Mission (and science) traceability (and some recent and upcoming HSO missions)

Craig DeForest (Southwest Research Institute)

Heliophysics Summer School, 8/15/2025

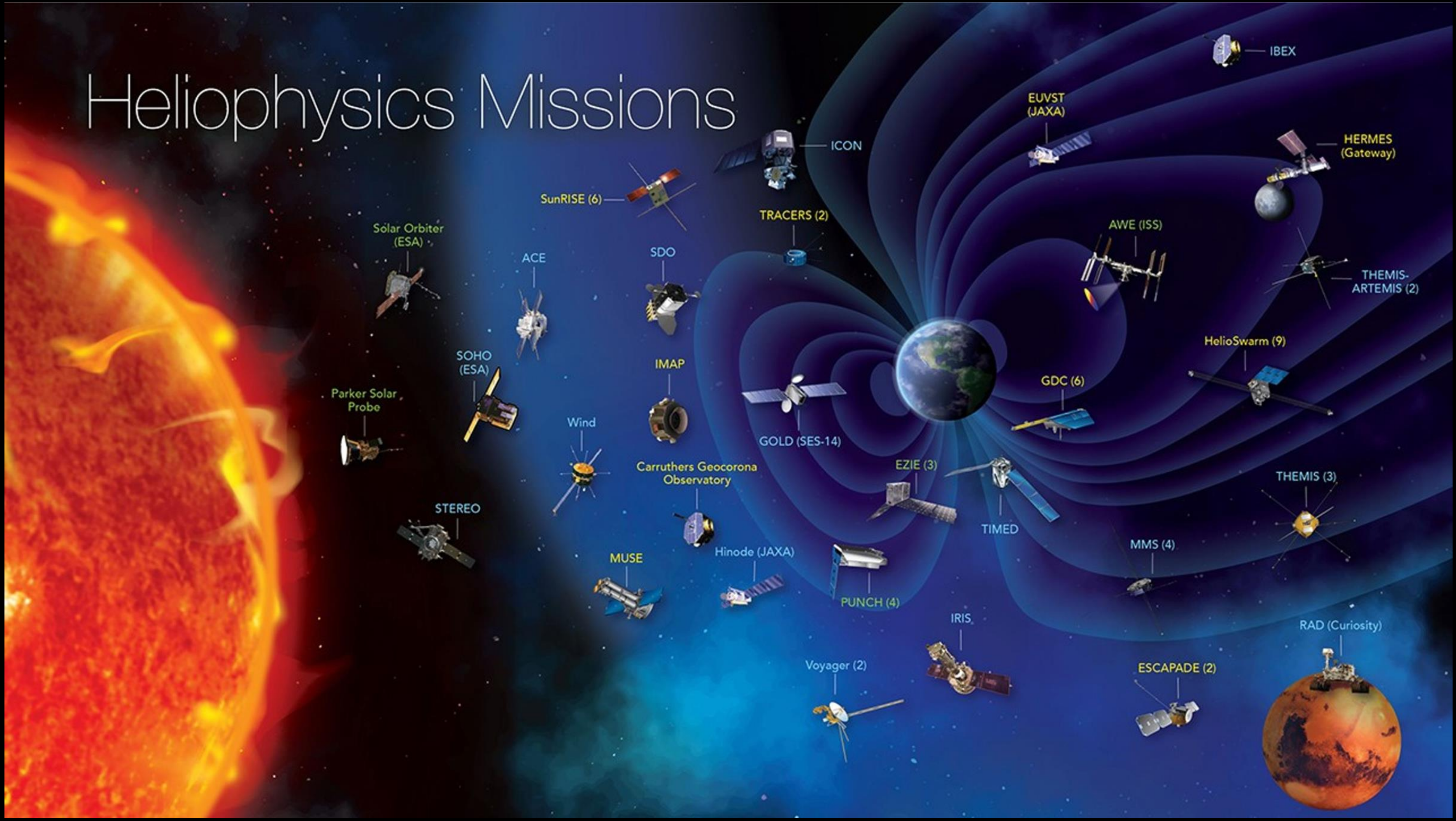
Outline

- A few Recent and Upcoming Heliophysics MIssions
- What are missions *for*?
- How To Design a Mission (or investigation!)
- Modes of instrument design
- A Tour of Mission Requirements and Traceability
  - PUNCH (cover in detail)
  - CubIXSS (a second example)
- Thoughts on traceability and *your* science

Refresher

A Few Recent and Upcoming Heliophysics Missions

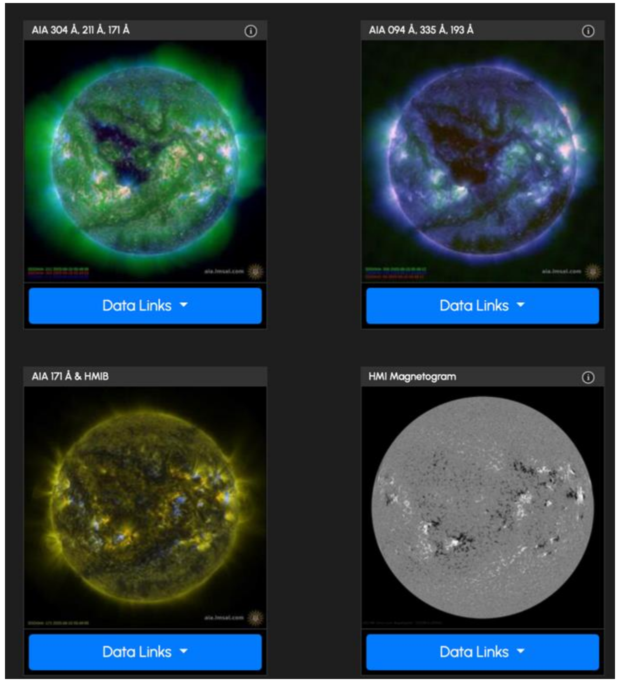
So many missions!

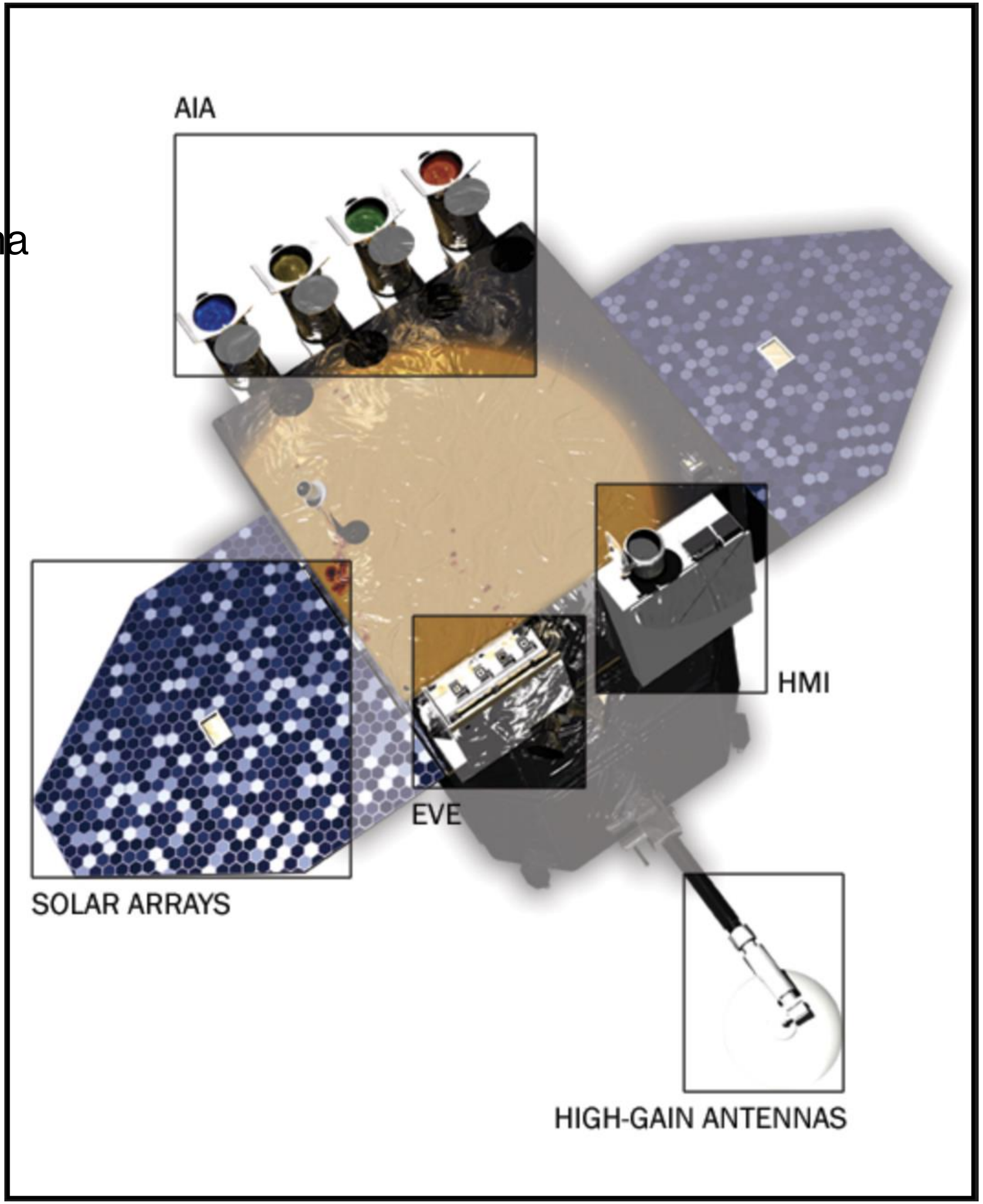


Solar Dynamics Observatory (SDO)

- Remote-sensing observatory
- AIA: High-volume, high resolution EUV images of the corona
- HMI: Doppler/magnetograph
- EVE: Full-disk Sun-as-a-star spectrograph

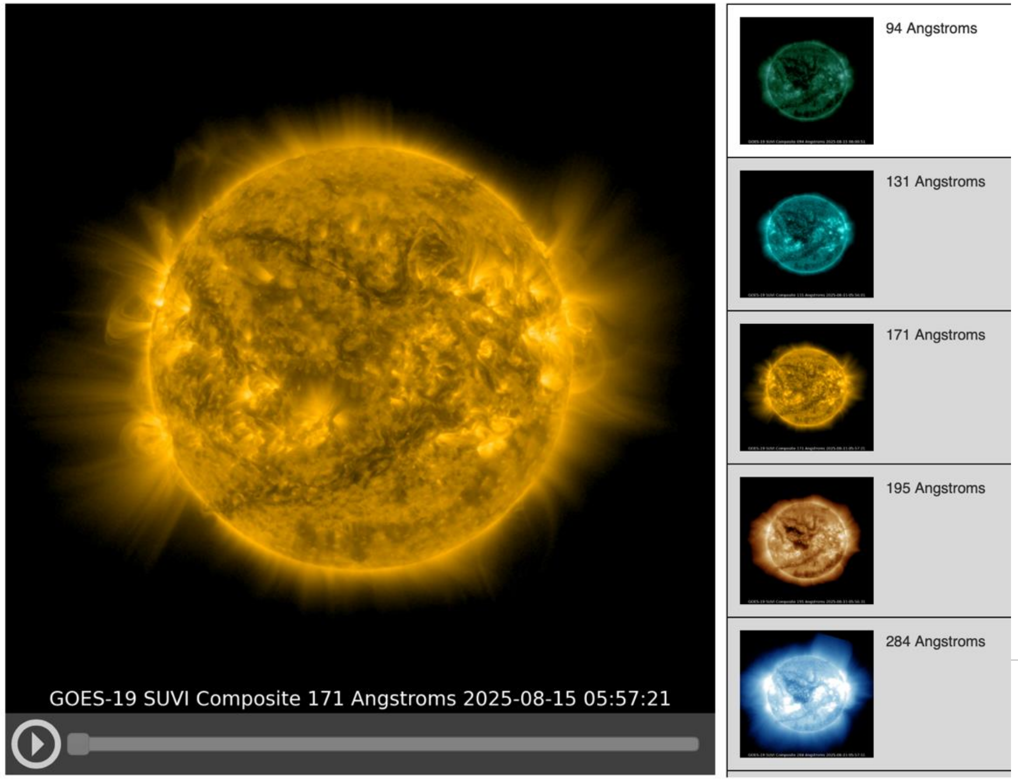
- **Mainstay of solar imaging and coronal physics**

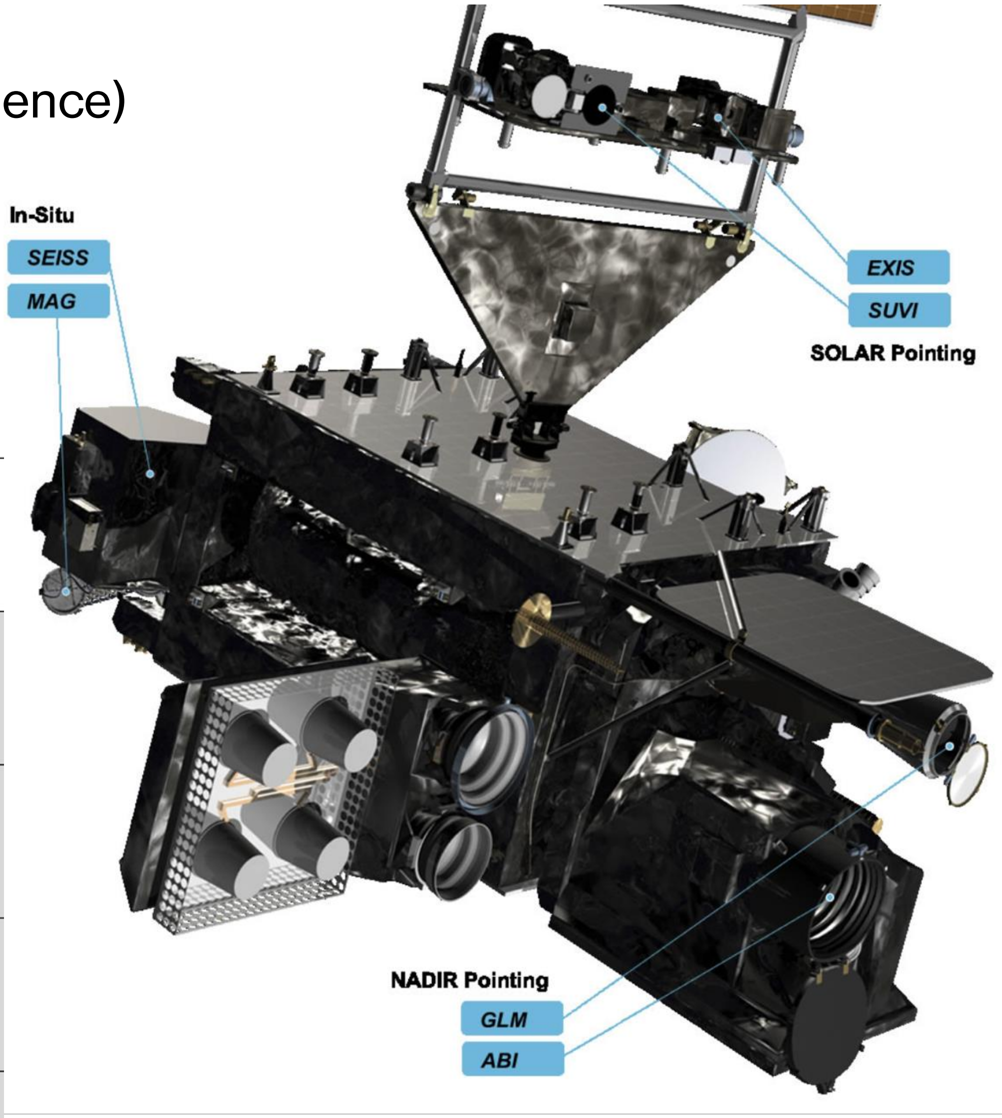




GOES Solar Ultraviolet Imager (GOES/SUVI)

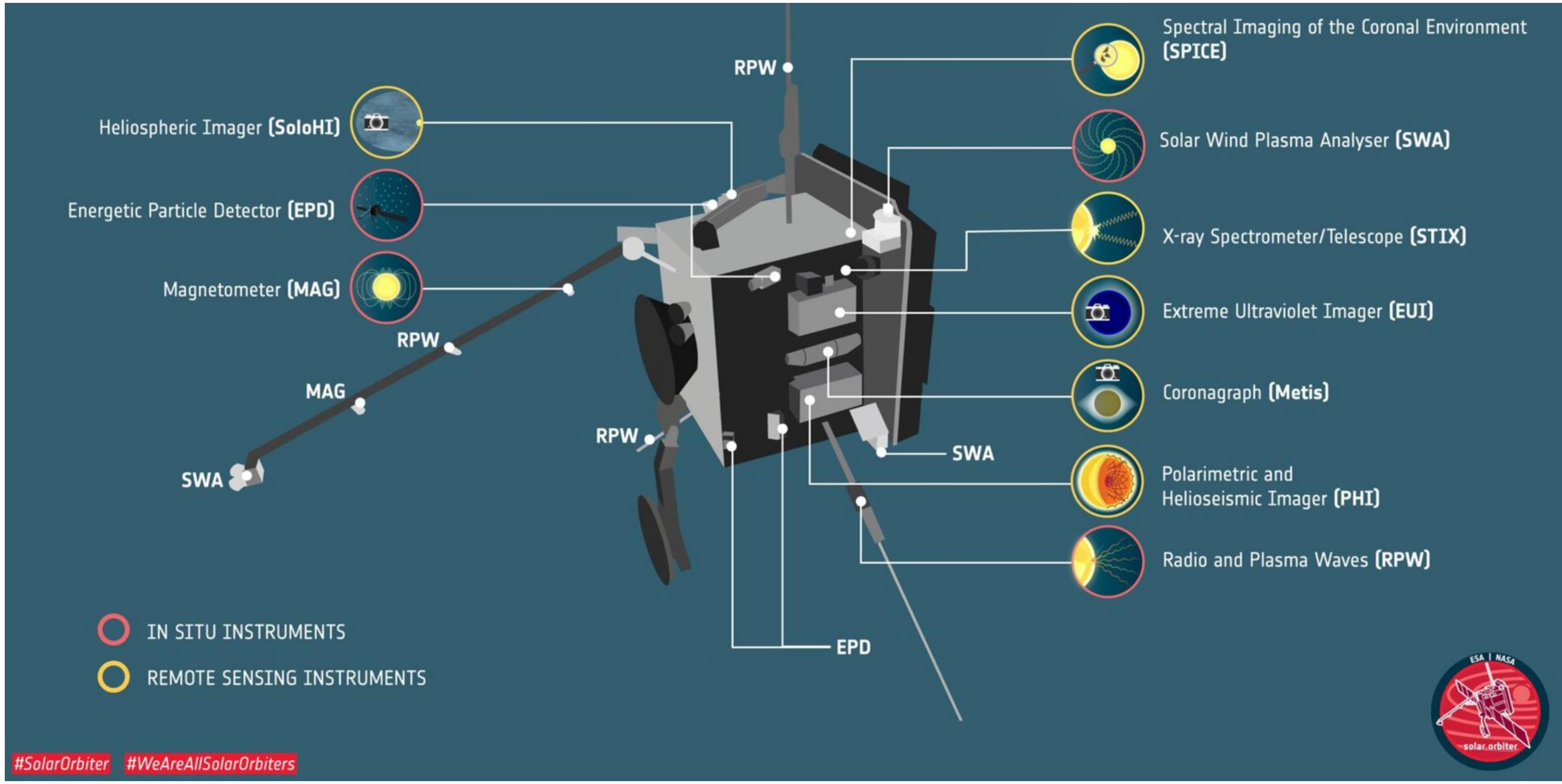
- Operational space-weather forecast instrument
- Comparable to SDO/AIA (larger FOV, higher sensitivity, lower cadence)





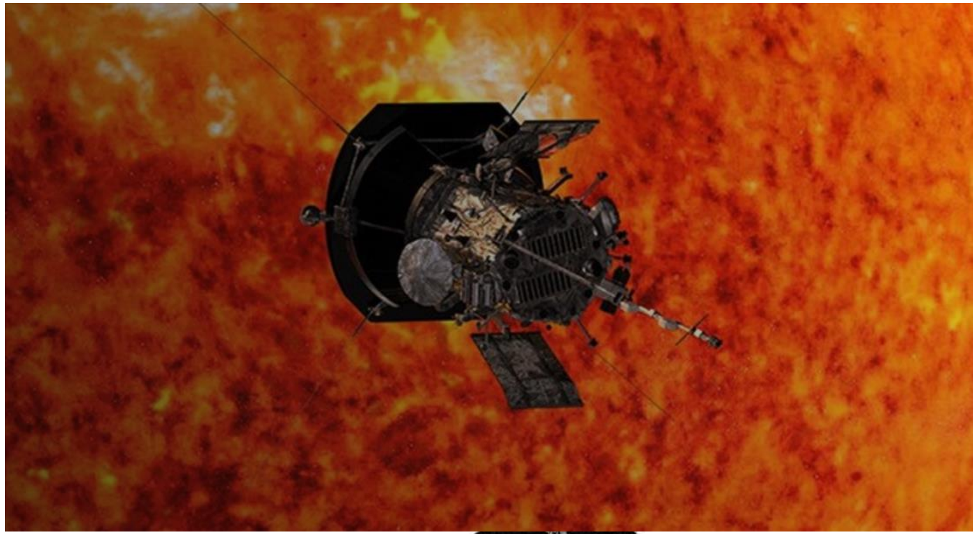
Solar Orbiter (SOLO)

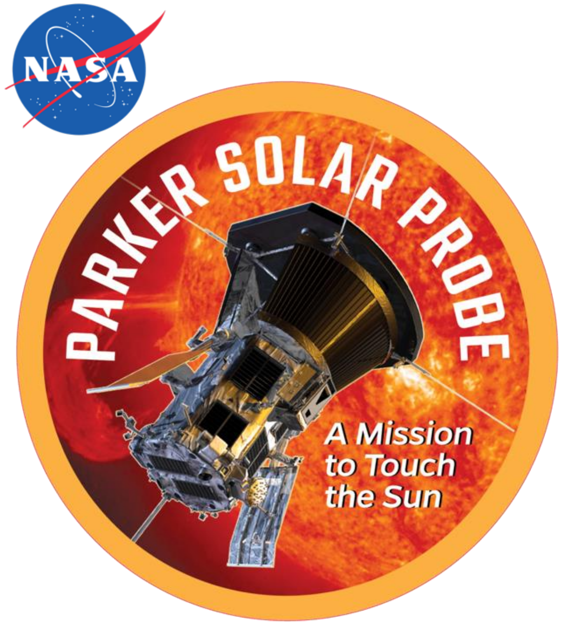
- Multipurpose solar observatory
- Full remote-sensing and in-situ instrument suites
- Elliptical orbit (~0.3 AU perihelion)
- High inclination (30°) for polar views

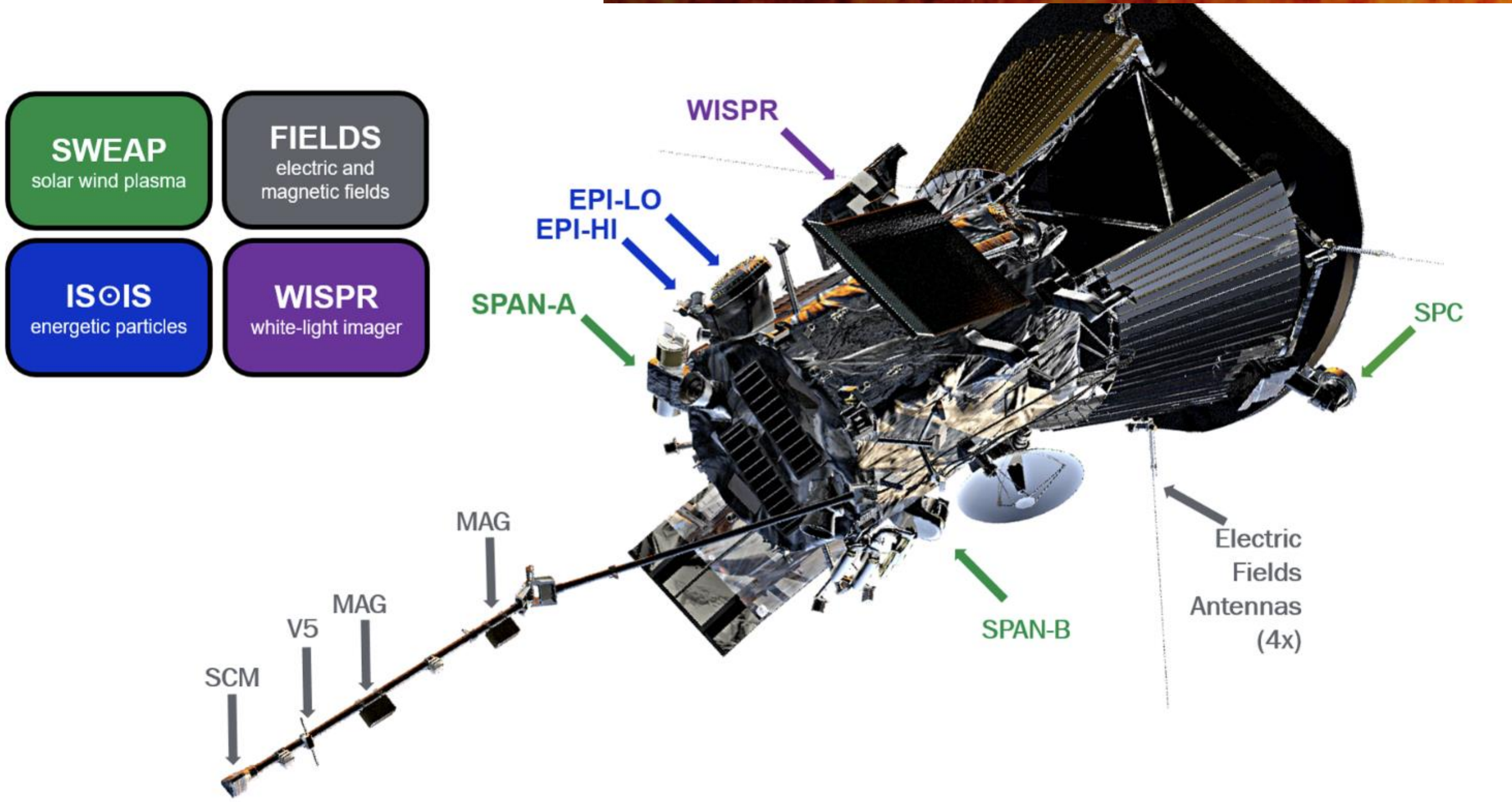


Parker Solar Probe (PSP)

- Highly elliptical orbit
- Full in-situ suite *in the solar corona*
- Local wide-angle imaging (WISPR)
- New perihelion pass about every 4 months

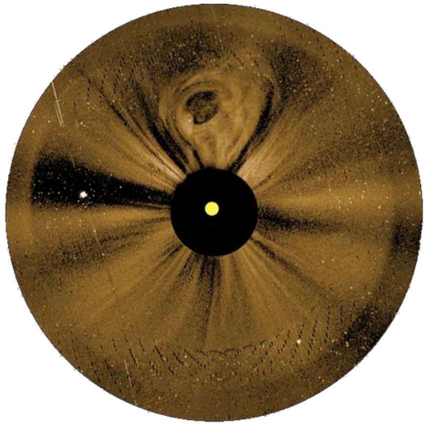


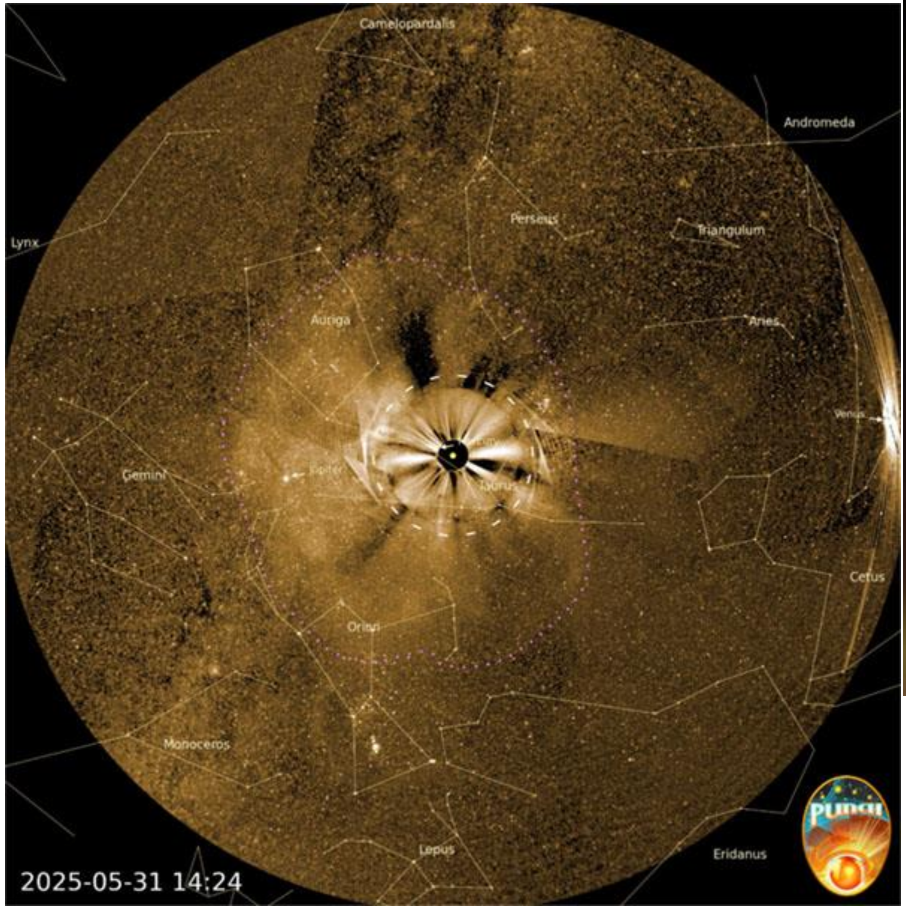


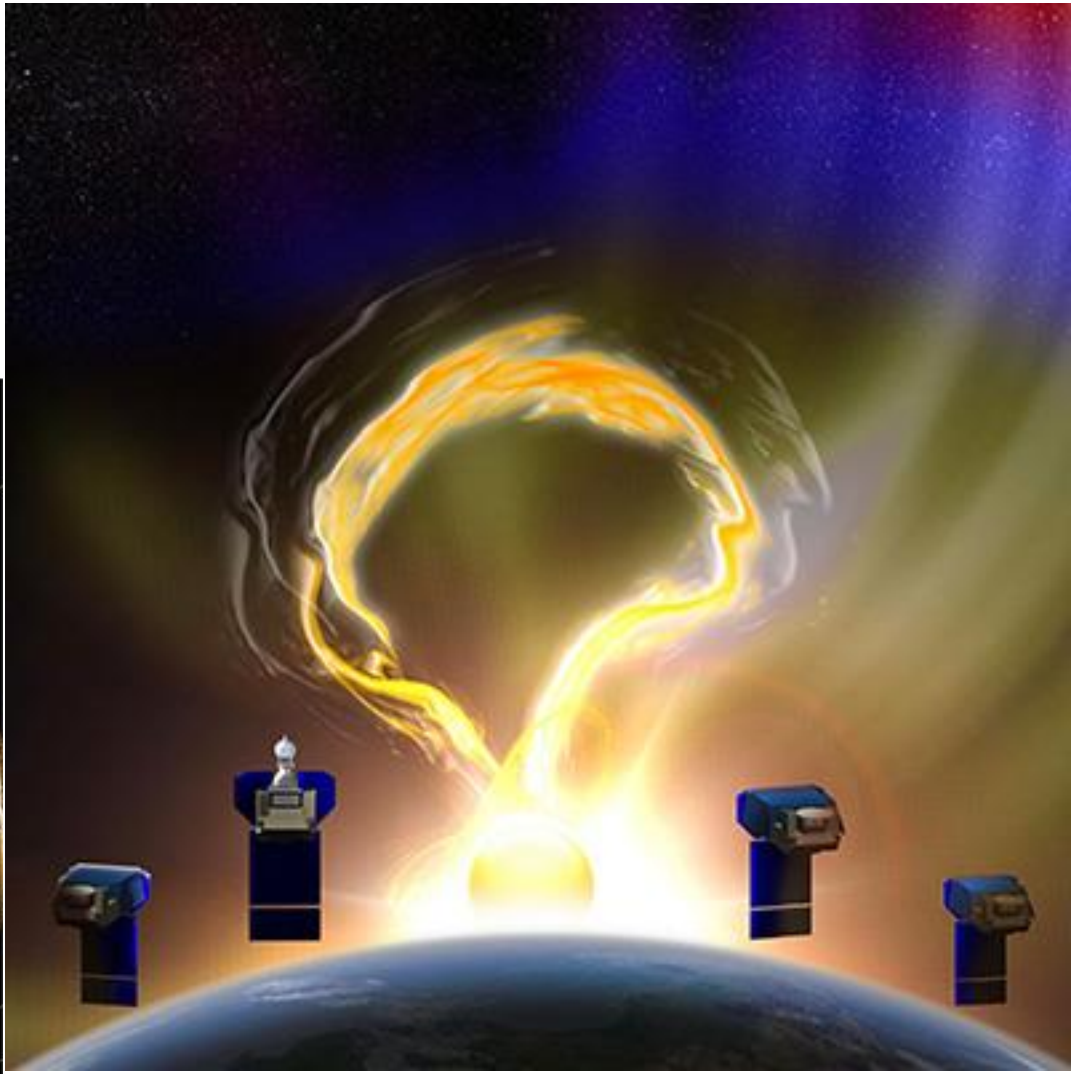


PUNCH

- Wide – angle coronagraph
- 90° wide field of view
- 3-D views of the corona and solar wind
- In commissioning now (on orbit)

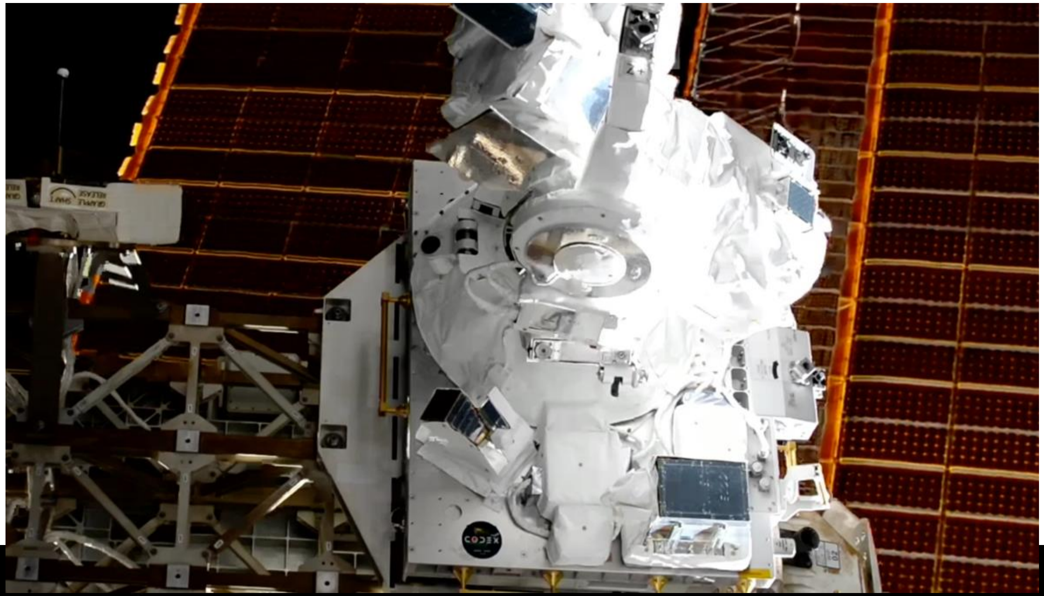


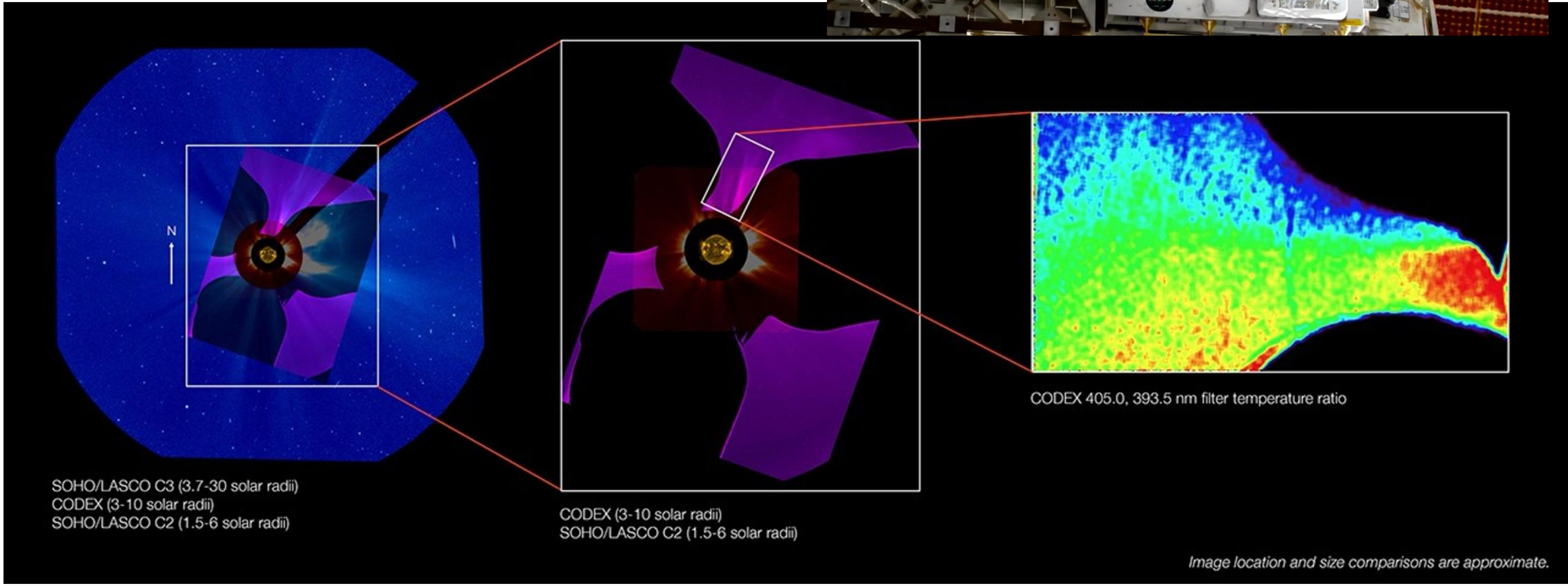




Coronal Diagnostic Experiment (ISS/CODEX)

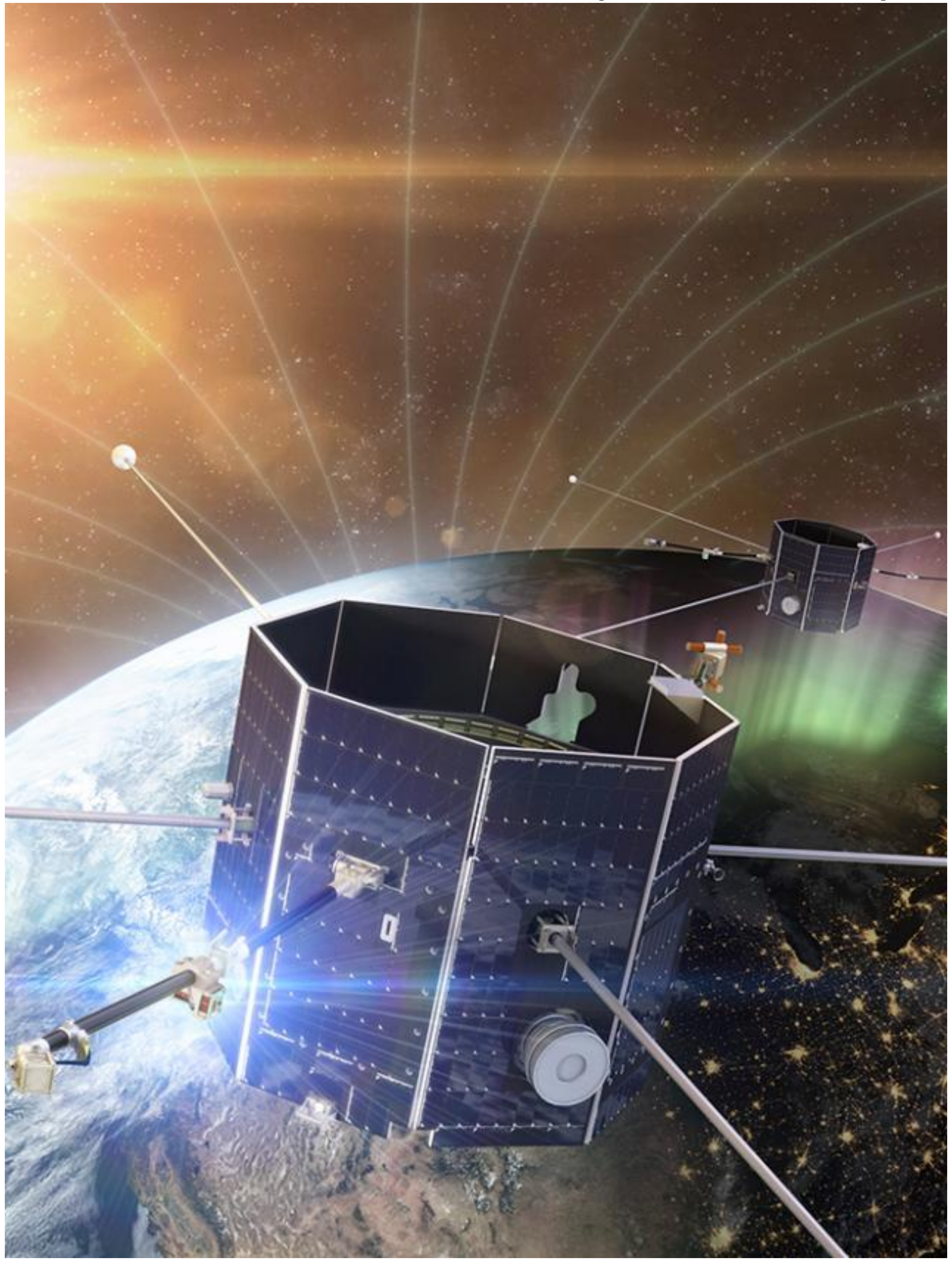
- Coronagraph with spectral information
- Diagnoses outflow and temperature of the corona
- Campaign observations from ISS
- Operational now





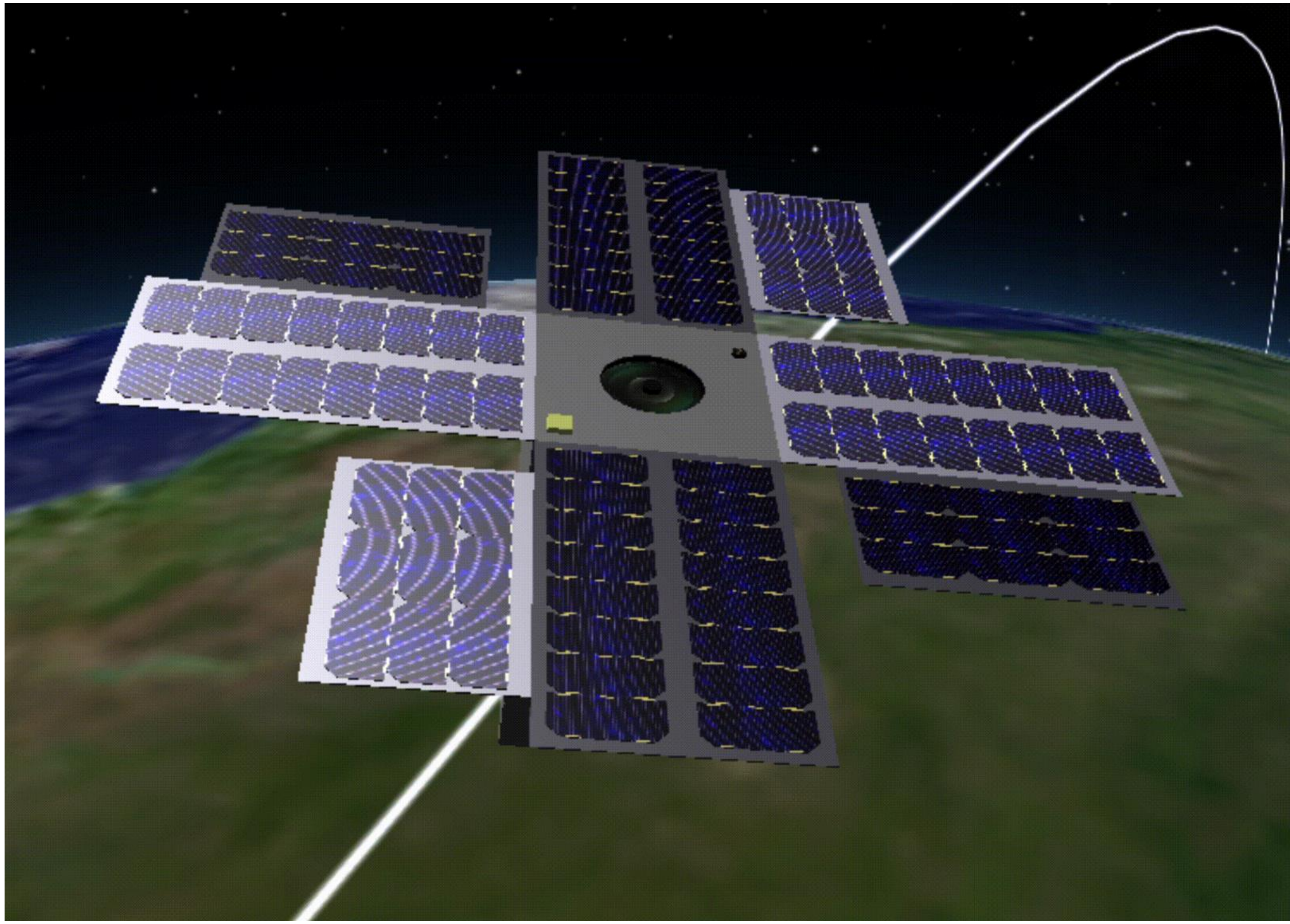
Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites (TRACERS)

- Studies terrestrial effects of the solar wind
  - Magnetometer, Electron sensor, Ion sensor
- Twin spacecraft
- In commissioning now



Polarization and Directivity X-ray Experiment (PADRE)

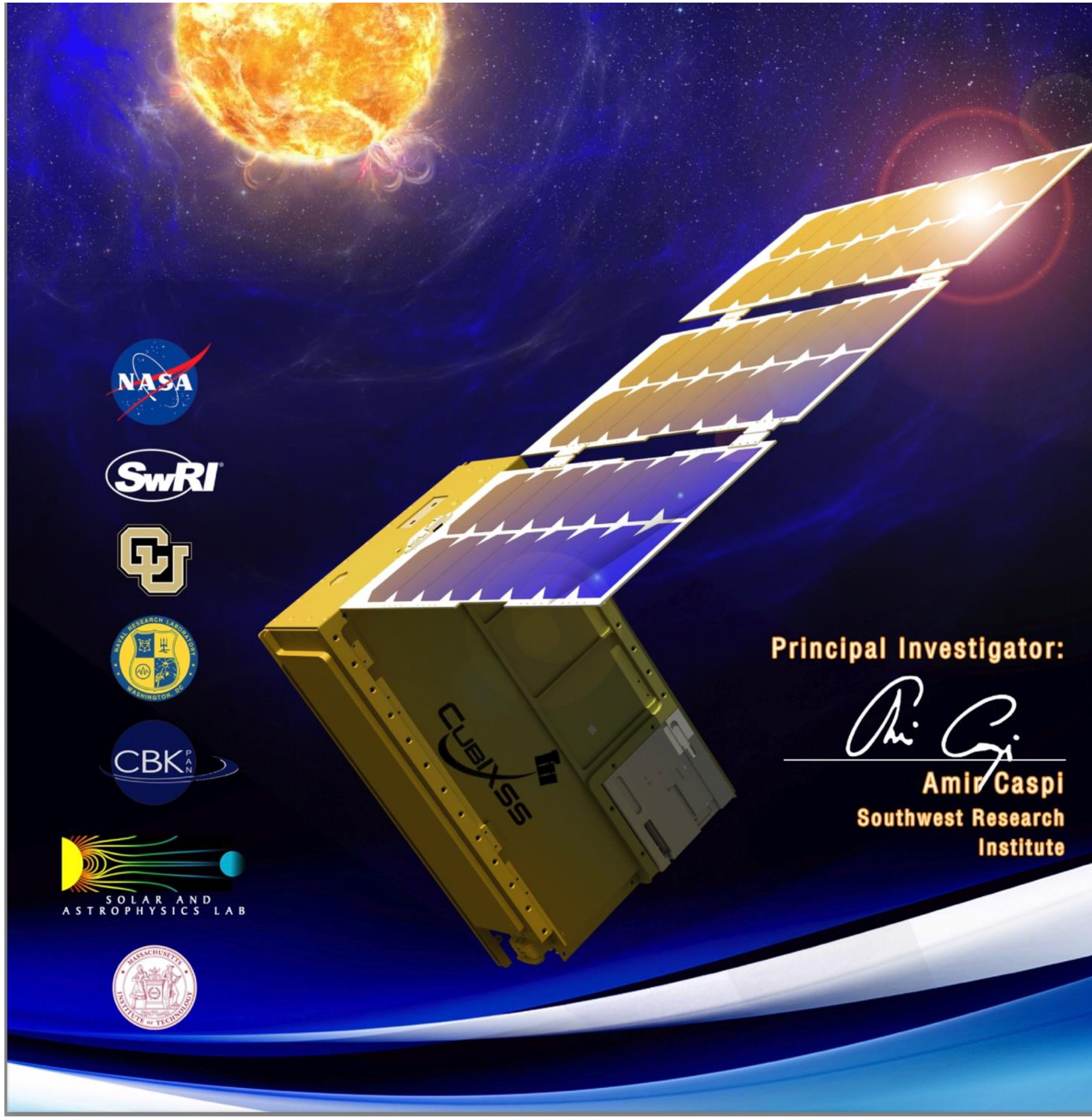
- Will measure hard X-ray polarization and direction from solar flares
- Instruments:
  - MeDDea – directional HXR detector
  - SHARP – HXR polarimeter
- On orbit now! (Commissioning)



Cubesat Imaging X-ray Solar Spectrometer (CubIXSS)

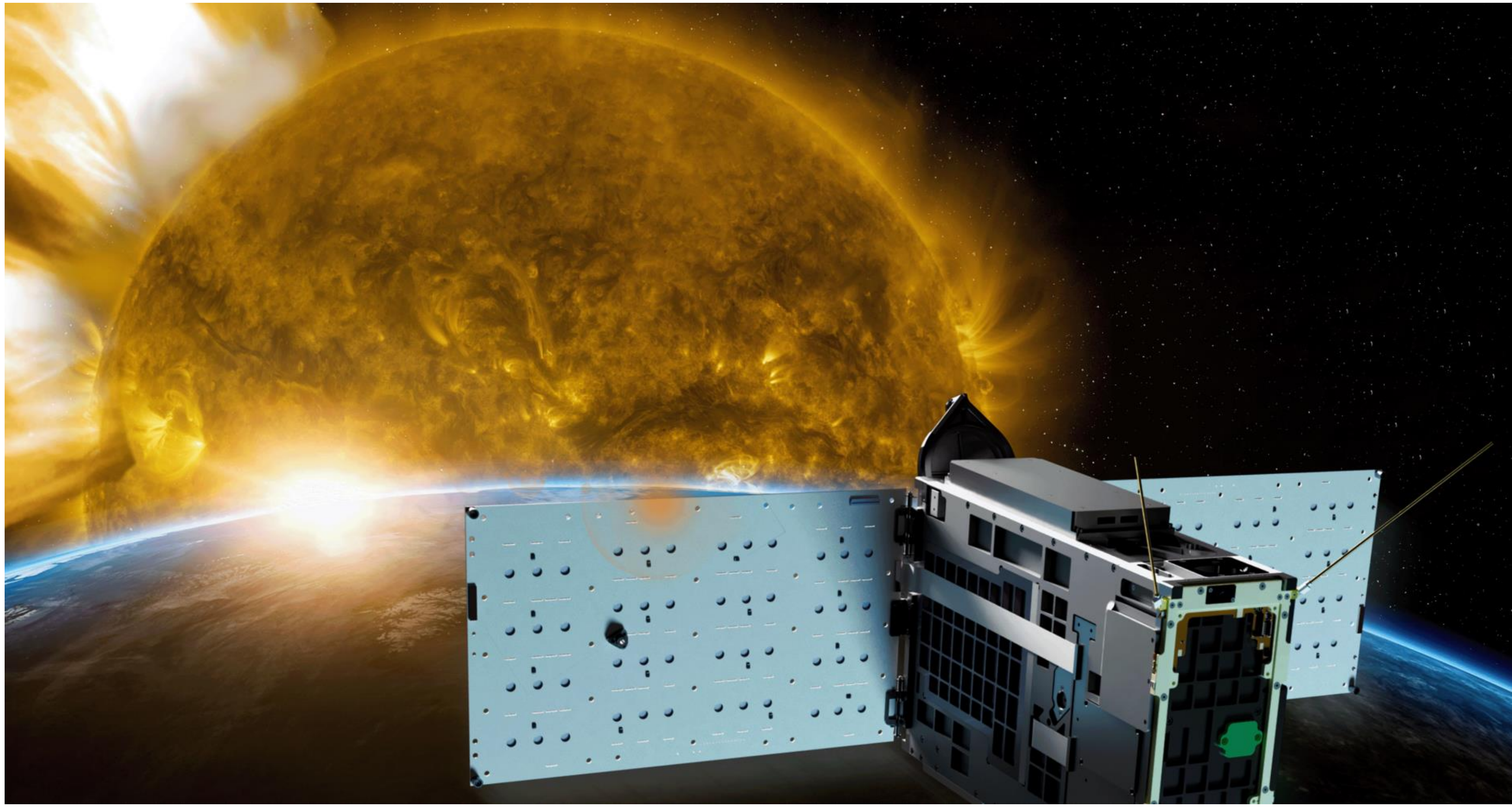
- X-ray Imaging and Imaging Spectroscopy satellite
- In development – scheduled for launch in 2026

- Instruments:
  - MOXSI: Spectral imager for X-rays
  - SASS: Multi-channel X-ray spectrometer



Sun Coronal Ejection Tracker (SunCET)

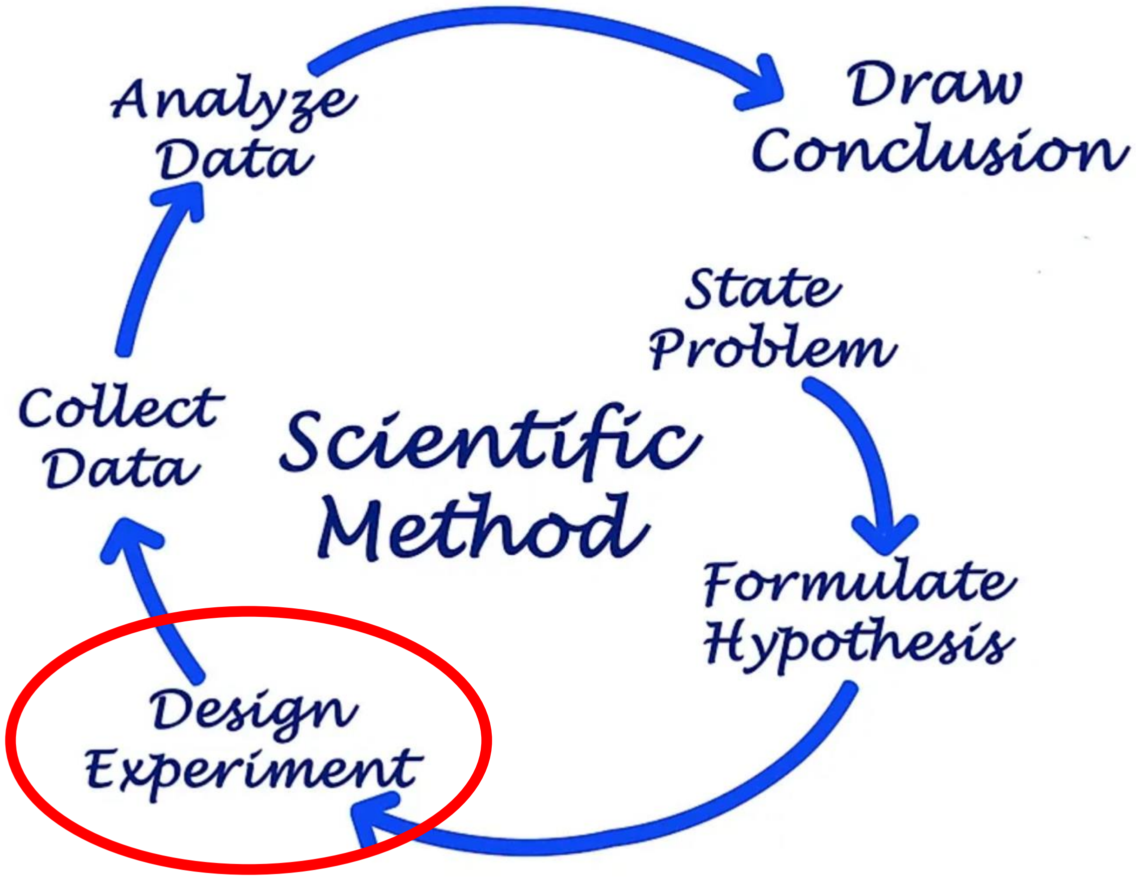
- Wide-field EUV imager tracks CMEs and other effects through the middle corona
- CubeSAT
- Scheduled for launch: 2025 October



SunCET

What are missions *for*?

Review: the scientific method as a six-step process

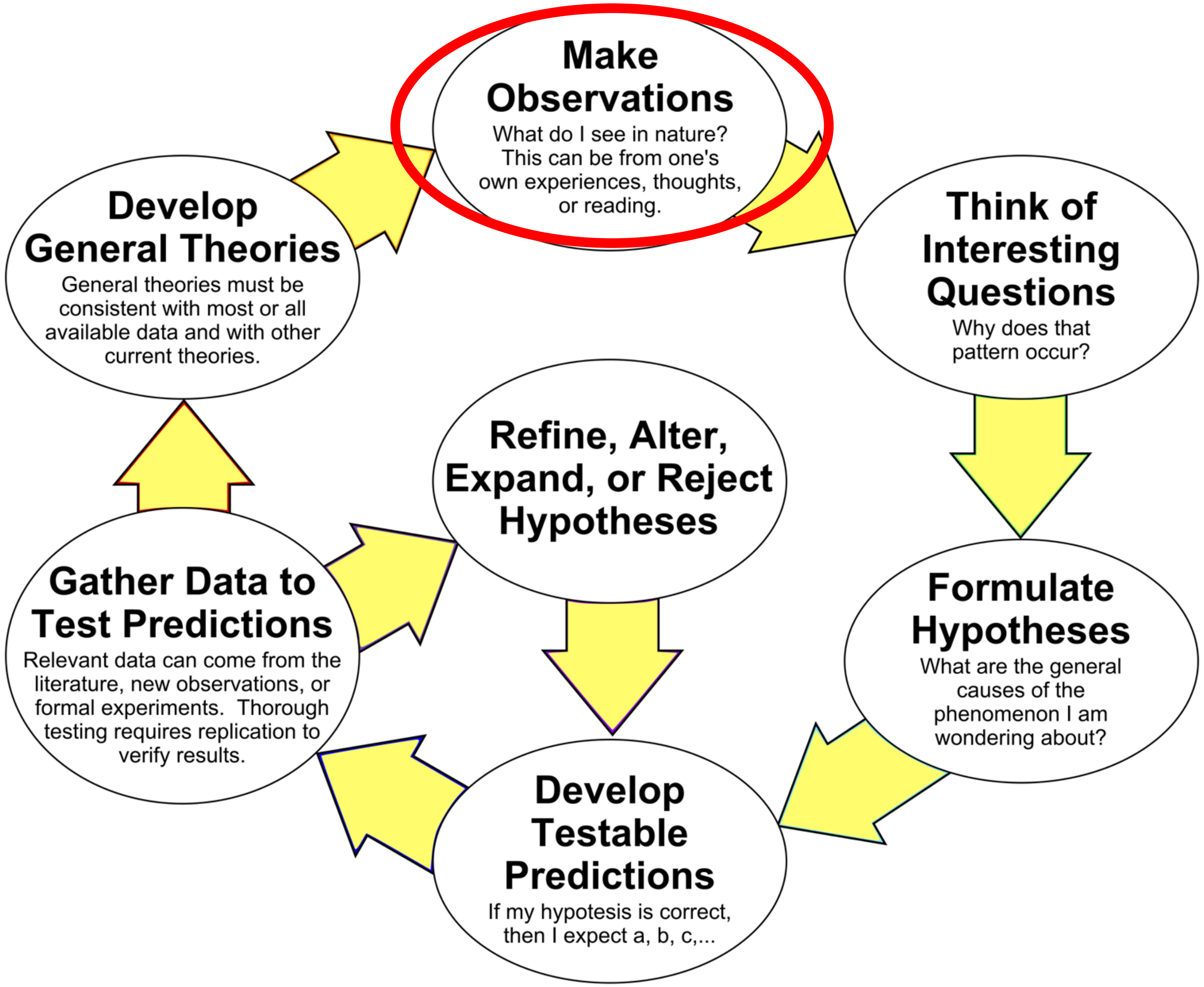


• Missions are *designed* to close specific scientific questions.

Review: the scientific method as an ongoing process

- Missions are *useful* for general investigation beyond their design science.

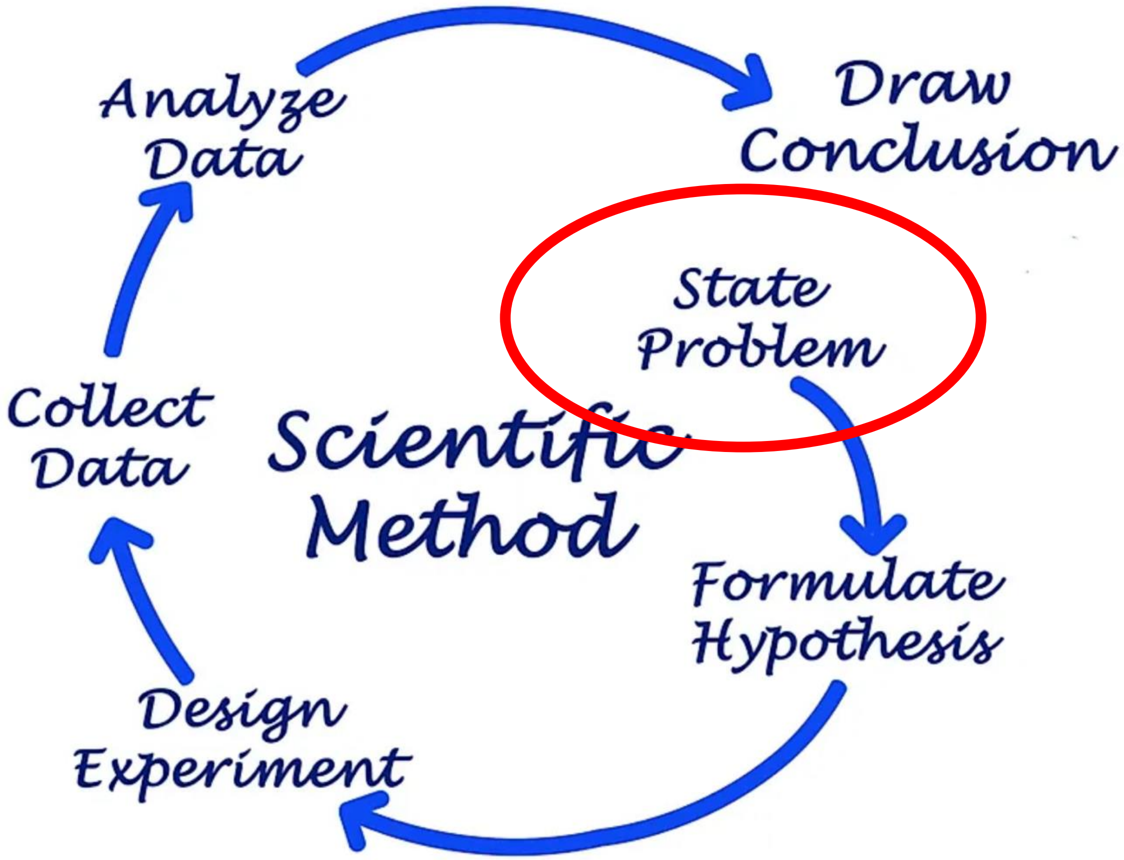
- Missions are *designed* to close specific scientific questions.



How To Design a Mission (or investigation)

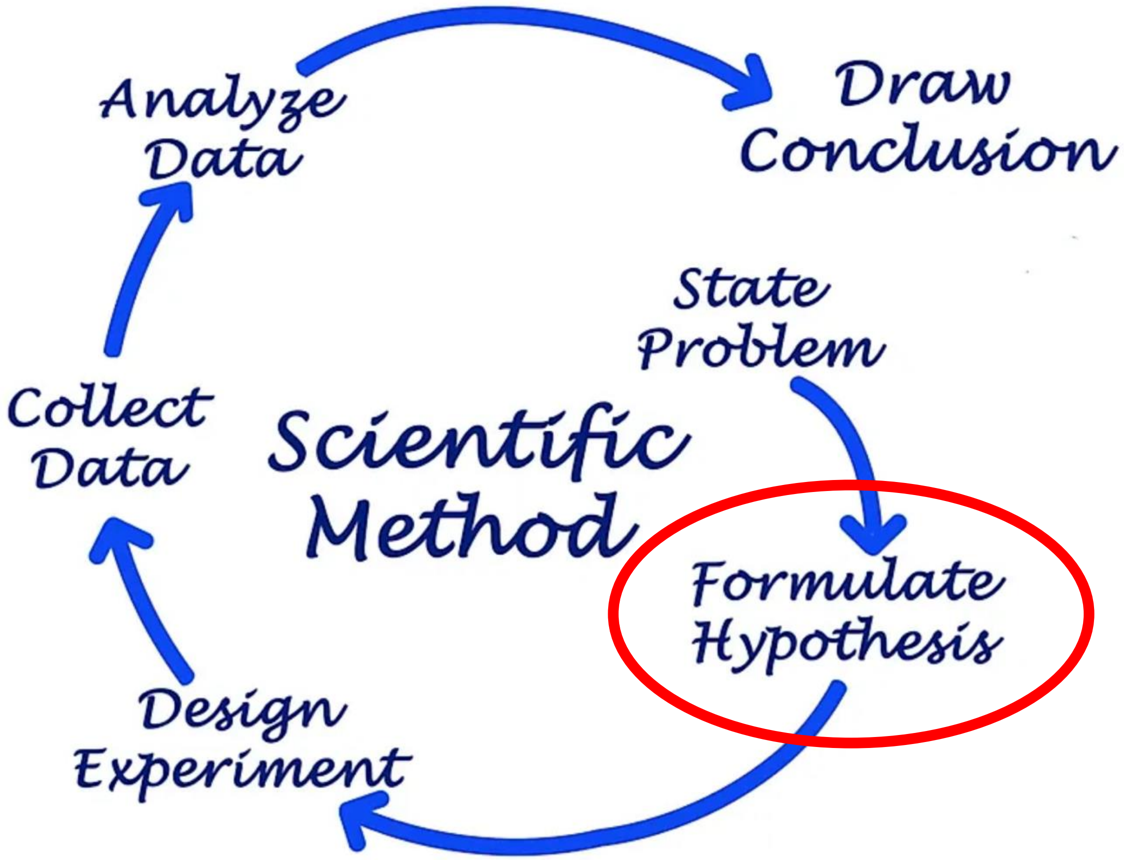
Planning a scientific investigation (or mission)

- For a science grant or one-off investigation: what problem are you trying to solve? Is it compelling enough to warrant your time and/or someone else's money?
- For a mission or observatory: what *suite* of compelling questions will motivate the entire community?



Planning a scientific investigation (or mission)

- This step is important, but more complex than two words.
- Think about how to solve the problem:
    - Developing *wholly new understanding*?
    - Discriminating *existing hypotheses or models?*
- Think about closure: is your hypothesis testable? Can you (in principle) falsify or support it?
- A well-formed question or hypothesis is essential and discriminates “doing science” from “enjoying a hobby”.



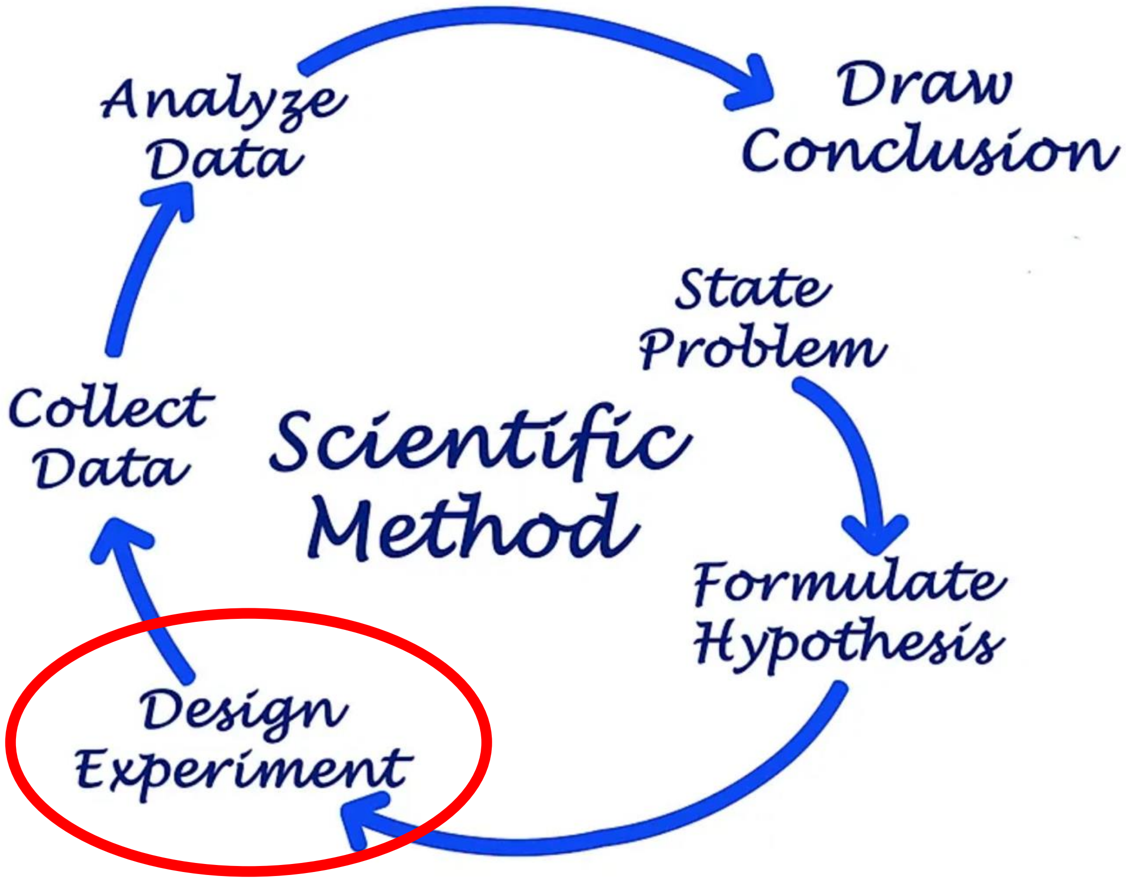
Planning a scientific investigation (or mission)

• Traceability enters here! (investigation or mission)

- What measurements or analyses are *required* in order to close the science?

- Can your experiment or analysis make those measurements?

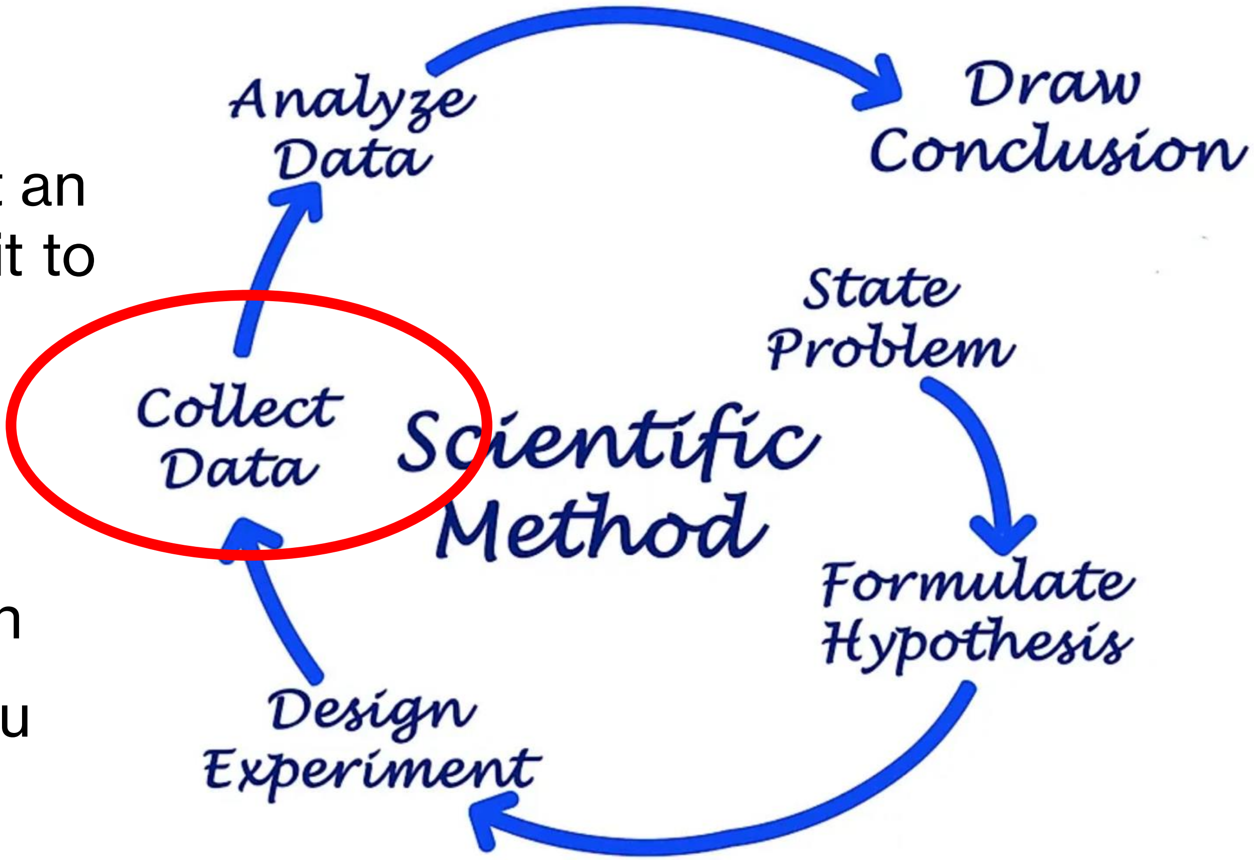
• Formulate requirements to break down the large problem of suitability, into smaller problems you can verify as you build.



Planning a scientific investigation (or mission)

- Planning for data collection is just as important as planning the instrument or measurement
- How much data to you need? Having built an experiment or model, how will you operate it to get the data that you do need?

  - PUNCH or SDO: continuous operation
  - IRIS: weekly planning
  - DKIST: Competitive telescope allocation
  - New solar simulation code – how will you operate it?
  - Catalog of observations – how will you select them and/or reduce to find a pattern?

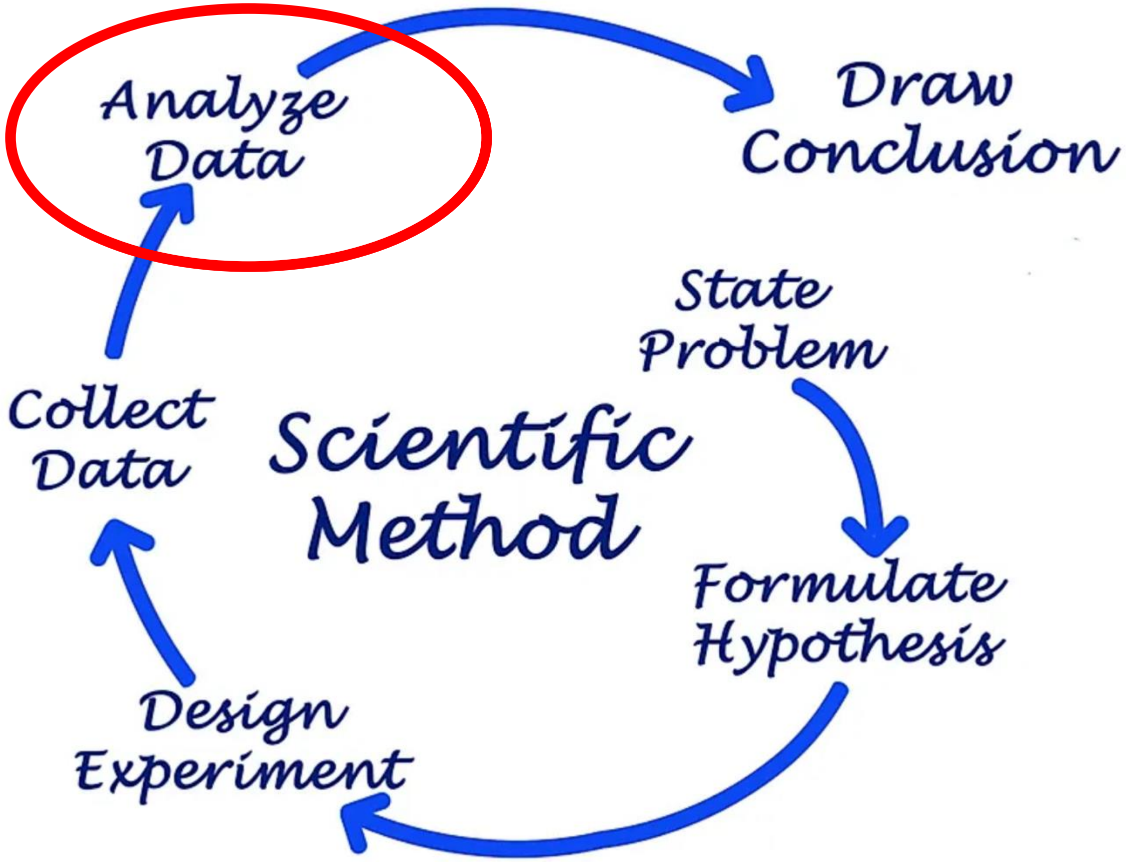


Planning a scientific investigation (or mission)

- Data analysis: plan what you need to do with the data (or simulation results or whatever) to close the science.
- This is surprisingly hard for many early-career researchers to plan!
- Requires resources:

    - Missions: science team selection and resource allocations

    - Investigations: computer time, researcher hours, effort planning

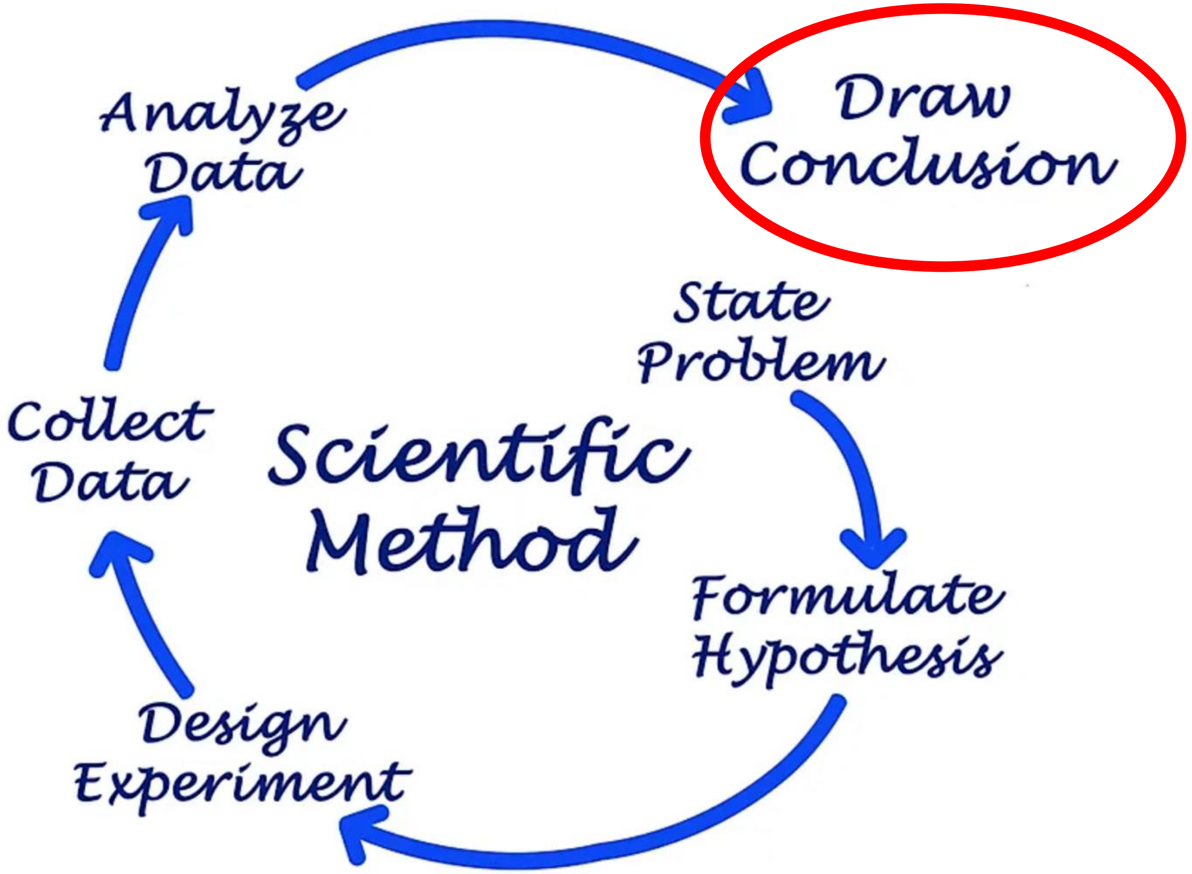


Planning a scientific investigation (or mission)

- While planning: how will you close the science?

- A *traceable* plan or investigation connects across all six steps.

- In proposals: *closure* sections generally talk about how you'll examine the results of analysis after producing data using the tools, to check the hypothesis – thereby addressing the original problem



Modes of instrument design

A historic discovery instrument (Lyot coronagraph)

- *On display at L'Observatoire de Paris (Meudon)*

- *Made by Lyot from materials at-hand in the lab; aligned "by eye" with hand-ground optics and scraps of wood*

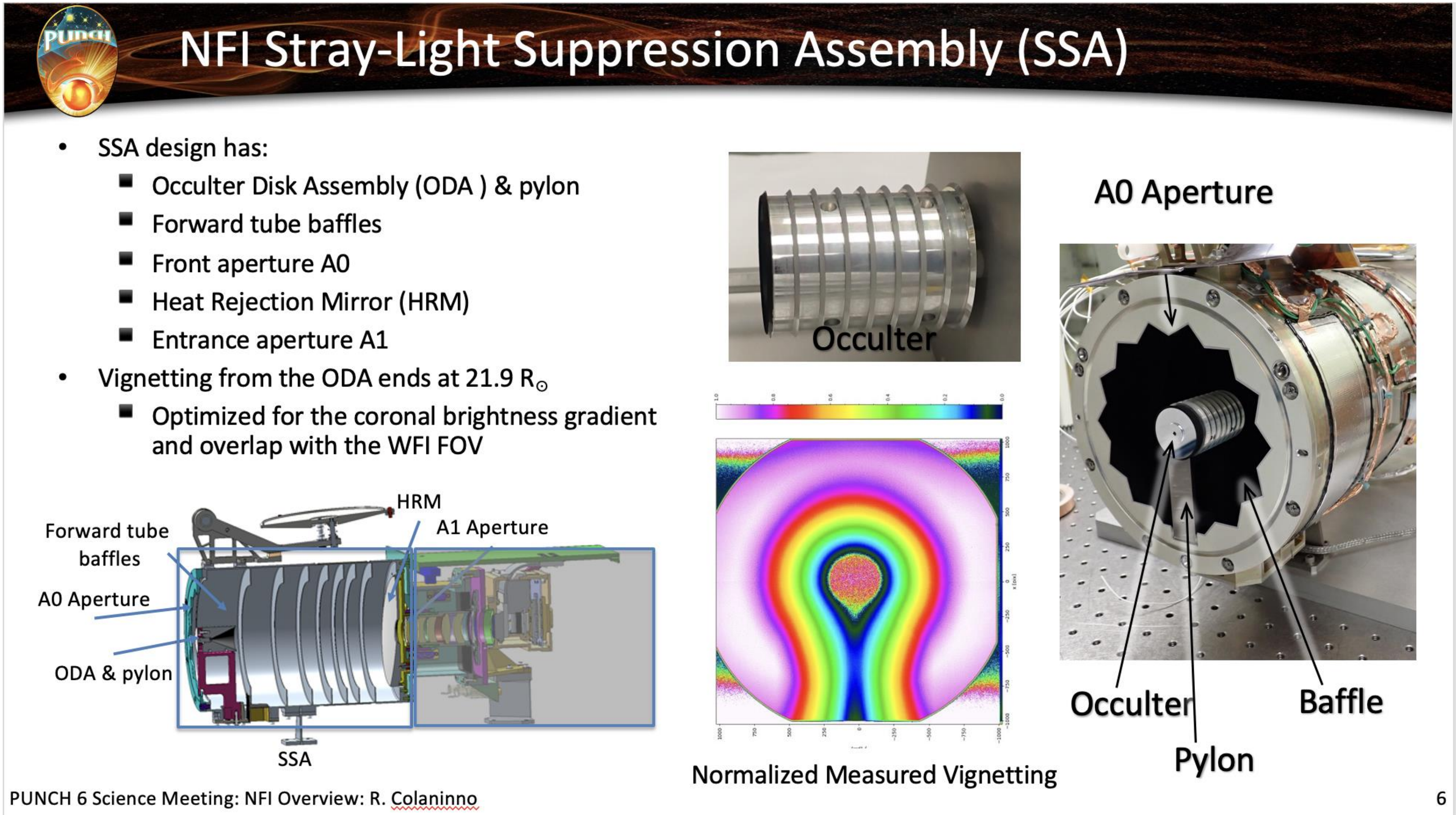
- *First working coronagraph*

- *Cost: ~ 1 FTE-year*

- ***Requirements flow was mostly informal (Lyot's expertise)***

A modern sophisticated instrument (PUNCH/NFI coronagraph)

- Design is refined to improve on 100 years of prior instruments
- Precision-designed occulter
- Budgeted stray light
- Specified tolerances, roughness, and 10µm precision alignment
- Cost: ~ 40 FTE-years
- **Requirement flow from overall performance to individual part specification is critical.**



A modern proof-of-concept instrument: CATEcor coronagraph

- Wholly new design for a coronagraph

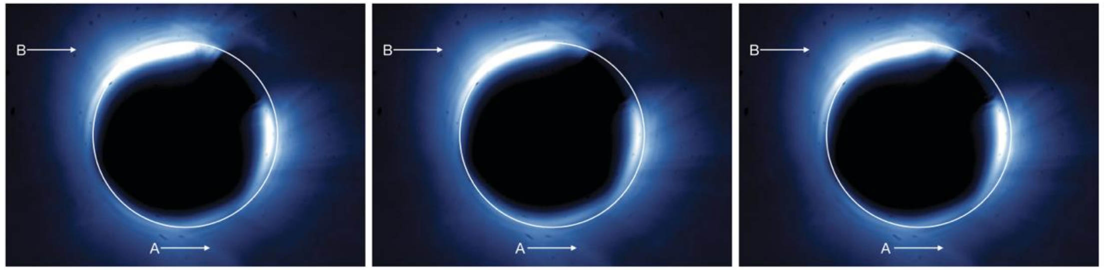
- Careful design with low-cost execution (3D printing!)

- Used mostly commercial parts

- “targeted precision”: design was engineered to tolerate misalignments and reduce cost

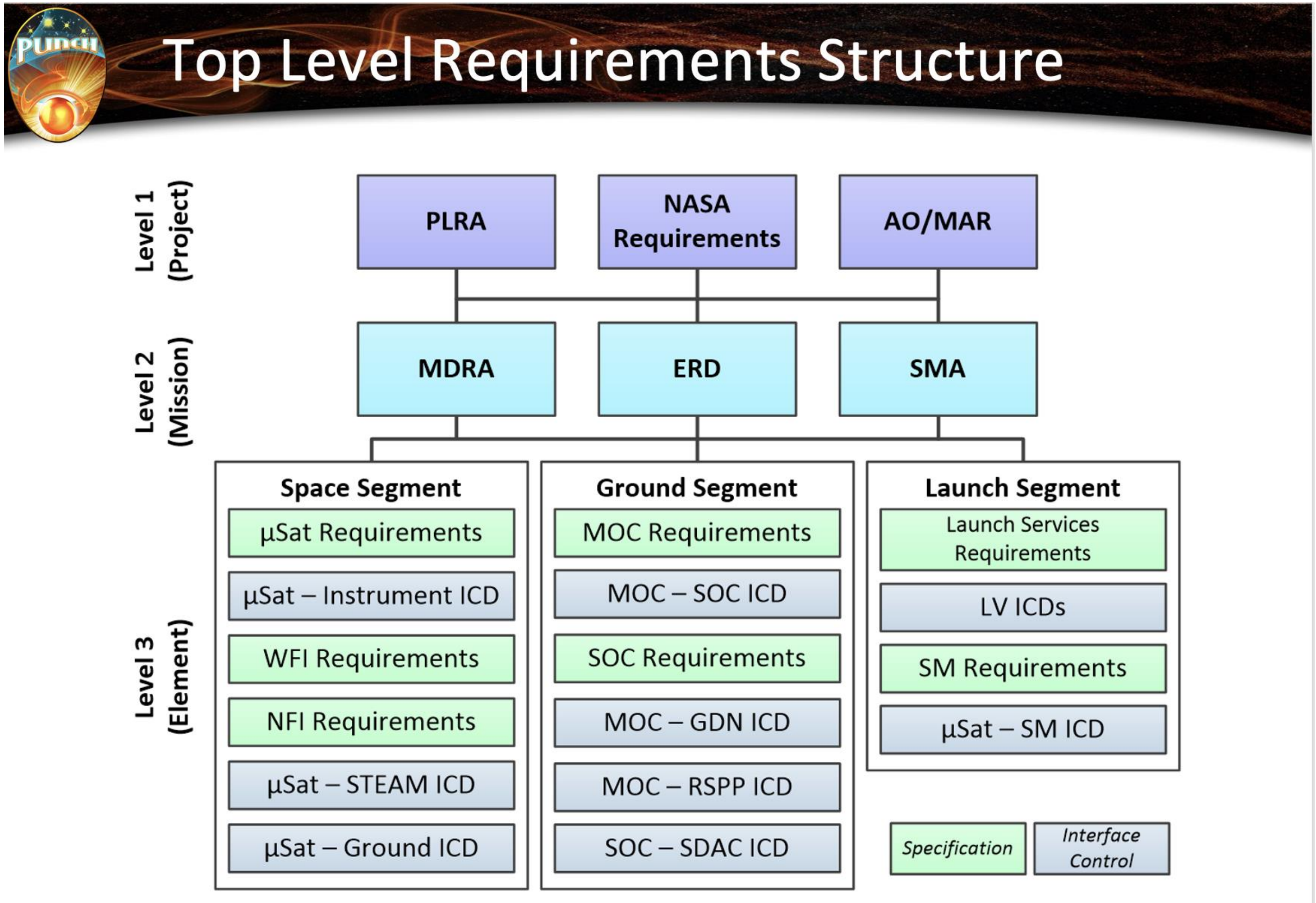
- Cost: <0.5 FTE-year

- **Understanding requirements flow allowed rapid development and testing of CATEcor.**

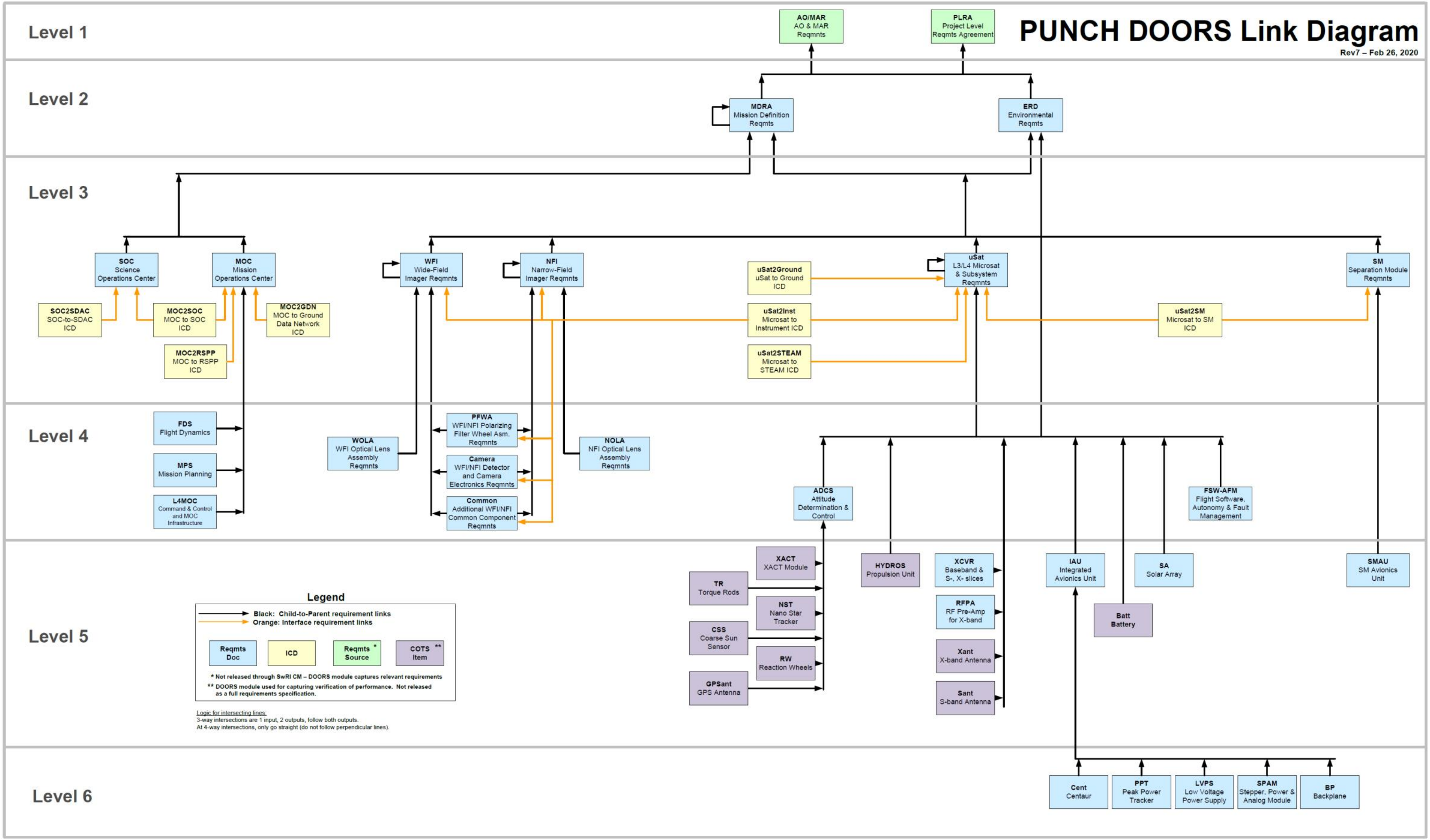


Mission-level requirements definition

PUNCH Top-level requirements flowdown is complex!



It got far more complex than that!

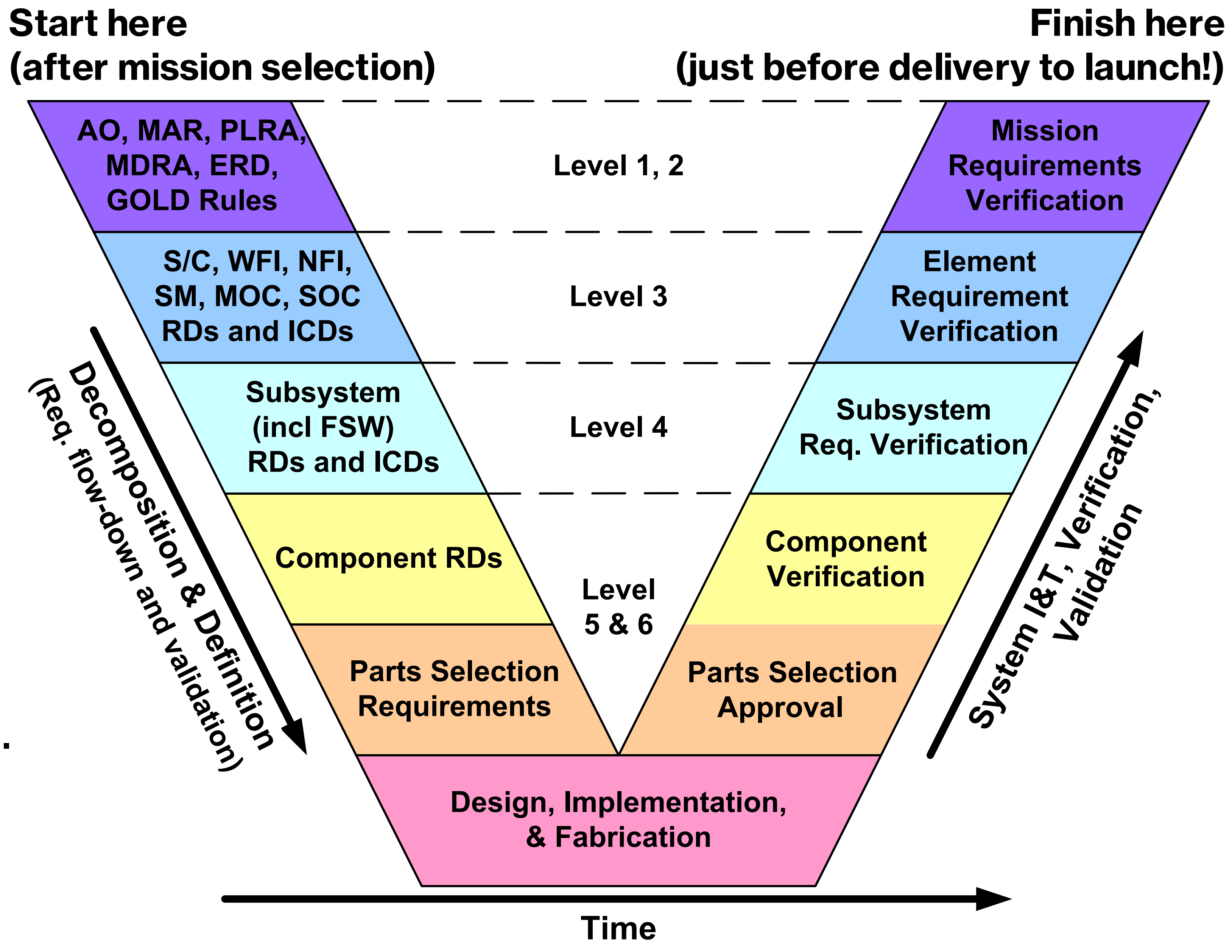


Requirements guide the mission development process

Requirements definition is a formalized way of defining *what, exactly, you need...*

...so you know what do do ...

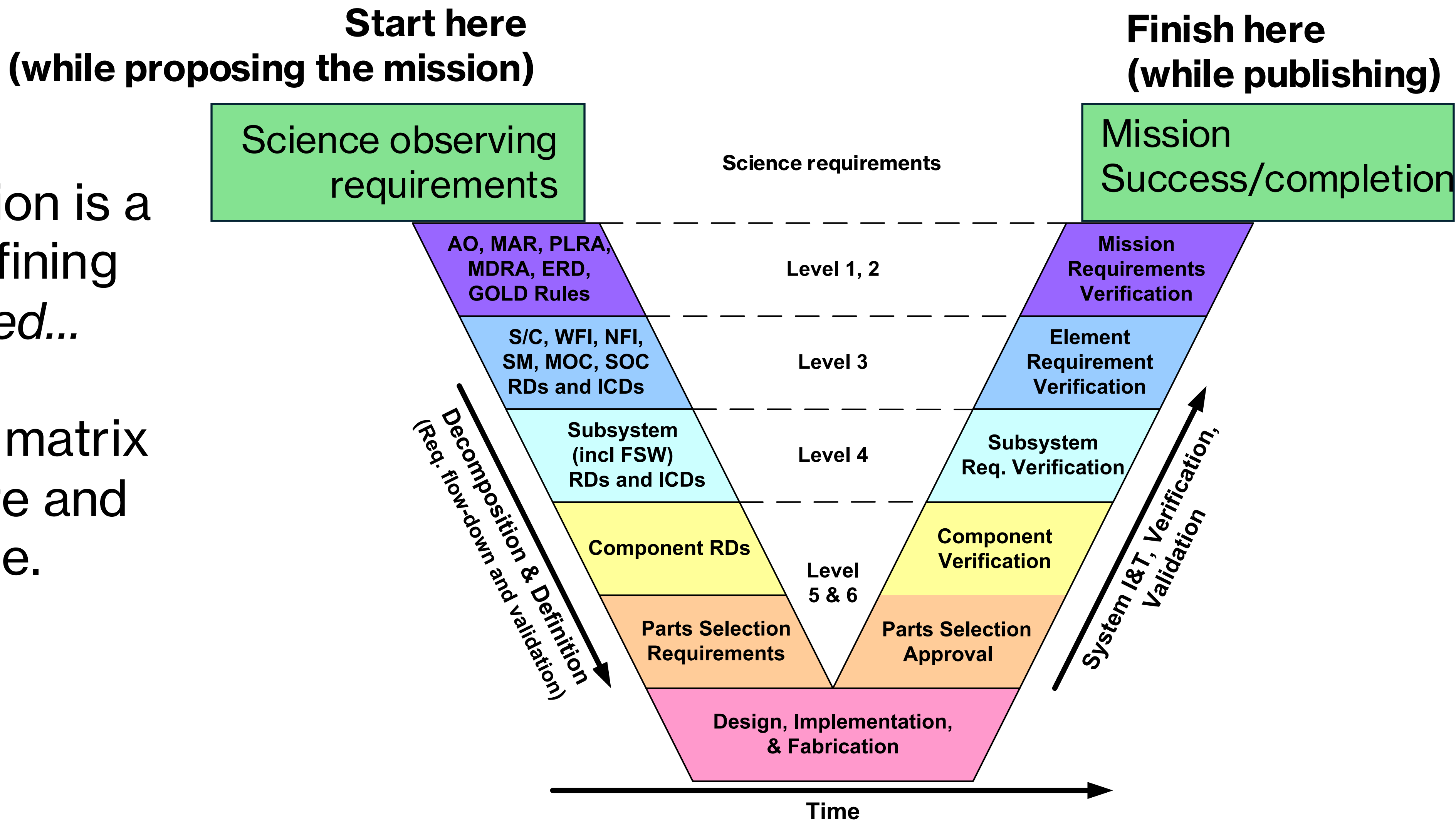
... and can also verify when you've done it (and can stop).



Mission development is all about the science

Requirements definition is a formalized way of defining *what, exactly, you need…*

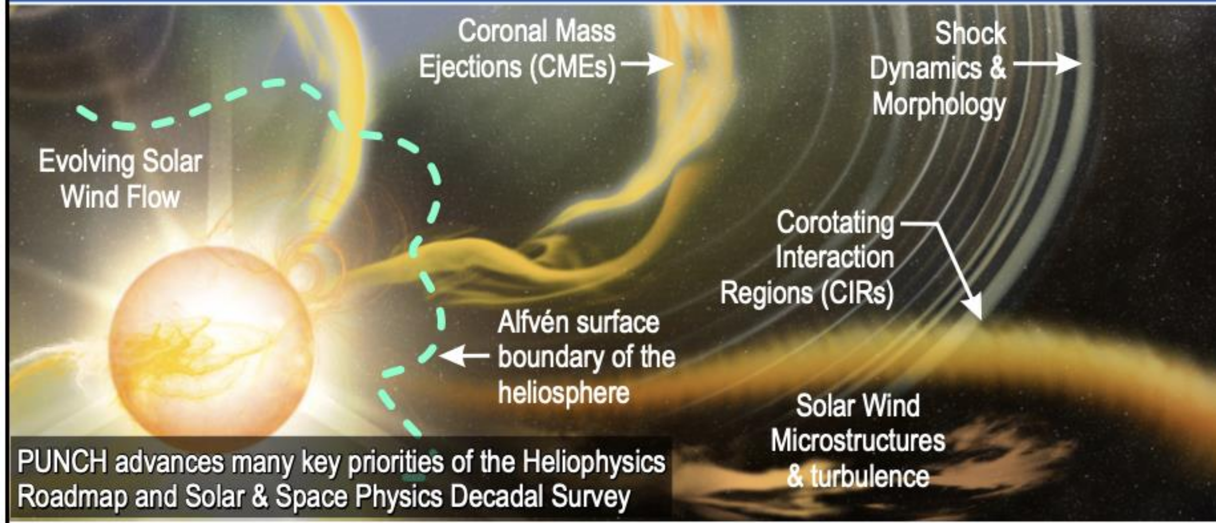
…and the traceability matrix lays out exactly where and why those needs arise.



The PUNCH Fact Sheet: a science mission in a nutshell

Science Goal: To determine the cross-scale processes that unify the solar corona and heliosphere

Science Objectives



1. **Understand how coronal structures become the ambient solar wind.**
   - Map evolving solar wind flow
   - Identify microstructure and turbulence
   - Locate the Alfvén surface
2. **Understand the dynamic evolution of transient structures in the young solar wind**
   - Track CME's and their evolution in 3D
   - Measure CIR formation & Evolution
   - Determine large-scale shock dynamics

Mission Overview

PUNCH makes global, deep-field, 3D observations of the young solar wind from the solar corona to the inner heliosphere, closing a 50-year gap in measurement and understanding.

A constellation of 4 small satellites in Sun-synchronous LEO produces deep-field, continuous, 3D images of the corona and young solar wind from 6 $R_\odot$ to 180 $R_\odot$ in polarized visible light. Each spacecraft carries one imager. A Narrow-Field Imager (NFI) captures the entire outer corona. Three Wide-Field Imagers (WFIs) capture the inner heliosphere. A student x-ray spectrometer (STEAM) probes flare physics.

- Visible-light Thomson imaging from LEO
- 2-year science mission: 2022-2024
- Bridges & unifies solar, heliospheric physics
- Relevant to National Sp. Wx. Strategy
- Complements PSP & SolO missions
- Robust, feasible student collaboration

The PUNCH Traceability Matrix:
The core of the mission proposal, on one page

PUNCH Science Traceability Matrix FO2

Science Goal: PUNCH determines the cross-scale processes that unify the solar corona and heliosphere

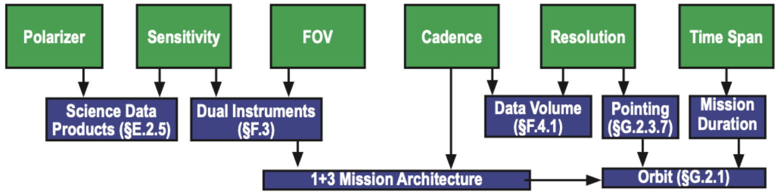
Science Objective	Science Questions	Science Measurements: Phys. Parameters	Science Measurements: Observables & Analysis Techniques	Science Measurement Requirements		PUNCH Derived Observations	Expected Scientific Results
1. **The Ambient Solar Wind:** Understand how coronal structures become the ambient solar wind.	1A. How does the young solar wind flow and evolve on global scales?	Corona/Solar Wind image-plane-projected speed as a function of radius and heliolatitude.	Small density inhomogeneities and their motion at all latitudes and spanning outer corona and inner heliosphere, via spatio-temporal Fourier spectra, auto-correlation, and kinematic tomography.	Polarizer	No	Solar wind speed: four radial positions (14 $R_\odot$/3.5°, 28 $R_\odot$/7°, 44 $R_\odot$/11°, 60$R_\odot$/15°) 4x daily.	Determine the solar wind flow and acceleration and its relationship to fast/slow solar wind streams; constrain global solar-wind models.
				Sensitivity†	15 $R_\odot$: 3.5×10^{-15} | 80 $R_\odot$: 4.2×10^{-16}		
				FOV	10-120 $R_\odot$; 270° az.		
				Cadence	8 min image pairs; <24 min gap between pairs		
				Time Span	3 months		
				Resolution	15 $R_\odot$: 3' | 80 $R_\odot$:6'		
	1B. Where and how do microstructures and turbulence form in the solar wind?	Location and evolution of visible density microstructures; morphological development of turbulence.	Statistics and evolution of density fluctuations, via auto-correlation, structure functions, and Fourier spectra; micro-structure evolution via photometric mass,image deblurring, and 3D polarization analysis.	Polarizer	Yes	Size, distribution, coherence time, and structure of solar wind variations vs. time and space; disposition and radial density profile of coronal structures in the young solar wind.	Discriminate between models of the origins of slow solar-wind variability; establish the role of turbulent processing in the solar wind; solve the solar-wind heating problem.
				Sensitivity†	15 $R_\odot$: 3.2×10^{-15} | 80 $R_\odot$: 1.0×10^{-16}		
				FOV	20-120 $R_\odot$; 270° az.		
				Cadence	40 min		
				Time Span	3 months		
				Resolution	15 $R_\odot$: 6'; 80 $R_\odot$: 8'		
	1C. What are the evolving physical properties of the Alfvén surface?	Extent of the inbound MHD fluctuation field and characterization of its outer boundary projected into the image plane	Local propagation characteristics of moving features in the solar system frame, as measured through velocity spectrum analysis of brightness fluctuations.	Polarizer	No	Wave and small feature flow speed and direction; presence and location of stationary inbound running waves; location, structure, and evolution of the outer boundary of the corona.	Measure, for the first time, the location and global geometry of the inner edge of the heliosphere and its relationship to coronal structure.
				Sensitivity†	15 $R_\odot$: 3.4×10^{-15} | 80 $R_\odot$: 1.9×10^{-16}		
				FOV	20-110 $R_\odot$; 270° az.		
				Cadence	20 min		
				Time Span	2x 1 month		
				Resolution	15 $R_\odot$: 3'; 80 $R_\odot$: 5'		
2. **The Dynami Solar wind:** Understand the dynamic evolution of transient structures in the young solar wind.	2A. How do coronal mass ejections (CMEs) propagate and evolve in the solar wind, in three dimensions?	Location, density, propagation direction, and speed evolution of CMEs and their fine scale structure, in three dimensions.	Photometry and morphology of CME substructures via image deblurring, 3D polarization analysis, photometric mass, and kinematic tomography.	Polarizer	Yes	3D velocity, location, and fine-scale structural anatomy of CMEs; distortion, structural evolution, mass, chirality, and entrained kinetic energy.	Determine how CMEs evolve, and how CME substructure affects large-scale propagation.
				Sensitivity†	15 $R_\odot$: 6.5×10^{-15} | 80 $R_\odot$: 1.5×10^{-16}		
				FOV	8$R_\odot$-160 $R_\odot$; 235° az.		
				Cadence	60 min		
				Time Span	15 months (10 large CMEs)		
				Resolution	15 $R_\odot$: 10'; 80 $R_\odot$: 15'		
	2B. How do quasi-stationary corotating interaction regions form and evolve?	Motion, evolution, locations, and density of large-scale features (waves, distortions, and shocks) driven by CIRs across the formation region and inner heliosphere.	Morphology and brightness of CIRs and associated transient features via kinematic tomography, photometric mass measurements, and 3D polarization analysis.	Polarizer	Yes	J map trajectories; density structure and morphology, waves, and distortions associated with interacting streams at the base of CIRs.	Determine the mechanisms responsible for CIR formation, what kinds of disturbances are launched from nascent CIRs, and how they develop into shocks.
				Sensitivity†	15 $R_\odot$: 3.73×10^{-15} | 80 $R_\odot$: 1.1×10^{-16}		
				FOV	20-110 $R_\odot$; 270° az.		
				Cadence	20 min		
				Time Span	6 months (>10 CIRs)		
				Resolution	15 $R_\odot$: 20' | 80 $R_\odot$:30'		
	2C: How do shocks form and interact with the solar wind across spatial scales?	Location, evolution, cross-scale spatial structure, and shock parameter (Mach ratio) of forward shocks driven by strong CMEs or CIRs.	Distortion (e.g., crinkles, bends) and brightness jump of shock fronts across a wide field of view via 3D polarization analysis, image deblurring, autocorrelation and structure functions.	Polarizer	Yes	Morphological evolution of density structures associated with hydrodynamic and turbulent instabilities in CME fronts and CIRs; association (or lack) of instability onset and shock "crinkles" with SEPs.	Measure, for the first time in high resolution, shock evolution in the solar wind. Identify role of large scale turbulence to SEP production, and importance of spatial instabilities to shock evolution.
				Sensitivity†	15 $R_\odot$: 3.5×10^{-15} | 80 $R_\odot$: 4.2×10^{-16}		
				FOV	20-120 $R_\odot$; 270° az.		
				Cadence	8 min image pair; <24 min gap between pairs		
				Time Span	8 months (5 CME shocked)		
				Resolution	15 $R_\odot$: 3'; 80 $R_\odot$: 6'		

Notes: † All sensitivities are in normalized, photometric units (relative to Sun central brightness, $B_\odot$), that have been averaged over a 1° square region of the sky and 4-minute interval of time. Spatial resolution and sensitivity requirements scale with distance from Sun. They are specified at 15 $R_\odot$ and 80 $R_\odot$ ($R_\odot$ = solar radius). Required sensitivities for questions using polarization have been tightened by a factor of two; this drives an L2 requirement that polarized images have sensitivity no coarser than double that of unpolarized images.

Science Measurement Requirements Drive Baseline Science Mission Requirements (§F.1)

Science Measurement Requirements	Driver	Baseline Science Mission Requirement (BSR)	PUNCH Performance	Margin: PUNCH Performance vs. BSR
Polarizer	1B, 2A, 2B, 2C	Yes	Yes	Meets
Sensitivity	1B	15 $R_\odot$: 3.2×10^{-15} 80 $R_\odot$: 1.0×10^{-16}	15 $R_\odot$: 1.2×10^{-15} 80 $R_\odot$: 3.7×10^{-17}	Exceeds: 15 $R_\odot$: 167% 80 $R_\odot$: 170%
FOV: Az	1A, 1B, 1C, 2B,2C	270°	360°	Exceeds: 30%
Cadence and Spatiotemporal Coverage	1A,2C	8 min image pairs; <24 min gap between pairs, 10--120 $R_\odot$	8 min image pairs; <24 min gap between pairs, 6--168 $R_\odot$	Exceeds: 67% inner; 40% outer
	1C,2B	20 min, 20--110 $R_\odot$	20 min, 6--118 $R_\odot$	233% inner; 7% outer
	1B,2A	40 min, 8--160 $R_\odot$	40 min, 6--180 $R_\odot$	33% inner; 12.5% outer
Time Span	2A	15 months	24 months	Exceeds: 60%
Resolution	1A,1C,2C	15 $R_\odot$: 3'; 80 $R_\odot$: 5'	15 $R_\odot$: 1' 80 $R_\odot$: 3'	Exceeds: 15 $R_\odot$: 200%; 80 $R_\odot$: 67%

Baseline Science Mission Requirements (L1; §F.1) Drive Mission Definition Requirements (L2; §M.10)



Mission Definition Requirements

Science Data Products: PUNCH Level 3 Science Data Products shall be B and pB images and solar wind speed maps.

Dual Instruments: PUNCH's FOV shall be divided between a narrow-field imager & three wide-field imagers.

Data Volume: The PUNCH constellation shall return 5.2 GB/day of raw science data.

Pointing: Each PUNCH Observatory shall provide pointing stability equal to or better than 28.8 arcsec over 75 seconds (allocation based on resolution requirement: §E.2.2).

Mission Duration: Each PUNCH Observatory shall observe for at least two years.

1+3 Mission Architecture: Each PUNCH Observatory shall host one PUNCH instrument.

Orbit: The initial orbit of each PUNCH Observatory shall maximize viewing of the heliosphere out to 45° elongation.

Science Goal: PUNCH determines the cross-scale processes that unify the solar corona and heliosphere

Science Objective	Science Questions	Science Measurements: Phys. Parameters	Science Measurements: Observables & Analysis Techniques	Science Measurement Requirements		PUNCH Derived Observations	Expected Scientific Results
1. The Ambient Solar Wind: Understand how coronal structures become the ambient solar wind.	1A. How does the young solar wind flow and evolve on global scales?	Corona/Solar Wind image-plane-projected speed as a function of radius and heliolatitude.	Small density inhomogeneities and their motion at all latitudes and spanning outer corona and inner heliosphere, via spatio-temporal Fourier spectra, auto-correlation, and kinematic tomography.	**Polarizer**	No	Solar wind speed: four radial positions ($14 R_\odot/3.5°$, $28 R_\odot/7°$, $44 R_\odot/11°$, $60R_\odot/15°$) 4x daily.	Determine the solar wind flow and acceleration and its relationship to fast/slow solar wind streams; constrain global solar-wind models.
				Sensitivity†	$15 R_\odot$: $3.5x10^{-15}$ | $80 R_\odot$: $4.2x10^{-16}$		
				FOV	10-120 $R_\odot$; 270° az.		
				Cadence	8 min image pairs; <24 min gap between pairs		
				Time Span	3 months		
				Resolution	$15 R_\odot$: 3' | $80 R_\odot$:6'		
	1B. Where and how do microstructures and turbulence form in the solar wind?	Location and evolution of visible density microstructures; morphological development of turbulence.	Statistics and evolution of density fluctuations, via auto-correlation, structure functions, and Fourier spectra; micro-structure evolution via photometric mass,image deblurring, and 3D polarization analysis.	**Polarizer**	Yes	Size, distribution, coherence time, and structure of solar wind variations vs. time and space; disposition and radial density profile of coronal structures in the young solar wind.	Discriminate between models of the origins of slow solar-wind variability; establish the role of turbulent processing in the solar wind; solve the solar-wind heating problem.
				Sensitivity†	$15 R_\odot$: $3.2x10^{-15}$ | $80 R_\odot$: $1.0x10^{-16}$		
				FOV	20-120 $R_\odot$; 270° az.		
				Cadence	40 min		
				Time Span	3 months		
				Resolution	$15 R_\odot$: 6'; $80 R_\odot$: 8'		
	1C. What are the evolving physical properties of the Alfvén surface?	Extent of the inbound MHD fluctuation field and characterization of its outer boundary projected into the image plane	Local propagation characteristics of moving features in the solar system frame, as measured through velocity spectrum analysis of brightness fluctuations.	**Polarizer**	No	Wave and small feature flow speed and direction; presence and location of stationary inbound running waves; location, structure, and evolution of the outer boundary of the corona.	Measure, for the first time, the location and global geometry of the inner edge of the heliosphere and its relationship to coronal structure.
				Sensitivity†	$15 R_\odot$: $3.4x10^{-15}$ | $80 R_\odot$: $1.9x10^{-16}$		
				FOV	20-110 $R_\odot$; 270° az.		
				Cadence	20 min		
				Time Span	2x 1 month		
				Resolution	$15 R_\odot$: 3'; $80 R_\odot$: 5'		
2. The Dynami Solar wind: Understand the dynamic evolution of transient structures in the young solar wind.	2A. How do coronal mass ejections (CMEs) propagate and evolve in the solar wind, in three dimensions?	Location, density, propagation direction, and speed evolution of CMEs and their fine scale structure, in three dimensions.	Photometry and morphology of CME substructures via image deblurring, 3D polarization analysis, photometric mass, and kinematic tomography.	**Polarizer**	Yes	3D velocity, location, and fine-scale structural anatomy of CMEs; distortion, structural evolution, mass, chirality, and entrained kinetic energy.	Determine how CMEs evolve, and how CME substructure affects large-scale propagation.
				Sensitivity†	$15 R_\odot$: $6.5x10^{-15}$ | $80 R_\odot$: $1.5x10^{-16}$		
				FOV	$8R_\odot$-160 $R_\odot$; 235° az.		
				Cadence	60 min		
				Time Span	15 months (10 large CMEs)		
				Resolution	$15 R_\odot$: 10'; $80 R_\odot$: 15'		
	2B. How do quasi-stationary corotating interaction regions form and evolve?	Motion, evolution, locations, and density of large-scale features (waves, distortions, and shocks) driven by CIRs across the formation region and inner heliosphere.	Morphology and brightness of CIRs and associated transient features via kinematic tomography, photometric mass measurements, and 3D polarization analysis.	**Polarizer**	Yes	J map trajectories; density structure and morphology, waves, and distortions associated with interacting streams at the base of CIRs.	Determine the mechanisms responsible for CIR formation, what kinds of disturbances are launched from nascent CIRs, and how they develop into shocks.
				Sensitivity†	$15 R_\odot$: $3.73x10^{-15}$ | $80 R_\odot$: $1.1x10^{-16}$		
				FOV	20-110 $R_\odot$; 270° az.		
				Cadence	20 min		
				Time Span	6 months (>10 CIRs)		
				Resolution	$15 R_\odot$: 20' | $80 R_\odot$:30'		
	2C: How do shocks form and interact with the solar wind across spatial scales?	Location, evolution, cross-scale spatial structure, and shock parameter (Mach ratio) of forward shocks driven by strong CMEs or CIRs.	Distortion (e.g., crinkles, bends) and brightness jump of shock fronts across a wide field of view via 3D polarization analysis, image deblurring, autocorrelation and structure functions.	**Polarizer**	Yes	Morphological evolution of density structures associated with hydrodynamic and turbulent instabilities in CME fronts and CIRs; association (or lack) of instability onset and shock "crinkles" with SEPs.	Measure, for the first time in high resolution, shock evolution in the solar wind. Identify role of large scale turbulence to SEP production, and importance of spatial instabilities to shock evolution.
				Sensitivity†	$15 R_\odot$: $3.5x10^{-15}$ | $80 R_\odot$: $4.2x10^{-16}$		
				FOV	20-120 $R_\odot$; 270° az.		
				Cadence	8 min image pair; <24 min gap between pairs		
				Time Span	8 months (5 CME shocked)		
				Resolution	$15 R_\odot$: 3'; $80 R_\odot$: 6'		

Notes: † All sensitivities are in normalized, photometric units (relative to Sun central brightness, $B_\odot$), that have been averaged over a 1° square region of the sky and 4-minute interval of time. Spatial resolution and sensitivity requirements scale with distance from Sun. They are specified at 15 $R_\odot$ and 80 $R_\odot$ ($R_\odot$ = solar radius). Required sensitivities for questions using polarization have been tightened by a factor of two; this drives an L2 requirement that polarized images have sensitivity no coarser than double that of unpolarized images.

…ale processes that unify the solar corona and heliosphere

Science Objective	Science Questions	Science Measurements: Phys. Parameters	Science Measurements: Observables & Analysis Techniques	Science Measurement Requirements		PUNCH Derived Observations	Expected Scientific Results
1. **The Ambient Solar Wind:** Understand how coronal structures become the ambient solar wind.	1A. How does the young solar wind flow and evolve on global scales?	Corona/Solar Wind image-plane-projected speed as a function of radius and heliolatitude.	Small density inhomogeneities and their motion at all latitudes and spanning outer corona and inner heliosphere, via spatio-temporal Fourier spectra, auto-correlation, and kinematic tomography.	**Polarizer**	No	Solar wind speed: four radial positions (14 $R_\odot$/3.5°, 28 $R_\odot$/7°, 44 $R_\odot$/11°, 60$R_\odot$/15°) 4x daily.	Determine the solar wind flow and acceleration and its relationship to fast/slow solar wind streams; constrain global solar-wind models.
				Sensitivity†	15 $R_\odot$: 3.5×10^{-15} | 80 $R_\odot$: 4.2×10^{-16}		
				FOV	10-120 $R_\odot$; 270° az.		
				Cadence	8 min image pairs; <24 min gap between pairs		
				Time Span	3 months		
				Resolution	15 $R_\odot$: 3' | 80 $R_\odot$:6'		
	1B. Where and how do microstructures and turbulence form in the solar wind?	Location and evolution of visible density microstructures; morphological development of turbulence.	Statistics and evolution of density fluctuations, via auto-correlation, structure functions, and Fourier spectra; micro-structure evolution via photometric mass,image deblurring, and 3D polarization analysis.	**Polarizer**	Yes	Size, distribution, coherence time, and structure of solar wind variations vs. time and space; disposition and radial density profile of coronal structures in the young solar wind.	Discriminate between models of the origins of slow solar-wind variability; establish the role of turbulent processing in the solar wind; solve the solar-wind heating problem.
				Sensitivity†	15 $R_\odot$: 3.2×10^{-15} | 80 $R_\odot$: 1.0×10^{-16}		
				FOV	20-120 $R_\odot$; 270° az.		
				Cadence	40 min		
				Time Span	3 months		
				Resolution	15 $R_\odot$: 6'; 80 $R_\odot$: 8'		
	1C. What are the evolving physical properties of the Alfvén surface?	Extent of the inbound MHD fluctuation field and characterization of its outer boundary projected into the image plane	Local propagation characteristics of moving features in the solar system frame, as measured through velocity spectrum analysis of brightness fluctuations.	**Polarizer**	No	Wave and small feature flow speed and direction; presence and location of stationary inbound running waves; location, structure, and evolution of the outer boundary of the corona.	Measure, for the first time, the location and global geometry of the inner edge of the heliosphere and its relationship to coronal structure.
				Sensitivity†	15 $R_\odot$: 3.4×10^{-15} | 80 $R_\odot$: 1.9×10^{-16}		
				FOV	20-110 $R_\odot$; 270° az.		
				Cadence	20 min		
				Time Span	2x 1 month		
				Resolution	15 $R_\odot$: 3'; 80 $R_\odot$: 5'		

Science Objective: what we are studying

Science Questions: Specific and well-formed

(Well-formed: there's a way to know when the question is answered)

Physical Parameters: What needs to be measured

Observables and Techniques: How to tackle the science question

Measurement requirements: Specific requirements that define what the mission (or investigation) has to do

top-level requirements flow from here

Derived Observations: What we expect to learn about the Sun by analyzing the data

Expected scientific results: How will this investigation change the field or the world?

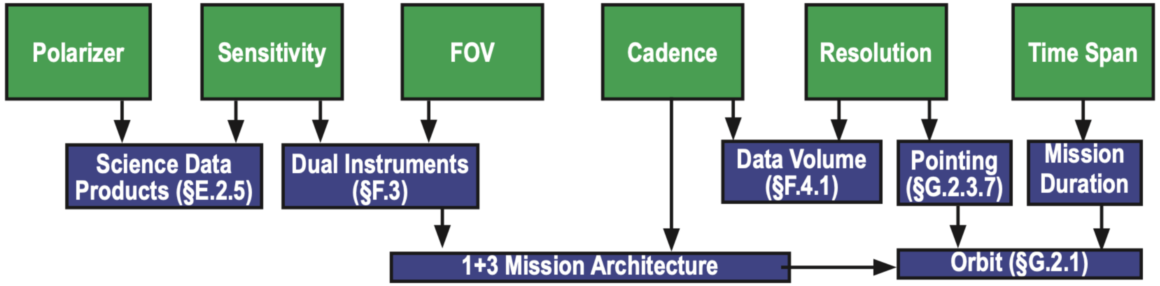
Requirements summary

- “Level 2” requirements define the mission as a whole.
- These flow from the observing requirements
- Instrument types, data products, data volume, orbit, etc.

Science Measurement Requirements Drive Baseline Science Mission Requirements (§F.1)

Science Measurement Requirements	Driver	Baseline Science Mission Requirement (BSR)	PUNCH Performance	Margin: PUNCH Performance vs. BSR
Polarizer	1B, 2A, 2B, 2C	Yes	Yes	Meets
Sensitivity	1B	15 $R_\odot$: 3.2×10^{-15} 80 $R_\odot$: 1.0×10^{-16}	15 $R_\odot$: 1.2×10^{-15} 80 $R_\odot$: 3.7×10^{-17}	Exceeds: 15 $R_\odot$: 167% 80 $R_\odot$: 170%
FOV: Az	1A, 1B, 1C, 2B,2C	270°	360°	Exceeds: 30%
Cadence and Spatiotemporal Coverage	1A,2C	8 min image pairs; <24 min gap between pairs, 10--120 $R_\odot$	8 min image pairs; <24 min gap between pairs, 6--168 $R_\odot$	Exceeds: 67% inner; 40% outer
	1C,2B	20 min, 20--110 $R_\odot$	20 min, 6--118 $R_\odot$	233% inner; 7% outer
	1B,2A	40 min, 8--160 $R_\odot$	40 min, 6--180 $R_\odot$	33% inner; 12.5% outer
Time Span	2A	15 months	24 months	Exceeds: 60%
Resolution	1A,1C,2C	15 $R_\odot$: 3’; 80 $R_\odot$: 5’	15 $R_\odot$: 1’ 80 $R_\odot$: 3’	Exceeds: 15 $R_\odot$: 200%; 80 $R_\odot$: 67%

Baseline Science Mission Requirements (L1; §F.1) Drive Mission Definition Requirements (L2; §M.10)



Mission Definition Requirements

Science Data Products: PUNCH Level 3 Science Data Products shall be B and pB images and solar wind speed maps.

Dual Instruments: PUNCH’s FOV shall be divided between a narrow-field imager & three wide-field imagers.

Data Volume: The PUNCH constellation shall return 5.2 GB/day of raw science data.

Pointing: Each PUNCH Observatory shall provide pointing stability equal to or better than 28.8 arcsec over 75 seconds (allocation based on resolution requirement: §E.2.2).

Mission Duration: Each PUNCH Observatory shall observe for at least two years.

1+3 Mission Architecture: Each PUNCH Observatory shall host one PUNCH instrument.

Orbit: The initial orbit of each PUNCH Observatory shall maximize viewing of the helio-sphere out to 45° elongation.

Polarimeter to Unify the Corona and Heliosphere

Level 1 Requirements

Craig DeForest

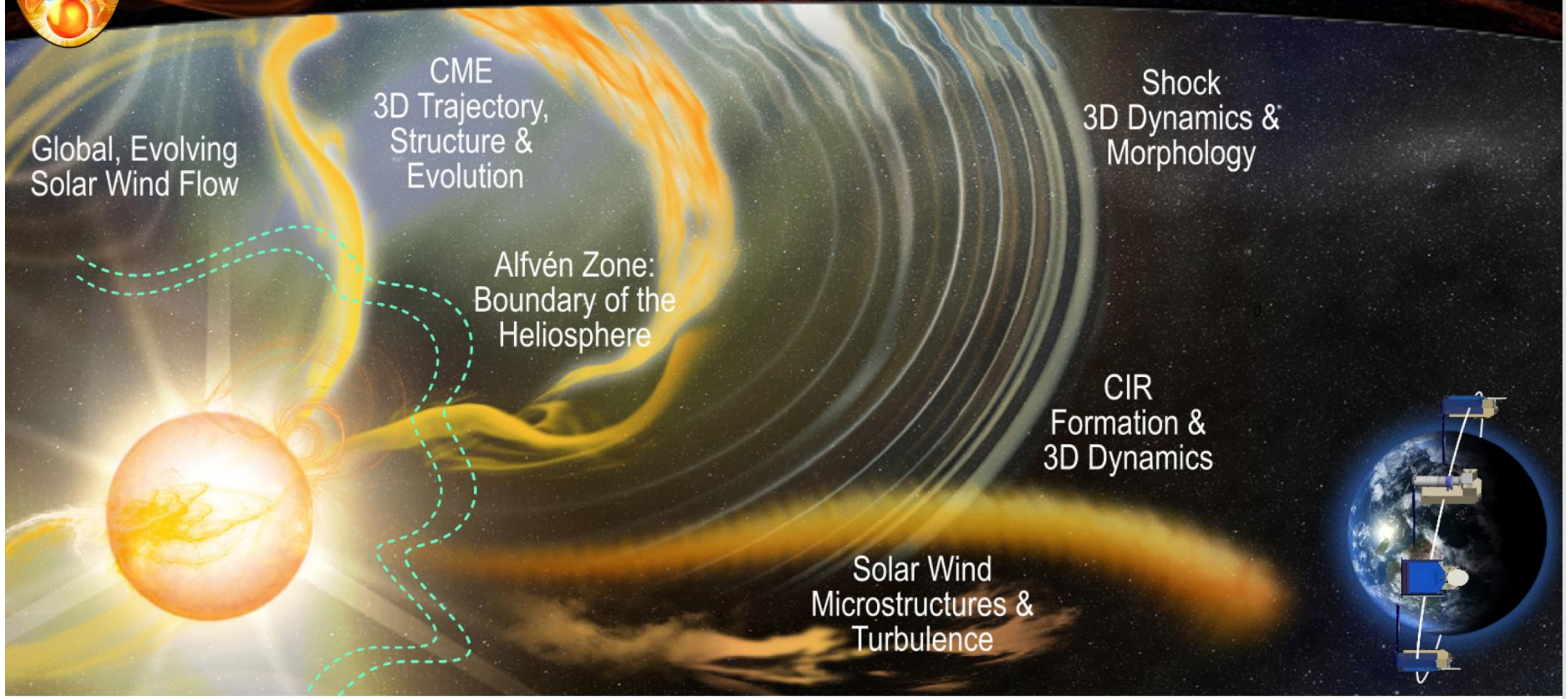
PUNCH PI

SRR/MDR

March 31-April 1, 2020

San Antonio, TX

PUNCH Science Goal & Objectives



PUNCH's **science goal:** comprehend the *cross-scale* physical processes – from microscale turbulence to the evolution of global-scale structures – that **unify the solar corona and heliosphere**.

1. **Understand how coronal structures become the ambient solar wind.**
2. **Understand the dynamic evolution of transient structures in the young solar wind.**

PUNCH has a clear science goal and high-level objectives

PUNCH Science Questions

1. Understand how coronal structures become the ambient solar wind.

1A: How does the young solar wind **flow and evolve** on global scales?

1B: Where and how do **microstructures and turbulence** form in the solar wind?

1C: What are the evolving physical properties of the **Alfvén Zone**?

2. Understand the dynamic evolution of transient structures in the young solar wind.

2A: How do **coronal mass ejections** (CMEs) propagate and evolve in the solar wind in 3D?

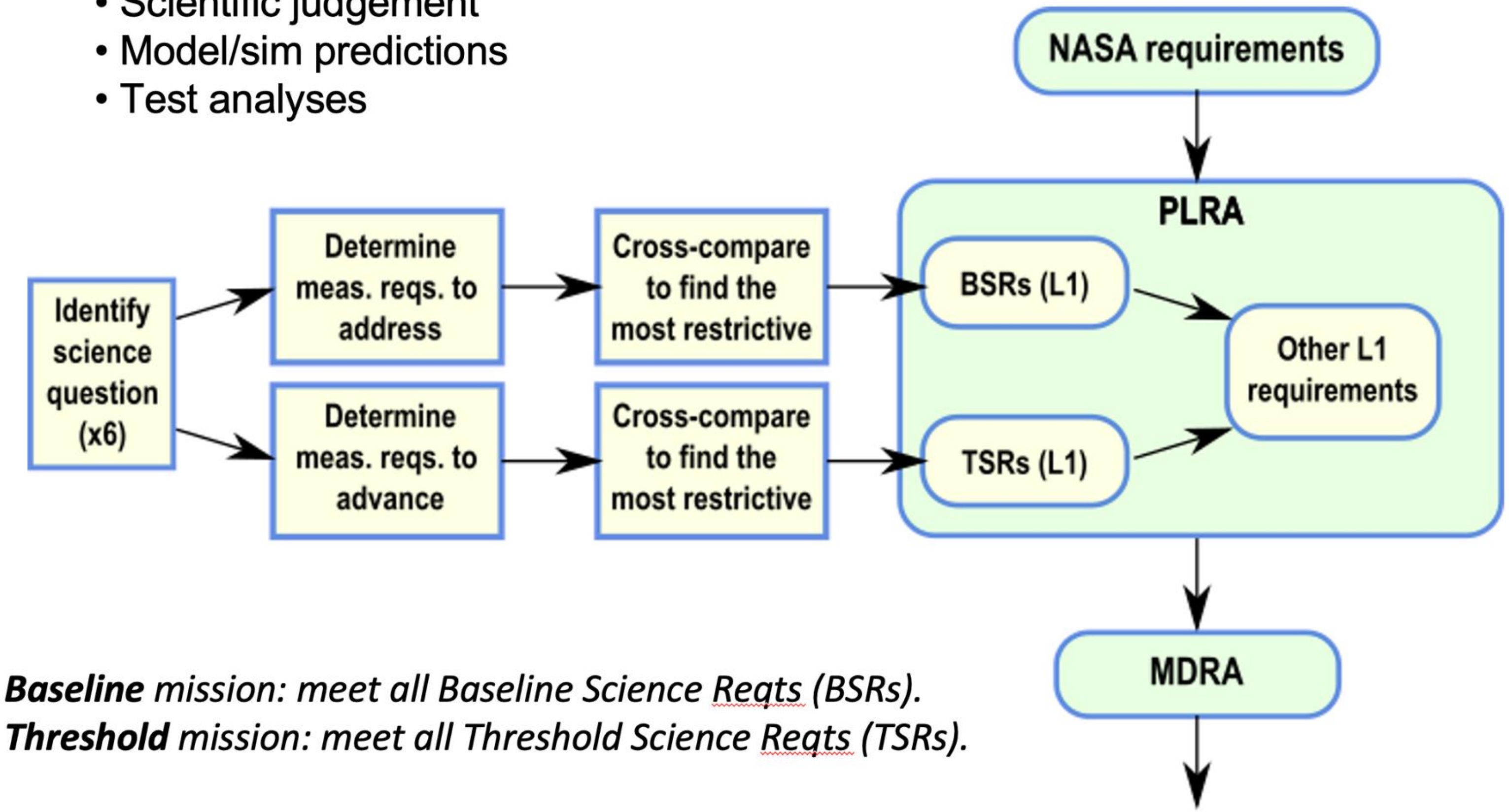
2B: How do quasi-stationary **corotating interaction regions** (CIRs) form and evolve?

2C: How do **shocks** form and interact with the solar wind across spatial scales?

PUNCH Objectives are divided into six well-formed science questions

L1 Requirement Definition Process

- Literature review
- Scientific judgement
- Model/sim predictions
- Test analyses



Baseline *mission: meet all Baseline Science Reqts (BSRs).*
Threshold *mission: meet all Threshold Science Reqts (TSRs).*

Definitional Measurement Requirements

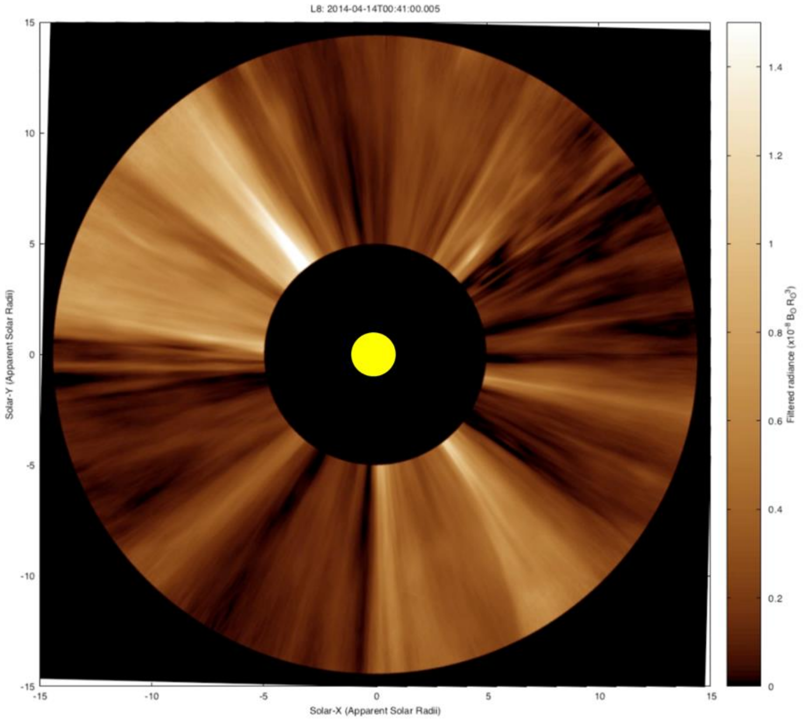
PUNCH science is *imaging* science.
Basic requirements are:

- **Field of View**: specified in polar coordinates (azimuth & apparent radius)
  Science Mission Requirements 1 & 2
- **Resolution**: Variable requirements by apparent radius from Sun
  Science Mission Requirement 3
- **Sensitivity**: [overall driving requirement]: variable with radius
  Science Mission Requirement 4
- **Polarimetry**: drives sensitivity; requires presence of a polarizer
  Science Mission Requirement 5
- **Spatiotemporal Coverage**: “time resolution” at each location
  Science Mission Requirement 6
- **Mission Duration**: “time field of view” for the mission
  Science Mission Requirement 7

BSR1: Azimuthal Coverage (FOV)

BSR1: Azimuthal Coverage *PUNCH **shall** acquire visible-light image data of the outer corona and inner heliosphere at minimum 270° in position angle around the Sun.*

- Azimuthal ("position angle") field of view is required to understand ambient solar wind flow.
- Ambient solar wind is roughly bimodal, with fast and slow streams.
- Understanding how coronal structures and boundaries relate to solar wind characteristics requires global measurements, spanning both polar and equatorial regions.



BSR1 Driver: Q1A

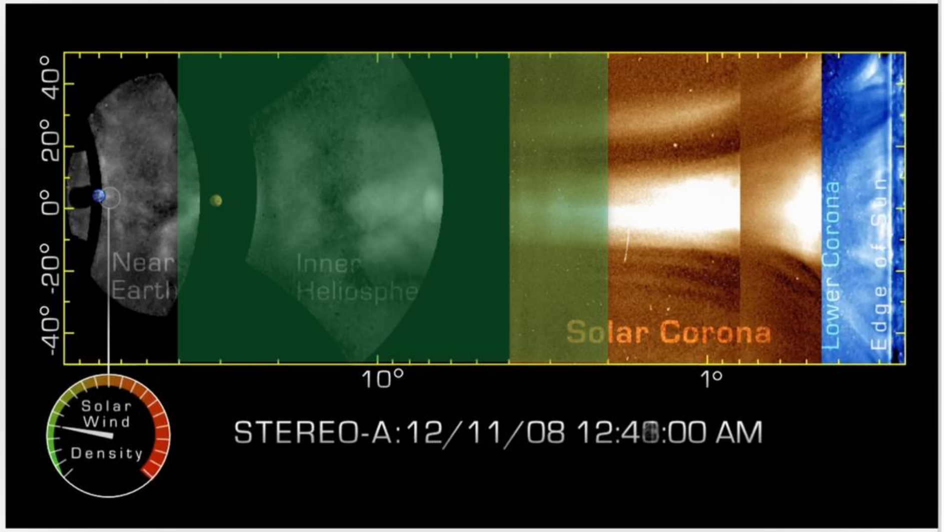
BSR1 Value: 270° around Sun

TSR1 Value: 270° around Sun

BSR2: Radial Coverage (FOV)

BSR2: Radial Coverage *PUNCH* ***<u>shall</u>*** *acquire visible-light image data at elongation angles ranging from at most 2° to at least 40° (8 $R_\odot$ to 160 $R_\odot$) relative to Sun center.*

- Radial field of view is required to span the boundary from the corona to the solar wind.
- Inner boundary: "coronal state" plasma before final acceleration, isotropic turbulence transition, or formation of stationary shocks
- Outer boundary: "wind state" plasma and final disposition of CMEs and CIRs

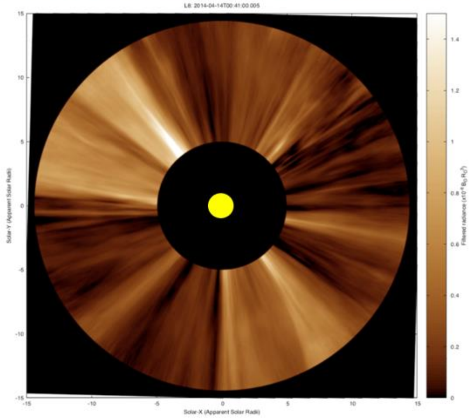


BSR2 Driver: Q1A, Q1B (inner); Q2A (outer).
BSR2 Value: 2°-40° from Sun
TSR2 Value: 6.25°-35° from Sun

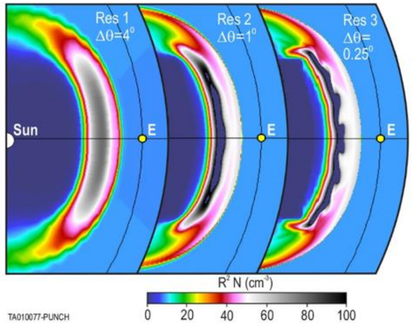
Note: $R_\odot$ defined as 0.25°

BSR3: Angular Resolution

BSR3: Angular Resolution *PUNCH **<u>shall</u>** acquire image data with angular resolution no coarser than 3 arcminutes at 3.75° (15 $R_\odot$) from Sun center and no coarser than 5 arcminutes at 20° (80 $R_\odot$) from Sun center.*



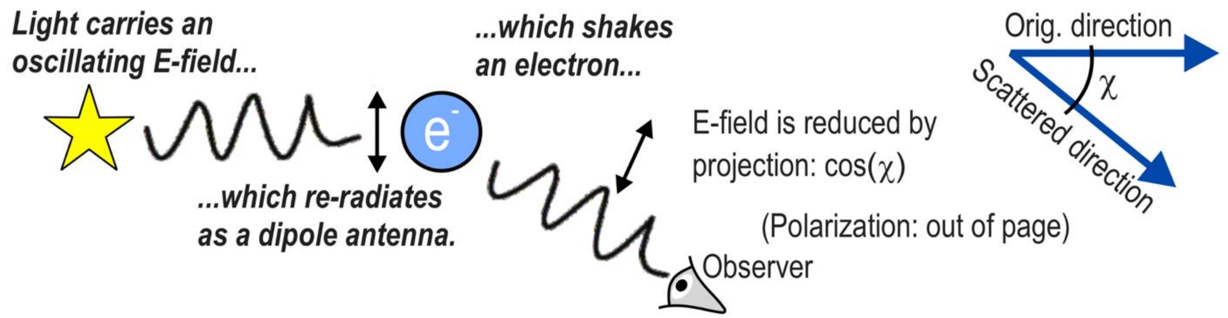
- PUNCH must resolve particular features of interest. Resolution is given at two radii (3.75° and 20°) spanning the flow regime shift.
- 3.75°: resolve solar wind tracers and faint features marking the Alfvén zone
- 20°: resolve flocculae detected by HI-1; image potential structure in shock fronts



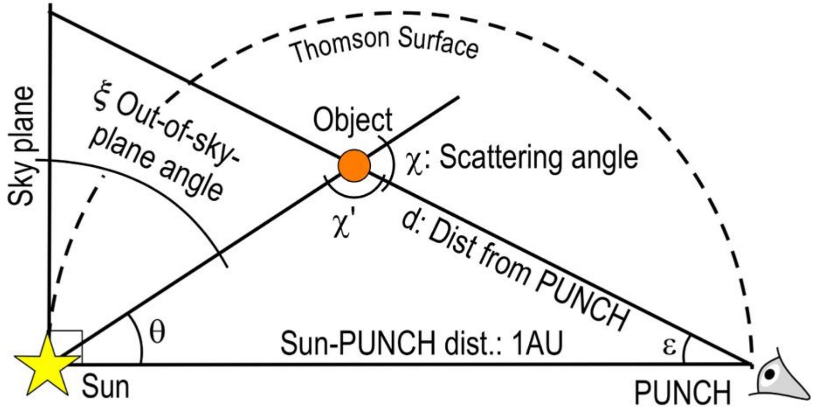
BSR3 Driver: Q1A, Q1C, Q2C (3.75°); Q2C (20°).
BSR3 Value: 3', 3.75° from Sun; 5', 20° from Sun
TSR3 Value: 6' throughout

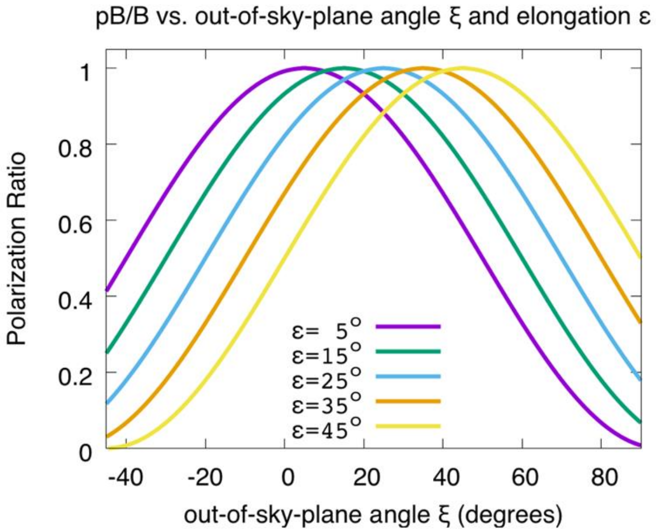
BSR4 & BSR6: 3D imaging through polarization

3D imaging drives photometric requirements. Here's how it works…

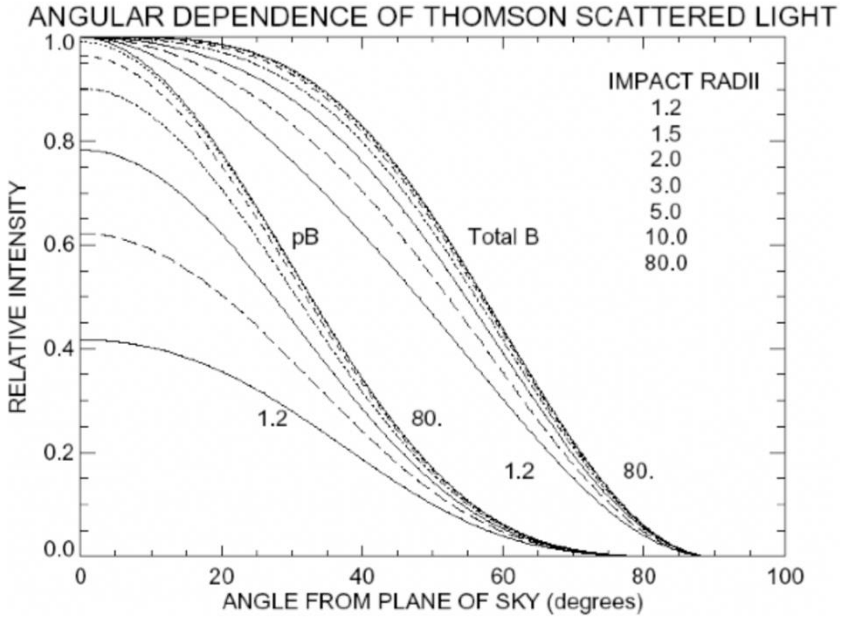


Thomson scattering geometry





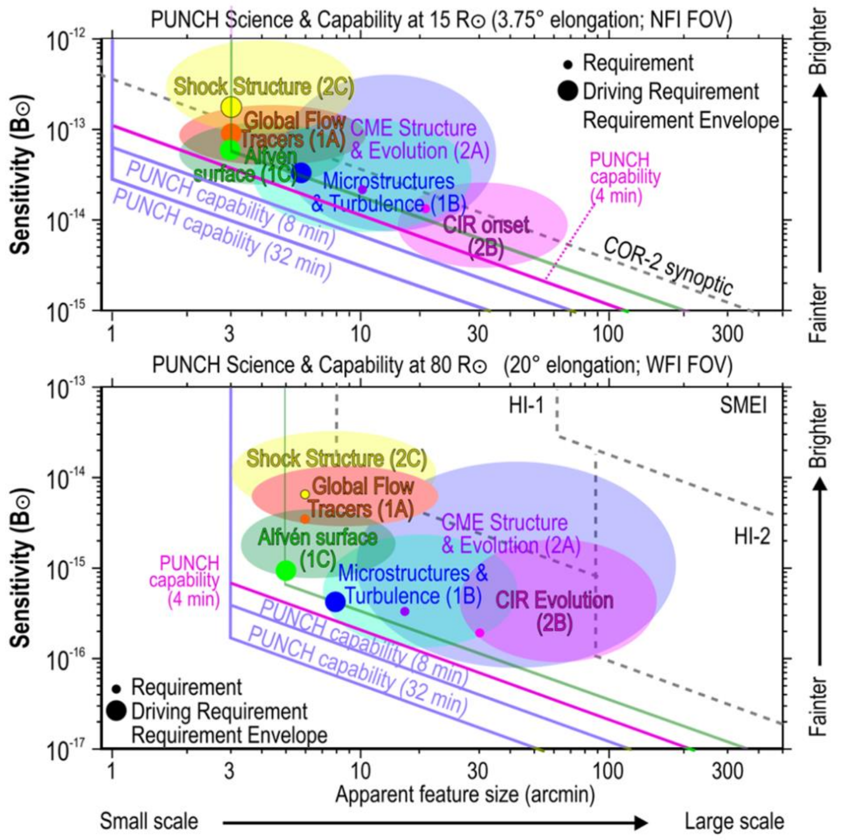
BSR4 & BSR6: 3D location and Photometry



- pB/B ratio determines χ angle
- Slope is approximately 0.44° per % polarization (pB/B: 10%-90%)
- 5° RMS error in 3D location requires SNR=10 in pB/B

BSR4: Normalization of sensitivity

- Photometric precision scales as 1/L for features of size L.
- Noise level is independent of feature brightness (dominated by background)
- "Sensitivity" is quoted as radiance required for SNR=1, at 1°x1° size scale, unpolarized.
  - Identify typ. feature radiance & size
  - Scale to standard size
  - Divide by required SNR
  - Scale for polarization (if relevant)
  - Result is "sensitivity" radiance
- Radiance is quoted in $B_\odot$ units for convenience in post-analysis.

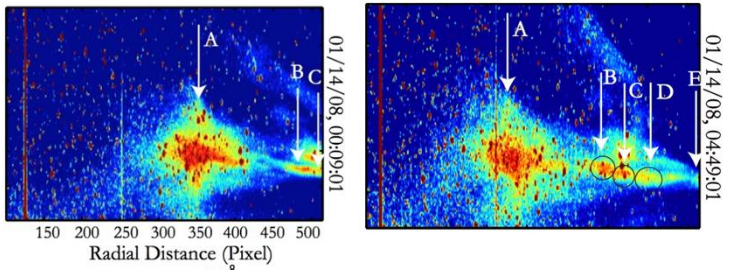


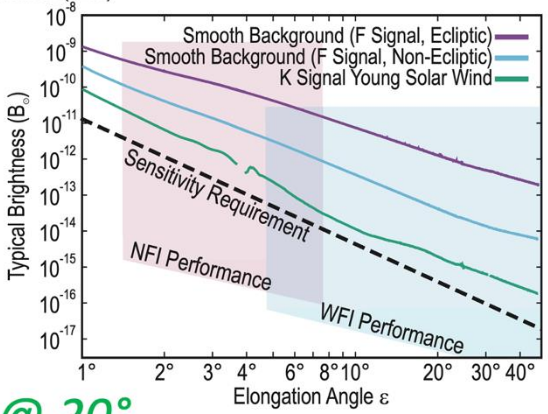
Note: Radiance is power/area/solid-angle; $B_\odot$ is the mean photospheric radiance.

BSR4: Photometric Sensitivity

BSR4: Photometric Sensitivity *PUNCH **shall** acquire images with an unpolarized, normalized, relative photometric sensitivity averaged over a 1° square region of the sky and 4-minute interval of time, of no more than 3.2x10^{-15} B$_\odot$ at a solar elongation angle of 3.75° (15 R$_\odot$), and no more than 1.0x10-16 B$_\odot$ at an elongation angle of 20° (80 R$_\odot$).*

- Photometric sensitivity is driven by the need to distinguish 3D location of small blobs (3.75°) and to discern the substructure of flocculae (20°) (Q1B).
- Alfvén zone detection (Q1C) *nearly* drives.
- Sensitivity is driven by the noise floor of the K corona signal (notional: dotted line at right), driving proportional photometric sensitivity of ~10^{-4}.





BSR4 Driver: Q1B

BSR4 Value: 3.2x10^{-15} B$_\odot$ @ 3.75°; 1.0x10^{-16} B$_\odot$ @ 20°

TSR4 Value: 1.0x10^{-15} B$_\odot$ @ 6.25°; 2.0x10^{-16} B$_\odot$ @ 20°

BSR5: Spatiotemporal Coverage

BSR5: Spatiotemporal Coverage *PUNCH **shall** acquire image data meeting the BSR4 sensitivity requirements, with sampling and spatial coverage encompassing at minimum the requirements described in Table 1.*

- Different science drivers have different cadence/coverage needs
- PUNCH takes advantage of relaxed cadence requirements at larger distances

Driving Question(s)	Table 1: Baseline sampling/coverage
1A, 2C	8 min image pairs, <24 min gap between pairs; 2.5°-30° (10-20 $R_\odot$) from Sun center
1C, 2B	20 min; 5°-27.5° (20-110 $R_\odot$) from Sun center
1B, 2A	40 min; 2°-40° (8-160 $R_\odot$) from Sun center

1A & 2C: Correlation requires two time scales: ~30 min for max speed sensitivity; ~8 min to capture rapid evolution at feature-crossing timescale

1B & 1C: uniform sampling at moderate uniform cadence enables Fourier methods

1B & 2A: longer cadence captures evolution time scale of features

BSR5 Driver: Mixed

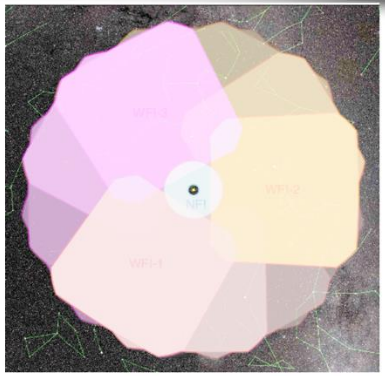
BSR5 Value: BSR4; Per Table 1

TSR5 Value: TSR4; Per Table 2

Driving Question(s)	Table 2: Threshold sampling/coverage
1A, 2C	8 min image pairs, <24 min gap between pairs; 7.5°-27.5° (30-110 $R_\odot$) from Sun center
1C	20 min; minimum 5° (20 $R_\odot$) wide annulus between 2.5°-20° (10-80 $R_\odot$) from Sun center
1B, 2A, 2B	45 min; 6.25°-35° (25-164 $R_\odot$) from Sun center

BSR 5: Coverage and Constellation Design

Constellation coverage of the full FOV is well understood



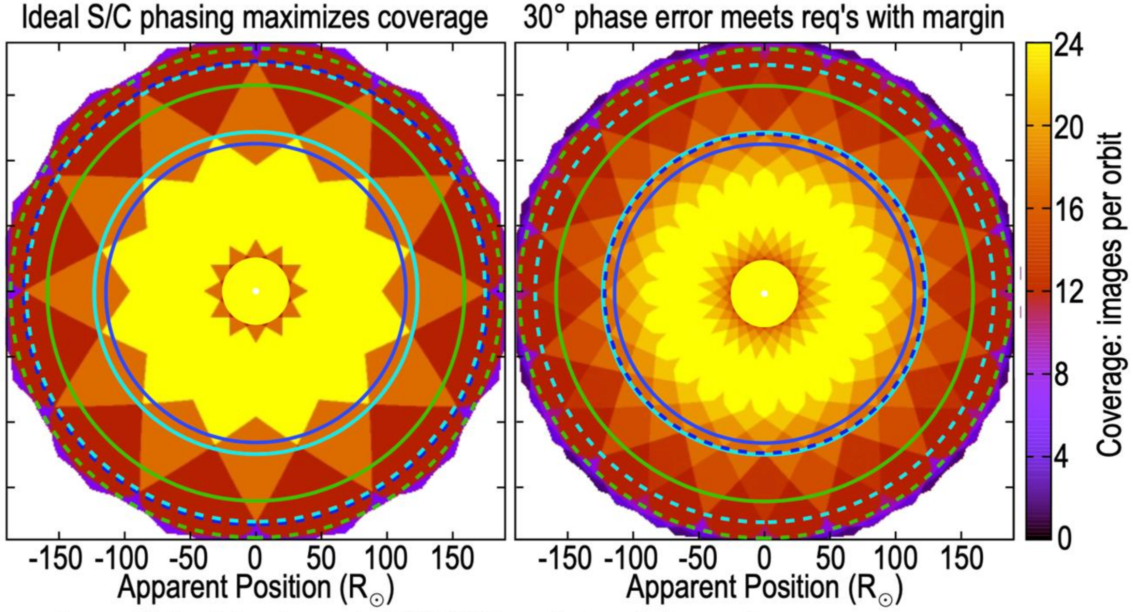
PUNCH Constellation covers its full FOV with orbital mosaics

BSR5 requires certain cadence coverage at all azimuths, inside of three particular apparent radii:

BSR5a: <24 min gap between pairs of images
- Requirement
- Capability

BSR5b: 20 min cadence
- Requirement
- Capability

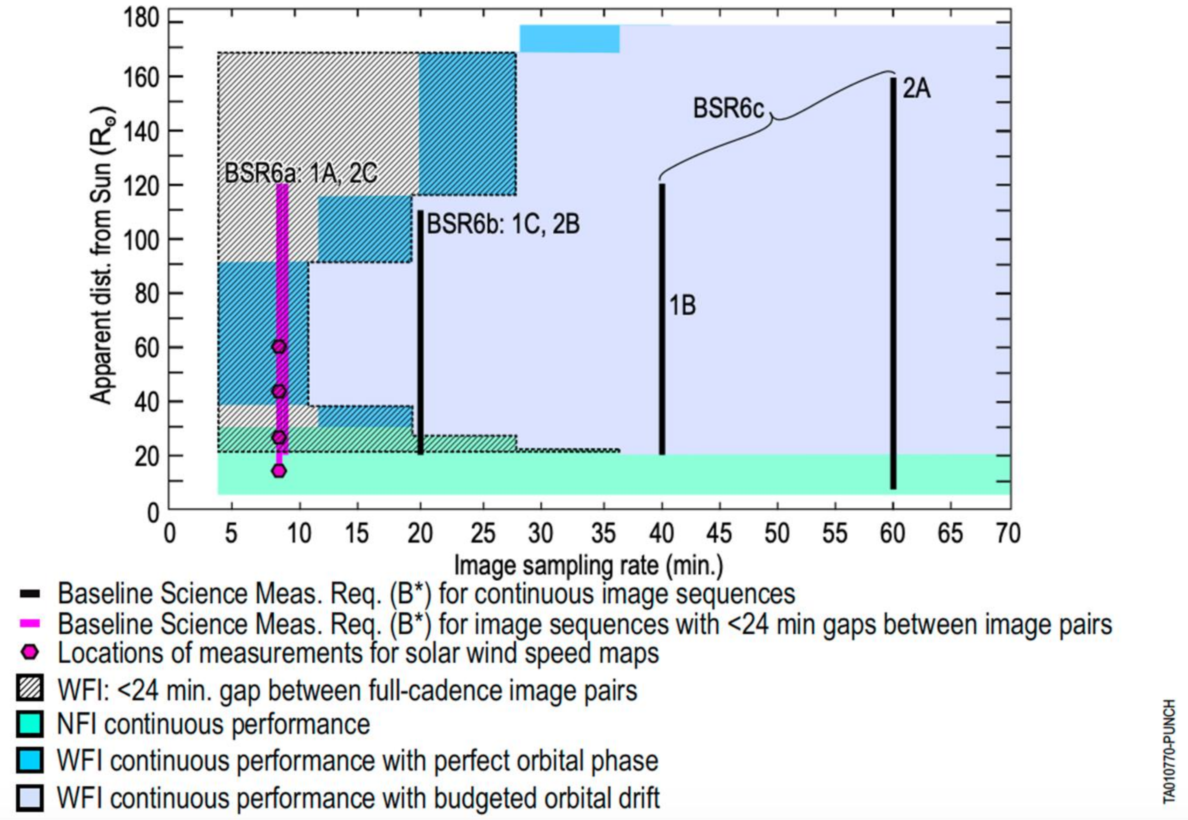
BSR5c: 40 min cadence
- Requirement
- Capability



BSR 5: Coverage of Baseline Requirements

Gaps in cadence tolerated

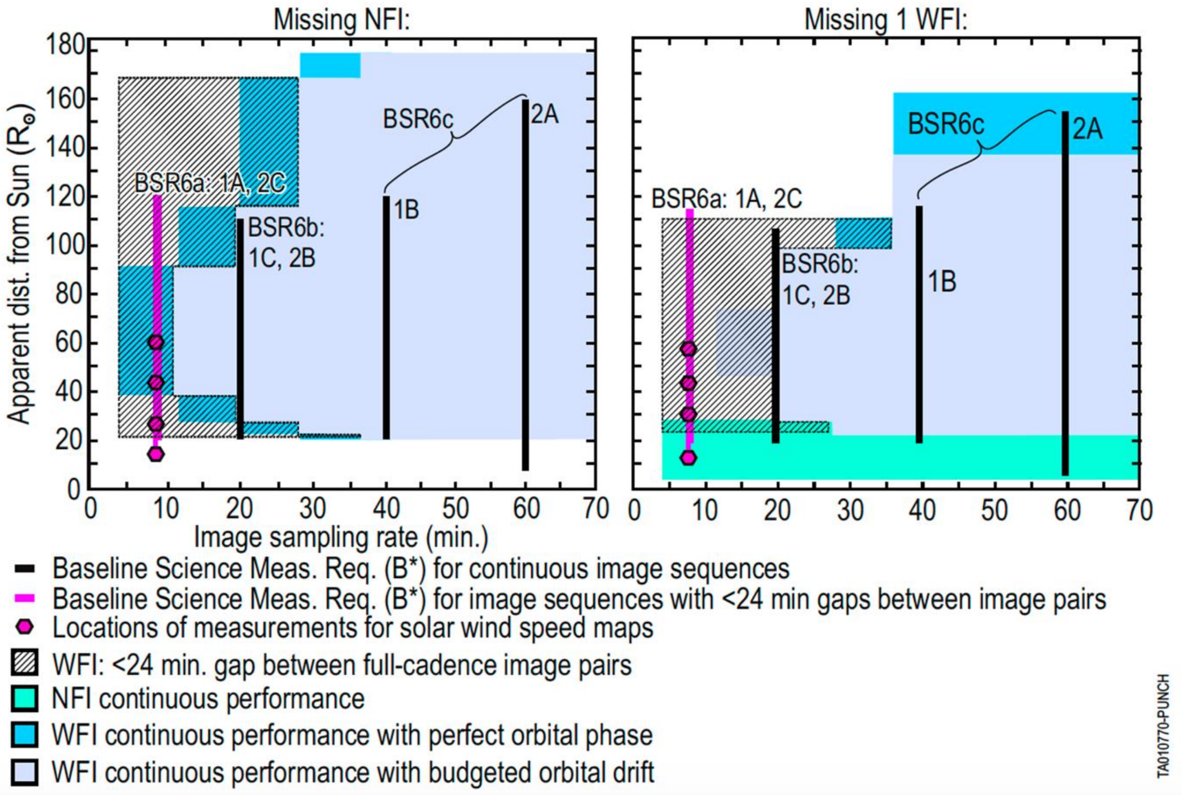
Includes orbital drift



BSR 5: Coverage Resilience

Gaps in cadence tolerated

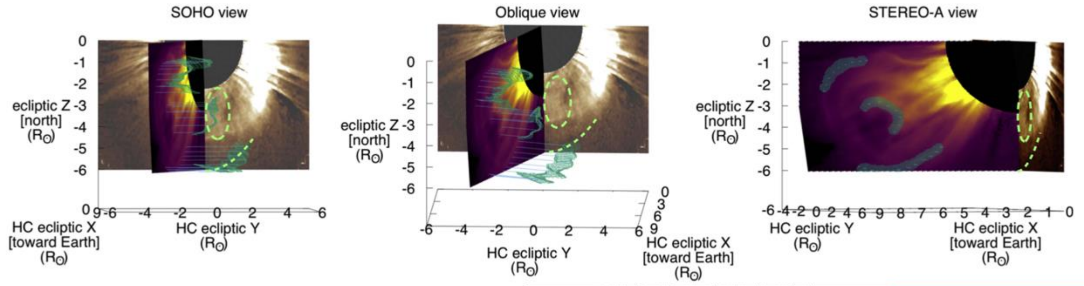
Includes orbital drift



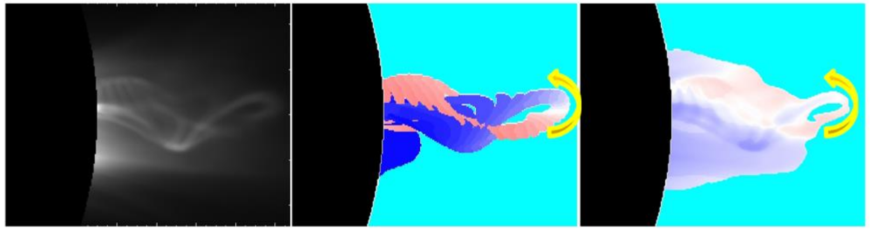
BSR 6: Polarization

BSR6: Polarization *PUNCH* ***shall*** *acquire polarized image sequences suitable for separation of the radial and tangential linearly polarized components of the light, with polarized photo-metric sensitivity levels no more than 2x coarser than the unpolarized requirement in BSR4.*

- 3D location of features requires polarization.
- Drivers are 3D location of solar wind features and tracking trajectory and structure of CMEs.
- Polarization has commonly been required by coronagraphs; PUNCH is the first polarizing heliospheric imager.



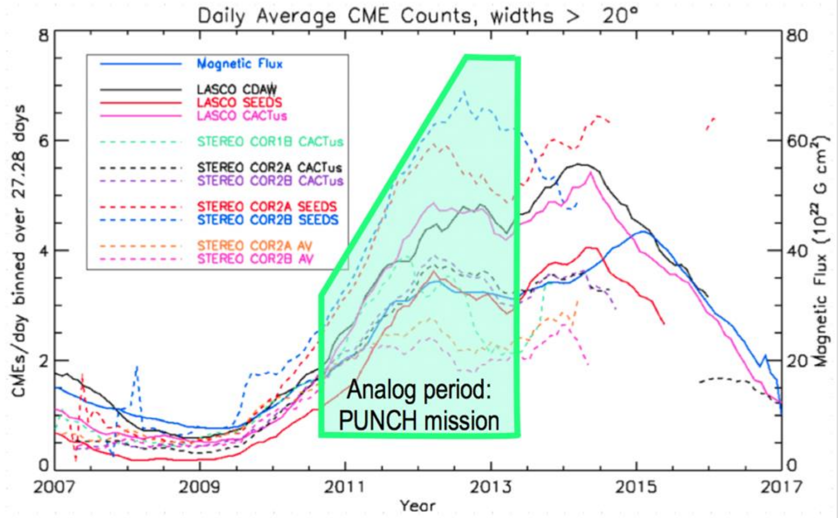
BSR6 Driver: Q1B,Q2A,Q2B,Q2C
BSR6 Value: Yes
TSR6 Value: Yes



BSR 7: Mission Duration

BSR7: Mission Duration *PUNCH* ***shall*** *observe and meet each of the BSR1-BSR6 requirements for a minimum total period of 15 months.*

- Duration is required to ensure enough large transient events for analysis.
- Science requirement is to observe 10 large, bright CMEs.
- Verifiable L1 requirement is referenced to mission only.
- CBE observation rate is 0.05 bright, front-side CME events per day. 15 month mission duration yields 11 expected CMEs with 2x margin.



BSR7 Driver: Q2A

BSR7 Value: 15 months

TSR7 Value: 5 months

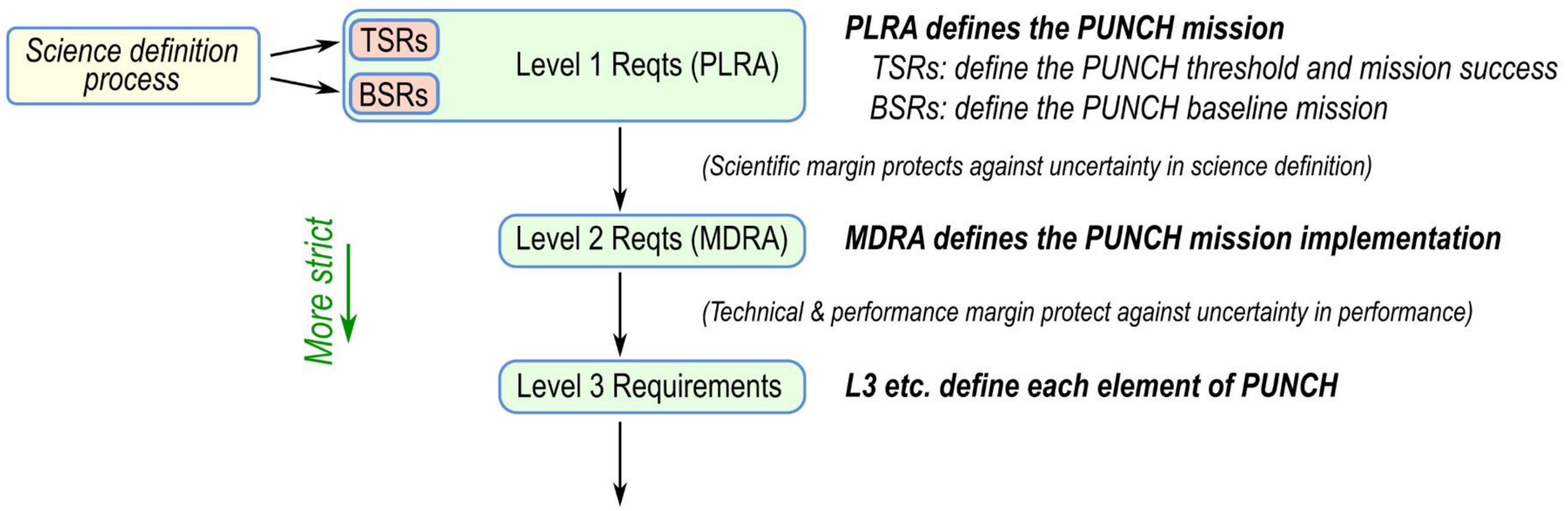
BSRs and Margin

- PUNCH has margin between L1 and L2 to account for uncertainty in the scientific drivers.

	L1 Req	L2 Req	L1 Value	L2 Value	L1-L2 Margin	Driver
BSR1	Az. Coverage	IDs 1061& 1063	270°	360°	33%	Wind flow
BSR2	Inner FOV	ID 1061 NFI FOV	2°	1.5°	33%	Uncertain Alfvén zone loc'n
BSR2	Outer FOV	ID 1063 WFI FOV	40°	40°	-	CME tracking & geometry
BSR3	Angular Resolution @ 3.75°	ID 1067 NFI Resolution	3"	2"	50%	Size of wind features
BSR3	Angular Resolution @ 20°	ID 1068 WFI Resolution	5"	3"	67%	Hypothesized shock features
BSR4	Norm. Phot. Sens. @ 3.75°	ID 1070 NFI Sensitivity	3.2E-15 B⊙	2.5E-15 B⊙	28%	Solar wind turbulence
BSR4	Norm. Phot. Sens. @ 20°	ID 1071 WFI Sensitivity	1.0E-16 B⊙	0.7E-16 B⊙	43%	Solar wind turbulence
BSR5	Spatiotemporal Coverage	ID 1152 Orbital Spacing	-	-	Yes	Mixed (See slides 14-16)
BSR6	Polarization	ID 1075 & ID 1076	Yes	Yes	-	3D structures
BSR7	Duration	ID 1092	15 mo.	24 mo.	60%	CME count

Managing to High-Level Requirements

- Level 1 requirements flow directly from science definition (Slide 4)
- Technical & performance margins are budgeted at each level as appropriate
- PUNCH **Baseline mission** meets the Baseline Science Requirements (BSRs)
- PUNCH **Threshold mission** meets the Threshold Science Requirements (TSRs)
- PUNCH **Mission success** is defined as meeting the TSRs
- PUNCH is designed and managed to meet the BSRs with margin.



- CubIXSS traceability matrix:

same idea, [slightly] different format.

- CubIXSS traceability matrix:

same idea, [slightly] different format.

Table 1: CubIXSS Science and Mission Traceability Matrix shows clear requirements flow from science to observables to instrument and mission

Science Question: What are the origins of hot plasma in solar flares and active regions?				
	Physical Parameter	**Observable**	•	**Result**
MO1	Abundances of low- & high-FIP ions from ~1 to ≳30 MK in multiple flares	SXR spectra comprising multiple lines (SNR > 10) & underlying continuum (SNR > 5) with <20% radiometric accuracy	↓	Improved understanding of flare heating mechanism, location, & timing
TO1	Abundances of low- & high-FIP ions from ~1 to ≳10 MK in multiple ARs	SXR spectral images (SNR > 10) for individual active regions with validation filtergrams & integrated spectra, <20% accuracy		Robust analysis techniques for spatially resolved AR spectra

	Requirement		**Performance**	**Science Justification & Drivers**	
SASS	Passband	1–20 keV	0.5–20 keV (Si), 5–50 keV (CdTe)	Observe low-/high-FIP ions w/in 1–30 MK & underlying continuum [MO1, TO1]	**Mission Top-Level Reqs – see below**
	E/ΔE	≥6 FWHM	13–88 (Si), 17–55 (CdTe) (in req. passband)	Resolve prominent line clusters & continuum shape; provide ground-truth for MOXSI spectra at high dynamic range [MO1, TO1]	
	Cadence[1]	≤60 s	1 s (flares), 1 min (quiescent)	Observe flare dynamics to distinguish gradual vs. impulsive heating [MO1]	
	Obs. Flux[2] (GOES lvl.)	Fl: M1–X1 AR: ≥A1	<B5 to >X5 (at req. cadence) ≥A1 (at 1-hour eff. integration)	Observe hot flares w/ sufficient duration with req. SNR at req. cadence [MO1] Observe AR evolution with req. SNR at 1-hour image-stacked effective integration [TO1]	
MOXSI	Passband	4–50 Å	1–55 Å	As for SASS	
	λ/Δλ	≥10 FWHM	**14–136** (**CBE** in req. passband)	Resolve prominent line clusters above continuum w/ required SNR [MO1, TO1]	
	Ang. Res.	≤100″	**29–39″ CBE** (FWHM)	Distinguish individual ARs (separation = any lat, ≥15° lon) [TO1]	
	Cadence[1]	≤60 s	20 s (flares), 5 min (quiescent)	As for SASS	
	Flux[2]	As for SASS	Fl: ≥M1; AR: ≥A1 (cad. as SASS)	As for SASS, see also footnote 2	
	Filtergrams[3]	2	4	Provide validation observations for overlappogram deconvolution results [TO1]	

1 Requirement driven by flares; active region requires ≤1 hour (achieved via ground stacking of high-cadence images); **2** Minimum flux yields >100 photons (SNR > 10) per integrated spectral feature using typical flare or AR spectrum, scaled appropriately, summed over $+1^{st}$ and -1^{st} orders; **3** With filter passbands overlapping MOXSI required passband.

Mission Top-Level Reqs.	**Mission Design Reqs.**	**Spacecraft Reqs.**	**Ground Sys. Reqs.**	**Ops. Reqs.**
Observe: ≥30 flares at or above M1.0 ≥30 ARs for at least 7 days	12-month mission Low-Earth orbit: ≥450 km perigee	Full-Sun FOV Pointing at Sun (3σ): ≤ 2.5′ control | ≤ 6″/s stability | ≤ 3″ knowledge	N/A	N/A
Accommodate instruments in space	Compatibility w/ CSLI launch Active/passive thermal mgmt. for instr. ops. ≤ 10 krad TID	6U CubeSat: ≤12 kg, ≤(36.6 × 23.9 × 11.6) cm^3 Power: Provide >25 W OA to EOL Temp range: –10 to +35 °C [operating] Radiation: Passive shielding, robust ops software	N/A	Regularly updated TLEs
Recover scientific measurements within program period	Low-Earth orbit: Inclination ≥15° ≥450 km perigee	≥472 MB/day ≥3 days on-board storage S-band transceiver ADCS slew rate ≥3°/sec	S band, ≥3.5m dish ≥31 min/day downlink @ ≥2 Mbps MOC/SOC at SwRI	Commanding of: Instr. / IDPU Pointing Downlink

Closing thoughts

Closing thoughts

- Traceable requirements let you know:
  - Will this project (mission, instrument, model, investigation) work?
  - When am I finished?

- Traceability and requirements are essential to the scientific process!
- Traceability matrices help define and communicate requirements – learn to use them!
- Requirements are a roadmap to *any* scale of investigation.
- Explicit requirement tracking is useful for small projects, essential for large projects