Planet S

UNIVERSITÉ
DE GENÈVE
FACULTÉ DES SCIENCES
Département d'astronomie

erc

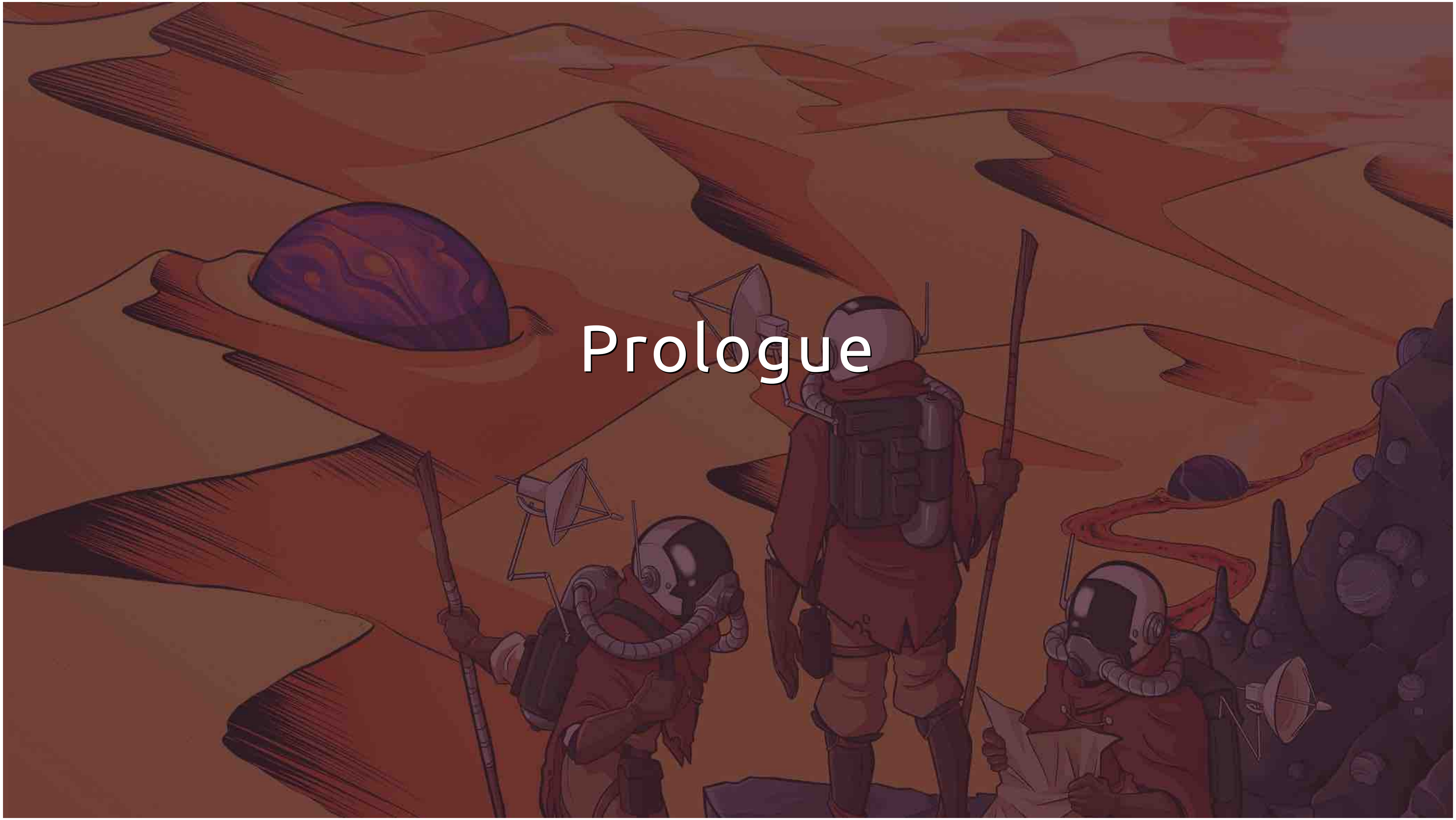
FROM THE DESERT INTO THE SAVANNAH

A TREK ACROSS THE EXO-NEPTUNES LANDSCAPE

Vincent Bourrier & the SPICE DUNE team

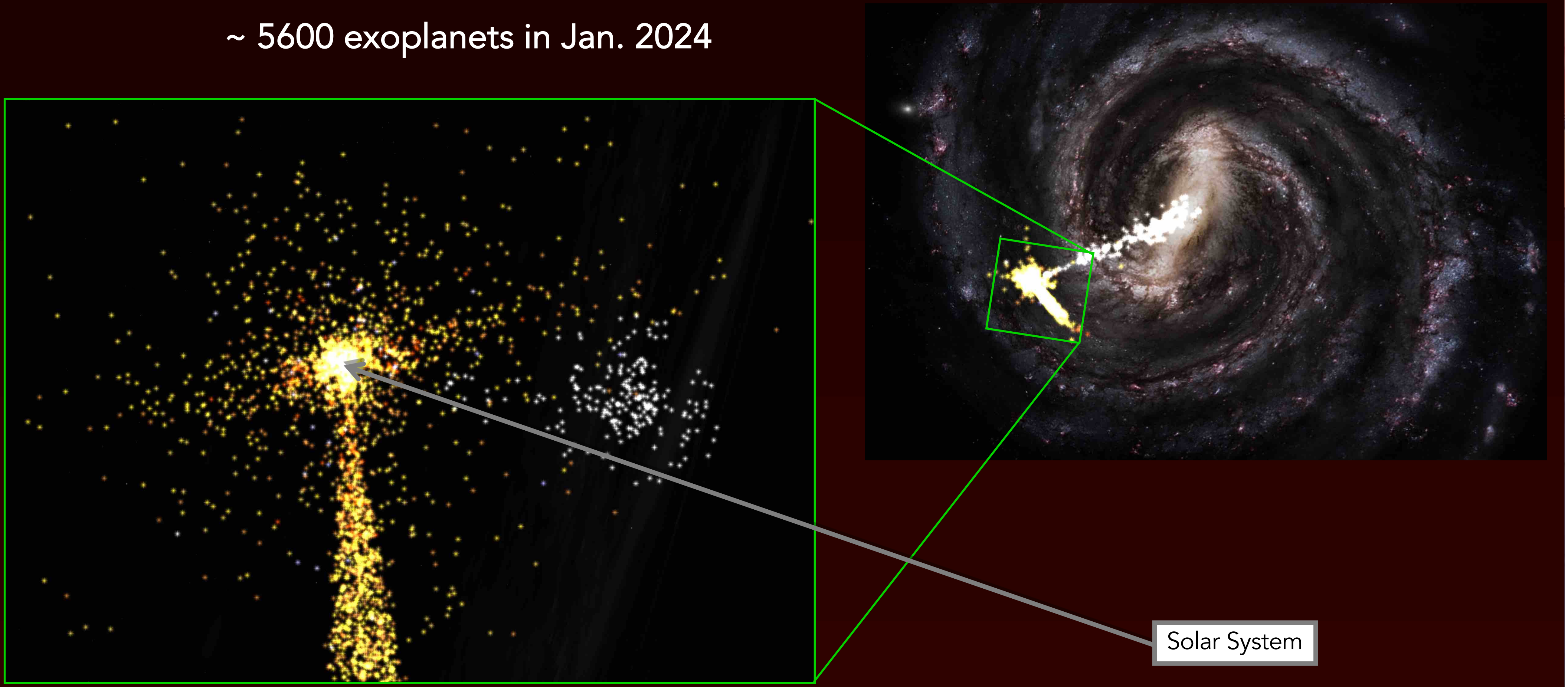
Lagrangre Seminar (OCA) – 9 Jan. 2024

Prologue



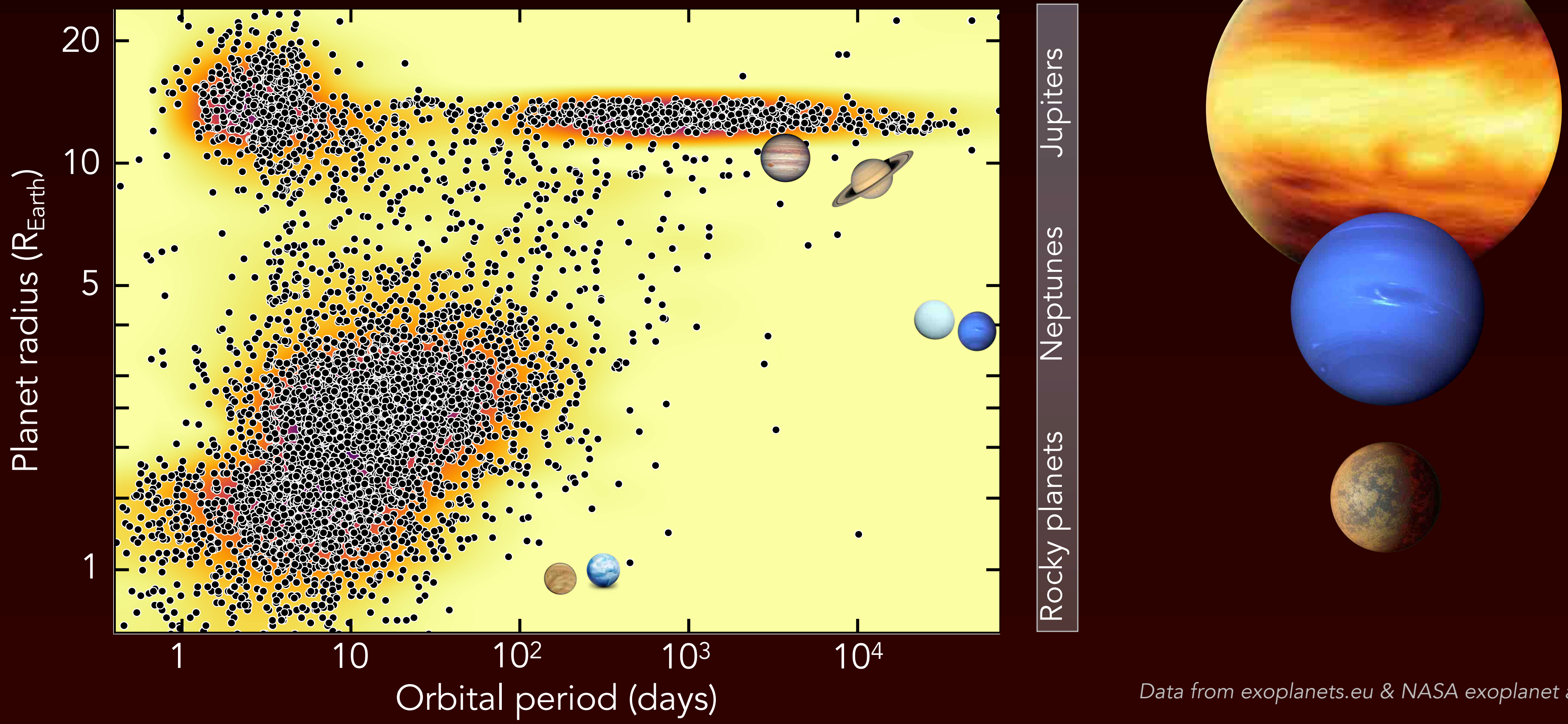
THE (KNOWN) EXOPLANET POPULATION

~ 5600 exoplanets in Jan. 2024



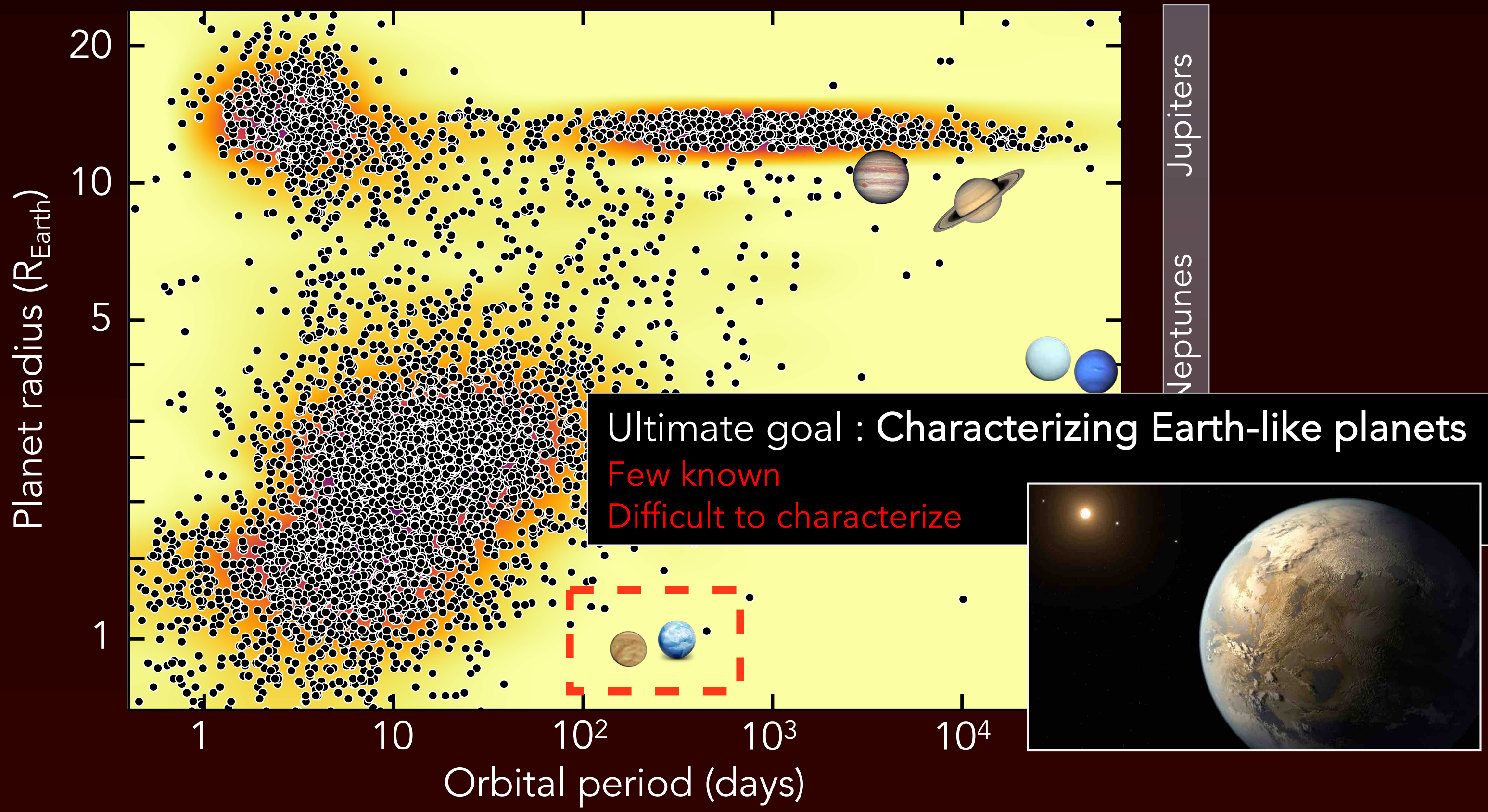
Credit: Eyes on Exoplanet (NASA)

A DIVERSE POPULATION



Data from exoplanets.eu & NASA exoplanet archive

A DIVERSE POPULATION

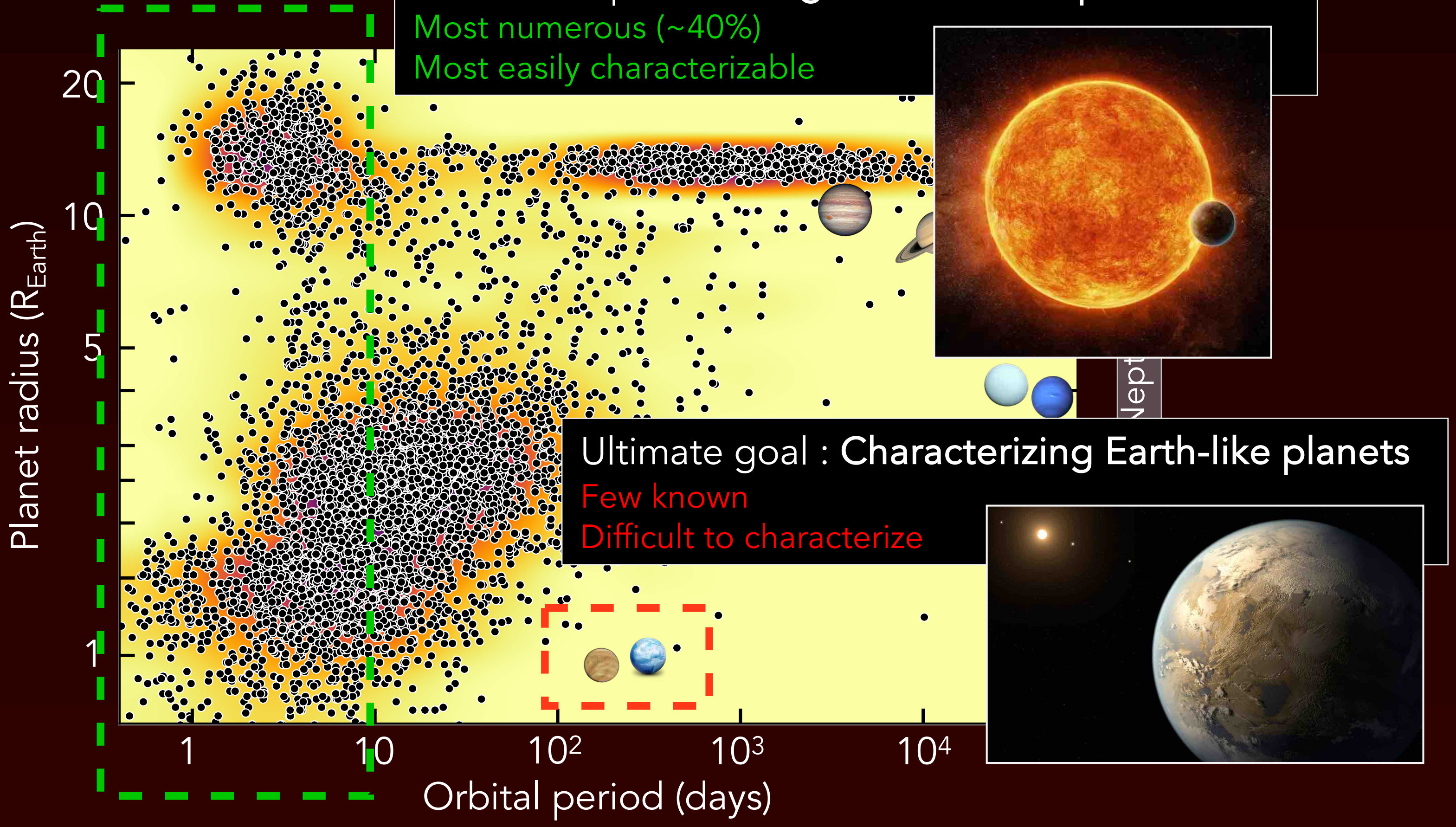


Ultimate goal : **Characterizing Earth-like planets**

Few known

Difficult to characterize

A DIVERSE POPULATION



A useful step : **Focusing on "close-in" planets**

Most numerous (~40%)

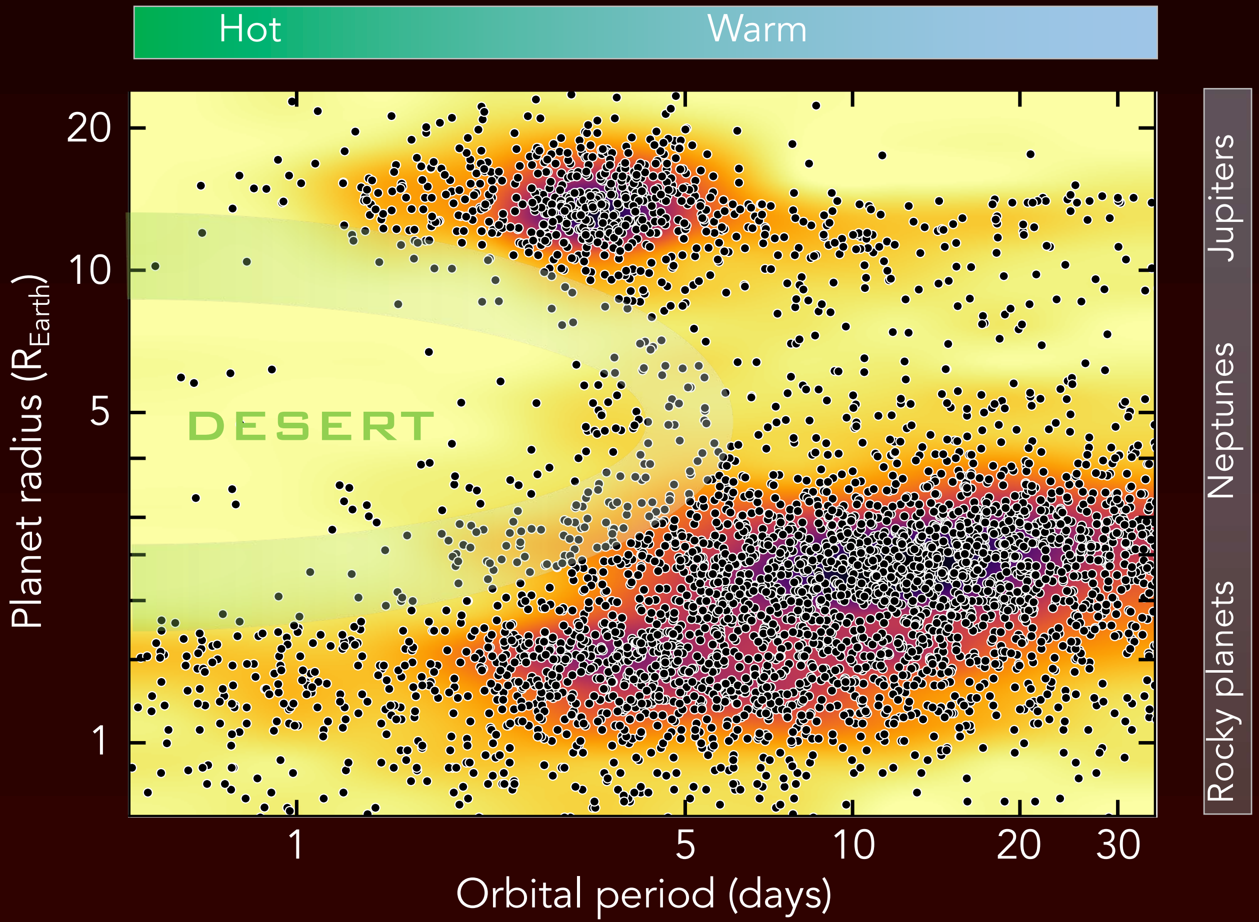
Most easily characterizable

Ultimate goal : **Characterizing Earth-like planets**

Few known

Difficult to characterize

CLOSE-IN PLANETS



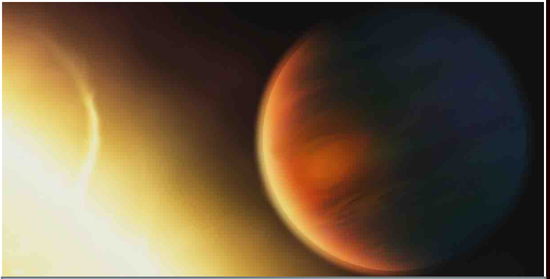
The Neptunian desert

e.g. Lecavelier des Etangs 2007, Penz+2008, Davis & Wheatley 2009, Ehrenreich & Desert 2011, Beaugé & Nesvorny 2013, Lundkvist+2016, Mazeh+2016

Marker of formation and evolution processes

ORIGINS OF THE DESERT ?

e.g. Lopez+2012, Jin+2014, Kurokawa+2014, Owen+2017

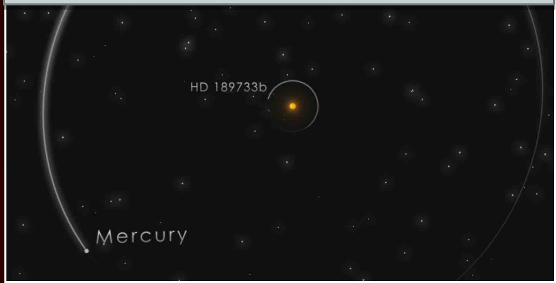


Atmospheric escape traced by **mass loss**

Relative roles ?

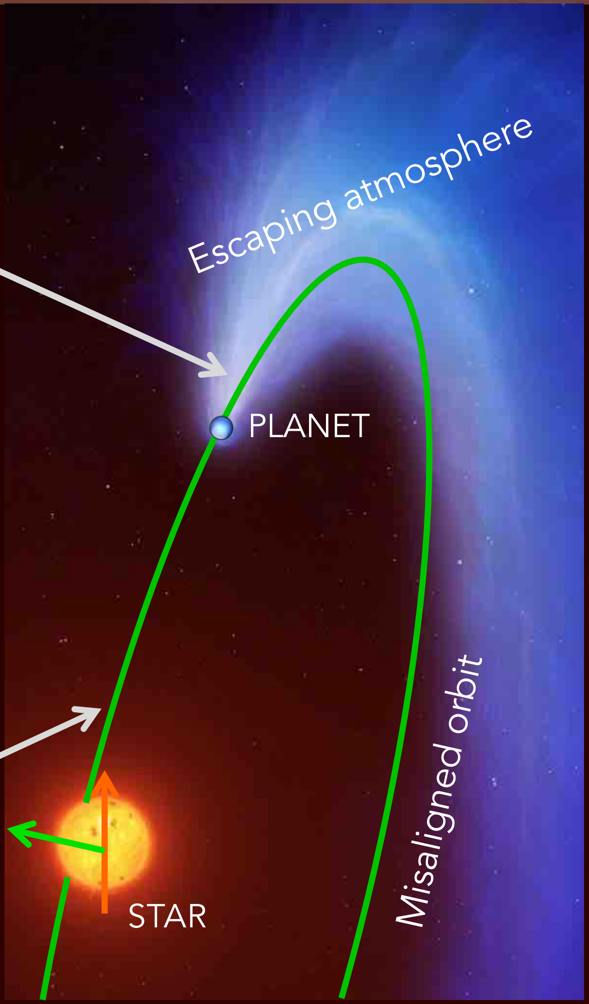
Not enough data

Migration traced by **orbital architecture**



e.g. Mazeh+2016, Bourrier+2018

See review by Owen+2018

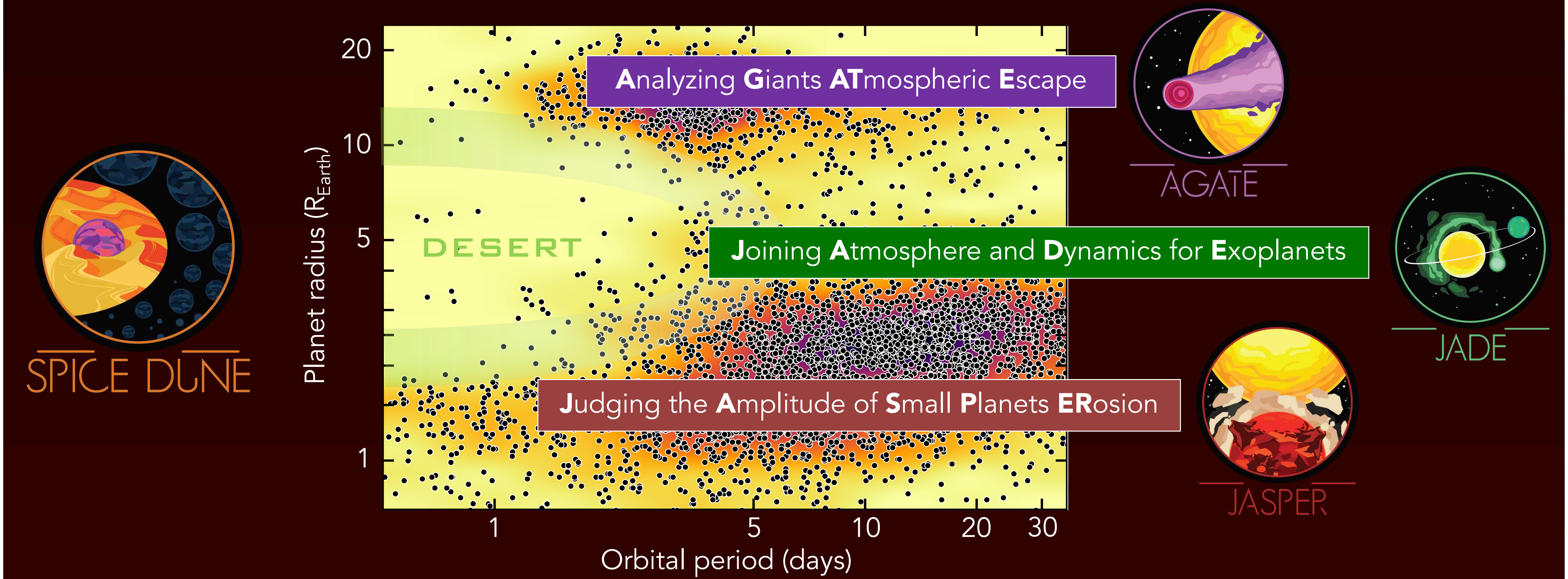


Credit: Mark Garlick/University of Warwick

SPECTRO PHOTOMETRIC INQUIRY OF CLOSE-IN EXOPLANETS AROUND THE DESERT TO UNDERSTAND THEIR NATURE AND EVOLUTION

Objectives: Understanding the origins of the desert to unveil the history of close-in planets

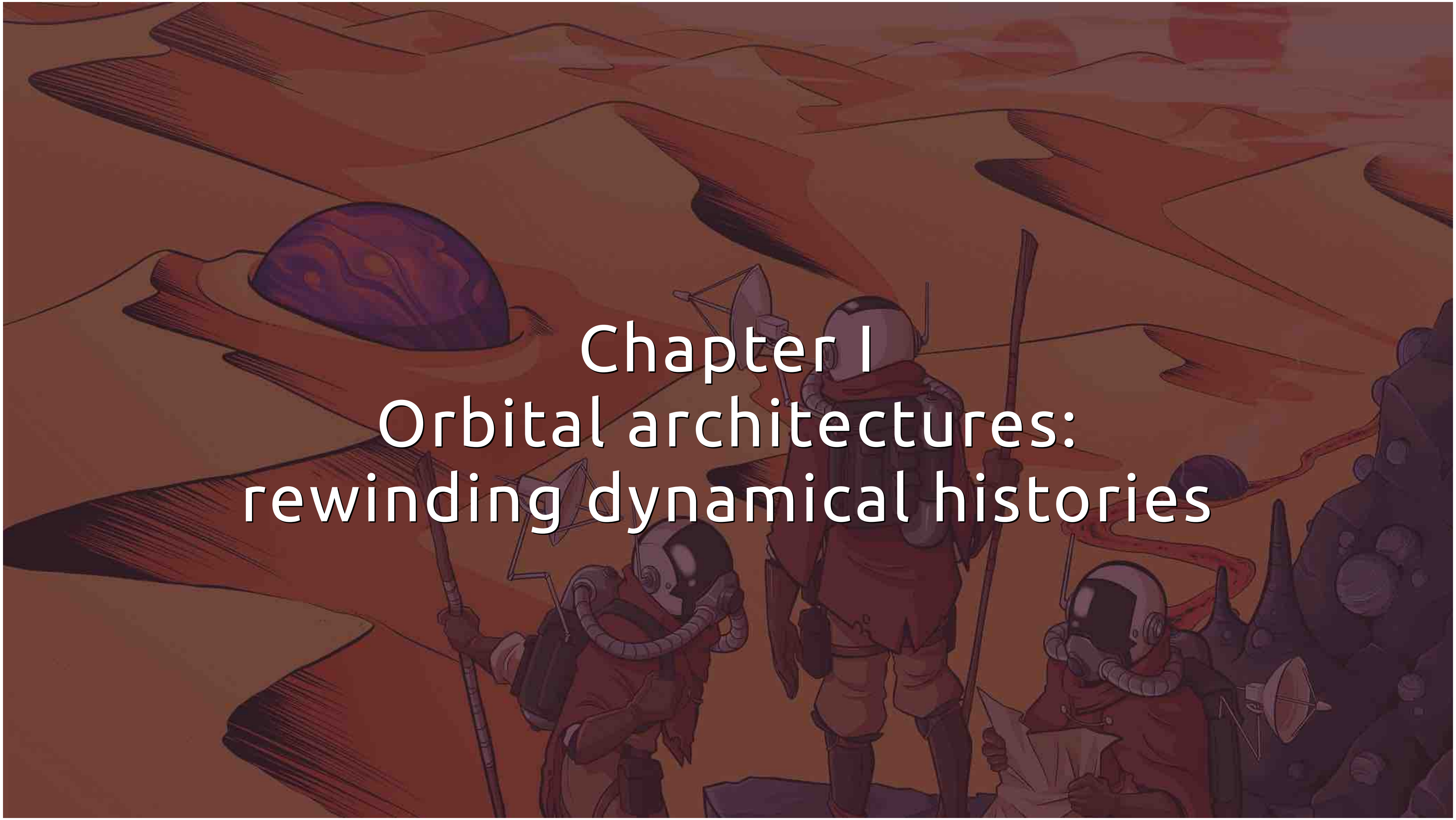
Approach: Gathering mass loss and architecture measurements to inform atmospheric and evolutionary models



Analyzing **G**iants **AT**mospheric **E**scape

Joining **A**tmosphere and **D**ynamics for **E**xoplanets

Judging the **A**mplitude of **S**mall **P**lanets **ER**osion



Chapter I

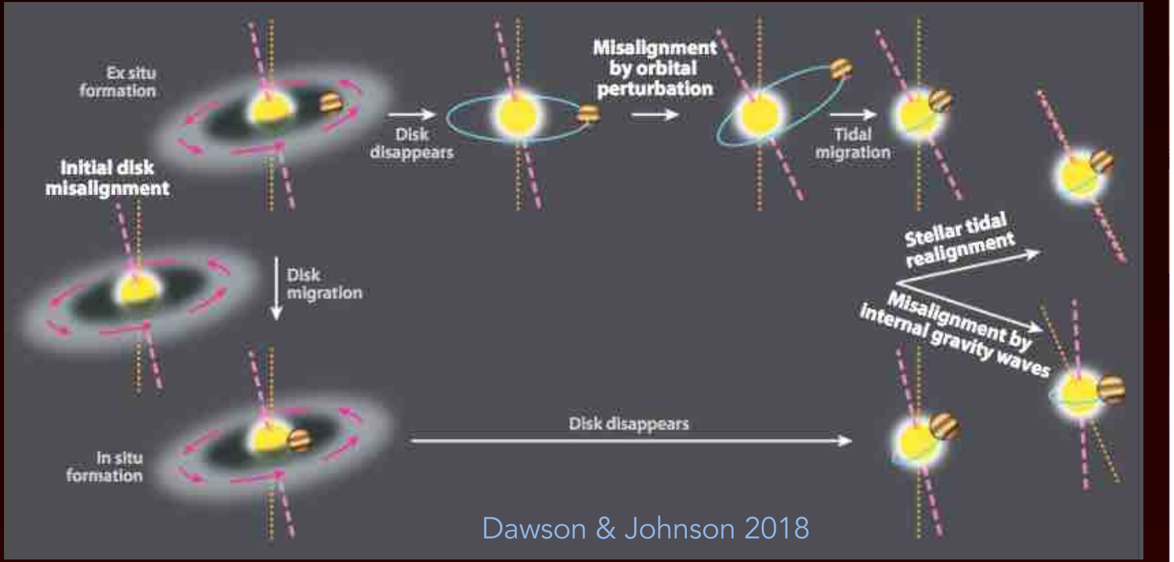
Orbital architectures: rewinding dynamical histories

DYNAMICAL HISTORIES

Alignment inherited from gas cloud collapse

(Possible) moderate primordial misalignment

- From the protoplanetary disk (Batygin 2012, Lai 2014)
- From the star
    - chaotic formation (Bate+2010, Fielding+2015)
    - internal gravity waves (Rogers+2012)
    - magnetic torques (Lai+2011)
    - gravitational torques (Tremaine 1991, Storch+2014)



Dawson & Johnson 2018

Evolution of orbital architecture via two main migration processes

- Primordial orientation maintained by disk-driven migration (Lin+1996, Baruteau+2016)
- Primordial orientation lost and large misalignment induced by high-eccentricity migration
    - planet–planet scattering (Ford+2008, Nagasawa+2008)
    - Kozai-lidov migration (Fabrycky+2007, Naoz+2011)
    - secular chaos (Wu+Lithwick 2011)

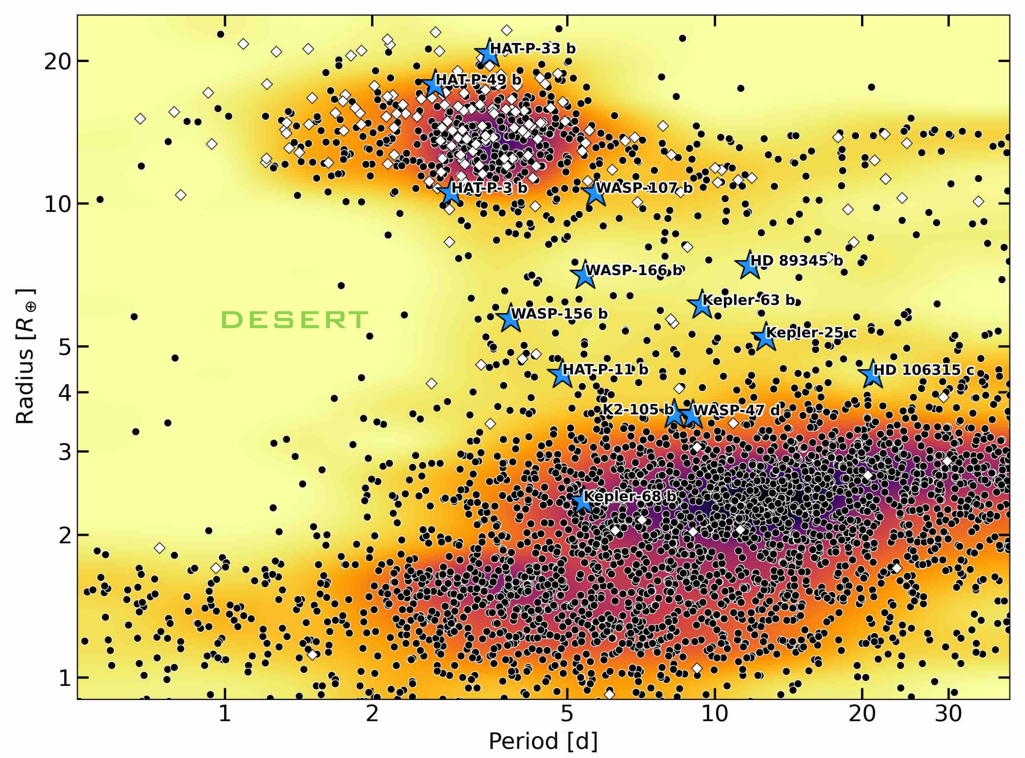
Variety of present-day orbital architectures and spin-orbit angles

DREAM I. ORBITAL ARCHITECTURE ORRERY

The **D**esert- **R**im **E**xoplanets **A**tmosphere and **M**igration program

Survey of 14 transiting planets at the borders of the desert with HARPS, HARPS-N, CARMENES

Homogeneous analyses to measure spin-orbit angles and atmospheric signatures

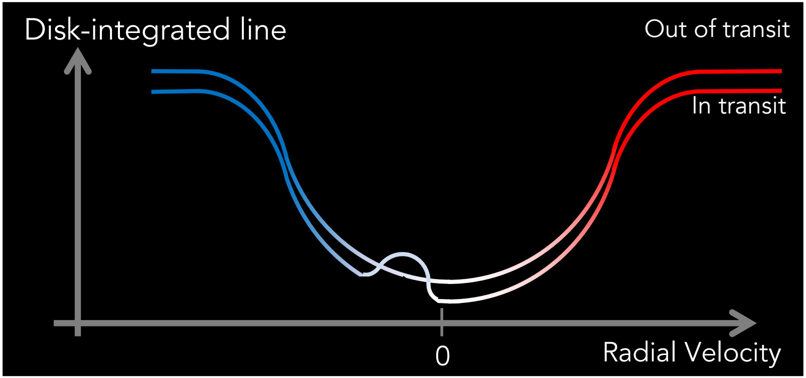


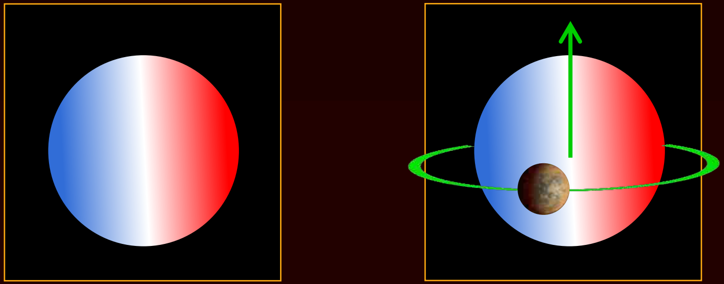
DREAM I (Bourrier+2023)

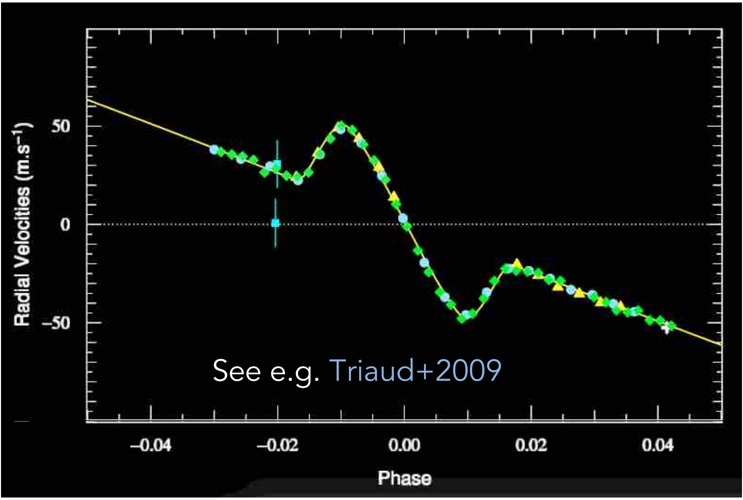
Relative roles of disk-driven and late migration in shaping the desert ?

Are Neptune-size planets undergoing a different dynamical evolution ?

RM EFFECT







See e.g. Triaud+2009

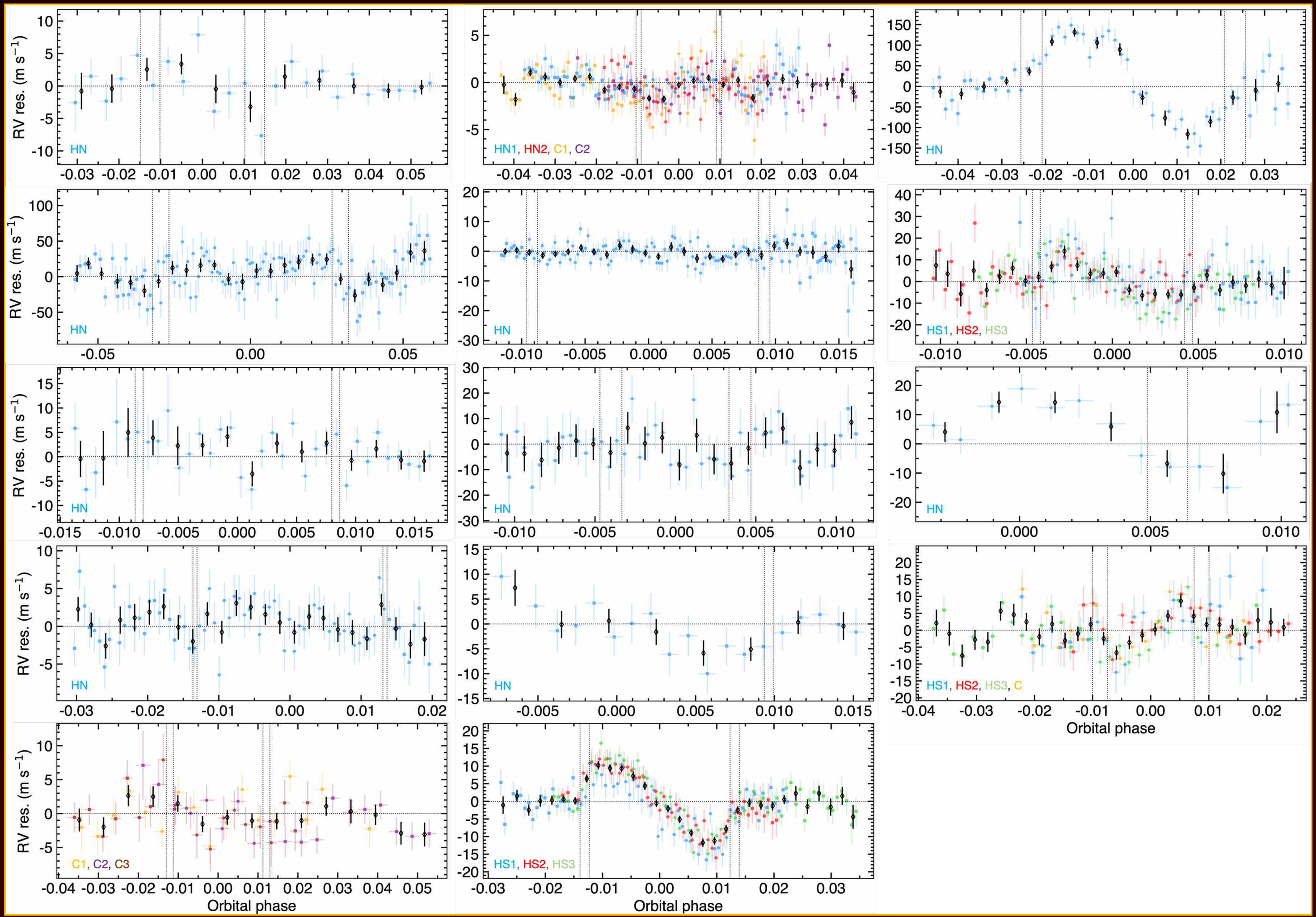
Velocimetric RM

Merges star + planet information into a single anomalous measurement

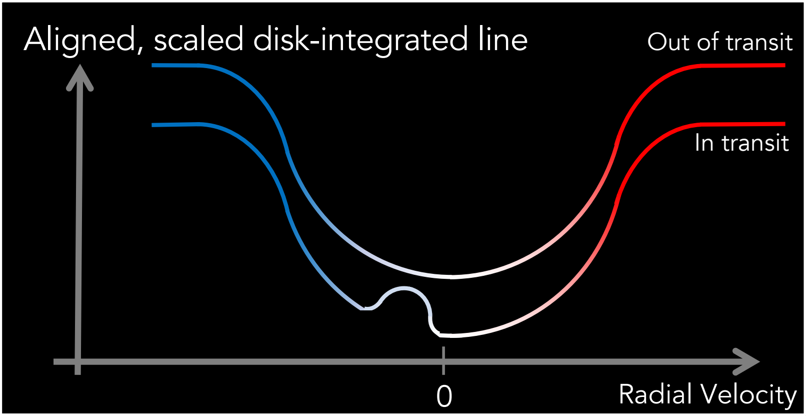
Loss of signal (favors large planets and fast rotators) and possible biases

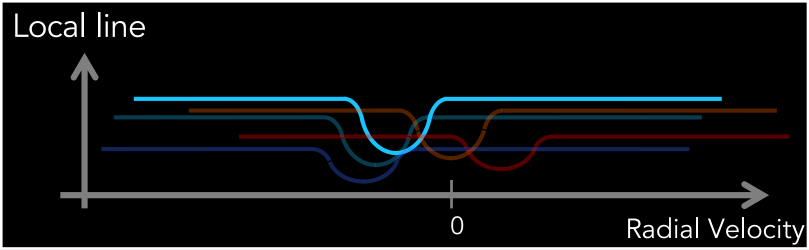
See e.g. Cegla+2016a

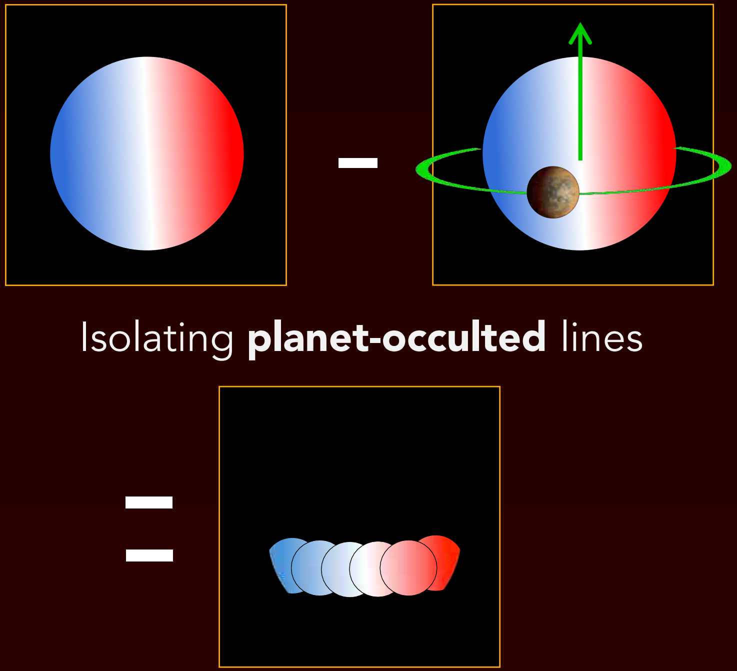
DREAM I. ORBITAL ARCHITECTURE ORRERY



RM EFFECT

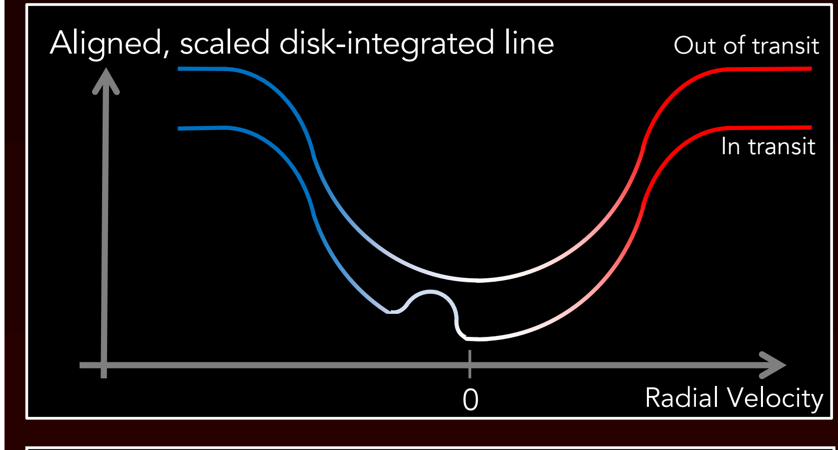

Aligned, scaled disk-integrated line

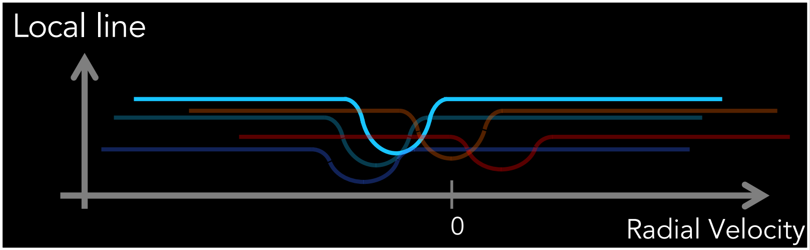

Local line

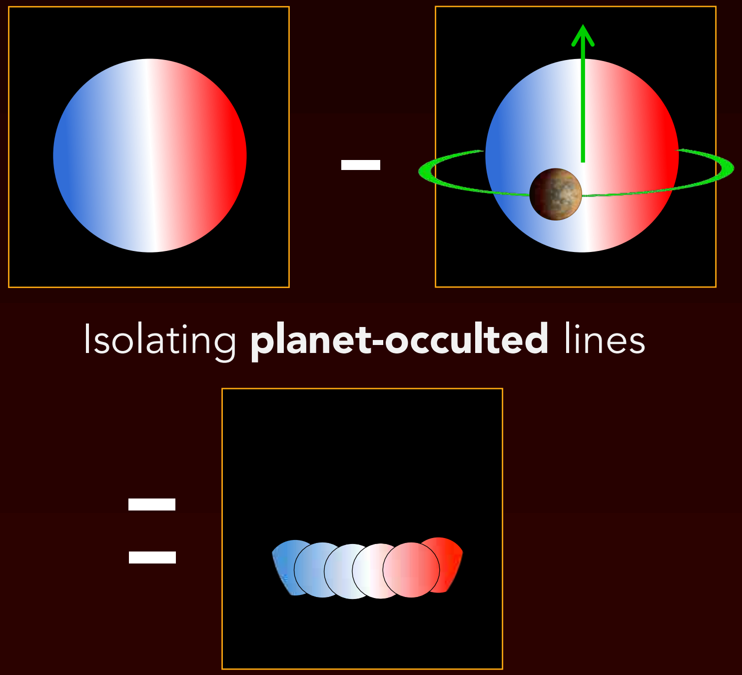


Isolating **planet-occulted** lines

RM EFFECT





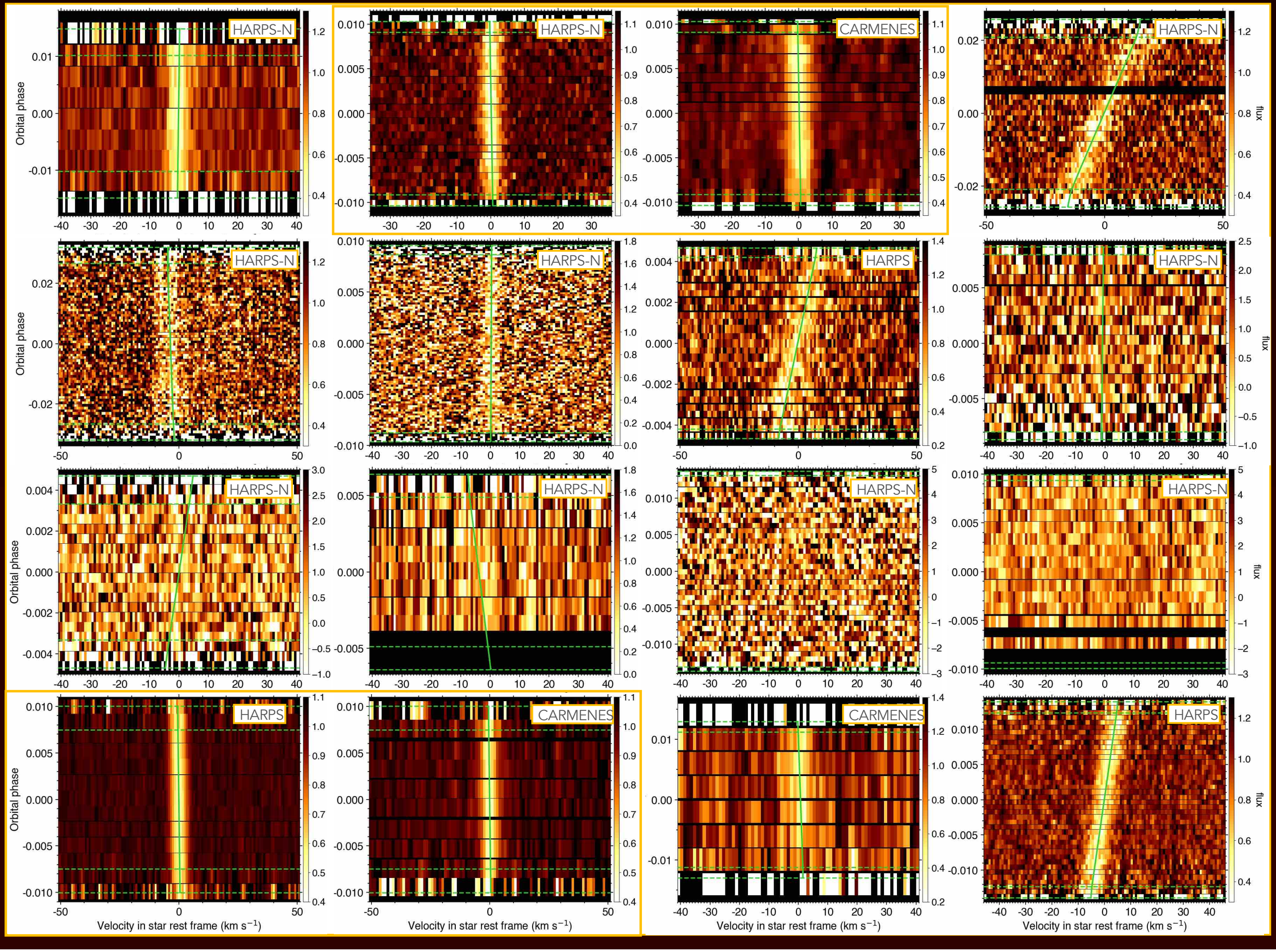


Isolating **planet-occulted** lines

- ➢ **Reloaded RM** (Cegla+2016b): fitting stellar surface RVs when lines detectable in each exposure
- ➢ **RM Revolutions** (Bourrier+2021): fitting all planet-occulted lines together with global model

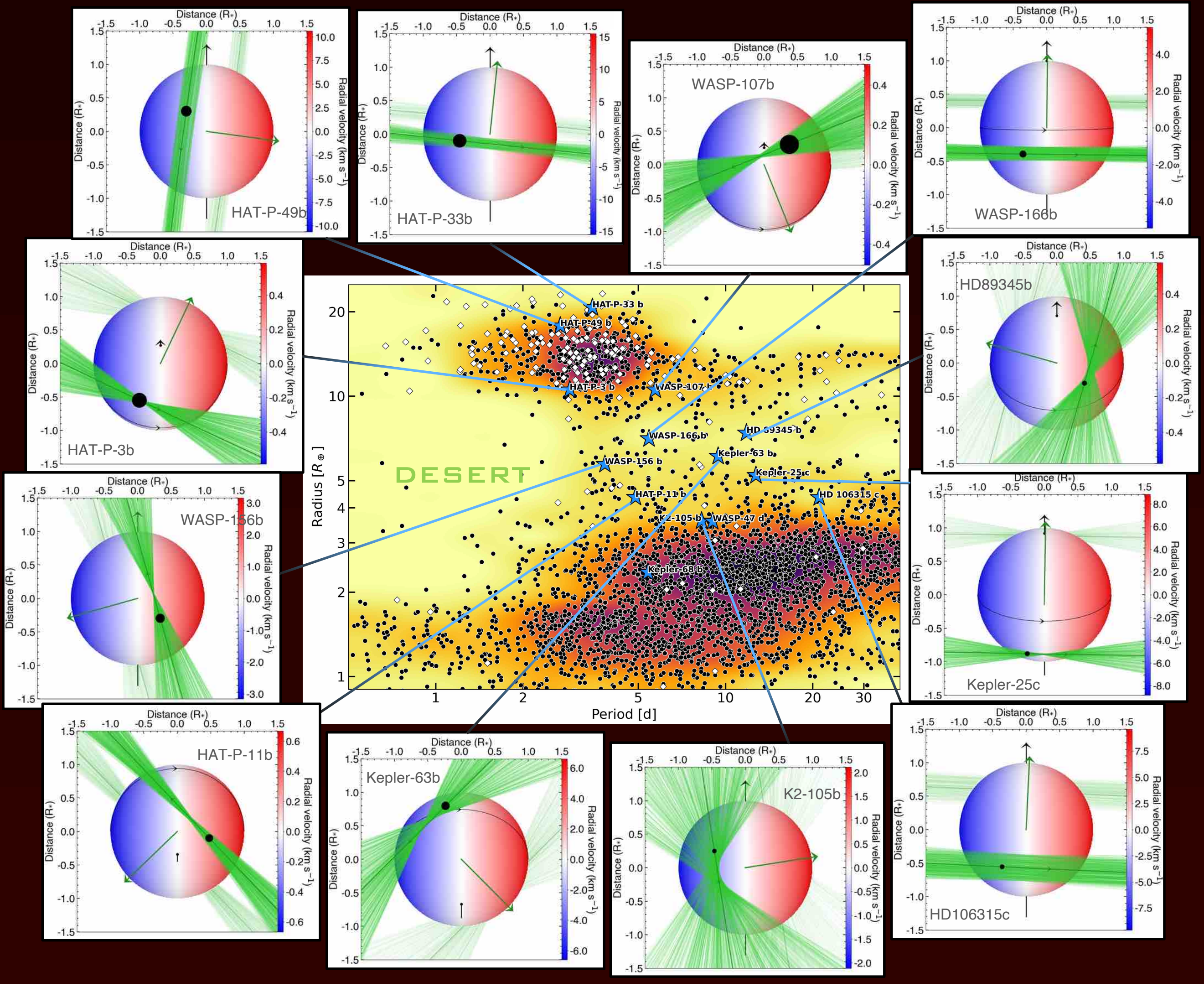
  Exploits as much information as possible
  Accounts for variations in line position & line profile simultaneously
  S/R boost : unlocks signal of small planets (<2 R_E) transiting faint stars

DREAM I. ORBITAL ARCHITECTURE ORRERY



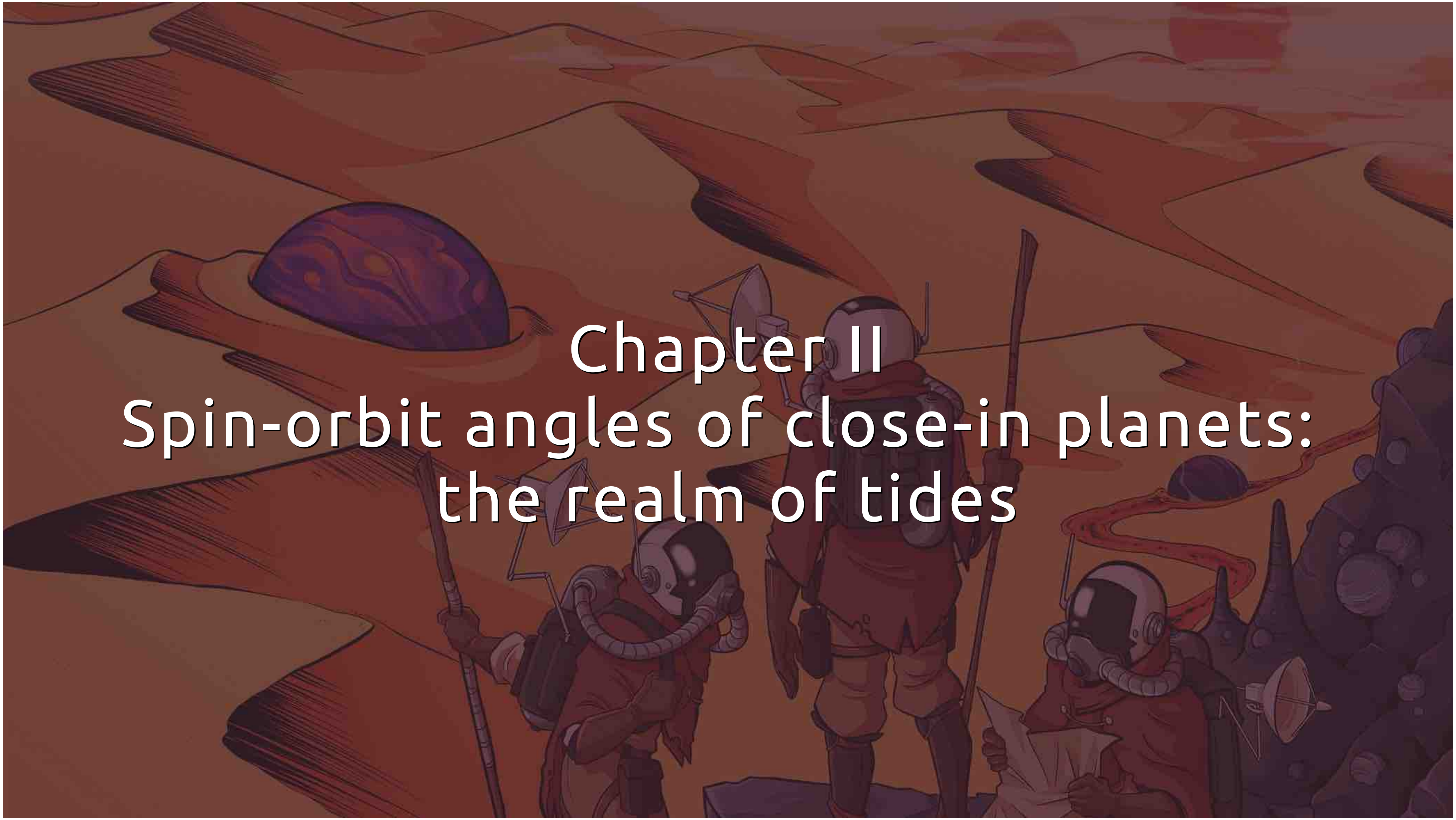
- 12 detections out of 14 planets
- 6 new spin-orbit angles
- 6 refined spin-orbit angles

DREAM I. ORBITAL ARCHITECTURE ORRERY



Substantial addition to known obliquity sample, especially in the Neptune regime

High fraction of polar orbits, supporting the role of late migration in shaping the desert



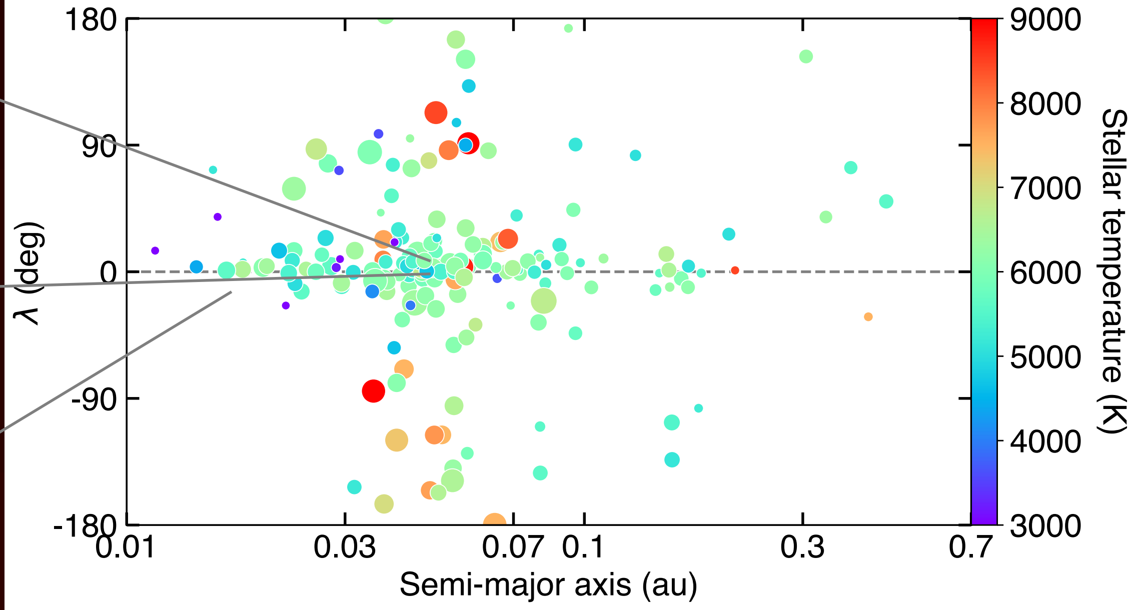
Chapter II

Spin-orbit angles of close-in planets: the realm of tides

SPIN-ORBIT ANGLES OF CLOSE-IN PLANETS

Need to study spin-orbit angles versus star / planet properties to disentangle dynamical processes

Possible trends with parameters that relate to tides raised in the star
see Winn+2010, Hebrard+2011, Triaud+2011, Albrecht+2012, Triaud+2018



More massive planets
are more aligned

Planets around cooler
stars are more aligned

Closer-in planets
are more aligned

DREAM II. UNDER THE LENS OF TIDES

DREAM II (Attia+2023)

Re-analysis of sky-projected spin-orbit angle distribution confirms trends with $\mathrm{T}_\star$, $\mathrm{M_p}/\mathrm{M}_\star$, and $\mathrm{a_p}/\mathrm{R}_\star$

Observational bias toward misaligned systems

Need for robust statistical framework to estimate stellar inclination $\mathrm{i}_\star$ and 3D spin-orbit angle ψ (e.g Crida+2014)

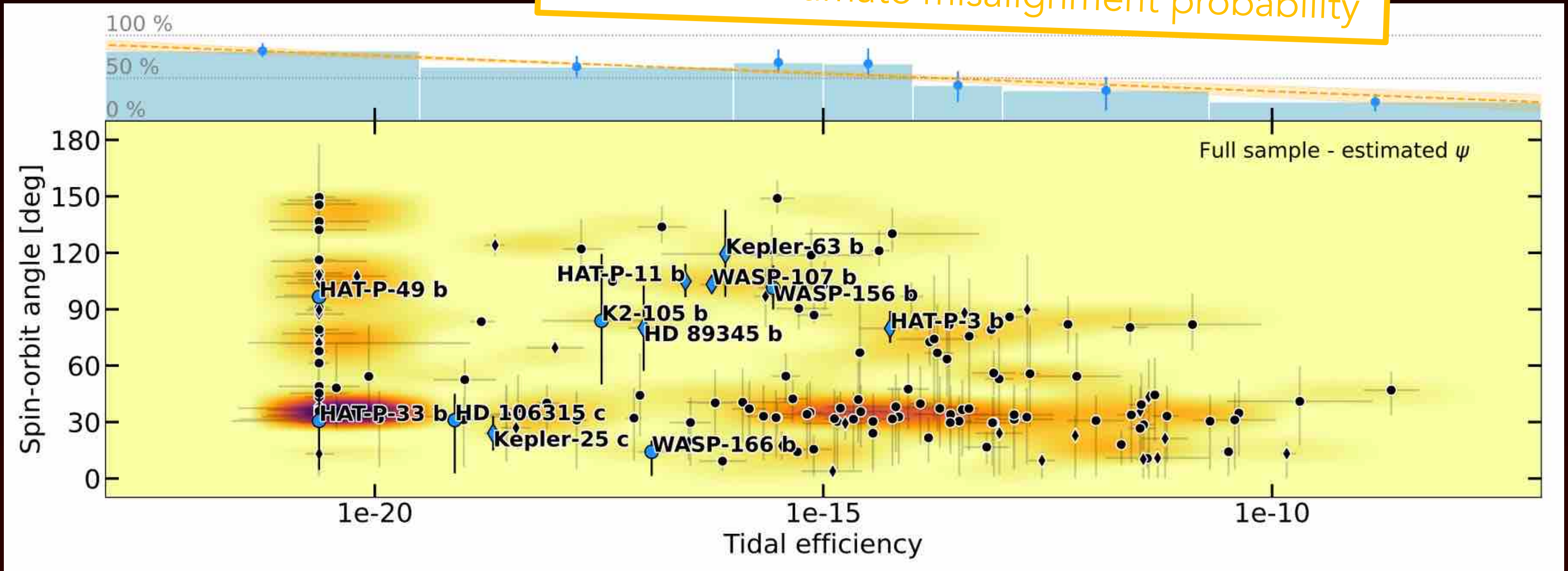
$$\cos\psi = \sin i_\star \sin i_{\mathrm{p}} \cos\lambda + \cos i_\star \cos i_{\mathrm{p}},$$

Need for general tidal efficiency parameter to assess global influence of tides (inspired by Albrecht+2012)

$$\tau \equiv \frac{M_{\mathrm{conv}}}{M_\star}\left(\frac{M_{\mathrm{p}}}{M_\star}\right)^2\left(\frac{a}{R_\star}\right)^{-6}$$

DREAM II. UNDER THE LENS OF TIDES

Formula to estimate misalignment probability

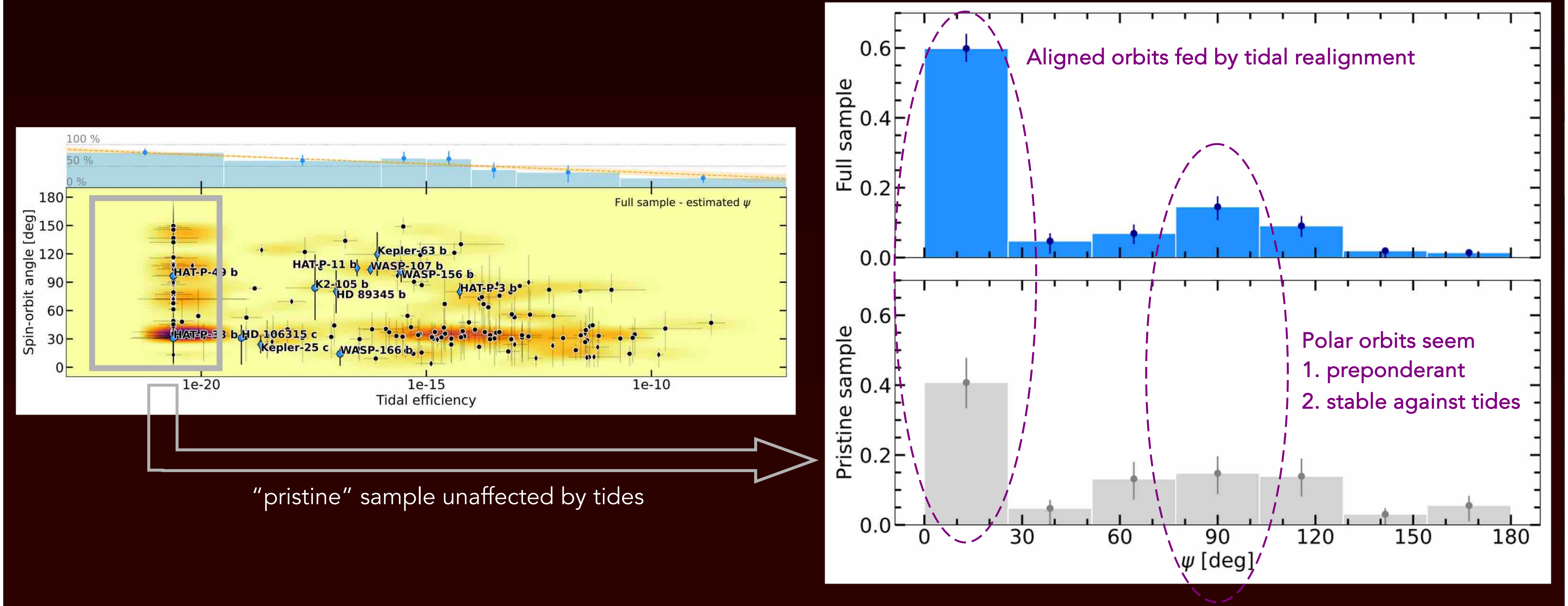


Unbiased sample of ~200 close-in planet 3D spin-orbit angles

Fraction of misaligned systems correlates linearly with tidal efficiency factor

Systems with negligible efficiency trace processes unaltered by tidal interactions

DREAM II. UNDER THE LENS OF TIDES

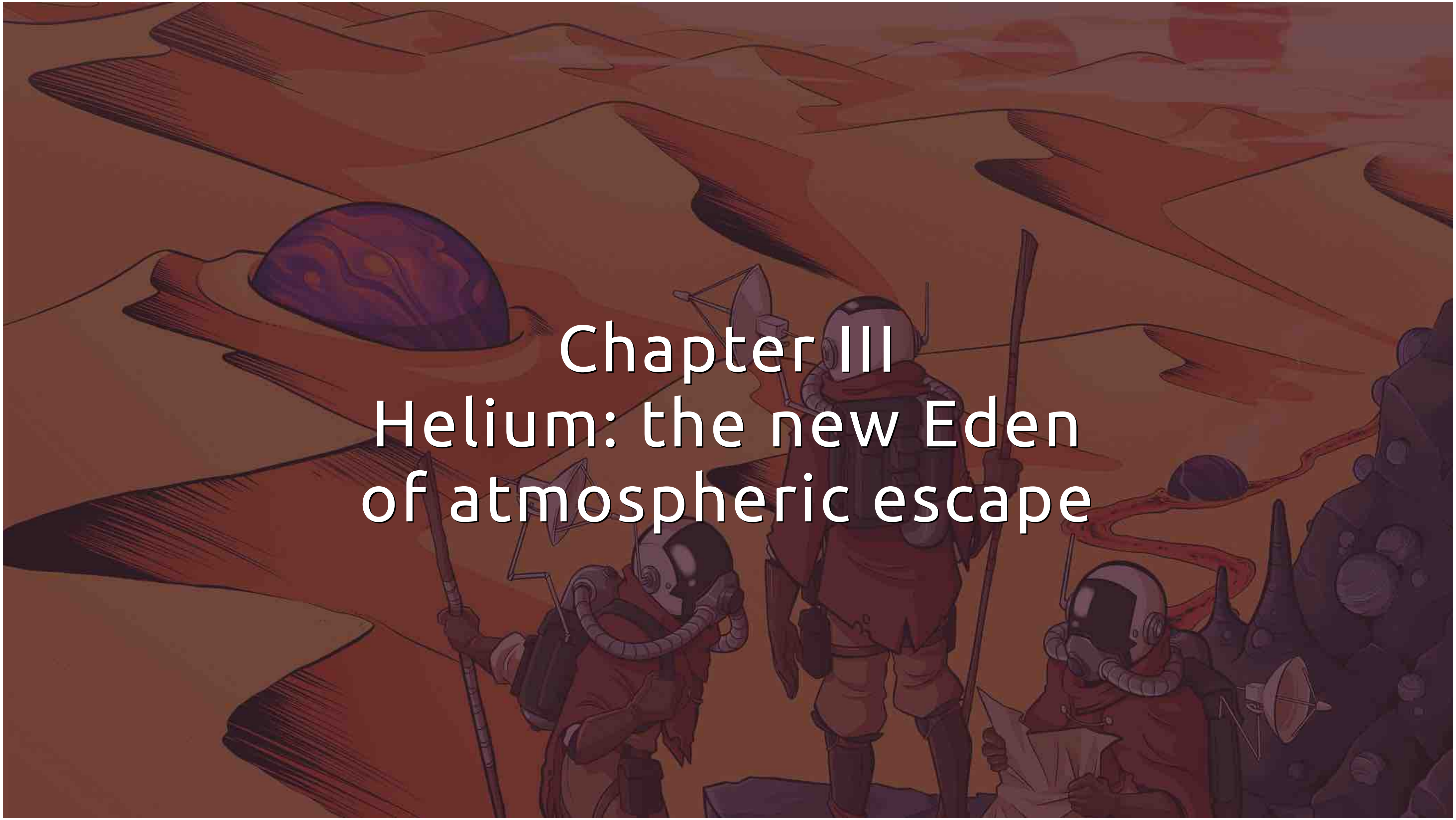


Aligned orbits fed by tidal realignment

Polar orbits seem
1. preponderant
2. stable against tides

“pristine” sample unaffected by tides

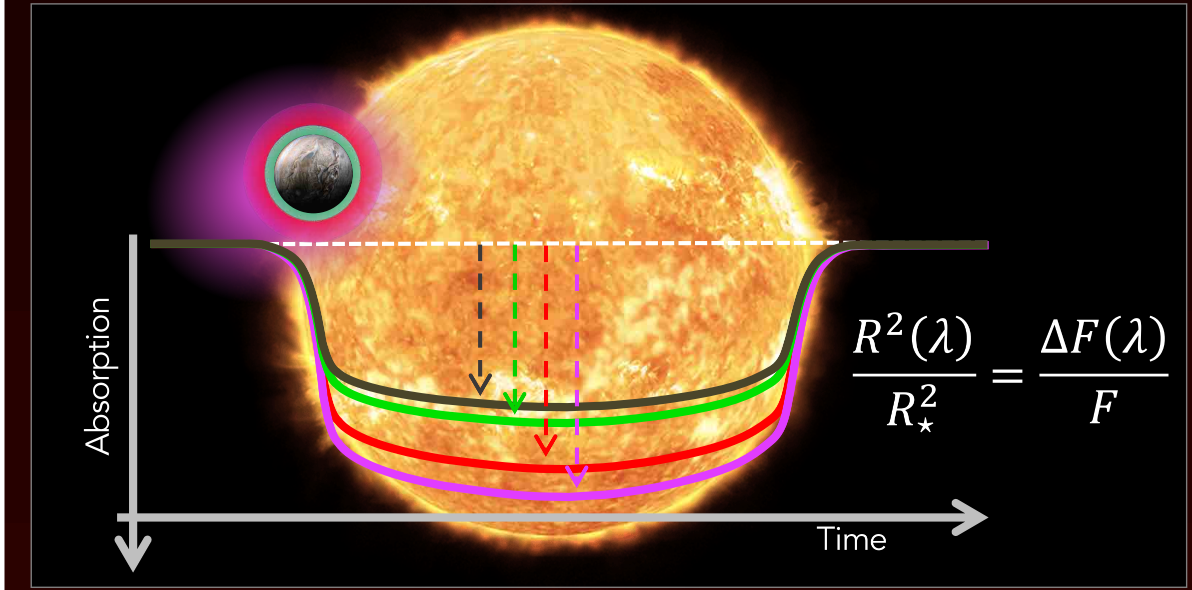
The desert and savannah may be preferentially populated by late dynamical migration.



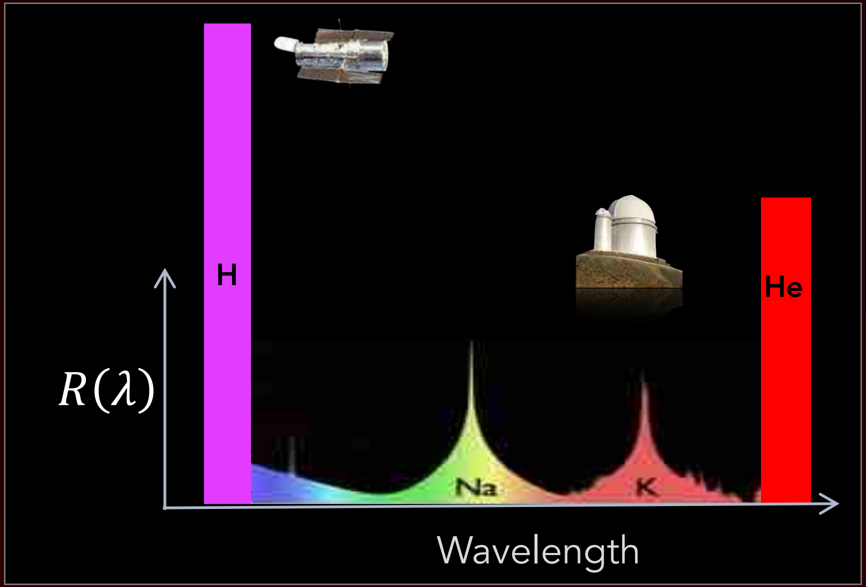
Chapter III

Helium: the new Eden of atmospheric escape

PROBING ESCAPE



$$\frac{R^2(\lambda)}{R_\star^2} = \frac{\Delta F(\lambda)}{F}$$



Neutral hydrogen (FUV)

(Vidal-Madjar+2003, Lecavelier+2012, Ehrenreich+2015, …)

- Probes exosphere
- Absorbed by interstellar medium
- No stellar continuum
- From space only

Metastable helium (near-IR)

(Spake+2018, Allart+2019, Nortmann+2018, …)

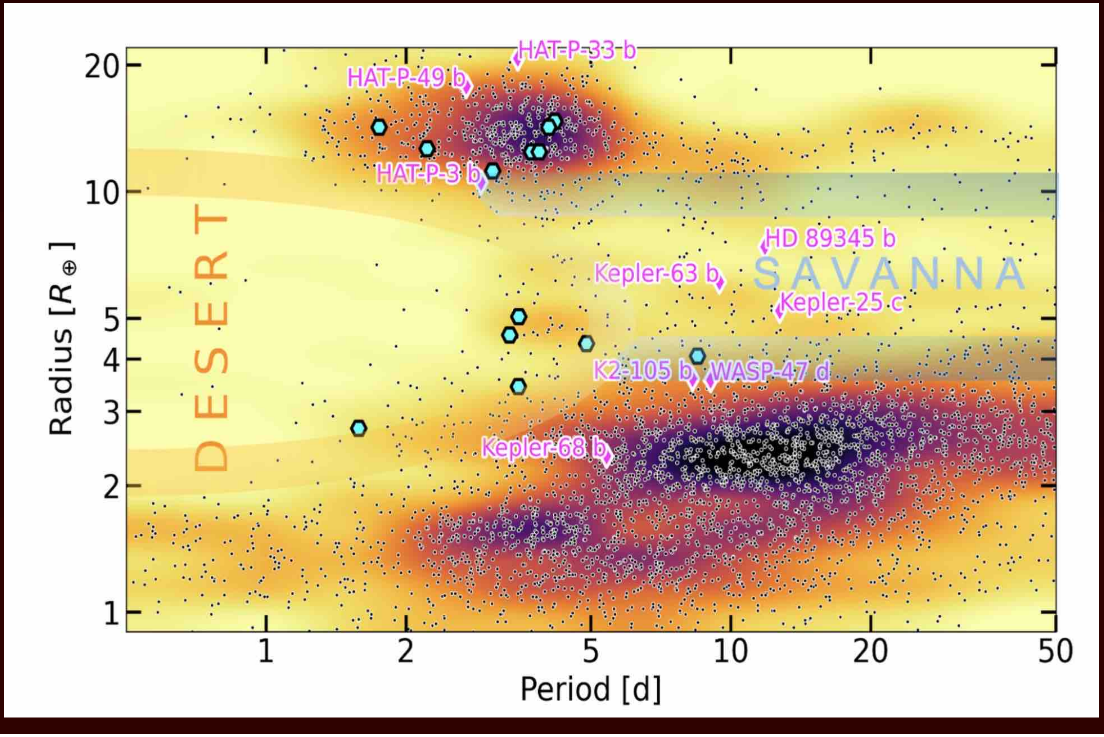
- Probes thermosphere and exosphere
- Not absorbed by interstellar medium
- Bright stellar continuum
- From ground and space

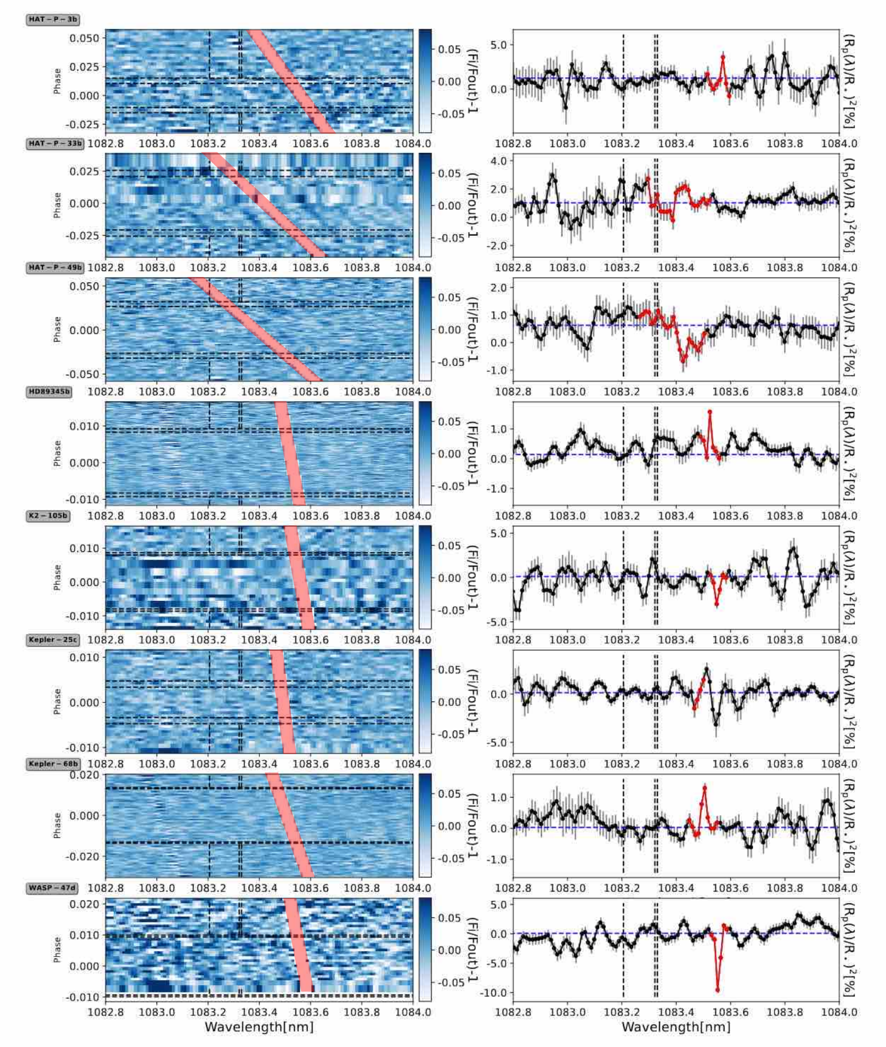
DREAM III. A HELIUM SURVEY IN PLANETS ON THE EDGE

DREAM III (Guilluy+2023)

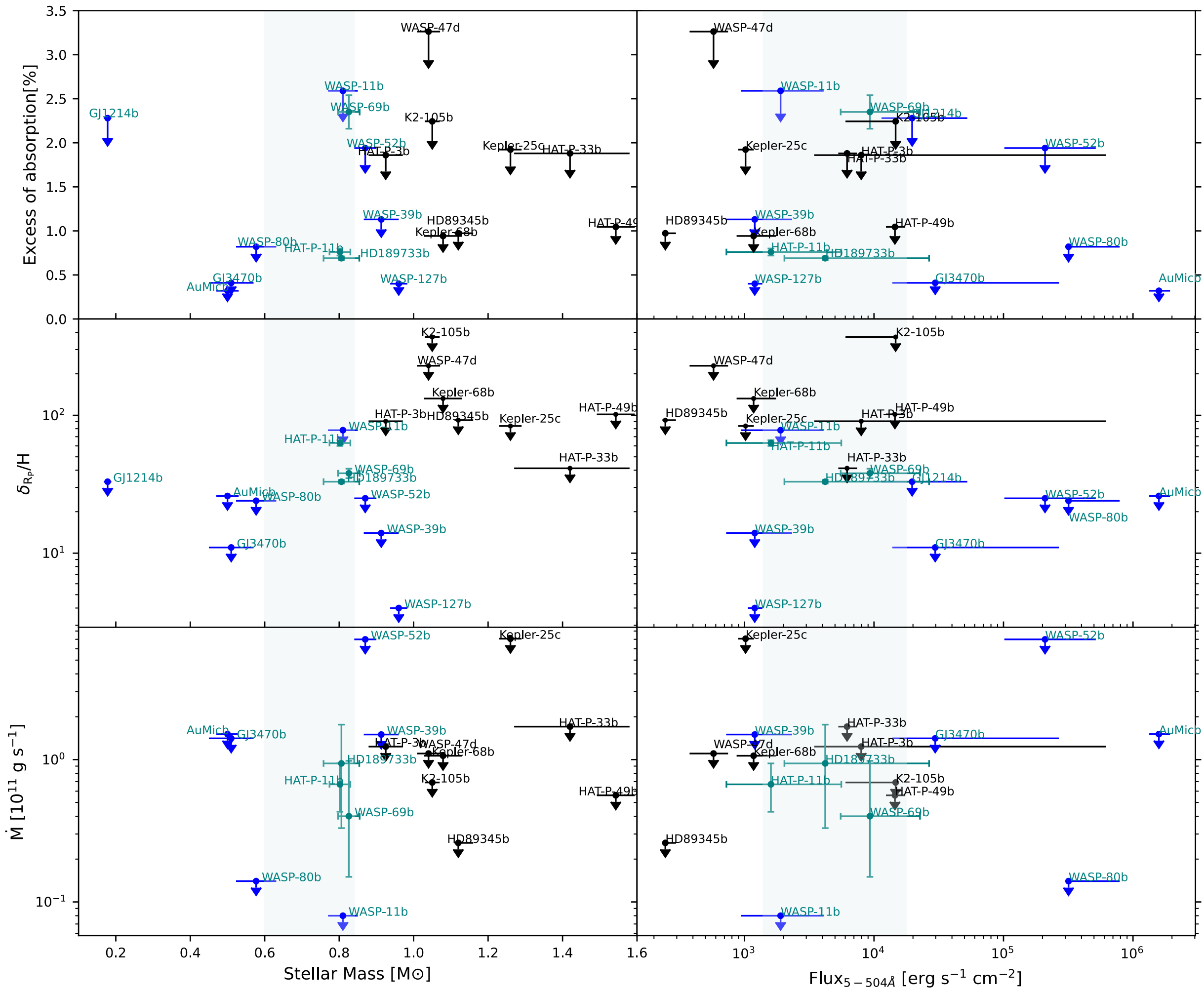
TNG/GIANO transit spectra of DREAM I sample

Same reduction as Allart+2023 sample





DREAM III. A HELIUM SURVEY IN PLANETS ON THE EDGE

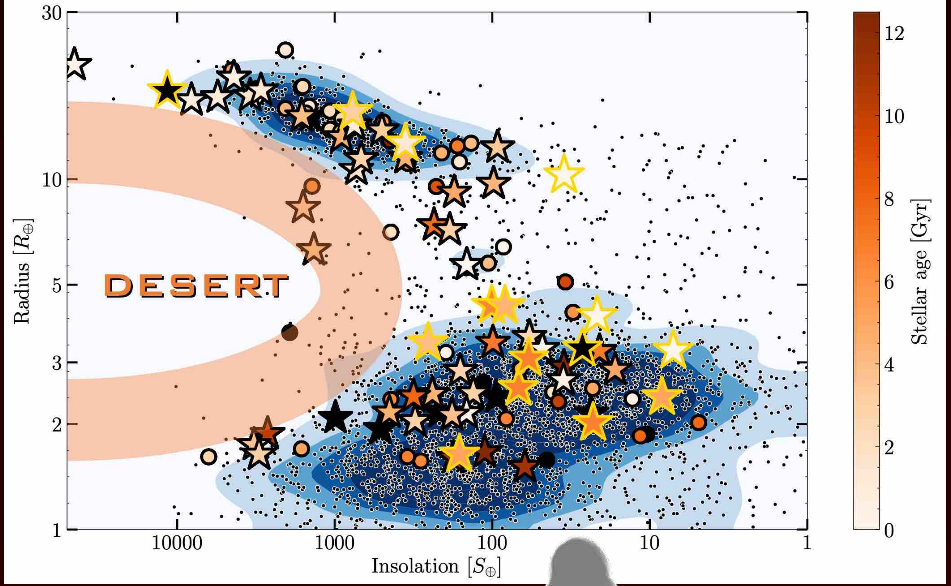


Upper limits on absorption, height, and mass loss

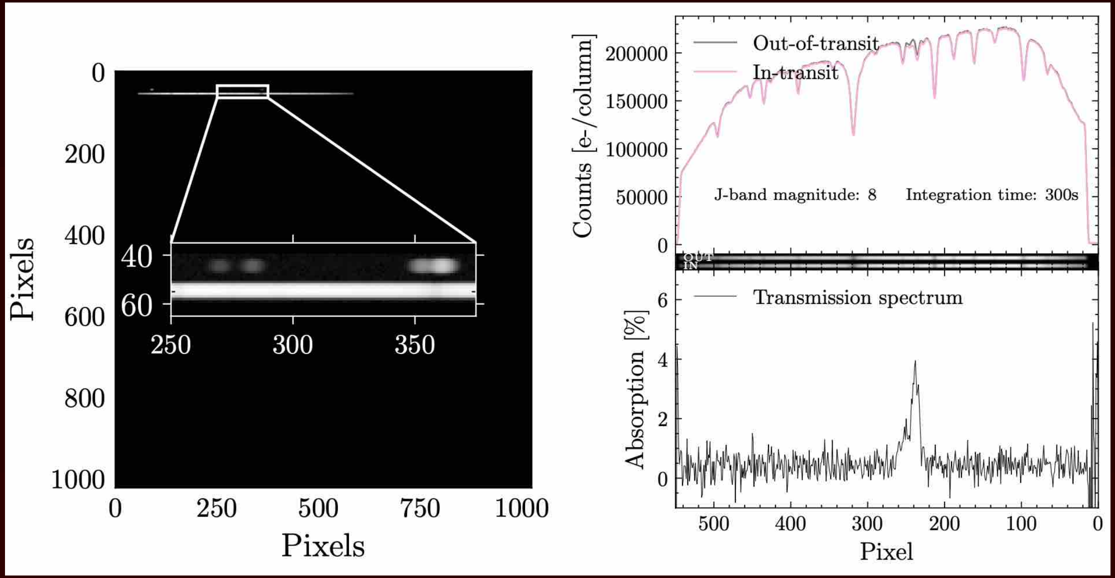
Supports correlation between stellar mass or XUV flux and He absorption, but not mass loss

Complex correlations : need for homogeneous surveys and analyses

NEAR-INFRARED GATHERER OF HELIUM TRANSITS

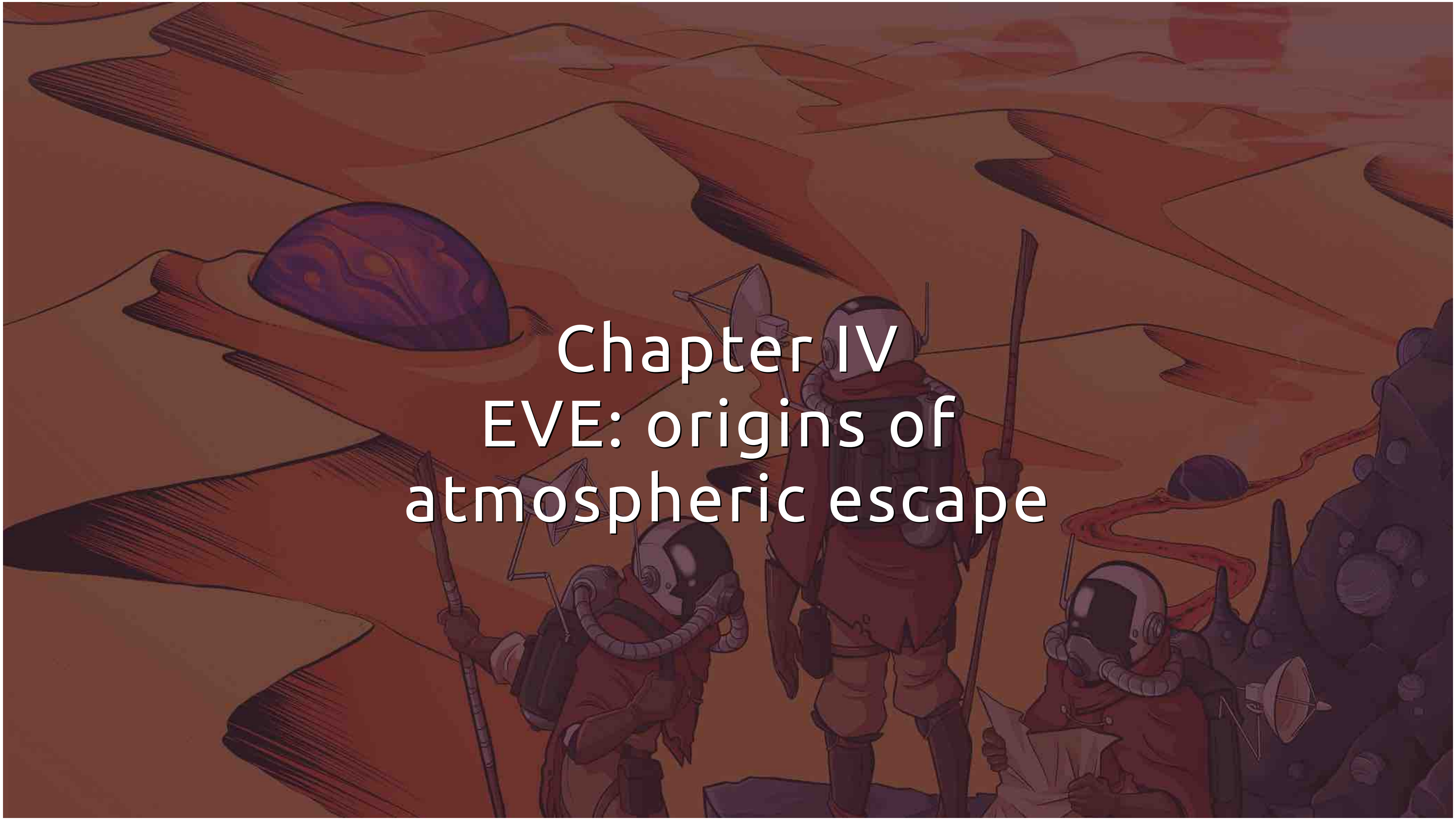


NIGHT: A compact, low-budget, high-resolution spectrograph to survey He in exoplanet systems



Credits: S. Bovay

See Farret Jentink+2023

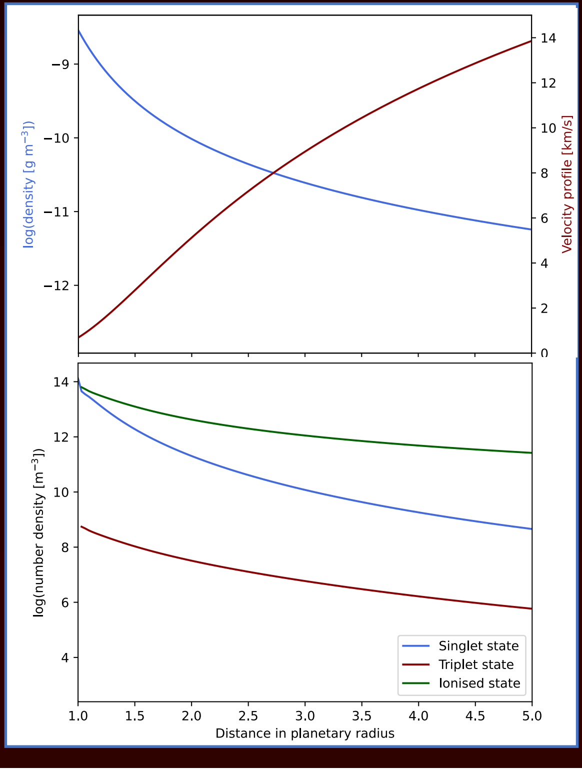


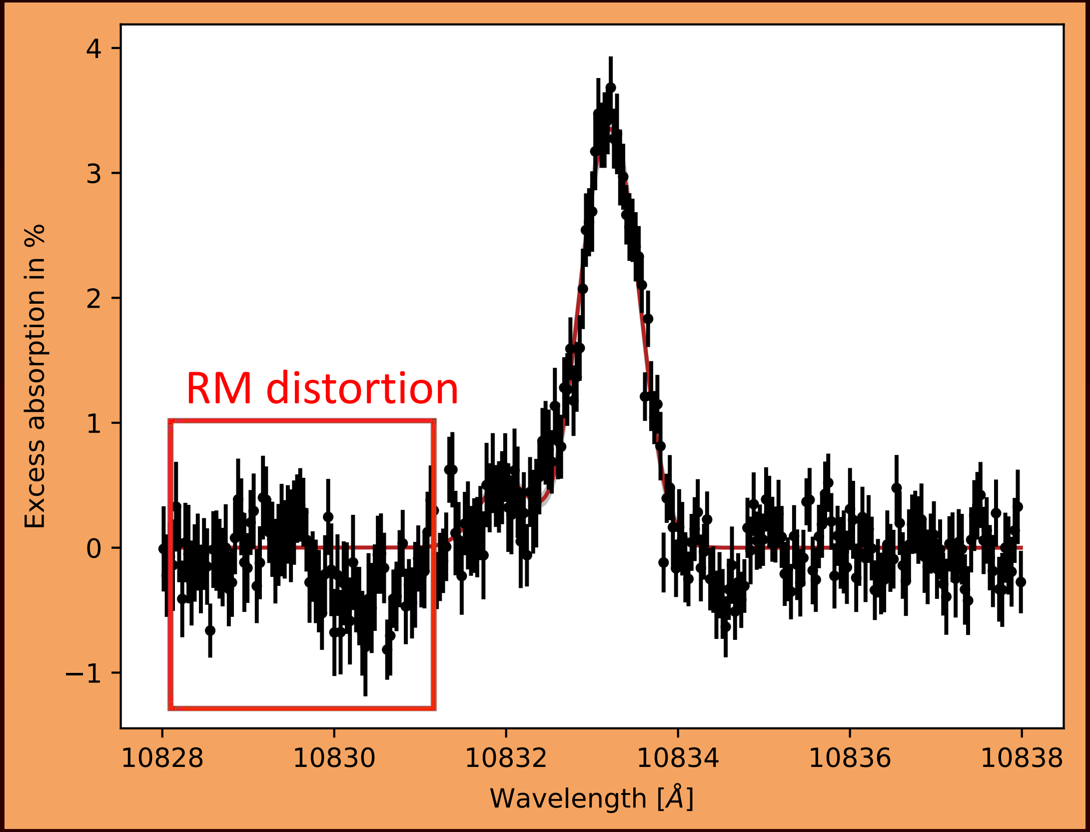
Chapter IV
EVE: origins of atmospheric escape

1D THERMOSPHERE

Use of *p-winds* (Dos-Santos+2022, based on Oklopcic & Hirata 2018) to constrain mass loss

- 1D code
- Parker wind approximation
- H/He chemistry
- Simplified radiative transfer



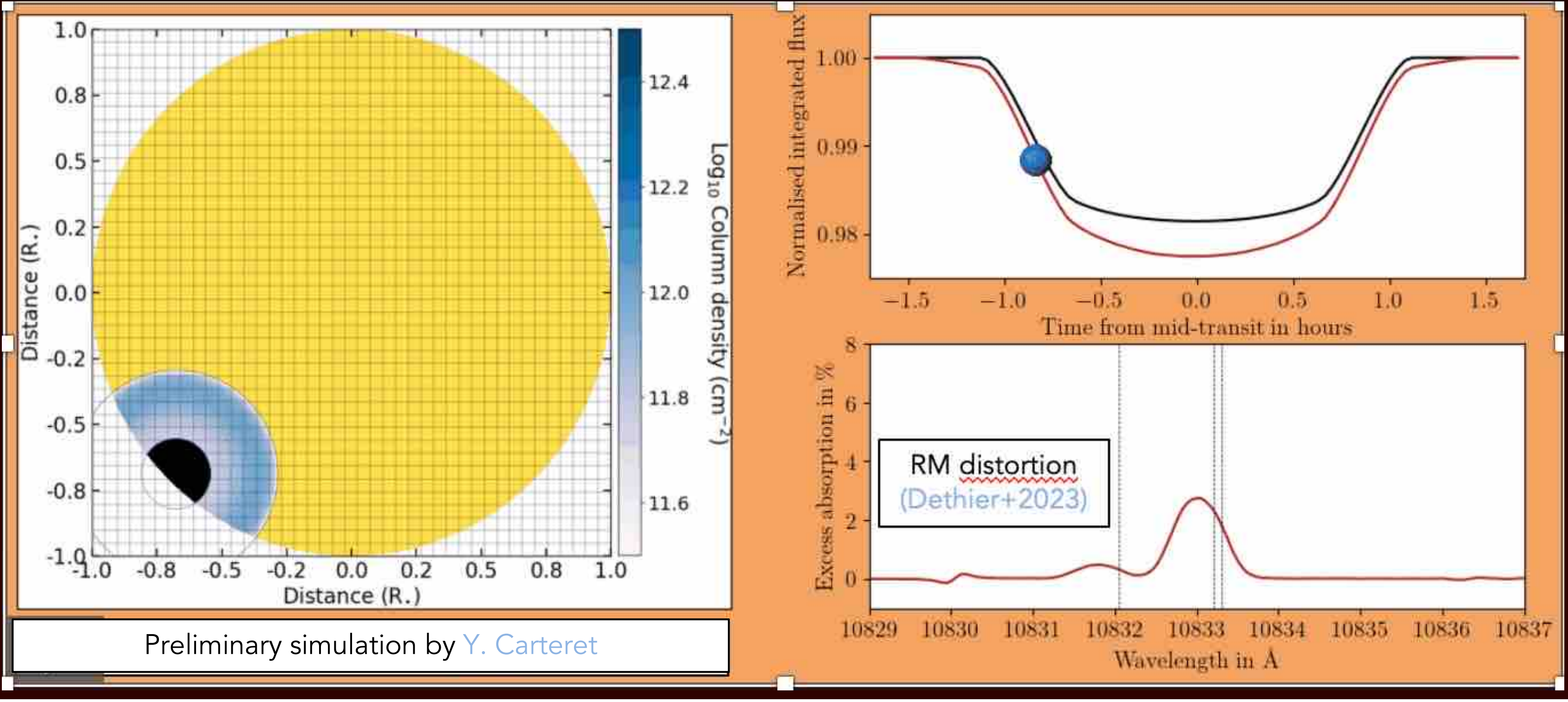


Simulation by Y. Carteret

1D THERMOSPHERE INTO 3D FRAMEWORK

Use of *EVE* (Bourrier+2013, 2016) to constrain mass loss

- 3D code
- Spatially & spectrally-resolved stellar grid
- Thermosphere (1D p-winds profiles)
- Simulates spectra as observed with instruments



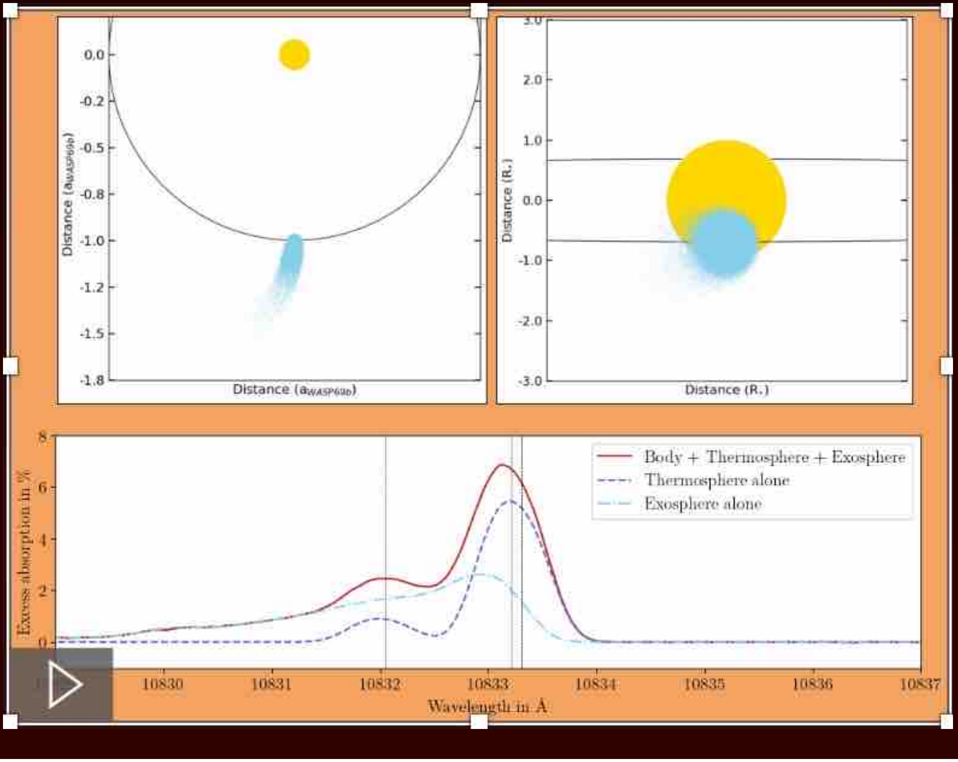
RM distortion (Dethier+2023)

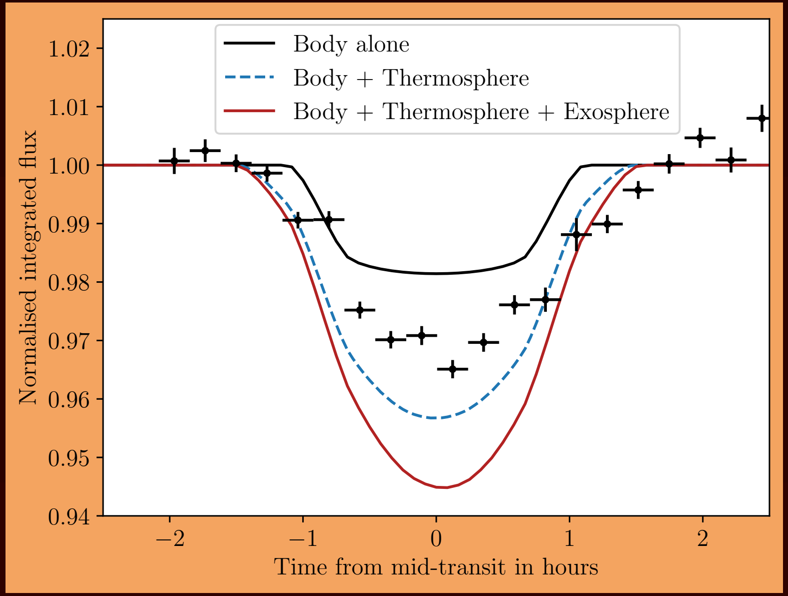
Preliminary simulation by Y. Carteret

1D THERMOSPHERE INTO 3D FRAMEWORK

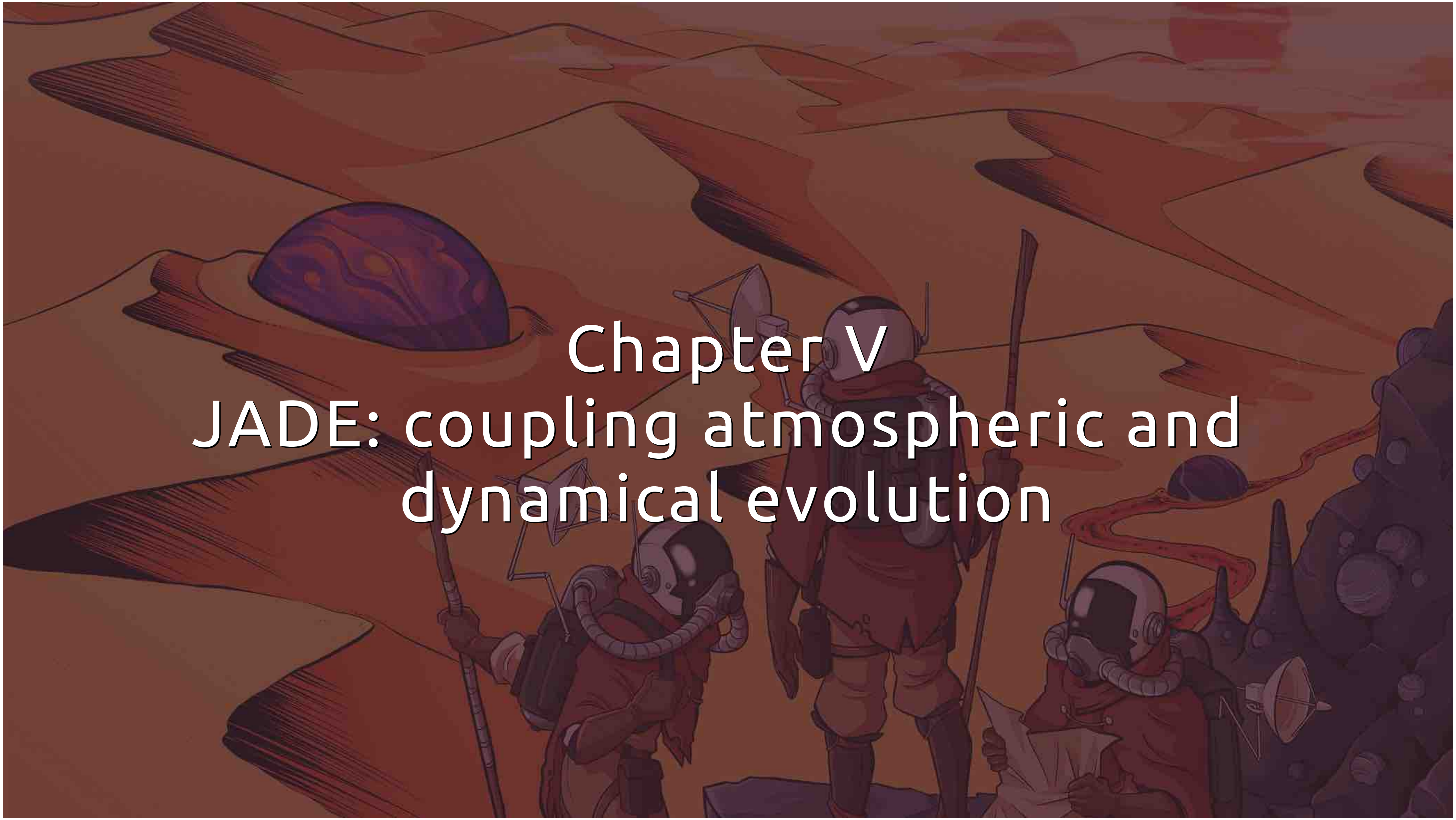
Use of *EVE* (Bourrier+2013, 2016) to constrain mass loss

- 3D code
- Spatially & spectrally-resolved stellar grid
- Thermosphere (1D p-winds profiles) coupled with exosphere (update by Y. Jaziri)
- Simulates spectra as observed with instruments





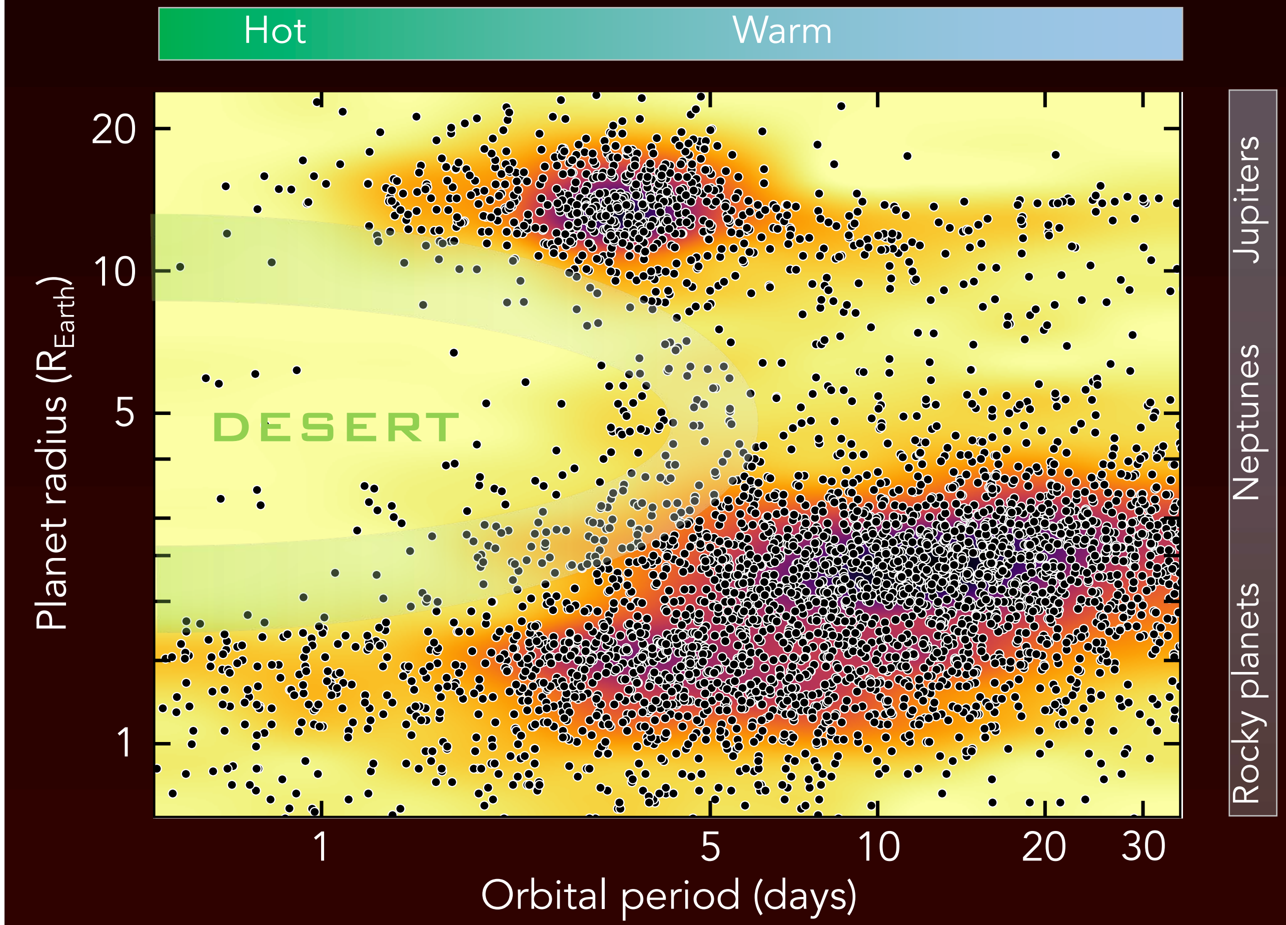
Preliminary simulation by Y. Carteret



Chapter V

JADE: coupling atmospheric and dynamical evolution

ORIGINS OF THE DESERT

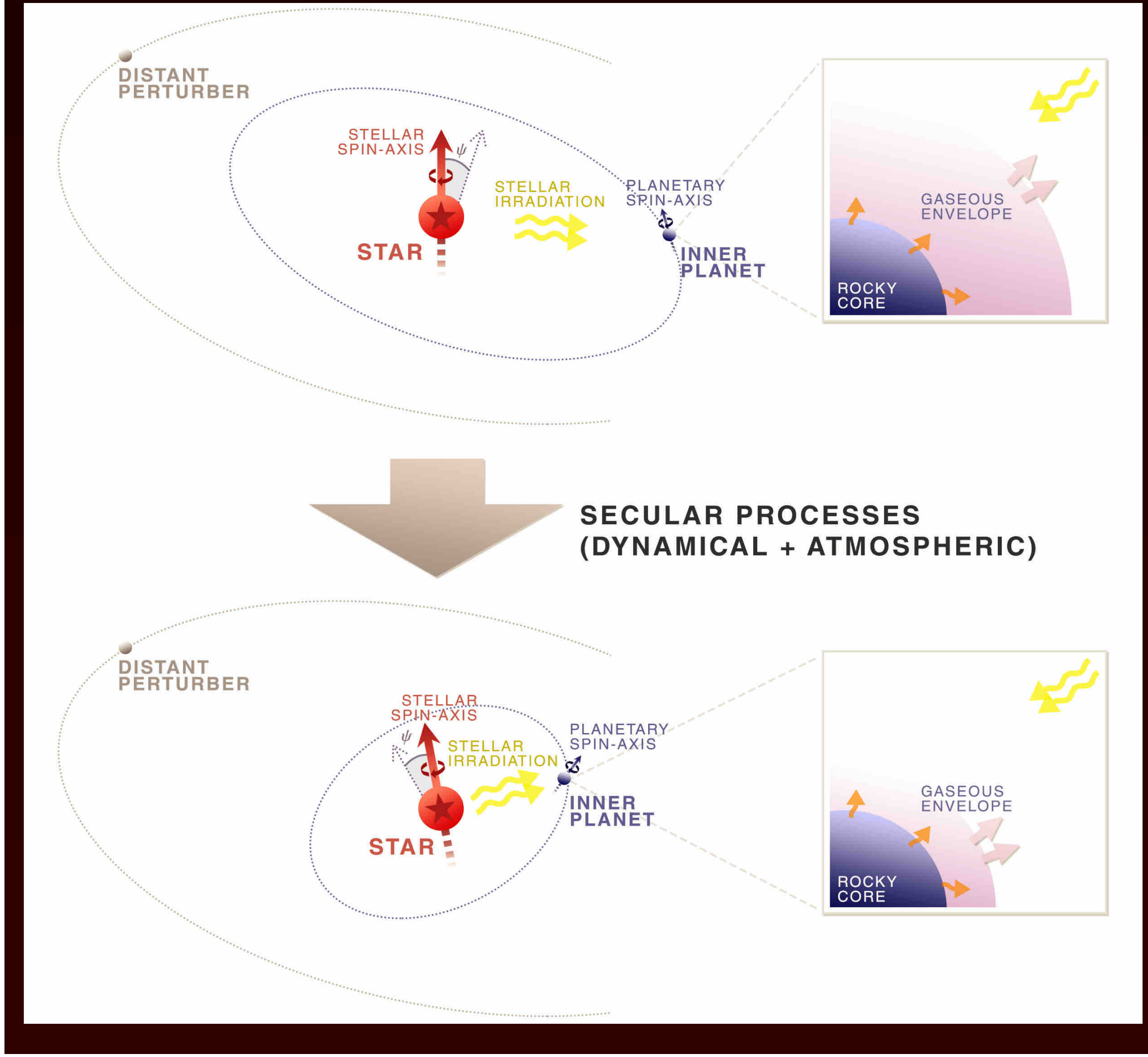


Disk-driven migration and early-on evaporation may not be dominant processes

High-eccentricity migration could delay the evaporation of a fraction of Neptunes

Need for orbital architecture & mass loss measurements to inform evolutionary models

THE JADE CODE

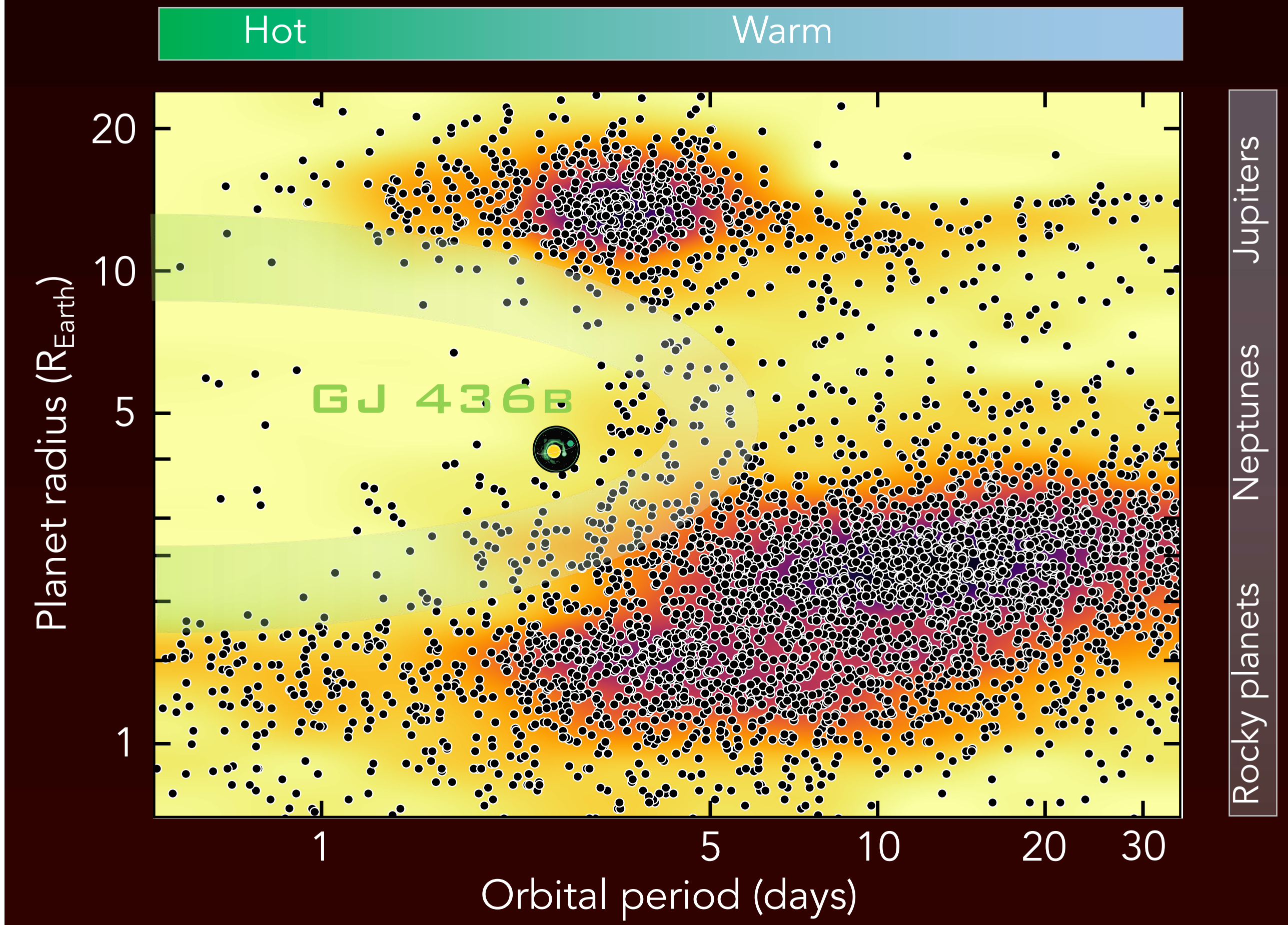


3D dynamical evolution of an evaporating planet at high precision over secular timescales

Attia+2021

Dynamics	Atmosphere	Star
. Outer perturber . Tidal effects . General relativity	. 1D structure . Photo-evaporation . Internal heating	. Evolving irradiation . Evolving spin . Contraction

GJ436B: FLAGSHIP APPLICATION



Eccentric orbit despite advanced age (e.g. Butler+2006, Torres+2008, Lanotte+2014)

Highly misaligned orbit (e.g. Bourrier+2021)

Strong evaporation (e.g. Kulow+2014, Ehrenreich+2015, Lavie+2017, dos Santos+2019)

Inner edge of the desert

How did it survive?

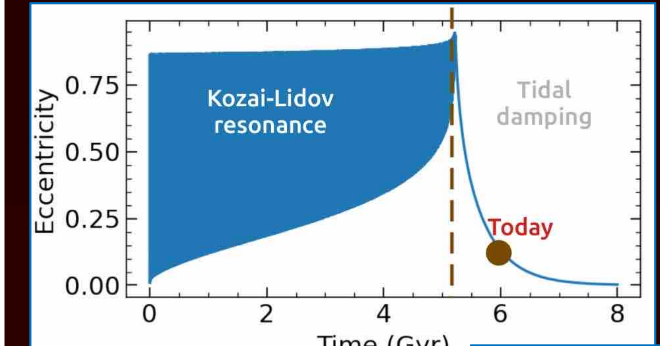
GJ436B: FLAGSHIP APPLICATION

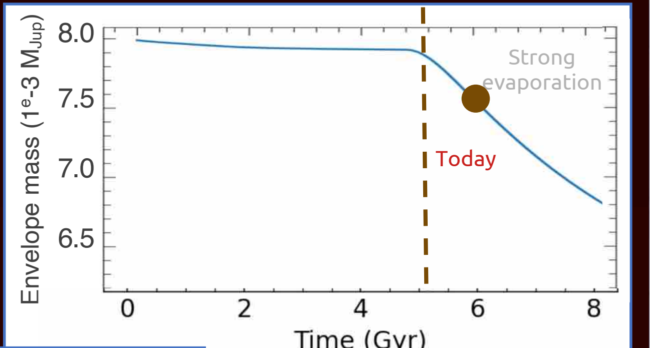
Spin-orbit angle measurements

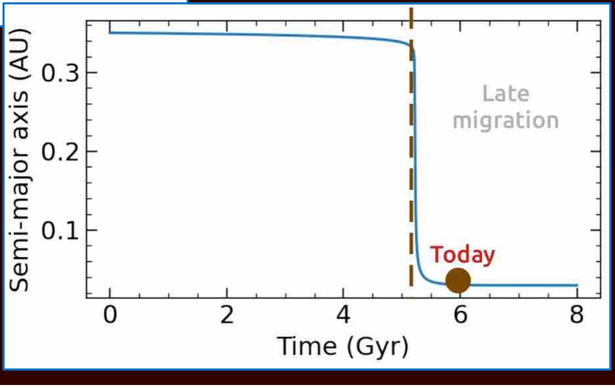
Mass-loss rate measurements

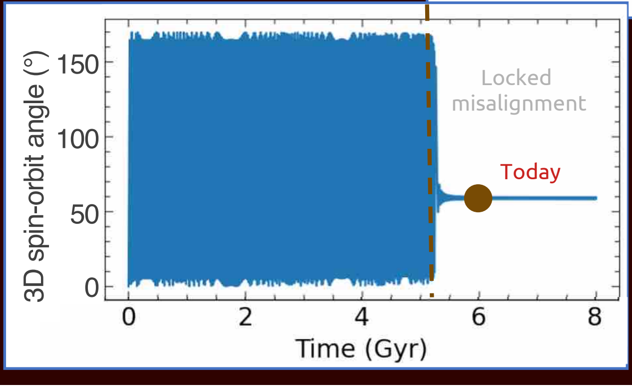
JADE

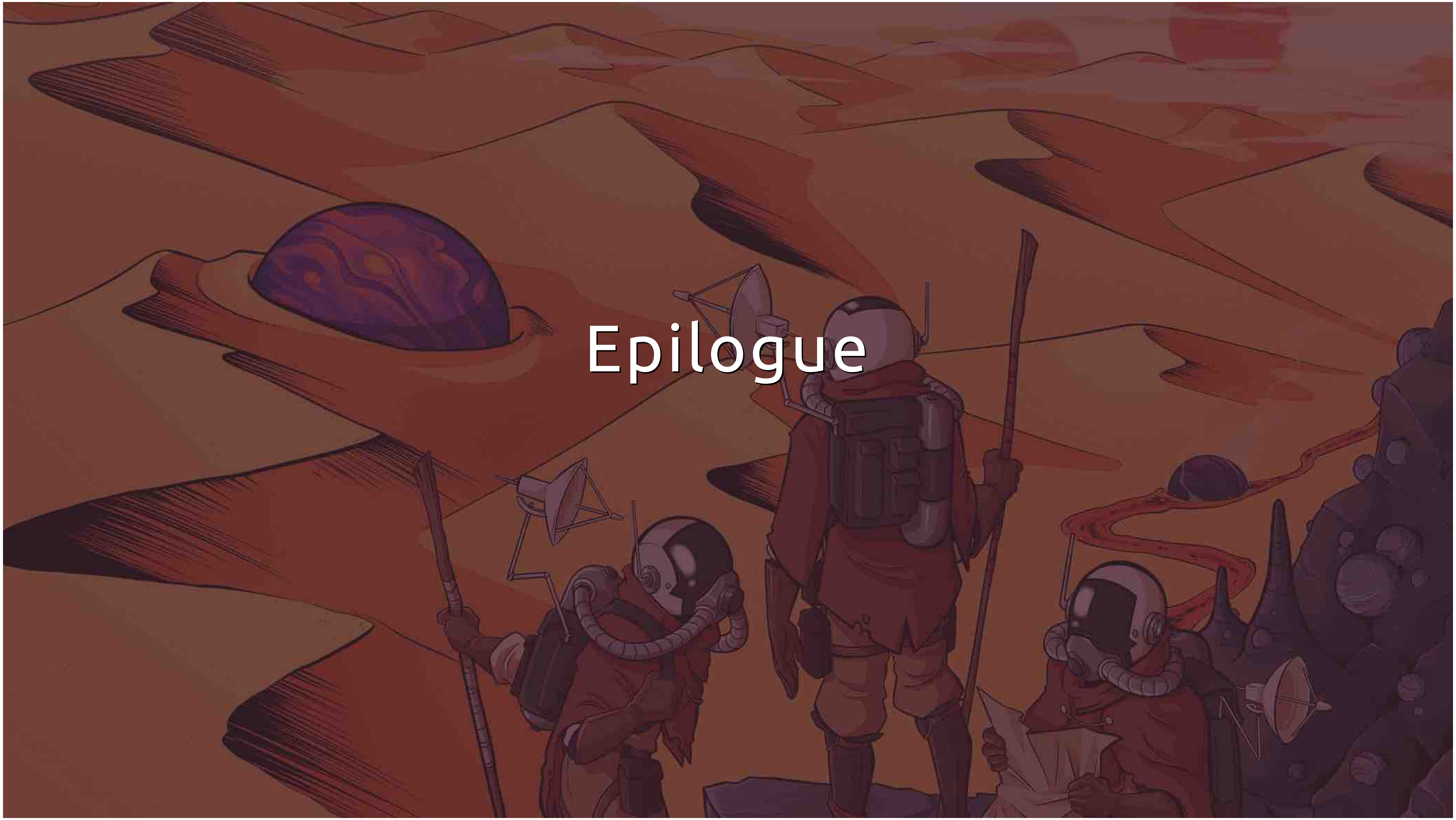
Attia+2021









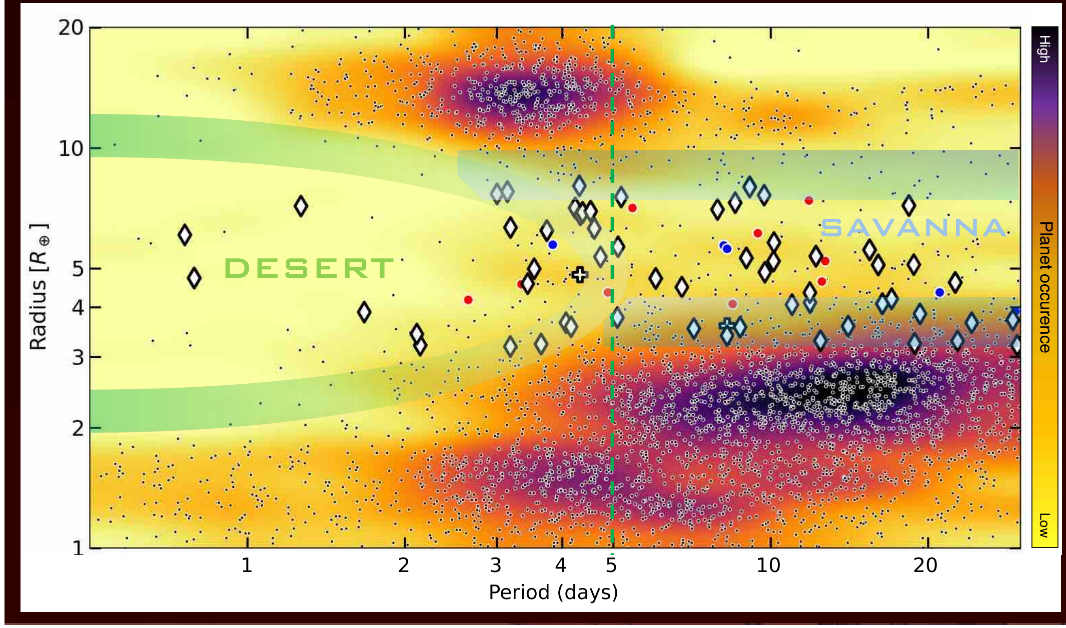


Epilogue

THE ATREIDES PROGRAM

Ancestry, **T**raits, and **R**elations of **E**xoplanets **I**nhabiting the **D**esert **E**dges and **S**avannah

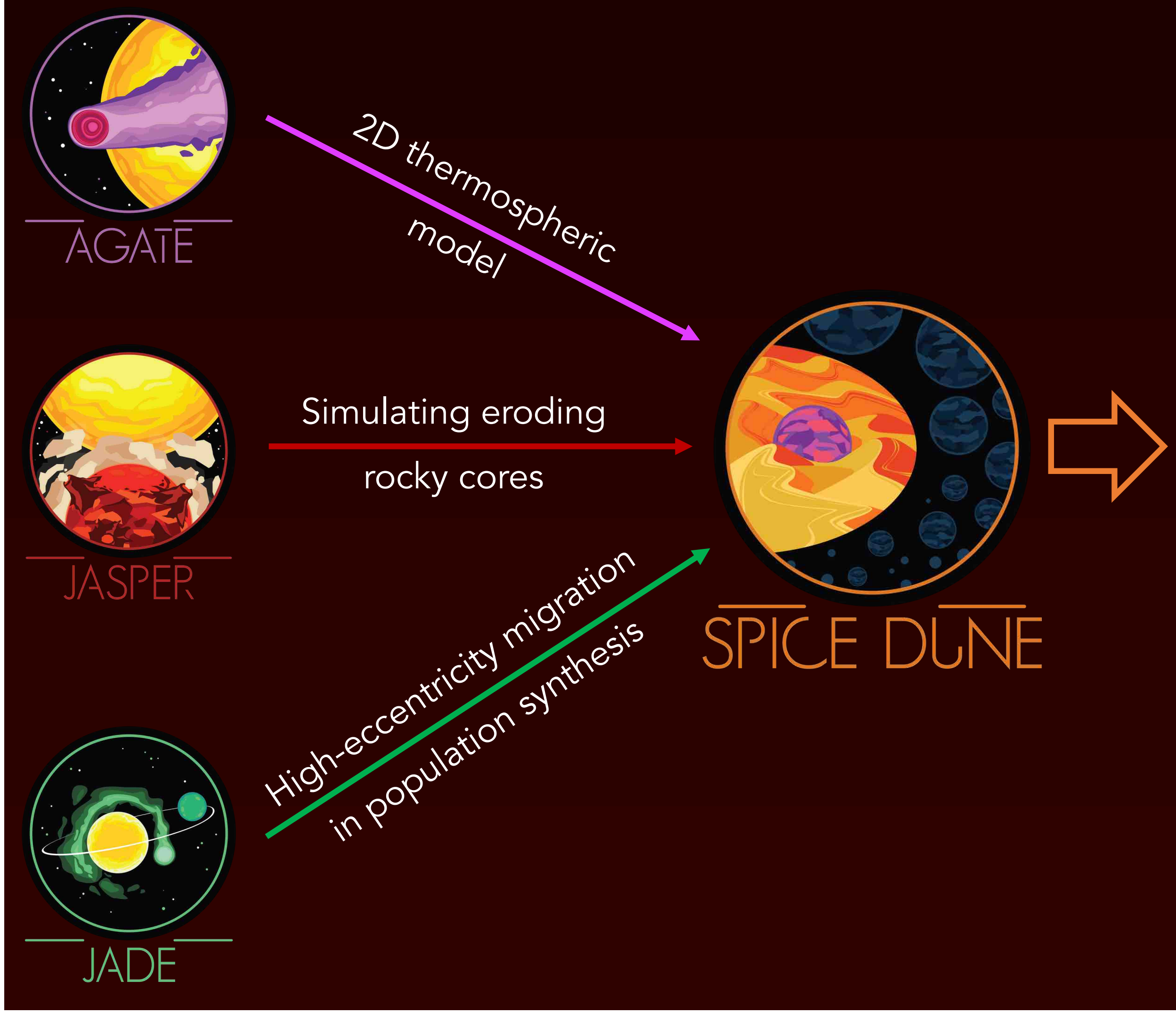
- Large program on VLT/ESPRESSO: 60 planet transits in 330 h over 2+ years
- Mini-GTO : ~60 collaborators (PI V. Bourrier, Observation managers M. Steiner & Erik Fridén)
- Transit spectroscopy goals: Building spin-orbit angle distribution of Neptunes over Desert and Savannah
  Probing planetary and stellar atmospheres



Major collaboration with NGTS

- Complemented by MUsCAT2, EulerCAM, STELLA
- Transit photometry for precise ephemeris
- Long-term photometry for rotation periods and activity

DREAMING ON…



AGATE

2D thermospheric model

JASPER

Simulating eroding rocky cores

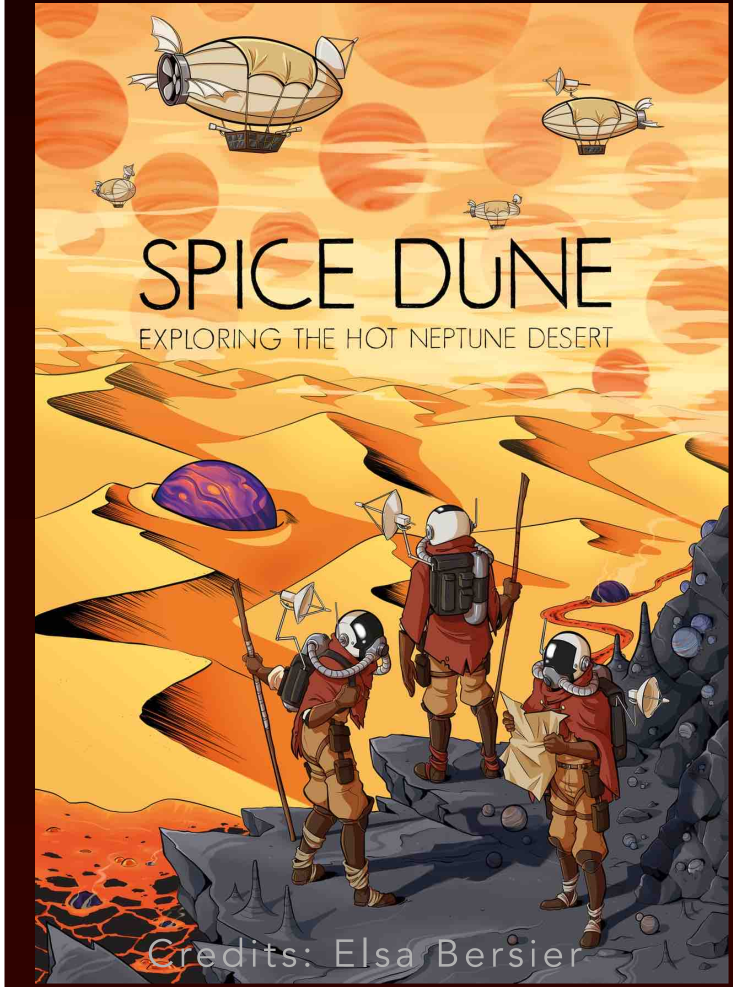
JADE

High-eccentricity migration in population synthesis

SPICE DUNE

- What fraction of warm Neptunes underwent early / late migration ?
- How did it impact their atmospheric erosion ?
- What are the evolutionary links between planets around the desert ?

WAKING UP MESSAGES



- Desert and Savannah encode information about evolutionary processes
- Helium signals trace atmospheric erosion but require finer interpretations
- Tides play a major role in shaping the architectures of close-in planets
- High-eccentricity migration may populate the rim of the desert
- Coupled atmospheric/dynamical simulations informed by samples of mass loss + spin-orbit angles are needed to decode exo-Neptunes origins