

THE LARGE UV / OPTICAL / INFRARED SURVEYOR (LUVOIR)

TELLING THE STORY OF LIFE IN THE UNIVERSE

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LUVOIR IS . . .



A community-driven, UV/O/IR observatory able to perform direct spectroscopy of dozens of exoEarth candidates, high-fidelity Solar System remote sensing, and transformative astrophysics



LUVOIR-A



15 m

LUVOIR-B

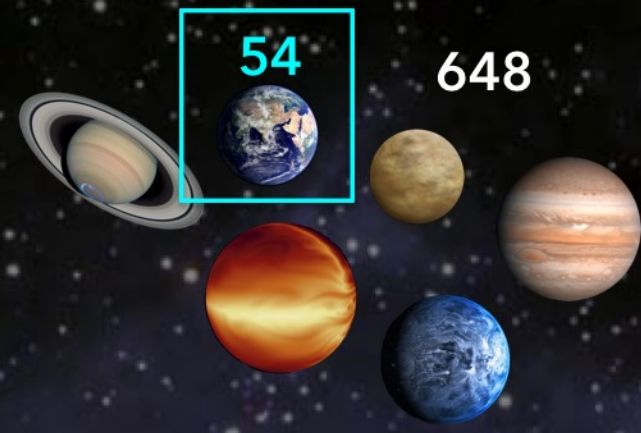


8 m

HST

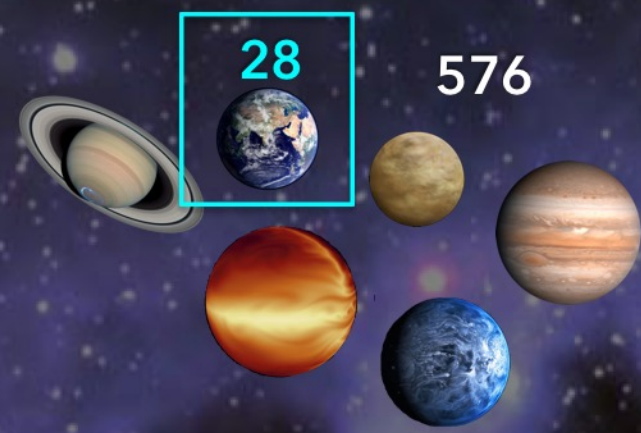


2.4 m



54

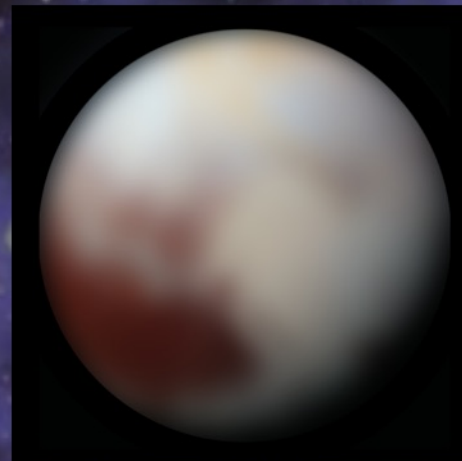
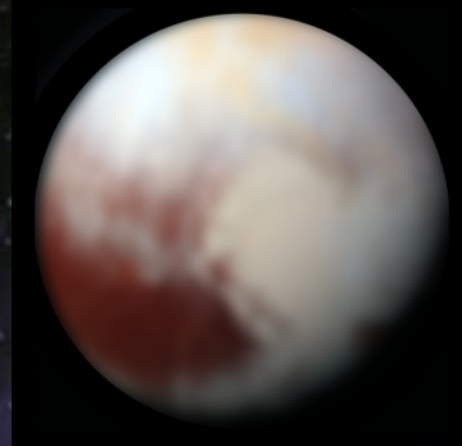
648



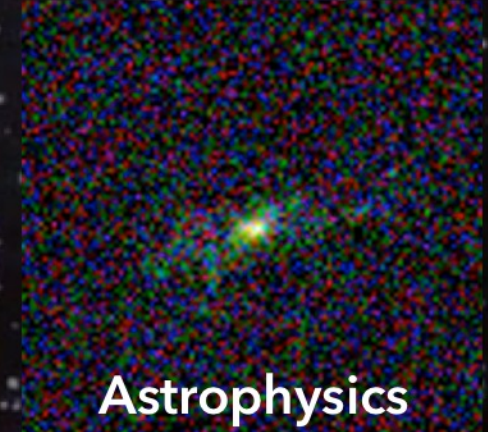
28

576

Exoplanets



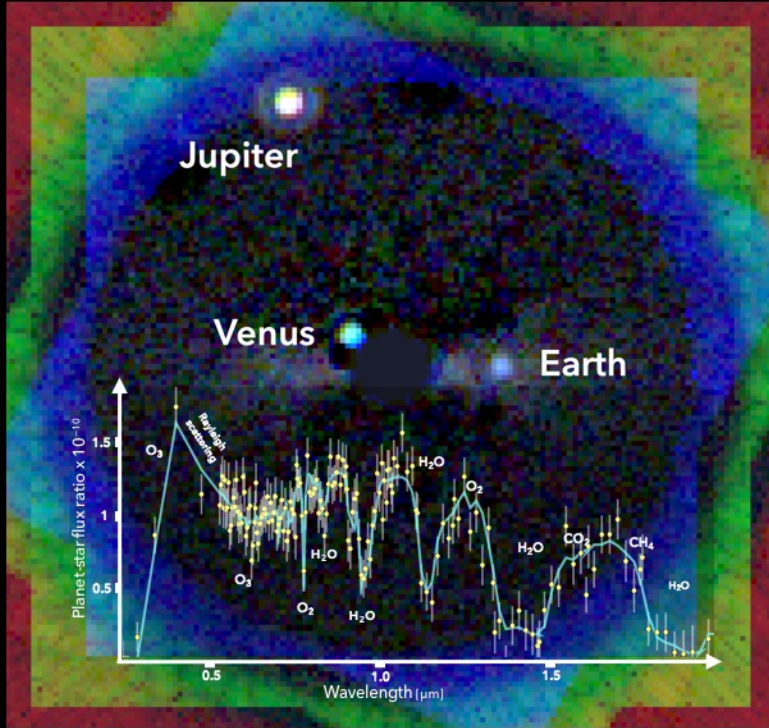
Solar System



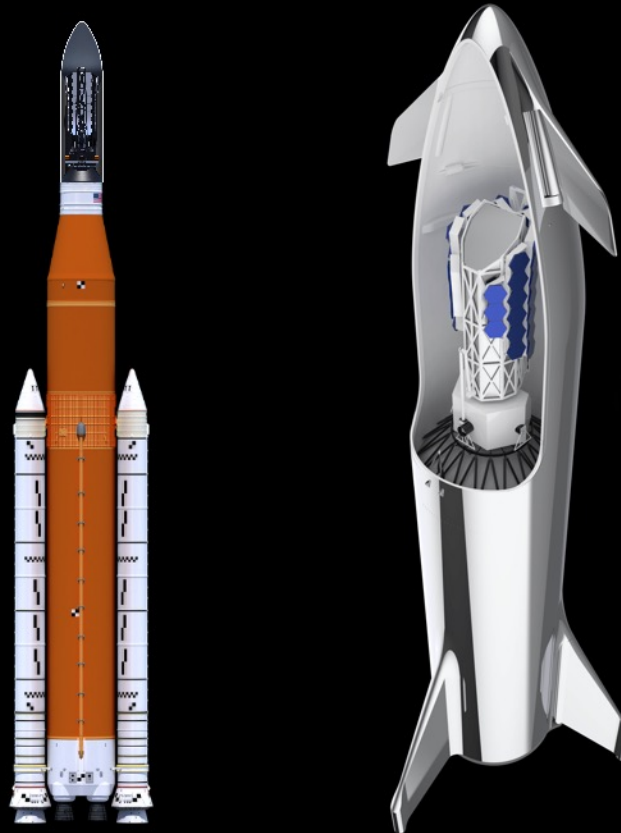
Astrophysics

LUVOIR is . . .

Powerful

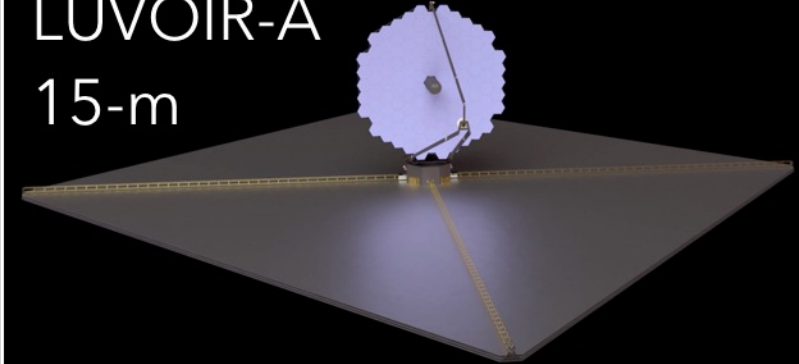


Feasible

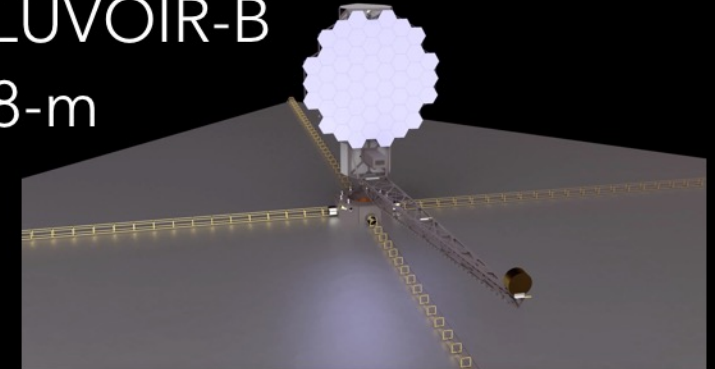


Executable

LUVOIR-A
15-m



LUVOIR-B
8-m



Ability to answer the questions of the 2030s and beyond

LUVOIR IS POWERFUL



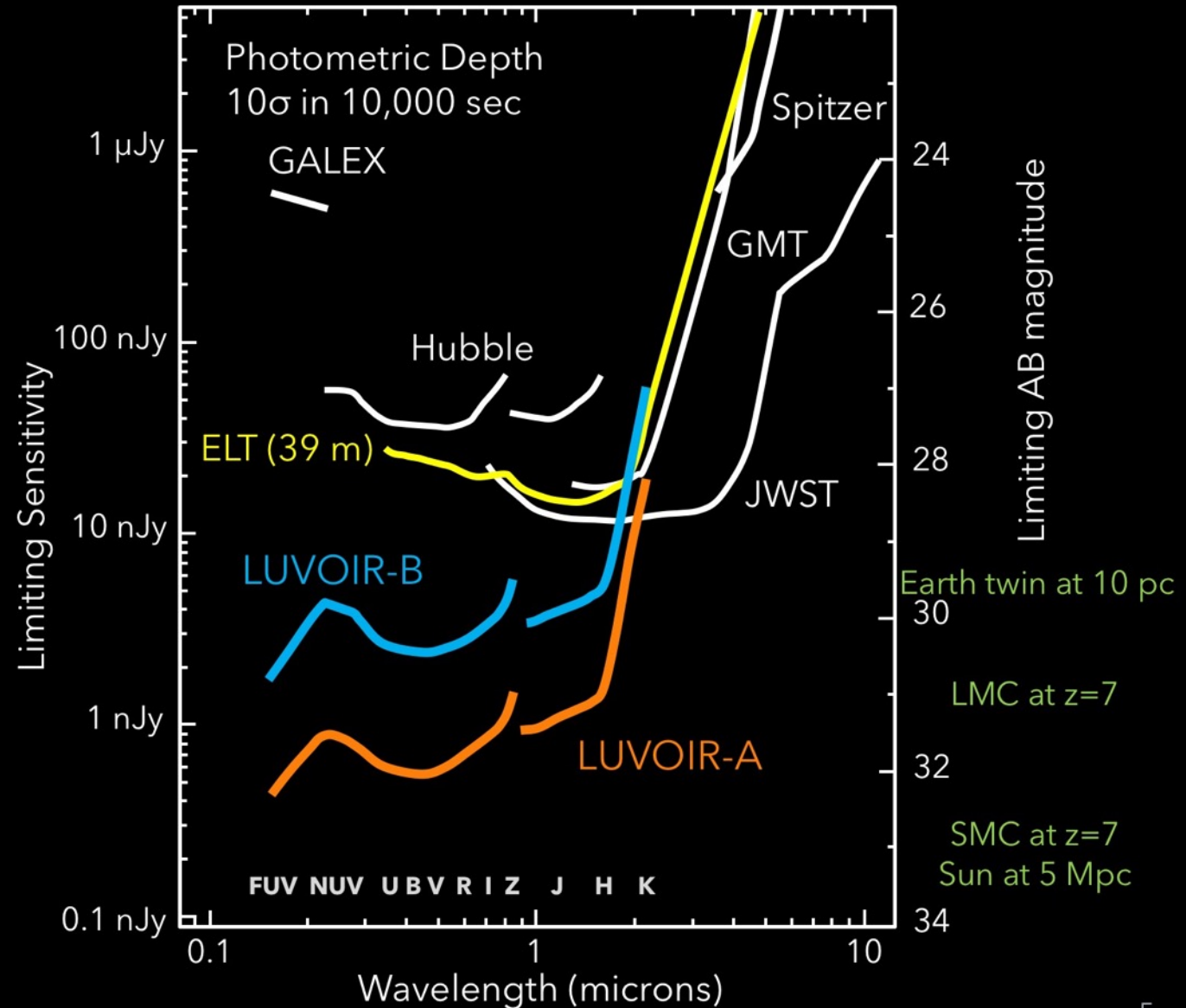
Are we alone?

What is the diversity of worlds?

How do planetary systems form?

What is the nature of dark matter?

How do galaxies evolve and form stars?



LUVOIR IS POWERFUL



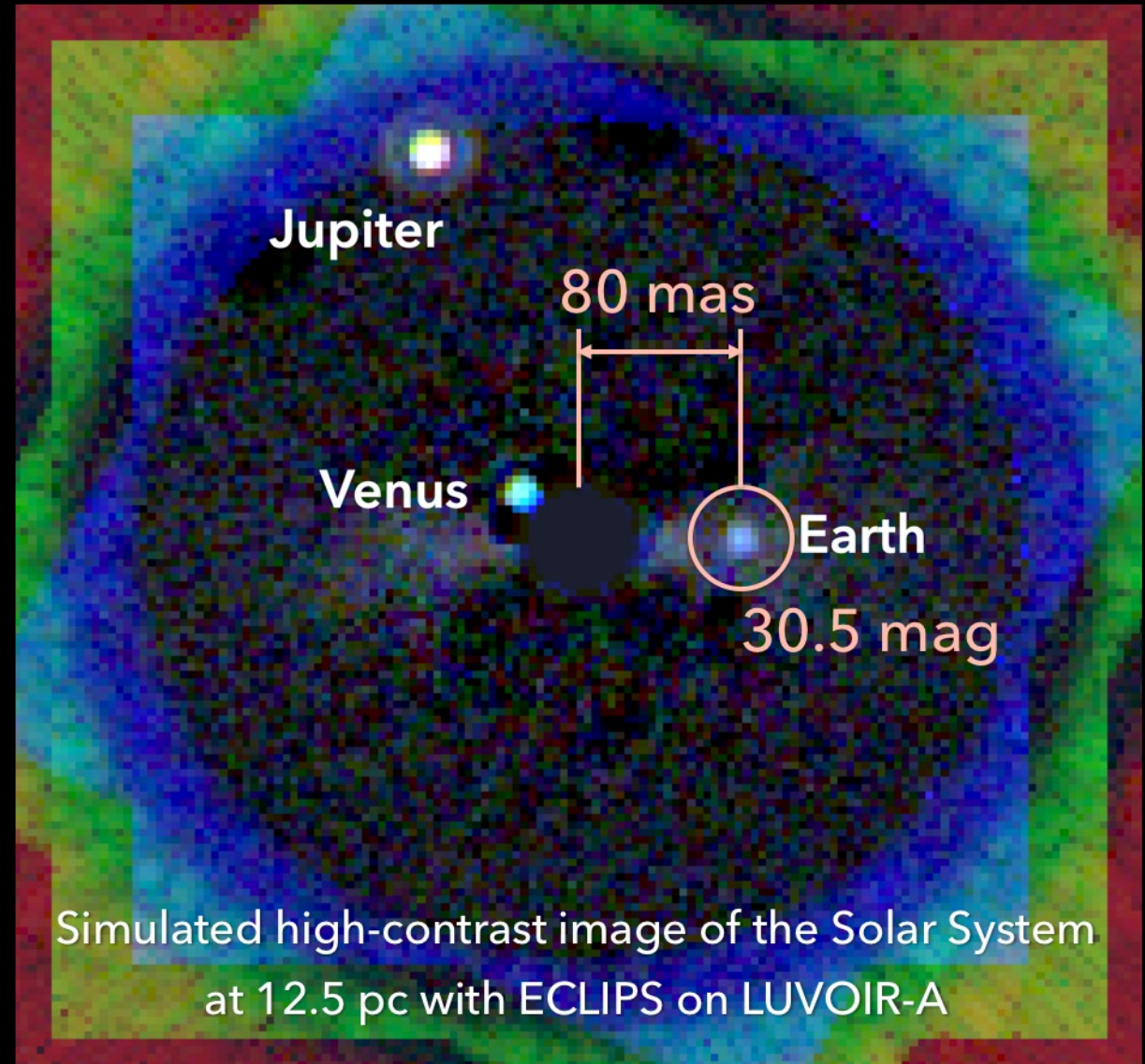
Are we alone?

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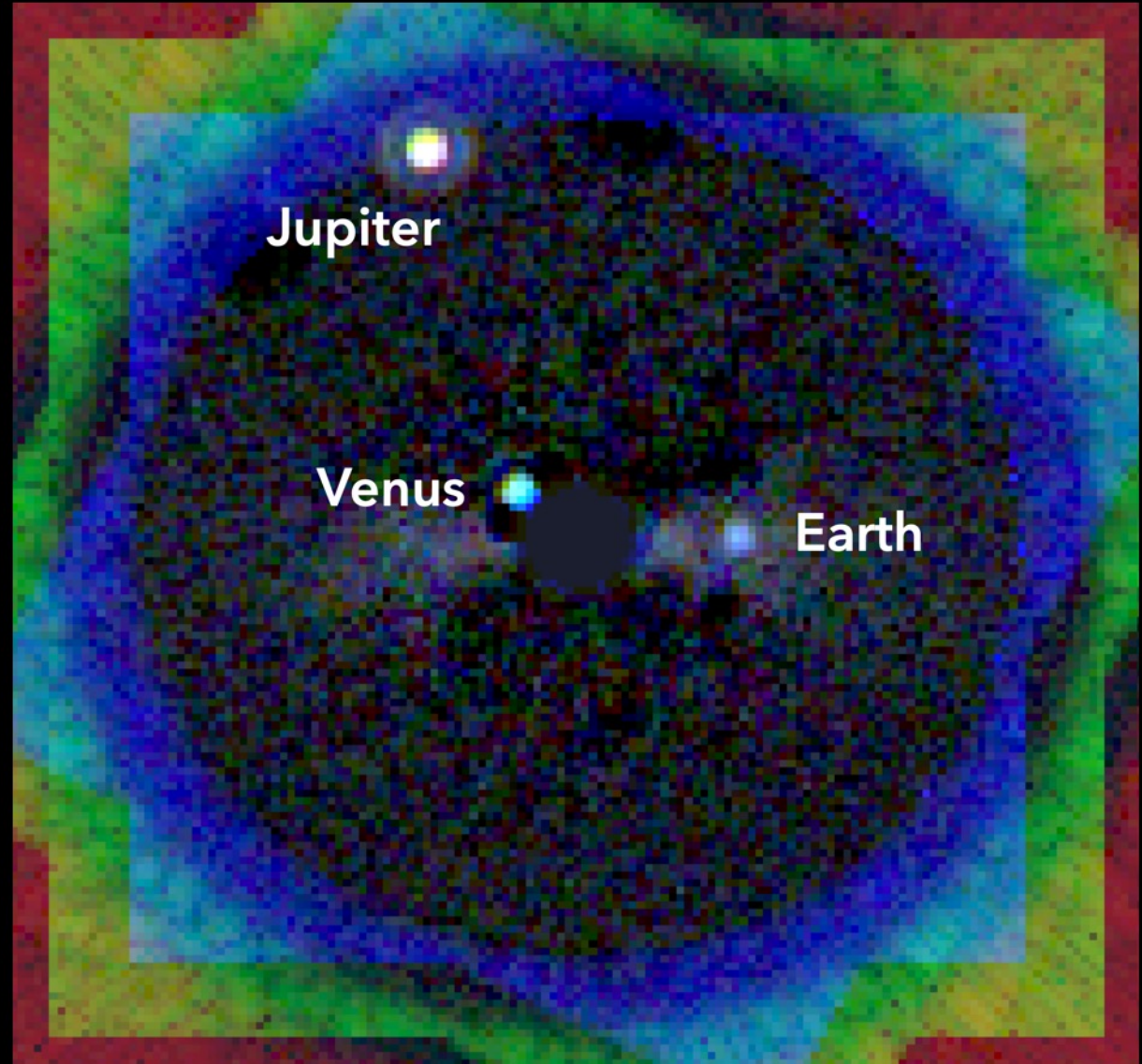
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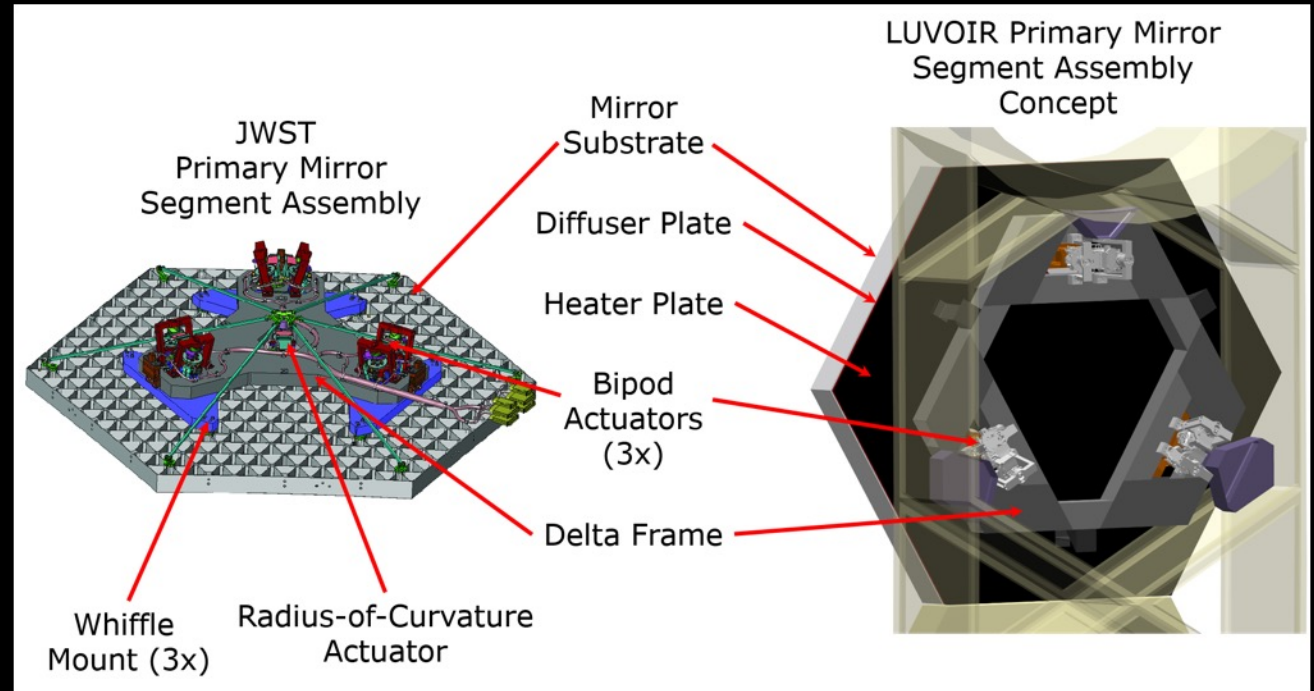
LUVOIR IS FEASIBLE

Design for stability
Detailed technology
development plan
Design from heritage



LUVOIR IS FEASIBLE

Design for stability
Detailed technology
development plan
Design from heritage



LUVOIR IS FEASIBLE



Design for stability

Detailed technology development plan

Design from heritage

Modular design eases I&T and transport

Warm telescope

Multiple future launch vehicles

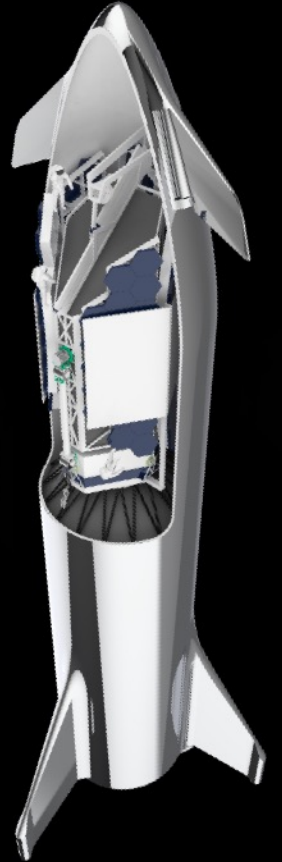
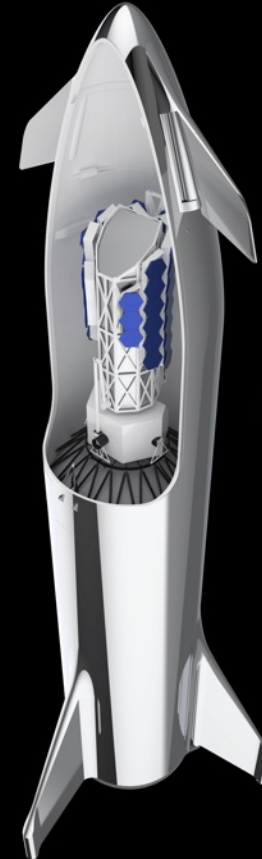
SLS
Block 1B



SLS
Block 2



SpaceX Starship
(Super Heavy booster not shown)



LUVOIR IS EXECUTABLE



A scalable family of designs to account for uncertainties in ...

Launch vehicles

Technology

Budgets

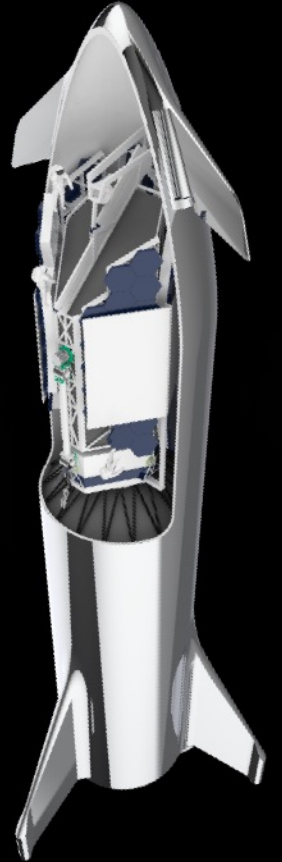
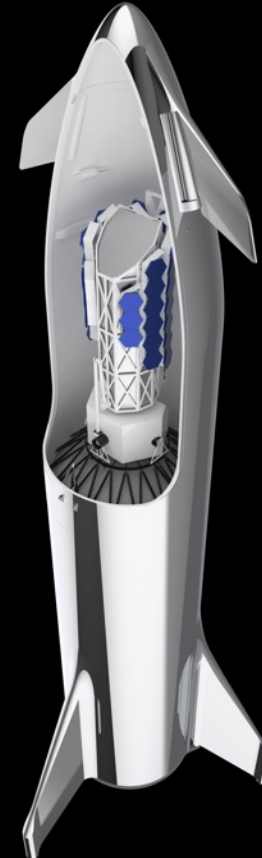
SLS
Block 1B



SLS
Block 2



SpaceX Starship
(Super Heavy booster not shown)



LUVOIR IS EXECUTABLE

A scalable family of designs to account for uncertainties in ...

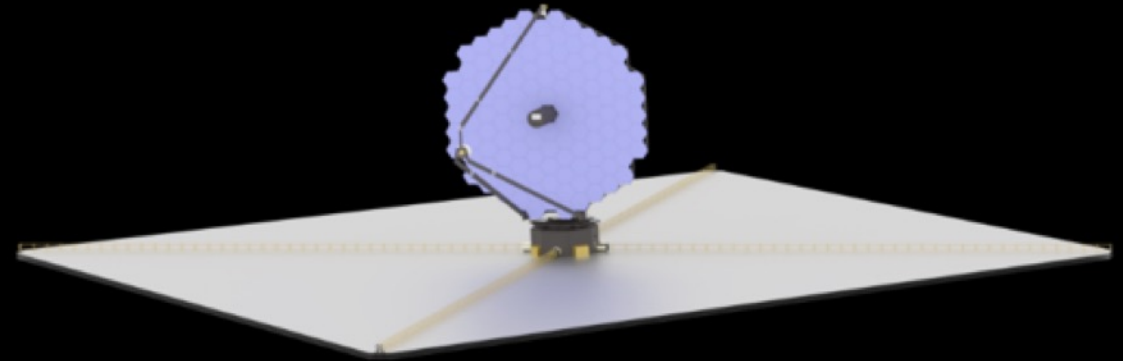
Launch vehicles

Technology

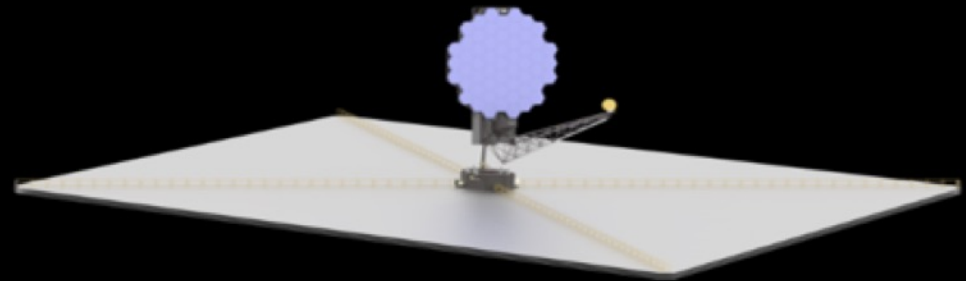
Budgets



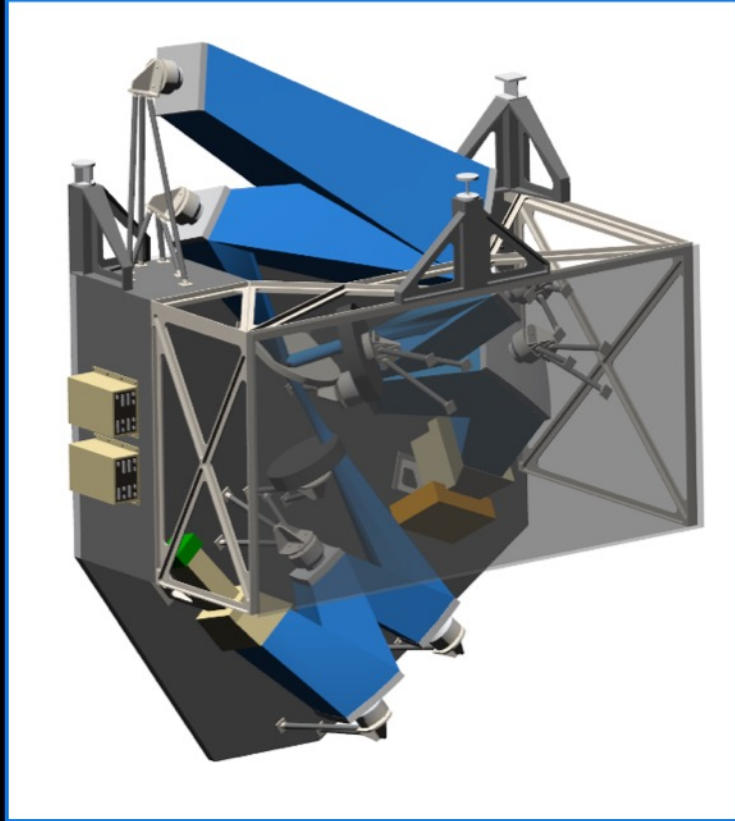
15-m on-axis LUVOIR-A
Collecting area: 155 m²



8-m off-axis LUVOIR-B
Collecting area: 43 m²



LUVOIR IS WELL-STUDIED



HDI opto-mechanical layout

A screenshot of a large, complex spreadsheet titled "The 362-line Master Equipment List for HDI-A". The spreadsheet is organized into multiple columns and rows, with a blue header section at the top. It contains detailed technical specifications, part numbers, and descriptions for various equipment components.

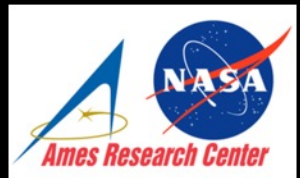
The 362-line Master Equipment List for HDI-A

Higher fidelity designs enable higher fidelity cost & risk estimation

LUVOIR IS FROM AND FOR THE COMMUNITY



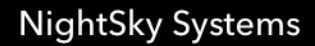
STDT



International Representatives



Industry Participation



The background is a collage of four celestial images arranged in a 2x2 grid, separated by thin white lines. The top-left image shows the Earth from space, with blue oceans and white clouds. The top-right image shows the swirling, brown and white clouds of Jupiter. The bottom-left image shows the reddish-brown, cratered surface of Mars. The bottom-right image shows a large, blue and white spiral galaxy against a dark background with several bright stars.

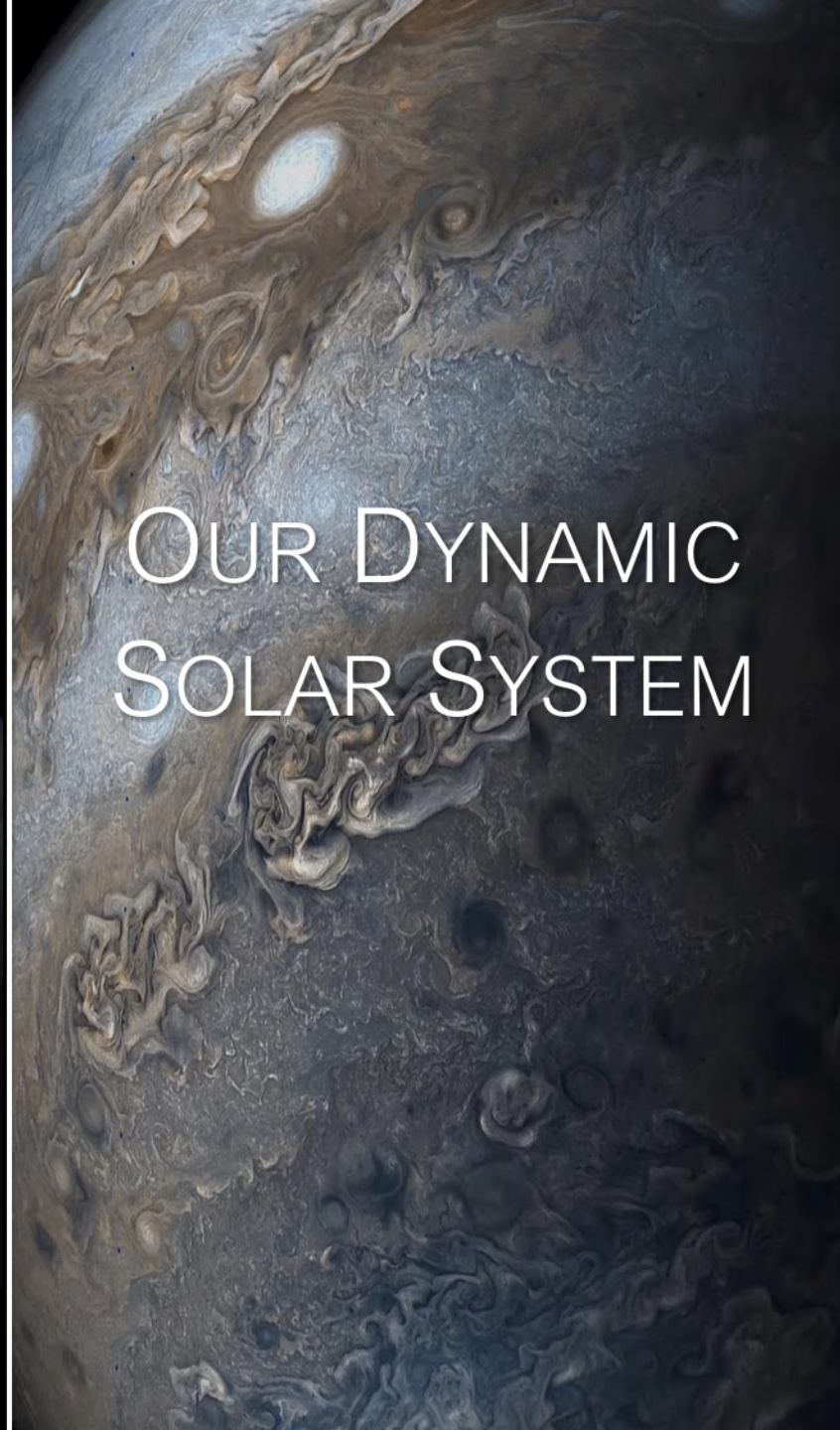
LUV OIR is POWERFUL

SCIENCE

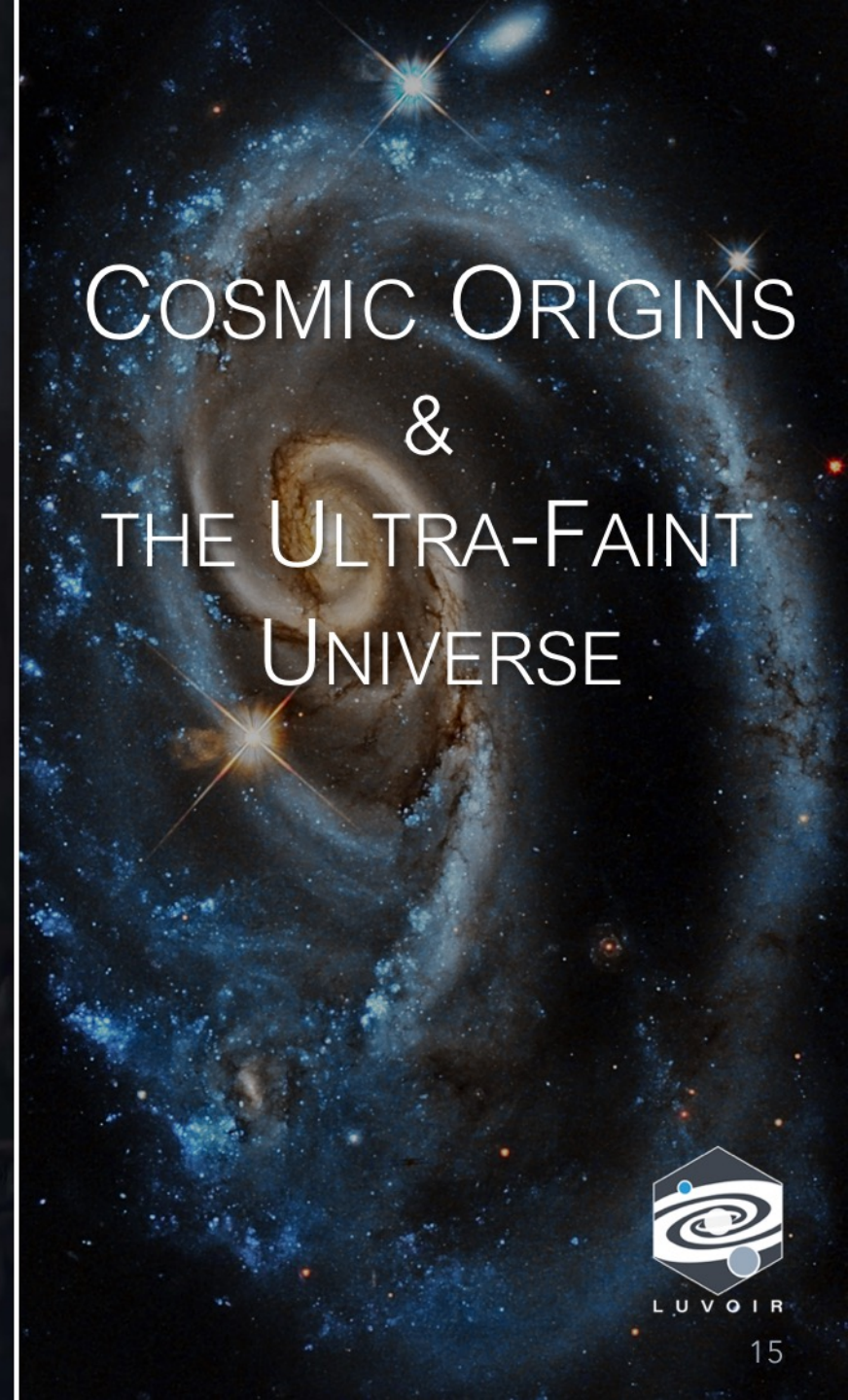
A composite image showing the blue and white swirling clouds of Earth in the upper left and the reddish, cratered surface of Mars in the lower right.

EXOTIC WORLDS

THE SEARCH
FOR LIFE

A detailed image of the planet Jupiter, showing its characteristic brown and white swirling cloud patterns and the Great Red Spot.

OUR DYNAMIC
SOLAR SYSTEM

A vibrant image of a spiral galaxy with a bright yellow core and glowing blue and white star-forming regions along its arms.

COSMIC ORIGINS
&
THE ULTRA-FAINT
UNIVERSE





AMBITIOUS GOAL DRIVES TELESCOPE SIZE



ARE WE ALONE?



DESIGNING A WELL-POSED SEARCH FOR LIFE EXPERIMENT



Finding Earth-like planets and life would be a momentous achievement

2008

Worlds Beyond: A Strategy for the Detection and
Characterization of Exoplanets
Report of the ExoPlanet Task Force
Astronomy and Astrophysics Advisory Committee

2010

New Worlds,
New Horizons

2013

Enduring Quests
Daring Visions
A Thirty-Year Roadmap for NASA Astrophysics

2018

The National Academies of
SCIENCES • ENGINEERING • MEDICINE
CONSENSUS STUDY REPORT

Need *space-based direct spectroscopy* to do it for exoplanets around
Sun-like stars

Washington, D.C.
May 22, 2008

AAAC Exoplanet
Task Force



NAS Astro2010 Decadal



NASA Astro Roadmap

EXOPLANET
SCIENCE
STRATEGY

NAS Consensus Study



THE SEARCH FOR LIFE

STEP 1
FIND THE HABITABLE PLANET
CANDIDATES

STEP 2
STUDY THE HABITABLE PLANET
CANDIDATES



LUVOIR

DEFINING HABITABLE CANDIDATES TO MAXIMIZE SUCCESS

Temperate

Allowing liquid surface water



“Conservative habitable zone”

Orbit semi-major axis
from 0.95 – 1.76 AU for
Sun-twin star

Rocky



Exclude mini-Neptunes

$R \leq 1.4$ Earth-radii

Learned from Kepler and
ground-based RV

Long-term substantial atmosphere

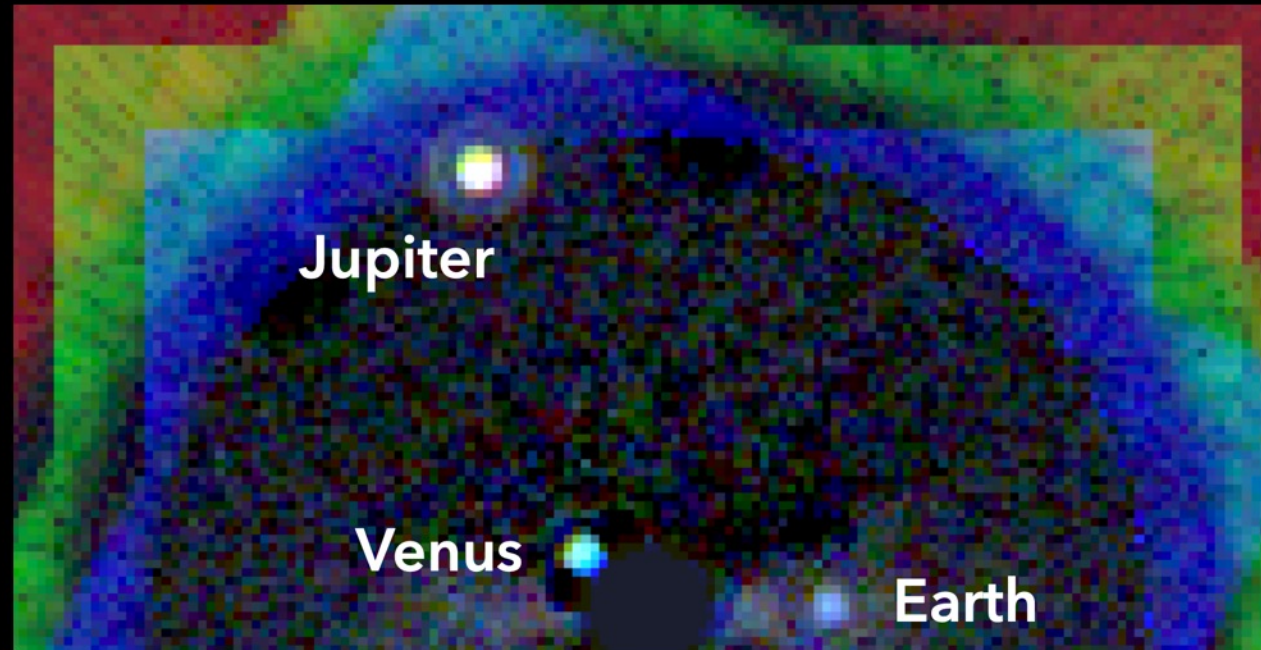


Exclude “Mars-like”
exoplanets

$R > 0.8 a^{-0.5}$ Earth-radii

a = orbit semi-major axis

THE HABITABLE PLANET SURVEY OBSERVATIONS



High-contrast direct imaging of *hundreds of stars* with LUVOIR ECLIPS.

Colors, orbits, & partial spectra for all habitable planet candidates

Simulated high-contrast image of the Solar System
at 12.5 pc with ECLIPS on LUVOIR-A

HOW MANY CANDIDATES DO WE NEED?

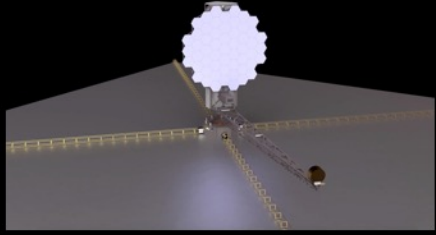
Are habitable planets common or rare?

Want order of magnitude increase in knowledge

Requirement : Measure frequency of habitable planets for values $>10\%$

Ensures scientifically valuable null result

HOW MANY CANDIDATES FOR $>10\%$ FREQUENCY?



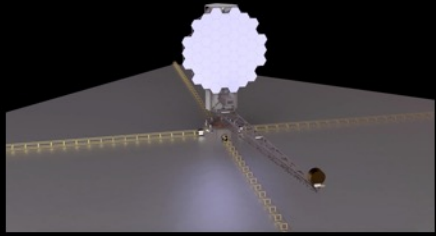
LUVOIR-B
8-m



28 candidates

Measure frequency of Earth-like planets if $>10\%$

WHAT IF EARTH IS EVEN MORE RARE?

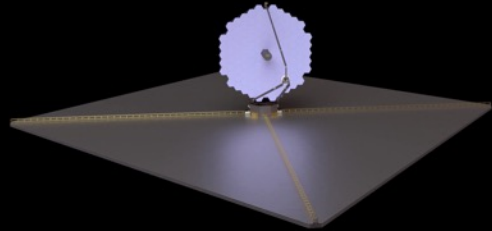


LUVOIR-B
8-m



28 candidates

Measure frequency of Earth-like planets if $>10\%$



LUVOIR-A
15-m



54 candidates

Measure frequency of Earth-like planets if $>5\%$

HOW DO HABITABLE PLANET CANDIDATE YIELDS SCALE?



Altruistic Yield Optimization (AYO)

Stark et al. (2014, 2015)

Monte Carlo code to simulate direct imaging surveys

Large number of **instrumental**, **astrophysical**, & **observational** parameters

Major advance over codes used for Astro2010

Same code with same input parameters used for HabEx

HOW DO HABITABLE PLANET CANDIDATE YIELDS SCALE?

Parameterization of AYO statistical results

$$Y \propto D^{1.97} (IWA)^{-0.98} (\eta_{Earth})^{0.96} (SNR)^{-0.76} A^{0.65} T^{0.35} \\ (PSF)^{-0.33} (Time)^{0.32} \Delta\lambda^{0.30} x^{-0.17} \xi^{-0.10}$$

Instrumental, astrophysical, & observational parameters all matter

YIELD AS A FUNCTION OF TELESCOPE DIAMETER

$$Y \propto D^{1.97}$$

Instrumental parameter

D = inscribed telescope diameter

20% decrease in diameter
35% decrease in yield

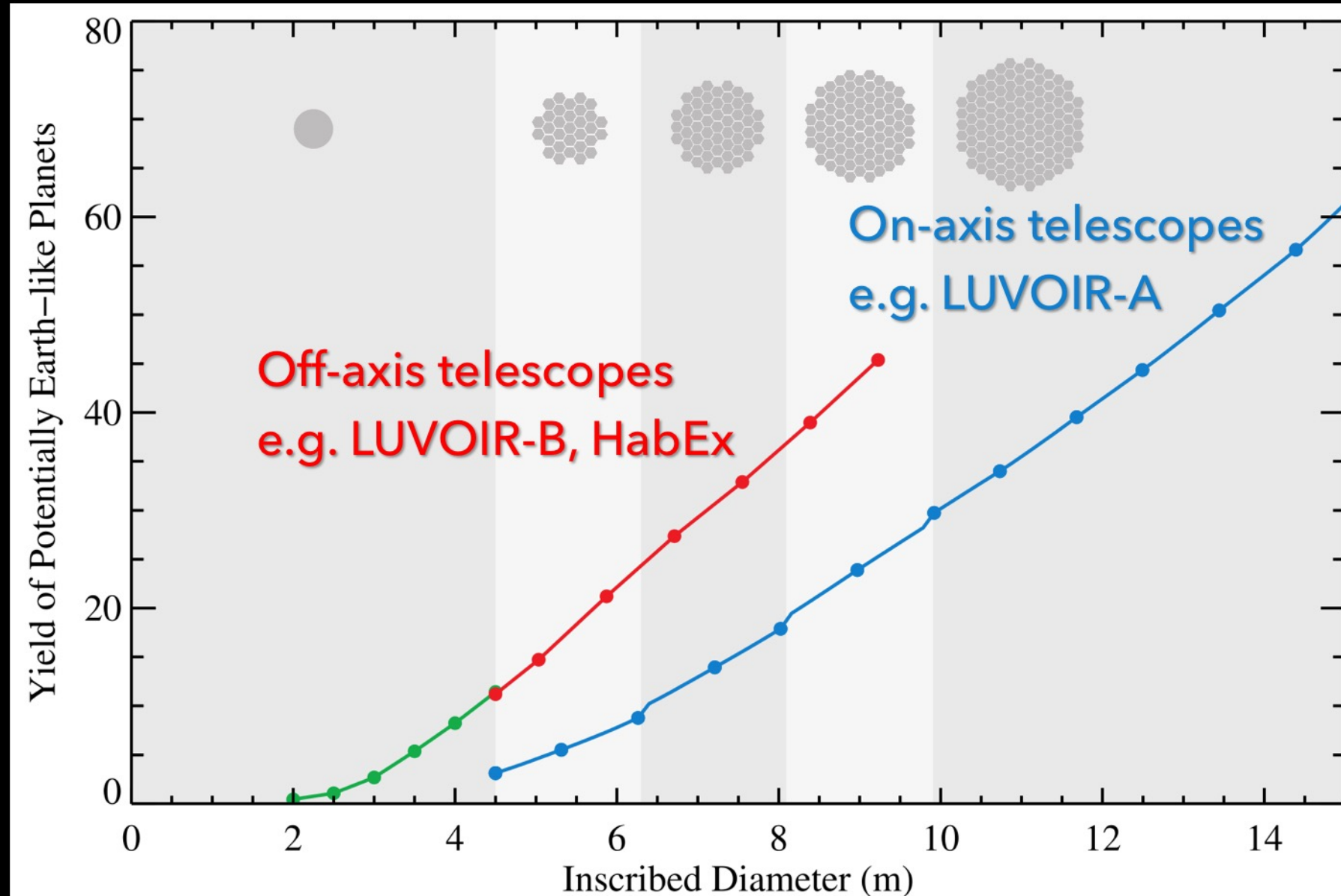
15-m LUVOIR-A
 $D=13.5$ m

54

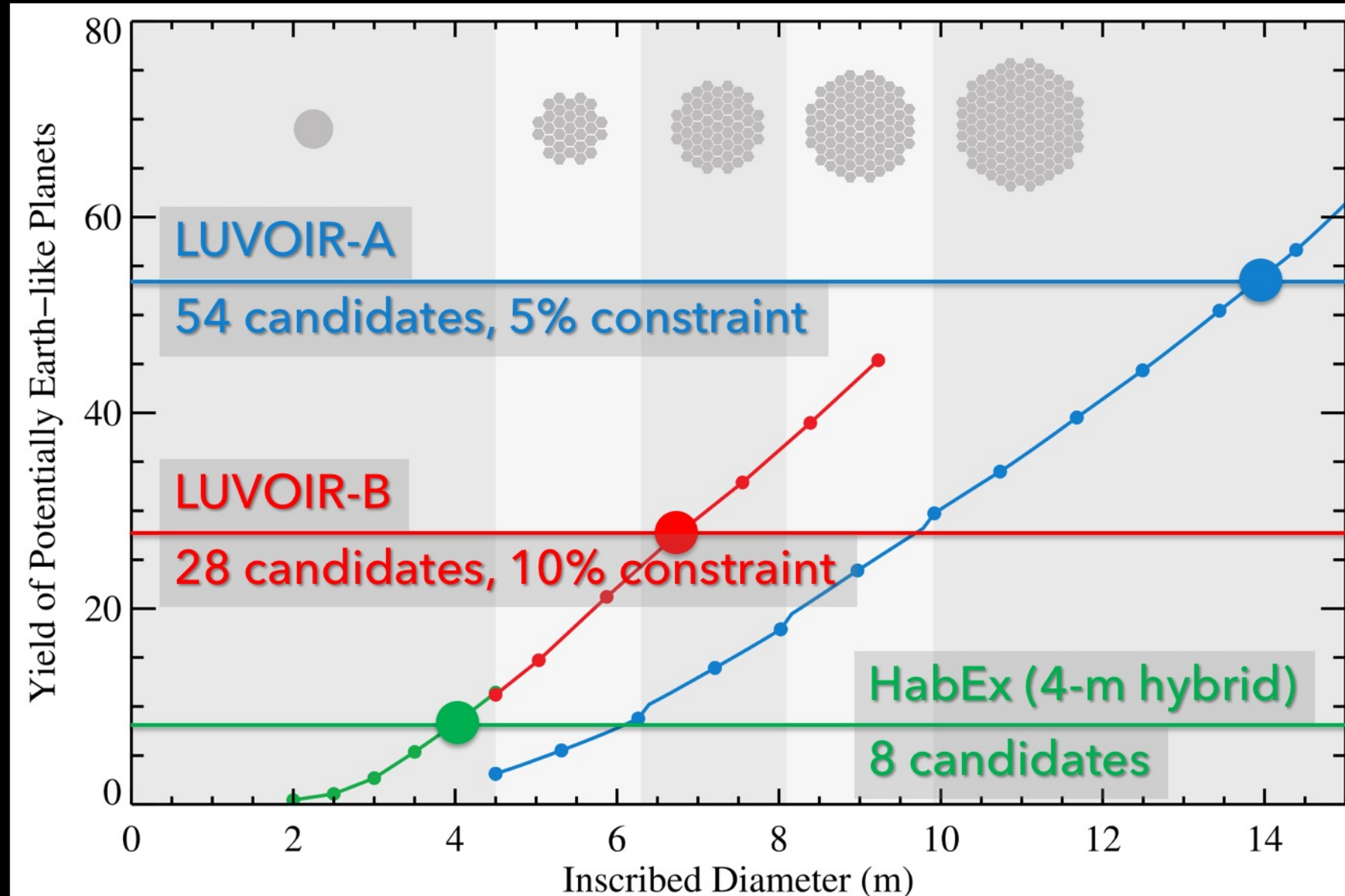
12-m LUVOIR-A
 $D=10.8$ m

35

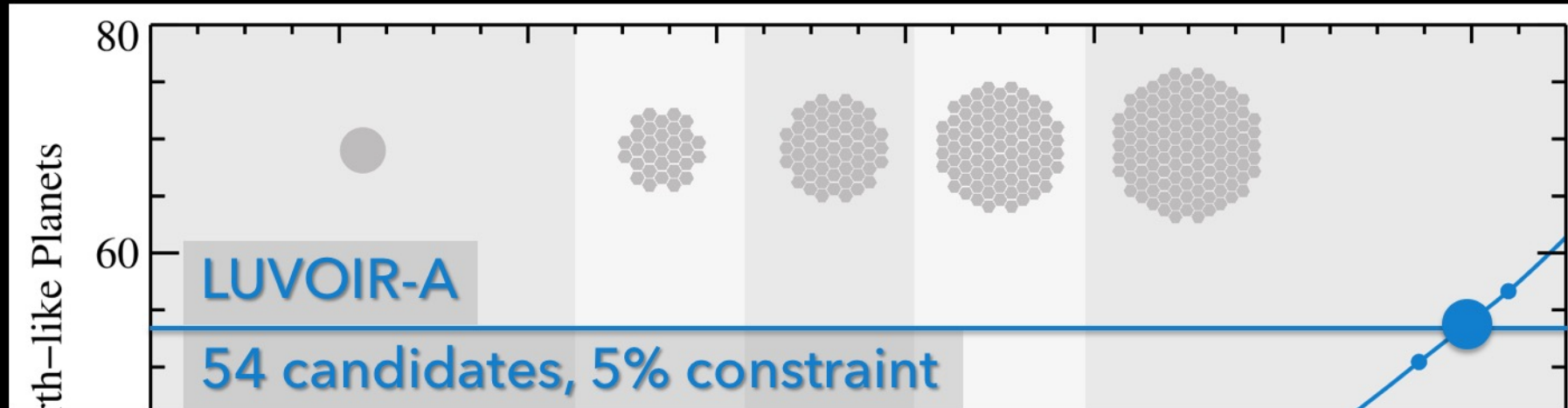
YIELD AS A FUNCTION OF TELESCOPE DIAMETER



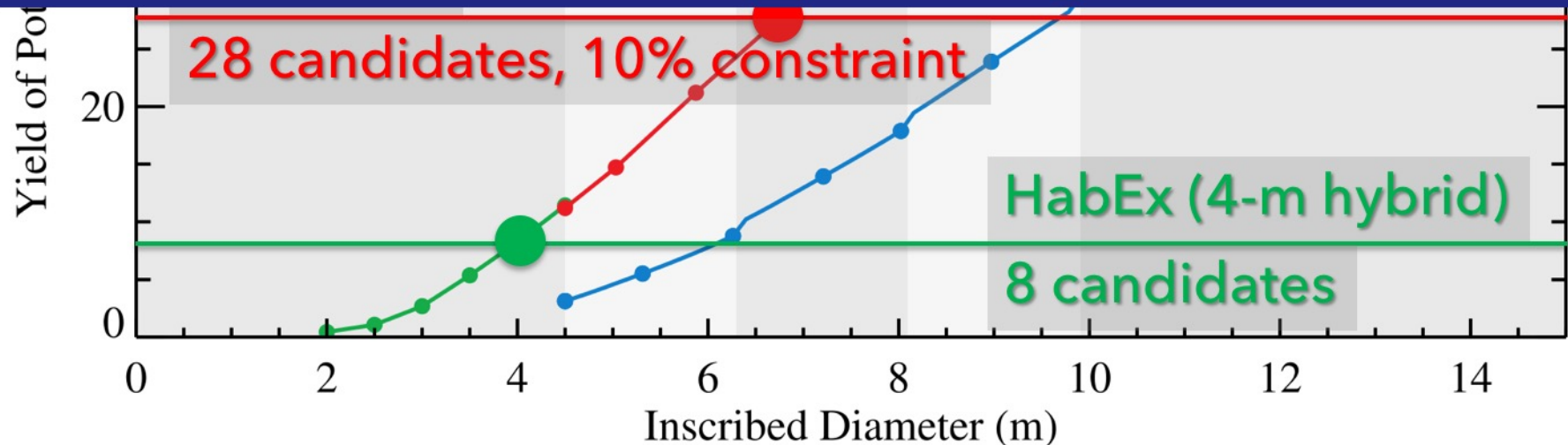
YIELD AS A FUNCTION OF TELESCOPE DIAMETER



YIELD AS A FUNCTION OF TELESCOPE DIAMETER



Telescope diameter has the strongest impact on the numbers of habitable planet candidates discovered



YIELD AS A FUNCTION OF η_{Earth}

$$Y \propto (\eta_{Earth})^{0.96}$$

Astrophysical parameter

η_{Earth} = occurrence rate of habitable planet candidates

ExoPAG SAG13 value ($0.24^{+0.46}_{-0.16}$)

67% decrease in η_{Earth}

64% decrease in yield

8-m LUVOIR-B

$\eta_{Earth} = 24\%$

28

8-m LUVOIR-B

$\eta_{Earth} = 8\%$

10

WHAT IF η_{Earth} IS LOWER THAN EXPECTED?

$$Y \propto (\eta_{Earth})^{0.96}$$

8-m LUVOIR-B

$\eta_{Earth} = 24\%$

28

LUVOIR-B finds a notable number of habitable planet candidates even if η_{Earth} is lower than expected

8-m LUVOIR-B

$\eta_{Earth} = 8\%$

10

67% decrease in η_{Earth}

64% decrease in yield

A LARGE SAMPLE ROBUSTLY TELLS THE STORY OF LIFE



First measurements of η_{water} and η_{life}

We can be "choosy"

We can select the most promising targets from the larger set for detailed study

A hedge against an uncooperative universe

e.g., lower than expected η_{Earth} , higher than expected exozodiacal dust

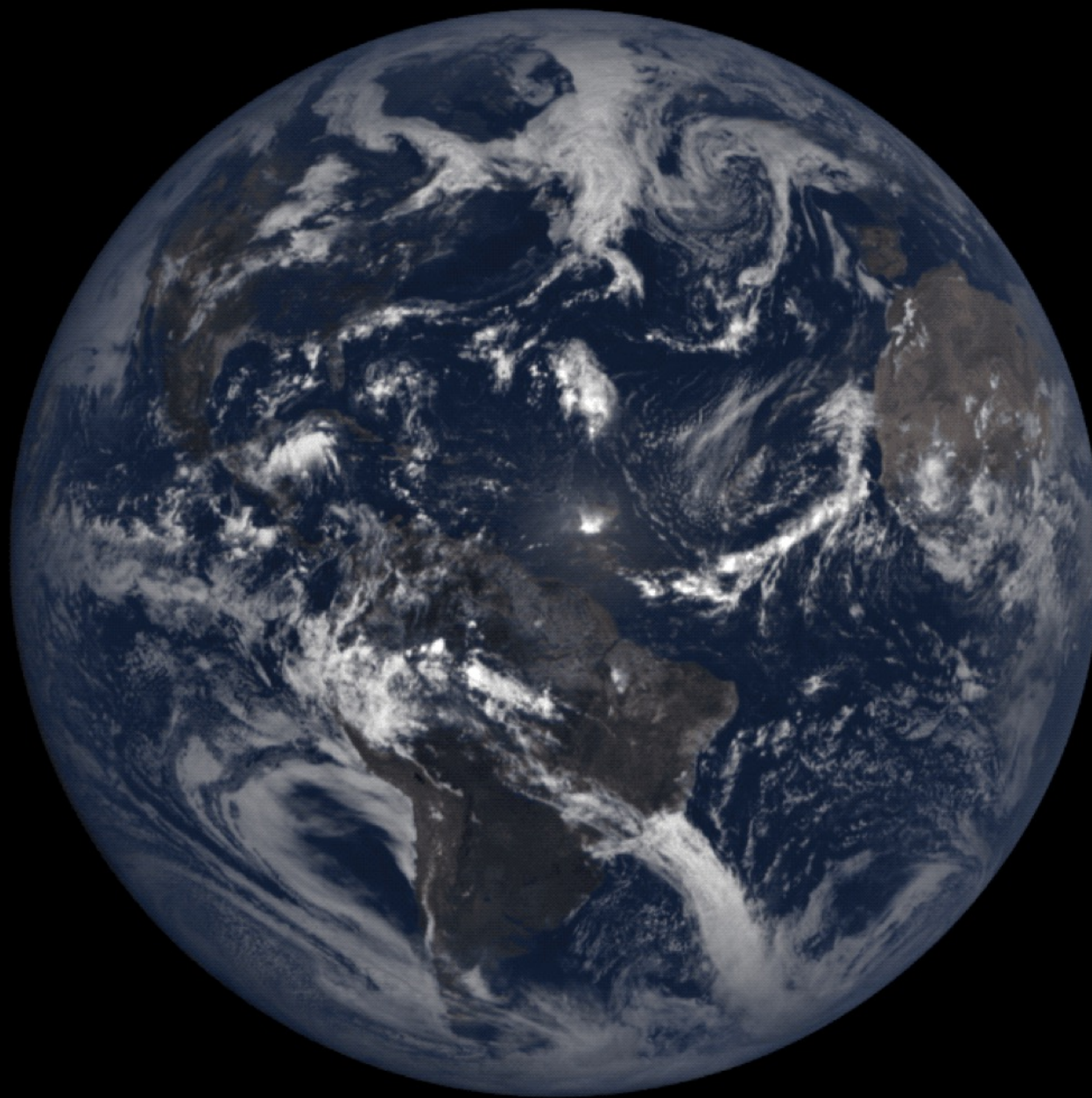


STEP 2

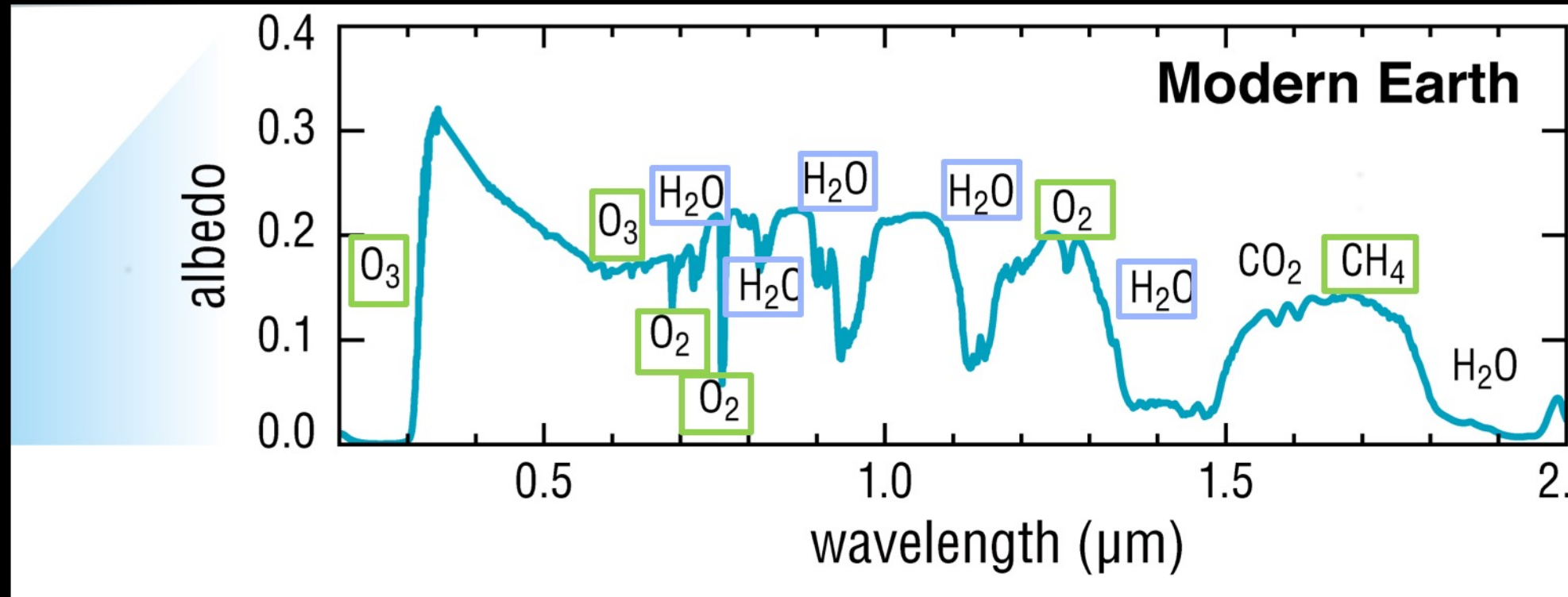
STUDY THE HABITABLE PLANET CANDIDATES

DRIVES
INSTRUMENT CAPABILITIES



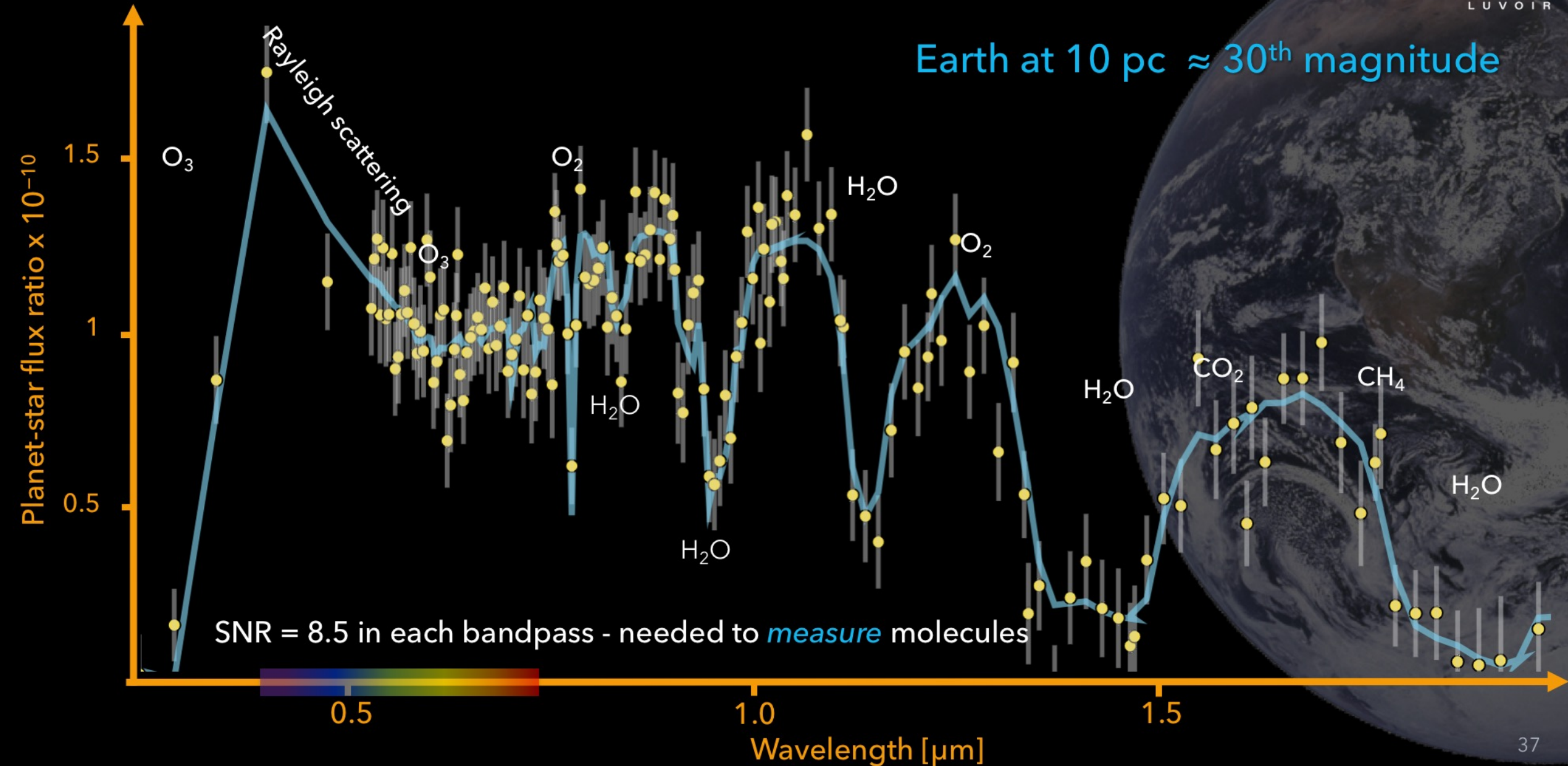


EARTH IS THE STARTING POINT

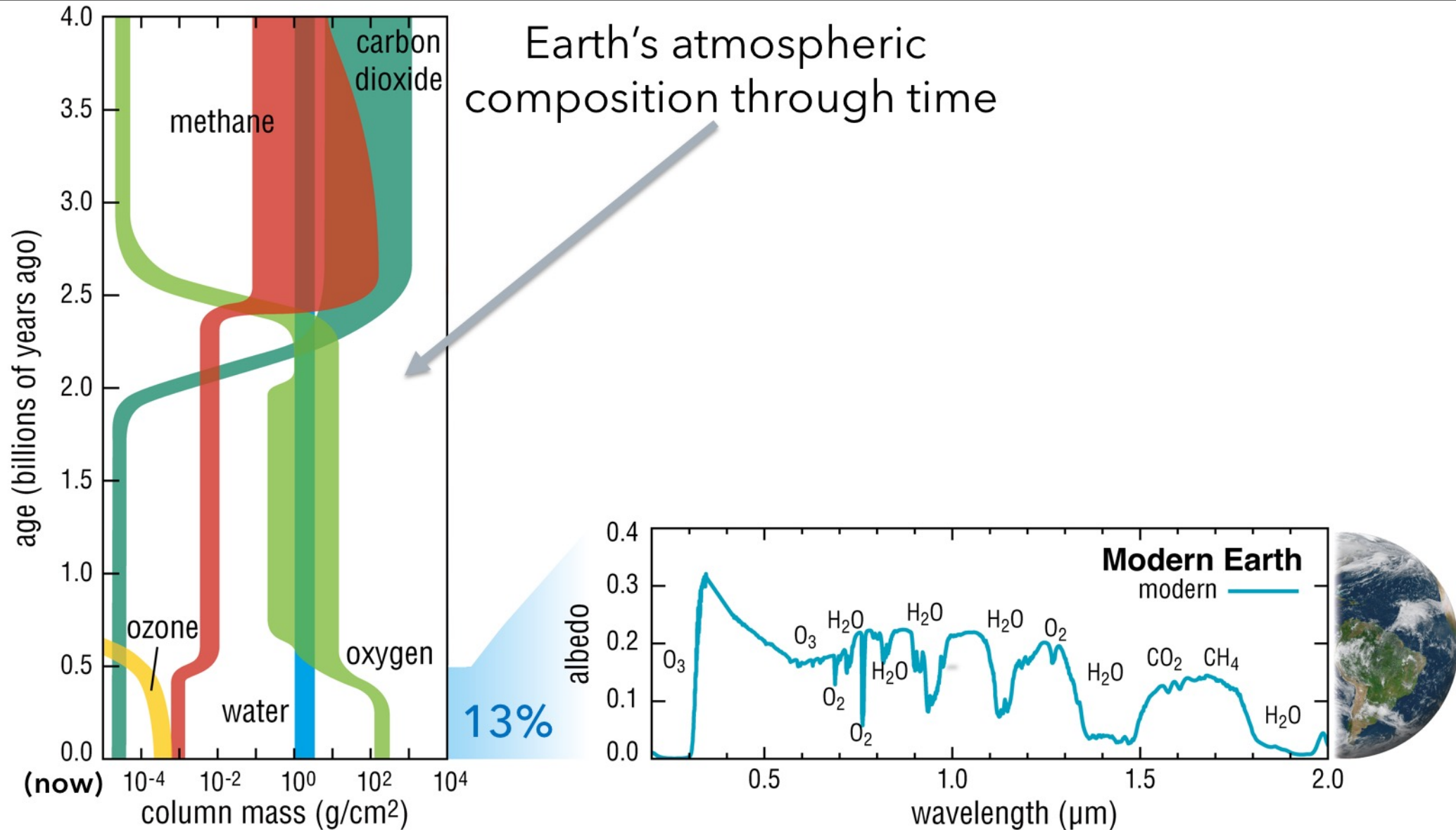


WHAT WOULD AN INHABITED EXOPLANET LOOK LIKE?

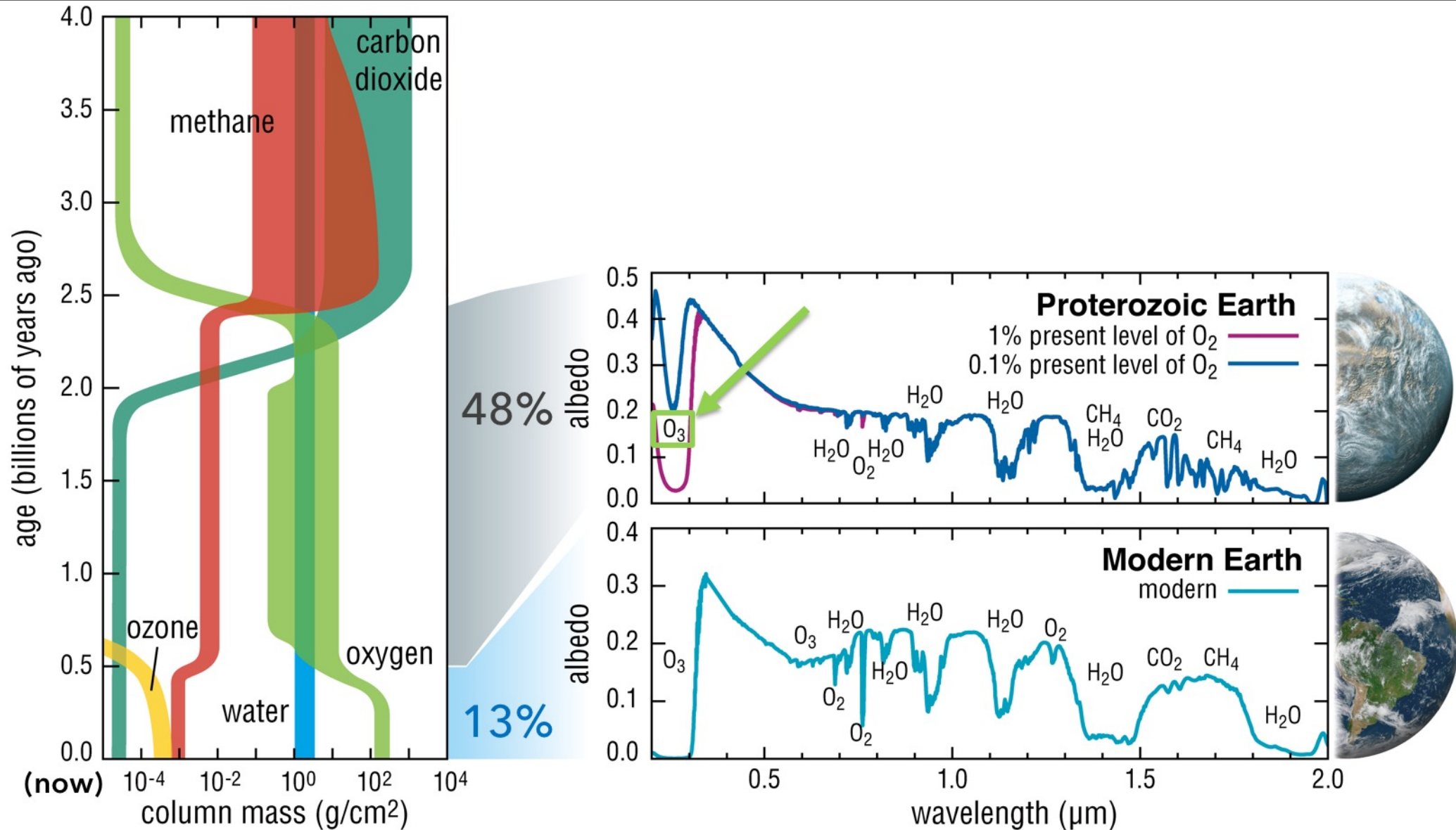
Earth at 10 pc $\approx 30^{\text{th}}$ magnitude



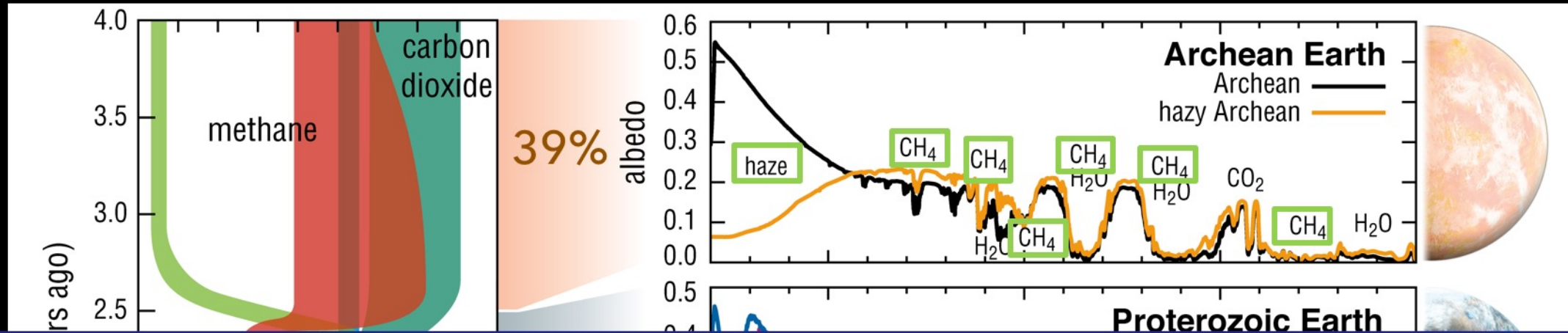
EARTH IS MORE THAN ONE PLANET



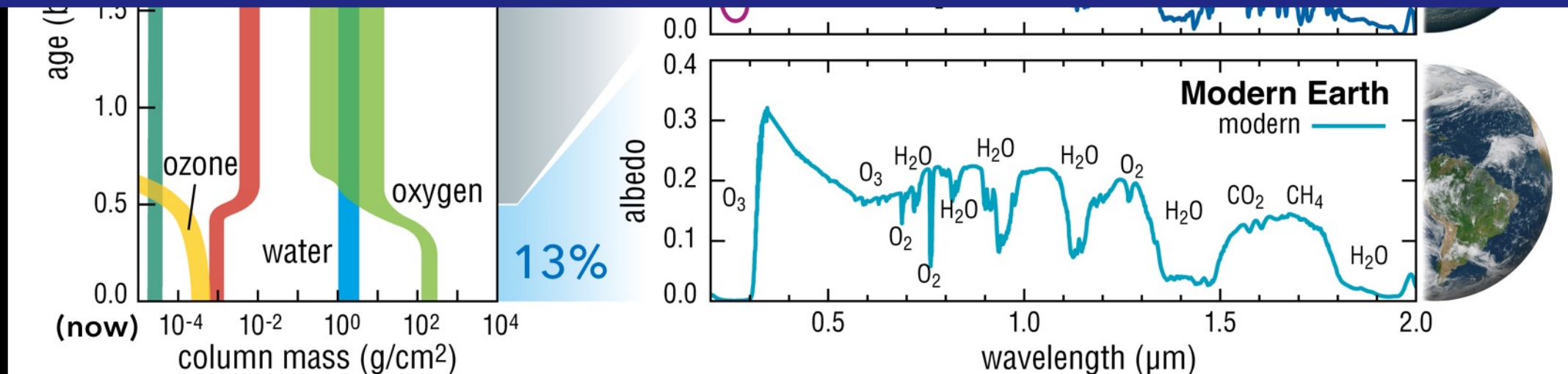
EARTH IS MORE THAN ONE PLANET



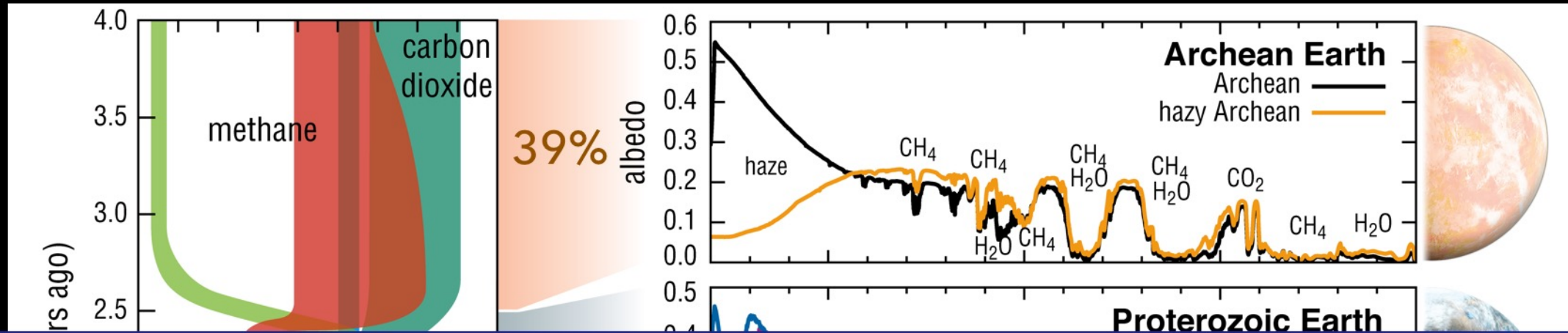
EARTH IS MORE THAN ONE PLANET



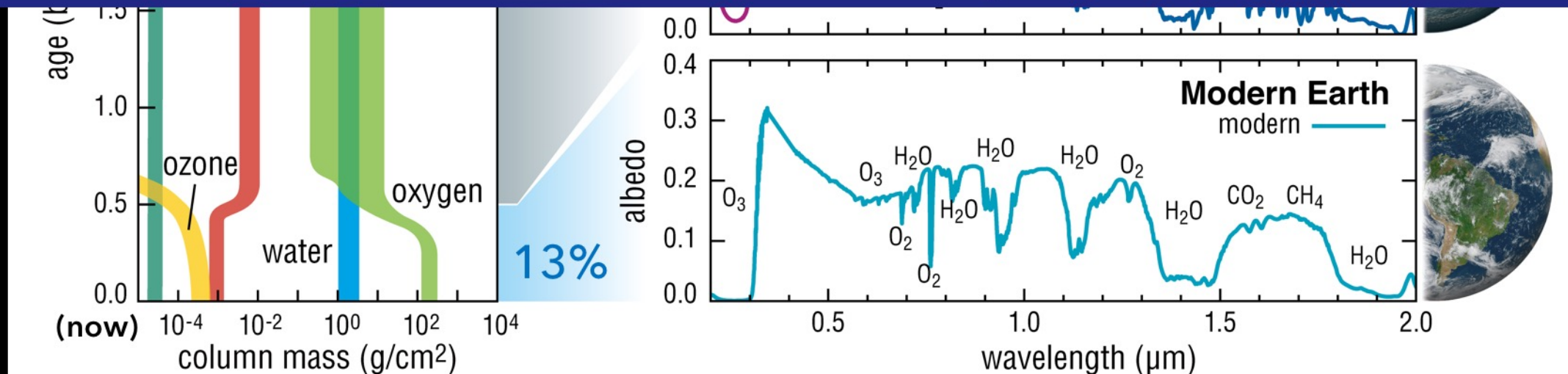
LUVUOIR accesses features able to robustly characterize & detect life on Earth over its *whole inhabited history*



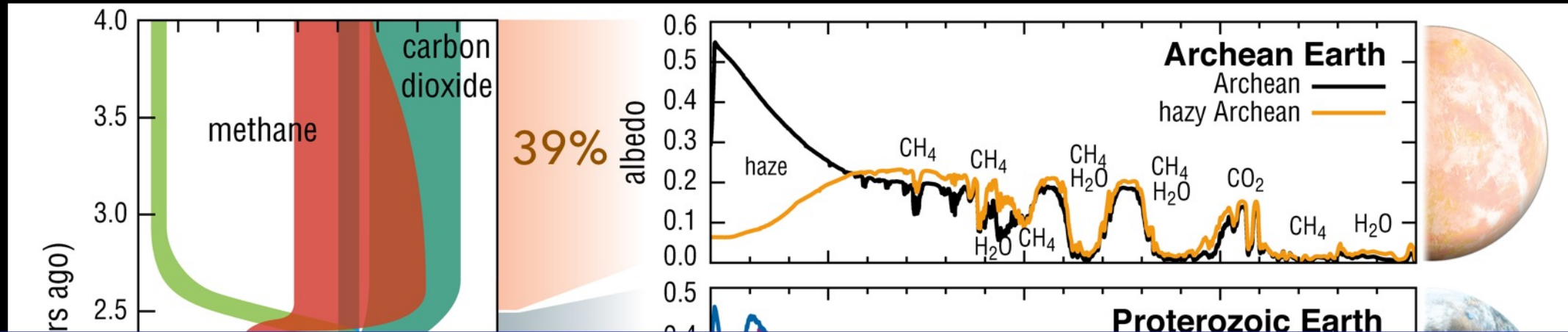
EARTH IS MORE THAN ONE PLANET



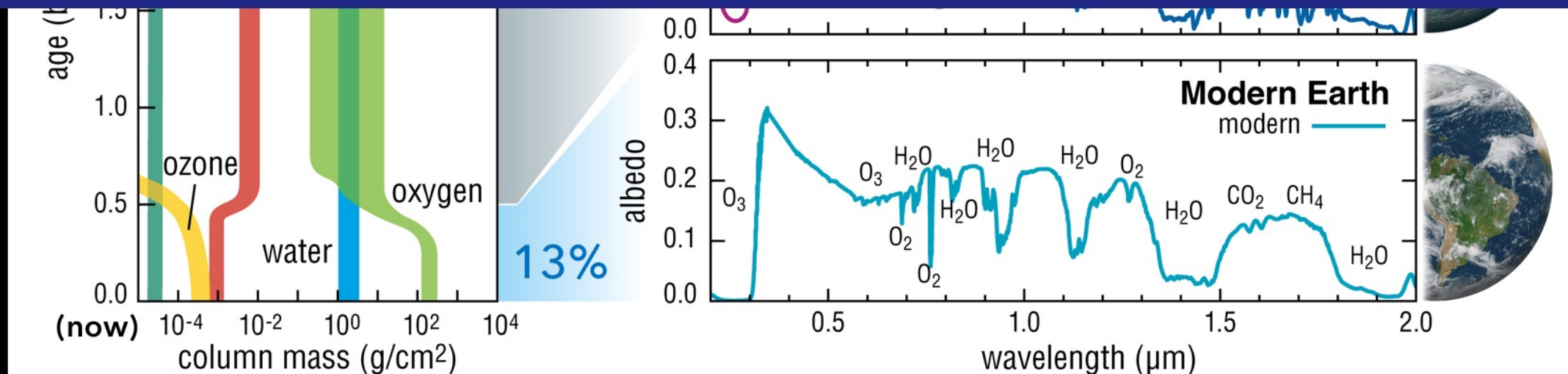
NUV wavelengths may be required to detect biosignatures for our planet's whole inhabited history (ozone, haze)



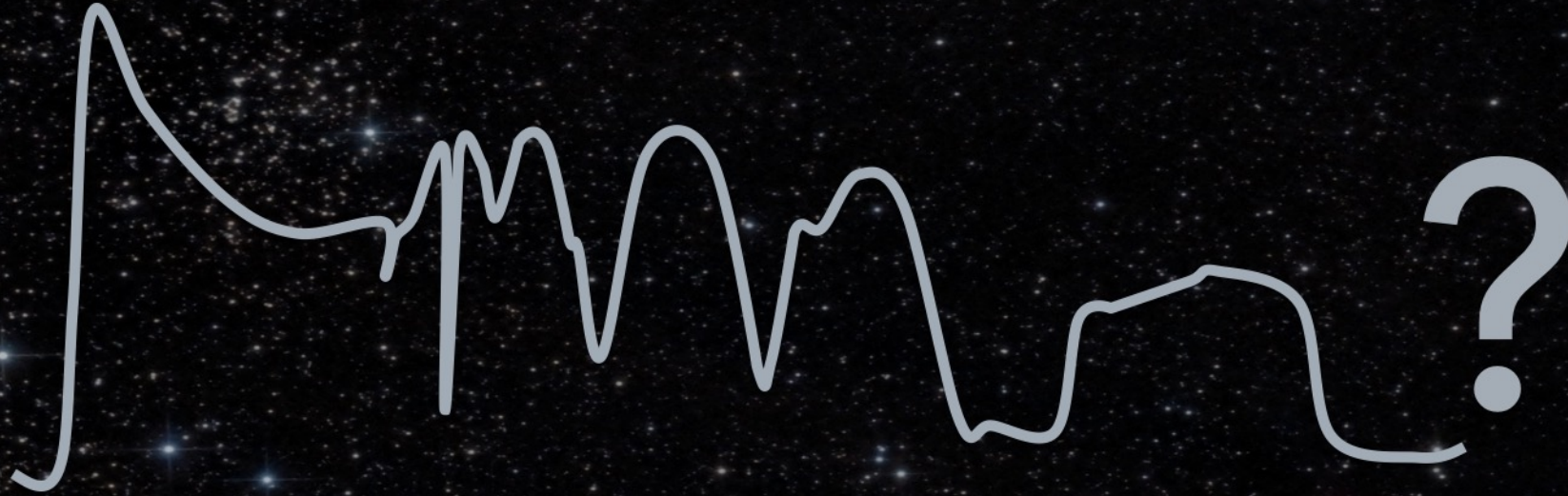
EARTH IS MORE THAN ONE PLANET



NIR wavelengths provide access to the bulk atmospheric constituents needed to calculate the planet's climate



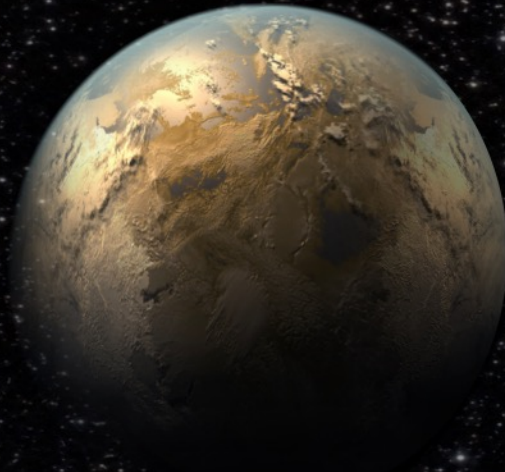
BIOSIGNATURES NEED CONTEXT



False positive?
True biosignature?

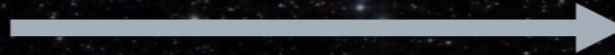
LUVOIR GIVES US THE NEEDED CONTEXT

planetary context



mass
atmosphere
surface properties

enabled by



ECLIPS

wide UV/VIS/NIR
wavelength range

HDI

< 1 μ as precision
astrometry

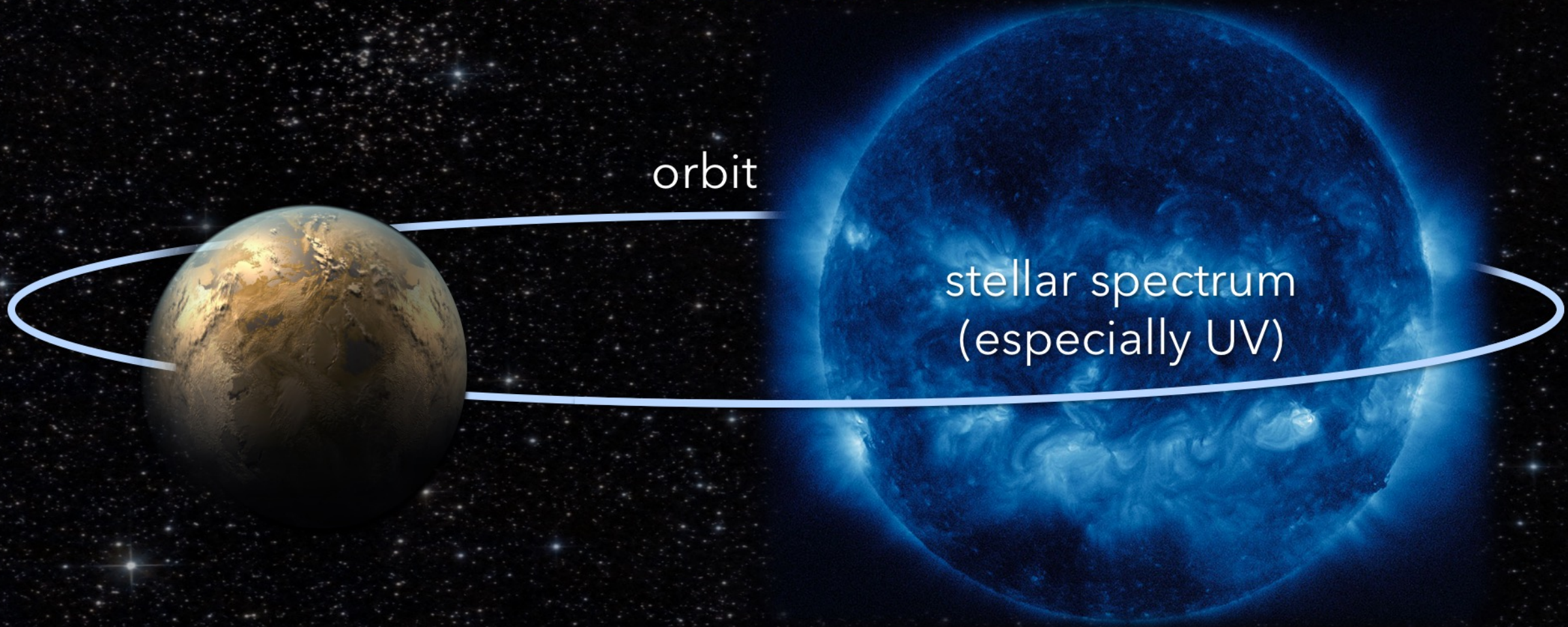
LUVOIR GIVES US THE NEEDED CONTEXT



orbital & stellar context

orbit

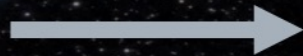
stellar spectrum
(especially UV)



LUVOIR GIVES US THE NEEDED CONTEXT

orbit

enabled by



ECLIPS
multi-epoch imaging

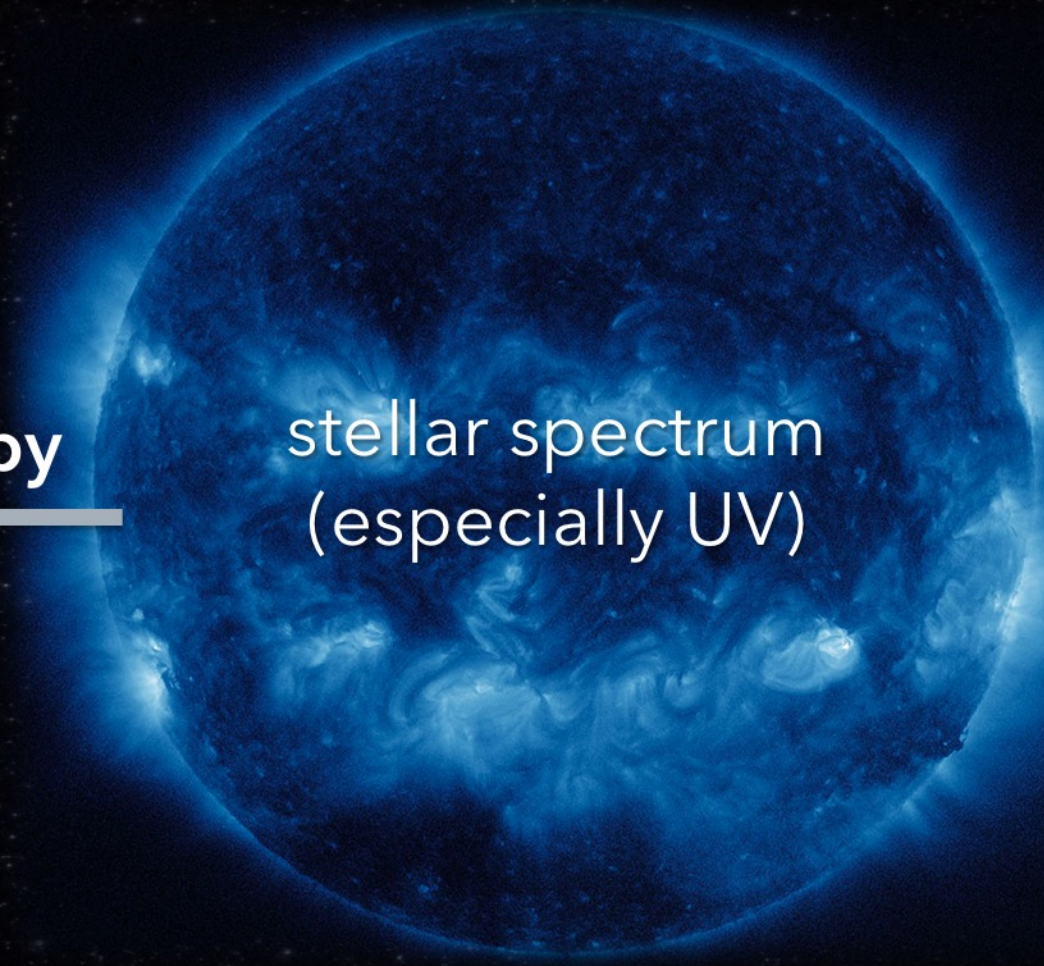
LUVOIR GIVES US THE NEEDED CONTEXT

LUMOS
100-1000 nm spectra

enabled by



stellar spectrum
(especially UV)



LUVOIR GIVES US THE NEEDED CONTEXT



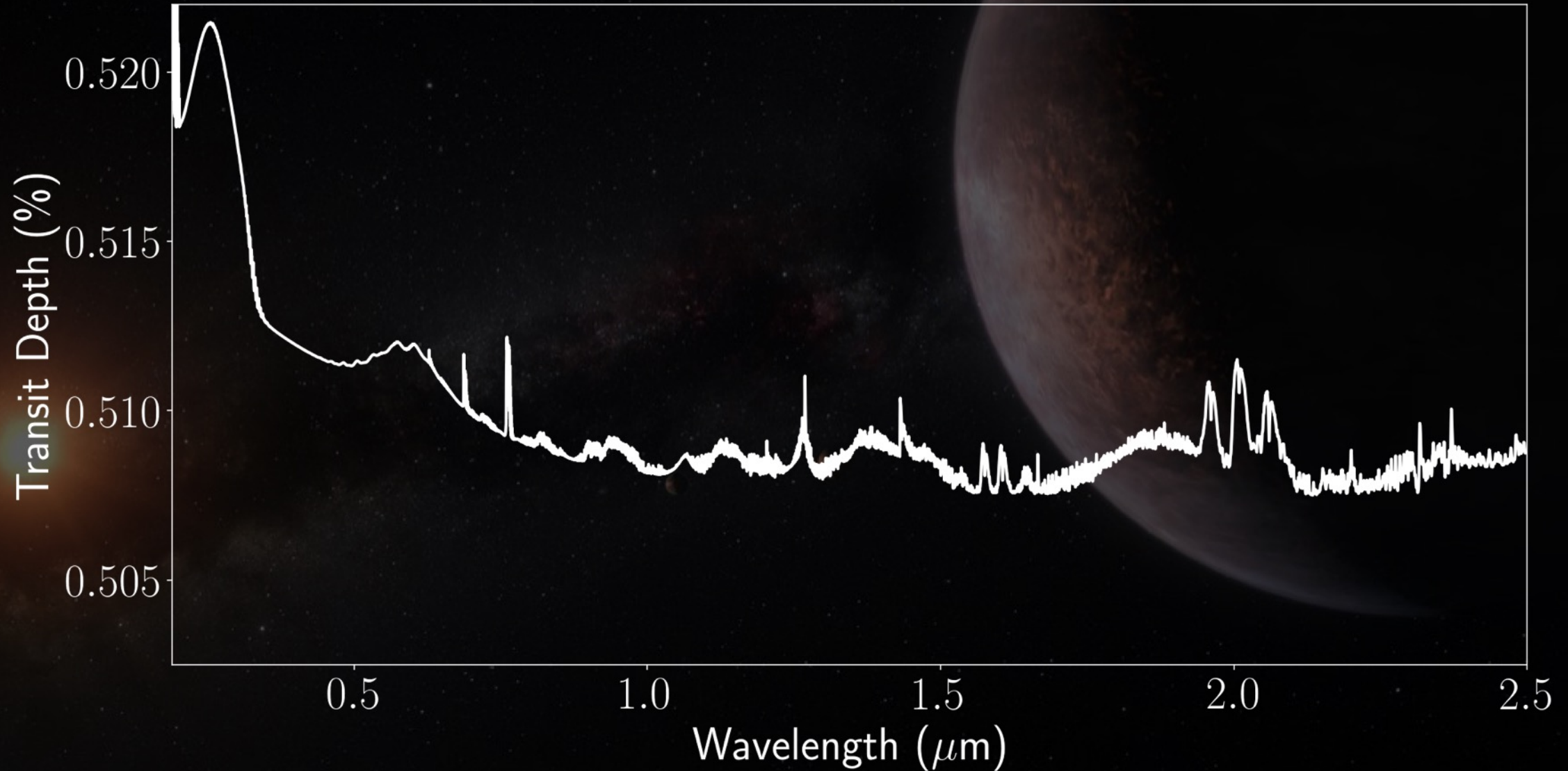
LUVOIR can distinguish every known ***false positive & false negative*** in the literature & accesses a wide range of biosignatures



What about transiting planets?

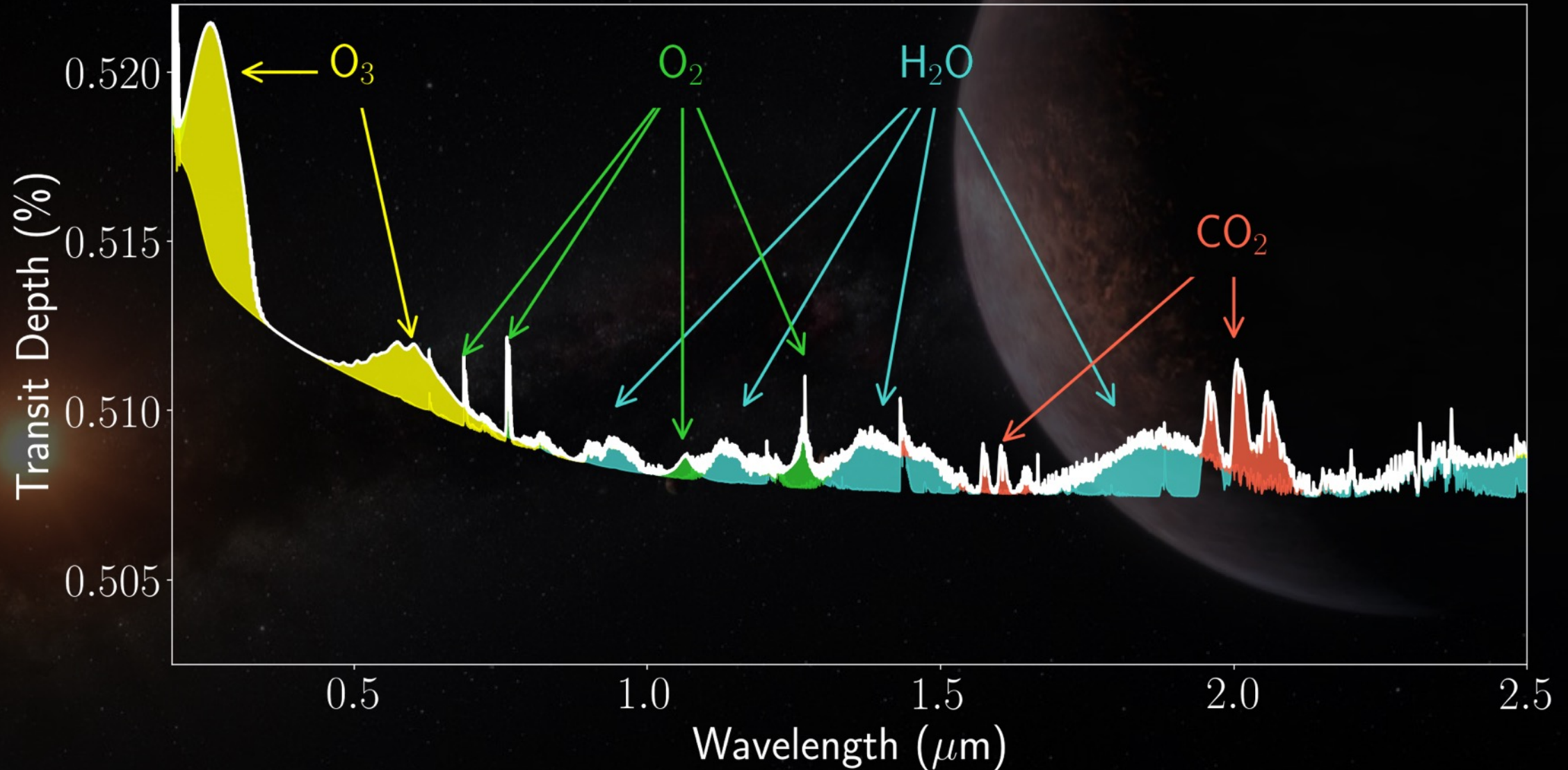
LUVOIR CAN OBSERVE TRANSITING PLANETS

TRAPPIST-1e as a habitable ocean world



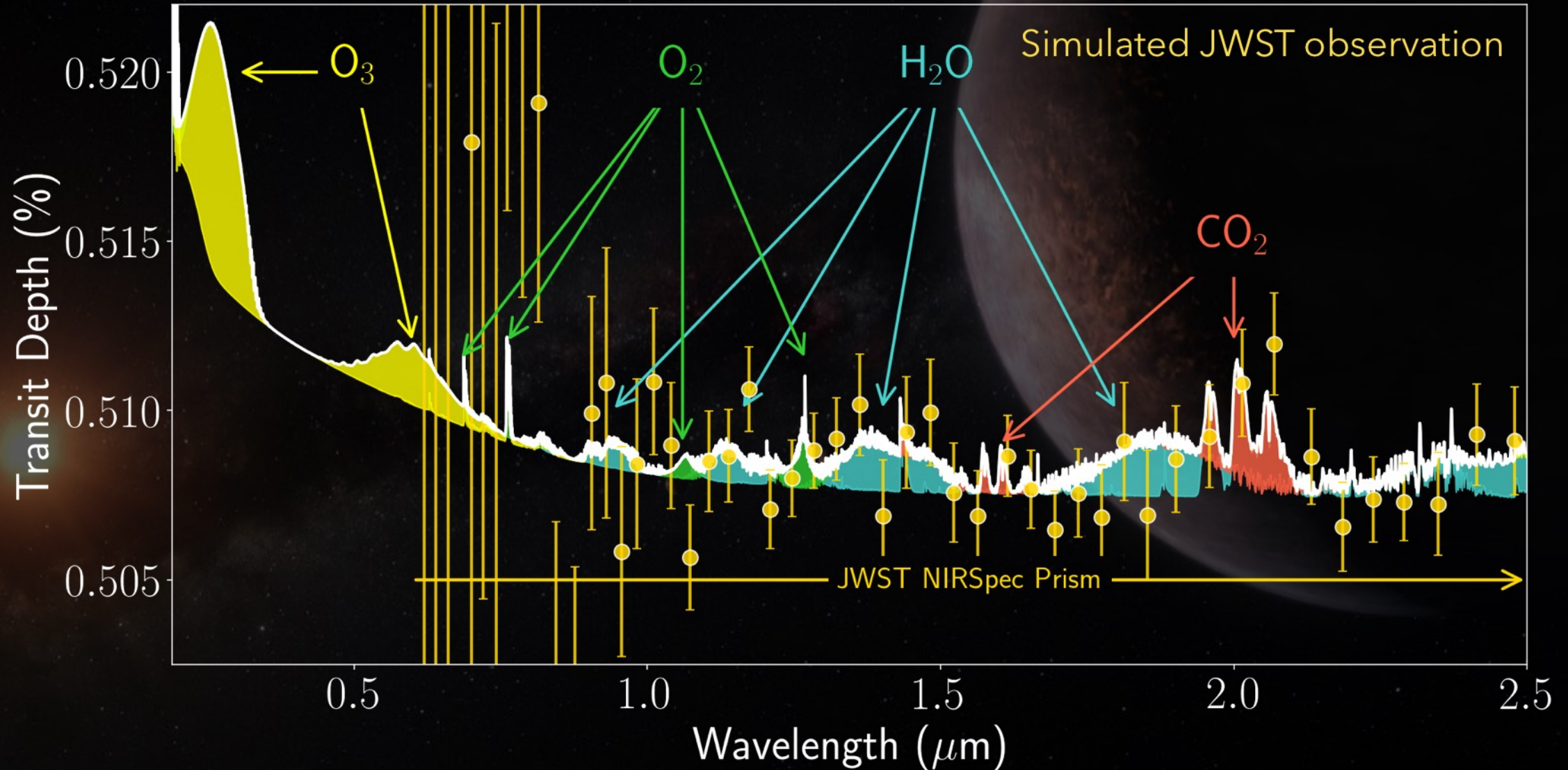
LUVOIR CAN OBSERVE TRANSITING PLANETS

TRAPPIST-1e as a habitable ocean world



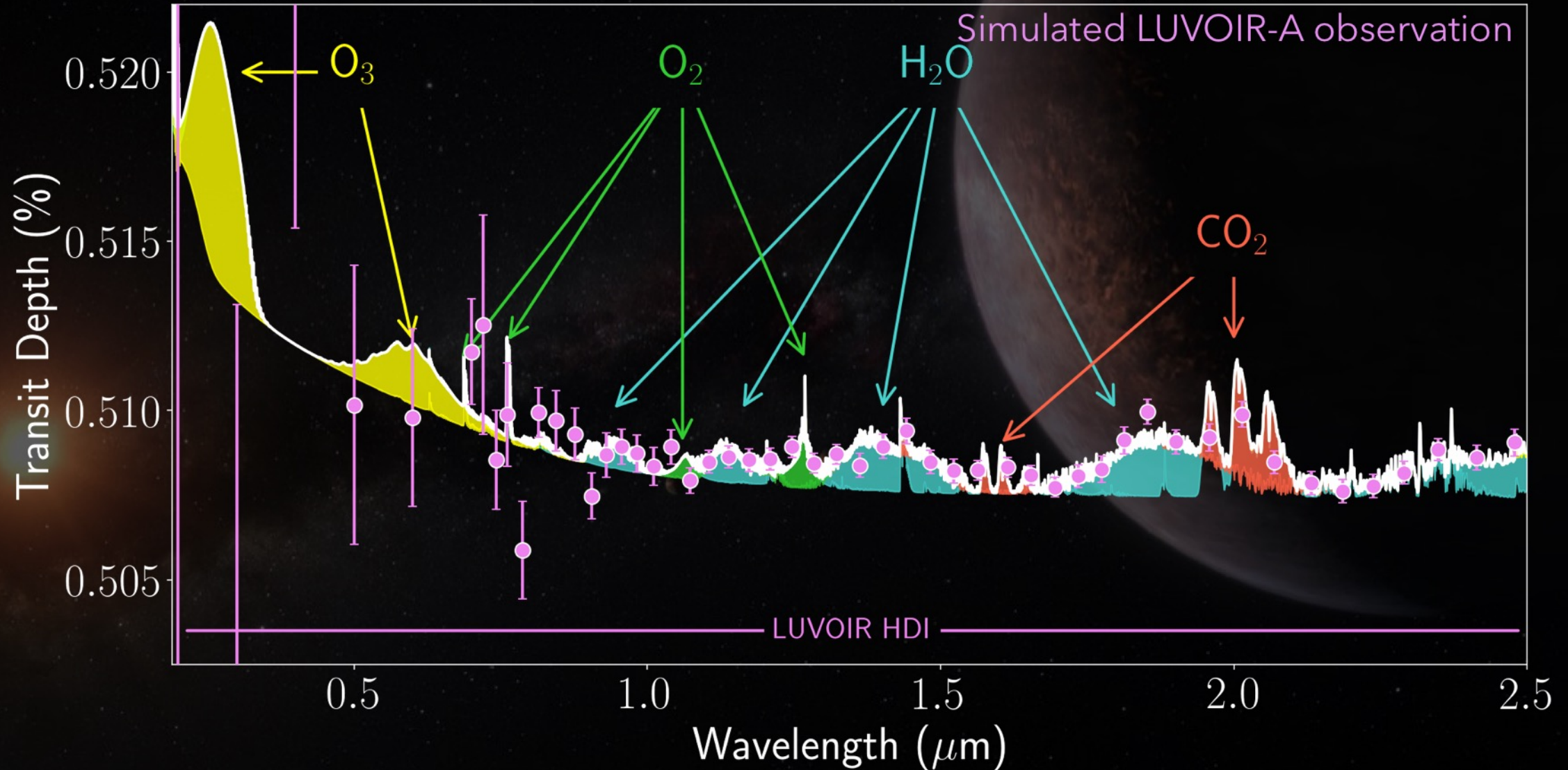
LUVOIR CAN OBSERVE TRANSITING PLANETS

TRAPPIST-1e as a habitable ocean world



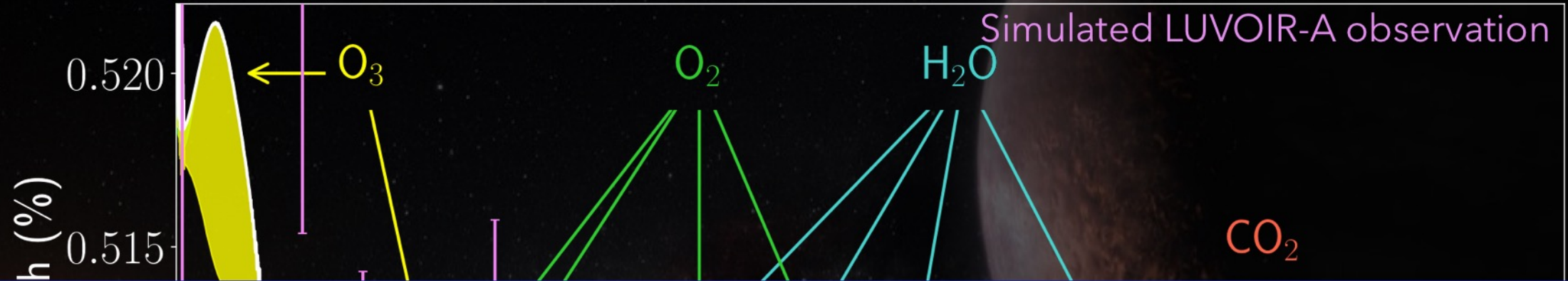
LUVOIR CAN OBSERVE TRANSITING PLANETS

TRAPPIST-1e as a habitable ocean world

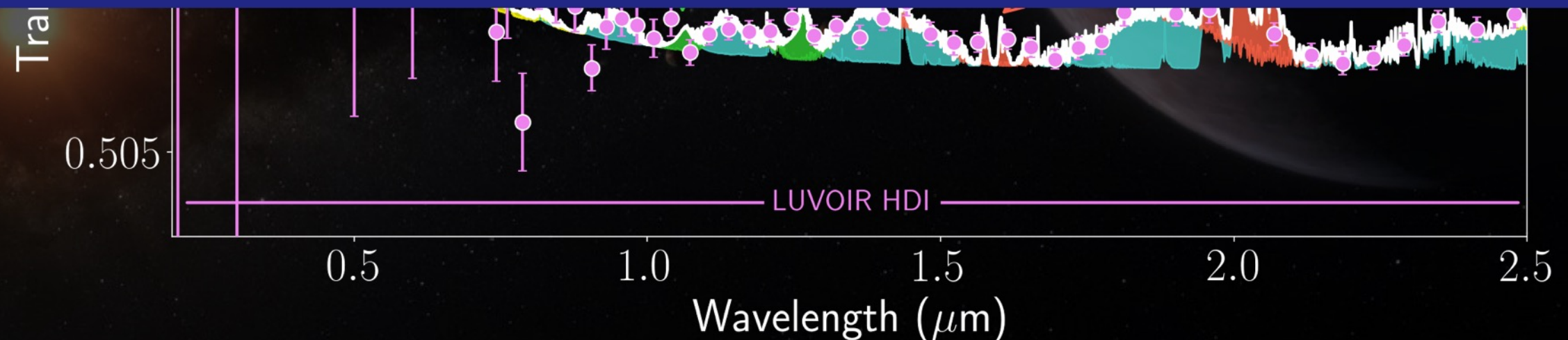


LUVOIR CAN OBSERVE TRANSITING PLANETS

TRAPPIST-1e as a habitable ocean world

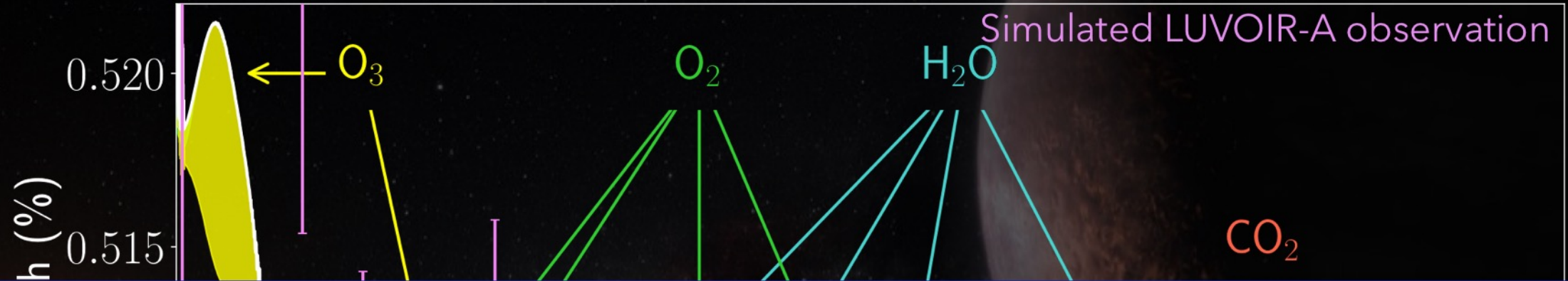


LUVOIR-A has **15x better** SNR at O_2 A band ($0.76 \mu m$)
and **4x better** SNR at $1 \mu m$ than JWST

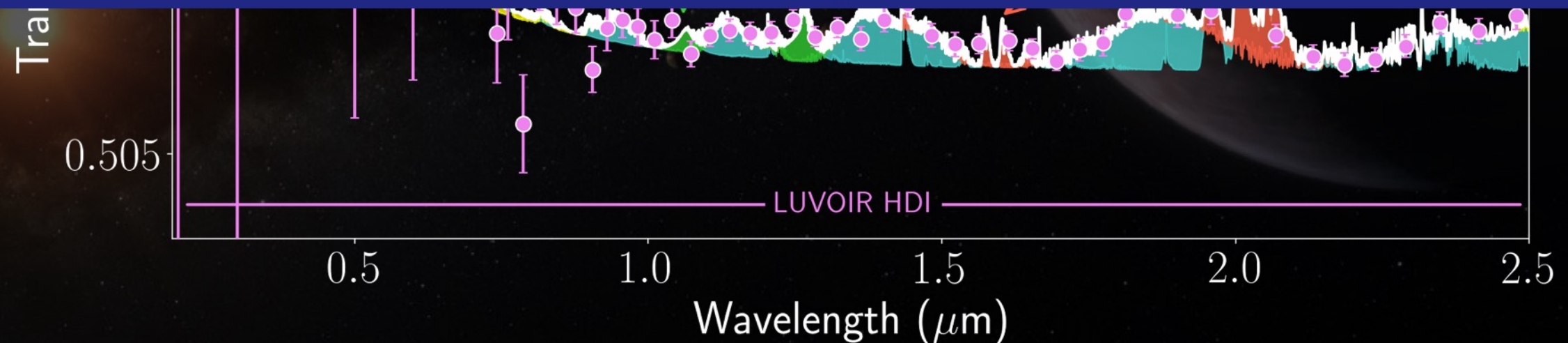


LUVOIR CAN OBSERVE TRANSITING PLANETS

TRAPPIST-1e as a habitable ocean world



LUVOIR transit observations will ***complement and extend*** observations with JWST & ground-based facilities



A LARGE, DIVERSE SAMPLE TELLS THE STORIES OF LIFE



What makes a planet habitable?

LUVOIR will empirically test ideas of habitability (e.g. habitable zone boundaries)

Habitability across contexts

Does habitability vary across stellar contexts? Across systems with different planetary architectures? Etc...

Are we alone?

Statistically meaningful chance of answering this question: **comparative astrobiology**

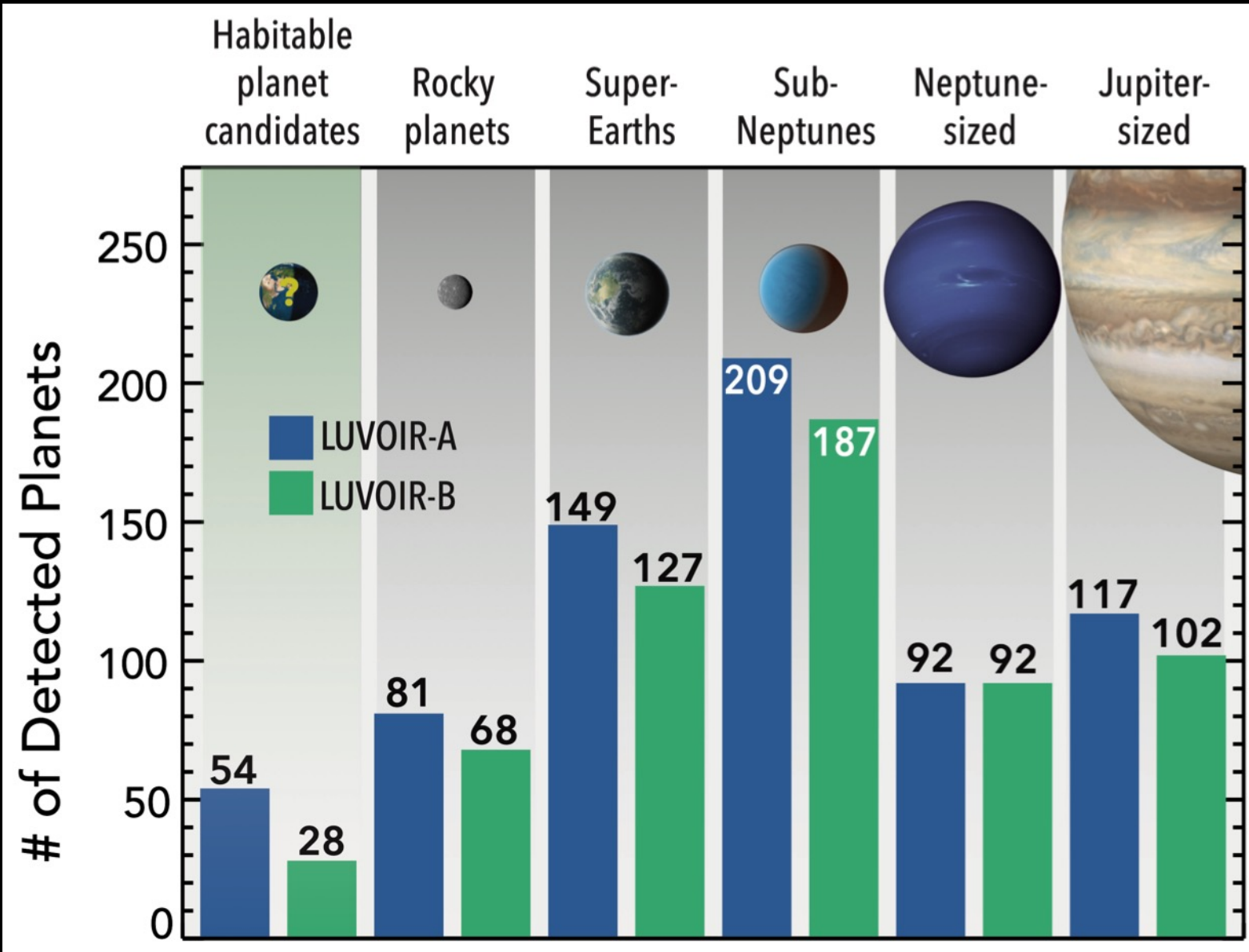


EXOTIC WORLDS

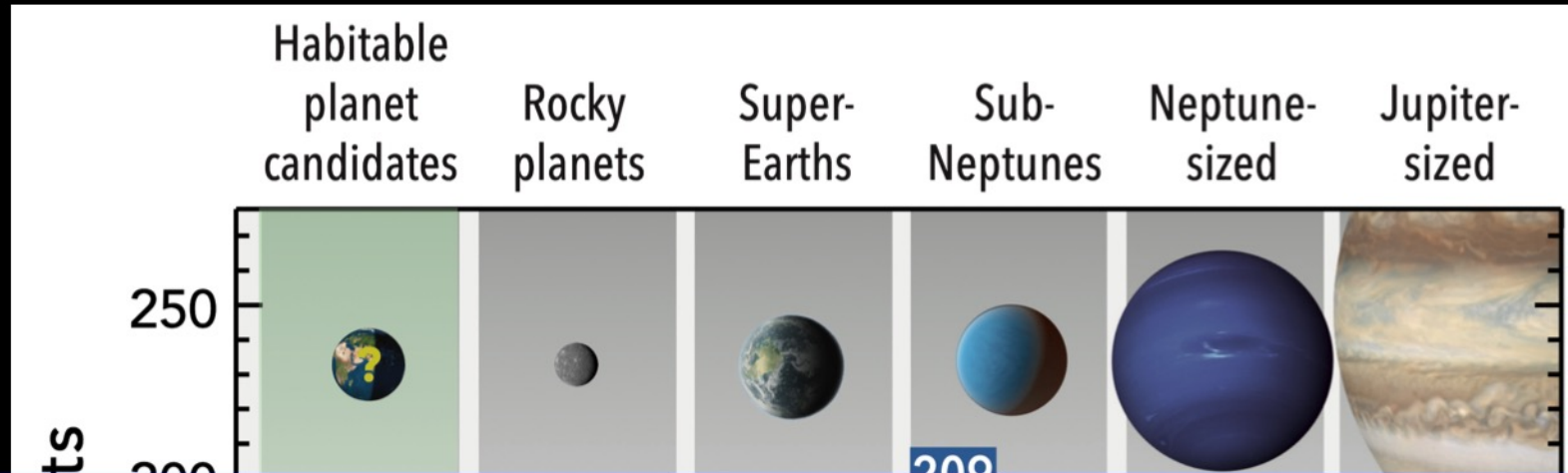


LUVOIR

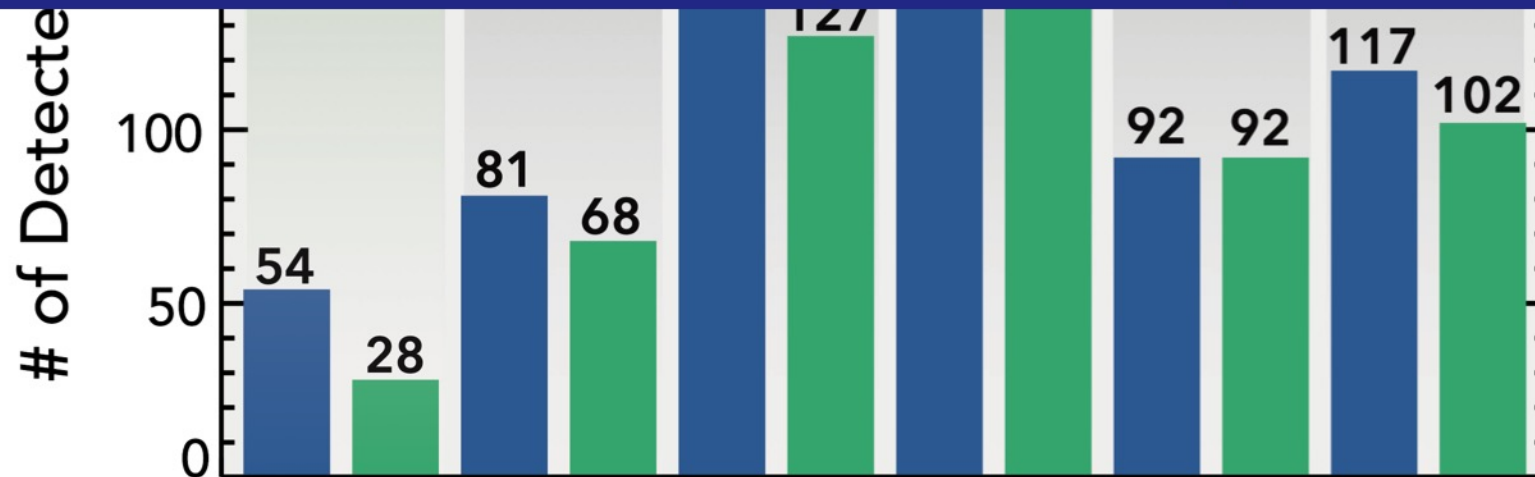
DOZENS OF HABITABLE CANDIDATES, HUNDREDS OF PLANETS



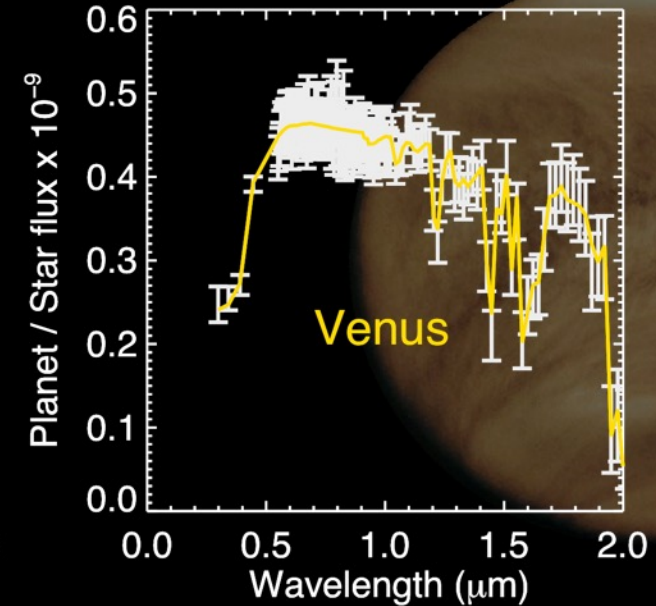
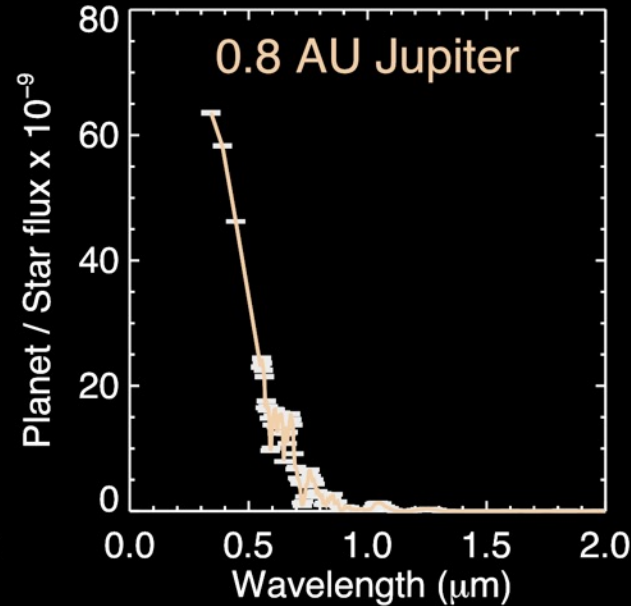
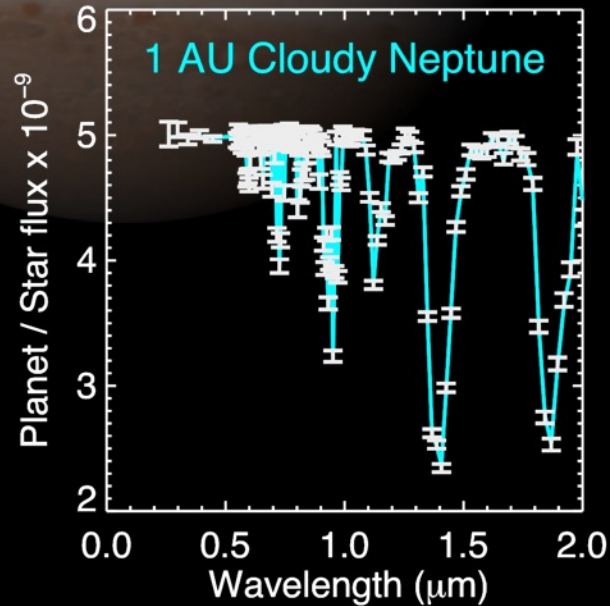
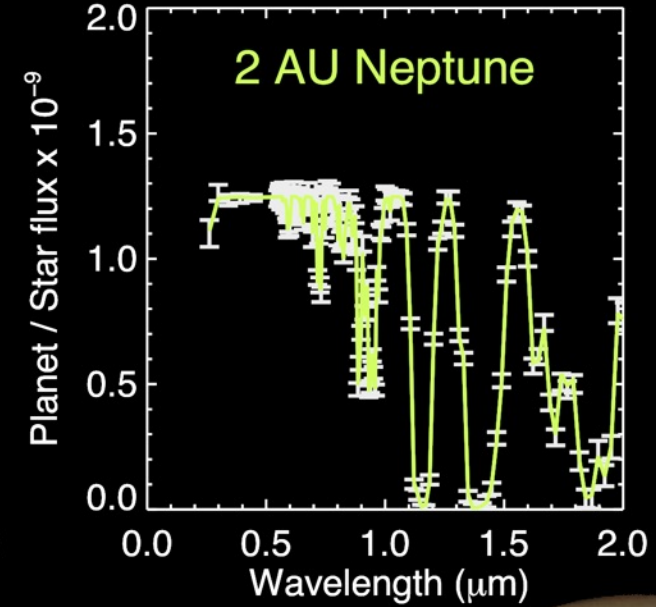
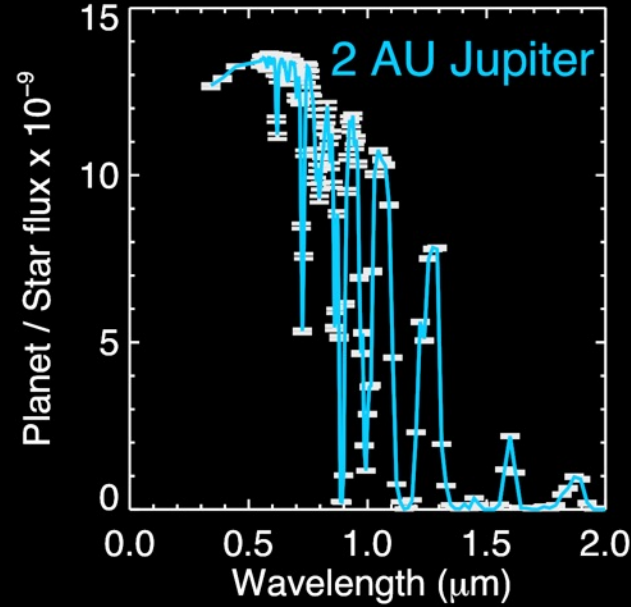
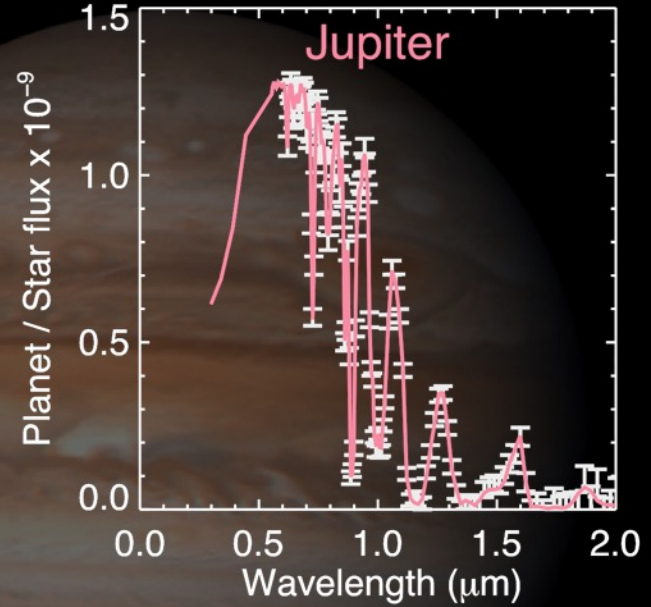
DOZENS OF HABITABLE CANDIDATES, HUNDREDS OF PLANETS



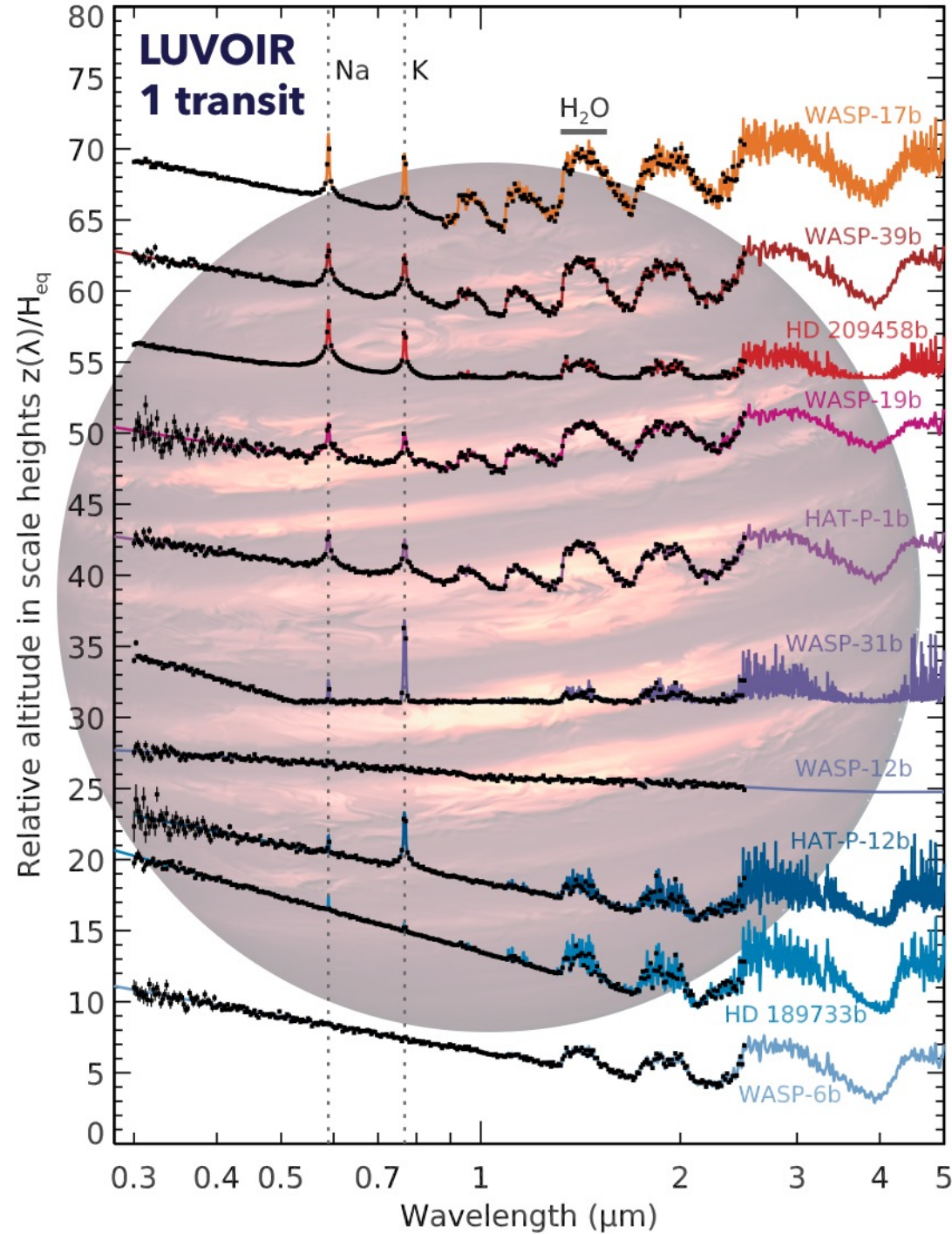
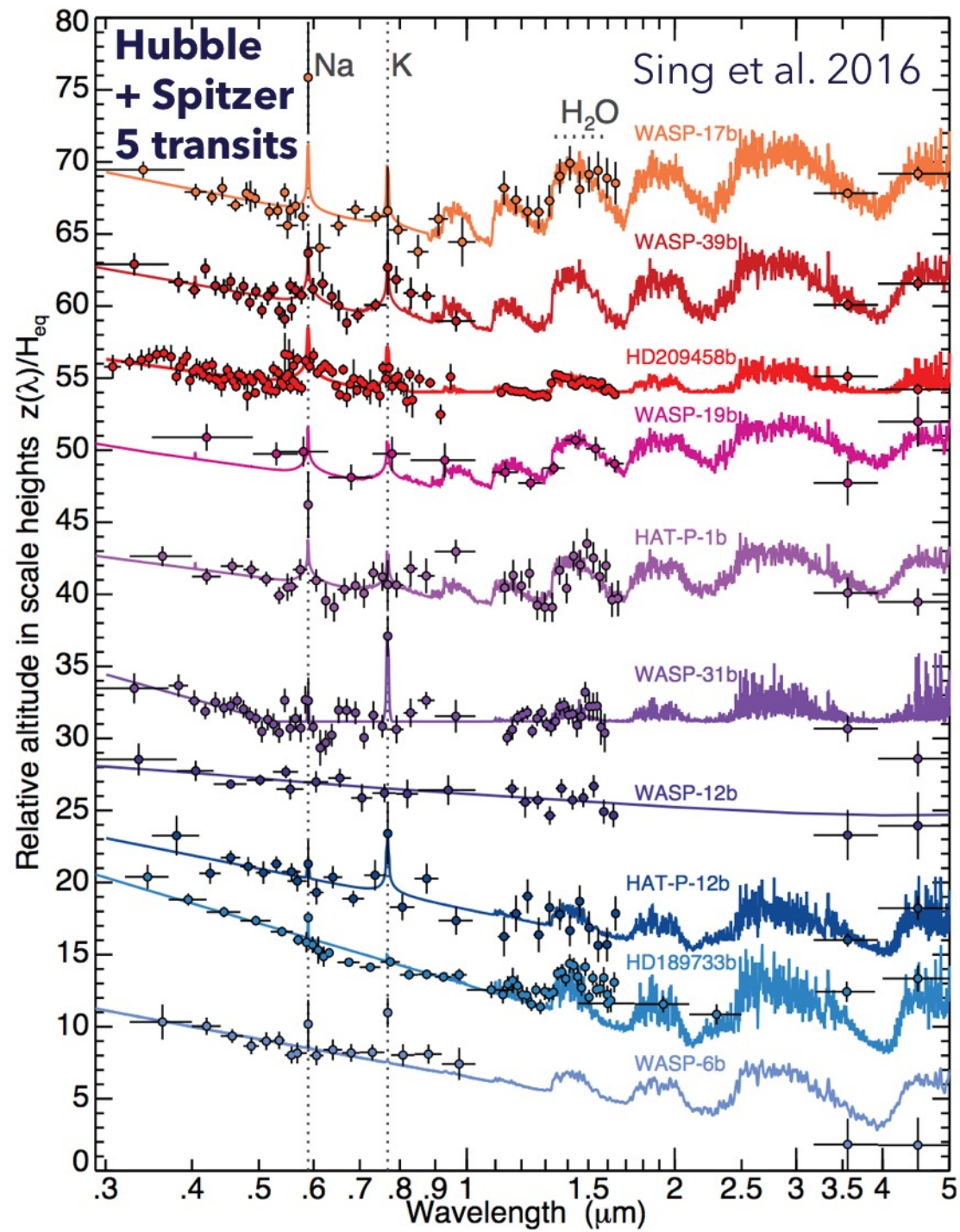
For every exoEarth candidate, LUV O I R will observe $>10x$ as many exotic exoplanets



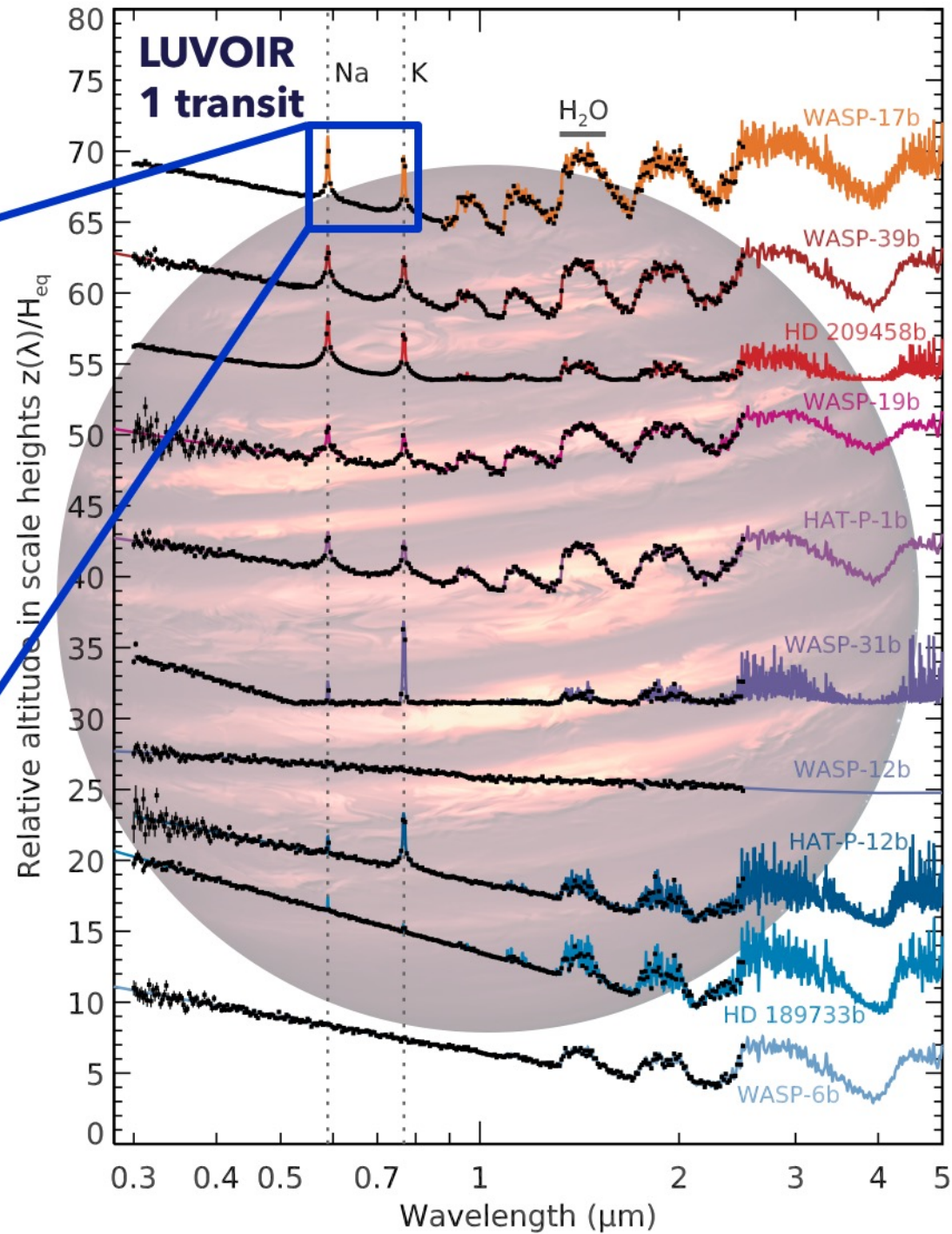
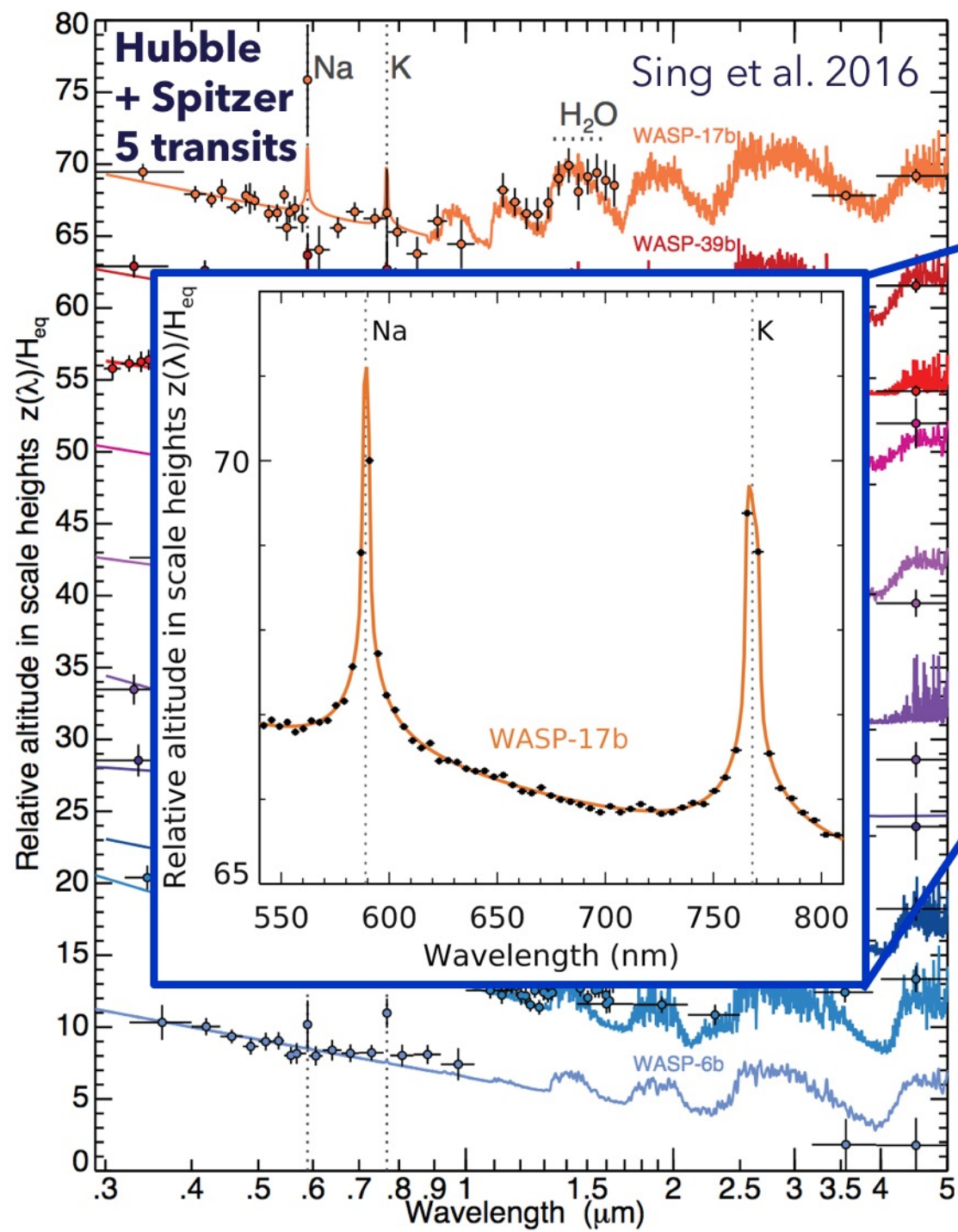
COLD TO WARM PLANETS



WARM TO HOT PLANETS

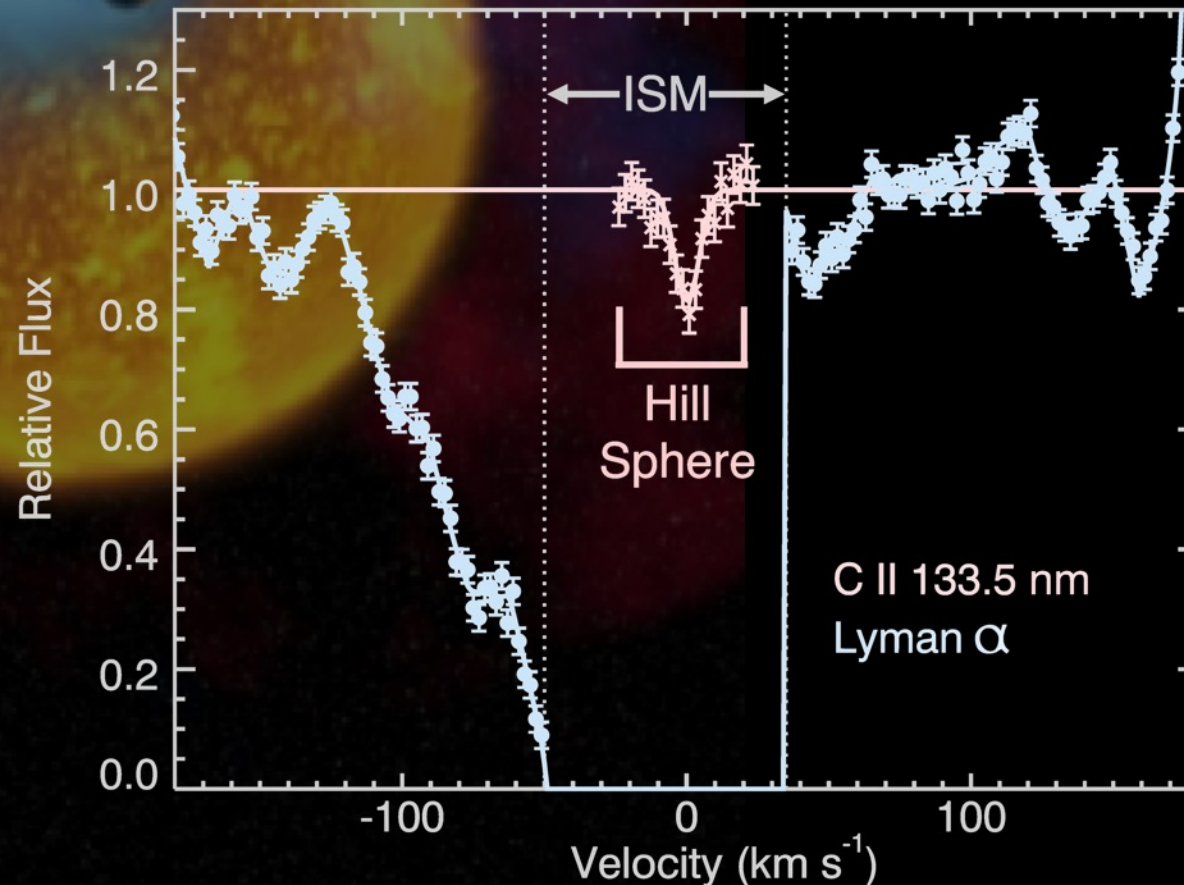


WARM TO HOT PLANETS

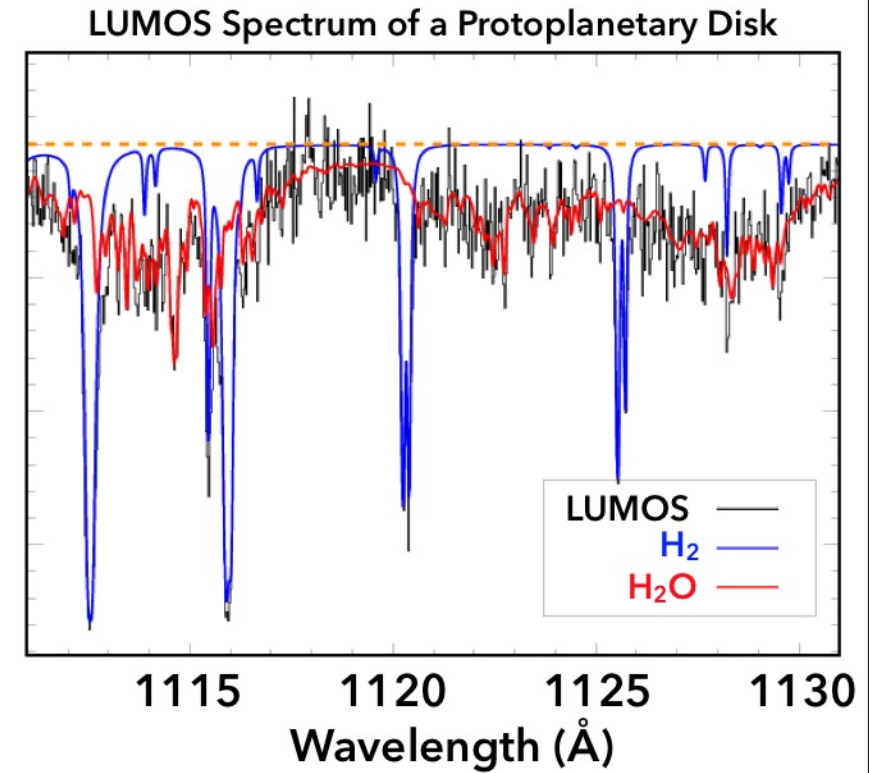
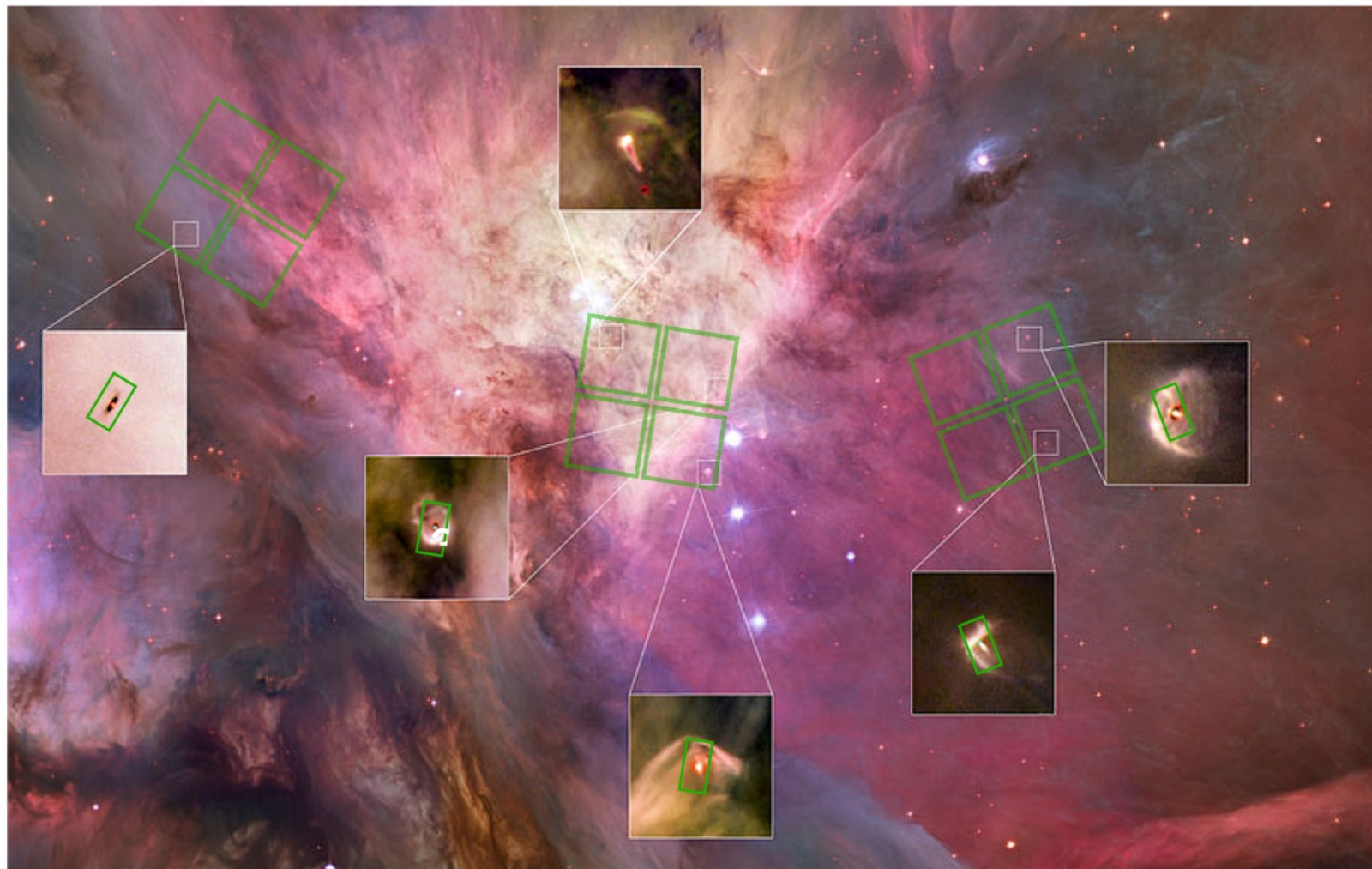


ATMOSPHERIC ESCAPE

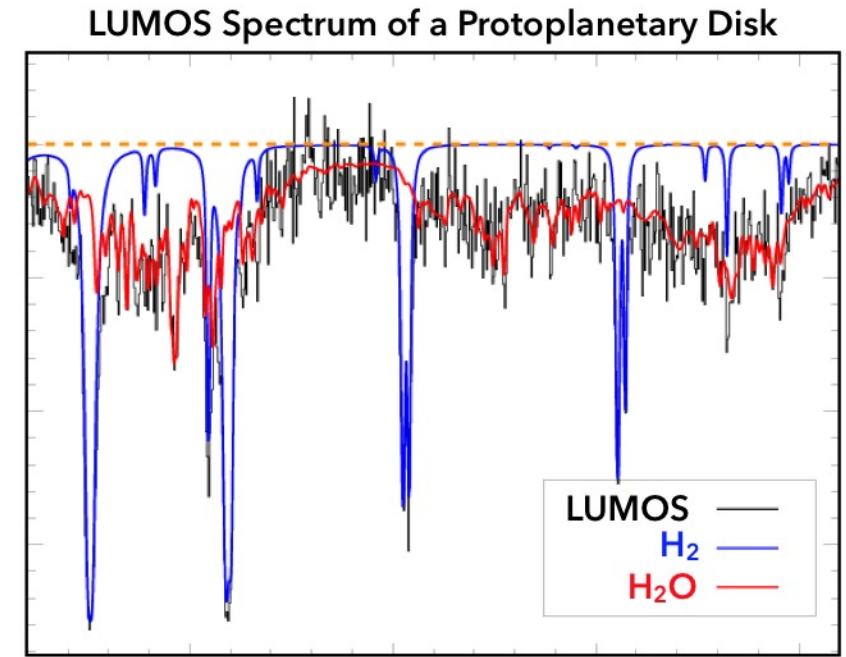
Escaping gas from a warm Neptune (GJ 436b)
detected in a **single far-UV transit spectrum** with LUVOIR



THE POWER OF MULTIPLEXING FOR PLANET FORMATION



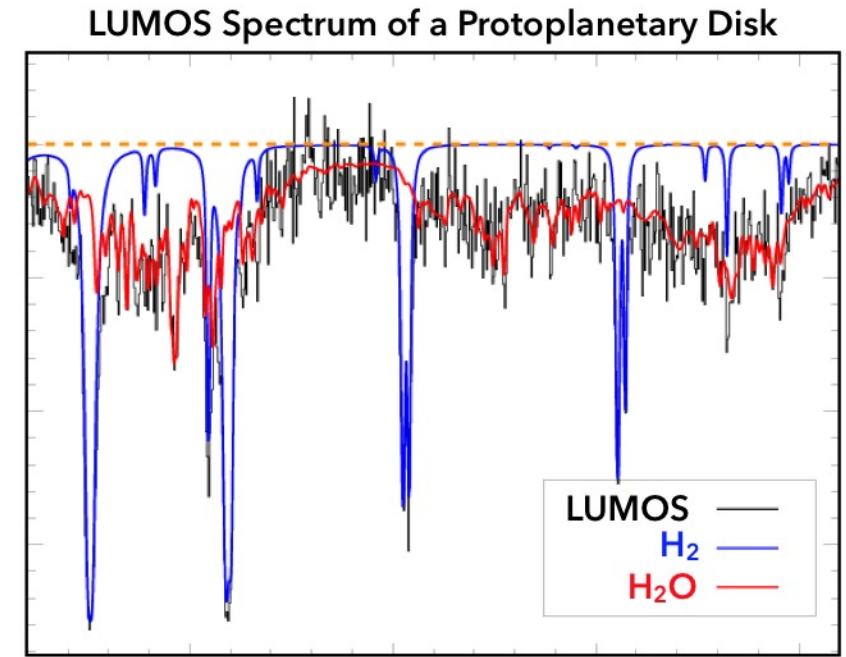
THE POWER OF MULTIPLEXING FOR PLANET FORMATION



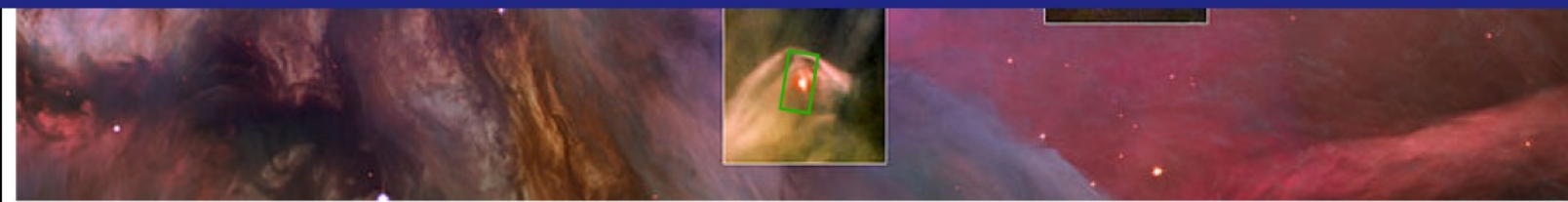
LUMOS can measure H₂ and water in *hundreds of simultaneous protoplanetary disk* FUV spectra



THE POWER OF MULTIPLEXING FOR PLANET FORMATION

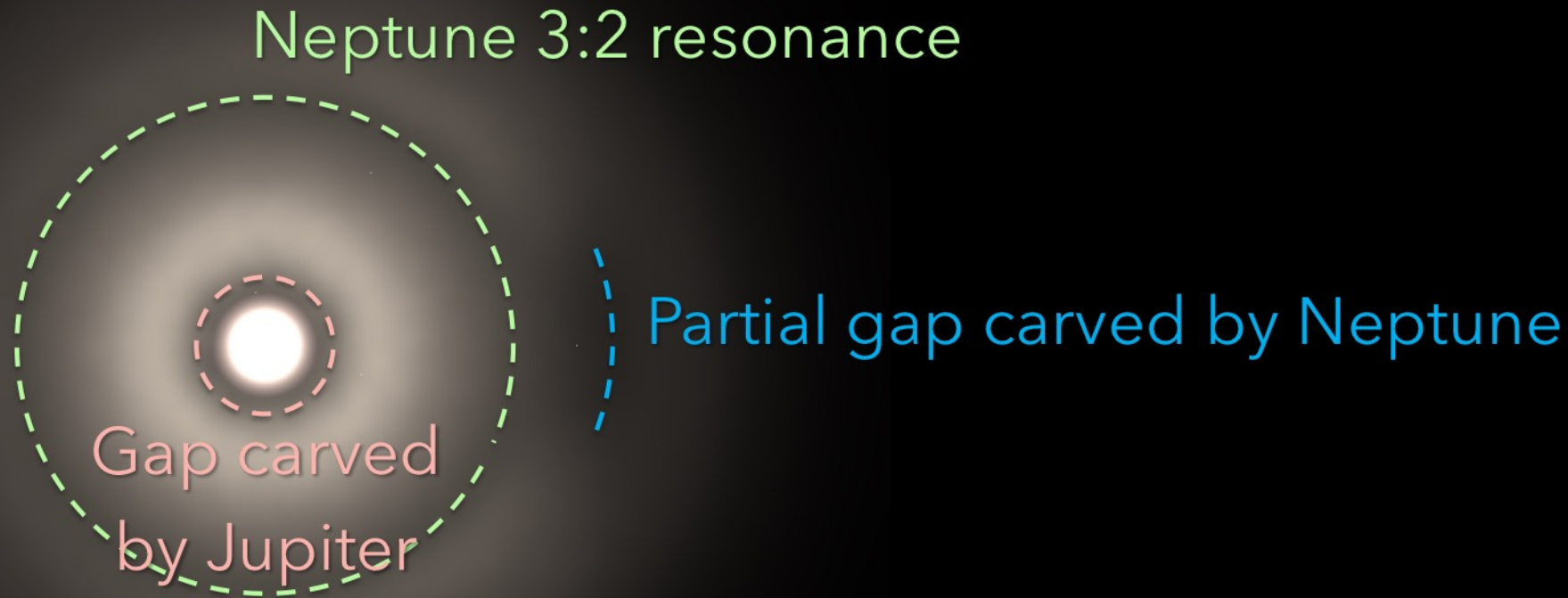


1 LUMOS map = 29 years of HST observations



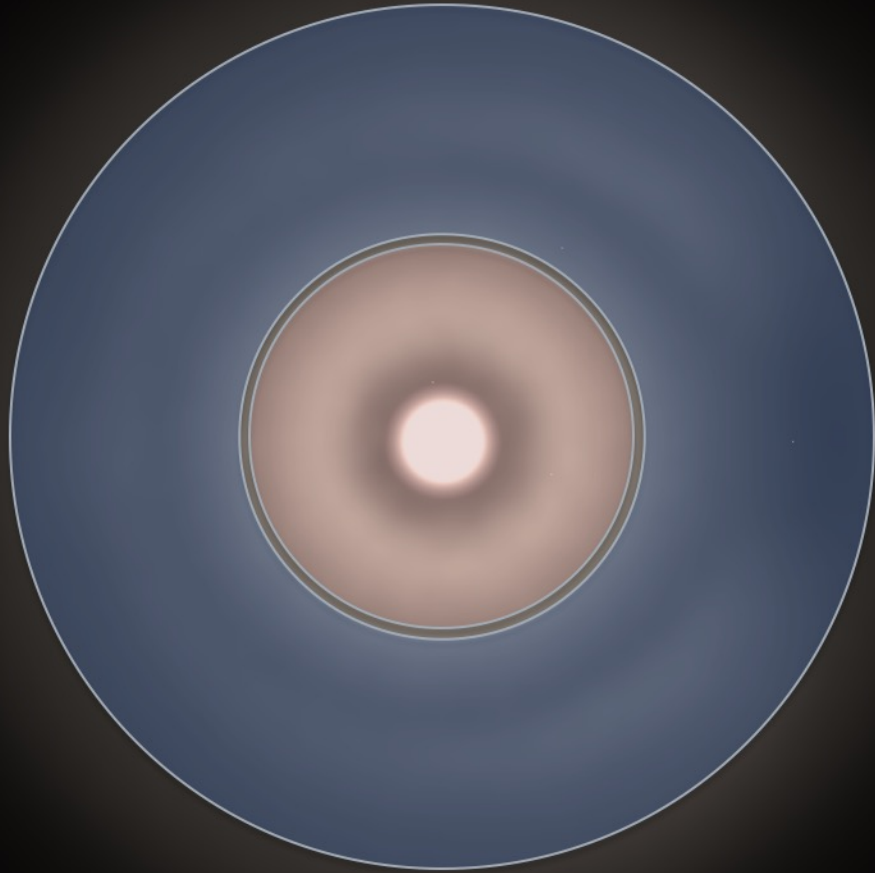
THE DYNAMICAL HISTORIES OF PLANETARY SYSTEMS

Planets + dust from planetesimal belts = complete system architecture



Solar System, with planets and
interplanetary dust

THE DYNAMICAL HISTORIES OF PLANETARY SYSTEMS



First high-resolution images of warm interplanetary dust from ECLIPS high-contrast imaging

Cold interplanetary dust from ALMA

THE DYNAMICAL HISTORIES OF PLANETARY SYSTEMS



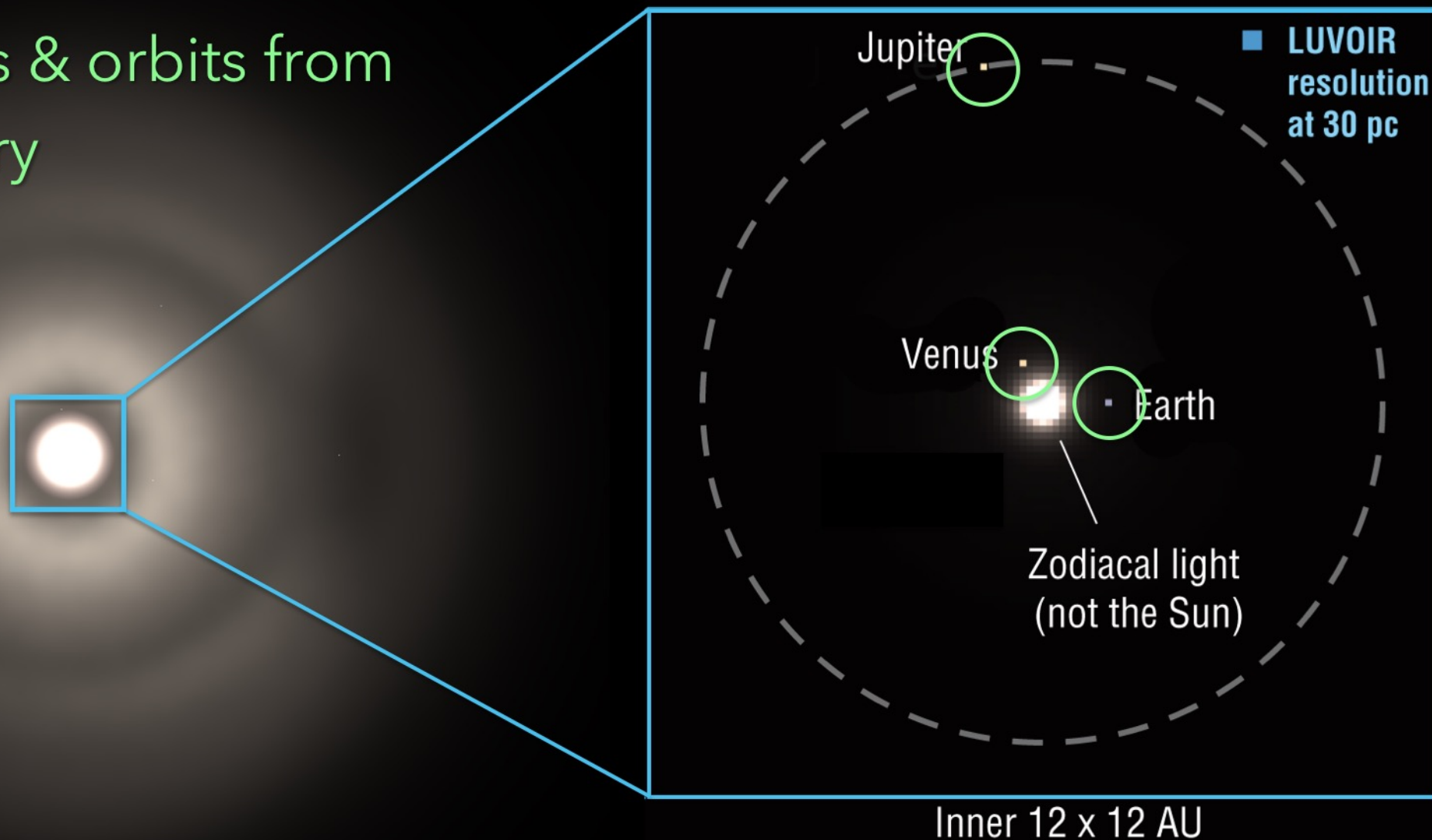
First high-resolution images of warm interplanetary dust from ECLIPS high-contrast imaging

LUV OIR disk & dust observations will ***complement and extend*** observations with ALMA & other ground-based facilities

Cold interplanetary dust from ALMA

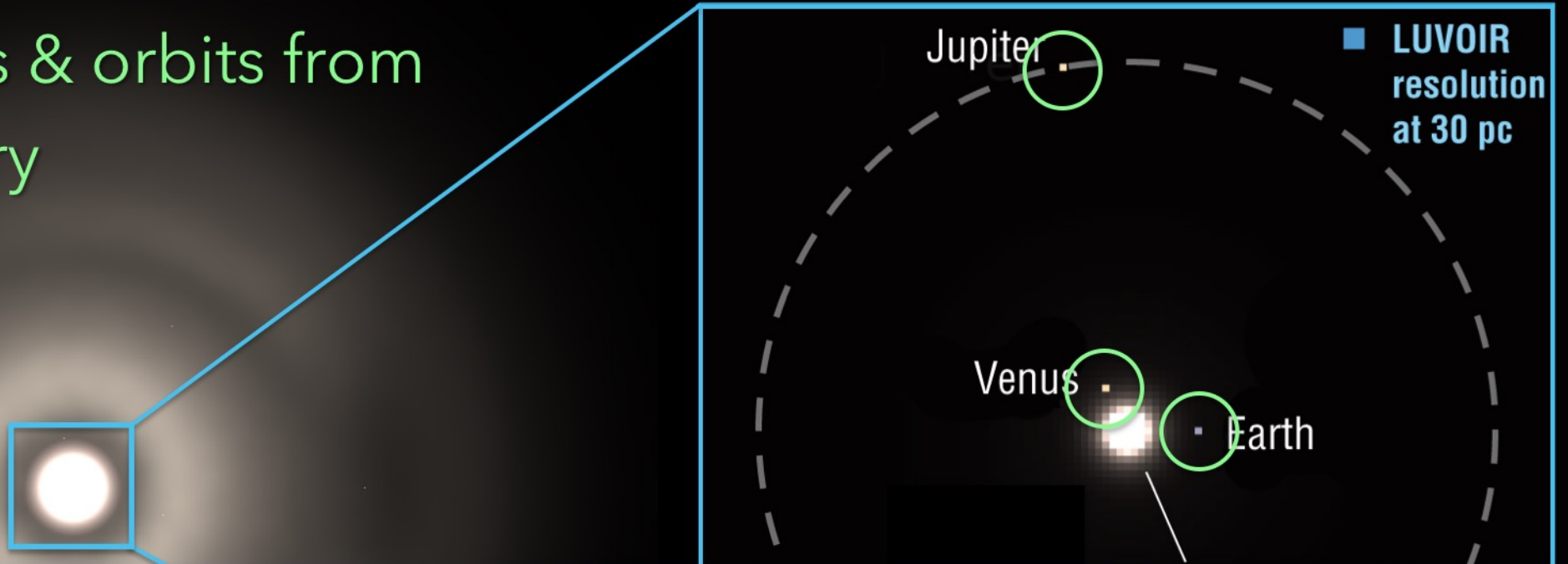
THE DYNAMICAL HISTORIES OF PLANETARY SYSTEMS

Planet masses & orbits from
HDI astrometry



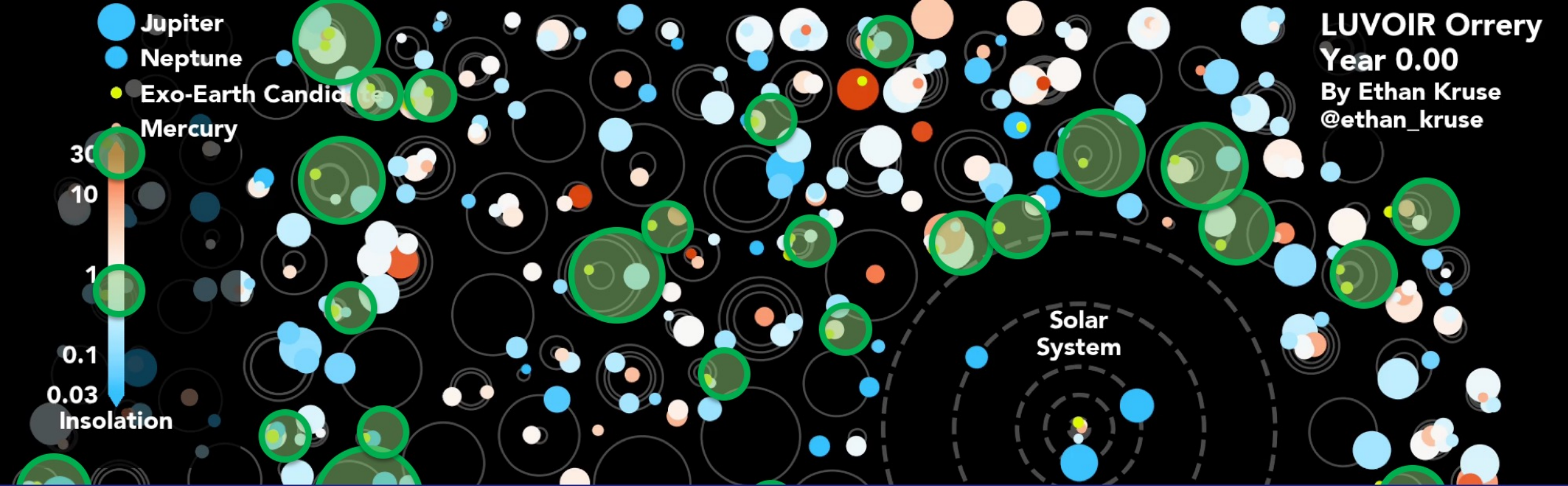
THE DYNAMICAL HISTORIES OF PLANETARY SYSTEMS

Planet masses & orbits from
HDI astrometry

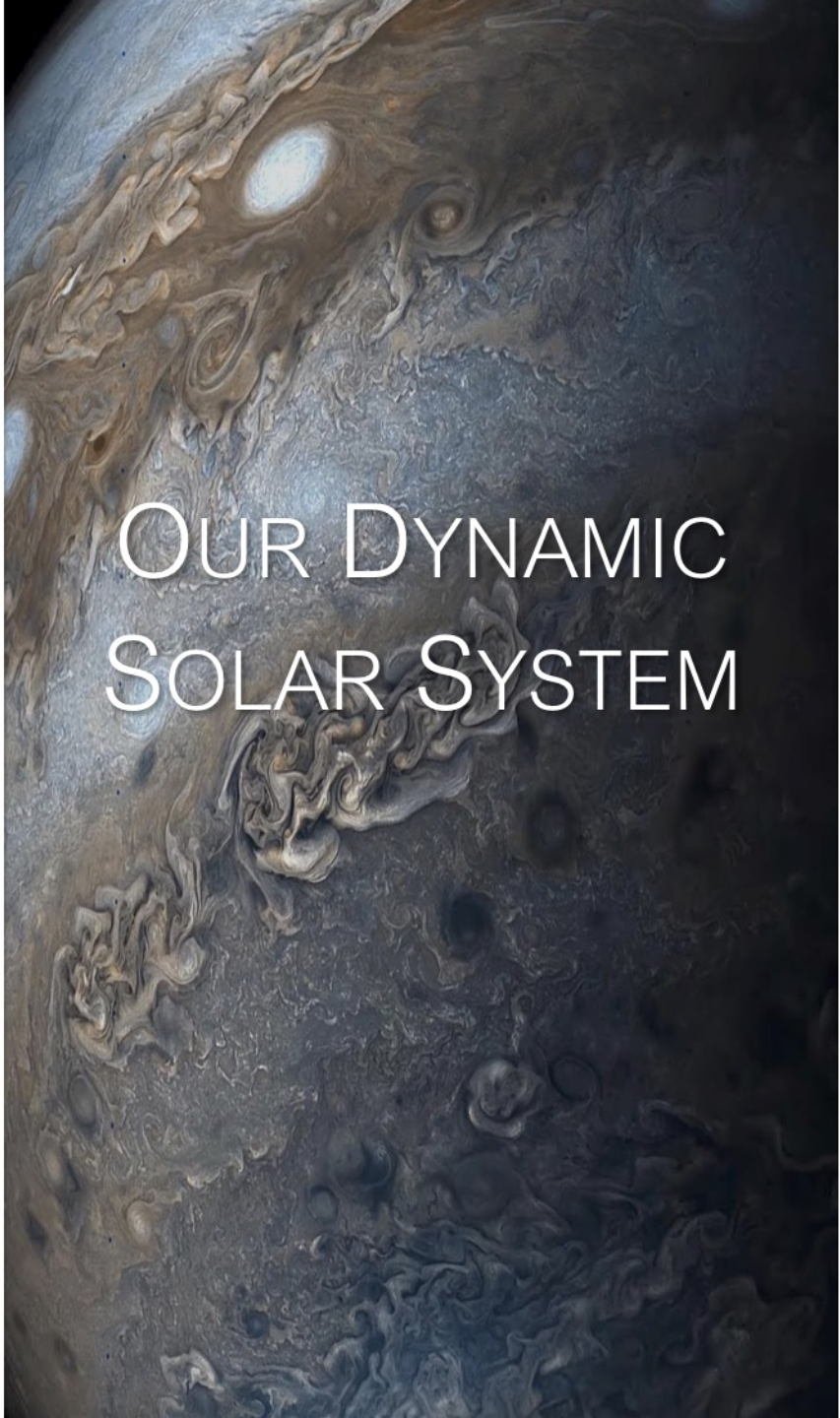


LUV OIR enables *high-fidelity dynamical modeling*
of whole exoplanetary systems

Inner 12 x 12 AU



LUVOR will answer questions we have *pondered for millennia*
and questions *we can't yet think to ask*



OUR DYNAMIC SOLAR SYSTEM



L U V O I R



Flyby-quality observations of Solar System bodies

Jupiter from JUNO at ~ 30 km resolution

Comparable to LUVOIR-A (~ 24 km at opposition)

THE HISTORY OF THE SOLAR SYSTEM IN SMALL BODIES

Ceres

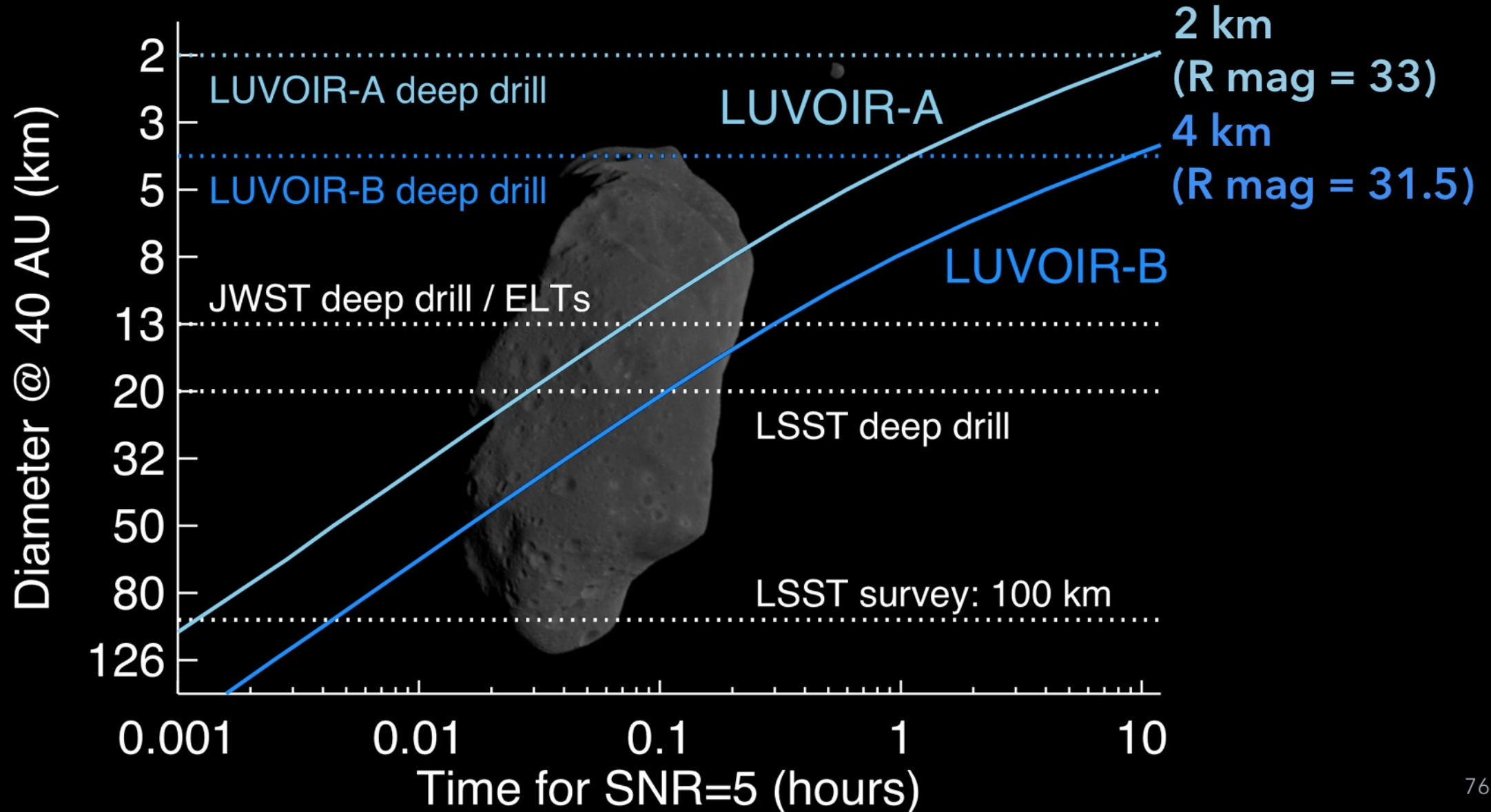
2.4-m

LUVOIR-B

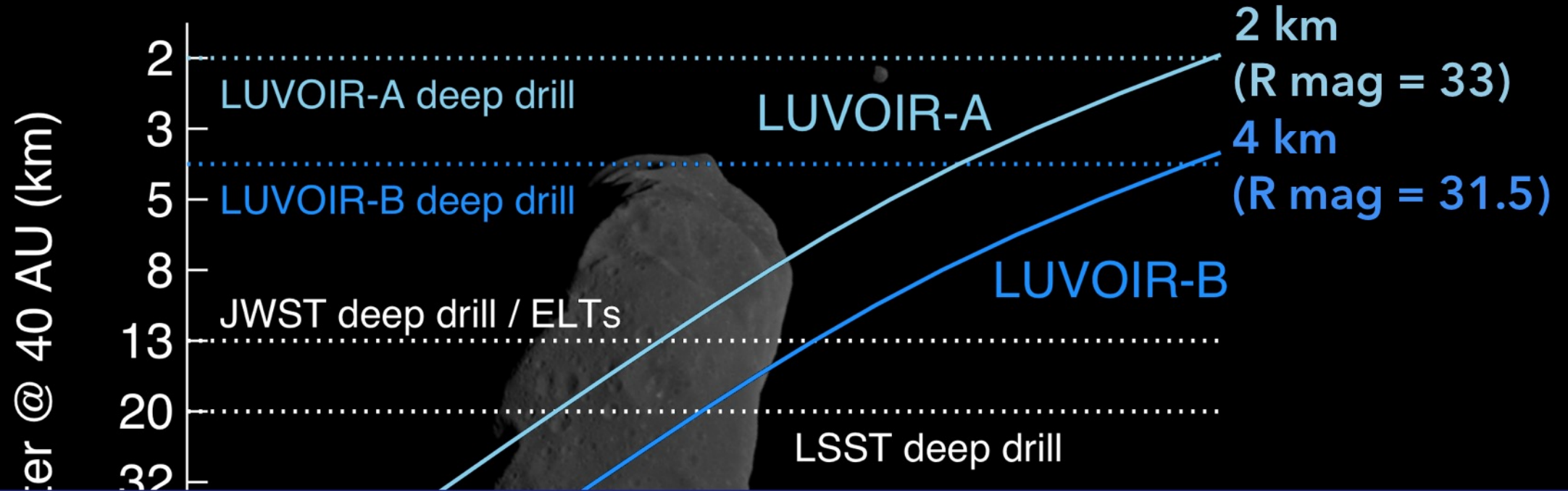
LUVOIR-A

LUVOIR can *monitor bodies throughout the Solar System*
with flexible cadence over long time scales

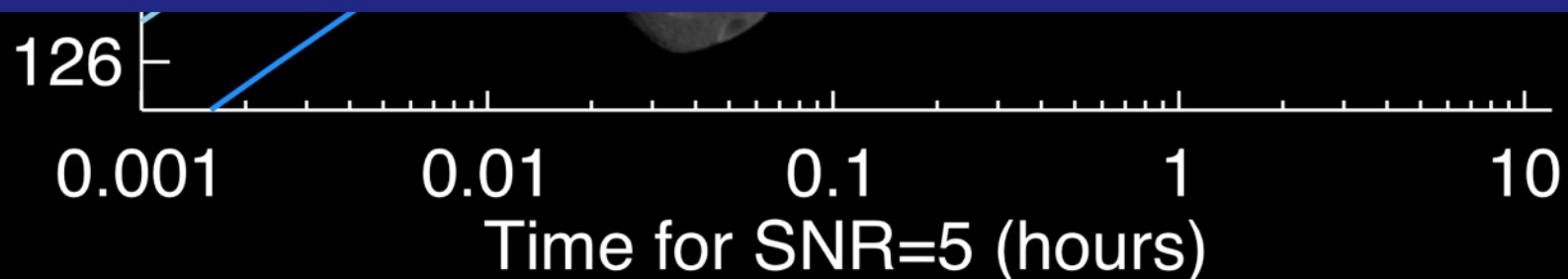
THE HISTORY OF THE SOLAR SYSTEM IN SMALL BODIES



THE HISTORY OF THE SOLAR SYSTEM IN SMALL BODIES



LUVOIR HDI has the sensitivity to see the ***Solar System's primordial planetesimals*** and constrain initial formation of planets



HABITABLE ENVIRONMENTS? SOLAR SYSTEM OCEAN MOONS

Europa in far-UV Lyman- α emission

HST

LUVOIR-B

LUVOIR-A

LUVOIR can ***monitor cryovolcanic activity*** from the Solar System's ocean worlds at high resolution

COSMIC ORIGINS & THE ULTRA-FAINT UNIVERSE



LUVAIR

THE COSMIC LANDSCAPE – BIG QUESTIONS

What does clustering on galactic scales reveal about the nature of dark matter?

How do galaxies and their gas co-evolve?

How do galaxies quench and stay that way?

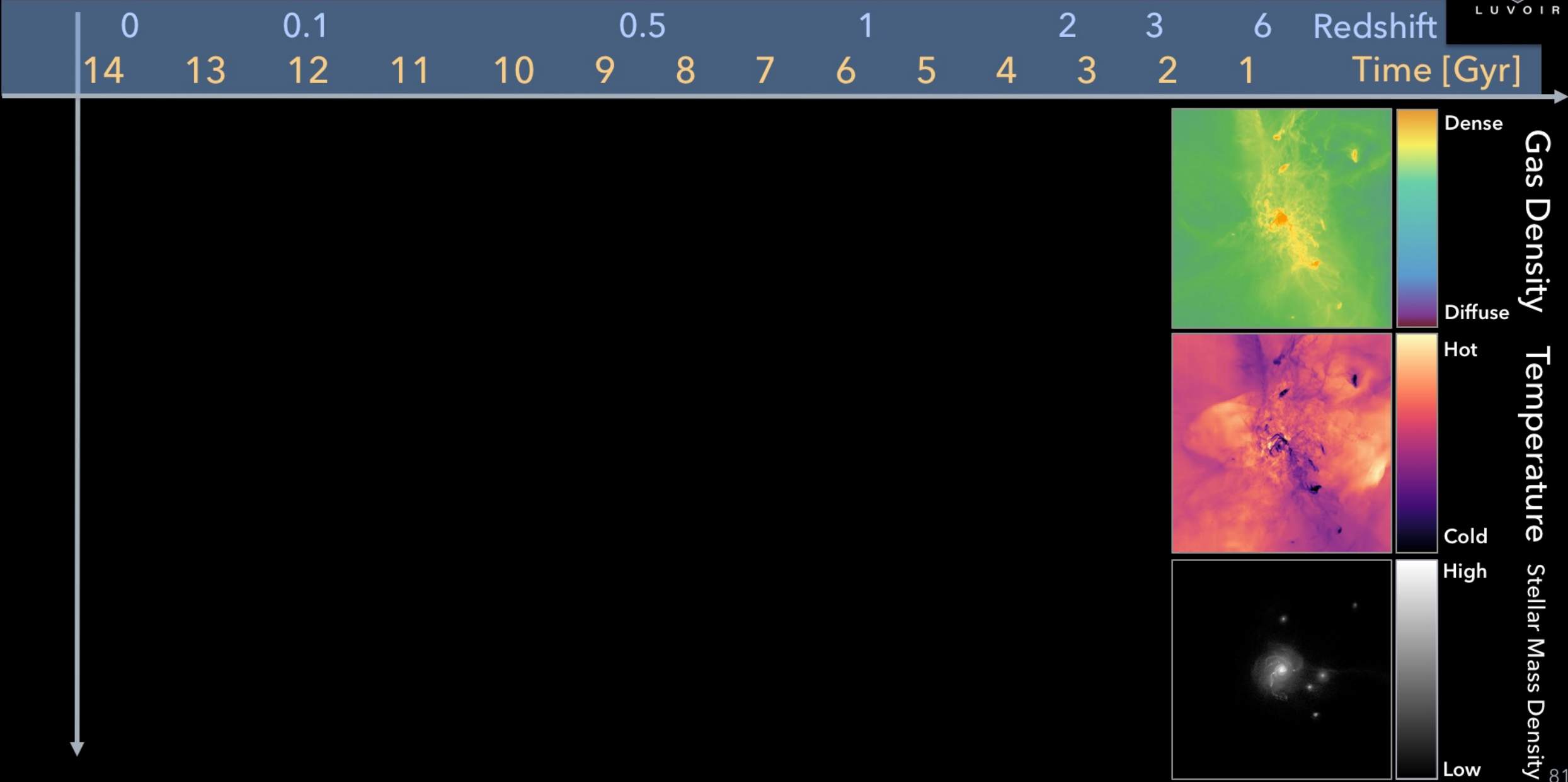
How are the chemical elements produced and distributed?

How do stars evolve and end their lives?

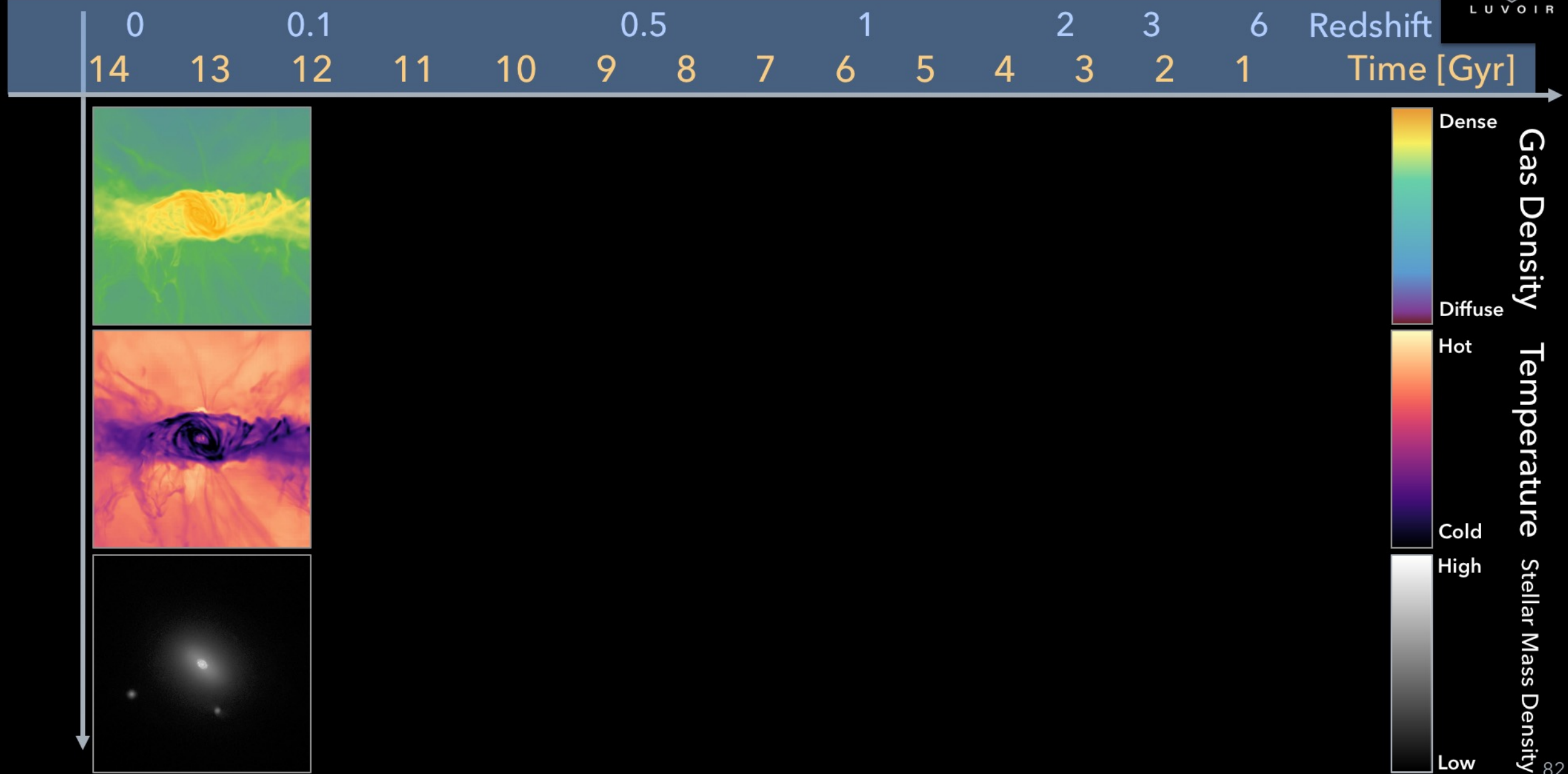
What are the stellar and galactic environments of the transient zoo?

LUVOIR addresses these big questions with **unprecedented sensitivity, resolution, and multiplexing** to push back the ultra-faint and ultra-small frontiers

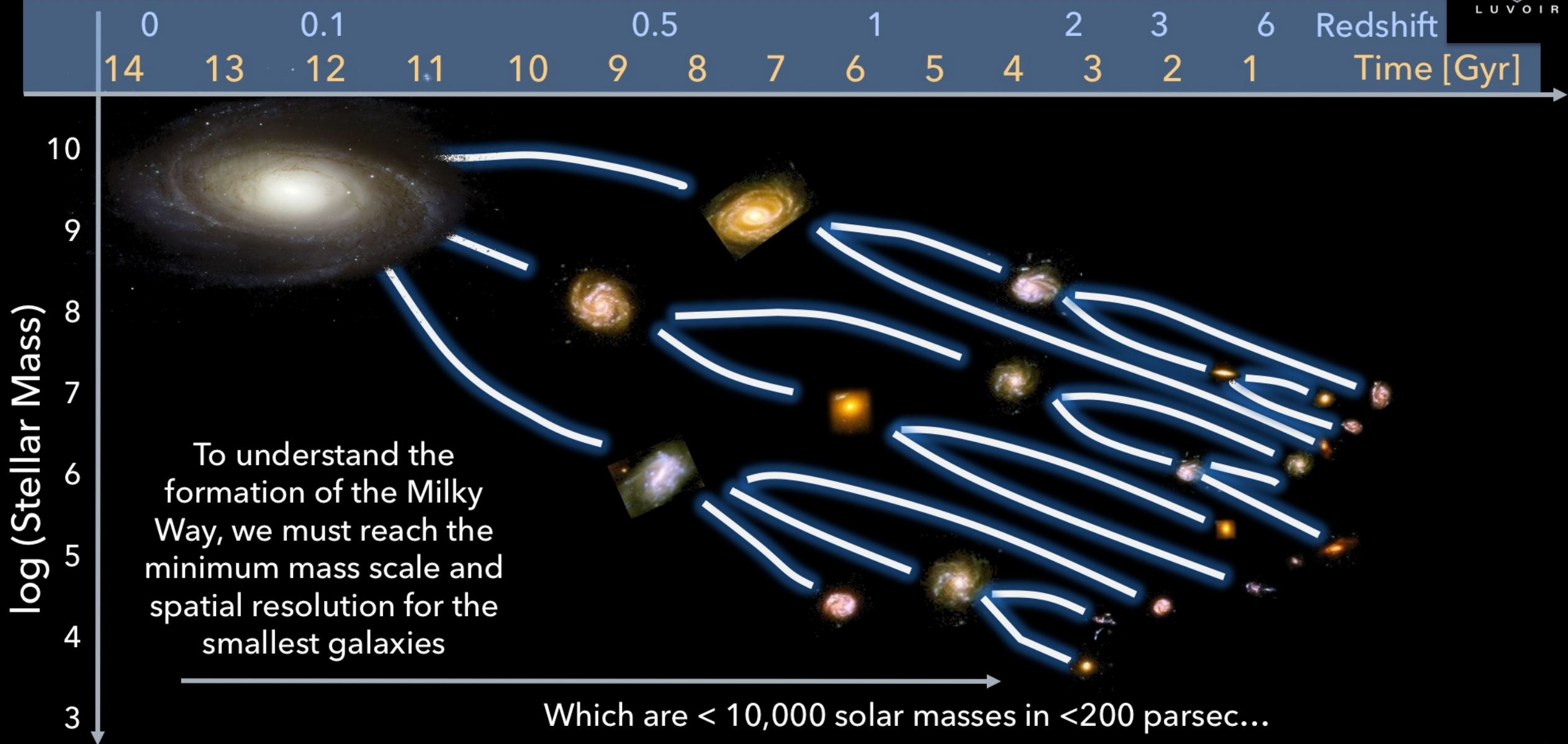
THE COSMIC LANDSCAPE – GALAXY FORMATION



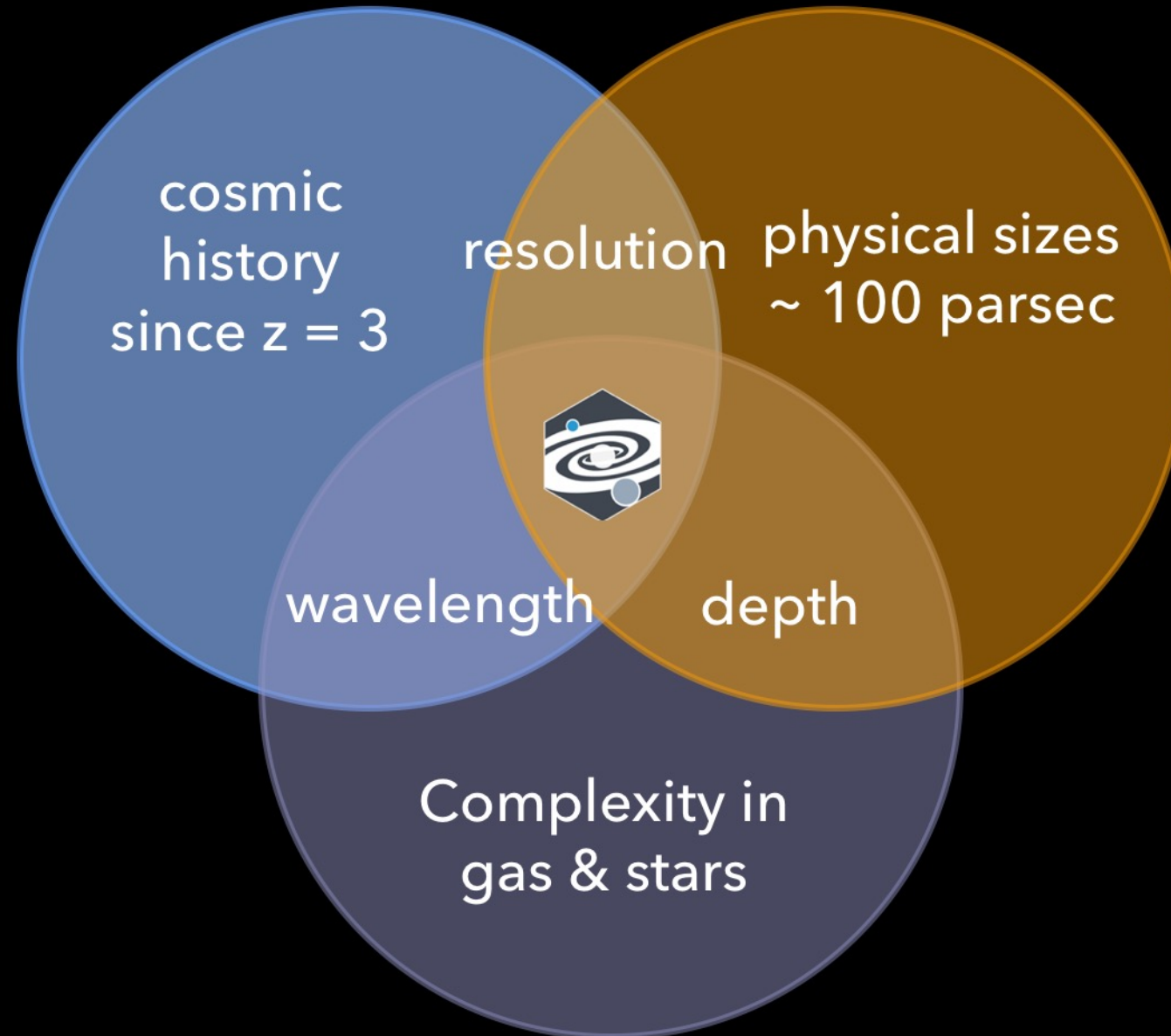
THE COSMIC LANDSCAPE – GALAXY FORMATION



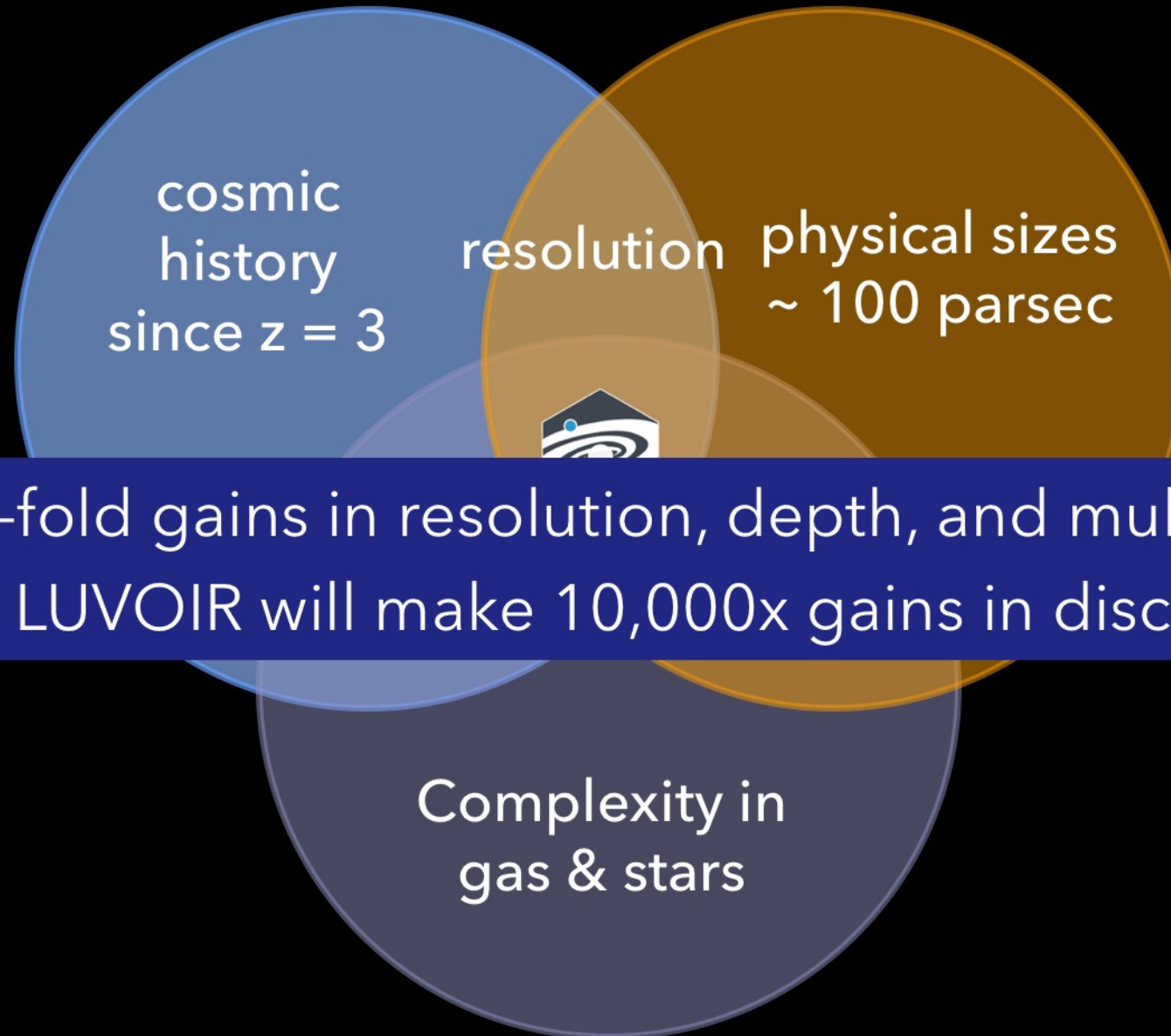
THE COSMIC LANDSCAPE - MILKY WAY ASSEMBLY



THE ESSENTIALS - RESOLUTION, DEPTH, AND WAVELENGTH

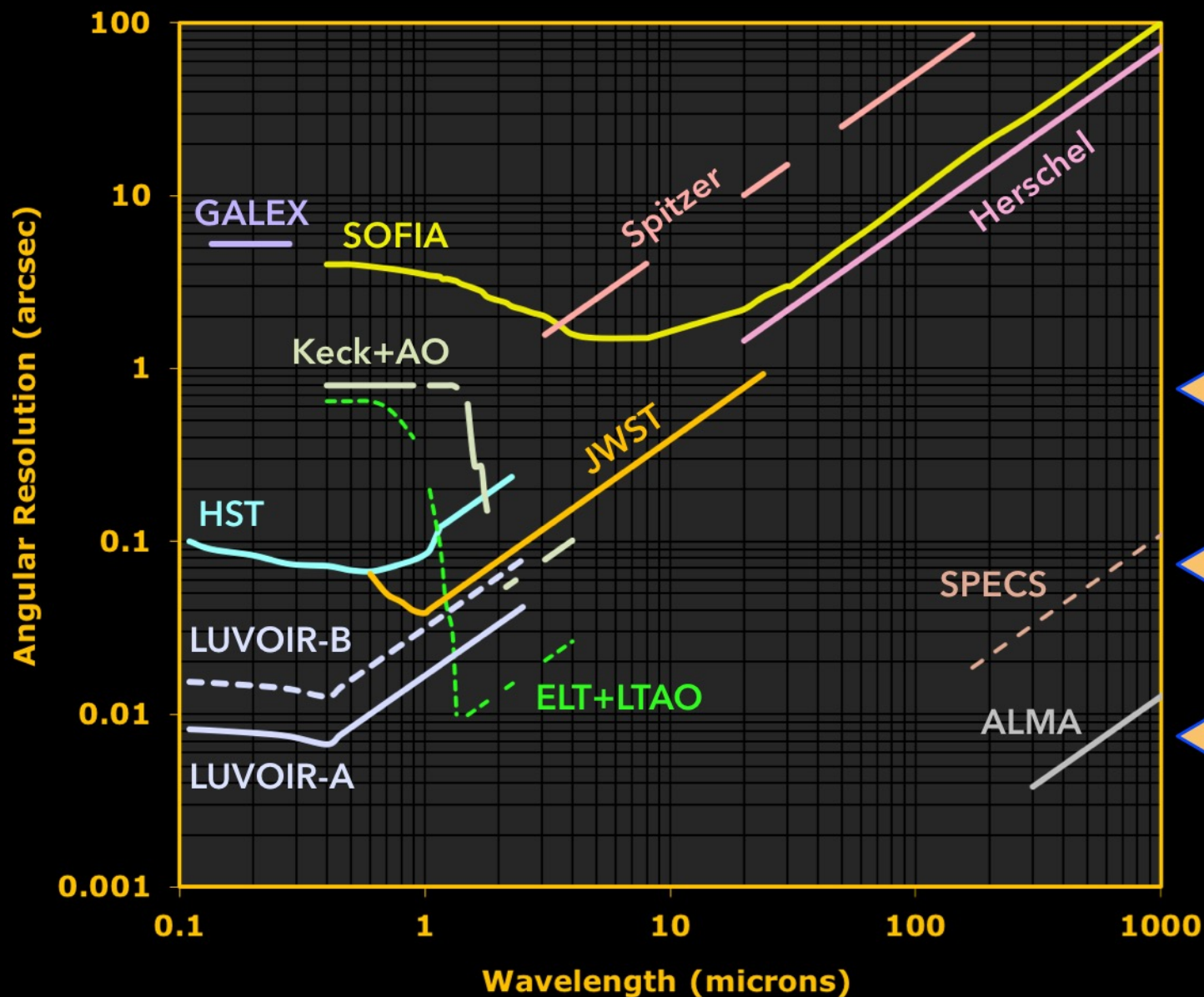


THE ESSENTIALS – RESOLUTION, DEPTH, AND WAVELENGTH



With 10 to 100-fold gains in resolution, depth, and multiplexing across the UVOIR, LUVOIR will make 10,000x gains in discovery space

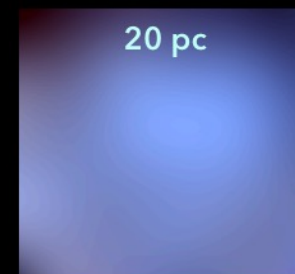
THE ESSENTIAL RESOLUTION



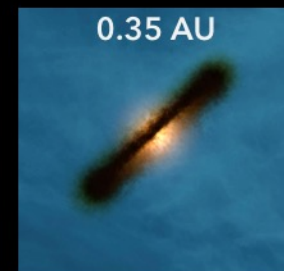
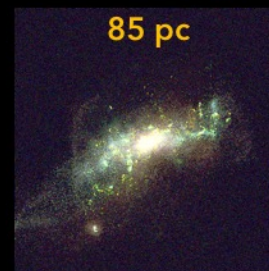
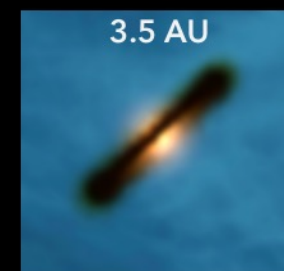
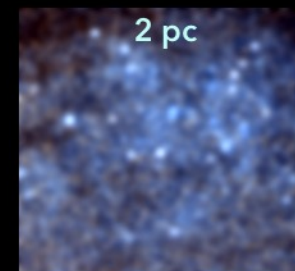
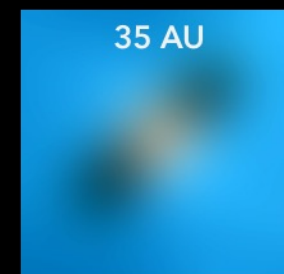
Spatial Resolution at $z = 2$



Spatial Resolution at 5 Mpc



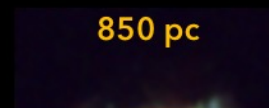
Spatial Resolution at 50 pc



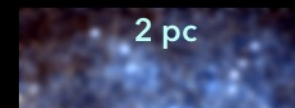
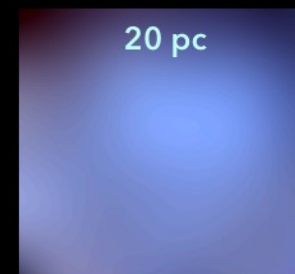
THE ESSENTIAL RESOLUTION



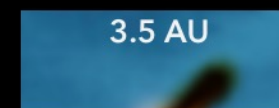
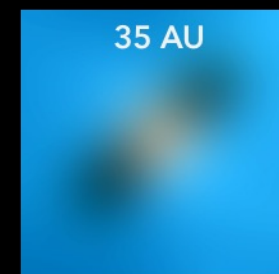
Spatial Resolution at $z = 2$



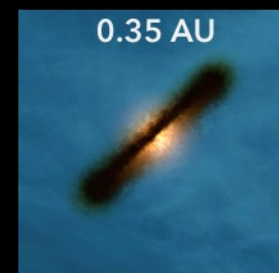
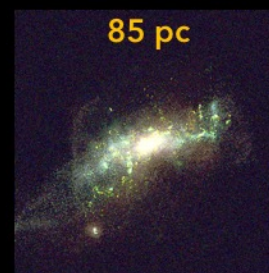
Spatial Resolution at 5 Mpc



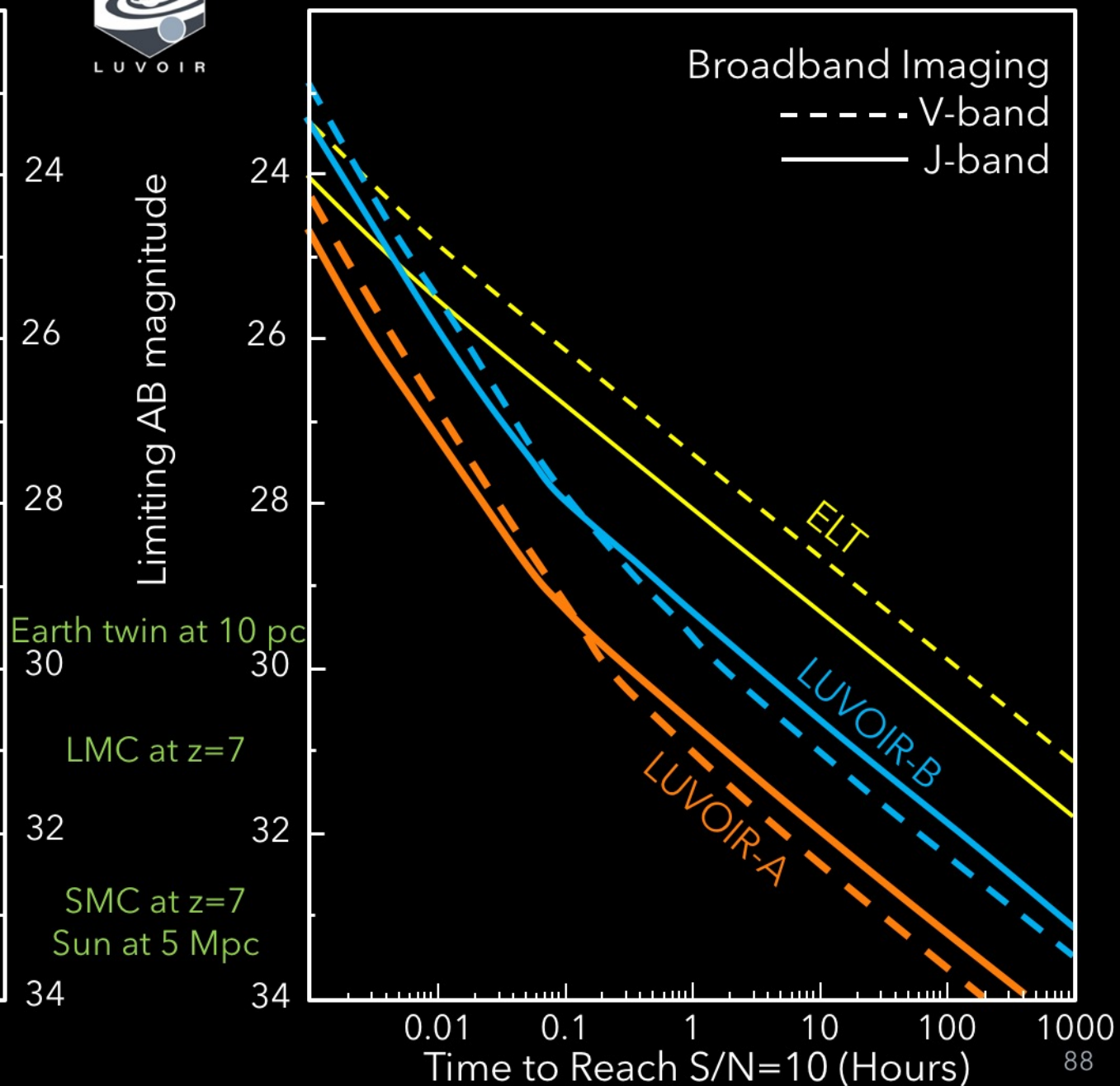
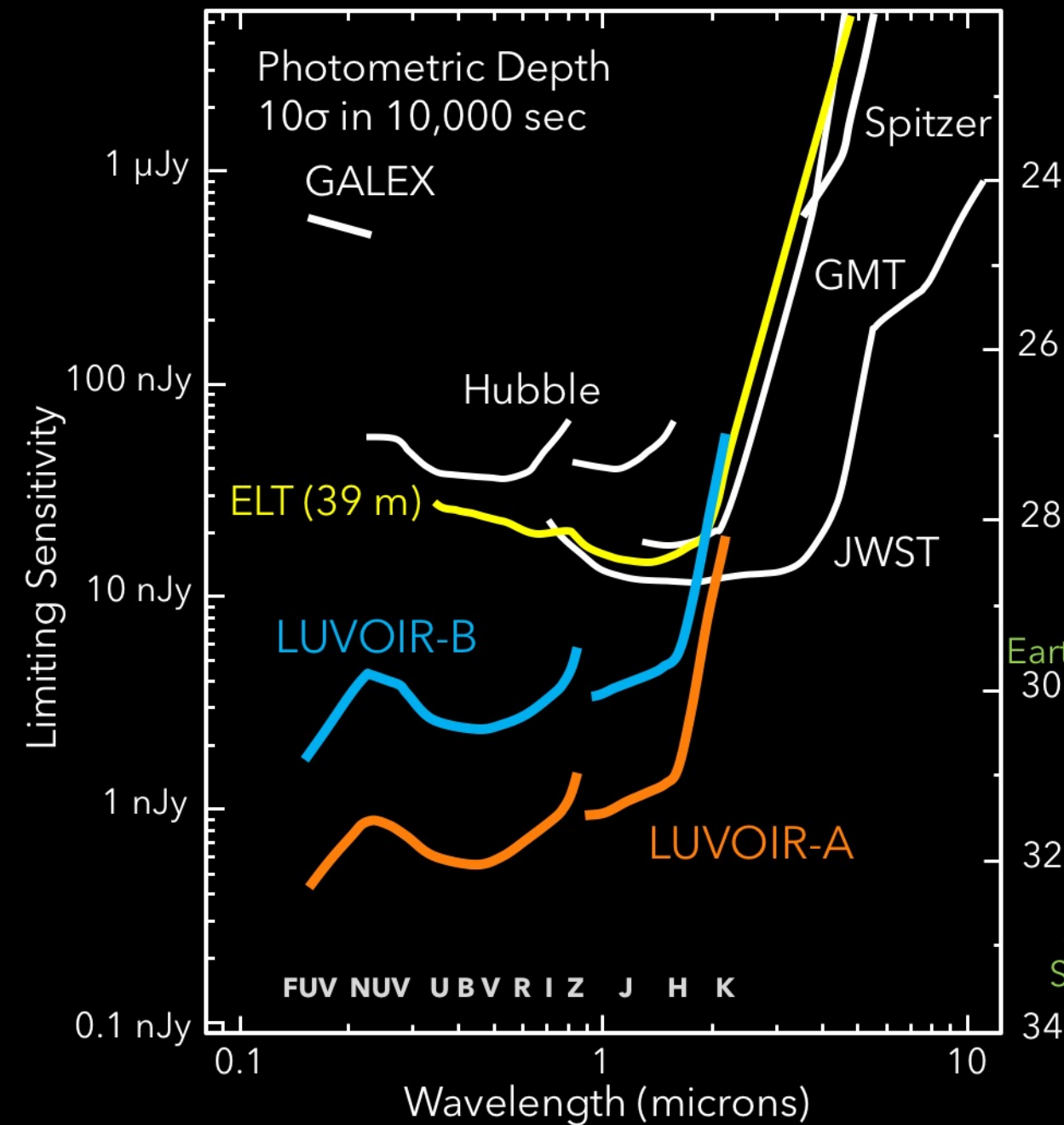
Spatial Resolution at 50 pc



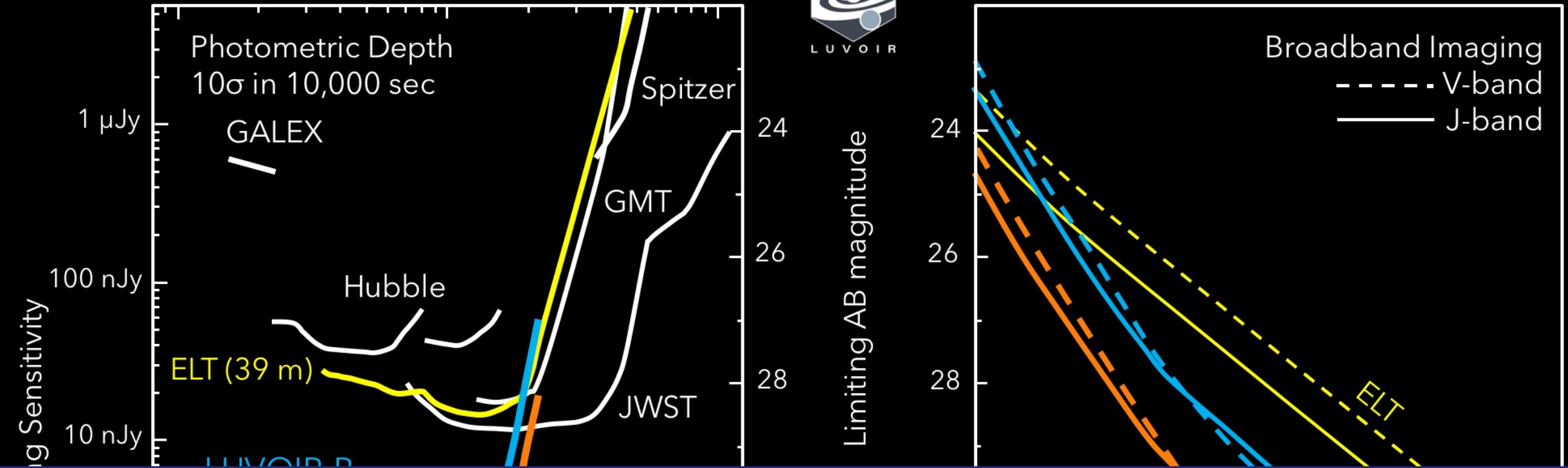
LUVOIR will resolve galaxies to 100 parsec scales at any redshift



THE ESSENTIAL DEPTH

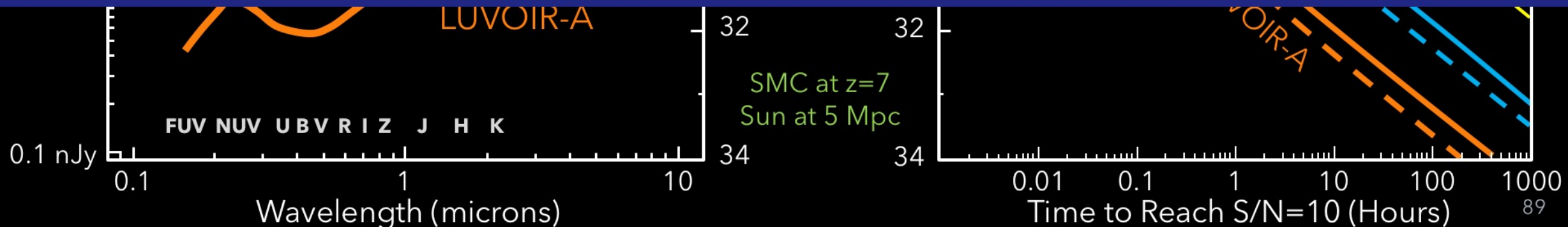


THE ESSENTIAL DEPTH



LUVOIR will reach AB = 34th magnitude in its deepest observations.

We have no idea what the sky looks like at that limit!

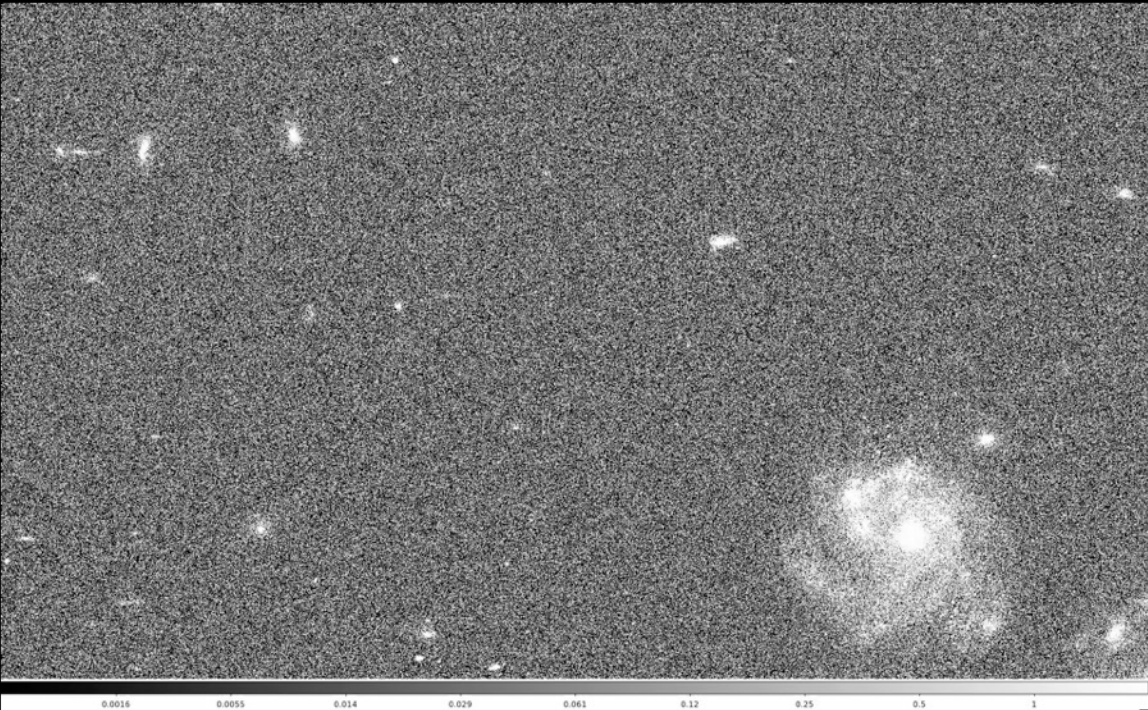


SEEKING THE BUILDING BLOCKS OF GALAXIES

Exposure Time: 100 seconds

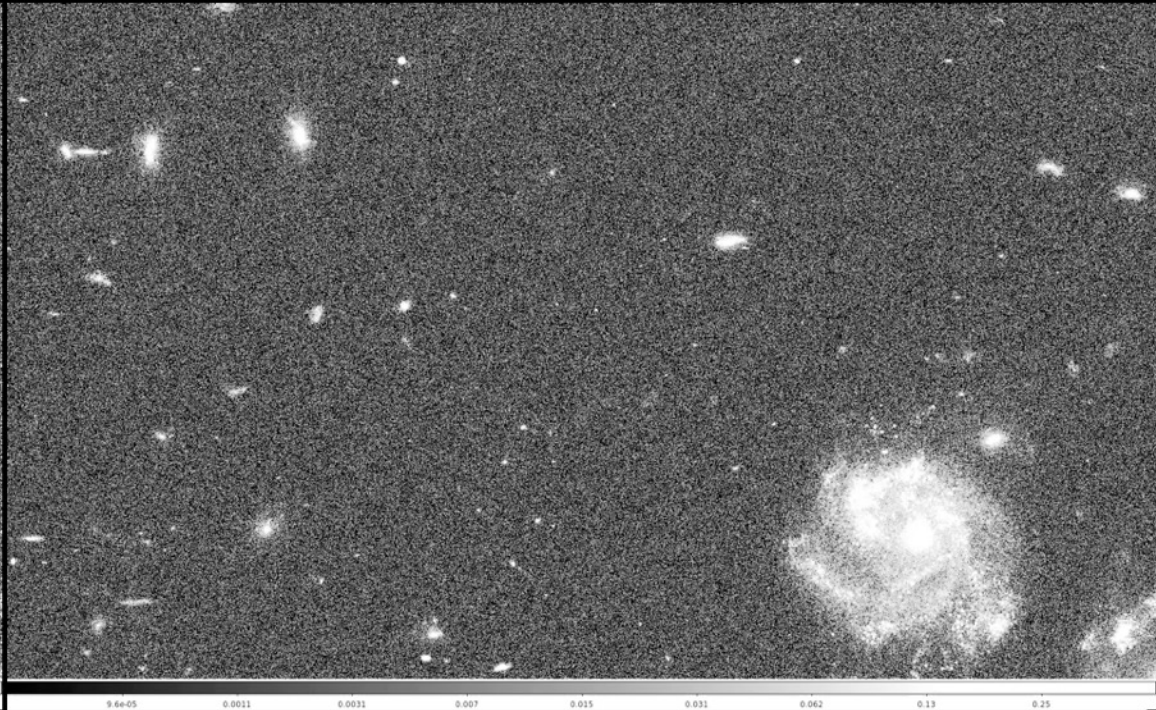
ELT (39 meter)

J-band, 5sig lim = 26.77 mag



LUVOIR-A (15 meter)

F850LP (z-band), 5sig lim = 28.00 mag

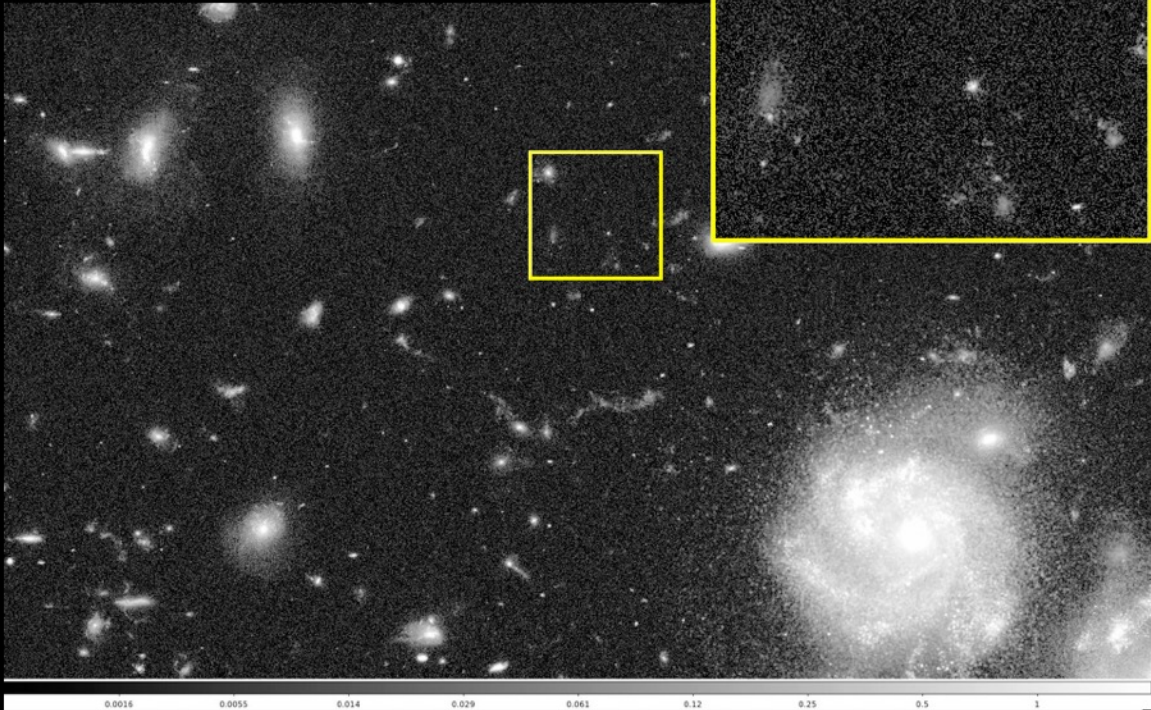


SEEKING THE BUILDING BLOCKS OF GALAXIES

Exposure Time: 398,107 seconds

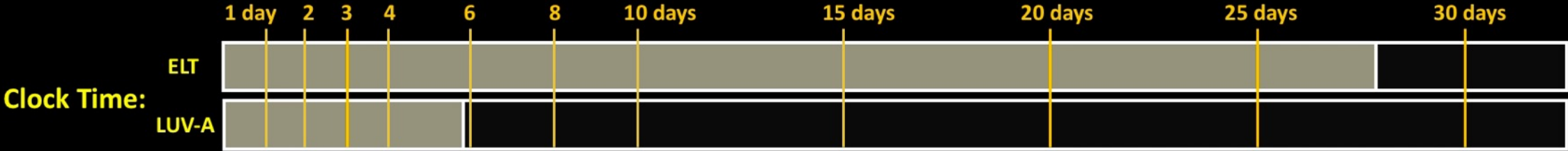
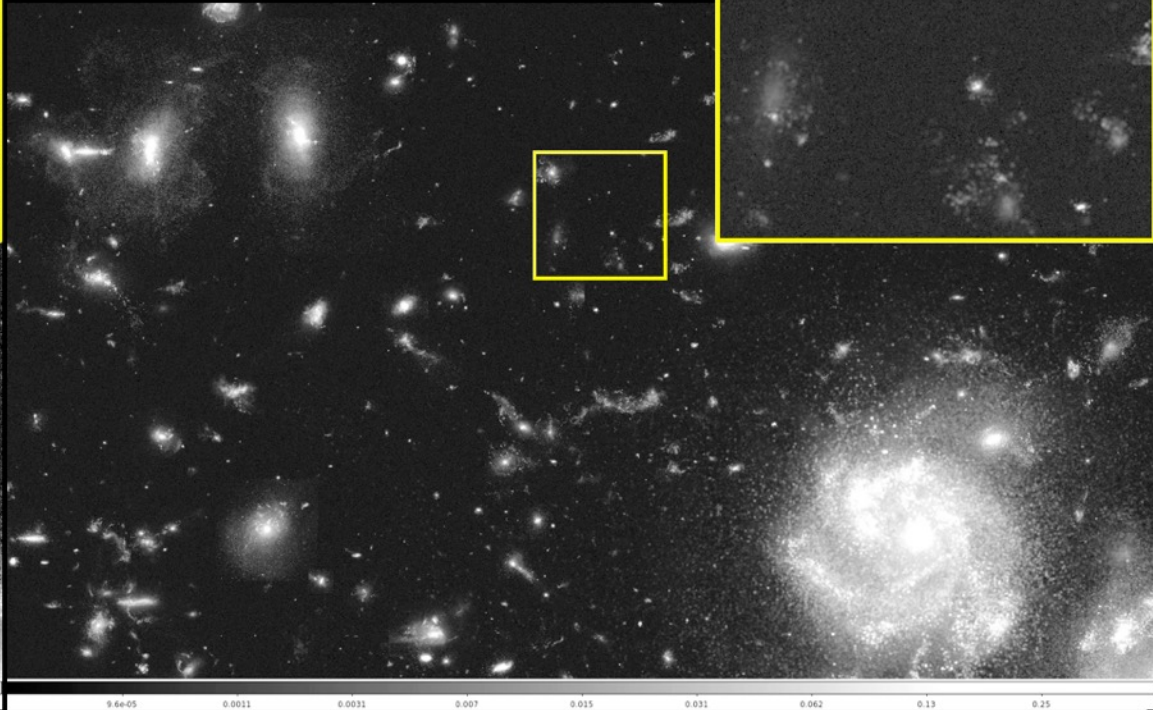
ELT (39 meter)

J-band, 5sig lim = 31.28 mag



LUV OIR-A (15 meter)

F850LP (z-band), 5sig lim = 33.56 mag



SEEKING THE BUILDING BLOCKS OF GALAXIES

Exposure Time: 398,107 seconds

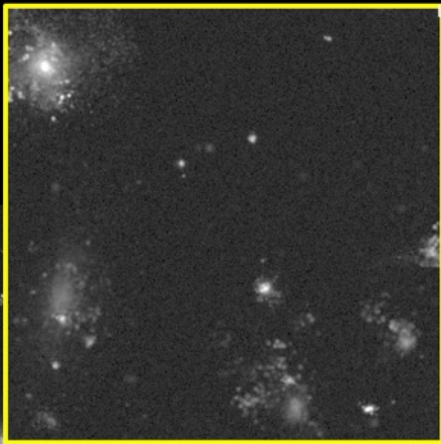
ELT (39 meter)

J-band, 5sig lim = 31.28 mag

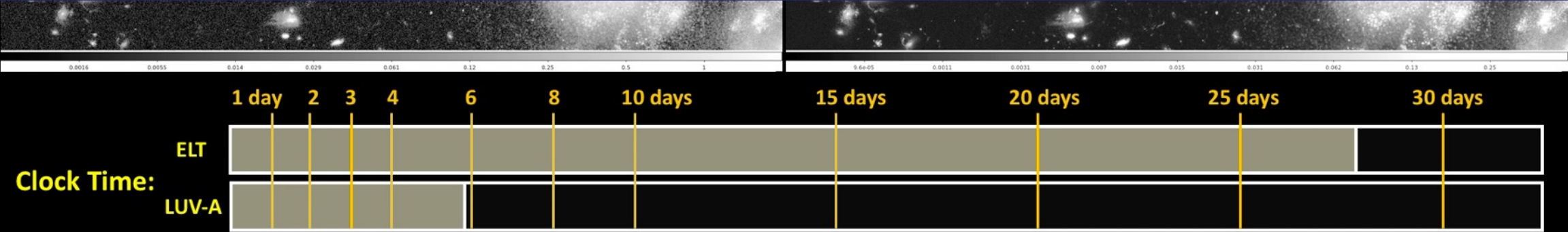


LUV OIR-A (15 meter)

F850LP (z-band), 5sig lim = 33.56 mag

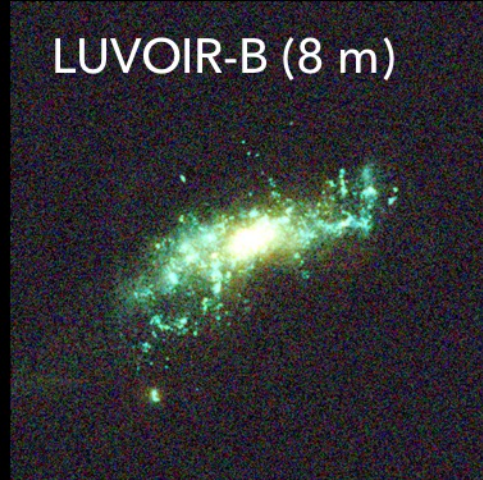


LUV OIR's *Deep Fields* – done in parallel with deep exoplanet observations – will reach the smallest mass scale of galaxy formation

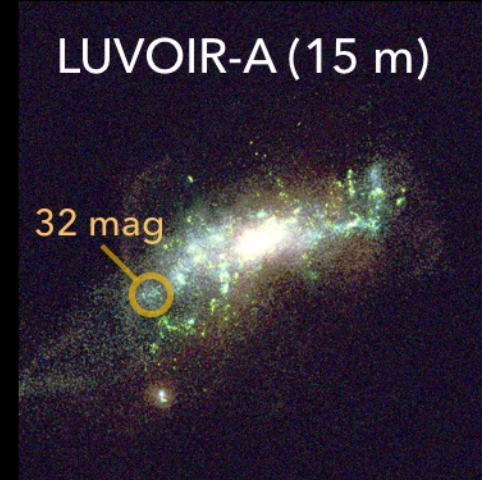


SEEKING THE BUILDING BLOCKS OF GALAXIES

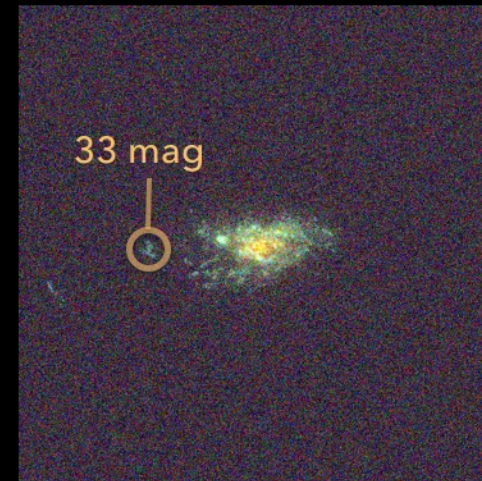
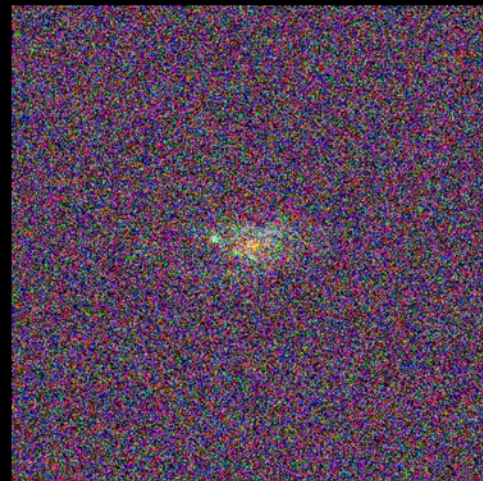
LUVOIR-B (8 m)



LUVOIR-A (15 m)

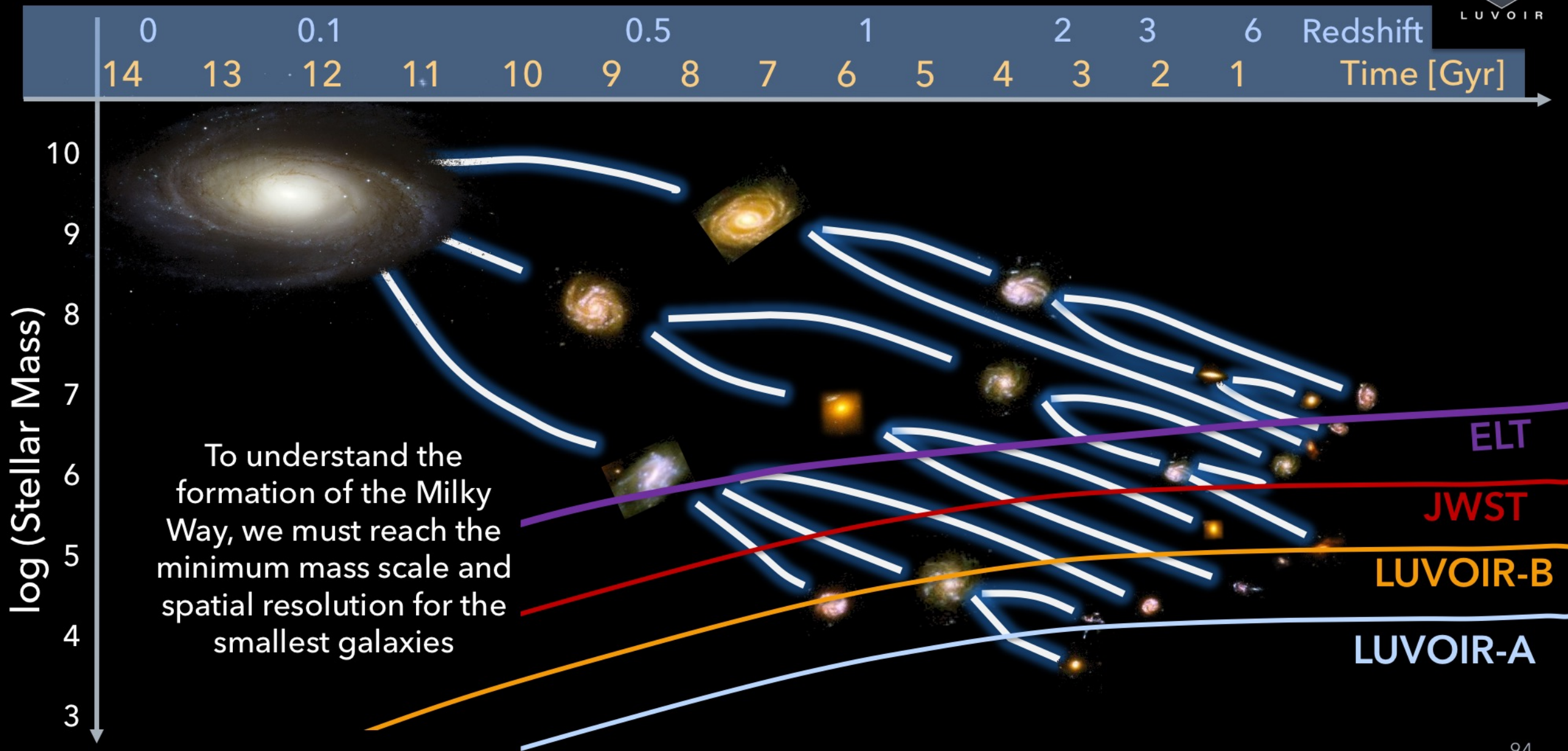


$z = 2$ galaxy, 10^9 solar masses ($m_{AB} \sim 25.5$)

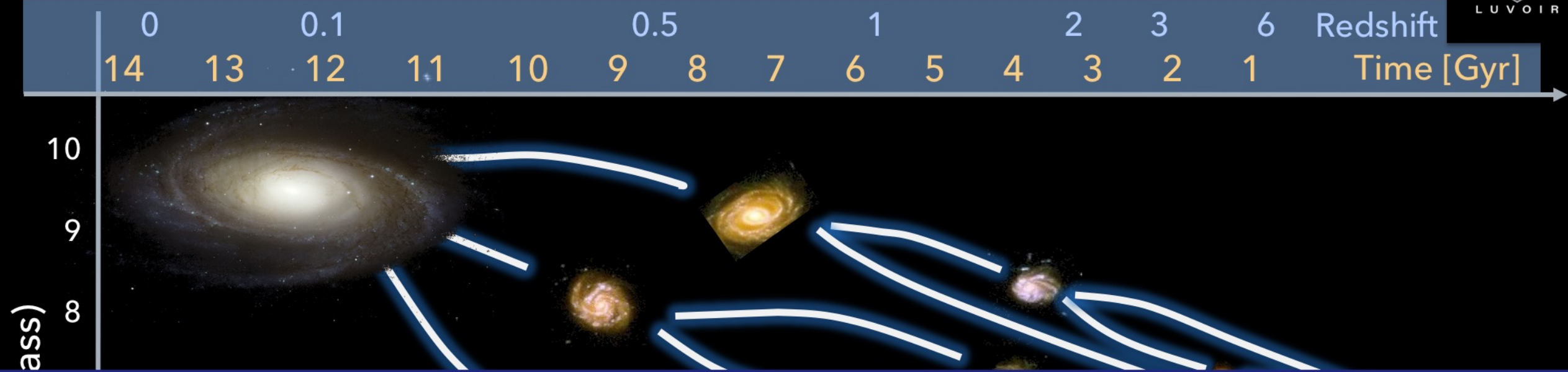


$z = 2$ galaxy, 10^6 solar masses ($m_{AB} \sim 30$)

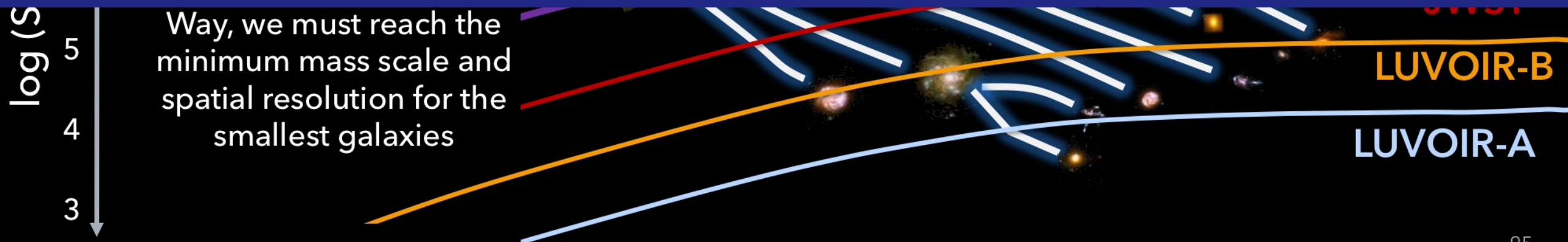
THE COSMIC LANDSCAPE - MILKY WAY ASSEMBLY



THE COSMIC LANDSCAPE – MILKY WAY ASSEMBLY

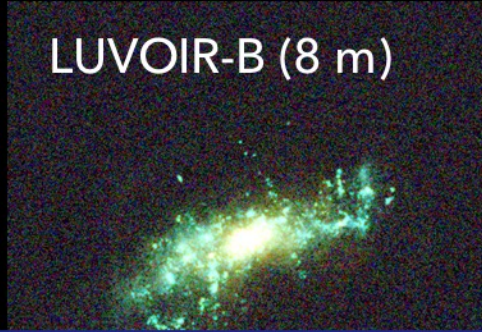


LUVOIR will trace the formation of galaxies down to the smallest mass scales at the earliest times

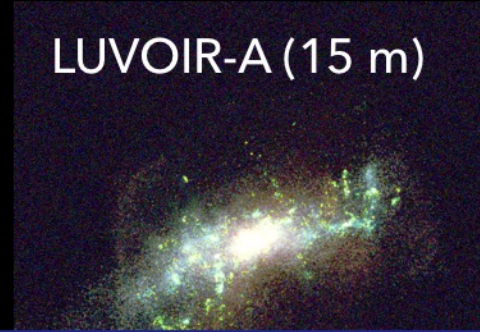


SEEKING THE HOME OF DIVERSE TRANSIENTS

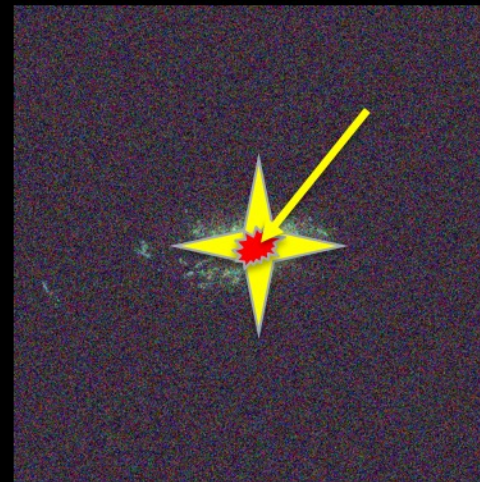
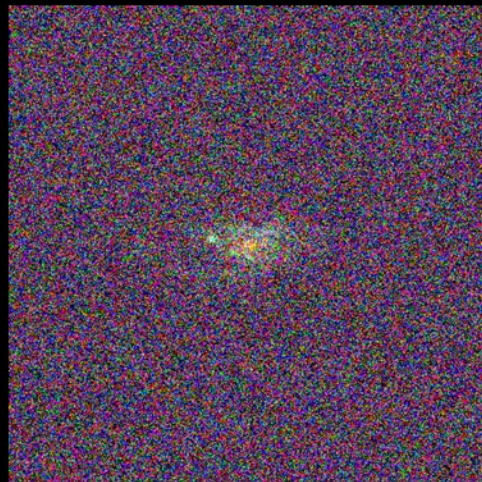
LUVOIR-B (8 m)



LUVOIR-A (15 m)

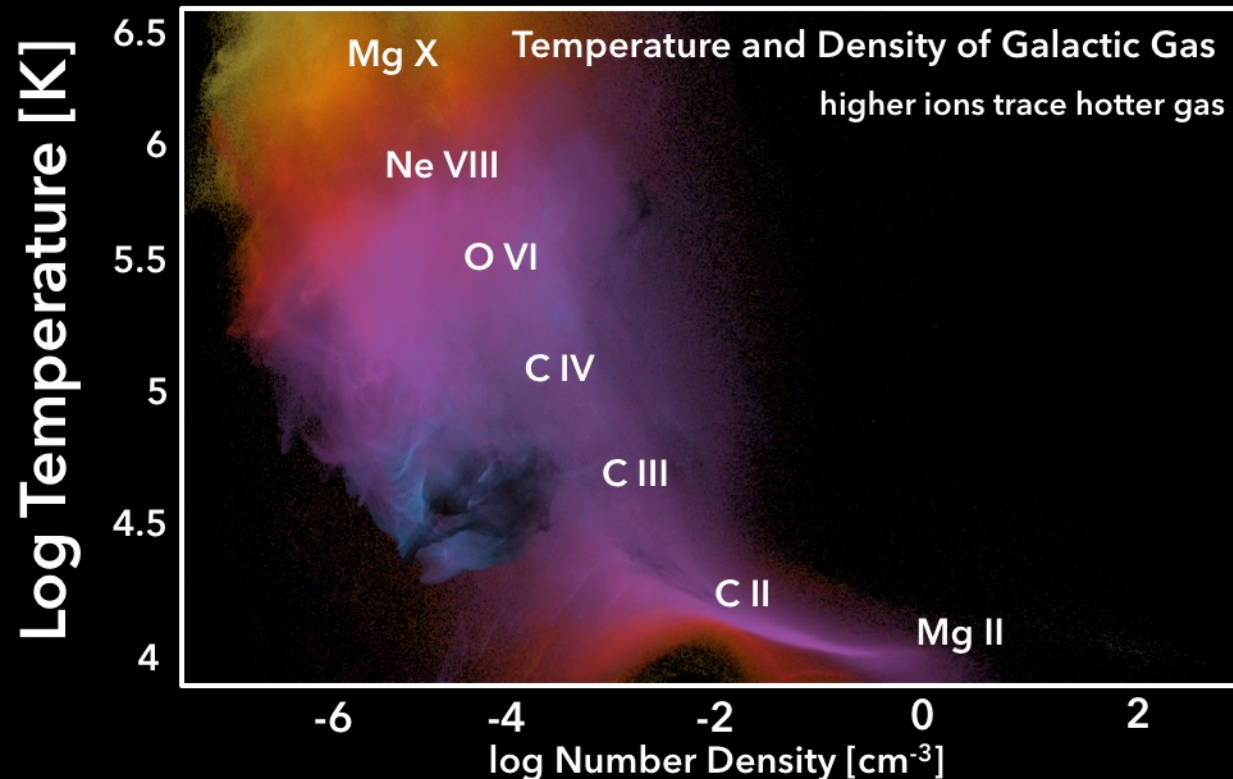
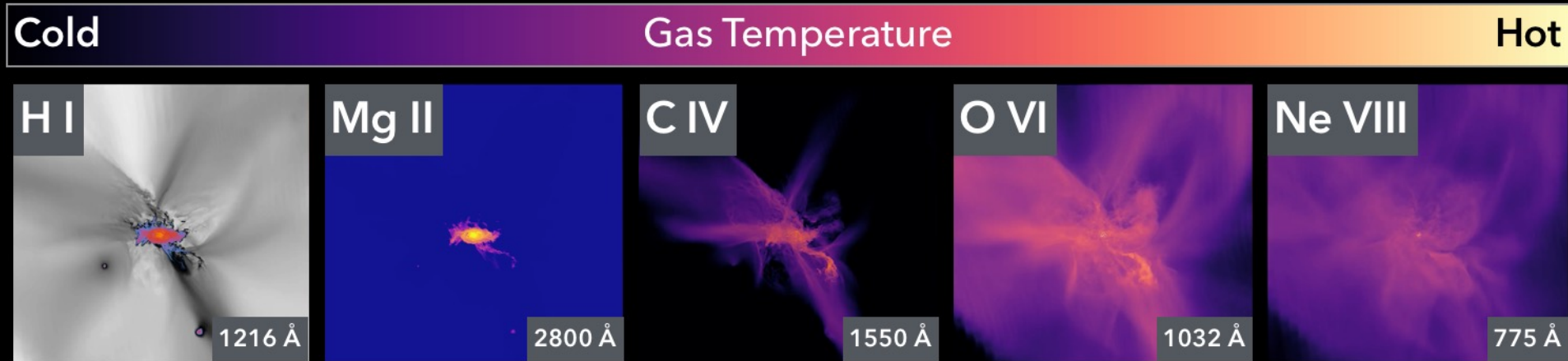


LUVOIR can follow the evolution of EM transients to $AB > 32$ and isolate their host environments to < 100 parsec accuracy

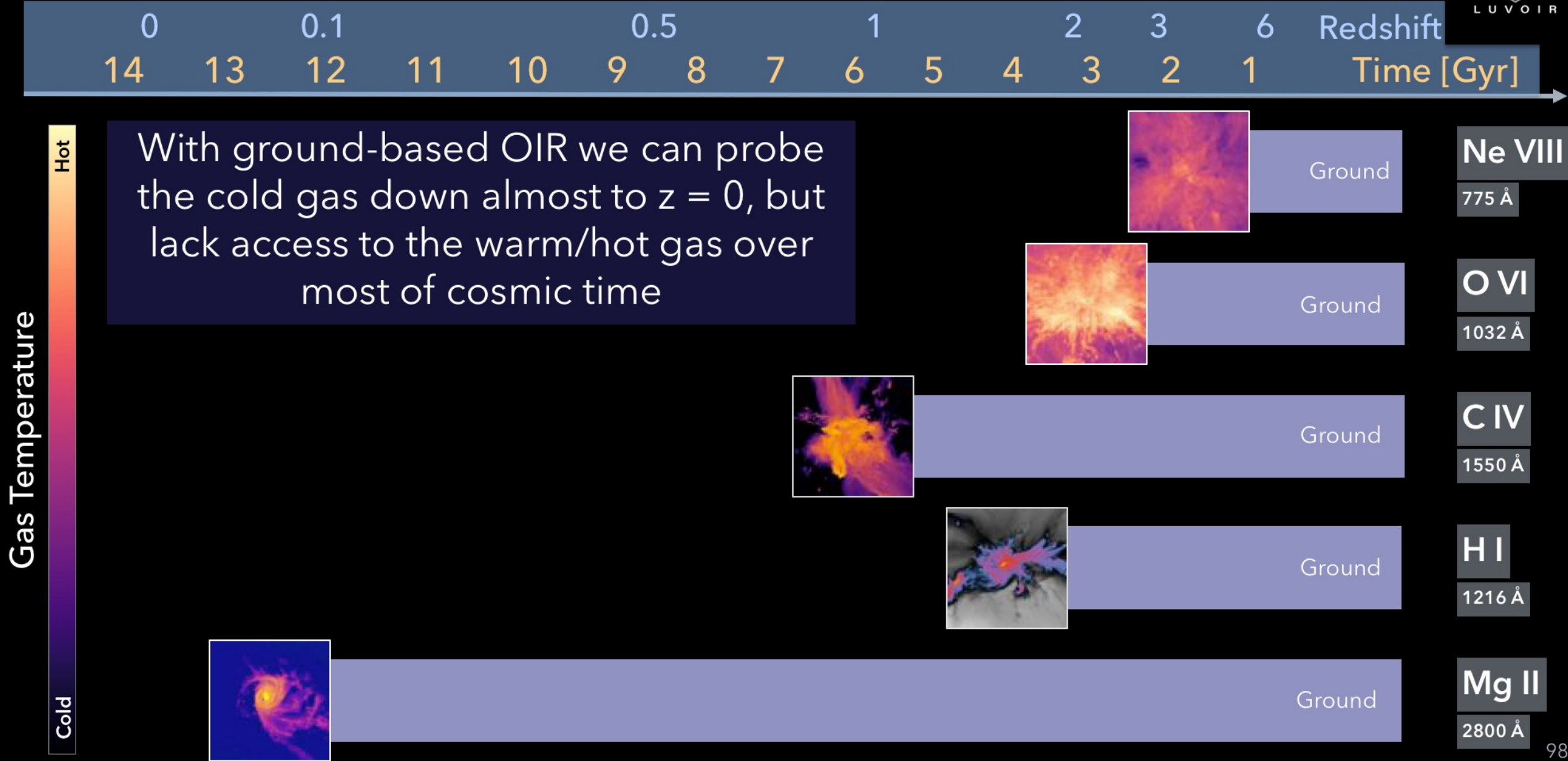


$z = 2$ galaxy, 10^6 solar masses ($m_{AB} \sim 30$)

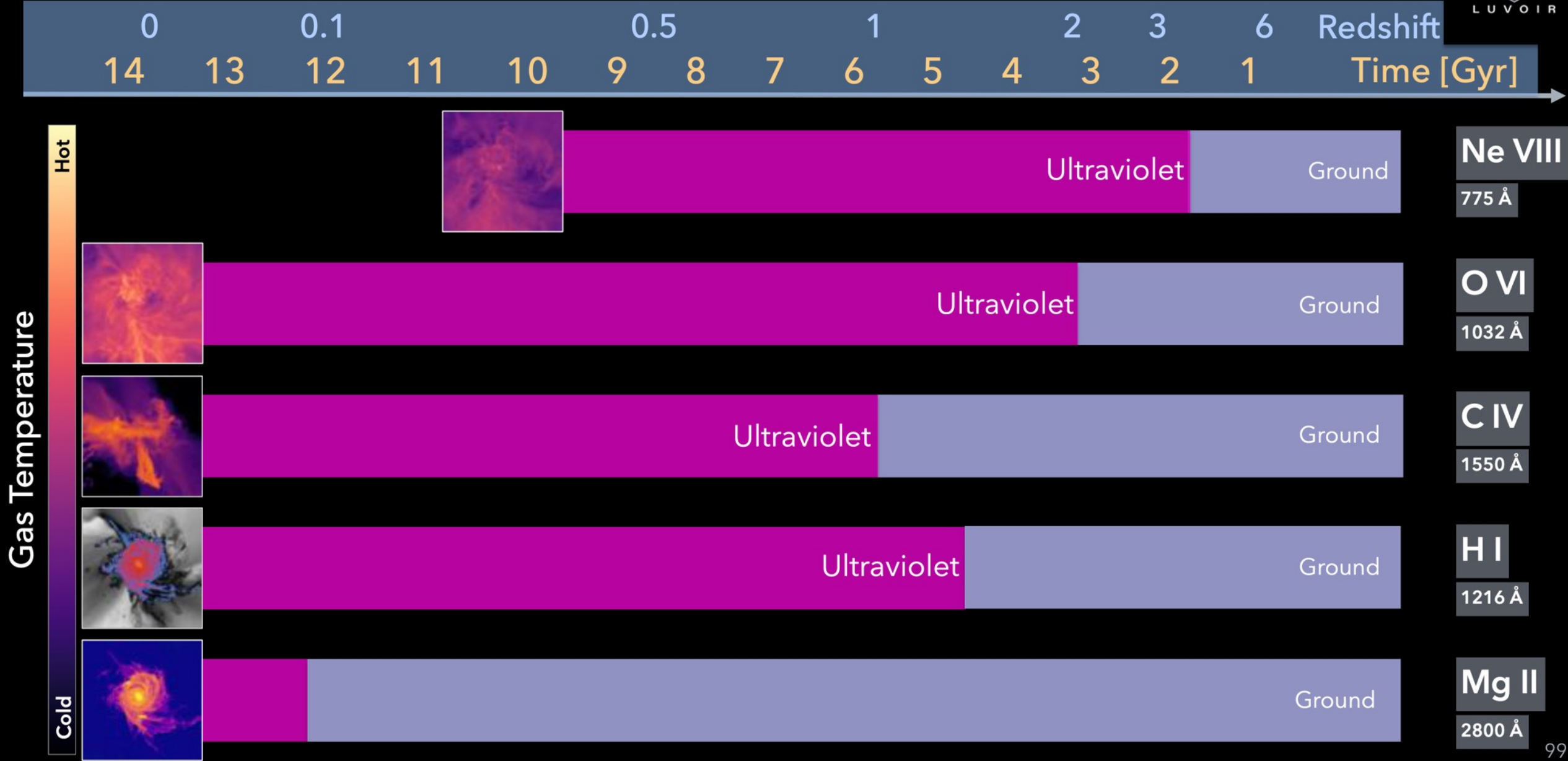
THE BARYON CYCLE AND THE ESSENTIAL ULTRAVIOLET



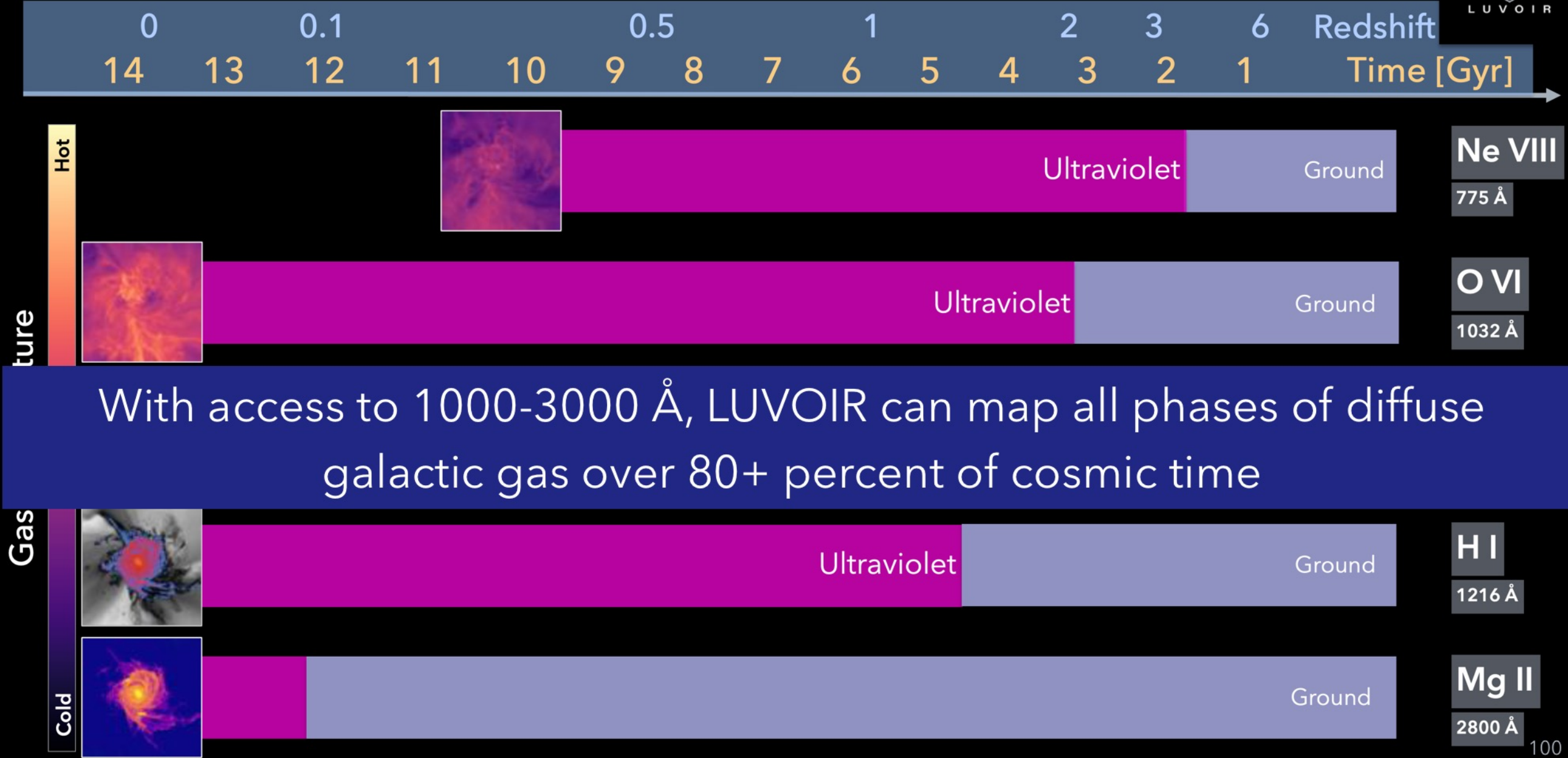
THE BARYON CYCLE AND THE ESSENTIAL ULTRAVIOLET



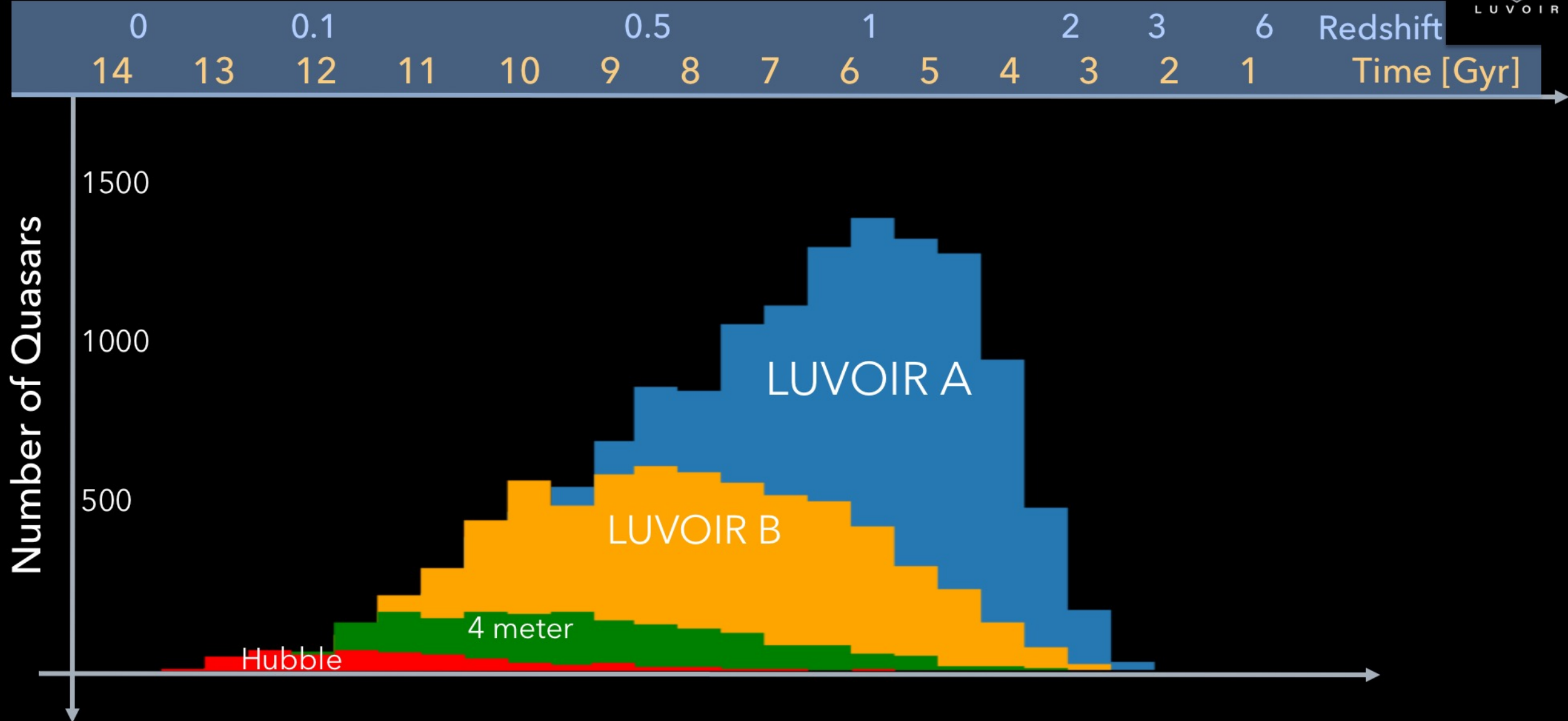
THE BARYON CYCLE AND THE ESSENTIAL ULTRAVIOLET



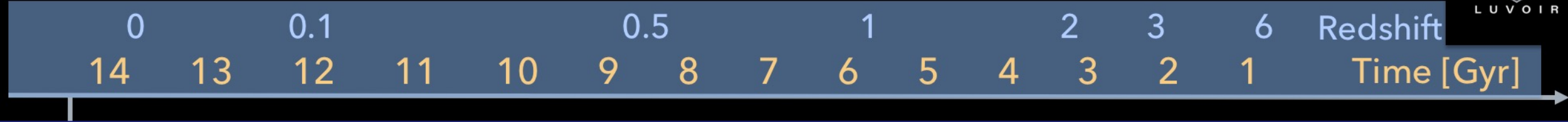
THE BARYON CYCLE AND THE ESSENTIAL ULTRAVIOLET



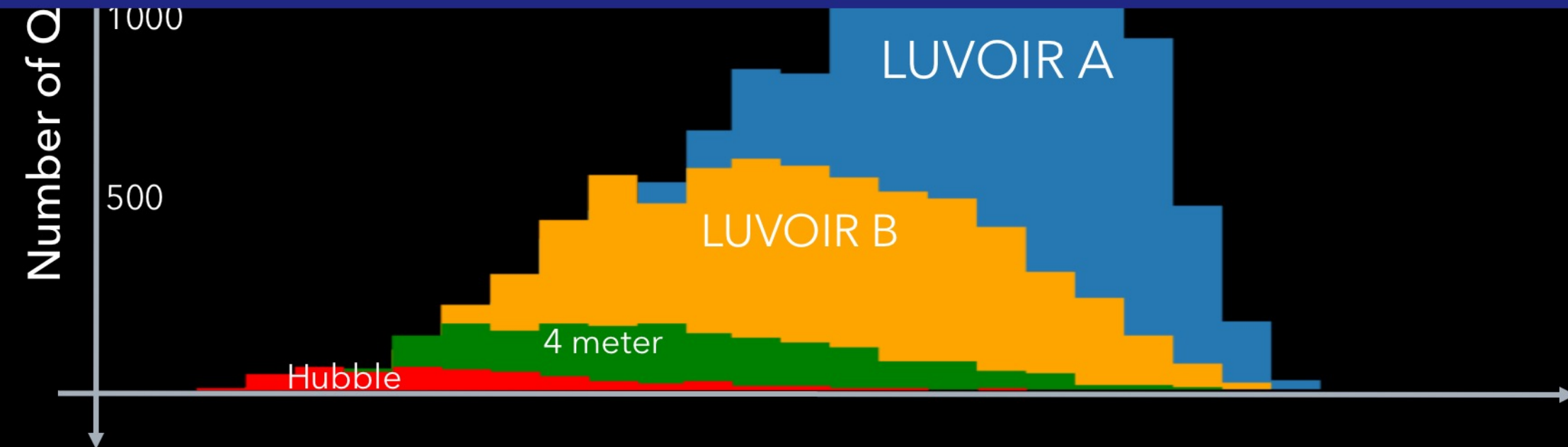
THE BARYON CYCLE AND THE ESSENTIAL ULTRAVIOLET



THE BARYON CYCLE AND THE ESSENTIAL ULTRAVIOLET



LUV OIR provides the UV sensitivity to reach faint background sources (QSOs and galaxies) at $z > 1-2$, allowing a full accounting of galaxies and their gas reservoirs over the last 80% of cosmic time



Diffuse

Dense

Gas Density

Cold

Hot

Gas Temperature

Early

Late

Star Formation Time

$t = 8.7 \text{ Gyr}$
 $z = 0.50$

Accretion

Recycling of outflows

Tidal Stripping

Ejective Feedback

Disk Star Formation

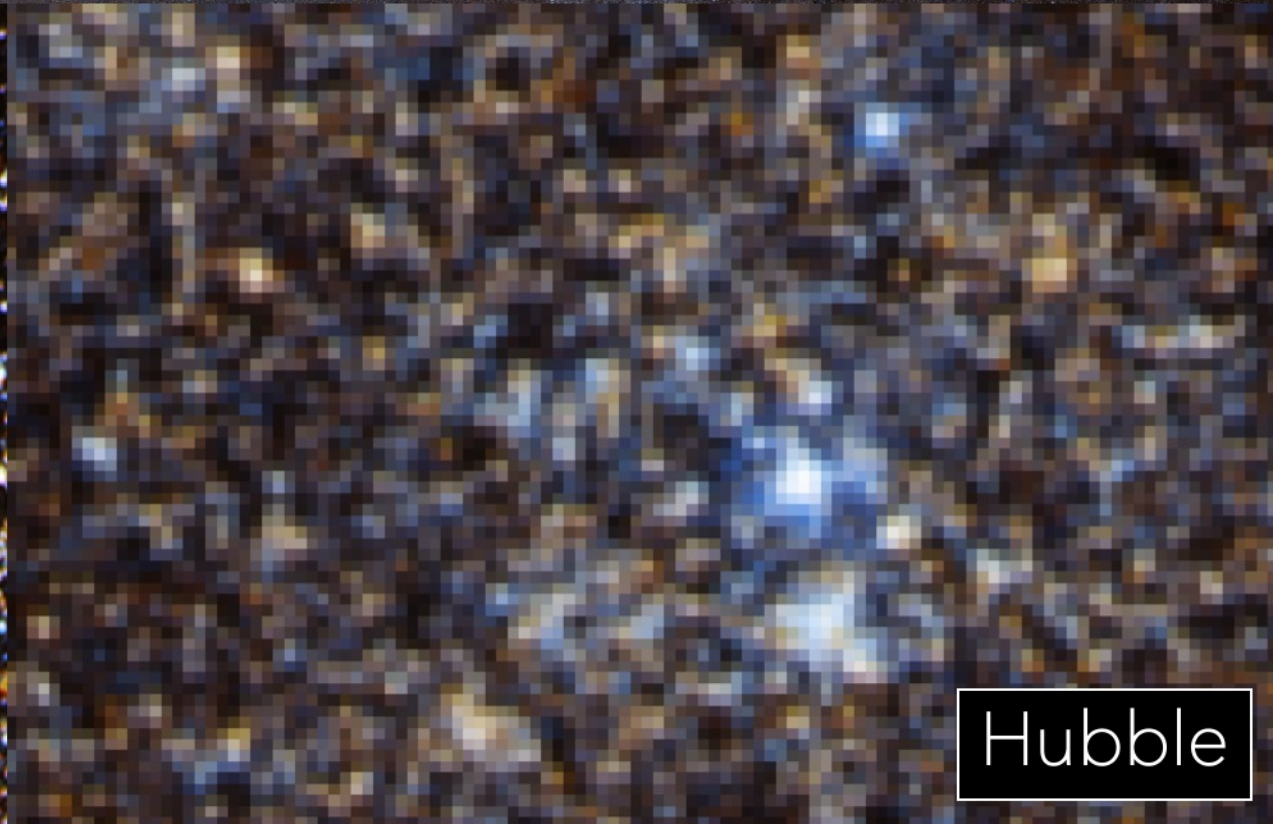
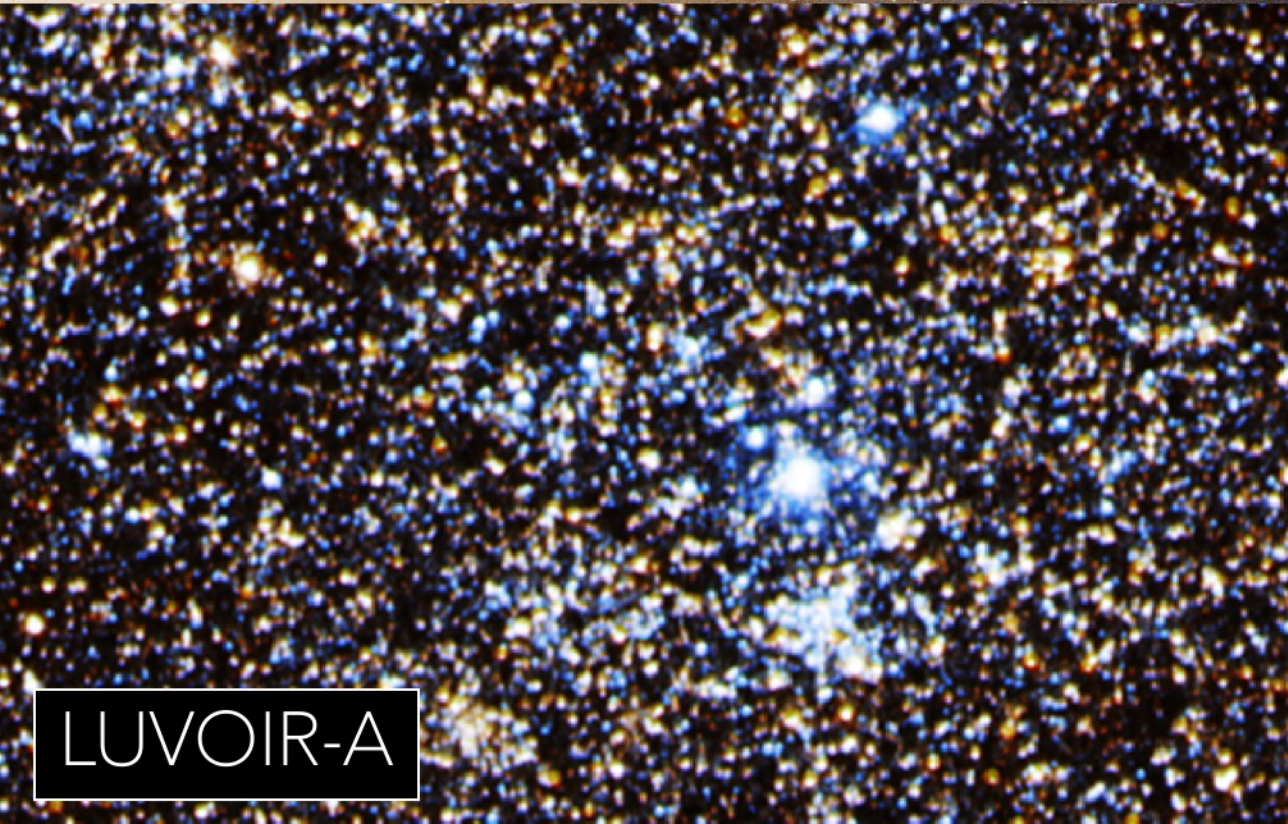
Stellar Streams

Dwarf Satellite Accretion

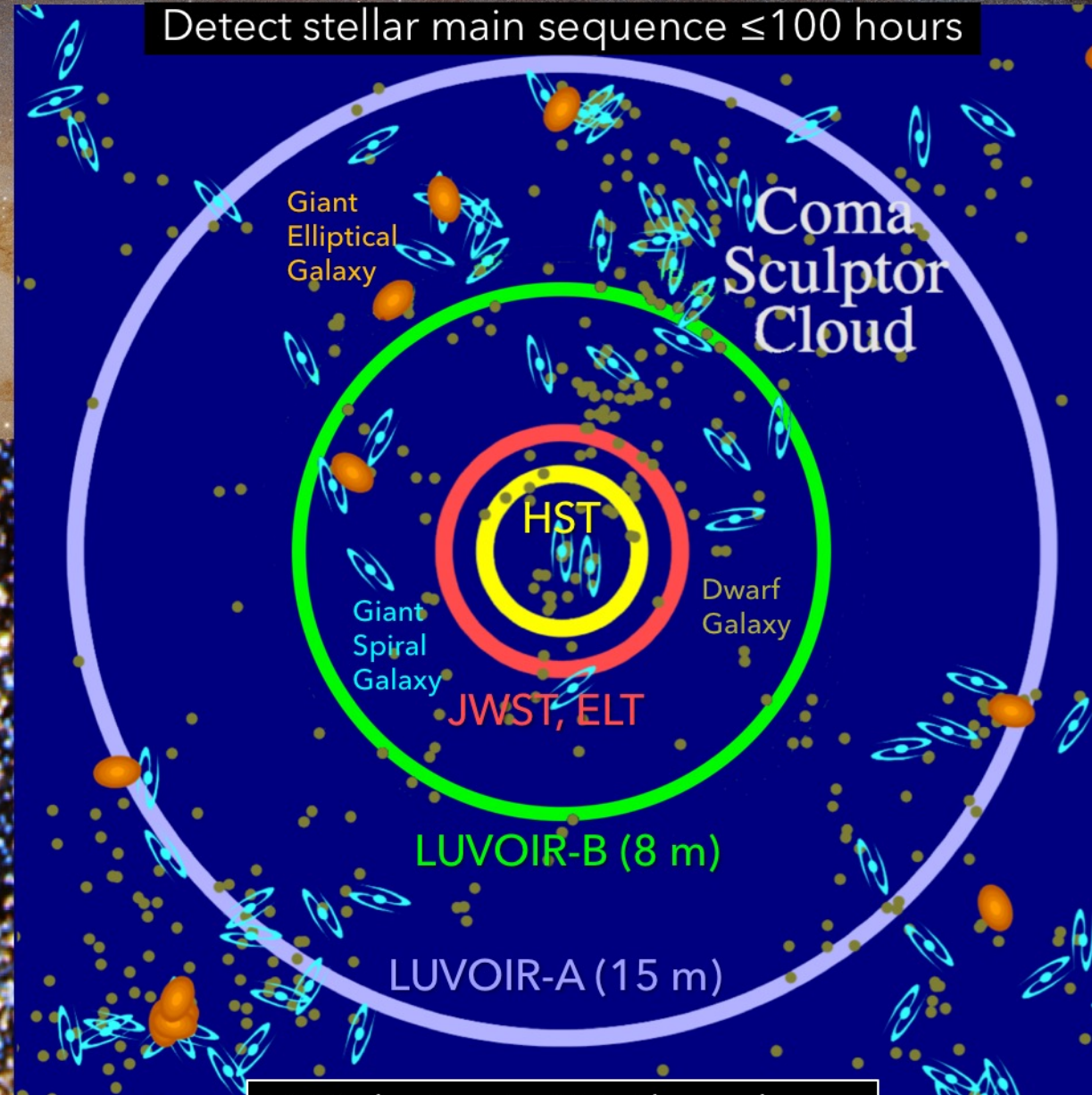
Peeples et al. (2019)

GALAXY FORMATION IS COMPLEX AND DYNAMIC

THE HISTORY OF A GALAXY IN ITS STELLAR POPULATIONS



THE HISTORY OF A GALAXY IN ITS STELLAR POPULATIONS

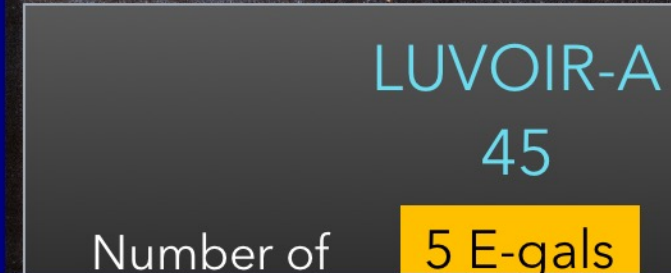
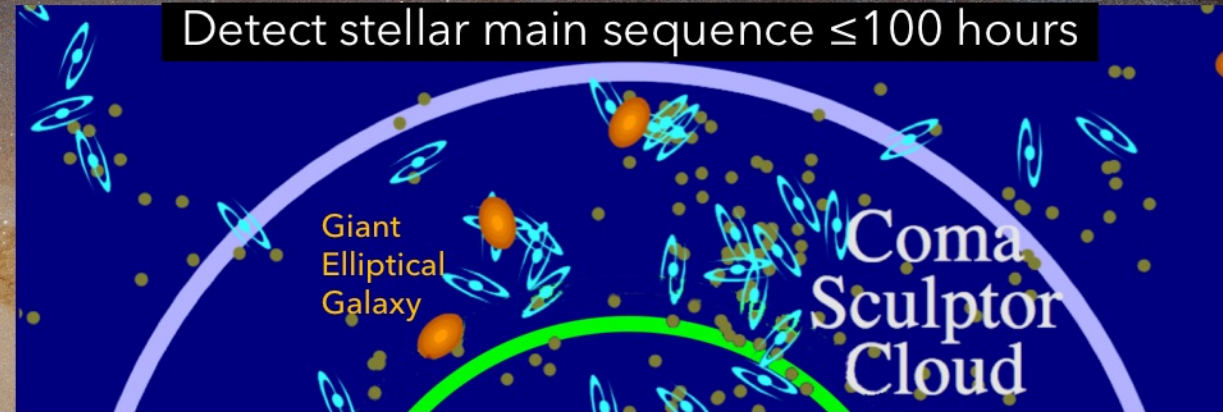


LUVOIR-A	
45	
Number of Large Galaxies Accessible within 10 Mpc	5 E-gals
LUVOIR-B	
13	
40 Spirals	
12 Spirals	
1 E-gal	

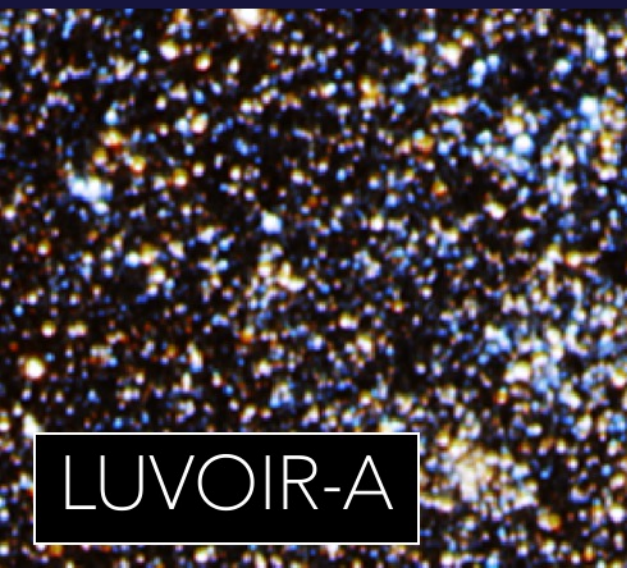
LUVOIR-A

HST clarity at $>35\times$ the volume

THE HISTORY OF A GALAXY IN ITS STELLAR POPULATIONS



LUVOIR will map the detailed histories of stellar populations in nearby galaxies up to 5x farther away than any other facility to trace their ages and chemical evolution with high accuracy

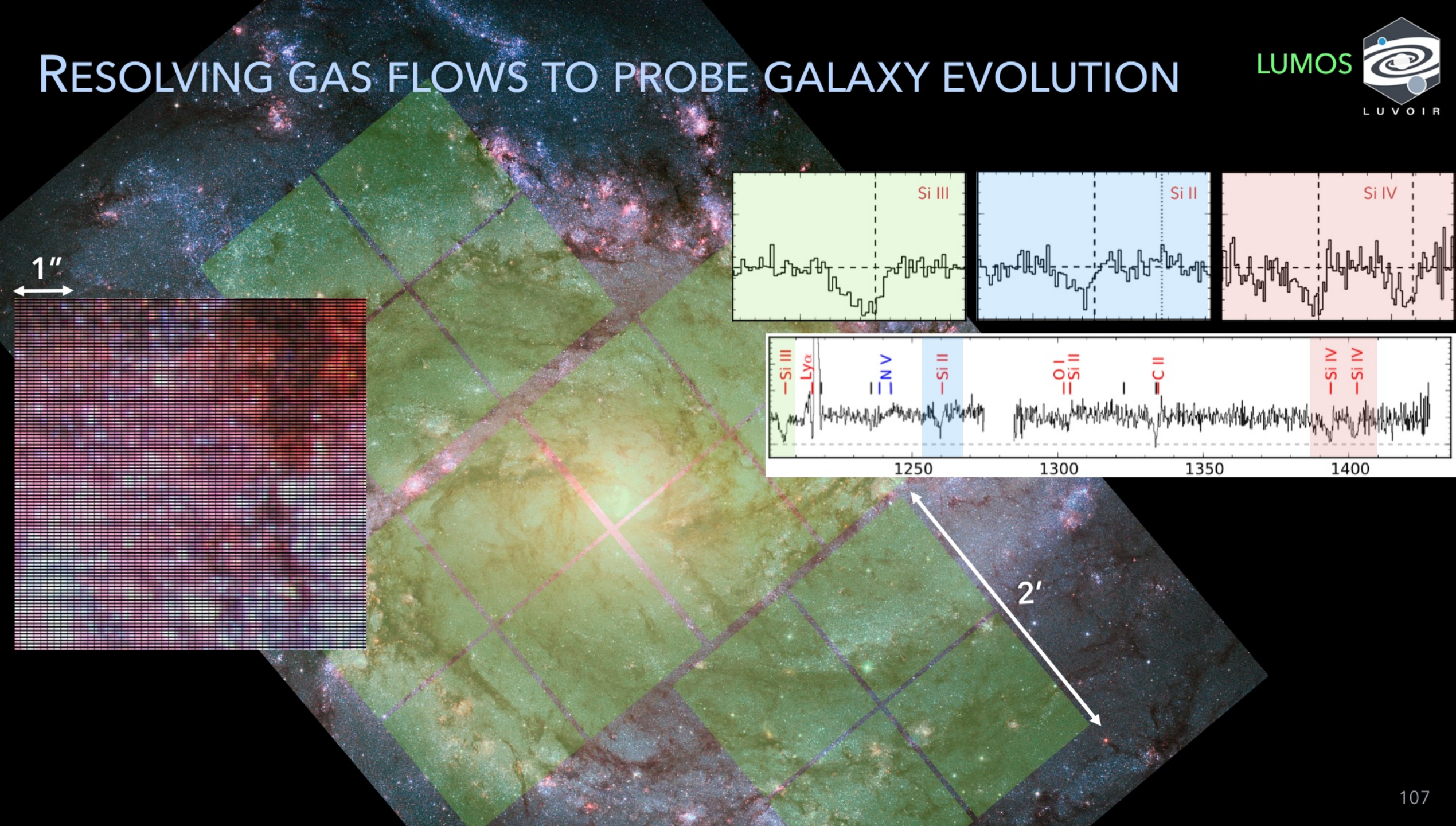


HST clarity at $>35\times$ the volume

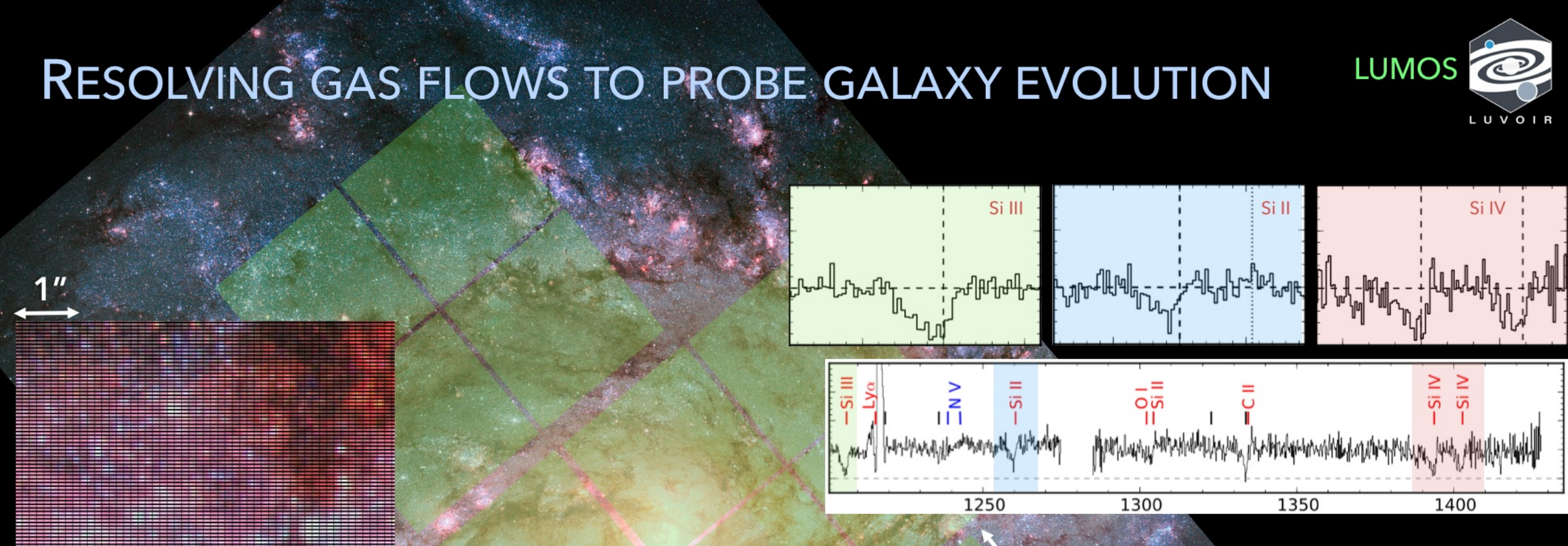


LUVOIR-A

RESOLVING GAS FLOWS TO PROBE GALAXY EVOLUTION



RESOLVING GAS FLOWS TO PROBE GALAXY EVOLUTION



LUVOIR will map the stars, gas, and dust that drive galaxy formation at <10 pc scales using UV spectroscopy >1000 times faster than Hubble

THE SCIENCE OF POLLUX

UV spectropolarimeter

CNES-supported instrument concept for LUVOIR-A

Polarimetry

UV

Visible

THE SCIENCE OF POLLUX

UV spectropolarimeter

CNES-supported instrument concept for LUVOIR-A

Polarimetry

Visible

Star-exoplanet interactions

Fundamental physics & cosmology

ISM and CGM

Stellar magnetic fields

AGN

Solar System

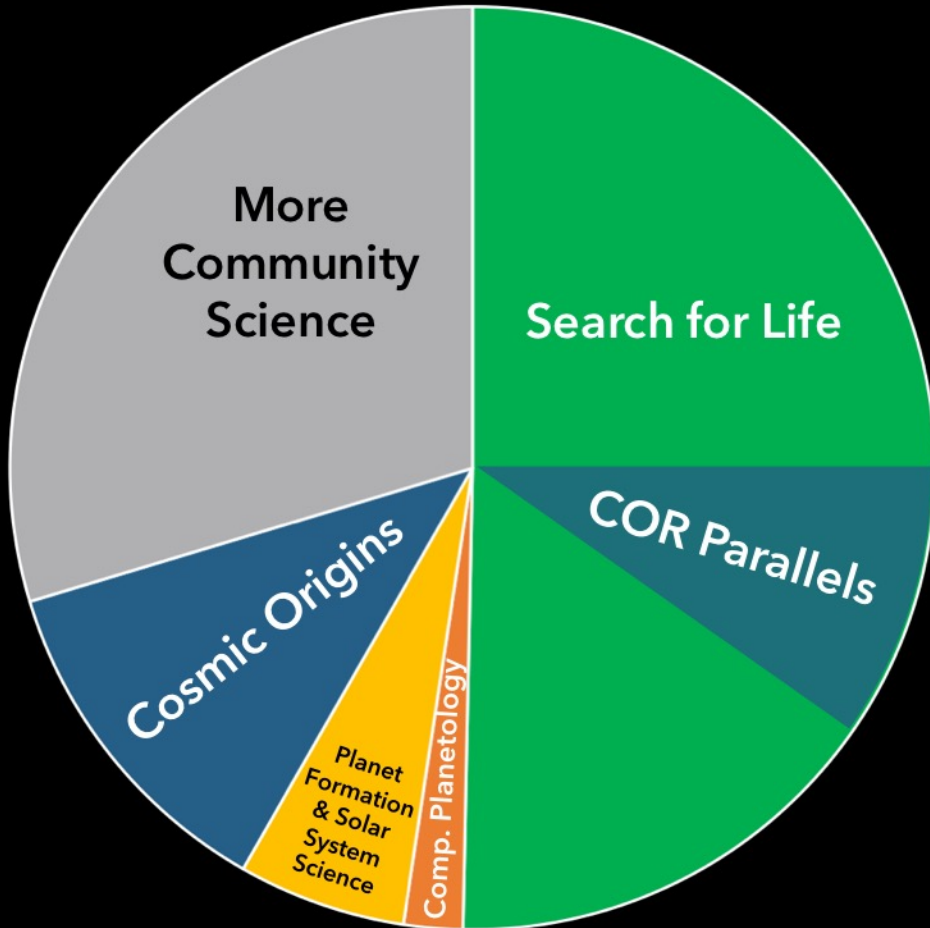
A vs. B – THE ASTROPHYSICS PERSPECTIVE



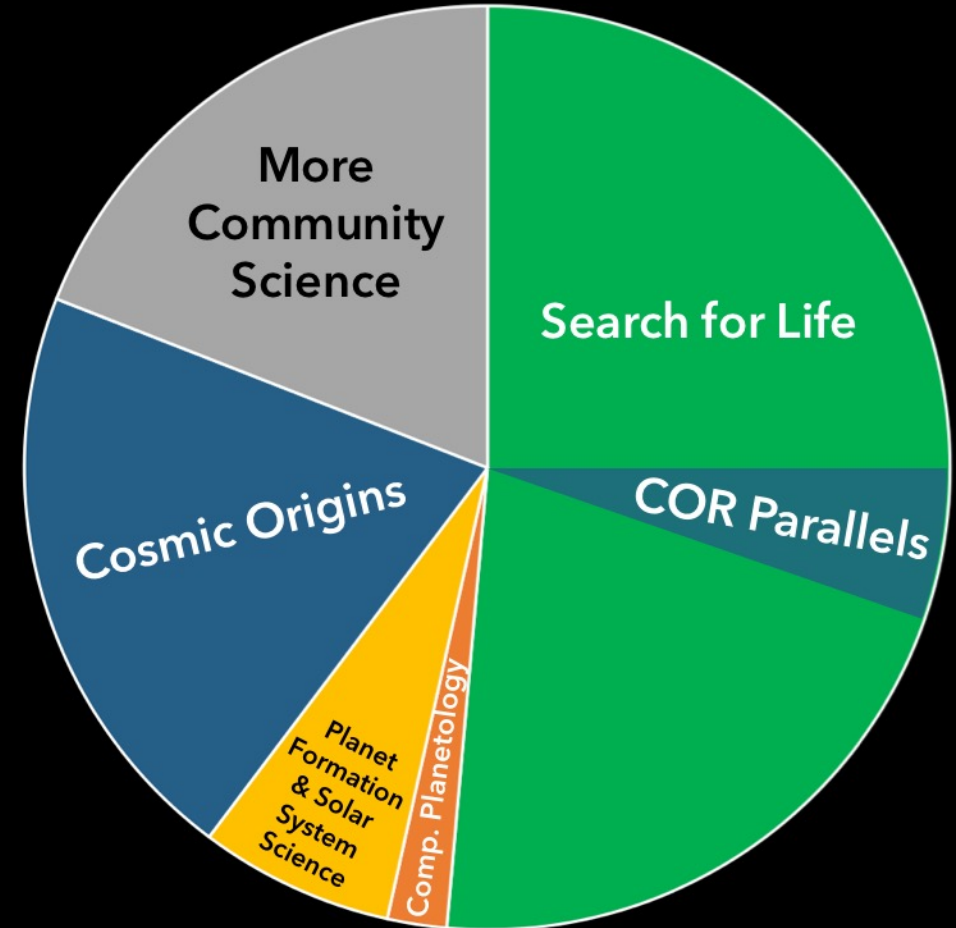
Science Metric	Aperture Scaling	LUVOIR-B	LUVOIR-A	Minimum Aperture
# Deep Fields performed in parallel with exoEarth survey with sufficient depth to measure hi-z LF turnover	D^4	1	12	11.5 m (>4 fields)
# E-gals within 10 Mpc where we can measure SFH directly from the stellar main sequence	$D^{3.5}$	1	5	8 m (≥ 1 gal)
Stellar mass detectable at $z > 1$ in a given exposure time	$D^{-3.4}$	$10^{4.9} M_{\odot}$ (at $z=7$)	$10^4 M_{\odot}$ (at $z=7$)	10.8 m ($M < 10^{4.5}$ at $z=7$)
# $z > 1$ QSO accessible in FUV	$D^{3.3}$	1600	6600	7.5 m (>1000)
Min. tangential velocity at 5 Mpc for dwarf dark matter studies	D^{-2}	44 km/s	13 km/s	7 m (< 50 km/s)
Lowest spatial resolution at $z > 1.7$ (at 500 nm)	D^{-1}	115 pc	61 pc	9 m (≤ 100 pc)

HOW MUCH SCIENCE CAN LUVOIR DO?

LUVOIR-A



LUVOIR-B



HOW MUCH SCIENCE CAN LUVOIR DO?

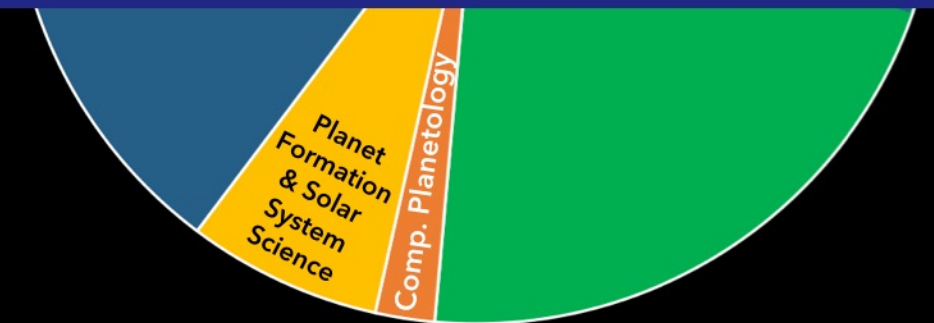
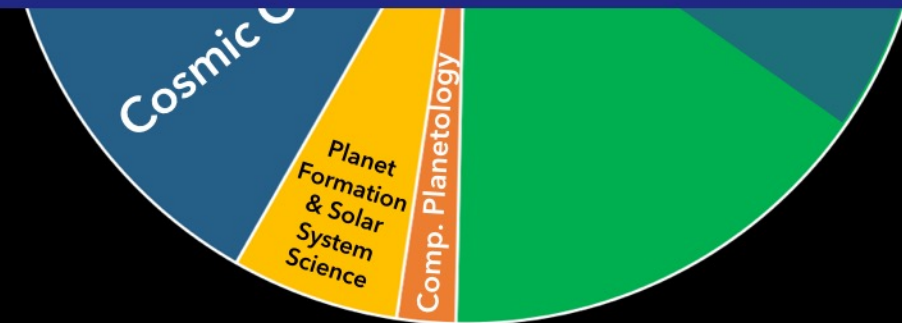
LUVOIR-A



LUVOIR-B



LUVOIR will accomplish all its signature science within less than five years without servicing



NEW DISCOVERY SPACES

LUVVOIR opens new avenues for discovery and serendipity. LUVVOIR will ...

- Reach 4-5 mag (40 - 100x) deeper than Hubble and 2-3 mag (6 - 16x) deeper than Webb or the ELTs
- Resolve 100 pc scales at any cosmic time
- Collect UV spectra >1000 times faster than Hubble
- Provide an ultra-stable imaging platform capable of micro-arcsecond astrometry



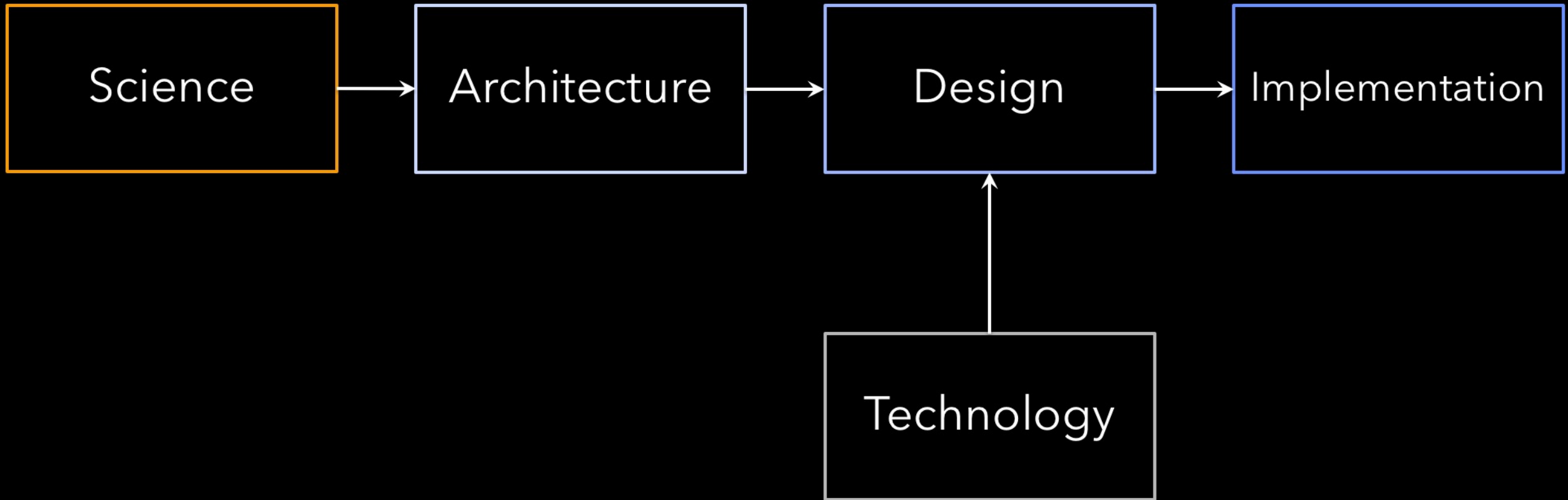
**What unknown
phenomena
will it bring into
view?**

The background of the slide is a dark, high-contrast image of a space telescope, likely the James Webb Space Telescope, with its large, segmented primary mirror and complex support structure visible against a black background.

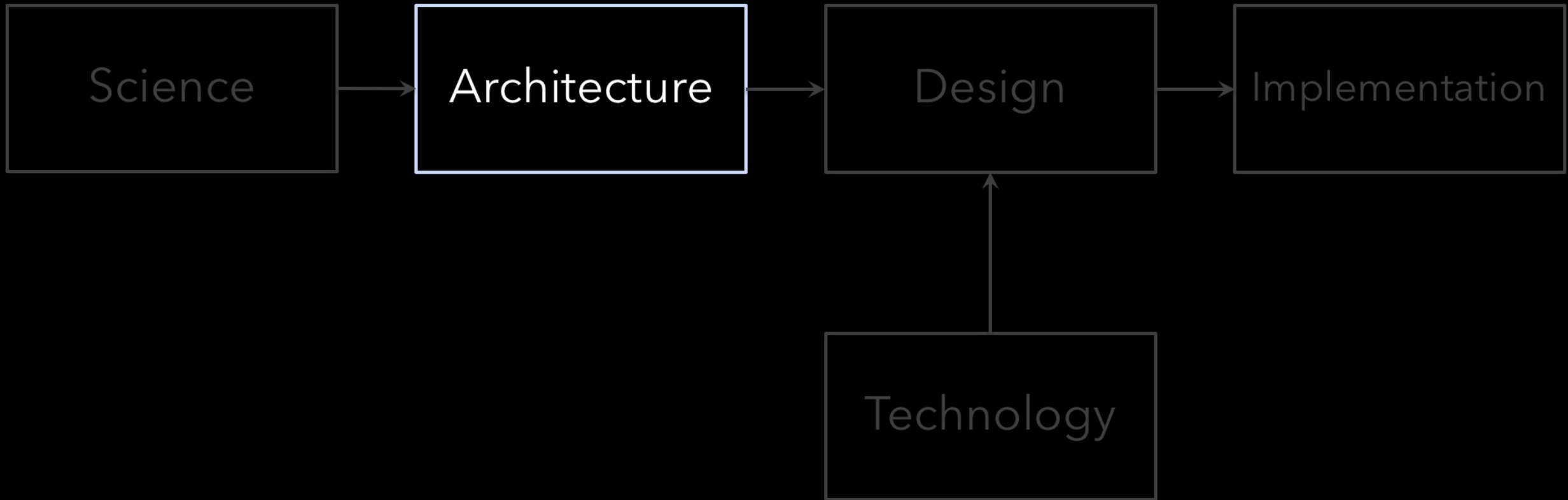
LUV O I R is FEASIBLE

DESIGN AND TECHNOLOGY

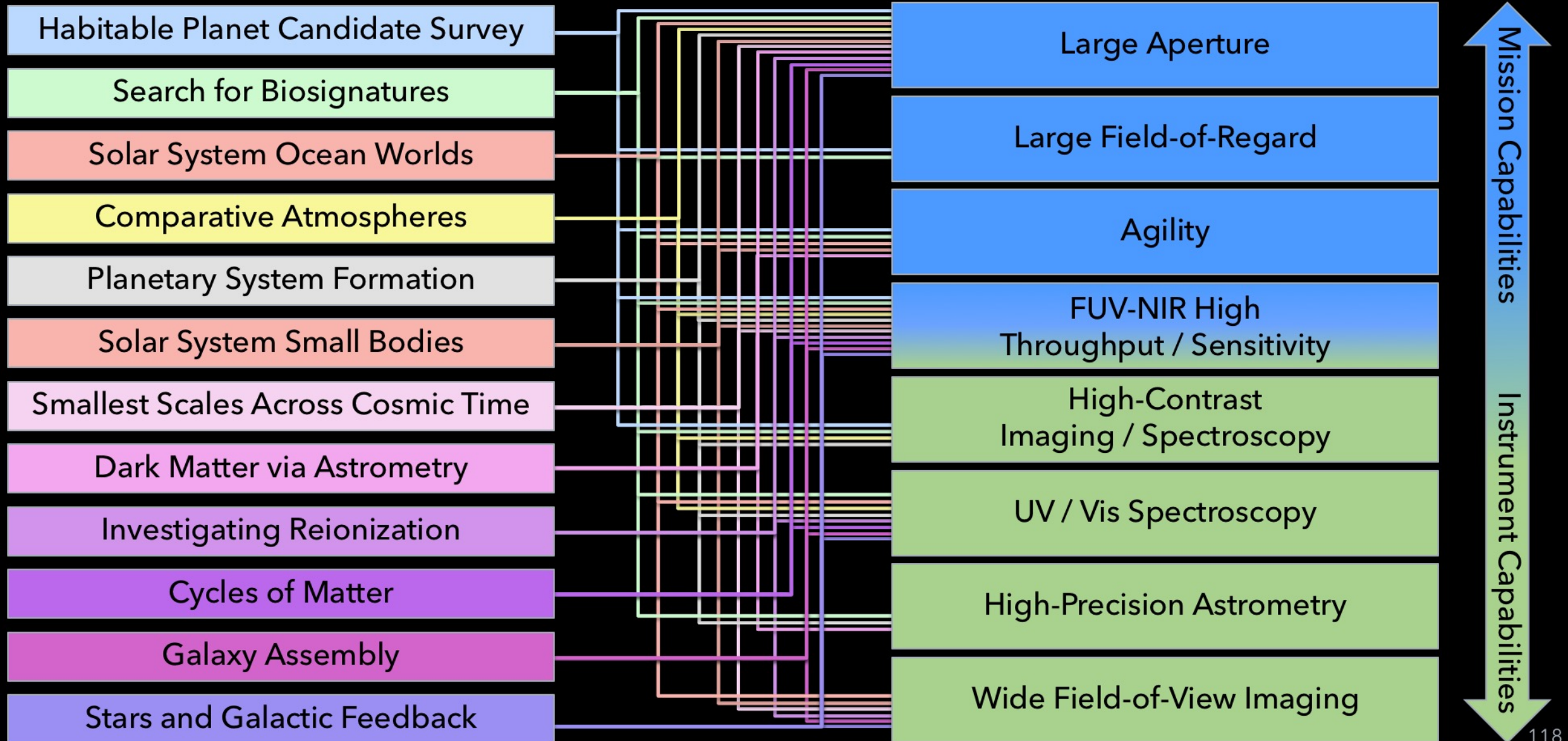
THE DESIGN PROCESS



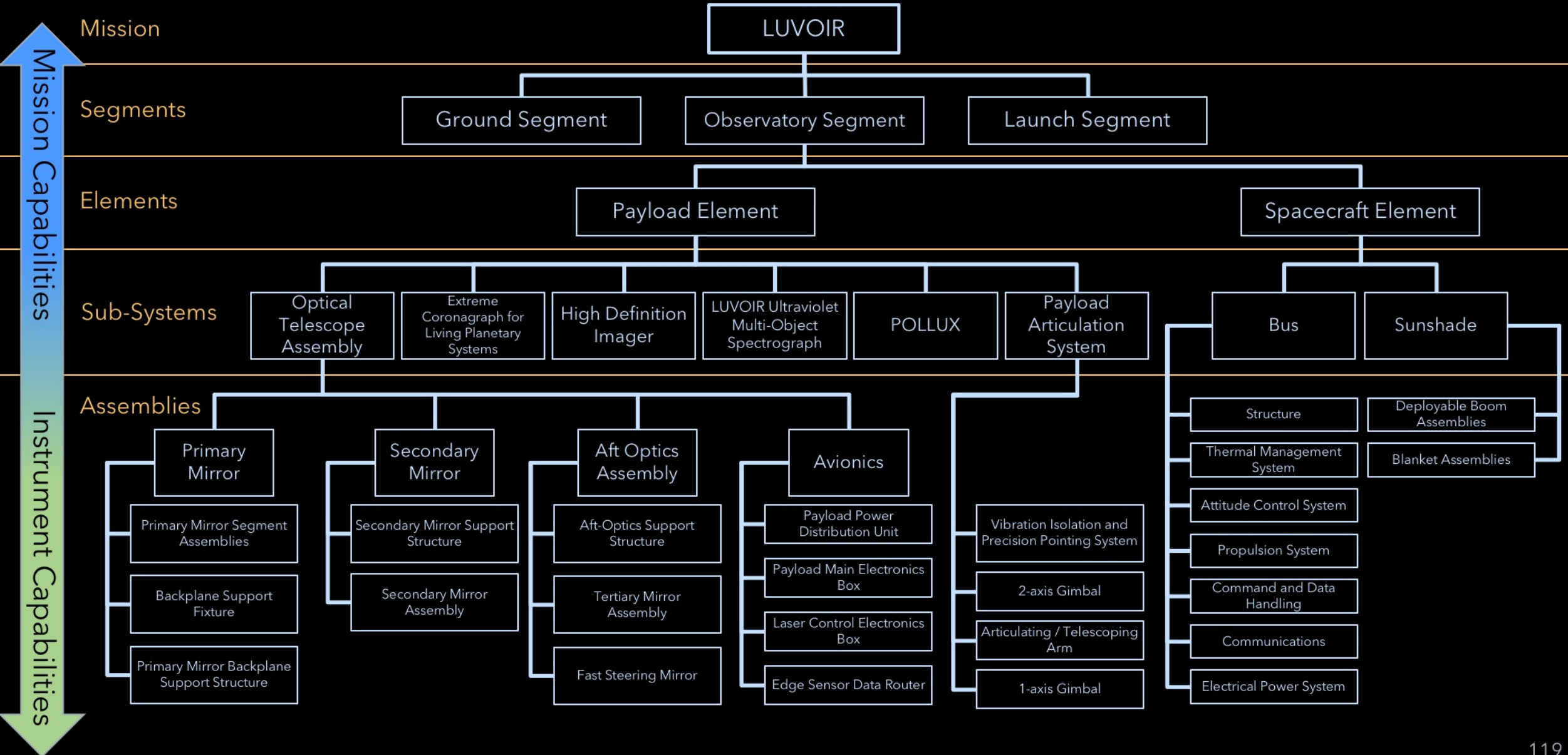
THE DESIGN PROCESS



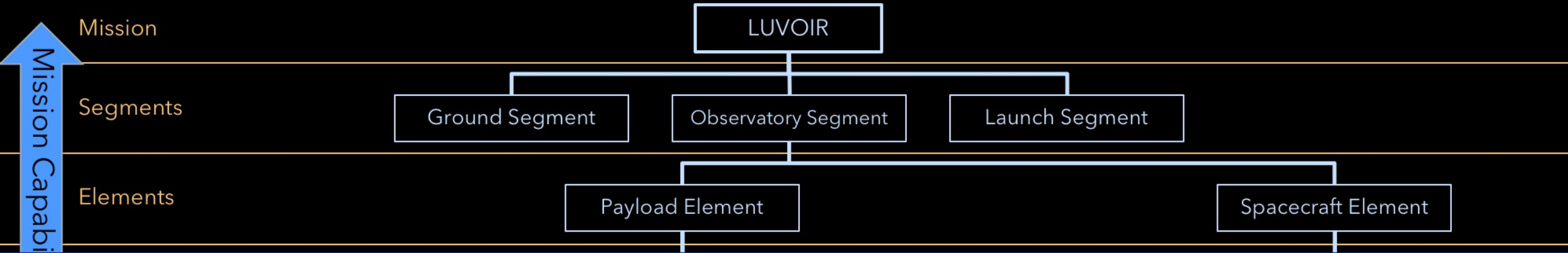
SCIENCE DRIVES OBSERVATORY CAPABILITIES



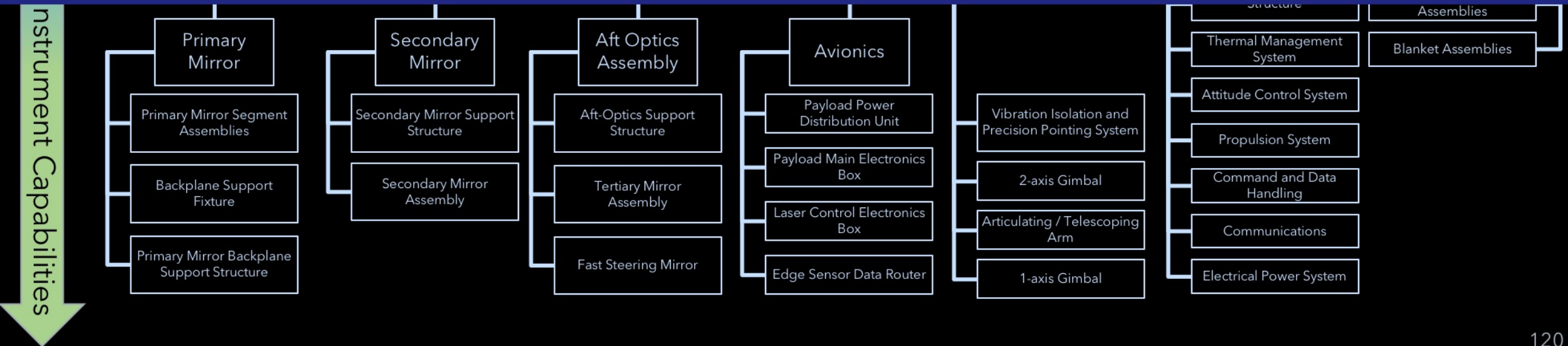
LUVOIR ARCHITECTURE



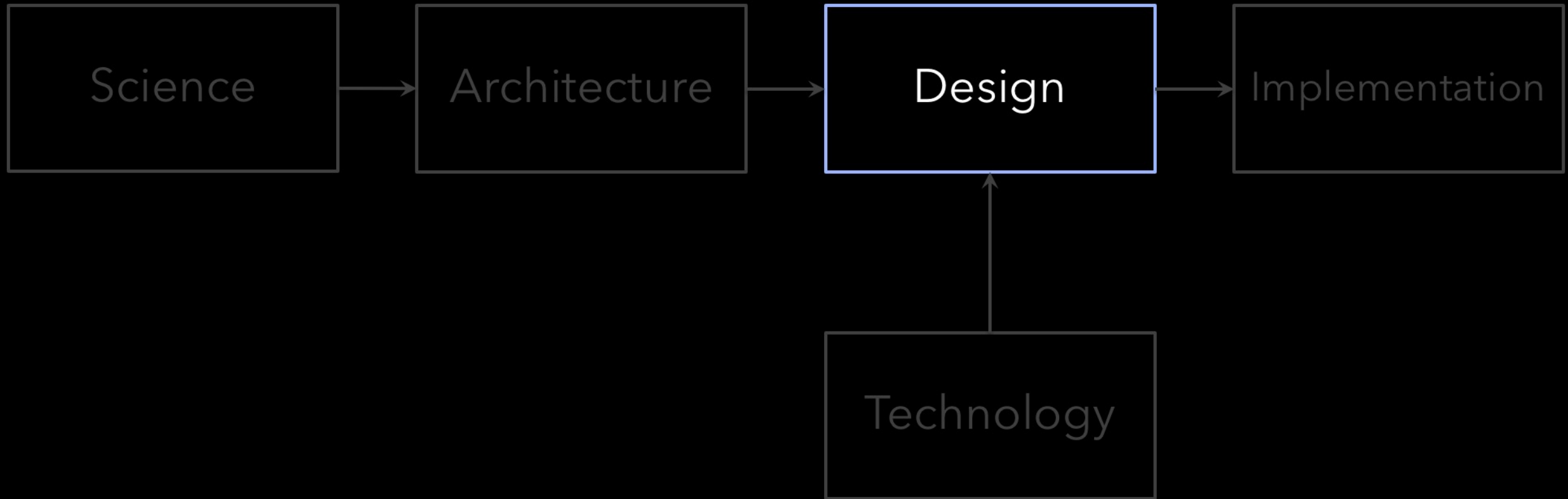
LUVOIR ARCHITECTURE



LUVOIR's scalable architecture informs every aspect of the mission concept from design, to technology, to implementation



THE DESIGN PROCESS



DESIGN DRIVER – HABITABLE PLANET CANDIDATE YIELD



$$Y \propto D^{1.97} (IWA)^{-0.98} (\eta_{Earth})^{0.96} (SNR)^{-0.76} A^{0.65} T^{0.35} \\ (PSF)^{-0.33} (Time)^{0.32} \Delta\lambda^{0.30} x^{-0.17} \xi^{-0.10}$$

Instrumental, astrophysical, & observational parameters all matter

DESIGN DRIVER – HABITABLE PLANET CANDIDATE YIELD



$$Y \propto D^{1.97} (IWA)^{-0.98} T^{0.35} (PSF)^{-0.33} \Delta\lambda^{0.30} \xi^{-0.10}$$

DESIGN DRIVER – HABITABLE PLANET CANDIDATE YIELD



$$Y \propto D^{1.97} (IWA)^{-0.98} T^{0.35} (PSF)^{-0.33} \Delta\lambda^{0.30} \xi^{-0.10}$$

Diameter drives
telescope size
and design

Inner working
angle drives
telescope size,
coronagraph
mask design, and
science
operations

Throughput
drives telescope
and coronagraph
optical designs,
spectrograph
designs, and
coatings

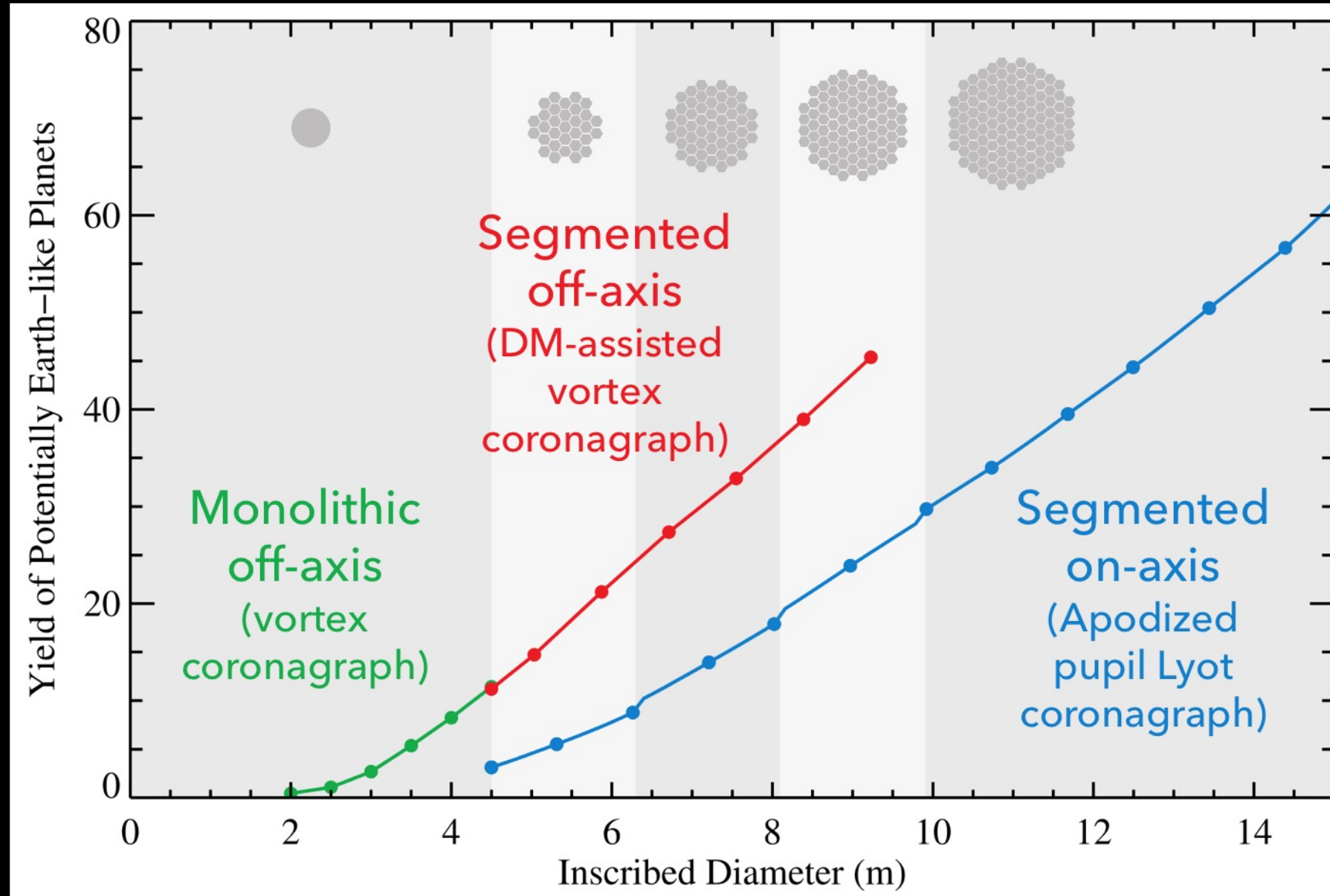
PSF sharpness
drives
telescope and
coronagraph
mask designs

Bandpass drives
the coronagraph
design, science
operations,
wavefront
sensing and
control, and
detector size

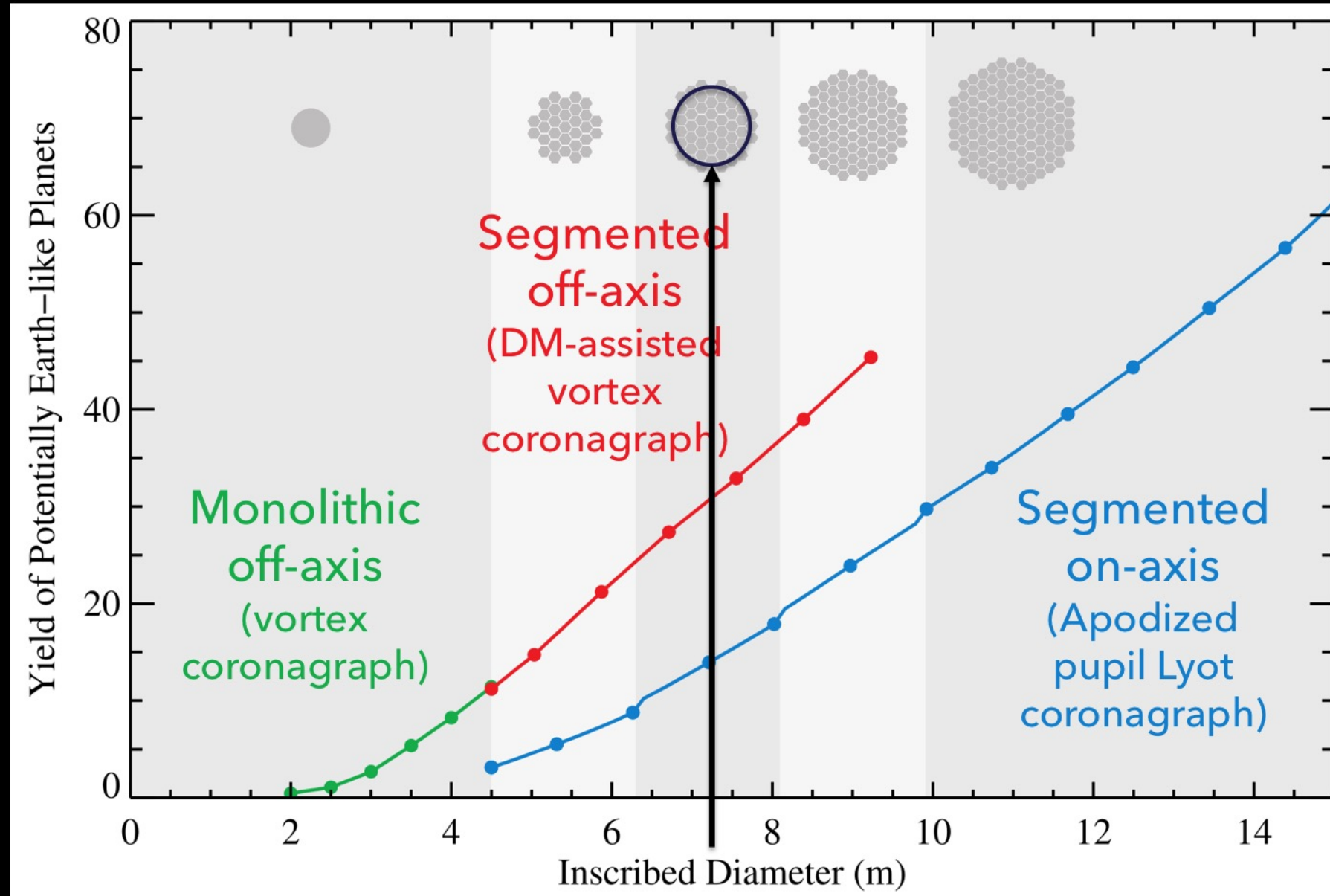
Contrast drives
the telescope
and coronagraph
designs, and
wavefront
sensing and
control

All these parameters must be optimized together, and in some cases traded against one another

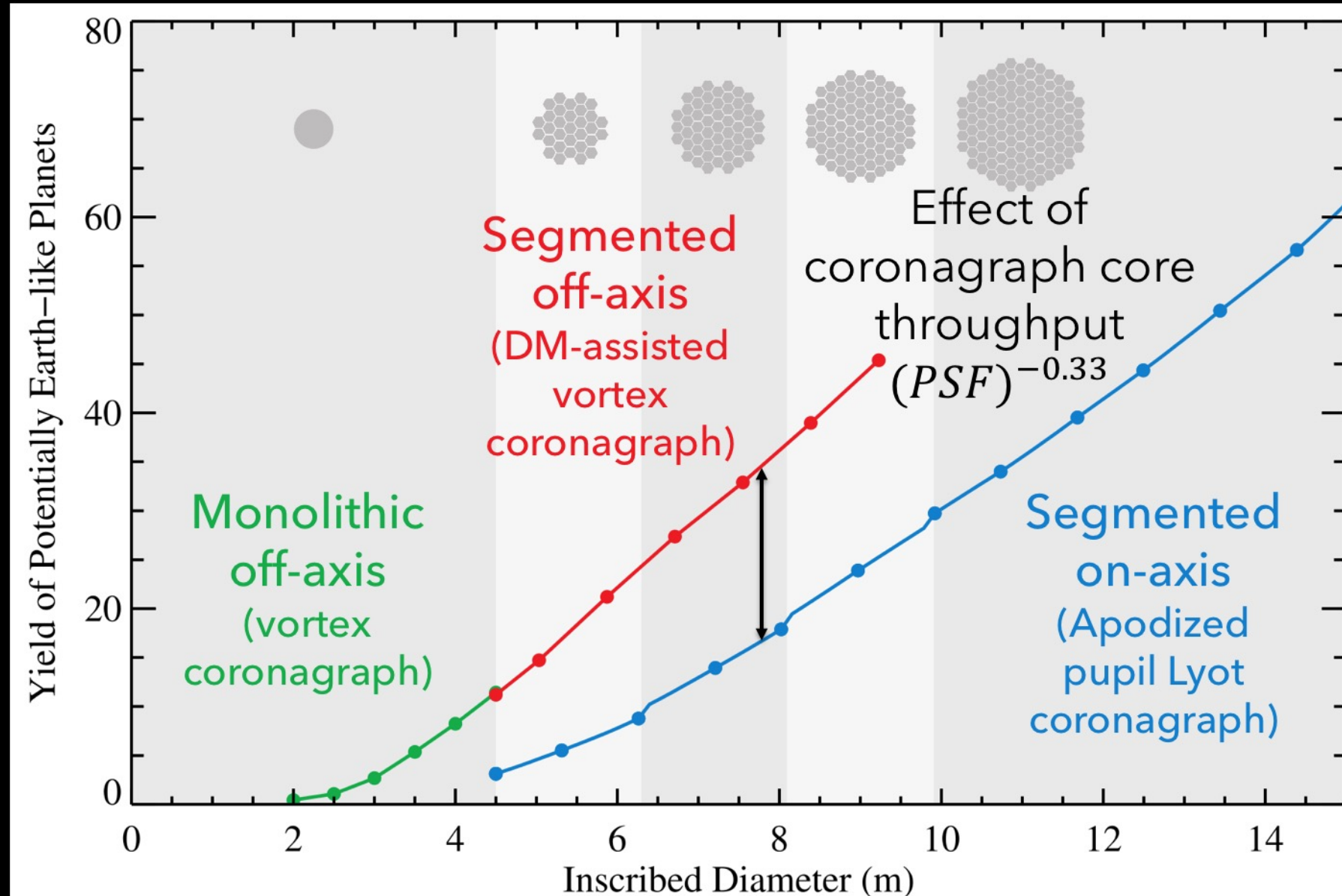
THE EXOEARTH TRADE SPACE



THE EXOEARTH TRADE SPACE



THE EXOEARTH TRADE SPACE



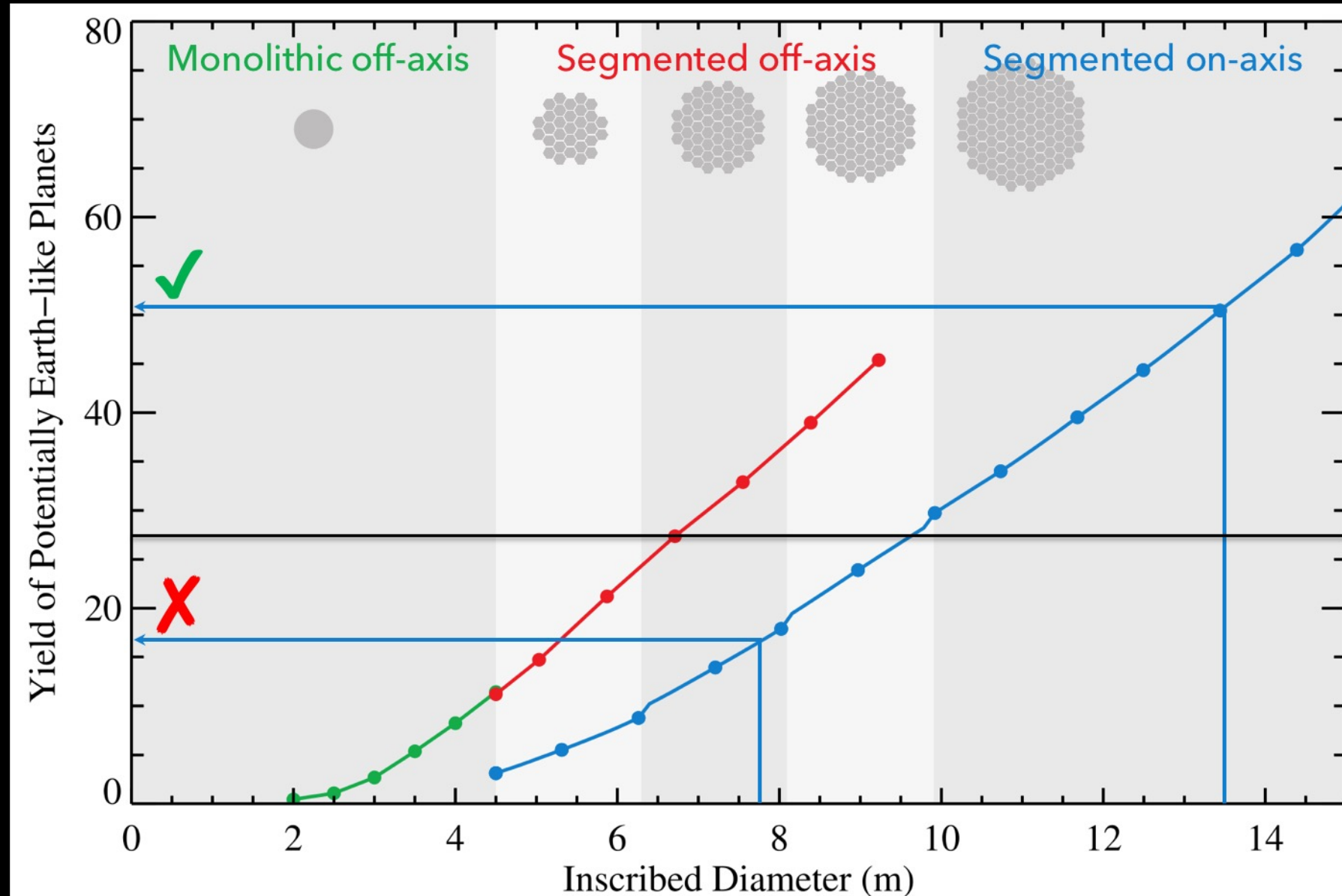
LAUNCH VEHICLE ACCOMMODATION

Scalable design allows us to be responsive to launch vehicle availability

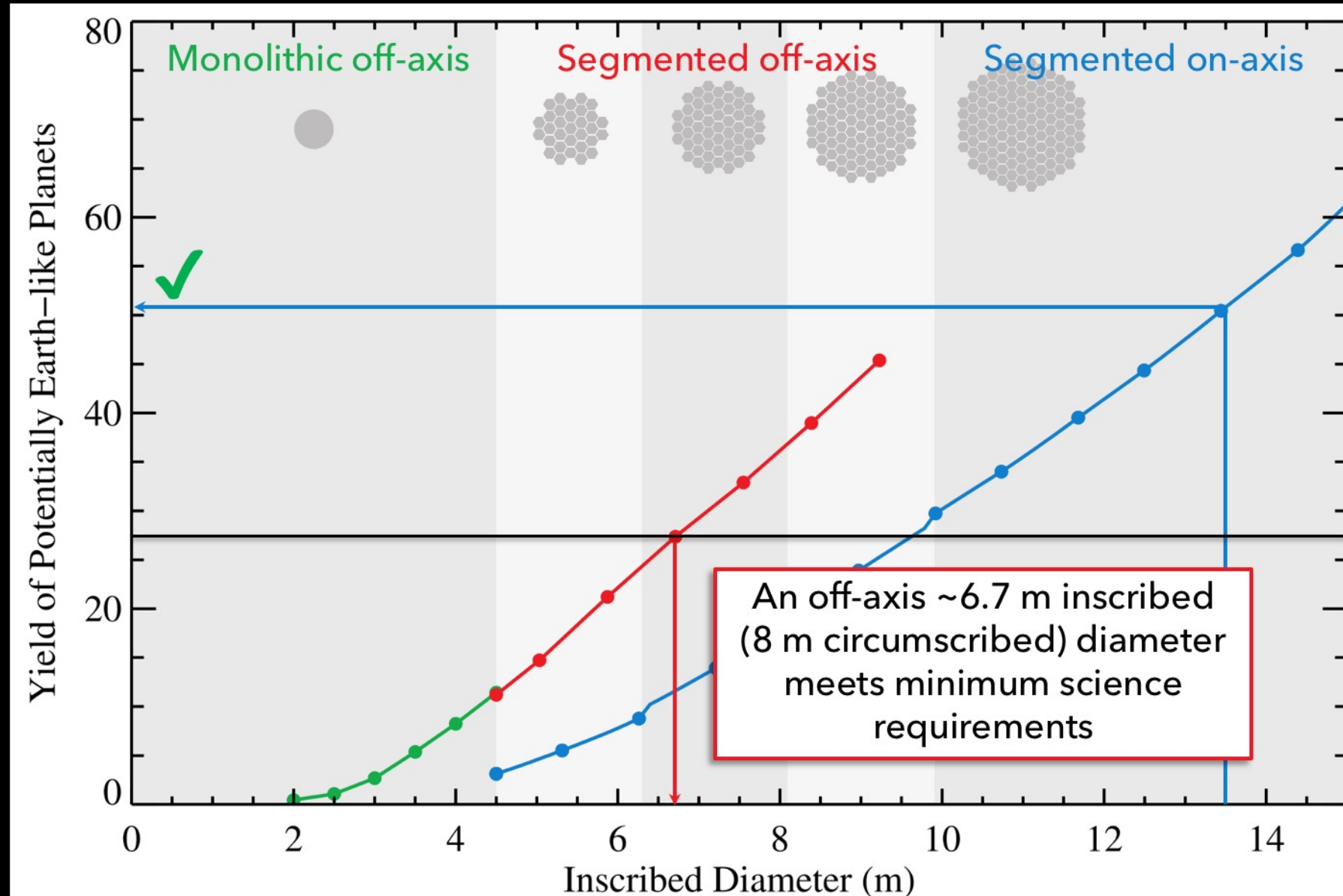
1. LUVOIR-A baselined for SLS Block 2 with 8.4-m fairing
 - ~15 m
 - (13.5 m inscribed diameter)
2. LUVOIR-B baselined for "industry standard" 5-m fairing
 - ~9 m
 - (7.7 m inscribed diameter)

Initially only considered on-axis designs to leverage JWST and ATLAST/HDST studies

THE EXOEARTH TRADE SPACE



THE EXOEARTH TRADE SPACE



LUVOIR-A

15-m, on-axis telescope

120 segments, 1.223-m flat-to-flat

155 m² collecting area

Four instrument bays

ECLIPS

LUMOS

HDI

POLLUX



Deployment movie at <https://asd.gsfc.nasa.gov/luvoir/design/>

LUVOIR-B

8-m, off-axis telescope

55 segments, 0.955-m flat-to-flat

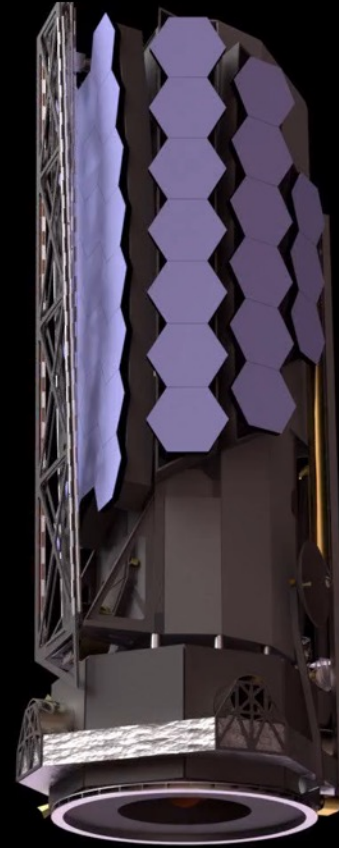
43.4 m² collecting area

Three instrument bays

ECLIPS

LUMOS

HDI



Deployment movie at <https://asd.gsfc.nasa.gov/luvoir/design/>

DESIGN DRIVER – CONTRAST STABILITY FOR EXO-EARTHS



Corresponds to wavefront stability of "10 pm per 10 minutes"

How do we enable that level of ultra-stability?

Through **design**

Through **control**

Through **tolerance**

ULTRA-STABILITY THROUGH DESIGN



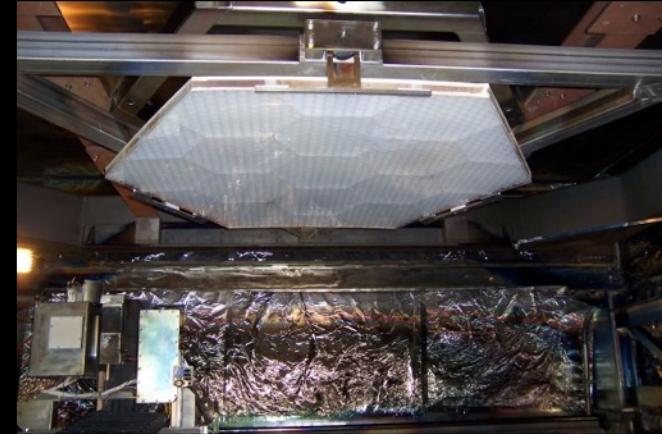
Actively heated (270 K) telescope,
where materials have near-zero CTE
and are well characterized

Easier to model and verify performance

Stiff mirror designs (~ 500 Hz first
mode) for stable performance without
surface figure actuators

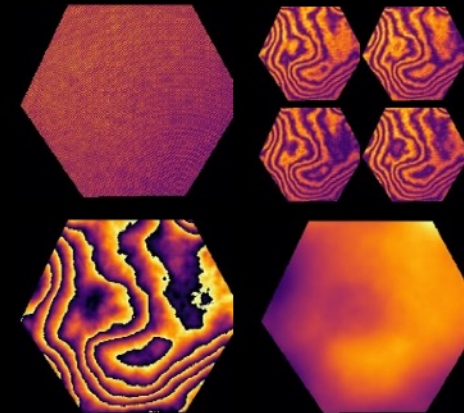
Easier to test on the ground in 1-g

Lightweight ULE mirror segment



Credit: L3/Harris

Picometer-scale dynamics measured
with high-speed interferometry



Credit: NASA GSFC

ULTRA-STABILITY THROUGH CONTROL

Milli-Kelvin-level thermal control of optics and structures

Minimizes thermal drifts

Picometer-level metrology (edge sensors & laser truss) and actuators

Effectively rigidizes primary mirror backplane and secondary mirror support

Active dynamic isolation physically separates payload from spacecraft

Minimizes dynamic disturbances

Sub-milli-Kelvin thermal control



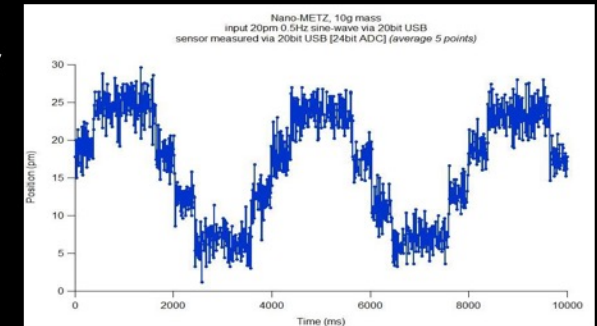
Credit: SAO / NASA GSFC

296.6504 K

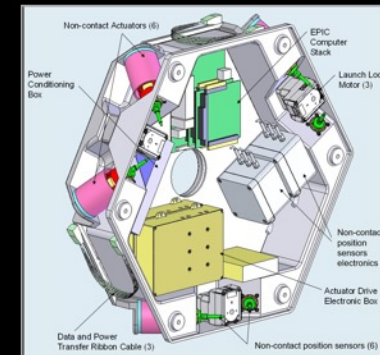
296.6500 K

296.6408 K

Measurement of 5 pm resolution piezo actuator at 1 Hz



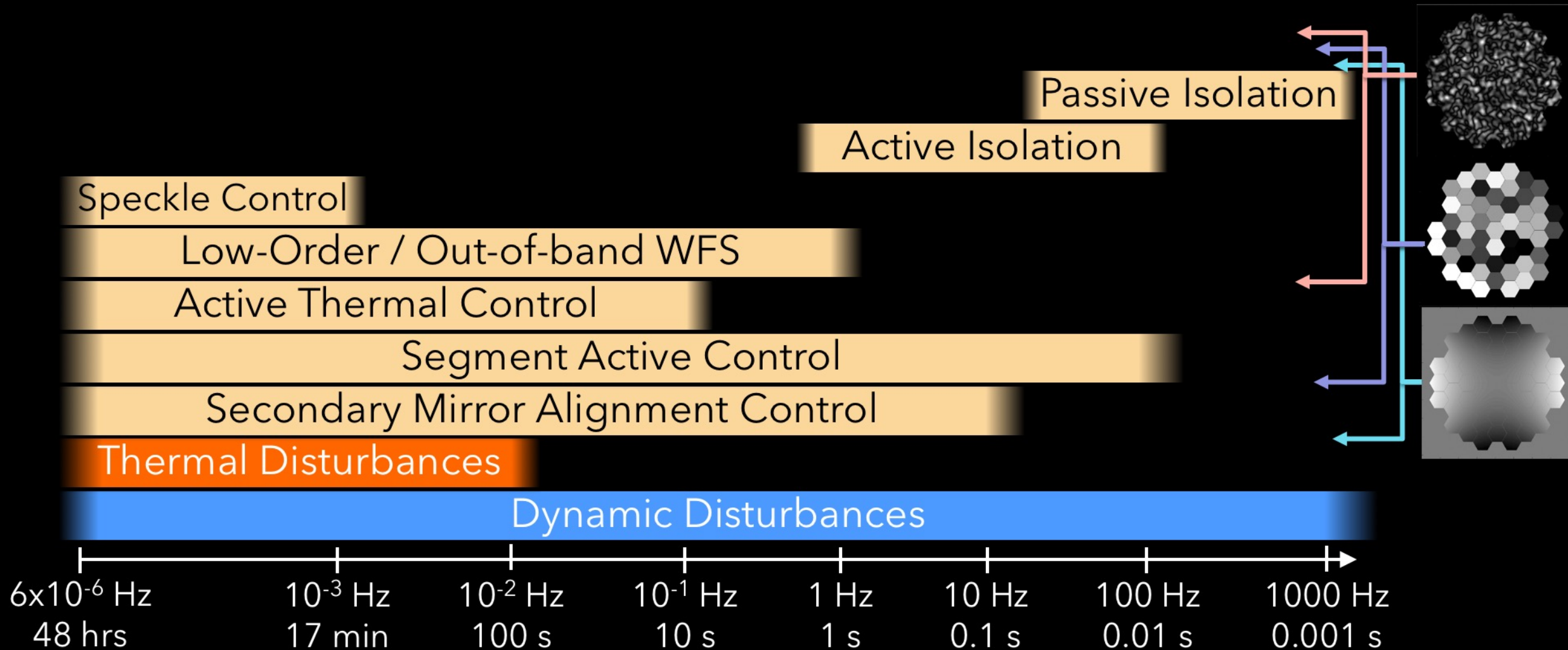
Credit: NASA GSFC



Credit: Lockheed Martin

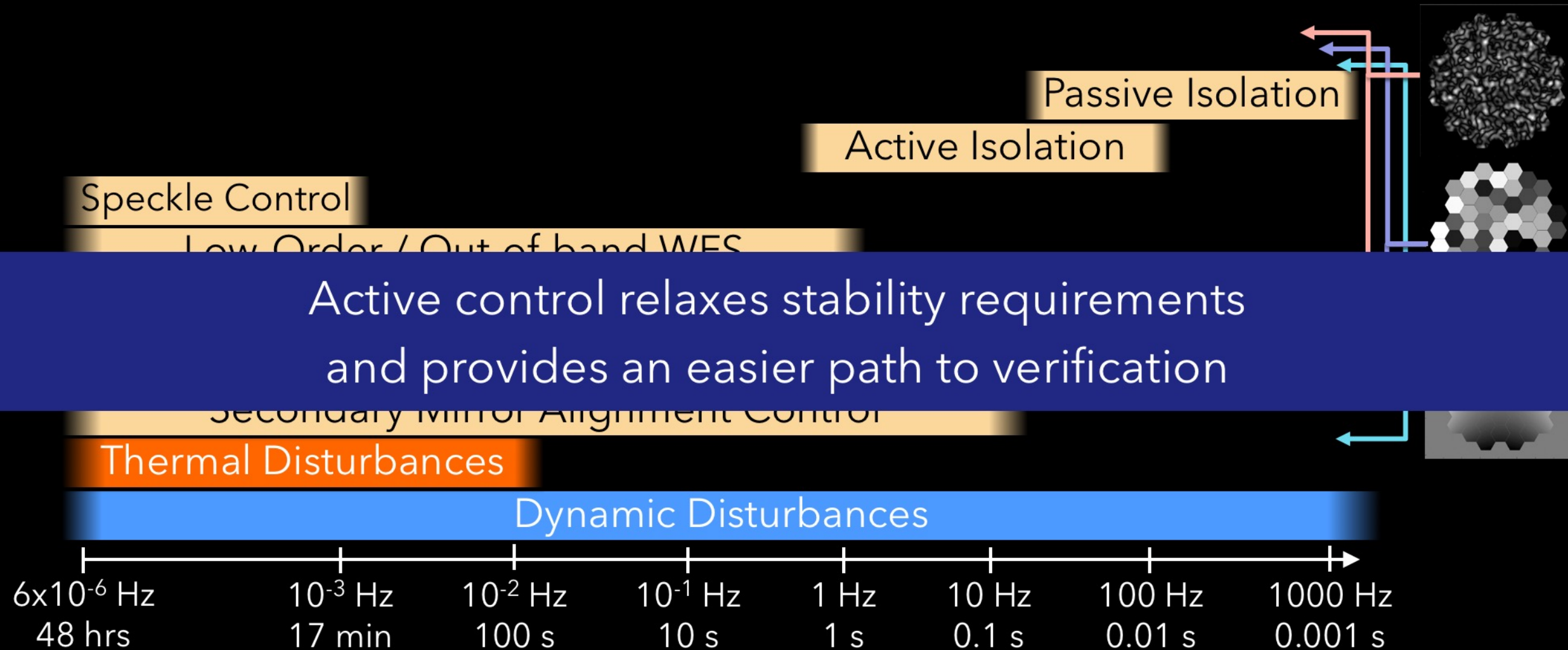
Vibration-isolation and precision pointing system

ULTRA-STABILITY THROUGH CONTROL



See "Ultra-stable Telescope Research and Analysis (ULTRA) Program Phase 1 Report",
Ball Aerospace, L3/Harris, Northrop Grumman, SGT, Space Telescope Science Institute

ULTRA-STABILITY THROUGH CONTROL



See "Ultra-stable Telescope Research and Analysis (ULTRA) Program Phase 1 Report",
Ball Aerospace, L3/Harris, Northrop Grumman, SGT, Space Telescope Science Institute

ULTRA-STABILITY THROUGH TOLERANCE



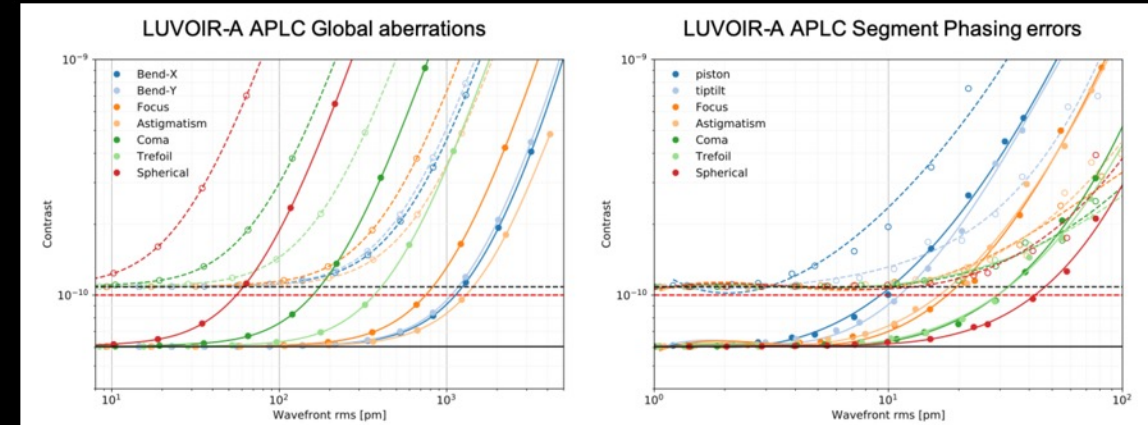
New coronagraph designs with tailored tolerance to certain wavefront modes

Relaxes requirements on modes that are harder to control

New post-processing techniques that are insensitive to contrast instability

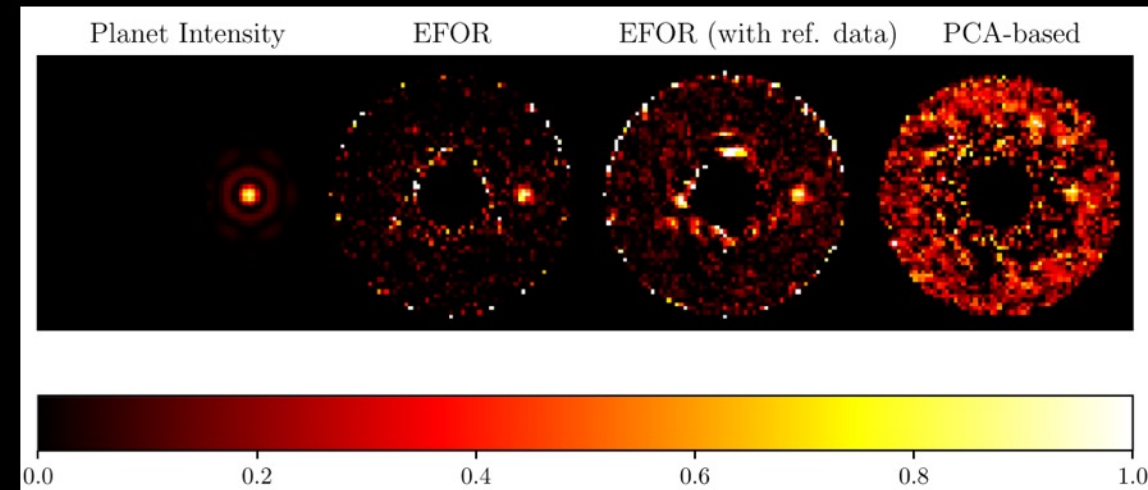
May allow for nanometers of wavefront instability, relaxing requirements

Contrast Sensitivity to Wavefront Errors



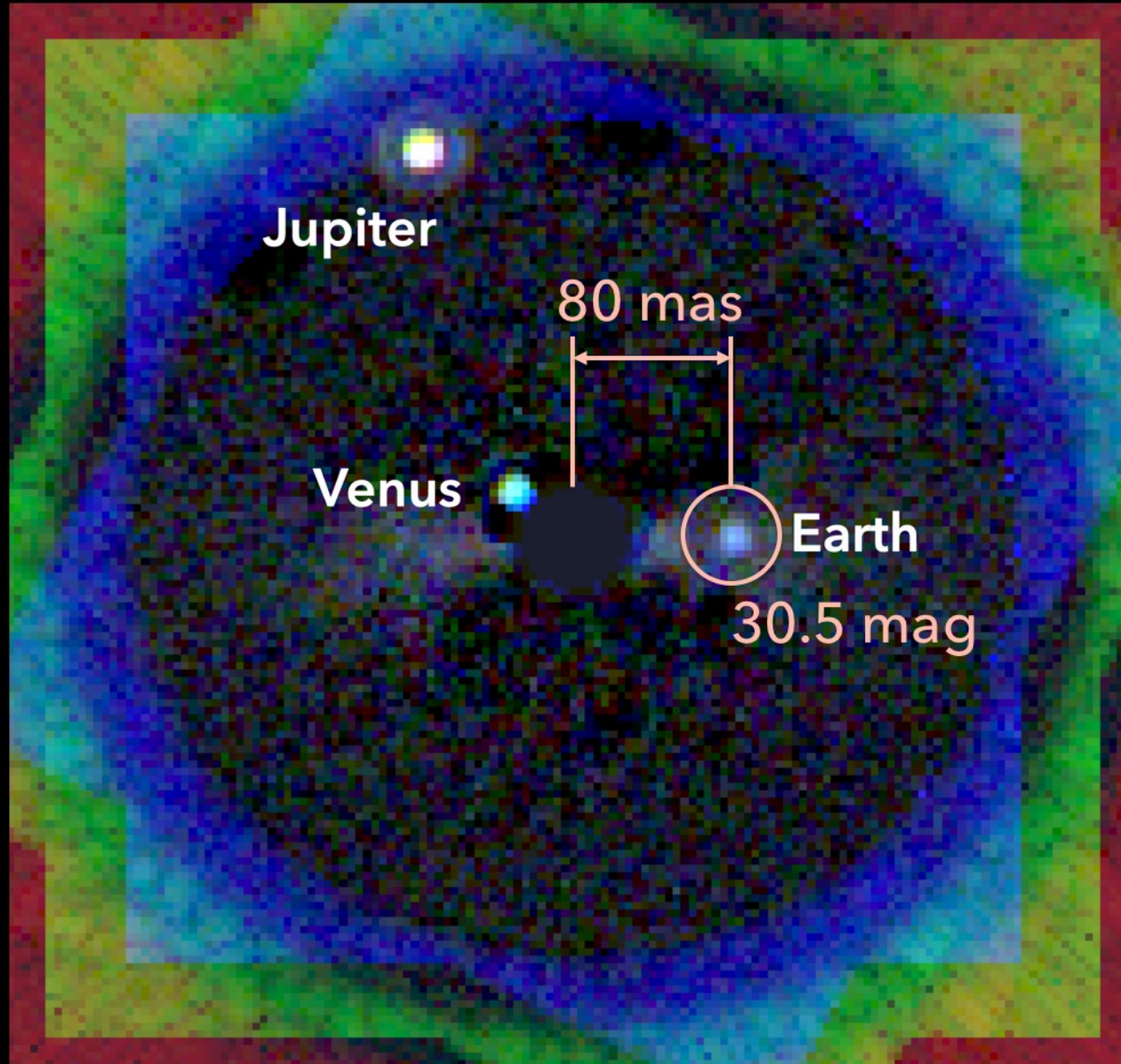
Credit: Juanola-Parramon / NASA GSFC

Post-processing Extraction of Exoplanet Image



Credit: Pogorelyuk / Princeton University

THE SOLAR SYSTEM, NOW WITH WAVEFRONT ERRORS



Solar System at 12.5 pc

60 hrs total integration time

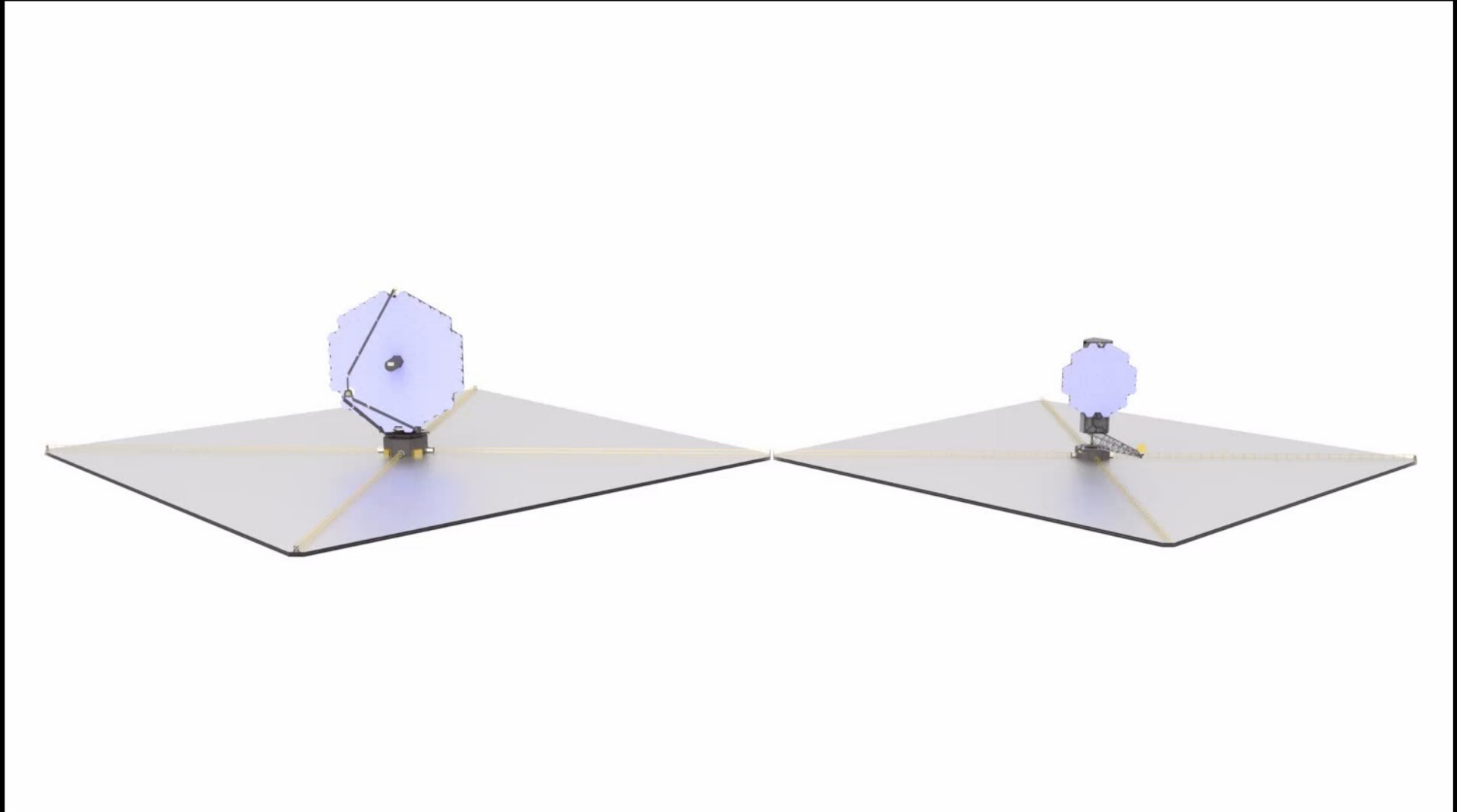
Roll subtraction used

10 pm of random piston, tip, and tilt on each segment

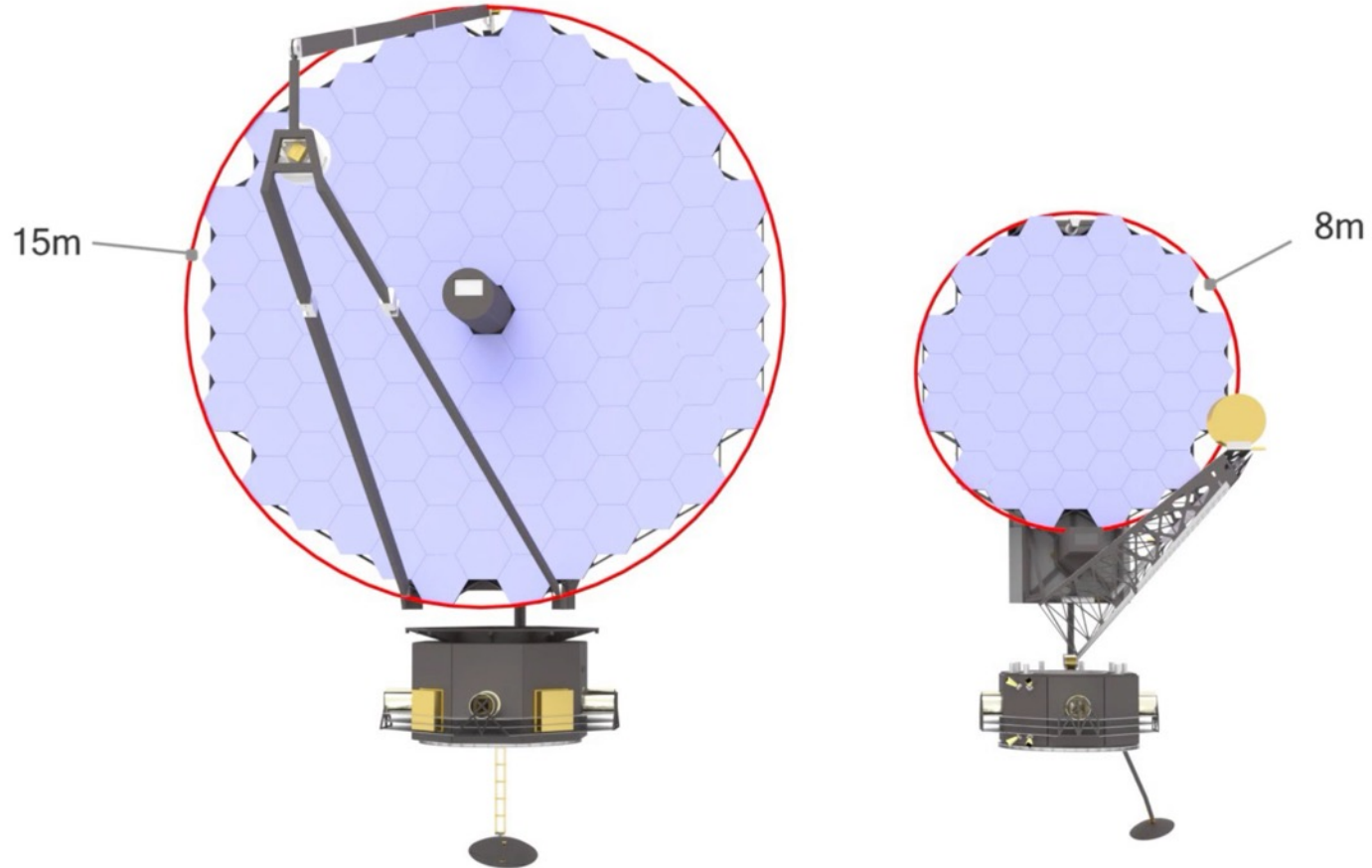
0.2 mas residual line-of-sight jitter

0.75 mas stellar diameter

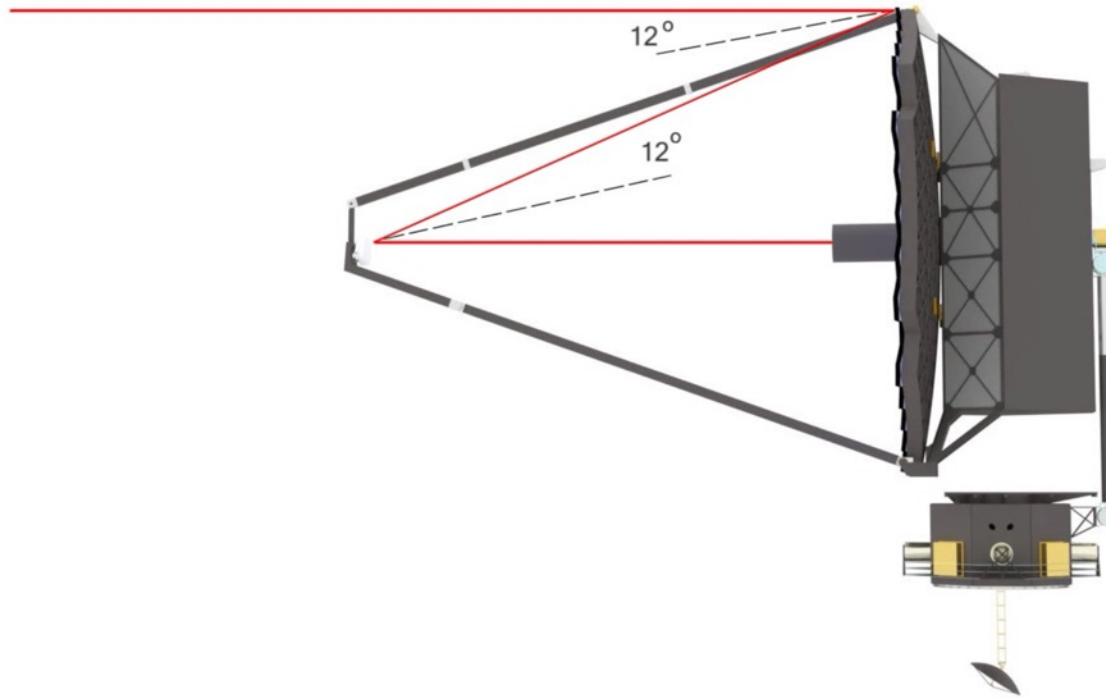
THE LUVOIR DESIGNS



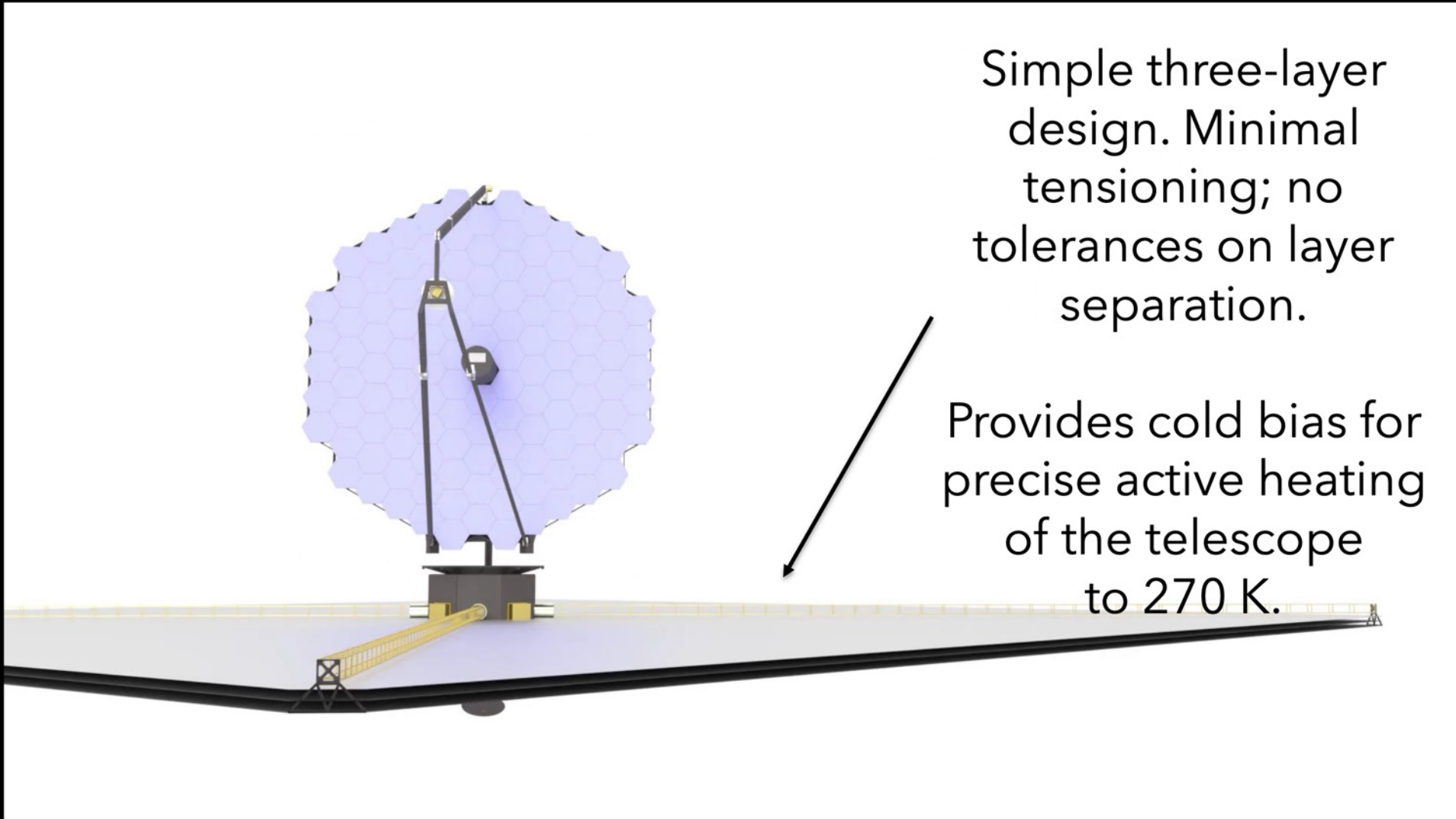
THE LUVOIR DESIGNS



MINIMIZE POLARIZATION ABERRATION



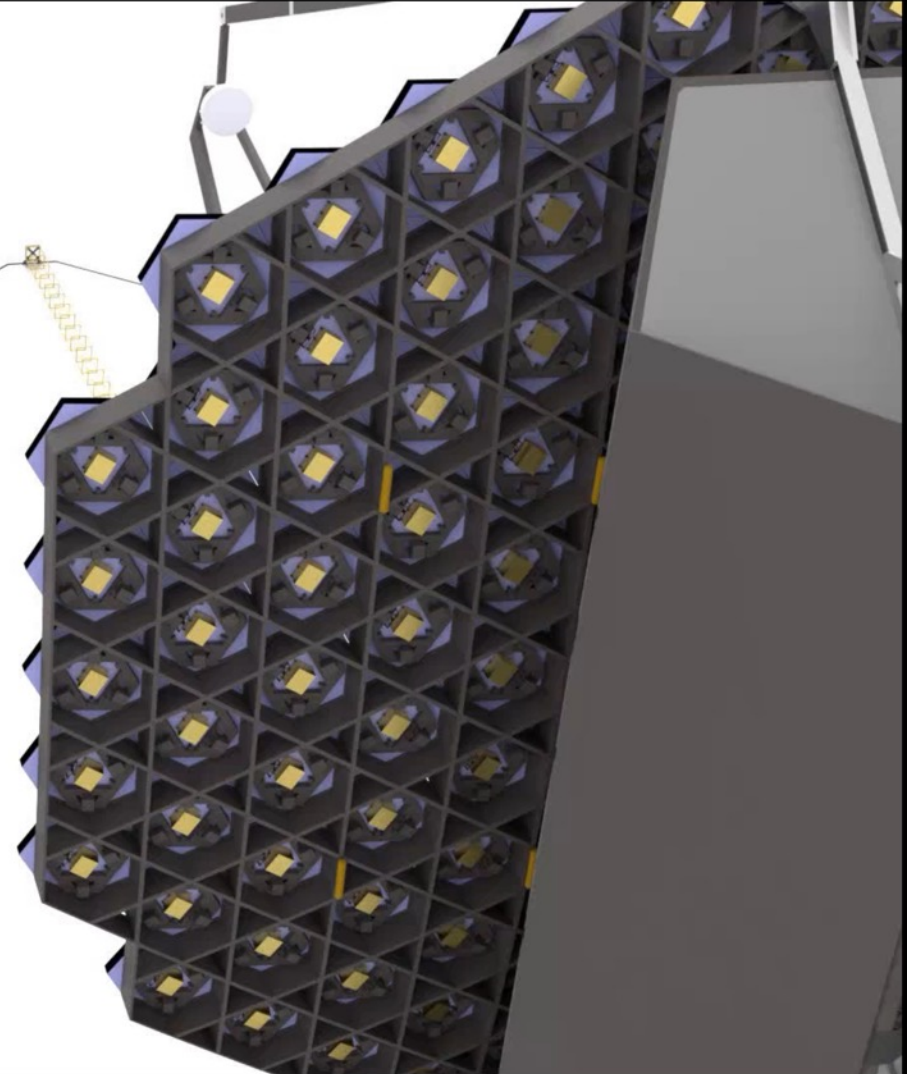
SUNSHADE DESIGN



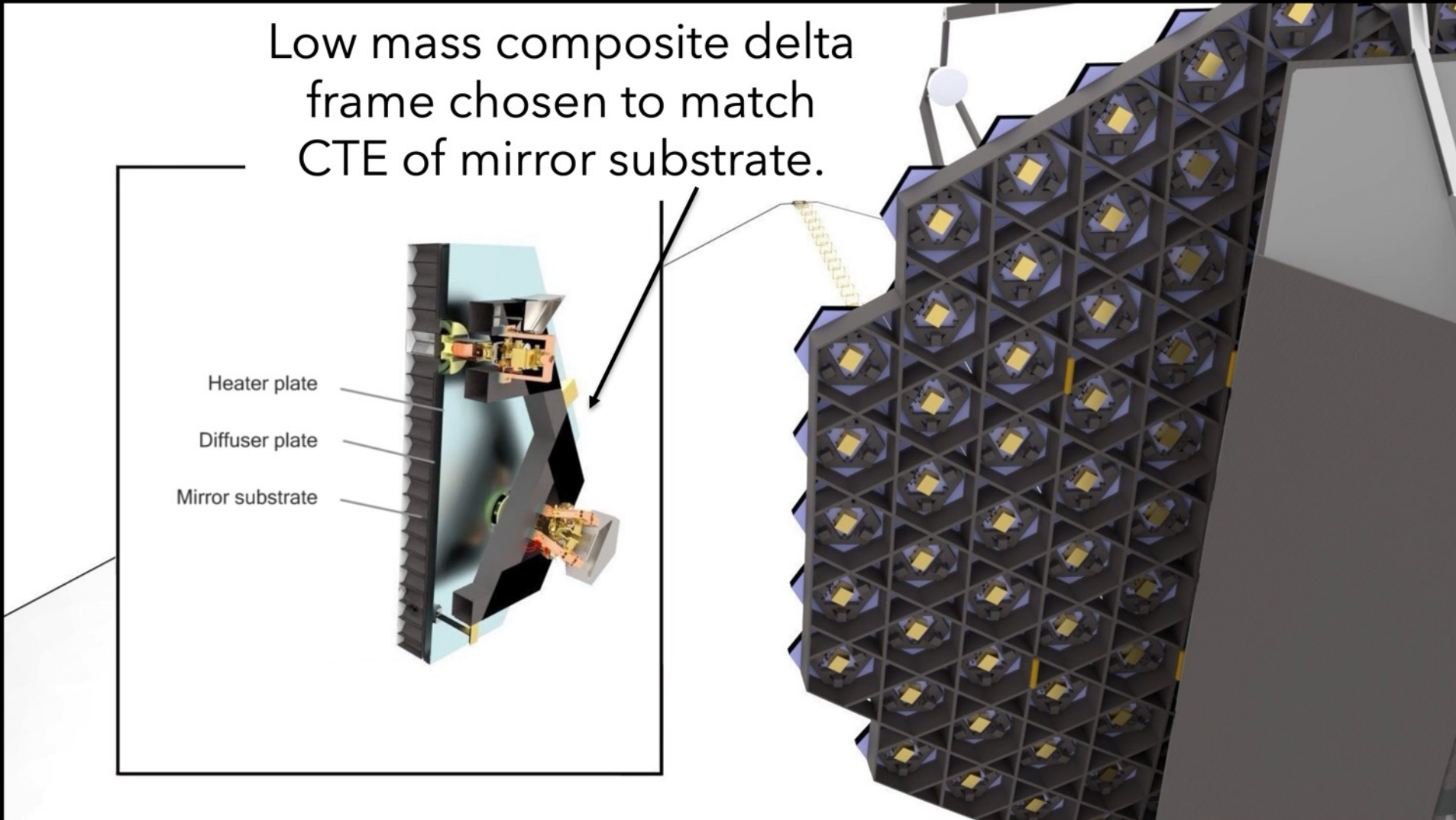
OPERATING TEMPERATURE

270 K operating temperature chosen to enable NIR science while minimizing contamination risk.

Mirrors and structure actively heated with milli-Kelvin precision.



OPERATING TEMPERATURE



VIBRATION ISOLATION AND PRECISION POINTING SYSTEM

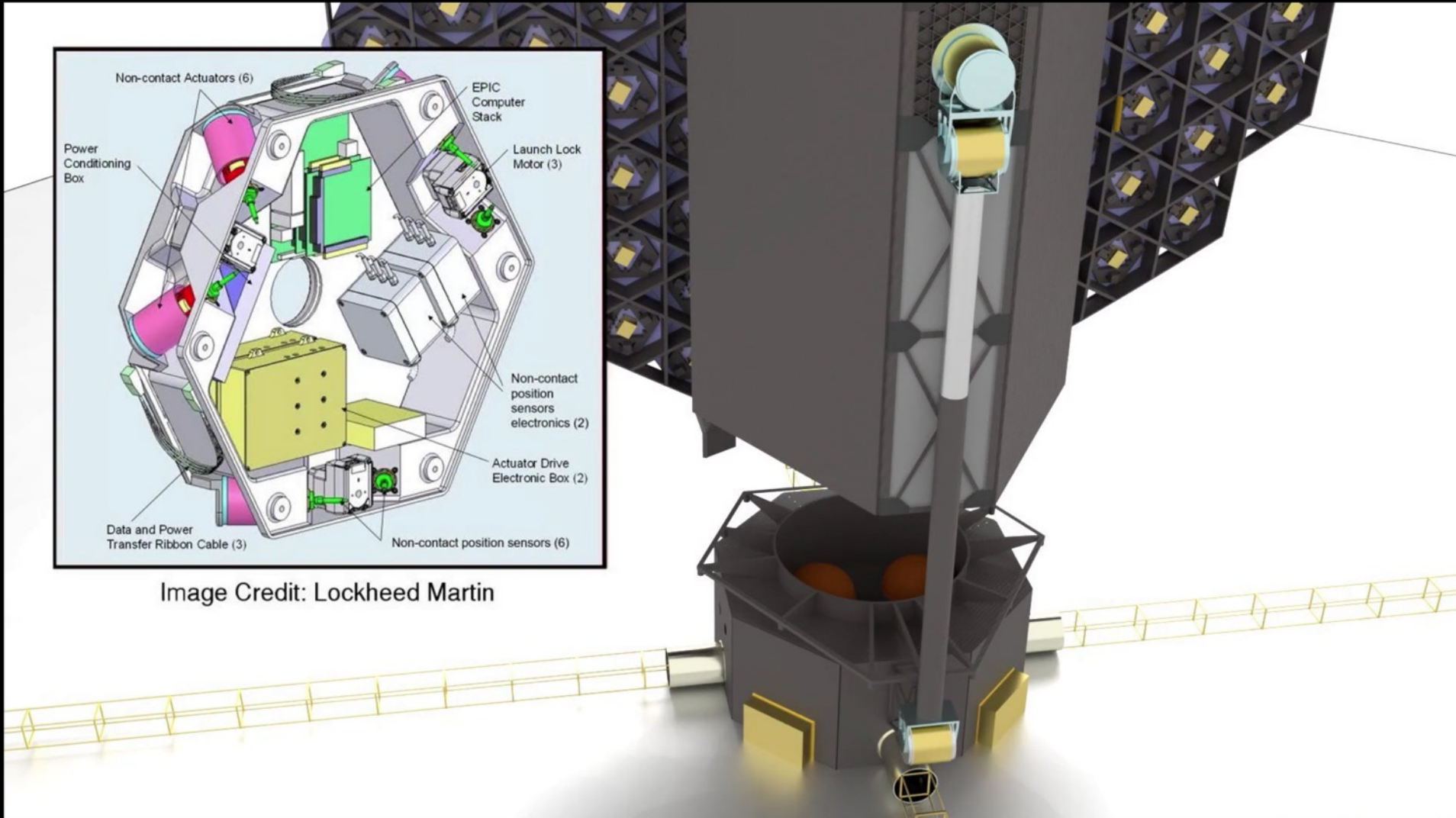
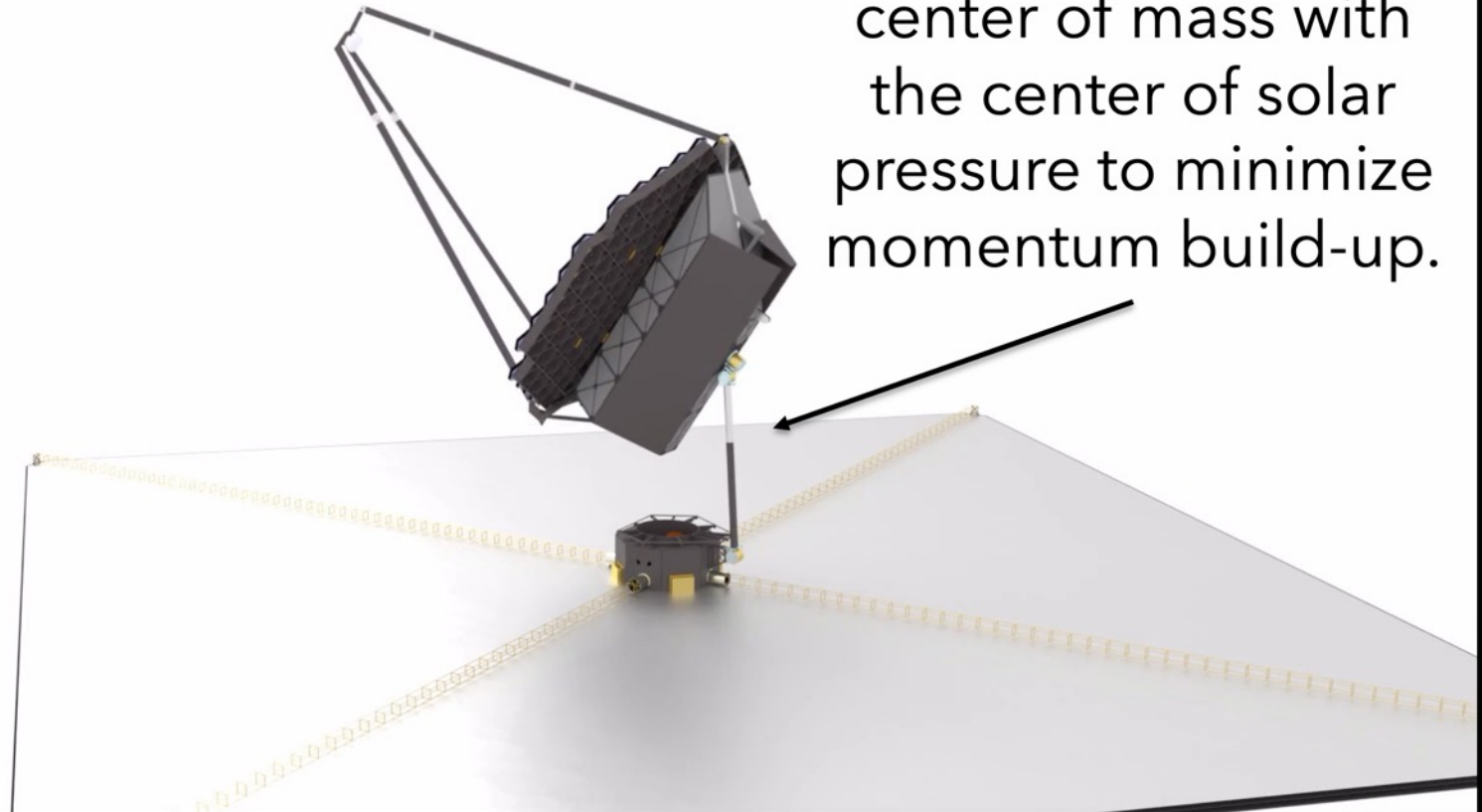


Image Credit: Lockheed Martin

See "System Level Segmented Telescope Design (SLSTD) Program Phase 1 Report" [Lockheed Martin](#),
Collins Aerospace, L3/Harris, Coherent

PAYLOAD ARTICULATION

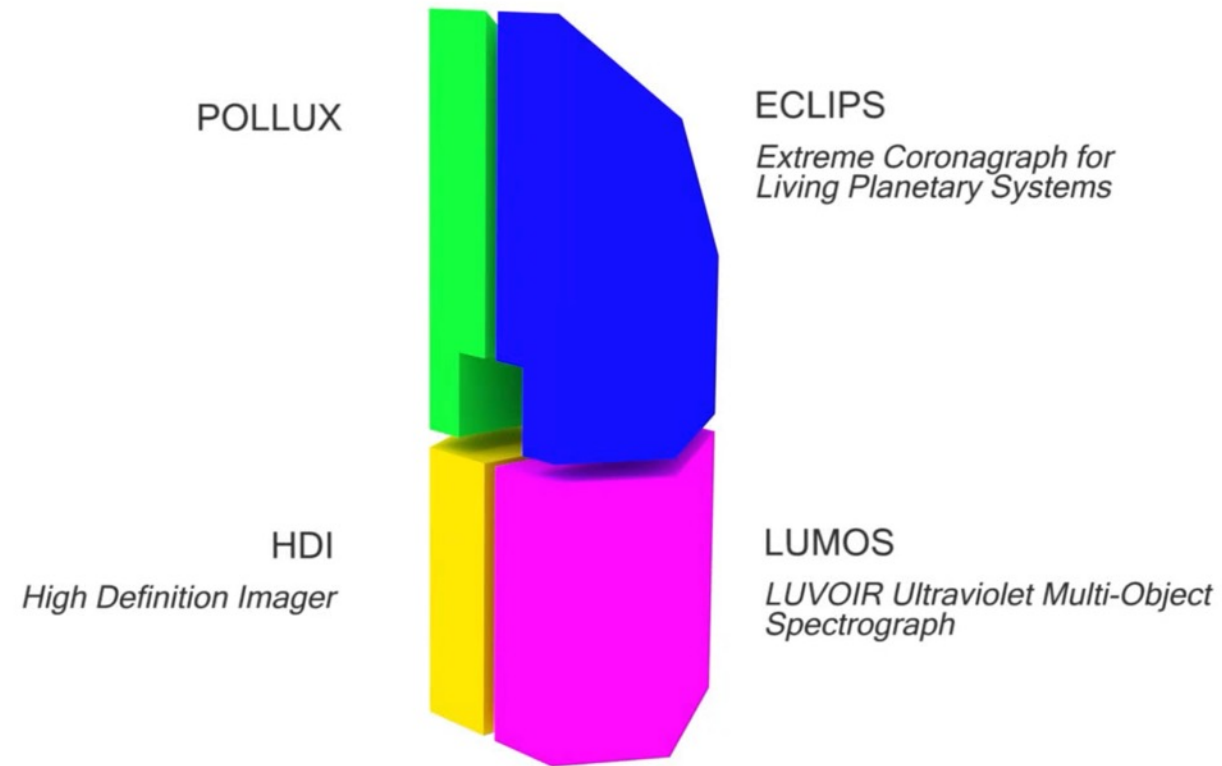
Gimbal arm maintains alignment of the observatory center of mass with the center of solar pressure to minimize momentum build-up.



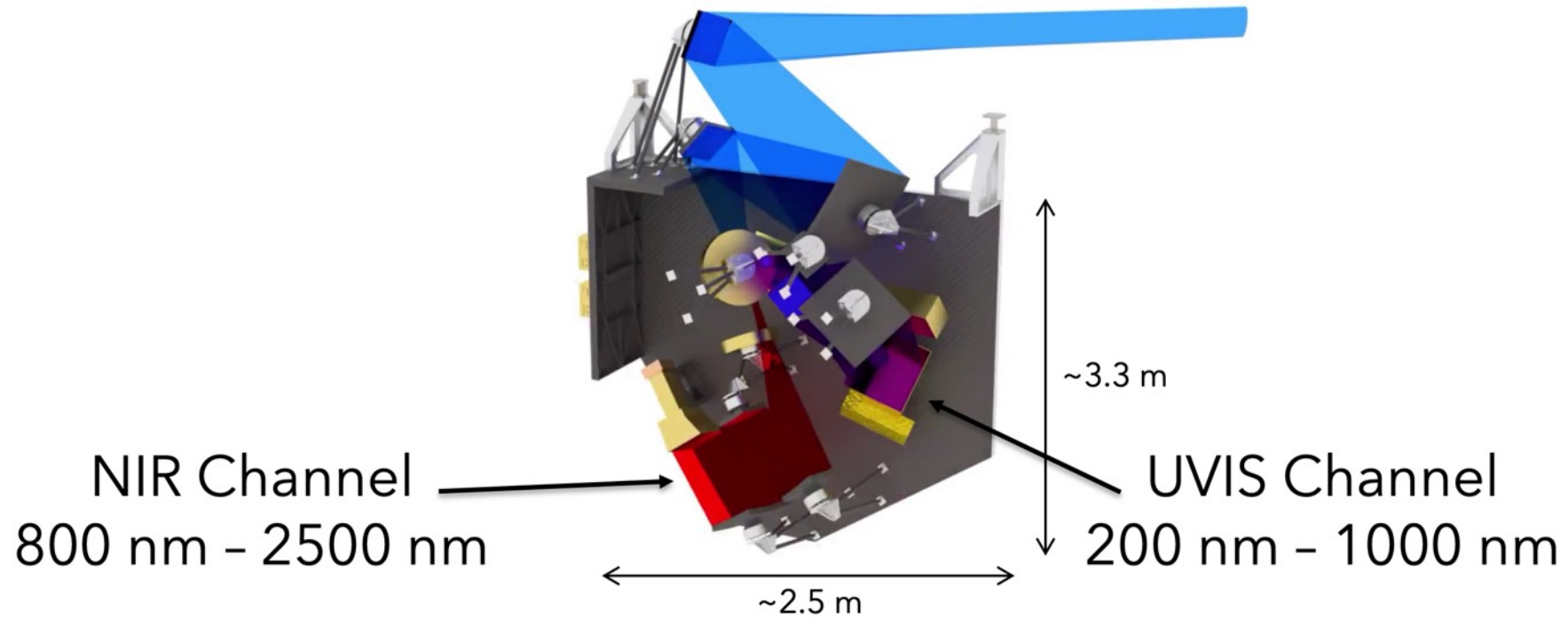
INSTRUMENT SUITE



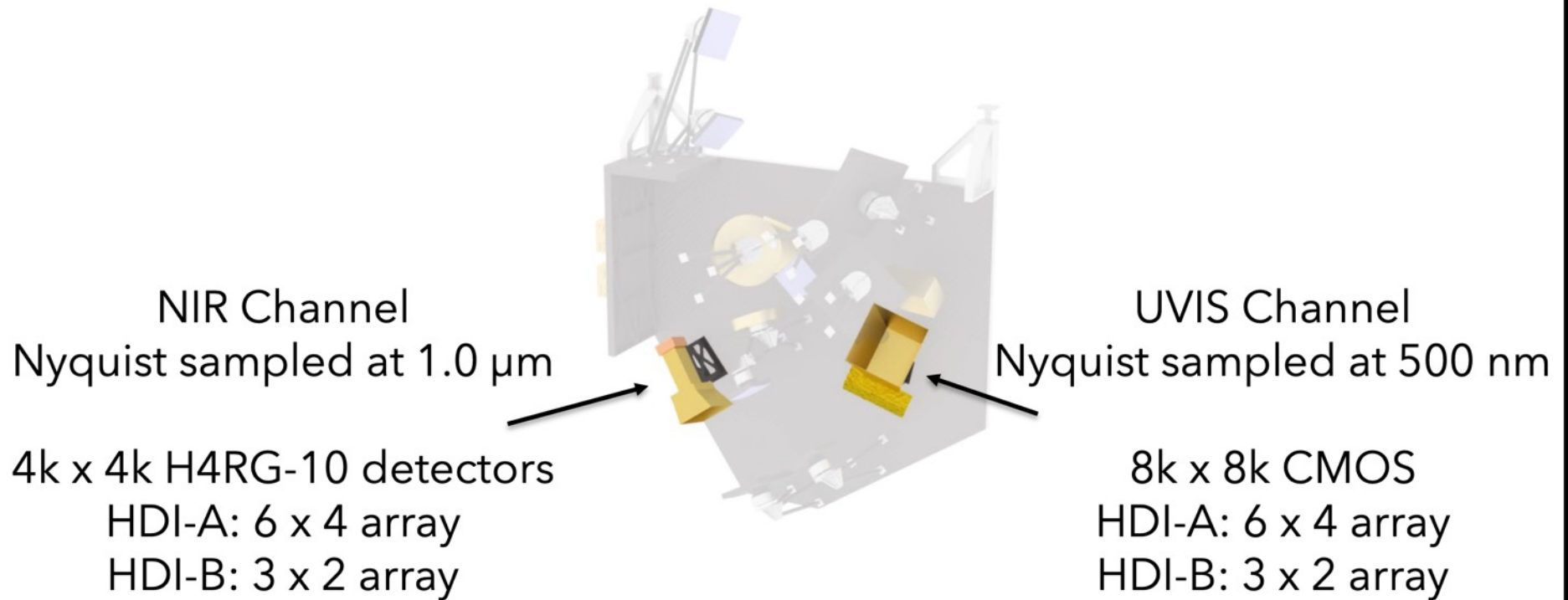
LUVOIR Instruments



HIGH DEFINITION IMAGER (HDI)



HDI – FOCAL PLANES



HDI – PRECISION ASTROMETRY

UVIS channel includes laser calibration system for precision astrometry.

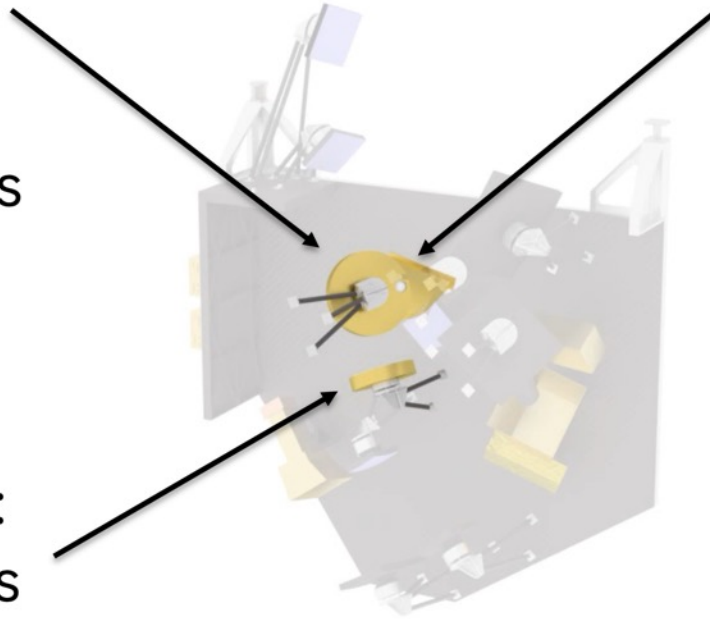


HDI – FILTER WHEELS

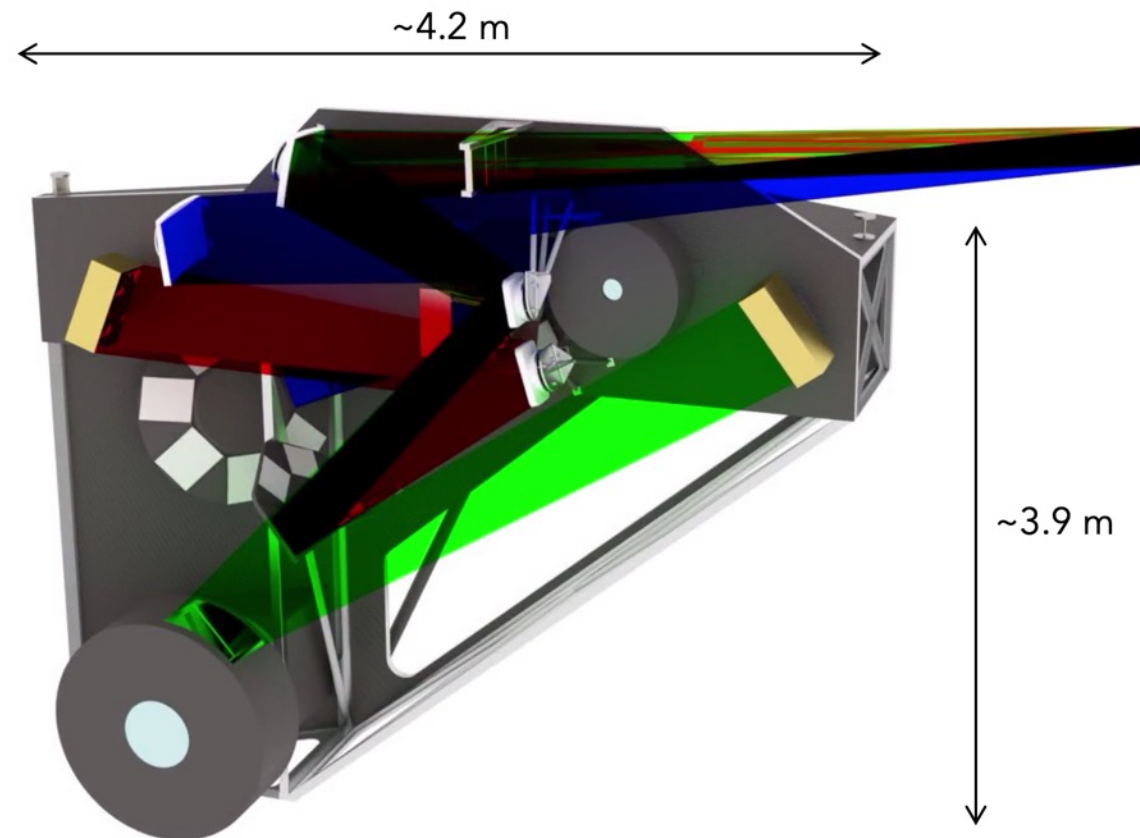
UVIS filter wheel:
39 science filters
2 grisms
4 weak lenses
2 dispersed
Hartman sensors

Channel select
mechanism:
5 slots that allow for
simultaneous or
individual channel
operation

NIR filter wheel:
24 science filters
2 grisms

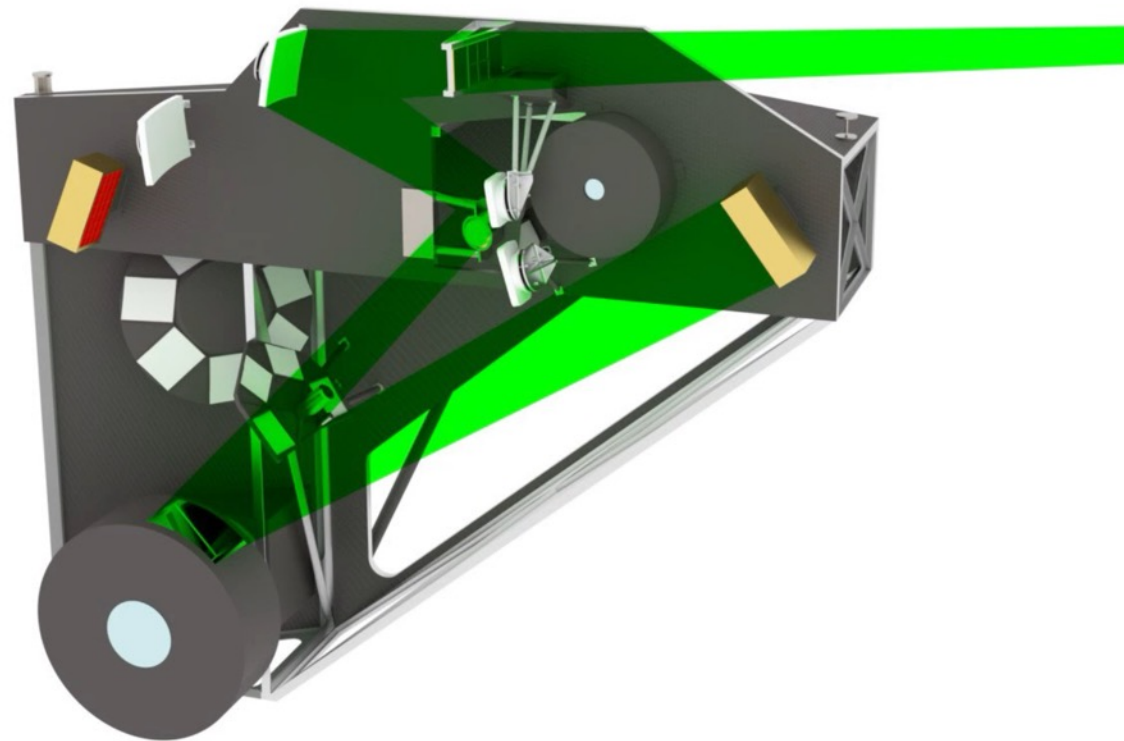


LUVOIR UV MULTI-OBJECT SPECTROGRAPH (LUMOS)



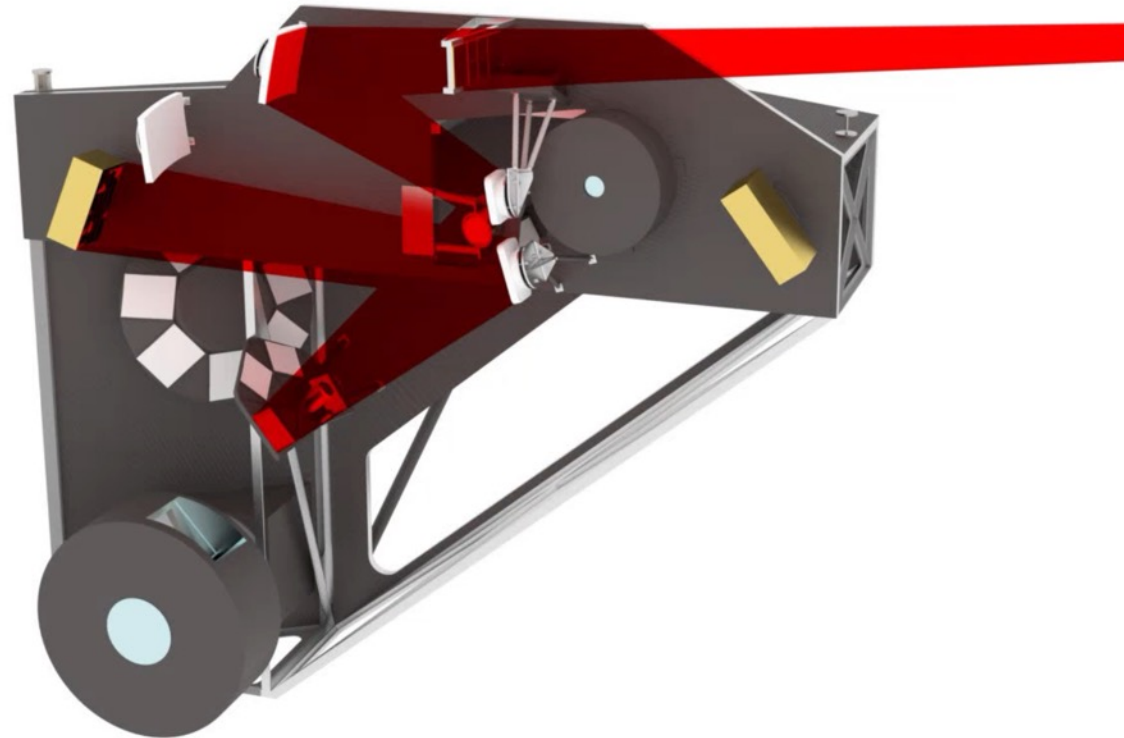
LUMOS – FAR-UV MULTI-OBJECT CHANNEL

Far-UV Multi-object Channel
100 nm – 200 nm



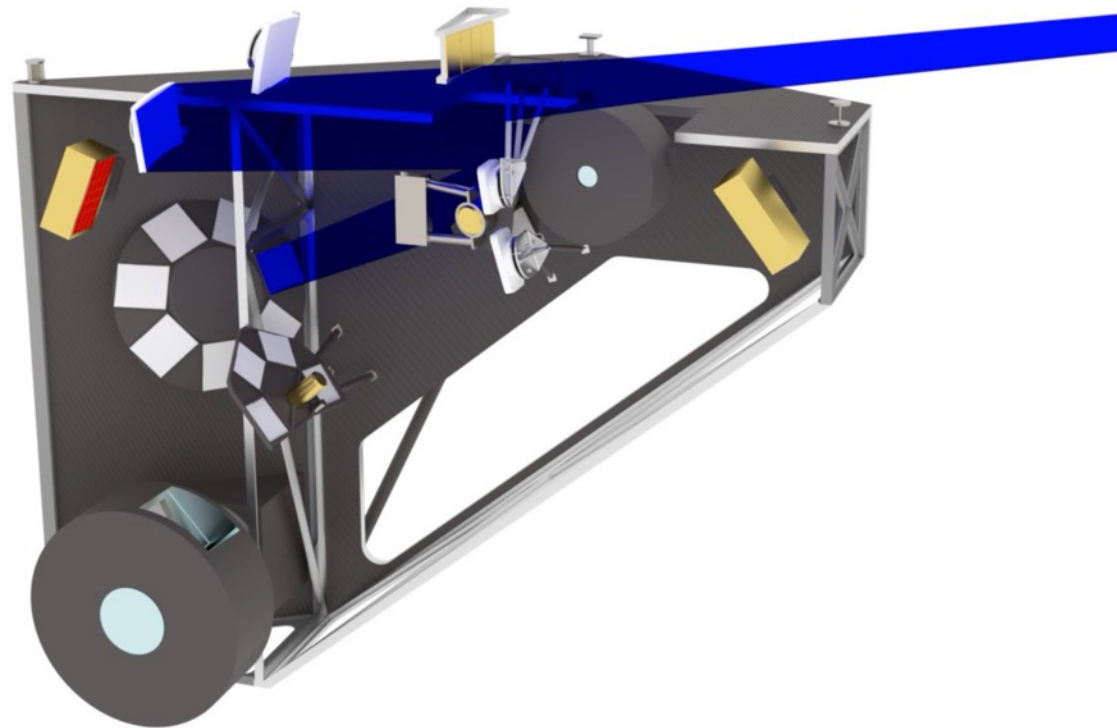
LUMOS – NEAR-UV / VIS MULTI-OBJECT CHANNEL

Near-UV / VIS Multi-object Channel
200 nm – 1000 nm

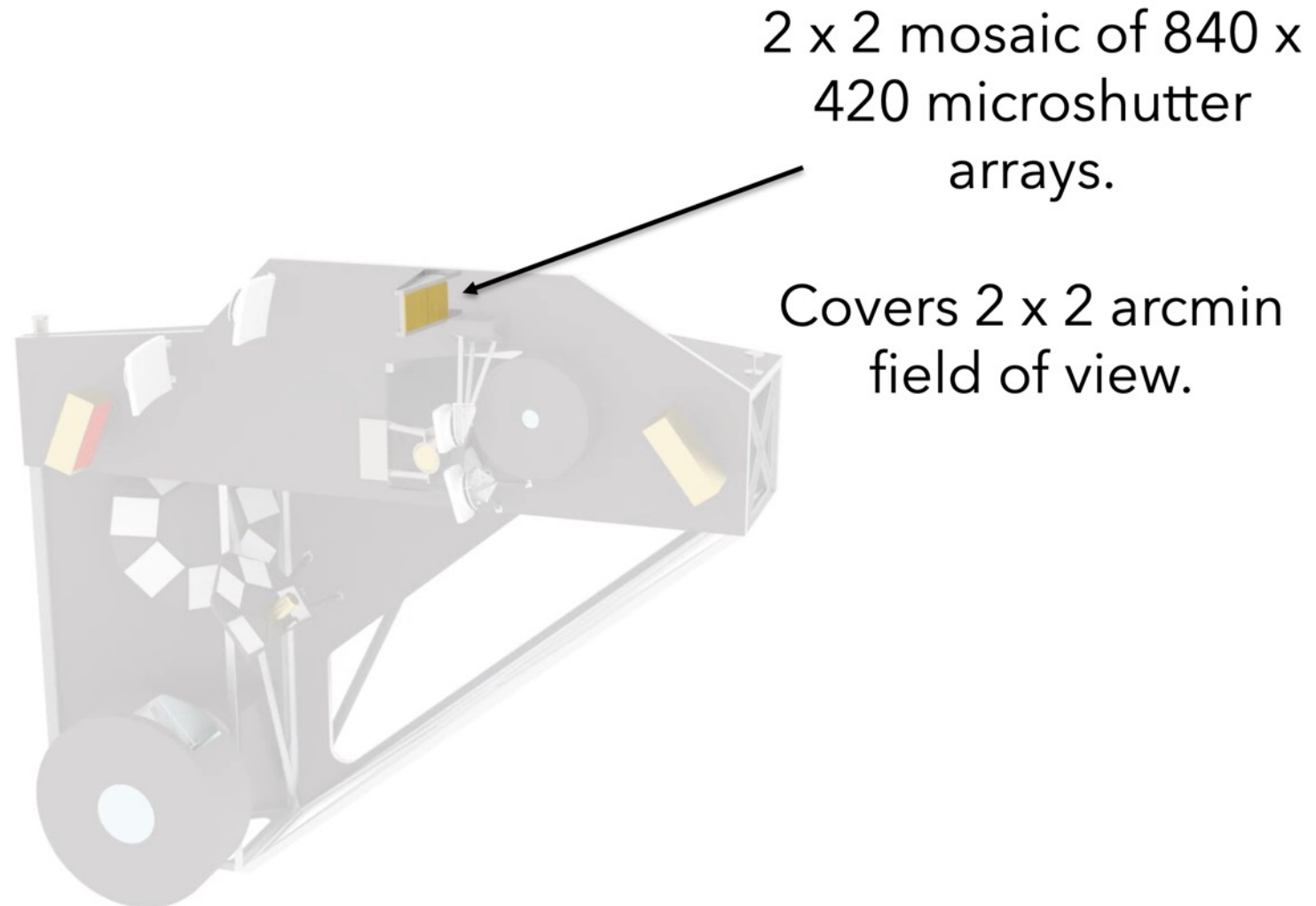


LUMOS – FAR-UV IMAGER

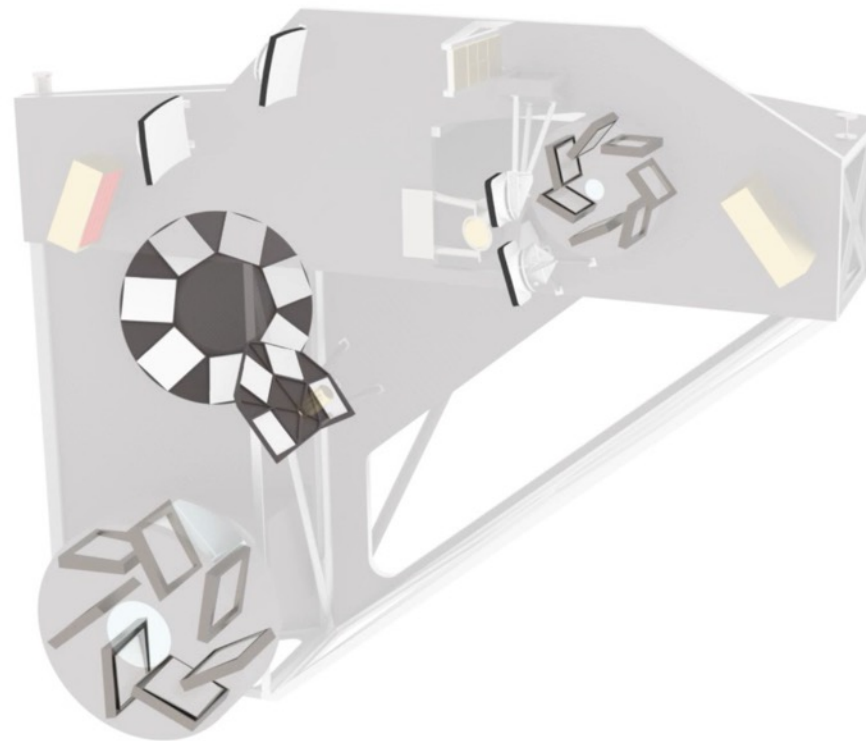
Far-UV Imaging Channel
100 nm – 200 nm



LUMOS – MICROSHUTTER ARRAY

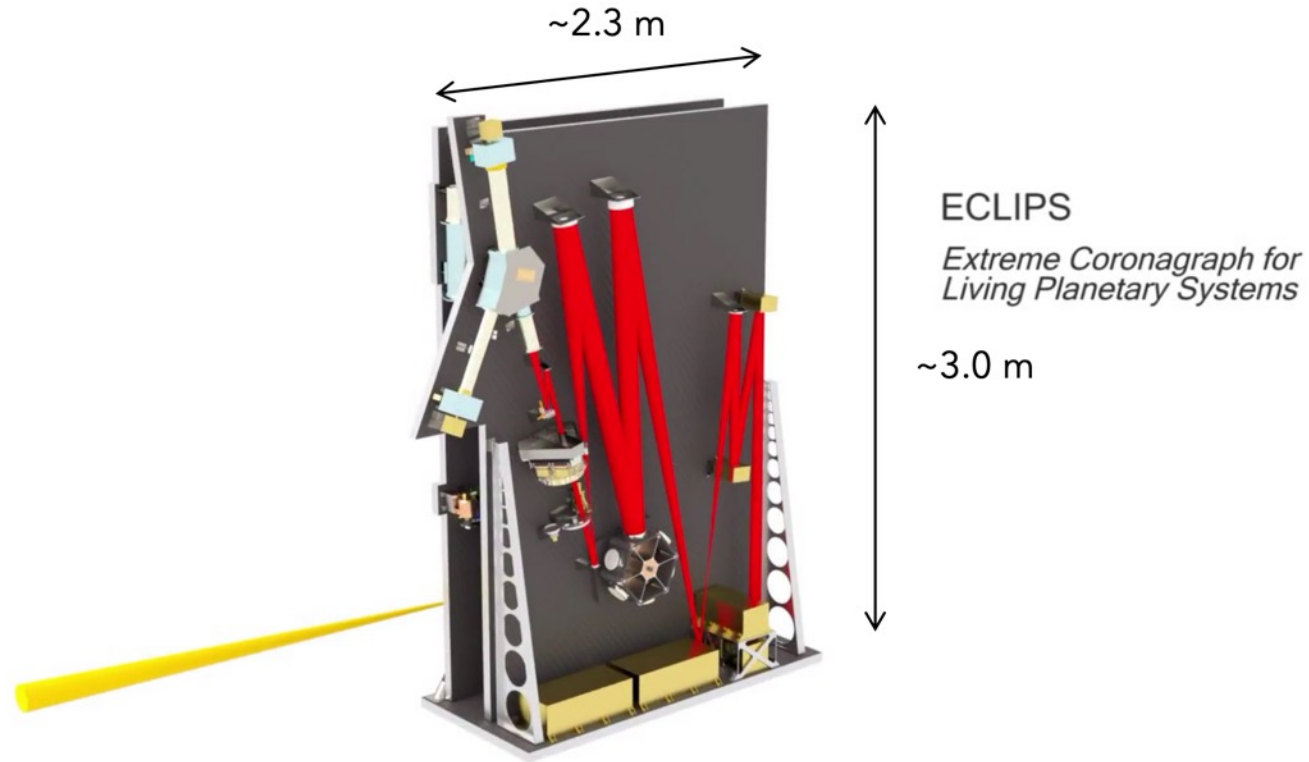


LUMOS – FAR-UV COATING



High-reflectivity Al +
LiF + MgF₂ coating
enables far-UV
sensitivity while
minimizing
environmental
degradation.

EXTREME CORONAGRAPH FOR LIVING PLANETARY SYSTEMS (ECLIPS)

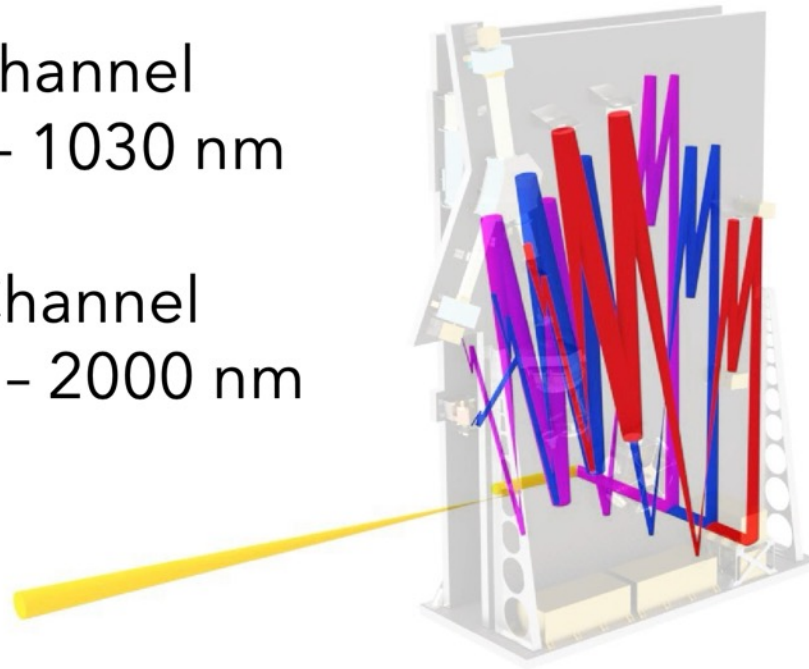


ECLIPS CHANNELS

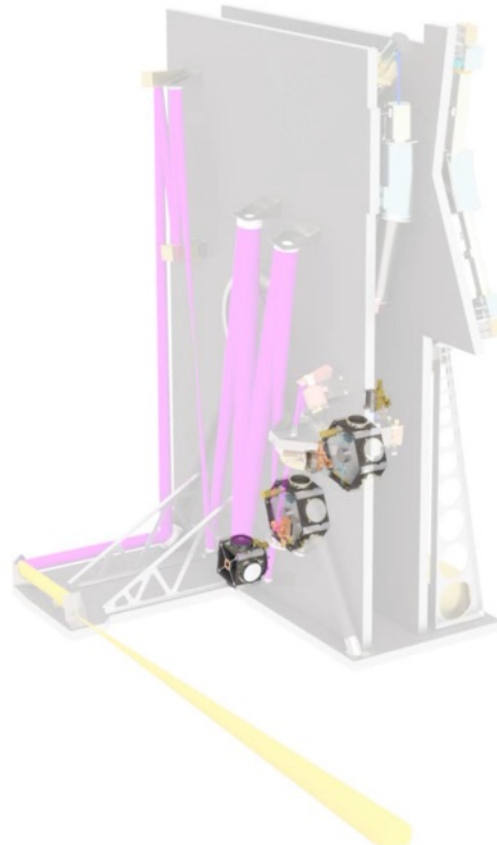
Near-UV Channel
200 nm - 525 nm

VIS Channel
515 nm - 1030 nm

NIR Channel
1000 nm - 2000 nm

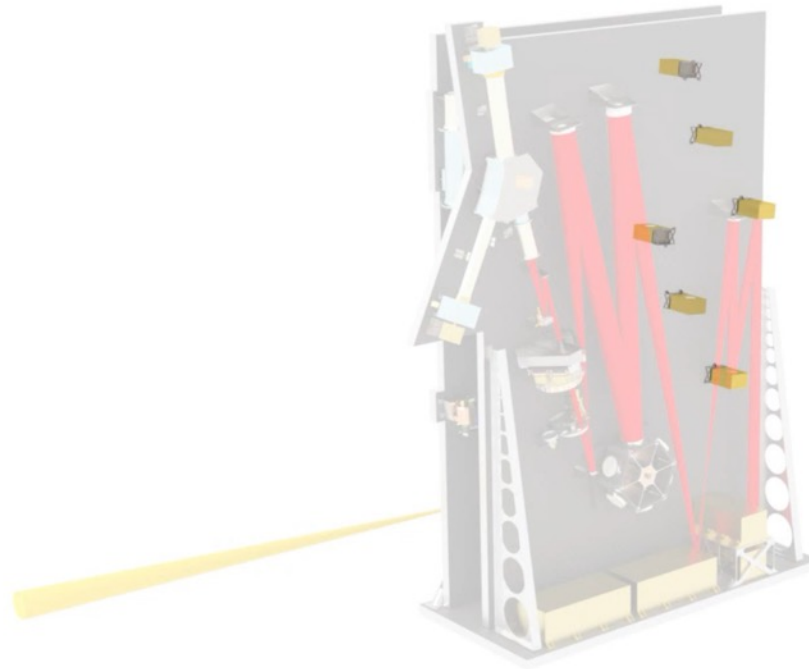


ECLIPS – CORONAGRAPH MASK WHEELS



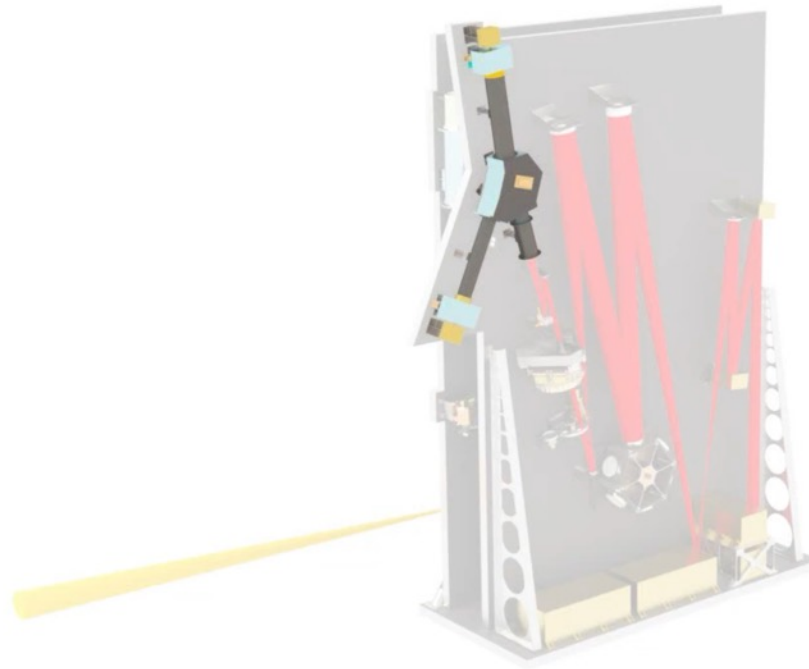
Each channel has an array of apodizing, focal plane, and Lyot stop masks to optimize the dark hole region to the observation.

ECLIPS – WAVEFRONT SENSING & CONTROL



Each channel has a low-order and out-of-band wavefront sensor and two deformable mirrors for wavefront control.

ECLIPS – SPECTROMETERS AND CAMERAS



NUV Channel

Imager

VIS Channel

Imager

R=140 integral field spectrograph

NIR Channel

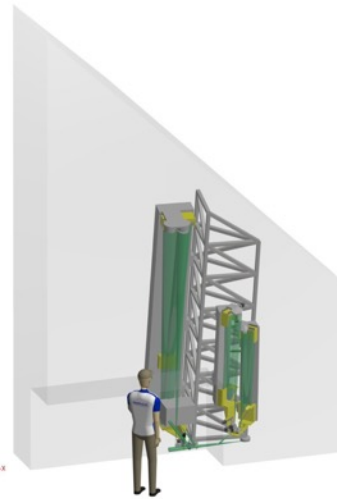
R=70 integral field spectrograph

R=200 point-source spectrograph

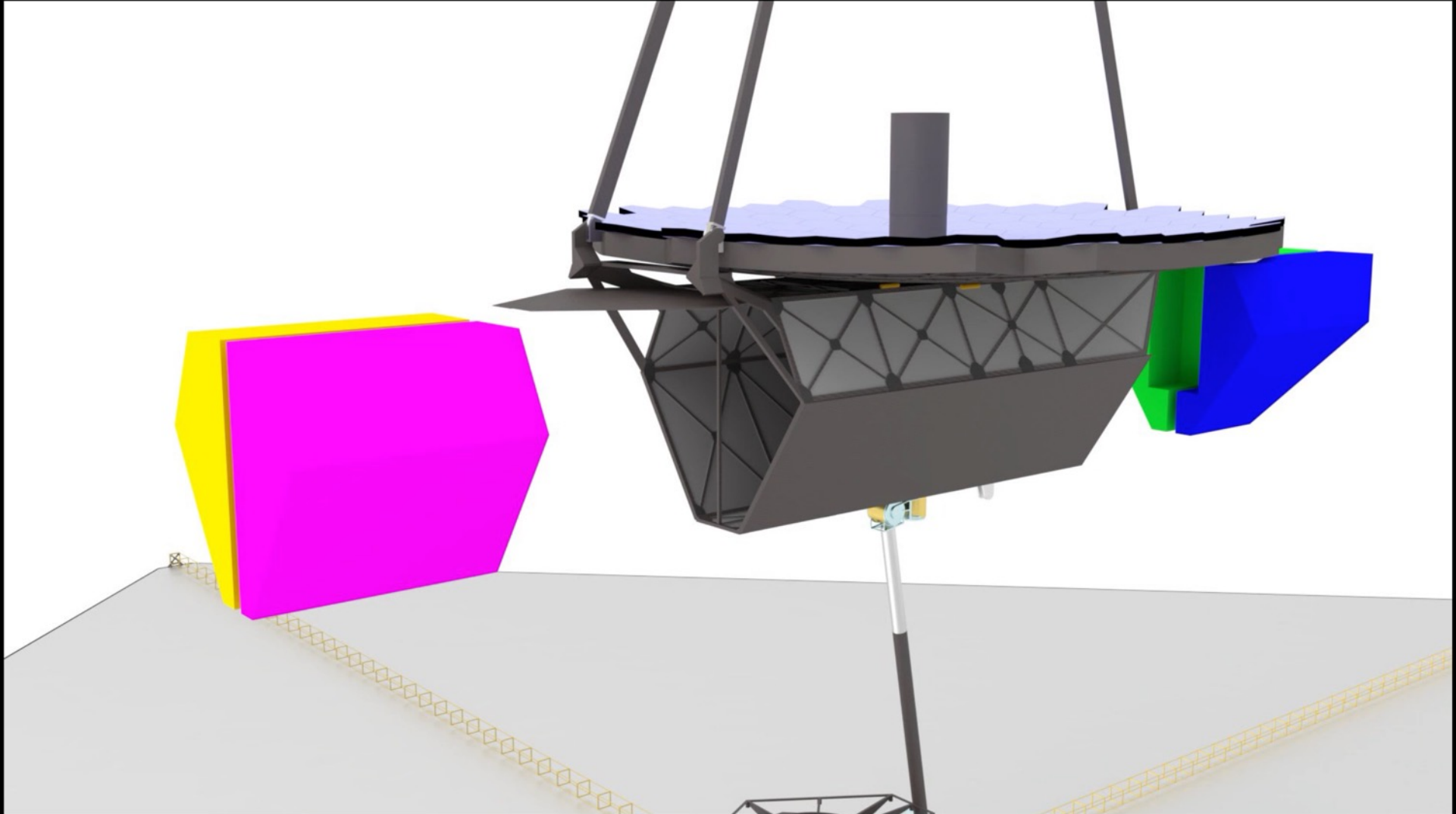
Instrument concept
contributed by
Centre National D'études
Spatiales.

$R=120,000$ UV
spectropolarimeter.

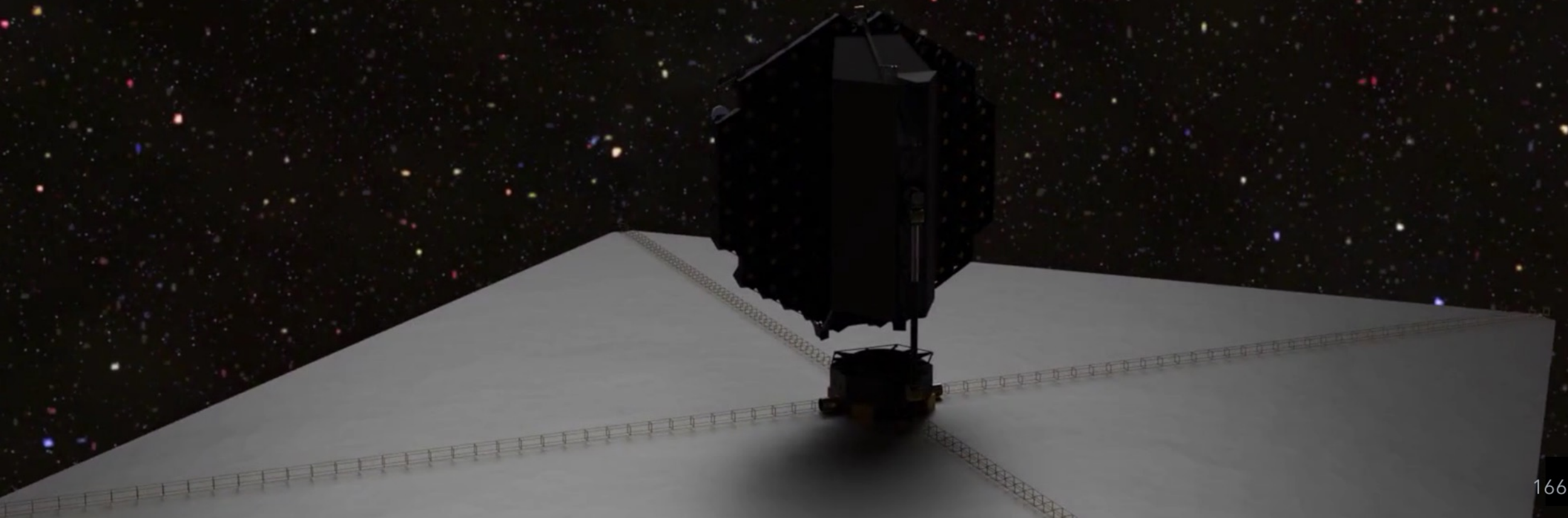
Circular+linear polarization
and unpolarized modes.



DESIGNED TO BE UPGRADEABLE



A powerful and feasible observatory to tell the story of life in the universe



TECHNICAL MARGINS



Resource	Growth Allowance	Margin
Mass	30%	Determined by LV
Power	40%	25%

Computed as a percent of the larger quantity

DO THEY FIT? LAUNCH VEHICLE OPTIONS

SLS
Block 1B

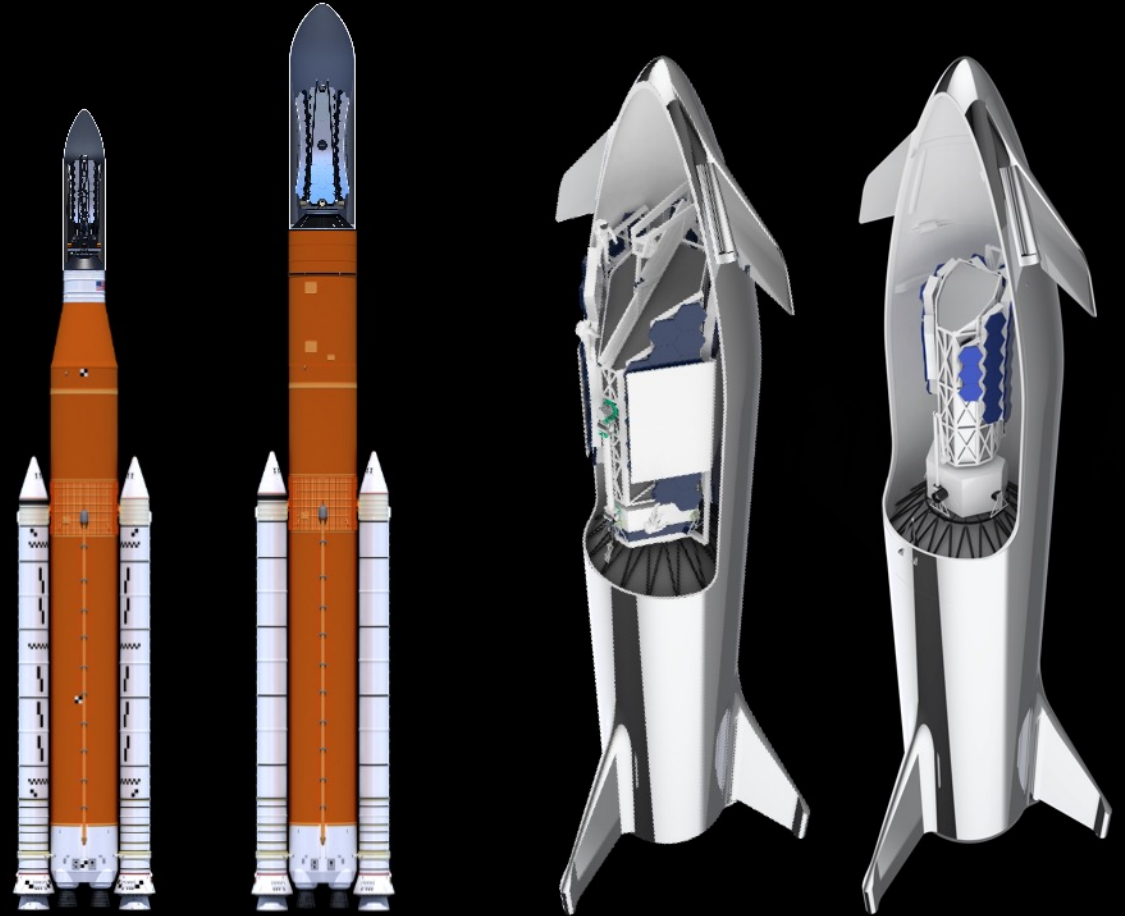
SLS
Block 2

SpaceX Starship
(Super Heavy booster not shown)

Mass Margin	LUVOIR-A	LUVOIR-B
SLS Block 1	X	23%
SLS Block 1B	16%*	44%
SLS Block 2	16%	54%
SpaceX Starship	75%**	86%
Blue Origin New Glenn	X	~20%

* Pending upgraded boosters

** Pending cargo fairing modification

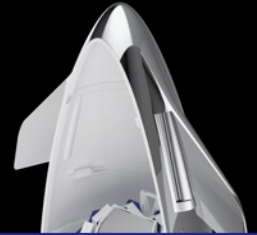
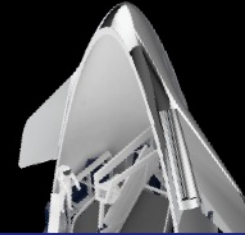


DO THEY FIT? LAUNCH VEHICLE OPTIONS

SLS
Block 1B

SLS
Block 2

SpaceX Starship
(Super Heavy booster not shown)



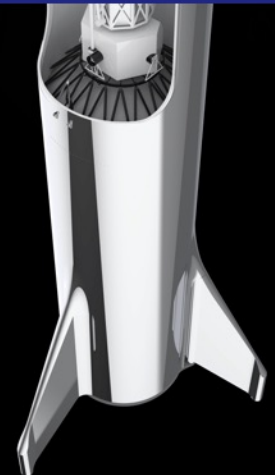
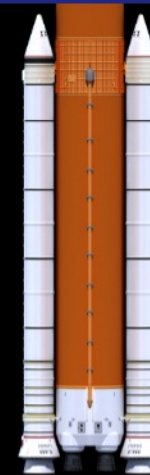
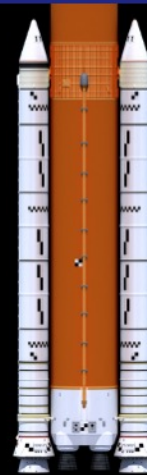
Mass Margin	LUV OIR-A	LUV OIR-B
SLS Block 1	X	23%

Each LUV OIR concept has multiple launch vehicle options

SLS Block 2	10%	51%
SpaceX Starship	75%**	86%
Blue Origin New Glenn	X	~20%

* Pending upgraded boosters

** Pending cargo fairing modification



FUTURE DESIGN TRADES

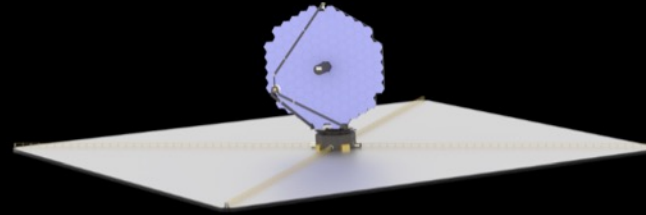


Simple scaling of current designs

Optimize aperture size

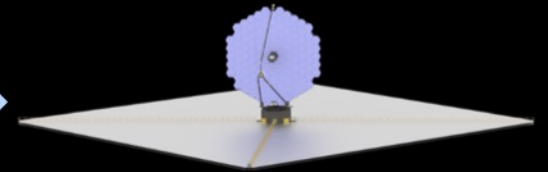
15-m LUVOIR-A

ExoEarth candidate yield: 54
Collecting area: 155 m²



12-m LUVOIR-A

ExoEarth candidate yield: ~35
Collecting area: ~99 m²



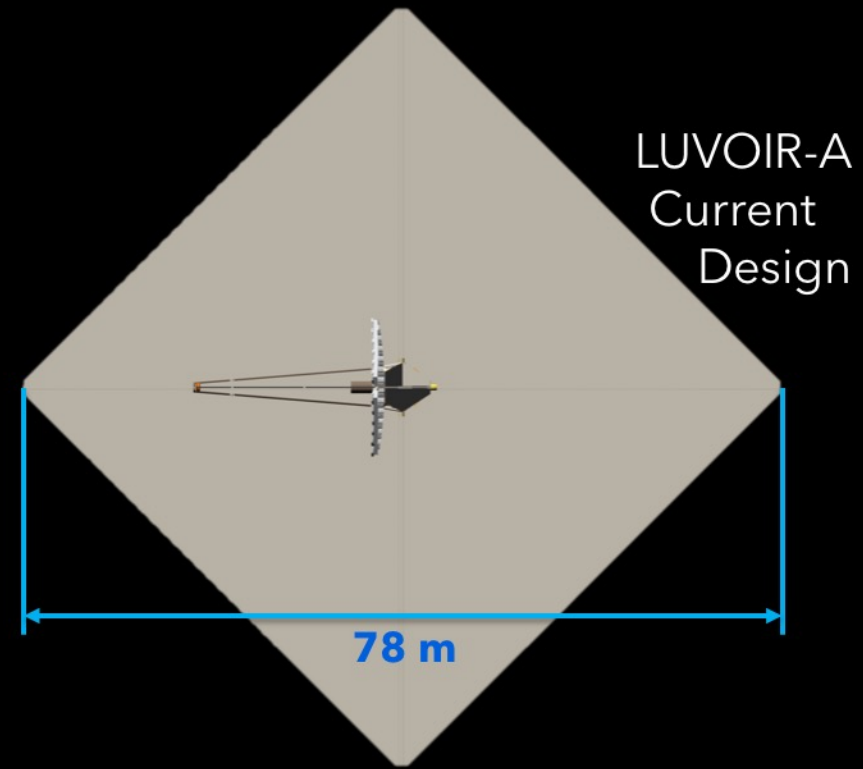
FUTURE DESIGN TRADES

Simple scaling of current designs

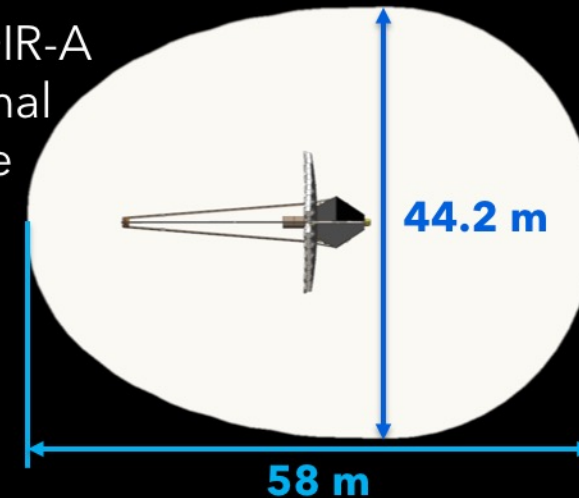
Optimize aperture size

Sunshade optimization

Explore options to reduce overall sunshade size and complexity



LUVOIR-A
Optimal
Shape



FUTURE DESIGN TRADES



Simple scaling of current designs

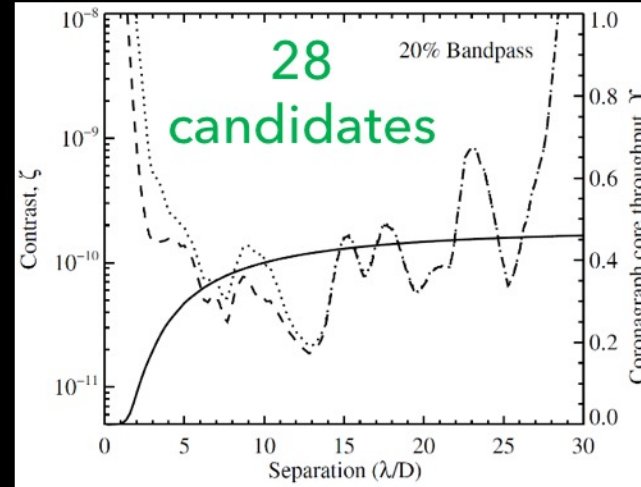
Optimize aperture size

Sunshade optimization

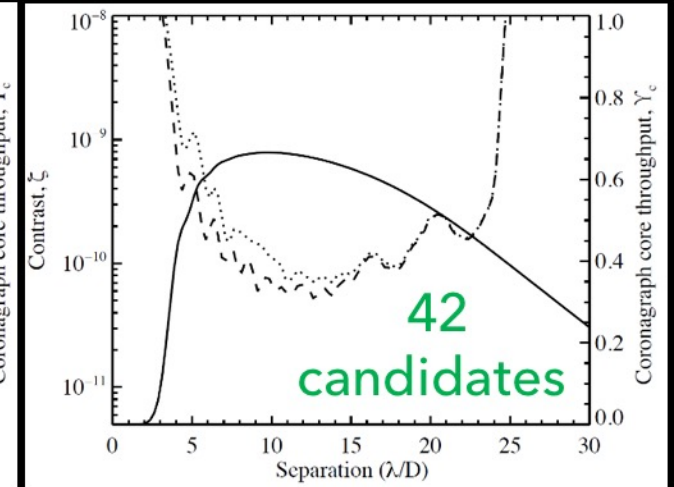
Explore options to reduce overall sunshade size and complexity

Coronagraph architecture selection

Continue to develop alternative coronagraph designs such as PIAA



DM-Assisted Vortex
Coronagraph
(DMVC)
LUVOIR-B Baseline



Phase-Induced Amplitude
Apodization
(PIAA)
LUVOIR-B Alternative

FUTURE DESIGN TRADES

Simple scaling of current designs

- Optimize aperture size

Sunshade optimization

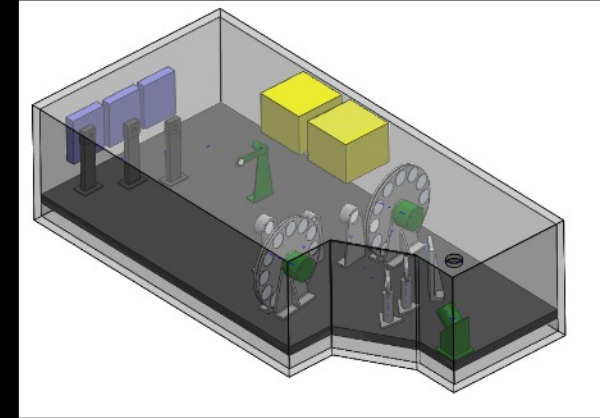
- Explore options to reduce overall sunshade size and complexity

Coronagraph architecture selection

- Continue to develop alternative coronagraph designs such as PIAA

Dedicated fine guidance sensors

- Separate guiding capability from HDI



"Hybrid" guider/wavefront sensor concept from 2010 ATLAST study

FUTURE DESIGN TRADES



Simple scaling of current designs

- Optimize aperture size

Sunshade optimization

- Explore options to reduce overall sunshade size and complexity

Coronagraph architecture selection

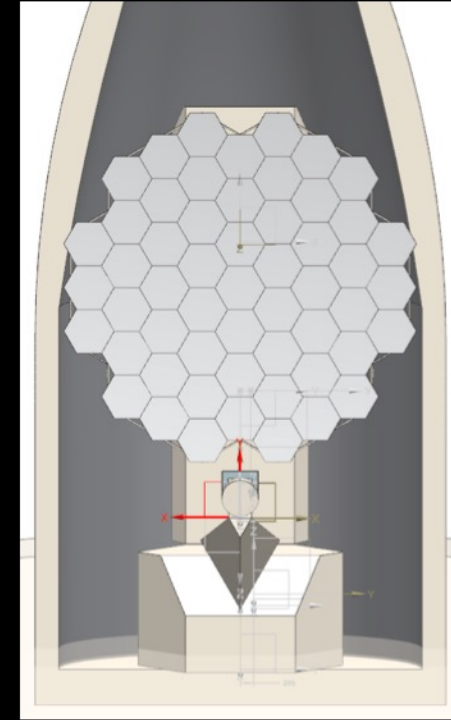
- Continue to develop alternative coronagraph designs such as PIAA

Dedicated fine guidance sensors

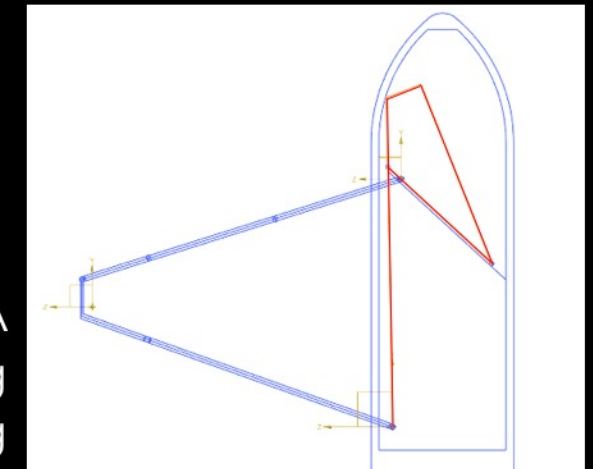
- Separate guiding capability from HDI

Stowed configuration

- New faring options enable different packaging

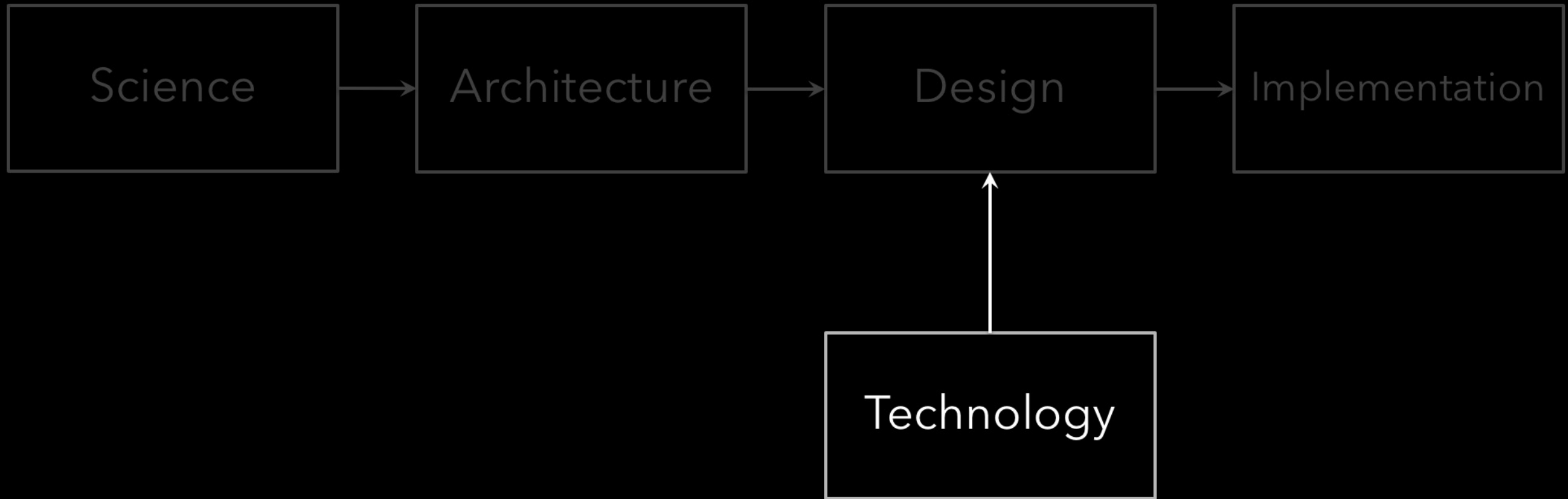


LUVUOIR-B nearly fits in Starship fairing with fully deployed primary mirror



Simpler LUVUOIR-A secondary mirror folding in new SLS faring

THE DESIGN PROCESS



HOW WE EVALUATED TECHNOLOGIES

Established a Technology Working Group

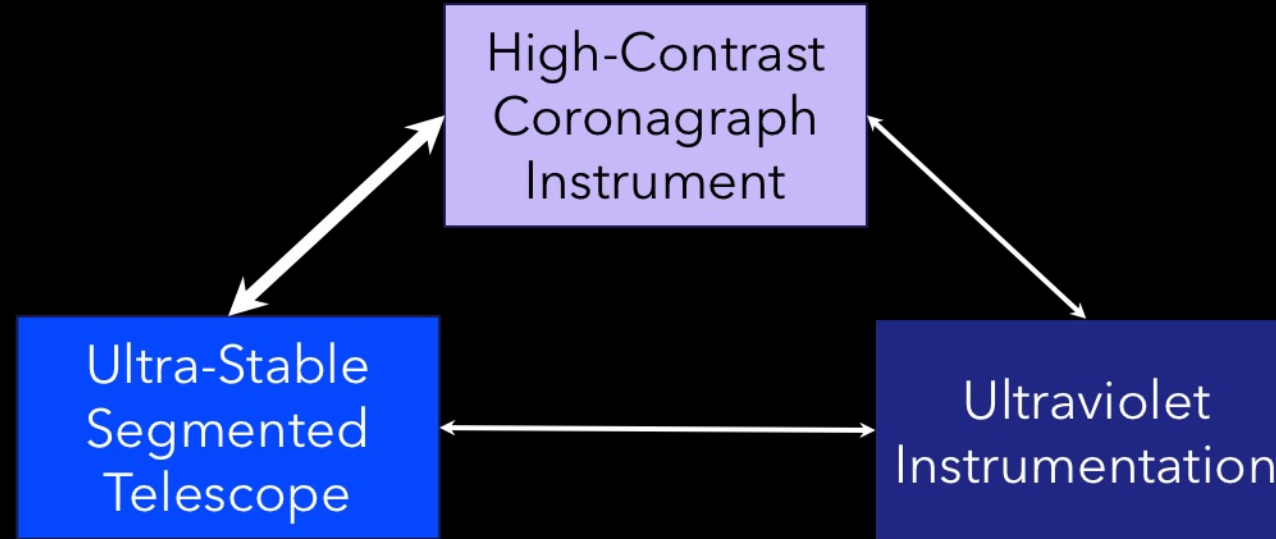
Over 90 subject matter experts from industry, academia, other NASA centers, and international organizations

Divided into sub-groups aligned with LUV OIR's technology needs

Ultra-stable structures, coronagraphs, detectors, coatings, and components

Assessed the current state-of-the-art for enabling technologies and defined a development plan for each

THREE TECHNOLOGY DEVELOPMENT SYSTEMS



Three development paths mature each of the technologies at the **system** level

Technology systems are coupled, and must be developed in parallel with cross-validation

HIGH-CONTRAST CORONAGRAPH INSTRUMENT – TECH COMPONENTS



Component	Implementation Options	Current TRL	Development Challenges
Coronagraph Architecture	Apodized-pupil Lyot	4	1×10^{-10} raw contrast $< 4 \lambda/D$ inner working angle High throughput and robust to jitter and stellar diameter
	Vortex	3	
	Phase-Induced Amplitude Apodization	3	
	Hybrid Lyot	3	
	Nulling	3	
Deformable Mirrors	MEMs	4	Large actuator count Actuator stability Surface quality
	Lead-Magnesium-Niobate	5	
Wavefront Sensing	Out-of-band	3	Picometer-sensing
	Low-order	6	
	Artificial Guide Star	3	
NUV/VIS Detectors	EMCCD	4	Radiation hardness Red-end quantum efficiency
	HMCCD	3	
NIR Detectors	HgCdTe Photodiode	5	Lower noise
	HgCdTe Avalanche Photodiode	4	

Blue items are currently included in the LUV OIR baseline designs

ULTRA-STABLE SEGMENTED TELESCOPE – TECH COMPONENTS



Component	Implementation Options	Current TRL	Development Challenges
Mirror Substrate	Rigid-body Actuated ULE	5	Low areal density; high stiffness Surface figure error
	Surface Figure Actuated ULE	4	
	Rigid-body Actuated Zerodur	4	
Actuators	Piezo-mechanical	3	Picometer actuation Stability Lifetime
	All piezo	3	
Edge Sensors	Capacitive	3	Picometer resolution in gap, shear, and angle dimensions
	Inductive	3	
	Optical	3	
Laser Metrology	Laser truss	4	Picometer sensitivity at 10 Hz loop rate
	High-speed speckle interferometry	3	
Vibration Isolation	Non-contact Isolation System	4	Low disturbance transmissibility with cable stiffness

Blue items are currently included in the LUVOIR baseline designs

ULTRAVIOLET INSTRUMENTATION – TECH COMPONENTS

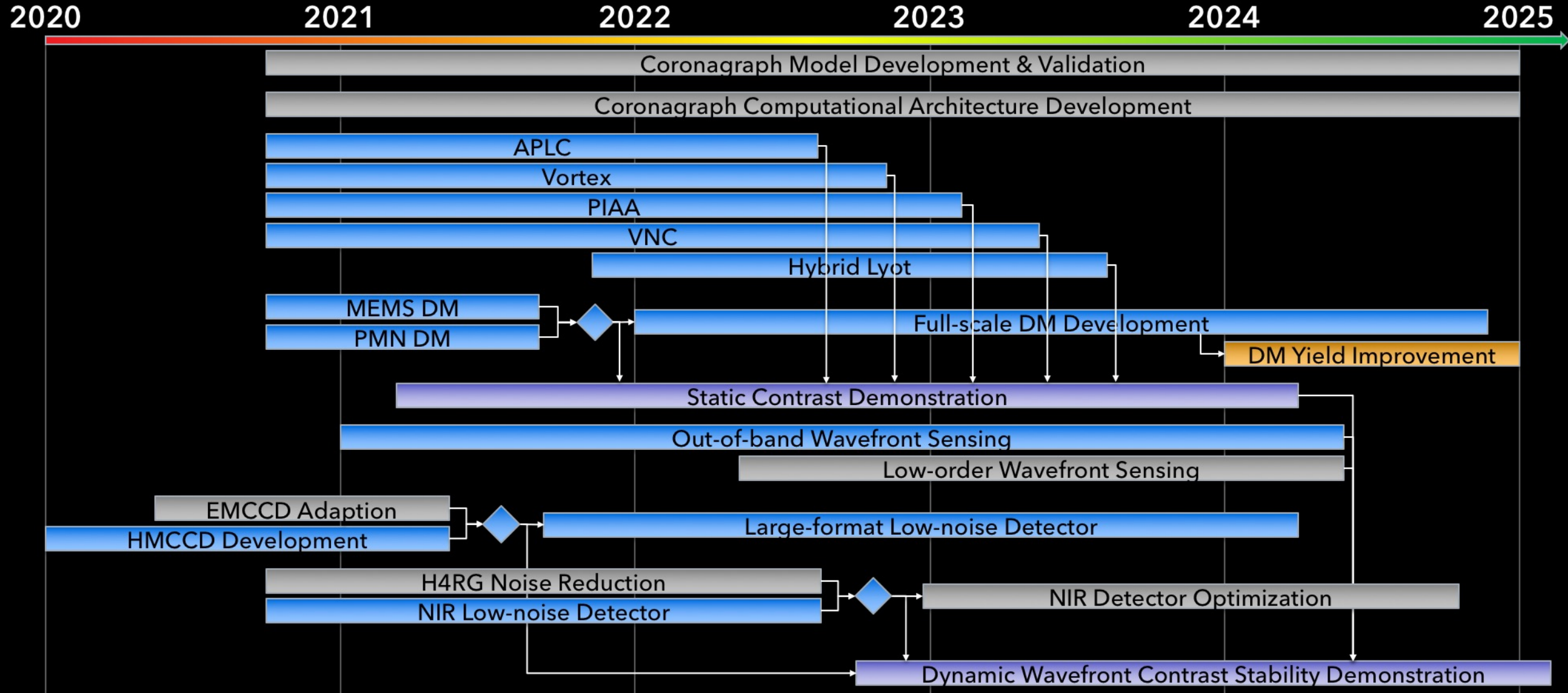


Component	Implementation Options	Current TRL	Development Challenges
Far-UV Broadband Coating	Al + eLiF + MgF ₂	3	Far-UV reflectivity
	Al + eLiF + AlF ₃	3	Coating repeatability
	Al + eLiF	5	Coating durability
Microshutter Arrays	Next-generation MEMs	3	Large-format
Large-format Microchannel Plates	CsI	6	Large format 100-200 nm sensitivity
	GaN	4	
	Bi-alkali	4	
	Funnel	4	
High-resolution Focal Planes	8k x 8k CMOS	4	Large format Low noise 3-side buttable for tiling
	4k x 4k CCD	5	

Blue items are currently included in the LUVOIR baseline designs

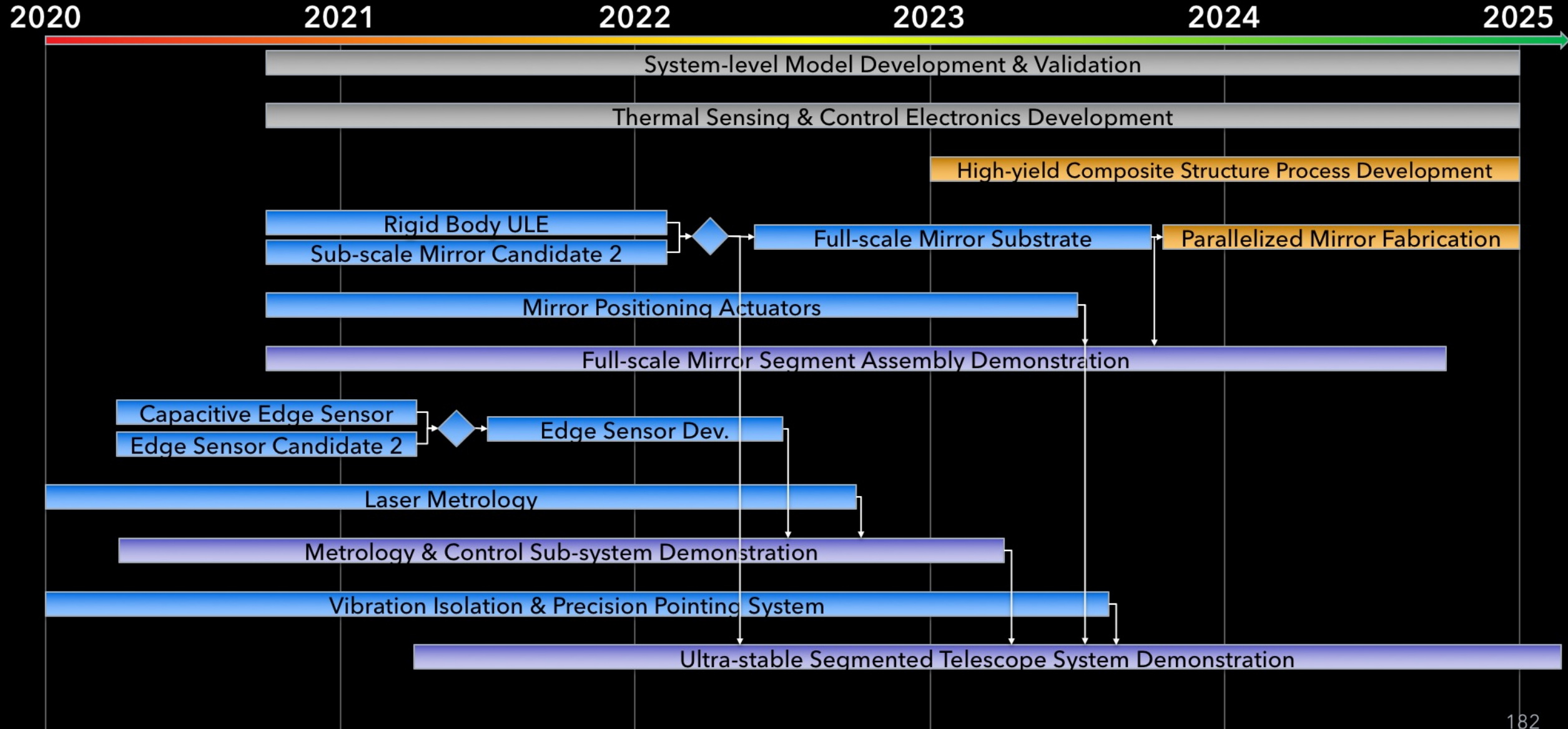
HIGH-CONTRAST CORONAGRAPH INSTRUMENT

Technology
Engineering
Manufacturing
Sub-system



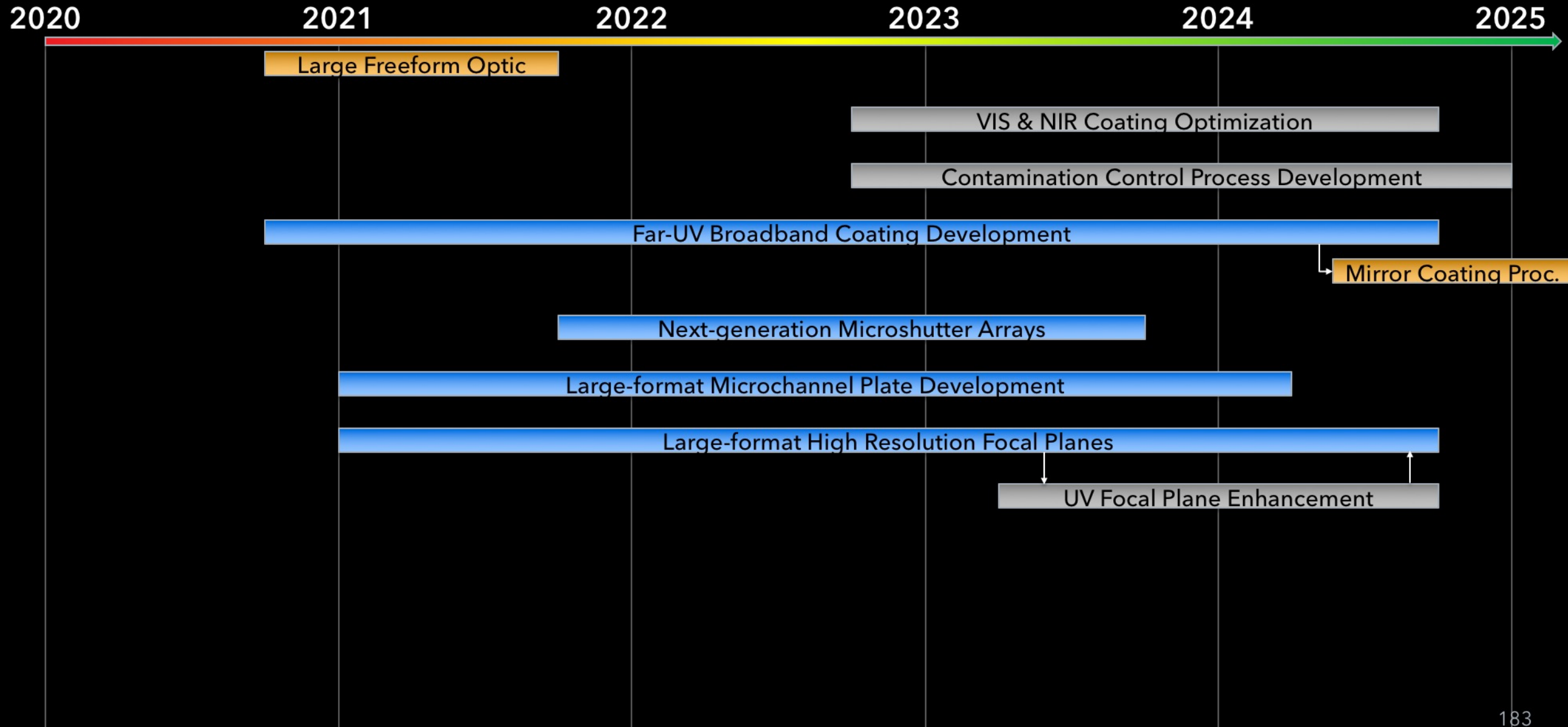
ULTRA-STABLE SEGMENTED TELESCOPE

Technology
Engineering
Manufacturing
Sub-system

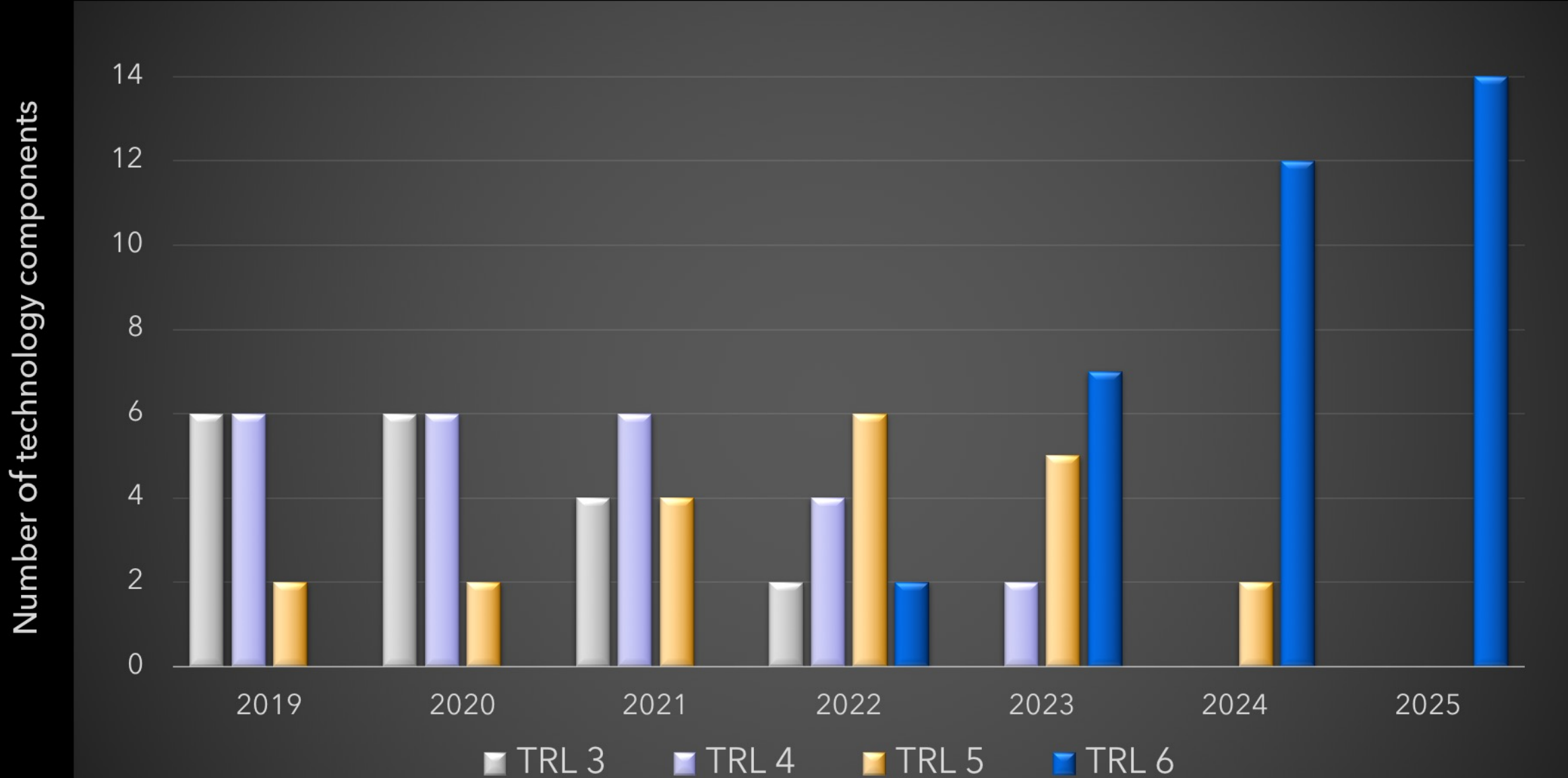


ULTRAVIOLET INSTRUMENTATION

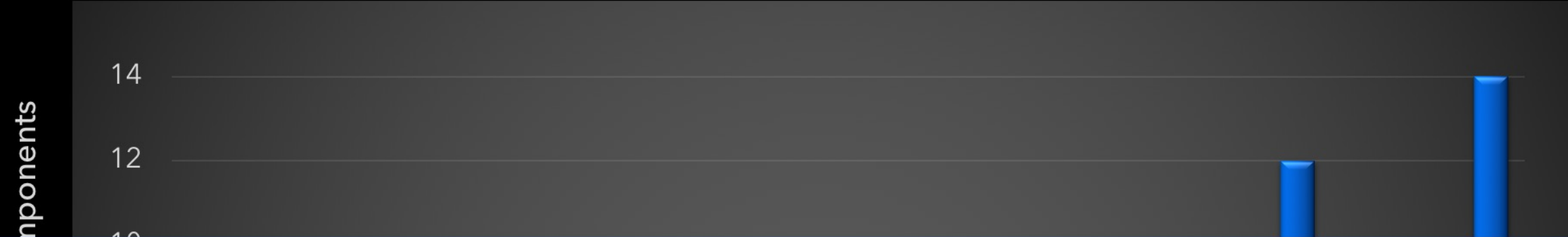
Technology
Engineering
Manufacturing
Sub-system



TECHNOLOGY TRL SUMMARY



TECHNOLOGY TRL SUMMARY

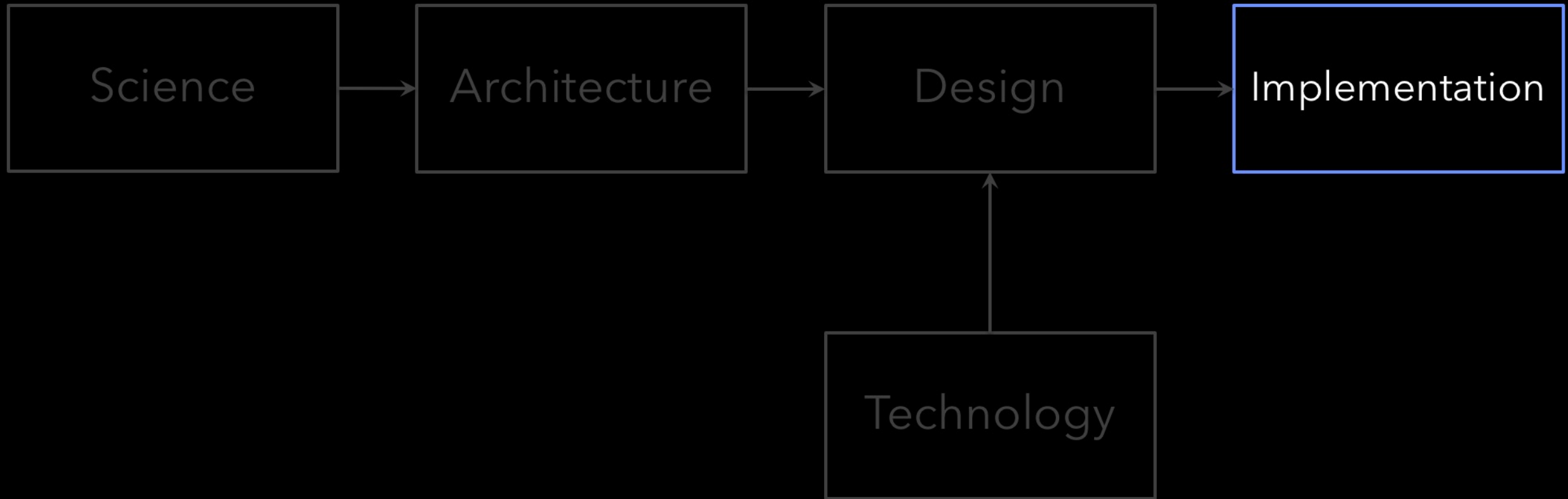


LUV OIR’s technology development plan matures all technology systems to TRL 6 by the start of Phase A



LUV OIR IS EXECUTABLE IMPLEMENTATION

THE DESIGN PROCESS

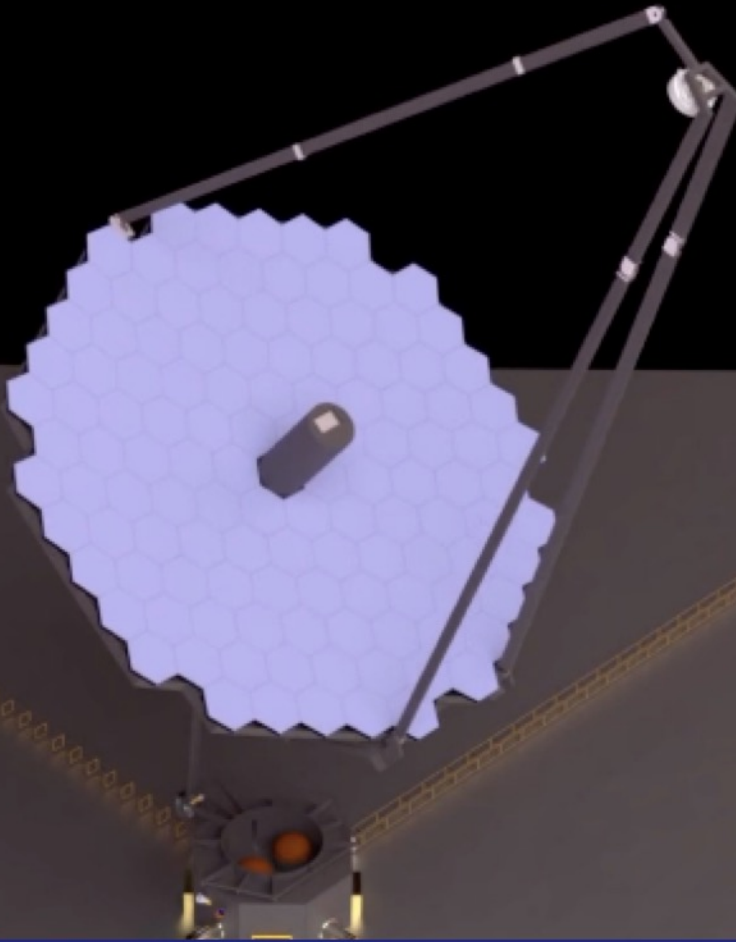




L U V O I R

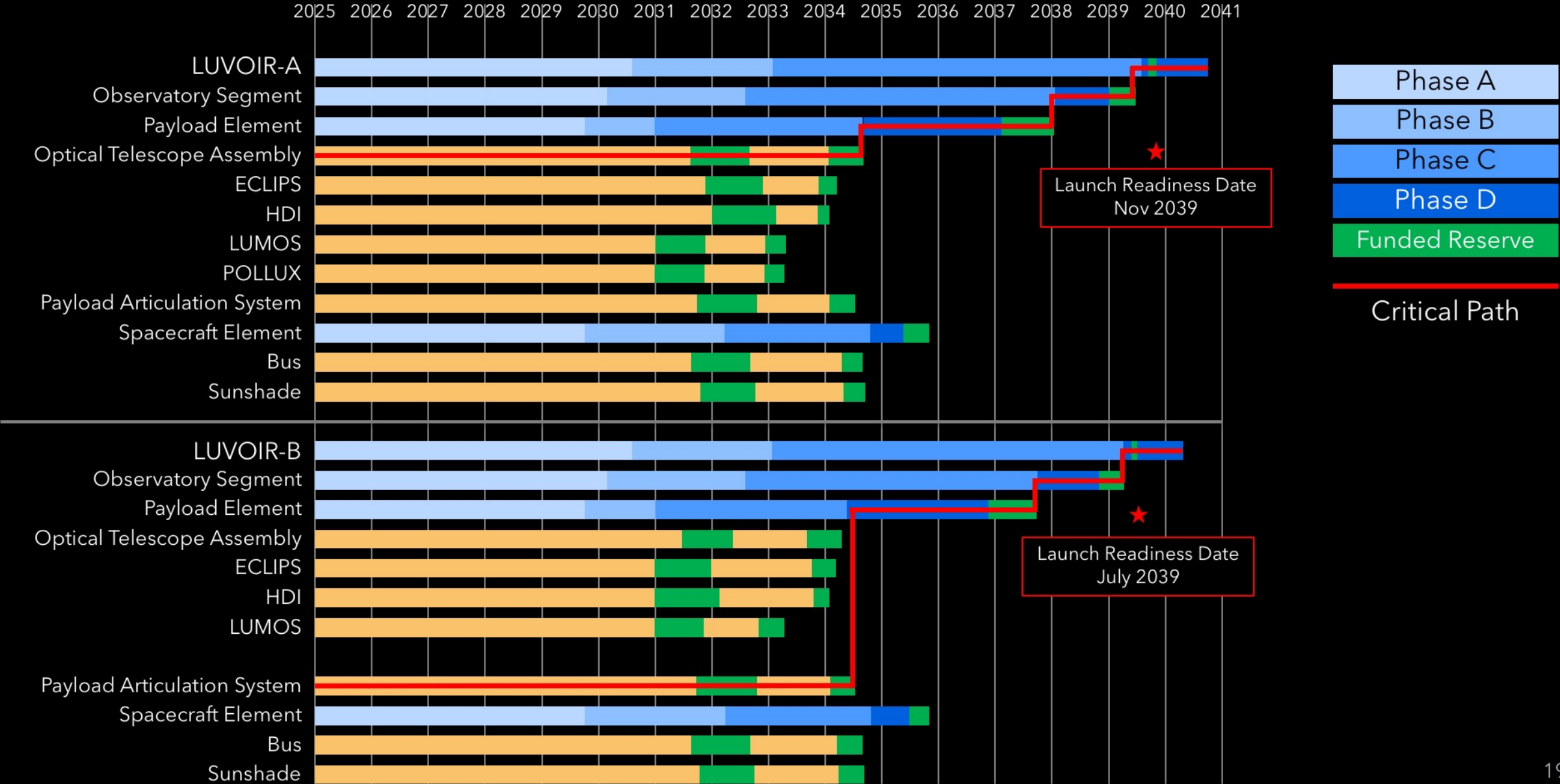
FINAL REPORT

How do we get from here ...



... to there?

DEVELOPMENT SCHEDULE THROUGH COMMISSIONING

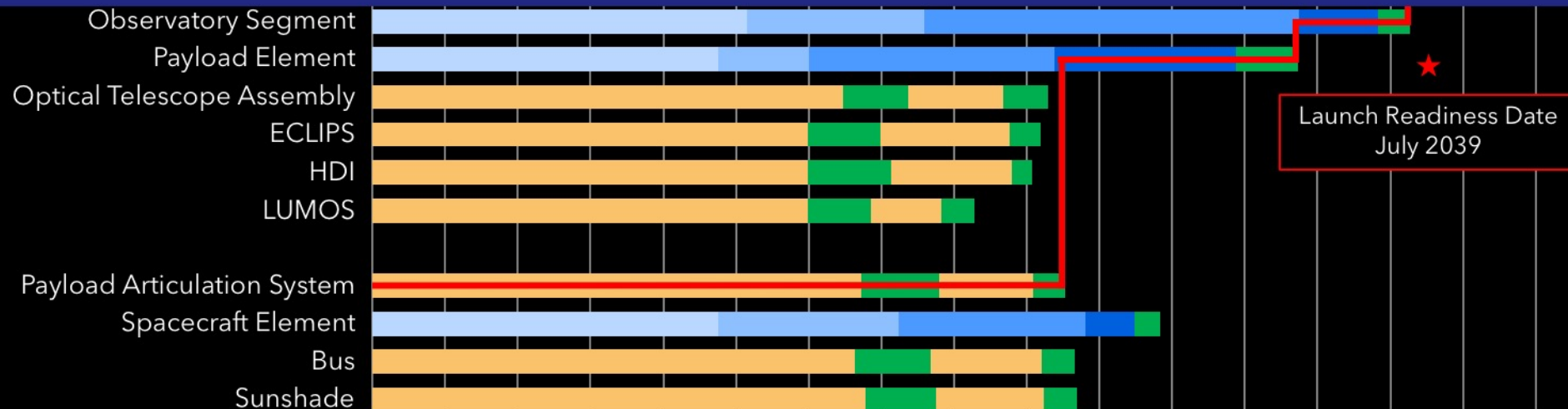


DEVELOPMENT SCHEDULE THROUGH COMMISSIONING

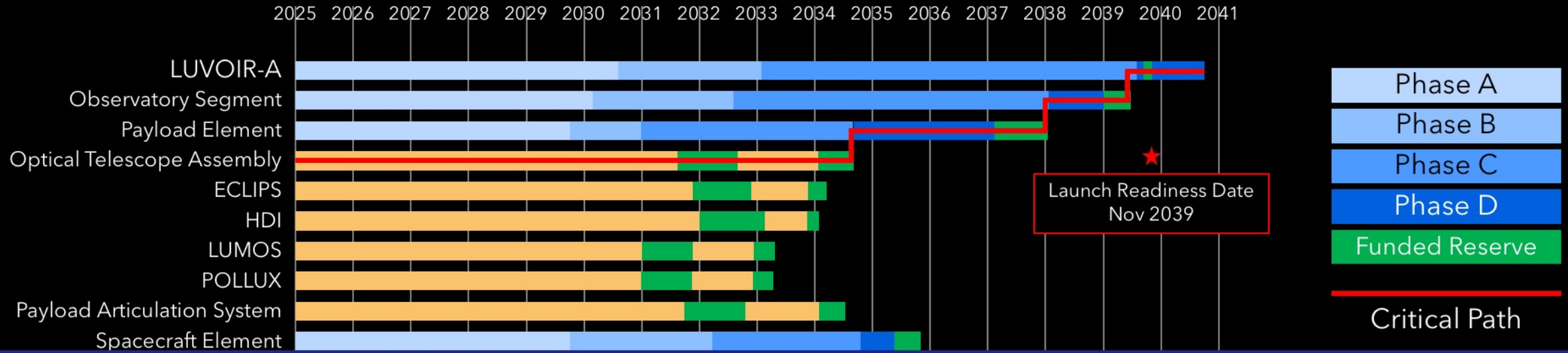


Funded schedule reserve is consistent with Aerospace guidance.

15 weeks / year at Assembly level and 18 weeks / year at all higher levels



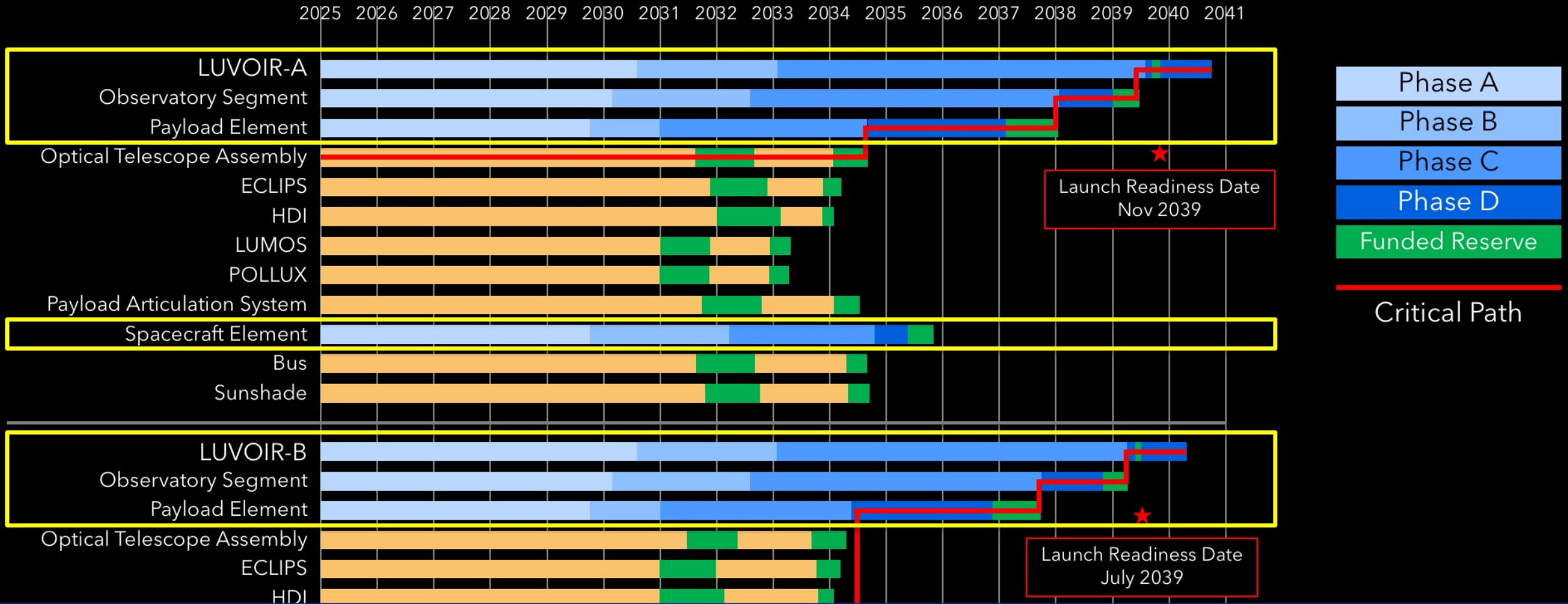
DEVELOPMENT SCHEDULE THROUGH COMMISSIONING



The schedule was limited technically, not fiscally



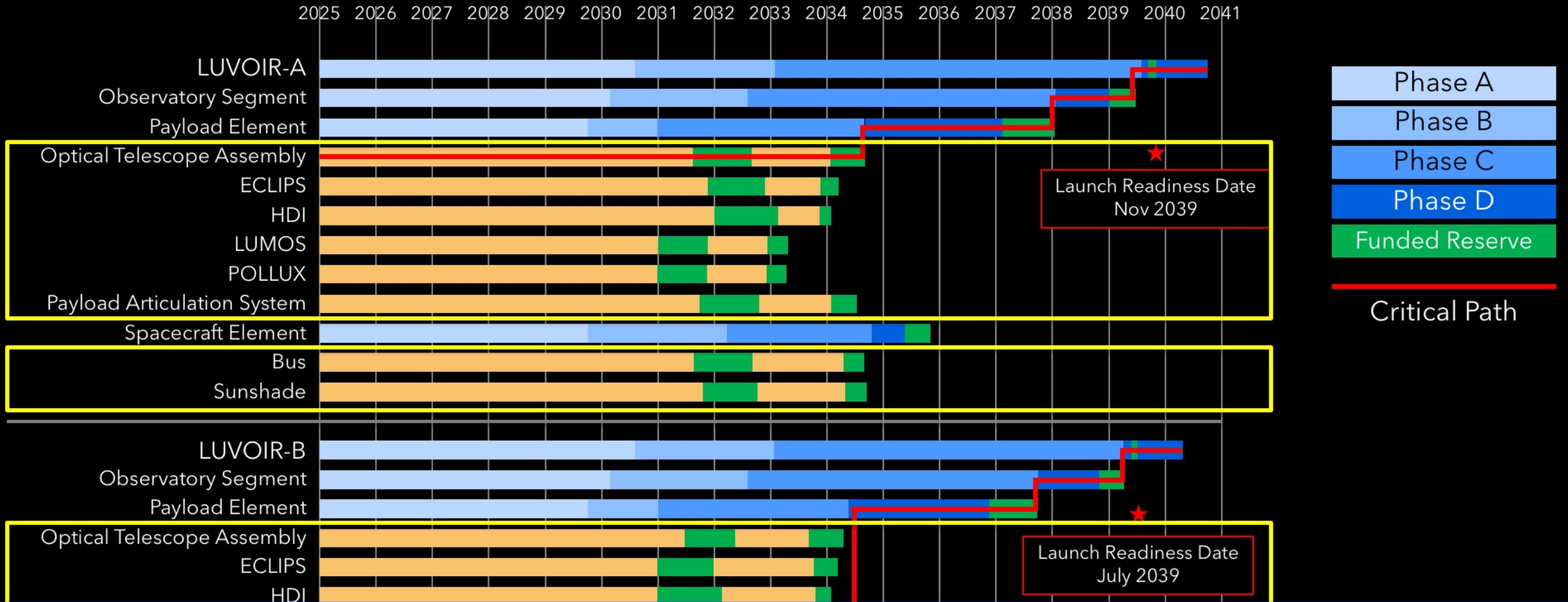
DEVELOPMENT SCHEDULE THROUGH COMMISSIONING



Government serves as the prime system developer and integrator at the Element and Segment Levels



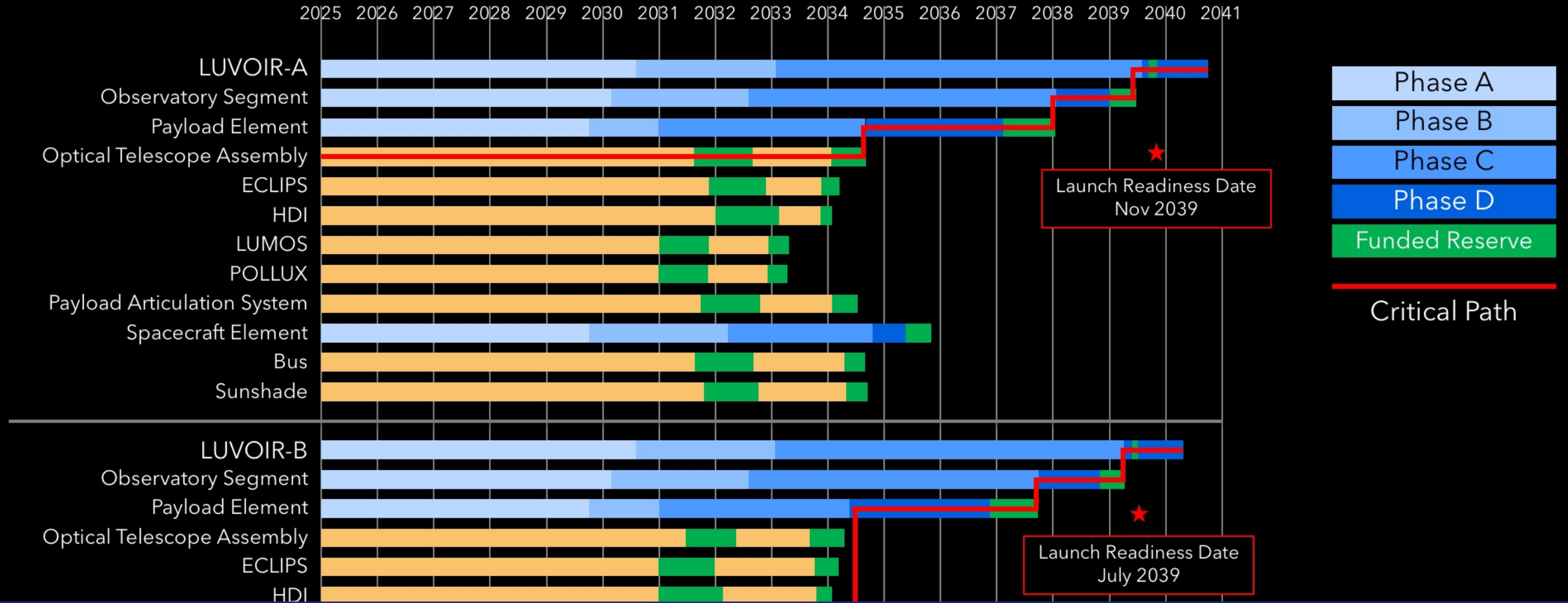
DEVELOPMENT SCHEDULE THROUGH COMMISSIONING



Requests for Proposals are issued at the sub-system level and the sub-systems are responsible for lower level assemblies and sub-assemblies



DEVELOPMENT SCHEDULE THROUGH COMMISSIONING



The development and integration & test sequencing at all levels has been highly optimized based on experience and many lessons learned

DEVELOPMENT SCHEDULE THROUGH COMMISSIONING



A detailed and accurate schedule is critical to long term planning



LIFE-CYCLE COST ESTIMATES



Phase A start through Phase E end						
Cost Model	FY20 (\$B)		RY (\$B)		TRL at KDP-A	TRL at PDR
	LUVOIR-A	LUVOIR-B	LUVOIR-A	LUVOIR-B		
Phase A Ready						
RAO					≥ 5	≥ 6
CEMA					≥ 6	≥ 6

RAO: Goddard Resource Analysis Office

CEMA: Goddard Cost Estimation, Modeling, and Analysis Office

LIFE-CYCLE COST ESTIMATES



Phase A start through Phase E end						
Cost Model	FY20 (\$B)		RY (\$B)		TRL at KDP-A	TRL at PDR
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Cost Model	FY20 (\$B)		RY (\$B)		TRL at KDP-A	TRL at PDR
	LUVOIR-A	LUVOIR-B	LUVOIR-A	LUVOIR-B		
Phase A Ready						
RAO	13 - 16	8 - 10			≥ 5	≥ 6
CEMA	15 - 16	11 - 12			≥ 6	≥ 6

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CEMA: Goddard Cost Estimation, Modeling, and Analysis Office

LIFE-CYCLE COST ESTIMATES



Phase A start through Phase E end						
Cost Model	FY20 (\$B)		RY (\$B)		TRL at KDP-A	TRL at PDR
	LUVOIR-A	LUVOIR-B	LUVOIR-A	LUVOIR-B		
Phase A Ready						
RAO	13 - 16	8 - 10	19 - 24	12 - 15	≥ 5	≥ 6
CEMA	15 - 16	11 - 12	20 - 24	15 - 18	≥ 6	≥ 6

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LIFE-CYCLE COST ESTIMATES



Phase A start through Phase E end						
Cost Model	FY20 (\$B)		RY (\$B)		TRL at KDP-A	TRL at PDR
	LUVOIR-A	LUVOIR-B	LUVOIR-A	LUVOIR-B		
Phase A Ready						
RAO	13 - 16	8 - 10	19 - 24	12 - 15	≥ 5	≥ 6
CEMA	15 - 16	11 - 12	20 - 24	15 - 18	≥ 6	≥ 6
Estimated cost ranges are 50% – 70% confidence level						

RAO: Goddard Resource Analysis Office

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LIFE-CYCLE COST ESTIMATES



Phase A start through Phase E end						
Cost Model	FY20 (\$B)		RY (\$B)		TRL at KDP-A	TRL at PDR
	LUVOIR-A	LUVOIR-B	LUVOIR-A	LUVOIR-B		
Phase A Ready						
RAO	13 - 16	8 - 10	19 - 24	12 - 15	≥ 5	≥ 6
CEMA	15 - 16	11 - 12	20 - 24	15 - 18	≥ 6	≥ 6
LUVOIR-A costs include integration of POLLUX, but not cost of POLLUX itself. LUVOIR-B costs do not include any international contributions. ESA interest in making an M-class contribution to NASA's next flagship mission.						

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LIFE-CYCLE COST ESTIMATES

Phase A start through Phase E end						
Cost Model	FY20 (\$B)		RY (\$B)		TRL at KDP-A	TRL at PDR
	LUVOIR-A	LUVOIR-B	LUVOIR-A	LUVOIR-B		
Phase A Ready						
RAO	13 - 16	8 - 10	19 - 24	12 - 15	≥ 5	≥ 6
CEMA	15 - 16	11 - 12	20 - 24	15 - 18	≥ 6	≥ 6
All cost estimates assume current serviceable designs. Removing serviceability is not expected to reduce costs because the design is modular for more than just servicing. Late definition of <i>how</i> servicing will be done could drive costs up and impact schedule.						

RAO: Goddard Resource Analysis Office

CEMA: Goddard Cost Estimation, Modeling, and Analysis Office

LIFE-CYCLE COST ESTIMATES

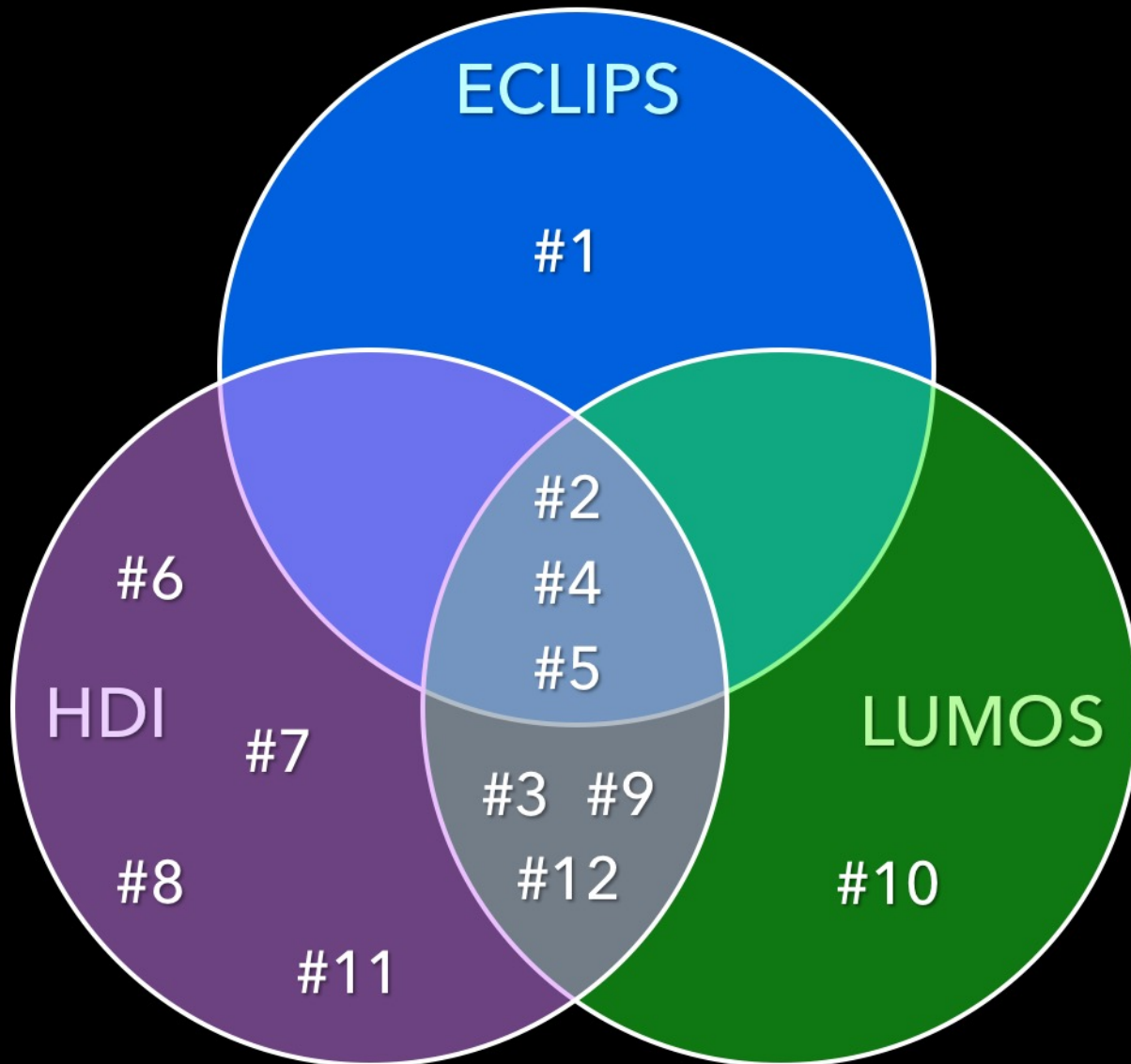


Phase A start through Phase E end						
Cost Model	FY20 (\$B)		RY (\$B)		TRL at KDP-A	TRL at PDR
	LUVOIR-A	LUVOIR-B	LUVOIR-A	LUVOIR-B		
Phase A Ready						
RAO	13 - 16	8 - 10	19 - 24	12 - 15	≥ 5	≥ 6
CEMA	15 - 16	11 - 12	20 - 24	15 - 18	≥ 6	≥ 6
LCIT opinion is GSFC cost estimates are conservative						

RAO: Goddard Resource Analysis Office

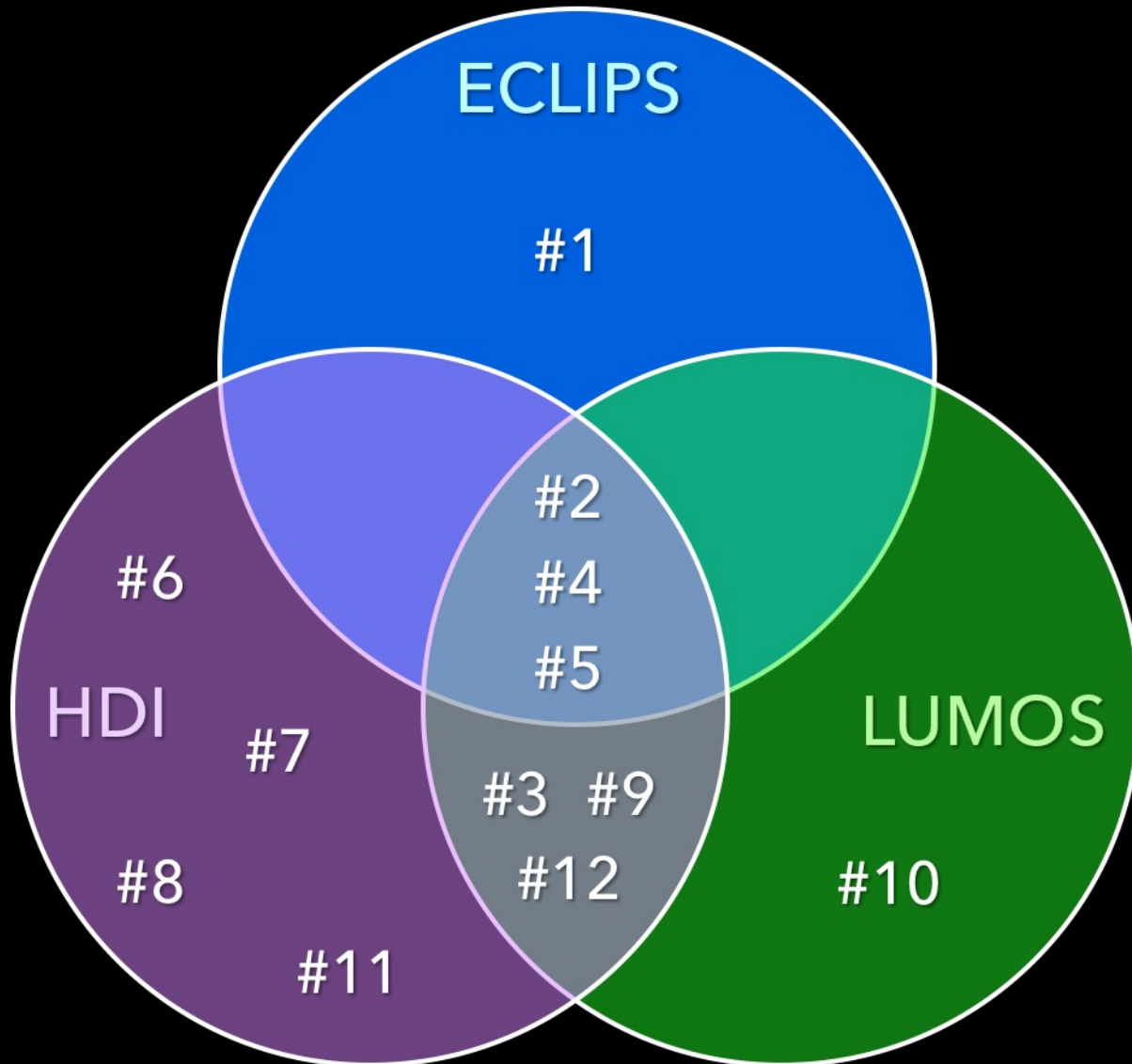
CEMA: Goddard Cost Estimation, Modeling, and Analysis Office

SCIENCE GOALS FOR EACH INSTRUMENT



#1	Habitable Planet Candidate Survey
#2	Search for Biosignatures
#3	Solar System Ocean Worlds
#4	Comparative Atmospheres
#5	Planetary System Formation
#6	Solar System Small Bodies
#7	Smallest Scales Across Cosmic Time
#8	Dark Matter via Astrometry
#9	Investigating Reionization
#10	Cycles of Matter
#11	Galaxy Assembly
#12	Stars and Galactic Feedback

COSTS FOR EACH INSTRUMENT



	LUVOR-A FY20 \$B	LUVOR-B FY20 \$B
ECLIPS	0.7 – 0.9	0.7 – 0.9
LUMOS	0.7 – 0.9	0.7 – 0.9
HDI	1.6 – 2.0	0.9 – 1.1
OTA	3.0 – 3.6	1.9 – 2.3

Estimated cost ranges are 50% – 70% confidence level

MINIMIZING RISK TO THE SCHEDULE AND COSTS

Many strategies and lessons learned are critical to implementing all future flagship missions, including LUV OIR

Integration and test needs early planning

- Sequencing of overall integration and test effort

- Scouting integration and test facilities

- Planning for verification by analysis

MINIMIZING RISK TO THE SCHEDULE AND COSTS

Many strategies and lessons learned are critical to implementing all future flagship missions, including LUV OIR

- Integration and test needs early planning

 - Sequencing of overall integration and test effort

 - Scouting integration and test facilities

 - Planning for verification by analysis

- Utilize pathfinders and engineering demonstration units

MINIMIZING RISK TO THE SCHEDULE AND COSTS

Many strategies and lessons learned are critical to implementing all future flagship missions, including LUV OIR

- Plan for parallel operations

 - Storyboard procedures

 - Remove bottlenecks

 - Design systems to be modular

MINIMIZING RISK TO THE SCHEDULE AND COSTS

Many strategies and lessons learned are critical to implementing all future flagship missions, including LUV OIR

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- Develop technology early along with industry and academic partners

MINIMIZING RISK TO THE SCHEDULE AND COSTS

Many strategies and lessons learned are critical to implementing all future flagship missions, including LUV OIR

- Plan for parallel operations

 - Storyboard procedures

 - Remove bottlenecks

 - Design systems to be modular

- Develop technology early along with industry and academic partners

- Establish a Pre-Phase A team to coordinate efforts before “marching army” starts

SEQUENCING OF INTEGRATION AND TEST



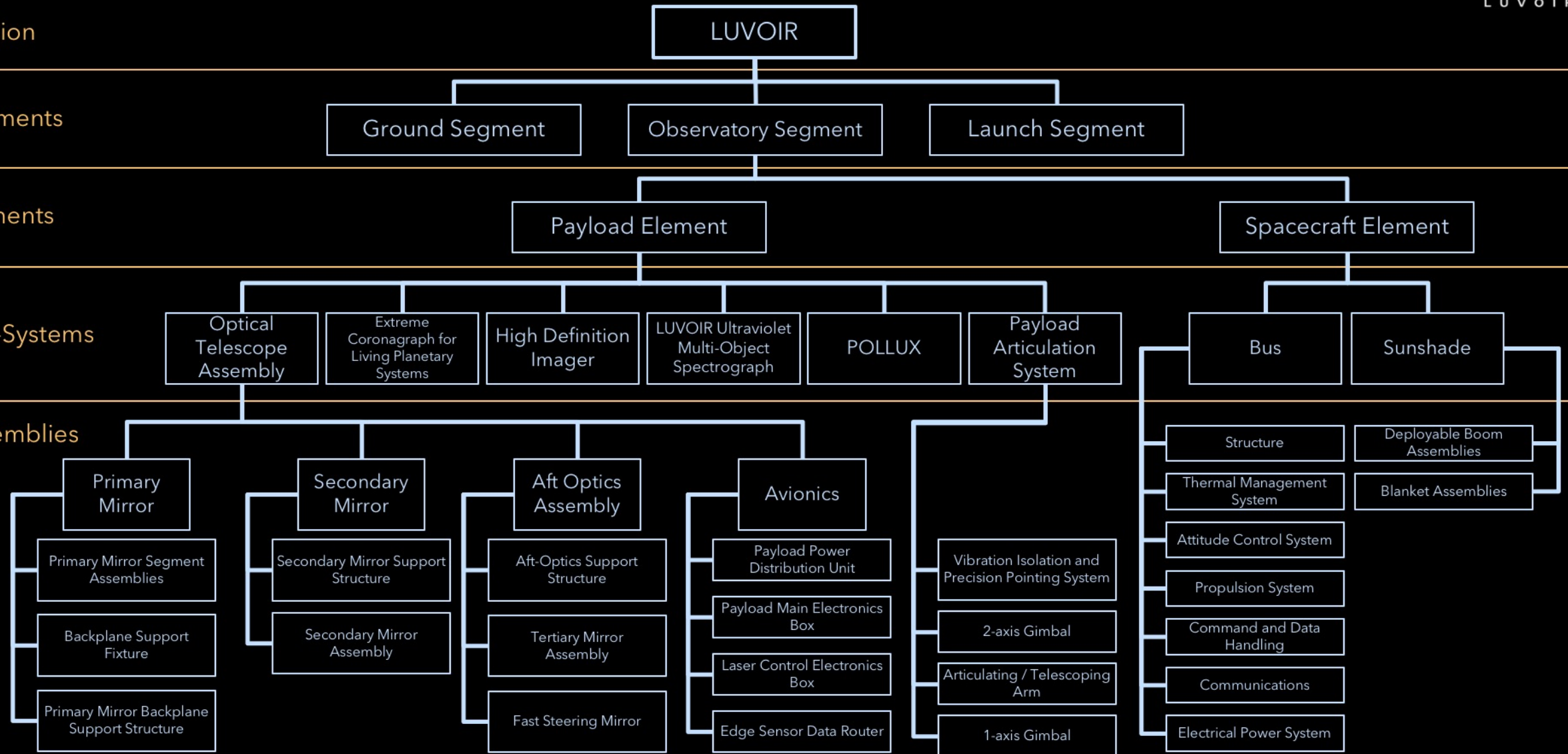
Mission

Segments

Elements

Sub-Systems

Assemblies



SEQUENCING OF INTEGRATION AND TEST



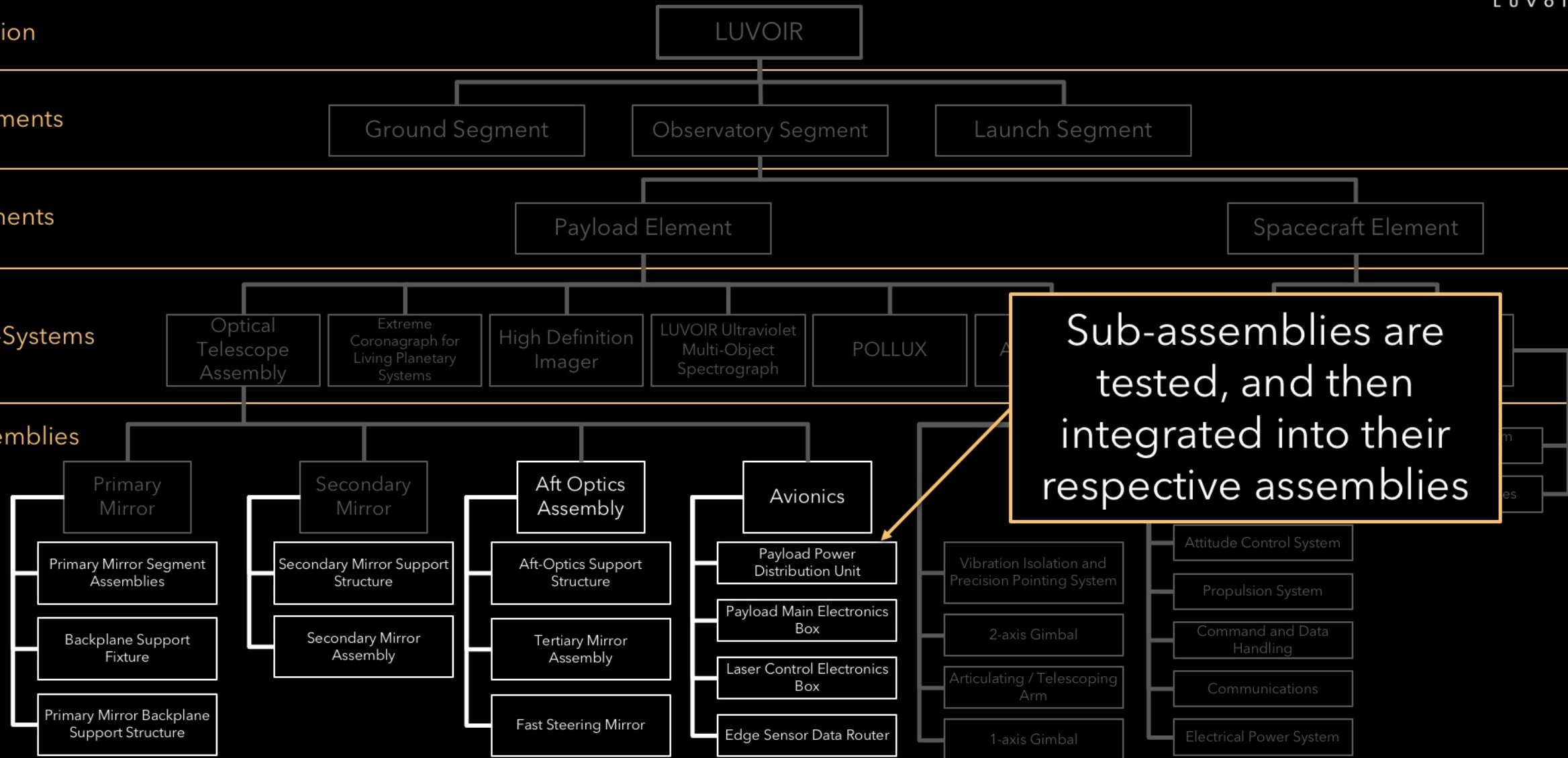
Mission

Segments

Elements

Sub-Systems

Assemblies



SEQUENCING OF INTEGRATION AND TEST

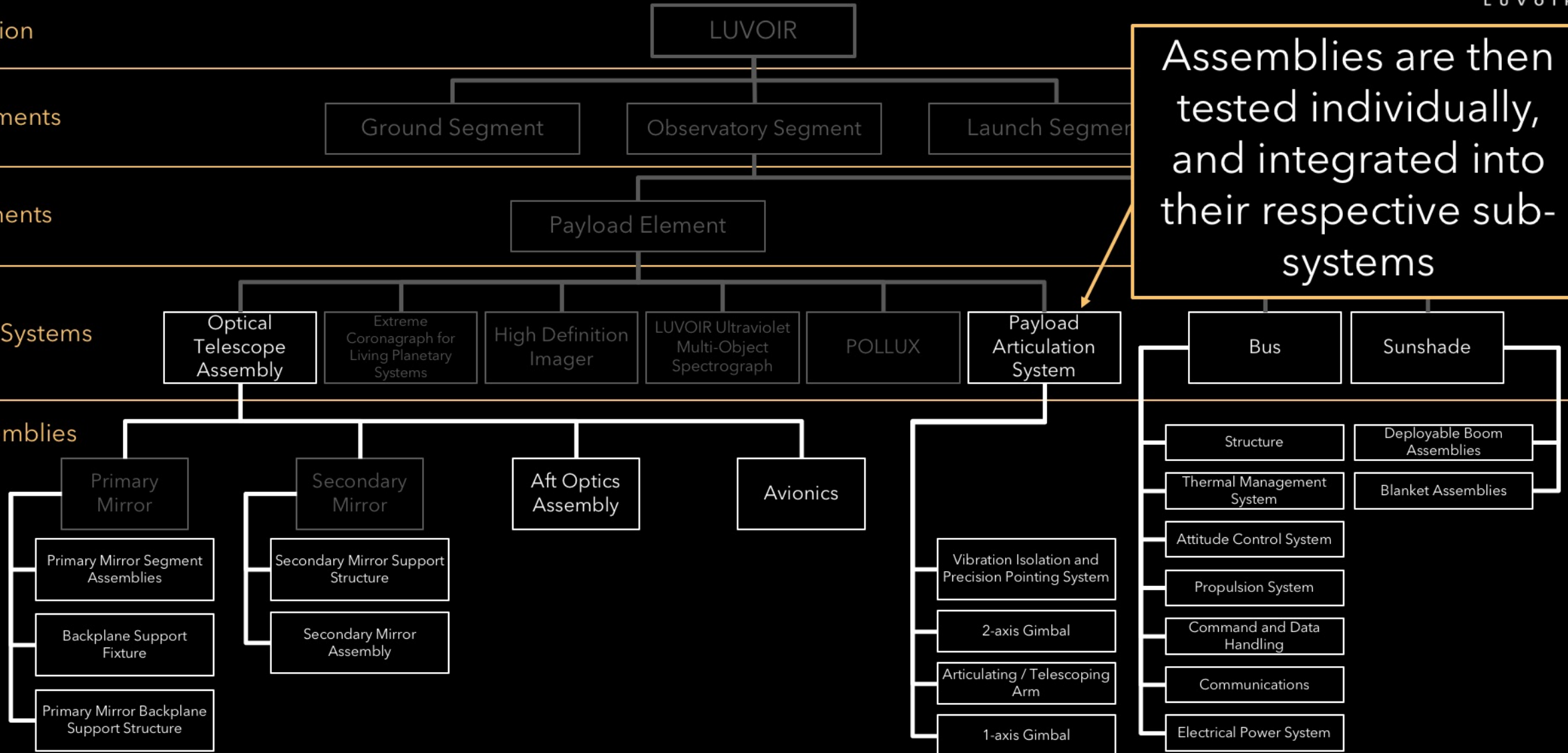
Mission

Segments

Elements

Sub-Systems

Assemblies



Assemblies are then tested individually, and integrated into their respective sub-systems

SEQUENCING OF INTEGRATION AND TEST



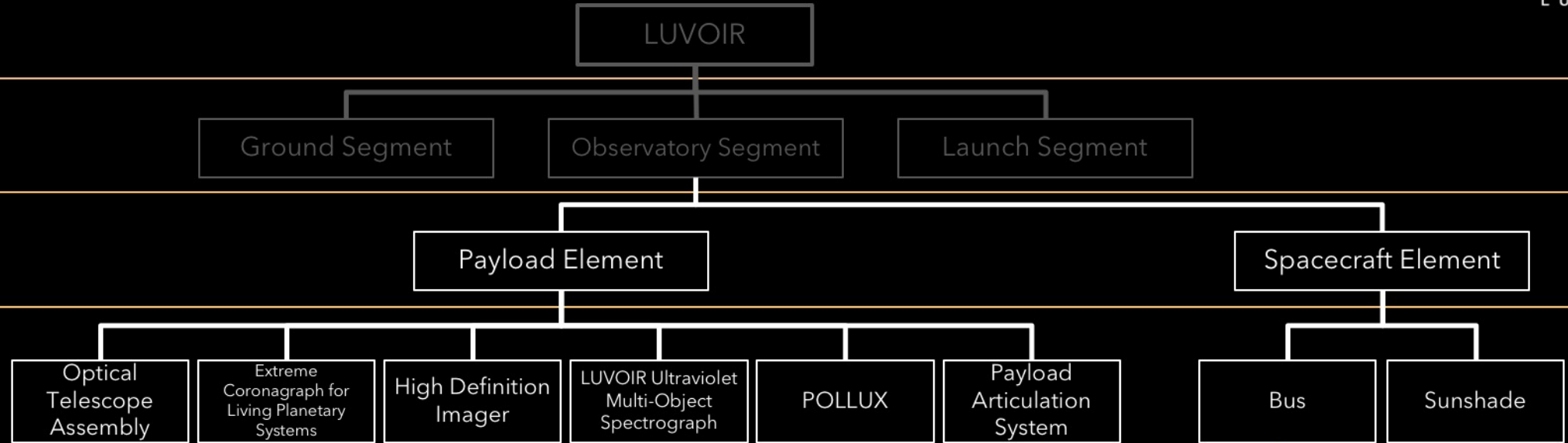
Mission

Segments

Elements

Sub-Systems

Assemblies



Sub-systems are tested individually, and then integrated into their respective elements

SEQUENCING OF INTEGRATION AND TEST



Mission

LUVOIR

Segments

Ground Segment

Observatory Segment

Launch Segment

Elements

Payload Element

Spacecraft Element

Sub-Systems

Assemblies

Elements are tested separately before being integrated into the observatory segment

SEQUENCING OF INTEGRATION AND TEST

Mission

LUV OIR

Segments

Ground Segment

Observatory Segment

Launch Segment

Elements

Sub-Systems

Assemblies

Final testing is
performed at the
observatory segment
level

SEQUENCING OF INTEGRATION AND TEST



Mission

LUVOR

Segments

Ground Segment

Observatory Segment

Launch Segment

I&T strategy reduces risk of having to remove pieces after assembly at higher levels, balanced with risk from multiple tests of low-level hardware

Sub-Systems

Optical
Telescope
Assembly

Extreme
Coronagraph for
Living Planetary
Systems

High Definition
Imager

LUVOR Ultraviolet
Multi-Object
Spectrograph

POLLUX

Payload
Articulation
System

Bus

Sunshade

Assemblies

Primary
Mirror

Primary Mirror Segment
Assemblies

Backplane Support
Fixture

Primary Mirror Backplane
Support Structure

Secondary
Mirror

Secondary Mirror Support
Structure

Secondary Mirror
Assembly

Aft Optics
Assembly

Aft-Optics Support
Structure

Tertiary Mirror
Assembly

Fast Steering Mirror

Avionics

Payload Power
Distribution Unit

Payload Main Electronics
Box

Laser Control Electronics
Box

Edge Sensor Data Router

Vibration Isolation and
Precision Pointing System

2-axis Gimbal

Articulating / Telescoping
Arm

1-axis Gimbal

Structure

Thermal Management
System

Attitude Control System

Propulsion System

Command and Data
Handling

Communications

Electrical Power System

Deployable Boom
Assemblies

Blanket Assemblies

INTEGRATION & TEST FACILITIES

Preliminary survey of I&T facilities has been completed and some facilities of suitable scale for LUV OIR have been identified



The GRC Space Simulation Chamber



LUV OIR in the GRC Space Simulation Chamber



INTEGRATION & TEST FACILITIES

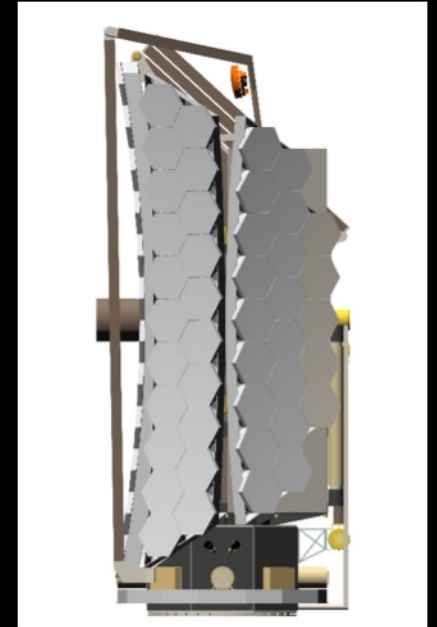
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The GRC Reverberant Acoustic Test Facility



LUV OIR in the GRC Reverberant Acoustic Test Facility



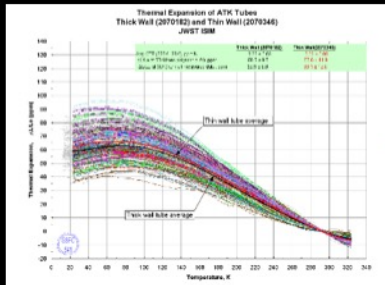
VERIFICATION BY ANALYSIS

As with many missions, the flight environment will be impossible to completely replicate on the ground

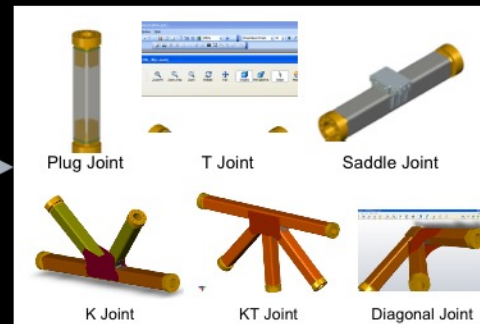
Verification by analysis with models that have been validated via tests will be used to show compliance with performance requirements

Integrated modeling has been used on previous programs such as Chandra and JWST and requires early coordination with product developments

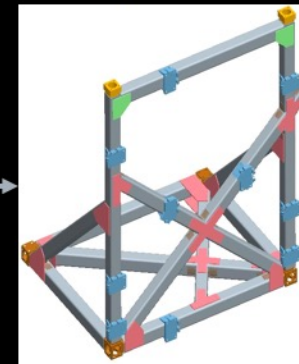
Detailed material characterization



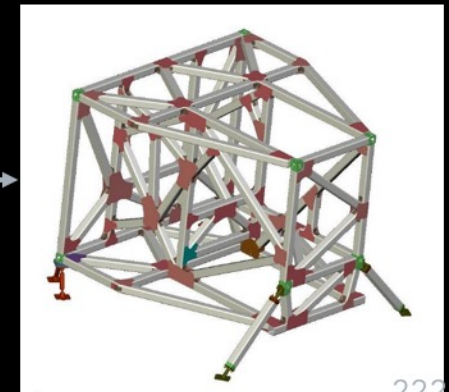
Joint development tests



Sub-assembly development tests



ISIM structure verification



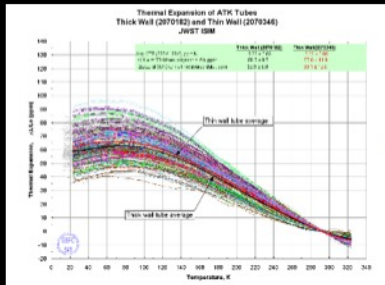
VERIFICATION BY ANALYSIS

As with many missions, the flight environment will be impossible to completely replicate on the ground

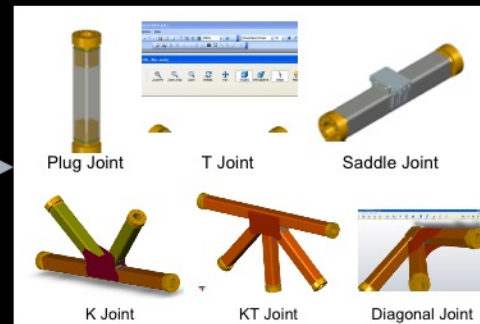
Verification by analysis with models that have been validated via tests will be used to show compliance with performance requirements

Including integration and test considerations into early planning is a key component for creating an optimized schedule by minimizing long-term unknowns

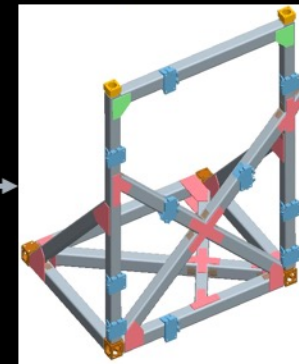
Detailed material characterization



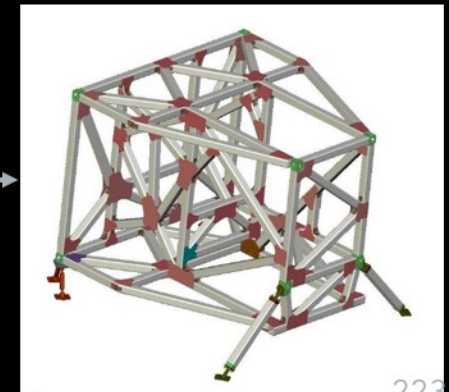
Joint development tests



Sub-assembly development tests



ISIM structure verification



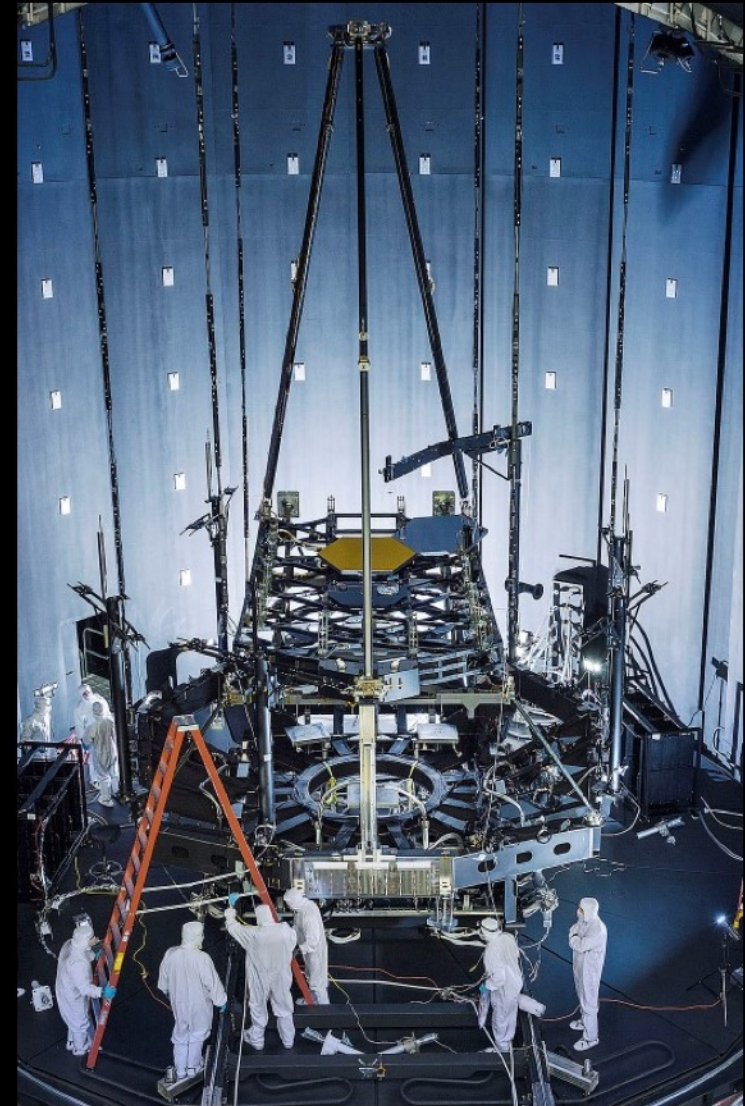
PATHFINDERS AND ENGINEERING DEMONSTRATIONS

Large flagship missions have shown the need for engineering pathfinders

They allow us to practice with and learn from non-flight hardware well off the schedule's critical path

We use them to...

- ... inform early designs
- ... practice integration procedures
- ... dry-run large and complex tests



JWST Pathfinder in Johnson Test Chamber

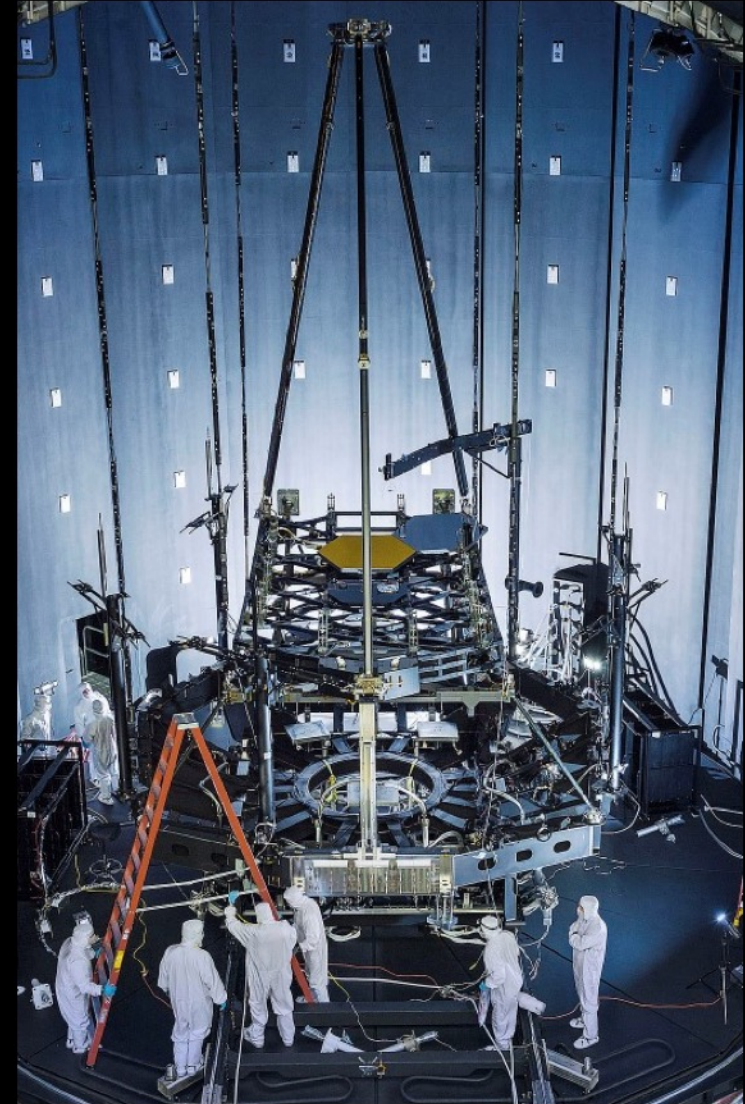
PATHFINDERS AND ENGINEERING DEMONSTRATIONS

Large flagship missions have shown the need for engineering pathfinders

They allow us to practice with and learn from non-flight hardware well off the schedule's critical path

Some envisioned pathfinders include...

- ... PMSA integration to the backplane
- ... Demonstrating primary mirror backplane module repeatability
- ... Sunshade deployments demonstrations

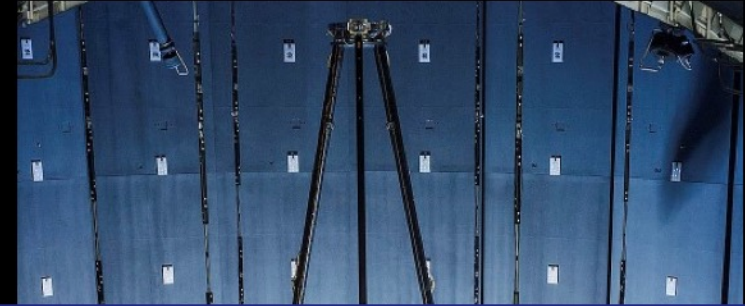


JWST Pathfinder in Johnson Test Chamber

PATHFINDERS AND ENGINEERING DEMONSTRATIONS



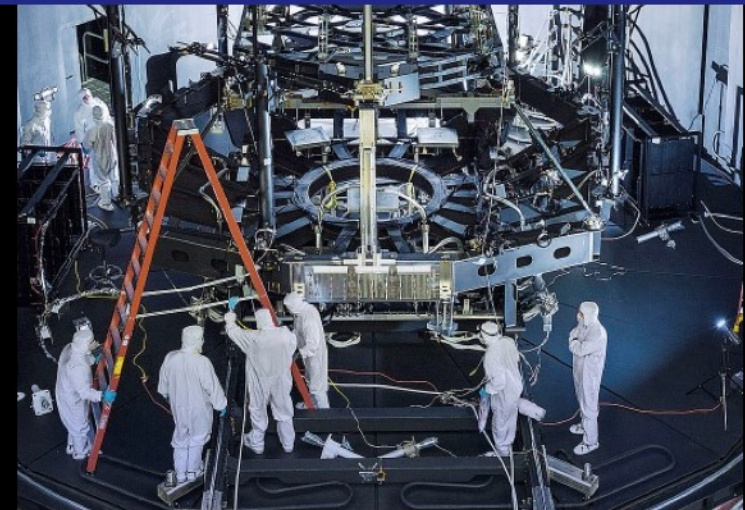
Large flagship missions have shown the need for engineering pathfinders



Pathfinders allow team to practice with non-flight hardware off the critical path, reducing risk to flight hardware and minimizing risk of schedule erosion

Some envisioned pathfinders include...

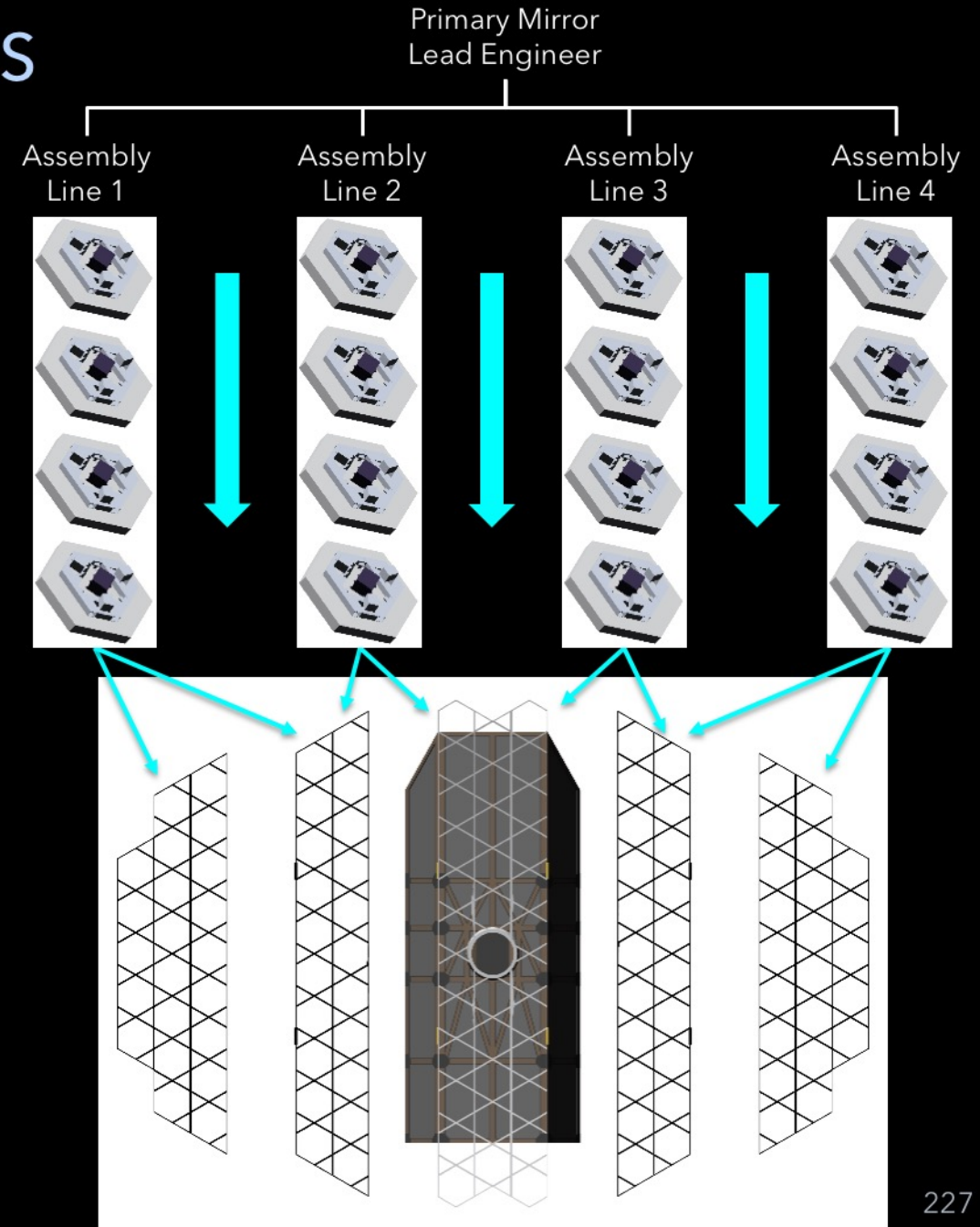
- ... PMSA integration to the backplane
- ... Demonstrating primary mirror backplane module repeatability
- ... Sunshade deployments demonstrations



JWST Pathfinder in Johnson Test Chamber

PLANNING FOR PARALLEL OPERATIONS

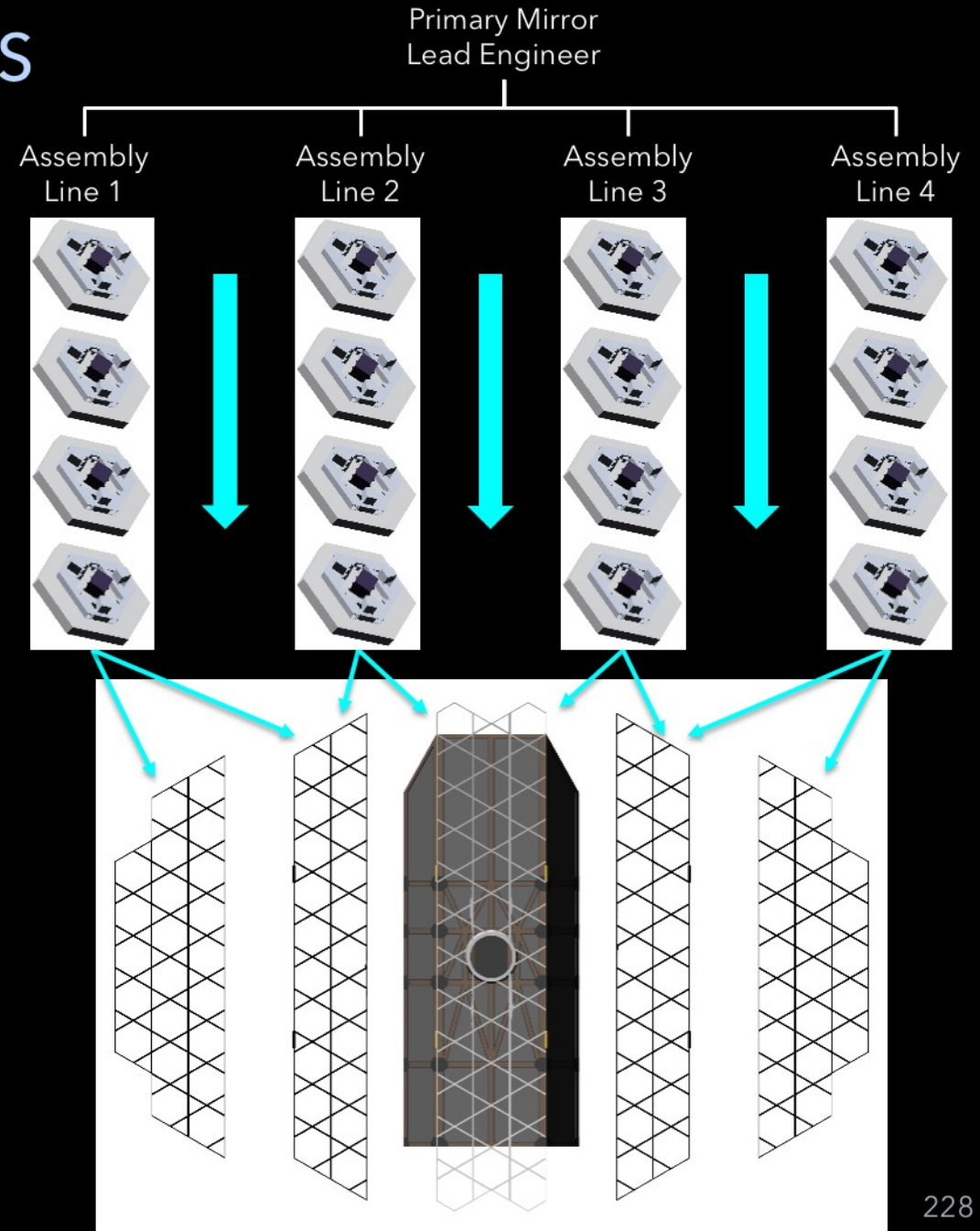
The Primary Mirror is an excellent example of why planning for parallel operations is critical



PLANNING FOR PARALLEL OPERATIONS

The Primary Mirror is an excellent example of why planning for parallel operations is critical

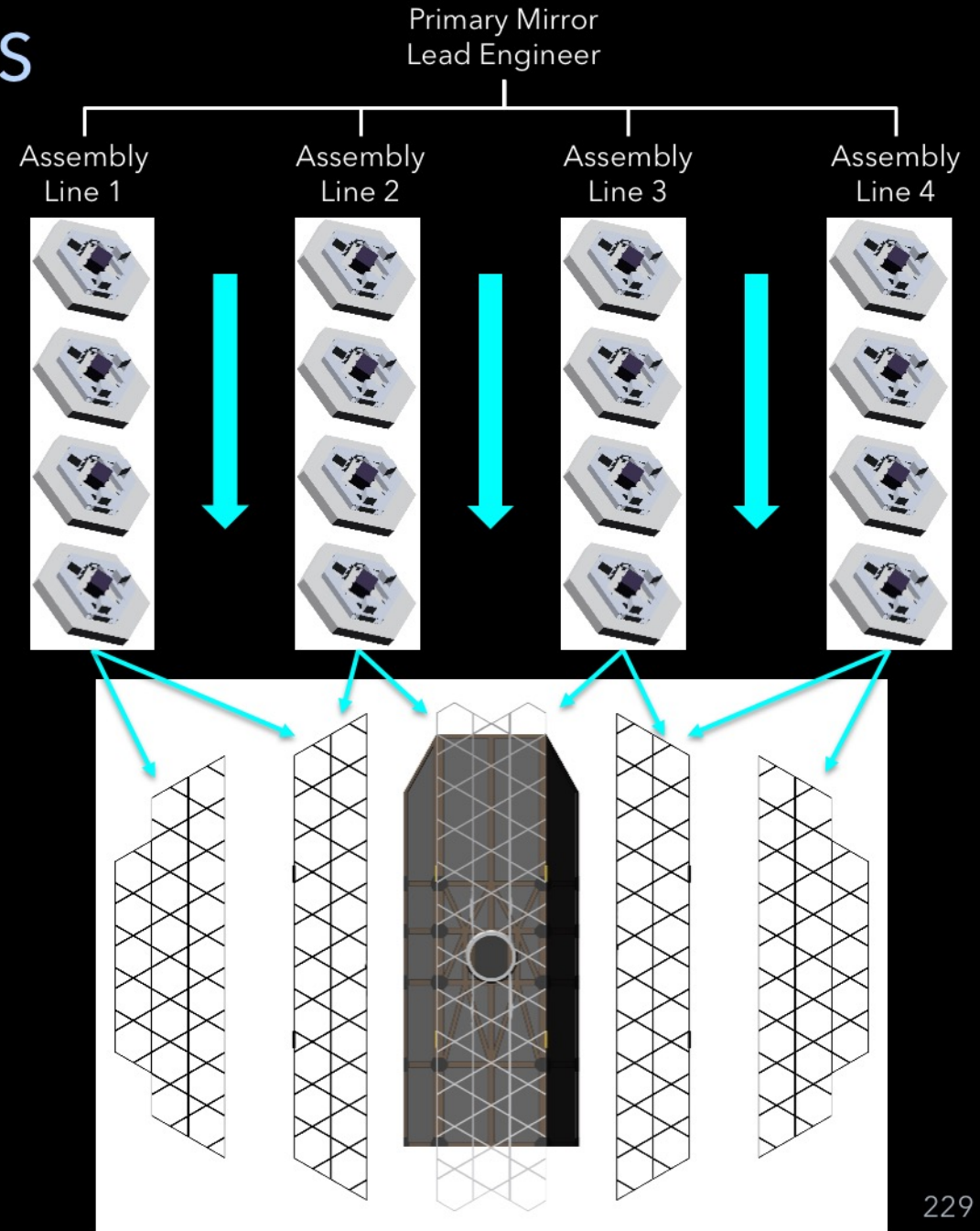
Long-term planning recognizes that PMSAs need to be manufactured, assembled, and tested in parallel



PLANNING FOR PARALLEL OPERATIONS

The Primary Mirror is an excellent example of why planning for parallel operations is critical

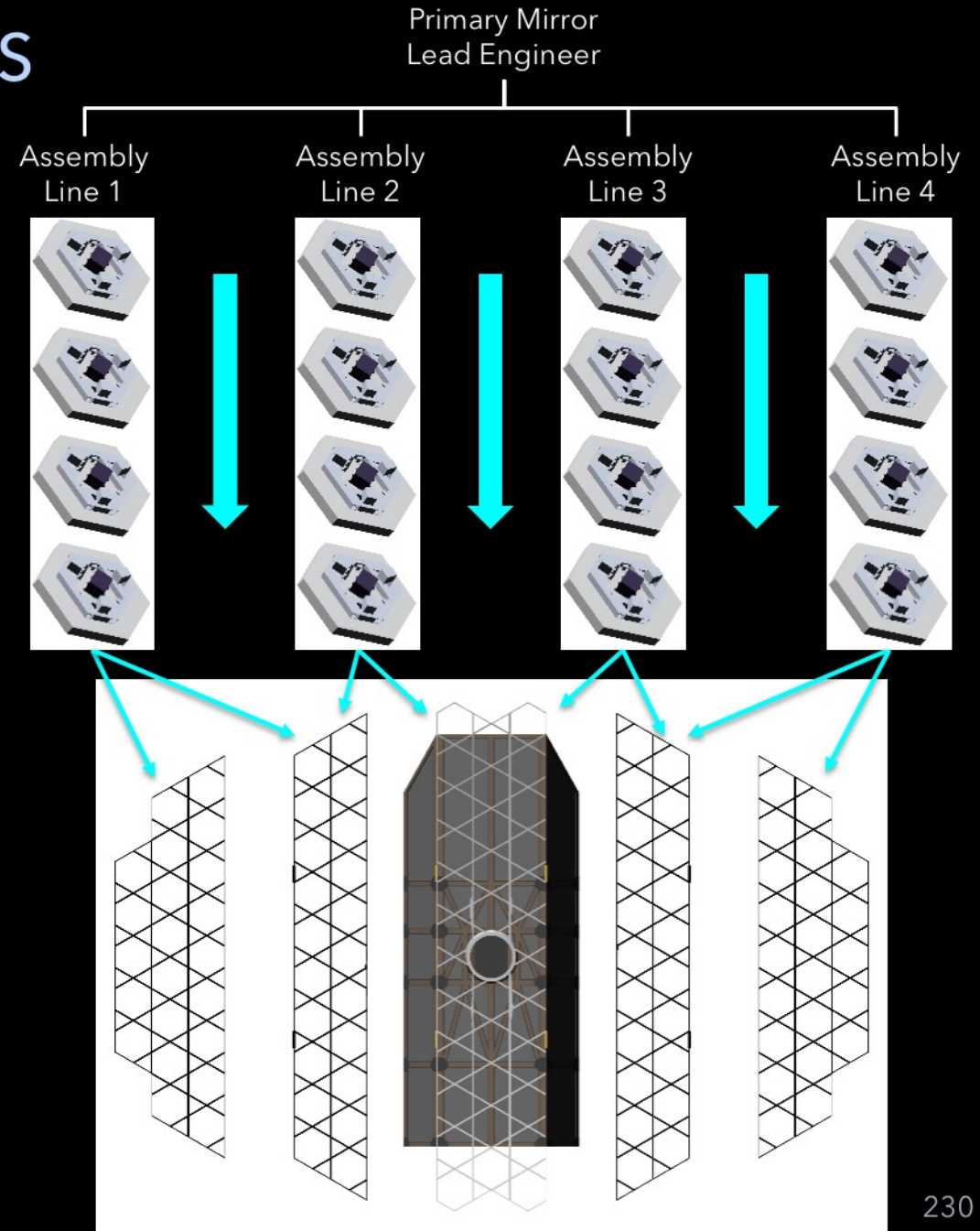
The assembly procedure needs to be storyboarded so that accurate procedures can be created



PLANNING FOR PARALLEL OPERATIONS

The Primary Mirror is an excellent example of why planning for parallel operations is critical

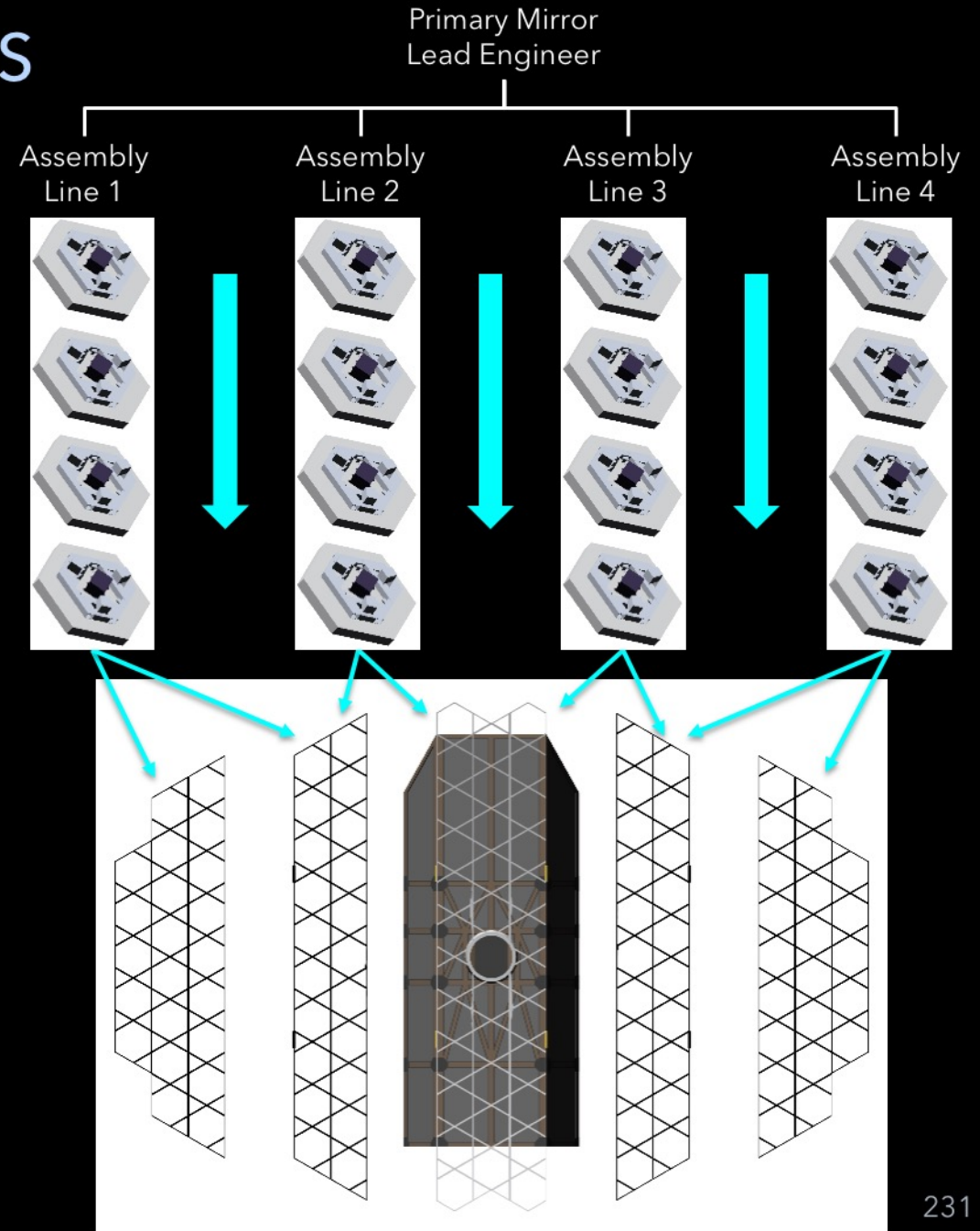
Pathfinders are used to practice both the PMSA assembly and the PMSA integration to the backplane



PLANNING FOR PARALLEL OPERATIONS

The Primary Mirror is an excellent example of why planning for parallel operations is critical

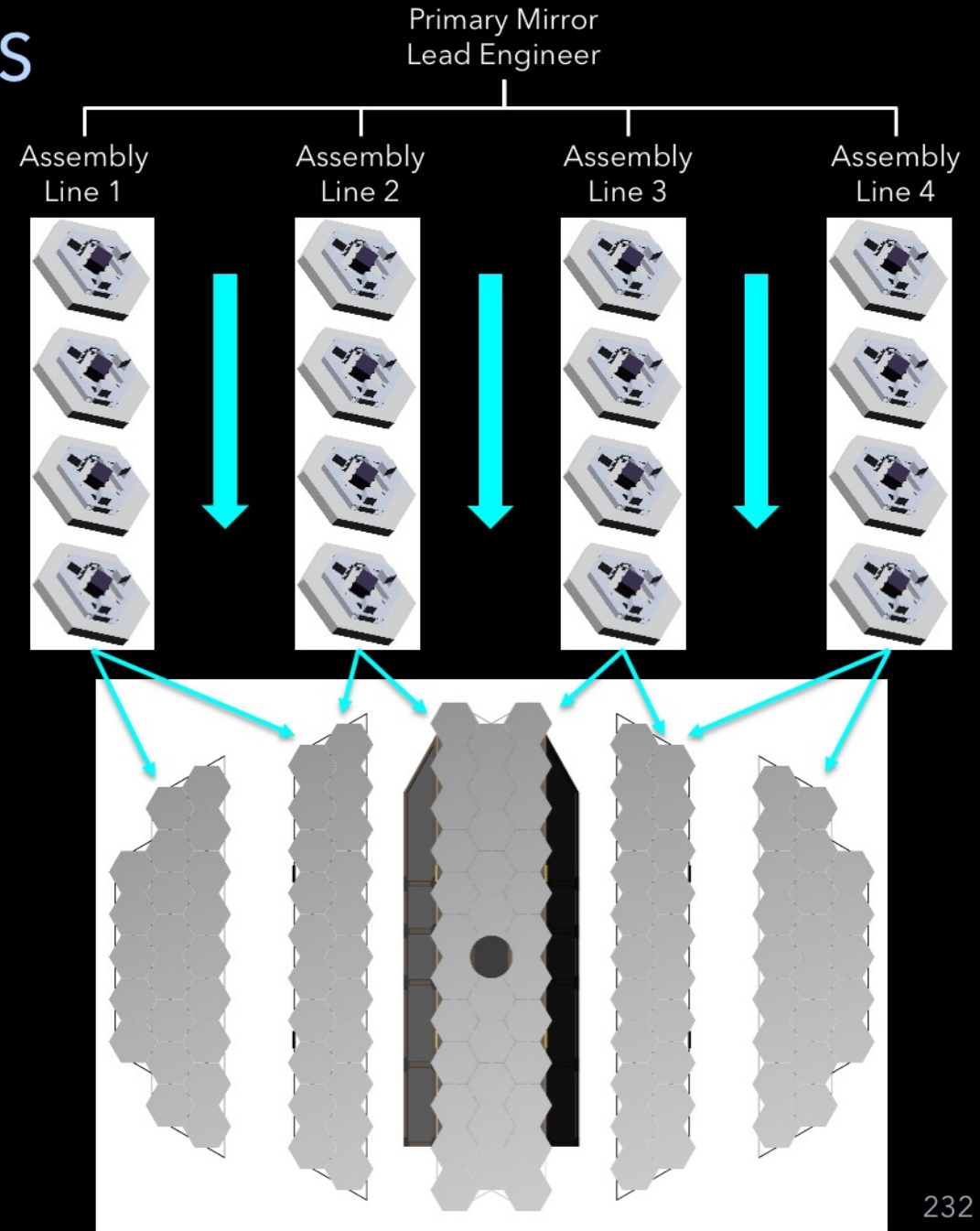
No one person can be the expert. Multiple teams need to be trained so that multiple "lines" can be run independently



PLANNING FOR PARALLEL OPERATIONS

The Primary Mirror is an excellent example of why planning for parallel operations is critical

The backplane is designed to be modular so that not 1, but 4 mirrors can be integrated simultaneously during I&T

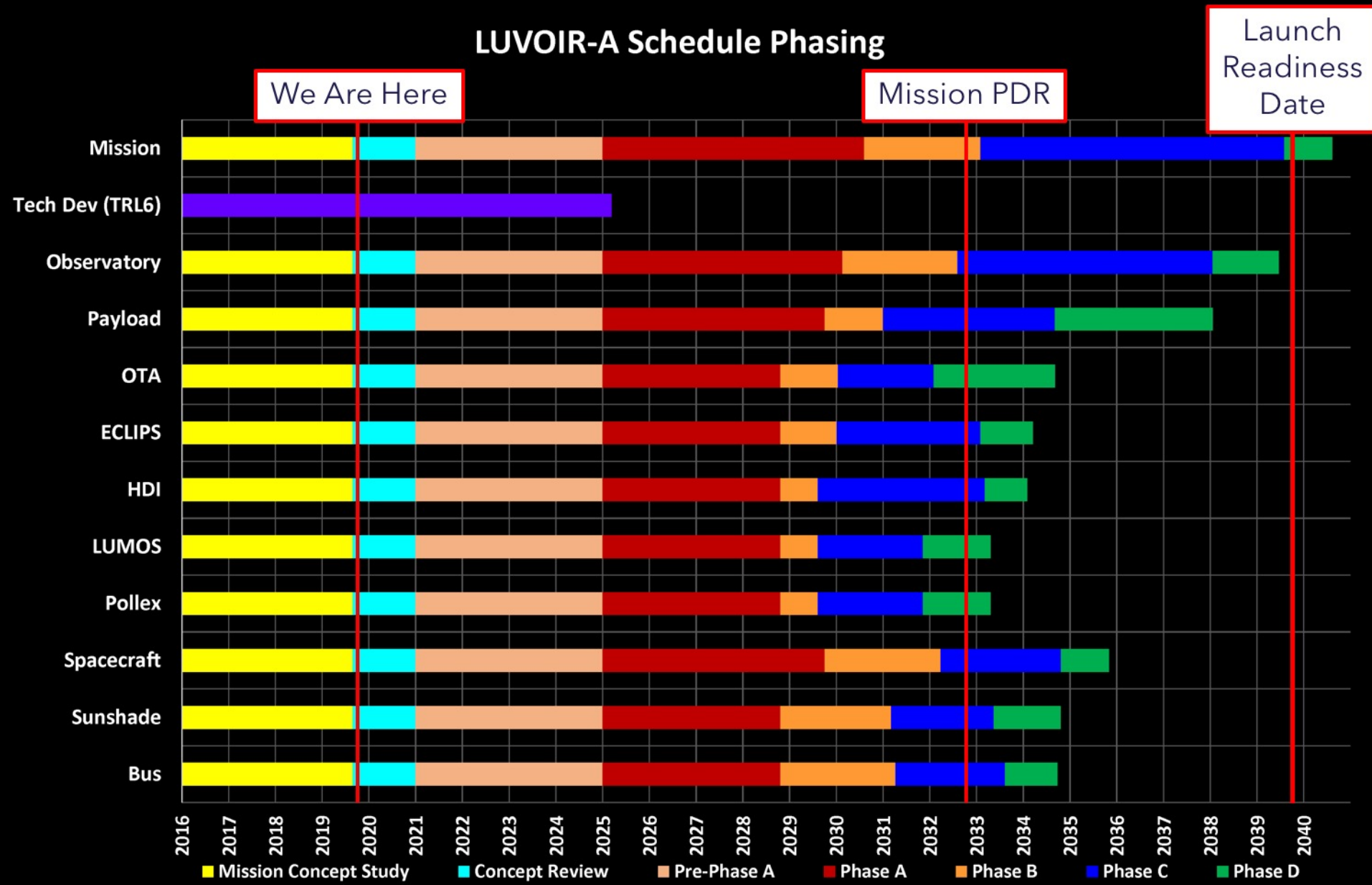


FINISH TECHNOLOGY DEVELOPMENT EARLY

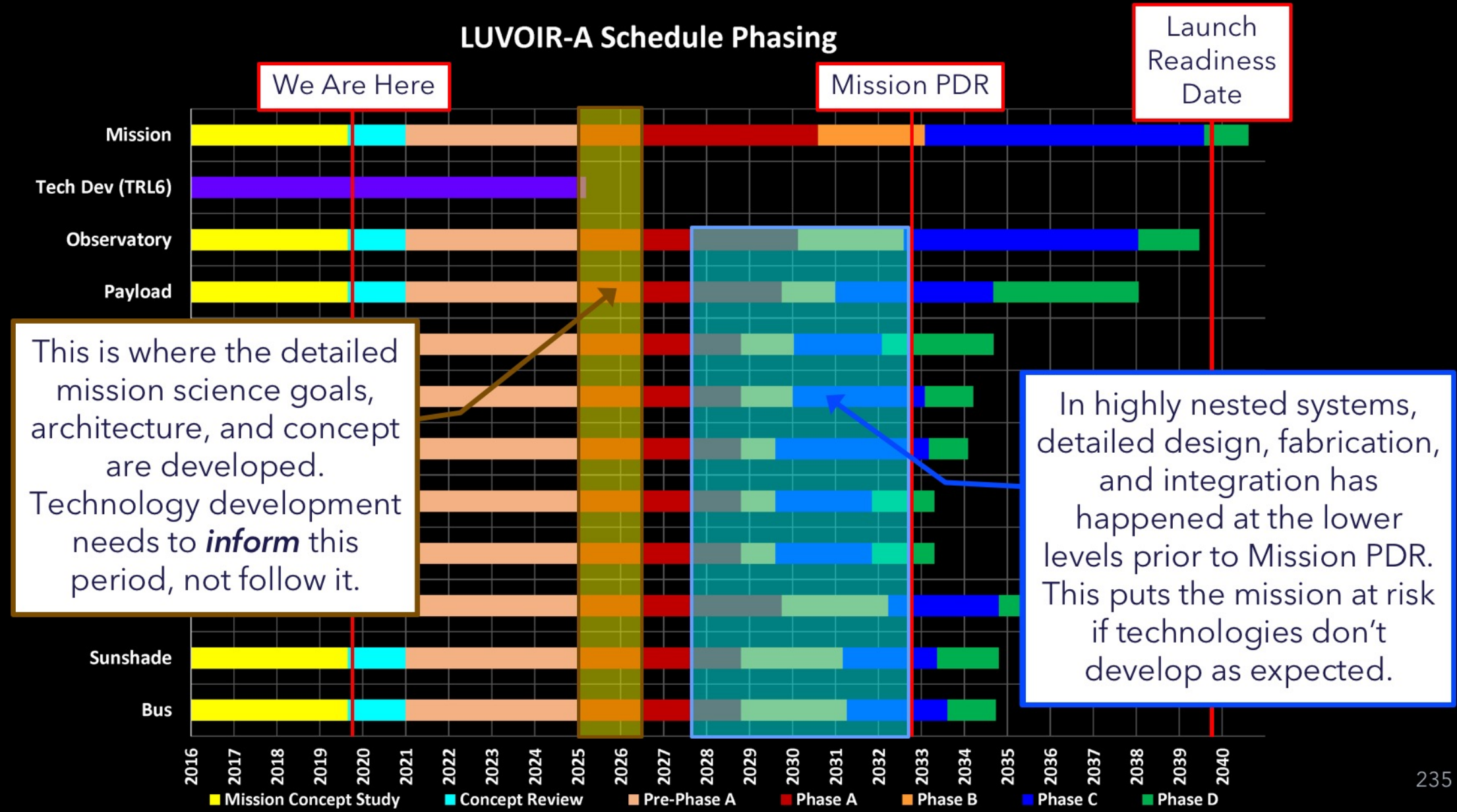


GAO-10-227SP cites a lack of “Technology Maturity” and “Design Stability” as top two causes of cost and schedule overruns in NASA projects

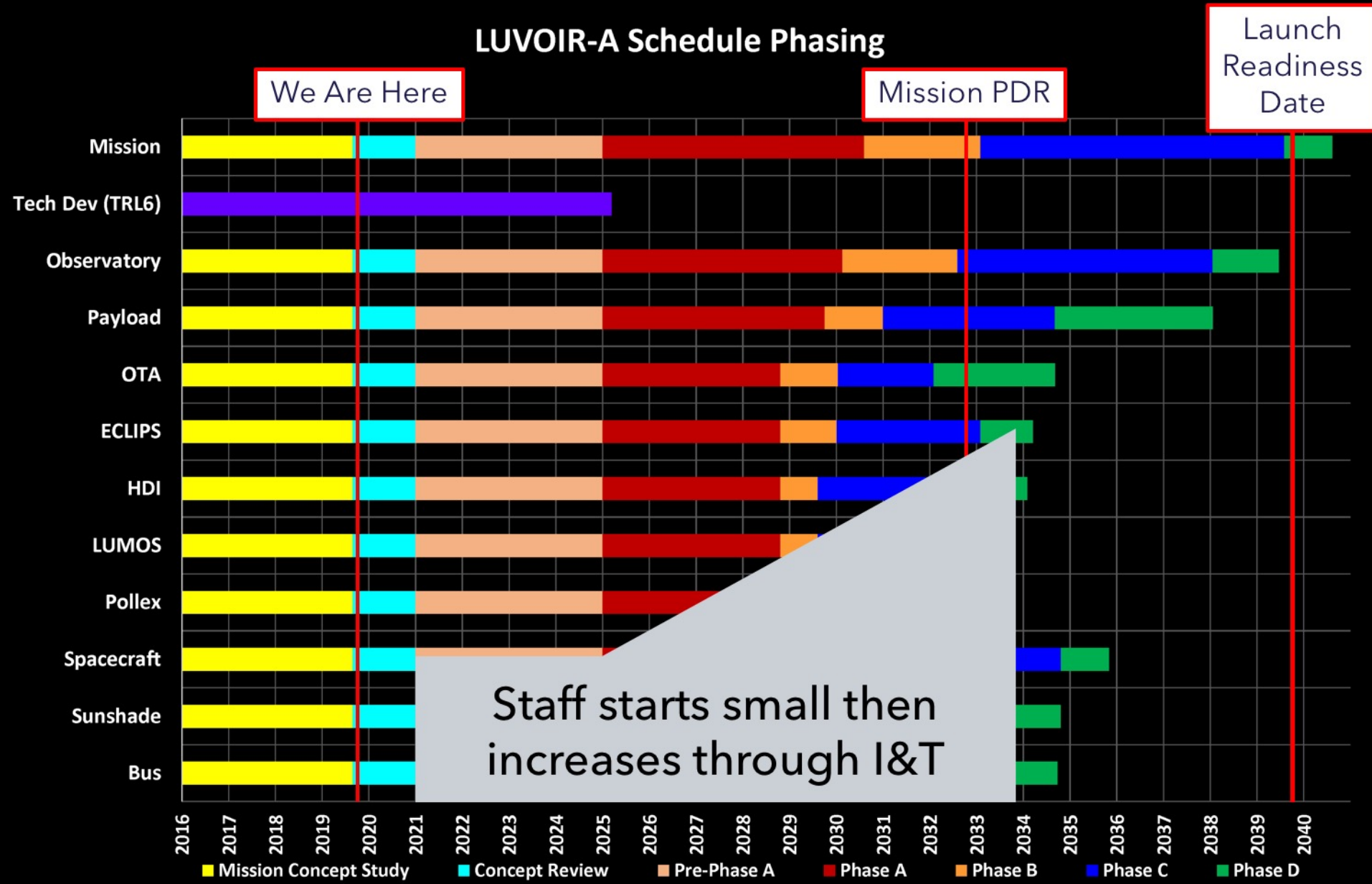
FINISH TECHNOLOGY DEVELOPMENT EARLY



FINISH TECHNOLOGY DEVELOPMENT EARLY



FINISH TECHNOLOGY DEVELOPMENT EARLY



FINISH TECHNOLOGY DEVELOPMENT EARLY

LUV OIR-A Schedule Phasing

Relative Costs

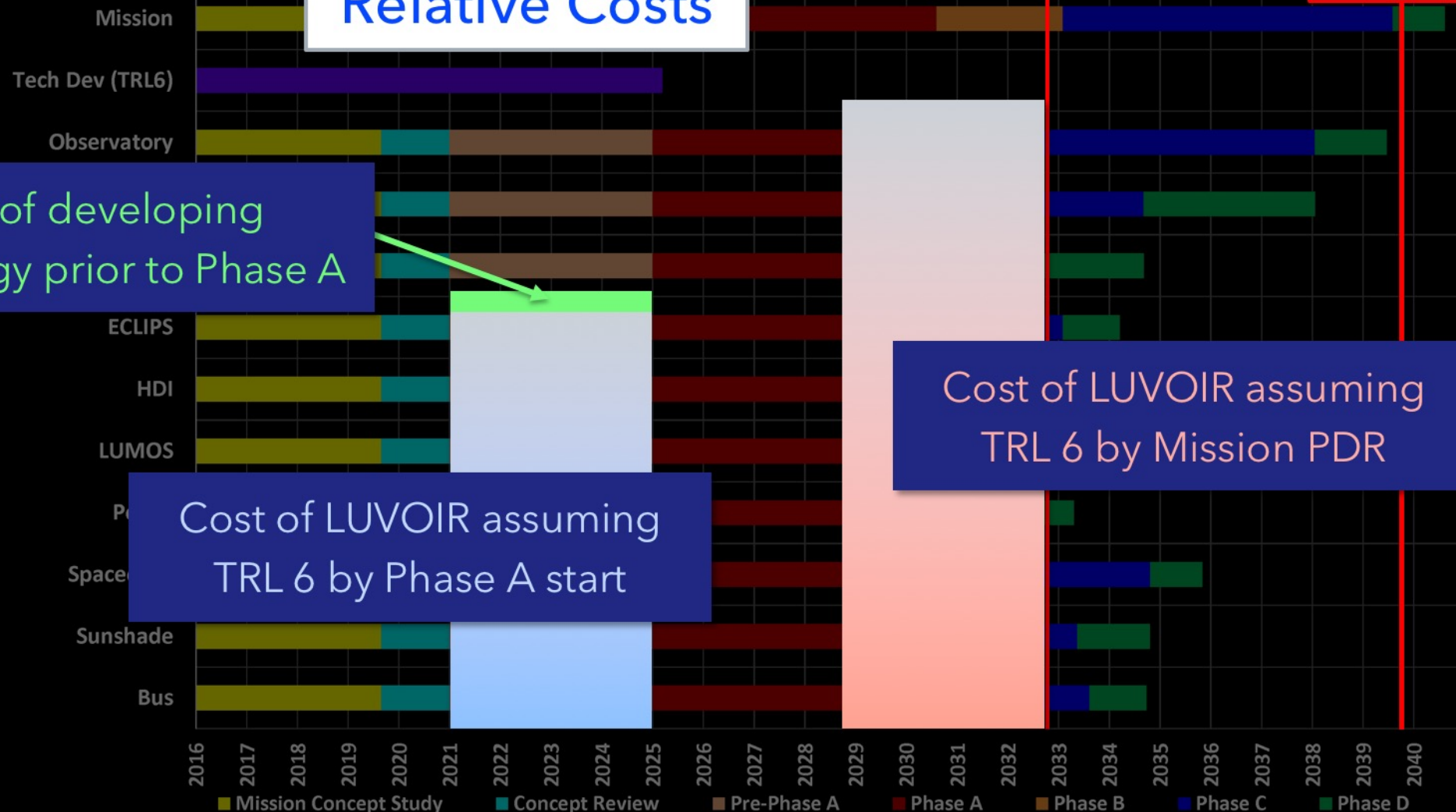
Cost of developing technology prior to Phase A

Cost of LUV OIR assuming TRL 6 by Phase A start

Cost of LUV OIR assuming TRL 6 by Mission PDR

Mission PDR

Launch Readiness Date



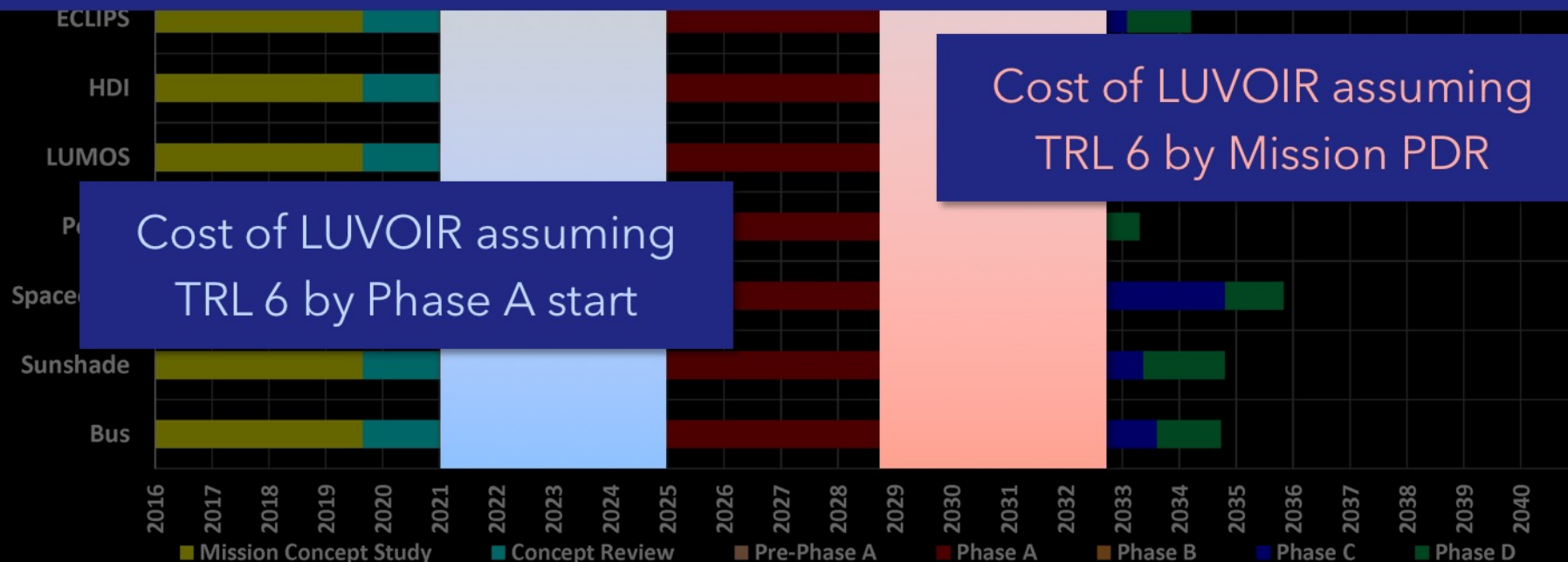
FINISH TECHNOLOGY DEVELOPMENT EARLY



LUV OIR-A Schedule Phasing



Developing technologies early minimizes the risk of schedule erosion and reduces overall costs

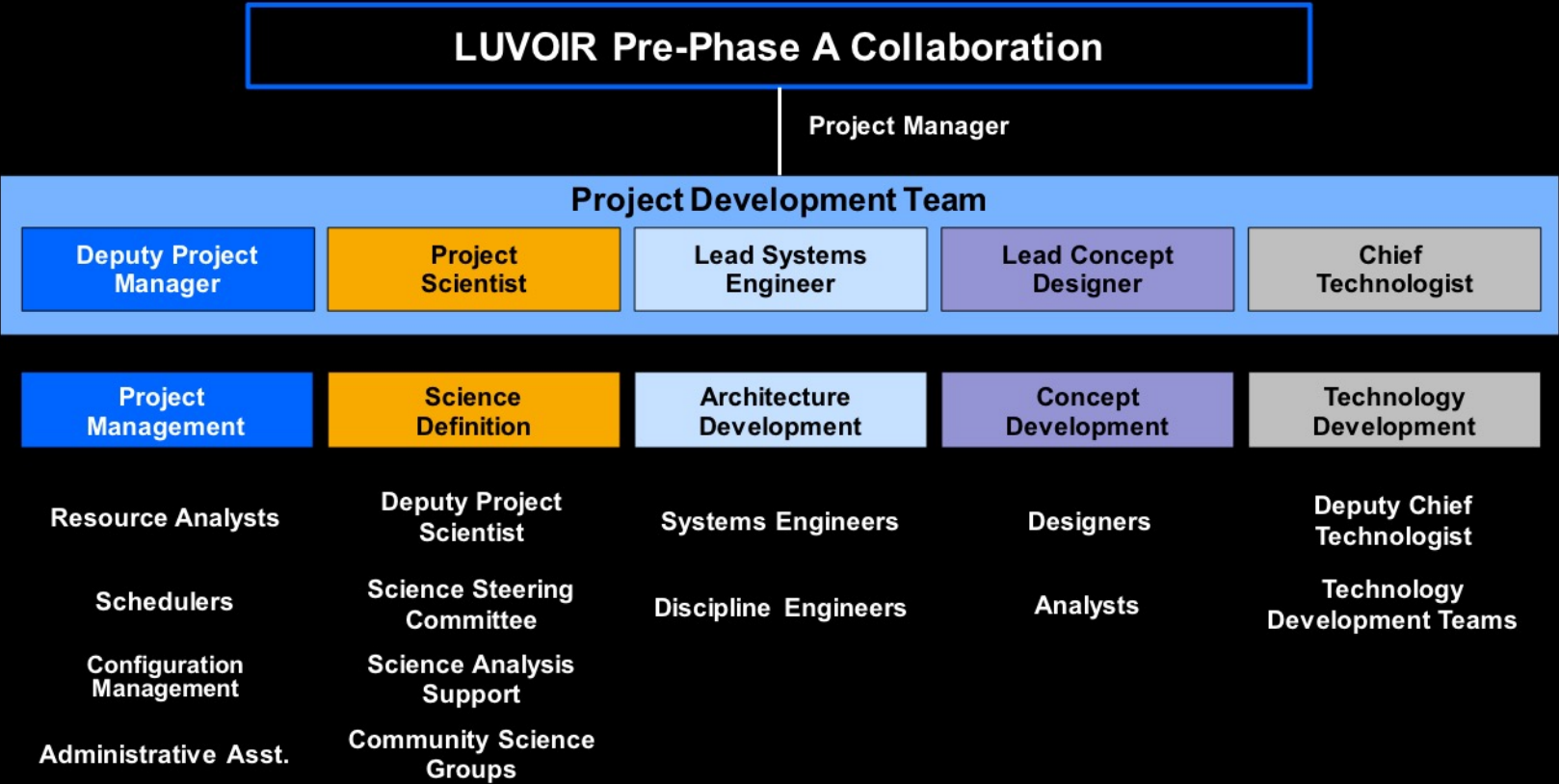


PRE-PHASE A



A successful flagship starts long-term work **before** staffing ramps up...

- Science definition
- Architecture & concept development
- Technology development
- Facility development planning
- Verification & validation planning
- Pathfinder/engineering demonstration planning
- Servicing approach & partnership
- Partner interface development



PRE-PHASE A

A successful flagship starts long-term work **before** staffing ramps up...

Science definition

Architecture & concept
development

Technology development

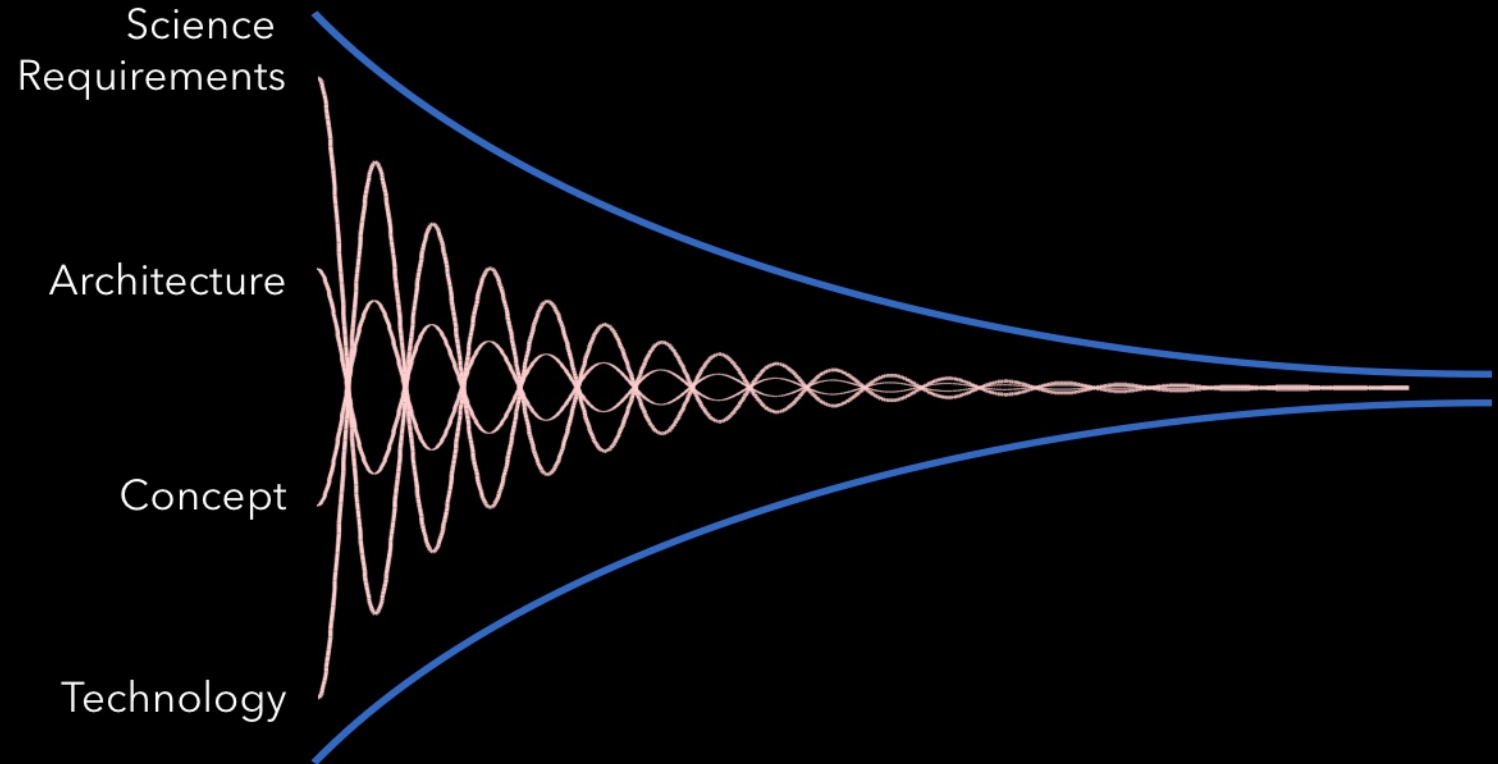
Facility development planning

Verification & validation planning

Pathfinder/engineering
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Servicing approach & partnership

Partner interface development



PRE-PHASE A

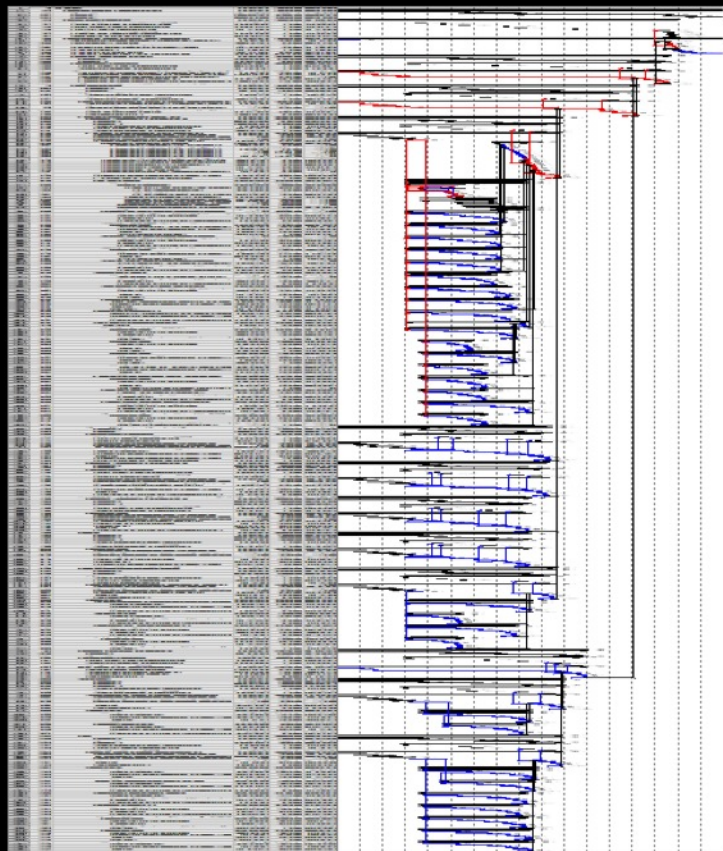


A successful flagship starts long-term work **before** staffing ramps up...

Establishing this work isn't the same as shifting Phase A early

This critical step between the Mission Concept Study and Phase A involves government, science community, industry, and partners to coordinate efforts, refine LUV OIR's definition, and ***prescribe how to proceed in Phase A***

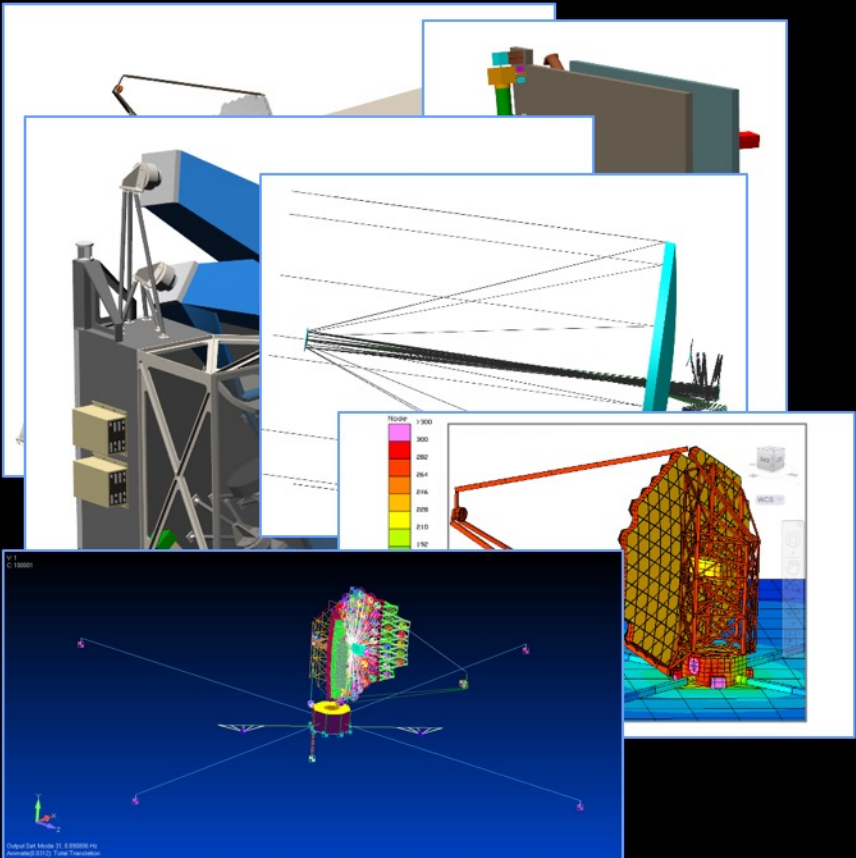
READY TO BEGIN



Mission Implementation Schedule

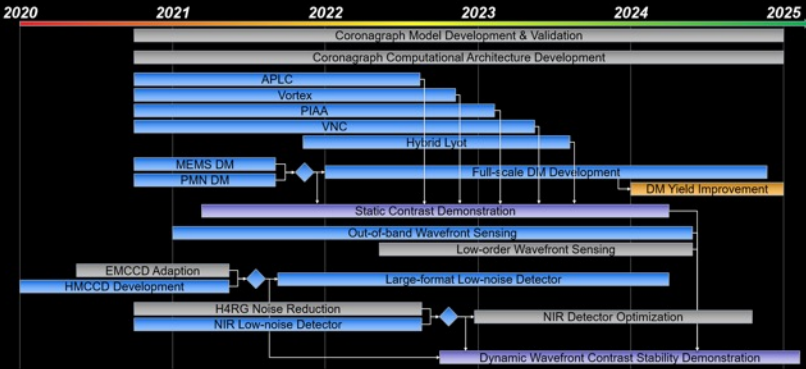
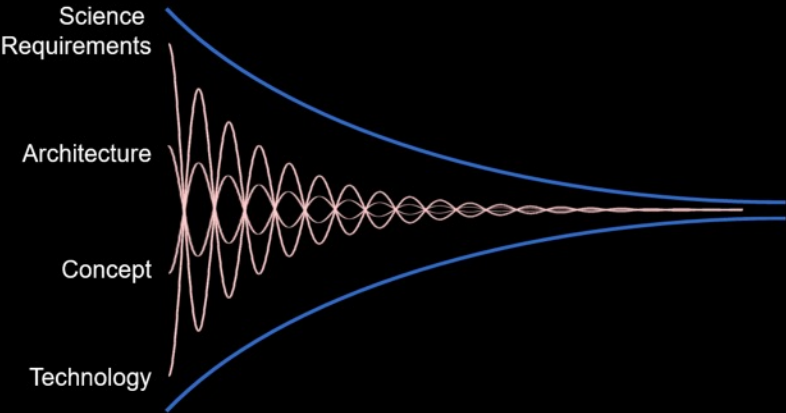
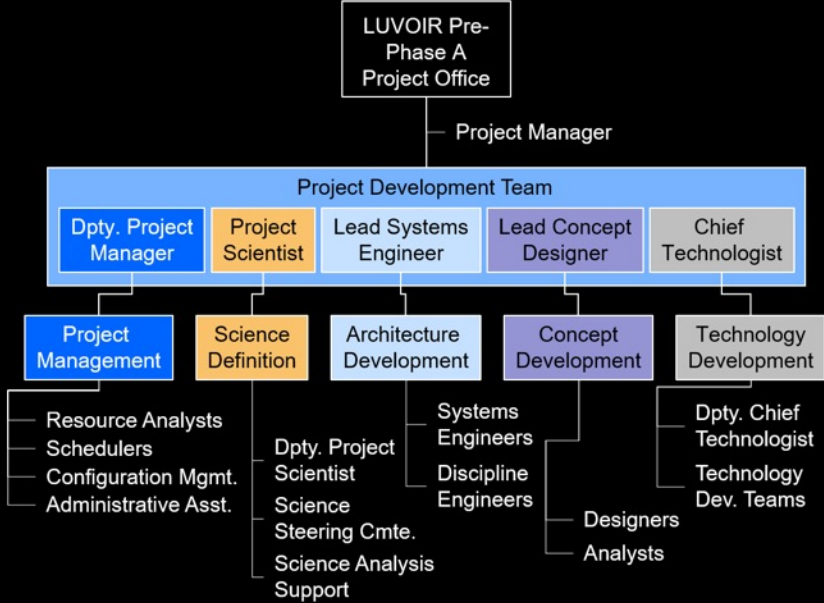
MASTER EQUIPMENT LIST (MEL)											
LEVEL	NAME (Mission or Payload Name)	UNIT MASS	# OF UNITS					FLIGHT HARDWARE MASS			N
	Subassembly / Component	Unit Mass [kg] (CR)	Cold Units	Hot Units	Flight Units	Flight Spares	ETU / Qual Unit	EM / EDU / Proto-type	Total Mass [kg] (CR)	Contingency [%]	Total Mass [kg] w/ Contingency (MEV)
TOTAL FLIGHT HARDWARE											
1	Optical Telescope Assembly A	18498.274	0	1	1				18498.274	24%	24268.857
2	Primary Mirror	10273.981	0	1	1				10273.981	21%	13008.302
3	Primary Mirror Segment Assembly (PMSA) Prescription A	60.860	0	6	6				365.158	19%	451.845
4	Minor Segment Substrate (Prescription A)	24.721	0	1	1				24.721	20%	30.901
4	Edge Sensor Sub-Assembly	0.008	0	6	6				0.096	30%	0.051
5	Edge Sensor Capacitive Plate	0.003	0	1	1				0.003	30%	0.004
5	Edge Sensor Capacitive Plate Mount	0.003	0	1	1				0.003	30%	0.004
4	PMSA Support and Actuation System	26.054	0	1	1				26.054	19%	32.324
5	Composite Flexure (Interface to substrate)	0.000	0	18	18				0.001	20%	0.002
5	Inner Puck	0.716	0	3	3				2.149	20%	2.686
5	Composite Blade Flexure	0.062	0	3	3				0.185	20%	0.231
5	Heater Plate Assembly	6.764	0	1	1				6.764	20%	8.454
6	Diffuser Plate	3.015	0	1	1				3.015	20%	3.769
6	Diffuser Plate Flexures	0.035	0	3	3				0.104	20%	0.130
6	Heater Plate	3.515	0	1	1				3.515	20%	4.394
6	Heater Plate Flexures	0.043	0	3	3				0.129	20%	0.161
5	Aligned Actuator Sub-Assembly	2.350	0	3	3				7.050	18%	8.570
5	Aligned Actuator	2.250	0	1	1				2.250	15%	2.647
6	Piezoelectric Actuator	0.050	0	2	2				0.100	30%	0.143
5	Delta Frame Sub-Assembly	9.905	0	1	1				9.905	20%	12.382
5	Delta Frame	8.681	0	1	1				8.681	20%	10.852
6	Flexure (Delta Frame to PMBS)	0.240	0	3	3				0.720	20%	0.900
6	Primary Mirror Segment Substrs	0.168	0	3	3				0.504	20%	0.630
4	PMSA Thermal System	0.827	0	1	1				0.827	20%	1.034
5	Thermal Strap (MSCE to Heater Plate)	0.460	0	1	1				0.460	20%	0.575
5	Temperature Sensors for Heater Plate Control	0.000	4	4	8				0.002	15%	0.003
5	Temperature Sensors for Heater Plate Telemetry	0.000	4	4	8				0.002	15%	0.003
5	PMSA Heaters	0.014	0	4	4				0.056	20%	0.070
5	Paint	0.047	0	1	1				0.047	20%	0.059
5	Epoxy and Adhesive	0.050	0	1	1				0.050	20%	0.061
5	Indium Foil	0.001	0	1	1				0.001	20%	0.001
5	Aluminum Foil Tape	0.208	0	1	1				0.208	20%	0.260

Master Equipment Lists



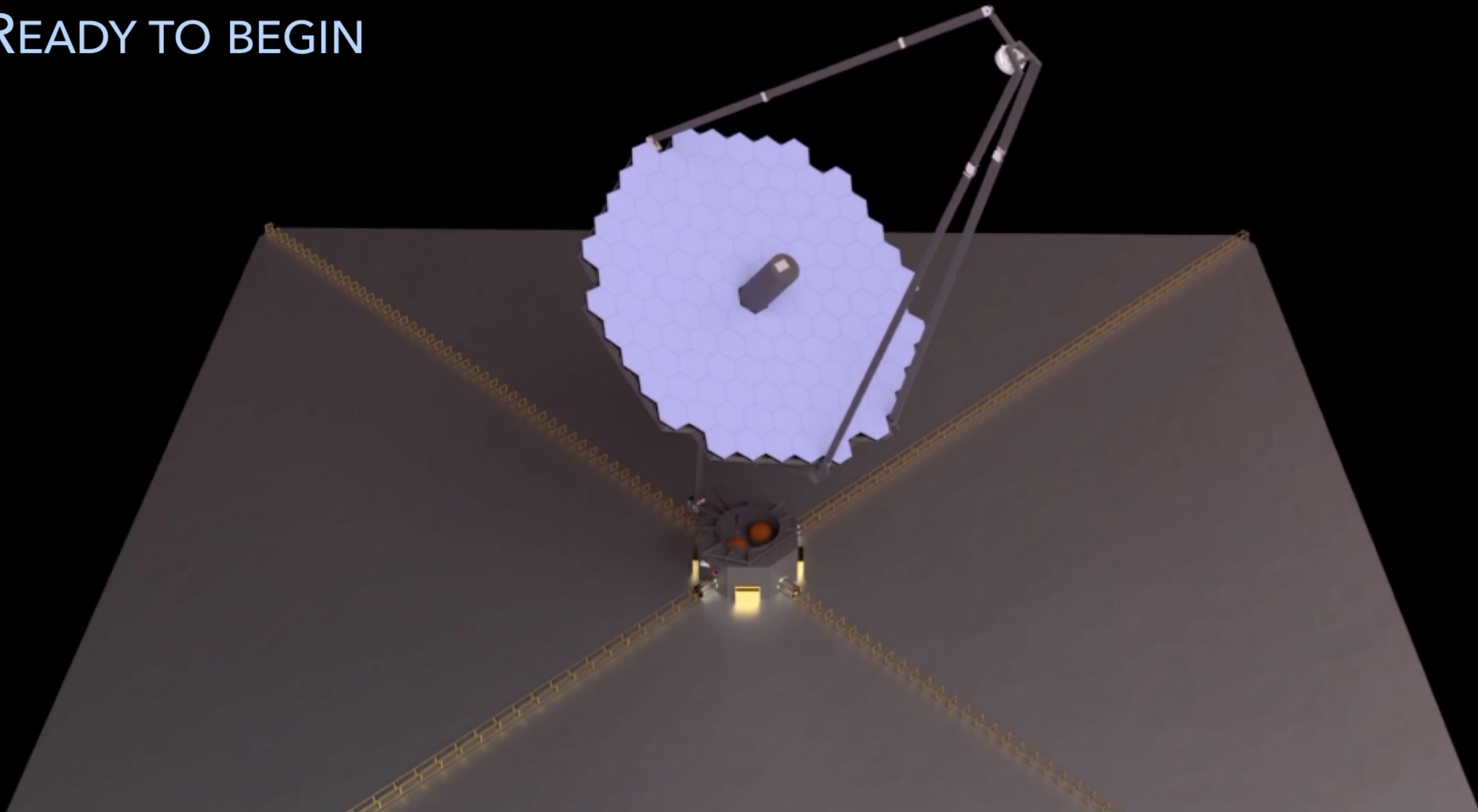
Detailed Models

READY TO BEGIN



Plans to proceed

READY TO BEGIN



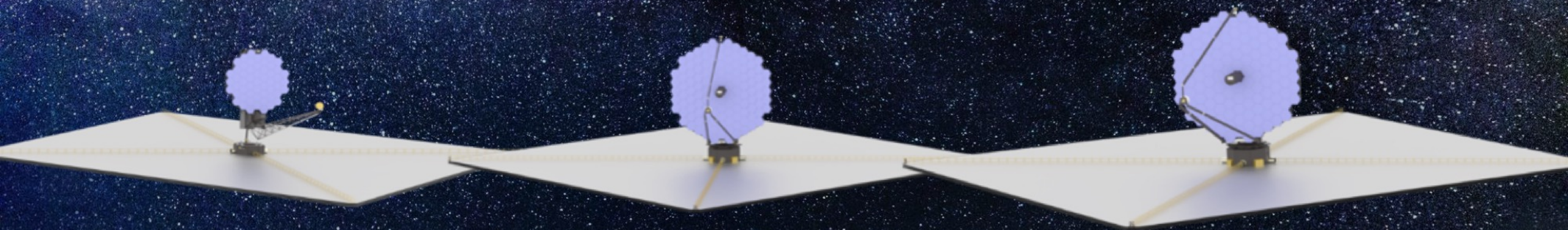


CLOSING REMARKS

LUVOIR IS NOT A NUMBER. LUVOIR IS A VISION



A community driven, UVOIR observatory able to perform direct spectroscopy of dozens of exoEarth candidates, high-fidelity Solar System remote sensing, and transformative astrophysics

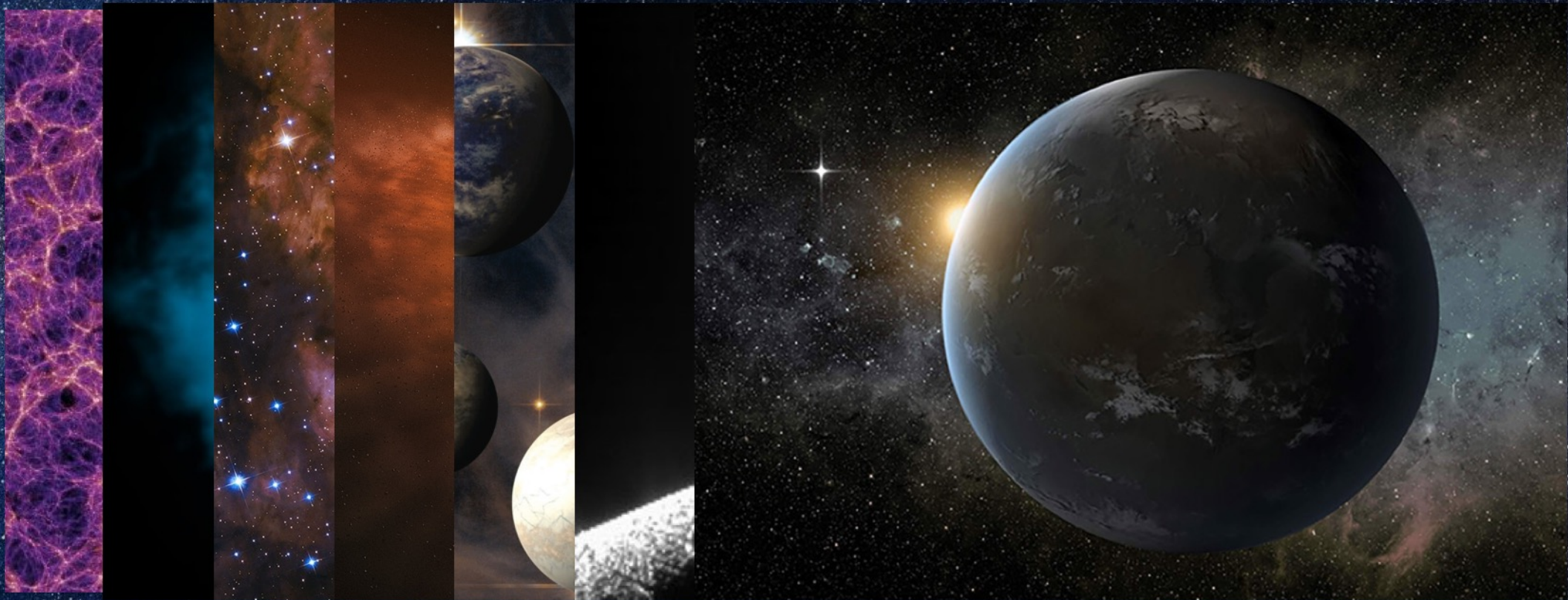


LUVOIR-B

Other LUVOIR?

LUVOIR-A

TELLING THE STORY OF LIFE IN THE UNIVERSE



SCIENCE LEADS

Build for what the science demands

Habitable Planet Candidate Survey

Search for Biosignatures

Solar System Ocean Worlds

Comparative Atmospheres

Planetary System Formation

Solar System Small Bodies

Smallest Scales Across Cosmic Time

Dark Matter via Astrometry

Investigating Reionization

Cycles of Matter

Galaxy Assembly

Stars and Galactic Feedback



SCIENCE LEADS

Build for what the science
demands

Build for the science that is still
unknown

Scientific Uses of the Large Space Telescope

AD HOC COMMITTEE ON THE LARGE SPACE TELESCOPE
SPACE SCIENCE BOARD
NATIONAL ACADEMY OF SCIENCES–NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C.
1969

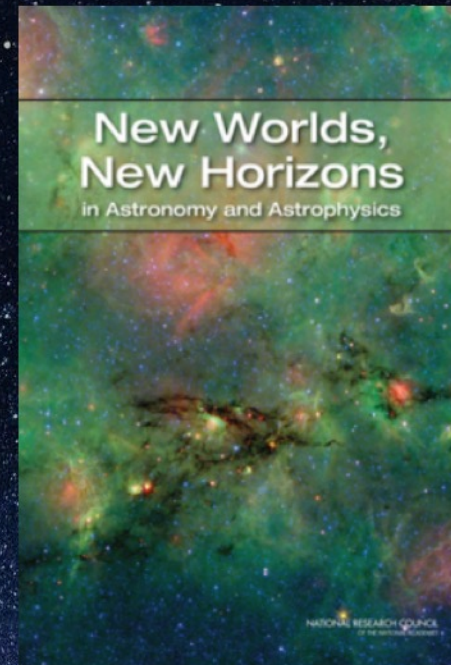


SCIENCE LEADS

Build for what the science demands

Build for the science that is still unknown

Build for the whole community



PROCEED WISELY

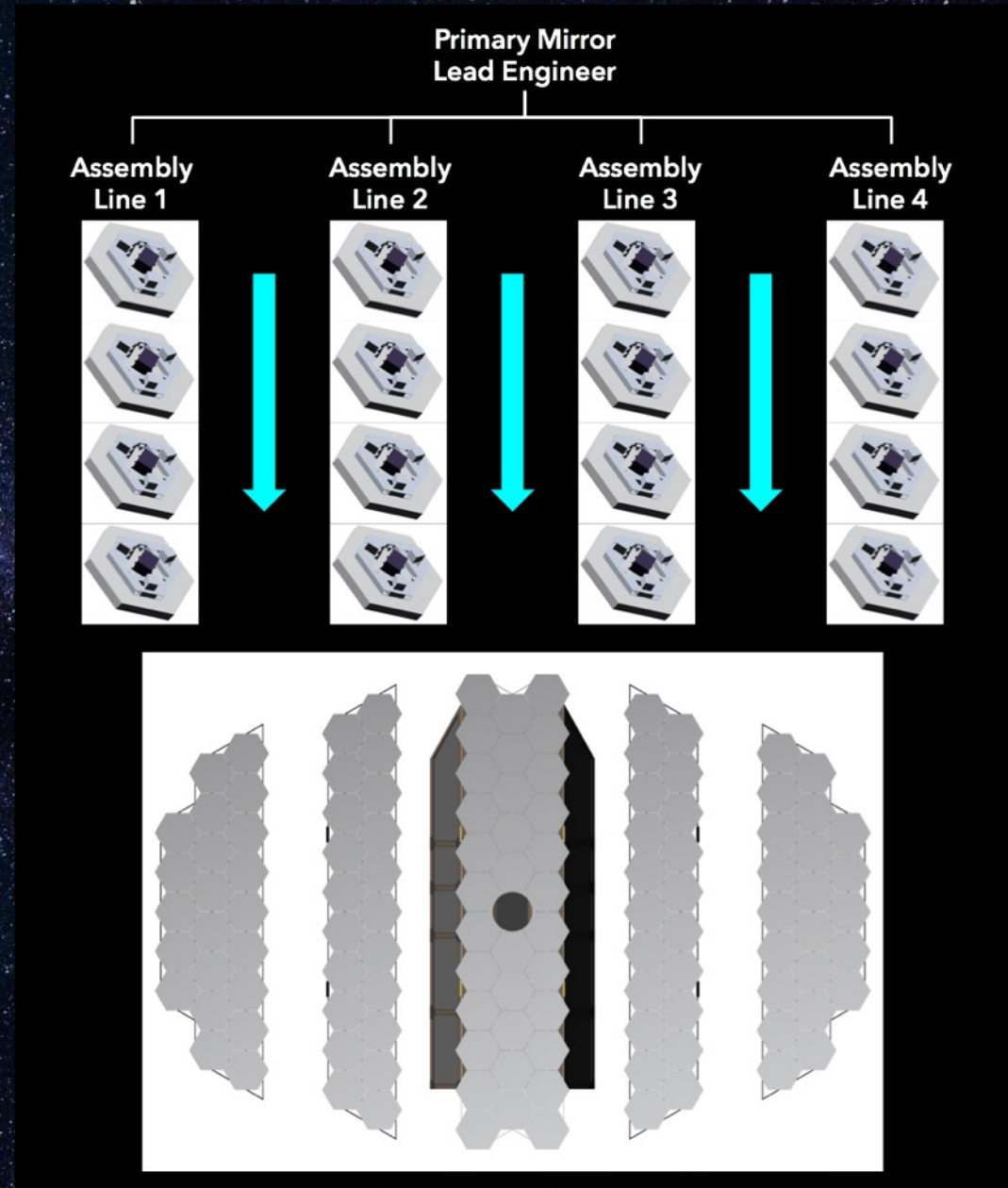
Plan carefully



PROCEED WISELY

Plan carefully

Build optimally



PROCEED WISELY

Plan carefully

Build optimally

Adapt strategically



Challenges and Potential Solutions to Develop and Fund NASA Flagship Missions

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Abstract—Large, strategic “Flagship” missions have unique characteristics that lead to challenging developmental difficulties for the National Aeronautics and Space Administration (NASA). Missions such as the Hubble Space Telescope (HST), James Webb Space Telescope (JWST), and

of these definitions as they are the most visible because of their potential for scientific discovery and expense and are also the finest, largest, and most important of NASA’s science missions. NASA Flagship missions are unprecedented in the science that they enable as they provide

Lessons We Learned Designing and Building the Chandra Telescope

Jonathan Arenberg (1) and Gary Matthews (2)
&

C. Atkinson (1), L. Cohen (4), C. Golisano, K. Havey, K. Hefner (3), C. Jones (4), J. Kegley (3), P. Knollenberg (1), T. Lavoie (3), J. Oliver (3), P. Plucinsky (4), H. Tananbaum (4), S. Texter (1) and M. Weisskopf (3)

(1) Northrop Grumman Aerospace Systems, One Space Park, Redondo Beach CA 90278, USA

(2) Excelsis, 1447 St. Paul Street, Rochester NY, 14606-0488, USA

(3) NASA Marshall Space Flight Center, Huntsville AL 35816 USA

Breaking the cost curve: applying lessons learned from the James Webb Space telescope development to build more cost-effective large space telescopes in the future

Lee Feinberg^a, Jonathan Arenberg^b, Dave Yanatsis^c, Paul Lightsey^d

^aNASA Goddard Space Flight Center, Greenbelt, MD; ^bNorthrop Grumman Aerospace Systems, Redondo Beach CA; ^cHarris Corporation, Rochester, USA; ^dBall Aerospace, Boulder, Colorado USA;

ABSTRACT

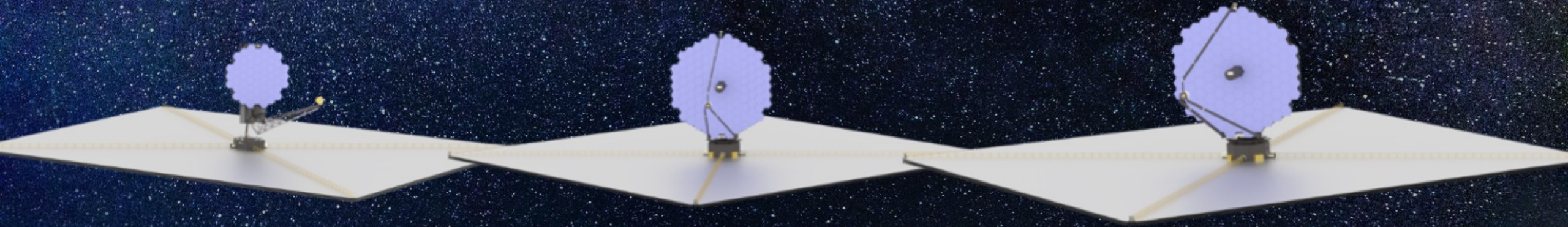
This paper looks at the key programmatic and technical drivers of the James Webb Space Telescope and assesses ways to building more cost-effective telescopes in the future. The paper evaluates the top level programmatics for JWST along with the key technical drivers from design through integration and testing. Actual data and metrics from JWST are studied to identify what ultimately drove cost on JWST. Finally, the paper assesses areas where applying lessons learned can reduce costs on future observatories and will provide better insights into critical areas to optimize for cost.

Keywords: ATLAST, LUVOIR, Exoplanet, HDST, Space Telescope

1. INTRODUCTION

"The most effective way to do it, is to do it."

Amelia Earhart



THE PATH FORWARD

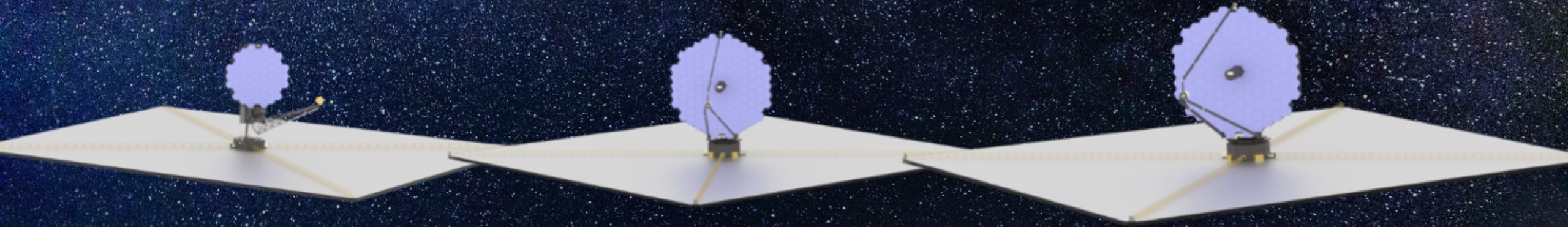


Advance the technology

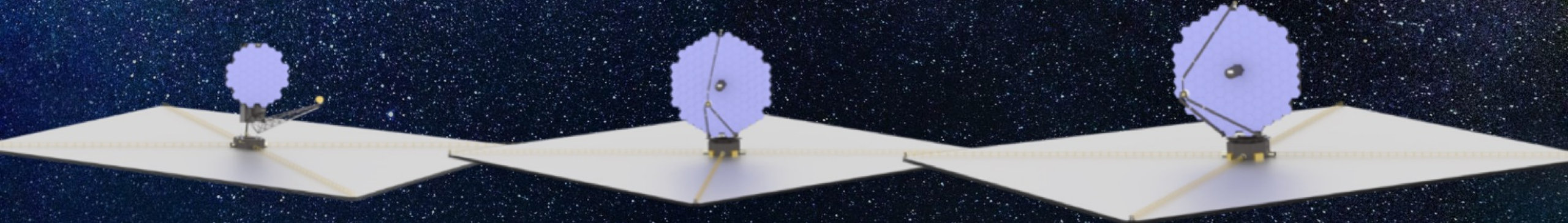
Incorporate the independent costing, TRACE, and Decadal inputs

Perform the trade studies

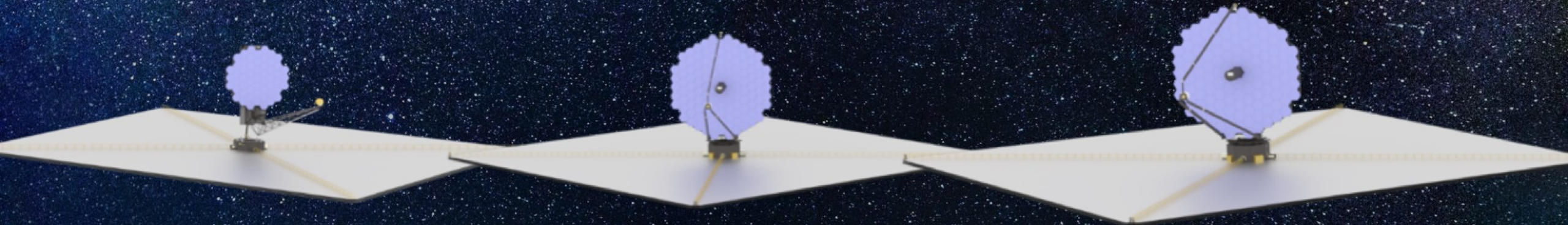
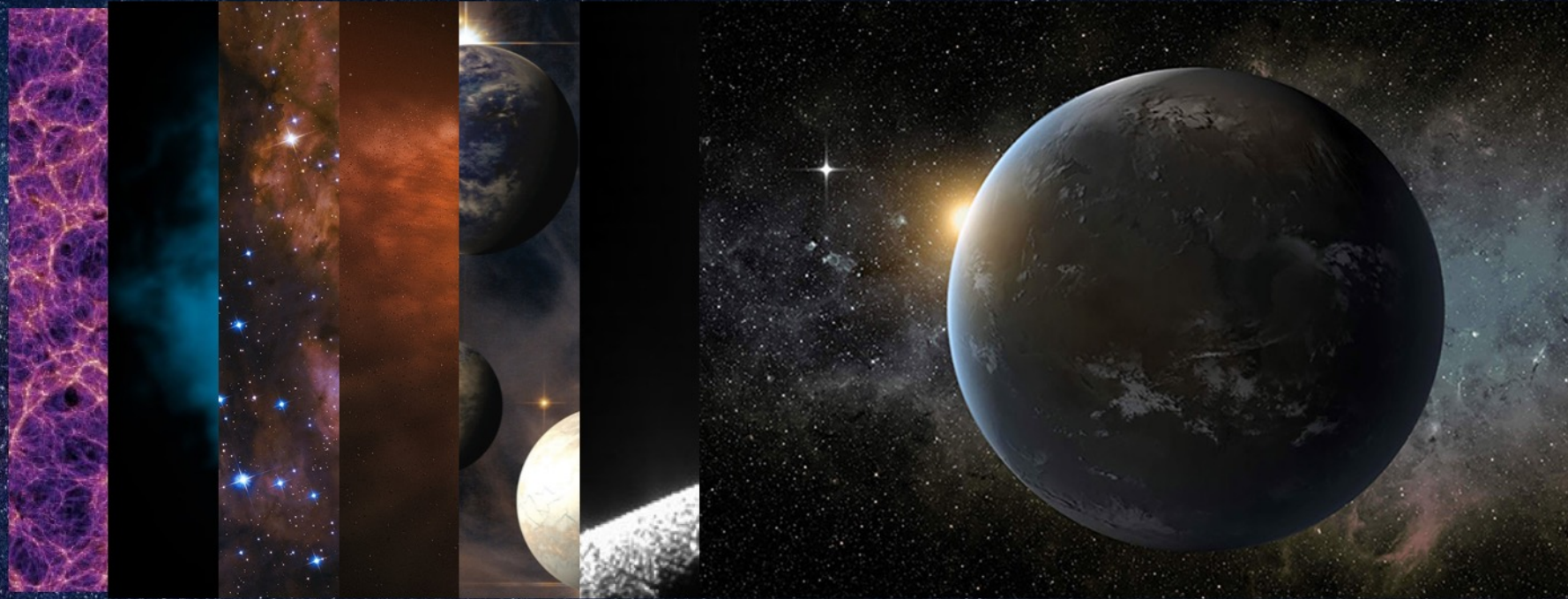
Begin the steps to translate The Vision into The Mission



LUVOIR IS A TEAM



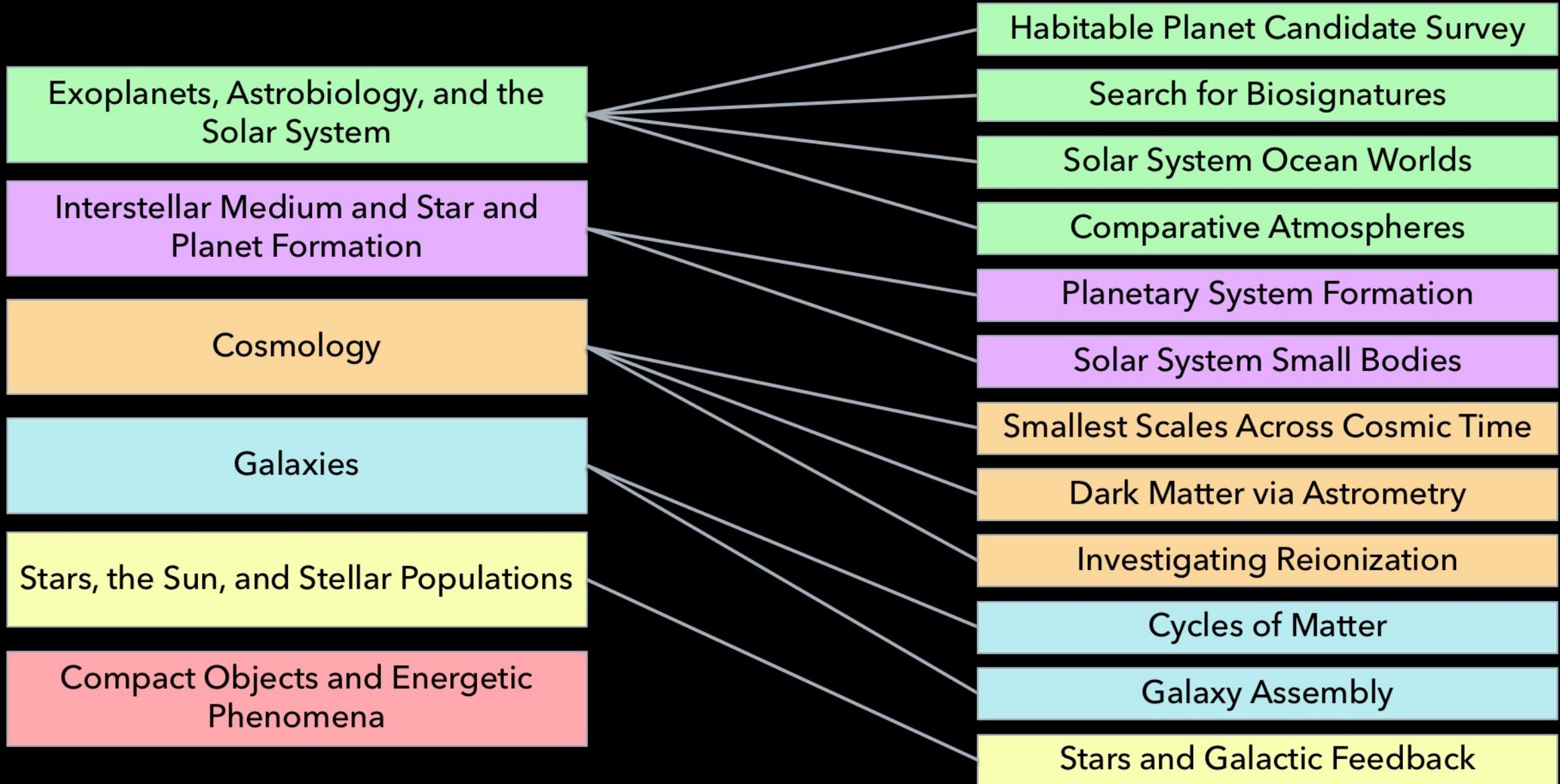
THANKS



BACKUP SLIDES

ASTRO2020 SCIENCE PANELS

SIGNATURE SCIENCE CASES



WHAT MEASUREMENTS AND OBSERVATIONS ARE NEEDED?



Is the star promising?

1. Use precursor information to establish target list

Is this a planet?

2. Multi-color point-source photometry and proper motion

Is the planet in the habitable zone?

3. Constrain orbits

Is there water?

4. Search for atmospheric water

What is the star like?

5. Characterize the star's activity level

How massive is the planet?

6. Determine planet masses

Are there signs of life?

7. Search for biosignatures & constrain H₂O abundance

Are the signs of life robust?

8. Check biosignatures aren't false positives

What is the atmospheric context?
Are there other biosignatures?

9. Extend spectrum - added features

How does the planet vary over its orbit?
(e.g. seasons)

10. Revisit

Signature

Science

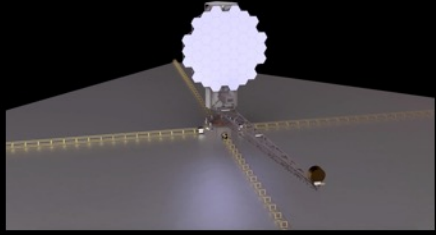
Case #1:

Finding habitable planet candidates

Signature Science Case #2

Searching for biosignatures and confirming habitability

HOW MANY CANDIDATES TO GUARANTEE AN EXO EARTH?

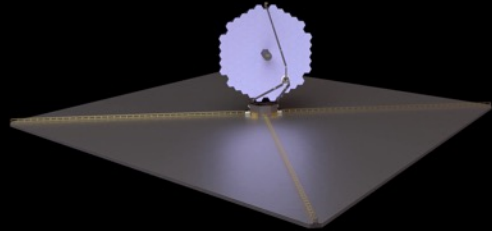


LUVOIR-B
8-m



28 candidates

Discover 1 habitable planet if only 10% are habitable



LUVOIR-A
15-m



54 candidates

Discover 1 habitable planet if only 5% are habitable

HOW DO HABITABLE PLANET CANDIDATE YIELDS SCALE?



Altruistic Yield Optimization (AYO)

Stark et al. (2014, 2015)

$$Y \propto D^{1.97} (IWA)^{-0.98} (\eta_{Earth})^{0.96} (SNR)^{-0.76} A^{0.65} T^{0.35} \\ (PSF)^{-0.33} (Time)^{0.32} \Delta\lambda^{0.30} x^{-0.17} \xi^{-0.10}$$

Instrumental, astrophysical, & observational

D = telescope diameter

IWA = coronagraph inner working angle

η_{Earth} = occurrence rate of habitable planet candidates

SNR = required signal-to-noise for broadband detection

A = geometric albedo of planet

T = end-to-end facility throughput

PSF = areal broadening of planet's PSF

Time = total exposure time for survey

$\Delta\lambda$ = instantaneous bandpass for detection

x = median V band surface brightness of exozodi

ξ = raw contrast in detection region at 550 nm

IMPACT OF EXOZODIACAL DUST ON YIELDS

$$Y \propto x^{-0.17}$$

Astrophysical parameter

x = median V band surface brightness
of exozodiacal dust

(distribution based on LBTI survey)

x = observed distribution

54

$x' = 10 x$

37

10x increase in x

1.5x decrease in yield

ESTIMATED HABITABLE CANDIDATE SPECTRAL YIELDS



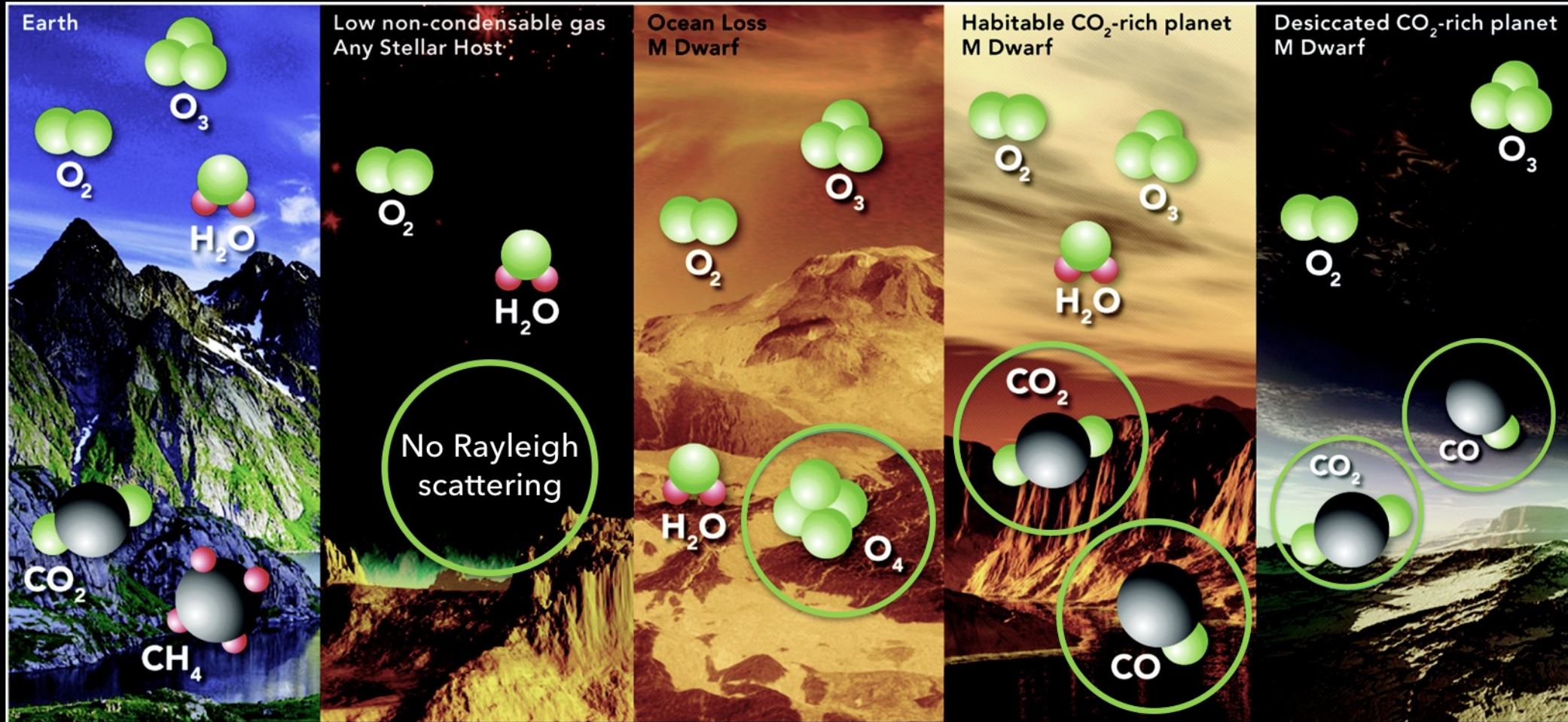
Measurements / Observations	SNR	LUV O I R-A		LUV O I R-B	
		6 month	12 month	6 month	12 month
Hab. planet candidates		54^{+61}_{-34}		28^{+30}_{-17}	
Orbits		54		28	
Host star spectra		54		28	
Mass measurements		54		28	
Spectra from 855–1045 nm (water)	5	54		28	
Spectra from 740–890 nm (O ₂ A band)	8.5	36	44	18	23
Spectra from 290–1030 nm (UV-Vis)	8.5	23	30	11	15
Spectra from 290–1460 nm	8.5	18	24	8	11
Spectra from 240–1770 nm	8.5	11	15	5	6
Spectra from 240–2000 nm	8.5	8	12	4	5
Spectra from 200–2000 nm	8.5	5	8	2	2

WHAT IS A BIOSIGNATURE? CONTEXT MATTERS

Sun-like star

Any star

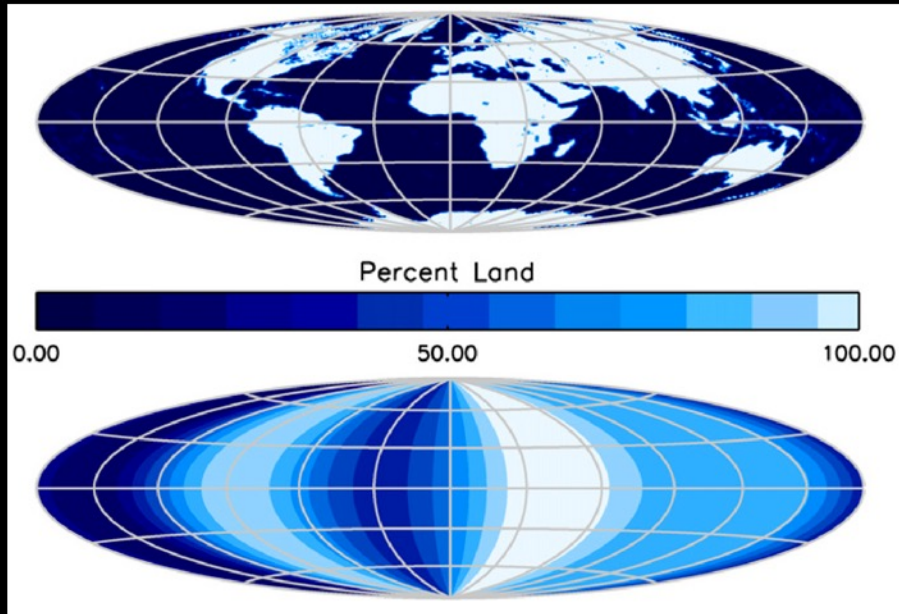
M dwarfs



Meadows et al. (2017)

METHODS FOR DIRECTLY DETECTING OCEANS

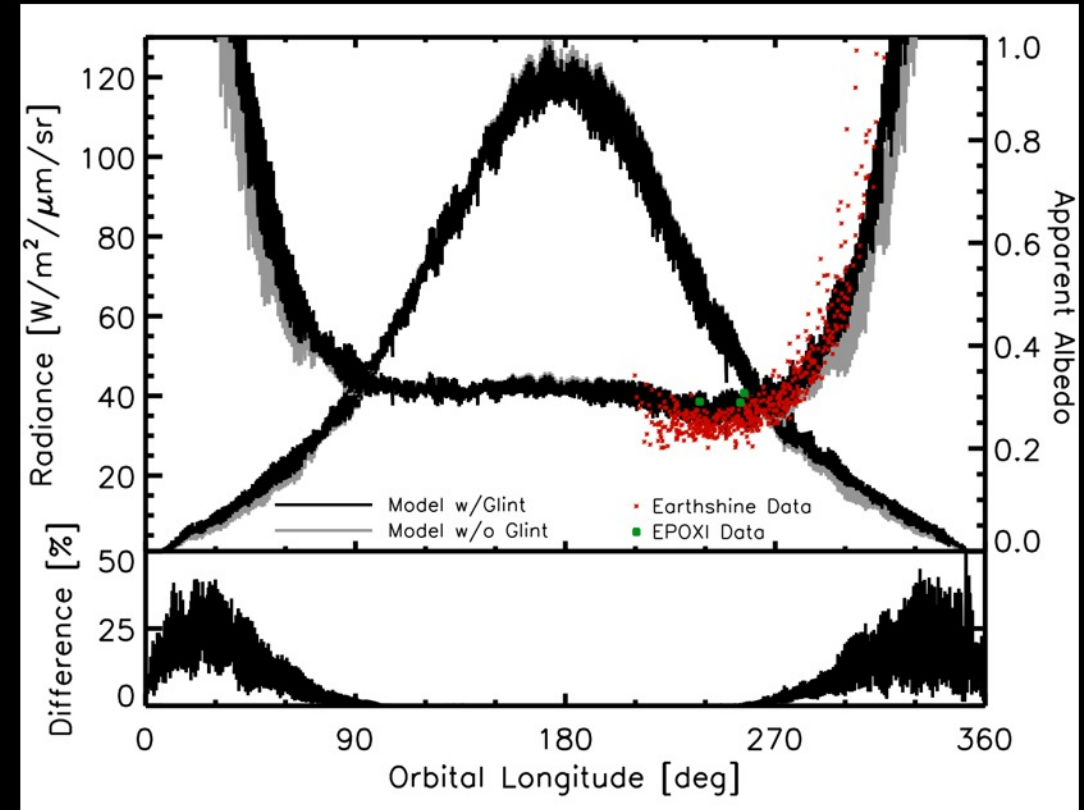
Longitudinal Surface Mapping



Cowan et al. 2009
Fujii & Kawahara 2012
Cowan & Strait 2013
Fujii et al. 2017, in prep

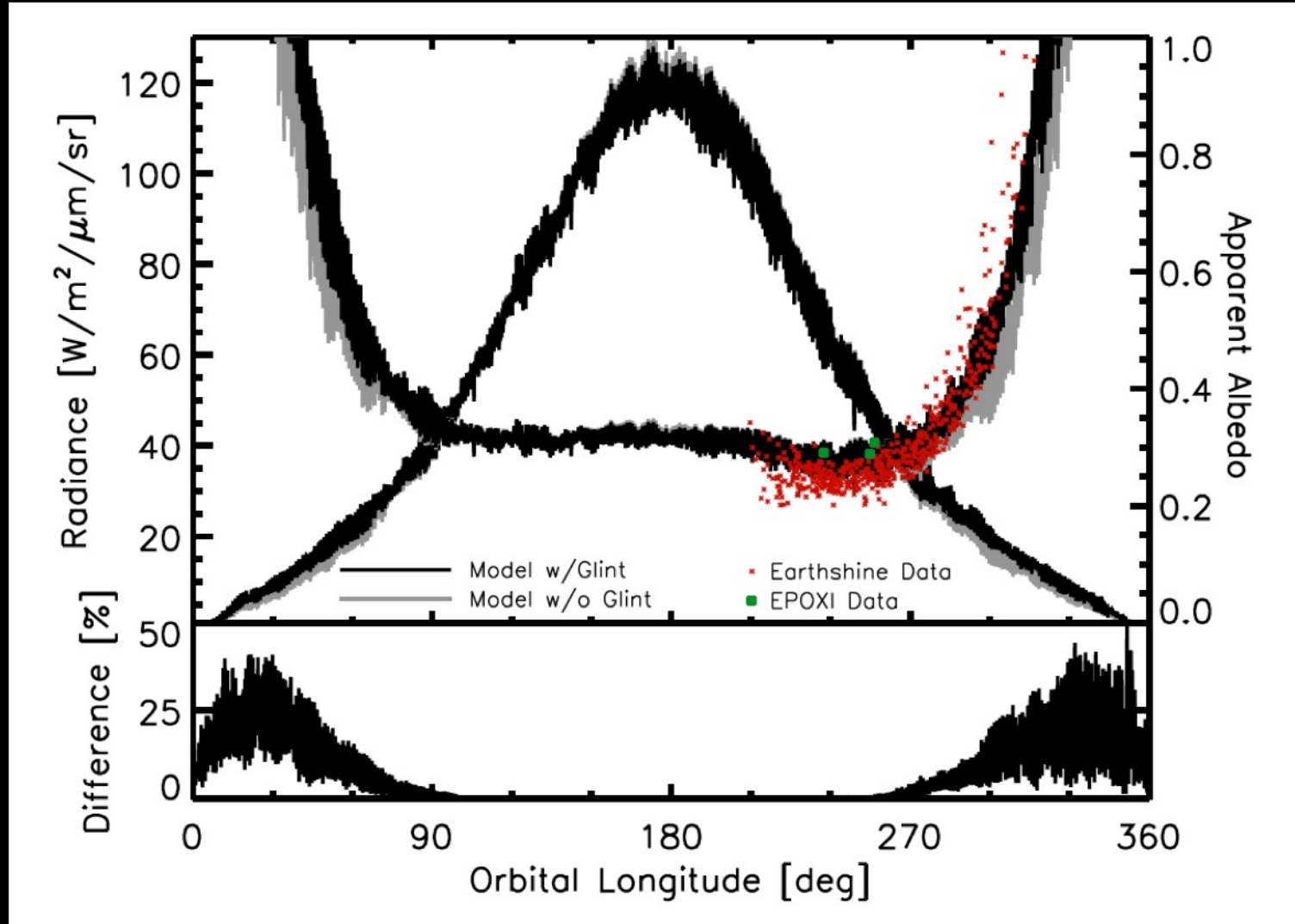
+

Ocean Glint



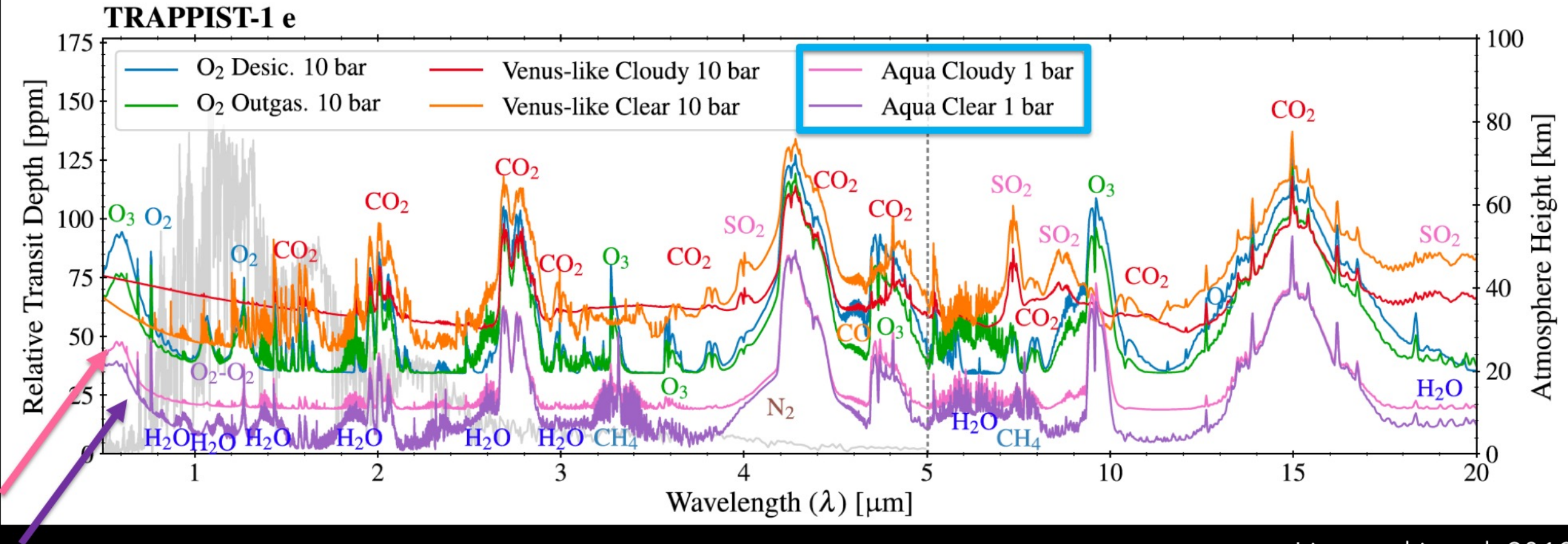
Robinson et al. 2010

DETECTING GLINT



Robinson et al. 2010

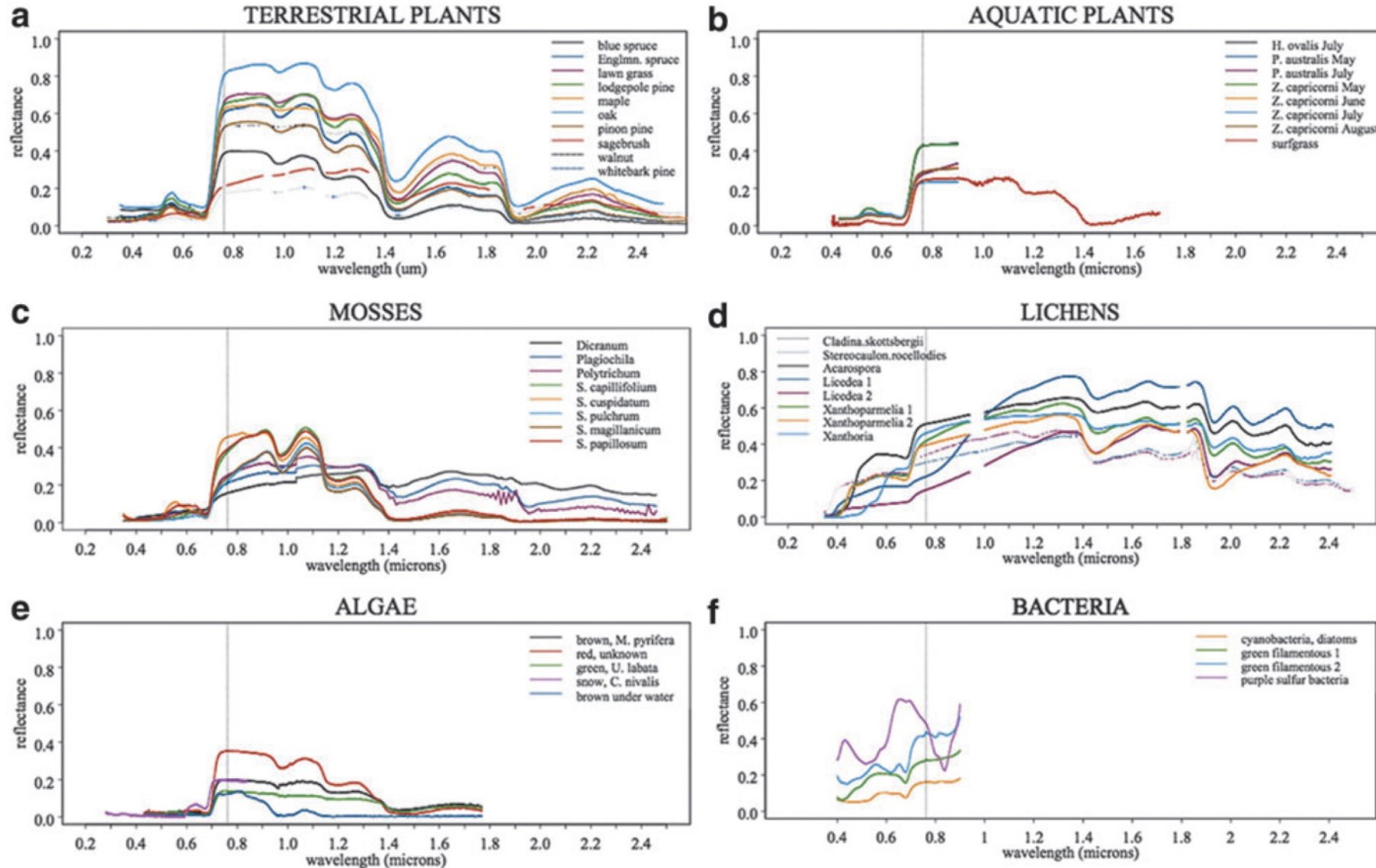
DIFFICULTY OF DETECTING WATER IN TRANSIT



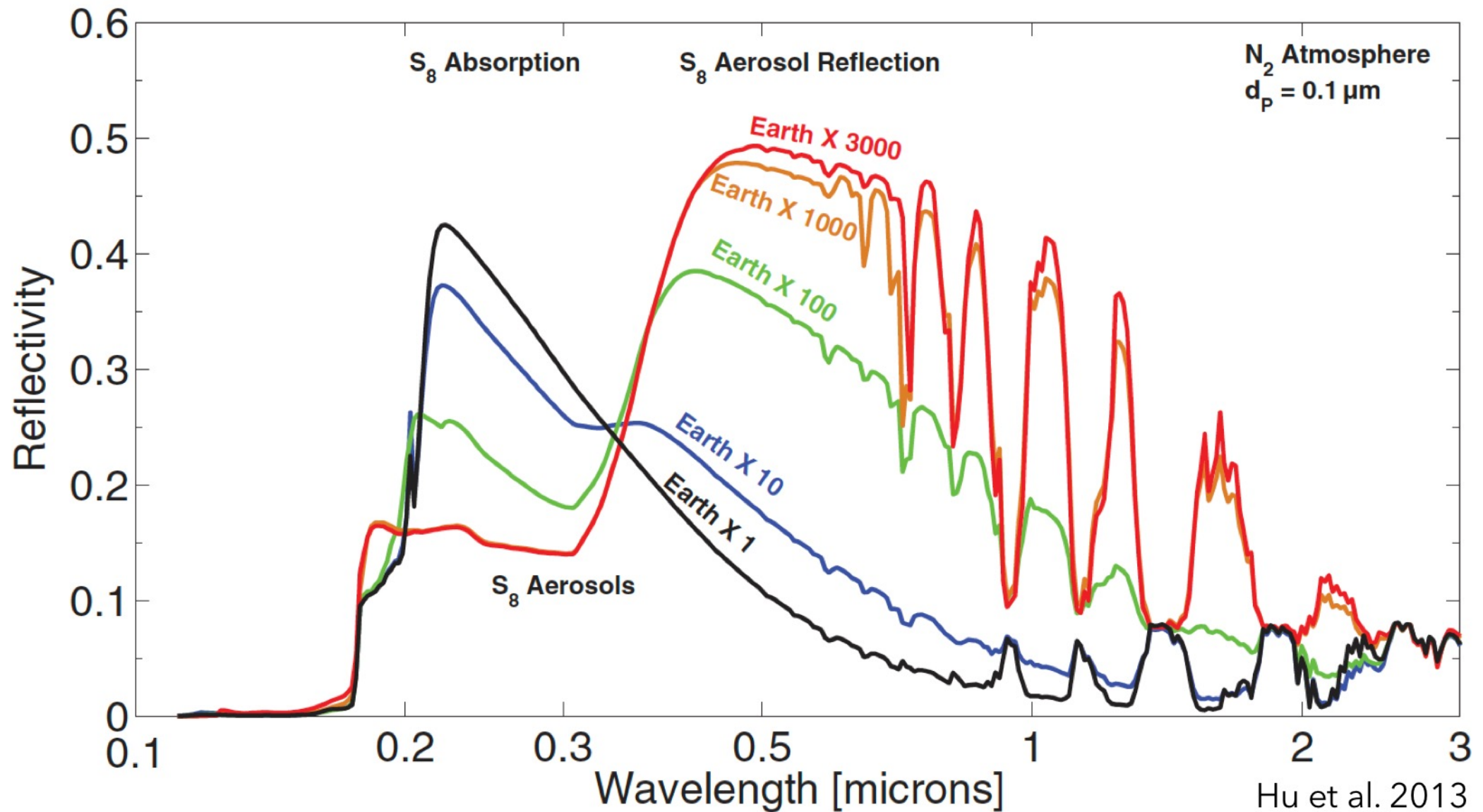
Lincowski et al. 2018

SURFACE REFLECTANCE BIOSIGNATURES

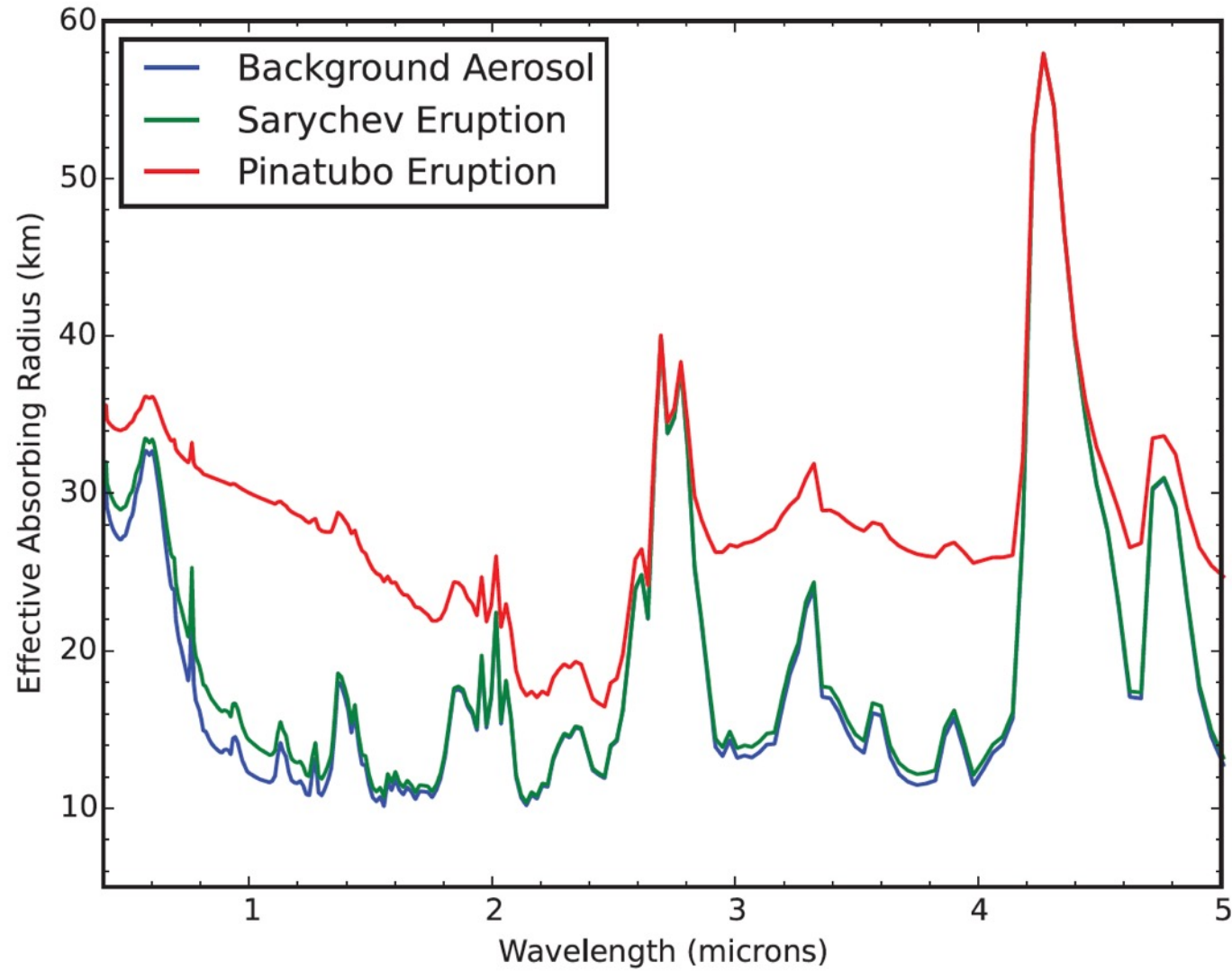
Schwieterman et al. 2018



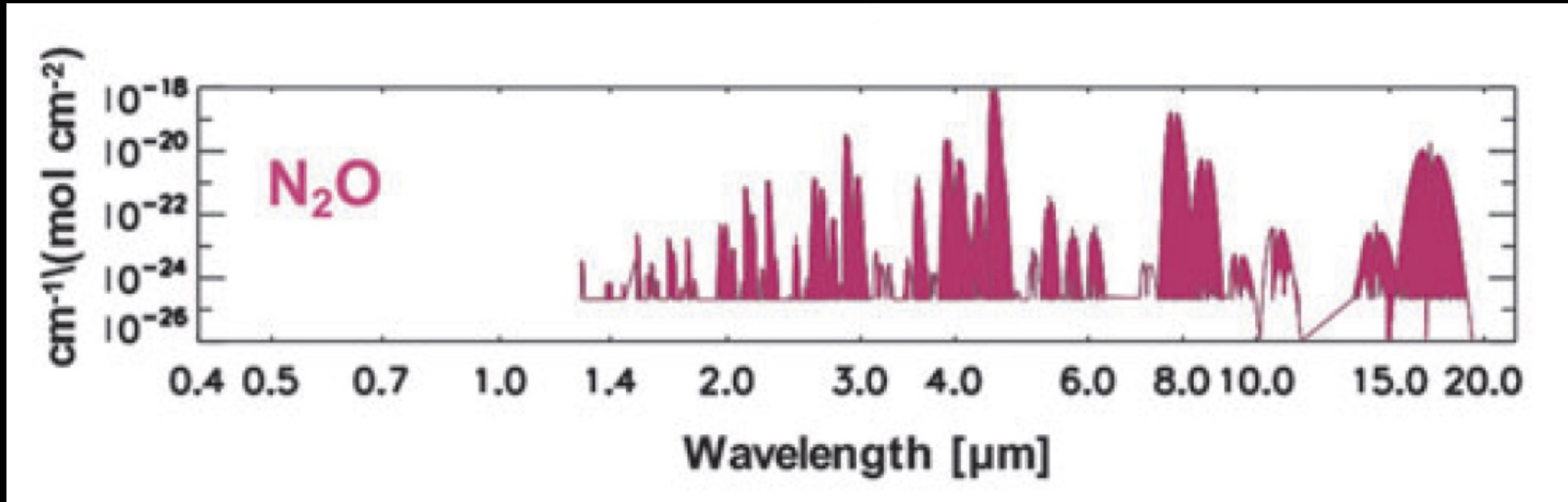
DETECTING VOLCANIC ACTIVITY



DETECTING VOLCANIC ACTIVITY

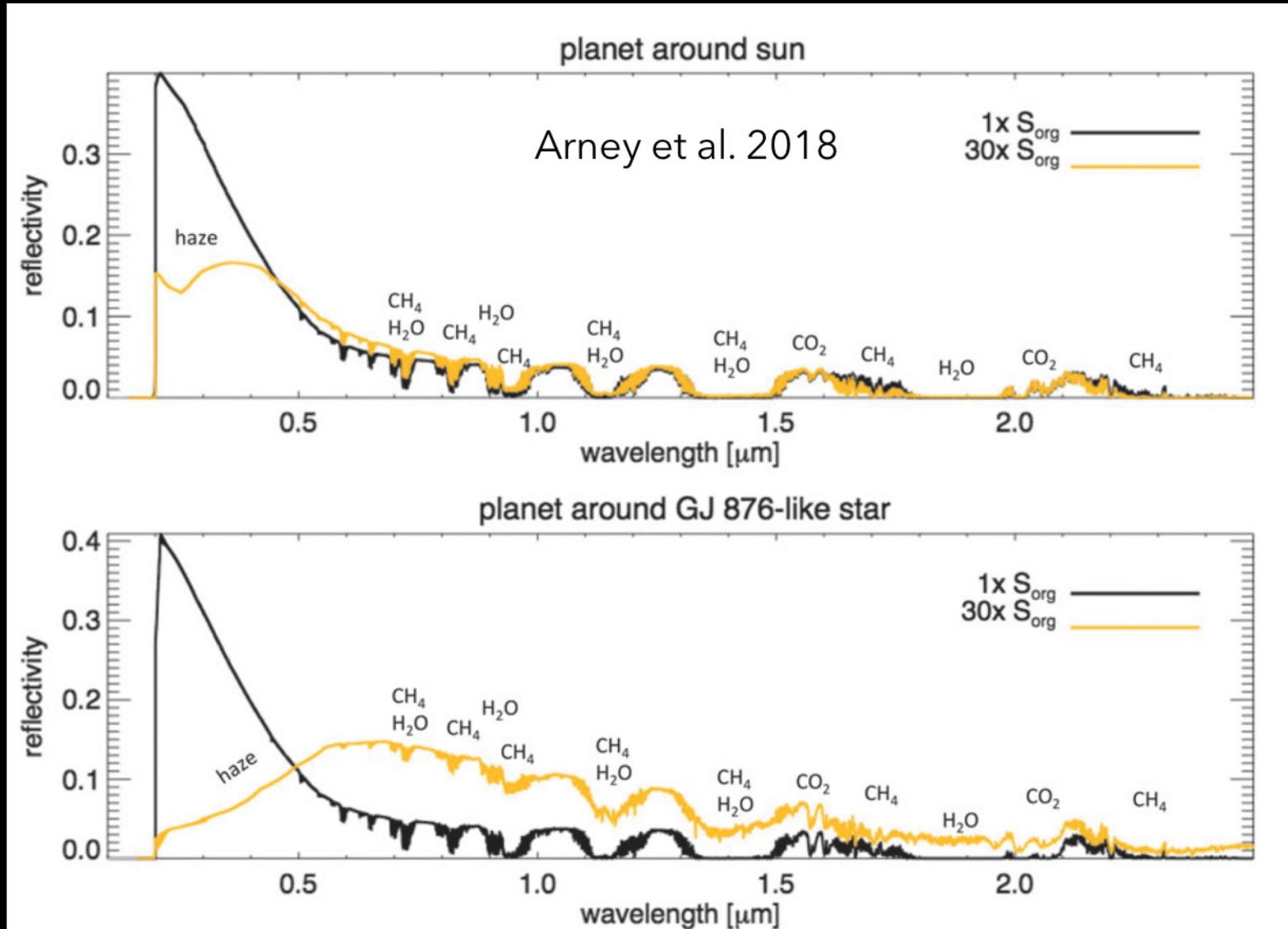


OTHER BIOSIGNATURES – N_2O IN THE PROTEROZOIC



Schwieterman et al. 2018

OTHER BIOSIGNATURES – HAZES AT ANOMALOUSLY LOW CH_4/CO_2 RATIOS AS INDICATORS OF OTHER ORGANICS

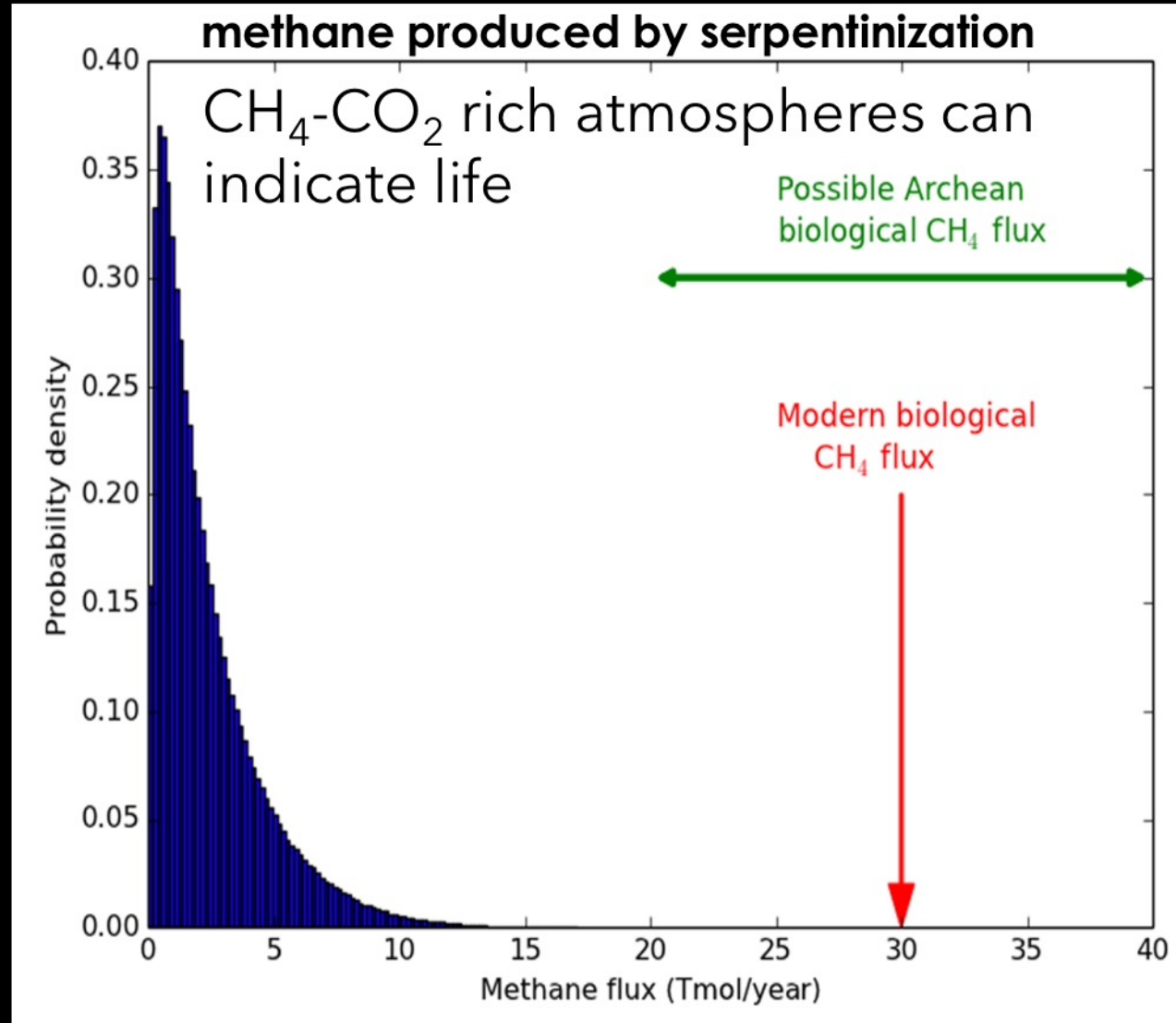


WHAT ABOUT NOVEL BIOSIGNATURES & BIOSIGNATURES YOU HAVEN'T THOUGHT OF?

Wide wavelength range maximizes chances of finding unexpected features (high risk, high reward)

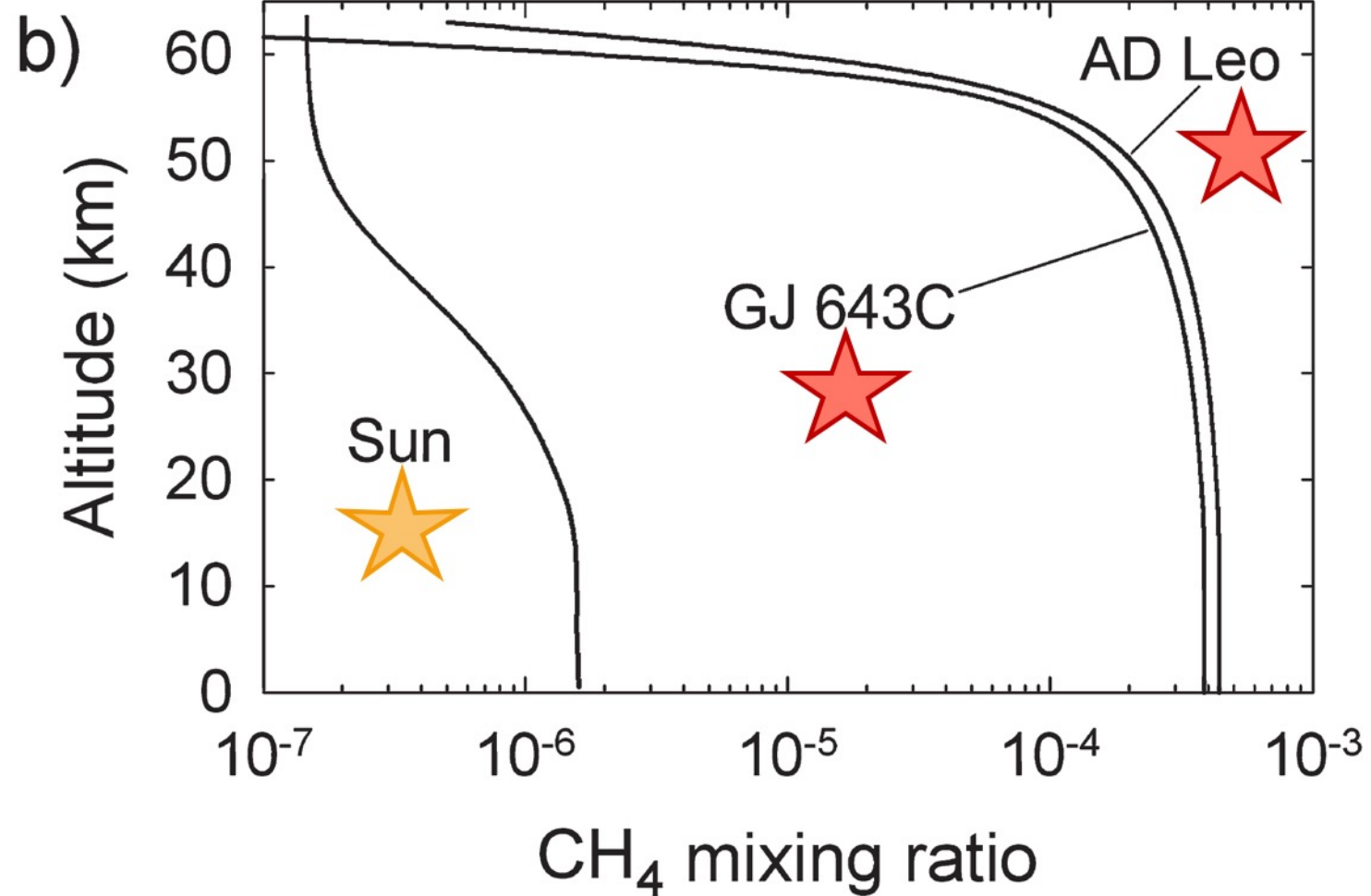
But we MUST be able to also target our best-studied biosignatures (O_2 , O_3 , CH_4) to maximize chance of success (low risk, high reward)

METHANE AS A BIOSIGNATURE

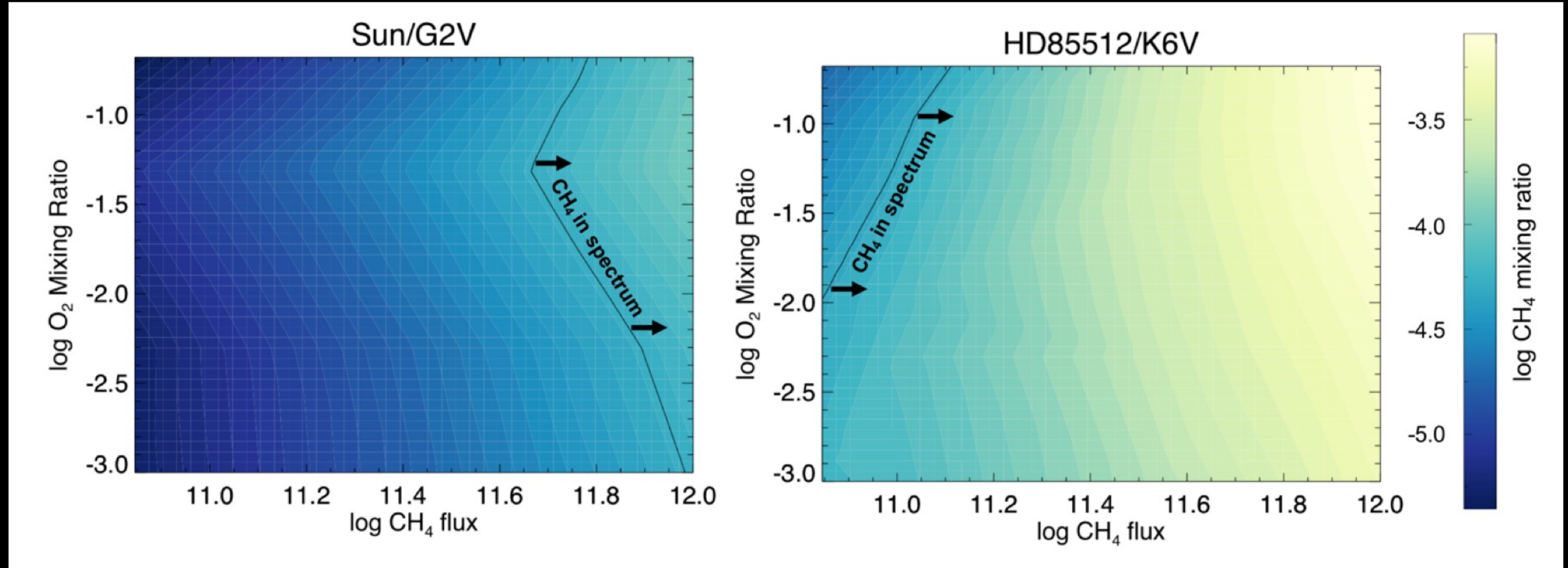


Krissansen-Totton et al. 2018

METHANE IN OTHER STELLAR CONTEXTS – M DWARFS



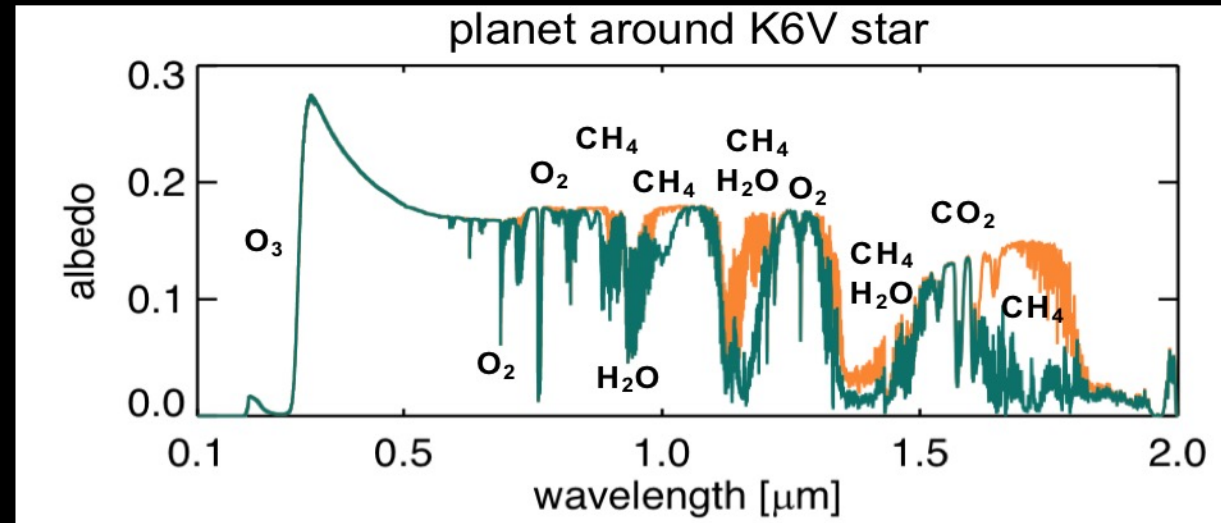
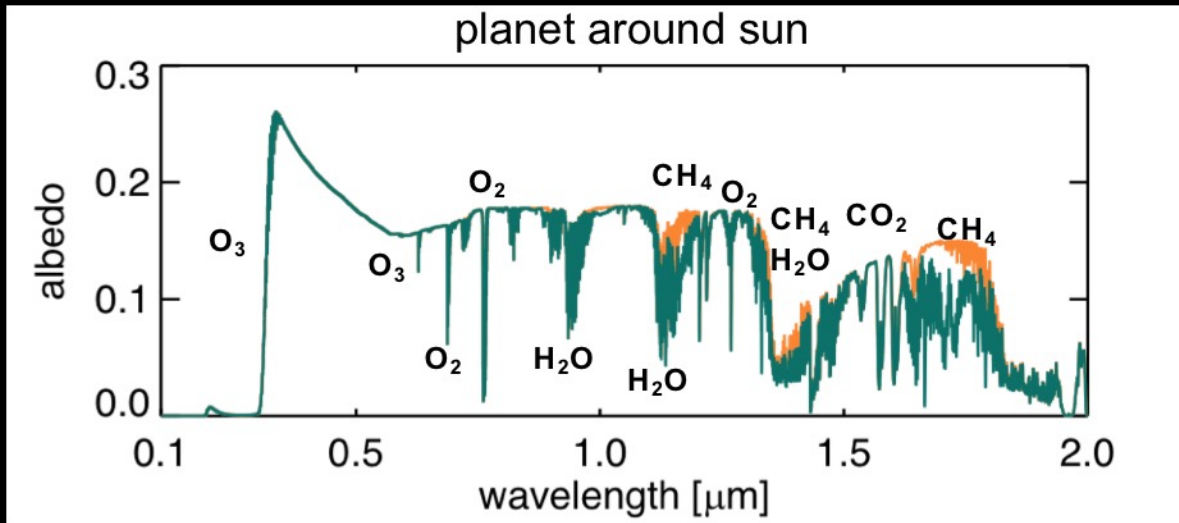
METHANE IN OTHER STELLAR CONTEXTS – K DWARFS



Planets around a K6V star could accumulate ~an order of magnitude more atmospheric methane compared to equivalent planets around the sun

METHANE IN OTHER STELLAR CONTEXTS – K DWARFS

All gases included
Methane excluded

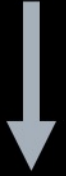


Methane AND oxygen is readily detectable for the planet around the K dwarf

Arney 2019

IT'S NOT JUST THE GASES

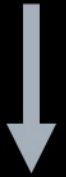
gas concentrations



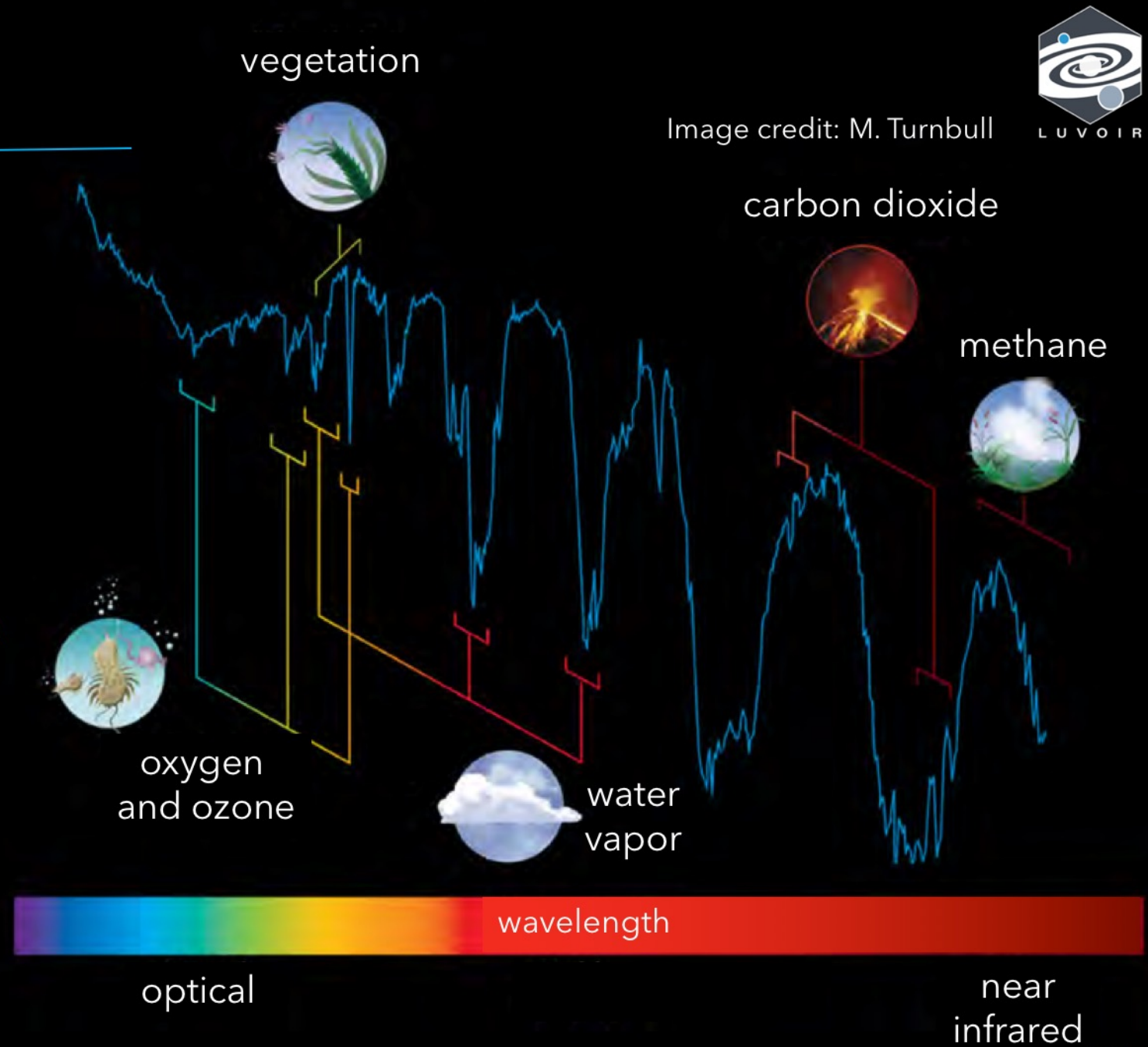
atmospheric context
+ stellar flux



atmospheric models

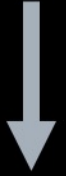


gas production rates



IT'S NOT JUST THE GASES

gas concentrations



atmospheric context
+ stellar flux



Production rates that cannot be explained by
abiotic processes point to biology



gas production rates

vegetation



Image credit: M. Turnbull



carbon dioxide



methane



and ozone



water
vapor



wavelength

optical

near
infrared

BIOSIGNATURES IN THE ECLIPS WAVELENGTH RANGE



Table 3-1. *Desired spectral features for biosignature assessment.*

Biosignatures & False Positive Discriminants (indicated with *)		
Molecules/Feature	UV-VIS wavelengths (0.2–1.0 μm)	NIR wavelengths (1.0–2.0 μm)
O_2	0.2, 0.63, 0.69, 0.76 (strong)	1.27
O_3	0.2–0.35 (strong), 0.5–0.7	
O_4 (O_2 - O_2)*	0.345, 0.36, 0.38, 0.45, 0.48, 0.53, 0.57, 0.63	1.06, 1.27 (strong)
CO^*		1.6
CO_2^*		1.05, 1.21, 1.44, 1.59
CH_4	0.6, 0.79, 0.89, 1.0	1.1, 1.4, 1.7
N_2O		1.5, 1.7, 1.78, 2.0
Organic haze	< 0.5	
Vegetation red edge	0.6 (halophile), 0.7 (photosynthesis)	

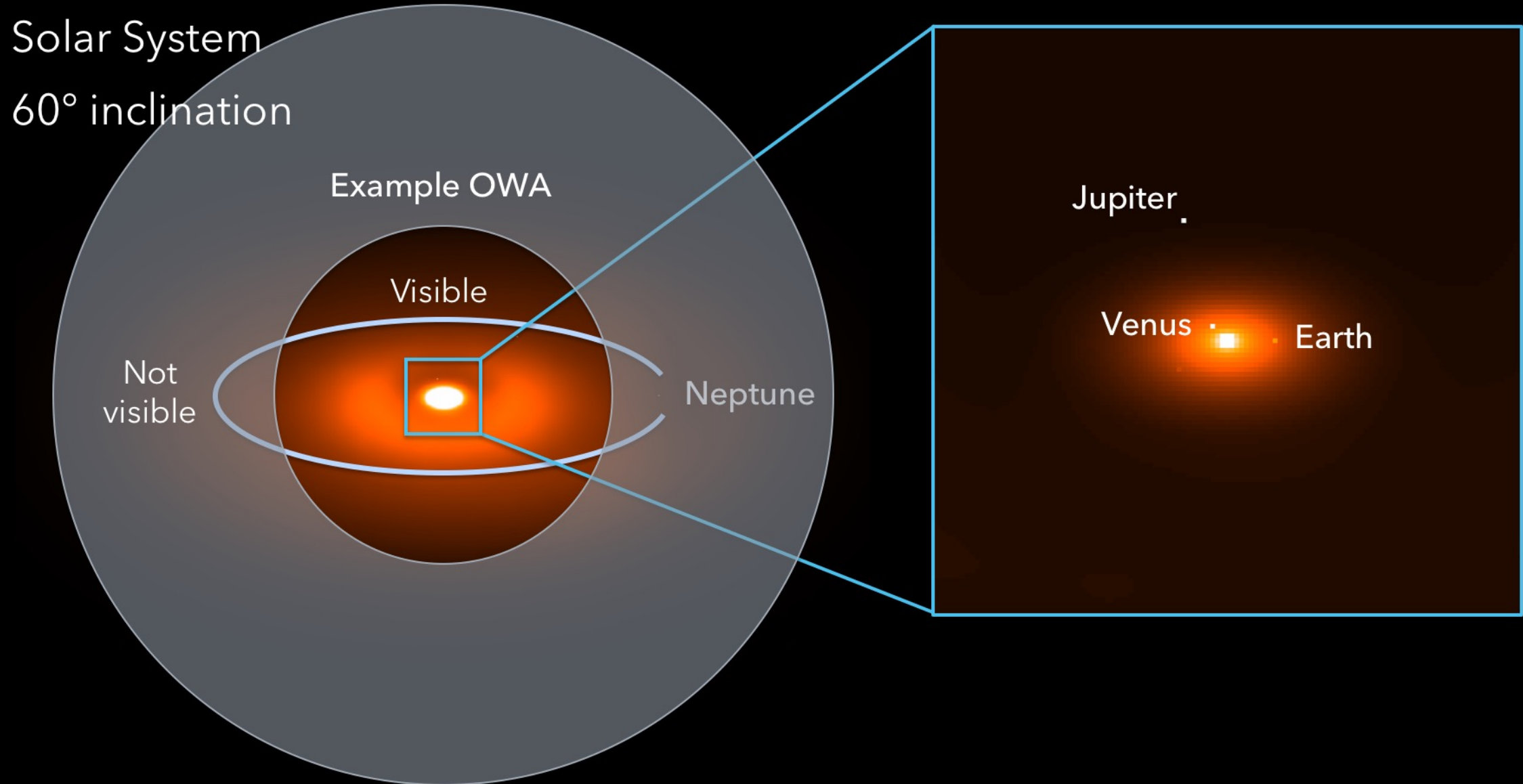
HABITABILITY FEATURES IN THE ECLIPS WAVELENGTH RANGE



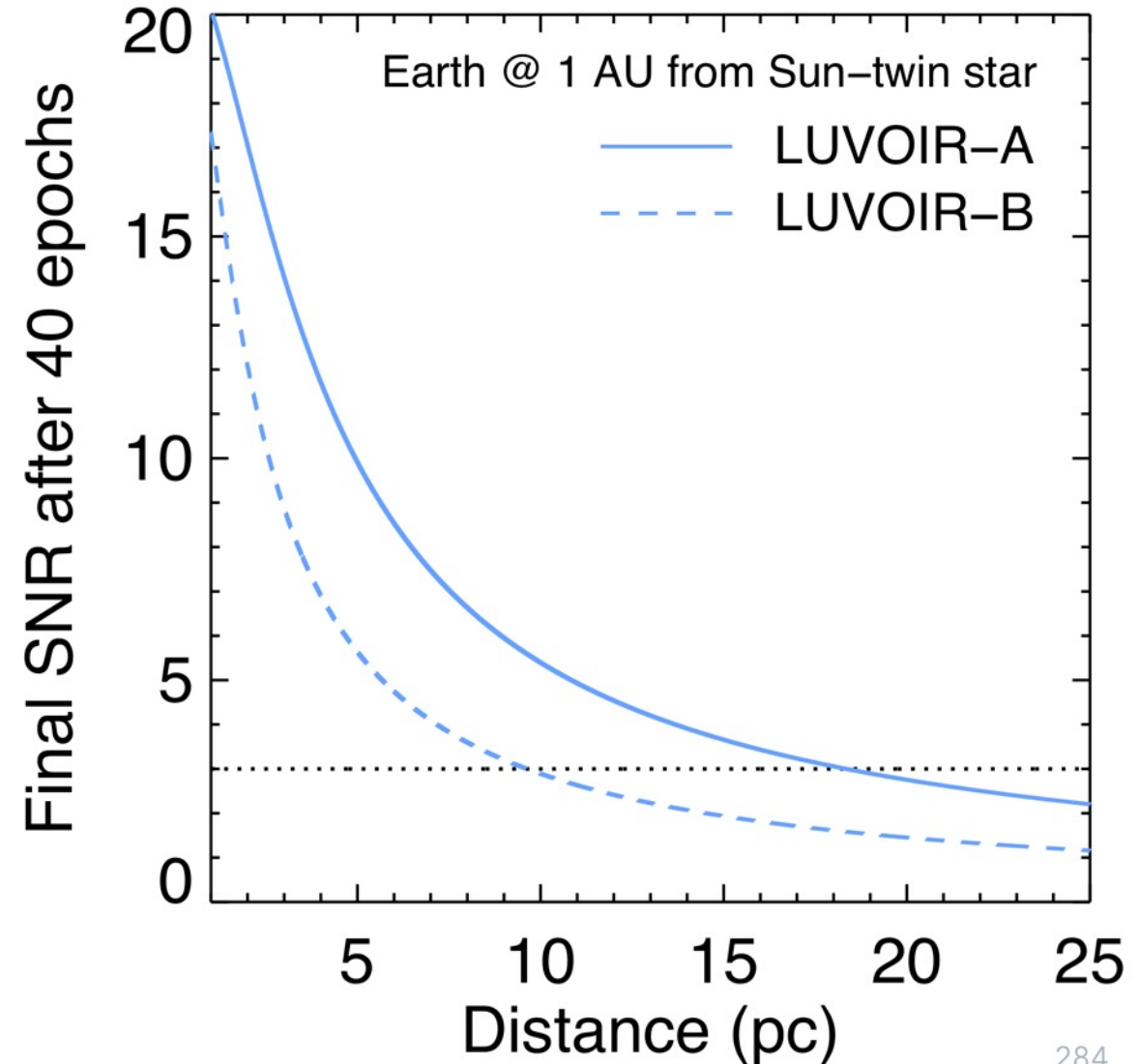
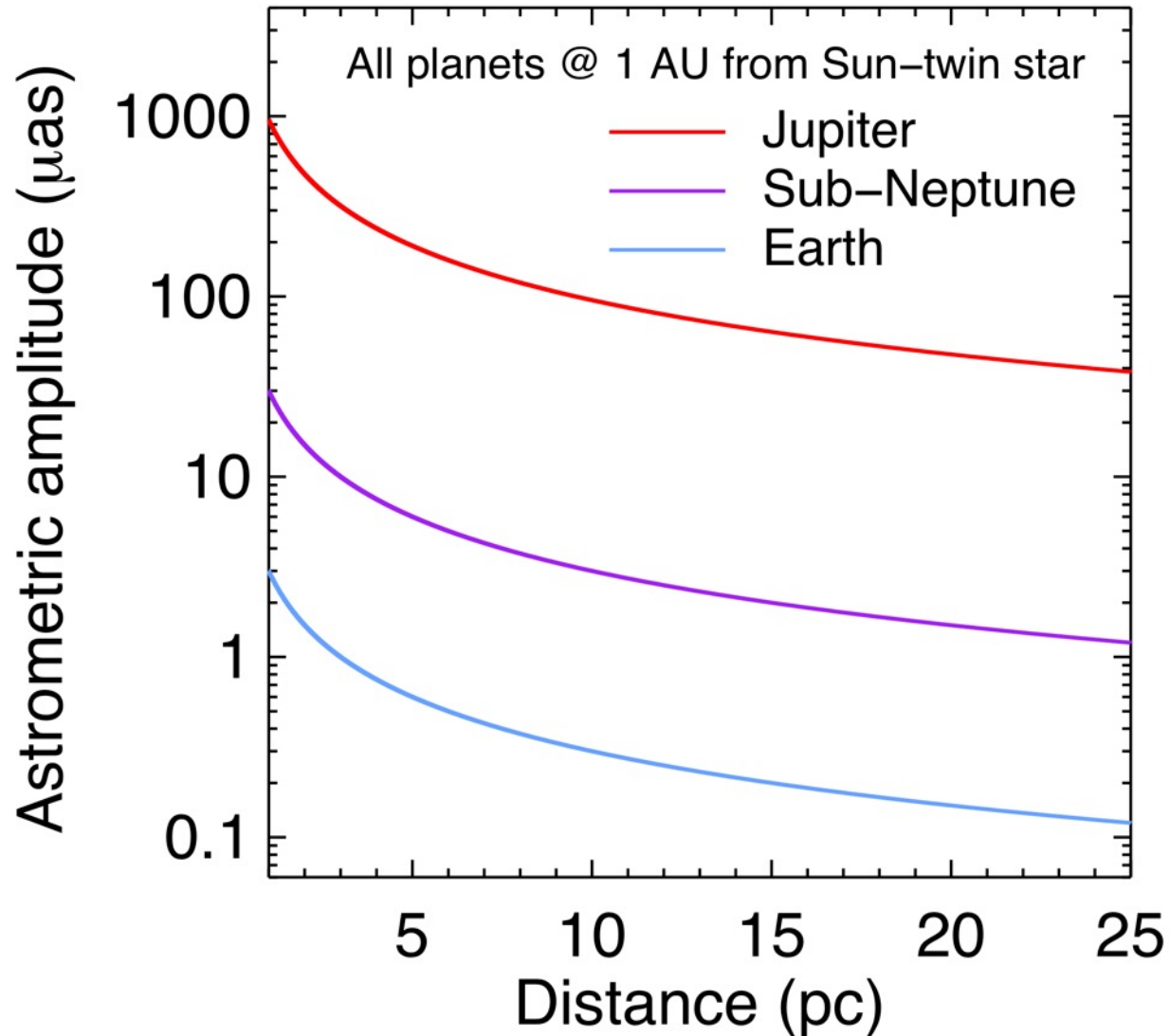
Table 3-2. *Desired spectral features for habitability assessment.*

Habitability Markers		
Molecules/Feature	UV-VIS wavelengths (0.2–1.0 μm)	NIR wavelengths (1.0–2.0 μm)
H ₂ O	0.65, 0.72, 0.82, 0.94	1.12, 1.4, 1.85
H ₂	0.64–0.66, 0.8–0.85	
CO ₂		1.05, 1.21, 1.44, 1.59
CH ₄	0.6, 0.79, 0.89, 1.0	1.1, 1.4, 1.7
S ₈	0.2–0.5	
H ₂ S	< 0.3	
SO ₂	< 0.3	
Ocean glint	0.8–0.9	1.0–1.05, 1.3
Rayleigh scattering	$\lesssim 0.5$	

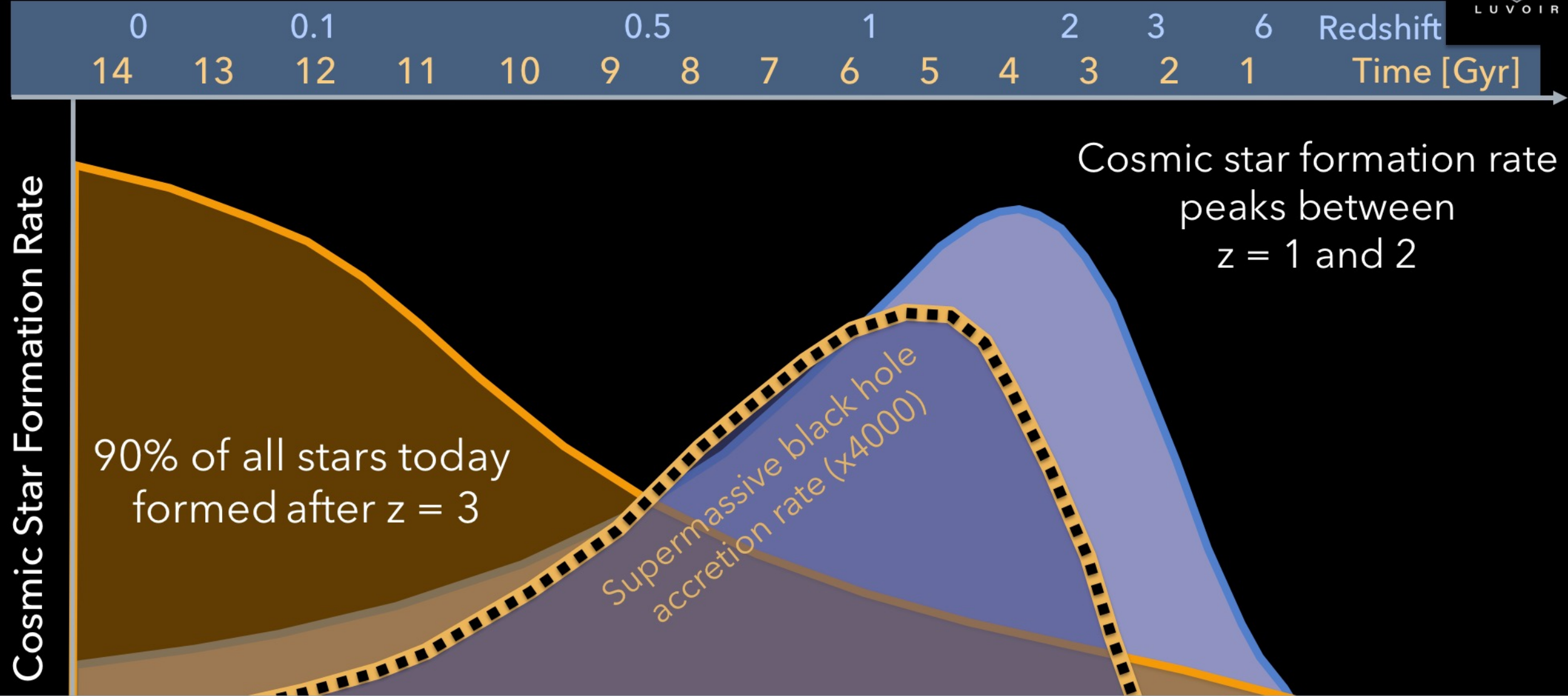
OBSERVING OUTER REGIONS OF PLANETARY SYSTEMS



LUVOIR ASTROMETRY

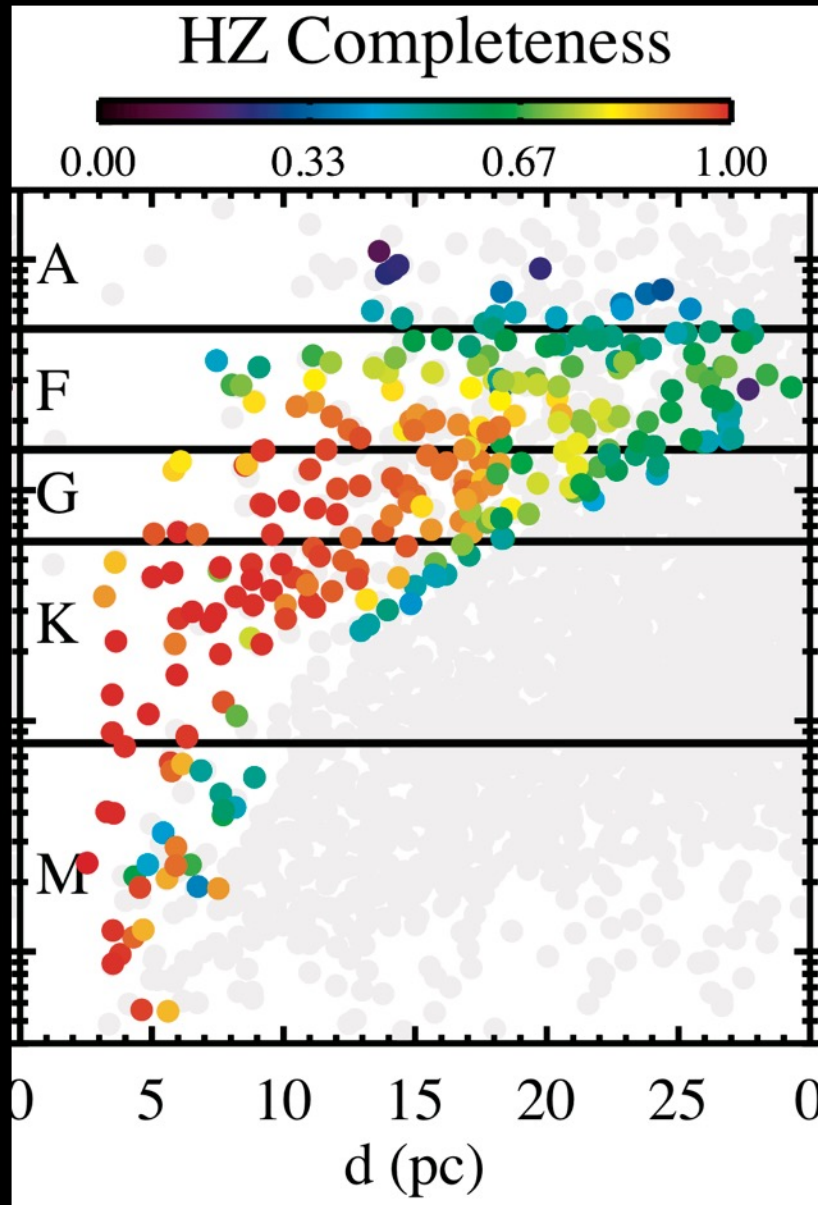


THE COSMIC LANDSCAPE – STAR FORMATION



Madau & Dickinson (2015) Hickox & Alexander (2018)

EXO-EARTH YIELDS AS A FUNCTION OF STABILITY



LUVOR-A

Limiting $\Delta \text{mag} = 26.5$

54 habitable planet candidates

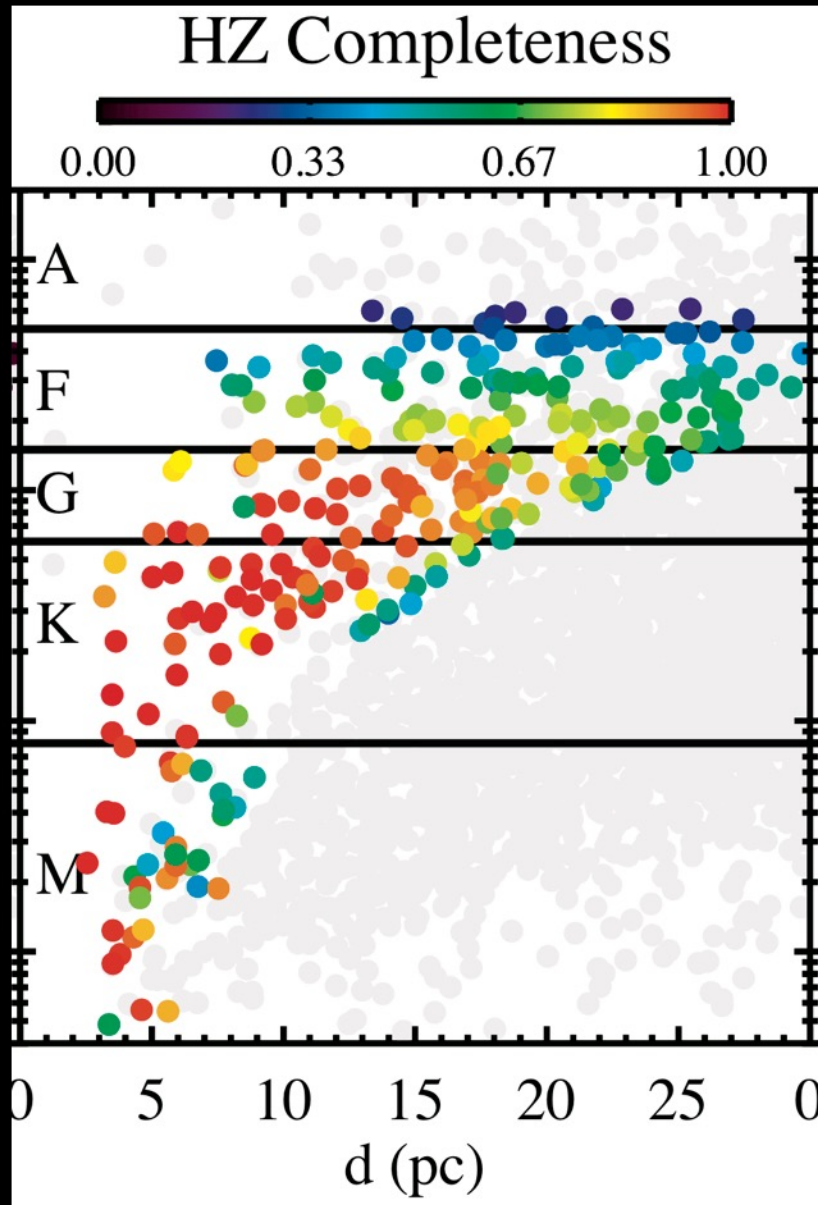
~ 8 pm segment piston / tip / tilt jitter
(residuals of telescope metrology)

~ 5 pm segment piston / tip / tilt drift
(residuals of closed-loop LOWFS/OBWFS)

Juanola-Parramon et al. (2019), SPIE, 1111702

<https://doi.org/10.1117/12.2530356>

EXO-EARTH YIELDS AS A FUNCTION OF STABILITY



LUVOIR-A

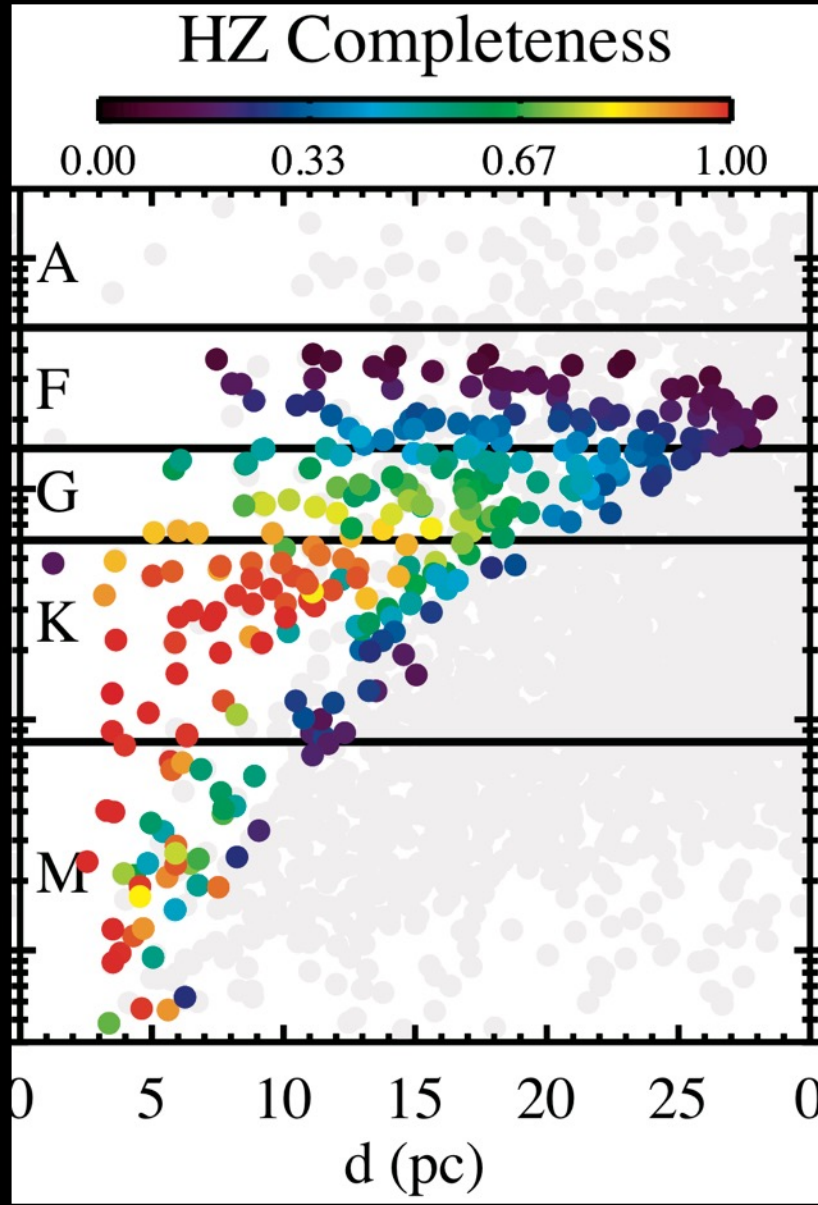
Limiting Δ mag = 26

52 habitable planet candidates (4% decrease)

Juanola-Parramon et al. (2019), SPIE, 1111702

<https://doi.org/10.1117/12.2530356>

EXO-EARTH YIELDS AS A FUNCTION OF STABILITY



LUVOIR-A

Limiting Δ mag = 25

42 habitable planet candidates (22% decrease)

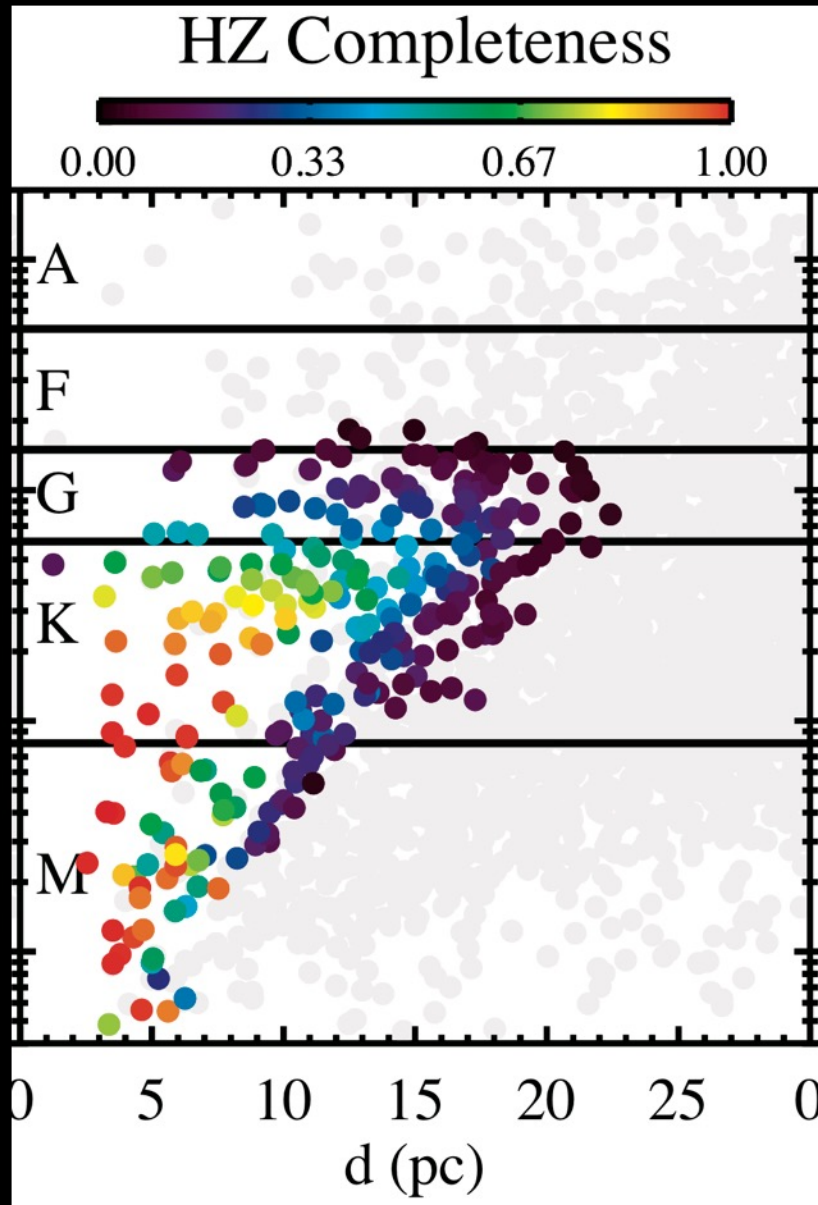
~ 30 pm segment piston / tip / tilt jitter
(residuals of telescope metrology)

~ 18 pm segment piston / tip / tilt drift
(residuals of closed-loop LOWFS/OBWFS)

Juanola-Parramon et al. (2019), SPIE, 1111702

<https://doi.org/10.1117/12.2530356>

EXO-EARTH YIELDS AS A FUNCTION OF STABILITY



LUVUOIR-A

Limiting $\Delta \text{mag} = 24$

27 habitable planet candidates (50% decrease)

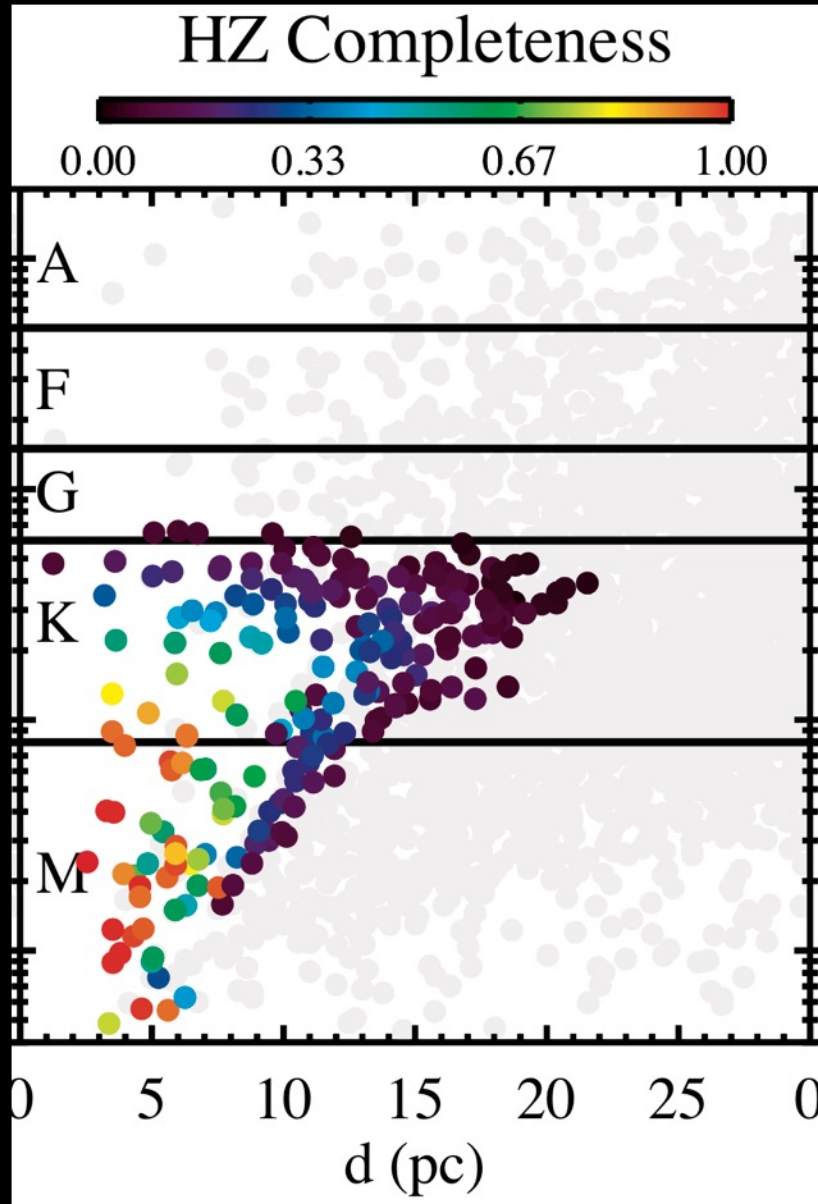
~ 40 pm segment piston / tip / tilt jitter
(residuals of telescope metrology)

~ 28 pm segment piston / tip / tilt drift
(residuals of closed-loop LOWFS/OBWFS)

Juanola-Parramon et al. (2019), SPIE, 1111702

<https://doi.org/10.1117/12.2530356>

EXO-EARTH YIELDS AS A FUNCTION OF STABILITY



LUVOIR-A

Limiting $\Delta \text{mag} = 23$

18 habitable planet candidates (67% decrease)

~ 50 pm segment piston / tip / tilt jitter
(residuals of telescope metrology)

~ 40 pm segment piston / tip / tilt drift
(residuals of closed-loop LOWFS/OBWFS)

Juanola-Parramon et al. (2019), SPIE, 1111702

<https://doi.org/10.1117/12.2530356>

NOT ALL WAVEFRONT ERRORS ARE EQUAL

Corresponds to wavefront stability of ~~"10 pm per 10 minutes"~~

Drift



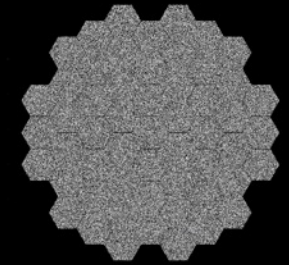
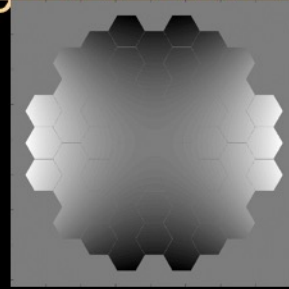
Jitter

Units of pm RMS	Optical Telescope Assembly Wavefront Stability Allocation			
	Total	Low Spatial Freq.	Mid Spatial Freq.	High Spatial Freq.
Total	158.0	153.2	38.1	6.1
< 0.002 Hz	91.2	87.3	26.2	-
0.002 – 0.010 Hz	91.2	87.3	26.2	-
0.010 – 1 Hz	87.5	87.3	5.2	-
1 – 10 Hz	18.6	17.5	5.2	-
> 10 Hz	18.6	17.5	5.2	-

Credit: Coyle et al. (2019), "Ultra-stable Telescope Research and Analysis (ULTRA) Program Phase 1 Report"

NOT ALL WAVEFRONT ERRORS ARE EQUAL

Corresponds to wavefront stability of ~~"10 nm per 10 minutes"~~



Drift



Jitter

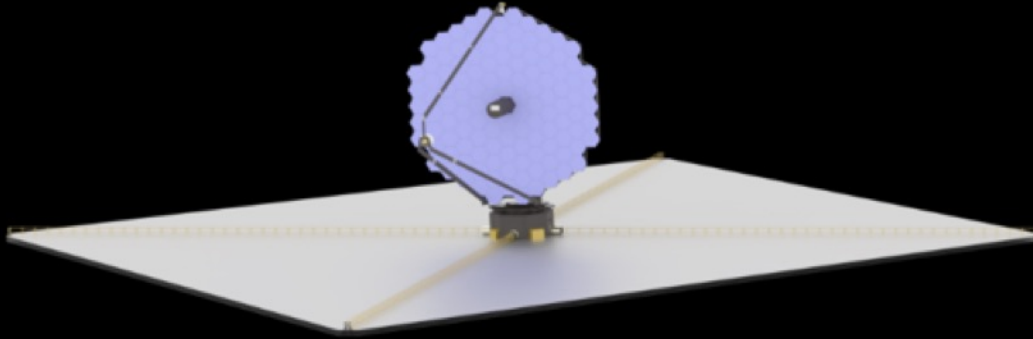
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> 10 Hz	18.6	17.5	5.2	-

Credit: Coyle et al. (2019), "Ultra-stable Telescope Research and Analysis (ULTRA) Program Phase 1 Report"

FUTURE DESIGN TRADE – SIZE SCALING

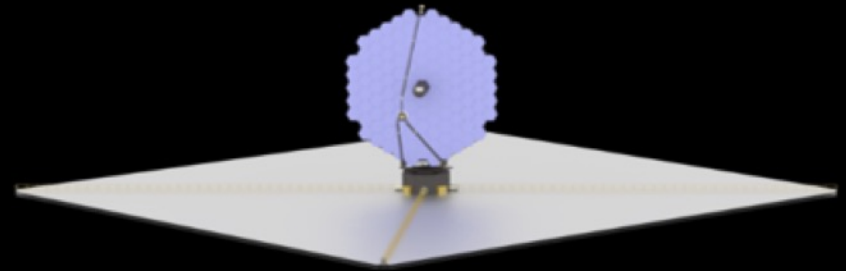
15-m LUVOIR-A

ExoEarth candidate yield: 54
Collecting area: 155 m²



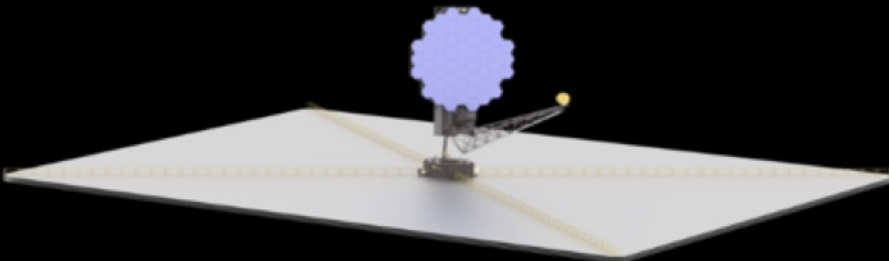
12-m LUVOIR-A

ExoEarth candidate yield: ~35
Collecting area: ~99 m²



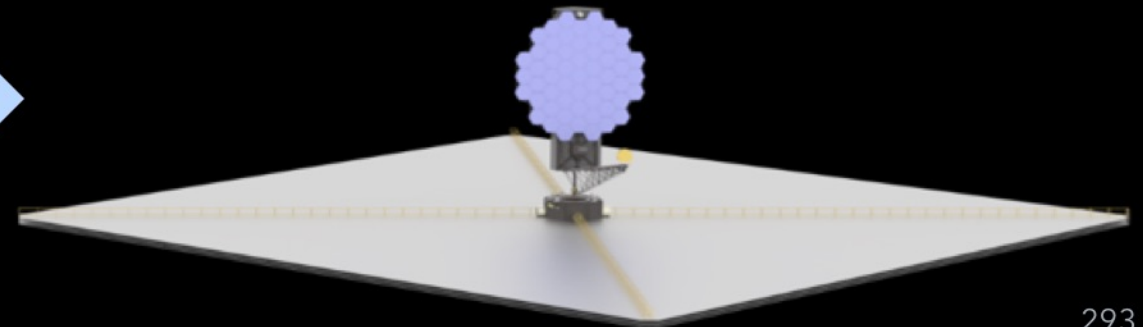
8-m LUVOIR-B

ExoEarth candidate yield: 28
Collecting area: 43 m²



10-m LUVOIR-B

ExoEarth candidate yield: ~38
Collecting area: ~68 m²



FUTURE DESIGN TRADE – SUNSHADE OPTIMIZATION



Trade Complexity for Mass

Trade Size for Science

Current Design:
3-layer separated
SLI

Alternate Design:
Single layer MLI

Current Design:
"Push out"
deployment

Alternate Design(s):
"Unroll"
deployment

Simpler sunshade

Smaller sunshade

Current Design:
Constrained angle
of incidence

Alternate Design:
Faster (more
compact) system

Current Design:
Symmetric shape

Alternate Design:
Optimal shape

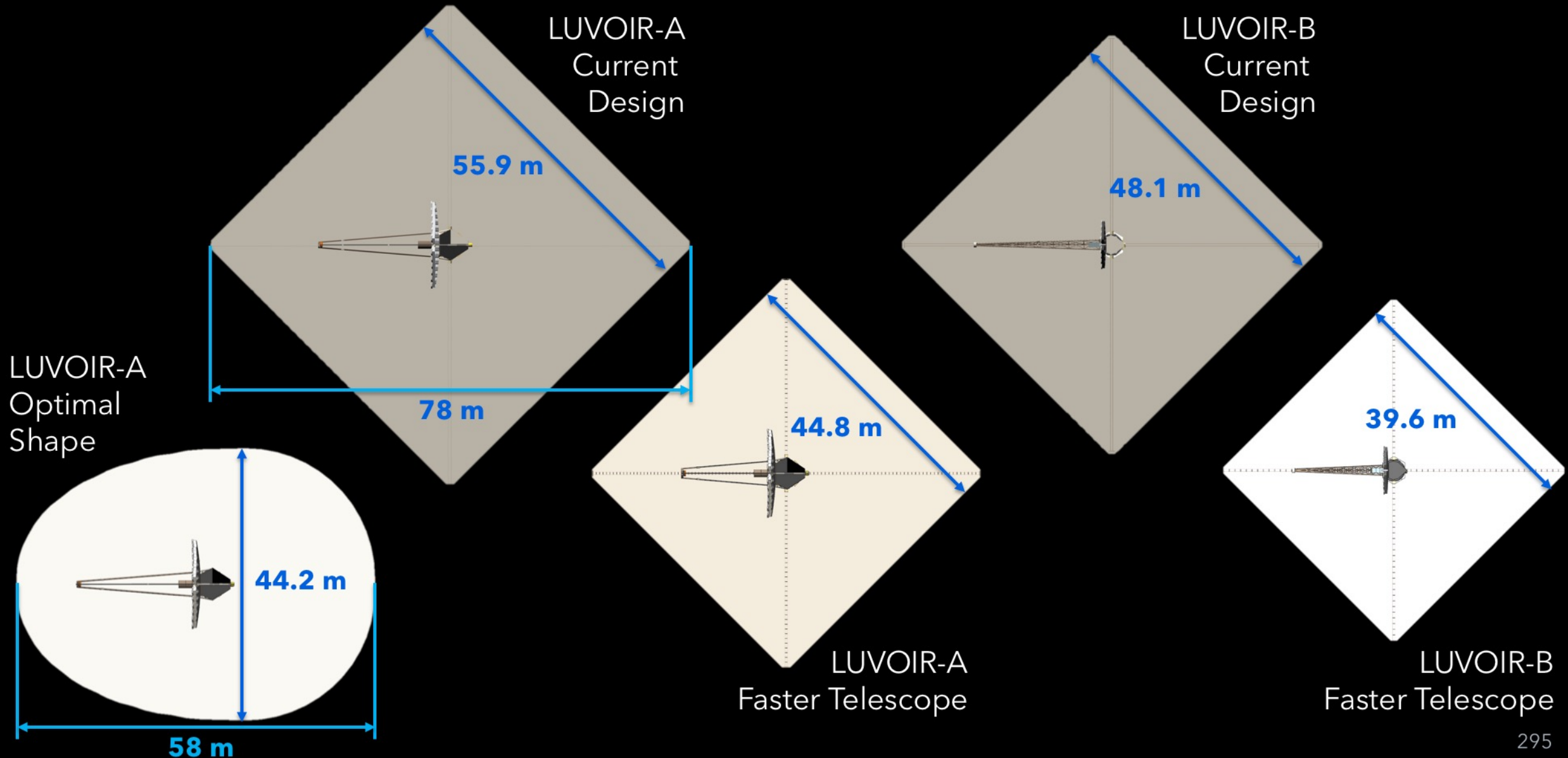
Current Design:
3-channel ECLIPS,
with polarization
sensitivity

Alternate Design:
2-Channel ECLIPS
(deferred NUV
capability)

Current Design:
Unrestricted
observing schedule

Alternate Design:
Schedule around
lunar orbit

FUTURE DESIGN TRADE – SUNSHADE OPTIMIZATION

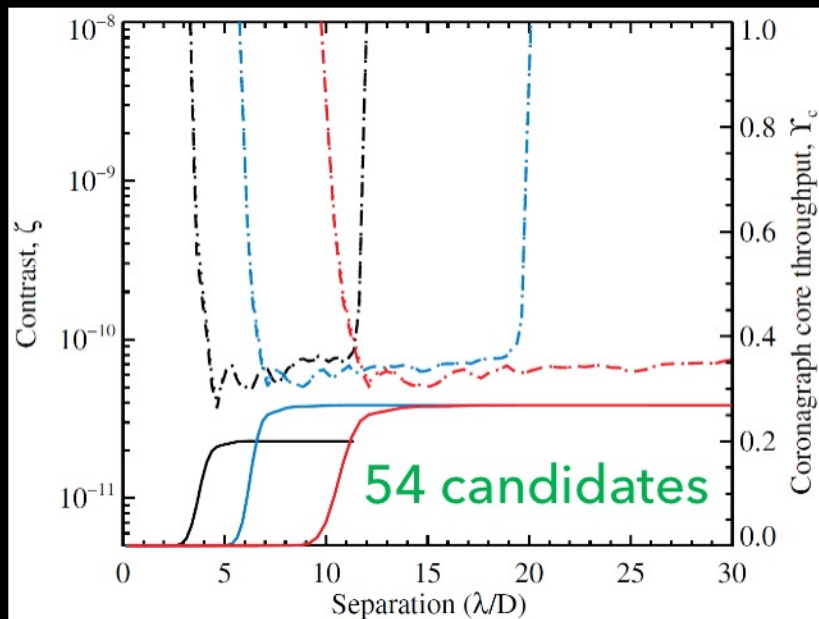


FUTURE DESIGN TRADE – CORONAGRAPH ARCHITECTURE

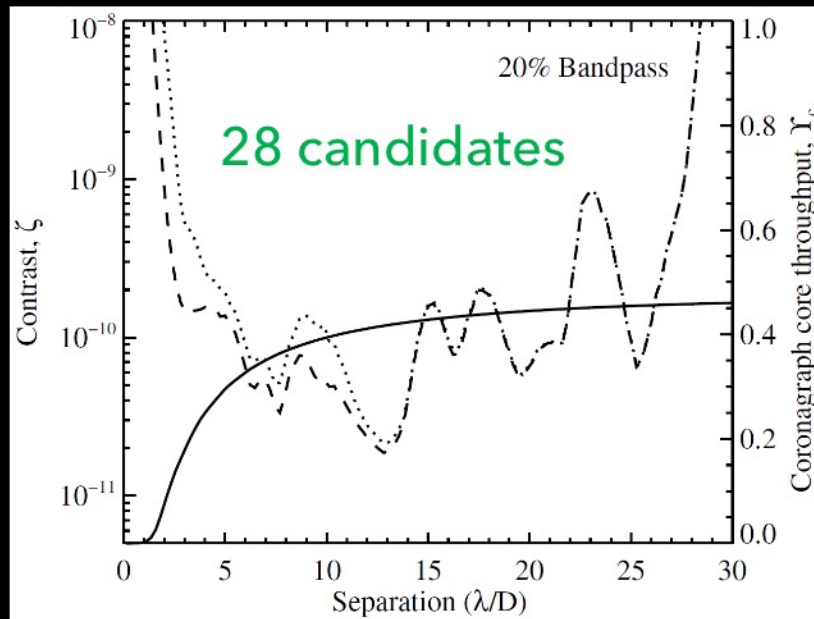


----- Contrast (left axis)

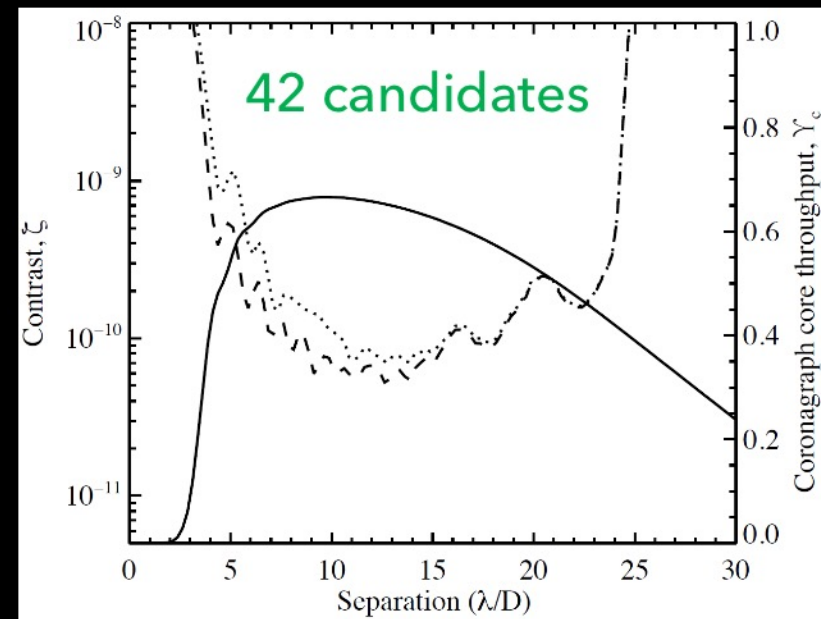
———— Core Throughput (right axis)



Apodized Pupil Lyot Coronagraph (APLC)
LUV OIR-A Baseline



DM-Assisted Vortex Coronagraph (DMVC)
LUV OIR-B Baseline



Phase-Induced Amplitude Apodization (PIAA)
LUV OIR-B Alternative

Work still to be done to determine optimal coronagraph architecture for each aperture type

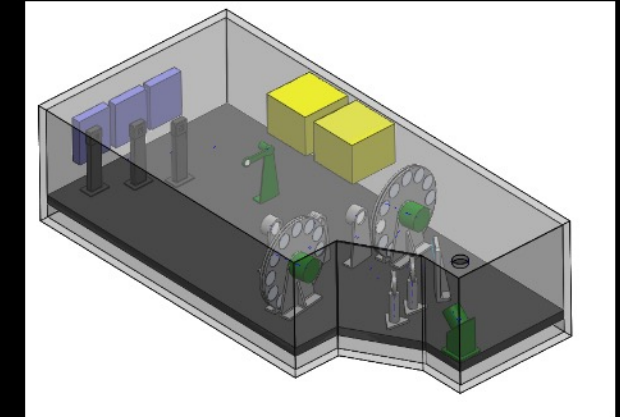
FUTURE DESIGN TRADE – DEDICATED FINE GUIDANCE SENSORS



	Current Baseline: Use HDI focal planes for fine guiding	
Pros	Same approach as WFIRST No additional instruments (mass, power, volume efficiency)	
Cons	Restricts types of detectors that can be used in HDI Limits field-of-view for guide-star availability Limits guide-star separation for roll sensitivity	

FUTURE DESIGN TRADE – DEDICATED FINE GUIDANCE SENSORS

	Current Baseline: Use HDI focal planes for fine guiding	Alternative: Dedicated fine guidance sensor(s)
Pros	Same approach as WFIRST No additional instruments (mass, power, volume efficiency)	Decouples guiding requirements from HDI's science requirements Can be more robust with multiple fine guidance sensors Hubble heritage
Cons	Restricts types of detectors that can be used in HDI Limits field-of-view for guide-star availability Limits guide-star separation for roll sensitivity	Requires separate instruments with their own mass, volume, power, data allocations

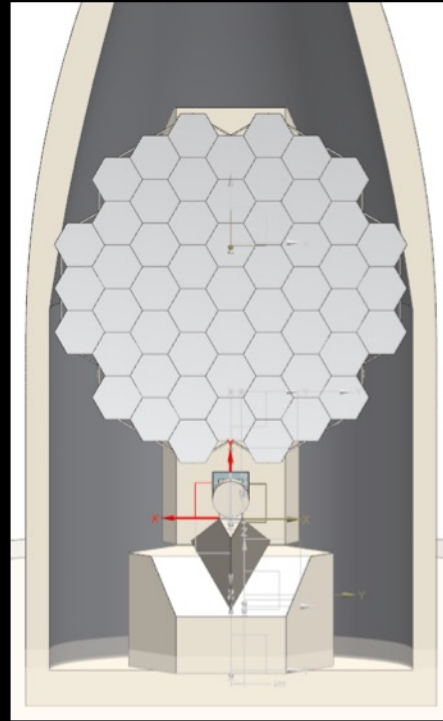


"Hybrid" guider/wavefront sensor concept from 2010 ATLAST study

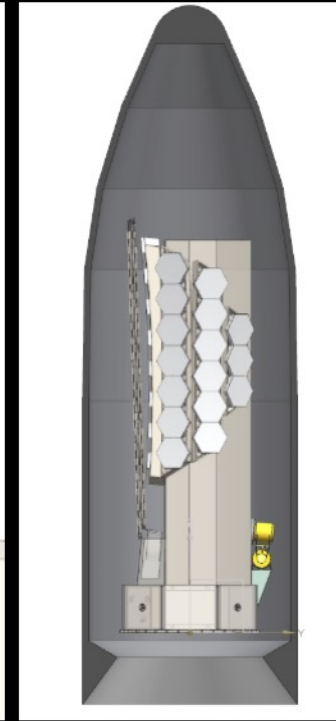
FUTURE DESIGN TRADE – STOWED CONFIGURATION

Continued development of launch vehicles since starting our study ...

New Glenn & Starship fairings allow for LUVOIR-B to launch with less complex deployments



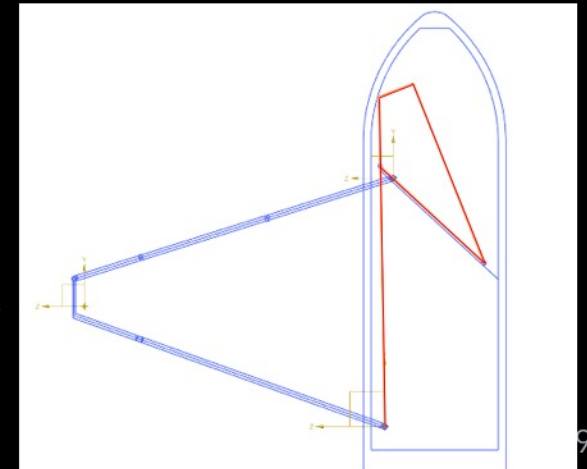
Starship



New Glenn

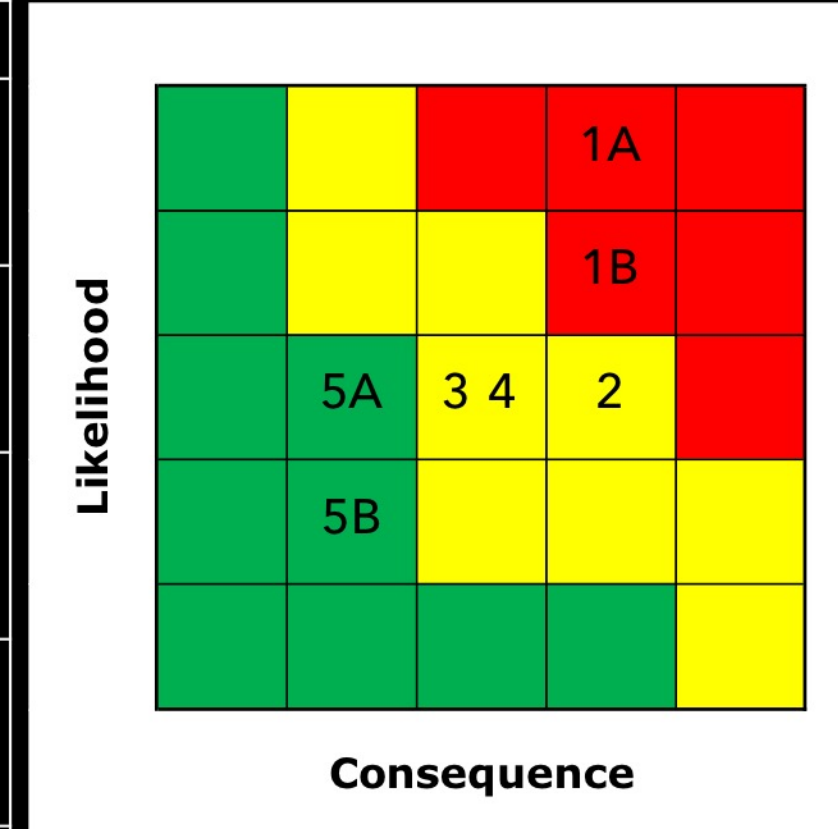
Updated SLS fairing simplifies LUVOIR-A secondary mirror folding

Simpler LUVOIR-A secondary mirror folding in new SLS fairing



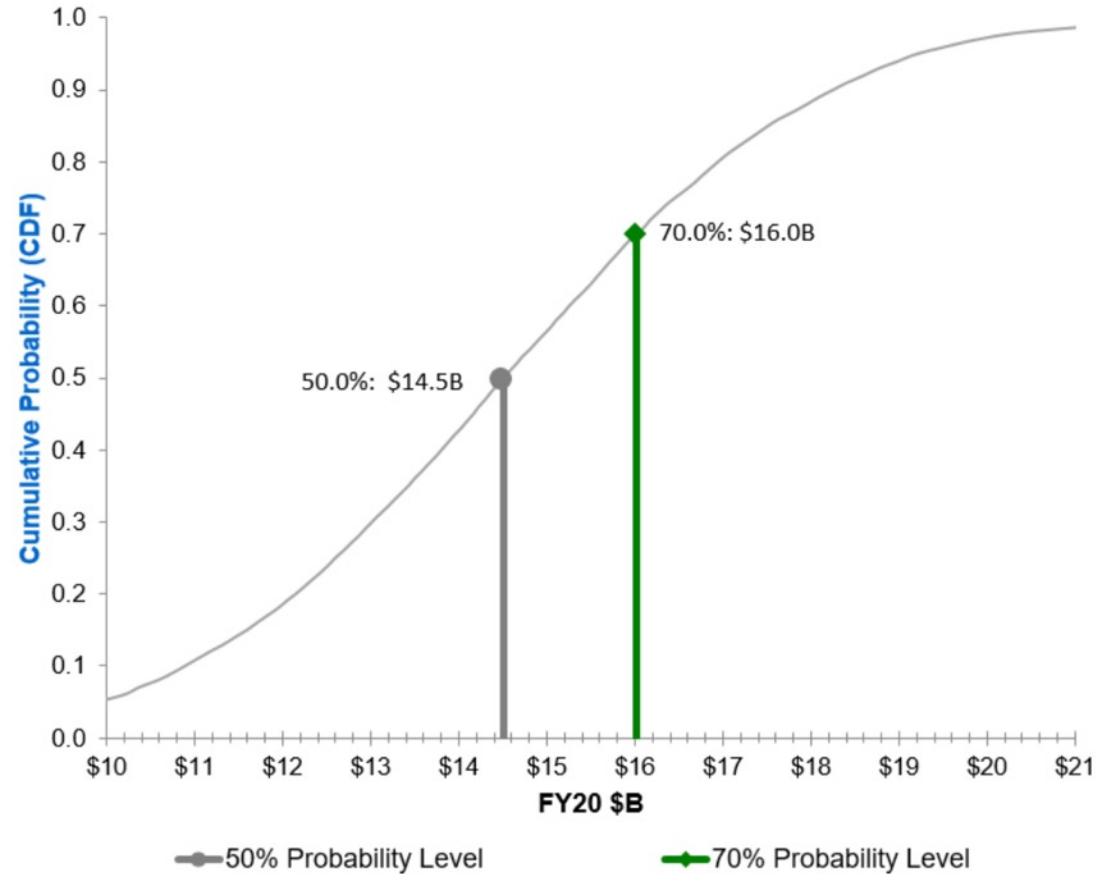
RISKS ...

ID	Description	Approach
1A 1B	Availability of integration & test facilities large enough to accommodate LUV OIR-A (B)	Research: Survey facilities in Pre-Phase A. Generate facility development plan
2	Cost and schedule risk of technology development plan	Mitigate: Include sufficient reserve in plan. Delay start of Phase A until technology development complete
3	Difficulty of verifying and validating LUV OIR's stability requirements	Mitigate: Emphasis on verification by analysis. Pre-Phase A plan to develop modeling capability
4	Uncertainty in contamination control practices on systems as large as LUV OIR	Research: Develop detailed contamination control plan in Pre-Phase A
5A 5B	Uncertainty in launch vehicle availability	Mitigate: LUV OIR's scalable architecture addresses this

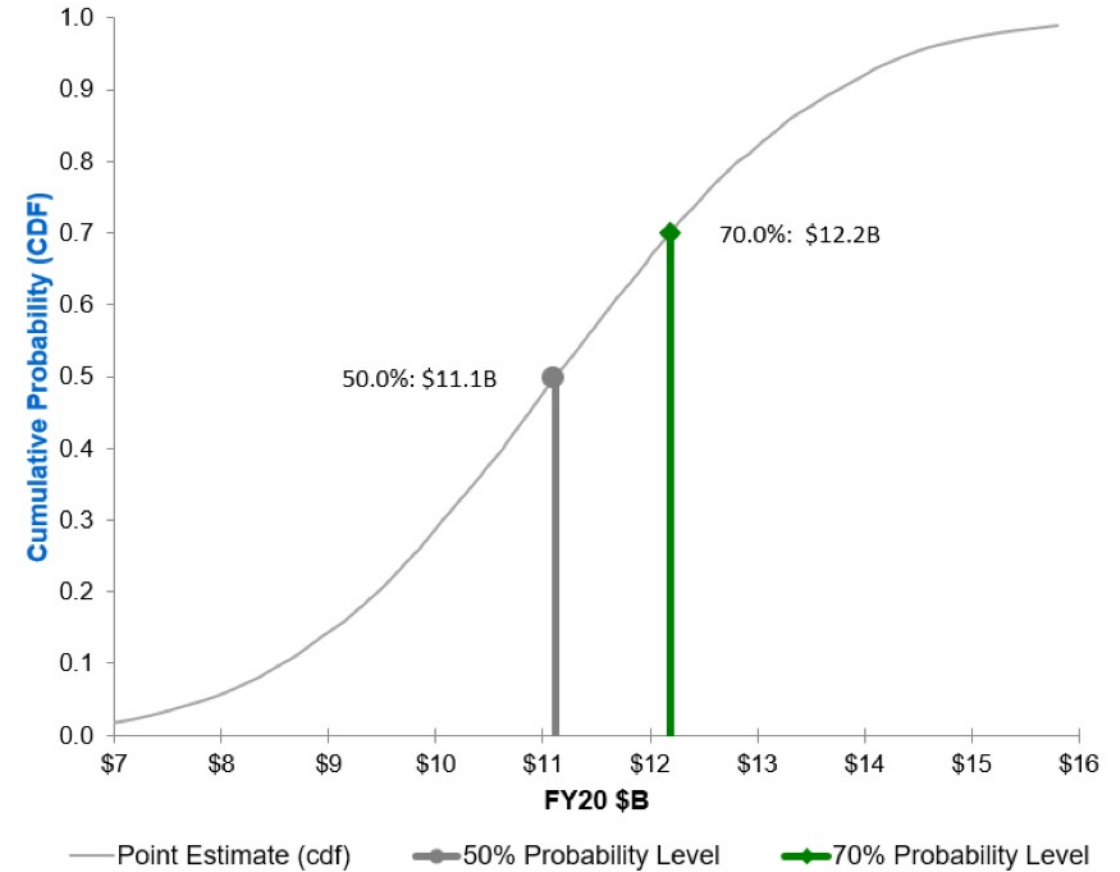


COST ESTIMATE S-CURVES

LUVOIR-A Mission S-Curve
No risk on Science, LV, Phase A, CV = 0.19
May 29, 2019



LUVOIR-B Mission S-Curve
No risk on Science, LV and Phase A
May 18, 2019



STRATEGIES FOR CHANGE

Recommend five strategies for cost- and schedule-efficient project management based on research

Bitten, R., et al., 2019, *Challenges and Potential Solutions to Develop and Fund NASA Flagship Missions*, IEEE, 978-1-5386-6854-2/19

Wiseman, J., 2015, *The Hubble Space Telescope at 25: Lessons Learned for Future Missions*, IAUGA 2258532W

Mitchell, D., 2015, *An Overview of NASA Project Management, MAVEN Magic, and Lessons Learned*

Martin, P., 2012, *NASA's Challenges to Meeting Cost, Schedule, and Performance Goals*, *OIG Report* IG-12-021

Feinberg, L., Arenberg, J., et al., 2018, *Breaking the Cost Curve: Applying Lessons Learned from the JWST Development to Build More Cost Effective Large Space Telescopes in the Future*, SPIE 10698-23

Arenberg, J., Matthews, G., et al., 2014, *Lessons We Learned Designing and Building the Chandra Telescope*, SPIE 9144-25

2004-2007, *Defense Procurement: Full Funding Policy - Background, Issues, and Options for Congress*, CRS Report for Congress, RL31404

O'Rourke, R., 2006, *Navy Ship Procurement: Alternative Funding Approaches - Background and Options for Congress*, CRS Report for Congress, RL32776

ALTERNATIVE FUNDING STRATEGY

Funding instability has routinely been cited as a cause of cost and schedule increases

Different approach for funding large missions : fund discrete blocks of work, not year-by-year

Not required to develop LUV OIR, but could provide better stability and oversight

Potentially useful for all large missions. See APC white papers by J. Crooke et al. and Hylan et al.

ALTERNATIVE FUNDING STRATEGY

