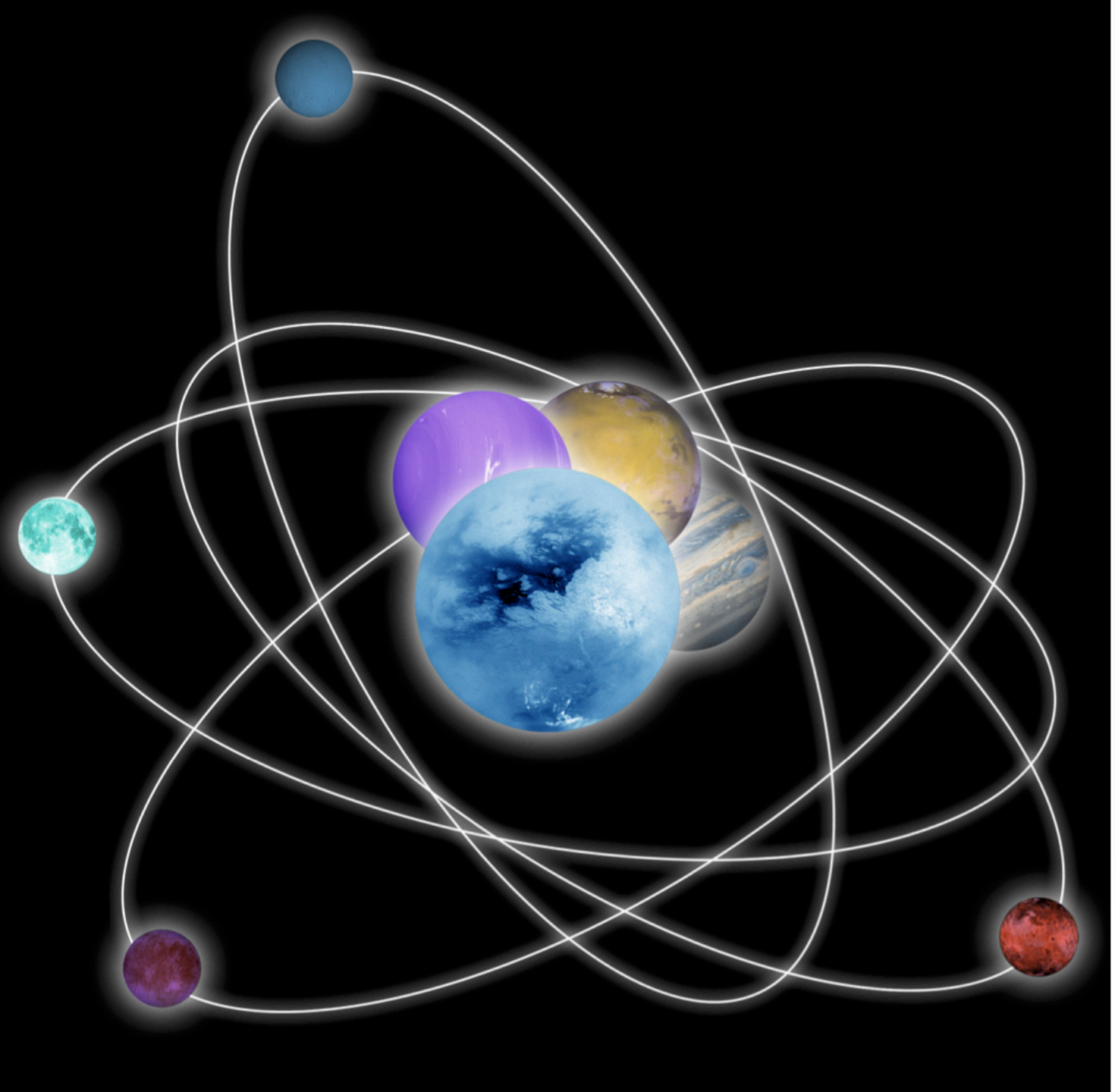


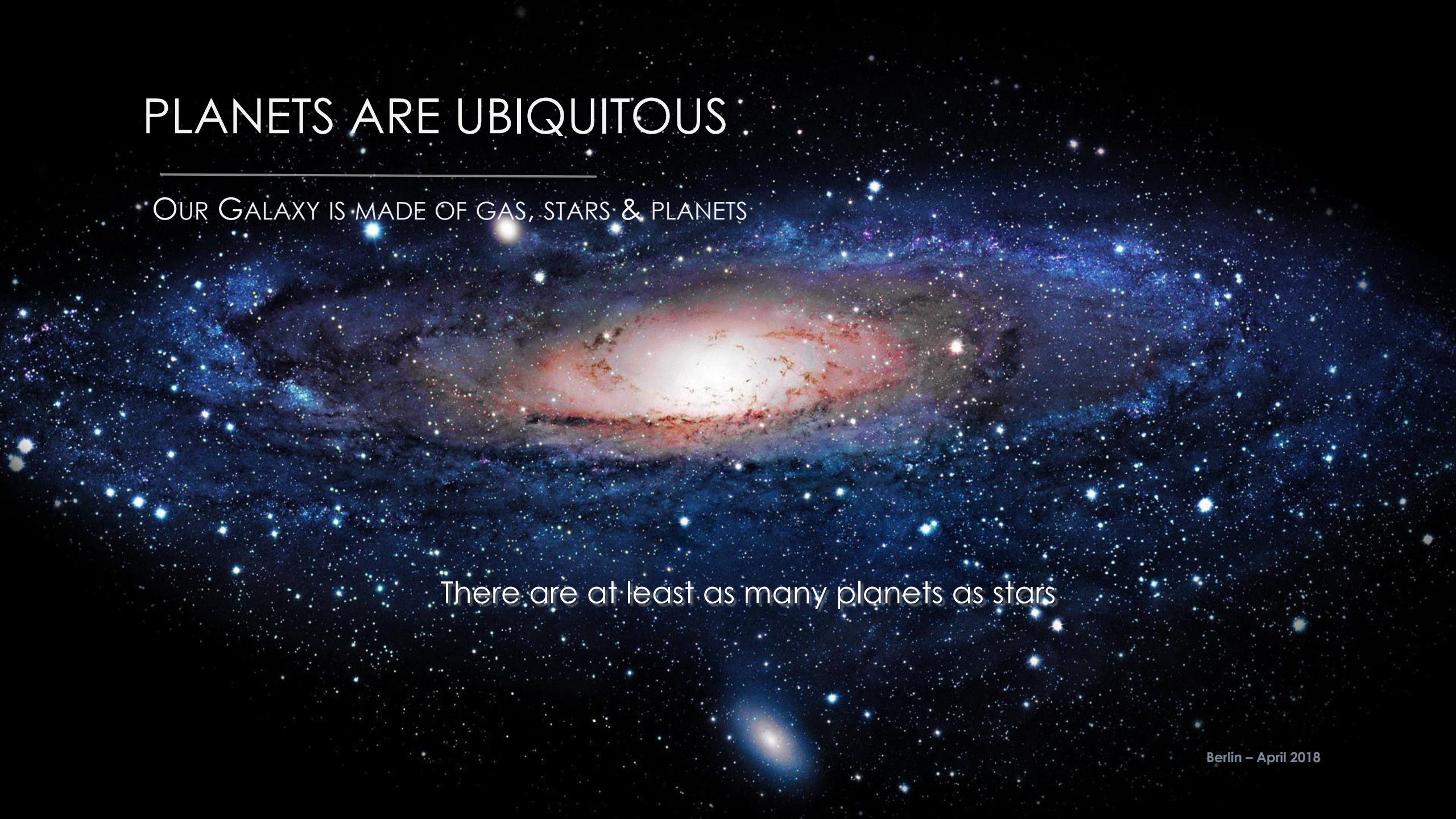
A chemical survey of Planets in our Galaxy

Giovanna Tinetti

Berlin – April 2018

PLANETS ARE UBIQUITOUS

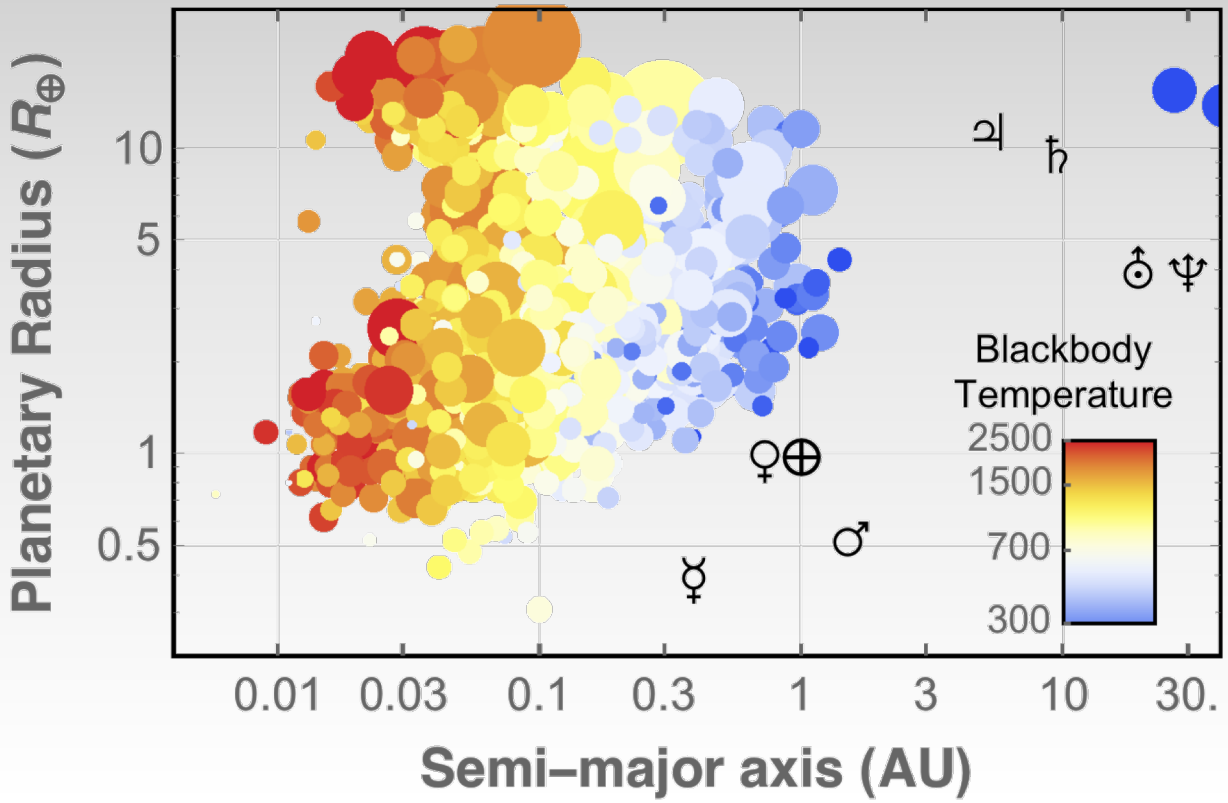
OUR GALAXY IS MADE OF GAS, STARS & PLANETS

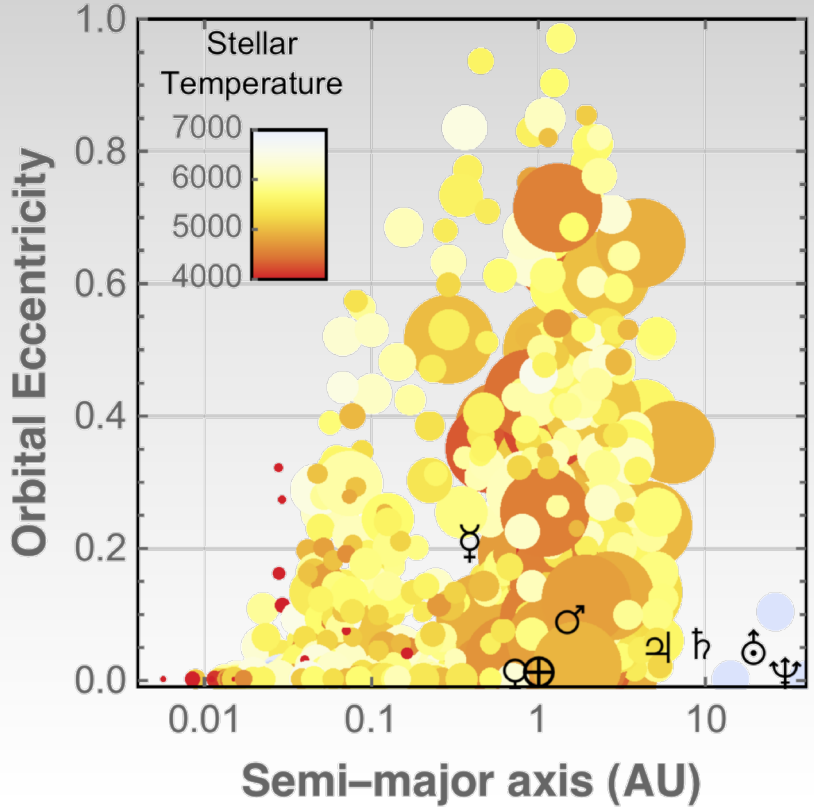


There are at least as many planets as stars

EXOPLANETS TODAY: HUGE DIVERSITY

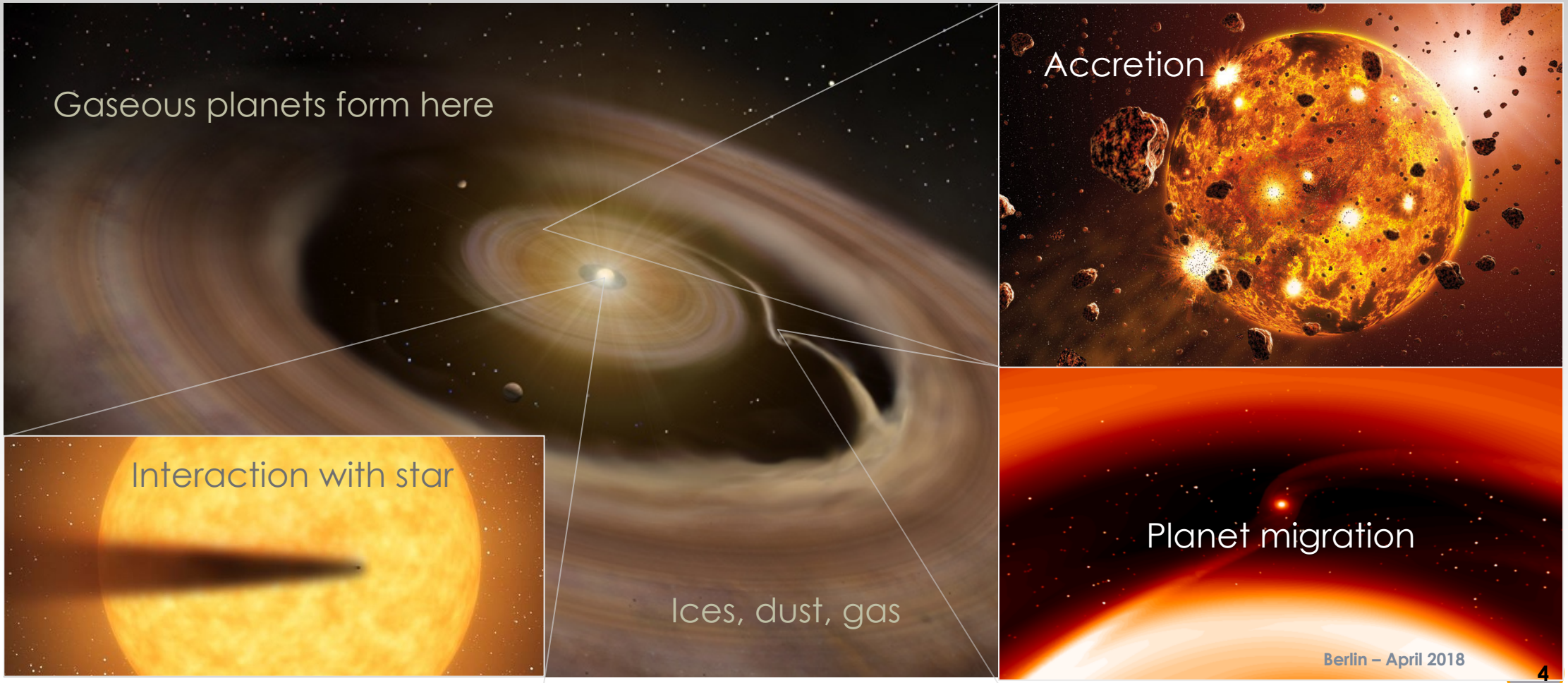
3800+ PLANETS, 2700 PLANETARY SYSTEMS KNOWN IN OUR GALAXY





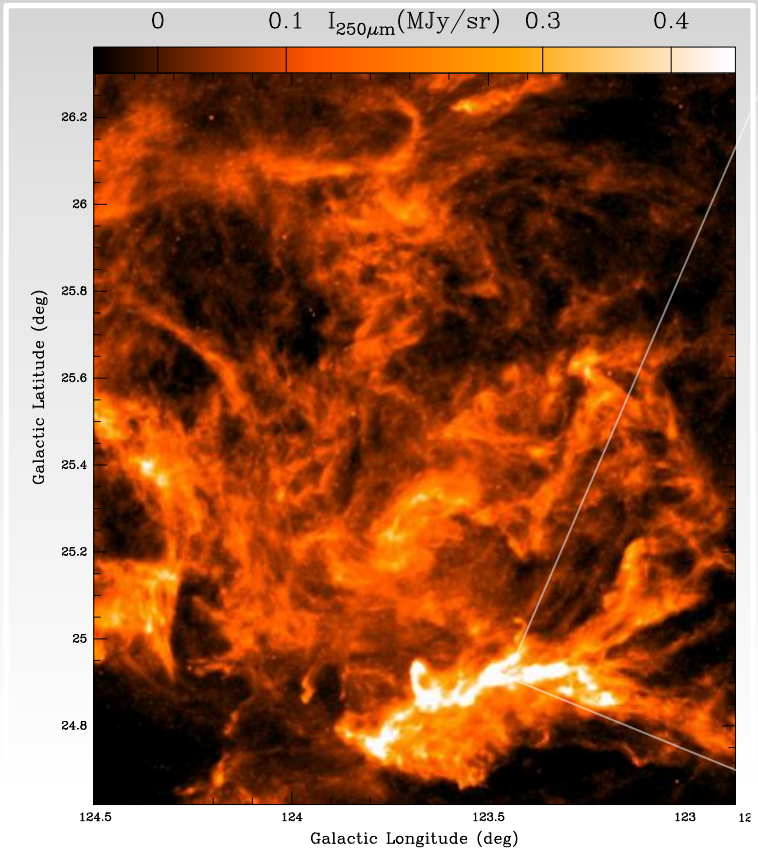
HUGE DIVERSITY: WHY?

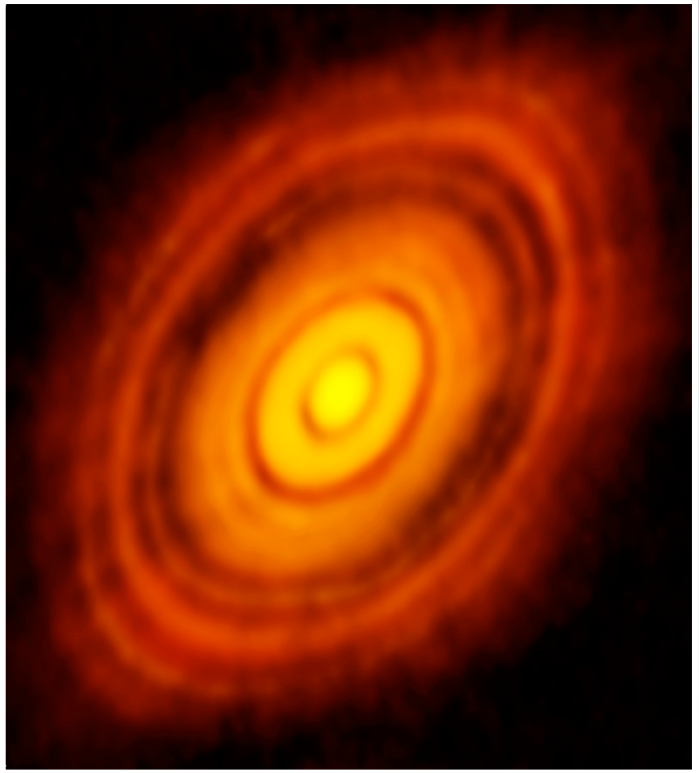
FORMATION & EVOLUTION PROCESSES? MIGRATION? INTERACTION WITH STAR?



STAR & PLANET FORMATION/EVOLUTION

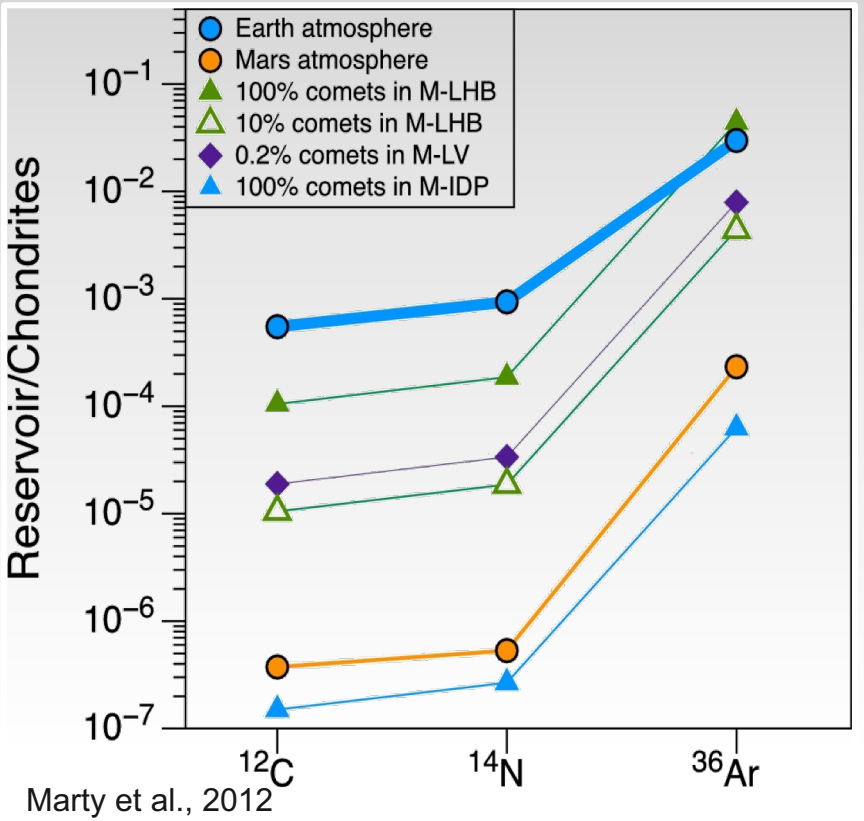
WHAT WE KNOW: CONSTRAINTS FROM OBSERVATIONS – HERSCHEL, ALMA, SOLAR SYSTEM





?

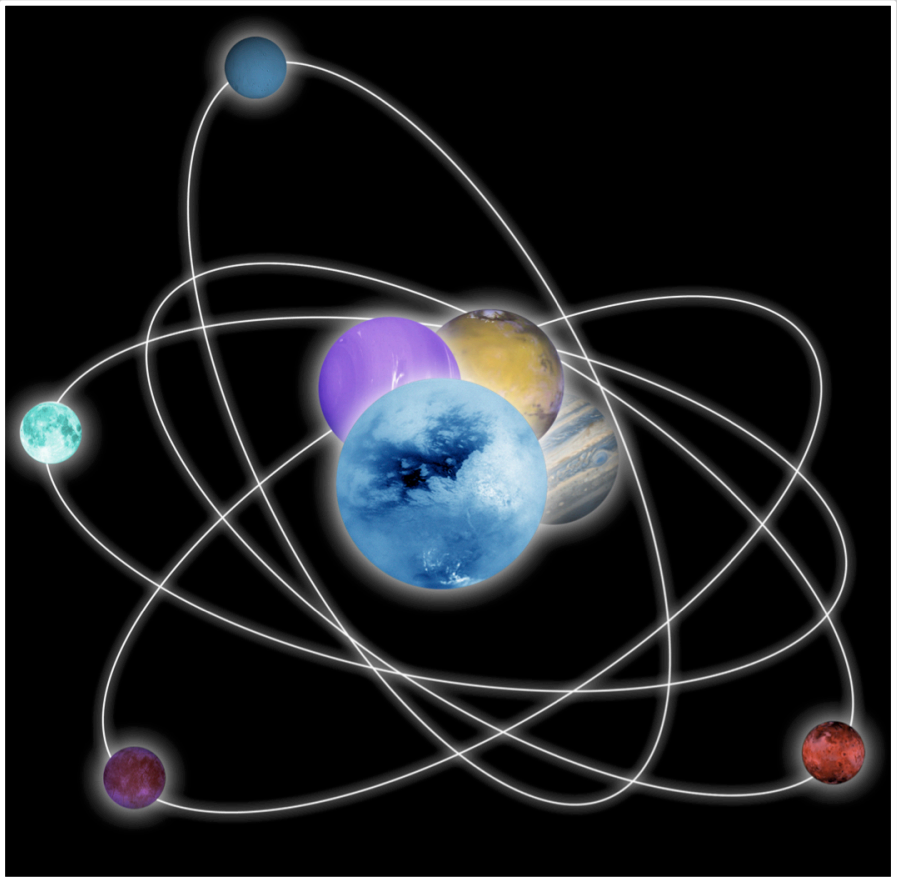
Measured elements in Solar system



Marty et al., 2012

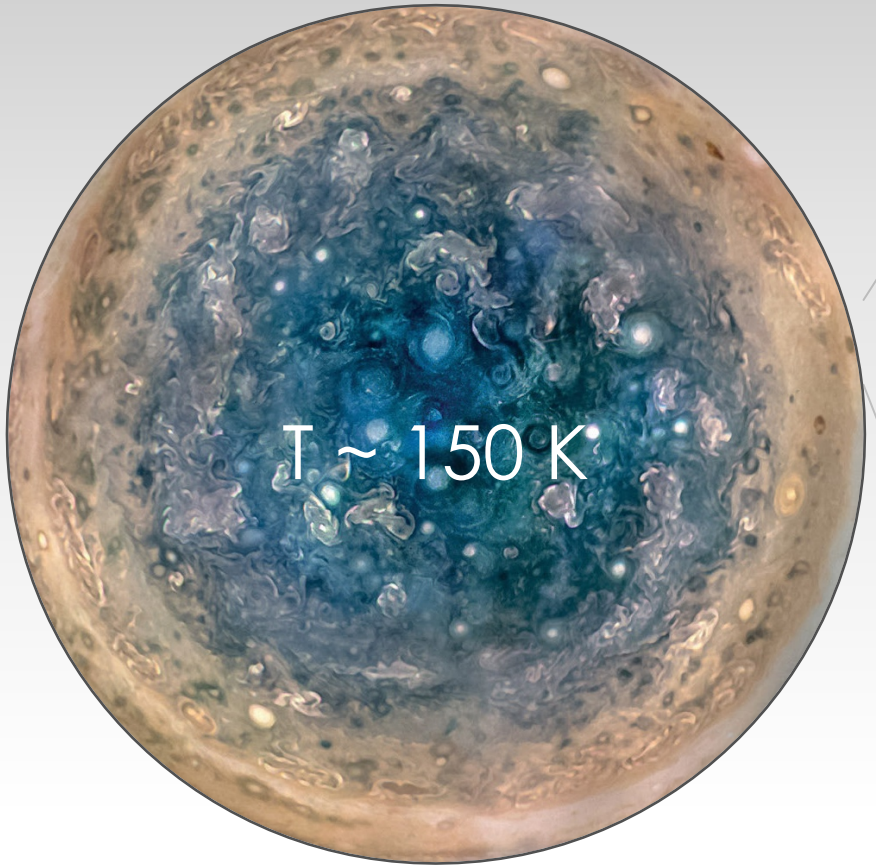
KEY EXOPLANET QUESTIONS

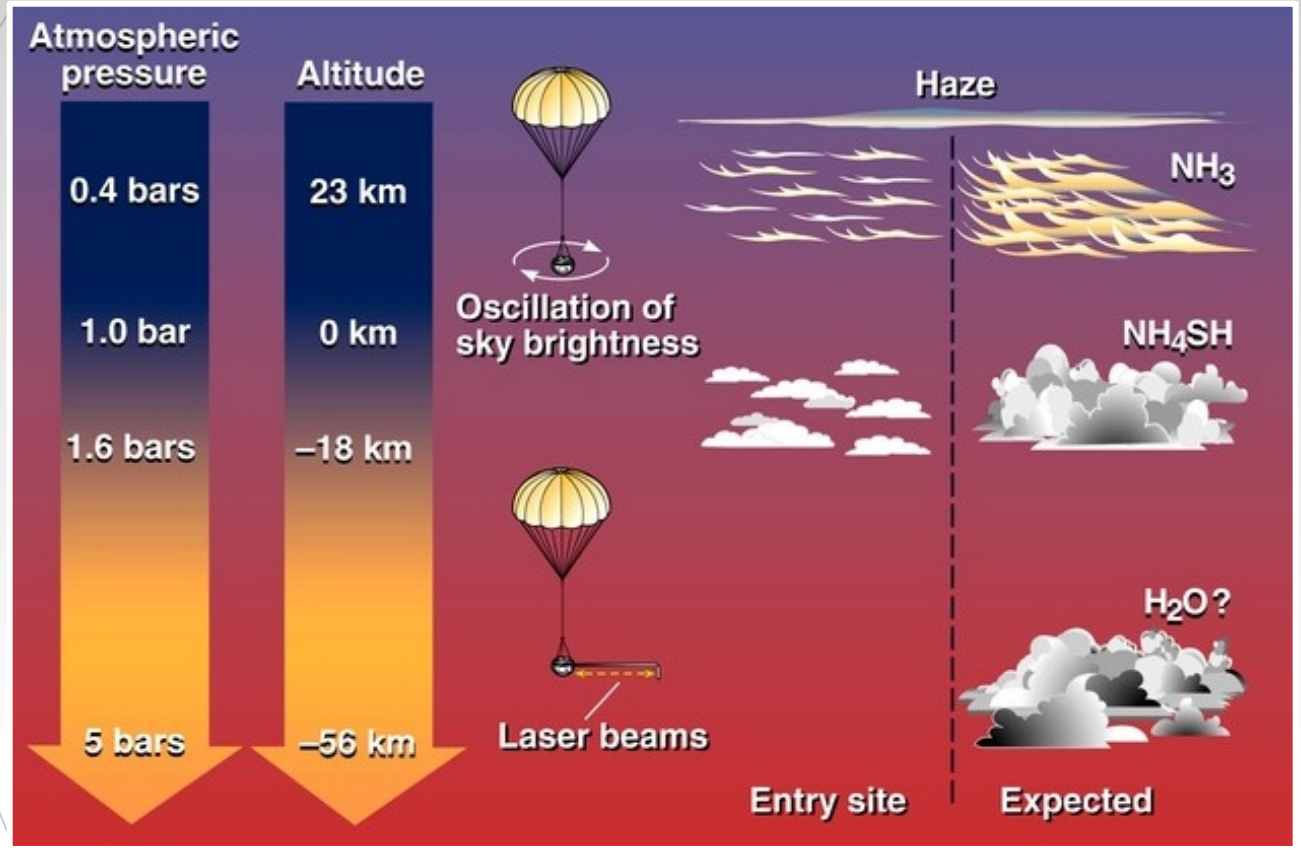
- How diverse are exoplanets chemically?
- Does chemical diversity correlate with other parameters?
  - How do planets form?
  - How do planets evolve?



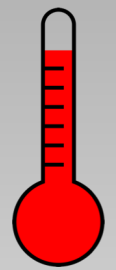
THE SUN'S PLANETS ARE COLD

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

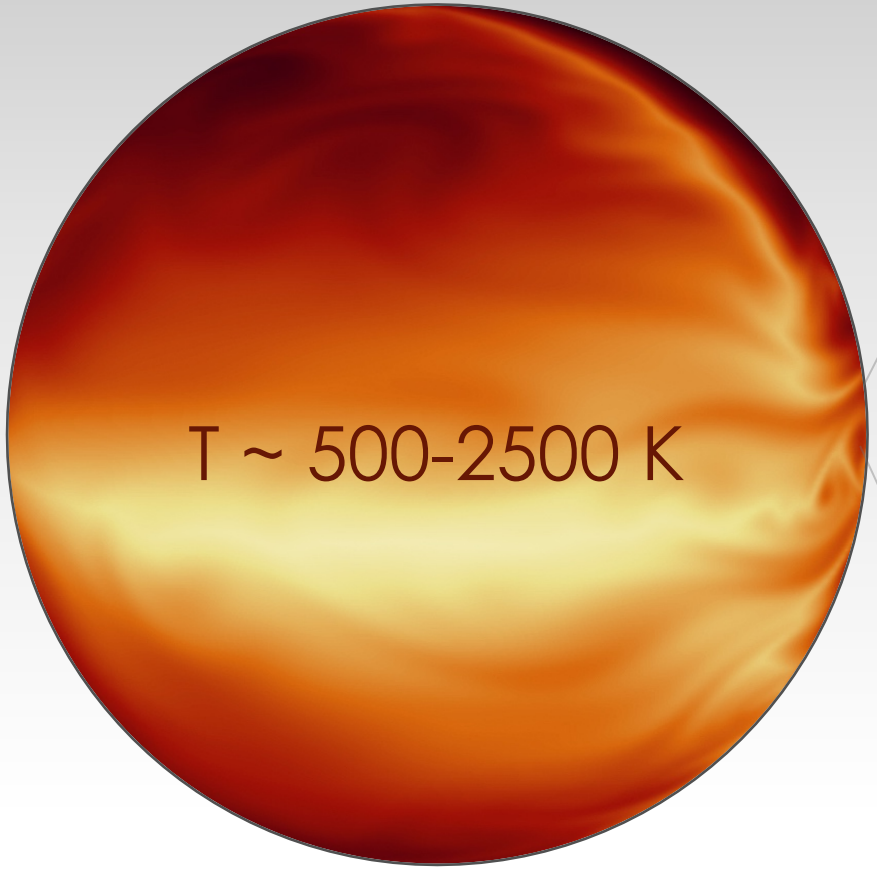


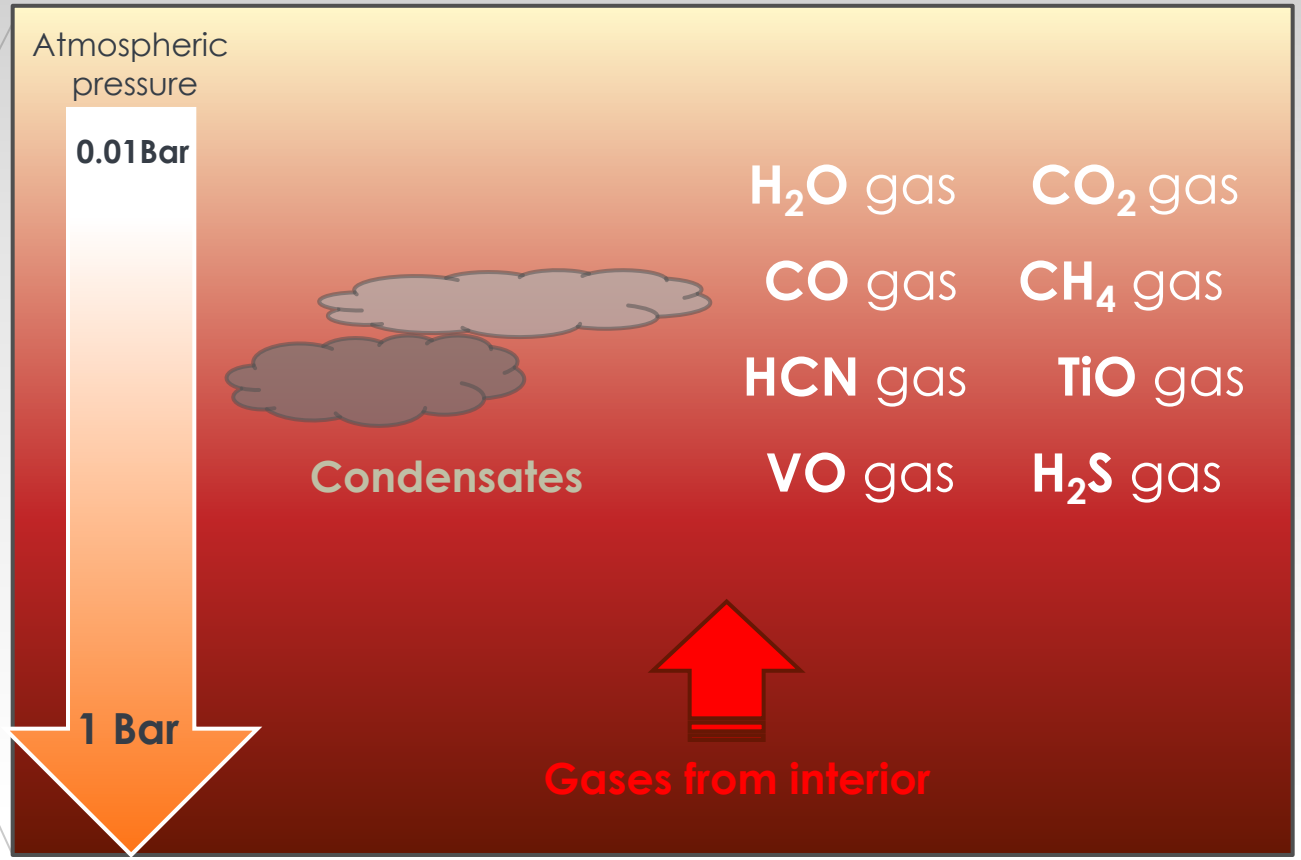


WARM/HOT EXOPLANETS



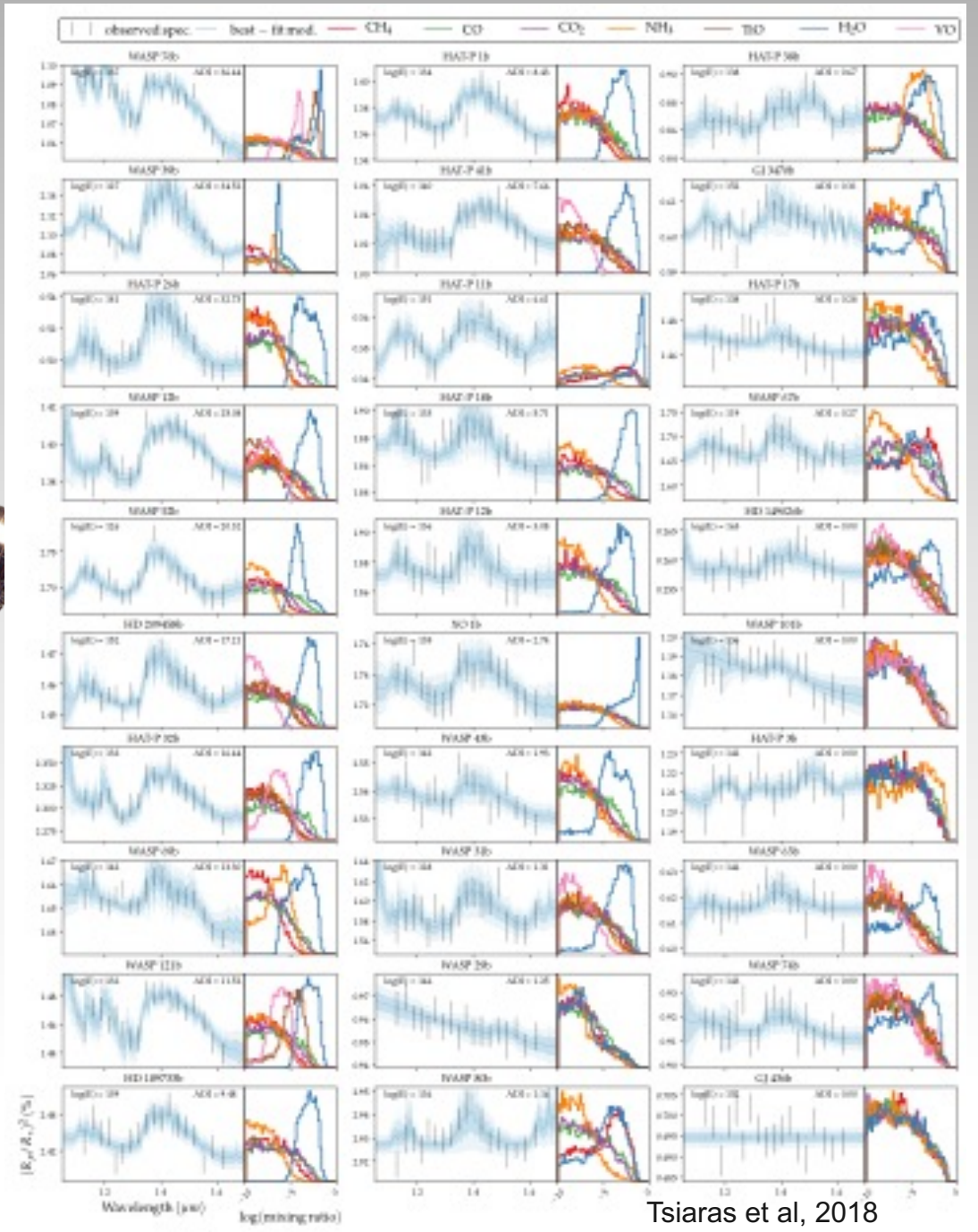
O, C, N, S (Ti, VO, Si) MOLECULES ARE IN GAS FORM





30 SHADES OF HOT-JUPITERS

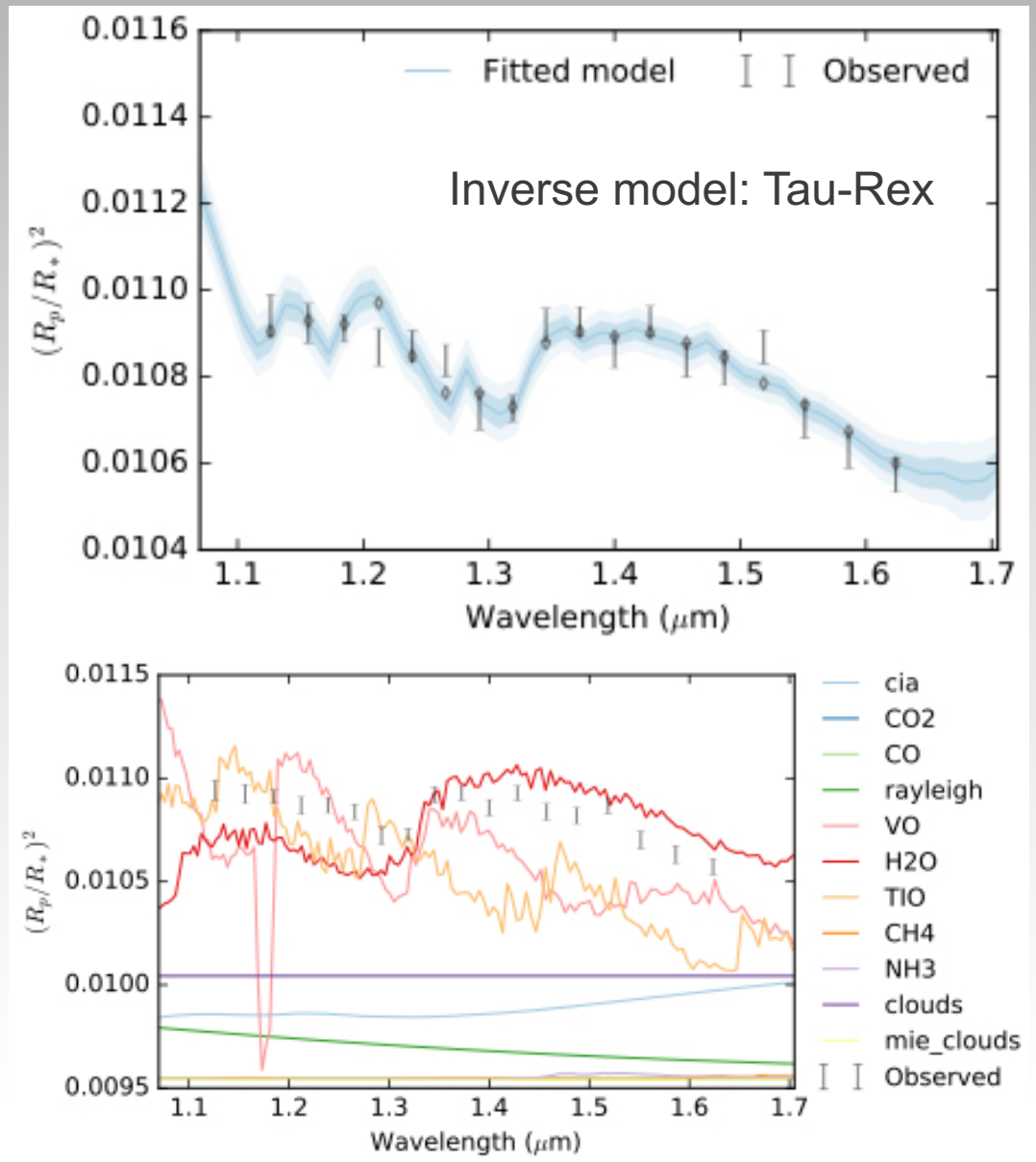
30 WFC3 SPECTRA ANALYSED AND INTERPRETED



Tsiaras et al, 2018

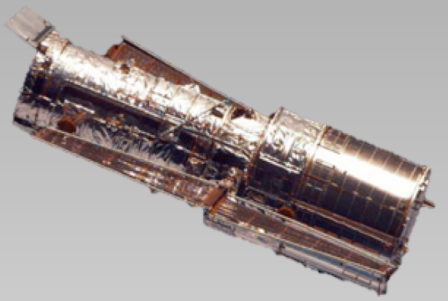
30 SHADES OF HOT-JUPITERS

30 WFC3 SPECTRA ANALYSED AND INTERPRETED

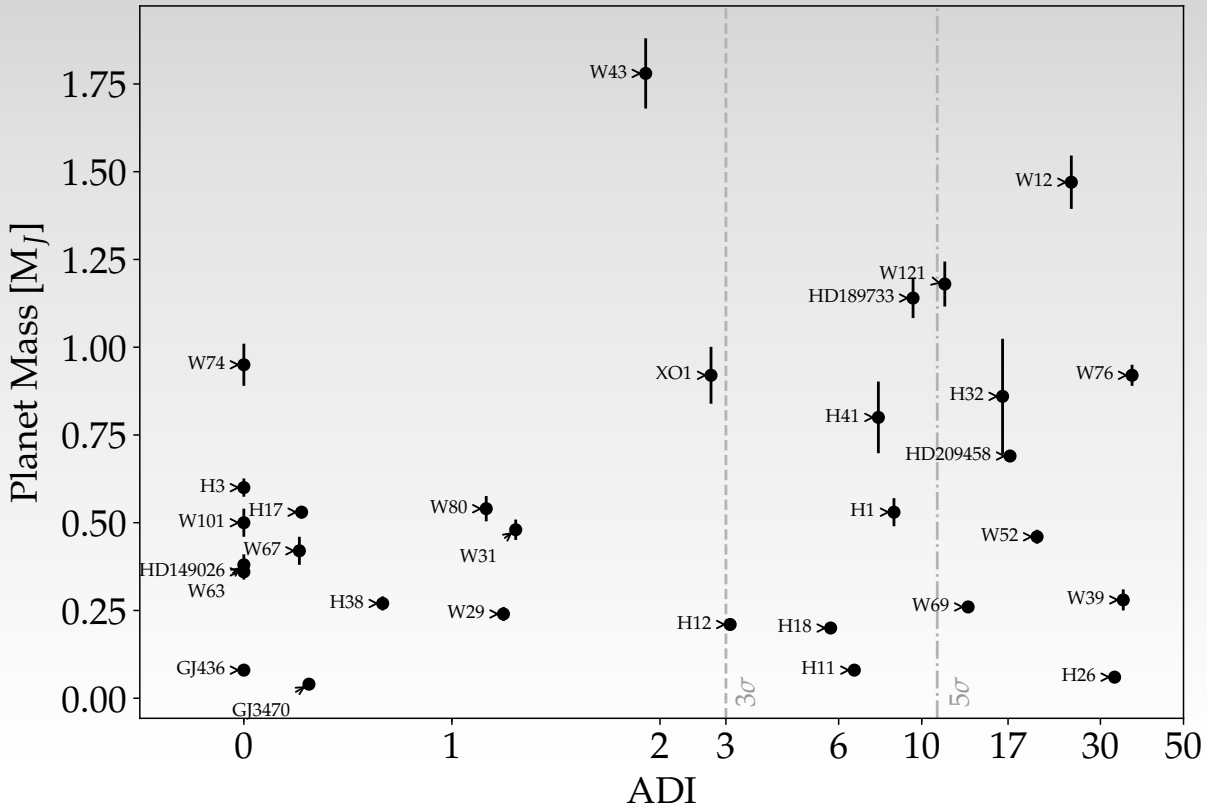


Tsiaras et al, 2018

30 SHADES OF HOT-JUPITERS

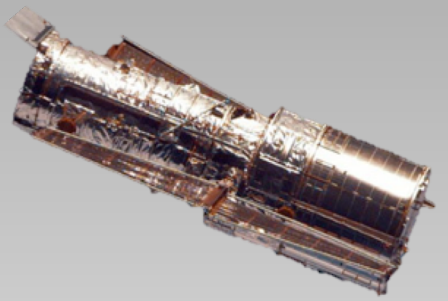


30 WFC3 SPECTRA ANALYSED AND INTERPRETED: **CORRELATION MASS/ATMOSPHERE**

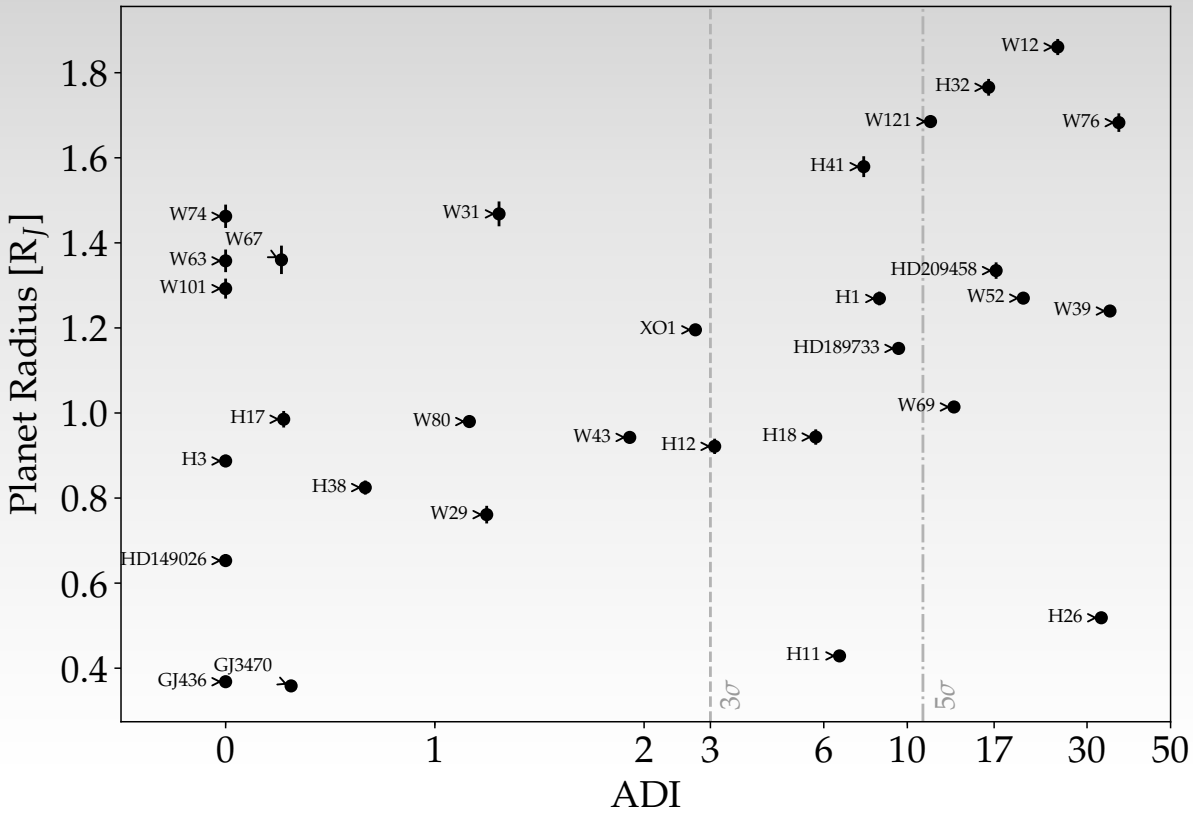


Tsiaras et al, 2018

30 SHADES OF HOT-JUPITERS

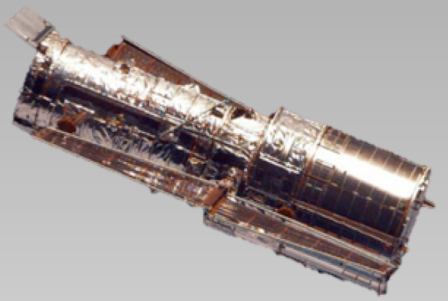


30 WFC3 SPECTRA ANALYSED AND INTERPRETED: **CORRELATION RADIUS/ATMOSPHERE**

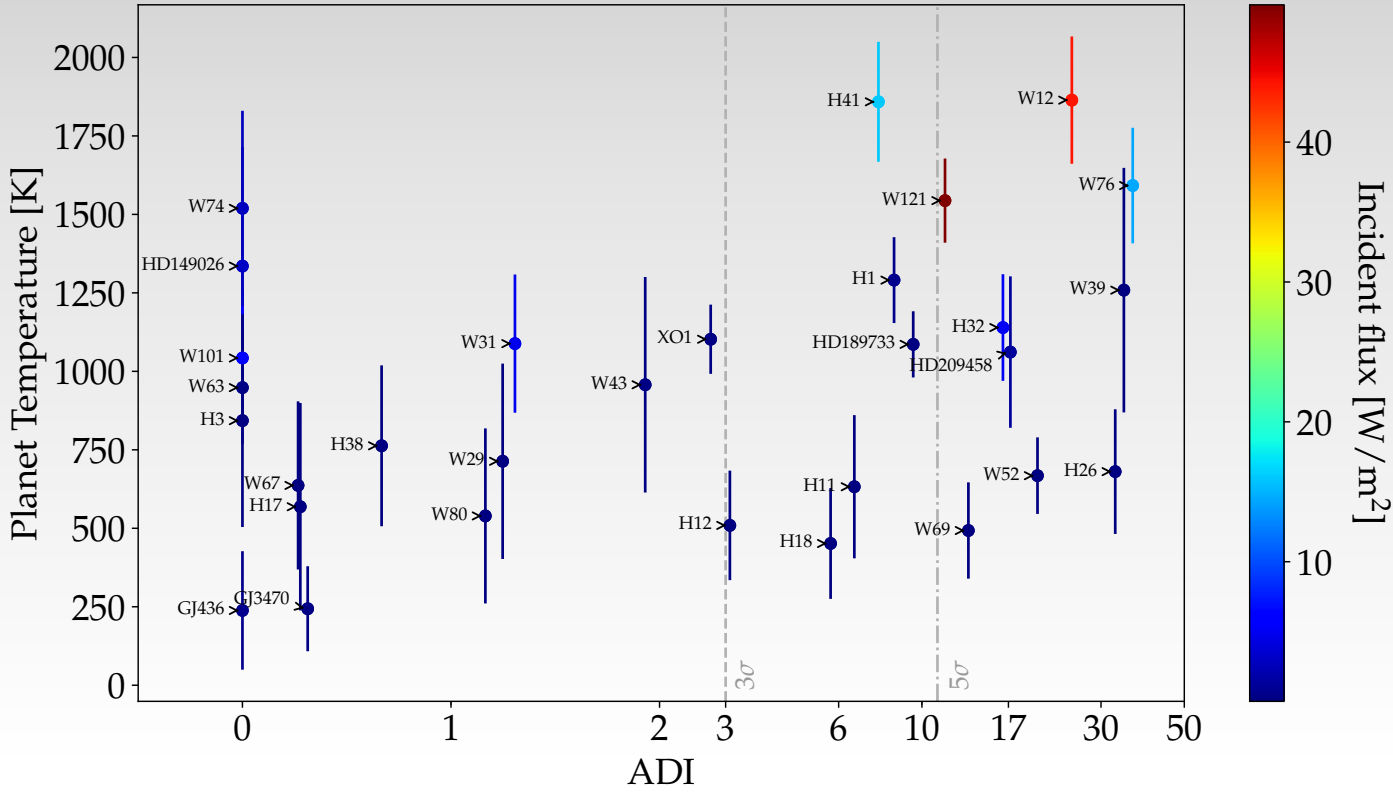


Tsiaras et al, 2018

30 SHADES OF HOT-JUPITERS



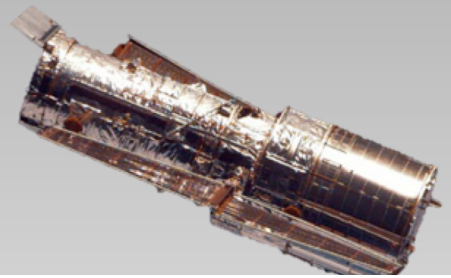
30 WFC3 SPECTRA ANALYSED AND INTERPRETED: **CORRELATION T-IRRADIATION/ATMOSPHERE**

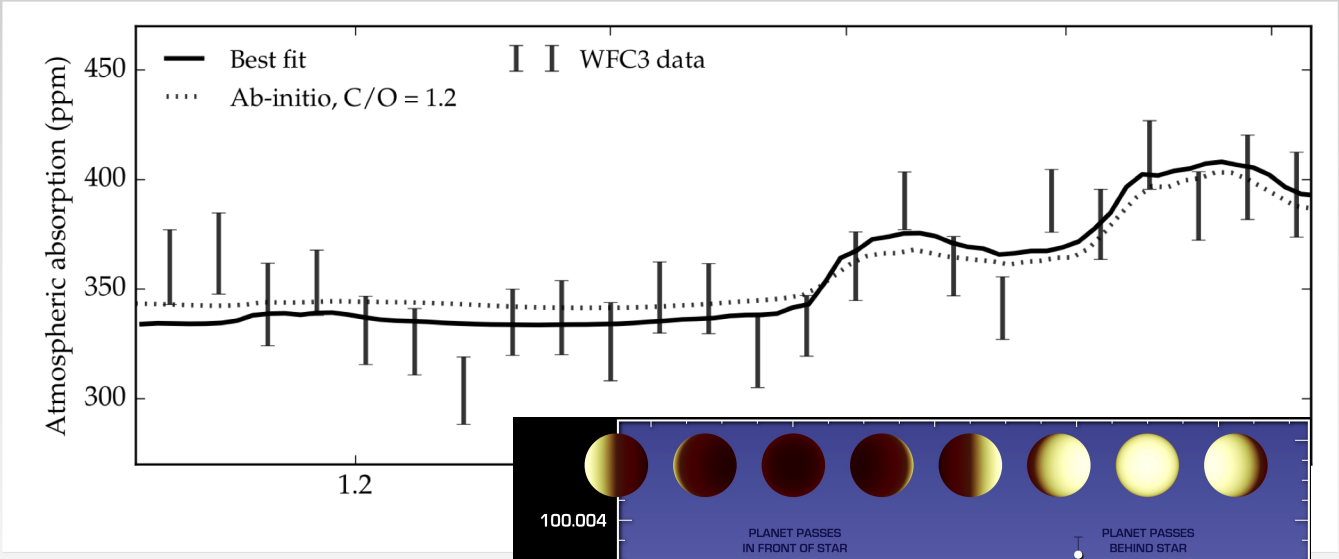


Tsiaras et al, 2018

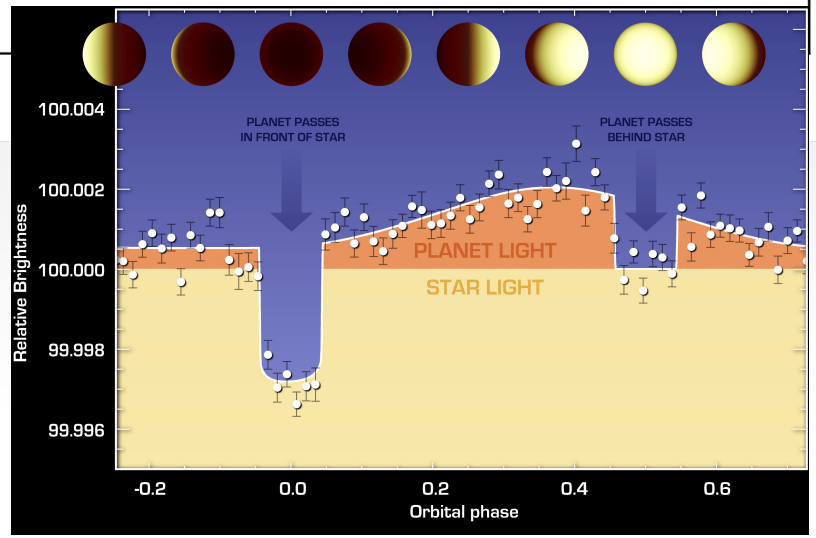
2 SHADES OF SUPER-EARTHS

55 CNC E & GJ1214B

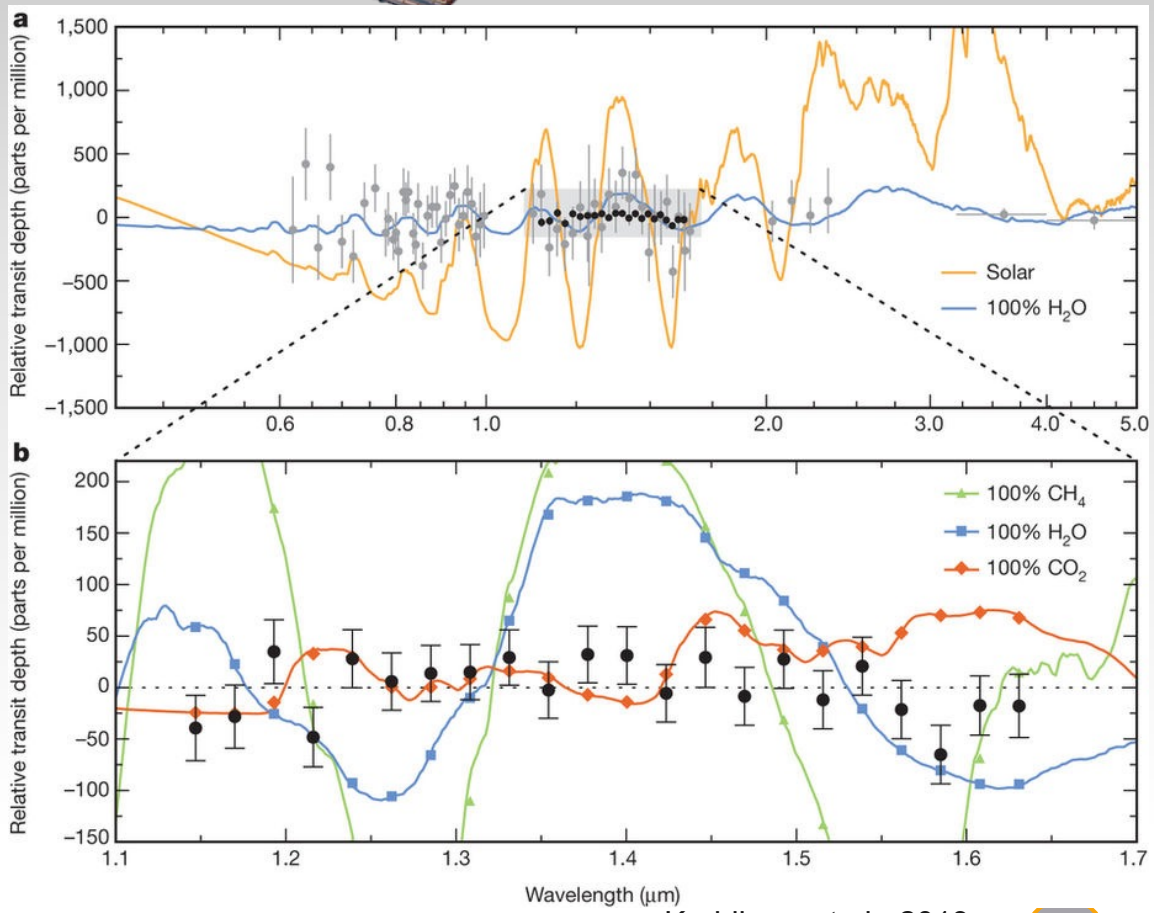




Tsiaras et al, 2016;



Demory et al., 2016



Kreidberg et al., 2013

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**

ExoLights + ExoAI

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

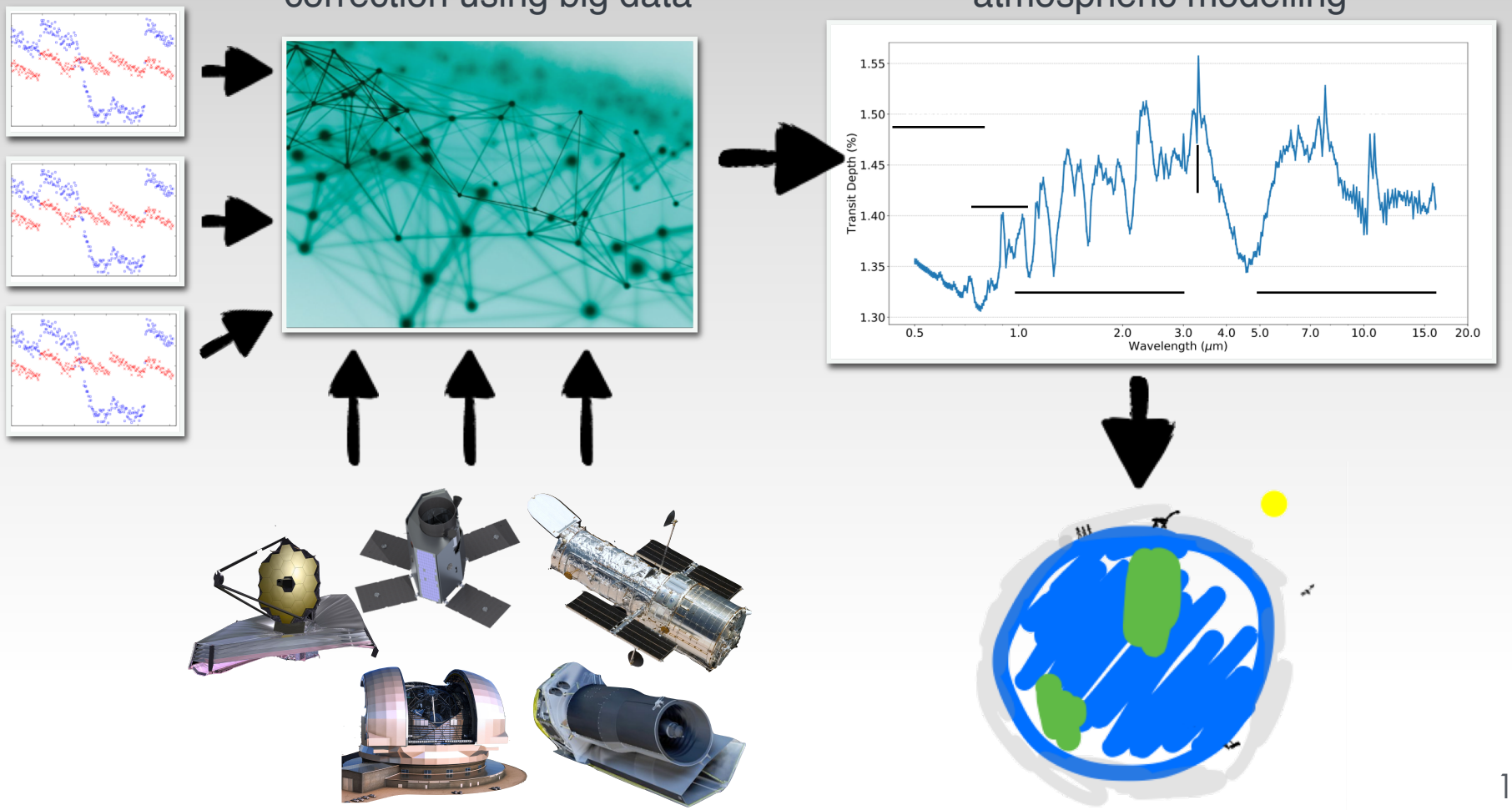
- Exoplanet atmospheres observations & data analysis
- Spectral modelling & interpretation
- New space mission concepts
- Infrastructure to analyse “big-data”

ExoLights is funded by ERC (PI G. Tinetti)
ExoAI funded by ERC (PI I. Waldmann)

Big data & exoplanets

Neural network data correction using big data

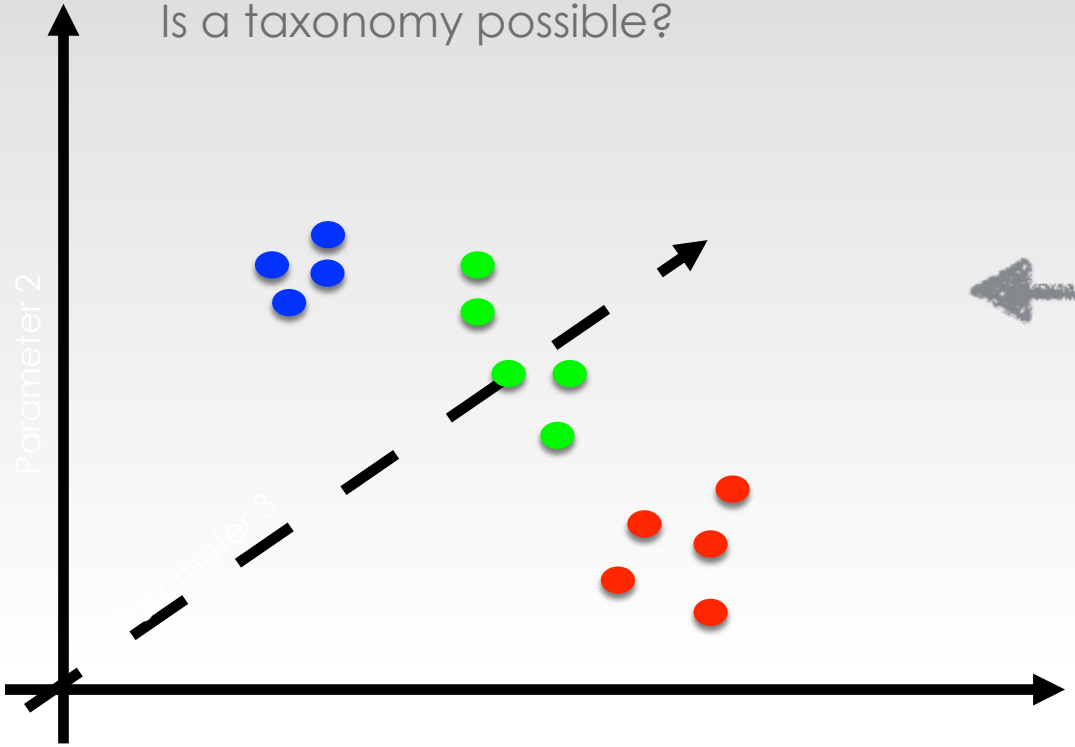
Bayesian inverse atmospheric modelling



Big data & exoplanets

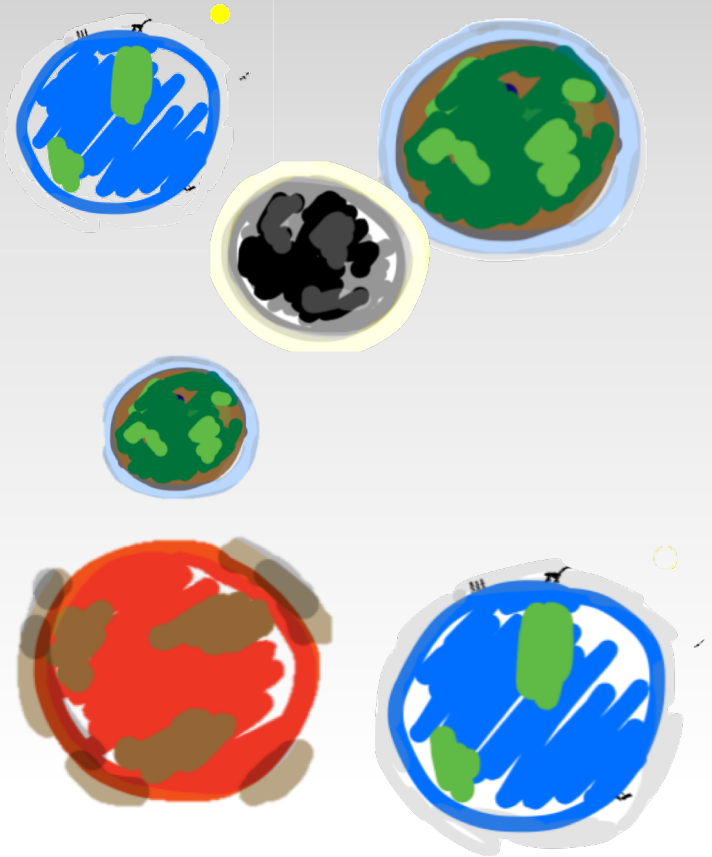
Planetary correlations and population analysis

Is a taxonomy possible?



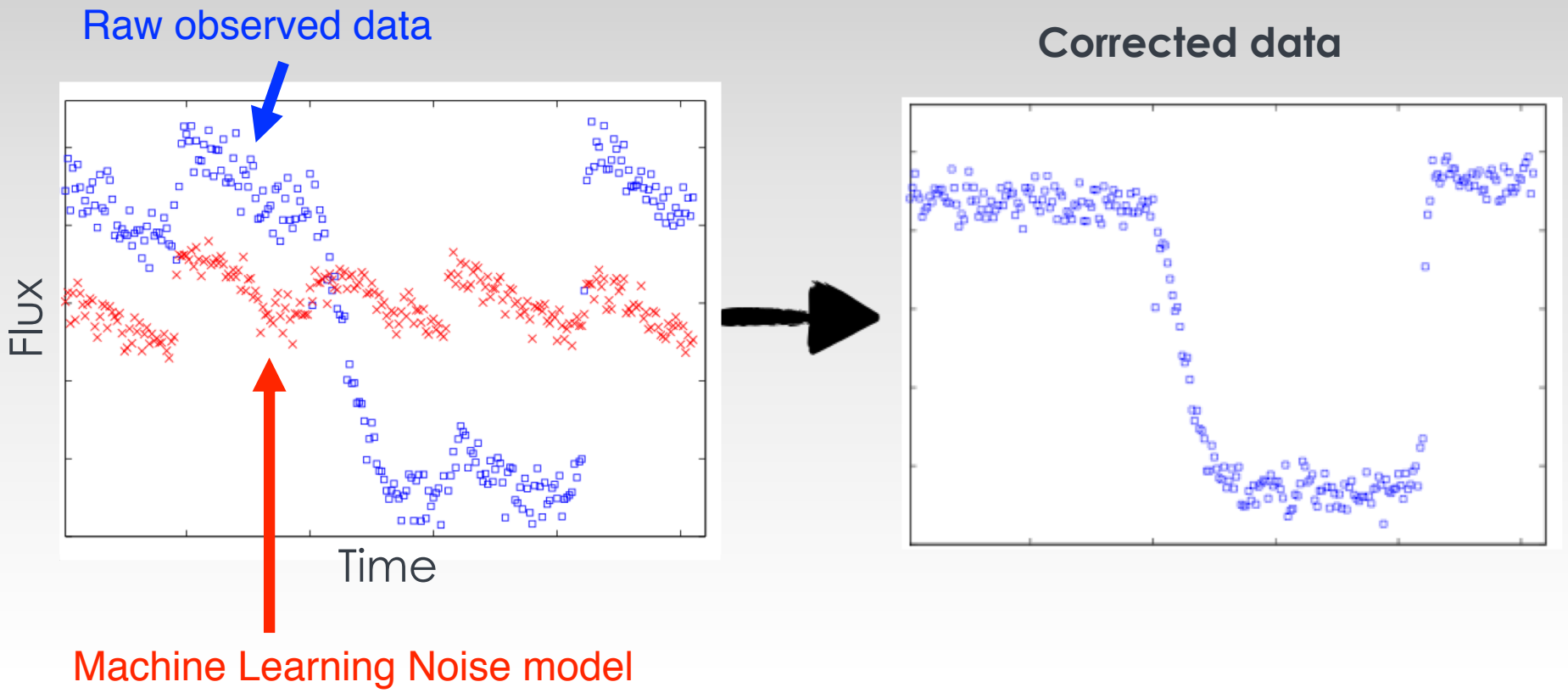
Atm. Parameter tensor map

Exoplanets analysed



MACHINE LEARNING & DATA ANALYSIS

SEVERAL TECHNIQUES TESTED ON HUBBLE, SPITZER, GROUND-BASED INSTRUMENTS

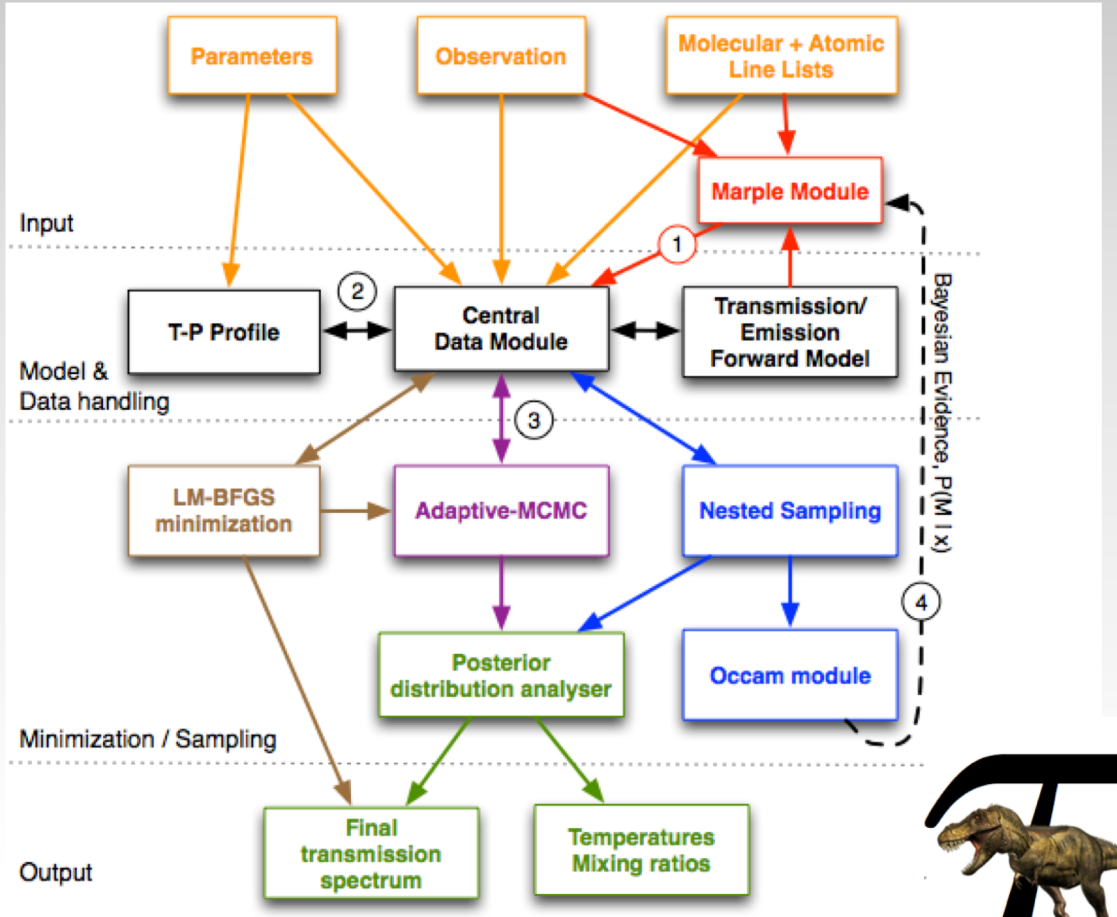


Waldmann, 2012, 2013, 2014, 2015; Morello et al., 2014, 2015a, b, 2016; Tsiaras and Varley, 2016; Tsiaras et al., 2016; 2018; Damiano et al., 2017

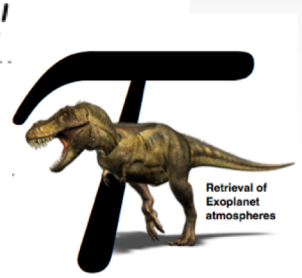
TAU-REX

SPECTRAL RETRIEVAL & INVERSE MODELS

- **Fully Bayesian Retrieval**
  - MCMC
  - Nested Sampling
- **Custom made opacity line-lists** from the ExoMol project
- Prior composition selection through **pattern recognition software**
- **Full parallelisation for cluster computing**



Waldmann et al., ApJ, 2015˚,b; Rocchetto et al., 2016



TAU-REX

SPECTRAL RETRIEVAL & INVERSE MODELS

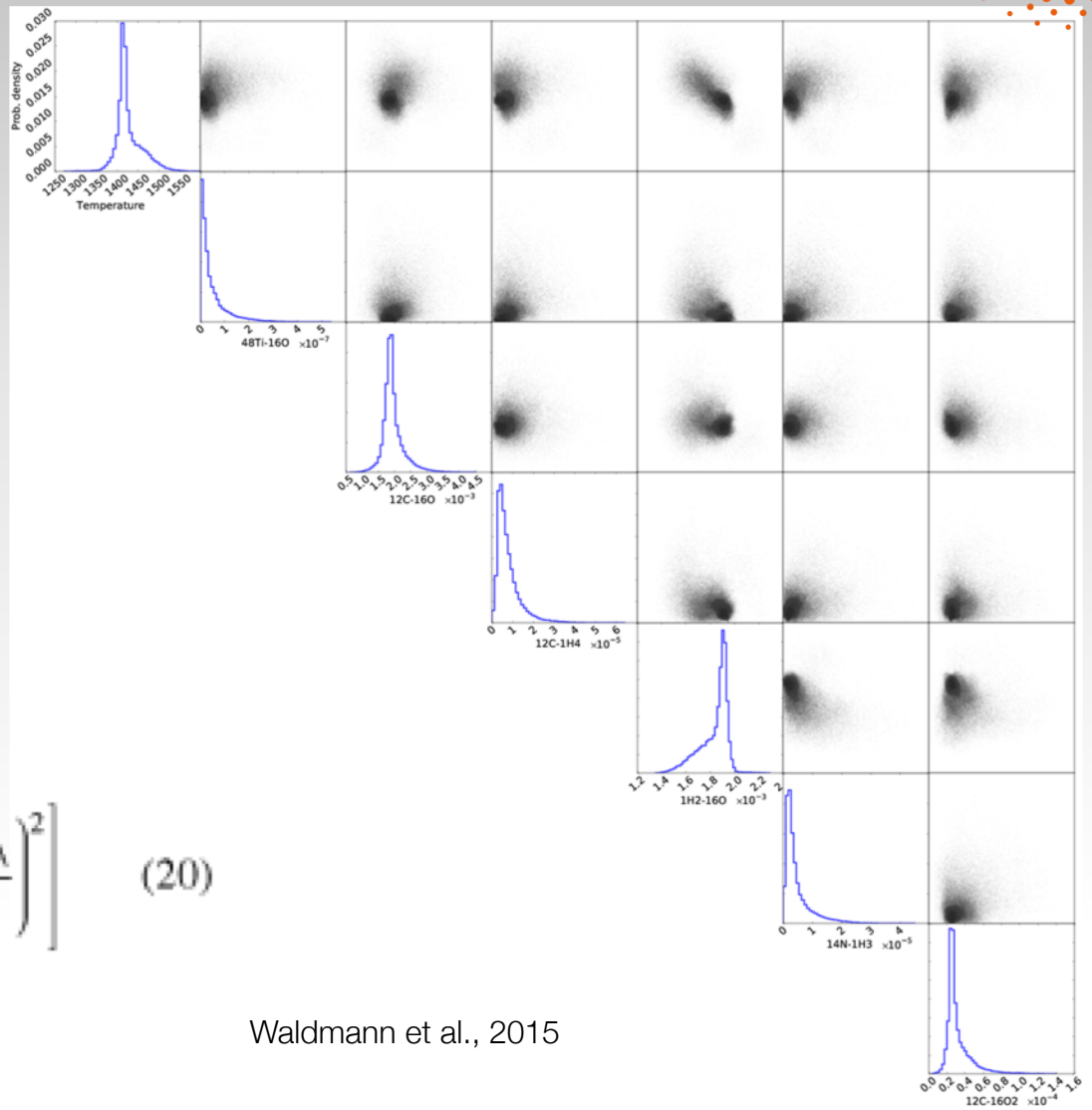
$$P(\theta|x, \mathcal{M}) = \frac{P(x|\theta, \mathcal{M})P(\theta, \mathcal{M})}{P(x|\mathcal{M})}$$

Posterior probability of the model parameters θ given the data x

Bayesian prior, assumed uniform

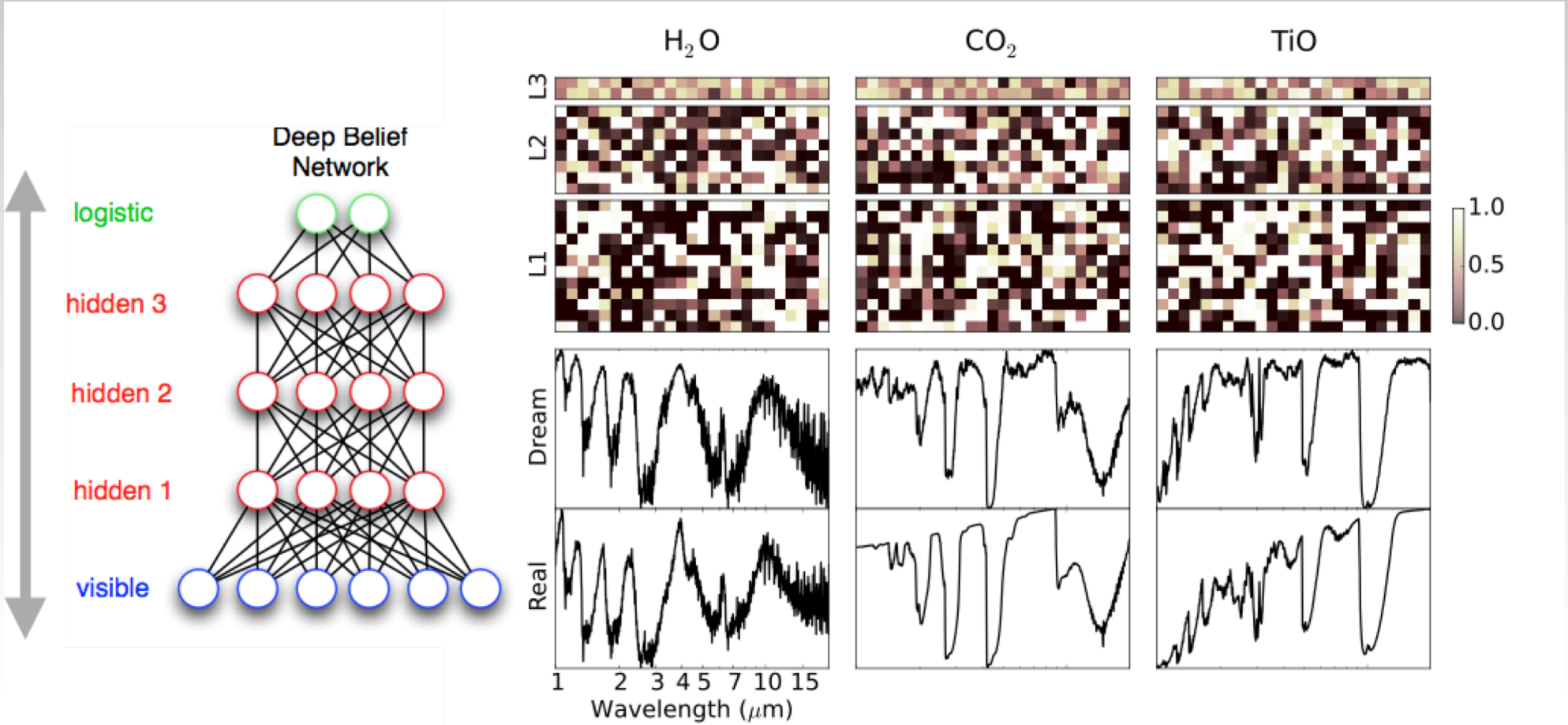
The likelihood:

$$P(x|\theta, \mathcal{M}) = \frac{1}{\varepsilon\sqrt{2\pi}} \exp\left[-\frac{1}{2}\sum_{\lambda}^{N}\left(\frac{x_\lambda - \mathcal{M}_\lambda}{\varepsilon_\lambda}\right)^2\right] \qquad (20)$$



Waldmann et al., 2015

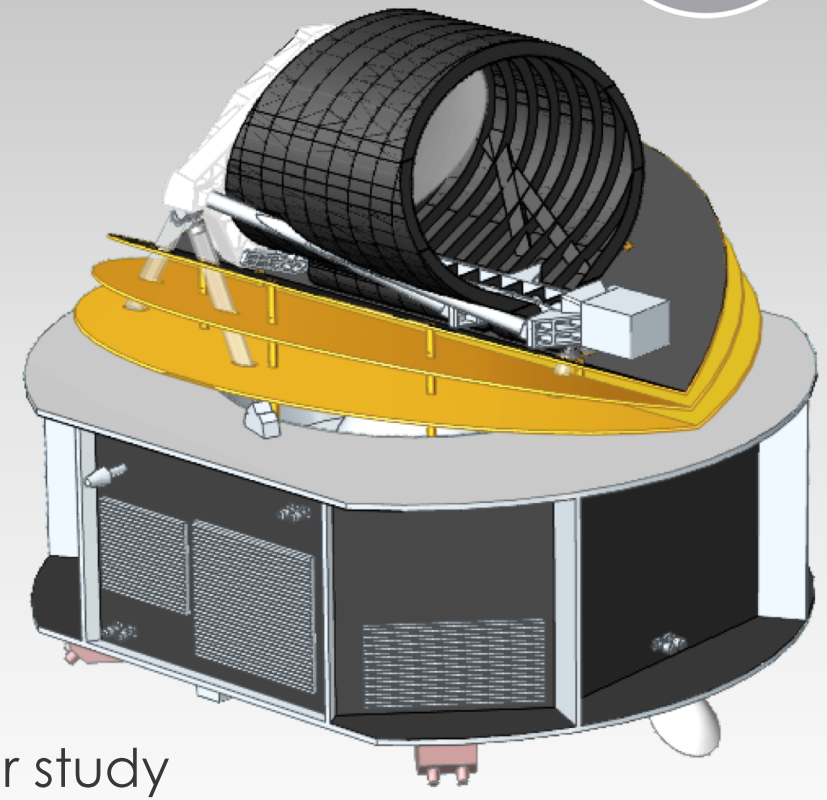
Deep Neural Network & exoplanets



Waldmann, 2016

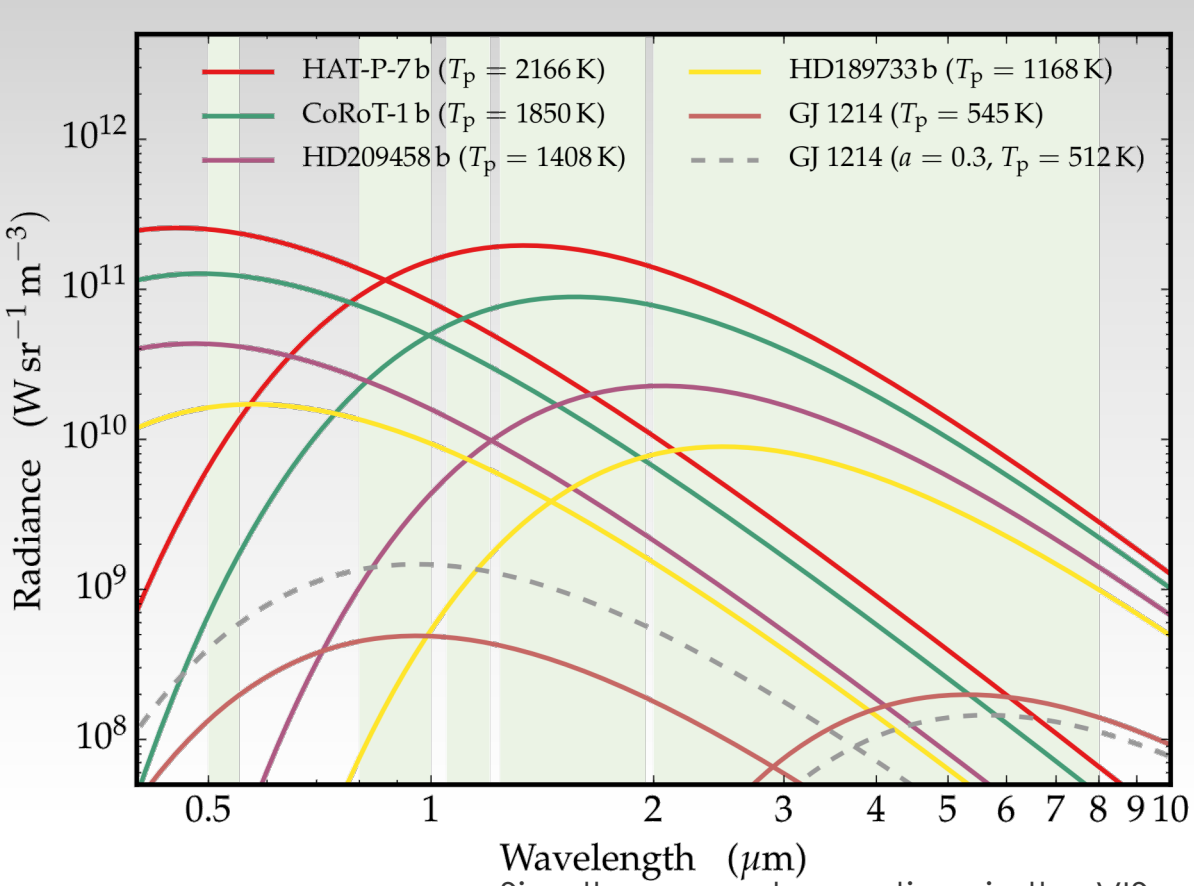
ARIEL – ESA M4 mission

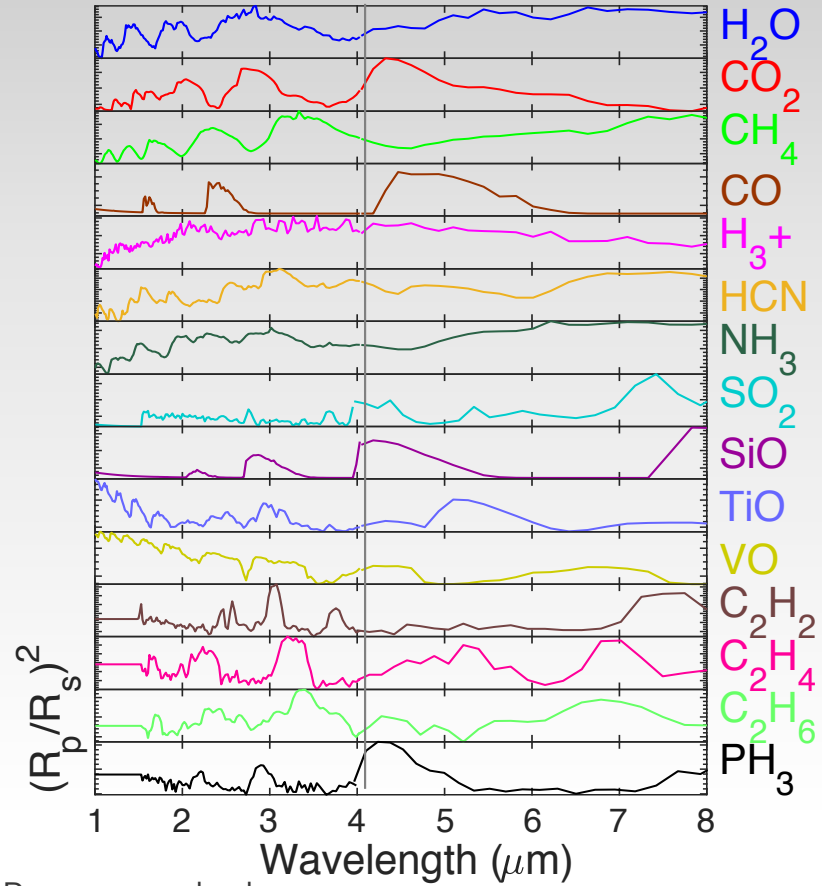
- 1-m telescope, spectroscopy from VIS to IR
- Satellite in orbit around L2
- ~1000 exoplanets observed (rocky + gaseous)
- Simultaneous coverage 0.5-7.8 micron
- Payload consortium: 15 ESA countries + NASA under study



A CHEMICAL SURVEY OF A LARGE POPULATION

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

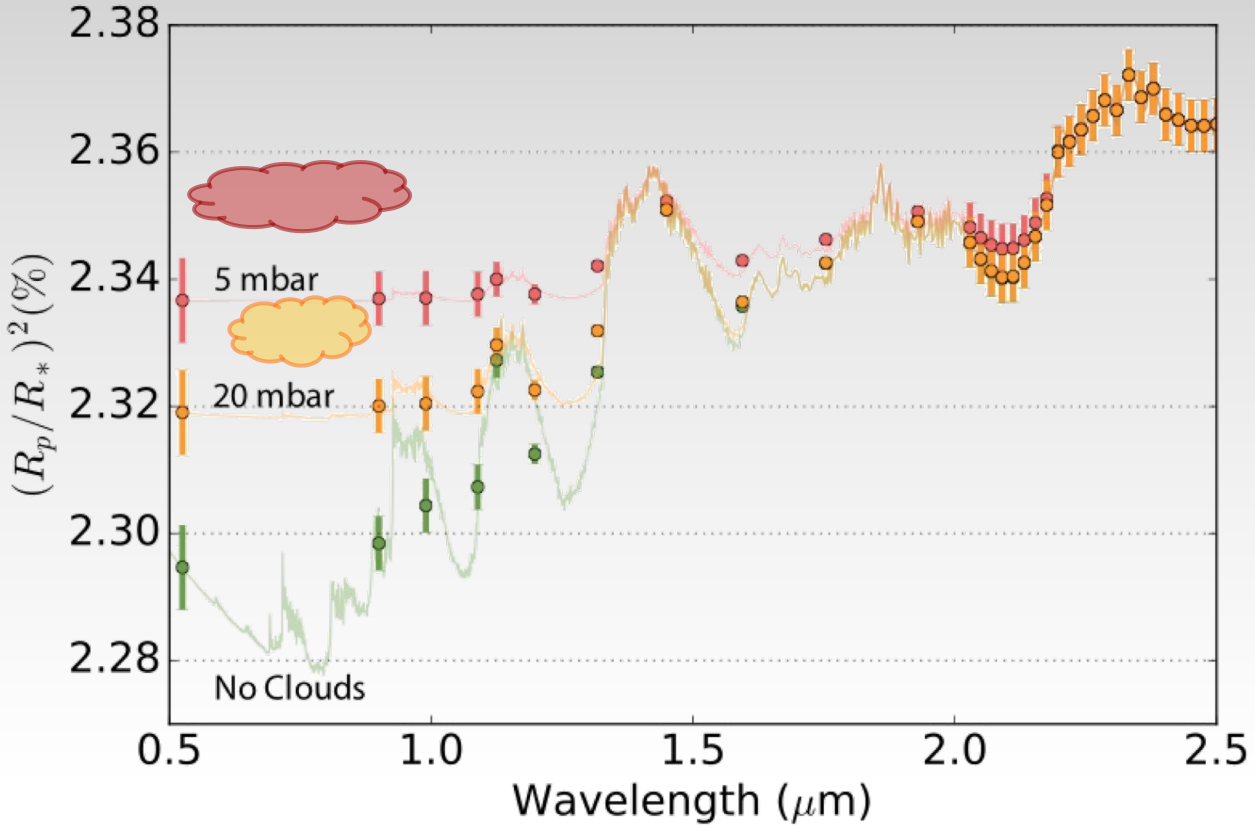


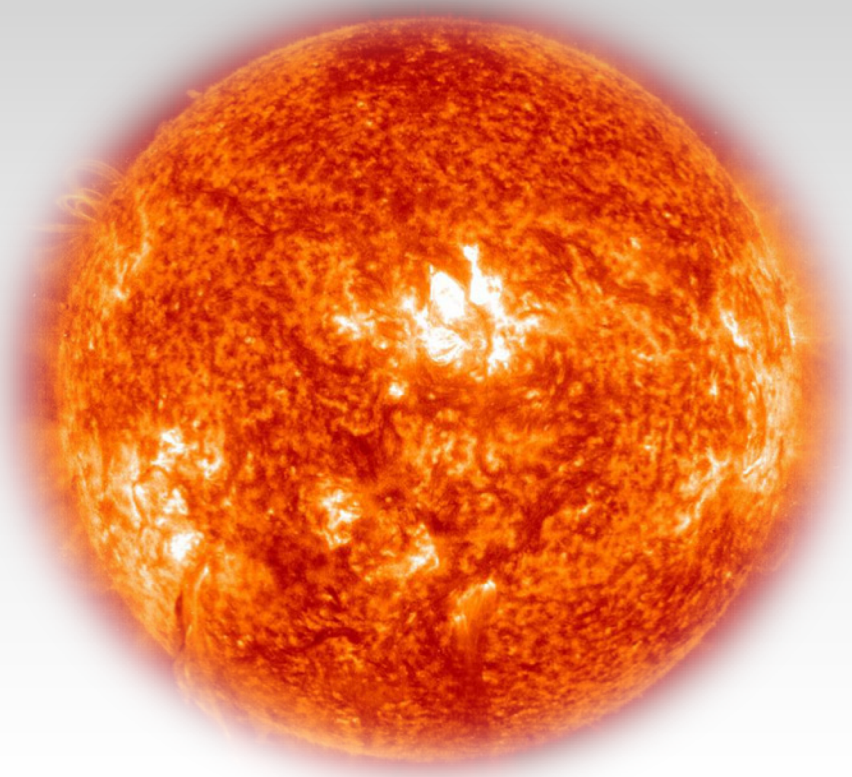


Simultaneous observations in the VIS and IR are needed

A CHEMICAL SURVEY OF A LARGE POPULATION

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



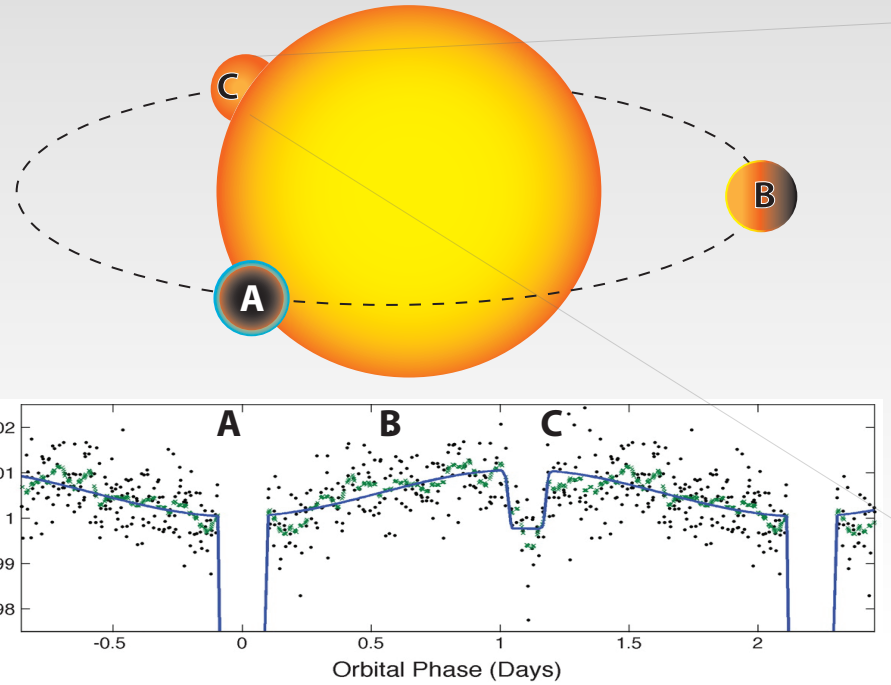


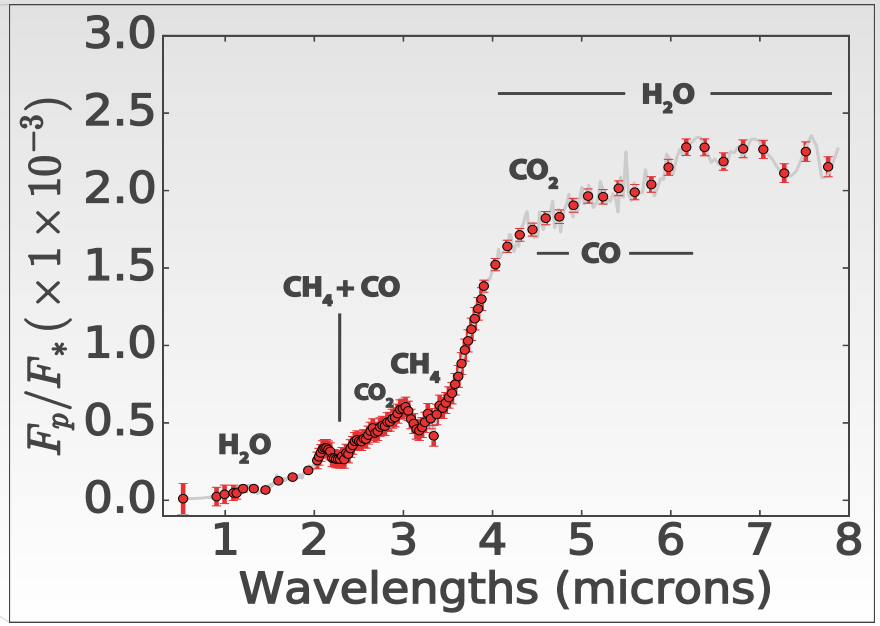
Simultaneous observations in the VIS and IR are needed

TRANSIT, ECLIPSE, PHASE-CURVE SPECTROSCOPY

AIMING AT 10 PPM STELLAR FLUX AT MULTIPLE WAVELENGTHS

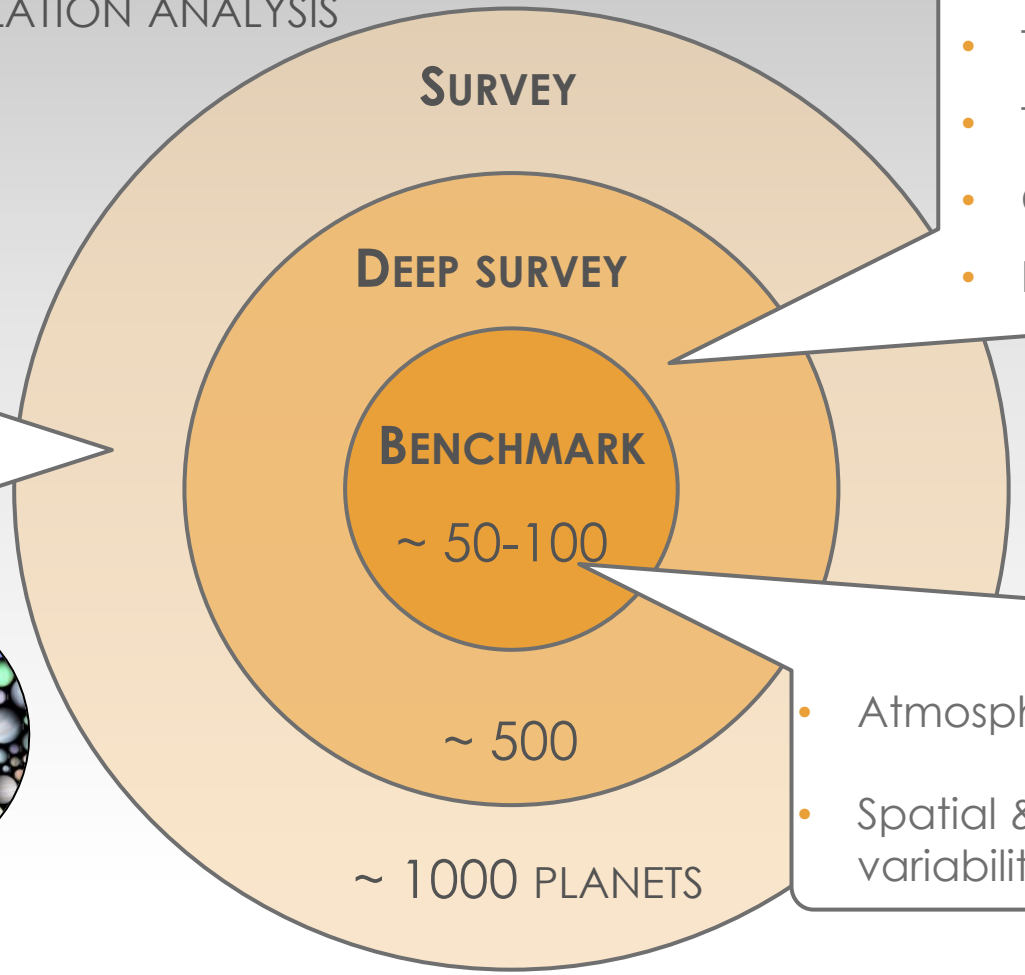
Through stable instrument, external calibration & proven postprocessing analysis



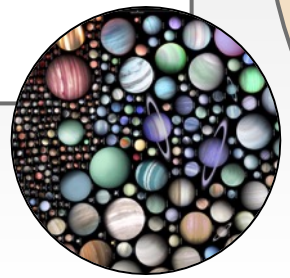


ARIEL 3-TIER APPROACH

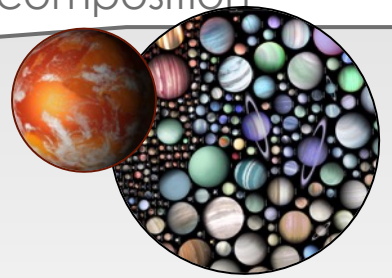
INDIVIDUAL PLANETS & POPULATION ANALYSIS



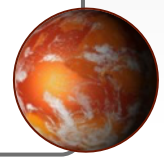
- What fraction of planets have clouds?
- Have small planets still retained H/He?
- Colour-colour diagrams
- Refinement of orbital/planet parameters in IR



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



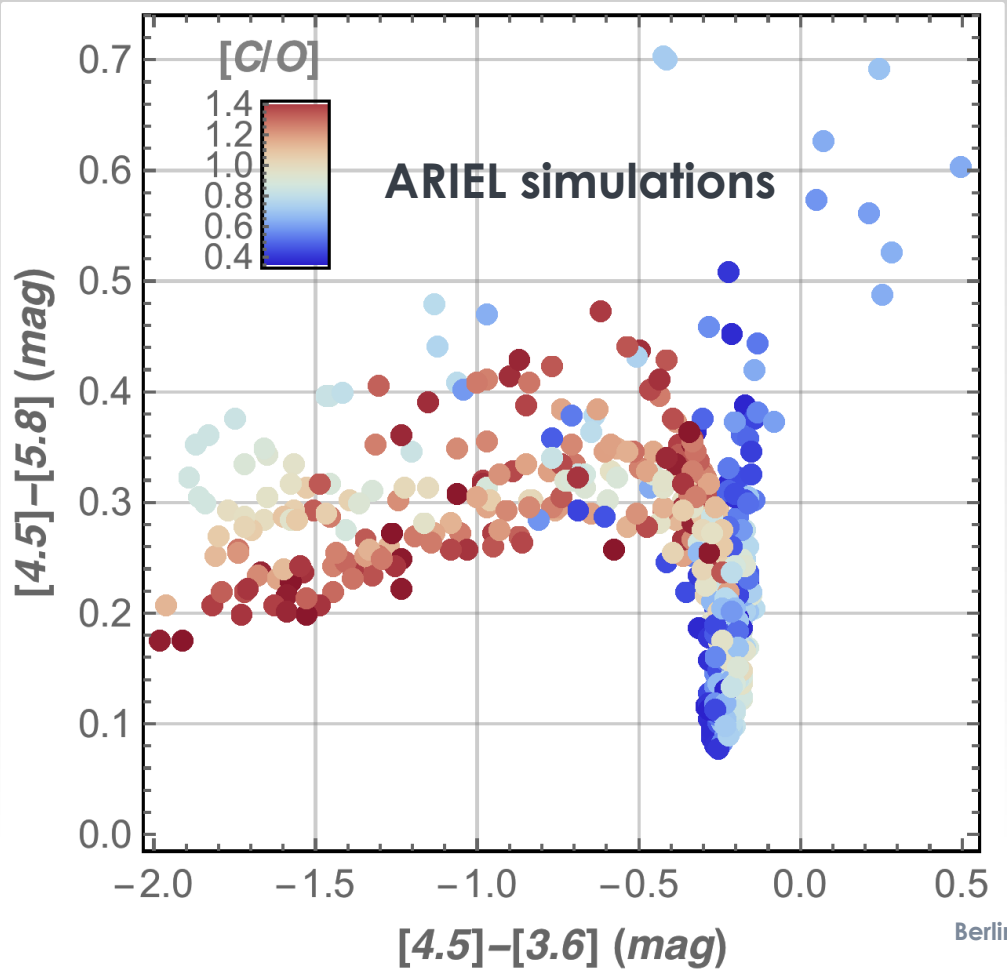
- Atmospheric circulation
- Spatial & temporal variability



POPULATION ANALYSIS

COLOUR-MAGNITUDE DIAGRAMS, PRELIMINARY CLOUD-CHARACTERISATION

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

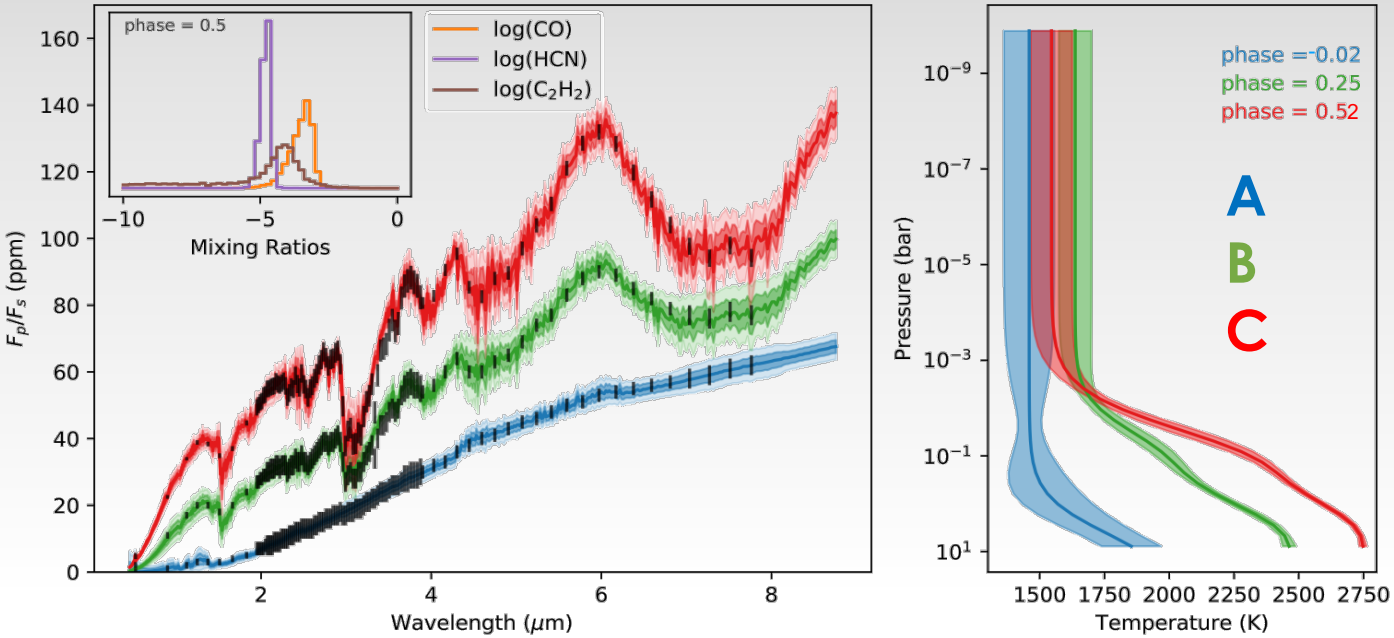


Triaud 2015;

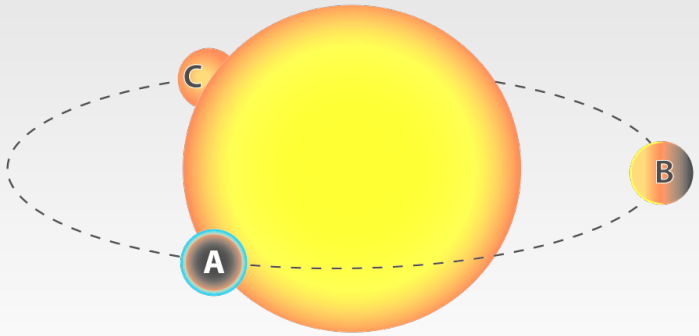
INSTANT & SHORT-TERM VARIABILITY

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

ARIEL phase-curve spectra, chemical composition & thermal profile



Planet orbiting around the star

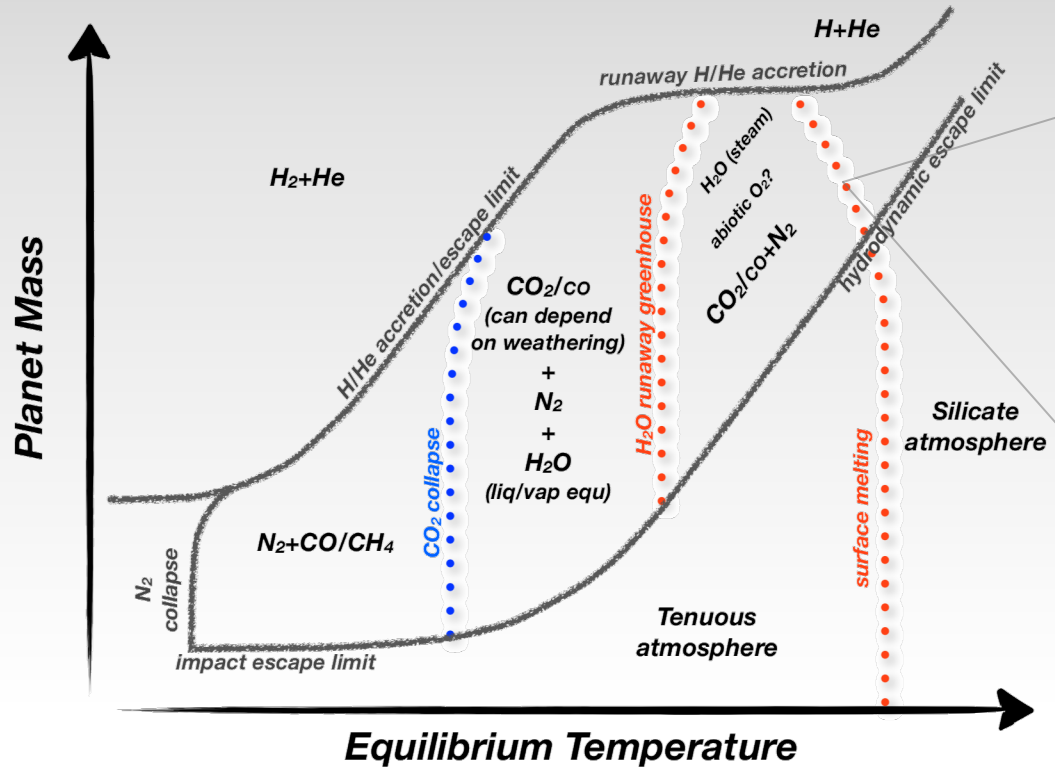


Snap-shots of an animation available at: http://bit.ly/2kGL4Wz

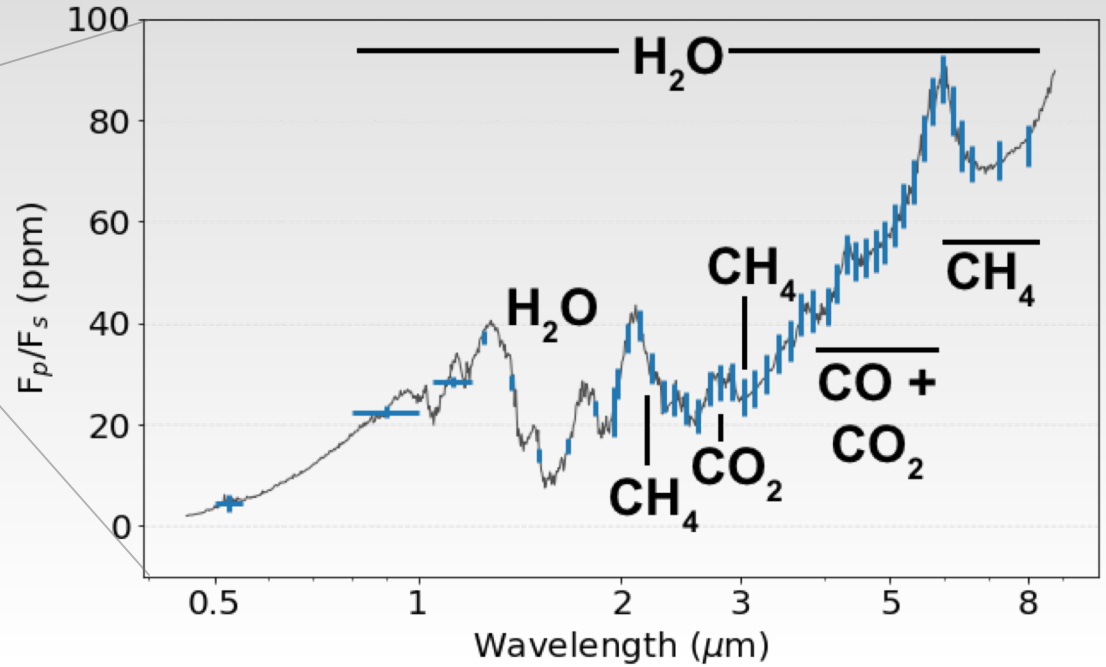
CHEMICAL DIVERSITY

CORRELATION WITH ANY OTHER KEY PARAMETERS?

Is this plot true? Where are the transitions?



ARIEL observations x 1000 planets

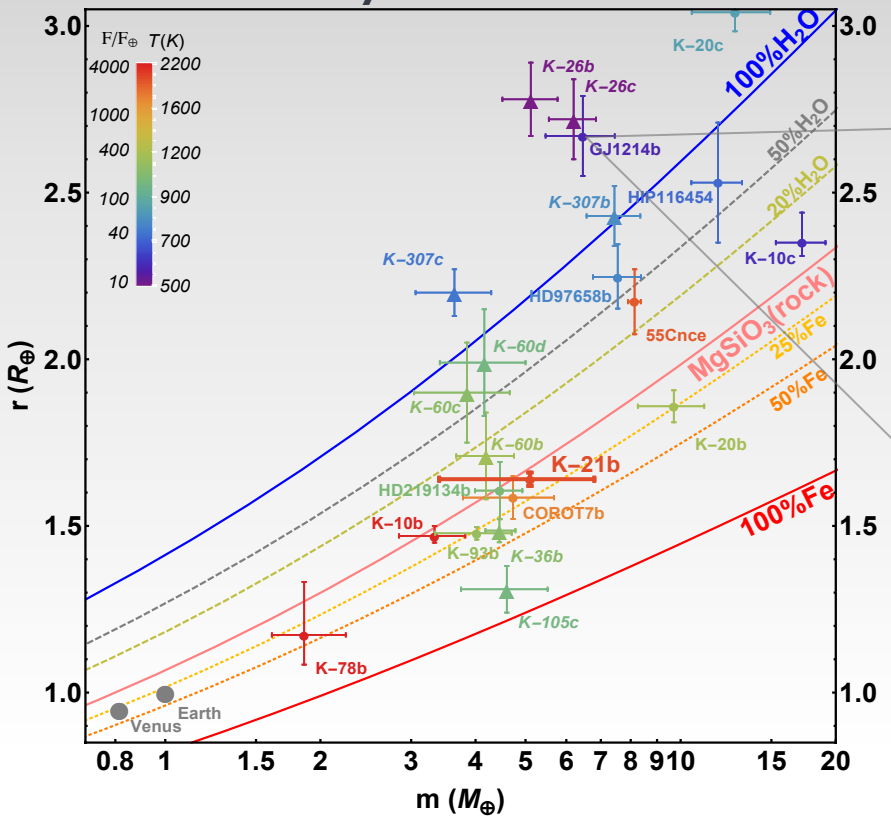


Forget and Leconte, 2013

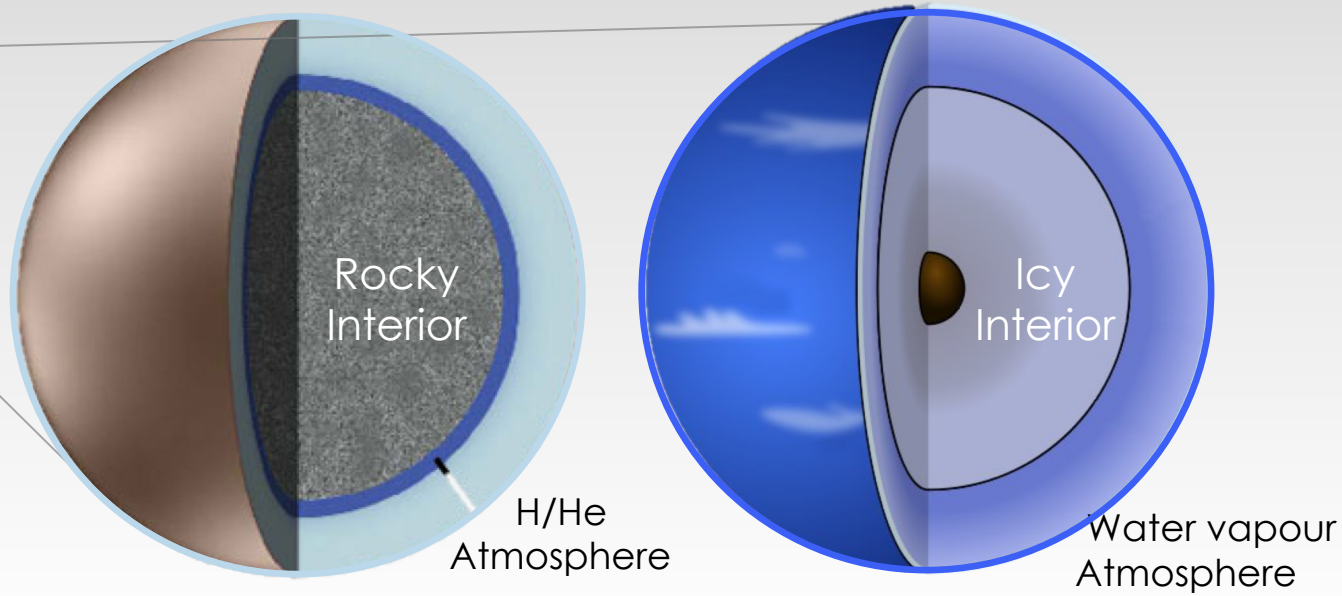
CHEMICAL DIVERSITY

ARIEL WILL CLARIFY CORRELATION WITH THE DENSITY

Density observations



Atmospheric composition through ARIEL will clarify the degeneracy



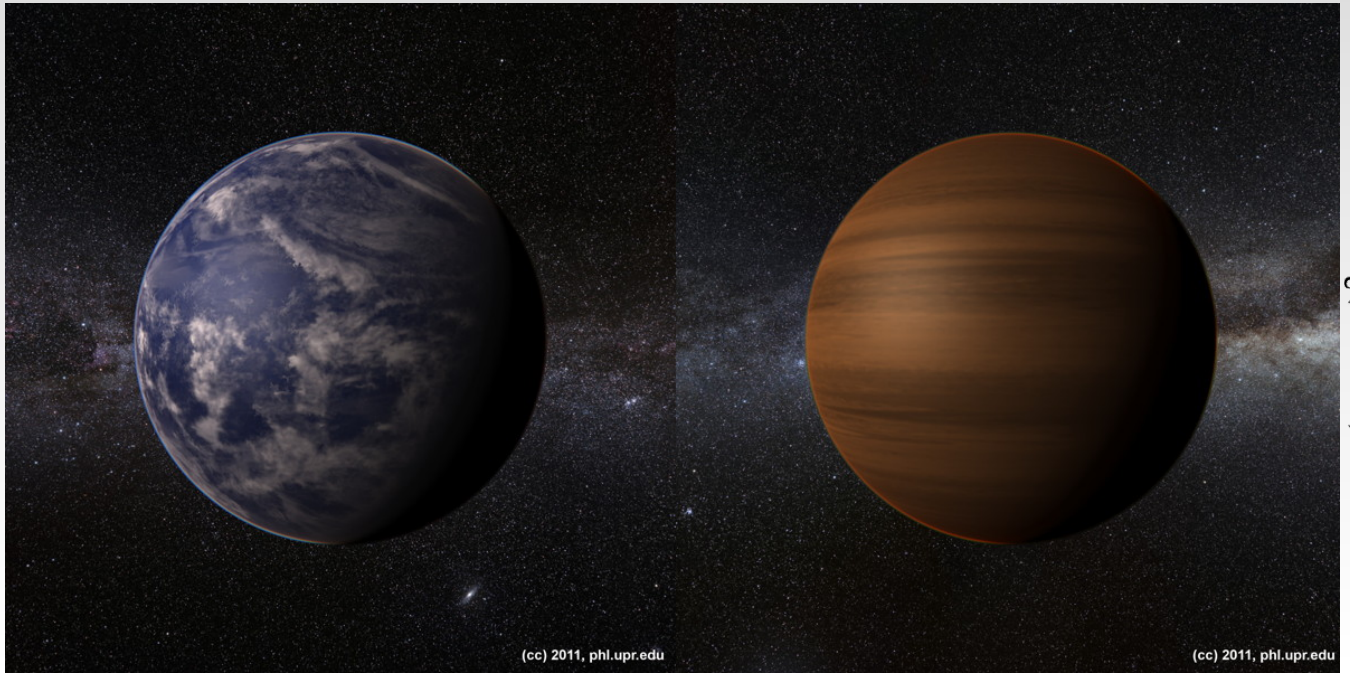
Same mean density – Different atmospheric signatures

Lopez et al., 2016; Valencia et al., 2013

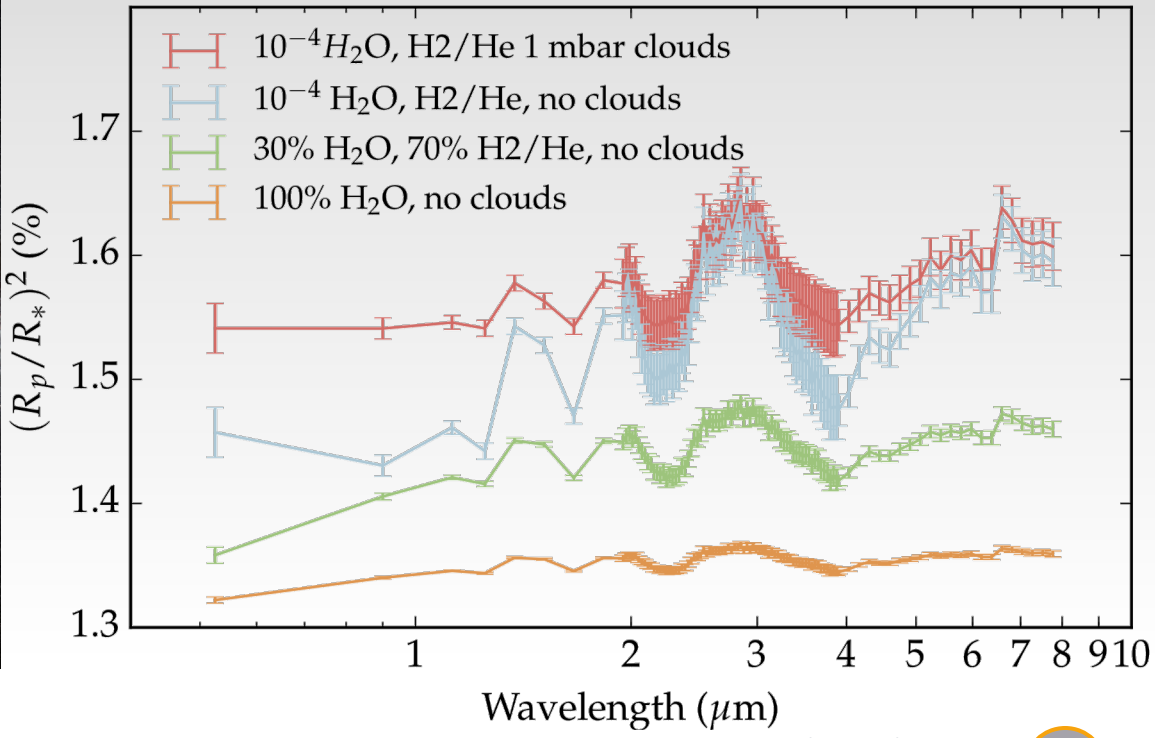
TERRESTRIAL-SUBNEPTUNES TRANSITION

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

Formation scenarios for small planets

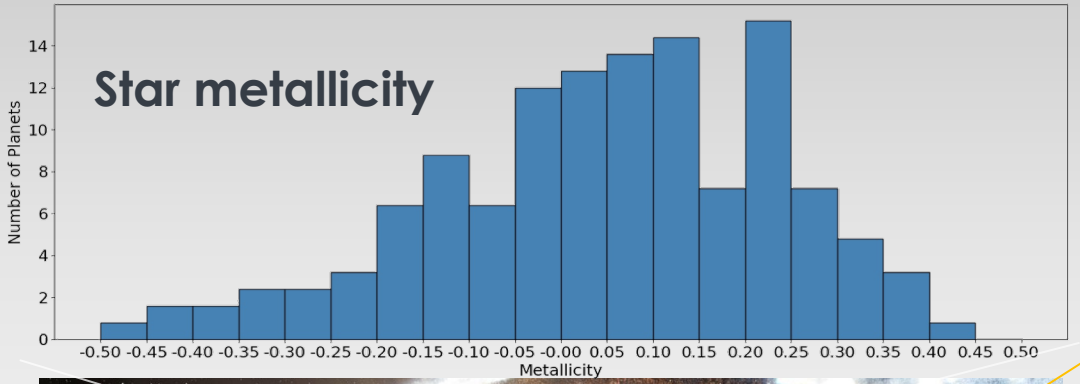


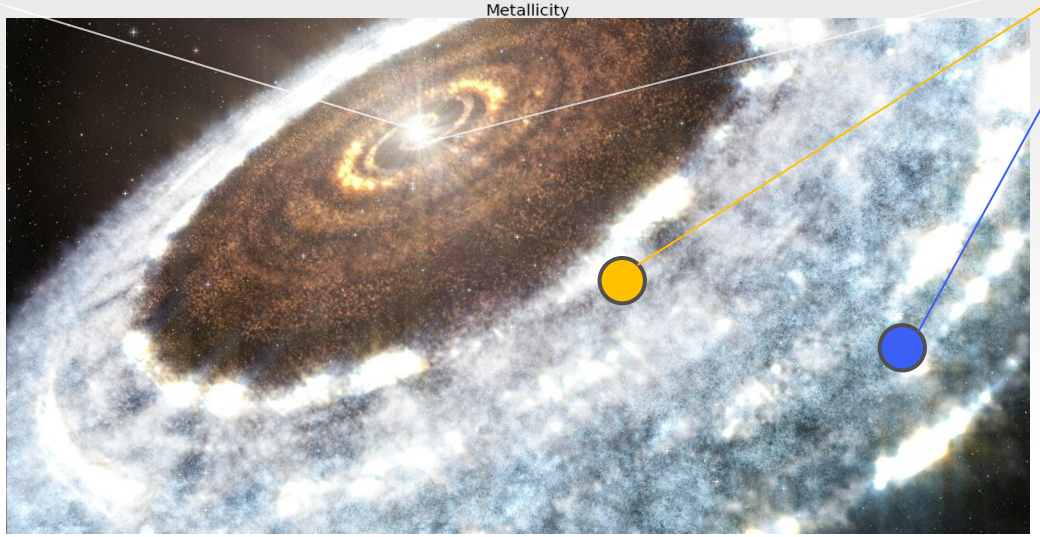
ARIEL observations for small planets

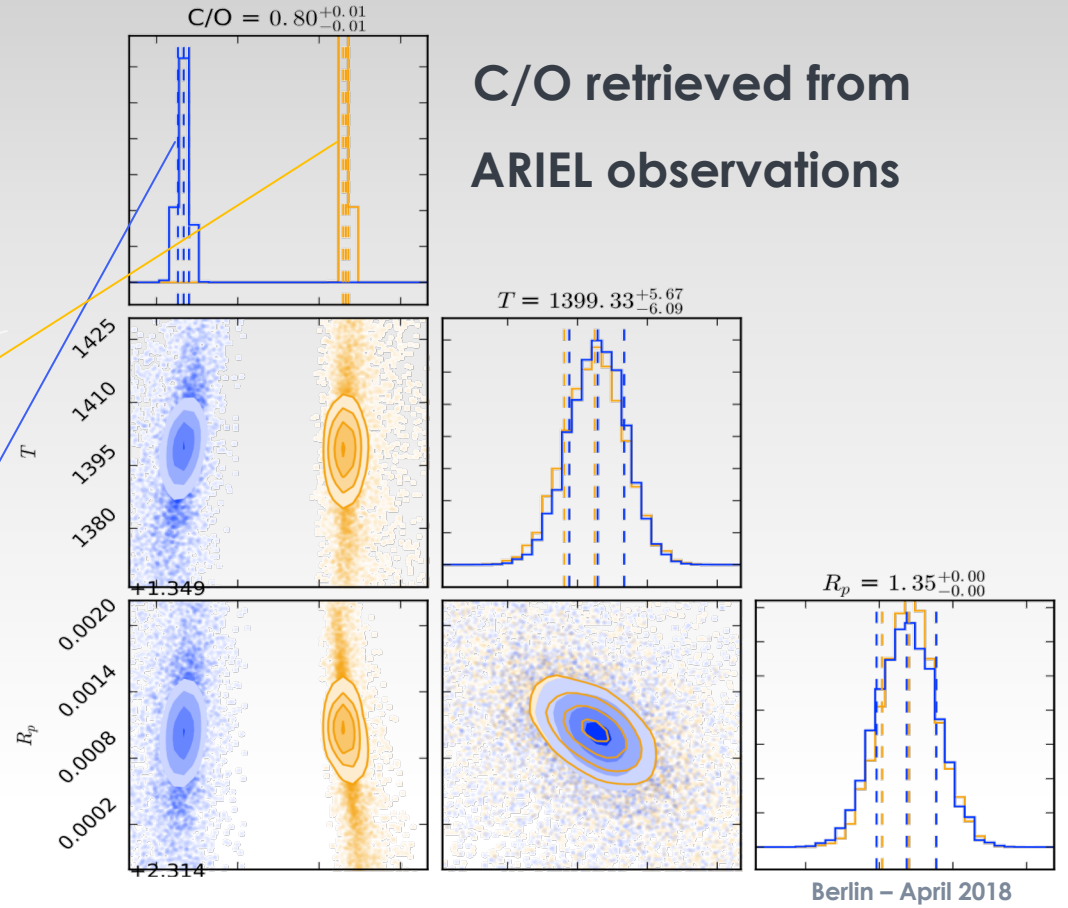


IS ELEMENTAL COMPOSITION CORRELATED …

…TO EXOPLANET PROVENANCE OR STELLAR METALLICITY?



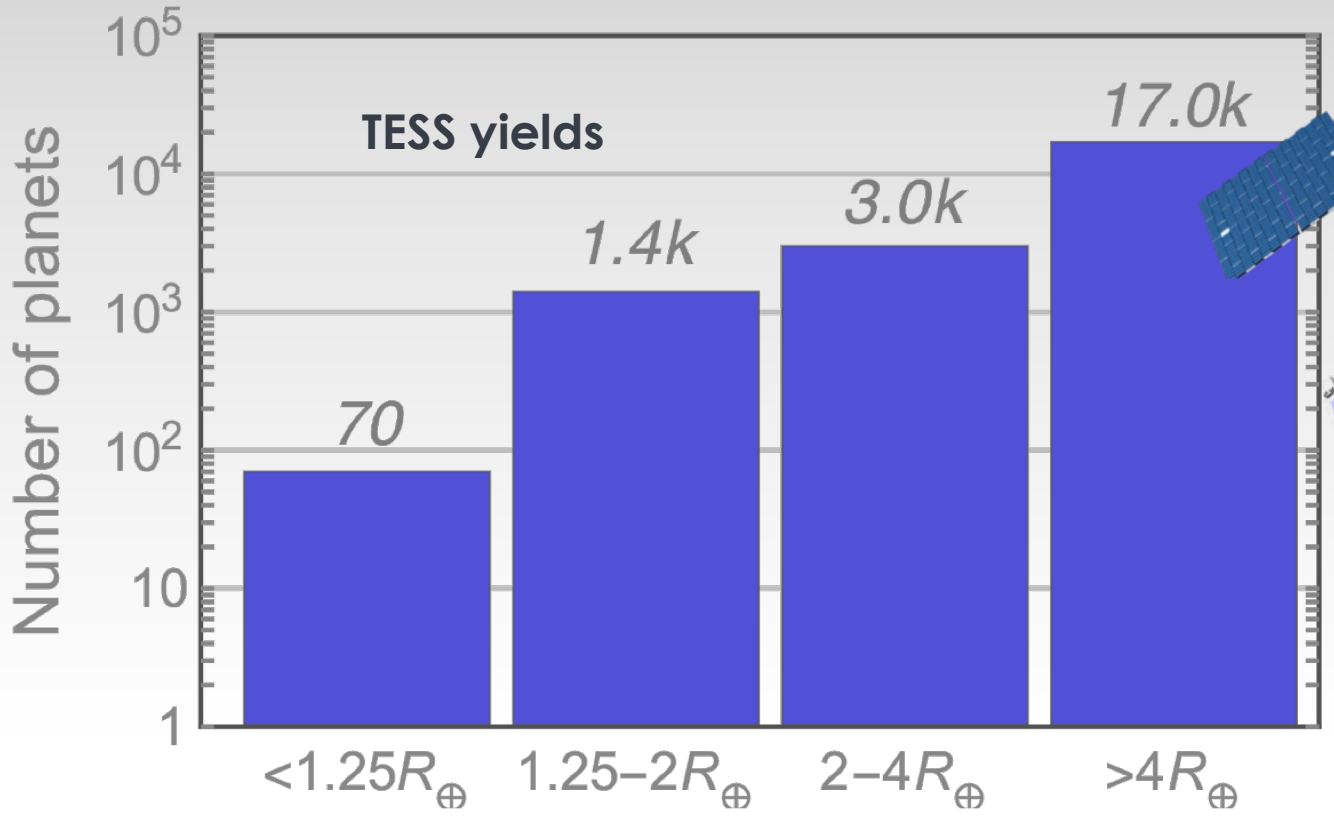


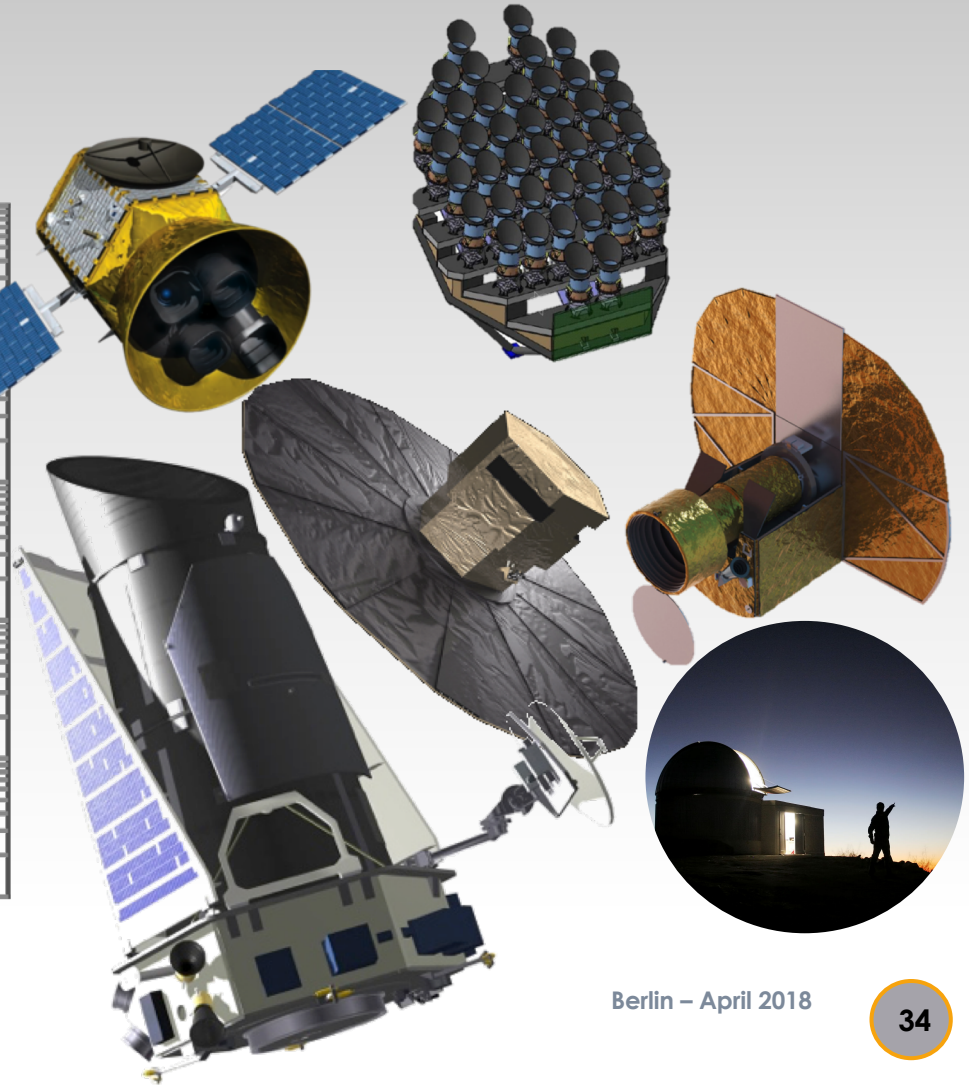


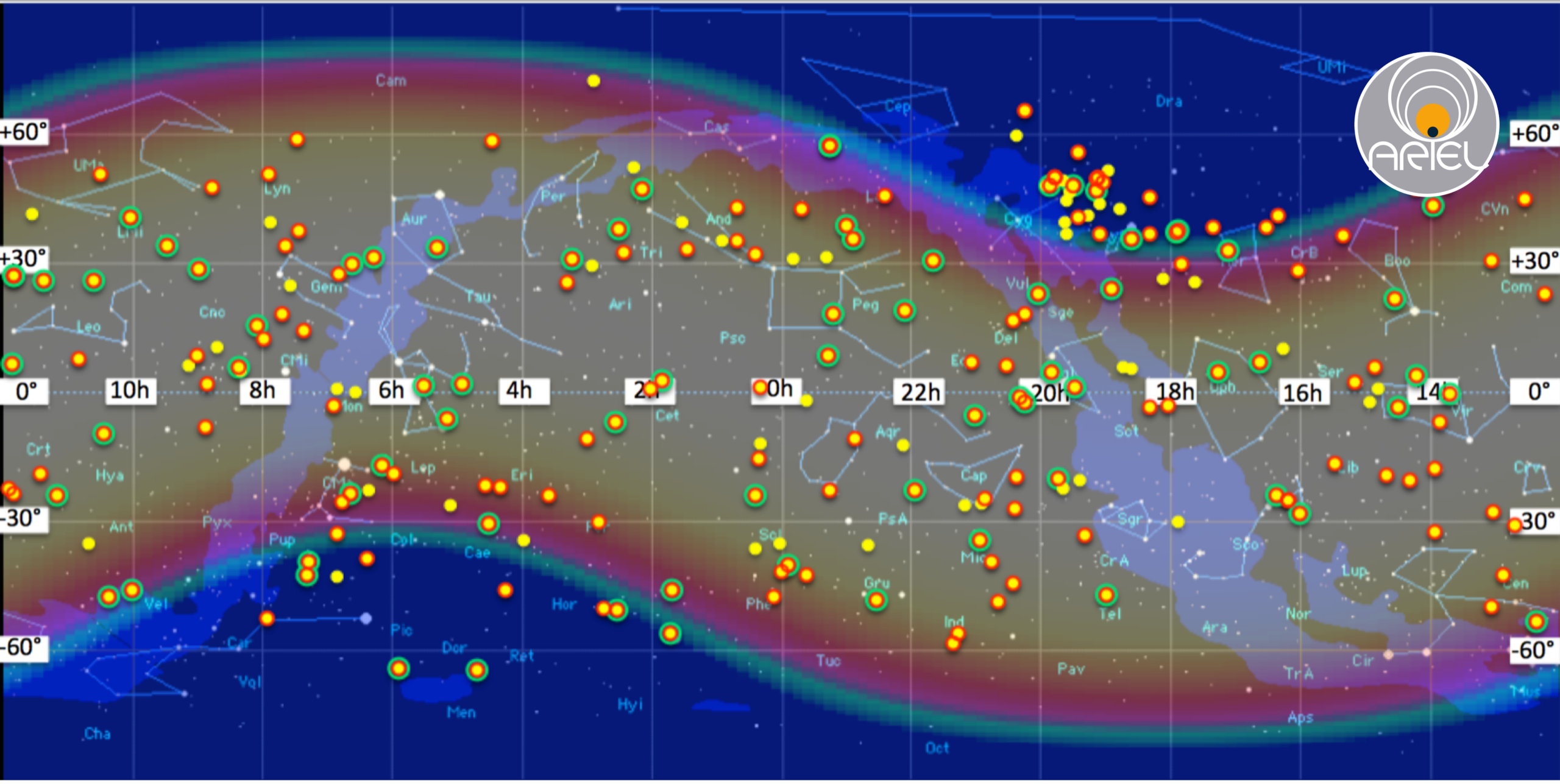
C/O retrieved from ARIEL observations

LARGE POPULATION OF WARM/HOT PLANETS

TODAY AND IN THE NEXT DECADE







Instantaneous Sky Visibility

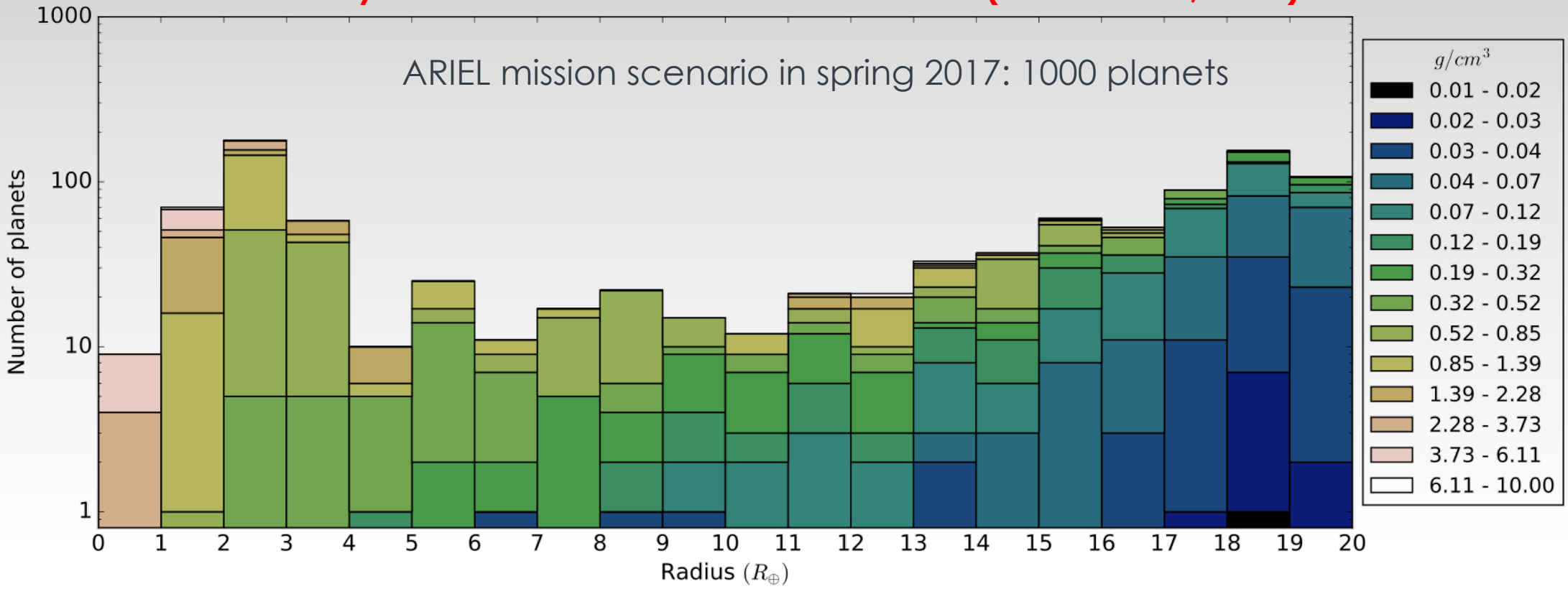
100% 80% 60% 40%

- Survey
- Deep
- Benchmark

DIVERSITY PROBED IN ARIEL CORE SAMPLE

PLANET SIZE, DENSITY, TEMPERATURE, STAR TYPE, METALLICITY

Already obsolete due to K2 new discoveries (Fulton et al., 2017)



Zingales et al., 2018

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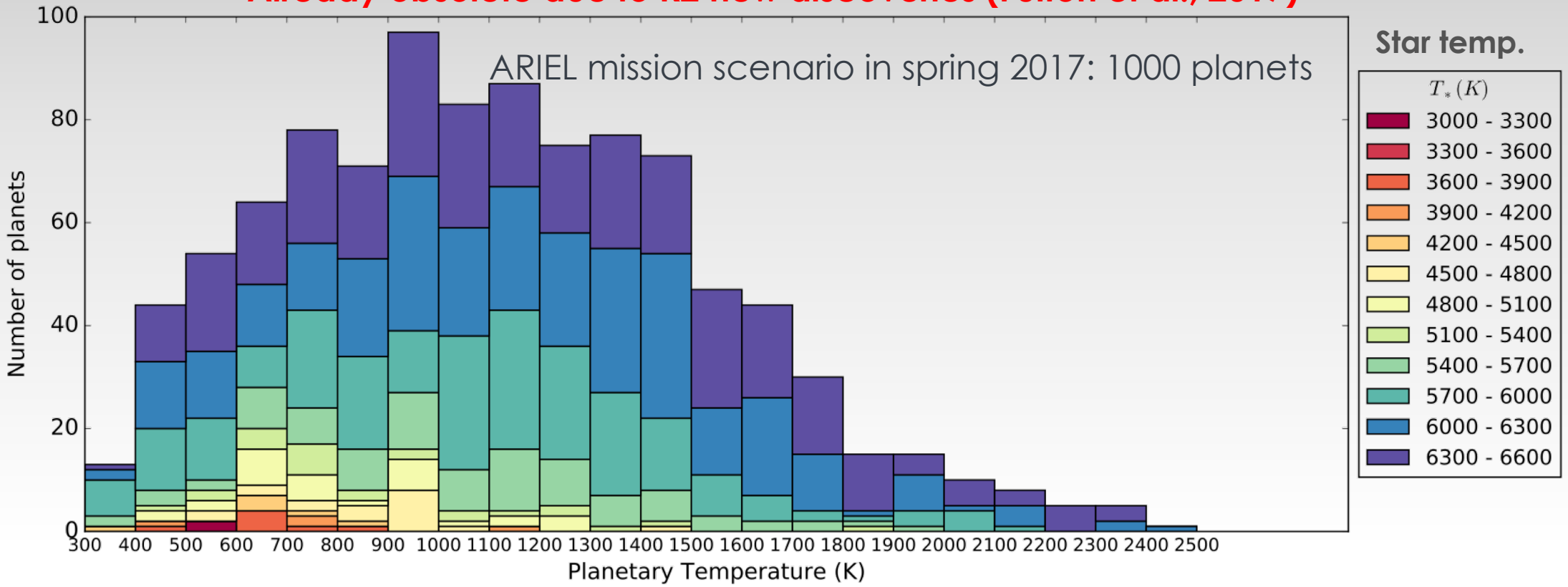
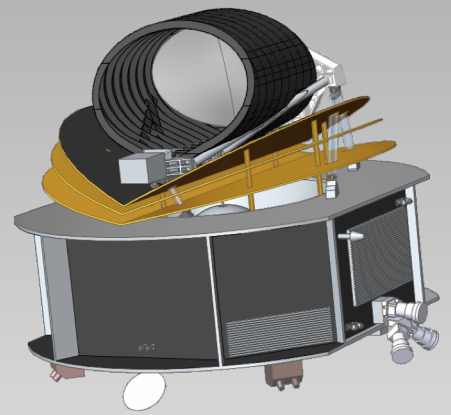


Zingales et al., 2018

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