# Multiscale astrobiology with the Vera C. Rubin Observatory Legacy Survey of Space and Time

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The Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) presents an unprecedented opportunity to advance the search for astrobiologically relevant data across diverse astronomical environments. Through its extensive imaging capabilities, LSST will enhance our inventory of Solar System objects and assess their potential astrobiological conditions. Beyond the Solar System, LSST will survey billions of stars, contributing to the detection of exoplanets, characterizing planetary atmospheres at a zeroth-order level, identifying transient phenomena, and exploring conditions within habitable zones. In this paper, we highlight LSST's unique contribution to astrobiology, complementing other missions and expanding the search for life beyond Earth in the coming decades.

## 1 Introduction

The Vera C. Rubin Observatory, formerly the Large Synoptic Survey Telescope, located at Cerro Pachón in Chile, is one of the next class of giant earth-based telescopes (left plot in Figure 1). It will house the world's largest digital camera ever fabricated for optical astronomy which will be used to collect hundreds of images of the Southern Hemisphere sky (right plot in Figure 1), collecting 20 TB of data every night, for 10 years, to produce a synoptic astronomical survey, the 'Legacy Survey of Space and Time' (Ivezić et al., 2019; Bianco et al., 2021). Its data will provide hitherto unseen details of our Universe. On a cosmological scale, it will provide the most detailed map of the distribution of dark matter in space and, hence, provide a measurement of the acceleration of the expansion of the universe, providing a stringent test of modern cosmology.

In parallel, the Vera C. Rubin Observatory will also be at the forefront of planetary science for the next decade. In our Solar system, LSST will be capable of detecting 90% of all near-Earth objects—asteroids with diameters > 300 m moving on orbits that pass close to our planet (see Schwamb et al., 2023, and references therein). The Observatory will also investigate comets and the Kuiper Belt, which is believed to contain nearly
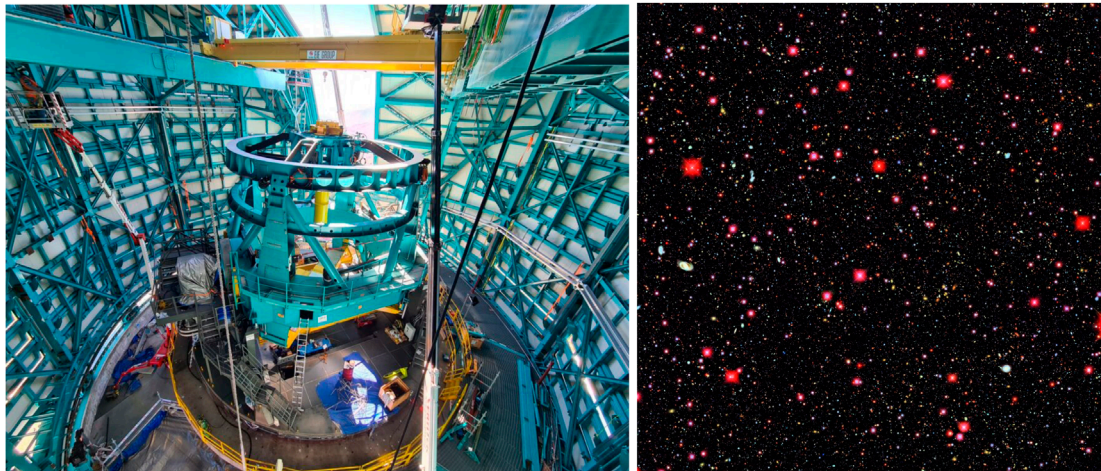
**FIGURE 1**
Left: LSST 3.2-Gpx digital Camera and Simonyi Survey Telescope. The telescope's three-mirror design (8.4 m, 5 m, and 3.4 m) enables rapid repointing within ~ 5 s. Image credit: Rubin Obs/NSF/AURA. Right: Image from the Deep Lens Survey (DLS) revealing ten times more galaxies per unit area than Sloan Digital Sky Survey (SDSS), while LSST will cover 50,000 times more area in six optical bands. Image credit: Deep Lens Survey/UC Davis/NOAO.

100,000 objects, including possibly $\sim \mathcal{O}(10)$ with sizes comparable to Pluto (~2,000 km in diameter). These objects are remnants of the Sun's protoplanetary disk—from which all the planets and their moons, including Earth, emerged nearly 5 billion years ago. As such, they hold nearly pristine records of the composition and dynamics of Solar system primordial material, providing invaluable insights into the prebiotic chemistry in our planetary system. Since the discovery of the first exoplanets, exoplanetary and solar system sciences have largely remained separate—former focusing on limited information from many systems, and the later on extensive data of a single system (Horner et al., 2020). LSST's ability to observe both types of objects offers a new avenue for bridging these fields. Missions like Kepler and Transiting Exoplanet Survey Satelite (TESS) have established transit photometry as the primary tool for detecting exoplanets, shifting the focus from earlier techniques like radial velocity (e.g., Deeg and Alonso, 2018). LSST will serve as a deep complement to the GAIA mission (see, e.g., Ivezić et al., 2012). LSST will use the GAIA catalog as its external reference system. For instance GAIA's Data Release three provides precise trigonometric parallax and photometric measurements for $\sim 1.5 \times 10^9$ objects down to $G \sim 20$ mag (Gaia et al., 2023). With full-sky coverage, GAIA is dense enough that each LSST observation will include tens to hundreds of GAIA stars. Over its 10-year lifespan, LSST's observations will extend this reach by more than four magnitudes across half the sky, with LSST data expected to surpass GAIA's precision[1]. This increased depth will allow LSST to identify and characterize faint stars and distant stellar populations, enabling new opportunities for exoplanet discovery and advancing astrobiological exploration.

In this paper we review LSST's transformative role in astrobiology, focusing on its technological capabilities, its multidata synergies, and interdisciplinary applications. Section 2 explores LSST's technological features for multiscale astrobiology across time, energy, and chemistry. Section 3 provides examples of astrobiological studies with LSST. Section 4 positions LSST role in multimodal data and multimessenger astrobiology. Section 5 overviews LSST as a platform for interdisciplinary collaboration. Finally, Section 6 concludes with short proposition of community organization.

## 2 LSST and multiscale astrobiology

A planet's location in the habitable zone alone does not confirm its habitability (Kaltenegger, 2017). Assessing habitability requires detailed atmospheric and surface observations, typically through spectroscopy. Advanced facilities like the James Webb Space Telescope excel in this domain (Bello-Arufe et al., 2022; Pham and Kaltenegger, 2021), but spectroscopy is resource-intensive (Pham and Kaltenegger, 2021). Photometry, by contrast, provides a faster method to classify and prioritize exoplanet candidates. Studies show that photometric colors effectively distinguish surface types (e.g., icy, rocky, or gaseous) and can indicate biosignatures [see Pham and Kaltenegger (2021)]. LSST photometry provides a rapid and complementary approach to detecting astrobiological signals by using temporal, spectral, and chemical composition variations in images and light curves.

On the temporal scale, LSST's frequent observations (with an average cadence of ~3 days) allow for continuous monitoring of both planetary systems and small Solar System bodies, such as Kuiper Belt Objects (KBOs). For instance, there are proposals to combine the capabilities of large-aperture ground-based telescopes with those of space-based observatories such as the James Webb Space Telescope (JWST) (Conrad and Veillet, 2018). Space telescopes provide a stable point spread function (PSF) due to the absence of atmospheric interference, whereas LSST's large aperture enables a broader

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1  See  Sections 2.4  and  3.3.2.3  in  https://docushare.lsstcorp.org/docushare/dsweb/Get/LPM-17

and deeper sky survey. This synergy may enhance astrobiological research, particularly in detecting key features of Solar System bodies, such as accurately measuring the absolute temperature of hot spots on Io's surface and characterizing volcanic processes. Additionally, changes in the color or brightness of a KBO over time, particularly when aligned with organic or water absorption features, could indicate dynamic processes like outgassing or surface changes (Collaboration et al., 2021). Outgassing events involving water vapor[2] can cause temporary brightness reductions and color shifts. Water ice and vapor exhibit distinct absorption features in the near-infrared (NIR), detectable by LSST's i, z, and y bands (700–1,050 nm). For example, a decrease in brightness within these bands compared to others could signal water vapor outgassing, offering insights into transient processes and the composition of these distant objects.

On the scale of the spectrum, LSST's six broadband filters—u (304.3–404.5 nm), g (385.6–566.3 nm), r (533.7–705.7 nm), i (669.9–837.8 nm), z (799.3–939.2 nm), and y (907.5–1,100 nm)[3]—approximate zeroth-order spectroscopy (Figure 2). Color indices, defined as magnitude differences between filters (e.g., g-r), can reveal stellar properties such as temperature and luminosity, which are critical for determining planetary habitability (Kopparapu et al., 2013). For example, cooler stars shift habitable zones inward, allowing conditions suitable for liquid water.

On the scale of chemical composition, LSST can detect biosignatures by analyzing variations in atmospheric and surface features through broadband photometry. Magnitude differences between filters, such as g-r, may reveal molecular absorption features indicative of key compounds like ozone ($O_3$) and methane ($CH_4$), which imprint distinct signatures in ultraviolet and infrared wavelengths in transit light curves, where wavelength-dependent absorption affects the depth of the transit (Campargue et al., 2023). Similarly, the 'vegetation red edge' feature, associated with vegetation, manifests as a sharp reflectance increase near for example, 700 nm for an Earth-like planet orbiting a Sun-like star, where photosynthetic organisms absorb visible light but reflect near-infrared. If present, this signature could induce brightness variations in phase curves, revealing surface vegetation coverage. Planets around cool M-dwarfs, which emit most energy in the near-infrared (NIR), could develop a VRE even beyond 1,000 nm (Takizawa et al., 2017), while those orbiting hotter F-type stars may have a bluer VRE to avoid photodamage (Lehmer et al., 2021). LSST's bands, though limited in infrared coverage, could help constrain these variations by identifying phase-dependent color changes, enabling statistical detection of exophotosynthetic adaptations over long timescales.

Additionally, molecular absorption by $CH_4$ and $O_3$ can induce measurable color variations of 0.1–0.3 magnitudes between filters, offering insight into atmospheric composition and potential astrobiological processes in color-magnitude diagrams, which differentiate planetary types based on broadband photometric measurements. Atmospheric properties can also be inferred from transit depths. Water vapor in the atmospheres of Hot Jupiters increases absorption in the i, z, and y bands. Methane-rich

Sub-Neptunes around cool M-dwarfs exhibit near-infrared (NIR) absorption but minimal absorption in the u, g, and r bands. Conversely, airless rocky planets display uniform transit depths. Organic molecules, such as chlorophyll, strongly absorb at 430 nm and 660 nm, detectable in the g and r bands (Kume, 2017). Similarly, functional groups like C-H, N-H, and O-H exhibit absorption features in the i, z, and y bands (Wu et al., 2014).

With a wide field of view (3.5°) and high sensitivity (8.4 m primary mirror), LSST will excel at detecting faint objects and transient events like exoplanet transits and comet activity (see Table 2 in Bianco et al., 2021). By integrating observations across time, energy, and chemistry scales, LSST offers a unique perspective on astrobiological signals, capturing their evolution and interplay over its mission. Recent analysis (Tyson et al., 2024) shows that glints from space debris will have minimal impact on LSST transient observations, as small debris produces very low signal-to-noise due to defocusing, and only rare, larger objects may create detectable but morphologically identifiable artifacts. Similar to the Sloan Digital Sky Survey (SDSS), which was initially planned for a limited duration but continued for over two decades due to its scientific success and instrument longevity, the Rubin Observatory LSST is expected to complete its 10-year baseline survey and may extend operations if the telescope remains in good health and new scientific opportunities arise.

# 3 Examples of astrobiological studies with LSST

## 3.1 Solar system

### 3.1.1 Detection of near-earth objects (NEOs) and potentially hazardous asteroids (PHAs)

Objects that are ejected from the main asteroid belt that can enter Earth-crossing orbits [see Jones et al. (2018)] are known as Near-Earth Objects (NEOs), including asteroids and comets with perihelion distances of ~ < 1.3 AU. A subset of NEOs, Potentially Hazardous Asteroids (PHAs), includes objects that are ≥140 m in diameter and pass within 0.05 AU of Earth. These objects are capable of surviving atmospheric entry and causing significant regional damage, making their monitoring essential for planetary defense.

Using its baseline survey strategy, LSST will detect 66% of PHAs and 61% of NEOs with $H \leq 22$ [see Jones et al. (2018)]. The LSST Data Preview 0.3 catalog, a hybrid dataset comprising both real and simulated Solar System objects—including asteroids, NEOs, Trojans, trans-Neptunian objects, and comets—illustrates the types of NEOs that LSST could observe (see Supplementary Figure S1). Simulations by Wagg et al. (2024) predict approximately 129 new candidates per night in LSST's first year—an eightfold increase over current discovery rates—but only 8.3% of these will be actual NEOs, the rest being faint Main Belt Asteroids (MBAs). Over 10 years, LSST could provide 36,500 new NEO discoveries. Optimizing follow-up systems to handle 64 candidates per night, as suggested by Wagg et al. (2024), would reduce this to 22,000 confirmed NEOs with 8.4% certainty while improving efficiency for global tracking networks.

NEOs are also of major astrobiology interest due to their potential to carry water, organics, and other life-forming materials. For example, the Apollo asteroid (101955) Bennu, a 500 m NEO,
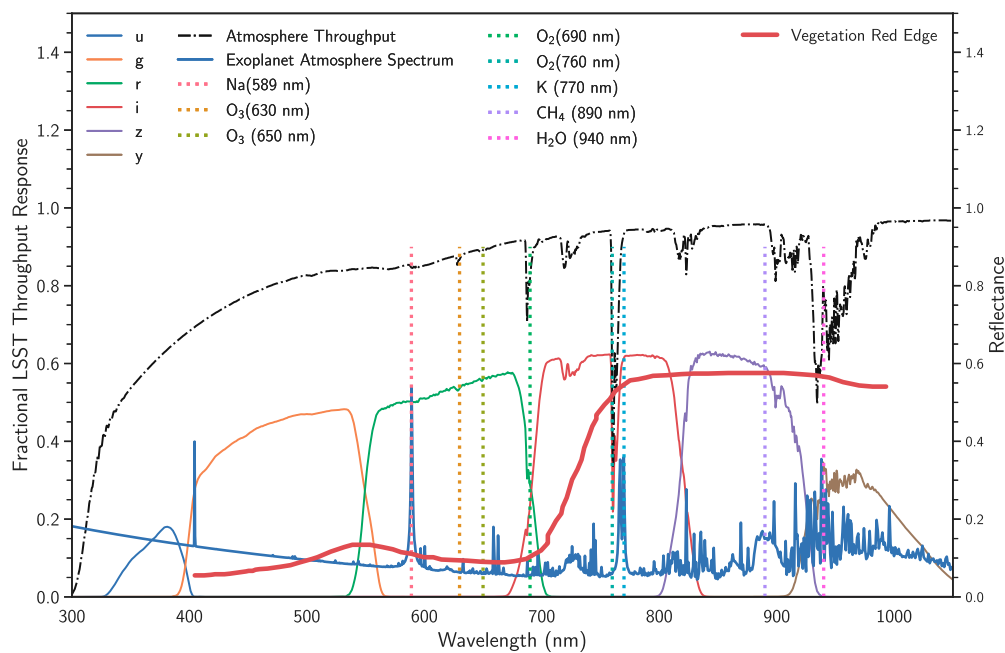
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**FIGURE 2**
The LSST throughput curves across the `ugrizy` bands (colored lines) represent the combined effects of the Rubin Observatory system[4], including mirrors, lenses, filters, detectors, and a fiducial atmosphere at 1.2 airmasses (black dash-dotted line). Overlaid is a scaled spectrum of a $2R_\oplus$ exoplanet atmosphere (solid blue line), orbiting a $1R_\odot$ star, modeled using `ExoTransmit` (Kempton et al., 2017). The Vegetation Red Edge (thick maroon line), from RapidEye Multi-Spectral Imager data [5], shows the reflectance increase near 700 nm. If an Earth-like exoplanet orbiting a Sun-like star harbored vegetation with similar photosynthetic properties, a comparable red edge feature could manifest in the exoplanet's phase curve, detectable as brightness variations in LSST's i band. LSST's repeated observations over 10 years could enable statistical reconstruction of such phase curves. Vertical dotted lines mark biosignature wavelengths.

was targeted by the OSIRIS-REx (Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer) mission, returning regolith samples containing carbon-rich dust, organic compounds, and clay minerals such as serpentine (see Lauretta et al., 2024, and references therein). Bennu's composition suggests it may have originated from an ancient ocean world, with discoveries of magnesium-sodium phosphate resembling compounds found on Enceladus and in Earth's soda lakes (Lauretta et al., 2024). Understanding the distribution of NEOs and PHAs is crucial for assessing their role in delivering prebiotic materials to Earth and other planets.

## 3.1.2 Characterization of comets and Kuiper Belt objects

Recent observations from the Subaru Telescope suggest that the apparent small size of the Kuiper Belt compared to other planetary systems may be the result of observational bias (Ivezić et al., 2019; Buie et al., 2024). A distinct cluster of objects appears to orbit in a 70–90 AU ring-like region, separated from the Kuiper Belt by a sparsely populated "valley" between 55 and 70 AU (Ohashi et al., 2023). Confirming this distant KBO region would imply structural similarities between the Solar and other planetary systems.

With its extensive sky coverage and depth, LSST is well-positioned to detect fainter, more distant KBOs, improving our understanding of the Solar System's outer structure. LSST DP0.3 contains classical KBOs clustering at low eccentricities ($e < 0.2$) near Neptune's orbit, while detached and extreme TNOs extend

beyond $a = 100$ AU with high eccentricities ($e > 0.5$). Comet-like TNOs exhibit high angular speeds near perihelion ($\geq 15$ arcsec/h), while classical TNOs have lower speeds ( $< 10$ arcsec/h) due to their near-circular orbits (see Supplementary Figure S2).

For KBO motion tracking along a reference axis, such as the ecliptic plane, the observed velocity component $v$ (arcsec/h), depends on the motion inclination $\alpha$ relative to this axis (Rousselot et al., 1999). In this context, the cadence constraint is given by Equation 1:

$$t_{\text{cadence}} \leq \frac{\theta_{\max}}{v \cdot \cos(\alpha)}, \tag{1}$$

where the $\theta_{max}$ is maximum allowable motion per observational interval.

For TNOs moving below 10 arcsec/h and $\alpha = 0$, a 90-min cadence suffices to maintain position within a 15-arcsec limit (see Schwamb et al., 2018). Moderate-speed TNOs (10–15 arcsec/h) will require a cadence of ~60 m (Bellm et al., 2022), and high-speed objects ($\geq 15$ arcsec/h) near perihelion would necessitate a $< 60$-minute cadence, although targeted follow-up may be required for objects with very high speeds (Bellm et al., 2022).

Expanding KBO detections with LSST has astrobiological implications. Identifying a diverse KBO population may suggest that the Solar System shares structural features with systems capable of hosting life. Our Solar system KBO long appeared to be very small relatively to other systems (e.g., Nilsson et al., 2010). If an extended KBO region ($\geq 70 AU$) is confirmed (Fraser et al.,

2024), it would challenge the "small parent nebula" hypothesis as a prerequisite for life[5], increasing the likelihood of finding other planetary systems with similar potential.

LSST's observations could detect collision clouds from recent impacts (Stern, 1996), which evolve on timescales of days to weeks, and enable systematic studies of small body nuclei before and after active events. These observations would improve our understanding of outgassing, space weathering, and the interiors of small objects (Collaboration et al., 2021). LSST may also detect cryovolcanic activity or resurfacing events on KBOs (Glein et al., 2024), revealing chemical reactions relevant to astrobiology. For example, a large cryovolcanic eruption could produce a temporary coma or atmosphere, increasing brightness and altering surface characteristics detectable by LSST. LSST's long-term monitoring is ideal for the revealing gradual changes in brightness or color due to cumulative cryovolcanic activity or seasonal variations.

Comets and KBOs serve as time capsules from the early Solar System, preserving conditions that shaped planetary formation. Comparative studies of their compositions and activities will refine models of Solar System evolution and highlight why some regions retained complex organics while others experienced greater geologic activity.

The Oort Cloud, extending up to halfway between the Sun and Alpha Centauri[6], might exchange cometary material with Alpha Centauri's cometary cloud. This could be explored as a potential pathway for "slow boat" interstellar probes taking millennia to traverse, relying on physics consistent with current technology (see Gilster, 2013).

## 3.2 Exoplanets

The LSST will allocate 90% of its observational time to regular cadence monitoring, with the remaining ~10% dedicated to high-cadence deep-drilling fields (see Bianco et al., 2021). Its extensive sky coverage, combined with the large number of target stars and densely sampled light curves, makes LSST a powerful tool for discovering transiting exoplanets, particularly in faint and distant stellar populations (Hambleton et al., 2023), that have been poorly explored in previous surveys (see Supplementary Table S1), extending to extragalactic distances (Jacklin et al., 2015). Early analyses of LSST's standard cadence (e.g., Lund et al., 2015) indicate sensitivity to transiting systems such as a $10R_\oplus$ planet orbiting a G-dwarf, a $4R_\oplus$ planet around a K-dwarf, and a $2R_\oplus$ planet orbiting an M-dwarf. Simulations by Jacklin et al. (2015) predict LSST will detect Hot Jupiters, Saturns, and Neptunes around solar-type stars up to seven kpc, as well as smaller planets around lower-mass stars at closer distances. The ability to detect ~1% brightness dips further suggests sensitivity to a diverse population of exoplanets across a wide range of stellar types and distances.

Ozone exhibits an absorption feature in the visible spectrum known as the Chappuis bands, occurring between 400–600 nm. LSST's g and r bands partially cover this range. Although LSST

lacks the spectral resolution to unambiguously identify ozone, variations in the SED inferred from LSST data that suggest an ozone feature could still be discerned, particularly when combined with additional data from JWST or other instruments. Among the prominent atmospheric features detectable in exoplanet atmospheres by both ground- and space-based facilities is Rayleigh scattering (Murgas et al., 2020). Rayleigh scattering, caused by molecules such as nitrogen or oxygen in an exoplanet's atmosphere, enhances the blue end of the visible spectrum. The scattering at 400 nm is approximately 9.4 times stronger than at 700 nm. LSST's u and g bands (320–550 nm) are particularly sensitive to this effect. An SED showing a Rayleigh scattering slope could indicate the presence of an atmosphere with significant amounts of these molecules, which are associated with life on Earth. Moreover, in hydrogen-dominated planetary atmospheres, Rayleigh scattering causes the measured planetary radius to increase toward blue wavelengths in the optical range (Murgas et al., 2020).

### 3.2.1 The role of dust in planetary climate and atmosphere development

The inner Solar System contains a diffuse zodiacal dust cloud formed by grains released by comets and asteroids as they pass through the Solar System. These particles spiral toward the Sun over millions of years due to the relativistic Poynting-Robertson drag (Borin et al., 2017), occupying the inner few astronomical units (AU). Numerical simulations of the orbital evolution of asteroidal dust particles have predicted two dense dust clumps—one leading and one trailing Earth, with the trailing clump being the denser of the two (Stark et al., 2013)—first observed by the Cosmic Background Explorer (COBE; Reach et al., 1995). On the other hand, KBOs are believed to be the dominant source of interplanetary dust particles in the outer solar system due to KBOs twofold collisons: mutual and with interstellar dust particles. New Horizons measurements through 55 AU show higher than predicted dust fluxes which remains unexplained but may involve KBOs (Doner et al., 2024).

The LSST will produce multi-color ugrizy images covering half the sky, with a depth of $r \sim 27.5$, median seeing of 0.7 arcsec in the r-band, and high photometric (≤1%) and astrometric (10 mas per epoch) precision. These data will allow high-resolution, multi-color studies of interplanetary dust (see e.g., Levasseur-Regourd et al., 2020)[7]. To study zodiacal light (ZL) in LSST images, it will be necessary to isolate ZL from other background sources. For instance, this might be done by (see e.g., Tsumura et al., 2023)$ZL(x,y) = S(x,y) - ISL(x,y) - DGL(x,y) - EBL(x,y)$, where $S(x,y)$ is the observed sky brightness, $ISL(x,y)$ is integrated starlight, $DGL(x,y)$ is diffuse galactic light, and $EBL(x,y)$ is extragalactic background light. Through its extensive sky coverage and high photometric precision, LSST will be able to measure ZL over a decade, advancing our understanding of Solar system dust and its role in planetary climate and atmospheric dynamics.

Only recently has the structure of dust populations around other stars, known as exozodiacal disks, become studied via spectral line observations. However, missions like Kepler (Arkhypov et al., 2019) been studied dust detection across larger samples of objects

through broadband photometry. For example, dust has been observed in rocky exoplanet tails (Garai, 2018) and at altitudes of ~3000 km in giant exoplanets due to atmospheric escape from stellar UV heating. Potential sources include moonlet erosion, satellite decay, volcanic activity, and magnetospheric capture of interplanetary dust, including exozodiacal particles (Arkhypov et al., 2019). Exozodiacal disks may also carry signatures of a star's habitable zone (HZ).

Exozodiacal light (exoZL), a faint, extended glow around stars, is 100–1,000 times fainter than Solar System ZL. LSST's angular resolution (0.7 arcsec) may detect exoZL around nearby stars, but separating it from brighter starlight and background noise remains challenging. Models by Stark (2011) show that resonant dust clumps formed by planetary trapping produce transit-like light curve minima. Jupiter-mass planets generate the strongest signals (amplitudes $\sim 10^{-4}$), while Neptune- and Earth-mass planets produce weaker signals ($\sim 10^{-5}$ to $10^{-6}$). LSST's ~825 visits over 10 years could detect exoZL if disk densities exceed 100 zodi. However, detecting clumpy structures or resonant rings requires high-cadence, high-precision observations, better suited to Kepler or JWST.

The Nancy Grace Roman Space Telescope, with its Coronagraph Instrument at Lagrange Point 2, will surpass LSST in sensitivity to warm exozodiacal dust in habitable zones (Douglas et al., 2022), particularly for rocky grains closer to stars (Ertel et al., 2020). Understanding exozodiacal dust chemistry offers unique insights into planetary formation and guides future missions to image habitable-zone planets.

Dust surges into Earth's atmosphere have been proposed to influence climate, potentially causing cooling events or contributing to glacial cycles (e.g., Muller and MacDonald, 1997). Milankovitch cycles of order ~100000 years, linked to Jupiter and Saturn's orbital precessions, affect Earth's eccentricity and inclination. These changes may create periodic windows for short-period comets to reach Earth, increasing dust fluxes with potential climatic consequences (see Rigley and Wyatt, 2022, and references therein).

## 3.3 Interstellar medium (ISM)

### 3.3.1 The ISM and prebiotic chemistry

The ISM, composed of gas, dust, and organic molecules, acts as both a repository and transit region for elements essential to life (Herbst, 2021). Planet formation in protoplanetary discs, which occurs over a few million years, may depend on late-stage gas infall from the ISM (Winter et al., 2024), potentially critical for forming life-bearing planets. The ISM is highly heterogeneous, with extreme conditions (Puzzarini and Alessandrini, 2024): temperatures from 10 to 200 K, densities of $1 - 10^8$ particles per cm$^{-3}$, and ionizing radiation. It consists mostly of gas (99%) and dust (1%), concentrated in "clouds." Dust grains, approximately 0.1 $\mu$m in size, are made of silicates and carbon compounds, serve as "chemical factories" where low temperatures allow barrierless reactions on icy surfaces (Guélin and Cernicharo, 2022). Cosmic rays and UV photons also drive suprathermal reactions, forming complex organic molecules (COMs) essential for prebiotic chemistry. Furthermore, in dense molecular clouds (10 K, $10^2 - 10^7$ particles per cm$^{-3}$), grains are coated with icy mantles containing CO, $CO_2$, $CH_4$,

NH$_3$, and $CH_3OH$. Reactions in these ices can produce prebiotic molecules without energetic radiation (Puzzarini and Alessandrini, 2024). For instance, carbamic acid ($H_2NCOOH$), a precursor to glycine, forms from ammonia and $CO_2$ at temperatures below 100 K (Puzzarini and Alessandrini, 2024).

LSST's Galactic science program will map ISM dust across the Milky Way and neighboring galaxies using five-color spectral energy distributions (SEDs) of main-sequence stars (see page 35 in Ivezić et al., 2019). This mapping will reveal variations in dust properties and their implications for habitability. LSST's multi-band photometry will also enable reddening ($R_V$) studies, helping to understand dust grain size and composition. Organic-rich dust regions, potentially shielded from destructive radiation, may act as "prebiotic nurseries," preserving favorable conditions for life-supporting chemistry. Beyond the Milky Way, LSST will study the ISM in the Large and Small Magellanic Clouds (LMC/SMC) and other Local Group galaxies. By comparing ISM characteristics, including density, metallicity, and radiation fields, LSST will assist in evaluating whether the conditions conducive to prebiotic chemistry are common or rare across the universe. LSST's sensitivity to low-surface-brightness (LSB) emission will allow detection of faint ISM structures, such as diffuse clouds and dust complexes. These stable environments, shielded from ionizing radiation, may support complex organic chemistry. LSST's long-term survey will also capture ISM dynamics, revealing changes that affect organic molecule distribution and stability.

Detailed ISM maps will provide critical insights into regions favorable for prebiotic hotspots. Variations in grain size, metallicity, density, and radiation fields will help pinpoint areas with optimal conditions for complex molecule synthesis. LSST will highlight regions with protective dust shielding or metal-rich environments conducive to life-forming processes. Another key area is active galactic nuclei (AGN) feedback and its influence on the ISM and exoplanets (Balbi and Tombesi, 2017). AGN-driven outflows and radiation may either hinder or enhance organic chemistry by altering molecular stability and dust shielding. For instance, recent observations of the Sgr A$^\star$ captured its unprecedented bright state in the near-infrared (Do et al., 2019). Observations of 6.4 keV Fe line emission suggest that in the past few centuries, Sgr A$^\star$ may have few relatively brief (up to ~10 yr) luminosity excursions by $\mathcal{O}(10^5)$. LSST will help identify Galactic regions where activity of Sgr A$^\star$ may affect prebiotic conditions. LSST's high-resolution ISM maps will also support Search for Extraterrestrial Intelligence (SETI) efforts by identifying regions where interstellar dust could scatter electromagnetic (EM) signals. Low-density areas may provide clearer communication windows for extraterrestrial intelligence (ETI), enhancing the detection of technosignatures in the radio, IR, and optical bands (Lampton, 2000).

## 3.4 Star and planet formation

### 3.4.1 Monitoring stellar activity and flaring stars

Stellar flares, transient events caused by magnetic reconnection in the stellar photospheres, are particularly common on M dwarfs. These events serve as indicators of stellar magnetic activity, correlating with age and rotation rates (Davenport, 2016). Flares have astrobiological implications, as their intense UV flux can

deplete planetary ozone layers or influence prebiotic chemistry, acting as both triggers and inhibitors of life (Ramsay et al., 2021).

Flares are challenging to capture in synoptic surveys like LSST due to their short-lived nature, often yielding only single-point detections. To address this, Clarke et al. (2024) have developed a method leveraging Differential Chromatic Refraction (DCR) to estimate flare temperatures from single-epoch detections. By modeling the DCR effect as a function of atmospheric column density, photometric filter, and flare temperature, they showed that flare temperatures ≥4,000 K can be constrained using single g-band observations at airmass $X > 1.2$, even under LSST's image quality standards favoring lower airmass.

Complementary methods can enhance LSST's ability to study flares. Time-domain segmentation in LSST's alert stream can trigger follow-up observations by fast-response telescopes, capturing multi-band data to constrain flare properties. Machine learning (ML) models trained on LSST data could identify flare candidates from single exposures. Stacking and probabilistic modeling of single-visit observations can reconstruct flare temperature and energy distributions, enabling statistical analyses of occurrence rates and properties.

Cross-matching LSST data with Gaia and TESS would also add value; TESS provides continuous light curves, while Gaia offers precise astrometry for multi-wavelength studies. A synthetic reference star framework in LSST images could further enable real-time analysis of flare-induced DCR offsets, revealing subtle astrometric shifts and temperature changes over time. These methods will refine flare emission models and clarify relationships between flare parameters (temperature, duration, energy) and stellar characteristics (spectral type, rotation, magnetic field strength). A catalog of flare temperatures will also guide candidate selection for biosignature surveys, given the atmospheric impact of intense flares (Clarke et al., 2023; Clarke et al., 2024).

### 3.4.2 Understanding the distribution of life-forming elements

The metallicity of a host star, particularly its iron content (Fe/H), correlates with the likelihood of planetary system formation, serving as a proxy for other heavy elements essential for planet formation and organic chemistry, such as C, N, O, and Si (Covone and Giovannelli, 2022). Phosphorus is also essential, as its scarcity in a star may result in planets that are unsuitable for life (Hinkel et al., 2020).

LSST's photometric metallicity measurements will provide an unprecedented dataset of approximately 200 million main-sequence F/G stars, extending to 100 kpc in the Galactic halo (see Ivezić et al., 2019, and references therein). LSST's observations will surpass Gaia, which is flux-limited at $r = 20.7$ (Hodgkin et al., 2021), and the Dark Energy Survey (DES) and Pan-STARRS, which lack critical u-band coverage (Bellagamba et al., 2012). LSST will also detect standard candles like RR Lyrae and classical novae up to 400 kpc, nearly reaching the Andromeda Galaxy, expanding our understanding of the Galaxy's outer structure and chemical evolution.

From an astrobiological perspective, LSST's stellar metallicity insights will aid in understanding conditions for planet formation and habitability. Probing metallicity patterns in the halo will identify regions enriched or depleted in heavy elements, informing

planetary formation potential in diverse Galactic environments. LSST's trigonometric parallax measurements for low-mass stars near the hydrogen-burning limit will map stellar populations driving chemical enrichment, contributing to models of Galactic habitability. Additionally, LSST's measurements of the white dwarf luminosity function will provide independent age estimates for the Galactic disk and halo, identifying ancient, stable systems with long-term habitability potential.

Cross-matching LSST's stellar metallicity catalog with spectroscopic surveys like 4MOST (de Jong et al., 2019) will refine biosignature searches by identifying regions rich in life-supporting elements. LSST's combined stellar and exoplanet datasets will enable Bayesian modeling to evaluate the likelihood of life under different metallicity thresholds and atmospheric conditions. By linking metallicity data with known atmospheric biosignatures, LSST can improve Bayesian posterior probabilities for the likelihood of life-supporting environments.

Synergies with spectroscopic studies, such as the Apache Point Observatory Galactic Evolution Experiment (APOGEE, Majewski et al., 2017), demonstrate the importance of mapping life-supporting elements. APOGEE has detected higher concentrations of heavy elements in the inner Galaxy, where stars are older, suggesting that essential life elements were synthesized earlier in the inner regions compared to the outer (Albareti et al., 2017).

## 3.5 Mapping the galactic habitable zone

Galactic habitability examines how large-scale environmental factors within a galaxy influence the abundance of planets conducive to life (see e.g., Dayal et al., 2015; Lacki, 2021). Key factors include (1) stellar population metallicity, which affects planet formation frequency; (2) high-energy events from massive stars, potentially driving mass extinctions; and (3) frequent stellar encounters in dense regions, which may destabilize planetary systems.

Analysis by Dayal et al. (2015), based on SDSS data, revealed that over 100,000 local galaxies lie on a remarkably thin plane in a 3D space defined by these parameters. The Milky Way, classified as "typically average," exemplifies this trend. Larger galaxies, particularly giant ellipticals lacking spiral structures, are more metal-rich and exhibit lower supernova rates, making them strong candidates for habitability. Remarkably, a giant elliptical at least twice the size of the Milky Way could support up to 10,000 times more habitable Earth-like planets due to its reduced high-energy activity and enriched metallicity.

The LSST will expand on SDSS's insights by observing billions of galaxies. Its deep, multi-band photometry will enable mapping of stellar populations and metal-rich regions, while high-cadence imaging will track supernovae, refining galactic habitability models by identifying low-radiation environments. LSST's photometric focus necessitates alternative methods to calculate star formation rates (SFRs) without direct spectroscopic data. UV-optical colors (e.g., u − g or u − r) serve as proxies for recent star formation, with calibrations available for estimating SFRs through empirical or ML models trained on datasets with known SFRs.

Programs like CIGALE (Code Investigating Galaxy Emission, Boquien et al., 2019) and LePhare (Photometric Analysis for Redshift Estimates, Arnouts and Ilbert, 2011) are designed for

spectral energy distribution fitting (Yang et al., 2020) and can estimate SFRs from photometry by modeling the contributions of young stars and dust attenuation[8]. ML models trained on galaxies with spectroscopic data from surveys like SDSS, DESI (Dark Energy Spectroscopic Instrument), or future follow-ups (e.g., Wide Spectroscopic Telescope-WST, 4MOST) can directly map LSST photometry to known SFRs. LSST's overlap with these surveys will enable robust calibrations, leveraging color, magnitude, and redshift to predict SFRs and extend our understanding of galactic habitability across diverse environments.

## 3.6 Biosignatures and technosignatures searches

### 3.6.1 Biosignatures

The search for life focuses on two primary goals (Saha et al., 2018): identifying planets with Earth-like conditions (Earth similarity) and exploring the broader potential for life (habitability). Beyond paired atmospheric biosignatures such as $O_2/CH_4$ and $O_3/CH_4$ (see Kaltenegger and Faherty, 2021, and references therein), surface features on exoplanets may also serve as critical indicators of life. One of the most studied surface biosignatures is the Vegetation Red Edge (VRE), a distinct spectral feature caused by the reflectivity of chlorophyll in plants, which sharply increases reflectance at wavelengths longer than ~750 nm, within LSST's i band (see Figure 2). For exoplanets, this feature could serve as a biosignature (Jonathan et al., 2023).

On Earth, the VRE is detectable as a global increase in the reflectance spectrum, with typical values around 50% for present-day vegetation (O'Malley-James and Kaltenegger, 2018), covering approximately 60% of the land surface. However, the VRE is not unique to modern plants, which only became dominant $7.5 \times 10^8$ years ago. Chlorophyll is present in many life forms, including cyanobacteria, algae, lichens, and corals. Earlier photosynthetic organisms could have produced similar spectral features, extending the potential detectability of photosynthetic life on exoplanets to $\sim \mathcal{O}(10^9)$ years ago (O'Malley-James and Kaltenegger, 2019). This broadens the scope of surface biosignature detection, allowing for the possibility of identifying ancient or non-vegetative photosynthetic life forms.

In addition to photosynthesis, other forms of life, including microorganisms and extremophiles, could significantly influence a planet's reflectance spectrum if they are widespread. Recent efforts, such as the development of spectral libraries for diverse microorganisms (Hegde et al., 2015), provide valuable data for interpreting these potential biosignatures. These libraries include reflectance measurements from the visible to near-infrared spectrum, offering a crucial tool for identifying and characterizing surface biosignatures on exoplanets[9].

The VRE could potentially be detected through the color index derived from LSST transit light curves. If an exoplanet's surface exhibits a VRE, a distinct increase in the $g − i$ color index would be observed. The g band (400–550 nm) captures visible reflectivity,

while the i band (700–850 nm) records the enhanced reflectivity from chlorophyll. By monitoring the color index during transit events, any significant deviation from expected values could indicate the presence of surface features like the VRE. This method could serve as an initial detection mechanism, warranting further spectral analysis of the exoplanet's surface to confirm the presence of photosynthetic life.

The distribution of stars < 300 pc of the Solar System, is fundamental in selecting targets for future spectroscopic space missions such as Habitable World Observatory (HWO) and Large Interferometer For Exoplanets (LIFE) aimed at studying exoplanetary atmospheres and detecting potential biosignatures and technosignatures. Although most stars in the Sun's vicinity are faint (Supplementary Figure S3), nearby F, G, K, and M stars ( < 50 pc) could be prime candidates for detailed atmospheric studies with upcoming space-based spectroscopic surveys (Tuchow et al., 2024; Quanz et al., 2022), complemented by supplementary insights from LSST data.

### 3.6.2 Technosignatures searches

Fast-moving objects (FMOs) in the LSST DP0.3 catalogue are characterized by high orbital eccentricity, small perihelion distances, and, in some cases, high inclinations (see Supplementary Figure S4). These result in rapid motion and increased brightness at perihelion distances, and swift positional changes across survey images. These features make FMOs briefly detectable but challenging to track, requiring high-cadence observations and advanced algorithms. For instance, an FMO moving at $v = 30$ arcsec/h, tracking it within a detection limit of $\theta_{\max} = 15$ arcsec requires an observation cadence of $t_{\text{cadence}} \leq 1 - 1.5$ h (see also Section 3.1). The search for FMOs complements efforts to detect technosignatures—potential markers of advanced extraterrestrial civilizations. LSST's wide-field surveys offer unique capabilities to identify such technosignatures (e.g., Davenport, 2019; Haqq-Misra et al., 2022; Hambleton et al., 2023), which may appear as anomalous orbital deviations due to artificial manipulation (Ginsburg et al., 2018) or non-natural transit signatures modulated to encode prime numbers or Fibonacci series (Arnold, 2005). While these methods risk anthropocentric bias, they underscore LSST's potential to uncover a broad range of signals.

LSST's high-precision astrometry can detect deviations in Solar System object orbits that suggest artificial manipulation, potentially identifying free-floating probes, surface-based constructs, or artificial satellites (NASA Technosignatures Workshop Participants, 2018). Searches for small bodies may inherently uncover anomalies via unusual orbits, colors, or light curves. Furthermore, technosignatures may involve spatial or temporal coordination, such as synchronized transiting systems or rebroadcasted natural astrophysical events (e.g., novae), which could signal extraterrestrial communication (Davenport, 2019). LSST's wide-field observations could also reveal phenomena like long-term stellar dimming or disappearing stars, indicative of artificial structures like Dyson spheres (see Suazo et al., 2024; Villarroel et al., 2022, and references therein).

A key challenge in technosignature searches is avoiding anthropocentric assumptions. Patterns like prime numbers or Fibonacci sequences reflect human biases toward mathematical relevance (Wigner, 1995). While mathematics may appear universal

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(Tegmark, 2008), it is argued to be shaped by human cognition (Lakoff and nez, 2000). Broader frameworks that incorporate non-traditional communication or structural forms are crucial (Döbler, 2020). To address possibility of non-traditional SETI signatures in the optical domain, recent studies by Megias Homar et al. (2023) highlight LSST's ability to detect millisecond Fast Optical Bursts (FOBs), which may represent technosignatures or unknown phenomena. These bursts, distinct from steady sources, produce anomalous spatial patterns. Simulations with neural network classifiers show LSST can isolate FOBs, mapping their duration-intensity space and predicting significant detections over its 10-year survey (Megias Homar et al., 2023). Complementary efforts like PANOSETI (Wright et al., 2019) will expand the search by targeting nanosecond laser pulses in optical and near-infrared spectra, reducing reliance on human-centered assumptions.

# 4 LSST's role in multimodal and multimessenger astrobiology

Over the past century, astronomical data have been primarily based on 2D images and 1D spectra or time series. Modern instruments like LSST are shifting this paradigm toward more complex, multi-dimensional data. LSST's multi-epoch survey will generate time-image cubes, capturing dynamic phenomena across time, similar to video sequences. Additionally, photometric light curves from multiple filters can be stacked to form data cubes that combine both temporal and spectral information. This high-dimensional dataset is central to LSST's role as an explorer of the 'Cosmic Haystack' (Tarter, 1985), enabling a systematic search for weak or infrequent signals, which may reveal astrobiological markers, technosignatures, or other anomalous phenomena.

The rise of multimessenger astronomy facilitates the integration of data from multiple observatories, such as LSST optical data, gravitational waves (GW), and neutrinos. Unlike radio surveys, which are limited to scanning a narrow spectral window at a given time, LSST's wide-field optical monitoring offers a systematic, time-resolved approach to detect potential artificial sources (Liu et al., 2020). By complementing GW and neutrino observations, LSST supports multi-messenger strategies that narrow the search space for astrophysical anomalies possibly linked to extraterrestrial intelligence (Sellers et al., 2022). For example, GW from rapidly accelerating massive objects, potentially interpreted as extraterrestrial spacecraft, might coincide with LSST's detection of unusual light curves and neutrino bursts that suggest advanced technology. Another scenario could involve GW from interacting massive objects, with LSST transits revealing atmospheric biosignatures and neutrino patterns indicating high-energy processes. Combining these observations offers a more robust framework for detecting extraterrestrial activity.

Multimessenger astronomy is essential for SETI, as it reduces false positives and strengthens signal detection through cross-validation (see also Wright, 2018). The number of technosignatures could far exceed biosignatures (Wright et al., 2022), highlighting the need for such integrated strategies. However, the vast space-time scales involved present significant challenges, requiring advanced methods for cross-validation, simulations, and theoretical analysis (Allen et al., 2019).

The spectral overlap between LSST and JWST (600–28,500 nm) facilitates multi-wavelength studies. In the 600–1,050 nm range, LSST's optical bands overlap with JWST, covering the r, i, z, and y bands[10]. This overlap enables a comprehensive characterization of exoplanetary atmospheres by combining JWST's infrared spectroscopy with LSST's time-domain photometry (Greene et al., 2016). Joint observations allow for the extraction of crucial atmospheric parameters, such as molecular absorption features, cloud properties, and thermal variations (Madhusudhan, 2019).

## 4.1 ML prospects for multimessenger technosignature detection

To efficiently analyze these multimodal datasets, the Structured Data Fusion (SDF) framework offers a powerful method for integrating diverse astrophysical observations. SDF represents datasets as high-dimensional tensors and applies decomposition techniques to identify shared structures across different types of data (Lahat et al., 2015). This approach has already been applied in multimodal astrophysical analyses, such as combining photometry, spectroscopy, and GW data to extract underlying physical processes (Cuoco et al., 2022). Importantly, the astronomical community has rising awarness of the worth of a multimodal approach. For example, the 'Multimodal Universe' collaboration capitalizes on observations available from a diversity of ground- and space-based telescopes forming a dataset of hundreds of millions of astrophysical objects and phenomena. Altogether, this comrises > 100 TB of open-access and copyright-free data spanning multiple observational modalities such as multi-channel and hyperspectral images, optical spectra, multivariate time-series, and an extensive array of associated scientific measurements (Audenaert et al., 2024). With LSST generating $\mathcal{O}(10^3)$ science frames nightly, the resulting data volume amounts to approximately 12 billion tokens per night, or over 4.4 trillion tokens annually (Smith and Geach, 2023). Recent advancements in ML (e.g., PyTorch[11]) allow for the efficient implementation of SDF, enabling scalable, real-time analysis of vast multimodal datasets. By leveraging these computational advances, LSST's synergy with other facilities can be optimized, leading to breakthroughs in exoplanet detection, technosignature identification, and astrobiological studies.

Recent development in quantum computing, deployed on platforms like Google Quantum AI (Arute et al., 2019) and IBM Quantum Services[12], offers the potential for adavancing multimodal data analysis. Despite ongoing debates about quantum advantage (e.g., Renaud et al., 2024), its integration into scientific pipelines for medical research is gaining momentum (Li et al., 2024). For instance, in astronomy hybrid quantum-classical models could help detect technosignatures by identifying anomalous periodic light curves and even artificial gravitational wave signals (Sellers et al., 2022). These models can encode latent representations using parameterized quantum circuits and decode them through classical

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10  https://webb.nasa.gov/content/about/faqs/facts.html

11  https://pytorch.org/

12  https://quantum.ibm.com/

neural networks, which show promise in reconstructing weak signals from noise (Kovačević et al., 2024).

## 4.2 LSST's follow up of GW events—kilonovae

Neutron star mergers generate kilonovae—high-energy explosions that synthesize and disperse heavy elements, including iodine and gold, which are essential for biochemistry and advanced technologies (Wehmeyer et al., 2023; Perkins et al., 2024). While GW detections from these events provide critical insights into merger dynamics, it is LSST's optical follow-up that constrains ejecta properties, tracking how these elements propagate through interstellar space. Over LSST's 10-year survey, up to three Galactic kilonovae are expected (Perkins et al., 2024), with JWST's infrared spectroscopy offering complementary data on r-process nucleosynthesis (Levan et al., 2024).

Recent observations of GRB 230307A, a kilonova similar to GW170817, confirmed the astrophysical production of iodine, highlighting the role of neutron star mergers in distributing biologically significant elements (Crockford, 2009). LSST is projected to detect more than 300 kilonovae within 1,400 Mpc, with 1%–10% classified as fast-evolving transients (Andreoni et al., 2021). Strategies for identifying these events include all-sky surveys and targeted follow-up of GW alerts from LIGO/Virgo (Ragosta et al., 2024).

By combining LSST light curves with JWST spectra, researchers can assess superheavy-element production in kilonova ejecta (Holmbeck et al., 2023). Notably, JWST has already detected tellurium—an r-process element relevant to life—suggesting that iodine and other biologically significant elements may also be present[13] (Levan et al., 2024). These elements, crucial for materials such as magnets and lasers (see Supplementary Figure S5), could influence planetary habitability and even the emergence of technologically advanced societies (Zhang et al., 2023). A Type III civilization, capable of harnessing a galaxy's energy, might rely on such elements for infrastructure and computational technologies (Zhang et al., 2023). Mapping their interstellar distribution with LSST and JWST will improve our understanding of both astrobiology and the conditions necessary for advanced technological evolution.

## 4.3 Neutrino event follow-up with LSST

Neutrinos have been proposed as a potential medium for interstellar communication, given their ability to propagate over cosmological distances with minimal attenuation (Pasachoff and Kutner, 1979). Experimental demonstrations have shown the feasibility of neutrino-based communication over short distances, such as the 1.035 km low-rate neutrino link established using the NuMI beam line and MINERvA detector (Stancil et al., 2012). In astrophysical contexts, brief, targeted signals synchronized

with transient events, such as supernovae or gamma-ray bursts (GRBs), have been suggested as Schelling points that could enhance signal detectability (Nishino and Seto, 2018). Learned et al. (2009) demonstrated that 6.3 PeV electron–anti-neutrino beams, undetectable from natural sources, could be used as extraterrestrial intelligence (ETI) signals if synchronized with such astrophysical events. Detecting such rare signals would require continuous monitoring by neutrino observatories and systematic cross-matching with transient detections.

The LSST survey is expected to detect millions of transient events, including supernovae, over its 10-year operational period (Gris et al., 2023). While supernovae generally exhibit slow-evolving light curves, they could function as Schelling points for synchronized ETI communication, particularly if accompanied by neutrino bursts (Learned et al., 2009). For example, the GW170817 neutron star merger produced unexpected neutrino signals (Fischbach et al., 2018), prompting discussions on possible non-astrophysical origins (Santos et al., 2020). Cross-matching LSST's transient detections with GW and neutrino data could help identify regions of interest (ROIs) for further investigation.

LSST's Field of View (FoV) is defined as $FoV_{LSST} = 3.5°$[14]. If ETI neutrino beams were to be detectable within LSST's observational range, their alignment and timing with astrophysical transients would be key factors for signal identification. This highlights LSST's role in multimodal searches for technosignatures, emphasizing the need for systematic observational strategies that integrate LSST optical detections with GW and neutrino datasets.

## 5 LSST as a platform for interdisciplinary collaboration

### 5.1 Bridging physics and astrobiology

A new and compelling connection between physics and astrobiology emerges from the study of dark matter candidates, such as ultralight bosons, and their interactions with supermassive black holes (SMBHs), altering their spin distributions and influencing phenomena like tidal disruption events (TDEs). Stars disrupted by SMBH tidal forces produce bright transient flares observable in sky surveys, with occurrence rates tied to black hole spins (Du et al., 2022). The LSST will measure TDE rates, offering a unique opportunity to detect ultralight bosons with masses in the $10^{-20}$ to $10^{-18}$ eV range or to constrain SMBH spin distributions, shedding light on preferences for maximal spins (Du et al., 2022).

On the other hand, TDEs may impact galactic centers by redistributing radiation and heavy elements, alternately sterilizing regions or enhancing conditions for life. LSST's unprecedented ability to track TDEs and transient events in real time will advance our understanding of galactic habitability. By observing SMBHs influenced by ultralight bosons, LSST will probe how dark matter may indirectly shape life-supporting environments. This example of synergy between fundamental physics and

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13  https://www.nasa.gov/missions/webb/nasas-webb-makes-first-detection-of-heavy-element-from-star-merger/

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14  https://www.lsst.org/scientists/keynumbers

astrobiology highlights LSST's transformative role in exploring life's cosmic context.

## 5.2 Citizen science in astrobiology

Citizen science plays a vital role in analyzing LSST's vast transient data, bridging gaps not addressed by automated systems (Balcom, 2015; Marshall et al., 2015). Platforms like Zooniverse[15], originally developed for Galaxy Zoo (Masters and Galaxy Zoo Team, 2020), enable public participation in projects. SETI@Home pioneered distributed computing for SETI signal analysis (Anderson et al., 2000), and citizen scientists have discovered phenomena such as the unusual light curve of KIC 8462852, linked to exocomets or technosignatures (see Hambleton et al., 2023, and references therein). Independent projects have also explored astrobiology and technosignatures, contributing to the field's growth (Villarroel et al., 2022).

Integration of Artificial Intelligence (AI) platforms enhances LSST-driven citizen science by enabling efficient anomaly detection within its vast data streams (Villarroel et al., 2022). Symbiotic learning, where humans and AI iteratively refine training sets, combines human intuition with machine precision to improve outcomes (Barrat, 2013). Projects like Backyard Worlds[16] and Planet Hunters TESS[17] demonstrate this approach by involving volunteers in identifying fast-moving objects and exoplanet transits, while SuperWASP and Supernova Hunters apply similar methods to classify light curves and detect real transients. These strategies could, and indeed should, be adapted to LSST's unprecedented data volumes, enhancing the potential for meaningful discoveries. Moreover, there are growing varieties of applications of self-suprevised learning algorithms that do not require prelabeled data in astronomical problems (Mesarcik et al., 2023). Such algorithms can be used in conjunction with humans for citizen science by enabling systems to label and interpret vast amounts of data autonomously, while human volunteers can validate, refine, and provide feedback on the AI's predictions (see e.g., Jiménez et al., 2023).

The Rubin Observatory partners with Zooniverse on astrobiology-related projects such as Daily Minor Planet and Active Asteroids[18]. LSST's multiepoch surveys are expected to generate unprecedented transient data volumes, making citizen scientists essential for identifying anomalies that automated pipelines might miss. By leveraging platforms like Zooniverse, the public could be trained to search for biosignatures (e.g., water or oxygen absorption lines) and technosignatures (e.g., artificial signals or unusual periodicities) within LSST's data.

Citizen scientists could further contribute to multimodal investigations by identifying coincident signals, such as gamma-ray bursts associated with gravitational wave detections, revealing environments near neutron star mergers. LSST's observations of exoplanet atmospheres may also uncover disequilibrium chemistry indicative of biological activity. These efforts emphasize LSST's pivotal role in combining public engagement and advanced science to advance astrobiology.

## 6 Conclusion

The Vera C. Rubin Observatory's LSST provides the astrobiology community enormous opportunities to develop its search for evidence for life having evolved elsewhere in the universe. In this paper, we have reviewed these opportunities. Through its extensive imaging capabilities it provides methods for detecting biosignatures and for mapping elementary compositions in stars, the ISM and exoplanets that are conducive to determining habitable regions. LSST will significantly extend our inventory of Solar System objects and, beyond the Solar System, survey billions of stars, contributing to the detection of exoplanets, characterizing planetary atmospheres and detecting the presence of flora through search for a 'red edge' in surface reflection spectra. Through the study of transient phenomena, LSST may provide a means for searching for technologically advanced civilisations. Thus, we encourage the astrobiology community to exploit the scientific opportunities of the Vera C. Rubin Observatory's LSST, perhaps through the creation of a specific topical science team working group.

## Author contributions

AK: Writing – review and editing, Writing – original draft, Visualization, Methodology, Conceptualization, Investigation. NM: Methodology, Conceptualization, Writing – review and editing, Supervision, Writing – original draft. AĆ: Supervision, Writing – review and editing.

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15 https://www.zooniverse.org/

16 https://www.zooniverse.org/projects/coolneighbors/backyard-worlds-cool-neighbors

17 https://www.zooniverse.org/projects/nora-dot-eisner/planet-hunters-tess

18 https://rubinobservatory.org/explore/citizen-science

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspas.2025.1594485/full#supplementary-material

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