

A Cryogenic Telescope for Far-Infrared Astrophysics: A Vision for NASA in the 2020 Decade

A white paper submitted to NASA's Cosmic Origins Program Office

C.M. Bradford^{*1,2}, P.F. Goldsmith¹, A. Bolatto⁴, L. Armus^{2,3}, J. Bauer^{3,1}, P. Appleton²,
A. Cooray^{5,2}, C. Casey⁵, D. Dale⁶, B. Uzgil^{7,2}, J. Aguirre⁷, J.D. Smith⁸, K. Sheth¹⁰, E.J. Murphy³,
C. McKenney^{1,2}, W. Holmes¹, M. Rizzo⁹, E. Bergin¹¹ and G. Stacey¹²

¹Jet Propulsion Laboratory

²California Institute of Technology

³Infrared Processing and Analysis Center, Caltech

⁴University of Maryland

⁵University of California, Irvine

⁶University of Wyoming

⁷University of Pennsylvania

⁸University of Toledo

⁹Goddard Space Flight Center

¹⁰NRAO, Charlottesville

¹¹University of Michigan

¹²Cornell University

May 1, 2015

Abstract

Many of the transformative processes in the Universe have taken place in regions obscured by dust, and are best studied with far-IR spectroscopy. We present the Cryogenic-Aperture Large Infrared-Submillimeter Telescope Observatory (CALISTO), a 5-meter class, space-borne telescope actively cooled to $T \sim 4$ K, emphasizing moderate-resolution spectroscopy in the crucial 35 to 600 μm band. CALISTO will enable NASA and the world to study the rise of heavy elements in the Universe's in the first billion years, chart star formation and black hole growth in dust-obscured galaxies through cosmic time, and conduct a census of forming planetary systems in our region of the Galaxy. CALISTO will capitalize on rapid progress in both format and sensitivity of far-IR detectors. Arrays with a total count of a few $\times 10^5$ detector pixels will form the heart of a suite of imaging spectrometers in which each detector reaches the photon background limit.

The Far-IR Science Interest Group will meet from 3–5 June 2015¹ with the intention of reaching consensus on the architecture for the Far-IR Surveyor mission. This white paper describes one of the architectures to be considered by the community. One or more companion papers will describe alternative architectures.

*bradford@caltech.edu

¹<http://conference.ipac.caltech.edu/firsurveyor/>

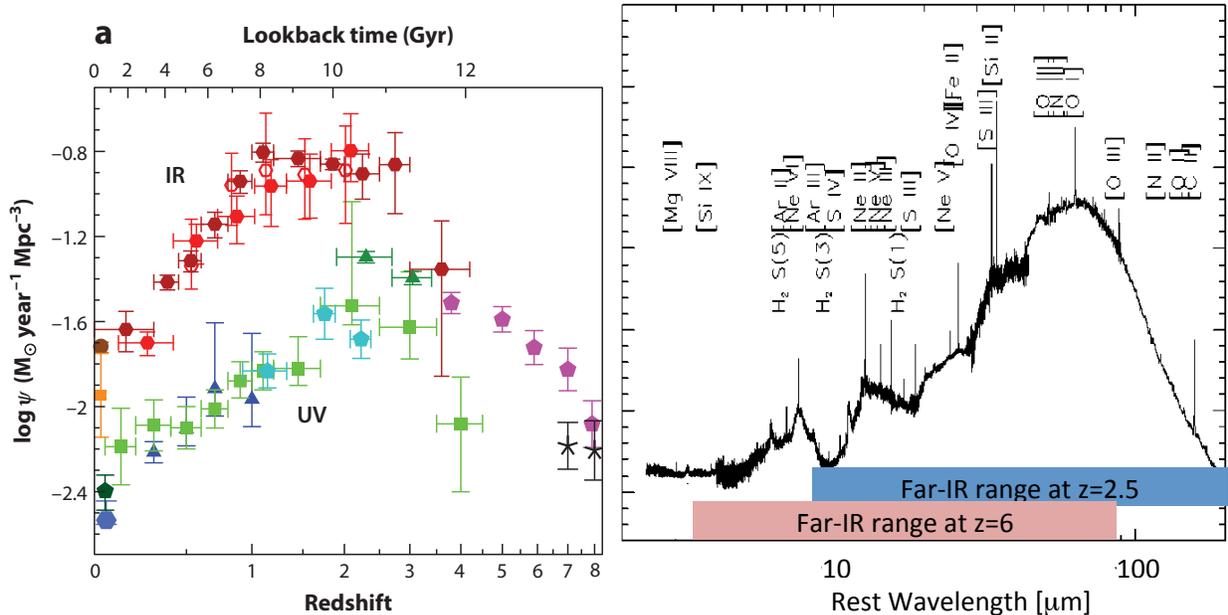


Figure 1: LEFT Cosmic star formation rate history as measured in the rest-frame ultraviolet, and far-infrared, reprinted from Madau & Dickinson, 2014 [43]. Red points are from Spitzer and Herschel, green and blue from rest-frame UV surveys. Purple points are from the Bouwens et al. [7, 6] based on deep Hubble fields using dropout selections. Right: Full-band spectrum of Circinus, a nearby galaxy with an active nucleus obscured by dust, obtained with the Infrared Space Observatory (ISO) [25, 49, 62]. This shows the range of ionized, atomic, and molecular gas cooling lines originating deep in the obscured core of the source. (Vertical axis is λF_{λ} , major ticks $5 \times 10^{-12} \text{ W m}^{-2}$.)

1 Introduction, Motivation

After the Cosmic Microwave Background (CMB) is accounted for, the remaining cosmic background light is the integrated emission from all stars and galaxies through cosmic time. The spectrum of this cosmic background shows two broad peaks with comparable observed flux density, one at $\sim 1 \mu\text{m}$, and one at $\sim 150 \mu\text{m}$. The long-wavelength component, called the Cosmic Infrared Background (CIB) [23, 19], is radiation from dust heated by stars or accreting black holes. Its prominence is a simple consequence of the fundamental link between the star formation and its fuel: the interstellar gas with obscuring dust. We now have strong evidence that most of the energy that has been produced by galaxies through cosmic time has emerged in the far-IR [53, 43]. The typical UV/optical photon from a young star has been absorbed by dust and re-radiated (see Figure 1). In general, rest-frame ultraviolet and optical-wavelength light does not access the obscured regions that dominate the activity in galaxies. Similarly, in nearby galaxies and in our own Milky Way, star-forming cores, embedded young stars, and protoplanetary disks all cool primarily through the far-infrared.

The spaceborne Spitzer and Herschel observatories have demonstrated the importance of the far-IR waveband, but it is only with sensitive spectroscopic capability that astronomers will have the opportunity to study in detail the inner workings of galaxies at cosmological distances and late-stage forming planetary systems. This capability has not yet been realized because it requires a combination of a cold telescope and very sensitive direct detectors. After 2 decades of development of superconducting detectors, and with the system-level experience gained with previous-generation cryogenic satellites, we are now in a position to field CALISTO, a large space telescope actively cooled to a few degrees K with $\sim 10^5$ individual far-IR detector pixels, each operating at the fundamental sensitivity limit set by the astrophysical background. This paper builds on the concept for CALISTO presented late last decade [26, 10]; it will be a large facility-class observatory launched to an earth-sun L2 halo orbit with at least a 5-year design lifetime. The key advance in the last decade is the progress in far-IR detector technology.

2 Motivation for Sensitive Wideband Far-IR Spectroscopy

The sensitive CALISTO platform is especially compelling for wideband spectroscopy, as Figure 2 shows and Table 1 presents. CALISTO will obtain full-band spectra of thousands of objects ranging from the first dusty galaxies to the most heavily enshrouded young stars and proto-planetary disks in our own Galaxy, as well as blind discovery of thousands more. These CALISTO spectra will directly address several key goals of modern astrophysics:

- 2.1 Measure the onset of heavy elements and the rise of organic molecules in the Reionization Epoch.
- 2.2 Chart the true history of cosmic star formation and its connection to supermassive black hole growth.
- 2.3 Measure clustering and total emission of faint galaxies below the individual detection threshold using tomographic intensity mapping of the far-IR emission lines.
- 2.4 Probe the cycling of matter and energy in the Milky Way and nearby galaxies.
- 2.5 Conduct a census of gas mass and conditions in protoplanetary disks throughout their evolutionary sequence.
- 2.6 Assess the origin, transport and cooling role of water in sources ranging from the solar system to distant galaxies.

2.1 The Reionization Epoch: the Rise of Heavy Elements and Dust

As the Universe is enriched from primordial H_2 to a medium which contains heavy elements and dust grains, the key cooling pathways shift from the quadrupole pure rotational H_2 lines (28, 17, 12, 9.7, 8.0, 6.9... μm) to a combination of the fine-structure transitions and the dust. CALISTO will probe all phases of this transition. For metallicity above $\sim 10^{-4}$ solar, fine-structure lines are believed to become more important than H_2 for gas cooling [54]. However, surprisingly powerful H_2 emitters (e.g., Stephan’s Quintet, Zw3146, and the $z=2.16$ ‘Spiderweb’ protocluster) have been found at low-redshift with Spitzer [50, 1, 16, 21, 52, 51]. Sources like Stephan’s Quintet may be analogs of early-Universe shocks produced in galaxy formation and AGN feedback, when dust and metals are emerging from the first cycles of enrichment. *For $z \sim 5-10$, the H_2 lines are redshifted into the far-IR, and remarkably, sources like Zw3146 and the ‘Spiderweb’ would be detectable in their H_2 lines with CALISTO even at $z \sim 8-10$.*

Once heavy elements are in place, the rest-frame mid-IR dust features may actually be the most practical probe of heavy elements at early times due to their large equivalent widths. Dust is believed to form as the first heavy elements are created, for example in pair-instability Population III supernovae remnants, and Spitzer has shown that the dust features are often the brightest features in the spectra of galaxies at all wavelengths. In particular, the polycyclic aromatic hydrocarbon (PAH) features at 6.2–17 μm are unambiguous, with to $15\times$ more power than the brightest atomic cooling lines, and act as sensitive probes of heavy element abundance for metallicity <0.2 [22]. Like the H_2 lines, most features are redshifted out of the JWST band, but not into the ALMA windows in the $z \sim 5-10$ era. CALISTO can detect these powerful bands at early epochs (Fig. 2), thus probing the transition from primordial H_2 to heavy-element cooling in the Universe’s first Gyr.

We refer the interested reader to white papers by Appleton et al., and Cooray et al. for further discussion on these aspects.

2.2 Charting the Cosmic History of Star Formation and Black Hole Growth

Far-IR and submillimeter continuum imaging surveys are now revealing cosmologically-significant populations of high-redshift galaxies which are so highly obscured that they emit nearly all of their energy in the mid-IR through submillimeter. These datasets, as well deep X-ray surveys show that much of the formative growth of stellar populations and black holes has been deeply obscured by dust for the bulk of the Universe’s history, and thus inaccessible to astronomers’ traditional diagnostic toolkit: rest-frame optical spectroscopy. With its excellent spectral sensitivity in the 35–600 μm band, CALISTO brings a powerful new toolkit to bear on these high-redshift galaxy populations: the rest-frame mid- to far-IR, where the dust becomes optically thin, and the dominant interstellar coolants lie (Fig. 1, right). CALISTO spectra of distant galaxies will:

- Provide an unambiguous redshift, or look-back time for each galaxy.
- For each, determine the total star formation rate in the galaxy and infer a spatial scale of the buried starburst regions [60] by comparing the intensities of the atomic gas coolants— Si^+ , C^+ , and O^0 —with the total far-IR continuum intensity. (The star formation extent may or may not be related to the spatial extent of the molecular gas reservoir which will be directly imaged with ALMA.) In aggregate, these measurements chart the time history of dust-obscured stellar power output, .
- Estimate the top end of the stellar mass function via its effect on the UV field and the resulting ionization structure reflected in the fine-structure lines of ions: O^{++} , Ne^{++} , N^{++} , S^{++} , and N^+ , Ne^+ .

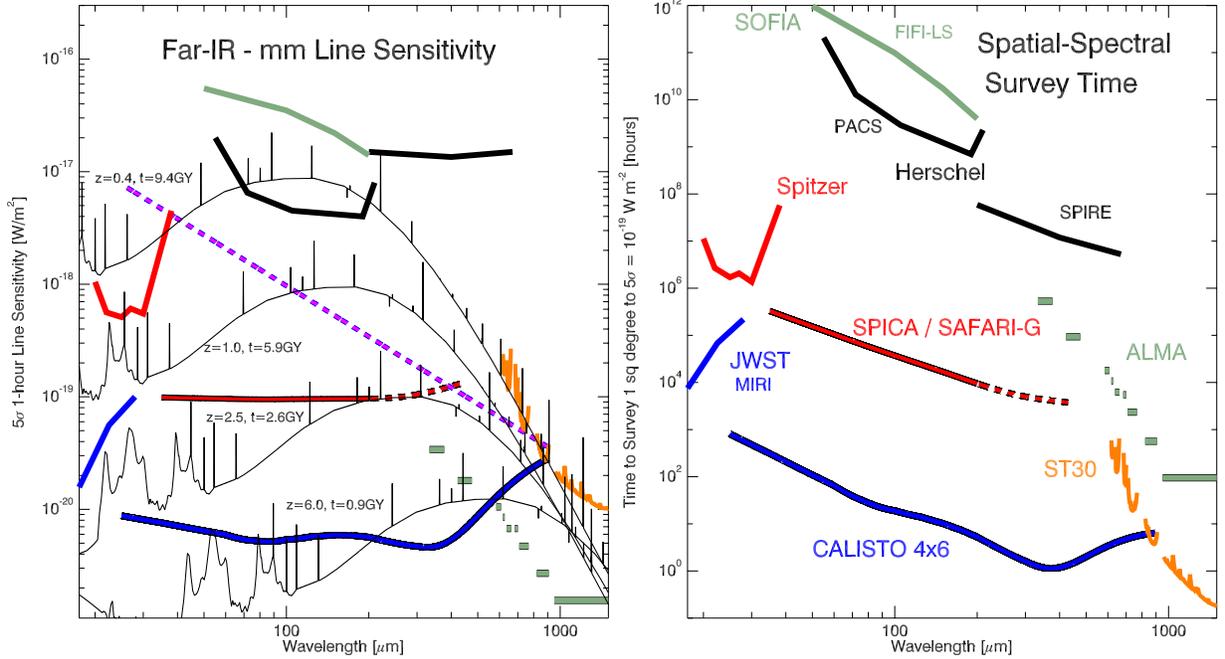


Figure 2: Spectroscopic sensitivities in the far-IR and submillimeter. Left shows the sensitivity in W m^{-2} for a single pointed observation. Galaxy spectra assuming $L = 10^{12} L_{\odot}$ at various redshifts are overplotted using light curves, with continuum smoothed to $R=500$. The magenta dashed line shows the sensitivity of a quantum-limited heterodyne receiver ($T_{\text{sys}}=h\nu/k$) in a bandwidth of 10 km/s. The right panel shows the speed for a blind spatial-spectral survey reaching a depth of 10^{-19}W m^{-2} over a square degree, including the number of spatial beams and the instantaneous bandwidth. CALISTO 4x6 refers to the baseline configuration, assuming $R=500$ grating spectrometers with 100 beams (a conservative figure) and 1:1.5 instantaneous bandwidth. Detectors are assumed to operate with $\text{NEP} = 2 \times 10^{-20} \text{W Hz}^{-1/2}$, a figure which has been demonstrated in the lab. The SPICA / SAFARI-G curve refers to the new configuration: a 2.5-meter telescope with a suite of $R=300$ grating spectrometer modules with 4 spatial beams, and detectors with $\text{NEP}=2 \times 10^{-19} \text{W Hz}^{-1/2}$. ST30 represents a 30-meter class wide-field submillimeter telescope in the Atacama, such as CCAT, equipped with 100 spectrometer beams, each with 1:1.5 bandwidth. ALMA band averaged sensitivity, and survey speed based on 16 GHz in the primary beam.

- Where present, directly measure the highly-ionized gas around the AGN itself with fine-structure transitions of high-ionization-state species such as Ne^{4+} and O^{3+} (ionization potential of 97 & 54 eV, respectively).
- Probe the warm ($\sim 1000 \text{K}$), dense (10^7cm^{-3}) molecular torus believed to exist around AGN. — a likely way-point as material is funneled from the host galaxy down to the accretion zone. It is expected to emit strongly in the high-J CO rotational transitions ($\lambda_{\text{rest}} \sim 50\text{--}80 \mu\text{m}$), easily detectable with CALISTO to $z=5$.
- In aggregate thereby track the fraction of energy release due to accretion and its relationship to the star-formation history.

Further information can be found in the Armus et al., whitepaper.

We emphasize that the excellent sensitivity of CALISTO is essential for these distant-galaxy measurements. Charting a complete history requires study of galaxies before, during, and since the putative era of peak star formation and black hole growth 2–6 Gyr after the Big Bang. To reach the first Gyr of the Universe ($z=6$) in the spectral probes demands a line sensitivity below 10^{-20}W m^{-2} , which in the far-IR is only achieved with an actively-cooled telescope and an optimized dispersive spectrometer as baselined for CALISTO. CALISTO will be used in 2 ways. 1) The instantaneous wideband coverage permits rapid follow-up of individual sources of interest, discovered for example with ground-based submillimeter continuum surveys, LSST, JWST or Euclid. 2) The simultaneous spatial multiplexing enables blind spatial / spatial surveys, which will discover many line-emitting sources blindly (on order 3–30 per 1-hour pointing) as well as reveal the underlying 3-D clustering of undetected sources in the residual signal.

Table 1: CALISTO Spectrometer Backends: R=500 Strawman Design

Parameter	40 μm	120 μm	400 μm	Scaling w/ D_{eff}
Dominant background	zodi dust	zodi. + gal. dust	tel. + CMB	...
Photon-noise limited NEP [$\text{W Hz}^{-1/2}$]	3e-20	3e-20	4e-20	...
Beam size	1.9''	5.9''	19''	$\propto D^{-1}$
Instantaneous FOV [sq deg]	4.0e-5	3.8e-4	2.3e-3	$\propto D^{-2}$
Line sensitivity W m^{-2} , 5σ , 1h	4.2e-21	3.3e-21	3.2e-21	$\propto D^{-2}$
Pt. sce. mapping speed [$\text{deg}^2 / (10^{-19} \text{W m}^{-2})^2 / \text{sec}$]	1.6e-4	2.4e-3	1.6e-2	$\propto D^2$
Surface bright. sens. per pix [$\text{MJy/sr } \sqrt{\text{sec}}$]	4.2	1.1	0.33	$\propto D^0$

Notes: Sensitivities assume single-polarization instruments with a product of cold transmission and detector efficiency of 0.25, and an aperture efficiency of 0.75. FOV estimate assume slit widths of $165 \lambda/D$ for the 40 and 120 μm examples, and 100 individual spectrometer backends for the 400 μm case.

2.3 Tomographic Intensity Mapping: Measuring Clustering and Absolute Cosmic Line Intensities.

In addition to studying individual galaxies, the large-throughput wide-band spectrometers on CALISTO will carry out blind 3-D intensity mapping, or tomography, using the bright far-IR fine-structure transitions described above (especially NeII, OI, OIII and (for $z < 2$) CII). This is an emerging technique that has grown out of the 21-cm tomography experiments and instruments targeting early-Universe CO and CII from the ground are now under development. As outlined in Visbal & Loeb 2010 [67, 68], Gong et al., 2011, 2012, 2013 [29, 28, 27], and Uzgil et al., 2014 [66] these datasets will reveal 3-D clustering due to large scale structure, even when individual galaxies are not detected. The amplitude of the clustering signal is the product of the galaxy to dark matter bias and the total mean intensity of a given spectral feature. With reasonable assumptions about the bias, this measurement can then can thus probe the total cosmic luminosity of each of the fine-structure transitions as a function of time, with a built-in redshift precision not available to the continuum surveys. It is a promising approach both for assessing the contributions of faint galaxies, particularly important early in the Universe's history. For good sensitivity to the large-scale signal, mapping over $\sim 1-2$ square degrees, with large depth in redshift provided by the spectrometer is sufficient; as Table 1 shows, this is possible for CALISTO with the high-throughput spectrometer.

2.4 Galaxy Archeology and Cycling of Matter in the Milky Way and Nearby Galaxies

Observations of the distant Universe are, by necessity, interpreted in the context of the Milky Way and nearby galaxies. These provide the windows into the details of the astrophysical processes that drive galaxy evolution: cycling of matter between stars and the interstellar medium (ISM), self-regulation of star formation, formation of stars on galaxy scales, and feedback from central AGN. With its exquisite surface brightness sensitivity (Table 1, 5th row), CALISTO will provide unparalleled mapping speed for integrated line and continuum emission with useful angular resolution (e.g. 8'' at 158 μm gives 300 pc resolution at 10 Mpc, or 1 kpc resolution at 25 Mpc). As noted above, the 35 to 600 μm region of the spectrum has a number of key transitions for the cooling of the neutral and molecular gas and the probing of ionized material: namely the bright fine structure transitions of [CII], [OI], [NII], [OIII], possibly [CI] (depending on the long-wavelength cutoff) and CO and H₂O among others.

PACS on Herschel gave us a flavor for the type of science that these observations enabled, but it was limited by the low mapping speed and sensitivity. The sensitivity of CALISTO will be a huge leap forward. The surface brightness sensitivity is independent of beamsize (thus telescope aperture) and can be translated directly into column density sensitivity for a given species if the gas excitation known (e.g. Crawford et al., 1985 [17], Madden et al., 1997 [44]). For example, for [CII] in atomic gas at $T = 100 \text{ K}$, $n_{\text{H}} = 10 \text{ cm}^{-3}$ (so [CII] is sub-thermally excited), CALISTO can detect (5σ) a column of $N_{\text{H}} = 1.8 \times 10^{19} \text{ cm}^{-2}$ in 100 sec. A similar result is obtained for ionized gas with an electron density of only 0.05 cm^{-3} (so [CII] is again sub-thermal). Denser gas is of course much easier to detect per unit column density. This sensitivity is multiplexed both spatially (~ 100 beams) and spectrally (full-band coverage), so that by rastering CALISTO's multi-beam spectrographs, it will be possible to map large regions in the Galaxy, and *thousands* of nearby galaxies in key far-IR transitions. The speed could be increased further if only one or a few individual lines are desired by using a dedicated Fabry-Perot type spectrograph coupling 2 spatial dimensions (so \sim several thousand beams).

For galaxies, the resolution will be comparable to what the VLA obtains for HI, though column density sensitivity

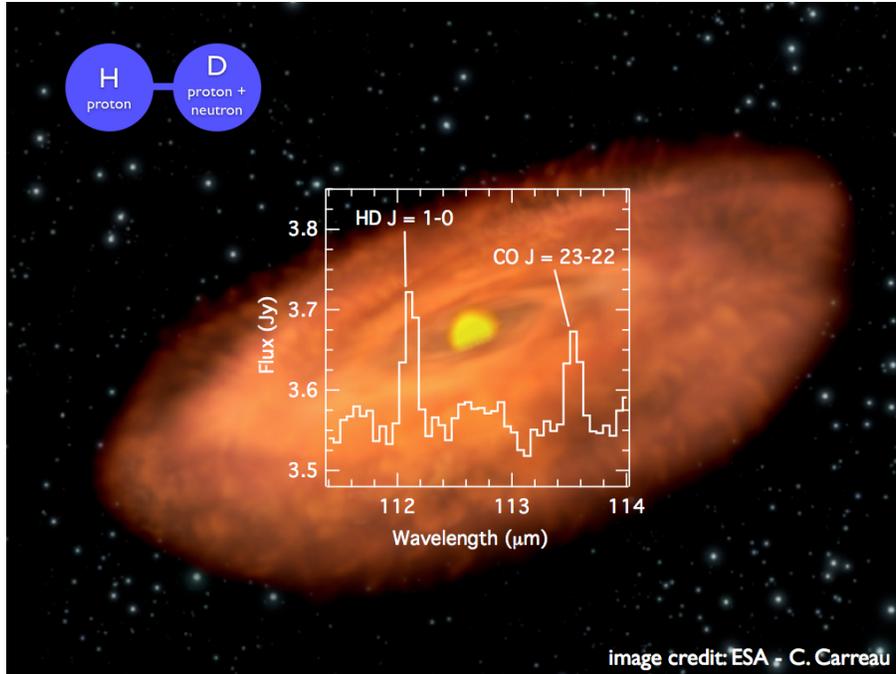


Figure 3: Hydrogen deuteride (HD) detected in the TW Hya protoplanetary disk, superposed on an artists conception of a young gas-rich disk. While not the strongest feature in the spectrum, HD is an excellent tracer of total molecular hydrogen mass, and CALISTO will be able survey HD as well as other key coolants in hundreds to thousands of such systems at various evolutionary stages reaching kilo-parsec distances.

is much better than the VLA at this resolution; it is a better match to the anticipated sensitivity of the SKA on this timescale. These measurements will provide a broad range of physical information such as metallicity indicators, radiation field estimators (from dust and line emission), and gas heating measurements. The maps will also reveal galaxy-scale galactic outflows in ionized species such as [CII], as well as faint outer disks and extra-planar structures.

2.5 Planetary-System Formation in the Milky Way: Gas in Disks

The evolution of circumstellar disks and their **gas** component is key to planet formation. Disks rapidly evolve from the primordial gas-rich phase to planetary systems largely devoid of gas. Even small amounts of residual gas at late stages can affect the settling and radial drift of dust grains, planetary migration, and eccentricity evolution. It is thus crucial important for understanding the formation of both terrestrial and Jovian worlds [64, 69, 38, 36]. Spitzer has detected many atomic, ionic and molecular gas emission lines that arise from the inner 1–20 AU regions of disks, but as Herschel has shown, the bulk of the disk mass is in the outer disk that emits primarily in the far-IR. The various emission lines in the CALISTO band originate from different regions of the disk and will trace the gas properties of disks as they evolve, form planets and eventually dissipate. In particular, the rotational fundamental of HD ($\lambda=112 \mu\text{m}$) has recently been shown using the Herschel PACS spectrometer to be a robust tracer for total gas mass in the closest planet-forming disk system [4]. HD is a direct analog to H_2 with similar chemistry and, with a small dipole moment, is emissive at the characteristic temperatures of the main disk mass reservoir.

Greater sensitivity is crucial for a full census of the evolutionary phases. Herschel was limited to the local ($d < 150 \text{ pc}$) star-forming environments where only low-mass star formation occurs. Only a small HD survey has been undertaken, producing 3 significant ($>3\sigma$) detections out of 7 systems. CALISTO will be approximately 1000 times more sensitive than Herschel PACS, thus probing the same source at $\sim 30\times$ larger distances (so for example $>1 \text{ kpc}$ for the TW Hya system shown in Figure 3), in total some $30,000\times$ larger volume. CALISTO will thus have access to many dense young clusters in giant molecular clouds, the dominant sites for low and high-mass star (and likely planet) formation.

Table 2: CALISTO Approximate Confusion Limits and Mapping Speeds

λ μm	Herschel σ_C mJy	estimated σ_C mJy	νL_ν z=2 L_\odot	νL_ν z=5 L_\odot	NEF _{inst} mJy \sqrt{s}	5 \times time s	5 \times time per sq deg h
50 μm	0.016	0.004	2.9e9	2.6e10	0.015	70	15
100 μm	0.15	0.038	1.3e10	1.2e11	0.024	2.1	0.11
200 μm	1.39	0.35	6.1e10	5.5e11	0.051	0.11	1.4e-3

Notes: Herschel σ_C values are based on a power law implied by the 100 and 160 μm map RMS values in PACS deep fields (Magnelli et al., 2013 [45]). We simply reduce this by a factor of 4 to obtain an estimated σ_C for CALISTO. Luminosity densities are then provided for 5 \times this depth, for z=2 and z=5. NEF_{inst} is the raw instrument sensitivity. Times to confusion limit are conservatively estimated at 5 \times the time required for the instrument per-beam RMS to equal σ_C . The time to a square degree assumes a 4000-beam camera.

2.6 Water in the Cosmos

Water is important both for its obvious astrobiological significance and because it is a critical coolant of star-forming gas. Recent Herschel observations have revealed water to be present in an enormous variety of regions in the solar system including asteroids (Ceres [39]), satellites (Enceladus [33]), comets, and planetary atmospheres (Jupiter [13]). The Herschel measurement of a deuterated to normal water abundance in comet 103P/Hartley2 identical to that on Earth [32], in comet 45P/Honda consistent with the Earth’s value [42], but a much higher value measured by Rosetta in comet 67P/ChuryumovGerasimenko [41] has dramatically renewed interest in the role of cometary impacts for the origin of the Earth’s oceans. The only way to make progress in this important area is to observe a significant statistical sample of comets of different types, as well as other primitive bodies in the solar system. This will require very high spectral resolution, and heterodyne instrumentation is optimal. In particular, a modest heterodyne focal plane array covering the frequencies of appropriate H_2^{18}O and HDO lines will be valuable as closer comets will be extended objects in CALISTO’s beam.

In the Galaxy, water has been studied in a variety of interstellar regions by SWAS and Odin, with the general conclusion that it’s abundance is low in the ISM. The much higher angular resolution and sensitivity of Herschel’s HIFI instrument has shown that water can be a uniquely powerful tracer of the collapse of dense cores [37]. Extension of this work to even higher angular resolution and sensitivity should enable determination of the full three-dimensional velocity field in a star-forming core. Very high spectral resolution is optimal for this work—Herschel for example detected a *single* protostellar disk (TW Hydrae) in water, but with a line width of only 1.5 km/s [34]. A small heterodyne array operating at the frequencies of one (or more) of the lower water transitions is thus the ideal instrument here as well. The result would be a major, fundamental advance in understanding how stars and planets are formed. With higher sensitivity it should be possible to survey many nearby disks and determine their gas-phase water content.

Finally, we now know that water is the second-strongest molecular line emitter in nearby galaxies [70]. Existing data are all unresolved spectrally, but indicate the importance of water vapor as a tracer of shocks and as a coolant of dense gas. The ground state (557 GHz) water line has not been observed (the atmosphere is opaque even from the Atacama for redshift less than 0.02, or 6000 km/s) but is expected to be very intense. With beamsizes of a few arcseconds, the CALISTO spectrometers can map the water emission from nearby galaxies with sufficient sensitivity and angular resolution to probe of their spiral density wave structure, shocks, and star formation.

3 Wide-Field Continuum Mapping

While not the primary thrust of this paper, CALISTO is also very sensitive platform for continuum mapping, particularly at the short wavelengths where the confusion limit can be fairly deep. The deep confusion limit combined with the speed provided by low background platform enables surveys of large areas of sky to interesting depths. Table 2 shows the estimated confusion RMS, obtained by simply reducing the Herschel PACS measured confusion limit (Magnelli et al., 2013 [45]) by a factor of 4. This is a conservative since at these fluxes, the counts are becoming shallow, allowing the depth to be increased quickly with reduced beamsize. Some estimates suggest that the 100 μm confusion limit is 10 \times deeper at 5-m than at 3.5 m (see the white paper by Caitlin Casey et al. in this submission). The last two columns in Table 2 show 5 \times the integration time to reach this estimated confusion RMS, first per beam, and then per square degree, assuming a modest 4000-beam camera. The factor of 5 insures ample margin in the time estimate, and assures that instrument noise is sub-dominant to confusion. At 100 μm , the 38 μJy depth corresponds to a Milky-Way type galaxy at z=2, well below the knee in the luminosity function for the peak of SF activity; this means that the bulk

of the light is thus resolved into sources. The speed in this band is impressive; a full sky survey at $100\ \mu\text{m}$ looks to be within reach in a ~ 4000 hour survey with the strawman 4000-beam camera.

For nearby galaxies and the Milky Way, the continuum sensitivity at the short far-IR wavelengths is a powerful probe of tiny amounts of interstellar dust, complementing the gas-phase disk and ISM studies described above. At the distance of the Magellenic Clouds, for example, the sensitivity translates to 10^{-3} earth masses of dust. This opens the possibility to carry out an essentially *complete survey of extragalactic debris disks around solar-type stars in the Clouds*.

3.1 Origin and Evolution of the Solar System studied with Trans-Neptunian Objects

Finally, we highlight a unique capability that CALISTO imaging provides for study of our Solar System’s origins. The majority of small bodies in the solar system reside between 30 and 50 AU and are referred to as the Trans Neptunian Objects, or TNOs. These minor planets represent material from the origin of the solar system, unmodified by its subsequent evolution. They are the source of the short-period comets which deliver volatile materials to the inner solar system [3]. TNO orbital inclinations can be impacted by resonances with Neptune, and a census of TNO positions and orbital motions out to 100 AU provides information about the dynamical history of the outer solar system. These measurements have been difficult with optical-wavelength detection techniques, as the albedos can be small. With its excellent sensitivity in the deep thermal IR (e.g. $\sim 100\ \mu\text{m}$), CALISTO can probe the thermal emission of TNOs directly, reaching for example 140 km objects at 100 AU, deeper than existing optical surveys. Increased depth should be possible by looking for objects which move from observation to observation in a given field; this should overcome the confusion limit. A second aspect to consider is the ability to detect halos of dust or possibly gas, some theories point to sublimation driven by CO even at several tens of AU [47]. Any such measurements of early cometary activity would constrain mass-loss rates, and the abundance of rarely-observed extremely-volatile species that may be relatively depleted in short-period comets

4 Architecture Choice

The scientific goals outlined above require excellent spectroscopic sensitivity, both for point sources and mapping, with full coverage between the $28\ \mu\text{m}$ cutoff of JWST MIRI and the onset of the ground-based windows at $\sim 600\ \mu\text{m}$. Accessing the earliest galaxies and most-evolved lowest-mass protoplanetary systems requires a line sensitivity of $10^{-20}\ \text{W m}^{-2}$, large instantaneous bandwidth, and moderate spectral resolving power ($R = \delta\lambda/\lambda \geq 500$). The requirement for ultimate sensitivity demands maximum collecting area, low telescope background, and high efficiency. Blind spectroscopic surveys over large fields will also be a part of the program, so the observatory must have enough throughput ($A\Omega$) to make use the large-format array technology now available. These crucial attributes are summarized in Table 3.

Collecting area per unit cost is maximized with a monolithic-aperture telescope, particularly since the entire telescope and instruments will be actively cooled. A single-dish telescope also naturally accommodates a wide range of instruments, for example the broadband imaging arrays, heterodyne receiver arrays, 2-D imaging spectrometers such as Fabry-Perot interferometers.

Table 3: CALISTO Basic Parameters

Parameter	Value
Telescope Temperature	$<4\ \text{K}$
Telescope Diameter	$\sim 5\ \text{m}$
Telescope Surface Accuracy	$1\ \mu\text{m}$
Telescope Field of View	1 deg at $500\ \mu\text{m}$
Instrument Temperature	50–100 mK
Total Number of Detectors	$1\text{--}5 \times 10^5$
Heat Lift at 4 K	$\sim 150\ \text{mW}$
Heat Lift at 20 K	$\sim 2\ \text{W}$
Data Rate	tbd

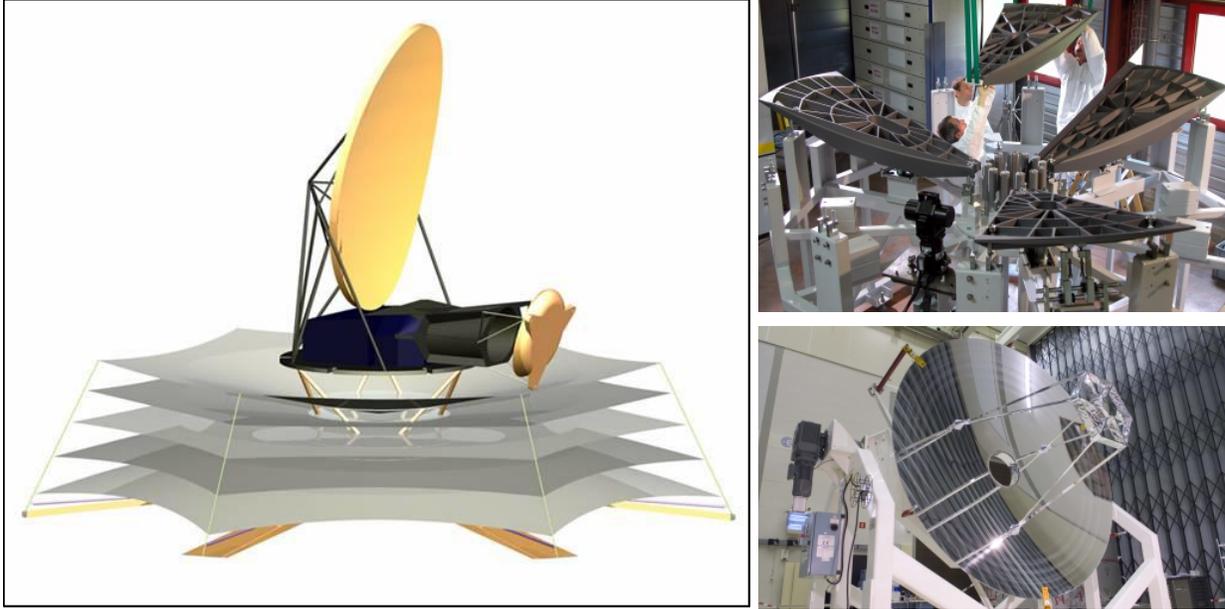


Figure 4: Left: CALISTO concept. 5-meter class telescope is actively cooled with closed-cycle coolers to ~ 4 K. Passive and active cooling are integrated in a design which features V-groove radiators as used on Planck and JWST. Right: Large cold telescope heritage: the 3.5-meter Herschel silicon carbide primary mirror, prior to assembly from 8 petals and figuring, and as integrated into the telescope.

5 Observatory and Telescope

5.1 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 CALISTO. Cooling will be provided by closed-cycle helium coolers, carefully integrated into a passive cooling architecture which uses 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. One aspect already clear is that the structure which supports the telescope for launch can not form the thermal path once on orbit, so a breakaway truss will be required. With this assumption, a conservative strawman estimate suggests that 150 mW of heat lift at 4 K will be ample, split roughly equally between overcoming the parasitics 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), to the tune of ~ 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.

5.2 Telescope Design

The detailed design of the CALISTO telescope is a key aspect of our proposed study. An example configuration is our point design described in Goldsmith et al., 2008 [26], and shown in Figure 4. This design features a 4×6 -meter monolithic primary mirror used off-axis, and a secondary mirror which is deployed with a single hinge mechanism. This provides an optimal collecting area in a non-deployed primary mirror which 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 thermomechanical properties, and given its success in the Herschel observatory, a system with comparable size and surface accuracy requirements to CALISTO. Other aspects are less clear, and there are several inter-related design choices that we propose to trade in our study, including:

1. On axis vs off-axis. As noted in Goldsmith 2008 [26], a benefit of the off-axis geometry is cleaner beams. However the off-axis construction will drive cost (delta to be studied), 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.
2. 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 which includes some on-orbit figure adjustment authority, either in the primary itself or in a smaller image of the telescope.
3. 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.

6 Detectors and Instrumentation

To address the scientific goals outlined above, the primary instrumentation for CALISTO is a suite of 5–8 moderate-resolution ($R\sim 500$) wideband spectrometers, which combine to span the full 35 to 600 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. These spectrometer approaches are described below, after an overview of the detector technology and system requirements for the readout.

Broadband imagers (cameras) are also possible on CALISTO, and this could be particularly powerful for the short wavelengths where the beam is small and the confusion limit is thus deep (Section 3). This will be addressed in the study, but since it does not strongly drive the detector performance or format, it is not discussed in this paper.

Higher-resolution 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 which could be brought in front of the grating backends, both of which potentially 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 2, but will be large, particularly at the long wavelengths.

Finally, we note the potential for 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 Galactic ISM studies as well as protostars and protoplanetary disks. As a guide to the sensitivity, the magenta curve increasing with frequency in Figure 2 shows the sensitivity of a quantum-limited receiver to a 10-km/s wide line. If the line profile itself is not of interest, and line confusion and line-to-continuum concerns are not a concern, then the direct detection system is more sensitive even at very narrow linewidths. These aspects will be addressed in the study.

6.1 Superconducting Micro-Resonator-Based Detector Arrays

Arguably the most important recent development for CALISTO is the progress in superconducting detectors based on high-Q resonators which can be multiplexed in the RF or microwave at high density ($\sim 10^3$ 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-IR pixel count in the hundreds of thousands to a million. For comparison, Herschel had a total of 3,686 far-IR direct detectors, and SPICA will have a comparable number (though at much greater sensitivity). In particular, the kinetic inductance detector (KID) relies on thin-film microresonators which change resonant frequency as quasiparticles created by absorbed photons shift the resonators' inductance [18, 40]. 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 the those of the SQUID-multiplexed bolometer systems in multiple groups worldwide (e.g. MUSIC [55] and NIKA / AMKID[48, 71]). The best reported sensitivities to date are $4 \times 10^{-19} \text{ W Hz}^{-1/2}$, more than sufficient for any ground-based or sub-orbital application. Further development is required to meet the requirements for CALISTO 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 shown in Figure 5 is a $350 \mu\text{m}$ KID camera built by members of the Caltech / JPL detector group [63, 46]. 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) (Figure 5).

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 [56, 11, 61, 20]. The QCD is a naturally small-volume device that is already demonstrating optical NEPs down to $2 \times 10^{-20} \text{ W Hz}^{-1/2}$, meeting CALISTO’s spectroscopy requirement, also shown in Figure 5.

6.2 Readout

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 CALISTO 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 pathfinders.

The path for CALISTO and other flight systems using this type of readout will be to develop a dedicated application specific integrated circuit (ASIC) which 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 $\sim 1\text{W}$. 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 CALISTO. 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 amps; 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 made to reduce power consumption of these devices; but amplifiers with good noise performance have been demonstrated with $700\mu\text{W}$ dissipation. A promising approach is a staged amplification which 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 kpixel system would dissipate 125 mW, a tractable load for 20 K.

6.3 Spectrometer Modules

Grating Spectrometers For the short wavelengths ($\lambda < 200 \mu\text{m}$), 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 \times 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 6.

Silicon-Immersed Waveguide Spectrometers For $\lambda > 200 \mu\text{m}$, conventional spectrometers become too large and bulky, so we will use waveguide spectrometers formed from high-purity float-zone silicon wafers. These devices have

²Reconfigurable Open-Architecture Computing Hardware

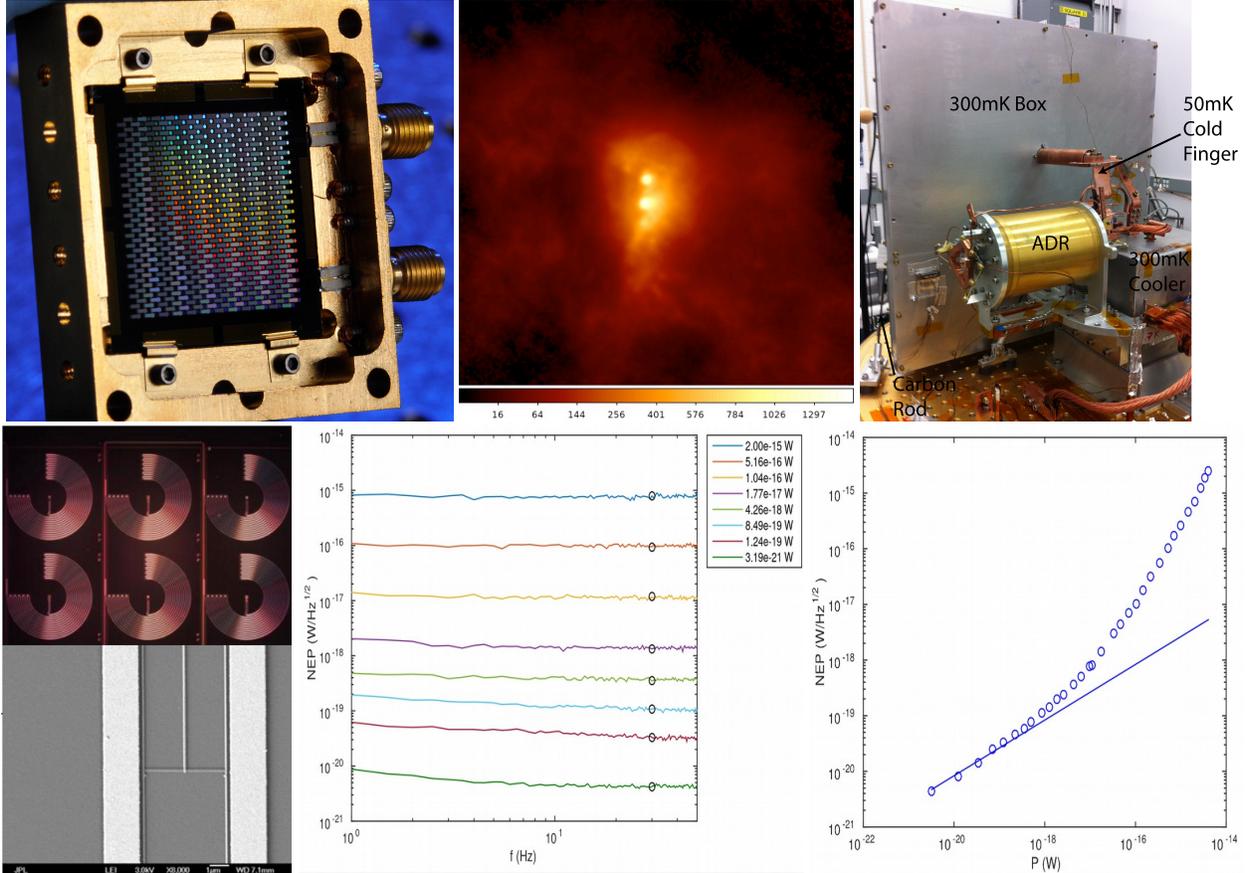


Figure 5: Sub-Kelvin Resonator-based detector technology. Above left shows the 432-pixel kinetic inductance detector (KID) array that forms the heart of the $350\ \mu\text{m}$ MAKO camera, and (center top) an image of SGR B2 obtained with MAKO at the Caltech Submillimeter Observatory (CSO). Below shows views and measured noise performance of a quantum capacitance detector (QCD). Both devices can be multiplexed in groups of $\sim 10^3$ per readout line and thus are viable detector technologies for the few- 10^5 total pixel counts we envision for CALISTO. The KID technology has demonstrated a high level of system maturity with the 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 CALISTO. Top right shows a prototype 300 mK / 50 mK cooling system which cools 10 kg with a flight-like mechanical suspension.

a size on order the resolving power $R \times \lambda/n$, where $n = 3.4$, the index of refraction of silicon. These spectrometers build on our success with Z-Spec[8], 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 $360\ \mu\text{m}$ could be achieved in a package $\sim 10\ \text{cm}$ by $10\ \text{cm}$ by $30\ \text{cm}$, with a mass of $\sim 6\ \text{kg}$ or less.

Superconducting On-Chip Spectrometers For the longest-wavelength CALISTO bands, a superconducting chip-based spectrometer can be used. This technology consists of a filterbank circuit formed from superconducting transmission line lithographically patterned onto silicon with an integrated detector array. Because it is a path-folding device, the dimensions can be quite small, as the photograph in Figure 6 shows. 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 filterbank spectrometers is proceeding rapidly (see the SPIE papers [57, 2, 30, 58, 31]) 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 $\lambda < 380\ \mu\text{m}$, but higher frequency operation is possible with higher-temperature superconductors, for example NbTiN, which could extend down to $200\ \mu\text{m}$. A similar capability can be provided by the μ -Spec system developed at Goddard [12], though this has a size similar to the silicon waveguide spectrometers for a given $\lambda \times R$ product.

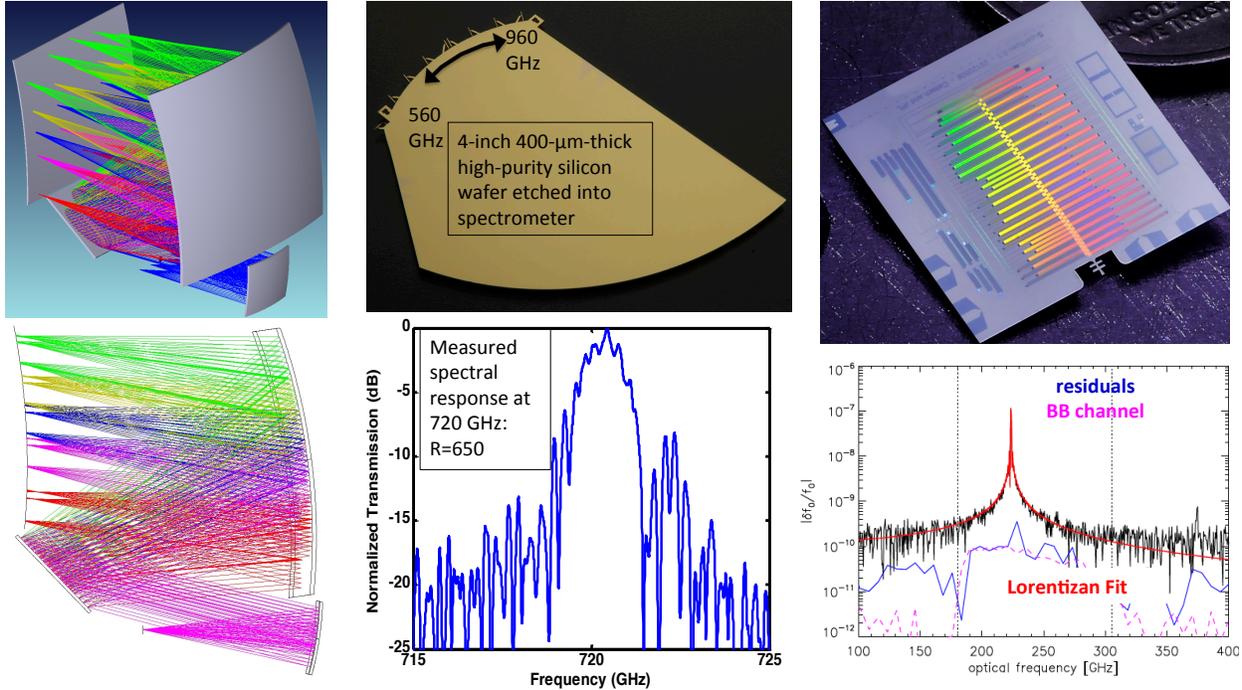


Figure 6: CALISTO spectrometer approaches. Left shows a conventional wide-band slit-fed echelle grating module as is envisioned for the short wavelengths. It processes a full 165-beam-long slit and a bandwidth of 1:1.5 at $R=400$ in a package which is $\sim 1800\lambda$ on a side. At longer wavelengths, a more compact architecture is required, and has spurred development of two new approaches, both of which have demonstrated basic functionality. At center is a silicon-immersed waveguide grating spectrometer; its size is on order $\lambda \times R/3.4$. At right is a superconducting filterbank spectrometer (SuperSpec), which can be used at the lowest CALISTO frequencies. The prototype pictured has 80 spectral channels with R ranging from 200 to 800 and is 1 cm in size.,

6.4 Cooling of the Instrument

To enable the very low detector NEP, and insure that there is negligible optical loading from the instrument, the full spectrometers 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 [24, 59]. Planck used an open-cycle dilution refrigerator [65] in which both ^3He and ^4He are expended. However, with an estimated total sub-K mass approaching 100 kg, the system for CALISTO 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 CALISTO 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 5.1.

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 [15], multi-stage adiabatic demagnetization refrigerators (ADR) [59], and hybrid coolers using ^3He sorption and ADR, as is baselined for SPICA / SAFARI [14]. We refer the reader to a paper comparing these options (Holmes et al., 2010 [35]), but scaling from our laboratory demonstrations and calculations for the BLISS study [9], we estimate that the cooler elements could require $\sim 30\%$ 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.

6.5 Data Rate

Ideally, the CALISTO 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-IR the approach is to scan map or modulate at some frequency, so on-board processing will require new algorithms, for cosmic-ray removal and map-making / demodulation.

Optical communications are a promising solution to the CALISTO 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 [5]. 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 of deep space communications, but this would probably not be required for CALISTO 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 (William Farr, personal communication), 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 CALISTO with only modest on-board compression.

7 Cost Landscape

CALISTO was studied by JPL Team-X in various exercises between 2005 to 2008. The telescope configuration described above, the associated cryocoolers, the deployed sunshade, an allocation for instruments, and operations for a 5-years mission were estimated to cost \$1.7 billion (FY2008\$). The breakdown is provided in Table 4. Of course, re-assessing this is an important aspect of our proposed pre-decadal study. One key point is that we are now advocating substantially more capable instrumentation for CALISTO. While the new frequency-domain multiplexing schemes naturally enable the large formats, we nevertheless expect that the increased scope will increase both the instrument and science terms in the budget (over the full mission life) relative to the 2008 estimate.

Table 4: CALISTO JPL 2008 Cost Estimate Breakdown

Item	Cost [\$M '08]
Management, Systems Eng., Mission Assurance	101
Payload System (primarily science instruments)	196
Flight System (incl. sunshield, telescope, coolers)	608
Operations and Ground Data System	132
Launch Vehicle	156
Assembly, Test and Launch Operations	53
Science	114
Education, Public Outreach	6
Mission Design	10
Reserves	330
Total Estimated Project Cost	1,706

Team-X also considered lower-cost options, ranging from reducing the aperture to a (Herschel-like) 3.5-meter circular telescope to eliminating some of the instrumentation (reducing cryogenic mass and data rate). For the lowest-cost of these, which combined both reductions, the estimate cost was \$1.1 B (\$FY06). Finally we note for comparison the as-built costs for the Herschel (\$1.1 Billion, per ESA), and Planck (\$700 M) missions.

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