How Precursor Science Impacts Mission Design:

Examples from the HabEx study STM

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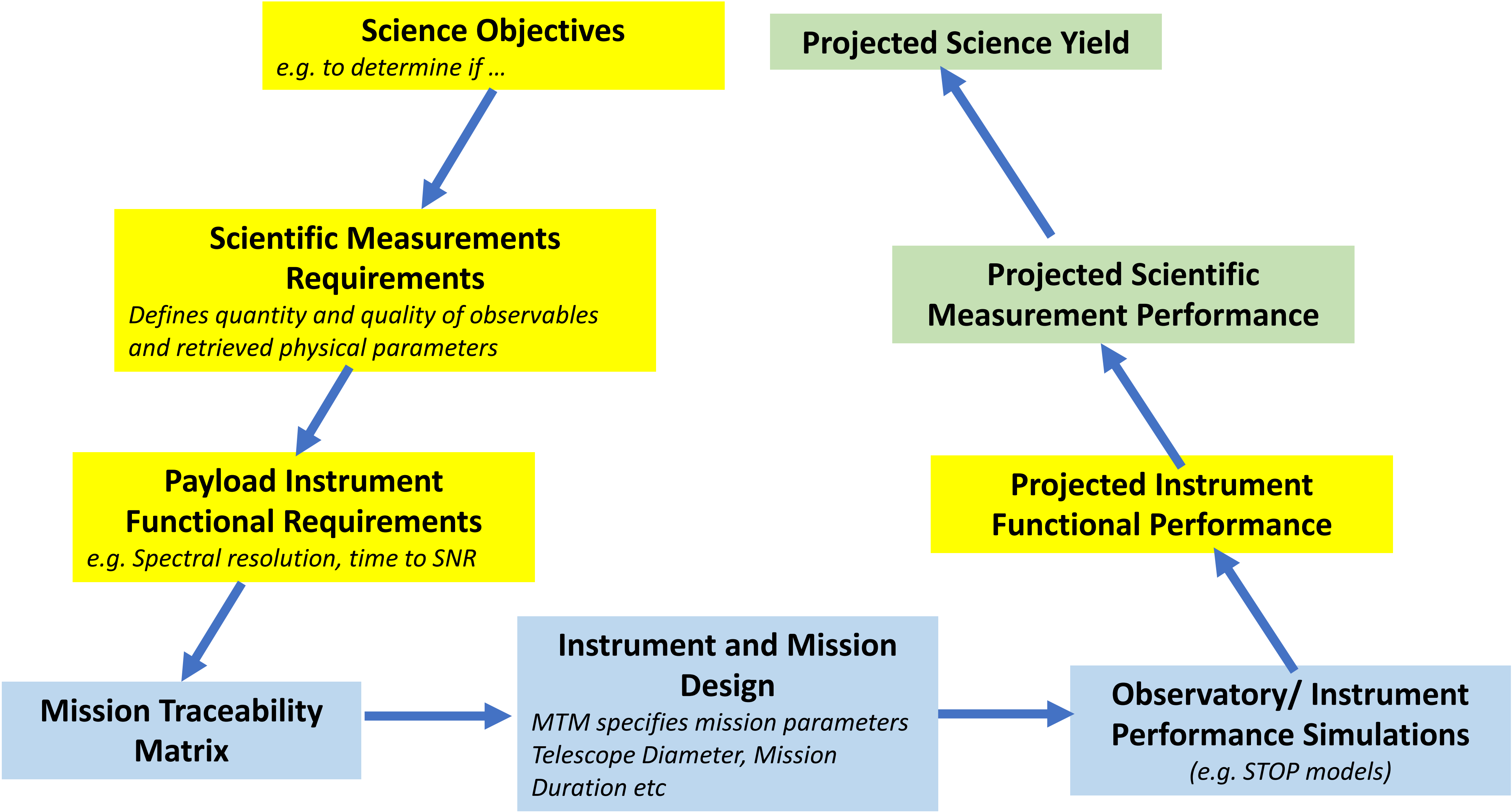
STM as a part of mission design



Science Objectives
e.g. to determine if …

Scientific Measurements Requirements
Defines quantity and quality of observables and retrieved physical parameters

Payload Instrument Functional Requirements
e.g. Spectral resolution, time to SNR

Mission Traceability Matrix

Instrument and Mission Design
MTM specifies mission parameters Telescope Diameter, Mission Duration etc

Observatory/ Instrument Performance Simulations
(e.g. STOP models)

Projected Instrument Functional Performance

Projected Scientific Measurement Performance

Projected Science Yield

HabEx STM Excerpt (1 of 5 pages)

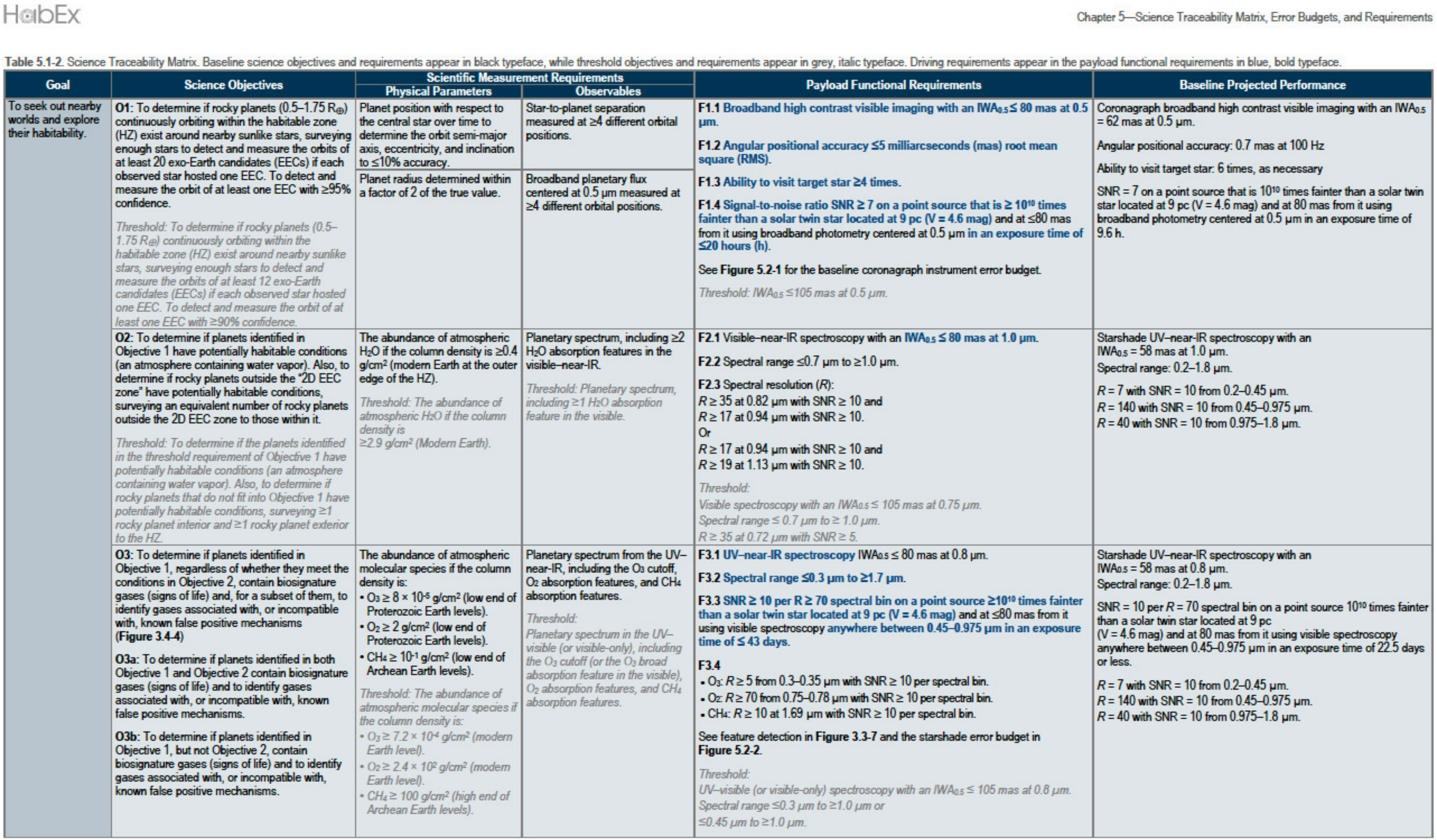
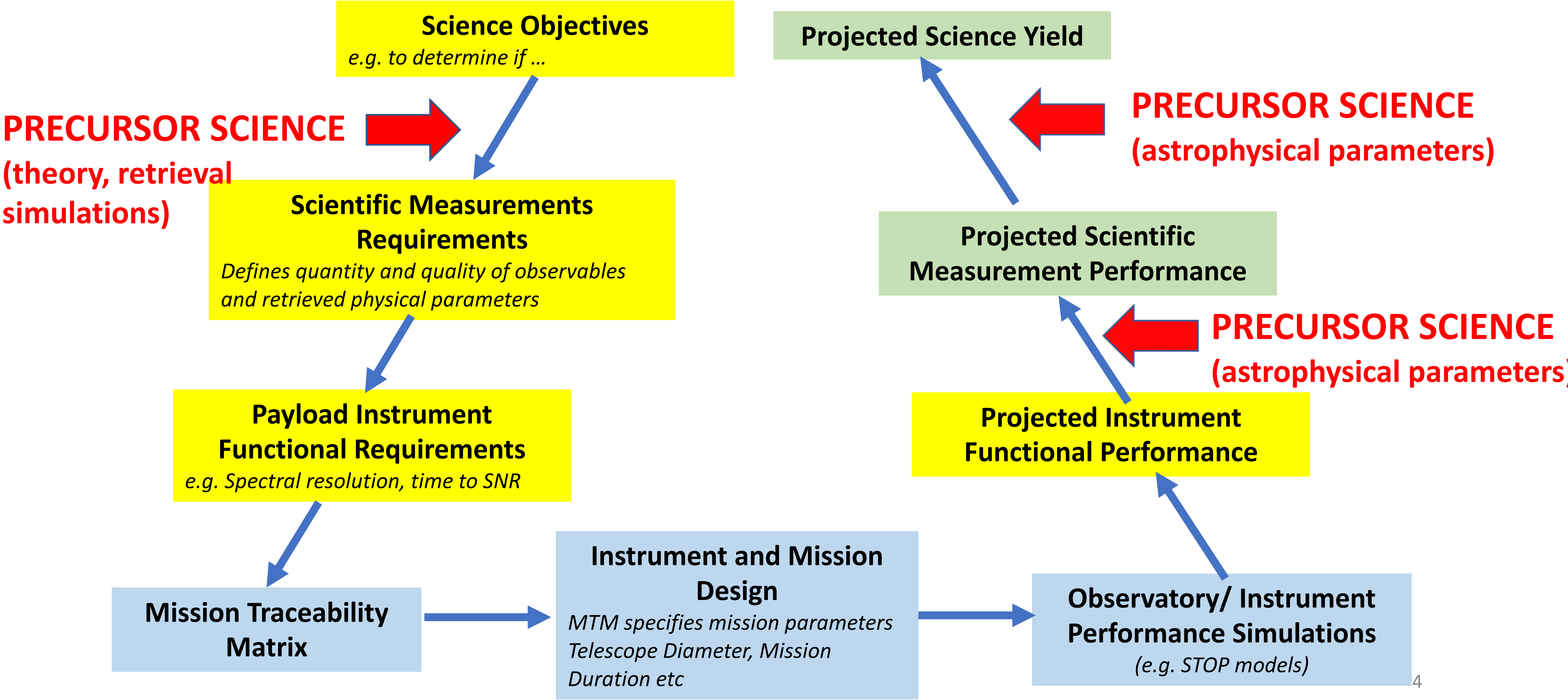


Table 5.1-2. Science Traceability Matrix. Baseline science objectives and requirements appear in black typeface, while threshold objectives and requirements appear in grey, italic typeface. Driving requirements appear in the payload functional requirements in blue, bold typeface.

Goal	Science Objectives	Scientific Measurement Requirements		Payload Functional Requirements	Baseline Projected Performance
		Physical Parameters	Observables		
To seek out nearby worlds and explore their habitability.	**O1**: To determine if rocky planets (0.5–1.75 $R_\oplus$) continuously orbiting within the habitable zone (HZ) exist around nearby sunlike stars, surveying enough stars to detect and measure the orbits of at least 20 exo-Earth candidates (EECs) if each observed star hosted one EEC. To detect and measure the orbit of at least one EEC with ≥95% confidence. *Threshold: To determine if rocky planets (0.5–1.75 $R_\oplus$) continuously orbiting within the habitable zone (HZ) exist around nearby sunlike stars, surveying enough stars to detect and measure the orbits of at least 12 exo-Earth candidates (EECs) if each observed star hosted one EEC. To detect and measure the orbit of at least one EEC with ≥90% confidence.*	Planet position with respect to the central star over time to determine the orbit semi-major axis, eccentricity, and inclination to ≤10% accuracy.	Star-to-planet separation measured at ≥4 different orbital positions.	**F1.1 Broadband high contrast visible imaging with an IWA$_{0.5}$ ≤ 80 mas at 0.5 µm.** **F1.2 Angular positional accuracy ≤5 milliarcseconds (mas) root mean square (RMS).** **F1.3 Ability to visit target star ≥4 times.** **F1.4 Signal-to-noise ratio SNR ≥ 7 on a point source that is ≥ 10^{10} times fainter than a solar twin star located at 9 pc (V = 4.6 mag)** and at ≤80 mas from it using broadband photometry centered at 0.5 µm **in an exposure time of ≤20 hours (h).** See **Figure 5.2-1** for the baseline coronagraph instrument error budget. *Threshold: IWA$_{0.5}$ ≤105 mas at 0.5 µm.*	Coronagraph broadband high contrast visible imaging with an IWA$_{0.5}$ = 62 mas at 0.5 µm. Angular positional accuracy: 0.7 mas at 100 Hz Ability to visit target star: 6 times, as necessary SNR = 7 on a point source that is 10^{10} times fainter than a solar twin star located at 9 pc (V = 4.6 mag) and at 80 mas from it using broadband photometry centered at 0.5 µm in an exposure time of 9.6 h.
		Planet radius determined within a factor of 2 of the true value.	Broadband planetary flux centered at 0.5 µm measured at ≥4 different orbital positions.		
	O2: To determine if planets identified in Objective 1 have potentially habitable conditions (an atmosphere containing water vapor). Also, to determine if rocky planets outside the "2D EEC zone" have potentially habitable conditions, surveying an equivalent number of rocky planets outside the 2D EEC zone to those within it. *Threshold: To determine if the planets identified in the threshold requirement of Objective 1 have potentially habitable conditions (an atmosphere containing water vapor). Also, to determine if rocky planets that do not fit into Objective 1 have potentially habitable conditions, surveying ≥1 rocky planet interior and ≥1 rocky planet exterior to the HZ.*	The abundance of atmospheric H_2O if the column density is ≥0.4 g/cm^2 (modern Earth at the outer edge of the HZ). *Threshold: The abundance of atmospheric H_2O if the column density is ≥2.9 g/cm^2 (Modern Earth).*	Planetary spectrum, including ≥2 H_2O absorption features in the visible–near-IR. *Threshold: Planetary spectrum, including ≥1 H_2O absorption feature in the visible.*	**F2.1** Visible–near-IR spectroscopy with an **IWA$_{0.5}$ ≤ 80 mas at 1.0 µm.** **F2.2** Spectral range ≤0.7 µm to ≥1.0 µm. **F2.3** Spectral resolution (R): $R \geq 35$ at 0.82 µm with SNR ≥ 10 and $R \geq 17$ at 0.94 µm with SNR ≥ 10. Or $R \geq 17$ at 0.94 µm with SNR ≥ 10 and $R \geq 19$ at 1.13 µm with SNR ≥ 10. *Threshold:* *Visible spectroscopy with an IWA$_{0.5}$ ≤ 105 mas at 0.75 µm.* *Spectral range ≤ 0.7 µm to ≥ 1.0 µm.* *$R \geq 35$ at 0.72 µm with SNR ≥ 5.*	Starshade UV–near-IR spectroscopy with an IWA$_{0.5}$ = 58 mas at 1.0 µm. Spectral range: 0.2–1.8 µm. $R = 7$ with SNR = 10 from 0.2–0.45 µm. $R = 140$ with SNR = 10 from 0.45–0.975 µm. $R = 40$ with SNR = 10 from 0.975–1.8 µm.
	O3: To determine if planets identified in Objective 1, regardless of whether they meet the conditions in Objective 2, contain biosignature gases (signs of life) and, for a subset of them, to identify gases associated with, or incompatible with, known false positive mechanisms (**Figure 3.4-4**) **O3a**: To determine if planets identified in both Objective 1 and Objective 2 contain biosignature gases (signs of life) and to identify gases associated with, or incompatible with, known false positive mechanisms. **O3b**: To determine if planets identified in Objective 1, but not Objective 2, contain biosignature gases (signs of life) and to identify gases associated with, or incompatible with, known false positive mechanisms.	The abundance of atmospheric molecular species if the column density is: • $O_3 \geq 8 \times 10^{-5}$ g/cm^2 (low end of Proterozoic Earth levels). • $O_2 \geq 2$ g/cm^2 (low end of Proterozoic Earth levels). • $CH_4 \geq 10^{-1}$ g/cm^2 (low end of Archean Earth levels). *Threshold: The abundance of atmospheric molecular species if the column density is:* *• $O_3 \geq 7.2 \times 10^{-4}$ g/cm^2 (modern Earth level).* *• $O_2 \geq 2.4 \times 10^{2}$ g/cm^2 (modern Earth level).* *• $CH_4 \geq 100$ g/cm^2 (high end of Archean Earth levels).*	Planetary spectrum from the UV–near-IR, including the O_3 cutoff, O_2 absorption features, and CH_4 absorption features. *Threshold:* *Planetary spectrum in the UV–visible (or visible-only), including the O_3 cutoff (or the O_3 broad absorption feature in the visible), O_2 absorption features, and CH_4 absorption features.*	**F3.1 UV–near-IR spectroscopy** IWA$_{0.5}$ ≤ 80 mas at 0.8 µm. **F3.2 Spectral range ≤0.3 µm to ≥1.7 µm.** **F3.3 SNR ≥ 10 per R ≥ 70 spectral bin on a point source ≥10^{10} times fainter than a solar twin star located at 9 pc (V = 4.6 mag)** and at ≤80 mas from it using visible spectroscopy **anywhere between 0.45–0.975 µm in an exposure time of ≤ 43 days.** **F3.4** • O_3: $R \geq 5$ from 0.3–0.35 µm with SNR ≥ 10 per spectral bin. • O_2: $R \geq 70$ from 0.75–0.78 µm with SNR ≥ 10 per spectral bin. • CH_4: $R \geq 10$ at 1.69 µm with SNR ≥ 10 per spectral bin. See feature detection in **Figure 3.3-7** and the starshade error budget in **Figure 5.2-2**. *Threshold:* *UV–visible (or visible-only) spectroscopy with an IWA$_{0.5}$ ≤ 105 mas at 0.8 µm.* *Spectral range ≤0.3 µm to ≥1.0 µm or* *≤0.45 µm to ≥1.0 µm.*	Starshade UV–near-IR spectroscopy with an IWA$_{0.5}$ = 58 mas at 0.8 µm. Spectral range: 0.2–1.8 µm. SNR = 10 per $R = 70$ spectral bin on a point source 10^{10} times fainter than a solar twin star located at 9 pc (V = 4.6 mag) and at 80 mas from it using visible spectroscopy anywhere between 0.45–0.975 µm in an exposure time of 22.5 days or less. $R = 7$ with SNR = 10 from 0.2–0.45 µm. $R = 140$ with SNR = 10 from 0.45–0.975 µm. $R = 40$ with SNR = 10 from 0.975–1.8 µm.

STM as a part of mission design



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(theory, retrieval simulations)

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PRECURSOR SCIENCE
(astrophysical parameters)

Projected Scientific Measurement Performance

PRECURSOR SCIENCE
(astrophysical parameters)

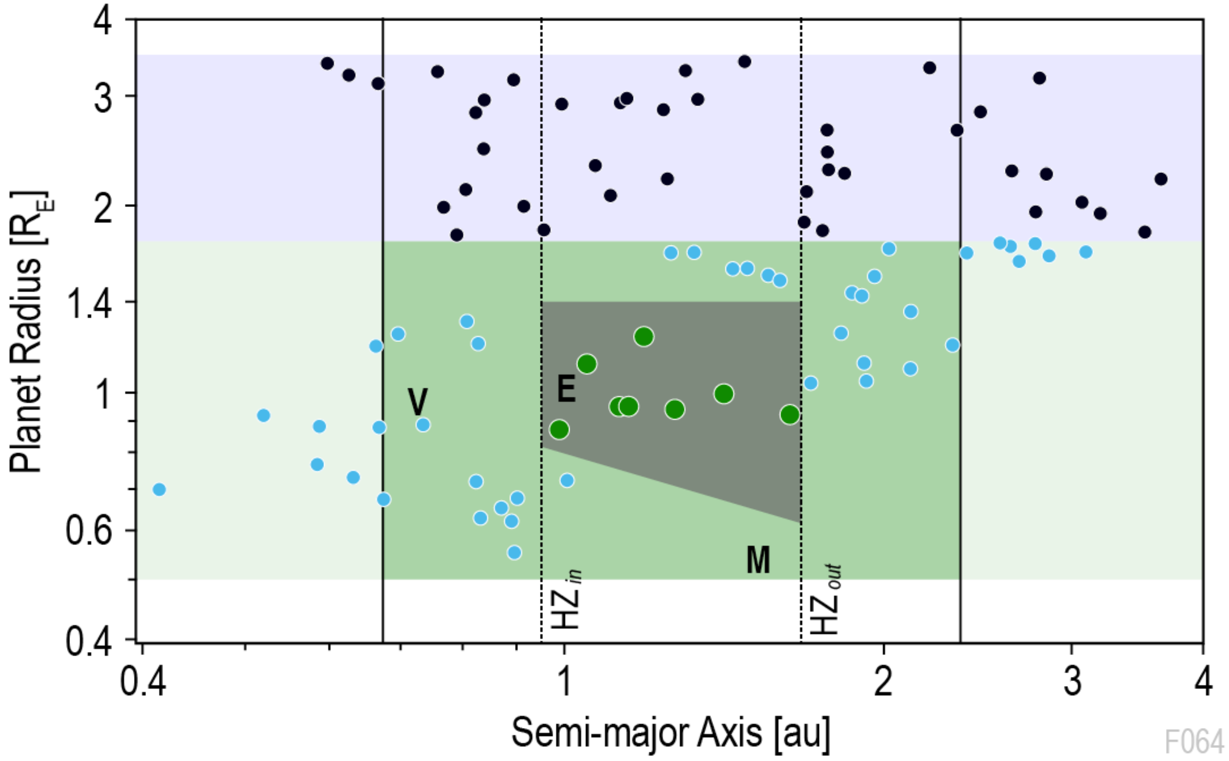
Projected Science Yield

HabEx STM Example #1

- Objective 1: “To determine if rocky planets continuously orbiting with the habitable zone exist around nearby stars, surveying enough stars to detect and measure the orbits of at least 20 exo-earth candidates (EECs) if each observed star had one […].”

- Precursor science examples (theory):
  - Define “rocky planets” (e.g. size range vs separation)
  - Define “habitable zone”

Impact of changing the definitions of HZ and exo-Earth size in the HabEx mission yield simulations (η_{Earth}=0.24)



For a given design science yield strongly depends on assumptions used to define an exo-Earth in the HZ.
For a given science yield objective, mission design is then strongly impacted by these assumptions.

HabEx STM Example #2 (more in Shawn’s talk)

- Objective 3: “To determine if planets identified in Objective 1 contain biosignature gases, and, for a subset of them, to identify gases associated with, or incompatible with, known false positive mechanisms”.

- Precursor science examples (theory & physical parameter retrieval):
  - Define biosignatures, molecules to be searched for, down to what abundance
  - Identify false positive mechanisms, associated molecules to be searched for, down to what abundance
  - Define spectral range, spectral resolution and signal-to-noise required, based on atmospheric retrieval simulations

HabEx STM Example #3

- Objective 1: “To detect and measure the orbit of at least one exo-Earth candidate with > 95% confidence.”
- Ties to the number of exo-Earth candidates (N) detected for given mission design and set of key astrophysical assumptions
- E.g (Stark et al. ApJ 2015), for a coronagraph-only system (no starshade), the total number of exo-Earths detected at V band and only spectrally characterized around 1 μm (R=50) to search for water follows:
  - $N \propto (D/10m)^{1.97} * (T/1yr)^{0.32} * (IWA/52\ mas)^{-0.98} * (BW/20\%)^{0.3} * (\eta_{Earth} / 0.1)^{0.96} * (ExoZodi/3zodis)^{-0.17} * (Albedo/0.2)^{0.65}$
  - Shows how astrophysical parameters impact mission design parameters at a given exo-Earth yield objective

- Precursor science examples (astrophysical parameters) :
  - **Refine eta_Earth value** (average number of HZ exo-Earths per star)
    - HabEx and LUVOIR used 0.24, as well as optimistic and pessimistic +/-1 σ estimates
    - E.g. reduce the impact of close-in bare sub-Neptunes when extrapolating Kepler data to Earth-sized planets at longer orbital periods
  - **Estimate exozodi brightness level at IROUV wavelengths**
    - HabEx and LUVOIR used best fit distribution derived from LBTI in the mid-IR , as well as pessimistic and optimistic +/-1 σ cases.
    - Conduct further exozodi measurements, especially at IROUV wavelengths
  - Assess detectability of exo-Earths embedded in dusty or clumpy exozodi disks
  - Fold in any prior detections of exo-Earths with other facilities
  - Refine master target list with vetted binaries

HabEx STM Example #4

- Objective 5b: “To determine or refine the architecture of individual planetary systems over orbital distances that include the inner HZ to Saturn-like orbits, observing enough sunlike stars to detect over 30 planets of each type (rocky, sub-Neptunes, and giants).”
- Precursor science examples (astrophysical parameters):
  - Planet demographics around sunlike stars: refine planet occurrence rates vs radius and separation
    - HabEx and LUVOIR used the ExoPAG SAG 13 results from RV data compilation and extrapolation, plus additional dynamical stability arguments
  - New observations of mature exoplanets with ground and space-based facilities

Thank you