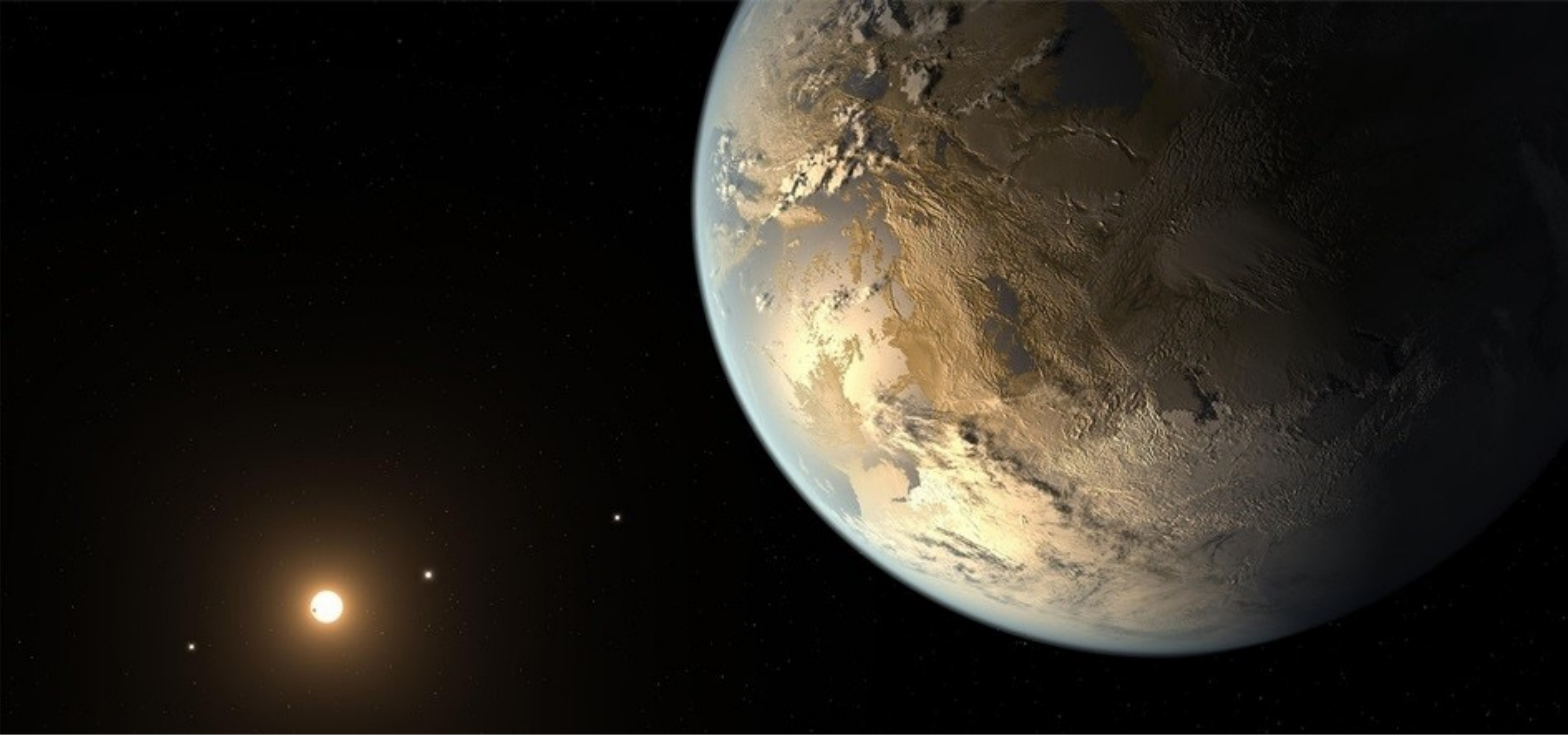


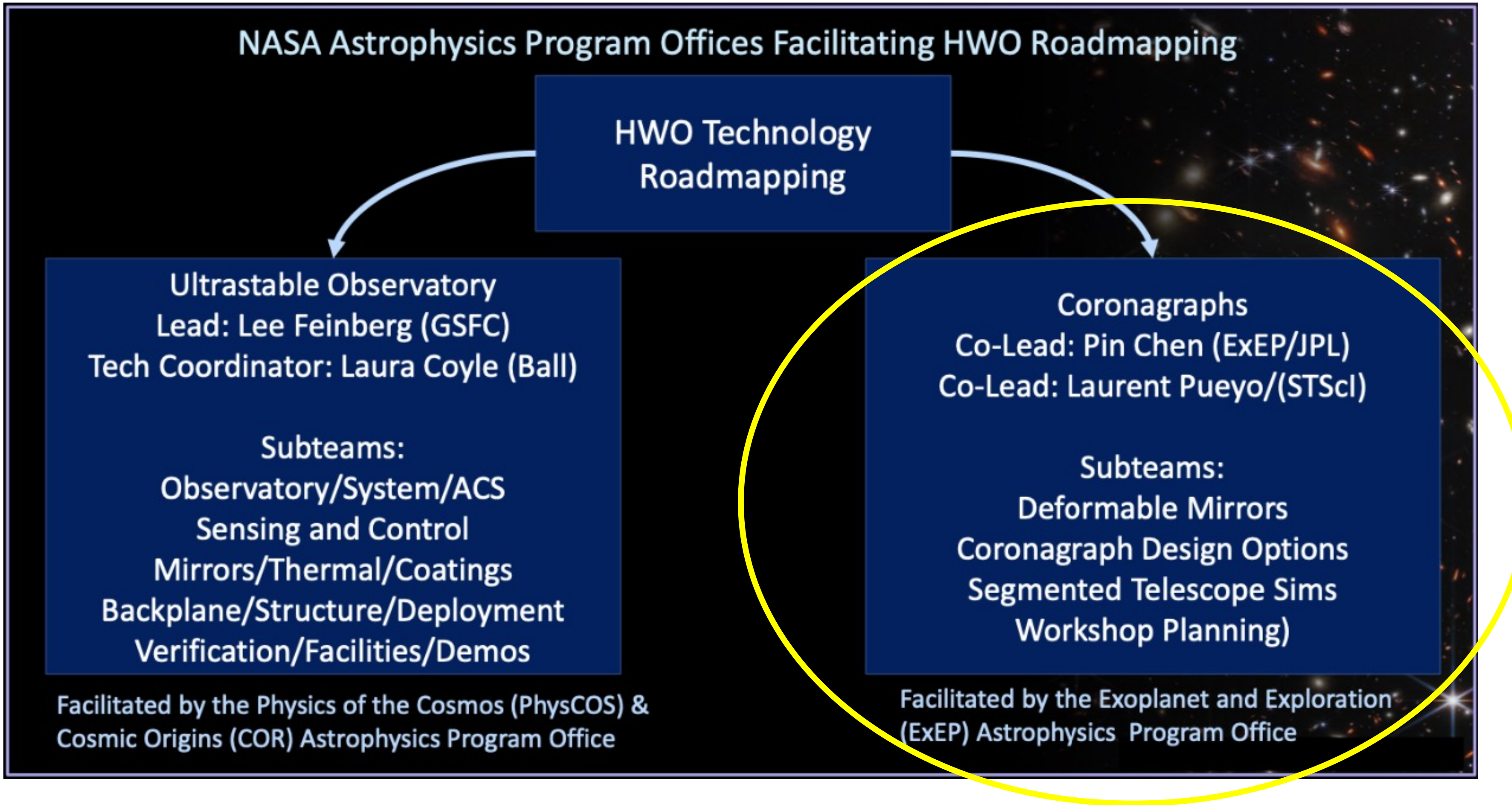
Towards Starlight Suppression for the Habitable Worlds Observatory Workshop

Coronagraph Technology Roadmap (CTR)

Pin Chen (NASA ExEP, JPL/Caltech), Laurent Pueyo (STScI), Nick Siegler (NASA ExEP, JPL/Caltech)
August 9, 2023

The Coronagraph Technology Roadmap Working Group (CTR-WG)

Organizational Context

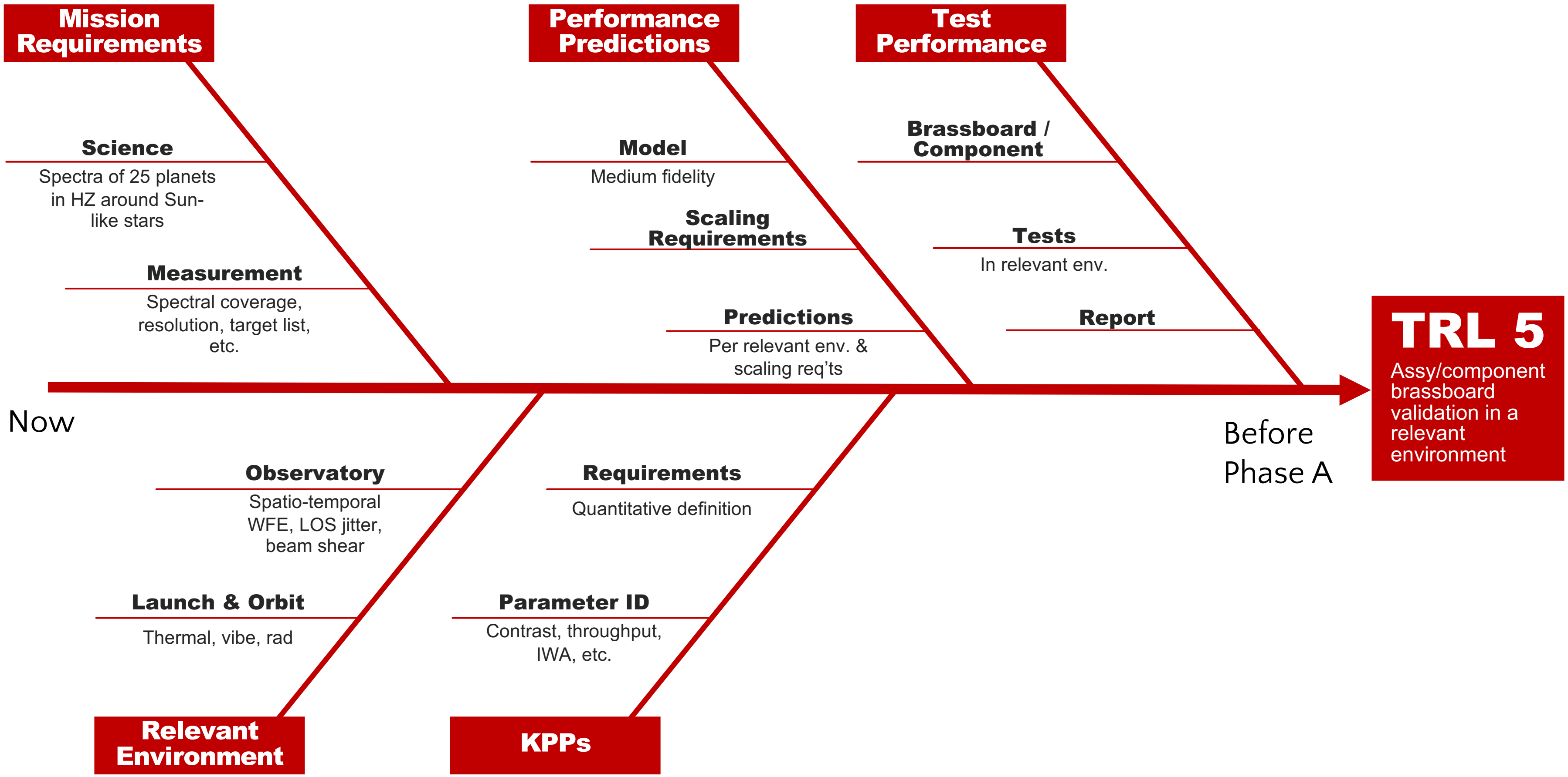


M. Clampin

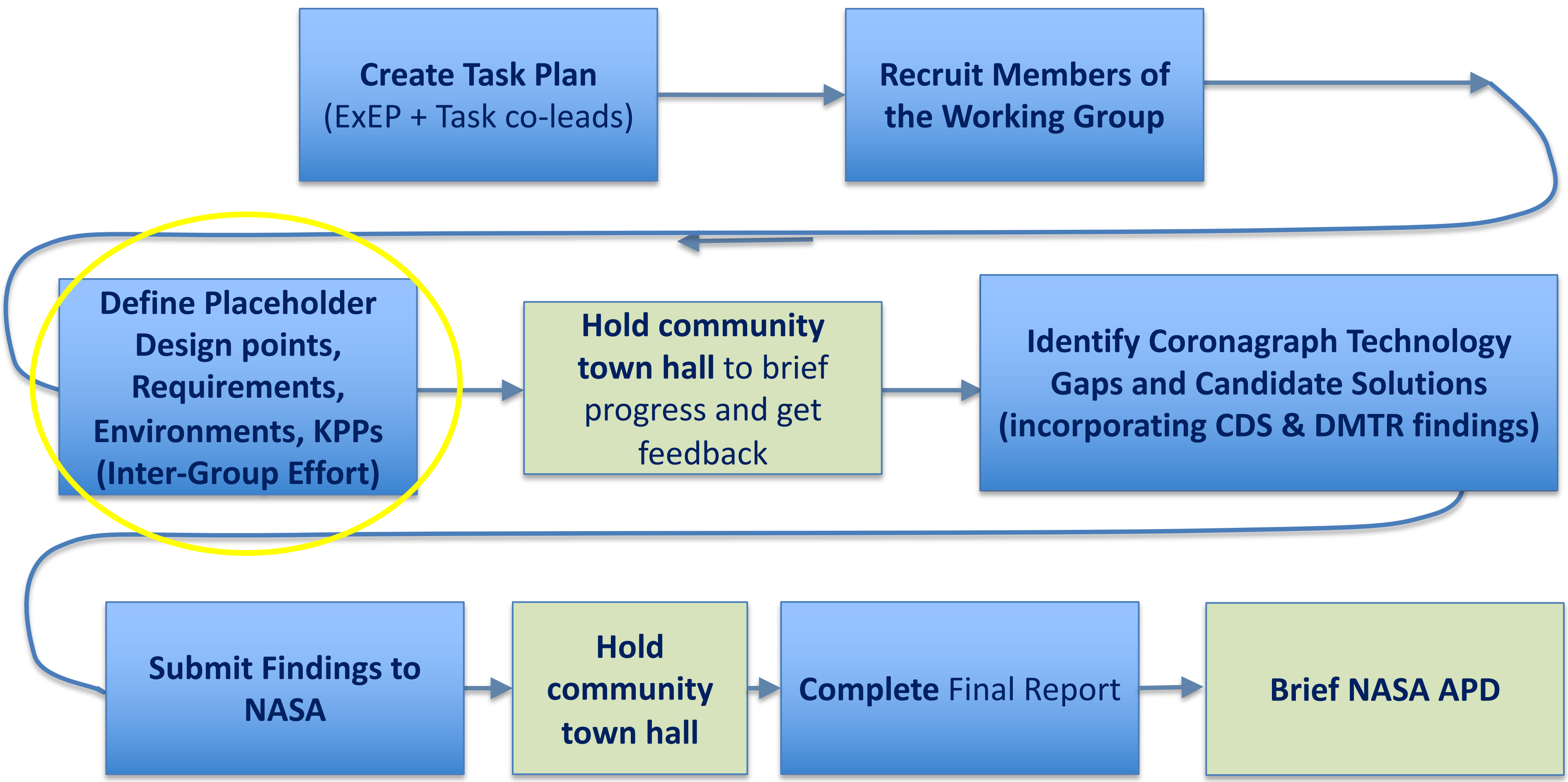
The Coronagraph Technology Roadmap Working Group

- The CTR-WG seeks to answer the following question:
  - Where, when, and how much does NASA need to invest in coronagraph technology to mature it to TRL 5 to enable the Habitable Worlds Observatory?
- The Working Group comprises 50+ participants from
  - NASA: ARC, ExEP, GSFC, HQ, JPL, MSFC
  - Academia: Caltech, MIT, N. Arizona U., Princeton, STScI, U. Hawaii
  - Industry: Northrop Grumman, Lockheed Martin, Ball Aerospace
  - International: NAOJ, U. Bern

A Graphical Summary of Necessary Inputs to Achieve TRL 5



Programmatic Flow



Design-Point Taskforce Leads

Vis

Vanessa Bailey

JPL
RST-CGI Instrument Technologist

Vis+IR

Olivier Guyon

UA, Subaru Telescope
HabEx STDT, LUVOIR STDT

Vis+UV

Roser Juanola-Parramon

GSFC, LUVOIR Study Office & Engineering Team

A Quick Tour

Preface

- Assuming HWO shall be able to
  1. search 100 effective habitable zones (i.e. attain 100 cumulative completeness) for planetary candidates and
  2. characterize candidate planets with sufficient spectral coverage to search for multiple biosignature molecules
- I'm also assuming a segmented primary mirror with 6-meter inscribed diameter
- I will name one or two key science cases (from LUVOIR Final Report) in each of the vis, UV, and IR bands
- Discuss one or two challenges in achieving the above-mentioned assumed requirements of completeness and characterization

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Science Case 1 for Vis: Search for Planet Candidates

- **<u>Challenge</u>**: Achieving ***wavefront stability*** to enable searching 100 effective HZs
- **<u>Background</u>**:
  - Raw contrast is important, but *not on its own* (Stark talk)
  - Raw contrast is important mainly as a factor amplifying the effect of residual ***wavefront changes***
  - Hence, observatory stability, spatio-temporal frequencies, observing scenarios, and WFS&C (wavefront sensing & control) systems are essential contexts in evaluating coronagraph performance (Pueyo talk)
  - Flux-ratio/contrast stability requirement:
    - Better than 10^{-11} between reference & target observations (assuming further postprocessing provides another factor of SNR enhancement)
  - **This is a key challenge for all wavelengths and science cases considered in this presentation**

Signature Science Case #1: Finding habitable planet candidates

Science Objective

Determine the occurrence rate of Earth-like conditions on rocky worlds around Sun-like stars.

Description

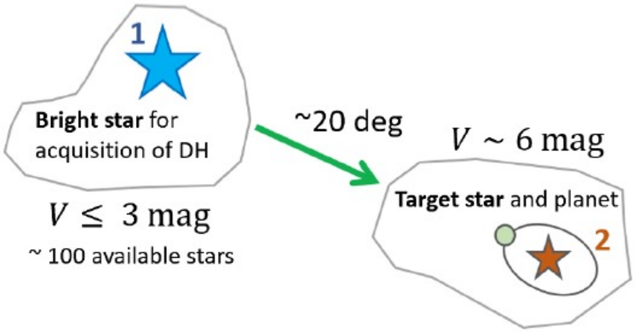
Find and study $\gtrsim$ 28 habitable planet candidates to discover at least 1 Earth-like planet orbiting an FGK star (at 95% confidence), for occurrence rates of habitable conditions $\gtrsim$ 10%.

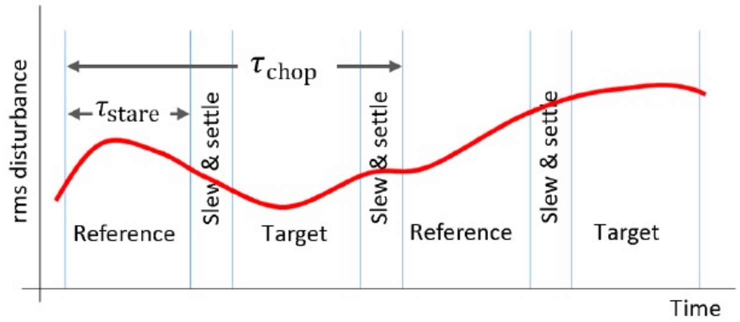
Key Functional Requirements

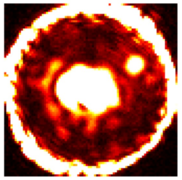
Inscribed telescope diameter	$\gtrsim$ 6.7 m
Total time	2 years
Inner working angle	$\lesssim 4\lambda/D$
Raw contrast	1×10^{-10}
Wavelength range	$\lesssim$ 500 nm to $\gtrsim$ 950 nm
Spectral resolution & SNR (near 940 nm for H_2O detection)	$R \gtrsim 70$, $SNR \gtrsim 5$

LUVOIR Final Report

Vis Science Case 1: Search for Planet Candidates







Nemati et al. 2020

$$I_1 \equiv |E|^2$$

$$I_2 = |E + \Delta E|^2 = |E|^2 + |\Delta E|^2 + 2Re\{E^* \Delta E\}$$

Static raw contrast

Perturbation

Cross term

$$\Delta I \approx |\Delta E|^2 + 2Re\{E^* \Delta E\}$$

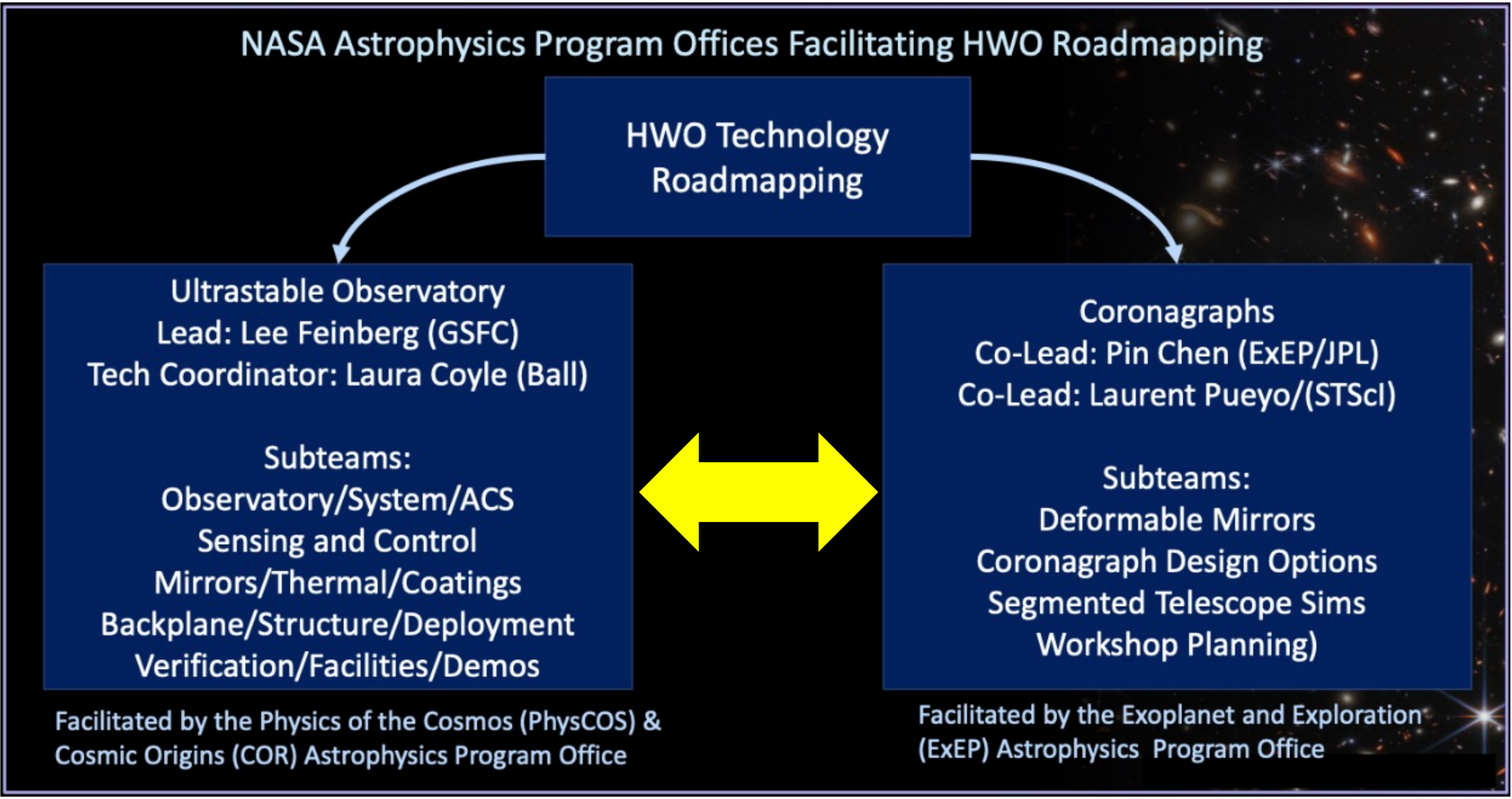
Cross term

ΔI: post-subtraction background intensity

Vis Science Case 1: Search for Planet Candidates

- By definition, static raw contrast ($|E|^2$) is constant → removed by reference subtraction (w/ residual shot noise)
- The mixing term ($2\mathrm{Re}\{E^* \Delta E\}$) is usually the dominant term impacting exoplanet detectability (noise floor)
- The table shows that raw contrast can be 10x worse, but a 3x improvement in wavefront stability returns the same detection limit
- Contributors to instability include movements of primary-mirror segments, telescope alignment drifts, and changes in DM surface figure
- **Observatory stability and coronagraph instrument performance are inextricably coupled (via the cross term)!**

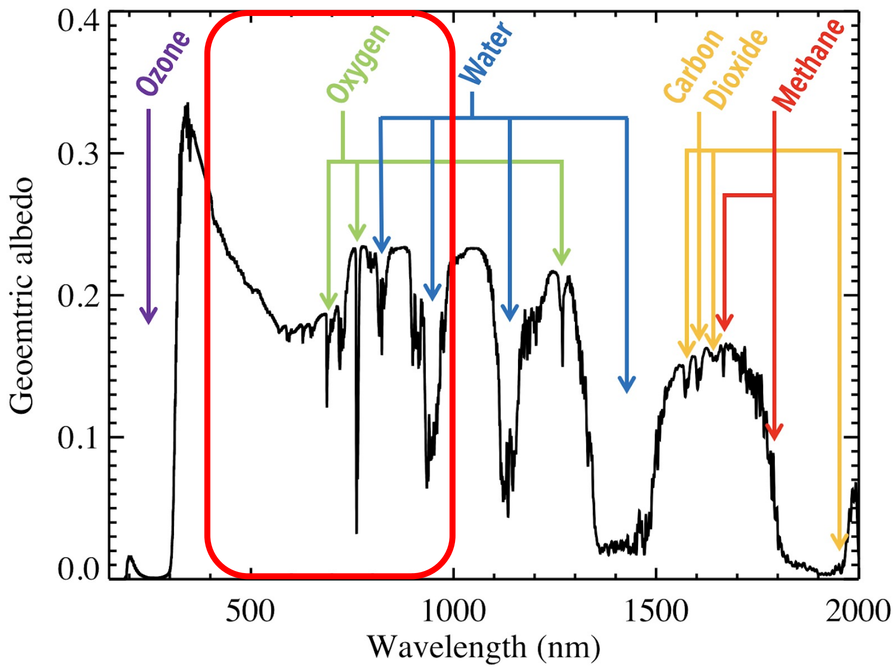
Residual WFE & instability	$|E|^2$ raw contrast	$|\Delta E|^2$	$2Re\{E^* \Delta E\}$	ΔI
$E = 7x10^{-6}$, $\Delta E = 7x10^{-7}$	$5x10^{-11}$	$5x10^{-13}$	$1x10^{-11}$	$1x10^{-11}$
$E = 2.3x10^{-5}$, $\Delta E = 2.3x10^{-7}$	$5x10^{-10}$	$5x10^{-14}$	$1x10^{-11}$	$1x10^{-11}$


NASA Astrophysics Program Offices Facilitating HWO Roadmapping
HWO Technology Roadmapping
Ultrastable Observatory
Lead: Lee Feinberg (GSFC)
Tech Coordinator: Laura Coyle (Ball)
Subteams:
Observatory/System/ACS
Sensing and Control
Mirrors/Thermal/Coatings
Backplane/Structure/Deployment
Verification/Facilities/Demos
Coronagraphs
Co-Lead: Pin Chen (ExEP/JPL)
Co-Lead: Laurent Pueyo/(STScI)
Subteams:
Deformable Mirrors
Coronagraph Design Options
Segmented Telescope Sims
Workshop Planning)
Facilitated by the Physics of the Cosmos (PhysCOS) & Cosmic Origins (COR) Astrophysics Program Office
Facilitated by the Exoplanet and Exploration (ExEP) Astrophysics Program Office

Vis Science Case 1: Search for Planet Candidates

- **Key Capability**
  - Ultra-stable observatory: The COR Ultra-Stable Observatory Roadmap Team is studying this critical topic [see Ultra-Stable Observatory session, Thursday morning]
- **Other Important Capabilities** [see Guyon + other Coronagraphy talks]
  - Wavefront sensing and control (WFS&C) in the coronagraph instrument to mitigate wavefront instabilities from the observatory [e.g. Potier et al. 2022 *JATIS,* Pueyo et al. 2022 *JATIS*]
  - Coronagraph dark field control [e.g. Currie et al. 2020 *PASP*]
  - Realtime DM surface monitoring [e.g. Ruane et al. 2020 *JATIS*]

Science Case 2 for Vis: H_2O & Modern-Earth O_2 Measurements



C. Stark

Signature Science Case #2: Searching for biosignatures and confirming habitability

Science Objective

Search for signs of global biospheres on rocky worlds around Sun-like stars by assessing the chemical state of planet atmospheres. Confirm liquid water.

Description

Measure abundances of key molecules (e.g., H_2O, O_2, O_3, CH_4, CO_2, CO) in the atmospheres of rocky exoplanets via direct spectroscopy. Perform other characterization observations to place the planets in context.

Key Functional Requirements

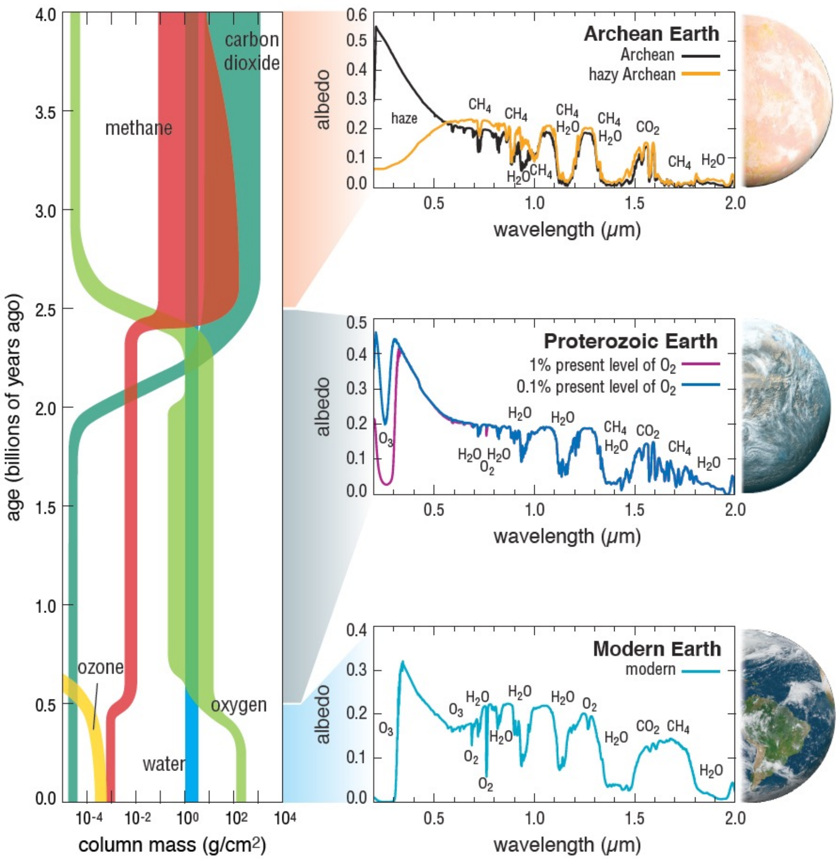
Inscribed telescope diameter	$\gtrsim$ 6.7 m
Total time	
LUVOIR-A	6.5 months
LUVOIR-B	6.2 months
Inner working angle	$\lesssim 4\lambda/D$
Raw contrast	$\lesssim 1\times10^{-10}$
Planet spectroscopy wavelength range	200 nm to $\gtrsim$ 1800 nm
Spectral resolution & SNR	
O_2 (760 nm)	$R\approx 140$, SNR$\gtrsim$8.5
H_2O (1120 nm)	$R\approx 70$, SNR$\gtrsim$8.5
CO_2 (1600 nm)	$R\approx 200$, SNR$\gtrsim$8.5
Astrometric precision for planet masses	<1 μas
Stellar spectroscopy wavelength range	100 nm to 1000 nm

LUVOIR Final Report

Science Case 2 for Vis: H_2O & Modern-Earth O_2 Measurements

- **<u>Challenge</u>**: Attaining low enough detector noise to achieve required SNR for retrieving gas abundances from observed spectra
- **<u>Background</u>**:
  - IFS observations requires sampling the planetary signal with ≥ 32 pixels/PSF: e.g. 896 pixels for R = 140, 20% BW ➔ Detector noise adds up
  - B. Nemati's error-budget analysis for exo-Earth characterization w/ 6-meter telescope:
    - **Cannot close budget for SNR>5**
    - Detector dark noise is the dominant term
  - Updated CGI detector test data should improve the SNR estimate, stay tuned
- **<u>Potential Mitigation Approaches</u>**
  - Further develop lower-noise detector technologies (Crill talk)
- **<u>Possible Trades</u>**
  - IFS vs. other spectrographs
  - Spectral resolution/BW vs. science return (Domagal-Goldman & Stark talks)

UV Science Case: O_3 Detection to Identify *Presence* of O_2



LUVOIR Final Report

- UV can tell you whether or not there is O_2, but cannot tell you how much [M. Damiano]
- How deep into the UV do we need to go? Will photometry suffice or do we need a spectrograph?
- Preliminary, independent studies by Mario Damiano and Amber Young suggest going out to 250 nm with a few photometry channels might suffice, pending further investigations

UV Science Case

- **Challenge**: Achieving adequate wavefront control and stability to characterize an adequate # of planets
- **Background**:
  - As state before, contrast/wavefront stability is important in all cases. Restated here to emphasize that it is a harder problem at shorter wavelengths.
  - Going to shorter wavelengths means the same wavefront error in physical dimension becomes a larger fraction of wavelength, leading to a proportionally larger phase error ($\Delta\varphi \sim 1/\lambda$).
  - Also note that speckle intensity scales as $(1/\lambda)^2$.
  - Capabilities/trade from Vis Science Case 1 apply here as well

UV Science Case: Additional Notes

- **Comment on the Impact of Low UV Throughput**
  - A modest rough estimate based on state-of-the-art puts system throughput (from telescope primary mirror to detector output) in the UV at ~ 3%
  - Nature presents us fewer bright targets in the UV compared to vis
  - How many viable UV targets are there?
  - Preliminary UV target list [E. Mamjek, K. Stapelfeldt, D. Savransky] indicate only a modest loss (26%) of viable targets compared to vis, mostly K stars

# of accessible targets (at GALEX NUV band for O3 detection)

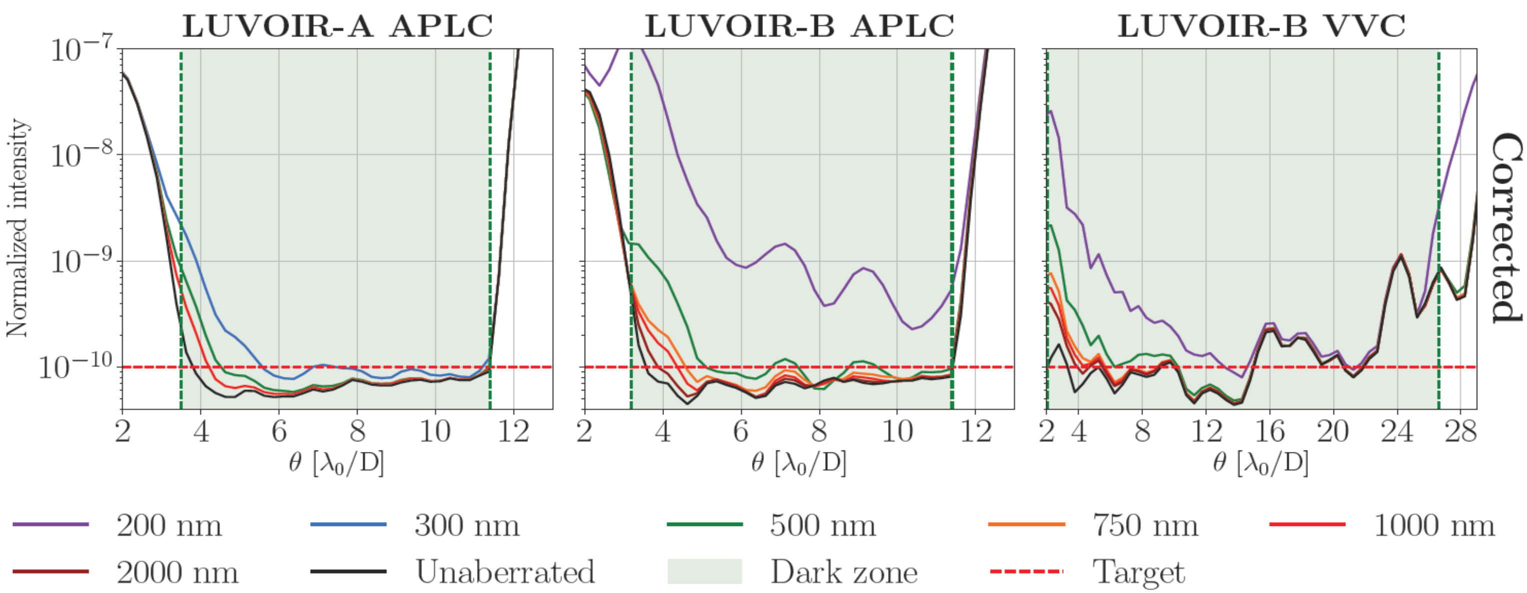
NUV throughput	3%	9%	18%
mag limit (NUV,AB)	35.64	36.84	37.64
N(total stars)	121	150	158*
N(F-type)	66 (max)	66 (max)	66 (max)
N(G-type)	45	55 (max)	55 (max)
N(K-type)	10	29	37
N(M-type)	0	0	0

* at 18% throughput, only missing 6 target stars (all K5V-M2V)

Updated *preliminary* estimates from K. Stapelfeldt & E. Mamajek (6/7/23) -
Thanks to D. Savransky for discussions and analysis related to stellar NUV photometry

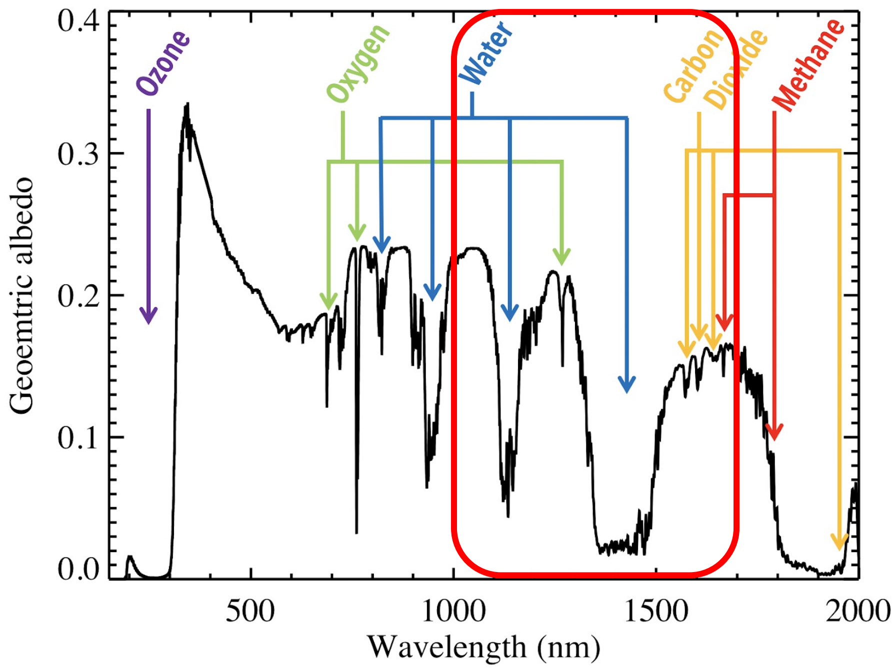
UV Science Case: Additional Notes

- <u>**Comment on Polarization Aberration**</u>
  - Contrast degradation due to polarization aberrations is especially pronounced at short wavelengths. However, the effect projects mainly into low-order aberrations (astigmatism). Thus, degradation occurs mostly at small working angles.
  - Mitigation
    - Most UV targets are at large working angles in terms of λ/D. Coronagraphs can be designed to mitigate effects of polarization aberration
    - 100 mas ➔ 12 λ/D @ λ = 250 nm, D = 6 m



Will & Fienup 2019

Science Case for IR: CO_2 Detection



Signature Science Case #2: Searching for biosignatures and confirming habitability

Science Objective

Search for signs of global biospheres on rocky worlds around Sun-like stars by assessing the chemical state of planet atmospheres. Confirm liquid water.

Description

Measure abundances of key molecules (e.g., H_2O, O_2, O_3, CH_4, CO_2, CO) in the atmospheres of rocky exoplanets via direct spectroscopy. Perform other characterization observations to place the planets in context.

Key Functional Requirements

Inscribed telescope diameter	$\gtrsim$ 6.7 m
Total time	
LUVOIR-A	6.5 months
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CO_2 (1600 nm)	R $\approx$ 200, SNR$\gtrsim$8.5
Astrometric precision for planet masses	<1 µas
Stellar spectroscopy wavelength range	100 nm to 1000 nm

LUVOIR Final Report

Science Case for IR: CO_2 Detection

- **Challenge**: Achieving sufficiently small inner working angle to characterize a sufficient number of planets
  - **Background**
    - 65 mas ➔ 1.2 λ/D @ λ = 1.6 μm, D = 6 m
    - State of the art: ~ 3 λ/D
  - **Potential Mitigation Approaches**
    - Optimize coronagraph design for small IWA
    - Sub-aperture nulling technologies
    - Photonic nulling technologies
    - Larger telescope
- **Challenge**:
  - Attaining sufficiently low detector read noise to achieve required SNR for retrieving gas abundances from observed spectra
  - For IR detectors at T below ~ 120 K read noise typically exceeds dark noise by orders of magnitude
  - **Mitigation Approach**
    - Further develop low-noise IR detector technologies (Crill's talk)

Parting Comments

- **Spectral coverage is a key trade to be conducted**
- **The observatory and coronagraph instrument performance are inextricably coupled and must be designed together**
- Wavefront stability is critical and will require multiple feedback-control systems
  - If using natural guide stars, photon rate imposes hard limits on attainable control bandwidth/gain [Potier et al. 2022]
  - Faster and higher spatial-frequency disturbances both diminish photon counts
- Critical coronagraph capability advancements include WFS&C, photon-counting detectors, throughput, and IWA (esp. in IR)
- High-fidelity integrated models, postprocessing, and manufacturability of optical components are critical as well
- Test facility: Will need to demonstrate **broadband** coronagraph system performance in **vacuum**, with a **dynamic OTA simulator** (Mennesson & Por talk)

Thank you!