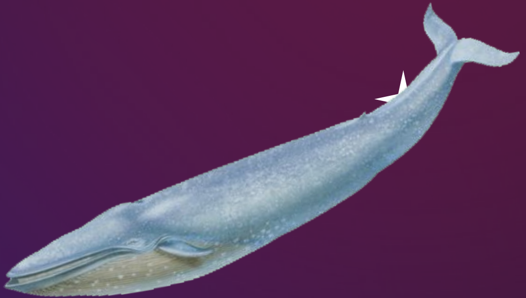
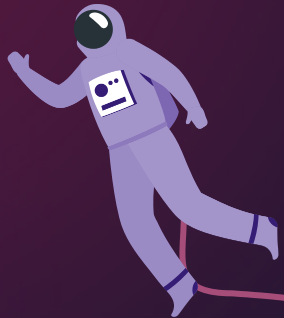
The Hitchhiker's Guide to the





# Drake Equation:

## Past, Present, and Future

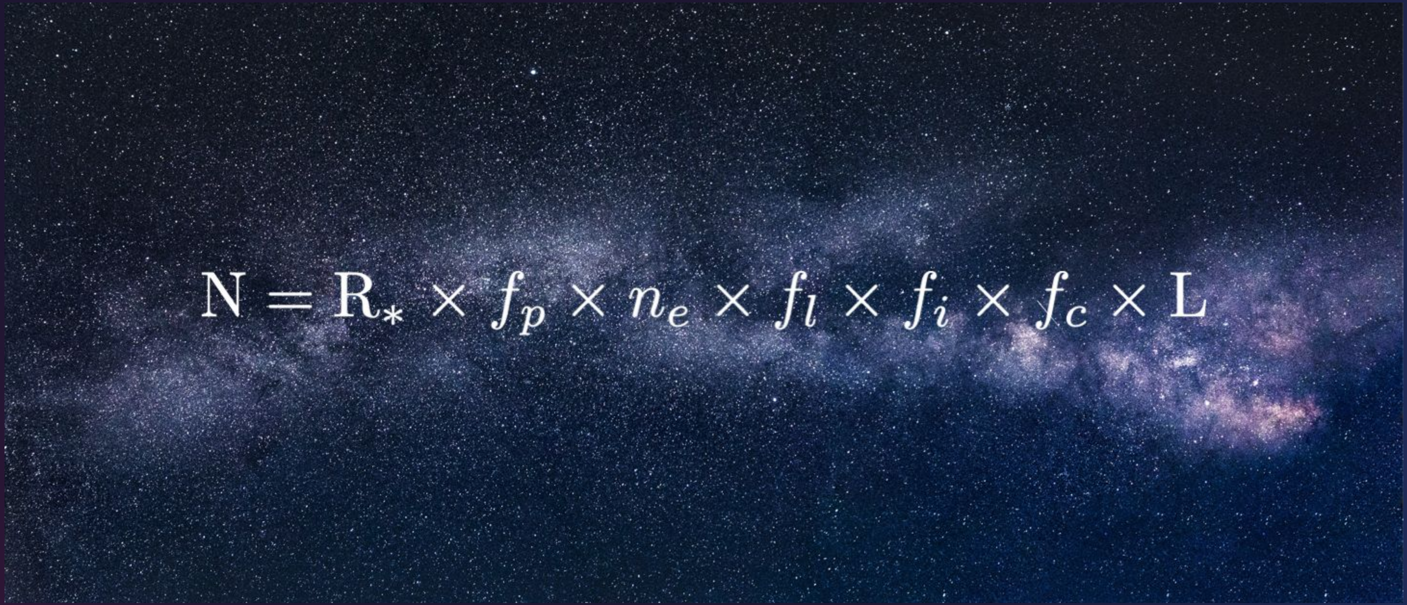
**Dr. Kaitlin Rasmussen (she/they)**

ExoExplorers Series — June 11, 2021

**University of Michigan | Heising-Simons Foundation**

# THE BIG QUESTION: ARE WE ALONE?

# THE BIG ANSWER:
# THE DRAKE EQUATION



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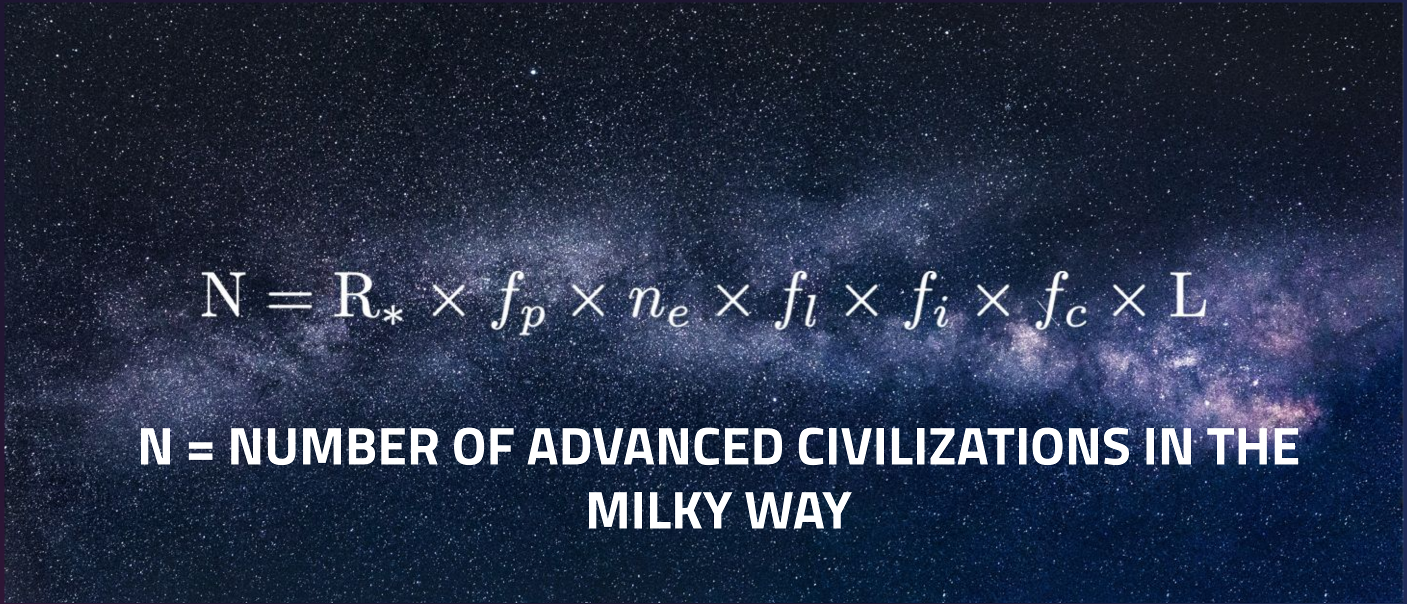
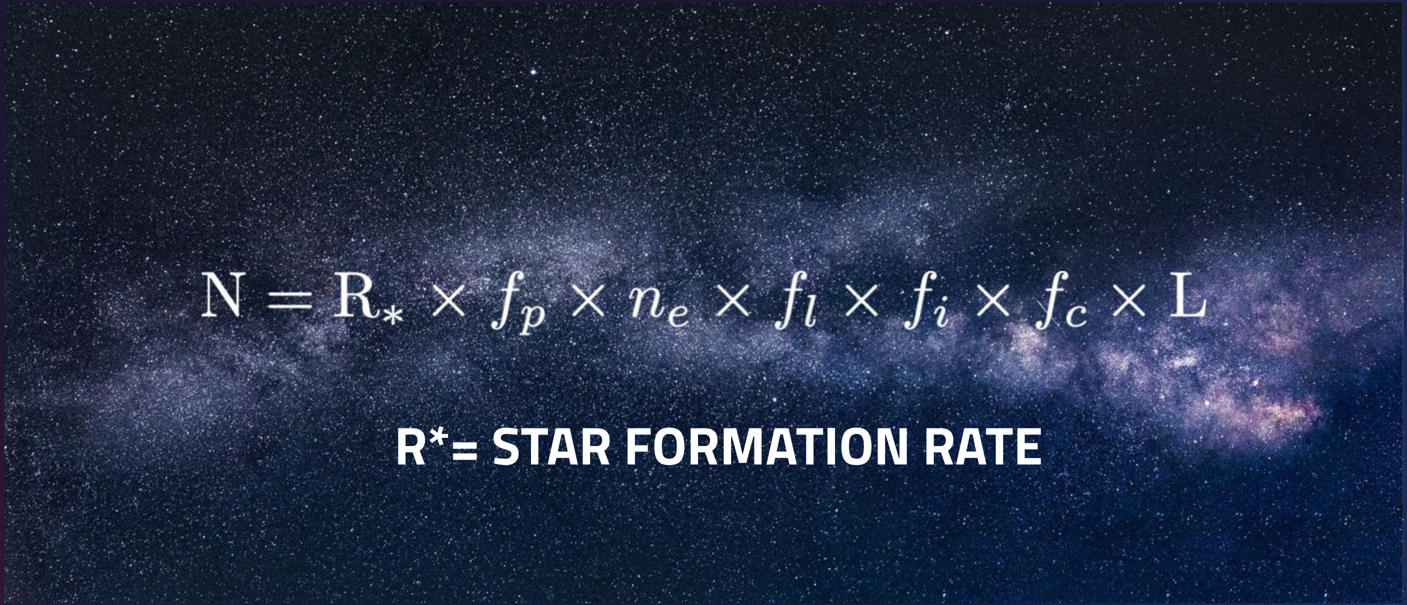
# THE DRAKE EQUATION



$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

**N = NUMBER OF ADVANCED CIVILIZATIONS IN THE MILKY WAY**

# THE BIG ANSWER:
# THE DRAKE EQUATION



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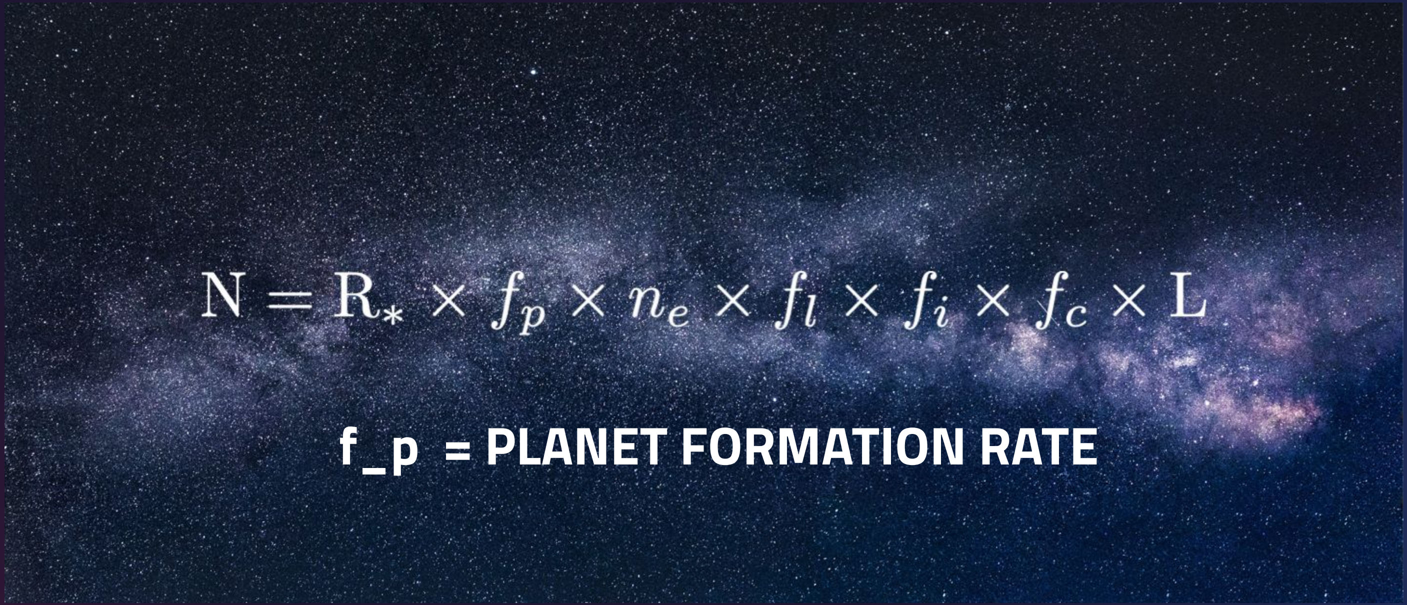

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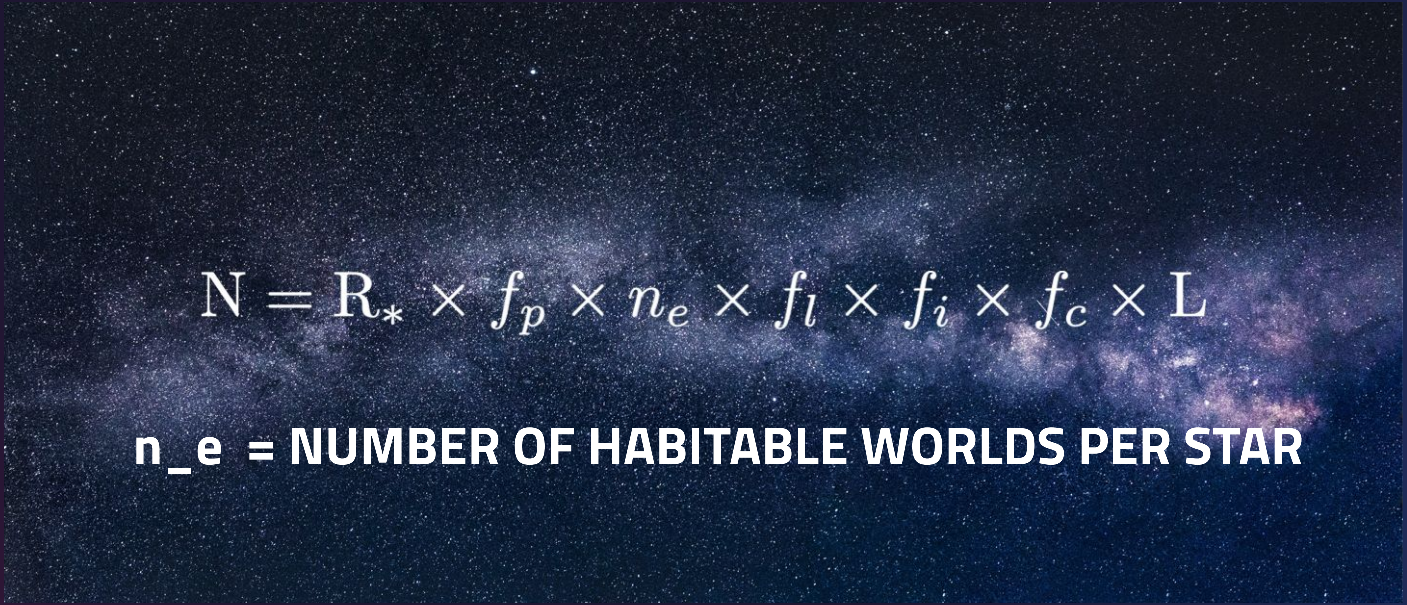

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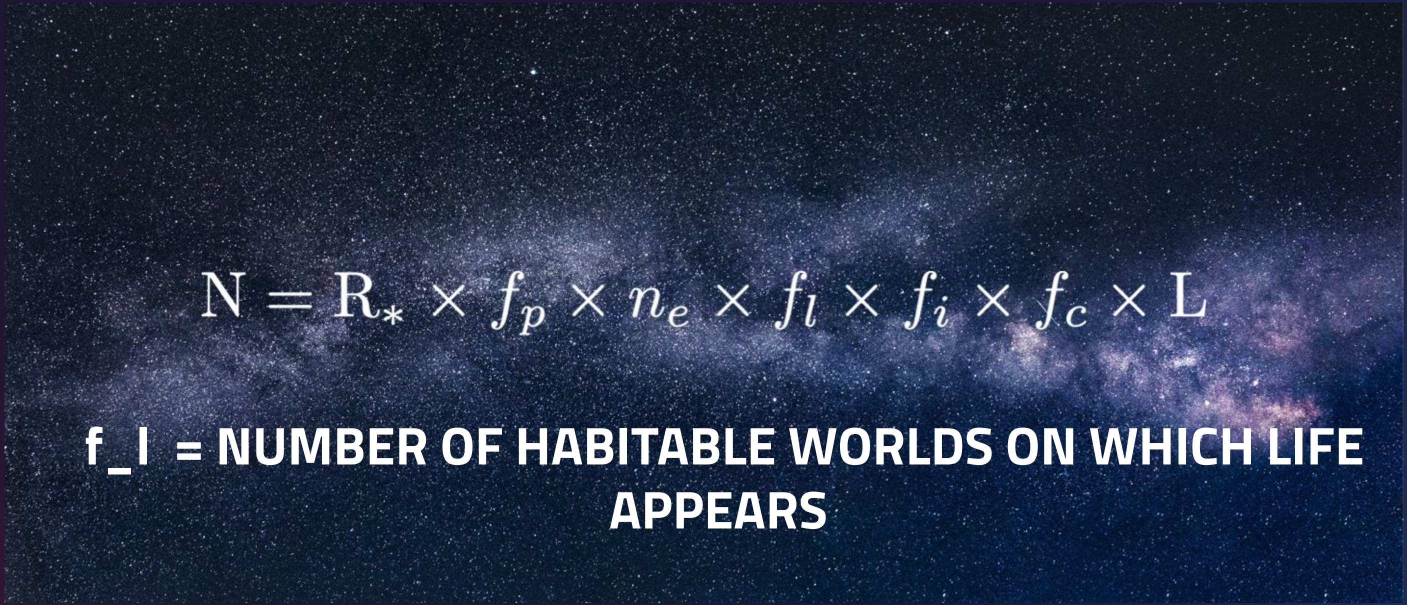
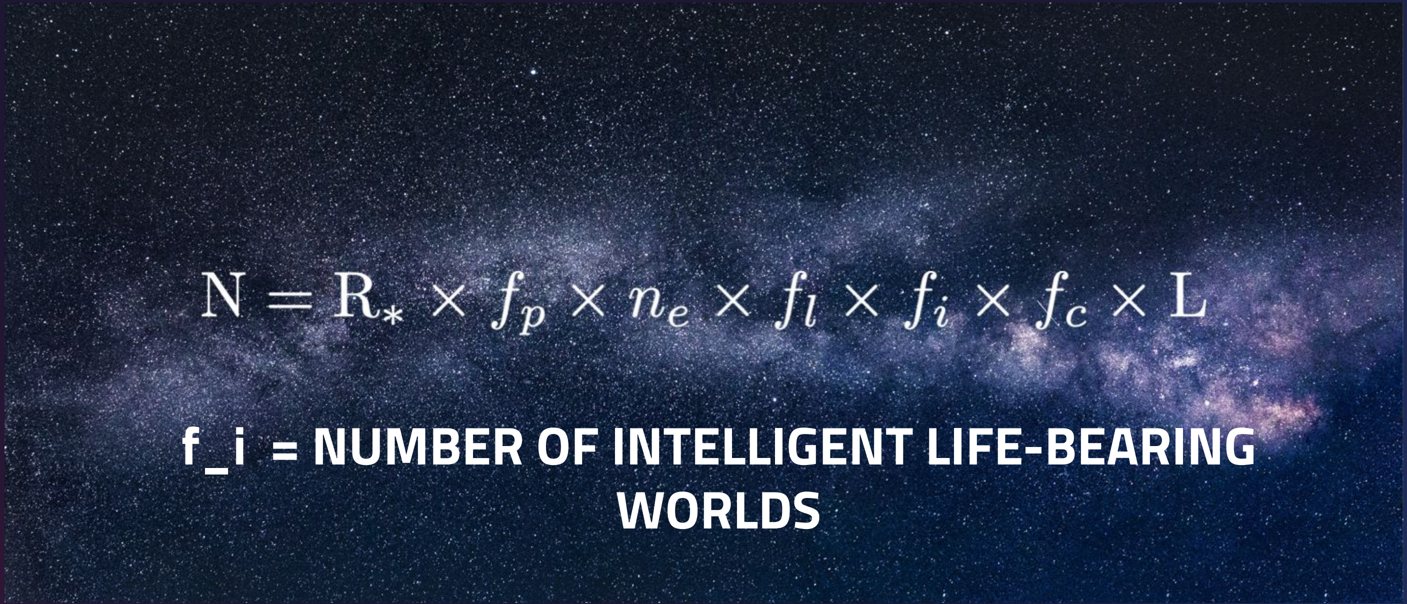


$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

**f_l = NUMBER OF HABITABLE WORLDS ON WHICH LIFE APPEARS**

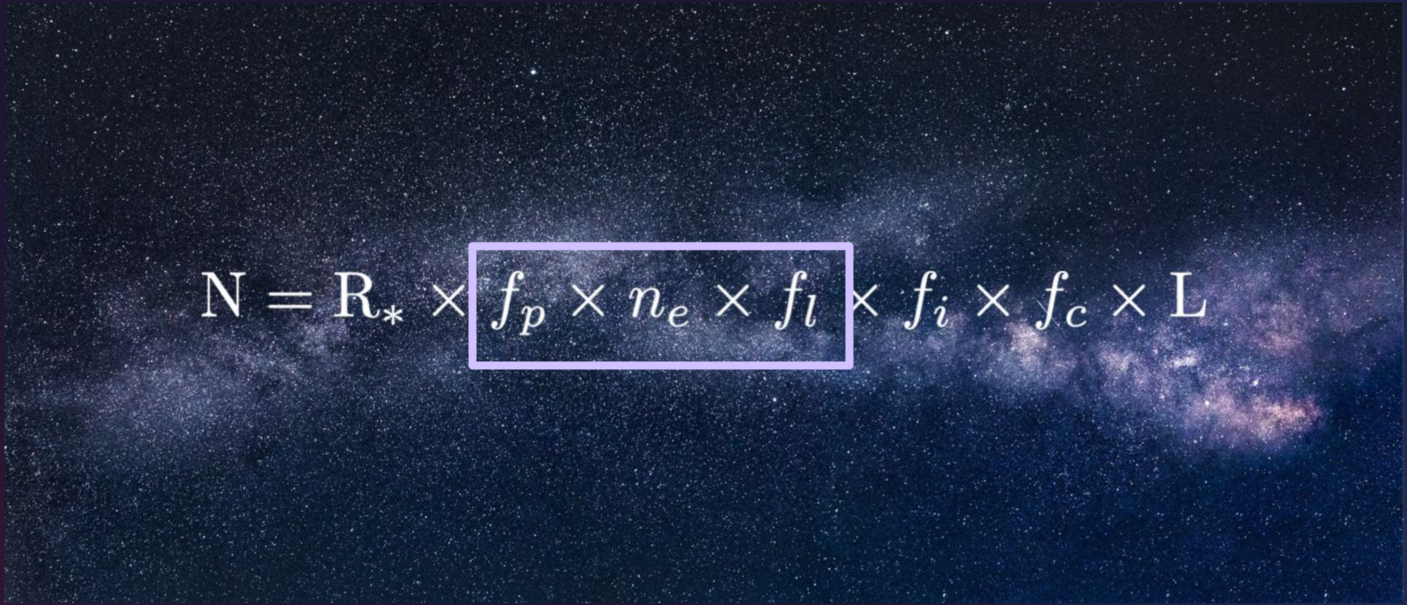
# THE BIG ANSWER:
# THE DRAKE EQUATION



# THE BIG ANSWER:
# THE DRAKE EQUATION

# THE BIG ANSWER:
# THE DRAKE EQUATION

# HOW CAN WE CONSTRAIN THIS?



# HOW CAN WE CONSTRAIN THIS?

$$f_p \times n_e \times f_l$$

PAST: WHEN DID PLANET FORMATION BEGIN IN THE UNIVERSE?

PRESENT: HOW CAN WE BETTER CONSTRAIN PLANETARY ATMOSPHERES?

FUTURE: HOW WILL WE BE ABLE TO TELL AN EXO-VENUS FROM AN EXO-EARTH?

# HOW CAN WE CONSTRAIN THIS?

$$f_p \times n_e \times f_l$$

**PAST: WHEN DID PLANET FORMATION BEGIN IN THE UNIVERSE?**

# THE SEARCH FOR EXOPLANETS AROUND METAL-POOR (ANCIENT) STARS WITH T(r)ESS (SEAMSTRESS)

Stars began to form soon after the Big Bang—but when did stars begin to have planets?

- ➔ What is the minimum metallicity for a planet to form?
- ➔ What kinds of planetary systems were they?
- ➔ Can an ancient star support life?

# WHERE DO WE BEGIN?

1. A large-scale transit survey
2. A large, overlapping sample of metal-poor stars

# WHAT SURVEYS ARE AVAILABLE?

# WHAT SURVEYS ARE AVAILABLE?

X

gaia

# WHAT SURVEYS ARE AVAILABLE?

X

# WHAT SURVEYS ARE AVAILABLE?

X

# WHAT SURVEYS ARE AVAILABLE?

X

gaia


SkyMapper

# WHAT SURVEYS ARE AVAILABLE?

X

# WHAT SURVEYS ARE AVAILABLE?

X

gaia

GALAH

SkyMapper

APOGEE

SDSS

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X

gaia

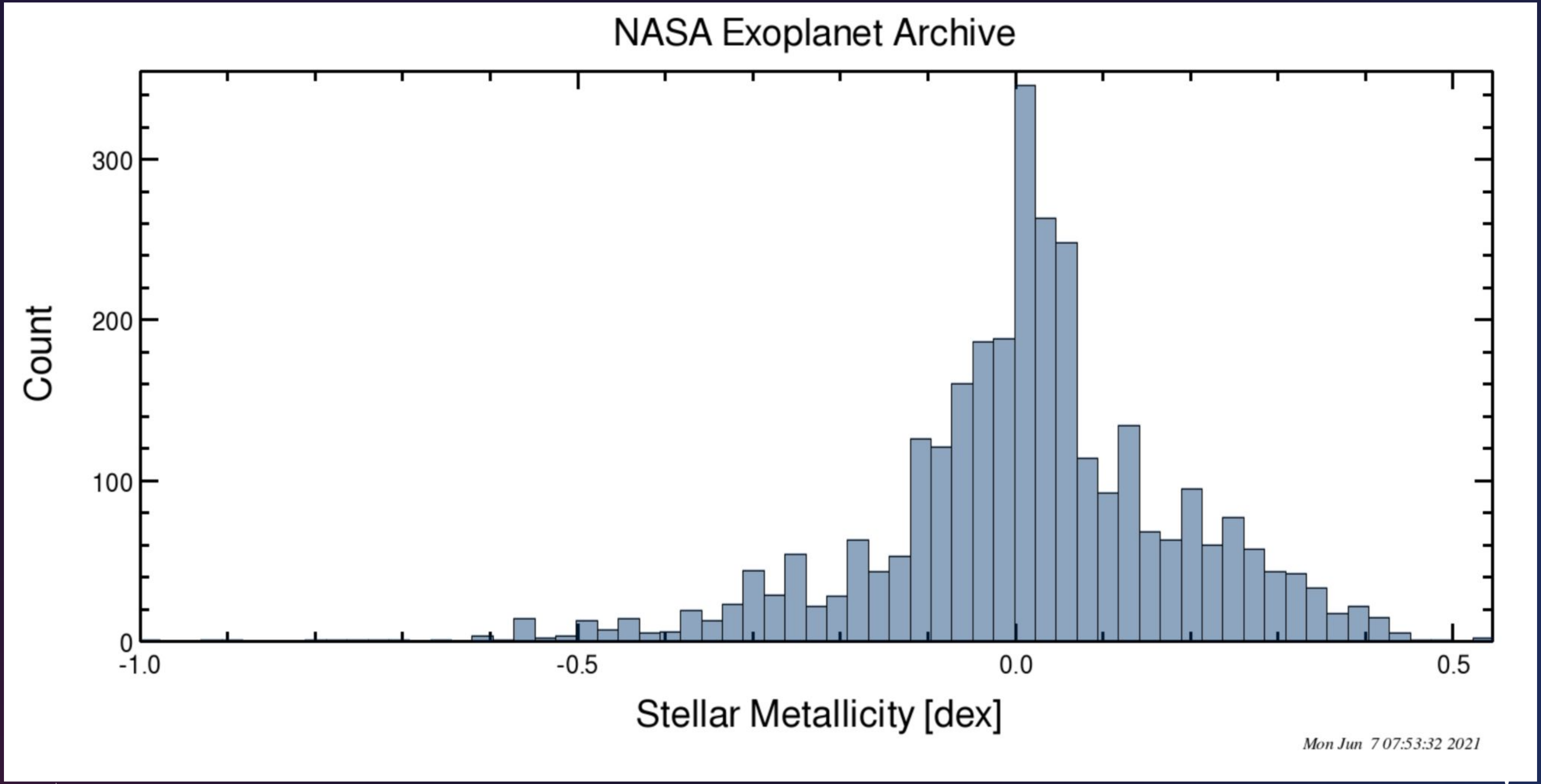
GALAH

SkyMapper

APOGEE

SDSS

# WHAT DATA ALREADY EXIST?



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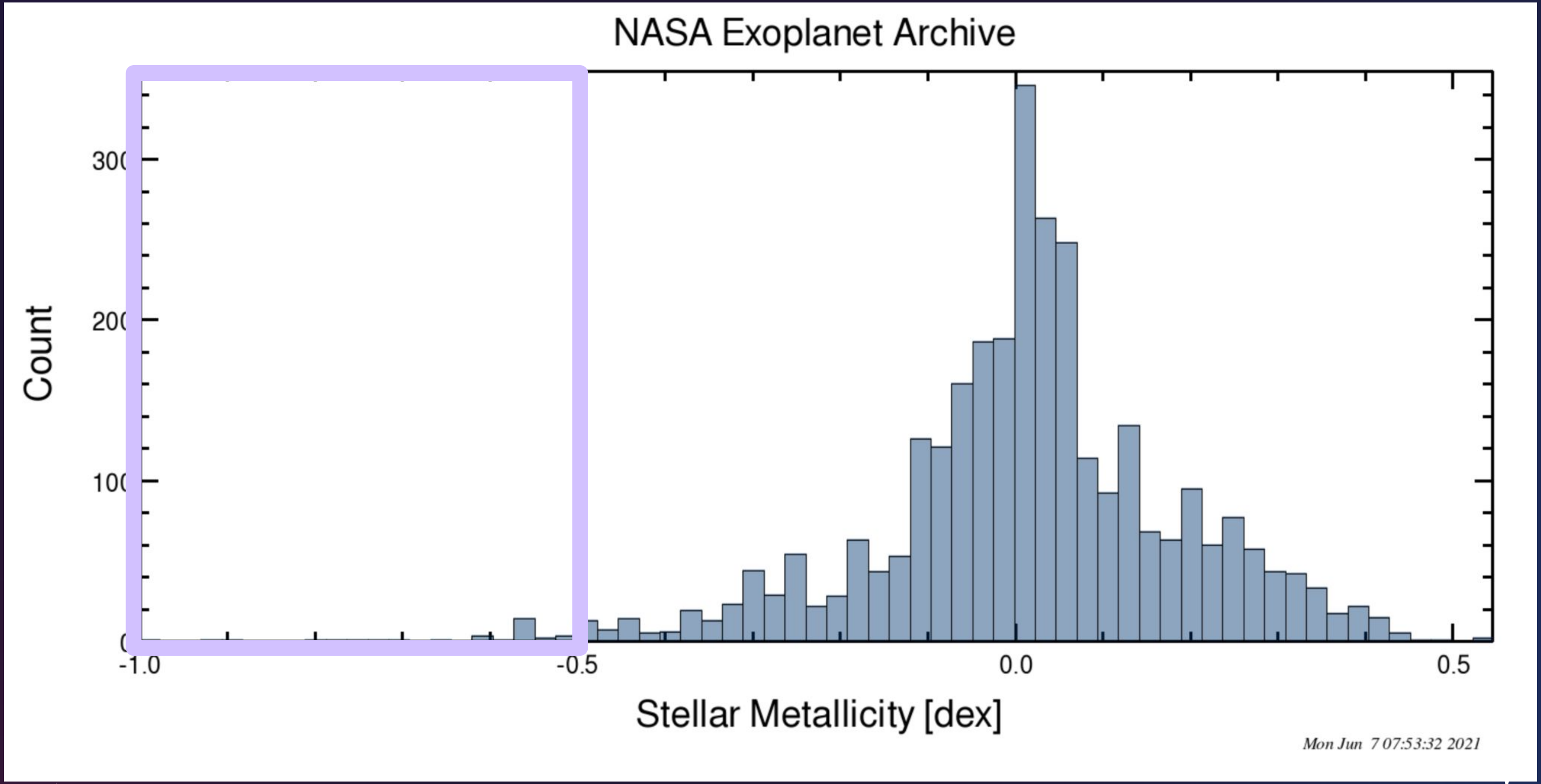

# THE SEAMSTRESS-SKYMAPPER PIPELINE

250,000,000 SkyMapper stars

75,000 metal-poor stars

28,000 TESS matches

3,200 TCEs

50 planet candidates*!

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50 planet candidates*!

*of which 28 remain

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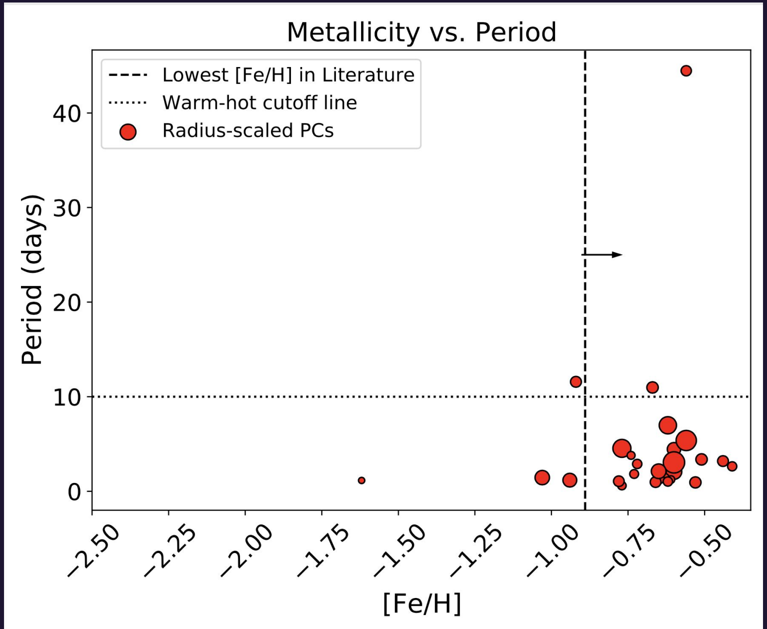
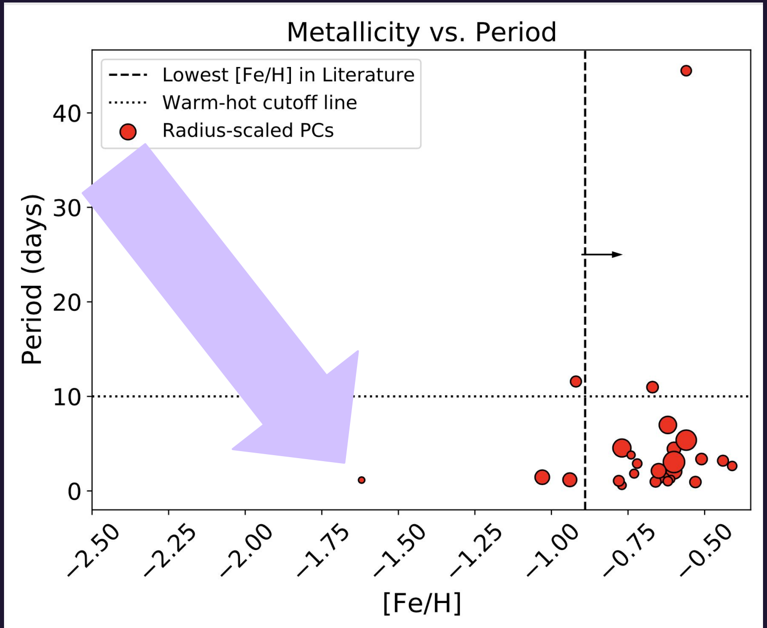


# THE SEAMSTRESS-SKYMAPPER PIPELINE

Period = 12 days
Mass ~ 10 M_earth
G star host



# IMPLICATIONS FOR THEORY

- We will, for the first time, be able to place empirical constraints on planet formation models at low metallicities
  - Low yield = models working as expected
  - Moderate yield = exceptions to models → chemical abundance dependence?
  - High yield = changes needed to models

# THE SEAMSTRESS-GAIA PIPELINE

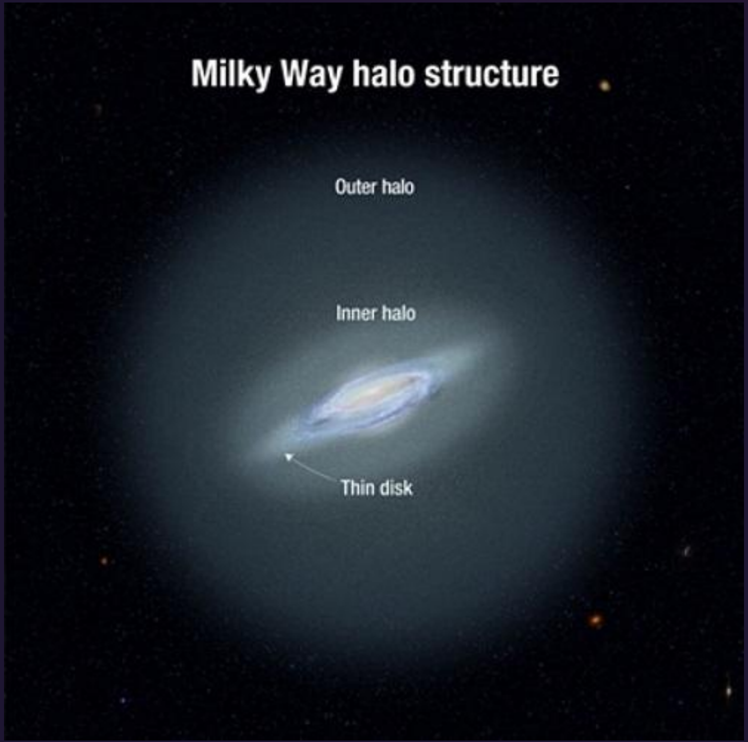
# THE SEAMSTRESS-GAIA PIPELINE


*heavy sample contamination by red giants

# NO PLANETS IN THE HALO?

The Milky Way's dual halo consists of the remnants of a large past merger (Gaia-Enceladus; inner halo) as well as remnants of the first dark-matter-dominated stellar systems (outer halo).

- Average metallicity: [Fe/H] = -2.2/-1.6 (outer/inner) (Carollo  et al. 2007)
- Empirical, galactic-population-based constraints on planet formation *for detectable (R_planet > 2 R_Earth) planets*
- Th/Eu cosmochronometry of metal-poor halo stars dates them at 10-12 billion years old



# OUR GALACTIC ORIGINS

$$f_p \times n_e \times f_l$$

PAST: WHEN DID PLANET* FORMATION BEGIN IN THE UNIVERSE?

- NEA says… "sometime after [Fe/H] = -1.0"
- SEAMSTRESS-SKYMAPPER says… "sometime after [Fe/H] = -1.6" (Rasmussen et al. 2021a)
- SEAMSTRESS-Gaia says… "2-4 billion years after the Big Bang" (Rasmussen et al. 2021b)

*TESS-detectable

WE ARE CONSTRAINING...

# PLANET FORMATION RATES IN THE EARLY UNIVERSE

THIS WILL TELL US...

# HOW LONG LIFE HAS EXISTED AND WHERE IN THE GALAXY TO FIND IT

# PRESENT:

$$f_p \times n_e \times f_l$$

HOW CAN WE BETTER CONSTRAIN PLANETARY ATMOSPHERES?

# HOW DO WE TELL IF A PLANET IS EARTH-LIKE?

**Before the biosignature*: How do we detect molecular species in planetary atmospheres?**

*the detection of a molecule or molecular pair which is generated by organic sources

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Before the biosignature: How do we detect molecular species in planetary atmospheres?

## High-Resolution Cross-Correlation Spectroscopy

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## High-Resolution Cross-Correlation Spectroscopy

→ The study of emitted or reflected light from an exoplanet

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→ A statistical comparison method
→ The study of emitted or reflected light from an exoplanet

# HOW DO WE TELL IF A PLANET IS EARTH-LIKE?

**Before the biosignature: How do we detect molecular species in planetary atmospheres?**

## High-Resolution Cross-Correlation Spectroscopy

→ Lots of data points in the spectrum
→ A statistical comparison method
→ The study of emitted or reflected light from an exoplanet

# WHAT ELSE DO WE NEED?
# DATA, METHODS, AND MODELS

High-Resolution Cross-Correlation Spectroscopy

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High-Resolution Cross-Correlation Spectroscopy

3D Atmospheric Models

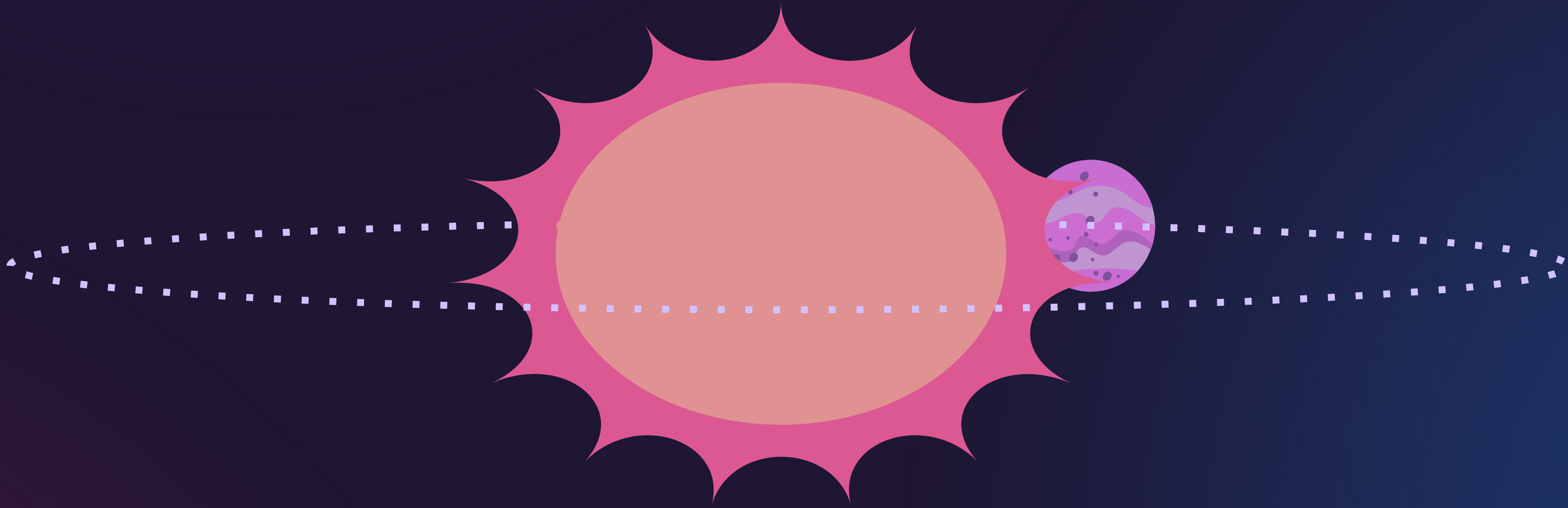
# WHAT ELSE DO WE NEED?
## DATA, METHODS, AND MODELS

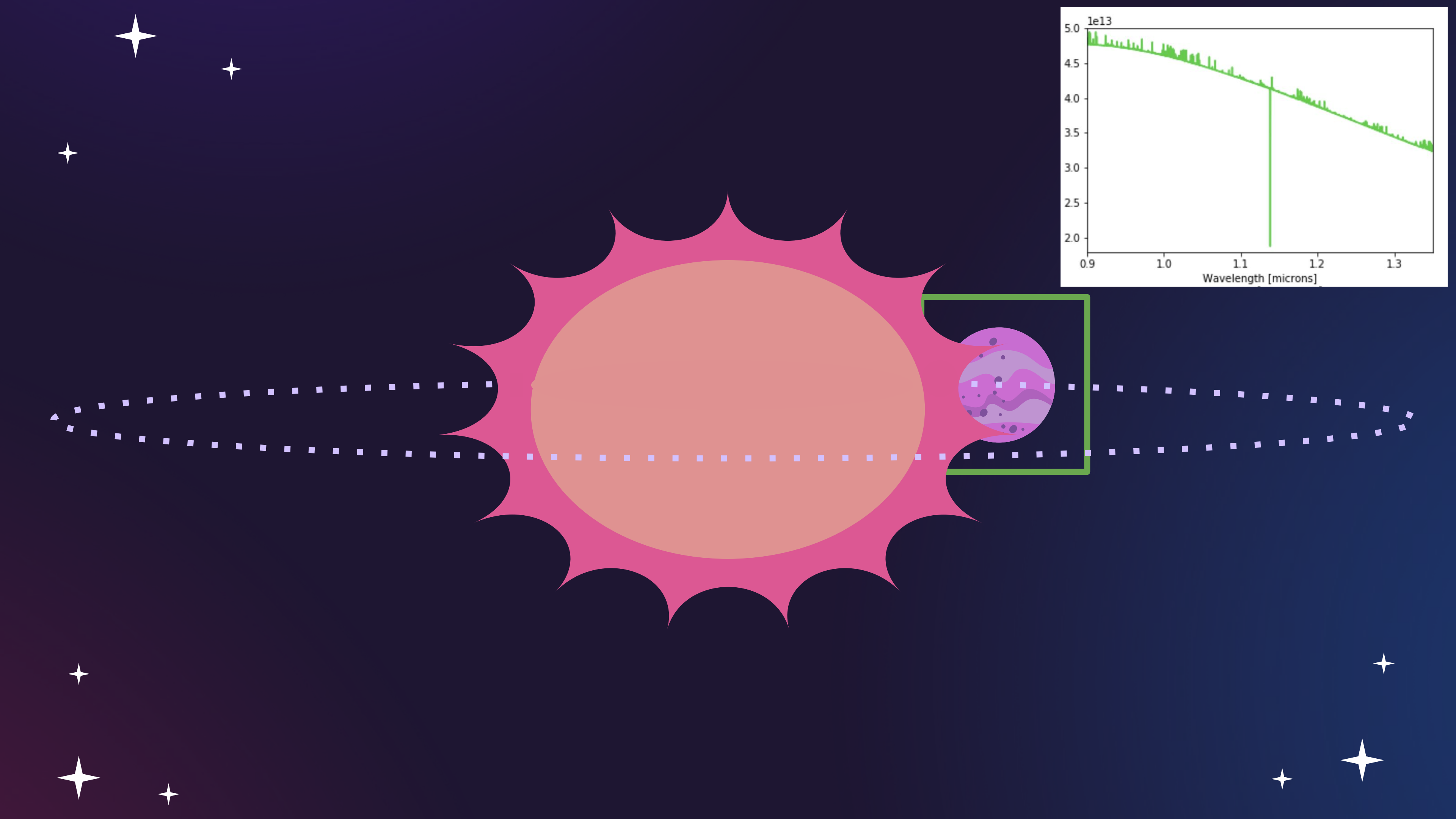
Multi-Epoch Observations

High-Resolution Cross-Correlation Spectroscopy

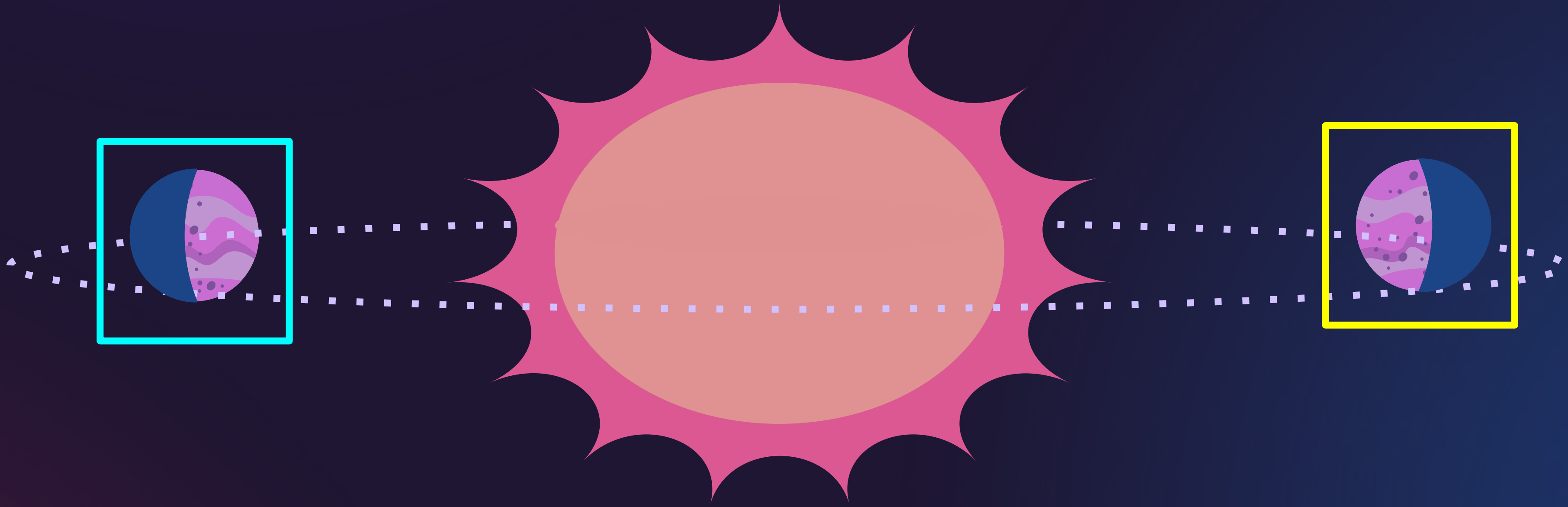
3D Atmospheric Models

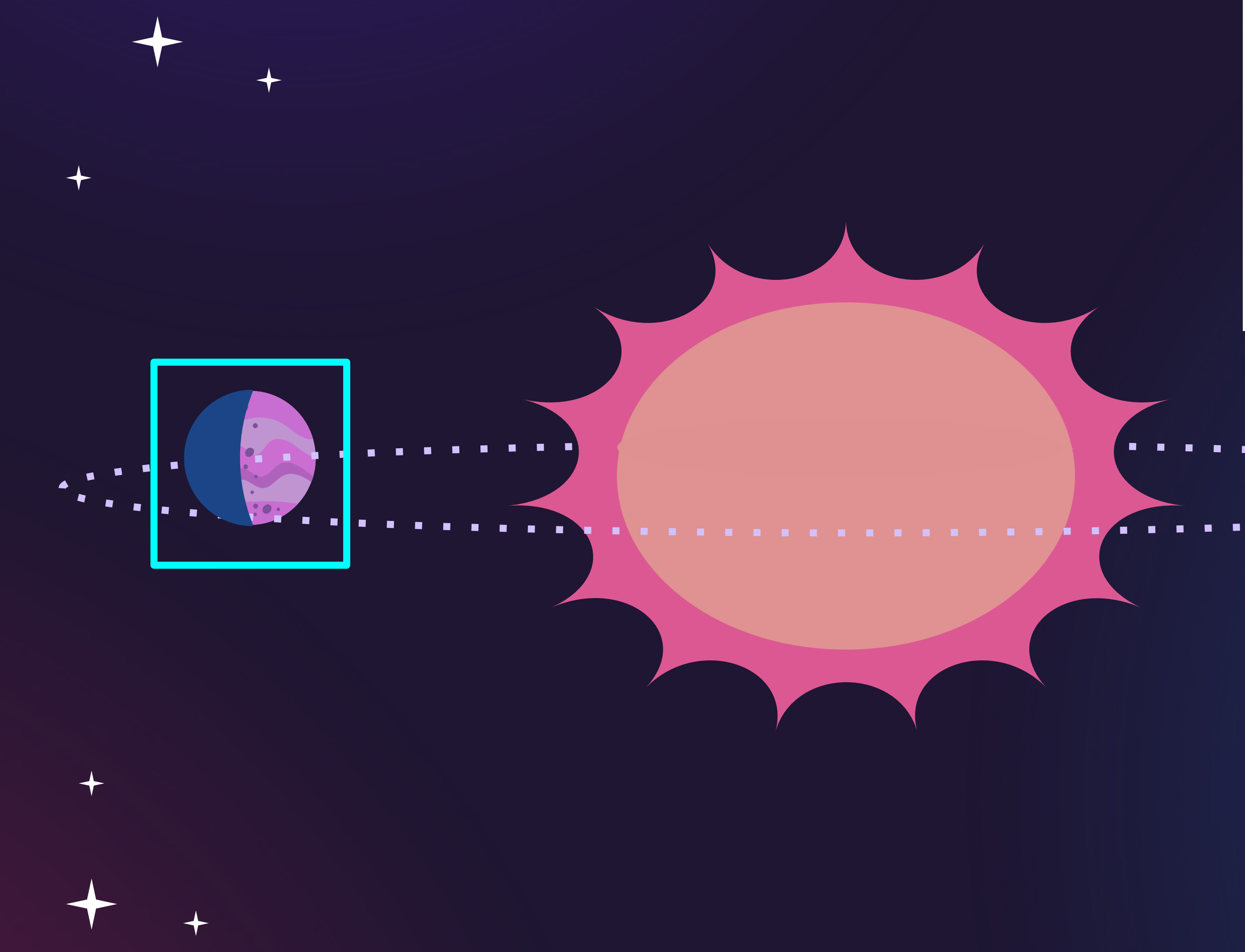
**Key Idea:** The planet's spectrum changes with phase

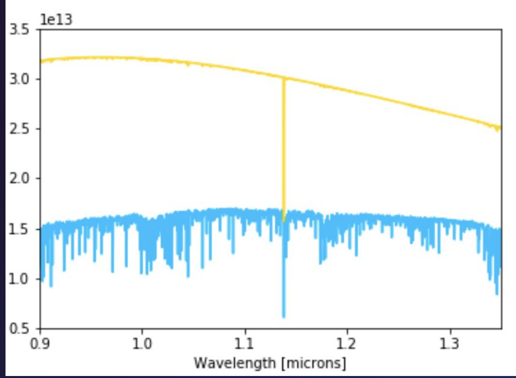



1e13
5.0
4.5
4.0
3.5
3.0
2.5
2.0
0.9
1.0
1.1
1.2
1.3
Wavelength [microns]

**Key Idea:** The planet's spectrum changes with phase



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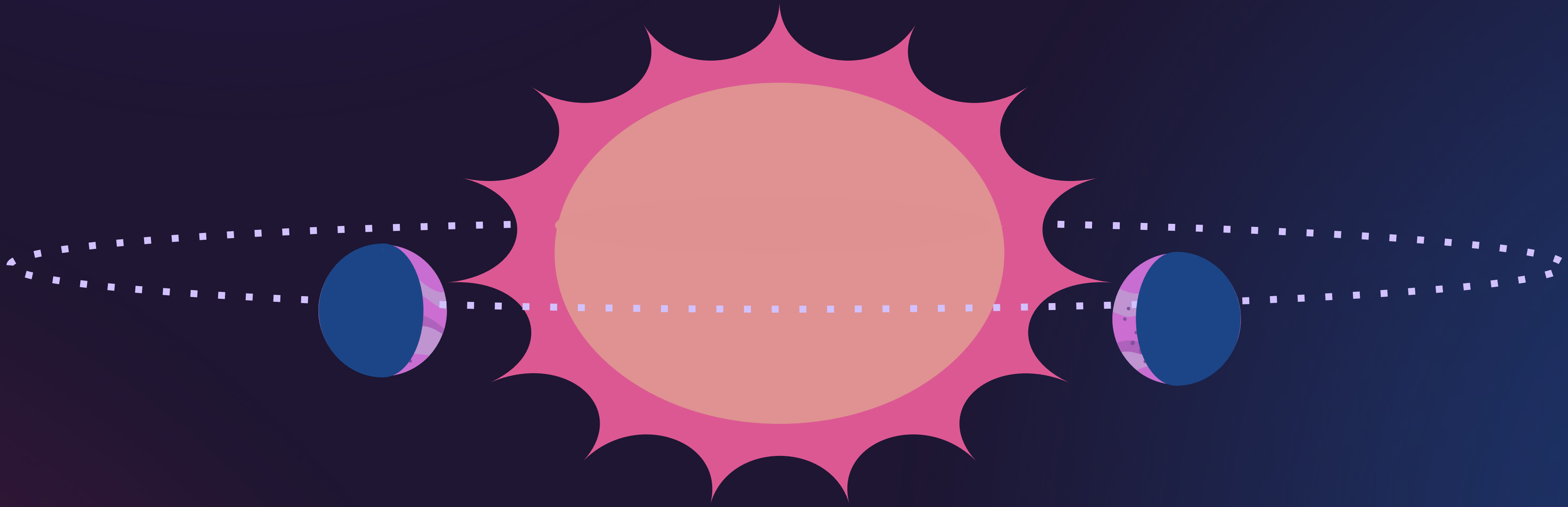

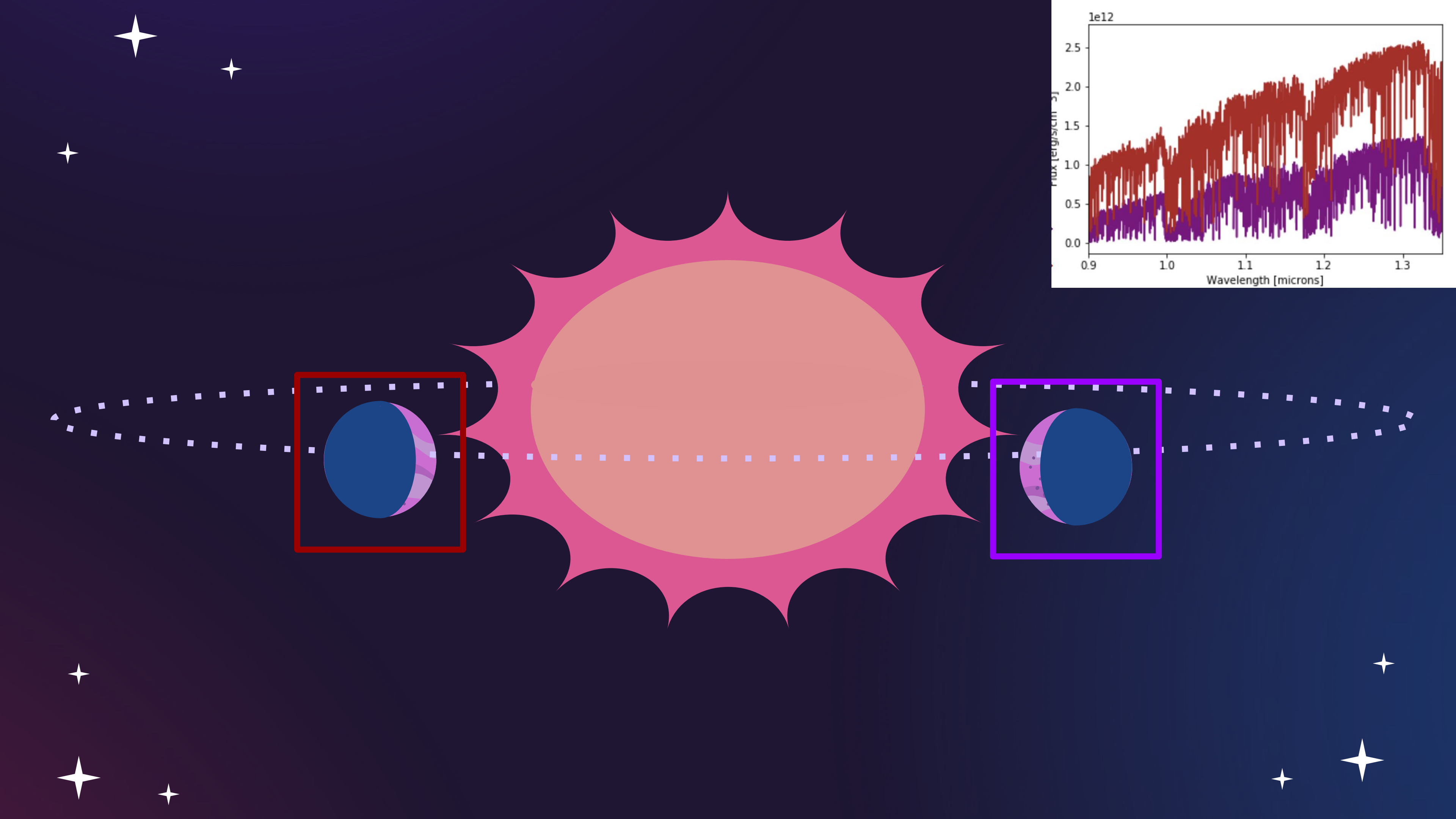
1e12
2.5
2.0
1.5
1.0
0.5
0.0
0.9
1.0
1.1
1.2
1.3
Wavelength [microns]

# PROCESS:

1. Collect multi-epoch spectra of planet
2. Extract the planet's signal from the Earth's atmosphere, and the star's signal
3. Cross-correlate the extracted data with the model
   a. Lockwood+ 2014 method
   b. Brogi & Line 2019 method

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} HYBRID METHOD

WARNING: JARGON AHEAD

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} **HYBRID METHOD**

1. Uses a highly customizable univariate spline function (`jifit`) for spectral normalization → this *improved the detection made in Beltz+ 2021 by* ***3 sigma***
2. Uses a variation of this spline function to fit out a smoothed median spectrum to eliminate tellurics and stellar lines *without relying on models → improves the detection made in Beltz+ 2021 by a total of* ***6.5 sigma***
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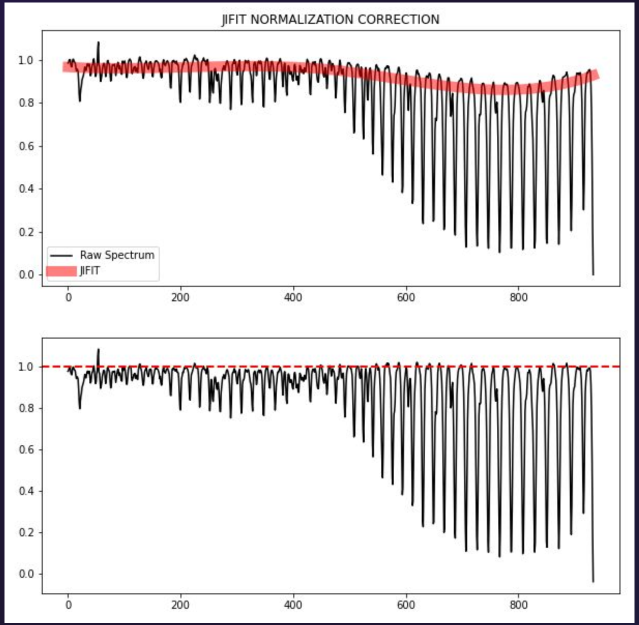
Rasmussen et al. 2021c

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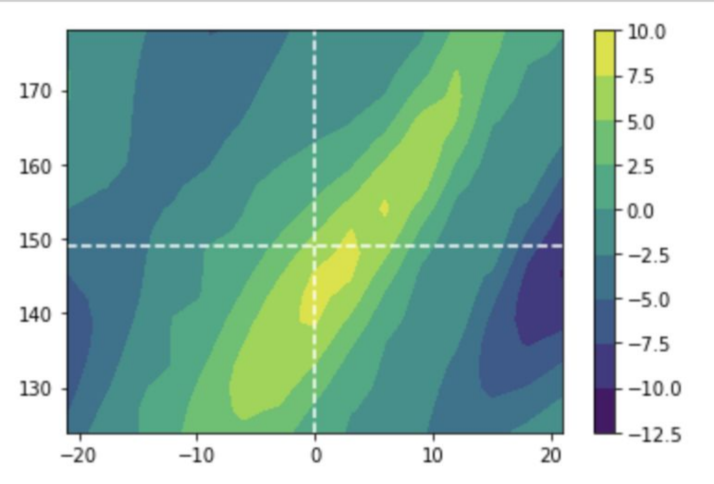
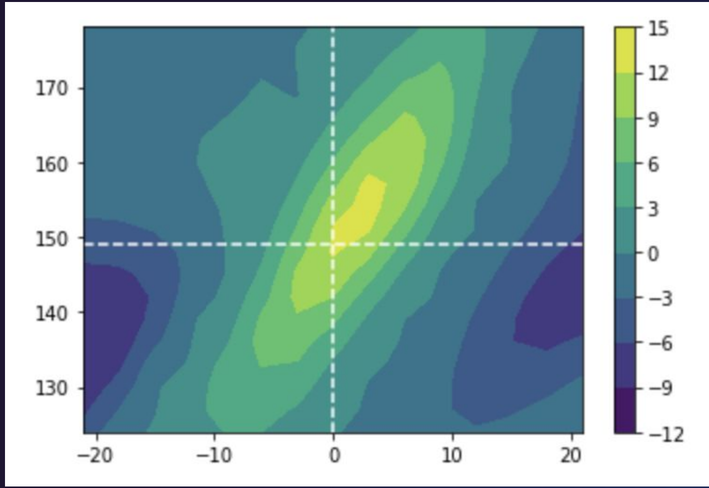
## BELTZ+2021 WITH JIFIT




## BELTZ+2021 WITH JIFIT AND RAHMAN SMOOTHING ROUTINE

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WE ARE ENABLING:

# THE CLEAREST AND MOST COHERENT PICTURES OF EXOPLANETS YET TAKEN

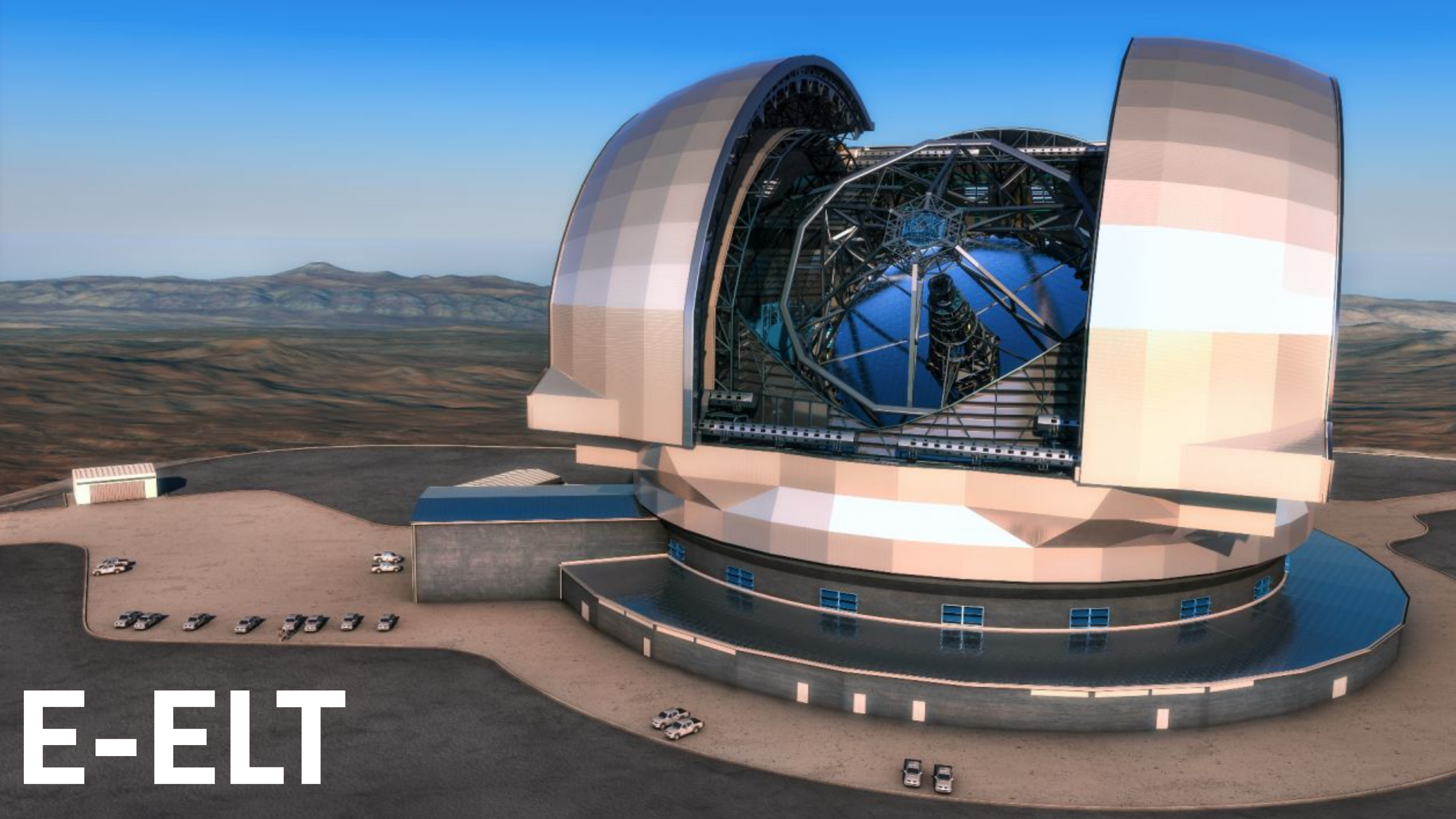
THIS WILL TELL US:

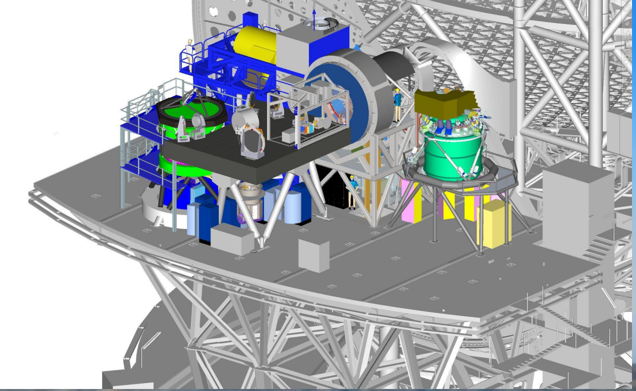
# COULD A GIVEN PLANET BE HABITABLE?

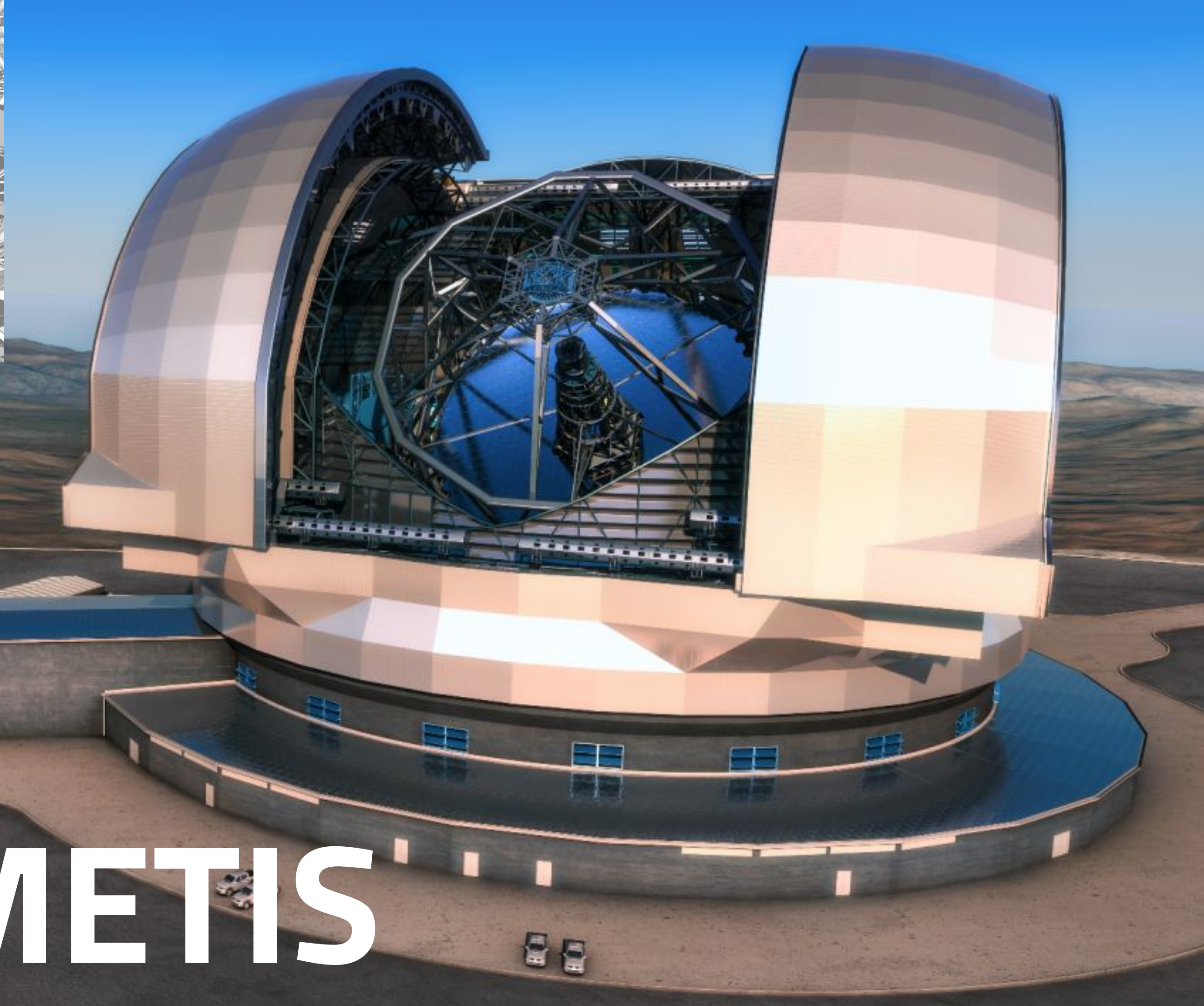
# FUTURE:

$$f_p \times n_e \times f_l$$

FUTURE: HOW WILL WE BE ABLE TO TELL AN EXO-VENUS FROM AN EXO-EARTH?


E-ELT



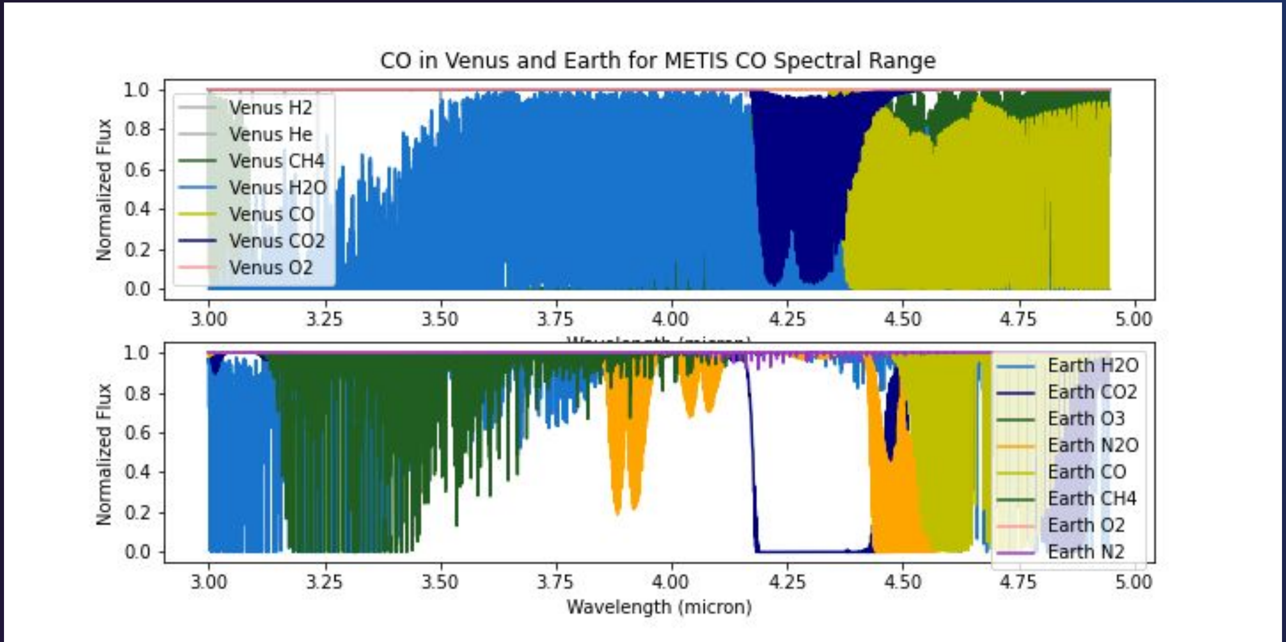


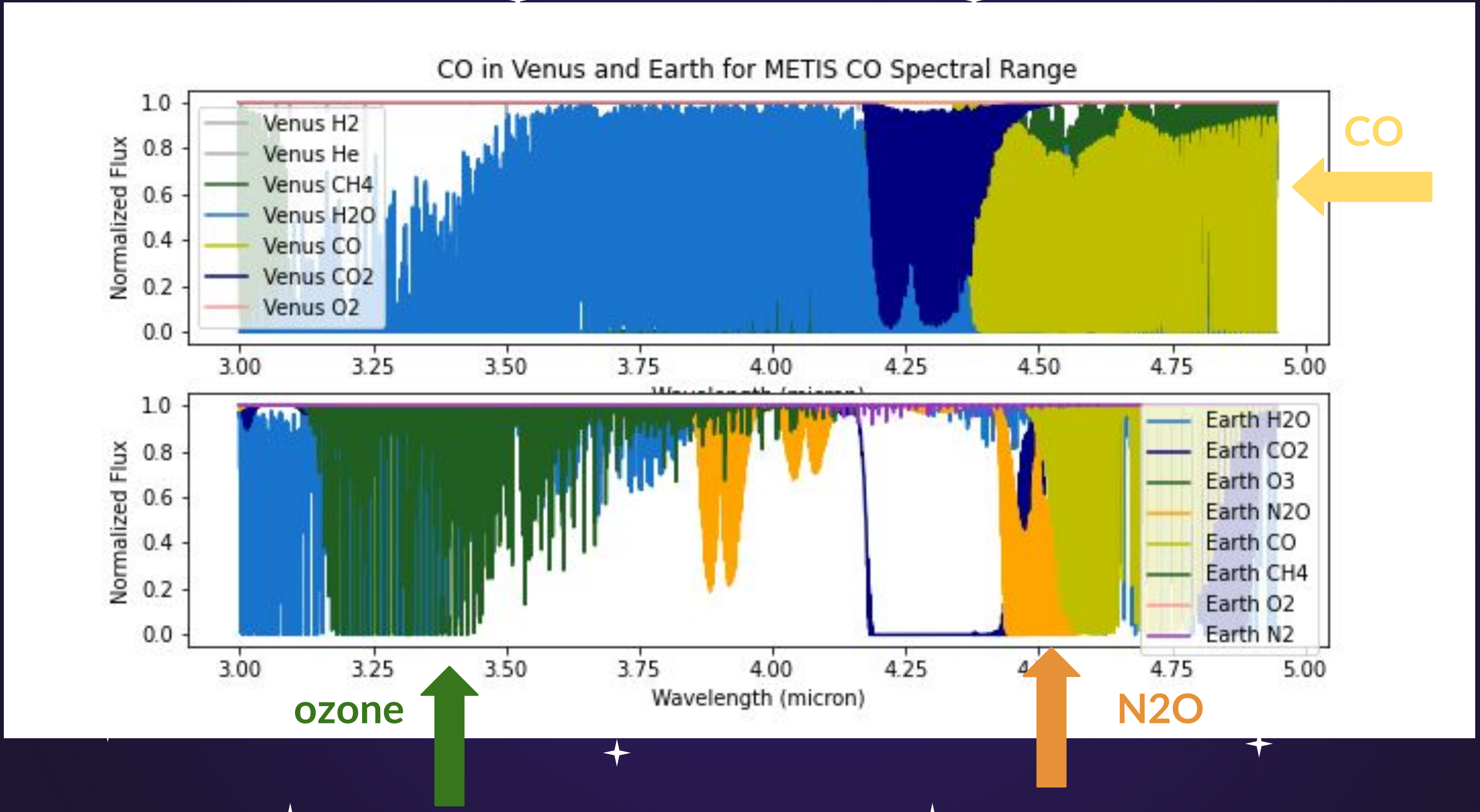
# E-ELT: METIS

**Source:** NASA Planetary Spectrum Generator

# VENUS

# EARTH



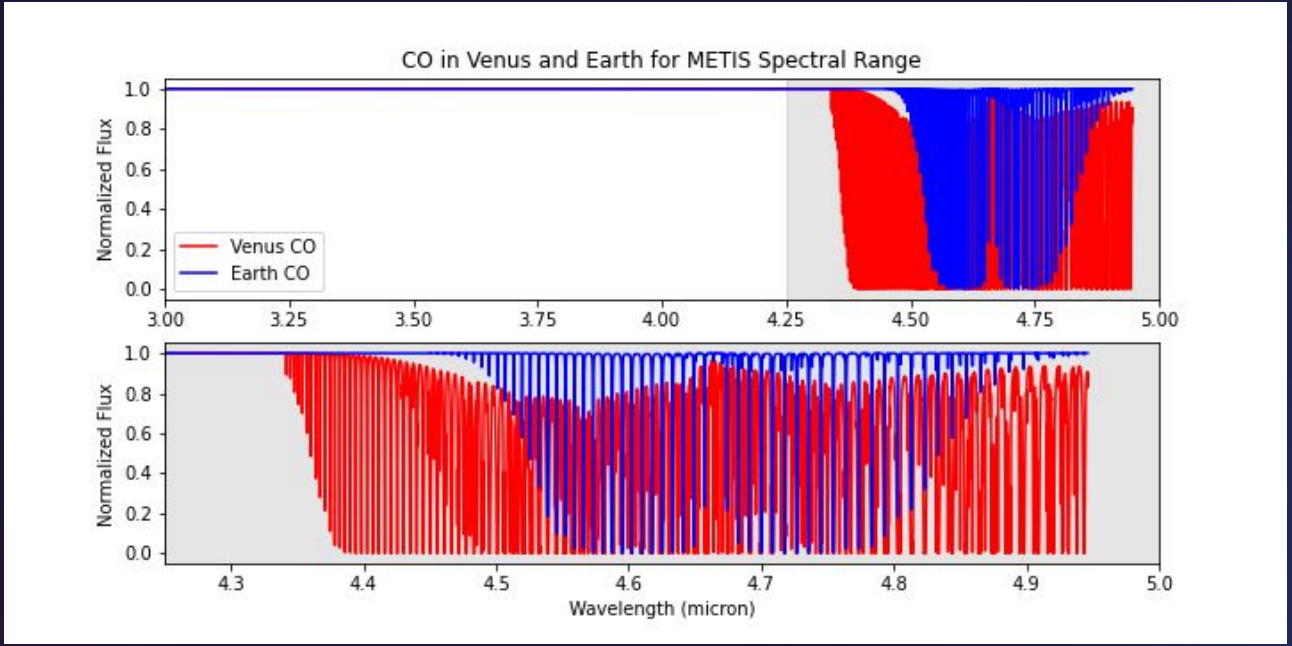

CO in Venus and Earth for METIS CO Spectral Range
Normalized Flux
Venus H2
Venus He
Venus CH4
Venus H2O
Venus CO
Venus CO2
Venus O2
Earth H2O
Earth CO2
Earth O3
Earth N2O
Earth CO
Earth CH4
Earth O2
Earth N2
Wavelength (micron)
CO
ozone
N2O

# LET’S TALK ABOUT CO:

CO can be considered an **anti-biosignature** due to the difficulty of creating life* when it is present in high amounts in the atmosphere (Wang 2015)

*as far as we know!

# LET'S TALK ABOUT CO:



VENUS CO: 17 PPM

EARTH CO: 0.15 PPM

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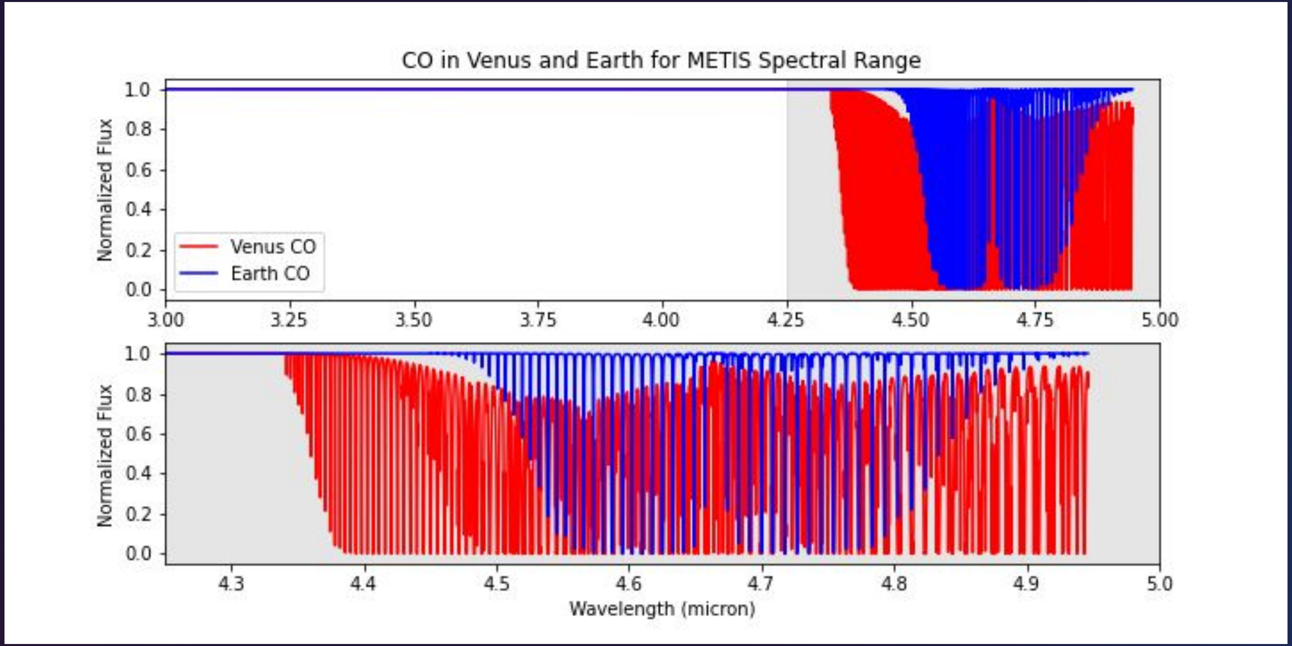

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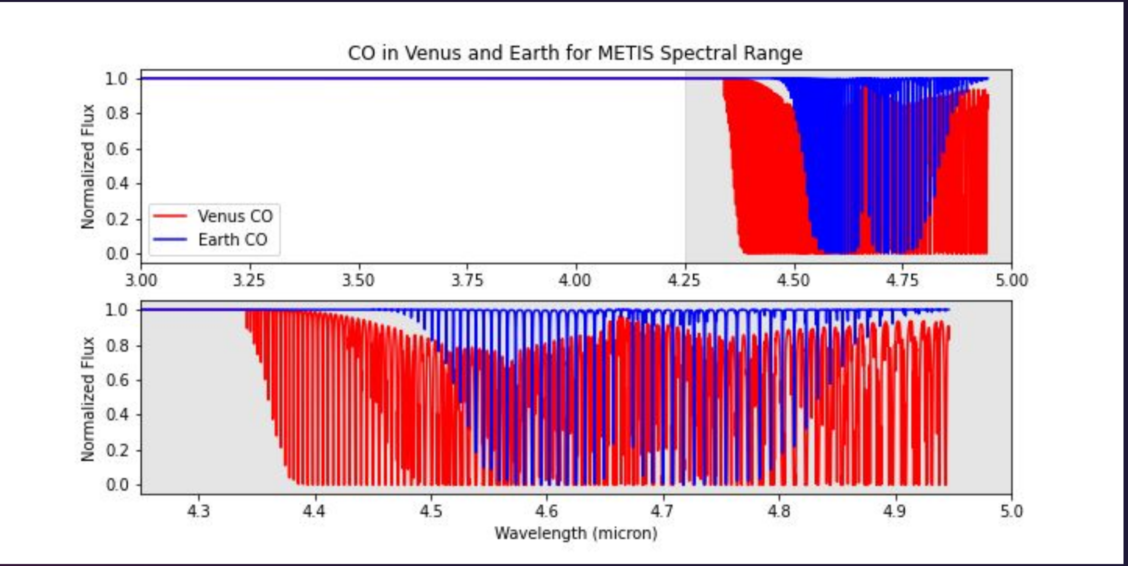


Different atmospheres → different CO band structure

Venus's CO band is wider, and the structure is "doubled" in some places

# HOW CAN WE TELL THE DIFFERENCE?

**Autocorrelation:** a statistical comparison of a spectrum against itself; i.e. a “perfect match” scenario

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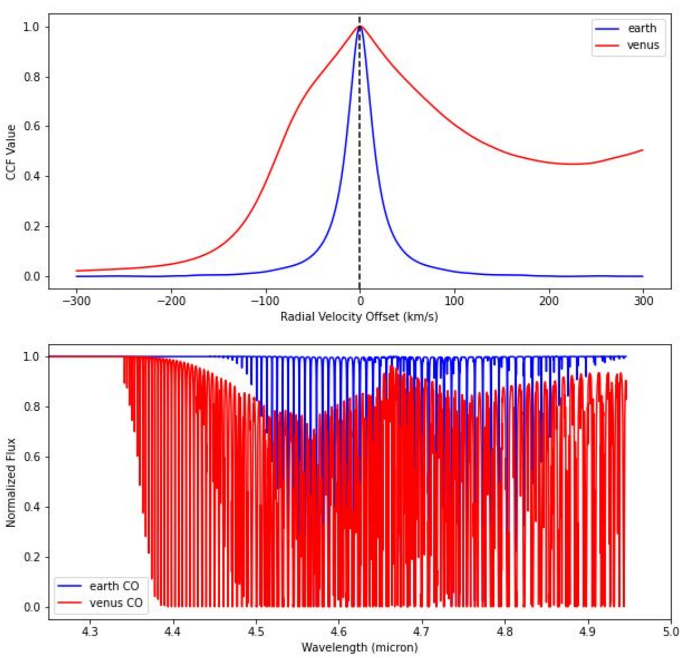
**Autocorrelation:** a statistical comparison of a spectrum against itself; i.e. a “perfect match” scenario

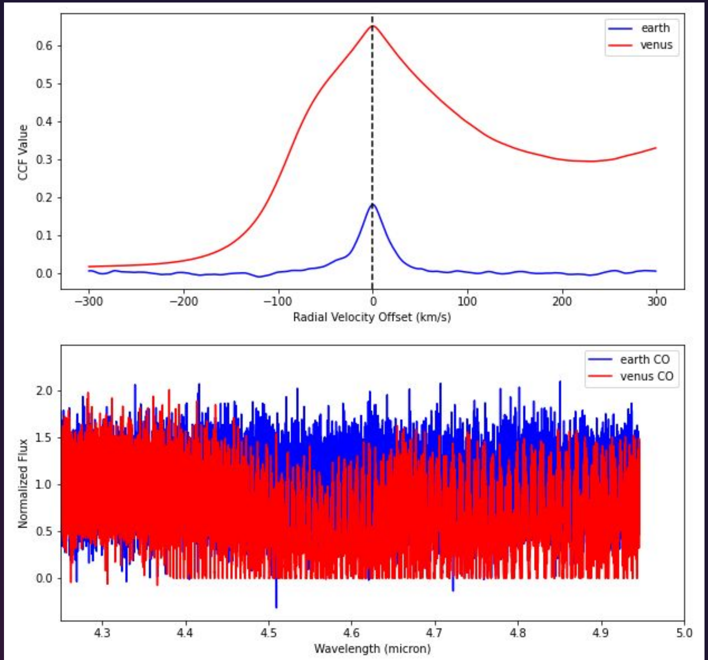
**Key Idea:** Sufficiently asymmetric spectra can have different autocorrelation functions

# HOW CAN WE TELL THE DIFFERENCE?



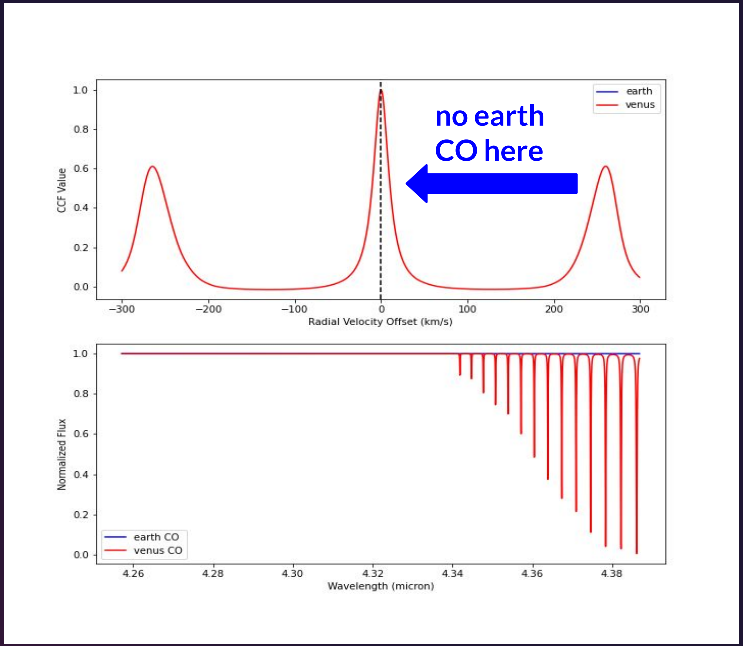

While Earth's CO band has a symmetric autocorrelation in the METIS range, Venus has an unusual shape → we can use this!

# HOW CAN WE TELL THE DIFFERENCE?




Even when we inject noise into the simulation, the pattern persists.

# HOW CAN WE TELL THE DIFFERENCE?



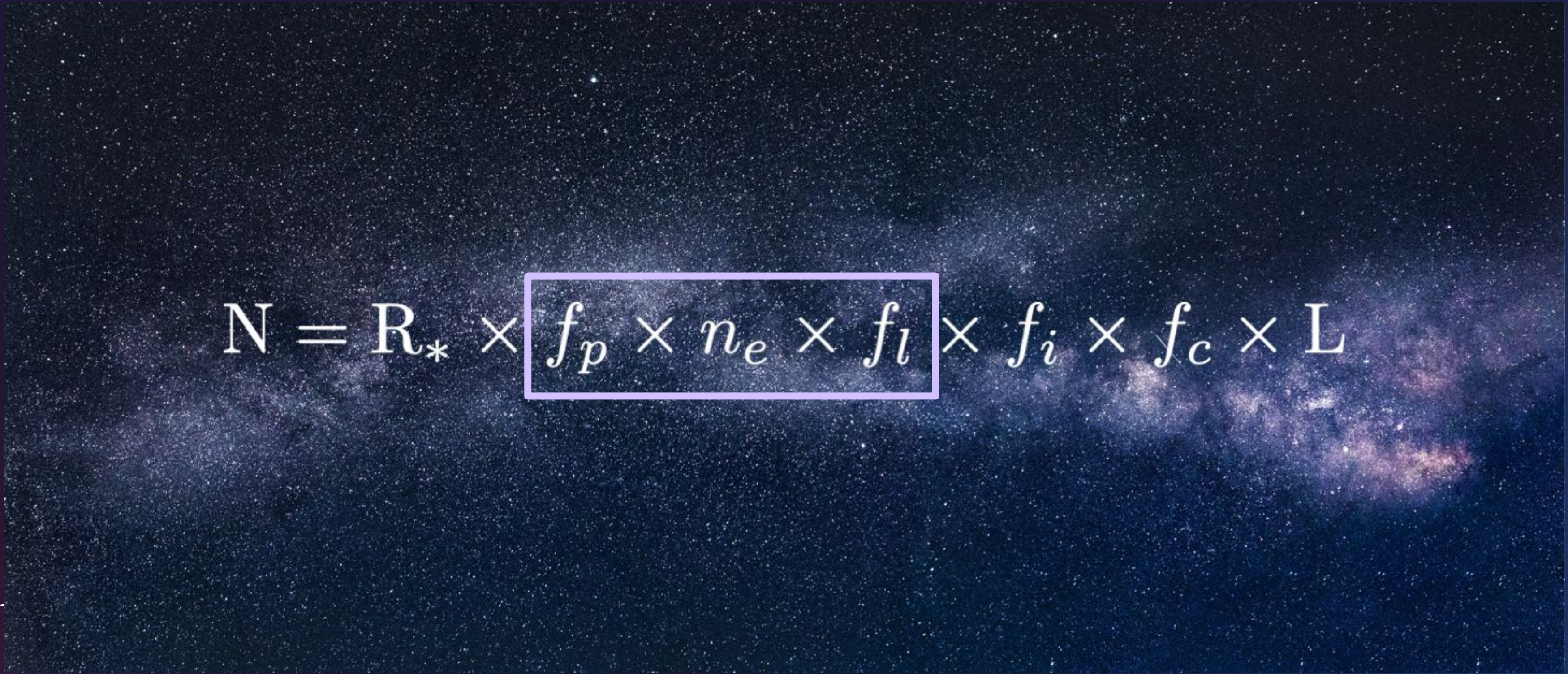

We can also iterate over wavelength ranges within the METIS range to constrain possible CO band structures.

WE ARE DIFFERENTIATING BETWEEN...

# EXO-EARTHS AND EXO-VENUSES USING THE CO ANTI-BIOSIGNATURE

THIS WILL TELL US...

# CAN LIFE DEVELOP ON A GIVEN PLANET?



$$N = R_* \times f_p \times n_e \times f_l \times f_i \times f_c \times L$$

# IN CONCLUSION…

1. CONSTRAINING PLANETARY LIFESPANS
2. IMPROVING OUR ABILITY TO CHARACTERIZE EXO-EARTHS
3. IDENTIFYING UNINHABITABLE WORLDS

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email: kcrasmus@umich.edu | kaitlinrasmussen.com | @toomanyspectra

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Josh Simon
Johanna Teske
Josh Pepper
Anna Frebel
Sara Seager
Ani Chiti
Sam Quinn
Jason Dittman
Fahin Rahman

**HRCCS Collaborators:**
Emily Rauscher
Hayley Beltz
Eliza Kempton
John Monnier
Michael Meyers
Matej Malik
Fahin Rahman
Alex Ji

**Anti-biosignatures Collaborators:**
Jayne Birkby
Sophia Vaughan
Matej Malik

# IN CONCLUSION…

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