

Statistical Signatures of Life

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*“The laws of physics and chemistry
are statistical throughout.”*

- E. Schrödinger

What about the “laws of life” ... ?

Network exobiosignatures

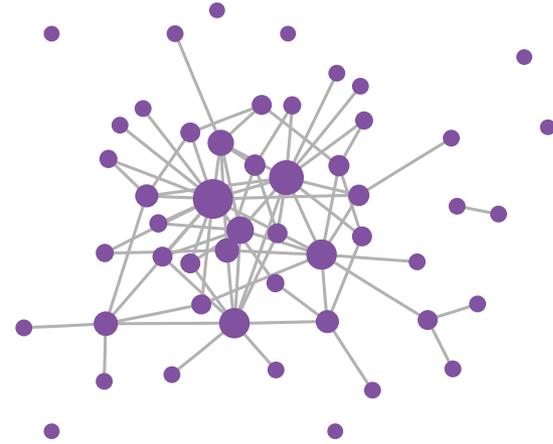
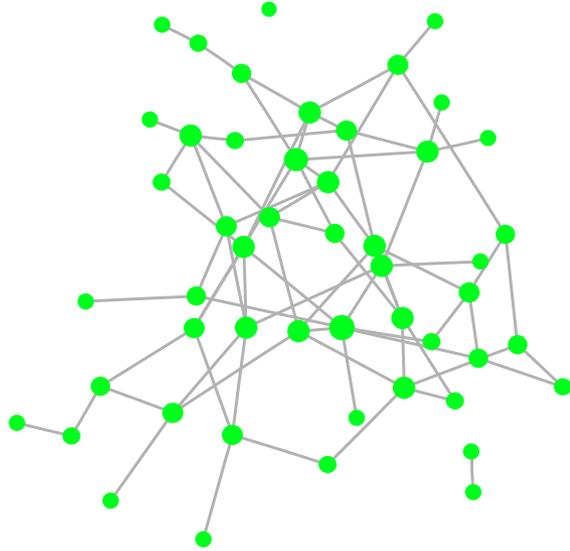
Are the “laws of life” statistical too, and can that inform our search?

Statistical searches for life

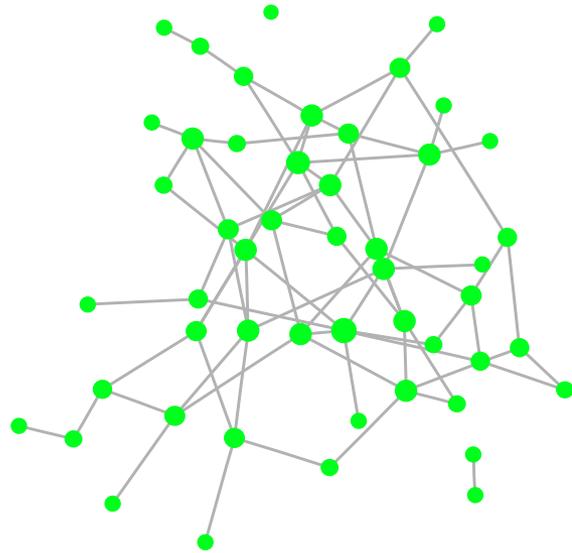
How can we constrain the probability of life in an ensemble of exoplanetary atmospheres?

**NETWORK
EXOBIOSIGNATURES**

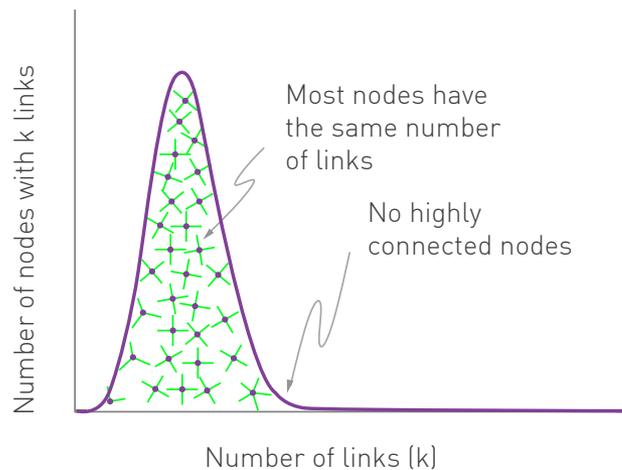
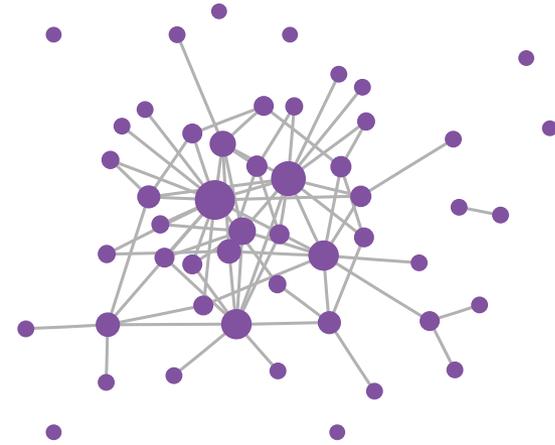
Crash course in network theory



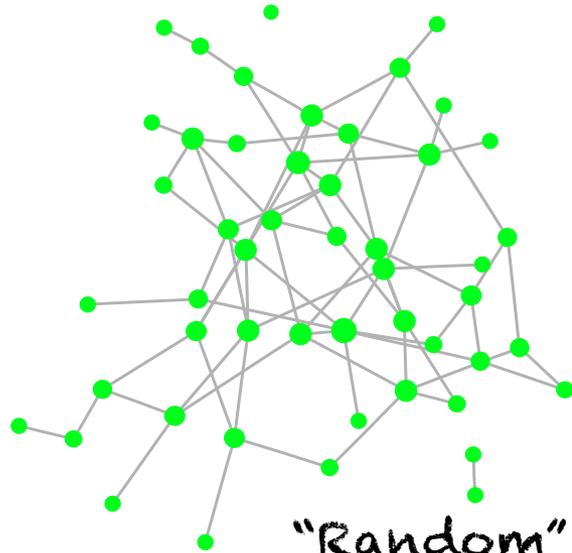
Crash course in network theory



POISSON

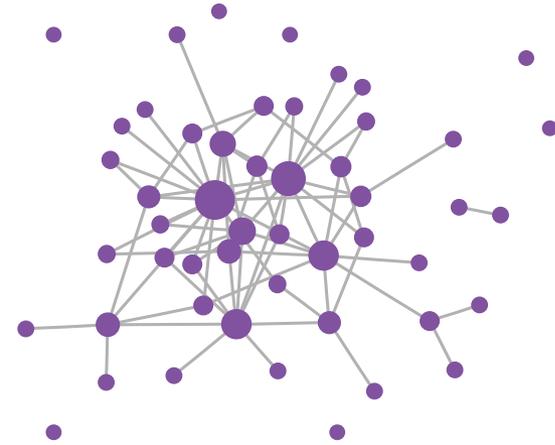
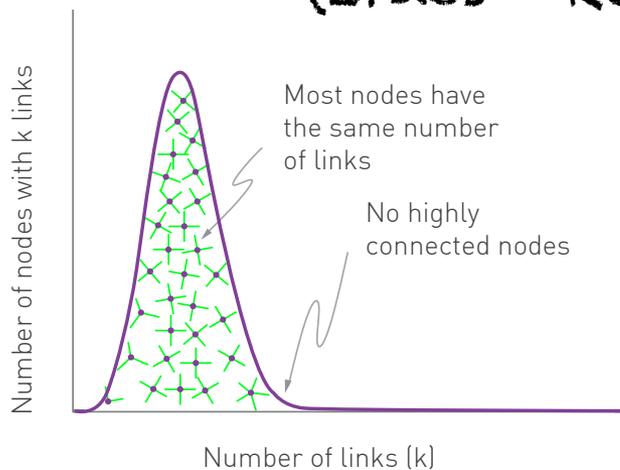


Crash course in network theory



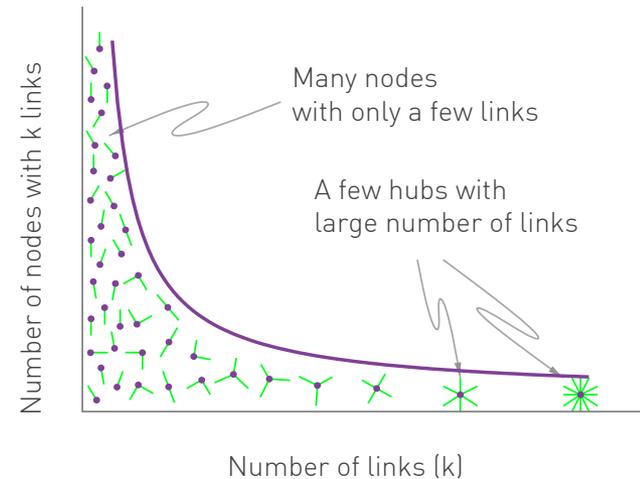
POISSON

"Random"
(Erdős - Rényi)



POWER LAW

"Scale-Free"

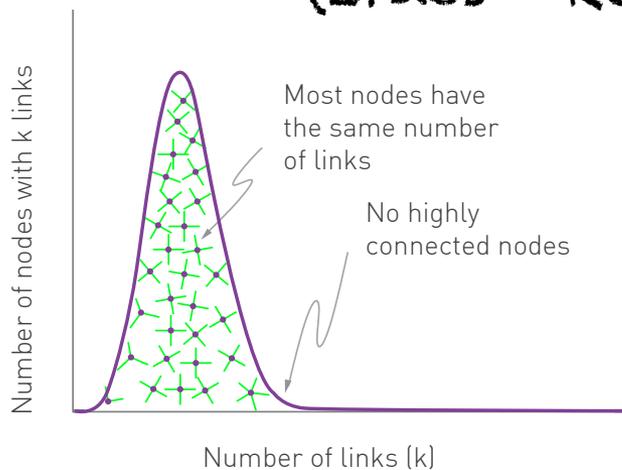


Crash course in network theory



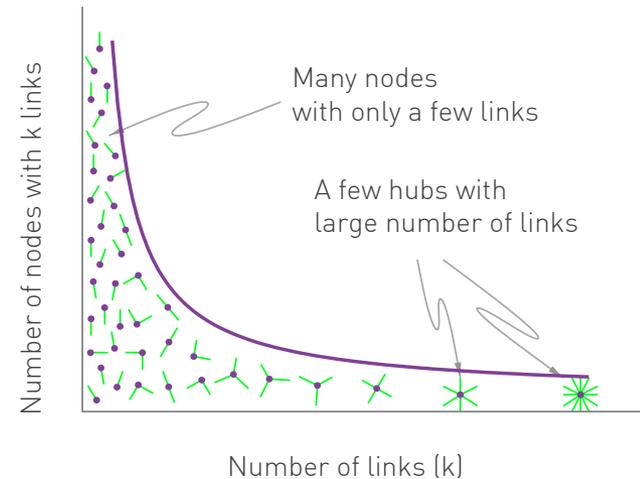
"Random"
(Erdős - Rényi)

POISSON

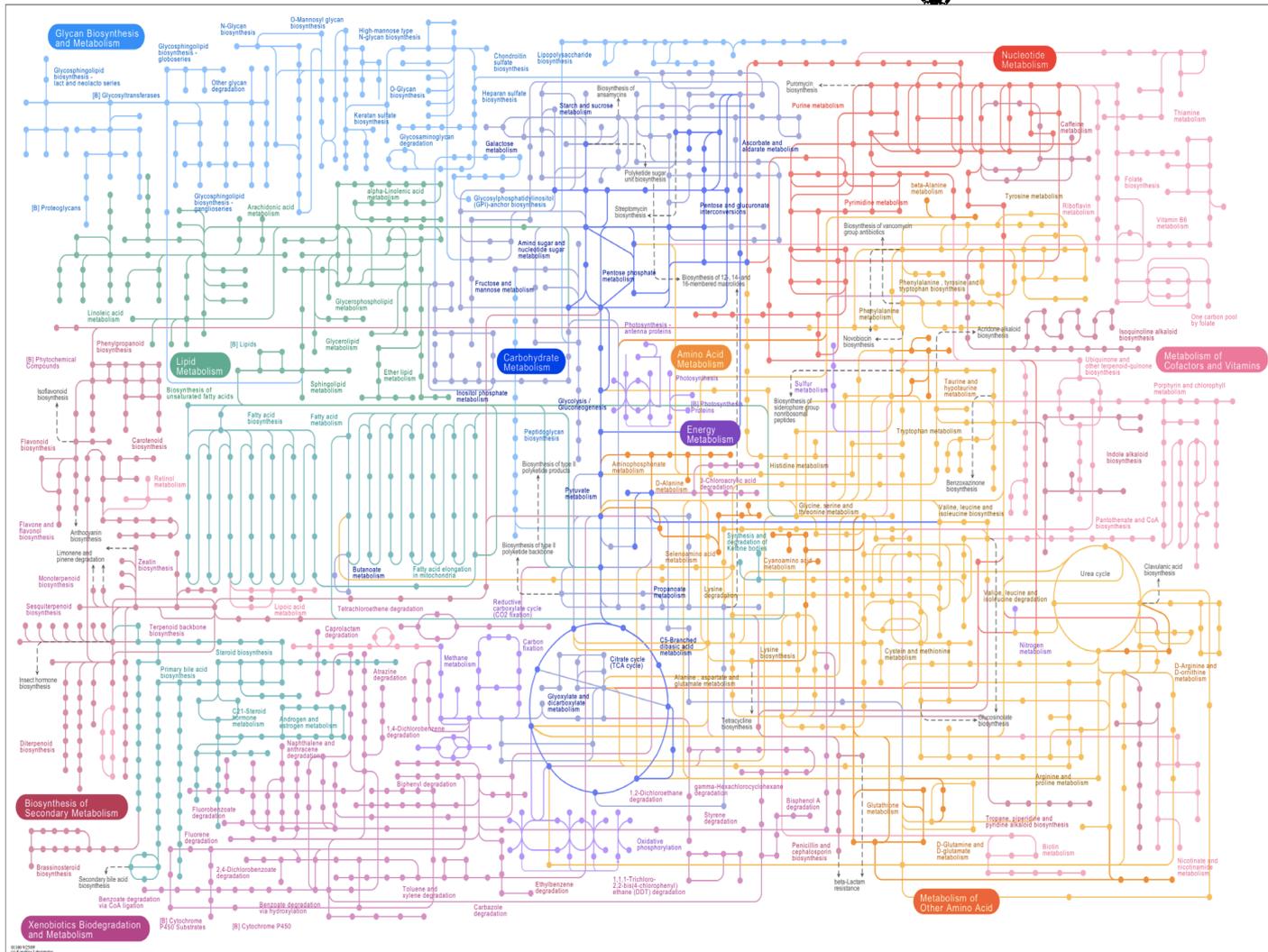


"Scale-Free"

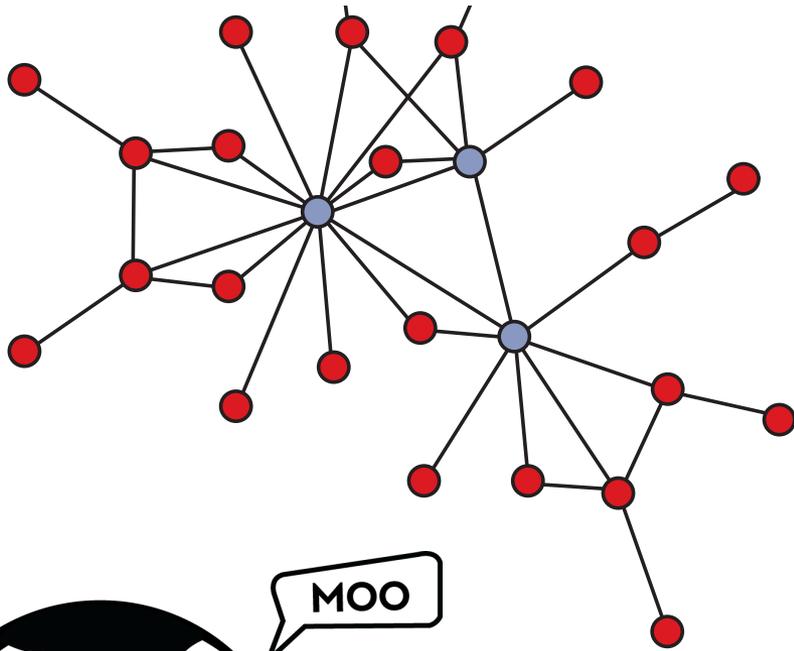
POWER LAW



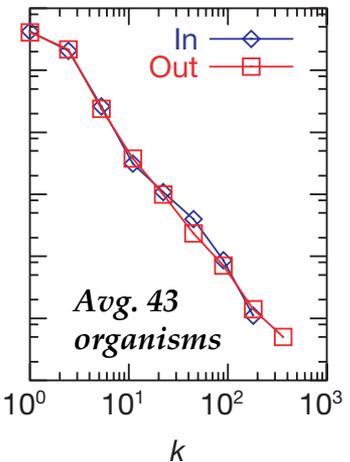
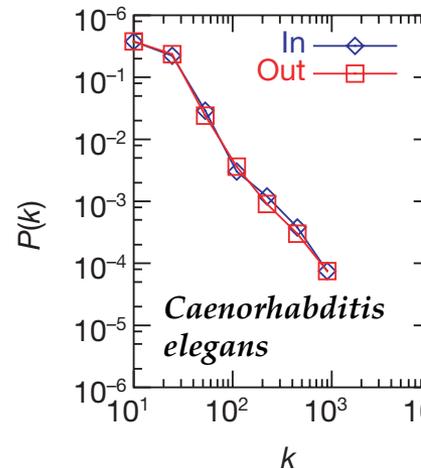
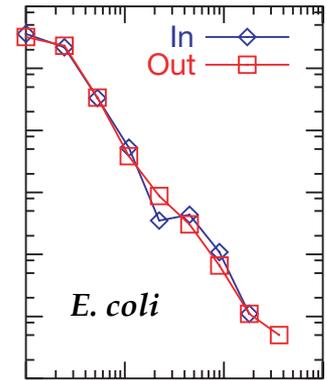
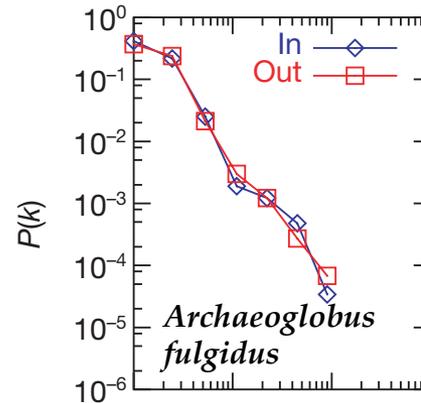
"Power-Laws" in biochemistry



"Power-Laws" in biochemistry



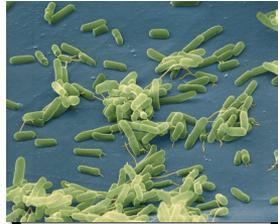
$$2 \leq \alpha < 3$$



Jeong *et al.* "The large-scale organization of metabolic networks" *Nature* (2000) 407: 651 – 654.

In physics, we usually associate “universal laws” with properties that are scale-invariant

Organisms



21,000 bacteria taxa

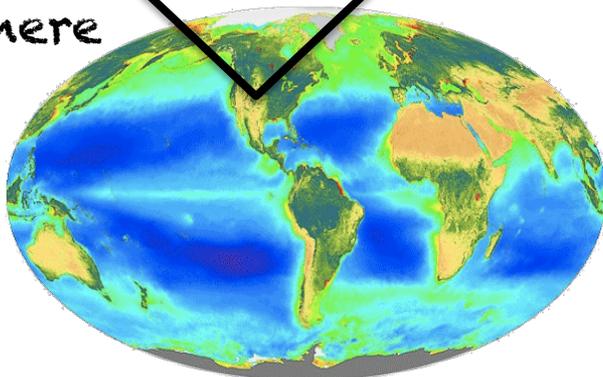
845 archaea taxa

Ecosystems



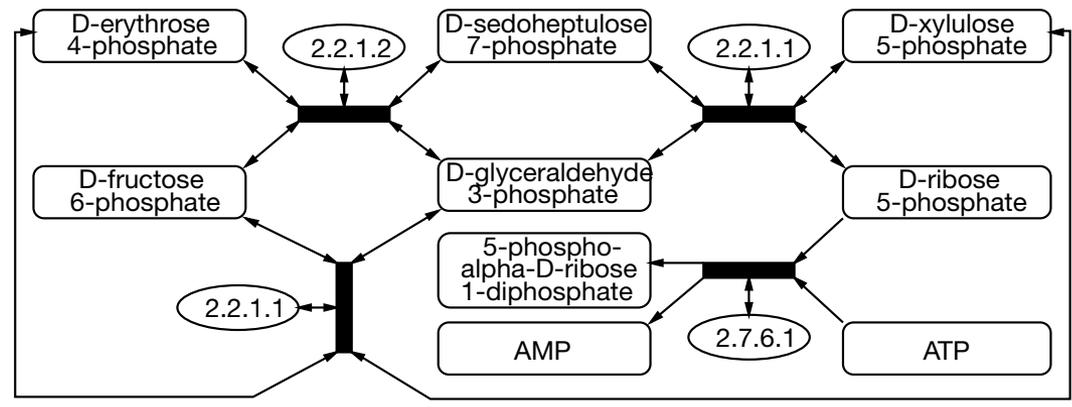
26 metagenomes (sampled from Yellowstone hot springs)

Biosphere

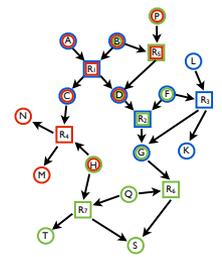
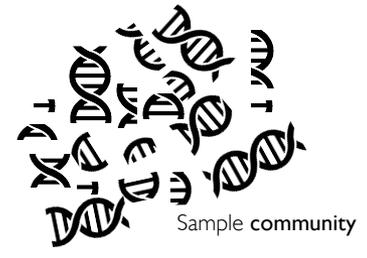


1 biosphere (generated by sampling *all* cataloged reactions in the Kyoto Encyclopedia of Genes and Genomes (KEGG))

Constructing biochemical reaction networks from genomic and metagenomic data



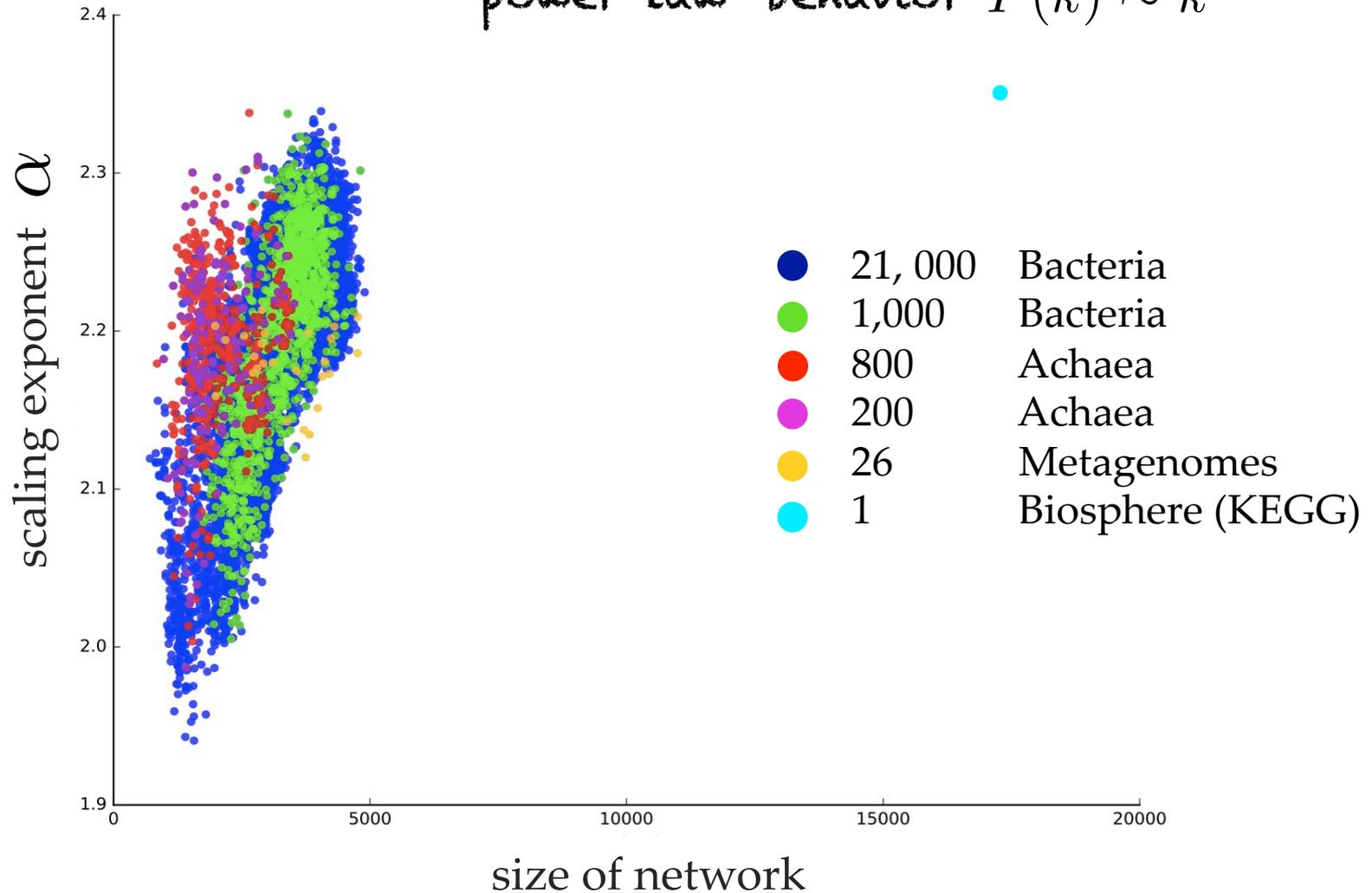
Real



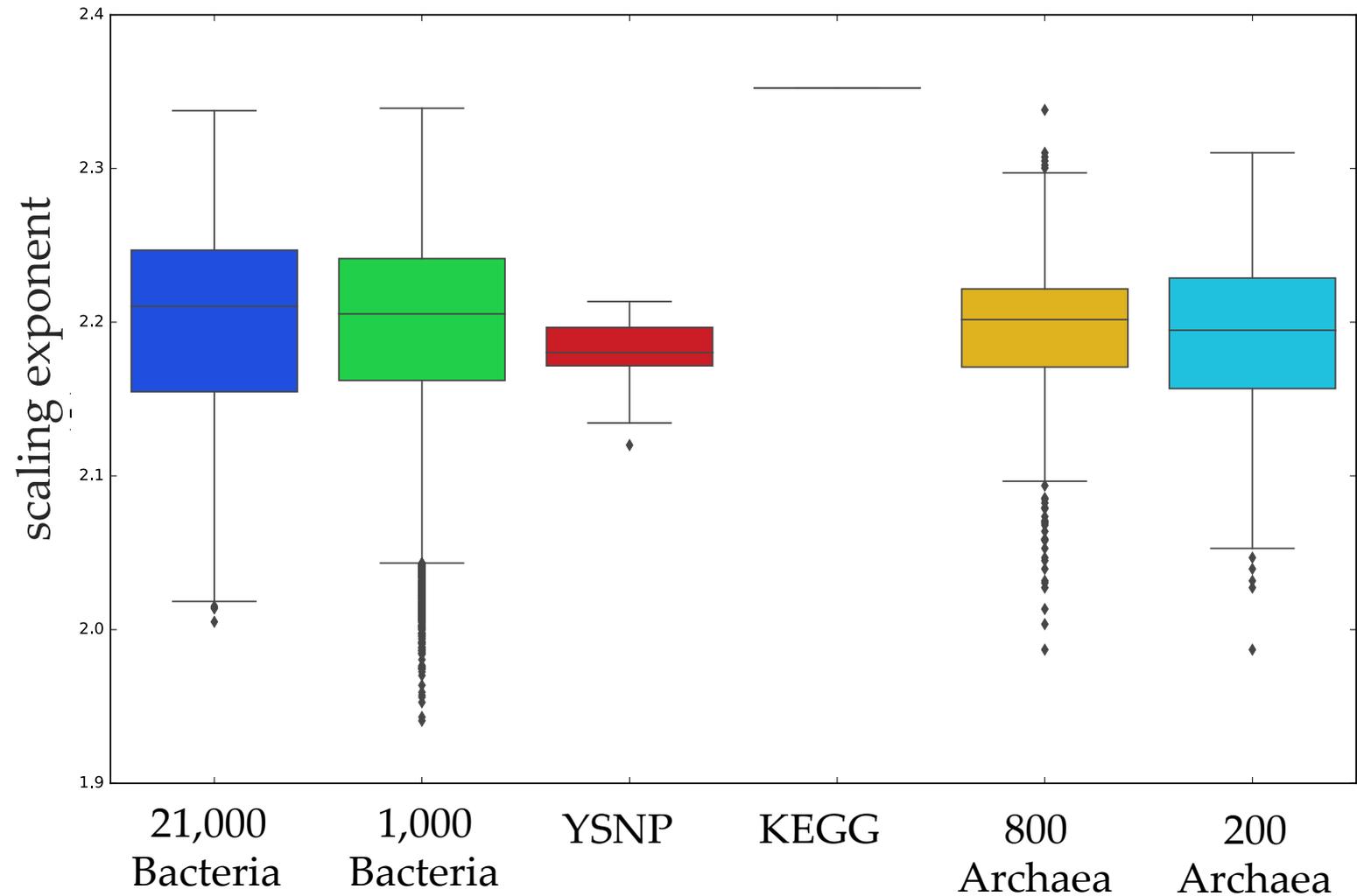
Sandefur *et al.* "Network representations and methods for the analysis of chemical and biochemical pathways" *Mol. Biosyst.* (2013) 9: 2189.

Earth's biochemistry is remarkably scale-invariant

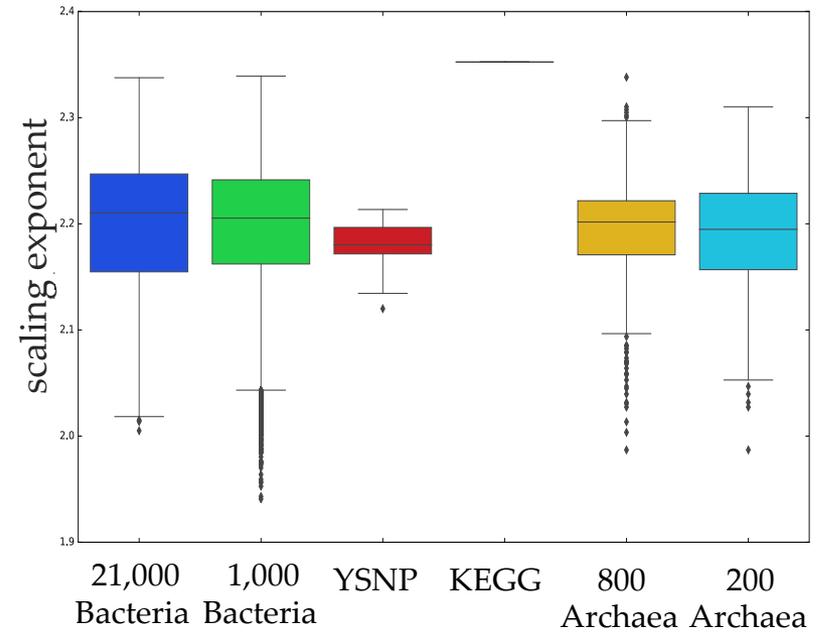
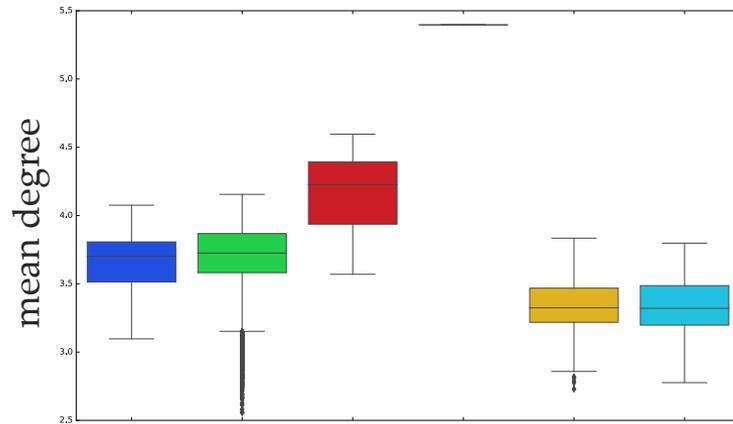
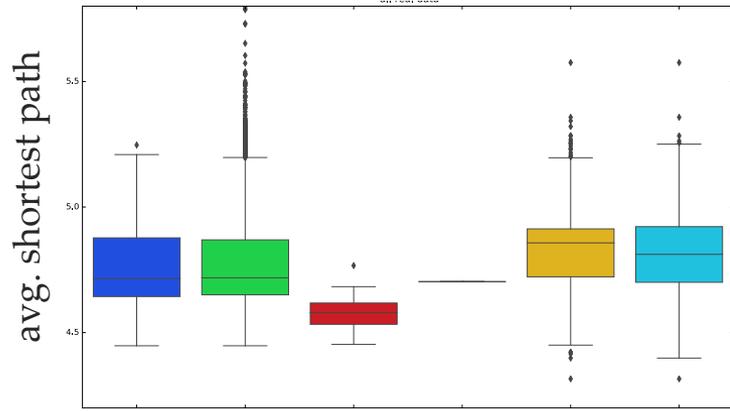
"power-law" behavior $P(k) \sim k^{-\alpha}$



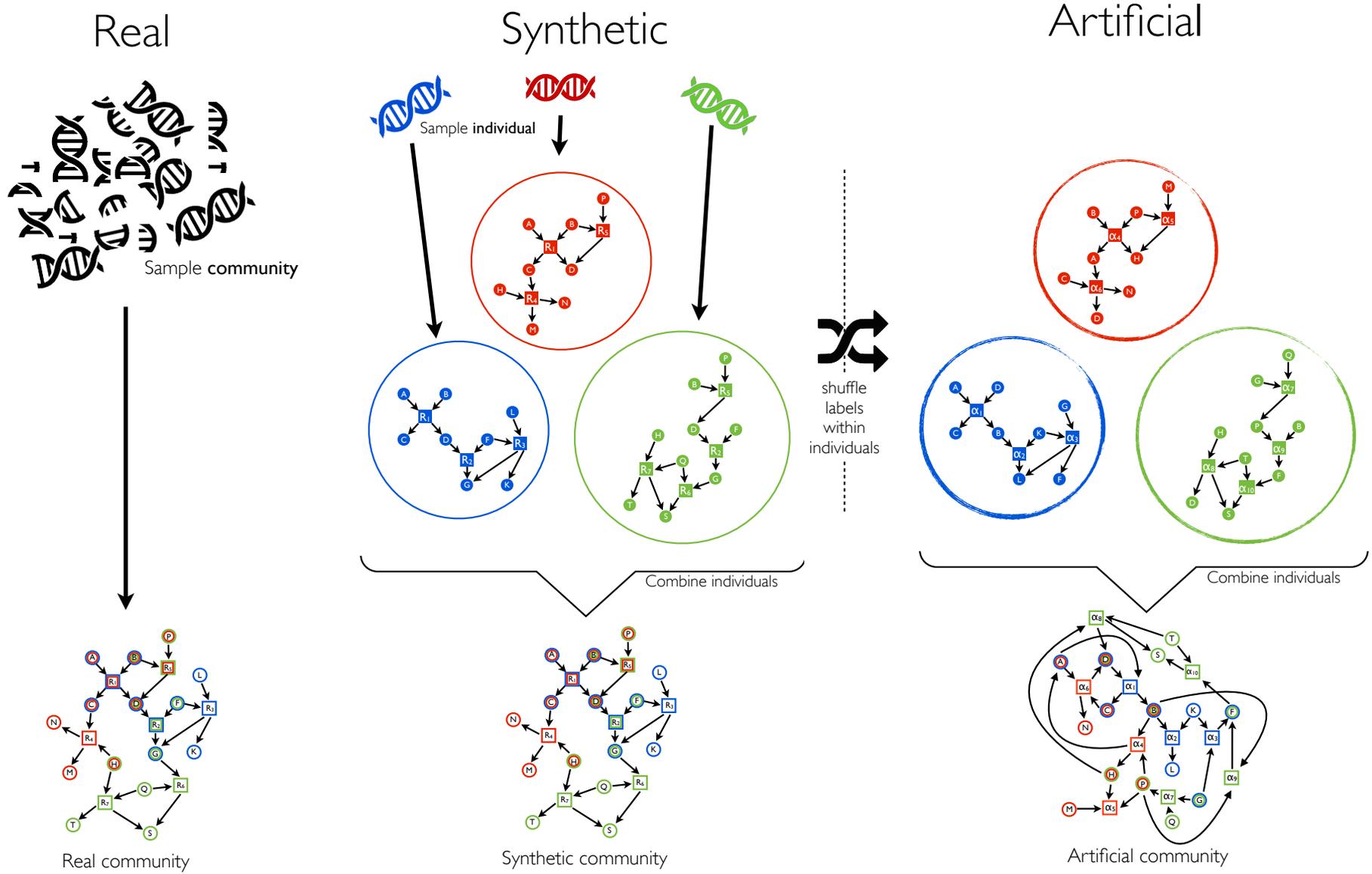
Earth's biochemistry is remarkably scale-invariant



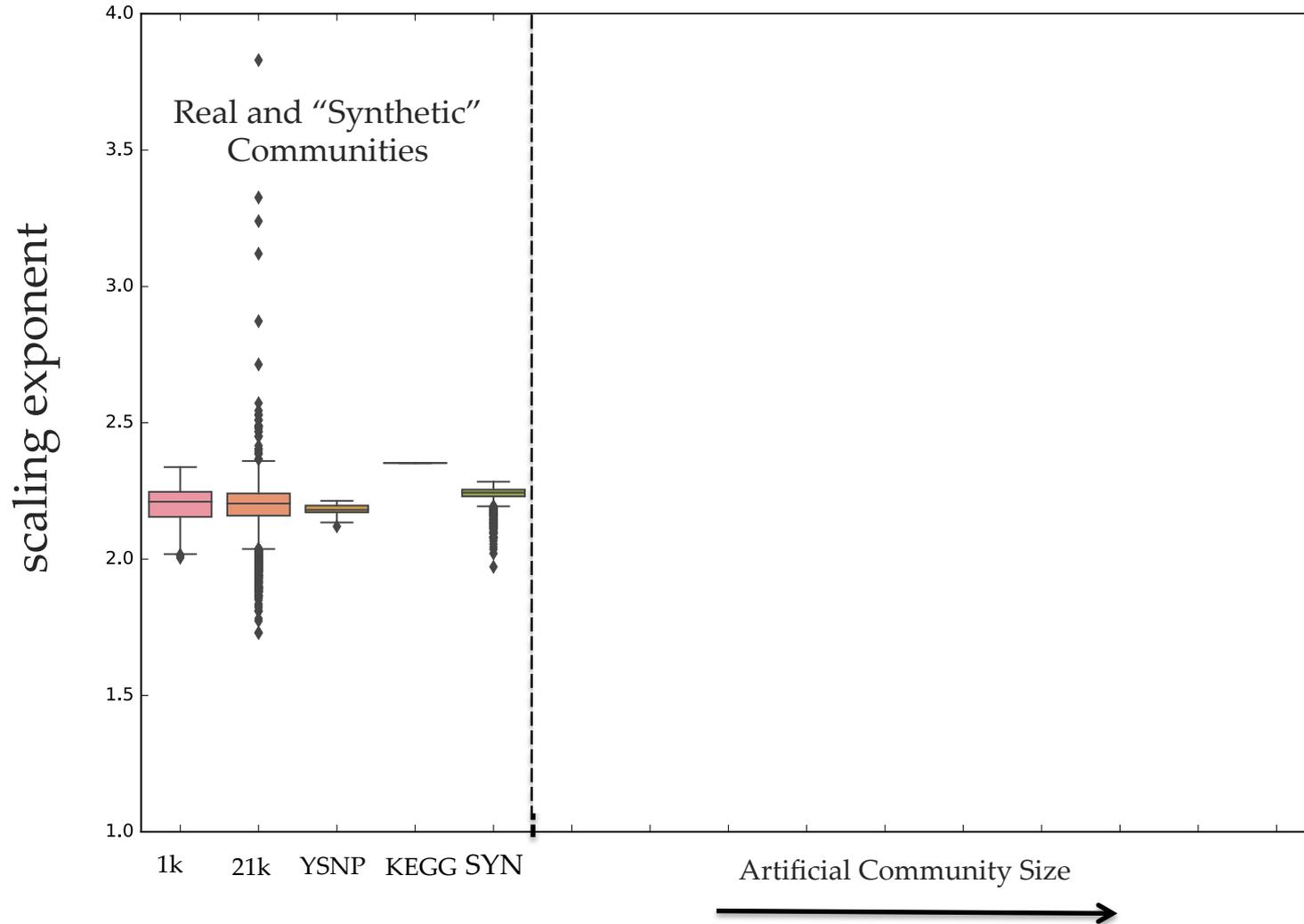
Earth's biochemistry is remarkably scale-invariant



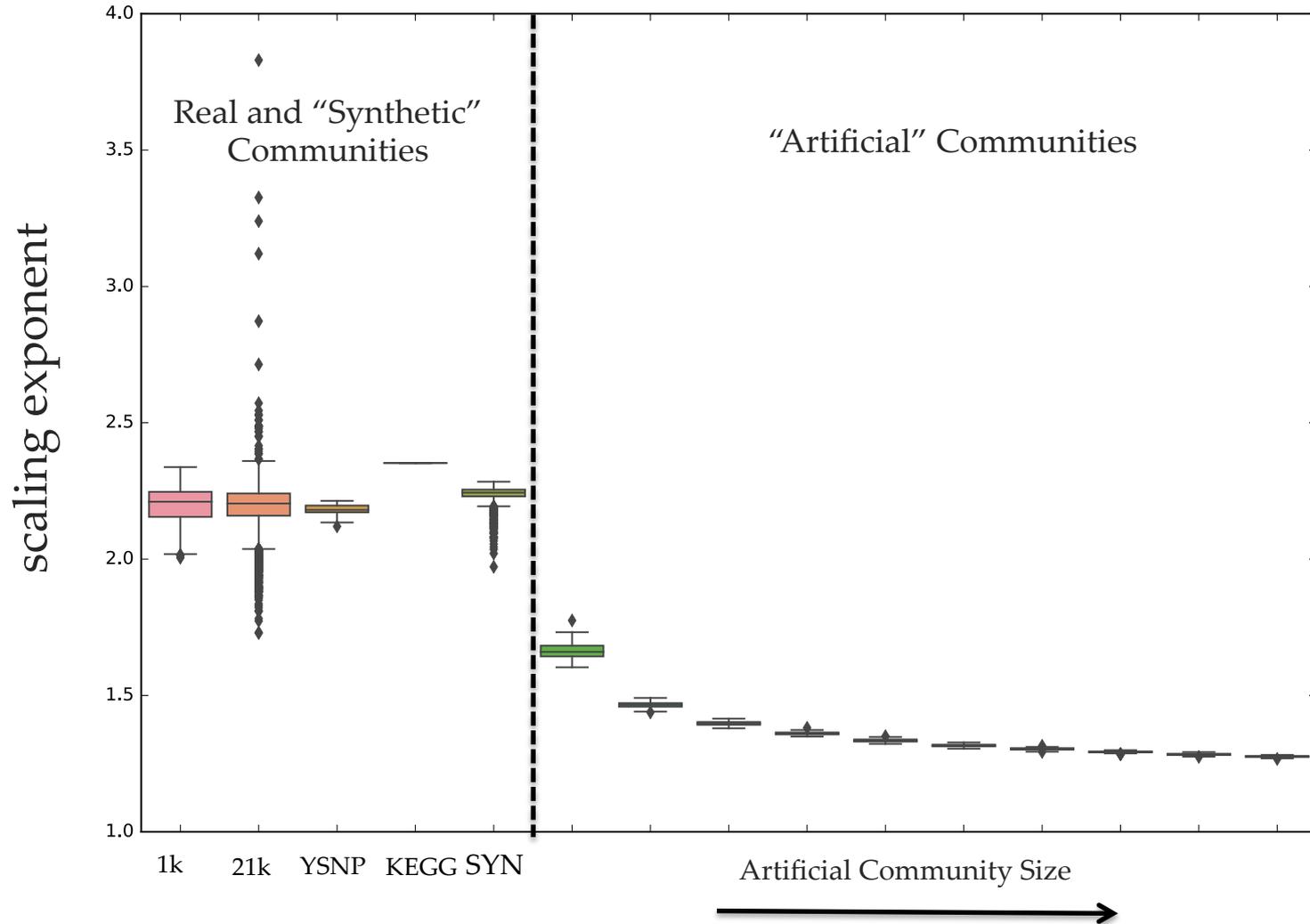
Are all reaction networks similarly scale-invariant?



Artificial networks with the same topology for individual organisms are not scale-invariant



Artificial networks with the same topology for individual organisms are not scale-invariant

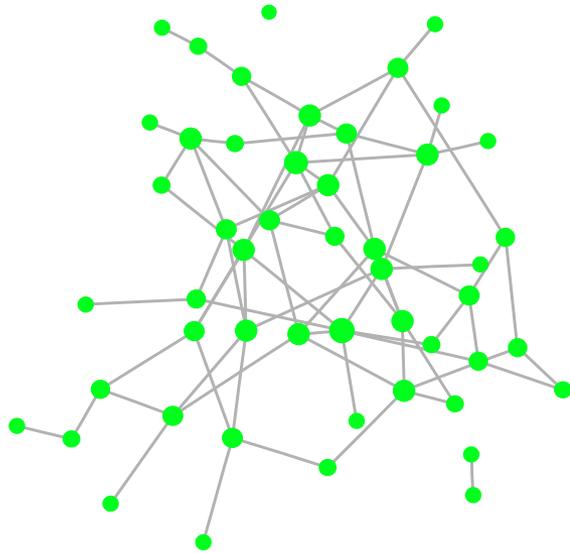


H. Kim, H.B. Smith, J. Raymond and S.I. Walker “Network theoretic constraints on biochemical diversity explain the universality of life on Earth” In prep

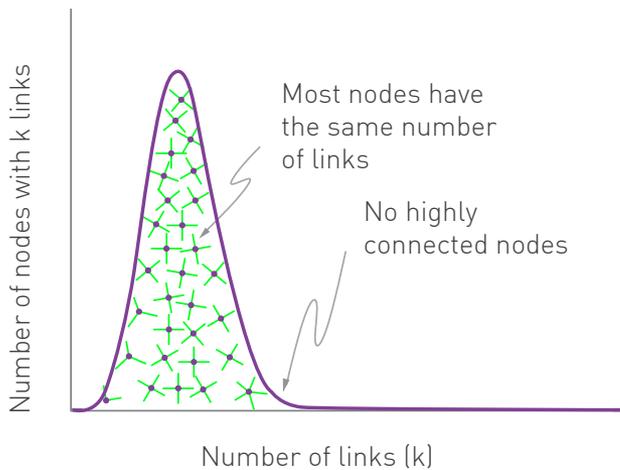
Statistical properties of networks as 'universal' exobiosignatures

- Earth's biochemistry exhibits remarkably *scale-invariant* topological properties, suggestive of *universal 'laws of life'*
 - *A Network Biosignature?*
- These are not an arbitrary property of chemical reaction networks, but instead *arise due to common core biochemistry and the 'dynamic order' of the biosphere*
 - *Will every inhabited planet have only one biosphere, and how does this affect detectability?*

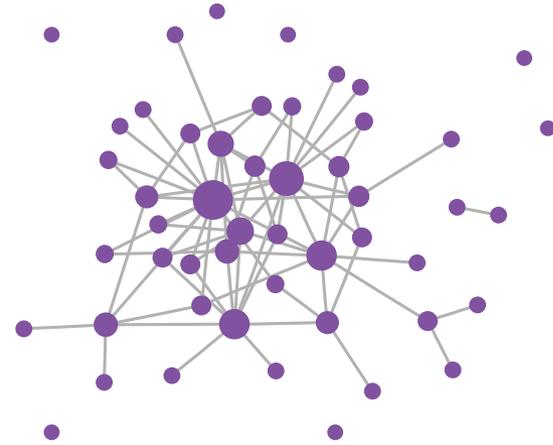
Not
"biological"



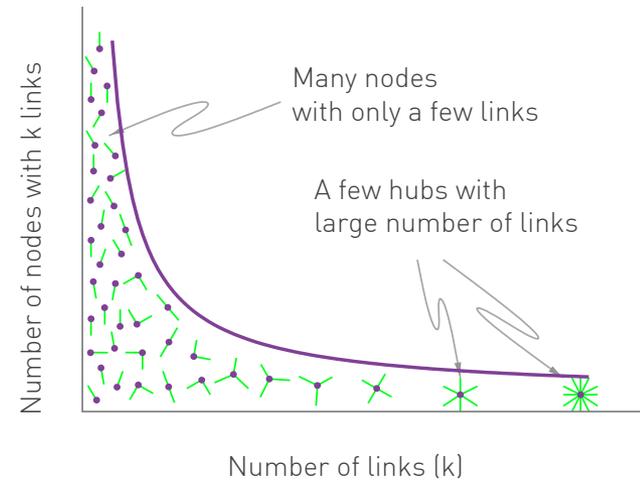
POISSON



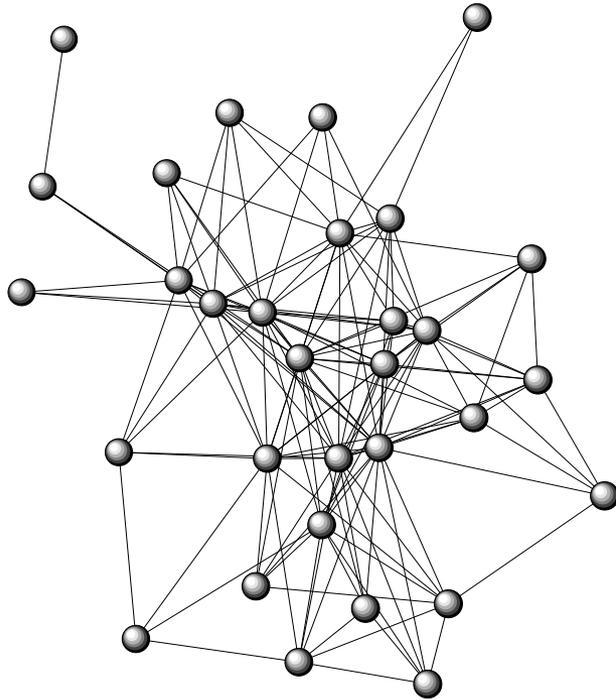
"biological"



POWER LAW

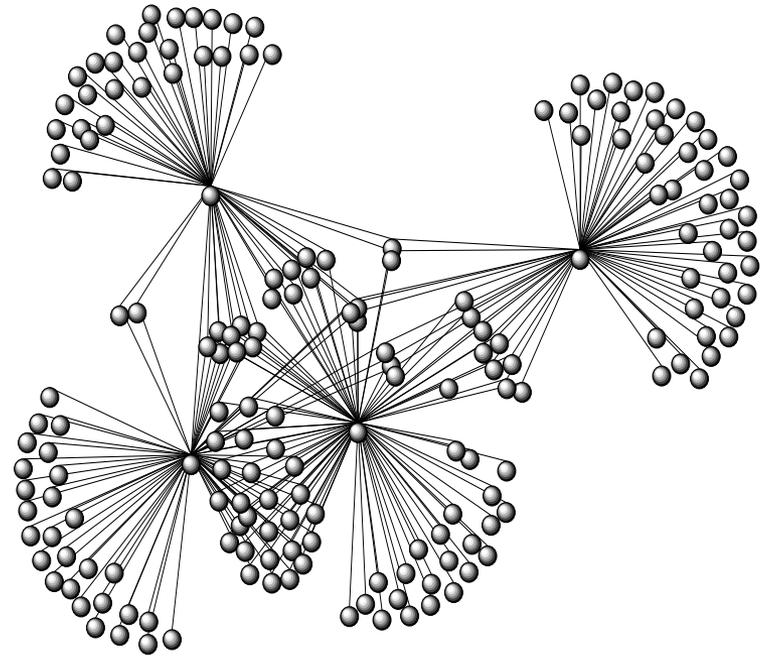


*Not detectable
"biology"*



Mars

*detectable
"biology"*



Earth

Sole and Munteanu. (2004) The large-scale organization of chemical reaction networks in astrophysics. *Europhysics Letters* 68.2: 170.

A network-theoretic comparison of inhabited and un-inhabited worlds

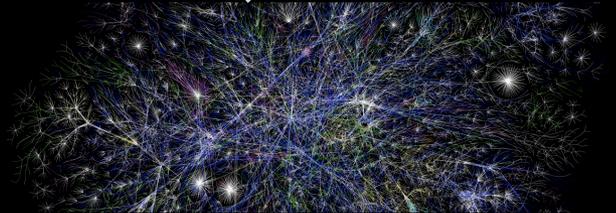
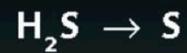
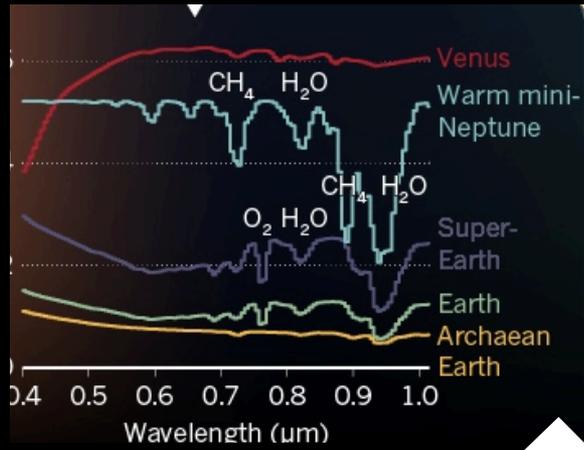
TABLE I – *Network characteristics: V = vertices; E = edges; $\langle K \rangle$ = mean degree; $\langle L \rangle$ = averaged shortest path; $\langle C \rangle$ = mean clustering; r = assortativity. See text for more details. ISM: Interstellar medium; HC : hydrocarbon chemical network of the giant planets*

	V	E	$\langle K \rangle$	$\langle L \rangle$	$\langle L_{rand} \rangle$	$\langle C \rangle$	$\langle C_{rand} \rangle$	r	r_{rand}	Modular
Earth	248	778	6.27	2.75	3.20	0.31	0.025	-0.31	-0.006	YES
Mars	31	144	9.29	1.89	1.73	0.61	0.31	-0.10	-0.007	NO
Titan	71	396	11.16	2.08	1.98	0.55	0.16	-0.17	-0.03	NO
Venus	42	175	8.33	2.07	1.94	0.59	0.20	-0.14	-0.06	NO
HC	39	270	13.85	1.65	1.64	0.68	0.37	-0.26	-0.06	NO
ISM	400	6102	30.51	1.99	2.01	0.52	0.07	-0.24	-0.006	NO
E.coli	741	2310	6.24	3.02	3.82	0.183	0.008	-0.17	0.004	YES

Sole and Munteanu. (2004) The large-scale organization of chemical reaction networks in astrophysics. *Europhysics Letters* 68.2: 170.

Statistical properties of networks as 'universal' exobiosignatures

1. Constrain current models for atmospheres of biotic and abiotic origin (if interested in having us look at your models, please talk to Tessa and Harrison!)
 - Is this a universal biosignature?
 - Are there false positives?
2. Develop methods for inferring network statistics directly from spectral data



STATISTICAL SEARCHES FOR LIFE



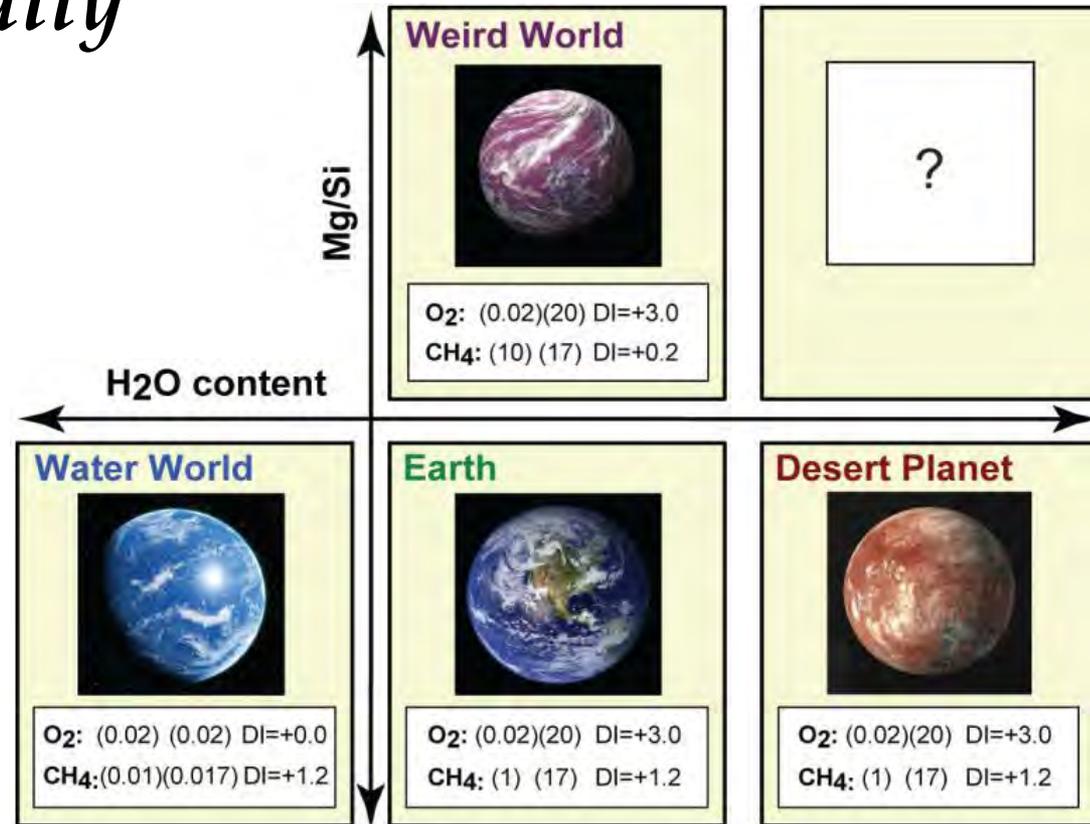
It's habitable, but is life detectable?

*“The laws of physics and chemistry
are statistical throughout.”*

- E. Schrödinger

Compositions of exoplanets will be evaluated probabilistically

ASU NEXSS
"Exoplanetary
Ecosystems"



Biosignatures will also be known probabilistically ...

Lenardic A., et. al. "The Solar System of Forking Paths: Bifurcations in Planetary Evolution and the Search for Life-Bearing Planets in Our Galaxy" *Astrobiology*. July 2016, Vol. 16, No. 7: 551-559.

What should be our goal?

Evaluate the implications of the various parameters for exoplanetary ecosystem detectability in a *quantitative* framework.

*Given a spectra detected on an exoplanet, what is the **probability** it is a product of life?*

This is a conditional statement:

$$P(\text{life} | D)$$

Conditional statements are naturally accommodated in Bayesian probability theory.

Bayes Theorem

$$P(H|D) = \frac{P(D|H)P(H)}{P(D)}$$

““Bayesian reasoning” is a fancy phrase for “the use of probabilities to present degree of believe, and the manipulation of those probabilities in accordance with the standard rules [of probability theory]”

-Simon DeDeo
Lecture on Bayesian
Reasoning for Intelligent People

Bayesian analysis in astrobiology

- Spiegel and Turner “Bayesian analysis of the astrobiological implications of life’s early emergence on Earth” *PNAS* (2012) 109: 395-400.
- Carter, B. and McCrea, W. “The anthropic principle and its implications for biological evolution” *Phil. Trans. R. Soc. A* (1983) 310:347 – 363.

P(Life) is unconstrained

Detectability depends on $P(\text{life})$

$$P(\text{life}|D) = \frac{P(D|\text{life})P(\text{life})}{P(D)}$$

"Odds" ratio:

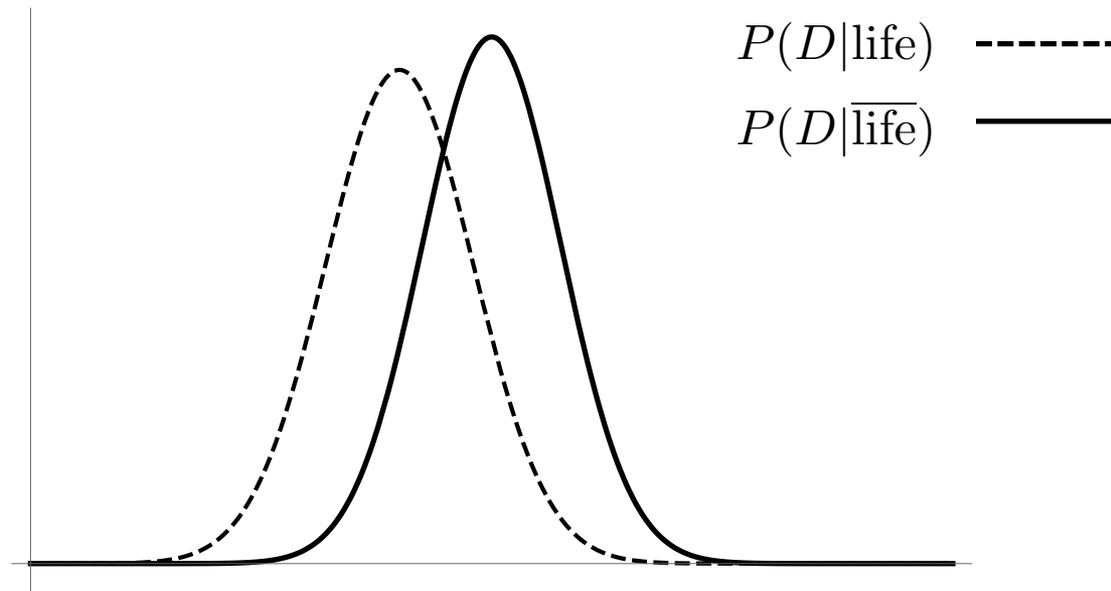
$$\frac{P(\text{life}|D)}{P(\bar{\text{life}}|D)} = \frac{P(\text{life})}{P(\bar{\text{life}})} \times \frac{P(D|\text{life})}{P(D|\bar{\text{life}})}$$

priors *likelihoods*

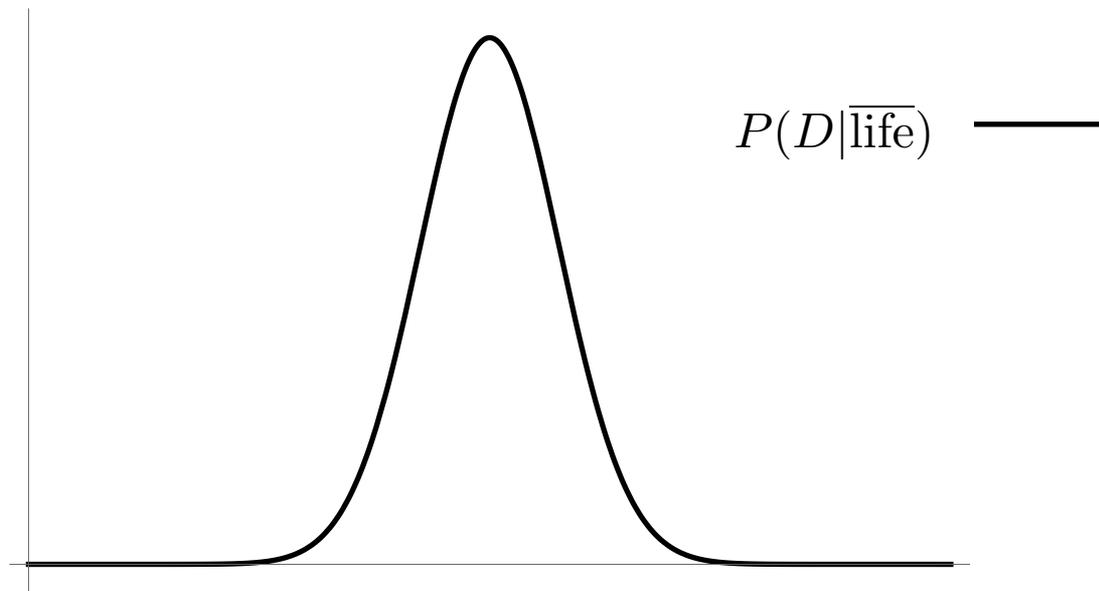
Bayes Factor

A toy example

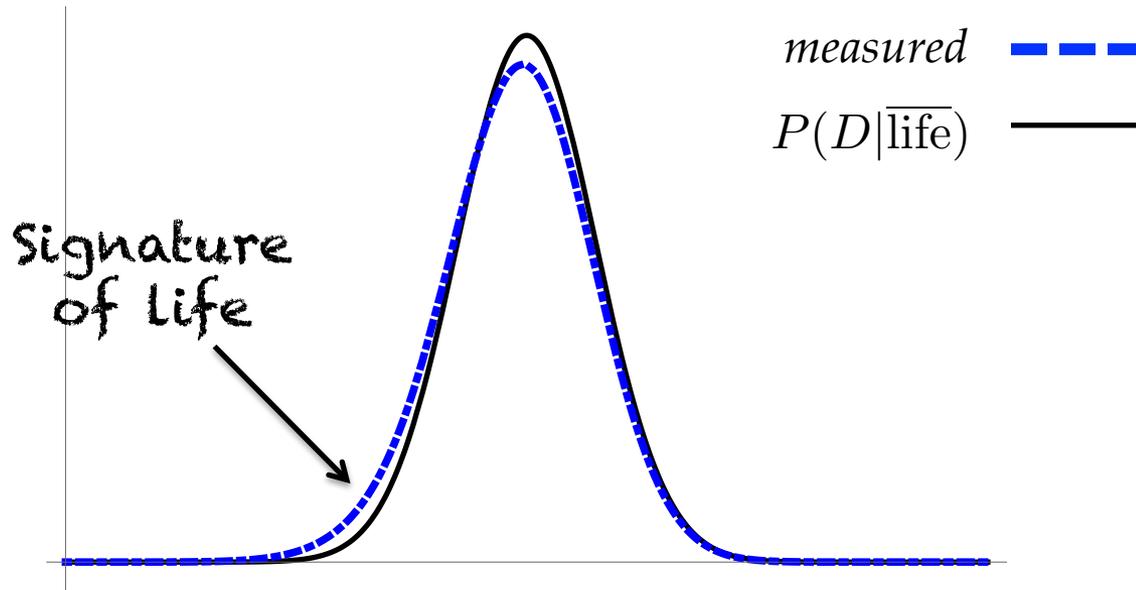
Assume $P(D|\text{life})$ and $P(D|\overline{\text{life}})$ are normally distributed.



A toy example

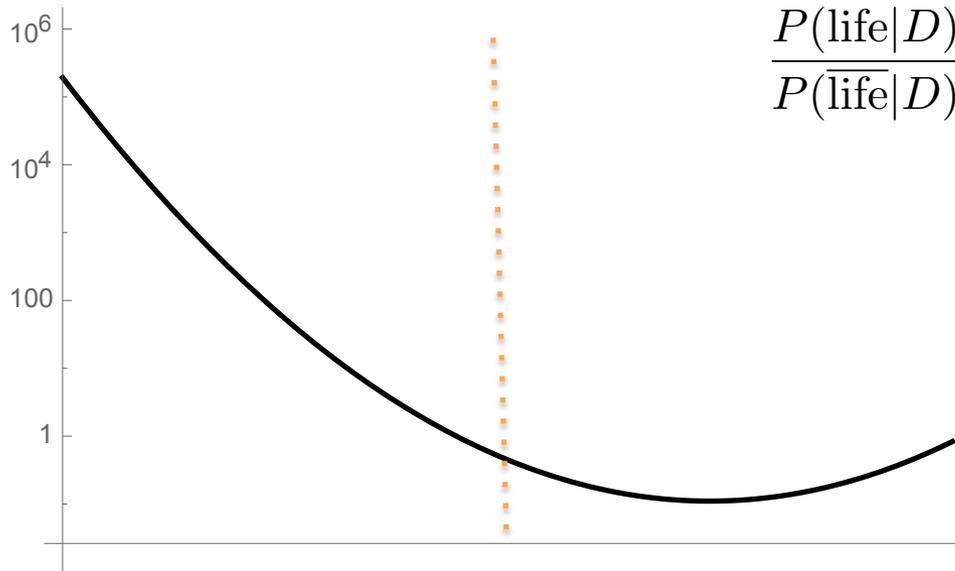


A toy example



A toy example

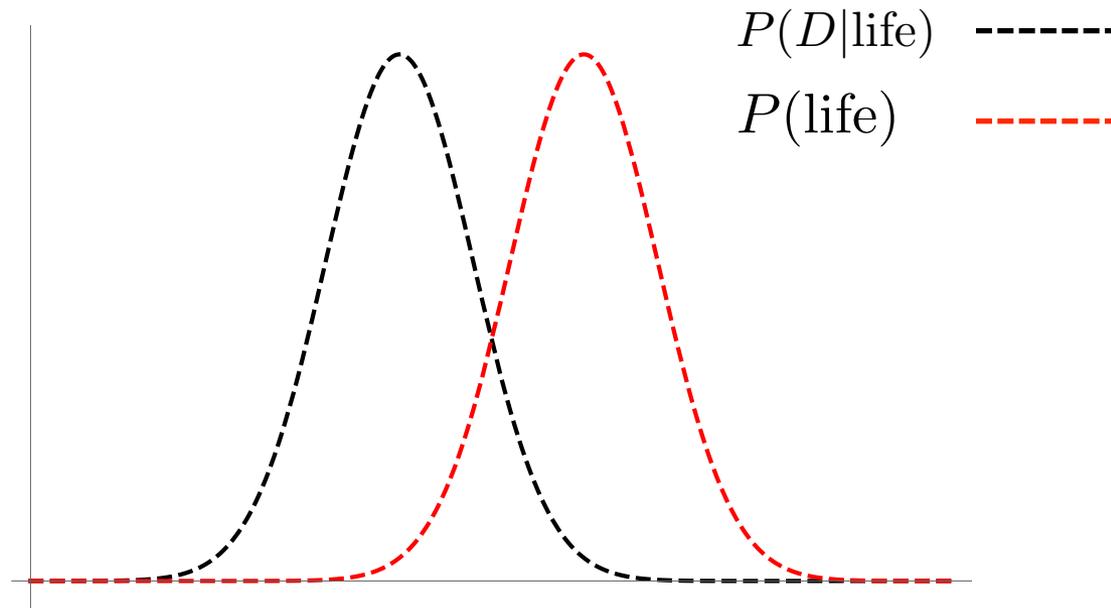
*Intuition is confirmed by the “Odds ratio”:
(assuming a flat prior)*



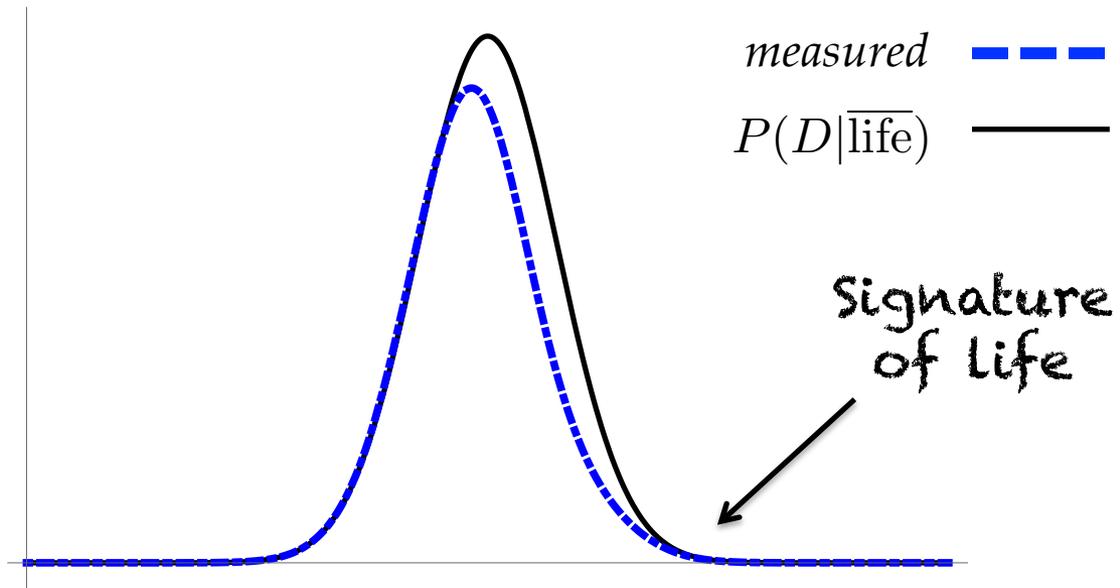
$$\frac{P(\text{life}|D)}{P(\bar{\text{life}}|D)} = \frac{P(\text{life})}{P(\bar{\text{life}})} \times \frac{P(D|\text{life})}{P(D|\bar{\text{life}})}$$

A toy example

What if the prior is not flat?

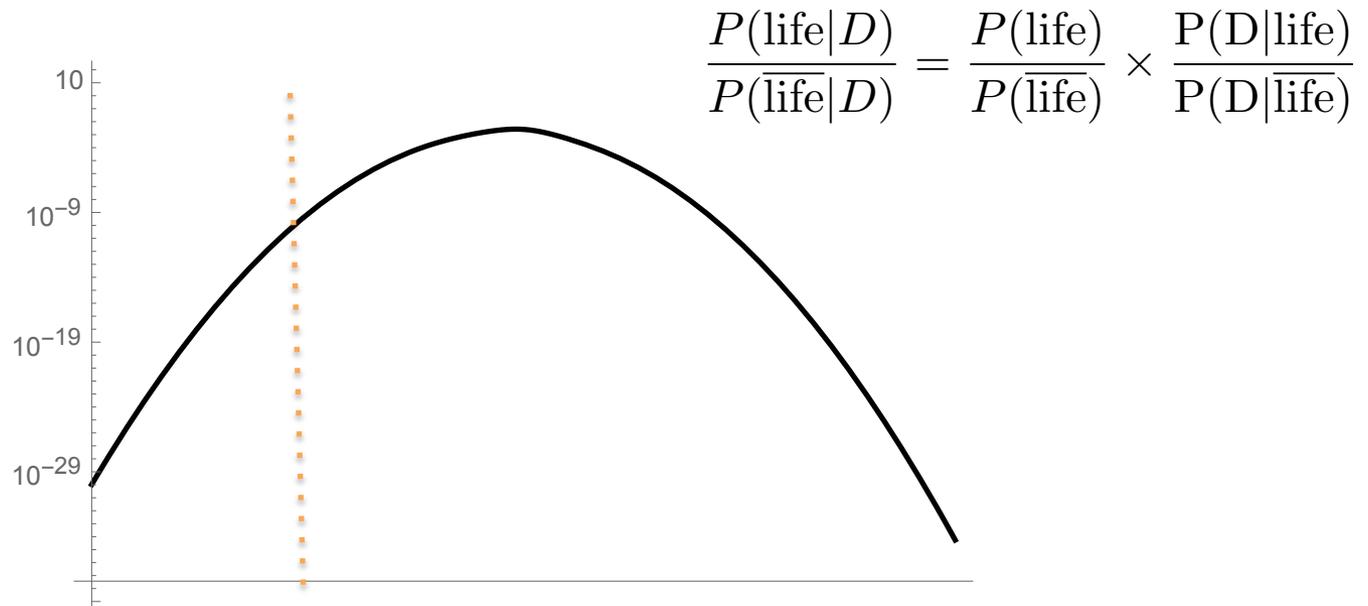


A toy example



A toy example

Our “Odds ratio” is very different:

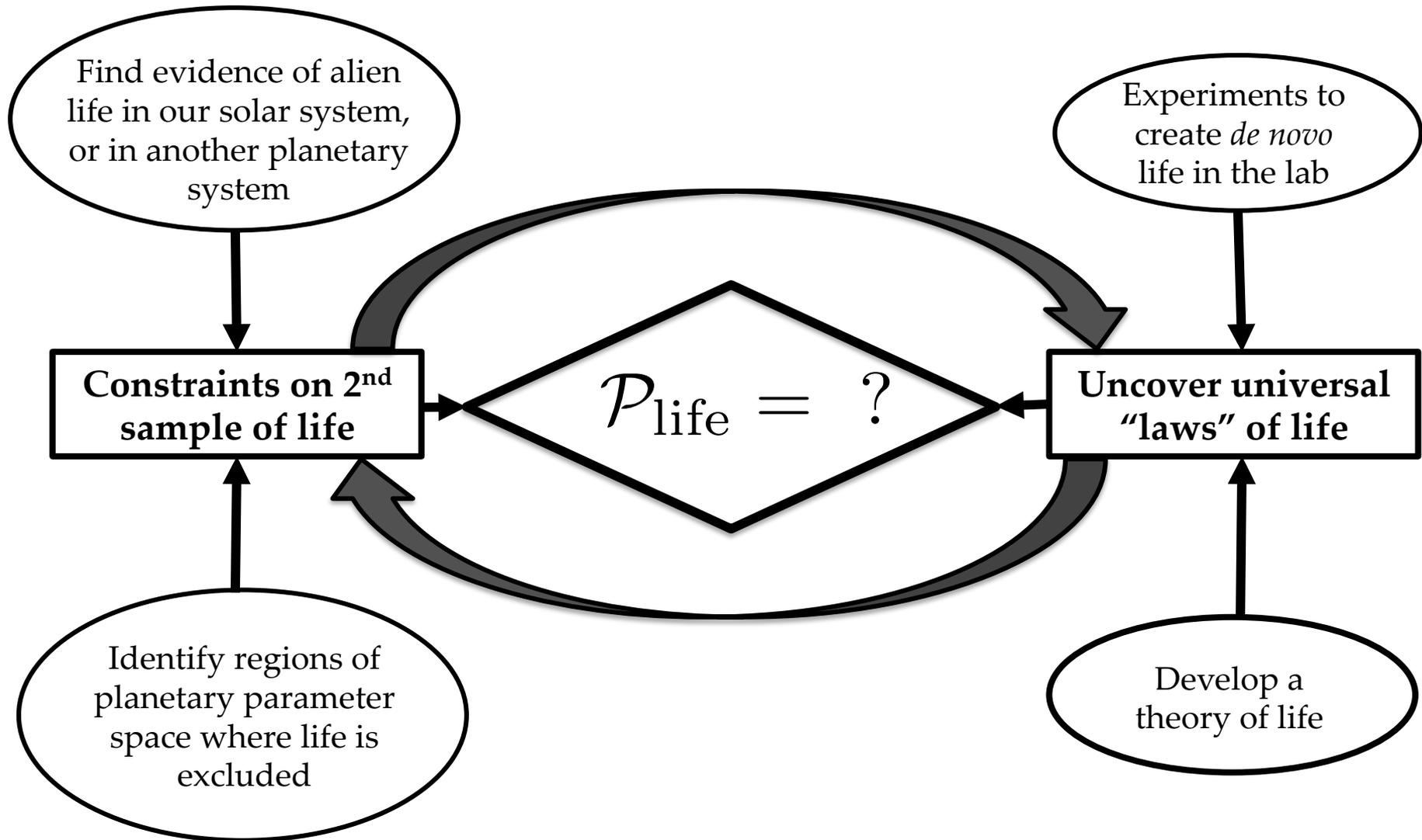


$$\frac{P(\text{life}|D)}{P(\bar{\text{life}}|D)} = \frac{P(\text{life})}{P(\bar{\text{life}})} \times \frac{P(D|\text{life})}{P(D|\bar{\text{life}})}$$

Detecting Life will depend on a number of factors

- Confidence level in abiotic sources
- Confidence level in biotic sources
- Size of statistical ensemble of exoplanets
 - *Our search strategies should be different if we target a few planets with high resolution or many with lower resolution.*
- The probability of life.

We should as a community be able to quantify these parameters to inform the best search strategies given available data.



“...living matter, while not eluding the "laws of physics" as established up to date, is likely to involve **other laws of physics**" hitherto unknown, which however, once they have been revealed, will form just as integral a part of science as the former”



“One can best feel in dealing with living systems how primitive physics still is.”



– *Albert Einstein*

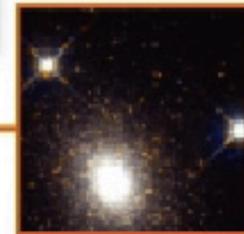
Life
?%



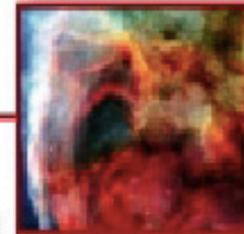
Heavy Elements
0.03%



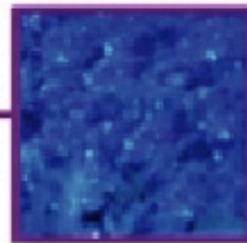
Neutrinos
0.3%



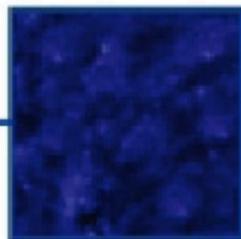
Stars
0.5%



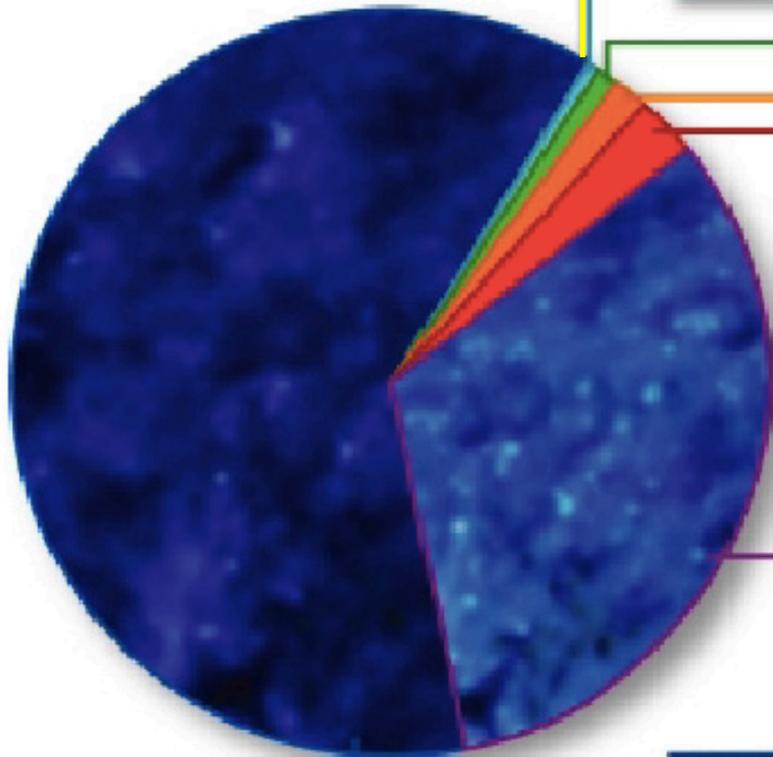
**Free Hydrogen
and Helium**
4%



Dark Matter
23%



Dark Energy
72%



Thanks!

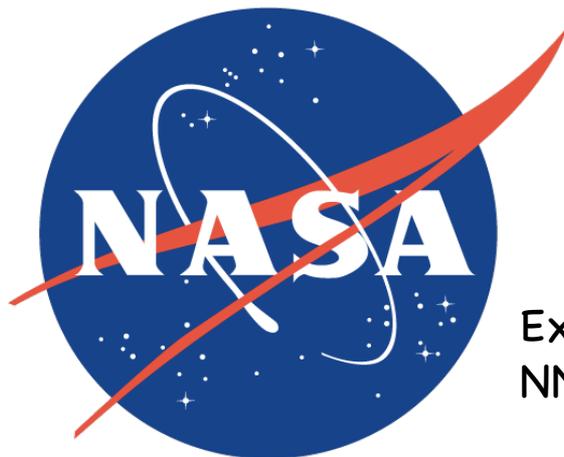
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ASU Nexus for Exoplanet System Science



Exobiology Grant No.
NNX15AL24G