Dynamical Mass Constraints on K2-33b

A 5–10 Myr-old possible precursor to sub-Neptunes?

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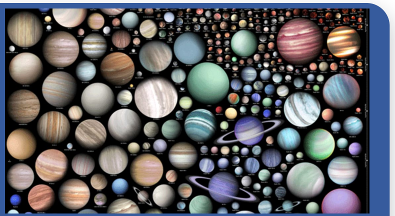
OUTLINE

Outline of the talk

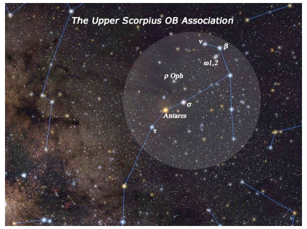
PART 1



Young Exoplanets: Context & Challenges

- A diverse, fast-growing population
- Why young systems (< 1 Gyr) matter
- Open questions: the Neptunian desert & the radius valley

PART 2



K2-33b: Characterising a Young Sub-Neptune

- The target
- The datasets: photometry + RV
- Joint photometry + RV analysis
- Results: radius, mass, density
- Implications for planet migration & evolution

Exoplanets: three decades of discovery

Since the first exoplanet around a Sun-like star (Mayor & Queloz, 1995), the field has grown exponentially and the diversity of planetary systems is only beginning to be understood.

1995
First exoplanet discovered (51 Peg b)

~10%
of solar-type stars host an Earth-sized planet

≥ 1
planet per star, on average, across the Galaxy

A diversity that goes beyond the Solar System

Rocky / super-Earths
Terrestrial composition
R <=1.6–1.8 $R_\oplus$

Mini-Neptunes / sub-Neptunes
Rocky core + volatile-rich envelope

Gas giants
Massive H/He envelopes
R >= 8–10 $R_\oplus$

Hot Jupiters
Giants on <= 10-day orbits
No clear origin yet

PART 1: MOTIVATION

Why look at young exoplanets?

Systems younger than 1 Gyr offer a window into the initial conditions of planet formation: migration, atmospheric loss, and gravitational contraction all leave an imprint

Search for young exoplanets in TESS candidate (TOI) light curves via the transit method

Measure dynamical masses via high-precision RV with ultra-stable spectrographs

Connect age, period, radius & mass to constrain formation, composition, migration & atmospheric models

THE CHALLENGES

Young stars are noisy

Fast rotation and strong magnetic activity drive photometric and RV variations that often exceed the planetary Keplerian signal.

5 exoplanets <= 1 Gyr with measured period, radius, and mass as of October 2020

Two puzzles in the exoplanet population

PUZZLE 1

The Neptunian Desert

Scarcity of planets with $R \approx 4\text{–}9\ R_\oplus$ on orbits less than 10 days (Mazeh+2016; Deeg+2023)

- Not an observational bias: smaller, harder-to-detect planets are common here
- Migration & atmospheric mass loss strip intermediate-mass planets of their envelopes

PUZZLE 2

The Radius Valley (Fulton gap)

Bimodal size distribution for small planets ($< 4\ R_\oplus$) with a trough near $1.8\ R_\oplus$.

- Photo-evaporation: timescales of tens of Myr
- Core-powered mass loss: Gyr timescales
- Planetesimal impacts, collisions: ~100 Myrs

Testing these mechanisms requires precise ages, radii AND dynamical masses at young ages

K2-33: a pre-main-sequence M dwarf in Upper Scorpius

- Belong to Upper Sco: **5-10 Myr**
- Spectral type: **~M3**
- Distance (Gaia DR3): **138.8 pc**
- Effective temperature: **3540 K**
- Stellar Mass: **0.571 $M_\odot$**
- Stellar Radius: **1.017 $R_\odot$**
- Rotation period: **6.29 ± 0.17 days**

THE CHALLENGE

- Fast rotation of v sin(i) = 8.2±1.8 km/s combined with faintness (V~16 mag) makes K2-33 one of the most demanding RV targets attempted for a young planet
- It requires the largest ultra-stable spectrograph in the southern hemisphere

K2-33b: a young planet discovery

Discovered independently by David+2016 and Mann+2016b in K2 light curves. Orbital period 5.42 days; radius initially found slightly larger than Neptune.

One of the few transiting exoplanets younger than 10 Myr known to date

A radius that depends on wavelength

Thao et al. (2023) derived a transit **40% shallower** than in the visible light, implying a ~25% smaller radius.

Proposed explanations: large cool-spot coverage (>50% of stellar surface), a low-mass core wrapped in a tholin haze, or a circumplanetary dust ring (Ohno+2022).

THE CHALLENGE

The mass settles it

A dynamical mass (and density) is the only way to confirm the true nature of K2-33b and constrain models of small-planet formation and evolution.

K2 photometry + ESPRESSO RV campaign

K2 PHOTOMETRY

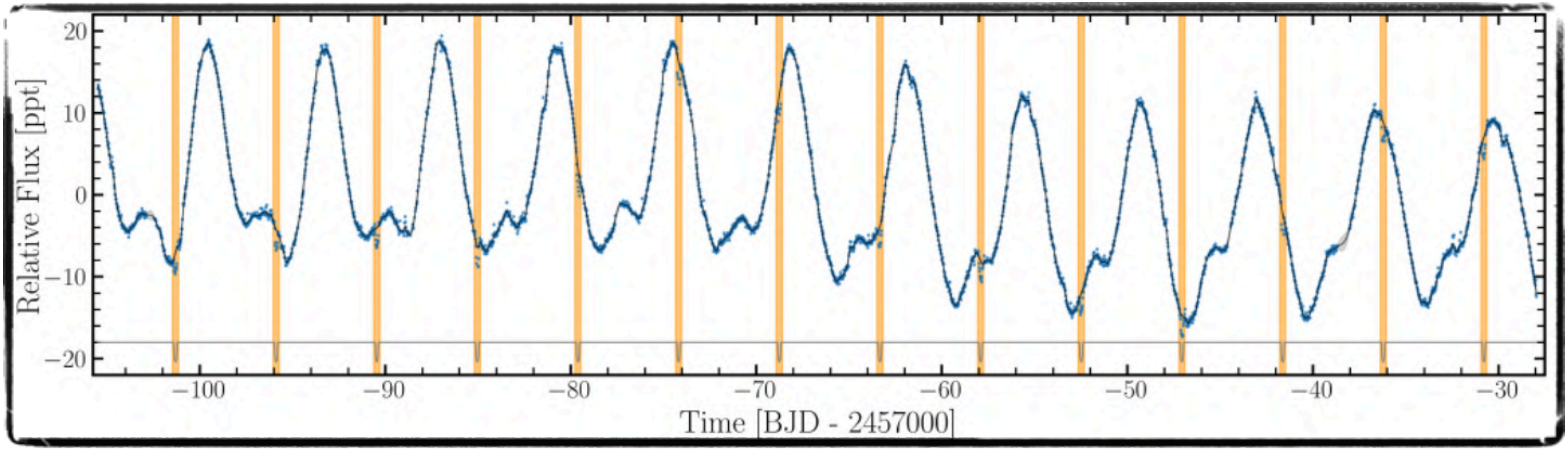
- Campaign 2 (2014)
- Reduction with EVEREST pipeline
- 30-minute cadence, 77.5-day baseline
- 14 transits of K2-33 b recovered
- Photometric dispersion: 8.7 ppt
- Double-periodic modulation from stellar activity; no significant flares

ESPRESSO RVs

- Only southern ultra-stable spectrograph suitable for this faint star
- Open-time programmes: 49 epochs over 93 days (Apr–Jul 2023)
- 44 spectra used, 5 discarded (including one Hα flare, transits)
- Custom serval extraction (red orders) due to faintness + fast rotation
- RV dispersion 25.2 m/s; median error 5.6 m/s

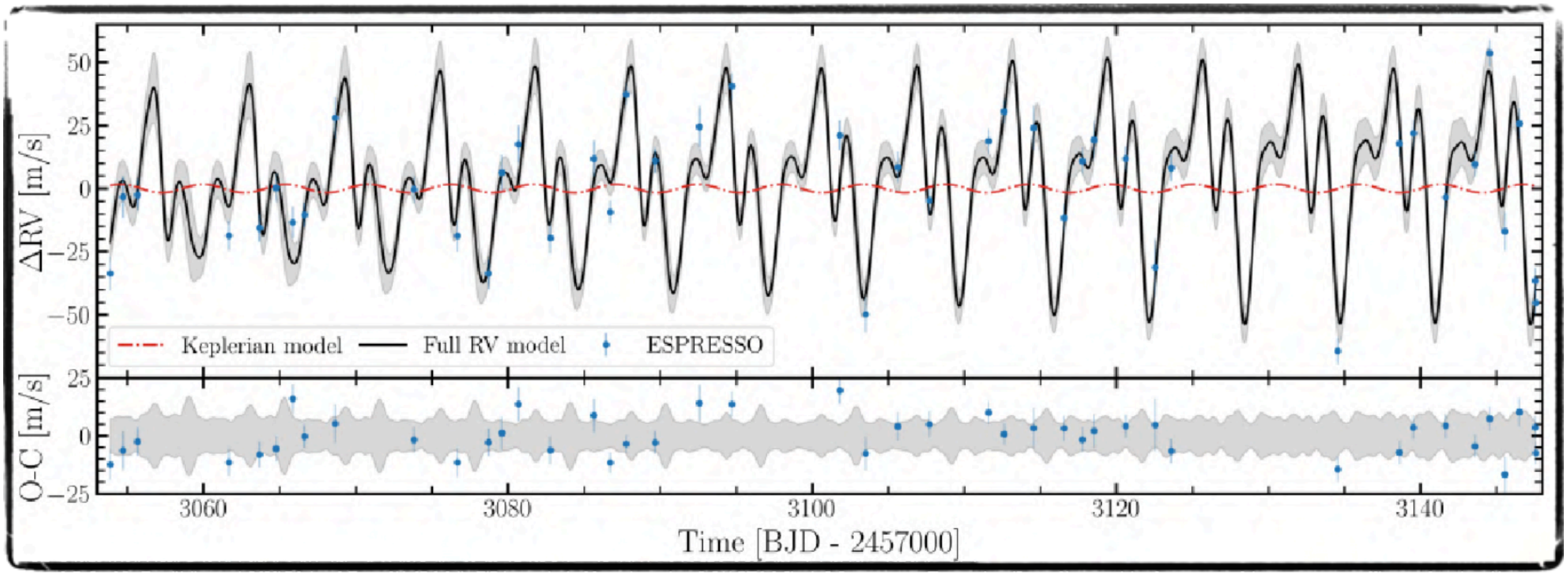
PART 2: ANALYSIS

The K2 light curve: activity and 14 transits

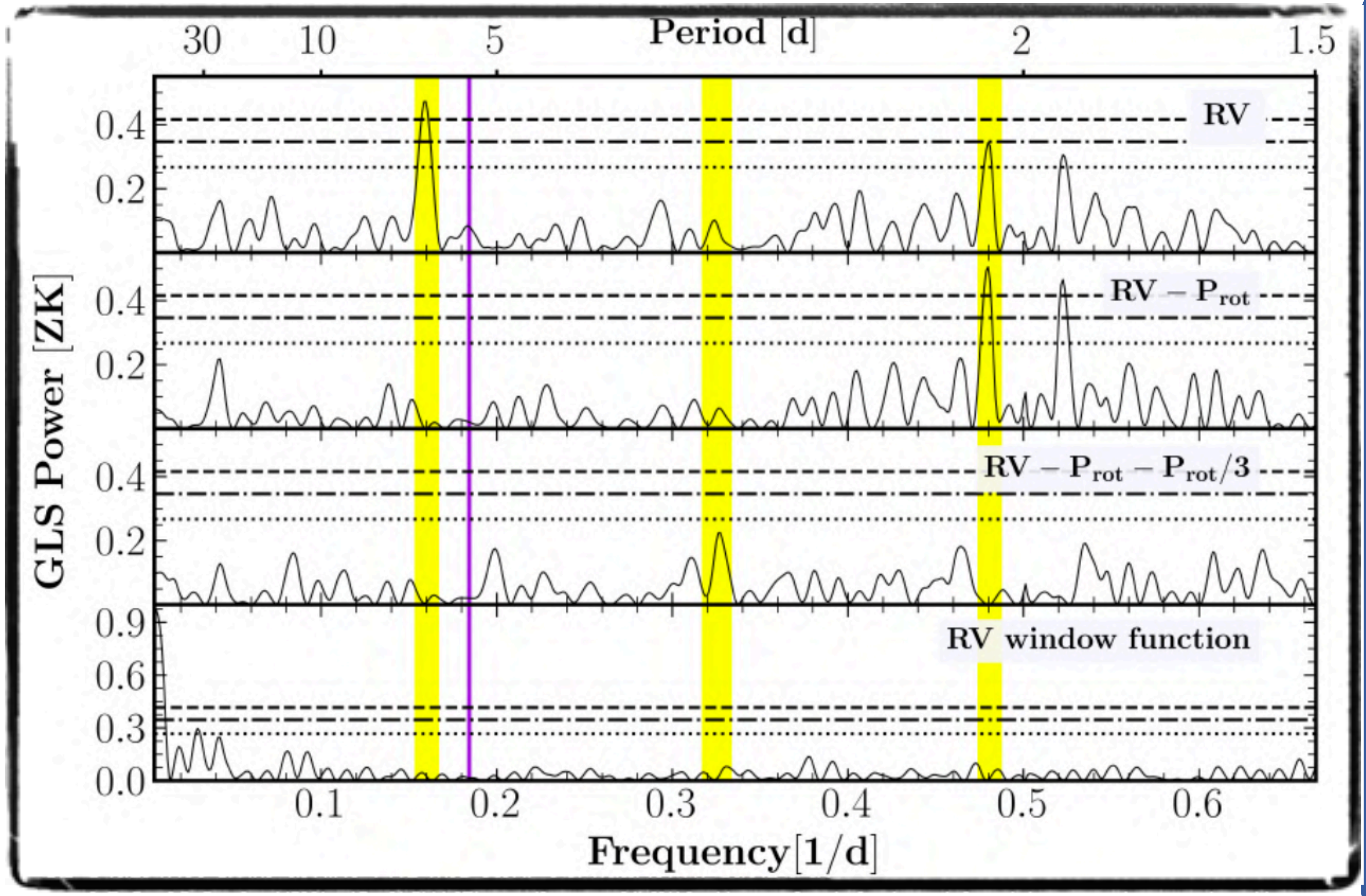


Stellar rotation (P_{rot} = 6.29 days) dominates the photometric variability; the 14 planetary transits of K2-33 b (orange bands) are clearly recovered on top of the activity signal.

RV curve of K2-33



RV data reveal stellar activity

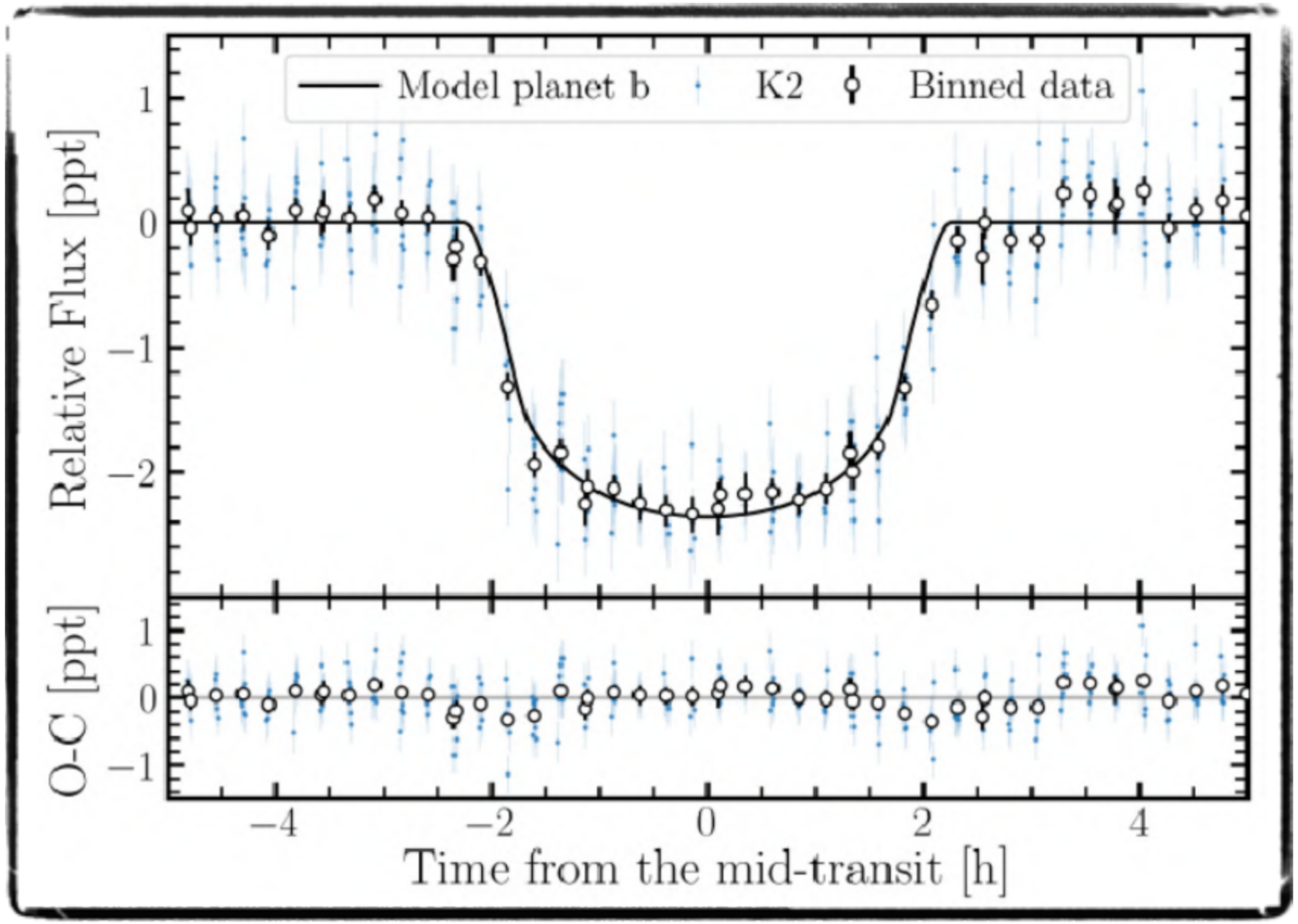


GLS periodogram

- Peaks (FAP < 0.1%) at stellar rotation period and 2nd harmonic: **6.26d & 2.08d**
- Non-significant residual peak = 1st harmonic of rotation: **3.06d**
- No significant peak at K2-33 b's orbital period: **5.42d**

==> The Keplerian signal is hidden within stellar activity. A full activity model is needed because a simple sinusoid is not enough

Joint photometry + RV fit: the transit, recovered



Phase-folded transit of K2-33b (K2 photometry, joint fit)

THE RESULTS

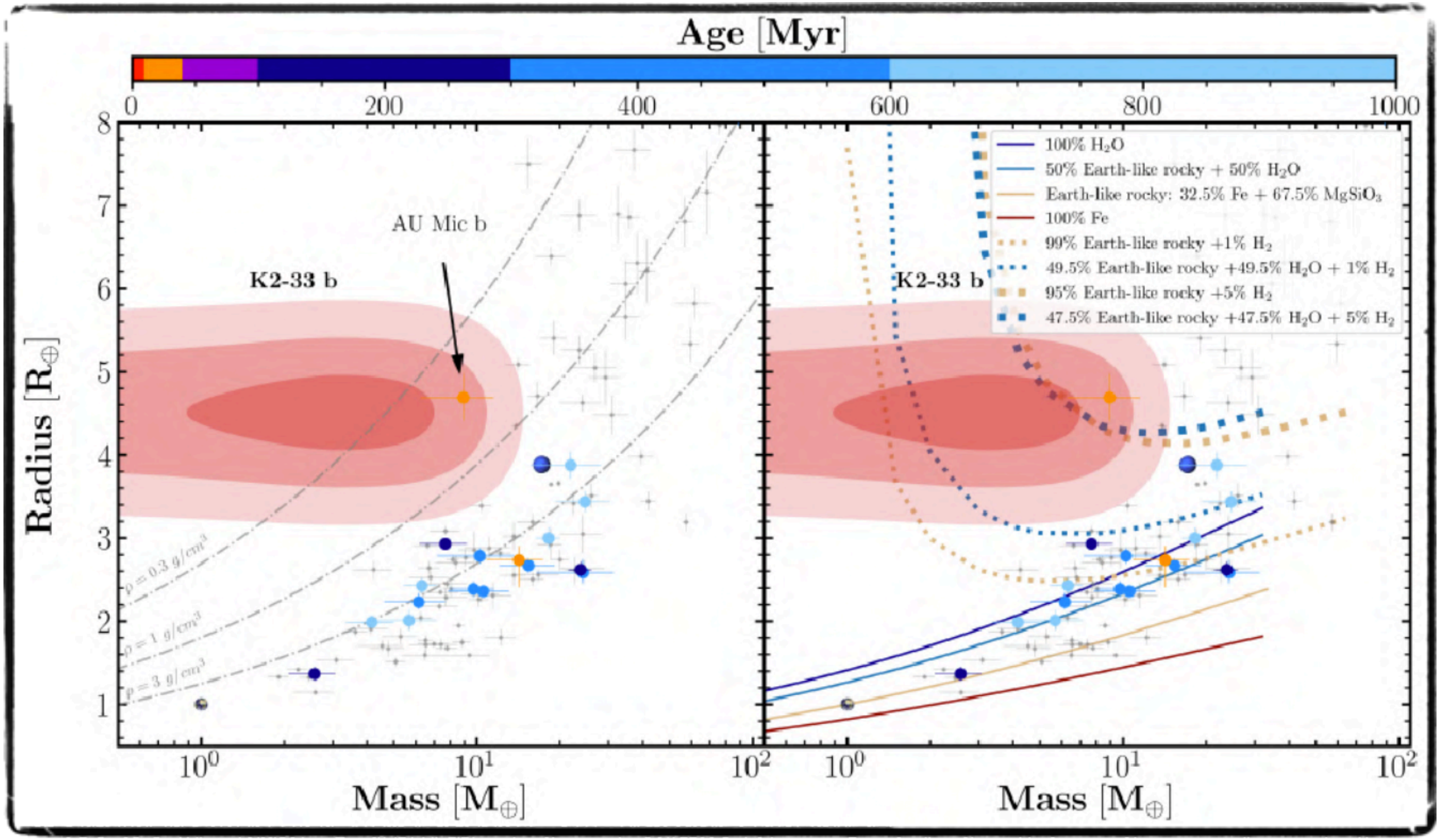
- Matches David+2016 & Mann+2016 (visible); deeper than Thao+23 (infrared, 0.0365 ± 0.0010): Rp/Rs = 0.0430 ± 0.0007
- Consistent with GLS: rotation period + its two harmonics: triple-periodic RV activity model
- No significant Keplerian detection below the ~15–20 m/s expected for an older, denser Neptune analogue: K <= 9.0 m/s (3 sigma)

K2-33b: radius, mass & density

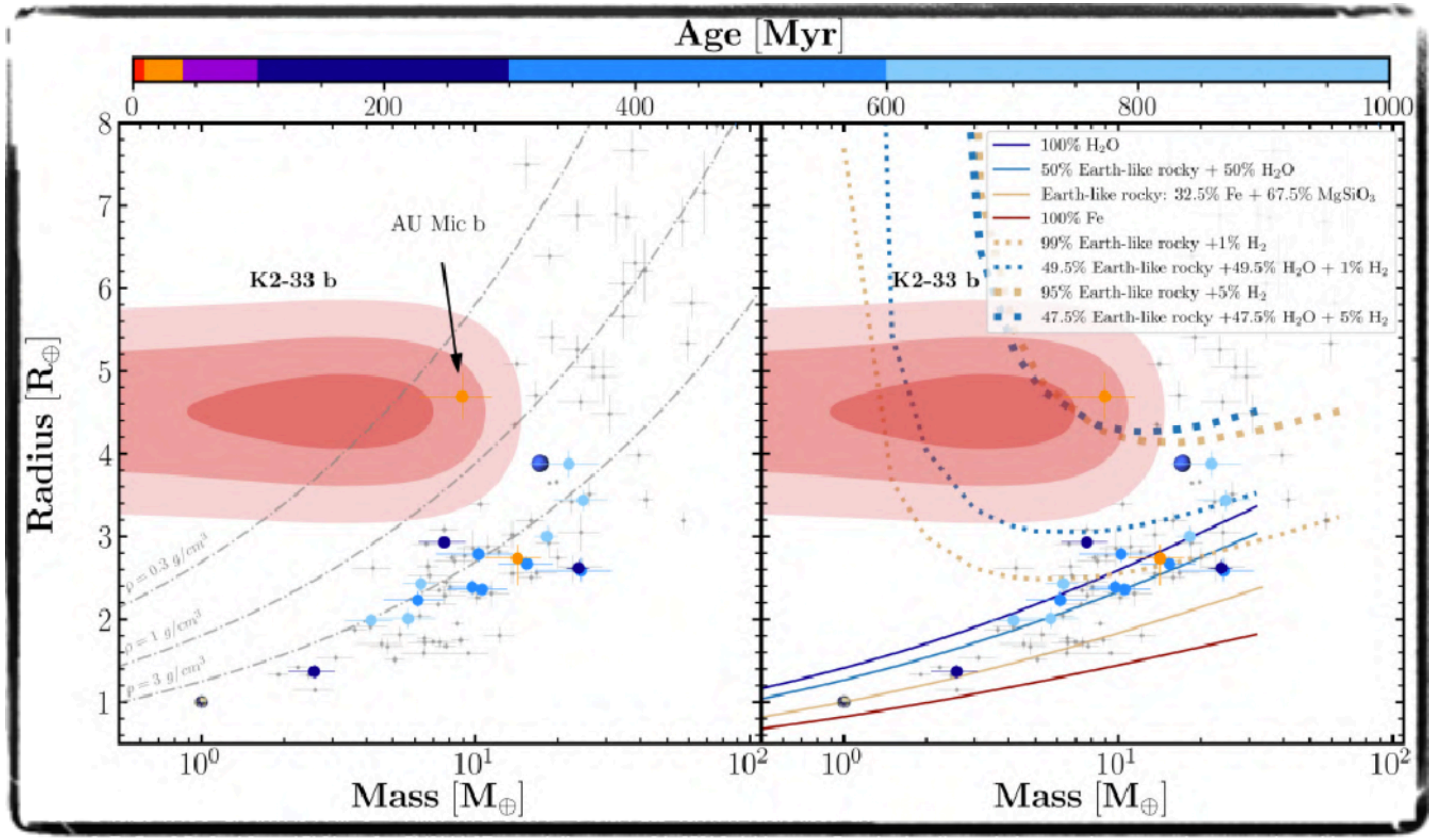
Parameter	Value	Notes
Radius (Rp)	**4.51 ± 0.45 $R_\oplus$**	Combining visible + infrared (Thao+23) transit depths
Mass (Mp)	**< 17.0 $M_\oplus$ (3σ)**	From the RV non-detection, K < 9.0 m/s
Density (ρ)	**< 1.12 g cm^{-3} (3σ)**	Consistent with a low-density, gas-rich planet
Semi-major axis (a)	**0.050 au (10.6 Rs)**	Orbital period P = 5.4248 ± 0.0002 days
Eq. Temperature	**776 K (A=0)**	Strongly irradiated, close-in orbit

The 3σ mass ceiling reflects the non-detection of the Keplerian signal, indicative of low density

PART 2: MASS-RADIUS RELATION



K2-33b in context: desert edge, gaseous, and migrating fast



THE RESULTS

- Sits at low-period edge of the Neptunian desert
- Mass lies at the low edge of the planet sequence, close to AU Mic b
- Interior models (Zeng+2019): needs a gaseous H_2 envelope (~1–5% by mass), regardless of core composition
- Migration to a short orbit within ≤ 5–10 Myr ==> a new upper limit on migration timescale
- May be losing its primordial envelope via photo-evaporation, consistent with predicted mass-loss rate (Hirano+2024)

TAKE HOME MESSAGES

Conclusions

(1) **Dynamical mass constraint achieved despite extreme stellar activity**

(2) **K2-33 b's place in the Neptunian desert / mass-radius diagram**

(3) **Implications for migration timescales and envelope evolution**

WHAT'S NEXT

Future work

(1) New RV data obtained with ESPRESSO to incorporate in the analysis

(2) Search for additional planets in the K2-33 system

(3) Find other siblings of K2-33b

Job opening in our group soon

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