THE BIG QUESTION: ARE WE ALONE?
THE BIG ANSWER: 
THE DRAKE EQUATION

\[ N = R_\ast \times f_p \times n_e \times f_l \times f_i \times f_c \times L \]
THE BIG ANSWER:
THE DRAKE EQUATION

\[ N = R_\star \times f_p \times n_e \times f_i \times f_l \times f_c \times L \]

\( N = \text{NUMBER OF ADVANCED CIVILIZATIONS IN THE MILKY WAY} \)
THE BIG ANSWER: THE DRAKE EQUATION

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

\[ R^* = \text{STAR FORMATION RATE} \]
THE BIG ANSWER: THE DRAKE EQUATION

\[ N = R_\star \times f_p \times n_e \times f_l \times f_i \times f_c \times L \]

\[ f_p = \text{PLANET FORMATION RATE} \]
THE BIG ANSWER: THE DRAKE EQUATION

\[ N = R_s \times f_p \times n_e \times f_l \times f_i \times f_c \times L \]

\[ n_e = \text{NUMBER OF HABITABLE WORLDS PER STAR} \]
THE BIG ANSWER:
THE DRAKE EQUATION

\[ N = R_\ast \times f_p \times n_e \times f_i \times f_i \times f_c \times L \]

f_l = NUMBER OF HABITABLE WORLDS ON WHICH LIFE APPEARS
THE BIG ANSWER:
THE DRAKE EQUATION

\[ N = R_\ast \times f_p \times n_e \times f_l \times f_i \times f_c \times L \]

\(f_i\) = NUMBER OF INTELLIGENT LIFE-BEARING WORLDS
THE BIG ANSWER:  
THE DRAKE EQUATION

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

\[ f_c = \text{NUMBER OF INTELLIGENT, TECHNOLOGICAL CIVILIZATIONS} \]
THE BIG ANSWER:
THE DRAKE EQUATION

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

\[ L = \text{AVERAGE LENGTH OF A TECHNOLOGICALLY CAPABLE CIVILIZATION} \]
HOW CAN WE CONSTRAIN THIS?

\[ N = R_\star \times f_p \times n_e \times f_l \times f_i \times f_c \times L \]
HOW CAN WE CONSTRAIN THIS?

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

HOW CAN WE CONSTRAIN THIS?

\[ f_p \times n_e \times f_l \]
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?
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WHAT SURVEYS ARE AVAILABLE?
WHAT DATA ALREADY EXIST?
WHAT DATA ALREADY EXIST?
THE SEAMSTRESS-SKYMAPPER PIPELINE

- 250,000,000 SkyMapper stars
- 75,000 metal-poor stars
- 28,000 TESS matches
- 3,200 TCEs
- 50 planet candidates*!
THE SEAMSTRESS-SKYMAPPER PIPELINE

250,000,000 SkyMapper stars

75,000 metal-poor stars

28,000 TESS matches

3,200 TCEs

50 planet candidates*

*of which 28 remain
THE SEAMSTRESS-SKYMAPPER PIPELINE

Metallicity vs. Period

- Lowest [Fe/H] in Literature
- Warm-hot cutoff line
- Radius-scaled PCs

Period (days) vs. [Fe/H]
THE SEAMSTRESS-SKYMAPPER PIPELINE

Period = 12 days
Mass ~ 10 M_{\text{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

1,000,000,000 Gaia stars
1,000,000 halo stars
4,000 TESS matches
700 TCEs
0 planet candidates*!
THE SEAMSTRESS-GAIA PIPELINE

1,000,000,000 Gaia stars

1,000,000 halo stars

4,000 TESS matches

2,000 TCEs

0 planet candidates*

*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: $[\text{Fe/H}] = -2.2/-1.6$ (outer/inner) (Carollo et al. 2007)
- Empirical, galactic-population-based constraints on planet formation for detectable ($R_{\text{planet}} > 2 R_{\text{Earth}}$) planets
- Th/Eu cosmochronometry of metal-poor halo stars dates them at 10-12 billion years old
OUR GALACTIC ORIGINS

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

- NEA says... “sometime after $[\text{Fe/H}] = -1.0$”
- SEAMSTRESS-SKYMAPPER says... “sometime after $[\text{Fe/H}] = -1.6$” (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:

 HOW CAN WE BETTER CONSTRAIN PLANETARY ATMOSPHERES?

\[ f_p \times n_e \times f_l \]
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
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
HOW DO WE TELL IF A PLANET IS EARTH-LIKE?

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→ The study of emitted or reflected light from an exoplanet
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High-Resolution Cross-Correlation Spectroscopy

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

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
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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
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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
3. Each spectrum in the series is cross-correlated with a 3D model of the exact phase of observation, leading to highly phase-sensitive results

WARNING: JARGON AHEAD
PROCESS:

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\textit{Rasmussen et al. 2021c}
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THE CLEAREST AND MOST COHERENT PICTURES OF EXOPLANETS YET TAKEN

THIS WILL TELL US:

COULD A GIVEN PLANET BE HABITABLE?
FUTURE:

FUTURE: HOW WILL WE BE ABLE TO TELL AN EXO-VENUS FROM AN EXO-EARTH?
E-ELT: METIS
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:
LET’S TALK ABOUT CO:

VENUS CO: 17 PPM
EARTH CO: 0.15 PPM
LET’S TALK ABOUT CO:

VENUS CO: 17 PPM
EARTH CO: 0.15 PPM

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
HOW CAN WE TELL THE DIFFERENCE?

**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
IN CONCLUSION...

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IN CONCLUSION...

1. CONSTRAINING PLANETARY LIFESPANS
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