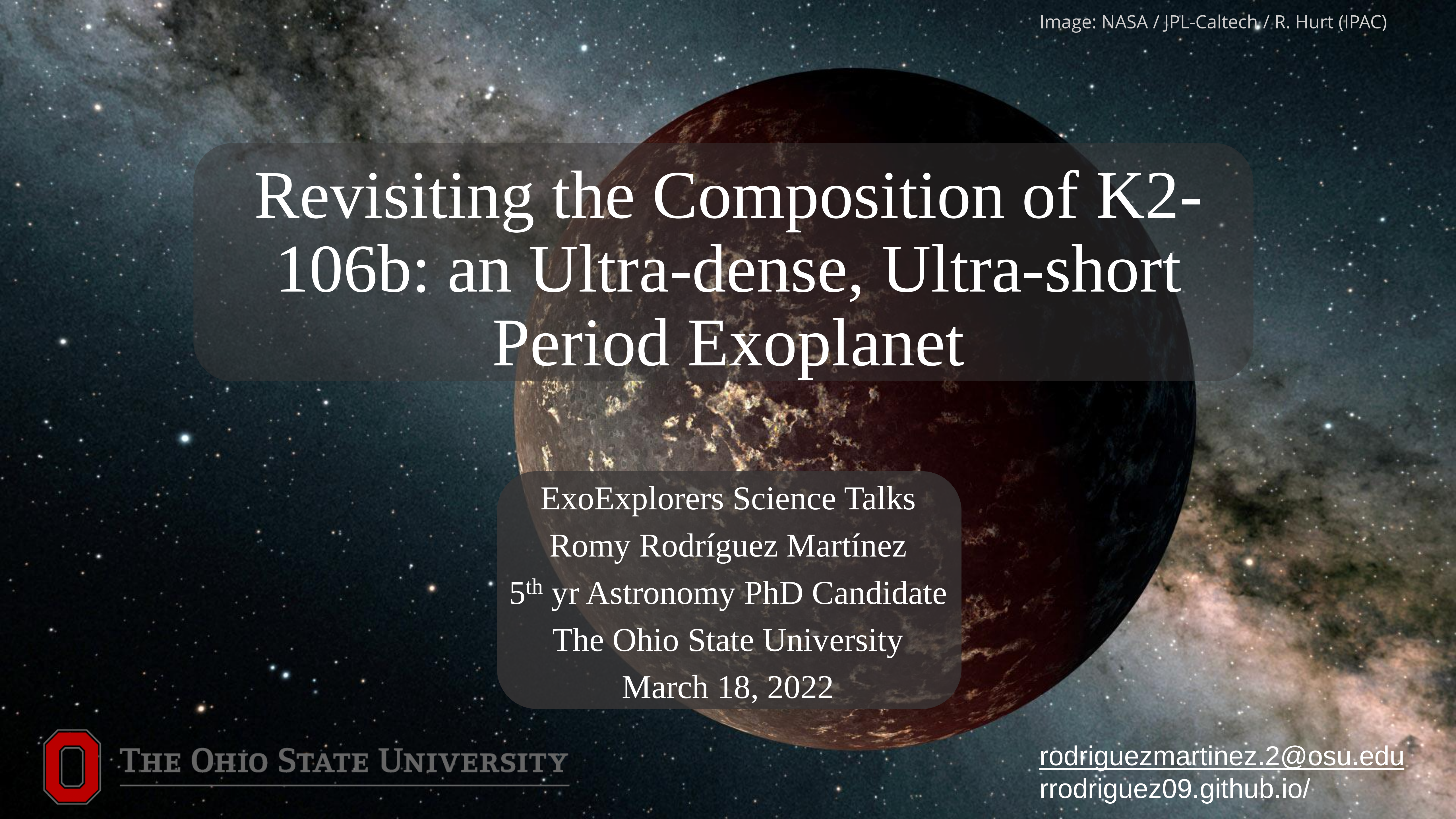
Image: NASA / JPL-Caltech / R. Hurt (IPAC)

Revisiting the Composition of K2-106b: an Ultra-dense, Ultra-short Period Exoplanet

ExoExplorers Science Talks

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March 18, 2022

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Image: NASA / JPL-Caltech / R. Hurt (IPAC)

Revisiting the Composition of K2-106b: an Ultra-dense, Ultra-short Period Exoplanet

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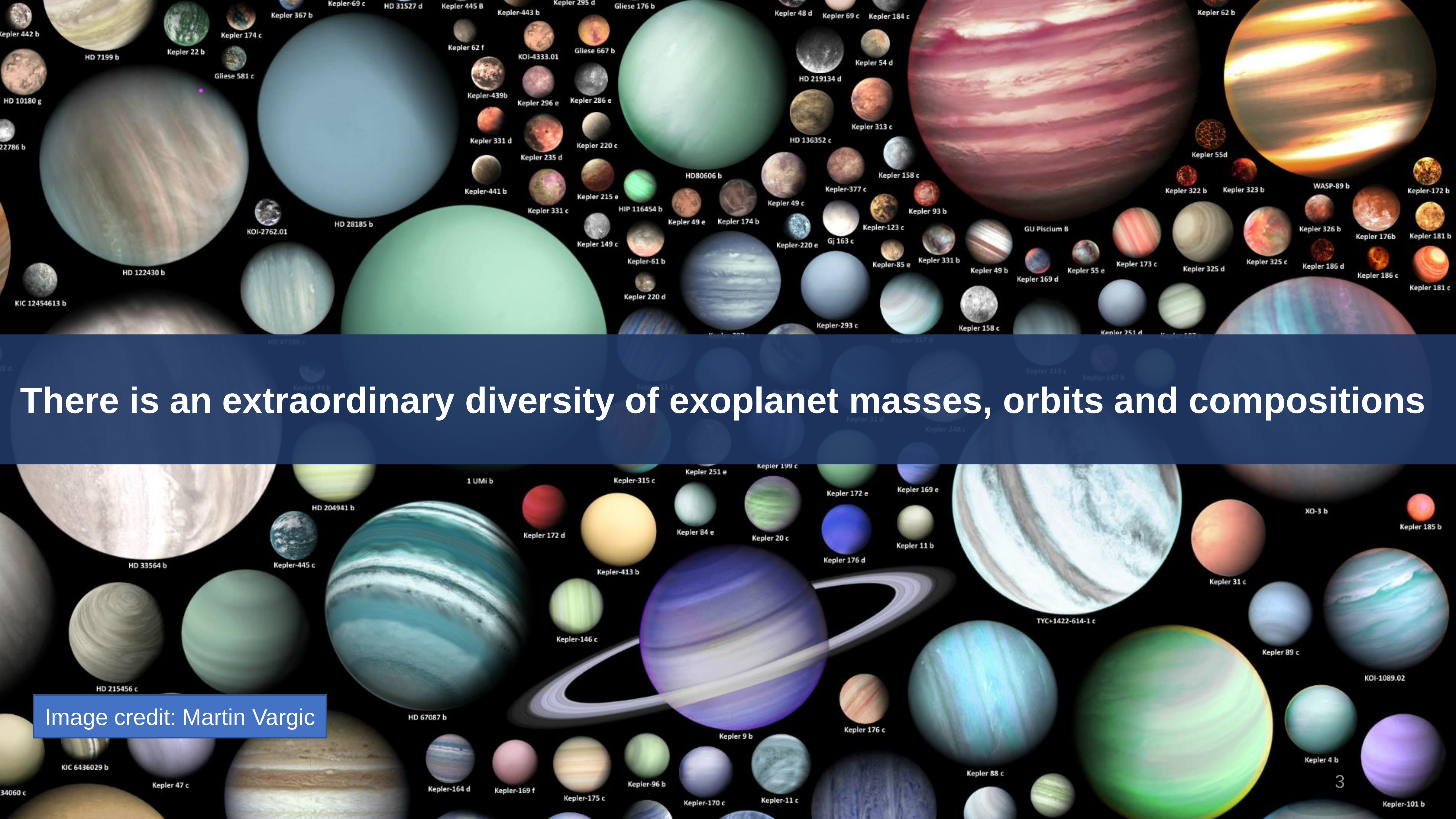
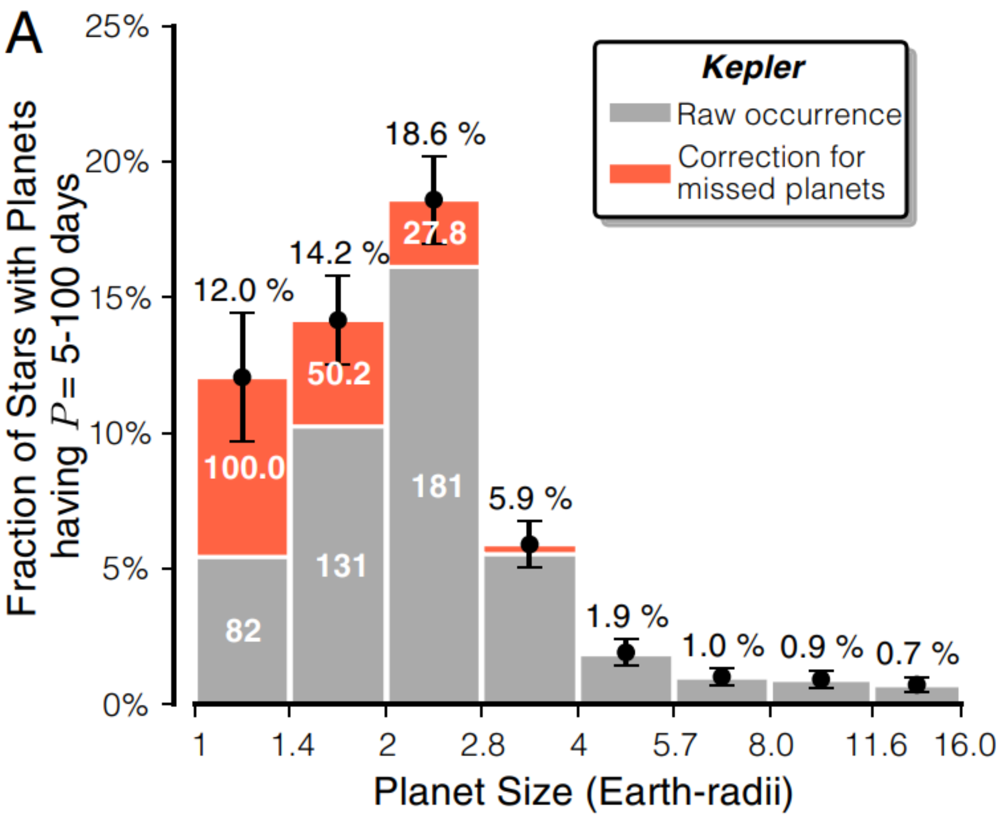


There is an extraordinary diversity of exoplanet masses, orbits and compositions

Image credit: Martin Vargic



Petigura et al. 2013

Exoplanets between 1–4 $R_\oplus$ are the ***most common*** in the Galaxy

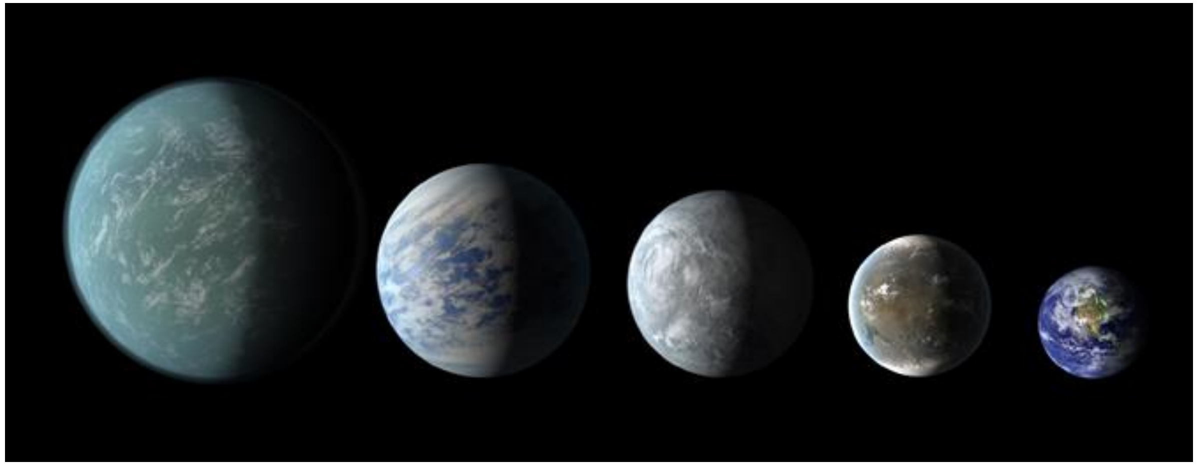
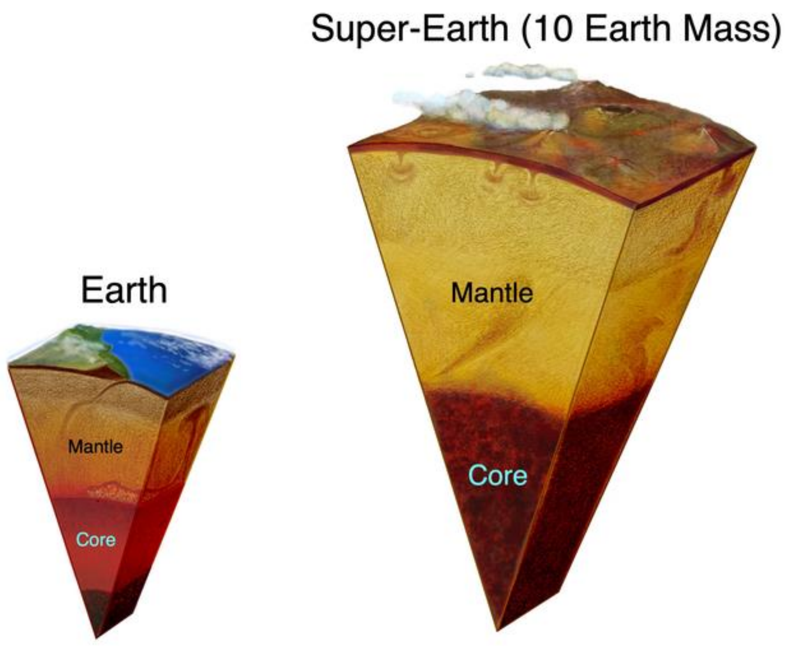


Image credit: NASA Ames/JPL-Caltech

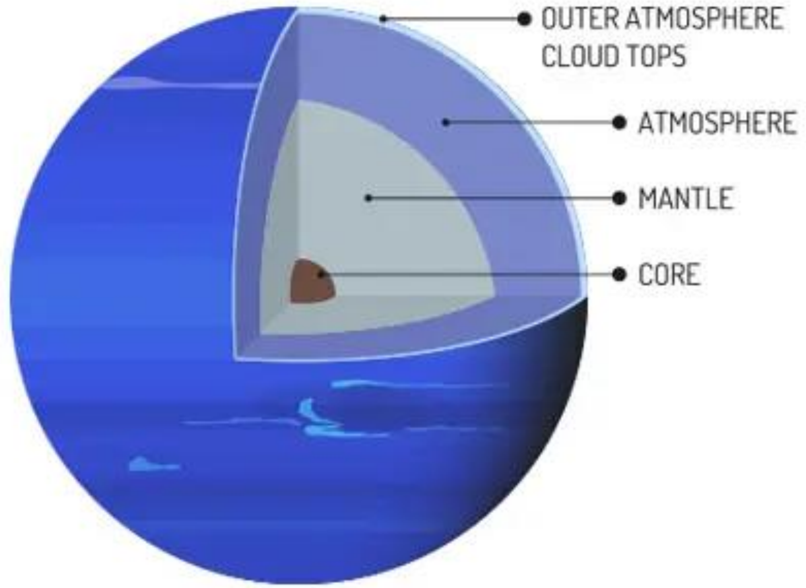
What are these planets made of?

Are they scaled up **Earths**…?

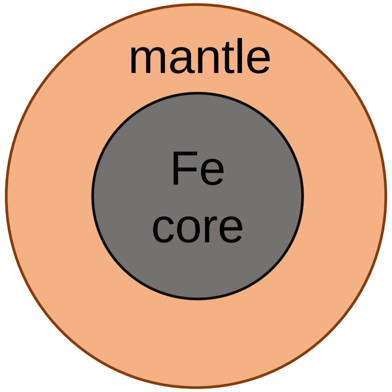


Credit: Kalliopi Monoyios

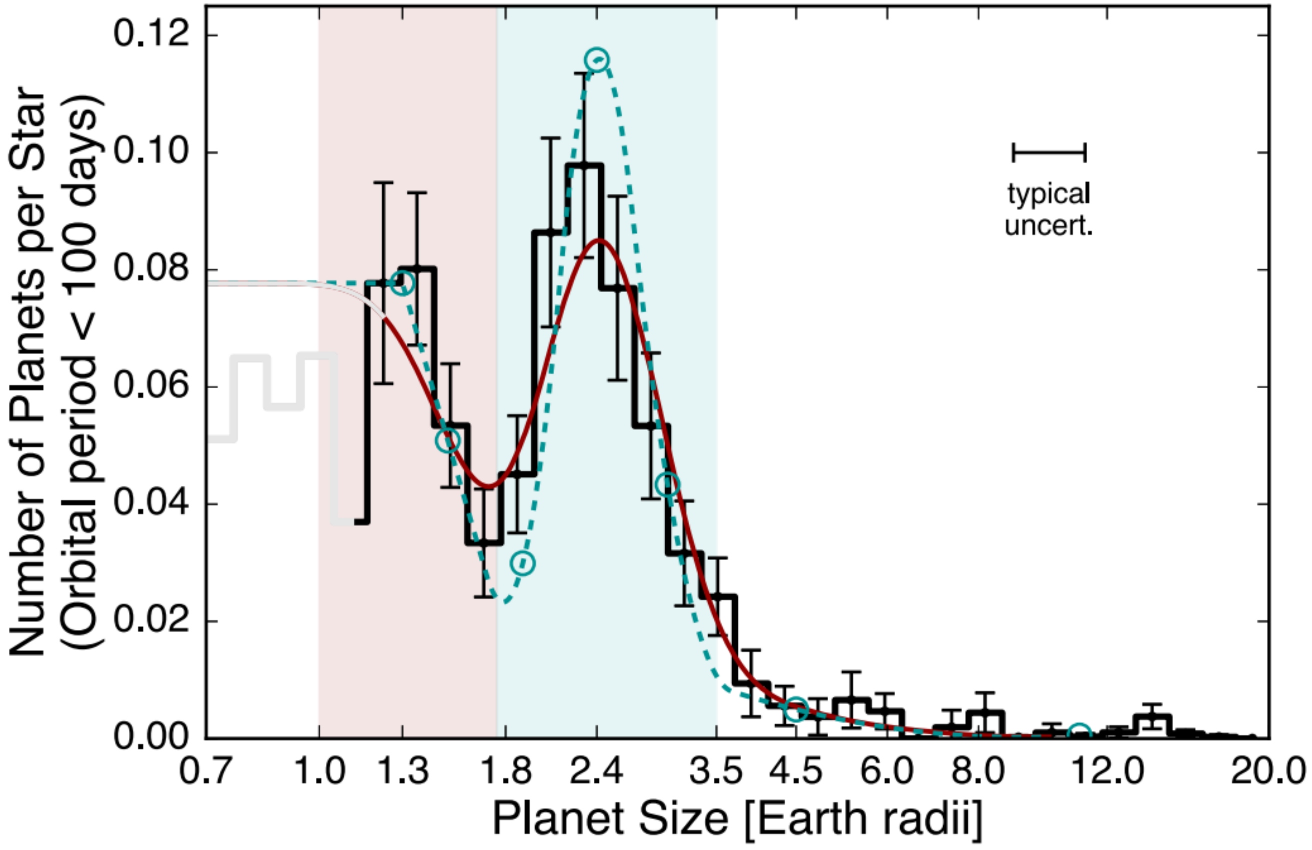
Or scaled down **Neptunes**?



Rocky



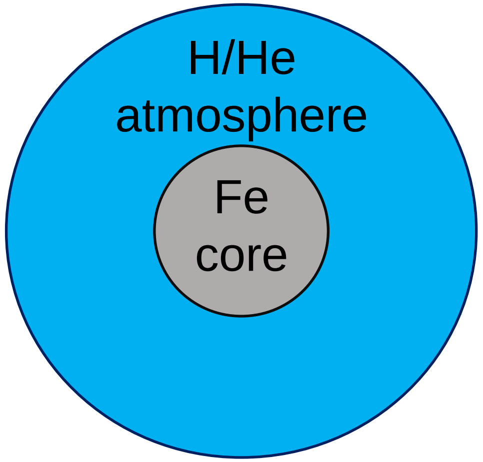
Building blocks: Al, Ca, Mg, Si, Fe, Na…



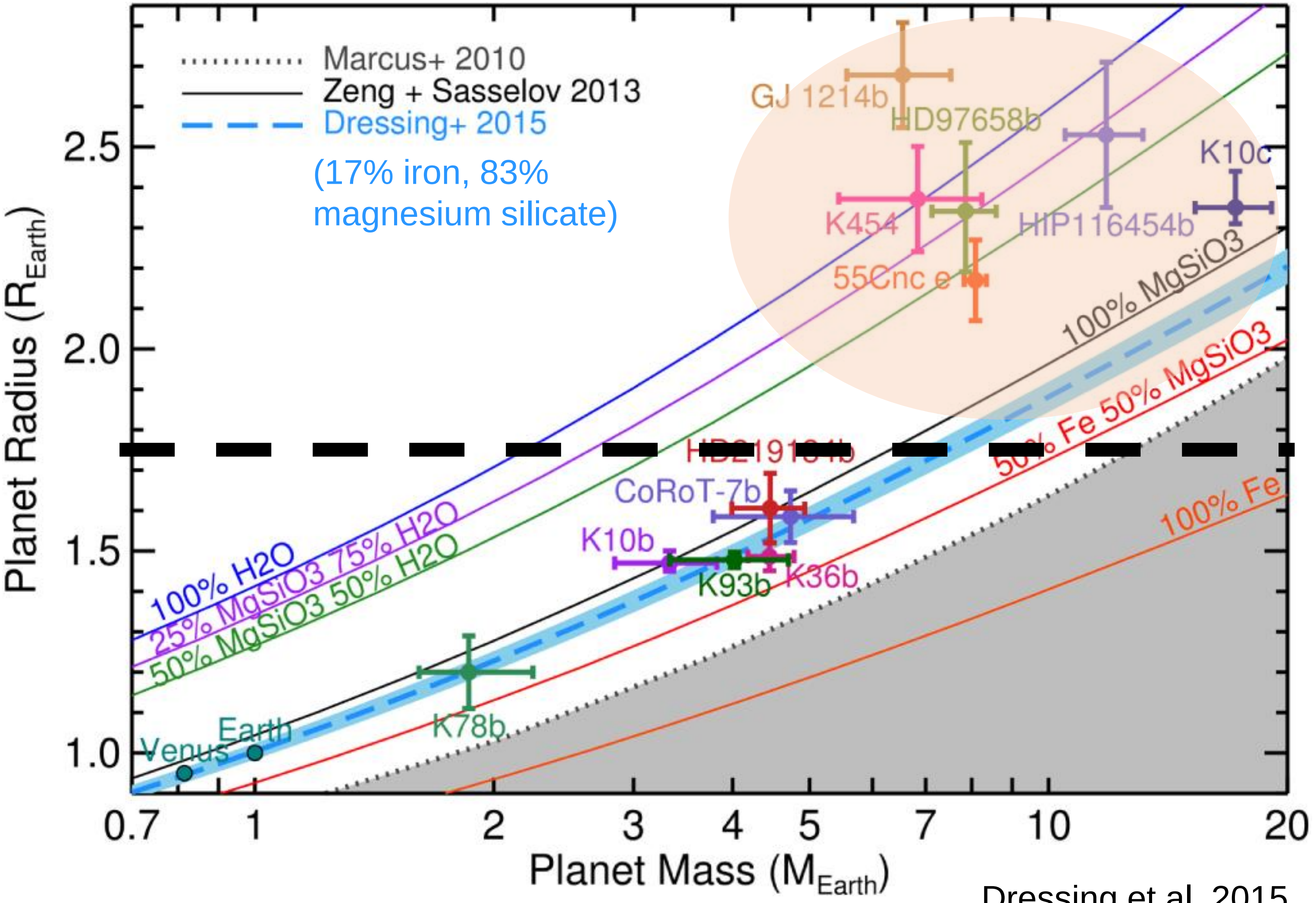
Fulton et al. 2017

Gaseous

Building blocks:
H, He
Ices: H_2O, NH_3, CH_4…



Small planets are compositionally more diverse

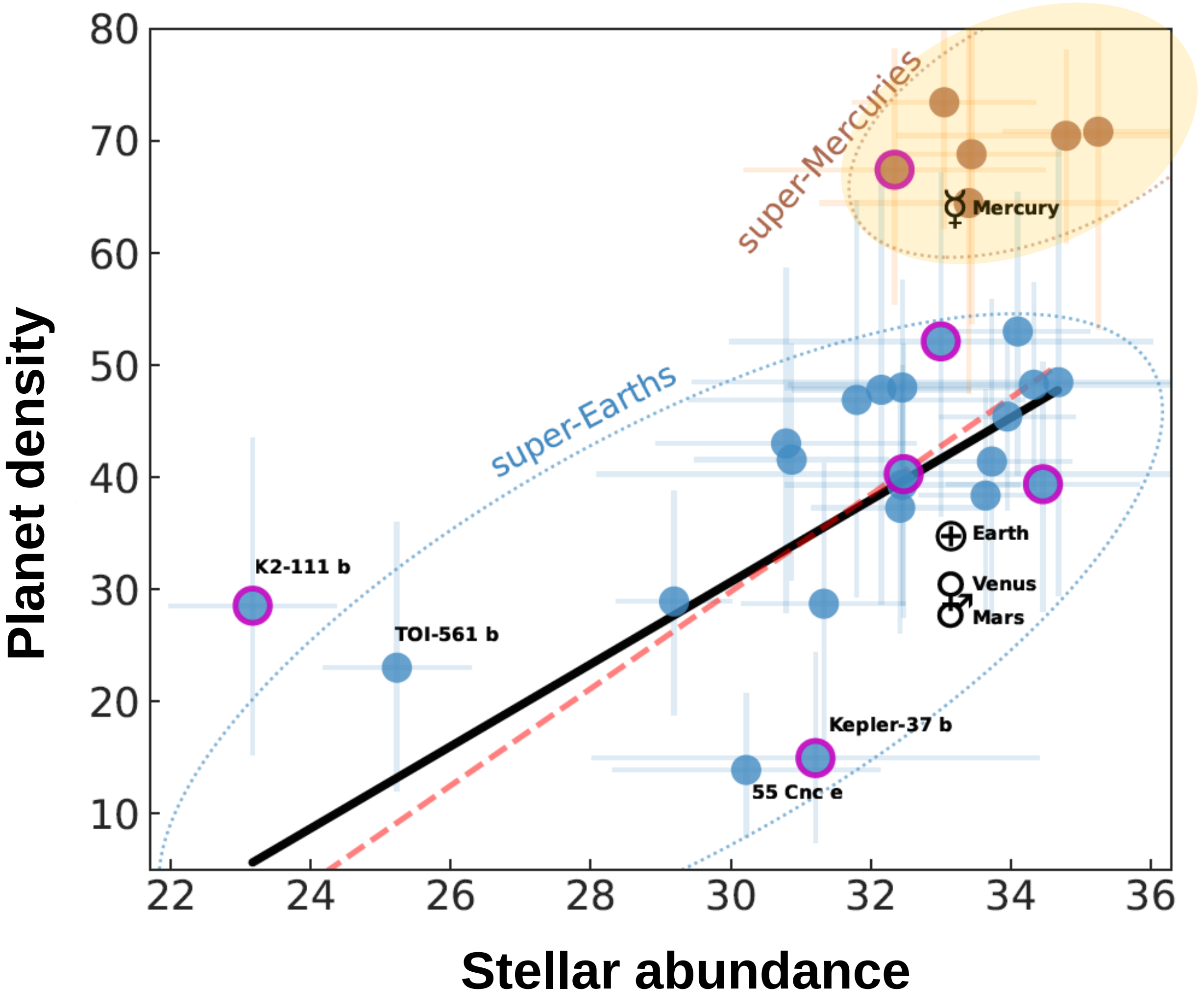


Dressing et al. 2015

Planets $\lesssim 1.5 R_\oplus$ are generally **rocky.** (Rogers et al. 2015)

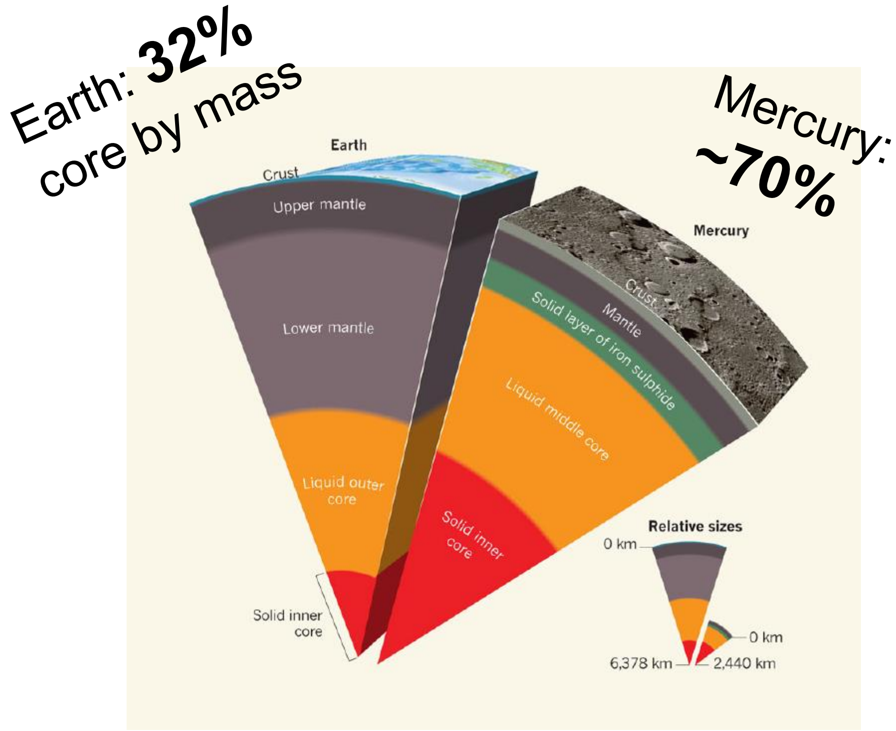
Planets between $1.5 - 4\ R_\oplus$ exhibit **more diverse compositions**.

Super-Mercuries



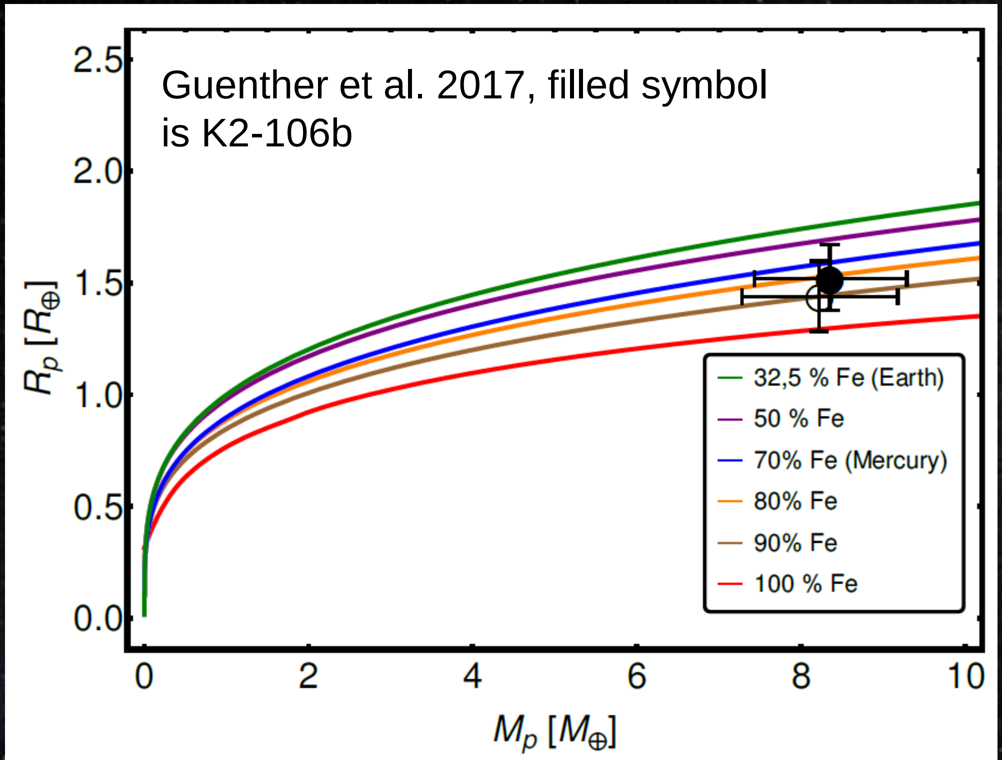
Adibekyan et al. 2021

planets with extremely **high densities**, consistent with a Mercury-like composition, i.e., 32% mantle, 68% Fe core. See K2-141b (Malavolta+18), K2-229b (Santerne+18), Kepler-107c (Bonomo+19), HD 137496b (Silva+2022)



Stevenson 2012

An ultra-dense, ultra short-period planet: K2-106b



EPIC 20674823, TIC 266015990

Distance: 245 pc, V= 12 mag

Period: 0.57 days

Mass: $8.36^{+0.96}_{-0.94}\ M_\oplus$

Radius: $1.52 \pm 0.16\ R_\oplus$

Density: $\mathbf{13.1^{+5.4}_{-3.6}\ g\ cm^{-3}}$

CMF = $80^{+20}_{-30}\%$

For reference, the Earth's density is ~5.5 g/cc

K2-106b (Adams et al. 2017, Guenther et al. 2017)

Is K2-106b really a super-Mercury?

- Preliminary work (Rodríguez-Martínez+21) showed that we could reduce the planet's density uncertainty.
- Improved **parallax** from Gaia DR2 gives us an improved estimate of the planet's radius.
- We combine planet interior models with a new statistical framework.

- **Goal:** to assess whether K2-106b is a true super-Mercury.

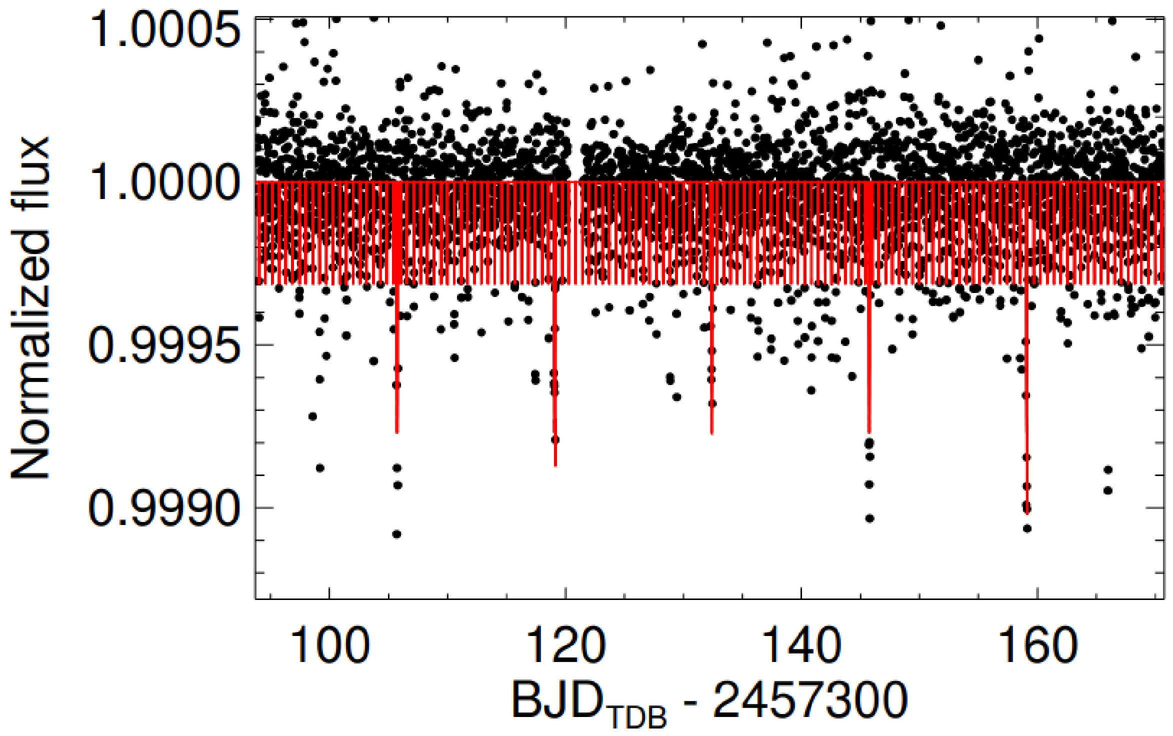
$$\left(\frac{\sigma_{\rho_p}}{\rho_p}\right)^2 \approx \left(\frac{\sigma_{K_\star}}{K_\star}\right)^2 + \left(\frac{\sigma_P}{P}\right)^2 + \left(\frac{\sigma_T}{T}\right)^2 + \left(\frac{\sigma_\tau}{\tau}\right)^2 + \left(\frac{\sigma_{R_\star}}{R_\star}\right)^2 + \left(\frac{\sigma_\delta}{\delta}\right)^2.$$

Rodríguez-Martínez et al. 2021

Revisiting K2-106b

- Used existing photometry and radial velocity data to characterize the system: a K2 light curve and 6 RVs.
- Used **EXOFASTv2** (Eastman+2013,17,19) to globally model the system.
- Use the MIST evolutionary tracks to constrain the properties of the star.

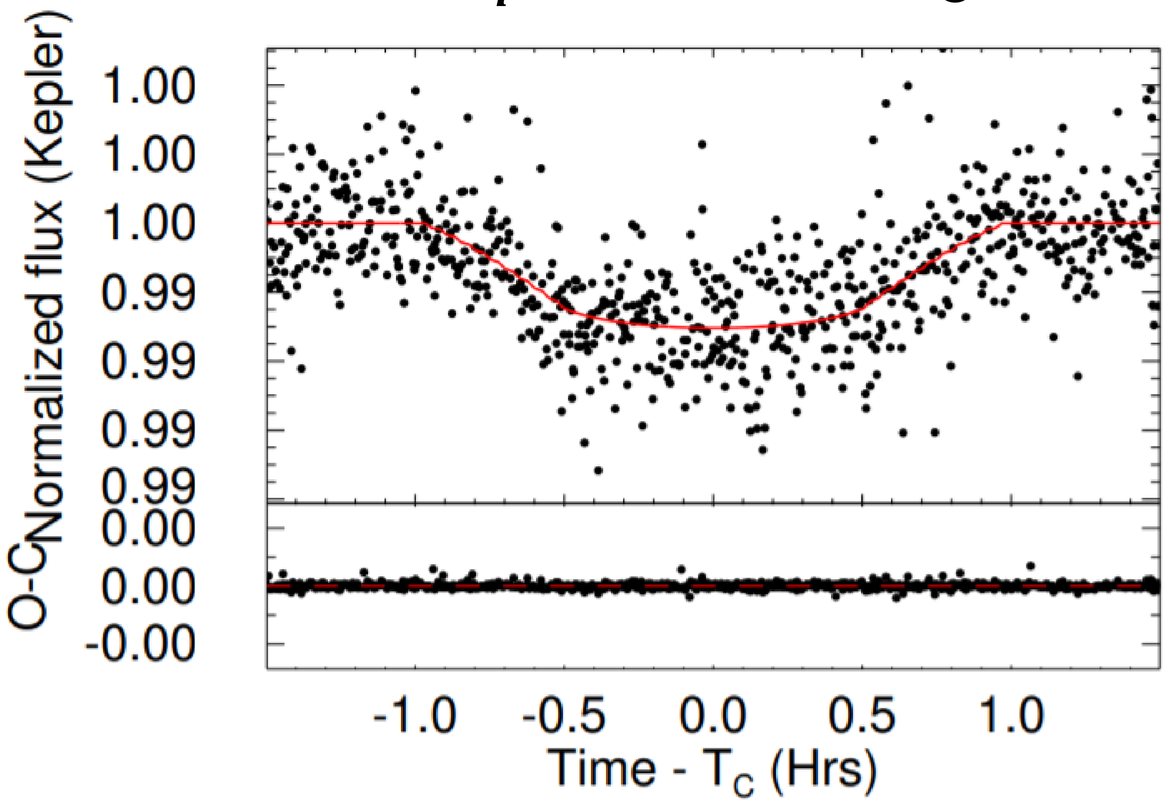
K2 lightcurve of the K2-106 system



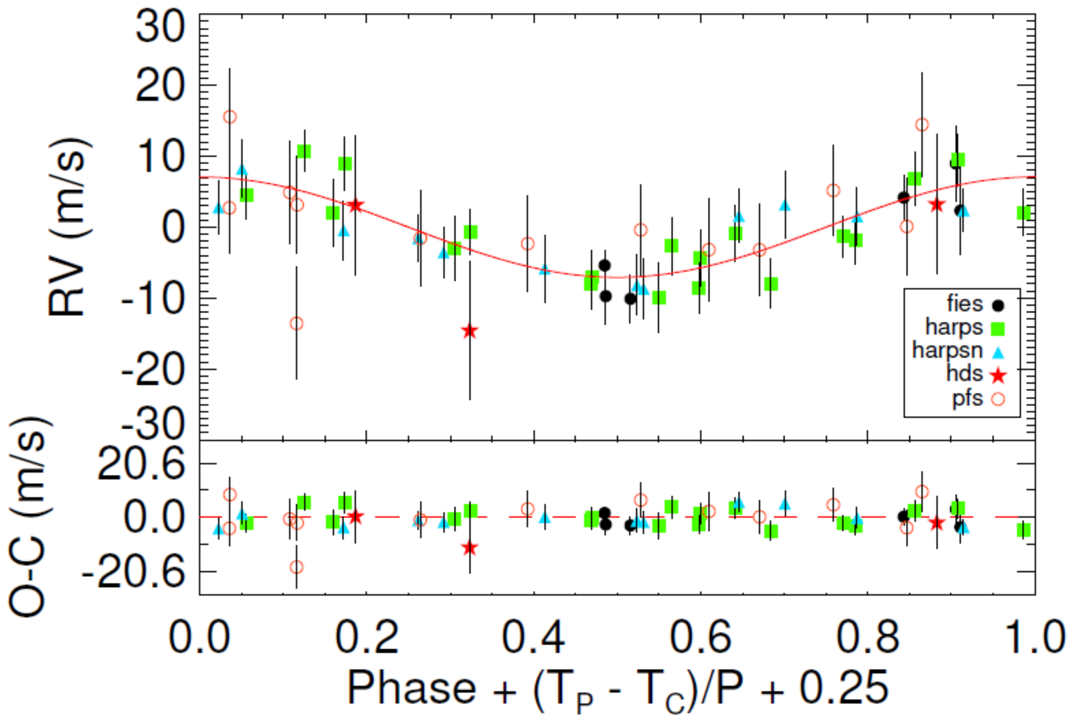
Rodríguez-Martínez et al. 2022 in preparation

Derived Planetary Parameters

$R_p = 1.71^{+0.069}_{-0.057} R_\oplus$



$M_p = 8.53 \pm 1.02\ M_\oplus$



Rodríguez-Martínez et al. 2022 in preparation

Derived Planetary Parameters: K2-106b

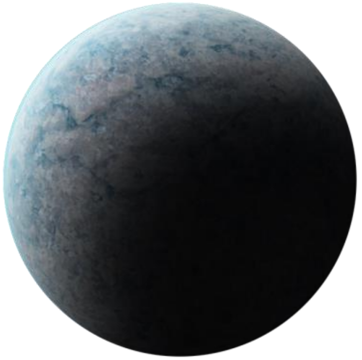
<u>This work</u>

$Period = 0.5\ days$
$M_p = 8.53 \pm 1.02\ M_{\oplus}$
$R_p = \mathbf{1.71^{+0.069}_{-0.057} R_{\oplus}}$
$T_{eq} = 2275^{+36}_{-32}\ K$

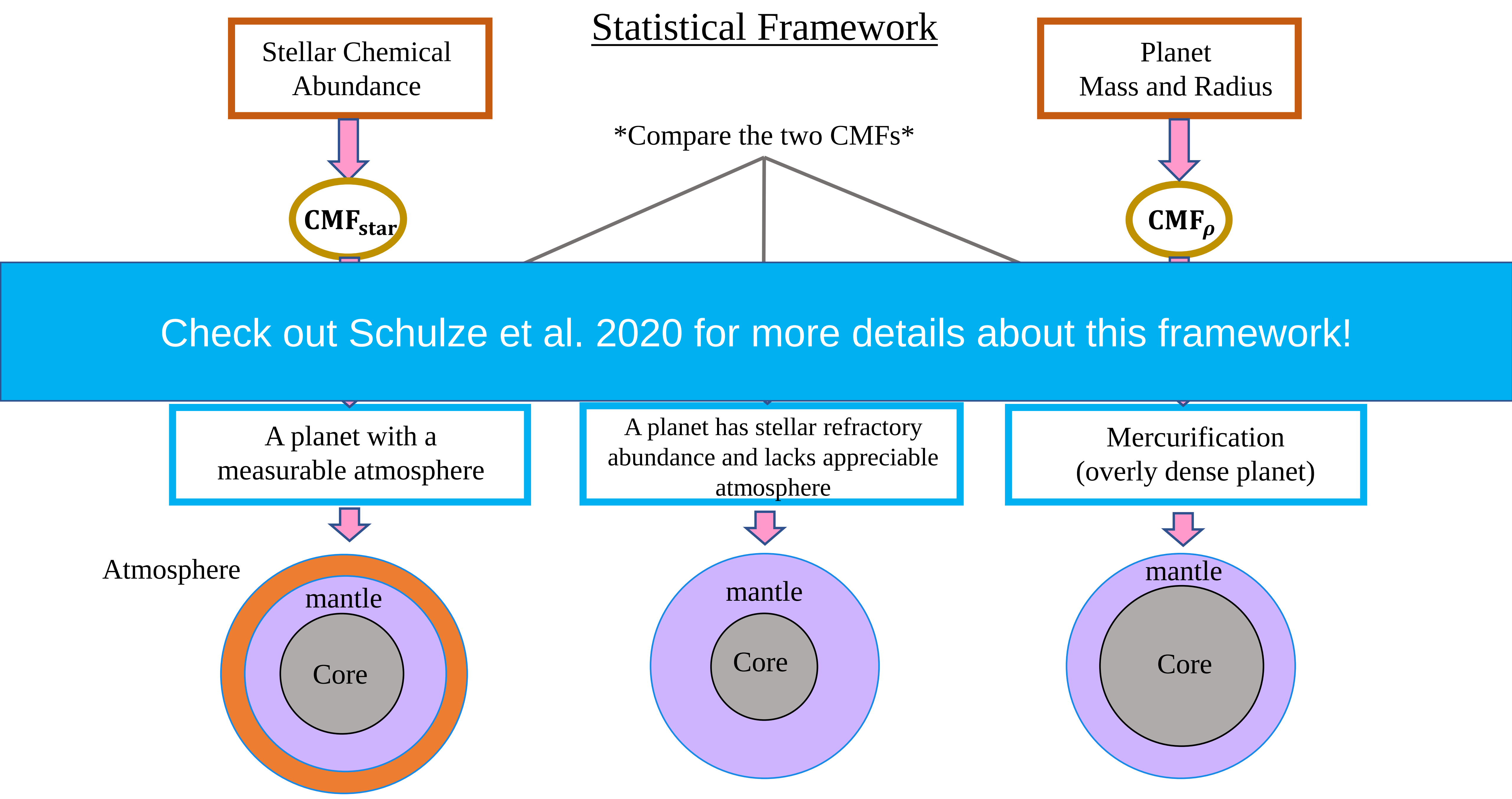
<u>Guenther et al. 2017</u>

$Period = 0.5\ days$
$M_p = 8.36^{+0.96}_{-0.94}\ M_{\oplus}$
$R_p = 1.52 \pm 0.16\ R_{\oplus}$
$T_{eq} = 2333^{+69}_{-57}\ K$

Reference	Planet density g/cm^3
Rodríguez-Martínez	$\mathbf{9.4 \pm 1.55}$
Guenther et al. 2017	$\mathbf{13.1^{+5.4}_{-3.6}}$
Dai et al. 2018	$\mathbf{8.50 \pm 1.90}$



We obtain a **lower density** than previously reported



Statistical Framework
Stellar Chemical Abundance
Planet Mass and Radius
Compare the two CMFs
CMF_{star}
CMF_{ρ}
Check out Schulze et al. 2020 for more details about this framework!
A planet with a measurable atmosphere
A planet has stellar refractory abundance and lacks appreciable atmosphere
Mercurification (overly dense planet)
Atmosphere
mantle
Core
mantle
Core
mantle
Core

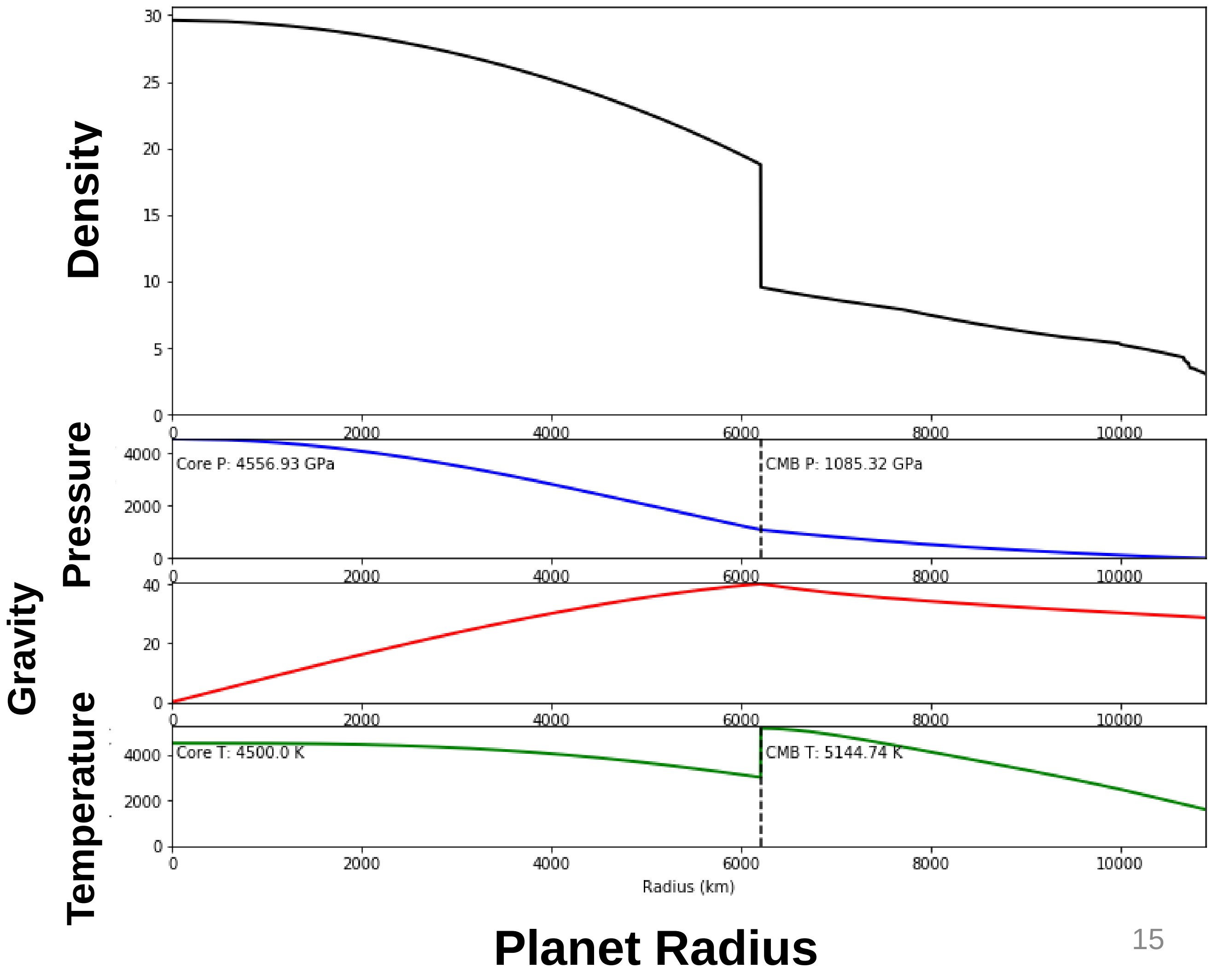
Calculating CMF_ρ

ExoPlex: Calculates the depth-dependent density, mantle, pressure, gravity profiles of planets. (Unterborn et al. 2018).

Assumes planet with Fe core and silicate mantle.

We obtain a CMF_ρ for K2-106 of $\mathbf{45^{+14}_{-16}}\%$

*Earth's CMF is **32%***



Calculating $\mathrm{CMF}_{\mathrm{star}}$

Molar refractory ratios. Requires **[Fe/H], [Si/H], [Mg/H]** abundances

$$\mathrm{CMF}_{\mathrm{star}} = \frac{\left(\frac{Fe}{Mg}\right) m_{Fe}}{\left(\frac{Fe}{Mg}\right) m_{Fe} + \left(\frac{Si}{Mg}\right) m_{SiO_2} + m_{MgO}}$$

m_i is the molar mass of species i.

Stellar Abundances

- Used iSpec (Blanco-Cuaresma+14,19) to estimate **Fe, Si, Mg abundances.**
- Used the synthetic spectral fitting method.

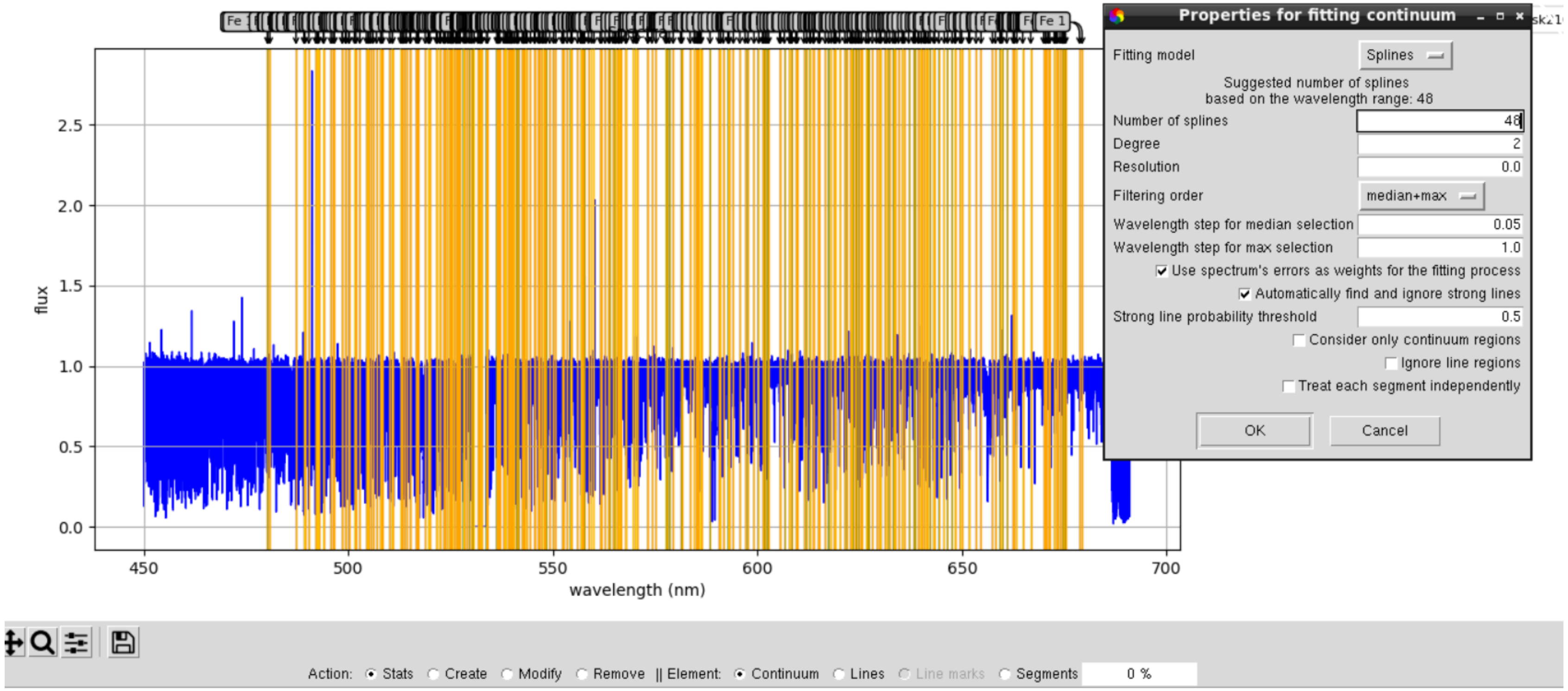
Abundances:

[Fe/H] = -0.03 ± 0.014

[Mg/H] = 0.04 ± 0.023

[Si/H] = 0.03 ± 0.067

HARPS spectrum, $R \approx 120{,}000$,
$\lambda = 450 - 691\ nm$



$\mathrm{CMF}_{\mathrm{star}}$ for K2-106

$$\mathrm{CMF}_{\mathrm{star}} = \frac{\left(\frac{Fe}{Mg}\right) m_{Fe}}{\left(\frac{Fe}{Mg}\right) m_{Fe} + \left(\frac{Si}{Mg}\right) m_{SiO_2} + m_{MgO}}$$

$$\frac{Fe}{Mg} = 0.71 \pm 0.17, \qquad \frac{Si}{Mg} = 0.93 \pm 0.25$$

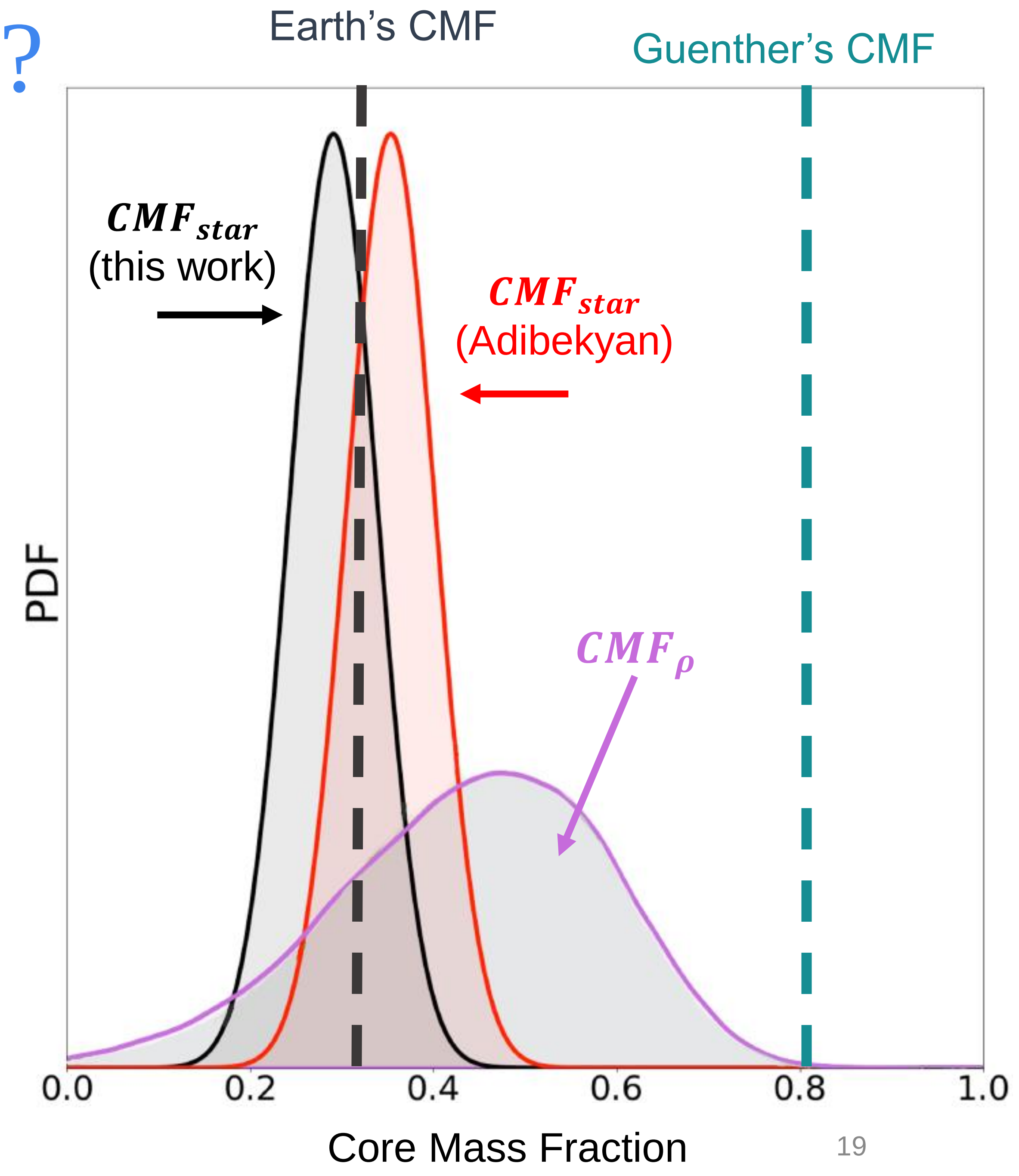
$$CMF_{star} = 0.29 \pm 0.06$$

$$CMF_{\rho} = 0.45^{+0.14}_{-0.16}$$

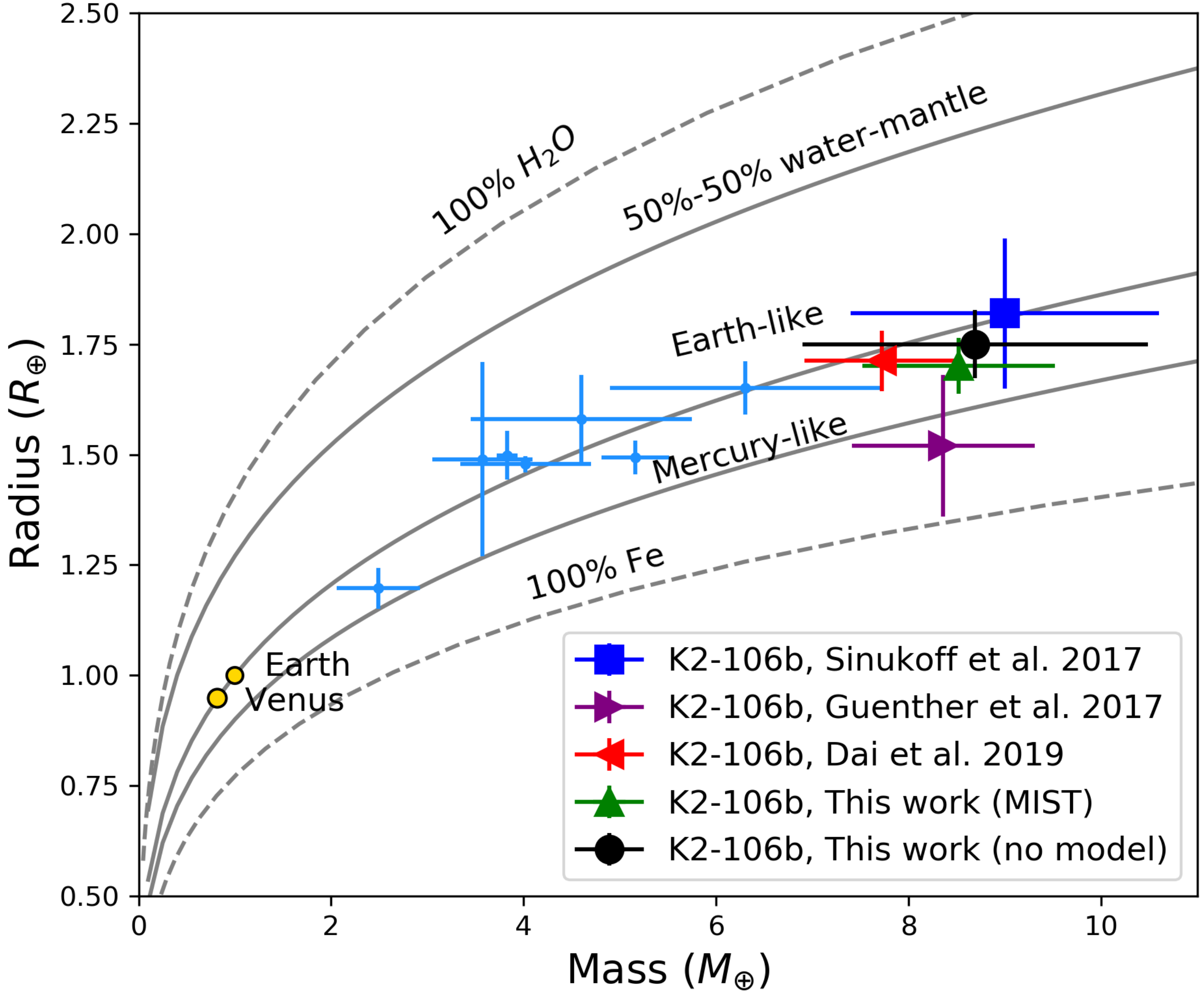
Is K2-106b a super Mercury?

Although K2-106b is highly dense and probably iron-enriched, we **cannot conclude** that it is a true Super-Mercury based on our formalism.

Instead, our analysis suggests that K2-106b is more consistent with an **Earth-like composition**.



Rodríguez-Martínez et al. 2022 in preparation

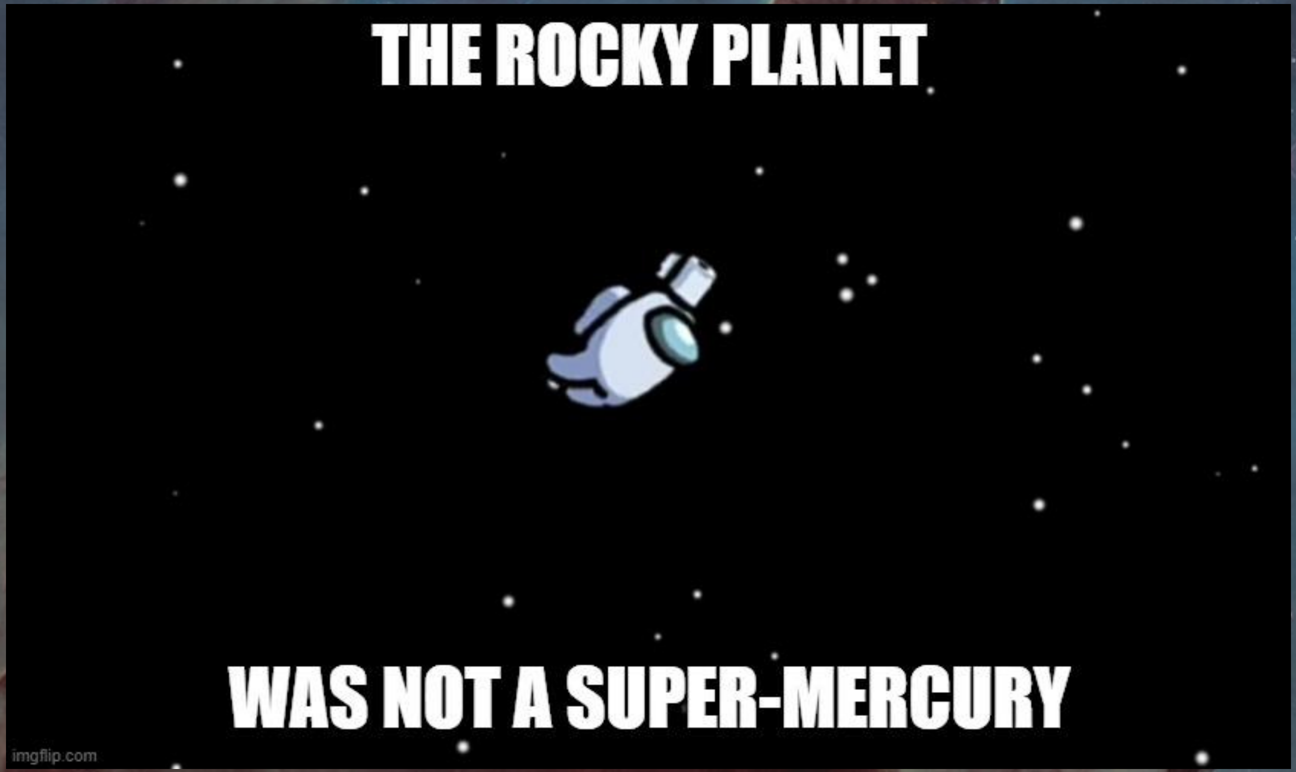


Rodríguez-Martínez et al. 2022 in preparation

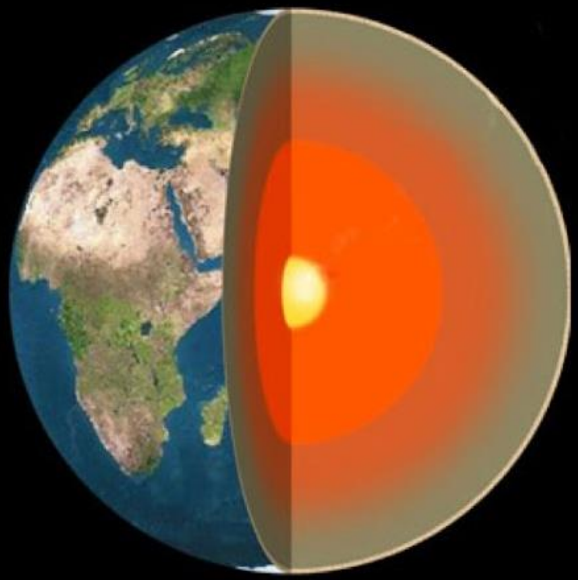
Conclusions

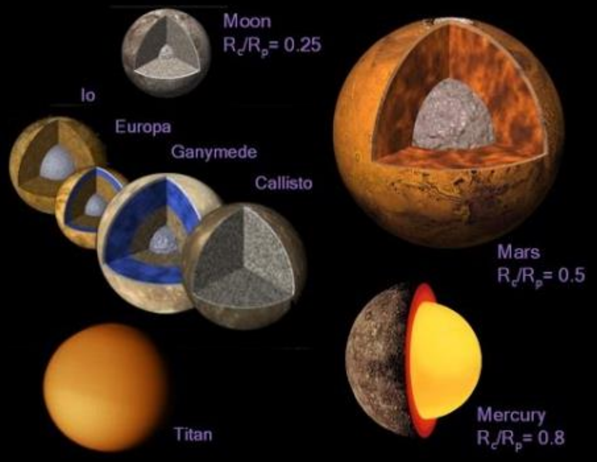
- We perform the most thorough characterization to date of the super-Mercury candidate K2-106b and find that it is unlikely to be a true super-Mercury.
- Our work implies that perhaps other super-Mercury candidates in the literature may not be as iron-rich as previously thought.
- To characterize the smallest planets, we will need host star abundances of Fe, Mg and Si, and precise planet masses and radii.
- We encourage the community to provide Fe/Mg/Si abundances so that we can make further progress on exoplanet composition.

Thank you for listening! Questions?



The bulk compositions of Earth, Venus, and Mars reflect the relative abundances of the major rock-forming elements in the Sun (Fe, Mg, Si)





Fe/Mg and Si/Mg ratios are similar in the planets and the Sun

CI chondrite meteorite

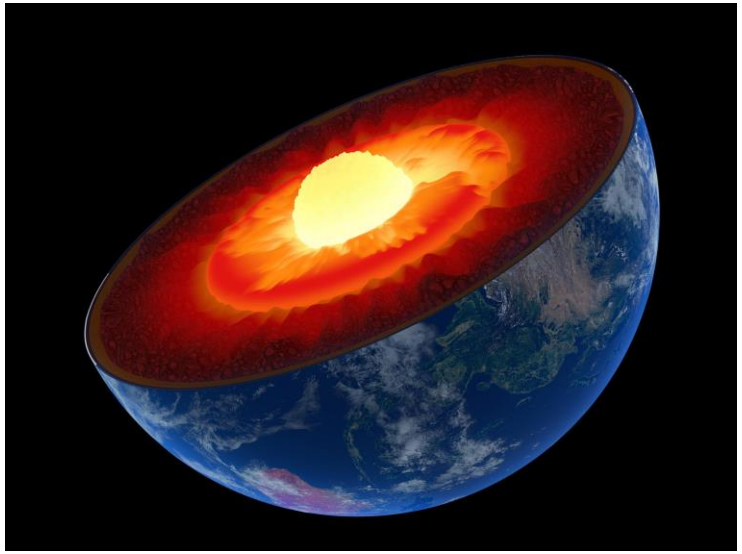
Core mass fraction (CMF)

- Defined as M_{core}/M_{planet}

The CMF controls important physical properties of the planet, such as:

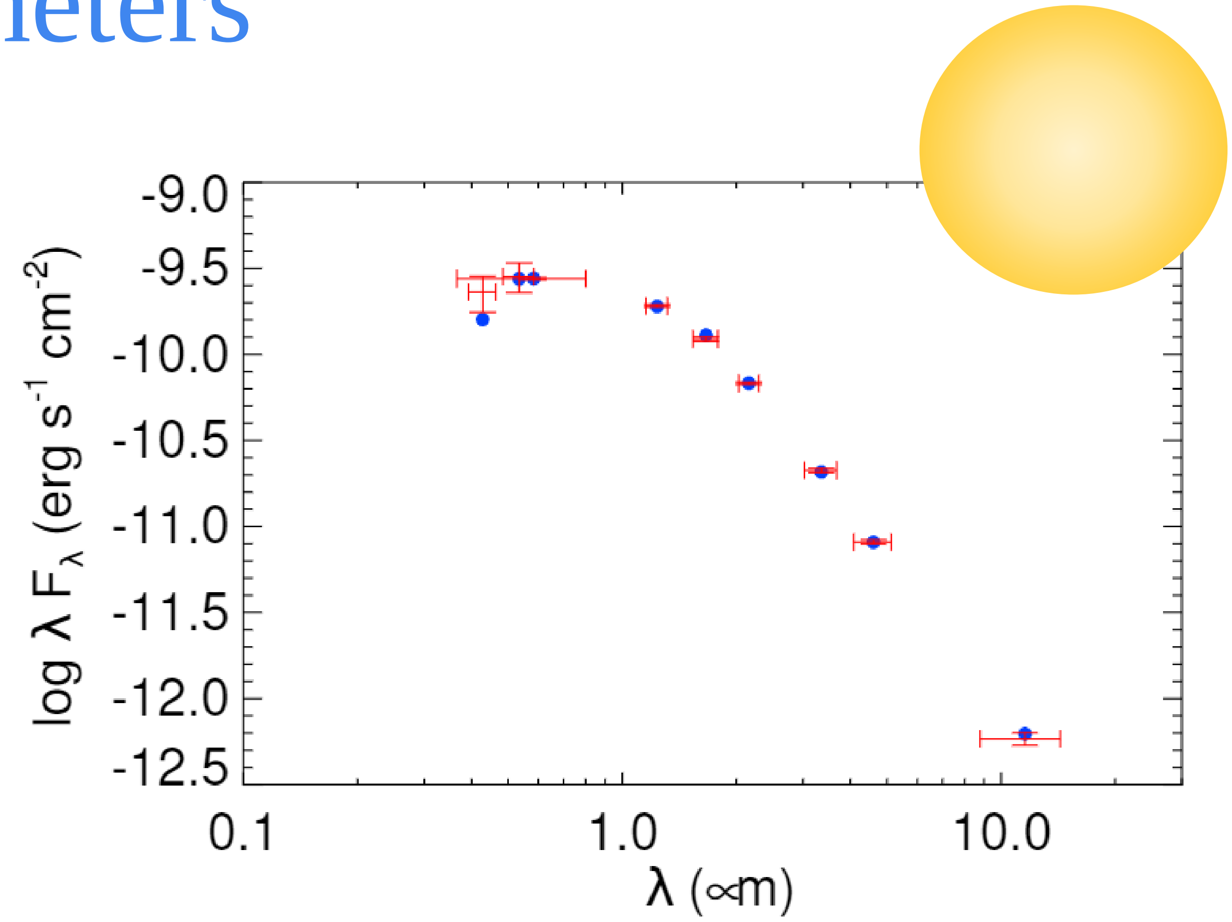
- The total mass
- The strength of the magnetic field
- The presence of an atmosphere

all of which are directly related to a planet's habitability.



Derived Stellar Parameters

$$T_{eff} = 5508 \pm 70$$
$$\log g_* = 4.44^{+0.033}_{-0.037}$$
$$M_* = 0.96 \pm 0.06\ M_\odot$$
$$R_* = 0.98 \pm 0.023\ R_\odot$$
$$\rho_* = 1.46 \pm 0.14\ g/cm^3$$
$$d = 245\ pc$$
$$V = 12.1\ mag$$



SED fit of the host star, K2-106

Abundance Measurements

This work (iSpec)	Adibekyan+21 (MOOG)
[Fe/H] = -0.03 ± 0.014	[Fe/H] = 0.10 ± 0.03
[Mg/H] = 0.04 ± 0.023	[Mg/H] = 0.07 ± 0.05
[Si/H] = 0.03 ± 0.067	[Si/H] = 0.05 ± 0.03

CMF_{ρ}

Reference	Planet density g/cm^3	Core-mass fraction (CMF_{ρ})
Rodríguez-Martínez (using constraints from MIST)	$\mathbf{9.4 \pm 1.55}$	45^{+14}_{-16} %
Rodríguez-Martínez (**without** constraints from MIST)	$\mathbf{9.1^{+1.9}_{-2.6}}$	39^{+19}_{-23} %
Guenther et al. 2017	$\mathbf{13.1^{+5.4}_{-3.6}}$	80^{+20}_{-30} %
Dai et al. 2018	$\mathbf{8.50 \pm 1.90}$	$40 \pm 23\%$

Future Targets:

- GJ 1132b
- GJ 357b
- LTT 3780 b
- Kepler-105 c
- L 98-59 c
- L 168-9 b
- Kepler-406 b
- Kepler-36 b
- K2-141 b
- Kepler-80 d
- L 98-59 d
- GJ 9827 b
- K2-291 b
- HD 80653 b
- Kepler-60 b
- TOI-1235 b
- K2-216

Well-characterized planets but are missing stellar **Fe, Mg and Si** abundances!!

Schulze et al. incl. **Rodriguez-Martinez**, in preparation

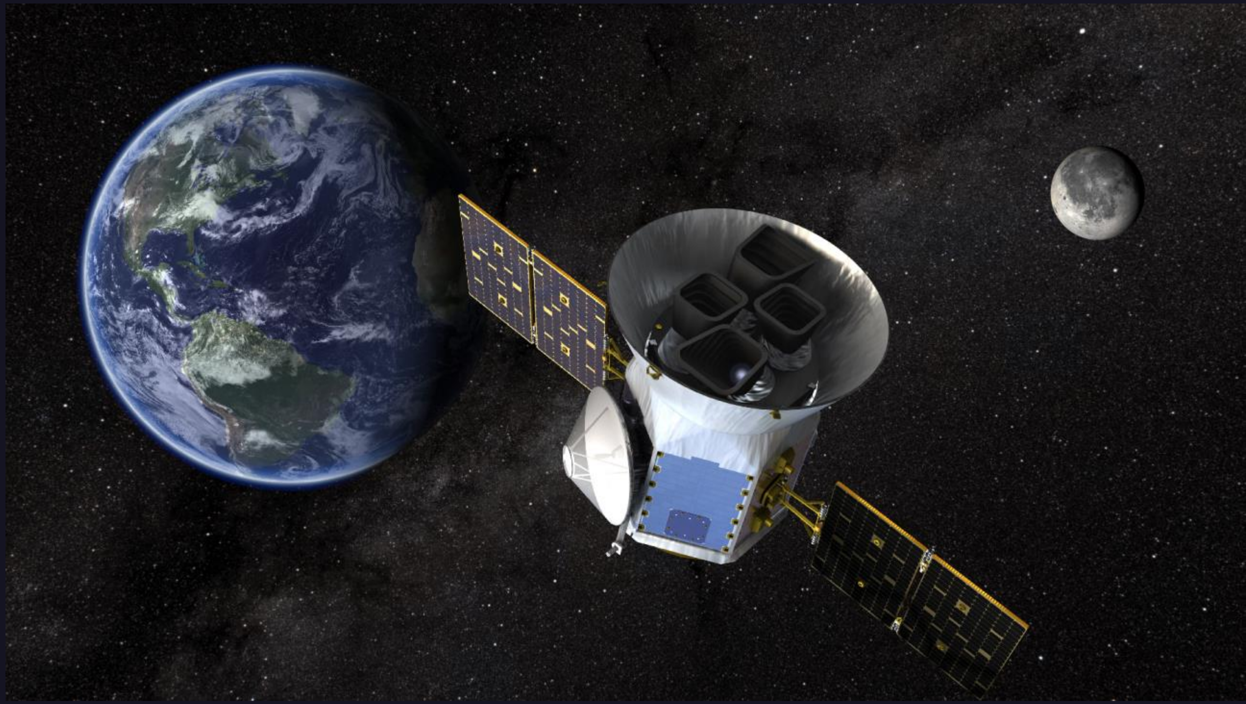
Transiting Exoplanet Survey Satellite (TESS)

- All-sky transit survey (>80% sky).
- 600-1000 nm
- Sensitive to $R_p < 1.75 R_\oplus$.

Goal: measure masses of

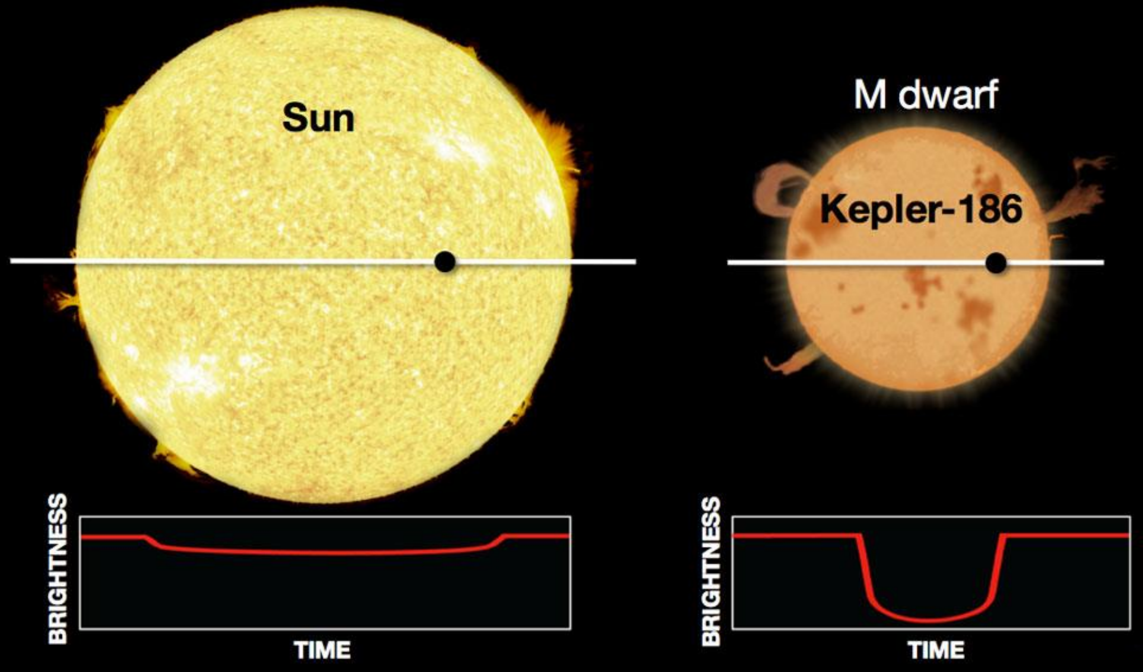
50 planets $R_p < 4 R_\oplus$.

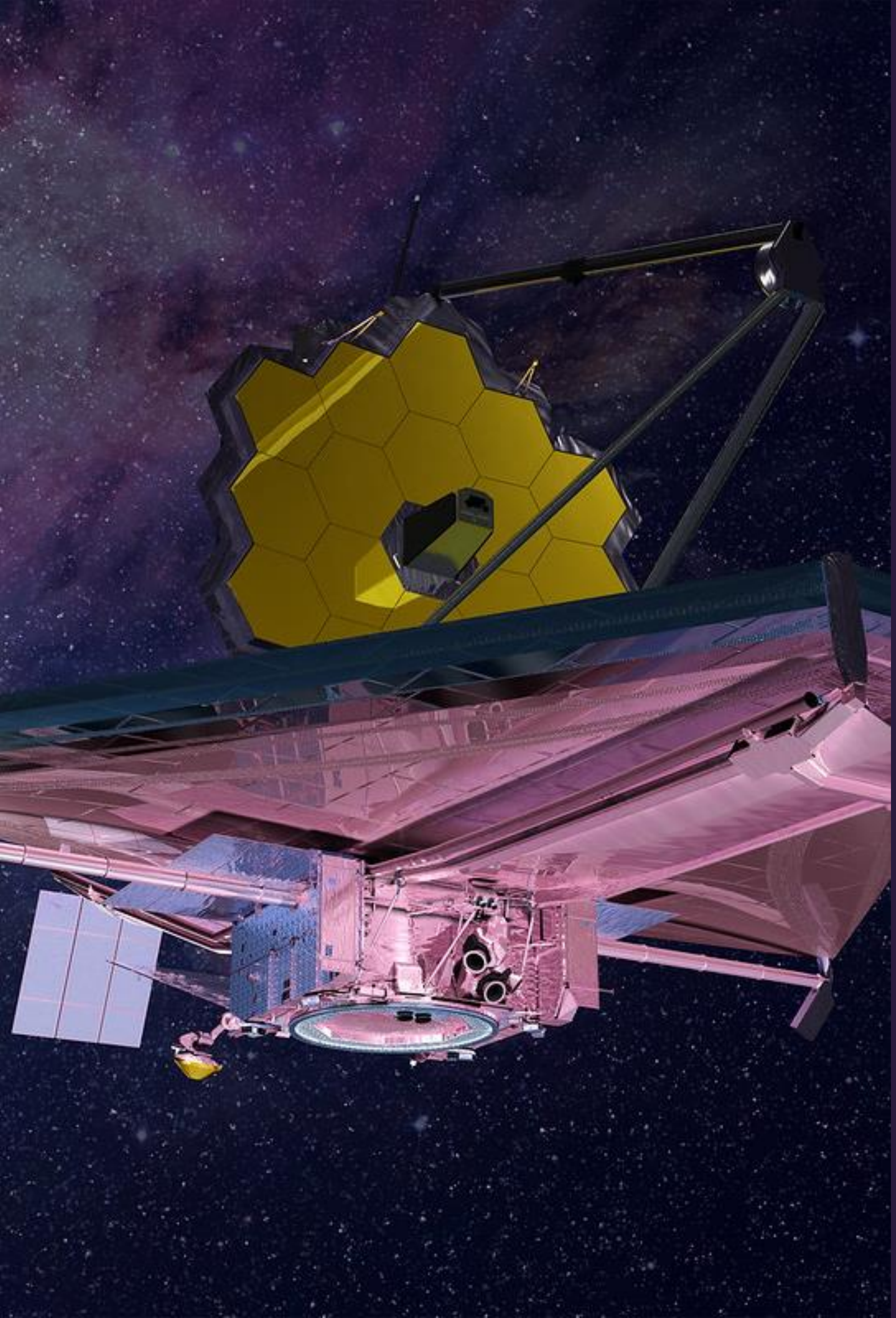
- There are currently >50 small planets with mass and radius measurements.



M-dwarf planets

- TESS yield studies predict ~hundred exoplanets around M dwarfs and ~2000 planets around FGK stars, of which ~300 would be $\lesssim 2R_{\oplus}$ (Ballard, 2018; Barclay et al. 2018)
- Planets around M-dwarfs are easier to detect with both the transit & RV method.
- They are also ideal targets to search for future atmospheric characterization & the search for biosignatures with JWST.





James Webb Space Telescope (JWST)

- ~6.5 m mirror
- 0.6 – 28 microns (visible to mid-infrared)
  - HST observes at 0.1 to 2 microns (UV to near-IR)
- JWST will:
  - Study the **atmospheres** of habitable exoplanets
  - Directly **image** exoplanets with a coronagraph
  - See planets in **transit** and take **spectra** (composition)
- One of our goals is to provide a ranked list of interesting targets (some of which should be potentially habitable) to observe with JWST.

Previous work: Schulze et al.

Planet	CMF_ρ	$\mathrm{CMF}_{\mathrm{star}}$	$P(\mathcal{H}^0)$ (%)	1σ Class	2σ Class
K2-229 b	$0.565^{+0.16}_{-0.20}$	0.29 ± 0.06	42	IHS	IHS
HD 219134 c	$0.42^{+0.13}_{-0.14}$	0.28 ± 0.09	70	IHS	IHS
Kepler-10 b	$0.13^{+0.15}_{-0.13}$	0.28 ± 0.05	65	IHS	IHS
HD 219134 b	0.29 ± 0.15	0.28 ± 0.09	100	IHS	IHS
Kepler-107 c	$0.70^{+0.10}_{-0.12}$	0.30 ± 0.07	1	SM	SM
HD 15337 b	0.34 ± 0.15	0.29 ± 0.07	96	IHS	IHS
K2-265 b	0.24 ± 0.24	0.33 ± 0.07	94	IHS	IHS
HD 213885 b	0.42 ± 0.09	0.31 ± 0.07	66	IHS	IHS
WASP-47 e	$0.155^{+0.14}_{-0.15}$	0.26 ± 0.07	80	IHS	IHS
Kepler-20 b	$0.26^{+0.14}_{-0.16}$	0.30 ± 0.10	98	IHS	IHS
55 Cnc e	$0.004^{+0.10}_{<0}$	0.31 ± 0.10	9	LDSP	IHS

CMF_star error

$$\left(\frac{X}{Y}\right) = 10^{\left(\left(\left[\frac{X}{H}\right]+A(X)_{\odot}\right)-\left(\left[\frac{Y}{H}\right]+A(Y)_{\odot}\right)\right)}$$

$$\sigma_{\mathrm{CMF_{star}}} = \sqrt{\left(\frac{\partial \mathrm{CMF_{star}}}{\partial\left(\frac{\mathrm{Fe}}{\mathrm{Mg}}\right)}\,\delta\left(\frac{\mathrm{Fe}}{\mathrm{Mg}}\right)\right)^2 + \left(\frac{\partial \mathrm{CMF_{star}}}{\partial\left(\frac{\mathrm{Si}}{\mathrm{Mg}}\right)}\,\delta\left(\frac{\mathrm{Si}}{\mathrm{Mg}}\right)\right)^2}.$$