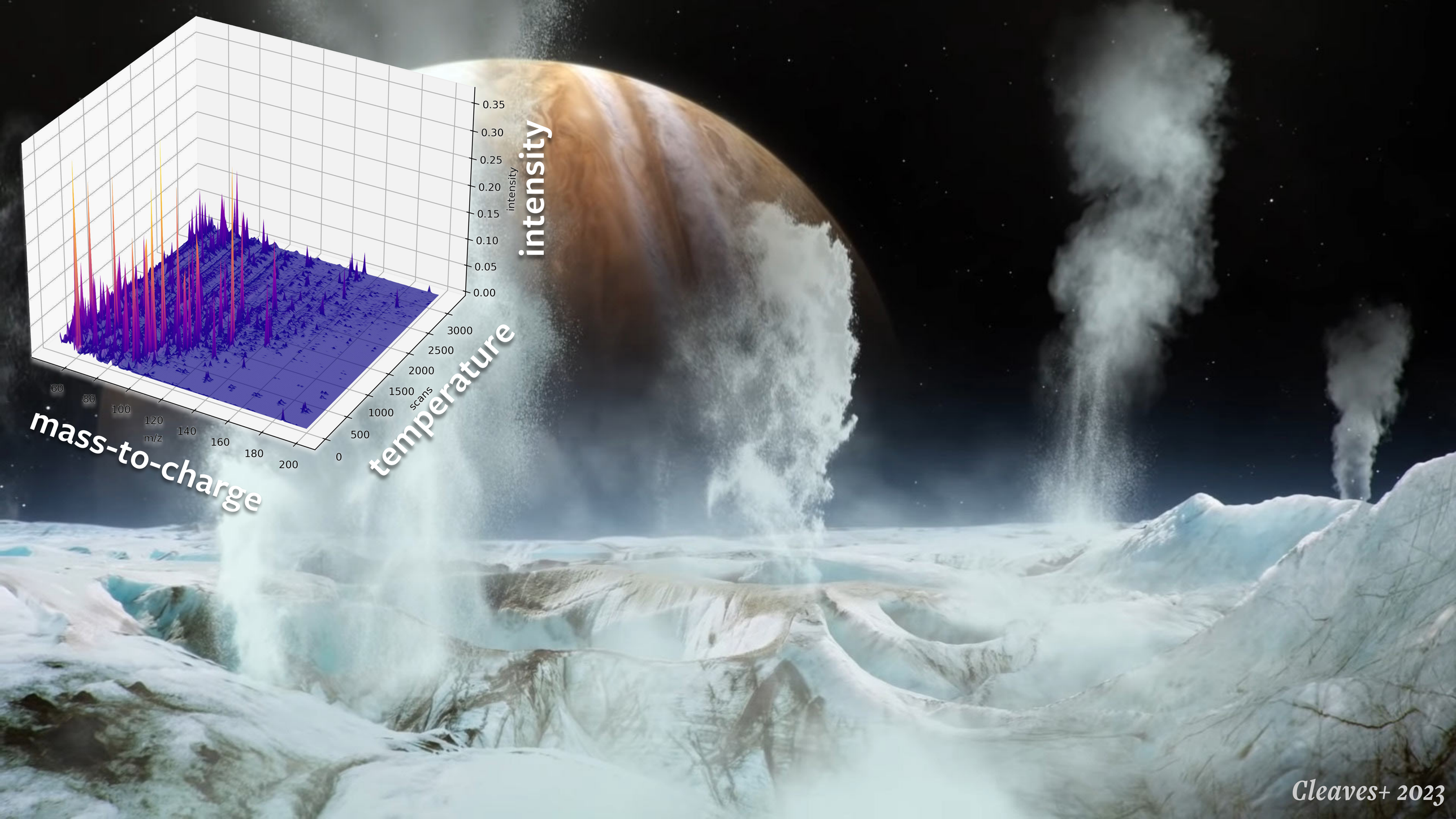
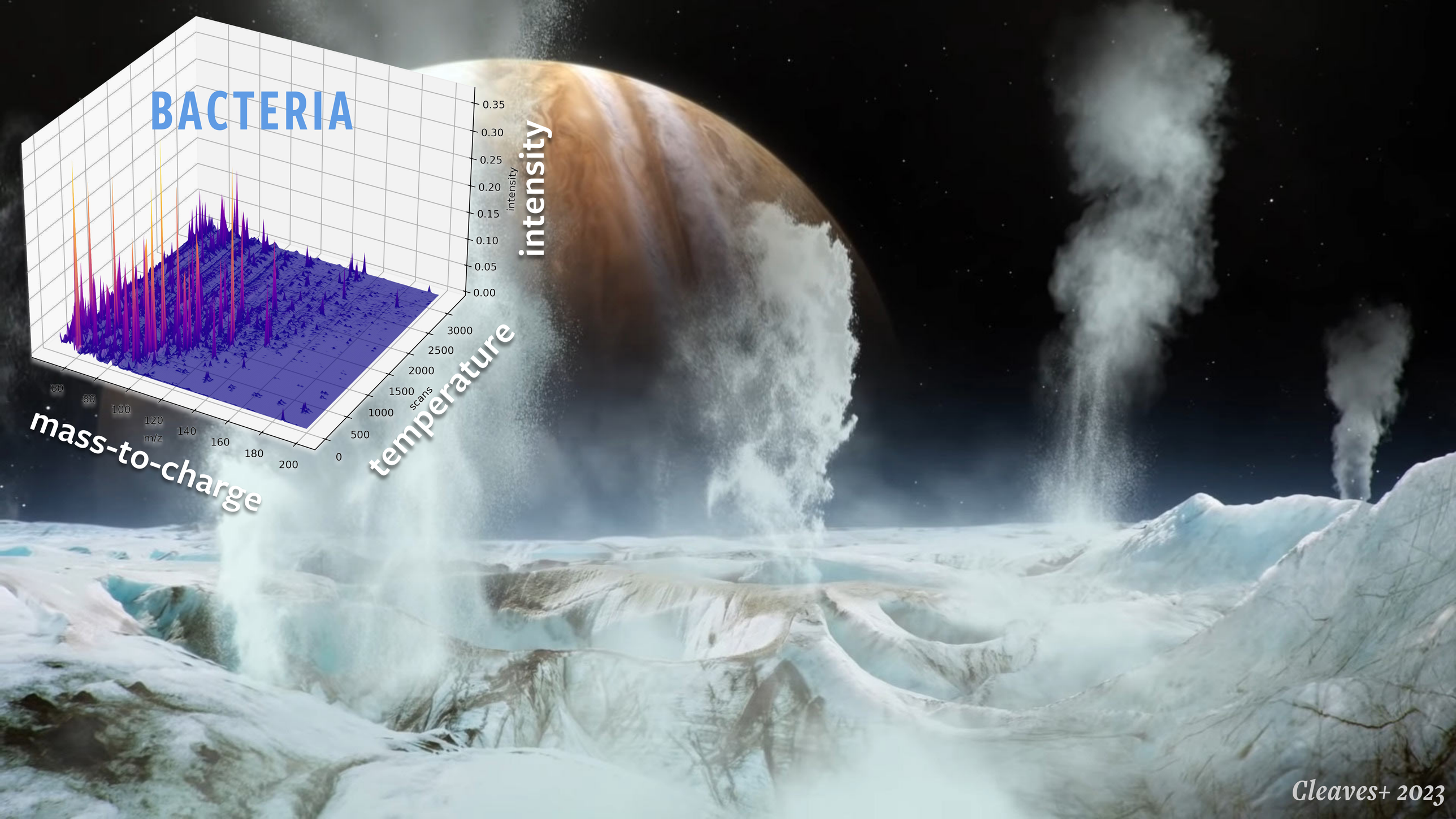
Pyrolysis–Gas Chromatograph–Mass Spectrometer



Cleaves+ 2023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0.30
0.25
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0.15
0.10
0.05
0.00
intensity
3000
2500
2000
1500
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scans
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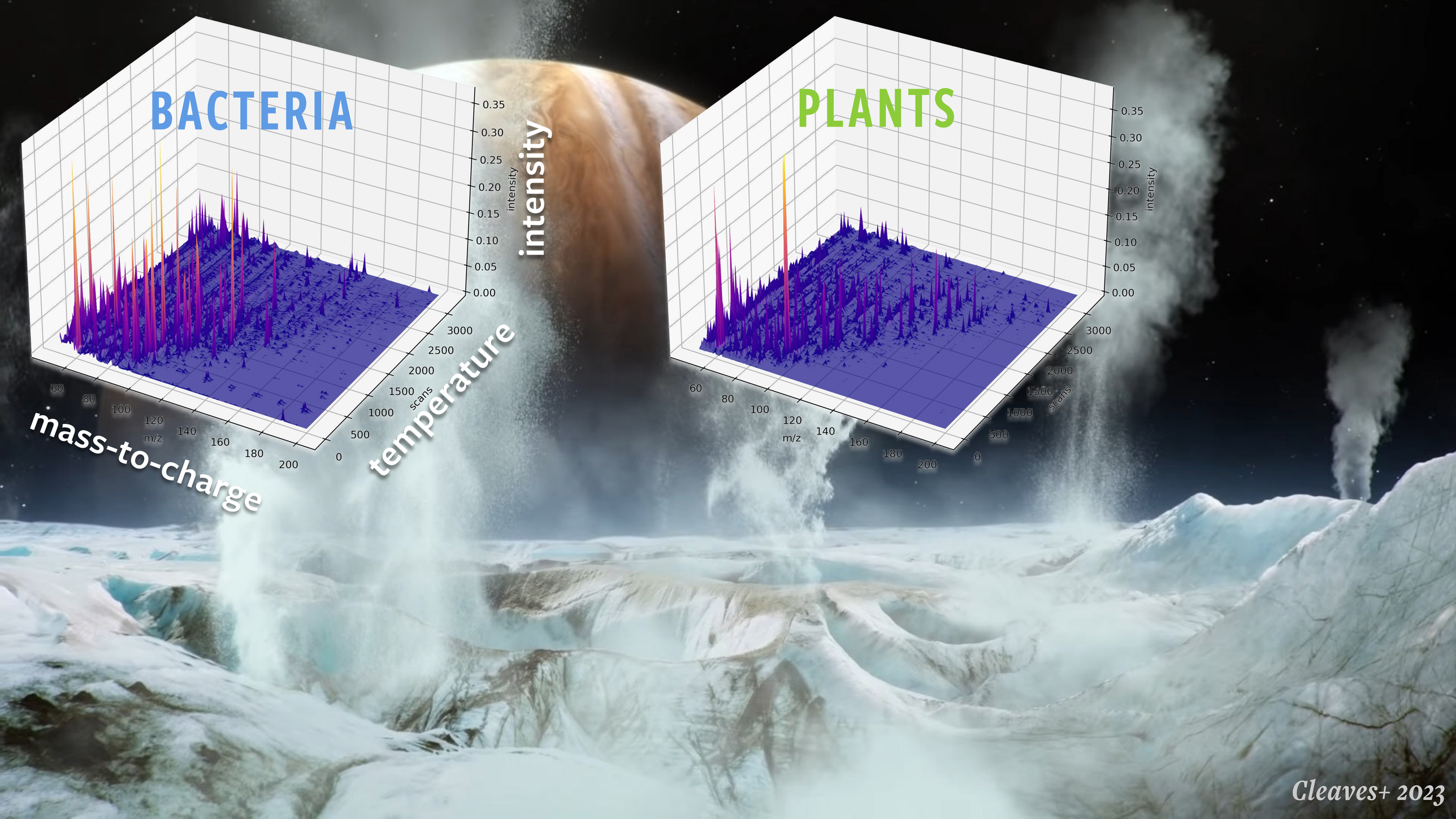
140
160
180
200
m/z
mass-to-charge
Cleaves+ 2023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PLANTS
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mass-to-charge
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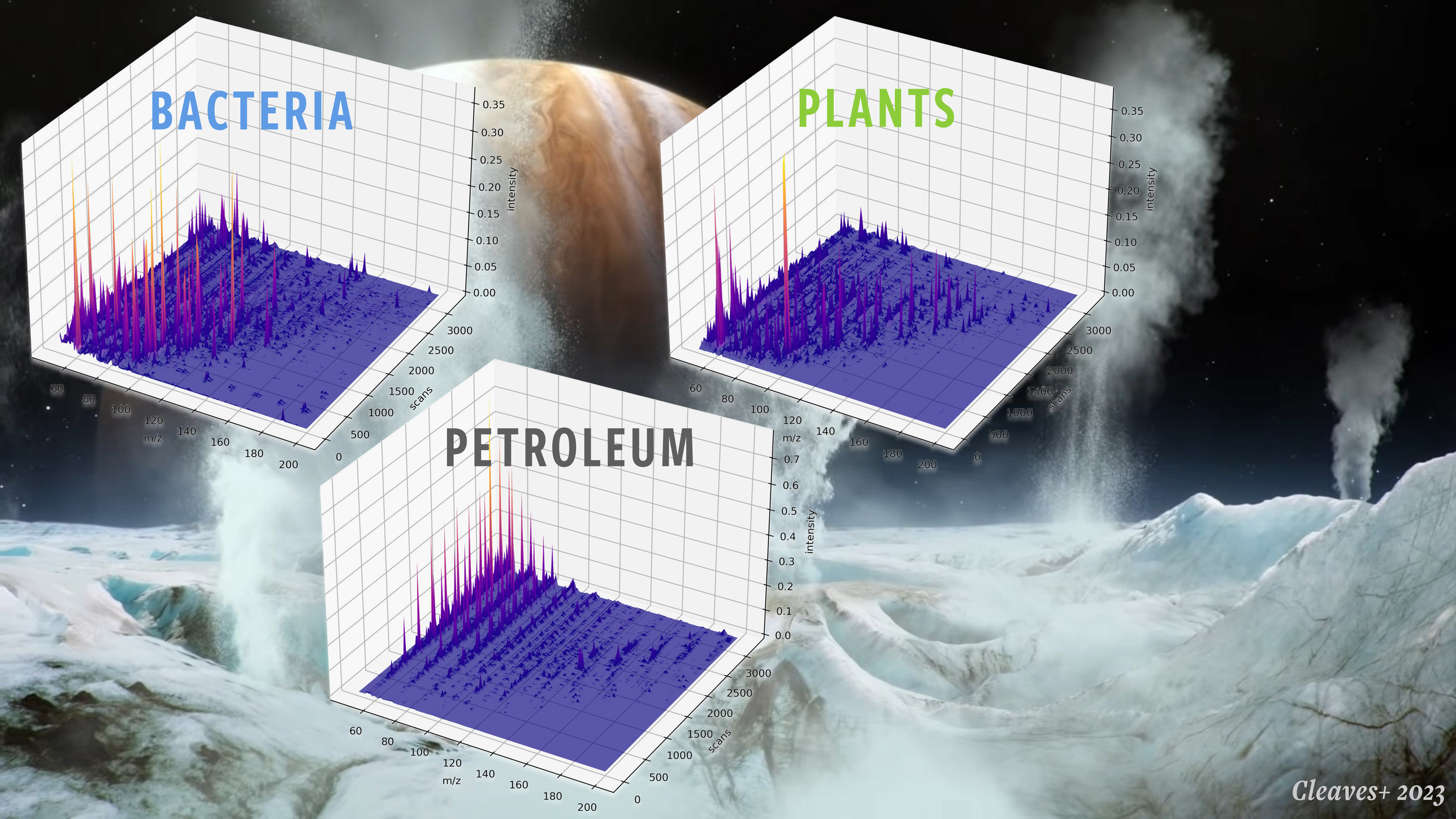
Cleaves+ 2023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PLANTS
PETROLEUM
m/z
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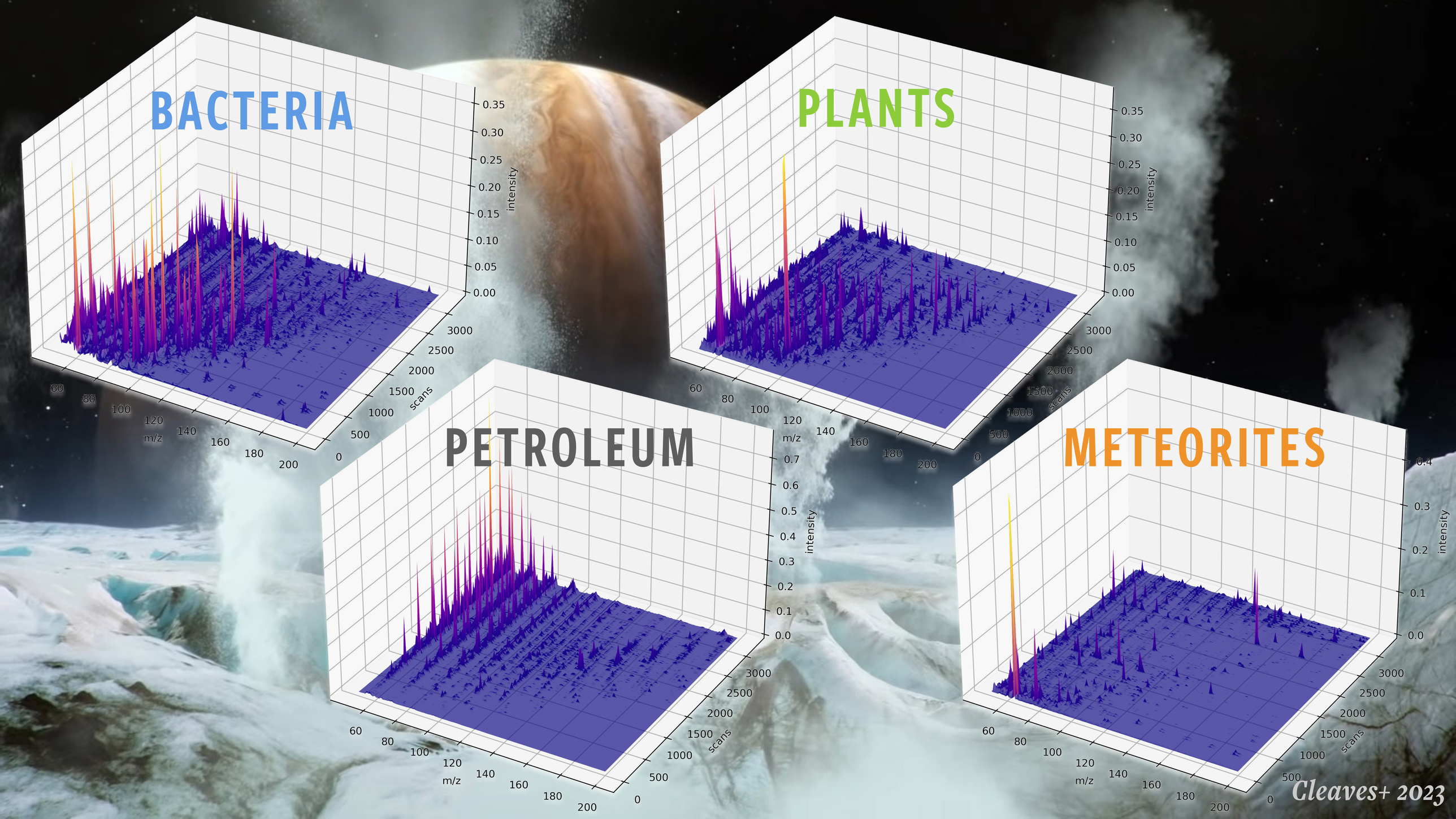
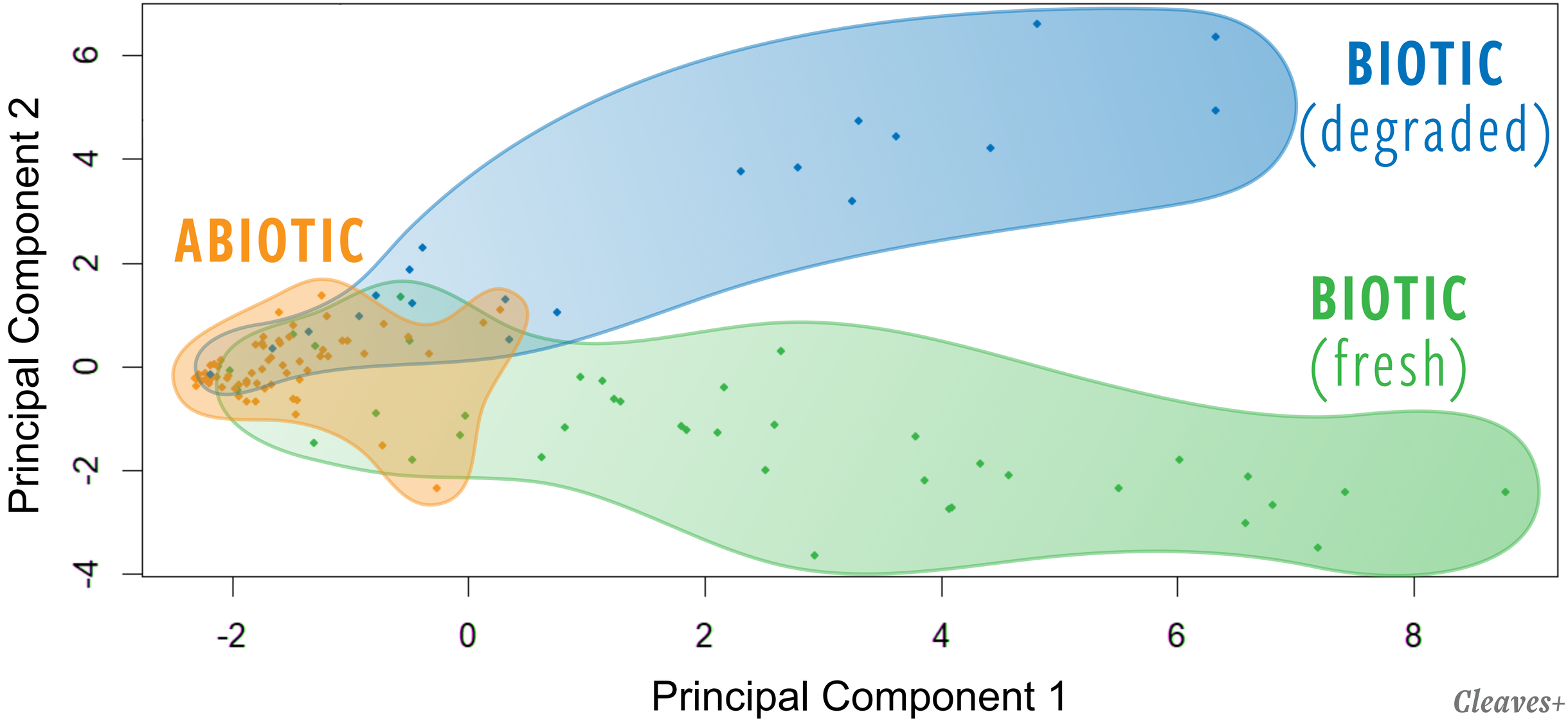

BACTERIA
PLANTS
PETROLEUM
METEORITES
m/z
scans
intensity
Cleaves+ 2023

We can distinguish biotic vs. abiotic samples with 90% accuracy

The algorithm can also tell **degraded** from **fresh** biotic (but we didn't tell it how to do this!)

Allows us to search for **potentially biological anomalies** on other worlds



Cleaves+ 2023

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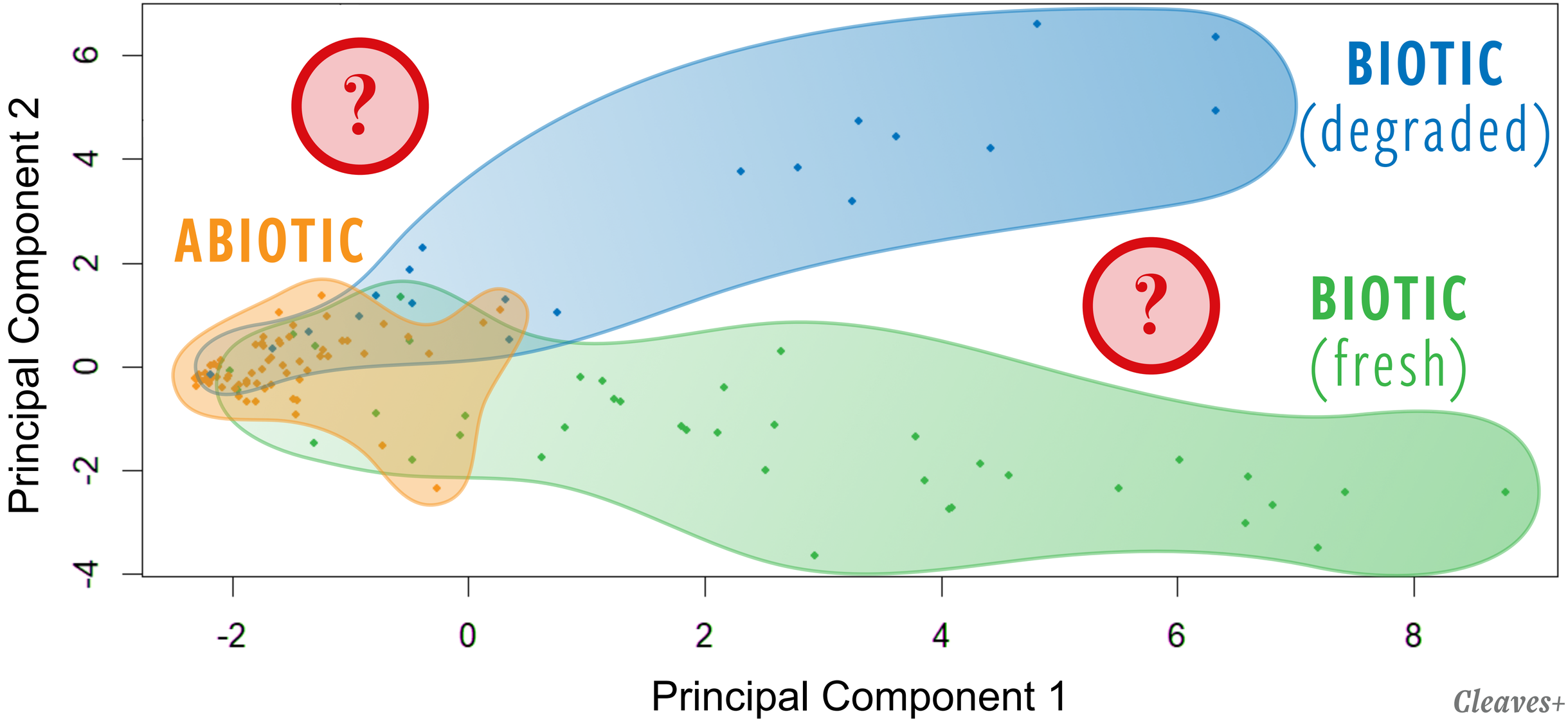


Cleaves+ 2023

A Robust, Agnostic Biosignature

BASED ON MACHINE LEARNING AND PYR-GC-MS

H. JAMES CLEAVES II

GRETHE HYSTAD

ANIRUDH PRABHU

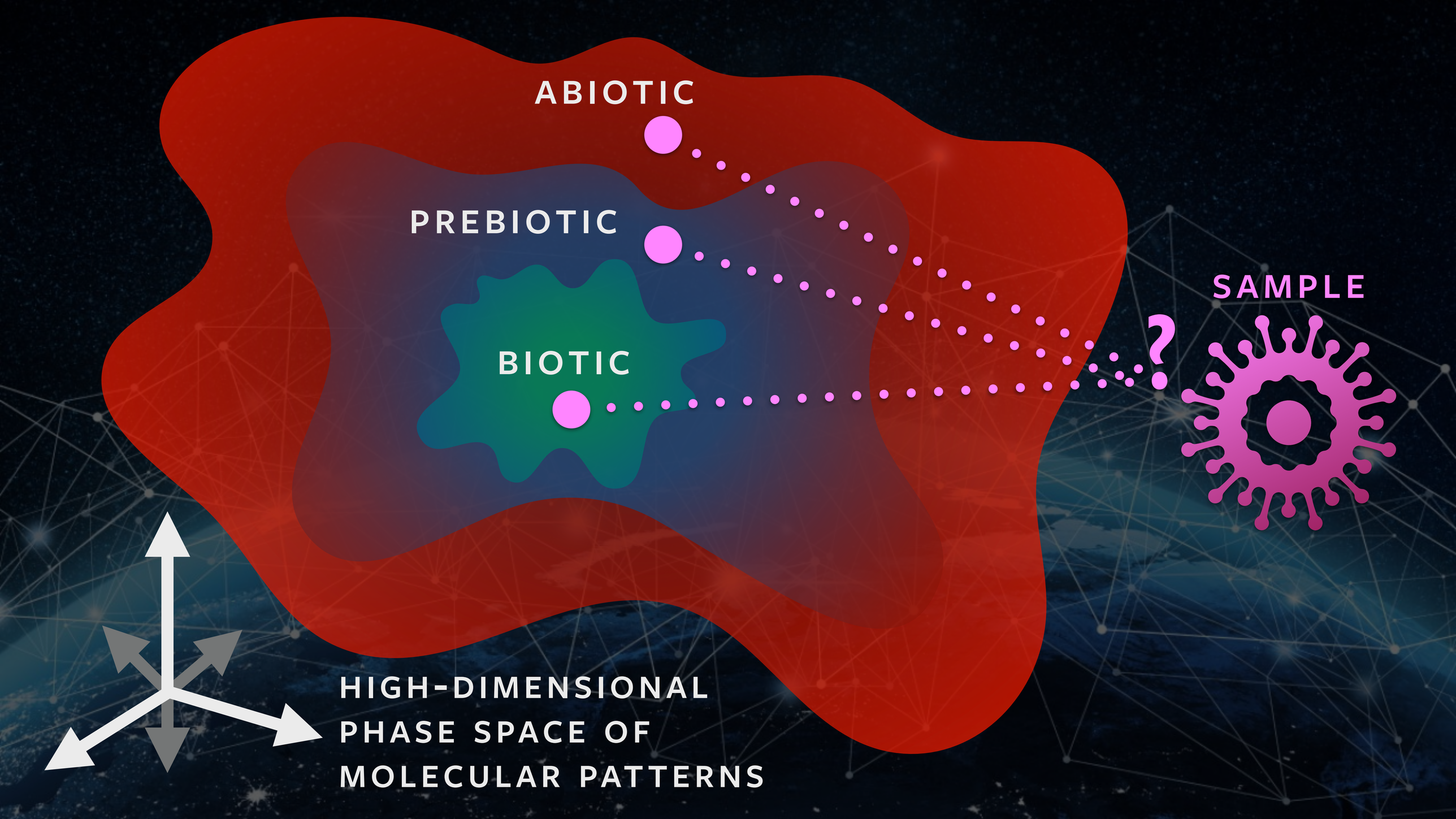
MICHAEL L. WONG

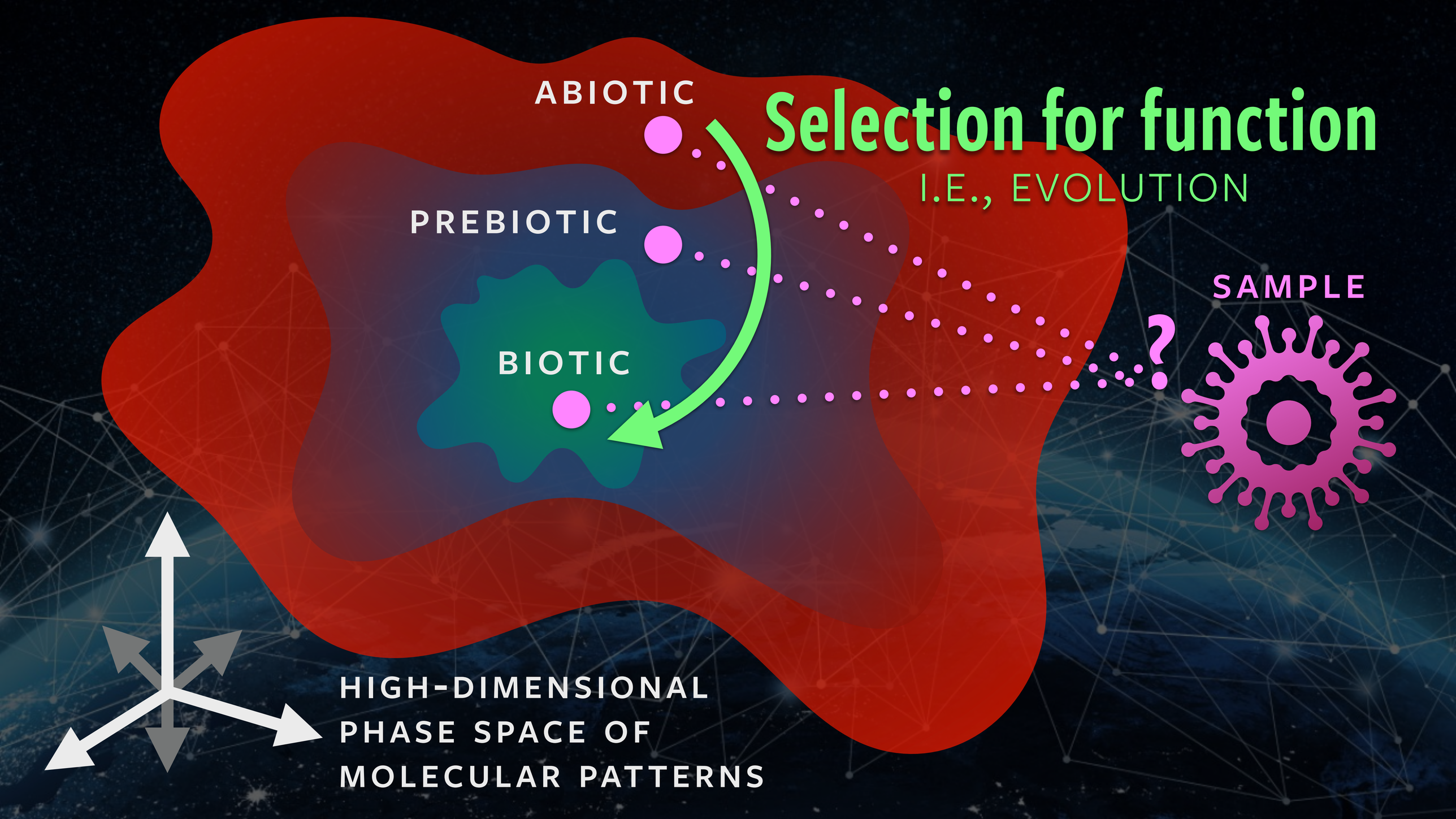
JOURNAL ARTICLE:
Cleaves et al. (in press) *PNAS*

ROBERT M. HAZEN

SOPHIA ECONOMON

GEORGE D. CODY


ABIOTIC
PREBIOTIC
BIOTIC
SAMPLE
?
HIGH-DIMENSIONAL
PHASE SPACE OF
MOLECULAR PATTERNS


ABIOTIC
PREBIOTIC
BIOTIC
Selection for function
I.E., EVOLUTION
SAMPLE
?
HIGH-DIMENSIONAL
PHASE SPACE OF
MOLECULAR PATTERNS

ON THE ROLES OF FUNCTION & SELECTION IN EVOLVING SYSTEMS

MICHAEL L. WONG

CAROL E. CLELAND

DANIEL ARENDS, JR.

STUART BARTLETT

H. JAMES CLEAVES II

JOURNAL ARTICLE:
Wong et al. (in press) *PNAS*

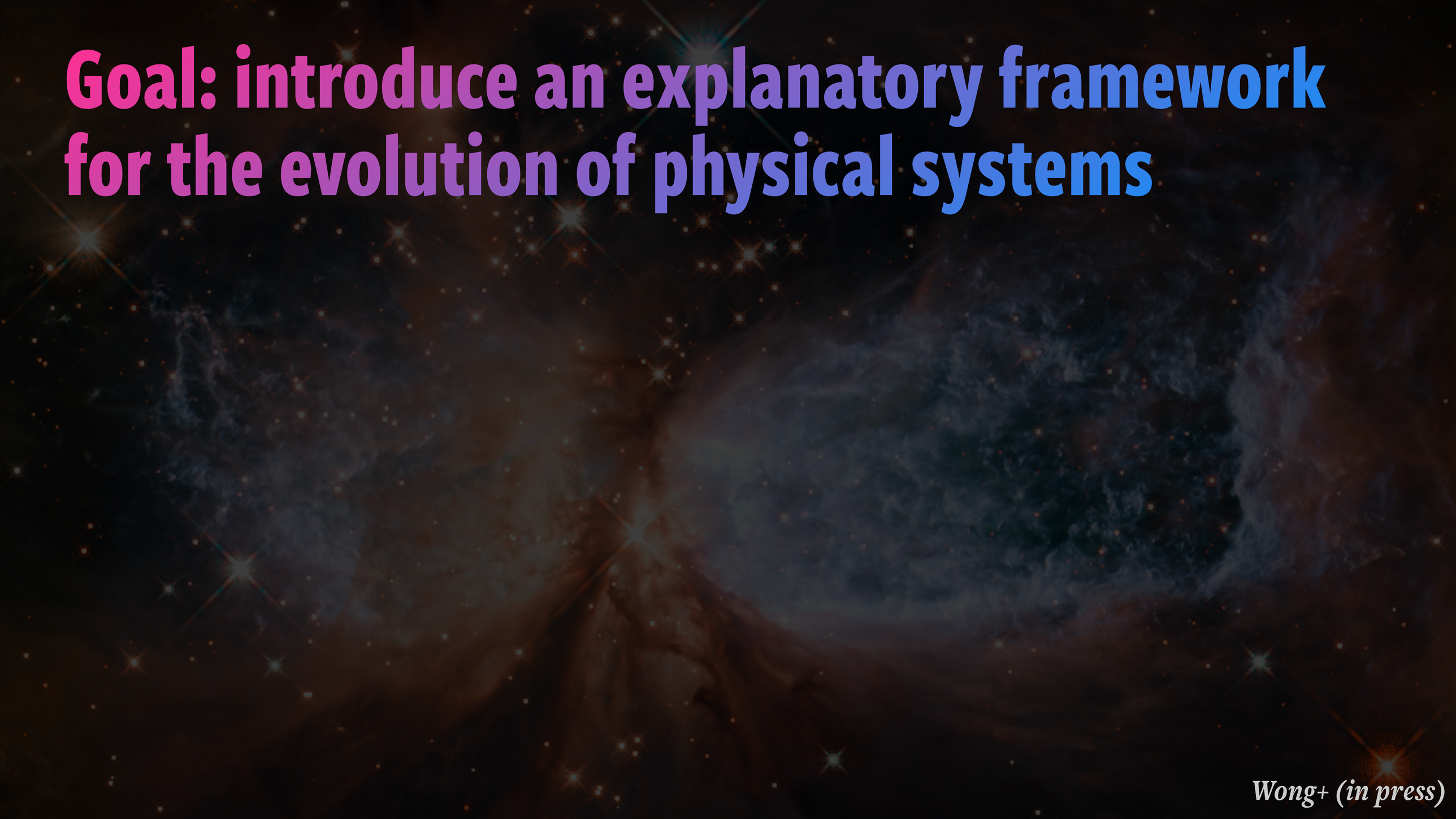
ROBERT M. HAZEN

JONATHAN I. LUNINE

ANIRUDH PRABHU

HEATHER DEMAREST

Goal: introduce an explanatory framework for the evolution of physical systems



Wong+ (in press)

Goal: introduce an explanatory framework for the evolution of physical systems

+ The second law of thermodynamics is the only **time-asymmetric** law so far articulated

Wong+ (in press)

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+ But the second law **does not explicitly address** the tendency for evolving systems to become increasingly complex with time

Wong+ (in press)

Goal: introduce an explanatory framework for the evolution of physical systems

+ The second law of thermodynamics is the only **time-asymmetric** law so far articulated

+ But the second law **does not explicitly address** the tendency for evolving systems to become increasingly complex with time

+ A “missing law” **must be consistent with** the second law but **may not inevitably follow** from it

Wong+ (in press)

Natural laws are built around conceptual equivalencies

Newton's law of gravity was built upon the property of having mass

AN APPLE'S FALL

PLANETARY ORBITS

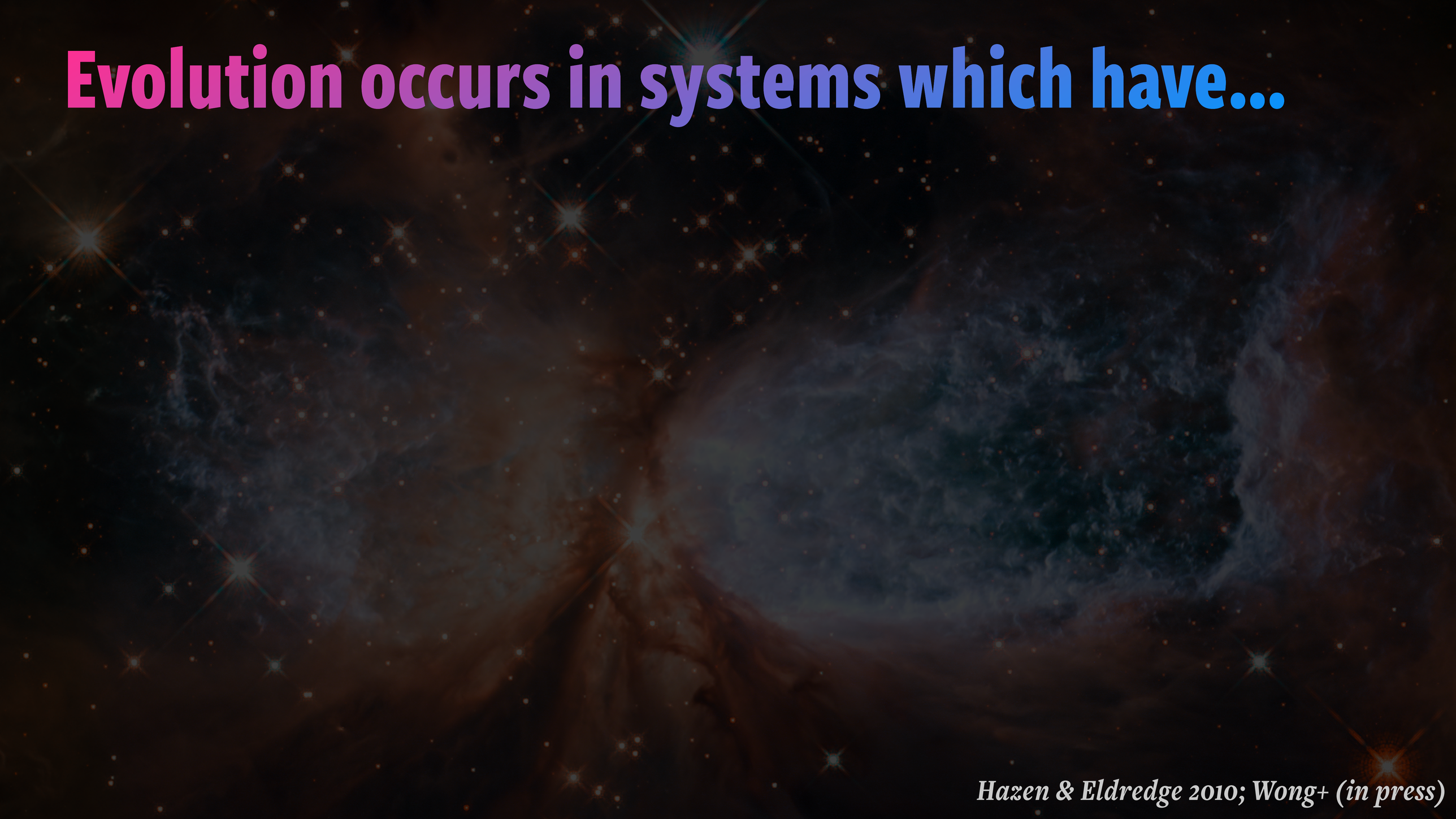
ATOMS + MOLECULES

Wong+ (in press)

1

What conceptual equivalencies underly all evolving systems?

Evolution occurs in systems which have...



Hazen & Eldredge 2010; Wong+ (in press)

Evolution occurs in systems which have...

1 A large number of interacting components

Hazen & Eldredge 2010; Wong+ (in press)

Evolution occurs in systems which have...

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2 A way to sample configuration space

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Evolution occurs in systems which have...

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3 Selection for function

Hazen & Eldredge 2010; Wong+ (in press)

Examples of evolution

1 Interacting components

2 A way to sample configuration space

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Wong+ (in press)

Examples of evolution

	1 Interacting components	2 A way to sample configuration space	3 Selection for function
Nucleo-synthesis	Protons, neutrons	Stellar fusion, supernovae, stellar mergers, etc.	Stability

Wong+ (in press)

Examples of evolution

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Wong+ (in press)

Examples of evolution

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Mineral evolution	Atomic elements	Mineral paragenesis in different *P*–*T*–*X* space	Stability
Biological evolution	Genes, cells, species, etc.	Mutations, HGT, recombination, etc.	Survival, propagation, etc.

Wong+ (in press)

2

What are the most fundamental selective forces? What functions does the universe “care” about?

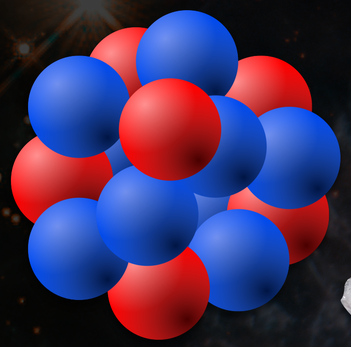
Sources of selection

Wong+ (in press)

Wong+ (in press)

Sources of selection

1 Static persistence



STABLE ISOTOPES

METASTABLE CRYSTALS

Configurations of matter tend to persist in time unless kinetically favorable avenues exist for their incorporation into more stable configurations

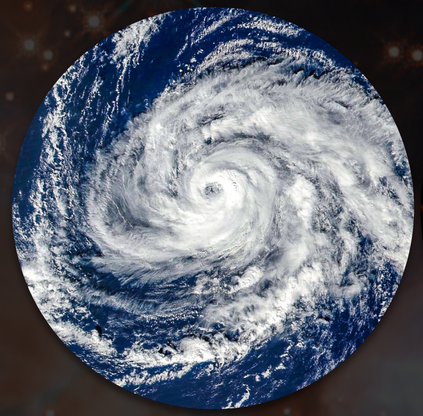
Wong+ (in press)

Sources of selection

1 Static persistence

2 Dynamic persistence

Emergent dynamic systems driven by thermodynamic dissipation



CONVECTION PATTERNS + CYCLONES

WILDFIRE

Functions **are processes that have causal efficacy over the system's dynamic persistence**

Wong+ (in press)

Sources of selection

1 Static persistence

2 Dynamic persistence

3 Novelty generation

The discovery of new functions that promote dynamic persistence raises a system's "kinetic barrier" against decay to equilibrium

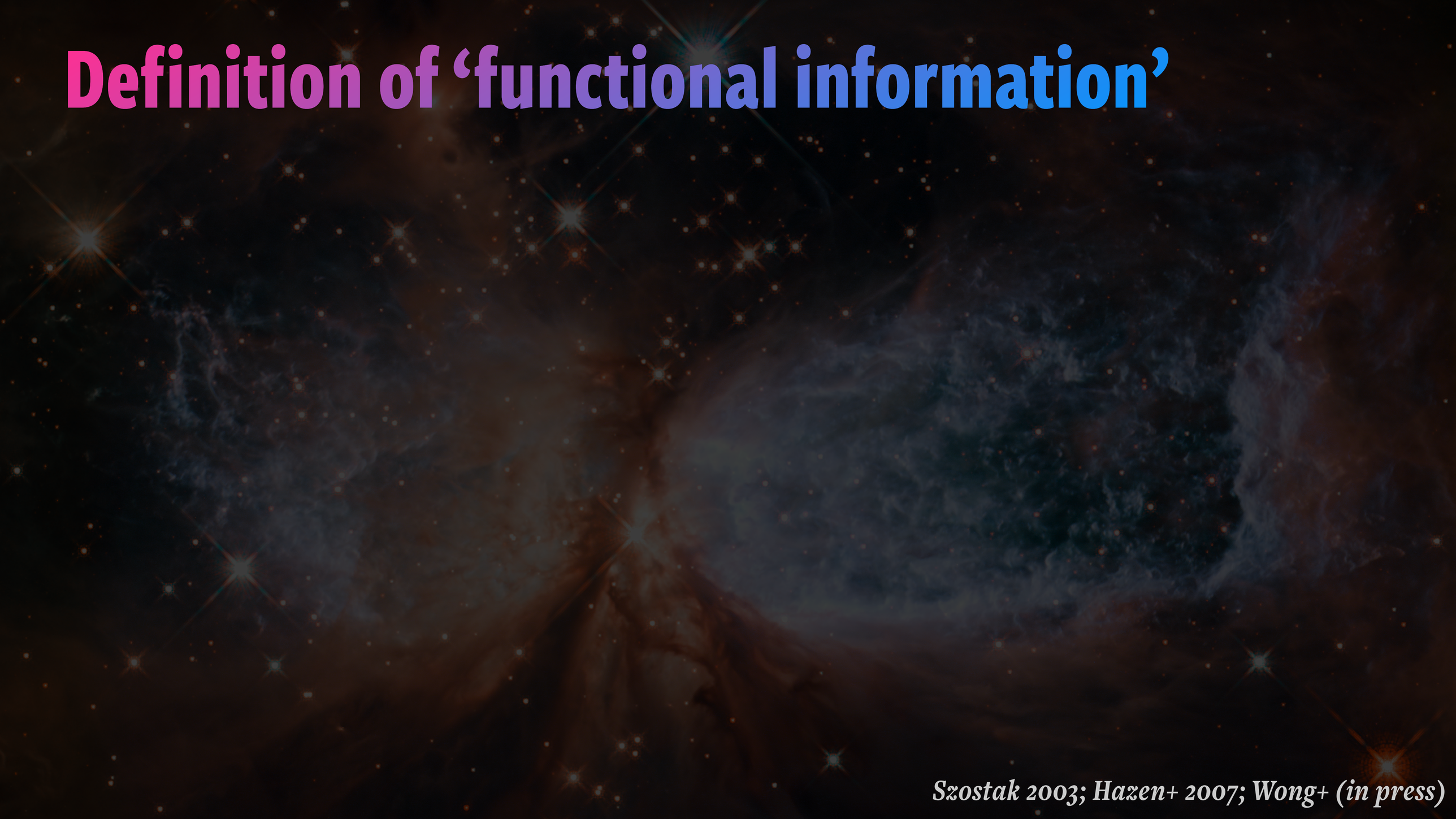
EXAPTATION, E.G., FEATHERS FOR FLIGHT

MUTATION RATE TUNING

3

Given a functional view of evolving systems, what is an auspicious ontology for a law of increasing complexity?

Definition of ‘functional information’



Szostak 2003; Hazen+ 2007; Wong+ (in press)

Definition of ‘functional information’

Given a system x and a degree of function E_x

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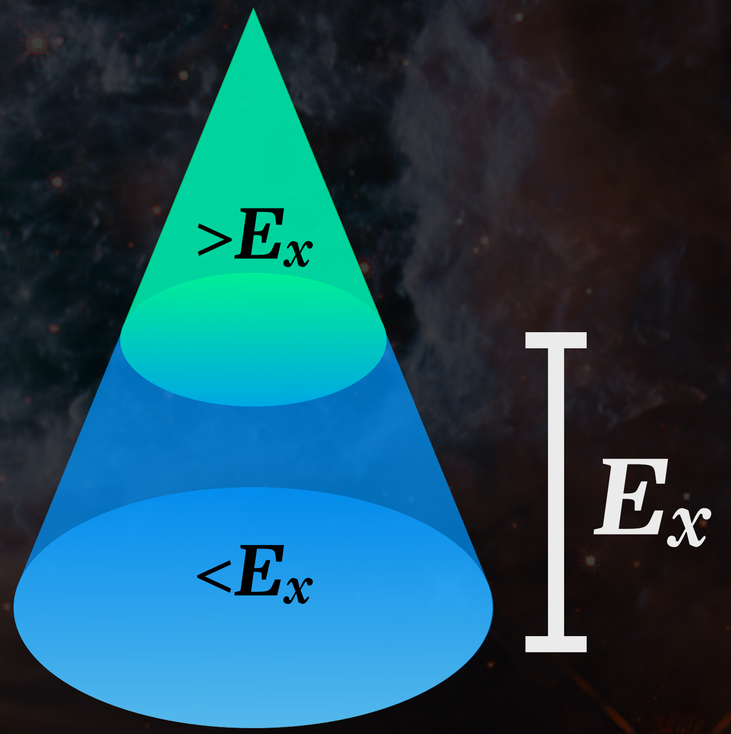
$F(E_x)$ is the **fraction of all possible configurations** of the system that possess a degree of function $>E_x$



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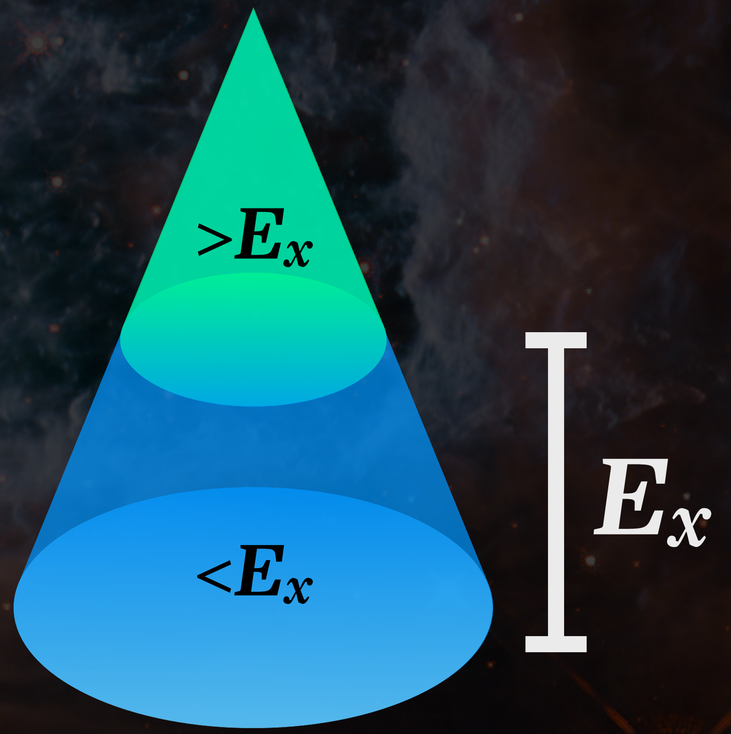
The functional information [bits] of the system is:

$$I(E_x) = -\log_2[F(E_x)]$$



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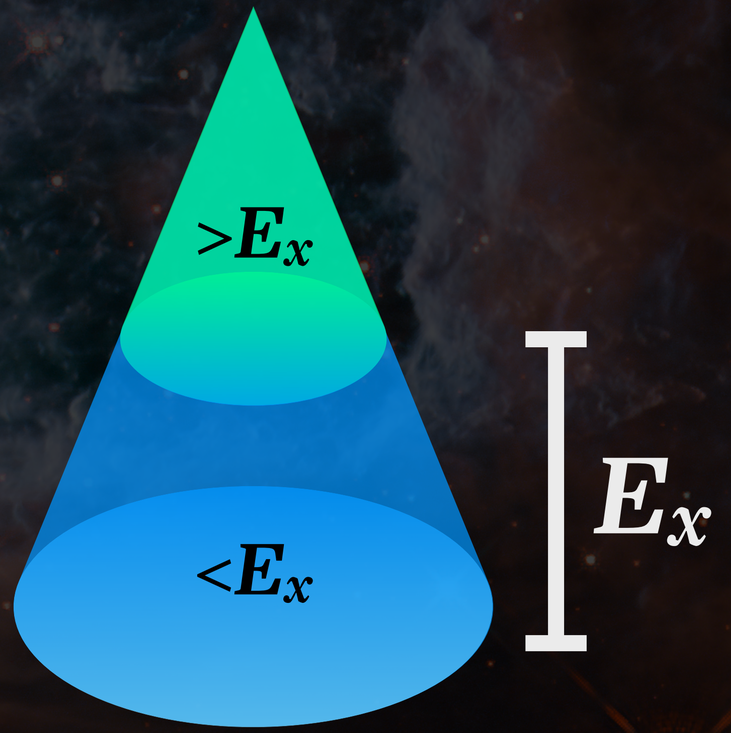
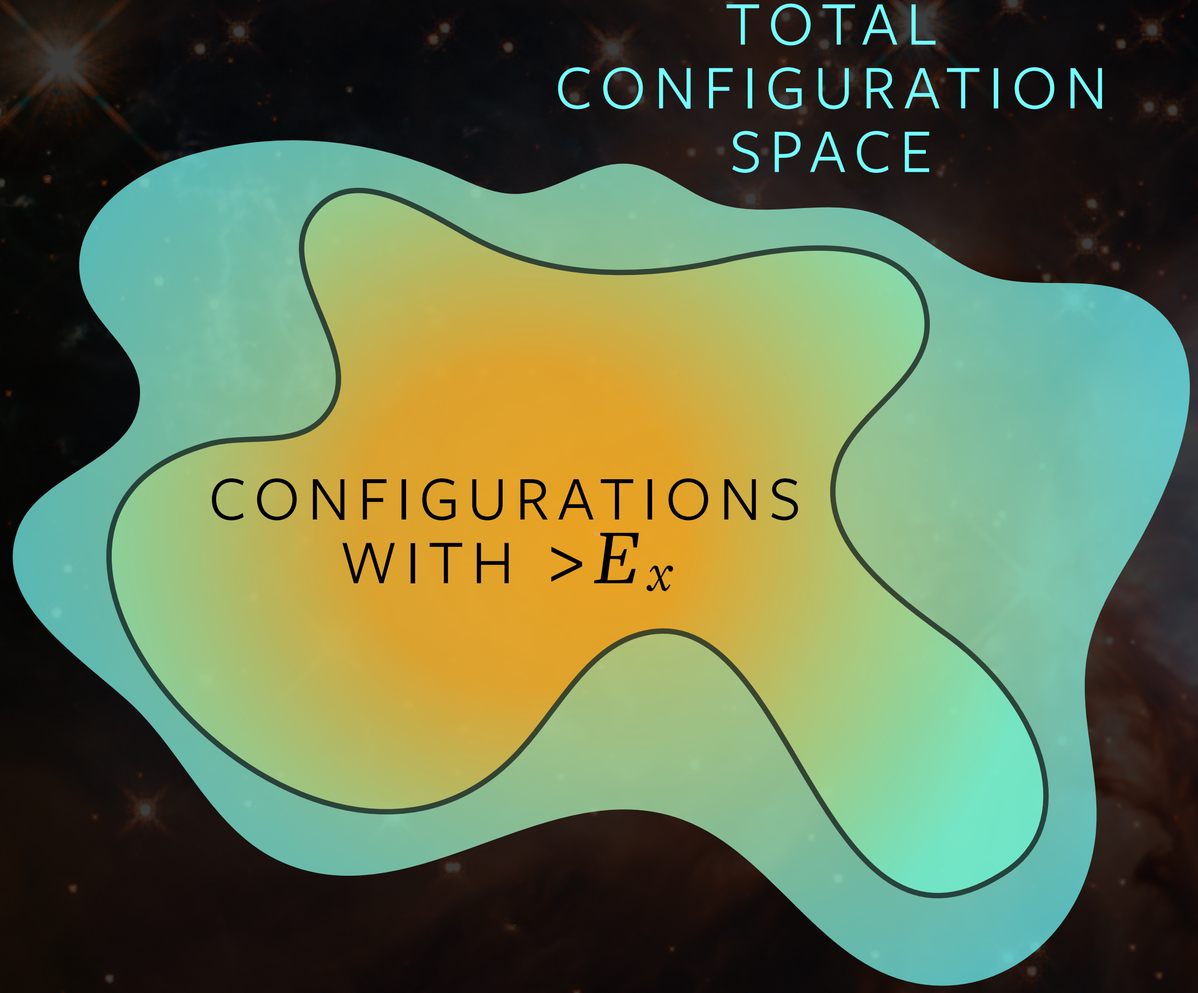
Why would $I(E_x)$ change with time?

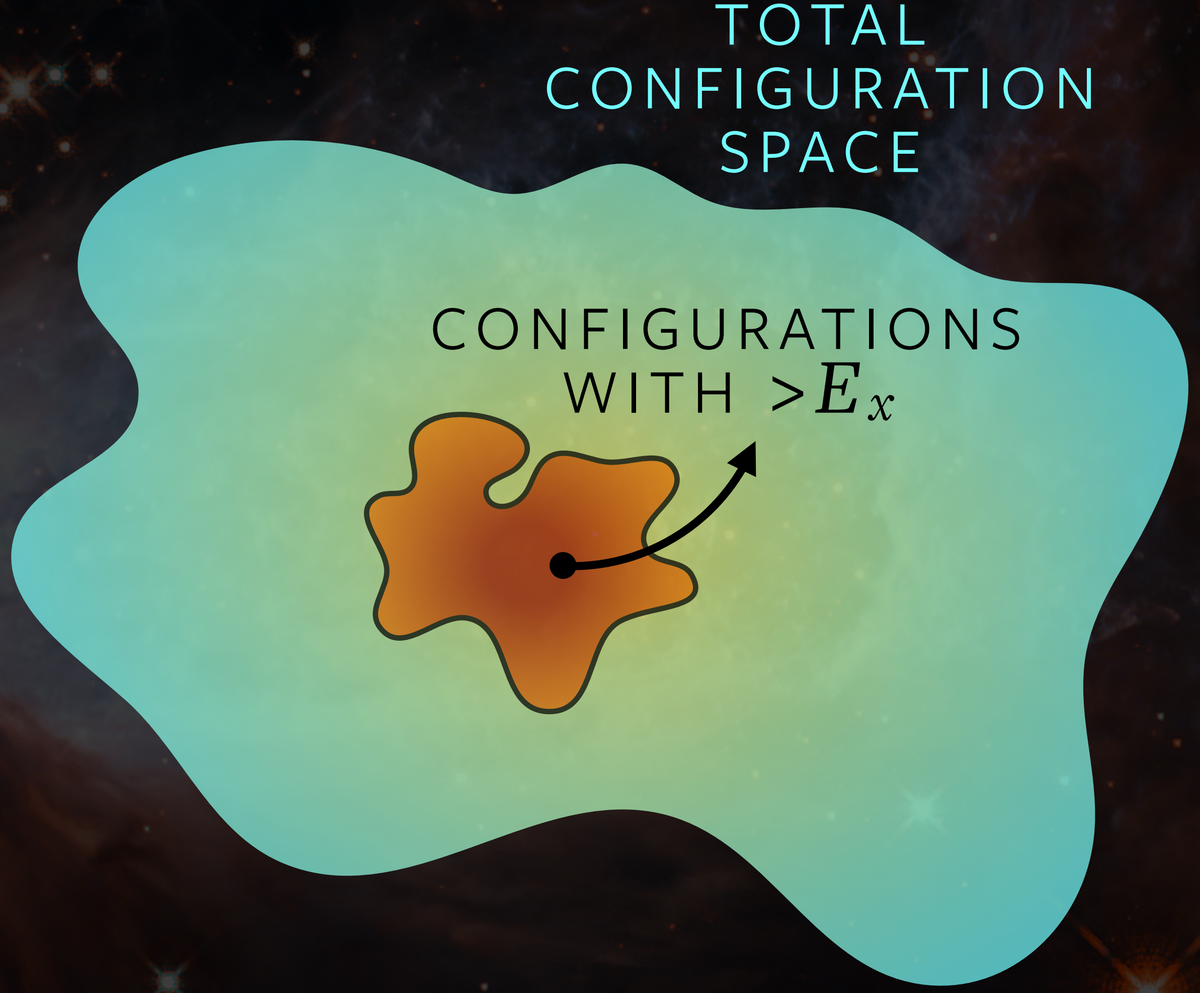


Szostak 2003; Hazen+ 2007; Wong+ (in press)

Wong+ (in press)

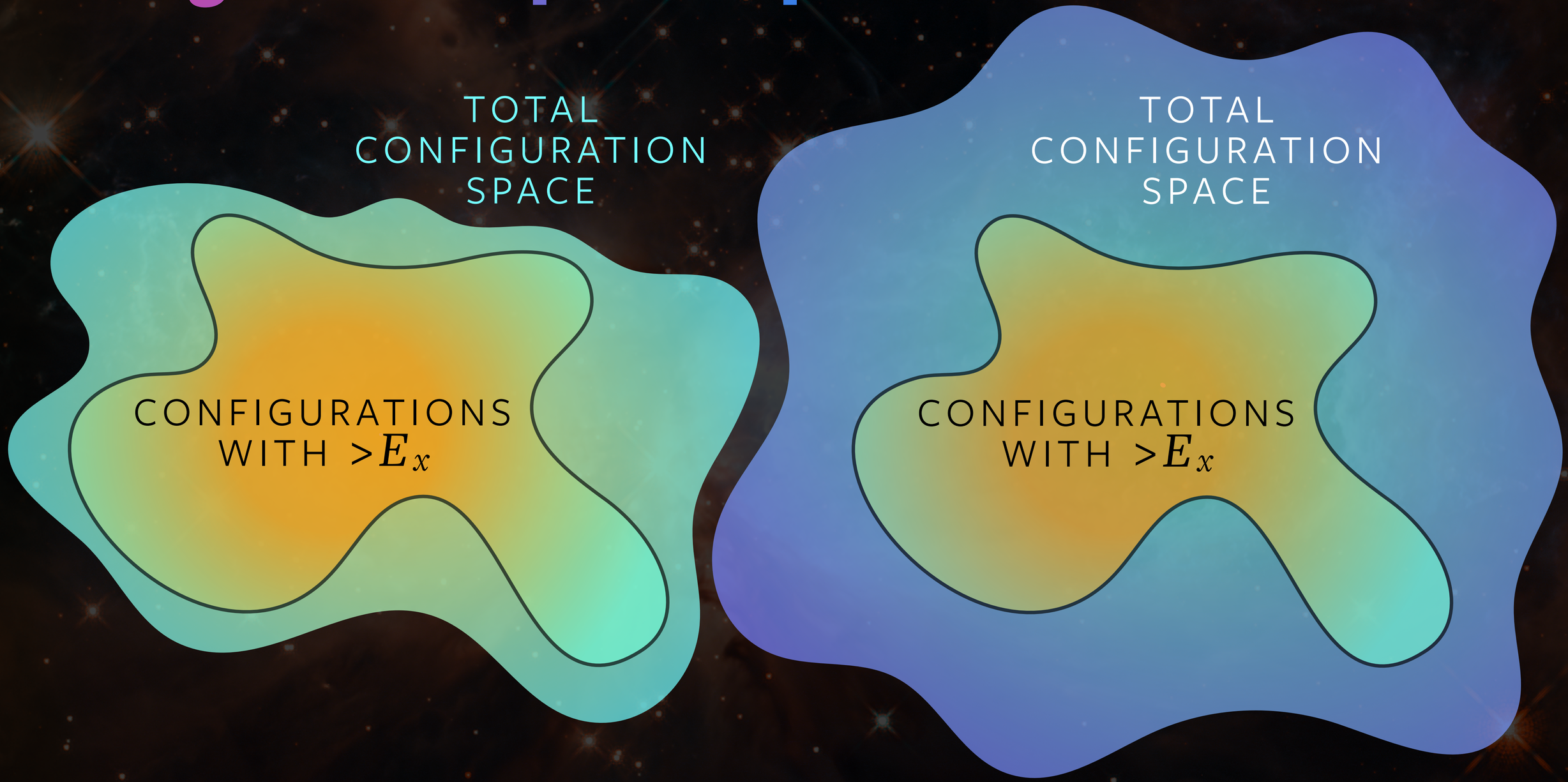
Strengthening selection pressures





Wong+ (in press)

Configuration space expansion



Example: Great Oxidation Event

Wong+ (in press)

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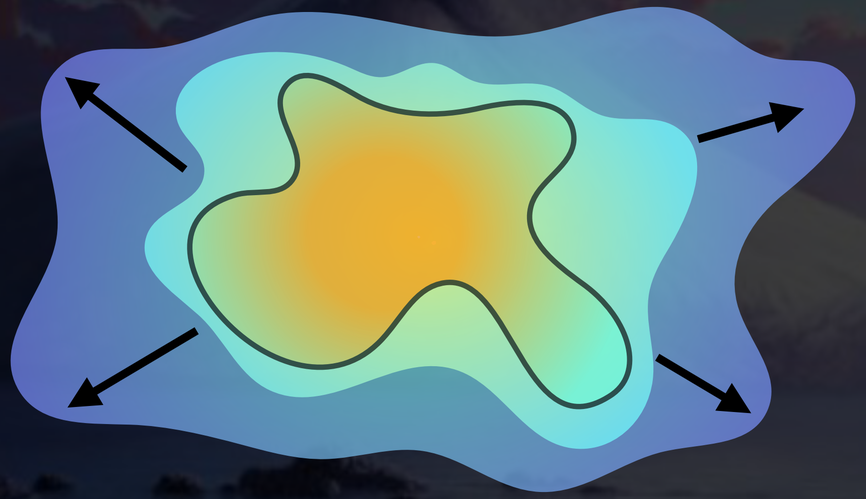

CONFIGURATION
SPACE EXPANSION

+ Abundant oxygen provided an extra source of component diversity

+ Atmospheric O_2 provided a new source of free energy to drive combinatorial exploration

Wong+ (in press)

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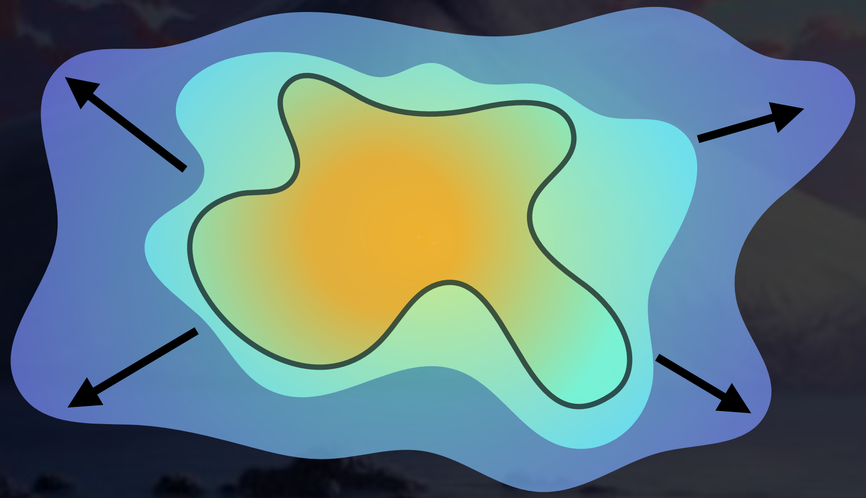

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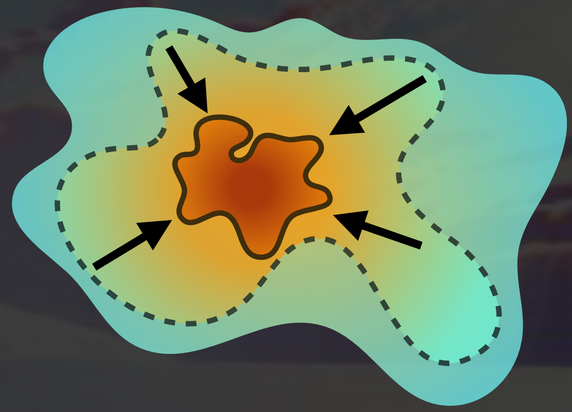

STRENGTHENING SELECTION PRESSURES

+ As a highly reactive oxidant, O2 also provided a new set of selective criteria for persistence

+ Consequent selection pressures arising from aerobic biology

Wong+ (in press)

We propose a new natural law: the law of increasing functional information

The functional information of a system will increase (i.e., the system will evolve) if many different configurations of the system are subjected to selection for one or more functions

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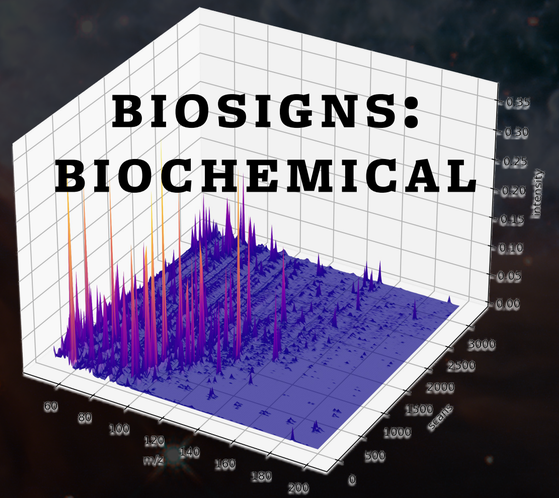
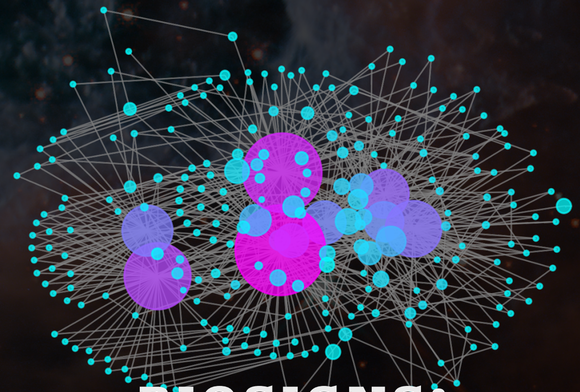
EVOLUTION WRIT LARGE

ORIGINS OF LIFE





BIOSIGNS: PLANETARY

Wong+ (in press)