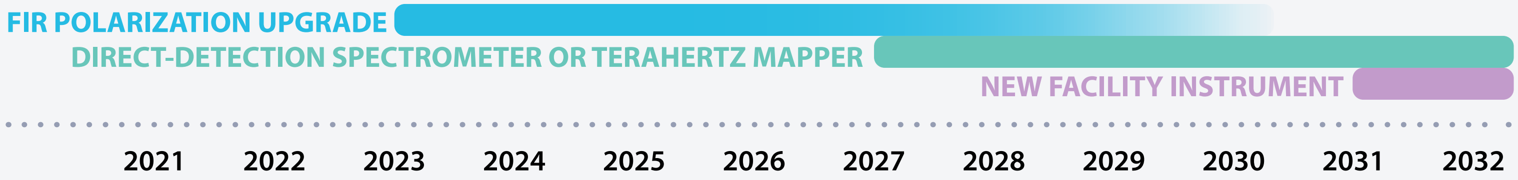
SOFIA
Instrument Roadmap



EXECUTIVE SUMMARY

From the discovery of water on the sunlit surface of the Moon to the detection of the first molecule to form in the infant universe, the Stratospheric Observatory for Infrared Astronomy (SOFIA) explores a vast astronomical parameter space to reveal critical new information about our solar system, our galaxy, and beyond. Because infrared emission is bright and widespread in astrophysically interesting regions, the light's tell-tale polarization and spectral signals can be analyzed in exquisite detail. These properties enable SOFIA to investigate the role of magnetic fields from star formation regions to galactic super winds and the dominance of feedback from the Orion bubble to cold quasars. New instrumentation utlizing the latest technology will enable SOFIA to make fundamental measurements in astrophysics such as the mass and water content of proto-planetary disks.

For at least the next decade, SOFIA will be the only facility that provides regular access to the far-infrared sky. Unlike space missions, SOFIA can repair, upgrade, and replace its instruments as science priorities evolve and technologies improve. This continual development allows SOFIA to outperform and significantly extend the legacies of previous instruments and prepare the groundwork for new missions. This *Roadmap* presents a plan to optimize SOFIA's future instrument suite based on science community input. SOFIA held two workshops with wide representation from astronomers: the first highlighted scientific goals and the second summarized instrument concepts. This *Roadmap* incorporates the community science priorities and instrumentation ideas from these workshops. For example, technology investment and readiness before a SOFIA instrument call is a critical step in the *Roadmap*.

New calls will solicit instruments developed to meet specified scientific goals. *Roadmap* Step 1 is an upgrade of the current High-Resolution Airborne Wideband Camera (HAWC+), improving its mapping speed of magnetic fields up to a factor of four. *Roadmap* Step 2 consists of the parallel development of associated technologies for two competing science goals: (a) a direct-detection spectrometer to characterize the mass of gas, water vapor, and water ice in proto-planetary disks and (b) a terahertz line mapper to determine the role of feedback in star formation and galaxy evolution. After a period of technology development, a technology assessment will guide decisions for Step 2. A call will then be issued to select the team to build and deliver this instrument to the SOFIA Project. *Roadmap* Step 3 is expected to be a call for a new instrument, with the science goals to be determined after additional community input.

This *Roadmap* will significantly expand SOFIA's discovery space and add impactful Legacy programs. It outlines a path to maximize SOFIA's scientific return with new or upgraded instrumentation. A direct-detection spectrometer increases SOFIA's sensitivity by a factor of 10 enabling reliable measurement of gas mass in proto-planetary disks. This will require accelerating the technology readiness of far-infrared direct detectors to ensure this capability in the next four to five years. A terahertz mapper increases SOFIA's mapping speed by a factor of 10 to substanitially improve studies of star formation and feedback. This will require continued development of heterodyne arrays. The community's interest in magnetic field surveys can be addressed immediately with existing technology.

Current and potential science cases were assessed at the first *Roadmap* workshop and align with SOFIA's three primary themes: Star and Planet Formation, the Path to Life, and Calibrating the Distant Universe. SOFIA science themes address NASA's strategic objective 1.1: "Understand The Sun, Earth, Solar System, and Universe," NASA Strategic Plan (2018) and align with NASA Astrophysics Roadmap (2013). These are organized by theme in Table 1, together with the measurement and instrumentation requirements that represent opportunities for developing new capabilities.

	Science Case	Required Measurement	New Instrumentation
Star and Planet Formation	Protoplanetary Disk Gas Masses	Velocity-resolved HD line at 112 µm	High-resolution direct-detection FIR spectrometer
	Star Formation Feedback	Entire star-forming-region (>deg^2), velocity resolved maps of FIR lines (C II, O I, O III, CO)	Wide-field FIR heterodyne mapper
	Role of Magnetic Fields in Star Formation	Polarization from entire molecular filaments (>deg^2)	FIR polarimeter with improved mapping speed
Path to Life	Astrochemistry and Disk Chemistry	Velocity resolved spectroscopy (H_2 pure rotations, light hydrides, H_2O, O I)	High-resolution MIR and FIR spectrometer, improved wavelength coverage and sensitivity
	Comets, Asteroids, Protoplanetary Disk Minerals and Ices	5–70 µm ice, mineral, PAH feature strengths	MIR moderate to low-res spectrometer with improved sensitivity
	Planetary Atmospheres and Cometary Gas	Med-res and high-res spectroscopy	Improved sensitivity
Calibrating the Distant Universe	Role of Magnetic Fields in Spiral Arms	Map entire nearby galaxies in FIR polarimetry	FIR polarimeter with improved mapping speed
	Evolution of Galaxies with Metallicity and Size	Wide-field spectroscopy of entire nearby galaxies in FIR lines (C II, O I, O III, N III)	Moderate resolution FIR spectrometer with wide field of view, improved mapping speed
	Transient phenomena	Monitoring of stellar eruptions, mergers, novae, and supernovae	Sensitive, rapid-response MIR/FIR photometer

TABLE 1. SOFIA'S SCIENCE CASES

MAKING THE MAGNETIC FIELD VISIBLE

Magnetic fields may be critically important in the astrophysics of star formation by providing magnetic pressure support against gravitational collapse. SOFIA HAWC+ observations are shifting the paradigm in our understanding of magnetic fields' role in star formation. Measuring the magnetic field strength and structure is challenging in most astrophysically interesting environments, but the HAWC+ instrument on SOFIA succeeds by observing the thermal emission and polarization from dust. The polarization is used to map the field shape and the Davis-Chandrasekhar-Fermi (DCF) method is used to estimate the field strength. Beautiful and impactful images like those in Figures 1 and 2 are not only making the field visible but have even inspired some to describe HAWC+ as the Van Gogh of the 21st century. The first step in determining if the magnetic field is important or even dominant is the ratio of the thermal pressure to the magnetic pressure. HAWC+ enables such measurements and indeed opens the universe to the physics of magnetic field modelling.

SOFIA is currently studying the shape of magnetic fields in galactic filaments and nearby galaxies. Figure 1 of the Orion nebula shows that material flows along field lines to the filament in the low-density regions, indicating that the flow is governed by the magnetic field. However, the field changes direction in the high-mass cores as gravity takes over, dragging the field lines with it. In the Serpens South Cluster, HAWC+ discovered how gravitational collapse occurs in the presence of strong magnetic fields. The fields re-align along dense gas filaments that funnel gas inflows fueling its star formation (Pillai et al., 2020). These magnetic field studies require large-scale mapping by HAWC+ at wavelengths from 50 to 200 µm. These wavelengths sample the peak of the spectral energy distribution, enabling temperature-selective tomography that separates cold clouds from warm cores and complements longer wavelength ground-based observations in the temperature-insensitive Rayleigh-Jeans part of the spectrum. A three-color survey of approximately 12 galactic filaments would take over 360 hours (1/3 of SOFIA's annual observing time) with the present mapping rate of HAWC+. With a factor of four increase, the filament survey could be completed within a single two-year Legacy program.

Because we observe from inside the Milky Way, the large-scale structure of our own galaxy is not readily apparent. In external galaxies, however, this structure is evident, with face-on galaxies showing spiral arms and edge-on galaxies revealing superwinds. This makes Milky Way and extragalactic studies complementary. The tremendous ranges of nuclear activity, galaxy size, metallicity, and star formation rate lead to a great diversity of galaxy properties. HAWC+ is revealing galaxy-wide magnetic field structures across all galaxy types leading to fundamental understanding of the origins of magnetic fields in galaxies. Galaxies have large-scale magnetic fields with spiral-like patterns (Figure 2), but they also have turbulent fields on smaller scales that are driven by stellar feedback. Both fields are generated by dynamo mechanisms, which convert kinetic energy to magnetic energy. Interacting galaxies have not yet been studied in far-infrared polarization: how will the magnetic fields from two galaxies react to mergers?

A survey of nearby galaxies could be performed with

Figure 1. Magnetic fields in the Orion Nebula, shown as streamlines over an infrared image taken by the Very Large Telescope in Chile, are regulating the formation of new stars. SOFIA's HAWC+ instrument is sensitive to the alignment of dust grains, which line up along magnetic fields, letting researchers infer the direction and strength (Chuss et al., 2019).

Figure 2. Magnetic fields in NGC 1068, or M77, are shown as streamlines over a visible light and X-ray composite image of the galaxy from the Hubble Space Telescope, the Nuclear Spectroscopic Array, and the Sloan Digital Sky Survey. The magnetic fields align along the entire length of the massive spiral arms — 24,000 light years across (0.8 kiloparsecs) — implying that the gravitational forces that created the galaxy's shape are also compressing the galaxy's magnetic field. This supports the leading theory of how the spiral arms are forced into their iconic shape known as "density wave theory." SOFIA studied the galaxy using far-infrared light (89 µm) to reveal facets of its magnetic fields that previous observations using visible and radio telescopes could not detect (Lopez-Rodriguez et al., 2020).

SOFIA to systematically address the relationship between the shape of the magnetic field and star formation at the relevant physical scales. An extragalactic survey of 18 modest-size (less than 0.2 deg^2) galaxies requires 175 hours but could be accelerated to a 44-hour program with a factor of four increase in mapping speed. The Large Magellanic Cloud, a neighbor to the Milky Way, provides insights into star formation at lower metallicities similar to the universe's peak epoch of star formation. Mapping the brightest four-square-degree regions in the Large Magellanic Cloud would require over 300 hours of observation with SOFIA's current capability but only 80 hours (a single flight series) with improved mapping speed.

STEP 1: FASTER MAGNETIC FIELD MAPPING WITH HAWC+

SOFIA's HAWC+ instrument allows, for the first time, high-sensitivity polarization measurements in the far-infrared at the peak wavelengths of thermal dust emission. This capability provides a rich discovery space for the study of magnetic fields in dusty star-forming regions, in both the Milky Way and external galaxies. The large proposal pressure and several promising Legacy programs demonstrates the high demand for HAWC+ by the community.

Upgraded detector arrays can increase SOFIA's magnetic field mapping speed by a factor of 4.

The HAWC+ detectors are packaged in pairs of two (Figure 3, far left image). HAWC+ can accommodate two pairs or four Transition-Edge Sensor (TES) detector arrays but currently has only three detectors. Moreover, the TES detectors in HAWC+ have only 50% usable pixels. Since only one pair of arrays is available for polarimetry, the instantaneous field of view and mapping speed of HAWC+ polarimetric observations is only half of its designed value. Procuring 4 high yield (>90% usable pixels) detector arrays will realize the full scientific potential of HAWC+. The magnetic field mapping speed will increase by a factor of four.

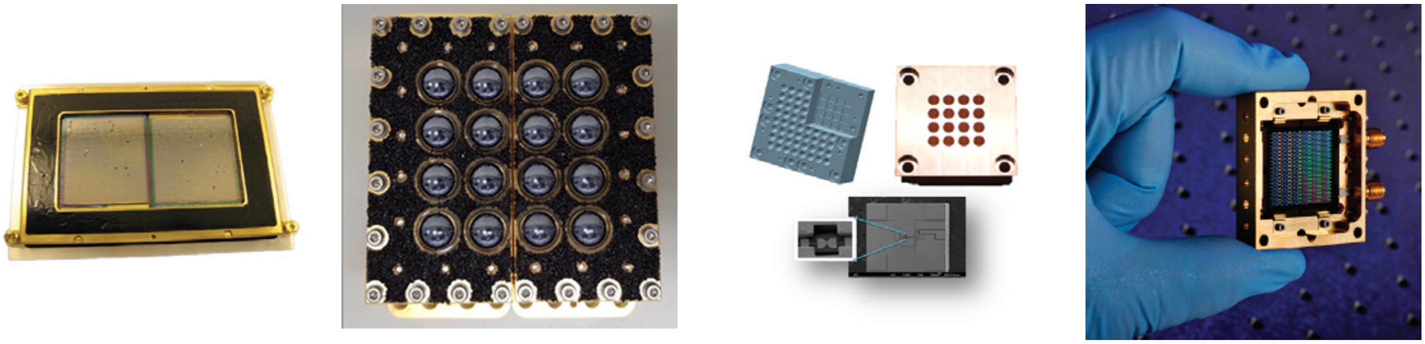


Figure 3. Detectors for potential SOFIA instruments, from left to right: TES detectors used in HAWC+ important for Step 1 (courtesy NASA Goddard); a 16-pixel THz heterodyne array to be used in the GUSTO instrument (courtesy U Arizona); and THz heterodyne array components being developed for the ASTHROS balloon mission (courtesy JPL) are both important developments for Step 2, Concept 2, the Terahertz mapper; KID detector array (C. McKenney, Caltech/NIST). Both TES and KIDs are important technology developments for Step 2, Concept 1 direct-detection spectrometers.

WEIGHING IN ON PROTOPLANETARY DISKS

SOFIA can make transformative measurements of the properties of protoplanetary disks, the sites of planet formation (Figure 4). The most critical parameters required in planet formation models are the total amount of gas in a disk and the amount of water in both solid and liquid forms. These factors are best determined using far-infrared spectroscopy. The total mass of gas remains controversial, with current estimates based on dust and CO measurements disagreeing by large factors. Where the Atacama Large Millimeter/submillimeter Array (ALMA) provides information from low-energy transitions of cold gas, SOFIA will add more robust gas estimates of the molecular hydrogen, the most abundant gas in the disks, by detecting the ground-state HD rotational line at 112 µm. The amount of water in the planet-forming region can be accessed via the many strong water lines in the 20–120 µm band. The James Webb Space Telescope (JWST) is only sensitive to warm, highly excited water lines near the star but not the cold-gas water lines that arise throughout the protoplanetary disk and serve as the best tracers of water during planetary system formation. Indeed, SOFIA's accessibility to the cold water lines is very complementary to measurements made by JWST and ALMA, which are not as sensitive to cold water lines. Therefore, far-infrared spectroscopy with SOFIA will be key to measuring the amount of water in the planet-forming zone and tracing the location of the snow line, where H_2O transitions from predominantly solid to vapor form.

In addition to using HD to weigh protoplanetary disks, a mid- to far-infrared direct-detection spectrometer would enable a significant increase in sensitivity for measuring D/H in cometary water, potentially pinpointing the origin of the Earth's oceans. The spectrometer could also measure gas in mature stellar systems, tracing late-time, large-scale collisions among planetary bodies. Far-infrared fine structure lines from stellar outflows, supernova shocks, and photodissociation regions will be readily detected with sufficient resolution to distinguish kinematics that determine future evolution and measure energy transfer from stars to the interstellar medium.

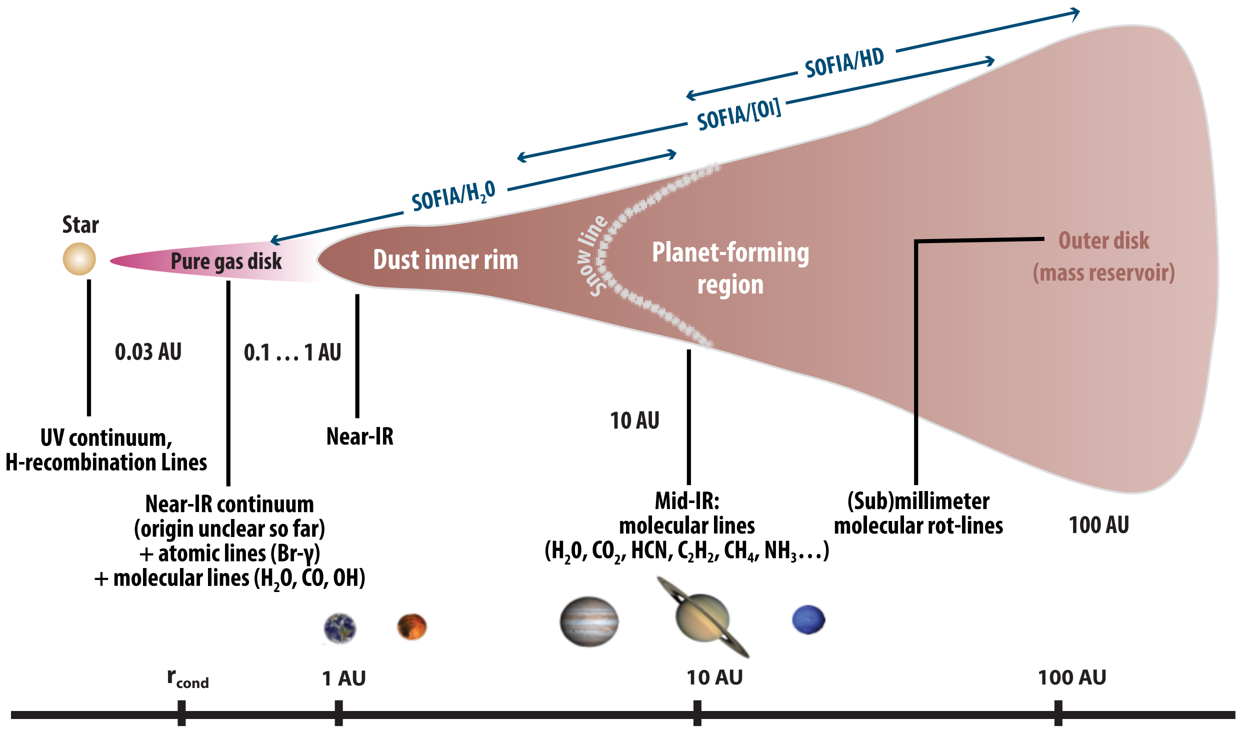


Figure 4. A direct-detection 30 to 120 µm spectrometer will probe protoplanetary disks from 1AU to 100 AU. Herschel and ALMA observations trace the cooler outer disk at distance > 10 AU. Unlike JWST, SOFIA can spectrally resolve the molecular lines, which can provide the location of the emission.

STEP 2 CONCEPT 1: DIRECT-DETECTION SPECTROMETER

A direct-detection spectrometer increases SOFIA's ability to observe mass-sensitive HD lines in protoplanetary disks by a factor of 10.

SOFIA, equipped with a suitable high-resolution ($R\sim10^5$) direct-detection spectrometer covering the wavelength range 25 to 122 µm, would be able to measure the total masses of protoplanetary disks in excess of a few times $10^{-3}\ M_\odot$, around stars of 1 $M_\odot$ or more. This wavelength range spans the ground-state rotational line of H_2 at 28 µm, numerous H_2O lines, and the HD line at 112 µm. Figure 5 shows model predictions for 112 µm HD 1–0 line fluxes (circles). The models are based on detailed, two-dimensional, gas+dust radiative transfer calculations using the RADLite code (Pontoppidan et al., 2009), and are consistent with similar, independent models (e.g., Trapman et al., 2017). The figure also shows the three previous Herschel-PACS detections (stars) and upper limits (arrows) (Bergin et al., 2013, McClure et al., 2016). The model symbols are color-coded to indicate the predicted, intrinsic line-to-continuum ratios of HD lines; resolving powers of ~100,000 are required to fully realize this constrast, and significantly lower resolving powers may result in low-contrast lines that are unlikely to be detectable by SOFIA. The predicted limit achievable by SOFIA, shown as a dashed orange line, demonstrates that detecting the HD line will be possible around solar mass stars with a direct-detection spectrometer. Both model predictions and observed line fluxes are scaled to the same distance of 125 pc, approximately corresponding to the nearest major reservoirs of protoplanetary disk targets in Ophiuchus, Upper Sco, Lupus, and Taurus.

The direct-detection spectrometer uses incoherent detectors, such as TES bolometers and KIDs, that can be a factor of 10 more sensitive than heterodyne spectrometers if detector technology can reach a Technology Readiness Level of 6 in order to achieve its goals. This report highlights the need for investment in detector technology to achieve these important scientific goals. The improved sensitivity in proto-planetary disks also relies on the high spectral resolution that will provide contrast between the lines and continuum of the proto-planetary disks. A spectral resolving power of $R\sim10^5$ will also support spectral line modelling of the water and HD lines that can pinpoint the location of the line's origin in the proto-planetary disk. The location of the water and HD lines are essential to understanding planetary system formation.

A high resolution direct-detection spectrometer on SOFIA will provide better sensitivity than the Herschel Space Observatory PACS spectrometer. During its short life, Herschel PACS demonstrated spectacular results of protoplanetary disks with water and HD lines in three disks that demand followup and a thorough investigation at higher spectral resolution. This first concept for Step 2

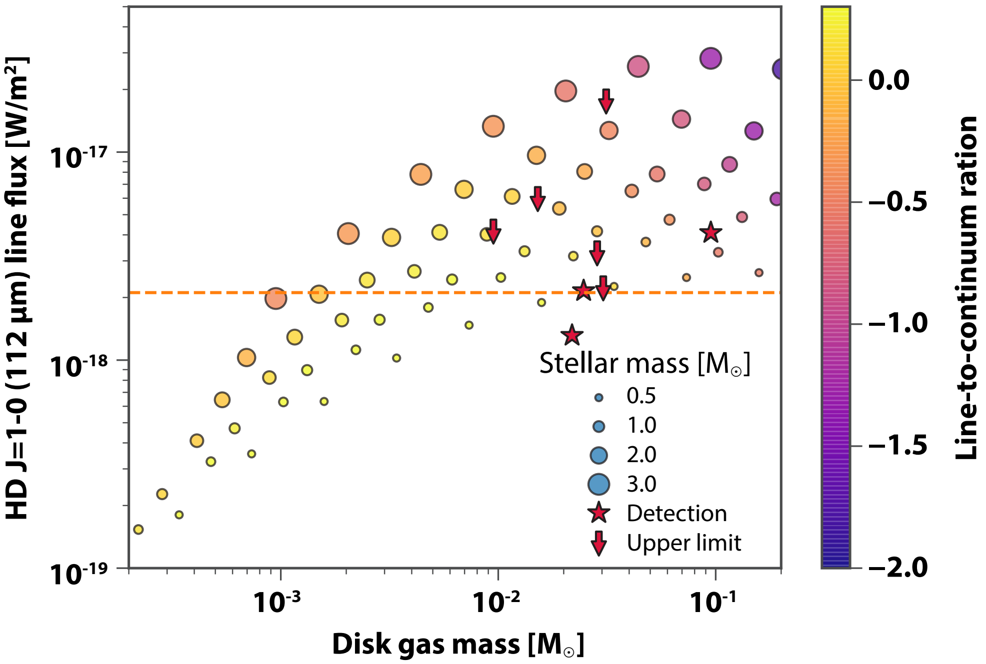


Figure 5. Model predictions for the HD 1-0 112 µm line fluxes (circles) for protoplanetary disks of different gas masses and stellar masses. Herschel PACS measured HD 112 µm line in only three protoplanetary disks (red stars) and obtained upper limits on five others (red arrows) before its mission end. SOFIA with a direct-detection spectrometer will enable a thorough investigaton of disk masses (orange line). (Pontoppidan, Bergin and Melnick)

would provide a crucial link between JWST and ALMA investigations in planetary system formation. Moreover it would provide a steppingstone both scientifically and technologically for the Origins Space Telescope, a large concept mission study for the Astro2020 decadal survey.

STAR-FORMATION FEEDBACK

The galactic ecosystem is largely a balance between star formation and stellar feedback, the input of energy by new stars back into the clouds from which they formed. Just as the magnetic field observations with SOFIA can trace a component of this large-scale evolution, velocity-resolved maps of star-forming regions and entire nearby galaxies in [C II] trace the energetics of the feedback on the giant molecular clouds. The cosmic cycle of star formation is an essential part of the evolution of the universe. The far-infrared fine structure line from [CII] at 158 µm is one of the most important tracers of star-forming activity in galaxies. Observations of [CII] have become more important recently because the cosmological redshift moves the line from distant galaxies into wavelengths detectable by ALMA. Many scientists use the strength of this spectral line as a direct indicator of the star formation rate in those high-redshift galaxies.

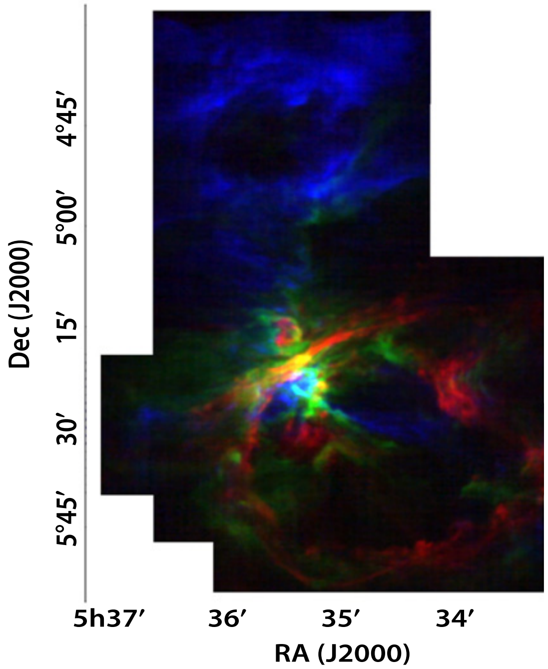


Figure 6. SOFIA/GREAT image of Orion covering 1 deg^2. The powerful wind from the newly formed star at the heart of the Orion Nebula is creating the bubble (black) and preventing new stars from forming in its neighborhood. At the same time, the wind is pushing molecular gas (color) to the edges, creating a dense shell around the bubble where future generations of stars can form (Pabst et al., 2019).

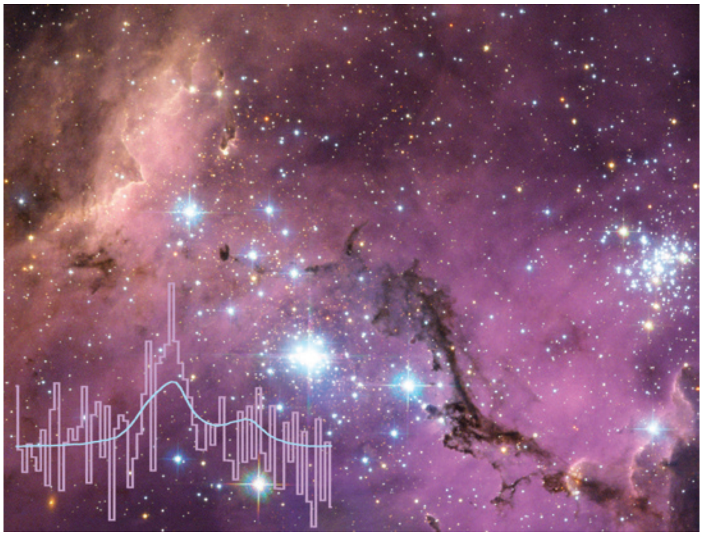


Figure 7. SOFIA spectrum (histogram) of [^{13}CII] emission in the star-forming region N159W superposed on an image from Hubble Space Telescope of the Large Magellanic Cloud. The blue curve is the scaled emission that would be expected if the [^{12}CII] emission from the same region were optically thin. The observed intensity of [^{13}CII] is stronger than the scaled emission, indicating that [^{12}CII] is optically thick (Okada, et al., 2019).

As this *Roadmap* is being written, SOFIA is performing a Legacy survey of star-forming regions in [C II], following a successful pilot study of Orion that revealed an expanding bubble created by stellar winds from θ^1 Ori C, the brightest star in the Trapezium (Figure 6). These observations demonstrated definitively that stellar winds, not photoionization or photodissociation, dominated the feedback process. These observations also showed that the rate of expansion of the bubble exceeds the escape velocity, so by the time θ^1 Ori C goes supernova, its molecular cloud will have already been destroyed. Results from the Legacy survey will determine if this wind-dominated feedback is common, rare, or unique to Orion.

Due primarily to SOFIA's multi-beam receiver and agile telescope, SOFIA is about 50 times faster at mapping velocity-resolved [C II] than Herschel. The studies benefit from covering larger areas in order to study emission, not just from the bright H II regions near massive stars, but also the surrounding material where the largest-scale stellar feedback becomes evident. The SOFIA image of

Orion with a million [C II] spectra (Figure 6) took 36 hours to create. With a factor of 10 increase in mapping rate, this data set could easily have been obtained in a single SOFIA flight. A 96-hour Legacy project is currently under way to observe large portions of 11 star-forming regions in [C II].

Increasing the mapping rate will allow all distinct star-forming regions in the Milky Way to be mapped in [C II]. These data will become a primary archival source of molecular column density and velocity structure of star-forming regions, enabling a definitive survey for large-scale star-formation feedback by massive stars. The galactic ecosystem on large scales is determined by material flowing through spiral density waves and agglomerating into giant molecular clouds and filaments that form stars and are then at least partially dispersed by winds and supernovae.

Observations in the nearby universe by SOFIA are helping to determine if using the [CII] 158 μm line as a star formation activity tracer is valid. Comparisons with the [^{13}C II] reveal more and more cases of optically thick [CII] emission from star-forming regions in the Milky Way and the Large Magellanic Cloud (Figure 7). These results indicate that the intensity of this line may be underestimated by a factor of two or more. SOFIA observations also show that other sources of energy such as the radiation and shocks produced by active galactic nuclei may contribute significantly to the [CII] emission, thereby altering the correlation between the line strength and star formation rate. Only by understanding these effects in the local universe, where the emitting regions are close enough to resolve their structures, can astronomers hope to understand galaxies that are so far away that they may appear as a simple point source.

STEP 2 CONCEPT 2: TERAHERTZ MAPPER

A terahertz mapper increases SOFIA's mapping speed of the dominant cooling line of the ISM by a factor of 10.

A terahertz mapper to address the stellar feedback science case will be a successor to SOFIA's current heterodyne spectrometer, German Receiver for Astronomy at THz (GREAT), thus far SOFIA's most scientifically productive instrument. GREAT's heterodyne technology provides high spectral resolution and a 7-pixel dual polarization array with unprecedented mapping speeds, about 50 times faster than Herschel for the resolved [C II] line. The GREAT team achieved this extraordinary performance by continually increasing the number of pixels and employing new, cutting-edge Local Oscillators (LOs) and back-ends. This allowed the addition of critical new frequencies to cover the most scientifically important far-infrared spectral lines, including fine structure lines like [O I], as well as HeH+, other light hydrides, and high-J CO transitions.

A new terahertz mapper can take full advantage of SOFIA's 8-arcmin field of view. A plausible, low-risk case for a 100-pixel instrument was made at the *Roadmap* workshops. Such large arrays would build on the development of smaller arrays now being fabricated for the Galactic/Extragalactic Ultralong duration balloon Spectroscopic Terahertz Observer (GUSTO). With about 14 times faster mapping speed, such an array would enable a new level of ambitious Legacy programs.

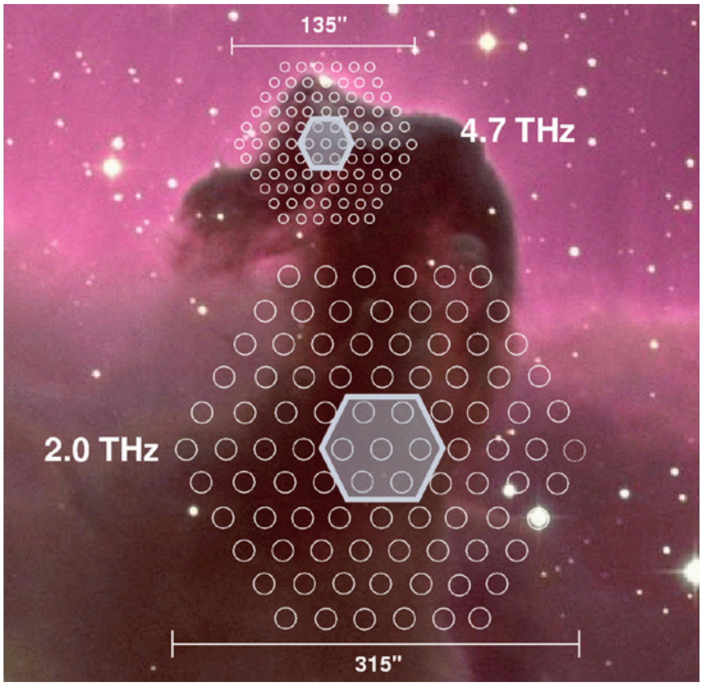


Figure 8. Coverage of the GREAT arrays in the [C II] 158 μm and [O I] 63 μm lines (shaded hexagons) compared to a notional terahertz mapper with 14 times faster mapping speed (circles). (Chris Walker)

To build a 100-pixel terahertz mapper for SOFIA (Figure 8) within five years would require technology development to refine integrated terahertz arrays, mixers, and readout electronics. Technology development for low-noise mixers, including Hot Electron Bolometers (HEBs), and possibly graphene-based mixers, are under way. Additionally, to support a terahertz mapper on SOFIA, technology development in LOs and low power-consumption spectrometers is also required. A 100-pixel terahertz mapper would deliver a factor of 14 faster mapping speed with at least the sensitivity currently achieved by SOFIA. With SOFIA's large focal plane, a 100-pixel array could enable a transformative ability to map statistically significant samples of star-forming regions across the Milky Way and of nearby galaxies.

STEP 3: A NEW FACILITY INSTRUMENT

Community input will help shape the instrument for Step 3.

The astronomical community stressed the need for an open call process for a new science instrument in 2026. The next instrument must provide a significant improvement in sensitivity or mapping speed to achieve new compelling science beyond SOFIA's current and Step 2 capabilities. An open call will not only promote a fair competition among instrument teams, but also foster new instrument concepts that capitalize on future technological breakthroughs and scientific discoveries.

The community input will be solicited for this Step 3 closer to time of the call. Several paths are possible. For example, in Step 2 of this *Roadmap*, a selection of a direct-detection spectrometer or terahertz mapper will already have been made. The other Step 2 instrument concept could be considered again for Step 3. SOFIA will also consider different instrument concepts as part of the 2026 technology assessment review (defined in more detail below). If only one concept is sufficiently mature for development, a call will be issued for that concept. Otherwise, a scientific scope review will select which goals are most promising and best utilize SOFIA's capabilities, and an open call for instrument proposals addressing those science goals will be issued.

THE ROADMAP

This *Roadmap* is born out of direct community engagement solicited by the SOFIA Project. The development of instrumentation and the scientific mission of the observatory are intertwined. SOFIA's current, upgraded, and new instruments will play an important role in NASA's portfolio of astrophysical capabilities. The principles driving the *Roadmap* included exploiting the current instrument capabilities, filling gaps that map to science cases with high discovery potential, and utilizing complementarity with current and near-future observatories.

The *Roadmap* has three core steps that have been endorsed by the community and that have a notional timeline as shown in Figure 9. A strategic and practical decision was made to avoid parallel development as this could put significant strain on mission resources and competing priorities. All three *Roadmap* steps lead to new hardware with new capabilities, and each step is front-loaded with time for technology development. Another strategic and practical decision was to allow ample time for instrument construction in order to maximize the chance for completion of each project.

The *Roadmap* will be actively managed throughout its execution to take full advantage of advancing technology assessment reviews that will serve as the key decision points. Technology development is critical for the success of SOFIA instruments. To avoid cost and schedule overruns, and to take into account lessons learned from prior instrument development, a technology readiness review will be conducted on the hardware components for any proposed SOFIA instrument. This strikes a reasonable balance between appropriate use of SOFIA as a testbed for subsystem technology development for future NASA missions, and reasonable assurance that SOFIA instruments selected for development will further SOFIA's mission. The 2022 technology assessment review will be a gate for *Roadmap* Step 2, developing a new instrument in 2023–2026. A similar review will occur for *Roadmap* Step 3.

Periodically assessing and evaluating instrument capabilities and phasing out obsolete or unproductive instruments are important components in the management of SOFIA's instrument suite. These processes reduce operational costs and focus resources on the evolving needs of the scientific community. A regular review and decommissioning process ensures that SOFIA offers the optimal instruments in each observing call for proposals. Based on science considerations, SOFIA will strategically change the instrument suite available in future calls, including offering instruments in alternate or staggered years. Decommissioning of instruments will also be considered after a thorough review. These reviews involve a series of metrics that align with the observatory's overall performance goals to analyze the efficacy of each instrument. The SOFIA Project Instrument Assessment Group performs the needed reviews.

Notional Timeline for SOFIA Instruments

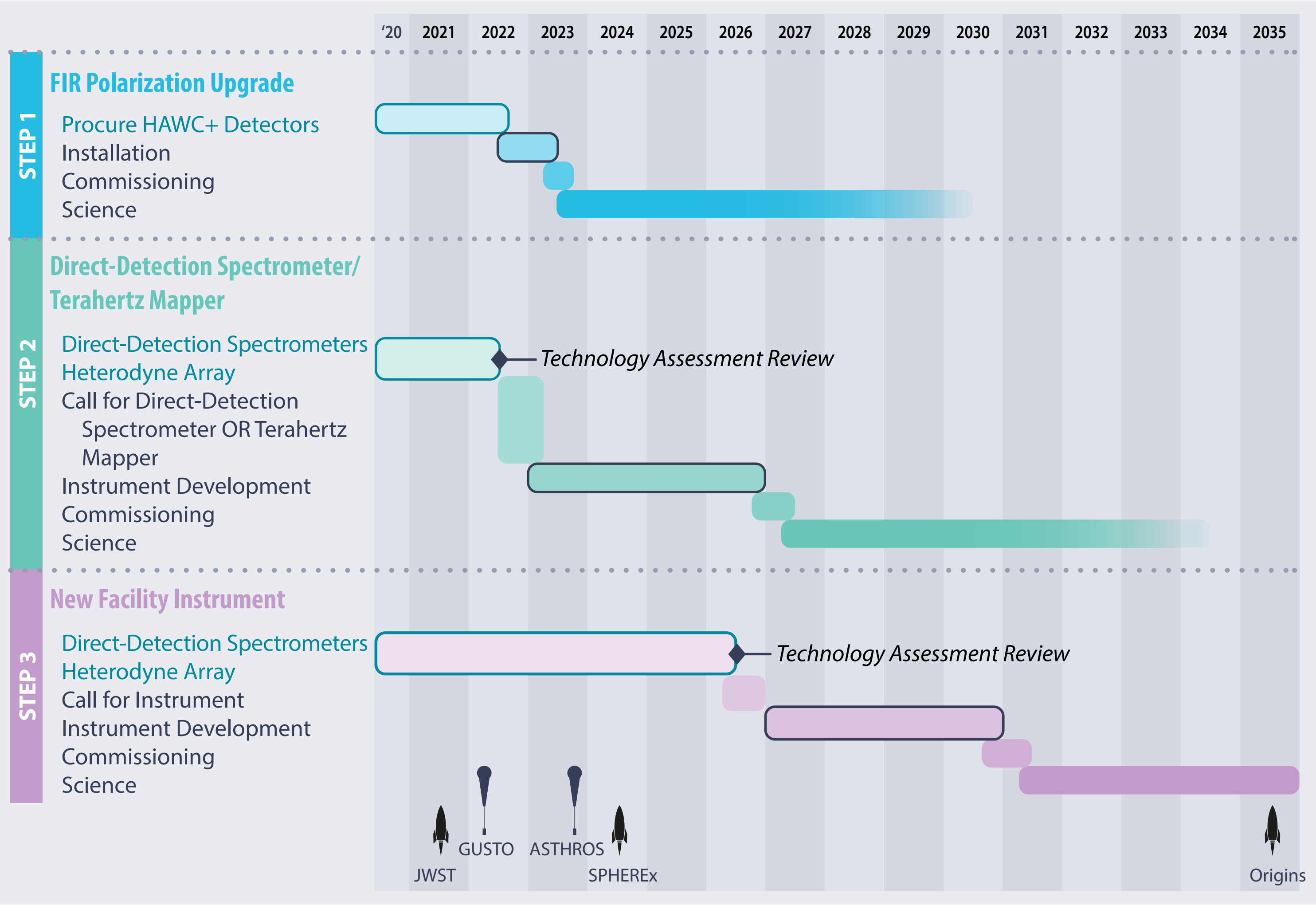


Figure 9. A notional timeline of the SOFIA Instrument Roadmap and its three steps, with technology reviews.

APPENDIX: COMMUNITY-DRIVEN ROADMAP

Workshop information, including schedules, presentations, and registrants, can be found on the SOFIA science center website:

Workshop 1: https://sofia.usra.edu/roadmap1

Workshop 2: https://sofia.usra.edu/roadmap2

The SOFIA Project conducted two workshops to identify the astronomical community's vision of SOFIA's scientific potential as well as the state of relevant technologies and instrument concepts. The workshops had a scientifically diverse set of speakers and participants (see Table 2). The workshop Scientific Organizing Committees had broad university and government scientist representation. Feedback from the attendees was collected in real time and documented, and a follow-up questionnaire on scientific capabilities and technological priorities was sent to all participants after the workshops. A community advisory group was formed and had two extensive real-time sessions after the workshops to ensure this *Roadmap* corresponds to the inputs from the astronomical community.

SOFIA's current and potential science cases were assessed at the first *Roadmap* workshop. The science cases align with SOFIA's three primary themes: Star and Planet Formation, the Path to Life, and Calibrating the Distant Universe. Table 1 lists the science cases organized by theme, together with the required measurement capability, the primary current science instruments SOFIA brings to bear on the case, and the gap that represents the opportunity for developing new capabilities.

The science cases highlighted in the *Roadmap* are a subset of those discussed at the workshop and in SOFIA publications; they were chosen because they were found to be of high scientific return with potential for significant improvement via instrument development.

	Topic	Speakers	Registrants	Attendees (max per day)	non-SOFIA Attendees	Institutions
Workshop 1	Science Cases and Capability	37	234	196	144	107
Workshop 2	Instrument Concepts	25	166	127	80	62

TABLE 2. INSTRUMENT ROADMAP WORKSHOPS

APPENDIX: THE SYNERGY OF SOFIA

Figure 10 places SOFIA on a timeline with past and future infrared observatories. The Spitzer Space Telescope began its primary mission in 2003, with capabilities from the near- to far-infrared (3.6–160 µm). In 2009, Spitzer's cryogens depleted, and while it continued to observe in the near-infrared (3.6–4.5 µm), it no longer had the ability to observe in the far-infrared. Herschel was launched about this time, with capabilities starting at 55 µm and going out to the submillimeter (55 to 672 µm). Its cryogens depleted in 2013, ending the mission and setting the stage for SOFIA, which attained full operational capability in 2014. SOFIA is designed for a potential lifetime of 20 years. It presently has instrumentation capable of performing science from the optical through the submillimeter (0.4 to 612 µm). The next big infrared-capable mission will be JWST (0.6 to 28 µm), but it will have no capabilities in the far-infrared. Where there are overlaps with SOFIA in the optical to mid-infrared, the large differences in sensitivity of the two facilities will mean that they will be performing very different types of science, or at least approaching the same science questions from different directions. The Origins Space Telescope, a far-infrared flagship mission, recently completed its concept study for the Astro2020 Decadal Survey, targeting a launch in the mid-2030s.

Figure 10. Timeline of Recent, Present, and Future Mid- to Far-Infrared Facilities.

SOFIA investigations of star-formation feedback are directly related to the study of the first galaxies in the universe, one of the primary science goals of JWST. High-redshift galaxies have distinctly higher star-formation rates and frequent galaxy-galaxy interactions, making them appear much different from local galaxies. By measuring the effects of stellar feedback in massive star-forming regions in the Milky Way, SOFIA will provide a calibration for such effects, which are likely to dominate the structure and evolution of early galaxies.

SOFIA high-spectral-resolution surveys with the Echelon-Cross- Echelle Spectrograph (EXES) provide dynamical and chemical information on massive protostars that affect the initial conditions for exoplanet formation. These spectra will be essential for interpreting and modeling the low-spectral-resolution features observed by JWST, which despite its greater sensitivity, will not be able to resolve individual transitions.

At present SOFIA is the only operational far-infrared facility that is available to the general astronomical community. It is complemented by other components of the NASA astrophysics portfolio as well as ground-based telescopes. For example, polarization experiments include the NASA Balloon-borne Large-Aperture Submillimeter Telescope — The Next Generation (BLAST-TNG), which would cover somewhat longer wavelengths (250–500 μm) and the French Polarized Instrument for Long-wavelength Observations of the Tenuous ISM (PILOT) that emphasizes diffuse emission at longer wavelengths (240–550 μm) and five times lower angular resolution than SOFIA. Ground-based capabilities for dust emission polarization at much longer wavelength exist at the James Clerk Maxwell Telescope (JCMT), Atacama Pathfinder Experiment (APEX), and Institut de Radioastronomie Millimétrique (IRAM), providing angular resolution comparable to SOFIA but only probing the Rayleigh-Jeans tail of the dust emission spectrum mixed with free-free emission. ALMA can provide spectacular angular resolutions of 0.2″ within a field of view of only one SOFIA beam. With its wide spatial coverage, SOFIA observations will provide critical context for the finely resolved ALMA observations that have a very limited field of view.

A terahertz mapper on SOFIA would provide higher angular resolution maps that are complementary to GUSTO and the Astrophysics Stratospheric Telescope for High Spectral Resolution Observations at Submillimeter-wavelengths (ASTHROS). GUSTO will make large-area surveys of the Milky Way (100 deg^2) and the Large Magellanic Cloud (24 deg^2) with 60 arcsec resolution, where 14 SOFIA beams fit into one of GUSTO's. ASTHROS will image star-forming regions in

[N II] lines at 122 and 205 µm; the 122 µm line becomes detectable at balloon altitudes but is absorbed by residual water vapor at SOFIA's altitude. SOFIA will provide critical observations of the primary photodissociation region lines from [C II] and [O I] to allow interpretation of ASTHROS observations of [N II].

SOFIA's discovery and mapping of water on the sunlit surface of the Moon complements NASA's multi-mission investigations of the mineral content and history of volatiles on planetary surfaces. Studying lunar water remotely with SOFIA is critical for future NASA missions, including the Volatiles Investigating Polar Exploration Rover (VIPER), a mobile robot that will explore the landscape near the Moon's South Pole in 2022, and the Artemis program that will return humans to the Moon by 2024. Directly related to the SOFIA studies are several CubeSats planned for launched with Artemis 1 — Lunar IceCube, Lunar Flashlight, and LunaH-Map — that will help investigate the possible presence of lunar water-ice.

Figure 11 shows SOFIA's current instrument capabilities as a function of resolving power and wavelength, compared to JWST and ALMA. Figure 12 shows the minimum detectable continuum and line flux for SOFIA's current and future instruments in comparison with the now expired space missions Spitzer and Herschel and the current capabilities of the Gemini Observatory.

Improving sensitivity and mapping speed through new instrumentation will help SOFIA realize its scientific potential.

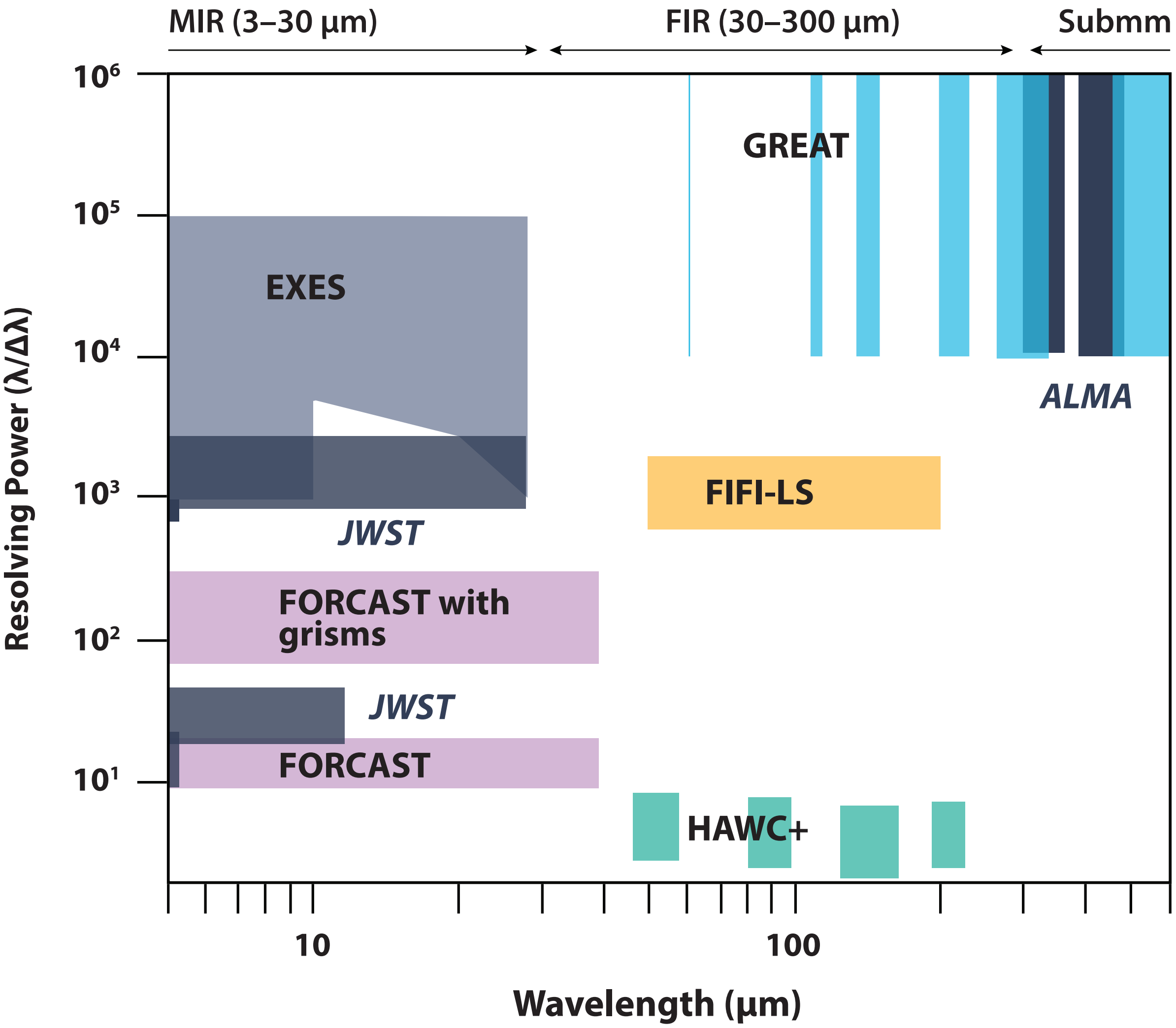


Figure 11. SOFIA's current instrument capabilities as a function of resolving power and wavelength, compared to JWST and ALMA.

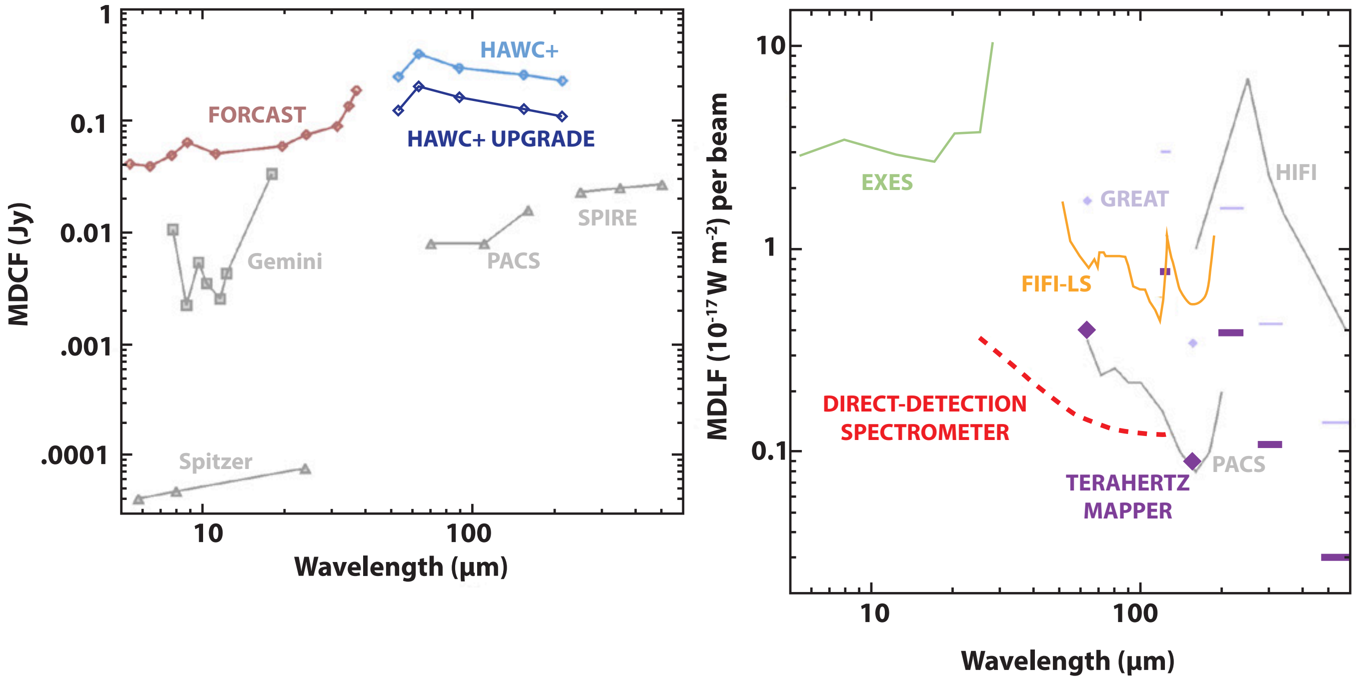


Figure 12. *(Left)* SOFIA's minimum detectable continuum flux (MDCF) for point-source photometry (4σ in 900 sec). Other observatories are in grey: PACS and SPIRE were on the Herschel mission that ended in 2013, and the Spitzer cryogenic mission ended in 2009. HAWC+ has polarimetric capability enabling magnetic field measurements, which PACS and SPIRE did not have, and its upgrade sensitivity is shown in navy blue. *(Right)* SOFIA's minimum detectable line flux (MDLF) for spectral mapping (4σ in 900 seconds per array, linewidth 5 km/s). The MDLF takes into account the mapping speed improvements by dividing by sqrt (number of beams or pixels) of the instrument. Also shown are HIFI and PACS spectrometers from the Herschel mission that ended in 2013. The red dashed line shows the direct-detection spectrometer-predicted sensitivity and reveals a potential area for science instrument development to offer significant gain to the community. The terahertz mapper is shown in purple.

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