From Early Galaxies to Habitable Planets: The Science Case and Concept for a Far-Infrared Surveyor

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1. Introduction

1.1. Background

The far-infrared spectral region is home to most of the energy emitted by a broad range of astronomical phenomena, from stars and planets in formation to young galaxies building their stellar populations and feeding nuclear black holes. The typical UV/optical photon from a young star over the history of the Universe has been absorbed by dust, so observations at these wavelengths probe only a fraction of the activity in galaxies over Cosmic time. In marked contrast, the far-infrared (FIR, 30-300 μm) provides direct access to the inner workings of galaxies and Galactic star-forming regions, and offers many of the most powerful spectroscopic diagnostics from ions, atoms, and molecules. These diagnostics probe HII regions around young stars, the gas surrounding powerful Active Galactic Nuclei (AGN), and the Interstellar Medium (ISM) in galaxies over a huge range of density and excitation. The far-infrared is the only part of the electromagnetic spectrum that provides a complete picture of all phases of the ISM, from atoms to complex organic molecules. The molecular transitions arise from the dense gas out of which stars and planets form, providing unique access to key biotic molecules such as water, the essential component of life. The far-infrared contains almost all the transitions with energies below 1000 K, thus providing the only way to probe the major reservoirs of water in proto-planetary disks, molecular clouds, and Solar system objects. Ice features found in the far-infrared can constrain whether ice is amorphous or crystalline, providing clues to the processing that precedes delivery to planet surfaces.

In addition to providing a unique window for unraveling star and planet formation, the far-infrared is invaluable for understanding the evolution of galaxies from the epoch of reionization to the present day. For redshifts $z > 2$, the key mid-infrared diagnostic features that probe all phases of the ISM from the ionized gas to molecular clouds will shift beyond the reach of JWST/MIRI, into the far-infrared. Key spectral features, such as those from Polycyclic Aromatic Hydrocarbons (PAHs) and the rotational transitions of molecular hydrogen, H_2, are accessible only to a sensitive FIR spectrometer in space. Similarly, only the far-infrared provides access to the spectroscopic diagnostic tools in the local Universe that are essential for understanding the energy balance in galaxies, and that are redshifted into the sub-mm regime that ALMA can access in the very distant Universe.

By 2025, we will have thoroughly explored the optical to mid-infrared wavelength region, using HST, JWST, LSST, Euclid and WFIRST, and the millimeter to radio region, using ALMA, the JVLA and the SKA. The far-infrared, however, will remain largely unexplored at sensitivities equivalent to the extremely low flux levels at which we will probe these other wavebands. While observations with ISO, Spitzer, Herschel, and SOFIA have demonstrated the richness of the far-infrared, an enormous leap forward is still possible with a large, cold telescope in space (Fig.1).

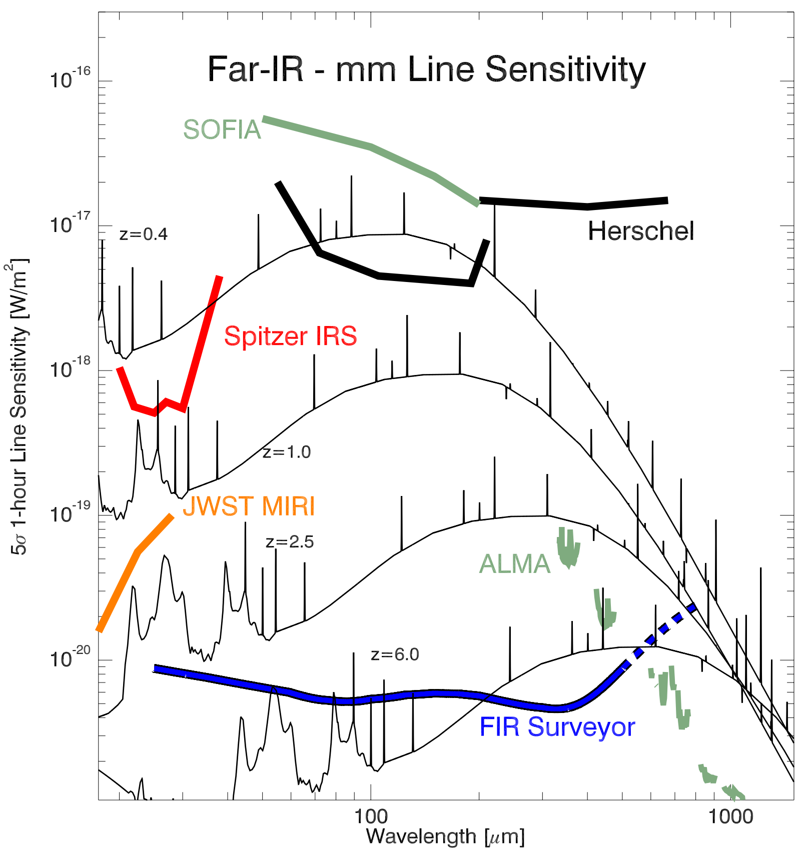

Fig. 1: The SED of a 10^{12} $L_\odot$ star-forming galaxy is shown at a series of increasing redshifts from z=0.4 to z=6. The sensitivities of Spitzer/IRS, JWST/MIRI, SOFIA, Herschel, and ALMA are shown. The sensitivity of the **FIR Surveyor** is shown in dark blue, delivering more than two orders of magnitude gain over existing and planned instruments in the far-infrared. The dotted line is a possible extension of the FIR Surveyor to 800 μm.

In the next decade we are poised to make extraordinary gains in the capabilities of far-infrared detectors, with 2-3 orders of magnitude improvements in both sensitivity per detector and in detector count. Euclid and WFIRST will have produced extremely large surveys over many thousands of square degrees to depths of 25 mag (AB), and JWST will explore the rest-frame optical and near-infrared spectra of the youngest galaxies to unprecedented depths. However, there will be no surveys of comparable sensitivity in the far-infrared, where most galaxies emit the bulk of their energy. Without a sensitive far-infrared space telescope, our picture of galaxy evolution and star and planet formation will be dangerously incomplete and biased. Much closer to home, there are still tremendous gains to be achieved in the far-infrared by observing the cold bodies that reside beyond 30 AU in the Solar System – the Trans-Neptunian Objects (TNOs). TNOs carry clues to the processes that created the Solar System and made the Earth habitable, but the basic properties of this population, such as their sizes and albedos, are highly uncertain. Between these extremes, a host of observations, from star forming regions in our Galaxy to detailed studies of the phase structure of the interstellar medium in nearby galaxies are possible with a sensitive FIR space telescope. Just as importantly, the huge gains in sensitivity and mapping speed of the next generation FIR space telescope envisioned here will reveal vast new landscapes through serendipitous discoveries of the hidden Universe.

1.2. Summary of the June 2015 FIR Community Workshop

In order to provide input to the NASA Program Analysis Groups as laid out by the Jan. 2015 NASA whitepaper, Planning for the 2020 Decadal Survey, a community workshop was held from 3-5 June 2015 in Pasadena, CA to help define the key science drivers and leading architecture for the **FIR Surveyor** (as put forward in the 2013 NASA Astrophysics Roadmap, **Enduring Quests, Daring Visions**). Approximately 150 members of the far-infrared community attended the workshop either in person or via webex. The workshop consisted of a number of invited science talks covering topics from the Solar System to the high-redshift Universe, as well as multiple science breakouts and group discussion over the three days. The talks, supporting workshop documentation, and description of the motivation for and goals of the workshop are available online at the following URL, http://conference.ipac.caltech.edu/firsurveyor/

Two leading architectures for the **FIR Surveyor** were identified before the workshop based on a number of FIR community meetings over the past 13 years. These architectures were a direct detection, cryo-cooled interferometer, and a large, cryo-cooled single aperture telescope. Both platforms provide the capability for sensitive imaging and spectroscopy in the far-infrared. Two days into the workshop, a straw poll was conducted of the participating US scientists. The clear outcome led to the consensus that the large, filled-aperture telescope is the architecture that could best provide the essential measurement capabilities to uniquely address the key science questions of the 2020's and 2030's. These questions are discussed in section 2, the single aperture telescope concept for the **FIR Surveyor** is presented in section 3, the advocated science and technology study is outlined in section 4, and approaches to key subsystems are discussed in section 5.

2. Scientific Goals

The quest for our Cosmic Origins requires us to understand the processes that transformed the primordial plasma with density variations of a few parts in a million into the highly structured Universe that we see today. The challenge for astronomers is to unravel the origin and evolution of galaxies, and the evolution of matter from atomic particles to the dust and volatiles that led to habitable planets and ultimately life on Earth.

Star and planet formation, galaxy assembly, and black hole accretion are fundamental processes that shape the evolution of the Universe. These processes often occur shrouded within interstellar gas and dust clouds that hide the detailed physics and chemo-dynamical evolution from view at short wavelengths. Therefore, a complete picture of cosmic evolution can only be built with sensitive observations of the dusty Universe in the far-infrared. While previous infrared observatories from IRAS to ISO, Spitzer and Herschel have brought into focus the wealth of information available at infrared wavelengths, today we stand on a threshold of technological advances that promise to transform our understanding of the dusty Universe.

Here we make the scientific case for the **FIR Surveyor**, a next generation space observatory that will characterize the formation and evolution of galaxies, stars and planets and perform large area spectral surveys to unprecedented depths. The FIR Surveyor will follow the cycling of baryons in and out of galaxies, measuring important gas and dust features at all epochs to unravel the mechanisms of feedback and self-regulation that have transformed them through cosmic time. The FIR Surveyor will peer into dusty stellar nurseries and proto-stellar disks to follow the refractory and volatile materials and the water that eventually aggregate into planets. The technology development for the FIR Surveyor will also lead to important advances necessary for space-based interferometry at FIR and other wavelengths that will enable us to ultimately map the Universe at high resolution in the Visionary Era as described in NASA's Astrophysics Roadmap. Our workshop identified two over-arching questions that are expected to drive astronomical research in the next decade, and to which the FIR Surveyor can make unique and fundamental contributions:

- **What controls the evolution of galaxies, the formation of stars and the growth of black holes through cosmic time?**
- **How did the composition of the Universe evolve from primordial gas to habitable planets?**

The next two subsections discuss these primary questions in more detail and the observations with a FIR Surveyor that will be needed to answer the primary questions.

2.1. What controls the evolution of galaxies, the formation of stars and the growth of black holes through cosmic time?

Answering this question requires a coordinated study, spanning the high-redshift universe, local galaxies, and studies of star formation and feedback in our own Milky Way. Since a significant fraction of the energy ever produced in galaxies is absorbed by dust and emitted in the far-infrared, this waveband encodes crucial information needed to understand the processes that regulate galaxy growth and evolution (Fig.2). Observations reveal that the galaxy mass function is complex, and not a simple scaling of that for dark matter halos. This difference is likely due to the complex interplay of star formation, black hole growth, feedback, and mass accretion. The far-infrared provides a unique window on the processes that regulate star formation, the growth of black holes, and the formation of metals across cosmic time from cosmological scales to the scale of individual proto-stellar systems. Below we outline some of the key outstanding questions in galactic evolution that can be addressed by a FIR Surveyor.

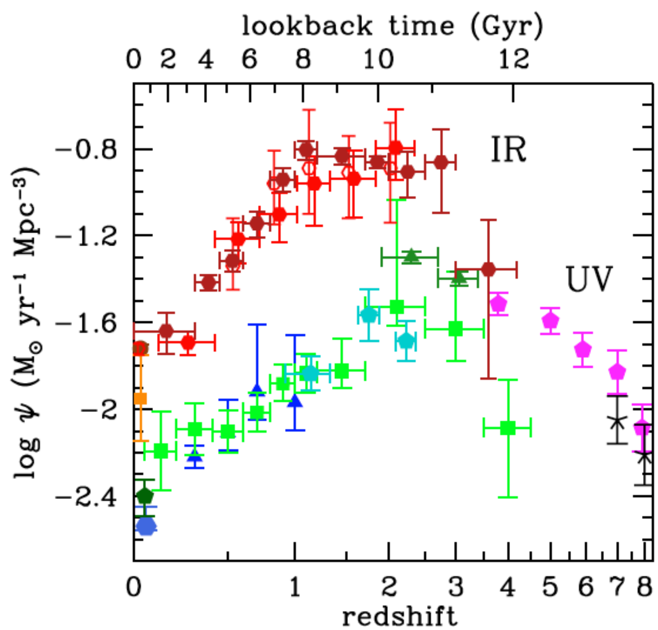

Fig. 2: Star formation densities in the IR and UV as a function of redshift from Madau & Dickinson (2014). The vast majority of the energy produced by young stars to z~3 emerges in the IR.

What physical mechanisms in galaxies and their environments drove the cosmic star formation history? Star formation and black hole growth are two of the most important processes that shape the evolution of the Universe of galaxies, and they regularly occur in regions shrouded deeply within interstellar gas and dust. Infrared observations show that the rates of cosmic star formation and black hole growth peaked during the first half of cosmic history, at a redshift of $z = 2 – 3$ (Fig.2). Precisely why the peak in the cosmic star-formation rate occurred at this epoch is still a mystery. Did galactic winds shut down star formation at $z < 2$, or were other processes, such as a change in the properties of the ISM, or a strangulation in the gas accretion rate, responsible? What is the cosmic history of the growth of dust and metals and how does it relate to the general picture we have of the star-formation rate evolution? To answer these questions and extend our understanding of galactic evolution before, during, and after the peak of activity, requires sensitive measurements of key diagnostic emission lines of the atomic and molecular gas as well as the dust continuum, a project that is uniquely suited to the FIR Surveyor (see Armus et al. whitepaper).

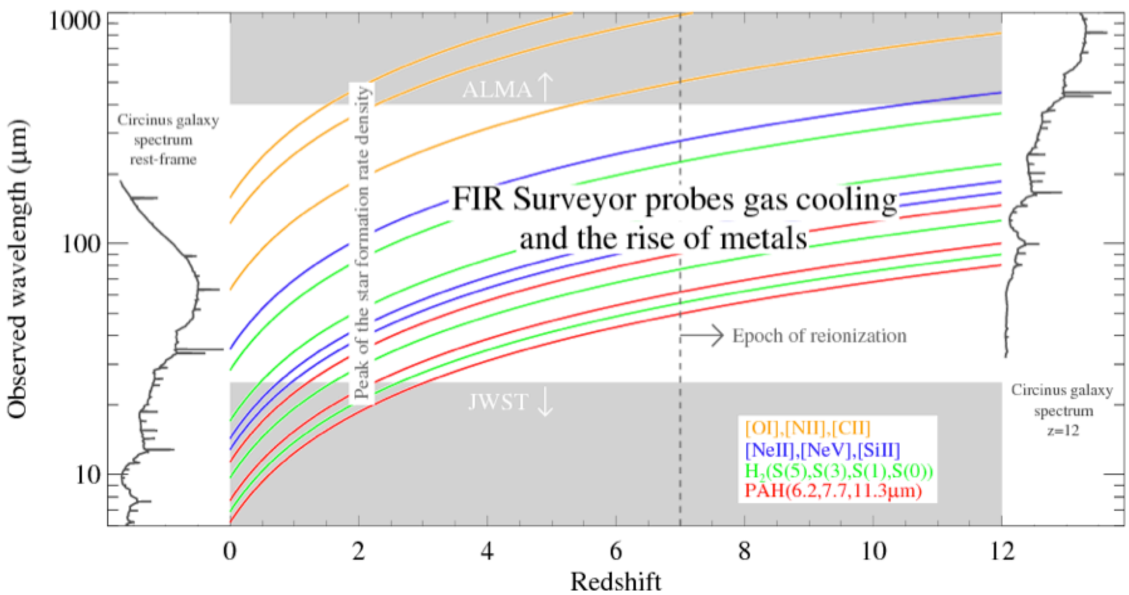

Fig. 3: Important infrared diagnostic lines as a function of redshift. With these lines the FIR Surveyor will be able to quantify AGN and star formation and constrain the conditions of the ISM in galaxies from the peak of the star formation rate density to the epoch of reionization. The rest-frame spectrum of the Circinus galaxy, a dust-enshrouded active galaxy, is shown on the left, and redshifted to z=12 on the right, to highlight the rich spectral region covered by the FIR Surveyor. The FIR surveyor will fill a crucial gap between JWST and ALMA by directly probing the emission from dust, atomic and molecular gas at high redshift.

For a FIR Surveyor operating between 25 and 400 μm, the most important diagnostic lines are available over a staggering range in redshifts, z = 1-10 (Fig. 3). AGN can be readily identified in the infrared both by the strength of high ionization emission lines, such as [NeV] and [OIV], and the presence of excess warm dust emission below 10 μm.

Similarly, Polycyclic Aromatic Hydrocarbon (PAH) features, which can be easily detected out to very high redshifts with a FIR Surveyor, are extremely strong in star-forming galaxies but weak in AGN (Fig.4), enabling a relatively clean estimate of the star formation rate in the dustiest galaxies. Physical conditions in star-forming regions in high-z galaxies can be probed using ratios of PAH bands, FIR fine-structure lines (e.g., [CII] 158 μm to z ~ 2.5 and [OI] 63 μm to z ~ 5.5) and the dust continuum. In fact, since the ratios of the bright FIR fine-structure lines are related to the compactness and gas density in the star-forming regions, observations at high redshift can provide independent estimates of the physical conditions of the starbursts even at modest spatial resolution. The longest integrations on high redshift galaxies reachable with Spitzer/IRS (only a handful of luminous z > 2 galaxies), together with detailed studies of local starburst galaxies, suggest that a depth of 10^{-20} W cm^{-2} is sufficient to detect PAH and bright FIR fine-structure lines in galaxies down to the LIRG level (SFR ~ 10 M_{sun}/yr) with the FIR Surveyor out to z ~ 6.

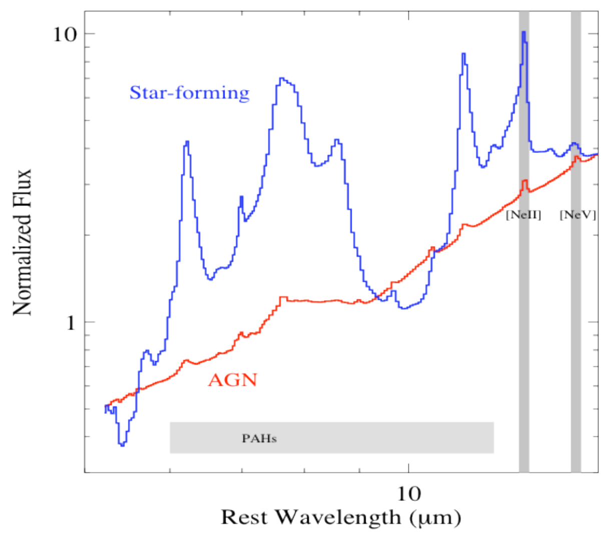

Fig. 4: Average rest-frame mid-infrared spectra of a pure star forming galaxy (blue) and strong AGN (red), normalized at 15 microns. Gray regions highlight the diagnostic power of the [NeV]/[NeII] line ratio and the PAH feature strengths at separating AGN and star formation activity.

What is the baryon flow within the dark matter web? How do baryons cycle from primordial gas to stars and back to gas within their dark matter halos? The prevalent view of structure formation conceives the cosmic web of dark matter as the foundation for the emergence of galaxies and their large-scale distribution. Gravitationally bound by dark matter halos strung along the web, baryons cool from diffuse gas to form stars and galaxies. Only a small fraction of the baryons actually make it into stars; why this is true is a central question in observational cosmology. Measurement of the gas and stellar content of halos as a function of their mass and redshift directly probe this baryon cycle. In the far-infrared, we can directly measure the build up of stars and the growth of black holes as well as trace large-scale structure through areal surveys of distant galaxies. The far-infrared wavelengths accessible from space are essential for teasing out the individual galaxies from SZ and CMB lensing signatures to the faint levels required to explore the low-mass halos (10^{12} - 10^{13} M_{sun}) that host the bulk of galactic formation.

A particular strength of the far-infrared is spectroscopy of molecular hydrogen, H_2, which is an important coolant of the warm molecular ISM, and the principal means of cooling primordial and very low metallicity ($Z \leq 3 \times 10^{-3}$ Solar) gas. The FIR Surveyor can detect H_2 emission to z > 6, will therefore be able to measure turbulent energy dissipation in galaxies that are less than a few hundred Myr old. The sensitive FIR Surveyor spectrographs will detect many H_2 lines simultaneously, enabling excitation, mass and total cooling power to be measured. The lowest level pure-rotational transitions of H_2 radiate entirely in the rest-frame mid-infrared, and probe molecular gas in the temperature range 100 - 1000 K. Spitzer observations of nearby galaxies revealed a sub-set of systems in which turbulence and shocks seem to dominate the heating of the diffuse molecular gas. In these galaxies, ranging from radio galaxies to compact groups to z~2 clusters, the line strengths often exceed that of other diffuse ISM coolants, like C^+ or neutral oxygen. The entire suite of rest-frame mid-infrared H_2 lines is shifted out of the JWST/MIRI range and into the far-infrared at moderate redshifts, thus providing a rare opportunity to use warm molecular gas to trace warm molecular gas over a large span of Cosmic time, and potentially detect the formation of the very first structures with the FIR Surveyor (see Appleton et al. whitepaper).

How do IR-bright galaxies trace the large-scale structure of the Universe? A sensitive large, cold telescope in space will enable deep continuum surveys in the far-infrared, going significantly deeper than any other existing or planned far-infrared survey and providing the ability to cross-correlate with the largest planned next-generation surveys at shorter wavelengths (e.g., LSST, Euclid, WFIRST). This synergy with other NASA missions and large ground-based projects makes the mapping capabilities of the FIR Surveyor extremely important for linking the dusty Universe with the visible and UV-bright galaxies. For example, at 100 μm a survey of the whole sky to a 5σ limit of 0.5 mJy could be done in about 1000 hours. This limit is three orders of magnitude deeper than the existing IRAS and Akari all-sky surveys. The FIR Surveyor will reach below the knee in the source counts, enabling the bulk of the cosmic far-infrared background radiation to be resolved into individual galaxies (see Casey et al. whitepaper). Based on current galaxy models, at 100 **μ**m the FIR surveyor could reach a 5 sigma confusion limit of ~450 μJy, corresponding to a star formation rate of 20 $M_\odot$ yr^{-1} ($L=10^{11}$ $L_\odot$) at z=2, well below the knee in the luminosity function at this time. At shorter wavelengths, the depth is even greater. Far-infrared continuum surveys with the FIR Surveyor will improve over existing Herschel/PACS surveys by at least three orders of magnitude in terms of the number counts of galaxies detected at 100 **μ**m.

The spectrometers provide the third dimension, and in this case source confusion is effectively eliminated, as sources can be identified through template fitting of their spectra. We envision blind 3-dimensional spectral surveys that would detect star-forming galaxies and buried AGN through their mid- and far-IR emission lines. As an example, a 2000-hour survey covering 10 square degrees can reach ~0.6-4 x 10^{-20} W m^{-2}, corresponding to the bright fine-structure transitions in LIRG-class galaxies out to z=2 and ULIRG-class galaxies to z=6. The PAH features, with the large equivalent widths, are detectable in even fainter systems. We estimate that such a survey would detect approximately two million galaxies. These surveys would provide a census of interstellar conditions starburst and AGN activity and galaxy clustering. A key feature of the far-IR surveys is the ability to do 3-D 'intensity mapping,' in which aggregate properties of the sources too faint to be individually detected can be measured through their clustering signal (see Cooray et al. whitepaper). With both the bright and the undetected sources, the Far-IR Surveyor could therefore measure the large-scale power in redshifted PAH features, atomic fine-structure and H_2 lines over a huge range of redshifts.

How and why do galaxies evolve from z~1 to now? How do these key drivers of galaxy evolution vary with galaxy morphology, mass, and environment? Over the last 7 Gyr, roughly half the age of the Universe, galaxies have evolved dramatically, with an overall decline in the merger rate, star formation rate, and black hole accretion. In this era galaxies acquired their present day forms and became the disk and elliptical galaxies embodied in the Hubble tuning fork diagram. At these relatively low redshifts, we can begin to separate and measure the phase structure of the ISM, and securely link global star formation rates and AGN activity to the properties of the gas in individual galaxies.

The processes that set the state of the reservoir of gas and the efficiency with which it can be converted into stars or accreted onto black holes are key elements in determining how galaxies evolve. These processes are intimately linked to the cycle of energy and mass between ISM phases, as well as the feedback processes from star formation and AGN that redistribute gas within galaxies, recycle processed baryons into galactic halos, launch massive galactic outflows, and in some cases stop further mass accretion from the intergalactic medium.

Observationally characterizing the state of the ISM and understanding the physical mechanisms involved in feedback is best done in the far-infrared, where the energetically important fine-structure lines, the peak of the dust continuum emission, and the highly-excited rotational lines of many molecules are found. COBE, ISO, Spitzer and Herschel made the first important strides towards characterizing these key drivers in our own Galaxy and in small samples of bright, nearby galaxies. With the FIR Surveyor we will be able to unleash the power of large, statistically significant samples, moving beyond case studies to surveys of significant samples spanning the full range of stellar mass, metallicity, morphology, environment, and AGN activity that are relevant to galaxy evolution. These surveys will provide the link to the high-redshift Universe through observations of the same tracers observed with ALMA at larger redshifts. For example, the FIR Surveyor will enable the *first* measurement of the [CII] luminosity function at $z \leq 1$. Since [CII] 158 μm is the dominant coolant of the neutral gas, the evolution of the [CII] luminosity function traces the heating and phase balance of the

ISM. Knowledge of these properties is crucial for understanding how galaxies evolved from z~1 to today.

Nearby galaxies (those with D < 100 Mpc) play a crucial role in understanding ISM physics and galaxy evolution. This population represents the present end-point of galaxy evolution, and the sources where we can disentangle many of the relevant astrophysical processes. In these objects the FIR Surveyor will easily separate nuclear from disk regions on kpc scales. Observations of the far-infrared atomic and molecular lines, and dust continuum emission provide a wealth of diagnostics of ISM phase balance and energetics including detailed accounting of heating and cooling, radiation field intensity and hardness, gas metallicity, shock indicators, X-ray and cosmic ray driven chemistry, and the mass and energy budget in the complex multi-phase structure of the ISM. These studies are enabled by the unique sensitivity, spectral coverage, and planned spectral resolution (R>10,000, ~30 km/s or better) of the FIR Surveyor, that synergistically complements JWST, SKA, and ALMA observations. Capable of obtaining [CII] at S/N~100 per spectral resolution element in a Milky Way at 500 Mpc in one minute, the proposed FIR Surveyor has the power to measure key spectroscopic far-infrared transitions in even the faintest phases of the ISM in samples of tens of thousands of galaxies, enabling the type of science in the far-infrared that is usually reserved for large optical spectroscopic surveys (e.g. SDSS). Unlike those, however, the FIR Surveyor will penetrate enshrouded nuclei and obscured star-forming regions in the disks, unlocking detailed studies that have only been hinted at with Spitzer and Herschel observations.

The FIR Surveyor will deliver a comprehensive picture of the interaction between the ISM, star formation, and AGN in galaxies during the formative era of present day galaxies. Its sensitivity and mapping capabilities make it possible to use a “wedding cake” tiered strategy to measure the dust continuum emission and far-infrared lines from thousands of galaxies, statistically populating bins of redshift to z~1. While Herschel has carried out surveys of dust continuum for galaxies in this redshift range, the far-infrared lines have not been observed for a truly representative galaxy sample at z>0.1. The far-infrared luminosity function will be a crucial link between the populations at cosmological distances that will be observed by ALMA and the local galaxies we can study in detail.

What role does feedback play in the assembly of the Hubble sequence across the last half of cosmic history? It is now recognized that feedback from star formation and AGN has a profound impact on galaxy evolution. By removing and redistributing gas in the galaxy and galactic halo, feedback processes play a major role in how galaxies evolve. Observations of FIR lines such as those of water, molecular hydrogen, and OH, have proven to be key diagnostics for constraining the amount of molecular mass entrained in galactic outflows. While outflows have been traced in the diffuse atomic gas in nearby galaxies for decades, the far-infrared absorption features first measured in a handful of nearby AGN and ultra-luminous infrared galaxies with Herschel unambiguously trace negative feedback on the cold molecular ISM, the same material out of which stars form. The FIR Surveyor will allow us to measure the impact of feedback on the galaxy population as a function of mass, morphology, star formation rate, and the power of a central AGN. In the local universe, the FIR Surveyor will probe gas and dust in galaxy outflows over a large range in galactic radius (Fig.5), allowing us to probe, not only the disruptive impact on small scales, but also the importance of ejecting metal enriched material into the IGM, linking these studies to those using background QSOs to probe galactic halo gas.

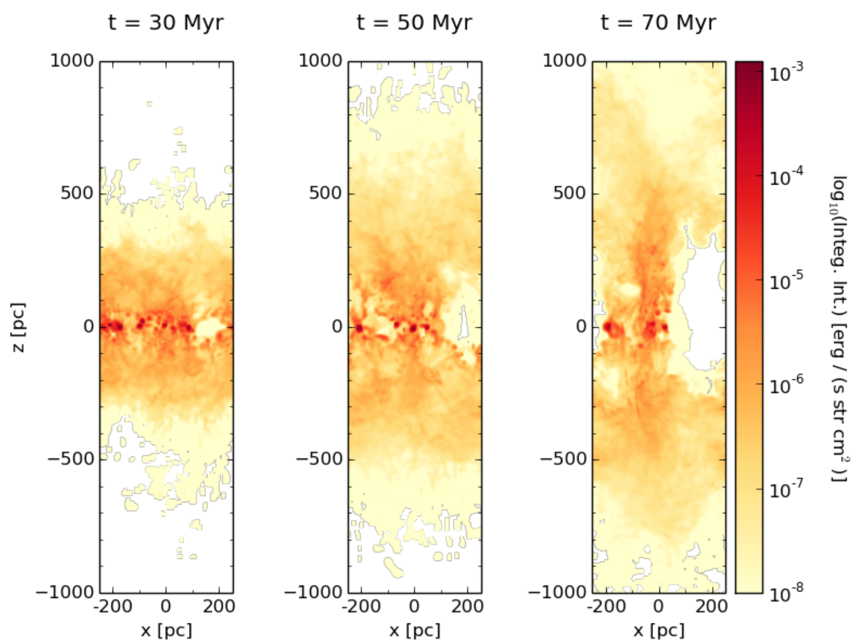

Fig. 5: Extraplanar [CII] emission as a probe of outflow activity. Simulations of stellar feedback in a galaxy disk, showing galactic outflows, visible in [CII] emission, being driven by star formation. The calculations use the SILCC simulations and include radiative transfer to compute [CII] emission (Walch et al. 2015). The FIR Surveyor is capable of imaging this faint emission (the lighter color corresponds to 10^{-11} W m^{-2} sr^{-1}, resulting in S/N>20 in one hour).

What controls the evolution of clouds to stars within a galaxy? Star formation within molecular clouds is roughly 100 times slower than would be expected if the molecular clouds were in free-fall collapse. Magnetic fields and turbulence are the prime suspects for slowing star formation on cloud scales. These may work by limiting the fraction of cloud mass that becomes sufficiently dense for gravity to dominate. When the star formation rate is measured versus the mass of dense gas, the relations are tighter than when total gas mass is used. To understand how clouds form stars, we must be able to follow the energy flow as traced by the FIR fine structure transitions such as [CII] and [OI] (Fig.6) and the high-J CO transitions. The J=4-10 CO lines are uniquely suited to tracing low velocity shocks associated with turbulent decay. Herschel was able to detect this signature in a few locations, indicating decay times comparable to the cloud crossing time. With the FIR Surveyor, we can target hundreds of star-forming regions, each requiring a few hours. At high spectral resolution, ~1 km/s, these observations will allow easy separation of PDR and shock emission.

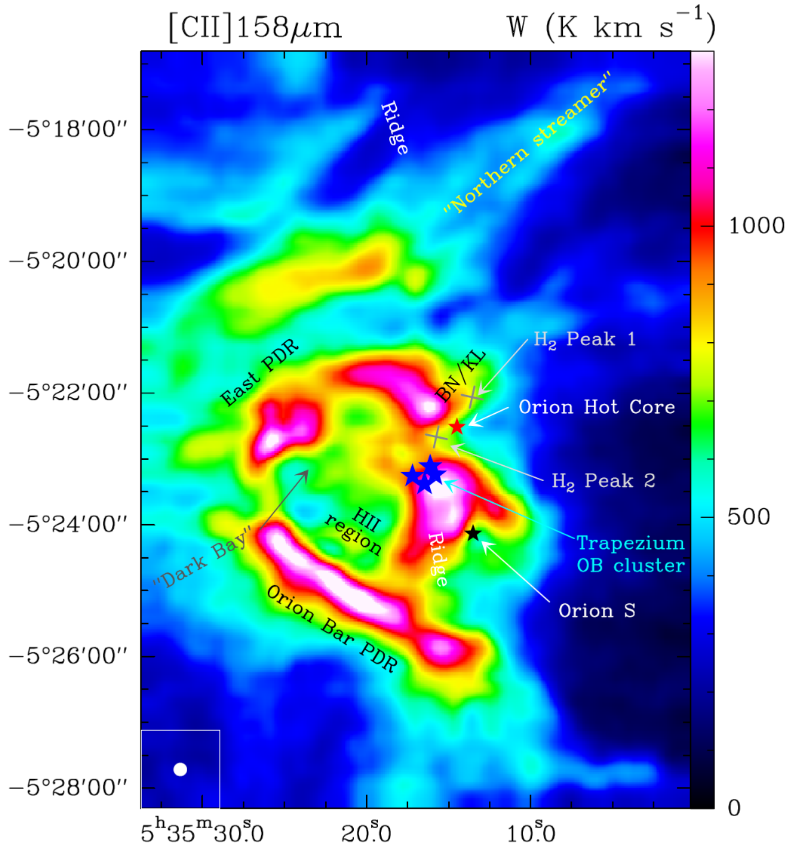

Fig. 6: [CII] emission from the Orion Molecular Cloud (Goicoechea et al. 2015). The color bar indicates the integrated intensity in K km/s. The "Orion Bar" PDR region is clearly visible, but other contributions to the emission can also be readily identified.

Another critical aspect for understanding star formation in the Galaxy is identifying the different phases of the ISM and in particular how the transition from atomic to molecular gas regulates the process. By comparing the [CII] 158 μm, HI and CO line profiles, it's possible to pinpoint the location of the different phases (PDR, atomic, molecular), even when more than one is present along a given line of sight. A survey at a velocity resolution at ~1 km/s over ~100 square degrees, with the FIR Surveyor, would require ~2000 hours with a 64 element R = 300,000 focal plane array.

A unique and important case in the study of star formation is the Galactic center, where clouds are distinctly warmer, but the dominant heating processes are poorly understood, and the star formation rate 10 to 100 times lower than expected from the dense gas mass. Much higher turbulence and the presence of a pervasive hot (500 K) gas component are likely explanations. The FIR Surveyor would greatly expand our understanding of the physical conditions in the Galactic Center. A survey of These will fine structure and high-J CO lines could cover the entire Central Molecular Zone, a few degrees in extent, in several hundred hours at a velocity resolution of 3 km/s.

What role do magnetic fields play in star formation? Star formation occurs in dense cores within molecular clouds, but major questions remain about the formation of cores and how fragmentation, collapse, and accretion processes control the initial mass function of newly formed stars, as well as the formation of accompanying planetary systems. One of the unknowns is the role of magnetic fields in channeling material into gravitationally bound condensations. A FIR Surveyor mission equipped with a polarimeter could measure the magnetic field configuration over large areas of molecular clouds in the Milky Way and fill in a critical gap between the low angular resolution data from Planck and modest sensitivity data to come from SOFIA and BLAST-Pol, and the much higher angular resolution that will come from ALMA. Reliable measurement over one to several square degrees of a 1% fractional polarization at a 0.25 Jy/beam level at ~250 μm is required, which is straightforward given the continuum sensitivity of the FIR Surveyor. Observations in multiple FIR bands between 30 and 300 μm will be ideal for unraveling the magnetic field in regions probed by dust at different temperatures.

Moreover, spectroscopy of key ions can reveal the fractional ionization (set by the local cosmic ray ionization rate), which determines the coupling between the magnetic field and the gas. The FIR Surveyor can map the variation of the cosmic ray ionization rate in diffuse gas with low molecular fraction across the Galactic disk. This can be done through absorption spectroscopy (target ions include OH^+ and H_2O^+), which will require relatively deep integrations towards a few hundred dust continuum sources throughout the Milky Way.

2.2. How did the composition of the Universe evolve from primordial gas to habitable planets?

Parallel to the macroscopic evolution of galaxies and large-scale structures, a microscopic evolution was transforming protons into a rich array of nuclei, giving rise to dust and the molecular Universe. The dust and volatiles are the sine qua non of habitable planets. The Earth has both liquid water and dry land, uncharacteristic of other terrestrial planets in the Solar system today; how did this come about? The growth of metals, dust, and volatiles with time tells us when habitable planets first became possible. Observing the flow of dust and volatiles from molecular clouds to protoplanetary disks generalizes the detailed studies possible within our Solar system, where it is possible to measure how these compounds are incorporated into planetary bodies.

What is the cosmic history of the rise of metals and dust? Spectroscopy of atomic fine-structure lines, PAH and silicate features, and H_2 can be used to trace the growth of dust and molecules at early epochs. The increase of heavy elements via nucleosynthesis, traces this chemical history. Observations of UV bright galaxies suggest that the conventional 'strong-line' rest-frame optical diagnostics, such as log ([N II]λ6584/Hα) and log([O III]/Hβ), may need recalibration at high-z. The only way to determine if this is also true in dusty starburst galaxies is to obtain sensitive far-infrared spectra. For example, the [OIII] 52 μm and 88 μm lines, and the [NIII] 57 μm line can provide an accurate determination of the oxygen abundance and the N/O abundance ratio. The strength of PAH emission is correlated with metallicity and provides further information about the composition of dust grains in high-z galaxies.

What controls the life cycle of interstellar dust? A unique power of the FIR Surveyor can be found in the study of the life cycle of dust. Dust plays a key role in galaxy evolution on many levels: it causes the extinction of UV/optical light and provides shielding for molecular regions, allowing them to cool and collapse to form stars; it heats the gas via the photoelectric effect in PDRs, thus determining the balance between the ionized and neutral phases; it plays a key role in radiatively-driven galaxy winds, launching enriched material out of galaxy disks into galaxy halos, and its abundance may determine the masses of stars at very low metallicities. Nonetheless, we do not understand the mechanisms of dust production and destruction in detail, and we are not able to predict the abundance or properties of dust in a galaxy with confidence.

Dust production in AGB stars does not seem to balance dust destruction by shocks. At the same time, dust is surprisingly abundant in some high-z galaxies. These and other observations have refocused attention on the necessity of significant dust production by supernovae. Recent evidence suggests that dust can be created and survive the reverse shock into the newly formed dust particles, but very few observations exist. Continuum measurements with the FIR Surveyor will enable groundbreaking studies in this area by permitting measurements of spatially resolved SEDs in the local Universe down to very low metallicities, enabling links between dust properties, stellar populations, and the gas-phase ISM. Continuum observations of a substantial sample of young supernova remnants at wavelengths from 30 to 300 μm are essential.

What is the trail of water from molecular clouds to planets in the habitable zone? High-sensitivity and high spectral resolution observations of low-lying gas-phase water transitions with the FIR Surveyor can probe the distribution of water vapor in dense cores collapsing to form new stars and planetary systems (Fig. 7). Together with gas-phase isotopic ratios, including the D/H ratio in the ISM and Solar system objects, in particular comets, can also be used to address this evolution (Fig. 8). This will require R > 300,000 spectroscopic observations of water, CO, and other gas-phase species, along with lower-resolution observations of water ice features. Crystalline water ice features from 40 to 60 μm, along with absorption features at shorter wavelengths probe the nature of ice mantles in protoplanetary disks.

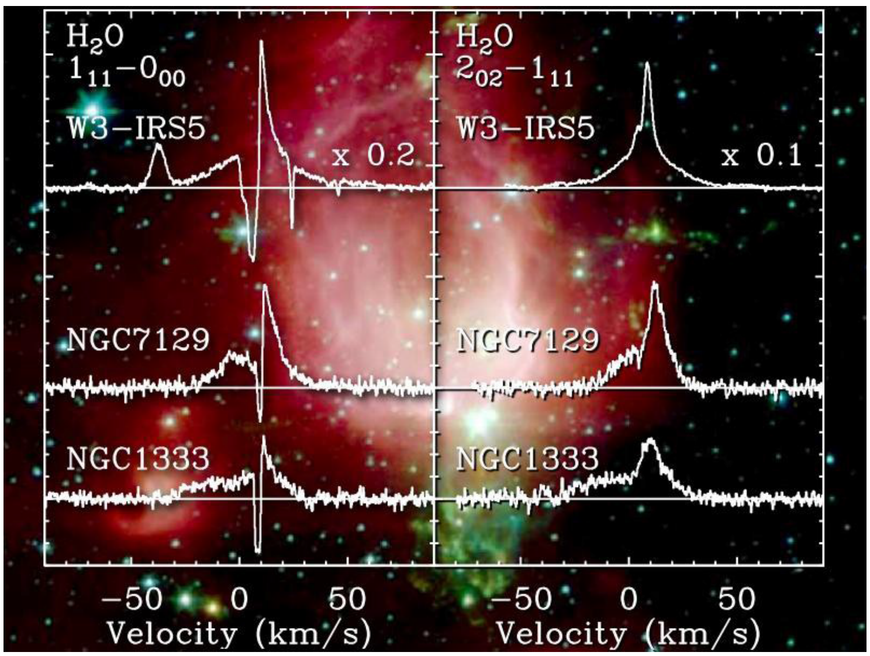

Fig. 7: Spectra of ground-state and excited rotational transitions of water vapor in three different sources, W3-IRS5, NGC 7129 and NGC 1333. The low-energy transition also shows strong, narrow absorption features from foreground water. From the WISH team website.

How are volatiles delivered from protoplanetary disks to habitable planets? The Earth is depleted by orders of magnitude in carbon, nitrogen, and water, relative to the primordial reservoirs. It is thought that volatile molecules, such as water and simple life-supporting organics, were delivered to an initially dry Earth some time after its formation. It is currently unknown whether this is a common property of exoplanets in the habitable zones around other stars. The ultimate composition of planets depend on the chemical composition and ice and gas reservoirs of protoplanetary disks, along with the subsequent evolution of their planetesimal population. While the primary carriers of carbon are easily detectable using ground-based observatories, the far-infrared offers exclusive access to [CII], the main carriers of oxygen ([OI], OH, H_2O gas and ice), and lines of NH_3, an important carrier of nitrogen.

The FIR surveyor will constrain the gas/ice ratio of water during the early gas-rich stages of planet formation and evolution. The strong 42 μm emission feature of water ice traces the bulk mass of solid volatiles in the disk, but due to a lack of sensitivity and wavelength coverage has been (tentatively) detected in just a few protoplanetary disks. While the wavelengths covered by JWST trace hot (~500 K) water vapor inside the surface snowline, water lines in the 50−100 μm region are formed in gas with temperatures of 50−200 K, making them key tracers of water in the deeper snow line region from a few AU out to the giant planet and comet-forming regions. The strong ground-state transitions of water vapor trace the cold outer disk, where most water is otherwise frozen as ice. The strongest transitions of NH_3, a key cometary volatile, also lie in the far-infrared, and at present there is only a single detection of this molecule in a disk. The FIR Surveyor will also be able to detect more optically thin isotopologues, making key cosmo-chemical probes in the Solar system such as D/H, $^{18}O/^{16}O$, and $^{15}N/^{14}N$ accessible for the first time in planetary regions.

How do the gas reservoirs evolve in protoplanetary disks? Disk gas masses are critical to understanding planet formation, but they are generally probed only by indirect methods. Since it is chemically equivalent to H_2, HD is a direct probe of gas mass. The fundamental rotational transition of HD was detected by Herschel in a handful of sources, and used to directly constrain the gas mass. An HD-derived mass breaks the degeneracy between mass and abundance for the other volatile tracers, allowing study of the chemical evolution of the volatile inventory and the implantation of ices and isotopic enrichments into planetesimals. By comparing the observed volatile distributions with volatiles in the present-day Solar system, the composition of giant exoplanet atmospheres and models of planet formation and evolution, we can understand how life-critical elements are delivered to habitable worlds and whether Earth is chemically typical in the Galactic zoo of terrestrial planets across the stellar spectrum.

With a cold, large telescope like the FIR Surveyor, equipped with sensitive spectroscopic instrumentation, we can extend observations of warm and cold volatiles to hundreds of systems, enabling direct statistics to be applied to the composition and evolution of planet-forming regions in disks around Solar-mass young stars (see Bergin et al. whitepaper). For selected systems, high spectral resolution observations can constrain the location of the HD by exploiting the velocity field determined by other facilities, such as ALMA.

How do planetesimal systems evolve? The final stages of planet growth are largely invisible, but the resulting debris disks provide clues about the ongoing processes. The primordial dust in these systems has largely aggregated into planets and small bodies and the primordial gas has either accreted onto the star or gas giants, or been swept away. Collisions among small bodies in massive asteroid and Kuiper Belts generate dust. Spectroscopy of this dust can reveal processes in planetesimal evolution that

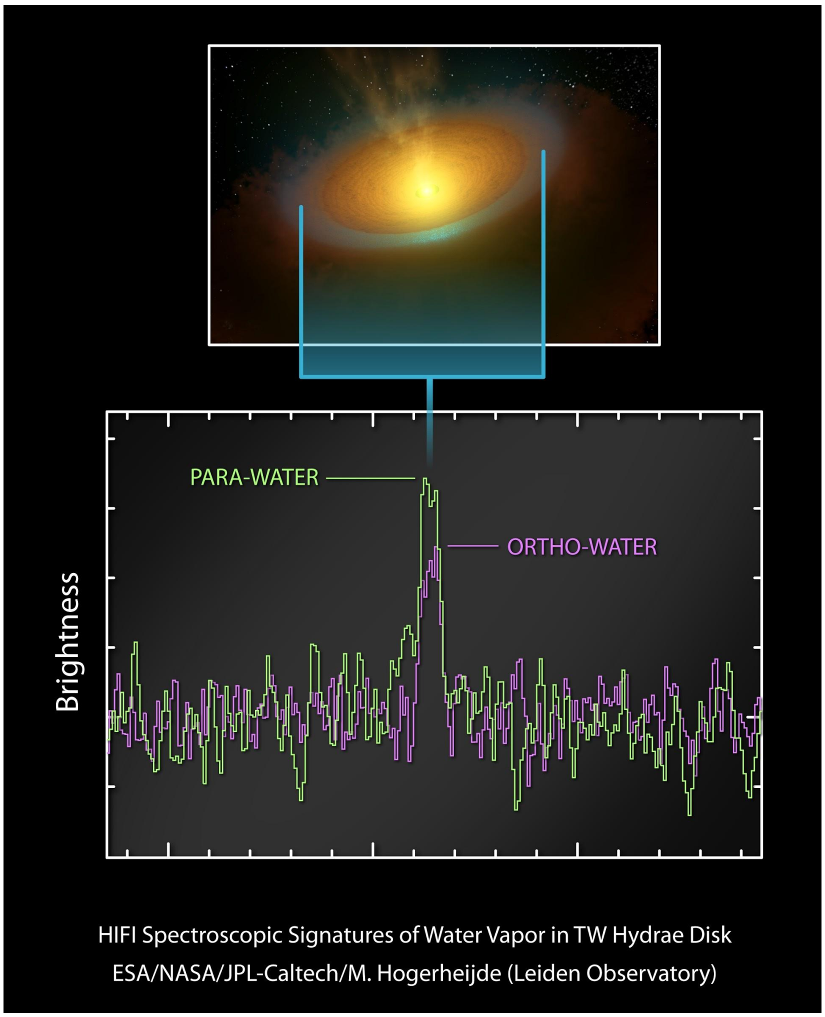

Fig. 8: Water vapor in the TW Hydrae protoplanetary disk as seen with Herschel/HIFI (Hogerheijde et al. 2011).

would otherwise be hidden. Spectroscopy with Spitzer/IRS has enabled detection of mineral species and Mg:Fe ratios in the warm dust consistent with production in giant collisions. ALMA observations have detected tenuous CO toward a handful of A-type stars in the 5−10 Myr old Upper Sco association, possibly the last gasp of the bulk gas, and toward 20 Myr old beta Pictoris, possibly sublimated gas from a swarm of comets in the outer regions of the planetary system.

The far-infrared provides critical access to atomic gas (e.g. [O I] at 63 μm and [C II] at 158 μm) and solid-state features (e.g. water ice at 42 and 63 μm, silicates at 69 μm) that constrain the bulk properties of the disk, the nature of the parent bodies, and the processing of the solids within the disk. Detections of water ice and vapor and the photo-dissociation products of water vapor (OH, and O) provide definitive evidence for comets, and can be used to calculate the water vapor production rate and constrain the CO:H_2O ratio. In addition, measurements of the shape and peak position of the 69 μm silicate feature could be used to uniquely constrain the crystallinity, size, and the Mg:Fe ratio of the cold dust. These constraints could be compared to those inferred by Spitzer and JWST for the warm dust based on observations of the 10 and 20 μm silicate features, to better constrain how dust is processed, radially mixed, and produced in young planetary systems.

Despite two Herschel Key Programs targeting debris disks, the sample size remains small, and relatively little is known about their far-infrared continuum emission and the detailed demographics of systems with dust. The FIR Surveyor will realize the diagnostic power of the far-infrared, first hinted at with Herschel, and study and statistically significant number of debris disks to constrain the evolution and diversity of exoplanetary systems. The FIR measurements will be combined with mid-infrared observations to determine whether the Solar System architecture is common or rare. Large studies, examining the correlation between far-infrared excess and planetary systems, would help us understand the relationship between dust in debris disks and planetary systems.

How was the architecture of the Solar System rearranged during the late stages of planetary system formation? Our best example of the processes that form planets and create habitable conditions is our own Solar system. However, the events that sculpted its particular morphology are not well defined. Compelling theories of Solar system evolution, such as the Nice and Grand Tack models, crafted to explain sets of observables (composition, physical structure, and mass), still await detailed measurements of the outer Solar system. Isotopic ratios serve as cosmogonic "thermometers" that trace physical variation across the disk and small body populations in the forming Solar system. The chemistry on cold interstellar grains (~10K) is greatly out of equilibrium, leading to high deuterium enrichments. Prior to Herschel, comets seemed to exhibit enrichment consistent with a formation temperature around 30 K. Herschel has detected water in short period comets with a terrestrial D/H, prompting some to suggest that ocean water was delivered by ecliptic comets (Fig. 9). However, the sample is extremely limited and more observations are necessary, as Rosetta measurements suggest significant variations. Similarly, comets also show ^{15}N enrichment. By combining FIR measurements of the D/H isotopic ratio of water with the

^{15}N isotopic ratio in comets, the FIR Surveyor can accurately determine the primordial conditions of our Solar System, and probe the origins of the small body populations.

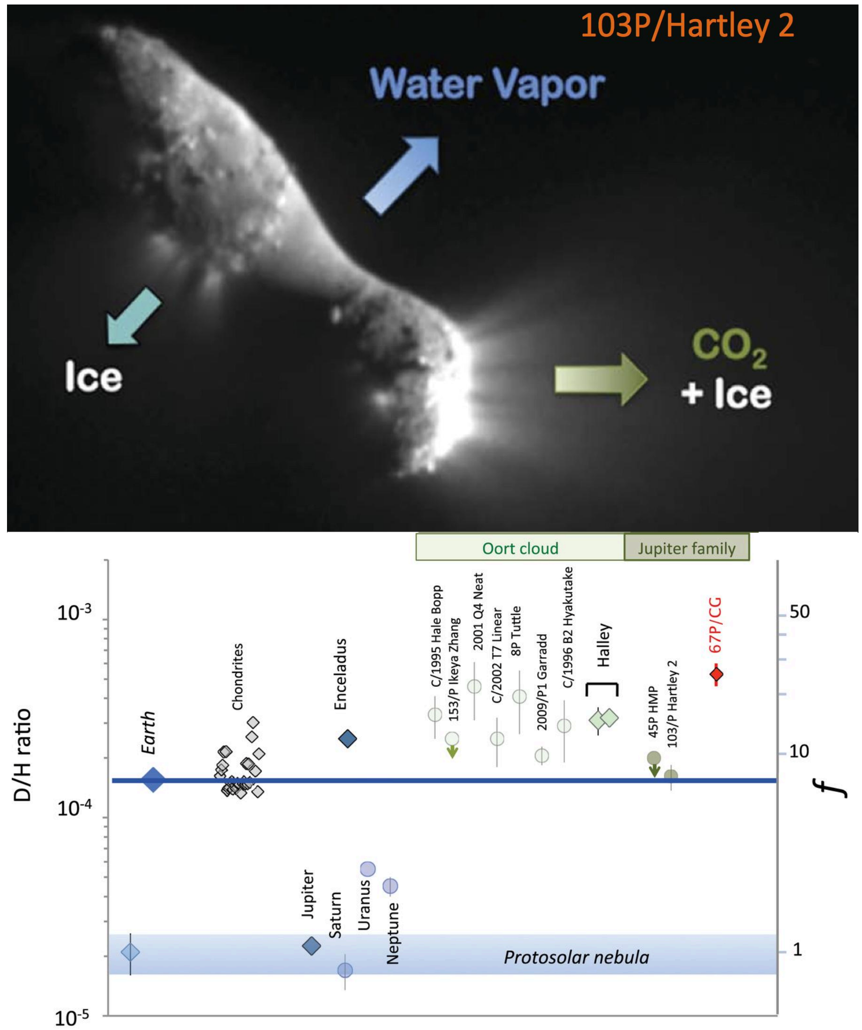

Fig.9: (Top) - Image of Comet 103P/Hartley 2, from A'Hearn et al. (2011). (Bottom) - D/H ratio measurements in comets compared to the planets and the protosolar nebula, from Altwegg, K. et al. (2015).

Trans Neptunian Objects (TNOs), located beyond 30 AU, comprise the Solar system's most primordial objects. Their orbits match the scales of most observed disk structures in other planetary systems. These bodies arise from the same reservoir as the comets that brought prebiotic material to the inner Solar System. Due to their relatively small size and large distances, their physical parameters are still poorly constrained. FIR observations, which cover the peak in the spectral energy distribution of these objects, are essential to constrain their thermal inertia, surface roughness and emissivity. Presently, ~1700 TNOs are known, with 82 having sizes ($\gtrsim 100$km) as measured with Herschel. The FIR Surveyor would have the ability to conduct a large survey, covering

≥1/10th of the sky, providing sensitivities to characterize faint small bodies down to ~10 km at distances > 50 AU. Such a survey would likely yield >10^4 TNO discoveries and ~100x more targets with accurate sizes (see Bauer et al. whitepaper). Multiple visits to fields, spaced hours apart, would place orbital constraints on these objects, and greatly limit confusion from background galaxies.

2.3. Summary of Survey Science and Example Surveys

The range of science facilitated by a FIR Surveyor is broad and deep. Observations will profoundly impact our understanding of the first galaxies to the buildup of volatiles in habitable planets. Sensitive photometric and spectroscopic observations covering a wide wavelength range are required to address the key science questions outlined above. For some important questions, a polarization capability is desired. While most of the extragalactic science could be achieved with grating spectrometers at modest spectral resolution, some programs clearly require very high resolution, R ~ 10^6, are these are best done, presently, via heterodyne techniques. We summarize the main science drivers and corresponding notional FIR Surveyor capabilities in Table 1.

Large projects, including both pointed components and one or more large multi-tiered, 'wedding cake' surveys would be well-matched to a number of the science topics discussed here, from a deep search for high-redshift dusty galaxies to a survey of TNO's. These would all be possible with the FIR Surveyor. Examples of the science enabled by such surveys with the FIR Surveyor are given below, and a few possible survey programs are outlined in Table 2.

Table 1: FIR Surveyor Science and Capabilities

Science Theme	Questions	FIR Surveyor Observations	FIR Surveyor Capabilities
The history of star-formation and black hole growth in galaxies	What physical mechanisms drive SF and BH growth in the early Universe? How do baryons flow in and out of galaxies?	Pointed observations of galaxies from z=1-10: PAH bands, FIR fine-structure lines, H2 and molecular absorption features, dust continuum SED	R~500, Full 25-400 μm coverage; 10^{-20} W m^{-2} line sensitivity
	How do IR bright galaxies trace the large-scale structure of the Universe?	Large area, blind continuum and spectral surveys. Spectroscopy over 10s sq. deg., continuum over 1000s of sq. deg.	Sensitivity and mapping speed. Wide-band multi-beam R~500 spectroscopy with large format arrays
	How do galaxies evolve over the last half of Cosmic time to populate the Hubble sequence?	Continuum and spectral line maps of thousands of z < 1 galaxies	Sensitive R~10,000 imaging spectroscopy with large format arrays.
	What regulates SF in clouds within a galaxy? What is the role of magnetic fields?	[CII], [OI] and high-J CO in ~ 100 galactic clouds and the Galactic Center. Polarization maps over 10 sq. deg. OH^+ and H_2O in >100 dust sources	R ~ 300000, polarimetry from 30-300 μm, sensitivity to ~1% fractional polarization at 250 μm.
The buildup of heavy elements and the formation of habitable planets	What is the cosmic history of the growth of metals and dust?	Fine structure lines, PAH, silicate features and H_2 in galaxies to z~10. Spatially-resolved continuum observations of young SNRs	Sensitive wideband R~500 survey spectroscopy throughout the far-IR.
	What is the water trail from molecular clouds to habitable planets? What is the gas and volatile structure of protoplanetary disks?	High resolution spectra of water, CO, HD, and other gas-phase species in dense cores and protoplanetary disks; low resolution spectra of water ice features	R~300,000 spectroscopy for gas-phase lines, and moderate-R capability (R>100) at <60 μm for solid-state features.
	How do planetesimal systems evolve?	Atomic gas lines, water ice/vapor, and silicate features in debris disks; shape and peak position of 69 μm silicate feature	25-400 micron survey spectroscopy at R~500, and sensitive R~10,000 measurements of key gas-phase coolants.
	How was the architecture of the Solar System rearranged during its late-stage evolution.	Large area continuum sky survey with low spectral resolution to find & characterize TNO SEDs.	Sensitivity and mapping speed to cover thousands of square degrees to the continuum confusion limit.

FIR Survey Science Highlights

- A 2,500 hr pointed survey could detect the bright mid and far-infrared fine-structure lines in over 2000 galaxies, accurately measuring star-formation and AGN accretion rates in even the most dust enshrouded systems at $z > 2-5$.

- A 2000 hr, 3-D spectral survey over 10 sq. degrees would detect over a million galaxies in FIR line emission, including over 10^5 at $z > 3$, providing redshifts and physical conditions in a sample unbiased by UV/optical selection effects.

- A deep 2,000 hr survey of 1 square degree can uncover redshifted H_2 cooling lines from young, low-metallicity galaxies at z~5-10, to a line luminosity of 10^9 - 10^{10} $L_{\odot}$

- A 2,000 hr survey could detect [CII] emission from extraplanar gas and relic outflows in 3,000 galaxies down to a HI column density of $N_H \sim 2\times10^{20}$ cm^{-2} for neutral gas with a density as low as 10 cm^{-3}, or detect the bright FIR cooling lines in thousands of Milky Way class galaxies out to z~1.

- An all-sky continuum survey would find every TNO in the Solar System with a radius of 145 km out to 100 AU from the Sun, almost every 45 km radius object within 60 AU (the outer edge of the Kuiper Belt), and gather the largest census of objects down to 10 km in radius.

- A 2,000 hr spectroscopic survey of the Milky Way could find water down to 1% of Solar System abundance, allowing the measurement water vapor, water ice, and the determination of the location of the snow line in 1,000 proto-planetary disks around stars with masses as low as 20% of the mass of the Sun.

- A survey of the Magellanic Clouds could detect every dusty circumstellar disk in those galaxies down to a dust mass of 100 M_{Earth}.

Table 2: Example Survey Programs

Deep Extragalactic Surveys

Pointed Spectroscopy of High-z Galaxies

Depth ($W\ m^{-2}$, 5σ)	Time (hrs)	Galaxies (#)	Time (hrs)	Area (40µm) (sq. deg.)	Area (400µm) (sq. deg.)
2.00E-21	4.0	500	2000	0.02	1.1
4.00E-21	1.0	2500	2500	0.10	5.8

Blind 3-D Spatial-Spectral Surveys

Area (sq. deg.)	Time (hrs)	Depth (40 µm) ($W\ m^{-2}$, 1σ)	Depth (400µm) ($W\ m^{-2}$, 1σ)	NEI (40µm) ($MJy\ sr^{-1}$)	NEI (400µm) ($MJy\ sr^{-1}$)
1	2000	1.4E-20	1.9E-21	4.4	0.06
10	2000	4.5E-20	5.9E-21	14	0.19
100	2000	1.4E-19	1.9E-20	44	0.6

Continuum Mapping

λ (µm)	Confusion (5σ, µJy)	Area (1000 hrs) (% full sky)	νL_ν at z=1 ($L_\odot$)	νL_ν at z=2 ($L_\odot$)	νL_ν at z=5 ($L_\odot$)
60	17	0.6% *	3.5E+08	2.0E+09	1.8E+10
70	28	2.3% *	5.0E+08	2.8E+09	2.5E+10
110	450	all sky §	5.1E+09	2.8E+10	2.6E+11
160	2900	all sky §	2.3E+10	1.30E+11	1.15E+12
250	9400	all sky §	4.7E+10	2.6E+11	2.4E+12

Nearby Galaxies Survey

Pointed Wideband Spectroscopy ($R=10^4$)

Depth (5-σ) (K @ [CII])	Depth (5-σ) ($W\ m^{-2}$)	Pointing time (mins)	Galaxies (#)	Pointings (# per gal)	Time (hrs)
400 µK	1.3E-19	5	3000	10	2500
900 µK	2.9E-19	1	3000	10	500

* assumes 8000 beam camera, which is 0.004, 0.005 deg^2 at 60, 70 µm

§ requires 1350, 40, 3 beam cameras at 110, 160, 250 microns

Galactic Plane Surveys

Wideband Spectroscopy (R=10^4)

K ([CII])	Depth (W m^{-2}) ([CII])	(W m^{-2}) ([OI])	Time (mins/point) ([CII])	Area 1000 hrs (sq. deg.)
900 µK	2.9E-19	7.3E-19	1	43
2.0 mK	6.50E-19	1.6E-18	0.2	215
4.4 mK	1.45E-18	3.6E-18	0.04	1076

High-Resolution Spectroscopy (R=3x10^5)

Depth		Pixels	Time	Area (1000 hrs) sq. deg.	
(K @ [CII])	(K @ [OI])	(#)	(mins/point)	(@[CII])	(@[OI])
20 mK	20 mK	64	60	0.22	0.03
200 mK	200 mK	64	0.6	22	3.4

Outer Solar System Continuum Surveys

Deep Ecliptic Latitude Survey, 4 observations/FOV#

Depth* (µJy, 5σ)	TNO radius (km @60 AU)	wavelength (µm)	Exposure (s)	Time (hrs)	Area (110µm) (% of sky)
3,5	10	70, 110	600	2000	5

TNO All sky Survey, > 11 observations/FOV#

Depth* (µJy, 5σ)	TNO radius (km @ 100AU)	Wavelength (µm)	Exposure (s)	Time (hrs)	Area (110µm) (% of sky)
115	135	110	1	500	100

* depth for a single exposure, assuming no significant background source.
# multiple observations are required to identify the source is moving, eliminate background source signal, and to calculate crude Vaisala orbits in the case of deep survey, or complete orbital elements for the all sky survey.

3. The FIR Surveyor Concept

3.1. Mission Requirements and Architecture

The scientific goals outlined in Section 2 create a set of measurement requirements for the FIR Surveyor mission, primarily centered on sensitive, wide-field spectroscopy. The observatory must provide the following:

- Complete spectral coverage from the cutoff of JWST/MIRI (25 μm) to the onset of the ground-based windows (500 μm) in wide bands, in order to access all redshifts and the full range of interstellar coolants in the Milky Way and local galaxies. Extension to even longer wavelengths is an option that we propose to address in the study.

- Line sensitivity better than 10^{-20} W/m^2 in pointed observations to enable observation of the earliest galaxies and most evolved, lowest-mass proto-planetary systems.

- Sufficient throughput (AΩ) in the spectrographs to enable spectral mapping to this depth over ~10 sq. deg. This requires ~100 beams at 100 μm.

- Continuum mapping capability over thousands of square degrees in a few key far-infrared bands, including resolving >90% of the far-infrared background into constituent sources at 100 μm. A polarization capability is desirable and a subject for future study.

- Very-high-resolution spectroscopy with sensitivity reaching 20 mK to permit resolved line profile measurements for key interstellar coolants, arrayed with 10-100 beams. This requirement is likely best met with a dedicated heterodyne spectrometer in addition to the direct-detection instruments.

The sensitivity requirements can only be met with a large collecting area, actively cooled to a few degrees K. For a given cost, collecting area is maximized with a single-aperture telescope, and this approach offers maximum flexibility for employing a range of scientific instruments. Cooling the large telescope requires an orbit that permits effective shielding of thermal radiation from the Earth and Sun; an Earth-Sun L2 halo or an earth-trailing Solar orbit would be suitable.. The survey requirements demand a mission life of at least 5 years, though our goal would be 10 years. The greatest challenge is the direct-detection instruments - they must have high efficiency and be limited by the zodiacal background, and carry a total of a few x 100,000 individual detectors. Table 3 summarizes the basic parameters of the facility (see Bradford et al. whitepaper). We describe below the baseline approach to each aspect in more detail.

Table 3. FIR Surveyor – Observatory Parameters

Parameter	Value
Telescope Temperature	< 4 K
Telescope Diameter	~5 m
Telescope Surface Accuracy	1 μm
Telescope Field of View	1 degree at 500 μm
Instrument Temperature	50-100 mK
Total Number of Direct Detectors	1-5 x 10^5
Heat Lift at 4 K	~150 mW
Heat Lift at 20 K	~1.5 W
Power Consumption for Coolers	~2000 W
Data Rate	~0.5 GBit / sec

3.2. Telescope Design

The detailed design of the FIR Surveyor telescope is a key aspect of our proposed study. An example configuration is shown in Figure 10. This design features a 4×6-meter monolithic primary mirror used off-axis, and a secondary mirror that is deployed with a single hinge mechanism. This provides an optimal collecting area in a non-deployed primary mirror that fits into a 5-m fairing. While other materials could be considered, the baseline approach is to use silicon carbide (SiC), which is attractive given its favorable thermo-mechanical properties, and given its success in the Herschel observatory, a system with comparable size and surface accuracy requirements to the FIR Surveyor we envision here. Other aspects are less clear, and there are several inter-related design choices that we propose to trade in our study, including:

- **On axis vs. off-axis:** A benefit of the off-axis geometry is cleaner beams. However, the off-axis construction will drive cost, and some of the beam effects might be mitigated by insuring that all supports are cold and absorbing. The scientific impact of the two options should be carefully quantified.

- **Active vs. passive:** Given the progress in silicon carbide active mirror technology, and the cost and complexity associated with verifying the large-scale figure accuracy of a large cryogenic telescope, the lowest-cost, lowest-risk option may be a telescope that includes some on-orbit figure adjustment authority, either in the primary itself or in a smaller image of the telescope.

- **Cost vs. telescope aperture:** A key aspect of our submission to NASA and the 2020 Decadal survey should be the run of cost with telescope and system size.

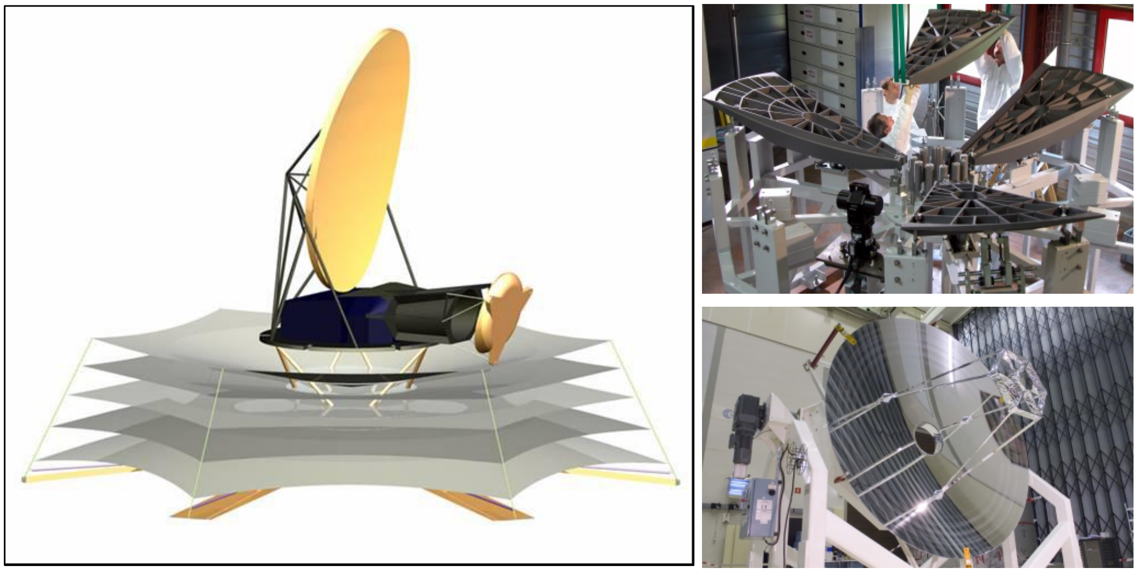

Fig. 10: (Left) The FIR Surveyor concept consists of a 5m class telescope, actively cooled to ~4K with closed-cycle, cryo-coolers. Passive and active cooling are integrated in a design which features V-groove radiators as used on Planck and JWST. (Right) An example approach to the Far-IR Surveyor primary mirror: the 3.5m Herschel silicon-carbide primary, prior to assembly from 8 petals (top) and as integrated into the telescope (bottom).

3.3. Observatory Cryogenics

Cooling all parts of the telescope and instrument environment to a few degrees K is essential for the excellent sensitivity, and this is a firm requirement for the FIR Surveyor. Cooling will be provided by closed-cycle helium coolers, carefully integrated into a passive cooling architecture, using staged V-groove radiators. The effectiveness of the V-groove system has been demonstrated with the ESA Planck telescope, which reached below 40 K on orbit. 4-K class space-flight coolers have been developed by industries worldwide: in the US as part of NASA's ACDTP program, and in Japan by Sumitomo. The Sumitomo 4.5 K coolers have successfully flown and are now undergoing life-cycle tests in preparation for SPICA.

A detailed thermal design will be part of the pre-decadal study, but the basic approach appears feasible. On aspect already clear is that the structure that supports the telescope for launch cannot form the thermal path once on orbit, so a breakaway truss will be required. With this assumption, a conservative estimate suggests that 150 mW of heat lift at 4 K will be ample, split roughly equally between overcoming the parasitic loads to the 4-K observatory, and supporting the sub-Kelvin coolers in the instruments. The most efficient design also employs active cooling at a state intermediate between the passive cooling floor and the cold telescope (e.g. 18–20 K), amounting to ~0.5 W for the parasitics, and perhaps another 1 W for the first stage amplifiers (see below). This can be naturally provided by Stirling stages in the US-built coolers, or as additional stand-alone coolers as in the Sumitomo architecture. The Sumitomo coolers require 2500 W supplied at the bus side per W of 4.5 K lift, or 450 W per watt at 18 K, so the total power requirement is ~1500 W, including a factor of 1.5 margin for cooler degradation through the mission life.

The system will also likely use a set of dedicated 2-K class coolers to back the sub-K cooling for the instruments. Sumitomo has demonstrated such systems in preparation for SPICA; they are essentially the same as the 4-K systems, but they use 3He as the working fluid. For most sub-K cooler architectures, the heat lift required at 2 K is a factor of ~3 lower than that at 4 K, which is about the factor by which the 2-K lift is reduced relative to that at 4 K for a given compressor power consumed.

3.4. Instrumentation and Detectors

To address the scientific goals, the primary instrumentation for the FIR Surveyor is a suite of 5-8 moderate-resolution (R~500) wideband spectrometers, which combine to span the full 35 - 500 µm range instantaneously with no tuning. The detailed arrangement of the modules in the focal plane and the degree to which multiple modules can couple to the same sky position simultaneously is a subject for the detailed study, but any given frequency channel will couple at least tens and up to 200 spatial pixels on the sky. The anticipated performance of the spectrometer suite is provided in Table 4, and the spectrometer approaches, as well as an overview of the detector and readout technologies are described in the Appendix.

Broadband imagers (cameras) are also envisioned for the FIR Surveyor. We expect that this will be particularly powerful at the shorter wavelengths where the beam is small and the confusion limit is reduced. The cameras will not drive detector sensitivity or format (they need only a few thousand detectors in each of 3-4 bands for the extragalactic surveys), so they are not discussed here, but will be addressed in the study. One key aspect to address is the potential for wide-field polarization measurements and the requirements that they impose on the imagers.

Higher-resolution direct-detection spectroscopic capability is another topic that is under consideration, will be addressed in detail in the study, but is not discussed in this document. Possibilities include etalons or Fourier-transform modules that could be placed in front of the grating backends. Both of these could offer an order of magnitude enhancement in spectral resolution. The former can be relatively compact but introduces a penalty for scanning. The latter preserves the fundamental sensitivity to within a factor of two, but will be large, particularly at the long wavelengths.

Finally, we note the desire to incorporate heterodyne spectrometer arrays. While not benefitting from the cryogenic aperture, phase-preserving spectrometers offer the only means of obtaining velocity information and detailed line profiles for Milky Way ISM studies as well as protostars and proto-planetary disks. Heterodyne arrays may be particularly compelling for a warm-mission phase, in which the telescope is passively cooled, either en route to or after the primary mission. A concept for this instrument is discussed in the Appendix.

Table 4: FIR Surveyor Spectrometer Backends (R=500)

Parameter	40 μm	120 μm	400 μm	Scaling with D_{tel}
Dominant Background	zodi. dust	zodi. dust	tel. + CMB	…
Photon-noise limited det. NEP [W $Hz^{-1/2}$]	3e-20	3e-20	4e-20	constant
Beam size [arcsec]	1.9	5.9	19	D^{-1}
Instantaneous FOV [sq. deg.]	4.0e-5	3.8e-4	2.3e-3	D^{-2}
Line sensitivity W m^{-2}, 5 σ , 1h	4.2e-21	3.3e-21	3.2e-21	D^{-2}
Point source mapping speed [deg^2 / (10^{-19} $Wm^{-2})^2$ / s]	1.6e-4	2.4e-3	1.6e-2	D^2
Surface brightness sensitivity	4.2	1.1	0.33	constant

4. FIR Surveyor Study Needed

The FIR Surveyor mission comes with the imprimatur of the *Enduring Quests, Daring Visions* NASA Roadmap, and also inherits the science priority of a US SPICA involvement as recommended by the *New Worlds New Horizons in Astronomy and Astrophysics* Decadal survey. A broad swath of the far-infrared community has now held detailed discussions to work out the general scope of the FIR Surveyor, resulting in a clear endorsement of the candidate concept described in section 3 to promote for NASA study. As defined in the January 2015 whitepaper, this study is intended to provide information for consideration by the 2020 Decadal Survey Committee, fulfilling the following objectives:

- Science case clearly outlining the mission's promise
- Design reference mission with notional payload
- Technology development needs
- Cost requirements assessment

To reach this goal, we outline the areas for focus in the study and how the study might progress. Since the science case is the primary discriminant in considerations of mission priority, this will be uppermost in the task list for the FIR Surveyor study. The range of science facilitated by the FIR Surveyor is vast and it will have profound consequences for our understanding of the Universe on all scales, from the first stars and galaxies to habitable planets. The science themes and key questions will need to be transformed into a set of detailed scientific requirements on the FIR Surveyor mission. A major example of these considerations is the proper combinations of wavelength range (especially simultaneous wavelength coverage), sensitivity, and spectral resolution needed, taking into account the number of objects, number of observations, and operational constraints that define the observing project. For certain projects, polarization capability may be important, and so the science cases that are enabled or benefited from this must be identified and assessed quantitatively. A suggested major observing project, that of a very wide field continuum survey, would require a combination of agility, field of view, field of regard, and capable detector arrays. Defining this survey is key to understanding both its scientific reach and the extent to which it drives the mission. The FIR Surveyor study will also need to consider how the mission should balance pre-defined surveys with a robust Guest Observer (GO) program. Given the range of science investigations and the depth of detail necessary to produce quantitative predictions and reliable requirements definitions, the FIR Surveyor STDT would be well served by engaging a broad segment of the far-infrared community.

To ensure that the FIR Surveyor achieves its full science potential, the study must outline the mission hardware and operational concept that best highlight its great power. First and foremost is the design of a high performance optical system, taking into account its cryogenic aspects and stray light performance. The mission concept will include the specifications of its instrument suite, including the identifications of how the focal plane is allocated and which instruments could operate in parallel. The combination of rapid surveying capability (for instance in wide field mapping, or in spectroscopy for studies of many objects across the sky) with the intrinsic limitations of field of regard implies that a fairly detailed observational scenario be worked out to understand how the mission must be operated to maximize scientific output.

While extensive analysis has been done on only a subset of the possible instrumentation suite, prior work suggests that the technology needs are well understood, and that a near-simultaneous program of maturation alongside the science mission concept will provide the Decadal committee with a balanced and prepared FIR Surveyor concept. The study should include an analysis and optimization of technology development requirements for large format arrays of sensitive detectors, capable spectrometer architectures, efficient band-covering heterodyne receivers, and of course sub-Kelvin refrigerators. Some of these technologies may require much of the rest of this decade (given recent funding levels) to advance to a state of readiness that will be convincing to the Decadal committee. A preliminary status report on a technology plan would be a beneficial very early product of the FIR Surveyor study, as the plan could permit the guiding of technology development resources in the most efficacious fashion.

A common thread in the discussion of the FIR Surveyor has revolved around the notion of a tightly controlled mission cost. It has been the intent of the FIR Surveyor workshop to envision a mission scope costing ~$1-2B, with the aim of realizing high science per dollar while maintaining a competitive cost profile. The FIR Surveyor workshop attracted participants from many NASA Centers: Ames, Marshall, Goddard, and JPL. Working in concert, these Centers can provide a wealth of technical resources to carry out all aspects of the FIR Surveyor study.

5. Appendix

5.1. Superconducting Micro-Resonator-Based Detector Arrays

Arguably the most important recent development for the FIR Surveyor is the progress in superconducting detectors based on high-Q resonators that can be multiplexed in the RF or microwave at high density (~10^3 detectors per octave of readout bandwidth on a single line). This greatly reduces the complexity of the cold wiring, and with careful design, enables an observatory with a total far-infrared pixel count in the hundreds of thousands to a million. For comparison, Herschel had a total of 3,686 far-infrared direct detectors. In particular, the kinetic inductance detector (KID) relies on thin-film microresonators that change resonant frequency as quasiparticles created by absorbed photons shift the resonators' inductance. The frequency shift may be monitored by recording the complex (amplitude and phase) transmission of an RF or microwave tone tuned to the resonant frequency. The response is linear provided changes in the loading are small. Due to the high quality factors (narrow linewidths) that can be achieved, thousands of KIDs may be read out on a single RF/microwave feed line, using no cryogenic electronics except a single cold (e.g. ~20 K) microwave amplifier.

KID performance has steadily improved, and device sensitivities are now approaching those of the SQUID-multiplexed bolometer systems in multiple groups worldwide (e.g. MUSIC and NIKA / AMKID). The best sensitivities reported to date are 4×10^{-19} W $Hz^{-1/2}$, more than sufficient for any ground-based or sub-orbital application. Further development is required to meet the requirements for FIR Surveyor spectroscopy, but there are clear pathways to improving sensitivity for low backgrounds, namely by boosting the response with smaller-volume inductors, and increasing the effective quasiparticle lifetime through the use of suspended structures. The system- level aspects are also maturing, with scientific measurements now underway with KIDs at multiple telescopes. As an example, the MAKO project is a 350 µm KID camera built by members of the Caltech / JPL detector group (Fig.11). It consists of 432-pixels read out with a single RF line, and is now operating very close to the the photon noise limit at the Caltech Submillimeter Observatory (CSO).

While the KID uses the photo-response of the resonator's inductance, another approach is to use the its capacitance to measure the density of photo-produced quasiparticles via their tunneling rate from a reservoir in which the photons are absorbed. This is the basis of the quantum capacitance detector (QCD), with roots in the technology of quantum computing. The QCD is a naturally small-volume device that is already demonstrating optical NEPs down to 2×10^{-20} W $Hz^{-1/2}$, meeting the FIR Surveyor's spectroscopy requirement.

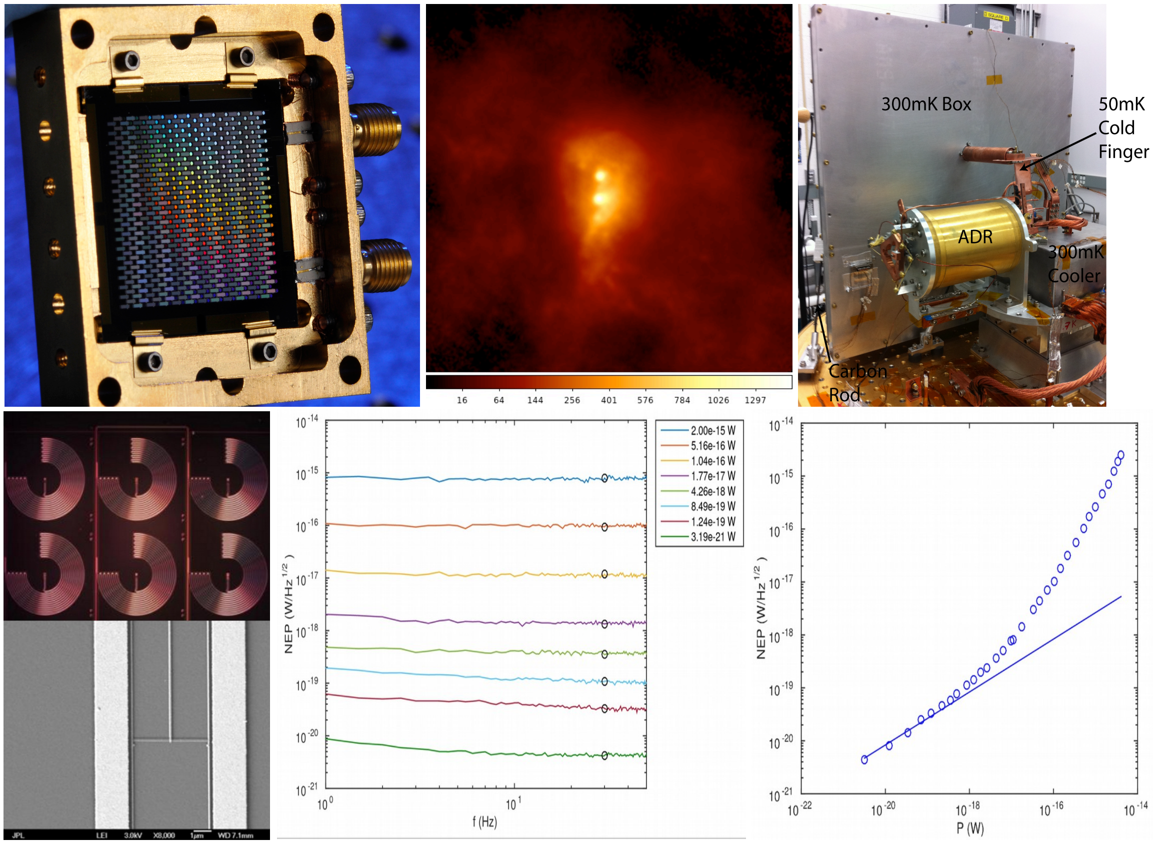

Fig. 11: Sub-Kelvin resonator-based detector technology. Above left shows the 432-pixel kinetic-inductance detector (KID) array that forms the heart of the 350-μm MAKO camera, and (center top) an image of SGR B2 obtained with MAKO at the Caltech Submillimeter Observatory (CSO). Below shows views and measured noise performance of a quantum capacitance detector (QCD). Both devices can be multiplexed in groups of ~1000 per readout line, and thus are viable detector technologies for the few-105 total pixel counts envisioned for the FIR Surveyor. The KID technology has demonstrated a high level of system maturity wtih readout, optical coupling, and operation on sky, while the QCD is already showing photon-shot-noise limited sensitivity at the very low backgrounds required for the FIR Surveyor. Top, right shows a prototype 300 mK / 50 mK cooling system which cools 10 kg with a flight-like mechanical suspension.

5.2. Readout for Micro-Resonator-Based Arrays

With resonator Qs of 10^5, 2000 devices can be arrayed per octave of readout bandwidth with negligible cross talk or frequency collisions. Assuming that a single RF line can carry 2 octaves (e.g. 100 MHz to 400 MHz), then this single line can service 4000 detectors. For each readout line, the KID or QCD readout consists of monitoring resonator frequencies with relatively straightforward, if computationally-intensive signal processing algorithms. The most important question for the space mission is the power consumption that will be required. The signal which interacts with the array must be digitized at ~500 Msamples per second, then Fourier transformed (FFT) at approximately the desired detector sampling rate, on order 1 kHz, so each FFT has on order 1 million points. The present Caltech implementation uses an FPGA on a ROACH2 platform; no effort has yet been made to reduce power consumption for this ground-based pathfinder.

The path for the FIR Surveyor and other flight systems using this type of readout will be to develop a dedicated application specific integrated circuit (ASIC) that combines the digitization, FFT, and tone extraction in a single chip. Scaling from 7-bit ASICs that have been developed, the estimated power consumption for a 2-GHz, 12-bit system that would service the 2-octave band described above is conservatively ~1W. Thus we anticipate that on order half a million pixels could be read out for a couple hundred watts of total power, well within the budget of a large mission such as the FIR Surveyor. This is an important topic for development / demonstration in the coming years.

Finally, the system requires cryogenic low-noise amplification on each readout line. The Caltech laboratory system uses silicon-germanium transistor amplifiers, they are currently operated at 4 K, but offer suitable noise temperatures at 20 K as well, so 20 K operation is feasible. As with the warm readout, little effort has been expended to reduce power consumption of these devices, but amplifiers with good noise performance have been demonstrated with 700 μW dissipation. A promising approach is a staged amplification that is integrated with the observatory cryogenic system: a low-power, moderate-gain stage at 20 K, combined with one or two higher-power, higher-gain stages closer to the warm side. At 1 mW per readout chain, the 125 amplifiers required for a 500 kilo-pixel system would dissipate 125 mW, a tractable load for 20 K (and a factor of 8 less than we assumed in our notional design).

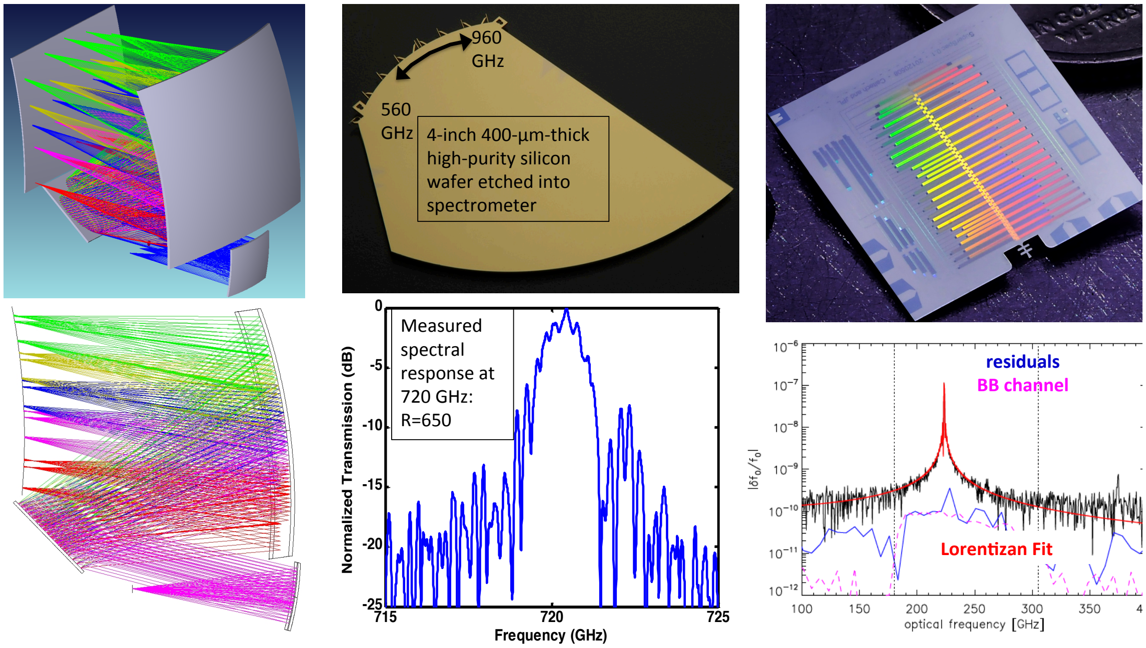

Fig. 12: Direct-detection spectrometer approaches. Left shows a conventional wide-band slit-fed echelle grating module as is envisioned for the short wavelengths. It processes a full 165-beam-long slit and a bandwidth of 1:1.5 at R=400 in a package which is ~1800λ on a side. At longer wavelengths, a more compact architecture is required, and this need has spurred development of two new approaches, both of which have demonstrated

5.3. Direct-Detection Spectrometer Modules

Grating Spectrometers: For the short wavelengths (λ < 200 μm), conventional first-order echelle gratings are a good choice, and each spectrometer will cover a bandwidth of 1:1.5, coupling to a planar 2-D array with ~200 spectral × 200 spatial pixels. Grating module sizes will range up to 30-40 cm, for example for a 130–200 μm module, with a mass less than 5 kg. An example grating module design is shown in Figure 12.

Silicon-Immersed Waveguide Spectrometers: For λ > 200 μm, conventional spectrometers become too large and bulky, so we will use waveguide spectrometers formed from high-purity float-zone silicon wafers. These devices have a size on order the resolving power R × λ/n, where n = 3.4, the index of refraction of silicon. These spectrometers build on our success with Z-Spec, and we have demonstrated R=700 operation in such a device, demonstrating that the dielectric loss is not a concern. Each spectrometer couples a single beam, but since each is 2-dimensional, they can be stacked, with detectors then arranged in 2-D sub-arrays, each coupling a frequency sub-band for all of the spectrometers in the stack. As a example, a stack of 100 grating module for 230 to 360 μm could be achieved in a package ~10 cm by 10 cm by 30 cm, with a mass of ~6 kg or less.

***Superconducting On-Chip Spectrometers*:** For the longest-wavelength FIR Surveyor bands, a superconducting chip-based spectrometer can be used. This technology consists of a filterbank circuit formed from superconducting trans- mission line lithographically patterned onto silicon with an integrated detector array. Because it is a path-folding device, the dimensions can be quite small. A complete a 200-channel wideband spectrometer 'pixel' could be packed into a thin silicon die with surface area of few square centimeters, so the chips could be arrayed into a 2-dimensional focal plane with as many as a few hundred units. Development of these filter- bank spectrometers is proceeding rapidly and a ground-based demonstration is anticipated in the next 2 years. At present the devices use niobium as the superconductor, which limits the operation to $\lambda < 380$ μm, but higher frequency operation is possible with higher-temperature superconductors, for example NbTiN, which could extend down to 200 μm. A similar capability can be provided by the μ-Spec system developed at Goddard, though this has a size similar to the silicon waveguide spectrometers for a given $\lambda \times R$ product.

5.4. Cooling the Direct-Detection Instrumentation

To enable the very low detector NEP, and insure that there is negligible optical loading from the instrument, the full spectrometer modules will likely be cooled to below 100 mK. No fundamental obstacles exist, as sub-100-mK cooling in space has been demonstrated in both Astro-H and Planck. The Astro-H soft X-ray calorimeter uses a multi-stage adiabatic demagnetization refrigerator (ADR) backed by a 1 K liquid helium bath in conjunction with closed-cycle 4-K class coolers. Planck used an open-cycle dilution refrigerator in which both ^{3}He and ^{4}He are expended. However, with an estimated total sub-K mass approaching 100 kg, the system for the FIR Surveyor will be much larger than either of these previous implementations. While some aspects could be scaled, the use of consumables is likely to be prohibitive for the FIR Surveyor system, and is undesirable as it limits the lifetime. A better approach will be a system similar to SPICA, in which the sub-K system is designed to interface with the facility 4K and 2K coolers described in Section 3.3.

One aspect that is immediately clear is that staging from the 2-K observatory heat sink, an intercept will be required at an intermediate temperature, e.g. 0.5 K. Multiple architectures are possible including closed-cycle dilution refrigerators, multi-stage adiabatic demagnetization refrigerators (ADR), and hybrid coolers using 3He sorption and ADR, as is baselined for SPICA / SAFARI. We refer the reader to a paper comparing these options, but scaling from our laboratory demonstrations and calculations for the BLISS study, we estimate that the cooler elements could require ~30% of the mass of the cold instruments, and that per 10 kg of cooled mass, they would require heat lifts at 5 mW at 4 K and 2 W at 1.7 K.

5.5. Heterodyne Instrument for the Far-Infrared Surveyor

The heterodyne instrument for the FIR Surveyor mission is driven by the demands of the high spectral resolution science program in section 2, but informed by (1) the advances in technology that already have taken place and are to be anticipated by the time that the design is frozen (5 to 10 years from now) and (2) the scientific discoveries of Herschel and the observations currently being undertaken with the GREAT and upGREAT instruments on SOFIA. We here outline a nominal instrument concept that can provide almost all of the desired observational capability, but which is technically and fiscally reasonable. The design is very flexible in that frequency bands can be added (or eliminated) and the size of the arrays can be increased or decreased without any significant overall instrument design changes. The overall design concept is based on providing:

- Maximum sensitivity for observing point sources, thus operating in dual polarizations
- Maximum mapping speed for studying extended sources and blind surveys, thus the baseline focal plane receiver arrays
- High spectral resolution (1 km/s or better) but sufficient instantaneous bandwidth to allow observations of the Galactic Center and nearby galaxies in a single spectrum, even for the highest frequency lines covered.

The architecture of the system is based on multiple arrays of individual heterodyne (mixer) frontends, each followed by a low noise IF amplifier, and with signal sent to a digital signal processor backend system. The individual mixers are based on the very successful designs developed for the Herschel HIFI instrument, but incorporating improvements made since, most notably in the upper frequency limit, instantaneous bandwidth, and in the associated local oscillator (LO) systems. Key aspects of the system architecture are

- all bands operate in dual linear polarizations

- all bands observe simultaneously, with a selected pixel co-boresighted for observation of small-angle sources. Optimum mixer designs will be selected for each band, with Superconductor Insulator Superconductor (SIS) mixers for frequencies below 1.5 THz, and Hot electron Bolometer (HEB) mixers for higher frequencies. For HEB mixers, new materials such as MgB_2 offer the possibility of increased bandwidth (up to 8 GHz) which will be particularly important for the OI line at 4.75 THz for which one gets only 63 km/s velocity coverage per GHz of IF (Fig. 13).

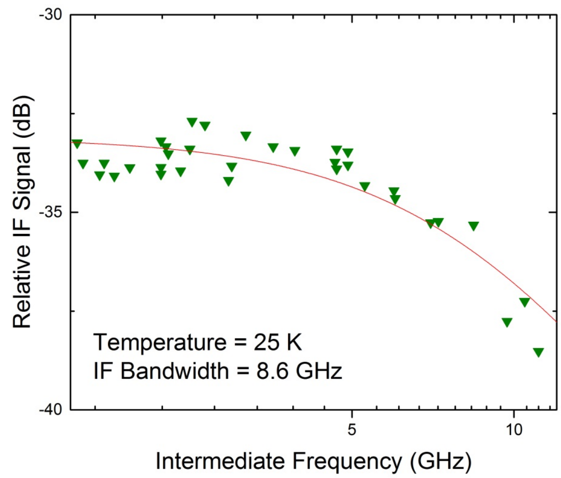

Fig. 13: Relative response curve of MgB_2 mixer showing good IF response; the -3 dB bandwidth is 8 GHz. (Figure courtesy of Dr. B. Karasik, JPL).

- Bandwidth of 8 GHz allows ~500 km/s coverage which is adequate for the Galactic Center and nearby galaxies.

- We have the option of employing balanced mixers for the lower-frequency bands, which dramatically simplifies LO injection.

- Recent development in ultra low-power IF amplifiers using SiGe transistors make it possible to cool all IF amplifiers to 4 K without excessive power dissipation, thus improving IF match and bandwidth.

- Solid state, frequency-multiplied local oscillators have advanced enormously relative to those used in Herschel/HIFI and we can now provide sufficient LO power to pump a 16 pixel array if desired, with a single chain. An example of the layout of a LO source for a 16 pixel array using a combination of shared and per pixel mutlipliers is shown in Figure 14. The Quantum Cascade Laser (QCL) has emerged as a practical LO source for highest frequency systems as demonstrated by the high frequency channel of the GREAT instrument. For the 4.7 THz band we baseline a QCL system, although frequency-multiplied LO chains are currently under development at JPL.

- A very significant recent development is affordable custom VLSI Application Specific Integrated Circuits (ASIC) which can be designed to combine important functions including digitizer, Fourier transform spectrometer, accumulator, buffer, and output interface into a single integrated circuit. Current units require less than 200 mW power and process 1 GHz bandwidth, but this is expected to increase to 6 GHz within the next year. Clearly, this capability and low power consumption (more than an order of magnitude less than the more common general-purpose Field Programmable Gate Arrays (FPGA) makes it possible to envision a submillimeter heterodyne array instrument with 100's of pixels each covering many GHz.

- From the viewpoint of many science goals for the FIR explorer, a number of spectral lines must be observed. The efficiency of such projects as well as the relative calibration accuracy achieved can be improved by simultaneous observation with receivers in different bands. While for extended sources this can be achieved by occupying adjacent positions in the focal plane, this is not applicable for point-like sources (e.g. protostellar disks and comets). The proposed receiver design is based on employing a number of Frequency Selective Surfaces (FSS), each of which transmits frequencies only above a specified cutoff frequency. The overall architecture includes first a beam switching/calibration mirror and calibration loads (similar to Herschel HIFI design), followed by a polarization grid to separate the polarizations. The signal in each linear polarization encounters a refocusing mirror followed by a FSS that transmits energy only in the highest-frequency band, which is coupled to the array of appropriate-sized feedhorns. All of the lower frequency energy is reflected, and encounters a second focusing mirror, which in turn sends it to a second FSS designed to pass signals in the second highest band, which go to the appropriate horn and mixer array. This is repeated as necessary for the number of bands required. The FSS loss in reflection is less than 1%, and in transmission only a few percent, so that the effect on the system sensitivity is very modest, and entirely acceptable when the vast increase in capability is considered. Figure 15 presents a schematic of a portion of the receiver architecture including 1 of the two polarizations of 3 of the 4 bands. Table 5 gives the key spectral lines for each band in the nominal 4-band configuration that we have examined. The fourth column is estimated double sideband noise temperature, and the fifth column is the rms single sideband antenna temperature uncertainty for a resolution of 1 km/s and a total integration time of 1 hour using position switching.

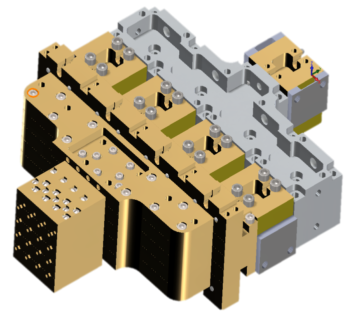

Fig.14: CAD drawing of 16 pixel LO array for 1.9 THz starting with ~75 GHz source followed by amplifiers, a frequency tripler to ~220 Ghz, and then two cascaded triplers for each pixel to derive the output power for each. The coupling to the mixers would be quasioptical. (Figure courtesy of Dr. J. Siles, JPL).

Table 5: FIR Surveyor Example Heterodyne Bands and Sensitivities

Band	Frequency (GHz)	Lines	T_n K (DSB) 1 km s^{-1}	ΔT K (SSB) 1σ, 1hr
1	490-560	[CI] $^3P_1$-$^3P_0$, HDO, $H_2{}^{18}O$,H_2O	90	0.003
2	1900-2200	[CII] $^2P_{3/2}$-$^2P_{1/2}$, [OI] $^3P_0$-$^3P_1$, CH,CO J=17-16	800	0.02
3	2600 - 2800	HD, [NII] $^3P_2$-$^3P_1$	1000	0.02
4	4500 - 4800	[OI] $^3P_1$-$^3P_2$	1000	0.02

- The system architecture is very flexible. Additional bands can be added as long as they are reasonably separated in frequency; typically a ratio of 1.25:1 between the lower end of higher-frequency band and upper end of lower-frequency band is required for good isolation. It should be possible, for example to add a band covering the 1.1-1.5 THz range that would include the $^3P_1$-$^3P_0$ [NII] transition as well as some interesting transitions of H_2O and HDO.

- Although the system does measure two linear polarizations separately, it is not designed to do spectral line polarimetry, as this capability is not called for in the science justification for the FIR Surveyor. If such measurements are more strongly indicated, the polarimetric capability could be enhanced by a rotating waveplate but this would almost certainly limit operation to a single band, and would add significant mechanical complexity.

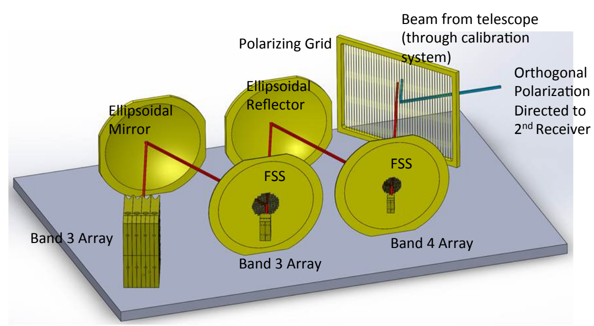

Fig. 15: Schematic of portion of the proposed instrument layout showing 3 of the 4 bands in 1 polarization (courtesy of Dr. A. Skalare, JPL).

5.6. Data Rate

Ideally, the FIR Surveyor system would be able to store fully-sampled data from all detectors at unit duty cycle. Assuming 16 bits at 100 Hz for 250 kilo-pixels creates a total raw rate approaching 0.5 Gbit per second, or 35 TBits per day. This is larger than currently-planned L2 missions which use Ka band DSN (e.g. Euclid plans 0.85 Tbits / day). Thus some form of on-board compression should be considered. Unlike optical / near-IR missions which point and stare, in the far-infrared the approach is to scan map or modulate at some frequency, so on-board processing will will require new algorithms, for cosmic-ray removal and map making / de-modulation.

Optical communications are a promising solution to the FIR Surveyor downlink challenge. The higher gain provided by the shorter-wavelength translates into a large increase in data rate for a given mass and power relative to a Ka band system, and this technology has been progressing steadily. In the last 2 years, NASAs Lunar Laser Communication Demonstration (LLCD) demonstrated successful laser communications including downlink at 622 Mbits / sec between a satellite in lunar orbit, the Lunar Atmosphere and Dust Environment Explorer (LADEE), and ground stations on the Earth. Optical communications is being pushed by the Planetary Division, and is featured in the coming call for Discovery mission proposals. L2 is particularly well-suited to optical communications, since L2 is always in the night sky. A baseline design, consistent with optical-communications development targets begins with an existing concept for a Deep-space optical Transceiver (DOT) that is now baselined for the Discovery mission – it is essentially a 22-cm telescope coupled to a few-W laser. The transmit power required depend on the collecting area of the receiver. NASA is considering a 12-meter class receiver on the timescale of 2025 to support deep space communications, but this would probably not be required for the FIR Surveyor at L2. For 1 Gbit / sec at L2, a 1-meter receiver requires 14 W of transmit power, but with a 3-meter receiver, the transmit power is a more reasonable 1.6 W, making the full system less on order 100 W including the actuation. Thus dedicated 3-meter class receivers at 1–2 sites could achieve data rates in excess of 14 Tbits/day with only 4 hours of downlink, corresponding to the full data rate from the FIR Surveyor with only modest on-board compression.