Overview and *Kepler* Update

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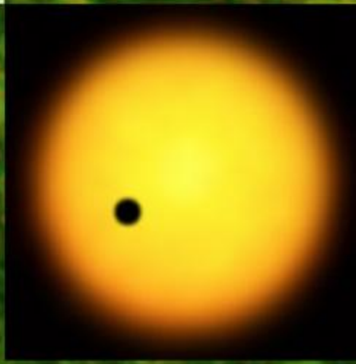
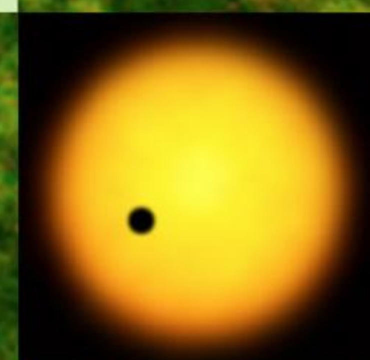


Credit: S. Cundiff

Exoplanets and the Planetary Origins of Life

Life is
a planetary phenomenon



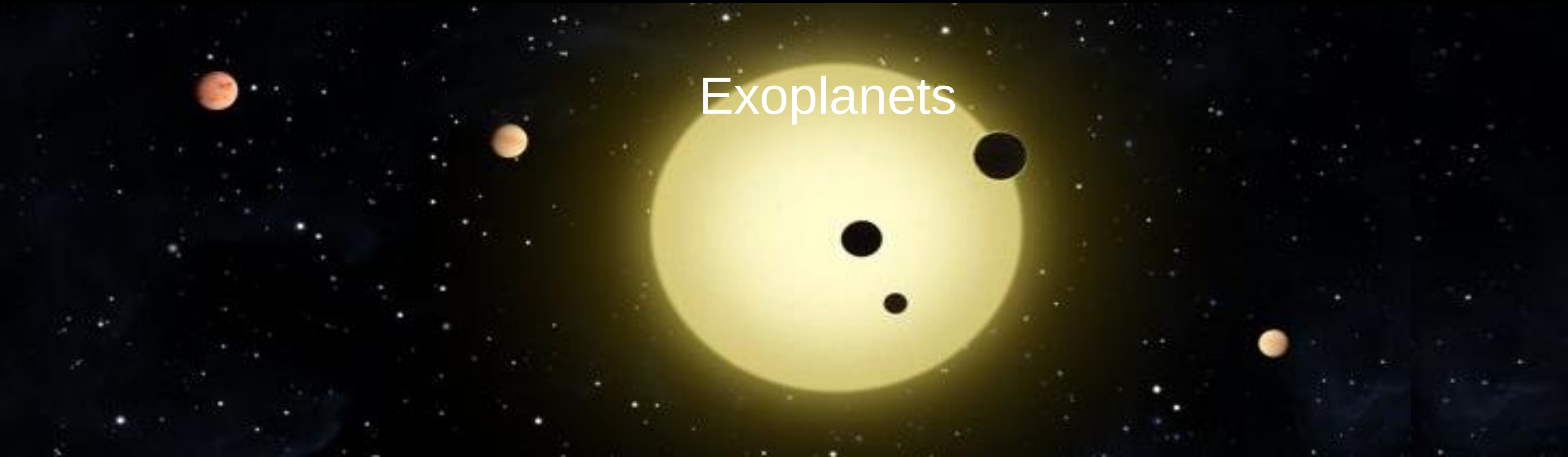
Life is a planetary phenomenon - origins

To help us narrow down pre-biotic initial conditions, we need:

- direct analysis of early-Earth samples – retrieved from the Moon,

or

- the broadest planetary context, beyond our Solar System,

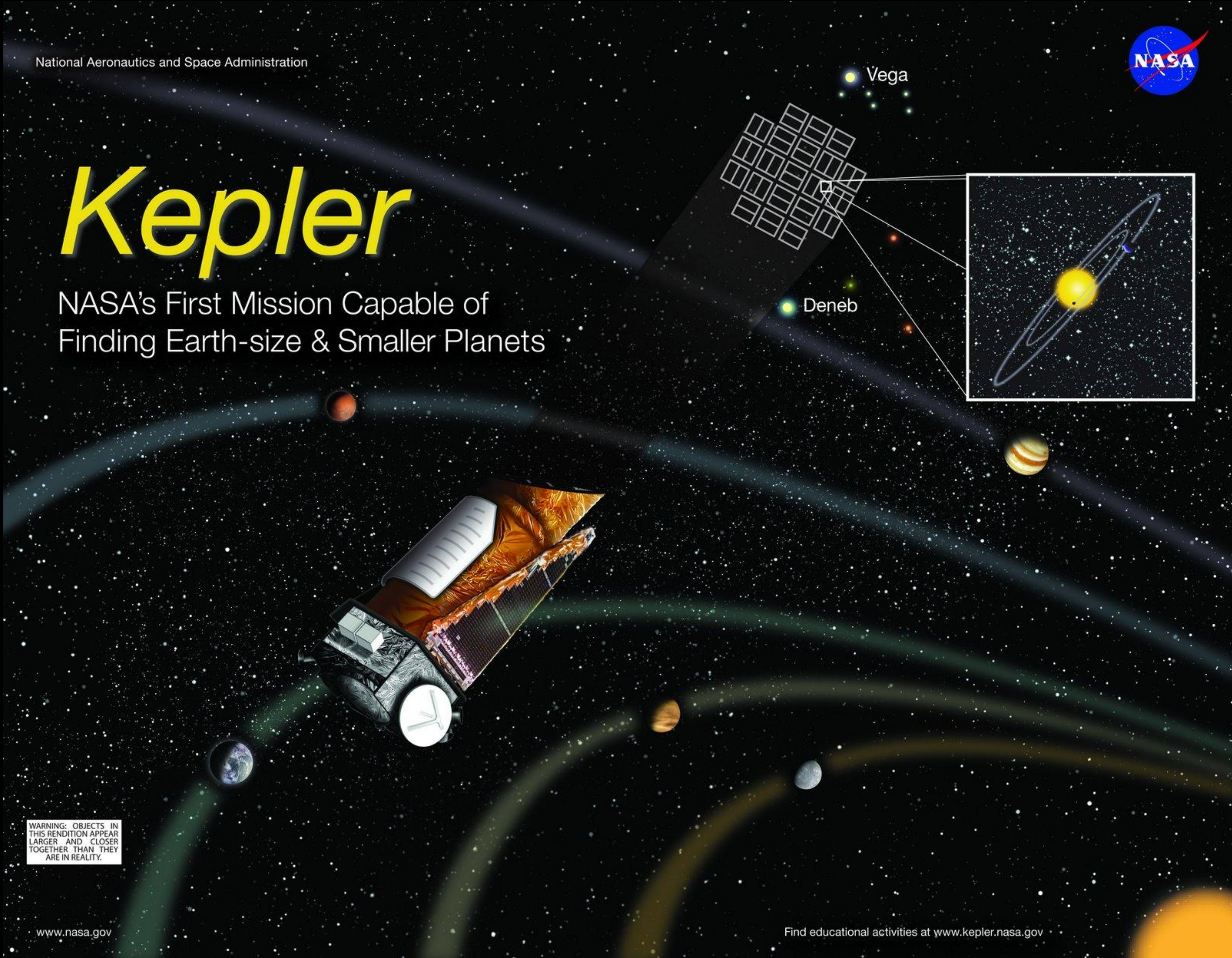


Outline:

1. Technical feasibility
   - Statistics: frequency of super-Earths & Earths
   - Remote sensing: successes & challenges
   - Opportunities to study pre-biotic environments

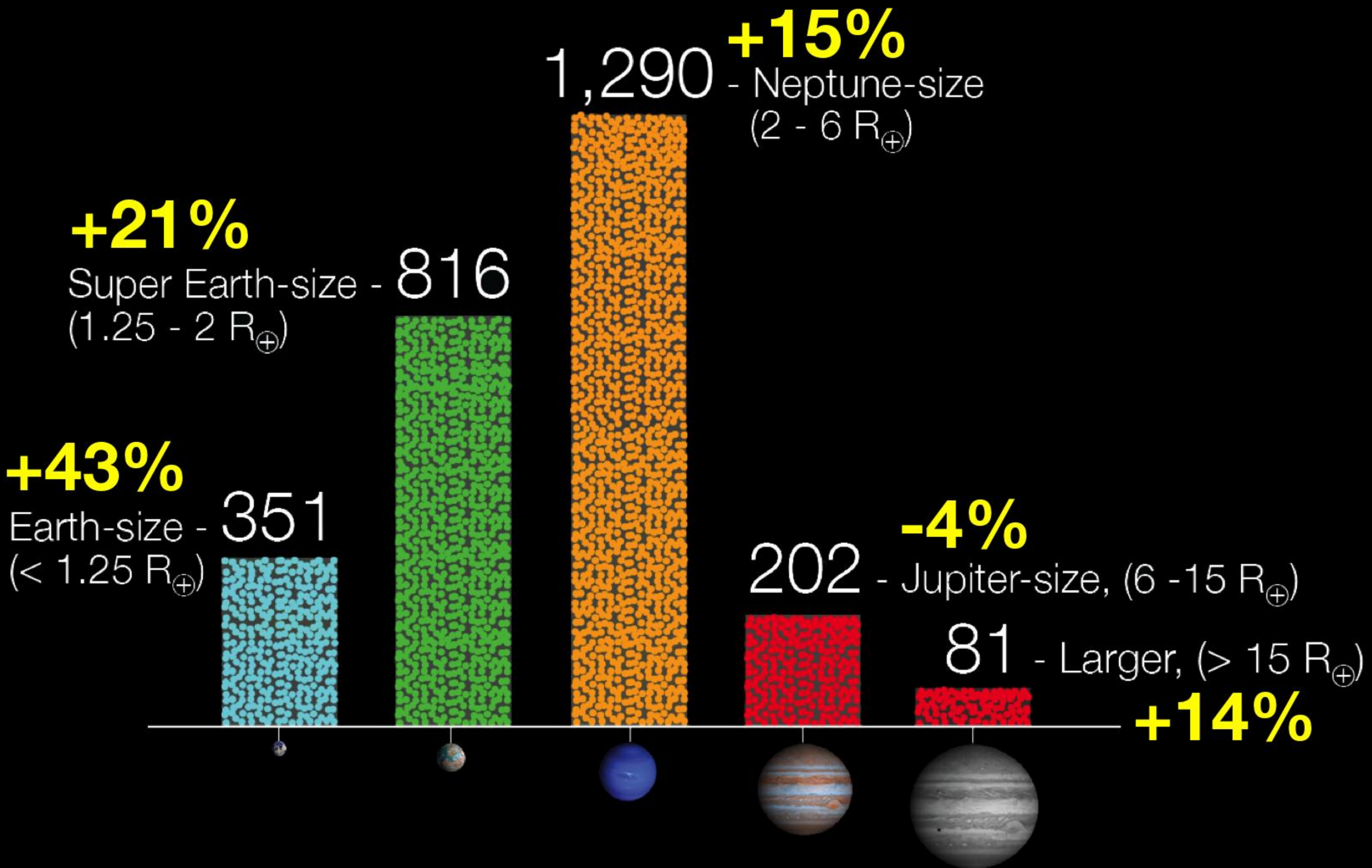
2. What should we do next – bio-signatures?
   - Yes, but are we prepared to interpret the spectra?
   - What to anticipate – geophysical cycles & UV light

3. Where geochemistry & biochemistry meet
   - Alternative biochemistries – do initial conditions matter?
   - Mirror life as a useful testbed to minimal cells.


National Aeronautics and Space Administration
NASA
Vega
Kepler
NASA's First Mission Capable of
Finding Earth-size & Smaller Planets
Deneb
WARNING: OBJECTS IN THIS RENDITION APPEAR LARGER AND CLOSER TOGETHER THAN THEY ARE IN REALITY.
www.nasa.gov
Find educational activities at www.kepler.nasa.gov

Sizes of Planet Candidates

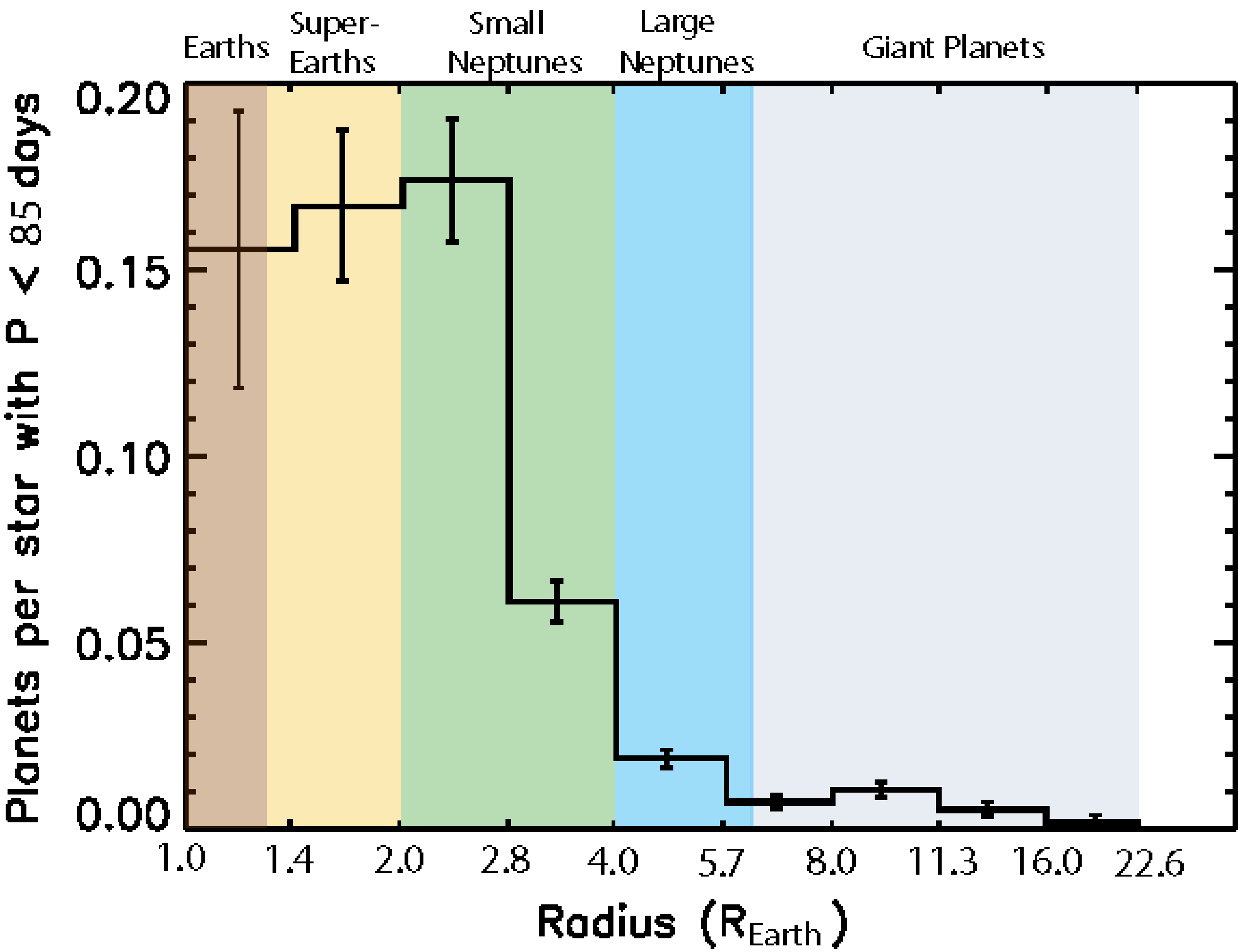
As of January 7, 2013



Burke et al (2013)

Kepler mission: planets per star

Statistical results to-date (22 months):



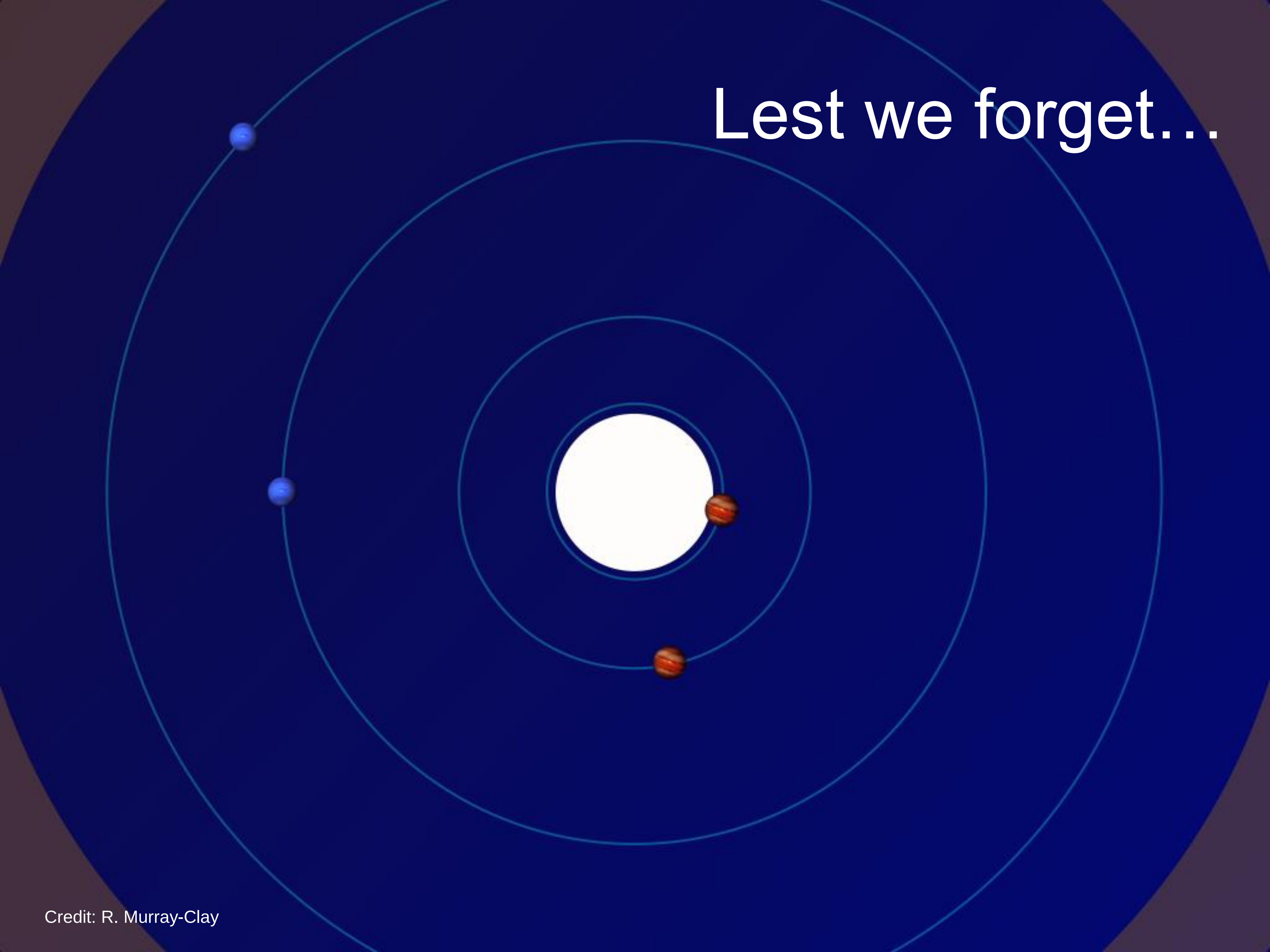
many small planets ($0.8 – 2\ R_E$):

> 40% of stars have at least one,

with P_{orb} < 150 days

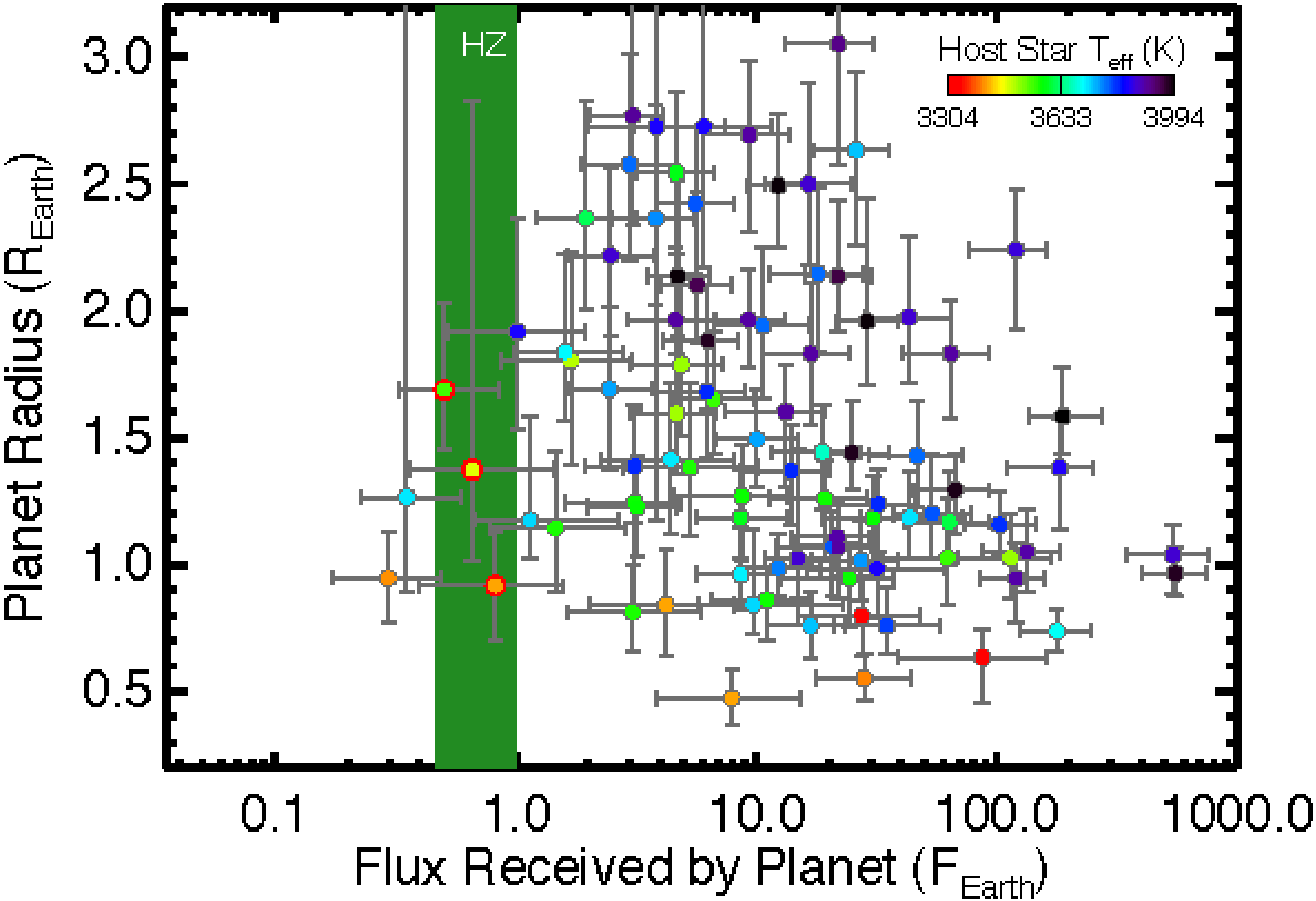
Fressin et al. (2013)

Lest we forget…



Credit: R. Murray-Clay

95 Planet Candidates Orbiting Red Dwarfs



Dressing & Charbonneau (2013)

M-Dwarf Planet Rate from *Kepler*

- The occurrence rate of **0.4 – 4 R_{Earth} planets** with periods < 50 days is **0.87 planets per cool star.**
- The occurrence rate of **Earth-size planets** in the **habitable zone** is **0.06 planets per cool star.**
- With 95% confidence, there is a **transiting Earth-size planet in the habitable zone** of a cool star **within 31 pc.**

Dressing & Charbonneau (2013)

Total in our Galaxy:

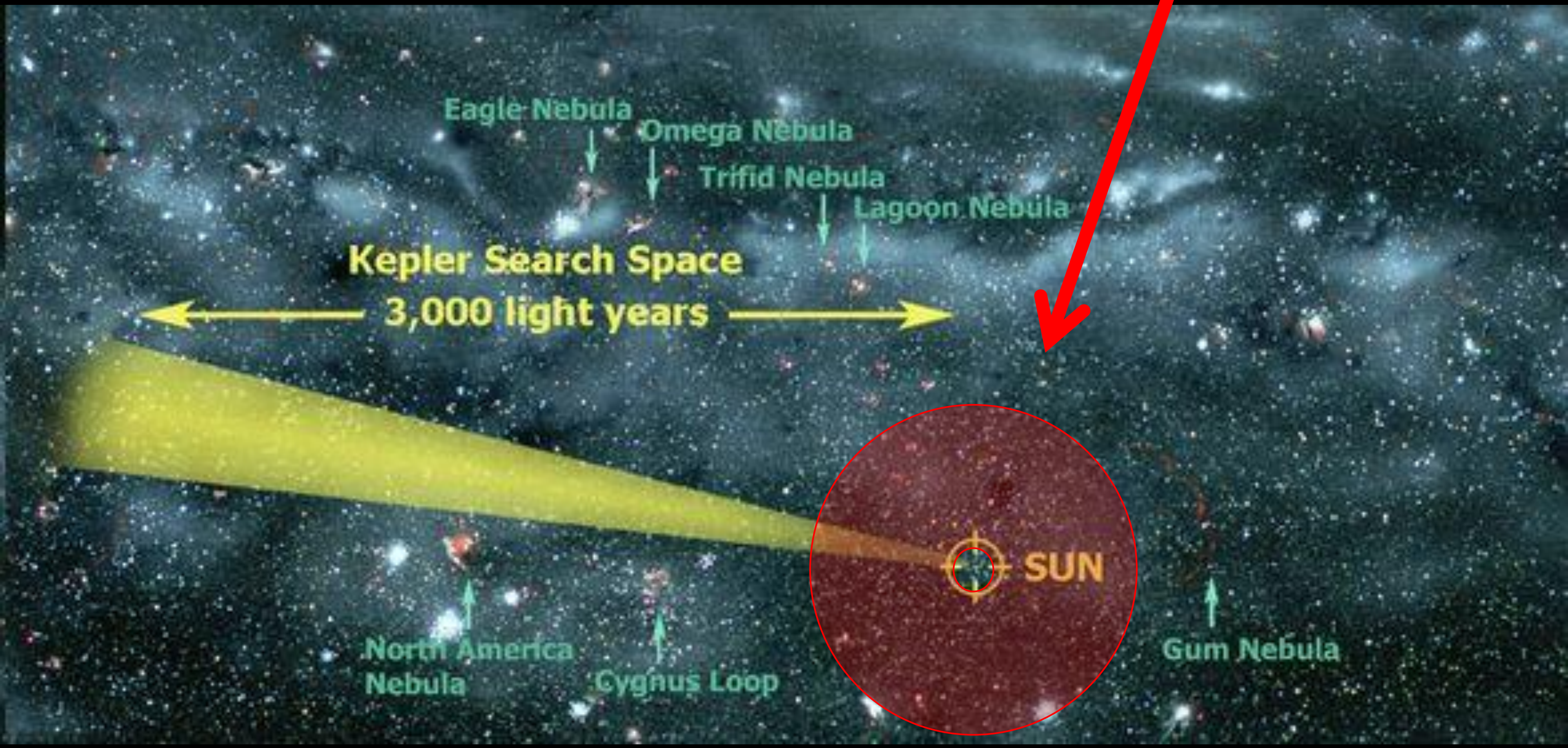
~ 200 $\times 10^6$ planets in HZ

($0.9 – 2\ R_E$)

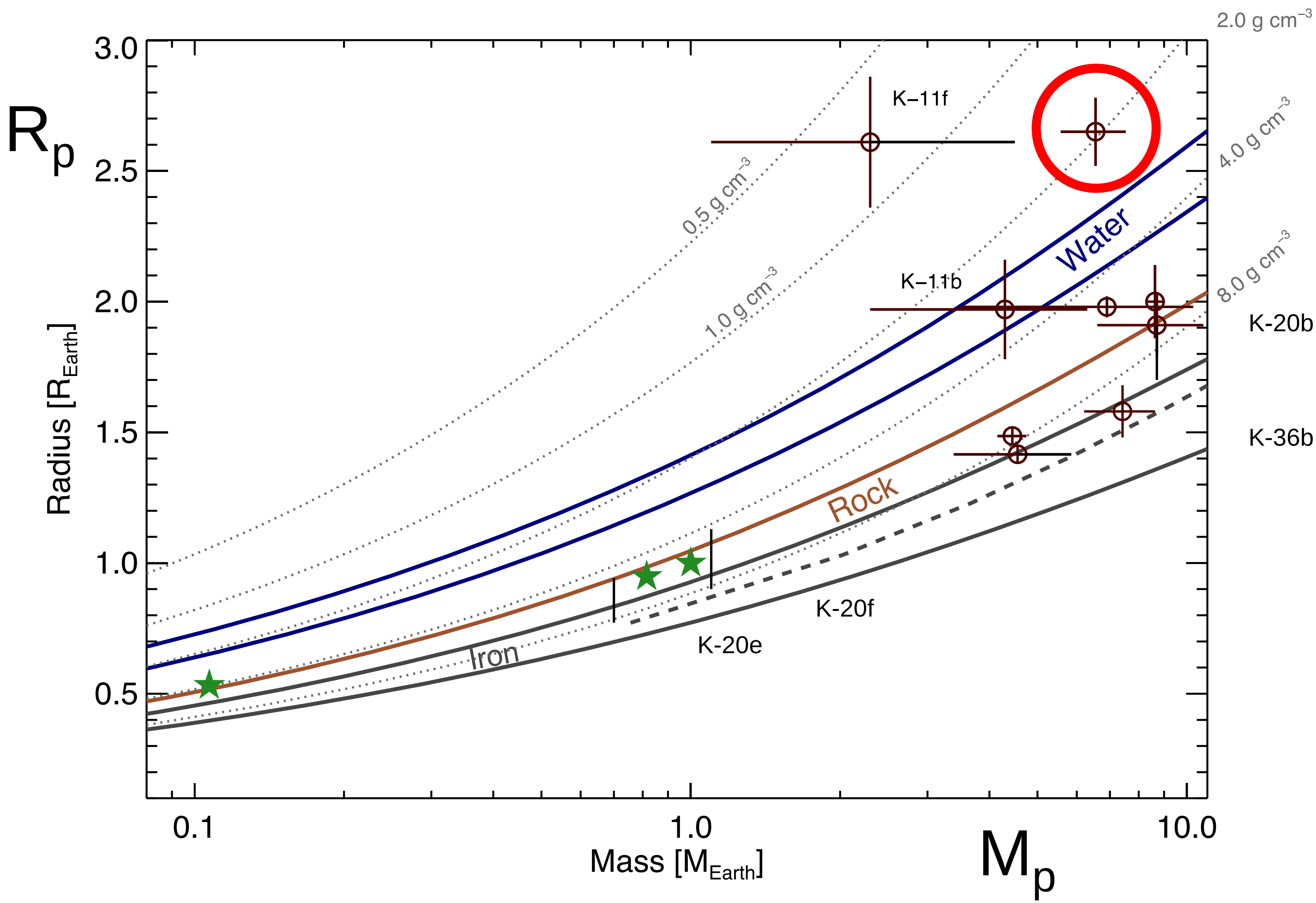
All-sky yield:

> 300 planets

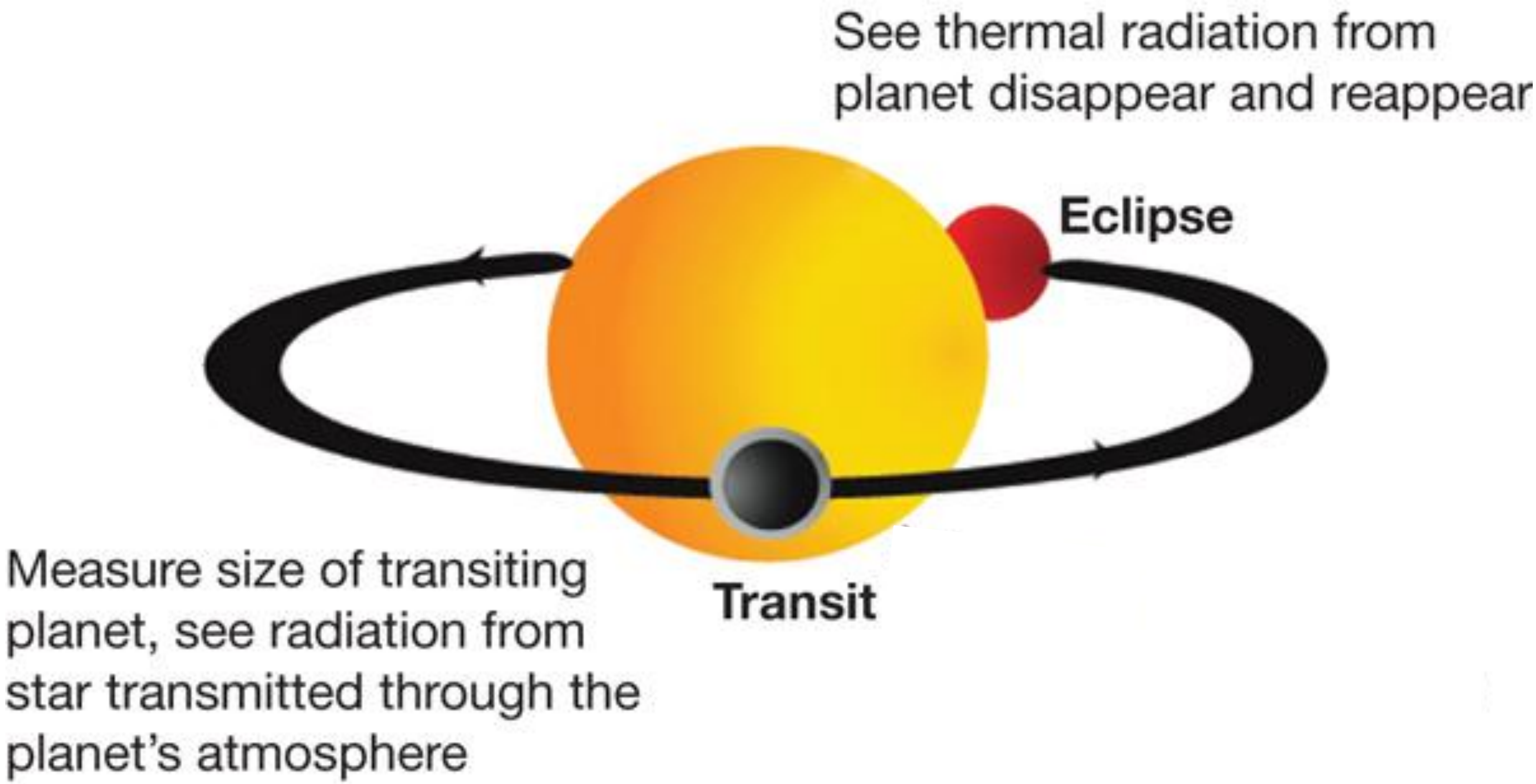
($0.9 – 2\ R_E$)



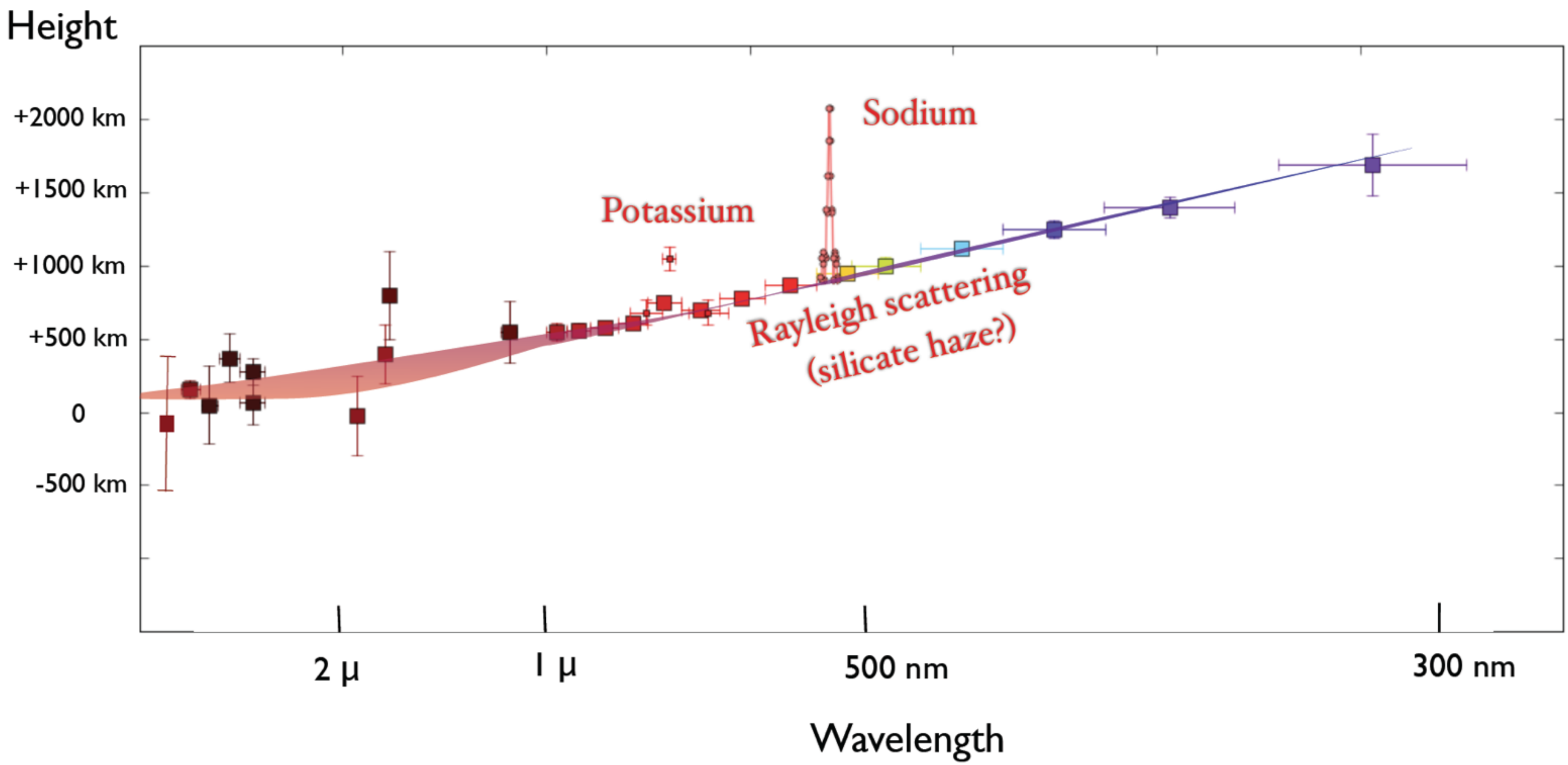
Earths and Super-Earths on the M-R Diagram



Spectroscopy of exoplanet atmospheres



Spectroscopy of an exoplanet (Hot Jupiter) (HD189733b)

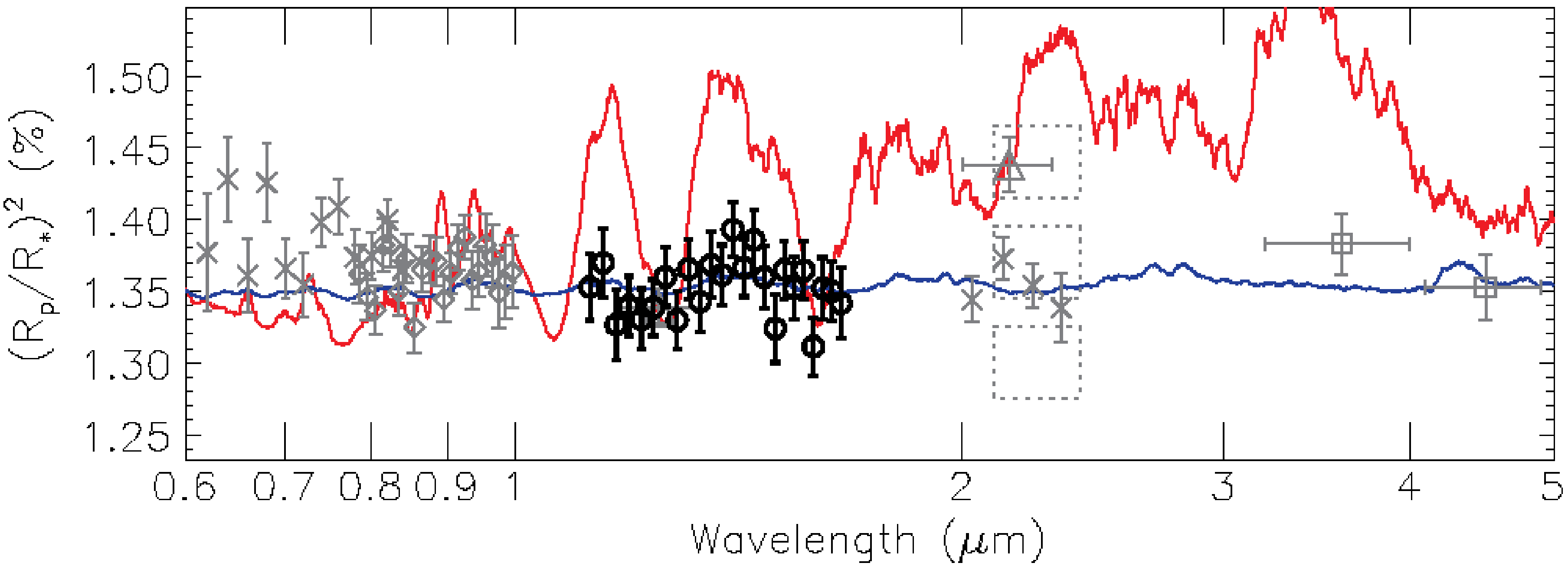


Identified: H_2O, CO_2, CH_4, CO
by Emission Spectroscopy in

Song et al. (2011): ~200 hours of HST/Spitzer

Transmission Spectroscopy

Spectroscopy of a super-Earth (GJ1214b)



Identified: H_2O (steam) by Transmission Spectroscopy

Berta et al. (2012);
Models: Miller-Ricci, Seager, Sasselov (2009),
Miller-Ricci, Fortney (2010)

Technical feasibility: a pathway

1. Discover nearby transiting super-Earths in HZ,
   orbiting small stars (K,M-dwarfs)
   - Easier to detect
   - HZ is at smaller orbits
   - Current technology – accurate mass, radius & age
   - *Example: GJ1214b ('b' is not in HZ)*
     Plans: NASA & ESA (under review)
2. Transmission & Emission spectroscopy
   - Similar levels now reached for GJ1214b
     Plans: NASA JWST (2018); NASA & ESA (under review);
     Ground-based ELT (METIS) & GMT (G-CLEF).

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Atmospheric bio-signature gases:

some metabolic byproducts that can dissipate in the atmosphere and accumulate to allow remote detection via specific spectral features

e.g., as in O_2 produced by cyanobacteria below

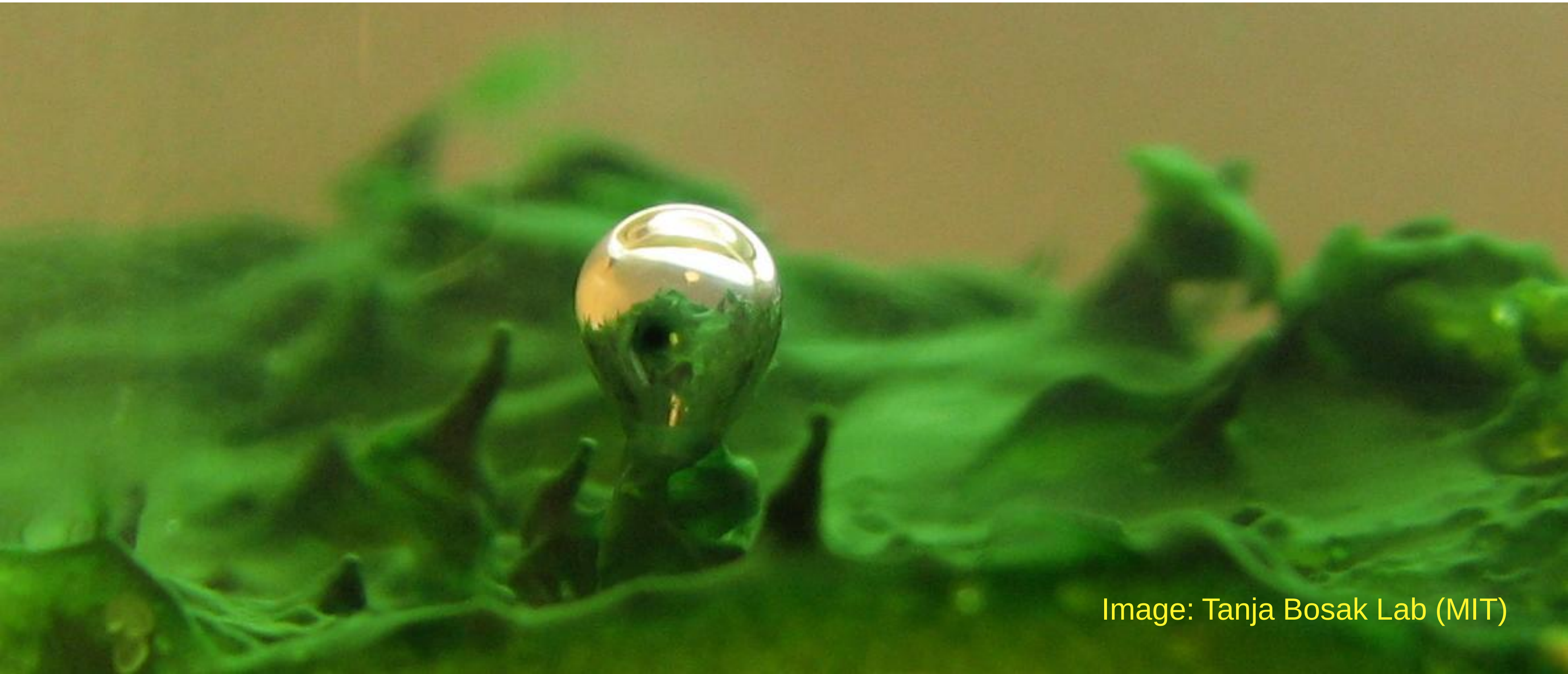


Image: Tanja Bosak Lab (MIT)

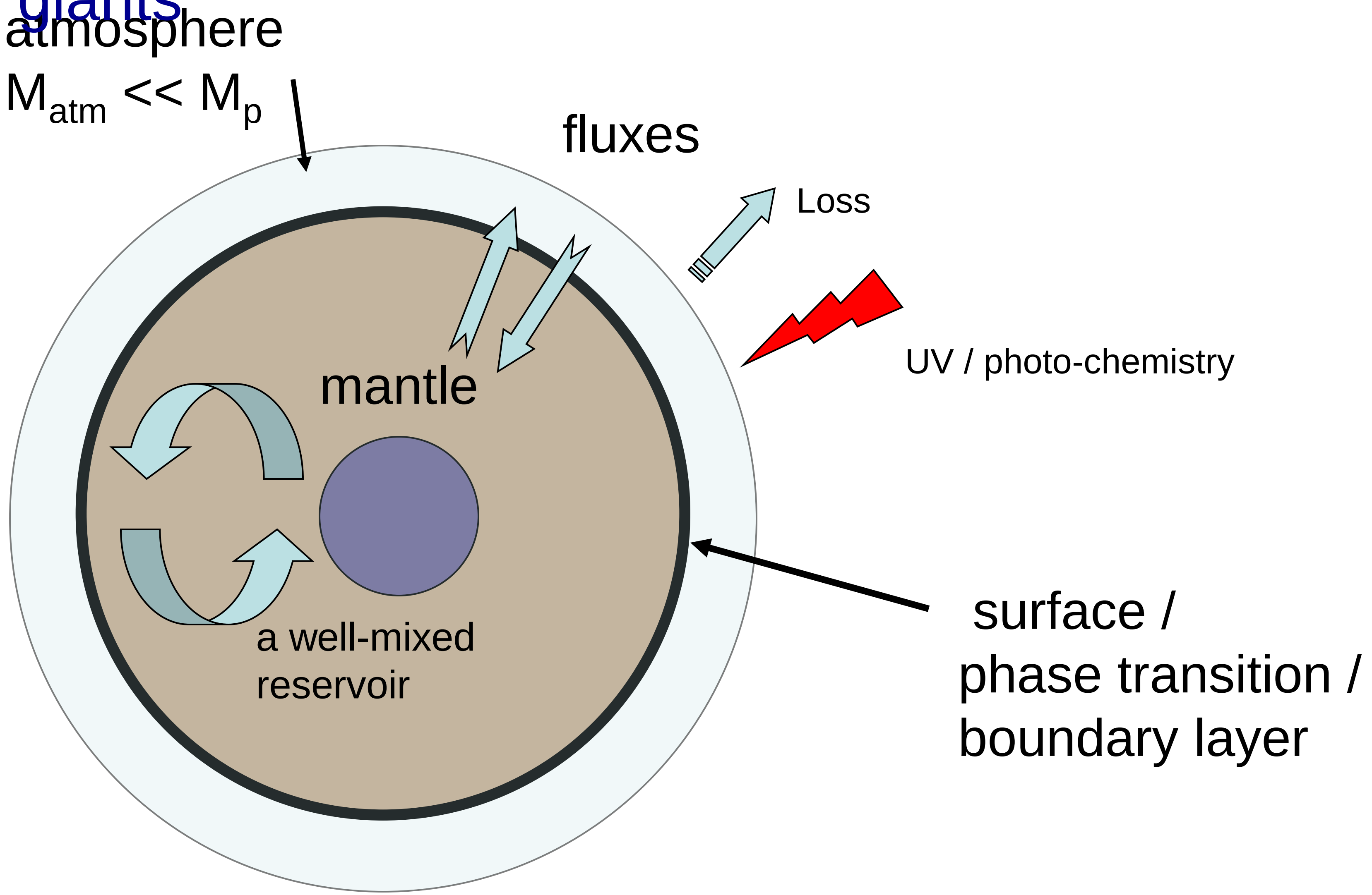
Atmospheric bio-signature gases:

some are not as common on modern Earth,
but given different environmental conditions…

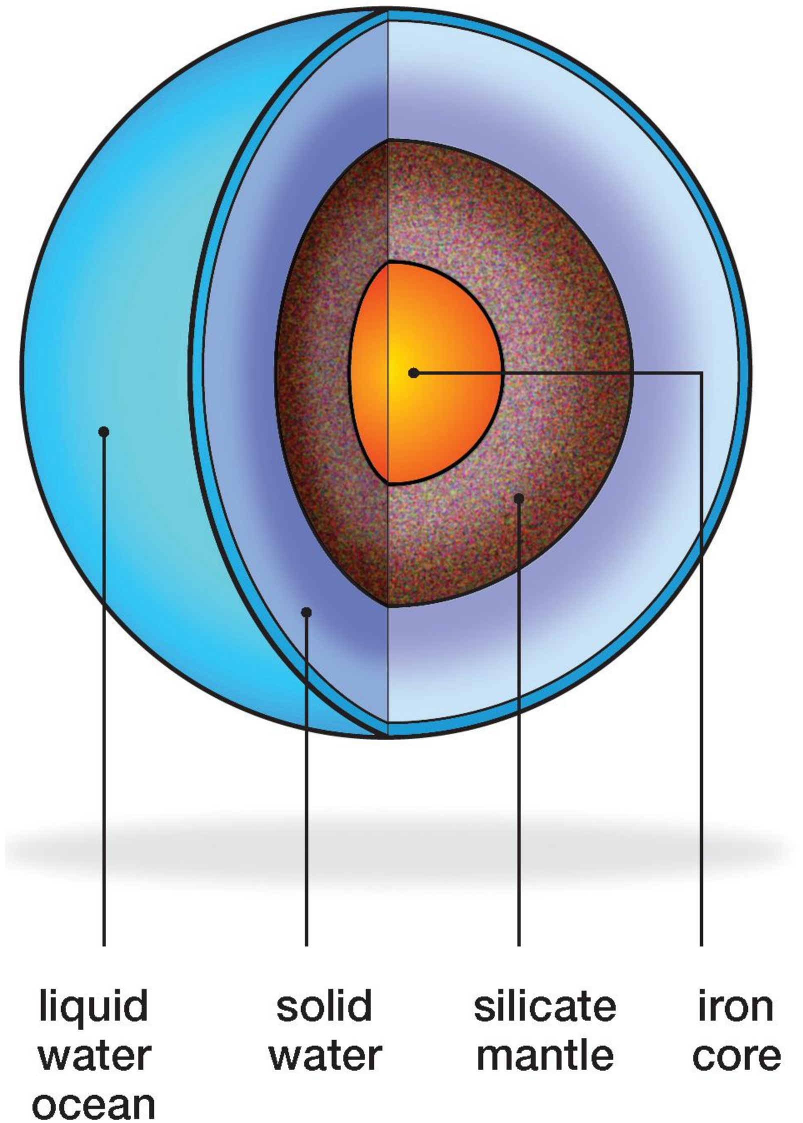
e.g., as in CH_4 produced by sulfur-loving bugs below

The "Spherical Cow" Planet

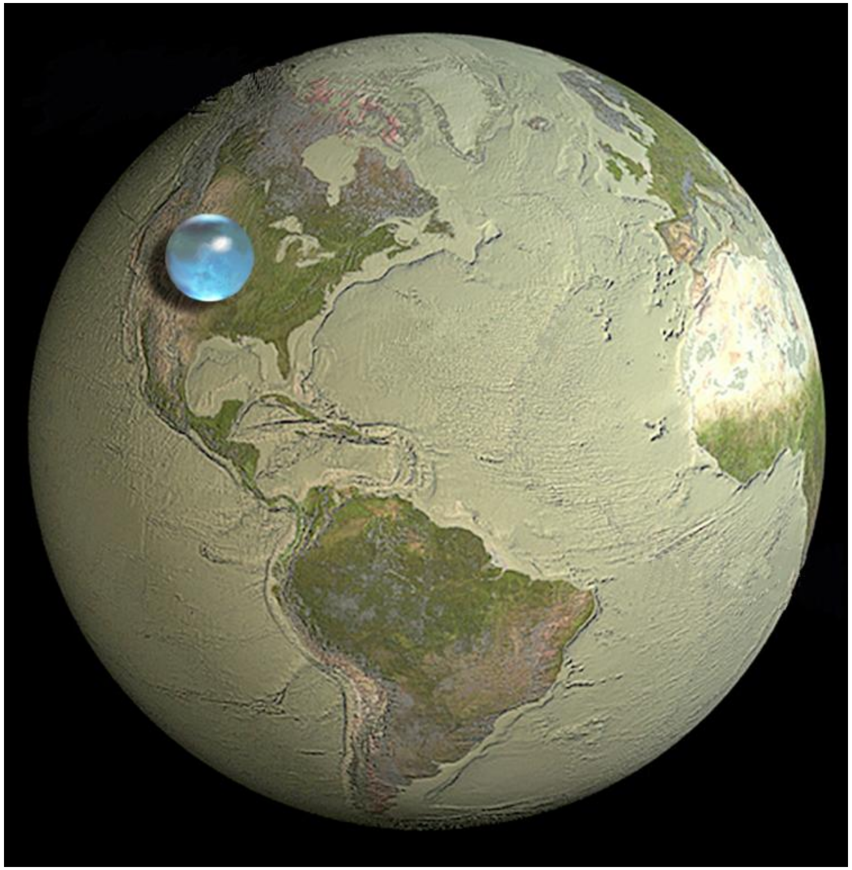
Earth & super-Earths *vs*. gas & ice giants



Water Planet

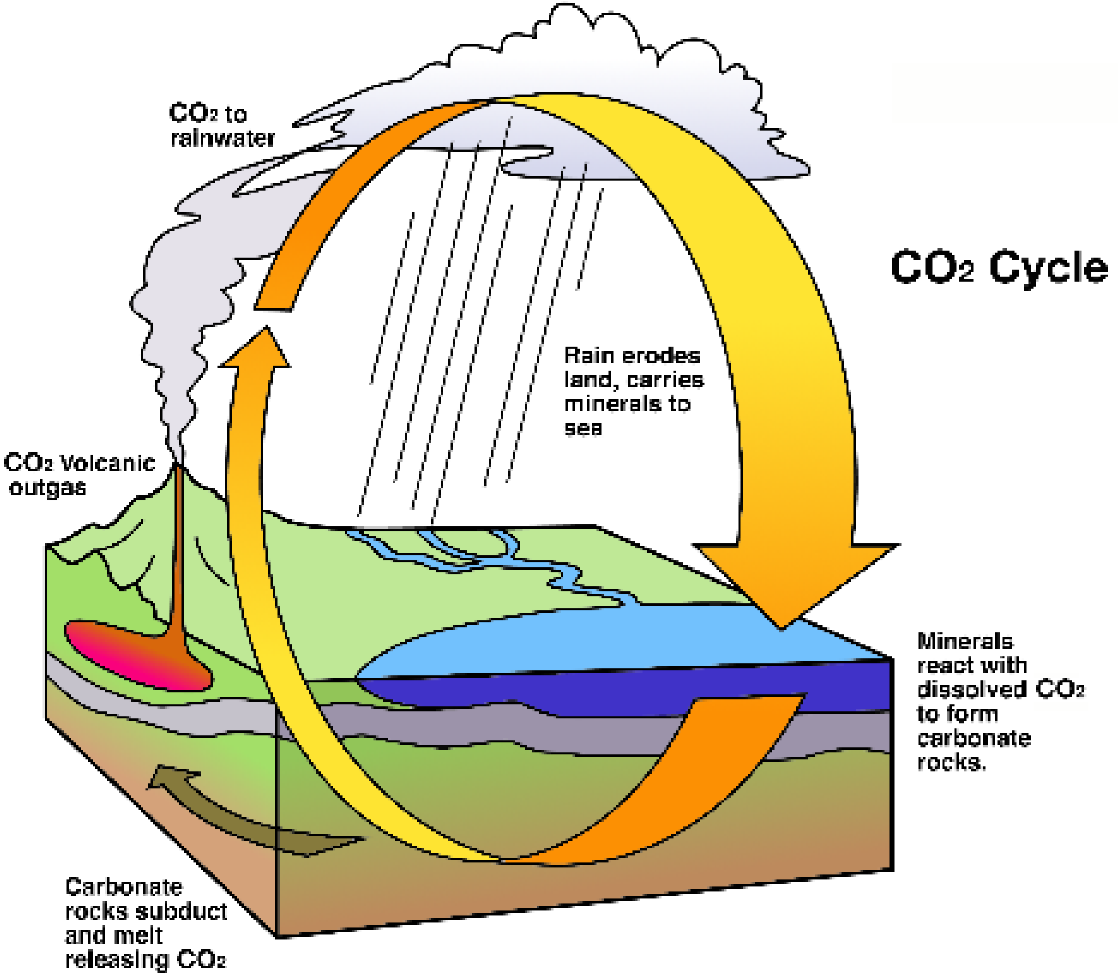


Earth's water



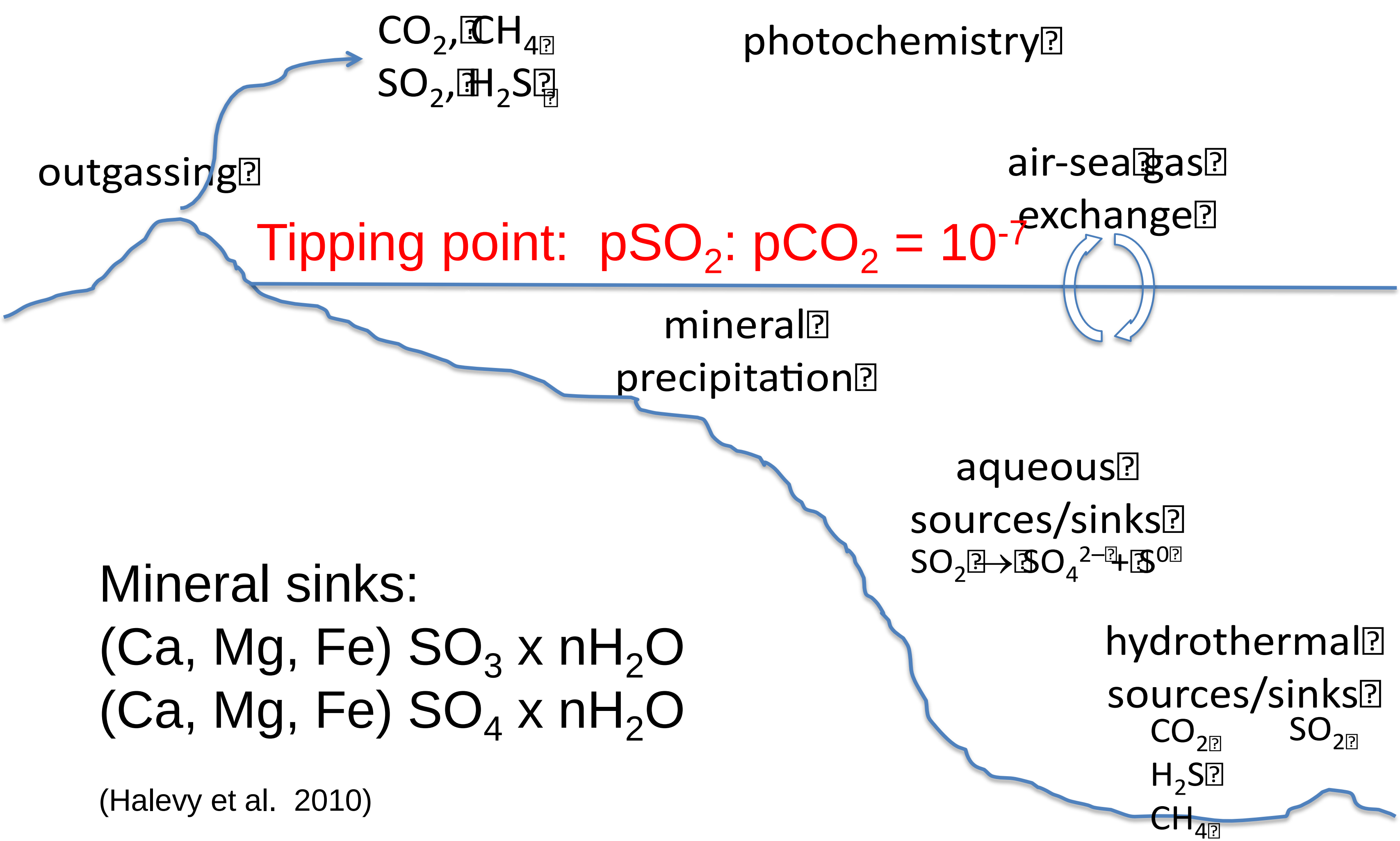
Super-Earths geochemistry,

e.g. the Carbonate-silicate cycle, or the Sulfur cycle, etc.



Planets of different initial conditions are “driven” to a set of geochemical equilibria by global geo-cycles over geological timescales.

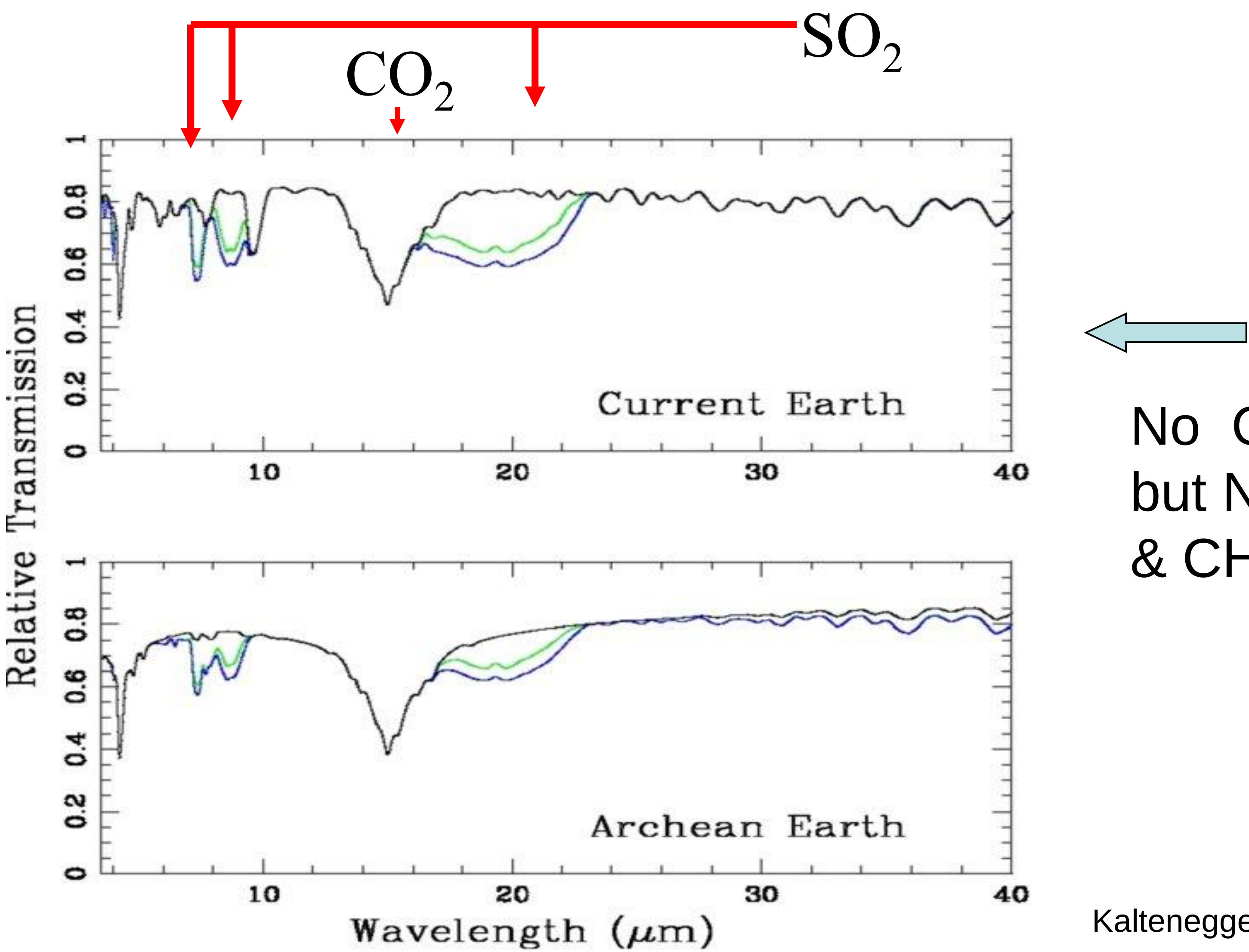
Sulfur Cycle



Mineral sinks:
(Ca, Mg, Fe) SO_3 x nH_2O
(Ca, Mg, Fe) SO_4 x nH_2O

(Halevy et al. 2010)

Simulated NASA *JWST* spectra of a Sulfur-cycle Earth-like planet



No O_2 or O_3 , but N_2 , CO_2 , & CH_4 .

Kaltenegger & Sasselov (2010)

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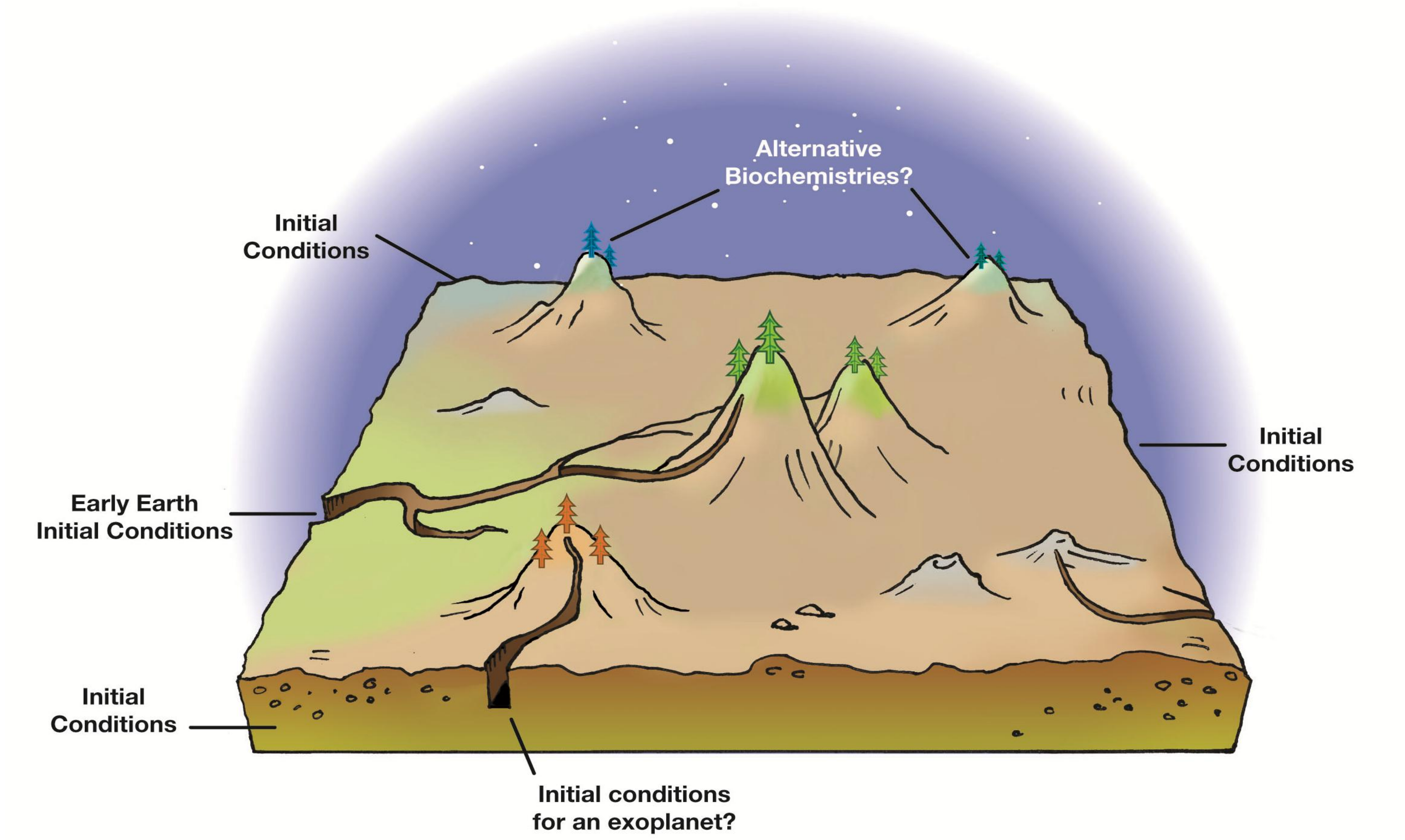
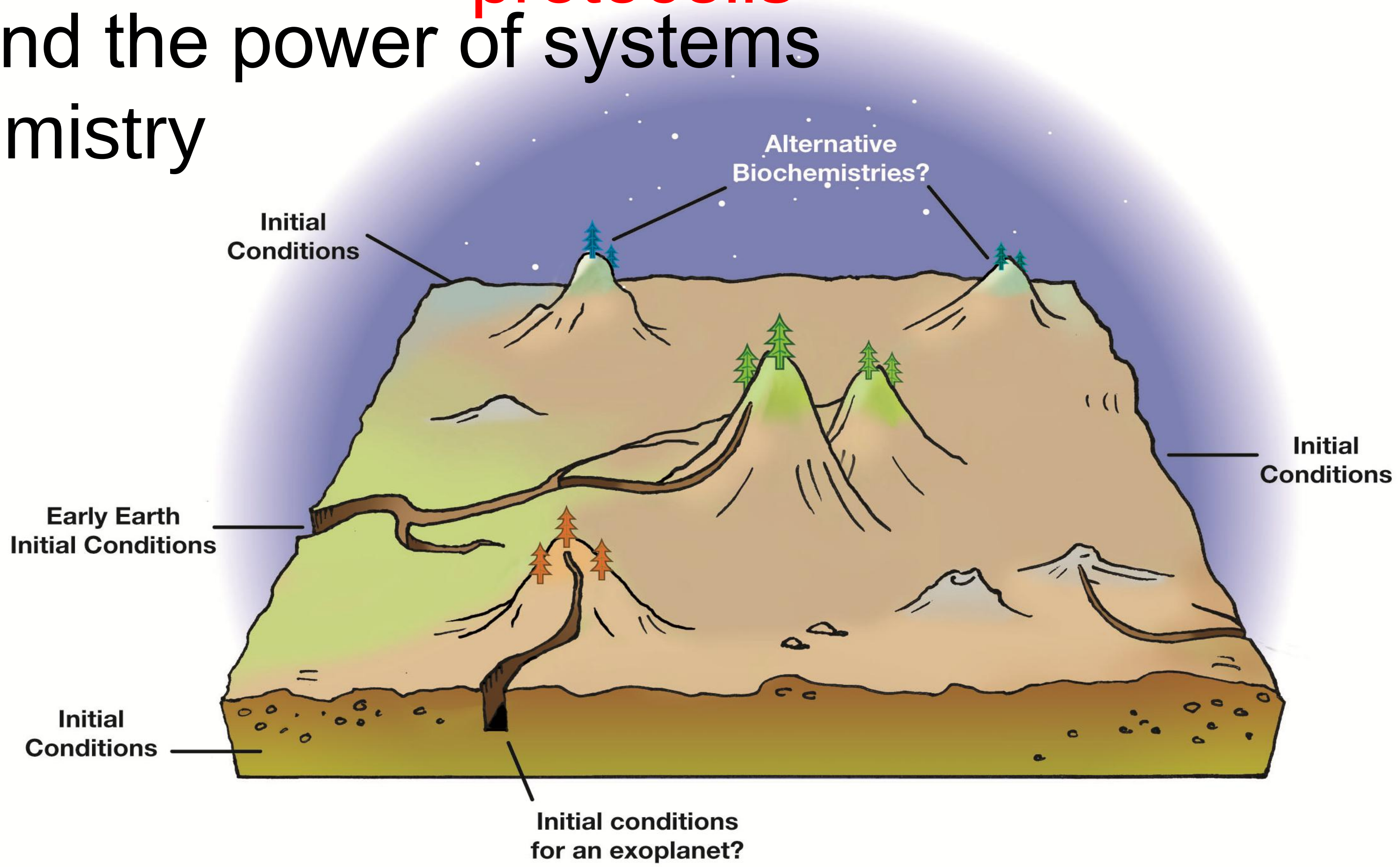
The Chemical Landscape

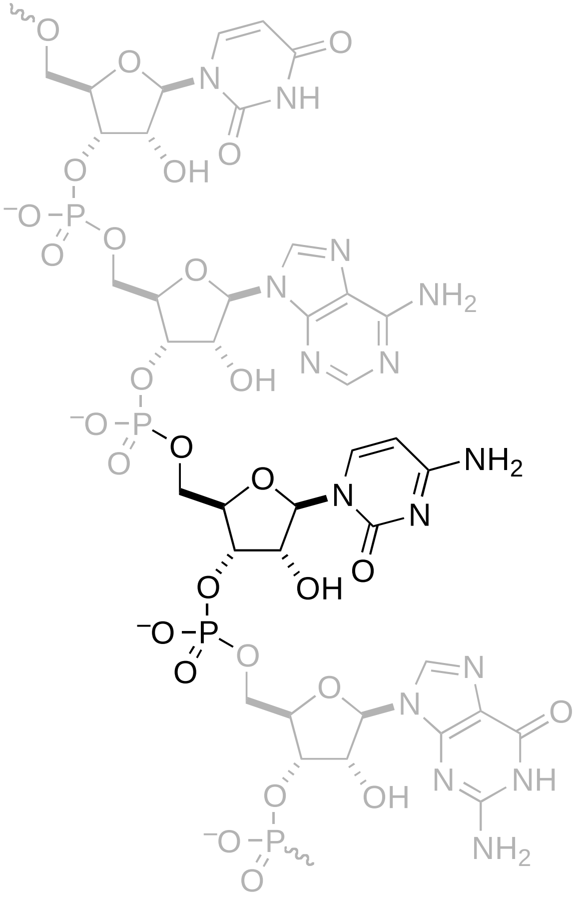


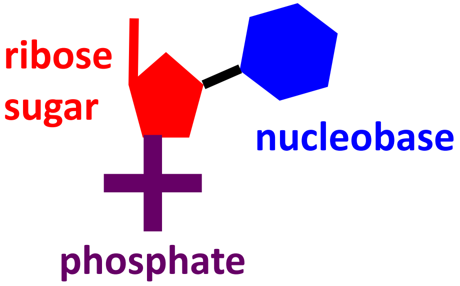
The emerging outline of a pathway from cyanide to nucleotides to RNA to protocells

…and the power of systems chemistry

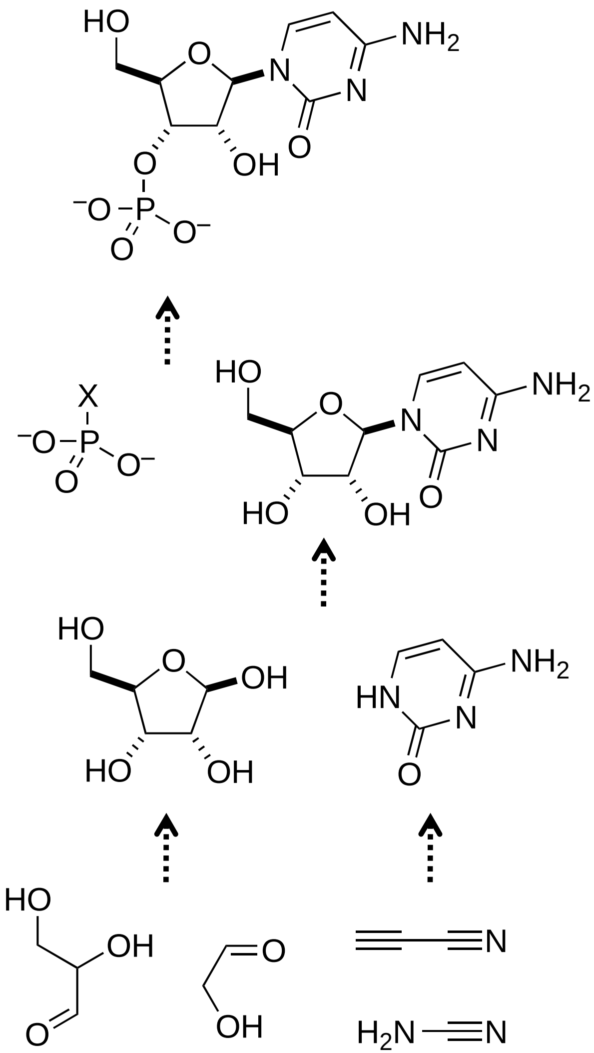


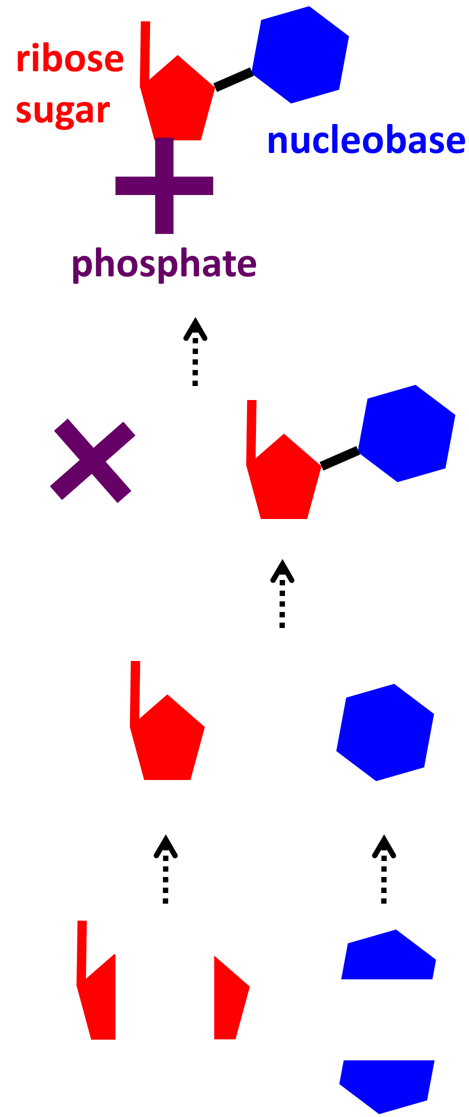
How do polynucleotide molecules, e.g. RNA arise?





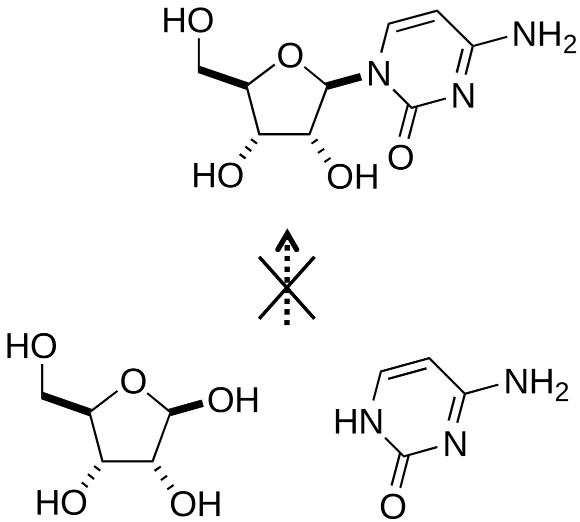
How did RNA arise? – the old approach

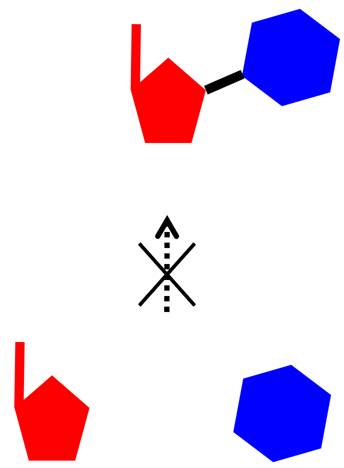




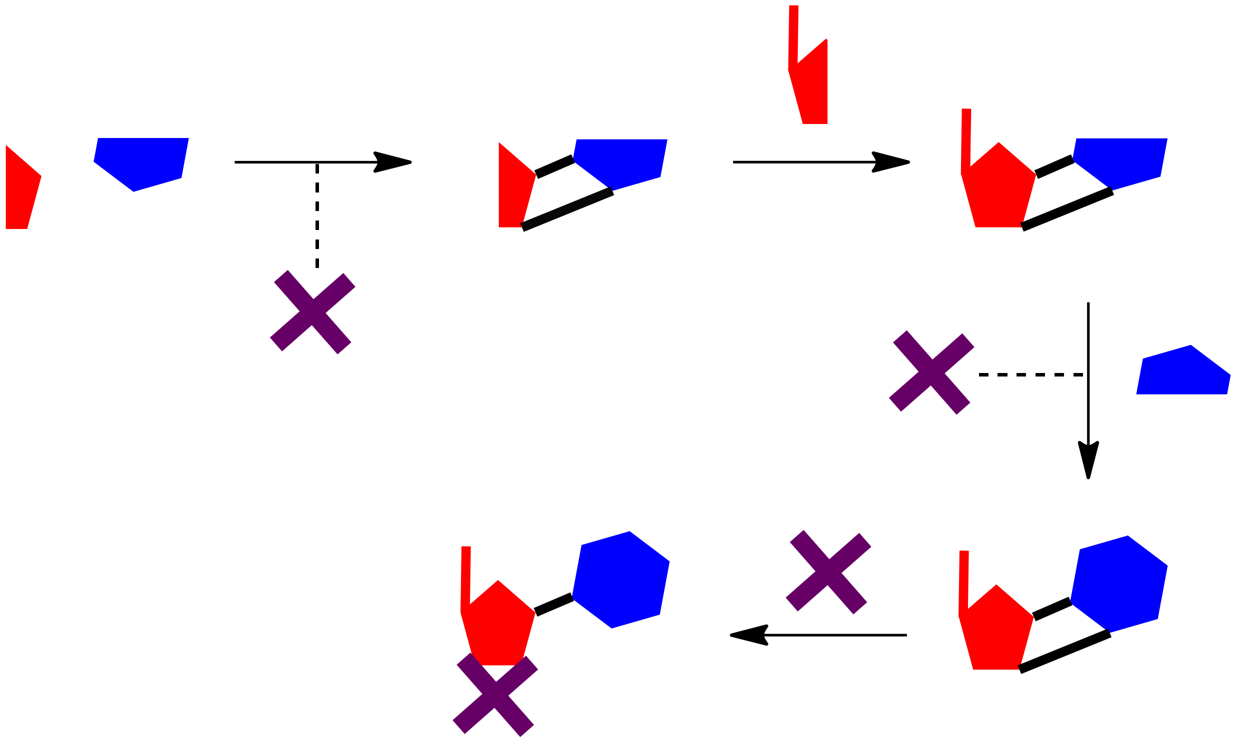
Sutherland Lab

The problem of joining ribose and nucleobases



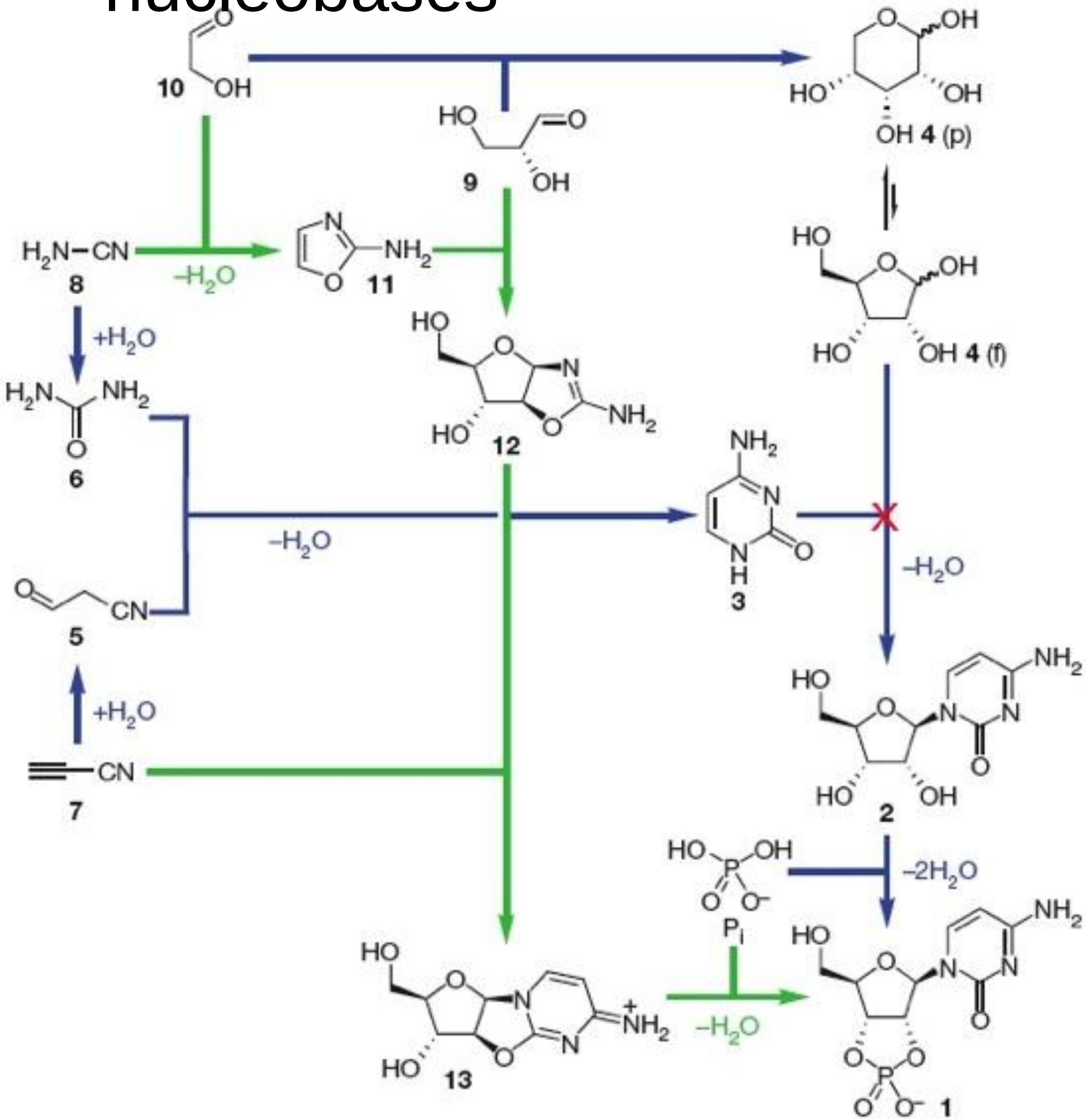


Bypassing ribose and the nucleobases



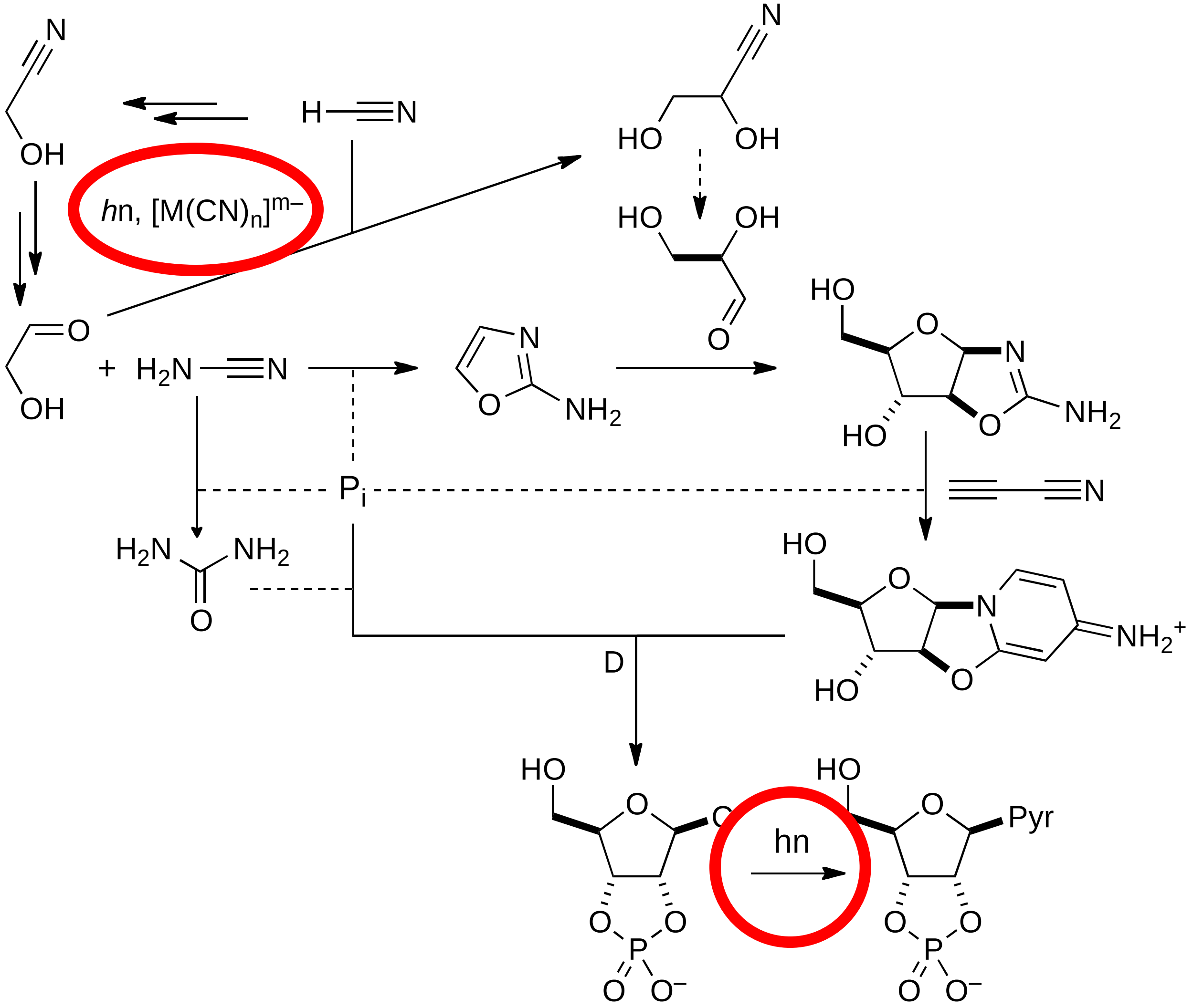
M. W. Powner, B. Gerland, J. D. Sutherland, *Nature* **2009**, *459*,

Bypassing ribose and the nucleobases



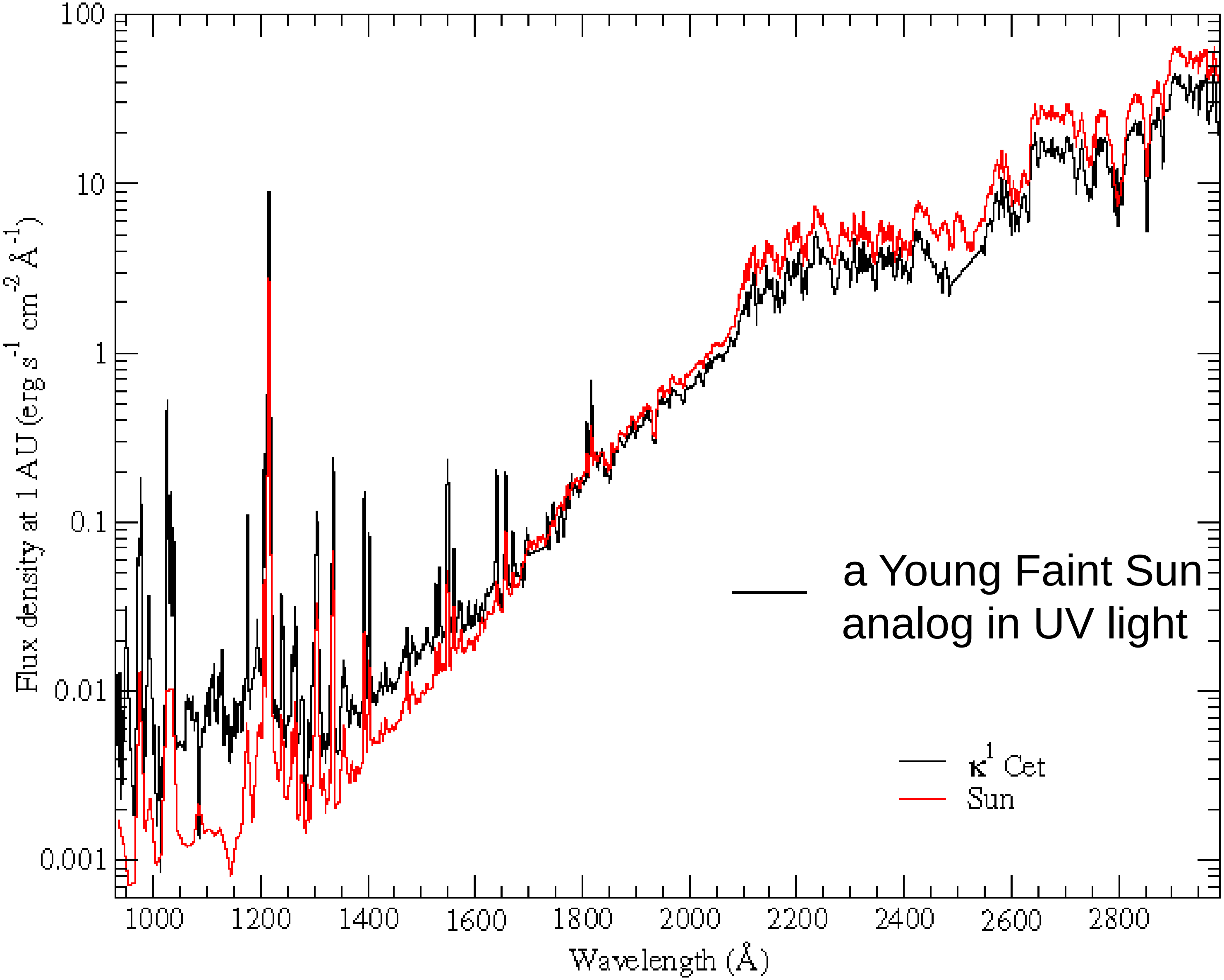
Powner, Gerland & Sutherland (2009)

Potential cyanometallate systems photochemistry



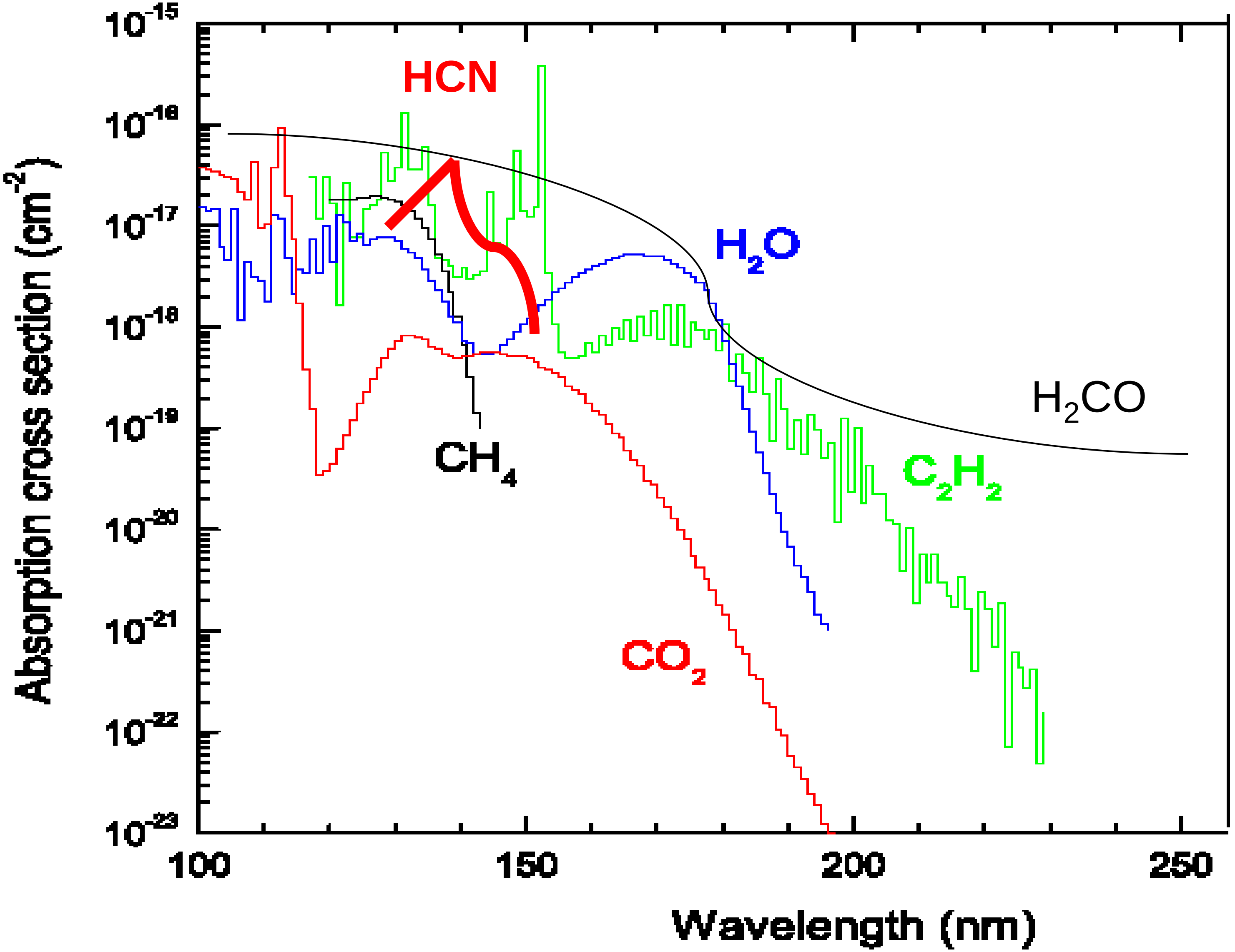
Sutherland Lab

Photochemistry: UV starlight



Ribas et al. (2010)

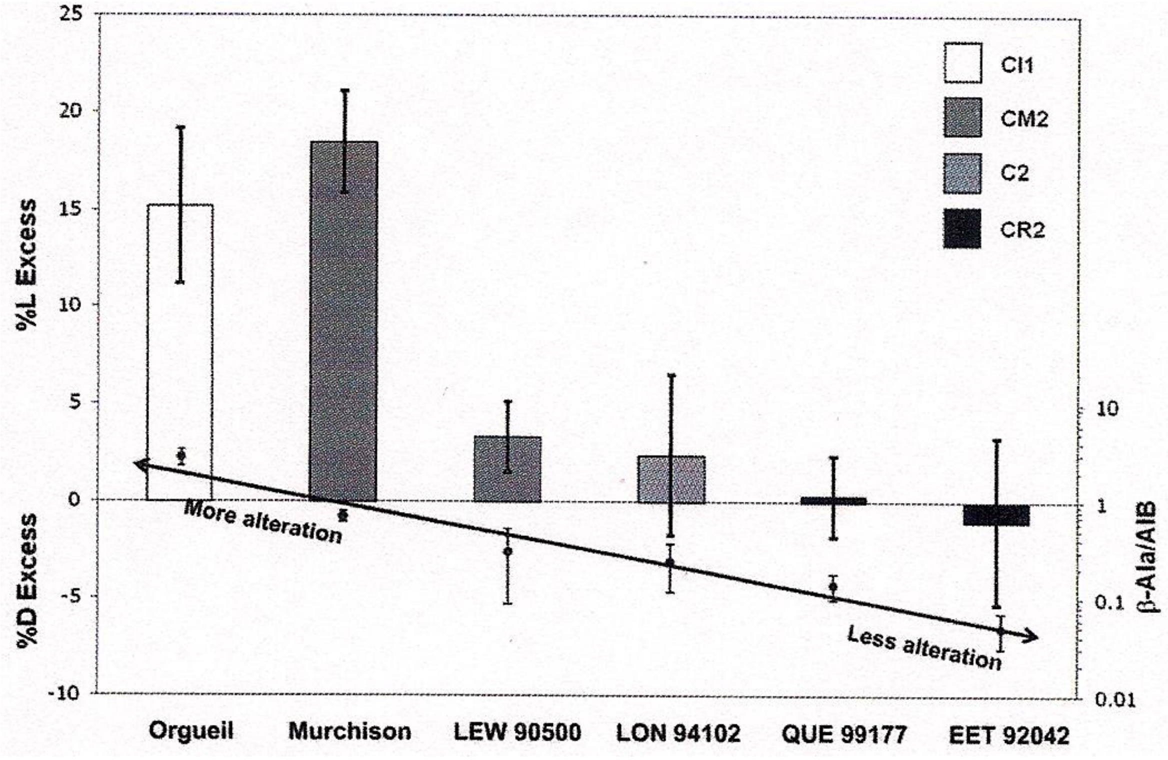
Photochemistry & UV starlight



Ribas et al. (2010); Cooper et al. (1986), Macpherson & Simons (1978)

The role and origin of homochirality:

1. The origin of symmetry breaking, *e.g.* meteorites;
2. A pure experimental bionic system –
   - possibly the best pathway to artificial minimal cells



(Glavin & Dworkin 2009)

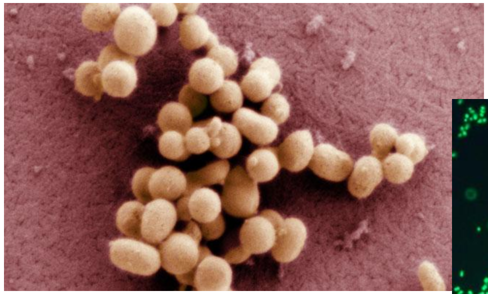
Building an artificial minimal cell – two directions

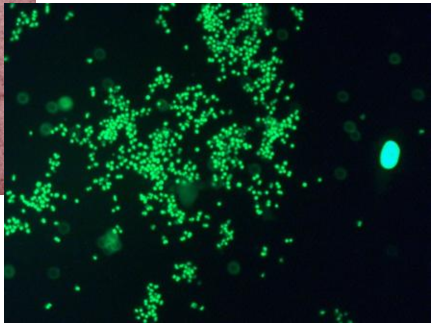
‘Top-down’

reduction of bacterial genomes
in vivo

M. genitalium (528 genes)
& *M. mycoides JCVI-syn1.0*
[Glass et al. 2006; Gibson et al. 2010]

H. cicadicola (188 genes)
[McCutcheon et al. 2009]

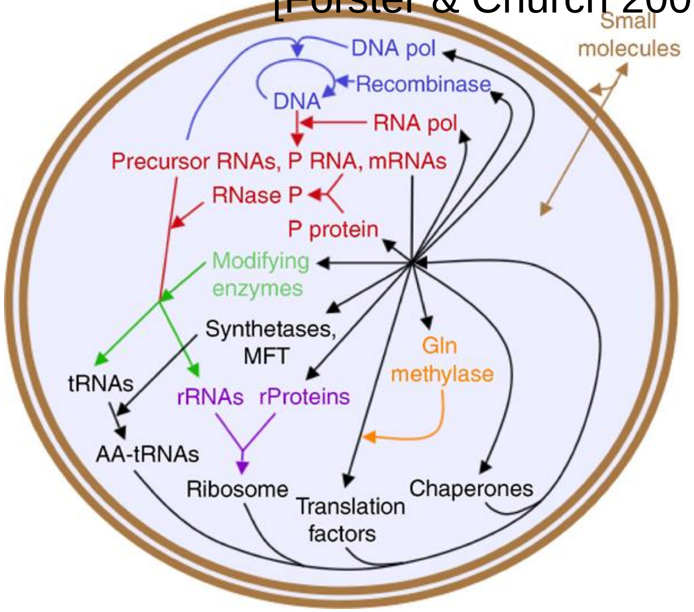




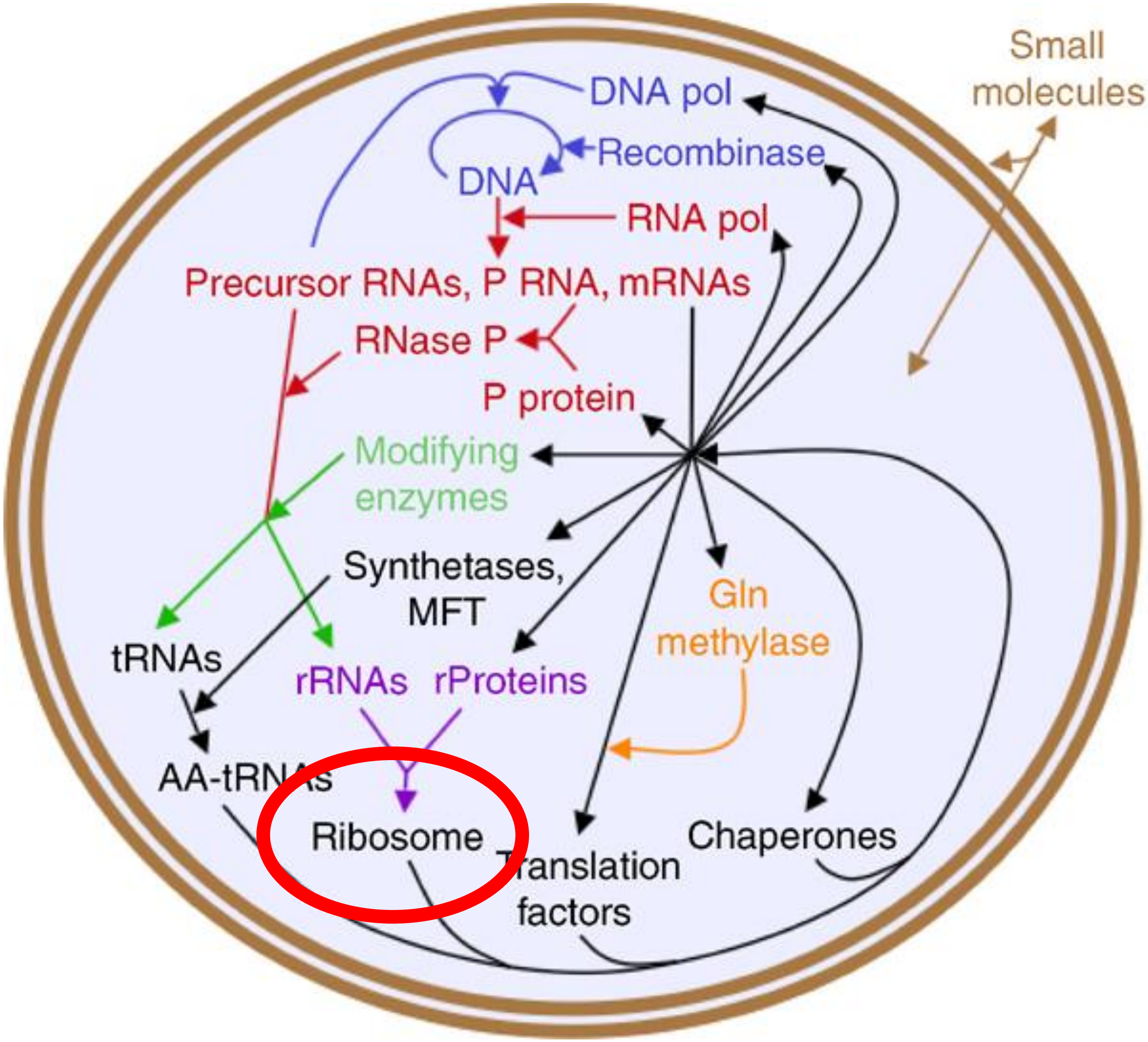
‘Bottom-up’

integration of DNA/RNA/protein
in vitro

Synthesizing self-replication by a DNA/RNA/protein system (151 genes)
[Forster & Church 2006]

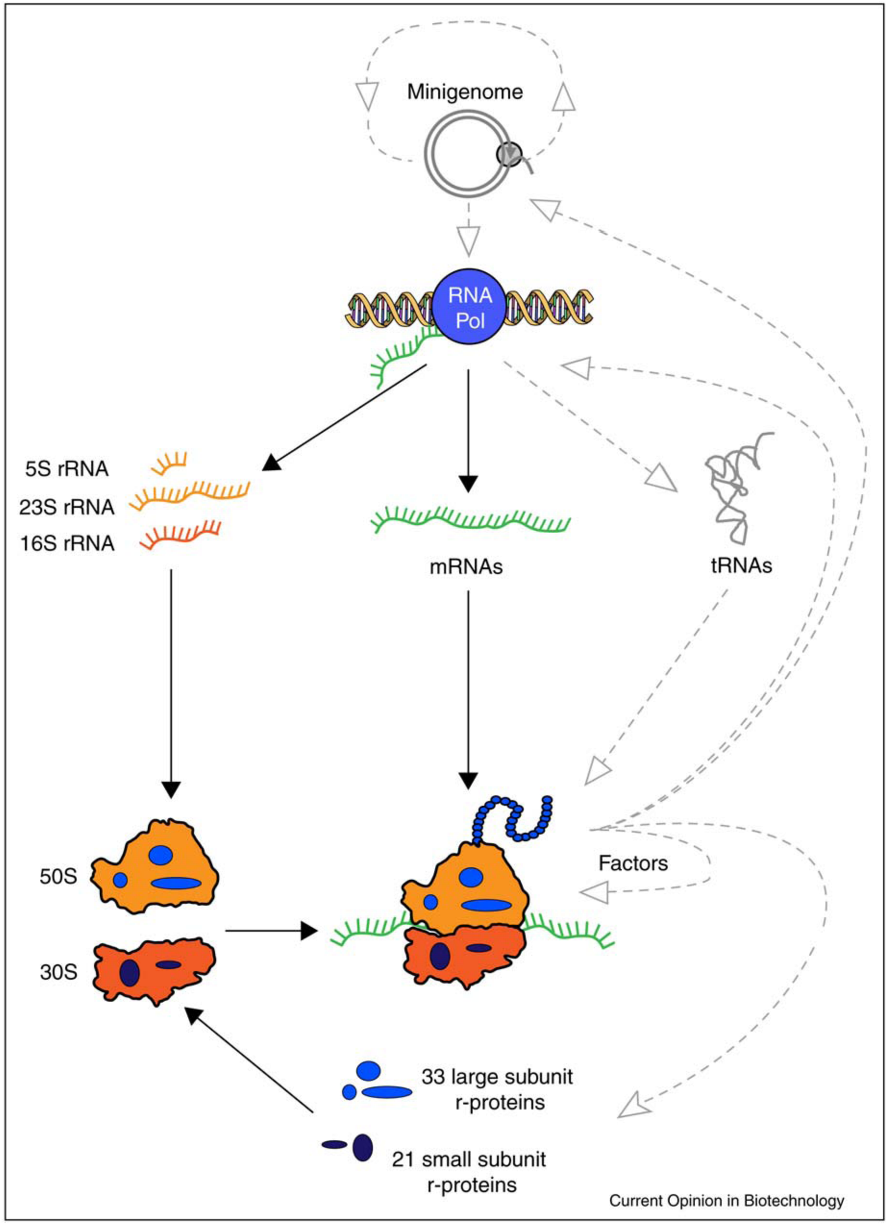


‘Bottom-up’ Approach: Basic Set



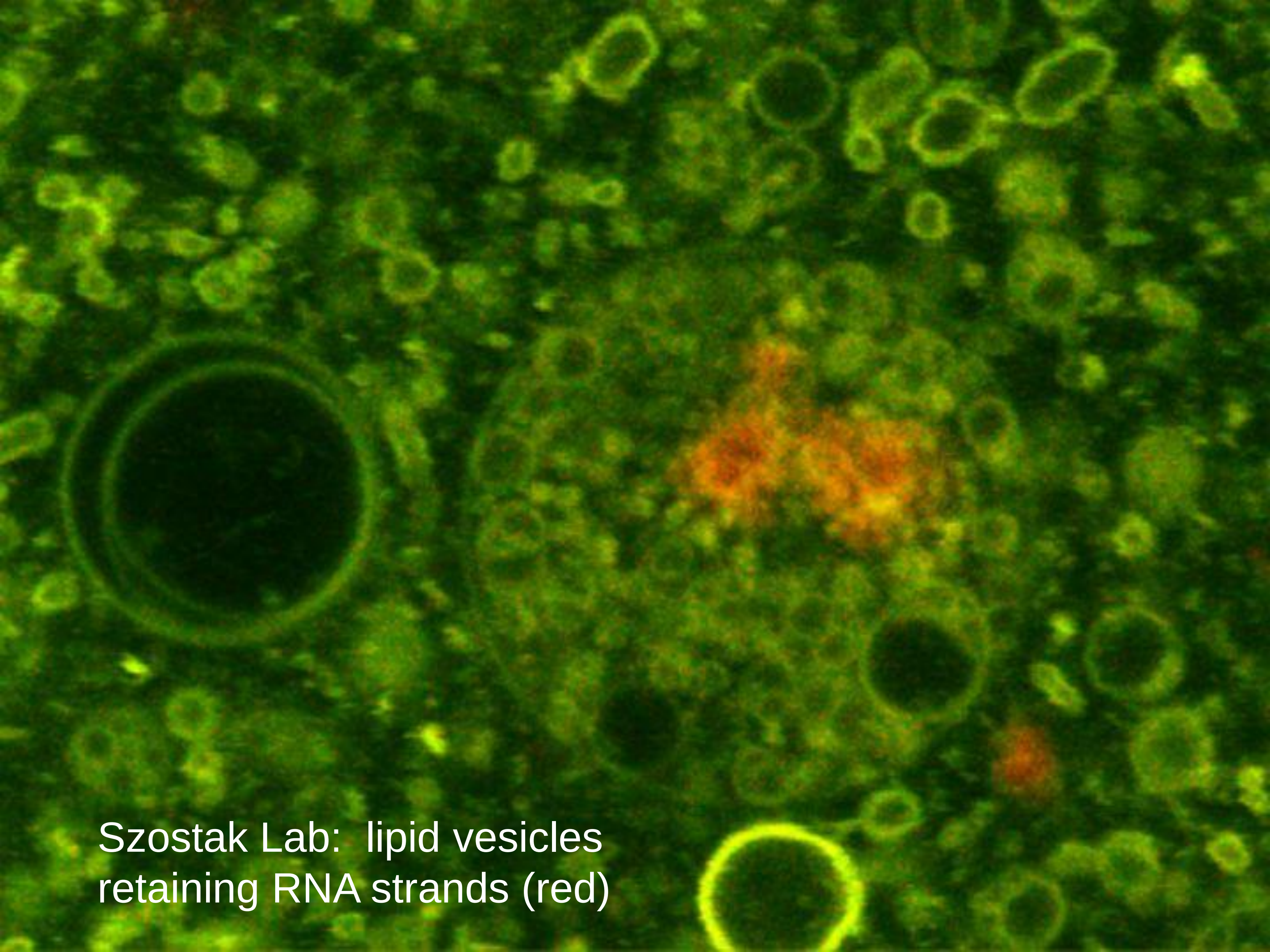
Forster & Church (2006)

‘Bottom-up’ Approach: Ribosome Assembly



Bold arrows: ribosome assembly & translation [Jewett & Church 2012]

Jewett & Forster (2010)


Szostak Lab: lipid vesicles
retaining RNA strands (red)

Summary

1. Is there life on other planets?
   – remote sensing of gases on Exo-Earths is upon us;
   – the value of the astrophysics perspective

2. Need to understand and classify solid exoplanets:

   a) Geophysics & connection to planet formation;
   b) Geochemistry & geo-cycles

3. Next step – the synergy with biochemistry is essential

4. Chemical Synthetic Biology – new transformative tools.