Do Pale Blue Dots have unique atmospheric disequilibrium and photometric color?

Joshua Krissansen-Totton and David Catling

Department of Earth and Space Sciences / Astrobiology Program

University of Washington

Outline

Part 1: On detecting biospheres from thermodynamic disequilibrium in planetary atmospheres

Joshua Krissansen-Totton, David Bergsman, David Catling, submitted to *Astrobiology*
http://arxiv.org/abs/1503.08249

Part 2: Can color be used to identify Earth-like exoplanets?

Joshua Krissansen-Totton, Eddie Schwieterman, Benjamin Charnay, Ty Robinson, Giada Arney, Victoria Meadows, David Catling, *in prep*.

PART 1: Basic question:

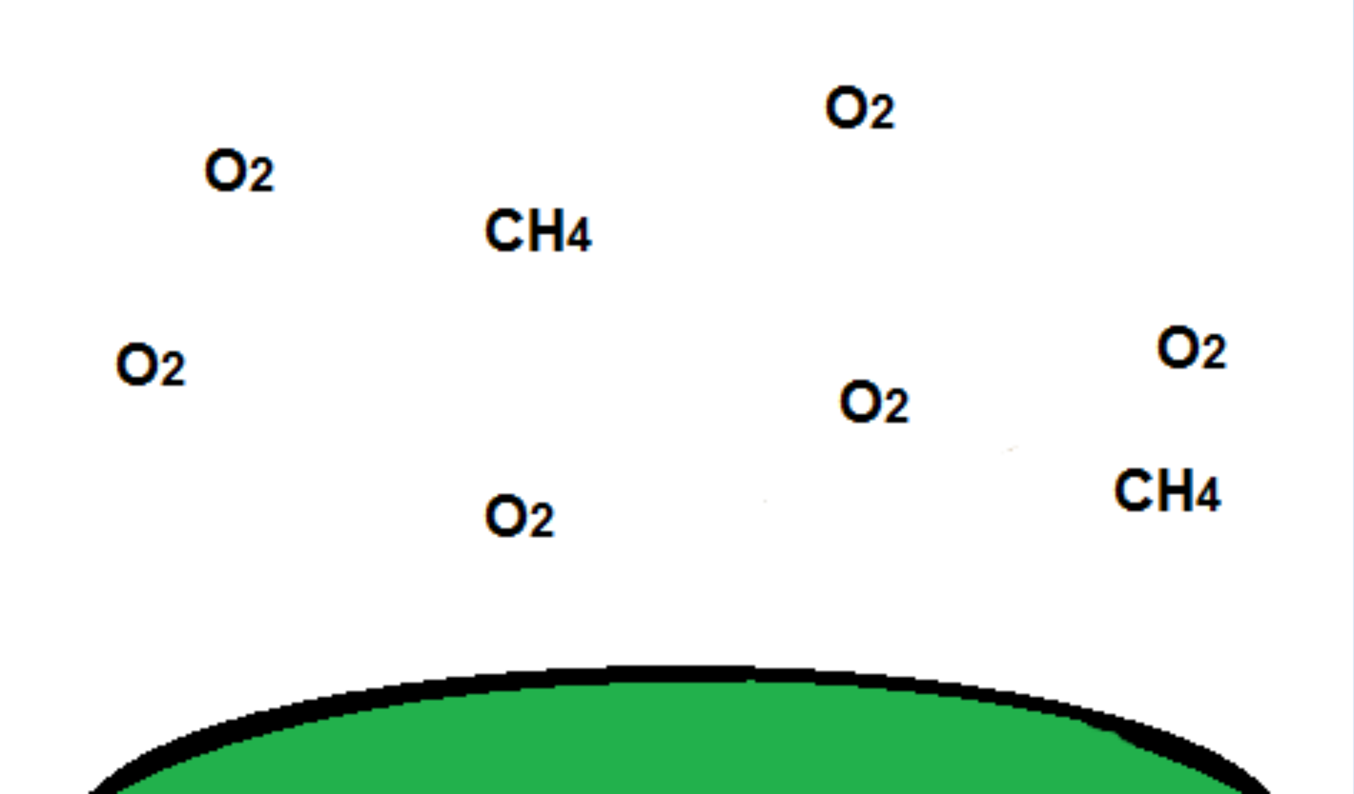
Given remote sensing data, what algorithm(s) could detect life?

Chemical disequilibrium as a sign of life?

James Lovelock (1965), Joshua Lederberg (1965) *Nature*

- "*Kinetic instability in the context of local chemical and physical conditions…*" *Lederberg*

- "*Search for…compounds in the planet's atmosphere that are incompatible on a long-term basis*" *Lovelock*



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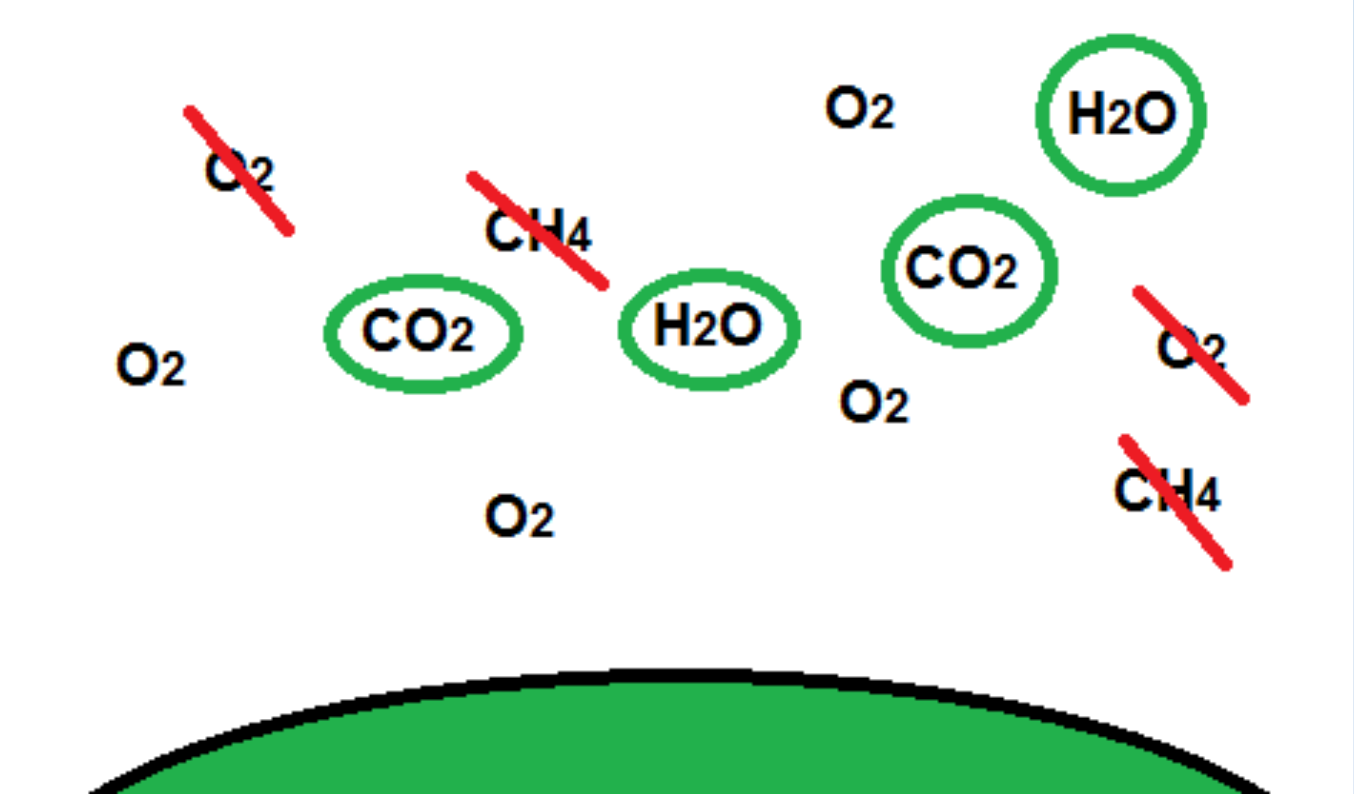

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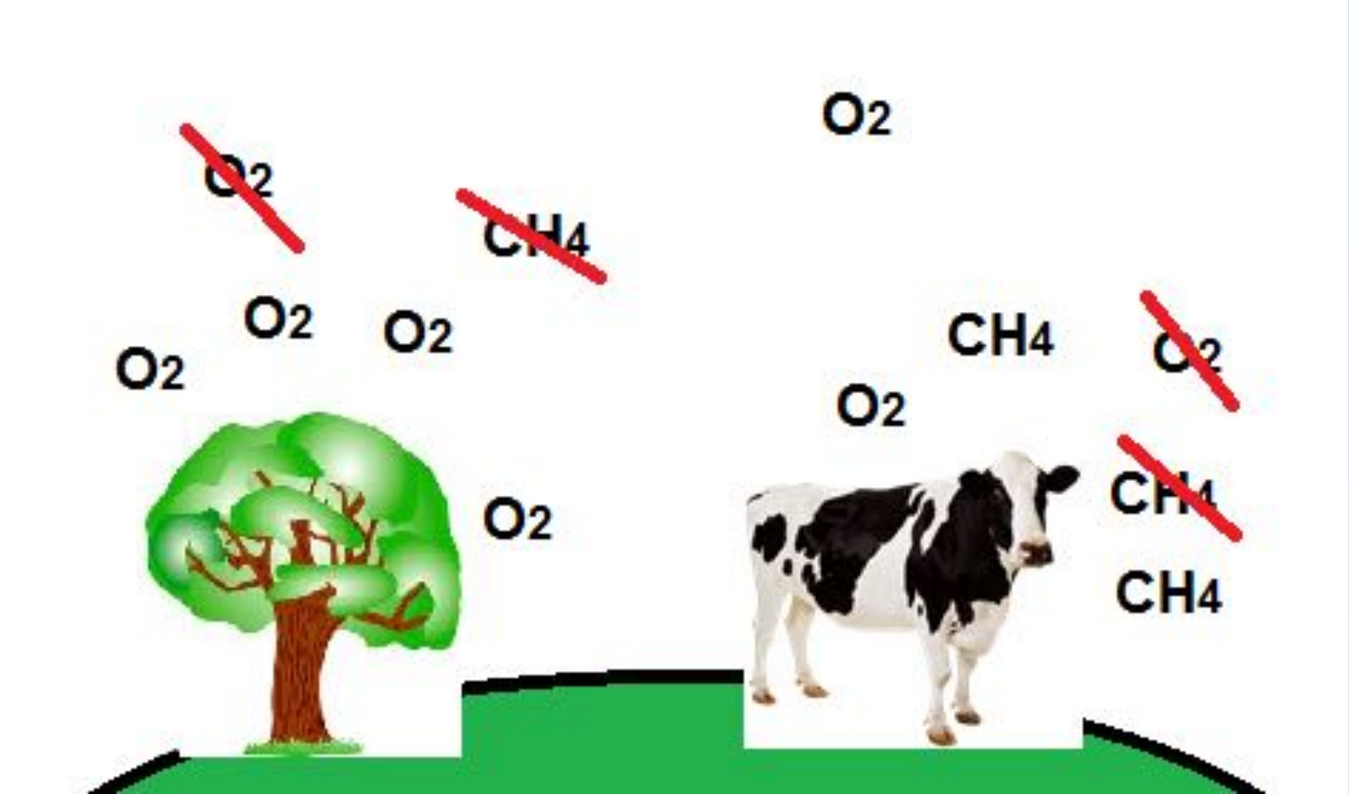
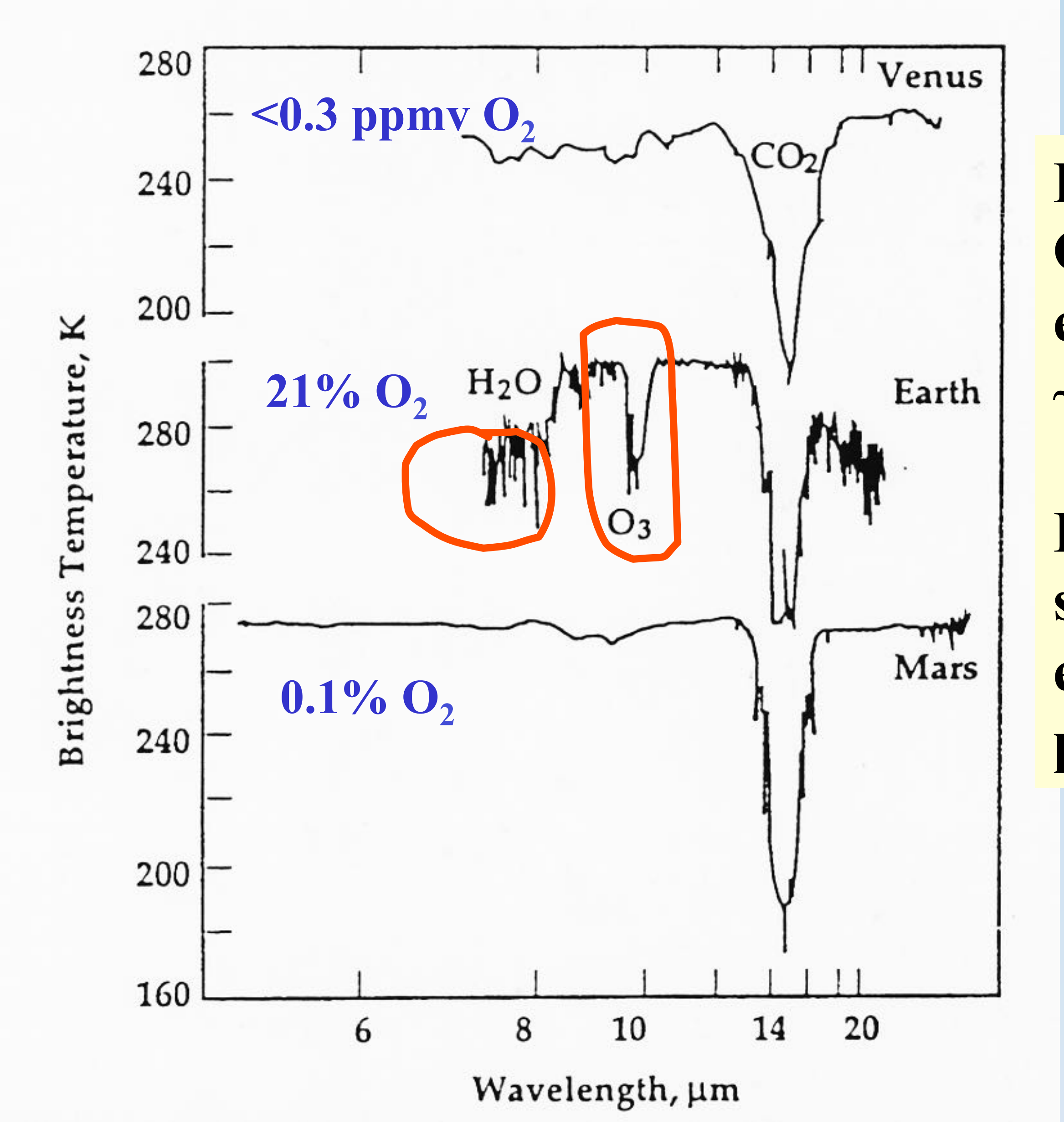


Modern incarnation: Biogenic gases in spectra



If photosynthesis ceased, O_2 decreases exponentially to <0.4% in ~10 m.y.

Proposed telescopes to search Earth-like exoplanets for O_2 and perhaps CH_4

Disequilibrium applies to waste biogenic gases, but it's nuanced:

1) ALL planetary atmospheres are in disequilibrium

- Geophysics competes with biology. How much?

2) Life feeds on disequilibrium so sometimes disequilibrium might mean "no one home" i.e.,

uneaten free food=> ~~no grad students~~

no life

Atmospheric disequilibrium as a biosignature on exoplanets?

DETECTING LIFE-BEARING EXTRASOLAR PLANETS WITH SPACE TELESCOPES

Steven V. W. Beckwith[1,2,3]
University of California, 1111 Franklin Street, Oakland, CA 94607-5200; steven.beckwith@ucop.edu
Received 2007 October 7; accepted 2008 May 27

ABSTRACT

One of the promising methods to search for life on extrasolar planets (exoplanets) is to detect its signature in the chemical disequilibrium of exoplanet atmospheres. Spectra at the modest resolutions needed to search for methane, oxygen, carbon dioxide, or water will demand large collecting areas and large diameters to capture and isolate the light from planets in the habitable zones around the stars. Single telescopes with coronagraphs to isolate the light from

Remote Sensing of Planetary Properties and Biosignatures on Extrasolar Terrestrial Planets

ASTROBIOLOGY
Volume 2, Number 2, 2002

DAVID J. DES MARAIS,[1] MARTIN O. HARWIT,[2] KENNETH W. JUCKS,[3] JAMES F. KASTING,[4] DOUGLAS N.C. LIN,[5] JONATHAN I. LUNINE,[6] JEAN SCHNEIDER,[7] SARA SEAGER,[8] WESLEY A. TRAUB,[3] and NEVILLE J. WOOLF[6]

tures (e.g., complex organic molecules and cells). Life may be indicated by chemical disequilibria that cannot be explained solely by nonbiological processes. For example, a geologically active planet that exhales reduced volcanic gases can maintain detectable levels of atmospheric oxygen

Quantifying drivers of chemical disequilibrium: theory and application to methane in the Earth's atmosphere

E. Simoncini[1,2], N. Virgo[1], and A. Kleidon[1]
[1]Max-Planck-Institute for Biogeochemistry, Hans-Knöll-Str. 10, 07745 Jena, Germany
[2]INAF, Astrophysical Observatory of Arcetri, 50124, Arcetri, Firenze, Italy
Correspondence to: E. Simoncini (simoncin@arcetri.astro.it)

Received: 29 October 2012 – Published in Earth Syst. Dynam. Discuss.: 23 November 2012
Revised: 6 June 2013 – Accepted: 25 July 2013 – Published: 11 September 2013

1965; Lippincott et al., 1966; Lovelock and Margulis, 1973; Sagan et al., 1993; Lenton, 1998). Disequilibrium by itself is not an unequivocal indicator of life, since it can also be caused by abiotic processes such as photochemistry or geothermally driven surface chemistry. In particular, photochemistry can produce substantial amounts of O_2 and O_3, as found in the Earth's stratosphere as well as on Venus

Some inconvenient truths about biosignatures involving two chemical species on Earth-like exoplanets

Hanno Rein[a,1], Yuka Fujii[b], and David S. Spiegel[c]
[a]Department of Environmental and Physical Sciences, University of Toronto, Toronto, ON, Canada M1C 1A4; [b]Earth-Life Science Institute, Tokyo Institute of Technology, Ookayama, Meguro, Tokyo 152-8550, Japan; and [c]Astrophysics Department, Institute for Advanced Study, Princeton, NJ 08540

Edited by Neta A. Bahcall, Princeton University, Princeton, NJ, and approved March 27, 2014 (received for review February 1, 2014)

The detection of strong thermochemical disequilibrium in the atmosphere of an extrasolar planet is thought to be a potential biosignature. In this article we present a previously unidentified kind of false positive that can mimic a disequilibrium or any other biosignature that involves two chemical species. We consider a sce-

a planet's atmosphere should not be considered as clear evidence for life. [Also note that the Earth might have never had a phase of strong, observable O_2/CH_4 disequilibrium (19).] There is a long list of abiotic sources that could also create a disequilibrium such as impacts (20), photochemistry (21), and geochemistry (14).

Remote life-detection criteria, habitable zone boundaries, and the frequency of Earth-like planets around M and late K stars

James F. Kasting[1], Ravikumar Kopparapu, Ramses M. Ramirez, and Chester E. Harman

sphere, as either methanogens would consume it (10), or alternatively acetogens would use it to produce acetate (11). So, the criterion of extreme thermodynamic equilibrium as a biomarker is directly contradicted.

FINDING EXTRATERRESTRIAL LIFE USING GROUND-BASED HIGH-DISPERSION SPECTROSCOPY

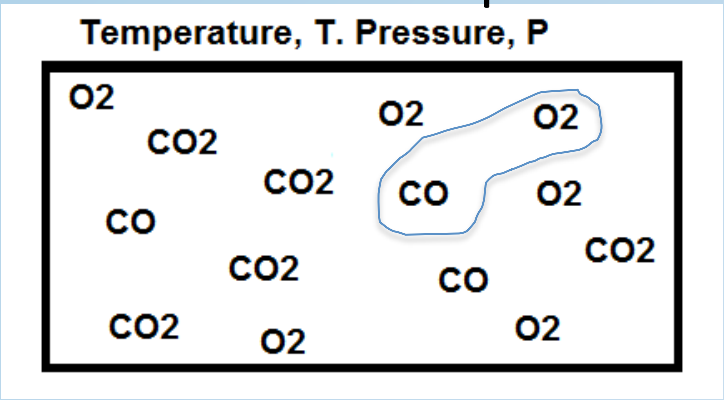
I. A. G. Snellen[1], R. J. de Kok[2], R. le Poole[1], M. Brogi[1], and J. Birkby[1]
[1] Leiden Observatory, Leiden University, Postbus 9513, 2300-RA Leiden, The Netherlands
[2] SRON, Sorbonnelaan 2, 3584-CA Utrecht, The Netherlands
Received 2012 October 8; accepted 2013 January 8; published 2013 February 5

ABSTRACT

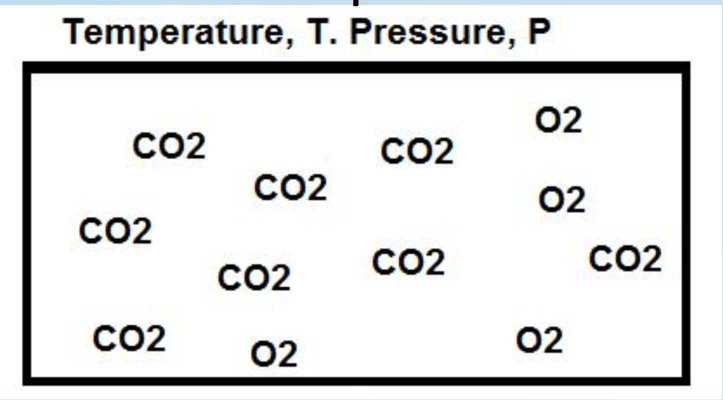
Exoplanet observations promise one day to unveil the presence of extraterrestrial life. Atmospheric compounds in strong chemical disequilibrium would point to large-scale biological activity just as oxygen and methane do in the Earth's atmosphere. The cancellation of both the *Terrestrial Planet Finder* and *Darwin* missions means that it is unlikely that a dedicated space telescope to search for biomarker gases in exoplanet atmospheres will be

Quantifying chemical disequilibrium

Observed atmosphere



Atmosphere if it were in chemical equilibrium



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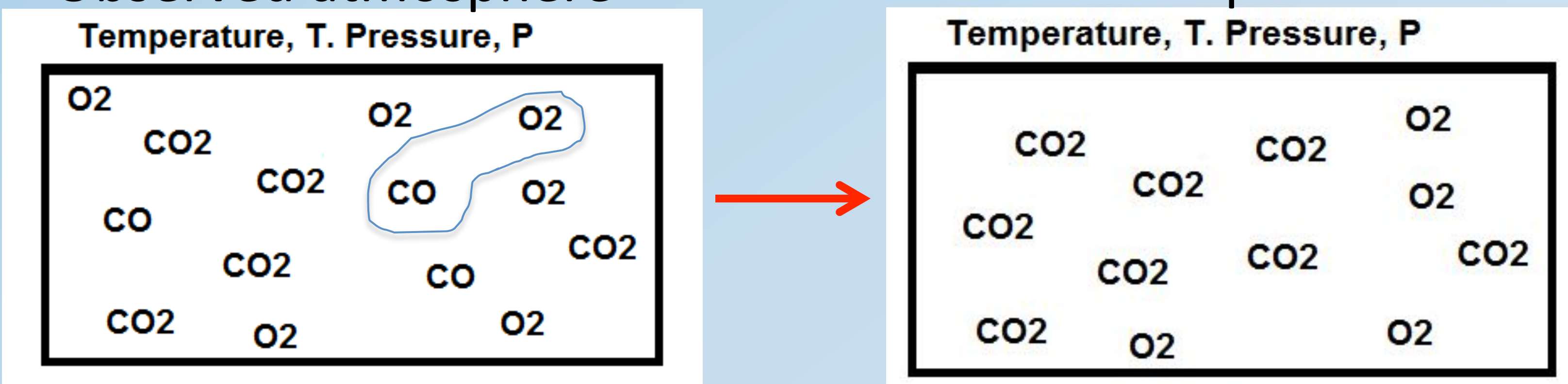


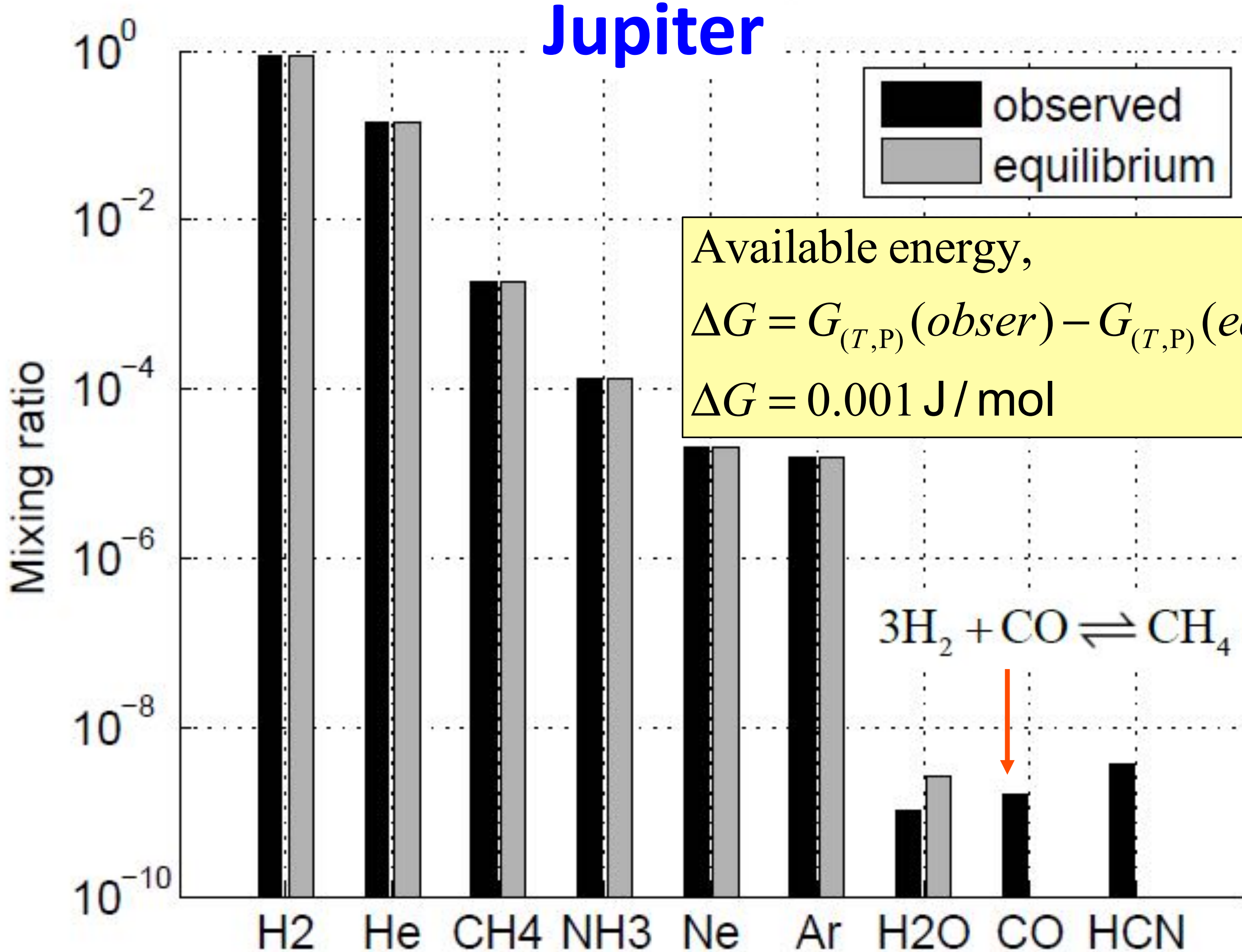
$$G_{(T,\mathrm{P})} = \sum_i n_i \left(G^{\circ}_{i\,(T,\mathrm{P}_r)} + RT\ln\left(\frac{P\gamma_i n_i}{n_{tot}}\right)\right)$$

We quantify disequilibrium as the change in Gibbs energy of the system during reaction to equilibrium:

$$\boxed{\text{Available energy, } \Delta G = G_{(T,\mathrm{P})}(observed) - G_{(T,\mathrm{P})}(equilibrium)}$$

Applied to Solar System atmospheres….

Jupiter



Available energy,

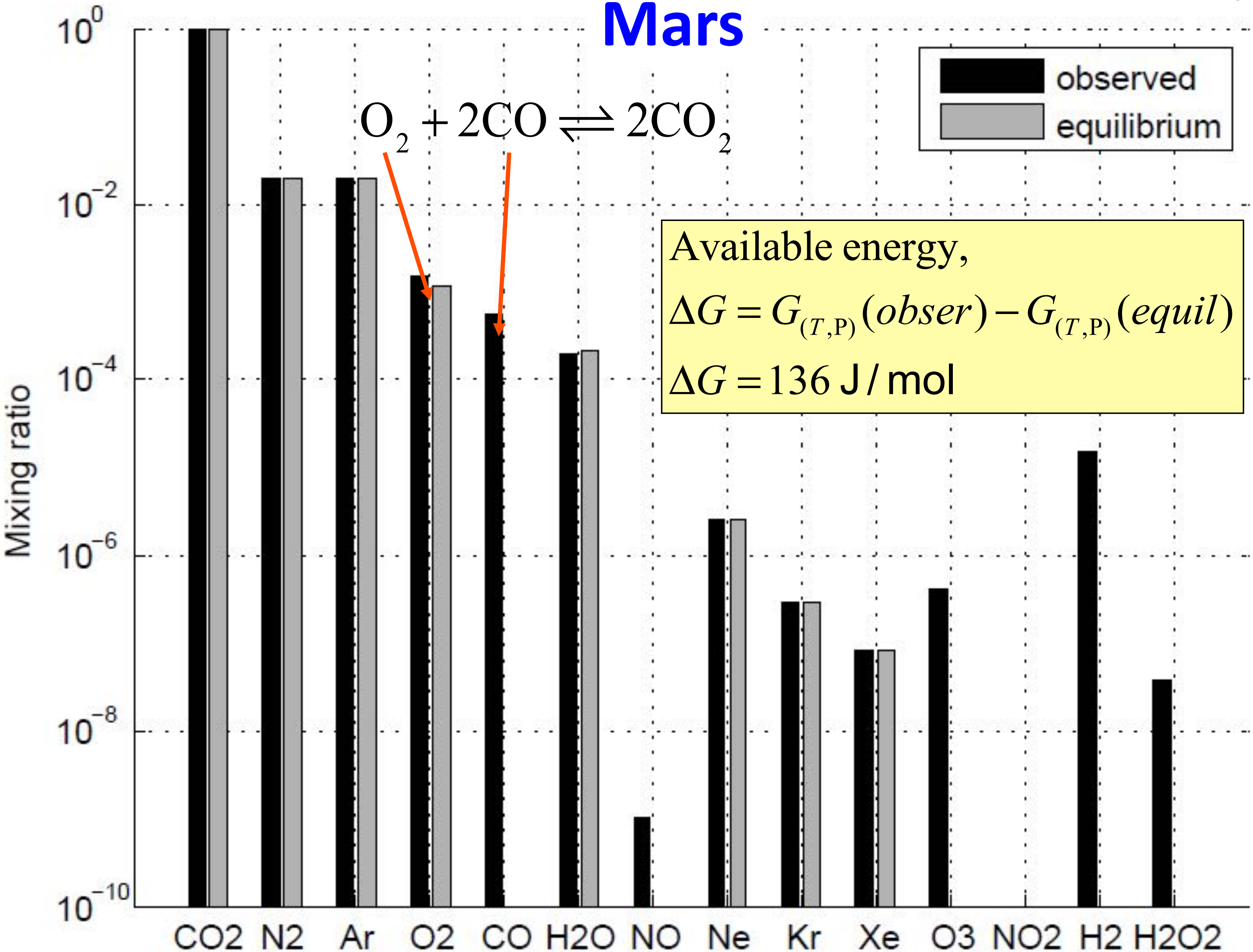
$$\Delta G = G_{(T,\mathrm{P})}(obser) - G_{(T,\mathrm{P})}(equil)$$

$$\Delta G = 0.001\ \mathrm{J/mol}$$

$$3\mathrm{H_2} + \mathrm{CO} \rightleftharpoons \mathrm{CH_4} + \mathrm{H_2O}$$

$$3\mathrm{H_2(g)} + \mathrm{HCN(g)} \rightleftharpoons \mathrm{CH_4(g)} + \mathrm{NH_3(g)}$$

Mars

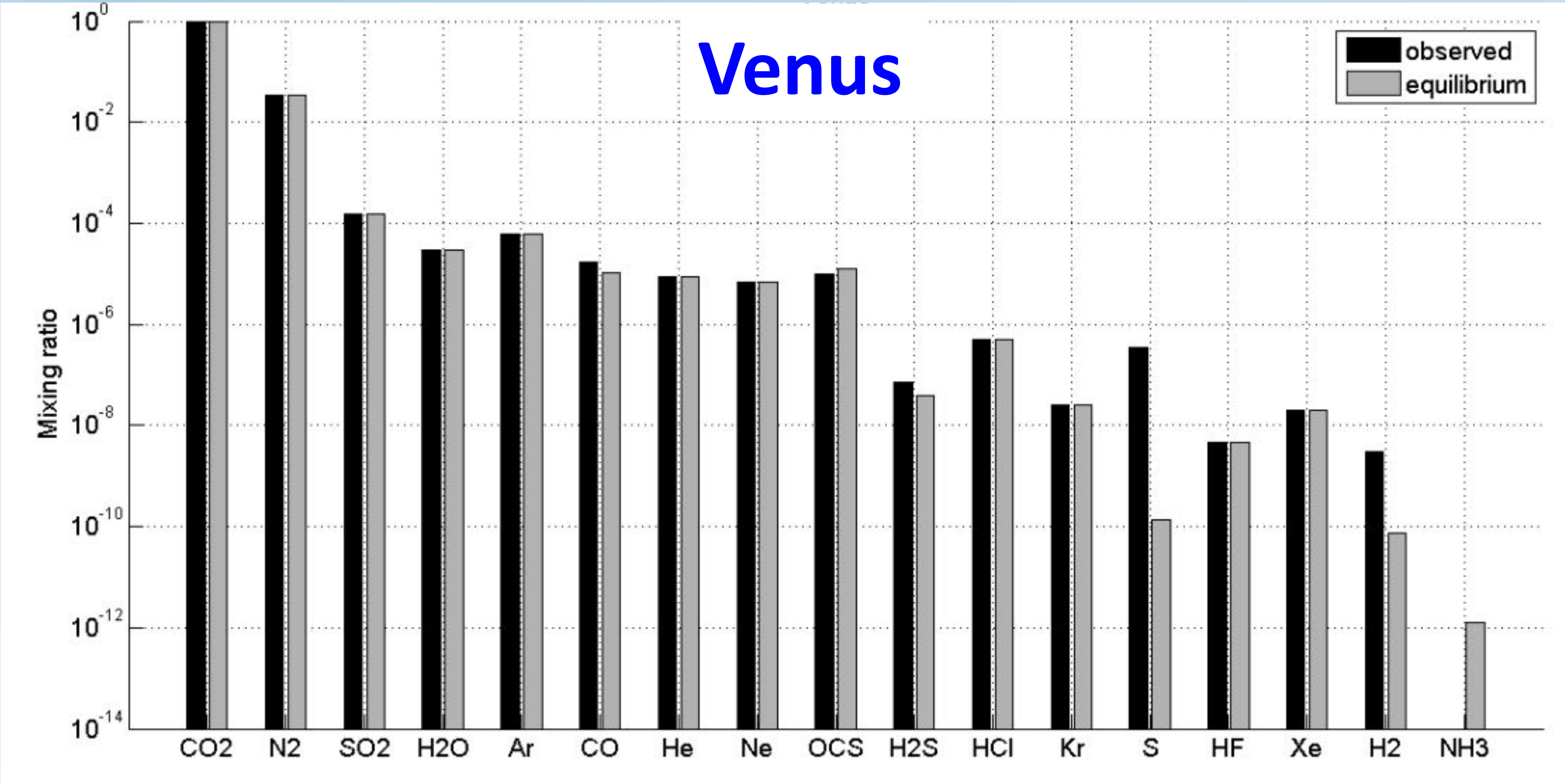


$$O_2 + 2CO \rightleftharpoons 2CO_2$$

Available energy,

$$\Delta G = G_{(T,\mathrm{P})}(obser) - G_{(T,\mathrm{P})}(equil)$$

$$\Delta G = 136\ \mathrm{J/mol}$$



Available energy,

$$\Delta G = G_{(T,\mathrm{P})}(obser) - G_{(T,\mathrm{P})}(equil)$$

$$\Delta G = 0.06 \text{ J/mol}$$

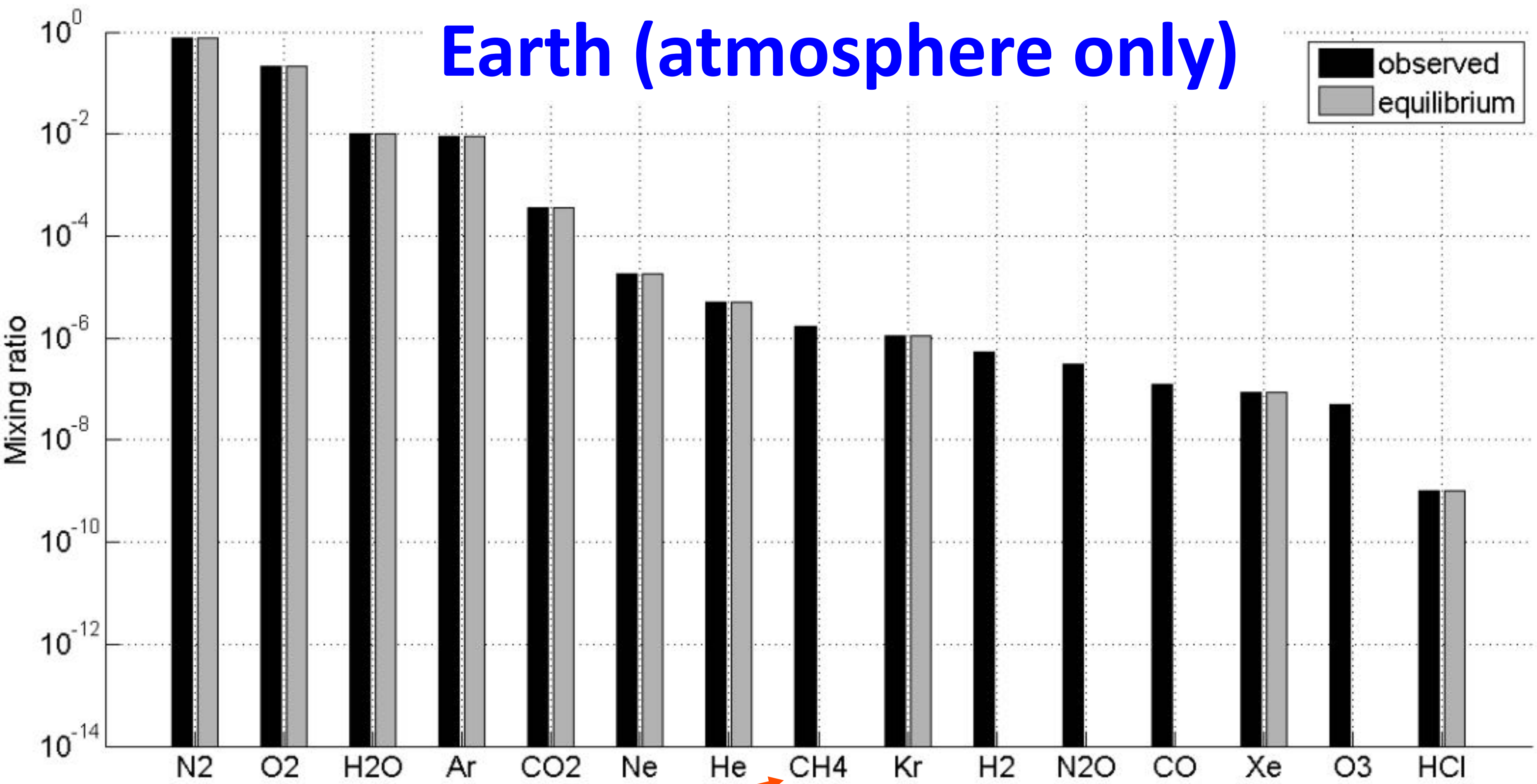
$$H_2S + CO_2 \rightleftharpoons H_2O + OCS$$

$$3CO + SO_2 \rightleftharpoons 2CO_2 + OCS$$

$$2CO_2 + S \rightleftharpoons SO_2 + 2CO$$

$$H_2 + S \rightleftharpoons H_2S$$

Earth (atmosphere only)



$$2O_2 + CH_4 \rightleftharpoons CO_2 + 2H_2O$$

Available energy,

$$\Delta G = G_{(T,\mathrm{P})}(obser) - G_{(T,\mathrm{P})}(equil)$$

$$\Delta G = 1.5\ \mathrm{J/mol}$$

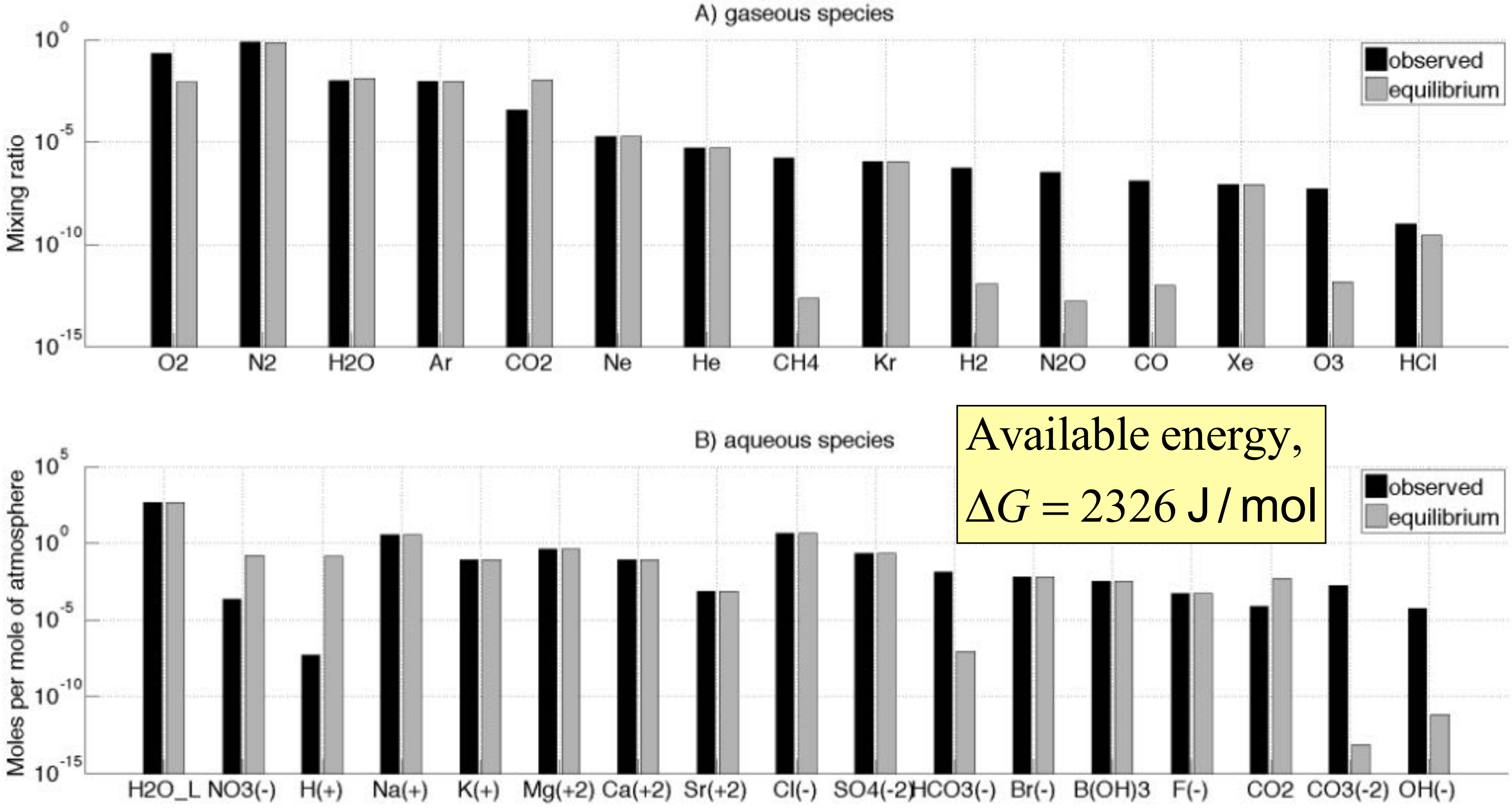
Typical surface of Mars

Typical surface of planet Earth

(2012: 13°S, mid-Atlantic, 3.8 km depth of water)

Photo credit: David Catling

Earth (atmosphere-ocean fluid envelope)



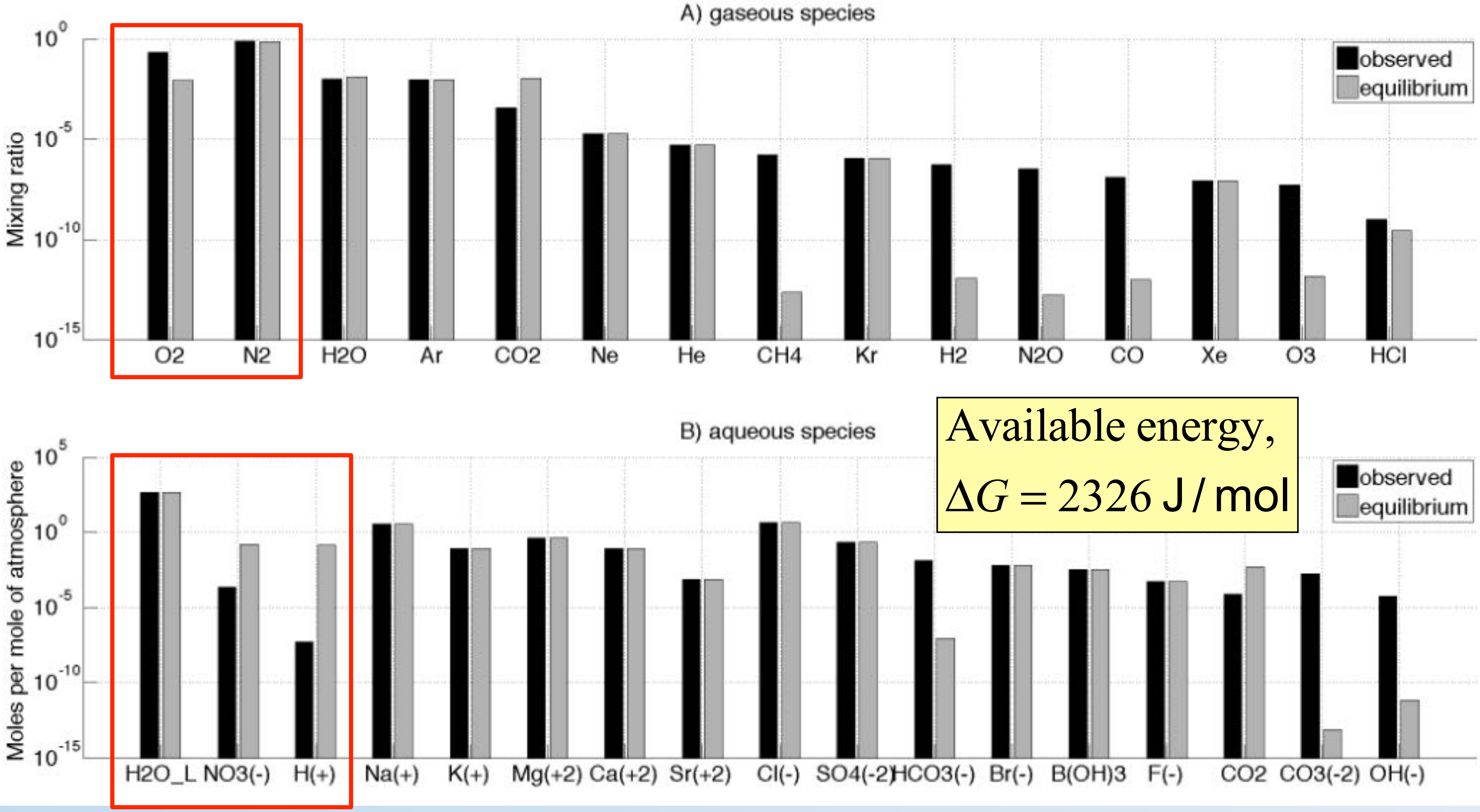
Available energy,

$\Delta G = 2326\ \mathrm{J/mol}$

$$2N_2(g) + 5O_2(g) + 2H_2O(l) \rightleftharpoons 4H^+(aq) + 4NO_3^-(aq)$$

Gilbert Lewis (1923): “starting with air and water…nitric acid should form. It is to be hoped that nature will not discover a catalyst for this reaction, which would… turn the oceans into dilute nitric acid”.

Earth (atmosphere-ocean fluid envelope)



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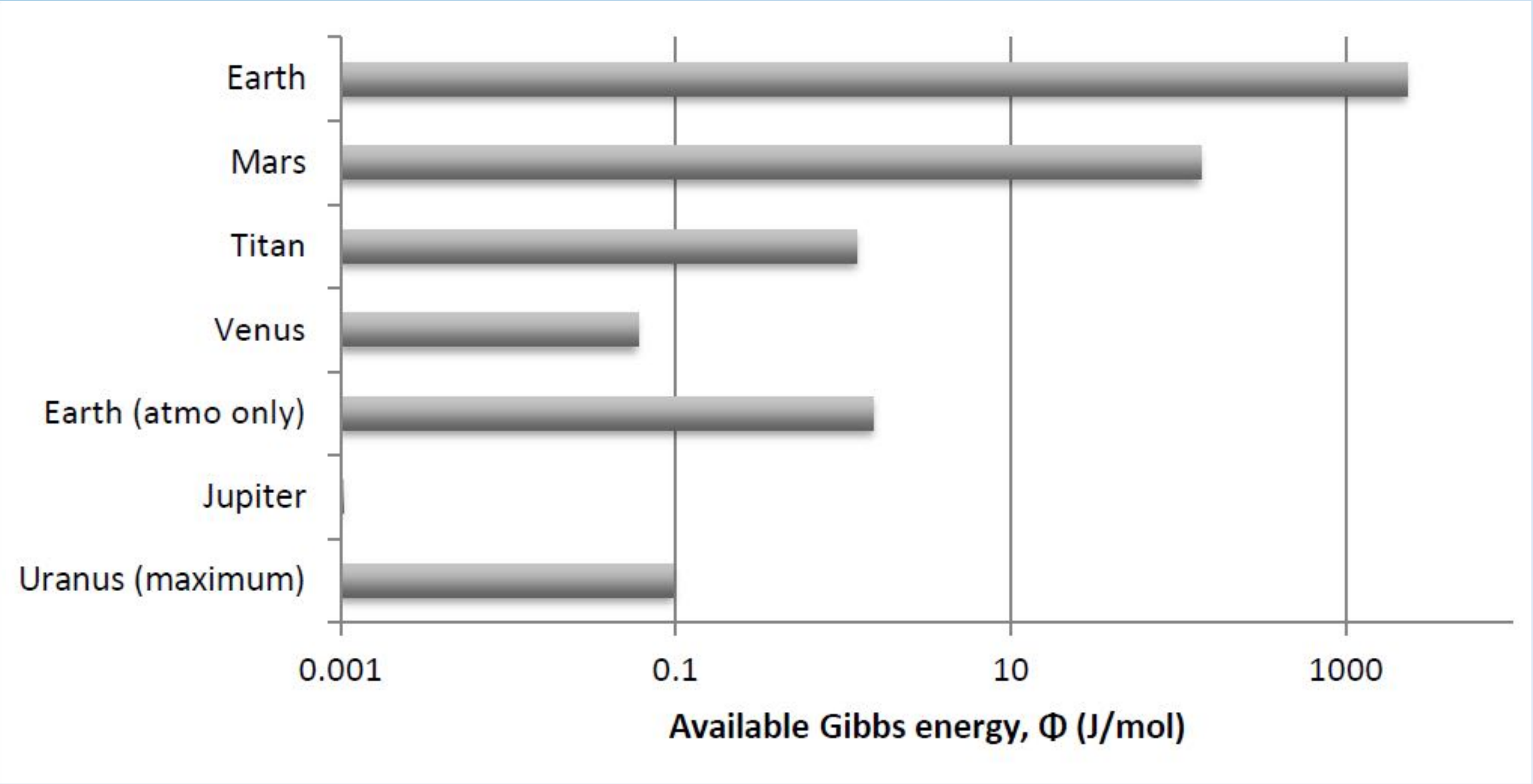
Earth has largest disequilibrium in the solar system



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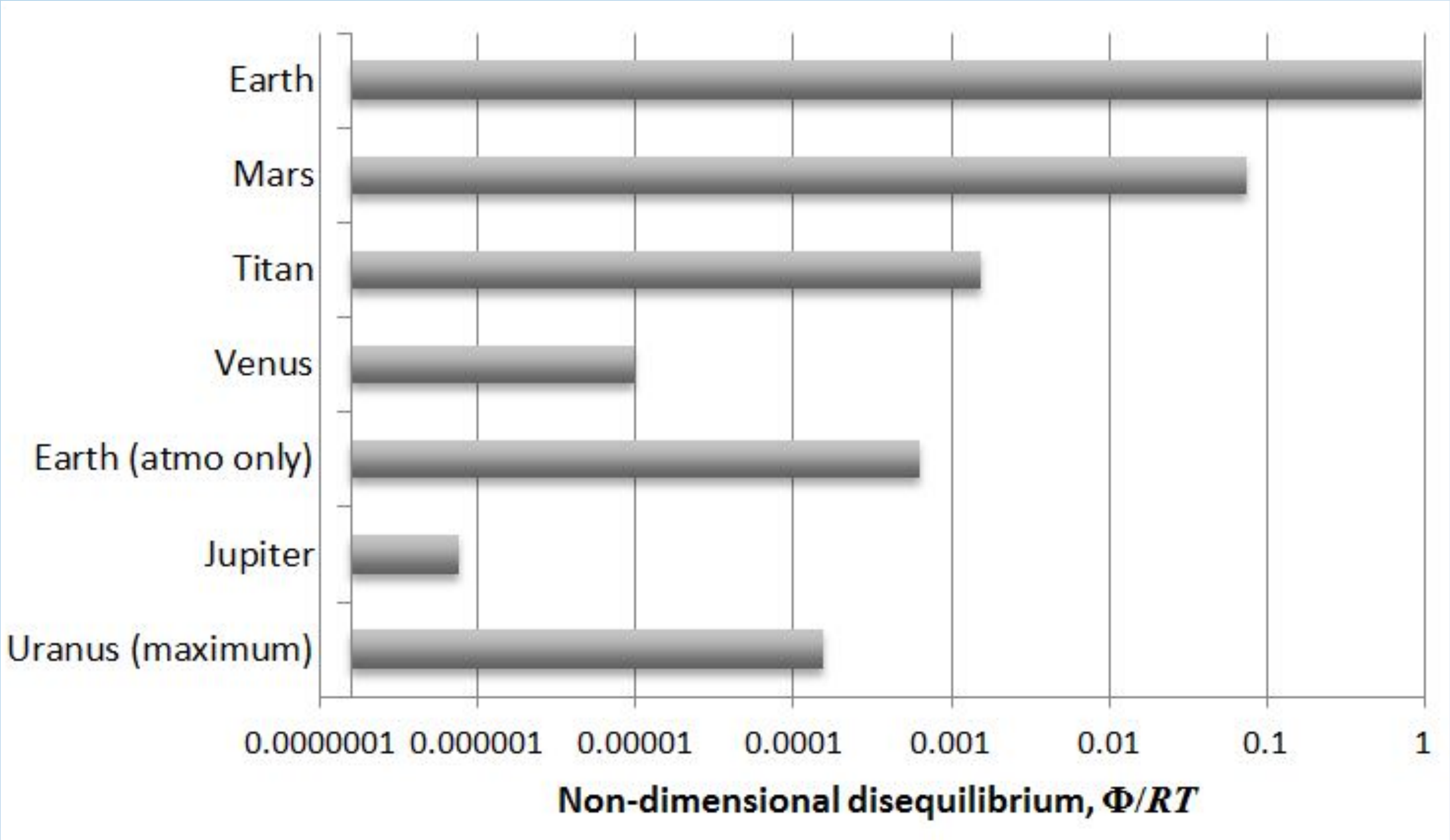

Only on Earth is available energy ≈ thermal energy of air

Is this practical for exoplanets?

- For exoplanets, **thermodynamic disequilibrium** could be computed directly from observations without any assumptions about gas fluxes.

- Bulk abundance, oceans, and total pressure are observational challenges, but have been considered by the Virtual Planetary Lab:
    - N_2 from N_2-N_2 dimer absorption, 4.3 μm (Schwieterman et al., 2015).
    - Ocean presence from glint + spectra (e.g., Robinson et al., 2010; 2014).
    - Pressure from O_2-O_2 dimer, 1.06 & 1.27 μm (Misra et al., 2014).

- Sensitivity tests to difficult-to-observe variables in the calculation show **relative insensitivity**

Sensitivity test

		Available energy, Φ (J/mol)
Temperature	T= 273.15 K	1634.78
	T= 288.15 K	2325.76
	T= 298.15 K	2824.48

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Pressure	0.1 bar	1354.20
	1.013 bar	2325.76
	10 bar	3891.96
	1000 bar	6878.35

Sensitivity test

Part 1

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	4	2314.26
	6	2325.71
	8.187 (Earth)	2325.76
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Salinity	0 mol/kg	2290.01
	1.1 mol/kg	2325.76
	11.1 mol/kg	2276.40

Sensitivity test

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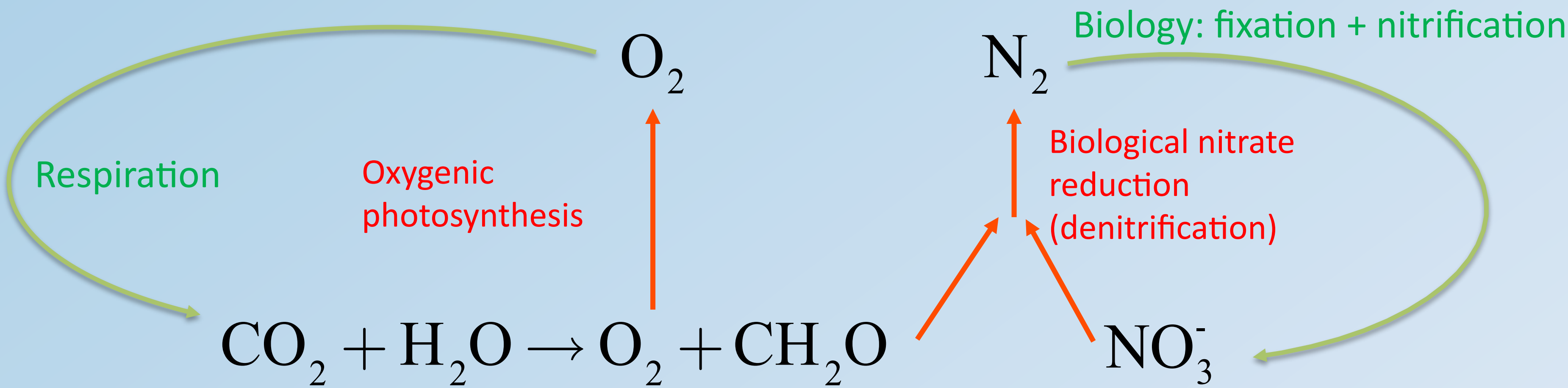
Salinity	0 mol/kg	2290.01
	1.1 mol/kg	2325.76
	11.1 mol/kg	2276.40
Ocean volume	0.1 Earth ocean	413.62
	0.5 Earth ocean	1442.95
	1 Earth ocean	2325.76
	2 Earth oceans	4188.27
	10 Earth oceans	8956.34
	50 Earth oceans	12626.22

See extra slides

What does disequilibrium mean?

- Sometimes thermodynamic disequilibrium means life.



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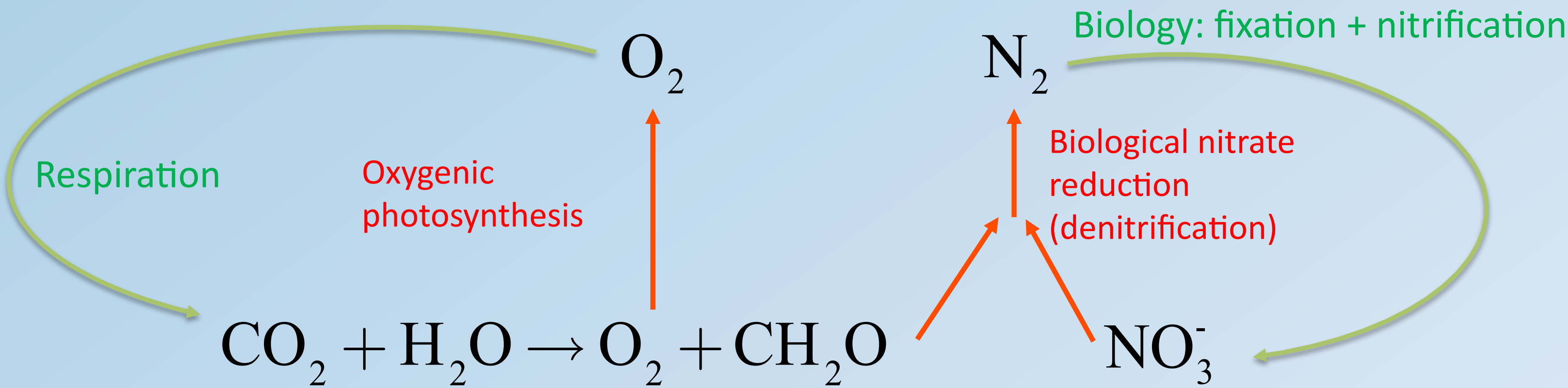
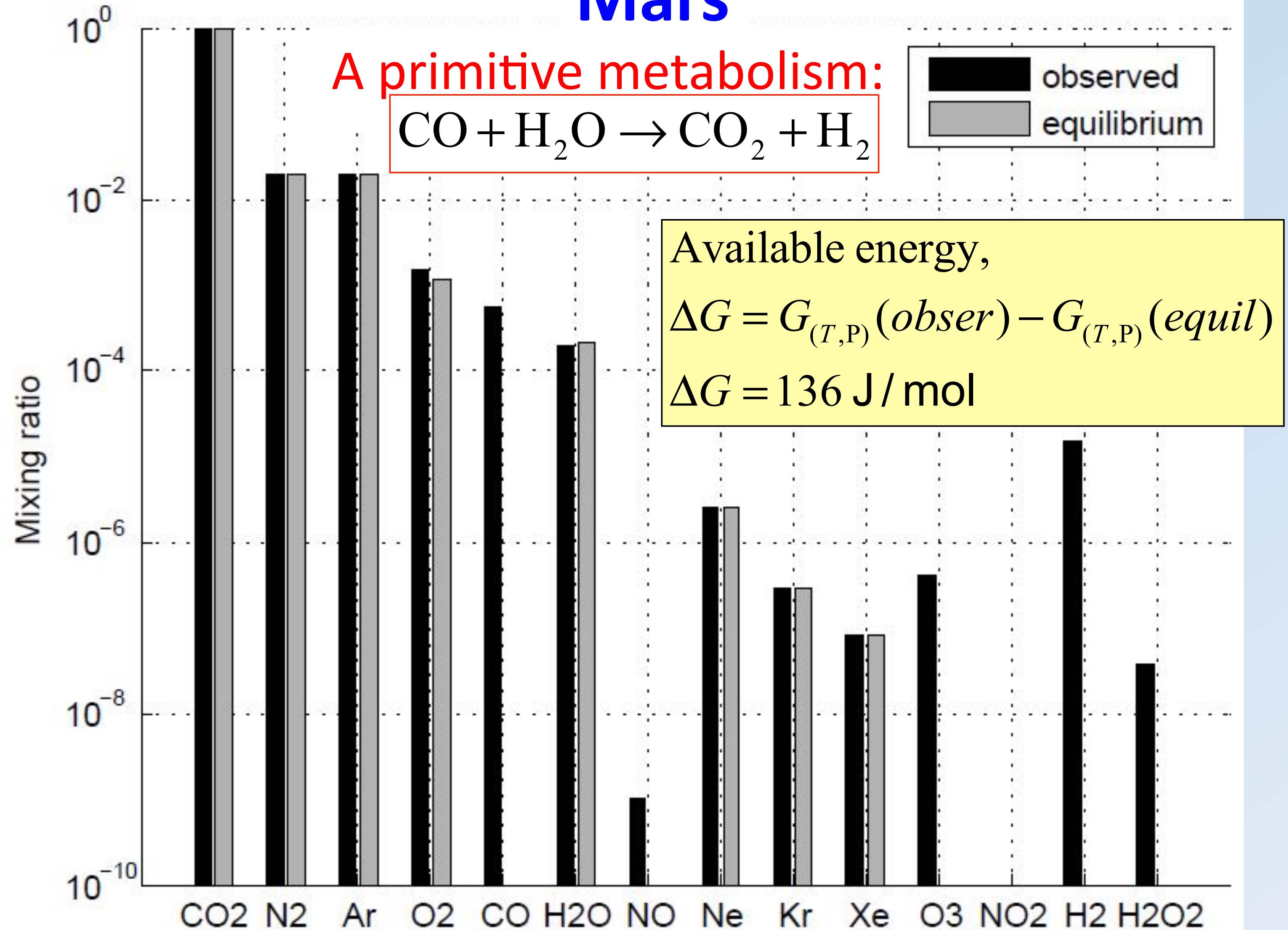


- Sometimes thermodynamic disequilibrium means the absence of life (**antibiosignature**). Large available energy = an "uneaten free lunch" -> no life exists.

Mars



Overabundant CO suggests no life today on the surface of Mars.
(Weiss et al. 2000; Zahnle et al. 2011)

What does disequilibrium mean?

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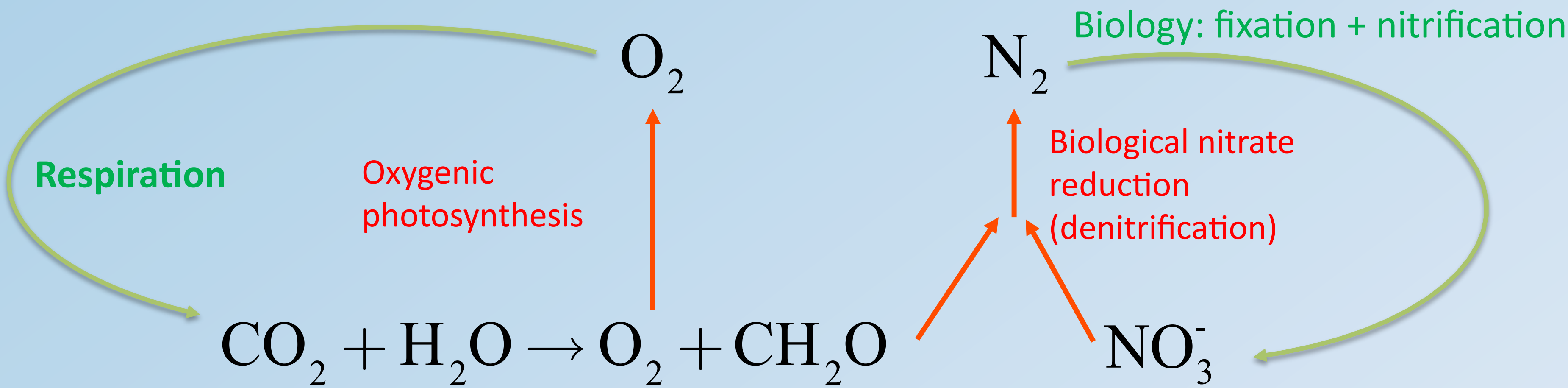


- Sometimes thermodynamic disequilibrium means the absence of life (**antibiosignature**). Large available energy = an "uneaten free lunch" -> no life exists.

- Conclusion: a single number metric like available energy has to be considered judiciously – **in context**.

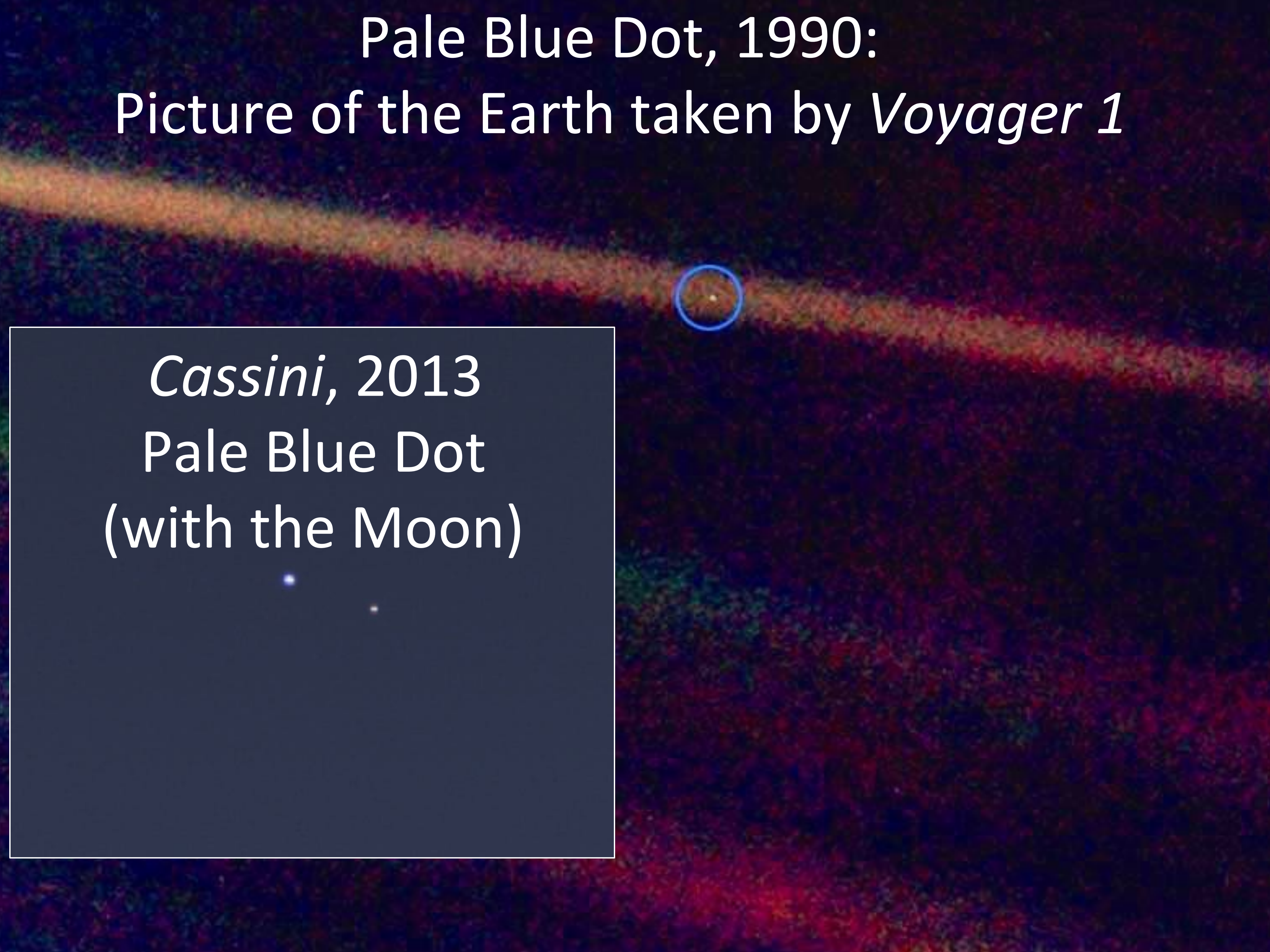
Part 1: Conclusions

- Earth has the largest disequilibrium in the Solar System, which is biogenic.

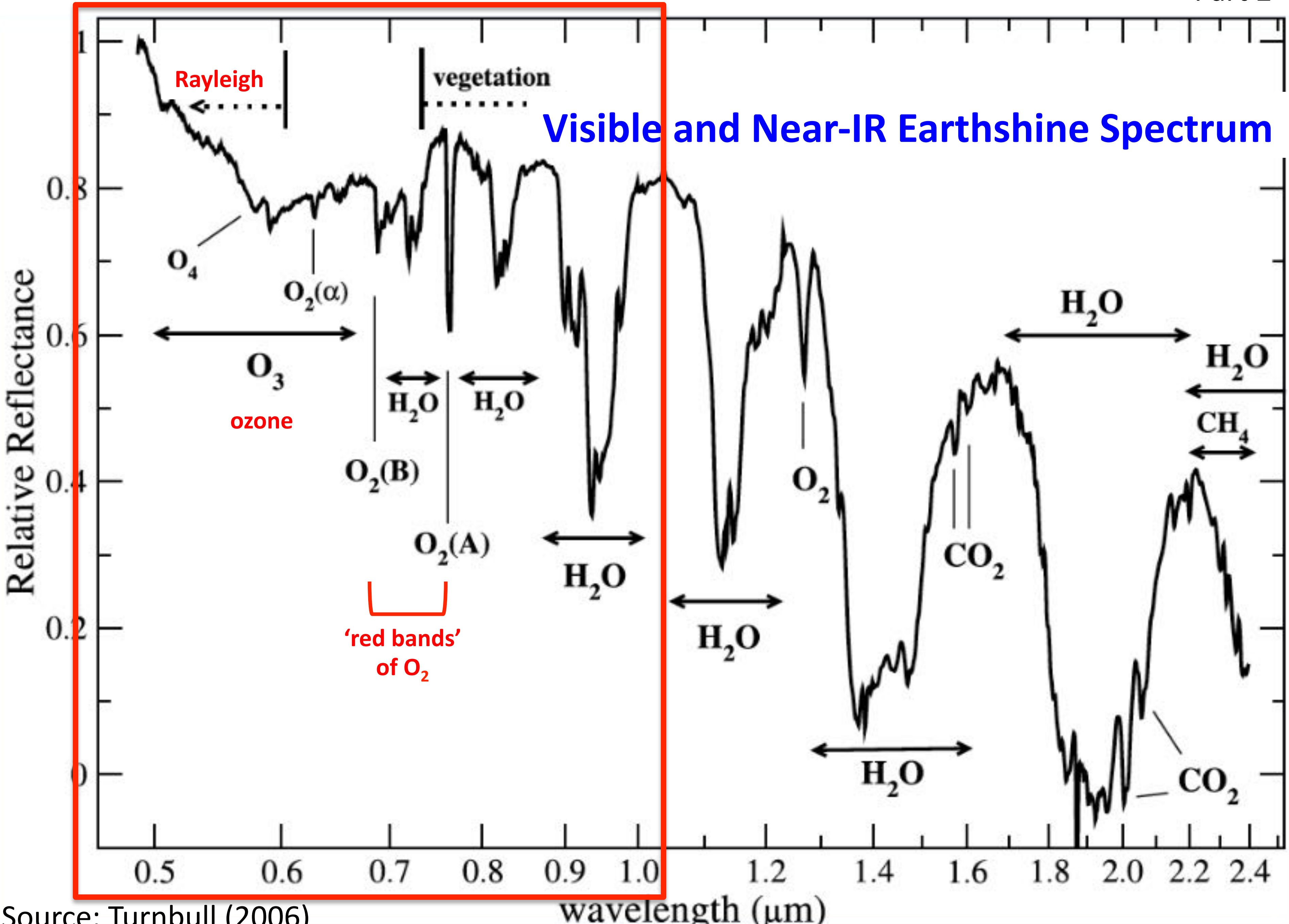
- The other Solar System planets have smaller disequilibria maintained by abiotic processes.

- For exoplanets, thermodynamic disequilibrium could be computed directly from observations without any assumptions about gas fluxes.

Part 2: Can color be used to identify Earth-like exoplanets?


Pale Blue Dot, 1990:
Picture of the Earth taken by *Voyager 1*
Cassini, 2013
Pale Blue Dot
(with the Moon)

Visible and Near-IR Earthshine Spectrum

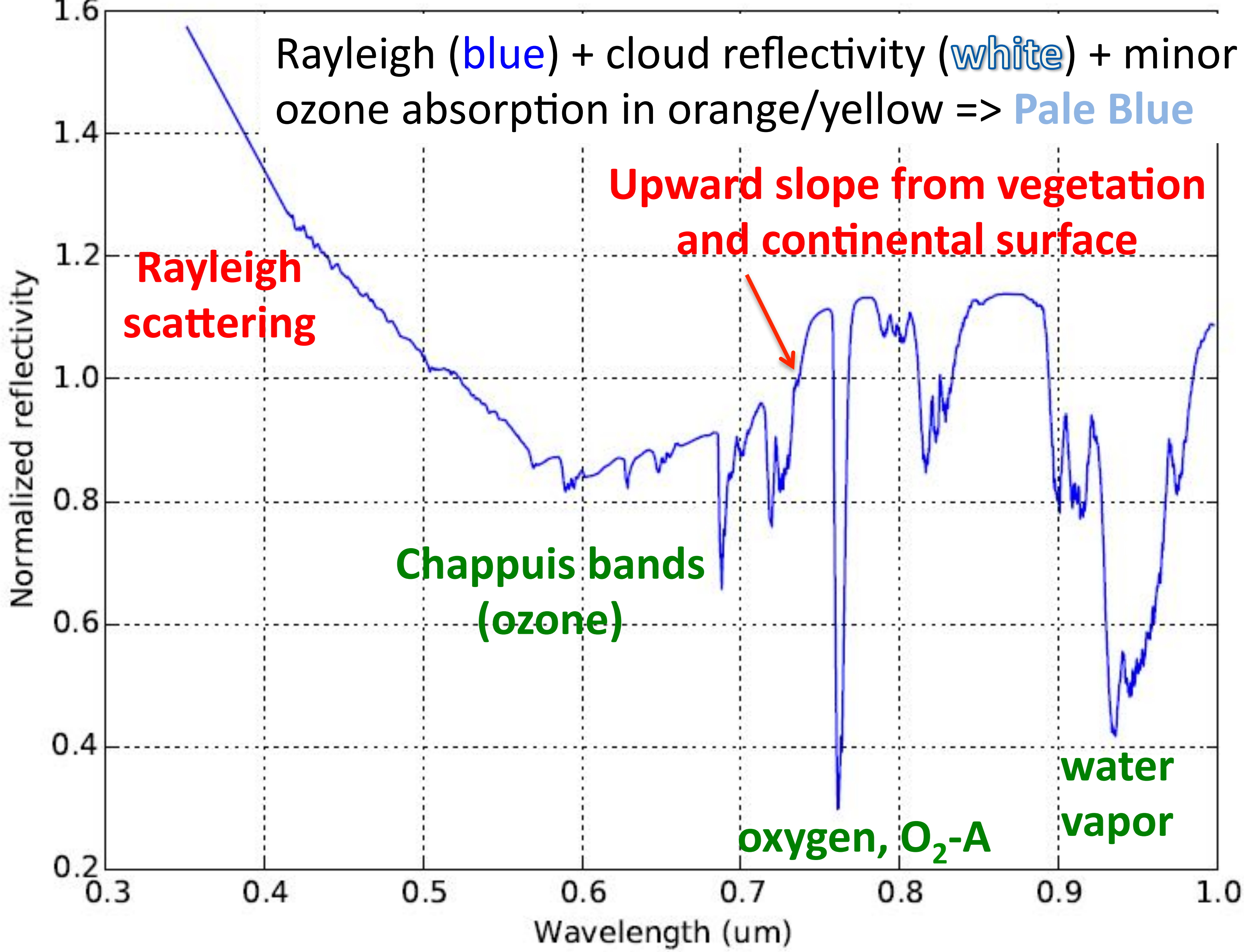


Source: Turnbull (2006)

Why is Earth a Pale Blue Dot?

Part 2

Rayleigh (blue) + cloud reflectivity (white) + minor ozone absorption in orange/yellow => Pale Blue



Is the "Pale Blue Dot" biogenic? Yes.

Where our project began: biogenic atmospheric chemistry and habitability:

1) **An O_2-rich atmosphere makes ozone (O_3)**

2) **An O_2-rich atmosphere (and rainfall) ensures a clear atmosphere**

O_3 absorption <340 nm generates excited oxygen, $O(^1D)$

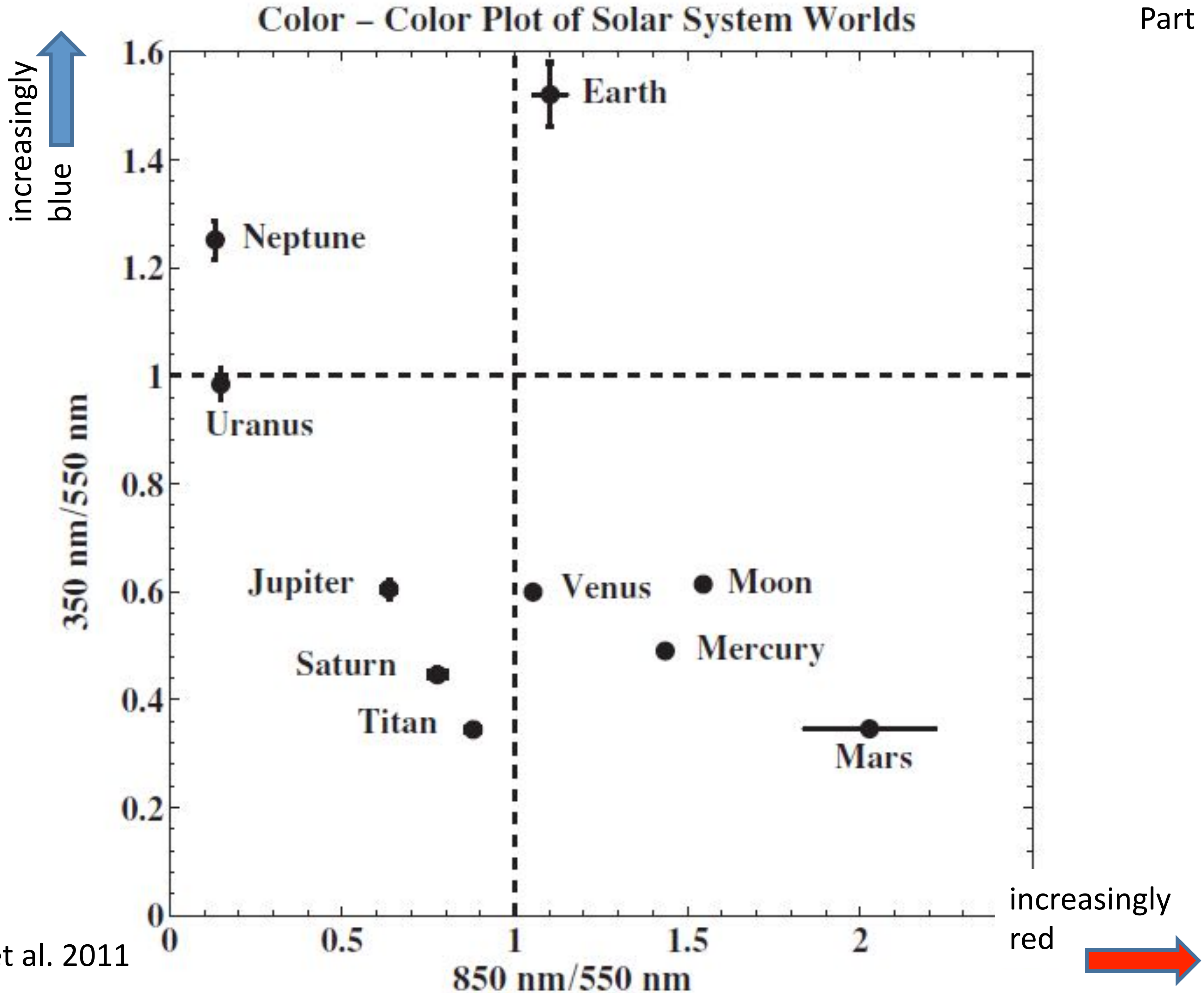
$$H_2O + O(^1D) \rightarrow OH + OH$$

Oxidizes H_2S, OCS, DMS to sulfate (NH_3 to NH_3-sulfate in troposphere) which rain out
Oxidizes CO, CH_4 and other hydrocarbons to CO_2 and H_2O
Result: air mostly transparent but Rayleigh scattering in near-UV, visible

Without high OH, you get organic haze
e.g., Archean Earth: CH_4 and associated hydrocarbons + haze

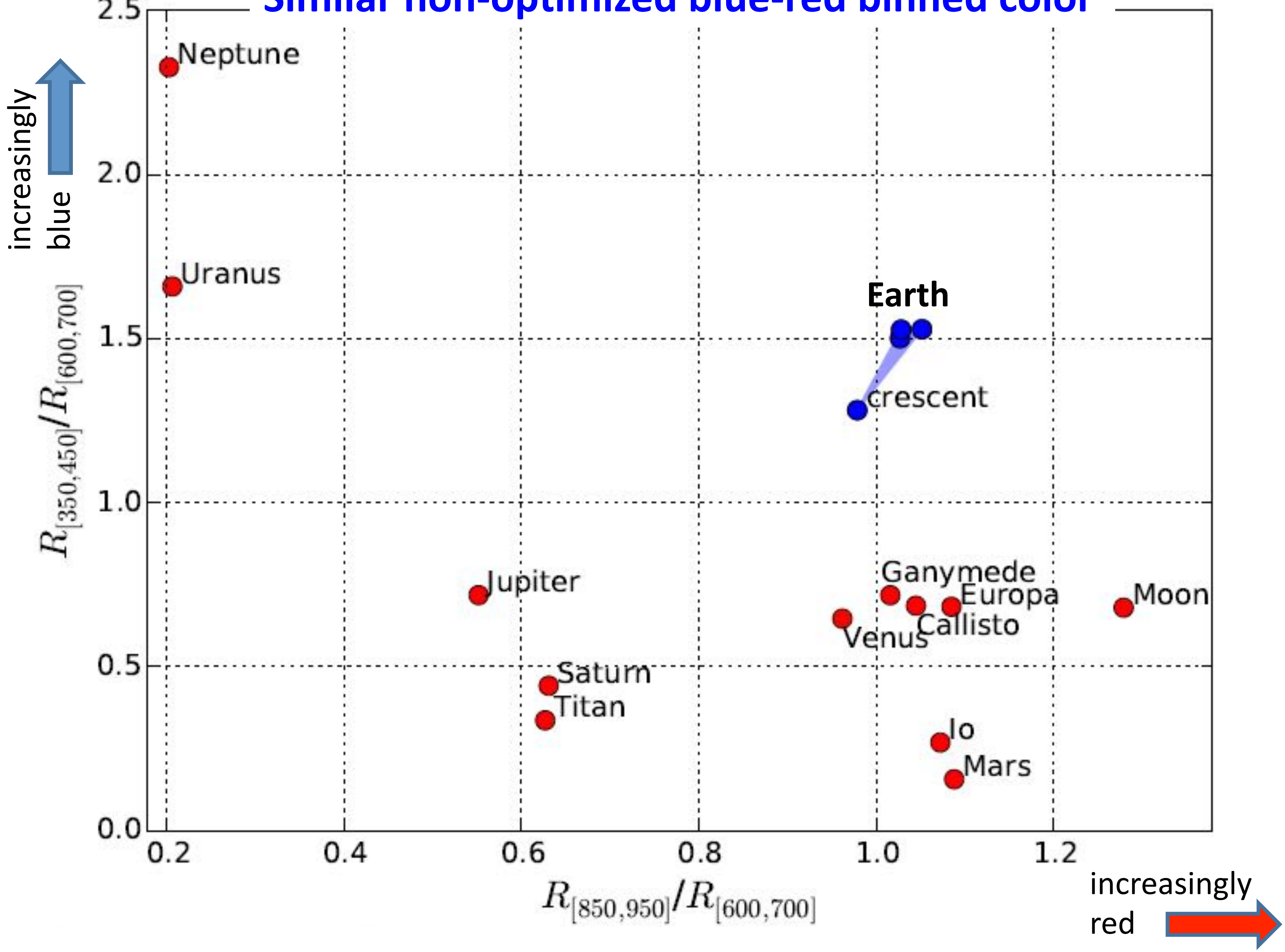
Review: Catling, D.C. (2015) Planetary Atmospheres, In G. Schubert (ed.), *Treatise on Geophysics* (2nd Ed.), vol. 10, Elsevier, New York, 429-472.

Part 2



Crow et al. 2011

Similar non-optimized blue-red binned color



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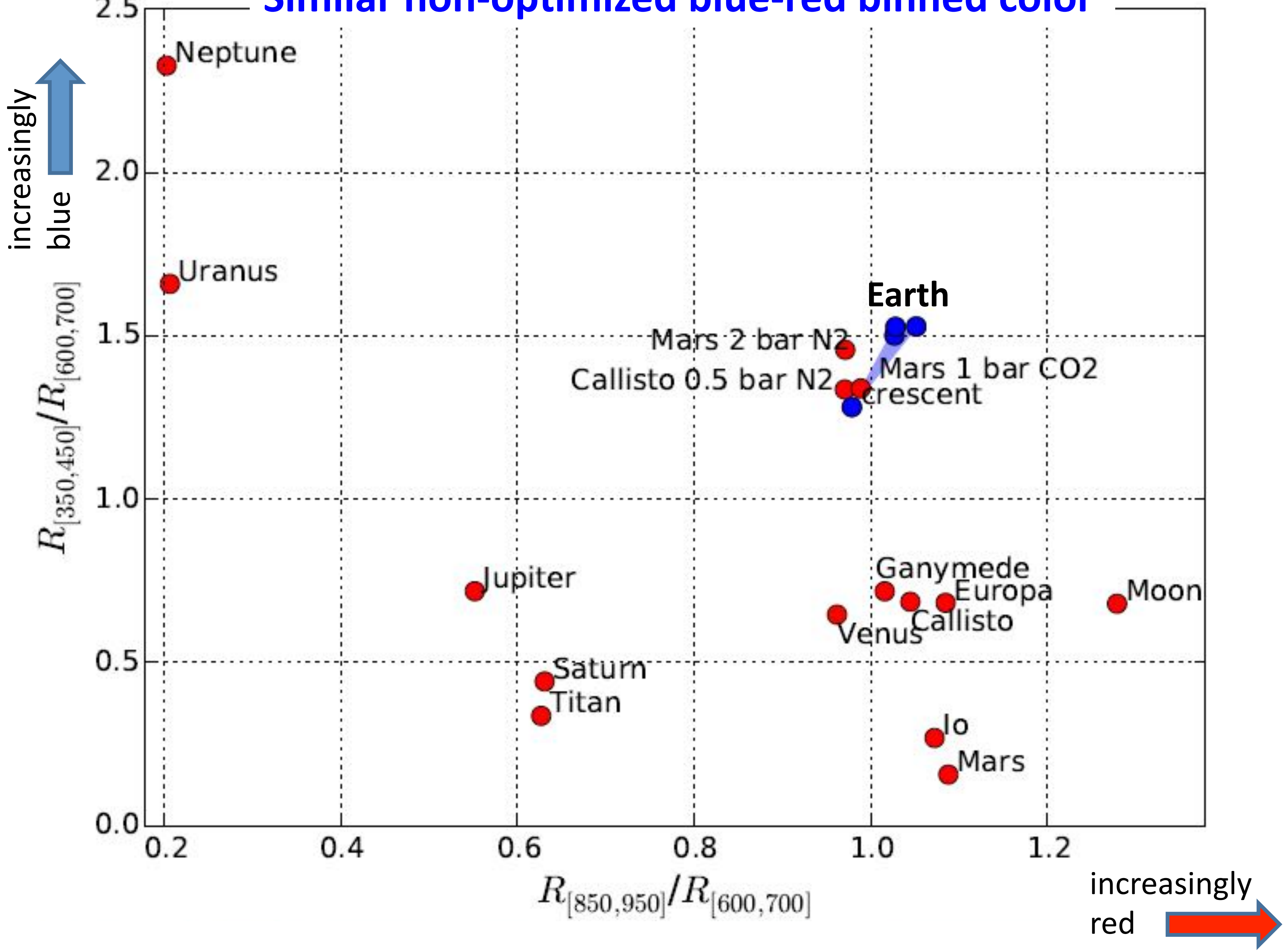
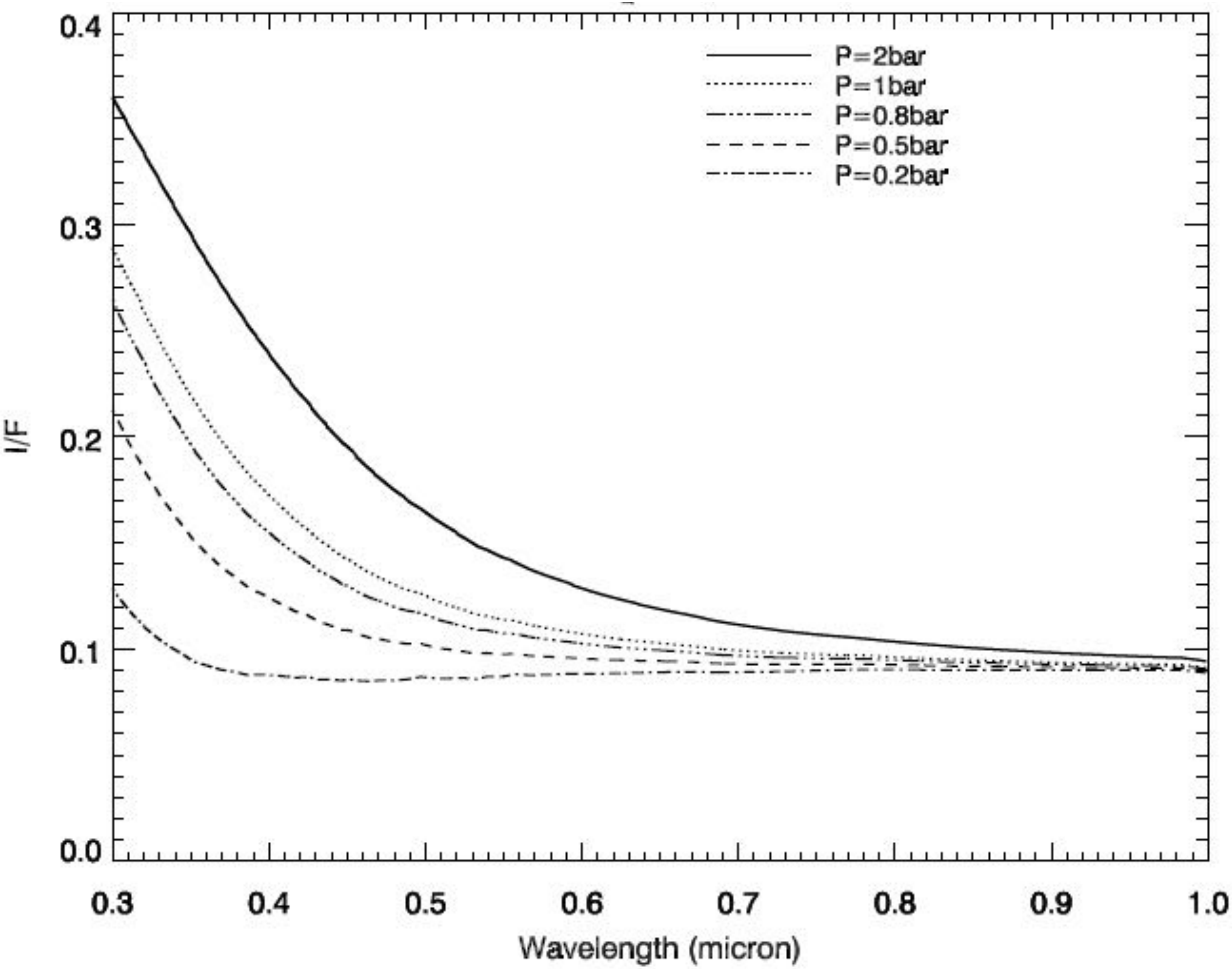
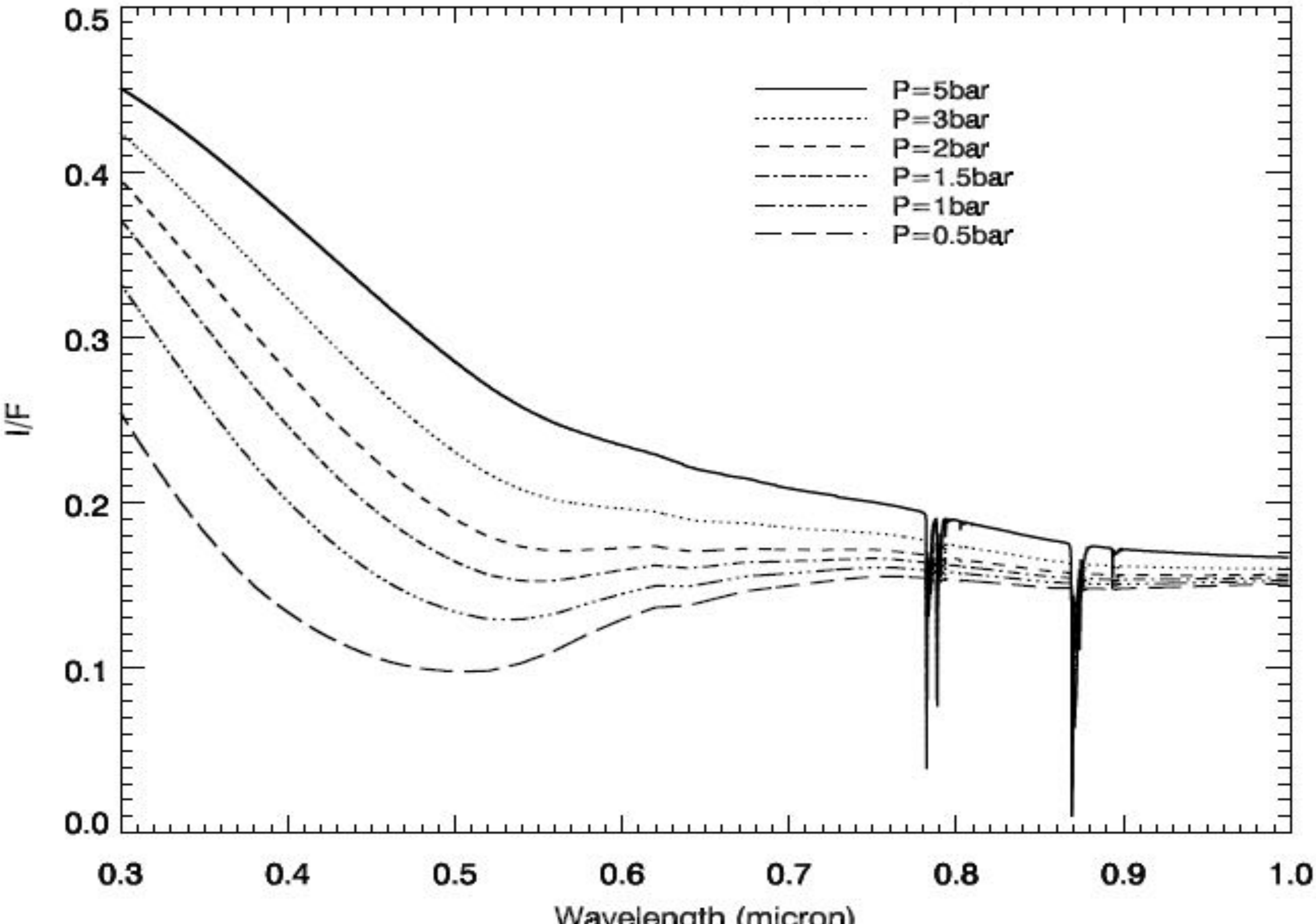


False-positive Pale Blue Dot?: 'Callisto' with N_2-only atmosphere



False-positive Pale Blue Dot?: 'Mars' with thick CO_2-only atmosphere



Can we do better than this?

Methods

Goal: Find the set of photometric bins that maximize Earth's distance from its nearest uninhabitable neighbor in color-color space.

Find color-color axes:

$$R_{[a_3,b_3]} / R_{[a_2,b_2]} = R_{red} / R_{green}$$

$$R_{[a_1,b_1]} / R_{[a_2,b_2]} = R_{blue} / R_{green}$$

Constraints:

- Non overlapping bins
- Minimum bin size 100nm
- Restrict to 350-1000nm.

Methods

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Constraints:

- Non overlapping bins
- Minimum bin size 100nm
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Uninhabitable false positives considered:

- Solar System objects
- Ensemble of model gas giants (Sudarsky et al., 2000)
- Mini-Neptunes (hydrogen dominated, thick steam)
- Runaway snowballs
- Galilean moons with thick N_2 atmospheres.
- Mars with varying pCO_2, N_2.

Constrained maximization of Pythagorean distance

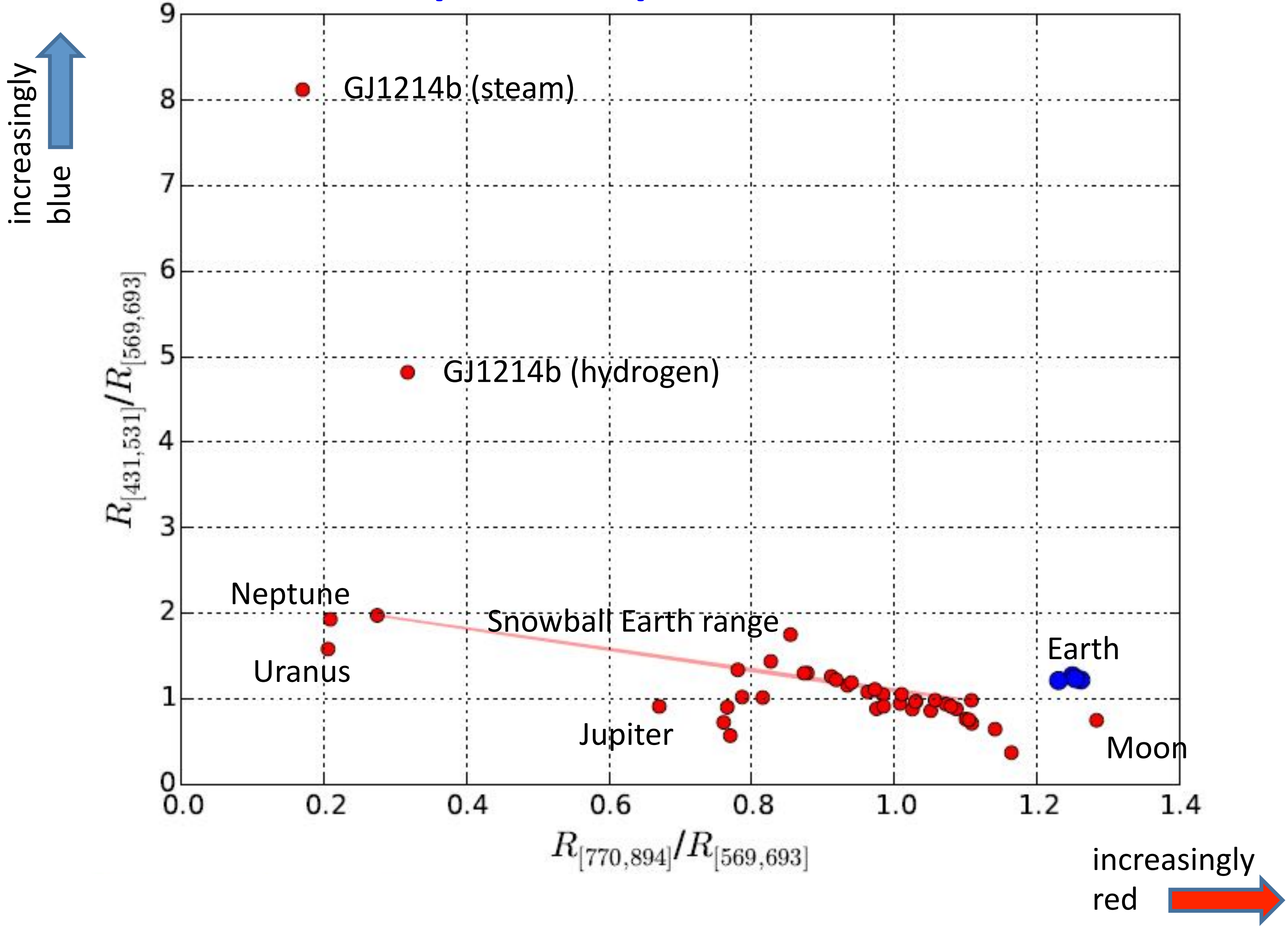
$$\underset{a_1,a_2,a_3,b_1,b_2,b_3}{maximize} \quad f\left(a_1,a_2,a_3,b_1,b_2,b_3\right)=$$

$$\min\left(\sqrt{\left[\left(R_{[a_1,b_1]}/R_{[a_2,b_2]}\right)_{Earth}-\left(R_{[a_1,b_1]}/R_{[a_2,b_2]}\right)_j\right]^2+\left[\left(R_{[a_3,b_3]}/R_{[a_2,b_2]}\right)_{Earth}-\left(R_{[a_3,b_3]}/R_{[a_2,b_2]}\right)_j\right]^2}\right)$$

$$subject\ to \quad \left\{\lambda_{\min}<a_1\right\},\left\{b_3<\lambda_{\max}\right\},\left\{a_i+m<b_i\right\},\left\{b_i<a_{i+1}\right\}, \quad i=1,2,3$$

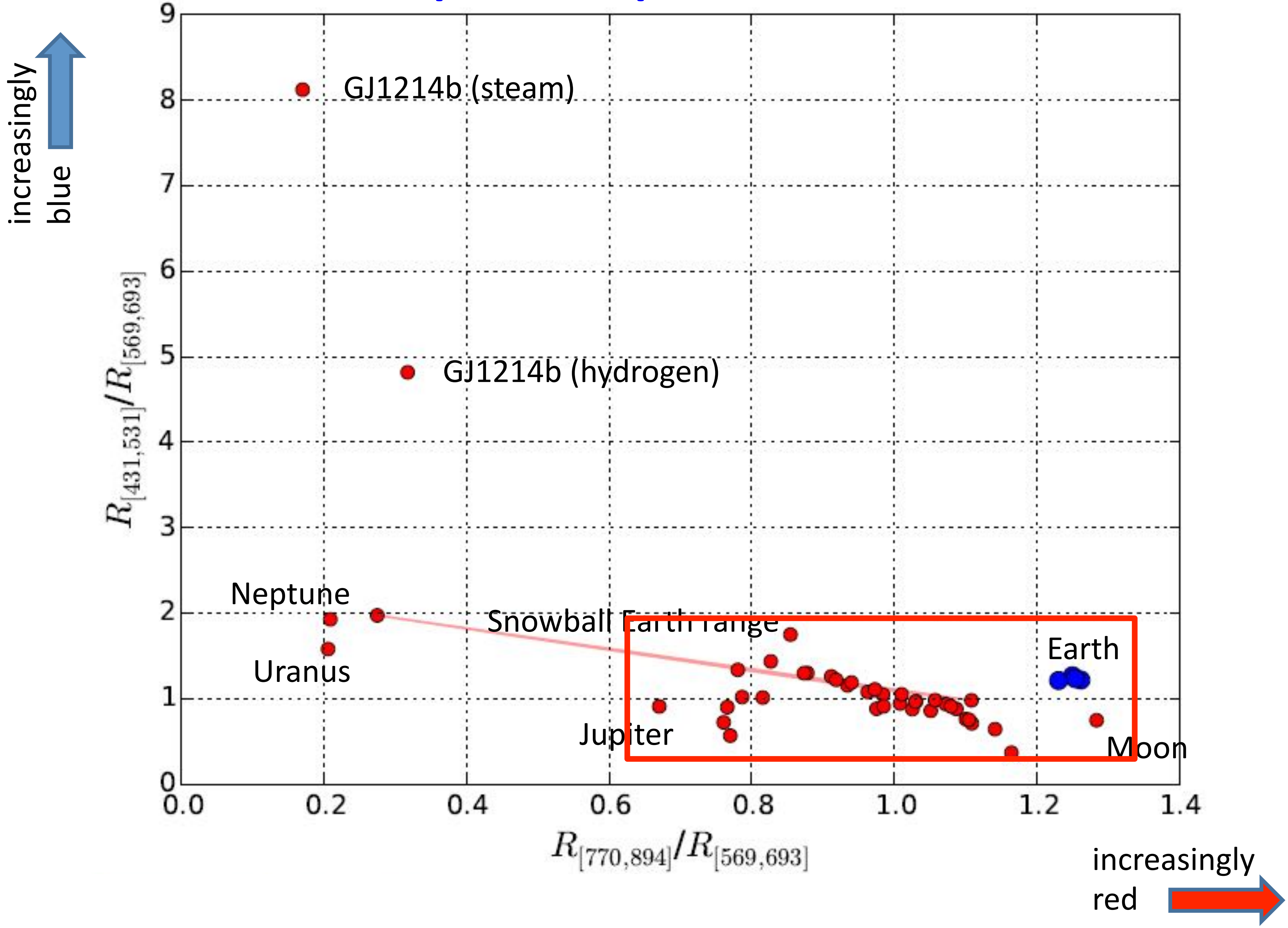
Nonlinear problem -> brute force solution

Optimal separation results

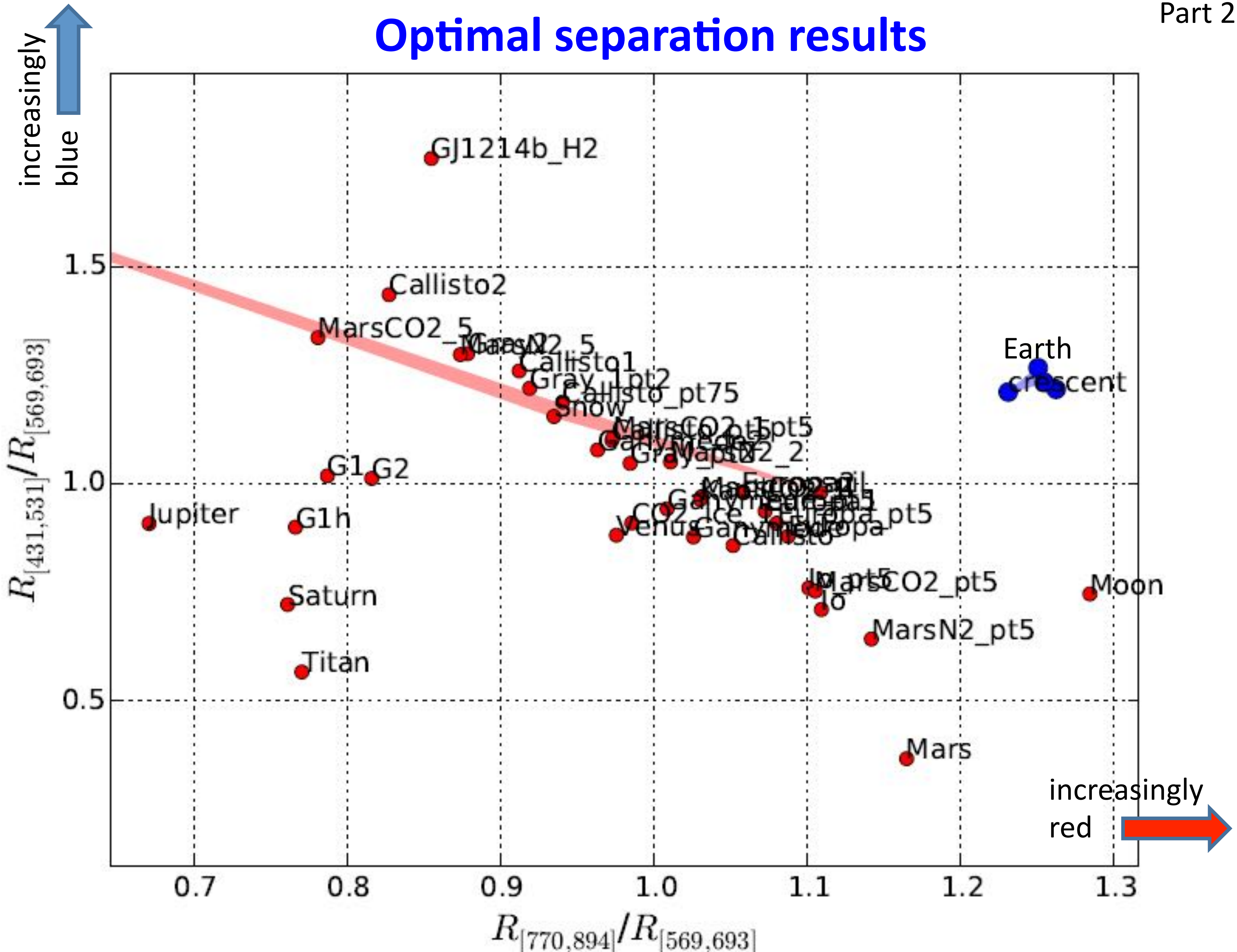


Part 2

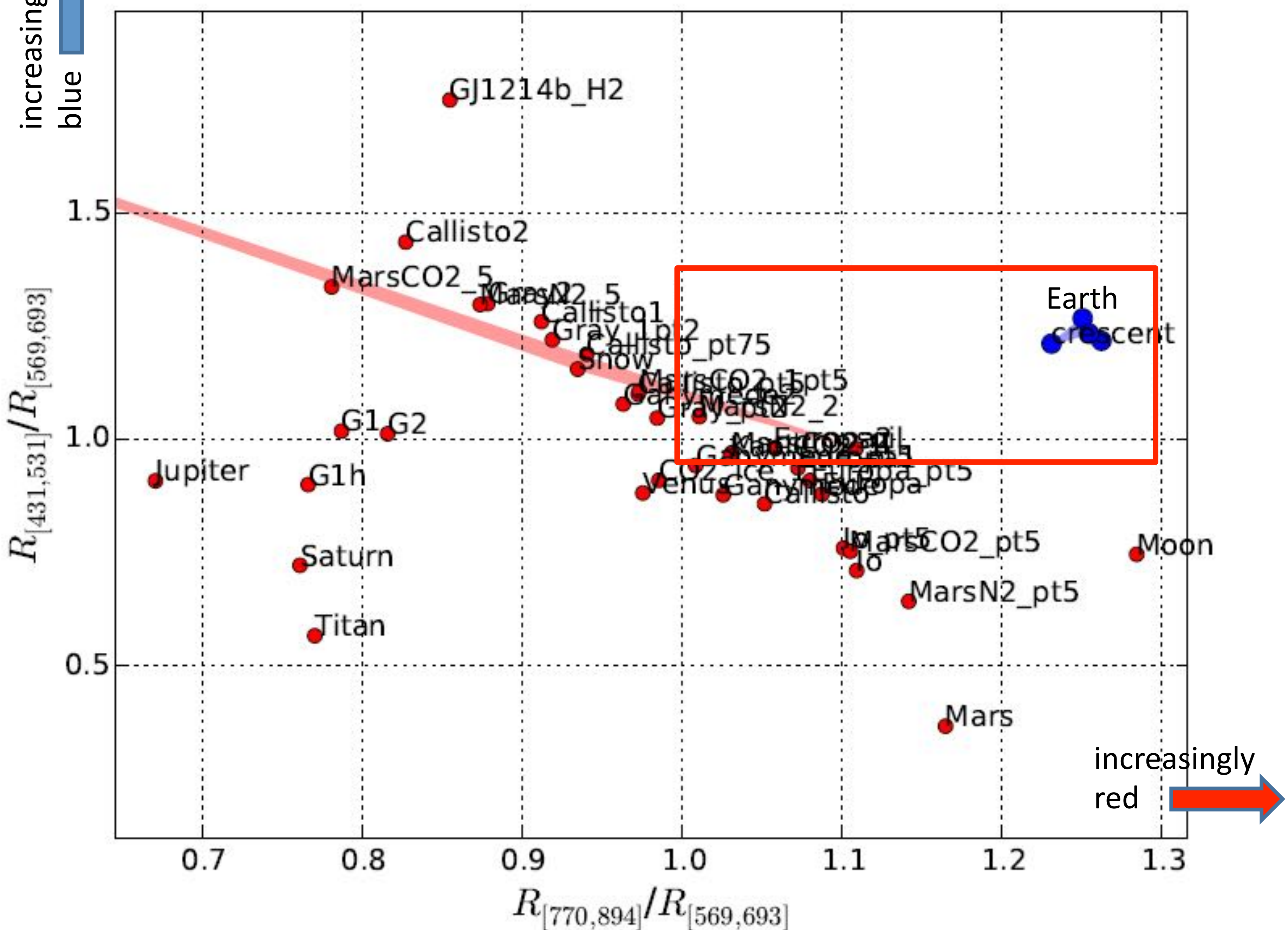
Optimal separation results



Optimal separation results

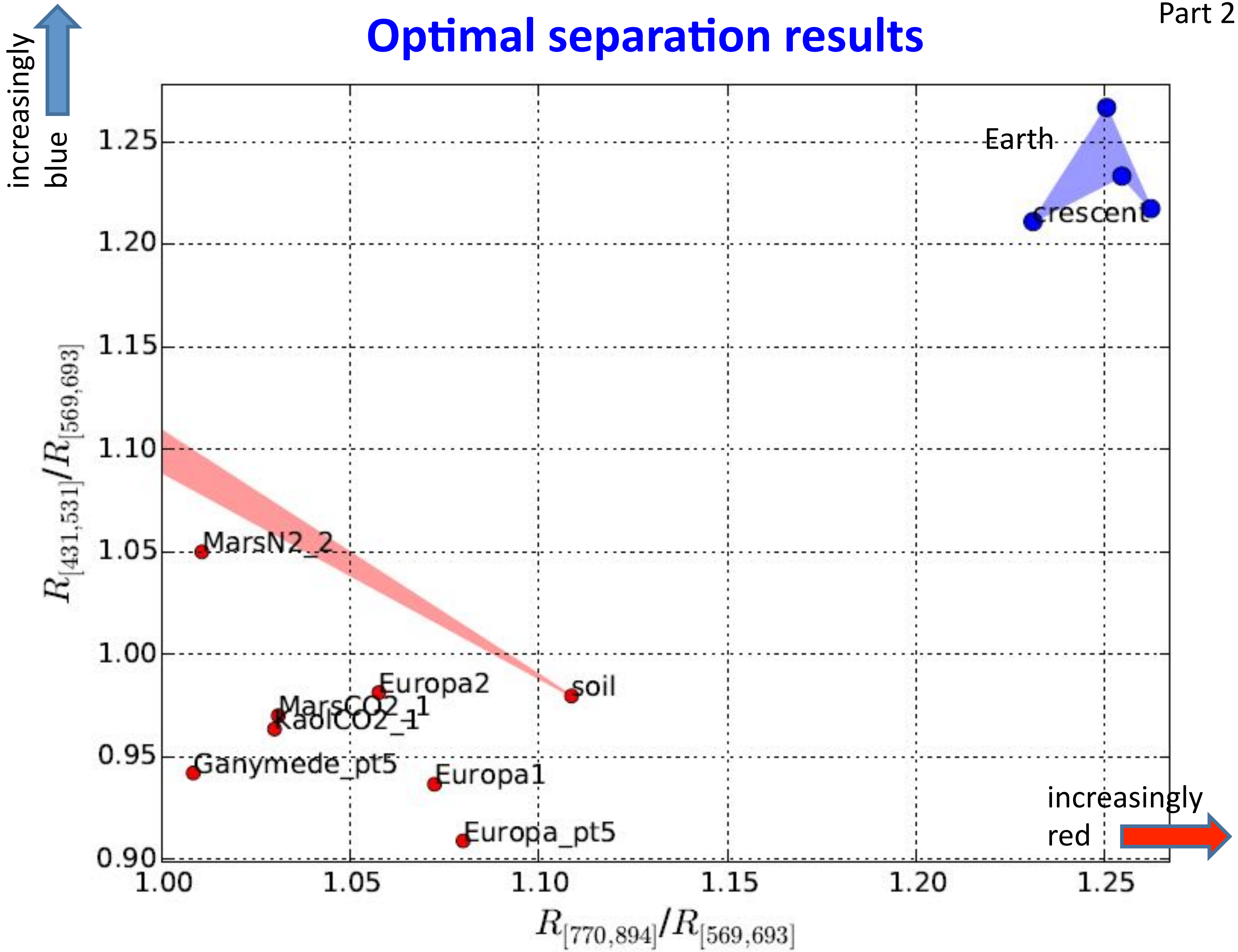


Optimal separation results



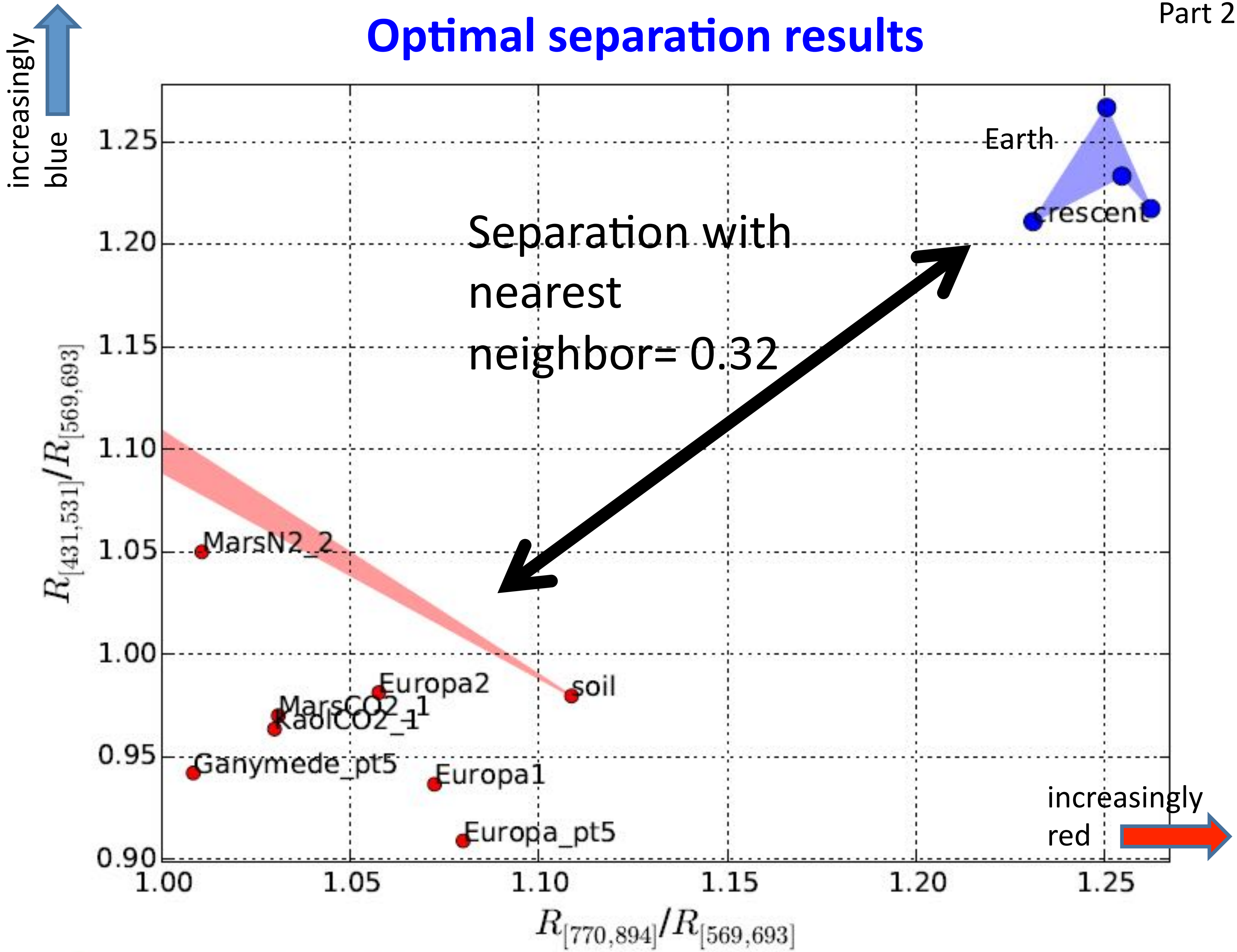
Part 2

Optimal separation results

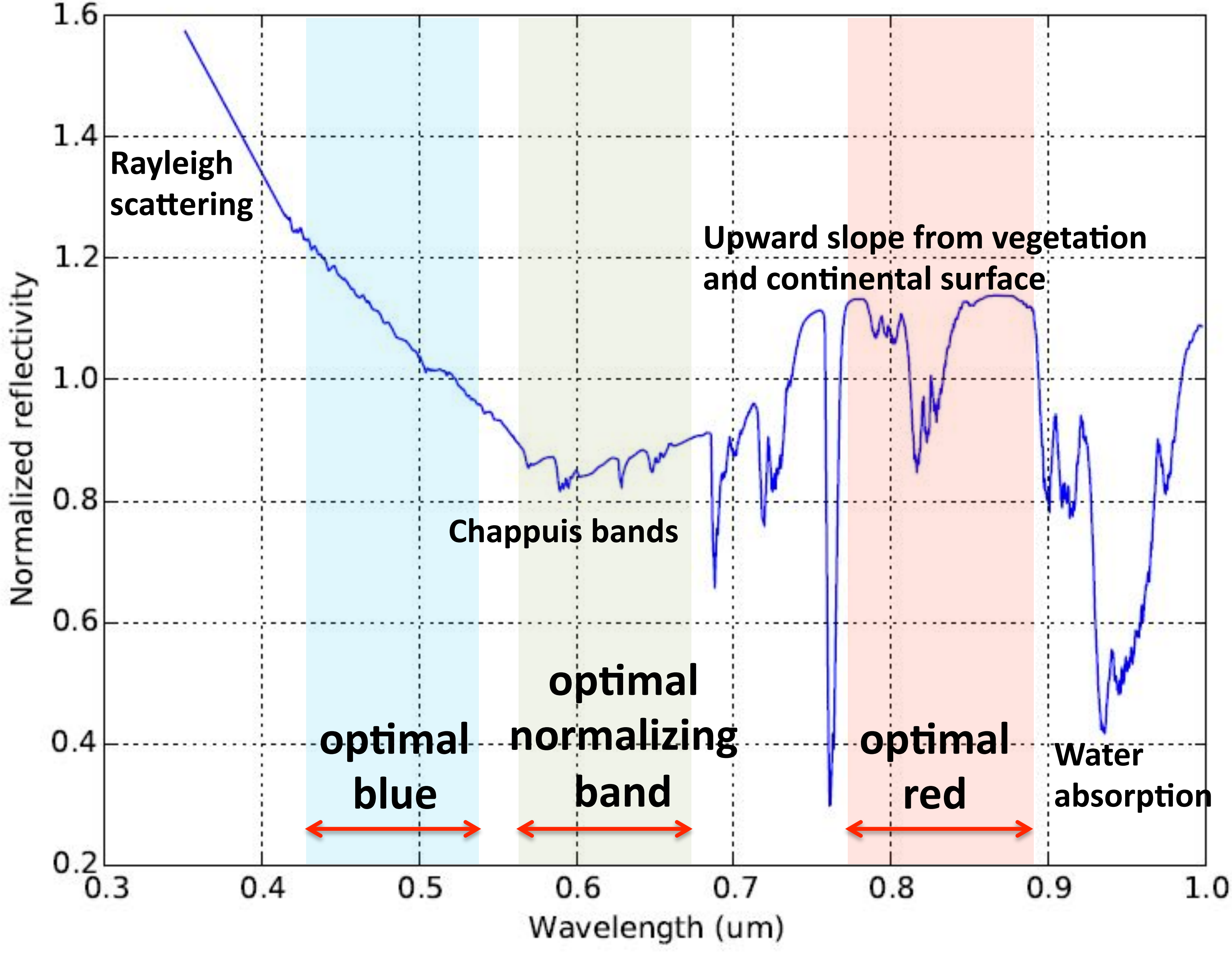


Part 2

Optimal separation results



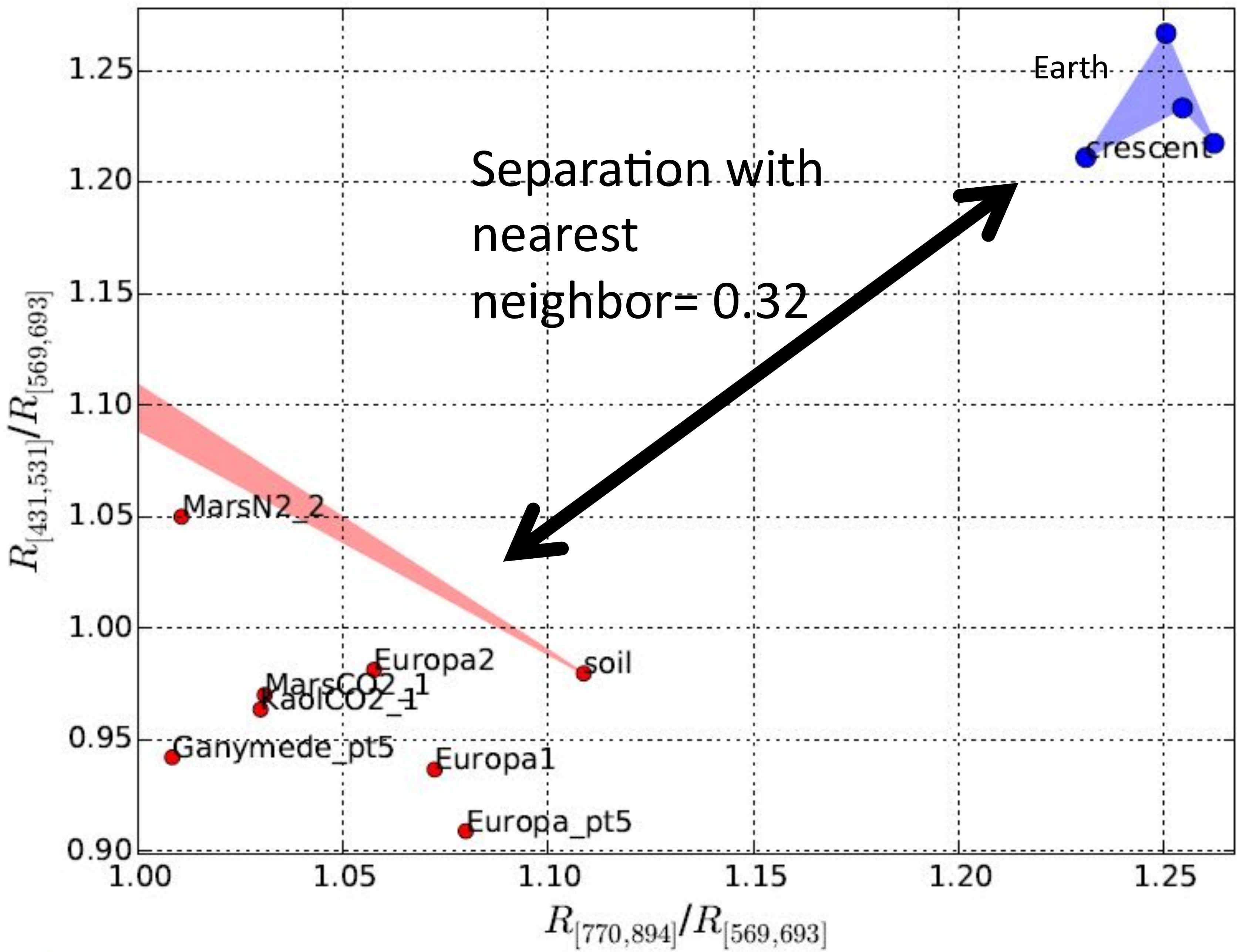
Earth spectrum with optimal filters



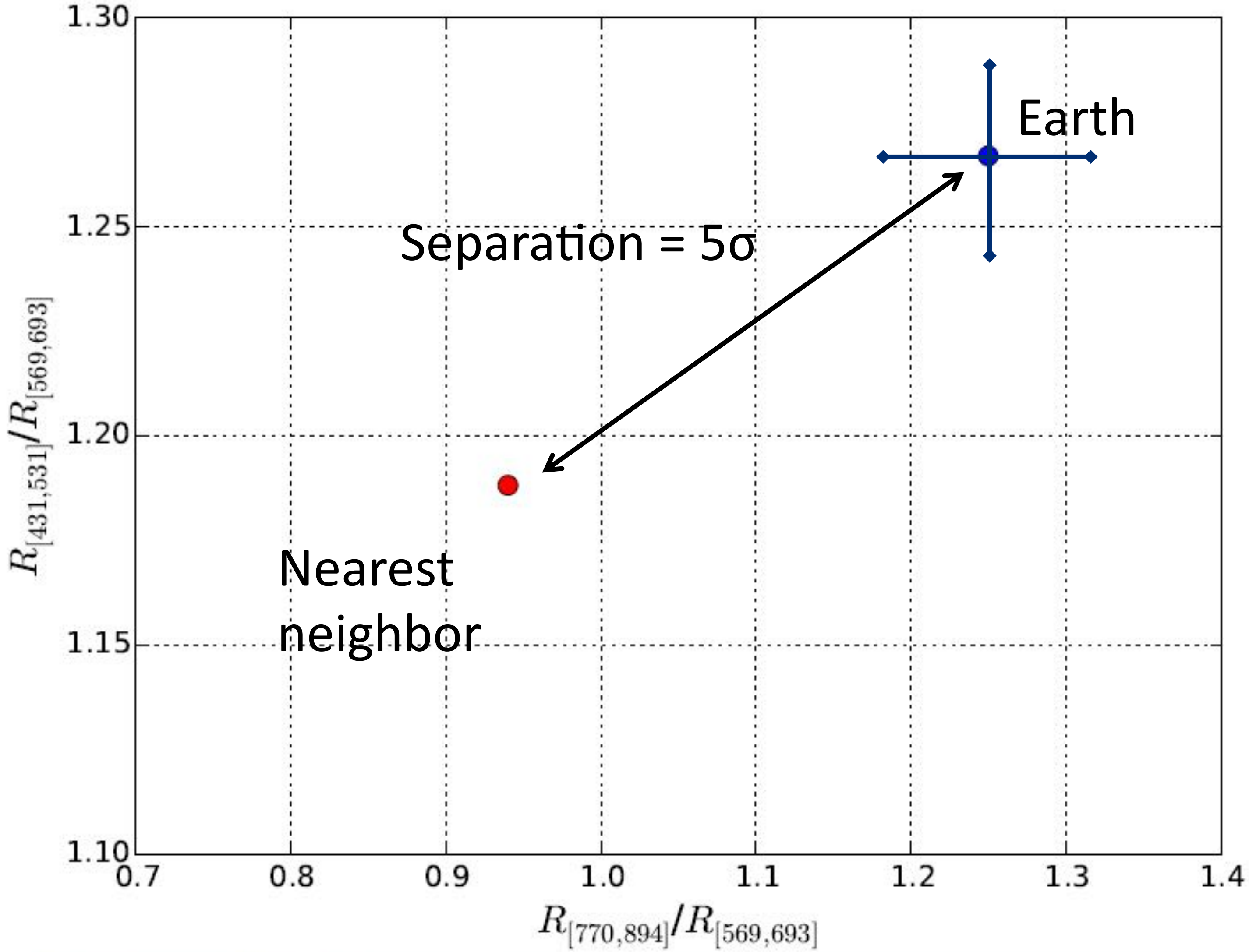
Additional tests were also done but little improvement:

- Change minimum bin size
- Generalize axes
- 4 bins instead of 3
- 3D plots
- different separation criteria

Optimal separation results



How long would it take to observe this unique color?



How long would it take to observe this unique color?

$$S/N = \frac{Q_{\mathrm{Planet}}}{\sqrt{Q_{\mathrm{Planet}} + Q_{\mathrm{Zodiacal}} + Q_{\mathrm{null}}}}$$

$$= \frac{F_{\mathrm{Planet}}}{\sqrt{F_{\mathrm{Planet}} + F_{\mathrm{Zodiacal}} + F_{\mathrm{null}}}} \sqrt{t_{\mathrm{color}}}$$

Bottom line: the integration time required to separate Earth to 5 sigma is *longer* than time required to obtain a spectra with S/N=5 and 10 nm resolution

Part 2: Conclusions on color

- With optimal photometric bins, Earth's color is unique compared to all known false-positives.

- However, the integration time required to resolve Earth's unique color is comparable to the time required to obtain a spectrum with ~10 nm resolution.

- Other results (not discussed) shows that it's even more difficult to identify the *Archean* (>2.5 Ga) Earth with photometry alone.

Take-home messages

Part 1: Earth's atmosphere-ocean reservoir has a large, biogenic disequilibrium, quantified here for the first time. Sets Earth apart from other planets. This could be observed for exoplanets, though interpretation of *thermodynamic disequilibrium* requires further work. Further work also must be done to examine *kinetic* metrics.

- preprint on arXiv; source code online upon publication

Part 2: Although Earth's color is unique, there's no practical advantage in restricting future observations to broad photometric bands. Moreover, identification of ancient Earths requires a spectrum of more fidelity.

Thanks!

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- Johnathan D. Toner
- Kathryn Cogert
- Chris Glein

Preprint available on arXiv
Code and associated databases will be made public upon publication