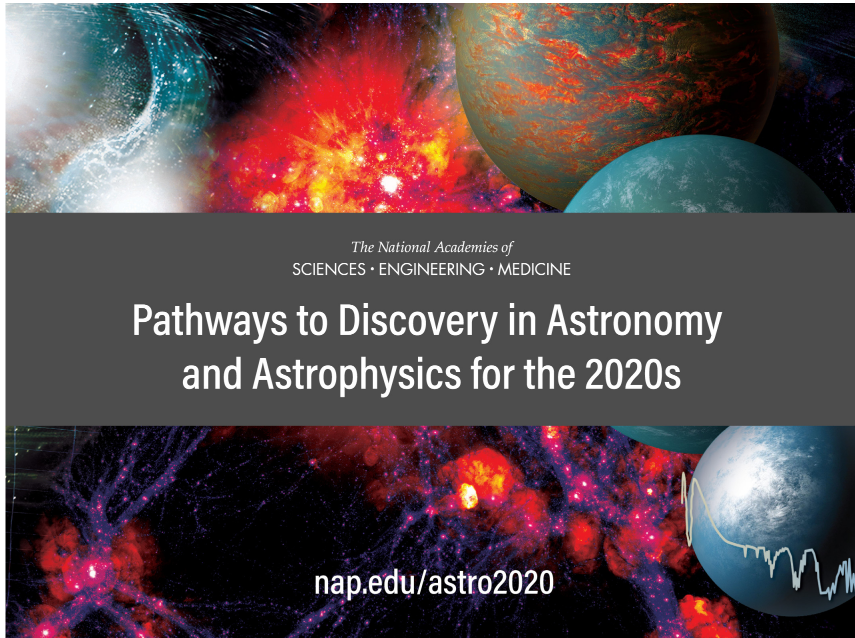
How to link science to architecture/trades and classify investigations as precursor, preparatory, follow-up, or other science



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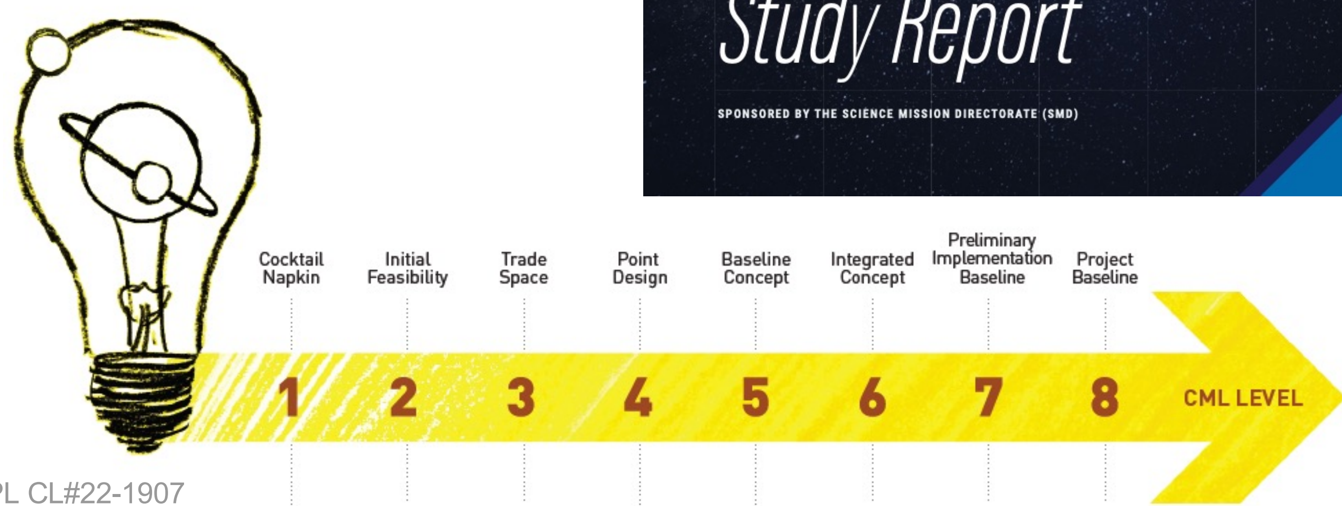
Large Mission Study Team
NASA Science Mission Directorate



Jet Propulsion Laboratory
California Institute of Technology

JPL CL#22-1907

Precursor Science

Science investigations that will inform mission architectures and trades with the goal of reducing mission design and development cost, scope, and risk where possible.

Enabling and Realizing Large Strategic Missions

Great Observatories Mission and Technology Maturation Program

Infrared/optical/UV mission

High resolution X-ray imaging mission

Far-IR imaging and spectroscopy mission

2022

Review

2032

Implement Infrared/optical/UV mission

Taken from 2020 Astrophysics Decadal Survey (Ref. [1])

Science Traceability: Going from Goals to Requirements

Goals	Questions	Objectives	Observables	Measurements
These come from NASA and the Decadal Survey, often verbatim and always at a high level	These come from science communities (i.e. ExEP Science Gap List) and help focus the science investigation	A concrete statement of what the science investigation will achieve and / or the hypotheses to be tested	The physical quantities and parameters that need to be observed (i.e. spectral lines, feature sizes, etc.)	What actually will be measured or detected, including any precision or accuracy requirements

- As we go from left to right, the details of ***and the rationale for*** the investigation are captured; we move from goals to requirements, causes to effects, and we provide focus
- Each progression requires models of the science (both expected conditions and behavior), experiment / measurement, and observatory / instrument performance
- We cannot skip any step – we must know the rationale as part of developing the requirements to effectively design the investigation and observatory

Science Traceability: Going from Goals to Requirements

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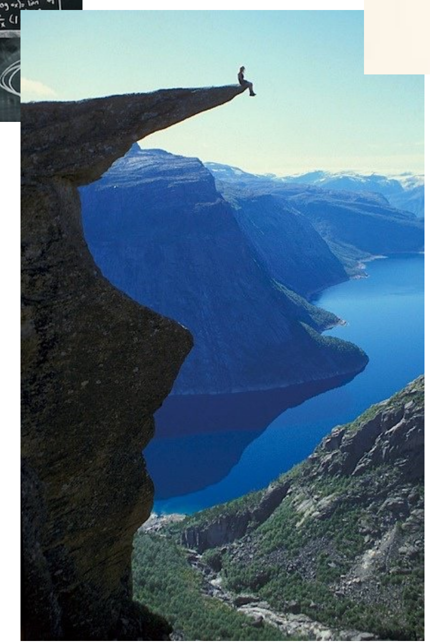
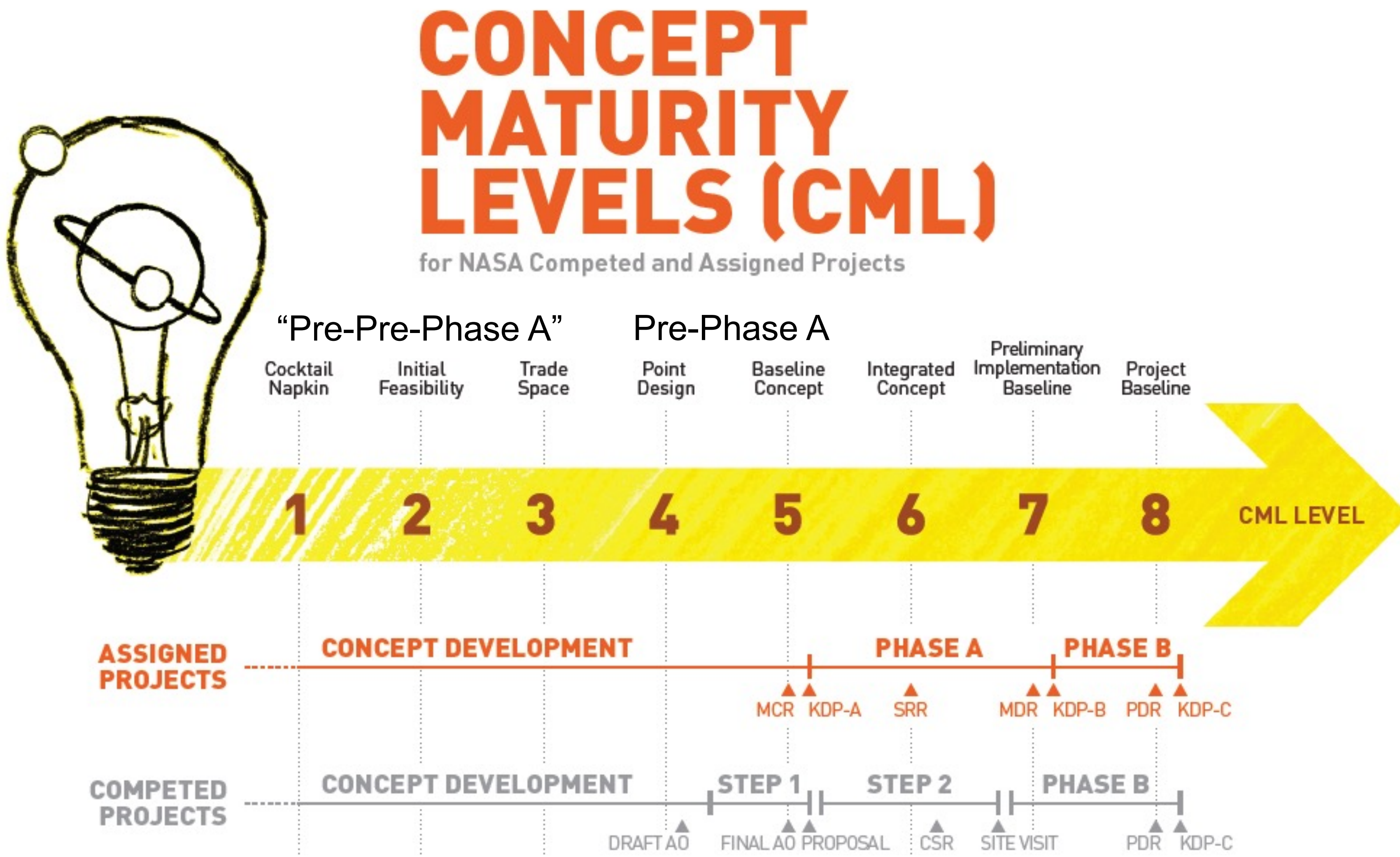
- The precursor science work will help move from left to right in this flow by providing not just the desired requirements and priorities, but the rationale for them and the “partials”
- It’s critical to have science participation in the iterative process of understanding the science drivers and then looking for a feasible, and eventually optimal, implementation
- In the end, the science objectives for the next Great Observatories will be developed with participation by the community, and there is a lot of great work to do!

Early Concept Challenges

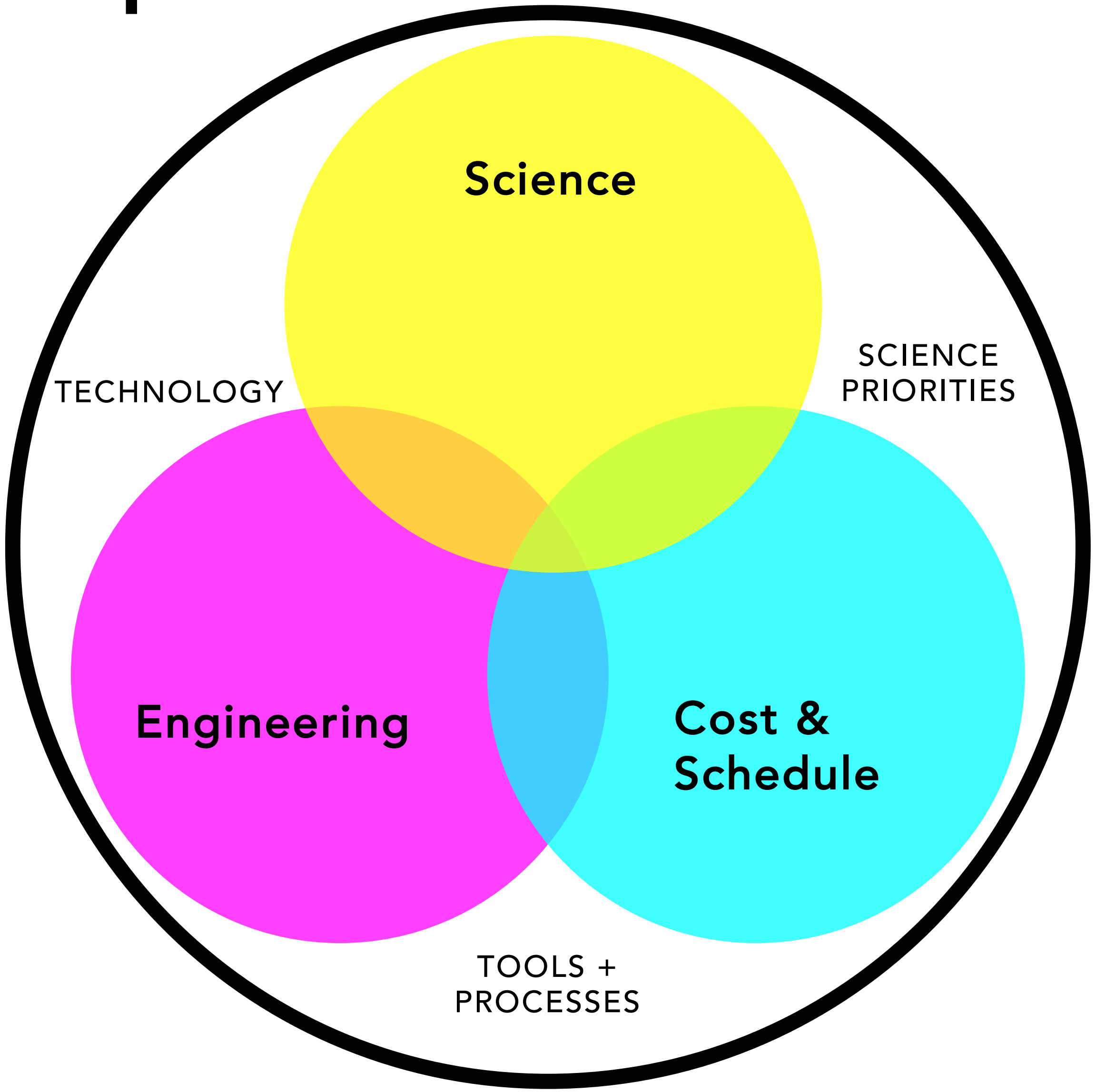




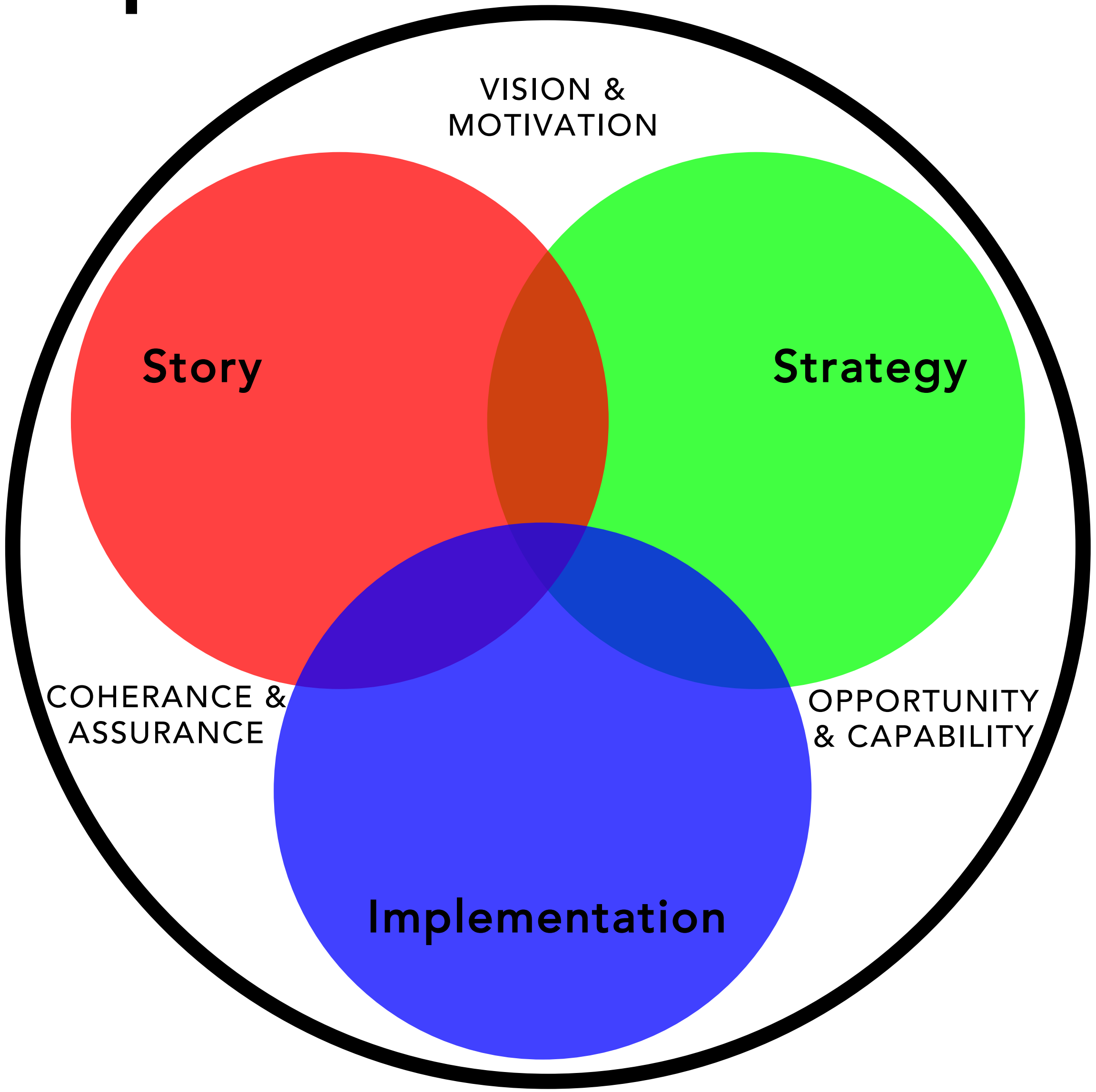
CL# 13-4156; See Refs. [2-5]

- The Concept Maturity Levels (CMLs) were developed to help guide concept teams through formulation progression, before Phase A to the Preliminary Design Review (PDR)
- NASA agrees to cost and scope at Key Decision Point (KDP)-C, right after PDR, but there are many steps along the way – even in pre-pre-Phase A!
- Pre-Phase A ends at KPD-A; A goal might be to reach CML 5 by the review recommended by Decadal Survey

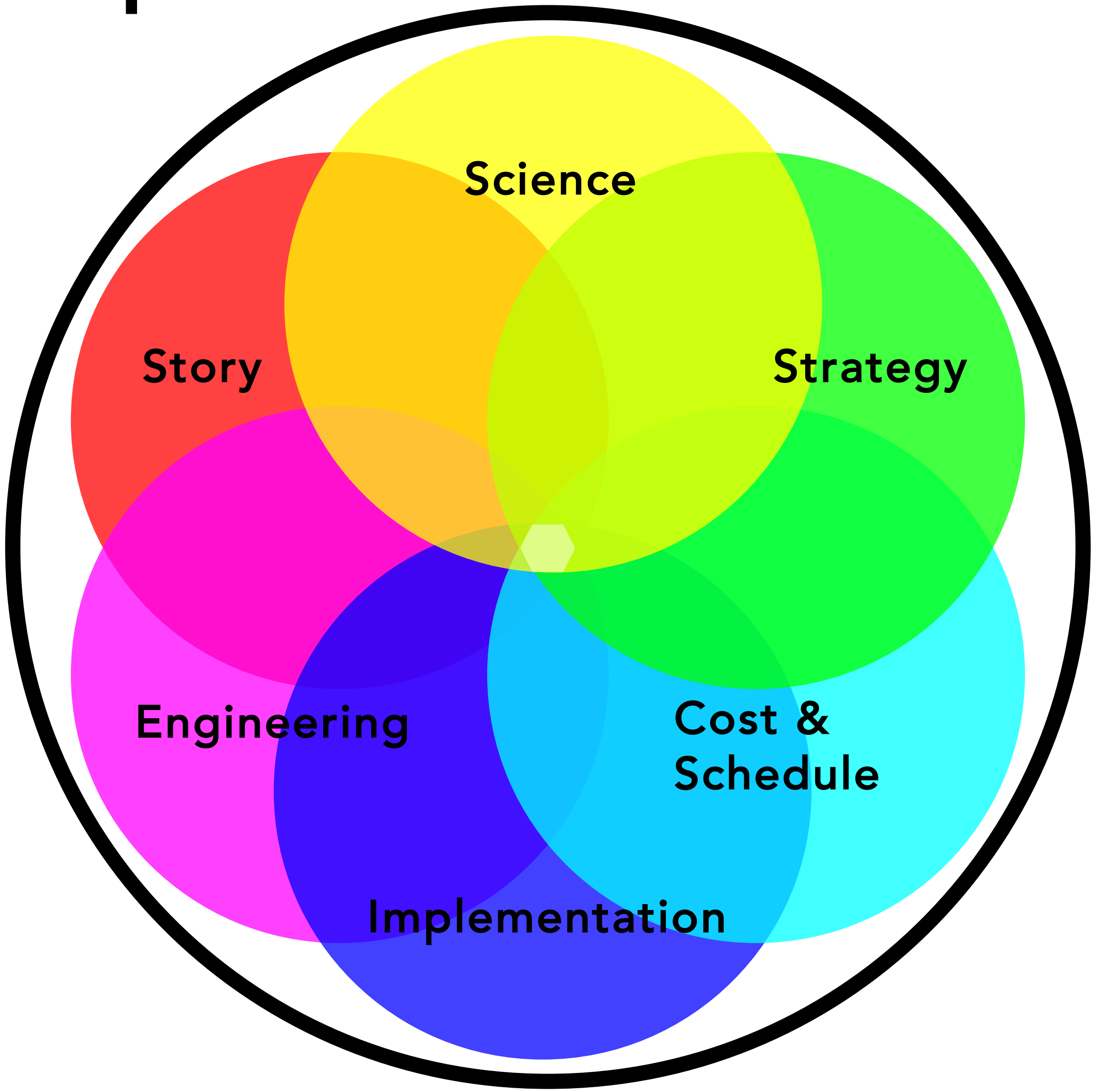
Concept Space



Concept Space



Concept Space



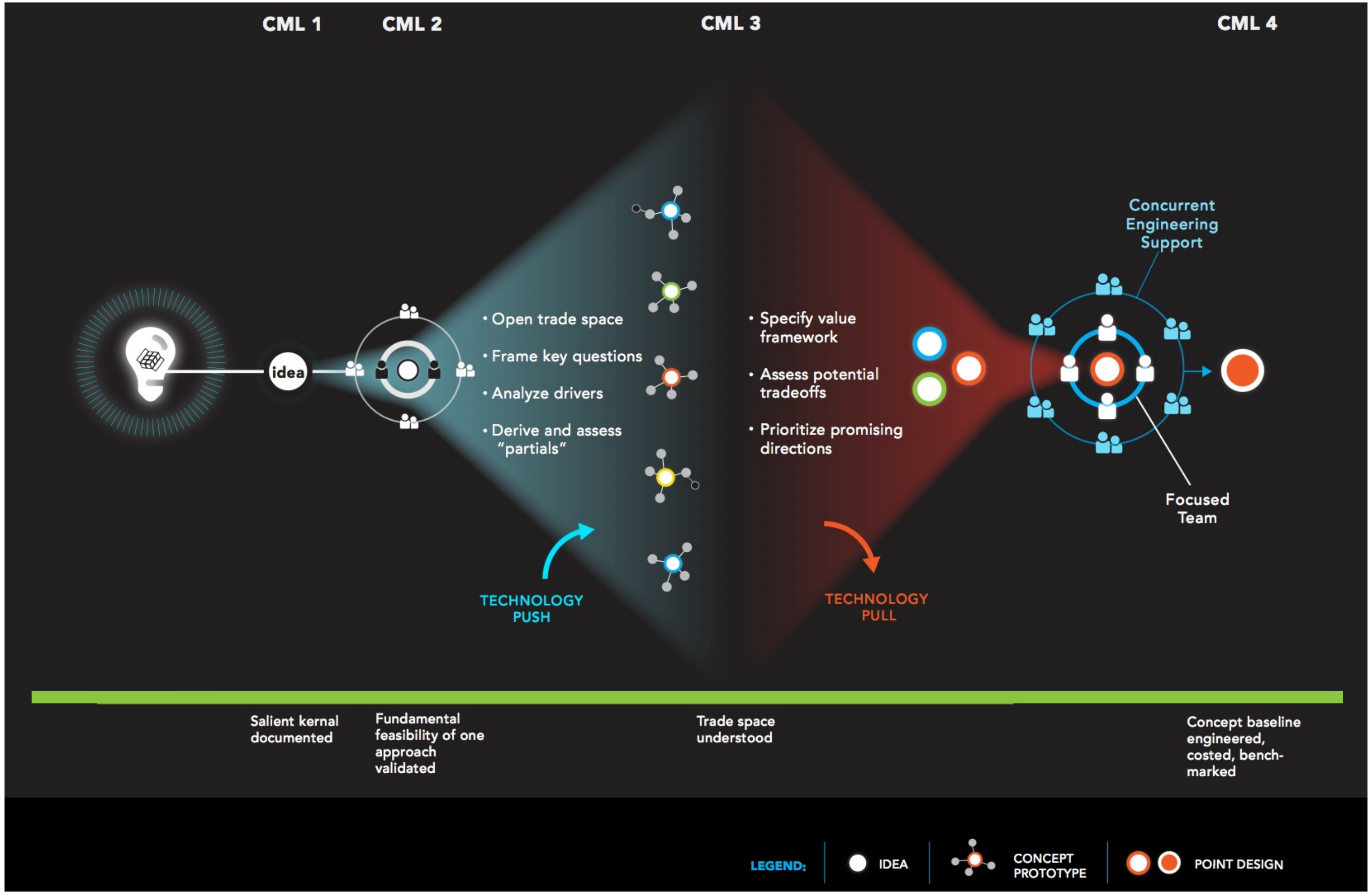
Research
Guide
Create
Question
Explore
Stretch
Narrate
Test
Discover
Evaluate
Reveal
Materialize

The Six Dimensions of Concept Maturity

Taken from Ref. 5

- Using CMLs helps concept teams understand the work that needs to be done in parallel during pre-Phase A
    - The Large Mission Study Report recommended using CMLs and SMD is studying how they can be incorporated into NASA's practices
- Each of the six dimensions of concept maturity has it's own set of expected status and evidence at each CML
- If any one dimension gets ahead or is not connected to the others, ideas and requirements can become "locked in" too early

Exploring the Trade Space Through CMLs



- Prior to Phase A (CML 1 - 4)
  - Requirement analyses and architecture trades will be conducted to quantify science in comparison to cost (clearly identifying mission requirements)
  - Descope options will be developed and documented during Pre-Phase A and evaluated at KDP-A to determine realism and feasibility of options
  - Program Office will ensure that independent assessments of architecture trades and descope options are conducted
- At KDP-A (CML 5)
  - Pre-Phase A architecture trades and descope options will be evaluated at KDP-A for assessment of mission concept maturity, technology maturity, risks, cost and schedule realism, and project maturity, to enable the making of early decisions and programmatic adjustments

How Are Trades Explored and Decisions Made?

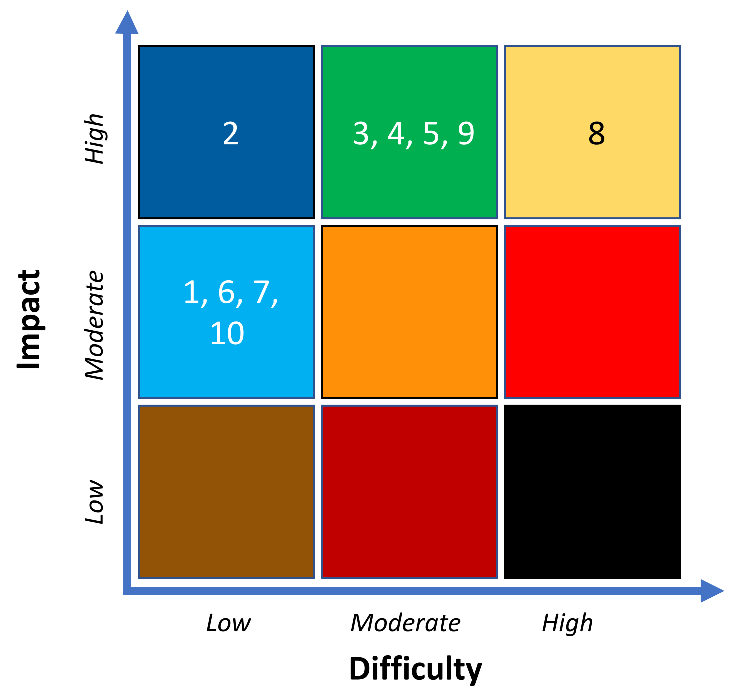
- Many, many different ways of reaching each CML (making decisions)
- My “Top 10” keys to success / best practices:
  - A well connected, diverse team of experts, across all 6 CML dimensions
  - Experienced leadership and inclusive mentorship with intentional feedback
  - A well defined, open process (i.e. criteria) that is communicated early-on
  - Stay focused on sharing, use the best tools for team access to latest data
  - Allow multiple cycles of prototyping ideas: create / test / learn / teach
  - Scrutinize ideas, not people – respectful questioning and active listening
  - Keep it at the right level: start high, dive deep, then come back up again
  - Set deadlines and don’t let any dimension of the concept get too far behind
  - Understand risks and uncertainties – be honest and quantitative
  - Document the outcome and rationale outward to build consensus

Some Notes on Early CMLs

- It includes both expanding and contracting, building off of what has been done before, but allowing for new advancements and ideas
  - We are definitely in the expansive phase, but not unconstrained
- We start with the science, but all parts of the concept need to mature together in parallel
  - Resist jumping to a point design or baseline too early – very challenging!
  - Understand the driving parameters and sensitivities in the design, which requires system models of the science, observatory, data processing, etc.
- It is an iterative process – get ideas out there early and test them
  - To enable discovery, we need to know our desires, capabilities and constraints
  - Using prototype ideas early helps us find the relations between science, engineering, and cost along with what models we need to evaluate options

Recommendations from the SMD Large Mission Study

Classification of Recommendations from the Large Missions Study



No.	Recommendation Title
1	*Pre-Phase A Team Composition*
2	*Pre-Phase A Architecture Trades and Descope Options*
3	*System Maturity Assessment*
4	*Technology Integration into Complex Systems*
5	*Analytical Tools*
6	*Cost and Schedule Estimation*
7	*Standing Review Boards (SRBs)*
8	*Instrument Selection Process*
9	*SMD Capabilities*
10	*Center Capabilities*

Taken from SMD "Large Mission Study Report" presentation, see Ref. [6] and link.

5

SMD Recommendation Disposition

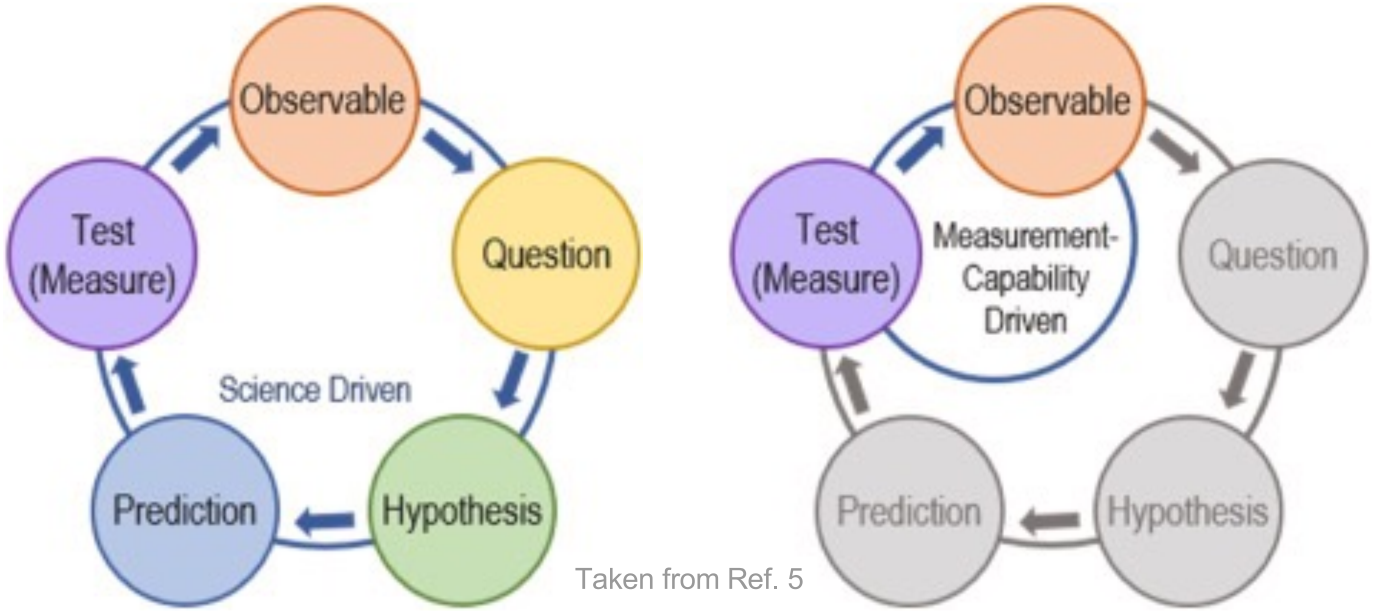
Bottom Line Up Front – SMD Large Missions Study Implementation Plan

No.	Large Missions Study Recommendation	Disposition	Large Missions Study Implementation Plan
1	*Pre-Phase A Team Composition*	Accept	Staffing will be based on needed skill sets and expertise (not based on availability of personnel). An Agency-wide search shall be conducted, followed by a nationwide search, if needed
2	*Pre-Phase A Architecture Trades and Descope Options*	Accept	Program Office will conduct independent assessment of Pre-Phase A architecture trades and descope options for evaluation at KDP-A. Implementation effective immediately.
3	*System Maturity Assessment*	Accept w/Follow-Up	Further action is required. A team, sponsored by the SMD DAA/P and led by the SMD Chief Engineer, will be formed for further investigation.
4	*Technology Integration into Complex Systems*	Partially Accept	Mandate increased scrutiny of technology maturity at reviews and KDPs. Implementation effective immediately. Further action is required - A strategic approach will be developed by the SMD Chief Technologist to identify technology needs and funding sources for technology development.
5	*Analytical Tools*	Partially Accept	Large strategic missions will incorporate common tool sets, when possible, and establish an agreed margin and risk philosophy with partners and providers early in the life cycle.
6	*Cost and Schedule Estimation*	Accept	Life cycle cost estimates shall be communicated in terms of bins for Pre-Phase A and ranges for Phases A and B to set external expectations. Implementation effective immediately.
7	*Standing Review Boards (SRBs)*	Accept	The SMD policy of convening the SRBs prior to MCR, and when required, convening of the Independent Review Boards (IRBs), has already been implemented. Initiating SRB kickoff meetings.
8	*Instrument Selection Process*	Partially Accept w/Follow-Up	Further action is required. A team led by the SMD Deputy AA for Research will be established. Modification of SMD policy may be required.
9	*SMD Capabilities*	Accept	Program Offices of large missions will be adequately staffed early in pre-formulation in order to perform programmatic assessments and oversight. Implementation effective immediately.
10	*Center Capabilities*	Accept	SMD and Centers have ownership and accountability of large strategic missions and will work closely to identify and solve problems. Implementation effective immediately.

The SMD Large Missions Implementation Plan will require an intentional shift in how we approach the development of our missions

6

Science in Early CMLs



Taken from Ref. 5

Developing early CML science cases is an iterative process, balancing our ambitions to discover and explore the universe within the reality of limited capabilities and resources

- For the best exploration of the trade space, science driven investigations address a specific question with testable hypotheses / predictions
  - They provide the rationale and help us derive science-driven requirements
  - We may not be able to completely answer the question or address all the hypothesis due to other constraints, but we can get a sense of science return vs. capability (usually model based)
- Science investigations based purely on measurement capability can be open ended, but hard for the rest of the concept team to derive requirements
  - We need to be able to have "discovery space", but when are we good enough?
  - Pushes the capability to the limit of what's feasible (often hard to know!)

Precursor Science: Feasibility or “Must Haves”

Science investigations that will inform mission architectures and trades with the goal of reducing mission design and development cost, scope, and risk where possible.

- At CML 2, we look for feasibility: the thresholds in ALL six concept dimensions that make a mission architecture acceptable (or not)
- For science, we must improve and expand our knowledge and understanding – but how far do we stretch ourselves?
- Use both hypothesis tests to determine *minimum* requirements and how far we need to improve on existing capability in our *discovery space*
- Often times, science feasibility can be shown as an “undiscovered country” plot, providing the requirement and rationale in one graphic

Examples of “Undiscovered Country” Plots for CML 2

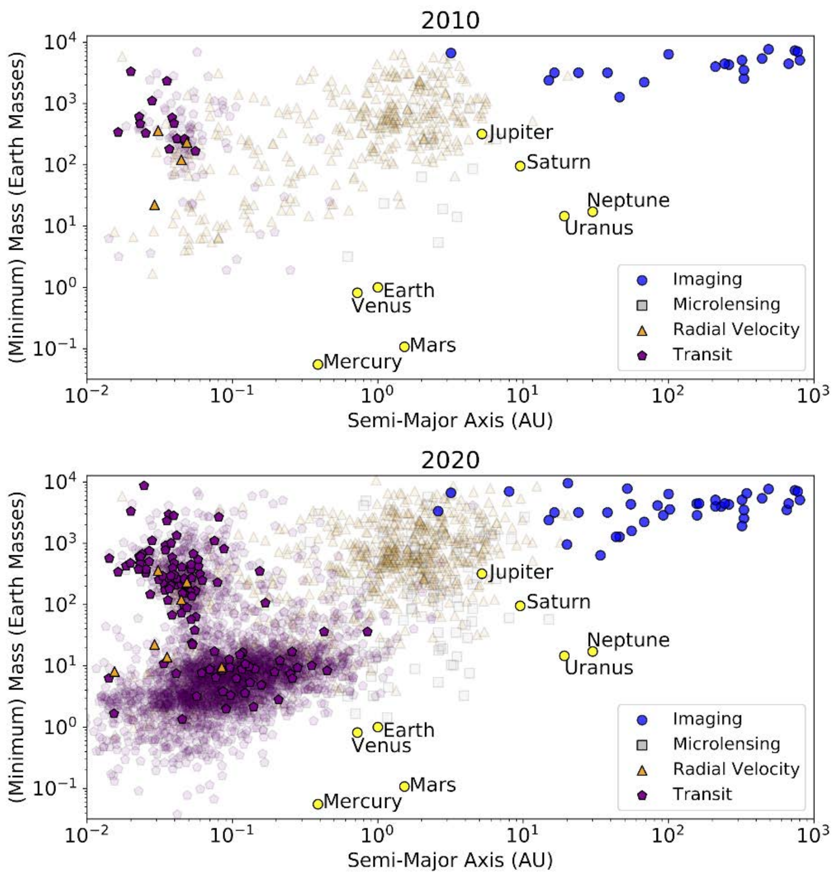


FIGURE 2.5 The population of known exoplanets in 2010 (*top*) and 2020 (*bottom*). Each symbol represents a known extrasolar planet, colored by initial discovery method. Hollow symbols are planets that have been discovered. Filled symbols are planets whose atmospheric composition have been *characterized* by measurements of its spectrum or brightness. Over the past decade astronomers have begun to move from the era of planetary census-taking to detailed characterization, and the next decades will both complete the missing parts of the census—planets like our own solar system—and see an explosion in characterization. SOURCE: D. Savransky and B. Macintosh, with data from the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program.

Taken from 2020 Decadal Survey Report, see Ref. [1]

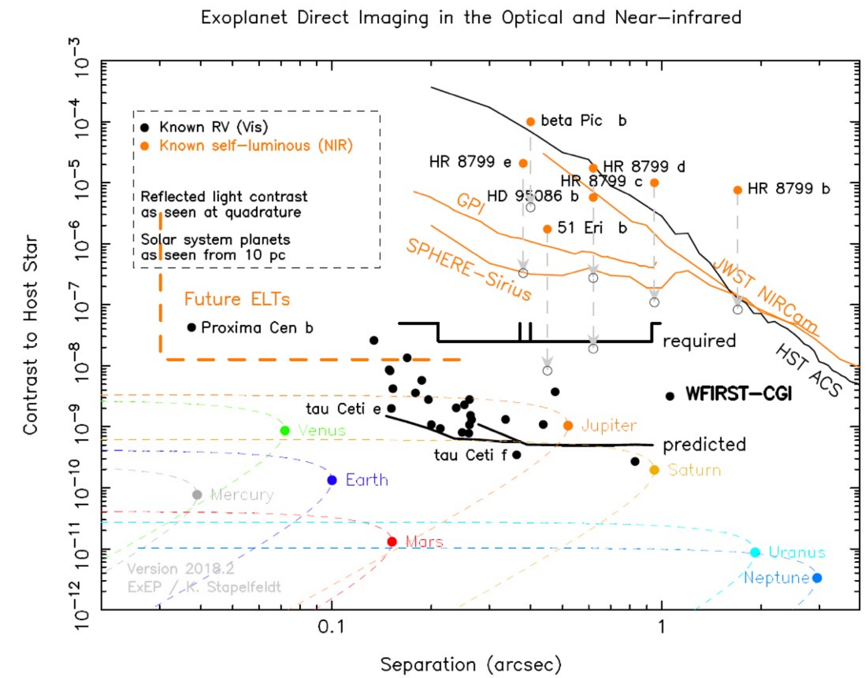


Figure 3: Contrast (ratio of planet brightness to host star brightness) versus apparent angular separation. The filled orange circles indicate the direct imaging of young, self-luminous planets imaged in the near-infrared by ground-based telescopes. Contrasts for the planets of the Solar System are for analogous planets placed 10 pc away. The solid black dots are contrast estimates of measured radial velocity planets, including Proxima Cen b. The orange curves show measured performance of ground-based coronagraphs. The GPI curve shows typical performance, while the SPHERE curve shows the best achieved performance to-date on Sirius. Achieved performance with HST/ACS coronagraphic masks, and the predicted performance of JWST/NIRCam masks are also shown. The predicted and required performance at 565 nm for the WFIRST coronagraph instrument (CGI) is shown as solid black curves. The “predicted” curves extending from 0.13” to 0.4” is based on performance achieved in a testbed. From 0.4” to 1”, performance is based on a coronagraph mask designed to maximize outer working angle. For consistency, the planets discovered in the near-infrared are shown with vertical arrows pointing to the predicted contrast ratios at visible wavelengths (WFIRST-CGI is expected to conduct science between 442 and 980 nm).

(Image Credit: NASA/JPL/Caltech)

Examples of "Undiscovered Country" Plots for CML 2

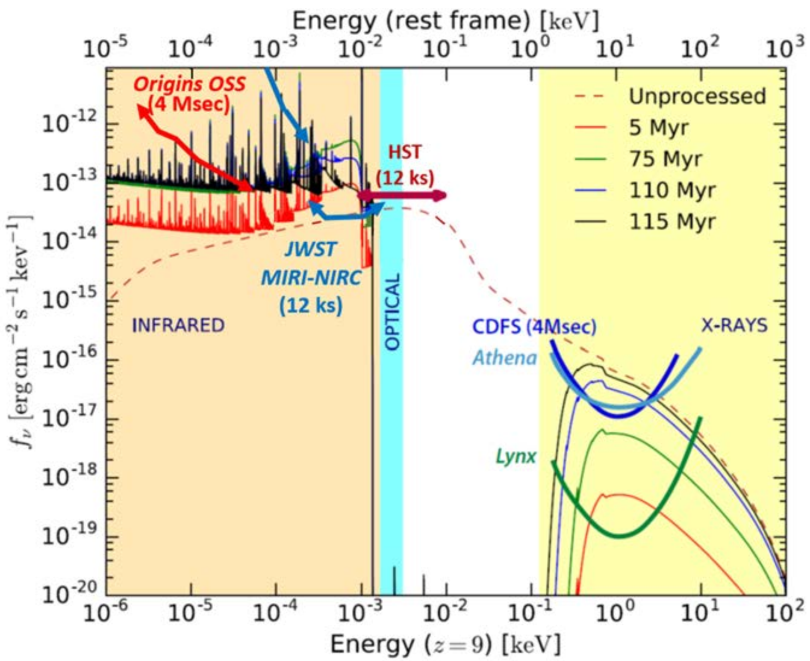
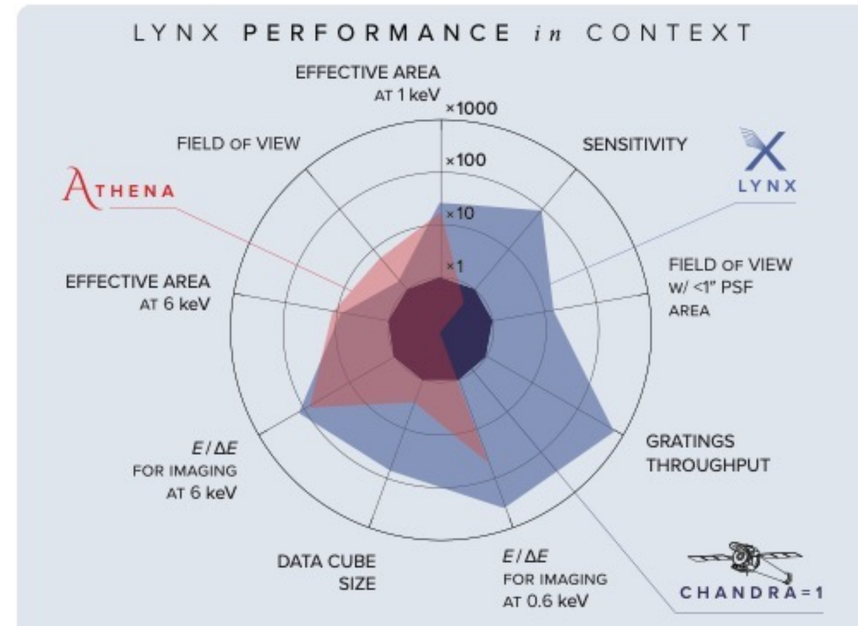


FIGURE J.4 FIR to X-ray spectral energy distribution for a black hole seed at z = 9. The Origins sensitivity curve is the thick red line with arrows on the upper left, the Lynx sensitivity curve is the thick green line on the lower right. Lynx detects all stages of black hole growth from 5 Myrs (thin, solid red line) after accretion begins, while Origins detects the later stages (> 75 Myr, thin green line). The Origins OSS sensitivity plotted is binned to a resolving power (RP) of 3. The [OIV] 25.9 um line is detectable by Origins at the native resolving power of 300 and is an important diagnostic of black hole mass and accretion rates. SOURCE: Adapted from F. Pacucci et al., 2019, Detecting the birth of supermassive black holes formed from heavy seeds, *Bulletin of the AAS*, 51(3). Retrieved from https://baas.aas.org/pub/2020n3i117. Reproduced with permission.

Taken from 2020 Decadal Survey Report, see Ref. [1]



The requirements established by the *Lynx* science pillars translate into the need for orders-of-magnitude performance gains along a number of key axes. The diagram above shows how these gains compare with the performance of *Chandra* (taken to be 1 on all axes) and *Athena* (shown in red). *Athena*, ESA's planned mission, will carry the first large X-ray microcalorimeter and make strides in energy resolution, effective area (especially at high energies), and field of view. It will not, however, make breakthrough gains across the board: not in sensitivity; not in sharp imaging; not in very high spectral resolution. *Lynx* makes primary breakthroughs along these axes, which are precisely the directions required by its science goals. *Lynx* and *Athena* can be viewed as orthogonal missions with different science goals and based on different strengths. *Athena*'s science centers on massive, wide surveys and detailed spectroscopy of relatively bright and isolated objects. With a combination of its high angular resolution, high throughput, and powerful spectroscopic capabilities, *Lynx* opens up the discovery space in the high redshift universe, crowded fields, feedback on galactic scales, and circumgalactic environments.

Taken from Lynx Concept Study Report, see Ref. [7]

Examples of “Undiscovered Country” Plots for CML 2

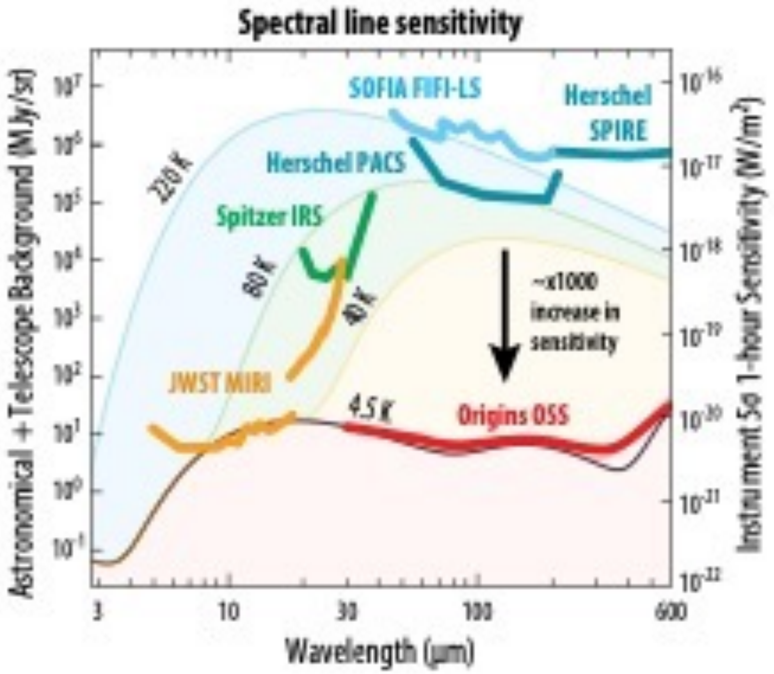


Figure ES-9: *Origins* taps into a vast, unexplored scientific discovery space, defined by a three-orders-of-magnitude improvement in sensitivity relative to all previously-flown far-infrared observatories. With a temperature of 4.5 K, *Origins'* sensitivity is limited by astronomical background photon noise (lower black curve). SOFIA (220 K), *Herschel* (80 K), and JWST (40 K) are shown in comparison with Origins (4.5 K). *Origins'* sensitivity bridges the gap between JWST/MIRI in orbit and ALMA on the ground.

Taken from Origins Concept Study Report, see Ref. [7]

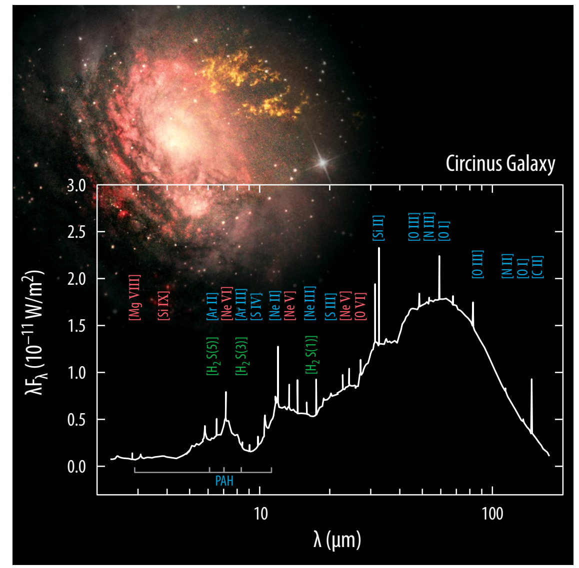


Figure 1-1: (Above) *Origins* measures the redshifts, star formation rates, black hole accretion rates, and metal and dust content in galaxies. The infrared spectrum of the nearby active galaxy, Circinus (see inset), is shown using Infrared Space Observatory data (Moorwood, 1999). Emission lines from highly ionized gas heated by the central active nucleus are marked in red, those coming from gas heated by young stars are marked in blue, and those from warm molecular gas are marked in green. PAH molecules are excited by UV photons, and emit broad features in the mid-infrared, through bending and stretching modes.

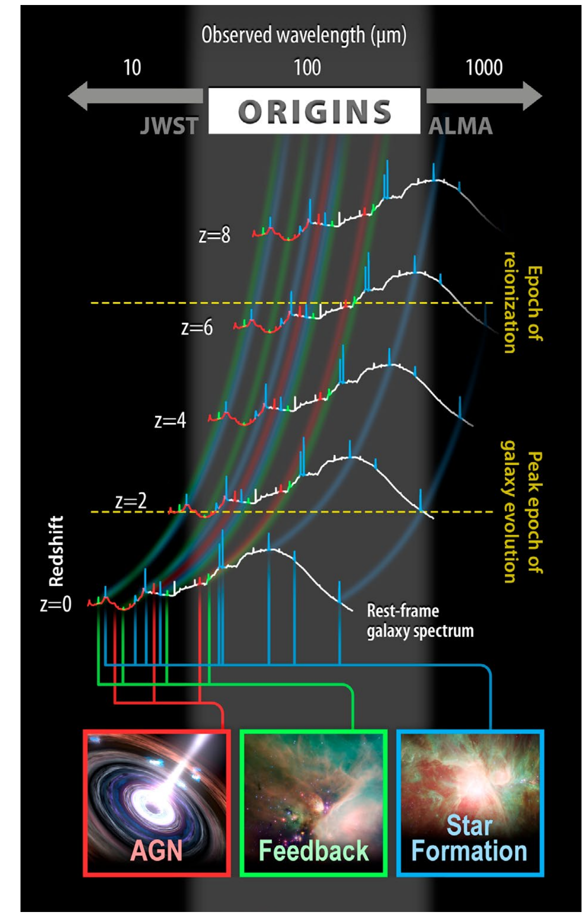


Figure 1-2: (Right column) The spectral reach of *Origins* over cosmic time. Schematic representation of how the key spectral diagnostic features of AGN (red), star formation (blue), and energetic feedback (green) move through the wide bandpass of the *Origins* Survey Spectrometer (OSS) with look-back time. *Origins* can measure all of these important processes over the entire history of galaxy evolution, filling in a key gap in wavelength and discovery space between JWST and ALMA. Taken from Origins Concept Study Report, see Ref. [7]

Precursor Science: Science Return Gradient or "Wants"

Science investigations that will inform mission architectures and trades with the goal of reducing mission design and development cost, scope, and risk where possible.

- At CML 3, we look for the *partials* or gradient of the quality of the science returned by the mission vs. some measurement parameter (i.e. bandwidth, resolution, etc.); *attempting to quantify this return is key*
- For science, we would always like to have better and more capability – but how does the science return really depend on the measurements?
- We can build off the "must haves" as a threshold or minimum science return, and then quantify the advantage of having even more capability
- This is often model based, but we need to quantify input and output uncertainties along with parameter sensitivities to be most useful

The Science Return Diagram

- Often challenging for science teams to determine exact requirements, but easier to come to more of a consensus on how the science improves vs. “X” parameter
- One tool that can help is to “diagram” one science question and evaluate the quality of return into four distinct levels
- For each candidate science question, determine the observables and then look for key measurement parameters that have the biggest impact on science return
  - Look for thresholds and cliffs – the partials
  - Provide rationale for each level

Science Return Diagram		
NASA Goal:		
Science Question:		
Science Objective: (hypothesis or discovery)		
Hypothesis Tests, Predictions, or Models		
Description	**Observables**	**Critical Scales**
If this, then that…or, To discover "X", we need this…	Key features and physical parameters	Spatial, temporal, spectral, etc.
Experiment Characteristics (quantitative narratives)		
Science Return	**Observables**	**Requirements**
State-of-the-Art (SOA): what is already known or observed? (Include projections for any mission past PDR); What are the key parameters for the mission?		
Enhancing: Take one observable / measurement (i.e. bandwidth, resolution, etc.) from the SOA and improve it - how much to make a new impact (answer some part of the science question)?		
Enabling: Beyond enhancing, allowing most, but not all, of the science question to be addressed with significant progress in advancing the field. (note: can have multiple options)		
Breakthrough: Addresses entire science question and / or distinguishes between all relevant hypothesis; recognized community wide as a significant advancement in the field.		

Science Return Diagram Example – Psyche Mission

Baseline Science
Threshold Science
Cost Cap

Small Body Example: Asteroid Structure

Science Return Level	Mission	Spatial Scale	Temporal Scale
State of the Art	Dawn	35 m/pixel	5.5 hours (LAMO)
Enhancing	Dawn s/c at new class of asteroid	35 m/pixel	5.5 hours (LAMO)
Enabling	Add a magnetometer & laser altimeter	35 m/pixel	5.5 hours (LAMO)
Breakthrough	Land on surface and return a sample	450 microns/pixel	Continuous

Taken from Ref. 5; LAMO = Low-altitude mapping orbit

- Example from early-on in the Psyche Mission formulation
- Note that the "water lines" were drawn later, after the engineering teams assessed the challenges associated with each level, while the science team converged on the baseline and threshold science requirements
- The science return levels can be distinguished by precision, accuracy, range, resolution, coverage, # of targets, etc. but each needs to have a description of what different science will be returned

Examples of Science Return Plots for CML 3

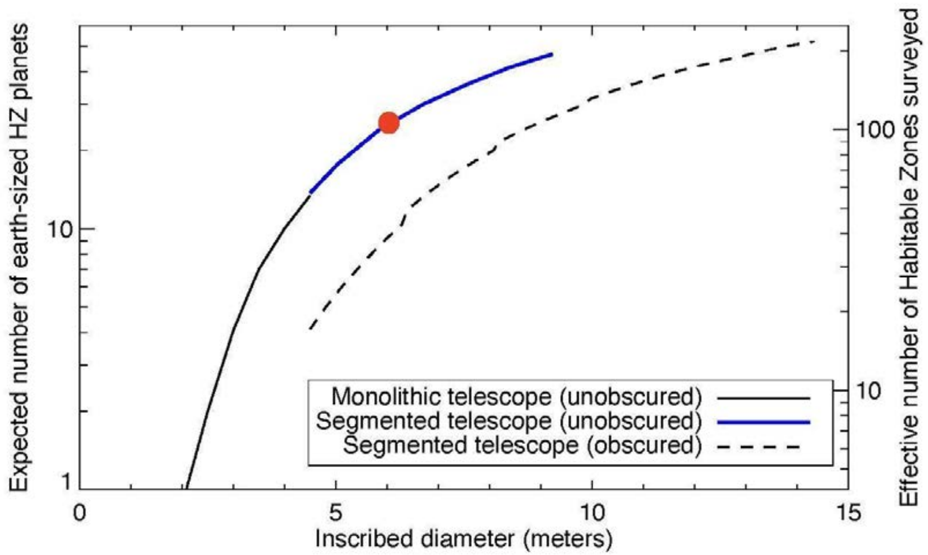


FIGURE 7.6 Potentially habitable exoplanet yield vs telescope diameter for different telescope architectures. Right axis shows the number of habitable zones surveyed (weighted by completeness); left axis shows the expected number of planets discovered assuming the occurrence rate of rocky planets in the optimistic habitable zones of different stars, eta_earth=0.24 (Bryson et al. 2021). The red dot shows the expected yield for the target 6-m inscribed diameter. NOTE: Habitable zone is defined as 0.95-1.67 AU for planets of 0.8-1.4 Earth radii. SOURCE: Adapted from C. Stark (Space Telescope Science Institute), D. Mawet (California Institute of Technology), and B. Macintosh (Stanford University).

Taken from 2020 Decadal Survey Report, see Ref. [1]

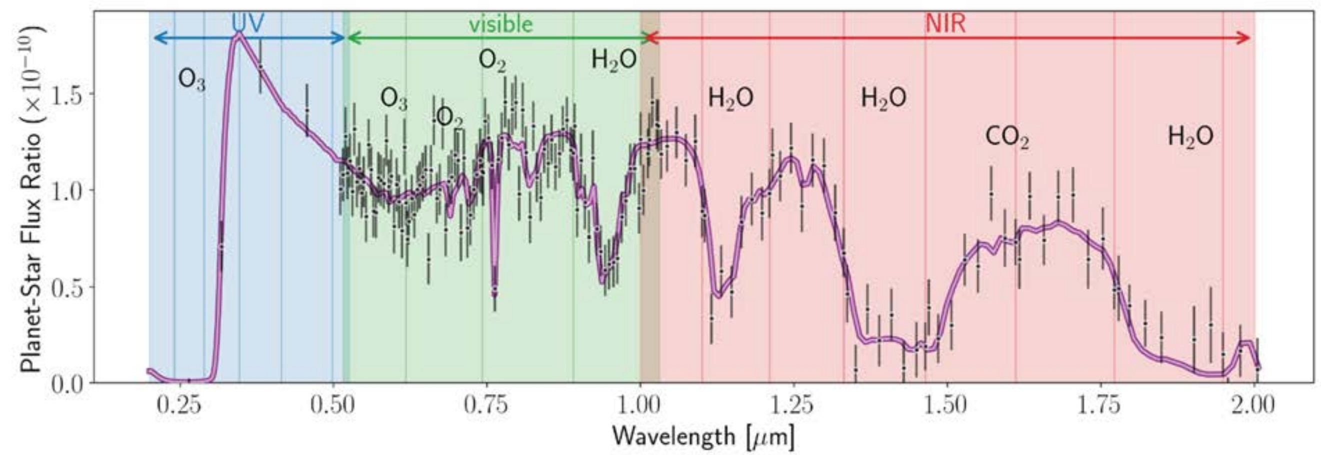
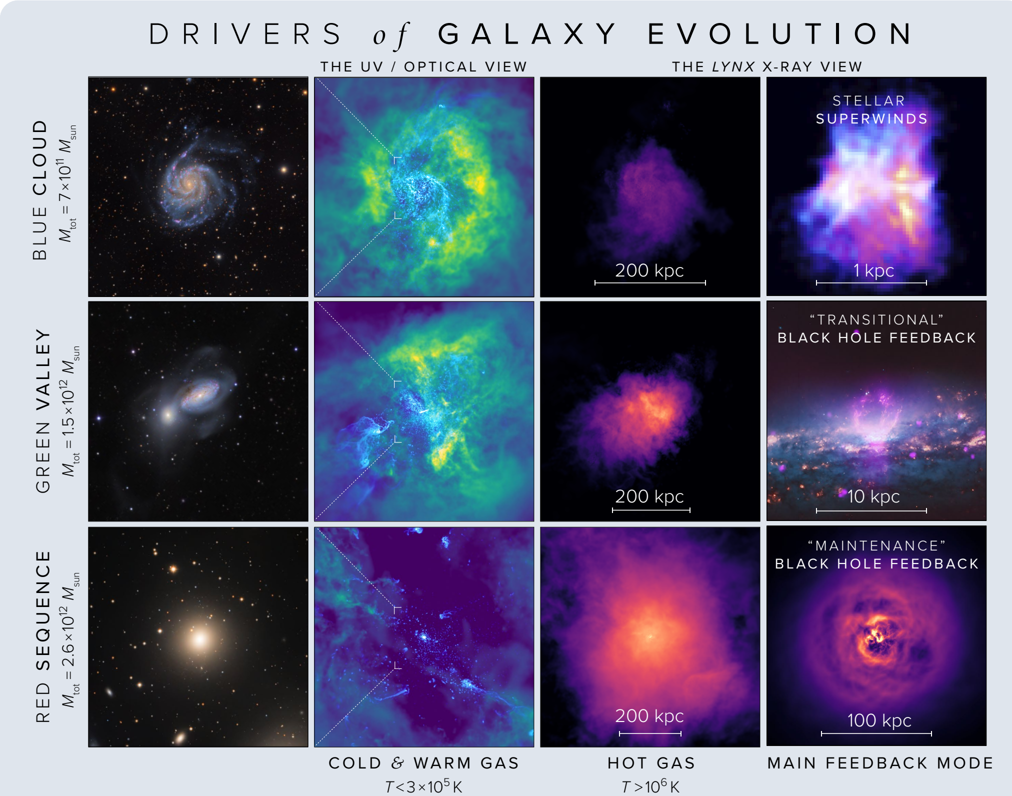


FIGURE I.1 Simulated UV-NIR exoearth spectrum that highlights absorption from several key molecules for biosignature detection such as ozone, molecular oxygen, water, and carbon dioxide. SOURCE: LUVOIR and HabEx final reports. Courtesy of J. Lustig-Yaeger (University of Washington).

Taken from 2020 Decadal Survey Report, see Ref. [1]

Examples of Science Return Plots for CML 3



KEY CAPABILITIES

- Map CGM in emission to $0.5r_{200}$: PSF < 1″, $A_{eff} = 2\,m^2$.
- Probe CGM in absorption at ~ r_{200}: gratings with $A_{eff} = 4{,}000\,cm^2$ and $\lambda/\Delta\lambda > 5{,}000$.
- Map velocities in ~ 100 km s^{-1} galactic outflows: microcalorimeter with $E/\Delta E = 2{,}000$ at $E = 0.6$ keV.
- Study AGN feedback in galaxies and clusters: microcalorimeter with 0.5″ pixels.

Taken from Lynx Concept Study Report, see Ref. [7]

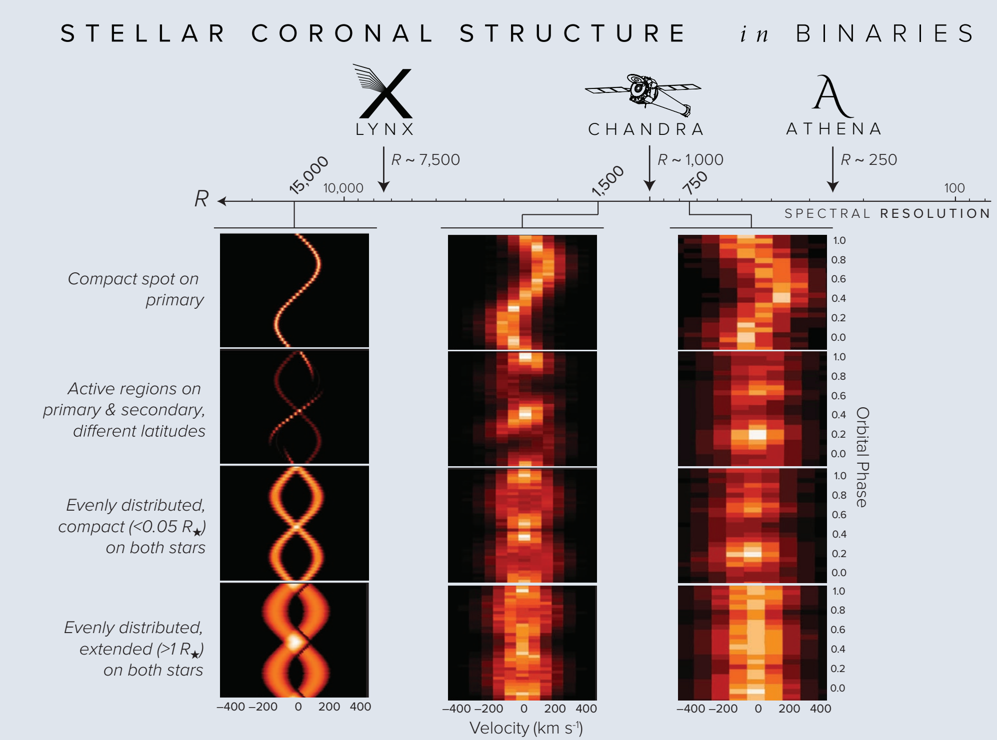


Fig. 3.3— The impact of X-ray spectral resolution on the ability to deduce coronal structures and the contribution from each member of a binary. Discriminants between various scenarios, such as those described in the leftmost column of text, are found only when the X-ray spectral resolution is sufficiently high. The panels, adapted from Fig. 10 of Hussain et al. [273], illustrate this effect for the case of the nearby binary YY Cen. The panels are arranged on a logarithmic axis of spectral resolution $(R = \lambda/\Delta\lambda)$ that increases toward the left. Only the exquisite spectral resolution delivered by the *Lynx* X-ray Grating Spectrometer, with a goal of $R \sim 7{,}500$, will enable us to clearly distinguish between these scenarios. *Chandra* and *Athena* are entirely unable to do so.

Taken from Lynx Concept Study Report, see Ref. [7]

Examples of Science Return Plots for CML 3

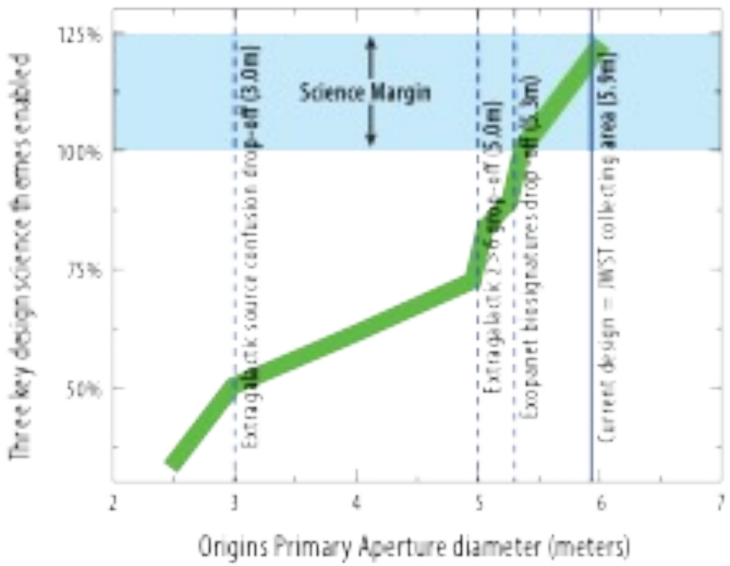


Figure ES-7: *Origins'* key science program requires a cold telescope with a primary aperture diameter of 5.3 m. This requirement comes primarily from the exoplanet science case to detect biosignatures in a 5-year mission, given that transit durations are fixed and sensitivity cannot be recovered with a longer single-epoch integration, unlike most other proposed *Origins* observations. The extragalactic study places an aperture size requirement of >5 m, based on the need to detect a statistically significant sample of galaxies at $z > 6$, to study the formation mechanisms and physical properties of dust and metals during reionization. The minimum primary aperture diameter is 3 m to enable an effective extragalactic and Galactic science program, where source confusion does not compromise the telescope's ability to conduct spectroscopic studies of galaxies at z = 2-3 and the sensitivity is not too poor to study water and gas in proto-planetary disks at the distance of Orion.

Taken from Origins Concept Study Report, see Ref. [7]

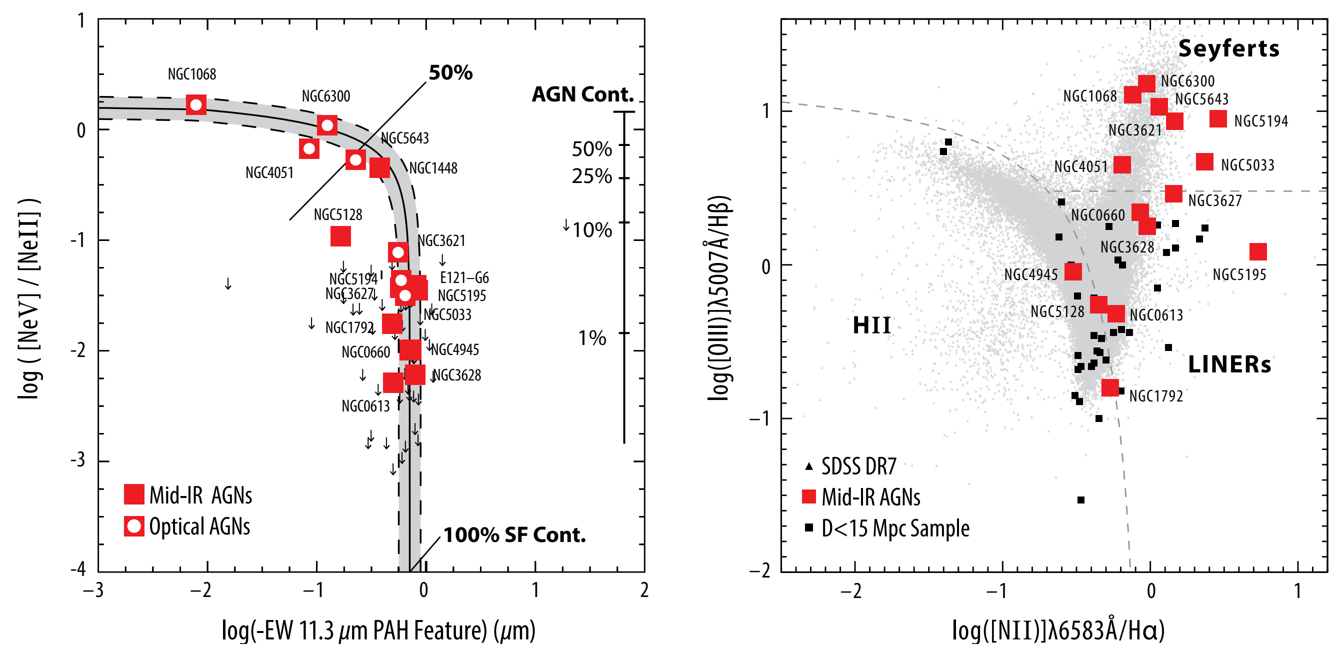


Figure 1-5: Diagnostic power of IR fine-structure lines for identifying and quantifying AGN. Traditional optical diagnostic line ratios can fail to detect highly obscured AGN. Here, buried AGN (red squares) are identified in a sample of nearby (D < 15 Mpc) galaxies via their mid-IR diagnostic lines with *Spitzer* IR spectroscopy (left) when optical diagnostics (right) suggest star forming or composite sources. The [NeV]/[NeII] and [OIV]/[NeII] (not shown) MIR line ratios are excellent measures of the AGN contribution, and the high ionization line luminosities can be used to estimate the black hole accretion rates. Figures adapted from Goulding & Alexander (2009).

Taken from Origins Concept Study Report, see Ref. [7]

One Trade Space Exploration / Decision Making Method for Complex, High-Value Problems: Kepner-Tregoe Matrix

- This is a process that has been used by NASA Astrophysics Division to look at high-level trades and make decisions
- Start with a decision statement, then determine the criteria and describe the options, then perform the evaluation (can be technical in nature), and finally identify risks and opportunities for each option
- You have the opportunity to contribute to the science ***Musts, Wants, and Risks*** through the precursor science call!

Decision Statement									
Description				*Option 1*		*Option 2*		*Option 3*	
	Feature 1								
	Feature 2								
	Feature 3								
Evaluation	**Musts**								
	M1			✓		✓		✓	
	M2			✓		?		?	
	M3			✓		✓		✗	
	Wants	*Weights*							
	W1	*w1%*		*Rel score*		*Rel score*			
	W2	*w2%*		*Rel score*		*Rel score*			
	W3	*w3%*		*Rel score*		*Rel score*			
		100%	Wt sum =>	*Score 1*		*Score 2*			
	Risks			C	L	C	L	C	L
	Risk 1			M	L	M	L		
	Risk 2			H	H	M	M		
Final Decision, Accounting for Risks									

C = Consequence, L = Likelihood

The Kepner-Tregoe Methods and associated decision matrix were developed by the Rand Corporation in the 1950's; see "The Rational Manager" by Kepner and Tregoe in 1965; See Ref [8].

For more details, see recent **"Choosing the Future: The Kepner-Tregoe Matrix for Complex Trades"** presentation and recording by Gary Blackwood (See Ref. [9]) at https://exoplanets.nasa.gov/exep/technology/tech_colloquium/

Precursor vs. Preparatory or Follow-up Science

To Summarize:

- **Precursor Science** informs the mission architecture and trades, which we need to start soon, so it's part of the next stage of the Great Observatory Maturation Program's "Analysis of Alternatives"
  - We need your help with this work now, looking for natural gaps, thresholds, and gradients in the science return vs. measurement parameters
- **Preparatory Science** informs data / interpretation or early operations; potentially from new observations, but needed just before or even after launch to help inform the best way to conduct investigation
- **Follow-up Science** provides additional data and investigations that follow up on discoveries or other science from the mission; occurs after launch or potentially with coordination / planning prior to launch

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Acronyms

- AO Announcement of Opportunity
- APD Astrophysics Division
- CML Concept Maturity Level
- CSR Concept Study Report
- KDP Key Decision Point
- MCR Mission Concept Review
- MDR Mission Definition Review
- PDR Preliminary Design Review
- SMD Science Mission Directorate
- SRR System Requirements Review

References

1. National Academies of Sciences, Engineering, and Medicine 2021. ***Pathways to Discovery in Astronomy and Astrophysics for the 2020s***. Washington, DC: The National Academies Press. https://doi.org/10.17226/26141.
2. R. Wessen, C.S. Borden, J.K. Ziemer, R.C. Moeller, J. Ervin, J. Lang, ***Space mission concept development using concept maturity levels***, in: AIAA Space 2013 Conference and Exposition, 2013, p. 5454. https://doi.org/10.2514/6.2013-5454.
3. K. Case, A. Nash, R. Wessen, J. Ziemer, ***The six dimensions of mission concept formulation***, in: SECESA 2016, 2016. Madrid, Spain, October 5-7, 2016.
4. J.K. Ziemer, R.R. Wessen, P.V. Johnson, ***Exploring the Science Trade Space with the JPL Innovation Foundry A-Team***, Journal of Concurrent Engineering, 26(1) 2018: 22-32. https://doi.org/10.1177/1063293X17740406.
5. Wessen, R. R., Propster, P., Cable, M., Case, K., Guethe, C., Matousek, S., Nash, A., Ziemer, J. (2022). ***Developing compelling and science-focused mission concepts for NASA competed mission proposals***. Acta Astronautica, 191, 502-509. https://doi.org/10.1016/j.actaastro.2021.12.002.
6. NASA SMD***, Large Mission Study Report***, https://science.nasa.gov/science-red/s3fs-public/atoms/files/SMD_LMS_eBook_report2.pdf, October 2020.
7. NASA APD, 2020 Decadal Survey Planning, Large Mission Concept Studies Final Reports, https://science.nasa.gov/astrophysics/2020-decadal-survey-planning.
8. Kepner, C.H. and Tregoe, B.B., ***The Rational Manager***, 1965.
9. Blackwood, G., ***Choosing the Future: The Kepner-Tregoe Matrix for Complex Trades,*** presentation and recording available at https://exoplanets.nasa.gov/exep/technology/tech_colloquium/, Feb. 28, 2022.

Backup Charts

NASA Flight Project Life Cycle

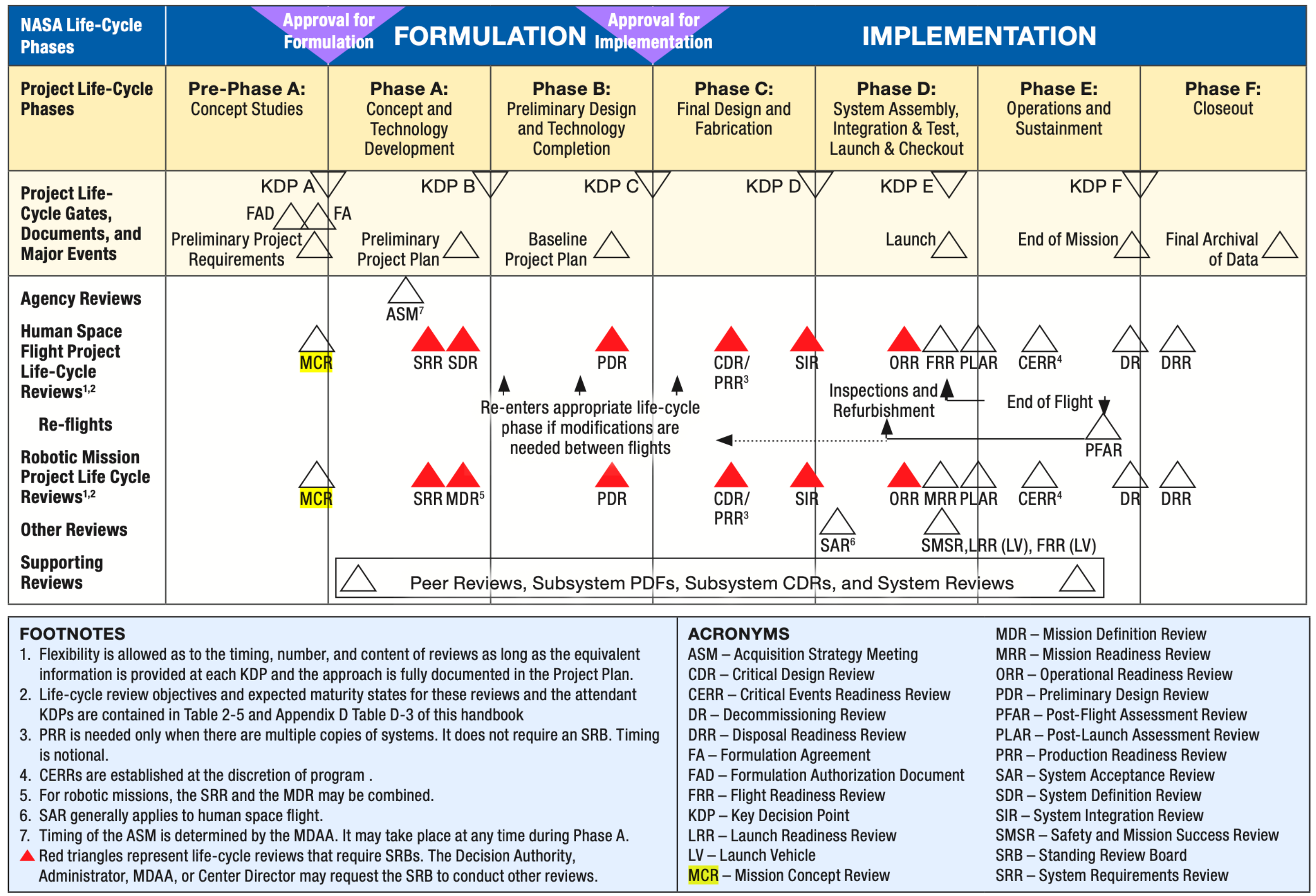
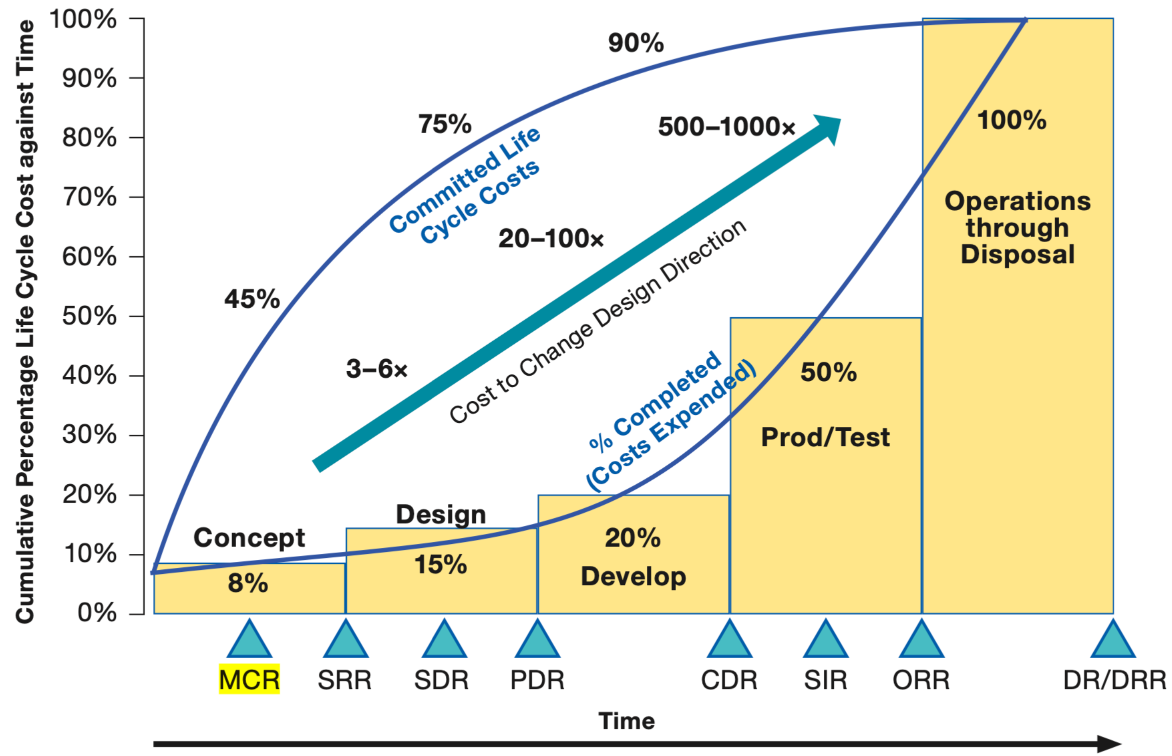


FIGURE 3.0-1 NASA Space Flight Project Life Cycle from NPR 7120.5E

Taken from NASA Systems Engineering Handbook, https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook_0.pdf

Mission Life Cycle Cost vs. Time



MCR	Mission Concept Review	**CDR**	Critical Design Review
SRR	System Requirements Review	**SIR**	System Integration Review
SDR	System Definition Review	**ORR**	Operational Readiness Review
PDR	Preliminary Design Review	**DR/DRR**	Decommissioning/Disposal Readiness Review

Adapted from INCOSE-TP-2003-002-04, 2015

Taken from NASA Systems Engineering Handbook, https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook_0.pdf