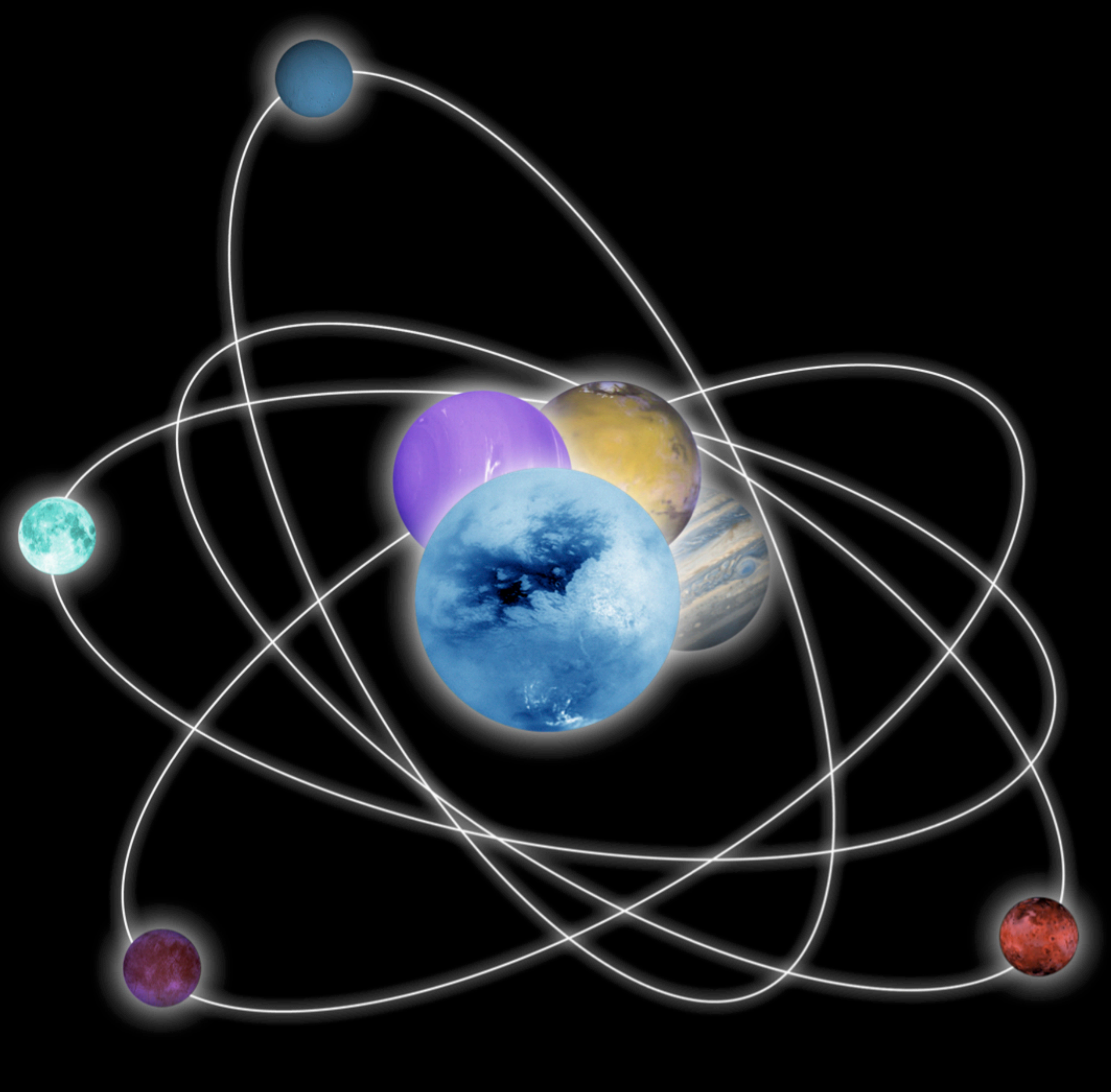


UCL

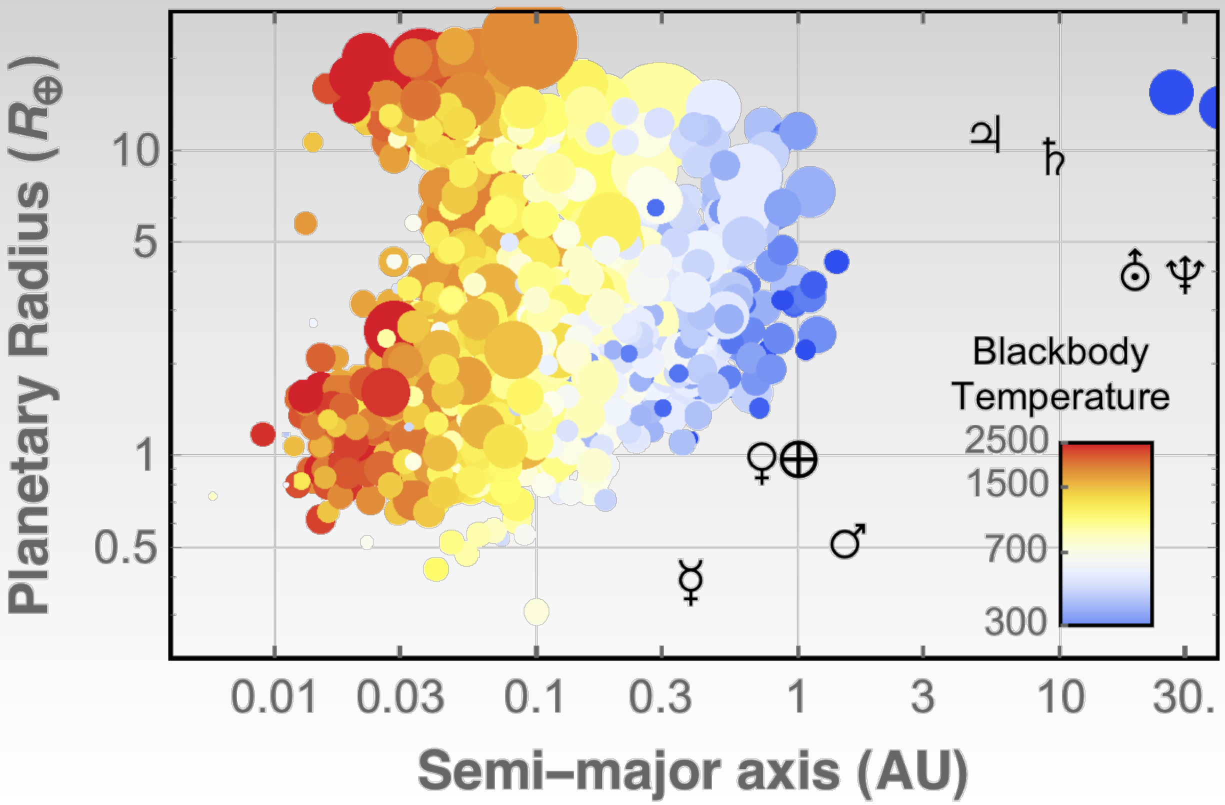
A chemical survey of exoplanets

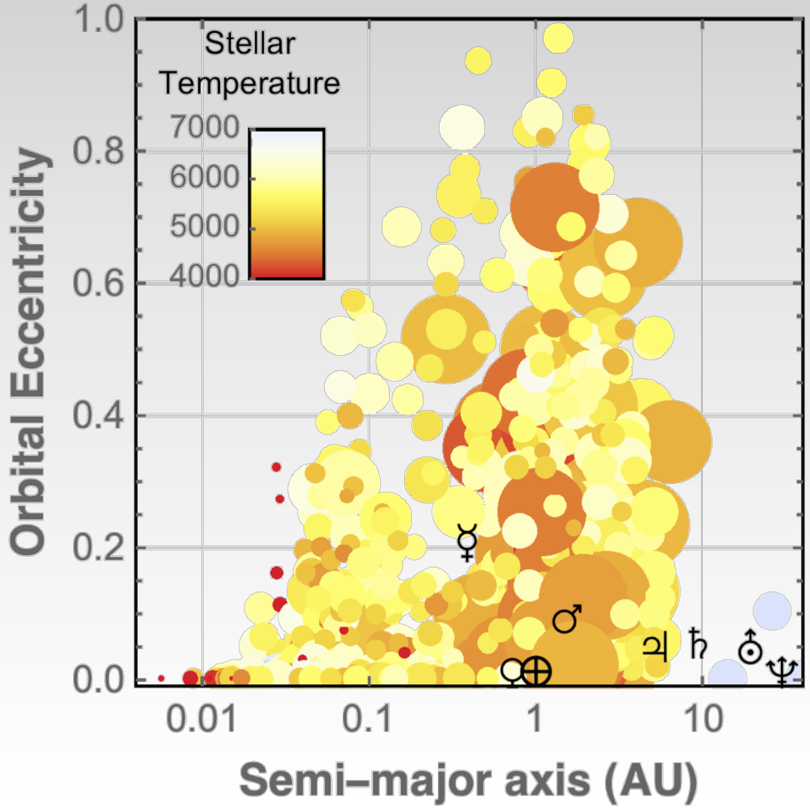
Giovanna Tinetti

RESCEU – Nov. 2017

EXOPLANETS TODAY: HUGE DIVERSITY

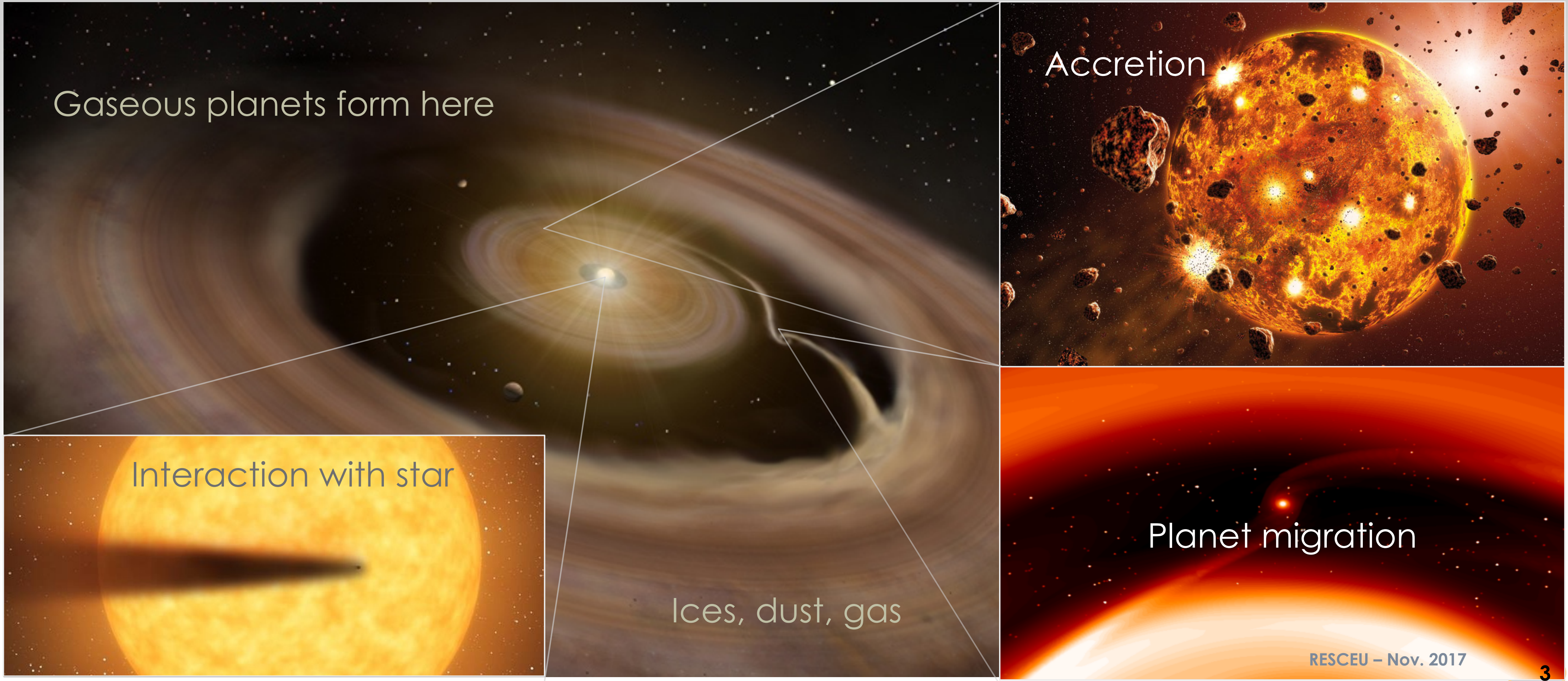
3700+ PLANETS, 2700 PLANETARY SYSTEMS KNOWN IN OUR GALAXY





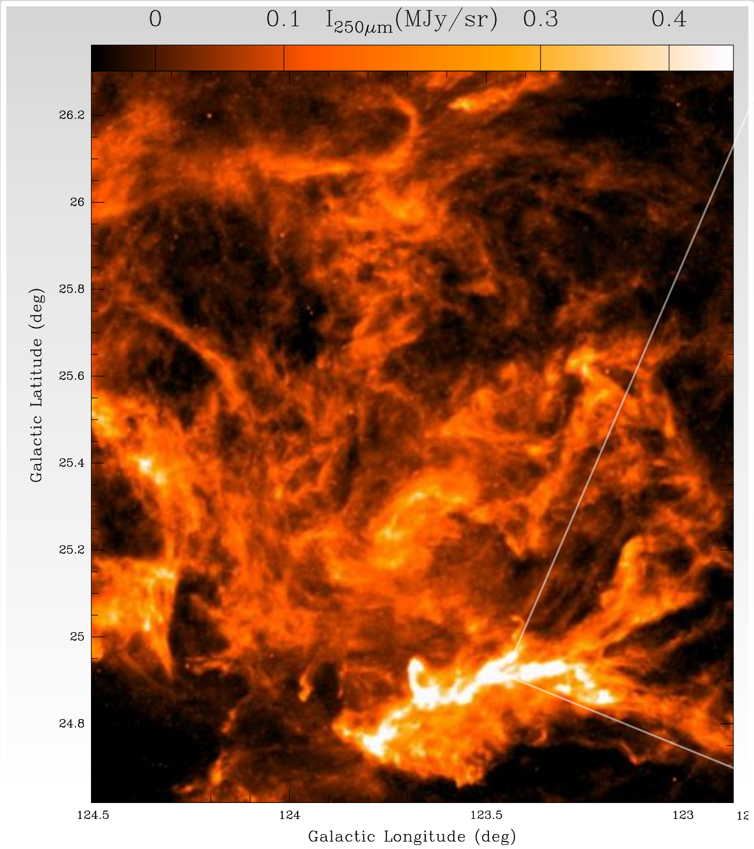
HUGE DIVERSITY: WHY?

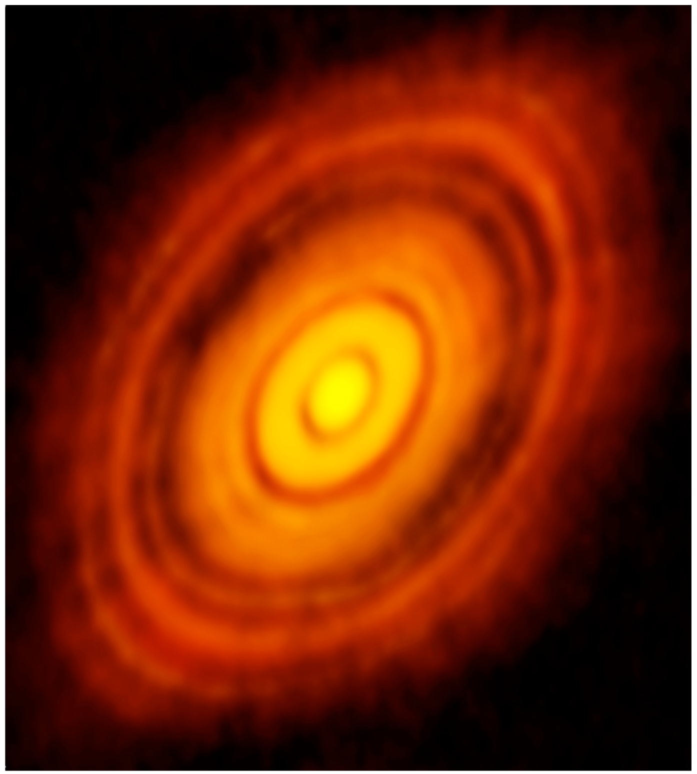
FORMATION & EVOLUTION PROCESSES? MIGRATION? INTERACTION WITH STAR?



STAR & PLANET FORMATION/EVOLUTION

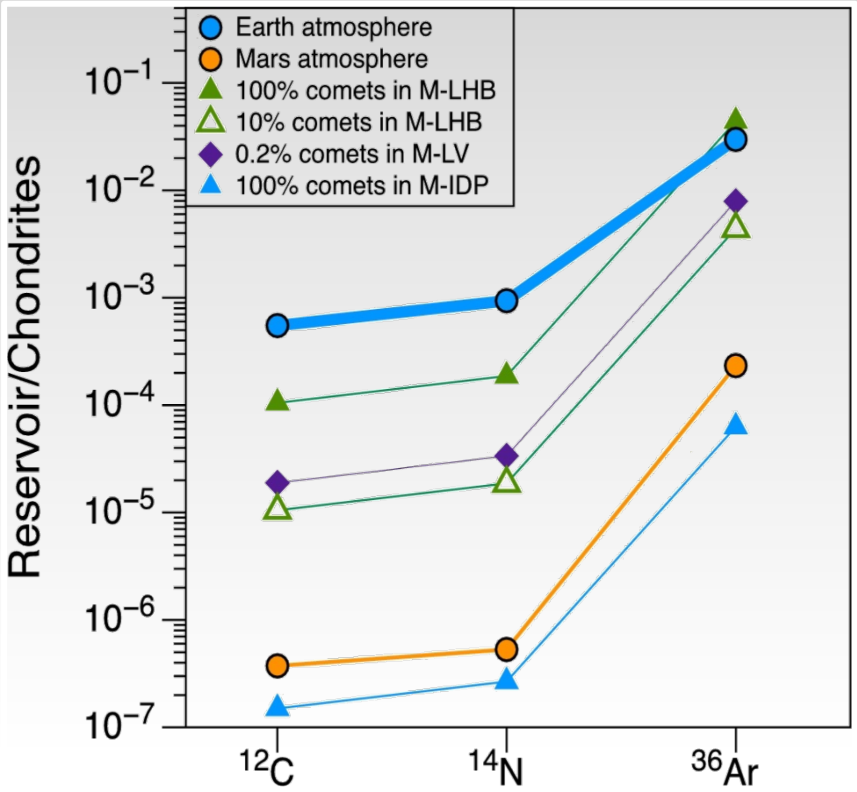
WHAT WE KNOW: CONSTRAINTS FROM OBSERVATIONS – HERSCHEL, ALMA, SOLAR SYSTEM





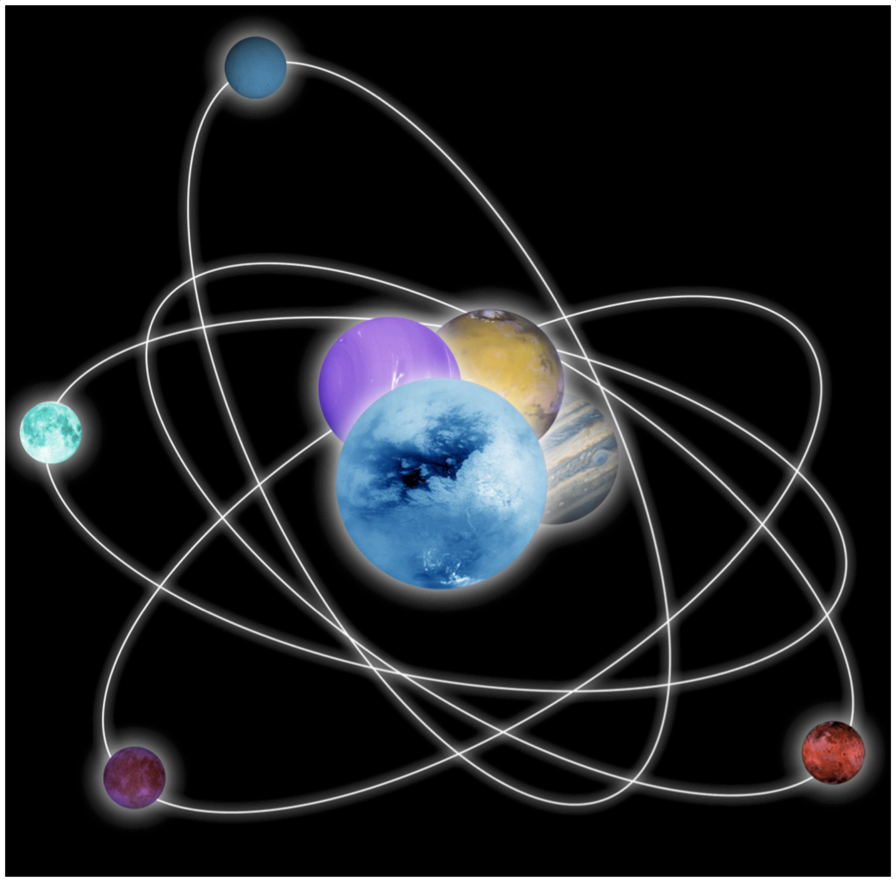
?

Measured elements in Solar system



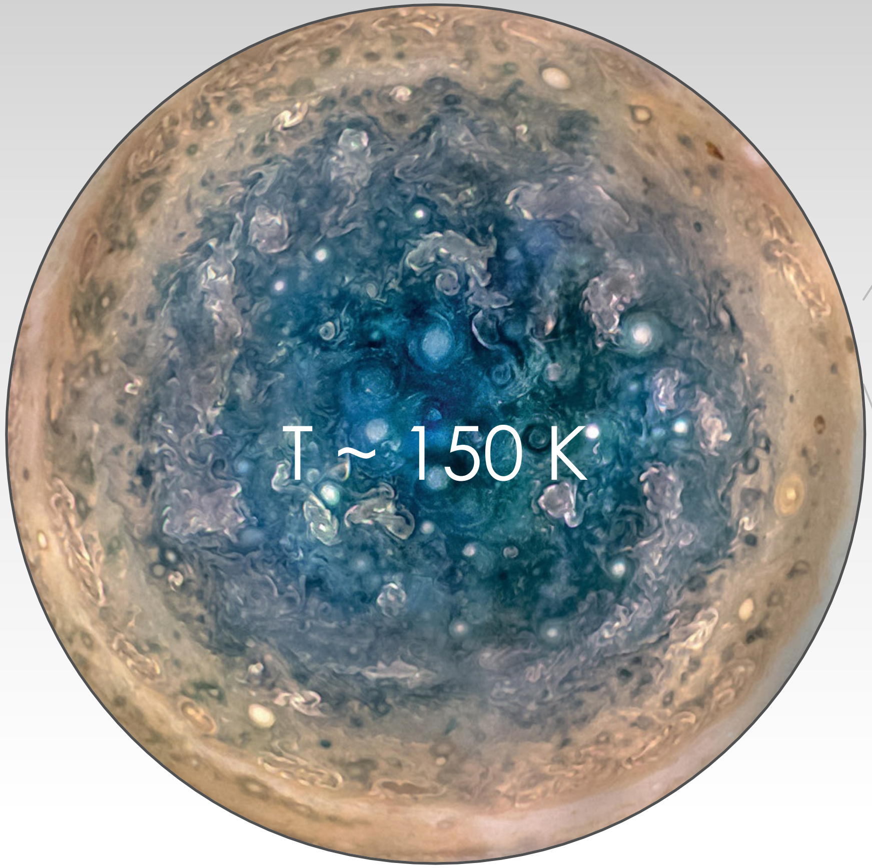
KEY EXOPLANET QUESTIONS

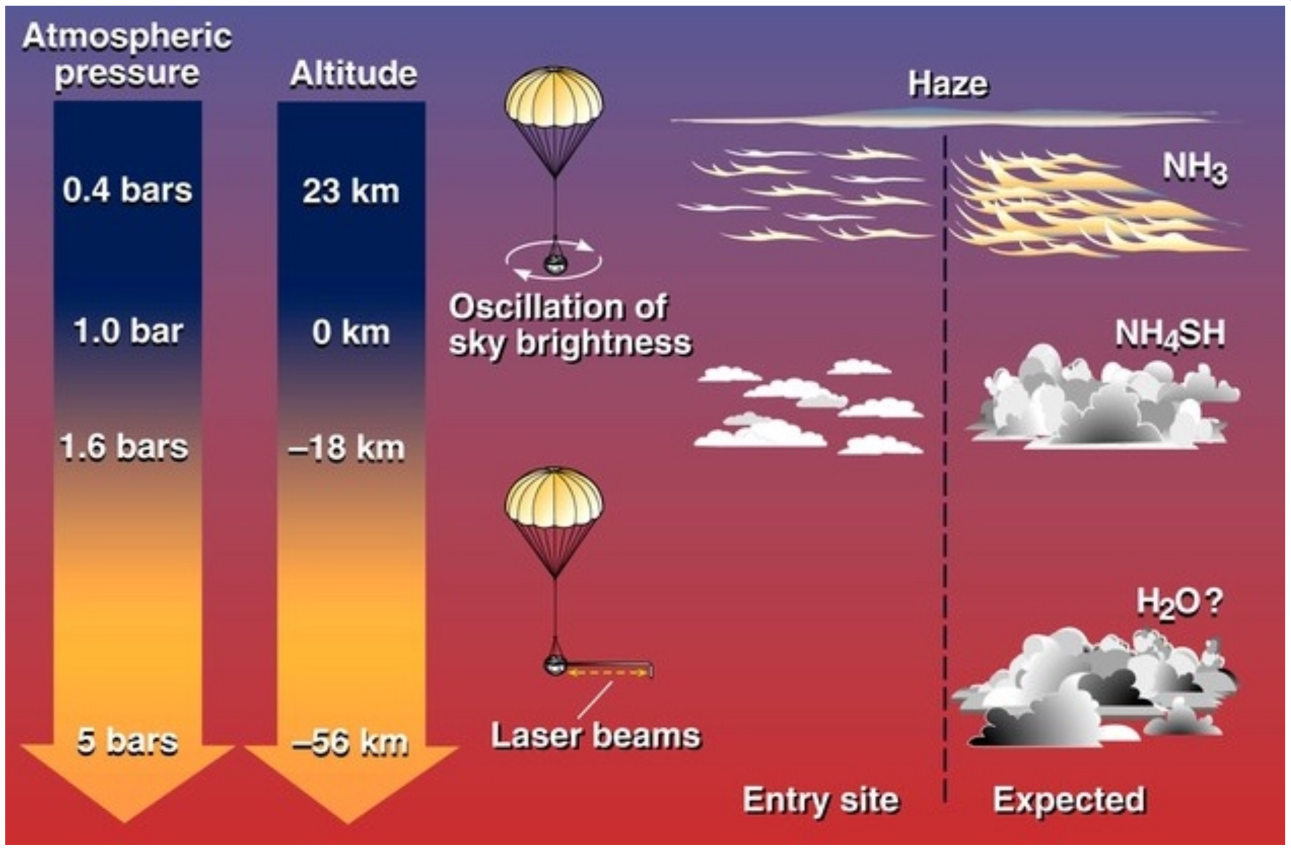
- How diverse are exoplanets chemically?
- Does chemical diversity correlate with other parameters?
  - How do planets form?
  - How do planets evolve?



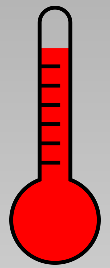
THE SUN'S PLANETS ARE COLD

SOME KEY O, C, N, S MOLECULES ARE **NOT** IN GAS FORM

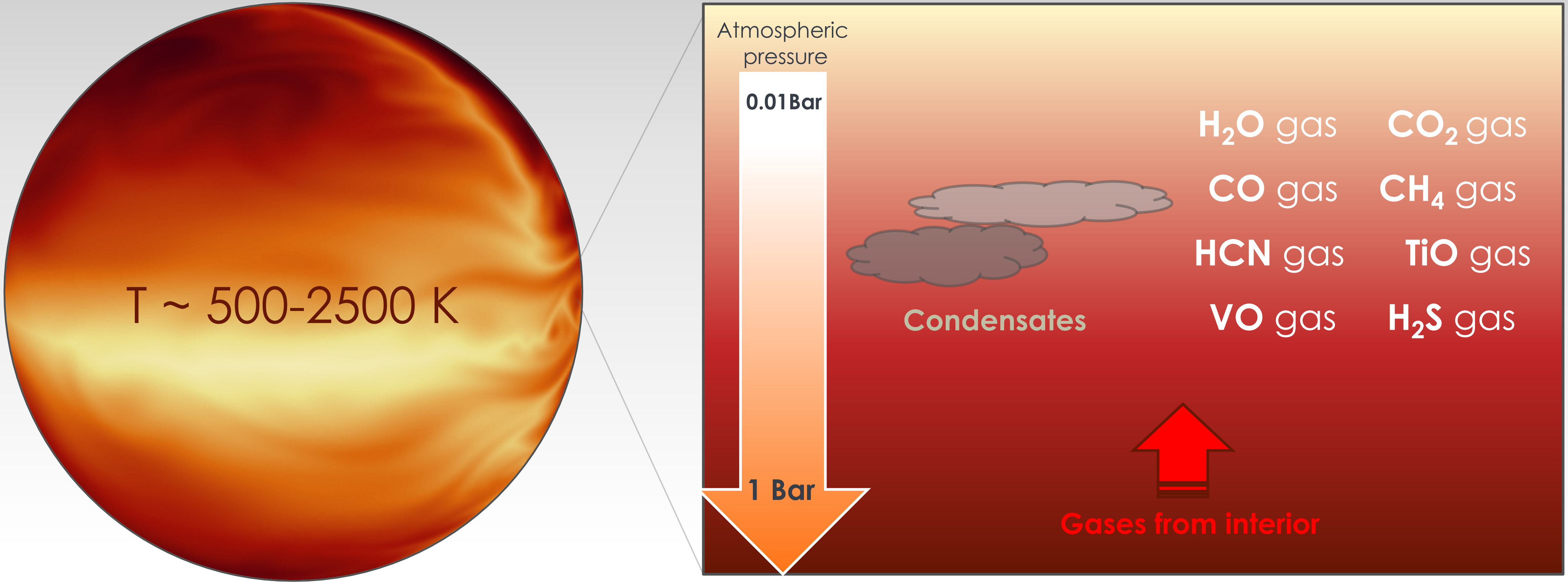




WARM/HOT EXOPLANETS

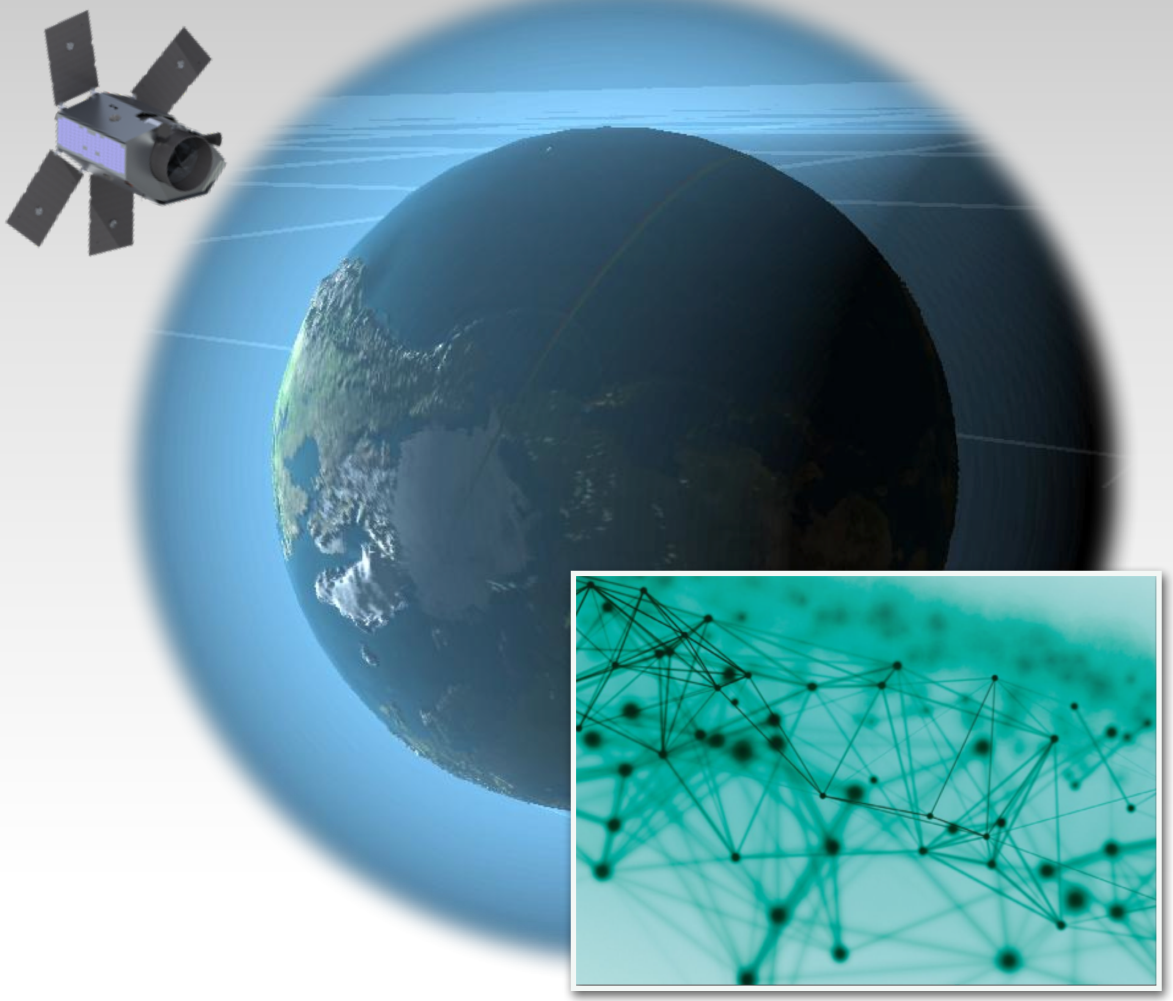


O, C, N, S (Ti, VO, Si) MOLECULES ARE IN GAS FORM



ExoLights + ExoAI

Observations & modelling of exo-atmospheres, Big-data & space missions

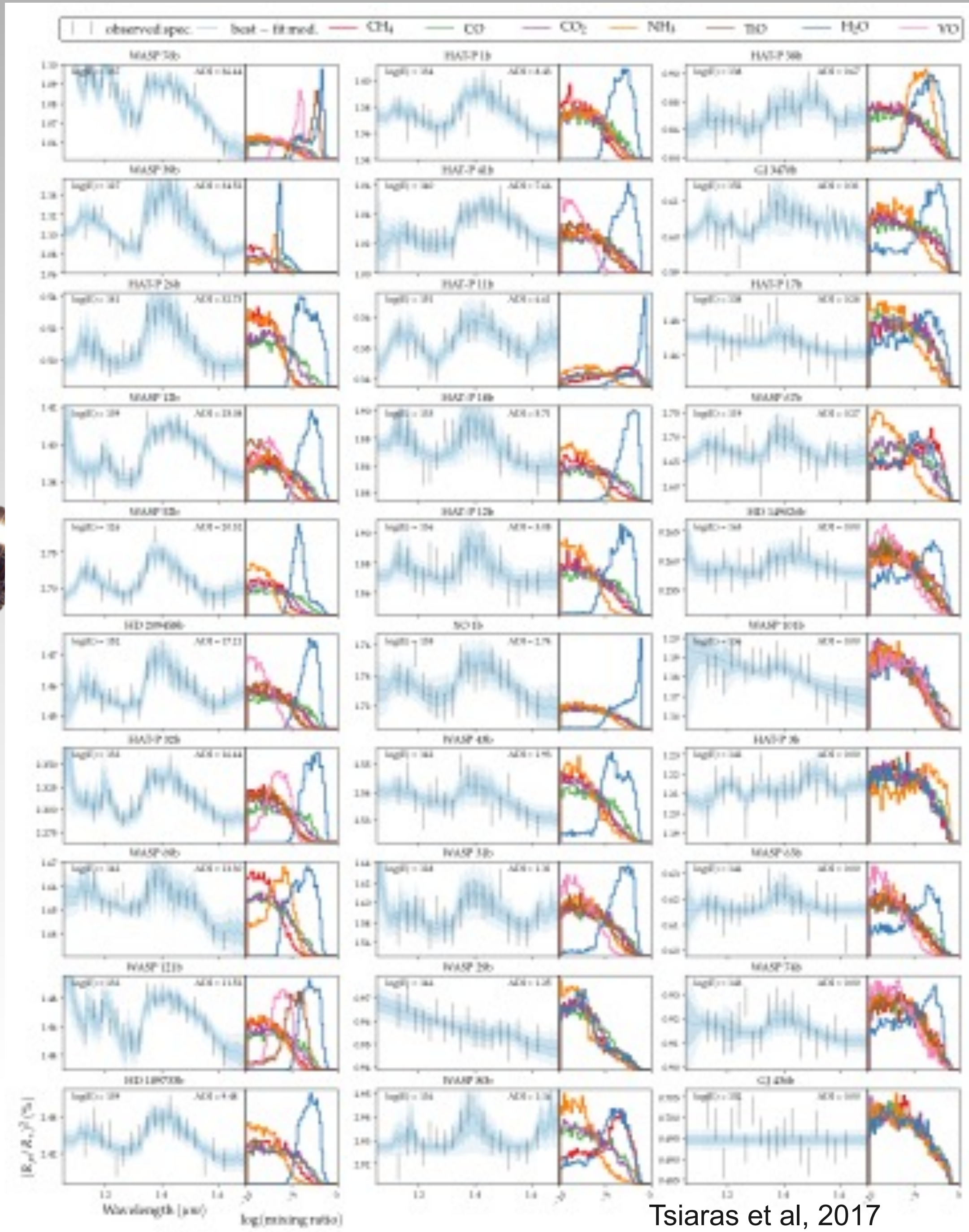


- Exoplanet atmospheres observations & data analysis
- Spectral modelling & interpretation
- New space mission concepts
- Infrastructure to analyse “big-data”

ExoLights is funded by ERC (PI G. Tinetti, 2014-2019)
ExoAI funded by ERC (PI I. Waldmann, 2018-2023)

30 SHADES OF HOT-JUPITERS

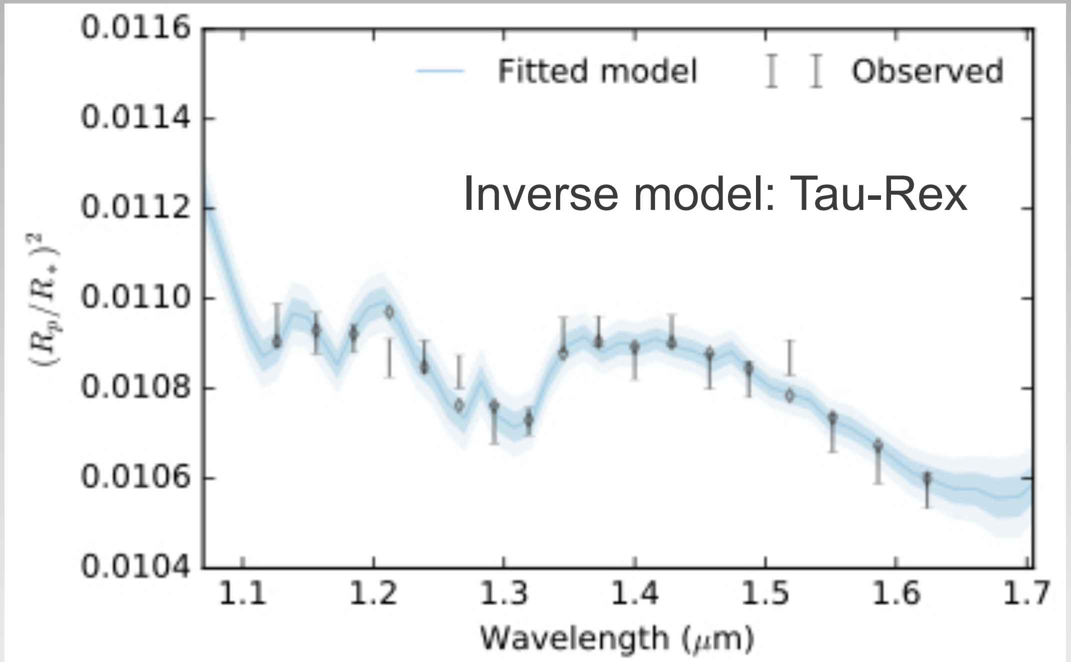
30 WFC3 SPECTRA ANALYSED AND INTERPRETED

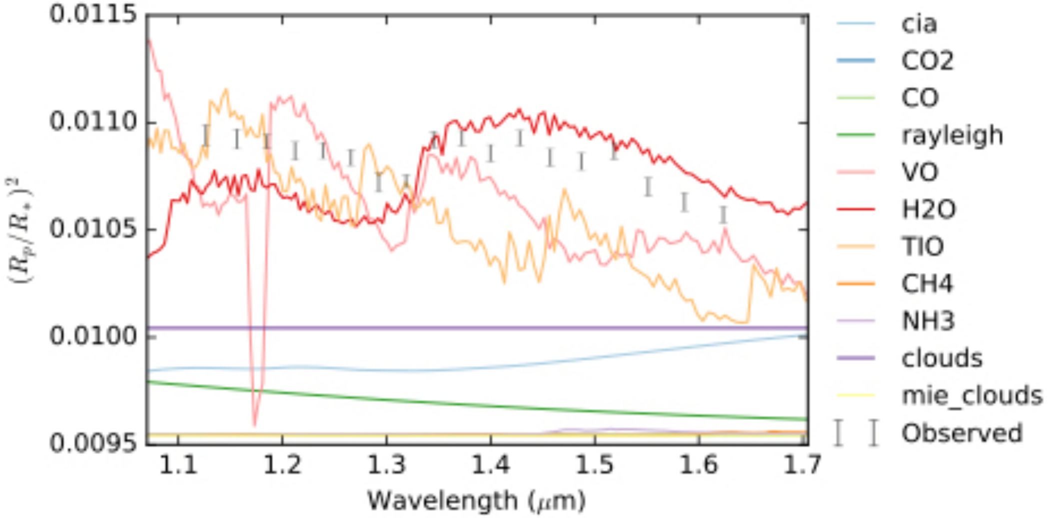


Tsiaras et al, 2017

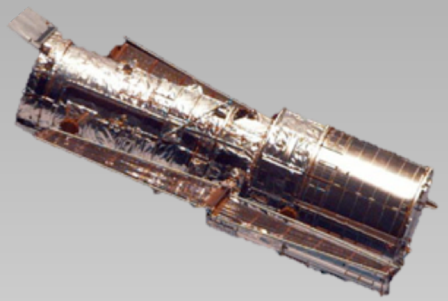
30 SHADES OF HOT-JUPITERS

30 WFC3 SPECTRA ANALYSED AND INTERPRETED



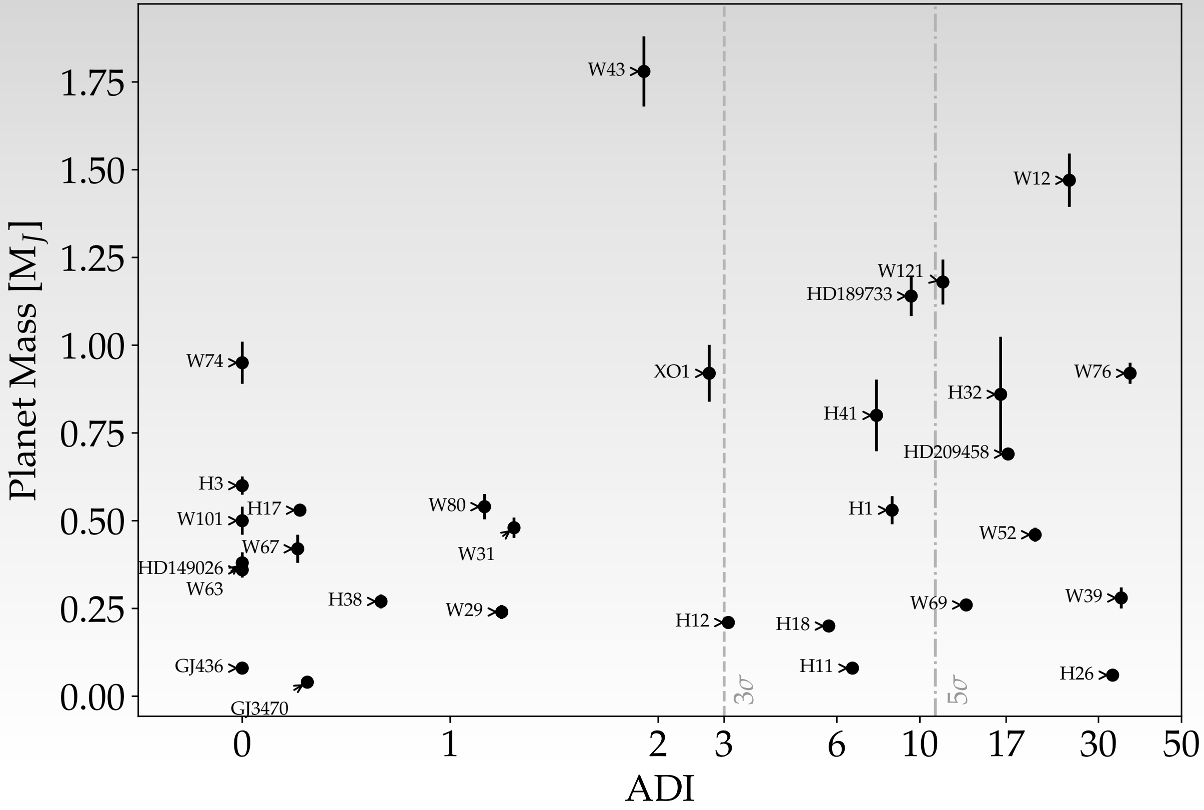


Tsiaras et al, 2017



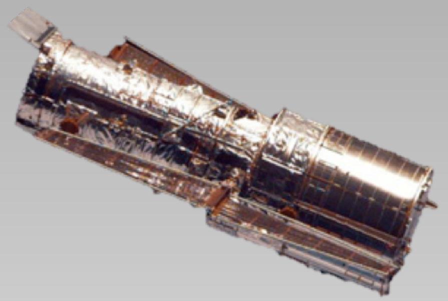
30 SHADES OF HOT-JUPITERS

30 WFC3 SPECTRA ANALYSED AND INTERPRETED: **CORRELATION MASS/ATMOSPHERE**

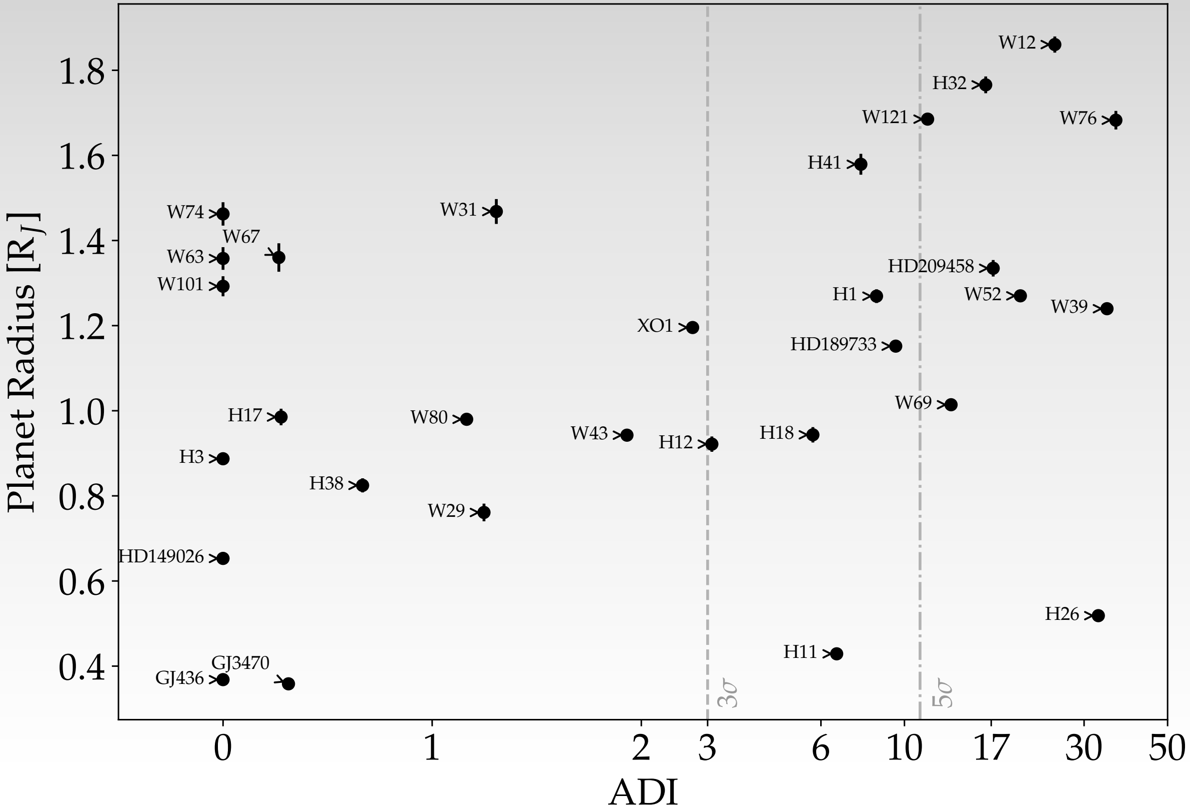


Tsiaras et al, 2017

30 SHADES OF HOT-JUPITERS

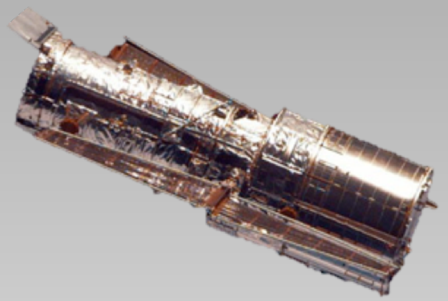


30 WFC3 SPECTRA ANALYSED AND INTERPRETED: **CORRELATION RADIUS/ATMOSPHERE**

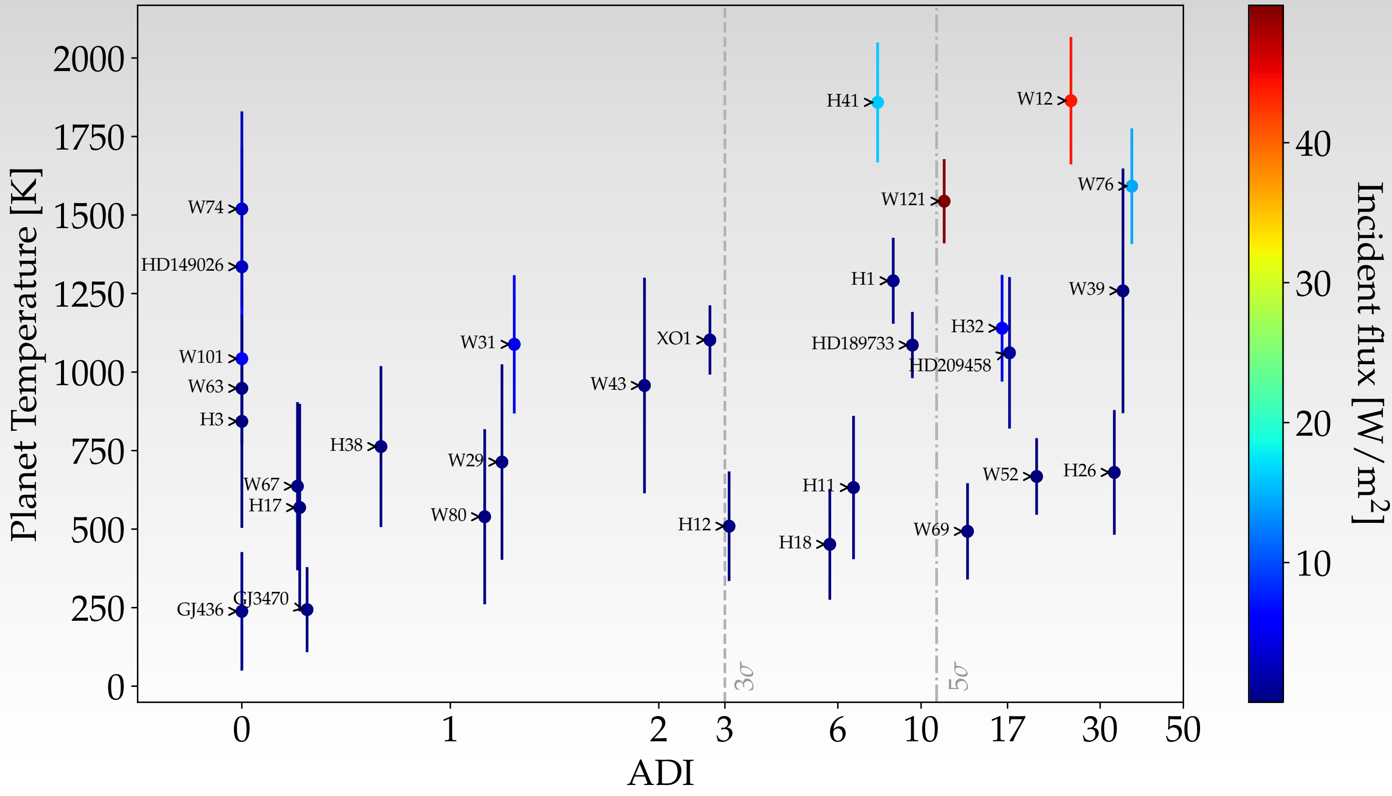


Tsiaras et al, 2017

30 SHADES OF HOT-JUPITERS



30 WFC3 spectra analysed and interpreted: **correlation T-irradiation/atmosphere**

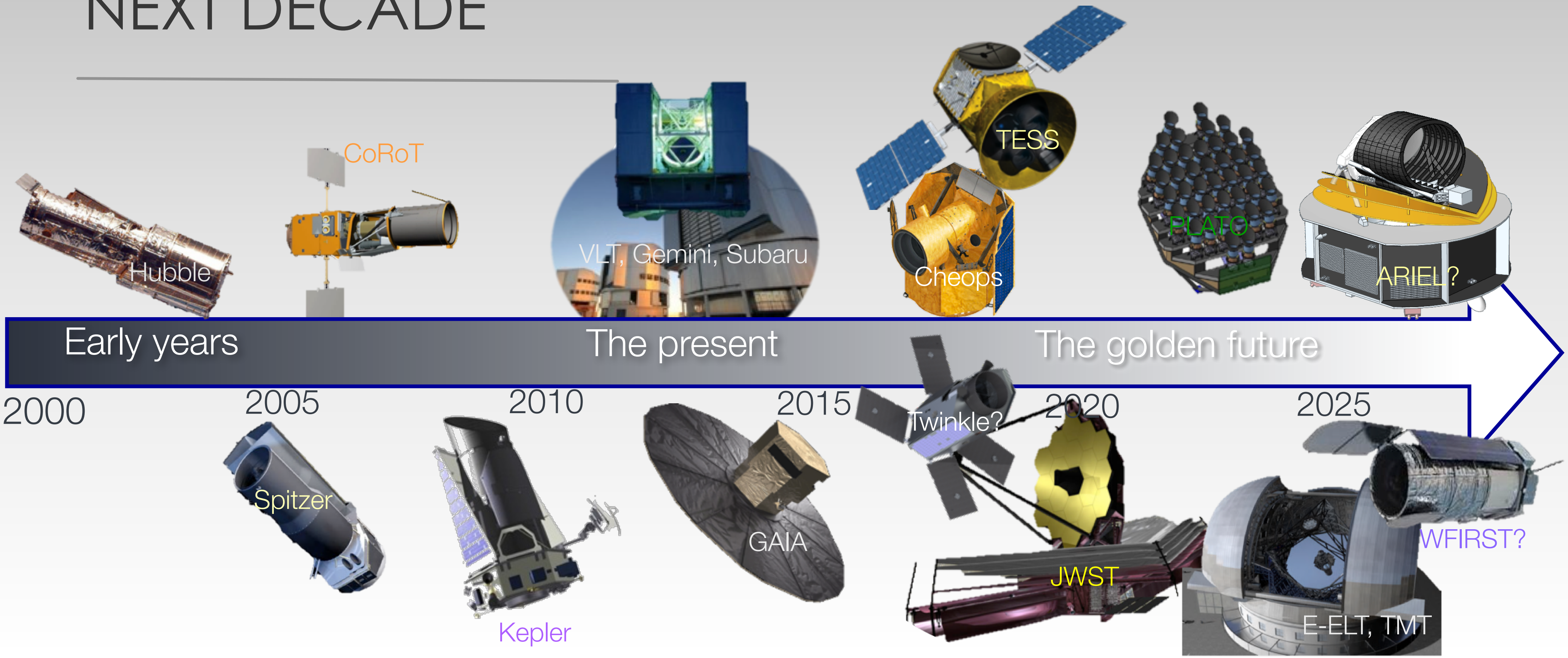


Tsiaras et al, 2017

ISSUES WITH CURRENT DATA

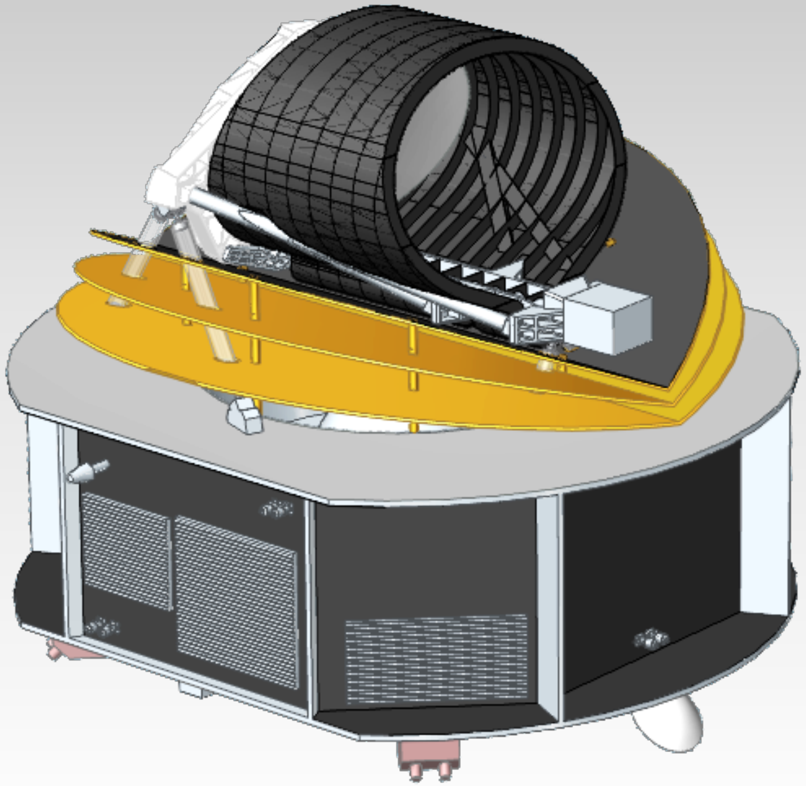
- WE ARE DEALING WITH LOW SNR & R OBSERVATIONS
- DATA ARE SPARSE, NOT ENOUGH WAVELENGTH COVERAGE
- BROAD WAVELENGTH COVERAGE IS NOT SIMULTANEOUS
- ABSOLUTE CALIBRATION AT THE LEVEL OF 10^{-4} IS NOT GUARANTEED!
- INSTRUMENT SYSTEMATICS ARE DIFFICULT TO DISENTANGLE FROM THE SIGNAL
- STELLAR ACTIVITY IS THE LARGEST SOURCE OF ASTROPHYSICAL NOISE
- WE NEED OBSERVATIONS ON A POPULATION OF OBJECTS TO DRAW CONCLUSIONS

NEXT DECADE


CoRoT
Hubble
VLT, Gemini, Subaru
TESS
Cheops
PLATO
ARIEL?
Early years
The present
The golden future
2000
2005
2010
2015
2020
2025
Spitzer
Kepler
GAIA
Twinkle?
JWST
E-ELT, TMT
WFIRST?

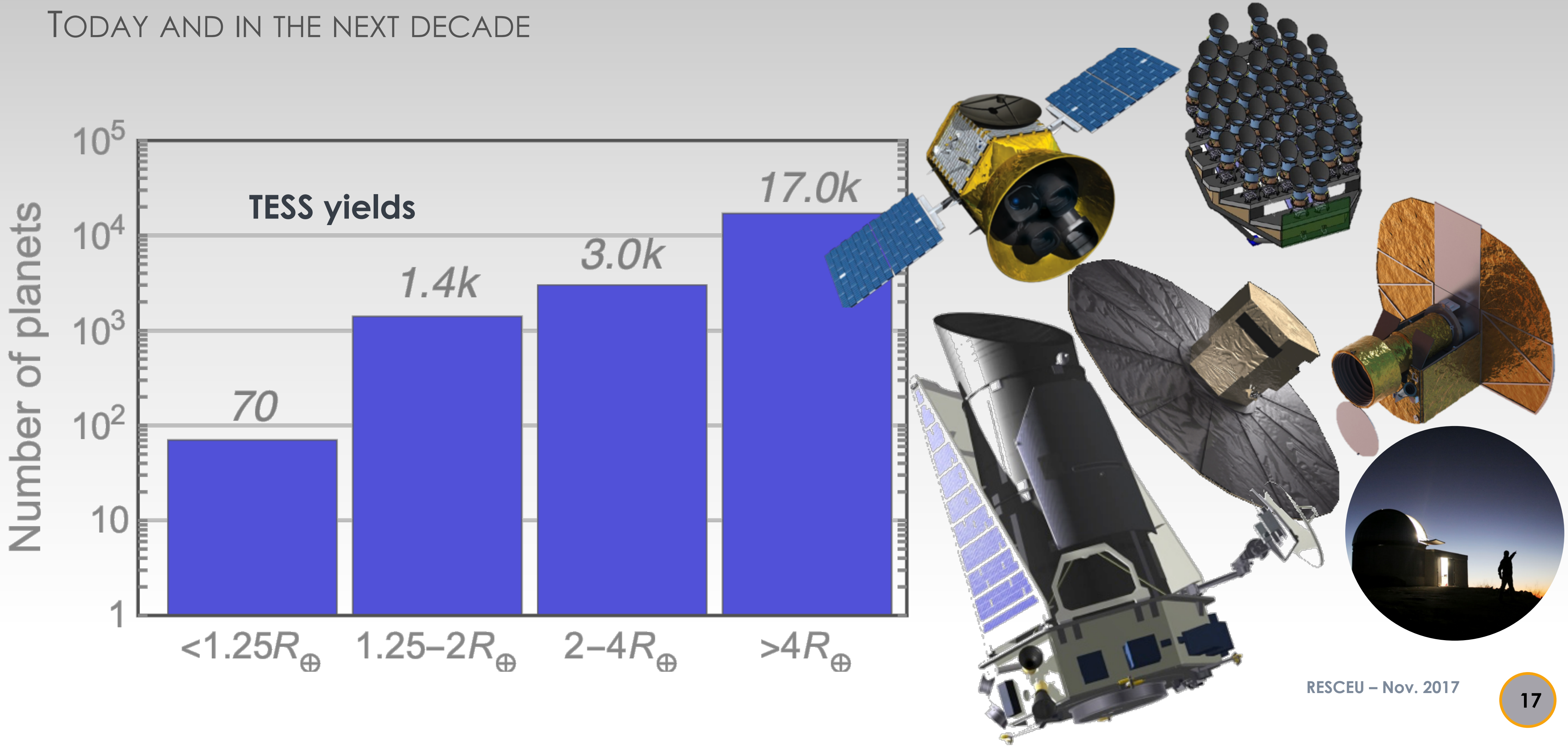
ARIEL – KEY FACTS

- 1-m telescope, spectroscopy from VIS to IR
- Satellite in orbit around L2
- ~1000 exoplanets observed (rocky + gaseous)
- Simultaneous coverage 0.5-7.8 micron
- Payload consortium: 11 ESA countries



LARGE POPULATION OF WARM/HOT PLANETS

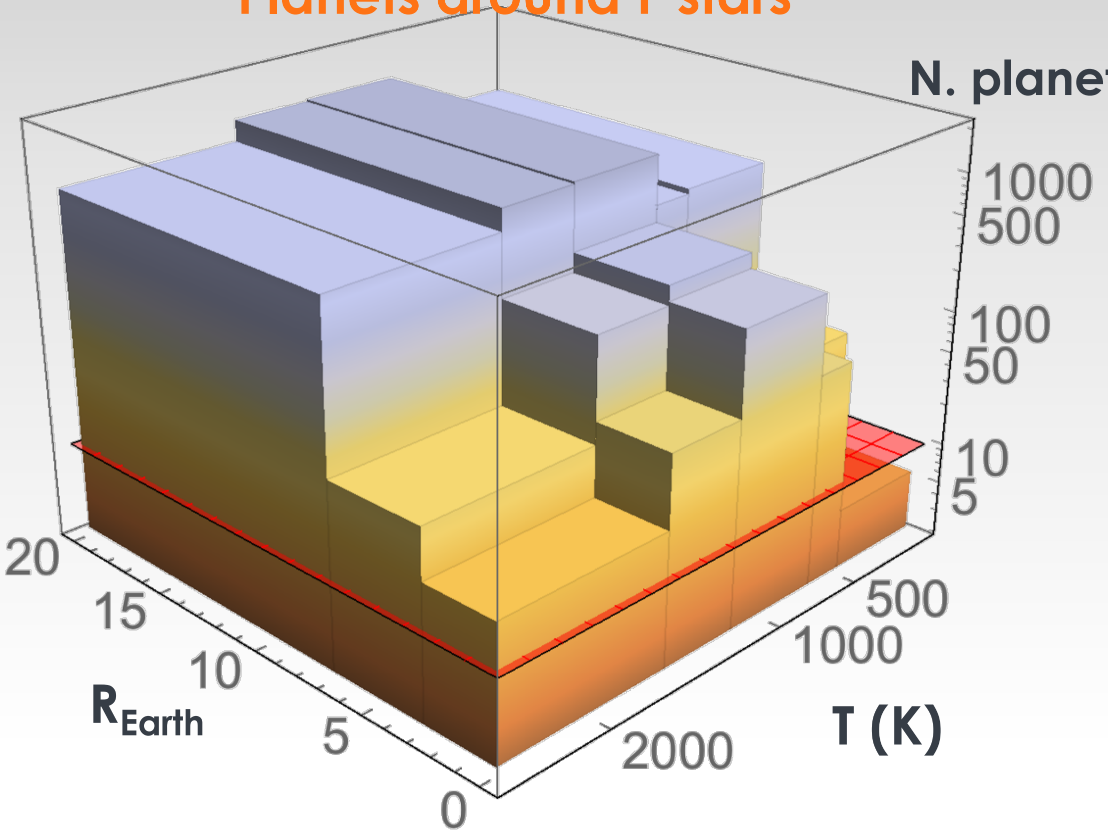
TODAY AND IN THE NEXT DECADE



LARGE POPULATION OF WARM/HOT PLANETS

SELECTED OUT OF 10,000 PLANETS OPTIMAL FOR CHEMICAL OBSERVATIONS

Planets around F stars



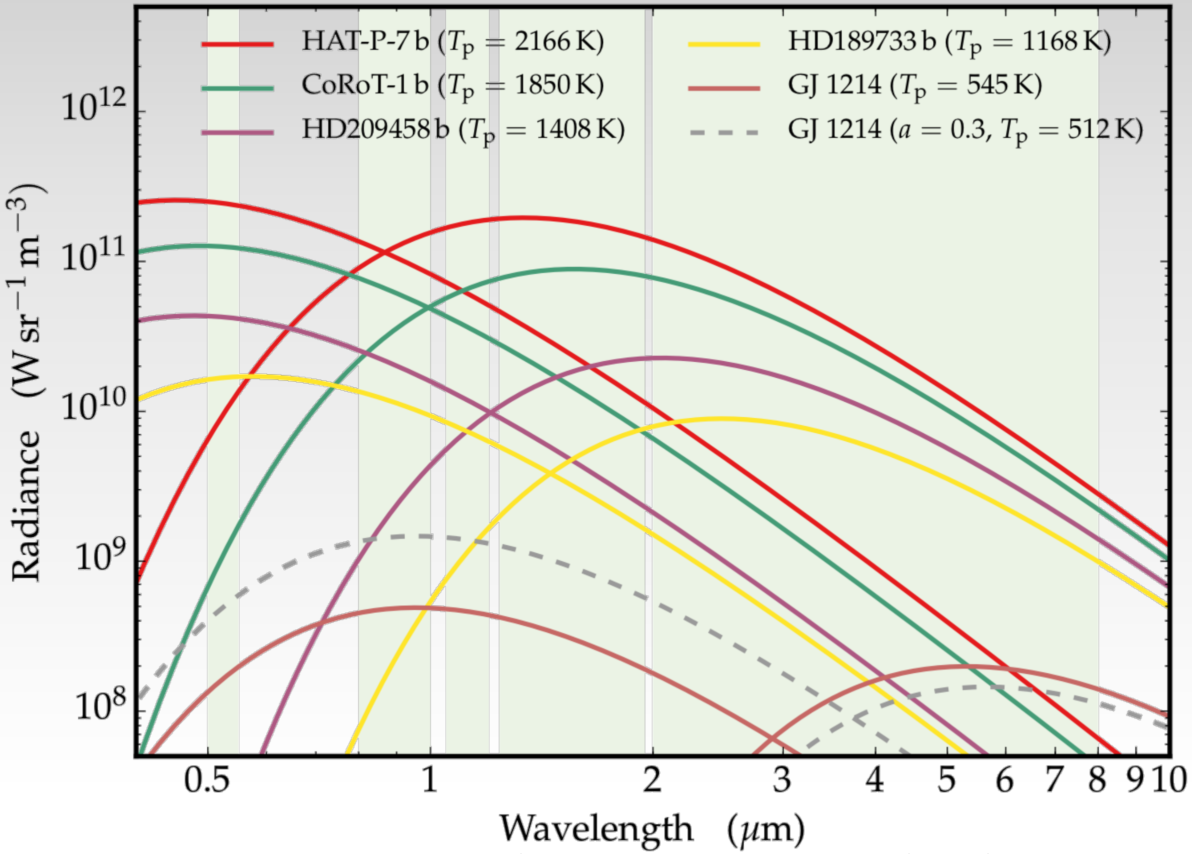
Parameter space to be sampled:

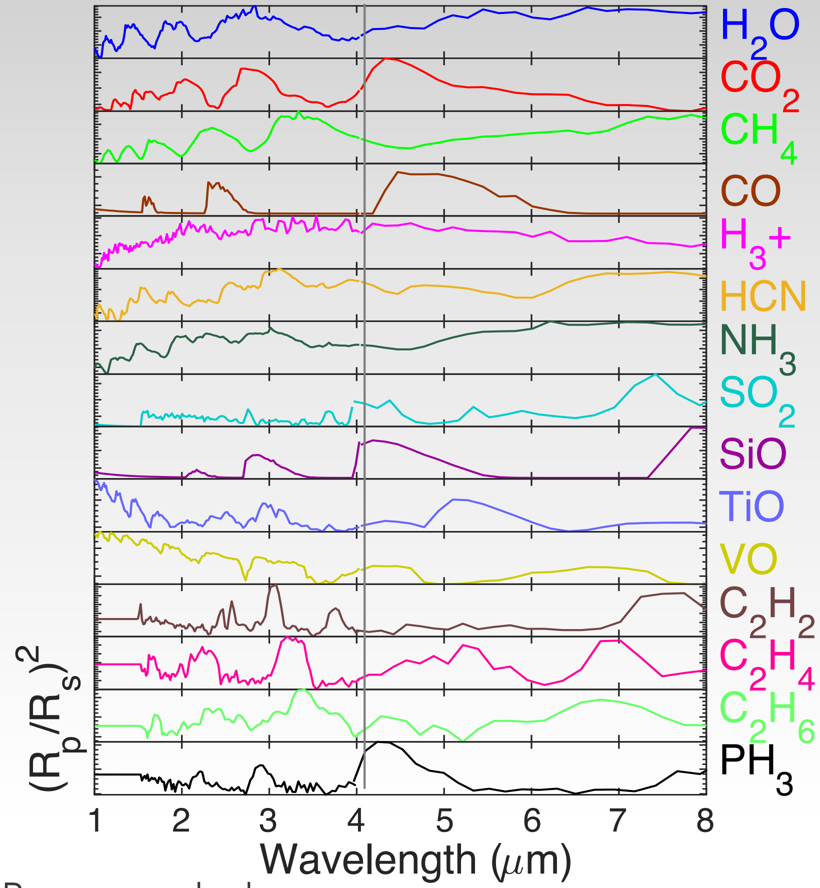
- Planet size (density)
- Temperature
- Stellar type
- Metallicity

The sample should have ~ 1000 planets

A CHEMICAL SURVEY OF A LARGE POPULATION

SCIENCE REQUIREMENTS: **EXOPLANET RADIATION, MOLECULAR** & CLOUD SIGNATURES, STAR ACTIVITY

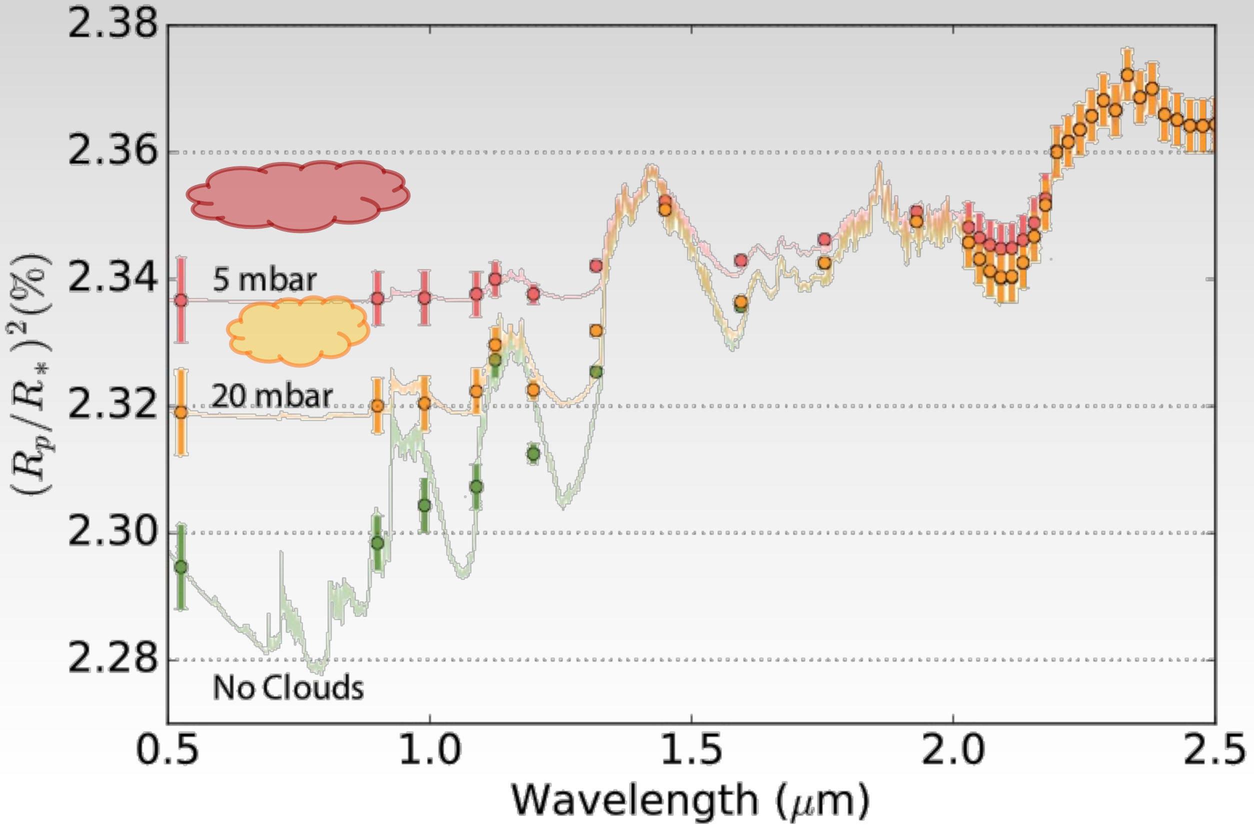


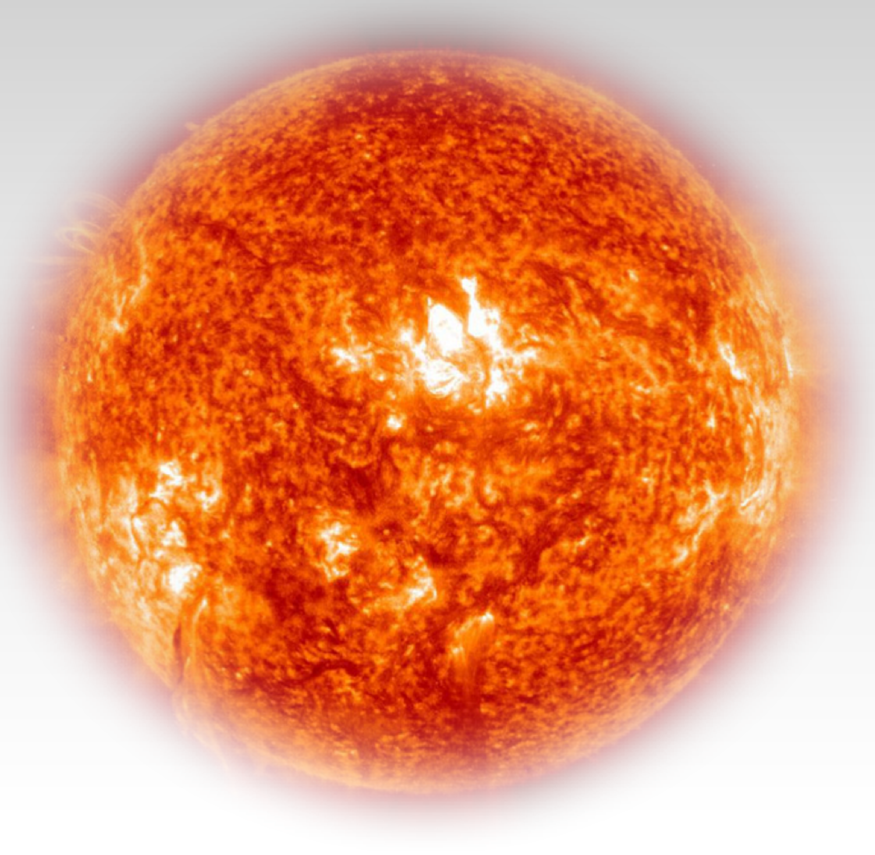


Simultaneous observations in the VIS and IR are needed

A CHEMICAL SURVEY OF A LARGE POPULATION

SCIENCE REQUIREMENTS: EXOPLANET RADIATION, MOLECULAR & **CLOUD SIGNATURES, STAR ACTIVITY**



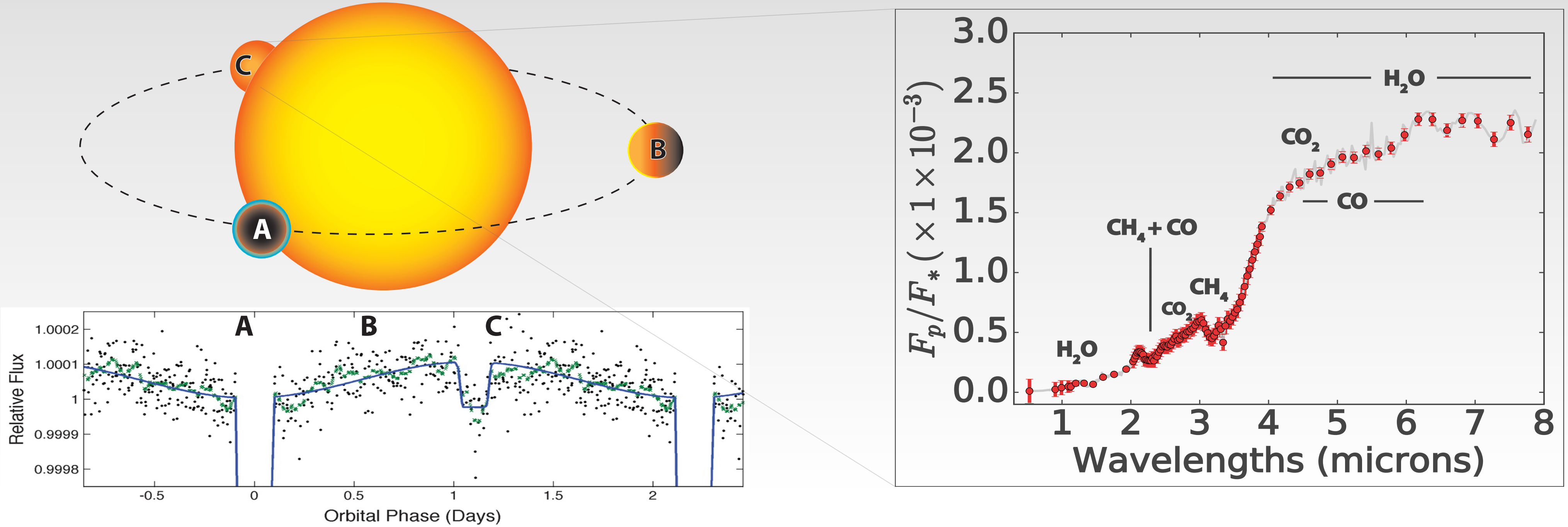


Simultaneous observations in the VIS and IR are needed

TRANSIT, ECLIPSE, PHASE-CURVE SPECTROSCOPY

AIMING AT 10 PPM STELLAR FLUX AT MULTIPLE WAVELENGTHS

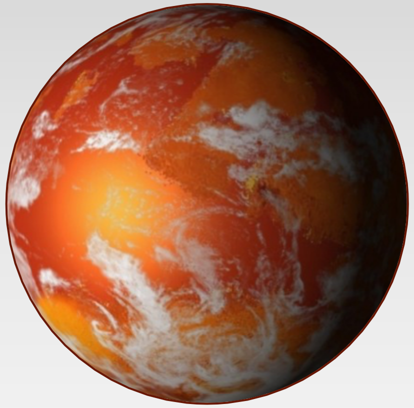
Through stable instrument, external calibration & proven postprocessing analysis



ARIEL KEY SCIENCE QUESTIONS

INDIVIDUAL PLANET

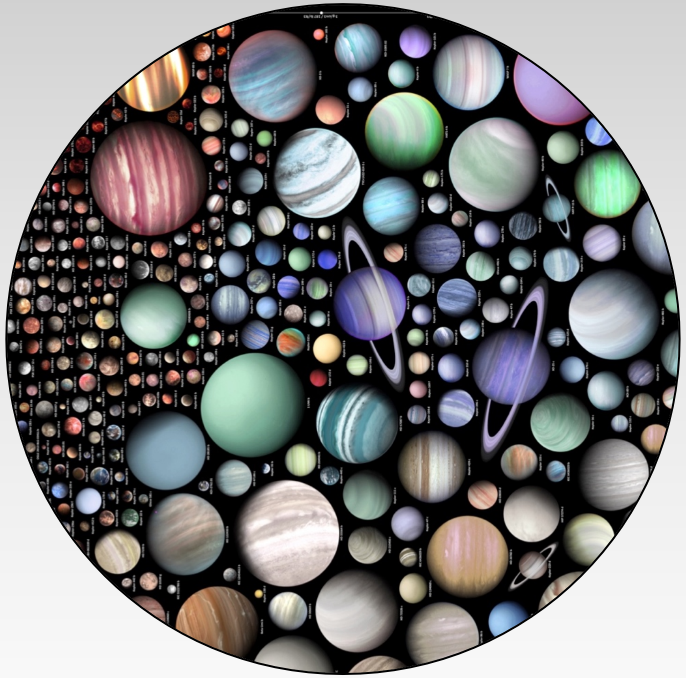
- **Individual planet: Instant & short-term variability**
    - Chemical composition
    - Atmospheric circulation + cloud pattern
    - Equilibrium or non-equilibrium chemistry?
    - Impact with stellar environment
- **Individual planet: Formation & long-term evolution**
    - Elemental composition
    - Coupling interior-atmosphere
    - Impact of stellar environment & system history



ARIEL KEY SCIENCE QUESTIONS

LARGE POPULATION OF DIVERSE PLANETS

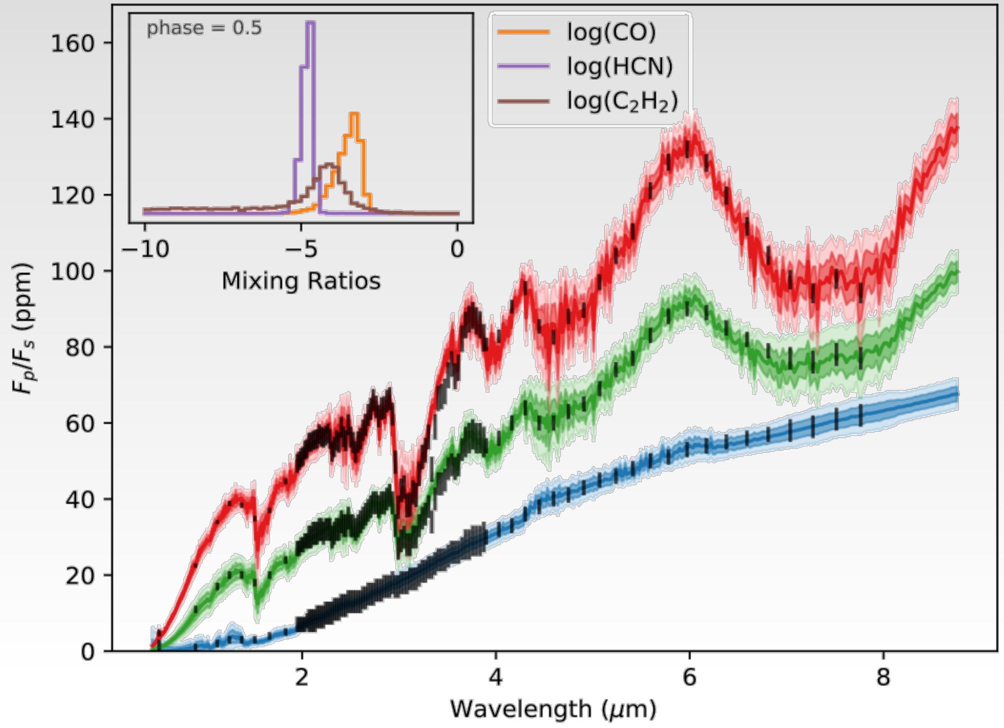
- **Large population: Instant & short-term variability**
  - Chemical diversity
  - Correlation chemistry - other parameters
  - Correlation clouds–temperature-stellar-type
  - How fast atmospheres change through time?
- **Large population: Formation & long-term evolution**
  - Correlation elemental composition planet provenance
  - Correlation elemental composition stellar metallicity
  - Coupling atmosphere-interior through time
  - Transition between terrestrial planets and sub-Neptunes

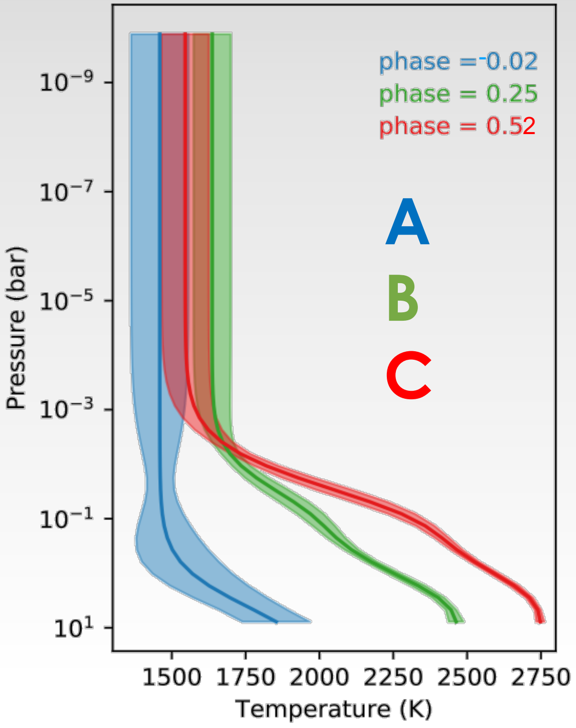


INSTANT & SHORT-TERM VARIABILITY

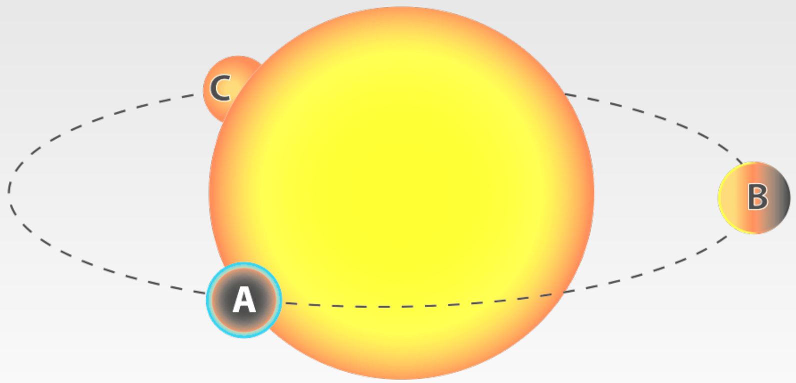
(NON)-EQUILIBRIUM CHEMISTRY? ATMOSPHERIC CIRCULATION? CLOUD PATTERN?

ARIEL phase-curve spectra, chemical composition & thermal profile





Planet orbiting around the star

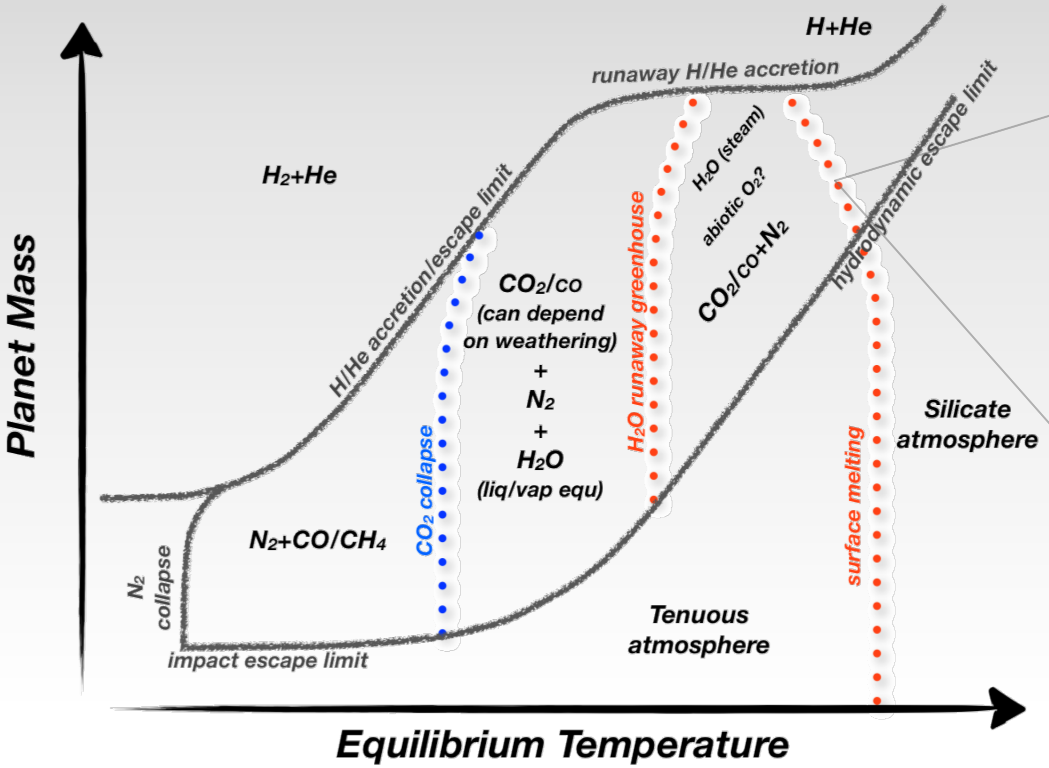


Snap-shots of an animation available at: http://bit.ly/2kGL4Wz

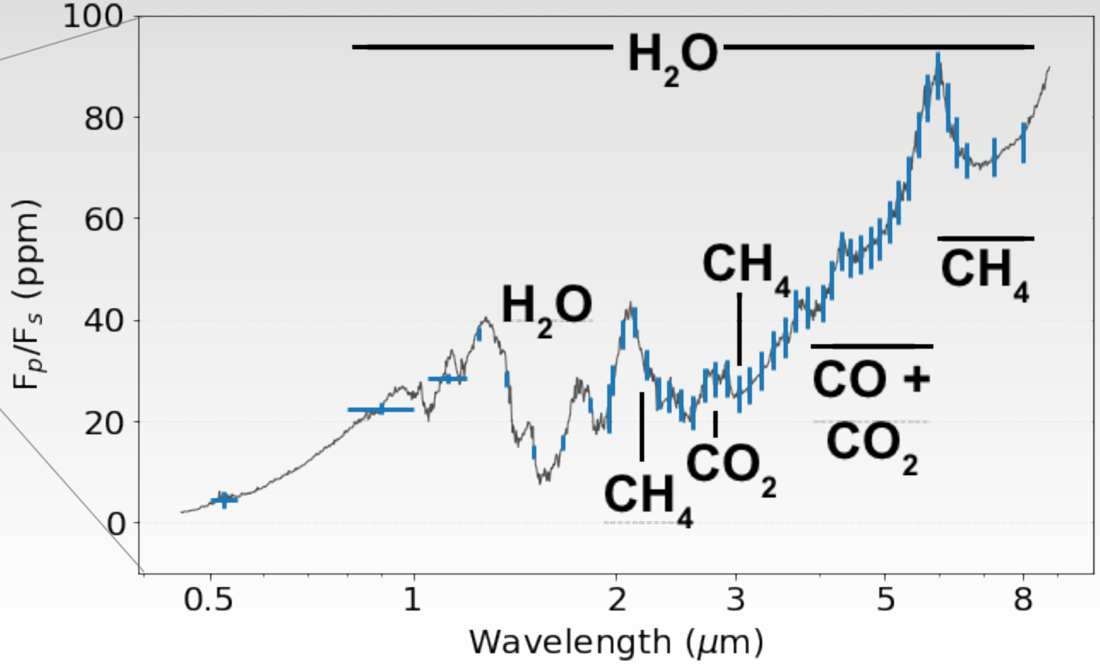
CHEMICAL DIVERSITY

CORRELATION WITH ANY OTHER KEY PARAMETERS?

Is this plot true? Where are the transitions?



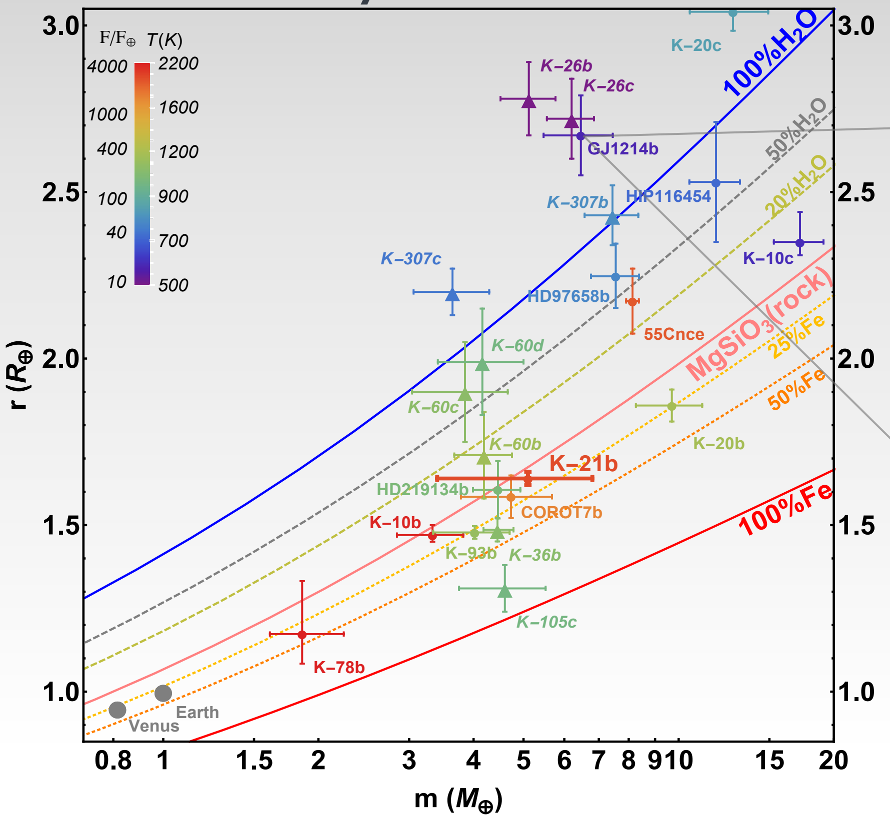
ARIEL observations x 1000 planets



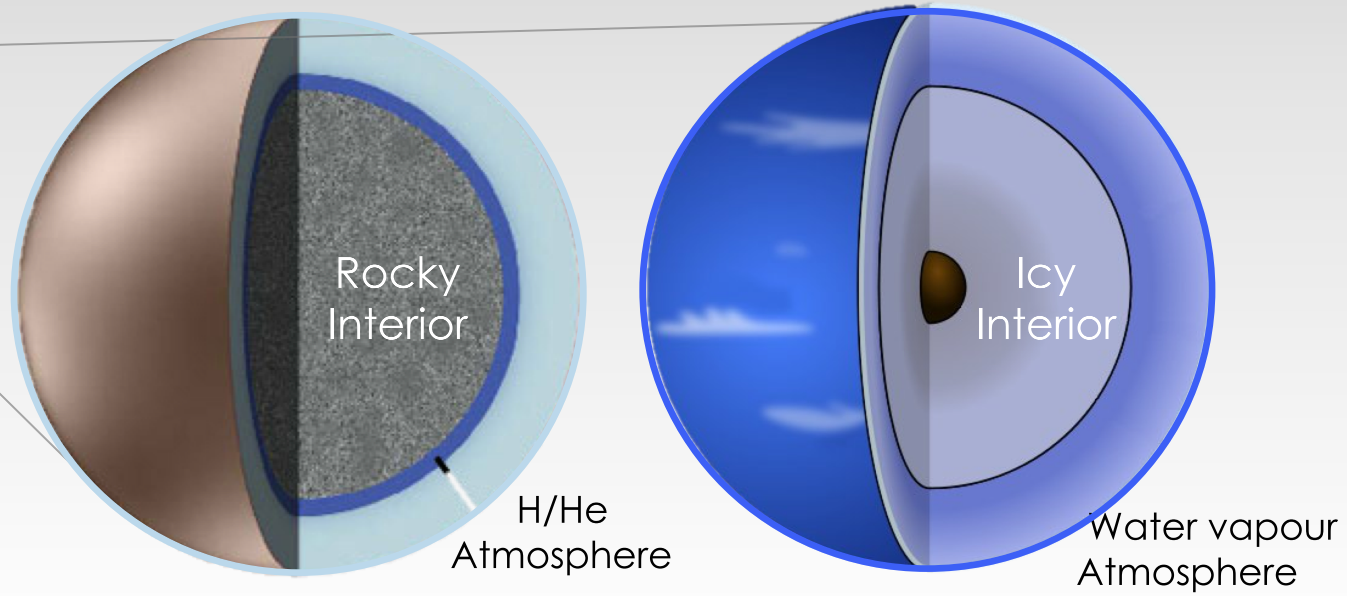
CHEMICAL DIVERSITY

ARIEL WILL CLARIFY CORRELATION WITH THE DENSITY

Density observations



Atmospheric composition through ARIEL will clarify the degeneracy

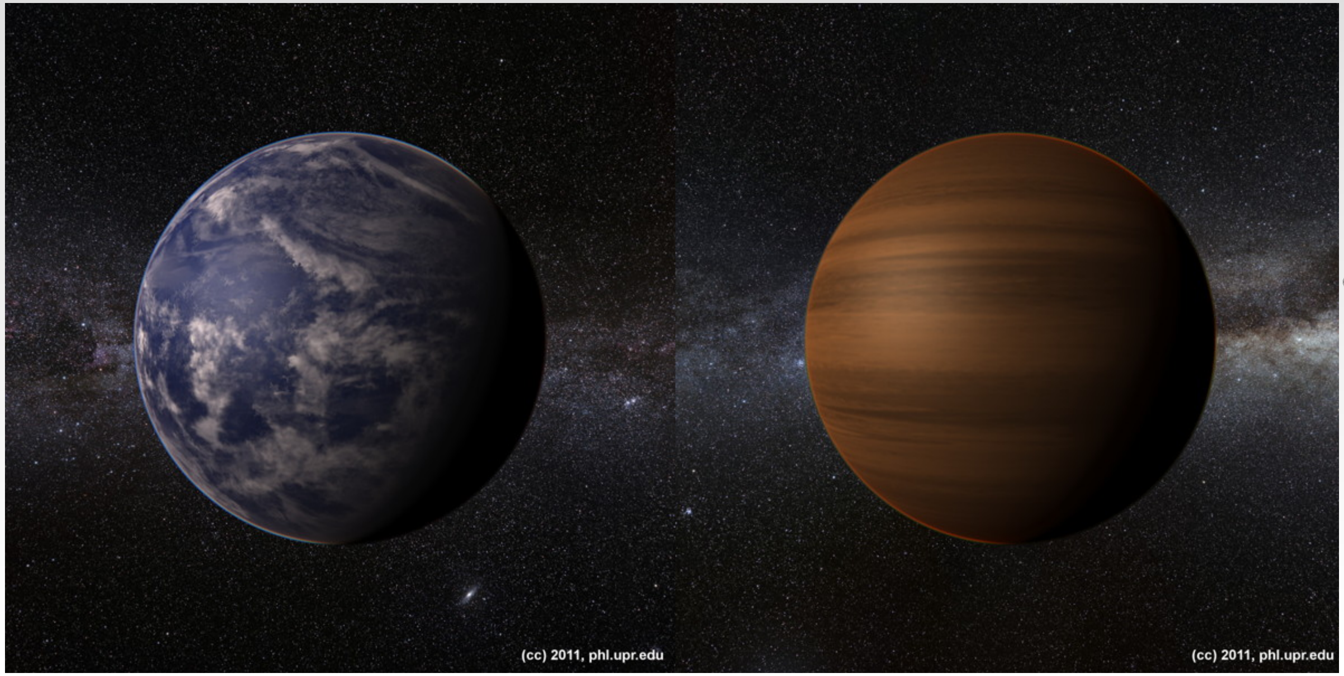


Same mean density – Different atmospheric signatures

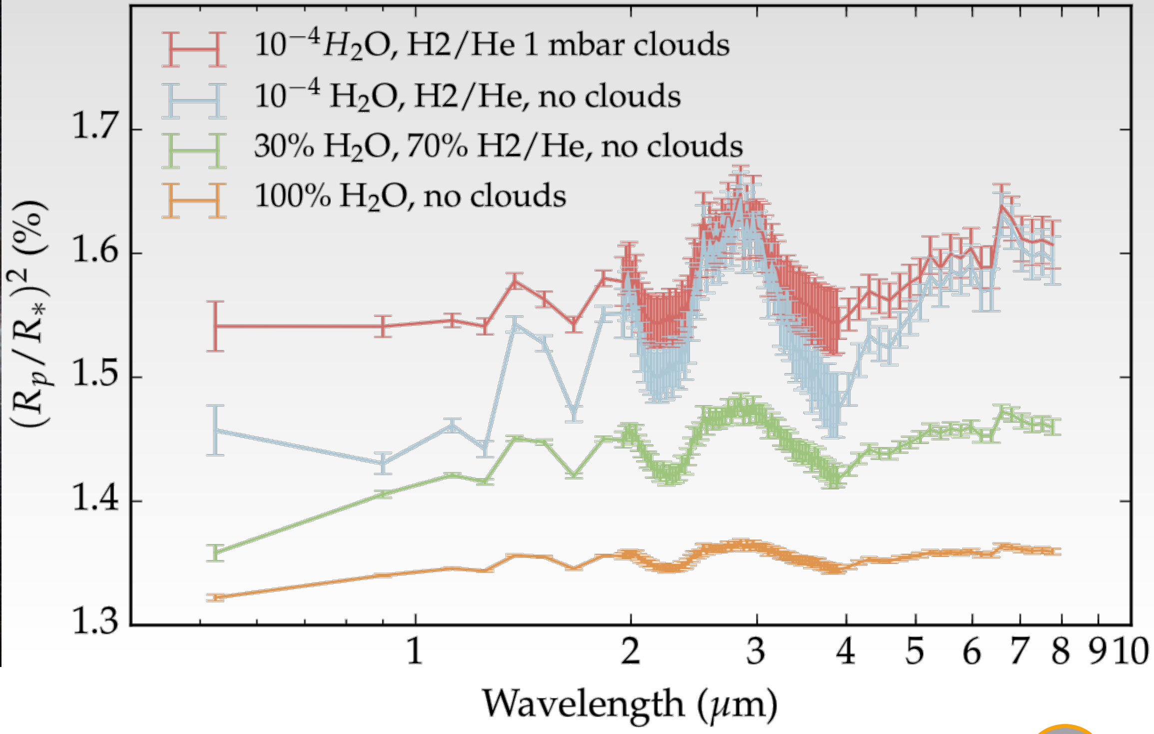
TERRESTRIAL-SUBNEPTUNES TRANSITION

ARE SUPER-EARTHS BIG TERRESTRIAL PLANETS, SMALL NEPTUNES? IS H/HE STILL THERE?

Formation scenarios for small planets

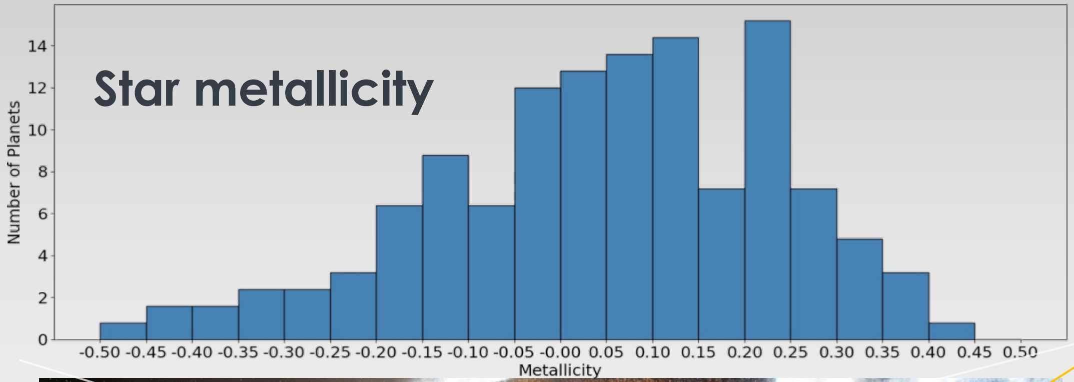


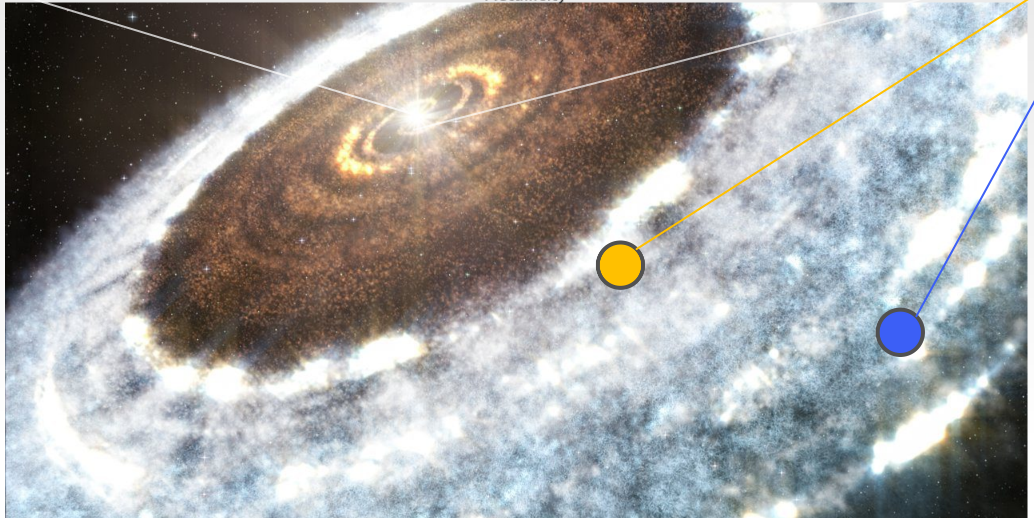
ARIEL observations for small planets

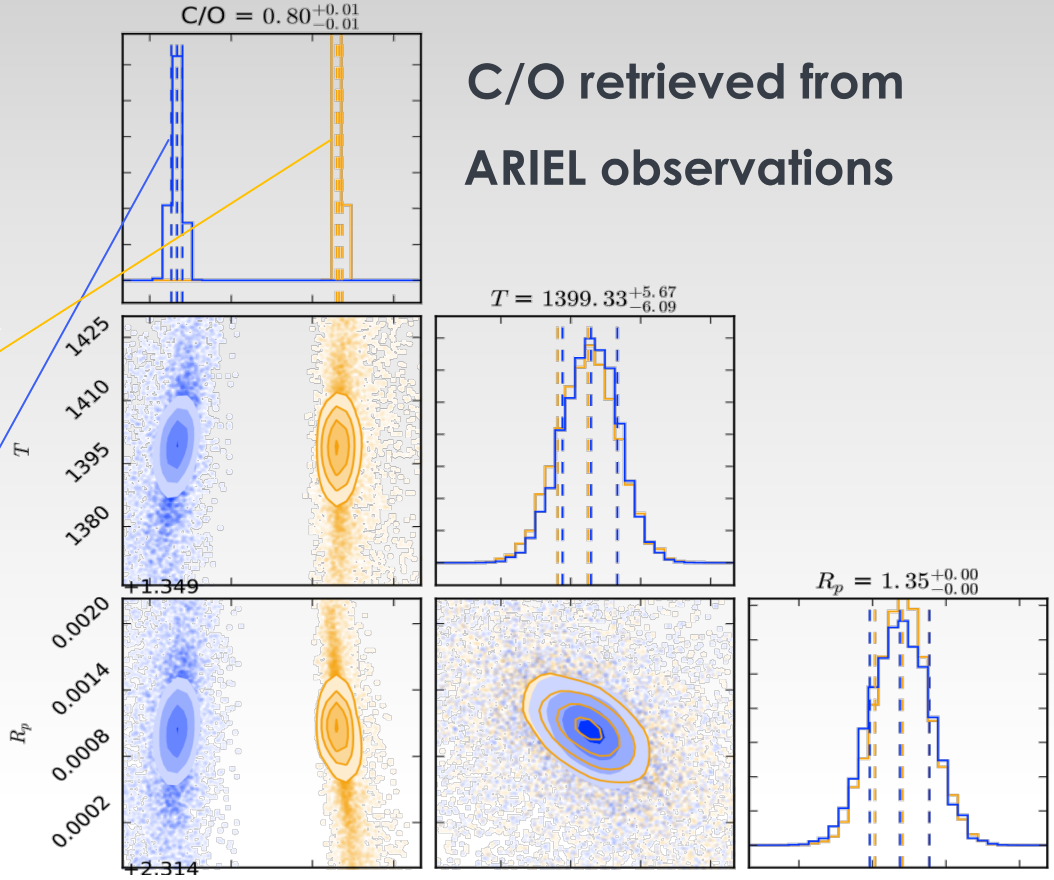


IS ELEMENTAL COMPOSITION CORRELATED …

…TO EXOPLANET PROVENANCE OR STELLAR METALLICITY?





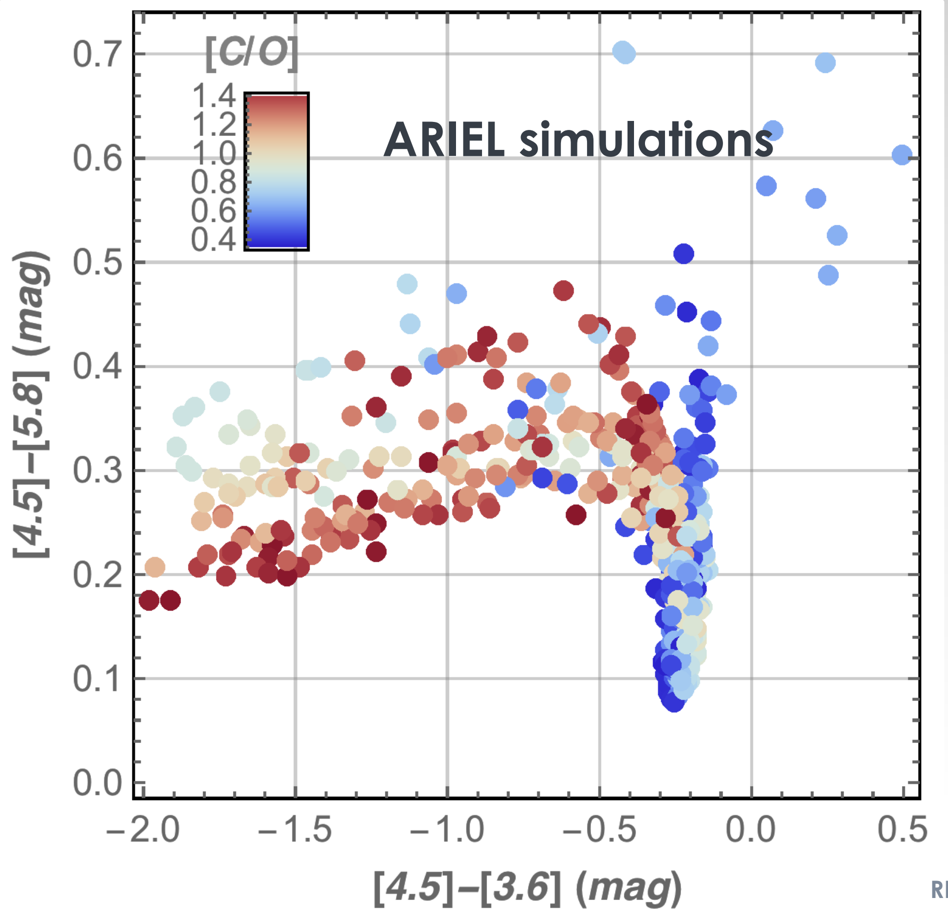


C/O retrieved from ARIEL observations

POPULATION ANALYSIS

COLOUR-MAGNITUDE DIAGRAMS, CLOUD-CHARACTERISATION

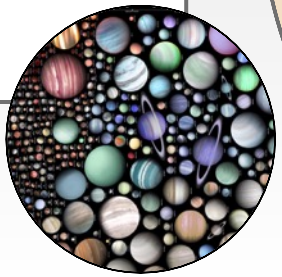
- Colour-colour diagrams and colour-magnitude diagrams in the IR and VIS will allow to identify **families of planets**

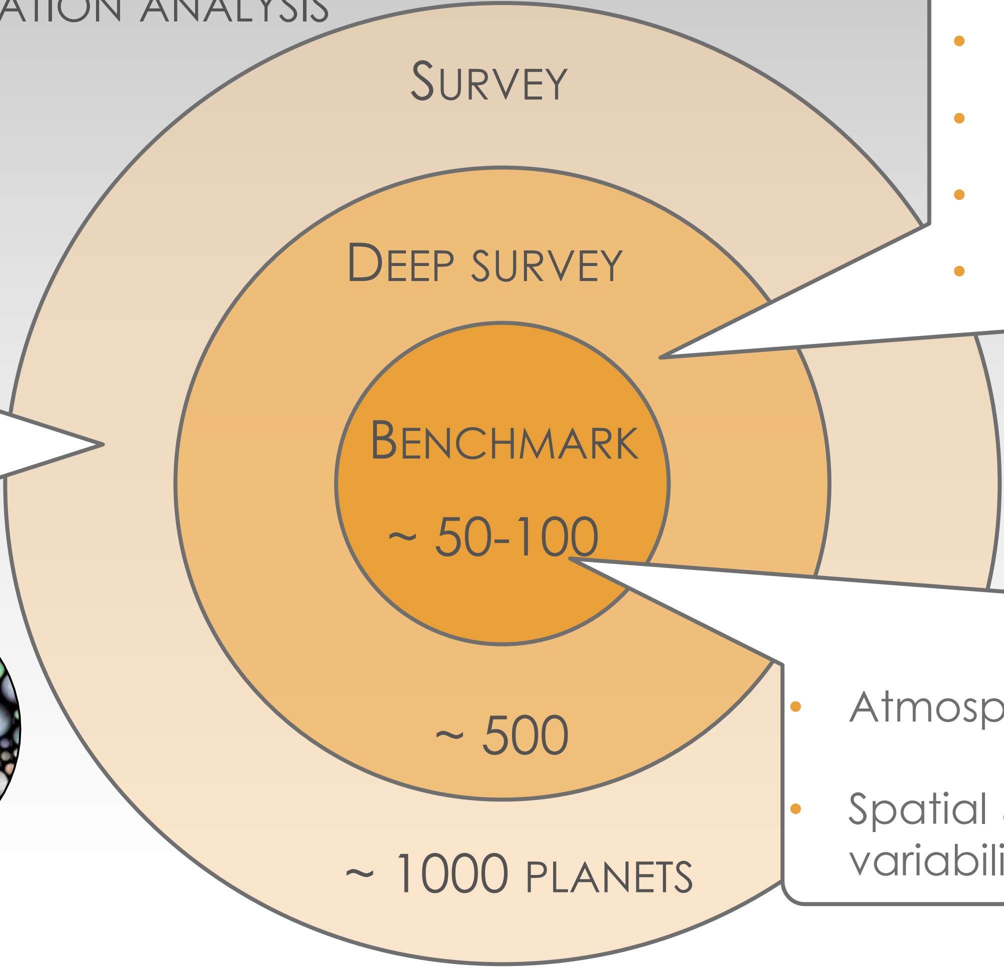


ARIEL 3-TIER APPROACH

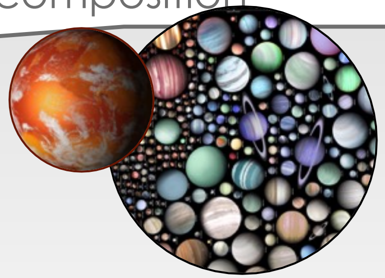
INDIVIDUAL PLANETS & POPULATION ANALYSIS

- What fraction of planets have clouds?
- Have small planets still retained H/He?
- Colour-colour diagrams
- Refinement of orbital/planet parameters in IR

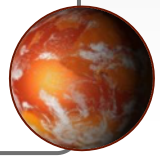




- Main atmospheric component
- Trace gases
- Thermal structure
- Cloud characterization
- Elemental composition

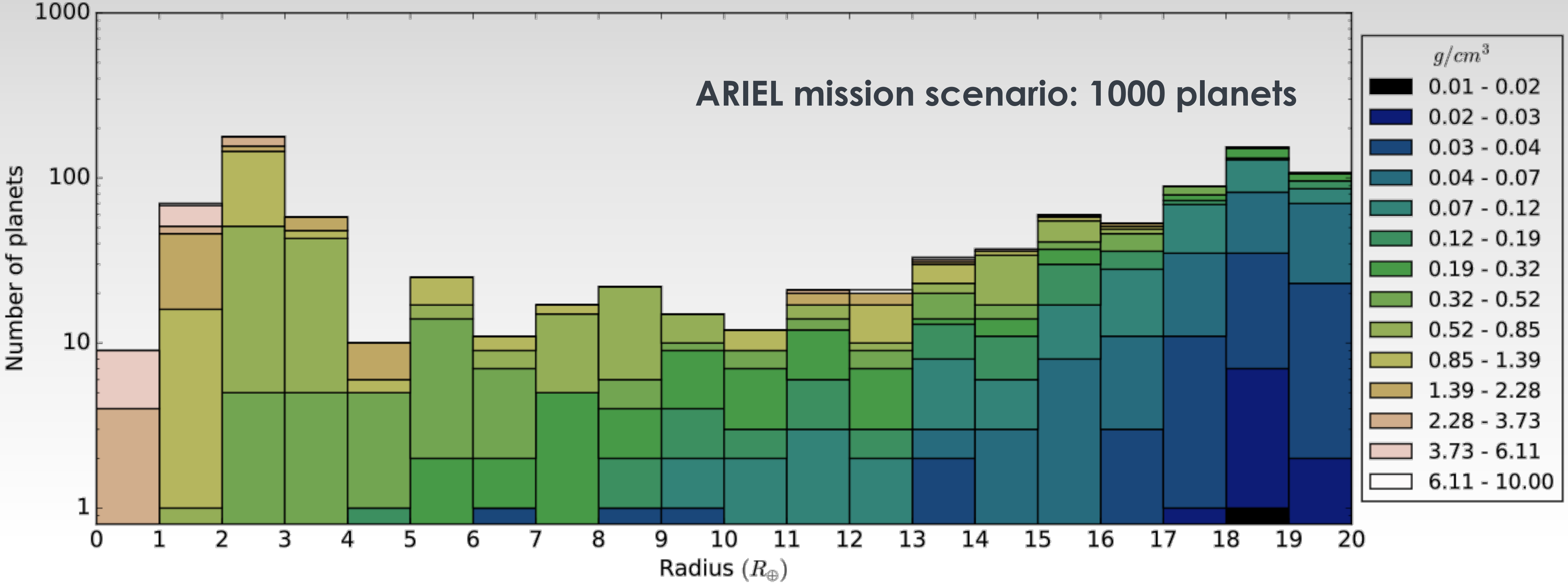


- Atmospheric circulation
- Spatial & temporal variability



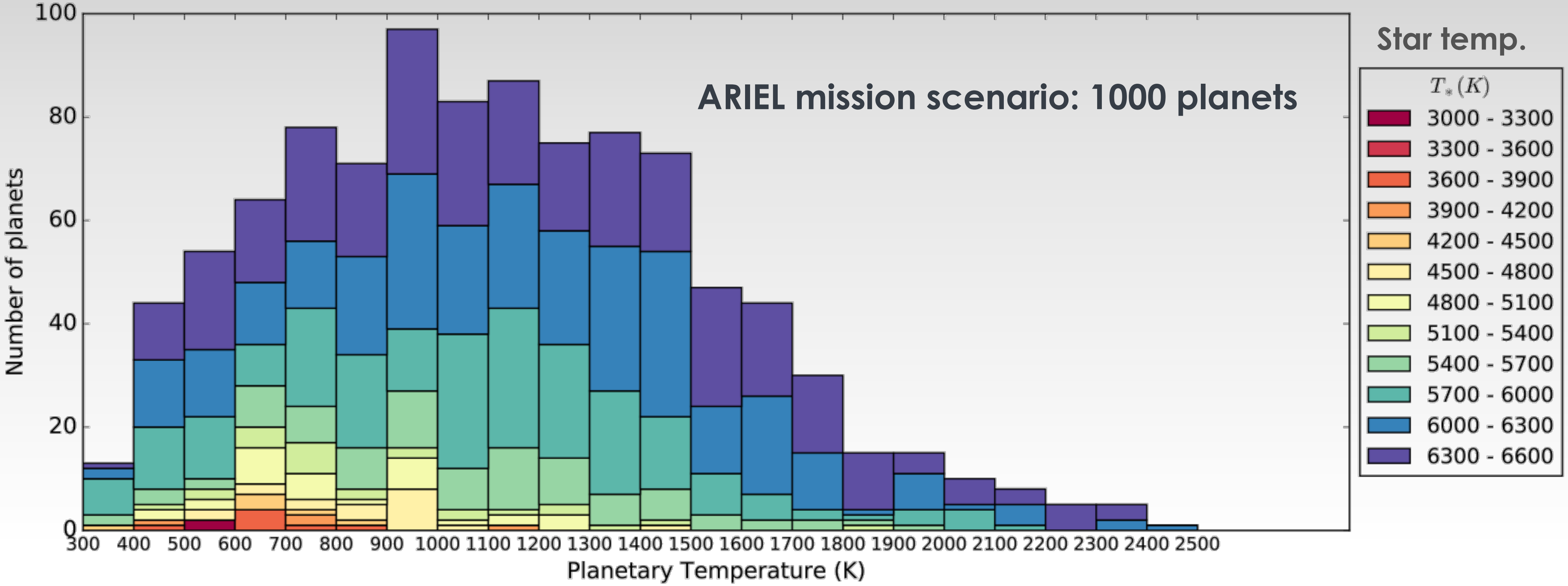
DIVERSITY PROBED IN ARIEL CORE SAMPLE

PLANET SIZE, DENSITY, TEMPERATURE, STAR TYPE, METALLICITY



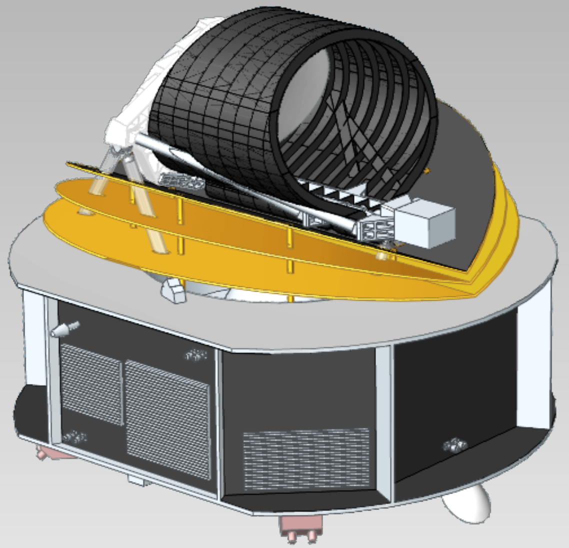
DIVERSITY PROBED IN ARIEL CORE SAMPLE

PLANET SIZE, DENSITY, **TEMPERATURE, STAR TYPE**, METALLICITY



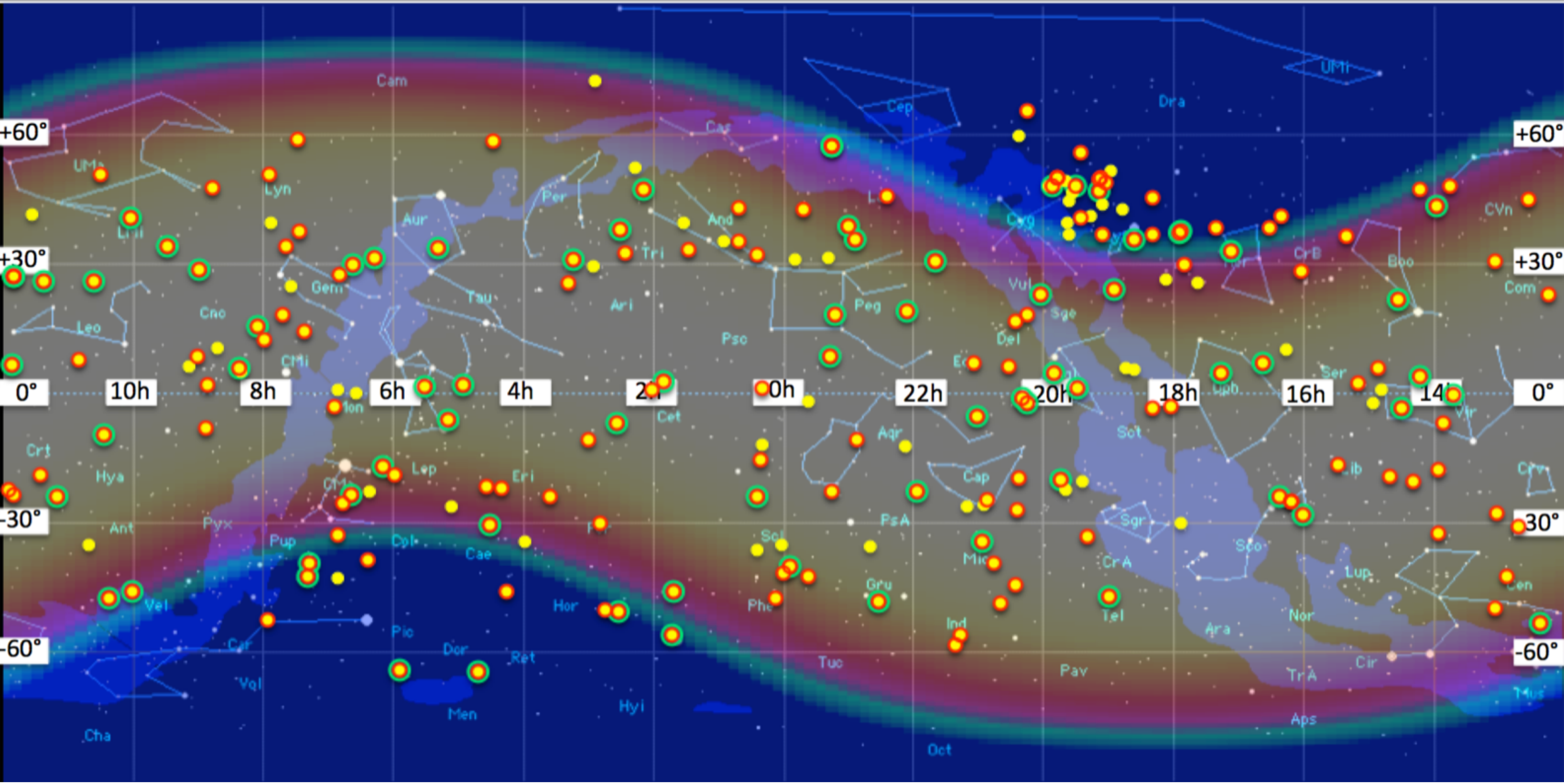
ARIEL – KEY REQUIREMENTS

- > 0.6m^2 collecting area telescope, high throughput
- Diffraction limited performance beyond 3 microns; minimal FoV required
- Observing efficiency of > 85%
- Brightest Target: K_{mag} = 3.25 (HD219134);
- Faintest target: K_{mag} = 8.8 (GJ1214)
- Photon noise dominated
- Temporal resolution of 90 seconds (goal 1s for phot. channels)
- Average observation time = 7.7 hours, separated by 70° on sky from next target
- Continuous spectral coverage between spectral bands.



Channel Name	Wavelength (μm)	Spectral Resolution Reqt / Design
VisPhot	0.5 – 0.55	Photometer
FGS-1	0.8 – 1.0	Photometer
FGS-2	1.05 – 1.2	Photometer
NIRSpec	1.25 – 1.95	R≥10 / 20 – 25
AIRS-Ch0	1.95 – 3.9	R≥100 / 102 – 180
AIRS-Ch1	3.9 – 7.8	R≥30 / 30 – 64


AIV
Coolers
Dichroics
Cold Payload Units
Telescope
Optical Bench
FGS
Common Optics
IR Spectrometer
Thermal Hardware
Cryoharness
Warm Payload Units
FGS Electronics
Instrument Control Unit
Telescope Control Unit
S/C CDMS
AIRS Spectrograph
Detector
Camera
Slit
Collimator
Prism
Fold Mirror
Detector
FGS Channel
Telescope
V-grooves
Tip-tilt
ARIEL



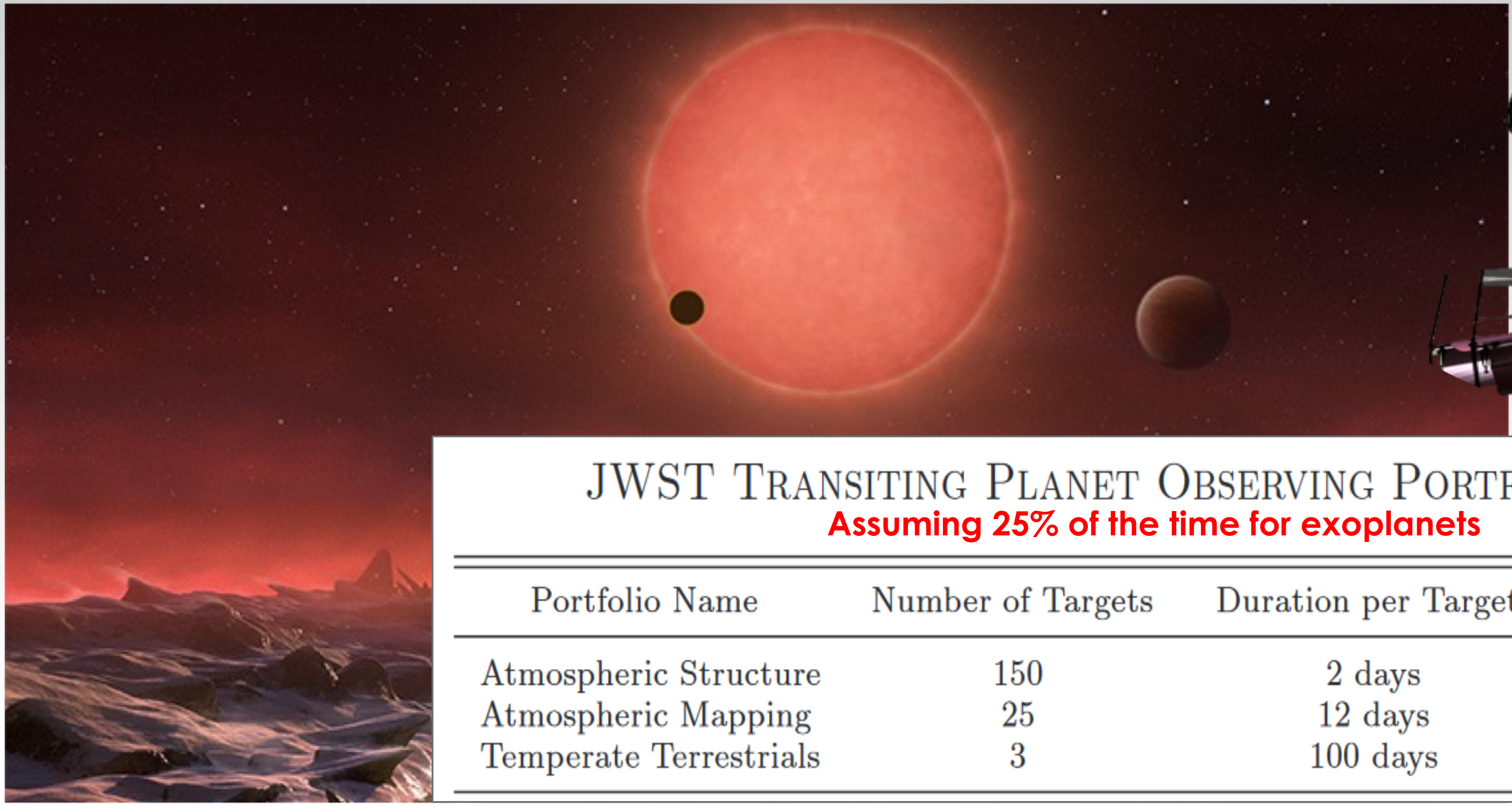
Instantaneous Sky Visibility

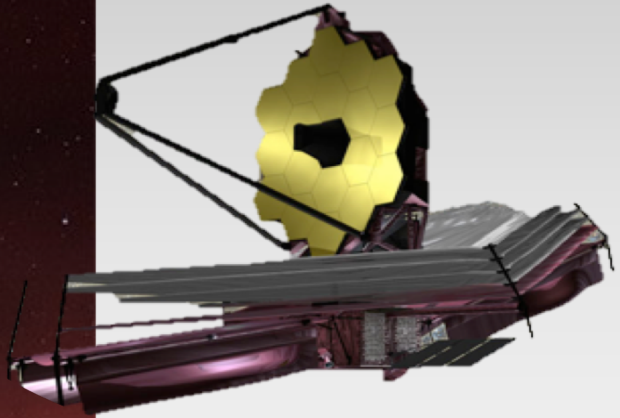
100% 80% 60% 40%

- Survey
- Deep
- Benchmark

SYNERGIES/COMPLEMENTARITIES WITH JWST

JWST CANNOT OBSERVE 1000 PLANETS





JWST Transiting Planet Observing Portfolios

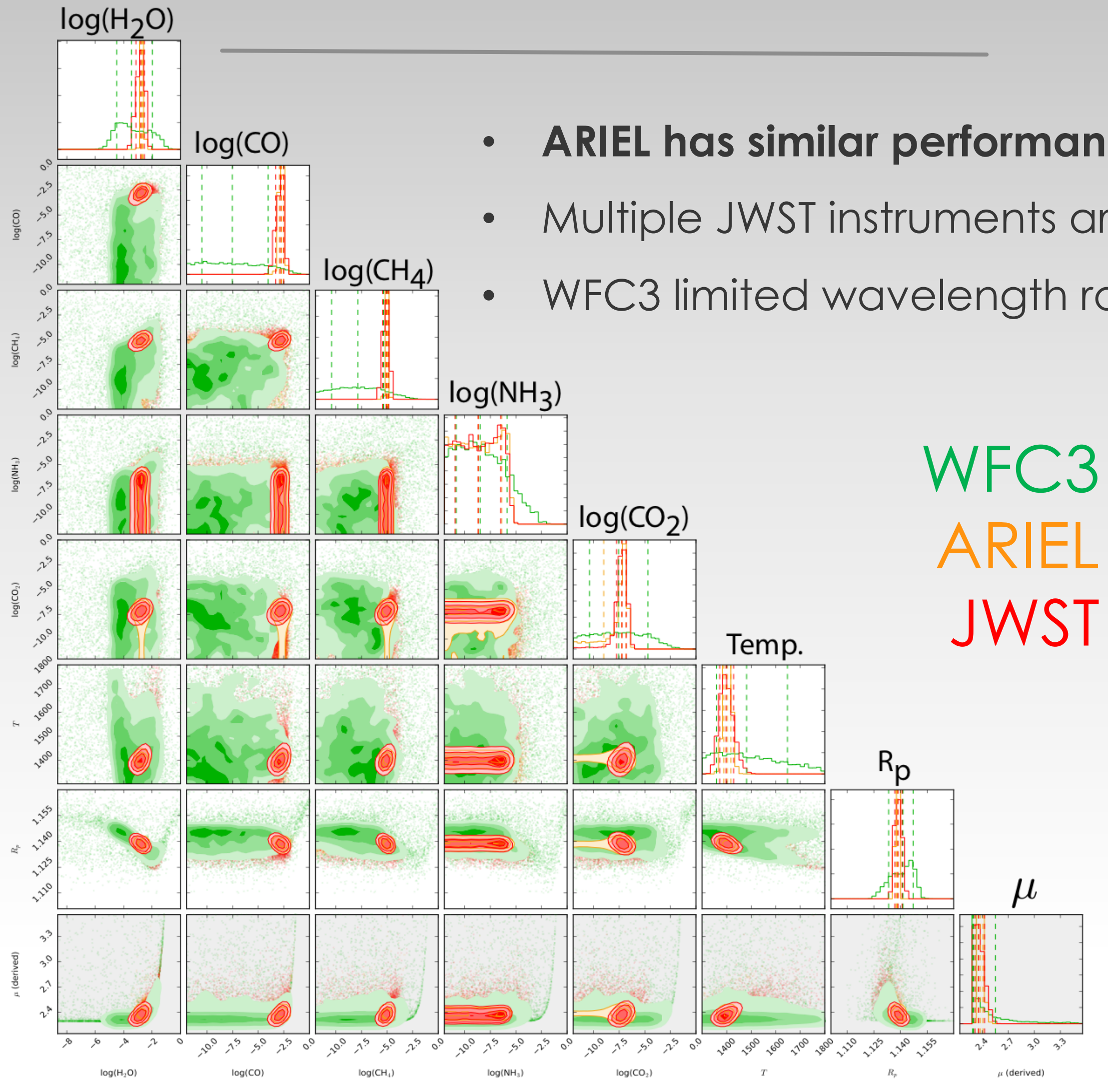
Assuming 25% of the time for exoplanets

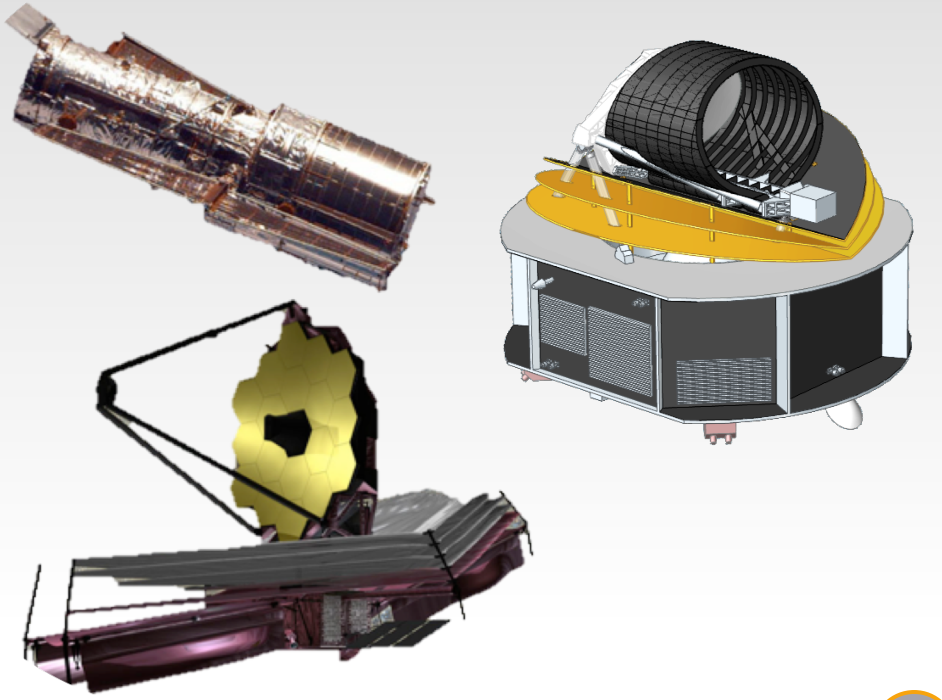
Portfolio Name	Number of Targets	Duration per Target	Total Time
Atmospheric Structure	150	2 days	300 days
Atmospheric Mapping	25	12 days	300 days
Temperate Terrestrials	3	100 days	300 days

Cowan et al. 2015

ARIEL OPTIMAL DESIGN & PERFORMANCES

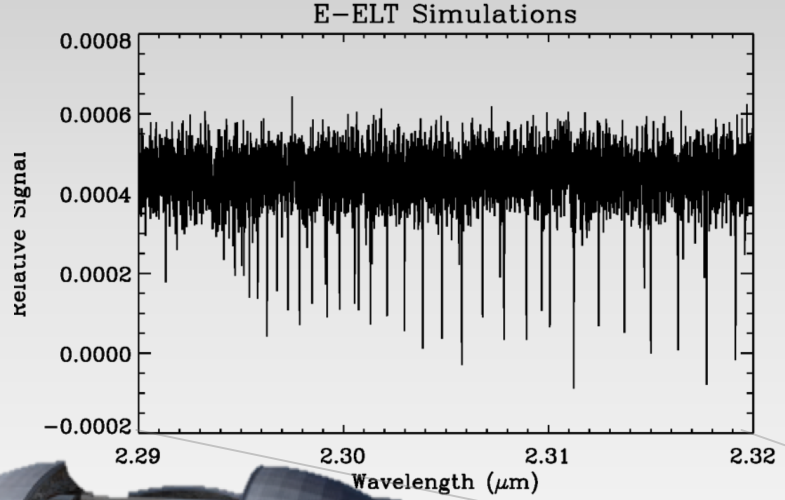
- **ARIEL has similar performances to JWST for warm/hot planets around bright stars**
- Multiple JWST instruments are combined here
- WFC3 limited wavelength range gives highly degenerate solutions

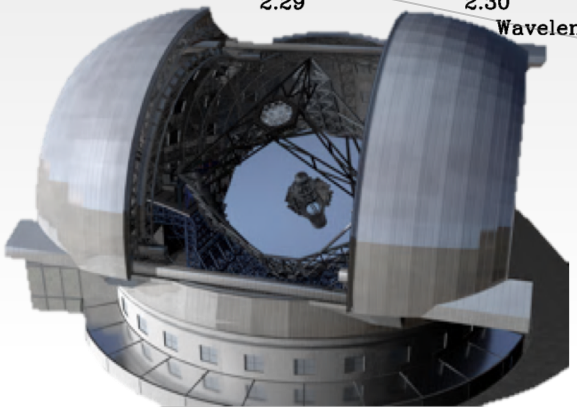


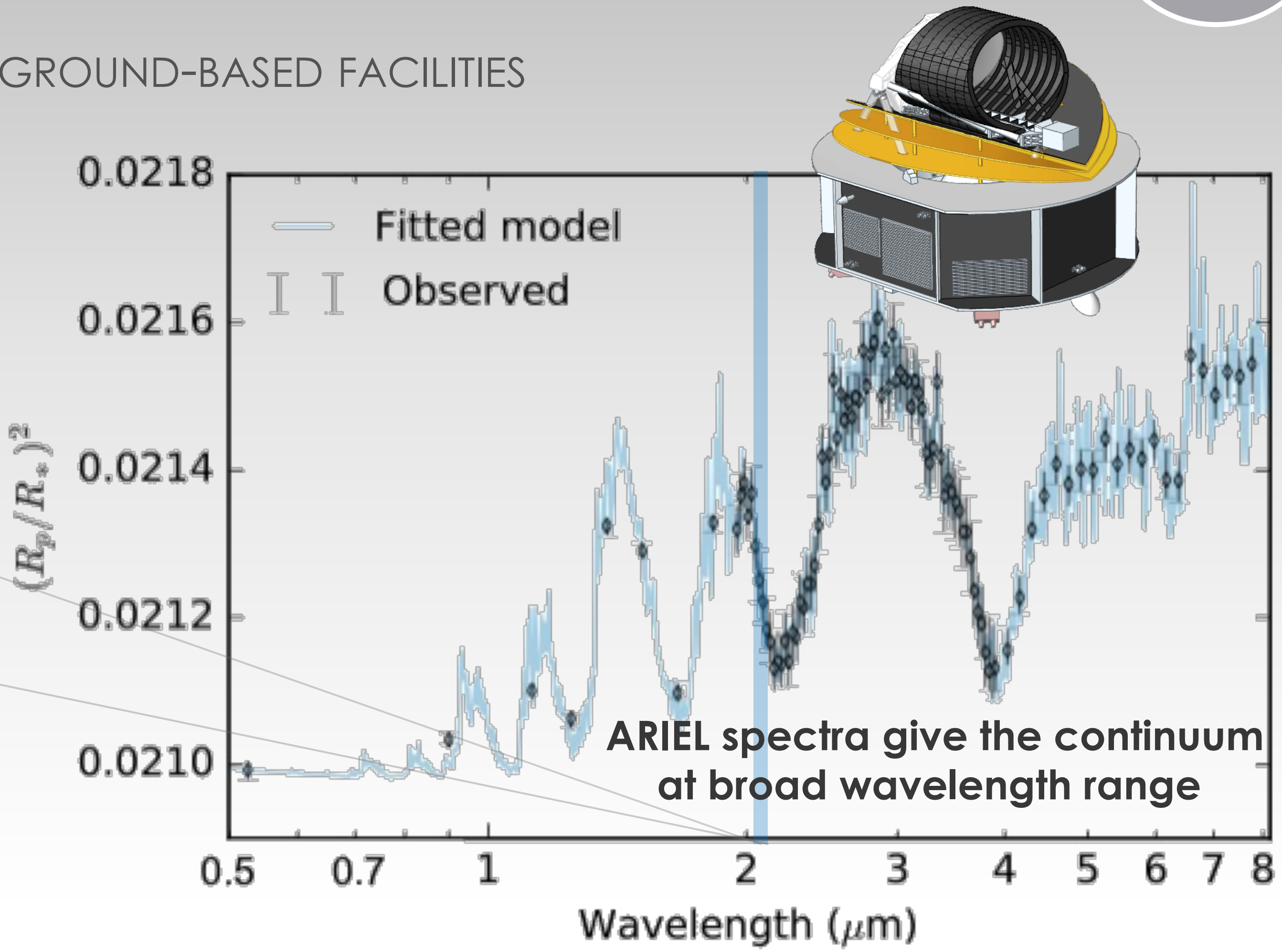


SYNERGIES/COMPLEMENTARITIES WITH ELT

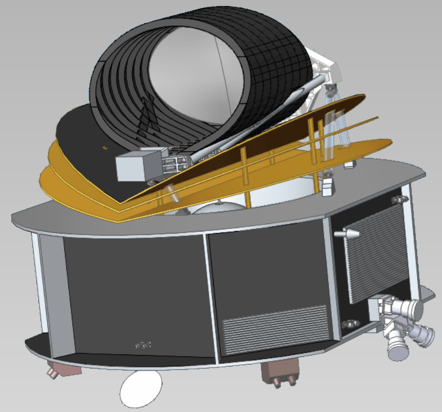
HIGHLY COMPLEMENTARY TO LARGE, GROUND-BASED FACILITIES







CONCLUSIONS



- Exoplanets appear to be ubiquitous in our Galaxy
- Current sample of discovered exoplanets is very diverse in terms of basic planetary/orbital parameters.
- Molecular & elemental composition can help to understand the nature and history of exoplanets
- Hubble, Spitzer, ground-based instruments have delivered pioneering observations of exoplanet atmospheres
- We need more accurate observations over a broader wavelength range (JWST) for a statistically large sample of planets (ARIEL) to understand the chemical diversity.
- ARIEL has been conceived to deliver the first chemical survey of ~ 1000 exoplanets, probing uniformly the gamut of planet and stellar parameters