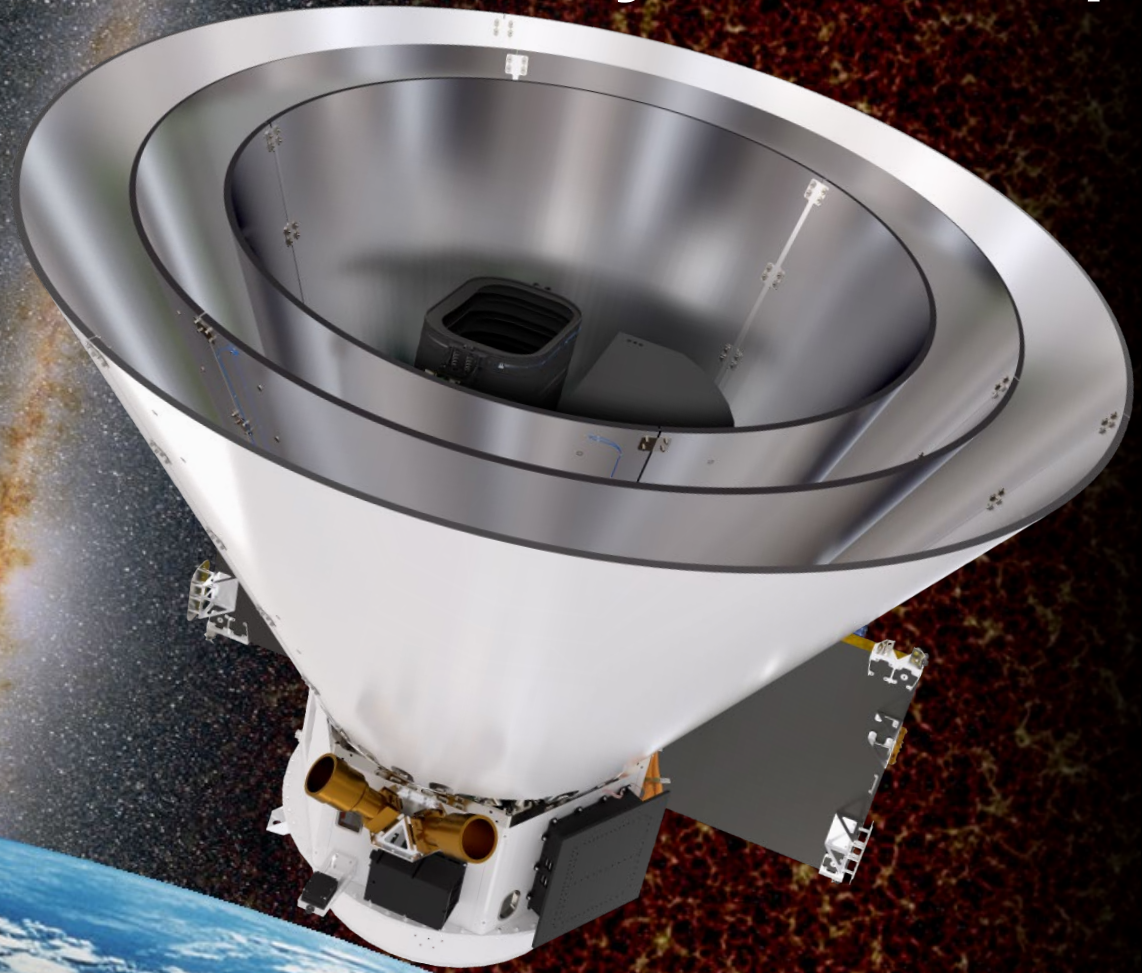
SPHEREx: An All-Sky Infrared Spectral Survey Satellite



Small Mission, Big Science

- Origin of the Universe
- Origin and History of Galaxies
- Origin of Water in Planetary Systems
- First All-sky Infrared Spectral Survey

Status Update

- Instrument Tested and Delivered
- Observatory I&T in Progress
- Working Observatory TVAC Anomalies
- Feb 2025 Launch

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SPHEREx ADDRESSES 3 FUNDAMENTAL QUESTIONS

Decadal Survey for Astronomy and Astrophysics 2020 Theme

How Did the Universe Begin?

New Messengers and New Physics: *What set the Big Bang in motion?*

How Did Galaxies Begin?

Cosmic Ecosystems: *How did the intergalactic medium and the first sources of radiation evolve from cosmic dawn through the epoch of reionization?*

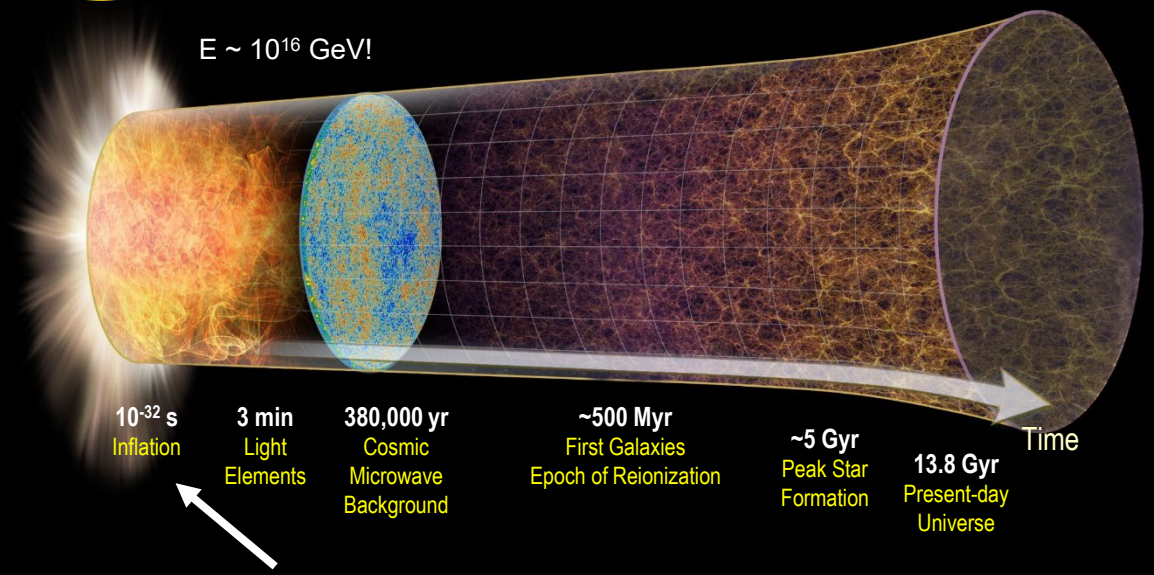
What are the Conditions for Life Outside the Solar System?

Worlds and Suns in Context: *How do habitable environments arise and evolve within the context of their planetary systems?*

…While Creating a Unique All-Sky Spectral Survey

Community interest: 73 non-team publications on SPHEREx, 41 SPHEREx team papers with 750 citations

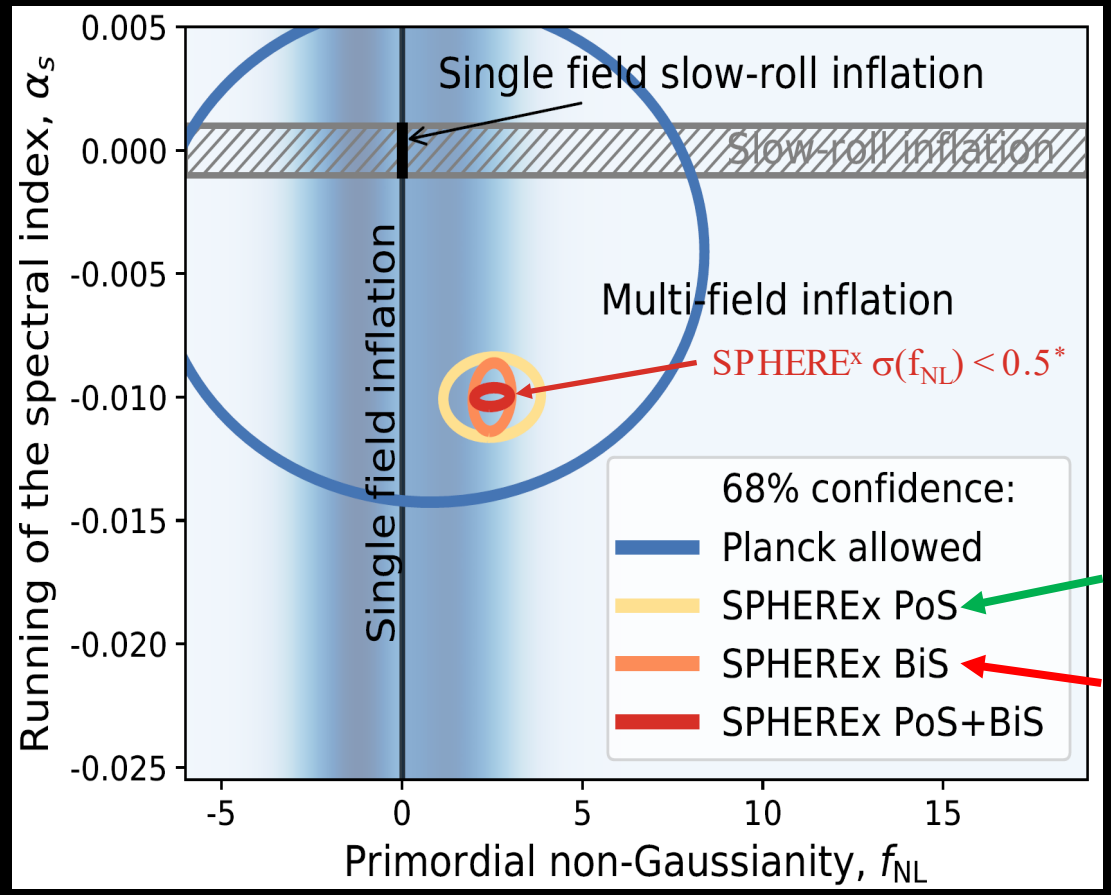
HOW DID THE UNIVERSE BEGIN?



Probing Inflation with Non-Gaussianity (f_{NL})

- **Single-field models** predict $f_{NL} < 0.01$
- **Multi-field models** predict $f_{NL} \gtrsim 1$
- **Non-inflationary models** (Steinhardt *et al.*) predict $f_{NL} \sim 1$

Did Multiple Fields Drive Inflation?

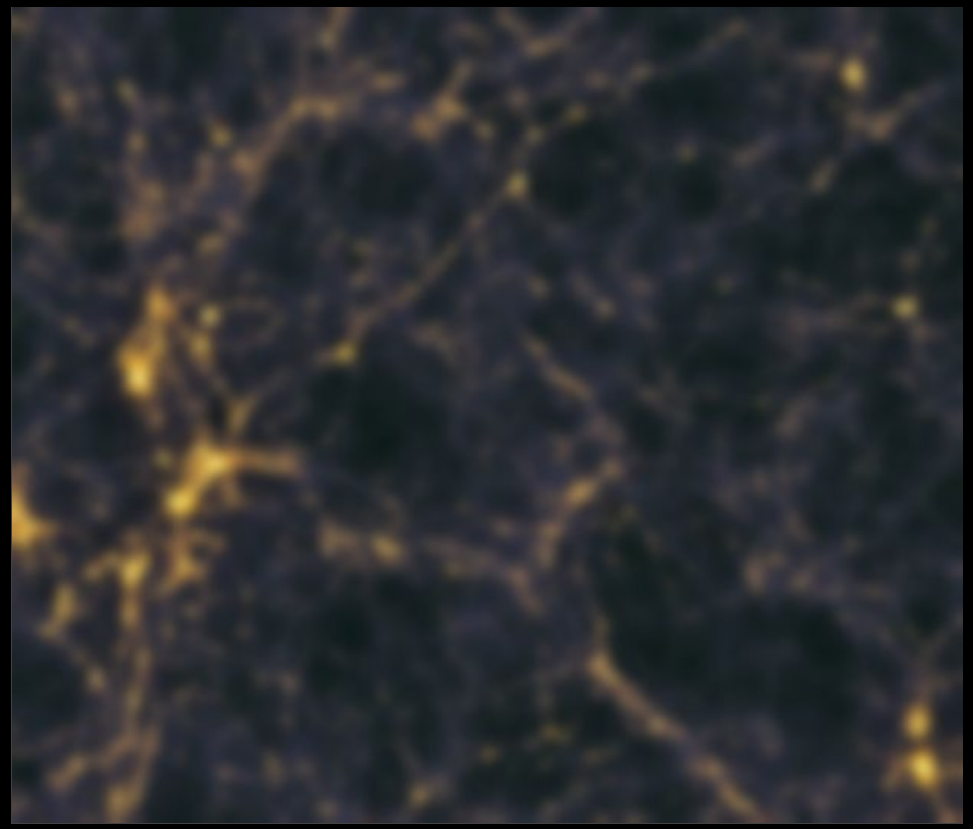


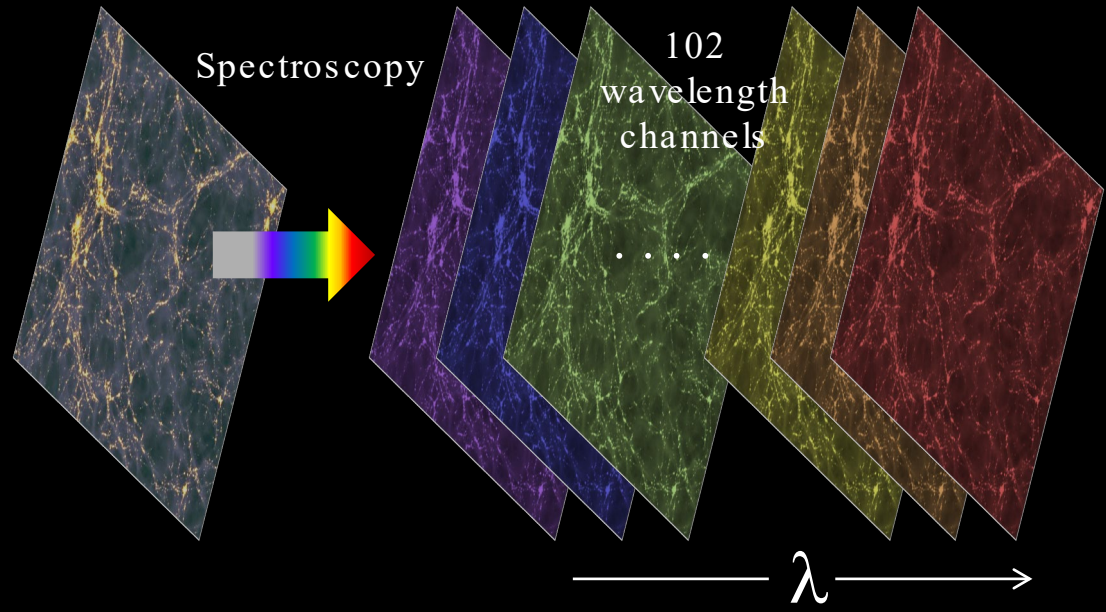
*Multi-tracer analysis exploiting LPNG bias (b_ϕ) may offer further improvement!

2020 Astro Decadal: "The search for primordial non-Gaussianity, either to detect a signal or to constrain f_{NL} to be below 1…is particularly important"

HOW DID GALAXIES BEGIN?

Intensity Mapping





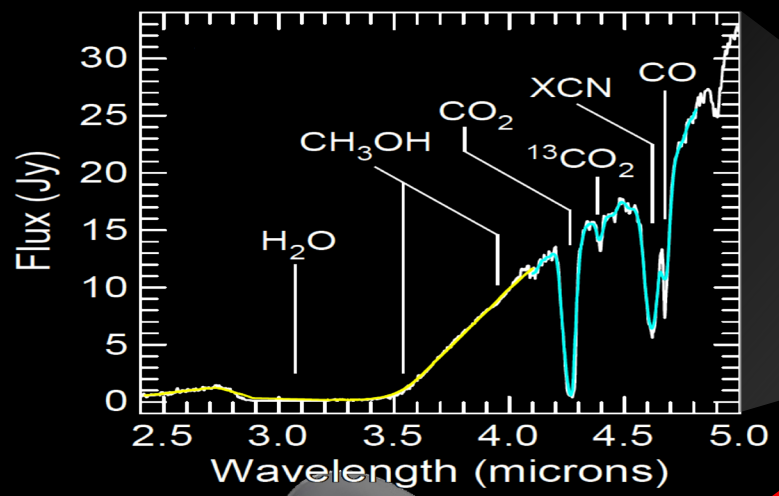
Spectral Decomposition Determines

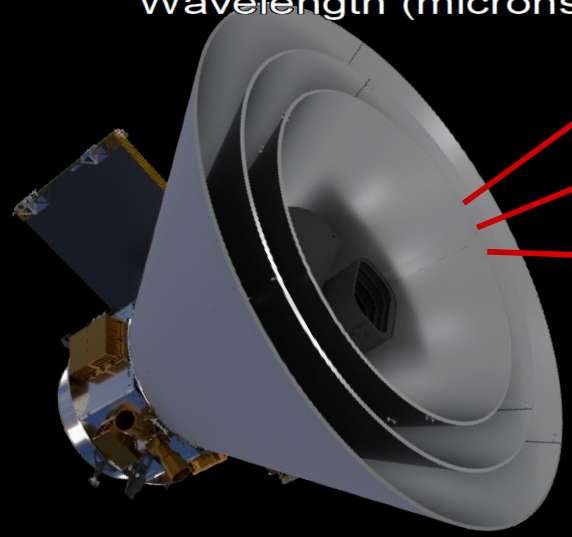
- Emission from all galaxies
- Dwarf galaxies responsible for reionization
- Diffuse emission from stripped stars
- Dark matter decay (?)

- Complements galaxy-by-galaxy surveys
- Method used on CIBER, Spitzer, Herschel, Planck

Intensity Mapping captures the light emitted from everything that gravitationally clusters

WHAT ARE THE CONDITIONS FOR LIFE OUTSIDE THE SOLAR SYSTEM?





Background star

Dense Clouds

Young Stellar Envelopes

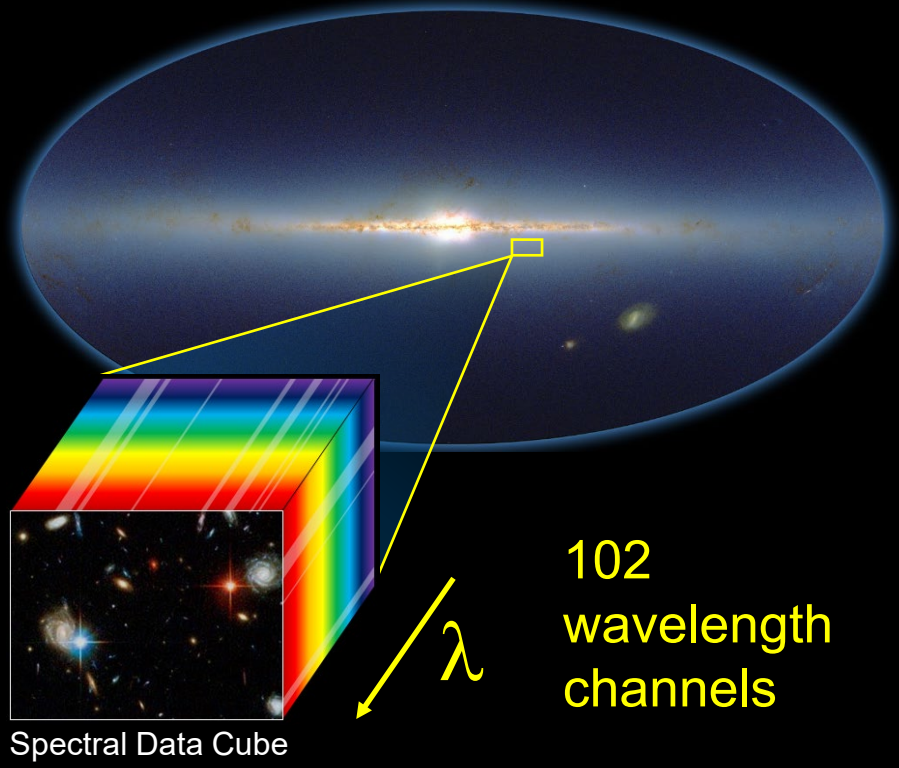
Protoplanetary Disks

Young Solar Systems

More than 99 % interstellar water is locked in ice: 'Follow the Water' means 'Follow the Ice'

SPHEREx PROVIDES A RICH ALL-SKY SPECTRAL CATALOG

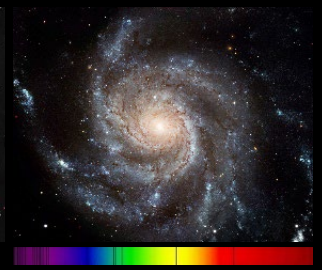
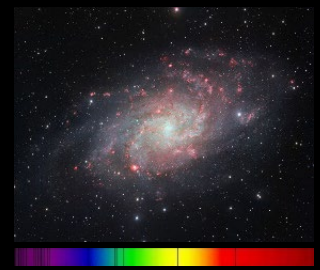
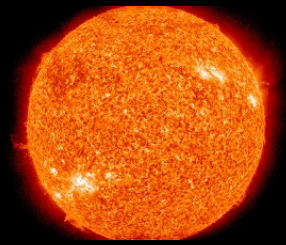
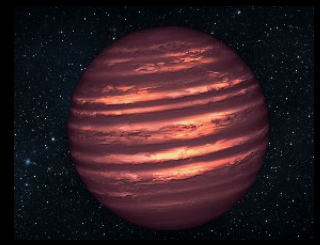
All-Sky Survey



102 wavelength channels

SPHEREx provides a new and unique dataset

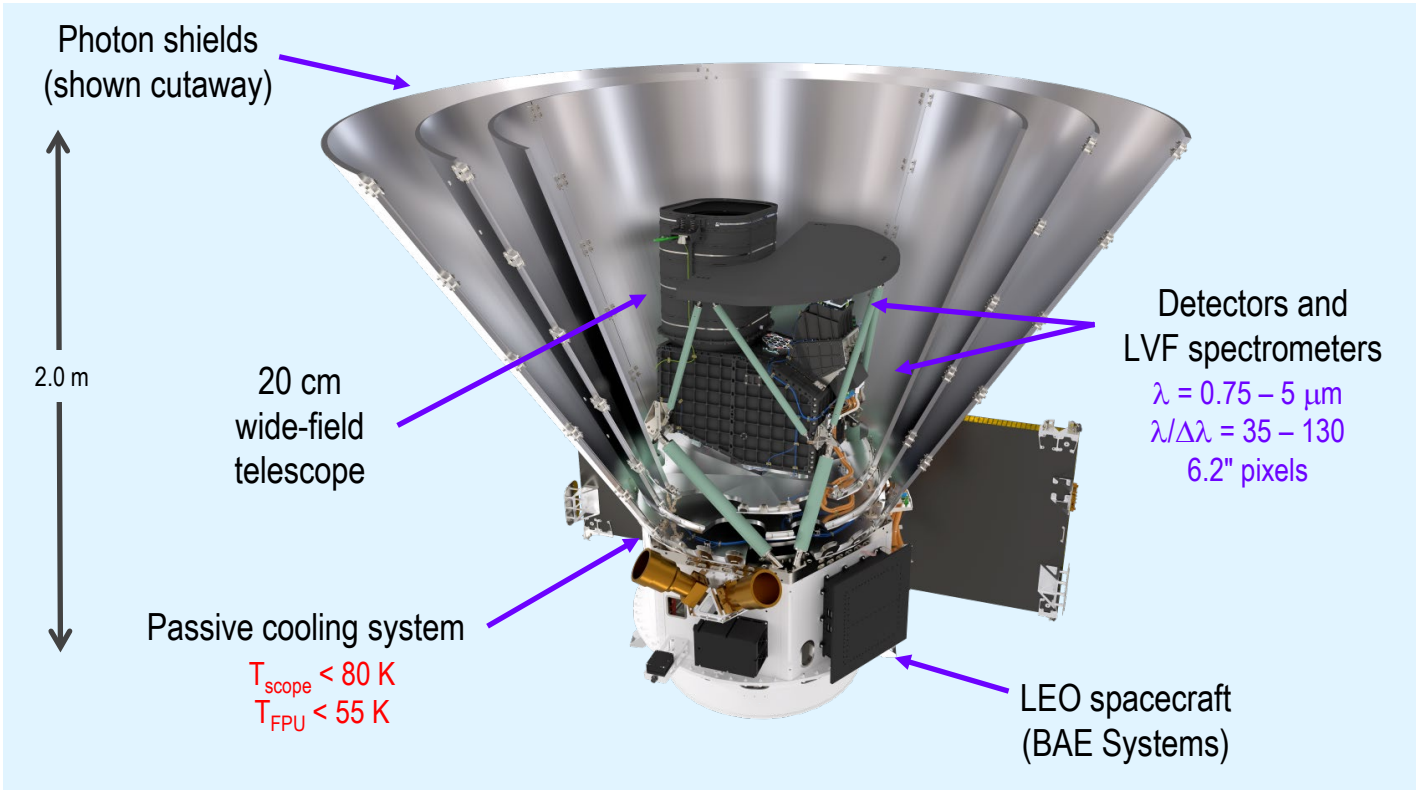
a complete near-infrared spectrum for every 6″ pixel on the sky

	Detected	Med. Accuracy Spectra	High Accuracy Spectra	Clusters
Galaxies	1.4 billion	120 million	10 million	100,000
				
	Main Seq. Spectra	**Dust-forming**	**Brown Dwarfs**	**Cataclysms**
Stars	> 100 million	10,000	> 400	> 1,000
				
	Quasars	**Quasars z >7**	**Asteroids & Comets**	**Galactic Line Maps**
Other	> 1.5 million	3 – 300?	100,000	PAH, HI, H_2
				

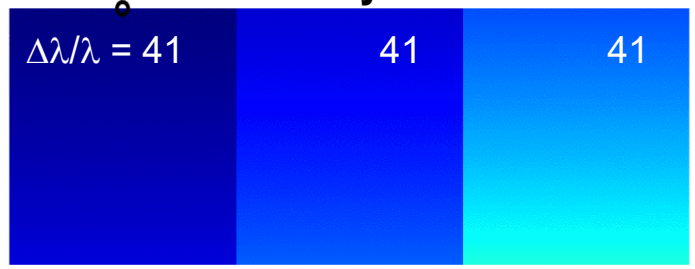
We expect many exciting discoveries to come from the community

- IPAC rapidly delivers calibrated ‘spectral images’ to public
- IPAC also provides analysis tools and catalogs for public use

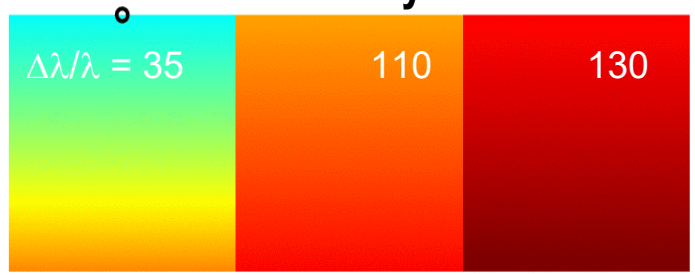
SPHEREx IN A NUTSHELL



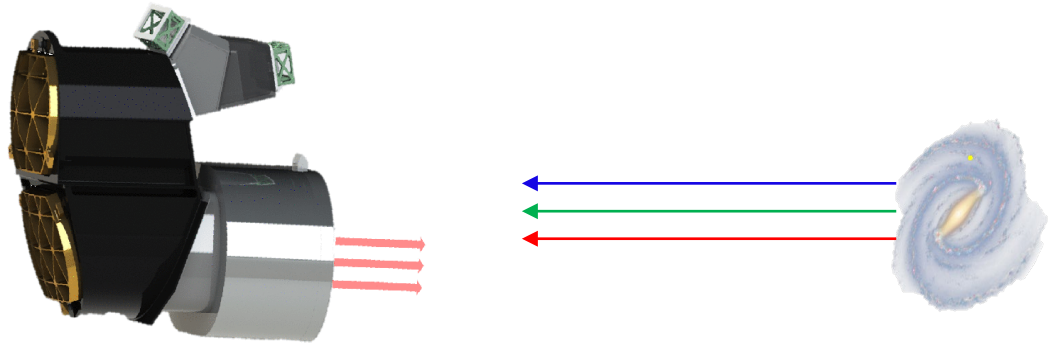
Reflected by Dichroic

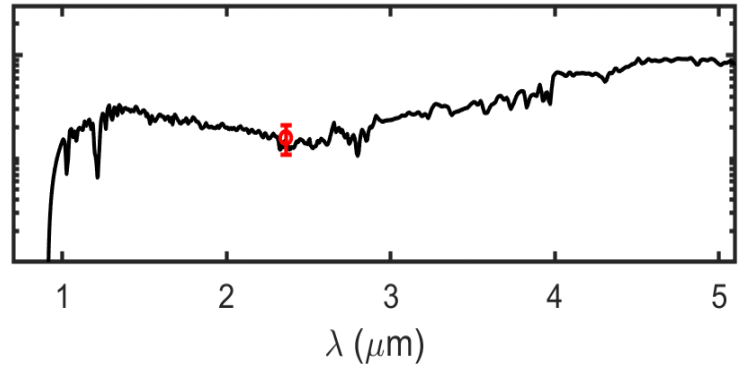


Transmitted by Dichroic



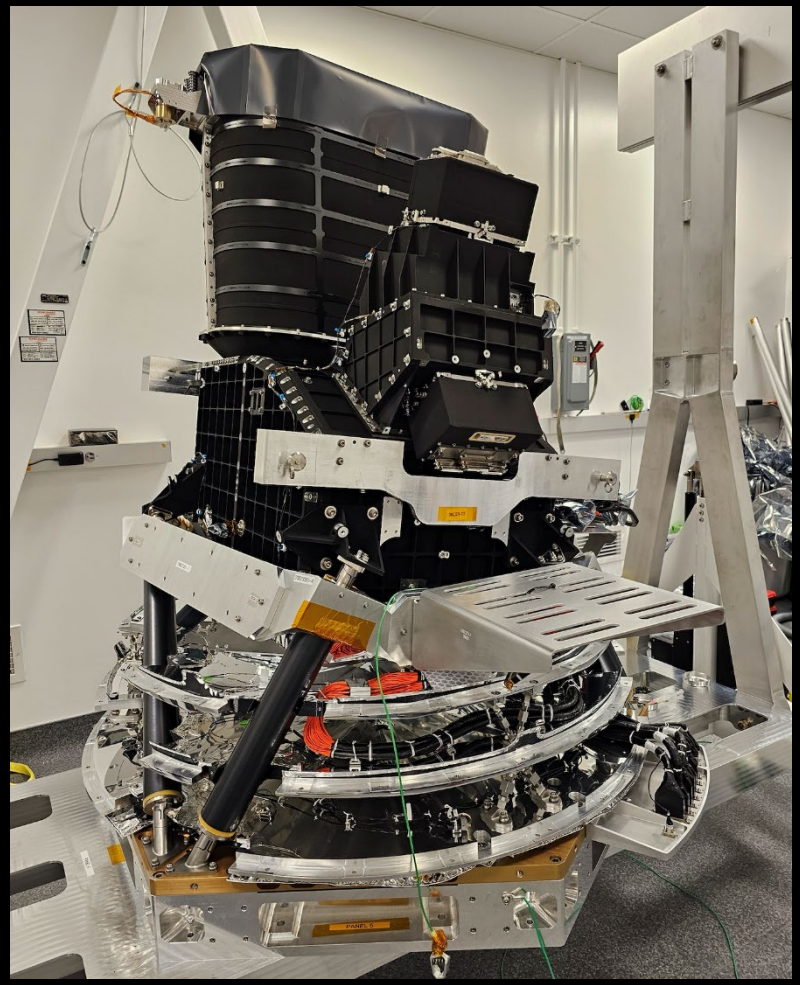
Pointing modulates the wavelength of observation





A complete spectrum in 51 exposures
Each exposure takes 112s
1 complete spectrum every 6 months

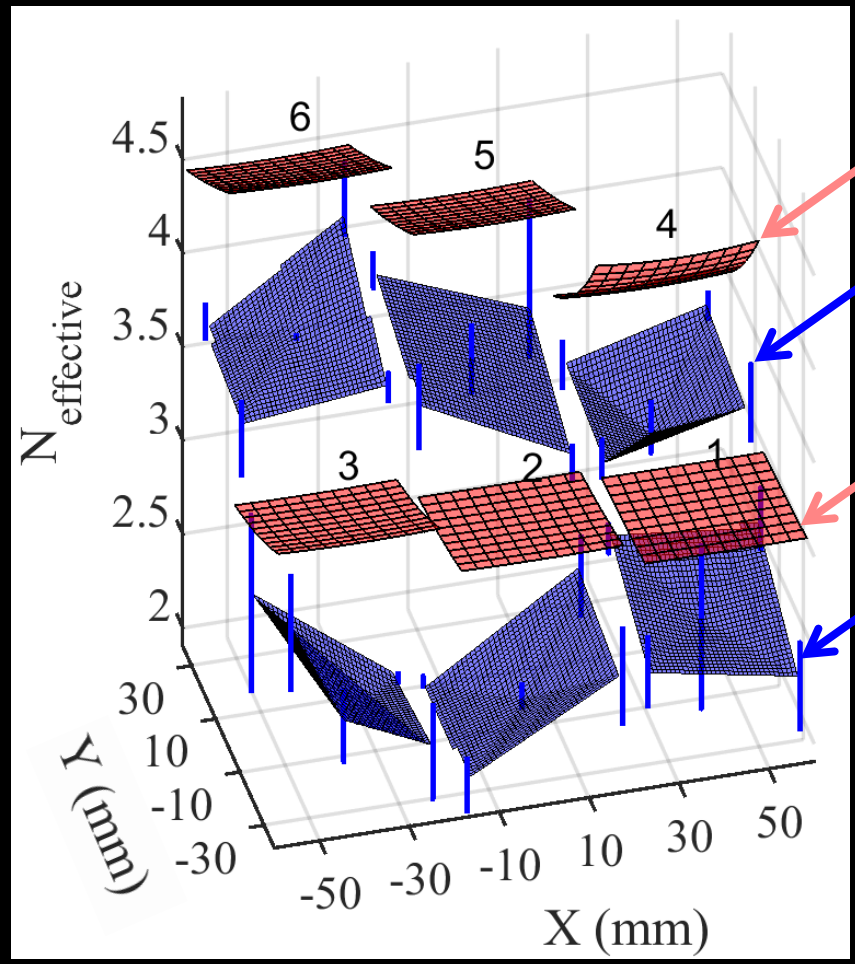
FLIGHT HARDWARE: ASSEMBLED PAYLOAD



The instrument (telescope + FPAs + V-grooves) has gone through 3 cryogenic focus tests and 1 spectral calibration at Caltech. Results are excellent. All 32x6 = 192 readout channels operate perfectly.

INSTRUMENT IS IN FOCUS POST-VIBE

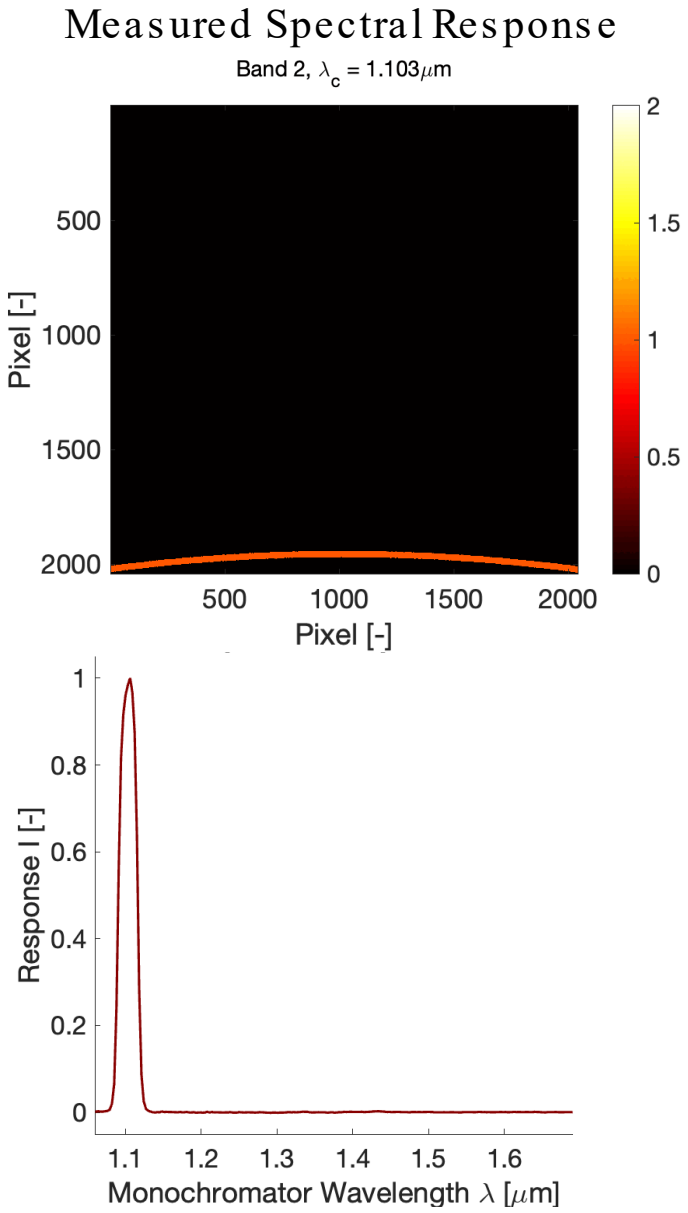
KASI Cryo-Vac chamber in action

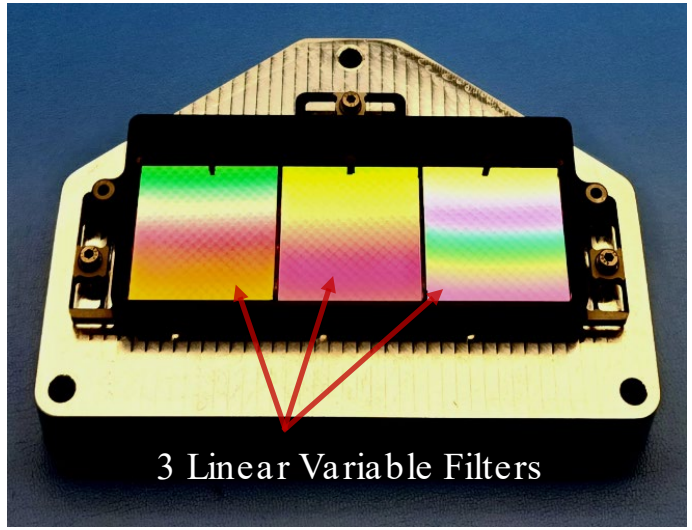


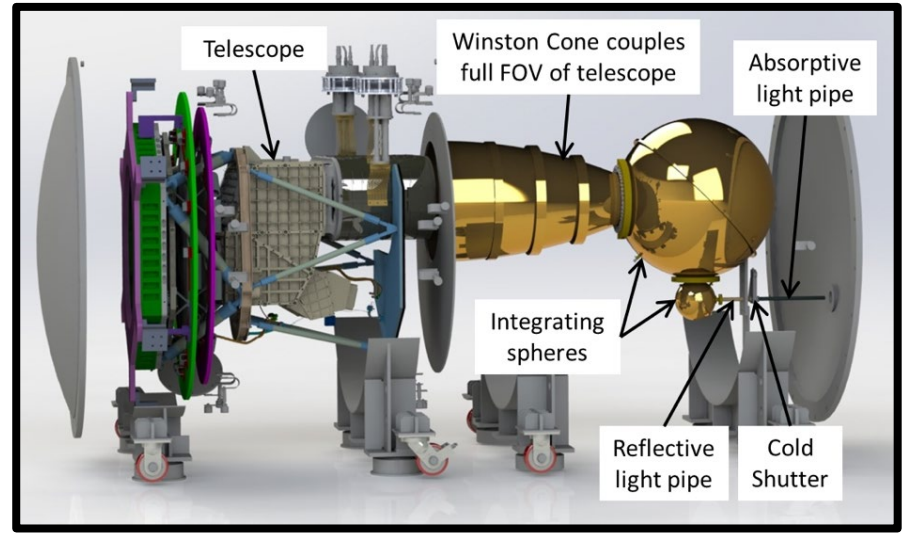
$N_{eff} = 1/\Sigma p_i^2$ measures the effective number of pixels in a point source.
Flux sensitivity scales as $\Delta F_\nu \alpha N_{eff}^{1/2}$

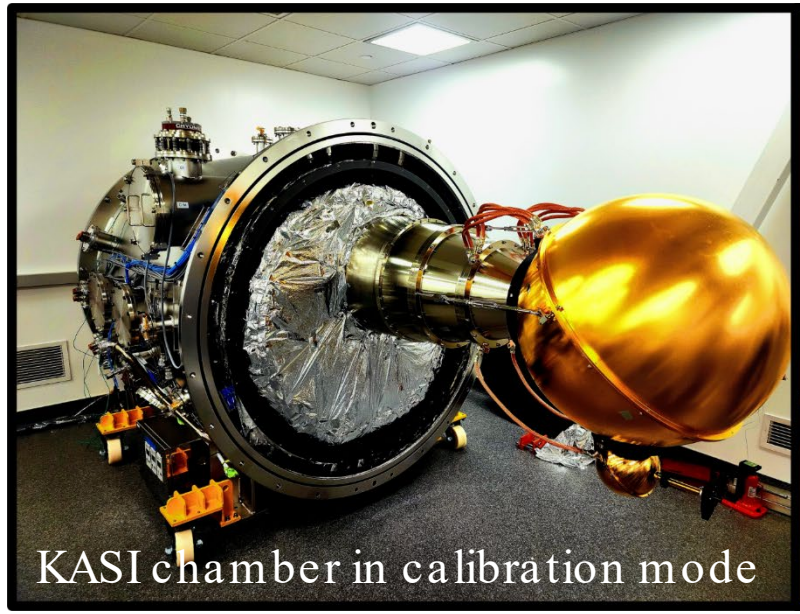
Telescope system was focused. It stays in focus after vibration and re-cooling. PSF generally exceeds best-case CSR scenario.

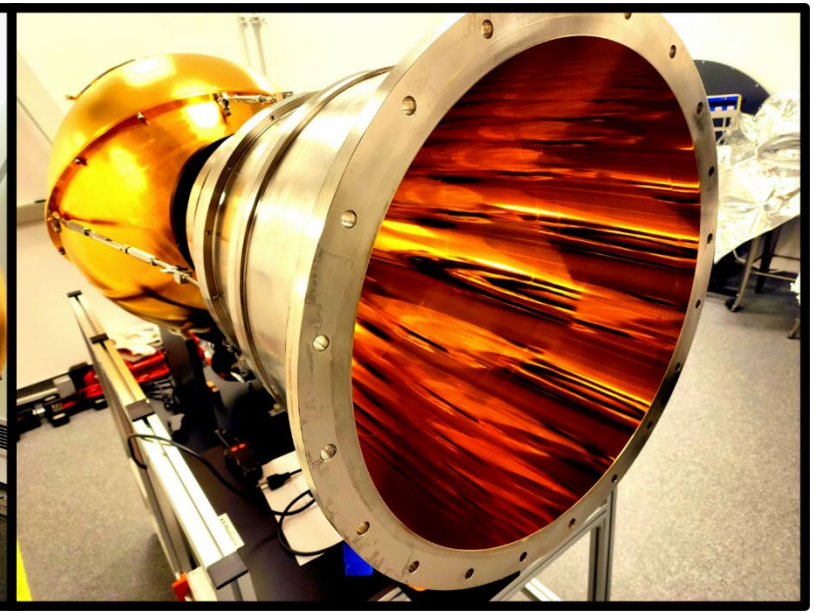
FOCAL PLANE SPECTRAL CALIBRATION



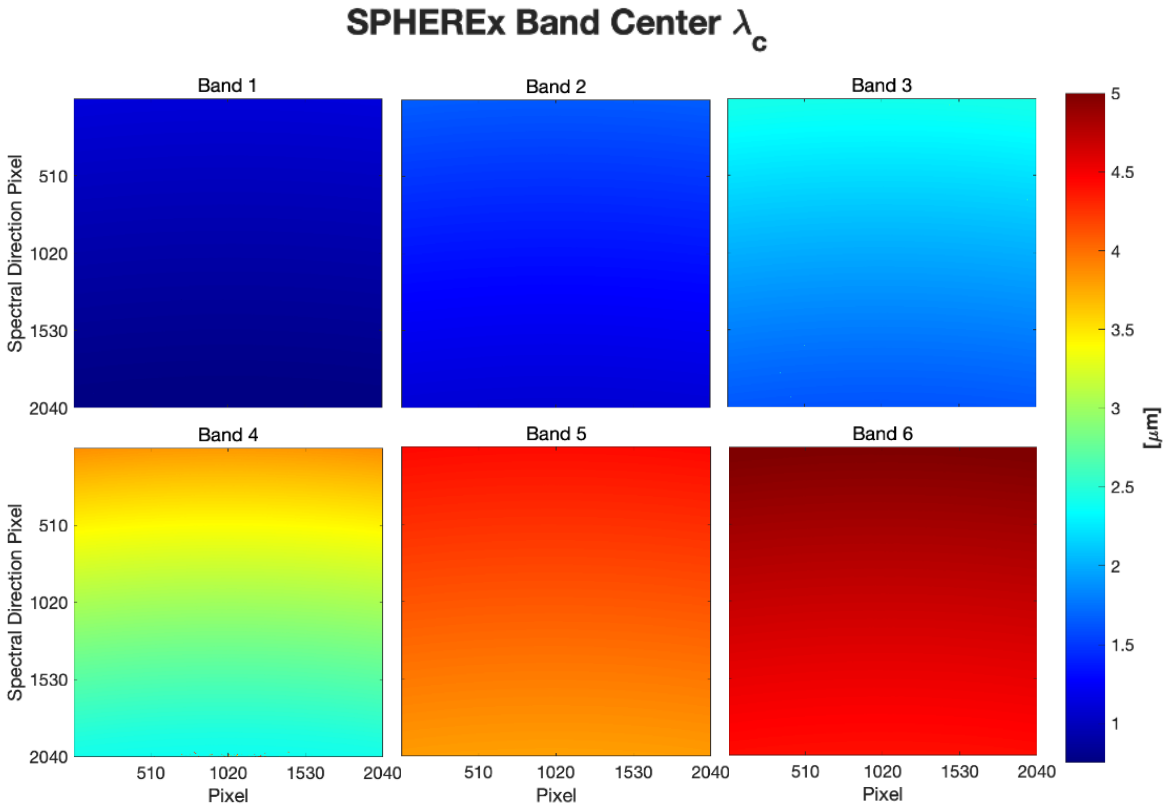


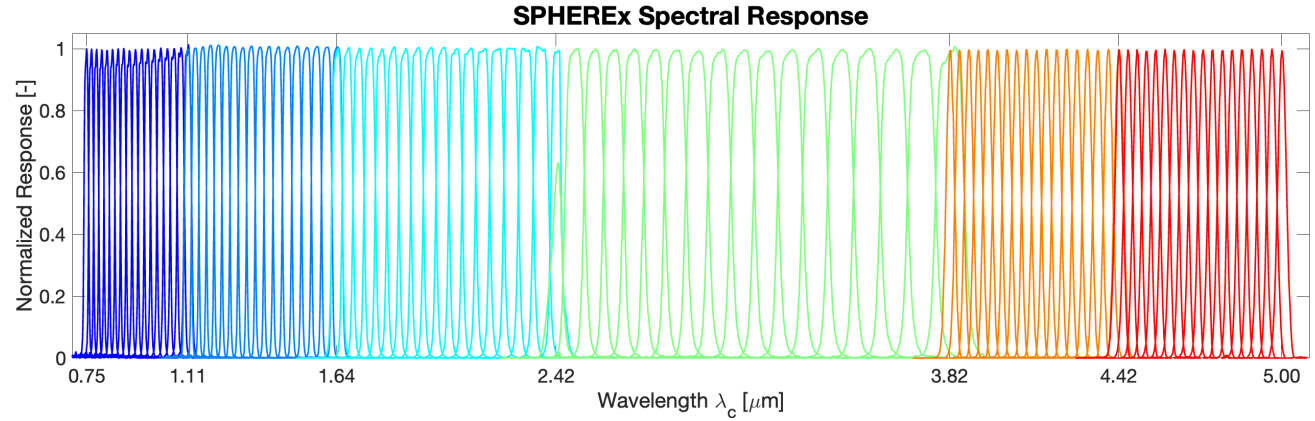


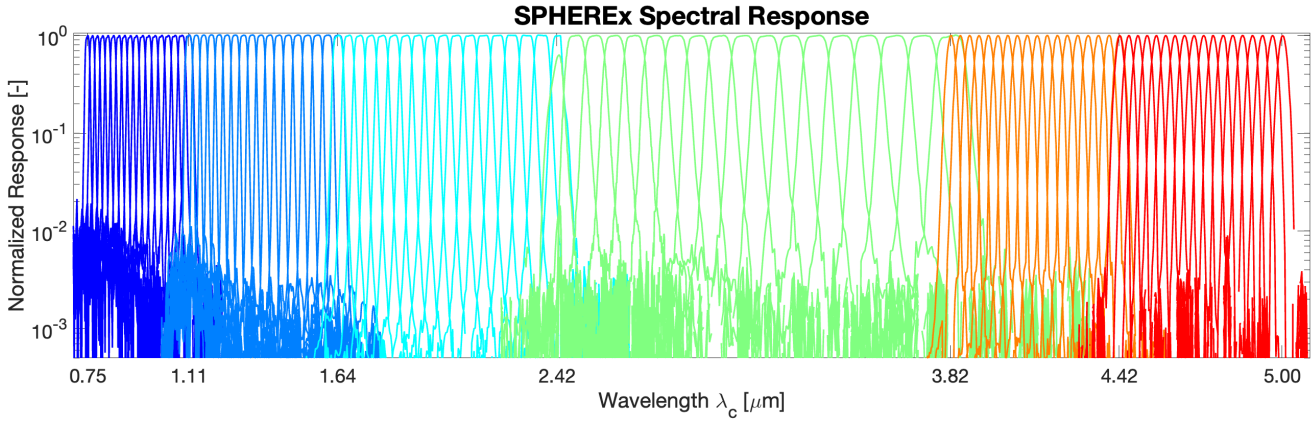




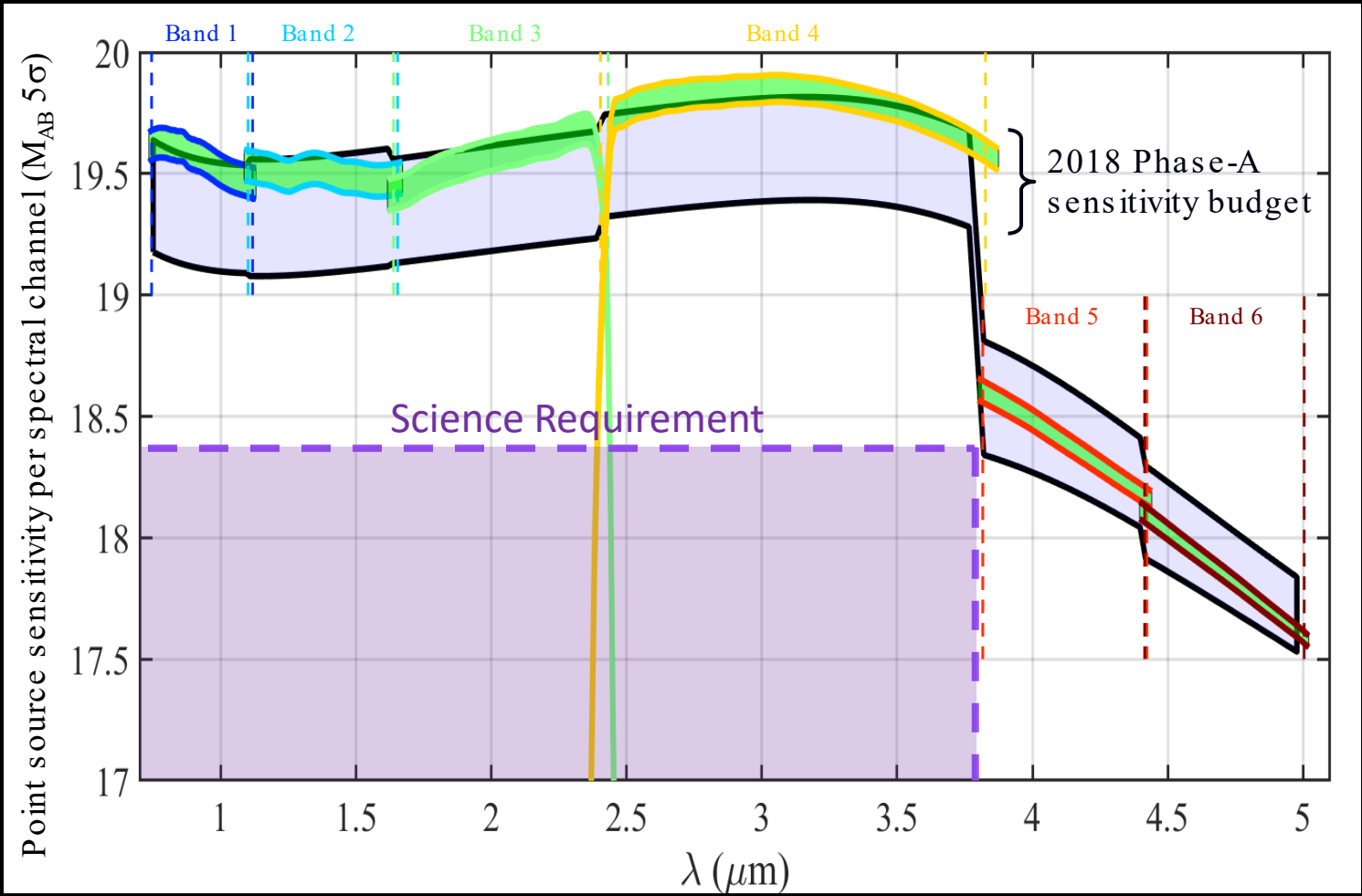
FULL FOCAL PLANE SPECTRAL CALIBRATION







POINT SOURCE SENSITIVITY BUDGET



Current estimate from measured hardware

- Filter optical efficiency
- Detector optical efficiency
- Electronics and detector noise
- Detector dark current

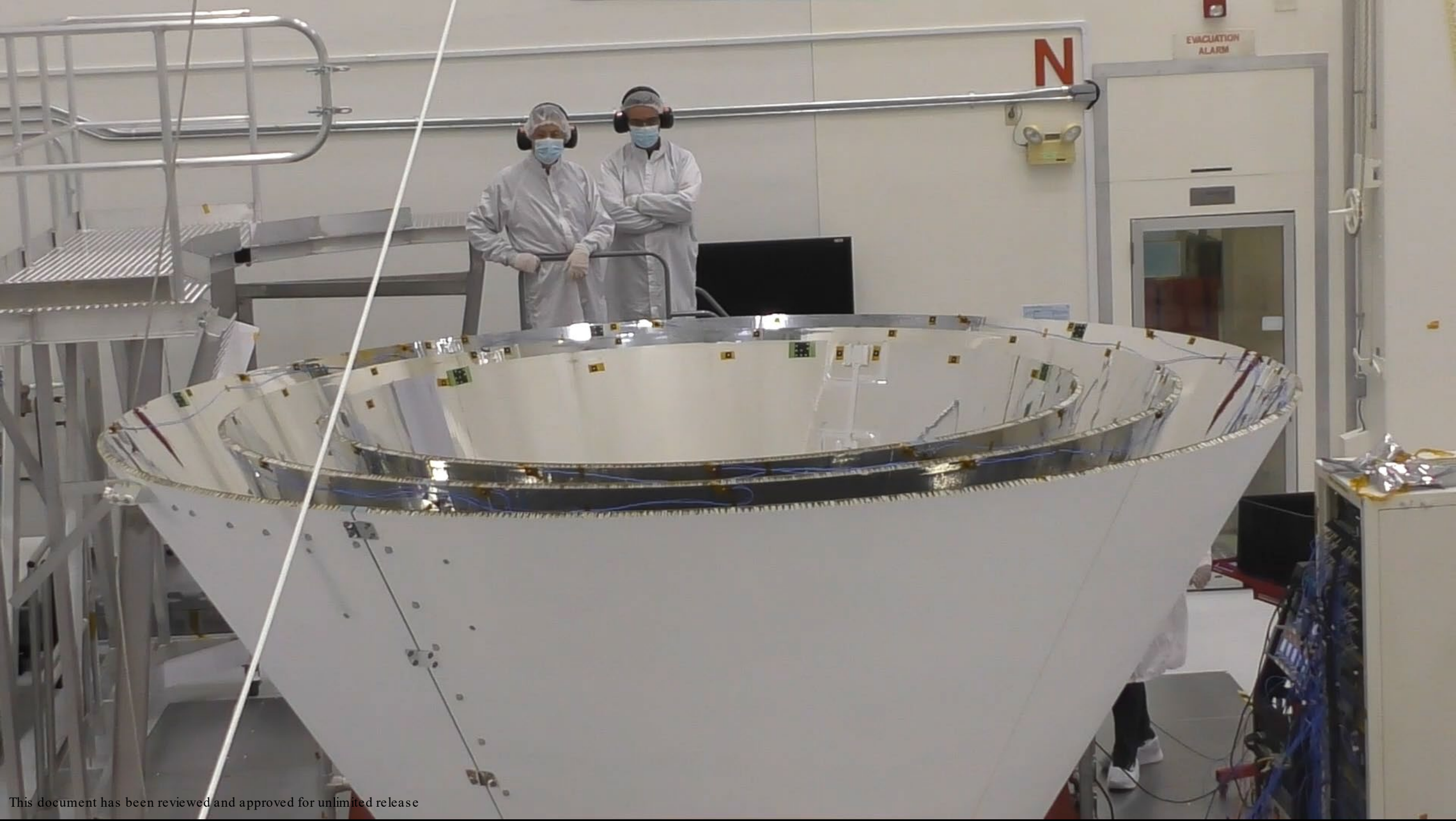
Unmeasured components use a range

- Telescope PSF (Phase-A range)
- Pointing jitter (Phase-A range)
- Integration time (78 % of Phase-A values)

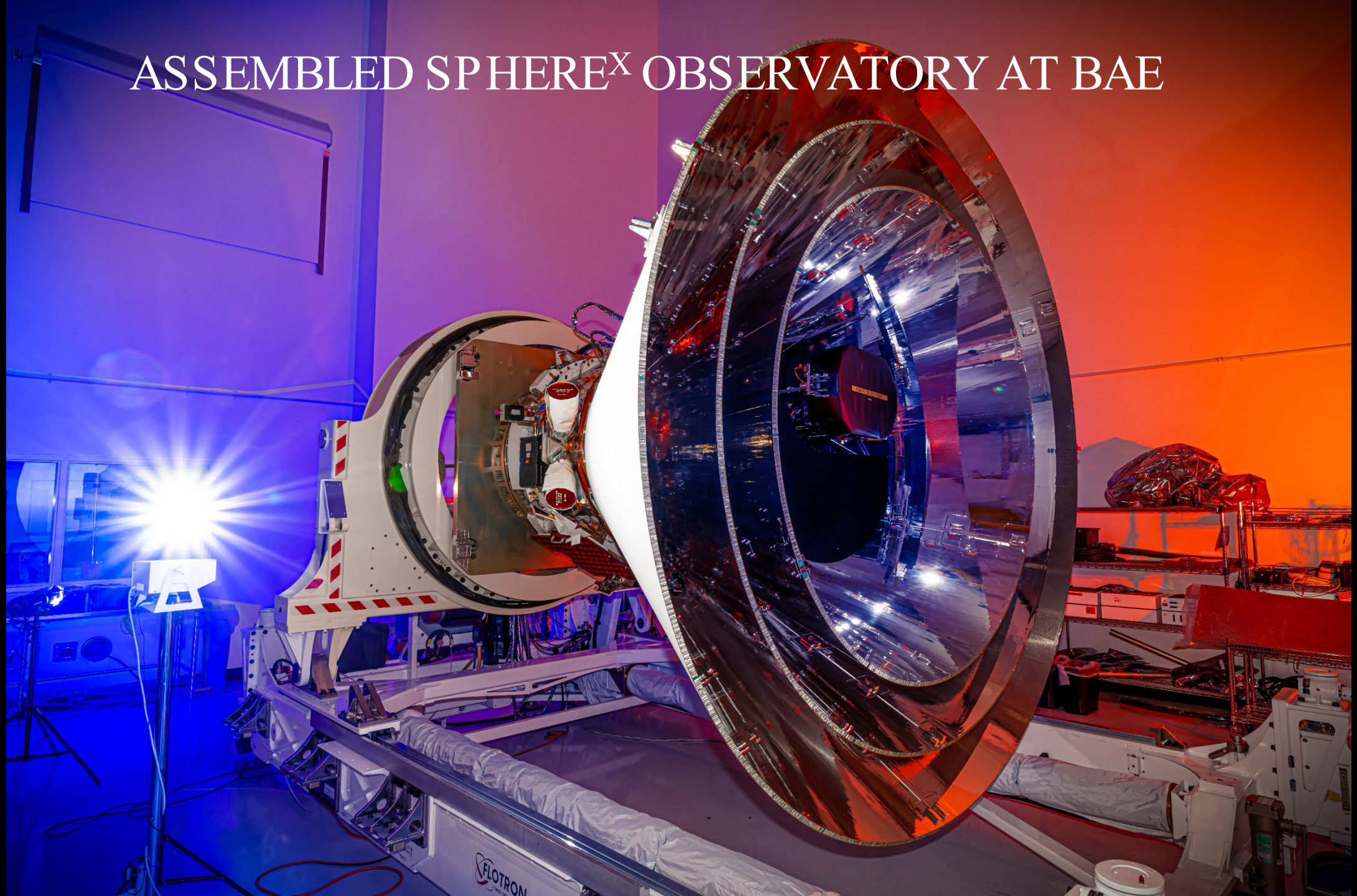
Comparing with 2018 Phase-A budget

- Bands 1-4 at best-case performance
- Bands 5-6 in the middle of range
- Uncertainties now much smaller

Sensitivity near best-case performance in bands 1-4, exceeding science requirement by factors of (2.5 – 4). Sensitivity in middle of Phase-A range for bands 5-6, exceeding science requirement by factors of (60 – 75).



ASSEMBLED SPHEREX OBSERVATORY AT BAE



SPHEREX THERMAL-VACUUM TEST 6/12 – 7/4

Observatory in TVAC at BAE, commanded from the EOMOC at JPL

SPHEREX OBSERVATORY THERMAL-VAC ANOMALIES

The reaction wheels showed several intermittent anomalies

- Not finding home on start-up
- Not responding to commands at high rotation speed if power were to be cycled
- Going into a faulted state due to voltage fluctuations
- Fault found on a NASA mission in development at higher wheel speeds not seen in TVAC testing, but it could affect SPHEREx in flight

- Meeting with wheel vendor July 15-17 determined the cause for all effects
- All anomalies can be addressed by modest changes to wheel electronics, firmware or operations
- Mitigation: return wheels to vendor for ~3 weeks (+shipping and rework at BAE) for modifications

Oscillations on a readout channel in Band 6

- Affects 0.5 % of pixels (1 of 192 readout channels)
- Does not appear at electronics temperatures above 5 C

- Mitigation: add MLI blanketing to electronics radiator to operate at somewhat higher temperature

Prime MWIR decontamination heater failed open

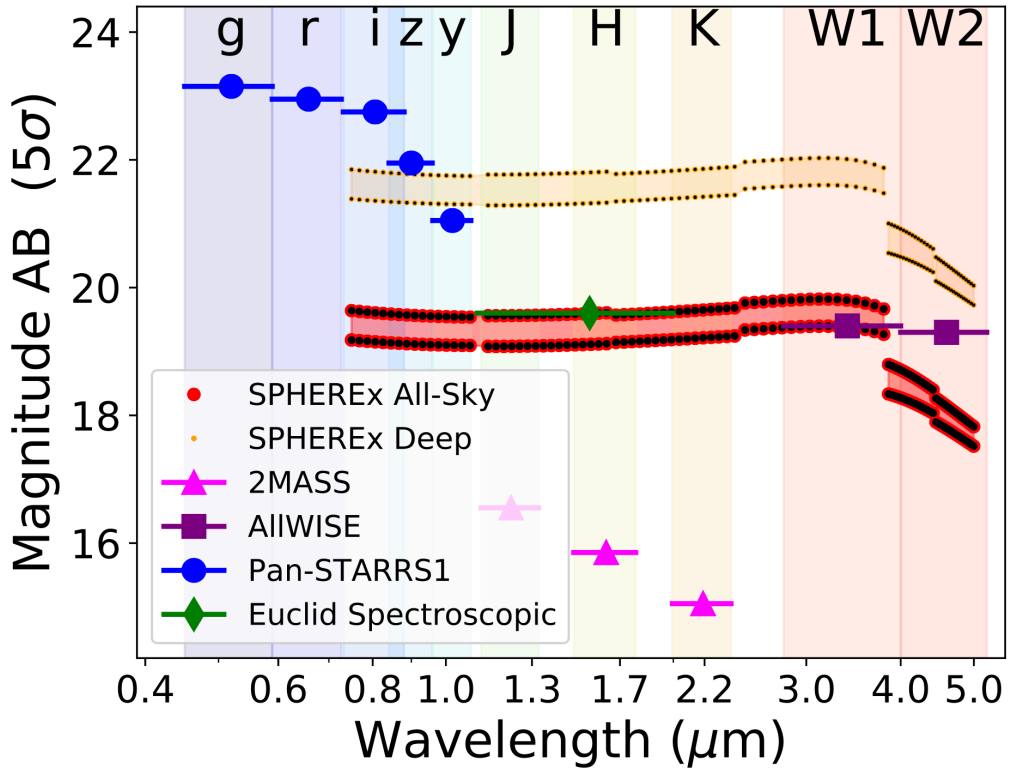
- Redundant MWIR heater works, and functioned throughout TVAC

- Mitigation: Decontaminate the MWIR focal plane without a heater using Earth infrared radiation

Project is developing solutions that fit in the funded schedule reserve of 62 days (vs. 24 days required)

PUBLIC DATA PRODUCTS AND TOOLS

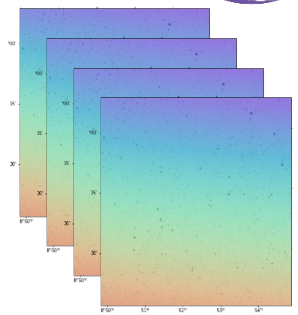
SPHEREx Point Source Sensitivity



Full science program restored at KDP-D in January 2024

Data are rapidly released via IPAC/IRSA

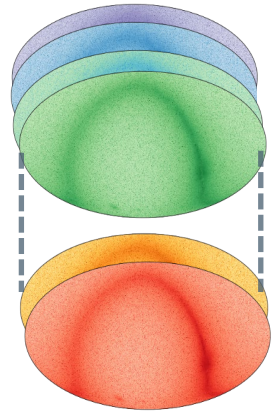
- Calibrated spectral images release within 2 months, updated following 2nd and 4th survey recalibration
- High-reliability catalog after 3rd survey
- Core science products at end of mission



Spectral Images

Exploration, analysis, and visualization tools

- On-the-Fly Mosaics
- Photometry on Known Position
- Spectral Data Cube Extractor
- Variable Source Extractor
- Source Discovery Tool



Data Cubes

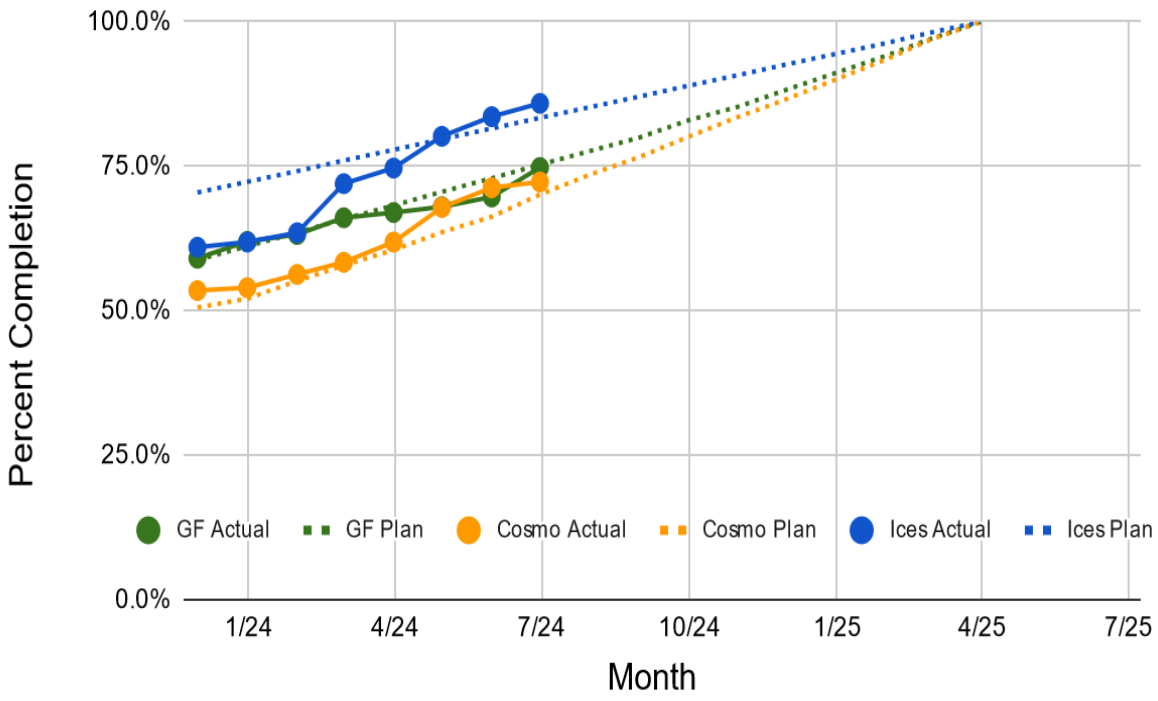
Processed data products

- Level-1 science: Redshift catalog, Ice catalog, deep field mosaics
- High-reliability catalog
- Low-mass star and brown dwarf spectra
- Exo-planet host star spectra
- Galaxy clusters from X-ray and mm-wave surveys
- Asteroid and comet spectra

→ proposed to NASA Planetary

CORE SCIENCE PIPELINE DEVELOPMENT

Proto-Pipeline Development



Level 4 proto-pipeline is the backbone of the science pipeline, allowing us to process data through to initial results for an early assessment of data quality and systematic errors. The proto-pipeline consists of 35 of the 50 analysis modules that comprise the full level 4 science pipeline.

Analysis Pipeline Structure and Staffing

- Level 1-3 (IPAC): heritage based. Ready to run at launch
- Level 4 (science team): employs new methods. Proto-pipeline to be ready to run at launch
- Estimated workforce for full science pipeline has been established and stable since PDR
- Three science peer reviews have tracked progress since 2020 and concur with our schedule and staffing plans

Level-4 Analysis in Phases C-D

- Extensive early development is needed, typical of cosmology
- To accommodate this, team operates without reserves
- Extensive simulation tools have been developed and validated to mesh with a full program for quantifying systematic errors
- Progress to proto-pipeline readiness goal is tracked monthly

Level-4 Analysis in Phases E-F

- Team has developed a plan consistent with reviewed workforce plus 10 % reserves
- Flexibility to adjust scope following a review 6 months after launch

CONCLUSIONS

SPHEREx Science Continues to be Exciting

- SPHEREx resonates with NASA's science goals and the 2020 Decadal survey
- Rapid survey data release; cosmology, galaxy formation and ices analyses
- Current budget is adequate to implement science, watching limited reserves carefully

SPHEREx Instrument is Performing Well

- Point source sensitivity is (2.5 – 4.0) times better than the science requirement
- Margins large and stable or increasing: completeness, pointing, PSF, &temperatures
- Systematic error budgets stable: stray light, gain stability, noise stability, persistence

Observatory Integration and Test

- Most demanding TVAC test has been completed
- Project working to address anomalies within its 62 days of funded schedule reserve

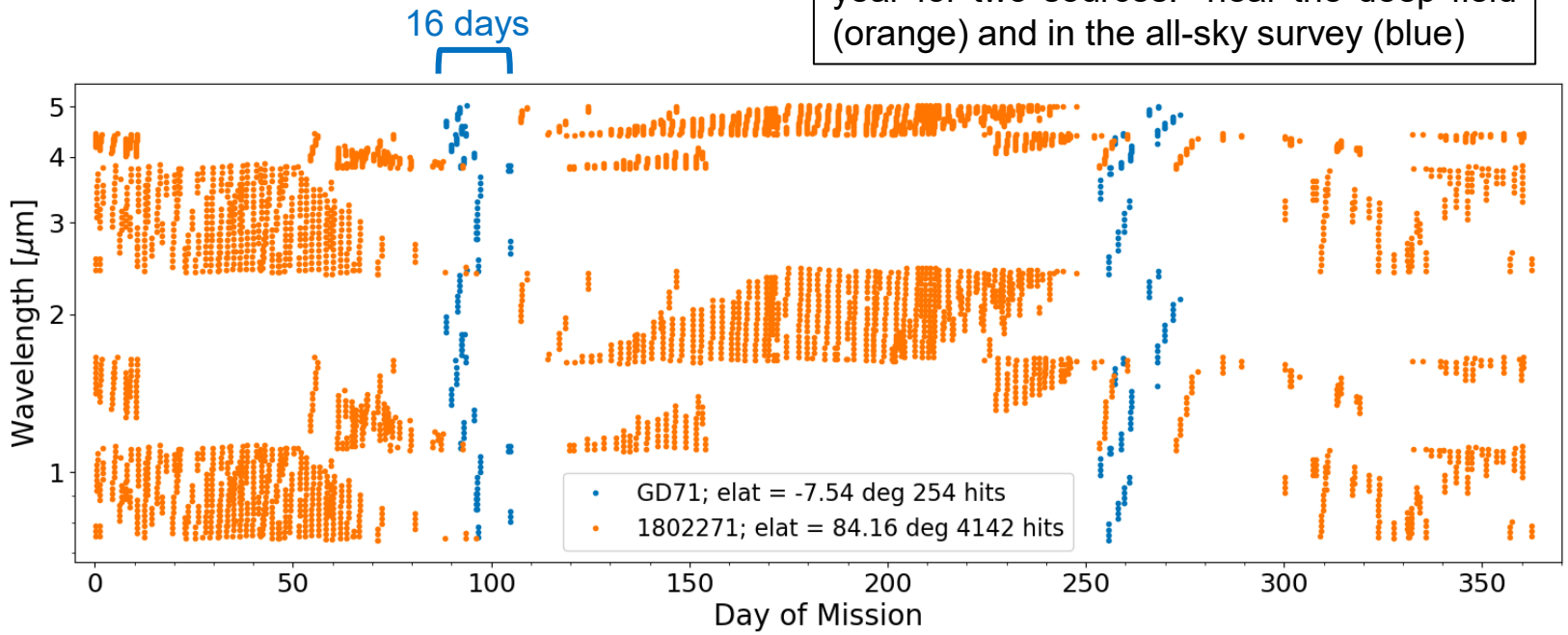
Caltech NASA Jet Propulsion Laboratory California Institute of Technology BAE SYSTEMS ipac CfA UCI ASU R·I·T Johns Hopkins University Arizona Argonne National Laboratory

BACKUP

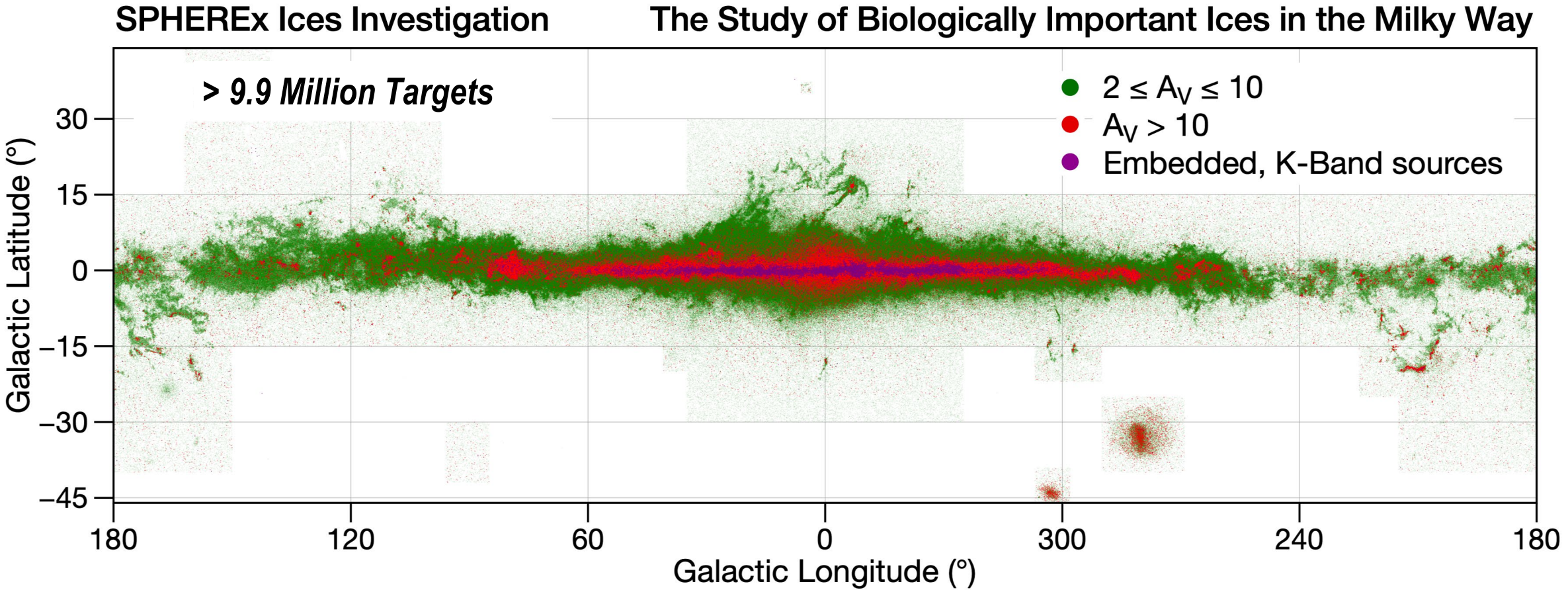
SPHEREx AND TIME-DOMAIN ASTRONOMY

- The SPHEREx all-sky survey will have 102 channels from 0.75 to 5 microns and 6” pixels
- In the two-year prime mission, the whole sky will be observed 4 times and deep fields at the NEP and SEP hundreds of times
  - SPHEREx deep fields are in the JWST continuous viewing zones
- SPHEREx utilizes linear variable filters, so the spectral measurements for each pixel are staggered in time
- Data will be available in 2 formats:
  - Primary measurements tagged with exact wavelength and time
  - Measurements time-averaged and interpolated onto a wavelength grid
- Spectra will be released in the High Reliability Source Catalog (after Survey 3 and after Survey 4) and users can also use the Spectrophotometry tool at IRSA to generate their own
- Example relevant science areas
  - Dust emission around main sequence and young stars
  - Comets and asteroids
  - Infrared variability of X-ray sources

Example of spectral sampling timing over 1 year for two sources: near the deep field (orange) and in the all-sky survey (blue)

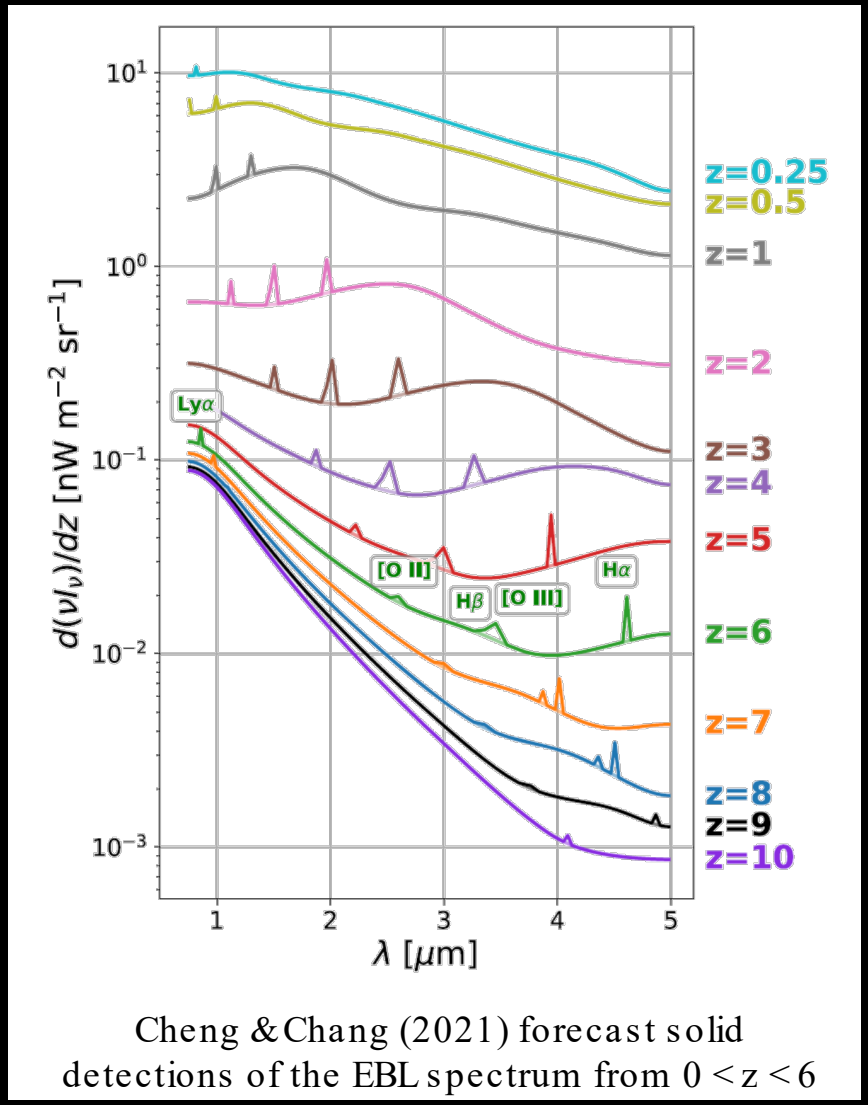


SPHEREx CONDUCTS A COMPREHENSIVE ICES SURVEY



LIGHT PRODUCTION IN REDSHIFT SLICES

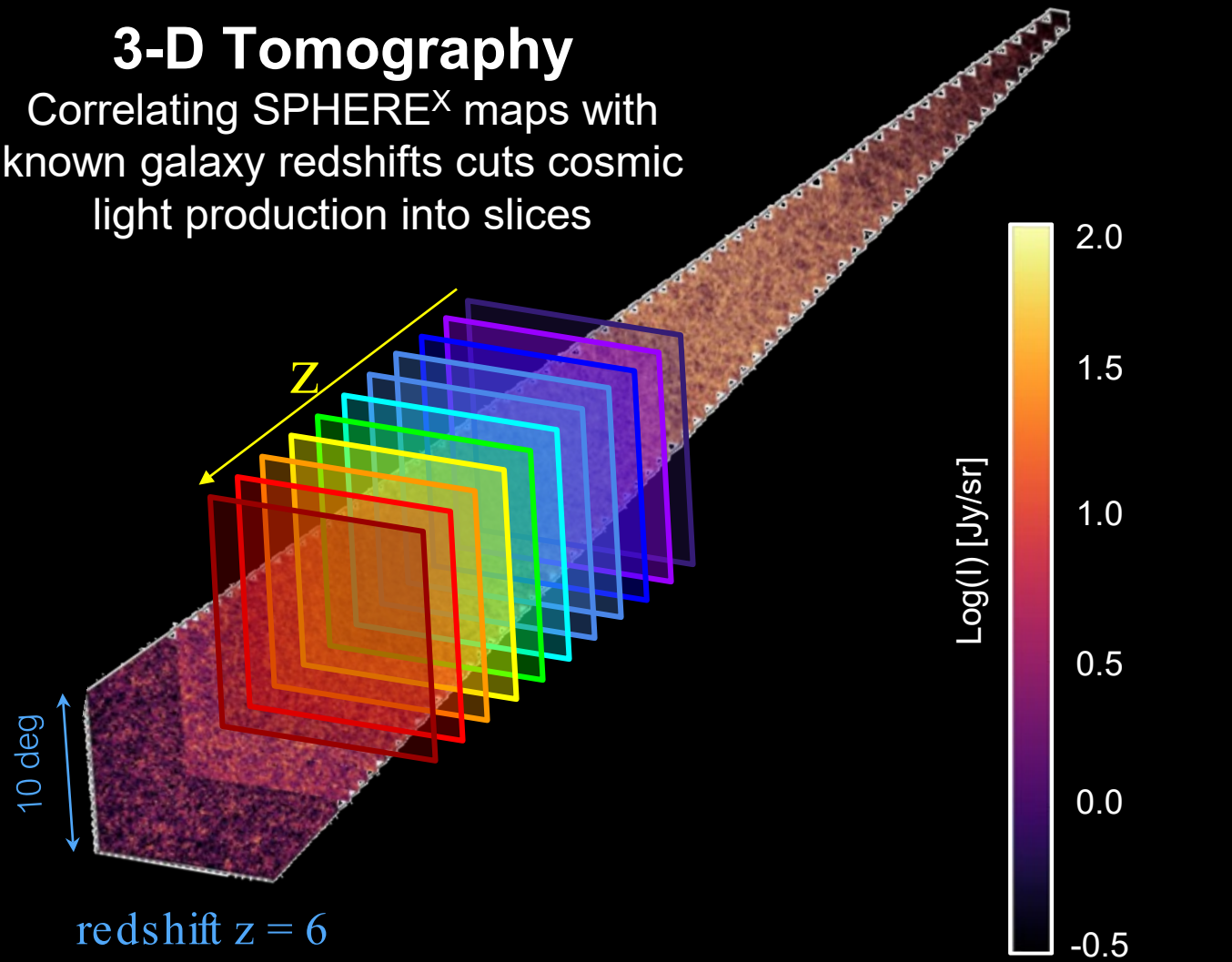
Cosmic Light Production vs. Redshift



Cheng & Chang (2021) forecast solid detections of the EBL spectrum from $0 < z < 6$

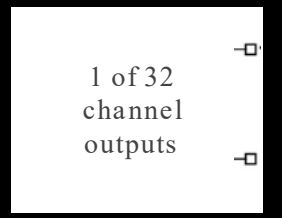
3-D Tomography

Correlating SPHEREˣ maps with known galaxy redshifts cuts cosmic light production into slices

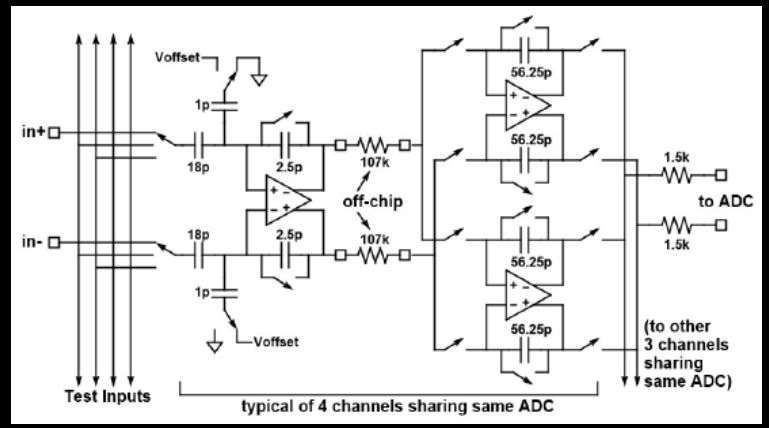


INTENSITY MAPPING WITH H2RG ARRAYS

H2RG

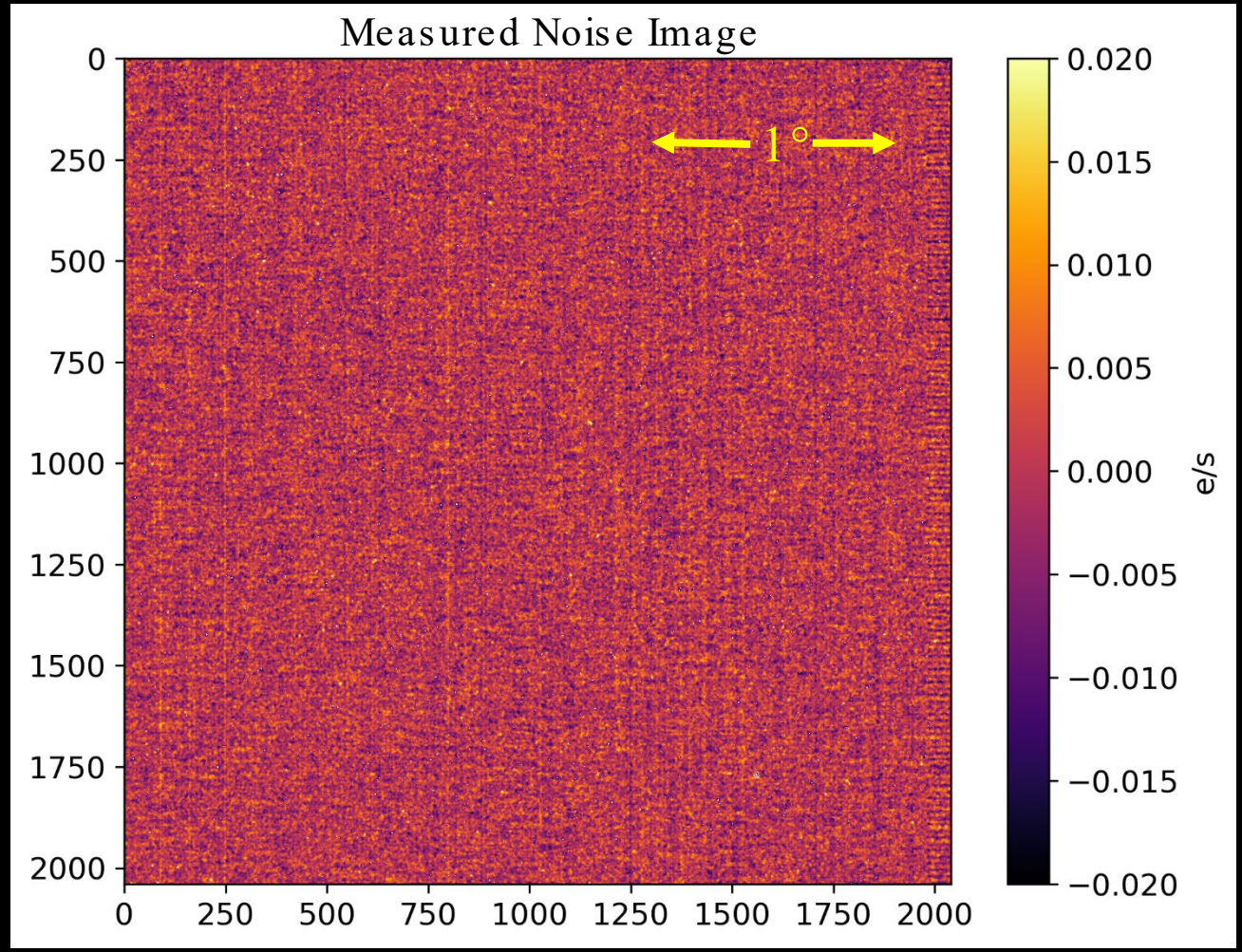


VIDEO8 Amplifier



Steps to Remove Spatial 1/f Noise

- Use VIDEO8: custom ASIC developed by Caltech
  - Low amplifier noise (< 2 e-)
- Switch inputs to ground intermittently
  - "Phantom pixels" in data stream
  - Removes amplifier drift and 1/f noise
- "Row Chopping" to skip rows in readout order
  - Mixes 1/f noise to high frequencies in y direction
- Subtract residual offset in each channel
  - Sources most of the remaining noise on x-axis
  - Can use reference pixels or channel median



Demonstrated noise control on the ~20′ angular scale of linear clustering