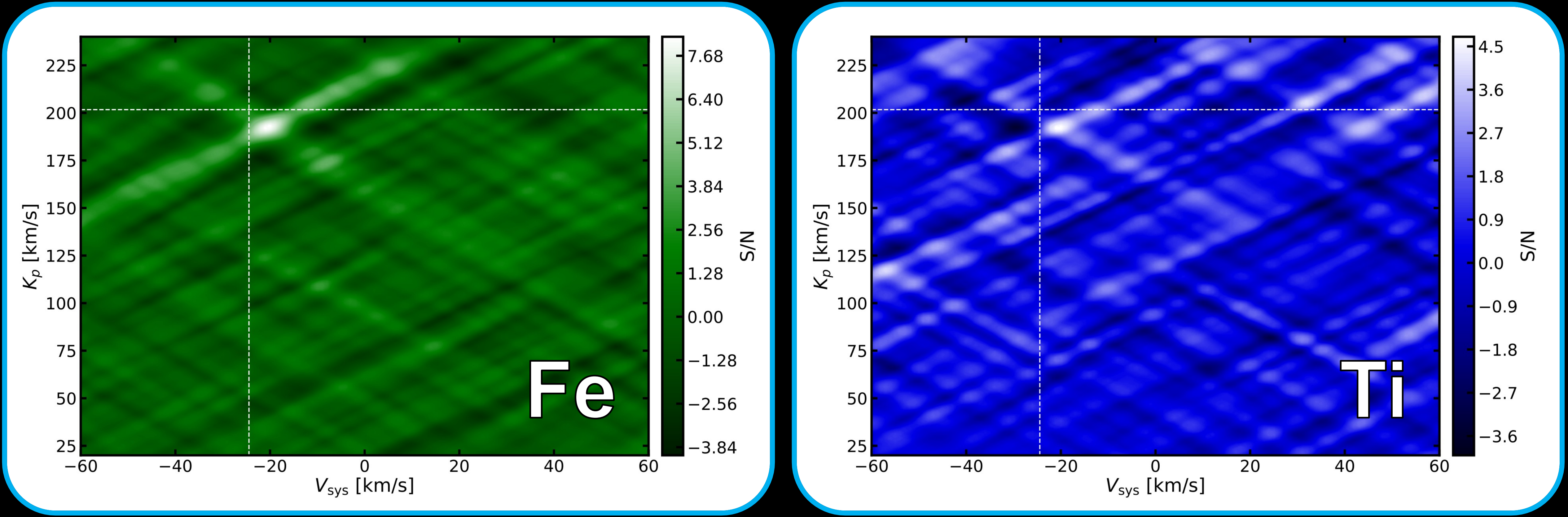


0.38 – 0.69 μm

0.95 – 1.8 μm

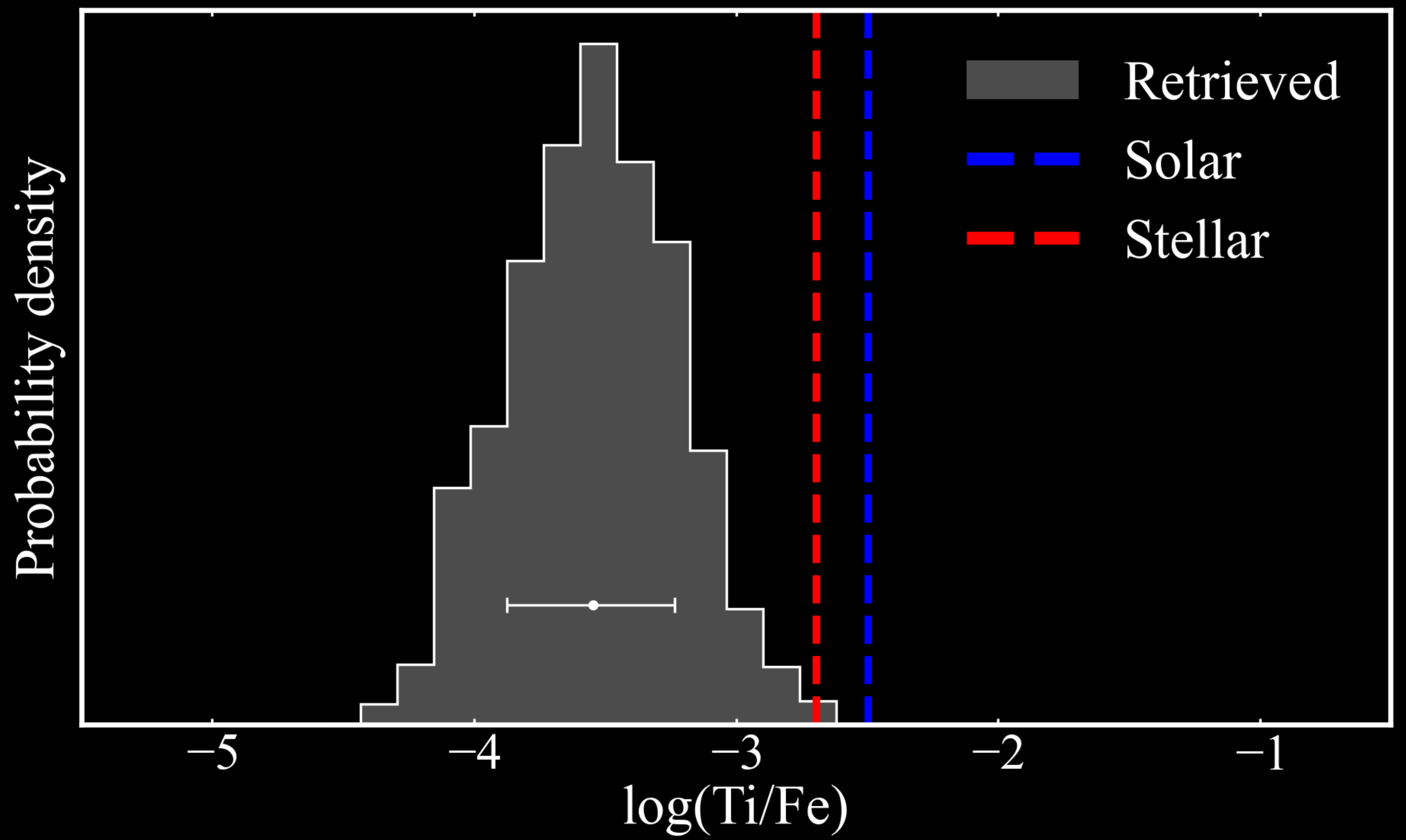
LOOKING FOR BLUE PLANETS AROUND RED STARS

Detection of Fe and Ti on WASP-189b



- ➢ Signals seen in emission, indicating a thermal inversion

Retrieved Ti/Fe ratio on WASP-189b



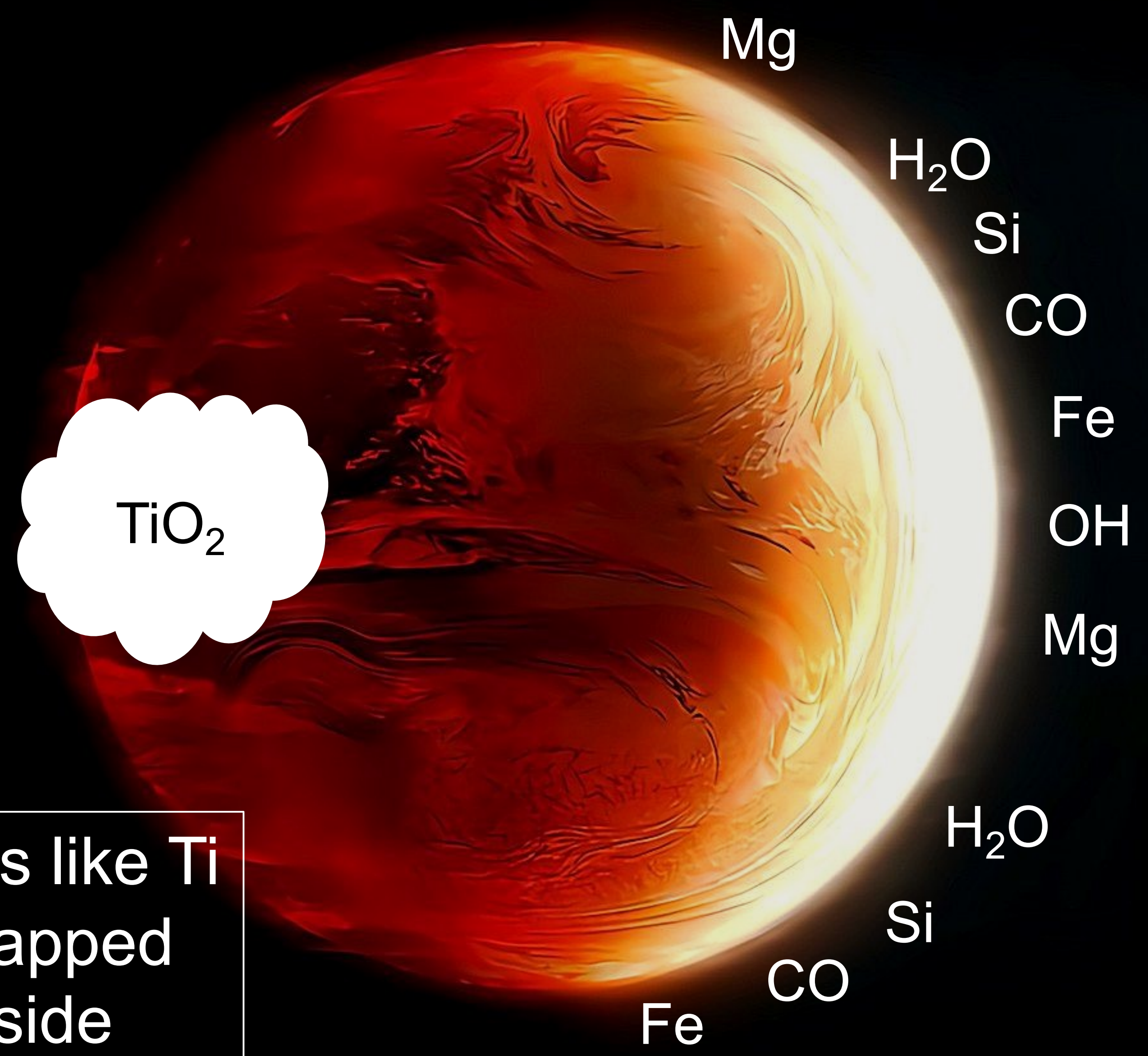
- WASP-189b has more Fe than Ti (relative to the solar/stellar ratios)

Where is the missing titanium?

- Some Ti in other molecular forms like TiO_2 and TiH (unlikely)
- TiO is under-estimated due to line list issues (likely)
- Equilibrium chemistry is not a valid assumption (possible)
- Star Fe/Ti ratio is even more subsolar than measured (unlikely)
- Some titanium is still partially cold-trapped (?)

`Cooler' ultra-hot Jupiter (WASP-76b)

Cold Nightside



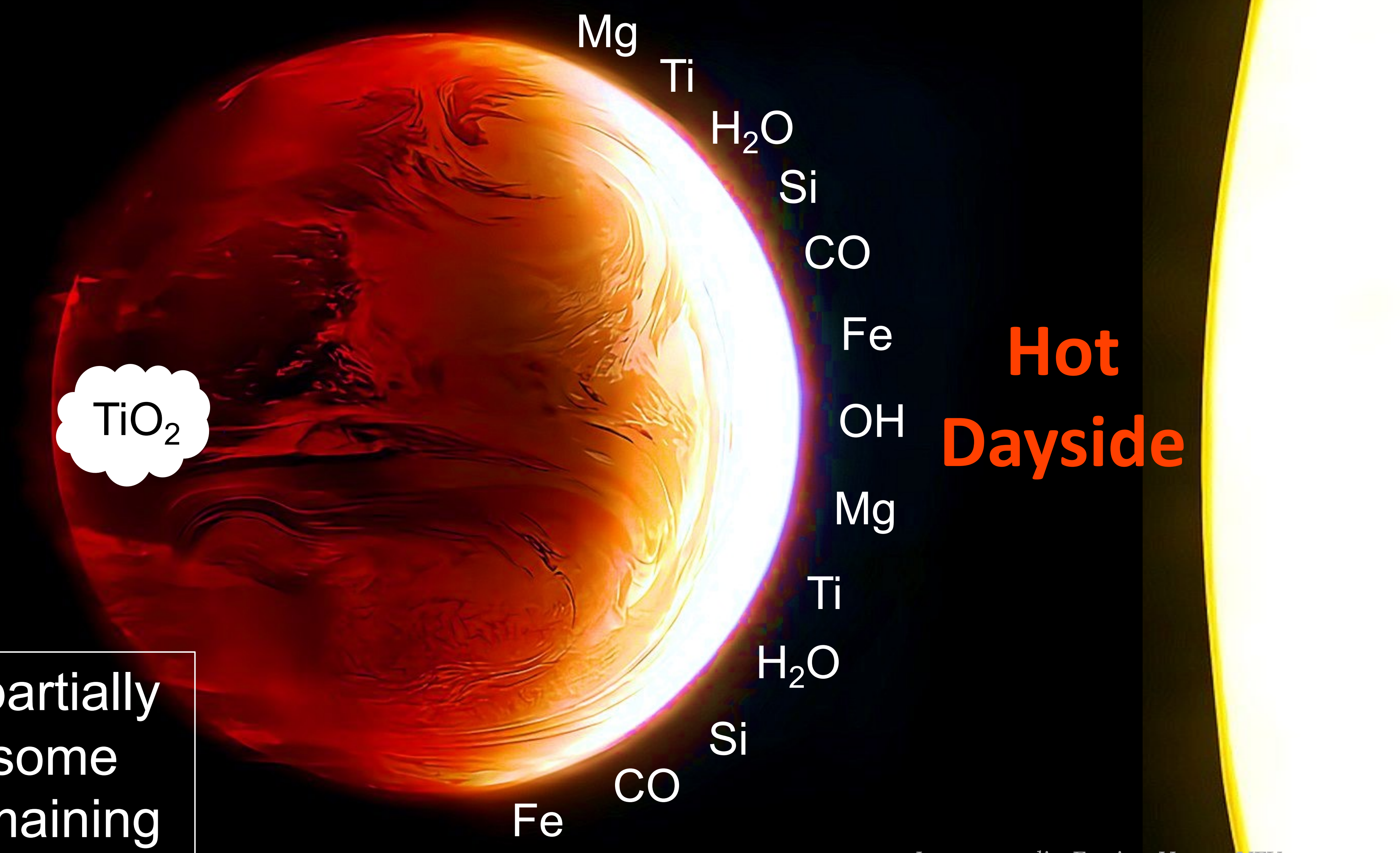
Hot Dayside

Ultra-refractories like Ti remain cold-trapped on the nightside

Image credit: Engine House VFX

`Hotter’ ultra-hot Jupiter (WASP-189b)

Cold Nightside



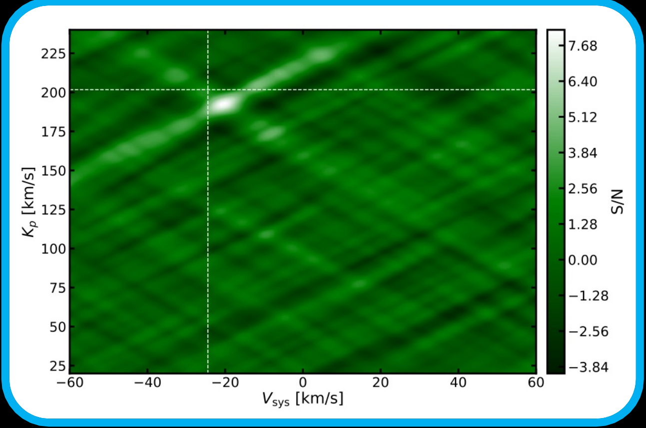
Hot Dayside

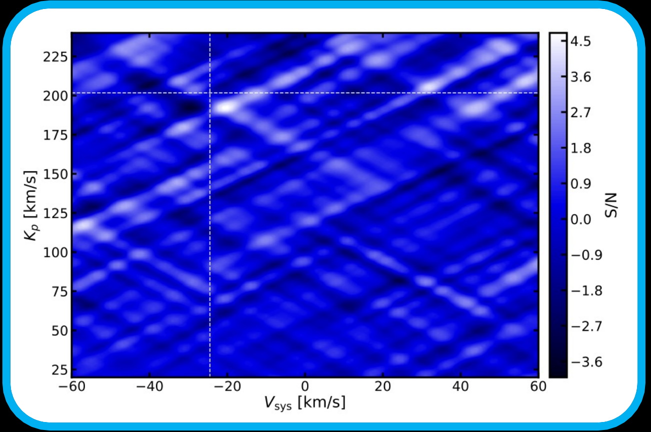
Ti cold-trap is partially broken, with some cloud mass remaining

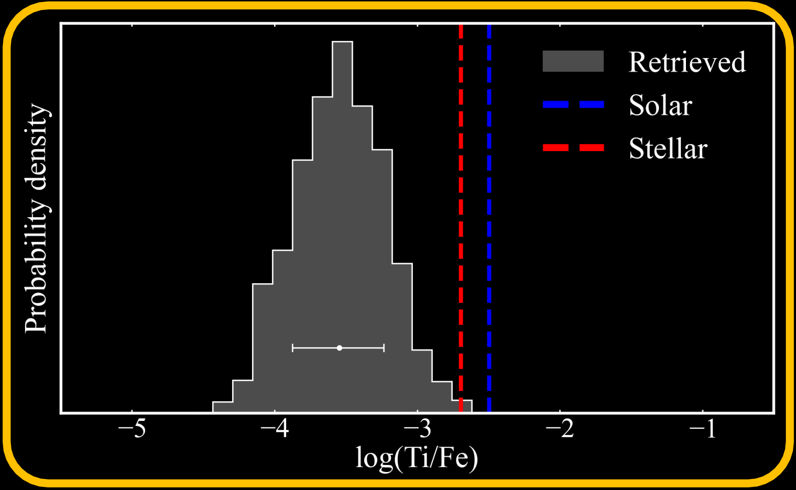
Image credit: Engine House VFX

Takeaways: WASP-189b

1. Neutral iron and titanium detected on the dayside of WASP-189b

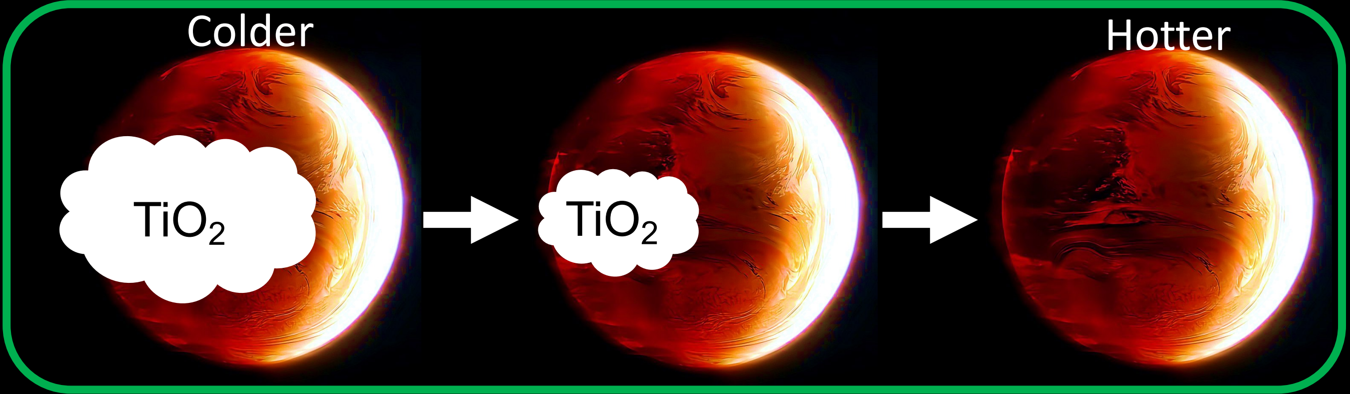






2. The titanium-to-iron ratio on WASP-189b is sub-stellar, hinting that some Ti is still unaccounted for

3. The release of titanium from the nightside cold-trap may be a gradual process



Merci