# Comparing the Evolution of Earth-like Exoplanets Orbiting FGKM Stars: An Information Theory Approach

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Planetary Science Informatics & Analytics
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# Motivation

Search for life in the universe limited by

Data

Difficult science

- What makes a planet habitable?
- How do we know if it hosts life?

Image credit: NASA

# Motivation

Search for life in the universe limited by:

~~Data~~ Not anymore!

Difficult science

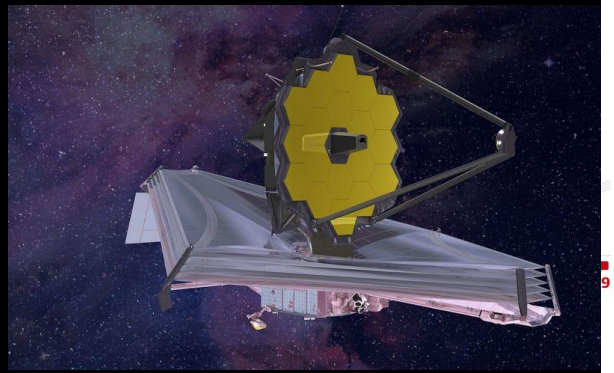
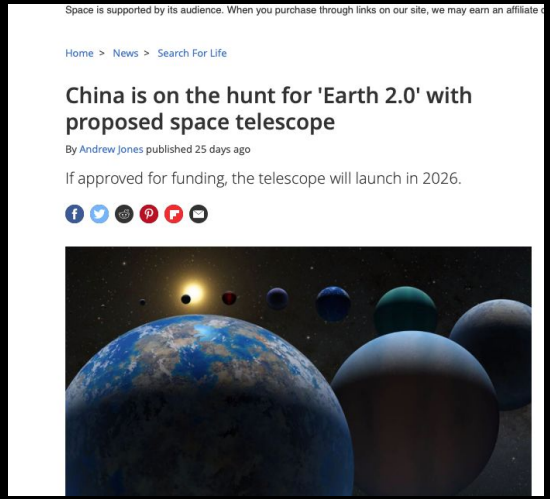


Image credit: NASA

**The telescope big enough to spot signs of alien life on other planets**

Engineers are about to blast away the top of a Chilean mountain to create a site for the European Extremely Large Telescope. It will allow us, for the first time, to directly observe planets outside the solar system

An artist's impression of the European Extremely Large Telescope (E-ELT).



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Home > News > Search For Life

**China is on the hunt for 'Earth 2.0' with proposed space telescope**

By Andrew Jones published 25 days ago

If approved for funding, the telescope will launch in 2026.

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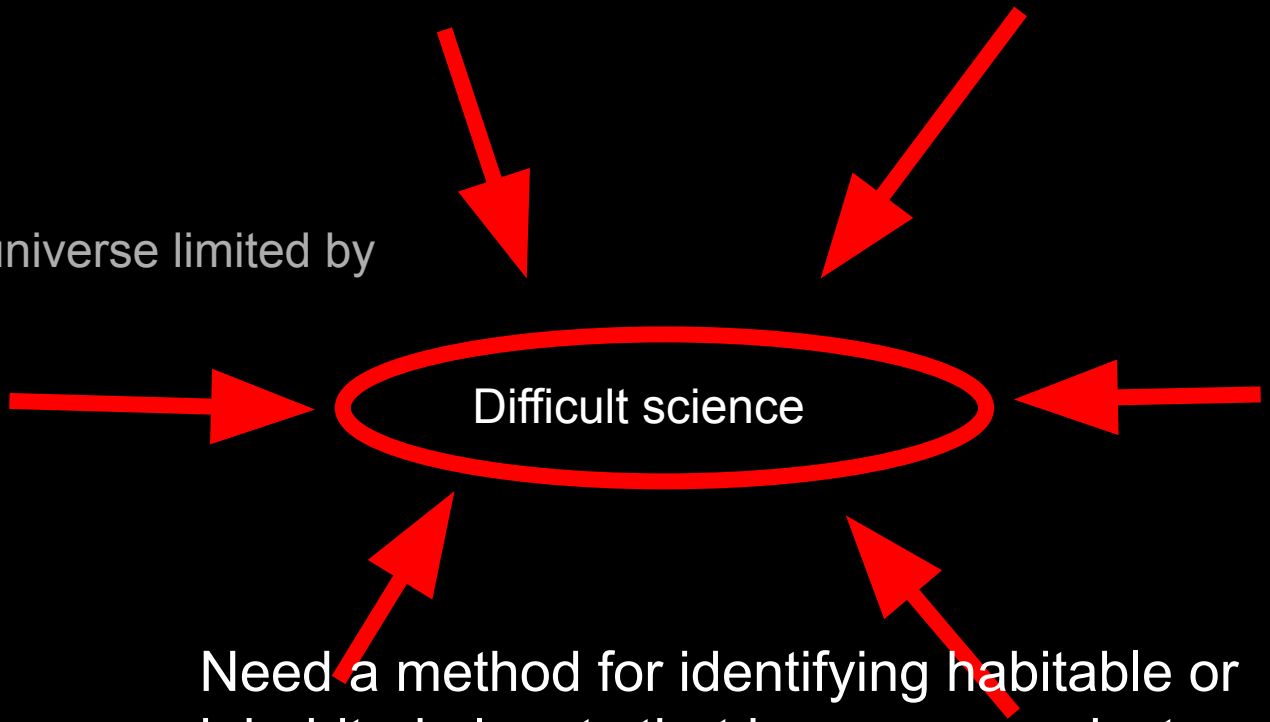


Need a method for identifying habitable or inhabited planets that bypasses conjecture

# Difficult Science

- Inner edge of habitable zone?
- Signs of habitability: water (liquid solvent), base for chemistry (carbon, silicates?)
- Has the atmosphere been stable enough to develop life? Protective magnetic field, plate tectonics, asteroid collisions?
- Biosignature: out-of-equilibrium chemistry (e.g. methane + ozone, methane + $O_2$) or geophysical source?

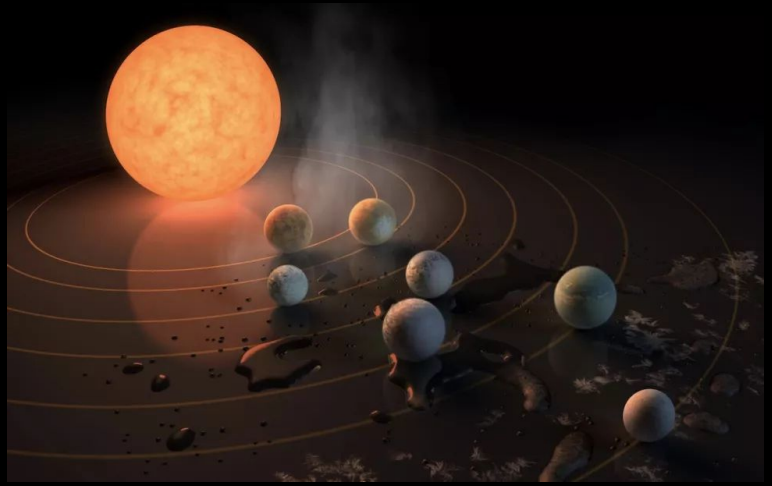

Image credit: NASA/JPL-Caltech

Minimize input knowledge looking for habitable or inhabited planets

# Outline

- Motivation & Introduction
- Information theory of spectra
- Importance of Earth in other contexts
- Results
  - Earth through the ages
  - $D_{JS}$ density traces biosignatures
- Conclusions

# Jensen-Shannon Divergence

Modal fraction:

$$p_\nu = \frac{D_\nu}{\sum_\nu D_\nu}$$

Transit depth at wavenumber v

- Strength of signal at a particular wavemode
- Probability mass function
- Introduced by Gleiser & Stamatopoulos 2012 [arXiv:1111.5597v3]

# Jensen-Shannon Divergence

Modal fraction

$$p_\nu = \frac{D_\nu}{\sum_\nu D_\nu}$$

Shannon entropy:

$$\mathcal{H} = \sum_\nu p_\nu log(p_\nu)$$

Probability of a state

Information contained in that state

# Introduction - Jensen-Shannon Divergence

Modal fraction

$$p_\nu = \frac{D_\nu}{\sum_\nu D_\nu}$$

Shannon Entropy

$$\mathcal{H} = \sum_\nu p_\nu log(p_\nu)$$

Kullback-Leibler Divergence:

$$\mathcal{D}_{KL}(p||q) = \sum_\nu p_\nu log(\frac{p_\nu}{q_\nu})$$

Difference between Shannon entropy of p…

… and entropy of swapping q with p

*Not symmetric on exchange of p and q!*

# Introduction - Jensen-Shannon Divergence

Modal fraction

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Shannon Entropy

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Kullback-Leibler Divergence

$$\mathcal{D}_{KL}(p||q) = \sum_\nu p_\nu log(\frac{p_\nu}{q_\nu})$$

$$r = \frac{1}{2}(p+q)$$

Jensen-Shannon Divergence:

$$\mathcal{D}(p||q) = \frac{1}{2}\mathcal{D}_{KL}(p||r) + \frac{1}{2}\mathcal{D}_{KL}(q||r)$$

Symmetrized $D_{KL}$

# Introduction - Jensen-Shannon Divergence

Modal fraction

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**Ian Stiehl:**
Searching for Biosignatures in Exoplanet Atmospheres: An Information Theory Approach

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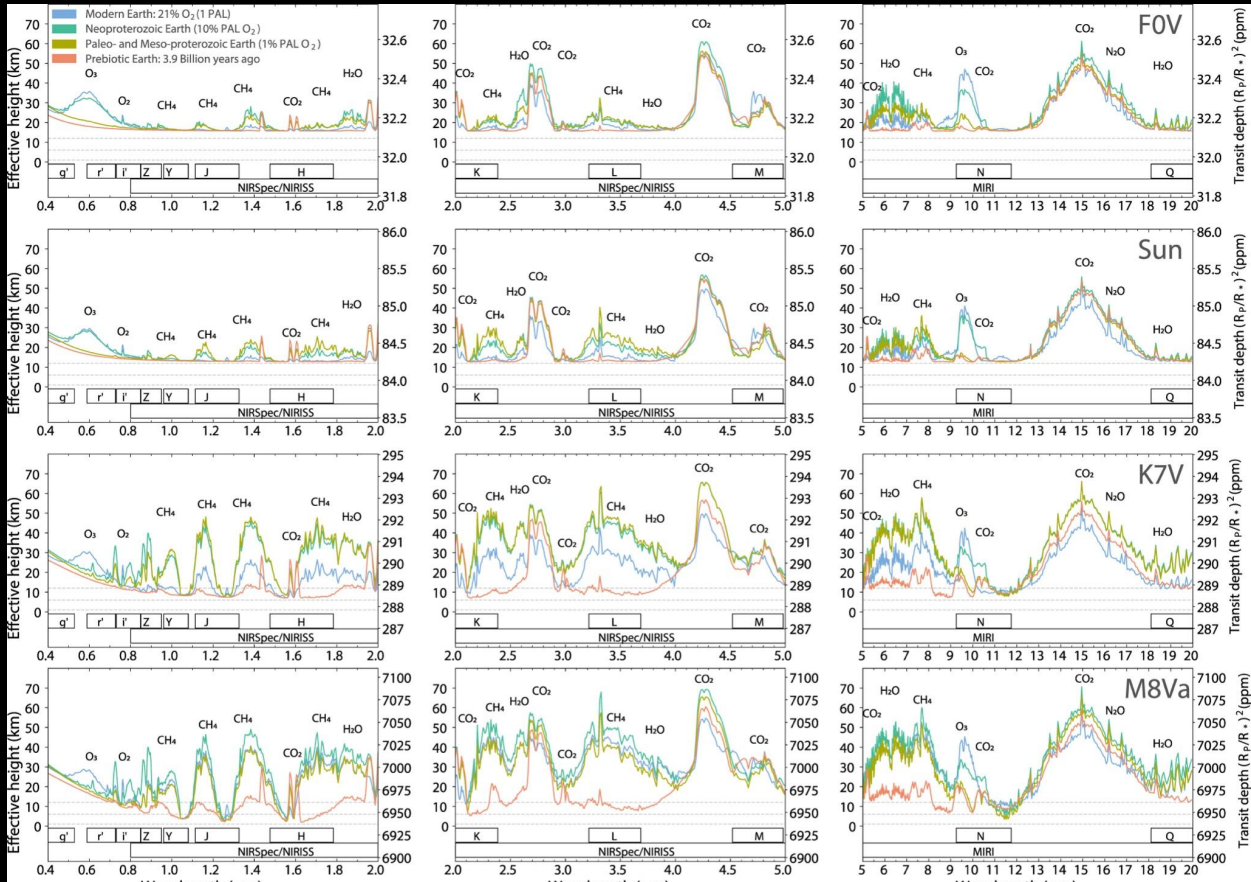
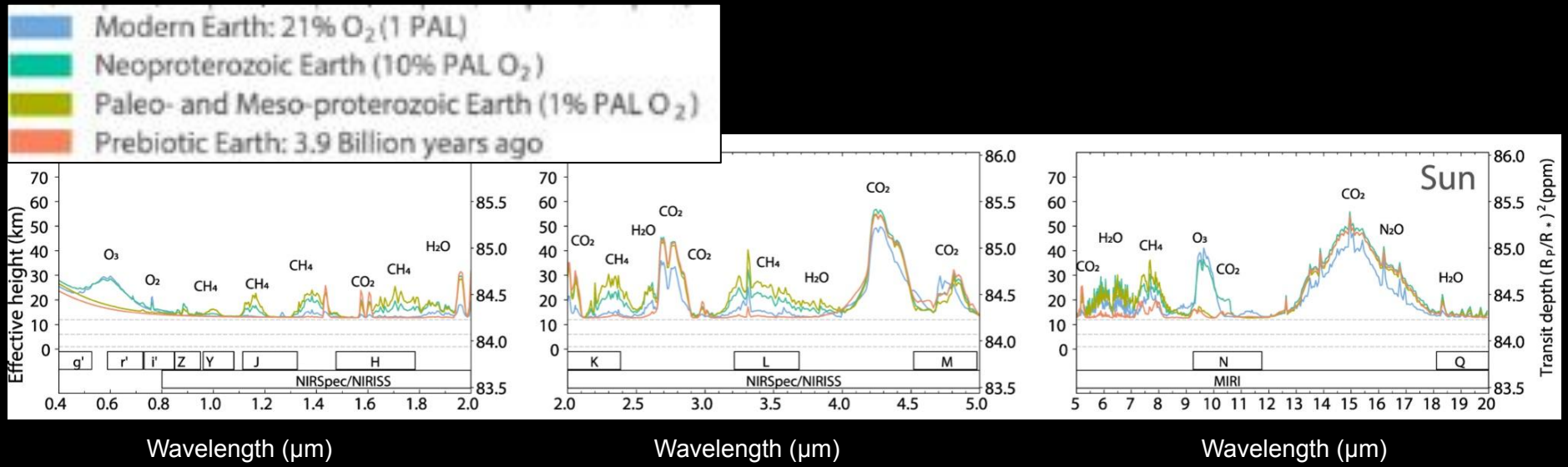
# Earth in other contexts

What if we observed Earth around another star? What if at an earlier stage of its evolution?




Kaltenegger et al.
arXiv:2010.01734

# Earth in other contexts

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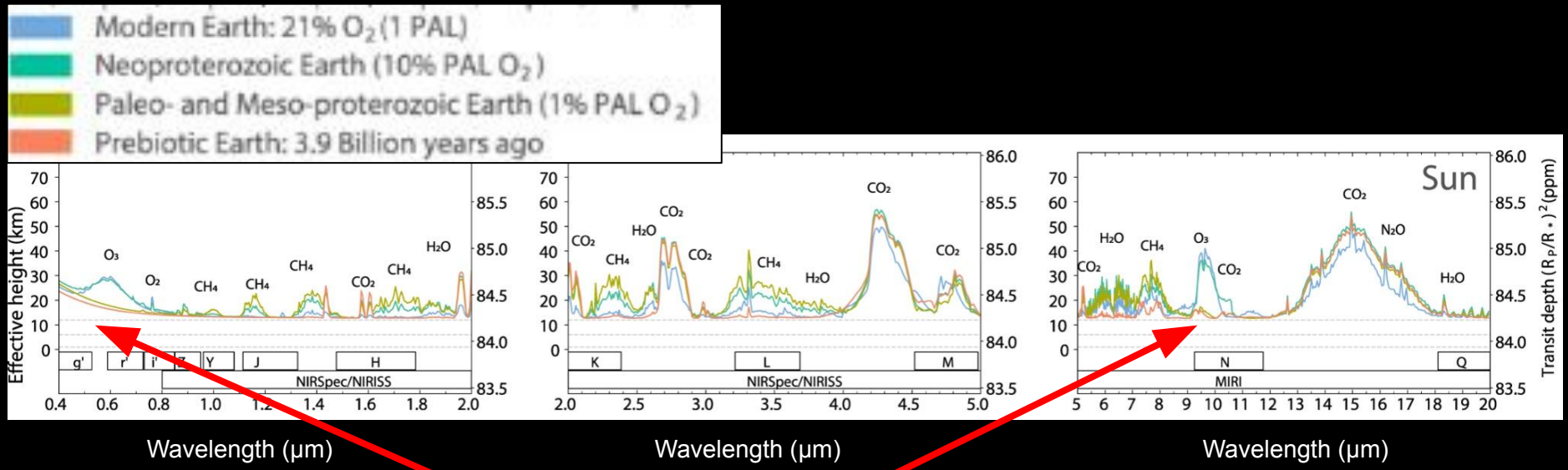
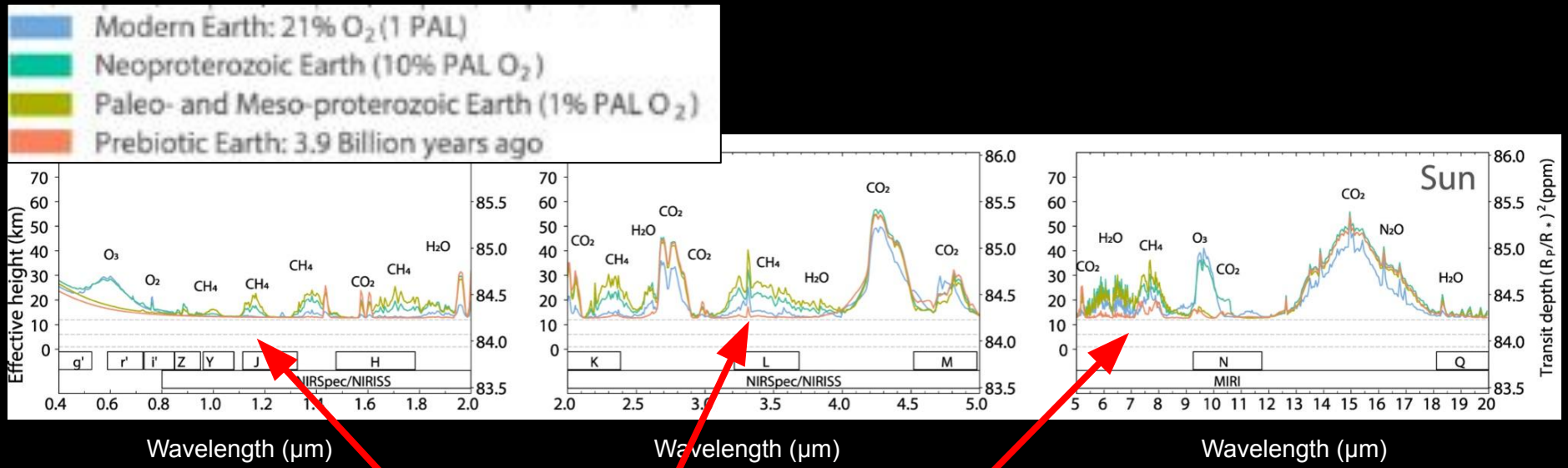
# Earth in other contexts




Large increase in ozone created by life

Kaltenegger et al. arXiv:2010.01734

# Earth in other contexts




Methane strongest in Proterozoic era (methanogens)

Kaltenegger et al. arXiv:2010.01734

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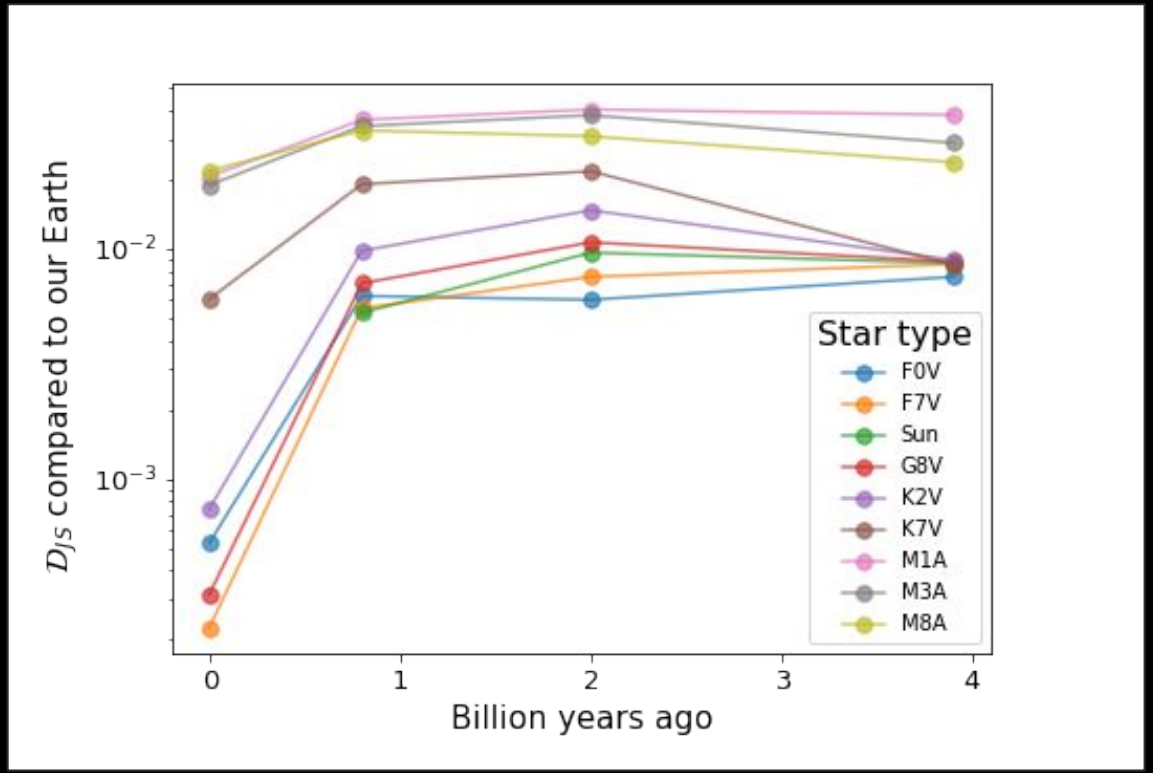
# Results - $D_{JS}$ ranges for Earth-like exoplanets

- $D_{JS}$ generally diverges from modern Earth as evolved backward in time
- $D_{JS}$ curves for different planets overlap



# $D_{JS}$ density

Modal fraction

$$p_\nu = \frac{D_\nu}{\sum_\nu D_\nu}$$

Kullback-Leibler Divergence

$$\mathcal{D}_{KL}(p||q) = \sum_\nu p_\nu log(\frac{p_\nu}{q_\nu})$$

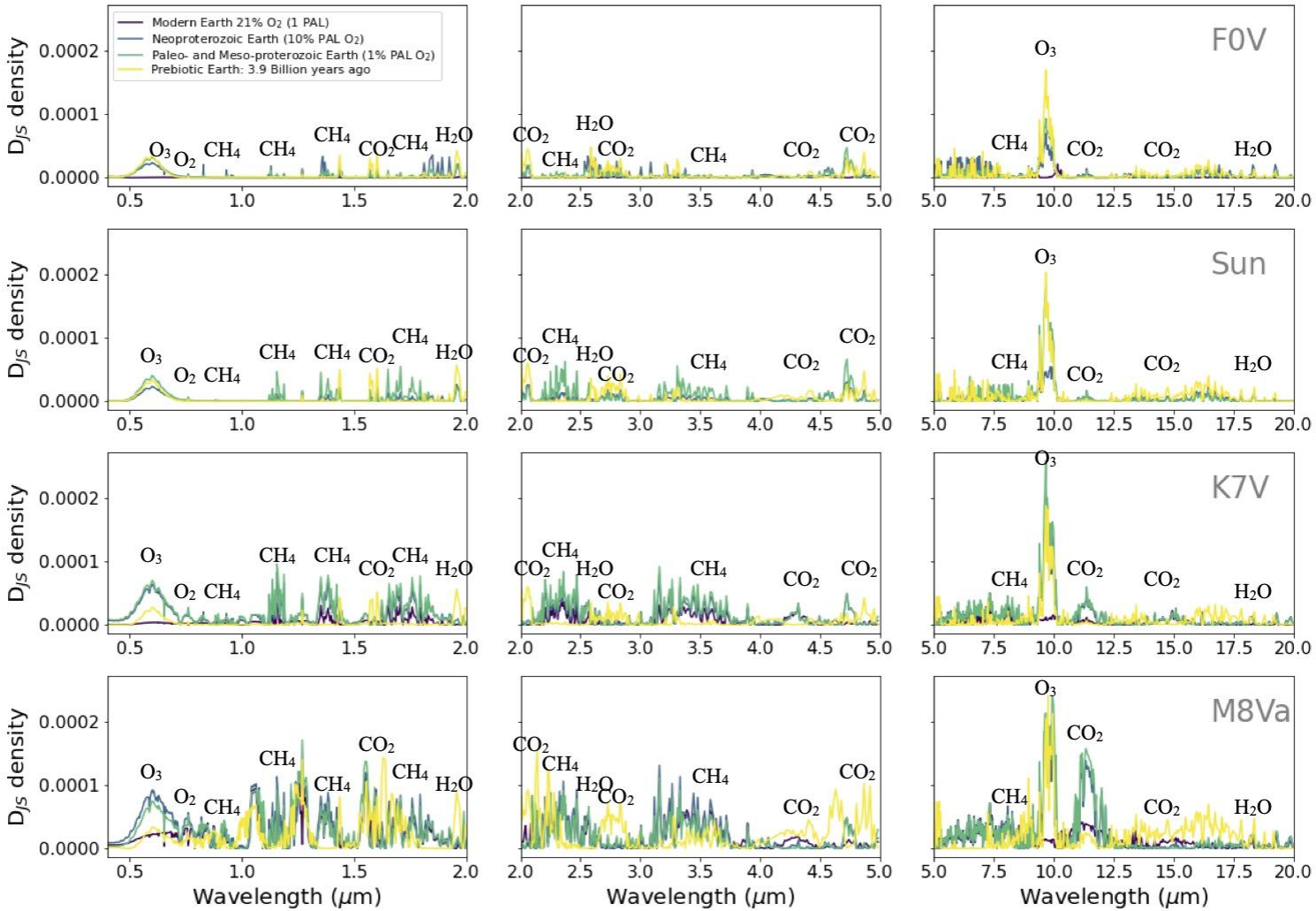
Kullback-Leibler density

$$\rho_{\mathcal{D}_{KL},\nu}(p||q) = p_\nu log(\frac{p_\nu}{q_\nu})$$

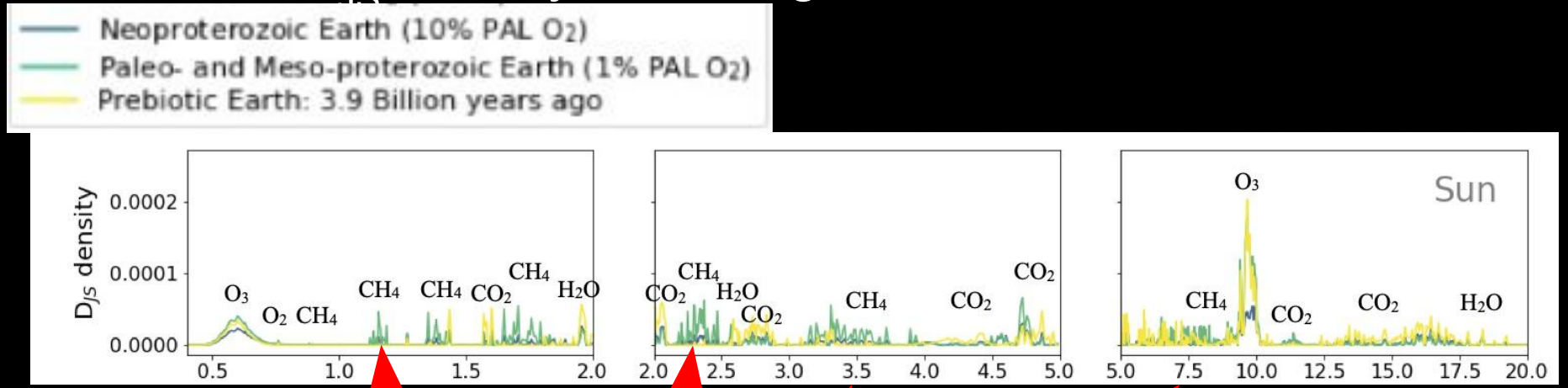
$$r = \frac{1}{2}(p+q)$$

Jensen-Shannon density

$$\rho_{\mathcal{D}_{JS},\nu}(p||q) = \frac{1}{2}\rho_{\mathcal{D}_{KL},\nu}(p||r) + \frac{1}{2}\rho_{\mathcal{D}_{KL},\nu}(q||r)$$

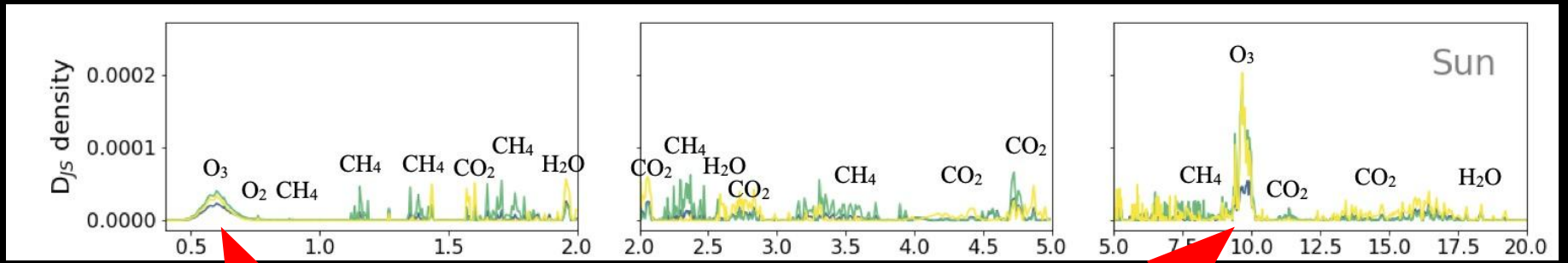

Modern Earth 21% O2 (1 PAL)
Neoproterozoic Earth (10% PAL O2)
Paleo- and Meso-proterozoic Earth (1% PAL O2)
Prebiotic Earth: 3.9 Billion years ago
DJS density
Wavelength (μm)
F0V
Sun
K7V
M8Va
O3
O2
CH4
CO2
H2O

# Results - $D_{JS}$ density for biosignatures




Methane - great methanogenesis in Neoproterozoic, decreased by modern Earth. $D_{JS}$ high for Paleo-, Meso-, and Neoproterozoic (green and blue lines)

# Results - $D_{JS}$ density for biosignatures




Ozone highest in modern Earth - great oxygenation event. Causes highest $D_{JS}$ for oldest (least biotic impact) Earth

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# Conclusions

- Data incoming. Need a way to find habitable & inhabited planets with minimal input knowledge
- $D_{JS}$ can identify Earth-like planets, trace evolution
- $D_{JS}$ density can trace biosignatures
- Gets information from *shape* of lines. Less input knowledge
- May observe Earth in other contexts (age, host star) - can still search for life

Image credit: NASA

**Contact me:**
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