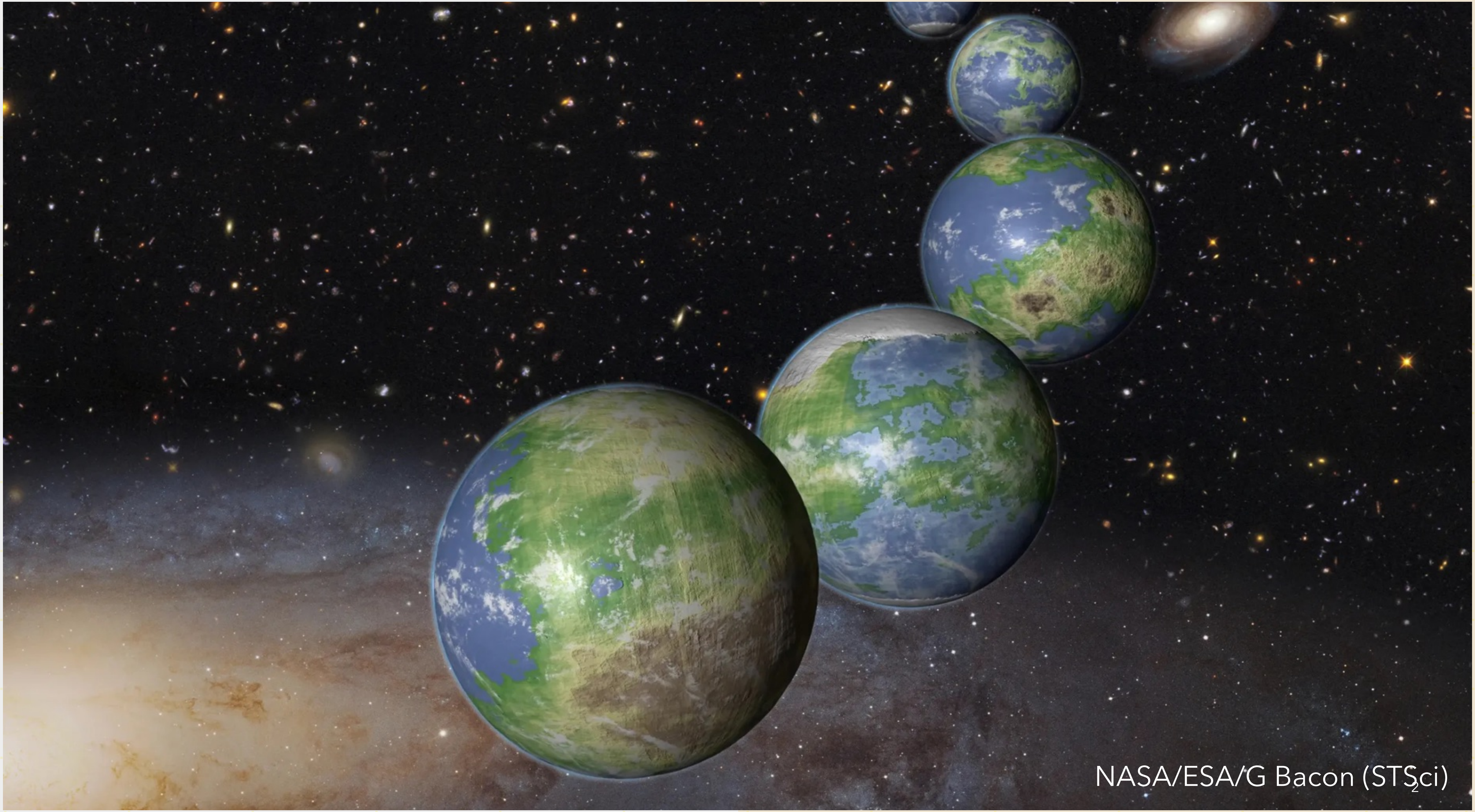
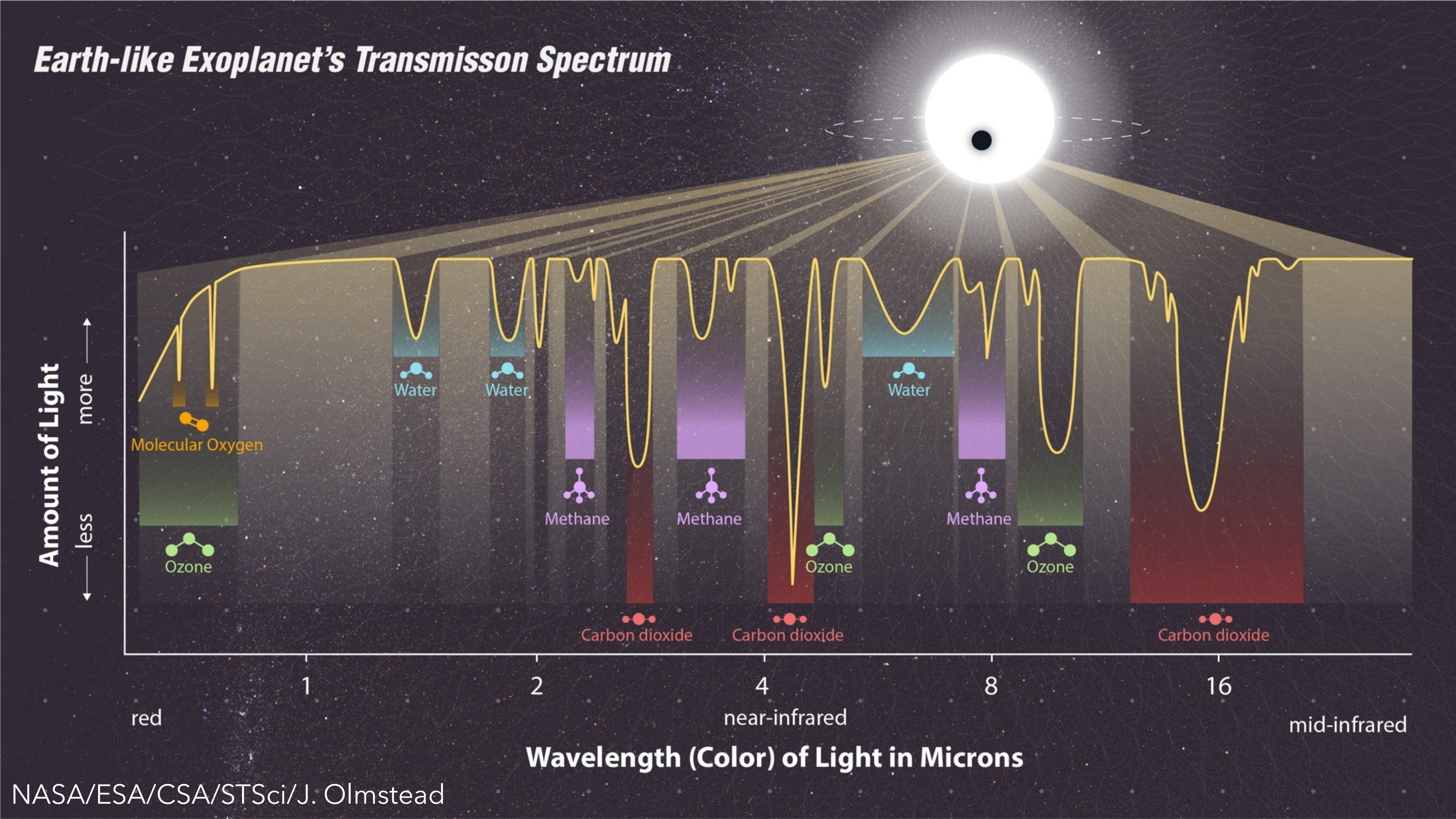
Methylated biosignatures: A new class of biosignatures

Michaela Leung

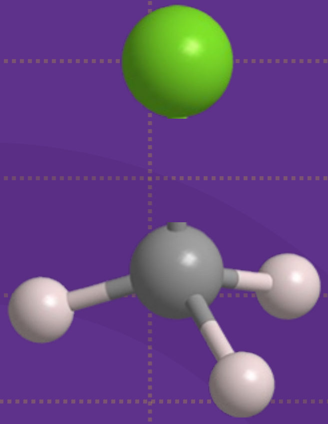
University of California, Riverside

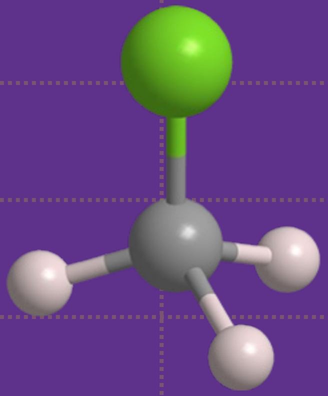

NASA/ESA/G Bacon (STScI)


Earth-like Exoplanet's Transmisson Spectrum
Amount of Light
more
less
Molecular Oxygen
Ozone
Water
Water
Methane
Carbon dioxide
Methane
Carbon dioxide
Ozone
Water
Methane
Ozone
Carbon dioxide
1
2
4
8
16
red
near-infrared
mid-infrared
Wavelength (Color) of Light in Microns
NASA/ESA/CSA/STScI/J. Olmstead

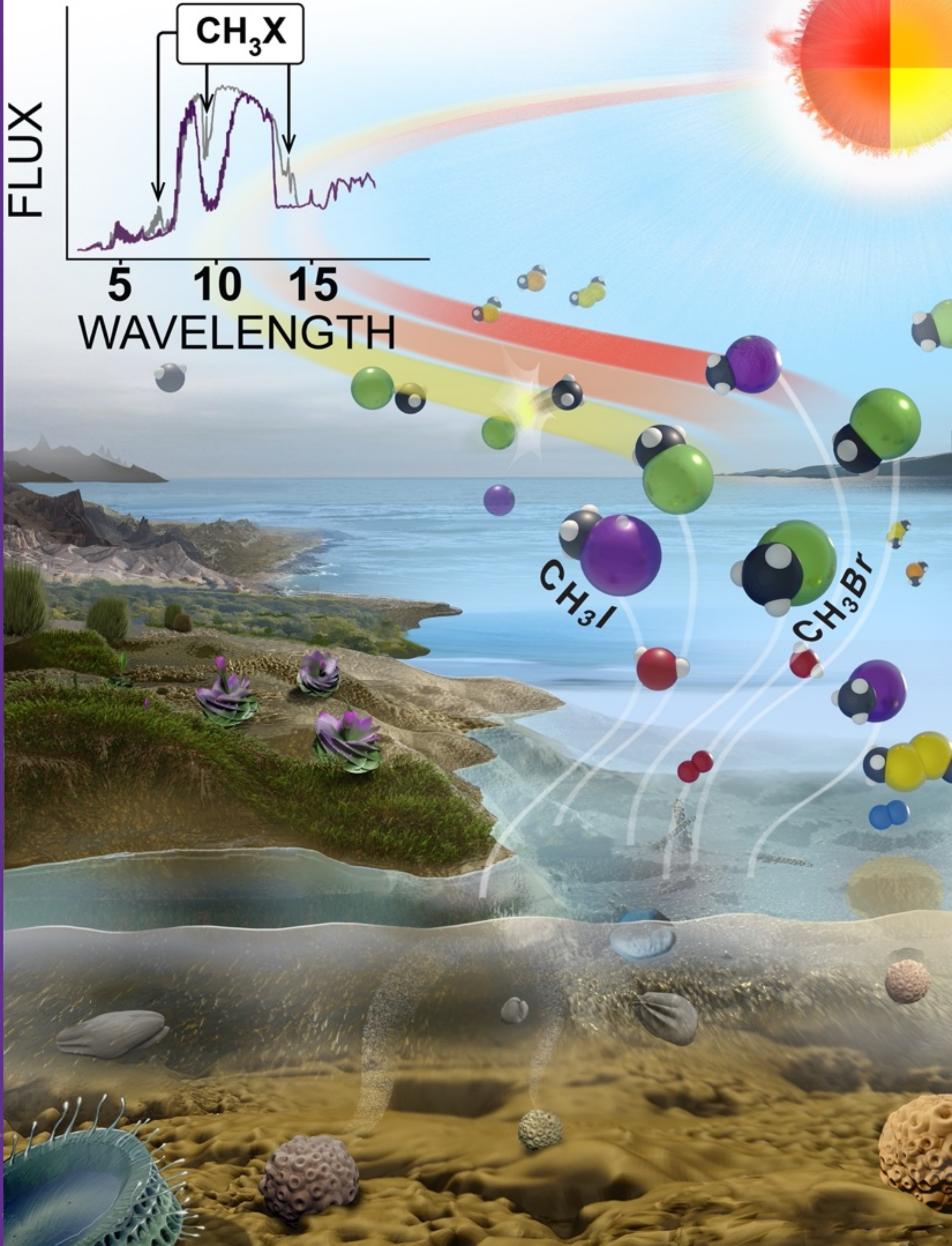
Contents

What is a methylated biosignature?





Sohail Wasif/UCR



Motivation

Why *methylated* biosignatures?

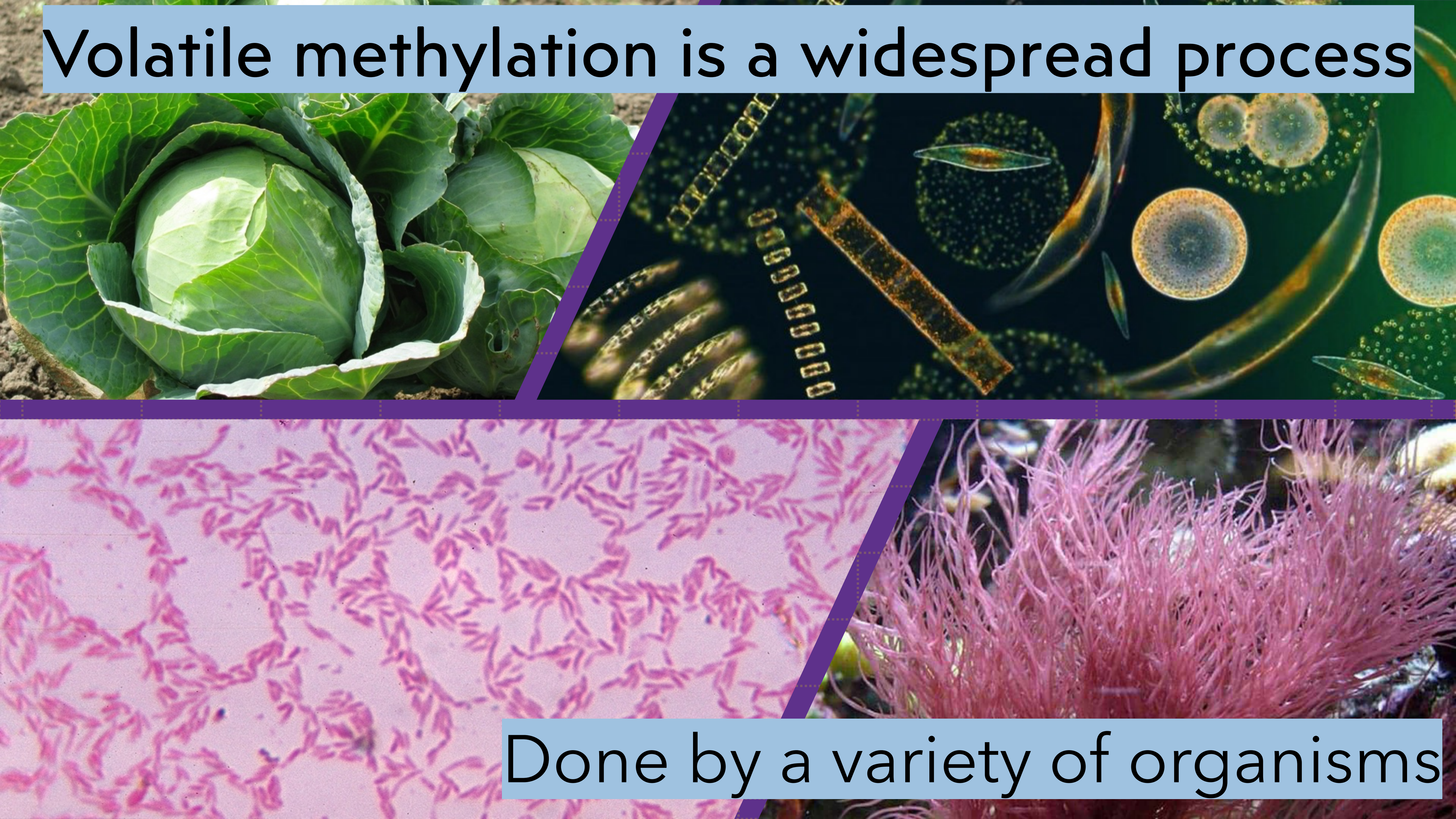
Why novel methylated biosignatures?

Low false positive potential

- Not produced at equilibrium
- Minimal quantities from planetary processes
- Exogenous delivery possible but highly limited

Volatile methylation is a widespread process

Volatile methylation is a widespread process



Done by a variety of organisms

Previous methylated biosignature studies show

Enhanced build up around M dwarf stars

- Lower NUV flux -> lower OH production
- OH radical main sink for CH_3Cl
- Segura et al 2005

Secondary ethane biosignature

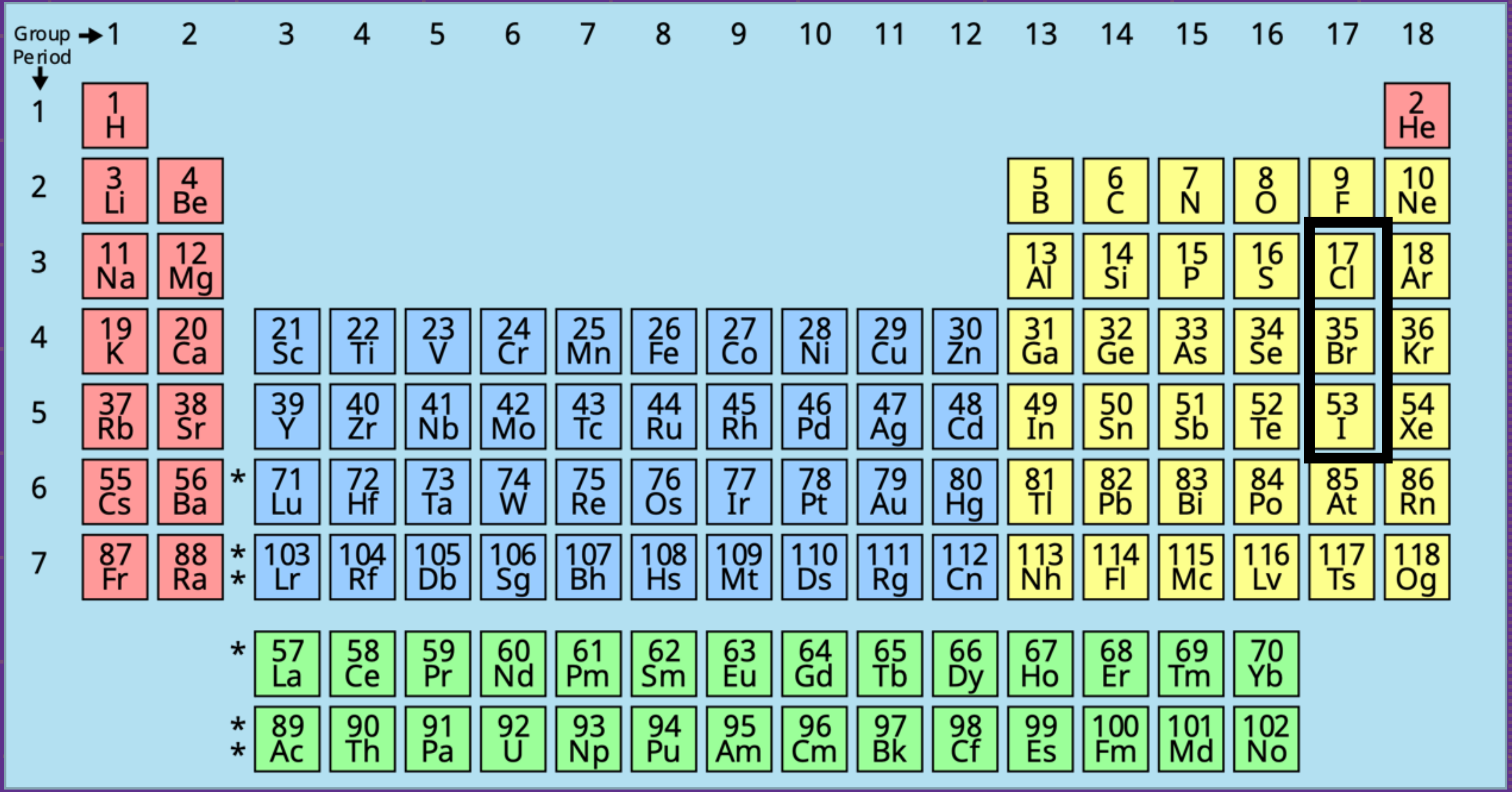
- Photolysis of $(CH_3)_2S$ and $(CH_3)_2S_2$
- Ethane signature near 11 um
- Domagal-Goldman et al 2011

Evaluation of halomethanes as biosignatures

Methylation utilizes many environmental substrates

Methylated Halogens

- CH_3Cl
- CH_2Cl_2
- $CHCl_3$
- CCl_4
- CH_3Br
- $CHBr_3$
- CBr_4
- CH_2BrCl
- $CHBr_2Cl$
- CH_3I
- CH_2I_2
- CHI_3
- $(CH_3)_2CHI$
- CH_2IBr
- $CHIBr_2$



Methods

01

Atmos – 1D photochemistry

(Arney et al., 2016)

02

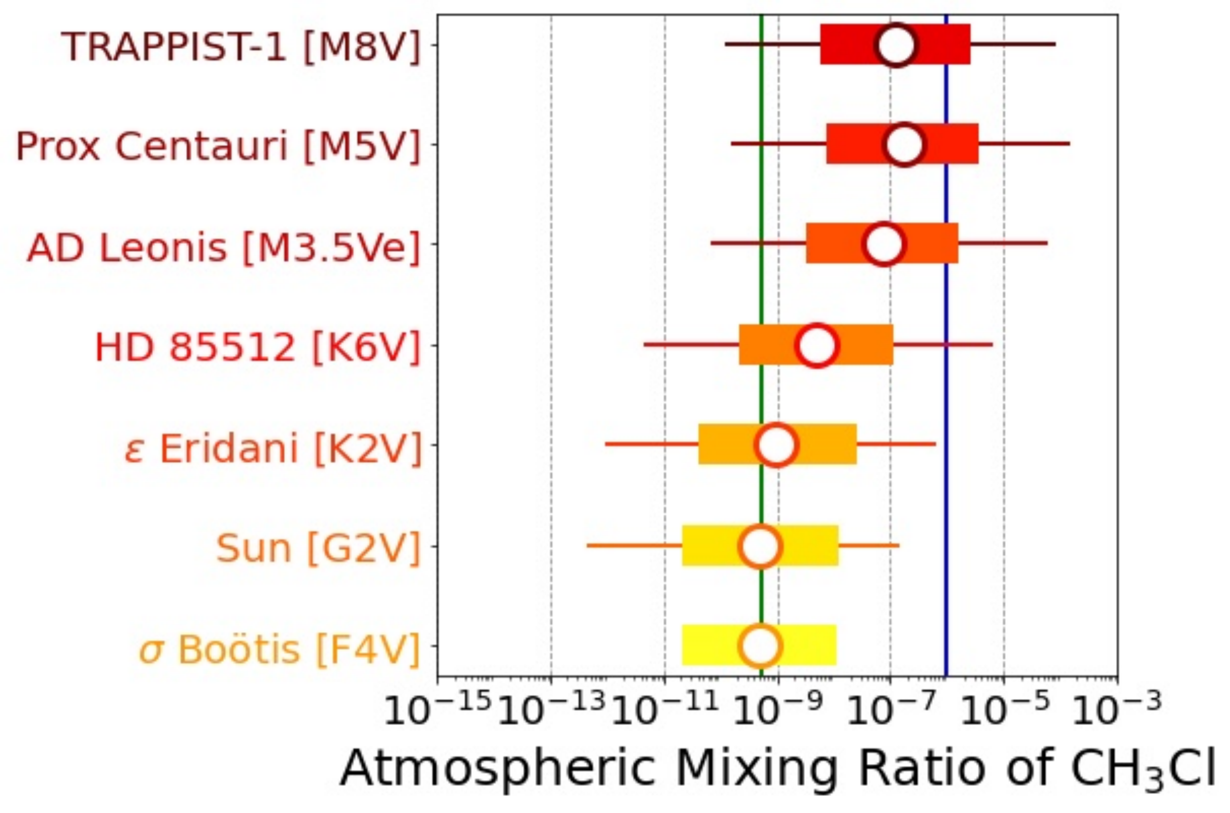
SMART – transmission and emission spectra (Meadows & Crisp 1996)

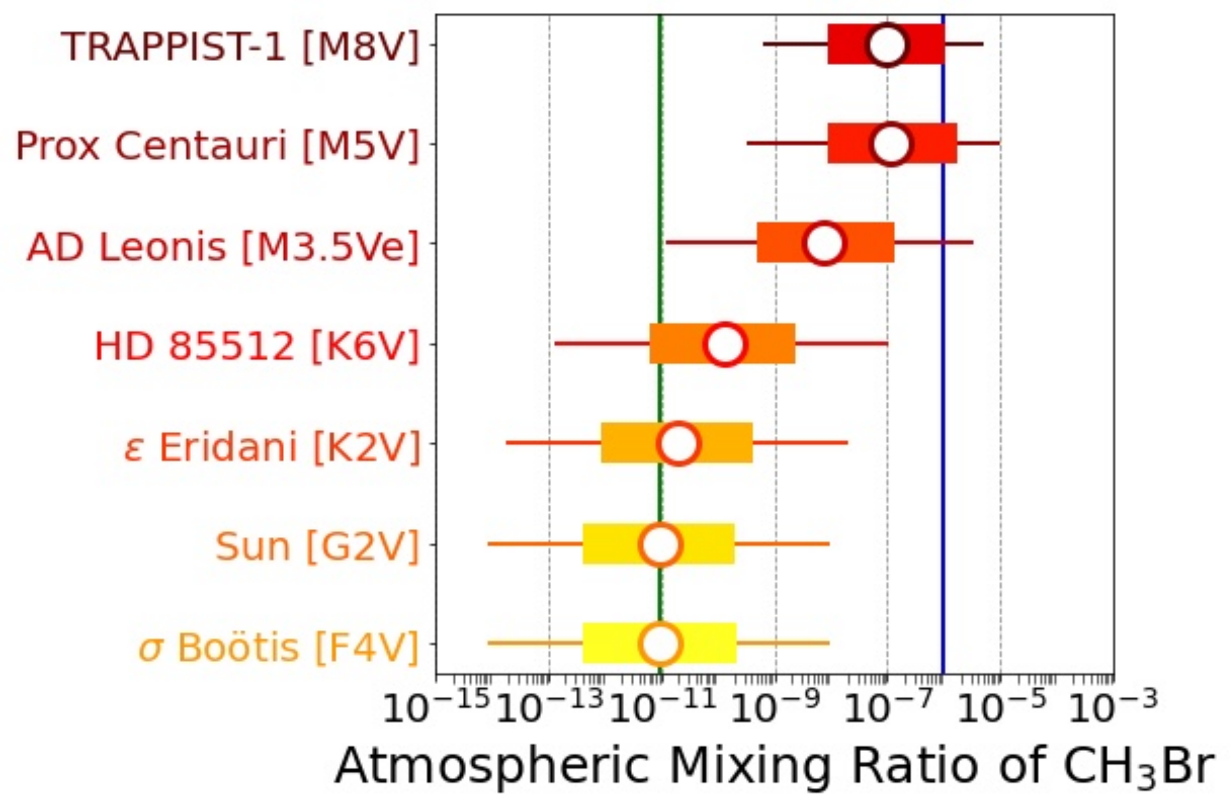
03

PSG - spectral & instrumental modeling

(Villanueva et al., 2018, 2022)

Photochemical Results – Leung et al., 2022





Using atmos 1D photochemical model (Arney et al., 2016)

Earth-like flux

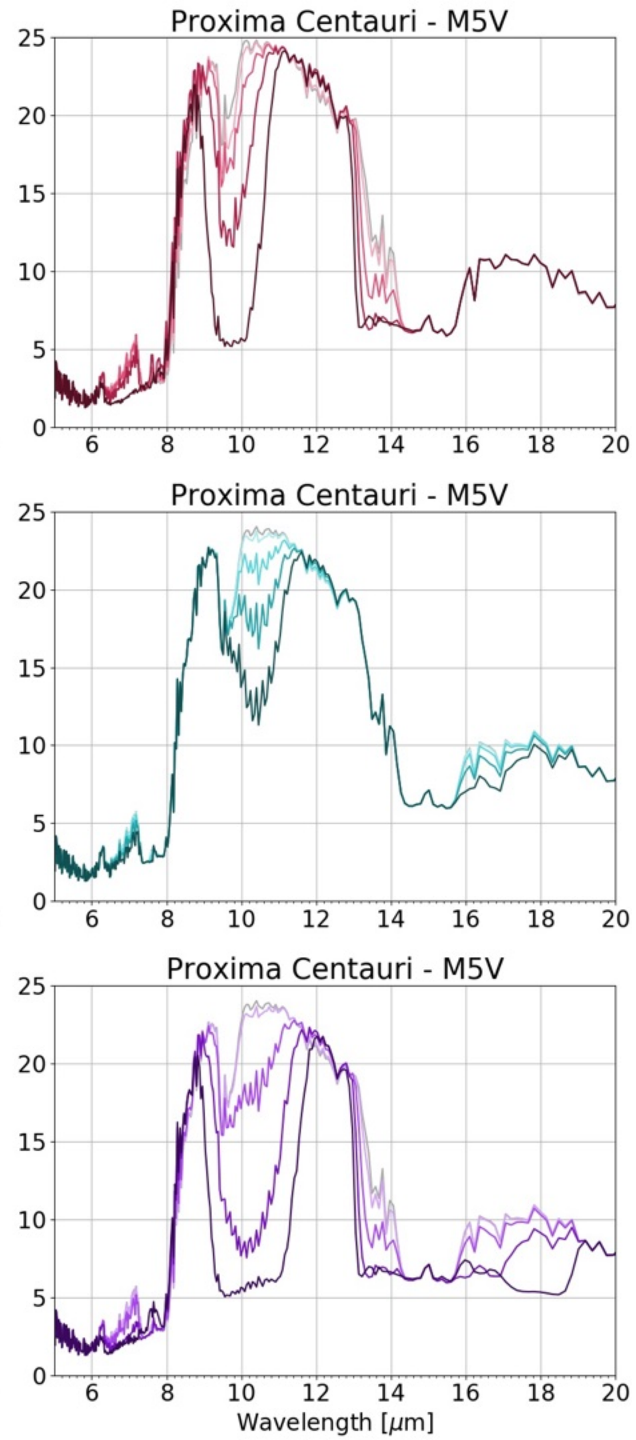
0.1 – 10x Earth-like flux

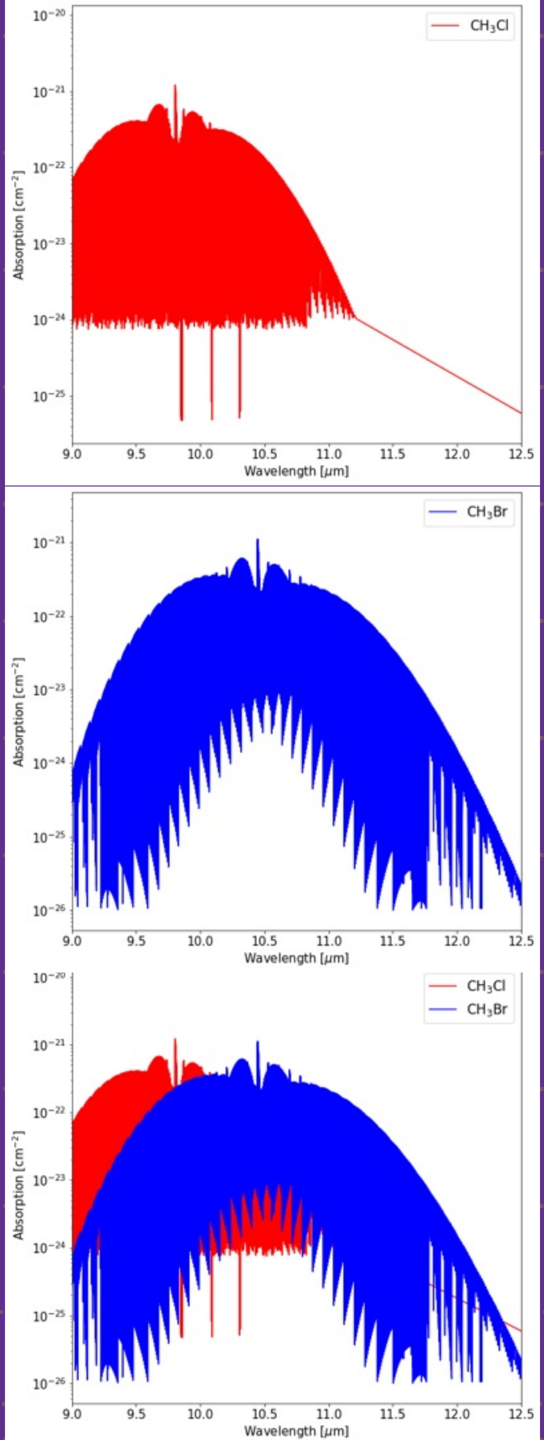
0.001 – 1000x Earth-like flux

Production of CH_3X gases

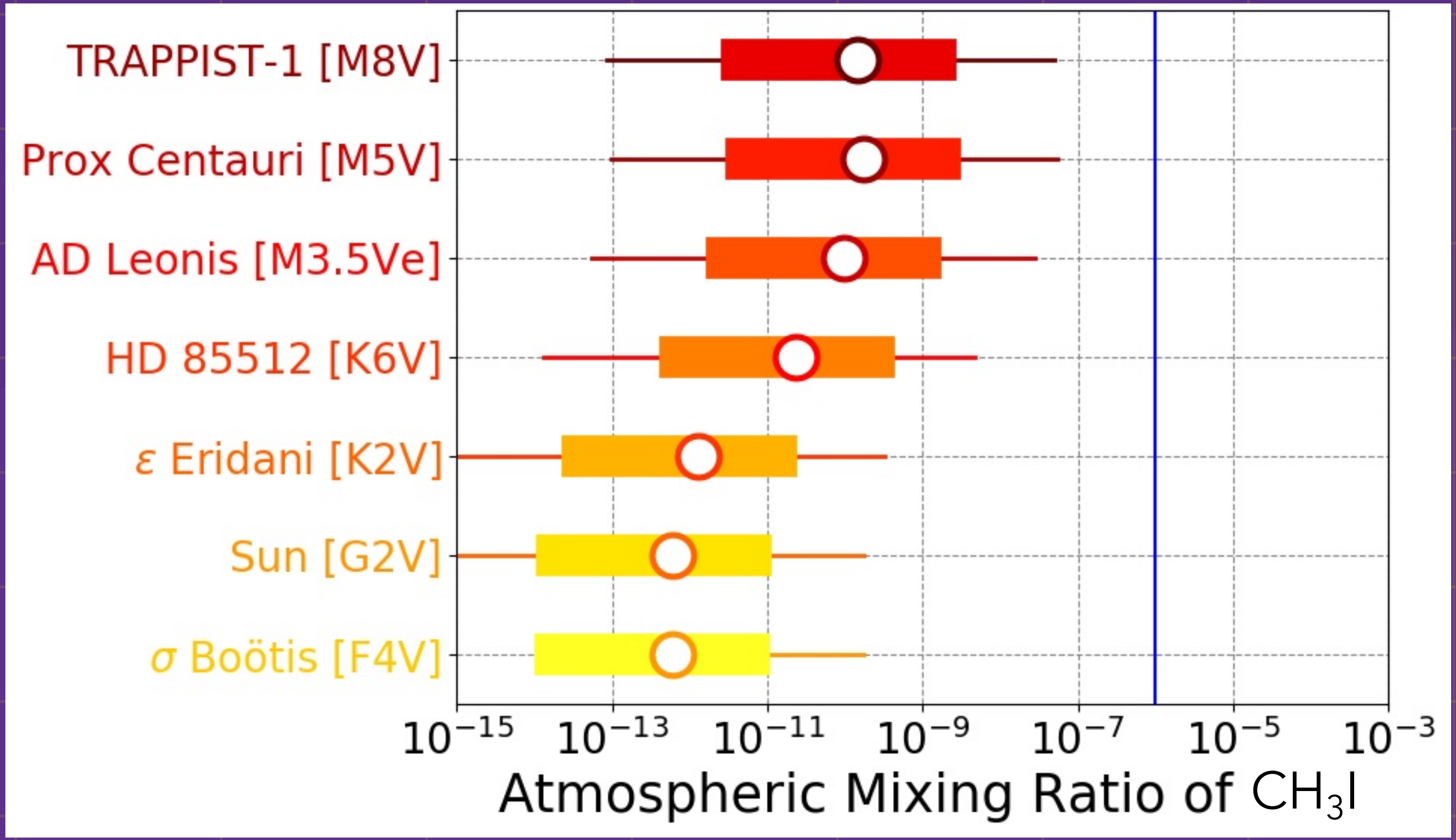
Gas	Environment	Flux (molec/cm²/s)	Globally Extrapolated Flux (Tg/yr)	Source
CH_3Cl	Globally averaged	2.25×10^8	3.08	Extrapolated from known mixing ratio
CH_3Cl	Conifer Forest	2.5×10^9	34.2	Dimmer et al., 2001
CH_3Cl	Salt Marsh	3.97×10^{11}	5440	Rhew et al., 2000
CH_3Br	Globally averaged	5.17×10^6	0.133	Yang et al., 2005
CH_3Br	Conifer Forest	6×10^7	1.55	Dimmer et al., 2001
CH_3Br	Salt marsh	2.93×10^{10}	755	Rhew et al., 2000
CH_3I	Globally averaged	5.51×10^6	0.004	Ziska et al., 2013
CH_3I	Salt Marsh	7.4×10^7	0.053	Manley et al., 2006
CH_3I	Rice paddy	7.36×10^9	5.3	Redeker et al., 2000

Additional productive environments include: forests, wetlands, swamps, open ocean





SMART moderate-resolution MIR emission spectra showing co-additive spectral effect (Leung et al., 2022)



Also considering co-varying levels of

- CH_3Cl
- CH_3Br
- CH_3I
- $CHCl_3$
- $CHBr_3$
- CHI_3
- CH_2Cl_2
- CH_2Br_2
- CH_2I_2

Earth-like flux

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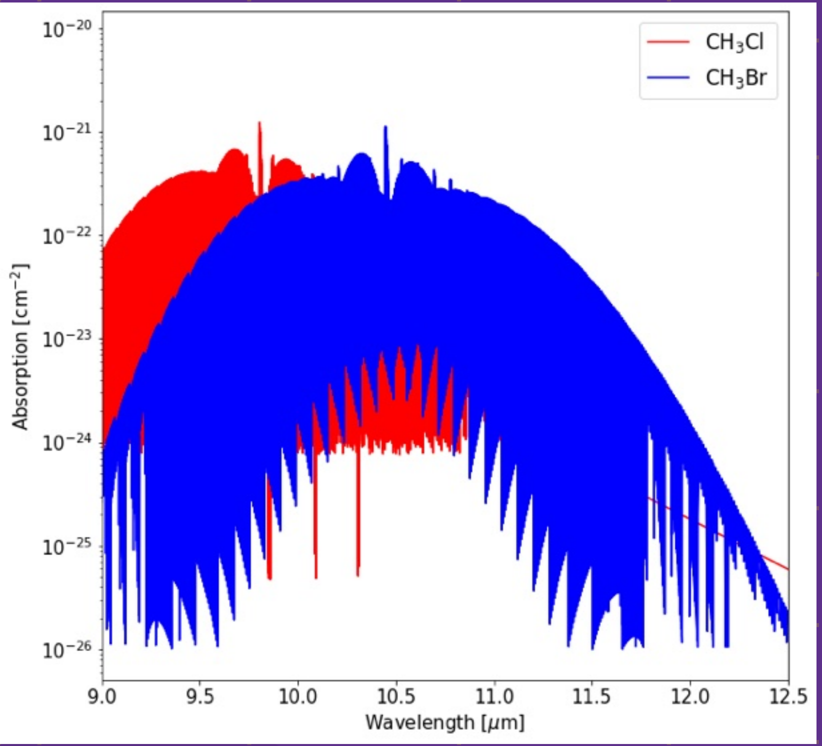
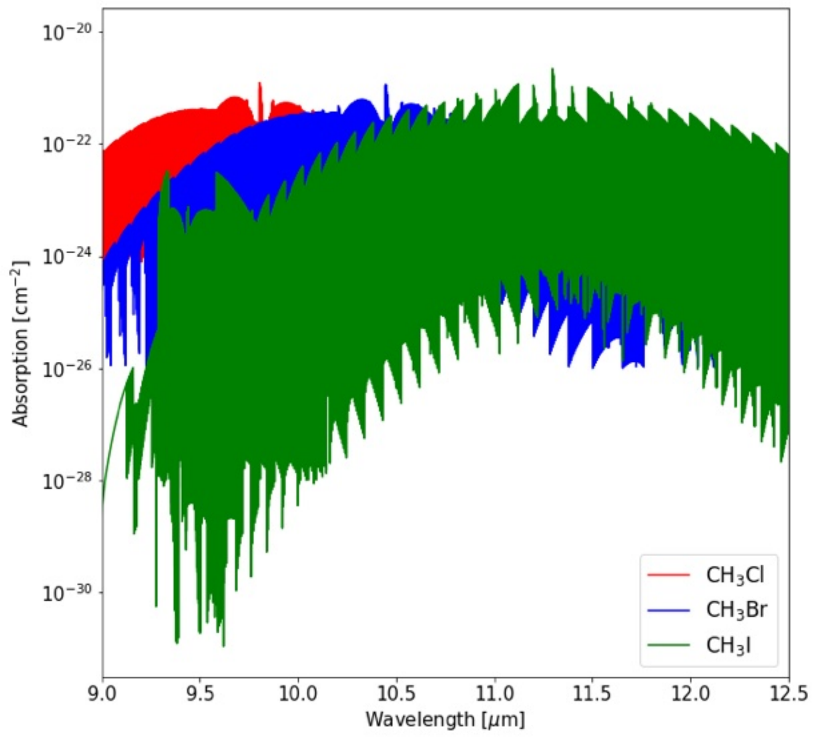
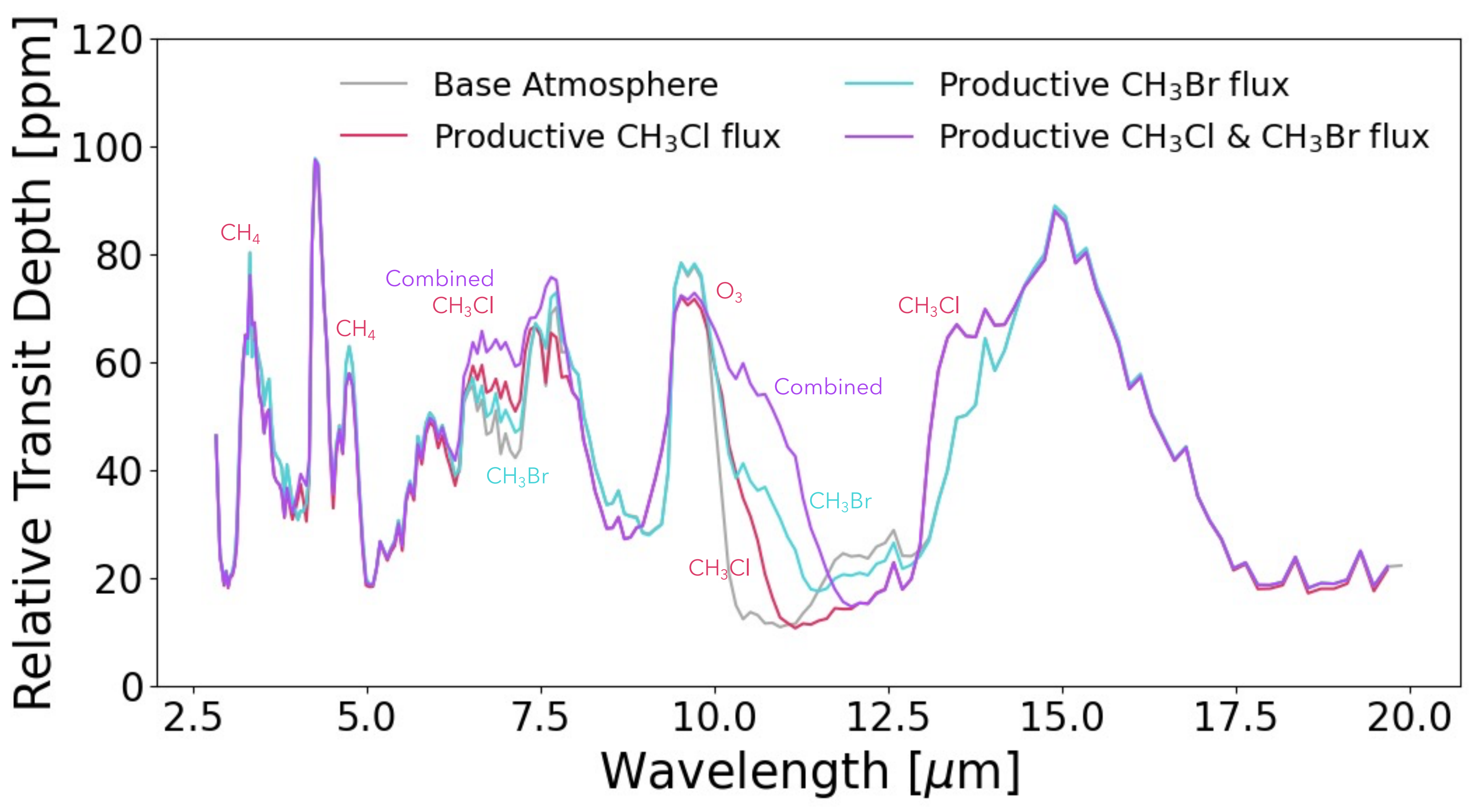
Photochemical Results





CH_3I will contribute to co-additive features

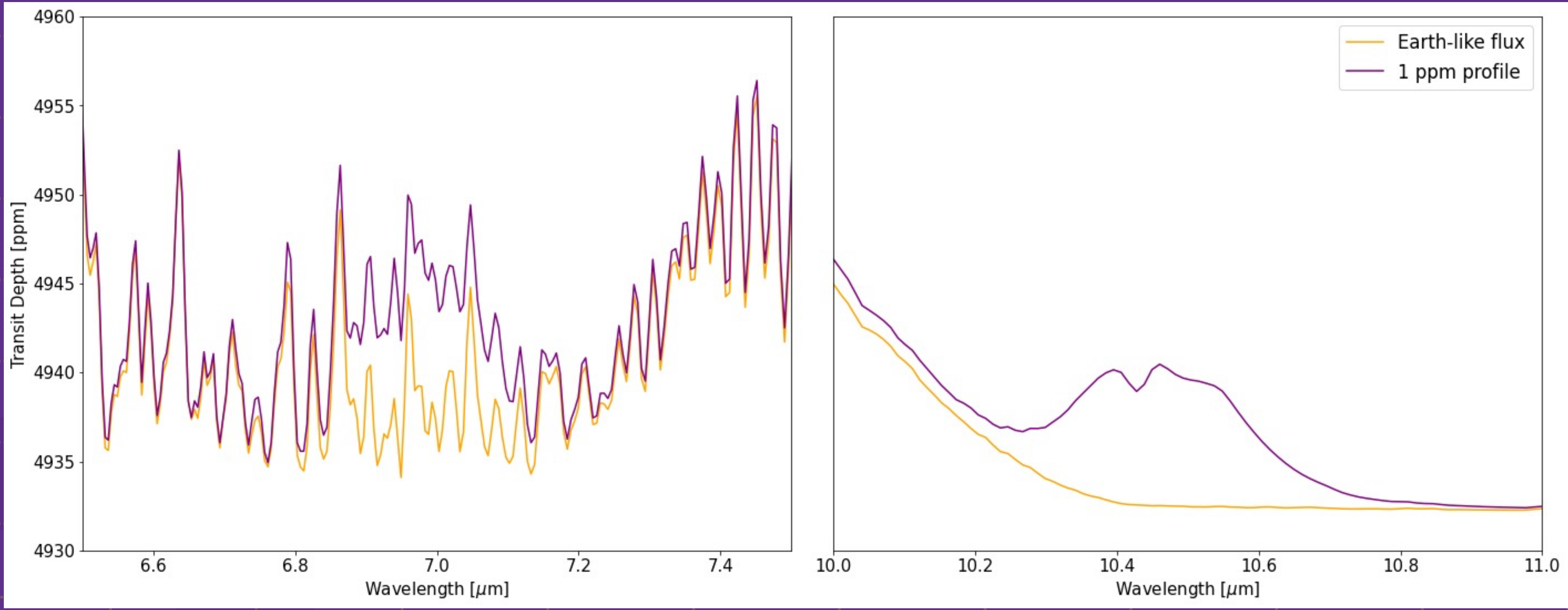
Previous simulated observations



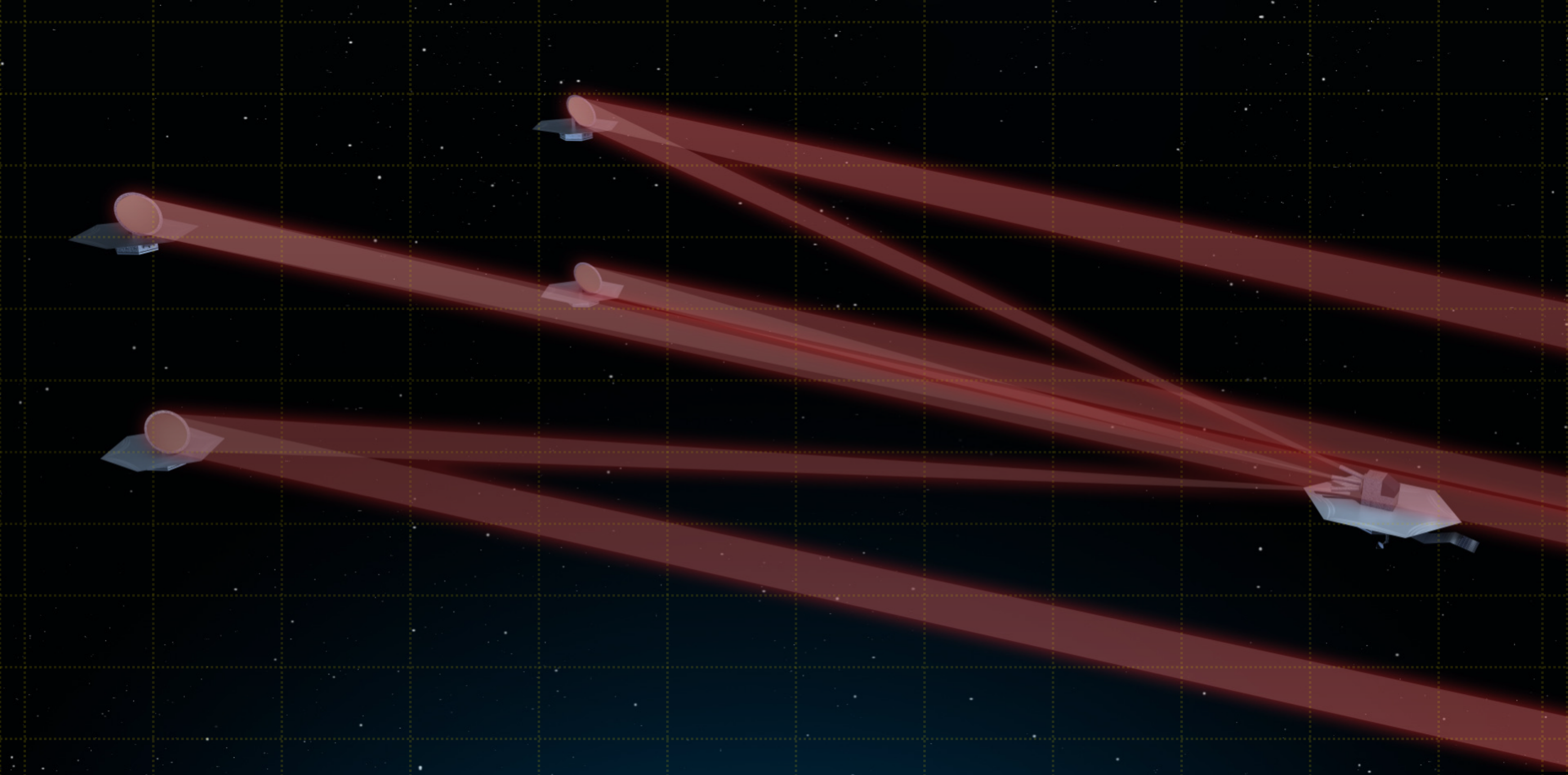
- 100x globally averaged Earth's flux

LIFE
LARGE INTERFEROMETER FOR EXOPLANETS

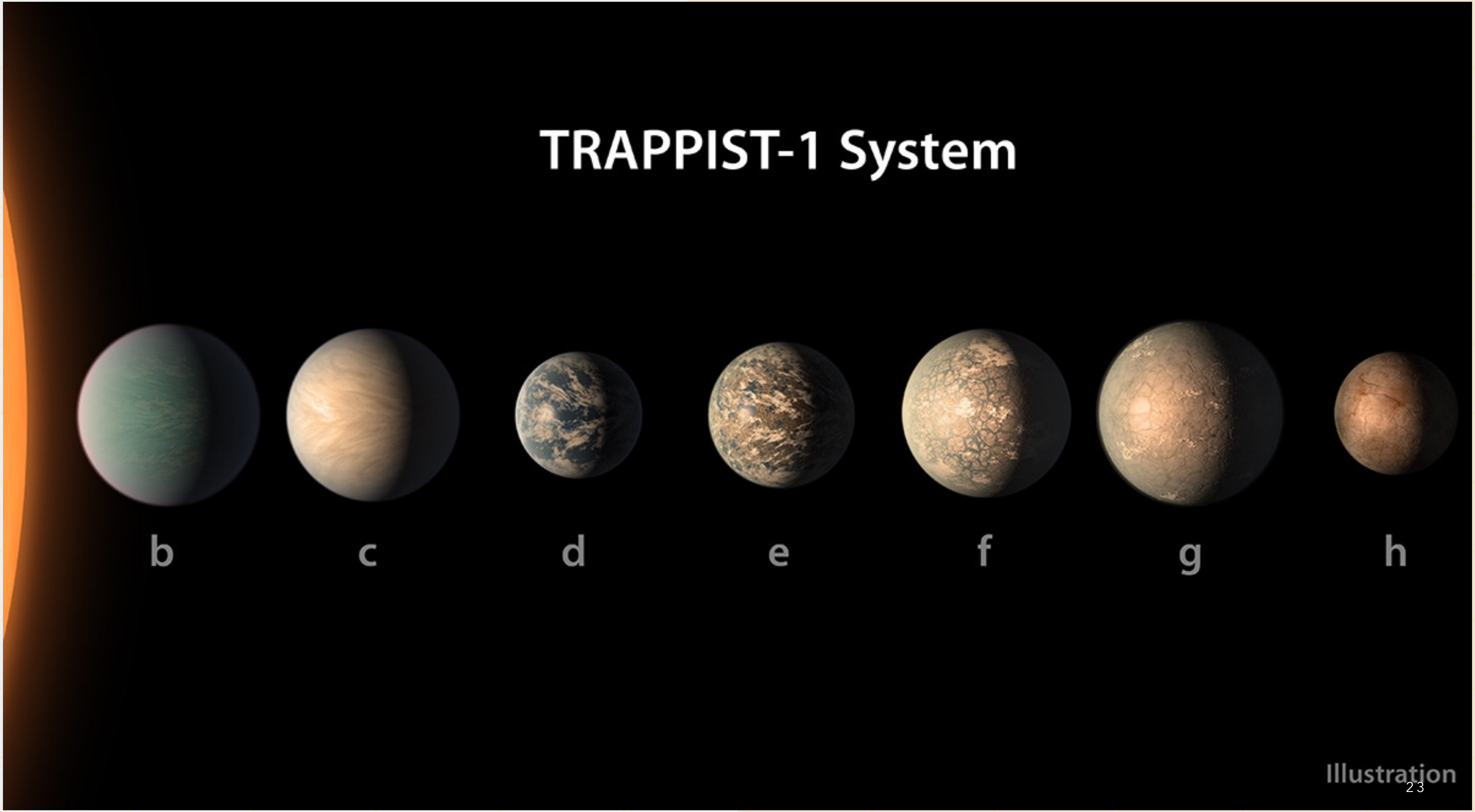
1 ppm CH_3I may be observable

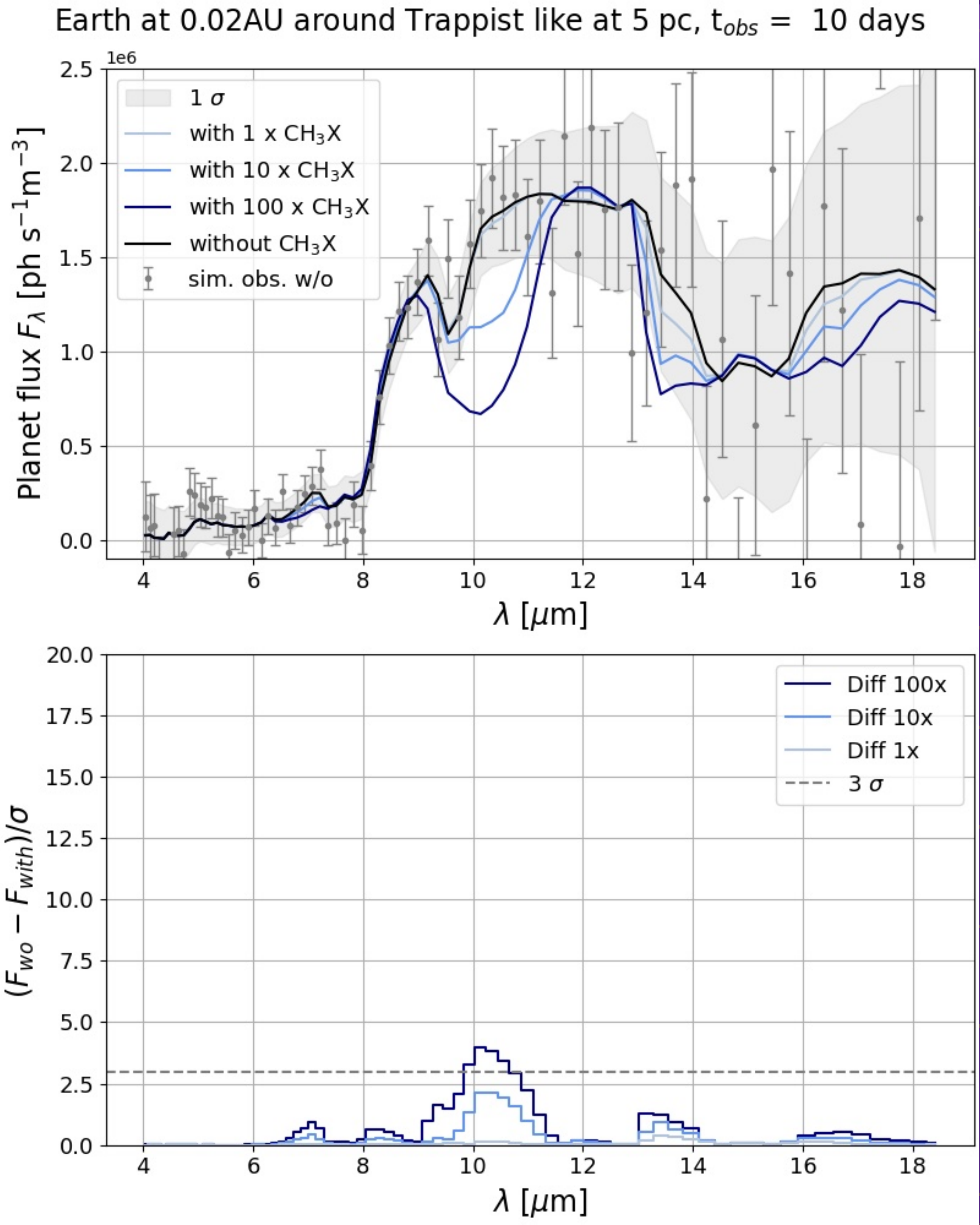


Detection of methylated gases with the Large Interferometer for Exoplanets (LIFE)

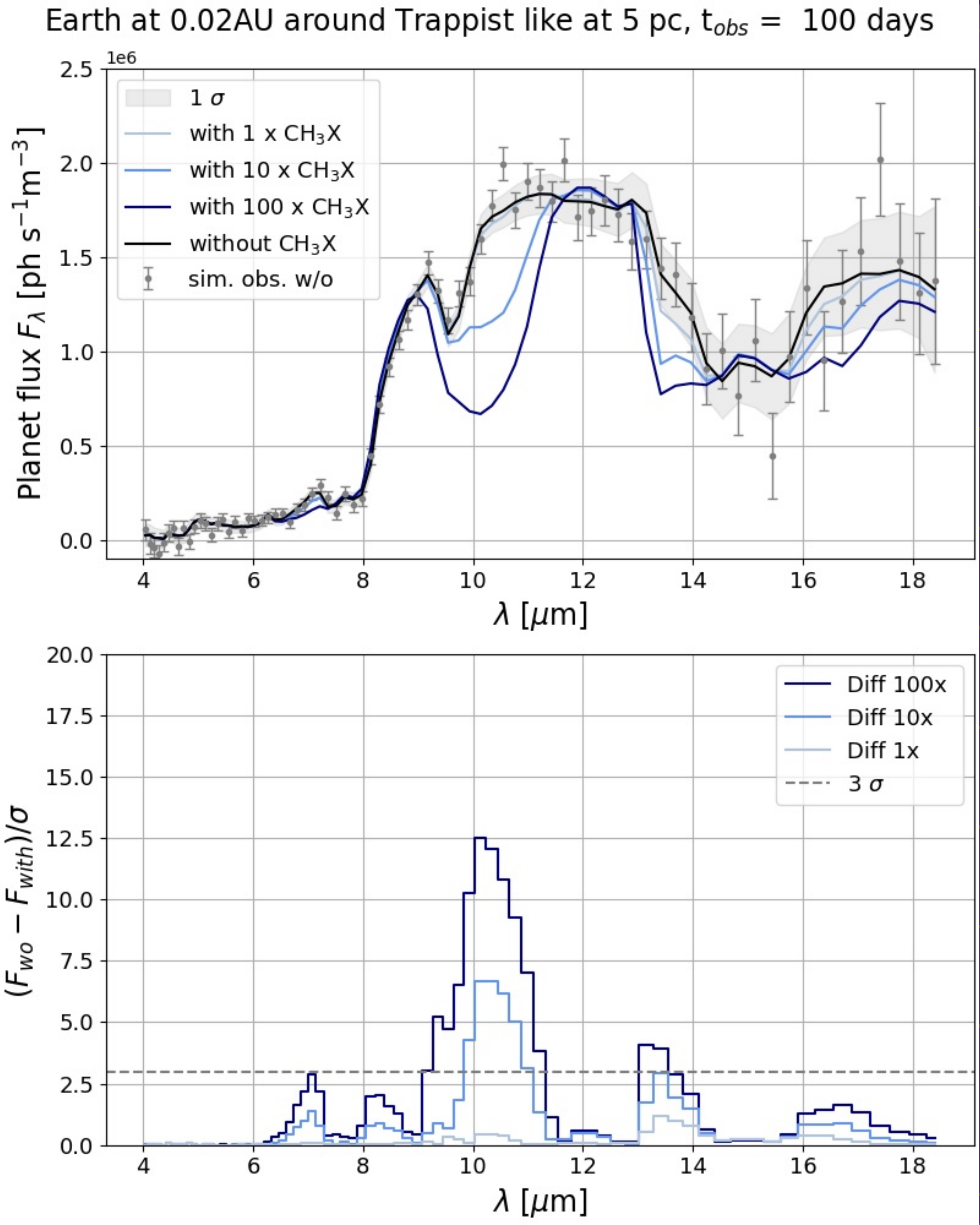


LIFE


TRAPPIST-1 System
b
c
d
e
f
g
h
Illustration



Earth at 0.02AU around Trappist like at 5 pc, t_{obs} = 10 days
1e6
Planet flux F_λ [ph s^{-1}m^{-3}]
1 σ
with 1 x CH_3X
with 10 x CH_3X
with 100 x CH_3X
without CH_3X
sim. obs. w/o
λ [μm]
$(F_{wo} - F_{with})/\sigma$
Diff 100x
Diff 10x
Diff 1x
3 σ
λ [μm]



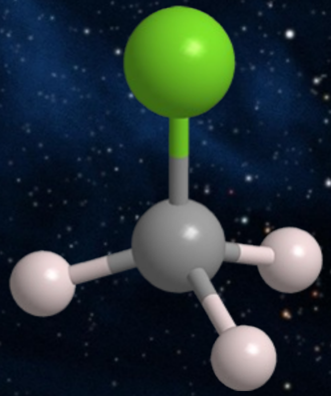
Earth at 0.02AU around Trappist like at 5 pc, t_obs = 100 days
Planet flux F_λ [ph s^{-1}m^{-3}]
1e6
1 σ
with 1 x CH_3X
with 10 x CH_3X
with 100 x CH_3X
without CH_3X
sim. obs. w/o
λ [μm]
$(F_{wo} - F_{with})/\sigma$
Diff 100x
Diff 10x
Diff 1x
3 σ
λ [μm]

Large Interferometer For Exoplanets (*LIFE*): TBD. The Detectability of Capstone Biosignatures in the Mid-Infrared - Sniffing Exoplanetary Laughing Gas and Methylated Halogens

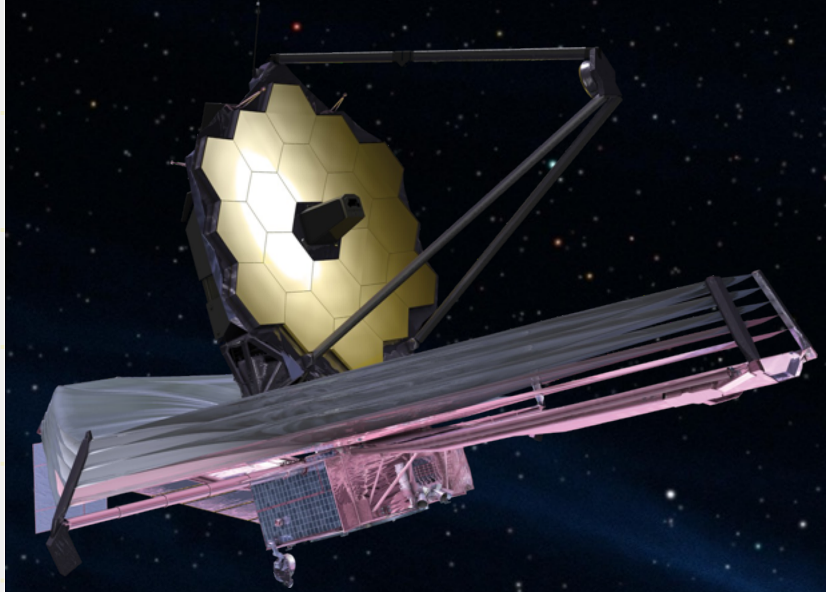
Daniel Angerhausen,[1,2] Daria Pidhorodetska,[3] Michaela Leung,[3] Janina Hansen,[1,2] Eleonora Alei,[1,2,4] Felix Dannert,[1,2] Jens Kammerer,[5,6] Sascha P. Quanz,[1,2,7] Edward W. Schwieterman,[3,8]

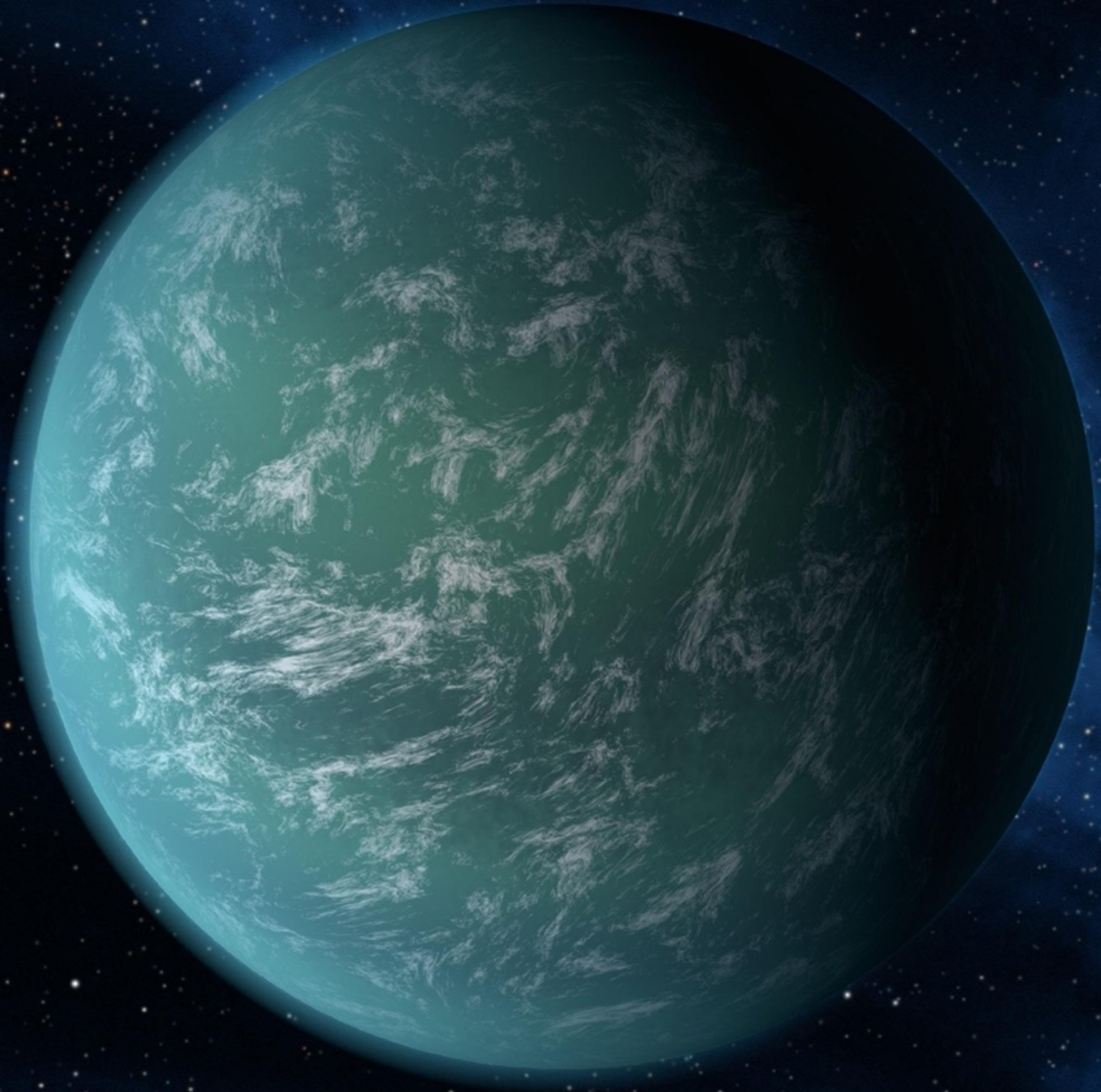
and the *LIFE* initiative

[1] *ETH Zurich, Institute for Particle Physics & Astrophysics, Wolfgang-Pauli-Str. 27, 8093 Zurich, Switzerland*
[2] *National Center of Competence in Research PlanetS, Gesellschaftsstrasse 6, 3012 Bern, Switzerland*
[3] *Department of Earth and Planetary Sciences, University of California, Riverside, CA, USA*
[4] *NPP Fellow, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[5] *European Southern Observatory, Karl-Schwarzschild-Straße 2, 85748 Garching, Germany*
[6] *Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*
[7] *ETH Zurich, Department of Earth Sciences, Sonneggstrasse 5, 8092 Zurich, Switzerland*
[8] *Blue Marble Space Institute of Science, Seattle, WA, 98154, USA*



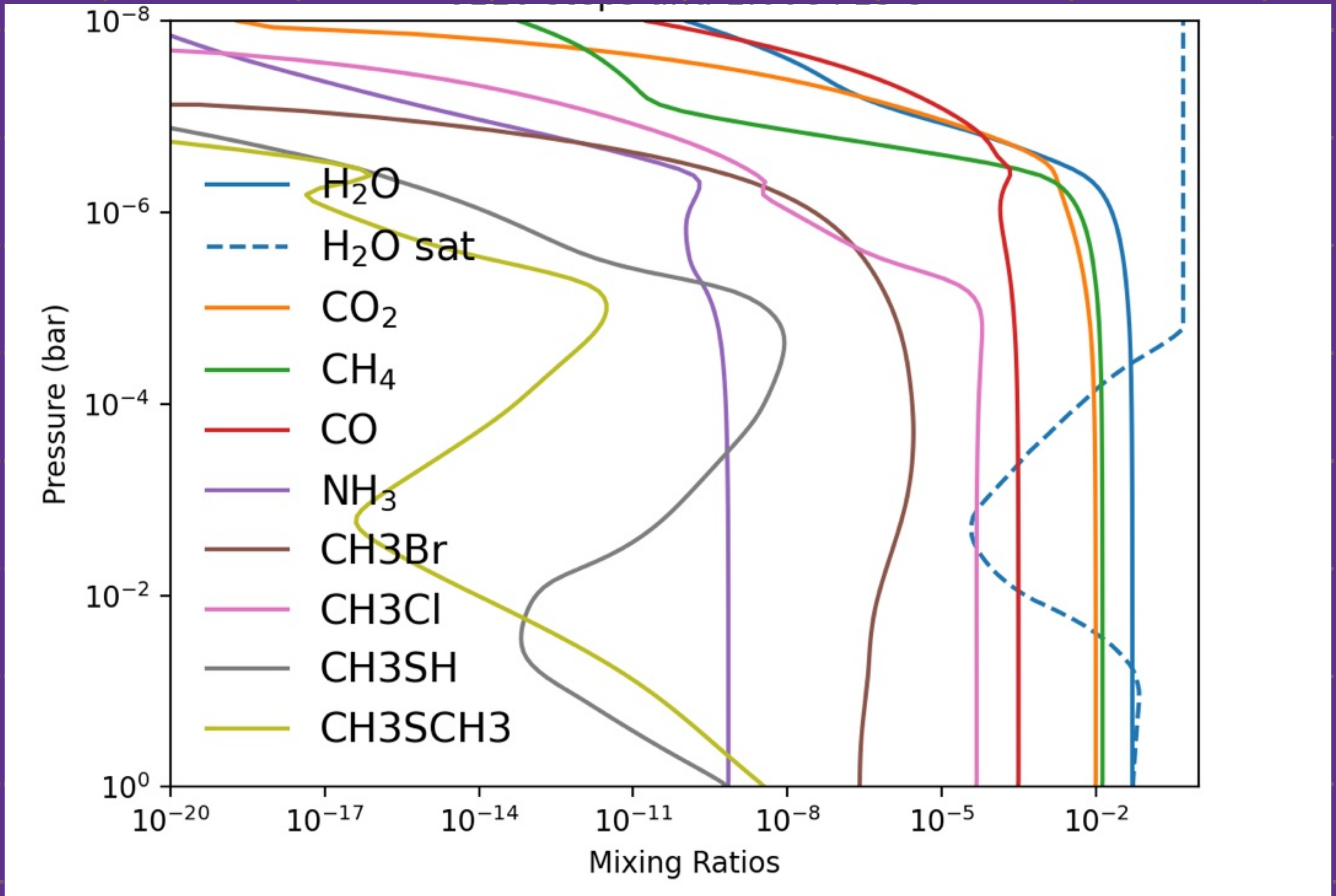
Future work





?

Preview – CH_3Cl may exceed ppm levels on Hycean type worlds for Earth-like fluxes



VULCAN, Tsai et al., 2024 K2-18b template

Section Takeaways

- Methylated halogens have a number of advantages as potential biosignatures due to their commonality and close ties to biological processes.
- Combined CH_3Cl and CH_3Br features may be detectable with future mid infrared missions such as LIFE.
- Future work will evaluate CH_3I and polyhalomethanes as well as exploring detectability in super-Earth atmospheres.

Methyl halides are only scratching the surface of methylated biogenic gases

Methylated Halogens

- CH_3Cl
- CH_2Cl_2
- $CHCl_3$
- CCl_4
- CH_3Br
- $CHBr_3$
- CBr_4
- CH_2BrCl
- $CHBr_2Cl$
- CH_3I
- CH_2I_2
- CHI_3
- $(CH_3)_2CHI$
- CH_2IBr
- $CHIBr_2$

Methylated Chalcogens

- $(CH_3)_2S$
- $(CH_3)_2S_2$
- CH_3SH
- $(CH_3)_2Se$
- $(CH_3)_2Se_2$
- CH_3SeS
- $(CH_3)_2SeS$
- CH_3SeH
- $(CH_3)_2Te$
- $(CH_3)_2Te_2$

Methylated Metal(loids)

- $(CH_3)_3As$
- $(CH_3)_2AsOH$
- $(CH_3)_3Sb$
- $(CH_3)_3Bi$
- $(CH_3)_2Hg$

Methylmercury as a sample organometallic biosignature

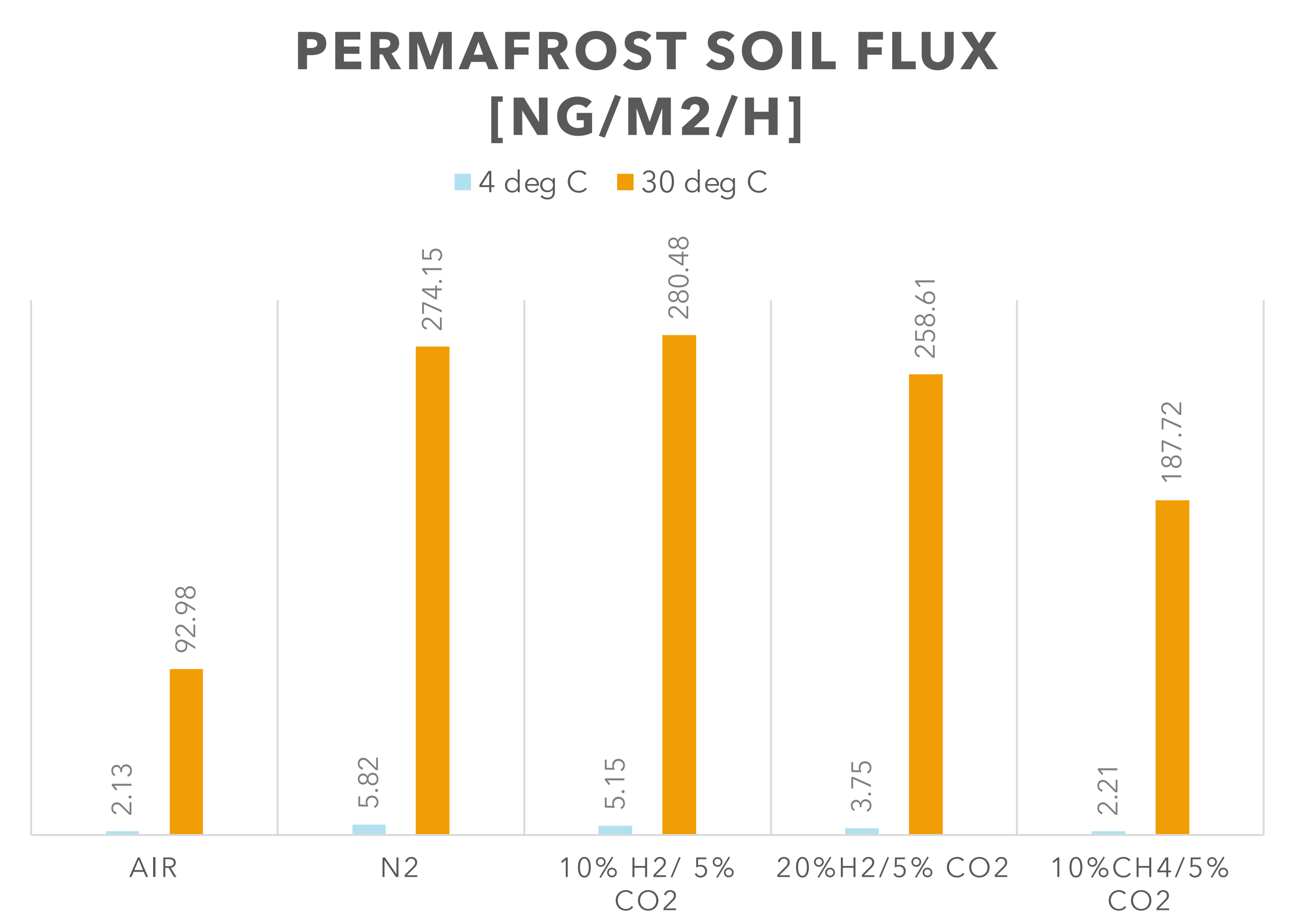
Vertically integrated simulations

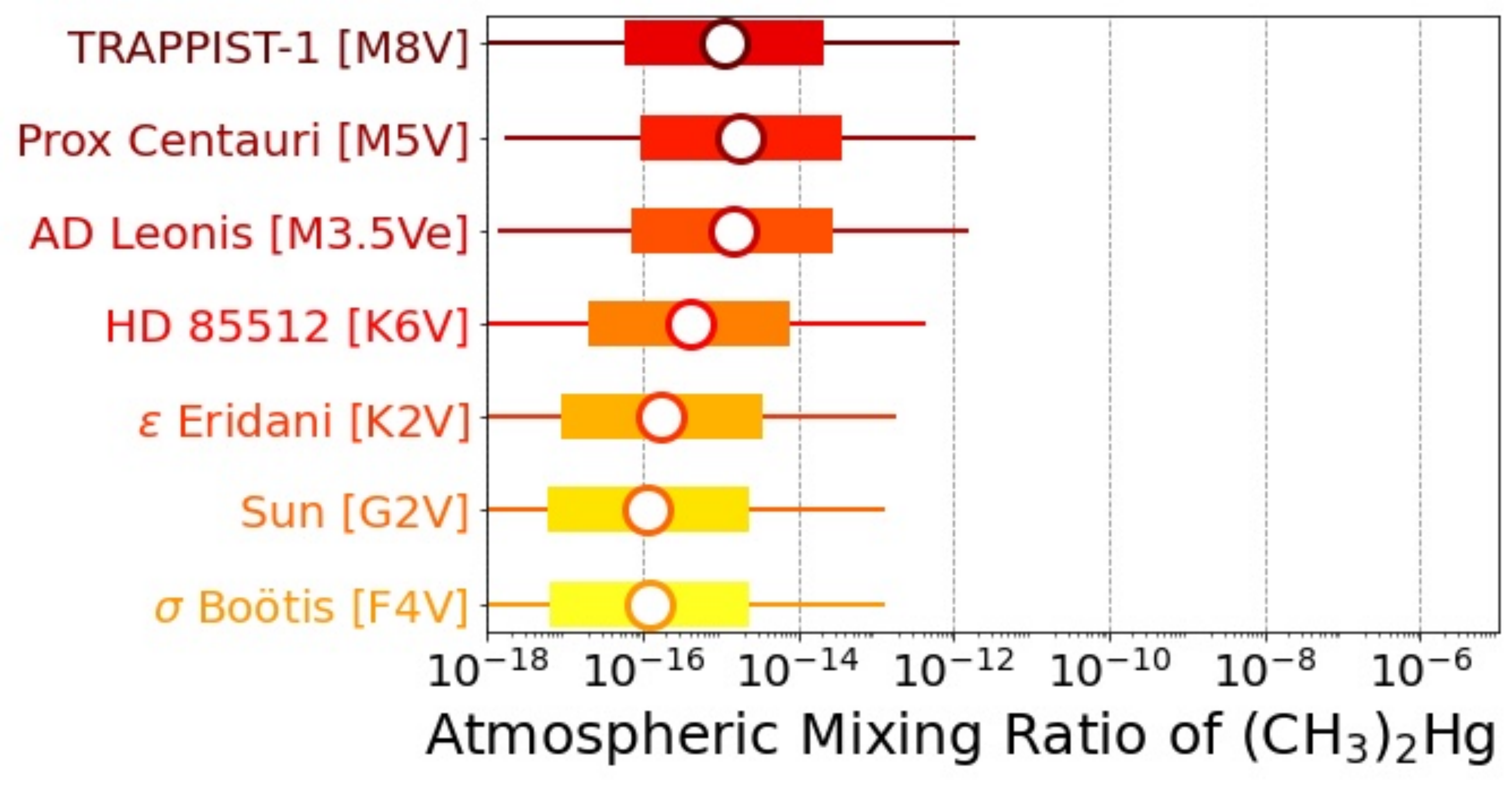
Flux measurements (laboratory)	For a variety of atmospheric conditions
Photochemical modeling	To determine atmospheric composition via chemical processing For a variety of stellar types
Spectral modeling	simulated observations for telescope configurations

Laboratory flux measurements

Ziming Yang
Oakland University

Expert in arctic soils and methylmercury measurements



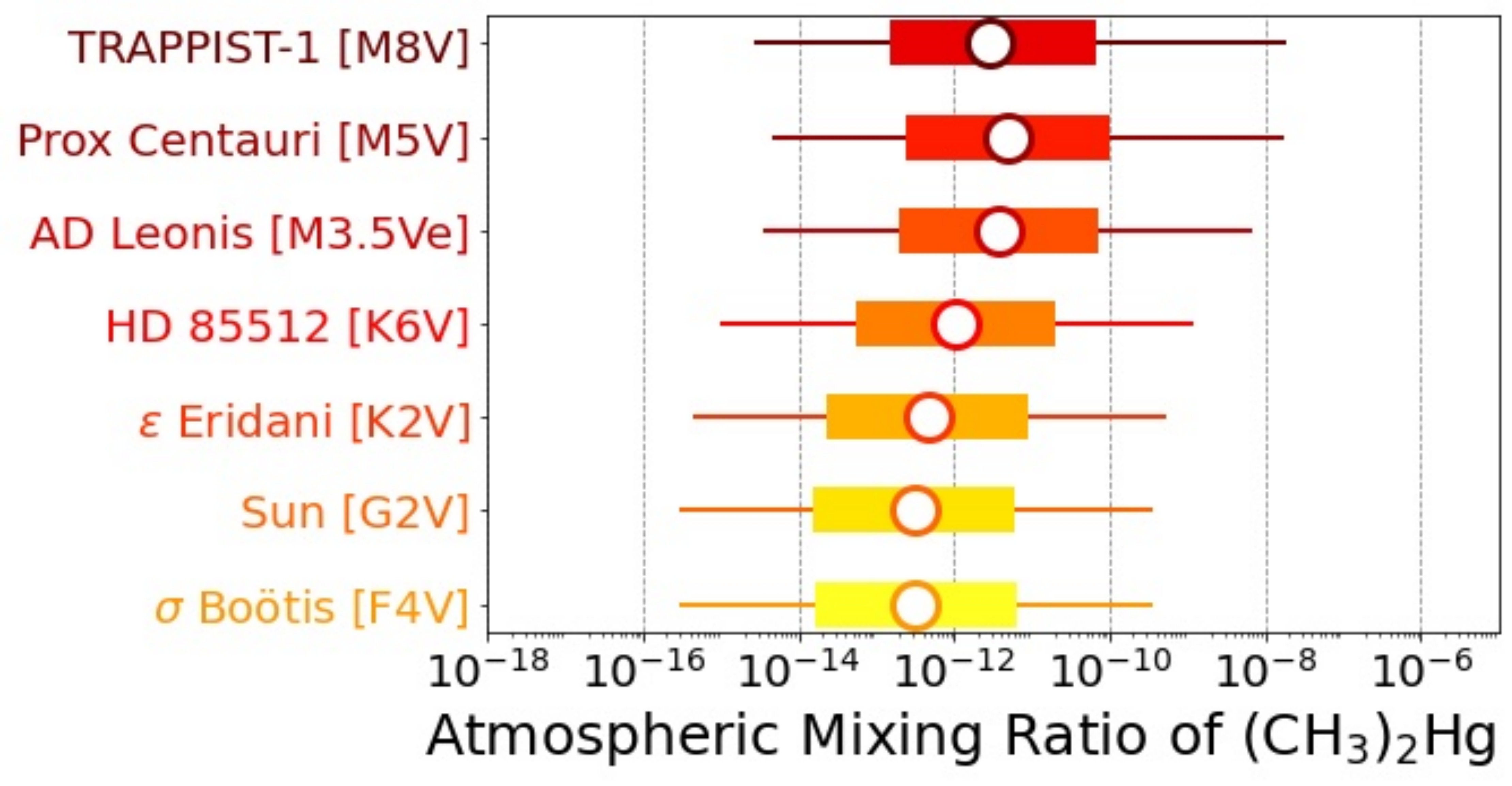


Earth-like flux

0.1 – 10x Earth-like flux

0.001 – 1000x Earth-like flux

Literature input flux



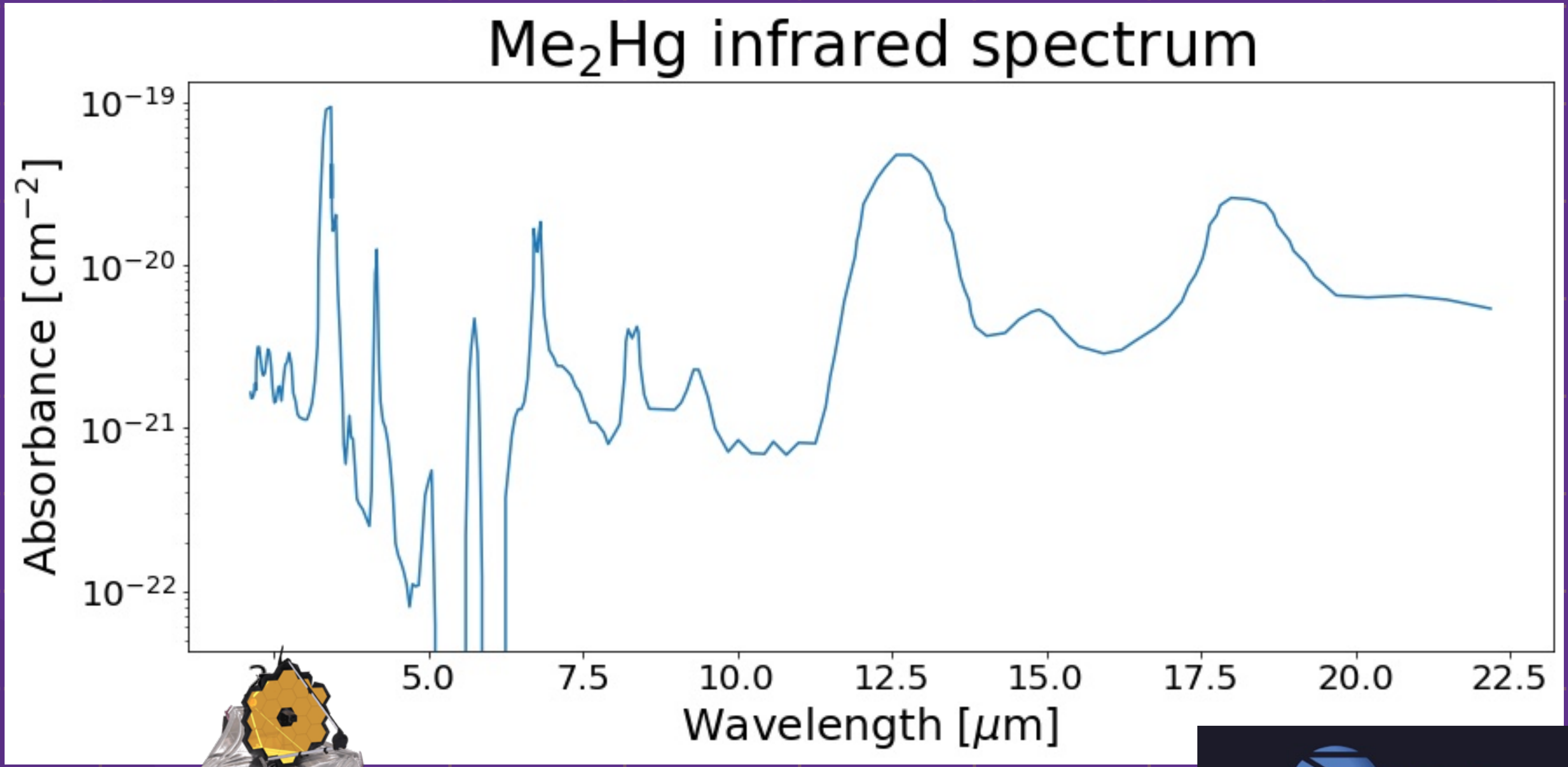
Earth-like flux

0.1 – 10x Earth-like flux

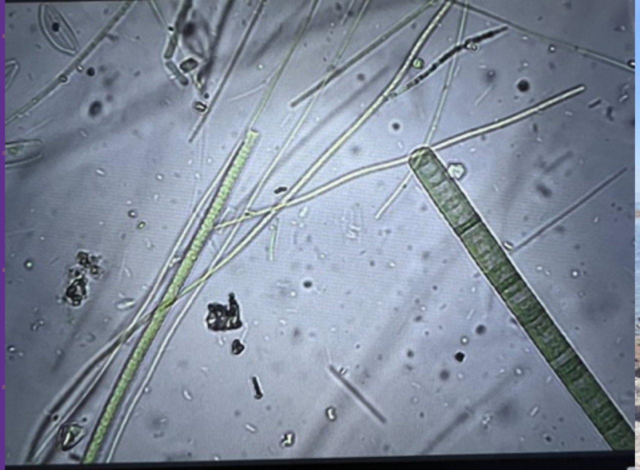
0.001 – 1000x Earth-like flux

Laboratory input flux

Next step: self consistent Hycean photochemical and spectral simulations



Fieldwork @ the Salton Sea to collect gas flux inputs (August 2023)



Collaborator: Niki Parenteau, NASA Ames Research Center

Section Takeaways

- Laboratory measurements to explore alternative planetary conditions are critical for understanding biosignature application.
- $(CH_3)_2Hg$ production is greatest under H_2-dominated temperate conditions.
- Further work will explore self consistent Hycean simulations.

Acknowledgments

- Advisor: Eddie Schwieterman
- Collaborators: Niki Parenteau, Thomas Fauchez, Shami Tsai, Ziming Yang, Akhil Benny
- Schwieterman Lab @ UCR

Conclusions

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- mleun019@ucr.edu

- Graduating June 2025 ☺

- Methylated gases may be applicable as biosignatures in a variety of planetary contexts.
- Increases in atmospheric accumulation for later type stars make methylated gases within reach with next generation mid-infrared telescopes such as the LIFE concept.
- Simulations of potential biosignatures require high quality context specific input measurements.

LIFE paper

CH_3Br paper

Additional work: applications of photochemical and spectral models

ExCITE-PM collaboration

The Astrophysical Journal Letters, 958:L15 (18pp), 2023 November 20
https://doi.org/10.3847/2041-8213/ad037c

The Importance of the Upper Atmosphere to CO/O_2 Runaway on Habitable Planets Orbiting Low-mass Stars

Sukrit Ranjan[1,2,3], Edward W. Schwieterman[3,4], Michaela Leung[4], Chester E. Harman[5], and Renyu Hu[6,7]
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[2] Center for Interdisciplinary Exploration and Research in Astrophysics/Department of Physics and Astronomy, Northwestern University, Evanston, IL 60201, USA
[3] Blue Marble Space Institute of Science, Seattle, WA 98104, USA
[4] Department of Earth and Planetary Sciences, University of California at Riverside, Riverside, CA 92521, USA
[5] Planetary Systems Branch, Space Science and Astrobiology Division, NASA Ames Research Center, Moffett Field, CA 94035, USA
[6] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[7] Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA
Received 2023 July 17; revised 2023 October 6; accepted 2023 October 9; published 2023 November 21

Modeling Atmospheric Lines By the Exoplanet Community (MALBEC) version 1.0: A CUISINES radiative transfer intercomparison project

Just accepted to PSJ

Other collaborations

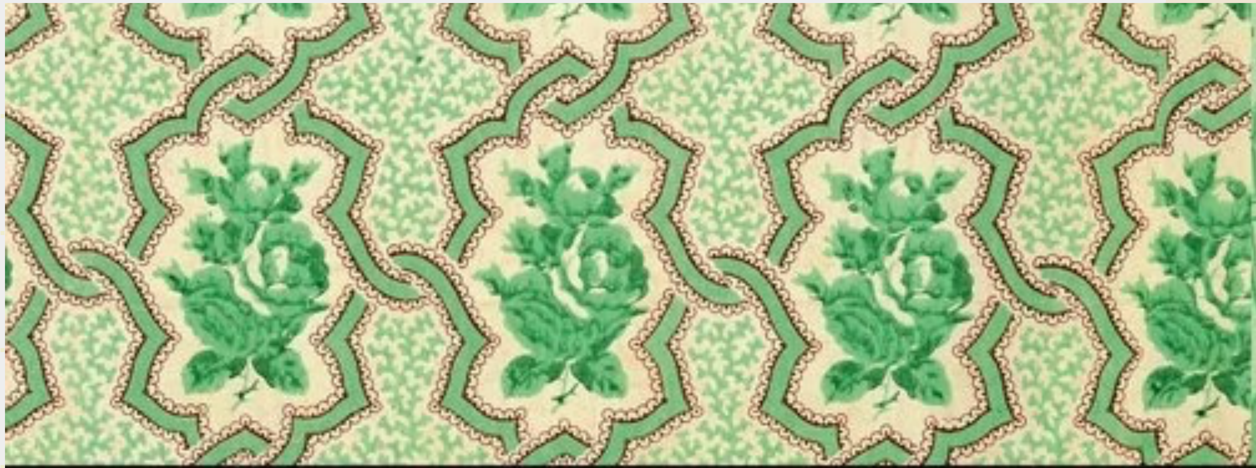
- CUISINES model intercomparisons
  - Photochemical Intercomparison for Exoplanets (PIE) ; protocol paper in prep
- Estimating pi with PIE: Constraining the Population Proportion of M-Dwarf Planetary Atmospheres with Planetary Infrared Excess (PI: Kristin Sotzen, JHU APL)
  - Photochemical and spectral simulations for non transiting planet detection pipeline

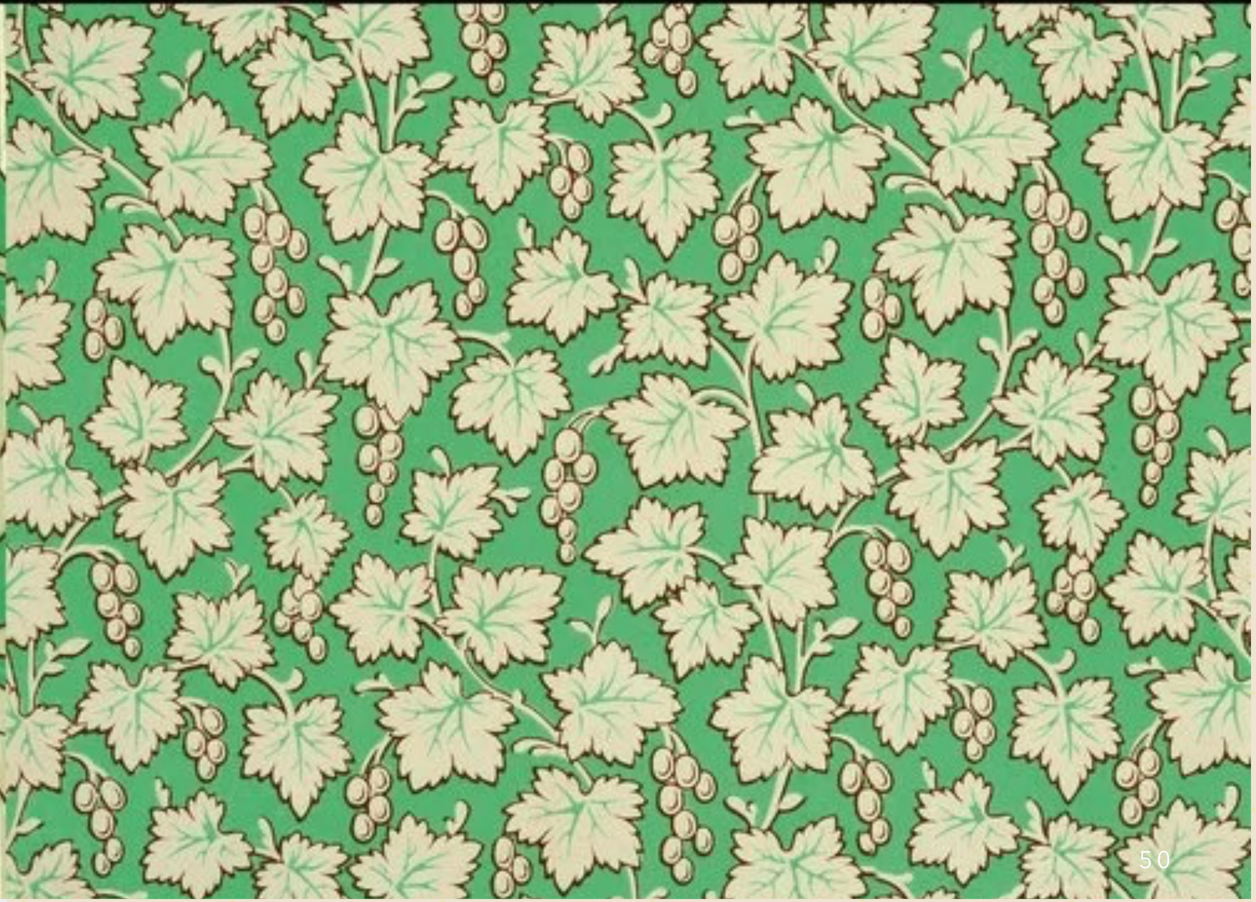
Field and Laboratory Measurements of Methylated Biogenic Gases with Implications for Astrobiology and Earth Science Research

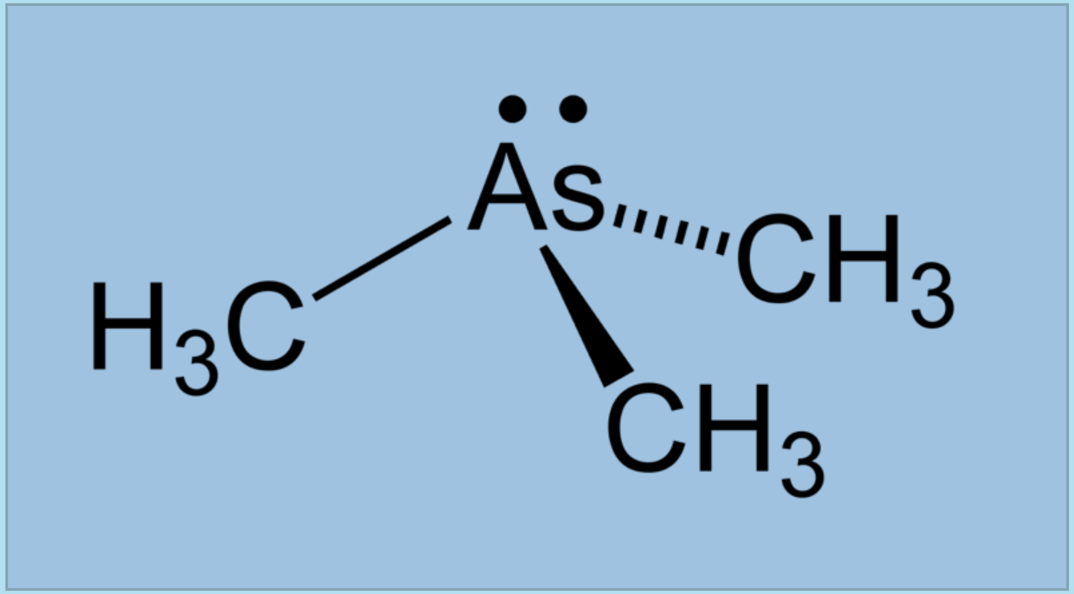
(proposal #2)

Motivation

What are methylated gases?



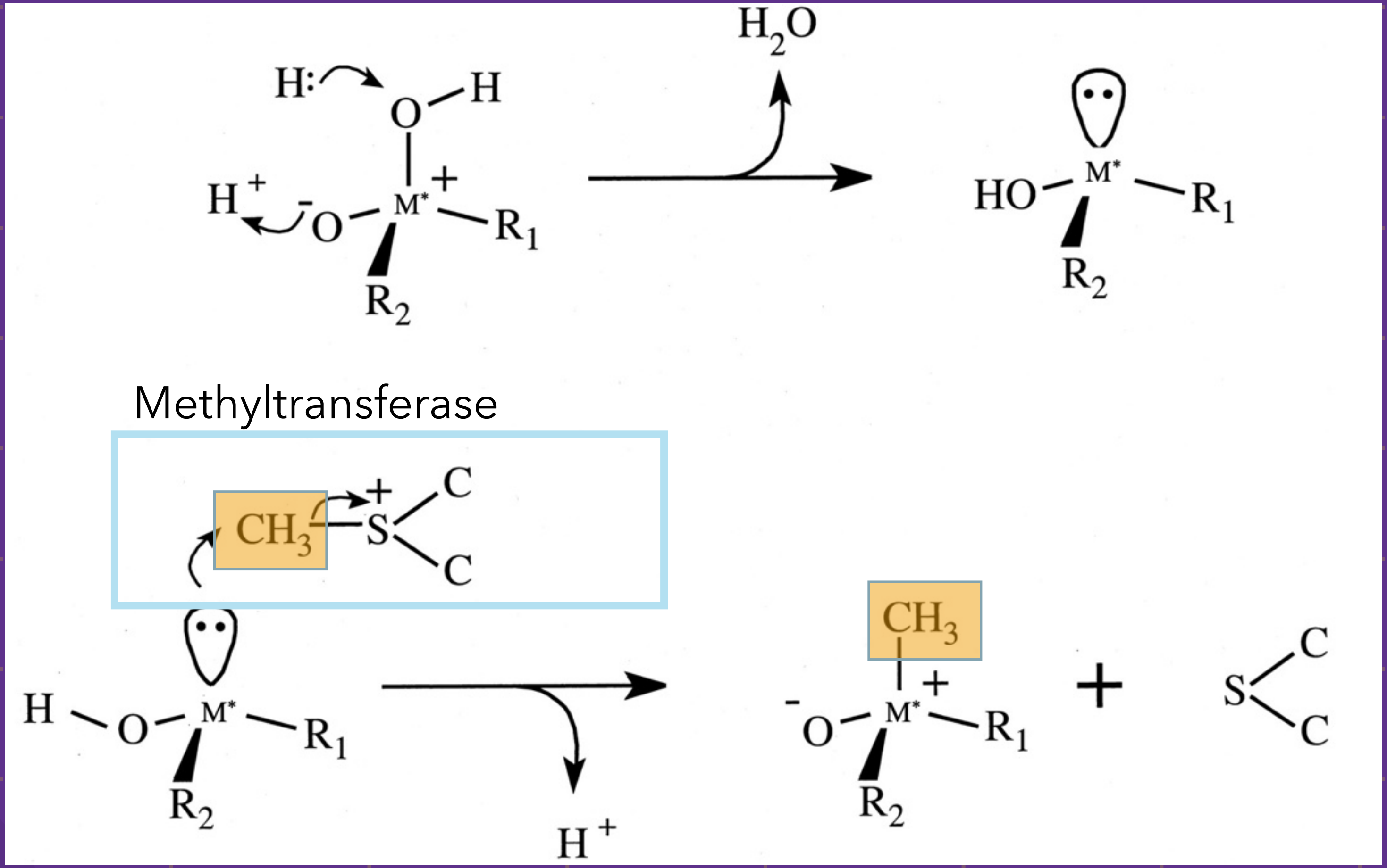





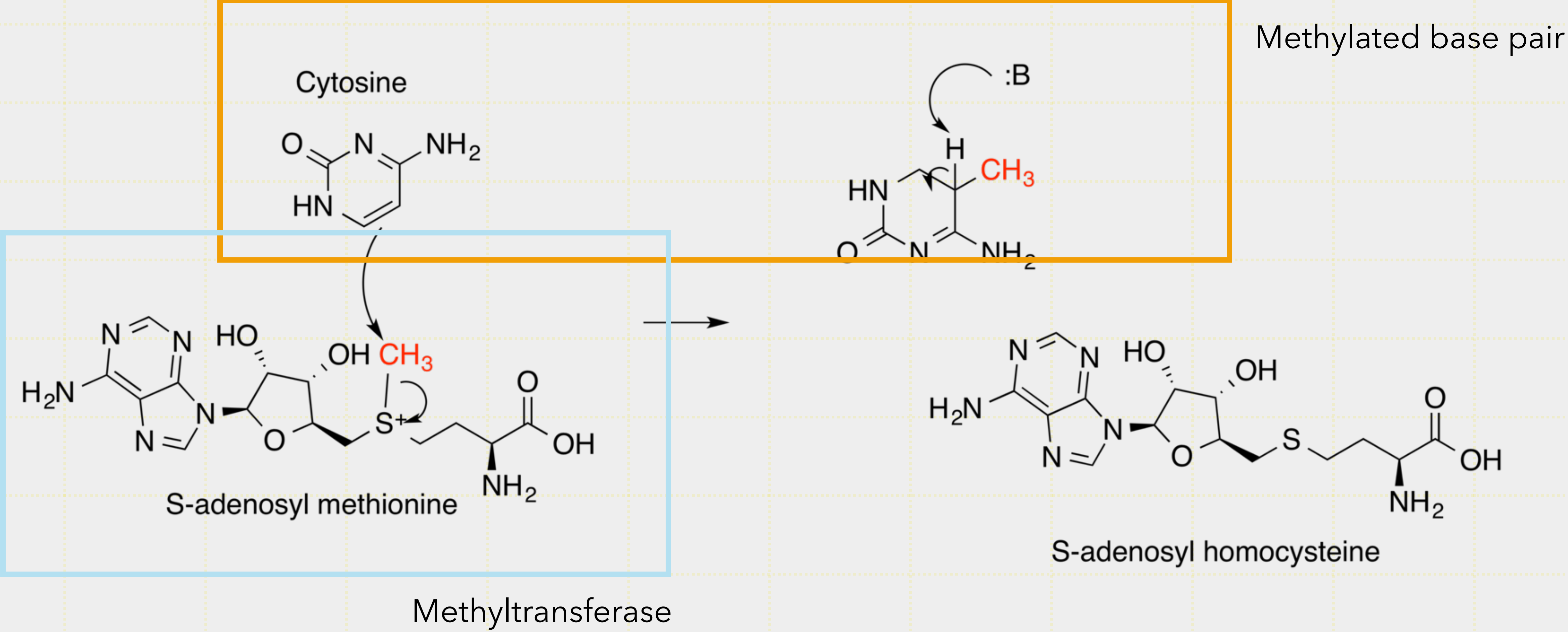
Trimethylarsenide is produced as a volatilization of environmental As

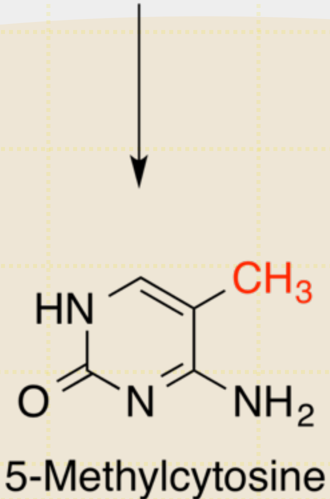
Fungi such as Scopolariopsis perform the methylation

The Challenger Mechanism



Manley and Chasteen 2002





Volatile methylation comes from DNA methylation, a widespread process seen in bacteria, plants, and animals

Image: wikipedia

Methylation utilizes many environmental substrates

Methylated Halogens

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- $CHCl_3$
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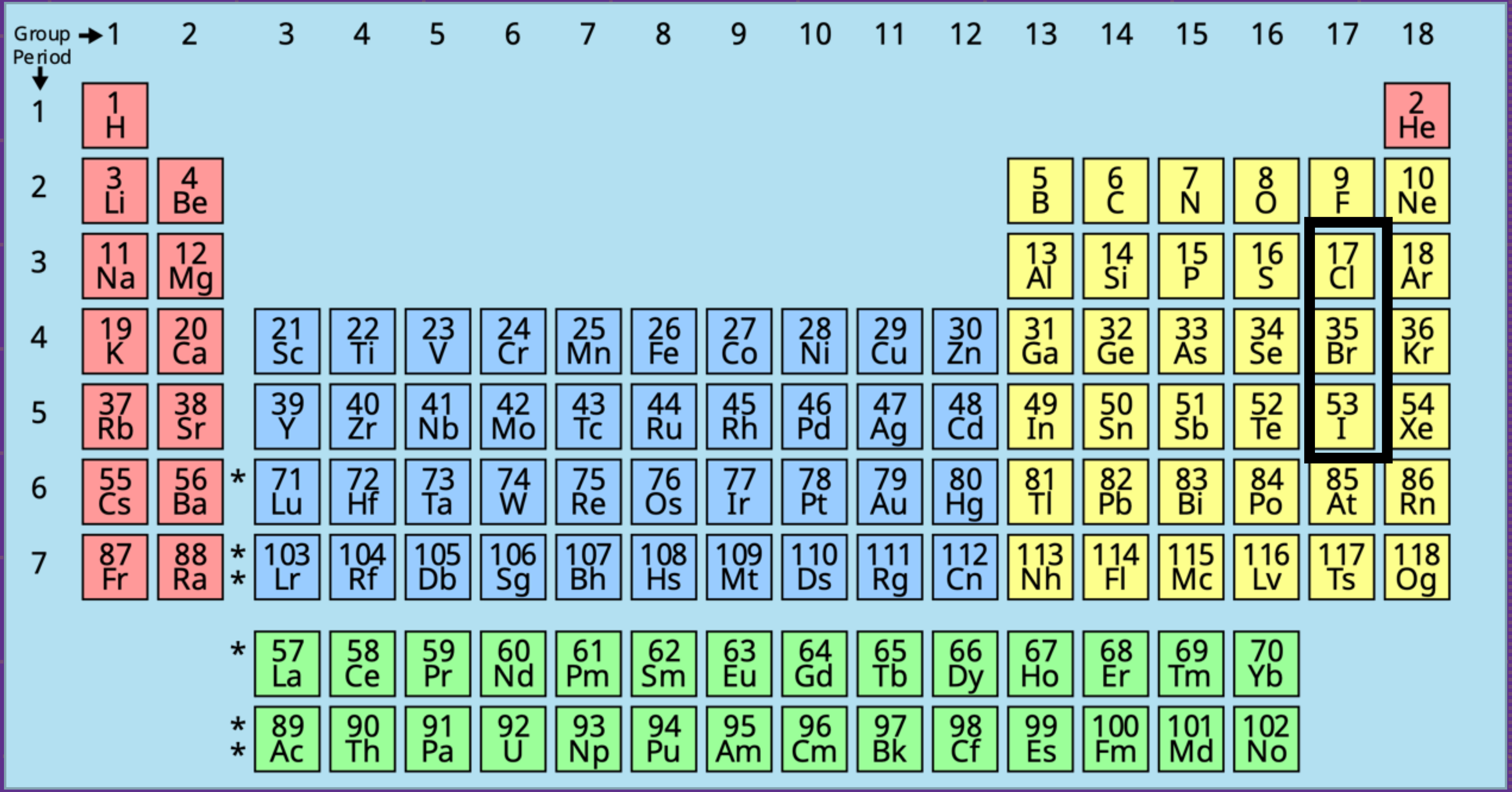

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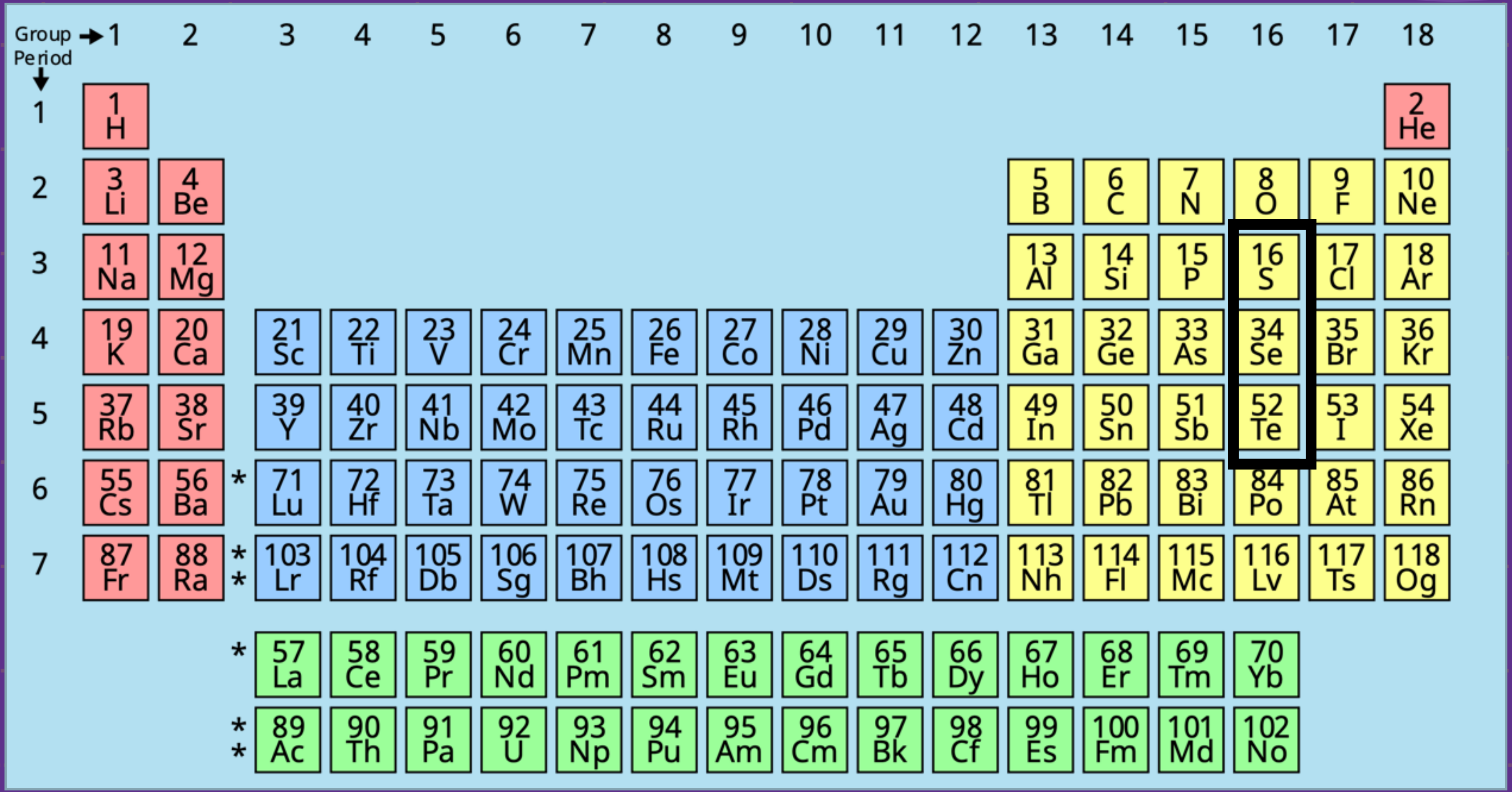
- $(CH_3)_2SeS$
- CH_3SeH
- $(CH_3)_2Te$
- $(CH_3)_2Te_2$



Methylation utilizes many environmental substrates

Methylated Metal(loids)

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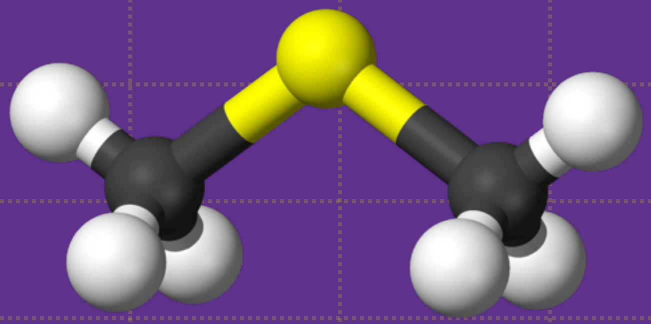
- $(CH_3)_2AsOH$
- $(CH_3)_3Sb$
- $(CH_3)_3Bi$
- $(CH_3)_2Hg$

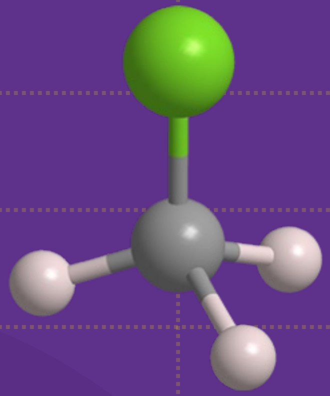
Group → / Period ↓	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

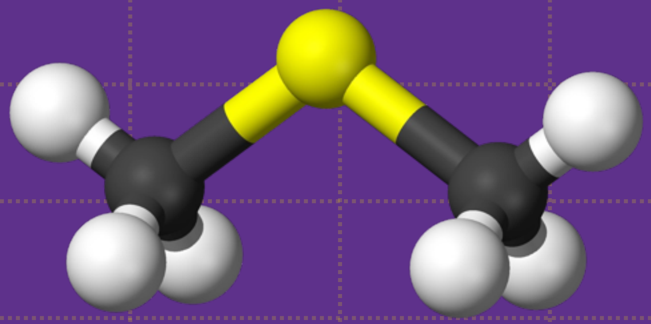
Methylated gases have applications to:

- Bioremediation
- Ozone monitoring (Halogens)
- Improving understanding of modern biogeochemical cycling of deep time proxies such as Se and I
- Exoplanet biosignatures



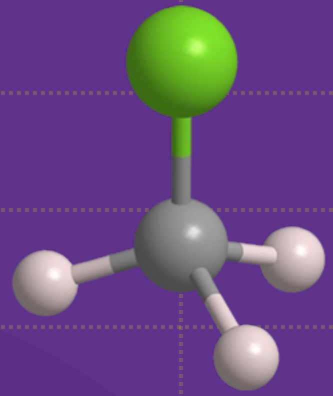
Methylation is a highly flexible and widespread process

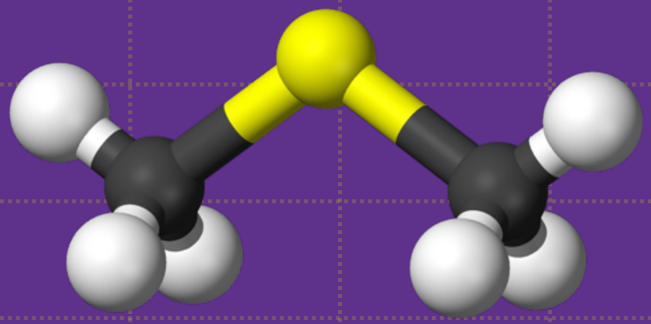


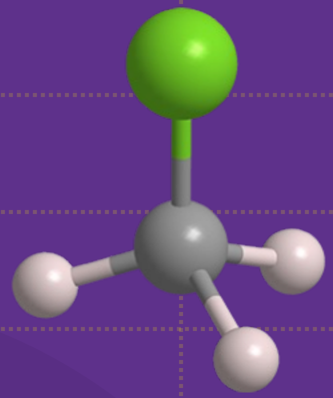


Methylation is a highly flexible and widespread process

With significant application potential







Methylation is a highly flexible and widespread process

With significant application potential

However, methylated gas fluxes are poorly constrained

Methylated gas fluxes may depend on substrate availability

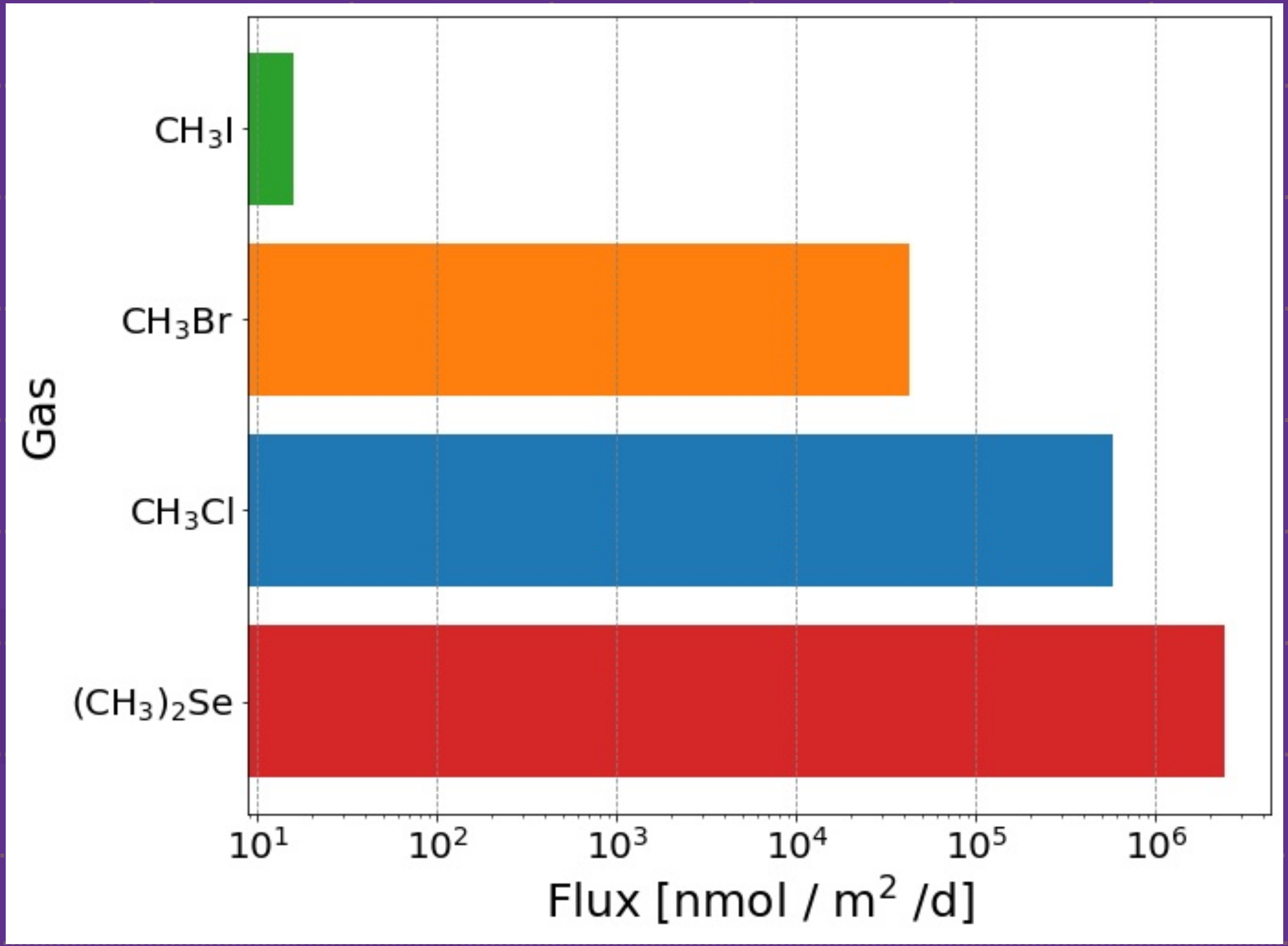
Most flux studies occur under laboratory conditions with artificial substrate levels

Substrate availability may highly regulate fluxes of methylated gases

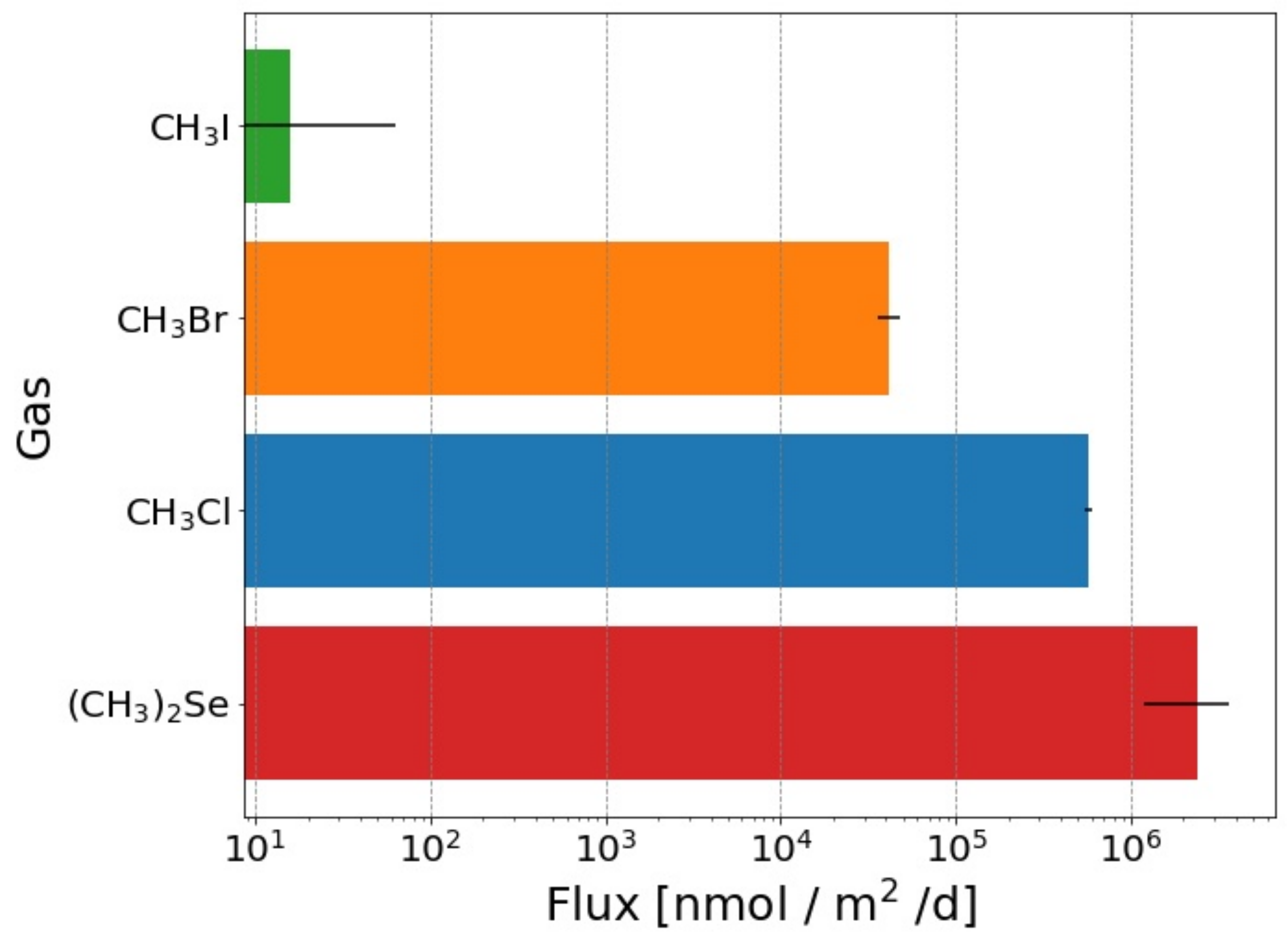
Local environments may strongly affect the production of methylated gases in an Earth or planetary system setting

Understanding of most productive conditions necessary for best application

Review of available flux data



Review of available flux data



First published: 15 May 1999

Published: 20 January 2000

Published: 20 January 2000

First published: 01 July 1996

In situ field campaign

I propose to measure *in situ* fluxes at a variety of environments in the Norris Geyser Basin at Yellowstone National Park

Yellowstone hydrothermal waters have high concentrations of potential substrates

Norris Geyser Basin waters largely preserve original geothermal water composition

In situ field campaign

I propose to measure *in situ* fluxes at a variety of environments in the Norris Geyser Basin at YNP with **known high potential substrate values**

- *Pearl Geyser (high As concentrations)*
- *Perpetual Spouter (high Cl concentrations)*
- *Dragon Spring (methylated As fluxes & genomes recorded)*
- *Unnamed high Se site*

Field methods

Qin et al., 2009 showing cyanidiales mats at the Dragon Spring

Hiden membrane inlet mass spectrometer

Measure in situ gas fluxes using membrane inlet mass spectrometer

- Probe can be directly inserted into water

Collect microbial mat samples and return to ARC lab

M. N. Parenteau
NASA Ames

Laboratory methods

Explore growth in anoxic conditions

Compare YNP samples to maintained laboratory Guererro Negro hypersaline mats

Explore diel sensitivity and photosynthetic response

Use extant 16S rRNA data if methylated gases recorded from Guererro Negro mats

Send field samples for 16S rRNA sequencing (collaboration with Joint Genome Institute)

2023
Field

Field collection of mat samples and in situ measurements

2024
Laboratory

Diel experiments & anoxic tests

Publication of results

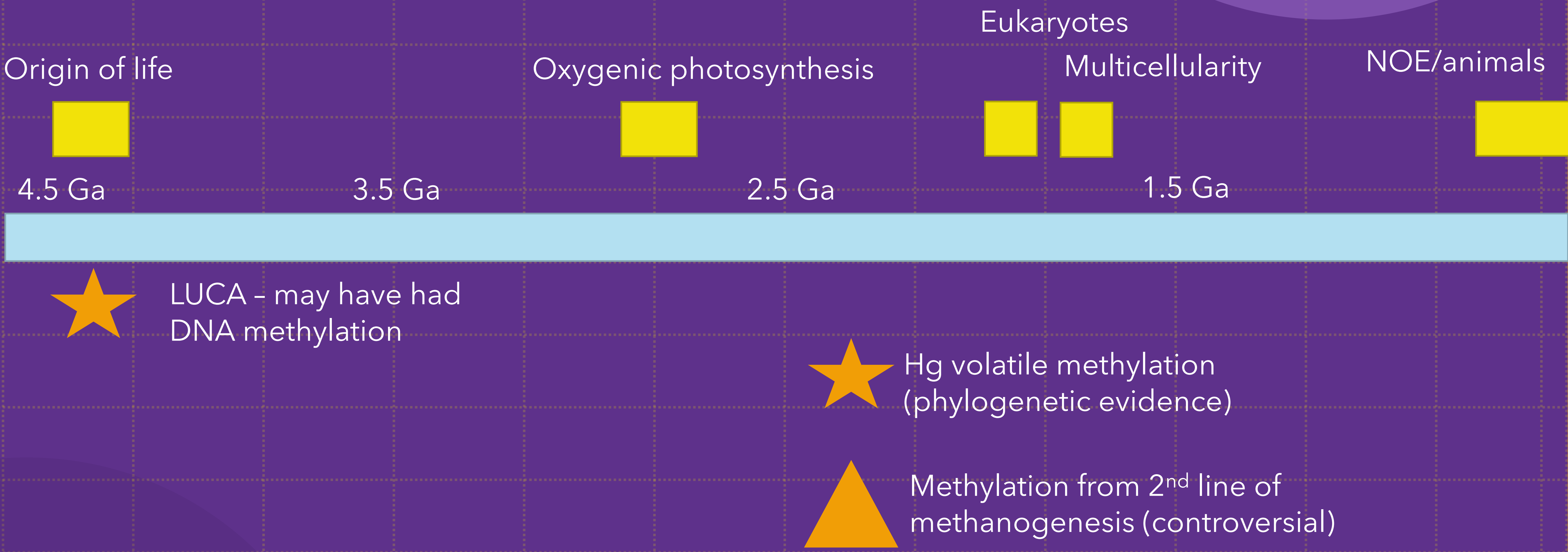
Guererro Negro mat methylated gas measurements

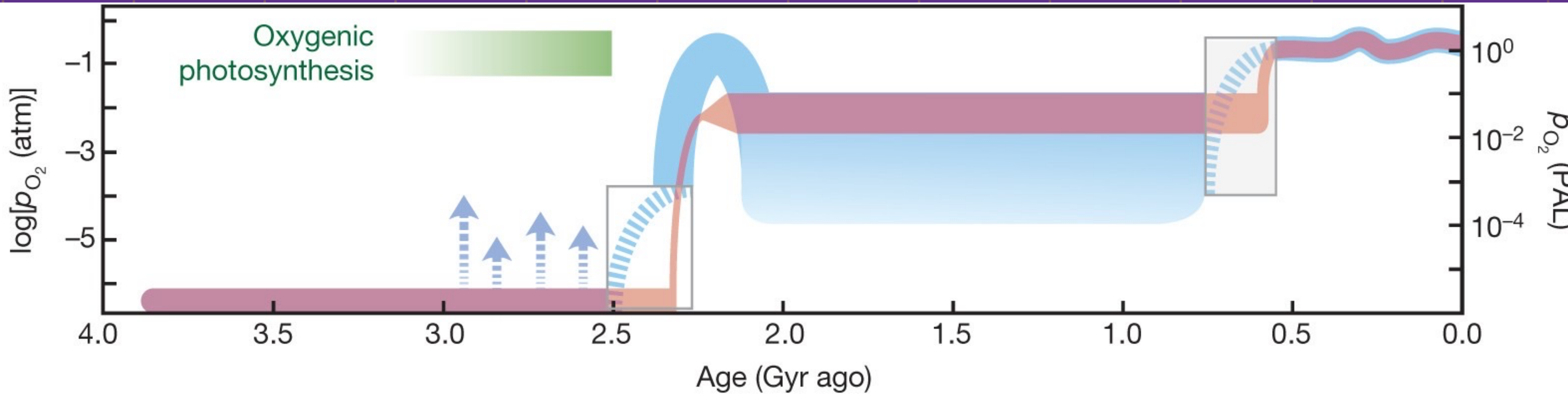
2025
Laboratory/Synthesis

Metagenomic Analysis

Publication of results

Questions / coffee break


Eukaryotes
Origin of life
Oxygenic photosynthesis
Multicellularity
NOE/animals
4.5 Ga
3.5 Ga
2.5 Ga
1.5 Ga
LUCA – may have had DNA methylation
Hg volatile methylation (phylogenetic evidence)
Methylation from 2nd line of methanogenesis (controversial)


Oxygenic
photosynthesis
log[p_{O_2} (atm)]
–1
–3
–5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Age (Gyr ago)
10^0
10^{-2}
10^{-4}
p_{O_2} (PAL)

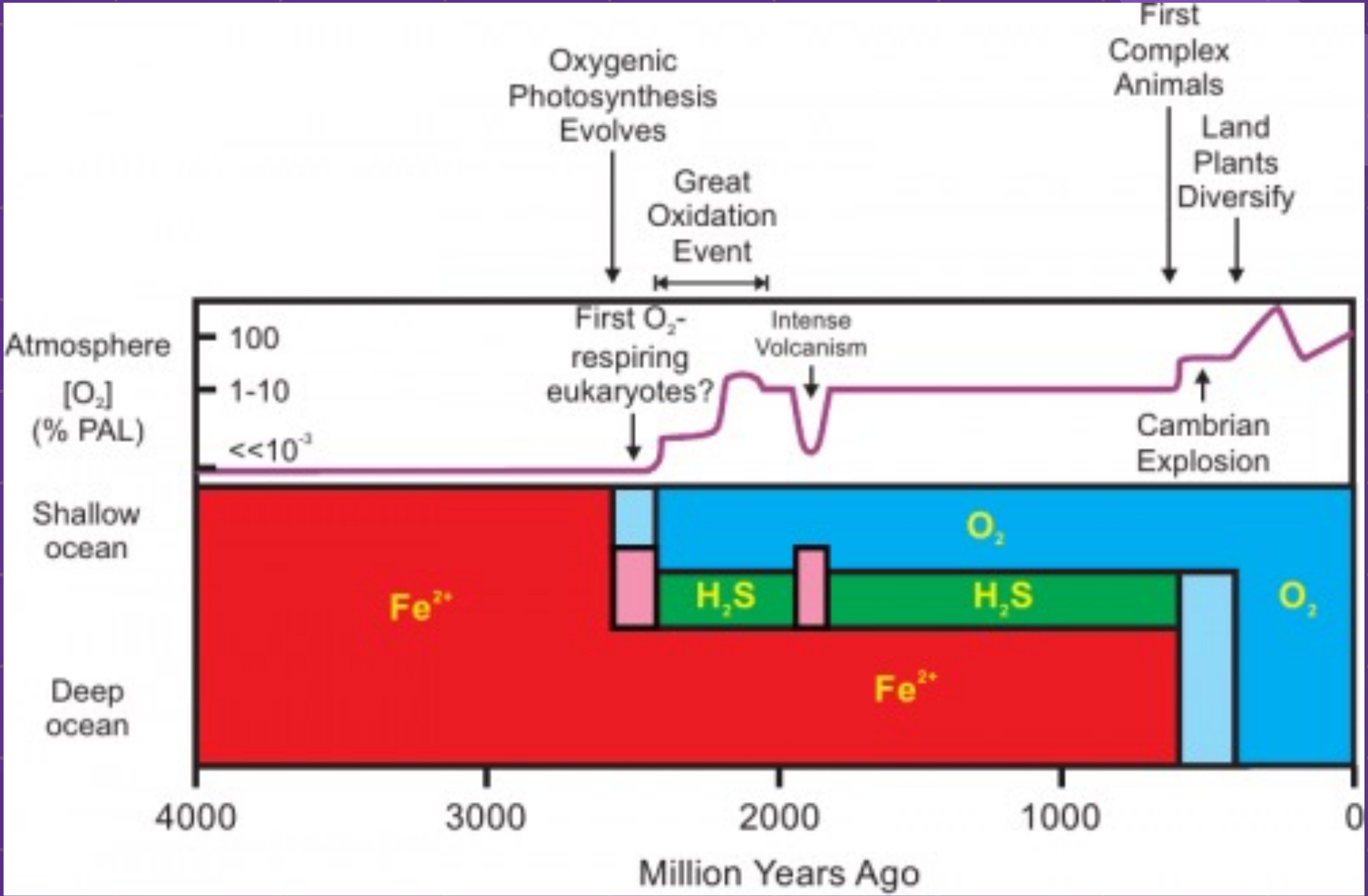
Build up scenarios

Earlier origin and wider radiation of volatile methylation

More highly productive environments

Productive envs can be produced by silicate weathering; older planet with weathering?

More efficient enzyme/process


First
Complex
Animals
Oxygenic
Photosynthesis
Evolves
Land
Plants
Diversify
Great
Oxidation
Event
Atmosphere
[O2]
(% PAL)
100
1-10
<<10-3
First O2-
respiring
eukaryotes?
Intense
Volcanism
Cambrian
Explosion
Shallow
ocean
Deep
ocean
Fe2+
O2
H2S
H2S
O2
Fe2+
4000
3000
2000
1000
0
Million Years Ago

Relative Solubility

CH_3Cl
5g/L

CH_3Br
15 g/L

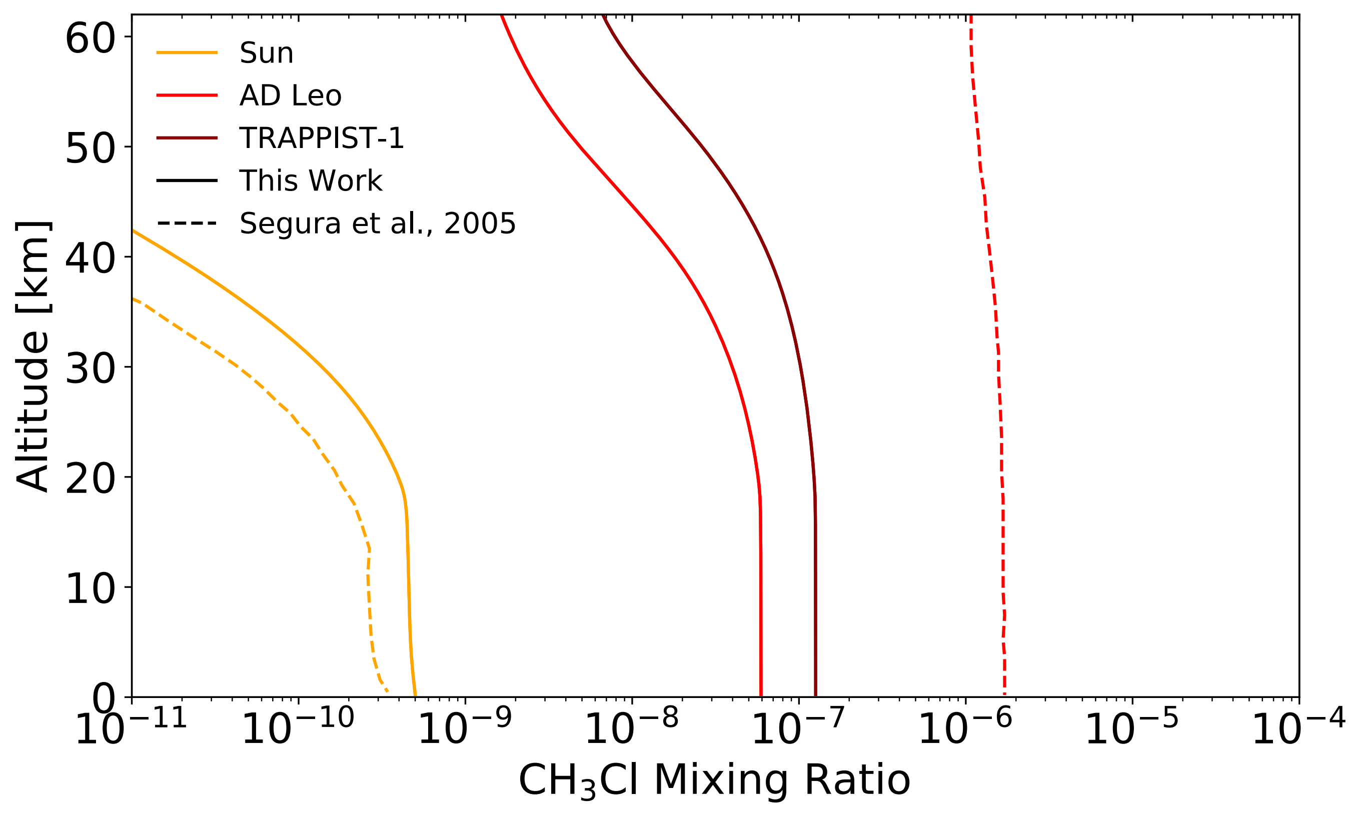
CH_4
20g/L

NaCl
36 g/L

CH_3Cl: Revisited

- Significant changes have been made to atmos since Segura et al., (2005) including updating all reaction rates
  - Domagal-Goldman et al (2011)
  - Arney et al (2016)
  - Lincowski et al (2018)
  - Teal et al (2022)

- Our version of the code produces lower estimates than previous results with CH_3Cl but maintains the same overall conclusions
  - Flux: 2.25 x 10^8 molec/cm^2/s or 3.08 Tg/yr
  - Surface MR: 0.5 ppb



Methylated gas consumption

Dominant sink temperate forest soils

Annual soil sink of CH_3Br (best studied) – 42 Gg/yr

(30% of global avg flux)

At higher dosing levels, CH_3Br is poisonous so it is not uptaken

In highly productive environments, uptake rate lower (< 1Gg/yr)

Expect trend to hold for other methylated gases

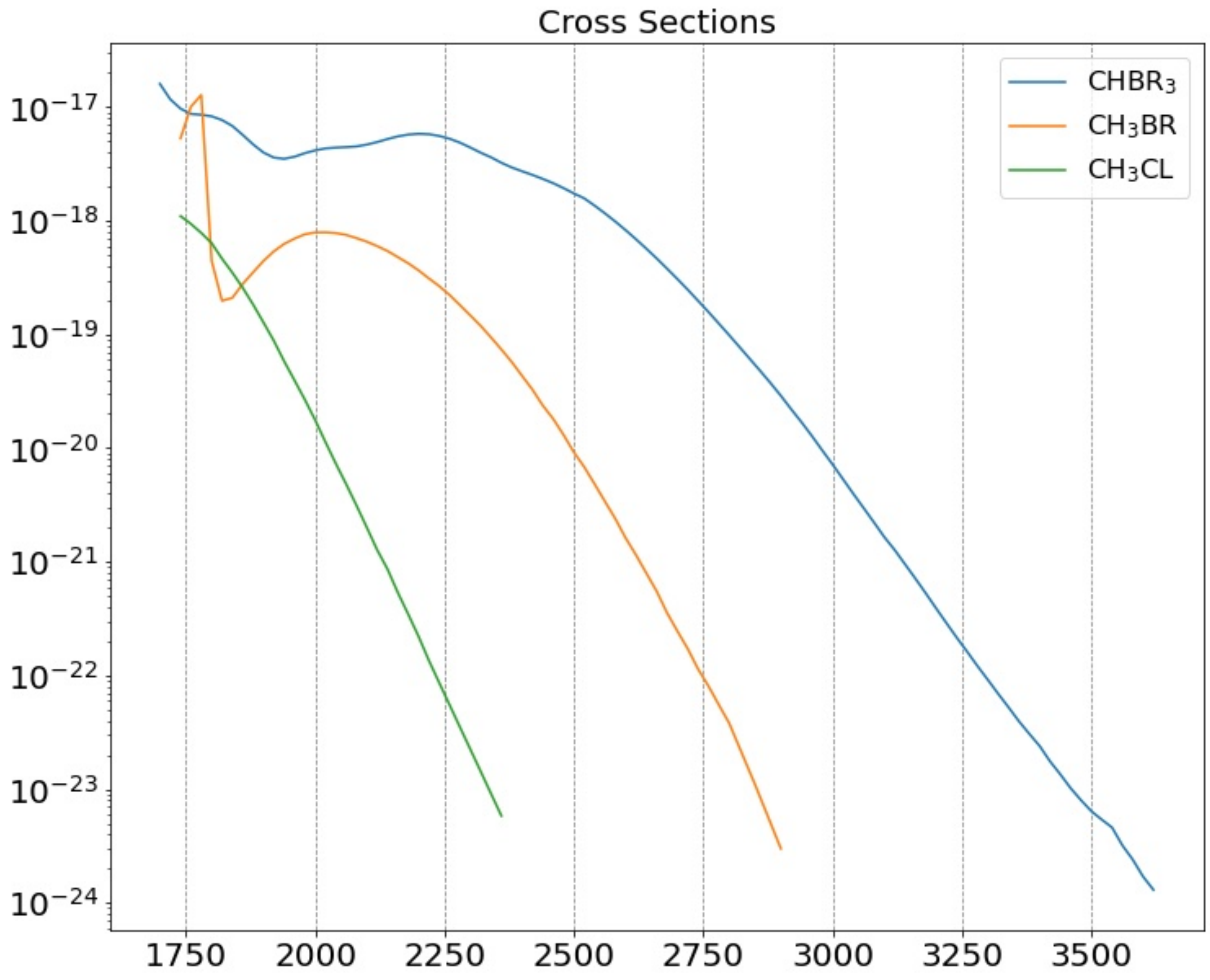
Limited but similar research for CH_3Cl

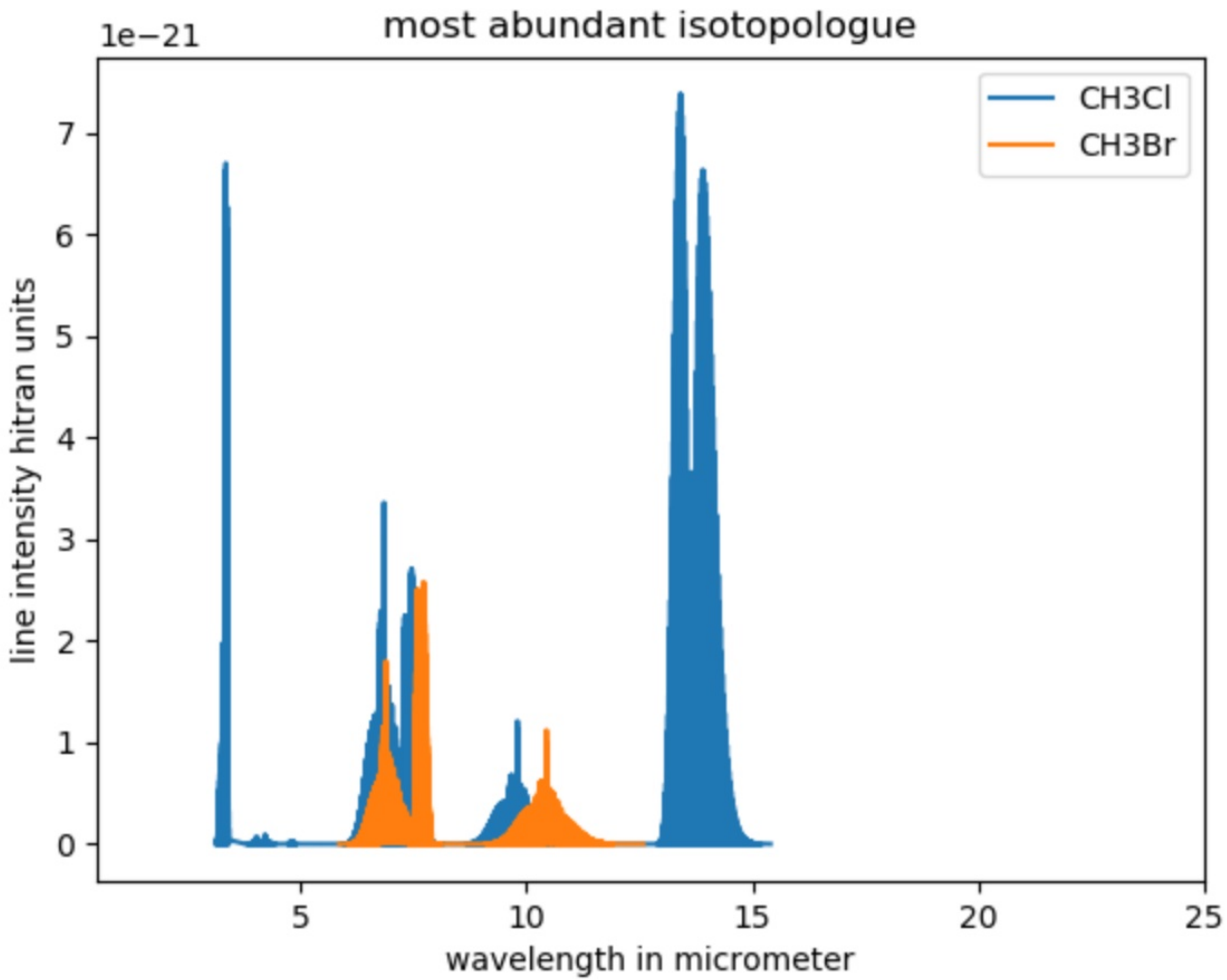
Halogens in the Environment

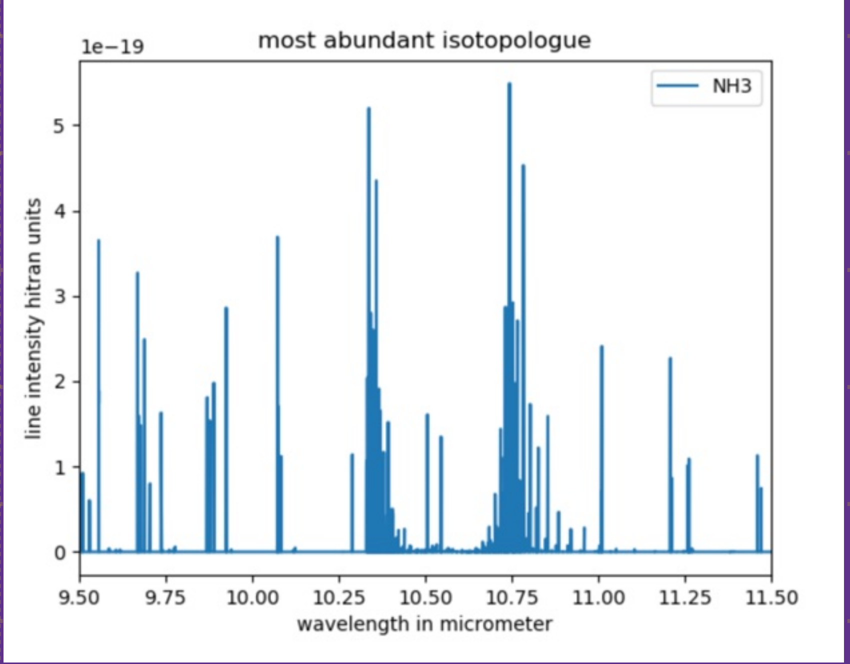
- F & Cl substitute into hydroxysilicates & appear in rare silicate minerals
- Br & I adsorb onto surfaces & can build up in marine seds
- Cl/Br/I enriched in marine sedimentary rocks
- F/Cl/Br lithophile, Cl/Br/I hydrophile, Br/I biophile, i/chalcophile

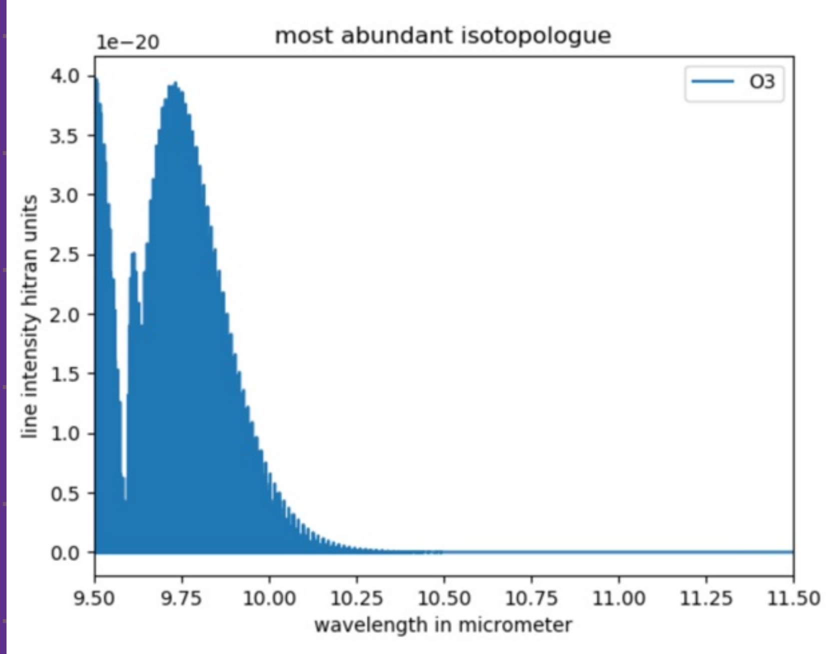
Chemical Species	Example Environments	Example Producers	Reference(s)
CH_3Cl	Marine, Terrestrial	Algae, Bacteria, Fungi, Plants	Tait & Moore (1995); Farhan Ul Haque et al. (2017)
$CHCl_3$	Marine, Terrestrial	Algae	Harper (1995); Macdonald et al. (2020)
CCl_4	Marine	Algae	Harper (1995)
CH_3Br	Marine	Algae, Bacteria	Paul & Pohnert (2011); Fujimori et al. (2012)
CH_2Br_2	Marine, Terrestrial	Algae	Montzka et al. (2011); Macdonald et al. (2020)
CH_2BrCl	Marine	Algae	Carpenter et al. (2003); Yokouchi et al. (2005)
CH_3I	Marine, Terrestrial	Algae, Bacteria	Manley et al. (1992, 2006)
CH_2I_2	Marine	Algae	Schall et al. (1994); Carpenter et al. (2003)
CHI_3	Marine	Algae, Bacteria	Carpenter et al. (2003); Fujimori et al. (2012)
$(CH_3)_2CHI$	Marine	Algae	Schall et al. (1997); Carpenter et al. (2003)
CH_2IBr	Marine	Algae	Carpenter et al. (2003)
$(CH_3)_2S$	Marine, Terrestrial	Algae, Bacteria	Stefels et al. (2007); Carrión et al. (2015)
$(CH_3)_2S_2$	Lacustrine, Marine, Terrestrial	Algae, Bacteria	Visscher et al. (2003); Hu et al. (2007)
$(CH_3)_2Se$	Lacustrine, Terrestrial	Bacteria, Fungi, Plants	Chau et al. (1976); Bañuelos et al. (2017)
$(CH_3)_2Se_2$	Lacustrine, Terrestrial	Bacteria, Fungi, Plants	Chau et al. (1976); Bañuelos et al. (2017)
CH_3SeS	Marine	Algae	Dungan et al. (2003)
$(CH_3)_2Te$	Laboratory / Potential Terrestrial	Bacteria, Fungi	Basnayake et al. (2001); Chasteen & Bentley (2003)
$(CH_3)_2Te_2$	Laboratory / Potential Terrestrial	Fungi	Chasteen & Bentley (2003)

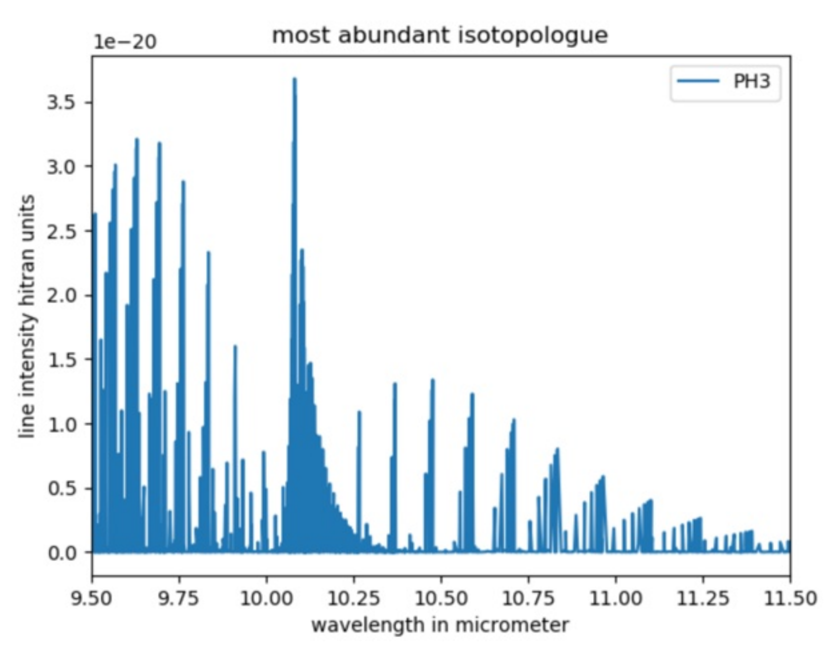
Selected gas flux production

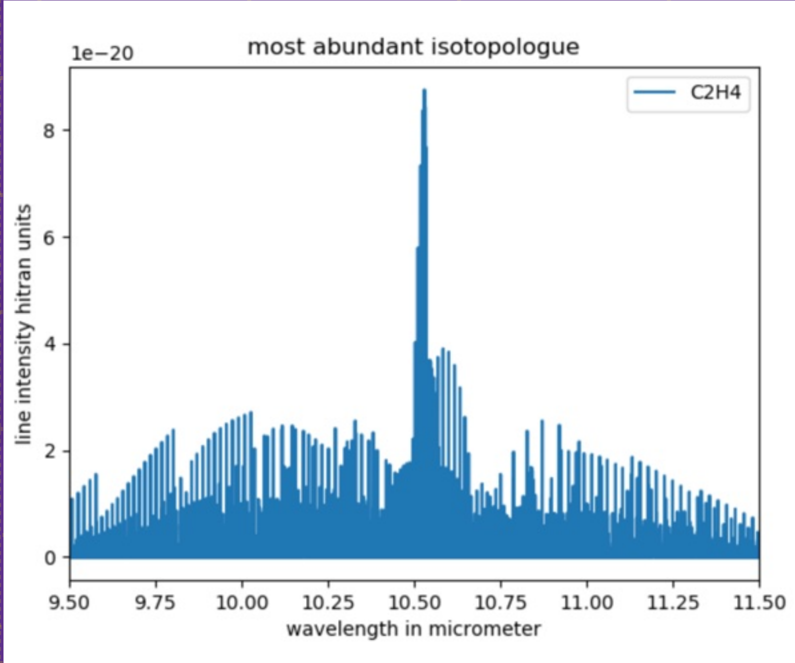

Cross Sections
CHBR3
CH3BR
CH3CL
10−17
10−18
10−19
10−20
10−21
10−22
10−23
10−24
1750
2000
2250
2500
2750
3000
3250
3500

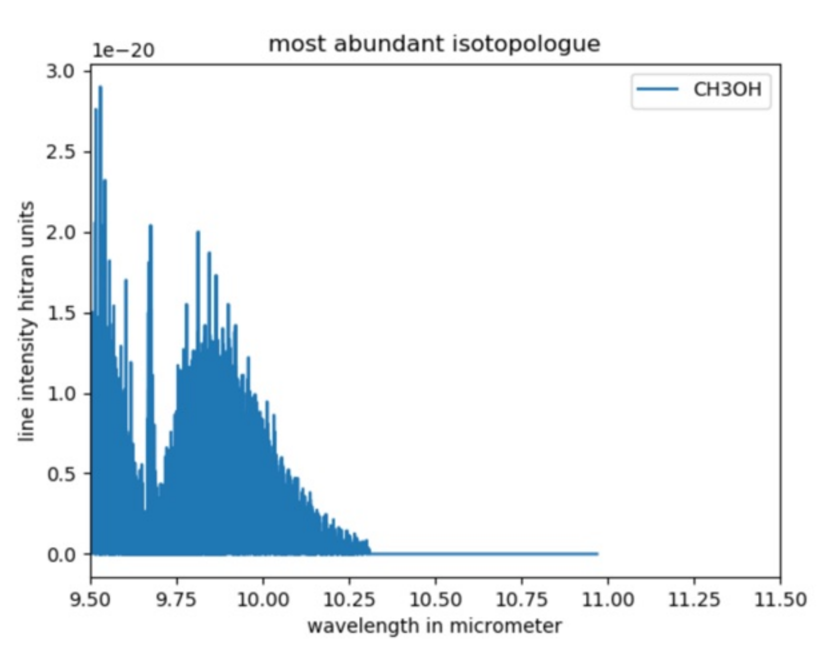

most abundant isotopologue
1e−21
line intensity hitran units
wavelength in micrometer
CH3Cl
CH3Br
0
1
2
3
4
5
6
7
5
10
15
20
25

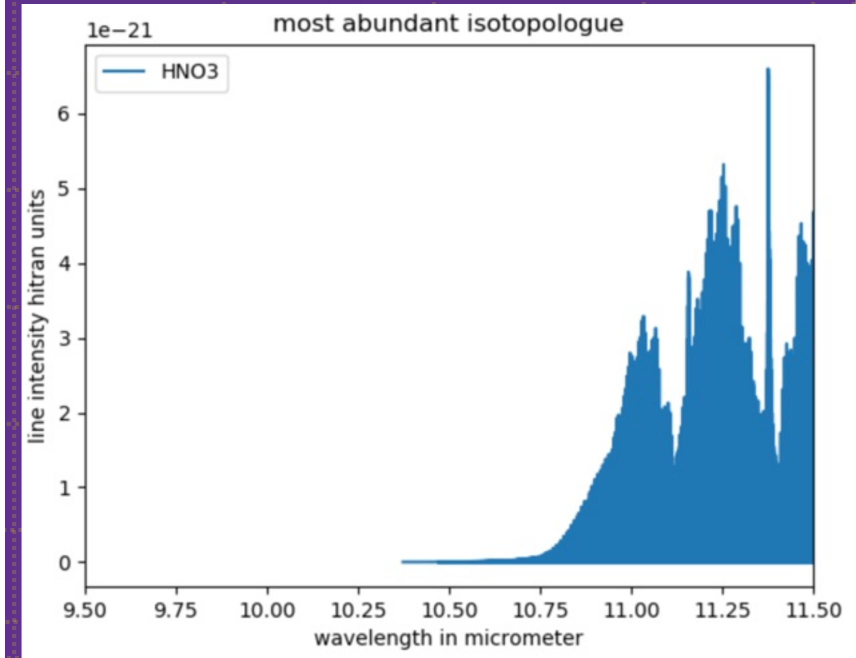

most abundant isotopologue
1e−19
NH3
line intensity hitran units
0
1
2
3
4
5
9.50
9.75
10.00
10.25
10.50
10.75
11.00
11.25
11.50
wavelength in micrometer

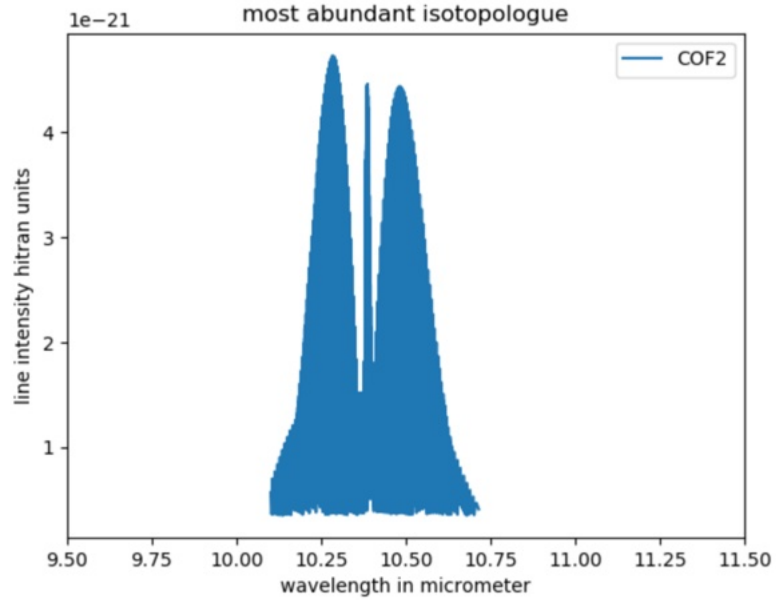

most abundant isotopologue
1e−20
O3
line intensity hitran units
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
9.50
9.75
10.00
10.25
10.50
10.75
11.00
11.25
11.50
wavelength in micrometer

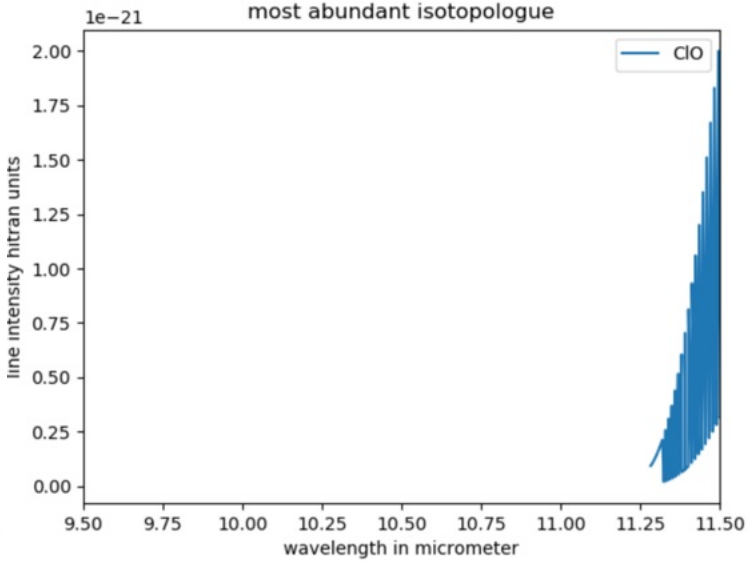

most abundant isotopologue
1e−20
PH3
line intensity hitran units
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
9.50
9.75
10.00
10.25
10.50
10.75
11.00
11.25
11.50
wavelength in micrometer

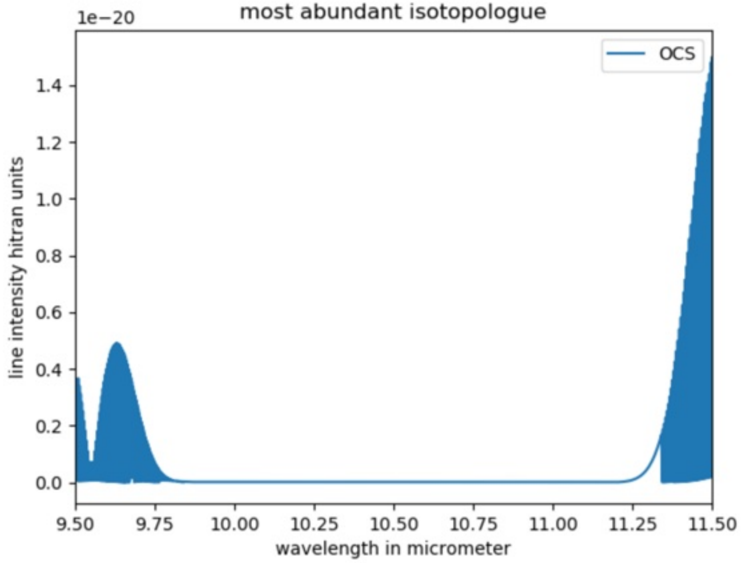

most abundant isotopologue
1e−20
C2H4
line intensity hitran units
0
2
4
6
8
9.50
9.75
10.00
10.25
10.50
10.75
11.00
11.25
11.50
wavelength in micrometer

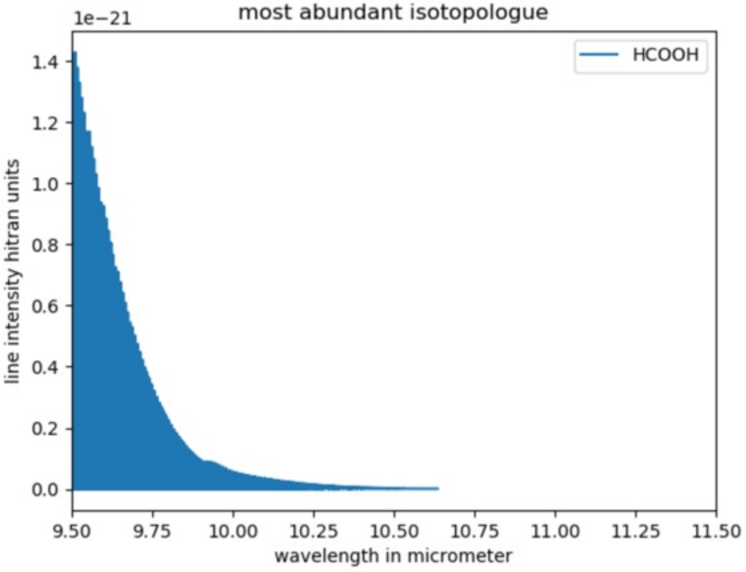

most abundant isotopologue
1e−20
CH3OH
line intensity hitran units
0.0
0.5
1.0
1.5
2.0
2.5
3.0
9.50
9.75
10.00
10.25
10.50
10.75
11.00
11.25
11.50
wavelength in micrometer

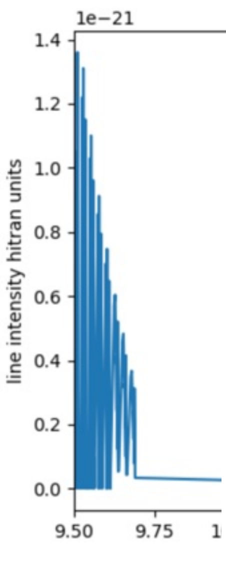

most abundant isotopologue
1e−21
HNO3
line intensity hitran units
0
1
2
3
4
5
6
9.50
9.75
10.00
10.25
10.50
10.75
11.00
11.25
11.50
wavelength in micrometer

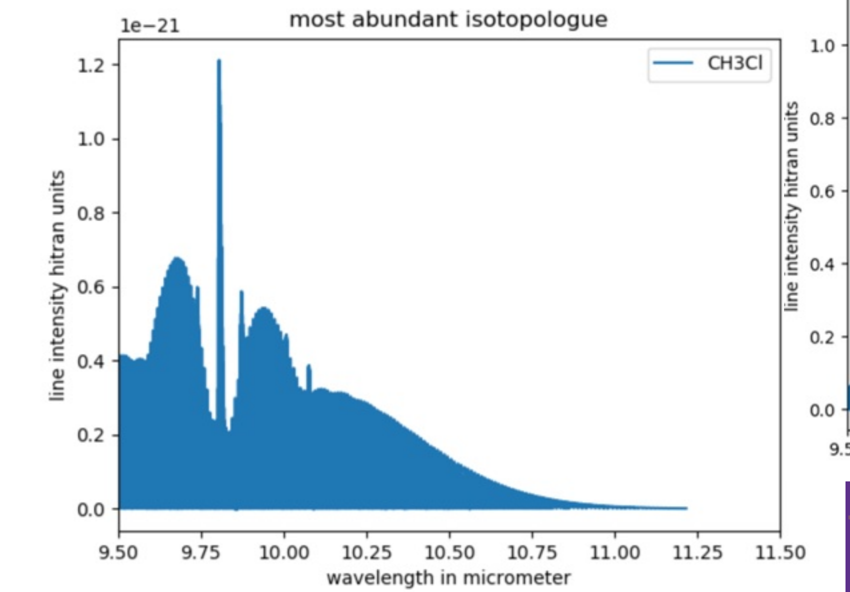

most abundant isotopologue
1e−21
COF2
line intensity hitran units
wavelength in micrometer

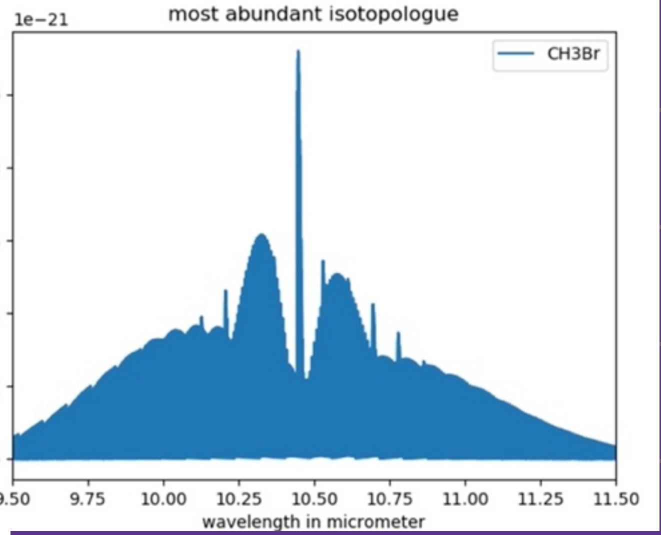

most abundant isotopologue
1e−21
ClO
line intensity hitran units
wavelength in micrometer


most abundant isotopologue
1e−20
OCS
line intensity hitran units
wavelength in micrometer

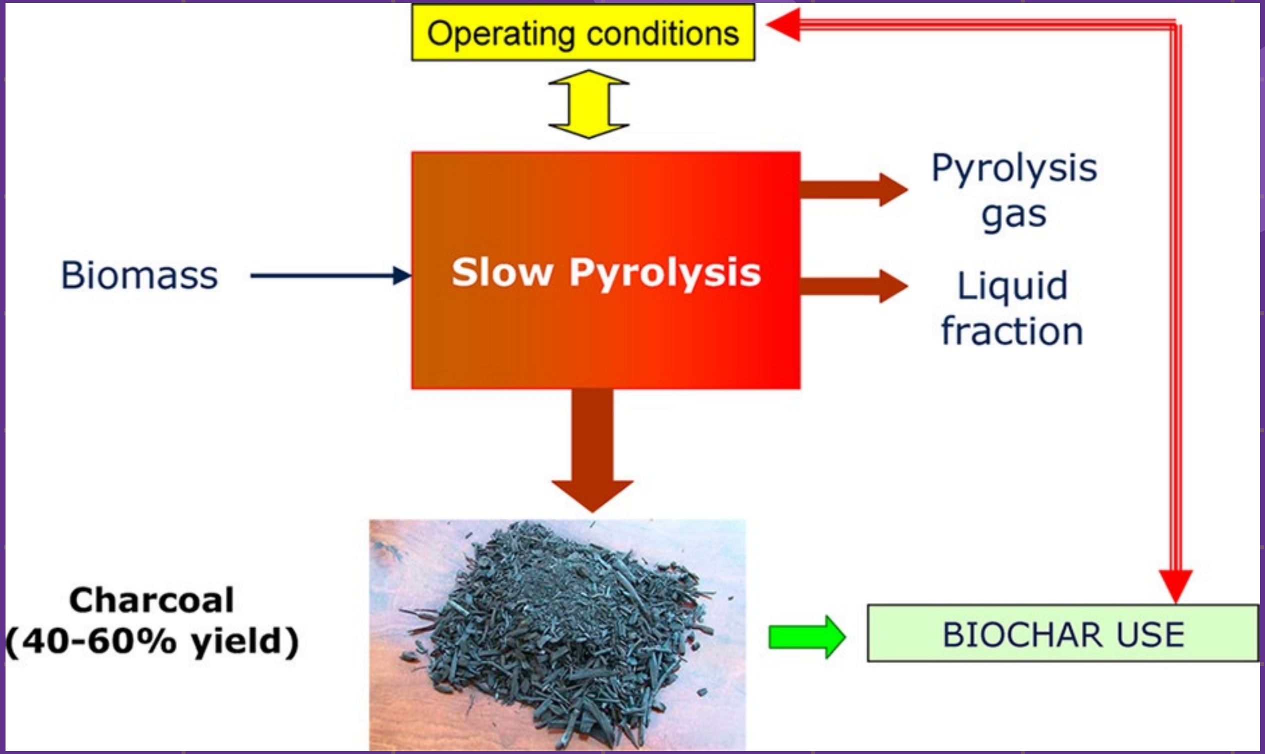

most abundant isotopologue
1e−21
HCOOH
line intensity hitran units
wavelength in micrometer


most abundant isotopologue
1e−21
HO2
line intensity hitran units


most abundant isotopologue
1e−21
CH3Cl
line intensity hitran units
wavelength in micrometer


most abundant isotopologue
1e−21
CH3Br
line intensity hitran units
wavelength in micrometer

- Orders of mag larger than biogenic signal
- Requires surface T=200K
- One off, quick event; would not have sustained signal like biogenic



- Exogenous delivery over 1st 80 Ma equivalent to 300 Gg
- Modern flux CH_3Cl 300,000 Gg/yr

Future work

Detection of methylated gases in super Earth atmospheres by JWST

Exploring additional methylated species through photochemical and spectral modelling

Laboratory and field measurements of fluxes of methylated gases to inform model input

Iodine species (CH_3I)

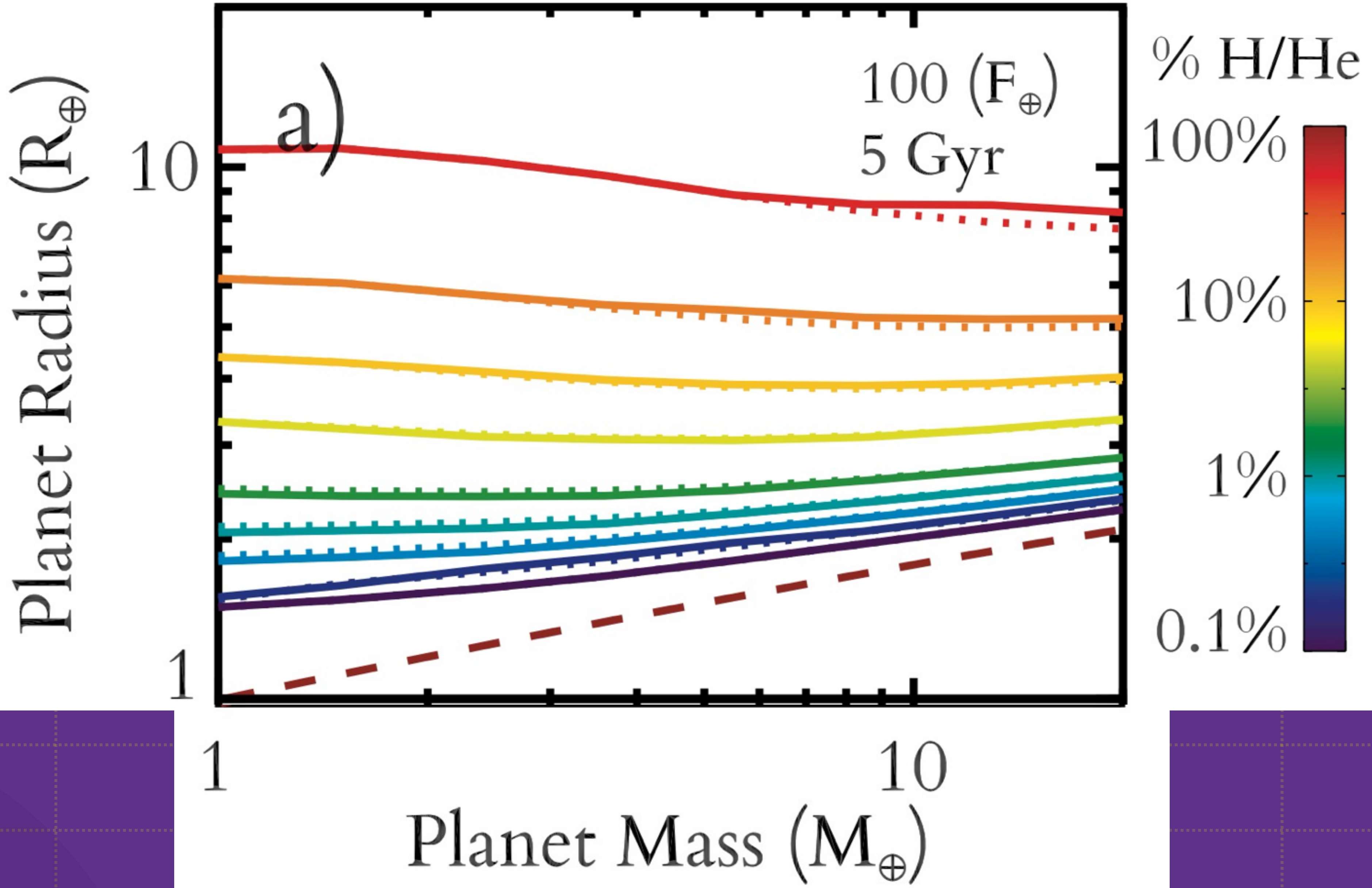
Organometallics such as $(CH_3)_3Hg$ (SciALog funded, Schwieterman)

Polyhalomethanes e.g. CH_2BrCl

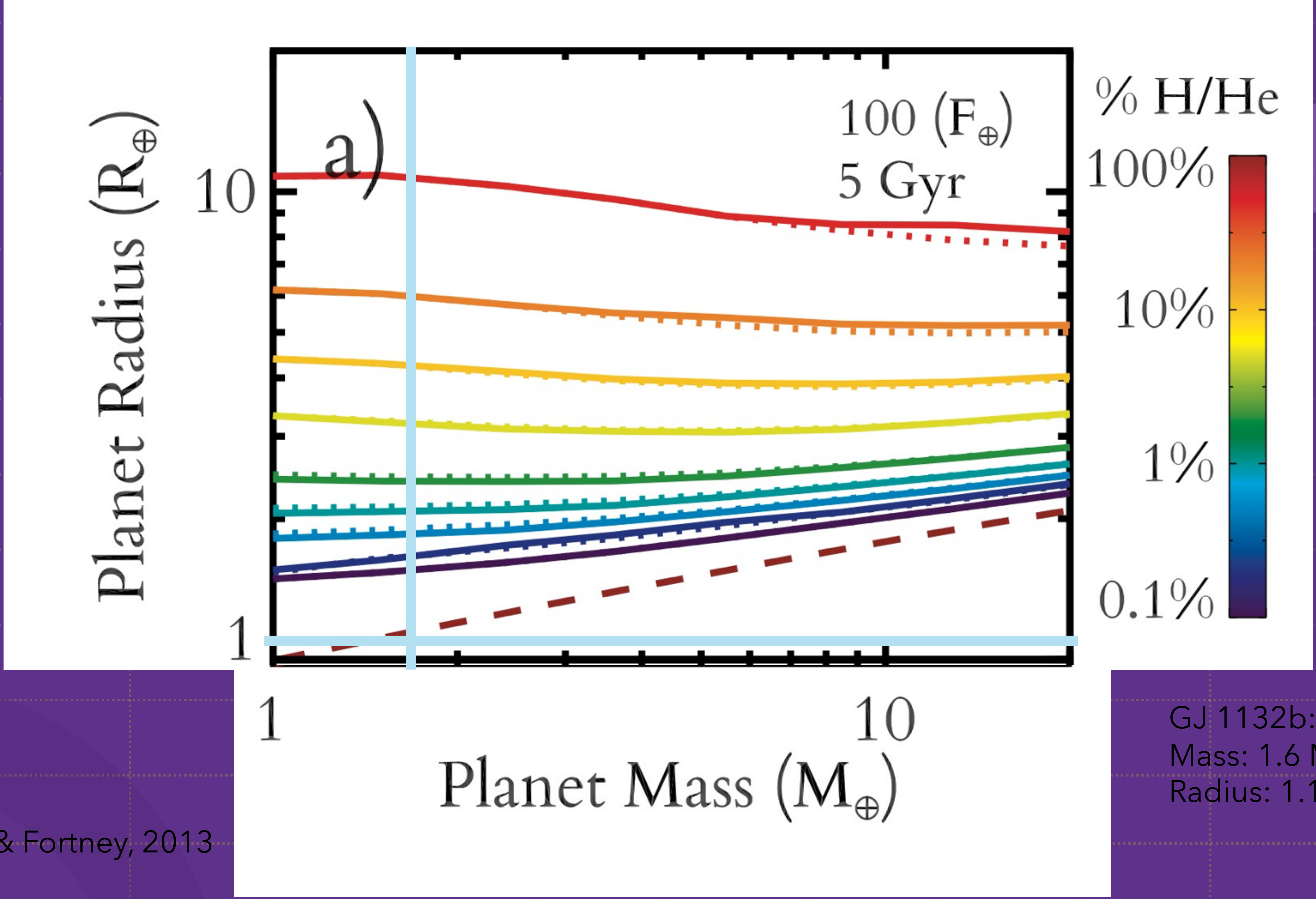
Methylated chalcogens e.g. $(CH_3)_2Se$

Super Earths & Biosignatures

- Oxidant source? No redox gradient
- Temperature – CIAs may be too effective
- Carbonate silicate cycle may shut off (if high pressure ices)
- Even if not, full ocean == no silicate weathering…
- How is H_2 retained?

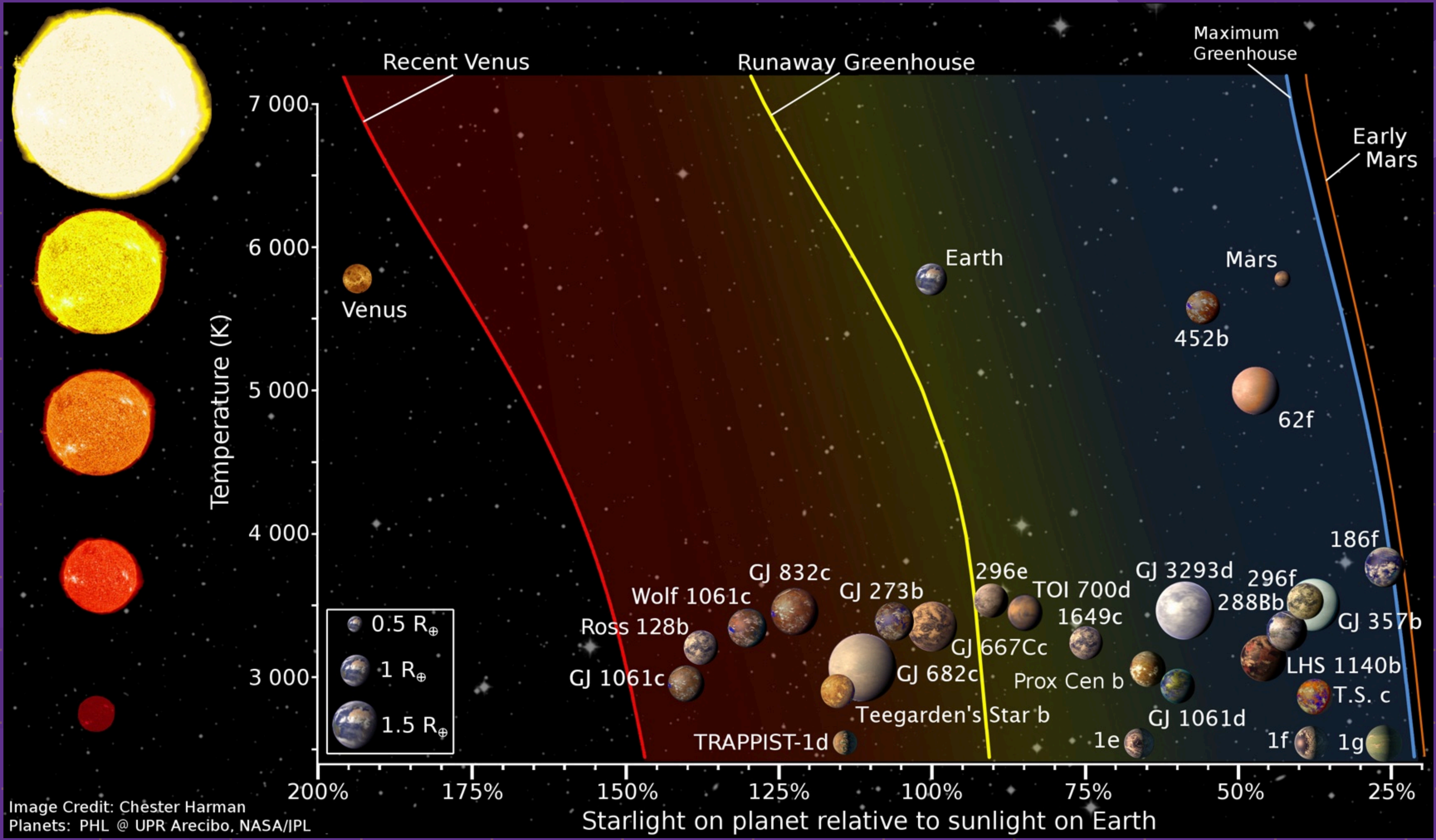


Lopez & Fortney, 2013

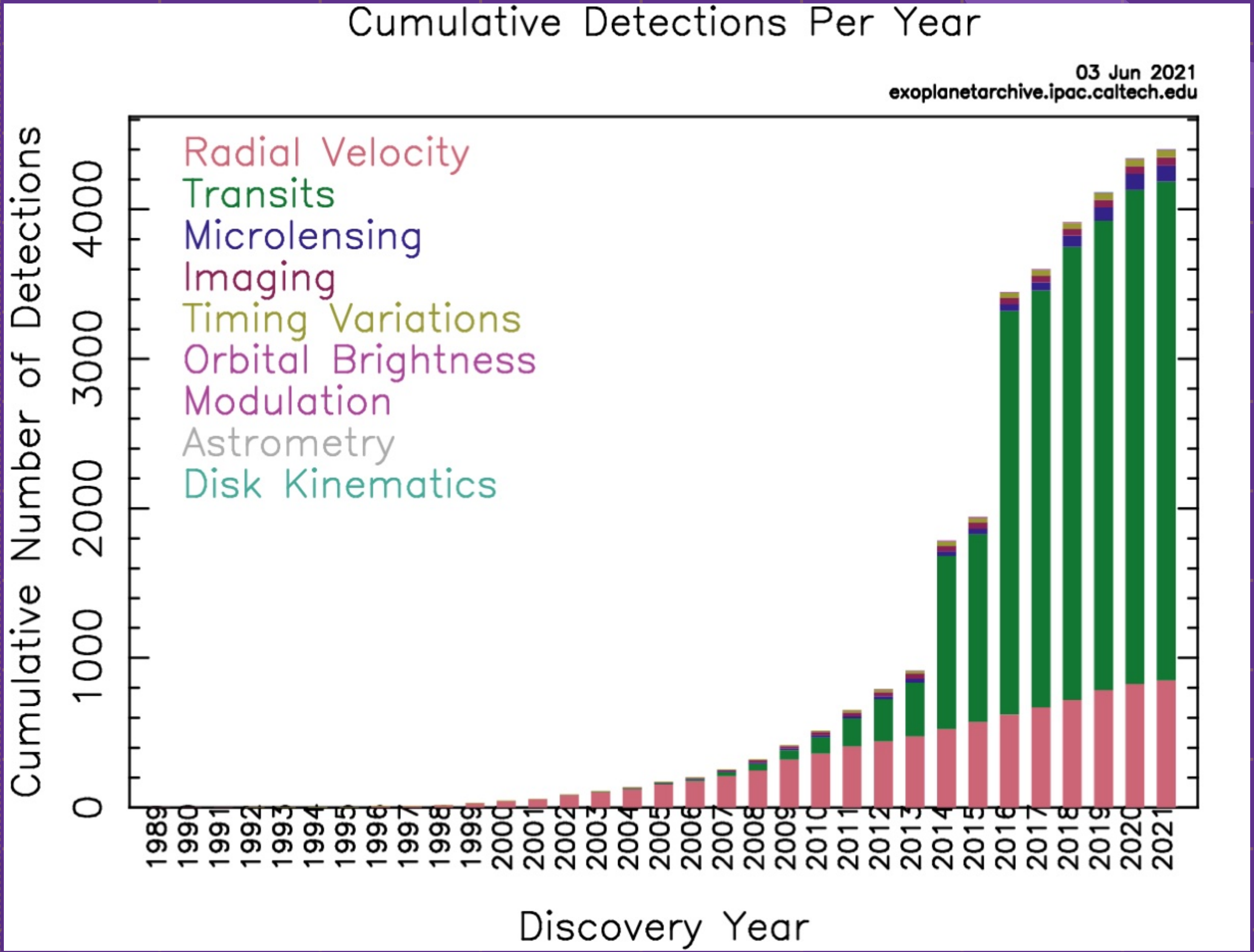


GJ 1132b:
Mass: 1.6 Me
Radius: 1.16 Re

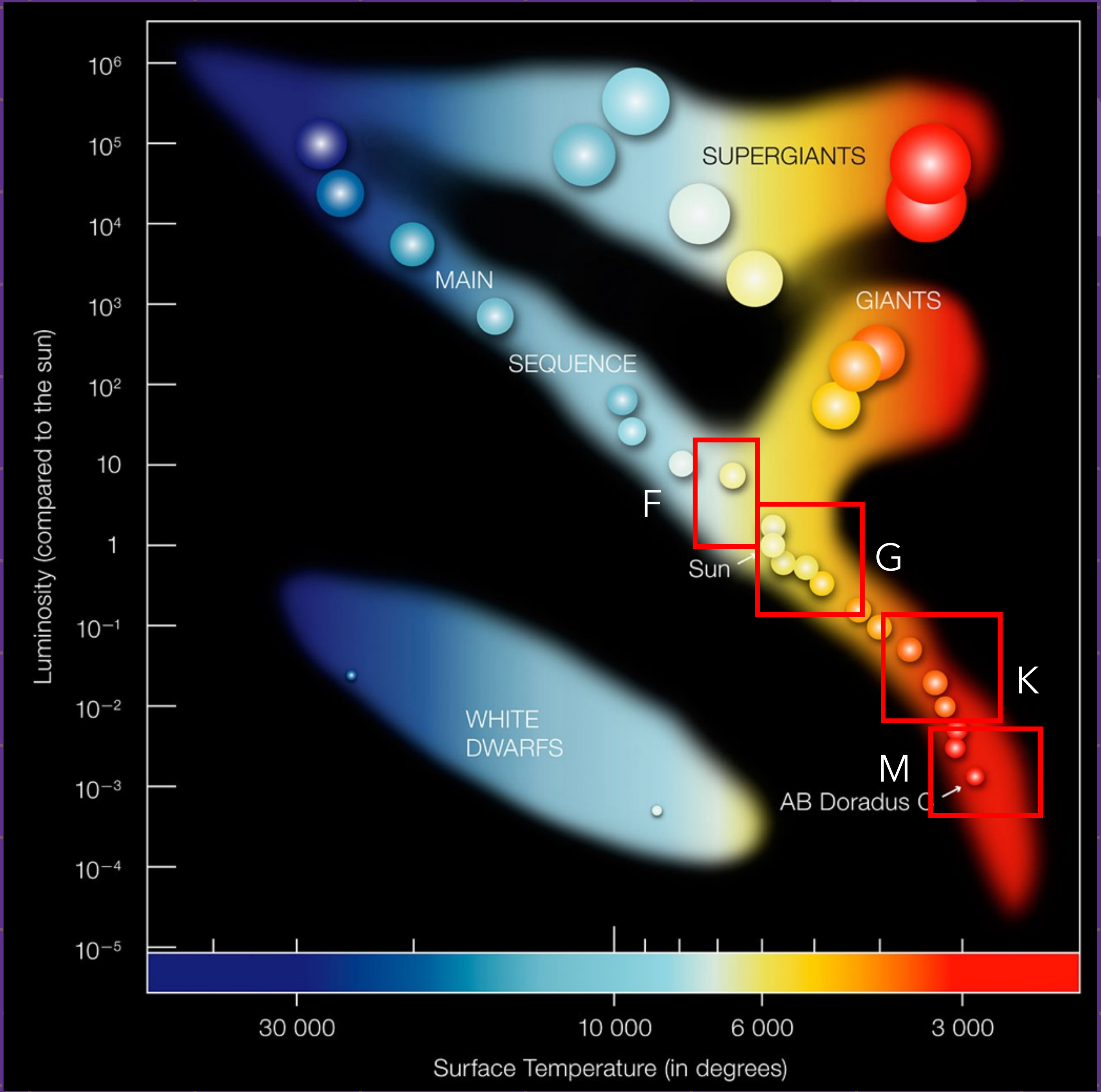
Lopez & Fortney, 2013



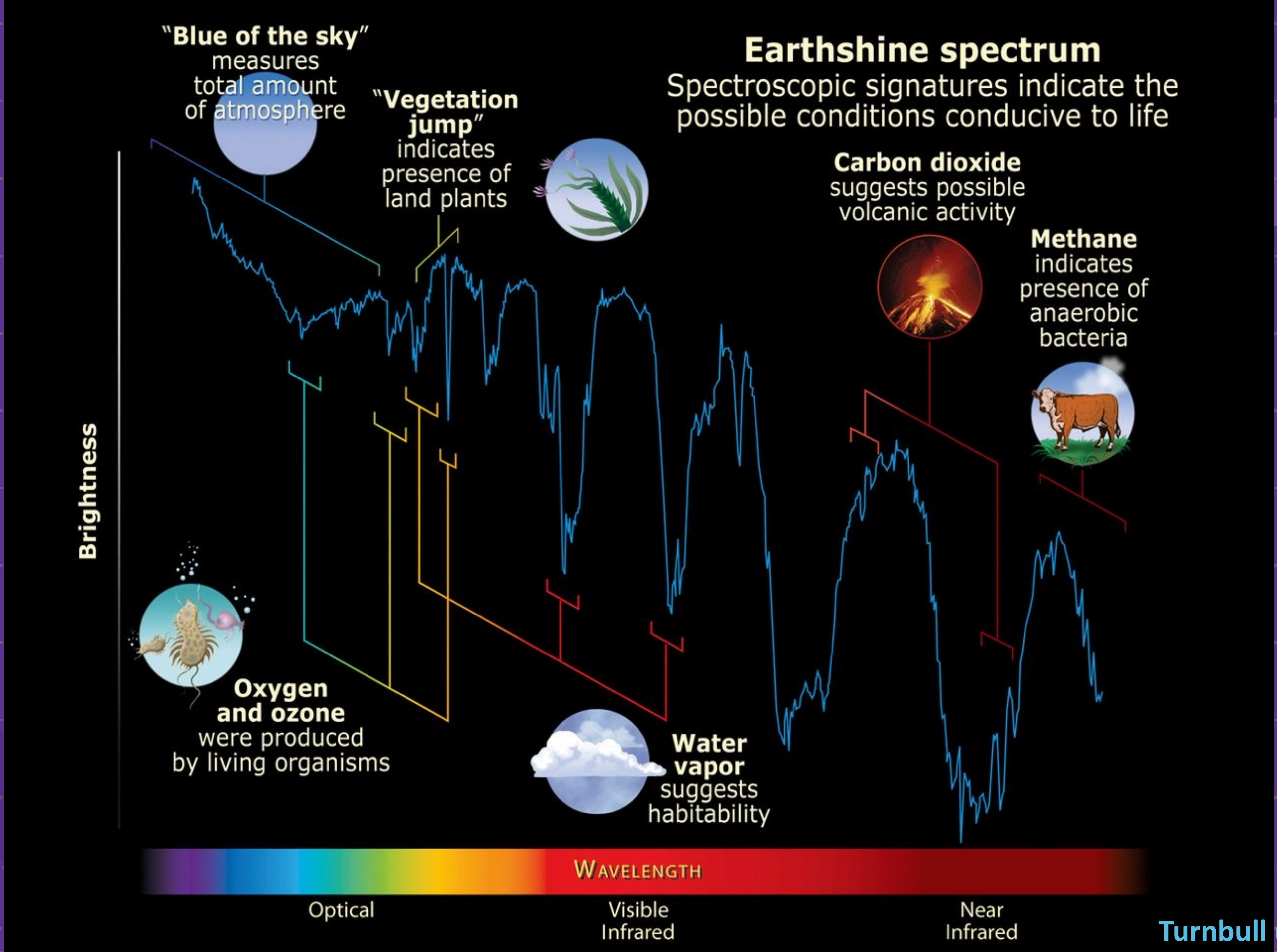
Recent Venus
Runaway Greenhouse
Maximum Greenhouse
Early Mars
7 000
6 000
5 000
4 000
3 000
Temperature (K)
Venus
Earth
Mars
452b
62f
186f
GJ 832c
GJ 273b
296e
TOI 700d
GJ 3293d
296f
288Bb
GJ 357b
Wolf 1061c
1649c
Ross 128b
GJ 667Cc
LHS 1140b
GJ 1061c
GJ 682c
Prox Cen b
T.S. c
Teegarden's Star b
GJ 1061d
TRAPPIST-1d
1e
1f
1g
0.5 R⊕
1 R⊕
1.5 R⊕
200%
175%
150%
125%
100%
75%
50%
25%
Starlight on planet relative to sunlight on Earth
Image Credit: Chester Harman
Planets: PHL @ UPR Arecibo, NASA/JPL



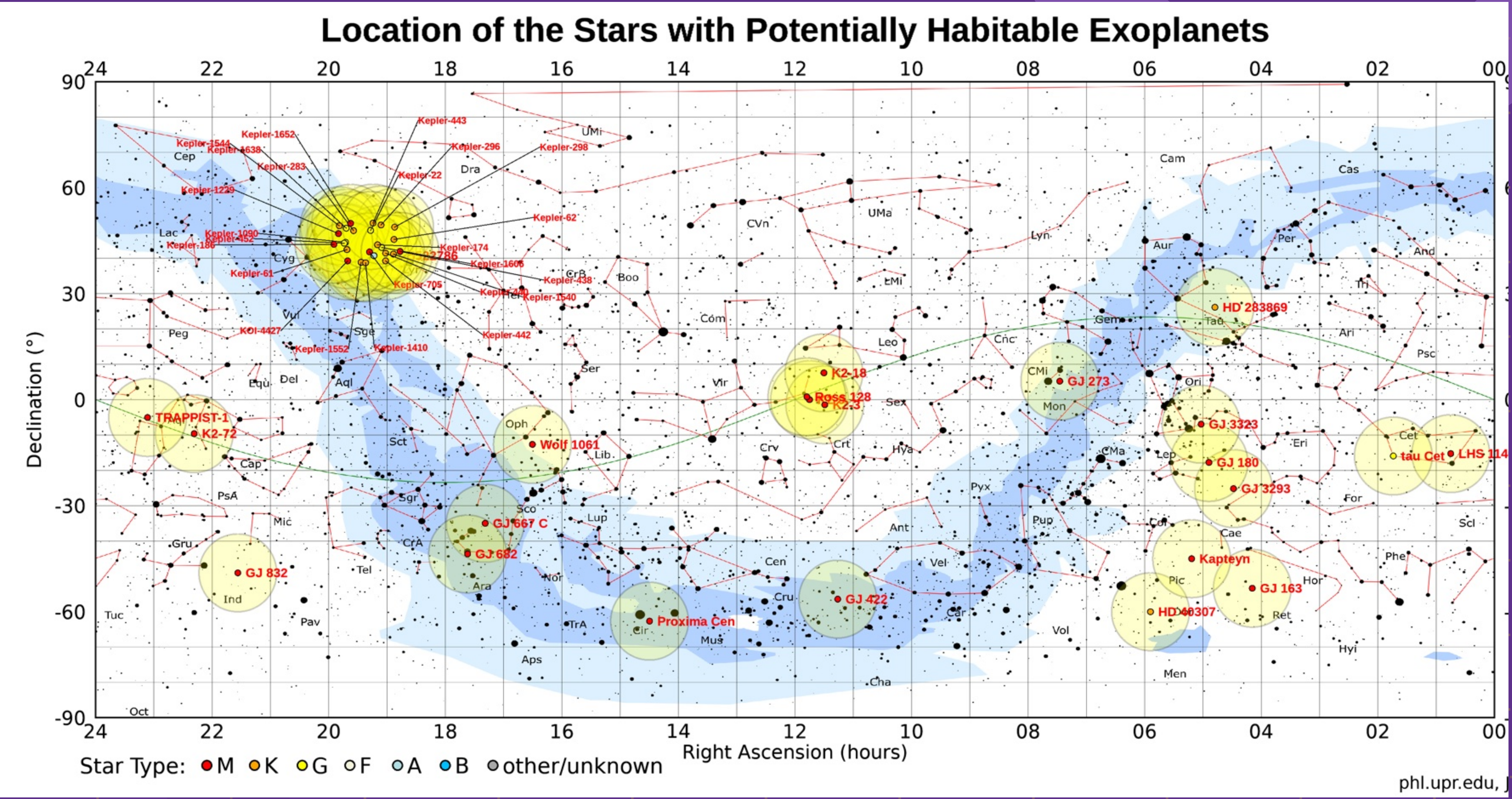
IPAC/CalTech Exoplanet Archive


10⁶
10⁵
10⁴
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
Luminosity (compared to the sun)
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
F
G
K
M
Sun
AB Doradus C
30 000
10 000
6 000
3 000
Surface Temperature (in degrees)

Credit: ESO



Turnbull (2006, 2014)



Location of the Stars with Potentially Habitable Exoplanets
Declination (°)
Right Ascension (hours)
Star Type: M K G F A B other/unknown
TRAPPIST-1
K2-72
Wolf 1061
GJ 667 C
GJ 682
GJ 832
Proxima Cen
GJ 422
K2-18
Ross 128
GJ 273
HD 283869
GJ 3323
GJ 180
GJ 3293
Kapteyn
GJ 163
HD 40307
tau Cet
Kepler-443
Kepler-1652
Kepler-296
Kepler-298
Kepler-22
Kepler-62
Kepler-283
Kepler-1229
Kepler-174
Kepler-186
Kepler-61
Kepler-705
Kepler-1540
Kepler-442
Kepler-1410
Kepler-1552
KOI-4427
phl.upr.edu,

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Spectral Units

- Resolving power = lam/d_lam
- Spectral res = d_lam