Biosignatures and the Search for Life on Other Worlds

How can we tell if a planet bears life from many light years away?

A **biosignature** is some form of physical evidence of the present or past existence of life on a planet.

A good biosignature is one that would persist for long periods of time, not be present without life, and be easily detectable.

One way to choose good biosignatures is to choose those that would reveal our own existence to species like us elsewhere in the universe.

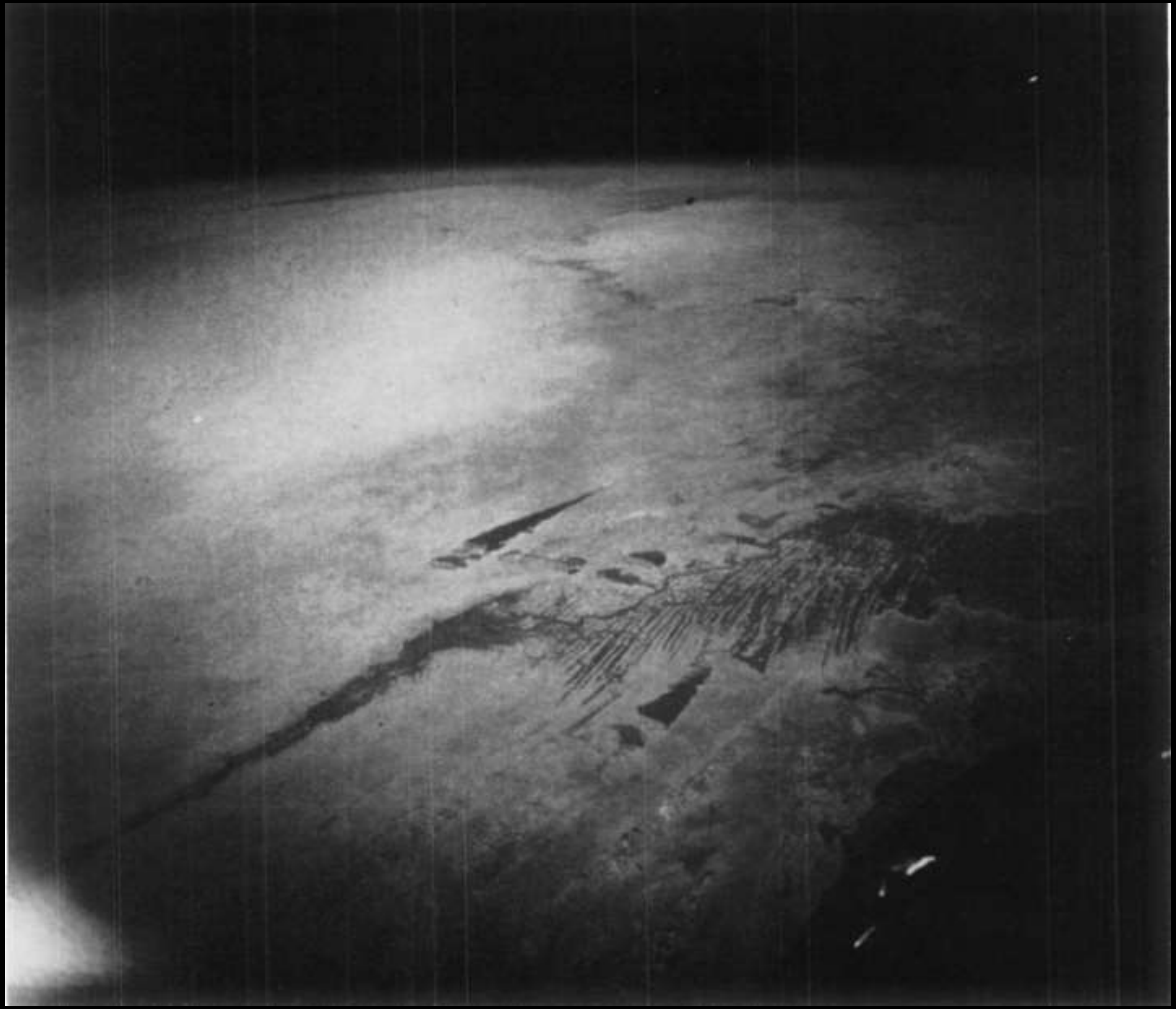
Could we actually detect ourselves from afar?

Credit: NASA/JPL

In 1971, prior to the arrival of the Viking landers on Mars, Sagan & Wallace explored this question using a series of aerial photos of Earth. Their photos may be similar to what the Breakthrough Starshot program could achieve at Proxima Centauri.

Credit: Breakthrough Starshot

Do you see any features in this image indicative of life?



Credit: Sagan & Wallace, 1971

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Studying the surface details of exoplanets is currently beyond our abilities, but we might be able to detect biosignature gases in their atmospheres.

Life on Earth has radically transformed our atmosphere.

It adds gases that wouldn’t be there otherwise, and maintains them there over billions of years.

Chemical systems tend toward equilibrium, in which the rates of forward and backward reactions are equal.

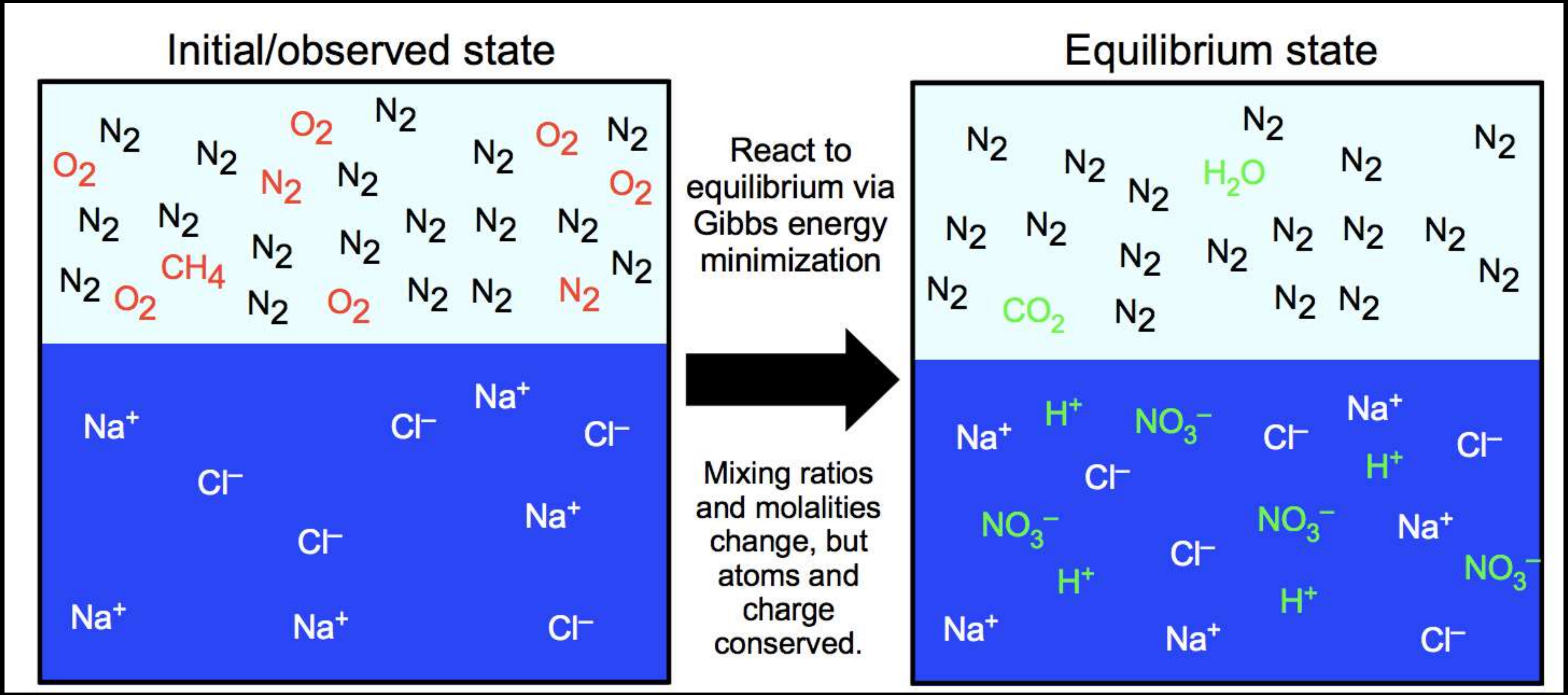
Life often keeps chemical systems out of equilibrium.

A non-equilibrium chemical system might be detectable over interstellar distances.

On Earth, animals produce CO_2 in large quantities, but so do many non-living chemical processes (e.g. volcanism).

O_2, on the other hand, is very reactive. Many non-biological processes remove O_2 from the atmosphere.

For example, over time, atmospheric O_2 and N_2 should react with the oceans to produce dissolved HNO_3 (nitric acid) until an equilibrium was achieved. (Krissansen-Totton et al. 2018)



On Earth, life keeps O_2 out of equilibrium (through processes such as photosynthesis and denitrification). This makes O_2 a possible **biosignature.**

However, O_2 can also be produced non-biologically, as for example when solar UV rays break down H_2O, and the H_2 escapes to space.

If there is no "sink" for the O_2, it can build up even without life, leading to false positive detections of life.

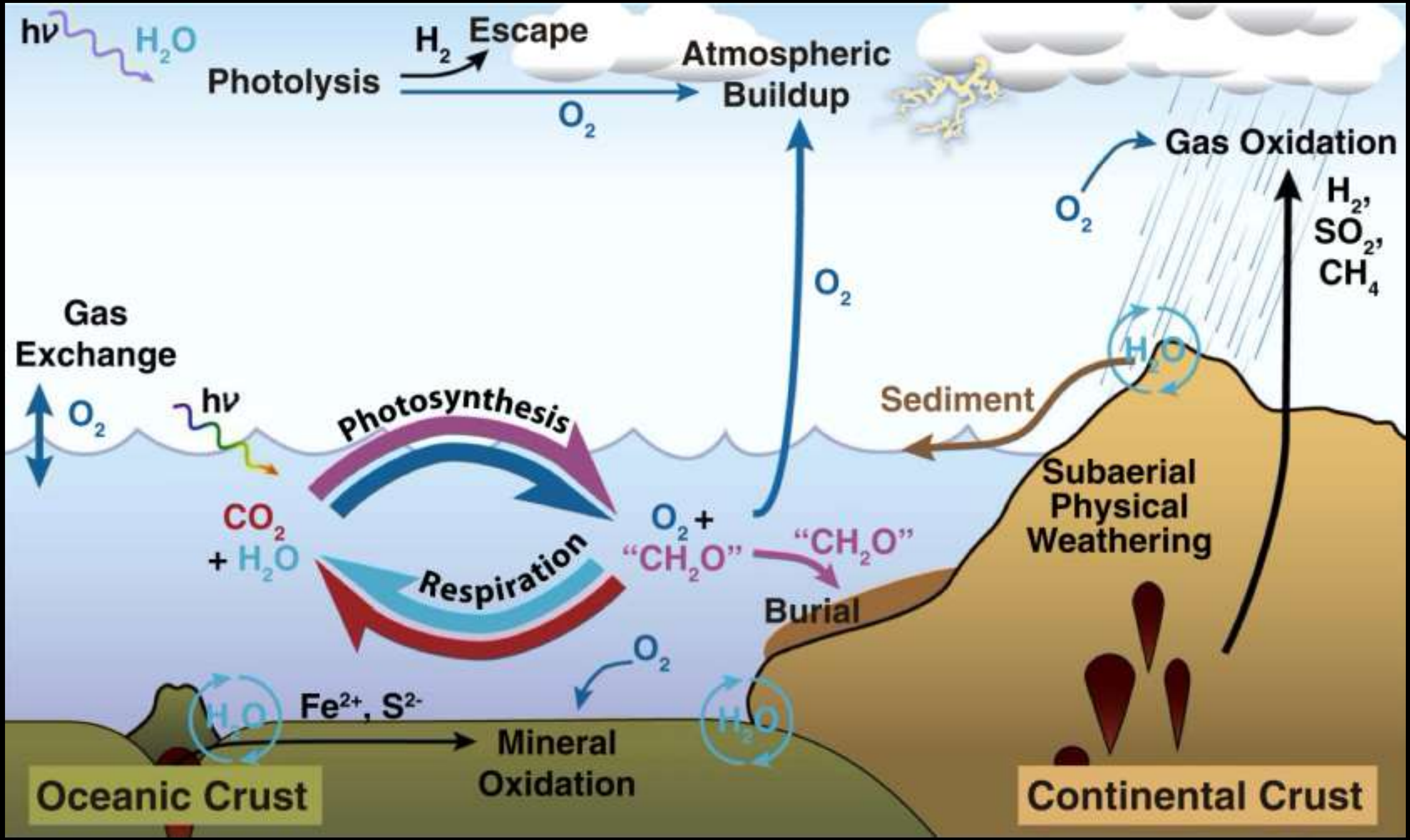
(Kasting, J. F. 1997, Origins Life)

Early in the history of Earth, “sinks” for oxygen removed it from the atmosphere even while life was present.

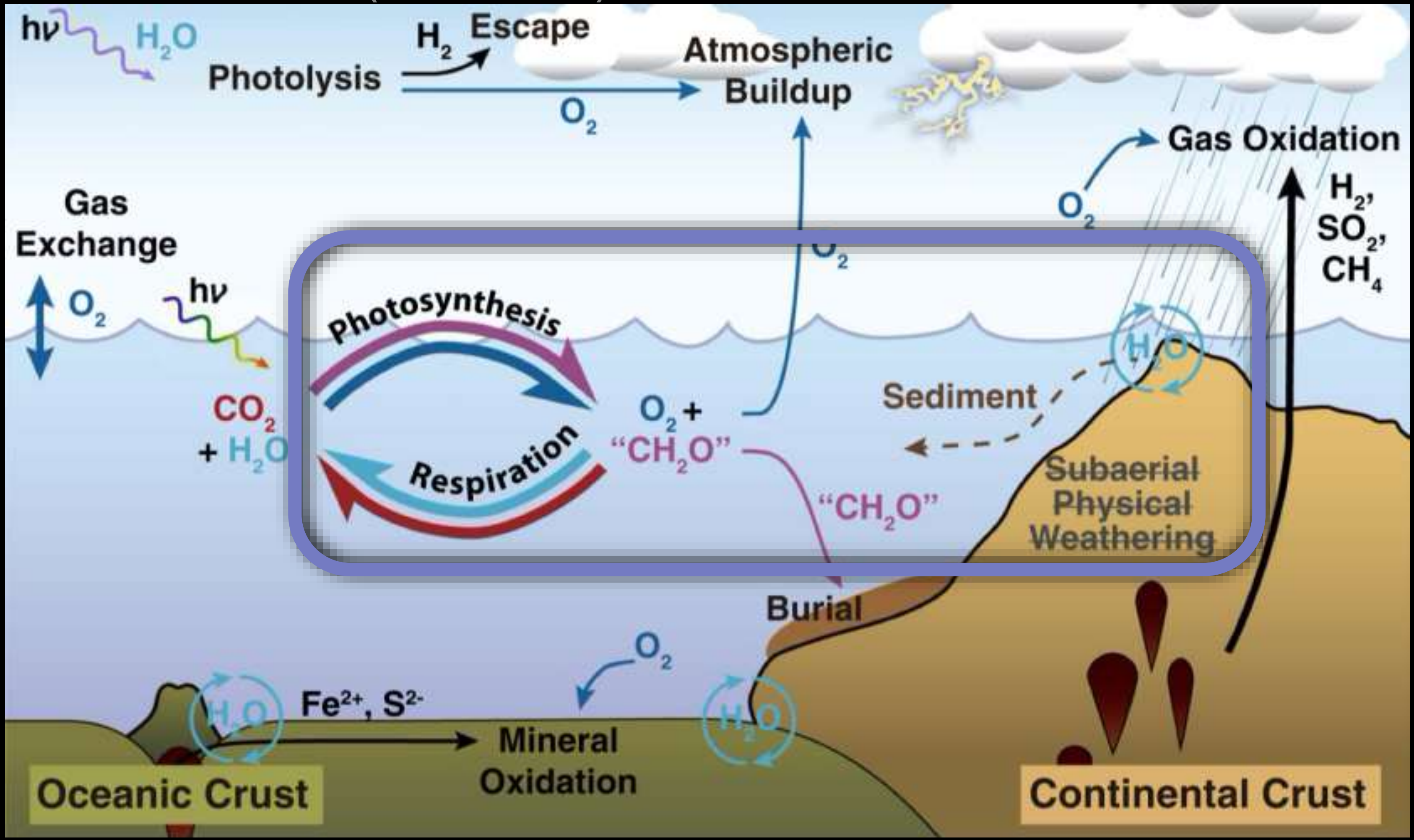
Thus, the non-detection of oxygen would have been a false negative. (e.g. Meadows et al. 2018)

Let’s consider hypothetical “oxygen cycles” on different types of potentially habitable planets.

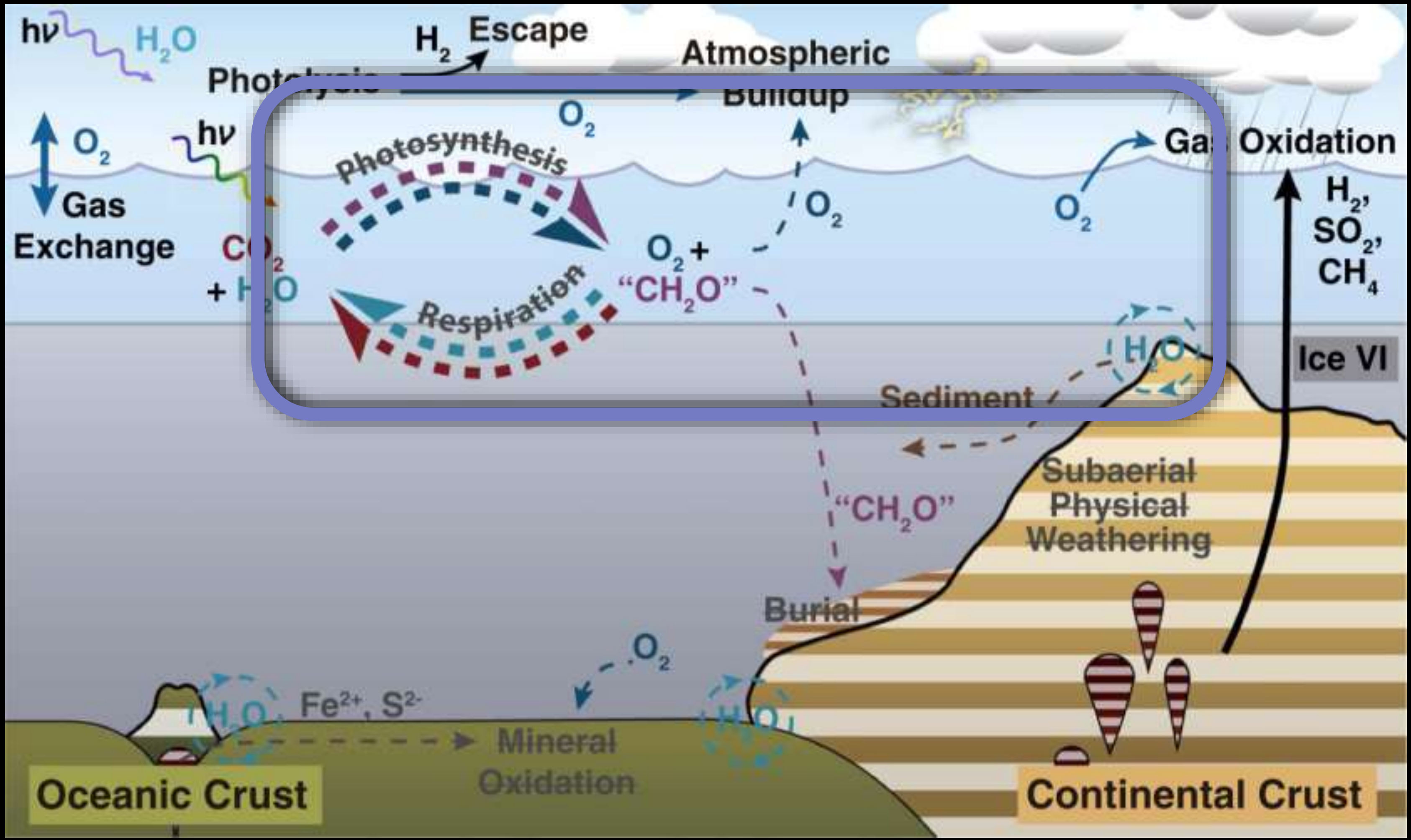
Aspects of the oxygen cycle on Earth, where life produces about 1000 times more O_2 than geological processes do. (Glaser et al. 2020)



Hypothesized aspects of the oxygen cycle on a pelagic planet. The shallow submersion of continents cuts off a necessary source of phosphorus, which reduces the rate of biological production of O_2 in the oceans. (Glaser et al. 2020)



Hypothesized aspects of the oxygen cycle on an ocean world. Burial of land under pressurized ice severely limits availability of N and P needed to sustain photosynthesis. (Glaser et al. 2020)



This analysis suggests that, even if pelagic and ocean worlds have abundant life, it may not produce enough oxygen to represent a secure biosignature.

Atmospheric gases whose concentrations vary with time (i.e. seasonally) may produce a more secure biosignature.

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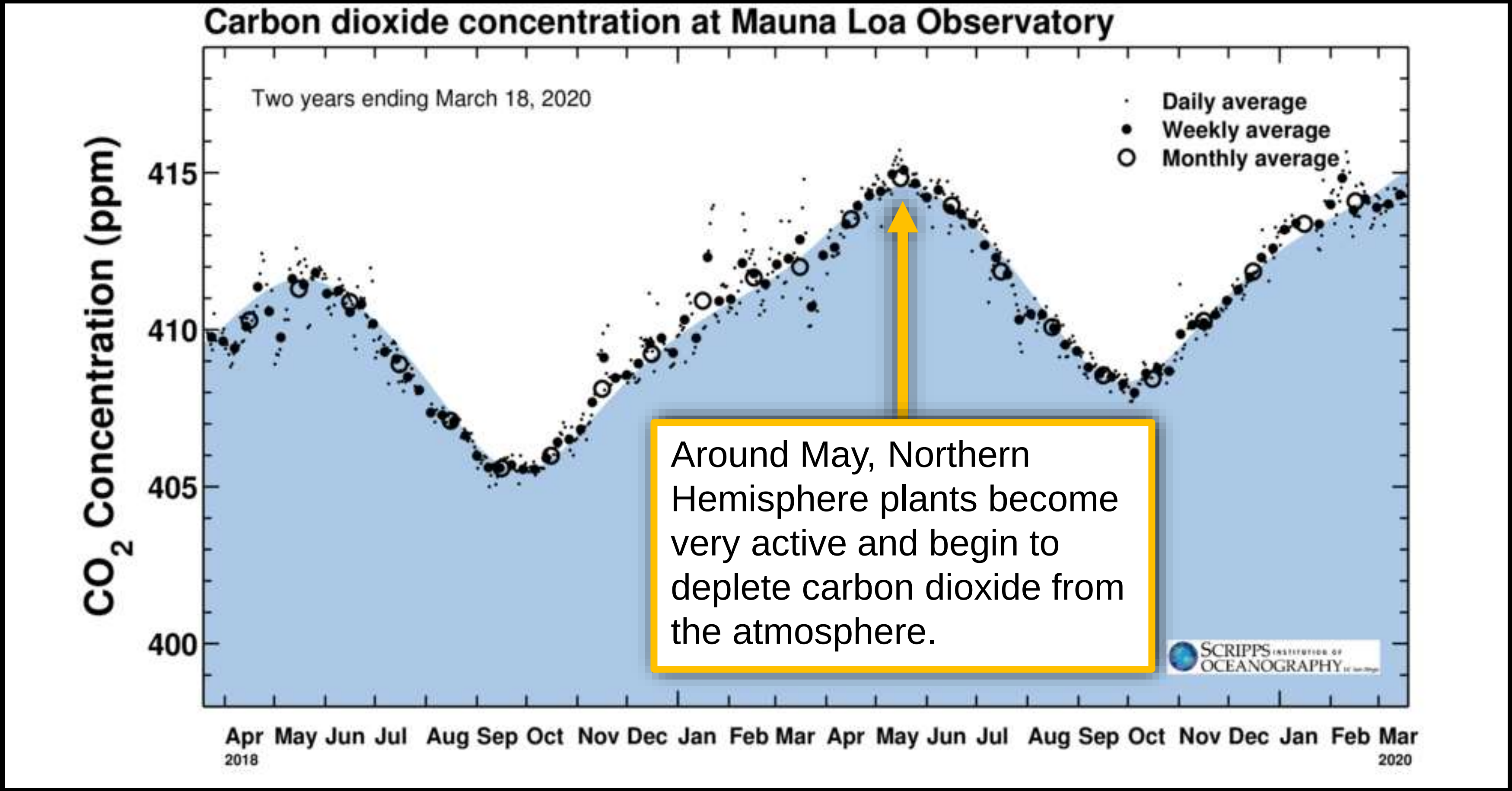
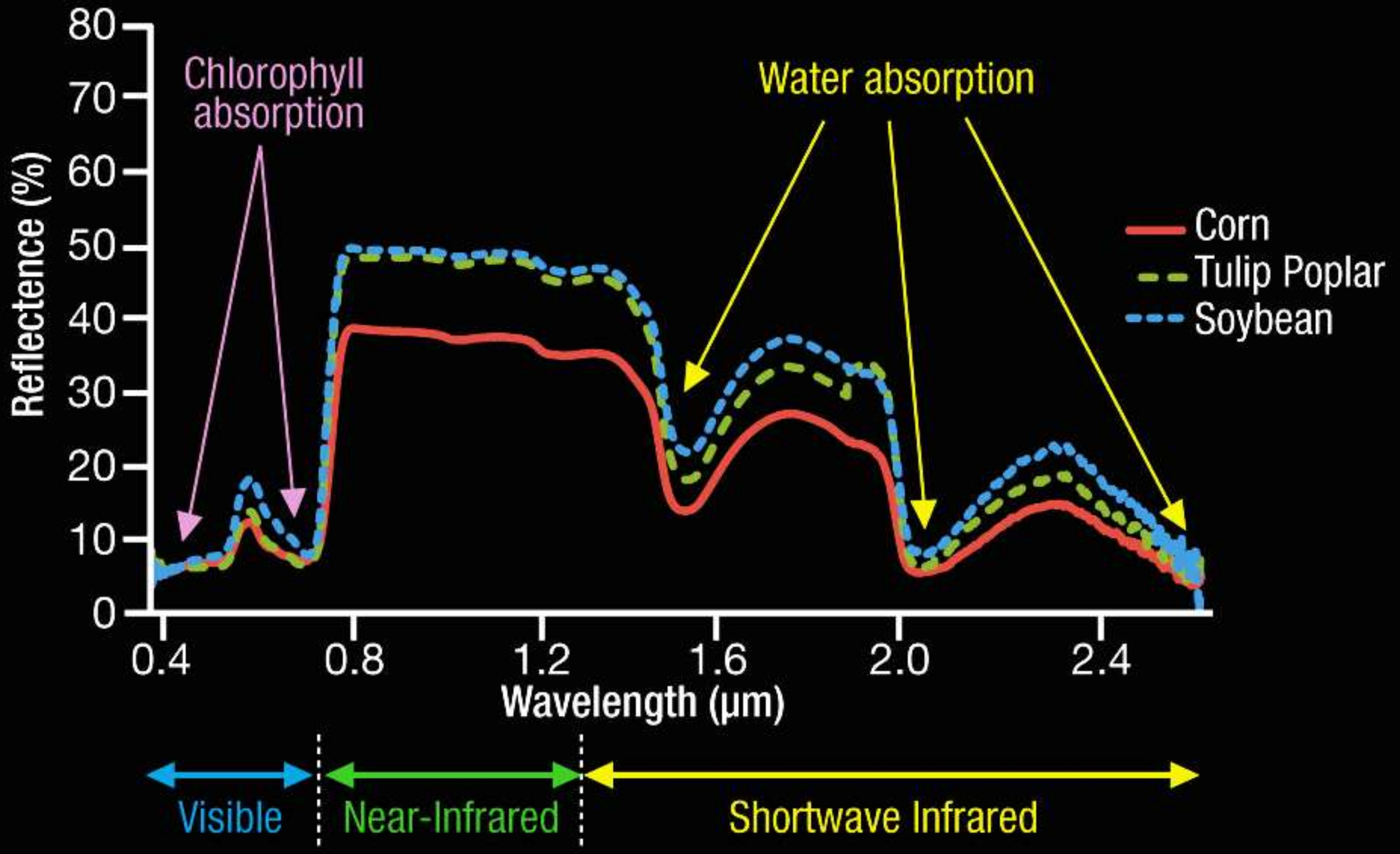
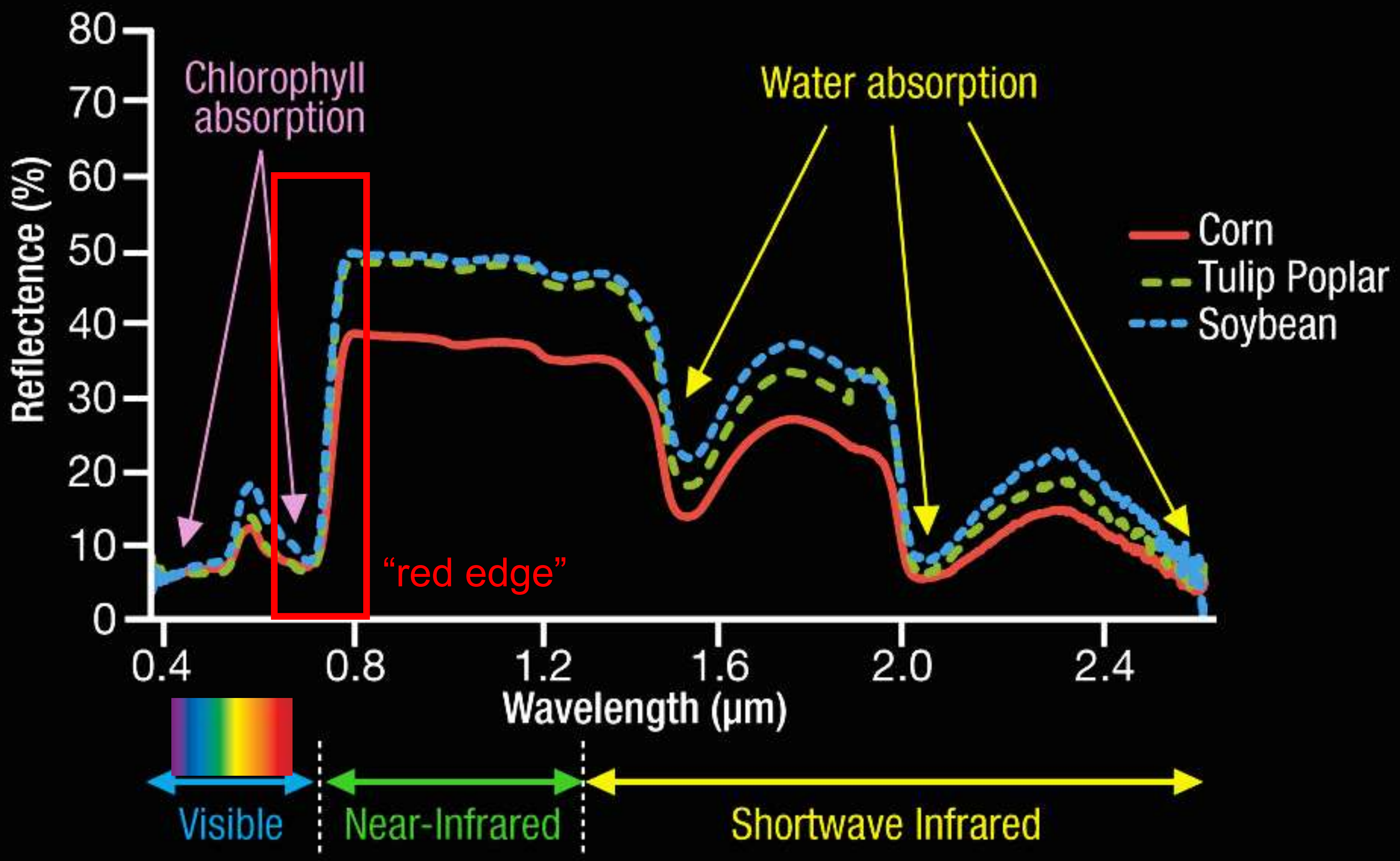


Other proposed biosignatures relate to surface features, such as the presence of photosynthesizing plants.



Credit: Eric Brown de Colstoun

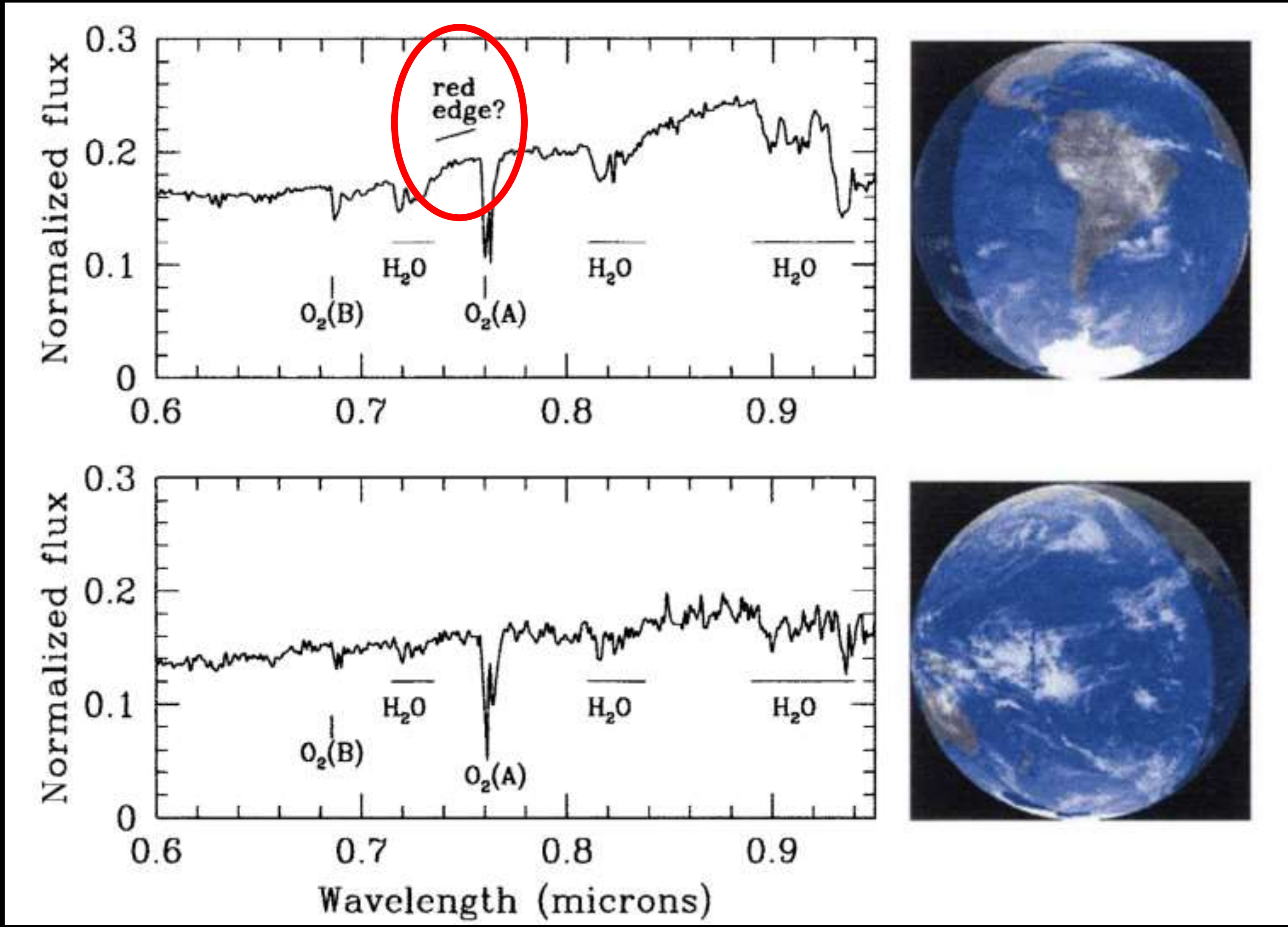


Credit: Eric Brown de Colstoun

This “red edge” may be a useful biosignature if extraterrestrial plants also use chlorophyll.

Can we detect it on our own planet?

Attempted detection of the red edge in light from Earth reflected off the Moon (Seager et al. 2005)

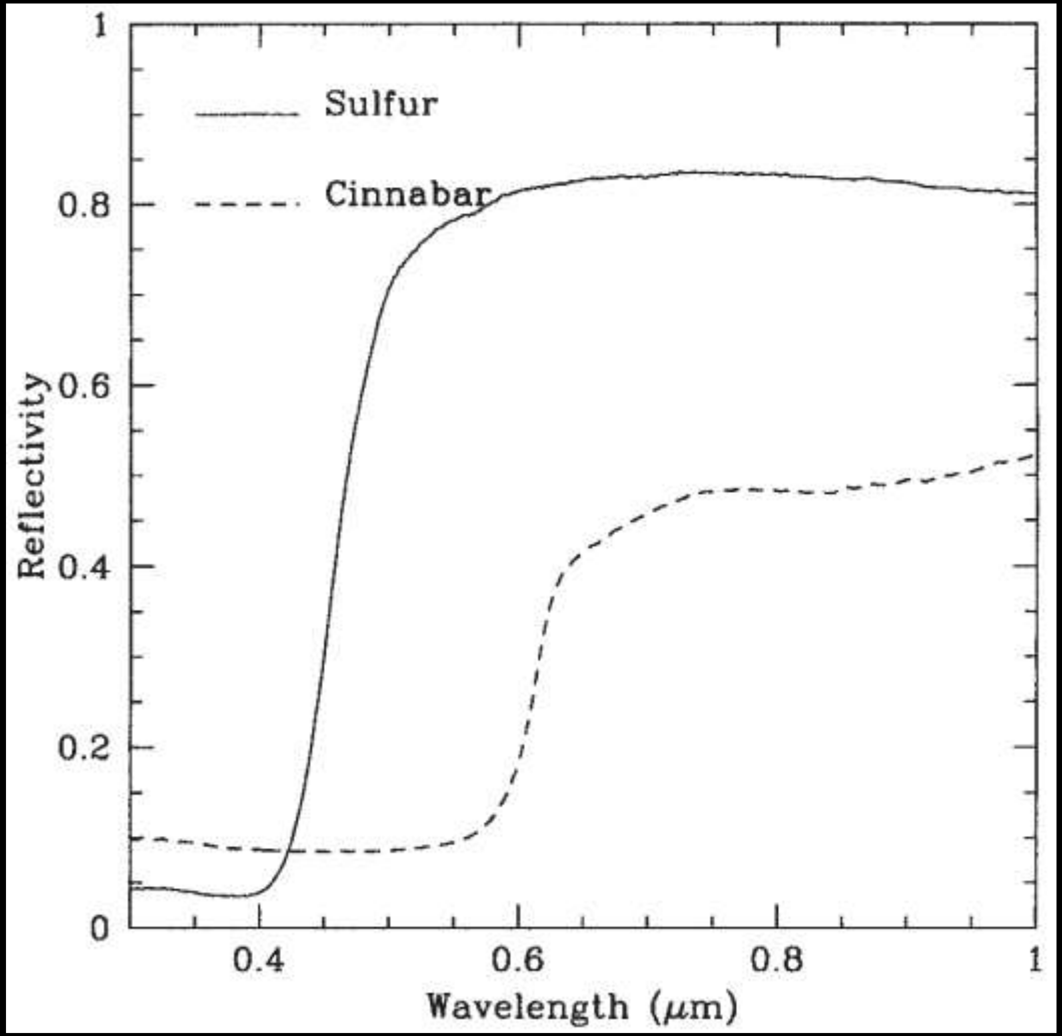


The whole Amazon rainforest is visible

After the Earth has spun and mainly ocean is visible.

Unfortunately, some minerals can mimic the red edge—another source of false positives.

(Clark et al. 1993)



What we need are complementary biosignatures whose false positives (and false negatives) would not overlap.

The Search for Extraterrestrial Intelligence: Signalling

Intelligence is the ultimate biosignature—life that radically transforms its environment.

Perhaps even life that *wants to be found*.

The **search for extraterrestrial intelligence (SETI)** refers to the search for signs of intelligent life in the cosmos.

Specifically, SETI has searched for attempts by extraterrestrial intelligence to communicate with us.

How can we possibly know what methods ET civilizations (ETCs) might use to communicate?

Image credit: Ben Mauro

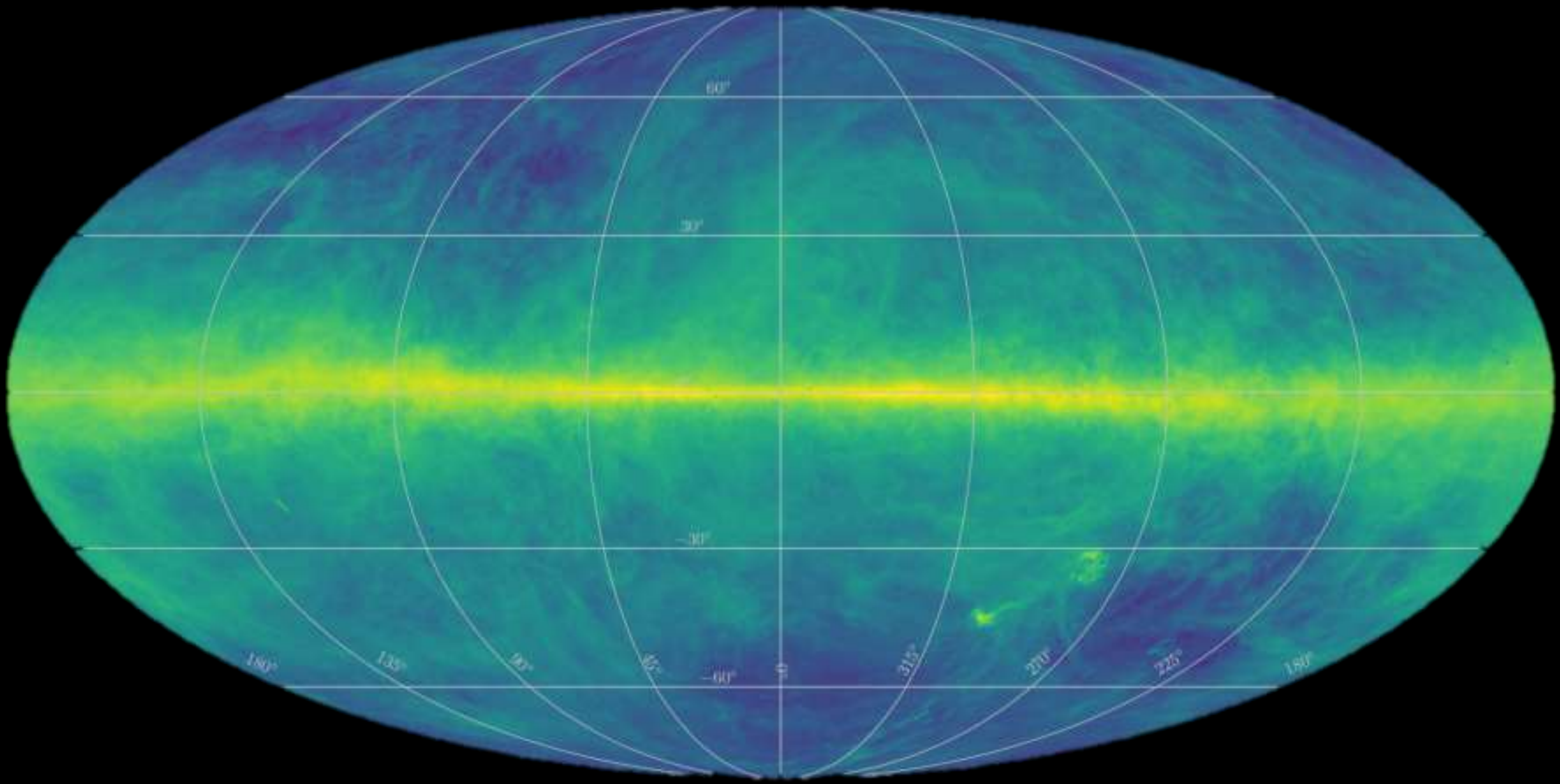
SETI searches have focused on the types of “signals” that we know could be transmitted across interstellar distances and received on Earth-like planets.

One such signal would consist of radio waves. But there are a vast number of different wavelengths of radio waves.

How could any civilization know which types of radio waves other civilizations might be looking for?

We could make a guess about their transmission and reception technologies, but it really would be a guess.

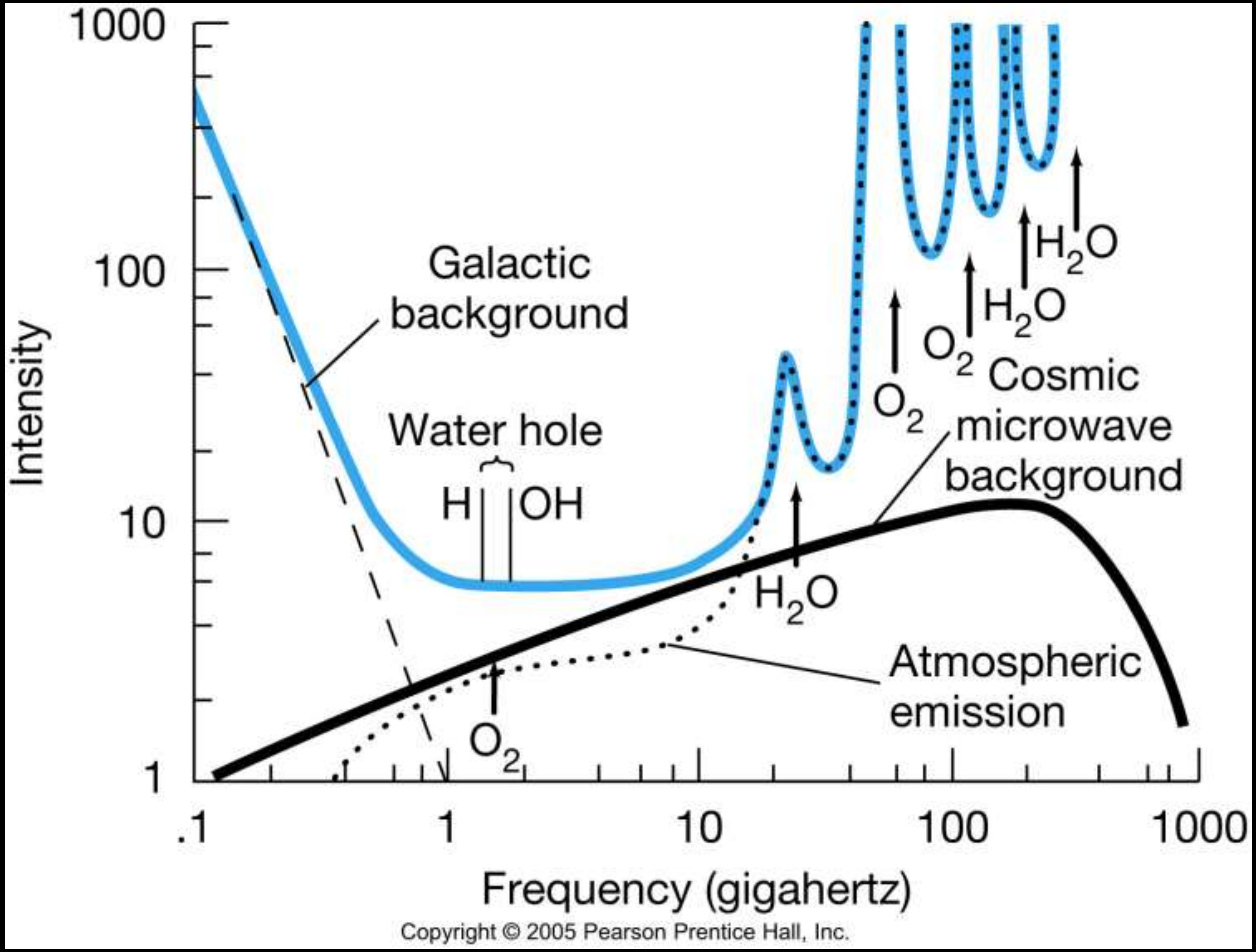
Recall that most of the matter in the universe is hydrogen. It’s everywhere, as seen in this all-sky map. It can’t be ignored. (Behkti et al. 2016)



Hydrogen produces radio waves at specific wavelengths.

This means that every technological civilization in the universe has a reason to develop the technology to study hydrogen.

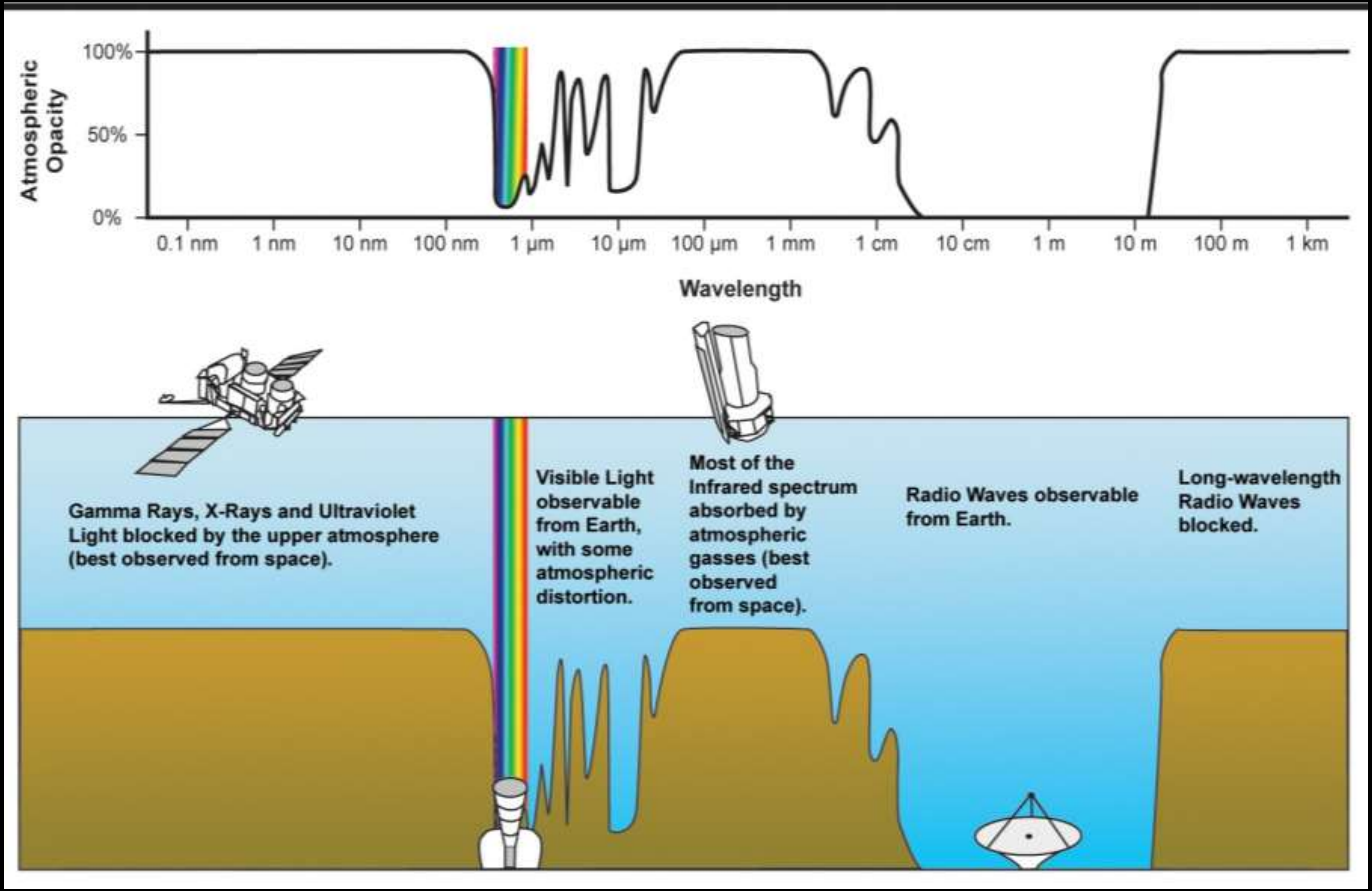
The **water hole** is the range of frequencies between those of the H atom and OH ion, at which Earth's atmosphere is transparent AND there are few natural sources of contaminating signals from space.



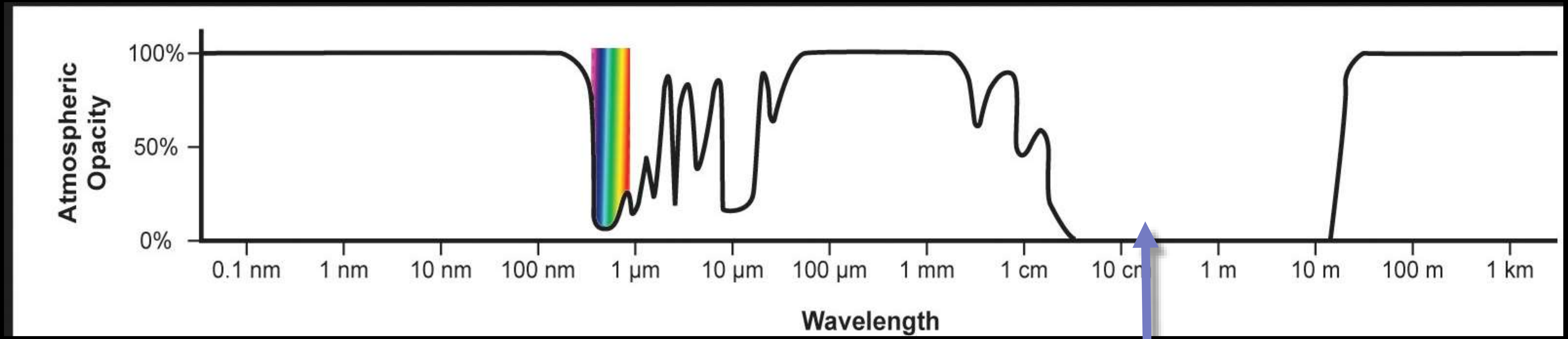
The name “water hole” is both a reference to the H/OH ions and an analogy with natural “watering holes” at which different species congregate.

Credit: Flickr user bettyx1138

Earth's atmosphere has two "windows of transparency" visible light, and microwave/radio light.



Credit: gsp.humboldt.edu/



Diffuse hydrogen gas naturally emits light at a wavelength of 21 cm (1420 MHz).

Extraterrestrial civilizations similar to our own would probably also live on planets whose atmospheres would be transparent to these wavelengths of light.

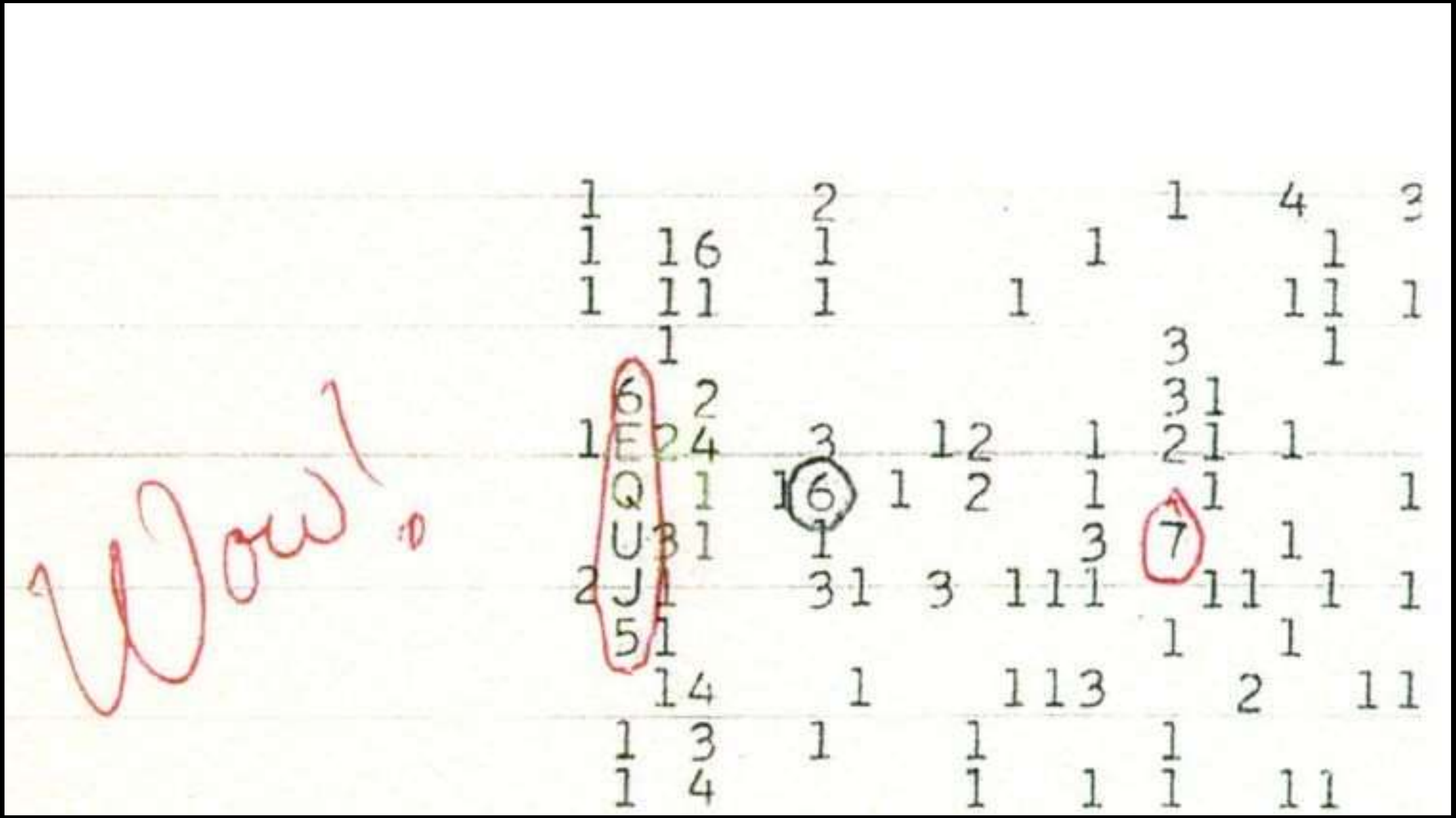
Credit: gsp.humboldt.edu/

SETI pioneer Frank Drake made the first SETI observations of nearby stars in the 1960s, using the 21 cm line of hydrogen.

This was called Project Ozma.

Credit: NRAO/AUI/NSF

In 1977, a very strong signal near 21 cm was detected by the Big Ear radio telescope. It's been dubbed the "Wow Signal". It didn't repeat and the source was never verified.



Credit: Big Ear Radio Observatory and North American AstroPhysical Observatory (NAAPO)

In late 2020, a candidate radio signal was detected from the direction of the nearest star, Proxima Centauri, which has a terrestrial planet in its habitable zone. It didn't repeat and was probably interference from Earth.

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Space

This article is more than **3 months old**

Scientists looking for aliens investigate radio beam 'from nearby star'

Tantalising 'signal' appears to have come from Proxima Centauri, the closest star to the sun

Ian Sample
Science editor
@iansample
Fri 18 Dec 2020 06.00 GMT

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The Parkes telescope in New South Wales, Australia, that picked up the radio waves in April and May last year. Photograph: CSIRO/PR IMAGE

SETI has had ups and downs over the decades, switching from one observatory to another and one funding source to another.

So far, no firm detections of signals from extraterrestrial civilizations have been made.

However, as former SETI Institute director Jill Tarter likes to say, all SETI searches to date amount to searching a single glass of water from all the oceans of Earth.

Credit: Marcio Jose Sanchez / AP

Radio SETI makes sense, for the reasons we've mentioned, but our atmosphere is also transparent to visible light.

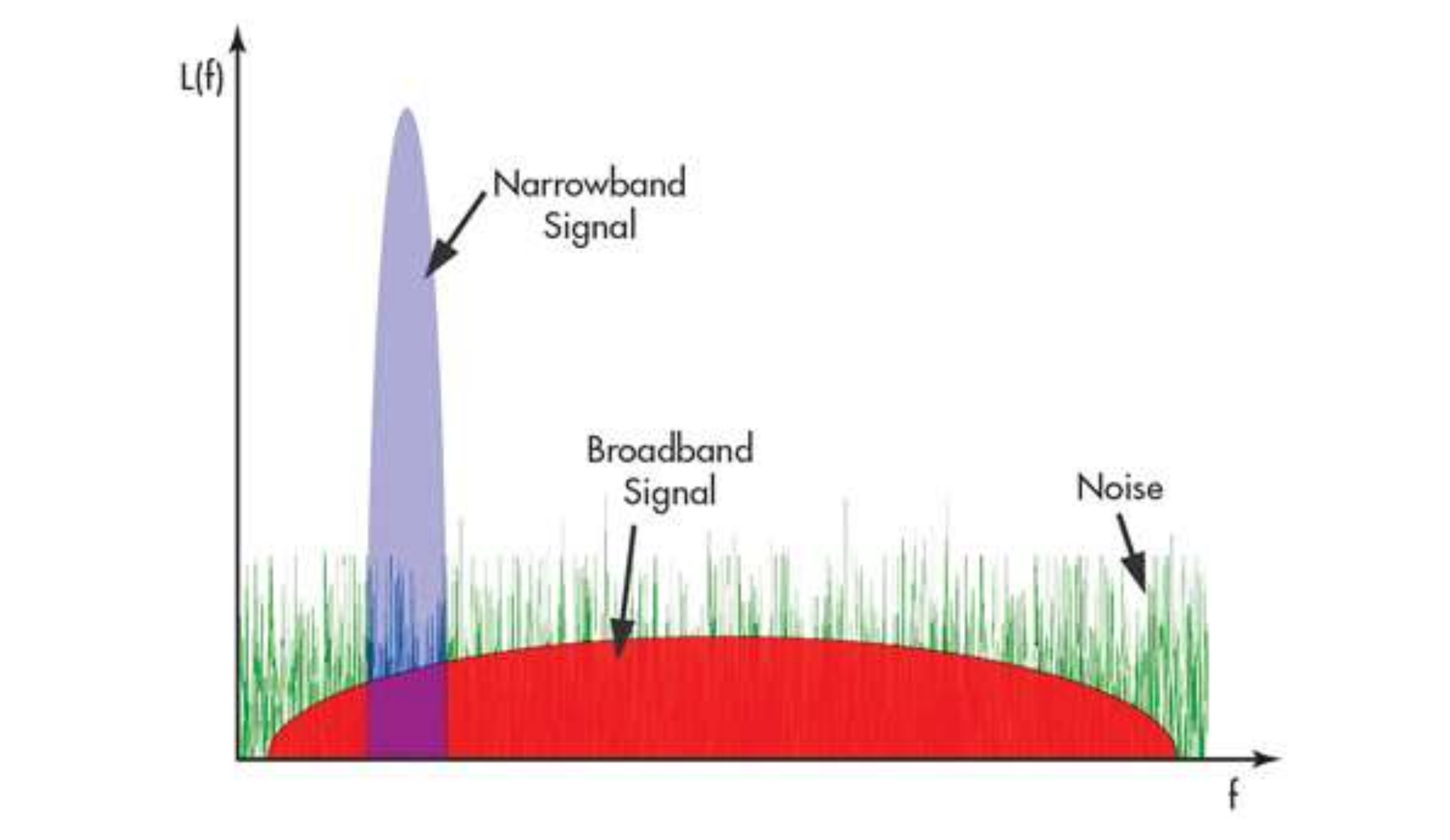
So, more recently, some of the focus has shifted to optical SETI.

Lasers can also be used to send messages over interstellar distances, and might be serendipitously detected by species studying many astronomical phenomena in visible or infrared light.

Credit: MIT

Most natural sources of light (whether visible, infrared, or radio) are "broadband", meaning that they consist of light of many, many different colours/frequencies (think of sunlight).

Narrowband signals are easier to detect against the background noise of the galaxy and are more clearly artificial.

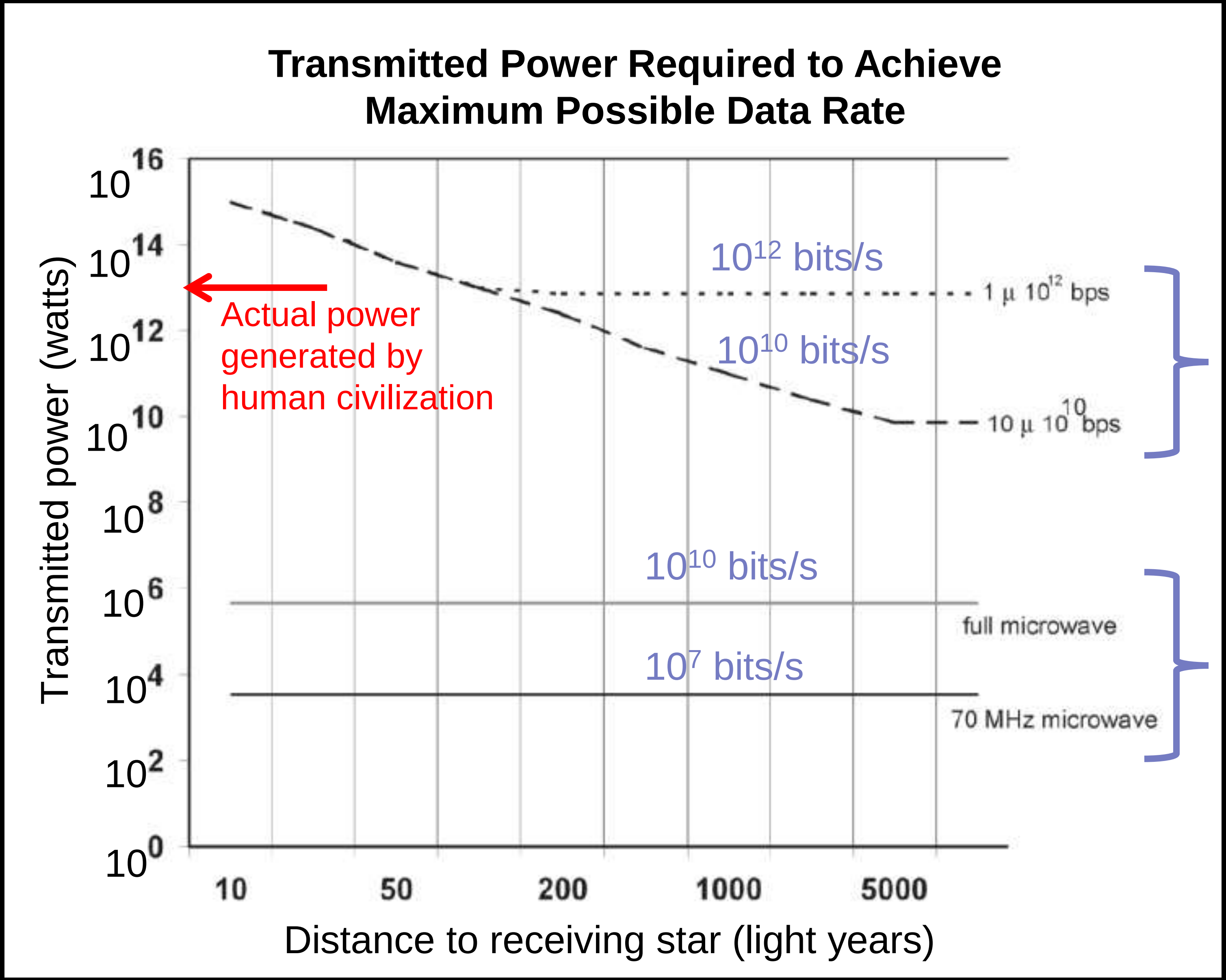


Credit: MWRF.com

Lasers are intrinsically narrowband (they consist of a single colour).

Radio signals can be made narrowband, but there are tradeoffs in information carrying capacity.

A major challenge in using lasers to send messages over interstellar distances is that the power requirements are much larger than for radio signals.



low and high data rate visible/near-infrared laser signals

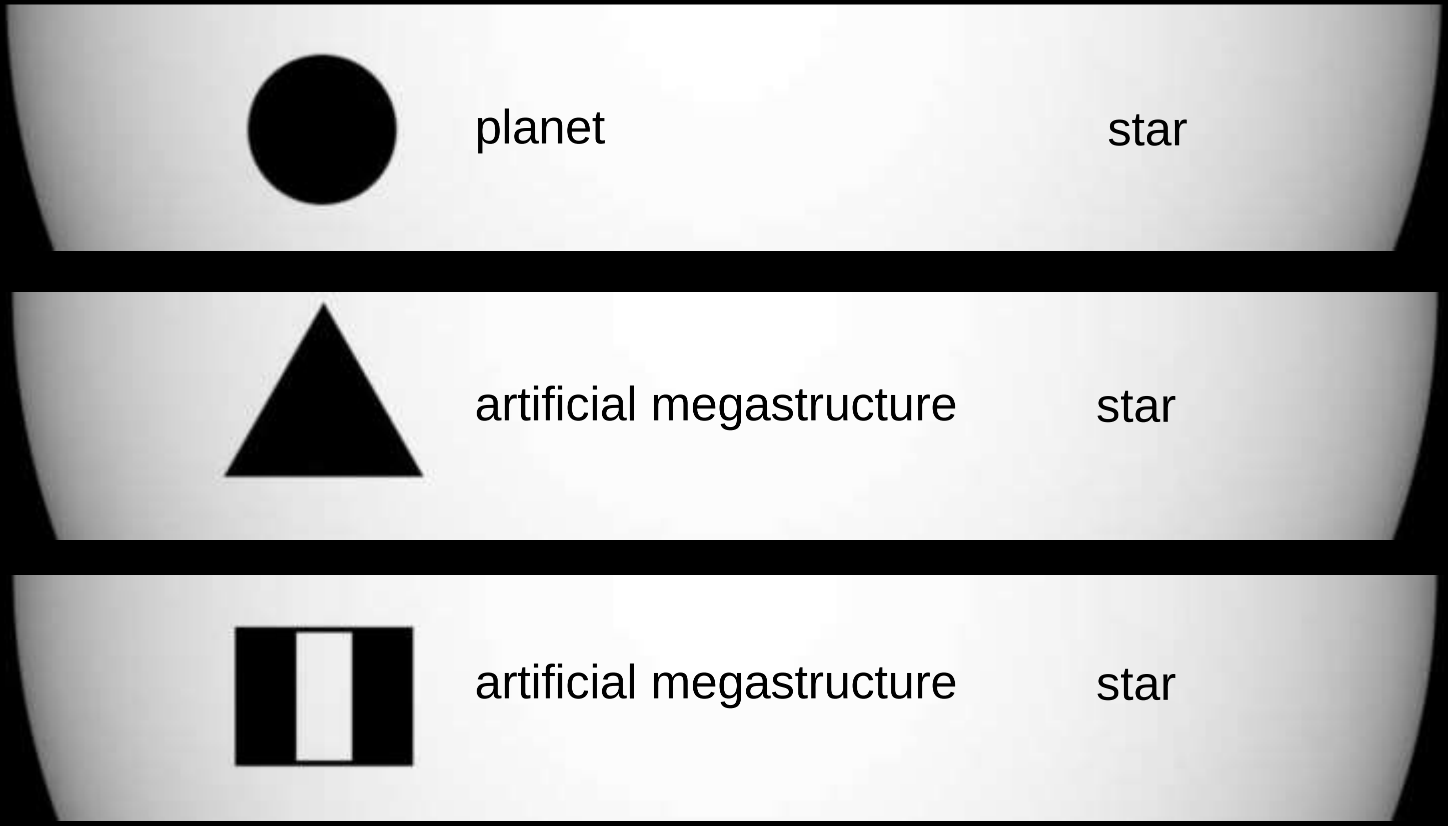
broad and narrowband radio signals

Credit: Shostak, 2013

The Search for Extraterrestrial Intelligence: Artifacts

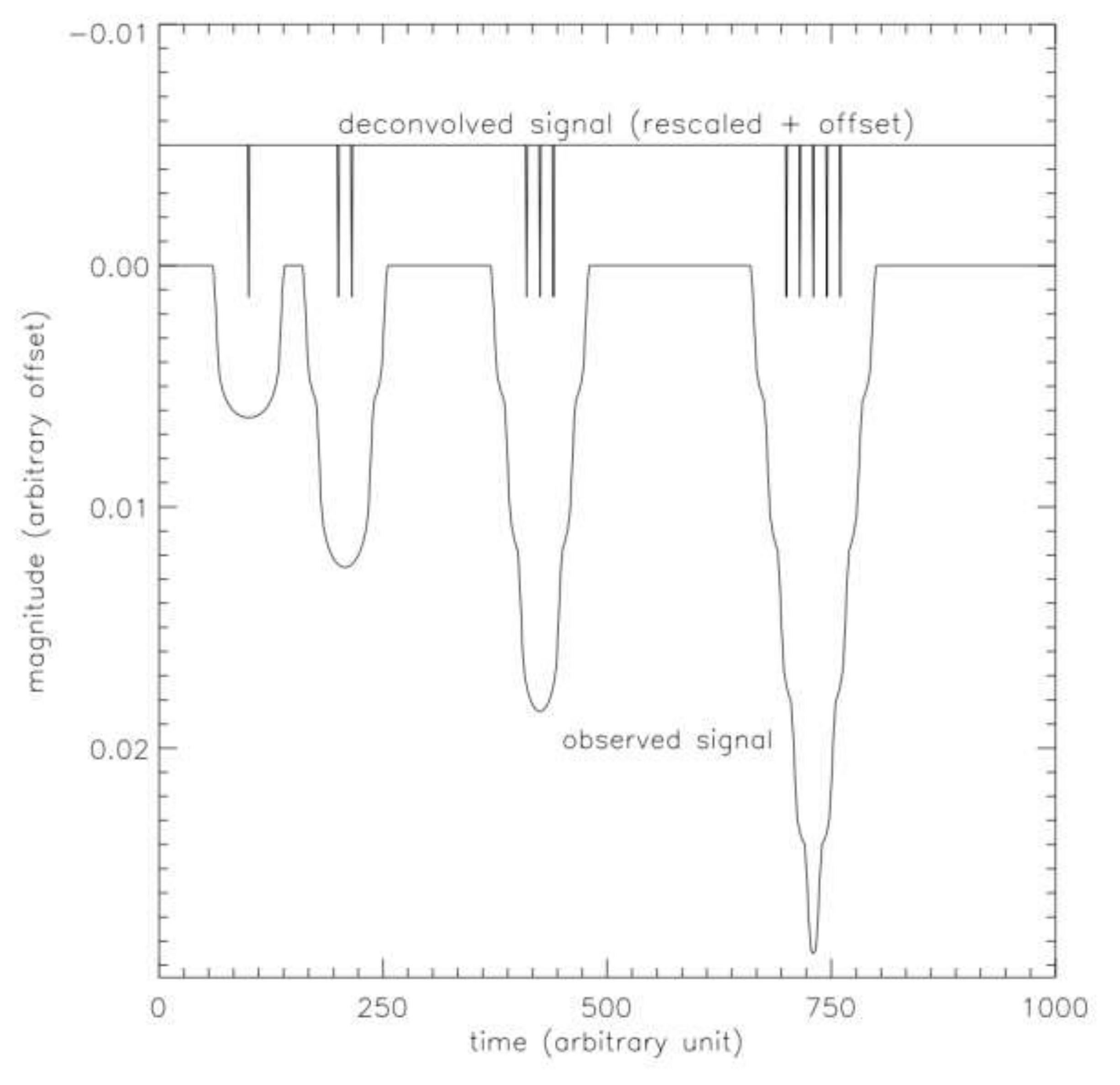
Instead of using transmitted signals to communicate, a civilization might choose to use megastructures or other artifacts.

Alien megastructures in orbit around their stars would produce characteristic transit signatures.



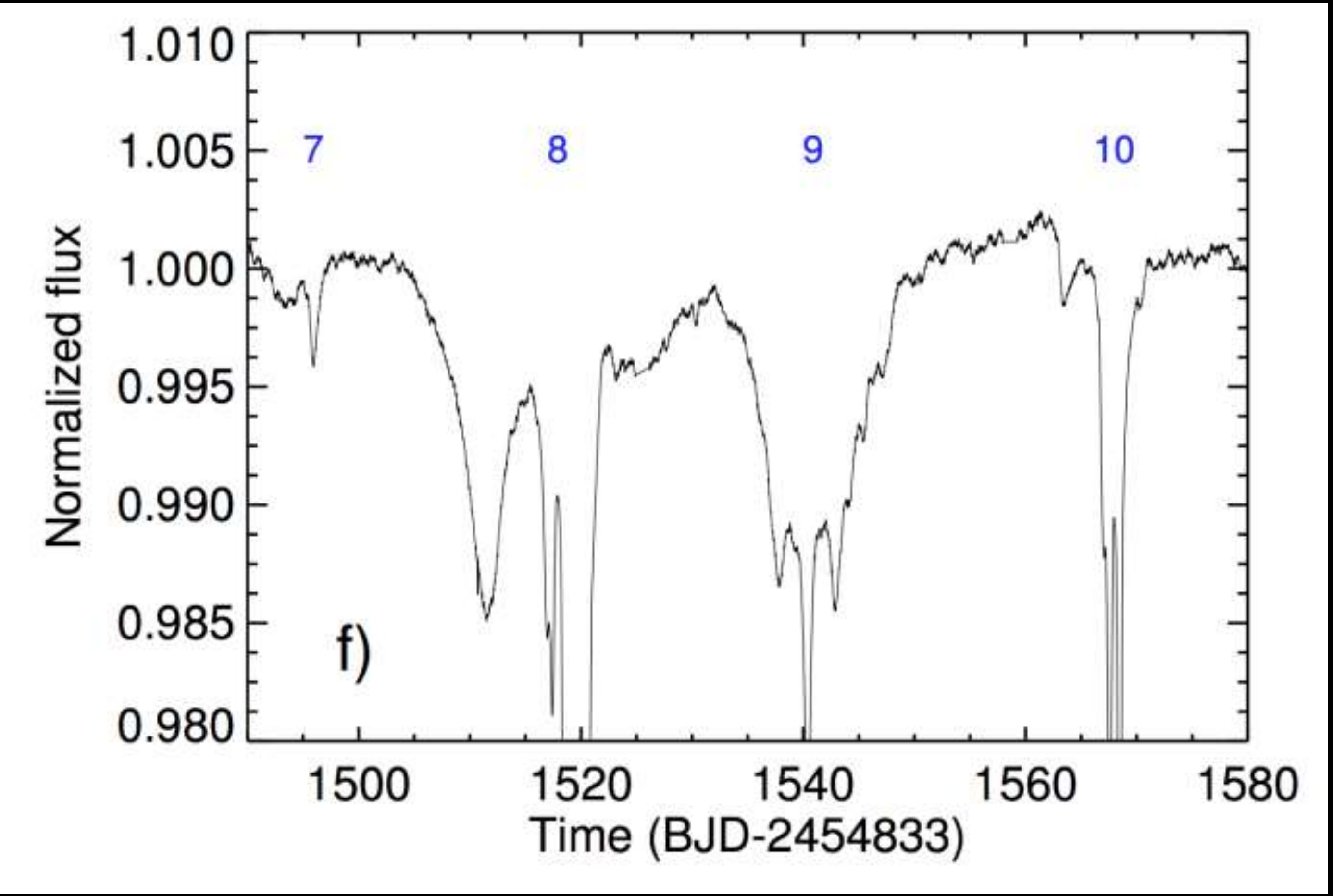
Credit: Arnold, 2005

ETCs could steer large structures into orbit around their stars to flash, for example, a sequence prime numbers or some other signal that would obviously be non-natural.



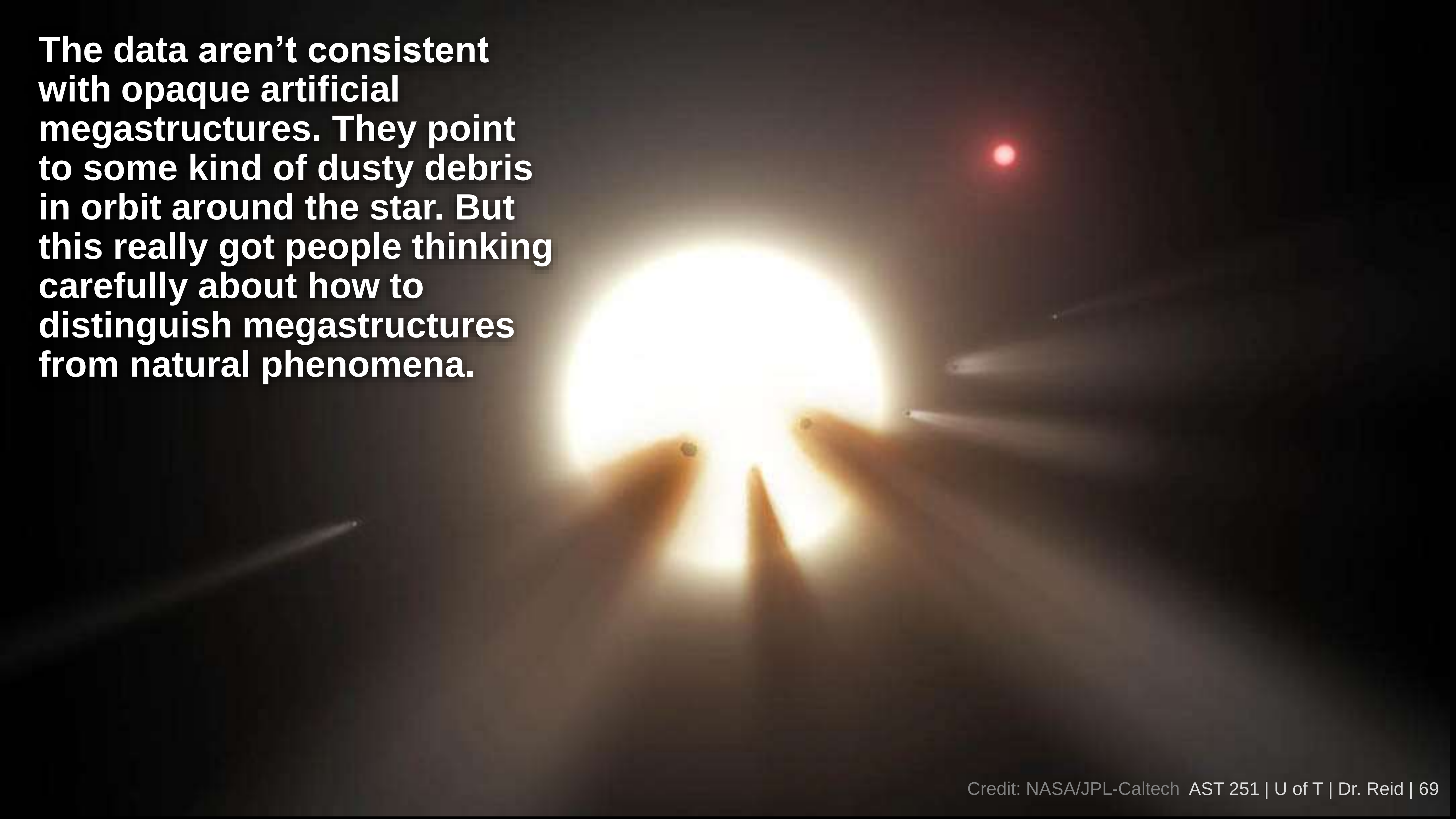
Credit: Arnold, 2005

In 2015, the Kepler Space Telescope detected large, irregular fluctuations in the light curve of the F-class star KIC 8462852, nicknamed “Tabby’s Star”



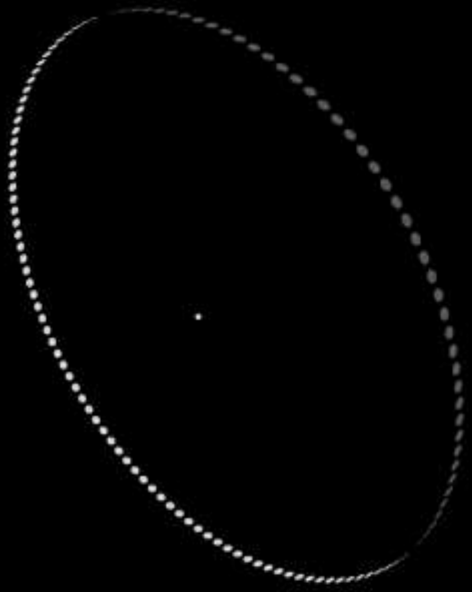
Credit: Boyajian et al. 2016

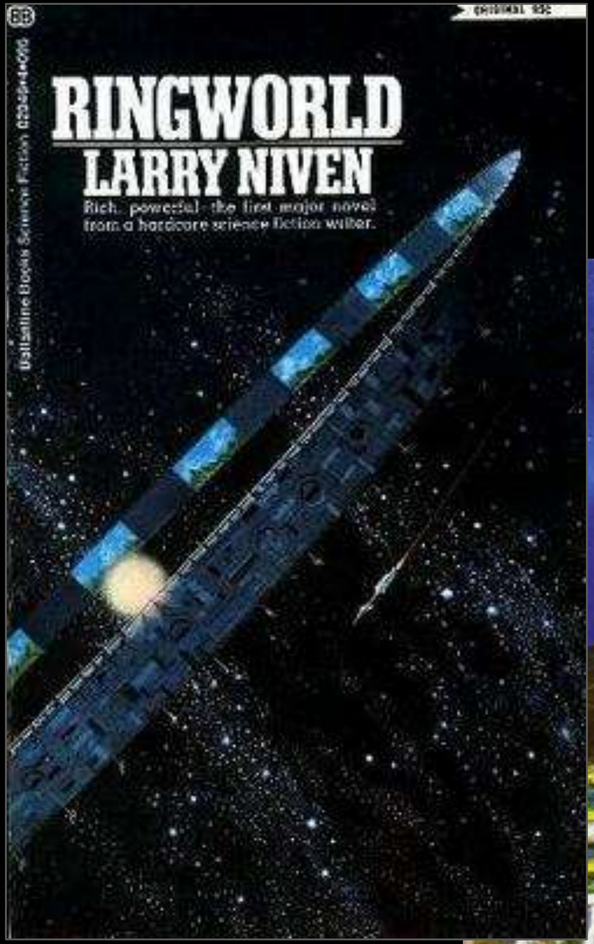
The data aren’t consistent with opaque artificial megastructures. They point to some kind of dusty debris in orbit around the star. But this really got people thinking carefully about how to distinguish megastructures from natural phenomena.



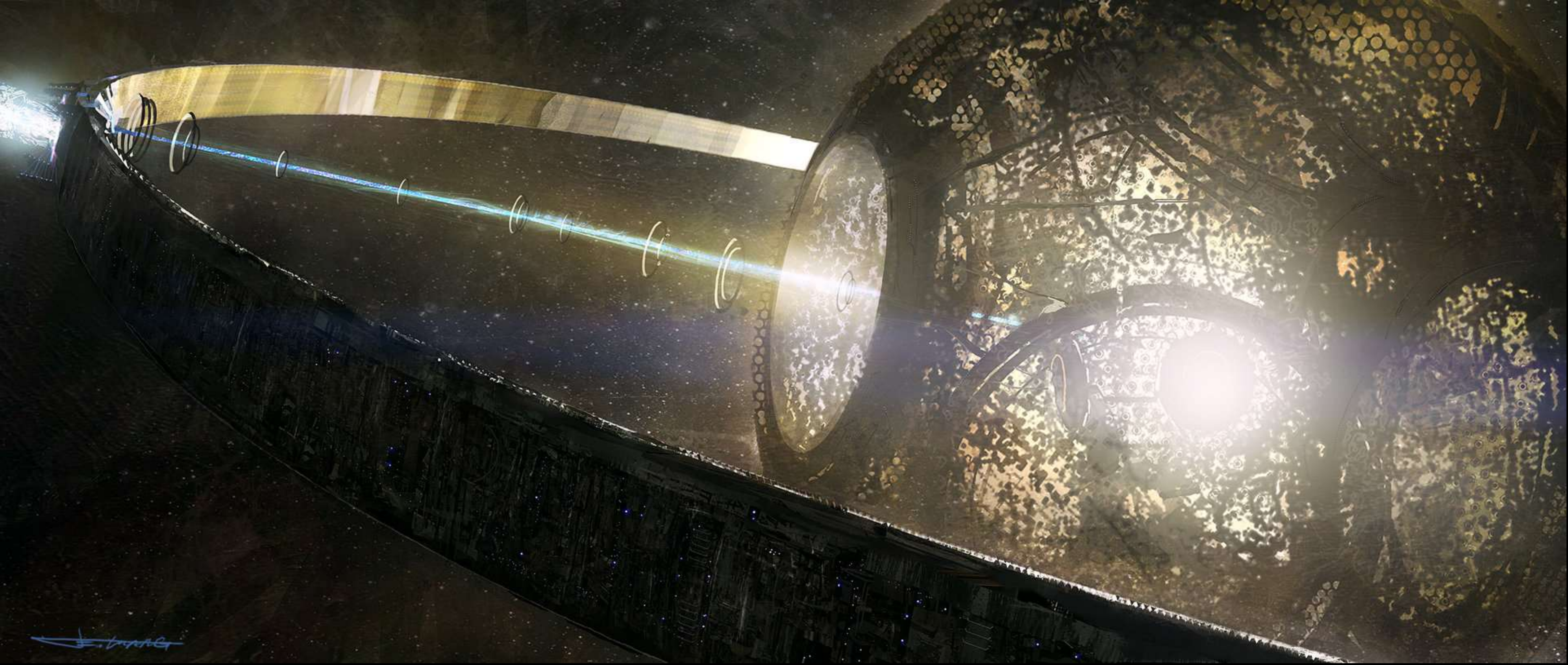
Credit: NASA/JPL-Caltech

A **Dyson ring** or **Dyson swarm** could consist of solar panels or habitats in orbit around a star, offering far more habitable space than a planetary surface.





Credit: Del Rey books; vedexent



A **Dyson sphere** would allow an advanced civilization to harness the entire energy output of a star.

Credit: Levy Wang

The **Kardashev Scale** attempts to categorize ETCs by the amount of energy they can manipulate:

Type I – can use all the energy received by their planet from their parent star

Type II – can capture all the energy of their parent star

Type III – can capture all of the energy of their parent galaxy

Tentative SETI searches have been conducted to look for the waste heat expelled by the enormous energy use of Kardashev Type II or III ETCs.

So far, no evidence of KII or KIII civilizations has been found.

Messaging Extraterrestrial Intelligence (METI)

Messaging Extraterrestrial Intelligence (METI) is the attempt to send information about ourselves to ETCs.

Our METI attempts have included both optical and radio messages, as well as artifacts.

Major question: if you could only have a one-time, one-way communication with an extraterrestrial, what would you say?

The 300m radio dish at the Arecibo Observatory in Puerto Rico was used for both SETI and METI, before it collapsed in 2020.

Credit: Arecibo Observatory

In 1974, the Arecibo Message was sent to the star cluster M13, 22,000 light years away.

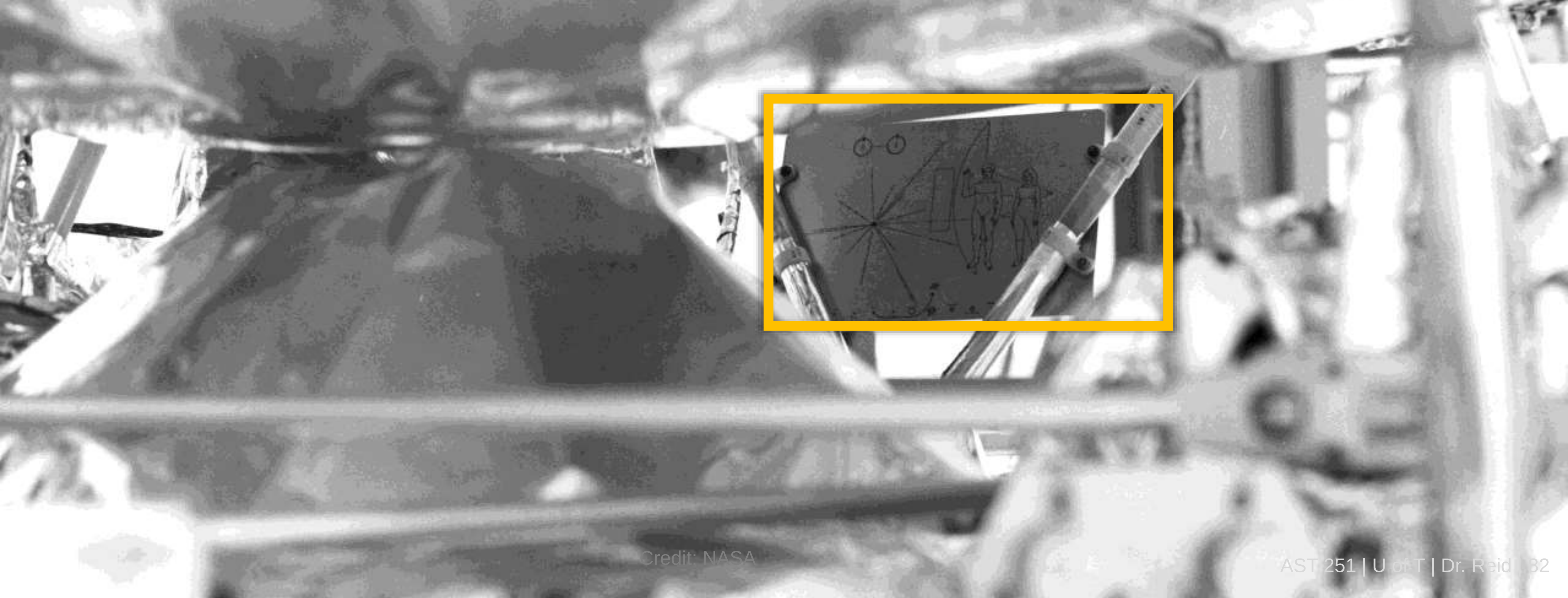
Credit: Adam Block, Mt. Lemmon SkyCenter, U. Arizona

Many other messages have been sent, including by the former Soviet Union, and groups around the world.

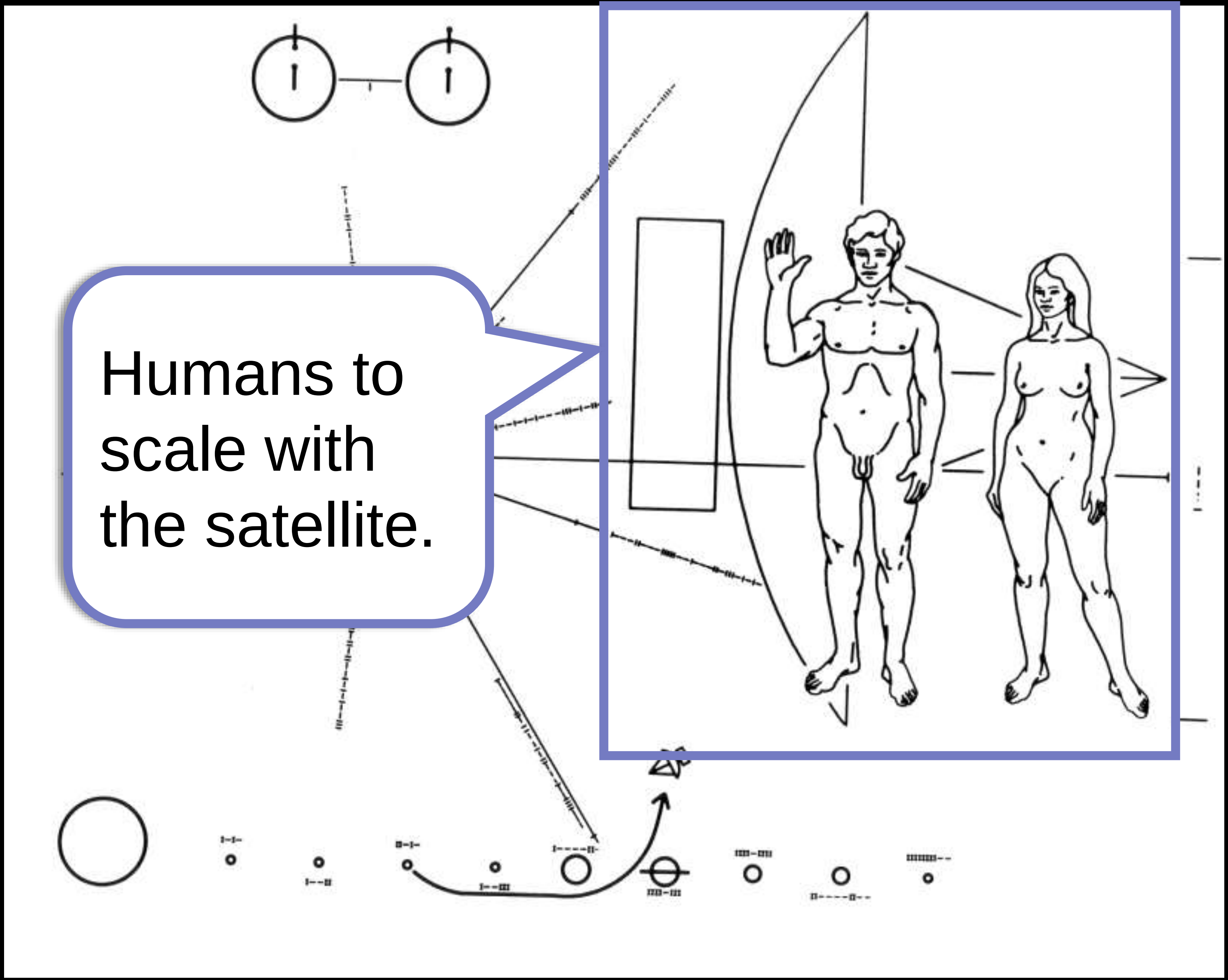
Another METI modality is to send physical objects beyond the solar system.

This has been done several times, including with several human spacecraft.

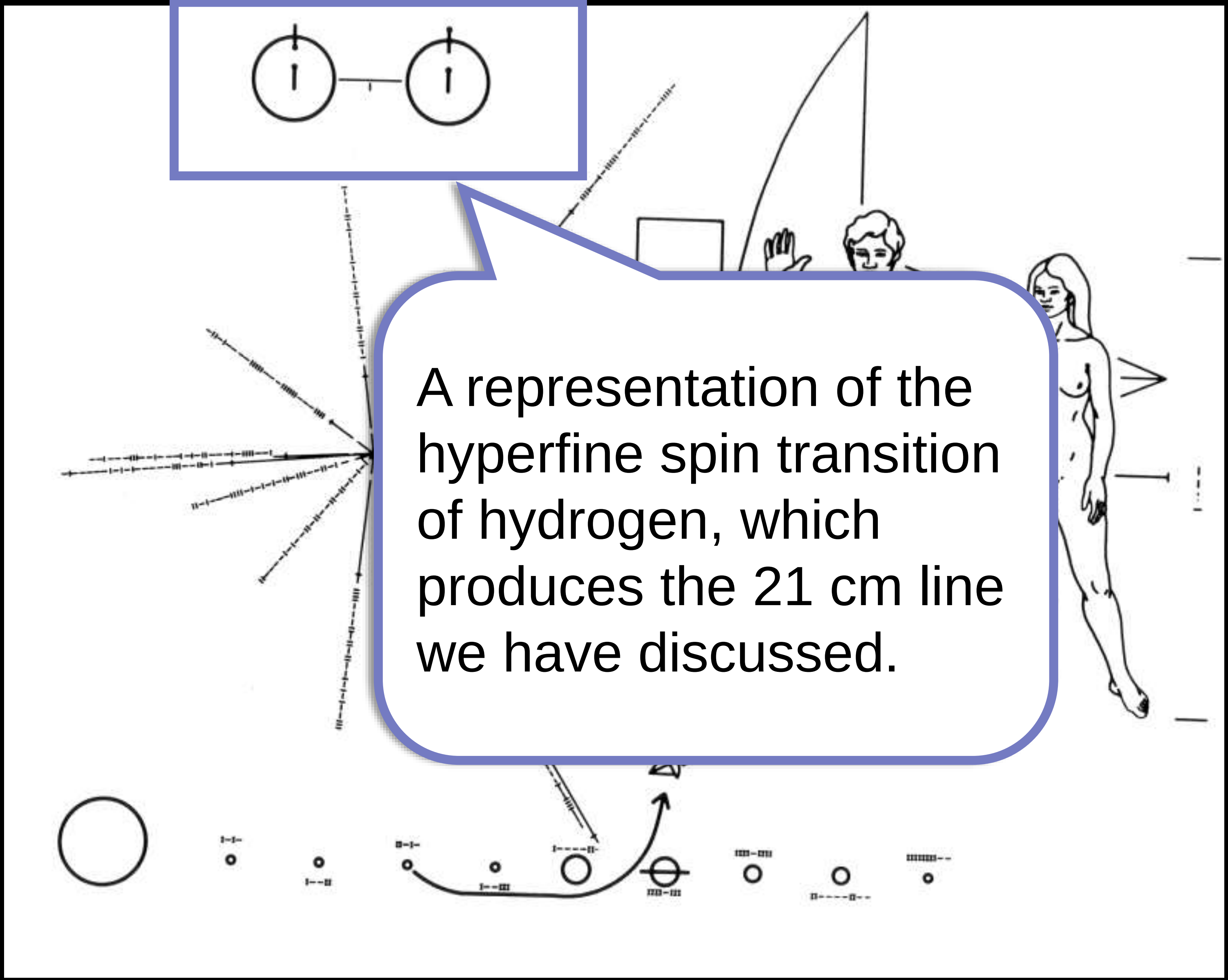
The Pioneer 10 and 11 spacecraft, launched in 1972 and 1973, both contained messages to ETCs on gold-anodized aluminum plaques.



Credit: NASA

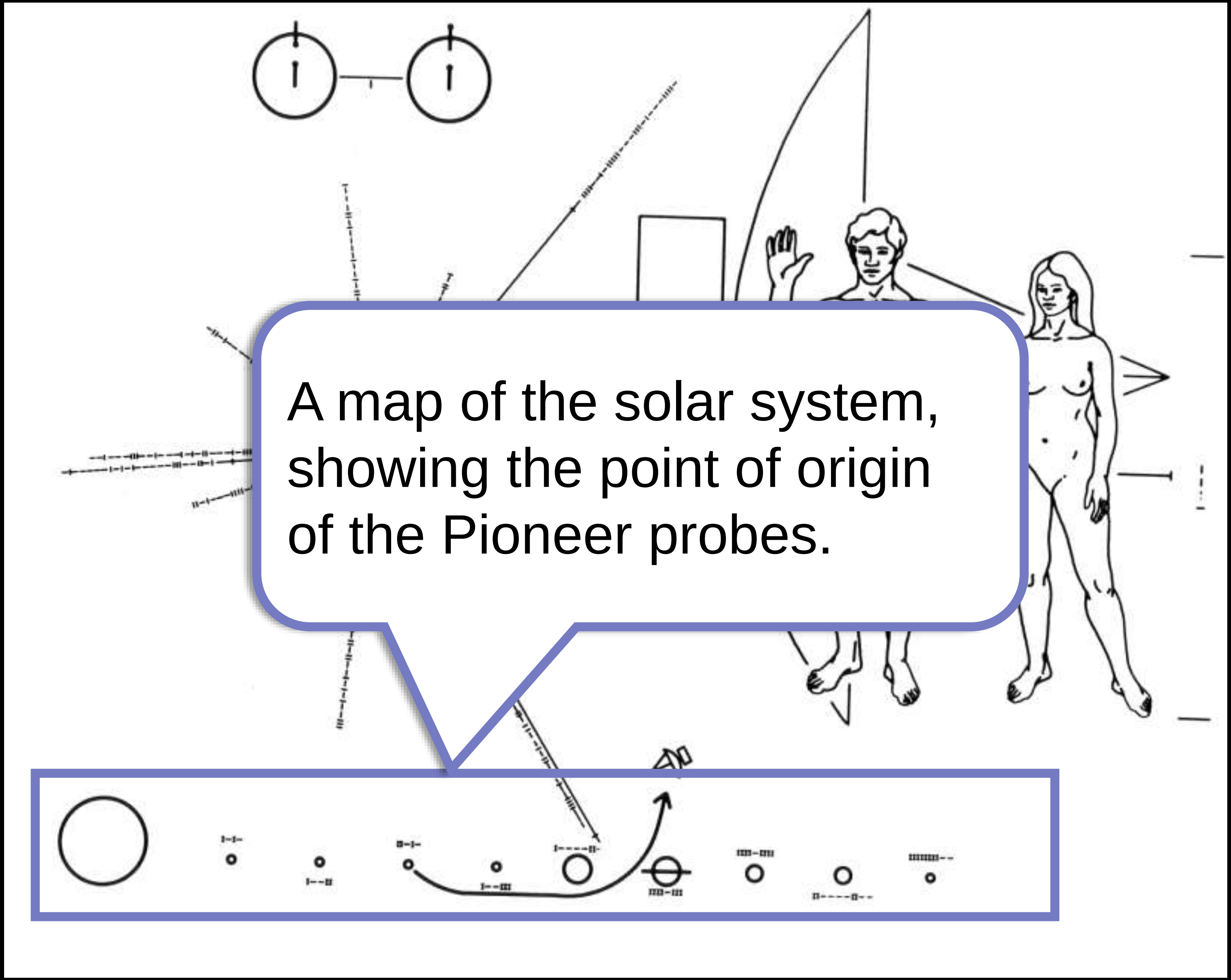


Credit: NASA



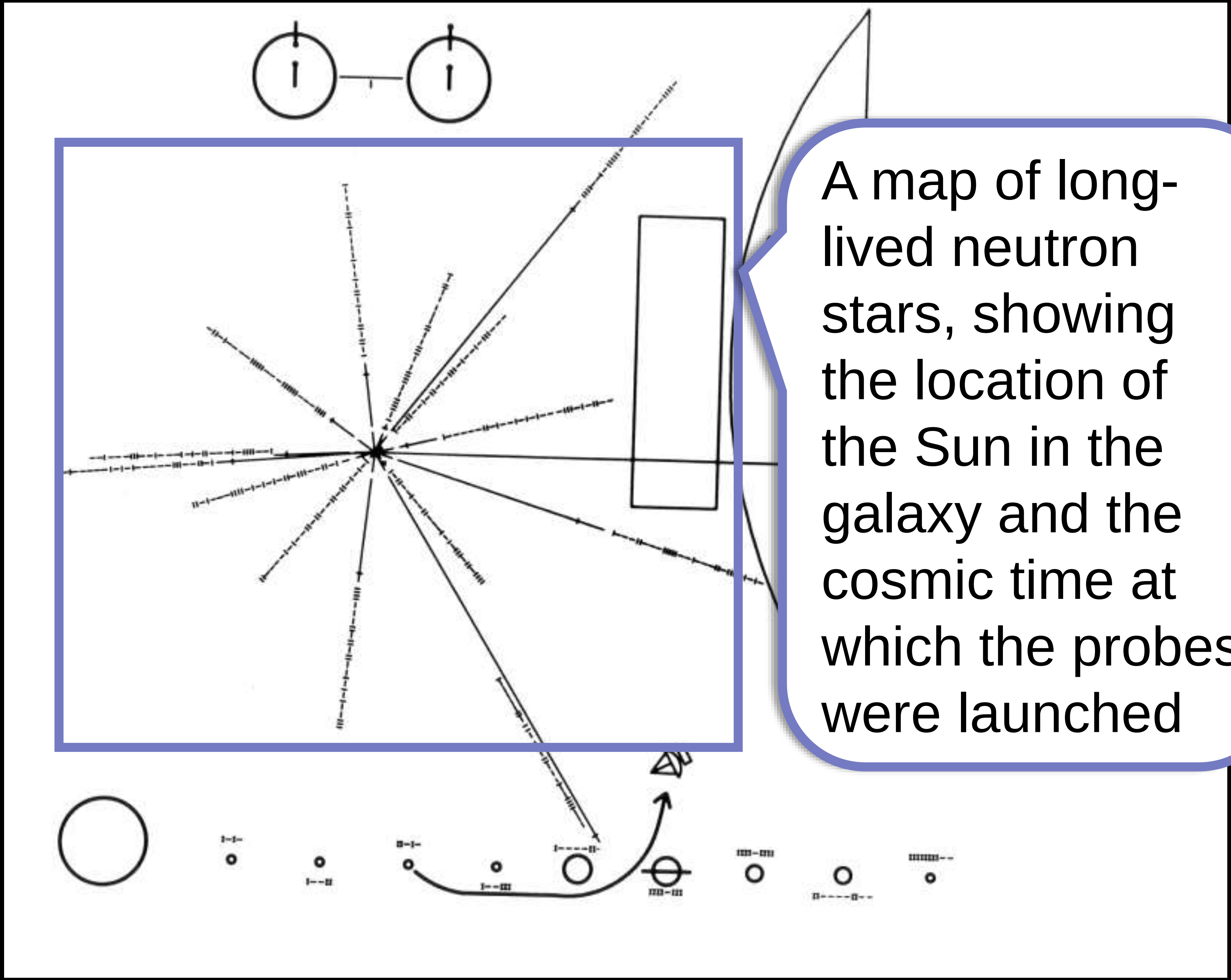
A representation of the hyperfine spin transition of hydrogen, which produces the 21 cm line we have discussed.

Credit: NASA



A map of the solar system, showing the point of origin of the Pioneer probes.

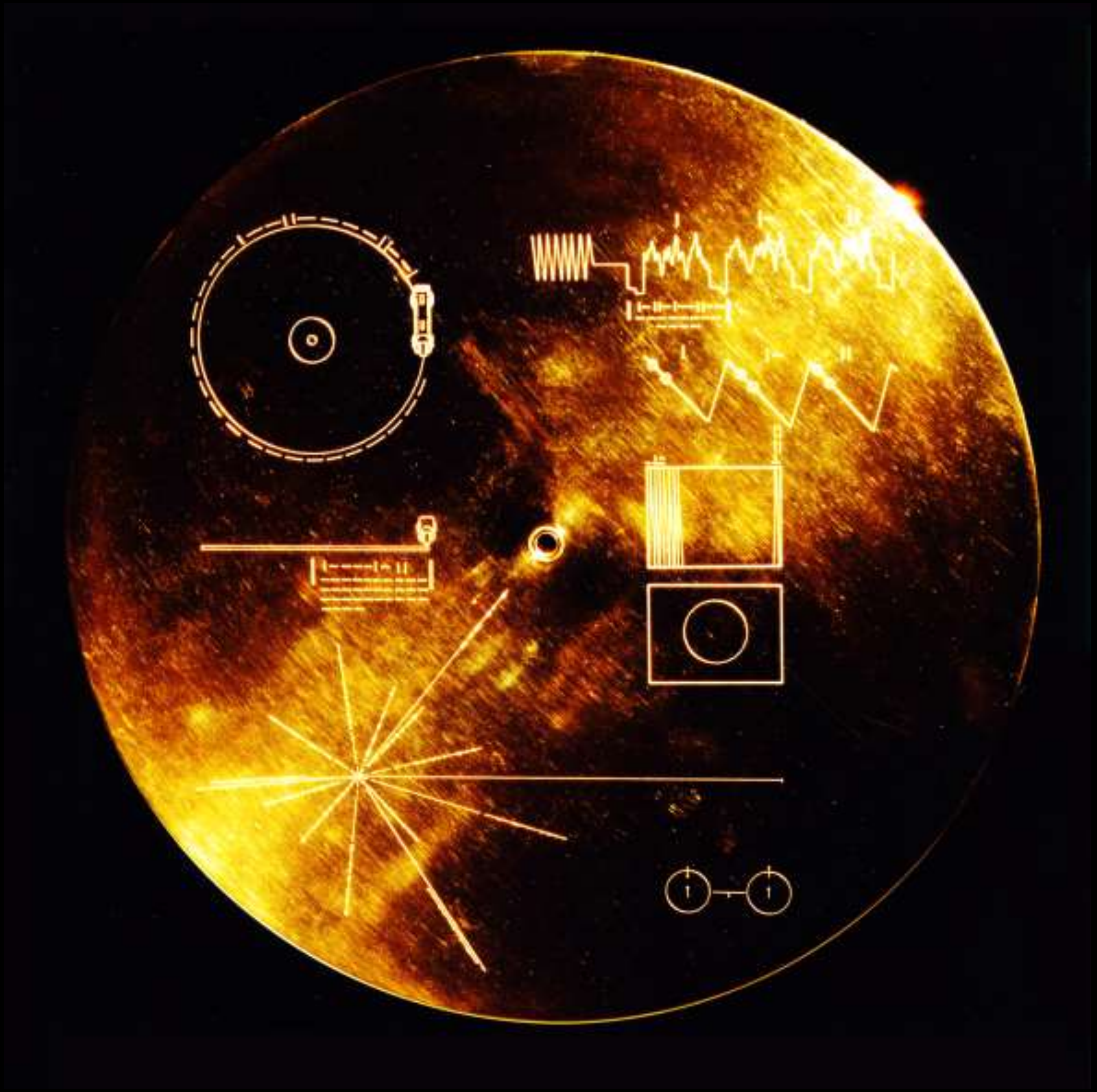
Credit: NASA



A map of long-lived neutron stars, showing the location of the Sun in the galaxy and the cosmic time at which the probes were launched

Credit: NASA

Voyager 1 and 2, launched in 1977, carried copies of the famous **Voyager Golden Record**.



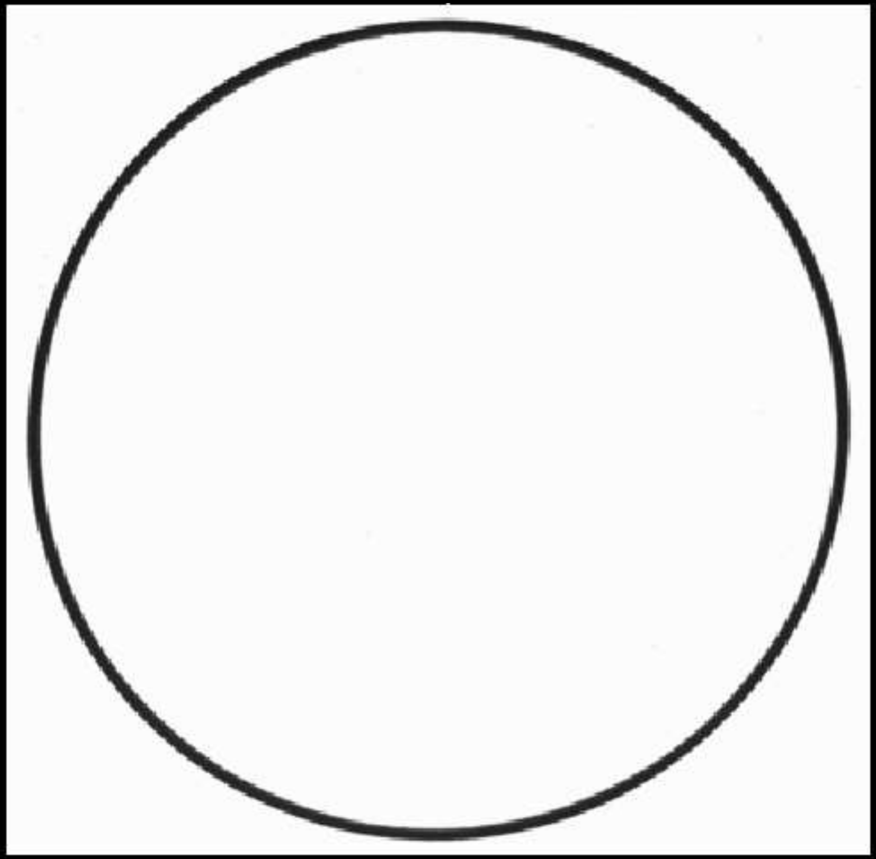
Credit: NASA

The back of each record is an actual old-school spinning record, encoding images and sounds.

Credit: NASA

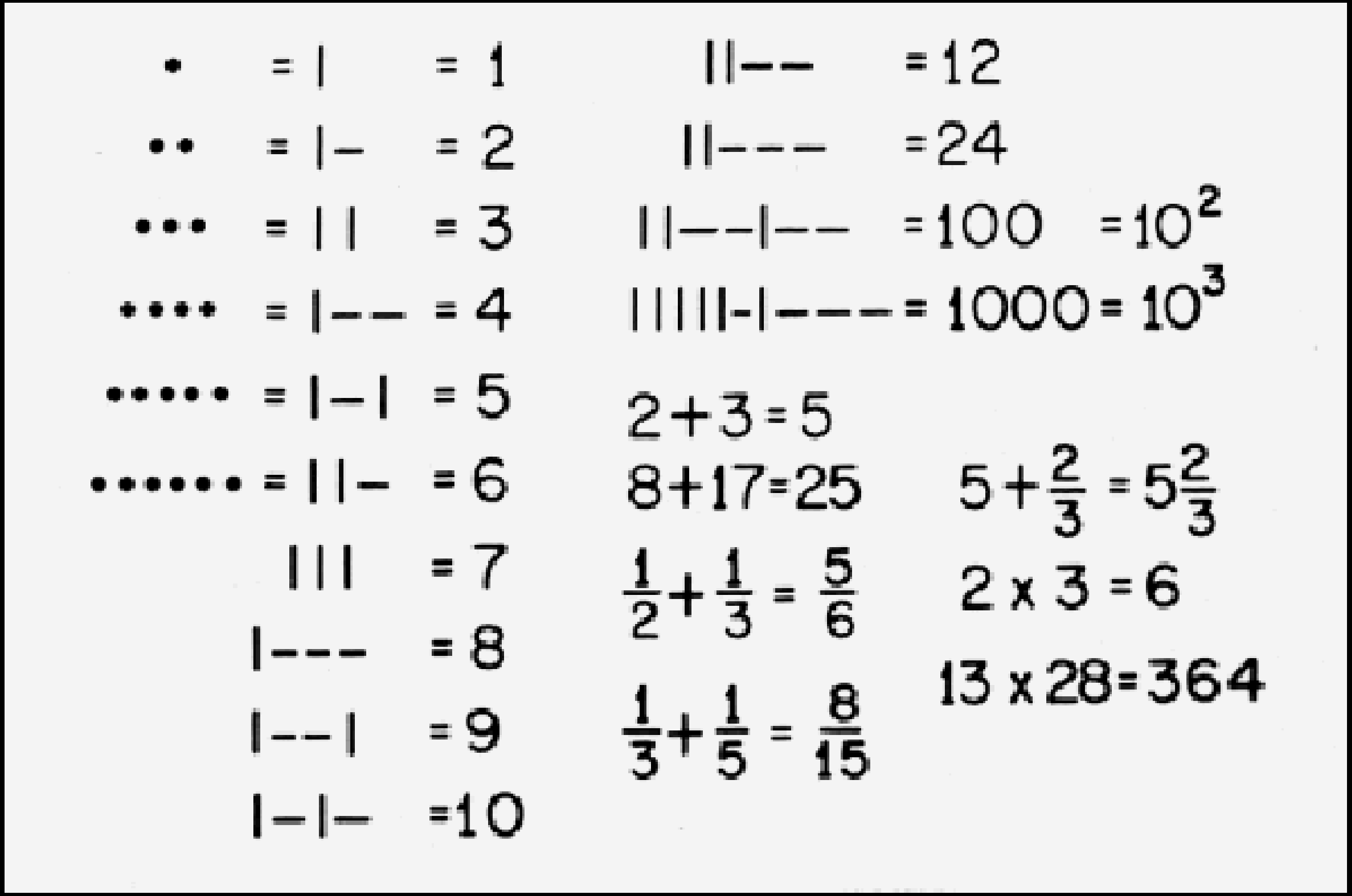
How do you communicate with an ETC, having no idea what they might be like?

The VGR starts with a circle, the implied instruction being "if this renders strangely, make it a circle and fix all the other images accordingly."



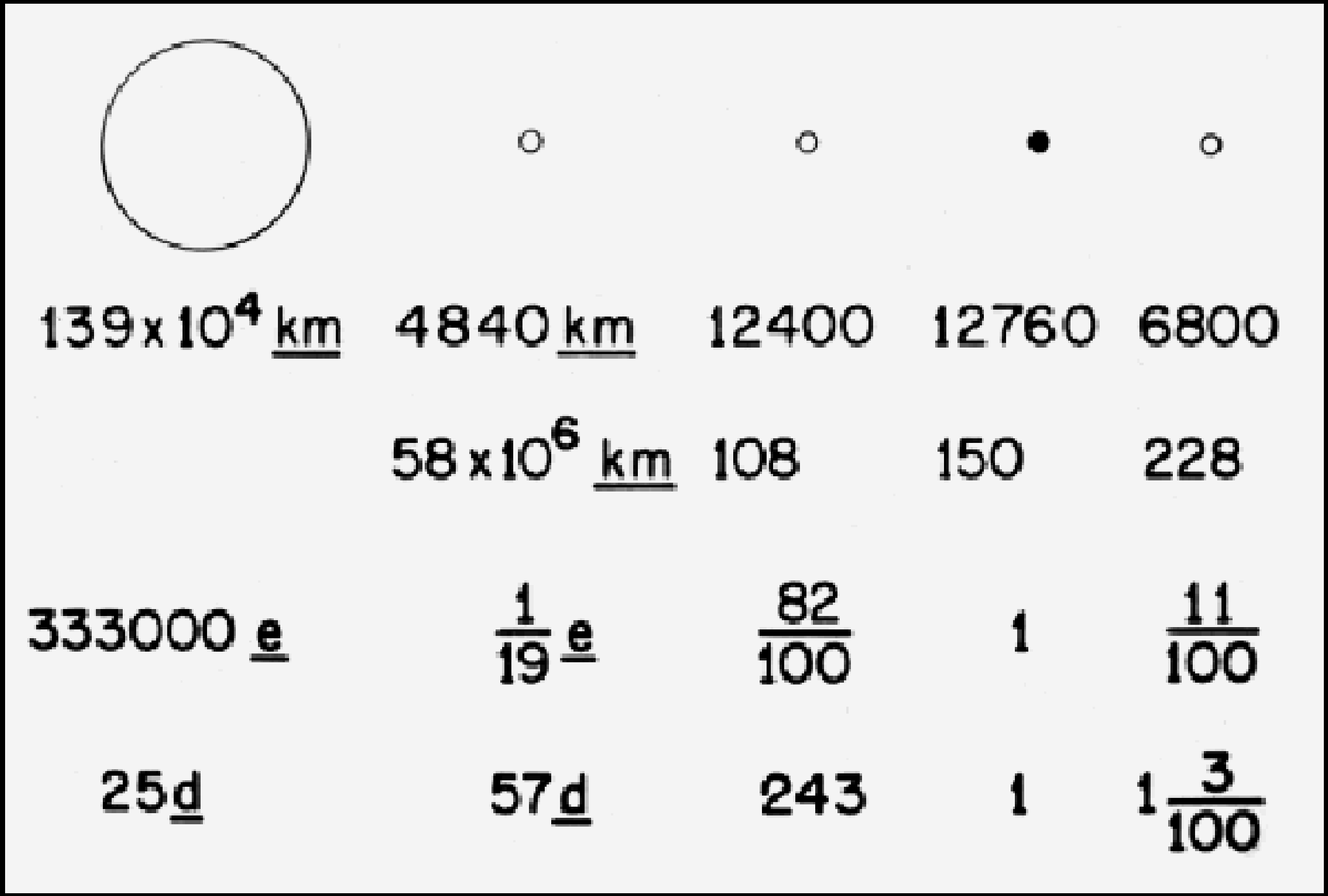
Credit: NASA

It goes on to explain our mathematics…



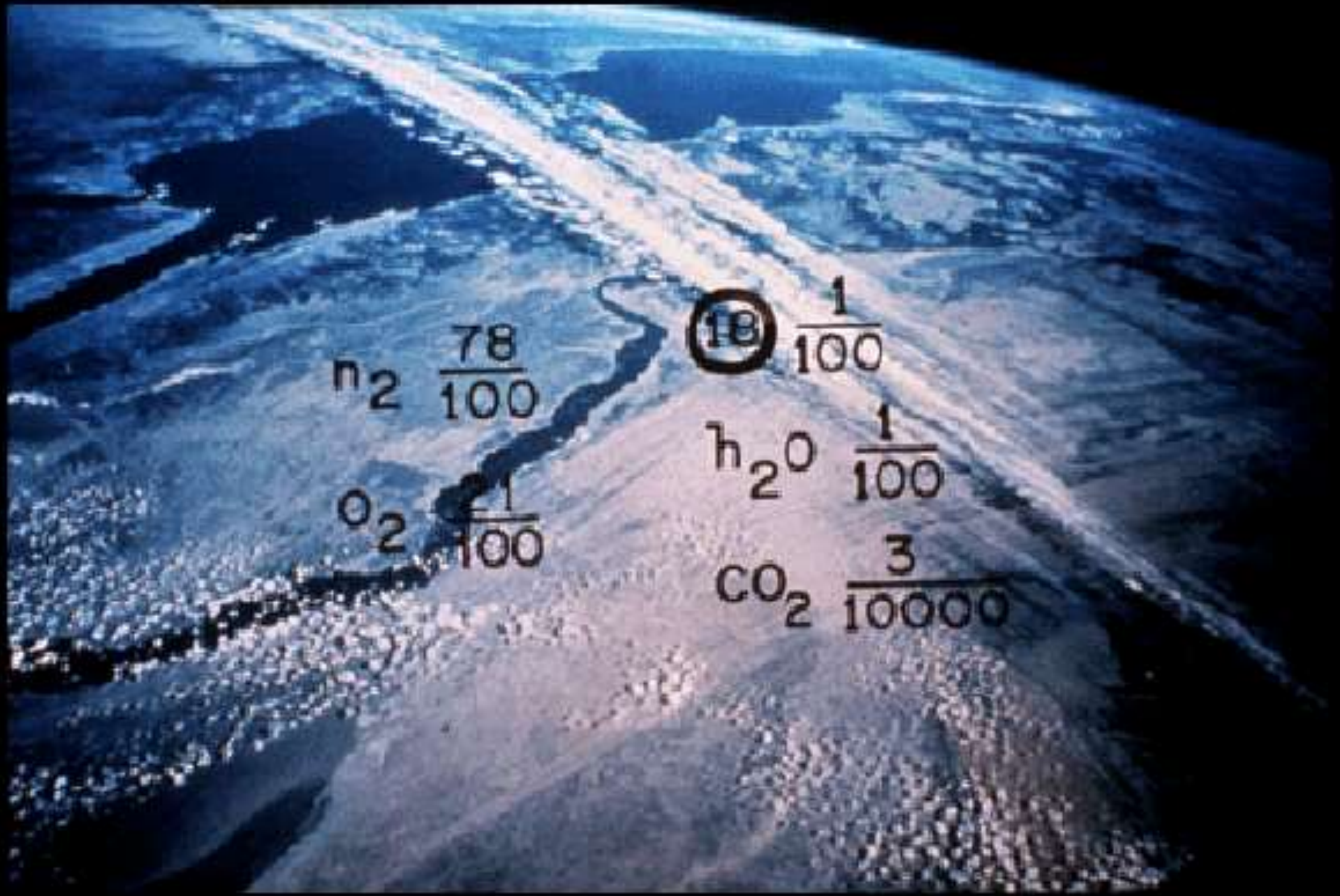
Credit: NASA

…to describe the solar system…



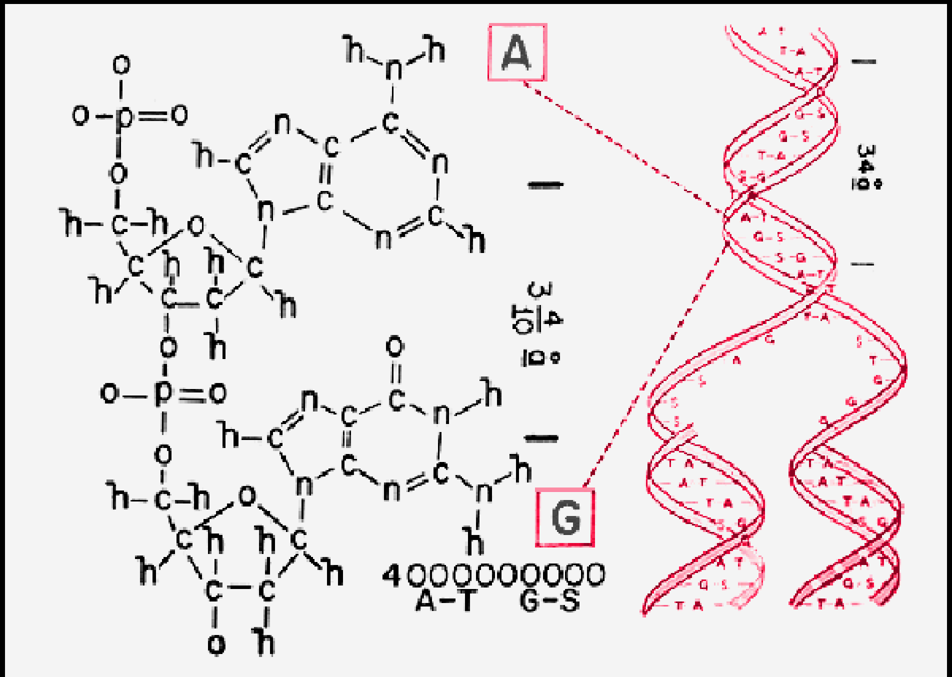
Credit: NASA

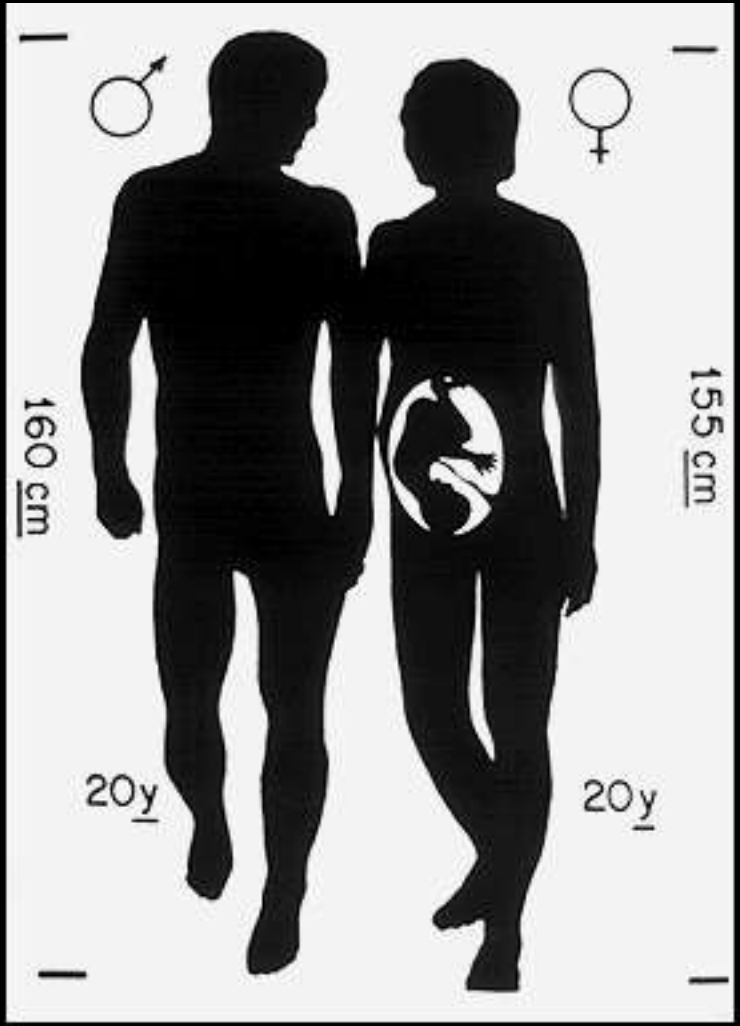
…to describe Earth…



NASA

…to summarize our biology…





Credit: NASA

…to show the diversity of our species…

Credit: NASA

…and to convey what our lives are like.

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It contains greetings in 56 languages.

Here is Canada’s greeting.

There were attempts to include communication from non-humans.

We remain on the lookout for similar attempts by other species to communicate with physical objects.

In October, 2017, an automated telescope in the Pan-STARRS network detected the first object of interstellar origin ever found in the solar system.

Asteroid `Oumuamua was already on its way out of the solar system when we found it (artist's conception).

Credit: ESO/M. Kornmesser

`Oumuamua has not made any sudden course changes and attempts to communicate with it or detect signals from it have all failed. It’s probably just a rock.

Credit: ESO/M. Kornmesser

A minority of astronomers, such as Avi Loeb at Harvard, believe that ‘Oumuamua was an artificial artifact of extraterrestrial origin.

Credit: Salon/Olivia Falcigno/Houghton Mifflin Harcourt

In Summary

- A robust detection of ET life will likely require the measurement of several carefully matched biosignatures
- Decades of radio and optical SETI searches have yielded no firm results, but only a tiny fraction of the Galaxy has been searched
- We continue to both send out artifacts and search for artifacts of other civilizations