Atmospheres of low-mass star planets

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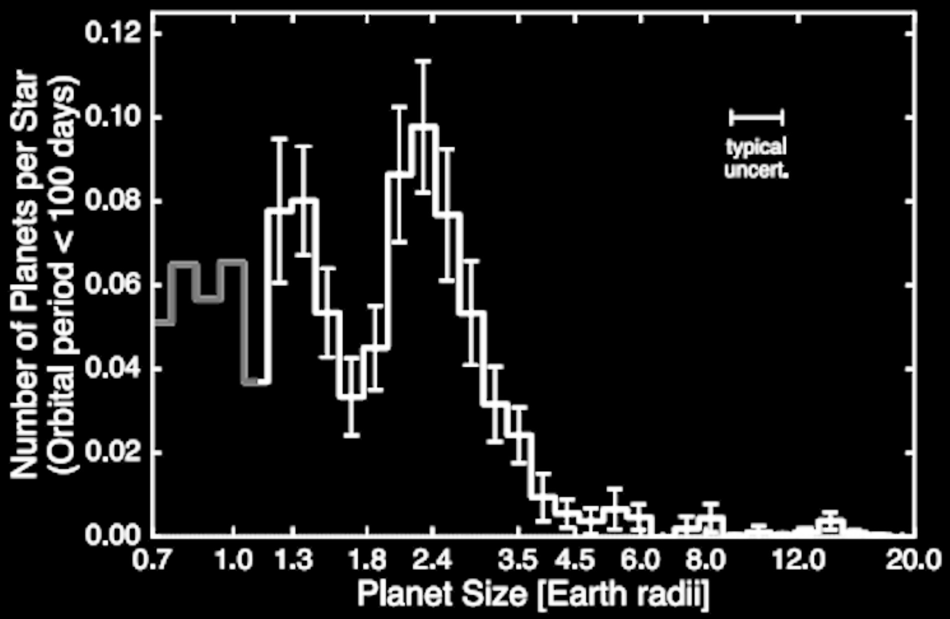
Evolution of atmospheres

(Earth/super-Earth-sized planets)

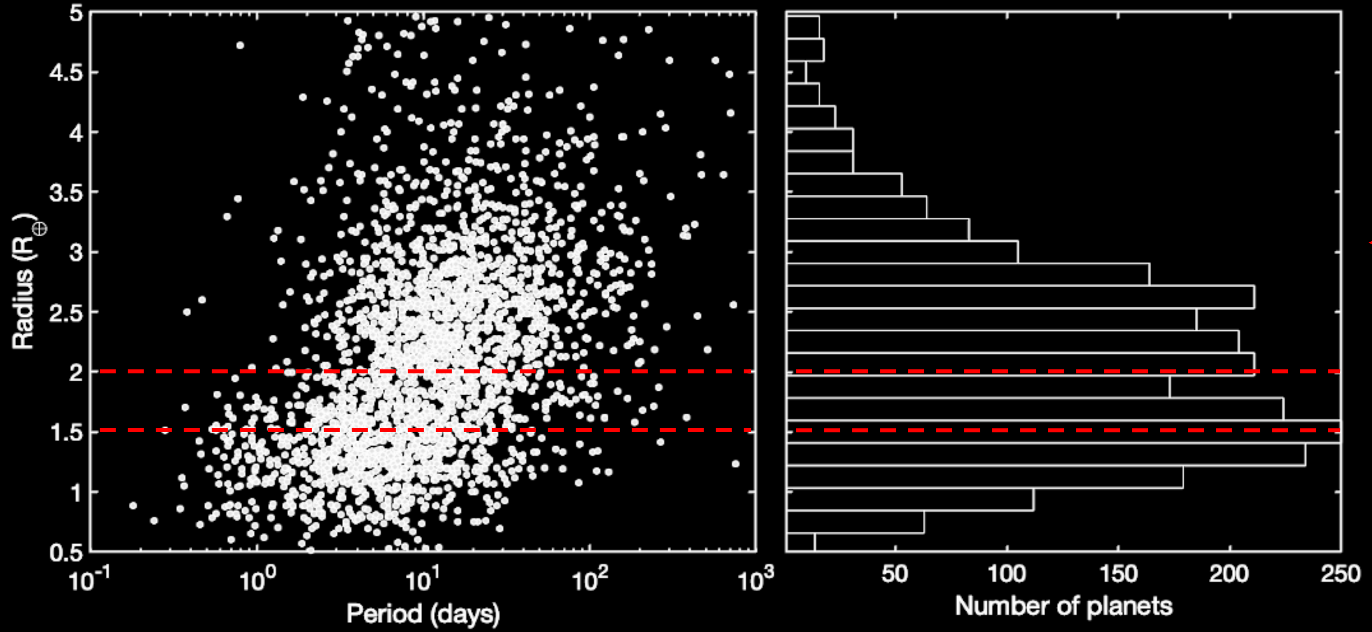
- Smaller planets = solid core (0.8-1.5 $R_\oplus$) + small but varying H/He (Owen & Wu 2017; Fulton et al. 2017)
- Evaporation → barren rocky Earth-sized or super-Earths or gaseous sub-Neptunes.

→ Bimodal distribution in radius-period plot → "**Radius gap**" at 1.5 – 2 $R_\oplus$ (Fulton et al. 2017)



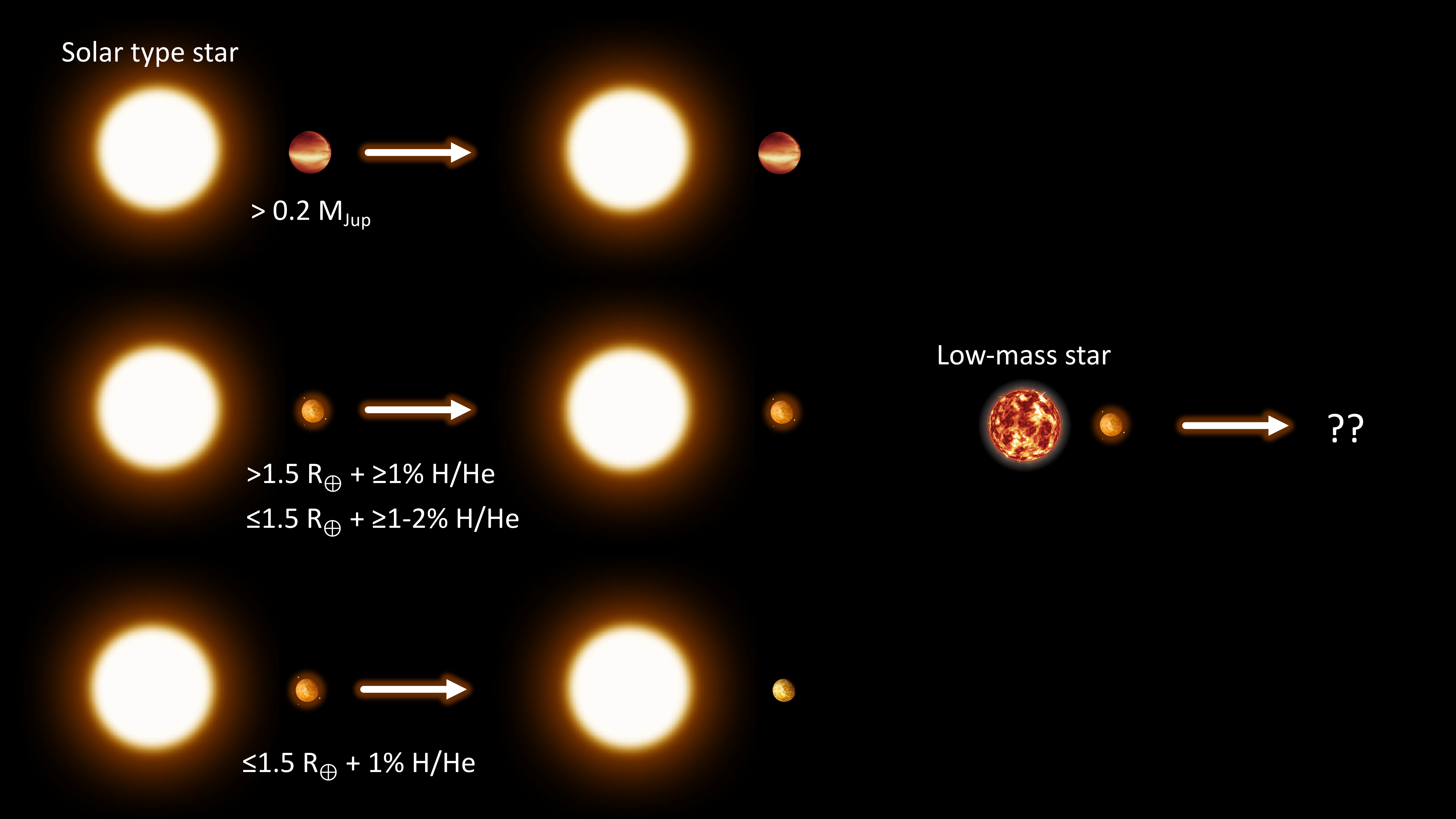
Planet occurrence rate of small planets around solar-type stars (Figure 7 in Fulton et al. 2017).

Solar-type stars
(T_{eff} = 4700 – 6500 K)



all stars

Left: Radius-period diagram for known exoplanets with radius smaller than 5 $R_\oplus$ as of April, 2021. **Right**: Histogram for planets shown on the left. Data source: NASA Exoplanet Archive, April 2023.



Solar type star
> 0.2 M_{Jup}
>1.5 $R_\oplus$ + ≥1% H/He
≤1.5 $R_\oplus$ + ≥1-2% H/He
≤1.5 $R_\oplus$ + 1% H/He
Low-mass star
??

Why low-mass stars?

✓ Mass < 0.65 $M_{\odot}$.

✓Most common stars.
(M-dwarfs: ~75% in Milky Way; ~10^{10} Earth-sized planets)

✓Small rocky planets around small stars → high transit depth.

→ Larger Doppler shifts.

→Habitable Zone (HZ) is relatively closer to the star.

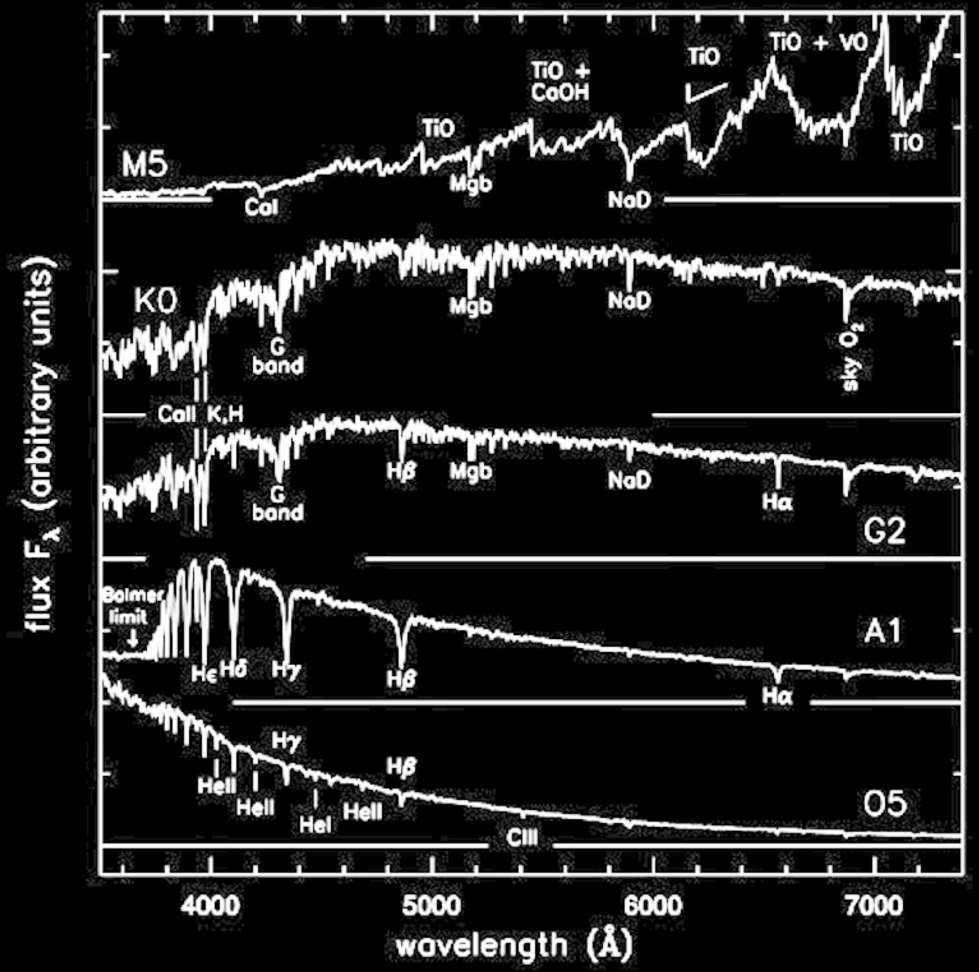
→Evaporation of H/He atmospheres → formation of secondary atmosphere → Habitability (maybe!)

✓Shorter orbit → Higher transit frequencies.

✓Spectral dominance in infrared (and NIR).

👎 Many molecular bands in stellar spectra.

👎 Stellar surface activities.



Ref: Henriques Stellar Classification, Oxford Press, 2013.

Evaporation marker: He I triplet at 1083 nm

- Advantages of He I:

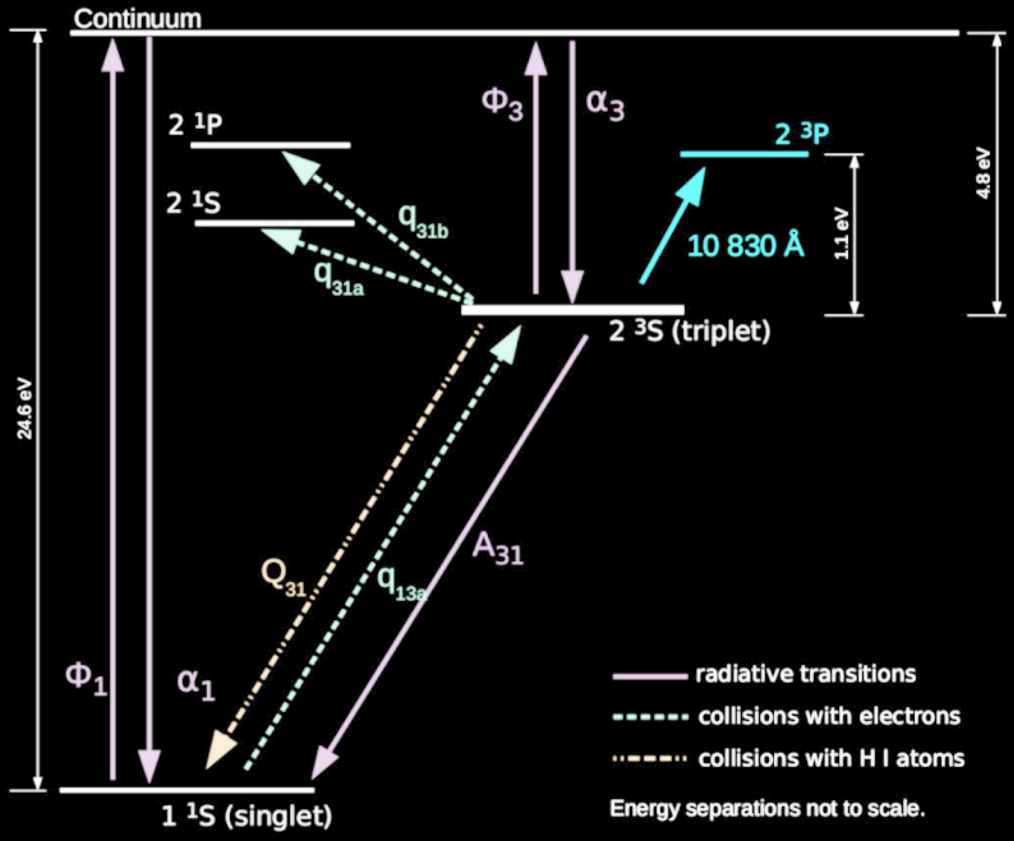
→Not affected by ISM or geocorona.

→Ground-based observation using high-resolution spectrograph on medium-to-large telescopes.

- **Best targets:** K-dwarfs and M-dwarfs

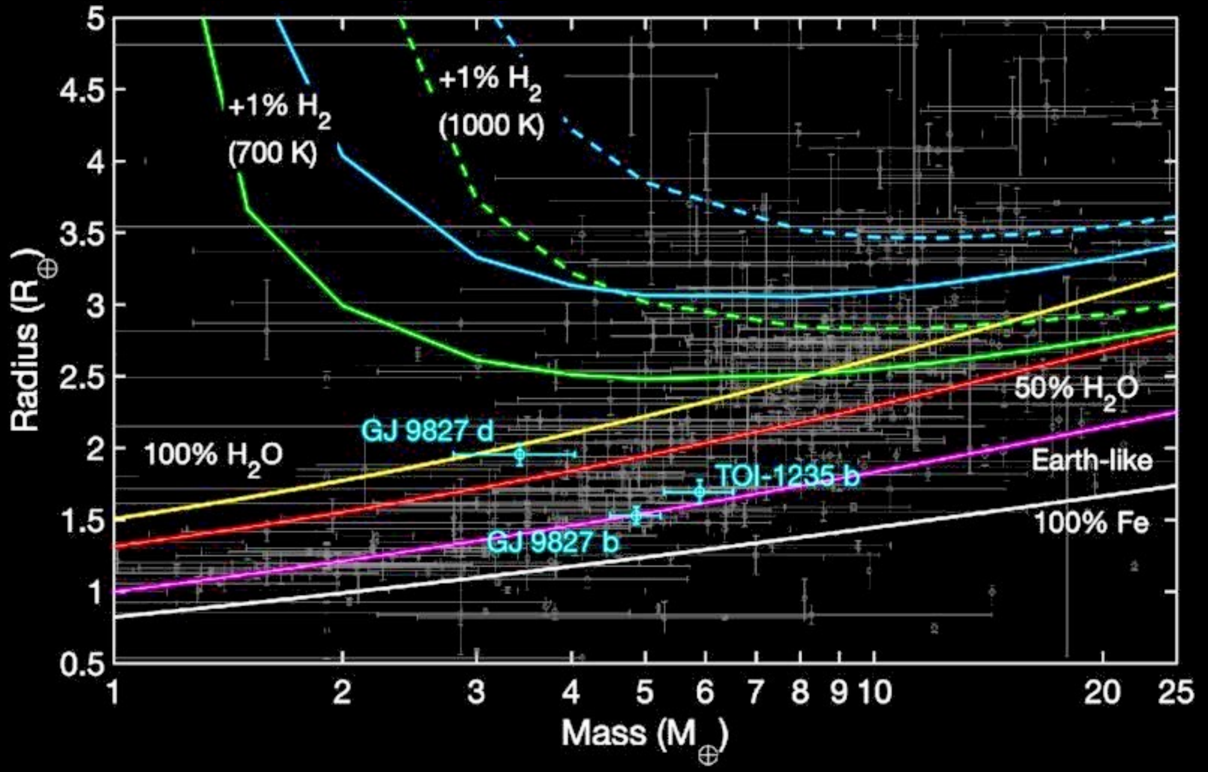
→ High XUV → High metastable He

→ Low mid-UV → High He in triplet state (Oklopčić 2019)



(Oklopčić & Hirata, 2018)

Targets of this study



Planet name	Radius ($R_\oplus$)	Mass ($M_\oplus$)	a (AU)	Spec. type
TOI-1235b**	$1.738^{+0.087}_{-0.076}$	$6.91^{+0.75}_{-0.85}$	$0.03845^{+0.00037}_{-0.00040}$	M0.5
GJ 9827b+	1.529 ± 0.058	4.87 ± 0.37	0.01866 ± 0.00019	K5
GJ 9827d+	1.955 ± 0.075	3.29 ± 0.64	$0.0555^{+0.00055}_{-0.00057}$	K5

Note: + Kosiarek et al. (2021) ** Cloutier et al. (2020);

Telescope and instrument

- Subaru 8.2m telescope

Elevation: 4207 m

Place: Mauna Kea, Hawaii

- Instrument: InfraRed Doppler (IRD)

(Tamura et al. 2012; Kotani et al. 2014)

R ~ 70,000

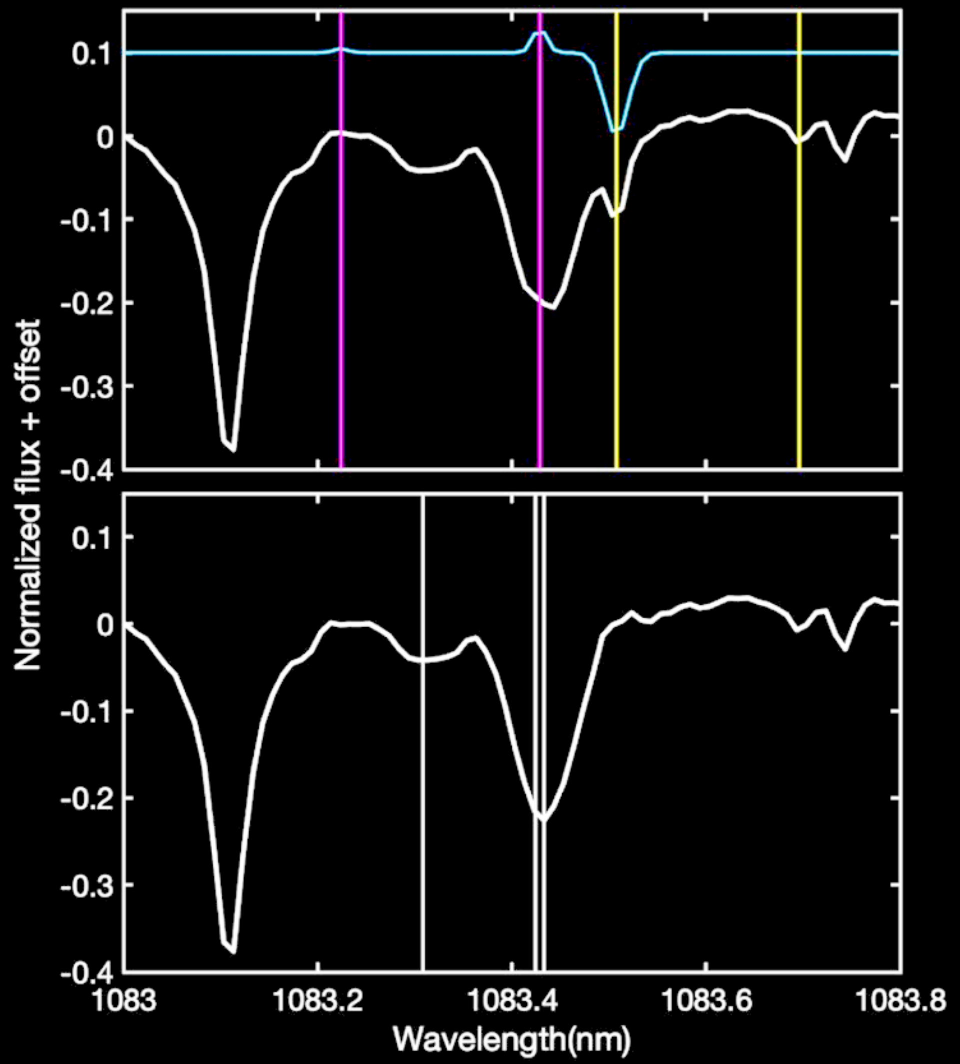
Wavelength coverage: 0.97 μm - 1.75 μm

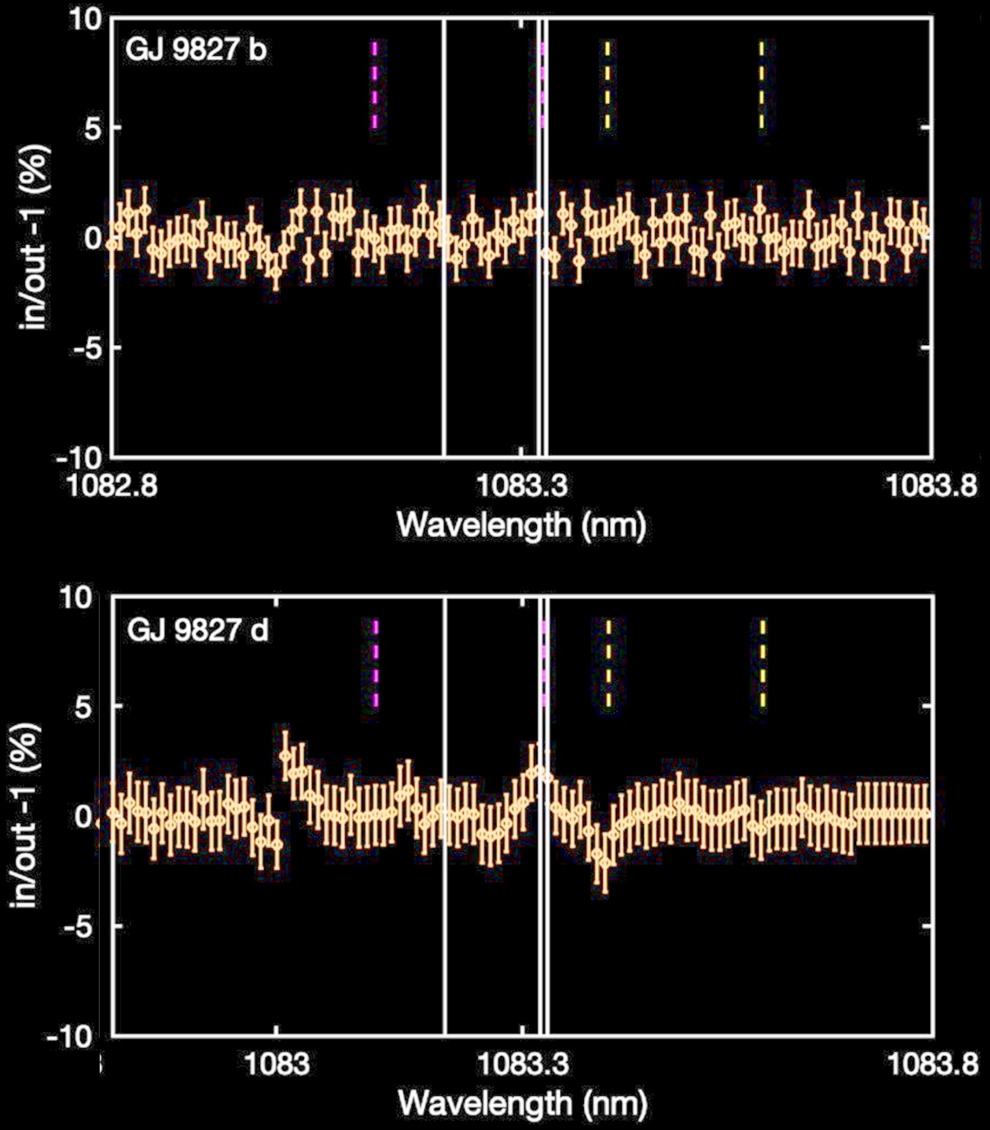
Wavelength calibration: Laser Frequency Comb (LFC)

Vacuum cooled optics and detectors

Throughput: 2-3% around 1000-1200 nm

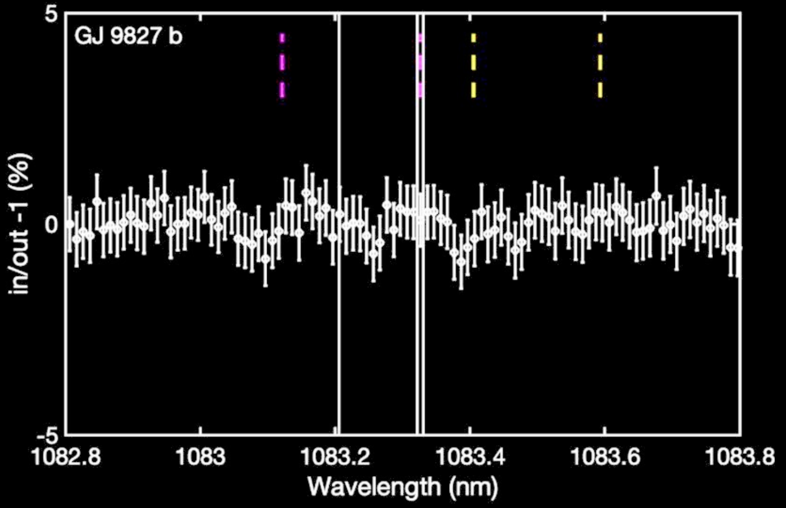
GJ 9827b and GJ 9827d – either side of radius gap

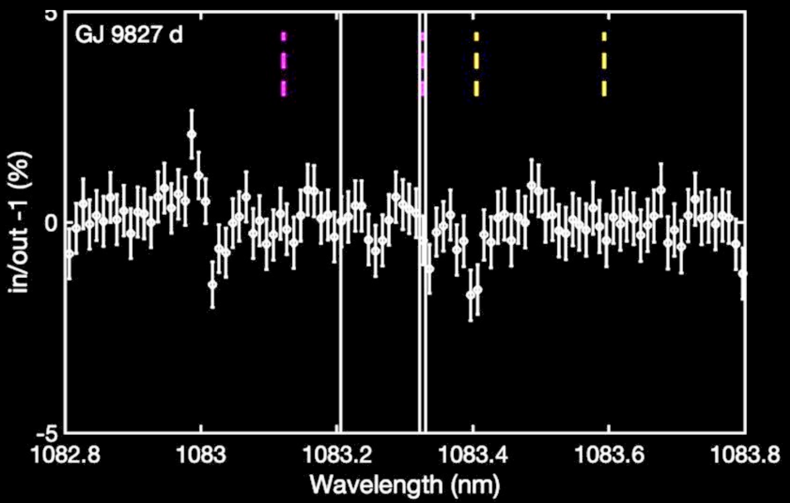


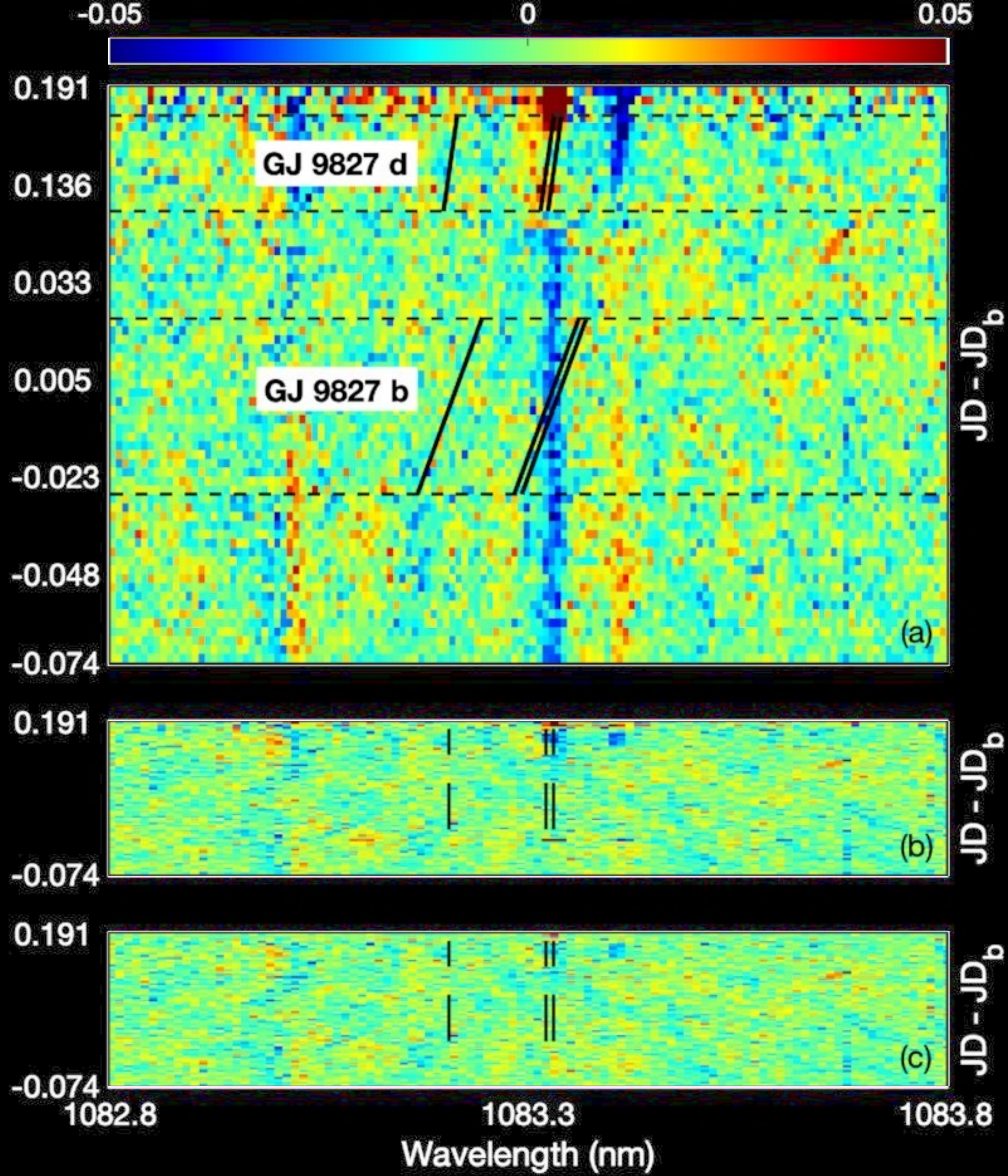


(Krishnamurthy et al 2023)

GJ 9827b and GJ 9827d







(Krishnamurthy et al 2023)

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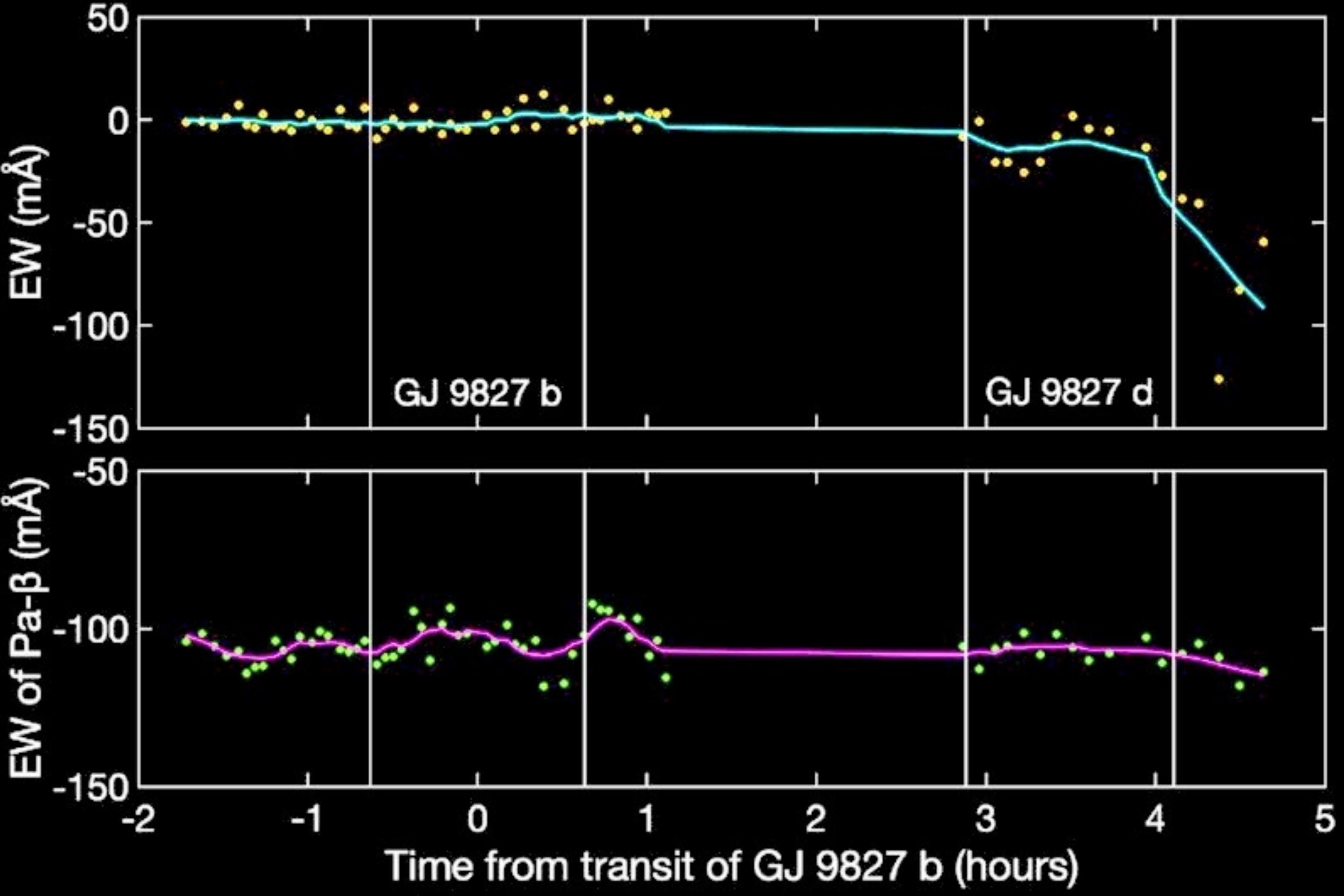
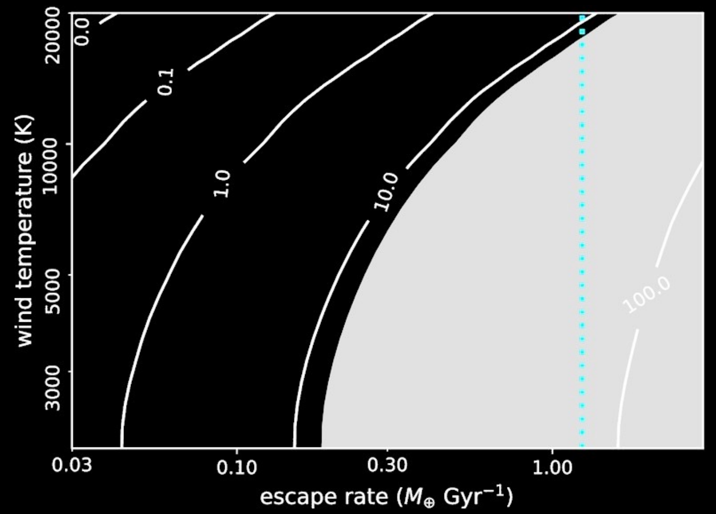
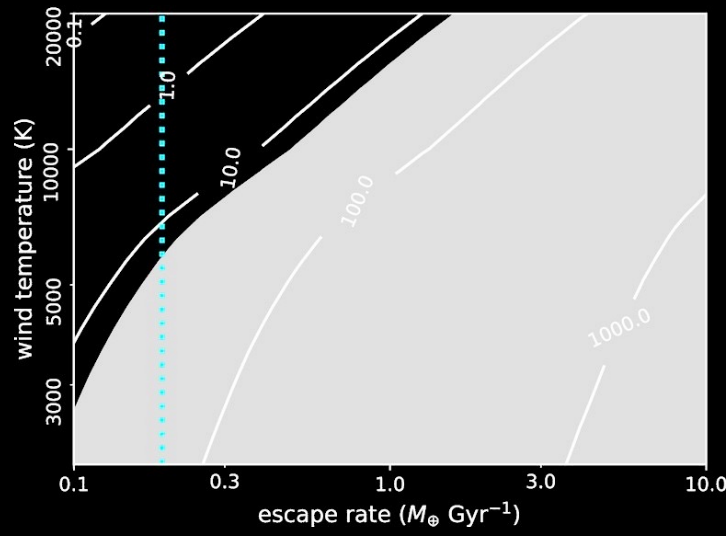
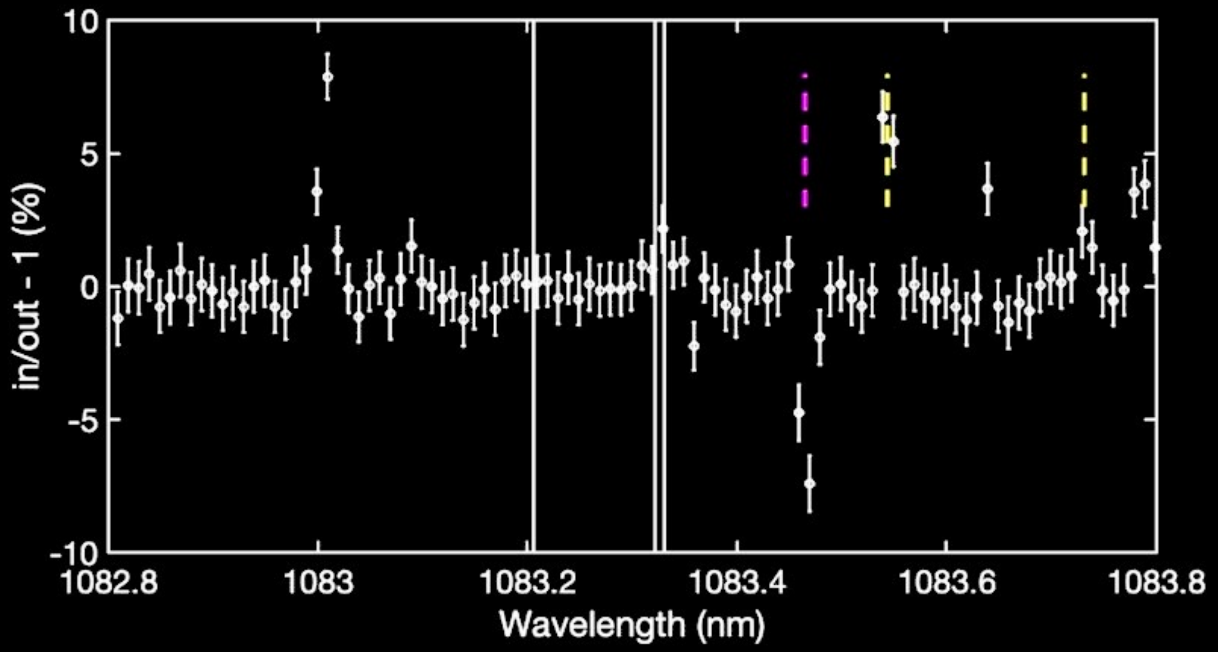


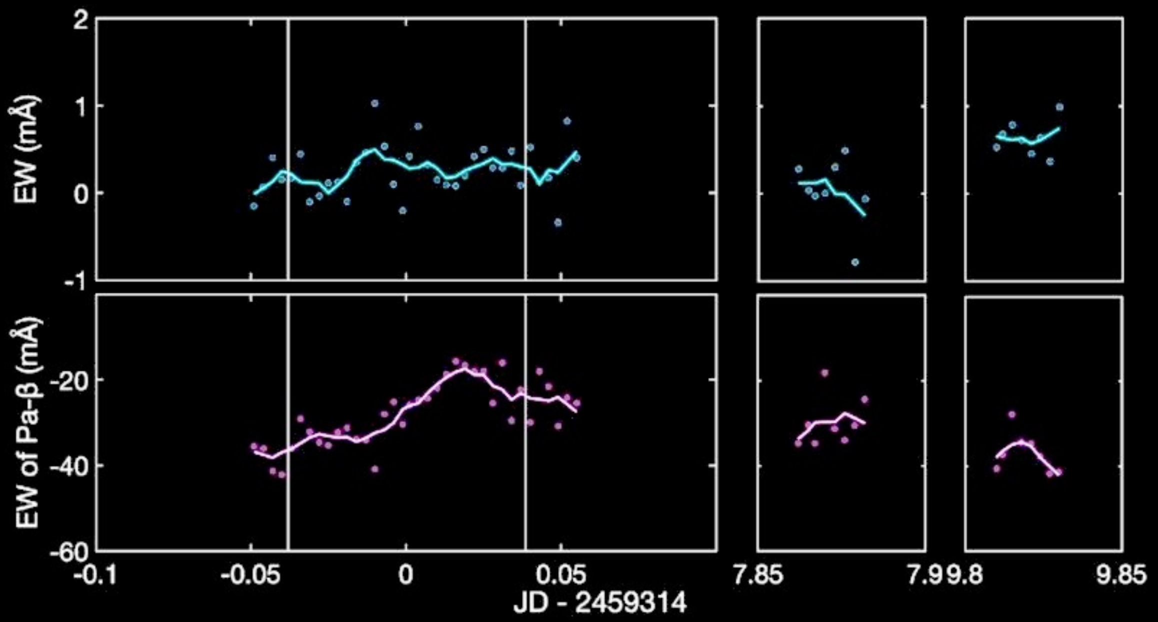




(Krishnamurthy et al 2023)

TOI-1235b – keystone super Earth in radius gap





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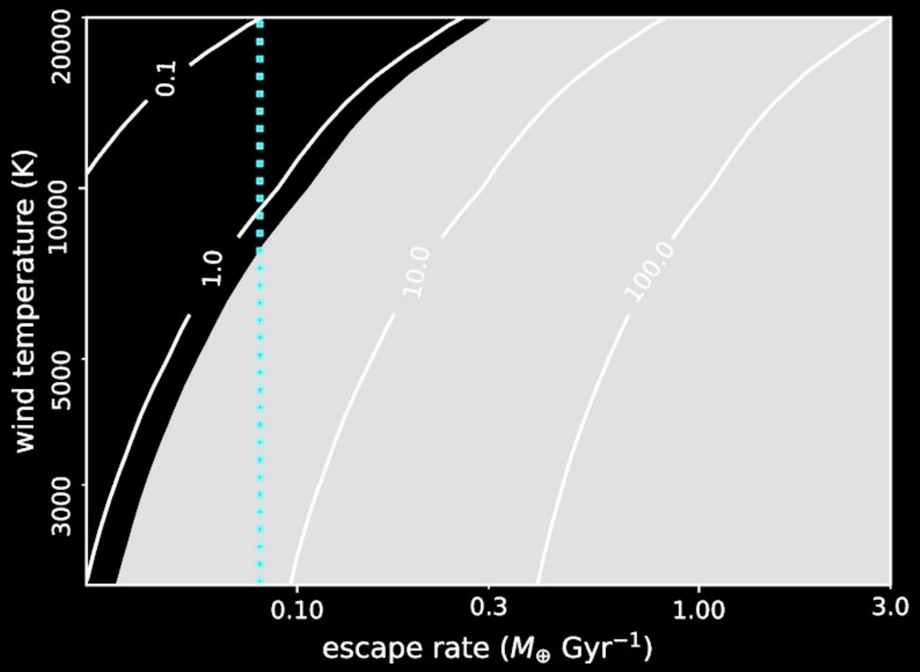
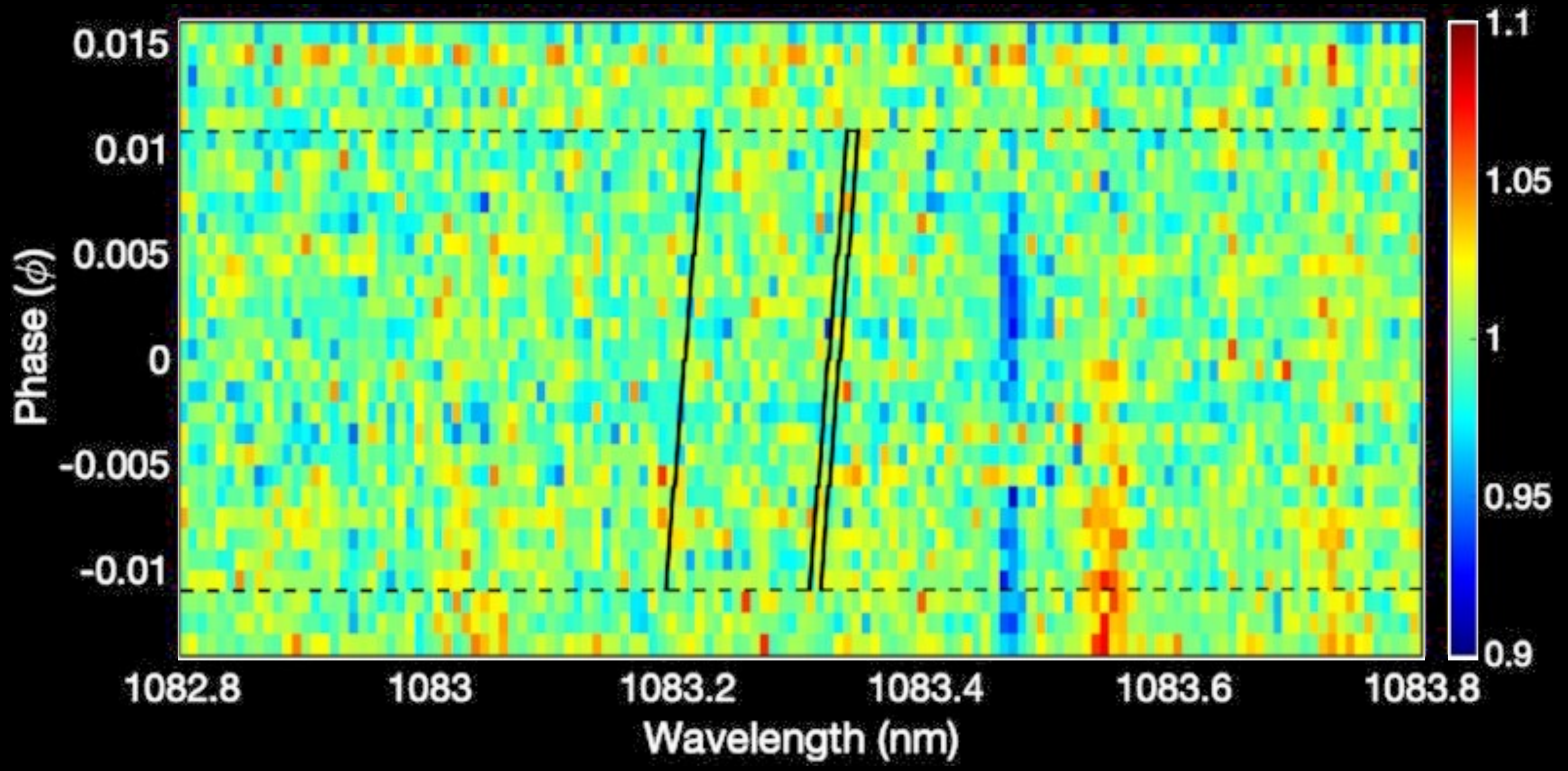




(Krishnamurthy et al 2023)

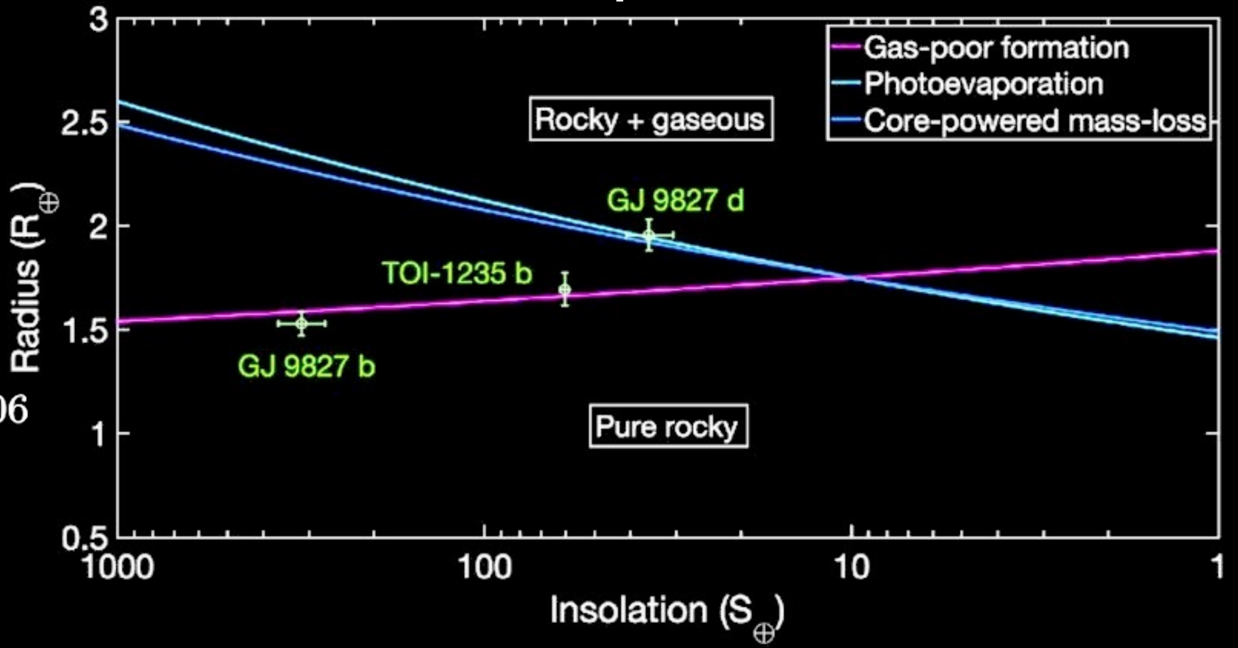
Photoevaporation in low-mass stars' planets?

- Models:

Photoevaporation process $r_{p,gap} \propto S_{\oplus}^{0.11}$

Planet's core-powered mass-loss $r_{p,gap} \propto S_{\oplus}^{0.10}$

Formation in gas-poor environment $r_{p,gap} \propto S_{\oplus}^{-0.06}$



- From TOI-1235b → rocky → supporting evaporation through photoevaporation and/or core-powered mass-loss.
- GJ 9827b and GJ 9827d → difficult to guess.

(Krishnamurthy et al 2023; Krishnamurthy et al. – in prep)

Telescope GO programs

- Subaru program: IRD-SSP (PI: Bunei Sato)
- Subaru program: S20A-UH104 (PI: Eric Gaidos)
- Subaru program: S20B-069 (PI: Vigneshwaran Krishnamurthy)
- Subaru program: S21A-100 (PI: Vigneshwaran Krishnamurthy)
- Subaru program: S21A-129 (PI: Teruyuki Hirano)