33rd Annual INCOSE international symposium

hybrid event

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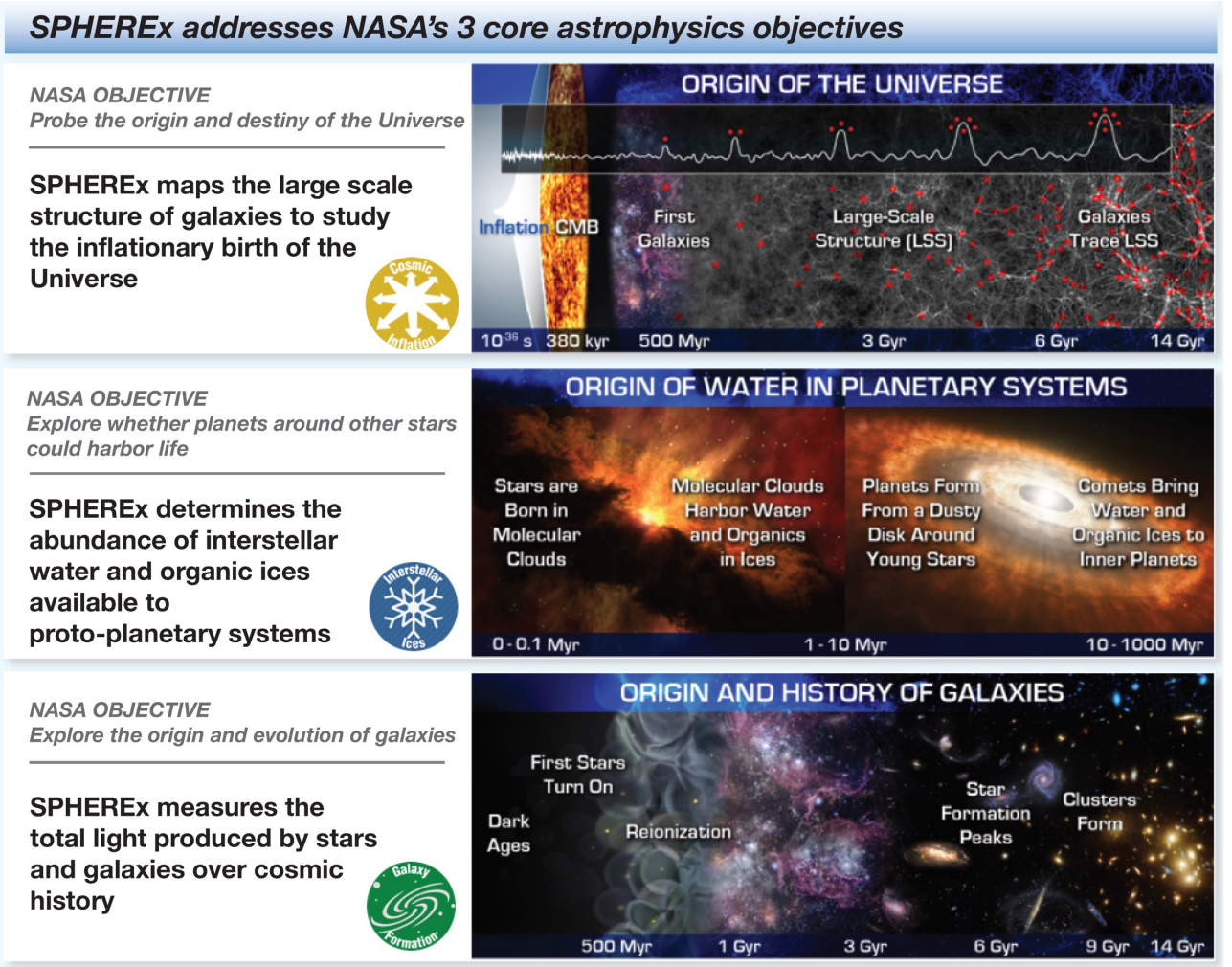
Systems Engineering Approach for the SPHEREx Telescope Mission

Jet Propulsion Laboratory
California Institute of Technology

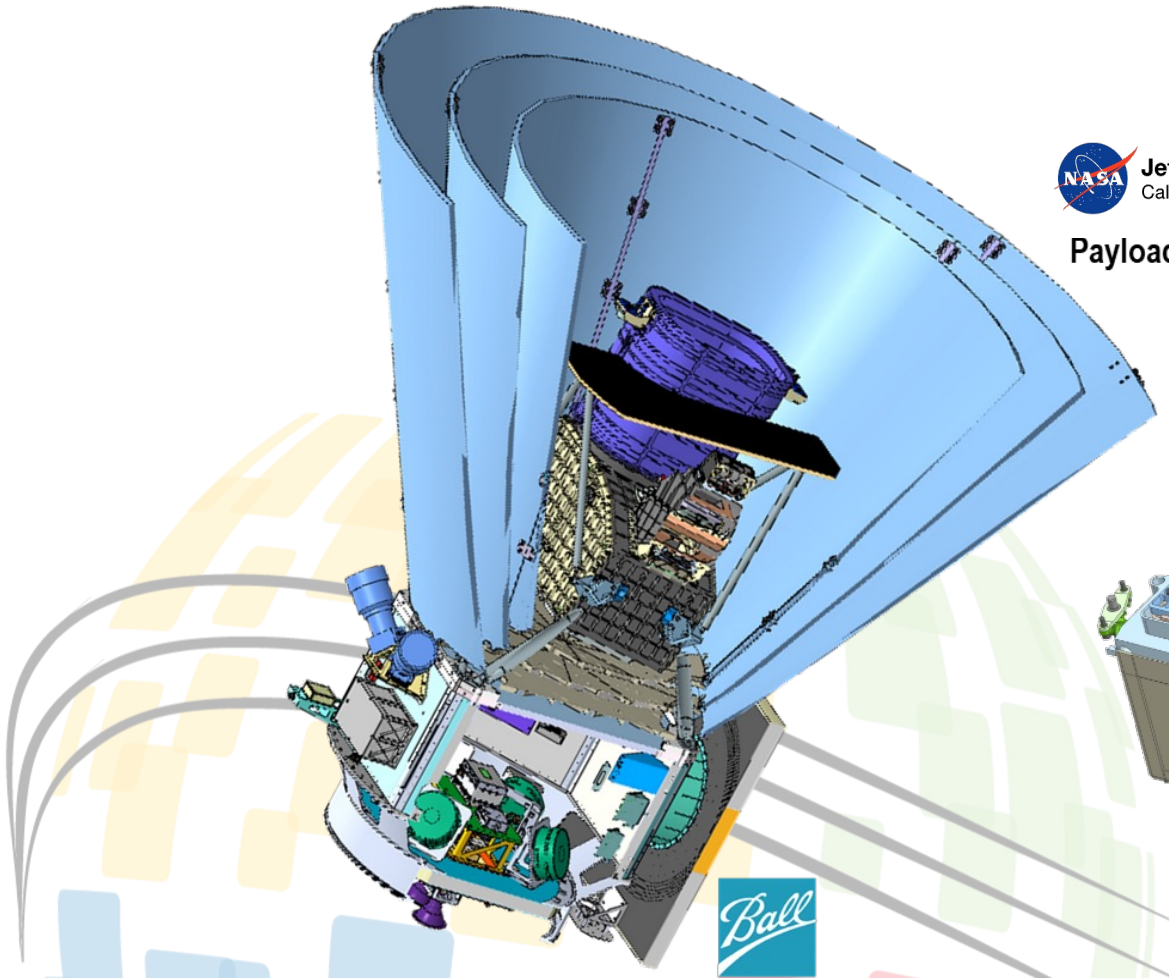
What is SPHEREx?

Spectro-Photometer for the History of the universe, Epoch of Reionization, and ices Explorer

- SPHEREx is a NASA Medium Explorer Mission, selected for implementation in January 2019, and assigned a Class C risk posture
- Now in the flight implementation phase of the project, SPHEREx will launch in February 2025
- This will be the first near-infrared all-sky spectral survey, delivering a powerful archive serving the broad astronomical community



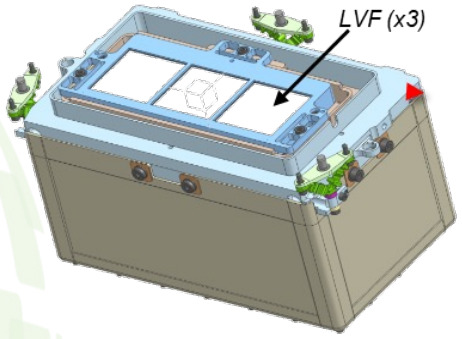
SPHEREx At-a-Glance



Jet Propulsion Laboratory
California Institute of Technology

Payload elements including:

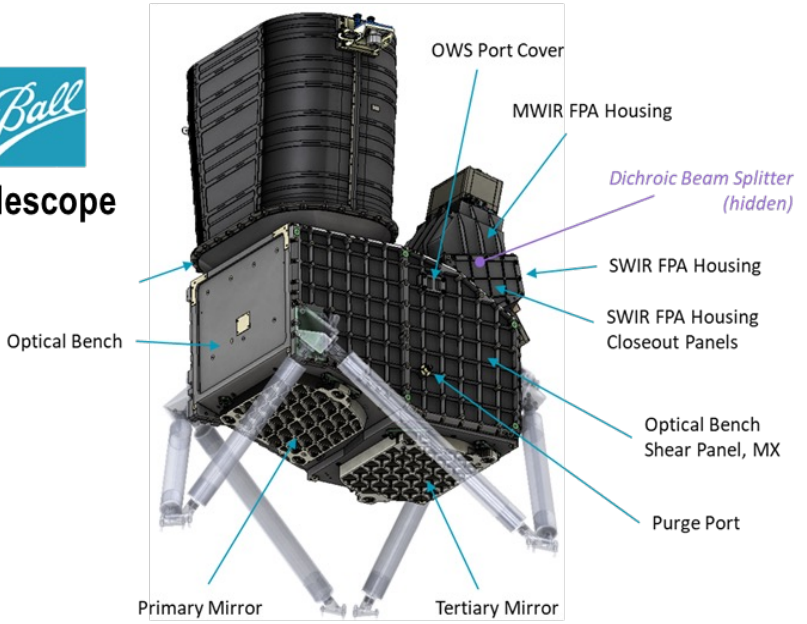
- Photon shield
- V-Groove radiator
- Bipods
- Focal plane assembly



Focal Plane Assembly

Spacecraft bus

Telescope



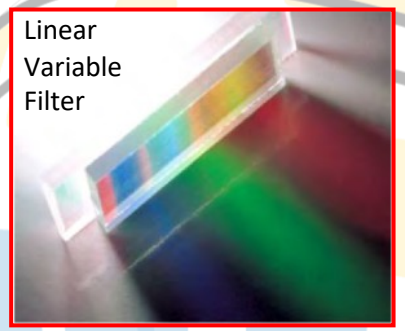
Caltech

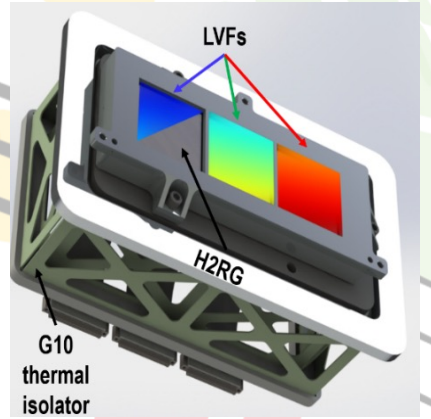
Instrument elements including:

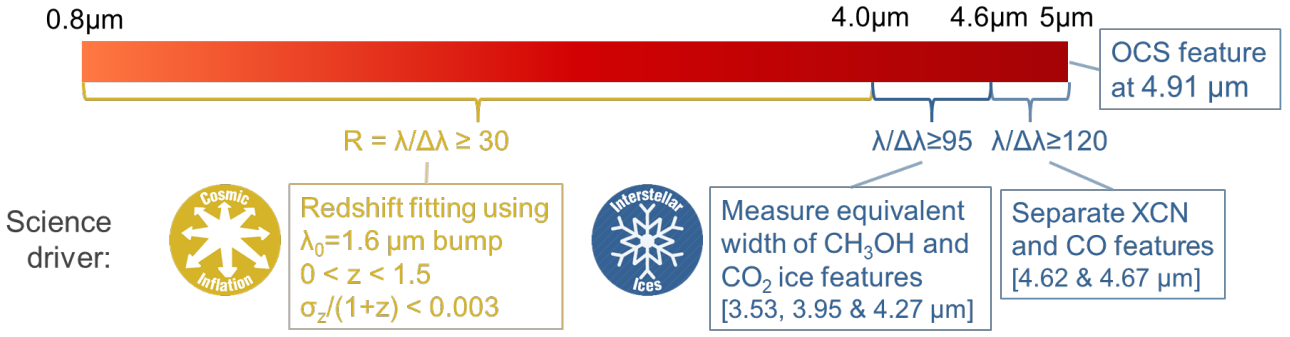
- Detectors – from Teledyne
- LVFs – from Viavi
- Instrument electronics – with UCB
- Instrument test chamber – from KASI
- Telescope and cover – from Ball

Innovative Optical Design Enables Science

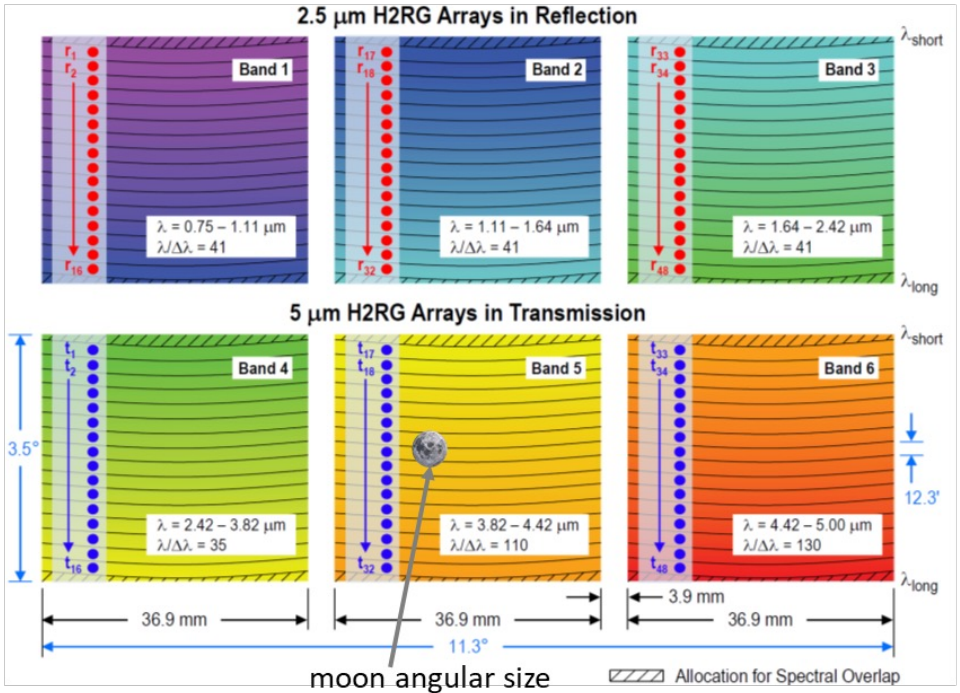
- 20 cm telescope achieves large AΩ using large FOV (3.5° x 11.3°)
- Survey 2x faster using beamsplitter to feed 2 focal planes (SWIR and MWIR), each with 3 H2RG detectors
- Spectral range and resolution driven by science need, enabled by Linear Variable Filters







LVFs cause wavelength sensitivity to vary spatially across detectors.



SPHEREx Partner Responsibilities

Jet Propulsion Laboratory
California Institute of Technology

Project Management
Systems Engineering
Mission Assurance
Payload Thermal and Mechanical
Mission System and Operations
Science Team

Spacecraft
Observatory I&T

Instr. Mission Assurance
Payload Management

Caltech

PI Institute
Science Team
Instrument
Science Data Processing

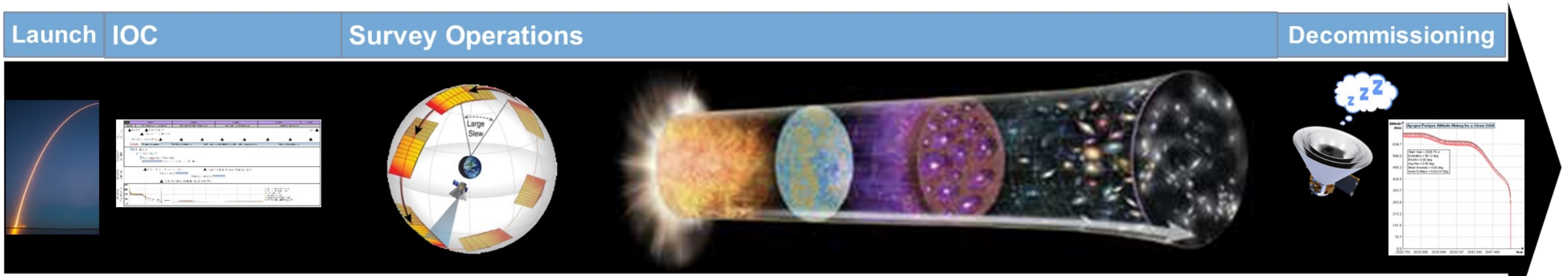
Telescope
Telescope Cover

Instrument Test Chamber
Ices Science

Science Team

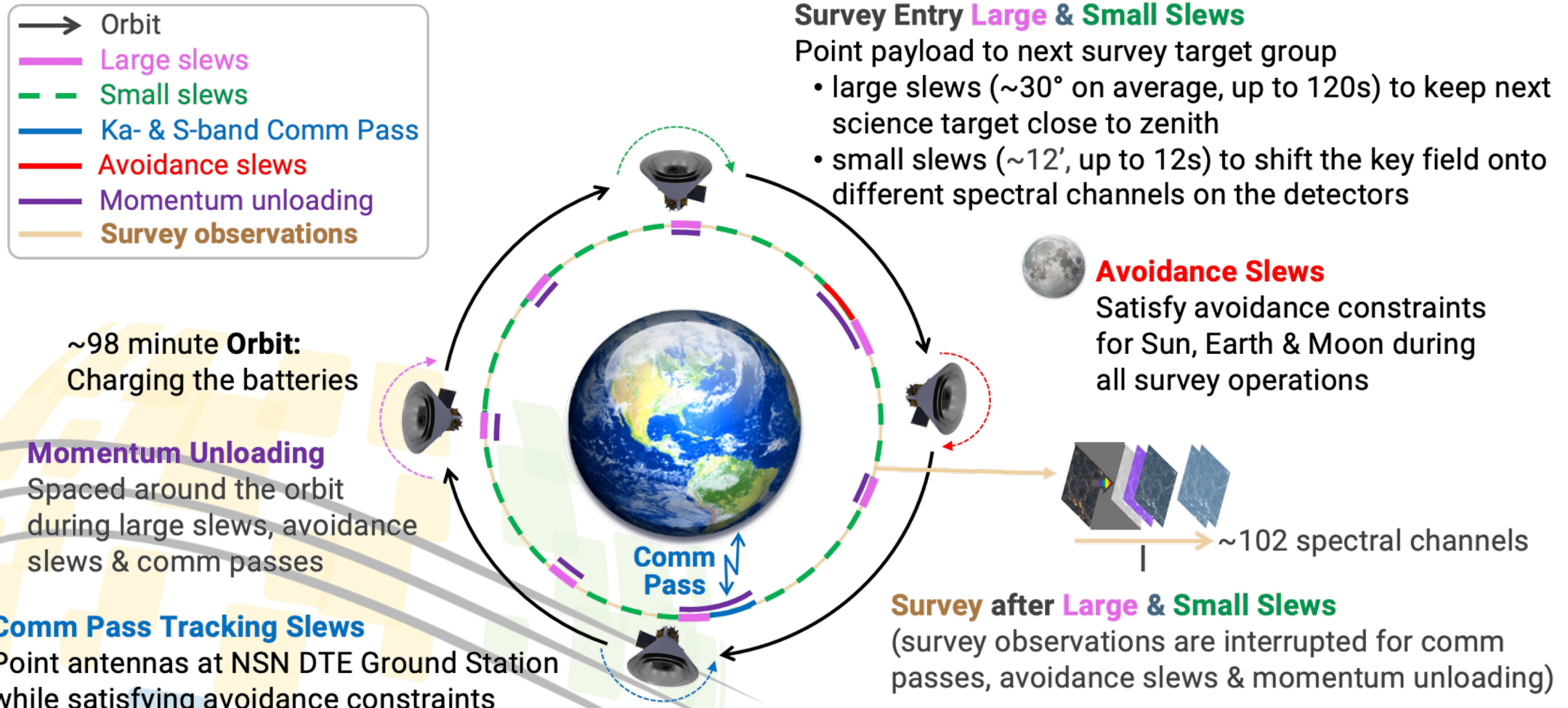
CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN
THE UNIVERSITY OF ARIZONA
THE OHIO STATE UNIVERSITY
UCI
Argonne NATIONAL LABORATORY
JOHNS HOPKINS UNIVERSITY
Arizona State University
RIT Rochester Institute of Technology

SPHEREx Mission Phases



~1 day	30 days	25 months	30 days
▪ T-24 hours ▪ Launch ascent ▪ S/C in passive launch state ▪ Separation ▪ De-tumble ▪ S/C *Auto Init* ▪ S/C power & thermally safe ▪ Acq of initial comms	▪ S/C checkout & calibration ▪ Telescope dust cover deployment ▪ Cooldown ▪ Decontamination ▪ Instrument checkout & calibration ▪ Science checkout	▪ **4 full-sky surveys** ▪ Uplink & execution of survey sequences with large & small slews, survey observations, comm passes, momentum unloading & avoidance slews ▪ Data downlink & distribution ▪ Pipeline processing	▪ Decommissioning review ▪ Observatory passivation & config for deorbit < 25 years ▪ Ground Ops decommissioning

Survey Operations



Project Systems Engineering Scope

- Project Systems Engineering focuses on the highest priority technical aspects of the project throughout the development and operations lifecycle, maximizing end-to-end science performance and understanding the sensitivity to key elements of the design.
- The Project Systems Engineer serves as the Engineering Technical Authority with an independent reporting path to the Laboratory Chief Engineer
- The ten Systems Engineering functions define the project-wide scope of this discipline across the project lifecycle:
  - Architecting
  - Requirements Definition
  - Interface Management
  - Analysis and Characterization of the Design
  - Technical Resources and Science Performance Management
  - Maintenance/Control of the Technical Baseline
  - Verification and Validation
  - Risk Management
  - Lead Systems Engineering Team
  - Conduct peer reviews across the project and lifecycle

Systems Engineering Occurs at all Project Levels

Project Systems Engineering Team Responsibilities (JPL)

- Develop & flow down project requirements
- Lead project level system trades
- Maintain the technical baseline
- Manage the risk management process
- Develop the system level fault tree
- Manage project level technical resources
- Lead the launch approval process
- Maintain the overall performance model
- Lead the EEIS development
- Coordinate project contamination control
- Lead project software systems engineering
- Lead materials and processes engineering
- Develop the Flight-Ground ICD effort
- Manage project inputs to the LV ICD
- Lead project verification & validation
- Develop the project Incompressible Test List
- Develop the project Test As You Fly Exceptions
- Prepares project waivers; JPL FPP & DP compliance assessments
- Leads IM/CM for the project
- Serves as the ley technical interface to the science team

Payload System Engineering (JPL/Caltech)

- Develop & flow down Payload System Requirements
- Perform Payload System level trades
- Manage Payload level technical resources
- Perform Payload level V&V
- Provide inputs to the Payload/Bus ICD

Flight System Engineering (JPL)

- Support insight/oversight of the Ball spacecraft development
- Support interface definition and documentation
- Develop & flow down Spacecraft Requirements

Bus System Engineering (Ball)

- Perform Bus System level trades
- Manage Bus System level technical resources
- Perform Bus System level V&V
- Provide inputs to the Payload/Bus ICD

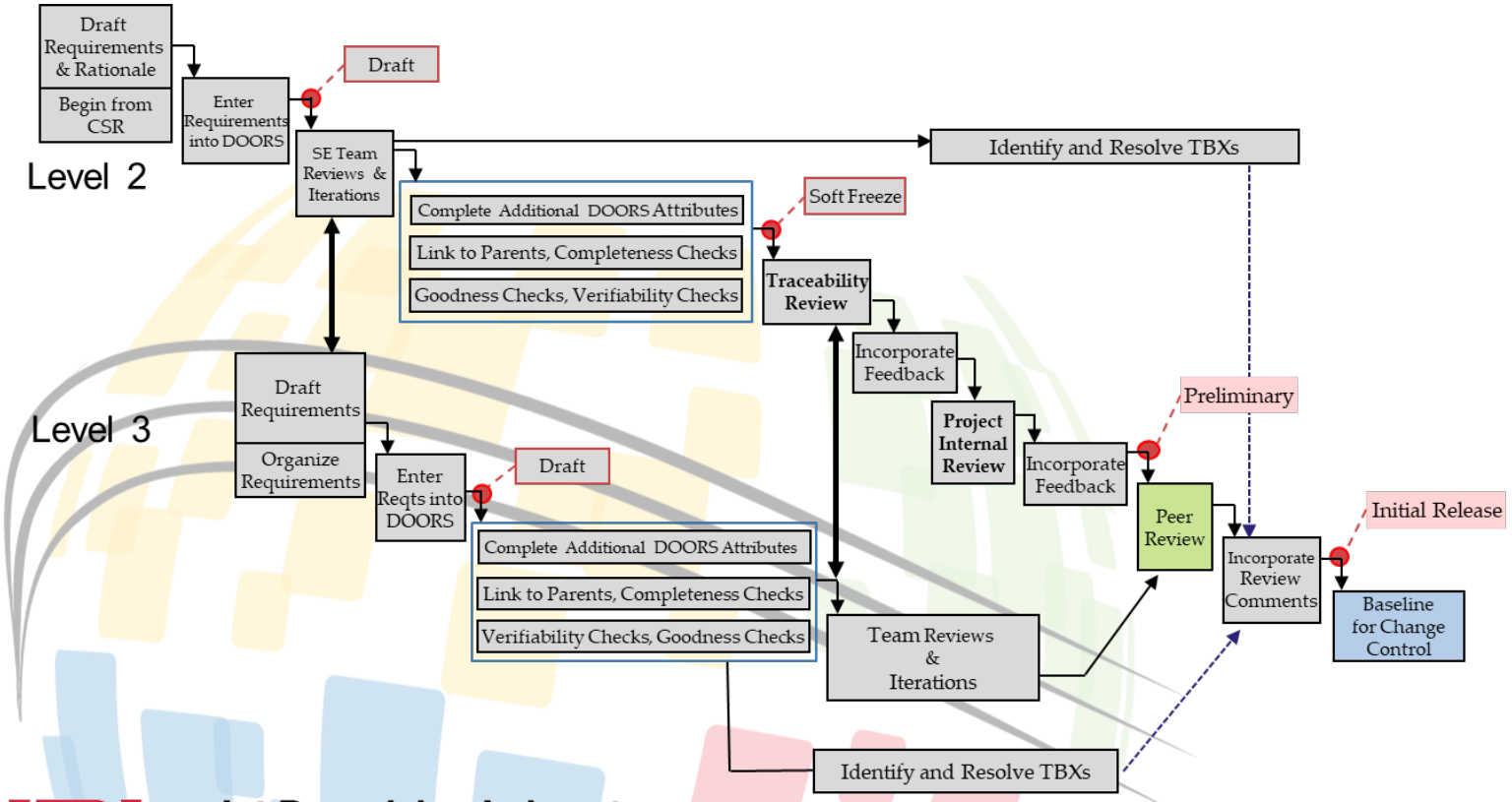
Mission System Engineering (JPL)

- Develop & flow down MD/NAV Requirements
- Develop & flow down MOS/GDS Requirements
- Perform Mission System-level trades
- Manage Mission System Resources
- Perform Mission System V&V
- Provide inputs to the Flight Ground ICD

The SPHEREx Project Systems Engineering Team (PSET) consists of technical subject matter experts from each element of the project, plus domain specialists to implement SE functions

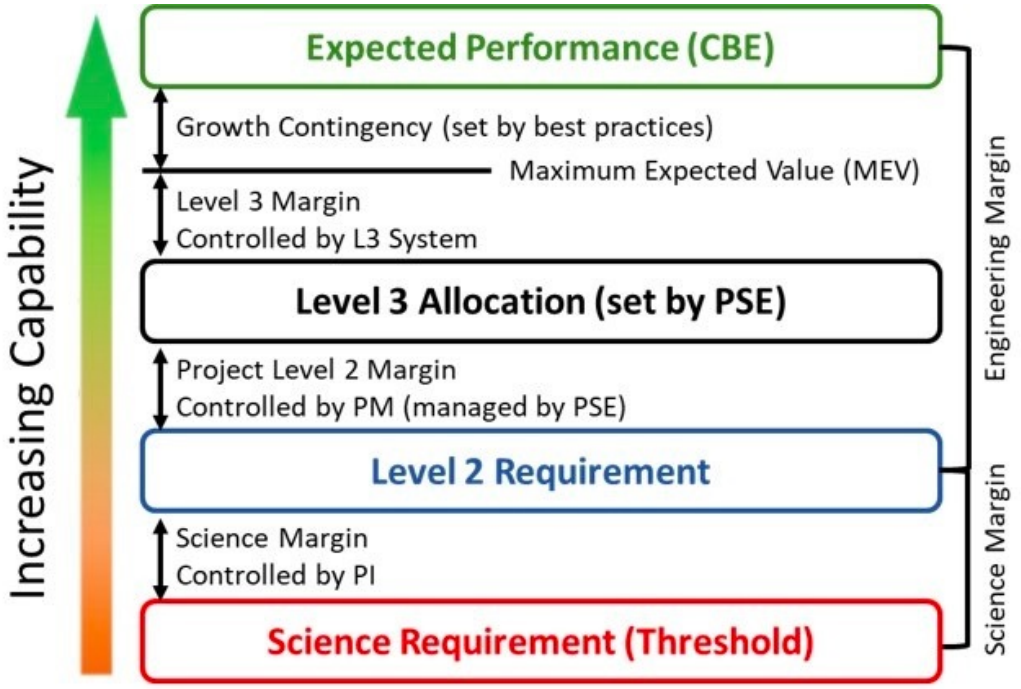
Requirements & Interfaces

The SPHEREx project requirements set the foundation for detailed design.



- Phase B comprised of formal requirements elaboration and flow down
  - While capturing each requirement, validity, conditional applicability, verifiability, robustness, and completeness checks were performed to ensure a quality requirement from the onset.
  - Full traceability is established from Level 1 to Level 4 in the formal database, and SPHEREx has maintained a current requirement baseline with the Project Change Control Board from Preliminary Design Review until today.

Managing Technical Resources & Margins

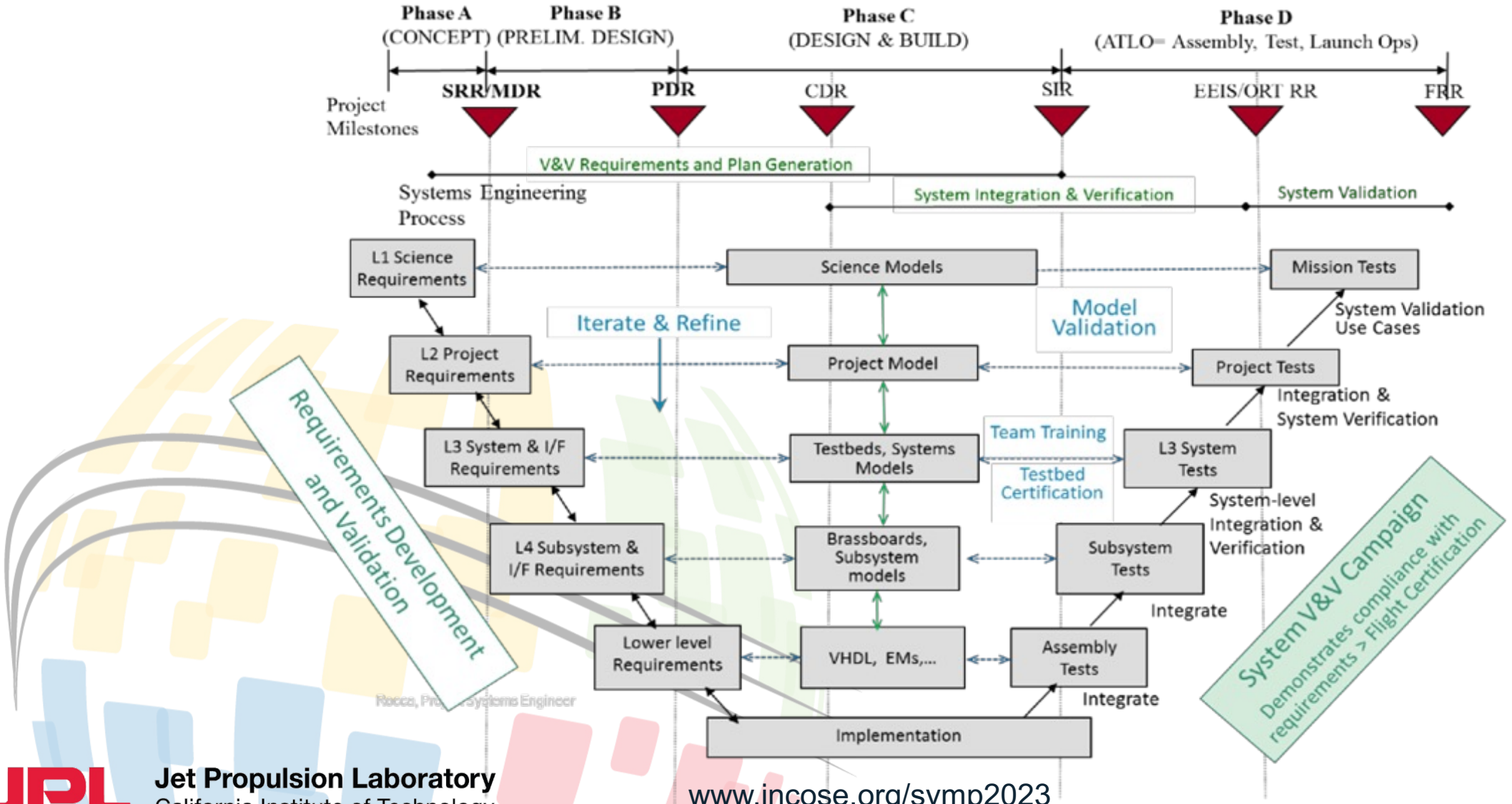


- The PSET manages all technical resources
- Technical margins above allocated requirement levels are held at the project level and adjudicated by Project Management for use in reducing technical risk
- The Principal Investigator holds science margin beyond the project allocated requirements
- SPHEREx formalizes this process with the Project Change Control Board, where requests to release project-held margin require approval of an Engineering Change Request
- Sixteen technical resources are tracked on a monthly cadence, and represent the key and driving requirements that need to be met in order to meet scientific goals

Performance Models and Simulation

- SPHEREx maintains several key project models and simulations used in support of trade studies, performance assessments, requirements verification and system validation
  - End-to-end science performance model: helped establish the science quantification, error budget, and traceability
  - Observation strategy/survey model: defines *a priori* how to execute the survey and achieve voxel completeness without violating avoidance constraints
  - Data pipeline model: enables a development framework for every step of the complex data processing, and allows parallel development of L1-3 and L4 modules
  - Sky Simulator: used to close the gap between what is possible for the instrument to produce on the ground and what it will produce in space—serves as the input to validate the pipeline
- Model-based methods are also put to use in several key areas to reduce 'person power' required, for example:
  - Requirement and Verification Activity burn-downs
  - Swimlane Visualization: connecting the burn-downs to the master schedule

The Verification & Validation Lifecycle



Innovative V&V Toolset

= automated

VA status
SEs focus on *closing VAs* by manually linking and reviewing closure packages and flowing VA to become "Approved"

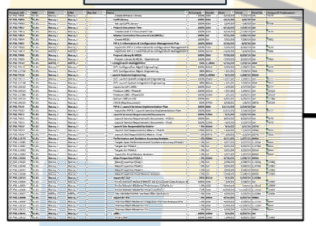
Reqt status
automatically pulled from:
a. linked VA status and
b. children reqt closure status

Children reqts

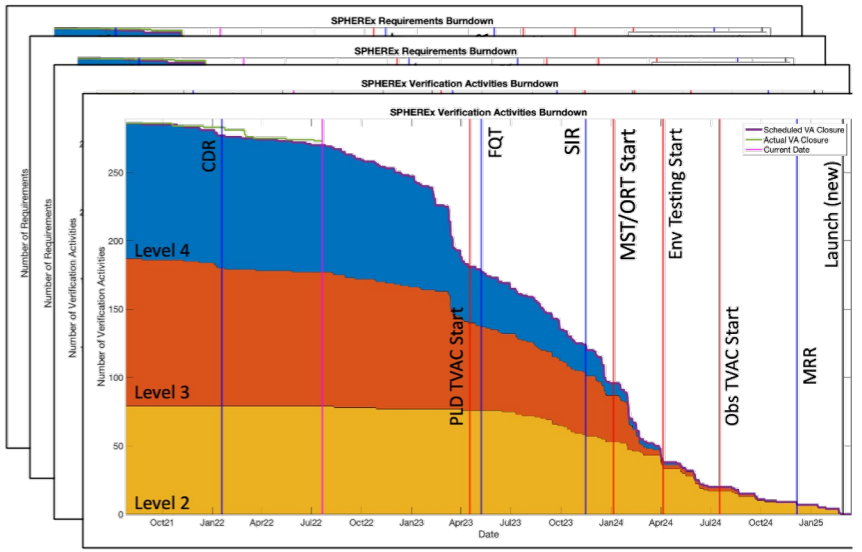
VA completion dates
associated with IMS milestones and input into DNG (with appropriate off-sets, as needed) and updated monthly

Reqt completion dates
automatically pulled from:
a. linked VA closure dates and
b. children reqt closures dates

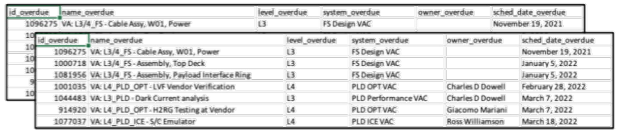
IMS



1. VA and reqt burndowns

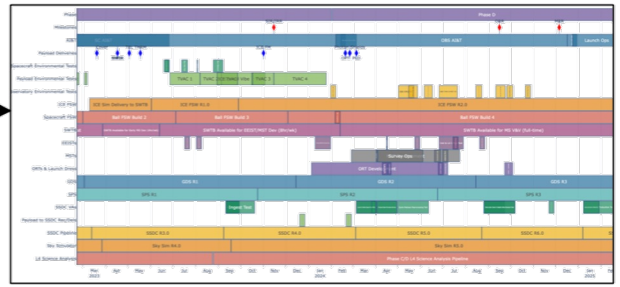


2. List of late and upcoming VAs and reqts

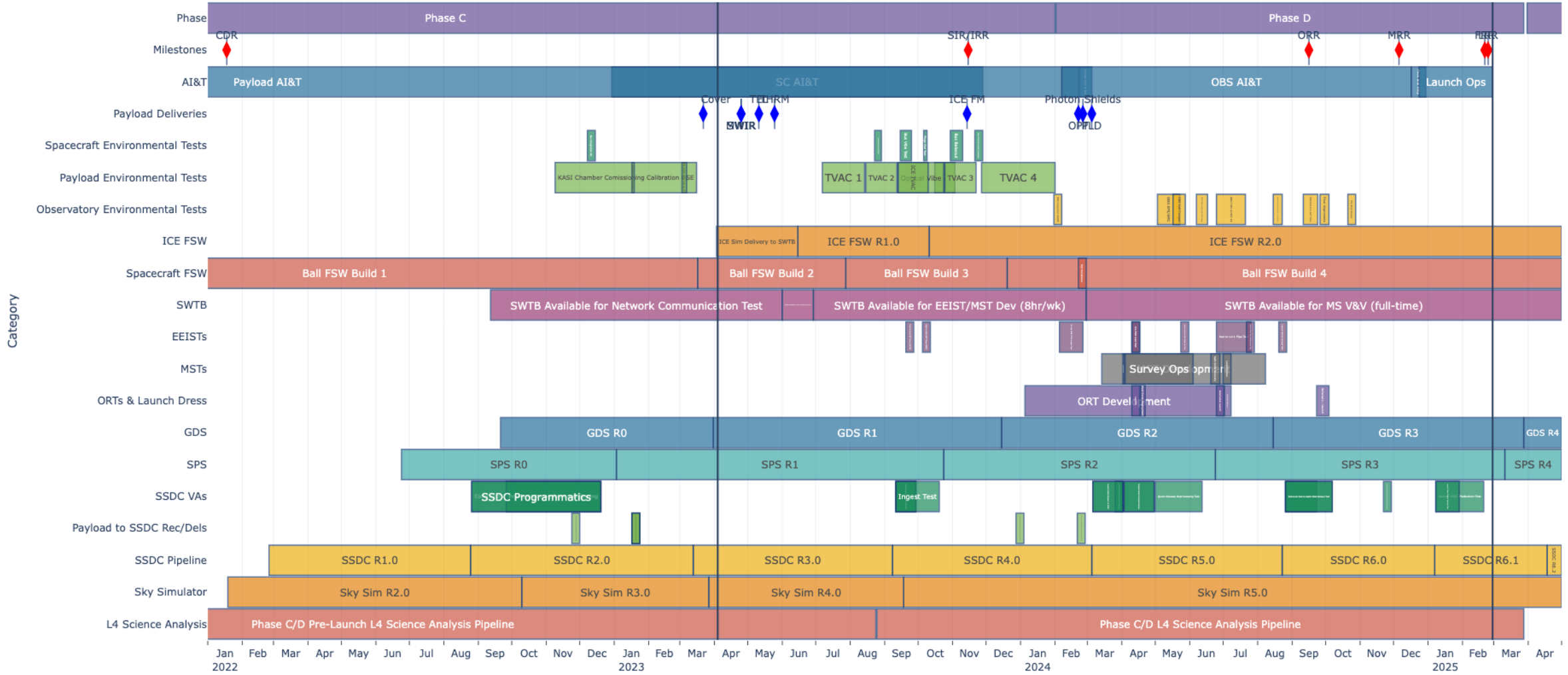


id_overdue	name_overdue	level_overdue	system_overdue	owner_overdue	sched_date_overdue
1096275	VA: L3/4_FS - Cable Assy, W01, Power	L3	FS Design VAC		November 19, 2021
1000718	VA: L3/4_FS - Assembly, Top Deck	L3	FS Design VAC		January 5, 2022
1081956	VA: L3/4_FS - Assembly, Payload Interface Ring	L3	FS Design VAC		January 5, 2022
1001035	VA: L4_PLD_OPT - LVF Vendor Verification	L4	PLD OPT VAC	Charles D Dowell	February 28, 2022
1044483	VA: L3_PLD - Dark Current analysis	L3	PLD Performance VAC	Charles D Dowell	March 7, 2022
914920	VA: L4_PLD_OPT - H2RG Testing at Vendor	L4	PLD OPT VAC	Giacomo Mariani	March 7, 2022
1077037	VA: L4_PLD_ICE - S/C Emulator	L4	PLD ICE VAC	Ross Williamson	March 18, 2022

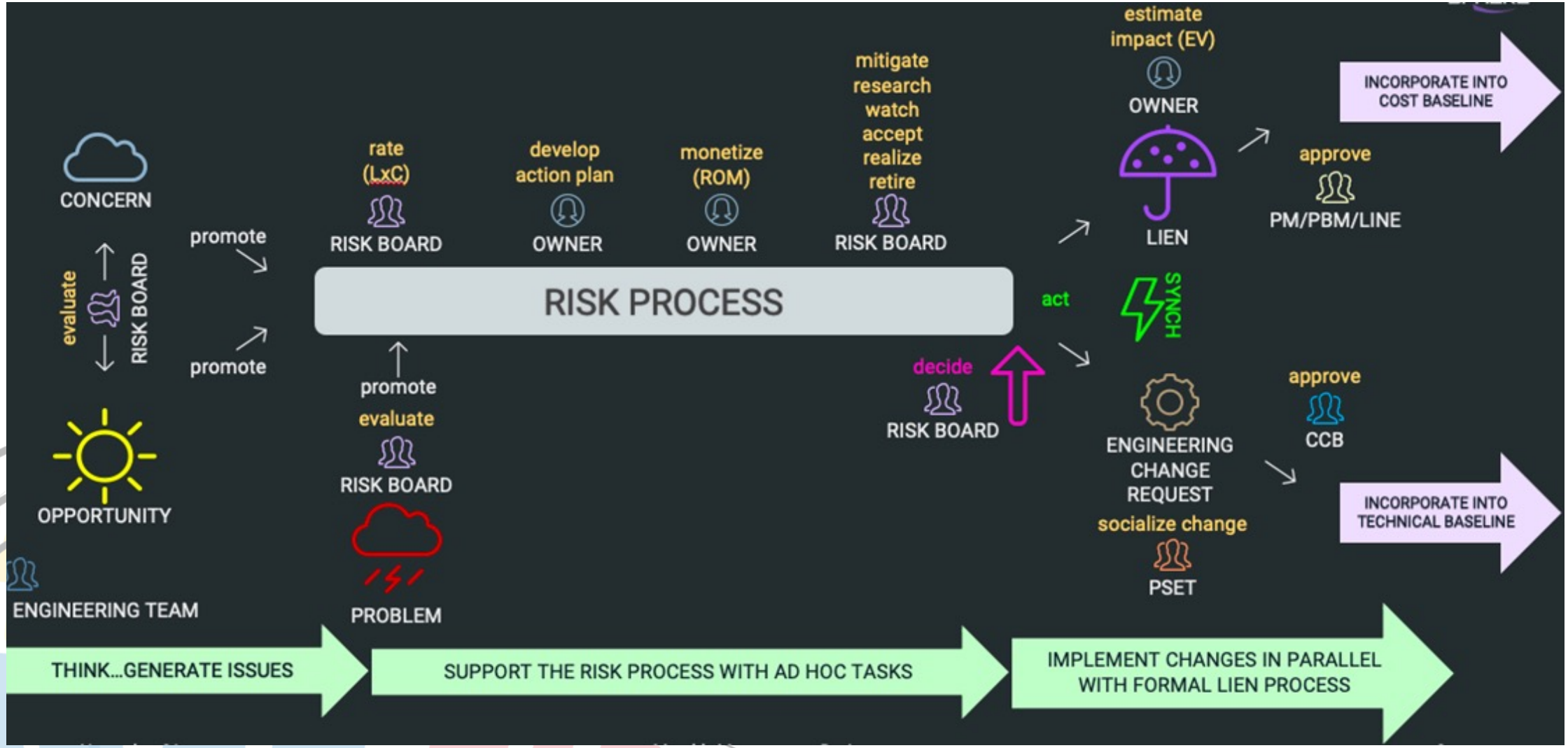
3. V&V schedule "swimlane" visualization



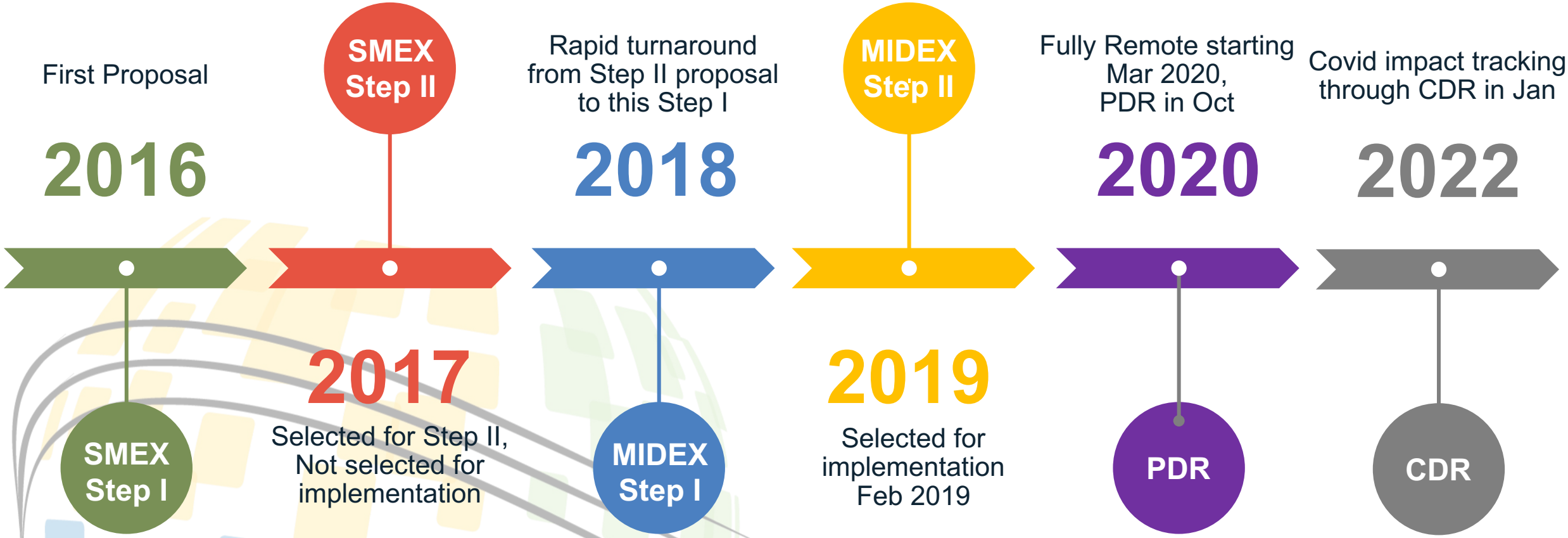
Swimlane Visualization



Integrated Risk/Lien/Change Process



Implementation Timeline (to date)



Key Implementation Challenge – Rideshare!

- SpaceX Falcon-9 LV selection, Jan 2021
  - Just 3 months after PDR
  - F9 could launch 3 SPHEREx' s stacked vertically!

- NASA SMD Rideshare Office initiated rideshare assessment shortly after launch vehicle selection
  - SPHEREx performed a formal compatibility assessment
  - Chief concerns: Water Thrusters as source of contamination, Dynamics interactions between SPHEREx telescope and PUNCH

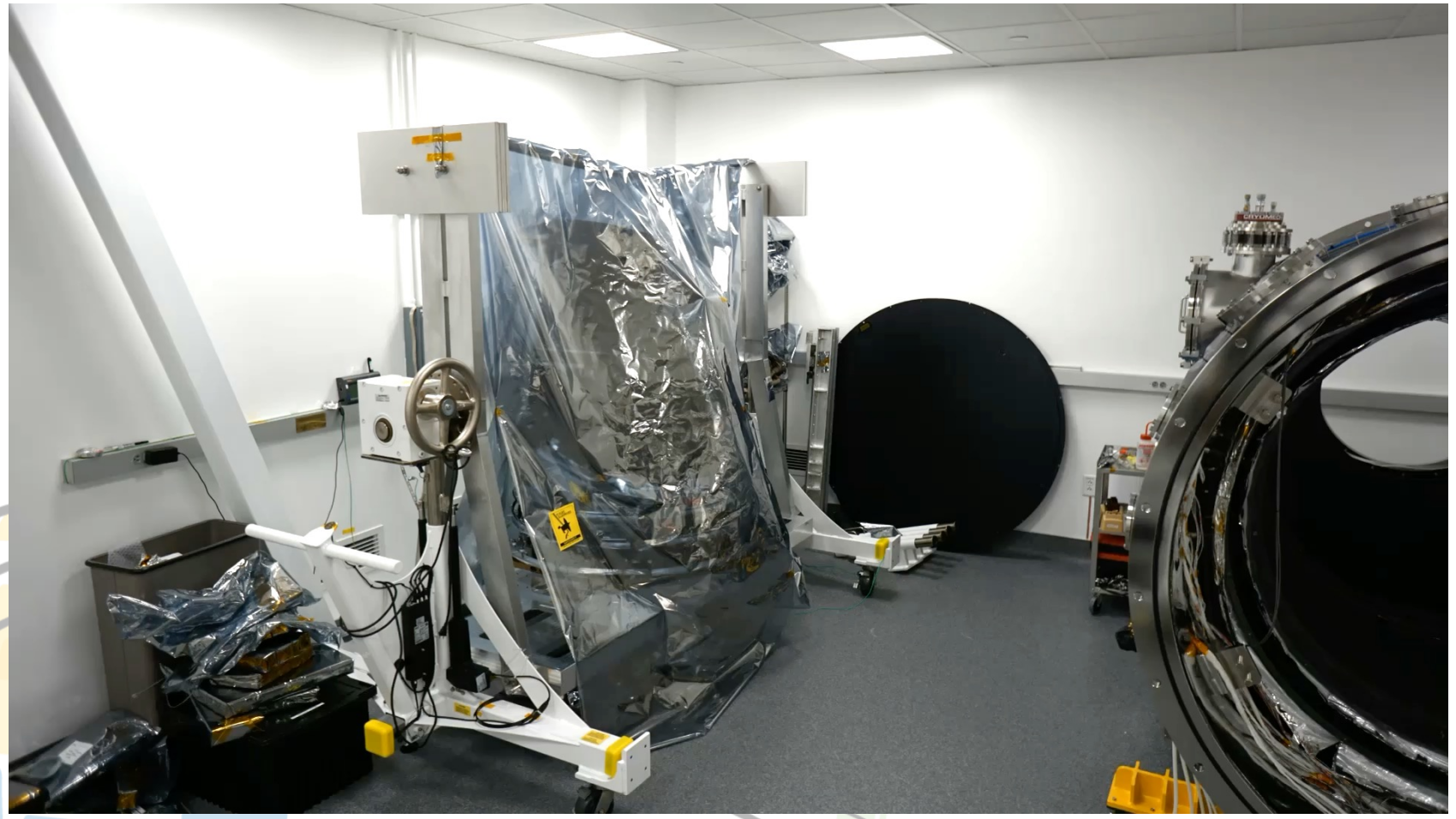
- The PUNCH 2016 Heliophysics Small Explorer mission was selected as our rideshare partner in Dec 2021
  - An early coupled loads analysis was performed

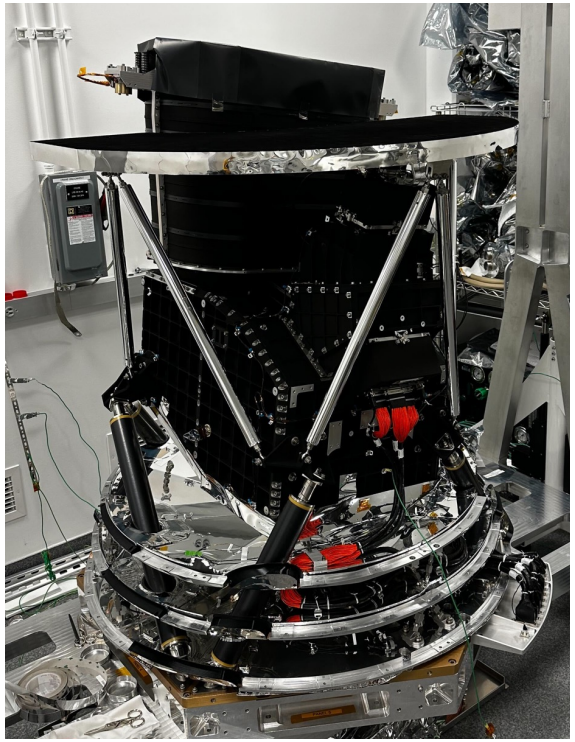
- PUNCH is a 'do no harm' rideshare partner, with SPHEREx as the primary payload
  - Close collaboration between the two missions and NASA's Explorers Program and Rideshare offices will continue through the rest of development to maintain compatibility

Key Implementation Challenge – Covid!

- Phase B start Feb 2019
  - Trade studies performed
  - Preliminary design work proceeds as planned
- Covid starts in Mar 2020
  - All Teams went home
  - Centers/Labs closed
- Teams focused on critical hardware tasks such as long lead procurements, materials testing, and prototype hardware/electronics developments
  - Tasks moved to individual home workshops
- Supply Chain impacts → design changes
  - Necessitated changing materials, working with different shops, etc.
  - Electronics parts sourced from NASA-wide searches of flight stores
- SPHEREx folded impact tracking into the Earned Value and Risk processes
- Launch Date Change due to Covid Impacts from Jun 24 to Feb 25
  - Coordinated with the NASA Astrophysics Division, the Explorers Office, and the Standing Review Board to release NASA-held reserve to fund this adjustment

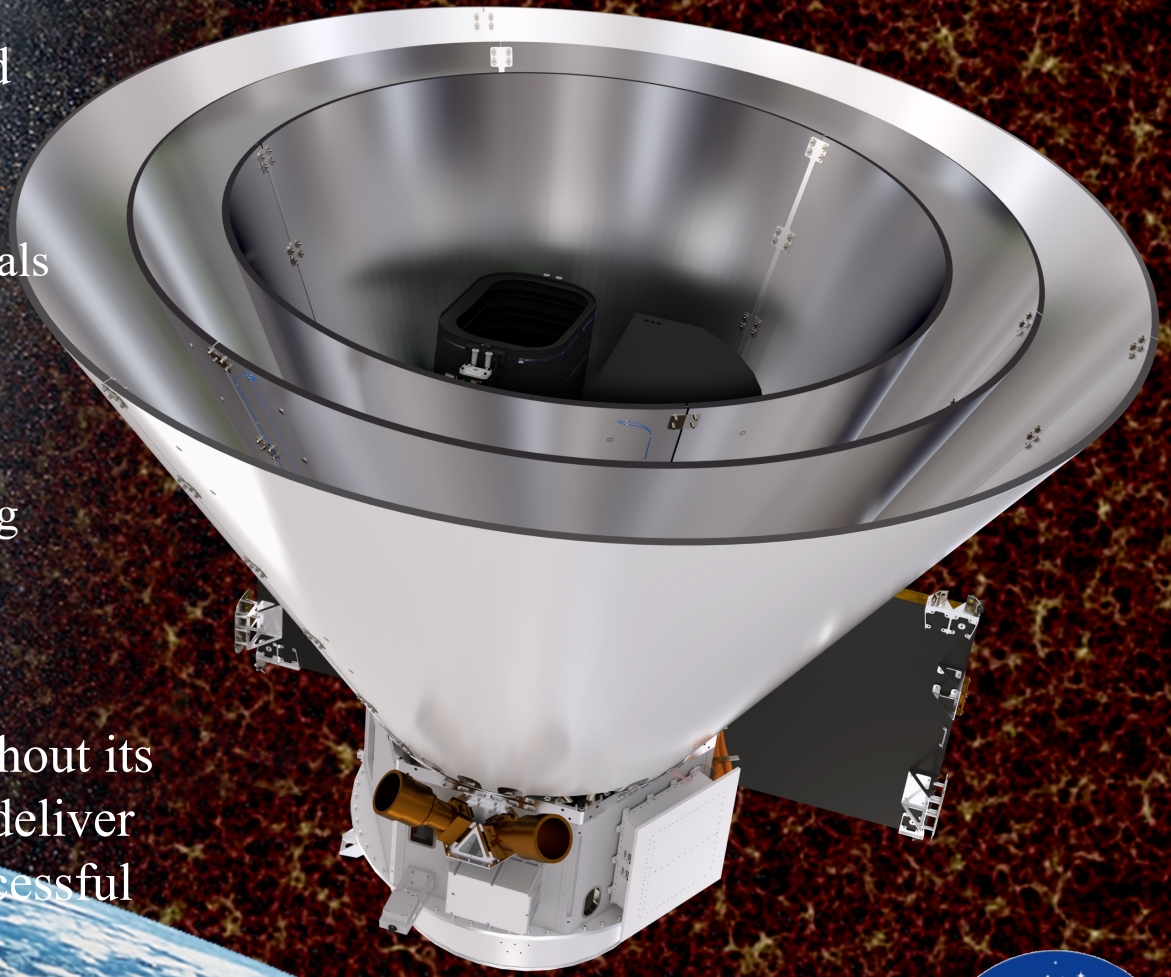
Now, fully assembled flight payload in TVAC….





In Summary…

- SPHEREx is developed within a Class C, cost-capped paradigm
  - The project implements collaborative processes that leverage the strengths of our institutions and individuals
- SPHEREx makes use of a close knit PSET that:
  - Embraces automation in its V&V process
  - Manages technical resources at several levels ensuring adequate reserves are held throughout
  - Has a transparent, integrated risk/lien/change process
- While the project has faced several challenges throughout its development, its ability to persevere and continue to deliver under its various constraints is largely due to this successful adaptation of larger NASA, JPL, and Ball Aerospace institutional systems engineering practices for this smaller, more risk-tolerant program



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