The Space Infrared Interferometric Telescope (SPIRIT): Recent Study Results and a New Study Plan

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Industry Partners

Ball Aerospace
Boeing
Lockheed-Martin
Northrop Grumman

By providing sensitive sub-arcsecond resolution images and integral field spectroscopy in the 25 to 400 micron wavelength range, the Space Infrared Interferometric Telescope (SPIRIT) will: (1) revolutionize our understanding of the formation of planetary systems and enable us to "follow the water" as these systems develop; (2) reveal otherwise-undetectable exoplanets; (3) probe the atmospheres of extrasolar giant planets; and (4) make profound contributions to our understanding of the formation, merger history, and star formation history of galaxies.

Recent scientific discoveries, advances in technology, a revised launch vehicle catalog, and new programmatic priorities in the US and abroad combine to make a new SPIRIT mission concept study timely. Previously SPIRIT was studied as a cost-capped Origins Probe mission with a PI-led science program, and the observatory was designed for launch on an Atlas V medium vehicle. We have begun to explore scientific and programmatic benefits and costs associated with an alternative facility-class version of the SPIRIT mission. Such a mission would present the astronomical community with a dramatically new set of measurement capabilities and enable paradigm-setting discoveries. The Origins Probe SPIRIT design concept provides integral field spectroscopy throughout the far-IR with sub-arcsecond angular resolution, spectral resolution $\lambda/\Delta\lambda = 3000$ in a 1 arcmin instantaneous field of view. Several possible design changes might come at a relatively modest cost and permit enhanced sensitivity, still higher angular or spectral resolution, and enlargement of the field of view. An architectural change would enable unrestricted access to the sky. A "Heavy" launch vehicle could accommodate a larger observatory, enabling the design changes we plan to study. SPIRIT's science operations could follow the Spitzer model.

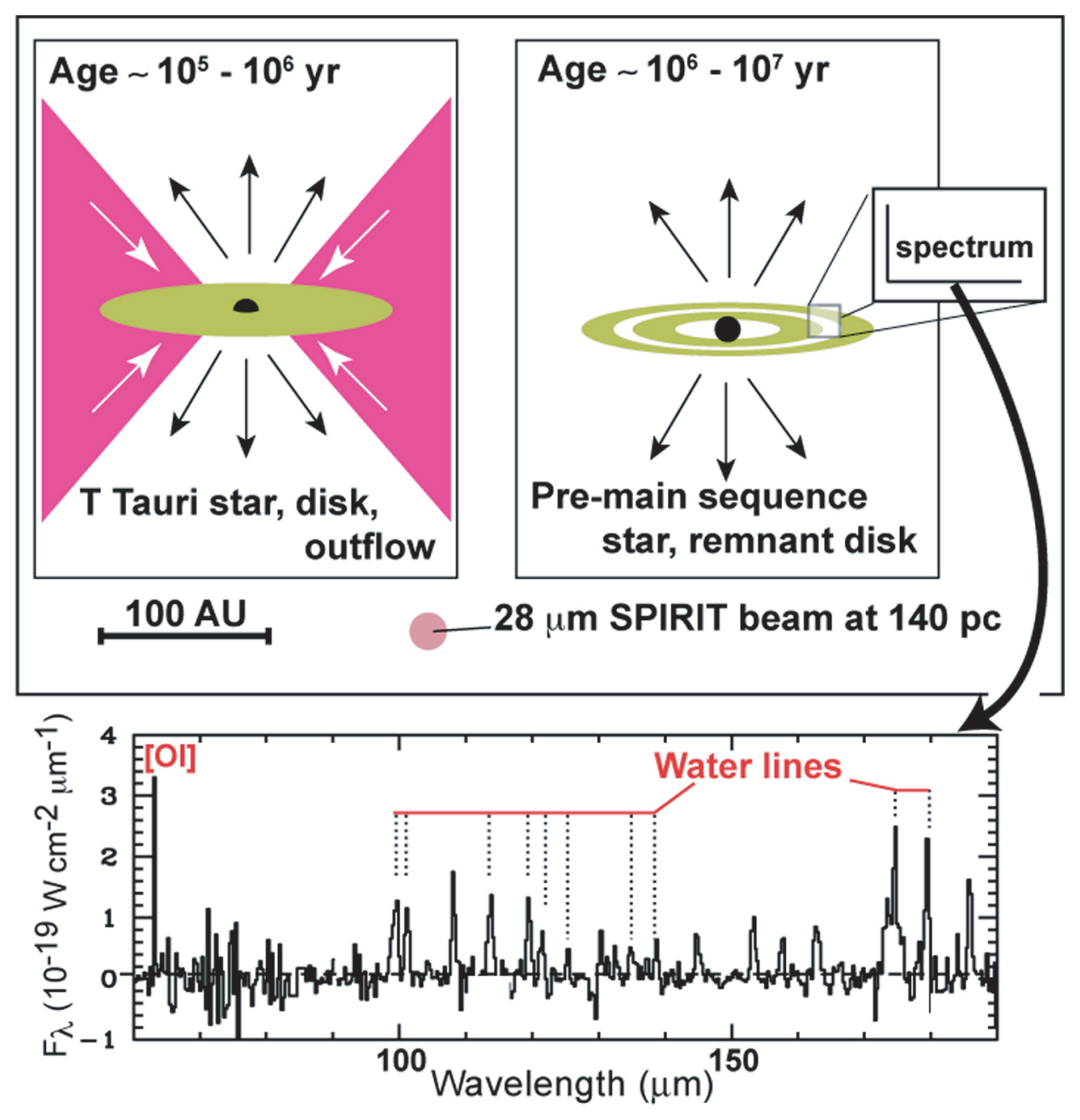
Results of the SPIRIT mission concept studies will be presented to the panels convened by the National Academies for the 2010 Astrophysics Decadal Survey. This paper summarizes SPIRIT's potential for ground-breaking scientific discovery, reviews features of the SPIRIT Origins Probe mission concept, and outlines our plan to study a facility-class version of the SPIRIT mission.

A New Context for SPIRIT

- new science (e.g., Spitzer spectroscopic observations of transiting exoplanets)
- new technology (e.g., JWST cryocooler and wavefront sensing and control technologies applicable to SPIRIT)
- exozodi structure reconnaissance needed before terrestrial exoplanet finding and characterization
- new launch vehicle price structure
- upcoming Decadal Survey

SCIENCE WITH SPIRIT

1. Learn how planetary systems form from protostellar disks, and "follow the water"



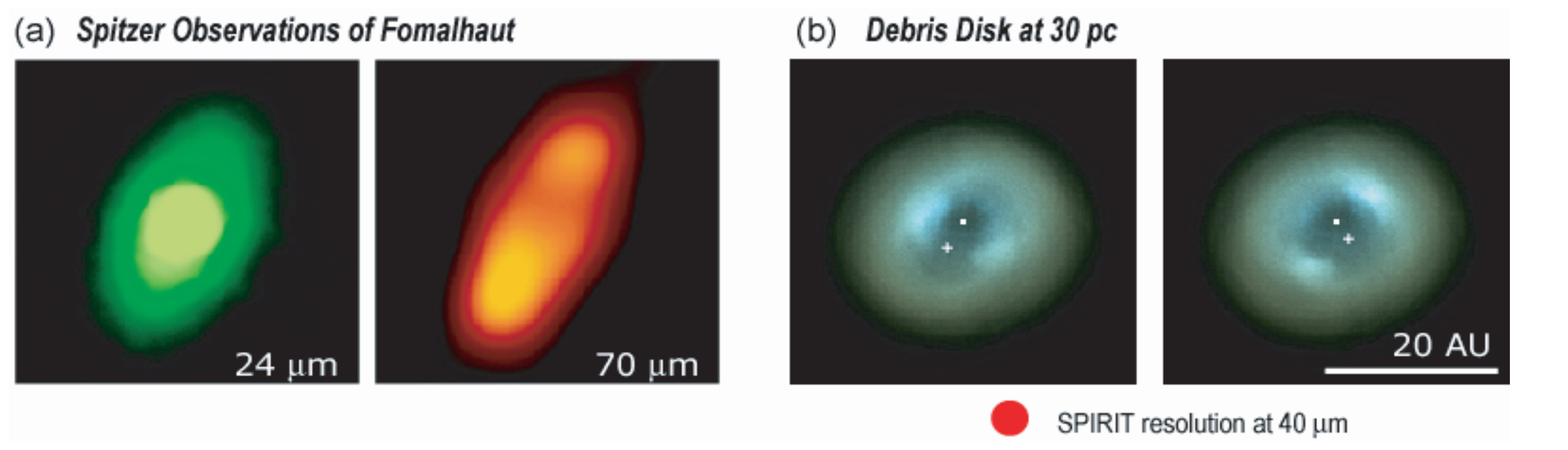
SPIRIT will image protostellar disks in their line and continuum emission, and map H_2, HD, H_2O, and C and O fine structure line emission in protoplanetary disks, providing a spectrum like the one shown here* at each of many spatial locations.

* Continuum-subtracted ISO spectrum of a Class 0 protostar (Nisini et al. 2000).

SPIRIT will access the rich far-IR spectrum of the H_2O molecule, map the water distribution in protoplanetary disks to study the formation of the water reservoir, and search for evaporating water in extrasolar comet trails. SPIRIT will map the distribution of frozen water by observing H_2O ice features at 44 and 63 μm.

Sub-arcsecond angular resolution will be needed to resolve the structures of interest.

2. Characterize the family of extrasolar planetary systems by imaging the structure in debris disks to understand how and where planets form, and why some planets are ice giants and others are rocky



Spatially resolved far-IR images of debris disks, and particularly multi-epoch observations, can be used to determine the locations, masses, and orbits of exoplanets that are undetectable with motion-dependent (astrometric or Doppler) techniques.

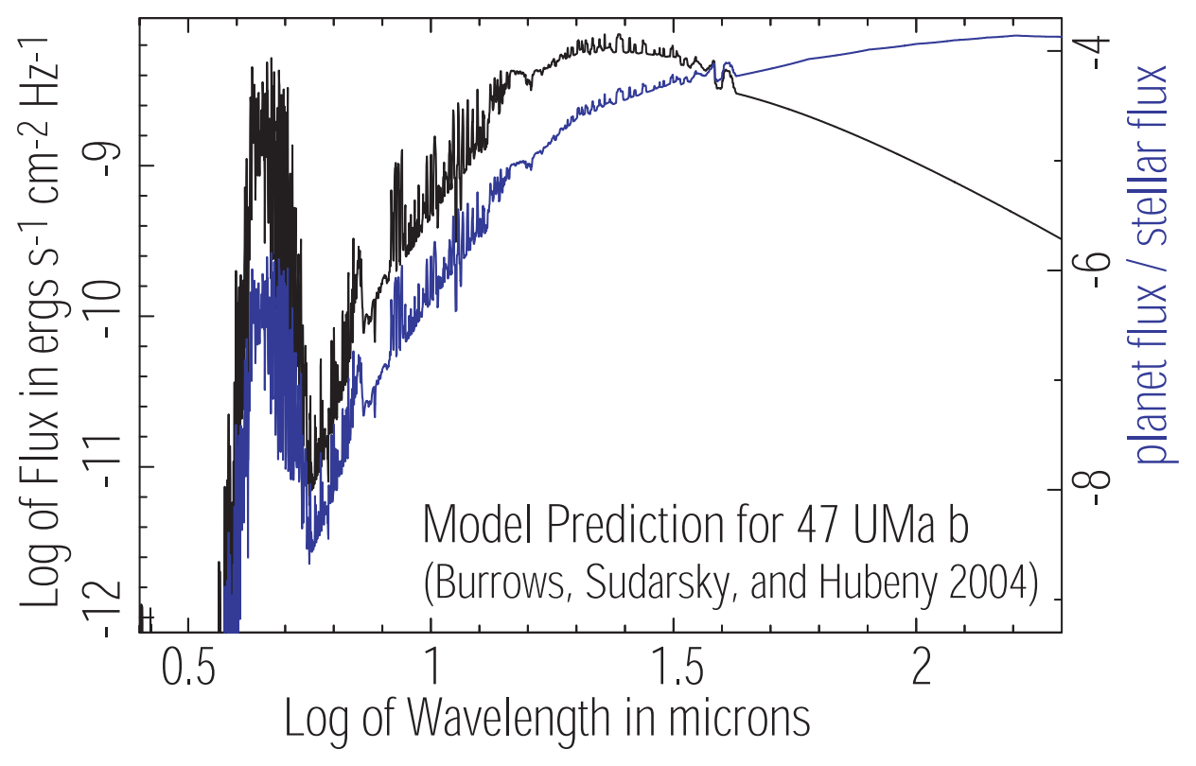
With angular resolution a hundred-fold better than that of Spitzer, SPIRIT will provide clear images of a large statistical sample of debris disks, enabling discoveries of new planets and a great improvement in our understanding of the factors that influence the evolution of planetary systems. Spitzer can only resolve four nearby debris disks, including Fomalhaut, shown here (a) at 24 and 70 μm (Stapelfeldt et al. 2004). The model images in (b), based on ε Eri but scaled to 30 pc, show the predicted far-IR emission at 40, 60, and 100 μm color-coded as blue, green, and red, respectively. The dust-trapping planet (+) is shown at two orbital phases, and the resonantly trapped dust grains can be seen to have moved.

3. Probe the atmospheres of extrasolar giant planets

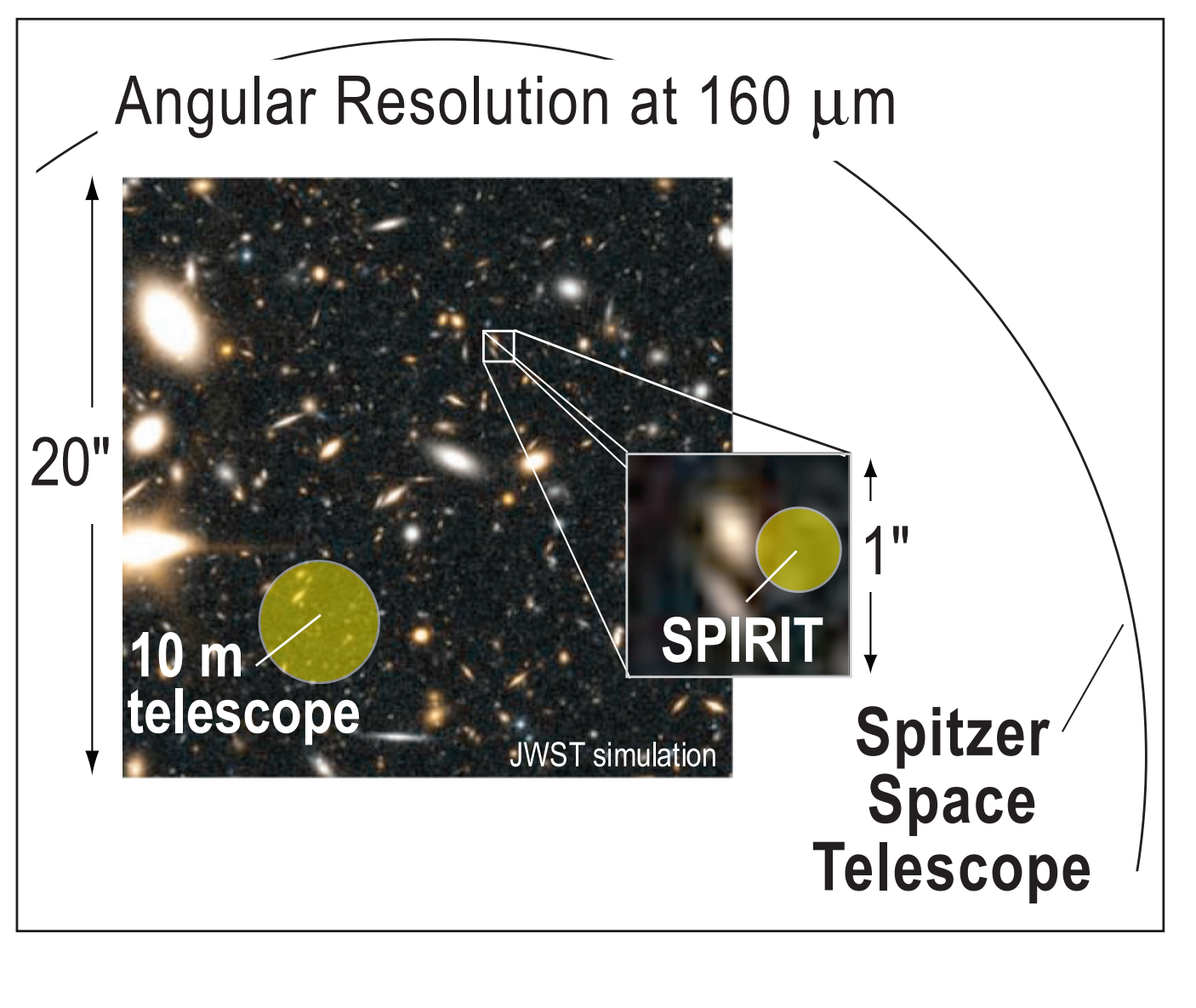
Spitzer observations of transiting extrasolar giant planets demonstrate the value of IR spectroscopy as a tool to constrain a planet's temperature structure and probe the composition of its atmosphere.

SPIRIT will measure the spectra of giant exoplanets at larger orbital distances. As SPIRIT's interferometric baseline changes the planet's fringes modulate while the star produces a stable fringe pattern. The modulated interferogram can be extracted and then Fourier transformed to obtain the spectrum of the planet.

Observations of the far-IR spectra of extrasolar giant planets will help us understand the internal structure, formation, and migration of these planets to smaller orbits, and to measure the composition of their atmospheres.



4. Learn how high-redshift galaxies formed and merged to form the present-day population of galaxies



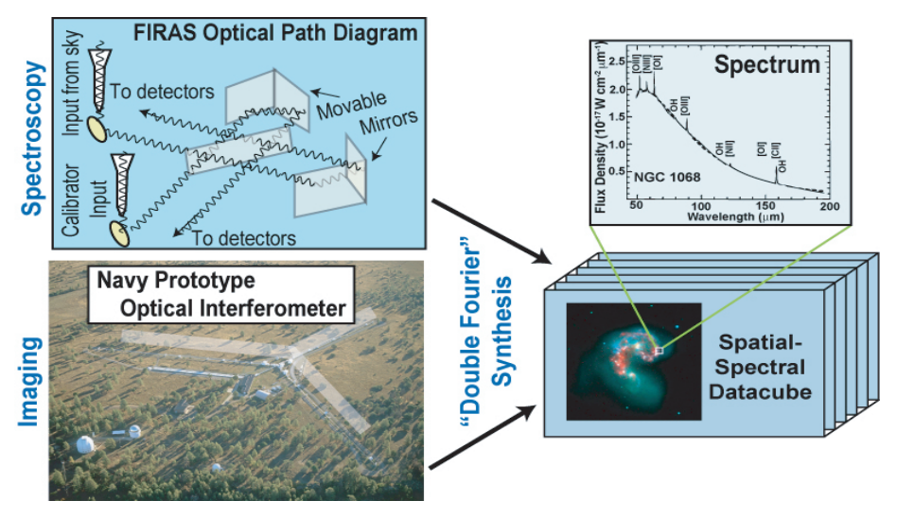
The James Webb Space Telescope (JWST) will probe the rest-frame *visible* spectrum in galaxies out to redshifts z > 10. The Atacama Large Millimeter Array (ALMA) will make corresponding measurements of the rest-frame far-IR spectrum in objects at redshifts z > 3. However, huge changes are thought to have occurred in galaxies since the time corresponding to redshift z = 3. An observatory capable of measuring both the far-IR dust continuum and emission lines from individual sources in the 0 < z < 3 range while simultaneously providing the angular resolution to study individual sources will bridge a significant gap in our knowledge.

Figure at left - SPIRIT will distinguish the emissions of individual high-z objects at 160 μm, a wavelength close to that of the brightest line in the spectrum of the Milky Way. Spitzer sees many objects per resolution element at this wavelength, and even a 10 m diameter telescope would be confusion-limited.

CONCEPTS FOR THE SPIRIT MISSION

Origins Probe Mission Concept

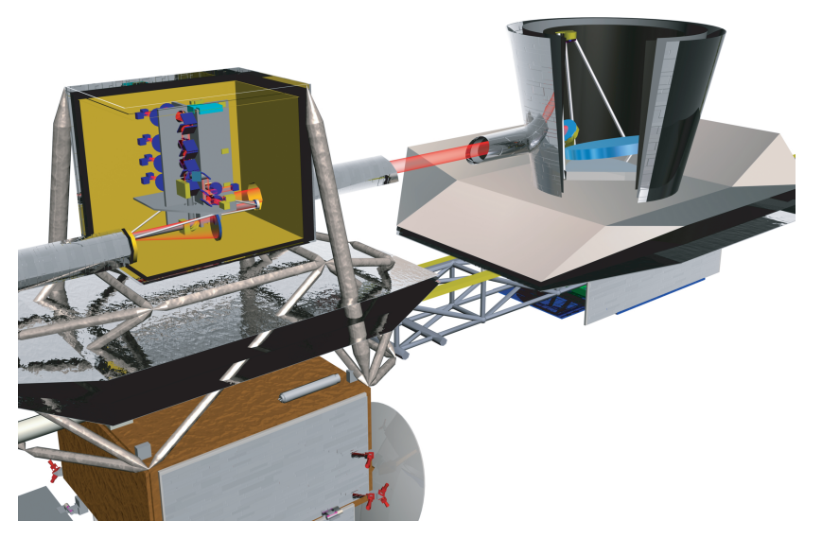
SPIRIT is a "double Fourier" interferometer; it produces high spatial and spectral resolution integral field spectroscopic data over its entire wavelength range. SPIRIT has two 1-m diameter light collecting telescopes and a central beam-combining instrument, all connected to a truss structure. Trolleys transport the telescopes to provide variable interferometric baselines ranging from 6 m to 36 m. The entire structure rotates during an observation while the rotation axis points toward the target field. Baseline sampling can be tailored to the expected spatial brightness structure in the scene and the *u*-*v* plane coverage can be dense, so SPIRIT will produce excellent images. An optical delay line is scanned for each baseline observed, yielding a set of white light interferograms, one for each pixel in SPIRIT's four pairs of detector arrays. Spectral information is available in these interferograms. The delay line is scanned through the distance required to (a) equalize path lengths through the two arms of the interferometer for all angles in a 1 arcmin wide FOV, and (b) provide spectral resolution R ~ 3000. After processing on the ground, the SPIRIT measurements yield a spatial-spectral data cube with sub-arcsecond angular resolution over a 1 arcmin square field and a spectrum for every resolution element.



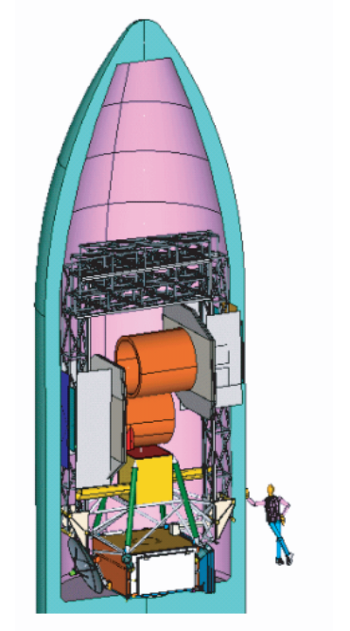
SPIRIT combines the capabilities of an imaging interferometer with those of a Fourier Transform Spectrometer to produce spatial-spectral data cubes.

SPIRIT's telescopes are cooled to 4 K and small arrays (up to 14 x 14 pixels) of Transition-Edge Sensor bolometers cooled to 50 mK are used to provide astrophysical background-limited sensitivity across a four-octave spectral range from 25 to 400 μm. An internal metrology system provides the information required to maintain optical system alignment and pathlength control. Near-IR point sources in the science field of view are used as phase references.

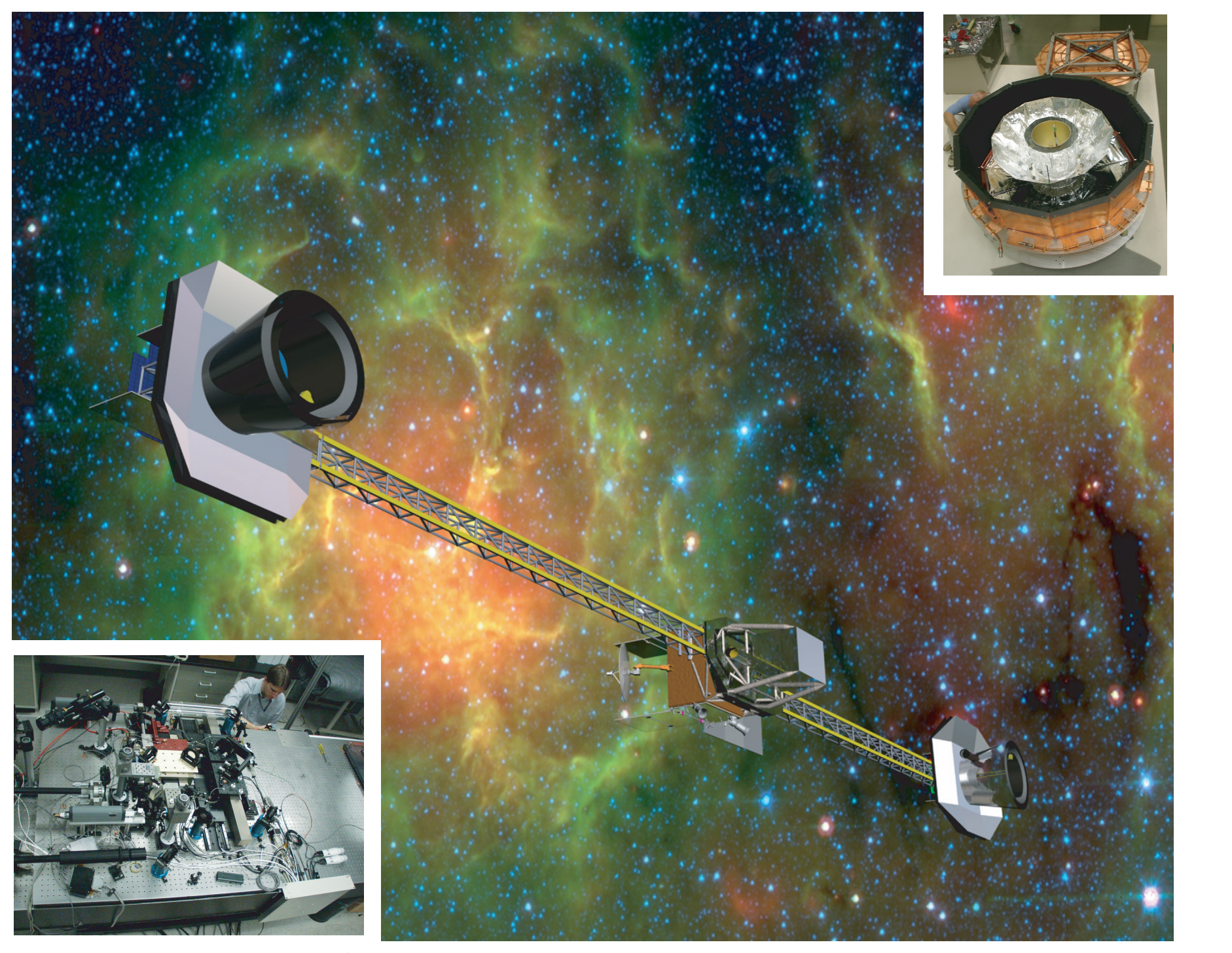
SPIRIT will operate in a large-amplitude Lissajous orbit around Sun-Earth L2. The instantaneous field of regard is limited by the size of the sun shades to a +/-20 deg cone around the anti-Sun direction. Over the course of a year, SPIRIT will have a 40-degree wide viewing zone around the ecliptic plane. The astronomical sources available in this zone enable fulfilment of the science objectives of the mission.



Two movable afocal off-axis telescopes and a single beam-combining instrument are the main components of the SPIRIT observatory.



The Origins Probe version of SPIRIT and its expendable launch support structure, when stowed for launch, are 8.7 m tall and fit into an Atlas V 5 m medium fairing dynamic envelope. A Delta IV Heavy vehicle has nearly twice the usable fairing volume and could hold a longer interferometer with larger telescopes.



In the Origins Probe concept for SPIRIT shown above the telescopes are positioned to measure a 36 m interferometric baseline. The Wide-field Imaging Interferometry Testbed (inset, lower left) replicates the functionality and behavior of SPIRIT. The testbed enables us to understand practical limitations of the wide-field spatial-spectral interferometric technique and to gain the technical ability to build a working far-IR interferometer for space reliably and quickly. Test results from a cryo-thermal engineering model (inset, upper right) agree well with pre-test thermal model predictions, giving us confidence that SPIRIT's telescopes and instrument module can be cooled with JWST-like cryocoolers.

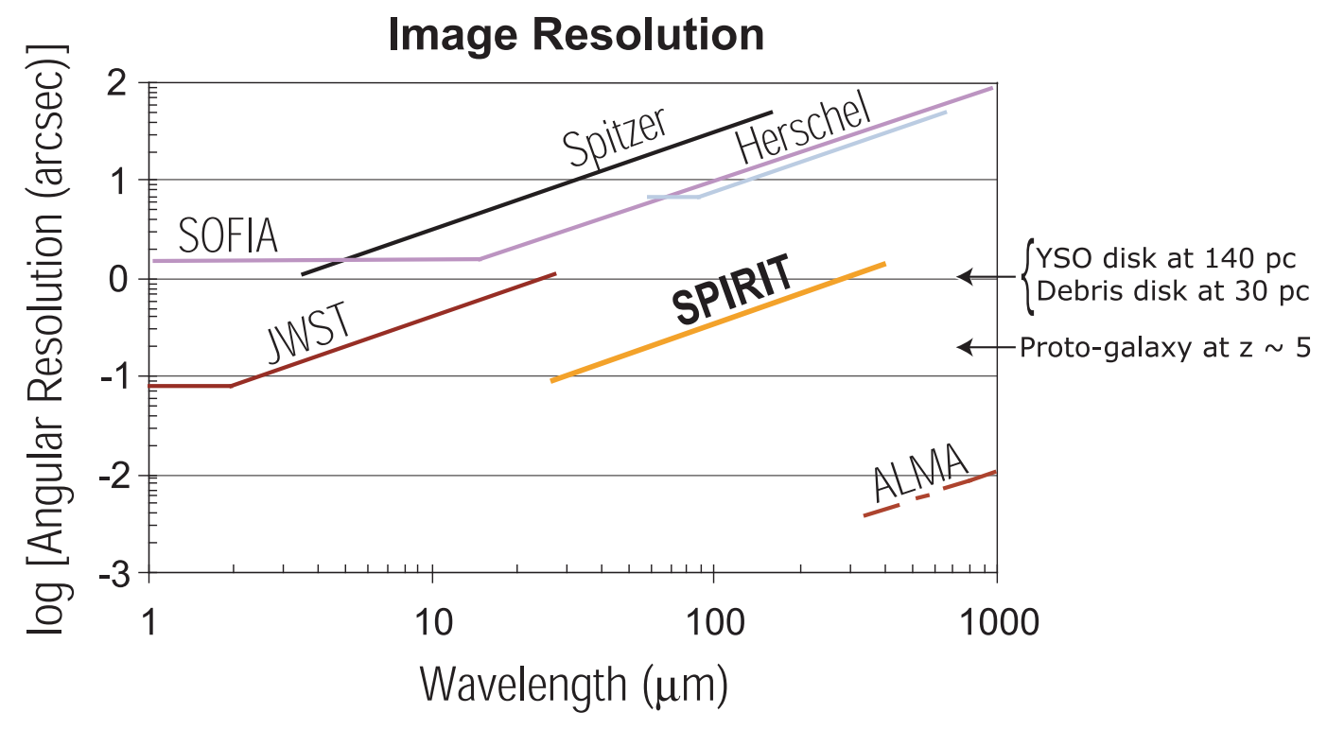
	SPIRIT Origins Probe	SPIRIT Facility-class (notional)
Key Requirements		
Wavelength Range, μm	25 - 400	25 - 400
Field of View, arcmin	1.0	2
Angular Resolution, arcsec	0.3 (λ/100 μm)	0.2 (λ/100 μm)
Spectral Resolution, $\lambda/\Delta\lambda$	~3000 at all wavelengths	>3000 at all wavelengths
Field of Regard	+/-20 deg around ecliptic plane	entire sky
Mission Life (on station), yrs	3 (with propellant for 5)	5 (with propellant for 10)
Average Time per Target, hrs	29	TBD
Science Data Rate (derived), Mb/s	5.4	TBD
Optics Temperature, K	4	4
Focal Plane Temperature, K	0.05	0.05
Uncalibrated Visibility	0.90	0.90
Phase B Start to Launch, months	72 (incl. 10 mo. margin)	TBD
Key Configuration Parameters		
Telescopes	Two off-axis, afocal	Two off-axis, afocal
Telescope Diameter, m	1.0	>1 (maybe ~2 - 3)
Instrument	Michelson beam combiner, double Fourier	Michelson beam combiner, double Fourier
Baseline range (min, max), m	6, 36	6, ~54
Structure	Rigid truss	Rigid truss
Cryocooling	ACTDP** (uprated) coolers	ACTDP** (uprated) coolers
Sunshield Location	Above boom	Below boom
Propulsion System	Hydrazine (monoprop.)	Hydrazine (monoprop.)
ACS Type/Accuracy	6 Rx whl 100 Nms / 5.0 arcsec	TBD
Star Trackers	Two on boom	Two on boom
Slew Rate (peak), deg per min	1	TBD
High Gain Antenna Type	Ka band, 2-axis gimbal	Ka band, 2-axis gimbal
Ground Contacts	2.0 hr/2 days DSN, Ka band	TBD
Observatory Mass (wet), kg *	4497	TBD
Instrument Power (EOL), W *	1081 for combiner + 1036 per collector telescope	TBD
Launch Vehicle and Fairing	5 m diam, Atlas V medium	5 m diam, Delta IV Heavy

* Mass & Power values shown include 25% contingency
** Advanced Cryocooler Technology Development Program

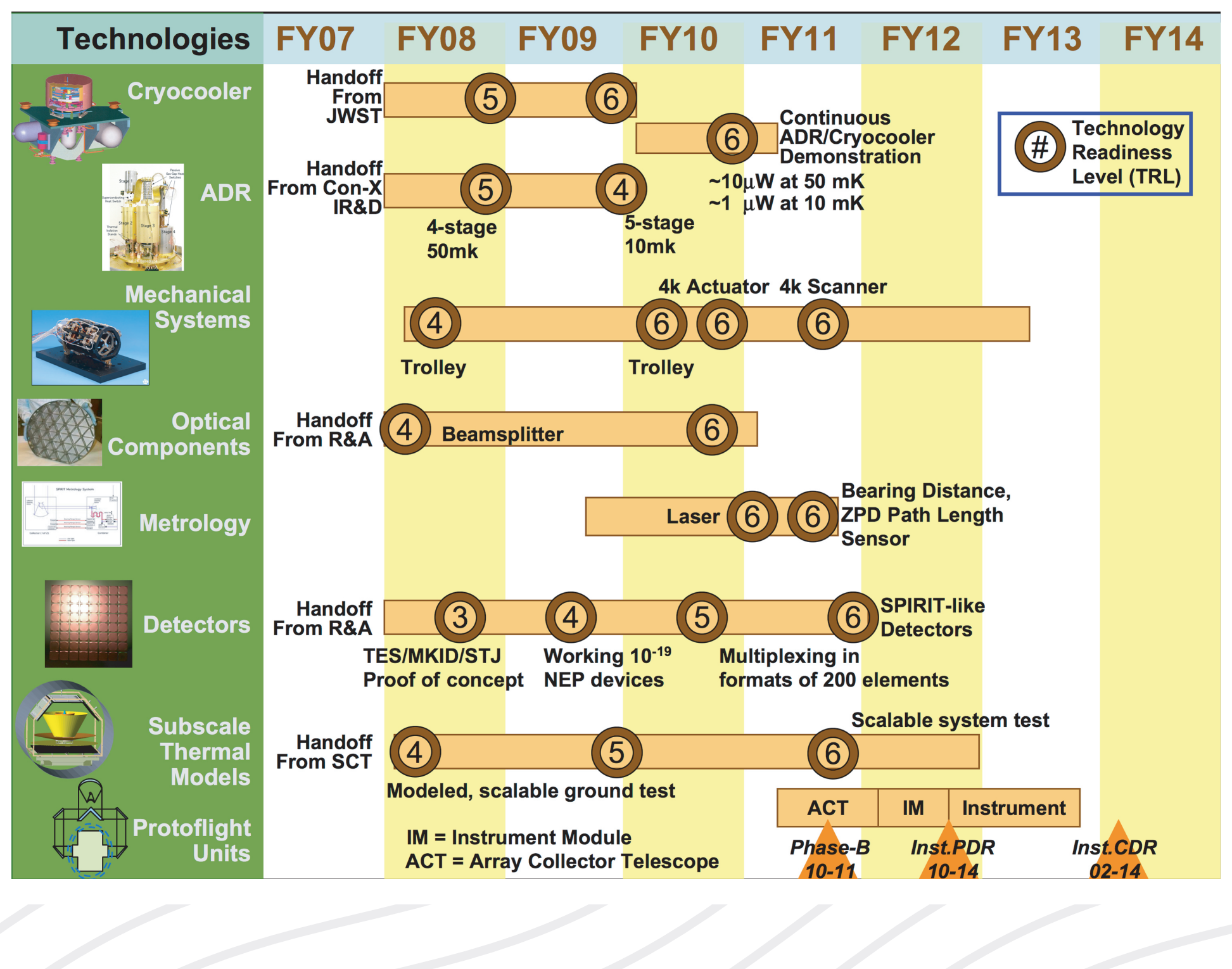
Facility-class Mission Options

Option	Benefit
Guest Observer program like Spitzer's	Greater scientific return
Longer mission lifetime	Greater scientific return; longer baseline for multi-epoch exoplanet observations
Larger light-collecting telescopes	Improved sensitivity
Longer boom for increased maximum baseline	Better angular resolution
Larger-format detector arrays	Wider instantaneous field of view
Longer optical delay scan range	Increased spectral resolution
Entire structure shielded by multi-layer sun shade	All-sky field of regard

SPIRIT will deliver one hundred times better angular resolution than Spitzer, and resolution comparable to that of JWST, but at ten times longer wavelengths, where protoplanetary disks, debris disks, and some galaxies emit most of their light.



SPIRIT TECHNOLOGIES



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