Let’s discover our ORIGINS

From First Light to Life
How does the universe work?
How do galaxies form stars, make metals and grow central supermassive black holes?

How did we get here?
How do the conditions for habitability develop during the process of planet formation?

Are we alone?
How common are life bearing planets around M-dwarf stars?

Discovery of new phenomena
Origins will open unprecedented discovery space in the Far-IR, what mysteries lay in wait?
★ **1000x more sensitive** than any previous far-IR mission

★ **5.9 m, non-deployed cold aperture (4.5K)**

★ **Low-risk** development, testing, and deployment

★ **Broad wavelength coverage**: 2.8 – 588 \( \mu \text{m} \)
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Equivalent difference for an optical telescope to achieve 1000 times higher sensitivity
★ 1000x more sensitive than any previous far-IR mission

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5.9 m, non-deployed cold aperture (4.5K)

Low-risk development, testing, and deployment

Broad wavelength coverage: 2.8 – 588 µm
Now is the time for a Far-IR revolution

★ Advances in technology are opening up unprecedented discovery space

★ **Key wavelength coverage** between JWST and ALMA

★ **Cannot be done from the ground**

★ **Simple architecture** with a **robust technology** development plan

arXiv:1912.06213
https://origins.ipac.caltech.edu/
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Origins probes galaxy ecosystems
Origins simultaneously traces AGN, Star Formation, and Feedback

Covers the gap from JWST to ALMA

Key diagnostics from the local universe to the epoch of reionization
Origins: 3D unbiased surveys of galaxies

★ Spectra for millions of galaxies over a few sq. degrees out to $z = 8$ in a 2000 hr blind survey
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Origins uniquely follows the trail of water, from protostars, through disks, to objects in our own solar system.
TRACING WATER EMISSION IN DISKS
Using HD, **Origins** can unambiguously trace 1000s of disks around stars of all masses. And study solar system objects to unveil the origin of Earth’s oceans.

Bergin et al. 2013
How does the universe work?
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Why M and K Dwarfs?

- **M and K dwarfs are common**
  - 75% of stars within 15 pc are M dwarfs

- **Rocky planets are common**
  - Expect to detect about a dozen HZ exoplanets transiting mid-to-late M dwarfs within 15 pc
  - Four such planets are already known (TRAPPIST-1d,e,f and LHS-1140b)

- **Advantages of small (rocky) planets transiting M dwarf stars**
  - Larger transit depths
  - Closer habitable zones (5 – 100 days)
  - Increased transit probability in HZ

T. Henry, RECONS Survey
Searching for life in Transiting Exoplanets
★ Origins will measure key habitability indicators
(may suggest presence of life, but can also be produced without life: e.g. H$_2$O, CO$_2$, O$_3$, CH$_4$, N$_2$O alone)

★ And uniquely probe biosignatures
(a combination of molecules that can only be produced by life: e.g. O$_3$ + CH$_4$ or O$_3$ + N$_2$O)

toward Habitable Zone planets with Earth-like atmospheres transiting mid-to-late M dwarfs
Origins will use a multi-tiered strategy to search for life

**Tier 1**
*Transit* observations to determine which planets have tenuous, clear or cloudy atmospheres (Np > 28)

**Tier 2**
*Eclipse* observations of clear planets to determine if they are temperate (Np > 14)

**Tier 3**
Search for bio-signatures (O₃+N₂O, O₃+CH₄) with additional transits of temperate worlds (Np > 10)

**Pre-select terrestrial M-dwarf planets** based on: (i) Planet radius and equilibrium temperature. (ii) Relative rank based on suitability for detailed atmospheric characterization. (iii) Pre-Origins observations with JWST, ELTs etc.
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Infrared: Unanticipated Discoveries with every new facility

Significant gain in sensitivity has resulted in unanticipated discoveries!

1980s
- **IRAS**
  - debris disks

2000s
- **Spitzer**
  - The Seven Wonders of TRAPPIST-1
  - multi-planet systems

2010s
- **Herschel**
  - Water vapor around Ceres

- **IR-bright galaxies**
- **cirrus, dust bands, Earth trailing dust**
- **In-falling gas in galaxy groups cool via \( H_2 \)**
- **Extraordinarily massive, starbursting galaxies ~800 Myr after Big Bang**
- **Water line cooling in galaxies**
- **asteroidal dust rain on white dwarfs**
Origins provides a ~100x field of view for $H_2$ mapping in near-by galaxies (vs JWST)

2” & 9” scale maps of ISM dust polarization to bridge Planck (2’) & ground (1”)

**Discovery Space of Origins**

Expectations from modern astrophysics

*Origins can be used as a uniquely valuable baseline in the Event Horizon Telescope.*

An Origins upscope can resolve blackholes above $10^9$ Msun throughout the full cosmic history

**Time domain:** Top (mid-IR): SPRITES, GW Counterparts. Bottom (far-IR): proto-stellar accretion

And lots and lots more!
Through the Astrophysics Roadmap, the community expressed interest in a “Far-IR Surveyor” mission.

The Origins Science and Technology Definition Team engaged 100s of members of the international scientific community and guided the development of the mission concept.

Guest Observers will use Origins to answer mission-driving science questions and make unexpected, transformative discoveries.

From the community, by the community, for the community... is for everyone!
Now is the time to discover our ORIGINS

★ Broad range of scientific studies, from Solar system to primordial gas cooling prior to the era of reionization.

★ Efficient 3D spectroscopic mapping enabled by wide area field of view (e.g., WFIRST vs. HST) and fast scan speed (e.g., Herschel/Planck)

★ Enabled by a 1000x gain in sensitivity in the far-IR relative to anything before.

★ Advances in detector and cryocooler technology are opening up unprecedented discovery space in a simple and robust technology

★ Key wavelength coverage between JWST and ALMA and cannot be done from the ground
Backup
Origins: Three Instruments

**OSS:** Origins Survey Spectrometer
- 25-588 µm R~300, *survey mapping*
- 25-588 µm R~43,000, *spectral surveys*
- 100-200 µm R~325,000, *kinematics*

**FIP:** Far-infrared Imager Polarimeter
- 50 or 250 µm, *Large area survey mapping*
- 1.75” @ 50  8.75” @ 200 PSF/FWHM
- 50 or 250 µm, *polarimetry*

**MISC-T:** Mid-Infrared Spectrometer Camera Transit
- *Ultra-Stable Transit Spectroscopy*
- 2.8-20 µm R~50-295
### Table 4: Instrument Capabilities Summary

<table>
<thead>
<tr>
<th>Instrument/Observing Mode</th>
<th>Wavelength Coverage (μm)</th>
<th>Field of View (FOV)</th>
<th>Spectral Resolving Power (R=λ/Δλ)</th>
<th>Saturation Limits</th>
<th>Representative Sensitivity 5σ in 1 hr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Origins Survey Spectrometer (OSS)</strong></td>
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<tr>
<td>Grating</td>
<td>25¼–588 μm simultaneously</td>
<td>6 slits for 6 bands: 2.7’ x 1.4” to 14’ x 20”</td>
<td>300</td>
<td>5 Jy @ 128 μm</td>
<td>3.7 x 10⁻²¹ W m⁻² @ 200 μm</td>
</tr>
<tr>
<td>High Resolution</td>
<td>25¼ 588 μm with FTS</td>
<td>Slit: 20” x [2.7” to 20”]</td>
<td>43,000 [112 μm/λ]</td>
<td>5 Jy @ 128 μm</td>
<td>7.4 x 10⁻²¹ W m⁻² @ 200 μm</td>
</tr>
<tr>
<td>Ultra-High Resolution</td>
<td>100¼ 200 μm</td>
<td>One beam: 6.7”</td>
<td>325,000 [112 μm/λ]</td>
<td>100 Jy @ 180 μm</td>
<td>~2.8 x 10⁻¹⁹ W m⁻² @ 200 μm</td>
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<tr>
<td><strong>Far-IR Imager Polarimeter (FIP)</strong></td>
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<tr>
<td>Pointed</td>
<td>50 or 250 μm (selectable)</td>
<td>50 μm: 3.6’ x 2.5’ 250 μm: 13.5’ x 9’ (109 x 73 pixels)</td>
<td>3.3</td>
<td>50 μm: 1 Jy 250 μm: 5 Jy</td>
<td>50/250 μm: 0.9/2.5 μJy Confusion limit 50/250 μm: 120 nJy/1.1 mJy</td>
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<tr>
<td>Survey mapping</td>
<td>50 or 250 μm (selectable)</td>
<td>60” per second scan rate, with above FOVs</td>
<td>3.3</td>
<td>50 μm: 1 Jy 250 μm: 5 Jy</td>
<td>Same as above, confusion limit reached in 50/250 μm: 1.9 hours/2 msec</td>
</tr>
<tr>
<td>Polarimetry</td>
<td>50 or 250 μm (selectable)</td>
<td>50 μm: 3.6’ x 2.5’ 250 μm: 13.5’ x 9’</td>
<td>3.3</td>
<td>50 μm: 2 Jy 250 μm: 10 Jy</td>
<td>0.1% in linear and circular polarization, ±1” in polar. Angle</td>
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<tr>
<td><strong>Mid-Infrared Spectrometer Camera Transit Spectrometer (MISC-TRA)</strong></td>
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<tr>
<td>Ultra-Stable Transit Spectroscopy</td>
<td>2.8¼–20 μm in 3 simultaneous bands</td>
<td>2.8–10.5 μm: 2.5” radius 10.5–20 μm: 1.7” radius</td>
<td>2.8–10.5 μm: 50–100 10.5–20 μm: 165–295</td>
<td>K~3.0 mag 30 Jy @ 3.3μm</td>
<td>Assume K~9.85 mag M-type star, R=50 SNR/sqrt(hr)&gt;12,000 @ 3.3 μm in 60 transits with stability ~5 ppm &lt; 10.5 μm, ~20 ppm &gt; 10.5 μm</td>
</tr>
</tbody>
</table>
Origins: Spitzer-like low-risk design

**Wavelength coverage:** 2.8-588 µm  
**Telescope:**  
- diameter: 5.9 m  
- area: 25 m² (=JWST area)  
- diffraction-limit: 30 µm  
- temperature: 4.5 K  
**Cooling:** long-life cryo-coolers  
**Agile Observatory for surveys:** 60” / second  
**Launch Vehicle:**  
- Large, SLS Block 1, Space-X BFR  
**Mission:** 10 year propellant, serviceable  
**Orbit:** Sun-Earth L2
Compared to JWST:
- fewer deployments
- modular design

Uses existing test facilities:
-re-uses Johnson Space flight Center Chamber A: end-to-end, “test as you fly”
**Origins: Key Technologies are on track**

**Far-IR:** TES, KIDS
- Improved sensitivity: $3 \times 10^{-20}$ W/Hz$^{1/2}$
- State of the art: $10^{-19}$ W/Hz$^{1/2}$
- Increase array size: $10^4$ pixels
- State of the art: 3000 pixels

**Mid-IR:** HgCdTe, Si:As, TES
- Improved relative spectral stability, 5 ppm
- State of art: 20-50 ppm

**Detectors:**
- Moore's Law

**Cryocoolers:**
- 4.5 K: Thanks MIRI/JWST + Hitomi!
- 50 mK: NASA Dev.
Origins:
Simpler Design = Shorter Timeline

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<tr>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
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<th>2036</th>
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<tr>
<td>Pre-Phase A</td>
<td>Phase A</td>
<td>Phase B</td>
<td>Phase C</td>
<td>Phase D</td>
<td>Phase E / Operations</td>
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<tr>
<td>Mission Milestones</td>
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<td>Selection</td>
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<td>KDP-B</td>
<td>KDP-C</td>
<td>KDP-D</td>
<td>KDP-E</td>
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<td>Flight Sys. Dev.</td>
<td>TRL 5</td>
<td>TRL 6</td>
<td>PDR</td>
<td>CDR</td>
<td>SIR</td>
<td>Delta SIR</td>
<td>PSR</td>
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</table>

telescope, instruments, spacecraft development, I&T

CPM/Observatory I&T, launch prep.

Launch
1000x more sensitive than any previous infrared mission

5.9 m, non-deployed cold aperture (4.5K)

Low-risk development, testing, and deployment

Broad wavelength coverage: 2.8 – 588 µm
Origins/FIP  Surveys LSST and WFIRST Areas

**Origins FIP = WFIRST HLSurvey**
1600hrs.

2200 deg, 40\(\mu Jy\)@50\(\mu m\) FWHM=1.75"

**LSST = Origins FIP**
1000hrs.

18,000 deg, 1mJy@250\(\mu m\)
FWHM=8.75"

**Herschel (black areas)**
1000^2 deg., 45mJy@250\(\mu m\)

FWHM=17.6"
Star Formation and AGN growth are heavily obscured by dust in galaxies

Whitaker et al. 2017

Hickox & Alexander 2018
Relative growth of stars and supermassive black holes in galaxies is relatively uncertain over cosmic time.
The Water Spectrum is a Temperature Distribution

Blevins et al. 2016
Origins measures gas mass of planet forming disks

HD J = 1-0

Flux density (Jy)

Wavelength (µm)

Disk gas mass (M_{\text{Jup}})

Origins-OSS etalon
Origins-OSS
SPICA-SAFARI
Model spectrum

10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3

112.04
112.06
112.08
112.10

SOFIA
Herschel
SPICA
Origins

F46
How did Earth get its water?

Remote Sensing
In situ measurements

Protosolar nebula
Biosignature Pairs

$(O_3 + CH_4, O_3 + N_2O)$

$H_2O$ and $CO_2$ are necessary, but not suggestive, of life

Origins: IR wavelengths rich in biologically interesting molecules
Origins will use a multi-tiered strategy to search for life

**Tier 1**
Transit observations to determine which planets have tenuous, clear or cloudy atmospheres (Np > 28)

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Eclipse observations of clear planets to determine if they are temperate (Np > 14)

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Pre-select terrestrial M-dwarf planets based on:
(i) Planet radius and equilibrium temperature.
(ii) Relative rank based on suitability for detailed atmospheric characterization.
(iii) Pre-Origins observations with JWST, ELTs etc.

Retrievals from 60 Transits (Per Telescope) of Earth, M8 star, Kmap=9.85, R=100

- Origins (MISC-T), 5 ppm noise floor
- JWST (NIRSpec/G395H + MIRI/LRS), 20+30 ppm noise floors

**Chemicals**
- CO₂
- N₂O/CH₄
- O₂/O₃
- H₂O
Figure 1-43: Molecular opacities of relevant habitability indicator (top) and biosignature (bottom) gases in the mid-infrared. Origins is sensitive to multiple bands for each molecular species, which is critical in breaking degeneracies between overlapping spectral signatures.
Exoplanet Science Strategy Report supports *Origins*

- A cooled near-to-far infrared (IR) mission such as the Origins Space Telescope (*Origins*) would advance exoplanet science both by providing inputs to the study of planet formation through investigations of protoplanetary disks and by allowing planetary atmospheric characterization via the transit method.

- For the study of protoplanetary disks, the committee considers such a mission to be potentially *transformative given its far-IR coverage*. High spectral resolution investigation of water lines would allow study of the spatial distribution of water across disks. Measurements of hydrogen deuteride (HD) lines would allow direct measurement of hydrogen masses of disks. Both would provide important information about the conditions under which planets form.

- Finding: The combination of transiting planet detection with TESS, mass measurements with radial velocities, and atmospheric characterization with JWST will be transformative for understanding the nature and origins of close-in planets. Future space missions with broader wavelength coverage, a larger collecting area, or reduced instrumental noise compared to JWST would have greater reach to potentially habitable planets.
For the direct study of exoplanets, *Origins*’ primary strength is in atmospheric characterization through transit spectroscopy in both primary and secondary eclipse. Like JWST, *Origins*’ mid-IR wavelength coverage allows secondary eclipse measurements to probe thermal emission from temperate atmospheres and detect a variety of key molecules using transmission and emission spectroscopy. Given sensitivity constraints, *Origins* would be able to characterize terrestrial-size planets in the liquid water habitable zone around mid- to late M-dwarfs but not around earlier-type stars, including Sun-like stars.

The currently proposed aperture, spectral resolution, and wavelength coverage of *Origins* do not differ substantially from JWST, and thus improvements over JWST in *Origins*’ ability to characterize atmospheres are primarily predicated on an improved instrumental noise floor. Since detector stability for transit spectroscopy was not a technology driver for JWST’s design, such an improvement is plausible, but not guaranteed.

The committee is excited about exploring the atmospheres of terrestrial planets in the habitable zones of M dwarfs. These planets may host life and, given the large of abundance of M dwarfs, may even be the most common habitable environments……the habitable zone of M dwarfs might not in fact be a habitable environment given its extreme exposure to high-energy stellar irradiation.