U.S. PARTICIPATION IN THE JAXA-LED SPICA MISSION: THE BACKGROUND-LIMITED INFRARED-SUBMILLIMETER SPECTROGRAPH (BLISS)

A PROGRAM REPORT FOR THE ASTRO 2010 DECADAL SURVEY*

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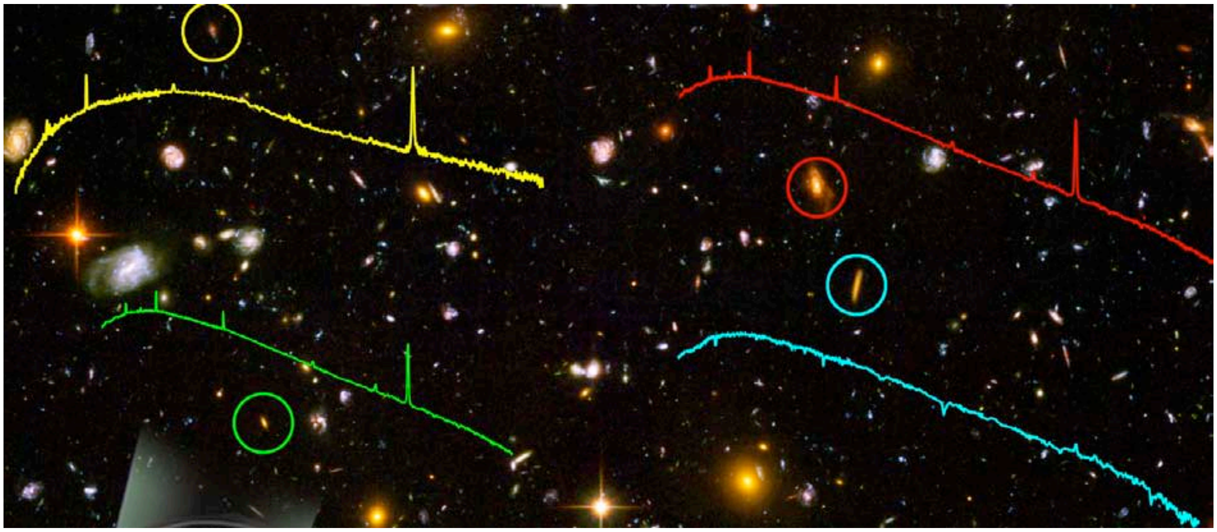

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Contents

Cover Image: Hubble Ultra Deep Field with ISO LWS spectra of nearby galaxies [1]. The spectra extend from 48 to 200 μm, a subset of the BLISS wavelength range for $0 < z < 3$. BLISS-SPICA will similar obtain spectra but at higher R and out to z$\sim$5. The circles show the BLISS-SPICA beamsize at 180 μm.

1 Executive Summary

We outline a plan for US participation in the Japanese-led Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission currently under development with launch envisioned in 2017. SPICA features a 3.5-meter telescope actively cooled to below 5K, operated at L2 with a 5-year lifetime. It will be the world's best and only space far-IR platform at the end of the coming decade. The large cold aperture offers the potential for mid-IR to submm observations which are limited only by the zodiacal dust emission and other natural backgrounds. If equipped with suitable instrumentation, SPICA can enable sensitivities comparable to JWST and ALMA but in the crucial and still relatively unexplored far-IR spectral range which carries half the photon energy ever produced in galaxies.

We have been working with the SPICA principals in a study of a sensitive US-built spectrometer BLISS which would be one of the main science instruments. The collaboration is compelling because US detectors for far-IR / submm wavelengths are world-leading, and our provision of BLISS has the potential to dramatically enhance the scientific return of SPICA. BLISS is envisioned to cover the $\lambda \sim 38$–$430\,\mu$m band with grating spectrometer modules using sensitive superconducting bolometers, and BLISS / SPICA will be 3–6 orders of magnitude faster than currently-planned facilities for broadband spectroscopic observations of distant galaxies. Over the lifetime of the mission, BLISS will obtain thousands of complete far-IR spectra of dust-obscured galaxies ranging from the local universe to redshift 6. In aggregate, these spectra will chart the history of star formation, black hole growth, and organic element production from 1 GY after the Big Bang to the present. An instrumental contribution to SPICA would also allow US scientific access to all the capabilities of SPICA, a great-observatories-class facility, at a cost well below a comparable US-led mission.

Participation in SPICA with an instrument such as BLISS is the top priority of the US far-IR astrophysics community for the coming decade.[‡] In addition to the scientific value, SPICA participation also provides a platform for advancing low-background far-IR focal-plane technologies, the key technical hurdle for our community's long-term plans: US-led cryogenic far-IR missions CALISTO/SAFIR and SPIRIT.

We face a limited window in which the US can join the mission. SPICA has entered a"pre-project phase", corresponding to a NASA Phase-A study in Japan; and ESA's Cosmic Visions program is funding a consortium of European scientists in a study of the SPICA telescope and an instrument. While the SPICA partners are interested in the U.S. far-IR capabilities, they will now proceed with or without US involvement, and instrument resource allocations (volume, mass, power) are currently being established. We hope for a timely positive recommendation from the Decadal Survey to enable NASA to initiate US participation while it is still possible.

The cost (with margin) to NASA for an instrumental contribution to SPICA, from inception through instrument delivery, mission operations, data archiving and instrument-team science is estimated at \$153M. This includes a 24–30 month technology maturation phase beginning in FY11 to enable the highest-performance instrument. In return for this investment, it is expected that the US scientific community would obtain access to all of SPICAs instruments in partner open time, as with ESA's Herschel. Like for Herschel, an additional \$139M (mostly post-launch) would allow US scientists to reap the full benefits of the mission through direct grants and a dedicated support center for data processing and archiving.

[‡] see http://www.ipac.caltech.edu/DecadalSurvey/farir.html

2 SPICA: An Unparalleled Opportunity in the Far-IR

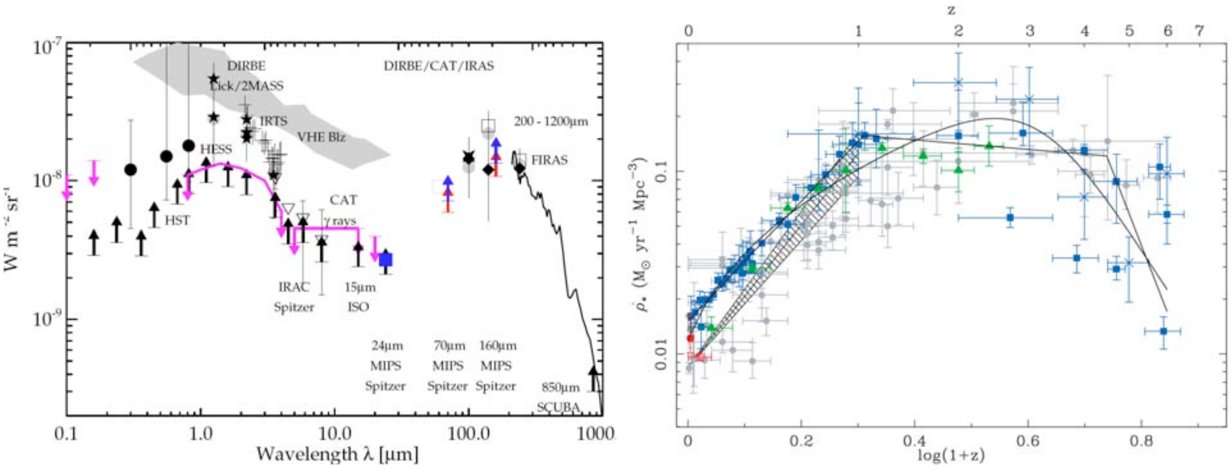

Figure 1: LEFT: Observational constraints on the intensity of the cosmic background radiation from radio to ultraviolet wavelengths from Dole et al.[2]). The two peaks, one in the optical/near-IR and one in the far-IR, have comparable energy density, implying that half of the energy released throughout the history of stars and galaxies is absorbed by dust. RIGHT: Star-formation history reprinted from Hopkins et al.[3]. The picture of a history peaking near z∼2 is compelling, but most of the plotted data are based on rest-frame optical / UV and employ uncertain but large (up to 5) extinction correction factors. The hatched region and green points are based on Spitzer 24 μm [4, 5], and rely on SED models to scale to total luminosities

The far-IR spectral regime is the repository of half the electromagnetic energy released in the history of stars and galaxies (see Figure 1), and offers the only opportunity to probe the details of embedded star and planet formation and the processes in dust-obscured galaxies. Yet the far-IR has remained a relatively unexplored frontier because sensitive far-IR measurements require a combination that has yet to be fully realized: a large cryogenic telescope above the atmosphere and sensitive far-IR focal-plane technologies. The multinational SPICA team is now poised to provide provide this capability. The most important attribute of SPICA is its sub-5 K temperature. *To understand this advantage, consider that at $\lambda = 100\,\mu\mathrm{m}$, even a well-designed passively-cooled $T \sim 80\,\mathrm{K}$ telescope such as Herschel is more than 10,000 times brighter than the natural astrophysical background due to solar-system and Galactic dust. Cooling the telescope to below 5 K virtually eliminates its emission relative to this background.* The sensitivity improvement afforded by a cold telescope can be dramatic, as resoundingly demonstrated with Spitzer's successes in the mid- and far-infrared with only an 85-cm aperture. SPICA is conceived in this same philosophy, and JAXA has invested significantly over the past decade to develop and verify closed-cycle 4-K and 2-K cryocoolers to enable a cryogen-free 5-year mission.

SPICA's large, cold aperture offers potential for great-observatory-class performance, and and the Japanese and European teams are studying powerful focal-plane instrumentation. Mid-IR camera and spectrograph modules will complement JWST MIRI by extending the wavelength coverage to 37 μm, enabling wide-field surveys, and providing $R \sim 30,000$ spectroscopy. A mid-IR coronagraph will take advantage of the clean point-spread function provided by the monolithic telescope. A far-IR imaging Fourier-transform spectrometer (SAFARI) proposed by the Europeans is a versatile imaging instrument and a variable-resolution spectrometer. The BLISS grating spectrometer we propose here offers the ultimate sensitivity for wideband extragalactic survey spectroscopy. SPICA is thus broadly poised to address

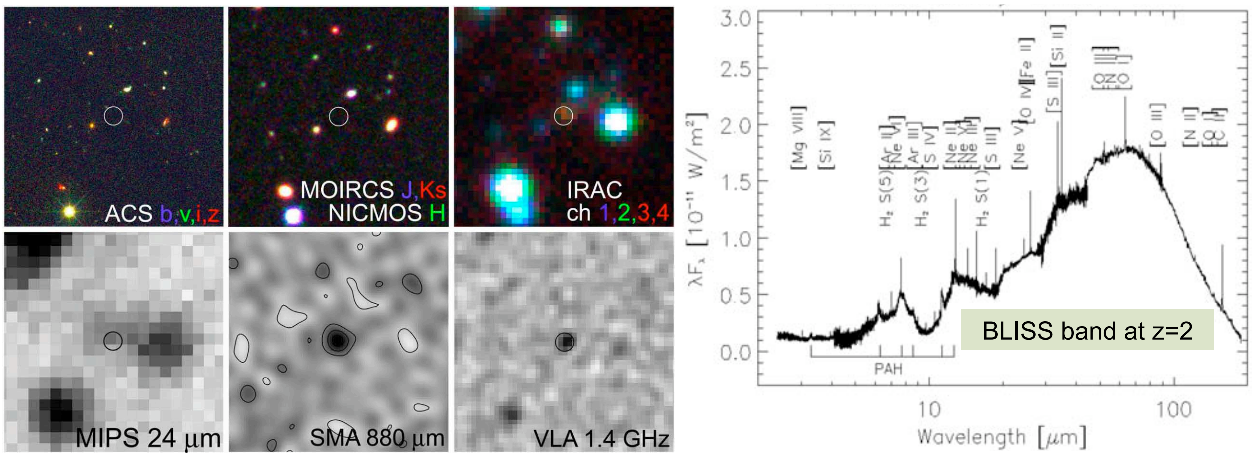

Figure 2: LEFT: Multiwavelength images (24″ on a side) toward a submillimeter-bright galaxy discovered with Scuba/JCMT in the GOODS-N field and confirmed using the SMA submillimeter interferometer (center bottom) which provides an accurate position [6]. The object is undetected in deep HST/ACS, HST/NICMOS, and Subaru/MOIRCS images, and is very faint in the Spitzer IRAC, Spitzer MIPS-24 μm, and VLA images. The redshift is unknown but thought to be $z \sim 4-6$. RIGHT: The complete mid- to far-IR spectrum of the Circinus galaxy from the spectrometers on ISO. The source is a nearby analogue of the high-z dusty LIRGs and ULIRGs. The spectral lines probe the contents and energy sources deep within the dusty core. BLISS on SPICA will for the first time obtain spectra such as these on galaxies throughout their history.

pressing scientific concerns such as: 1) Charting in detail the birth and evolution of stars and planetary systems in our own Galaxy, 2) Discovering when and how the stellar populations and black holes in galaxies came to be, and 3) Probing the rise of chemical elements in the Universe, including those of life. It is anticipated that through an instrumental contribution to SPICA, US scientists could pursue these questions and more through the partner open time. The proposed participation in SPICA has a close analogy with the NASA's arrangement with ESA for Herschel: scientifically enabling hardware contributions enables the NASA to provide US scientists with flagship-class capabilities for a relatively modest cost.

We focus here on issues 2) and 3) above, which are related to the evolution of galaxies and their contents, and are particularly addressed with the BLISS spectrometer.

2.1 Dusty Galaxy Populations

Nearly 2 decades after IRAS's discovery of LIRGs and ULIRGs in the Local Universe, the first submillimeter imaging from the ground has revealed a cosmologically-significant class of galaxies which have similar properties. Like the LIRGs and ULIRGs, these sources are powerful, but are so dusty that they emit up to 99% of their energy in the mid-IR through submillimeter. Optical and even near-IR counterparts for these "submm galaxies" are absent or difficult to find (see Figure 2). Submm surveys thus far are limited by sensitivity and confusion; they access only the brightest sources in the population which are among the most luminous objects in the universe: typically $L \geq 3 \times 10^{12}\ L_\odot$, implying incredible star formation rates ($\sim$1000 $M_\odot$ per year), massive AGN activity, or both buried beneath the dust. Redshifts for a subsample with optical counterparts suggest that they had a history similar to the quasars; peaking when the universe was 2–3 billion years old [7, 8, 9]. Given this timeframe, and their huge power output, it has been suggested that they may each represent a brief but important phase in which one of today's giant elliptical galaxies is assembled in a merger and forms the bulk of its stellar populations.

These bright sources are the tip of the iceberg, as most of the diffuse submm background light remains unresolved. More capable far-IR / submm imaging instruments are being deployed (e.g. SCUBA-2, SPT, LMT, Herschel SPIRE, CCAT), and it is expected that deep surveys will reveal thousands to tens of thousands of dusty galaxies in the first half of the Universe's history. What was the role of these dusty sources in the buildup of stellar mass, the growth of black-hole, and the rise of heavy elements?

These questions are difficult to answer. Even where counterparts exist, near-IR / optical measurements probe only a thin surface, and provide little information about the energy source. ALMA will be very powerful for detailed studies of spatial morphologies and kinematics, but it requires an a priori redshift, and measures only a single spectral transition at a time. *Sensitive wideband spectroscopy of the rest-frame mid- to far-IR with BLISS / SPICA will be the key to studying these galaxies as they form and evolve.* With sensitivities at or below $10^{-20}\,\mathrm{W\,m^{-2}}$, BLISS on SPICA will measure spectral features in LIRG- and ULIRG-class sources at all epochs: both those at redshifts of 1–3 which dominate the CIB energy at the historical activity peak (see Figure 1), but also galaxies well before this peak, in the first 1–2 GY of the Universe: $z \sim$ 3–6. (see Figures 3, 4).

2.2 Probing Embedded Star Formation and Black Hole Growth

In addition to immediately providing unambiguous redshifts, *far-IR–submm spectroscopy is the natural probe of astrophysics in dusty galaxies because it is immune to dust extinction, and therefore probes the entire galaxy.* Unlike the mm-wave tracers available from the ground at longer wavelengths (e.g. ALMA), the rest-frame mid-IR to submm transitions measured with BLISS / SPICA directly probe the interaction between the luminosity sources and the interstellar gas which powers them, specifically:

Extremely ionized gas in the coronal line regions within a few to tens of parsecs of an accreting black hole. This material is probed through the fine-structure transitions of Ne^{4+} ($\lambda = 14.3, 24.3\,\mu$m). With an ionization potential (IP) of 97 eV, Ne^{4+} unambiguously signals a buried AGN, and has been measured in many local-universe ULIRGs with the Spitzer infrared spectrograph [10, 11]. Similarly the $26\,\mu$m transition of O^{3+}, with an ionization potential of 54 eV is found in these regions, although young starburts can have significant O^{3+} emission [12, 13].

Starformation HII regions, the ionized bubbles around massive young stars are probed through fine-structure transitions of species with IP greater than 13.6 eV, including:

- Twice-ionized neon: N^{++}, IP=40 ev, $\lambda = 15.6, 36\,\mu$m,
- Twice-ionized oxygen: O^{++}, IP=35 eV, $\lambda = 53, 88\,\mu$m,
- Twice-ionized nitrogen: N^{++}: IP=30 eV, $\lambda = 57\,\mu$m,
- Twice-ionized sulphur: S^{++}: IP=23 eV, $\lambda = 19, 34\,\mu$m,
- Ionized neon: Ne^{+}: IP=21.6 eV, $\lambda = 12.8\,\mu$m, and
- Ionized nitrogen: N^{+}: IP=14.5 eV, $\lambda = 122, 205\,\mu$m.

In aggregate, this suite of lines measures relative elemental abundances, the total mass of HII regions, their density, and the UV-field hardness, fixing the mass of the the most massive stars in the IMF. Further details on these diagnostics can be found in the Stacey et al. and Armus et al. scientific whitepapers[§], but we highlight that through these diagnostics, *BLISS*

[§] available at http://www.ipac.caltech.edu/DecadalSurvey/farir.html

/ SPICA spectra can constrain the IMF as a function of cosmic time, answering questions such as: was the IMF really more top-heavy at earlier times as suggested by the discrepancy between stellar mass and energy release measurements?

Neutral atomic gas is most commonly associated with photo-dissociation regions (PDRs), the boundary between fully ionized HII regions, and the UV-shielded molecular clouds. It is in the PDR that the bulk of the stellar energy is absorbed and converted into far-IR radiation. The gas cools through only a small handful of fine-structure transitions, so each can carry an energy fraction $1 - 3 \times 10^{-3}$ of the total bolometric power. For dust-obscured systems, these lines are typically the dominant spectral lines at any wavelength:

- Ionized silicon: Si^+, IP=8.2 eV, $\lambda = 35\,\mu$m,
- Ionized carbon: C^+, IP=11.3 eV, $\lambda = 158\,\mu$m, and
- Neutral oxygen: O^0, $\lambda = 63, 145\,\mu$m.

Measurement of these line intensities together with the far-IR continuum constrain the gas density and the total UV field strength, parameters which can be combined to infer a physical size or spatial extent of the starburst regions (not to be confused with the quiescent molecular gas, which will be imaged with ALMA). *BLISS/SPICA measurements of the neutral gas coolants will therefore answer questions like: Did star-forming systems evolve from highly-distributed systems (like M82 scaled to tens of kpc) to the compact nuclear-dominated ULIRGs (e.g. Arp220) we see in the present day?*

While not common in our nearby galaxy sample, it is believed that within ~1 kpc of a nuclear accretion zone, X-rays will be the dominant heating source for the gas. In these X-ray dominated regions (XDRs) [14], the X-rays penetrate though the bulk of the cloud unimpeded by the dust, and heat the gas directly. The result is that for XDRs the gas receives a large fraction (tens of percent) of the total X-ray input energy. The gas cools through the same channels as for the PDR, but individual lines such as the OI 63 μm and SiII 35 μm lines can each carry as much as 10% of the total input X-ray energy! *For a truly AGN-dominated system, the spectrum observed with BLISS / SPICA is expected to show neutral gas coolants which are unusually powerful relative to the dust continuum.*

UV-shielded dense molecular gas is the fuel reservoir for star formation and nuclear accretion, and understanding the heating and cooling of molecular material constrains theories of star formation and black hole growth. Ground-based submillimeter observations of CO have shown that much of the molecular material in nearby IR-bright, starburst galaxies can be 30–100 K or warmer [15, 16]. For such material, the most important molecular cooling channels are in the far-IR / submm, including the mid- to high-J CO, but also water and other light hydrides such as OH, CH. *BLISS / SPICA spectra of warm molecular material will measure its total cooling, thereby providing insight into its heating processes: UV from young stars, X-rays from AGN, or turbulence-driven shocks.*

Dust features due to polycyclic aromatic hydrocarbons (PAHs) at 6.2, 7.7, 8.6, 11.3, 12.7, and 17 μm can be used together with the fine-structure lines to distinguish star formation from AGN energy sources, since the small grains which are the carriers of these features are easily destroyed in the harsh enviorments around an AGN. PAH equivalent widths have been used to estimate the starburst-AGN fractions in dusty galaxies out to $z = 3$ with Spitzer [17, 18].

2.3 Discovery Potential: Primordial Cooling and Early Dust

The huge sensitivity advance provided by BLISS / SPICA is likely to provide some additional unforeseen discoveries about the earliest galaxies. As the Universe is enriched from primordial

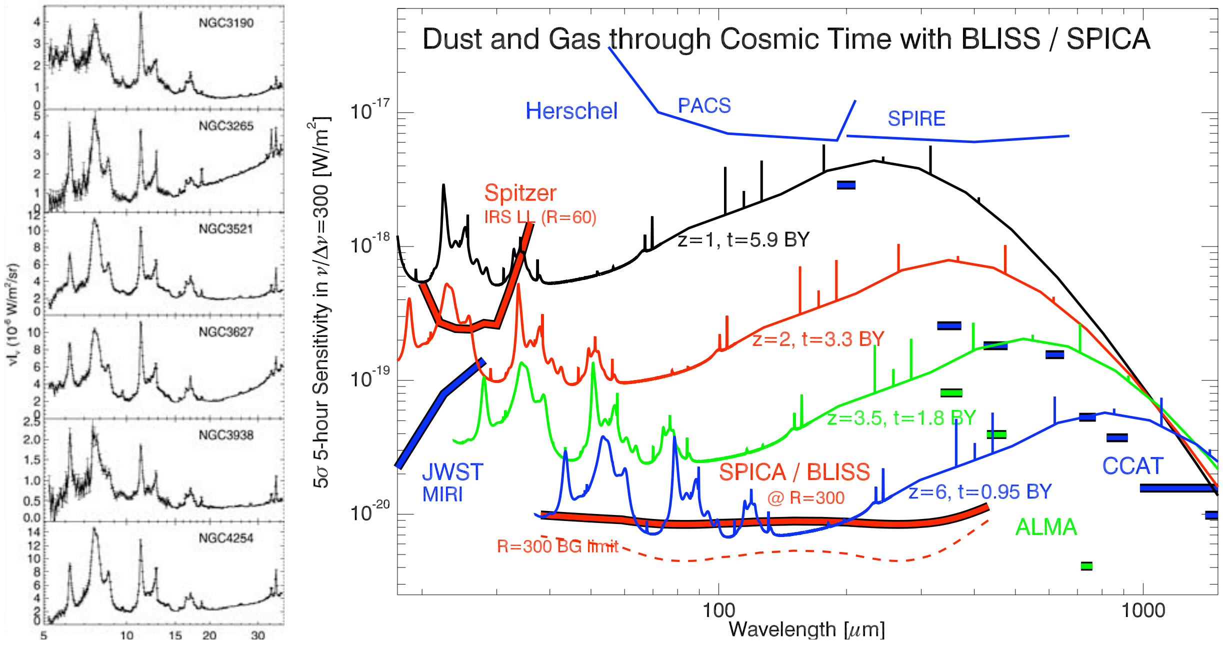

Figure 3: LEFT: Spitzer SINGS mid-IR spectra of nearby galaxies showing the powerful emission features from polycylic aromatic hydrocarbons (PAHs) [13]. RIGHT: the BLISS / SPICA sensitivity and redshifted galaxy spectra using the local-universe template and assuming $L = 10^{12}$ $L_\odot$. The mid-IR PAH features and the bright fine-structure lines are accessible for galaxies as early as 1 GY after the Big Bang.

H_2 to a medium which contains heavy elements and dust grains, the key cooing pathways shift from the quadruple pure rotational H_2 lines in the rest-frame mid-IR (28, 17, 12, 9.7, 8.0, 6.9... μm) to a combination of the fine-structure transitions discussed above and the dust. For metallicity above $\sim 10^{-4}$ solar, fine-structure lines are believed dominate the cooling over H_2. However, surprisingly powerful H_2 emitters (e.g., Stephan's Quintet, 3C326) have been found at low-redshift with Spitzer [19, 20], highlighting the importance of H_2 as a coolant of shocked gas and perhaps providing local analogs of galaxy formation and AGN feedback operating in the early Universe. *Remarkably, the* H_2 *lines in 3C326 would be detectable with BLISS / SPICA even at* $z \sim 8-10$, *highlighting the potential for study of primordial material in this epoch.* The onset of dust can be traced with the mid-IR PAH features. Spitzer has shown that, where present, these are the most powerful features in the spectra of galaxies, both locally and out to $z \sim 3$. *Here too, the wavelength coverage of BLISS is perfectly poised and the sensitivity sufficient to probe these features in the first GY.*

[1] Fischer et al. 1999, **ASP Conf. Ser.** 177: 175–181.
[2] Dole et al. 2006, **A&A** 451: 417–429.
[3] Hopkins and Beacom 2006, **ApJ** 651: 142–154.
[4] Le Floch et al. 2005, **ApJ** 632: 169–190.
[5] Pérez-González et al. 2005, **ApJ** 630: 82–107.
[6] Wang. et al. 2009, **ApJ** 690: 319–329.
[7] Chapman et al., 2005, **ApJ** 622: 772-796.
[8] Valiante et al., 2007, **ApJ** 660: 1060–1071.
[9] Pope et al., 2006, **MNRAS** 370: 1185–1207.
[10] Armus et al., 2007, **ApJ** 656: 148–167.
[11] Farrah et al., 2007, **ApJ** 667: 149–169.
[12] Brandl et al., 2006, **ApJ** 653: 1129–1144.
[13] Smith et al., 2007, **ApJ** 656: 770–791.
[14] Maloney et al., 1996, **ApJ** 587: 171–185.
[15] Ward et al., 2003, **ApJ** 656: 770–791.
[16] Bradford et al., 2003, **ApJ** 586: 891901.
[17] Pope, et al., 2009, **ApJ** 675: 1171–1193.
[18] Menendez-Delmestre, et al., 2009, ArXiv, Mar 09.
[19] Ogle et al., 2007, **ApJ** 668: 699–707.
[20] Appleton et al., 2006, **ApJL** 639:L51–L54.

3 Technical Overview: SPICA and BLISS

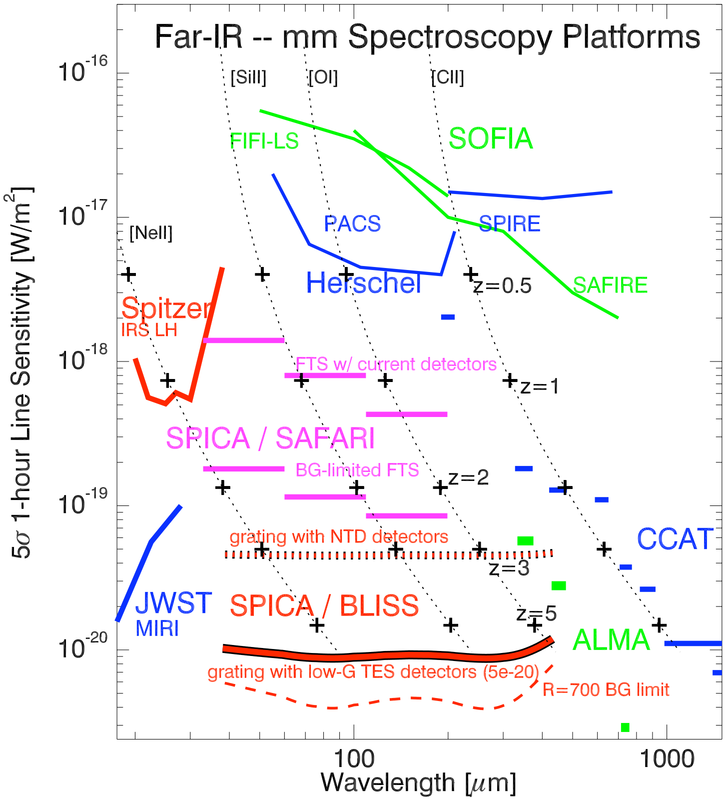

Figure 4: Sensitivity of far-IR spectroscopy platforms. (Observing speed scales as the inverse square of the sensitivity). All values were obtained from web pages and relevant literature. The red SPICA-BLISS curves are calculated assuming a 3.5-meter telescope with 75% aperture efficiency and 25% total instrument transmission in a single polarization. Sky backgrounds are average values appropriate for the North Ecliptic Pole. The light dashed curved at bottom shows the photon background limit, the heavy curve above it assumes a detector noise-equivalent power (NEP) of 5×10^{-20} W Hz$^{-1/2}$, achievable with transition-edge superconducting bolometers. The dotted upper red curve shows the performance possible with demonstrated detector technology. As a guide to the astronomical capability, overplotted are spectral line intensities from ULIRG at various redshifts assuming a fractional line intensity of 10^{-3}, a median value in the local universe, and the current cosmology ($\Omega_{vac} = 0.73$, $\Omega_{mat} = 0.27$, $H_0 = 71$).

The far-IR remains a frontier with huge potential improvements because existing far-IR spectroscopy platforms operate far from the ultimate sensitivity limitation: photon noise from the zodiacal dust and Galactic cirrus. In regions of low zodi and cirrus, the photon noise on a cold (sub-5 K) telescope can be up to four orders of magnitude lower than that produced by a passively-cooled (∼80 K) telescope (Figure 4). This translates into factors of 10^4–10^8 speed improvement in obtaining a complete spectrum for a distant galaxy.

3.1 The SPICA Cryogenic Mission

SPICA is being led by the Japanese infrared astrophysics community and their space agency JAXA (Japanese Aerospace and Exploration Agency). Prof. Takao Nakagawa is the PI, and details can be found in his articles [21, 22]. SPICA builds on the heritage of previous Japanese cryogenic missions, especially AKARI, but will include several advances which facilitate the 3.5-m, 4.5-K aperture, and enable the 5-year mission:

1. SPICA will employ a warm-launch architecture, similar to that used with Spitzer, substantially reducing the cryostat mass and volume. A careful system-level thermal design optimally combines radiative and active components [23].
2. Closed-cycle coolers will be used instead of a liquid cryogen vessel. Joule-Thomson (JT) coolers will provide the 4.5 K base, with support from two-stage Stirling coolers at 20 K. To support focal-plane instruments, an additional ^{3}He JT stage with lift of more than 10 mW at 1.7 K will also be employed. These cryocoolers are the enabling technology for the observatory, and JAXA's investments in this area have proven very successful in the AKARI coolers [24] and demonstrated prototypes for SPICA [25].

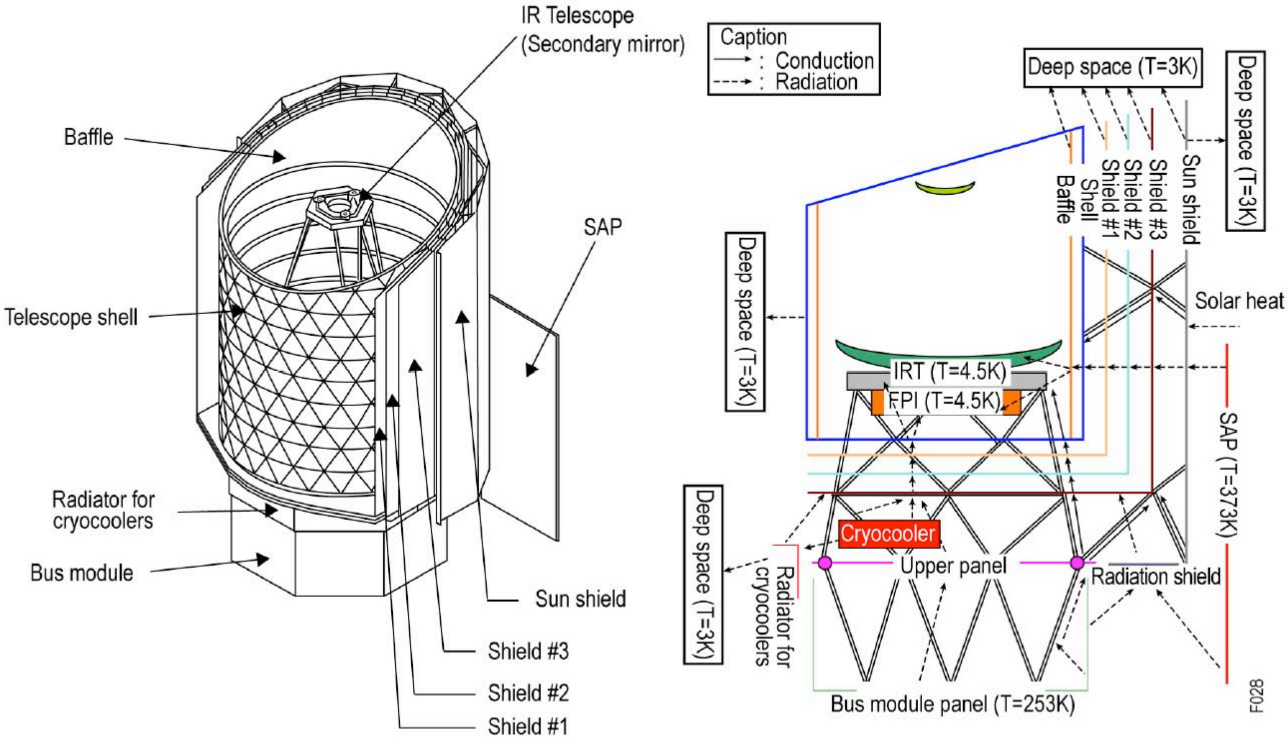

Figure 5: SPICA Spacecraft and Thermal Design

3. SPICA will operate at the Earth-Sun 2nd Lagrange (L2) point, simplifying the shielding and maximizing the effectiveness of radiative and active cooling.

SPICA's telescope is under ESA-funded study in Europe: the baseline concept is to employ the silicon carbide technology developed for Herschel [26]. Several focal-plane instruments are under study for SPICA in addition to BLISS, summarized in Table 1 [27]; it is anticipated that these instruments would be available to US observers as part of the partner open time.

3.2 The BLISS Spectrograph

The philosophy of BLISS is to optimize capability for spectroscopic follow-up of distant (=unresolved) galaxies with unknown redshifts. Key design parameters are therefore ultimate sensitivity and total instantaneous bandwidth. For suitable detectors, the most sensitive approach is a diffraction grating, where the photon bandwidth on a single detector is comparable to the spectrometer resolution. This is the approach for BLISS, and *we emphasize that its excellent point-source sensitivity is complementary with the 2-D survey capability of SAFARI, which will find interesting objects for detailed study with BLISS.*

A single grating spectrometer only efficiently couples a single octave of bandwidth, so the full BLISS instrument is a series of spectrometer modules. Design details are being iterated, pending the physical resource availability of the observatory, especially cryogenic mass. The working BLISS concept is five bands covering the 38–433 μm range at $R \sim 700$, all coupling the same position on the sky through the use of a polarizer and dichroic filters. This single 'bank' of spectrometers is duplicated so the full instrument couples two adjacent sky positions, separated by 1–$2'$(2–3 beams at the longest-wavelegnth). The astronomical

Table 1: SPICA Focal Plane Instruments Under Study Other than BLISS

Instrument	Description / Capabilities
MIRACLE	**A mid-IR camera** with 2–3 bands, each with a 6′ field of view: SHORT is 5–26 μm, LONG is 20–37 μm, and both have a prism or grism mode baselined to provide low-resolution spectroscopy ($R \sim 100$). A 35–50 μm channel is also under consideration.
MIRMES	**A medium-resolution mid-IR echelle spectrometer** will provide $R \sim 1000$ over the 10–37 μm range. The total instantaneous field of view will be 103 (378) arcsec^2 for the short- (long-) wavelength modules, providing a survey capability which complements the deep measurements with JWST MIRI.
MIHRES	**A high-resolution ($\mathbf{R \sim 30,000}$) echelle spectrometer** for the 4–8 μm and 12–18 μm bands, MIRHES will allow detailed study of Galactic regions for which the JWST spectrometers will become spectrally confused.
SCI	**The SPICA coronagraph instrument** is a mid-IR coronagraph with both imaging and low-resolution spectroscopy ($R \sim 20 - 200$) capability to take advantage of the clean PSF provided by the monolithic (not segmented) telescope. Details can be found in [28].
SAFARI	**A 30–200 μm imaging Fourier-transform spectrometer (FTS)** under study by a European consortium [26]. The field of view is 2′× 2′, and the resolving power is variable up to a few thousand. Detectors are TBD, with photoconductors, bolometers, and kinetic-inductance detectors under consideration.

source will be interchanged between the two banks with a cryogenic chopping mirror at an image of the secondary; this provides the necessary modulation for the bolometers, as well as redundancy against losing a spectral channel entirely if a detector in one bank fails.

BLISS will employ two types of broadband grating. The WaFIRS system demonstrated at $\lambda = 1$ mm in the Z-Spec instrument [29, 30] on Mauna Kea will be used for the longer wavelengths. Its offers a very compact size and minimum mass, so it is used for the longer wavelengths for which the conventional modules would be prohibitively massive. To ease fabrication tolerances for the two shor-wavelength bands, BLISS will employ conventional cross-dispersed echelle grating modules, similar to those used for the high-resolution modules of the Spitzer infrared spectrograph (IRS) [31], but with a new an maximally-compact design. Each WaFIRS module will have 768 detectors arrayed along the focal arc, while for the echelle spectrometers, the 960 detectors are assembled in 1-D strips of a 2-D plane to match the positions of the grating orders. The active absorbing area on each detector ranges from 190×310 μm for the shortest-wavelength band to 2100×340 μm for the longest-wavelength band. The total number of detectors required is 4224, and we baseline TES detectors (Figure 7 and Section 4.1), read out with a cryogenic MUX in groups of 32 (described in Section 4.2).

3.3 BLISS Systems Design

To approach the photon background limit, the TES bolometers envisioned for BLISS must be cooled to 50 mK, and the system will have stringent stray light, EMI mitigation, and thermal performance requirements. BLISS thus uses a multi-stage approach as shown in Figure 6. Mounting to the 4.5 K SPICA instrument bench is a 1.7 K stage which houses the sub-Kelvin refrigerators (Section 4.3) which in turn supports a 400 mK thermal intercept stage, from which the spectrometer modules themselves are stood off. A radiative and electromagnetic shield encloses each stage, and titanium support members connect them with sufficient mechanical rigidity and thermal isolation. We have analyzed the thermal and mechanical concept in detail, including all known thermal loads to 50 mK and the operation

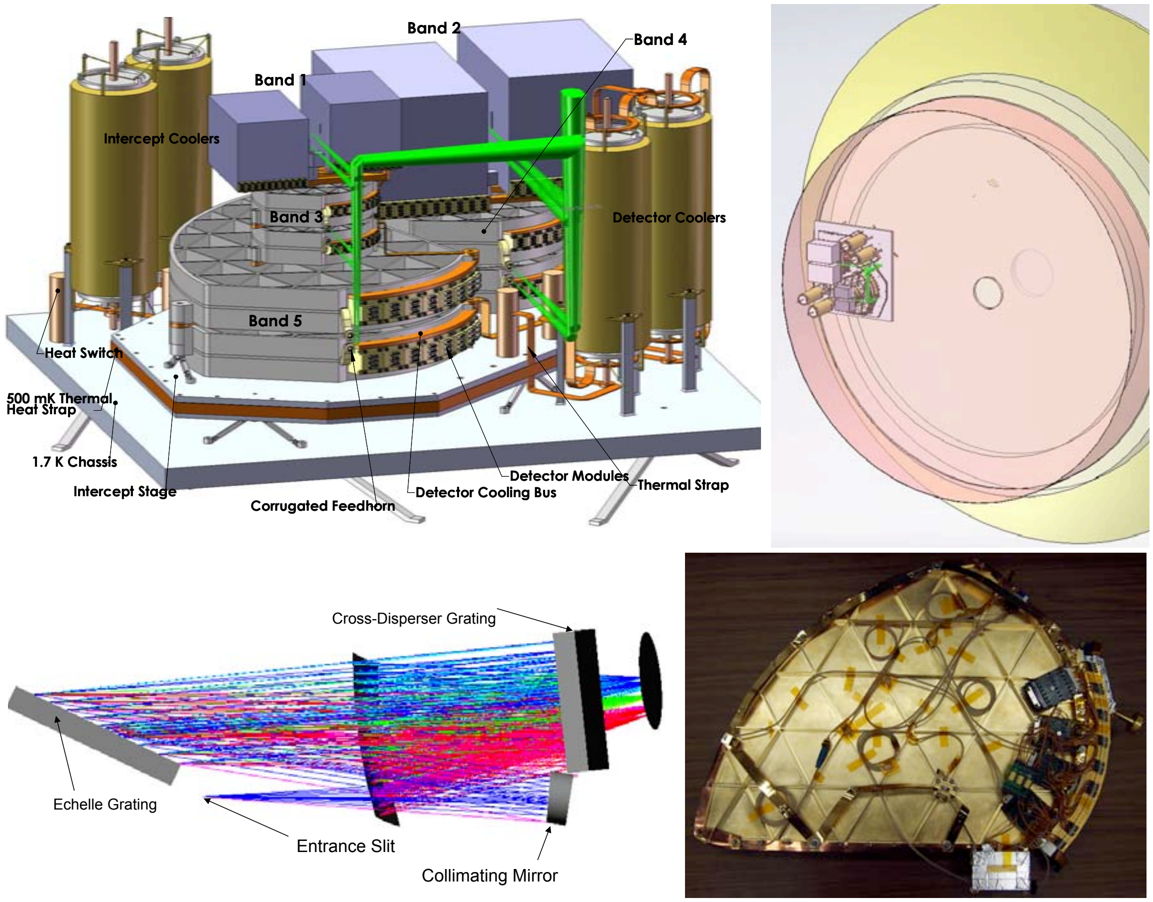

Figure 6: Top: Proposed layout of the BLISS modules in the SPICA instrument envelope. 10 total spectrometers cover two sky positions in 5 bands. The two shortest-wavelength bands use the conventional cross-dispersed echelle spectrometer in the lower left. For the longer wavelengths, the 2-D waveguide grating demonstrated in the Z-Spec instrument (lower right) is used. For both the linear dimensions scale with $\lambda \times R$. A polarizer separates the incident light into two polarizations, one feeding bands 1, 3, 5, the other bands 2, 4, through the use of dichroic filters (beams shown schematically in green with slow $f\#$ for clarity). Radiation shields on the 1.7 K and 500 mK stage are removed for clarity. The upper right shows BLISS inside the SPICA 2.5-m × 40-cm instrument enclosure beneath the 3.5-m telescope. A pickoff mirror (not shown) relays an off-axis field to the BLISS, which will sit some distance from the telescope boresight. The pickoff and instrument offsets allows the shorter-wavelength instruments to access the central boresight region.

of the refrigerator to insure that it can be achieved. The cryogenic mass of the current BLISS concept is 50 kg, and it requires a heat lift from the facility 1.7 K cooler of 5 mW, well within its capability.

3.4 Minimum Instrument

Achieving the goal performance for BLISS requires the technology program described in Section 4, but we emphasize that we could begin construction today on an extremely capable spectrograph using demonstrated flight-ready technology. We have developed a complete instrument design named BASS (Bolometer Array Survey Spectrograph) based on the semiconductor-sensed bolometers (known as NTD Ge bolometers) now on the launch pad in Herschel and Planck. These devices are extremely robust and well-characterized, and as Figure 4 shows, can provide sensitivity improvements of 2-3 orders of magnitude relative to

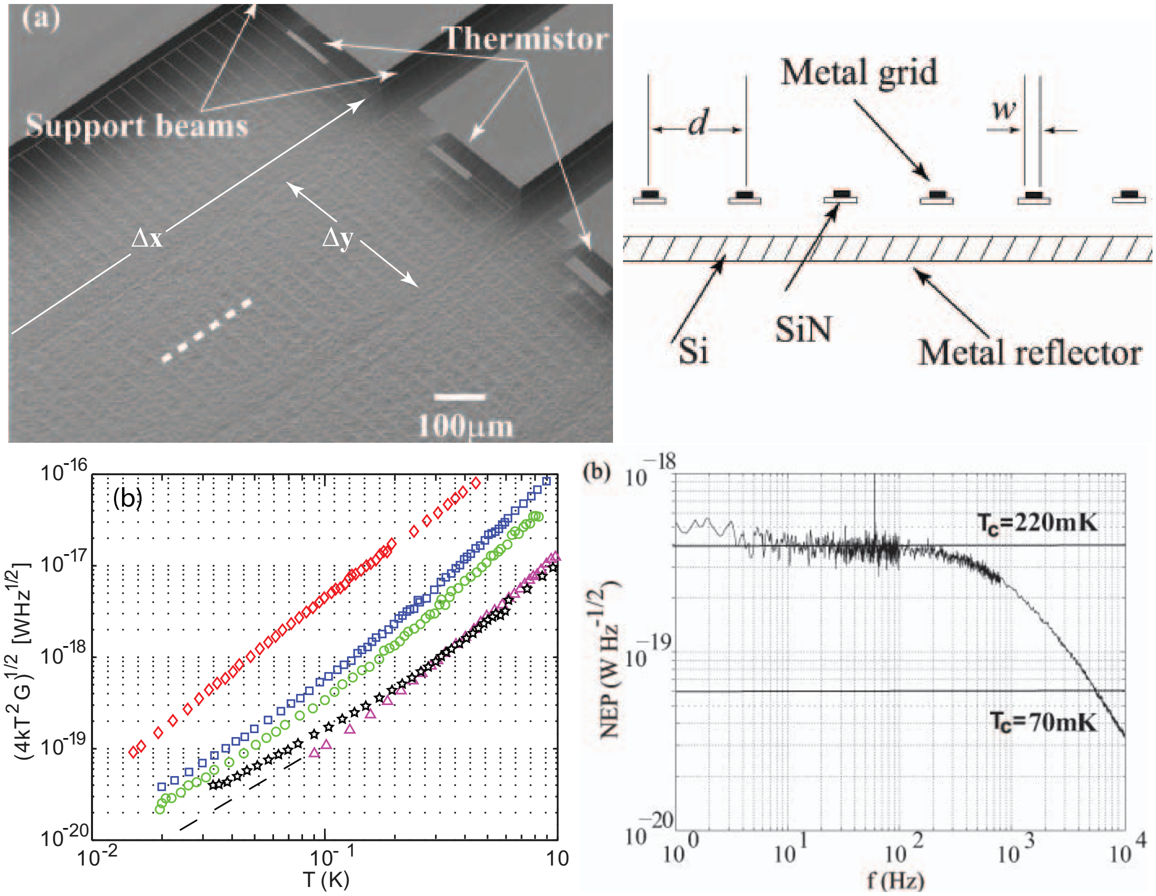

Figure 7: Results in low-G TES development. TOP: A TES array segment designed for the long-wavelength module of BLISS. Each absorber is $\Delta x = 300\,\mu m$ wide by $\Delta y = 2000\,\mu m$ long, and the support beams are $1000\,\mu m$ long by $0.25\,\mu m$ thick by $0.4\,\mu m$ wide (beams extend beyond figure). A thin gold film deposited onto the absorber rungs matches the sheet impedance of the device to that of free space, and when combined with a quarter-wave backshort (TOP, R), the absorption efficiency can exceed 80%, as demonstrated with the Herschel and Planck bolometers. BELOW, L: Measured thermal conductance (G) data plotted in NEP units, showing that we have achieved thermal isolation to achieve sensitivities well below $10^{-19}\,\mathrm{W\,Hz^{-1/2}}$. The symbols correspond to different beam geometries; the stars represent a device similar to the one shown above. BELOW, R: Noise measurement of a leg-isolated device at 220 mK; results are as predicted from the G data. Operated at $T_C = 70\,\mathrm{mK}$, the device will realize NEP $= 6 \times 10^{-20}\,\mathrm{W\,Hz^{-1/2}}$.

Herschel, and remains more sensitive than SAFARI. Array format is limited, but still sufficient to cover the far-infrared band at R=200–300; higher than the successful and widely-used low-res spectrograph modules on Spitzer. Instead of the continuous 50 mK refrigerator, we would use a single-shot configuration similar to that demonstrated in the Suzaku mission. A full description and costing of BASS is available for reference at the BLISS webpage¶.

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¶`http://www.submm.caltech.edu/BLISS/`

4 Technology Development Program

We plan a technology program to realize the full scientific capability of SPICA's cold telescope, aiming to achieve background-limited sensitivity for far-infrared spectroscopy. The technology program benefits SPICA scientifically, and also enhances US capabilities by providing a targeted application for which to aggressively pursue the detector and cooling technologies needed for SAFIR/CALISTO and SPIRIT. This program is analogous to US development program for the SPIRE and HIFI instruments on Herschel, where cutting-edge technologies were developed and selected based on readiness dictated by the Herschel schedule. We reiterate that, as described in Section 3.4, a very capable instrument could be built even if the program does not realize all of its goals.

The emphasis of the technology program is to demonstrate that detector and cooling *systems* are compatible with SPICA. TES bolometers have already demonstrated the required thermal isolation and heat capacity, and higher NEP analogs are currently carrying out scientific observing programs. Larger format SQUID multiplexers are already in use in ground-based instruments. The sub-K coolers have been demonstrated in space in single-shot configurations. The issue is to take these component technologies and demonstrate an instrument which is compatible with the cooling, EMI, and optical interfaces presented by SPICA. The technology program will ultimately produce a development model with background-limited detectors, which is tested with these interfaces.

4.1 High-Sensitivity Bolometers

The target sensitivity for BLISS detectors is a noise-equivalent power of NEP $= 5 \times 10^{-20}\,\mathrm{W\,Hz^{-1/2}}$. The most suitable approach given SPICA's timescale is to array superconducting transition-edge-sensed (TES) bolometers with a SQUID-based multiplexing readout (MUX). Thermally and mechanically, the detector itself derives from from the micro-mesh bolometer—a silicon nitride membrane patterned into a grid absorber suspended by thin legs from the thermal bath. These devices have shown excellent overall performance with semi-conducting sensors, and are now poised for launch on Herschel and Planck.

The addition of the TES sensor offers the potential for larger array formats through the MUX, and higher sensitivity through reducing the detector response time. This technology has matured steadily, and kilo-pixel TES arrays are being widely used (see Section 4.2).

To approach the background limit for space spectroscopy, one must reduce the intrinsic temperature-fluctuation noise due to phonon fluctuations between the absorber and the thermal bath: $\mathrm{NEP_{phonon}} \simeq \sqrt{4\mathrm{kT^2G}}$, where G is the thermal conductance between the absorber and bath, T is the bolometer temperature. For a 50 mK base temperature available with current cooler technology, one must reduce G to ∼10 fW/K to approach the BLISS photon NEP. The device in Figure 7 achieves this. The suspended absorber is connected to the substrate through four $\mathrm{Si_xN_y}$ support beams. The low value of G is obtained by making the aspect ratio (length to the cross-sectional area) of the support beams very large [32]. Noise measurements with a TES at 220 mK confirm the thermal noise, and the lower-T superconducting films are under fabrication now to demonstrate the ultimate sensitivity.

The response time of existing devices is 100 ms, using the natural electro-thermal speedup of the TES. Improvements are expected, but this is adequate for BLISS since the instrument operates in a simple chopping mode. Similarly, the device's natural dynamic range is ∼1000, ample for extragalactic observations, but can be extended to 10^5 with the use of a dual TES.

4.2 Superconducting Multiplexer

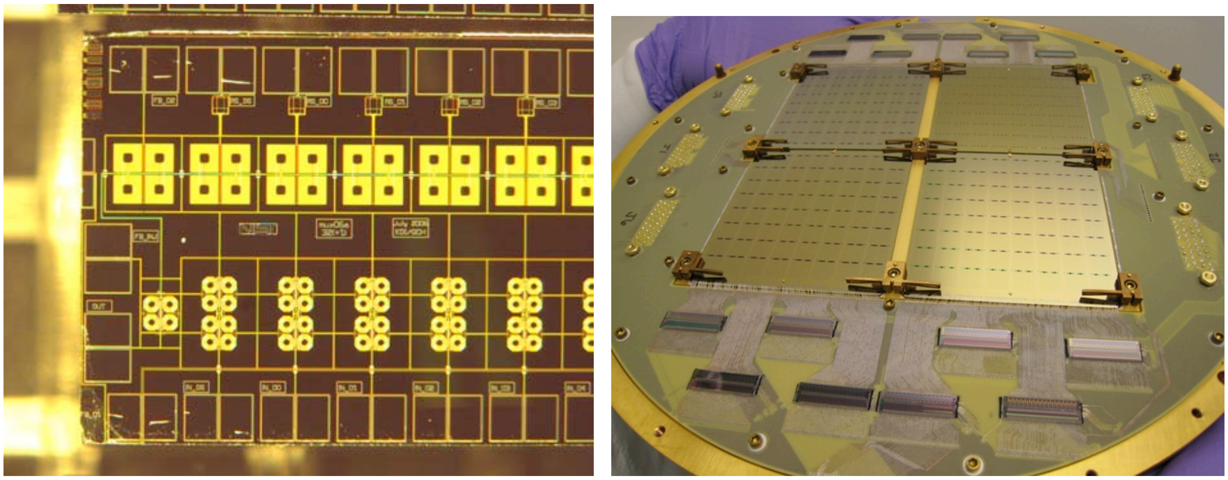

Figure 8: LEFT: Photo micrograph of a portion of a working 32-channel time-domain SQUID multiplexer (TDM) from NIST Boulder. Eight channels are shown. RIGHT: A 512-pixel TES focal plane for Keck, a CMB polarization experiment which uses the NIST MUX.

The pixel count for BLISS makes it essential to multiplex the bolometer signals at the cold stage. Fortunately, over the past several years, technology for cryogenic multiplexing of TES bolometers has matured significantly, and SQUID-based time-domain multiplexed (TDM) readouts developed at NIST Boulder are currently able to multiplex in groups of up to 40 detectors at the low-temperature stage, introducing negligible amplifier noise. TDM readouts have been / are being produced for numerous experiments (Table 2)

Table 2: Experiments Using NIST Time-Domain SQUID Multiplexer with TES Bolometers

Name	Description	Total N_{pix}	Status
MUSTANG	Ground-based 3 mm camera	64	operating
ACT	Ground-based CMB	3,072	operating
GISMO	Ground-based 2 mm camera	128→1,280	operating
SCUBA-2	Ground-based submm camera	10,240	commissioning
Keck	Ground-based CMB pol	2,336	commissioning
SPIDER	Balloon-borne CMB pol	2,624	integration
ZEUS2	Ground-based submm spectrometer	660	integration

We envision a NIST collaboration to develop a flight MUX for BLISS. The circuit will use the now-standard 32-element linear MUX architecture [33] shown in Figure 8, but with several modifications to accommodate the lower NEP of the BLISS detectors. First is a chip with lower power dissipation at the cold stage to accommodate the large pixel count and small power budget. A reduction of power dissipation by a factor of about 8 will be accomplished by reducing the critical current of the SQUID switches and increasing the SQUID input inductance and shunt resistance. We note that even in the face of the lower NEP in the bolometers, the desired SQUID parameters are not extreme, and are similar to those used in some previous SQUID designs. A second modification will be to incorporate a larger inductive filter in front of the SQUID switches, enabling a lower frequency and thus lower power dissipation in the room temperature drive electronics relative to the ground-based and suborbital experiments.

4.3 Sub-100 mK Refrigerators

The very low NEP and optical loading of the BLISS detectors requires that the BLISS focal plane modules be cooled to T$\sim$50 mK with a system that rejects heat to SPICA's 1.7 K cooler ($P_{\mathrm{max}} = 5\,\mathrm{mW}$). The current state-of-the-art sub-K flight coolers is limited to ^{3}He sorption coolers on IRTS and Herschel/SPIRE ($> 280\,\mathrm{mK}$ in a single shot mode), the Planck open-cycle dilution refrigerator (100 mK, $<$200 nW, 2.5 year life due to expendables), and the ASTRO-E Adiabatic Demagnetization Refrigerator (ADR) (60mK, single shot). All cooled cold stages with mass $<$2 kg, much smaller than BLISS. Fortunately with some enhancements, both ADR and dilution approaches both could meet the needs of BLISS.

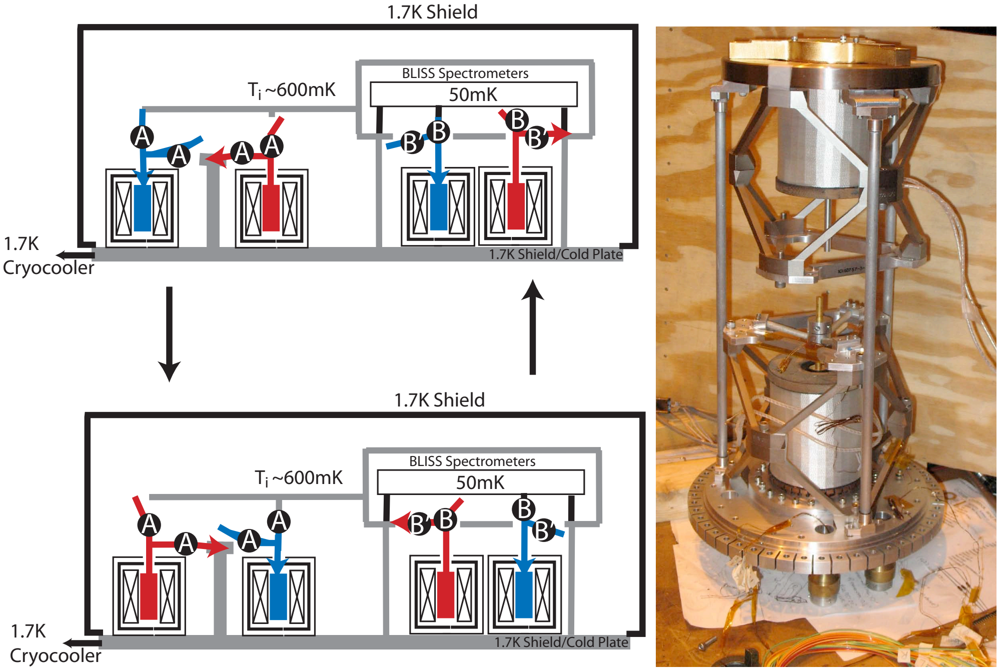

Figure 9: LEFT: Schematic of 2-stage continuous ADR envisioned for BLISS. The blue rectangles represent paramagnetic salt pills absorbing heat at operational temperature; the red indicate pills which are dumping heat while recycling to the next higher temperature stage. Arrows indicate heat flow. The upper and lower frames represent the two phases of the operational cycle. RIGHT: Prototype hardware: a single-shot dual stage system to verify salt pills and parasitic loads.

Adiabatic Demagnetization Refrigerators (ADRs) are ideal for a long-duration mission because only electrical power is required, there are no expendables and no moving parts. To adapt the basic approach to the needs of BLISS two advances are baselined 1) to include an intercept stage at T$\sim$500 mK, greatly reducing the load on the 50mK stage, and 2) to operate the system in a continuous mode: possible with a proper configuration of multiple salt pills and heat switches. Figure 9 shows the BLISS design and hardware prototypes, further details can be found in the SPIE paper [34], and Holmes et al. (2009).

A Closed-Cycle Dilution Refrigerator is second promising approach being developed by Benoit et al. (CNRS-CRTBT, Grenoble France), the group responsible for the Planck (open-cycle) dilution cooler. Early demonstrations are promising and while this approach has somewhat more complicated spacecraft interface requirements than the ADR, it may offer a mass savings.

5 Project Schedule

5.1 SPICA Schedule

In the last year, SPICA has entered a"pre-project phase", corresponding to a NASA Phase-A study in Japan; and ESA's Cosmic Visions program has begun funding the European consortium in their study of the SPICA telescope. While the European and Japanese partners are interested in the U.S. far-IR capabilities, they are moving forward in the schedule shown in Figure 10 with gates and down-selects set by JAXA and ESA. The mission development will now proceed with or without US involvement, and opportunities for US participation are reduced as time passes.

JAXA and the SPICA PI have indicated that all international partners contributing key hardware must be place by the System Definition Review (SDR), scheduled for ∼January 2011. This is the technical precursor to the Project Approval Review (for management / cost) which will occur at most 6 months later. Together, the two reviews represent the go / no-go decision for SPICA in Japan, and beyond this point, major changes to the focal-plane complement and major new partnerships will be difficult or impossible.

Of course, the concept design is underway now, and instrument resource allocations (volume, mass, power) are currently being established. If the US is to have a meaningful

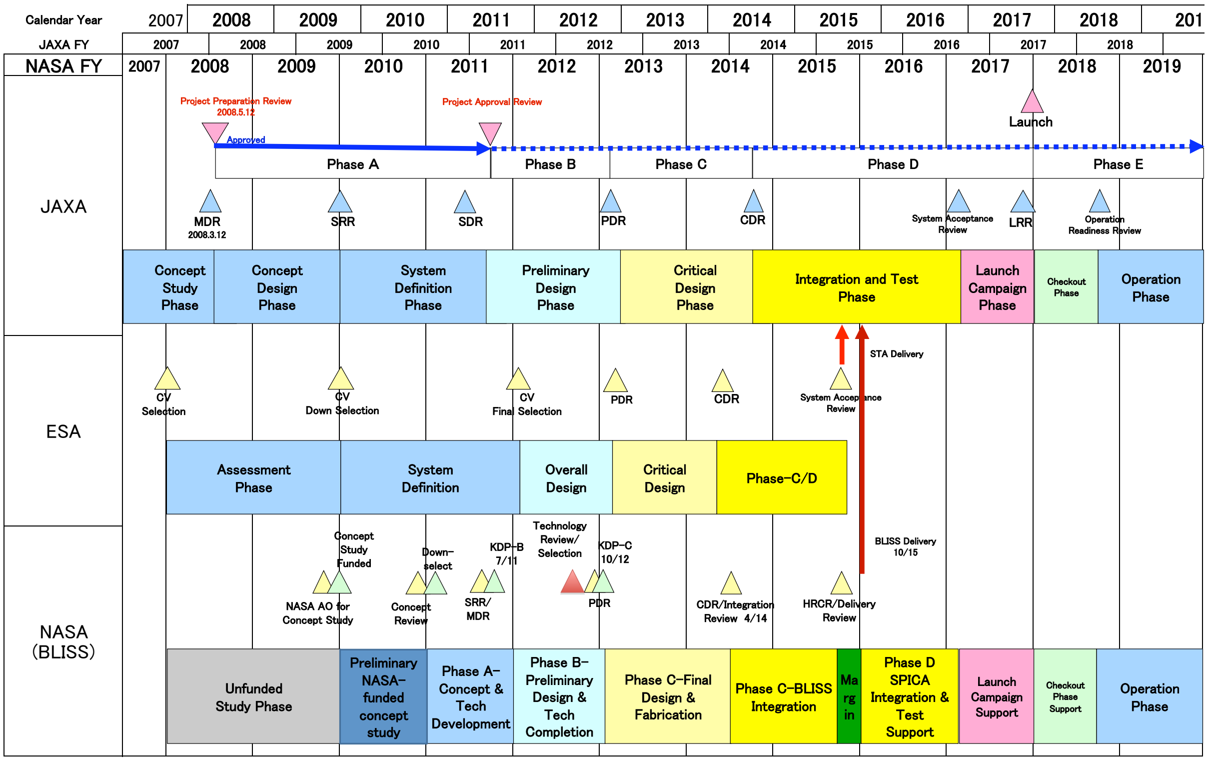

Figure 10: SPICA schedule (build phase), showing key dates for JAXA and ESA, and our approach for BLISS. Note that the JAXA fiscal year is 6 months out of phase with the NASA fiscal year. Phase E extends for 5 years, to 2023.

role in the mission, we must be formally involved in these processes starting as soon as possible to preserve options for US participation. The funding requirements are very modest for this period, but an endorsement by NASA is important. It is therefore our hope that a positive recommendation from the Decadal Survey will enable NASA to initiate steps for formal US participation.

5.2 BLISS Schedule

The working BLISS schedule is driven by working backward from the requirement to deliver the instrument hardware to JAXA for integration with the observatory at the end of CY2015, sufficiently in advance of launch to allow full end-to-end system tests. The BLISS instrument PDR is 3 years before the required delivery, allowing 16 months each for fabrication and integration of the flight instrument, plus margin. BLISS PDR is thus in September 2012, and also aligns with the ESA and JAXA PDRs. **Just prior to PDR, in mid-2012, is the date for which all BLISS technology selections must be made; designs up to this point will carry multiple options** to employ the TES detectors if they are ready, but also to accommodate the semiconductor-sensed bolometers as a fall back. Of course, the instrument interfaces will be defined before this time, and the BLISS instrument designs will be tailored to provide the greatest capability for a given detector approach within the constraints of the allocated resources. Prior to technology selection and PDR is Phases A and B, is a combination of technology development and instrument design.

Per the Astro2010 instructions, we begin the costed mission cycle in phase-A in FY 2011. However, as Figure 10 shows, it is our hope that a small concept study might be possible in FY10, in order to negotiate instrument allocations with JAXA and ESA.

5.3 Data Processing, U.S. Community Support, SPICA Mission Support

To take full advantage of the mission, we anticipate and have costed a program in which US scientists can benefit from the mission: a US operations center for data processing and archiving as well as direct grants to the US community. This begins in Phase D and operates throughout Phase-E (see Figure 11).

6 Organization, History, and Current Status

The team submitting this RFI has been in place for 5 years. BLISS was originally funded by NASA as an Origins Probe concept study in 2004. This allowed us to define the instrument concept and begin a dialog with the SPICA study team about both technical issues: thermal, mechanical, and optical interfaces; and programmatic issues such as time allocation and data access. As the instrument concept has taken shape, the Japanese team has expressed a commitment to operating SPICA in a modern "great observatory" style, with open time for partner nations, likely including solicitations for large legacy programs, and a finite proprietary period for any data (∼1 year), after which it becomes public.

Building on the development of the science case and the realization of the potential of the grating spectrometer approach, a small NASA research grant ($290k/year for FY06–FY08) was awarded for the development of transition-edge superconducting detectors for BLISS. This work has produced encouraging results summarized in Figure 7, and Section 4.1.

Meanwhile, the scientific interest in BLISS and in the US participation in SPICA has broadened and intensified with the resounding success of Spitzer, an 85-cm cryogenic telescope. The astronomical community now awaits the launch of the ESA Herschel 3.5-m telescope, an observatory enabled by key US detector technology contributions and now demonstrating broad scientific interest by US representation in key observing program selections. SPICA represents the only planned far-infrared observatory operating in the 2020's decade after Herschel. The huge gains possible with the cold telescope are recognized, and SPICA participation is now the top priority of the US far-IR astrophysics community, as outlined in a community consensus document prepared for Astro2010 led by Martin Harwit.[‖] This is the same group that has brought forward the concepts for large US-led cryogenic observatories (SAFIR, CALISTO) and interferometers (SPIRIT). Providing BLISS for SPICA is not only a huge step forward scientifically, but serves as a crucial demonstration platform for the key technologies that will be required for these billion-dollar-class future flagships.

The minimum mission (see Section 3.4) was proposed to the 2008 Small Explorer (SMEX) call named "BASS" as a mission of opportunity. The proposal[**] received excellent scientific reviews, and the $70M instrument cost (no community support included) was confirmed by the external panel. The scientific debrief summary was:

- "The scientific goals of [BLISS] + SPICA will have high scientific impact if achieved and cannot be accomplished with Herschel or SOFIA."
- "[BLISS] + SPICA provides the unique opportunity for making a broader set of observing capability in the far-infrared available to the US community."
- "[BLISS] + SPICA fills in the spectral range between JWST and ground-based submm and mm facilities ALMA and CCAT."

At that time SPICA was not yet approved in either Japan or Europe (it is now approved and under study by both space agencies), and the SMEX schedule and cost constraints are not a good match to flagship-class instrument for a major observatory.

Now, with Phase-A started in both Japan and Europe, SPICA must now proceed, regardless of US participation. NASA management recognizes the potential value in SPICA participation through an instrumental contribution, but in the face of budget pressures, awaits an endorsement from the Decadal Survey before making a strategic decision.

[‖] available at `http://www.ipac.caltech.edu/DecadalSurvey/farir.html`

[**] available at `www.submm.caltech.edu/BLISS`

7 Cost Estimate

The anticipated total cost to NASA for SPICA participation would include both the hardware development and integration, but also support for data processing and archiving and direct grants to the US scientific community to make use of SPICA data after launch. The cost for the BLISS instrument as currently envisioned is well-estimated. The cost of the data support, archiving, and community support is less well-constrained, as it will depend on the US allocation of observing time and SPICA's instrument configuration, details which would be worked out once the US participation is initiated. We have taken the US involvement in ESA's Herschel mission as a model for this, a program for which the US scientific community is reaping large benefits from modest but crucial hardware contributions.

7.1 BLISS Instrument Cost

To estimate the cost of a BLISS instrument, the JPL Team X group has worked with the scientific / technical study team to consider the necessary development, the design and fabrication of all the subsystems, as well as integration, test, delivery to JAXA, and support after launch. The figures include the cost of technology maturation, especially for the detectors, a major thrust early in the program. The Team-X estimated total cost to NASA to build, integrate, and support the BLISS instrument is \$120 M, not including reserves. With reserves the total estimate is \$153 M. The breakdown is provided in Table 3 below, with detailed assumptions following.

Table 3: BLISS Instrument Cost Estimate from JPL Team X

ITEM	COST FY08 \$M
Optics	6.9
Structures	10.9
Thermal Systems	9.0
Detectors and Cold Electronics	33.3
Warm Electronics	14.0
Software	1.1
Management, Sys. Eng., and Mission Assurance, ITAR compliance	17.6
Integration and Test	7.4
Science Team in Phases B, C, D (1.5 FTE, 5.5 years)	3.2
Assembly, Test, and Launch Operations (3 FTE, 1.5 years)	1.5
Instrument team science in Phase E (5 FTE, 5 years)	7.5
DSN Support (1/3 of SPICA downlink requirements)	4.3
Ground Data System	3.6
Reserves (30% in Phases A-D)	30.8
Reserves (15% in Phase E)	1.9
Total (including reserves)	153

Costing Assumptions for the BLISS Instrument Hardware and Integration

- BLISS is 10 individual spectrometer modules, each providing R$\sim$700 over nearly an octave of bandwidth and each of which couples a single position on the sky. The modules are in pairs, so that the spectral range from 38 to 430 μm is divided into 5 bands, and each band is coupled to two sky positions simultaneously.

- Mechanically, BLISS mounts to the 4.5 K SPICA instrument interface, but there is an additional thermal interface with the SPICA 1.7 K cooler.
- All spectrometers and the detectors are cooled to 50 mK with a custom magnetic refrigerator, built as part of the instrument.
- A thermal intercept at a temperature of 0.4–0.5 K is employed to for a reduce the parasitic loads (conducted and radiated) on the instrument
- The detectors are absorber-coupled transition-edge superconducting bolometers (TESes), of which there are 4224 in total. They are read out with a superconducting 50 mK multiplexer using a time-domain row-column switched readout.
- Three or perhaps for mirrors are required for relaying the beam from the telescope focal plane to the instrument, these are mounted to a 4 K stage. One is a chopping mirror which modulates the light from an astronomical source between the two spectrometer banks.
- Development in advance of the flight engineering is included for the detectors and their readout systems.

7.2 US SPICA Scientific Operations – Estimated Cost

To make optimal use of the hardware investments, support for data processing and US community scientic support would be required. Following the working model of Herschel, we envision three essential components to the effort. The estimates are based on Spitzer and Herschel experience at the Infrared Processing and Analysis Center (IPAC):

1. BLISS Instrument Support, including (i) software for instrument commanding and operations, starting during development phase; (ii) data processing software, calibration, including test phase, development and on-orbit updates; and (iii) data archiving and access.
2. Technical User Support for SPICA users in the U.S., including (i) technical support for the US community, access to data, analysis software, and information other than BLISS; and (ii) data archiving for non-BLISS data.
3. Data Analysis Funding to US community, in the amount of 15.5 M$/yr, comparable to Herschel budget inflated to 2009. We assume a similar level of US community interest, though it must be pointed out that this is still to be negotiated.

The summary is shown in Table 4. The cost is based on FY2009 rates at IPAC, and includes task management and science time, hardware costs, travel and support services. This table assumes a 5-year prime mission, and adds close-out costs (documentation and processing for nal archive) equivalent to one year of operations.

The estimates above assume that JAXA has responsibility for all basic aspects of mission and science operations. However, JAXA may well request NASA contributions to science operations on elements besides BLISS, such as: (i) adapting the Spitzer Observation Planning Tools for SPICA, as was done for Herschel; (ii) framework for pipeline data processing for all SPICA instruments, again leveraging pipeline developments for Spitzer, and allowing

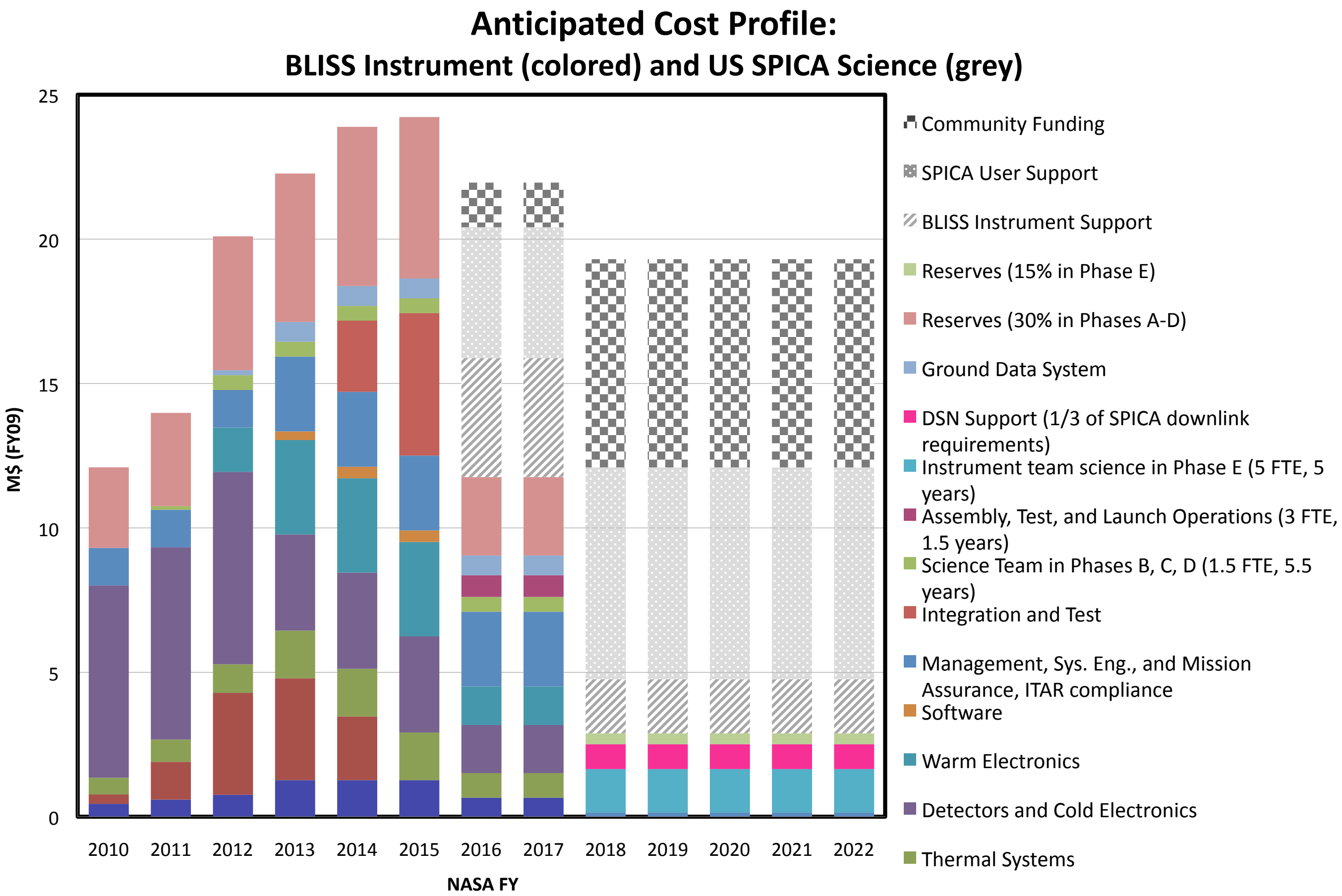

Figure 11: Anticipated cost profile for BLISS and US scientific participation.

the SPICA instrument teams to focus on algorithms; (iii) framework for data analysis tools available to users for post-pipeline processing; and (iv) design and software for SPICA data archive. These items are not scoped here since they have not been discussed with our Japanese colleagues, but their cost could range from two to twenty million in 2009$.

Table 4: US Scientific Support for SPICA Mission – Estimated Cost (FY09 $M)

Item	Phase C/D	Phase E
BLISS Instrument Support	8.3	9.4
SPICA User Support	9.1	36.7
Direct Grants to US Community	3.1	77
Total Cost	20.5	123.1
Total Life Cycle Cost	143.6	