

# New *SPICA*: the next crucial step after *AKARI* for future mid- and far-infrared astronomy

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## ABSTRACT

*SPICA* (*SP*ace *I*nfrared telescope for *C*osmology and *A*strophysics) is a future mid- and far-infrared astronomy mission after *AKARI*, *Spitzer* and *Herschel*, with a 2.5 m telescope actively cooled below 8 K. Thanks to the cryogenically-cooled telescope as well as the advanced instrument technologies, *SPICA* provides unprecedented high sensitivity in spectroscopy, photometry and polarimetry. In particular *SPICA* enables detailed spectroscopy with continuous coverage from mid- to far-infrared ranges for the first time. *SPICA* has the following key science objectives: (1) revealing the rise and fall of galaxy formation over cosmic time, (2) understanding star formation from filaments to galaxies, and (3) tracing the gas, dust and ice in planet forming systems.

The definition of the previous *SPICA* mission has been revisited since 2014, and now, new *SPICA* is re-defined as an international project between JAXA and ESA, with a combination of a strategic L-class mission of JAXA and a Cosmic Vision M-class mission of ESA. If selected, *SPICA* will launch in the late 2020s and operate for a goal lifetime of 5 years. *SPICA* carries onboard the mid-infrared instrument SMI as well as the far-infrared instruments SAFARI-SPEC and -POL; the former is the Japanese-led instrument developed and managed by a university consortium. In this paper, we describe the current status of the *SPICA* project, the *SPICA* science goals, and the conceptual design of SMI, mostly focusing on the importance of the *AKARI* heritage from scientific and technical points of view.

**Keywords:** Instrumentation: photometers, polarimeters, spectrographs – Space vehicles: instruments – Telescopes – Infrared: general, galaxies, ISM, planetary systems

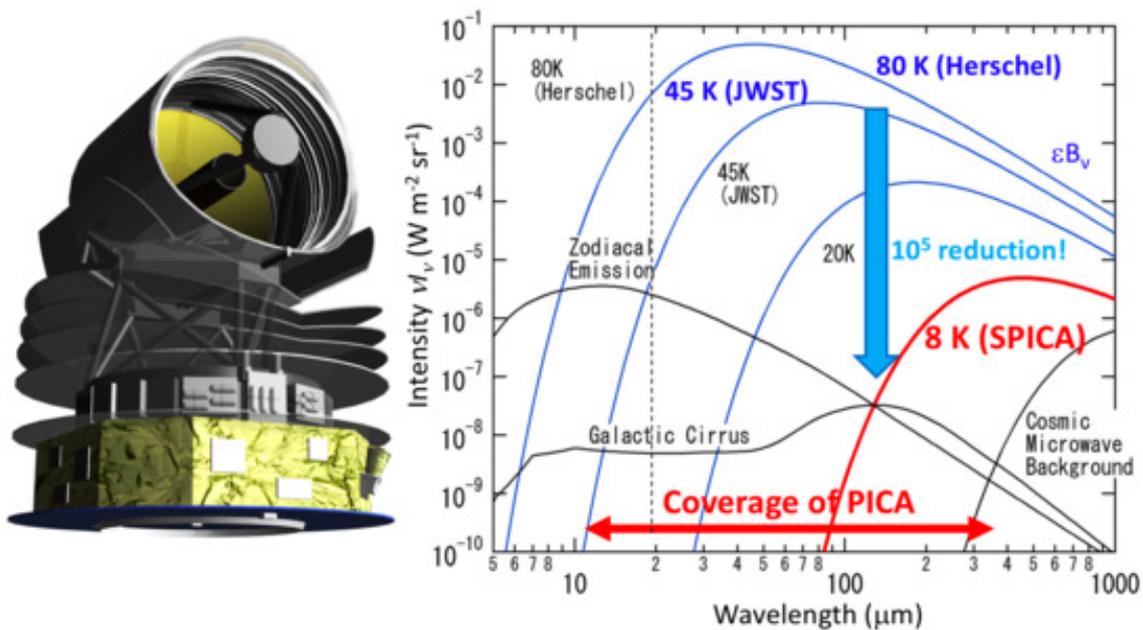
## 1. CURRENT STATUS OF *SPICA*

*SPICA* (*SP*ace *I*nfrared telescope for *C*osmology and *A*strophysics) is a future mid- and far-infrared astronomy mission after *AKARI*, *Spitzer* and *Herschel*, with a 2.5 m telescope actively cooled below 8 K by mechanical cryo-coolers in combination of passive radiative cooling to space (Nakagawa et al. 2015, 2017; Roelfsema et al. 2017). The definition of the previous *SPICA* mission has been revisited since 2014, and now, new *SPICA* is re-defined and proposed as an ESA-led international project with JAXA as a major partner and with participation of many institutes and universities in Japan, Europe, U.S., Canada, Taiwan and so on. In Japan, *SPICA* is now allocated to the third slot for a series of the ISAS/JAXA 2020s Strategic L-class Missions. We passed Mission Definition Review at JAXA in 2015 and our current activity is funded in Phase A1. On the European side, we submitted our Cosmic Vision M5 proposal to ESA in October 2016 with about 600 supporters in total; as of writing this paper, we are still waiting for the announcement from ESA on the result of the first selection. After the selection, we will soon start agency-level coordination on the project workshare plan and ESA-JAXA joint technical feasibility study as well as preparation for System Requirement Review at JAXA. If finally selected, *SPICA* would launch in the late 2020s and operate for a goal lifetime of 5 years.

Thanks to the cryogenically-cooled telescope as well as the advanced instrument technologies, *SPICA* provides unprecedented high sensitivity in spectroscopy, photometry and polarimetry. Although the aperture of the telescope has been reduced to 2.5 m from 3 m of that of the previous *SPICA* mission, the sensitivity itself is significantly improved thanks to the progress in the detector technology and further optimization of the instrument design. The imaging performance of the telescope is designed to be diffraction-limited at 20  $\mu$ m, which has been degraded from that of the previous *SPICA* mission where it used to be 5  $\mu$ m, but enabling us to make the *SPICA* project more cost-effective and affordable, and

avoid inefficient overlap of the observational wavelength coverage with *JWST*. *SPICA* carries on-board two kinds of the focal-plane instruments: SMI (SPICA Mid-infrared Instrument; Kaneda et al. 2016; Sakon et al. 2016) and SAFARI (SPICA Far-infrared Instrument; Pastor et al. 2016; Roelfsema et al. 2017). SMI has three spectroscopic channels and an imaging mode: low-resolution ( $R \sim 50\text{--}120$ ) spectroscopy covering a wavelength range from 17 to 36  $\mu\text{m}$  (SMI/LR), mid-resolution ( $R \sim 1200\text{--}2300$ ) spectroscopy from 18 to 36  $\mu\text{m}$  (SMI/MR), high-resolution ( $R \sim 28000$ ) spectroscopy from 12 to 18  $\mu\text{m}$  (SMI/HR), and a wide-field ( $10' \times 12'$ ) broad-band ( $R \sim 5$ ) photometry at 34  $\mu\text{m}$  (SMI/CAM). SMI/CAM is designed to be operated simultaneously as a slit-view for SMI/LR. SAFARI has two functions: one is spectroscopy at  $R \sim 300$  and  $\sim 10,000$  for a wavelength range from 34–230  $\mu\text{m}$  (SAFARI-SPEC) and the other is imaging polarimetry at 100, 200 and 350  $\mu\text{m}$  (SAFARI-POL). More details about the specifications of the *SPICA* mission and the focal-plane instruments are summarized in Roelfsema et al. (2017). Most importantly *SPICA* enables detailed spectroscopy with continuous coverage from mid- to far-infrared ranges for the first time, which bridge the gap between *JWST* (*James Webb Space Telescope*) and ALMA (Atacama Large Millimeter/submillimeter Array).

*SPICA* adopts a cryogen-free architecture, and therefore the mission lifetime is, in principle, likely to be limited by the lifetime of the cryogenic system consisting of mechanical coolers as well as the passive V-groove cooling structure taken from the *Planck*-type configuration (Ogawa et al. 2016; Shinozaki et al. 2016). *SPICA* uses three kinds of cryo-coolers: 20 K-class two-stage Stirling coolers, 4 K-class Joule-Thomson coolers and 1 K-class Joule-Thomson coolers, which have heritage from the past Japanese missions *AKARI*, *JEM/SMILES* and *ASTRO-H*. Hence one of the most important technologies for *SPICA* is mechanical cryo-coolers, the cryogenic system of which is currently being developed and tested in collaboration with the Athena team. We expect that the lifetime of *SPICA* would be 5 years as a goal plus an optional extension. Thanks to the cryogenically-cooled ( $< 8\text{ K}$ ) telescope that would be secured with meticulous thermal design of the cryogenic system, *SPICA* would achieve ultra-low background in the mid and far-infrared. As can be seen in Figure 1, the thermal radiation from the *SPICA* telescope is reduced down to the level smaller than or comparable to the natural background radiation consisting of the Zodiacal emission and Galactic cirrus emission, which is a huge improvement from the *Herschel* telescope at  $\sim 80\text{ K}$  in the far-infrared and the *JWST* telescope at  $\sim 45\text{ K}$  in the mid-infrared, importantly contributing to the achievement of the unprecedented high sensitivities with *SPICA*.



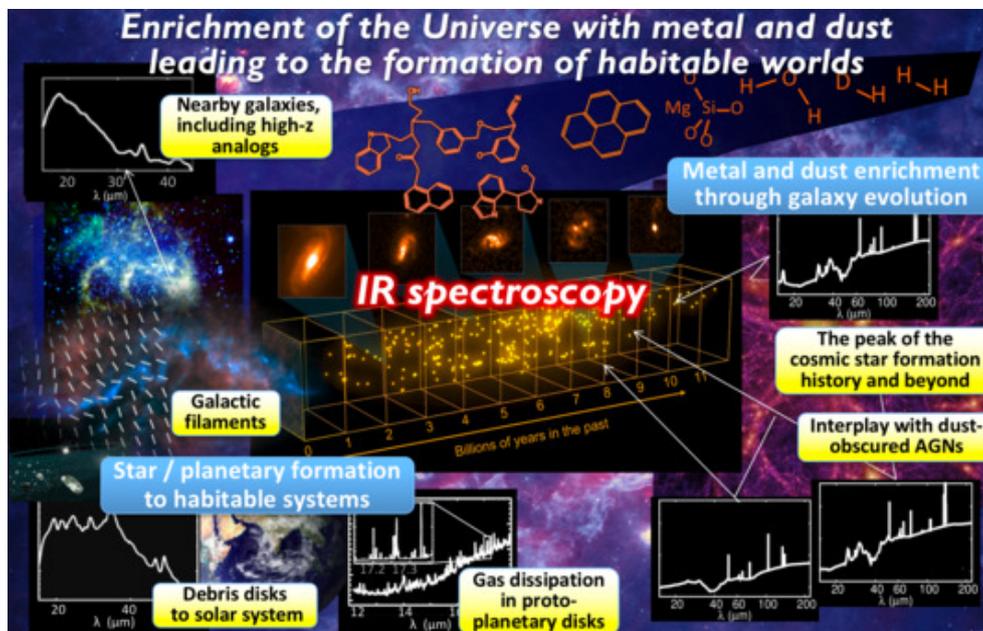
**Figure 1.** (Left) Configuration of new *SPICA*, which is based on the *Planck* heritage. The 2.5 m telescope is cooled below 8 K with mechanical coolers and radiative cooling to space, and without using cryogen. (Right) Spectra of the thermal radiation from telescopes as a function of temperature, compared with typical spectra of the natural background radiation.

## 2. *SPICA* SCIENCE GOALS

As its top-level science goal, *SPICA* would reveal the process that enriched the Universe with metal and dust, leading to the formation of habitable worlds, the concept of which is visualized in Figure 2. For the achievement of the science goal, galaxy evolution as well as star and planetary system formation is key processes to be understood through detailed mid- to far-infrared spectroscopy, as well as far-infrared polarimetry for the formation of Galactic filaments. In the ESA Cosmic Vision M5 proposal, we set the *SPICA* key science objectives as follows: (1) revealing the rise and fall of galaxy formation over cosmic time, (2) understanding star formation from filaments to galaxies, and (3) tracing the gas, dust and

ice in planet forming systems. After submission of the M5 proposal, a series of white papers dedicated to those *SPICA* key science objectives have been published (Fernández-Ontiveros et al. 2017; González-Alfonso et al. 2017; Gruppioni et al. 2017; Kaneda et al. 2017; Spinoglio et al. 2017), submitted (van der Tak et al. 2017), or being prepared (André et al., Egami et al., Nakagawa et al., Kamp et al., in prep.).

Regarding the process of the galaxy evolution, *SPICA* aims to reveal the underlying physics on the evolutionary histories of the cosmic star-formation rates and the black-hole accretion rates in galaxies over cosmic time (e.g., Madau & Dickinson 2014). What causes the rises of the activities of star-forming galaxies and active galactic nuclei toward their peaks at around  $z = 1-3$  and what triggered the precipitous declines of their activities from their peaks toward the present Universe? The redshift range of  $z = 1-3$  corresponds to the cosmic time where dust extinction is most severe, making the mid- and far-infrared spectroscopy that is in practice free from extinction extremely useful. On the other hand, regarding the processes of the star and planetary system formation, *SPICA* contributes to understanding the formation mechanism of Galactic filaments in star-forming regions and the gas dispersal process in planet-forming disks through the measurement of the magnetic fields and kinetic energy of gas in turbulent motions for the former and the contents and the kinematics of gas and water with the HD, H<sub>2</sub> and H<sub>2</sub>O lines for the latter (Trapman et al. 2017; Notsu et al. 2016, 2017). *SPICA* will also perform detailed mineralogy of dust in planet-forming disks. As summarized in Roelfsema et al. (2017), the wavelength range of *SPICA* contains an enormous amount of spectral diagnostic gas lines and dust bands which would reveal how the material evolution interplays with the galaxy evolution as well as the star and planetary system formation.



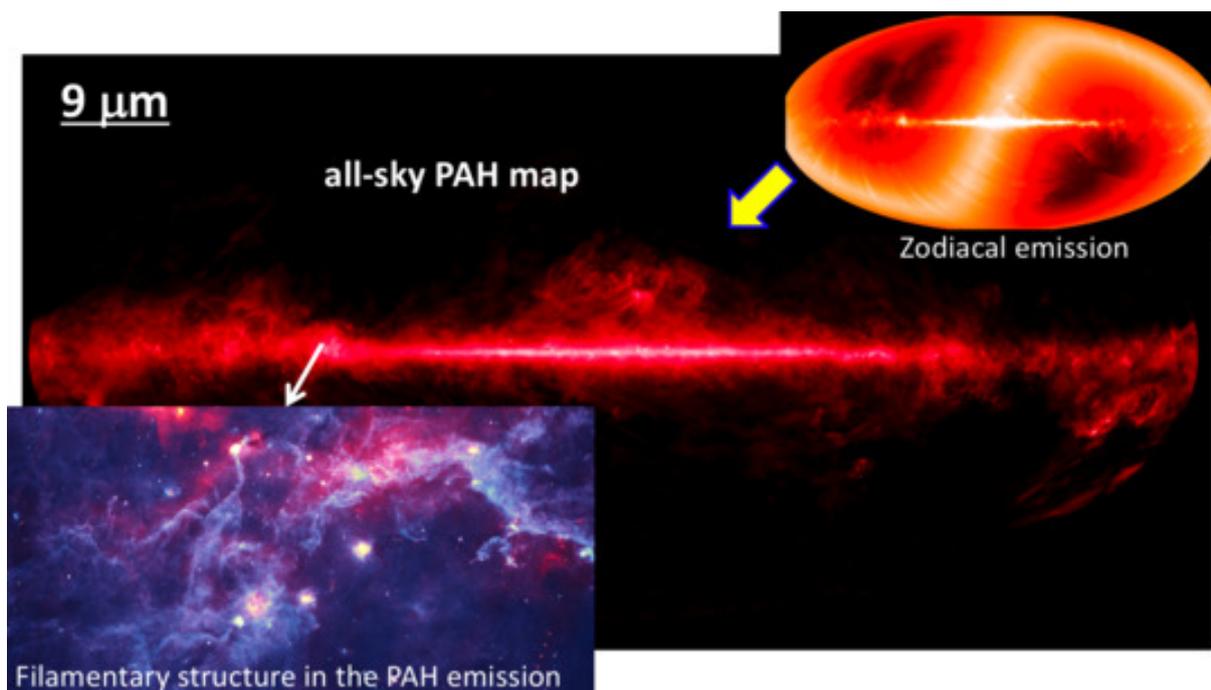
**Figure 2.** Schematic image to show the overall goal and objectives of the *SPICA* science program. The top-level goal, “Enrichment of the Universe with metal and dust, leading to the formation of habitable worlds”, is divided into two parts: “Metal and dust enrichment through galaxy evolution” and “Star and planetary formation to habitable systems”. To achieve the former part, *SPICA* will study the peak of the cosmic star formation history and beyond, their interplay with dust-obscured AGNs, and nearby galaxies including high- $z$  analogs through infrared spectroscopy. To achieve the latter part, *SPICA* will study Galactic filaments in star-forming regions, gas dissipation processes in proto-planetary disks and dust mineralogy in debris disks and the solar system through infrared imaging polarimetry and spectroscopy.

### 3. *AKARI* HERITAGE FOR *SPICA*

*AKARI* has provided important heritages for *SPICA* from both technical and scientific points of view. The most important technical heritage would probably be mechanical cryo-coolers; *AKARI* adopted the hybrid cryogenic system consisting of 180-liter liquid helium and cryo-coolers for the first time in space (Nakagawa et al. 2007), which was successfully operated during the  $\sim 5$ -year lifetime of *AKARI*. Another important technical heritage is the SiC mirrors of the *AKARI* telescope (Kaneda et al. 2007); the *AKARI* mirrors were the world-first cooled SiC mirrors in space. *Herschel* also adopted a SiC telescope. The *AKARI* telescope has the effective diameter of 69 cm with the wavefront error of  $\sim 0.5 \mu\text{m}$  RMS, operated at 6 K with the secondary-mirror focal adjustment mechanism. On the other hand, the *Herschel* telescope has the effective diameter as large as 3.28 m with the wavefront error of  $\sim 6 \mu\text{m}$  RMS, operated at 80 K with no focal adjustment mechanism. The *SPICA* telescope is designed to have the effective diameter of 2.5 m with the wavefront error of  $\sim 1.4 \mu\text{m}$  RMS, operated at  $< 8$  K with 5-axis optical adjustment mechanism for the secondary mirror. Hence the *SPICA* telescope

calls for more stringent requirements than those of *AKARI* and *Herschel* as a whole, and both heritages are important for *SPICA*.

From scientific point of view, *AKARI* has produced all-sky maps in the mid-infrared (Ishihara et al in prep.) and far-infrared (Doi et al. 2015; Takita et al. 2015). Figure 3 shows the *AKARI* all-sky map in the 9  $\mu\text{m}$  band, especially providing us information on rare targets to be studied with follow-up spectroscopy in an unbiased manner. Since the 9  $\mu\text{m}$  band brightness from our Galaxy is usually dominated by the polycyclic aromatic hydrocarbon (PAH) emission in the interstellar space, the 9  $\mu\text{m}$  band map is a unique product as the world-first all-sky PAH map. The near-infrared spectroscopy of *AKARI* has also produced many unique science results particularly on the PAH and ice features for the nearby Universe. For example, significant changes of the intensity ratios of the aromatic 3.3  $\mu\text{m}$  to aliphatic 3.4–3.6  $\mu\text{m}$  features are found within the galaxy M82 (Yamagishi et al. 2012) and also from galaxy to galaxy (Kondo et al. 2017). Yamagishi et al. (2015) performed a systematic study of the H<sub>2</sub>O and CO<sub>2</sub> ice features for star-forming galaxies to find that the abundance ratio of the H<sub>2</sub>O ice to the CO<sub>2</sub> ice changes significantly with the evolutionary stage of a galaxy.

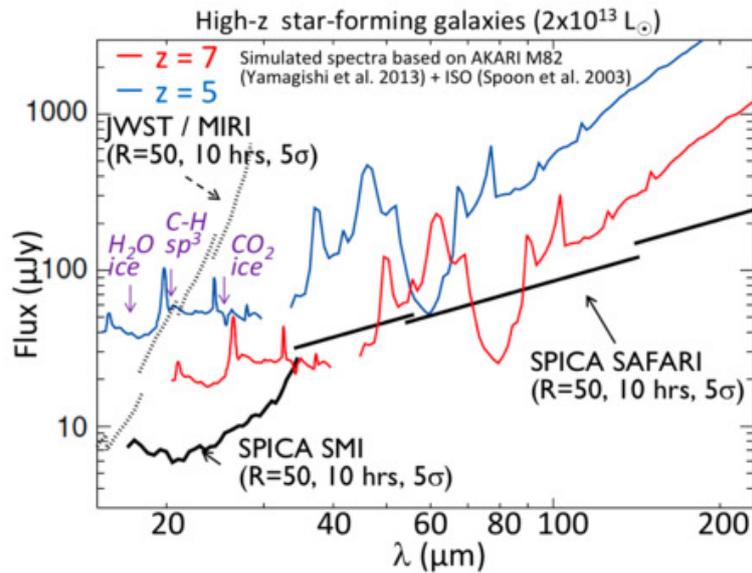


**Figure 3.** *AKARI* all-sky map in the 9  $\mu\text{m}$  band. The original all-sky survey data are dominated by the Zodiacal emission as shown in the upper right figure. In order to obtain a reliable all-sky map in the mid-infrared, precise modelling of the Zodiacal emission is particularly important (Kondo et al. 2016; Takaba et al. 2017). A filamentary structure like the filaments revealed by *Herschel* can be seen in the close-up image in the lower left figure.

*SPICA* can access the PAH features at high redshifts, while *JWST* studies those at relatively low redshifts. Figure 4 shows simulated spectra of star-forming galaxies with  $L_{\text{IR}} = 1 \times 10^{13} L_{\odot}$  at  $z = 5$  and 7, which are compared with the sensitivity limits of *SPICA*/SMI, SAFARI, and *JWST*/MIRI with the same conditions. The figure clearly demonstrates the *SPICA*'s advantage of spectroscopic sensitivities over *JWST* at wavelengths longer than 17  $\mu\text{m}$ , especially wide-range low-resolution spectroscopy suited for studies of dust features. *SPICA*'s mid- and far-infrared spectroscopy of high- $z$  galaxies provides the opportunity to detect the PAH features (and silicate features as well from high- $z$  quasars) at most distant galaxies ever observed. *SPICA* would enable not only detection but also characterization of the first organic matter (and mineral) in the Universe through inter-band ratios and band profiles. *SPICA* would also expand the results of the *AKARI* near-infrared spectroscopy on the ice features and the aromatic/aliphatic features for the nearby Universe to the high- $z$  Universe.

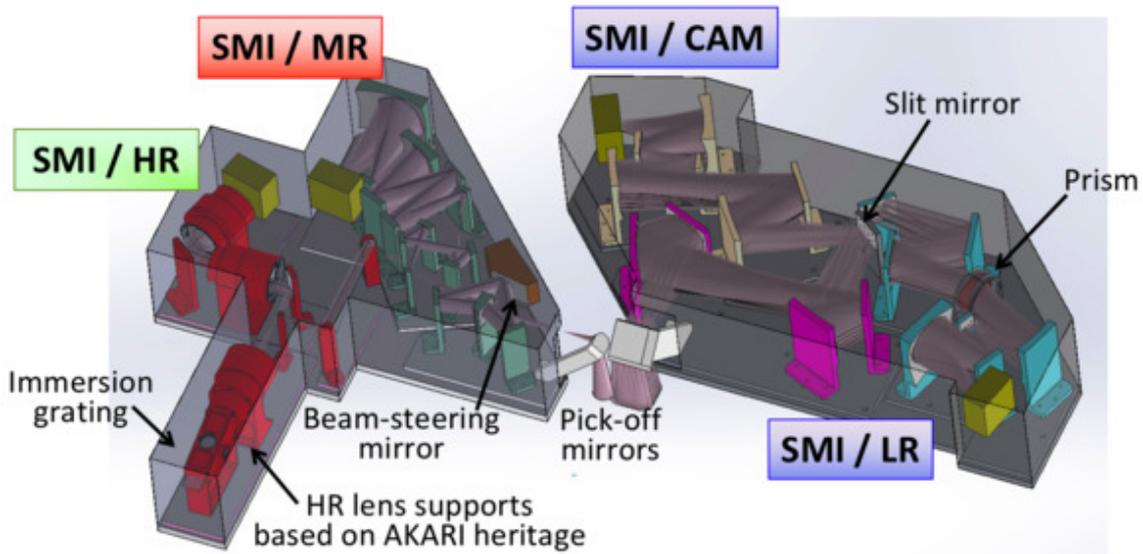
#### 4. CURRENT DESIGN OF *SPICA* MID-INFRARED INSTRUMENT (SMI)

The *SPICA*/SMI Japanese university consortium, in collaboration with Taiwan ASIAA, is responsible for the development of the mid-infrared instrument (Kaneda et al. 2016; Sakon et al. 2016), which is designed to provide a longer wavelength coverage and higher spectral mapping efficiency (i.e., higher spectral survey speed) compared to *JWST*, in addition to high-resolution spectroscopic capability. The SMI spectrometer/camera covers the wavelength range from 12 to 36  $\mu\text{m}$  with four separate channels, SMI/LR, /CAM, /MR and /HR with unprecedented high sensitivity. Figure 5 shows the current structural design of SMI. The total volume, mass and stiffness of the instrument are designed to meet the system requirements specified by JAXA. Our mechanical design concept is such that SMI should meet the stiffness requirements



**Figure 4.** Simulated spectra of star-forming galaxies with  $L_{\text{IR}} = 1 \times 10^{13} L_{\odot}$  at  $z = 5$  and  $7$ . For comparison, the sensitivity limits of *SPICA*/SMI, SAFARI, and *JWST*/MIRI are shown together with the same conditions ( $R = 50$ , 10 hours,  $5\sigma$ ).

by itself (i.e., without the instrument optical bench) with the Eigen frequency higher than 150 Hz as a whole and the Eigen frequency higher than 300 Hz for each optical component.



**Figure 5.** Current structural design of SMI, which consists of two big boxes; one is for SMI/LR and /CAM while the other is for SMI/MR and HR. Every mechanical component is designed to meet the stiffness requirements. Optical light paths are shown in grey lines for each channel

SMI/LR is a multi-slit prism spectrometer with a wide field-of-view using four  $10'$  long slits to execute low-resolution ( $R = 50$ – $120$ ) spectroscopic surveys with continuous coverage over the  $17$ – $36 \mu\text{m}$  wavelength domain. In SMI/LR, a  $10' \times 12'$  slit viewer camera, SMI/CAM, a broad band imager centered at  $34 \mu\text{m}$ , is implemented to accurately determine the positions of the slits on the sky for pointing reconstruction in creating spectral maps. Two Si:Sb  $1\text{K} \times 1\text{K}$  detectors are used, one for /LR and the other for /CAM. In Figure 5, the light passing through the slits is dispersed by the prism and focused on the /LR detector, while the light reflected on the slit mirror is focused on the /CAM detector. In the SMI/LR spectral mapping mode, the multi-slit spectrometer and the camera are operated simultaneously, yielding multi-object spectra from  $17$  to  $36 \mu\text{m}$  and  $R = 5$  deep images at  $34 \mu\text{m}$ .

SMI/MR and SMI/HR are two independent grating spectrometers covering the wavelength range  $18$ – $36 \mu\text{m}$  with  $R = 1300$ – $2300$ , and  $12$ – $18 \mu\text{m}$  with  $R = 28000$ , respectively. Because of their different operational wavelength ranges, the channels use different types of detectors, a  $1\text{K} \times 1\text{K}$  Si:Sb array for /MR and a  $1\text{K} \times 1\text{K}$  Si:As array for /HR. The SMI/MR

employs a combination of an Echelle grating and a cross-disperser to achieve a spectral resolution of  $R \sim 2000$  with a slit length of  $1'$ . For SMI/HR, an immersion grating is combined with a cross-disperser to yield  $R = 28000$  for a slit length of about  $4''$ . As shown in Figure 5, a beam-steering mirror is implemented to enable spectral mapping of small areas ( $1' \times 1' \sim 2' \times 2'$ ). We adopt the *AKARI* design for the lens supports of SMI/HR.

Prime science drivers are high-speed PAH spectral mapping of galaxies at  $z > 0.5$  with SMI/LR, wide-area surveys of obscured AGNs and starburst galaxies at  $z > 3-5$  with SMI/CAM, and velocity-resolved spectroscopy of gases in protoplanetary disks with SMI/HR. Complementary to these specific functions, SMI/MR provides more versatile spectroscopic functions, bridging the gap between *JWST*/MIRI and *SPICA*/SAFARI. We have performed conceptual design studies of SMI, and found a solution which satisfies the science requirements with relatively high technology readiness levels and practically available technical resources. Details of the result of the conceptual design study and sensitivity estimation can be found in Kaneda et al. (2016) and Sakon et al. (2016).

## 5. SUMMARY

*SPICA* is a future mid and far-infrared mission after *AKARI*, *Spitzer* and *Herschel*. Based on the *Planck*-type configuration, *SPICA* will employ a 2.5 m telescope actively cooled below 8 K by mechanical cryo-coolers in combination of passive radiative cooling to space. With the two focal-plane instruments, SMI and SAFARI, *SPICA* key science program will focus on high-sensitivity mid- and far-infrared spectroscopy and far-infrared polarimetry. *AKARI* has provided us with several important heritages for *SPICA*: the mechanical cryo-coolers and SiC telescope from the technical aspect as well as the all-sky maps and near-infrared (and far-infrared) spectral data from the scientific aspect. The Japanese nation-wide university consortium will develop the *SPICA* Mid-infrared Instrument (SMI) in collaboration with Taiwan ASIAA. Hence *SPICA* is our next crucial step after *AKARI* for future mid- and far-infrared astronomy.

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