

SPECTROSCOPIC DETECTION OF PHOSPHINE AND DIMETHYL SULFIDE AS POTENTIAL BIOSIGNATURES IN THE ATMOSPHERE OF THE SUB-NEPTUNE K2-18b WITH THE JWST/NIRSpec INSTRUMENT

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Abstract: The sub-Neptune K2-18b has become the most discussed object in the search for life beyond the Solar System. JWST transmission spectroscopy of its hydrogen-rich atmosphere has yielded firm detections of methane and carbon dioxide and a contested, repeatedly re-examined signal attributed to dimethyl sulfide — a molecule that on Earth is produced almost exclusively by marine life. Phosphine, a second gas long proposed as a biosignature, belongs to the same assessment problem. This article does not attempt to adjudicate whether the dimethyl sulfide signal is statistically real; independent reanalyses disagree, and that disagreement is treated here as data rather than as a question to be settled. Instead, the article advances a conceptual argument that holds whichever way the statistics fall. Drawing on fifteen Scopus-indexed studies and seven institutional sources, I introduce and develop the principle of detection–biogenicity decoupling: on a hydrogen-rich sub-Neptune, the atmospheric properties that maximize the spectroscopic detectability of a candidate biosignature molecule — low mean molecular weight, an extended scale height, a large transit signal, and a reducing photochemistry — are the same properties that maximize its abiotic production and accumulation. Detectability and biogenic diagnosticity are therefore not independent; they are structurally anti-correlated. The very features that make K2-18b an efficient JWST/NIRSpec target make it an inefficient biosignature target. The principle is supported by three lines of evidence: the spectral degeneracy of the candidate molecules with abiotically plausible species such as ethane in the NIRSpec range; the demonstrated abiotic synthesis of dimethyl sulfide in cometary and interstellar environments entirely devoid of life; and the photochemical plausibility of organosulfur and phosphorus chemistry in a hydrogen-dominated envelope. The implication is that a NIRSpec detection, however statistically robust, cannot by itself constitute a biosignature on a hydrogen-rich world, and that biosignature assessment must shift from the detection of a molecule to the demonstration that its abundance exceeds the abiotic ceiling for its specific planetary context.

Keywords: K2-18b, biosignatures, dimethyl sulfide, phosphine, JWST NIRSpec, sub-Neptune atmospheres, detection–biogenicity decoupling.

INTRODUCTION

No exoplanet has carried as much public expectation as K2-18b. A sub-Neptune of roughly 8.6 Earth masses orbiting a cool red dwarf 124 light-years away (NASA Exoplanet Archive, 2024), it sits within the region around its star where a planet could, in principle, support liquid water

(Tsiaras et al., 2019). When JWST turned its instruments on the planet, the result was a transmission spectrum of a hydrogen-rich atmosphere containing methane and carbon dioxide at high confidence, together with a weaker feature that the discovery team attributed, tentatively, to dimethyl sulfide (Madhusudhan et al., 2023; National Aeronautics and Space Administration, 2023). On Earth, dimethyl sulfide is produced almost entirely by marine phytoplankton; it has essentially no large abiotic source on our planet. The suggestion that the same molecule might be present in the atmosphere of a distant world was, understandably, reported as the strongest hint yet of life beyond the Solar System.

The history since that announcement is a cautionary one, and it is the reason this article is framed the way it is. A follow-up campaign with JWST's mid-infrared instrument reported a strengthened signal, now attributed to dimethyl sulfide or the related molecule dimethyl disulfide, at a confidence the discovery team placed near three standard deviations (Madhusudhan et al., 2025). Independent groups then reanalyzed the same data. A comprehensive reanalysis of the near-infrared spectrum, using multiple data-reduction pipelines and retrieval codes, confirmed methane but found no statistically significant evidence for dimethyl sulfide (Schmidt et al., 2025). A joint analysis spanning all three JWST instruments concluded that the mid-infrared data are fit equally well by molecules such as ethane, and that the evidence for dimethyl sulfide and dimethyl disulfide is insufficient (Luque et al., 2025). The detection, in short, is contested, and the contestation is itself instructive.

This article takes a deliberate decision at the outset. It does not attempt to determine whether the dimethyl sulfide signal is statistically real. That question is being actively litigated by groups with direct access to the data and the retrieval machinery, and it would be presumptuous, and probably futile, for a synthesis article to add another verdict to a disagreement among specialists. The disagreement is instead treated here as a datum — a fact about the state of the evidence that any honest assessment must incorporate. The question this article asks is different and, I will argue, prior: even if the dimethyl sulfide signal were confirmed beyond statistical doubt, would a NIRSpec detection of dimethyl sulfide or phosphine on K2-18b constitute a biosignature? The phrasing matters. The conditional is doing real work. I want to ask what a detection would mean, not whether there is one.

The reason for posing the question this way is that the two candidate molecules in the title — dimethyl sulfide and phosphine — are routinely described as biosignature gases, and that description quietly imports a conclusion. Phosphine was proposed as a biosignature on the grounds that, in an oxidized terrestrial-type atmosphere, it has no known abiotic source at appreciable abundance (Sousa-Silva et al., 2020). Dimethyl sulfide was proposed on similar grounds. But K2-18b does not have an oxidized terrestrial-type atmosphere. It has a hydrogen-dominated, chemically reducing envelope, and the abiotic chemistry of such an envelope is a different problem from the abiotic chemistry of Earth's air. A molecule that is a reliable biosignature in one atmospheric context may be an unremarkable photochemical product in another. The label travels; the underlying logic does not.

Three hypotheses organize the analysis. The first holds that the spectral features attributed to dimethyl sulfide and phosphine in the NIRSpec wavelength range are not uniquely diagnostic of those molecules, because they overlap with the absorption bands of abiotically plausible species — ethane and other methyl-bearing carbon compounds in particular — so that a NIRSpec detection cannot, on spectral grounds alone, establish the identity of the carrier. The second hypothesis, which is the conceptual core of the article, holds that on a hydrogen-rich sub-Nep- tune the atmospheric properties that maximize the spectroscopic detectability of a candidate biosignature molecule are the same properties that maximize its abiotic production, so that detectability and biogenic diagnosticity are structurally anti-correlated rather than independent. The

third holds that the current K2-18b evidence does not meet the standard of proof that a biosignature claim requires, and that the disagreement among independent reanalyses is itself a symptom of a marginal signal rather than of a genuine detection awaiting confirmation.

The original contribution of this article is the principle named in the second hypothesis, which I term detection–biogenicity decoupling. The principle is a single conceptual claim: for hydrogen-rich sub-Neptunes, detectability and biogenicity are anti-correlated, because the low mean molecular weight, extended atmospheric scale height, large transit signal, and reducing photochemistry that make a molecule easy to detect with transmission spectroscopy are the same conditions that supply abiotic production pathways and allow the molecule to accumulate. The principle reframes the K2-18b debate. It implies that the question is not whether dimethyl sulfide is present, nor even at what statistical confidence, but whether the retrieved abundance exceeds the abiotic ceiling for a hydrogen-rich envelope — and that a NIRSpect measurement, which constrains the abundance but says nothing about the ceiling, cannot answer that question on its own. To my knowledge the literature on K2-18b discusses spectral degeneracy and abiotic production as separate caveats; it has not articulated the structural anti-correlation between detectability and diagnosticity as a single named principle. Naming it, and showing that it holds independently of how the statistical dispute is resolved, is the contribution.

The article is structured as follows. The next section reviews the observational and theoretical literature on K2-18b and biosignature gases and sets out the methodology. A Research Results section presents a molecular inventory of the candidate species and develops the decoupling principle. Three analytical sections then examine the spectral degeneracy problem, the abiotic production pathways available in a hydrogen-rich envelope, and the consequences of the decoupling principle for how biosignature claims should be evaluated. The conclusion returns to the three hypotheses and identifies the observations that could, in principle, break the decoupling.

LITERATURE REVIEW AND METHODOLOGY

Literature Review

The literature relevant to this article divides into four strands: the characterization of K2-18b itself, the hycean-world hypothesis, the JWST observations and their reanalyses, and the theory of biosignature gases.

The characterization of K2-18b began with the detection of water vapor in its atmosphere. Tsiaras et al. (2019), using Hubble Space Telescope spectroscopy, reported water absorption and described the planet as the first habitable-zone world with a detected atmosphere; Benneke et al. (2019), analyzing overlapping data, concurred on the water detection but emphasized that the hydrogen-dominated envelope makes the planet emphatically not an Earth analog. The distinction set the terms of everything that followed. K2-18b is a sub-Neptune — larger and more gas-rich than a rocky planet — and the central interpretive question has always been what lies beneath its hydrogen atmosphere.

The hycean-world hypothesis is the answer that has driven the search for biosignatures. Madhusudhan et al. (2020) modeled the interior and atmosphere of K2-18b and found a range of solutions in which a liquid-water layer could exist beneath the hydrogen envelope. Madhusudhan et al. (2021) generalized this into the concept of hycean worlds: sub-Neptunes with deep liquid-water oceans under hydrogen-rich atmospheres, argued to be promising and observationally accessible habitats. The hycean hypothesis is what makes the dimethyl sulfide question urgent — if K2-18b has a habitable ocean, a marine biosignature gas would be the expected signpost. But the hypothesis is not the only interpretation on offer. Wogan et al. (2024)

showed that the JWST data are equally consistent with a gas-rich mini-Neptune that has no habitable surface at all, and favored that interpretation on grounds of simplicity. Shorttle et al. (2024) argued that K2-18b may be too hot for a liquid-water ocean and that a magma ocean beneath the hydrogen envelope reproduces the observed spectrum. The interior of K2-18b remains genuinely unresolved, and the biosignature question cannot be cleanly separated from that unresolved interior.

The JWST observations and their reanalyses form the third strand and the most contested. Madhusudhan et al. (2023), using JWST's NIRISS and NIRSpec instruments, reported methane at high confidence, carbon dioxide at lower confidence, and a tentative dimethyl sulfide feature. Madhusudhan et al. (2025) added mid-infrared data and reported a strengthened organosulfur signal near three standard deviations. Against these, three independent analyses pushed back. Schmidt et al. (2025), reanalyzing the near-infrared spectrum with multiple pipelines, confirmed methane at high confidence but found neither carbon dioxide nor dimethyl sulfide to be statistically significant. Luque et al. (2025), in a joint analysis of all three JWST instruments, found that ethane and other methyl-bearing molecules fit the mid-infrared data as well as dimethyl sulfide does, and concluded that the evidence for the organosulfur biosignature is insufficient. The disagreement is not about the data, which all groups share; it is about data reduction, retrieval modeling, and the assessment of statistical significance. That the same spectrum yields a biosignature in one analysis and a flat-line-compatible non-detection in another is, I argue later, a fact of central importance.

The theory of biosignature gases is the fourth strand, and it belongs to a search whose strategic priorities have been articulated at the community level (National Academies of Sciences, Engineering, and Medicine, 2019). Sousa-Silva et al. (2020) made the case for phosphine as a biosignature, modeling the atmospheres in which it could accumulate to detectable levels and emphasizing that the strength of the case depends entirely on the absence of abiotic sources in the relevant atmospheric context. Dimethyl sulfide has been argued to be an observable biomarker specifically on hycean worlds, which is why its tentative appearance on K2-18b was treated as significant (Madhusudhan et al., 2023). But the abiotic-source question, which Sousa-Silva et al. (2020) flagged as decisive, has since been answered in an unwelcome direction. Hänni et al. (2024) reported evidence for dimethyl sulfide in the matter of comet 67P/Churyumov-Gerasimenko — an environment with no plausible biology — establishing that the molecule has an abiotic synthetic pathway. Subsequent work has detected dimethyl sulfide in the interstellar medium. The molecule that was proposed as a biosignature on the grounds that it lacks abiotic sources has now been found in two abiotic settings. This is the single most consequential development for the K2-18b biosignature claim, and it is the empirical anchor of the present analysis.

Two instrument references complete the picture. The NIRSpec spectrograph, described by Jakobsen et al. (2022) and characterized for exoplanet work by Birkmann et al. (2022), is the instrument whose data underpin the near-infrared detections; the broader JWST mission is described by Gardner et al. (2023). These references matter here because the decoupling principle is, in part, a claim about what an instrument operating in the NIRSpec wavelength range can and cannot establish, and that claim has to be grounded in the instrument's actual spectral coverage and resolution.

What the literature has not done, in my reading, is connect its scattered caveats into a single structural claim. The spectral degeneracy of dimethyl sulfide with ethane is noted (Luque et al., 2025); the abiotic synthesis of dimethyl sulfide is documented (Hänni et al., 2024); the hydrogen-rich photochemistry that could produce organosulfur and phosphorus species is discussed in the hycean literature. Each is treated as a separate caveat appended to a detection claim. The contribution of this article is to argue that these are not separate caveats but facets of one principle,

and that the principle has a definite structure — an anti-correlation between detectability and diagnosticity — that the caveat-by-caveat treatment obscures.

Research Methodology

The methodology is conceptual and synthetic. The article does not present new observations or new retrievals; it develops a principle and tests it against the published record. The work proceeded in four steps.

The first step was the assembly of a molecular inventory. For each candidate biosignature molecule relevant to K2-18b — dimethyl sulfide, dimethyl disulfide, and phosphine — and for the two firmly discussed context molecules, methane and carbon dioxide, I recorded from the cited literature the principal absorption bands that fall within the 0.6 to 5.3 micron range covered by NIRSpec (Jakobsen et al., 2022; Space Telescope Science Institute, 2023), the spectrally overlapping or confounding species that absorb in the same region, and the abiotic production pathways that have been proposed or demonstrated for a hydrogen-rich environment. The underlying JWST observations of K2-18 b, and the data products on which the cited retrievals are based, are archived and documented by the mission's science operations (European Space Agency, 2023) and distributed through the Mikulski Archive for Space Telescopes (Space Telescope Science Institute, 2024). The inventory is presented as Table 1 and is the empirical basis for the spectral-degeneracy argument.

The second step was the articulation of the decoupling principle. I examined, one by one, the atmospheric properties that make a molecule detectable in transmission spectroscopy on a sub-Neptune — low atmospheric mean molecular weight, large scale height, a large planet-to-star radius contrast that amplifies the transit signal, and a chemically reducing environment that favors particular molecular families — and asked, for each, whether the same property also bears on abiotic production or accumulation. The principle is the finding that every one of these detectability-enhancing properties is also a biogenicity-degrading property. The principle was then stated as a single proposition and its scope defined: it applies to hydrogen-rich sub-Neptunes and does not apply, or applies far more weakly, to oxidized terrestrial atmospheres.

The third step was a robustness check against the statistical dispute. Because the principle is intended to hold regardless of whether the dimethyl sulfide signal is real, I tested it against both outcomes. If the signal is a statistical artifact, the principle is not needed to dismiss the biosignature claim, but it explains why even a real detection would not rescue it. If the signal is genuine, the principle is exactly what is needed, because it shows that a genuine detection of dimethyl sulfide on a hydrogen-rich world is consistent with a lifeless planet. The principle, in other words, is constructed to be insensitive to the dispute it is meant to clarify, and the methodology includes the explicit verification that it is.

The fourth step was the derivation of the principle's consequences for biosignature assessment, including the reframing of the central question from the abundance of a molecule to the relationship between that abundance and the abiotic ceiling for the planet's specific context. Here I should state a limitation candidly. The article asserts that abiotic pathways exist for dimethyl sulfide and phosphine in a hydrogen-rich envelope, and it grounds the dimethyl sulfide claim firmly in the cometary and interstellar detections (Hänni et al., 2024). The quantitative abiotic ceiling — the maximum abundance that abiotic chemistry can sustain in K2-18b's specific atmosphere — is not computed here, because computing it requires a photochemical model of that atmosphere that is beyond the scope of a synthesis article. The principle establishes that the ceiling is non-zero and probably substantial; it does not establish its exact value. That is a real limitation, and it is revisited in the conclusion. What the principle does establish is structural: that the

ceiling cannot be assumed negligible on a hydrogen-rich world, and therefore that a detection cannot be read as a biosignature without it.

RESEARCH RESULTS

The synthesis produced two principal results: the molecular inventory of Table 1, and the decoupling principle that the inventory and the atmospheric analysis jointly support.

The molecular inventory, presented in Table 1, organizes the five relevant species by their spectral behavior in the NIRSpec range and their abiotic accessibility in a hydrogen-rich atmosphere. Two patterns emerge from it. The first is that the two firmly discussed molecules, methane and carbon dioxide, are not biosignatures on K2-18b under any interpretation: both have abundant abiotic sources in a reducing or a mixed envelope, and their detection, however robust, carries no biological information. The second pattern is the one that matters for the candidate biosignatures. Dimethyl sulfide and dimethyl disulfide absorb in the carbon–hydrogen stretch region near 3.4 microns, a region they share with ethane and with other methyl-bearing carbon compounds; phosphine absorbs near 4.3 microns, overlapping the strong carbon dioxide band. In every case, the candidate biosignature molecule's principal NIRSpec feature is spectrally degenerate with a molecule that is abiotically unremarkable. The inventory thus supports the first hypothesis directly: the NIRSpec features are not uniquely diagnostic of the candidate molecules.

The decoupling principle is the second and central result, and it can be stated as a single proposition. On a hydrogen-rich sub-Neptune, the atmospheric properties that maximize the transmission-spectroscopy detectability of a candidate biosignature molecule are the same properties that maximize that molecule's abiotic production and accumulation; consequently detectability and biogenic diagnosticity are not independent variables but structurally anti-correlated ones. The supporting argument runs property by property. A hydrogen-rich atmosphere has a low mean molecular weight, which produces a large atmospheric scale height; the large scale height is what makes transmission features deep and detectable, and it is also what allows a photochemically produced trace molecule to be distributed through a large, observable atmospheric column. The chemically reducing environment of a hydrogen-dominated envelope favors the hydrogenated and methylated molecular families to which dimethyl sulfide, dimethyl disulfide, and phosphine all belong; the same reducing chemistry that builds the spectral feature builds the molecule abiotically. The extended, low-gravity-scale-height atmosphere that the hycean hypothesis identifies as observationally favorable is, by the same token, photochemically productive. There is no property in the list that enhances detectability without also enhancing abiotic supply. That exhaustiveness is what makes the relationship a principle rather than a coincidence.

A consequence follows immediately, and it is the result with the sharpest operational edge. The hycean framework selects, as its most promising biosignature targets, precisely the hydrogen-rich sub-Neptunes with the most extended atmospheres — because those are the planets whose biosignature gases are easiest to detect. The decoupling principle says that those same planets are the ones on which a detected biosignature gas is hardest to attribute to life. The target-selection criterion and the diagnosticity criterion point in opposite directions. K2-18b is not an unlucky special case; it is the predictable result of selecting biosignature targets by detectability on a class of planet where detectability and diagnosticity are anti-correlated.

Molecule	Principal NIR-Spec band(s)	Spectrally overlapping species	Plausible abiotic pathway in an H ₂ -rich envelope	NIRSpec-alone status
<i>Methane (CH₄)</i>	~3.3 μm C–H stretch	Few in this band; well isolated	Thermochemistry and interior outgassing; ubiquitous in reducing envelopes	Robustly detected; not a biosignature
<i>Carbon dioxide (CO₂)</i>	~4.3 μm	Phosphine band lies close	Ubiquitous; no biological information in this context	Detected (contested strength); not a biosignature
<i>Dimethyl sulfide (DMS)</i>	~3.4 μm C–H stretch region	Ethane (C ₂ H ₆); other methyl-bearing carbon species	Photochemistry of H ₂ S with CH ₄ ; abiotic synthesis demonstrated in cometary and interstellar matter	Contested; not uniquely diagnostic
<i>Dimethyl disulfide (DMDS)</i>	~3.4–3.5 μm	DMS; ethane; methyl-bearing species	Organosulfur photochemistry in a reducing atmosphere	Contested; degenerate with DMS
<i>Phosphine (PH₃)</i>	~4.3 μm and ~2.9 μm	CO ₂ near 4.3 μm	Disequilibrium phosphorus chemistry in deep, reducing, H ₂ -rich layers	Not robustly claimed for K2-18b; abiotically plausible

Table 1. Molecular inventory of the candidate and context species relevant to K2-18b within the JWST/NIRSpec wavelength range (0.6–5.3 μm).

Band positions are approximate and indicate the spectral regions where each species absorbs within the NIRSpec range (Jakobsen et al., 2022; Birkmann et al., 2022). The abiotic-pathway column draws on Sousa-Silva et al. (2020) for phosphine and on Hänni et al. (2024) for the demonstrated abiotic synthesis of dimethyl sulfide. “NIRSpec-alone status” refers to what near-infrared transmission spectroscopy can establish without complementary observations or modeling.

One result deserves to be stated separately because it bears on the third hypothesis. The disagreement among the independent analyses of the K2-18b spectrum is not a temporary state of incomplete knowledge that more careful work will resolve in a single direction. It is, on the decoupling account, the expected signature of a marginal signal sitting in a spectral region crowded with degenerate carriers. When the same data yield a biosignature under one retrieval and a flat-line-compatible non-detection under another (Schmidt et al., 2025; Luque et al., 2025), the most economical reading is not that one team has erred but that the signal is at the level where reduction and modeling choices dominate the outcome. The persistence of the disagreement is therefore itself a result — evidence about the strength of the evidence.

THE SPECTRAL DEGENERACY PROBLEM IN THE NIRSpec RANGE

A transmission spectrum is a record of how much starlight a planet's atmosphere absorbs at each wavelength as the planet crosses its star. Where a molecule absorbs, the planet appears slightly larger; the pattern of those apparent-size variations encodes the atmospheric composition. The interpretation rests on a premise that is easy to state and easy to forget: that each spectral feature can be attributed to a specific molecule. When two molecules absorb in the same wavelength region at the resolution of the instrument, that premise fails, and the failure is called spectral degeneracy. The degeneracy problem is the subject of the first hypothesis, and Table 1 shows that it afflicts every candidate biosignature molecule relevant to K2-18b.

Consider dimethyl sulfide. Its strongest absorption accessible to NIRSpec lies in the carbon–hydrogen stretch region near 3.4 microns. This is not a quiet part of the spectrum. Ethane absorbs there. So do other small methyl-bearing carbon molecules. The retrieval that attributes a 3.4-micron feature to dimethyl sulfide is, in effect, choosing dimethyl sulfide from a set of candidates that all fit the same bump, and the choice is governed by the priors, the assumed atmospheric model, and the treatment of the data baseline. Luque et al. (2025) made exactly this point empirically: in their joint analysis, ethane fit the mid-infrared data as well as dimethyl sulfide did. When two molecules fit equally well, the spectrum does not contain the information needed to distinguish them, and reporting one of them as detected is reporting a modeling choice as a measurement.

Phosphine presents the degeneracy in a different and in some ways starker form. Its accessible bands include a feature near 4.3 microns — and 4.3 microns is the location of the strong carbon dioxide band. Carbon dioxide is present in K2-18b's atmosphere on every analysis; it is one of the firmer detections. A weaker phosphine feature sitting beneath or beside a strong carbon dioxide band is in an unfavorable position for unambiguous retrieval, because the dominant absorber sets the local continuum against which the weaker one must be measured. This is a generic difficulty for phosphine in the near-infrared, and it is one reason that, unlike dimethyl sulfide, phosphine has not been the subject of a headline detection claim on K2-18b. The article includes phosphine not because it has been claimed but because the user of the biosignature label applies it to phosphine as readily as to dimethyl sulfide, and the degeneracy analysis shows why a NIRSpec phosphine detection would face the same interpretive obstacle.

The degeneracy problem has a structural fix and a structural limit, and both are worth stating. The fix is wavelength coverage and resolution. A molecule that is degenerate with another in one band may be separable in a second band where the two diverge, and higher spectral resolution can split features that blend at low resolution. This is precisely why the K2-18b campaigns moved from the near-infrared to the mid-infrared instrument: the mid-infrared offers different bands and a different set of degeneracies (Madhusudhan et al., 2025). But — and this is the limit — moving to a new band trades one degeneracy for another rather than eliminating degeneracy as such. The mid-infrared analysis of Luque et al. (2025) found dimethyl sulfide degenerate with ethane in that range too. Degeneracy is not a flaw in a particular dataset that a better dataset removes; it is a generic feature of low-to-moderate-resolution transmission spectroscopy of molecules with overlapping band structures, and the candidate biosignatures are unlucky in having carbon–hydrogen and band positions that coincide with abundant, abiotically dull species.

It is worth being fair to the discovery team's position here, because the degeneracy argument is sometimes pressed too far. Madhusudhan et al. (2023, 2025) did not claim that dimethyl sulfide was the only possible carrier; they reported it as the best fit within their retrieval framework and assigned it a modest statistical confidence. A best fit is a legitimate scientific statement. The objection raised by the degeneracy analysis, and by Luque et al. (2025), is not that the discovery

team fabricated a signal but that the gap between best fit and confirmed identification is, in a degenerate spectral region, much wider than a casual reading of a detection announcement would suggest. The honest summary is that NIRSpec, and JWST transmission spectroscopy more broadly, can establish that the atmosphere absorbs in a particular region; it cannot, in a crowded region, establish without further assumption which molecule is responsible. The first hypothesis is supported: the features are not uniquely diagnostic.

ABIOTIC PATHWAYS IN A HYDROGEN-RICH ENVELOPE AND THE DECOUPLING PRINCIPLE

Suppose, for the sake of the argument, that the spectral degeneracy were somehow resolved — that a future observation established beyond doubt that dimethyl sulfide, specifically, is present in K2-18b's atmosphere at a definite abundance. Would that be a biosignature? The decoupling principle says no, and this section explains why, by examining what a hydrogen-rich envelope can do without any biology at all.

The biosignature case for dimethyl sulfide and for phosphine was always conditional. Sousa-Silva et al. (2020) were explicit that phosphine qualifies as a biosignature only in atmospheric contexts that lack abiotic sources for it; the molecule is a biosignature on an oxidized terrestrial-type planet because, there, the oxidized chemistry suppresses its abiotic production. The argument for dimethyl sulfide ran the same way: on Earth it is made by life and essentially nothing else, so its presence elsewhere would point to life. The conditional clause — in the absence of abiotic sources — was the load-bearing part of both arguments, and it was a clause about a specific atmospheric chemistry.

K2-18b does not satisfy that clause. Its atmosphere is hydrogen-dominated and chemically reducing, and the abiotic chemistry of a reducing hydrogen envelope is not the abiotic chemistry of Earth's air. In a hydrogen-rich environment, photochemistry acting on hydrogen sulfide and methane can build carbon–sulfur bonds; the methylated organosulfur family to which dimethyl sulfide and dimethyl disulfide belong is exactly the family that a reducing, methane-rich, sulfur-bearing photochemistry tends to produce. Phosphorus chemistry behaves analogously: in a sufficiently reducing, hydrogen-rich setting, phosphine is not the thermodynamically forbidden molecule it is in Earth's atmosphere but a plausible disequilibrium product of deep-envelope chemistry. The conditional clause that made these molecules biosignatures was a clause about oxidized atmospheres, and K2-18b is the opposite of an oxidized atmosphere.

The empirical anchor for this argument is not theoretical at all. Hänni et al. (2024) reported evidence for dimethyl sulfide in the matter of comet 67P/Churyumov-Gerasimenko. A comet is a body with no biology, no ocean, and no atmosphere worth the name; it is about as far from a biosphere as a Solar System object can be. The detection of dimethyl sulfide there, and the subsequent detection of the molecule in interstellar gas, establishes as a matter of observed fact — not of modeling — that dimethyl sulfide has abiotic synthetic pathways and can accumulate in environments wholly devoid of life. The molecule that was nominated as a biosignature on the strength of having no abiotic source has been found, twice, with no biology anywhere near it. After Hänni et al. (2024), the conditional clause of the dimethyl sulfide biosignature argument is not merely doubtful in the K2-18b context; it is known to be false in at least two other contexts.

This is the point at which the decoupling principle becomes more than a caution. The principle states that detectability and biogenicity are anti-correlated on hydrogen-rich sub-Neptunes, and the reducing photochemistry just described is half of the reason. The other half is the detectability side. The properties that make K2-18b a good JWST target — the hydrogen-dominated composition, the low mean molecular weight, the large scale height, the deep transmission

features — are not incidental to the abiotic chemistry; they are the same physical conditions. A low mean molecular weight means a hydrogen-dominated atmosphere means a reducing environment means abiotic organosulfur production. A large scale height means a deep, observable atmospheric column means a large reservoir in which a photochemically produced trace molecule is distributed and made visible. One cannot select for the first member of each of these pairs without selecting for the second. The detectability of a candidate biosignature on K2-18b and its abiotic producibility are not two facts that happen to coincide; they are one fact described twice.

The principle has a corollary that is worth making explicit, because it inverts a piece of received wisdom. The hycean-world program treats hydrogen-rich sub-Neptunes with extended atmospheres as the most promising biosignature targets, on the entirely correct observation that their biosignature gases are the easiest to detect (Madhusudhan et al., 2021). The decoupling principle does not dispute the detectability claim; it disputes the inference from detectability to promise. A planet on which a biosignature gas is easy to detect, but on which the same gas is also easy to make without life, is not a promising biosignature target — it is a planet on which a positive detection is uninformative. The most observationally favorable targets are, for biosignature purposes, among the least diagnostic. That is an uncomfortable conclusion for a target-selection strategy built on detectability, and I do not state it lightly, but it follows from the principle, and the principle follows from the physics.

I should mark the boundary of the argument honestly. The decoupling principle establishes that the abiotic ceiling for dimethyl sulfide and phosphine on a hydrogen-rich sub-Neptune is non-zero and, given the reducing photochemistry, probably substantial. It does not establish the numerical value of that ceiling. It is conceivable — and this is the one route by which a hydrogen-rich world could still yield a biosignature — that the abiotic ceiling for a particular molecule is low enough that a sufficiently high retrieved abundance would exceed it. Whether that is the case for dimethyl sulfide on K2-18b is a quantitative photochemical question that this article does not answer and that, as far as I am aware, has not yet been answered definitively in the literature. What the principle establishes is that the question must be asked, and that a detection reported without reference to the ceiling has answered only half of what a biosignature claim requires.

CONSEQUENCES FOR BIOSIGNATURE ASSESSMENT AND THE STANDARD OF EVIDENCE

If the decoupling principle holds, it changes what a biosignature claim has to demonstrate. This section develops that change and connects it to the third hypothesis, which concerns the standard of evidence.

The conventional structure of a biosignature claim, as it has been applied to K2-18b, has two parts: detect the molecule, and note that the molecule is biogenic on Earth. The decoupling principle shows that this structure is incomplete on a hydrogen-rich world, because the second part — biogenic on Earth — is a statement about Earth's oxidized atmosphere and does not transfer to a reducing one. The claim needs a third part: a demonstration that the retrieved abundance exceeds the abiotic ceiling for the planet's specific atmospheric context. Detection establishes a numerator; the biosignature inference also requires a denominator, the abiotic ceiling, and NIR-Spec measures only the numerator. A detection reported as a biosignature is a fraction reported with its denominator left blank.

This reframing is, I think, the most useful consequence of the principle, and it generalizes beyond K2-18b. For any candidate biosignature on any world, the question that matters is not is the molecule present but does its abundance exceed what abiotic chemistry can supply in this context. On an oxidized terrestrial planet the abiotic ceiling for phosphine or dimethyl sulfide is

low, the denominator is small, and a modest detection clears it; that is what made these molecules good biosignatures in the first place. On a hydrogen-rich sub-Neptune the ceiling is high, the denominator is large, and a detection of the same absolute abundance no longer clears it. The molecule has not changed. The context has, and the context sets the denominator. A biosignature is not a property of a molecule; it is a property of a molecule-in-a-context, and the decoupling principle is the statement that the contexts easiest to observe are the contexts with the largest denominators.

The third hypothesis concerned the standard of evidence, and the principle bears on it in a specific way. The K2-18b dimethyl sulfide signal has been assessed by its discoverers at a confidence near three standard deviations (Madhusudhan et al., 2025) and by independent reanalyses as not statistically significant (Schmidt et al., 2025; Luque et al., 2025). A natural response is to wait for more data to settle the statistics. The decoupling principle suggests that settling the statistics, while valuable, would not settle the biosignature question, because even a five-standard-deviation detection of dimethyl sulfide on K2-18b would be a detection of a molecule with a substantial abiotic ceiling on that planet. Statistical confidence speaks to whether the molecule is there. It is silent on whether the molecule, if there, was made by life. A standard of evidence for biosignatures that counts only statistical confidence is therefore measuring the wrong thing, or rather only one of two things that both need measuring. The community standards for life-detection claims have begun to recognize this, distinguishing the detection of a candidate signal from the exclusion of abiotic and instrumental explanations (National Aeronautics and Space Administration, 2024), and the decoupling principle gives that distinction a physical basis for the specific case of hydrogen-rich worlds.

What, then, would it take to break the decoupling — to obtain a genuine biosignature from a hydrogen-rich sub-Neptune? Three routes are visible, and none is available from NIRSpec transmission spectroscopy alone. The first is the quantitative abiotic ceiling: a photochemical model of K2-18b's specific atmosphere, validated as far as possible, that computes the maximum abiotic dimethyl sulfide abundance, against which a retrieved abundance could be compared. If the retrieved abundance robustly exceeded the modeled ceiling, the decoupling would be broken for that planet. The second route is chemical context: the detection not of a single molecule but of a chemical disequilibrium — a combination of gases that abiotic chemistry cannot jointly sustain — which is a far more demanding observation but a far more diagnostic one. The third route is a different class of target: terrestrial planets with oxidized atmospheres, where the abiotic ceiling is genuinely low and the conventional two-part biosignature logic still holds. Each of these routes accepts the decoupling principle and works with it; none of them is a way of reading a NIRSpec detection on a hydrogen-rich world as a biosignature, because the principle says there is no such way.

A closing observation about K2-18b specifically. The planet has been, by any measure, scientifically productive: it has driven the development of the hycean-world hypothesis, sharpened the methods of exoplanet transmission spectroscopy, and forced the community to think hard about what a biosignature claim requires. None of that is diminished by concluding that K2-18b is a poor biosignature target. A planet can be an excellent natural laboratory for atmospheric physics and a poor laboratory for the detection of life, and K2-18b appears to be both. The decoupling principle is not a verdict against K2-18b. It is an argument that the search for life should not be concentrated on the planets where a biosignature gas is easiest to see, because those are, by the principle, the planets where seeing it tells us least.

CONCLUSION

K2-18b has been described, at various points in the last three years, as the strongest hint yet of life beyond the Solar System. This article has argued that the description rests on an inference that does not hold for the class of planet K2-18b belongs to. The argument did not require taking a side in the statistical dispute over whether the dimethyl sulfide signal is real; it was constructed to hold either way, and the three hypotheses can now be addressed against it.

The first hypothesis held that the spectral features attributed to dimethyl sulfide and phosphine in the NIRSpec range are not uniquely diagnostic. The molecular inventory of Table 1 confirms it: dimethyl sulfide and dimethyl disulfide are degenerate with ethane and other methyl-bearing species near 3.4 microns, and phosphine is degenerate with carbon dioxide near 4.3 microns. The empirical demonstration by Luque et al. (2025) that ethane fits the K2-18b mid-infrared data as well as dimethyl sulfide does is the decisive evidence. A NIRSpec detection identifies a spectral region of absorption; in a crowded region it does not, without further assumption, identify the absorber.

The second hypothesis — the conceptual core of the article — held that on a hydrogen-rich sub-Neptune the properties that maximize a candidate biosignature's detectability are the same properties that maximize its abiotic production, so that detectability and biogenic diagnosticity are structurally anti-correlated. This hypothesis is confirmed by the property-by-property analysis: low mean molecular weight, extended scale height, large transit signal, and reducing photochemistry each enhance detection and each enhance abiotic supply, with no member of the list enhancing one without the other. The confirmation is reinforced by the empirical fact, established by Hänni et al. (2024), that dimethyl sulfide is produced abiotically in cometary and interstellar matter — the conditional clause on which its biosignature status depended is now known to fail outside oxidized atmospheres.

The third hypothesis held that the current K2-18b evidence does not meet the standard a biosignature claim requires, and that the disagreement among independent reanalyses is a symptom of a marginal signal. This is confirmed, with an important refinement supplied by the decoupling principle: the evidence fails the standard not only, and not mainly, because the statistical significance is contested, but because statistical significance is the wrong sole criterion. Even a high-significance detection of dimethyl sulfide on K2-18b would leave the biosignature claim incomplete, because it would establish the molecule's presence without establishing that its abundance exceeds the substantial abiotic ceiling of a hydrogen-rich envelope. The disagreement among reanalyses is real and diagnostic of a marginal signal; but settling it would not, on its own, deliver a biosignature.

The principal original contribution of this article is the principle of detection–biogenicity decoupling: the claim that, for hydrogen-rich sub-Neptunes, detectability and biogenicity are structurally anti-correlated, with the consequence that a transmission-spectroscopy detection of a candidate biosignature gas — however statistically robust — cannot by itself constitute a biosignature on such a world. The principle reframes biosignature assessment from the detection of a molecule to the comparison of its retrieved abundance against a context-specific abiotic ceiling, and it explains, rather than merely laments, why the most observationally favorable targets are among the least diagnostic. To my knowledge the K2-18b literature has treated spectral degeneracy and abiotic production as separate caveats appended to detection claims; the contribution here is to show that they are facets of one principle with a definite anti-correlation structure, and that the principle holds independently of the statistical dispute it clarifies.

Four limitations bound the conclusions. The first, and the most important, is that the article establishes the abiotic ceiling for dimethyl sulfide and phosphine on a hydrogen-rich sub-

Neptune as non-zero and probably substantial, but does not compute its numerical value; that computation requires a dedicated photochemical model of K2-18b's atmosphere, and until it exists the principle establishes that the ceiling matters without saying exactly how high it is. The second is that the analysis is specific to hydrogen-rich sub-Neptunes and deliberately does not apply to oxidized terrestrial atmospheres, where the conventional biosignature logic remains sound; the principle is a statement about a planetary class, not about biosignatures in general. The third is that the article synthesizes published observations and retrievals rather than performing its own, and it therefore inherits whatever systematic uncertainties attend the underlying spectra. The fourth is that the interior of K2-18b — ocean, magma ocean, or gas-rich mini-Neptune with no surface — remains unresolved (Wogan et al., 2024; Shorttle et al., 2024), and the biosignature discussion is to that extent built on an uncertain foundation.

Three directions for future work follow. The first is the quantitative abiotic ceiling: a validated photochemical model of K2-18b that computes the maximum abiotic dimethyl sulfide and phosphine abundances, converting the decoupling principle from a structural argument into a numerical test. The second is the pursuit of chemical disequilibrium rather than single molecules — combinations of gases that abiotic chemistry cannot jointly sustain — as the biosignature observable for hydrogen-rich worlds, since a disequilibrium is far less vulnerable to the decoupling than any single molecule. The third is a reconsideration of target selection: if detectability and diagnosticity are anti-correlated for hydrogen-rich sub-Neptunes, the search for life may be better served by harder-to-observe oxidized terrestrial planets, where a detection, once achieved, actually means what the biosignature label says.

The discovery of methane and carbon dioxide on K2-18b is a genuine achievement of JWST and of the NIRSpec instrument, and the tentative organosulfur signal, real or not, has been scientifically generative. But the step from a detected molecule to a detected biosphere is longer than the early reporting suggested, and on a hydrogen-rich sub-Neptune it is longer still. The decoupling principle is an attempt to measure that step honestly. Its conclusion is sobering rather than encouraging: the planet on which we can most easily see a biosignature gas is, for that very reason, the planet on which seeing it proves least. That is not a counsel of despair. It is a redirection — toward the abiotic ceiling, toward disequilibrium, and toward the targets where a detection would still mean what we want it to mean.

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SPEKTROSKOPSKA DETEKCIJA FOSFINA I DIMETIL-SULFIDA KAO POTENCIJALNIH BIOSIGNATURA U ATMOSFERI SUB-NEPTUNA K2-18b POMOĆU JWST/NIRSpec INSTRUMENTA

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Sažetak: Sub-Neptun K2-18b postao je najdiskutovaniji objekat u potrazi za životom izvan Sunčevog sistema. JWST transmisiona spektroskopija njegove vodonikom bogate atmosfere dala je pouzdane detekcije metana i ugljen-dioksida te osporavan, više puta preispitivan signal pripisan dimetil-sulfidu — molekuli koju na Zemlji proizvodi gotovo isključivo morski život. Fosfin, drugi gas dugo predlagan kao biosignatura, pripada istom problemu procjene. Ovaj članak ne pokušava utvrditi je li signal dimetil-sulfida statistički stvaran; nezavisne reanalize se ne slažu, a to neslaganje se ovdje tretira kao podatak, a ne kao pitanje koje treba riješiti. Umjesto toga, članak iznosi konceptualni argument koji vrijedi bez obzira na ishod statističkog spora. Oslanjajući se na petnaest SCOPUS-indeksiranih studija i sedam institucionalnih izvora, uvodim i razvijam princip dekuplovanja detekcije i biogenosti: na vodonikom bogatom sub-Neptunu, atmosferska svojstva koja maksimiziraju spektroskopsku detektabilnost molekule kandidata za biosignaturu — niska srednja molekularna masa, proširena visinska skala, velik tranzitni signal i redukciona fotohemija — ista su ona svojstva koja maksimiziraju njenu abiotsku proizvodnju i akumulaciju. Detektabilnost i biogena dijagnostičnost stoga nisu nezavisne; one su strukturno antikorelisane. Upravo ona svojstva koja čine K2-18b efikasnim JWST/NIRSpec ciljem čine ga neefikasnim ciljem za biosignaturu. Princip podupiru tri linije dokaza: spektralna degeneracija molekula kandidata s abiotski uvjerljivim vrstama poput etana u NIRSpec rasponu; demonstrirana abiotska sinteza dimetil-sulfida u kometnim i međuzvjezdanim okruženjima potpuno lišenim života; te fotohemijska uvjerljivost organosumporne i fosforne hemije u vodonikom dominiranoj atmosferi. Implikacija je da NIRSpec detekcija, koliko god statistički pouzdana, ne može sama po sebi predstavljati biosignaturu na vodonikom bogatom svijetu, i da se procjena biosignatura mora pomjeriti od detekcije molekule ka dokazivanju da njena zastupljenost premašuje abiotski plafon za njen specifičan planetarni kontekst.

Ključne riječi: *K2-18b, biosignature, dimetil-sulfid, fosfin, JWST NIRSpec, atmosfere sub-Neptuna, dekuplovanje detekcije i biogenosti.*