

THE EXOPLANET PERSPECTIVE

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Lecturer in Astrophysics

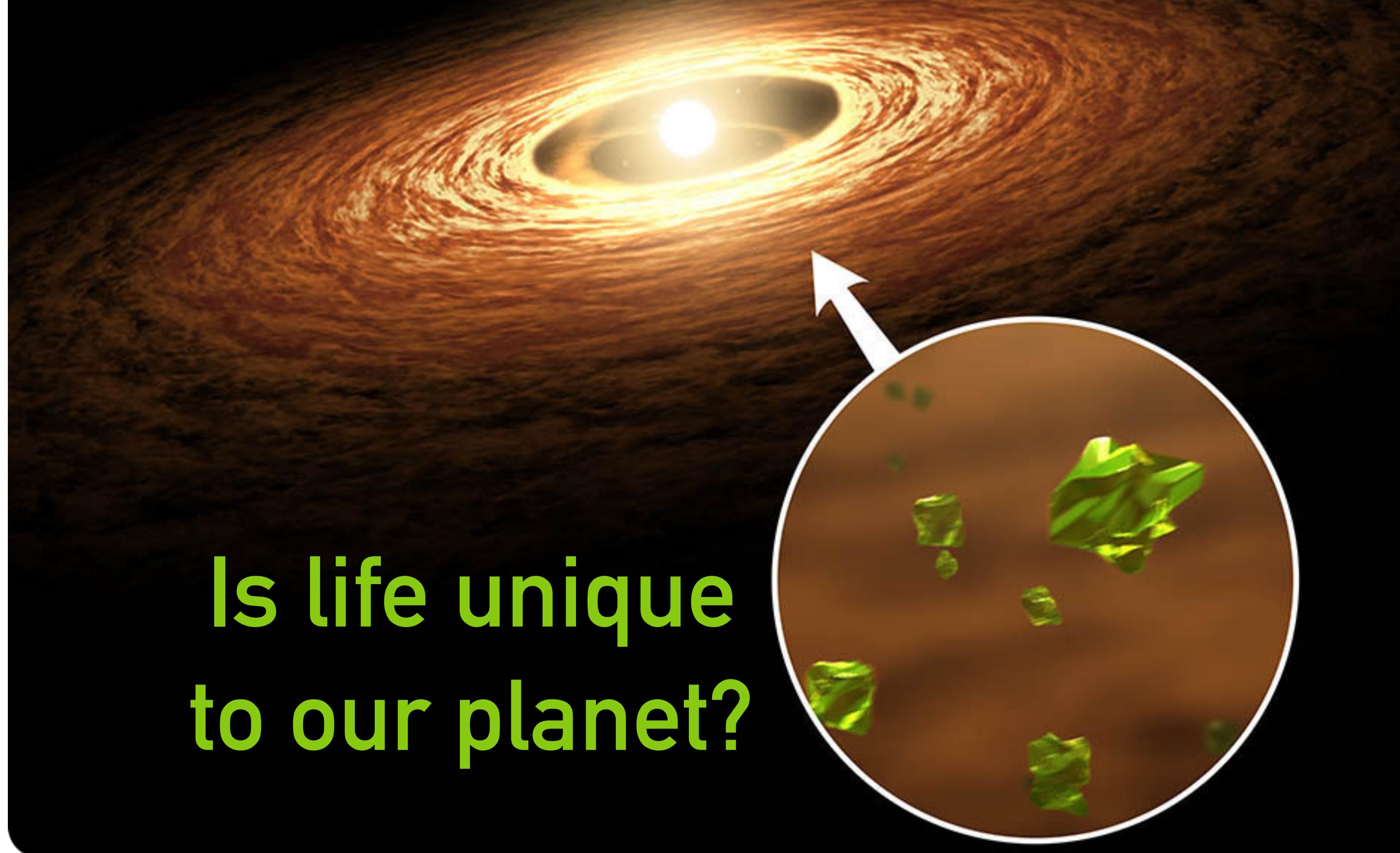
University of Bristol



University of
BRISTOL

THE BIG QUESTIONS IN ASTRONOMY

How do stars and planetary systems develop and evolve?

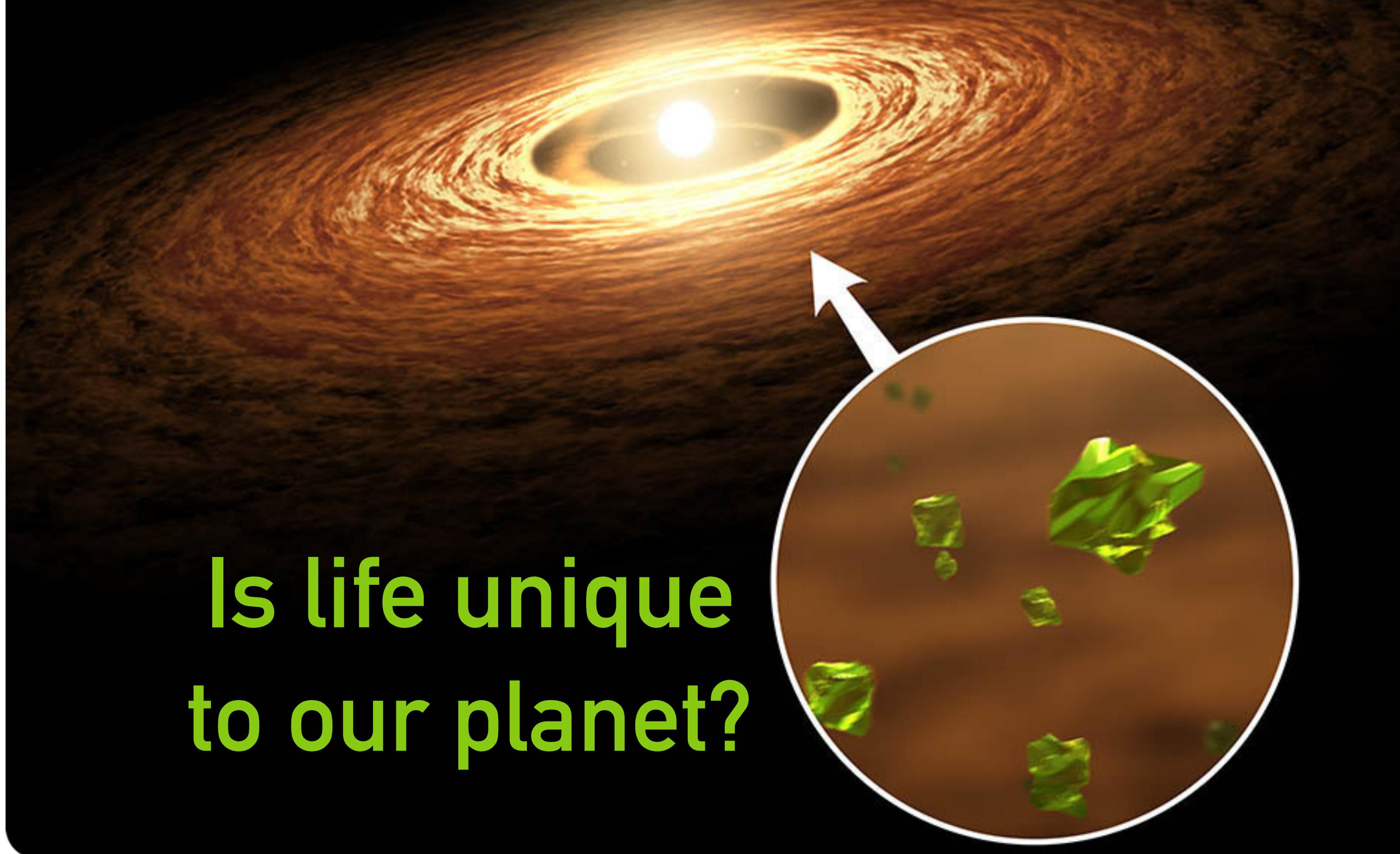


Is life unique to our planet?

1. What are the demographics of exoplanet, masses, radii, stellar hosts, etc.?
2. What are the atmospheres of different exoplanets composed of?
3. Can we trace any of that information to formation scenarios, or to potential for life?

THE BIG QUESTIONS IN PLANETARY SCIENCE

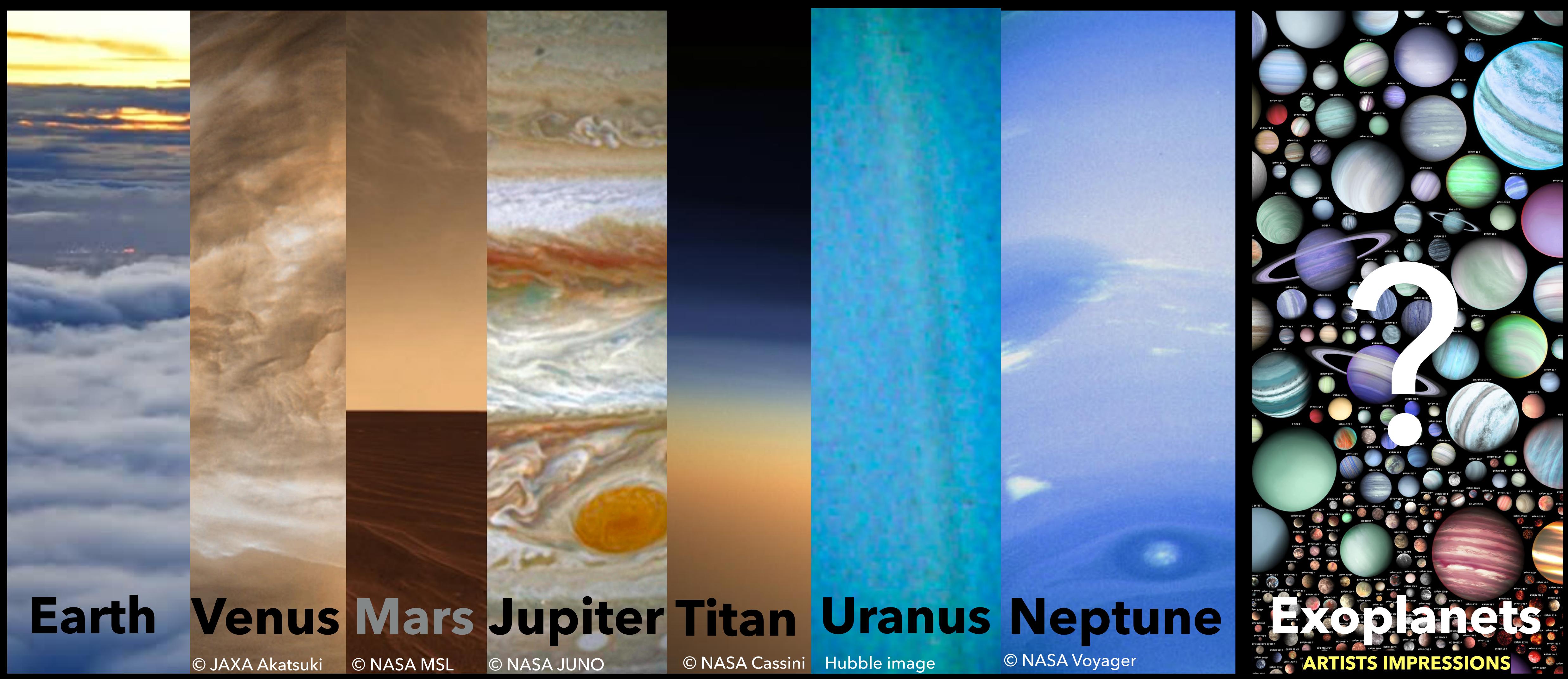
How did the solar system develop and evolve?



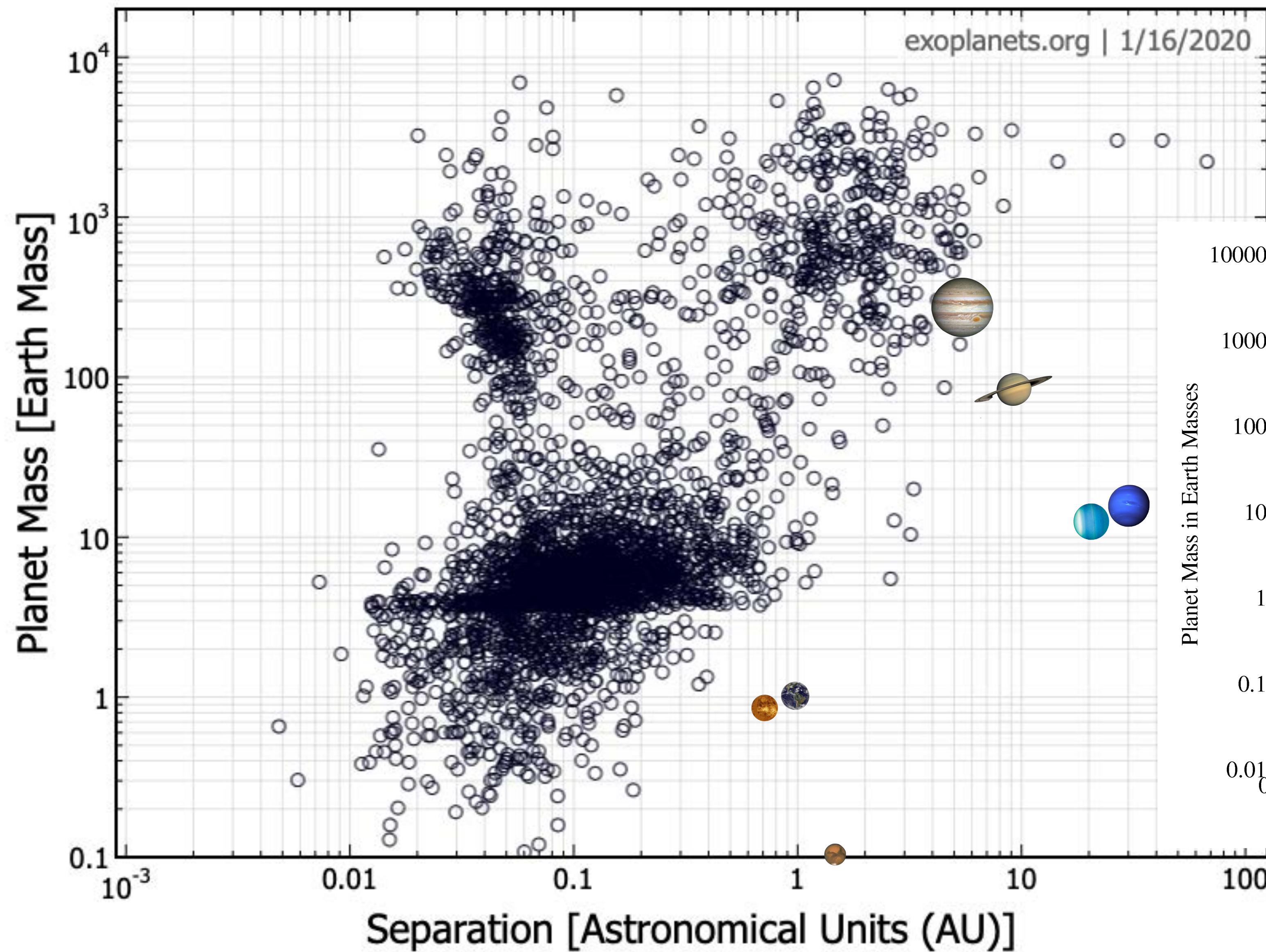
Is life unique to our planet?

- 1. What is the diversity for habitability: masses, radii, distance, radiation, magnetic fields?**
- 2. What are the atmospheres of solar system planets made of and how did they evolve?**
- 3. What are the processes and timescales of planet formation?**

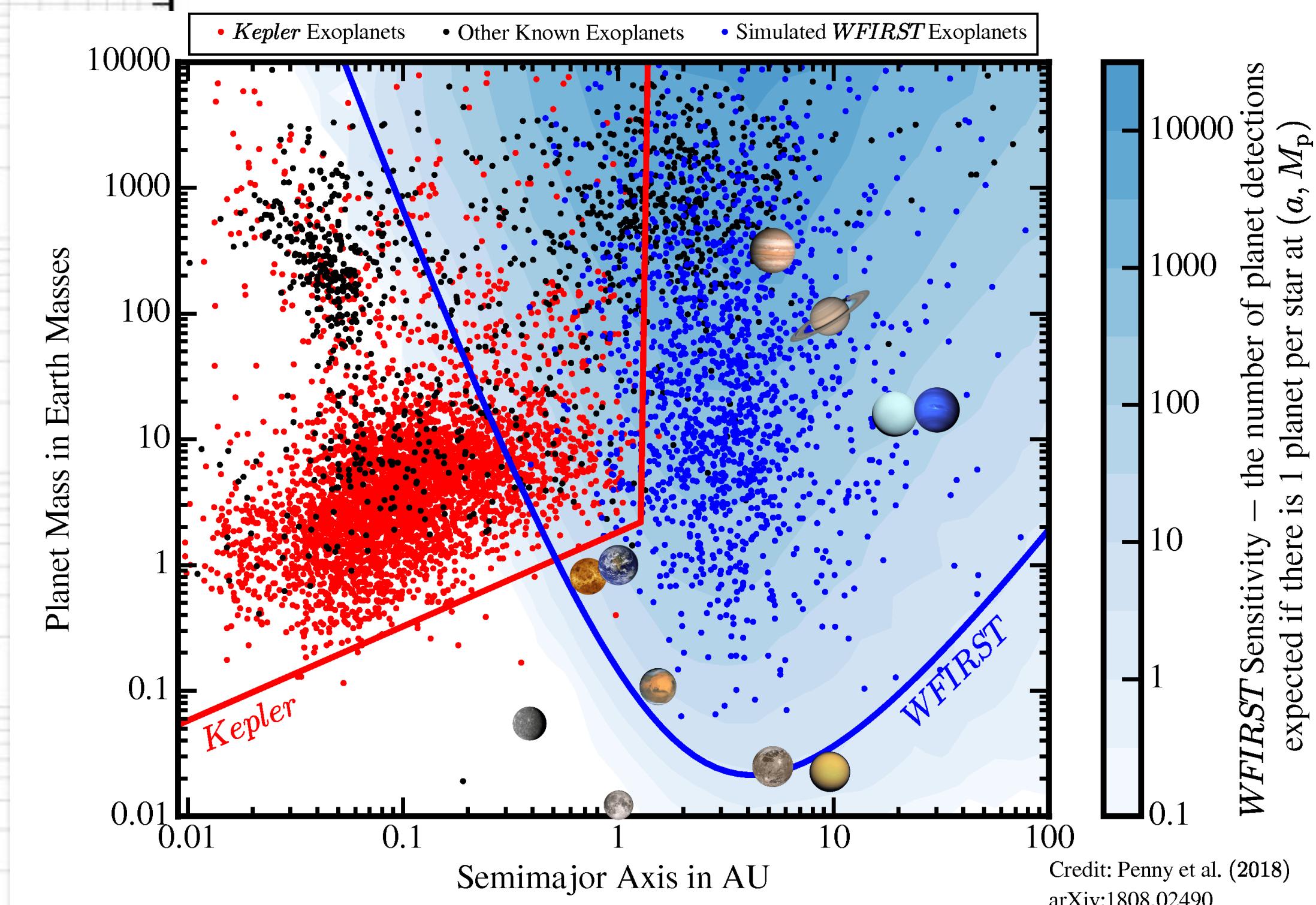
FROM THE SOLAR SYSTEM TO EXOPLANETS



A LOOK AT THE EXOPLANET POPULATION AND DEMOGRAPHICS



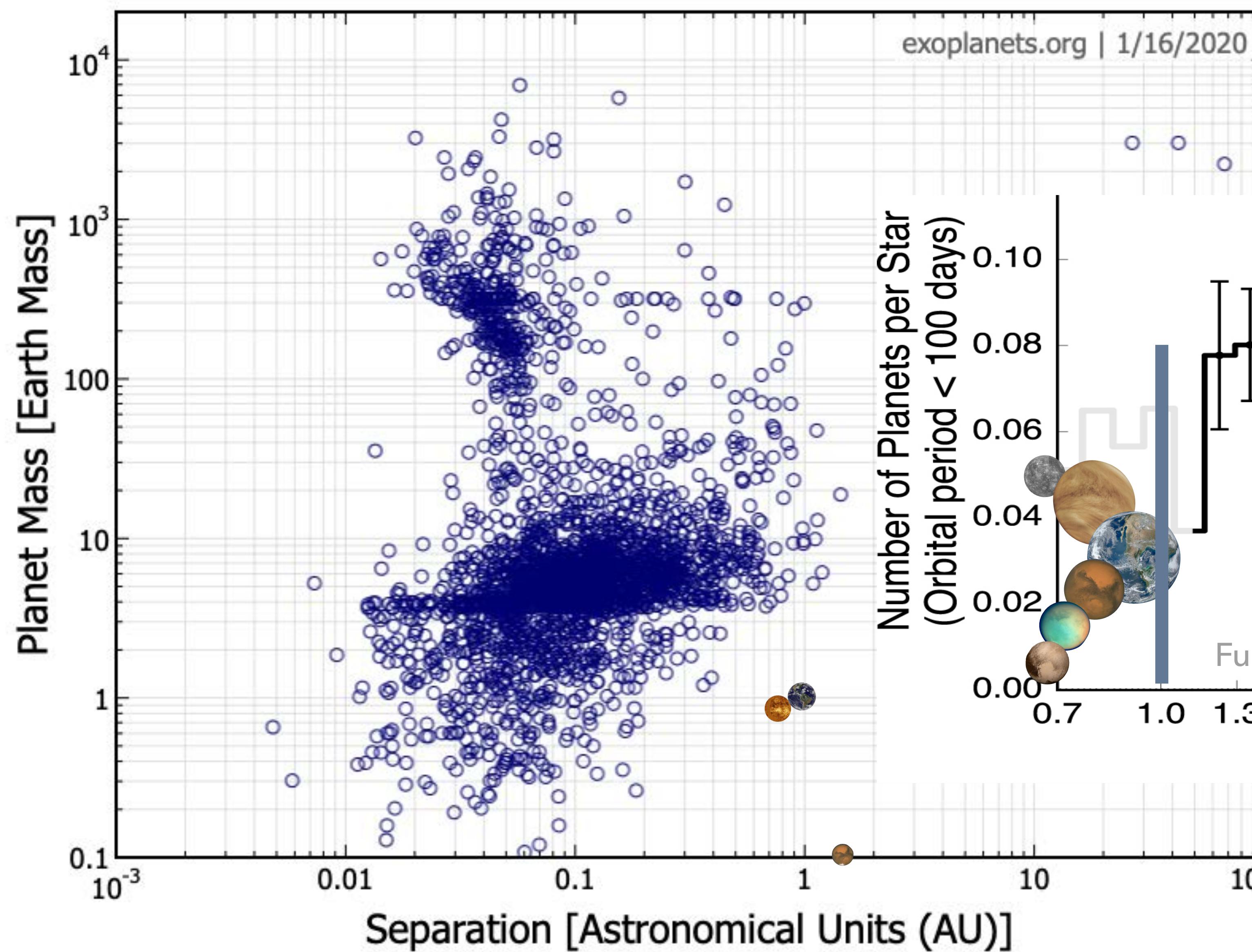
1. What is the diversity of exoplanet types, masses, radii?



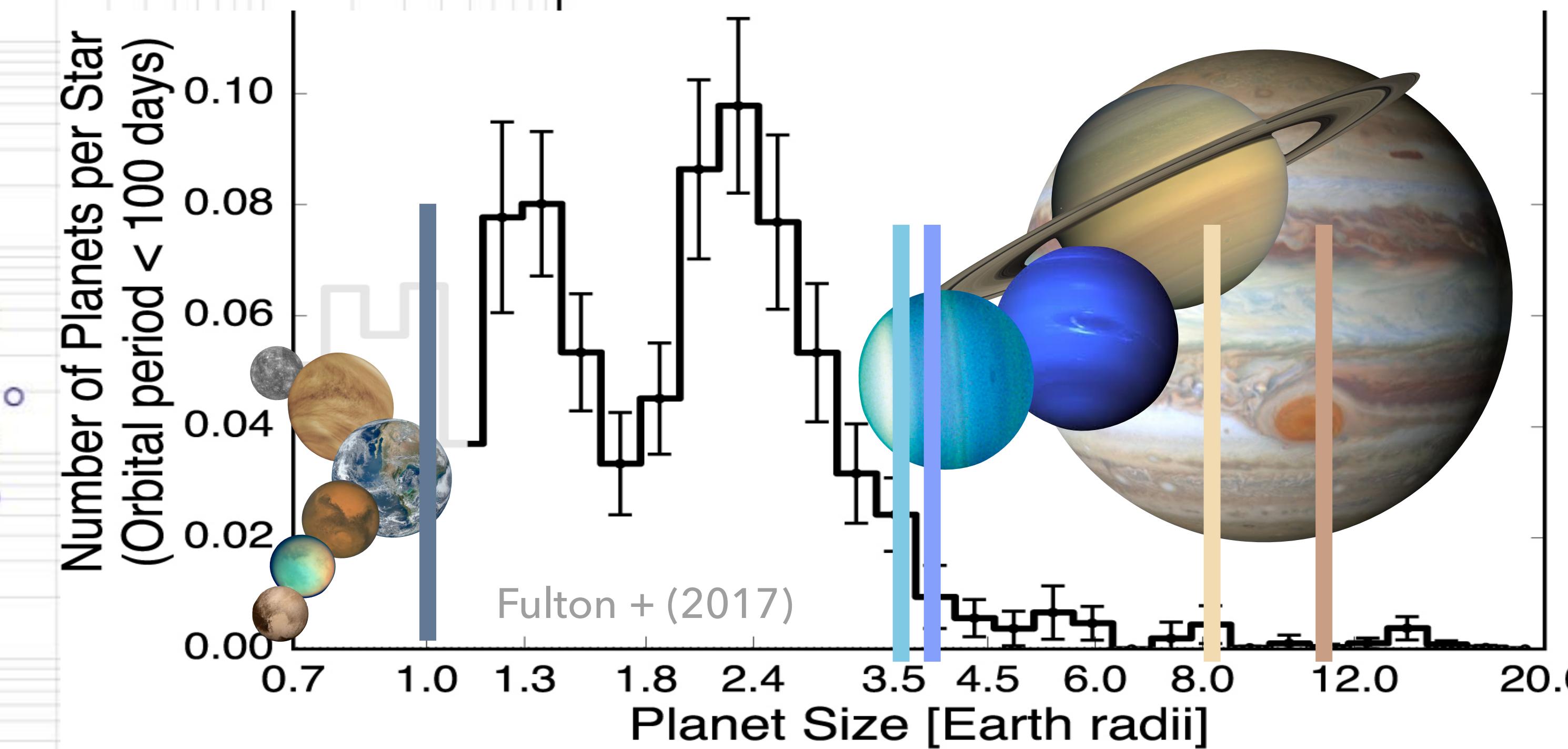
WFIRST Sensitivity – the number of planet detections expected if there is 1 planet per star at (a, M_p)

Credit: Penny et al. (2018)
arXiv:1808.02490

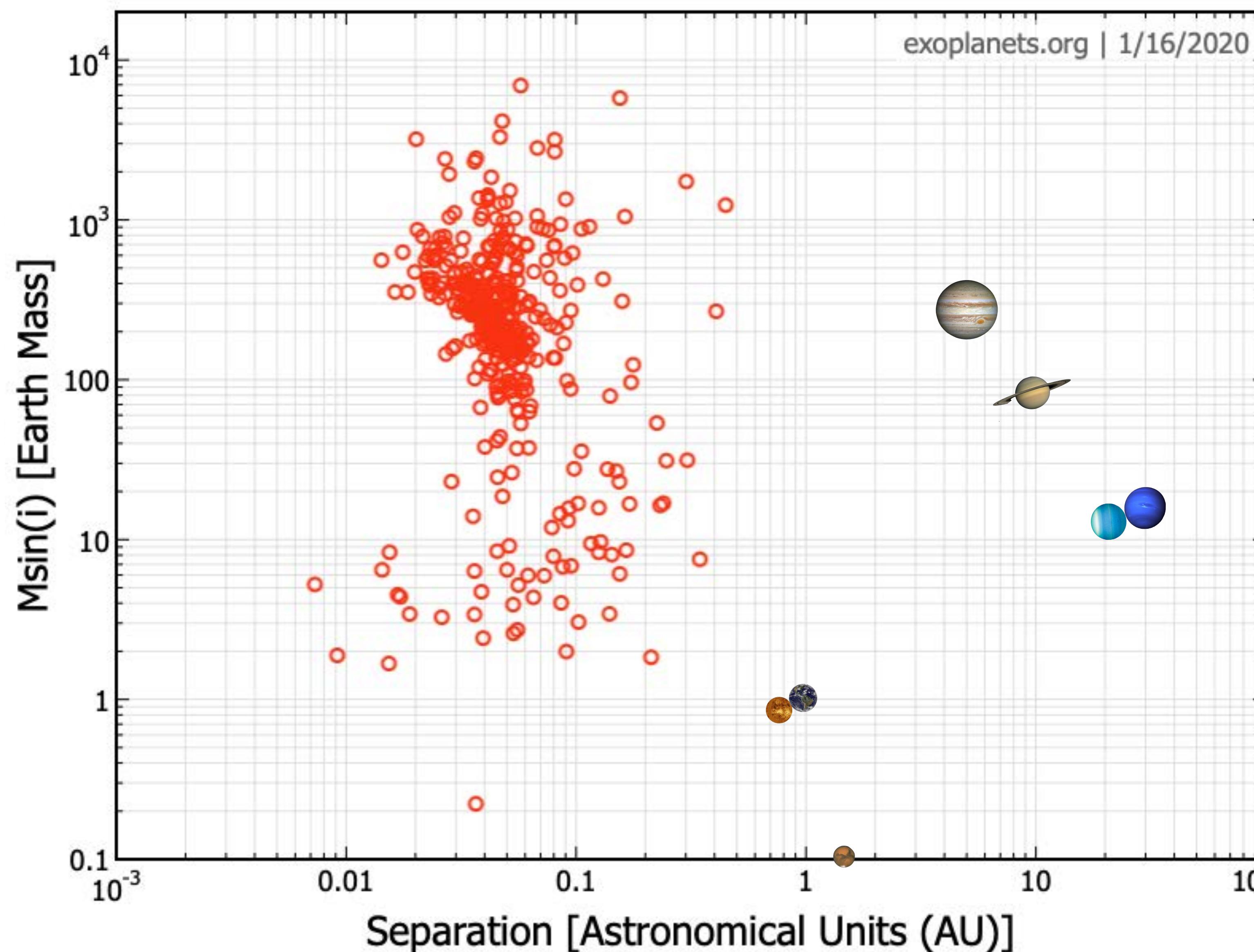
A LOOK AT THE EXOPLANET POPULATION OF SMALL WORLDS



1. What is the diversity of exoplanet types, masses, radii?

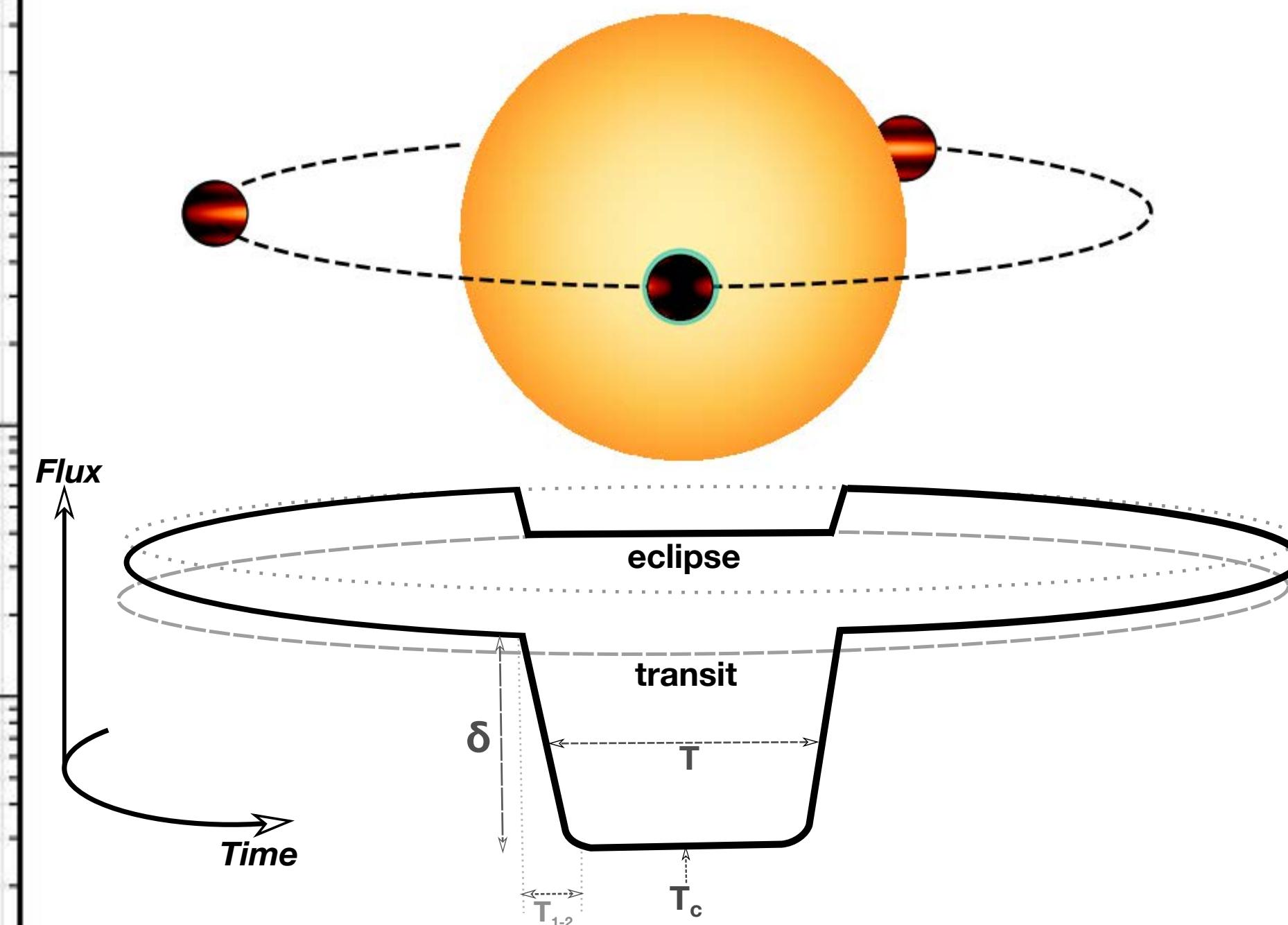


EXOPLANETS WITH MEASURED MASS AND RADII

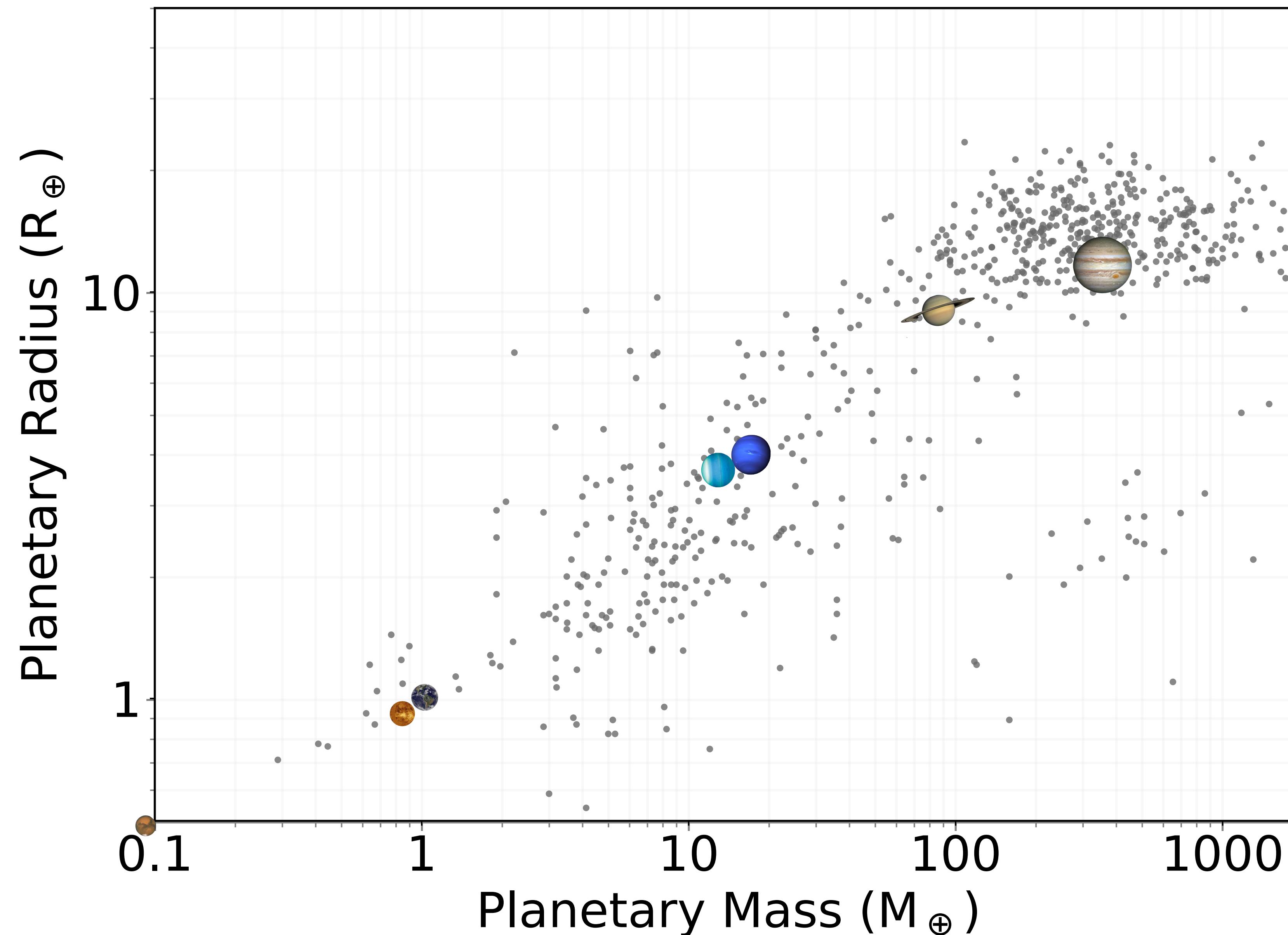


1. What is the diversity of exoplanet types, masses, radii?

Transiting planets have directly measured radii



THE MASS / RADIUS CHARACTERIZATION PHASE SPACE

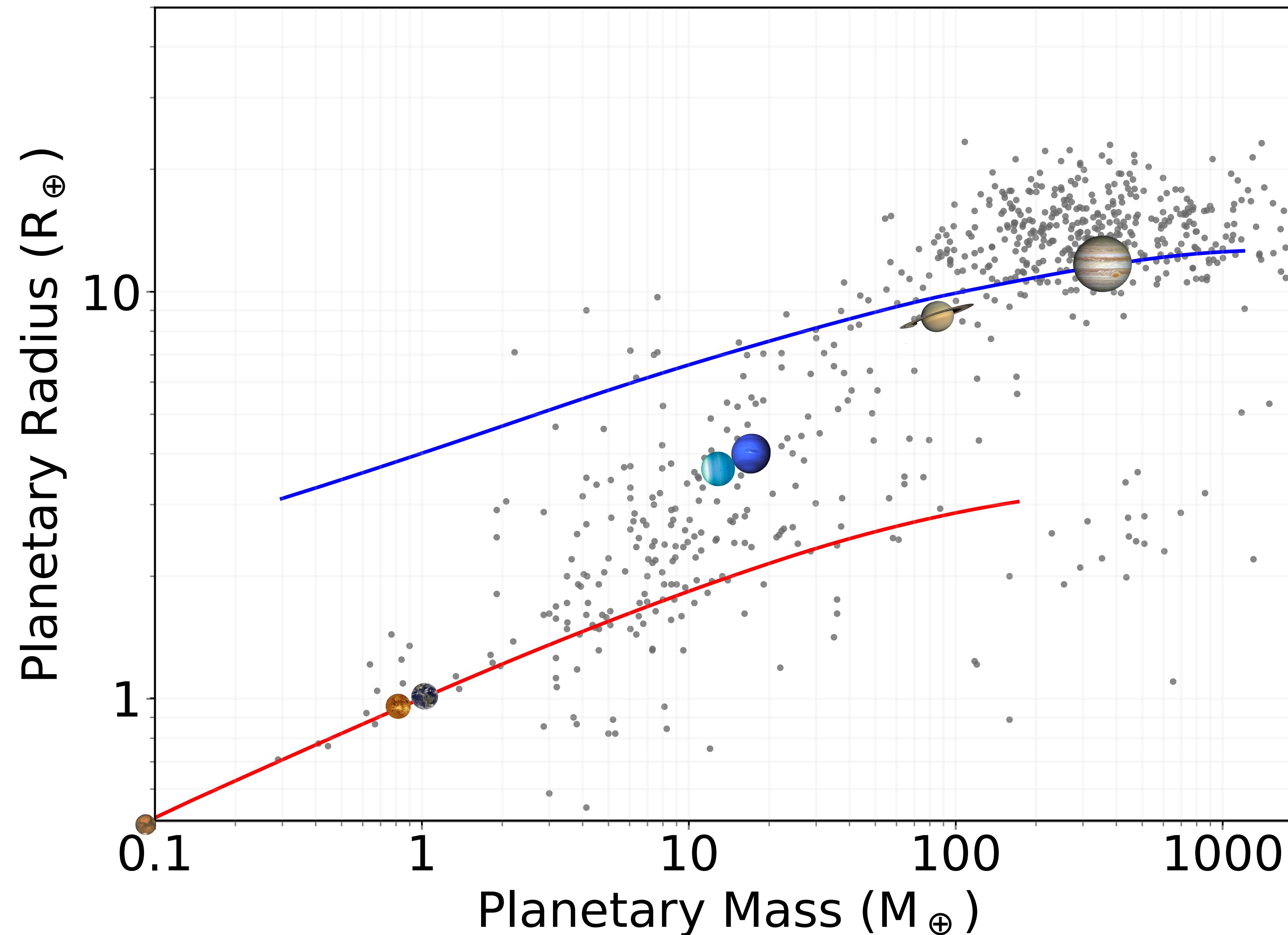


2. What are the atmospheres of different exoplanets composed of?

DATA: NASA exoplanet archive

Hannah Wakeford, @stellarplanet

THE MASS / RADIUS CHARACTERIZATION PHASE SPACE



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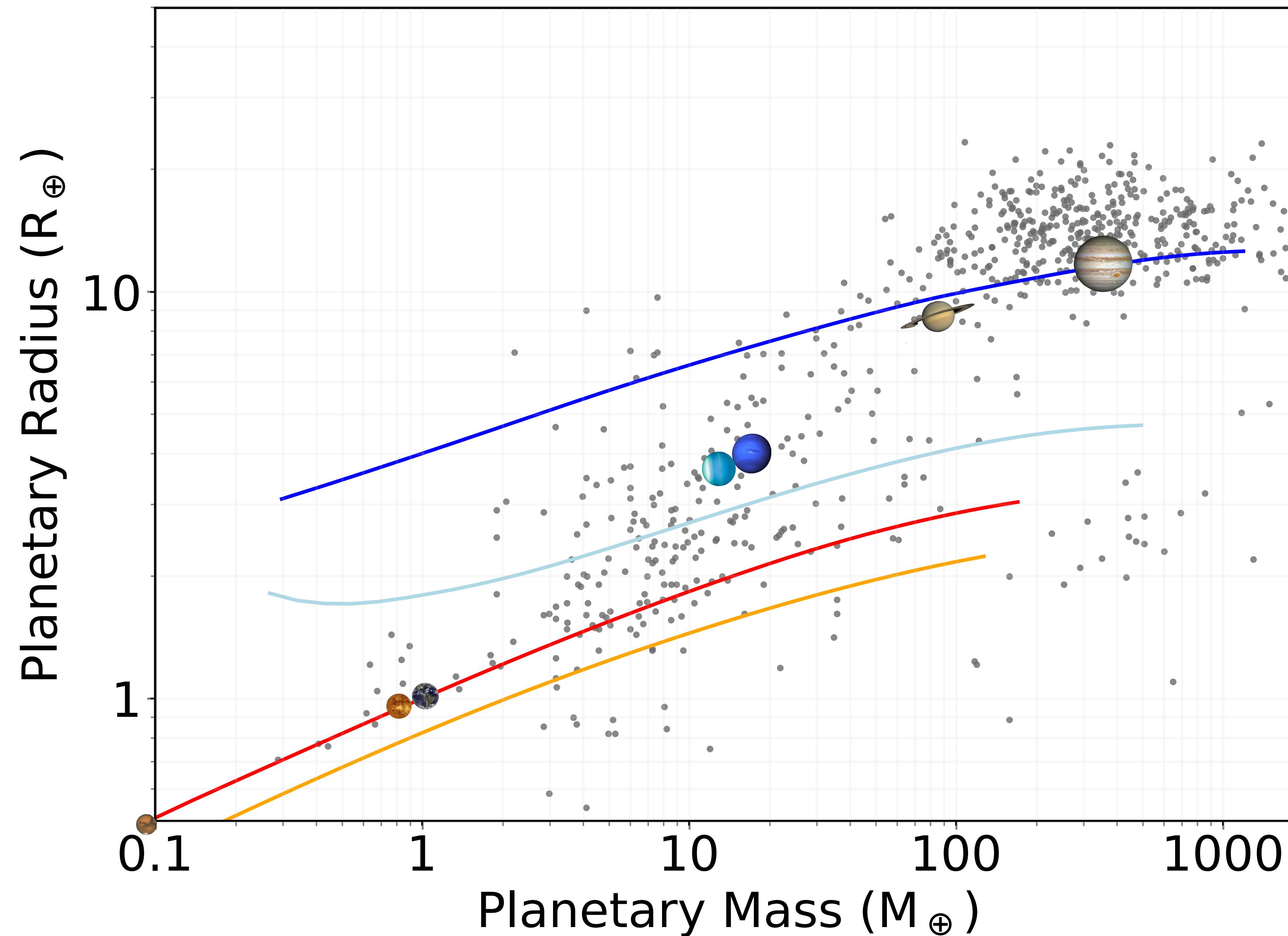
Cold Hydrogen

Earth-like Rocky
(32.5% Fe+67.5% MgSiO_3)

MODELS: Zeng+ (2019)
PNAS, 116

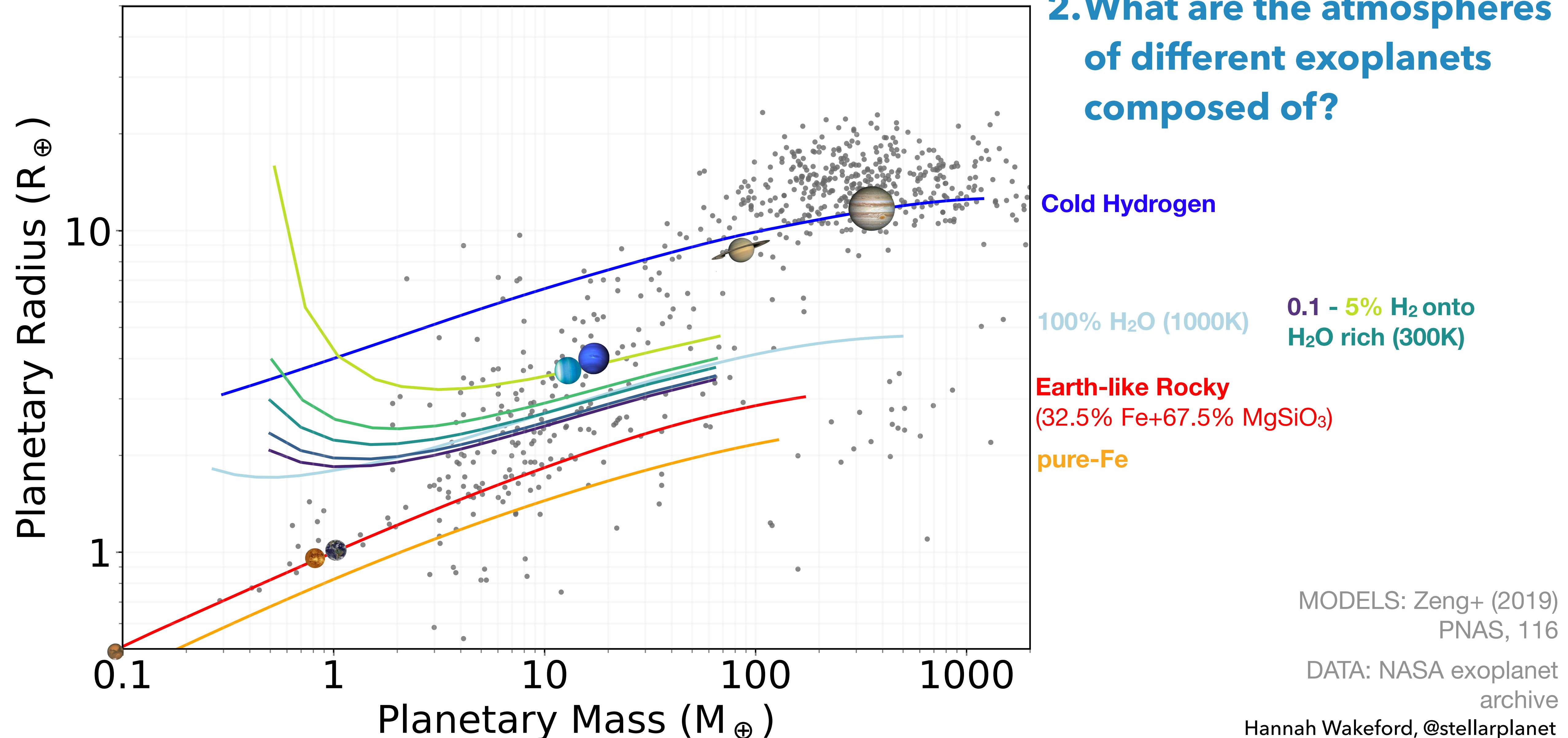
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THE MASS / RADIUS CHARACTERIZATION PHASE SPACE

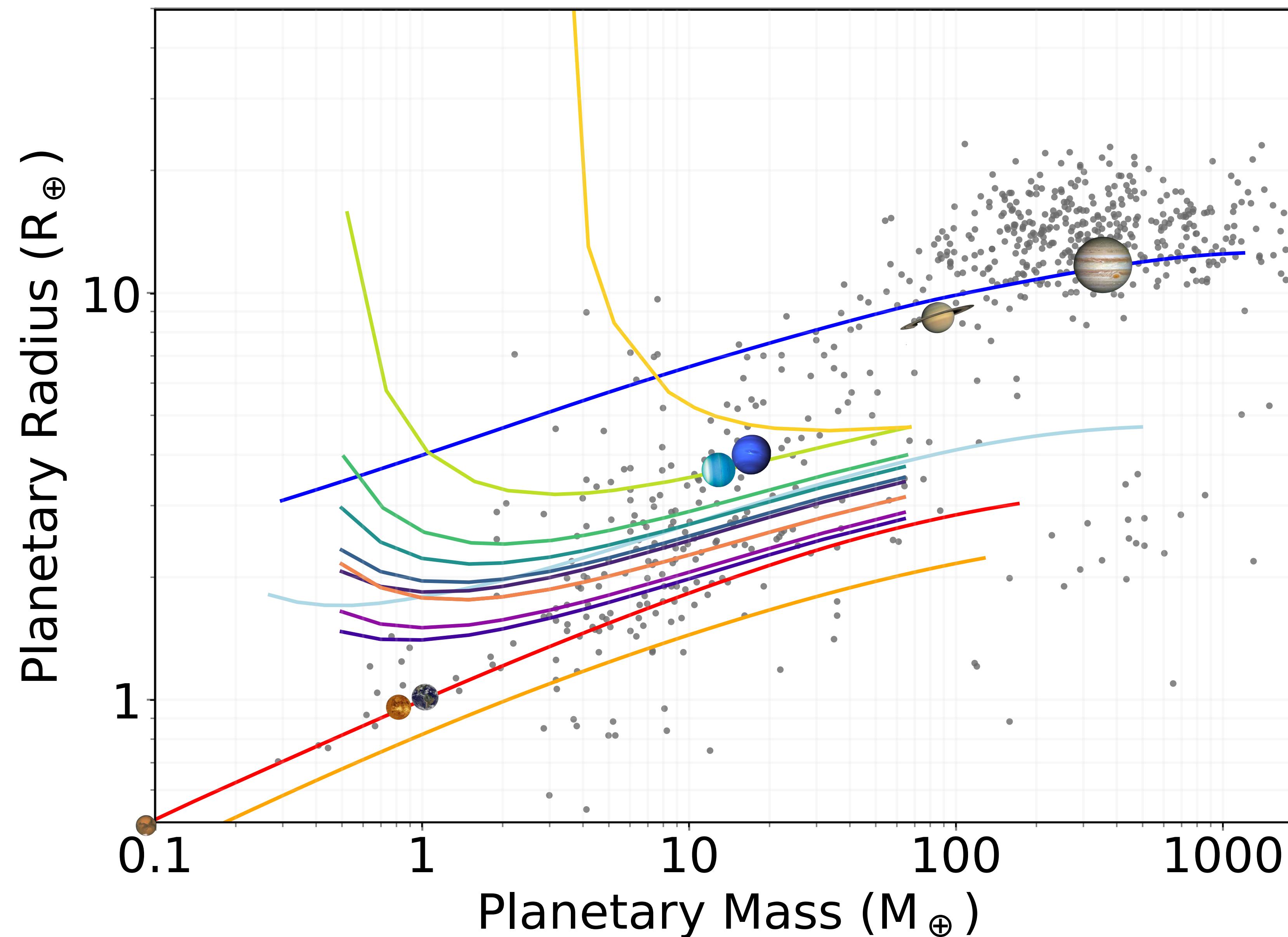


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THE MASS / RADIUS CHARACTERIZATION PHASE SPACE



THE MASS / RADIUS CHARACTERIZATION PHASE SPACE



2. What are the atmospheres of different exoplanets composed of?

Cold Hydrogen

100% H₂O (1000K)

Earth-like Rocky
(32.5% Fe+67.5% MgSiO₃)

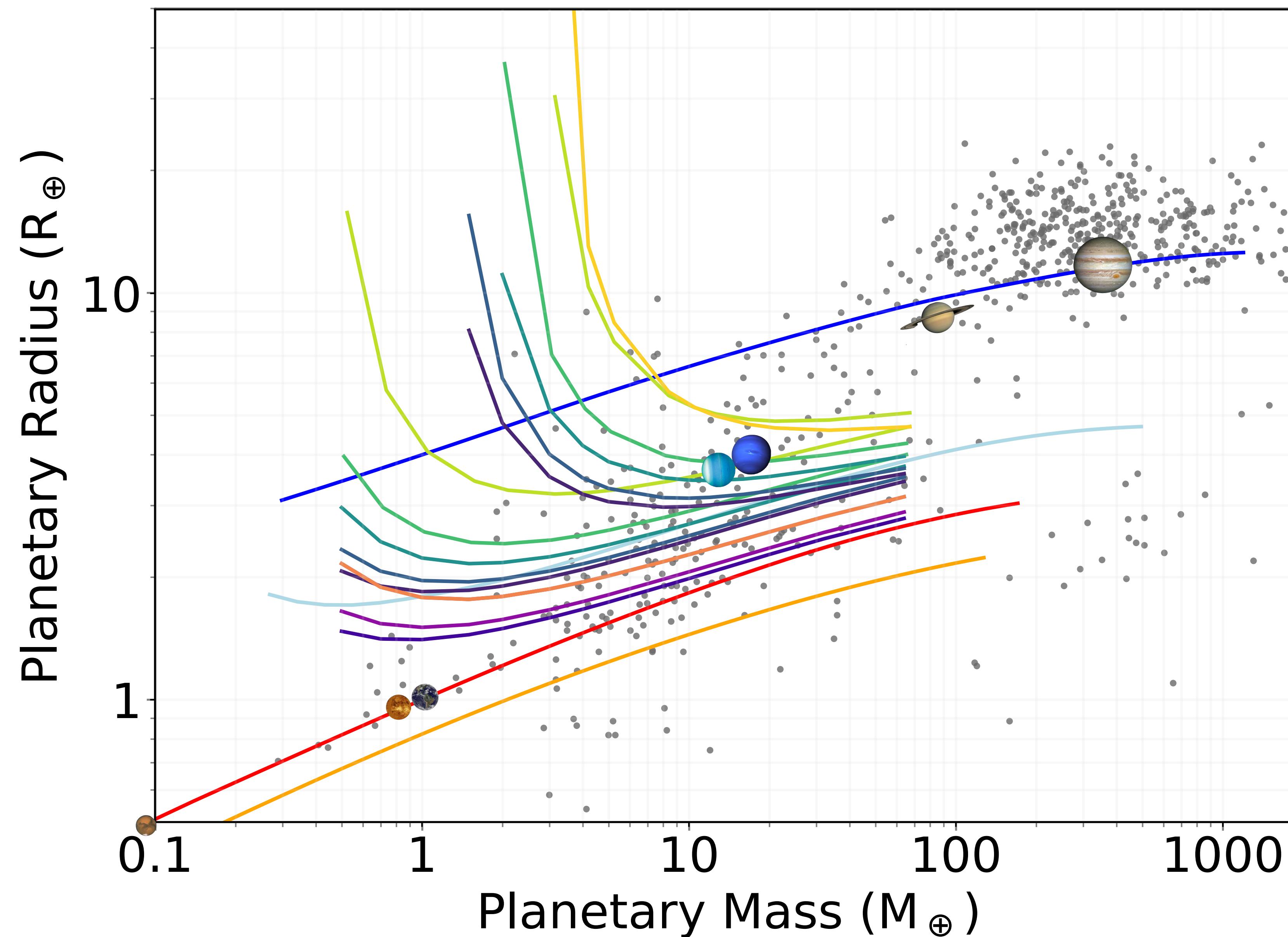
pure-Fe

0.1 - 5% H₂ onto H₂O rich (300K)
0.1 - 5% H₂ onto H₂O rich (1000K)

MODELS: Zeng+ (2019)
PNAS, 116

DATA: NASA exoplanet archive

THE MASS / RADIUS CHARACTERIZATION PHASE SPACE



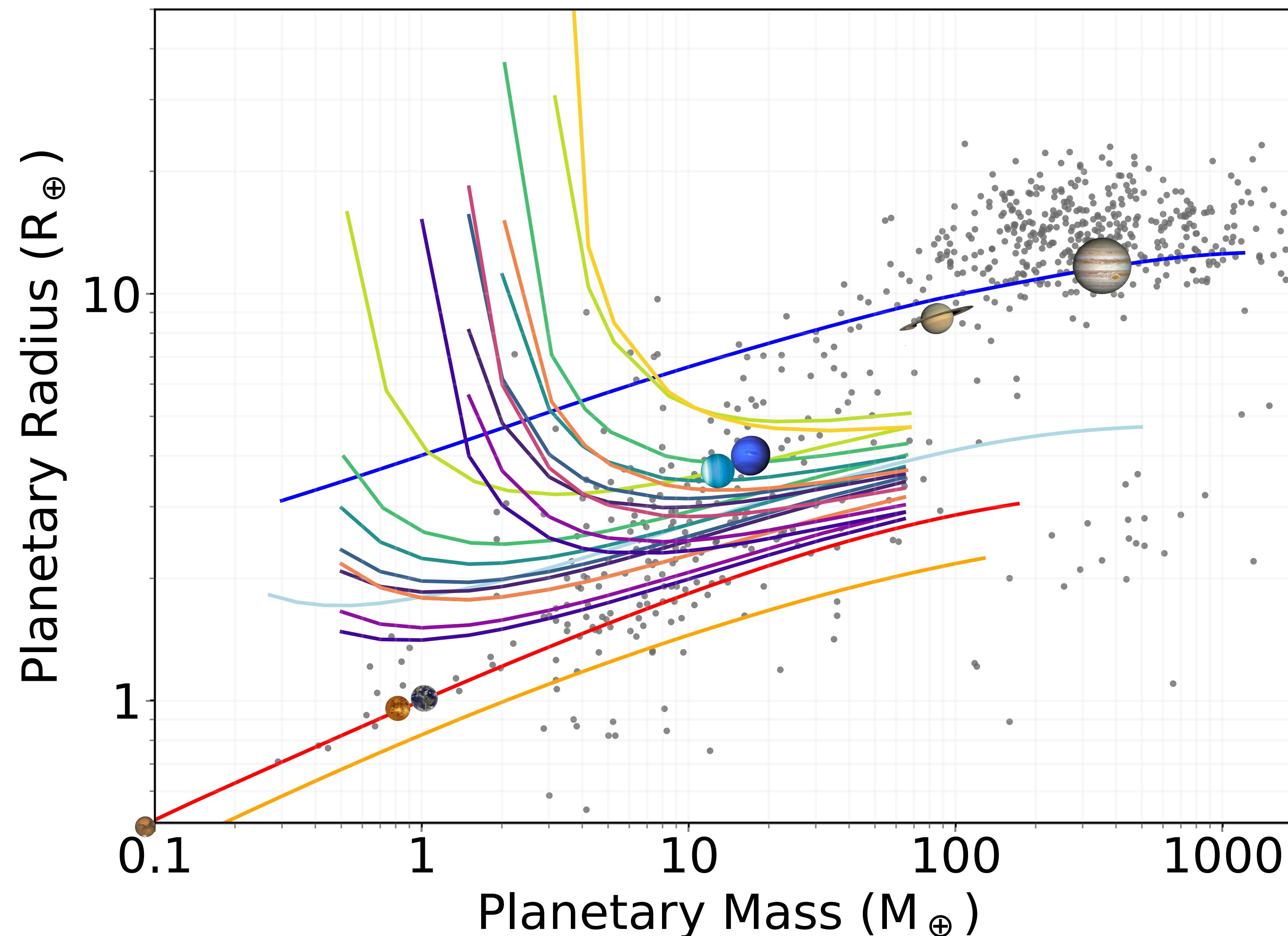
2. What are the atmospheres of different exoplanets composed of?

- Cold Hydrogen** 0.1 - 5% H_2 onto rock rich (300K)
- 100% H_2O (1000K)
- Earth-like Rocky** (32.5% Fe+67.5% $MgSiO_3$)
- pure-Fe**

MODELS: Zeng+ (2019)
PNAS, 116

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THE MASS / RADIUS CHARACTERIZATION PHASE SPACE

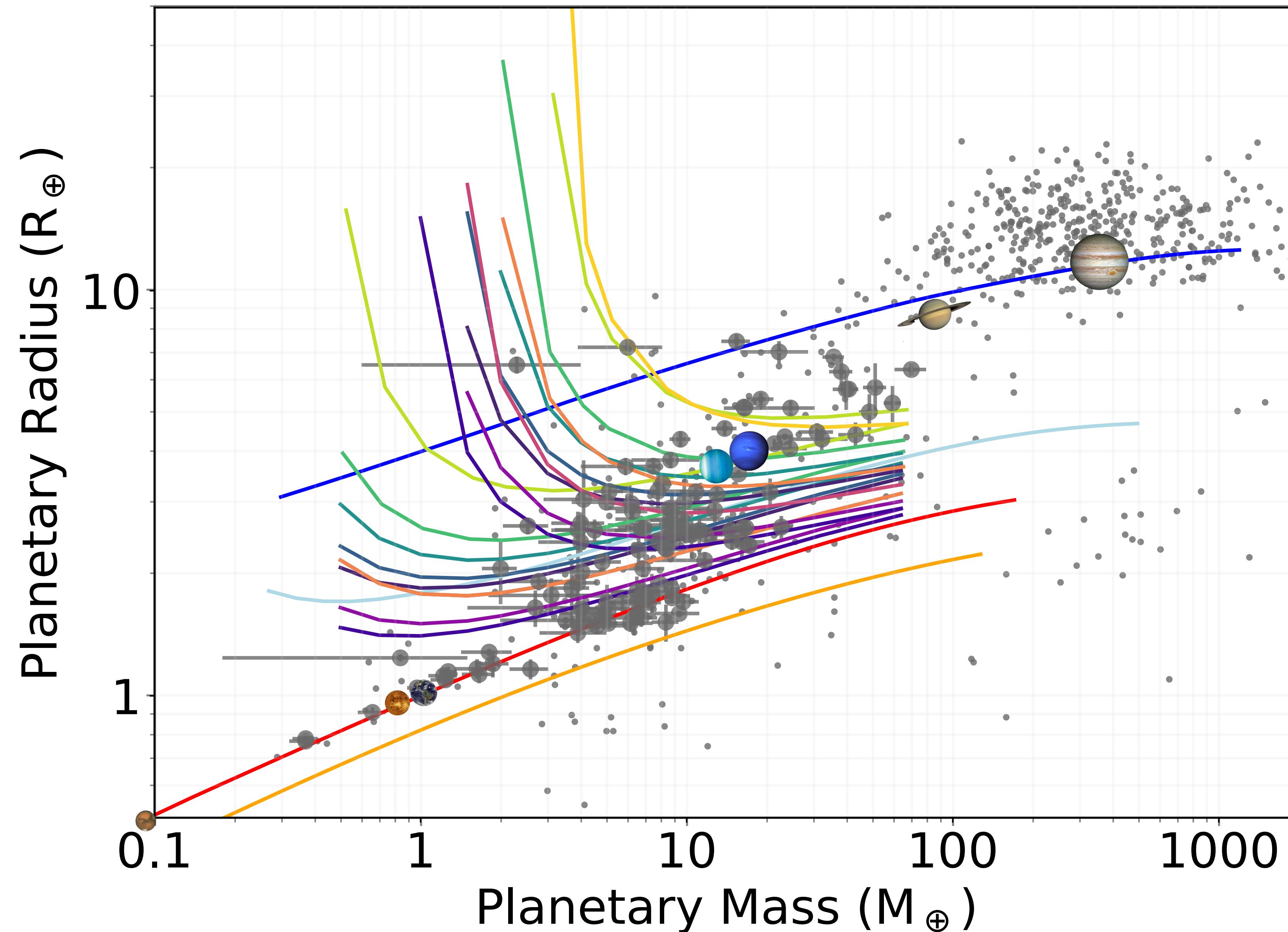


2. What are the atmospheres of different exoplanets composed of?

- 0.1 - 5% H_2 onto rock rich (300K)
- 0.1 - 5% H_2 onto rock rich (1000K)
- 0.1 - 5% H_2 onto H_2O rich (300K)
- 0.1 - 5% H_2 onto H_2O rich (1000K)

Hannah Wakeford, @stellarplanet

THE MASS / RADIUS CHARACTERIZATION PHASE SPACE



2.What are the atmospheres of different exoplanets composed of?

Cold Hydrogen

100% H₂O (1000K)

Earth-like Rocky (32.5% Fe+67.5% MgSiO₃)

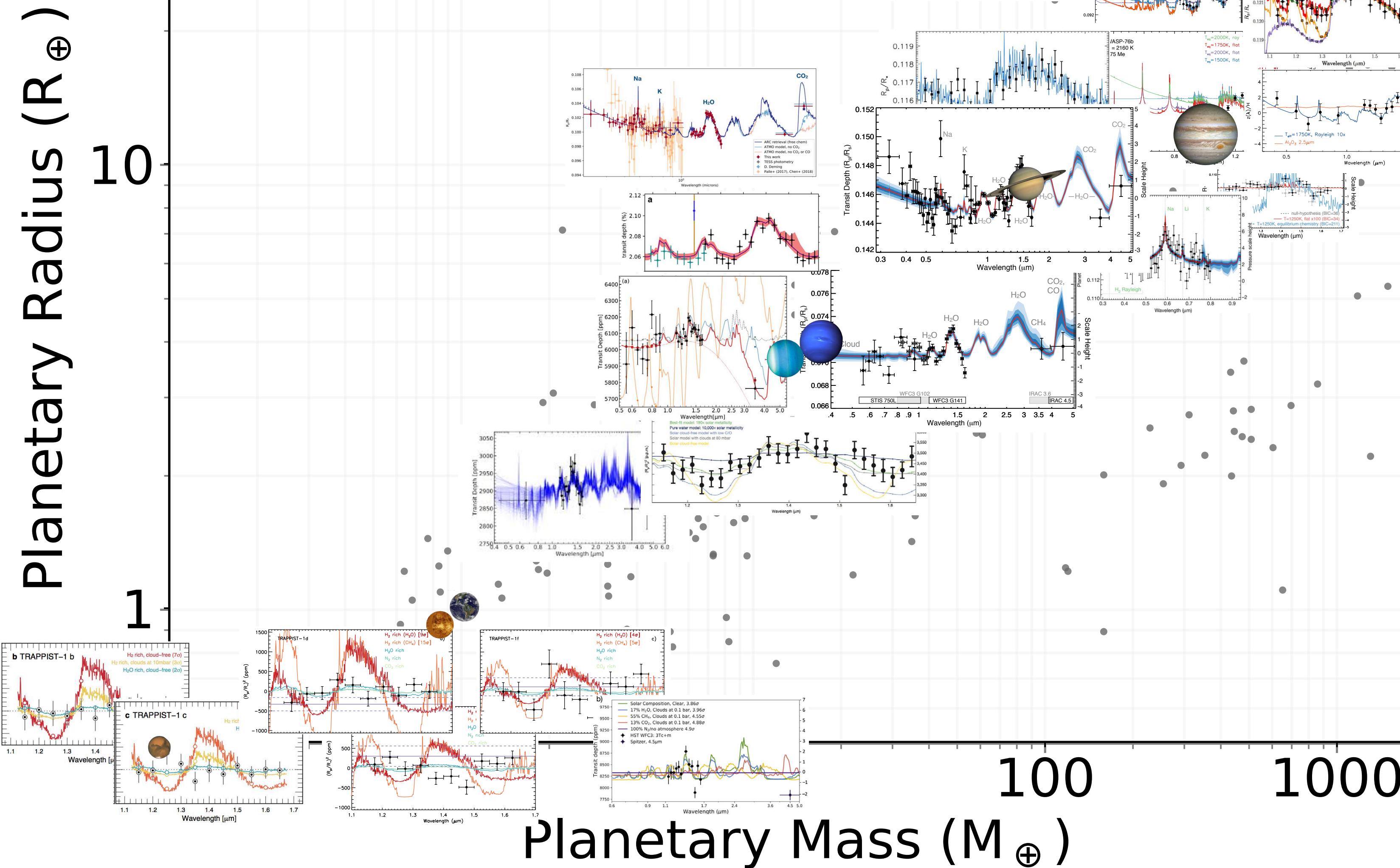
pure-Fe

MODELS: Zeng+ (2019) PNAS, 116

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MEASURING THE ATMOSPHERIC COMPOSITION OF EXOPLANETS



2. What are the atmospheres of different exoplanets composed of?

Bound atmospheres

| | |
|------------------|---------------------------------|
| H ₂ | TiO? |
| He | VO? |
| Na | SH? |
| K | NH ₃ ? |
| H ₂ O | FeH? |
| CO | Fe? |
| CO ₂ | H ₂ S? |
| HCN | C ₂ H ₂ ? |
| CH ₄ | |
| H- | |

Escaping atmospheres

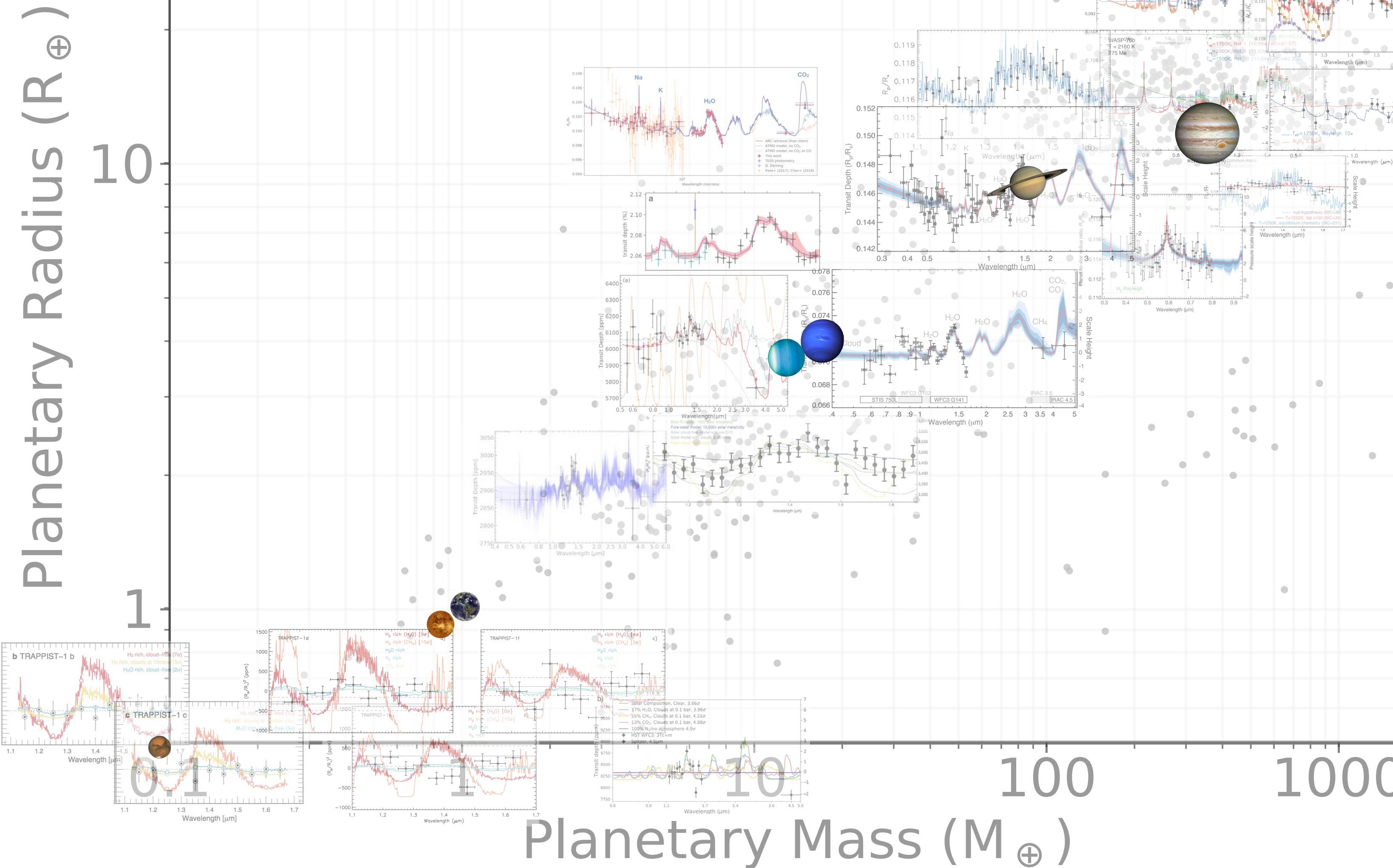
| | |
|----------------------------------|--|
| H ₂ | |
| He | |
| Fe | |
| MgSiO ₃ | |
| Mg ₂ SiO ₄ | |
| MnS | |
| Na ₂ S | |
| ZnS | |
| KCl | |
| H ₂ O | |

Clouds?

- Al₂O₃
- CaTiO₃
- Fe
- MgSiO₃
- Mg₂SiO₄
- MnS
- Na₂S
- ZnS
- KCl
- H₂O

Benneke+ (2019); Bruno+ (2018); de Wit, Wakeford+ (2016, 2018); Evans+ (2016, 2018); Fraine+ (2014); Kreidberg+ (2014, 2015); Nikolov+ (2018); Sing+ (2016); Spake+ (2018, 2020); Wakeford+ (2013, 2016, 2017a, 2017b, 2017c, 2018, 2019)

BUT WHAT IS THE GROUND TRUTH?



2. What are the atmospheres of different the Solar System planets composed of?

Bound atmospheres

Na
O₂
N₂
CO₂
Ar
H₂
He
CH₄
CO
H₂O

Escaping atmospheres

Ne

NH₃

NO

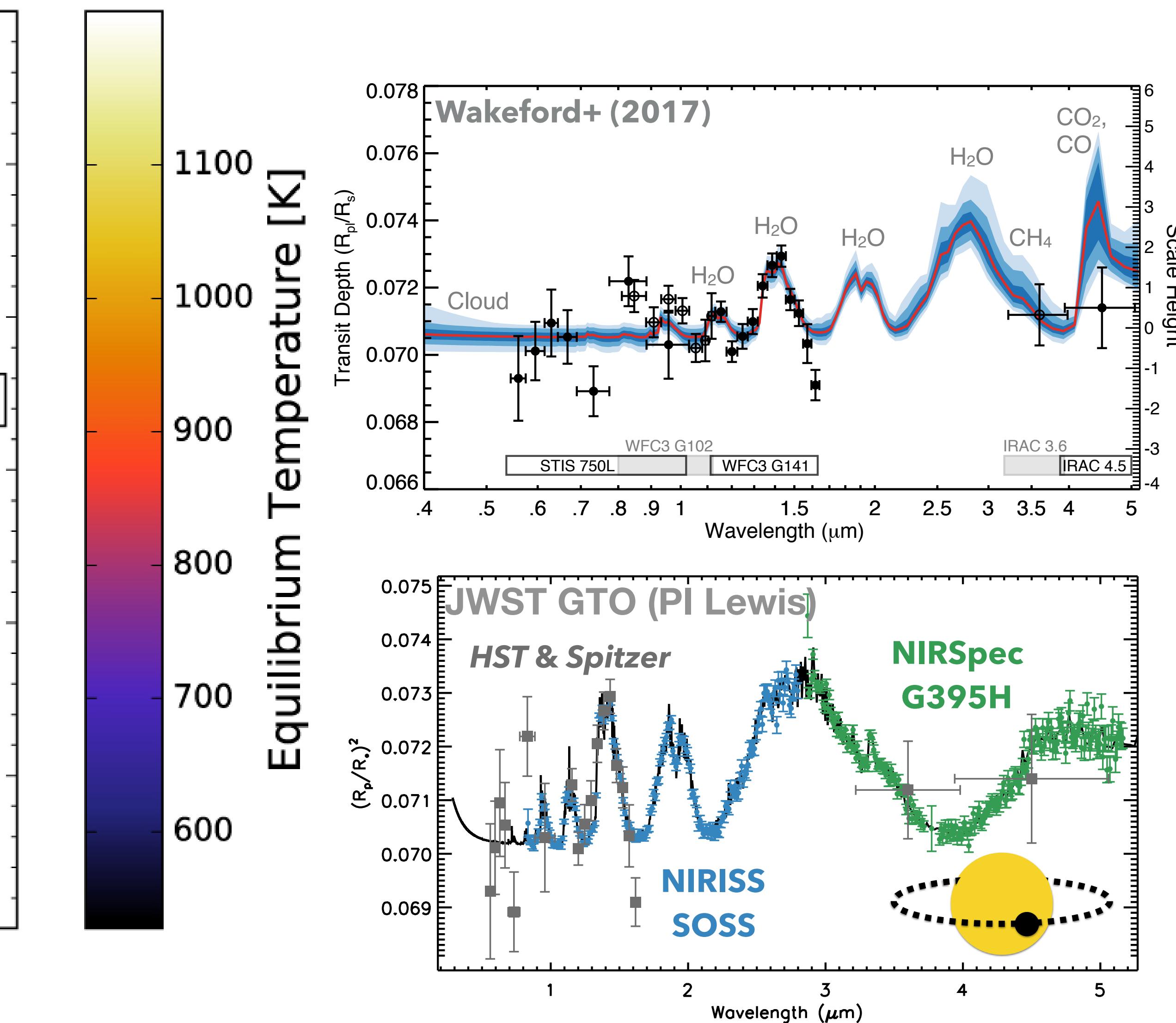
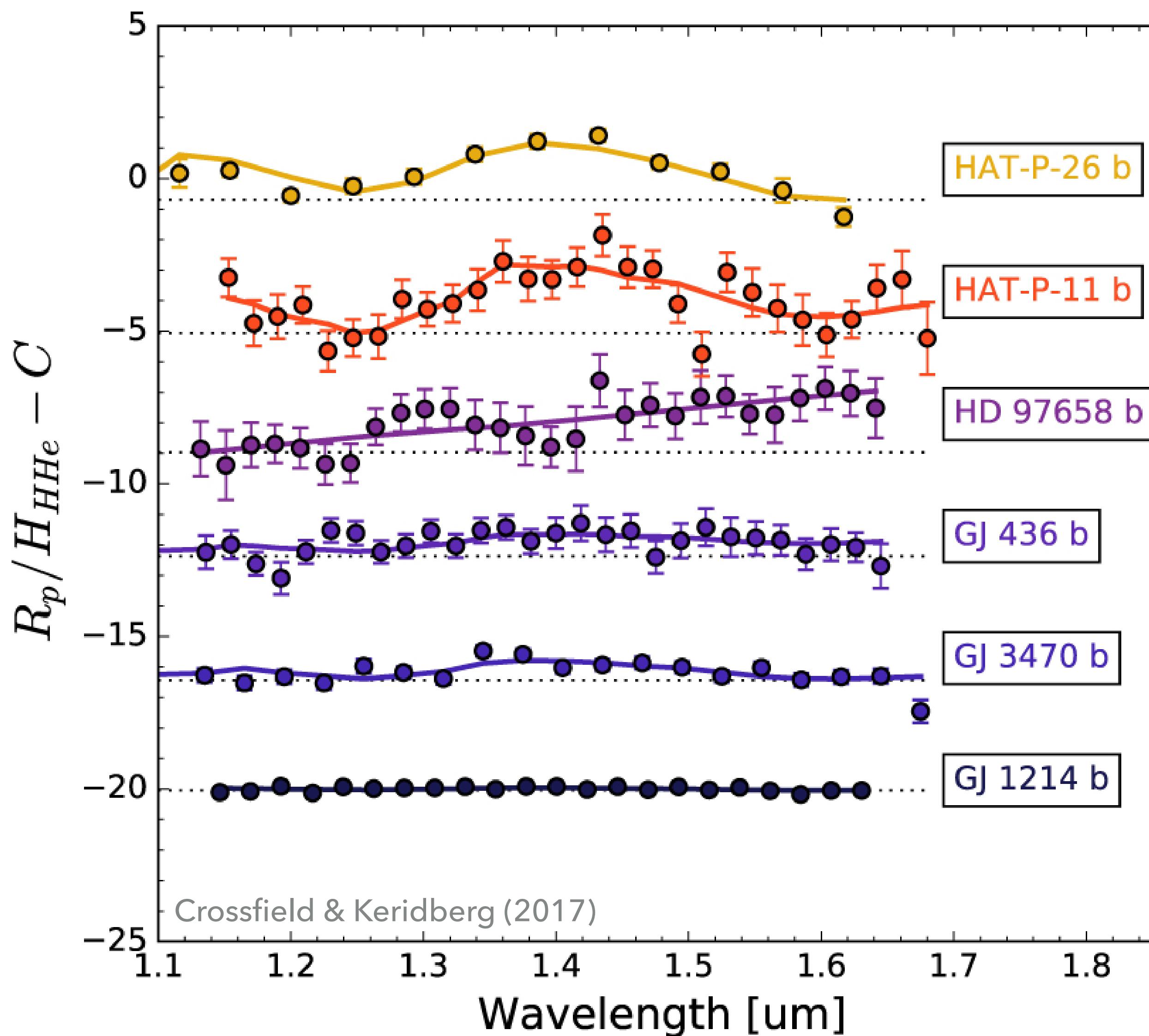
H
H₂O
CO₂
NH₃
CH₄
CH₄

Clouds?
H₂SO₄
H₂O
CO₂
NH₃
CH₄
CH₄

Photochemical hazes

NEPTUNE-SIZED EXOPLANETS: HYDROGEN- TO H₂O-DOMINATED?

HAT-P-26b



JWST TRANSITING GTO TARGETS

15/32

~Neptune/sub-Neptune

WASP-107b [T,E]

GJ 436b [E]

LTT 9779 (TOI-193) [P]

HAT-P-26b [T,E]

GJ 3470b [T,E]

GJ 1214b [T]

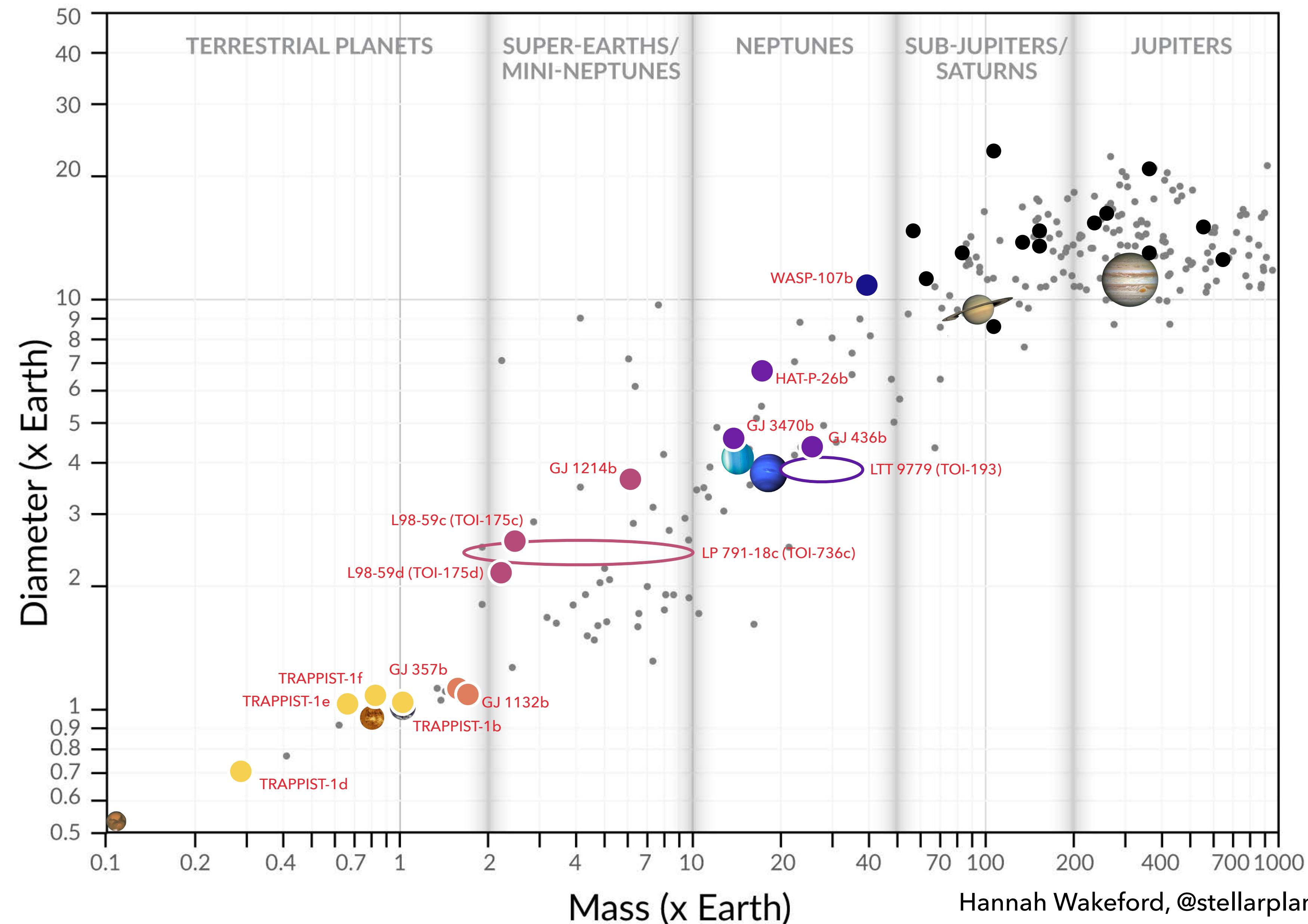
L98-59c, d (TOI-175c, d) [T;T]

LP 791-18c (TOI-736c) [T]

GJ 1132b [E]

GJ 357b [T]

TRAPPIST-1b, d, e, f [E;T;T;T]



GROUND TRUTH: WHAT DO WE NEED / WANT TO KNOW?

Formation

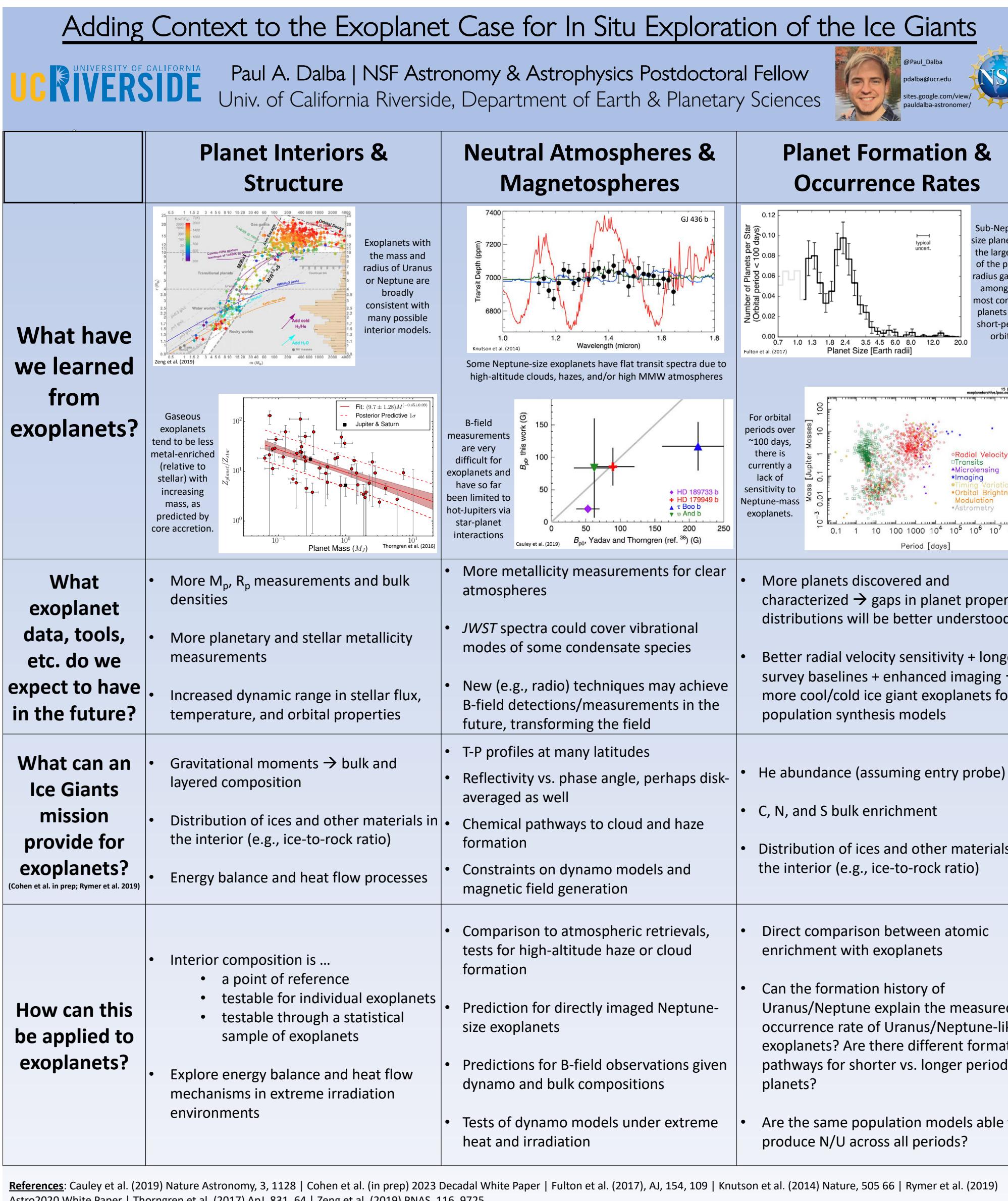
- What is the internal structure of the planet, core, layers, atmosphere?
- Can we constrain the internal heat flux?
- How might giant impacts effect their formation and evolution?
- Where were the planets when they formed?
- How are their magnetic fields generated?

Atmospheres

- Is it a primary or secondary atmosphere?
- What is the composition and structure of the upper atmosphere?
- How does the atmosphere change with latitude?
- What are the abundances of the material in the atmosphere? How do they relate to solar?
- What clouds are coming in the atmosphere?
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- What type of vertical and horizontal mixing is there?
- What is the Temperature structure?
- What is the bulk metallicity of the atmosphere?
- Is the atmosphere in equilibrium?
- What photochemical processes are going on?

How did the solar system & exoplanets form and evolve?

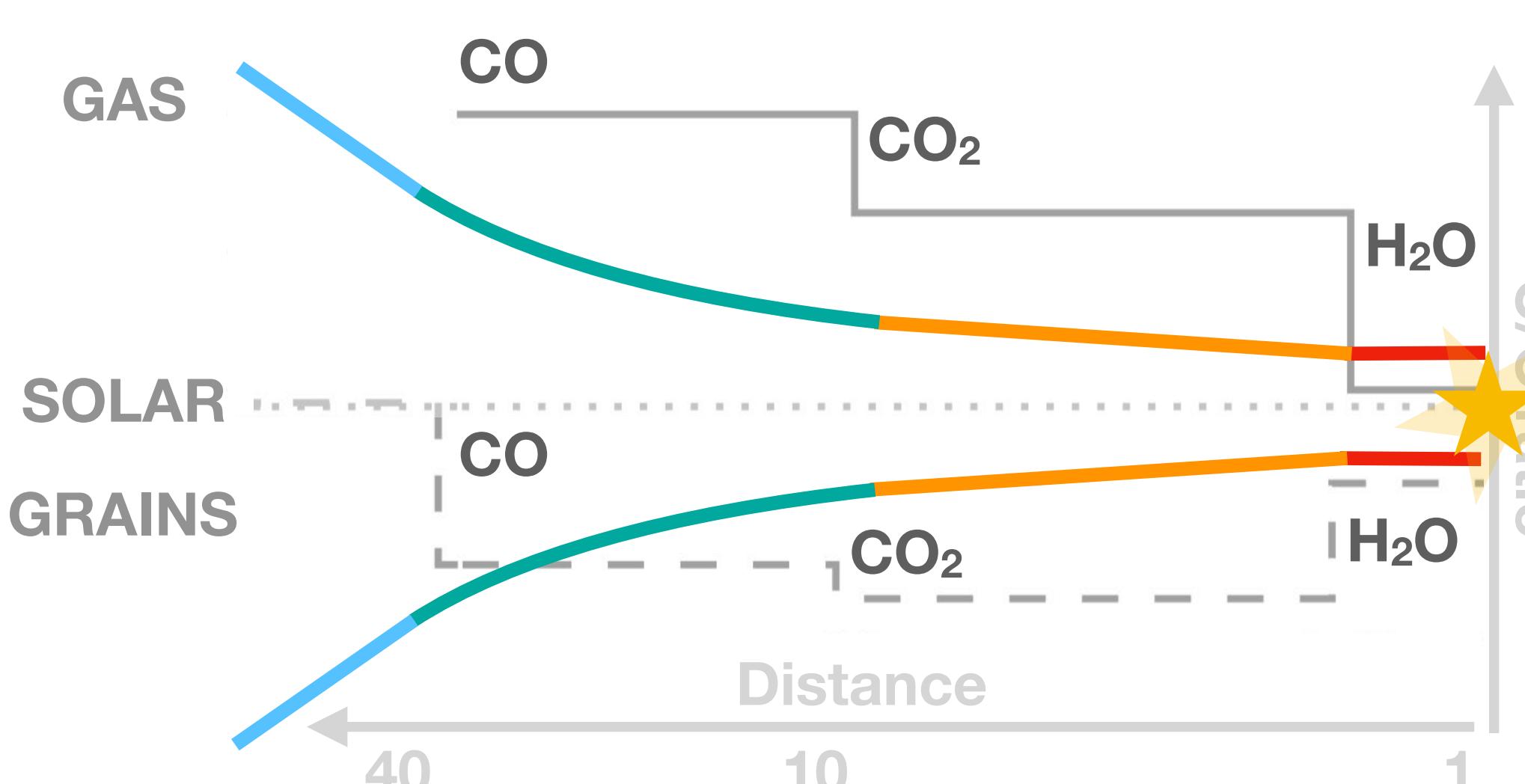
GROUND TRUTH: WHAT DO WE NEED / WANT TO KNOW?



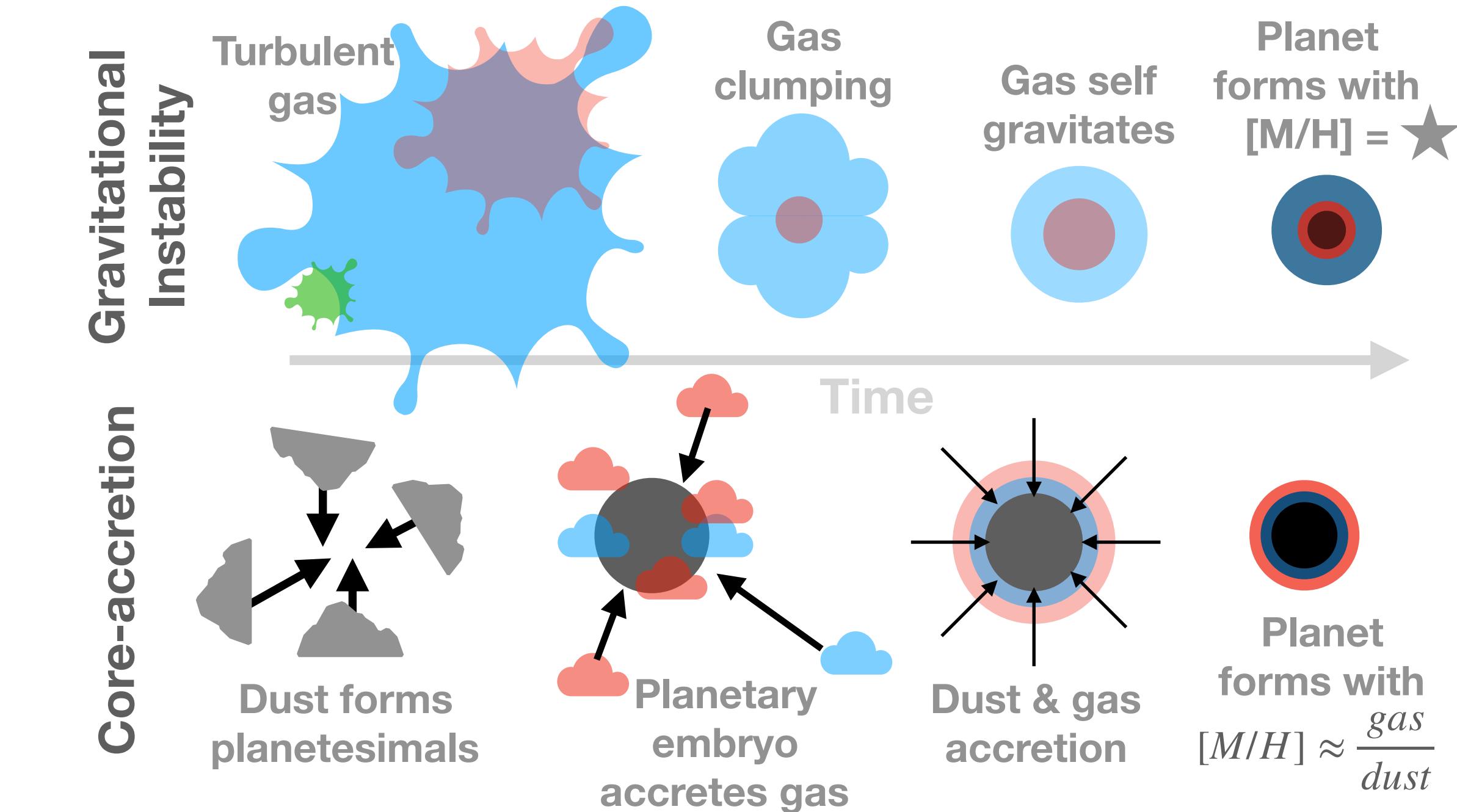
Talk to Paul Dalba about his poster and discuss some of these questions and more!

CAN COMPOSITION GIVES US CLUES TO PLANET FORMATION?

Accretion of C-rich gas between H₂O, CO ice lines could explain C/O of exoplanets.



The solar system giant favor the core-accretion theory where lower mass planets have increased metallicity.



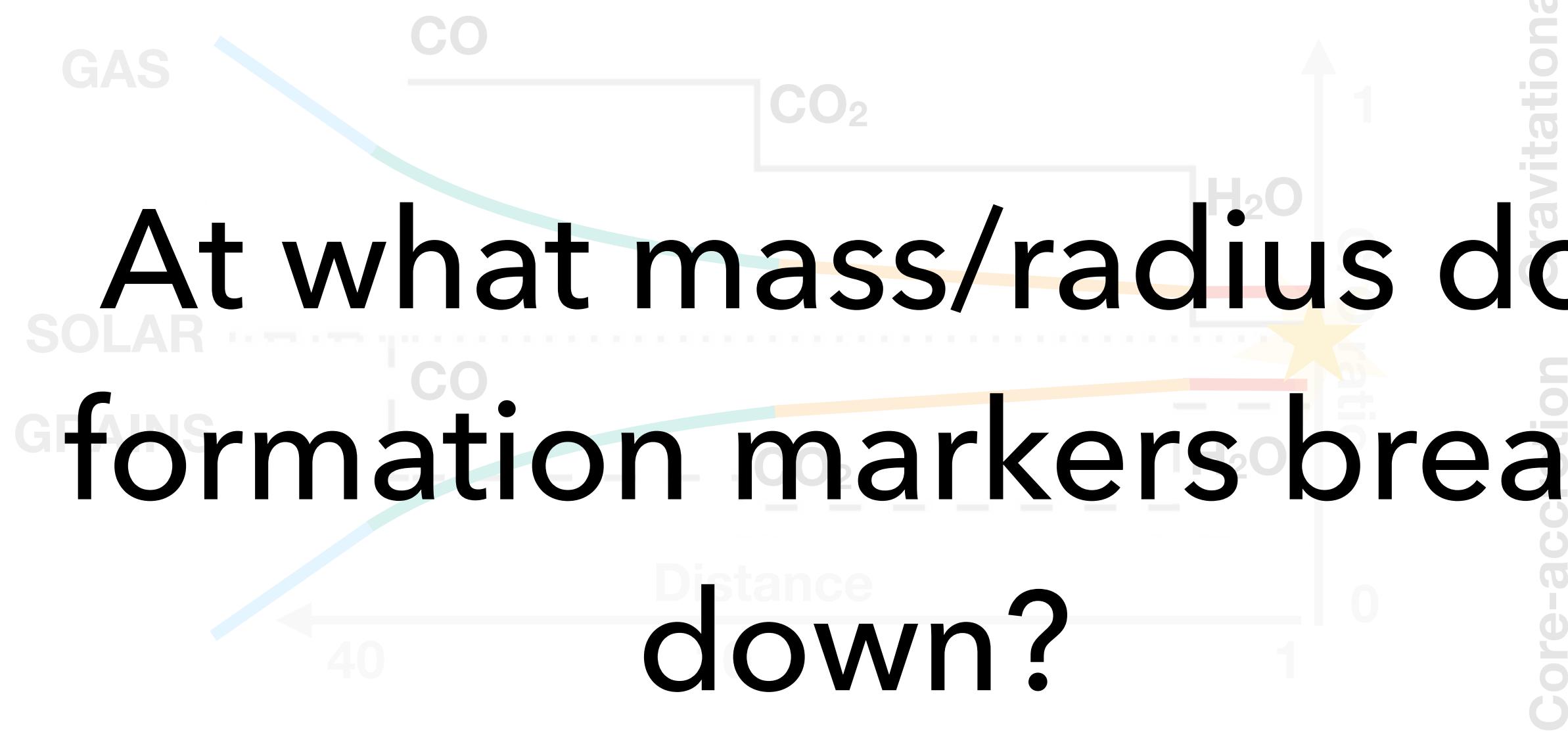
Öberg+ (2011, ApJ)
Boss (1997, Science)
Pollack (1996, Icarus)

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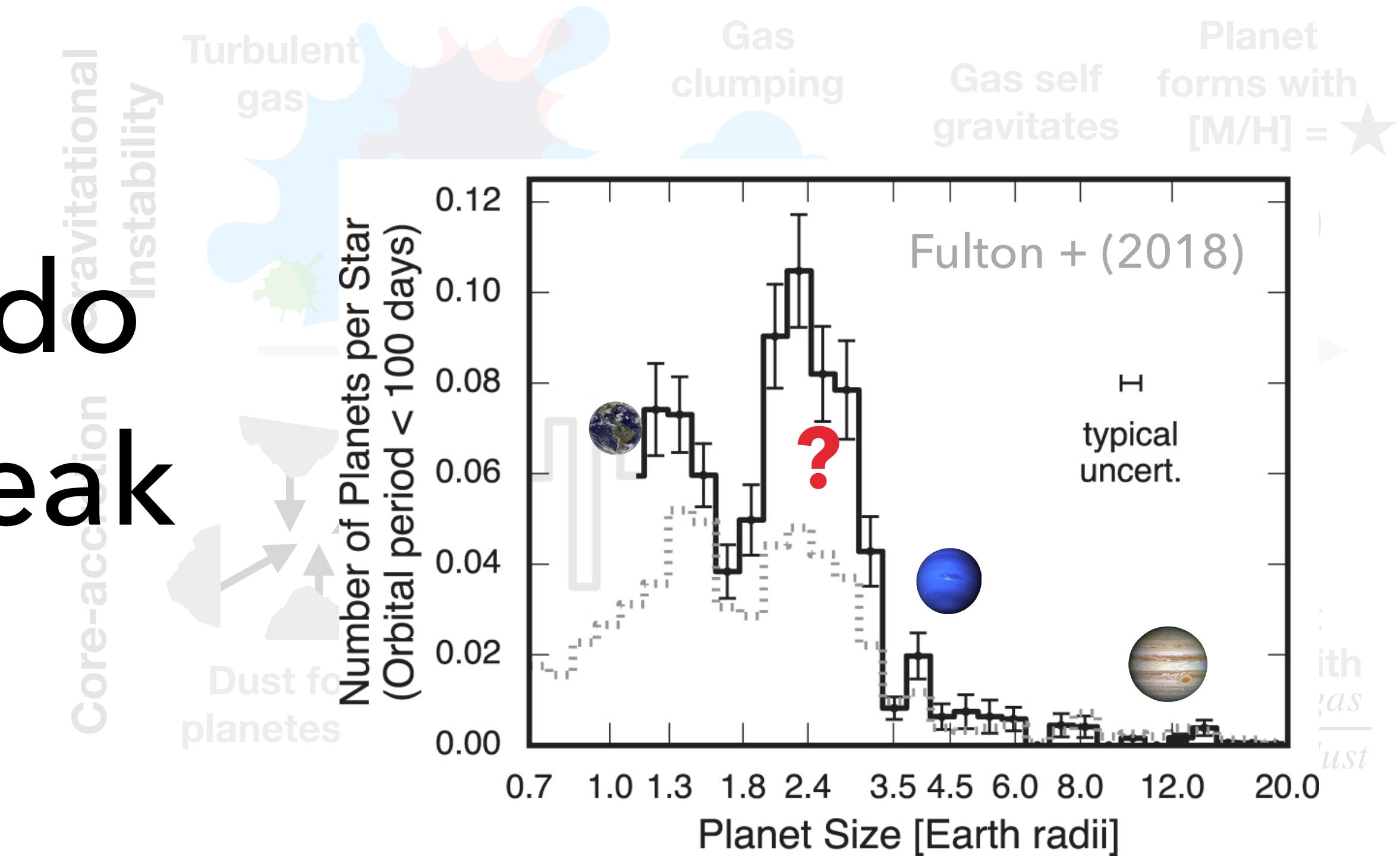
Accretion of C-rich gas between H₂O, CO ice lines could explain CO₂ of exoplanets.

At what mass/radius do formation markers break down?

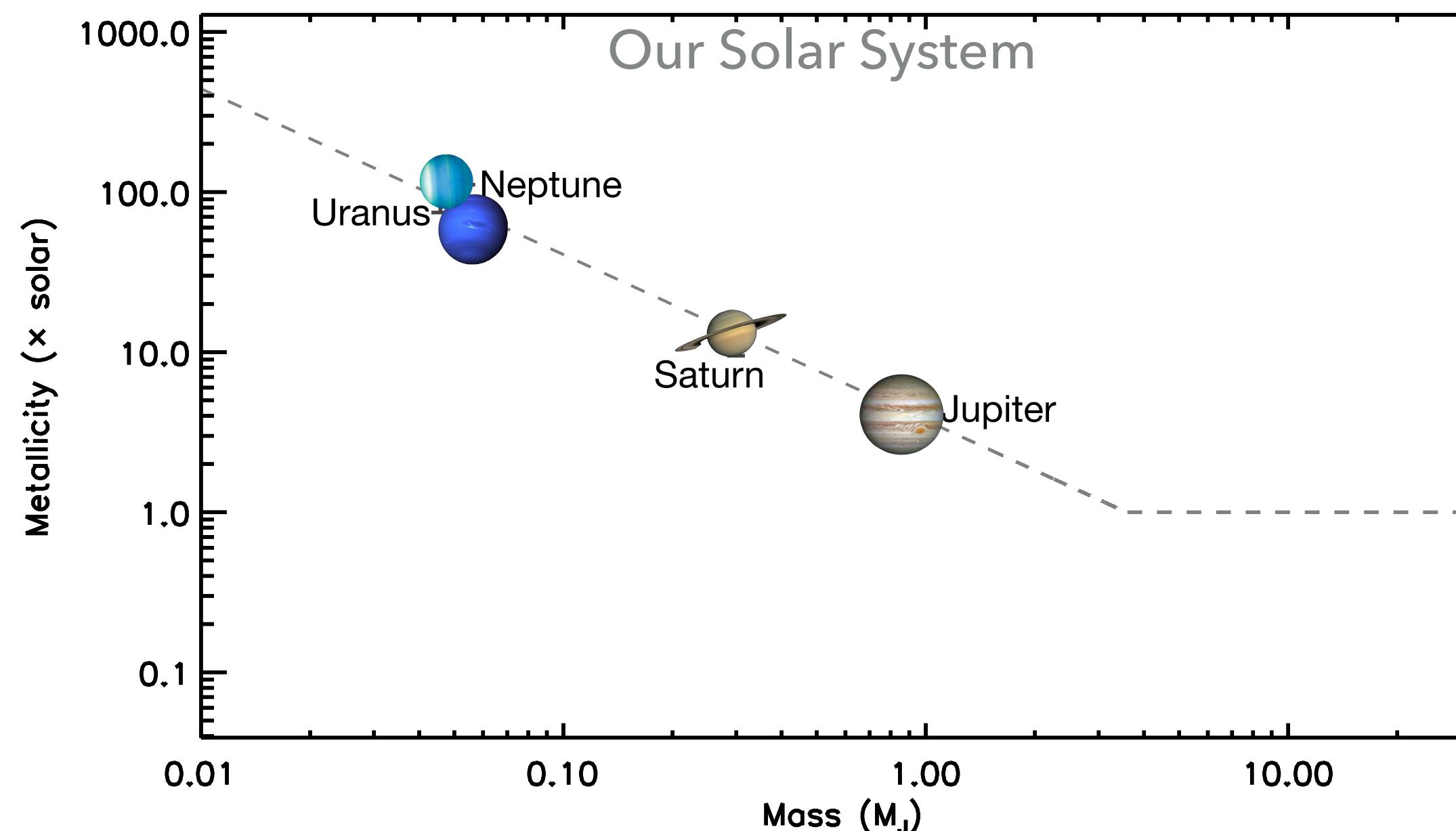


Öberg+ (2011, ApJ)
Boss (1997, Science)
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The solar system giant favor the core-accretion theory where low mass planets have increased metallicity.



LOOKING AT FORMATION INDICATORS RELATIVE TO THE SOLAR SYSTEM

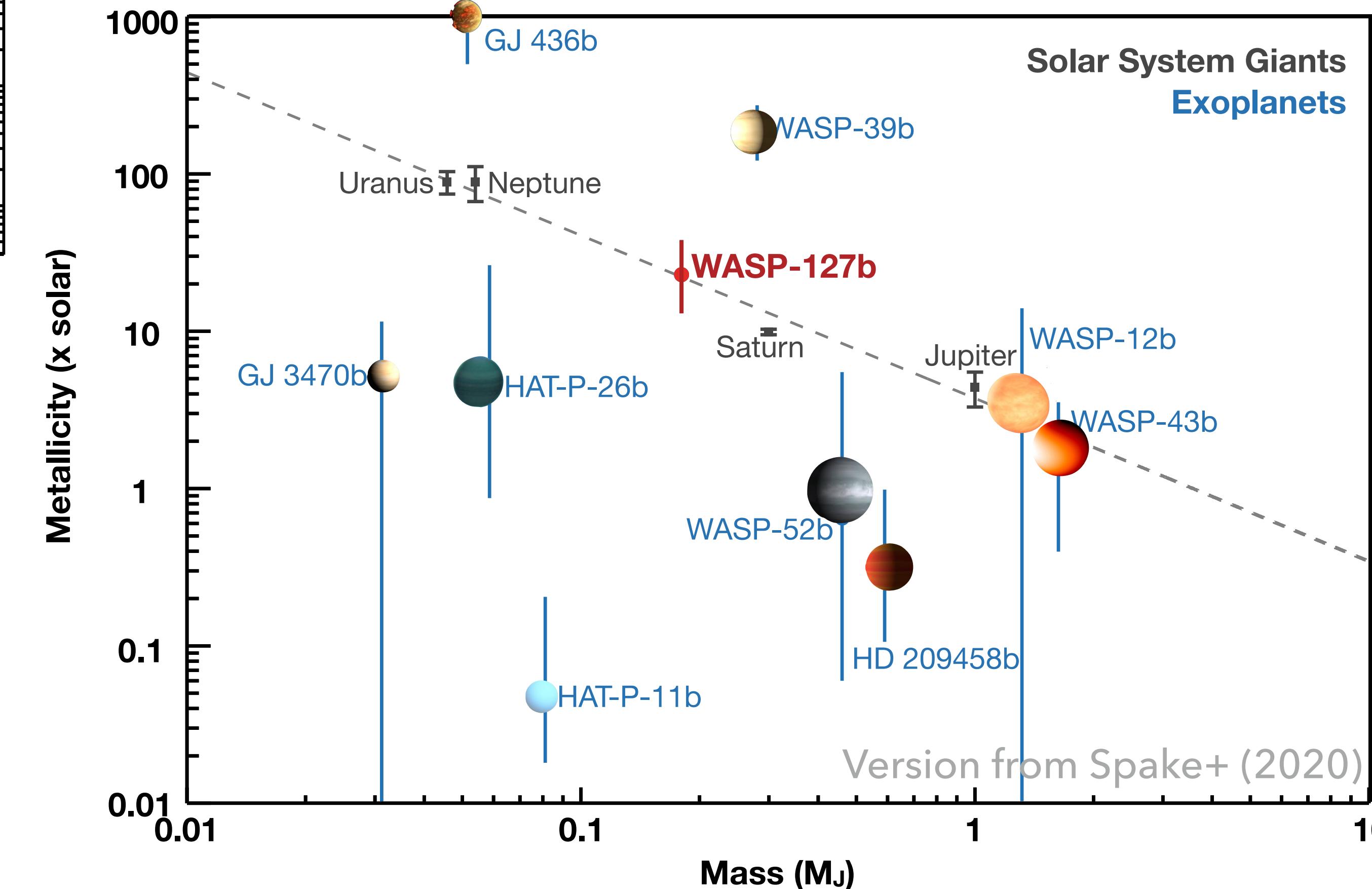


**What are the best indicators
to measure formation
processes?**

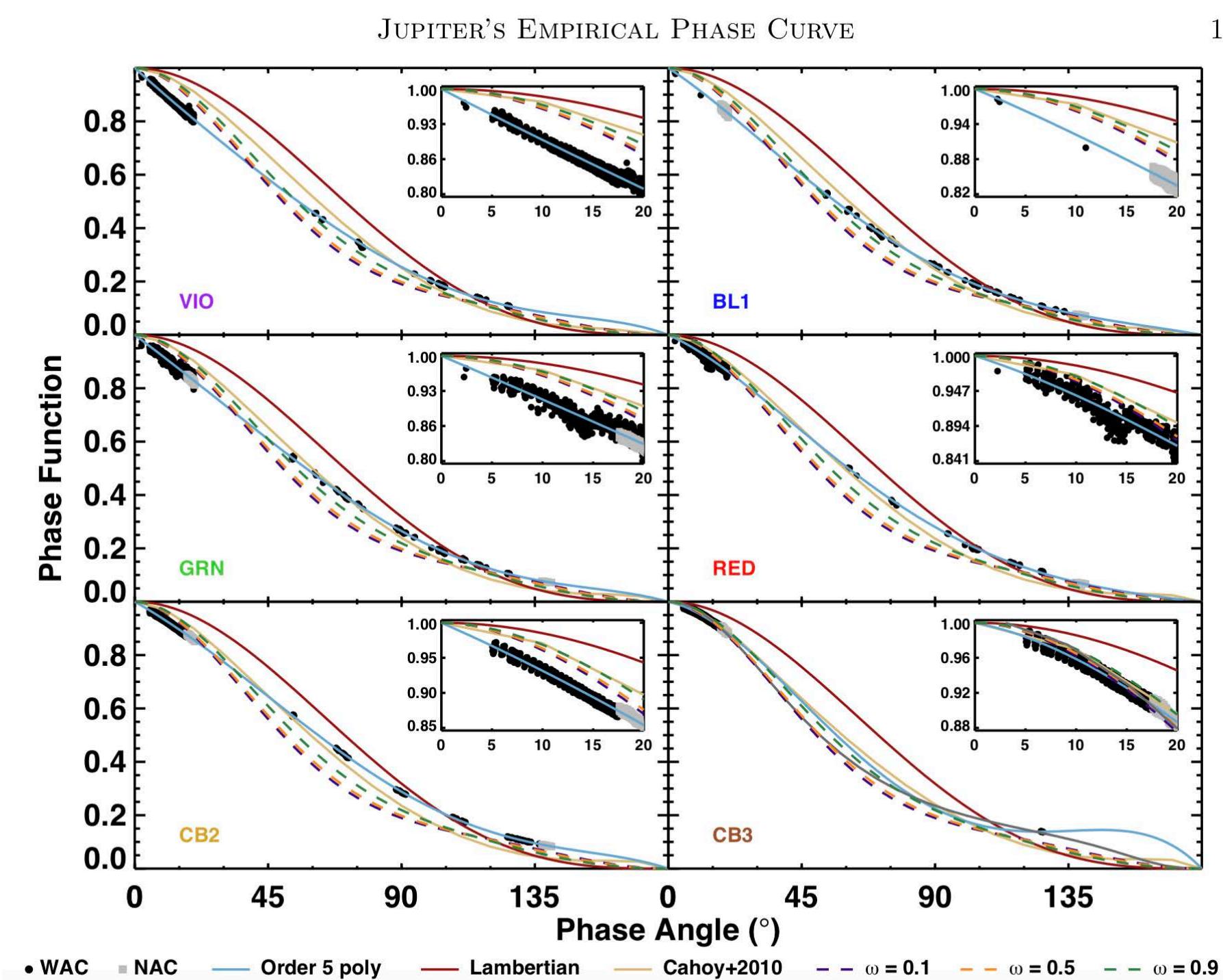
Position, mass, stellar type,
galactic location, etc.

Exoplanets do not neatly fit the trend in atmospheric metallicity and mass.

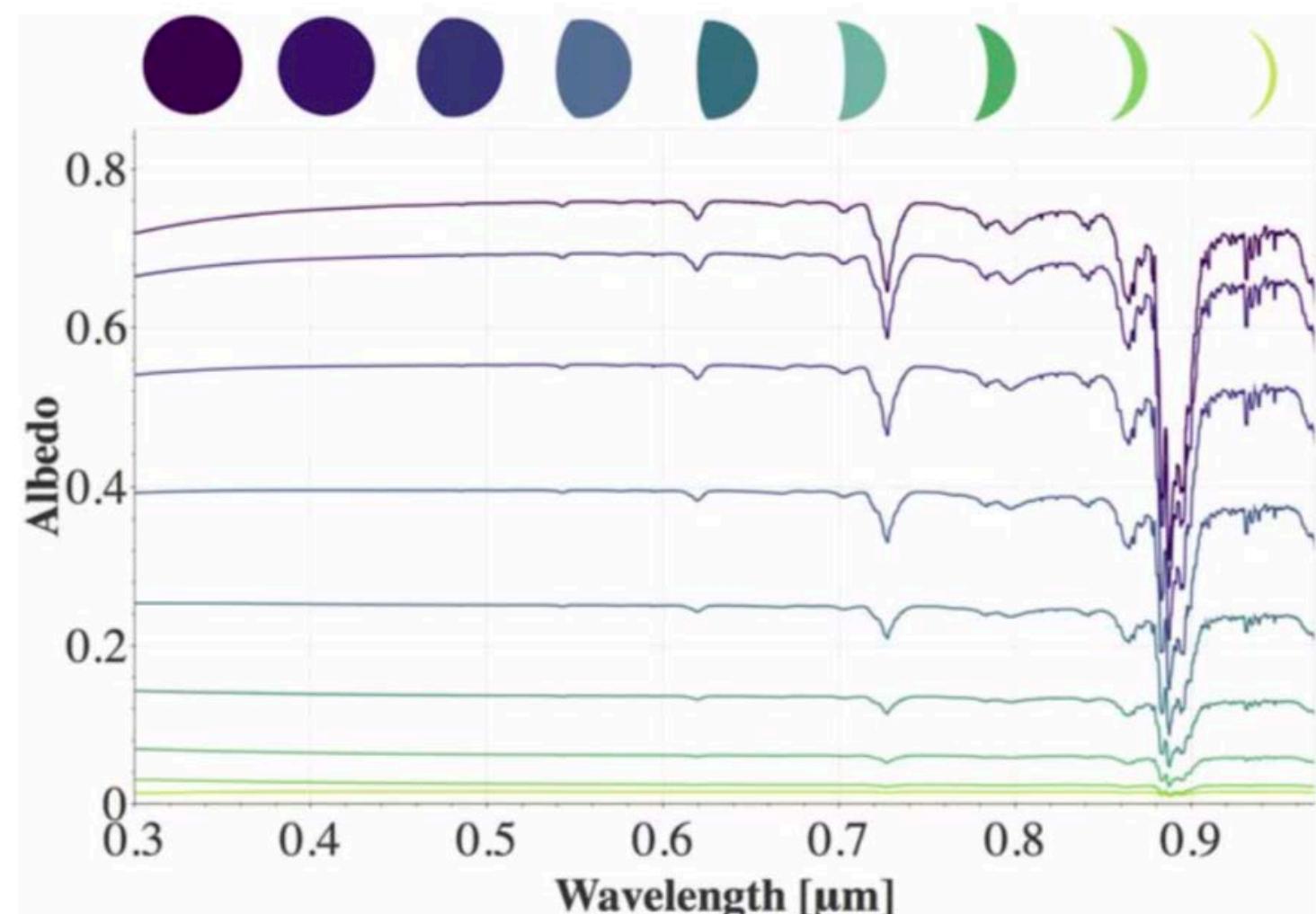
Exoplanets



DIRECT IMAGING - PHASE ANGLES - POLARISATION?



Mayorga+ (2016)



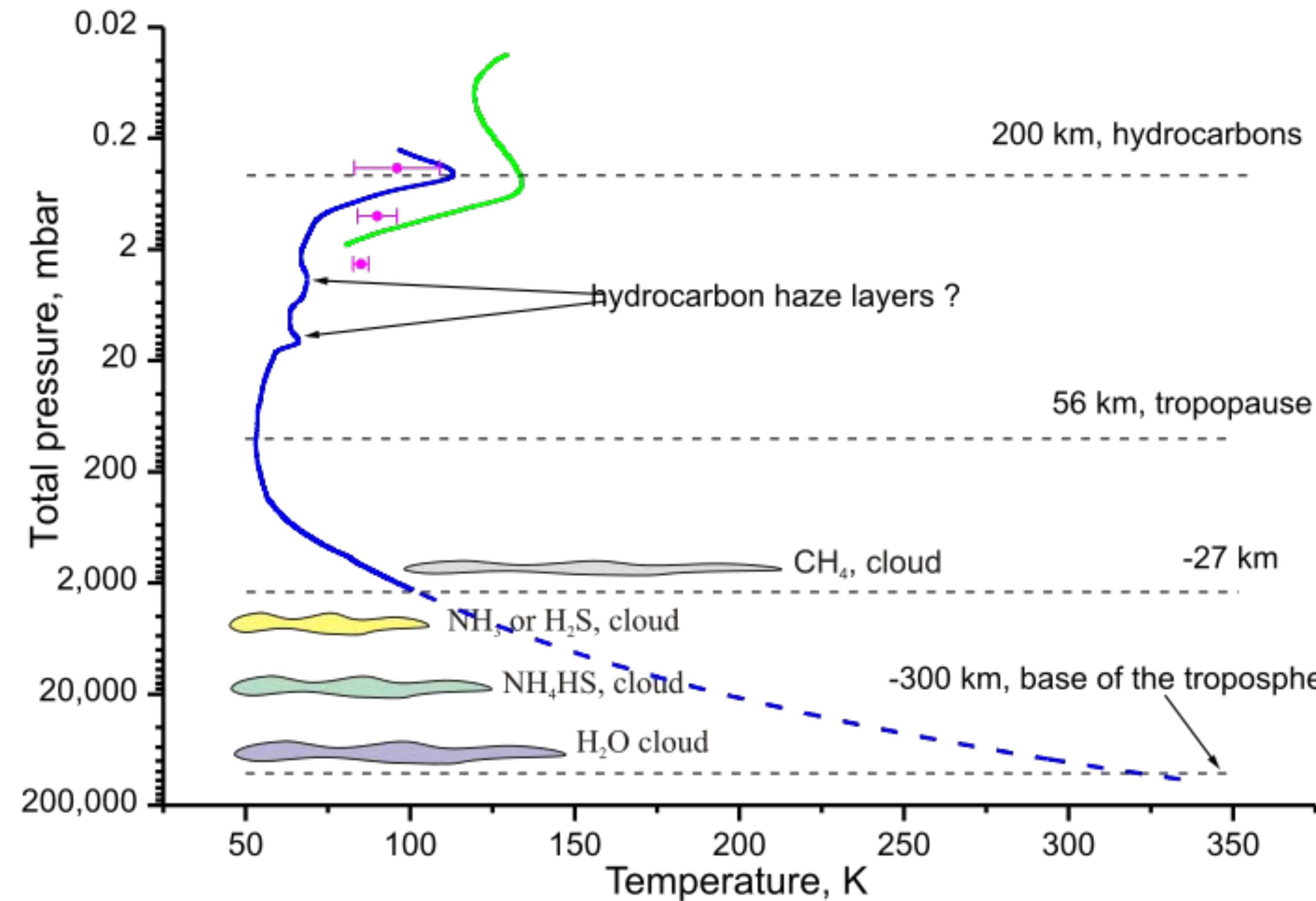
Batalha+ (2018)

Casini and JUNO have taught us the importance of knowing which part of a planet you are looking at.



The measured albedo of directly imaged exoplanet or those in reflected light will depend on both phase and latitude.

WHAT LIES BELOW THE CLOUDS?



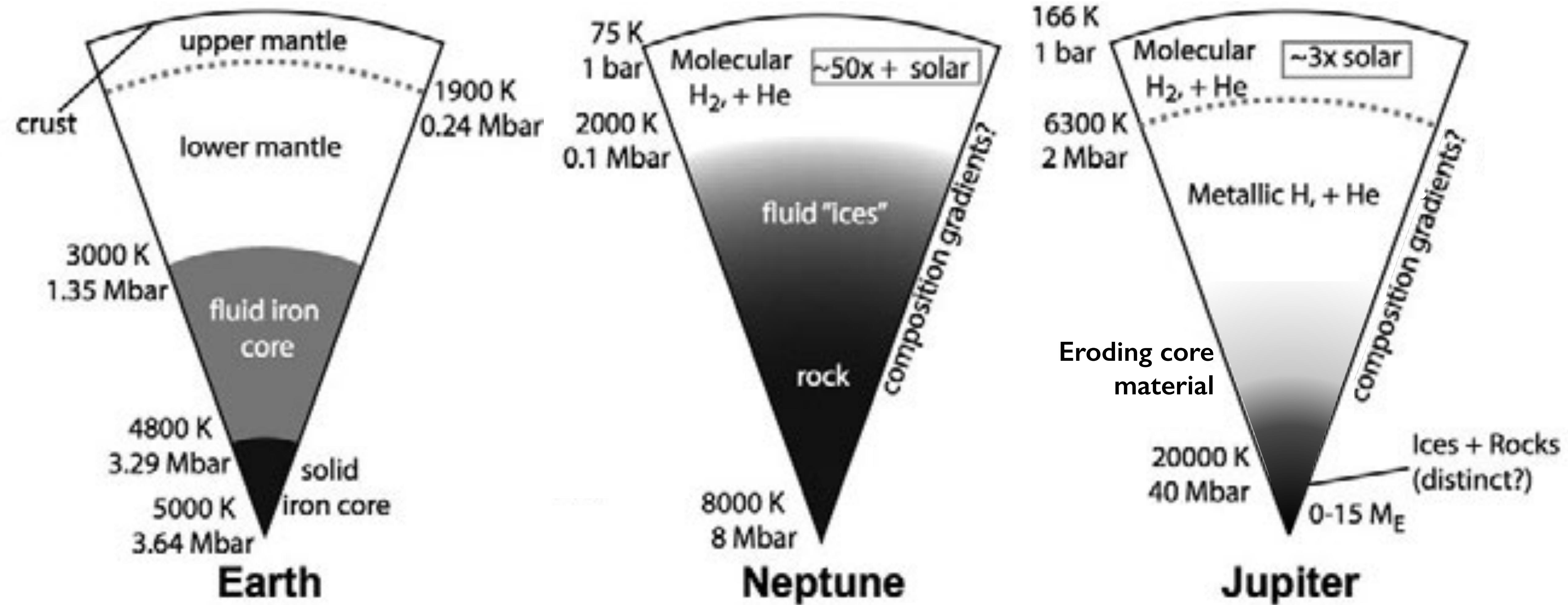
Does the atmospheric metallicity mean anything?

How important is dynamics and mixing to the composition of the observable atmosphere?

What are the clouds hiding?

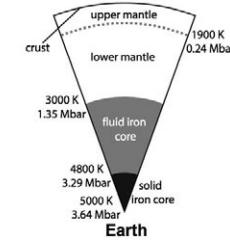
How is the measured energy budget impacted by the atmospheric structure?

WHAT IS THE INTERNAL STRUCTURE FOR DIFFERENT PLANET MASSES?



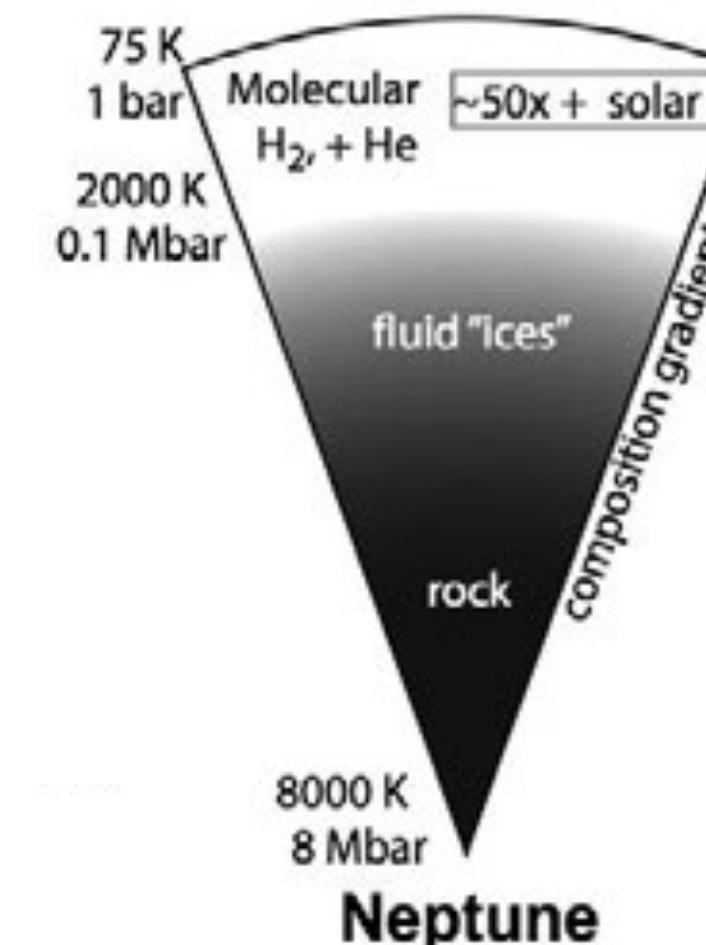
WHAT IS THE INTERNAL STRUCTURE FOR DIFFERENT PLANET MASSES?

What is the internal heat flux?
 How has it evolved through time?
 How does this affect the atmospheric composition?

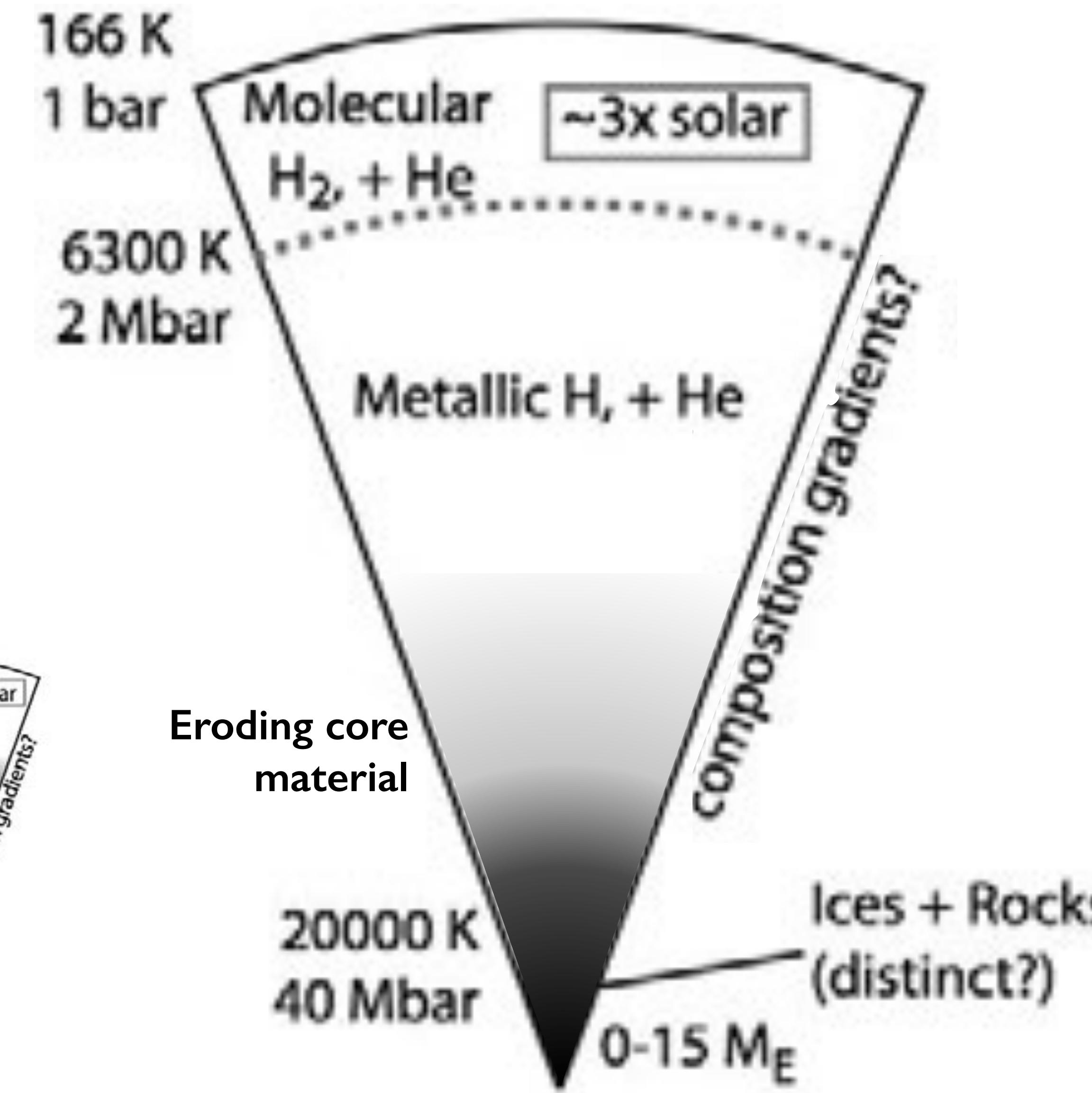


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mini-Neptunes

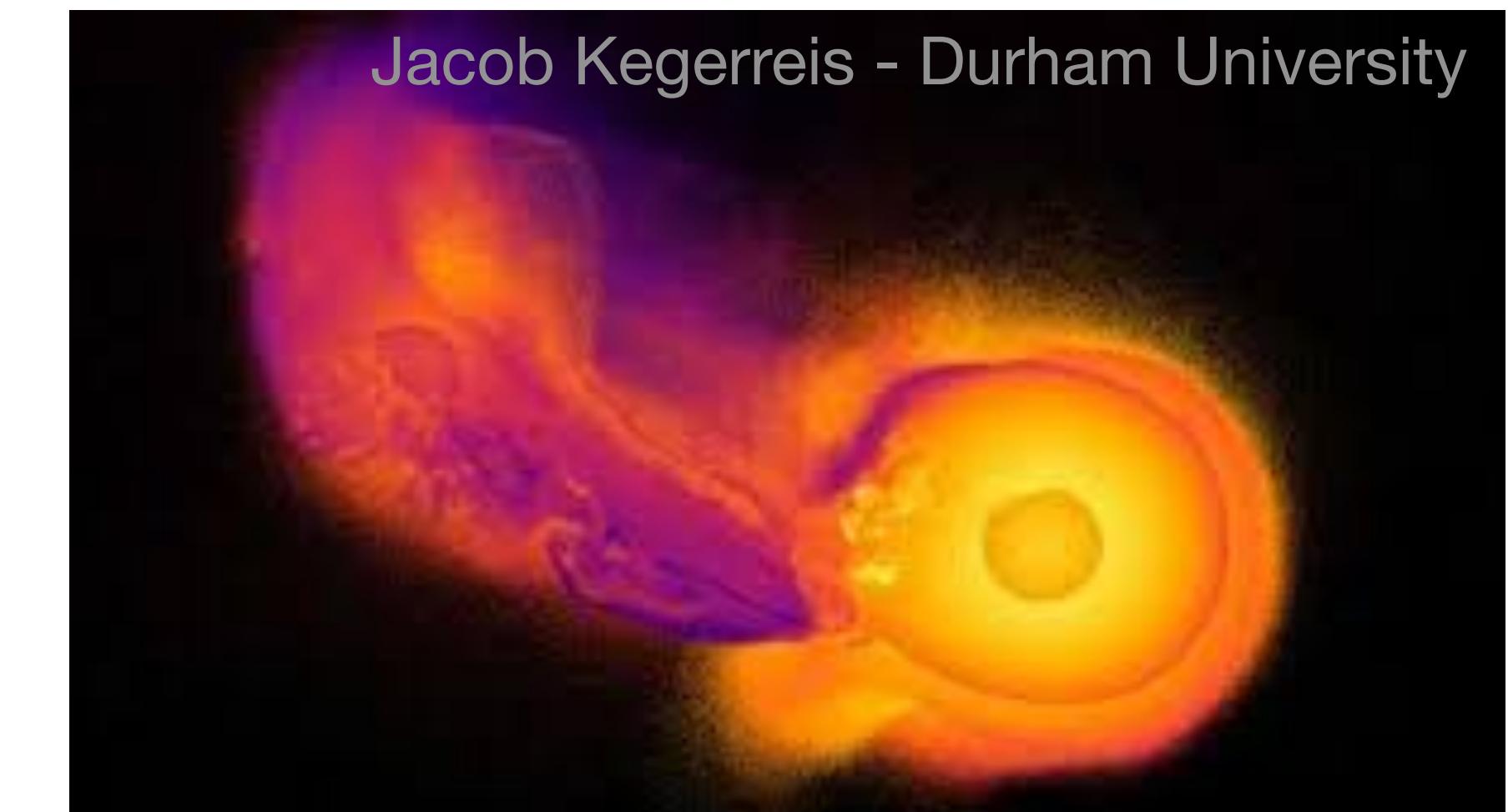
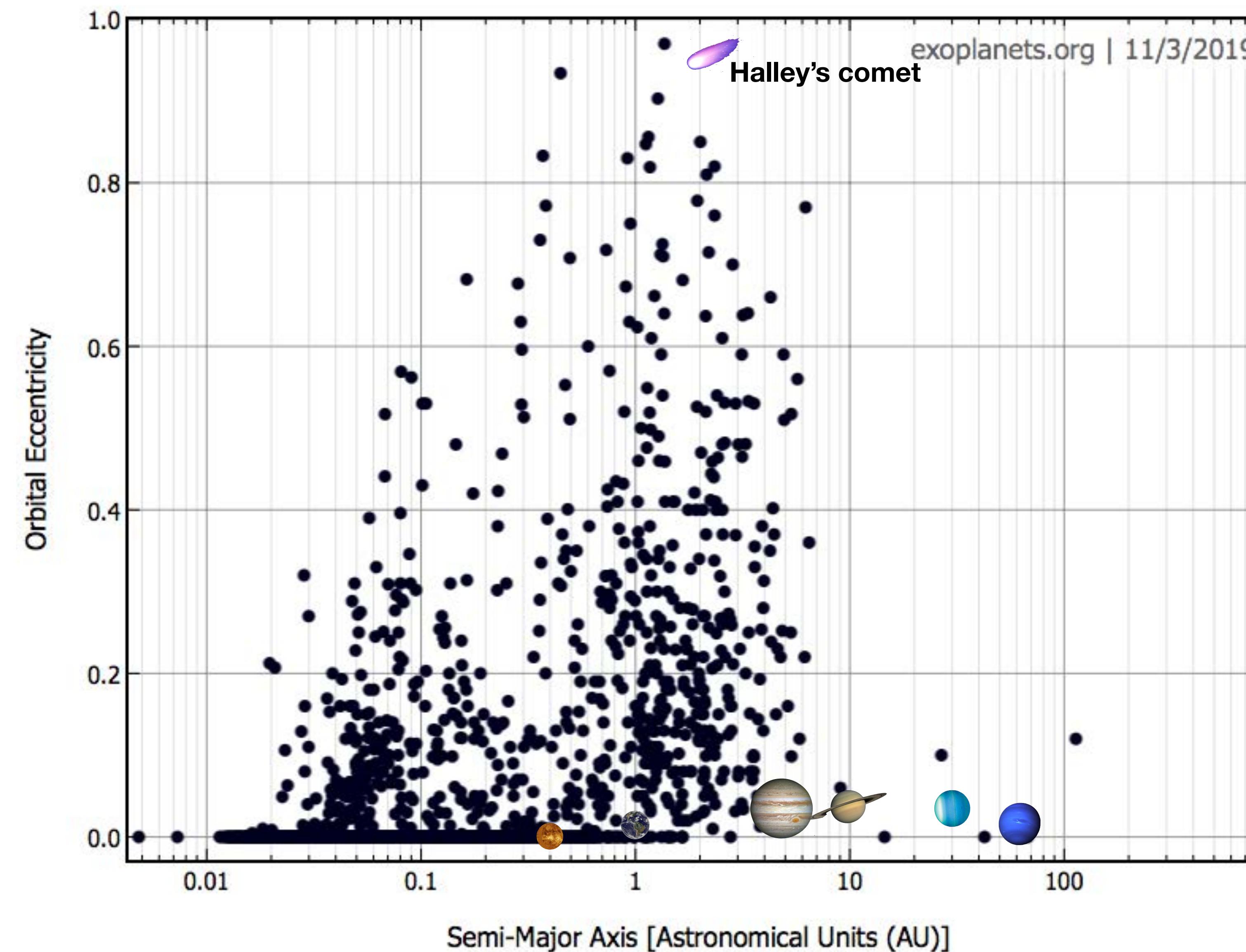


TO SCALE?



HOW MIGHT IMPACTS OR MIGRATION EFFECT THE PLANETS PROPERTIES?

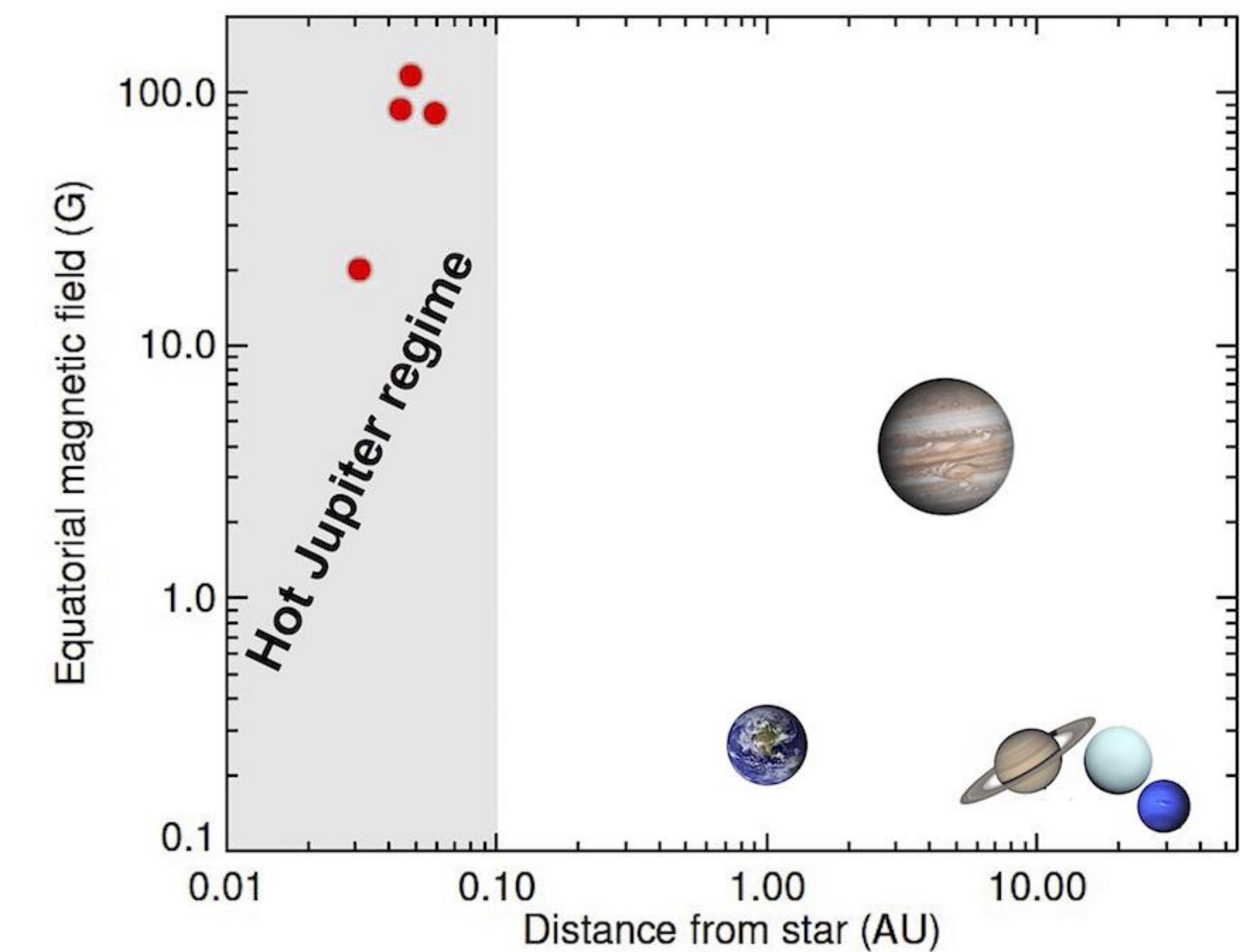
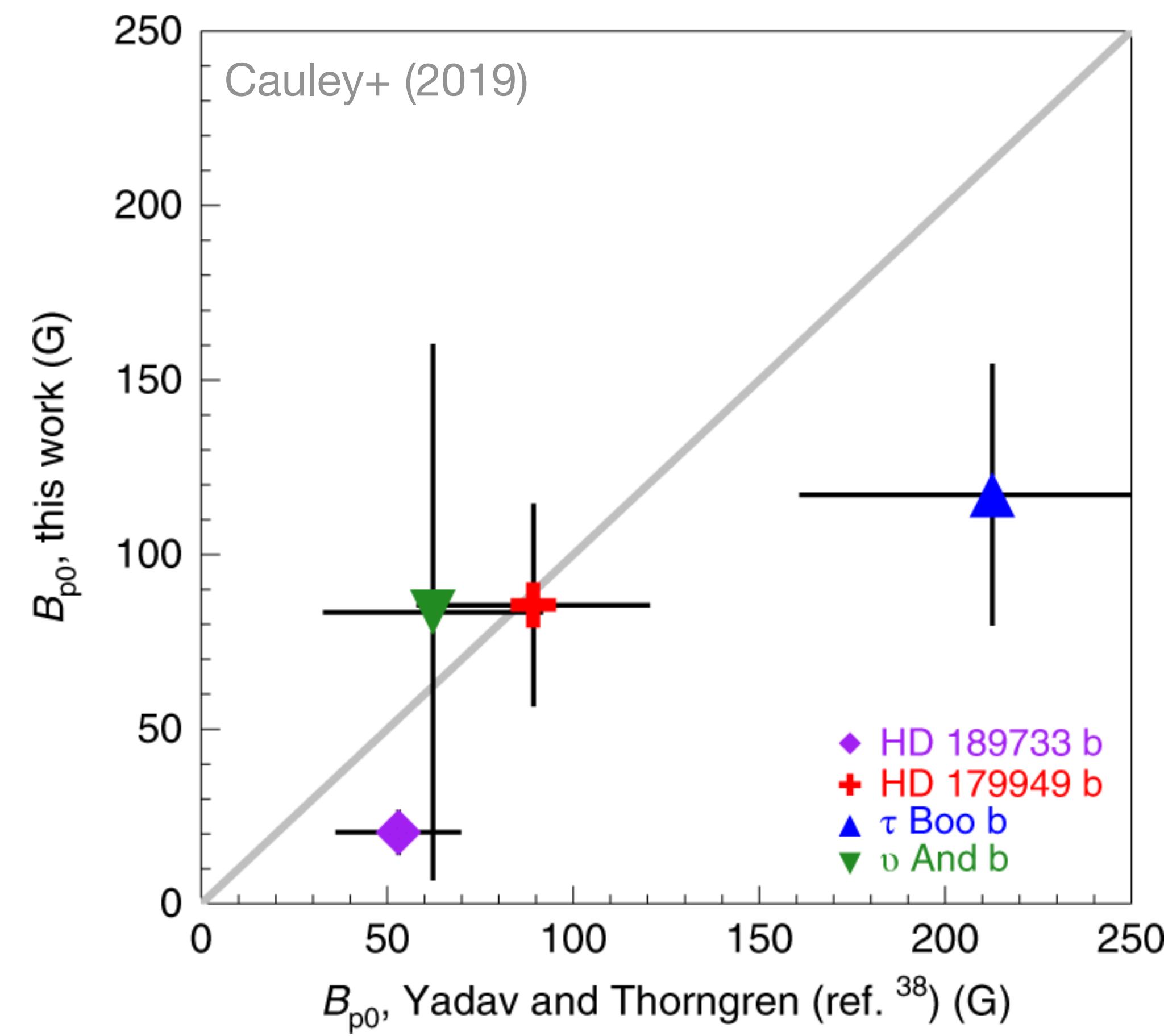
Complex orbital characteristics are rare in our solar System but ubiquitous in the galaxy



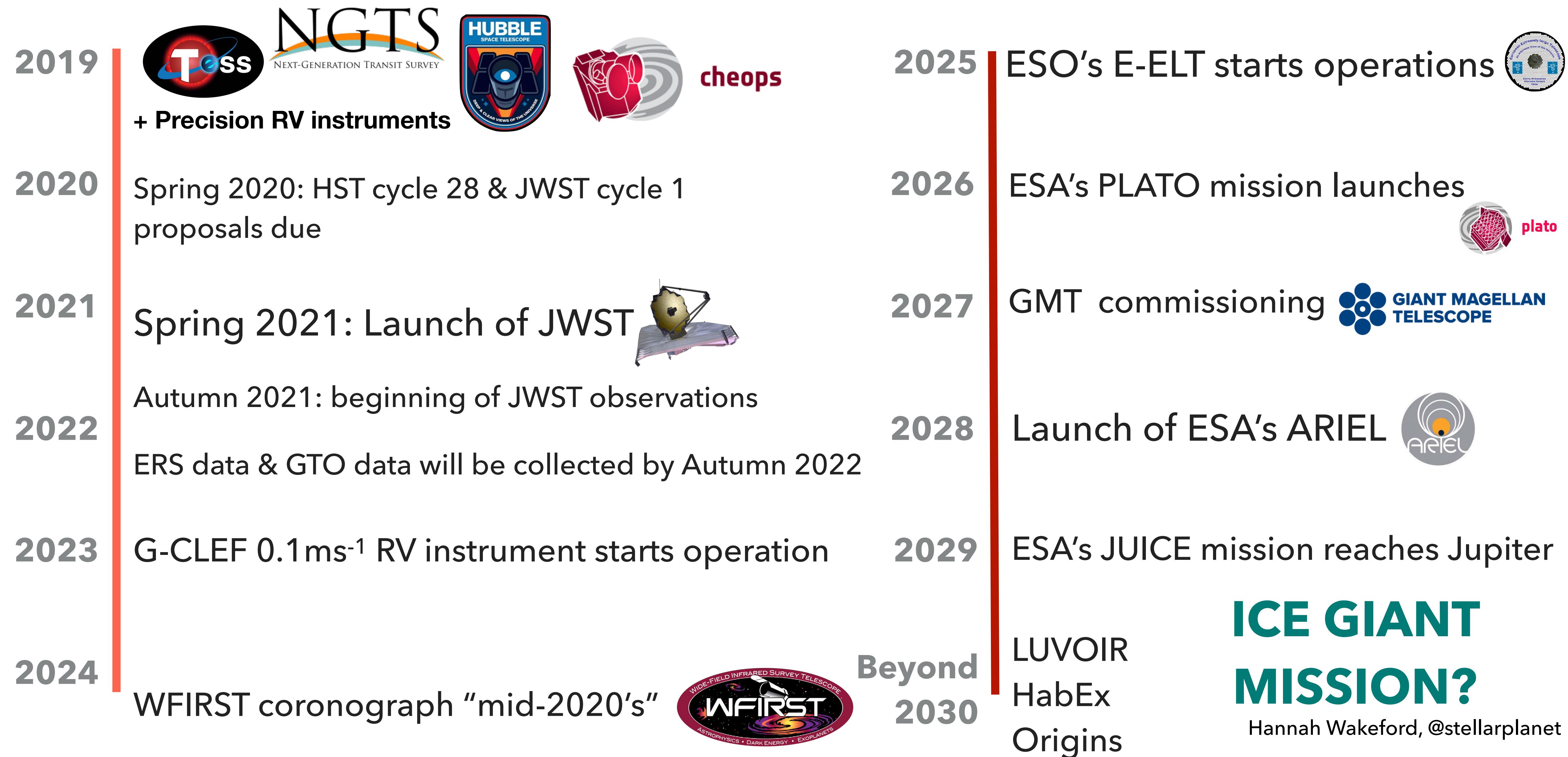
How does an impact
changed the assumptions
about the atmosphere?

MAGNETIC FIELD MAGNITUDES FOR EXOPLANETS

The current measurements are for giant planets larger and more massive than Jupiter.
 Should we expect Neptune-sized and smaller worlds to have multi-polar magnetic fields?
 What is the main driving mechanism?



EXOPLANET CHARACTERIZATION TIMELINE



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