Advancing JADE:

Evolution of hot Sub-Neptunes with Water-Enriched Atmospheres

E. Wong, V. Bourrier, C. Mordasini,
J. Owen, C. Dorn, M. Valatsou,
P. Eggenberger, J. A. Egger,
Y. Alibert, J. Leconte

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UNIVERSITÉ DE GENÈVE

PlanetS
National Centre of Competence in Research

Advancing **JADE**:

Evolution of hot Sub-Neptunes with Water-Enriched Atmospheres

Joining
Atmosphere and
Dynamics for
Exoplanets

Gitlab access

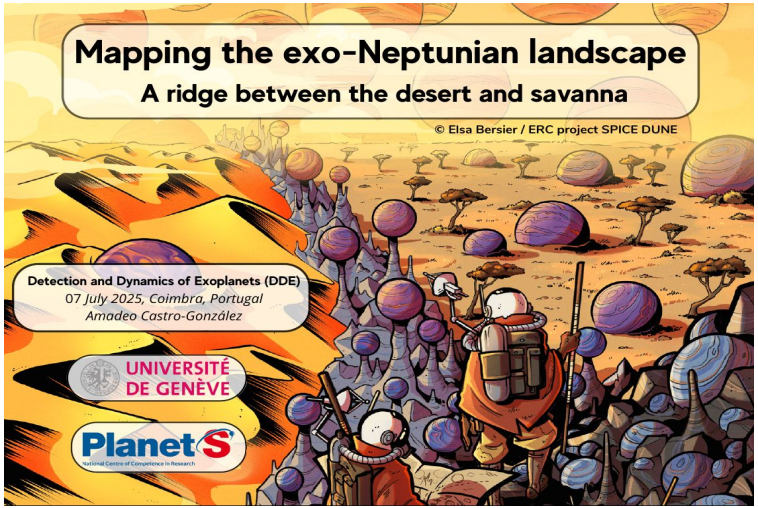
The Neptunian landscape

Vincent Bourrier

From the Desert into the Savanna:
a trek across the exo-Neptunian landscape

Amadeo Castro-González

Mapping the exo-Neptunian landscape.
A ridge between the desert and savanna



The Neptunian landscape

Neptunian-sized:

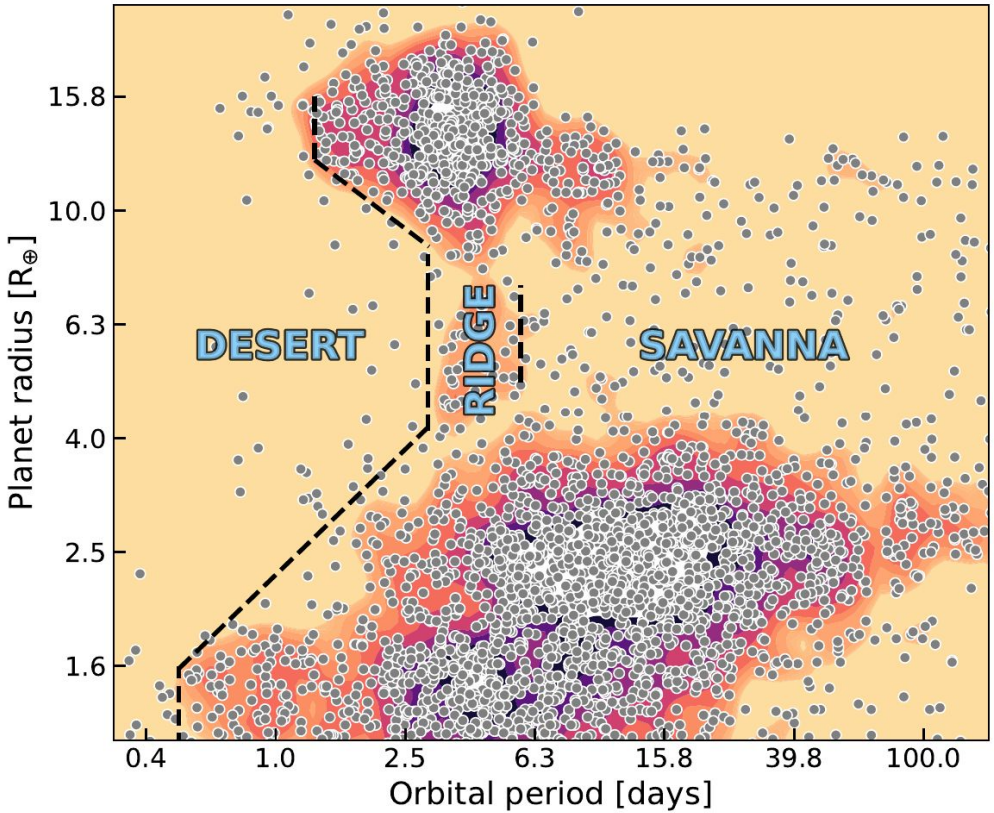
$3.8 \sim 8.5\ R_\oplus$ ($1.0 \sim 2.2\ R_{\Uparrow}$)

Desert: very few detection at <3.2 days (e.g., Lecavelier des Etangs 2007; Davis & Wheatley 2009, Castro-González et al. 2024)

Ridge: Overdensity at 3.2 to 5.7 days

Savanna: Sparsely populated

Radius-period plot by Castro-González et al. (2024).



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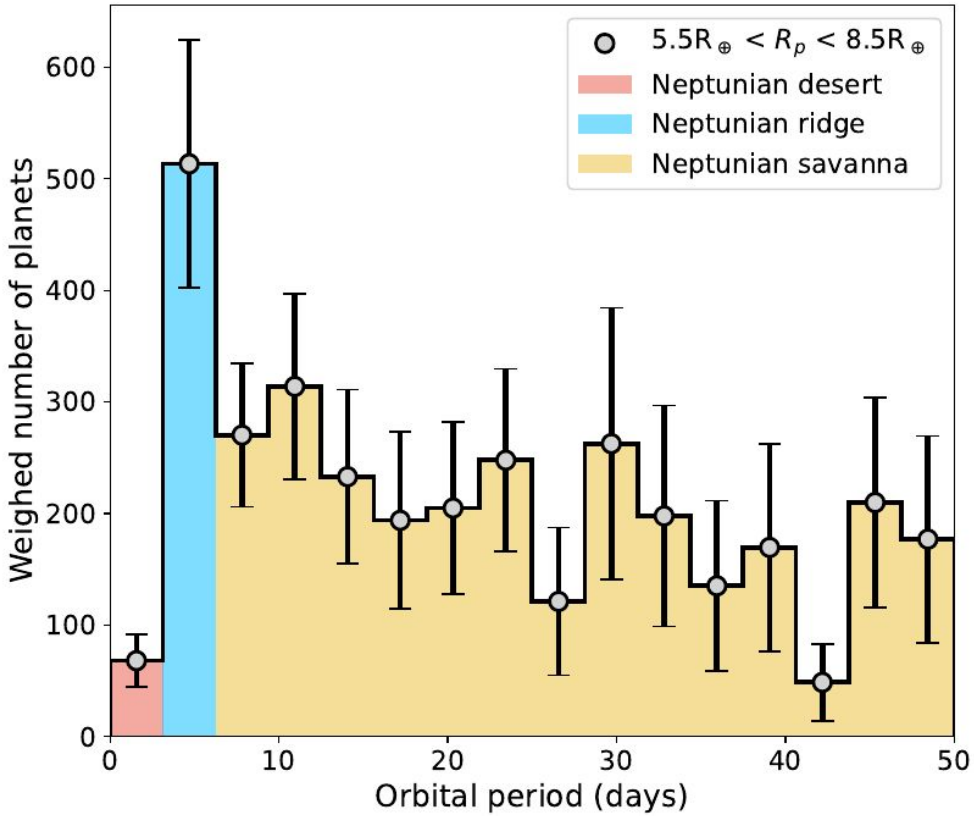
Shape drop in Desert

Pile-up at Ridge

Gentle decline into Savanna

The population distribution…
- reflect the primordial distribution? or
- shape by migration/evaporation/other process?

Castro-González et al. (2024).

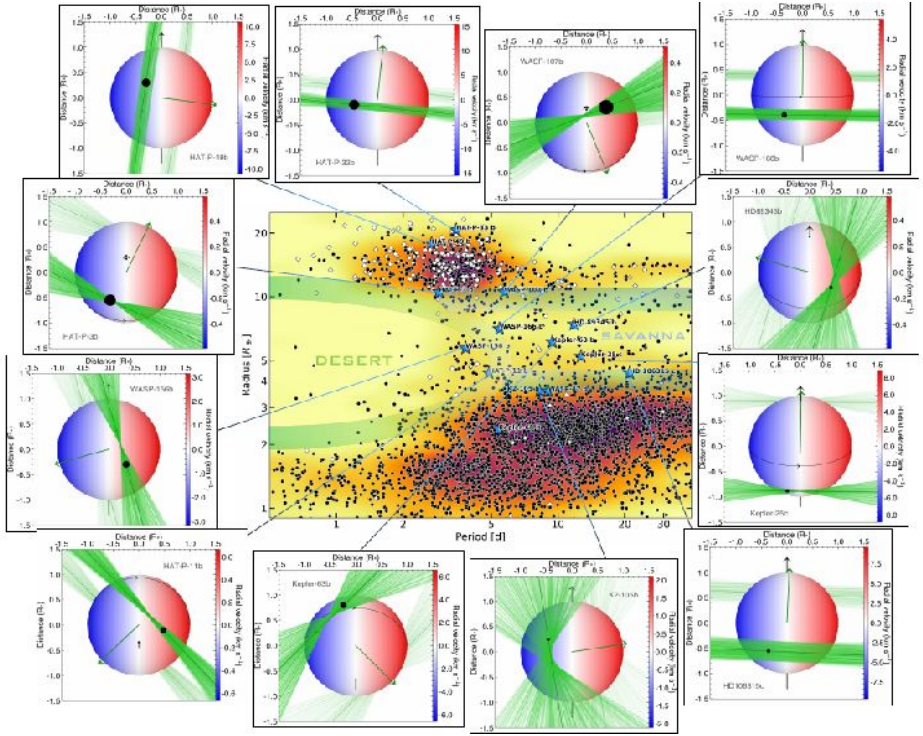


The Neptunian landscape

Neptune Ridge planets:

- Moderate eccentricity
- Highly misaligned orbit
- Old planetary system

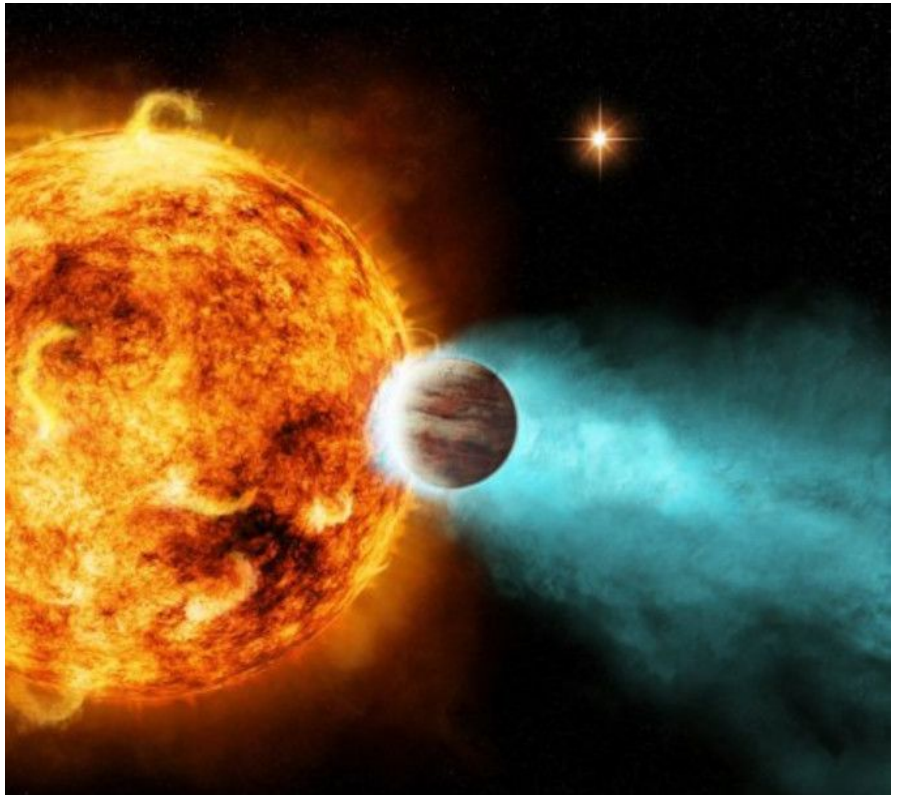
Spin–orbit angles of close-in exo-Neptunes
(Bourrier et al. 2023; Fig. 1)



The Neptunian landscape

Neptune Ridge planets:

- Moderate eccentricity
- Highly misaligned orbit
- Old planetary system
- Still has atmosphere or losing atmosphere despite being high irradiated
- Smaller size (or mass): less resistant to photoevaporation by host start



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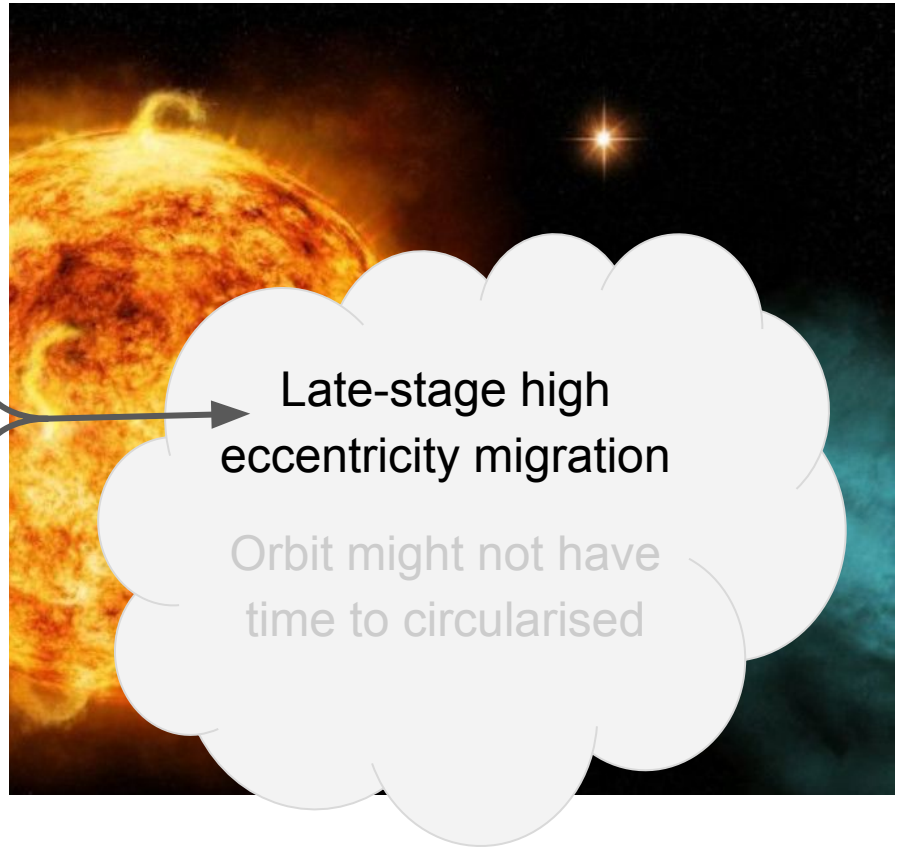

The Neptunian landscape

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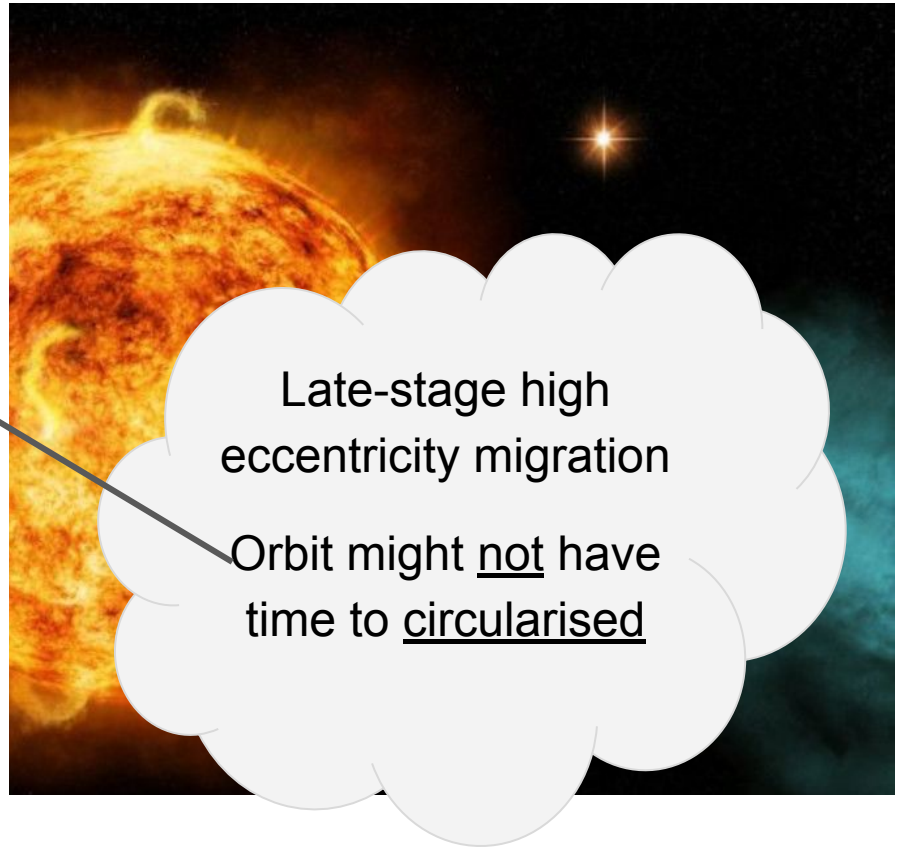
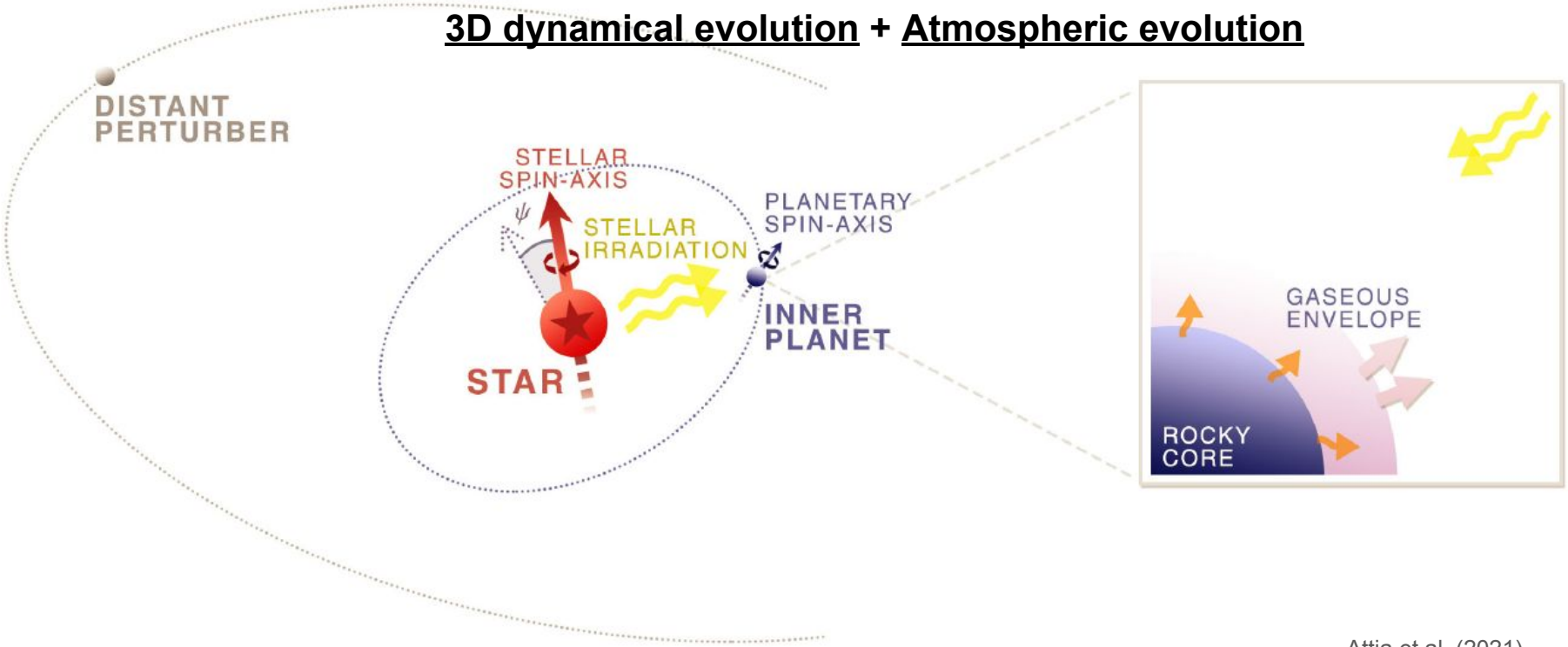


JADE code (v. 1.0)

Github

JADE

3D dynamical evolution + Atmospheric evolution



Attia et al. (2021).

JADE code (v. 1.0)

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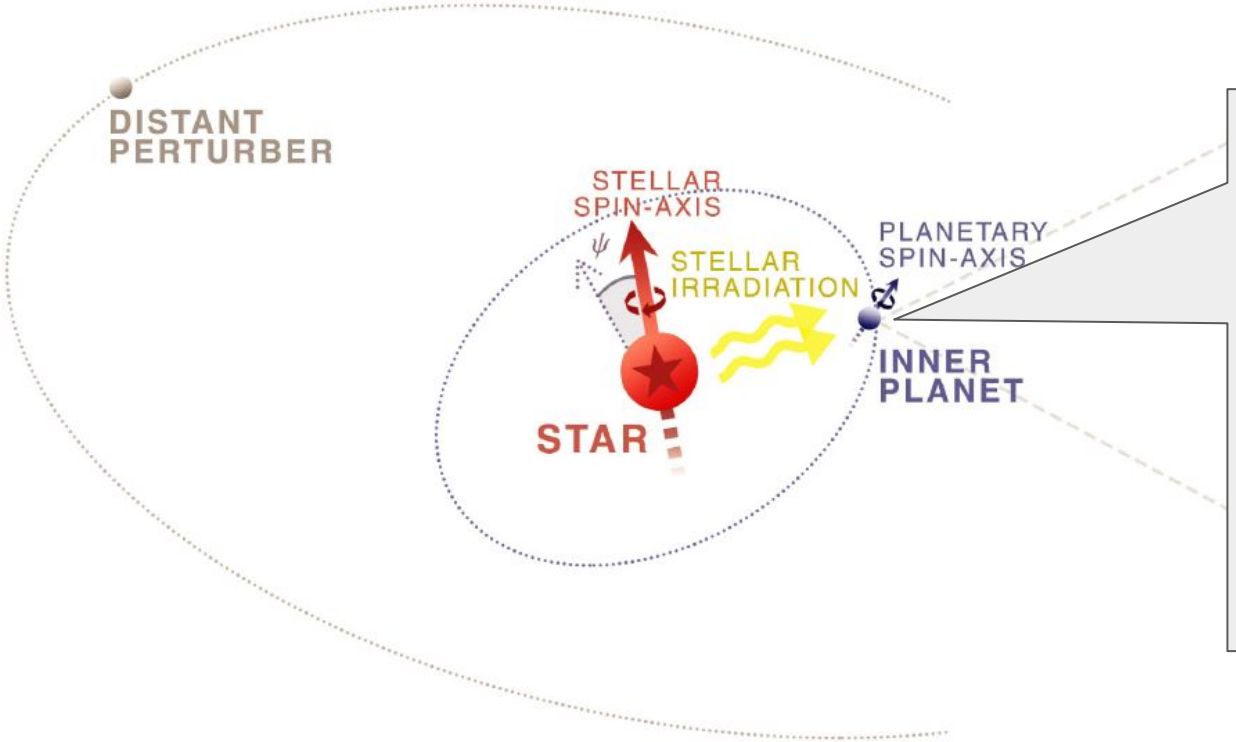
JADE



3D dynamical evolution:

- High eccentricity migration with distant perturber
- Tidal damping and circularization

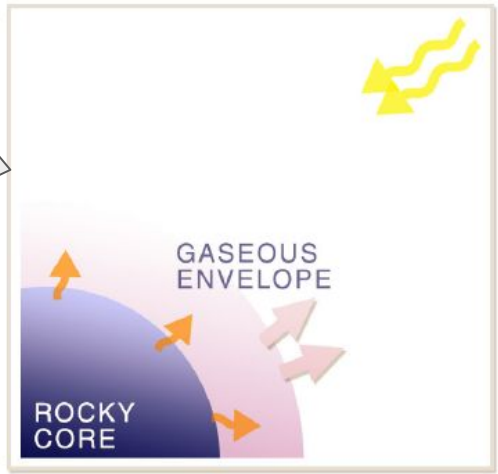
JADE code (v. 1.0)

Github

JADE

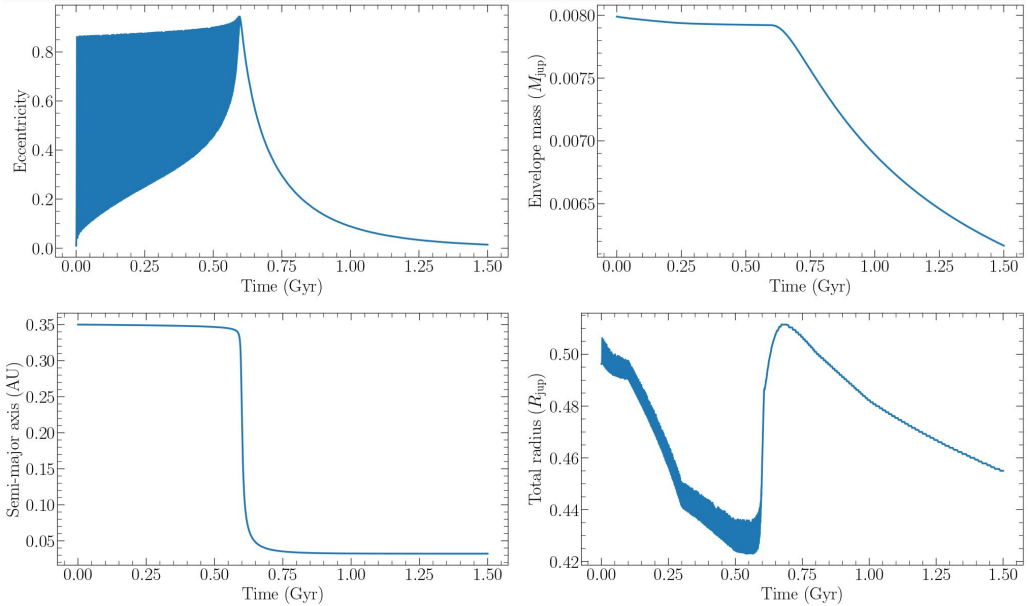
<u>Atmospheric evolution</u>:

- Mass loss: photoevaporation
  - intrinsic host star X-rays and UV luminosity (GENEV stellar evolution model)
  - Stellar irradiation changes with orbital distance
- Change of envelope structure:
  - Change in temperature (due to above)
  - Planet's core-power heating (young planet)



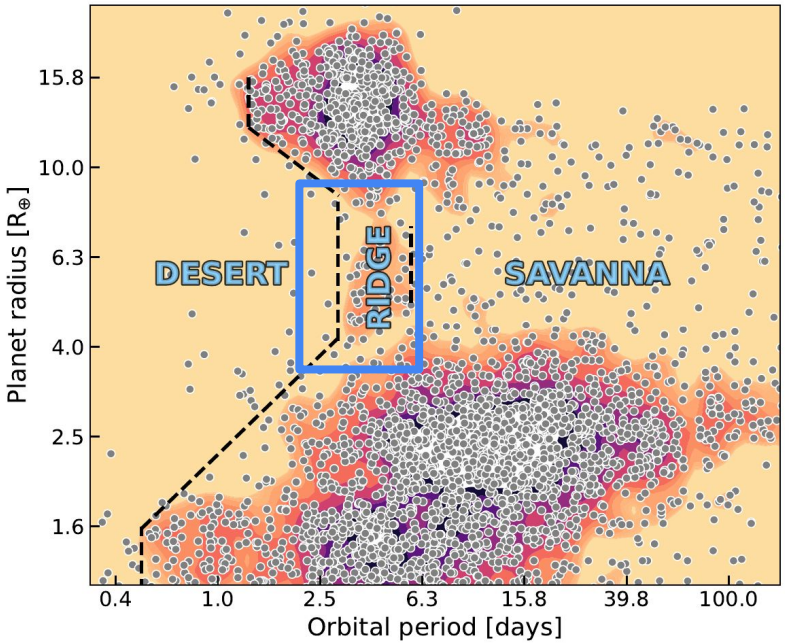
Example of coupled dynamical & atmospheric evolutions

Exoplanet along the Neptunian ridge

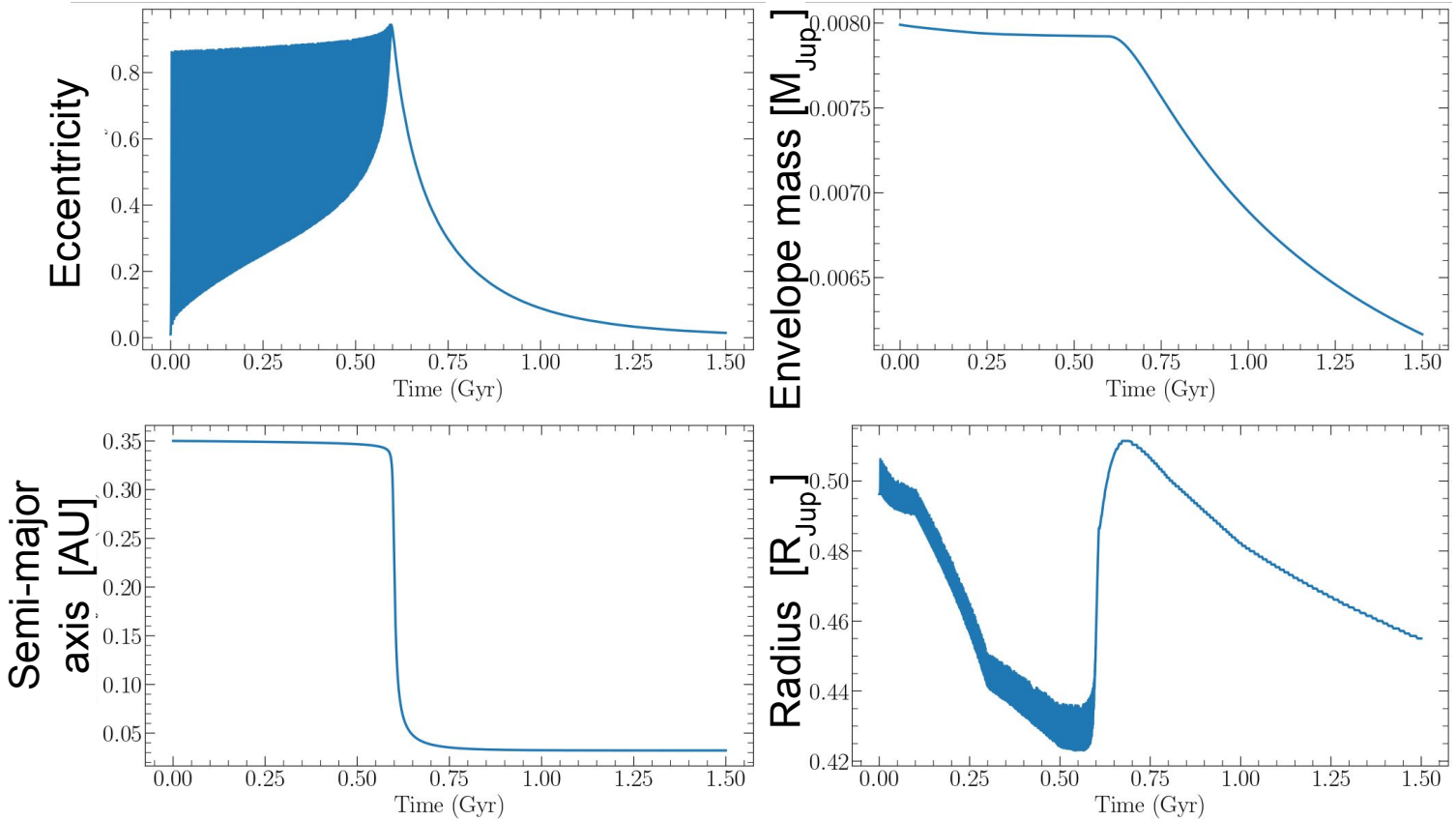


Attia et al. (2021).

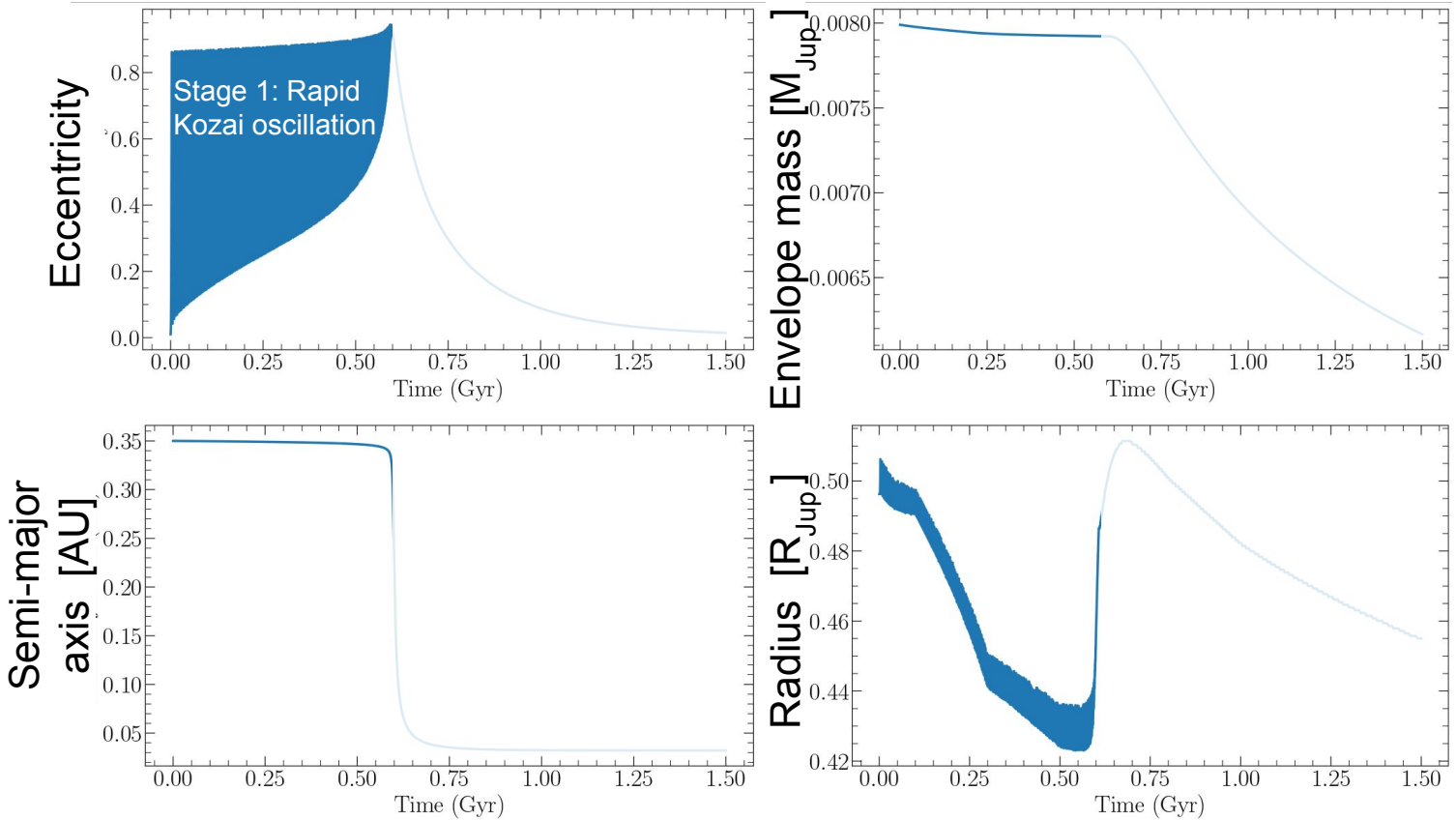
Radius-period plot by Castro-González et al. (2024).



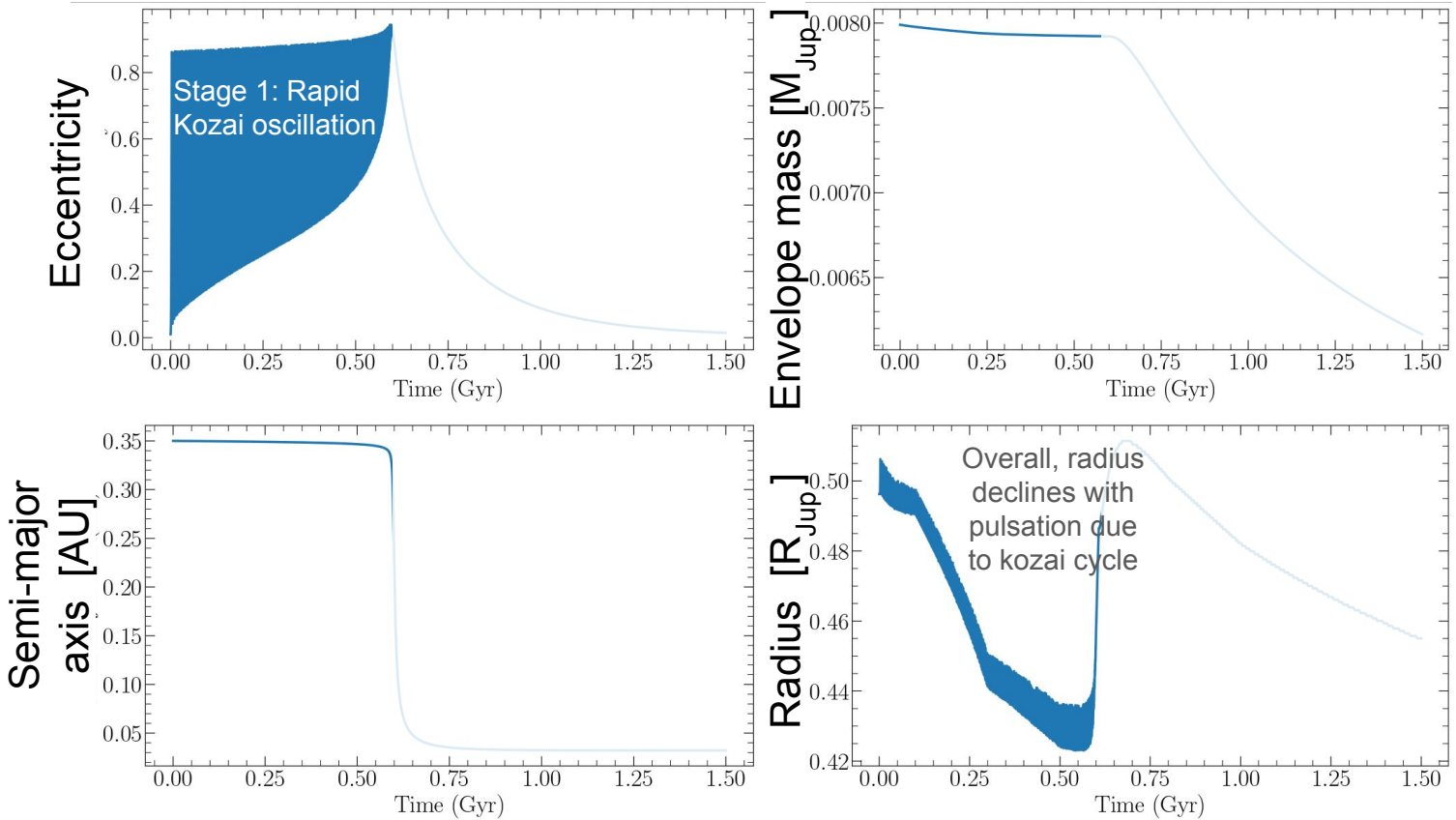
Example of coupled dynamical & atmospheric evolutions



Example of coupled dynamical & atmospheric evolutions



Example of coupled dynamical & atmospheric evolutions



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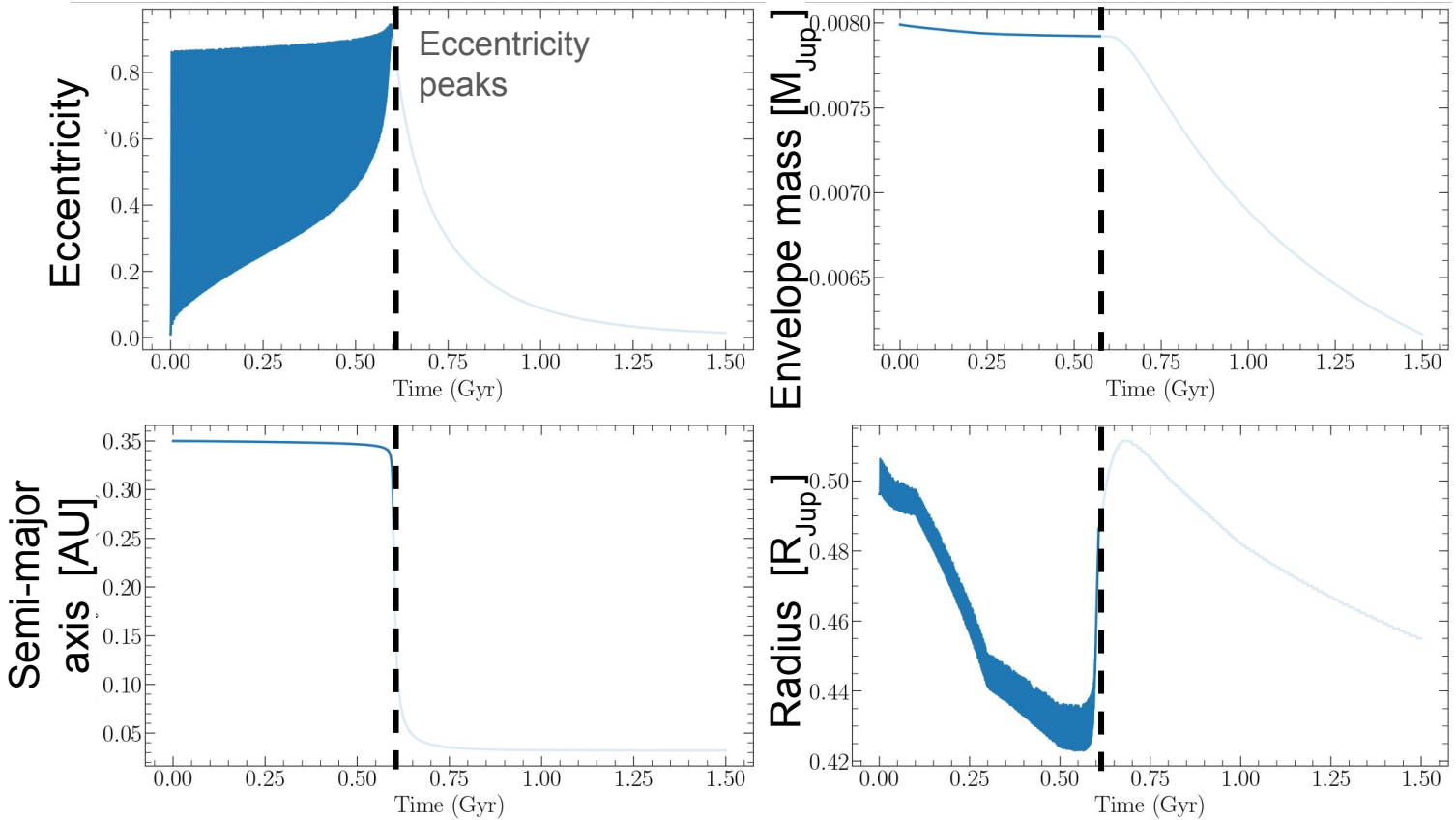

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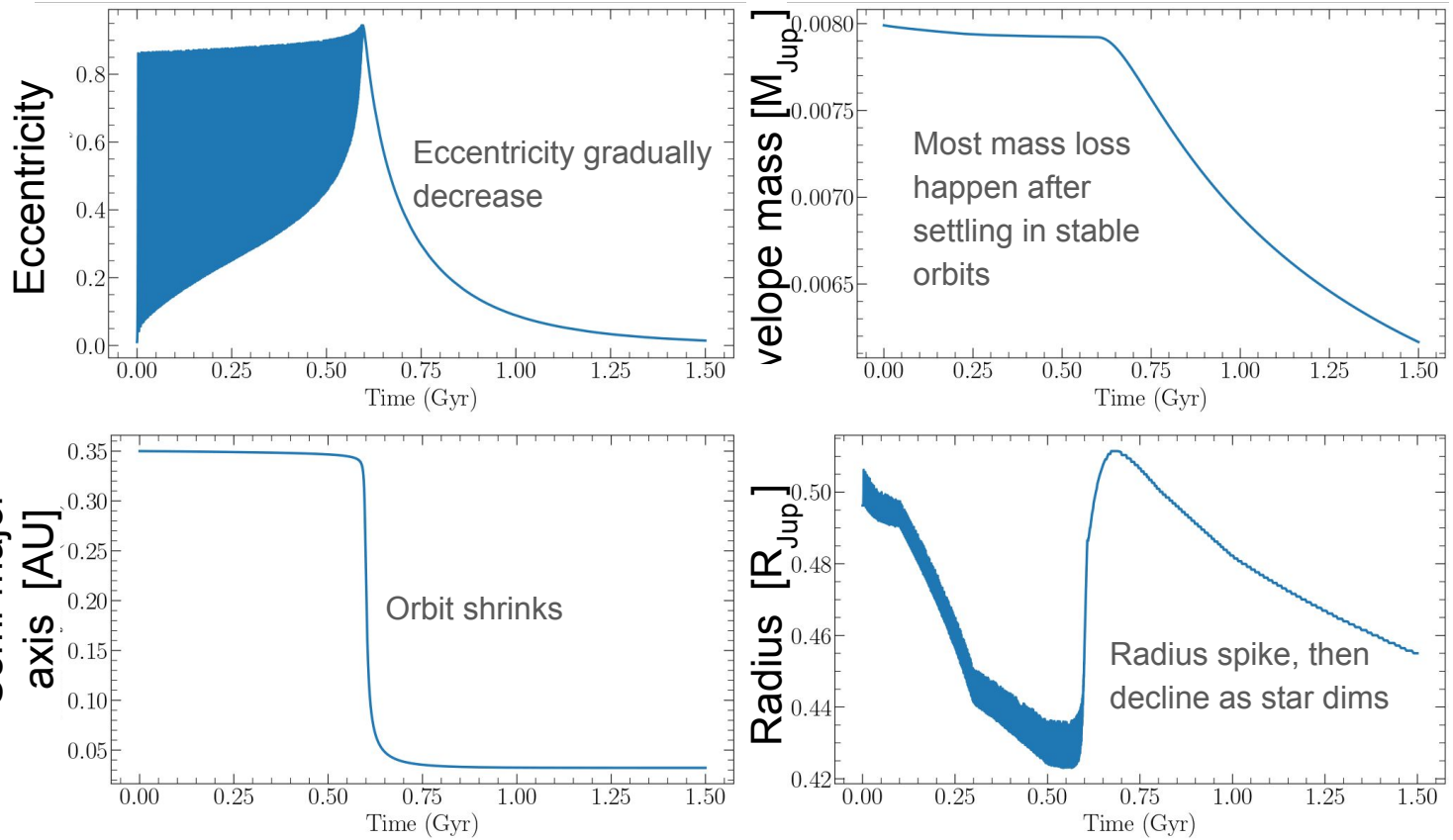


Versatility of JADE

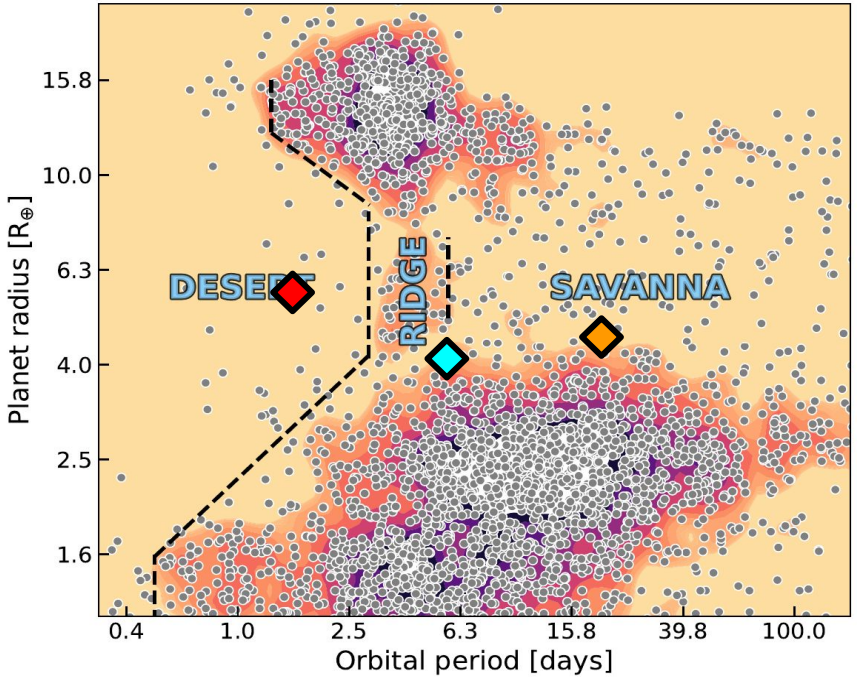
Not just HEM of Neptunian desert/ridge

- Internal structure retrieval
- Retrieval framework for the entire evolution

Decouple the dynamical and atmospheric evolution

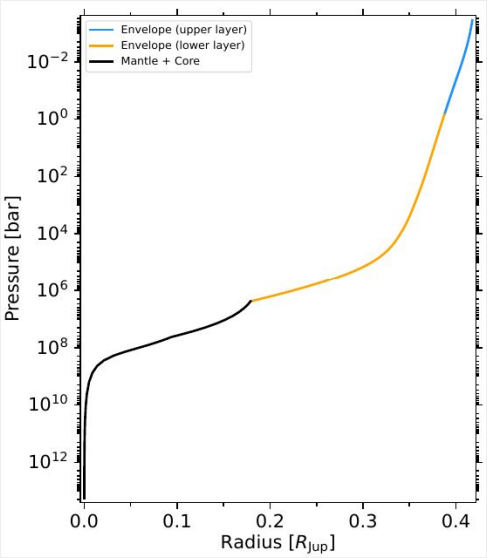
- Pure atmospheric:
  Early disk-drive migration in stable orbit
- Pure dynamics:
  Orbits around a faint star

Radius-period plot by Castro-González et al. (2024).



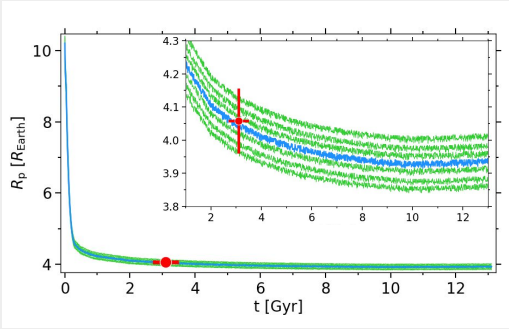
Steps of JADE

Step 1:
Internal Structure Retrieval



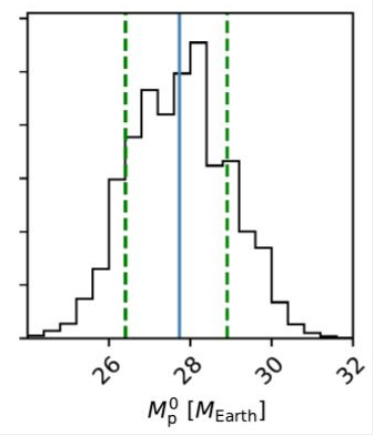
Step 2: Long-term evolution of dynamics and/or atmosphere.

Diff initial conditions



Ilaria et al. (in.prep)

Step 3: Built posterior distribution to find the best initial condition or evolutionary path.

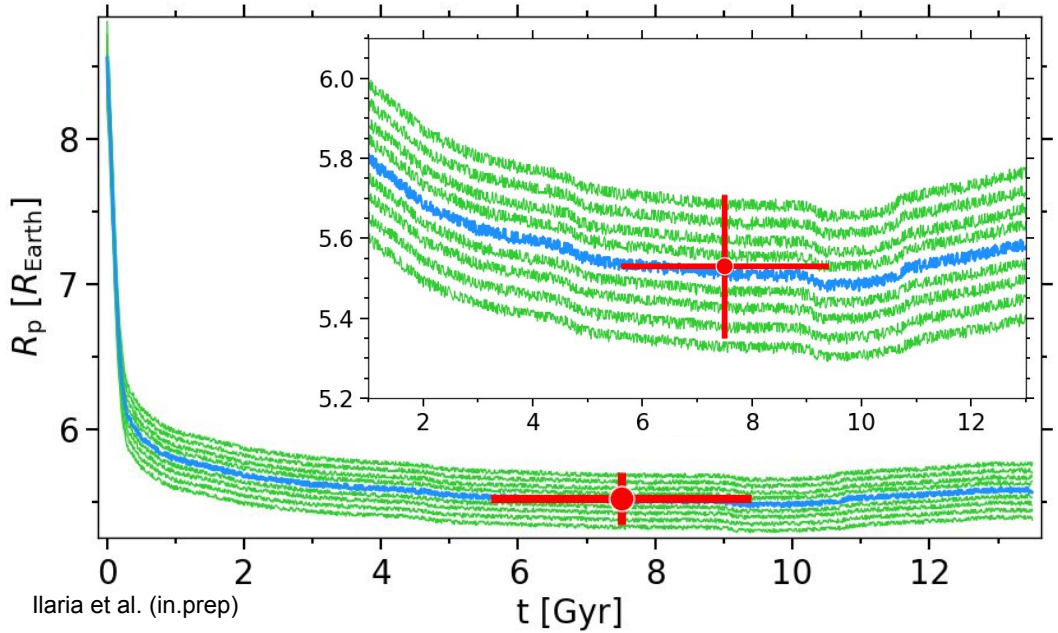


Ilaria et al. (in.prep)

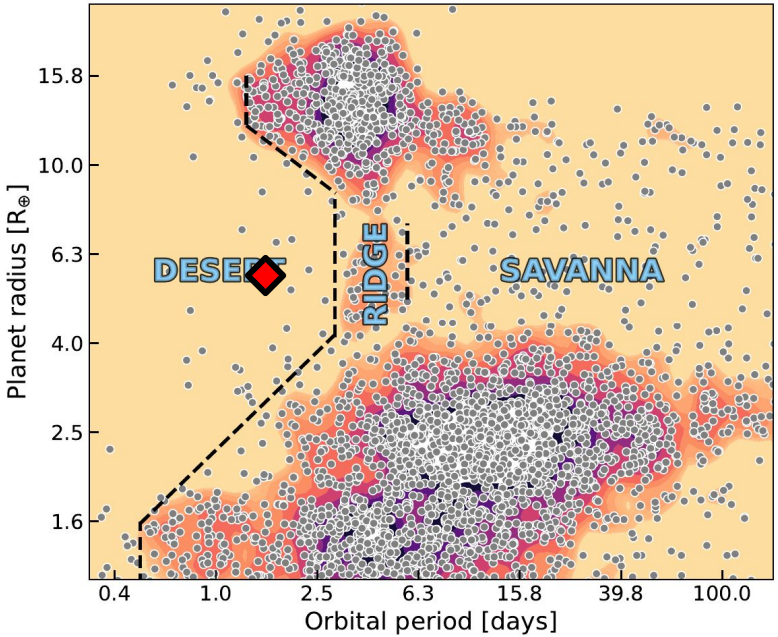
JADE's application of pure atmospheric evolution

TOI-3863b: Desert

1.5 days, 5.53 ± 0.18 $R_\oplus$, 53.7 ± 2.9 $M_\oplus$



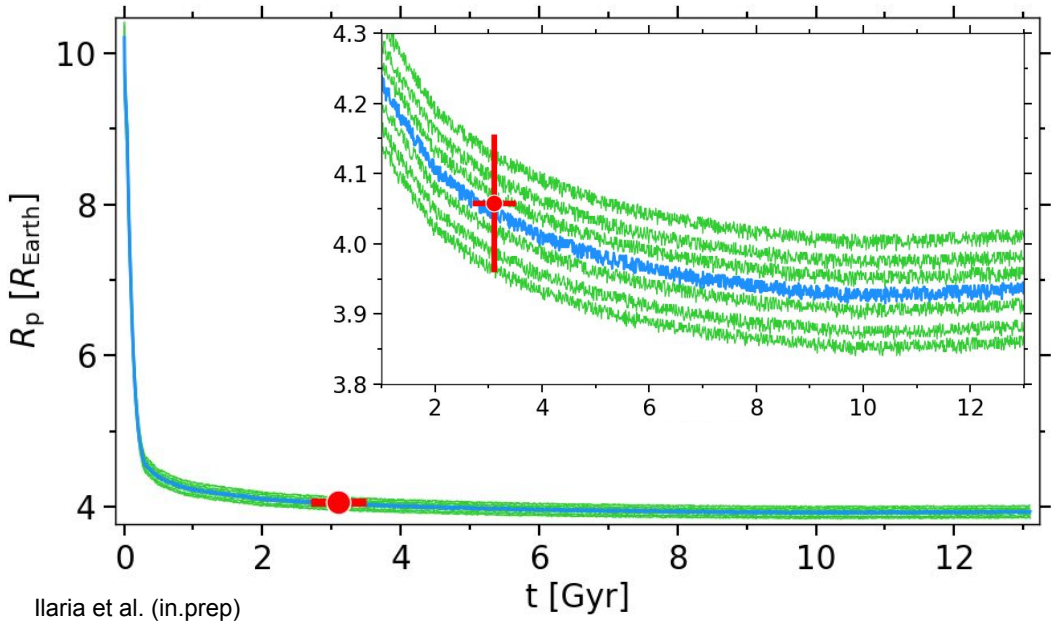
Ilaria et al. (in.prep)



JADE's application of pure atmospheric evolution

TOI-1472b: Ridge

6.3 days, 4.06 ± 0.10 $R_\oplus$, 18.0 ± 0.85 $M_\oplus$



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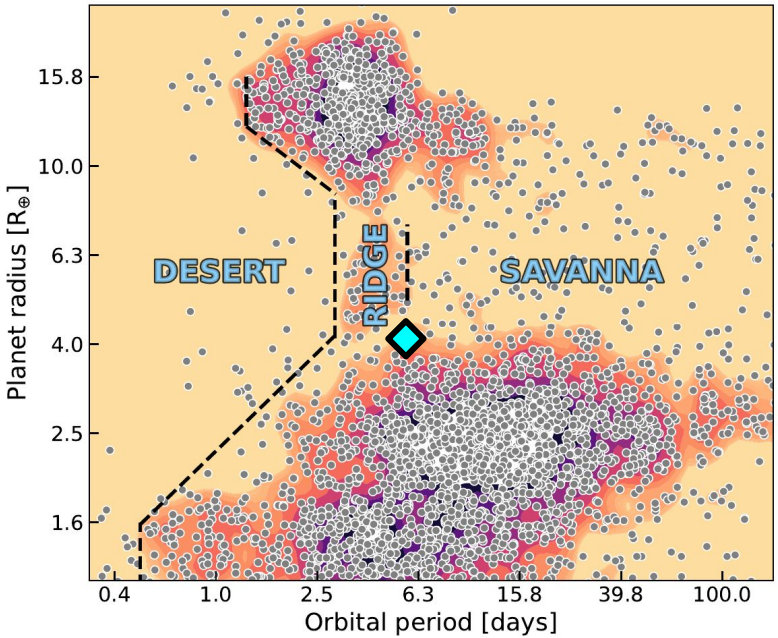
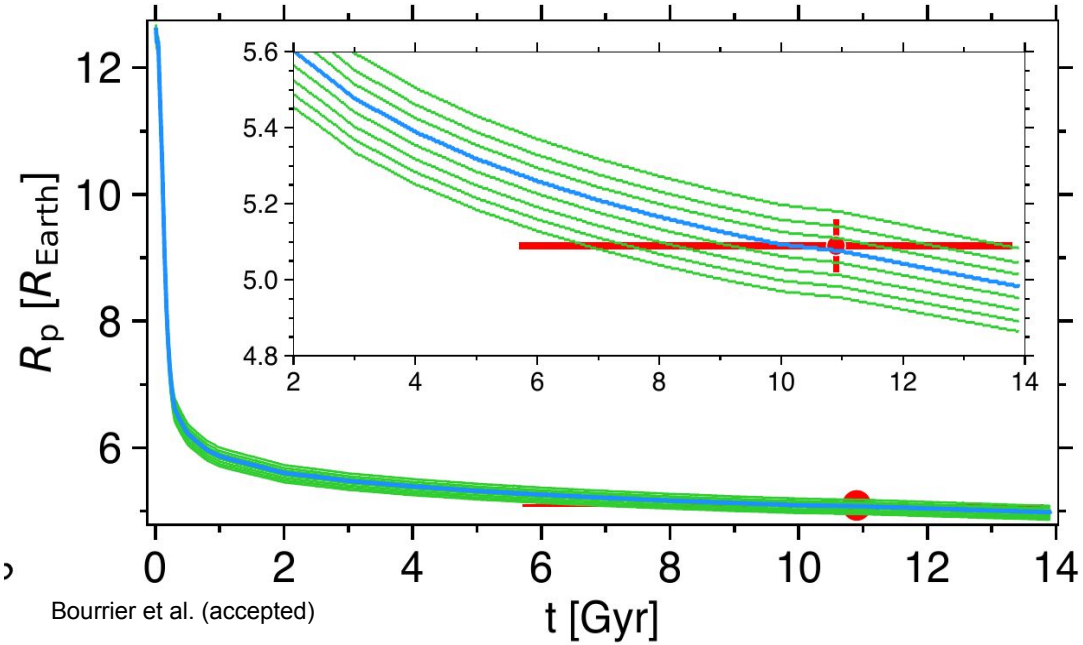


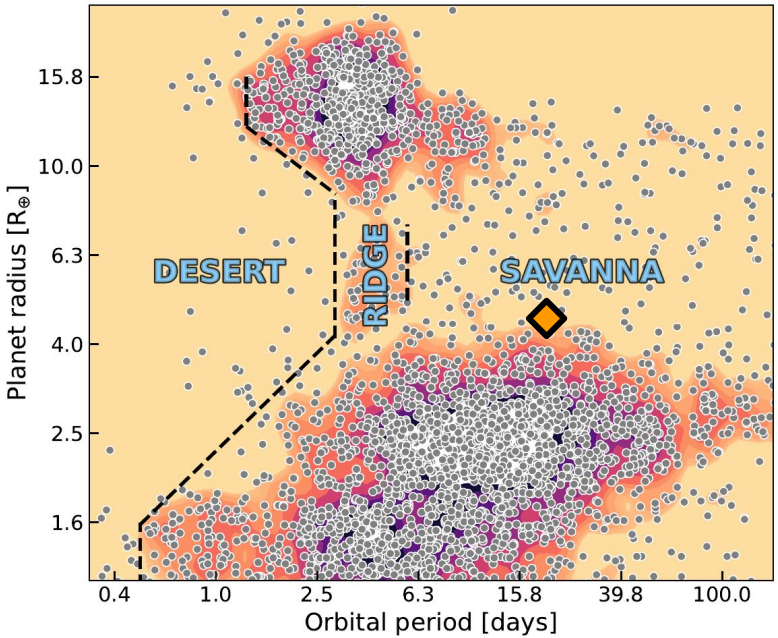
JADE's application of pure atmospheric evolution

TOI-421c: Savanna

16 days, 5.09 ± 0.07 $R_\oplus$, 14.1 ± 1.4 $M_\oplus$



Bourrier et al. (accepted)



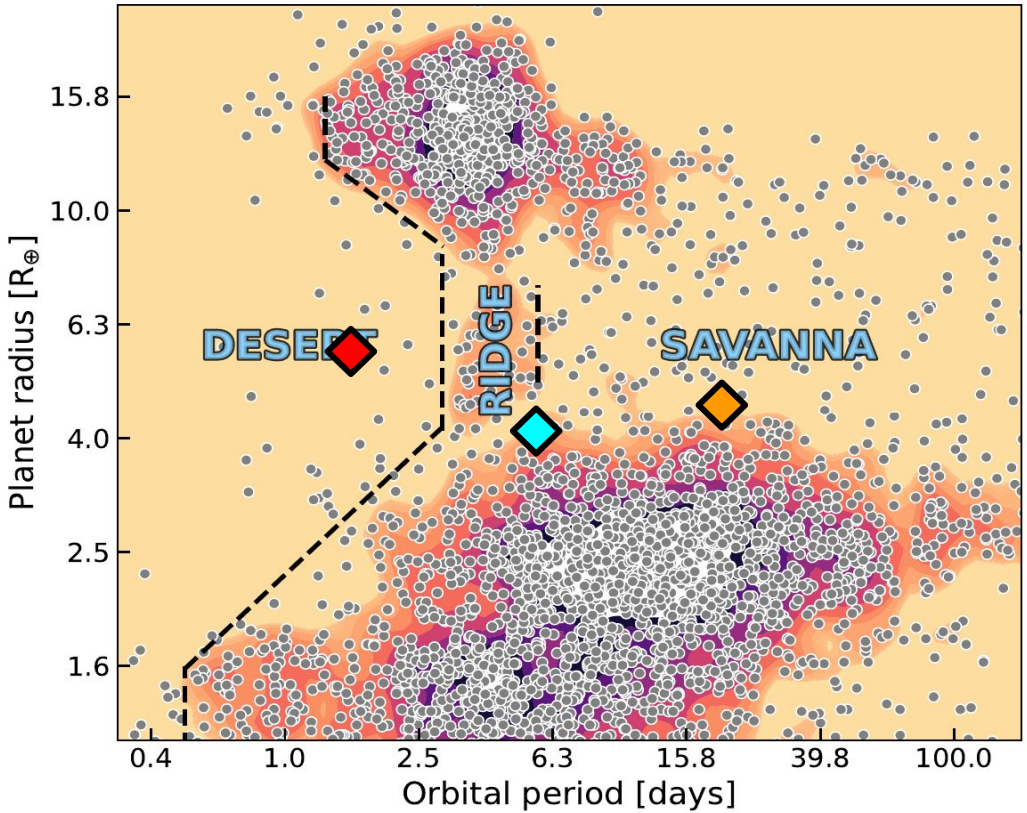
Sub-Neptunes

Desert boundary is less clear toward smaller size, e.g., sub-Neptune

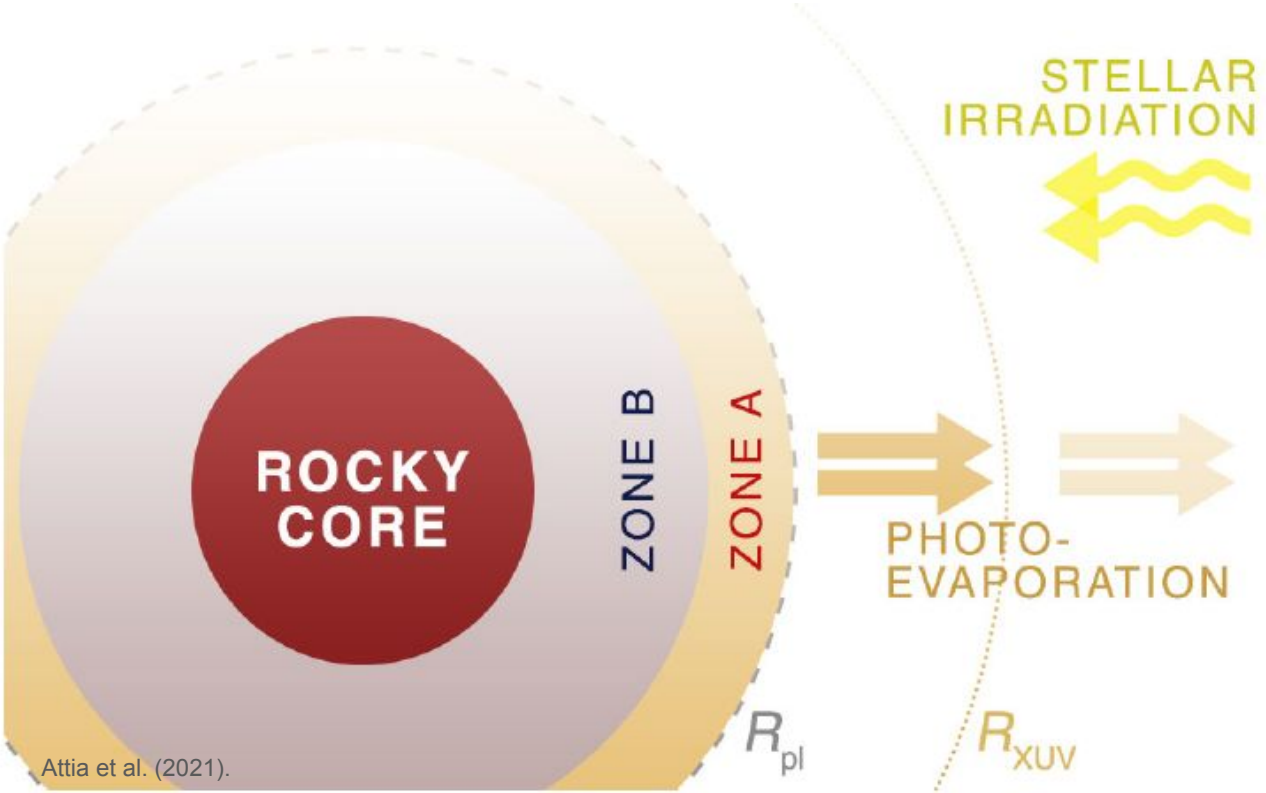
Worth to study:

- sub-Neptune's origin
- connection with Neptune
- fraction/characteristic (radii, masses, etc.) of the planets that ends up in desert/ridges/savanna

Radius-period plot by Castro-González et al. (2024).



Internal structure retrieval

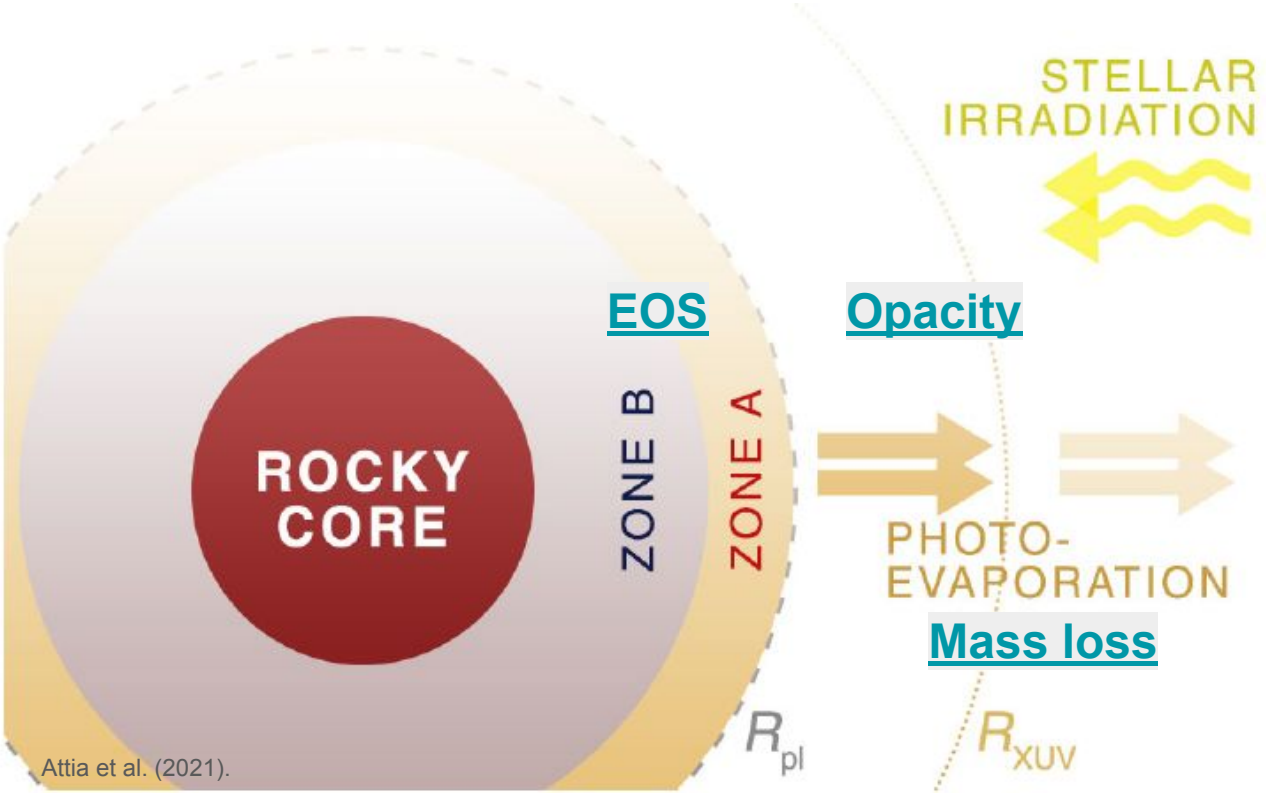


Attia et al. (2021).

Zone A:
Upper layer aborbs optical + IR

Zone B:
Lower layer is opaque

Internal structure retrieval



Attia et al. (2021).

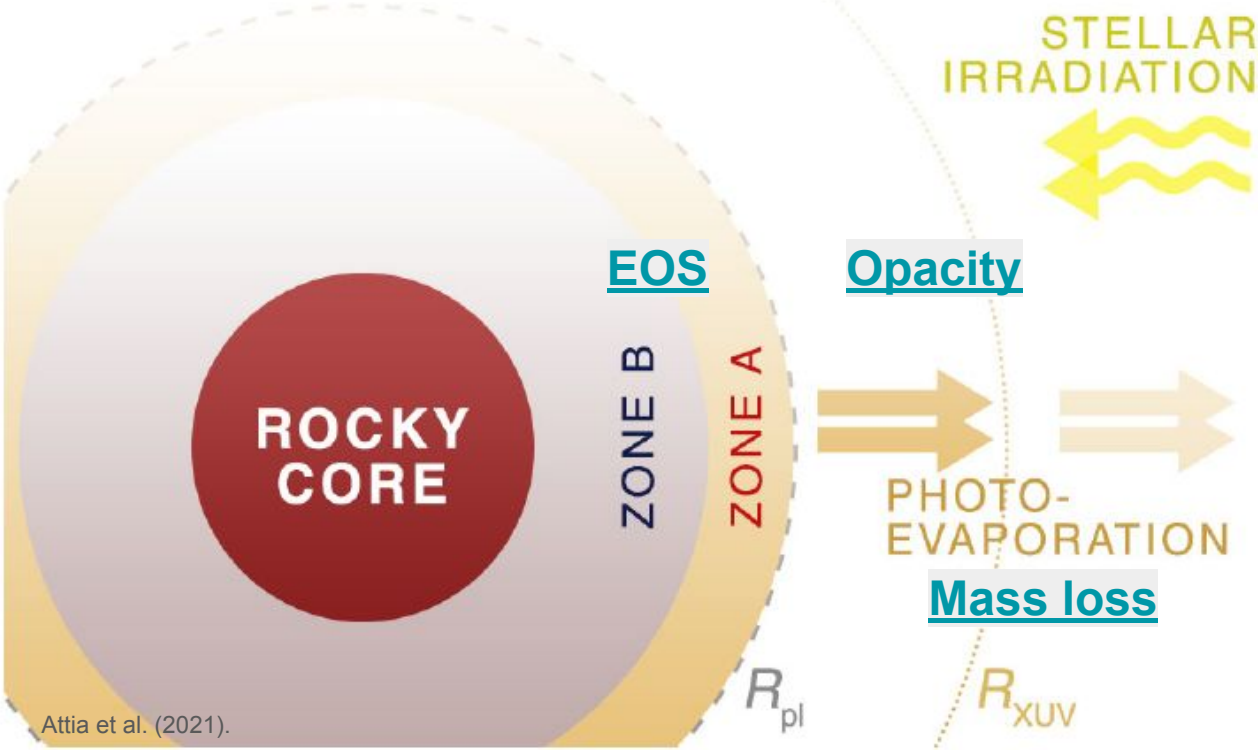
H/He dominated
- good for hot-Jup
- not accurate for sub-Nep

Updates:

- Equation of state
- Opacity
- Mass loss

Internal structure retrieval with mixed water atmosphere

Water mass fraction : 0.0 (dry) to 1.0 (pure water vapour)



Attia et al. (2021).

EOS & Opacity

- AQUA (Mordasini, 2015)
- Opacity (Freedman et al 2014, Haldemann, 2019)

With C. Mordasini & Y. Alibert

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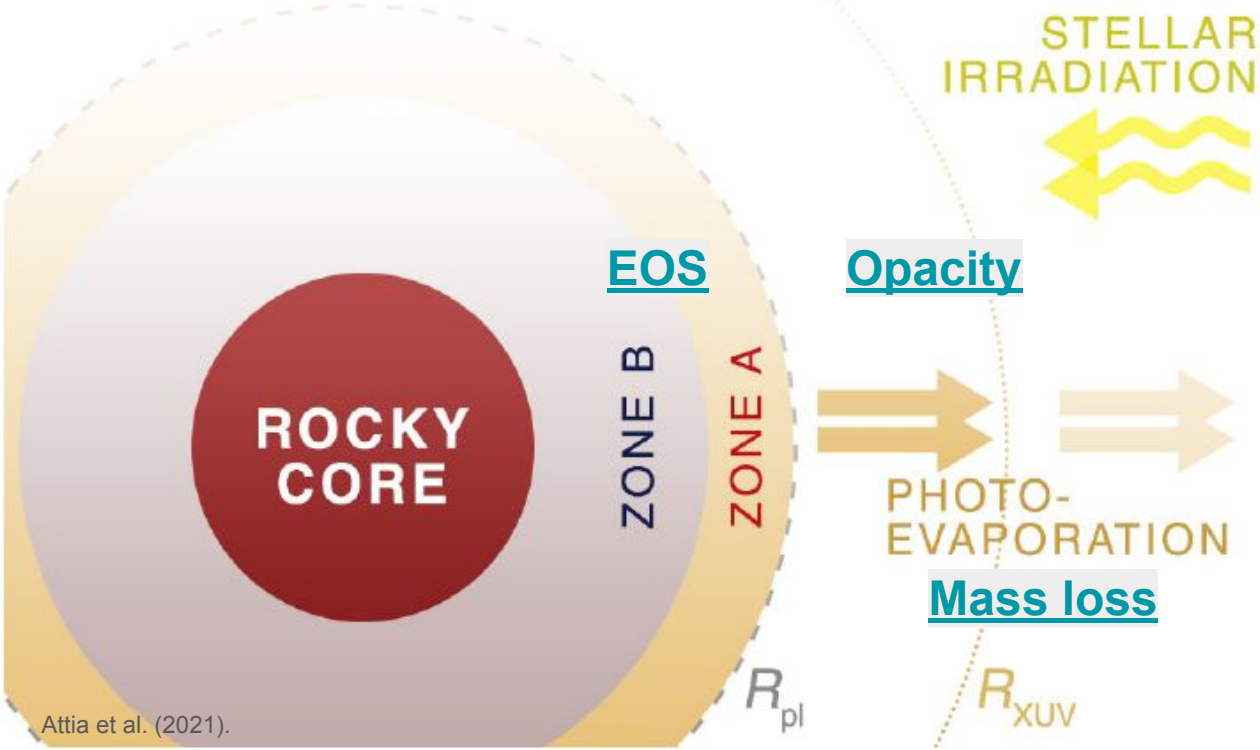


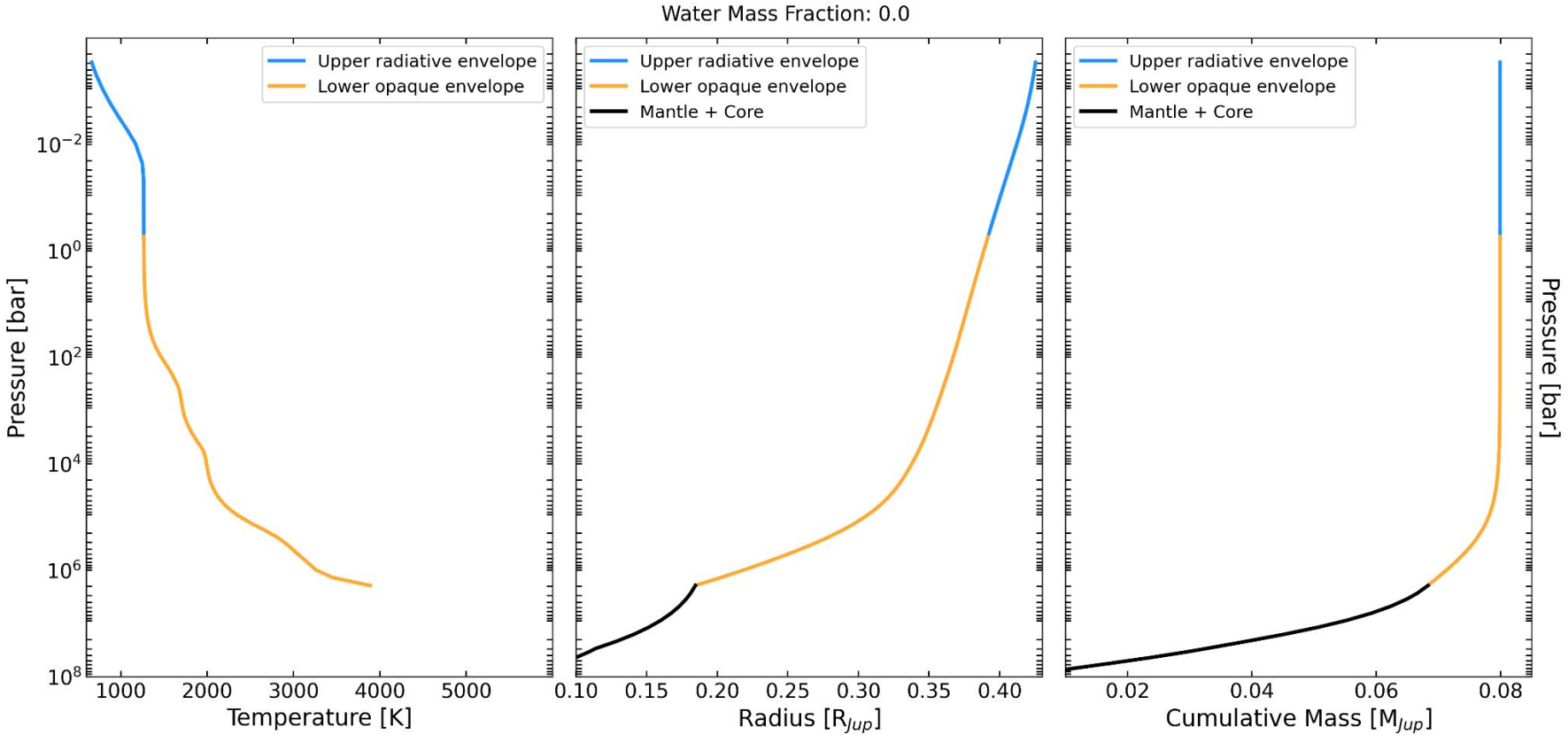
Attia et al. (2021).

Photo Evaporative Mass Loss & Chemical Fractionation Model

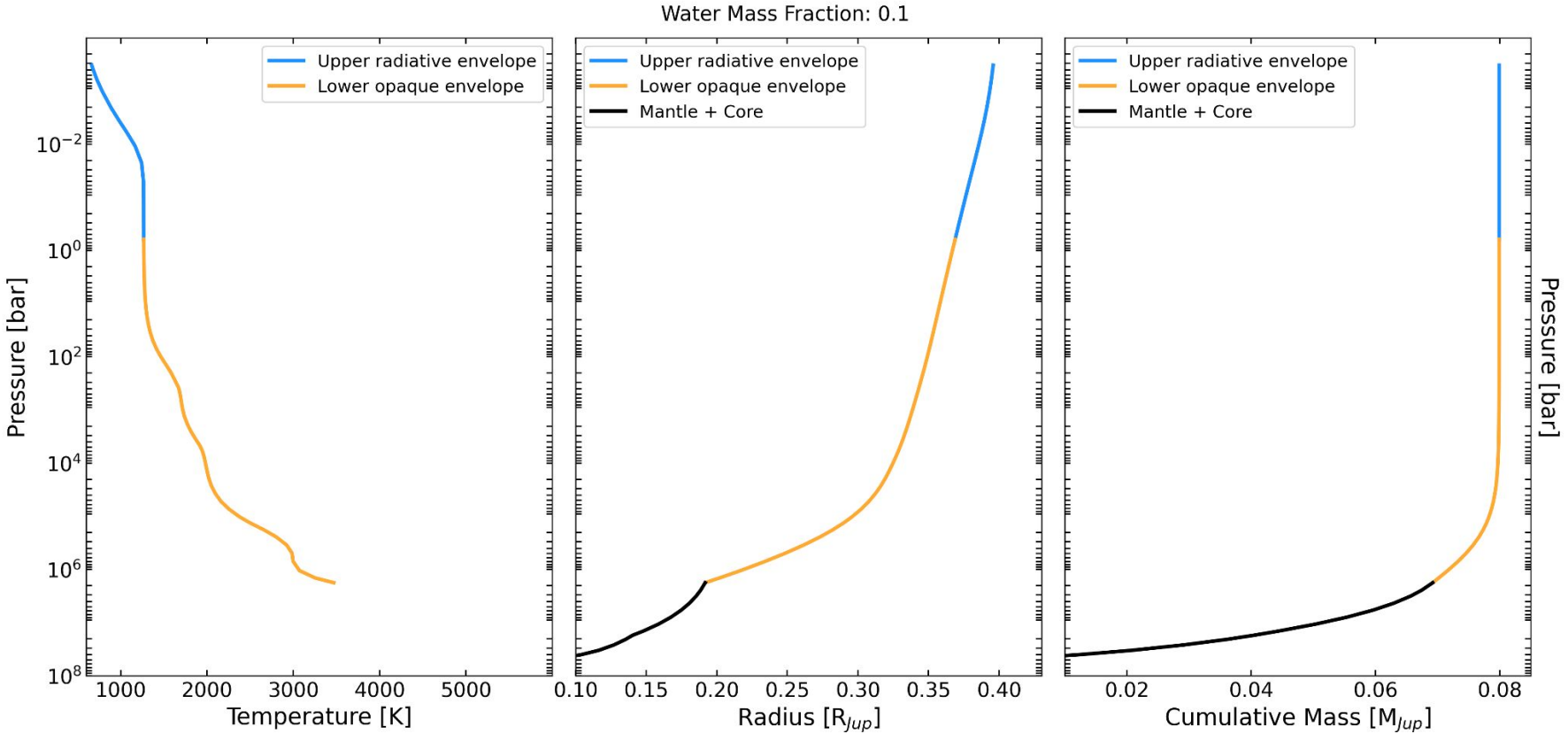
With C. Dorn & M. Valatsou

ETH zürich

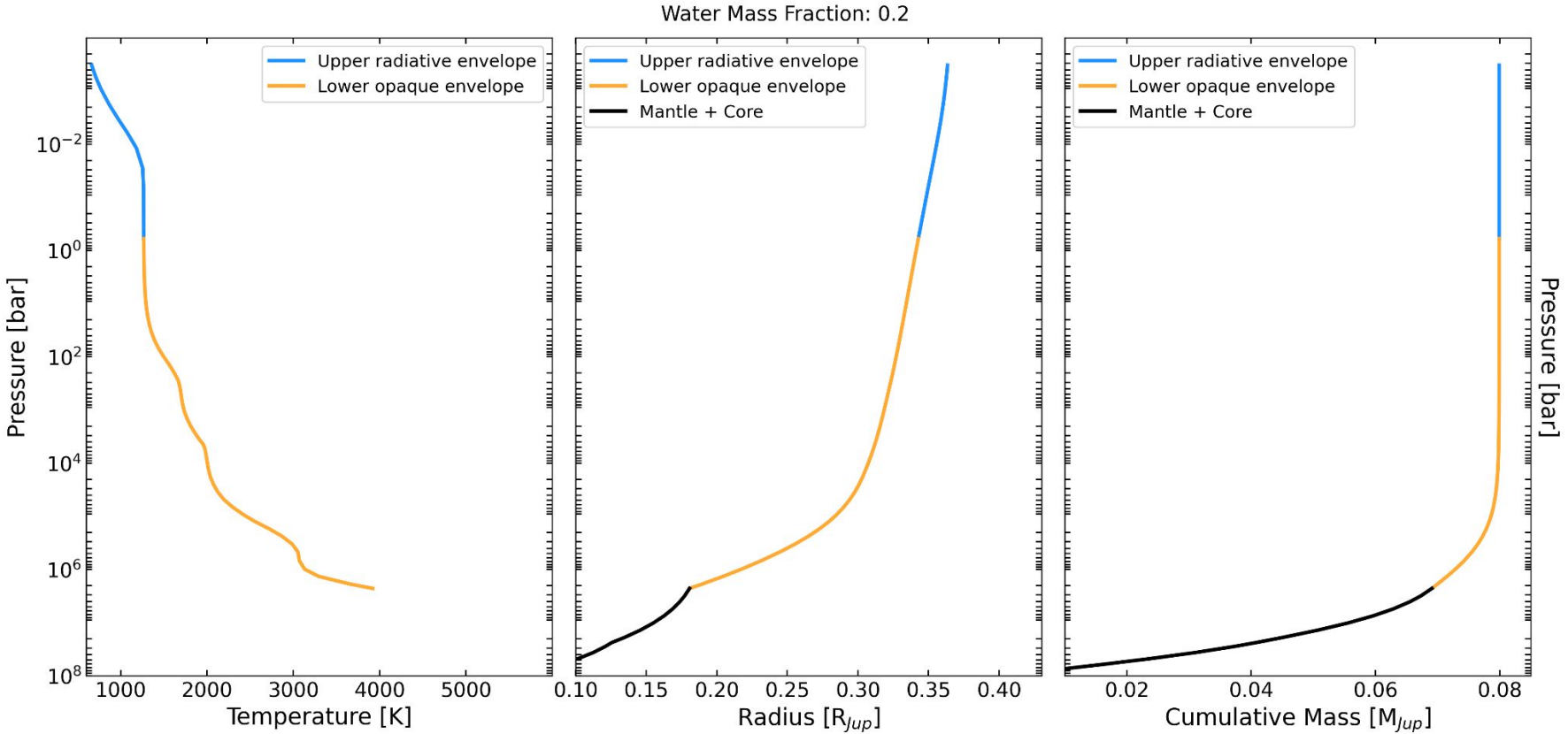
Atmosphere profiles with mixed water (0.0 = dry)



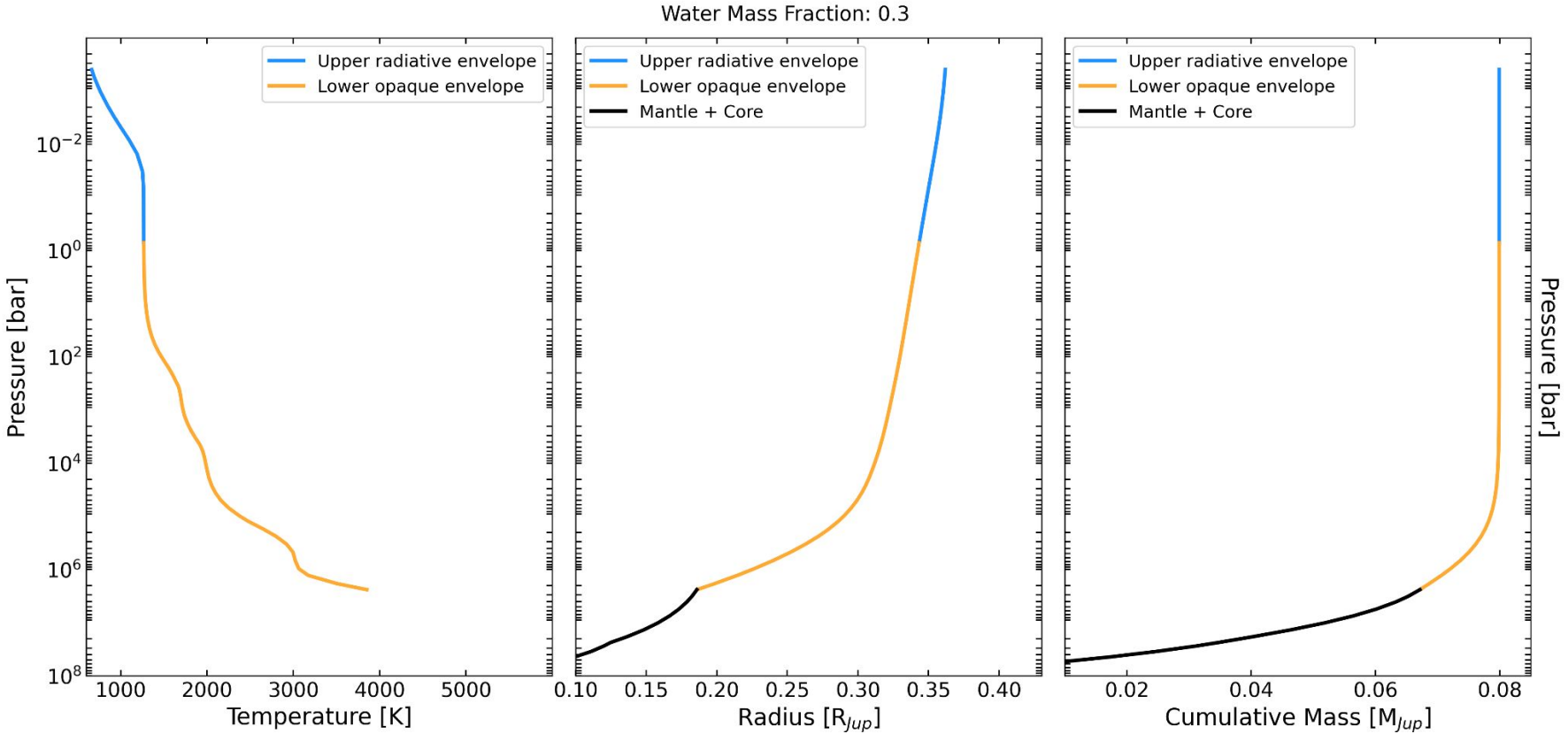
Atmosphere profiles with mixed water (0.1)



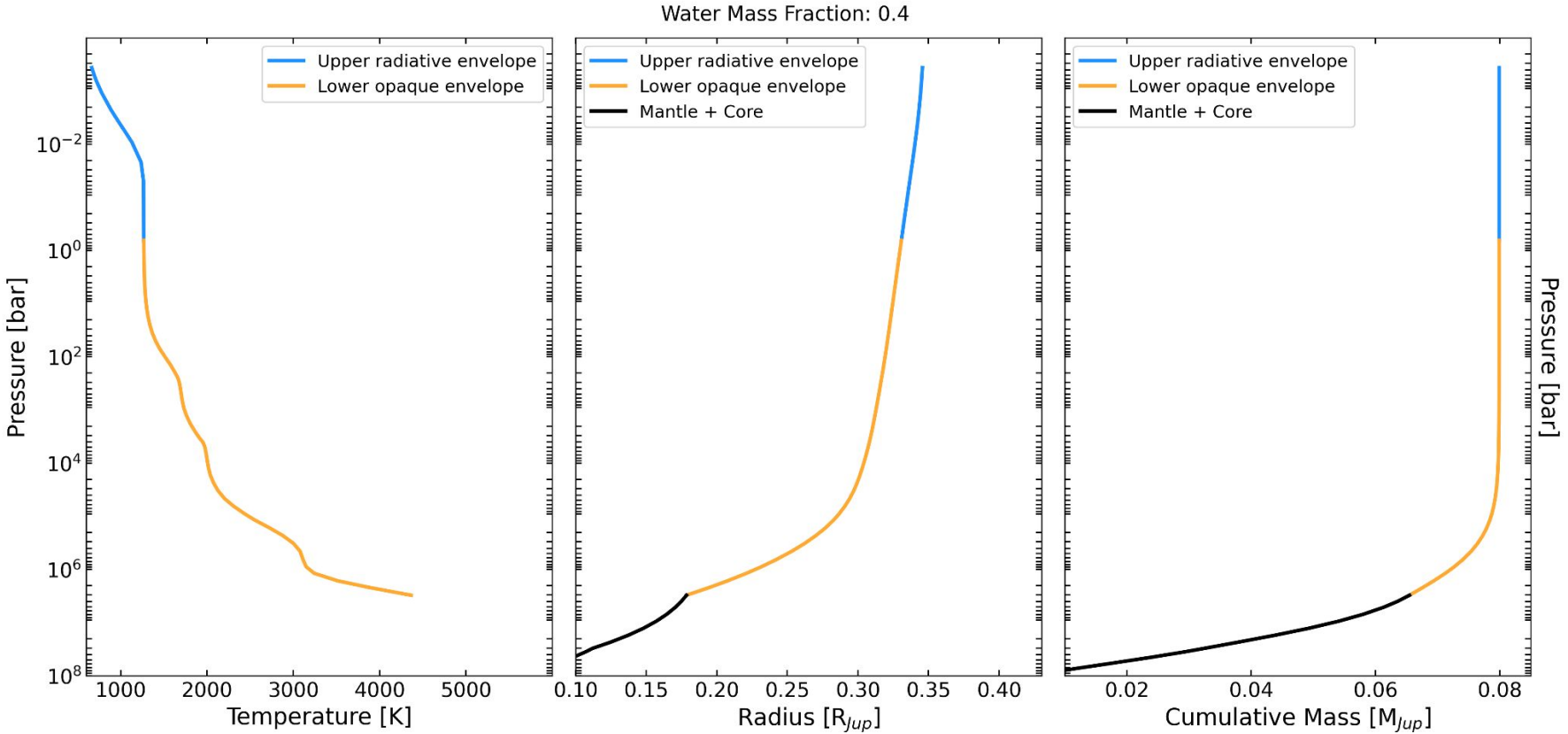
Atmosphere profiles with mixed water (0.2)



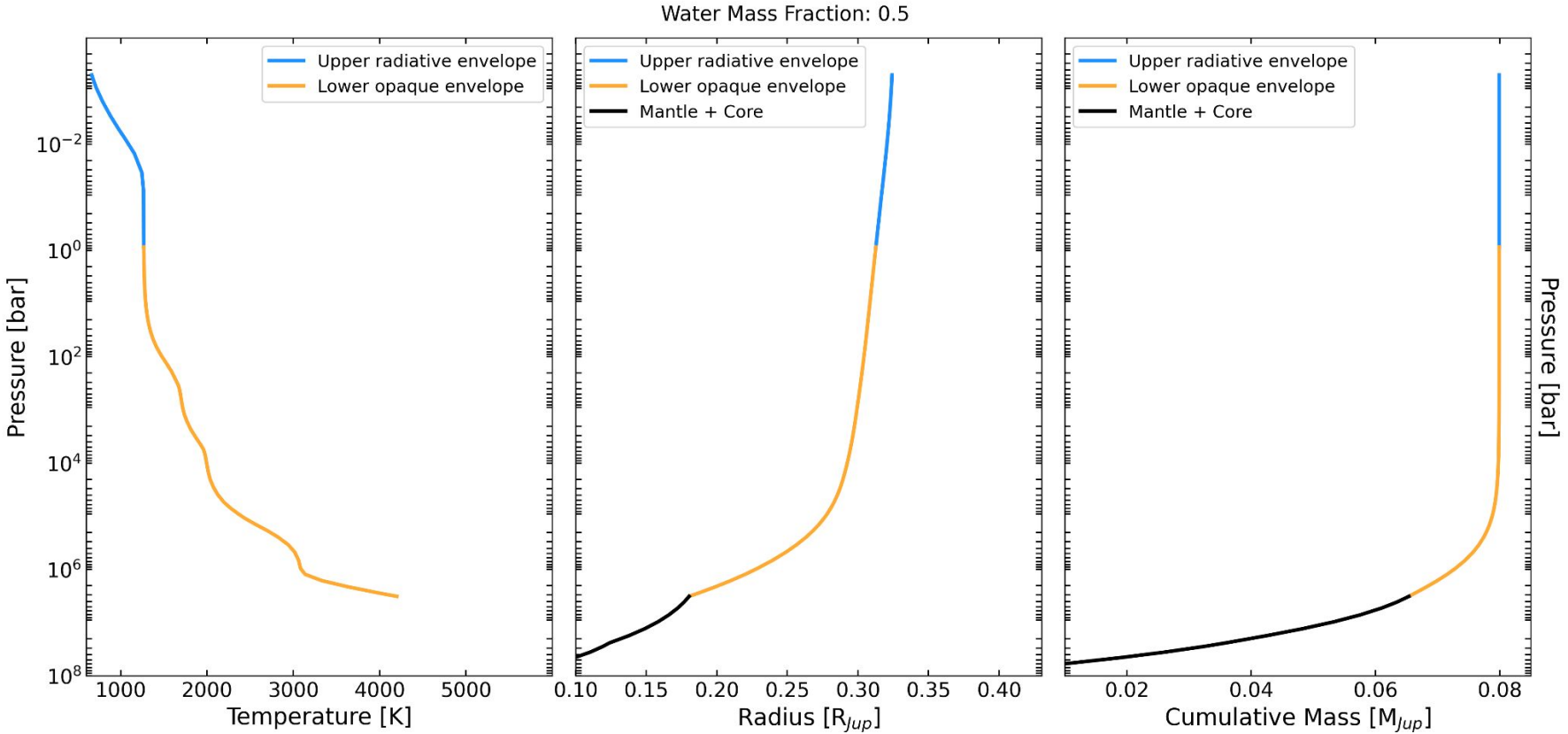
Atmosphere profiles with mixed water (0.3)



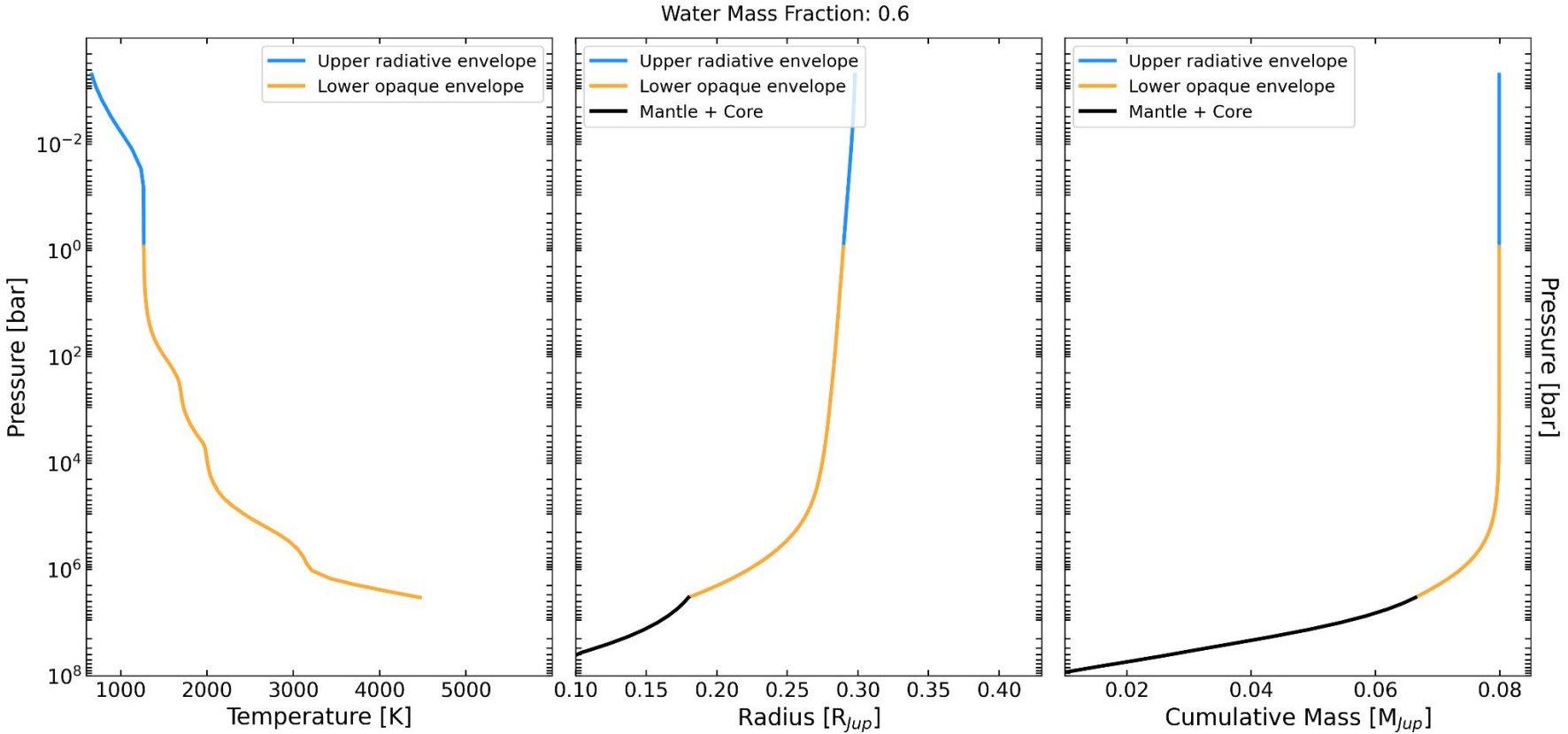
Atmosphere profiles with mixed water (0.4)



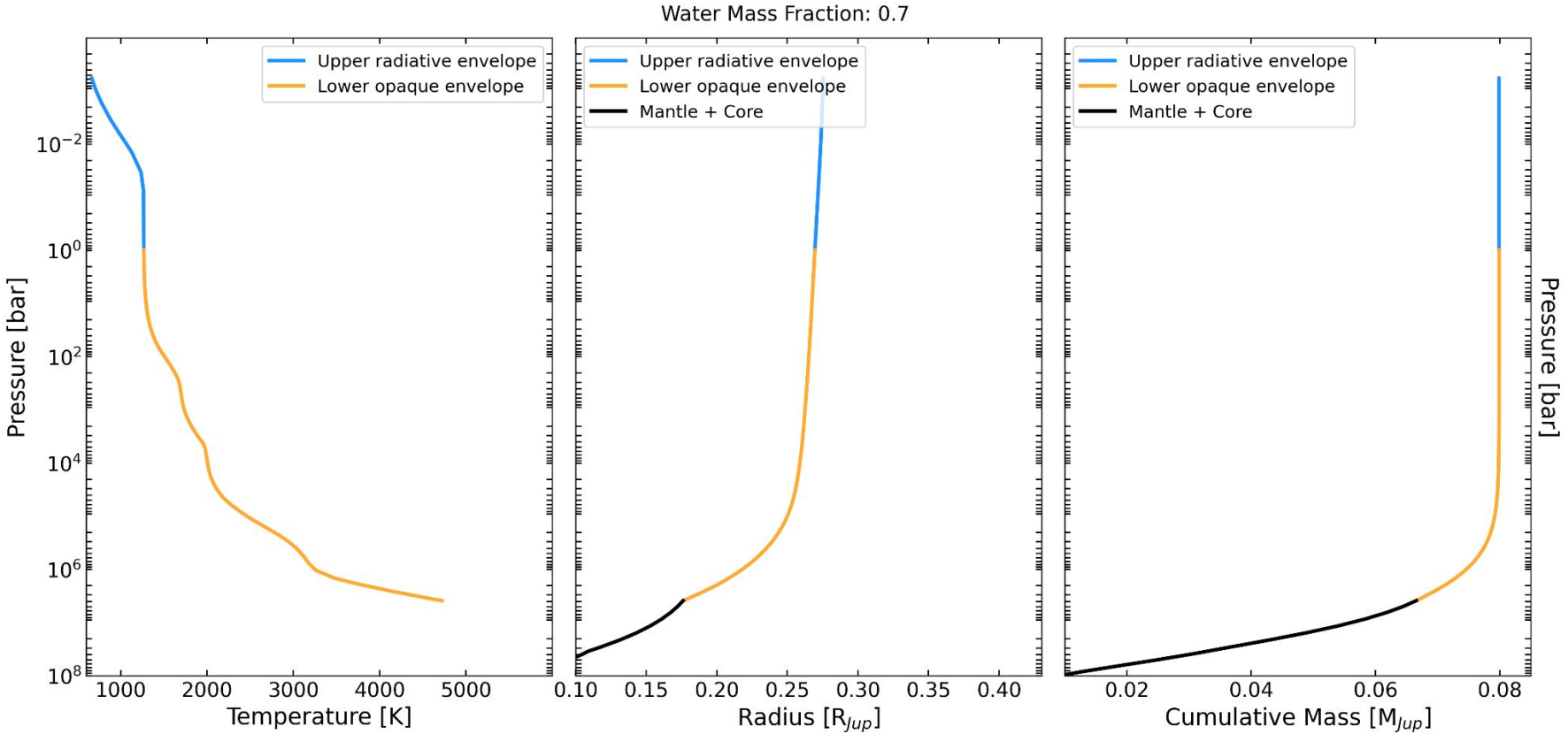
Atmosphere profiles with mixed water (0.5)



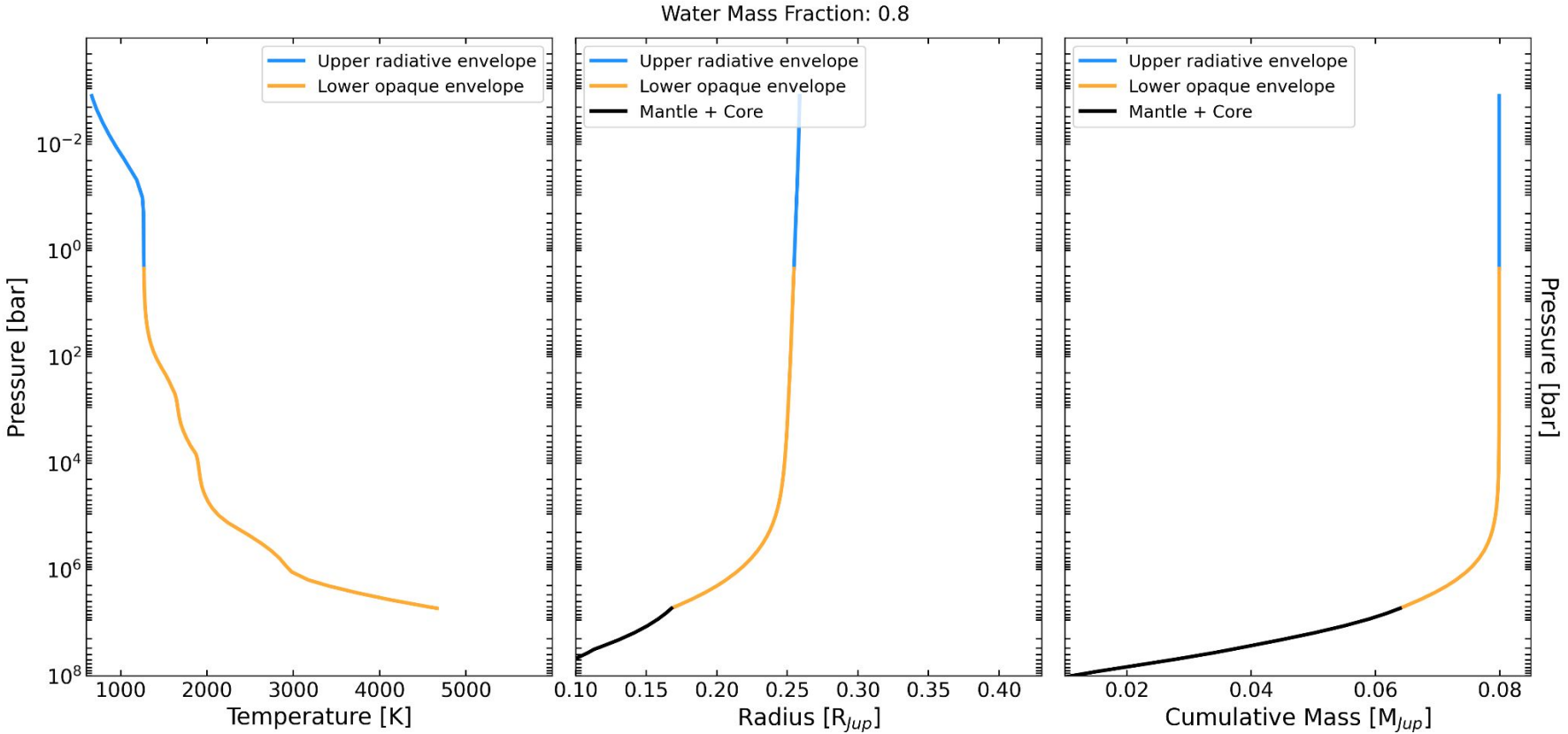
Atmosphere profiles with mixed water (0.6)



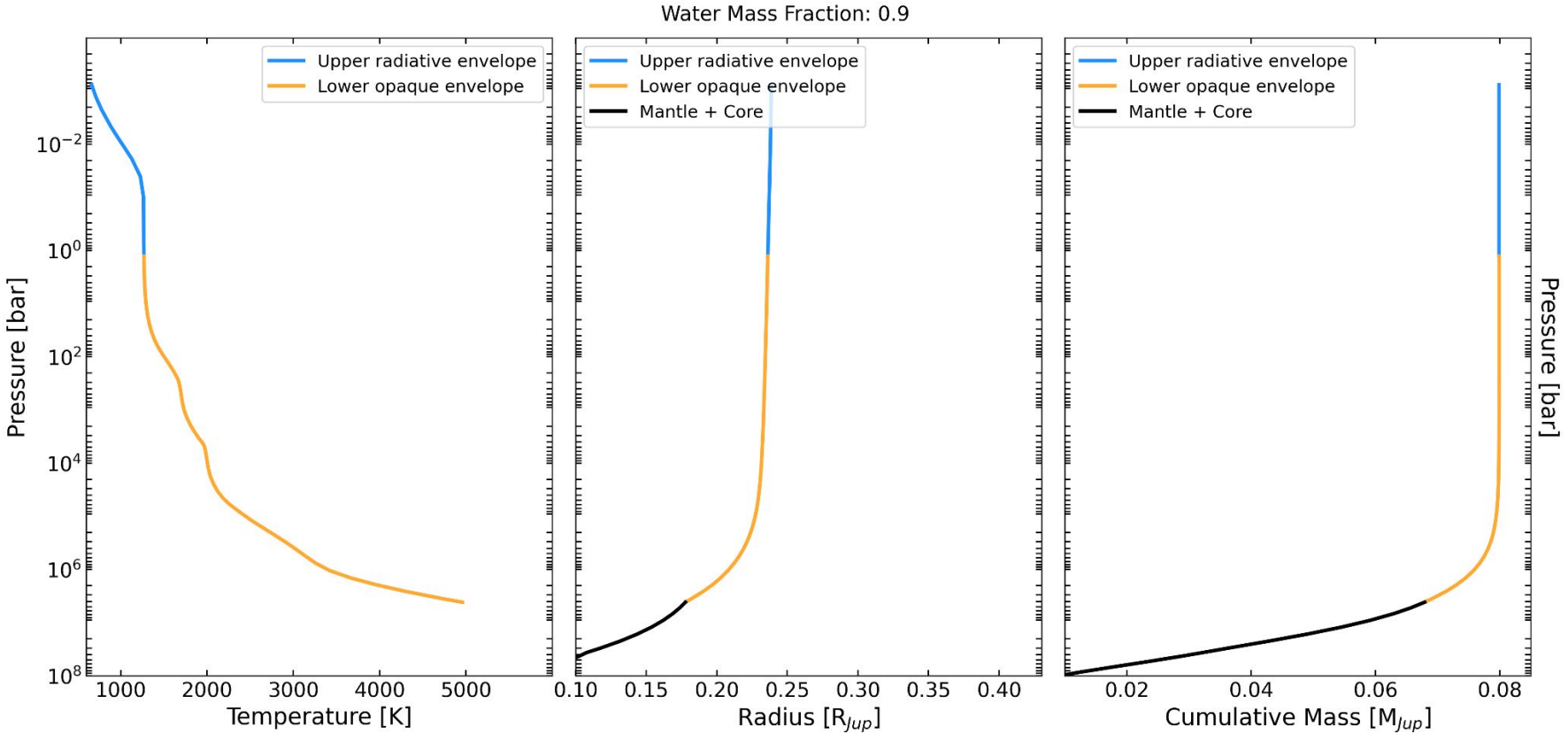
Atmosphere profiles with mixed water (0.7)



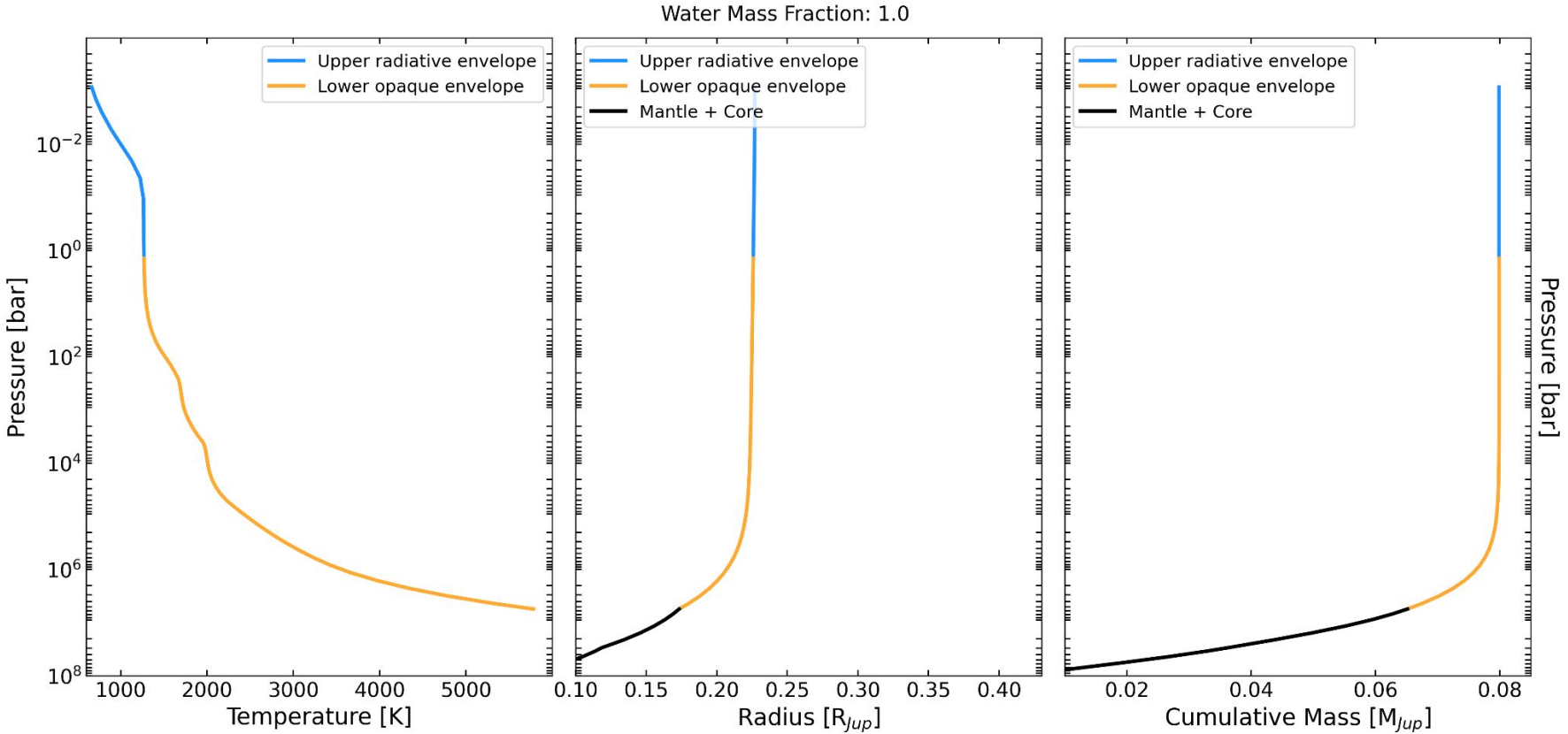
Atmosphere profiles with mixed water (0.8)



Atmosphere profiles with mixed water (0.9)



Atmosphere profiles with mixed water (1.0 = full water vapour)



Overview

Github

Couple dyn + atm evolution
across Neptunian landscape

For Observers:

Open source, fully documented
(release by end of 2025).

For Dynamicist:

Contribution via Git.
Adding new dynamics scenario,
e.g., HEM in multi-planets system,
or irradiation & dynamics in binaries.