STUDENT-LED PROJECTS *at the* ASTROBIOLOGICAL FRONTIER

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RECENT ADVANCES *in* ORIGINS, HABITABILITY, & BIOSIGNATURES

MADELINE CHRISTENSEN

LUCAS M. FIFER

EMERSYN SLAUGHTER

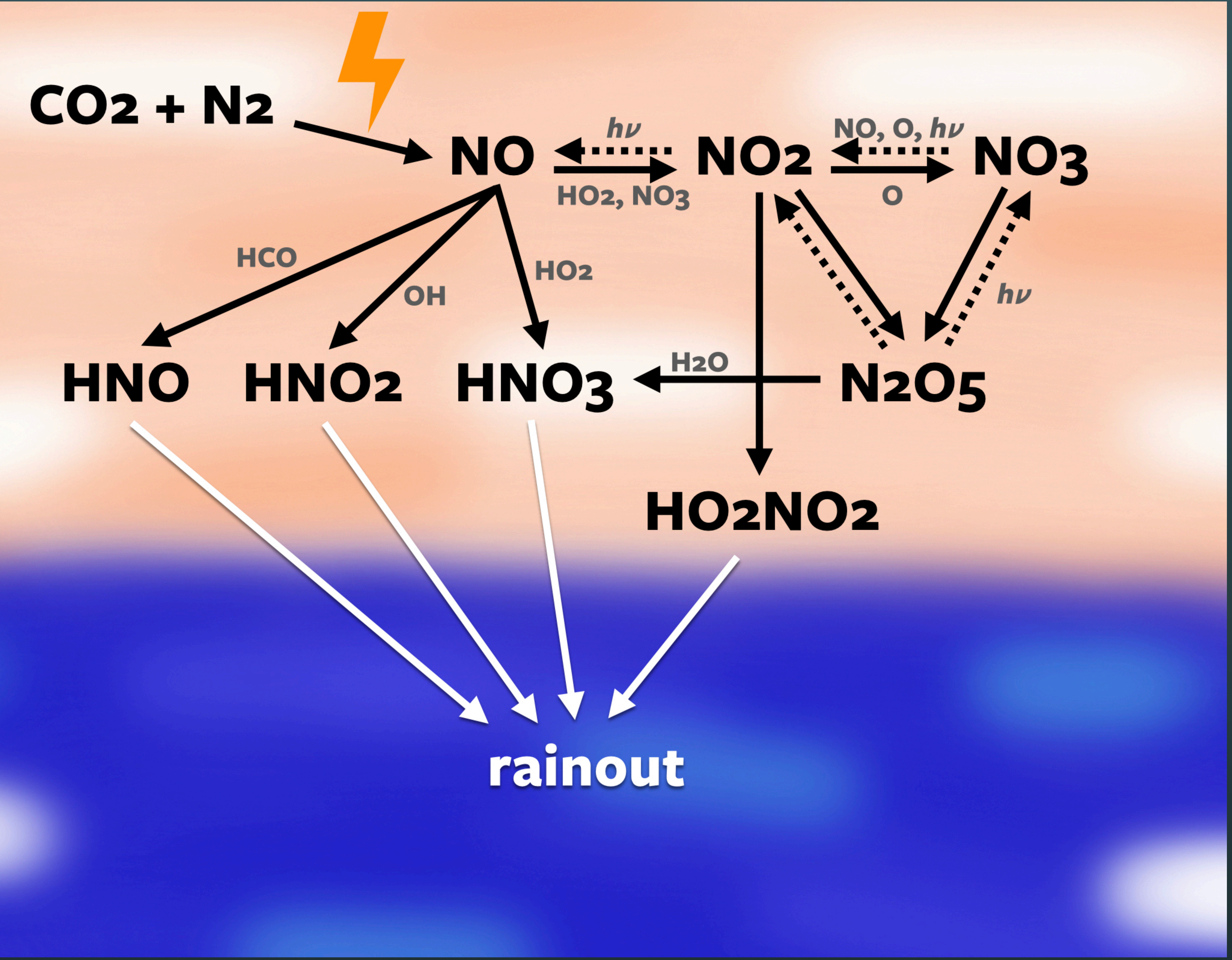

Nitrogen Fixation on Early Earth
SETTING THE STAGE FOR LIFE'S EMERGENCE
MADELINE CHRISTENSEN
DANICA ADAMS
MICHAEL L. WONG
PATRICK DUNN
YUK L. YUNG
JOURNAL ARTICLE:
Christensen et al.
2024 *Life* 16(5)

CO2, N2, H2O
HNOx
DISEQUILIBRIA
pH ~ 5
CO2, NO3⁻
pH
pH ~ 11
H2, CH4
redox
SERPENTINIZATION
after Wong+ 2017b; Russell+ 2014

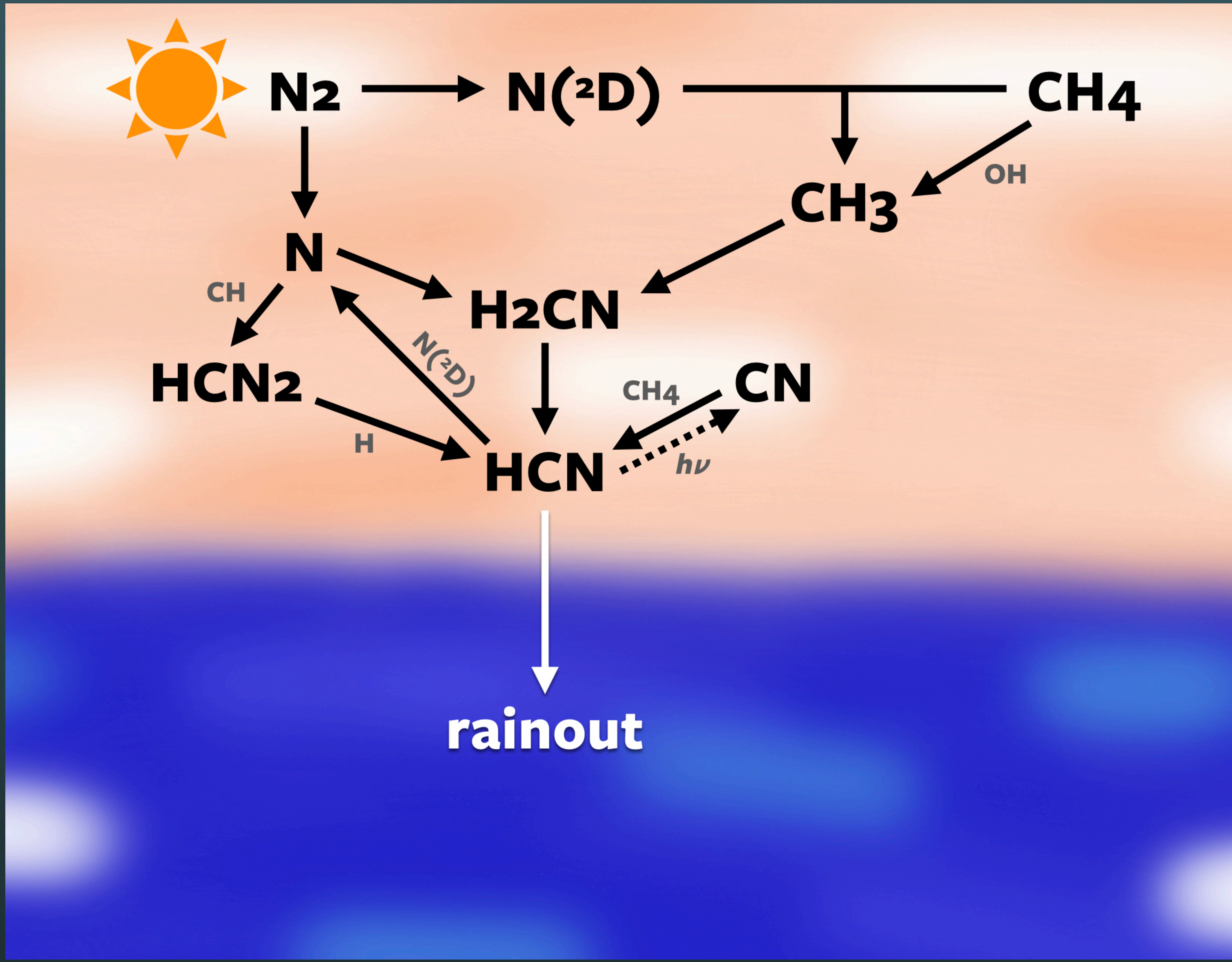

CO_2, N_2, H_2O
HNO_x
DISEQUILIBRIA
pH ~ 5
CO_2, NO_3^-
pH
pH ~ 11
redox
H_2, CH_4
SERPENTINIZATION
after Wong+ 2017b; Russell+ 2014

Modeling nitrogen fixation

Lightning + CO_2 + N_2 = NOx

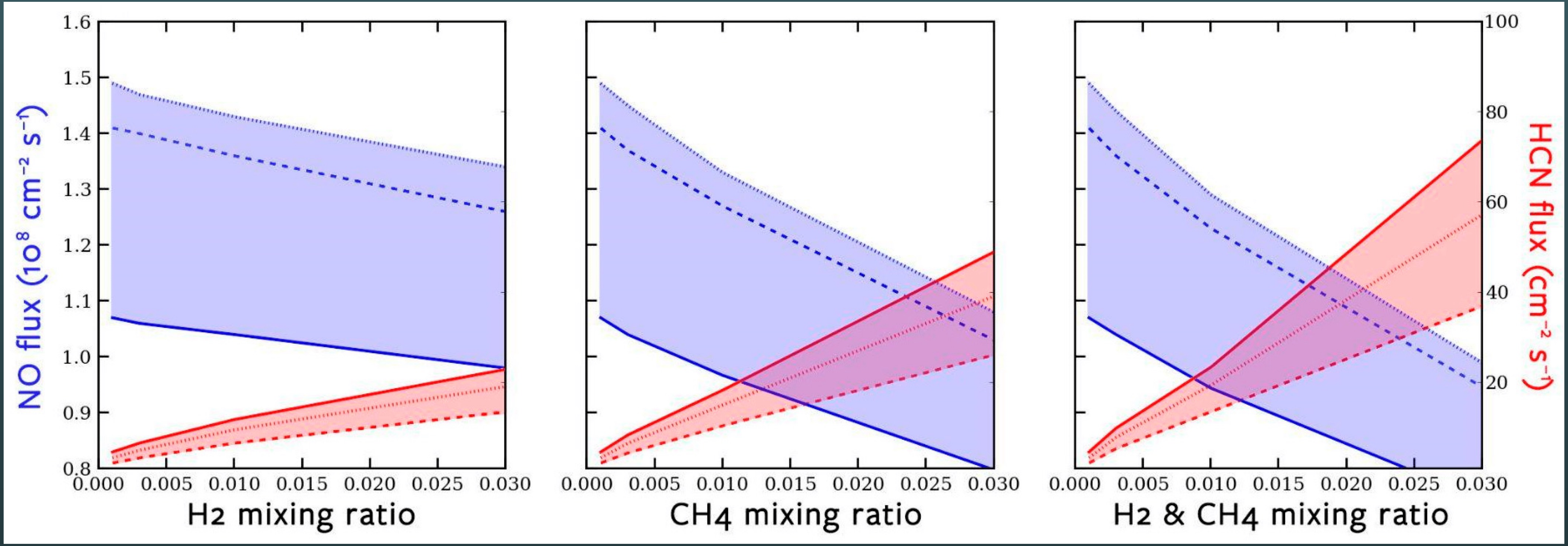


Solar Energetic Particles + N_2 + CH_4 = HCN



Adams+ 2021; Christensen+ 2024

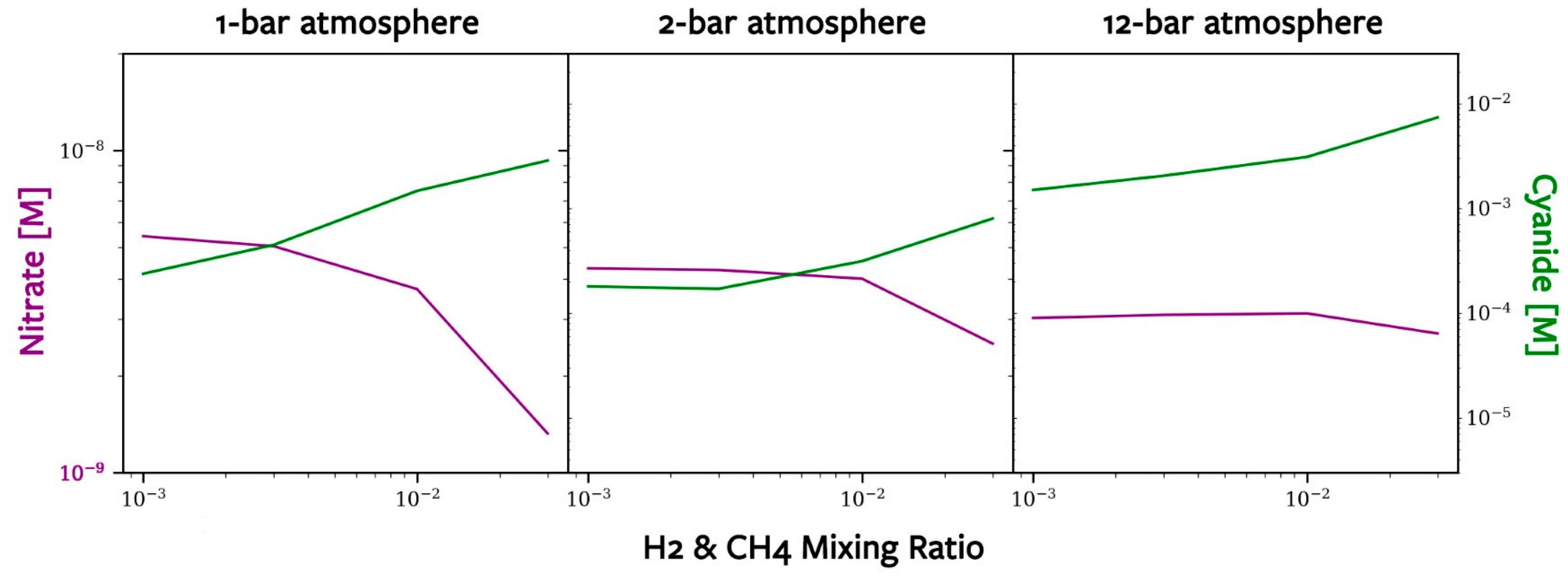
Lightning-induced NO & HCN



Of order 1 × 10^8 molecules NO/cm²/s produced via lightning on early Earth

Christensen+ 2024

Ocean concentrations of NOx and HCN

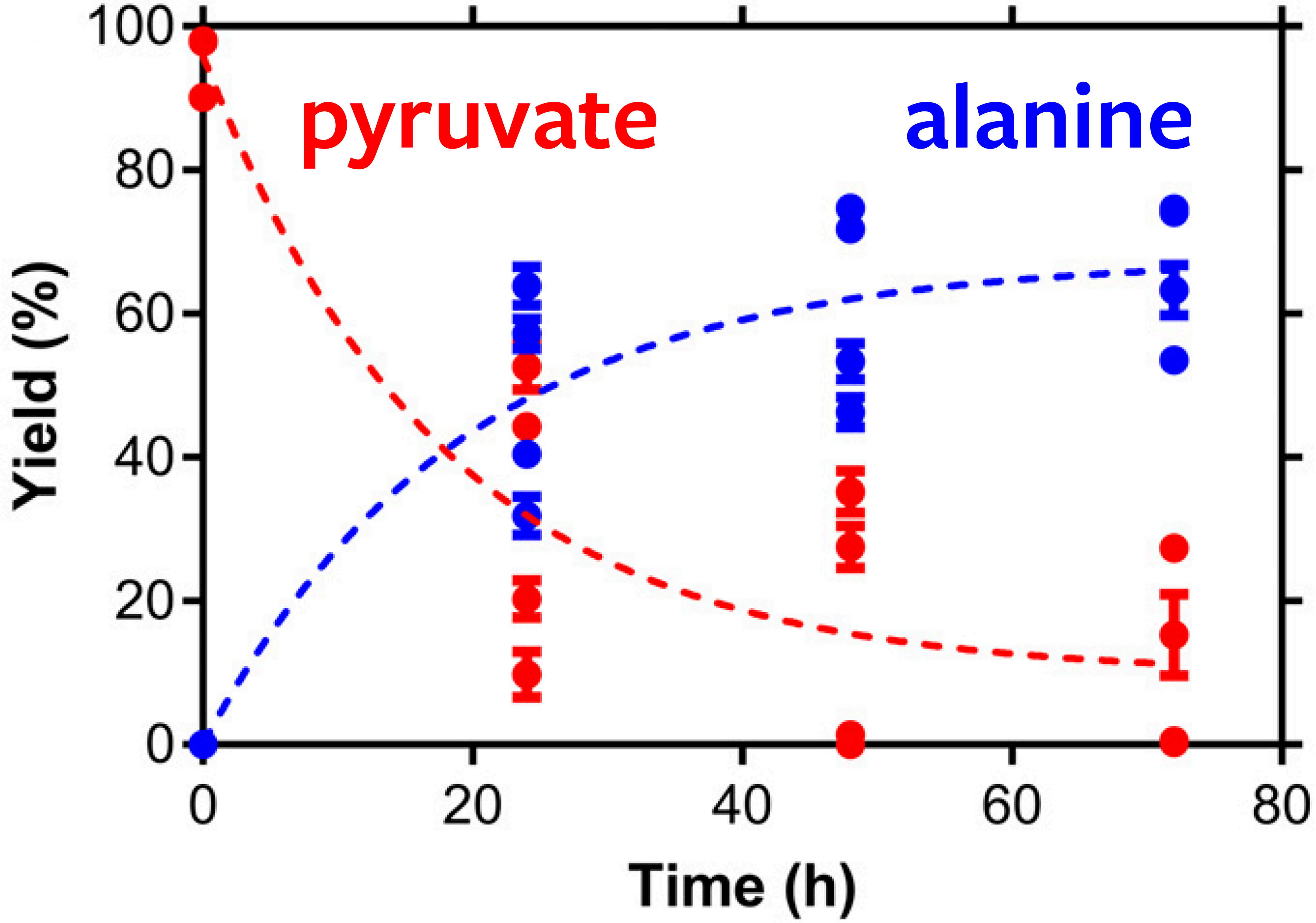


A NOx concentration of 10^{-9}–10^{-8} M is expected for the bulk Hadean ocean

Christensen+ 2024

Barge+ 2019

Fixed nitrogen → amino acids



LAURIE BARGE


Green Rust
$[\sim Fe^{2+}{}_4 Fe^{3+}{}_2(OH)_{12}][CO_3]\cdot 3H_2O)$

NOx on early Earth

Wong+ 2017b; Christensen+ 2024

NOx on early Earth

Proto-metabolic systems may have been driven into existence by chemical disequilibria at alkaline hydrothermal systems

Wong+ 2017b; Christensen+ 2024

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NOx could have contributed to emerging life by serving as:

- High-potential electron acceptors
- Sources of fixed nitrogen

Wong+ 2017b; Christensen+ 2024

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Implications for origin-of-life experimental work

Wong+ 2017b; Christensen+ 2024

NOx on early Earth

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- Sources of fixed nitrogen

Implications for origin-of-life experimental work

We can model the amount of atmospheric nitrogen fixation—but do we know that this actually occurred?

Wong+ 2017b; Christensen+ 2024

Stern+ 2015

NITROGEN OXIDES ON MARS

Rocknest (aeolian): 110–300 ppm
John Klein (mudstone): 70–260 ppm
Cumberland (mudstone): 330–1,100 ppm

Nitrate-Dependent Fe^{2+} Oxidation (NDFO) on Early Mars

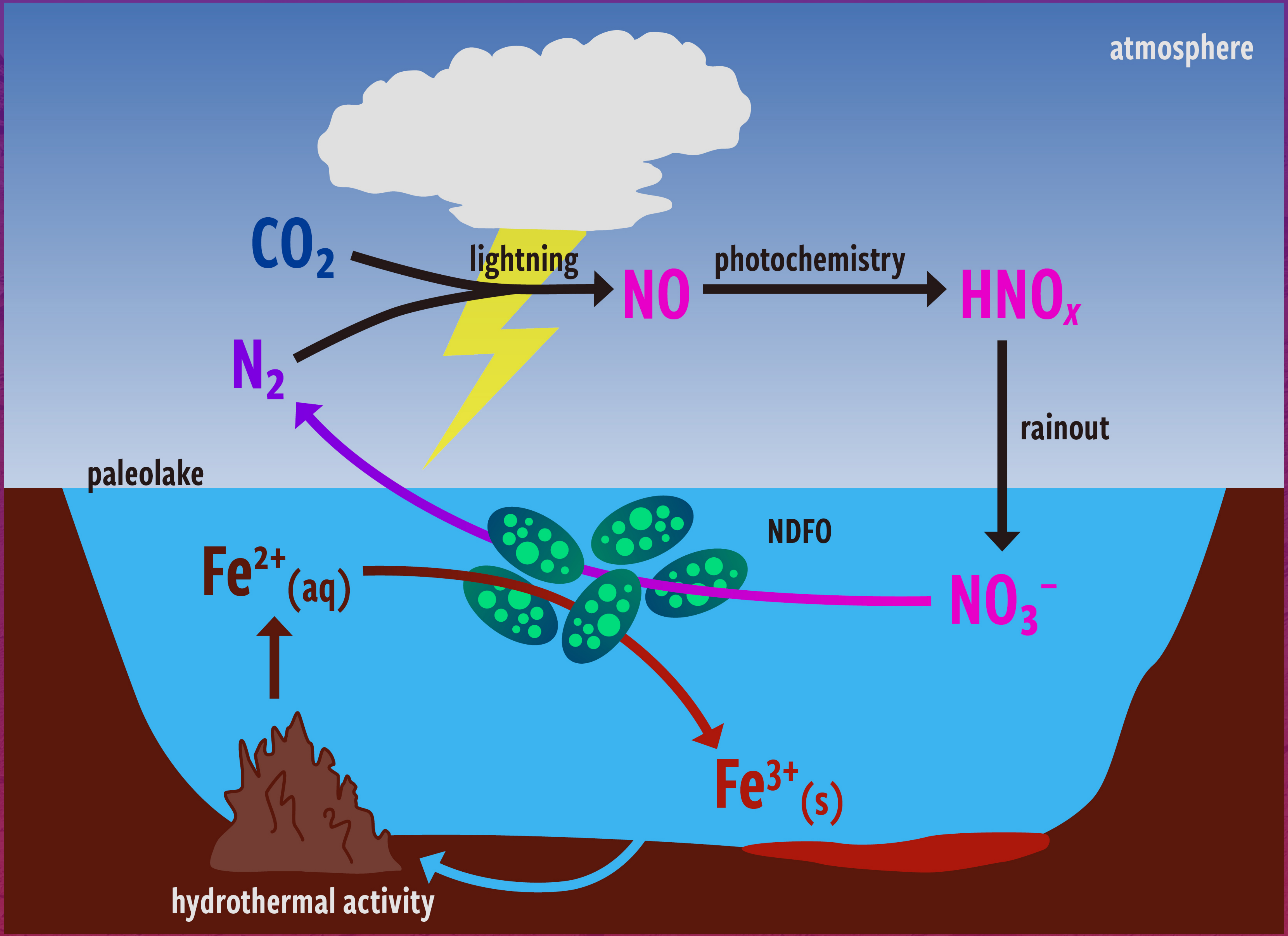
IMPLICATIONS FOR INTERPRETATION OF GALE CRATER ORGANICS

JOURNAL ARTICLE:
Fifer & Wong 2024
***Astrobiology* 24(6)**

LUCAS M. FIFER

MICHAEL L. WONG

Nitrate-dependent Fe^{2+} oxidization (NDFO)



NDFO would be a plausible metabolism on early Mars

How much life could have existed at Gale?

How does the [C_{org}] at Gale compare to that left by an NDFO ecosystem?

Price+ 2018; Fifer & Wong (2024)

1

NOx rainout rate
Adams+ 2021

&

NOx photo-destruction rate

→

Available Gibbs free energy

1 NOx rainout rate *Adams+ 2021* & NOx photo-destruction rate → Available Gibbs free energy

2 Available Gibbs free energy & Biological efficiency → Size of microbial community

Fifer & Wong (2024)

1

NOx rainout rate
Adams+ 2021

&

NOx photo-destruction rate

→ Available Gibbs free energy

2

Available Gibbs free energy

&

Biological efficiency

→ Size of microbial community

3

Size of microbial community

&

Cell turnover rate

Paleolake lifetime

Burial & sulfurization

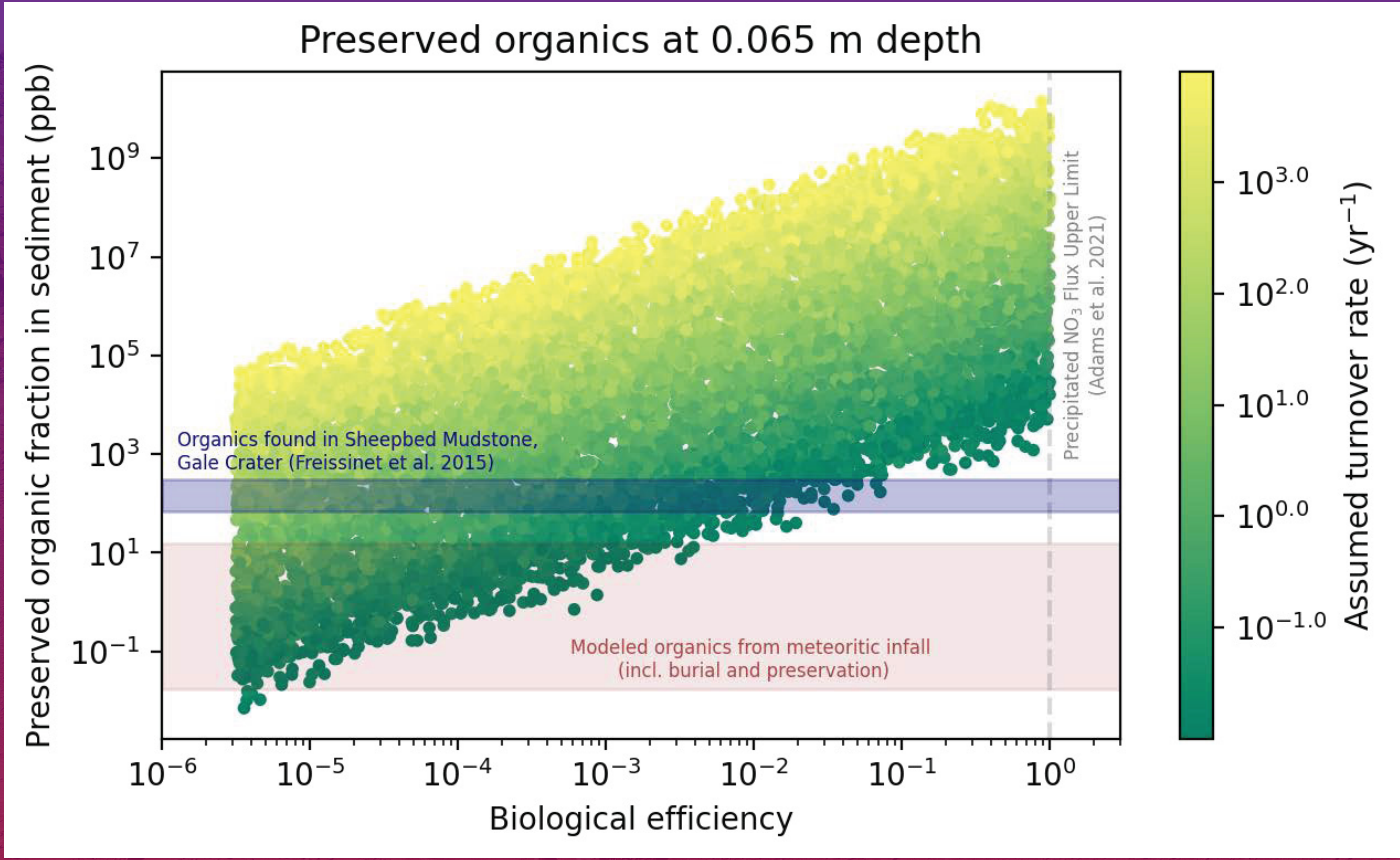
Radiation exposure

→ Preserved organic concentration

Fifer & Wong (2024)


1
NOx rainout rate
Adams+ 2021
&
NOx photo-destruction rate
Available Gibbs free energy
2
Available Gibbs free energy
&
Biological efficiency
Size of microbial community
Cell turnover rate
Constrain biodynamics via measurements
3
Size of microbial community
&
Paleolake lifetime
Burial & sulfurization
Radiation exposure
Preserved organic concentration
Fifer & Wong (2024)

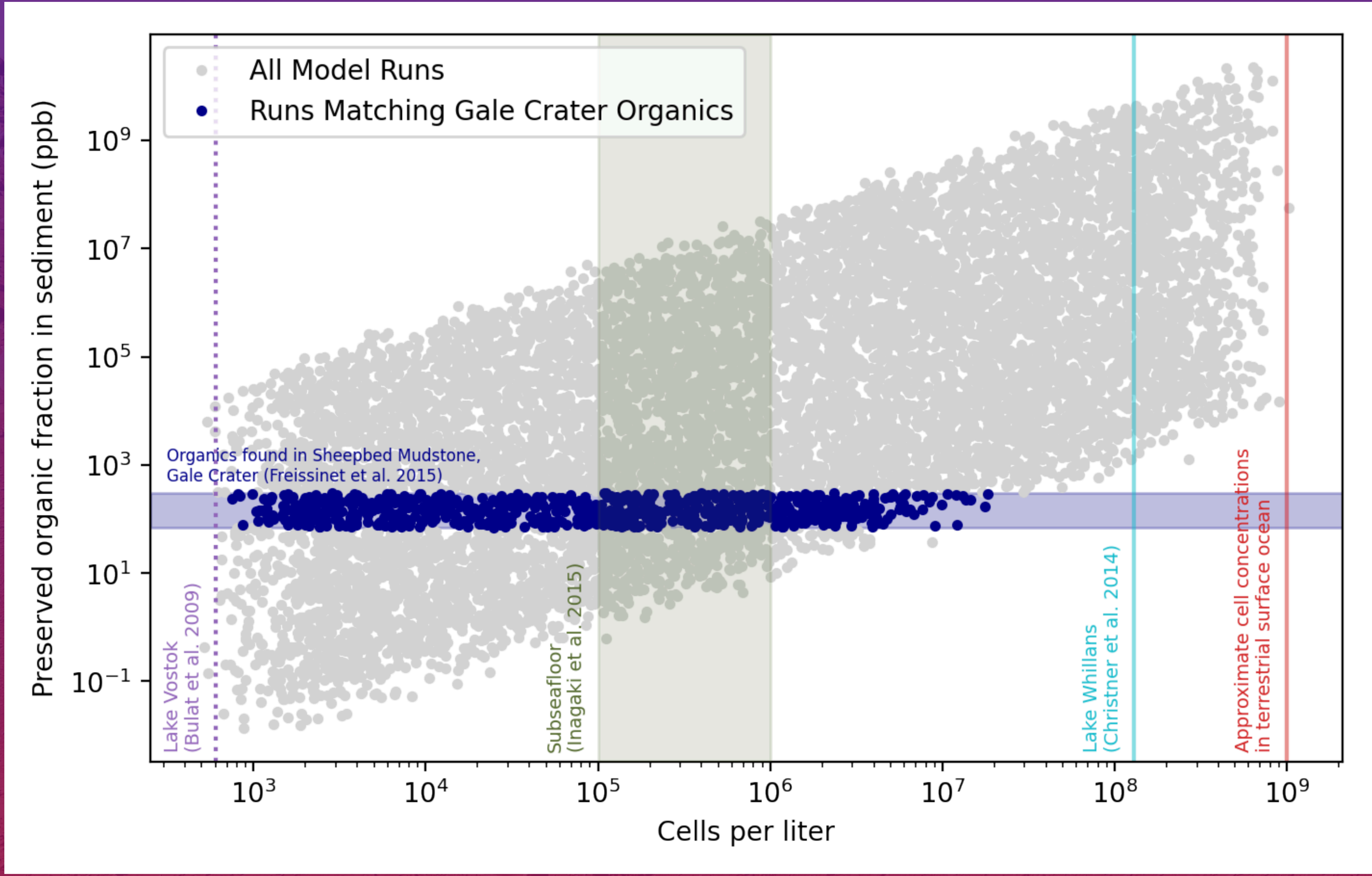
$[C_{org}]_{possible} >> [C_{org}]_{measured} > [C_{org}]_{meteoritic}$



There was abundant free energy on early Mars in the form of NOx and reduced Fe

Fifer & Wong (2024)

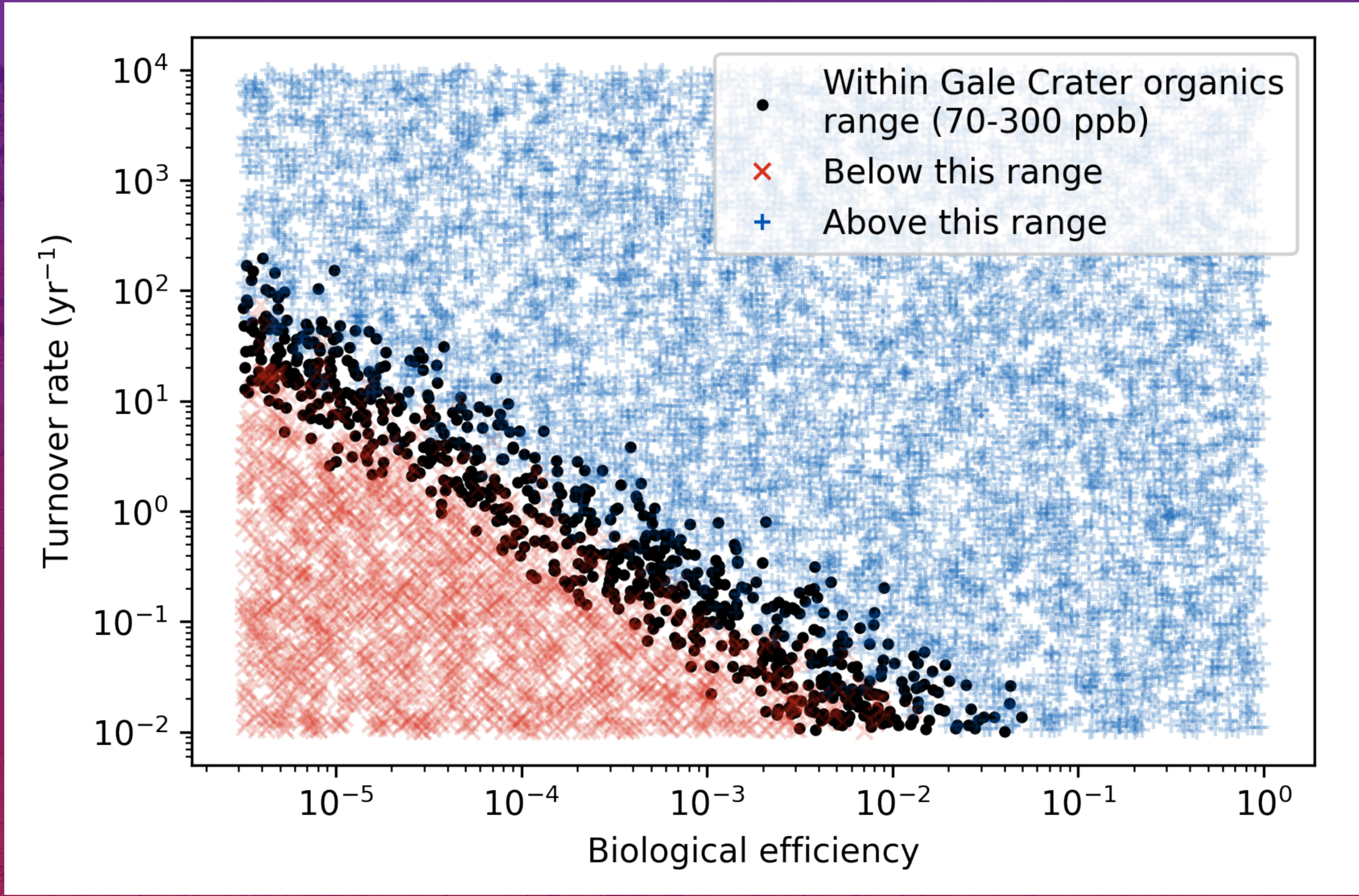
$[C_{org}]$ constrains cell density to <10^7 cells/L



Much smaller than modern terrestrial oceans, but consistent with Earth's subseafloor

Fifer & Wong (2024)

[C_{org}] constrains biological efficiency to <0.05



Life would not be limited by free energy, but something else: phosphorus?

Fifer & Wong (2024)

Habitability & biosignature preservation on Mars

Fifer & Wong (2024)

Habitability & biosignature preservation on Mars

Meteoritic infall cannot explain the abundance of organics at Gale

+ Other sources include photochemistry, hydrothermal activity, and biology

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There was abundant free energy on early Mars in the form of NOx and reduced Fe

+ Life would not be limited by free energy, but something else: phosphorus?

A hypothetical NDFO community in Gale crater would have been limited to $<10^7$ cells/L

+ Much smaller than modern terrestrial oceans, but consistent with Earth's subseafloor

Fifer & Wong (2024)

IT'S TIME TO DEVELOP NOVEL

IN-SITU BIOSIGNATURE TECHNIQUES

FOR SOLAR SYSTEM EXPLORATION

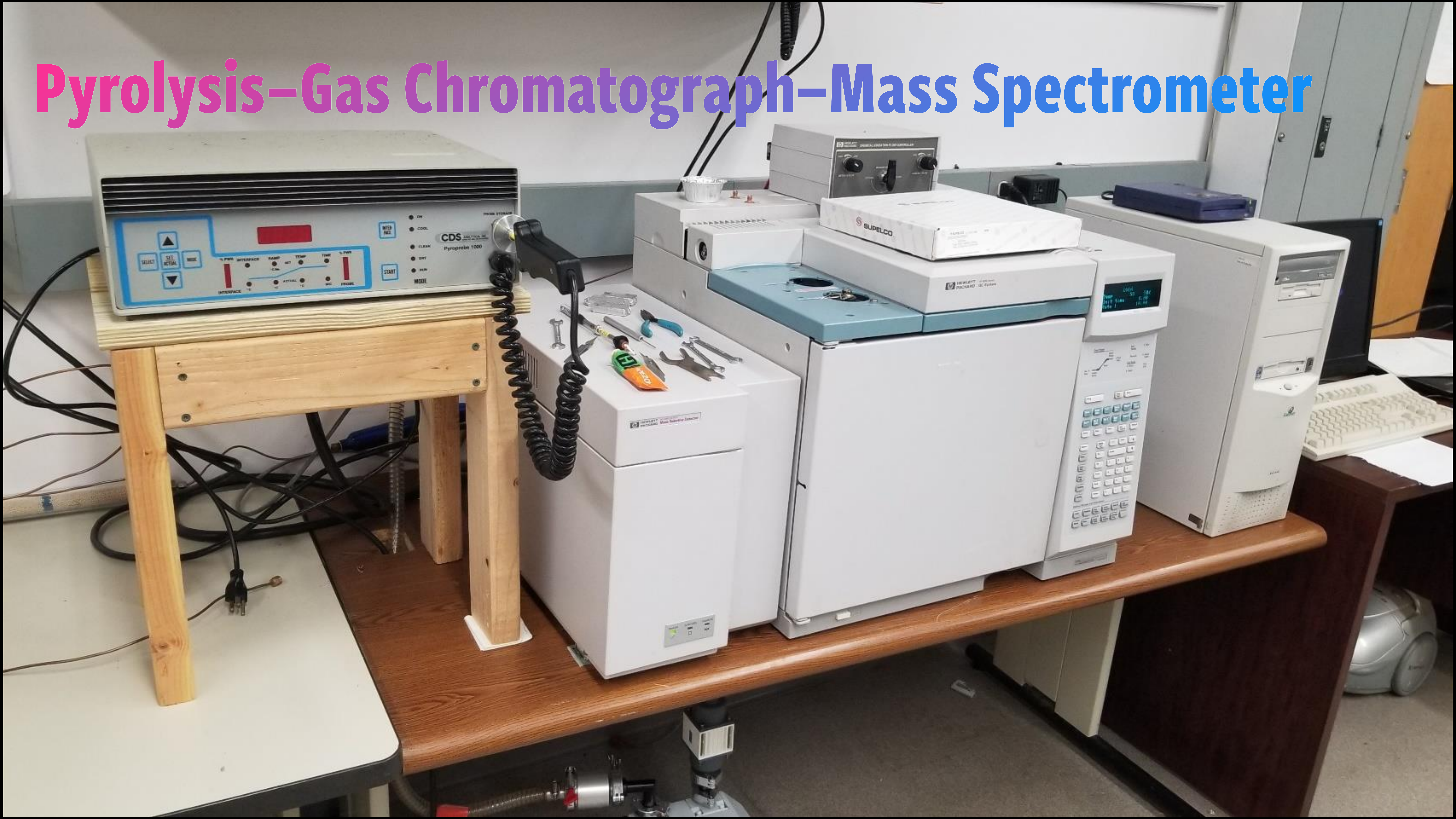
EMERSYN SLAUGHTER

MICHAEL L. WONG

JOURNAL ARTICLE:

Slaughter et al. (in prep.)

Pyrolysis–Gas Chromatograph–Mass Spectrometer



0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
intensity
intensity
3000
2500
2000
1500
1000
500
0
scans
time
60
80
100
120
140
160
180
200
m/z
mass-to-charge
Cleaves+ 2023

BACTERIA
intensity
0.35
0.30
0.25
0.20
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0.10
0.05
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intensity
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Cleaves+ 2023


BACTERIA
PLANTS
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0.15
0.20
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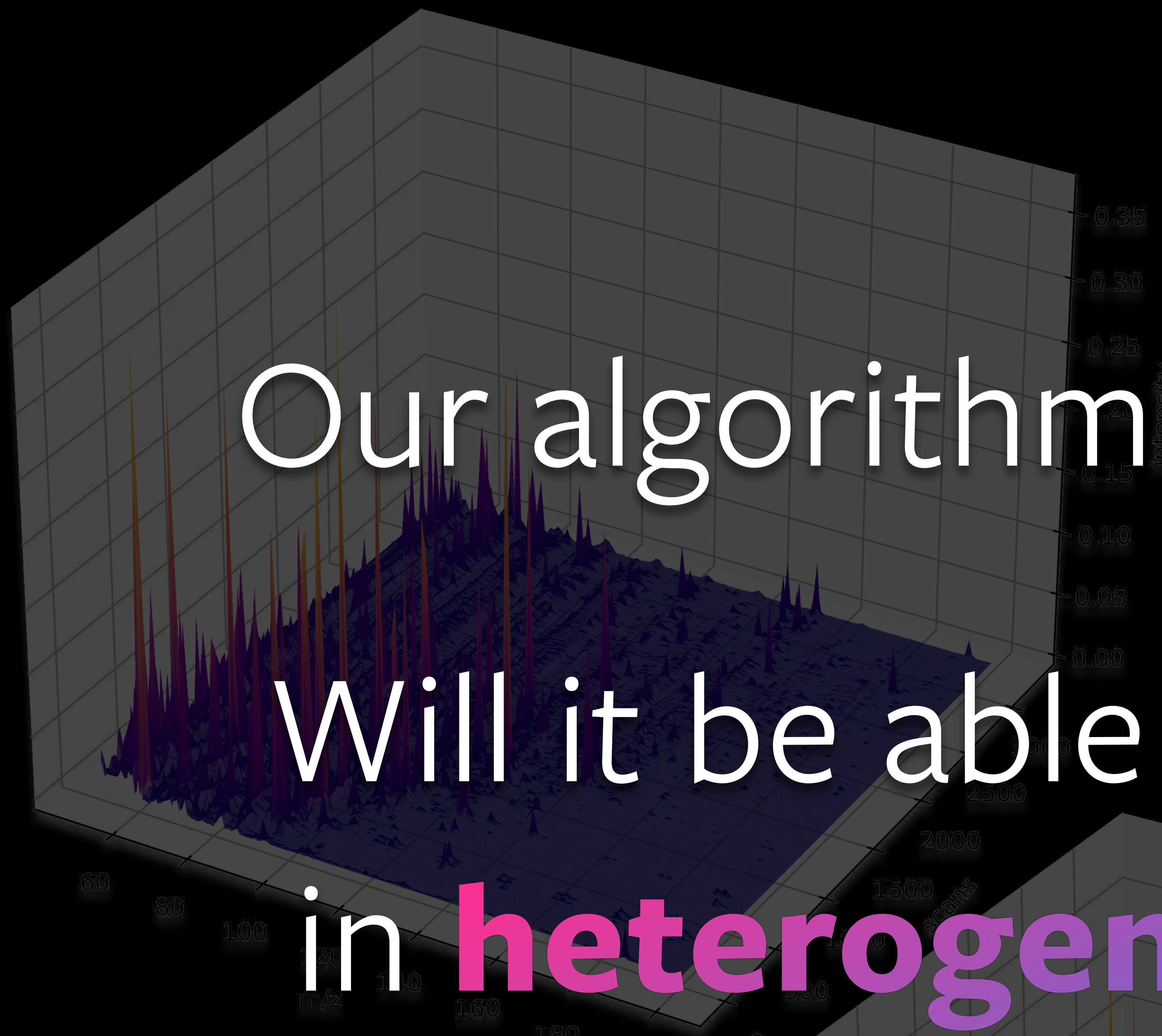
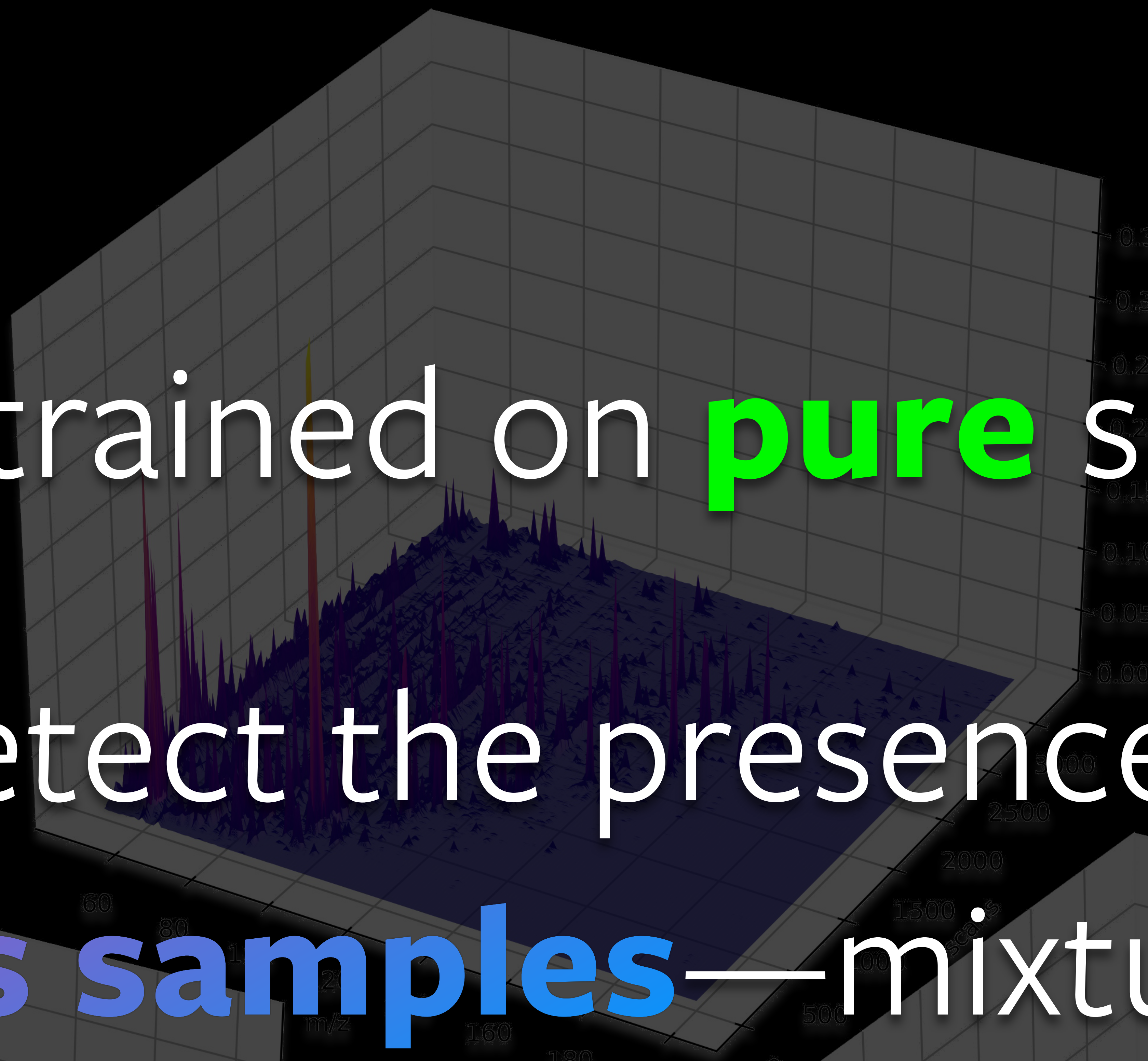
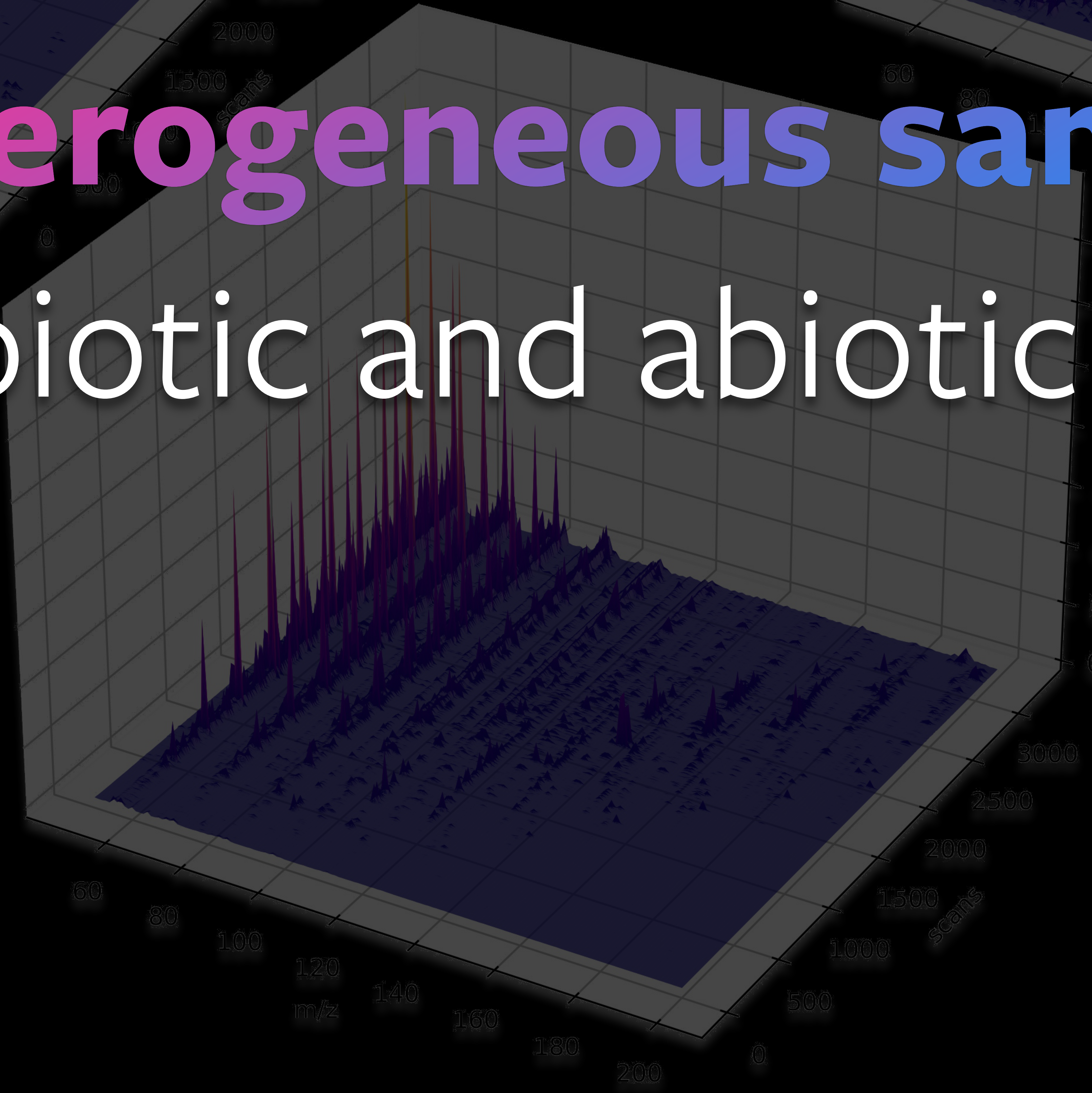
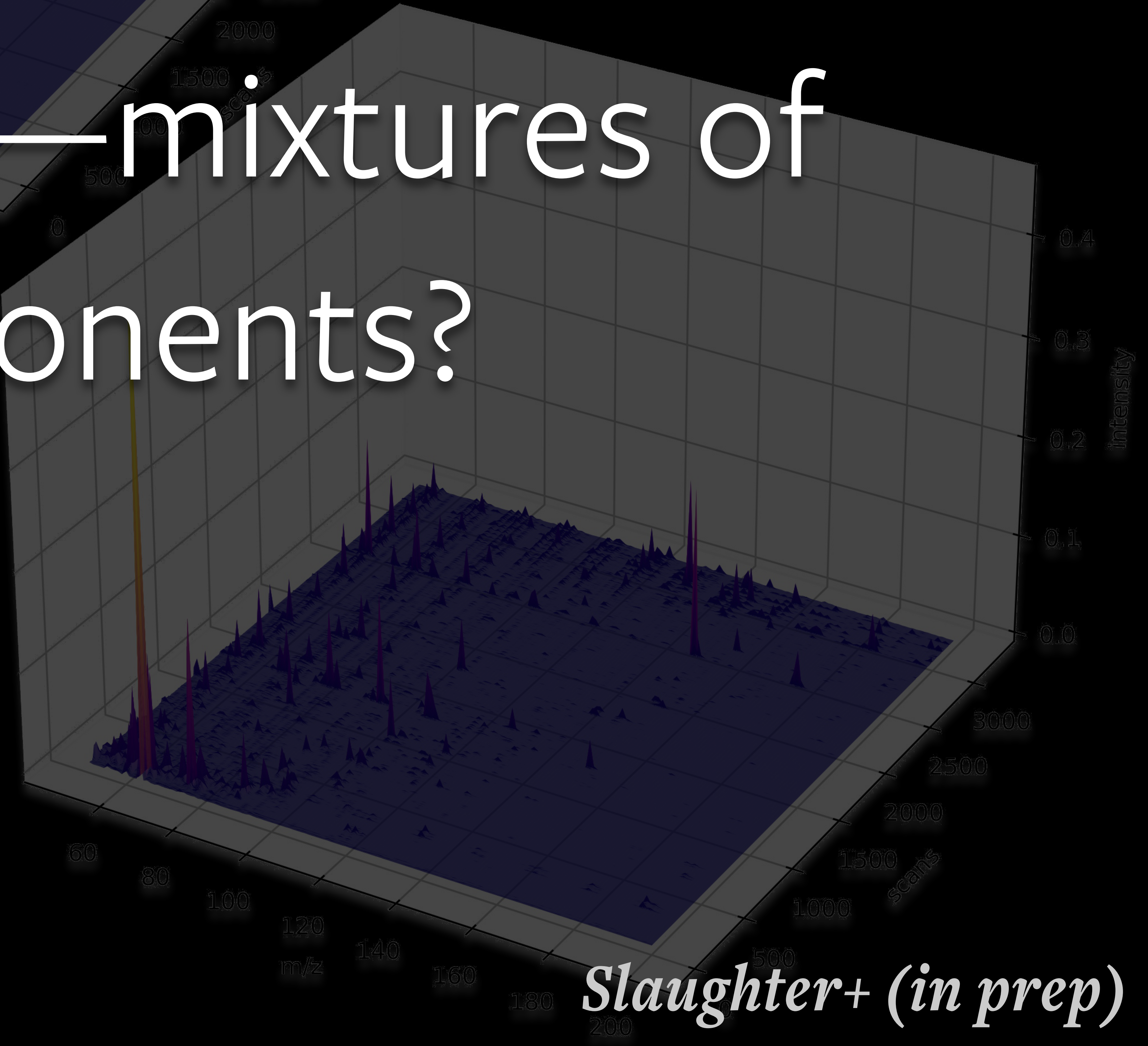
0.30
0.35
Cleaves+ 2023


BACTERIA
PLANTS
PETROLEUM
intensity
scans
m/z
Cleaves+ 2023


BACTERIA
PLANTS
PETROLEUM
METEORITES
intensity
scans
m/z
Cleaves+ 2023

Our machine learning algorithm can distinguish **biotic** from **abiotic** samples with **90% accuracy**

Cleaves+ 2023

Our algorithm was trained on **pure** samples.

Will it be able to detect the presence of life in **heterogeneous samples**—mixtures of biotic and abiotic components?

Slaughter+ (in prep)

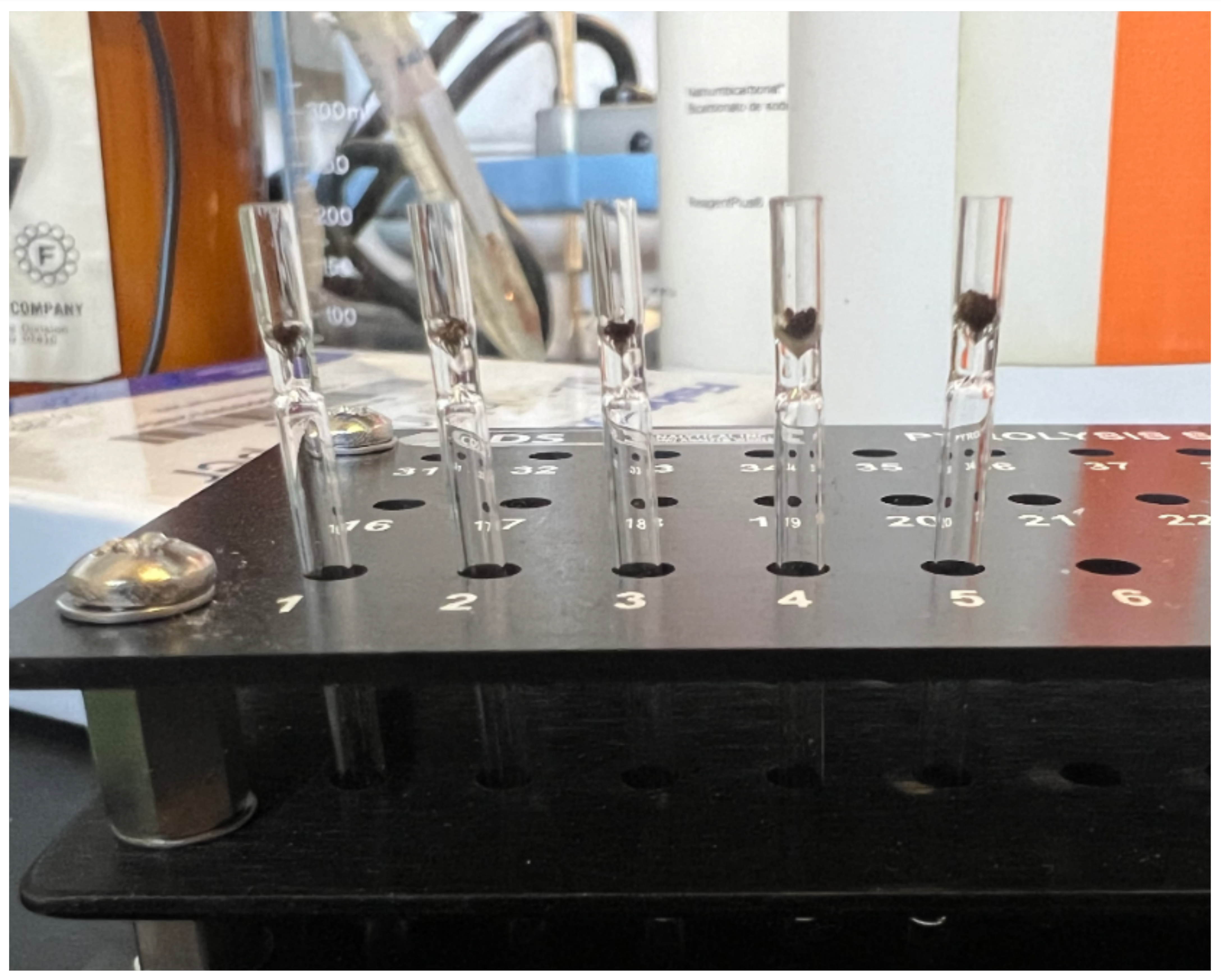
BIOTIC

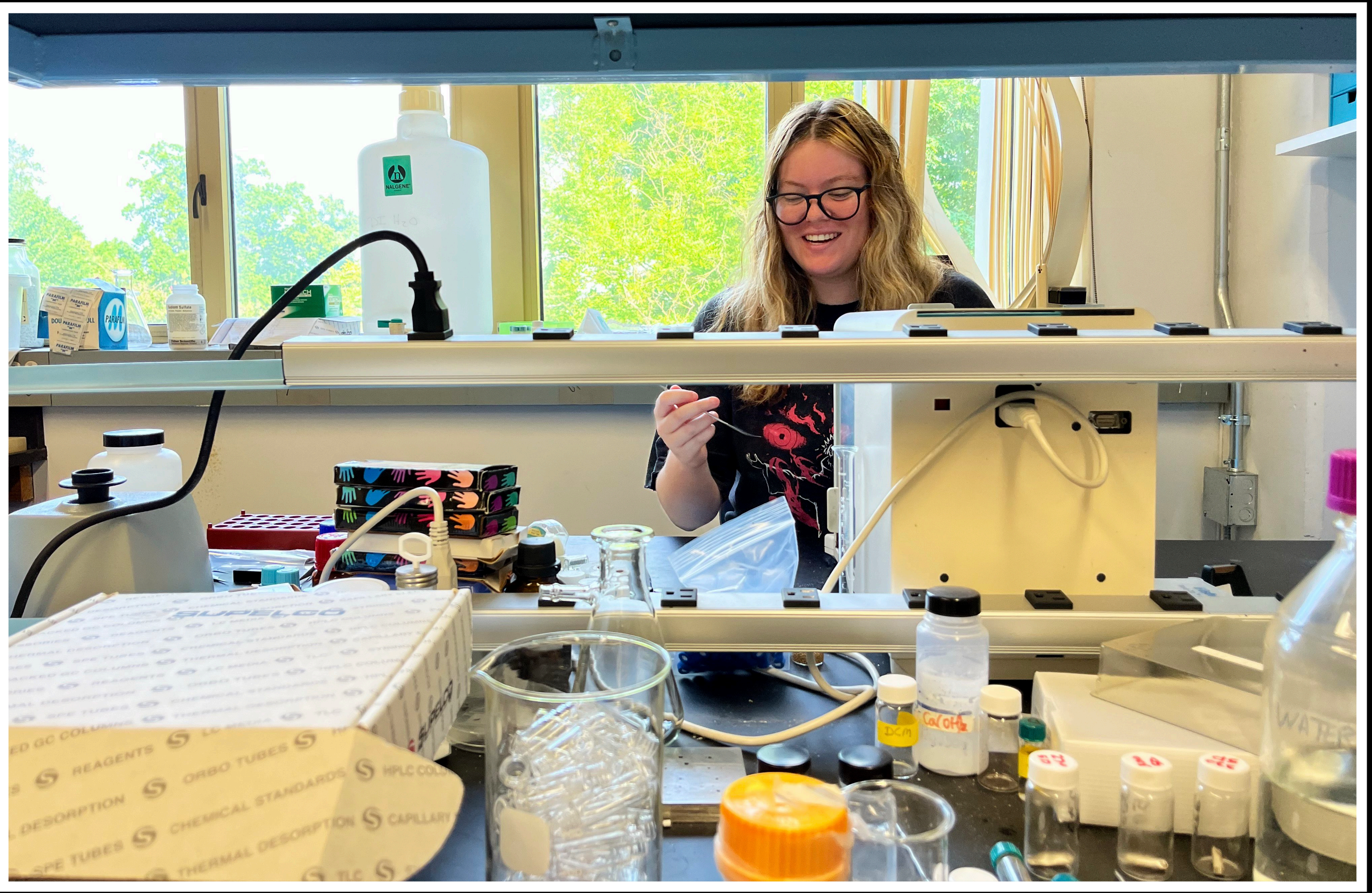
yeast (eukaryote)
cyanobacteria (bacterium)
halobacterium (archaeon)
metasequoia (45 Ma fossil wood)

90:10
66:33
50:50
33:66
10:90

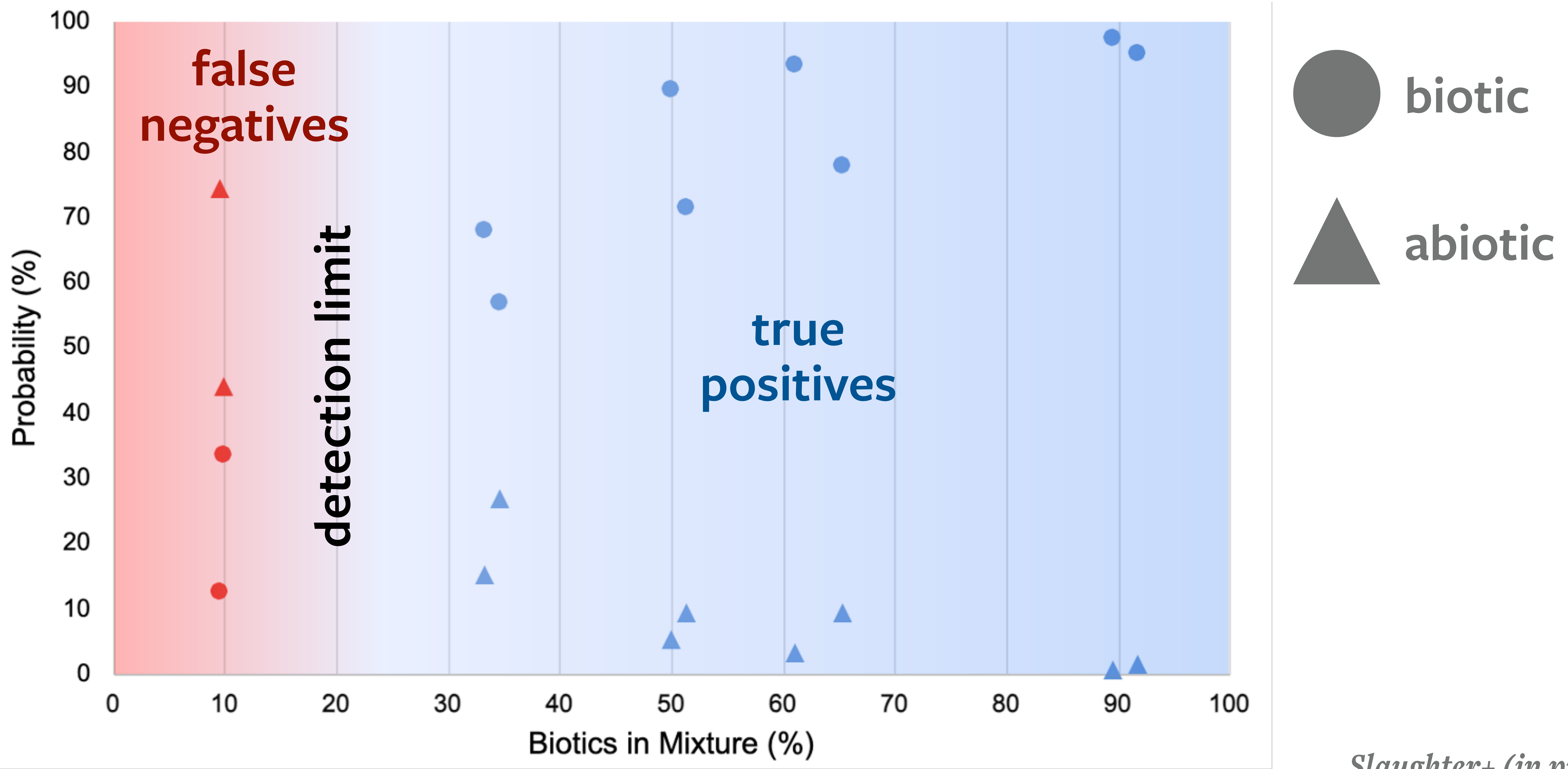
ABIOTIC

synthetic insoluble organic matter
(meteorite substitute)



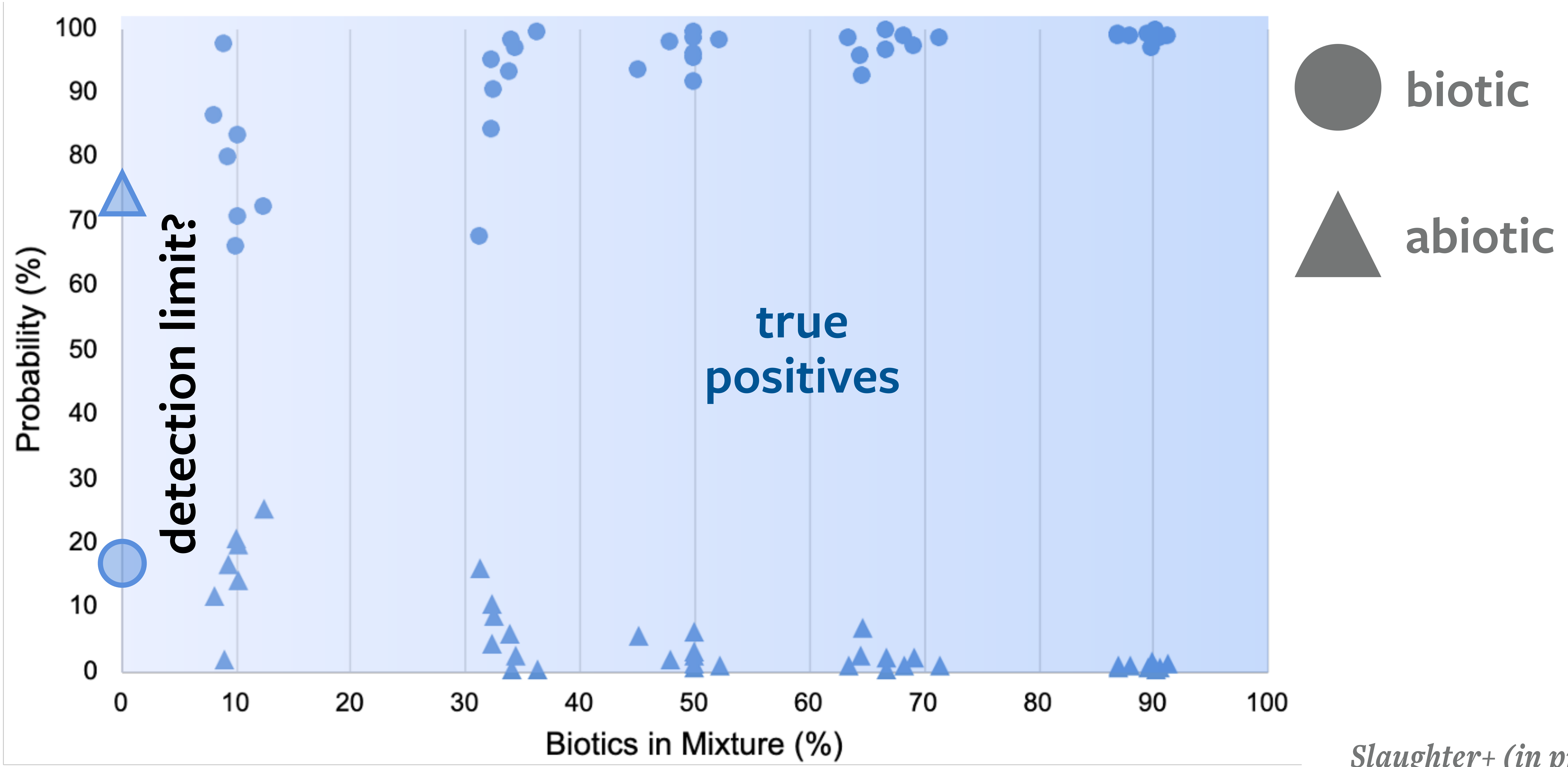


Mixtures with aged biotic samples



Slaughter+ (in prep)

Mixtures with fresh biotic samples



Slaughter+ (in prep)

The search for life in the solar system

Slaughter+ (in prep)

The search for life in the solar system

A robust, agnostic biosignature technique based on pyrolysis–GC–MS combined with machine learning

Slaughter+ (in prep)

The search for life in the solar system

A robust, agnostic biosignature technique based on pyrolysis–GC–MS combined with machine learning

This technique is capable of detecting trace amounts of life against a background of abiotic organic molecules

+ Detection limit **10–30%** for **aged** biotic matter
+ Detection limit **<10%** for **fresh** biotic matter

Slaughter+ (in prep)

The search for life in the solar system

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Implications for future astrobiological missions and interplanetary sample return

Slaughter+ (in prep)

MADELINE CHRISTENSEN

Set the stage for the emergence of life on Earth by quantifying nitrogen fixation via lightning and solar energetic particle deposition

LUCAS M. FIFER

Quantified the productivity of plausible biology on early Mars, constrained by measurements of organics preserved at Gale crater lake

EMERSYN SLAUGHTER

Advanced a bio-signature technique based on py–GC–MS + machine learning by quantifying detection upper limits for biotic–abiotic mixtures