HWO and LIFE

Authors:

Mouillet, D.
Laugier, R.

Outline

→ No breaking news but making sure we all share common information

- Missions general architecture
- Science ambition
- On-going development organization
- Technical challenges

Space missions enabling the characterization of exosystems, down to a diversity of temperate rocky planets

- Dozens of systems to be deeply observed:
  - Taking benefit from all prior knowledge on exoplanets and host stars characterization
  - With a strong sorting preference towards nearby stars
- High contrast: Inner Working Angle and Sensitivity as primary drivers of the concept
- Importance of probing various spectral signatures, and both reflected light / thermal emission

- Motivates large-scale space missions (>> L mission), for a wide community,
- Planned on a (short !) 2-decade timescale, and on a world-wide framework

- Expertise legacy from past (space and ground-based !) projects

Mission architectures and instrument concepts

Next generation telescopes and flagship missions are needed

Synergies between different missions and ground-based telescopes for the direct detection of terrestrial exoplanets

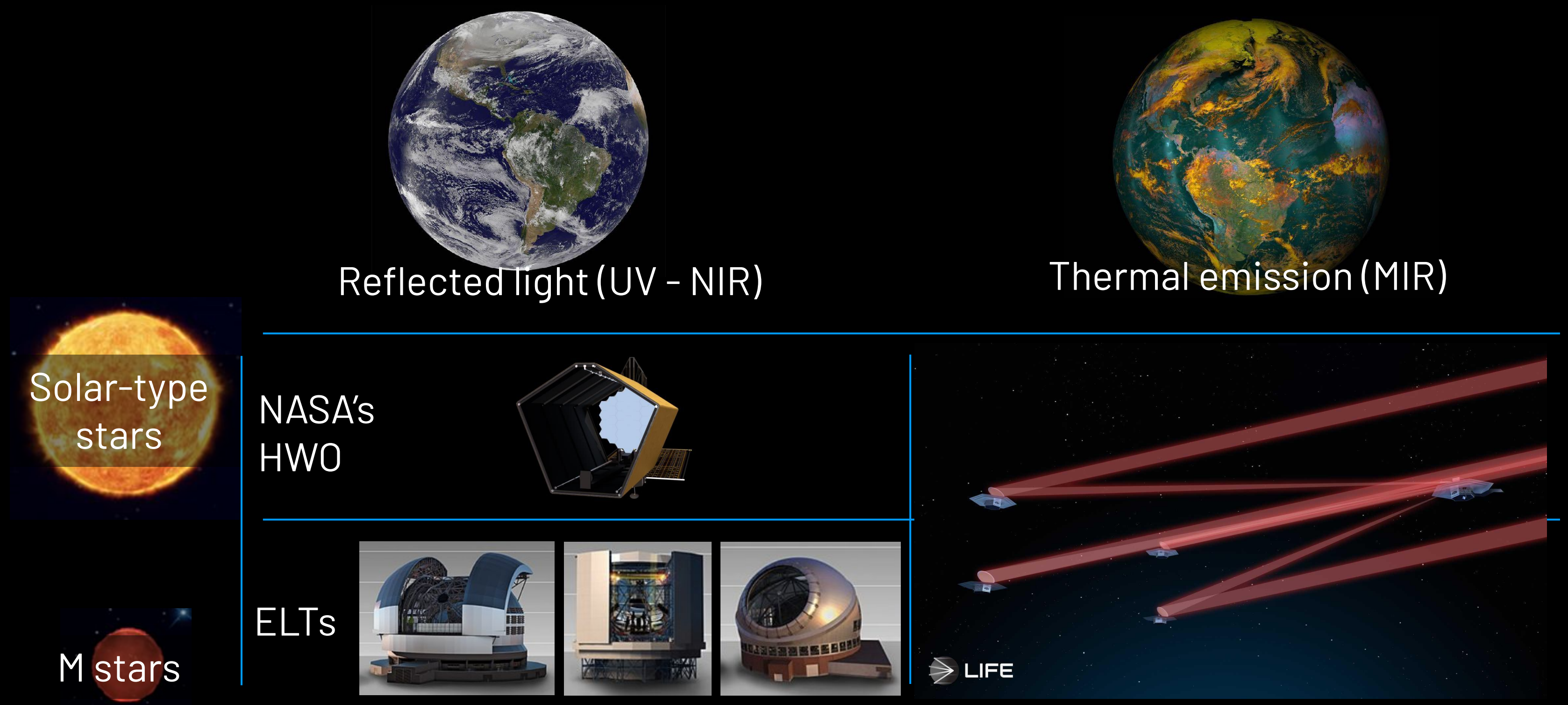
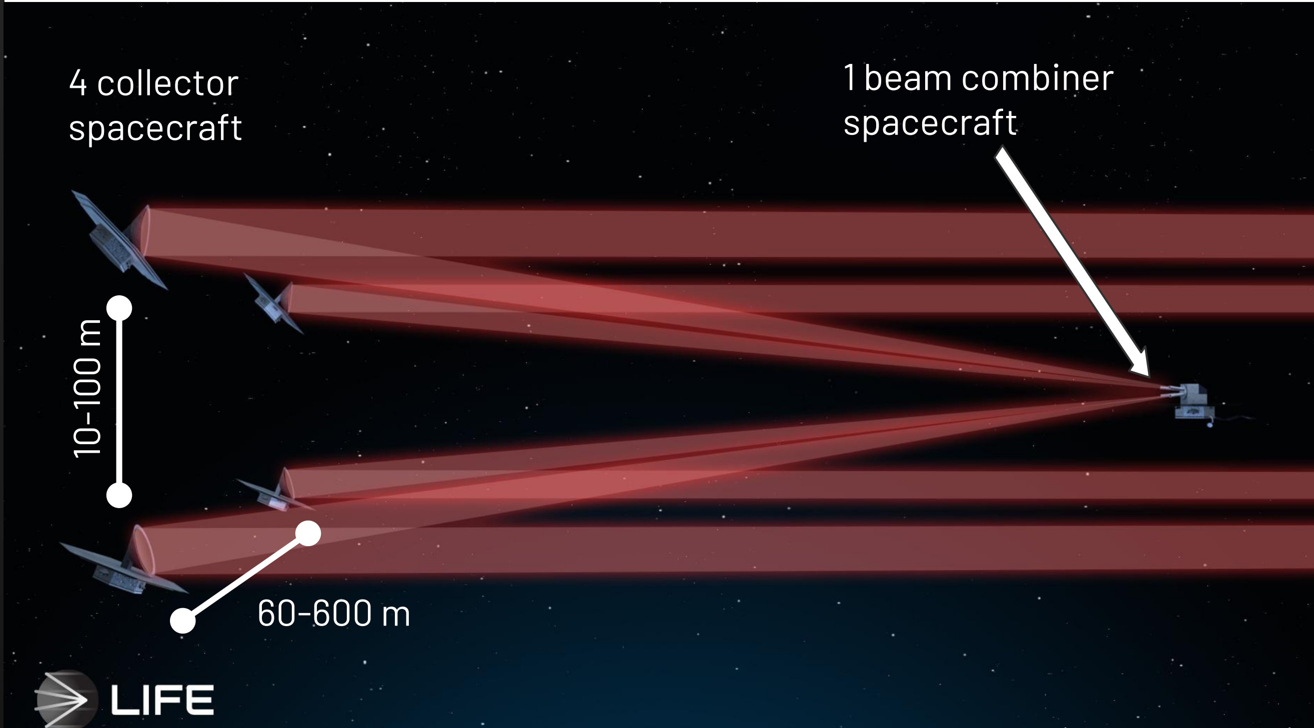


Image credit: NASA, LIFE Initiative, ESO, TMT, GMT

The LIFE mission
initial concept

- LIFE = Large Interferometer For Exoplanets
- ...is a space-based formation-flying mid-infrared (nulling) interferometer
- ...consists of 4 collector spacecraft separated by tens to hundreds of meters and a beam combiner
- ...covers the mid-infrared wavelength range between **~4-18.5 μm** with a spectral resolution of R ~ 100 (tbc)

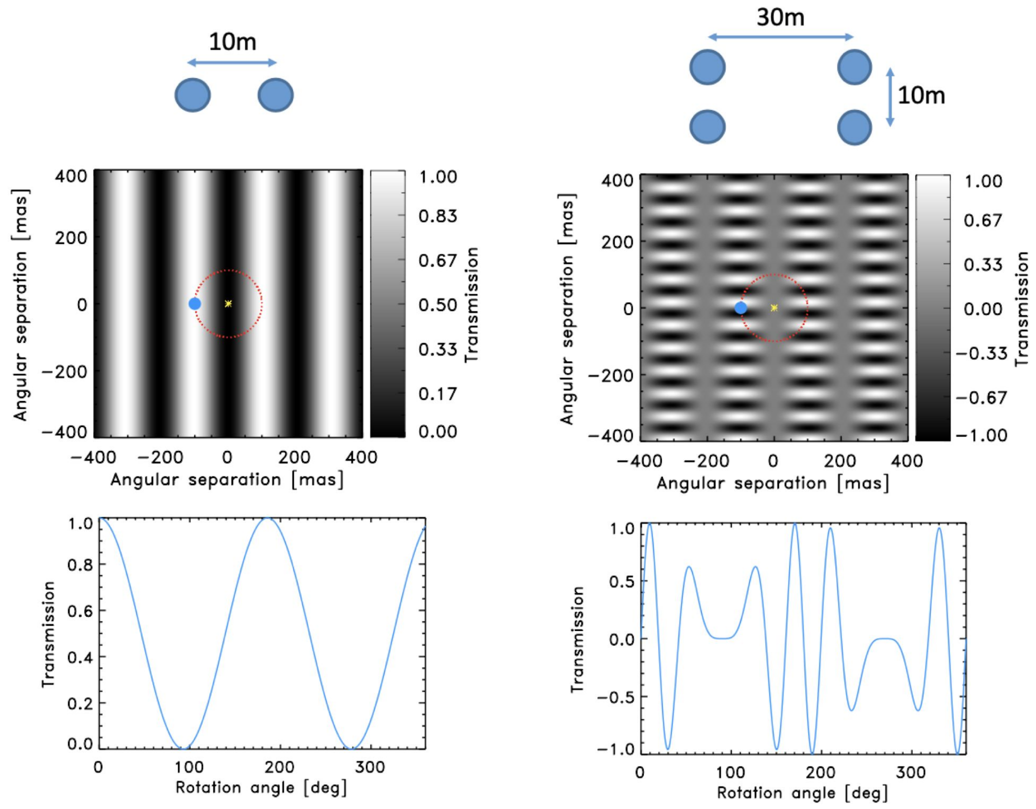


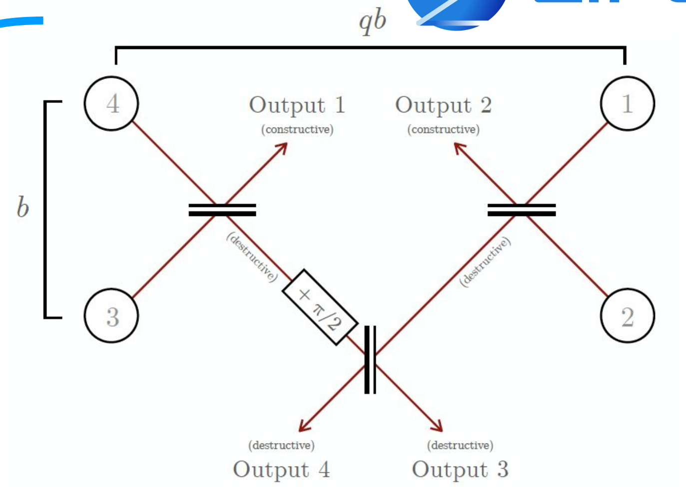
Artist impression of LIFE concept (credit: LIFE initiative)

Quanz et al. A&A 664, A21 (2022)

Nulling Interferometry in a nutshell

Example: Earth-Sun system seen from 10 pc at 10 micron wavelength





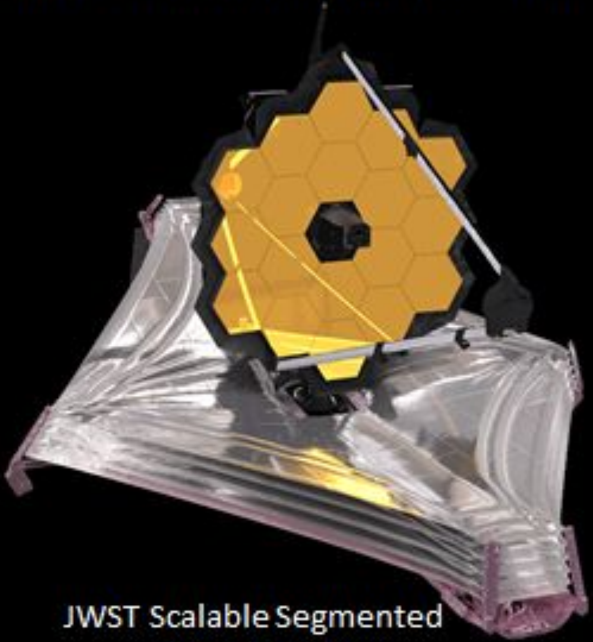
- In one branch, a $\pi/2$ phase shift is introduced to enable the difference map
- Phase chopping between Outputs 3 & 4 makes instrument less susceptible to perturbation

Defrere et al. (2018); Dannert et al. (2022)

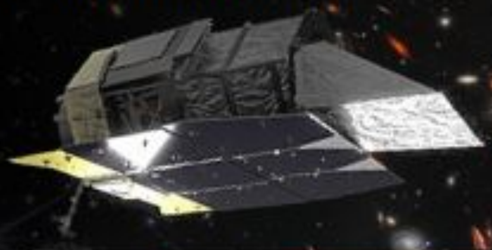
2. Evolve relevant technologies and architecture: Consider previous investments

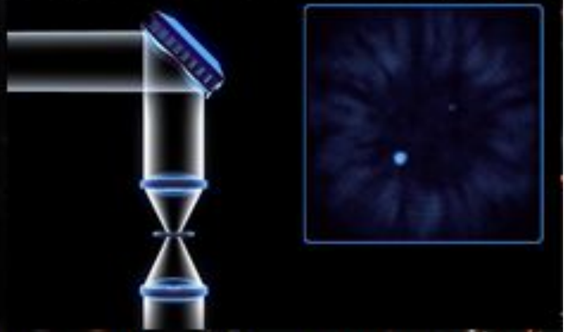
NASA's decades-long investments in developing large space telescopes pay off with awe-inspiring science results

Hubble Space Telescope
UV-Vis-NIR Flagship
Serviceability



JWST Scalable Segmented
Observatory
L2 Operations

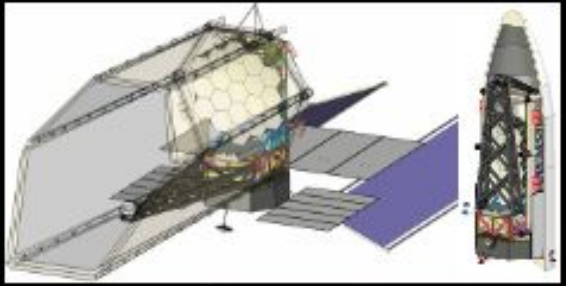




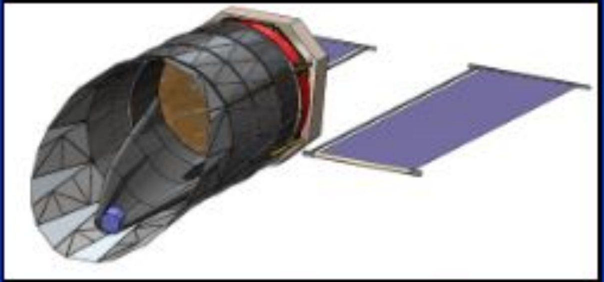
Nancy Grace Roman Space Telescope
High-Contrast Imaging
Vis-NIR Detectors

Focus on new challenges, not inventing new ways to do things we know how to

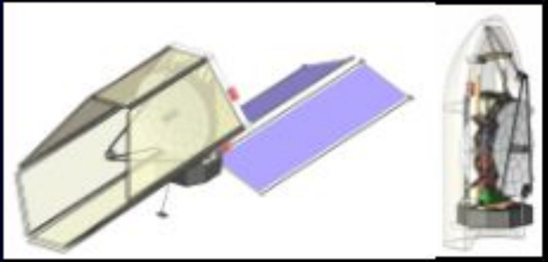
Notional Exploratory Analytic Cases



EAC1	Assumption	Comments
Launch Vehicle	New Glenn	7m diameter Fairing
Mass	Bottoms up estimate	
#of Mirrors	19 Hex Segments	1.65m point to point
Teelscope Diam + Config	Off-Axis, 6M ID/7.2m OD	
Deployment	JWST-like Wings, Hinged tower	



EAC2	Assumptio n	Comments
Launch Vehicle	New Glenn or Starship	9m diameter Fairing
Mass	Bottoms up estimate	
#of Mirrors	6+1	3m central mirror, 6 Keystone
Telescope Diam+Config	Off-Axis, 6m Circ.	
Deployment	SM hinged, Barrel only	



EAC3	Assumptio n	Comments
Launch Vehicle	New Glenn or Starship	9m diameter Fairing
Mass	Bottoms up estimate	
#of Mirrors	34 Keystone	
Telescope Diam+Config	On-Axis, 8m Circ.	Large FOV Hybrid OOFS Guider
Deployment	JWST-like Wing, SM	

HWO PRELIMINARY SPECS & CANDIDATE INSTRUMENTS

Telescope

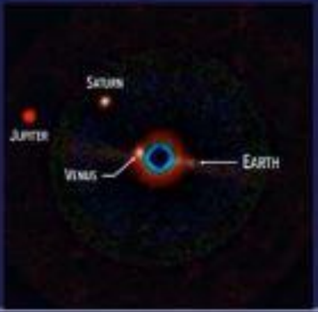
Diameter	6+ meters
Bandpasst	100 nm (TBR)-2500nm
Diffr. Lim. Wavelength, Line of Sight	.5um, .4mas LOS

Integral Field Unit: Ultraviolet, Optical TBD

Coronagraph*

High-contrast imaging and imaging spectroscopy

Bandpass	.35um-1.7um
Contrast	$\lesssim 1 \times 10^{-10}$
$R\ (\lambda/\Delta\lambda)$	Vis: ~140 NIR: ~70, 200



High-Resolution Imager

UV/Vis and NIR imaging

Bandpass	~200–2500 nm
Field-of-View	$\sim 3' \times 2'$

~67 science filters + grism

High-precision astrometry?

UV Multi-Object Spectrograph

UV/Vis multi-object spectroscopy and FUV imaging

Bandpass	~100–1000 nm
Field-of-View	$\sim 2' \times 2'$
Apertures	$\sim 840 \times 420$
$R\ (\lambda/\Delta\lambda)$	500–50,000

NUV High Contrast Instrument from 250nm Ozone: TBD

GSFC-5500)

Note: Expect instrument suite to iterate, some may be 2nd generation

LIFE
LARGE INTERFEROMETER FOR EXOPLANETS

Habitable Worlds OBSERVATORY

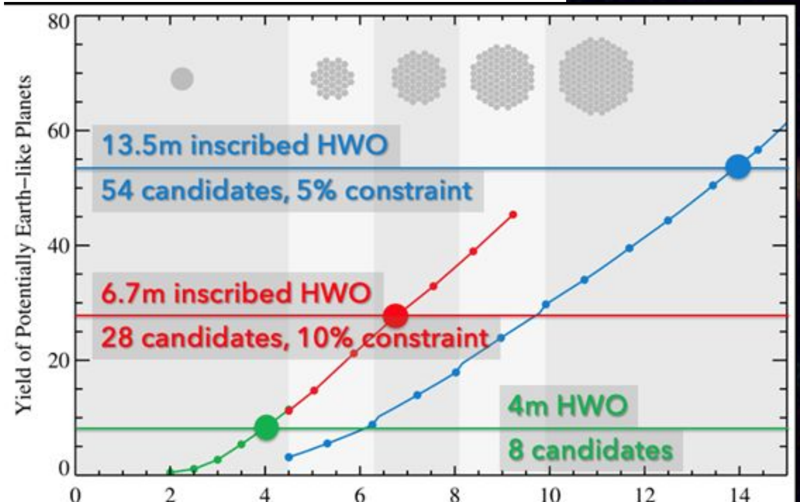
Exoplanet science ambitions

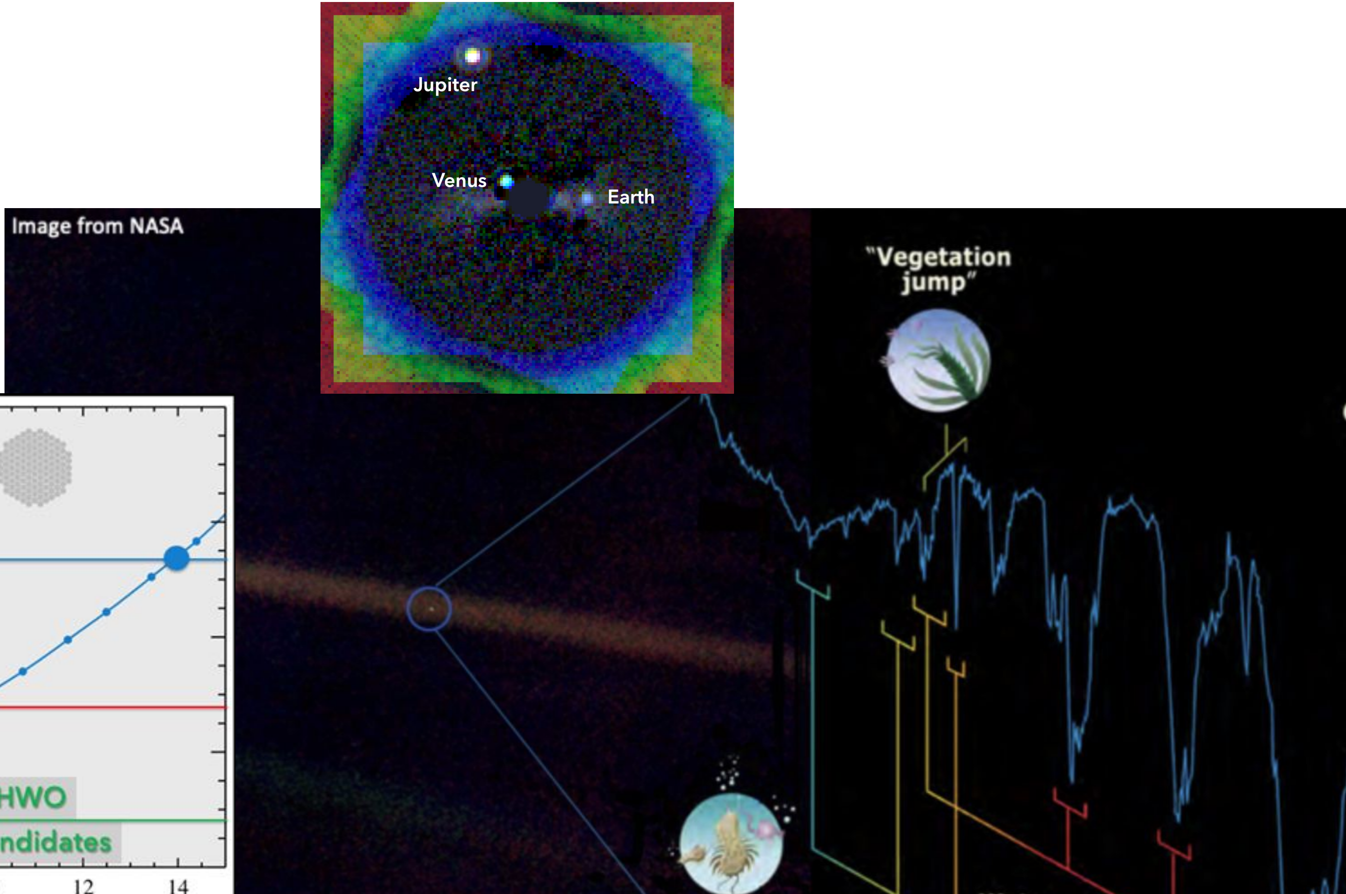
HWO: a wide-community observatory

Main Science case working groups:

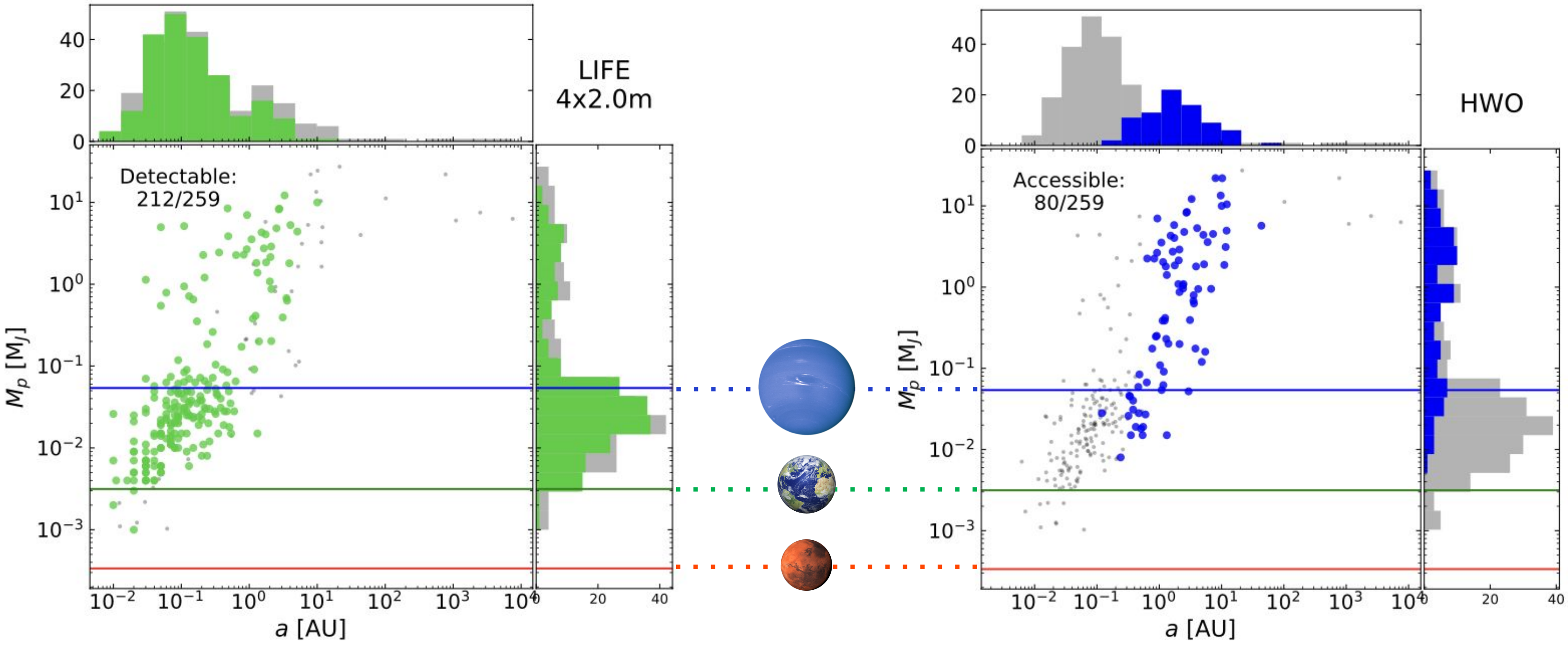
- **Galaxy growth** (IGM, AGN, ionizing, dark sector)
- **Evolution of elements**
  (stars pop & formation, explosions)
- **Solar system in context**
  (solar system, exosystems: demographics, characterization, formation-evolution)
- **Living worlds**
  (biosignatures possibilities / interpretation, target stars)

HWO driven by the most demanding exoplanetary driver



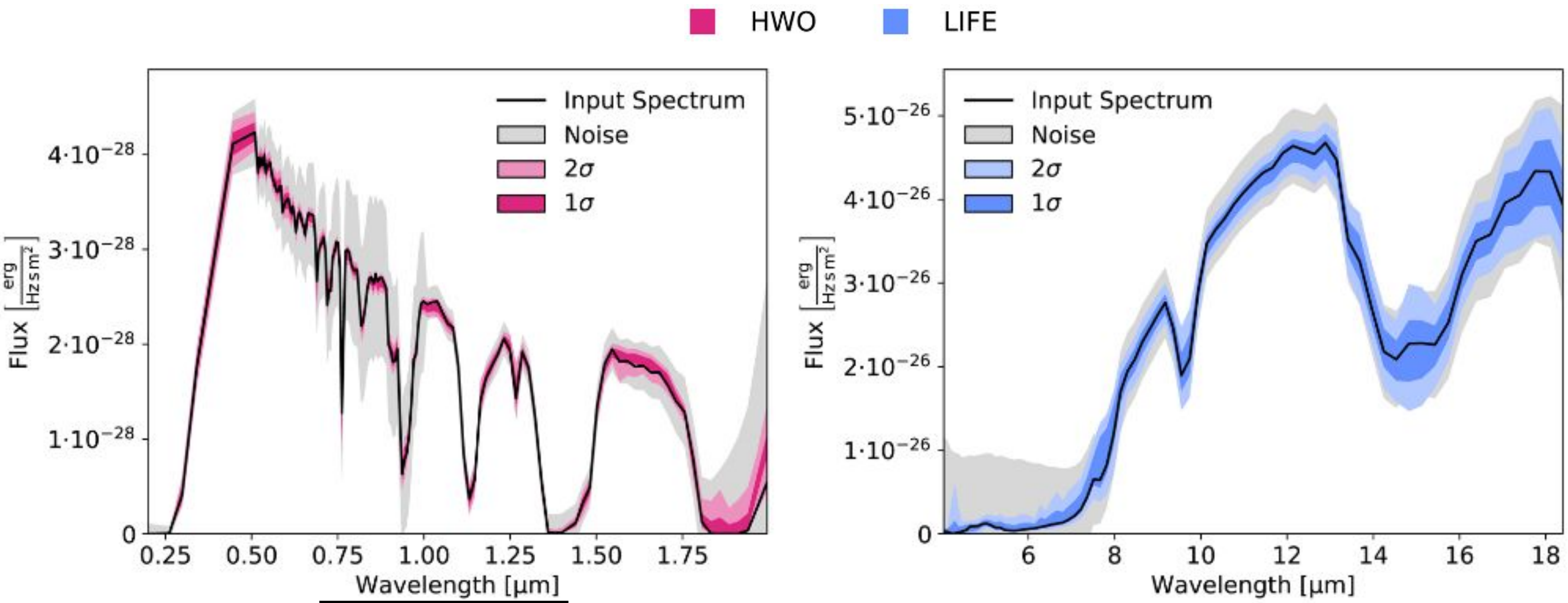


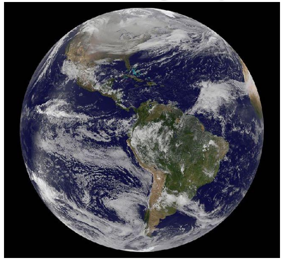
Characterizing known planets from day 1



Carrión-González et al. (2023)

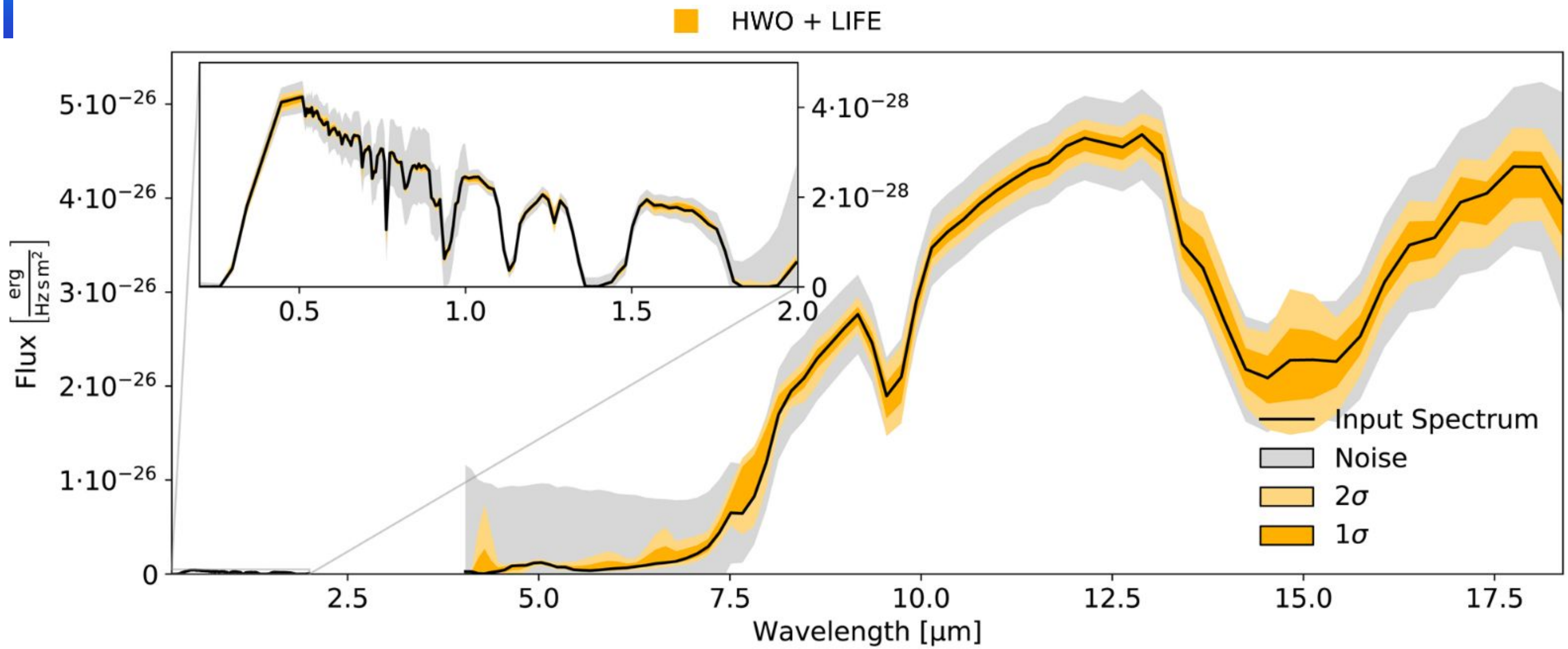
Synergy in atmospheric retrieval





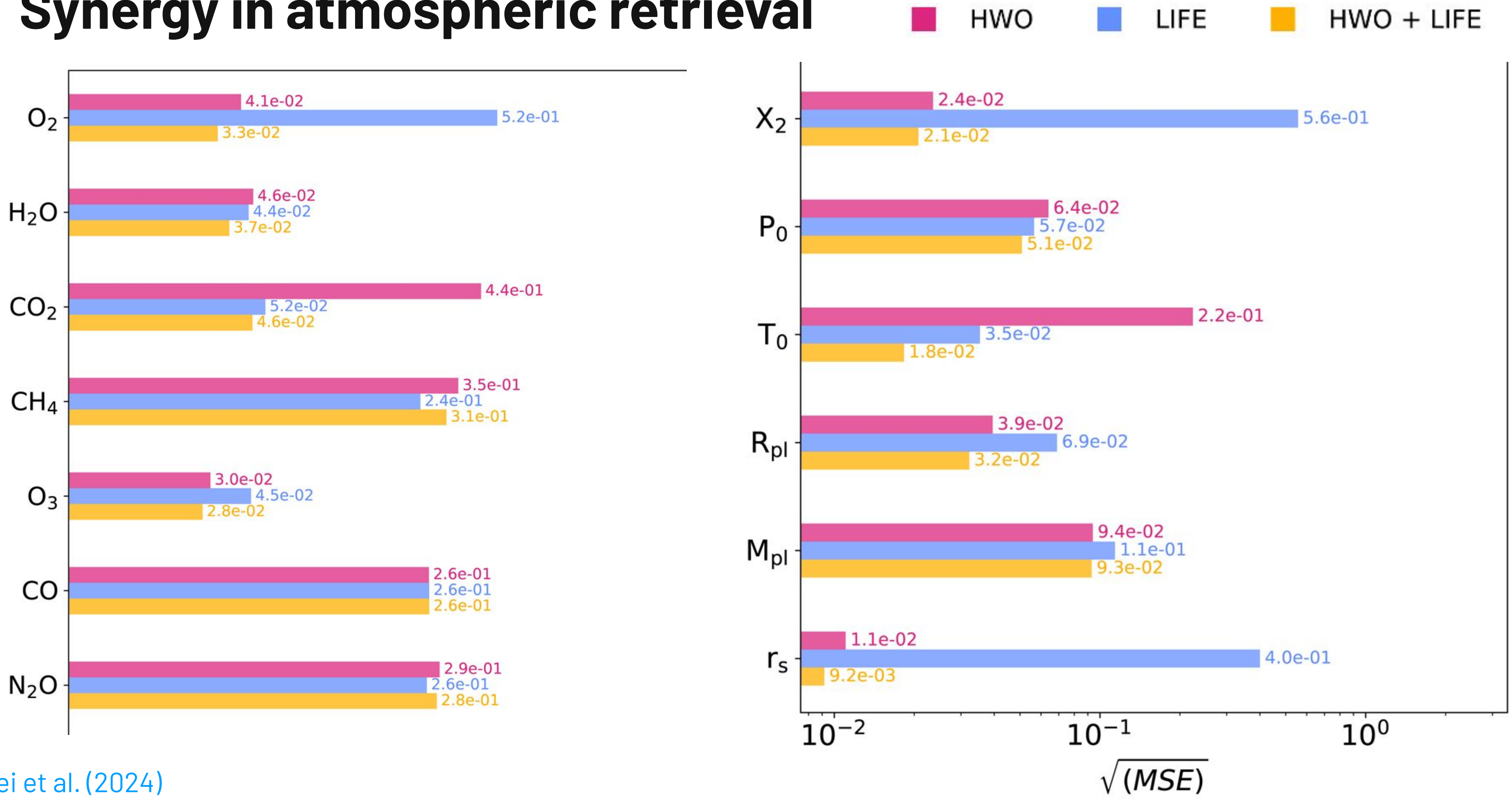
Alei et al. (2024)

Synergy in atmospheric retrieval



Alei et al. (2024)

Synergy in atmospheric retrieval



Alei et al. (2024)

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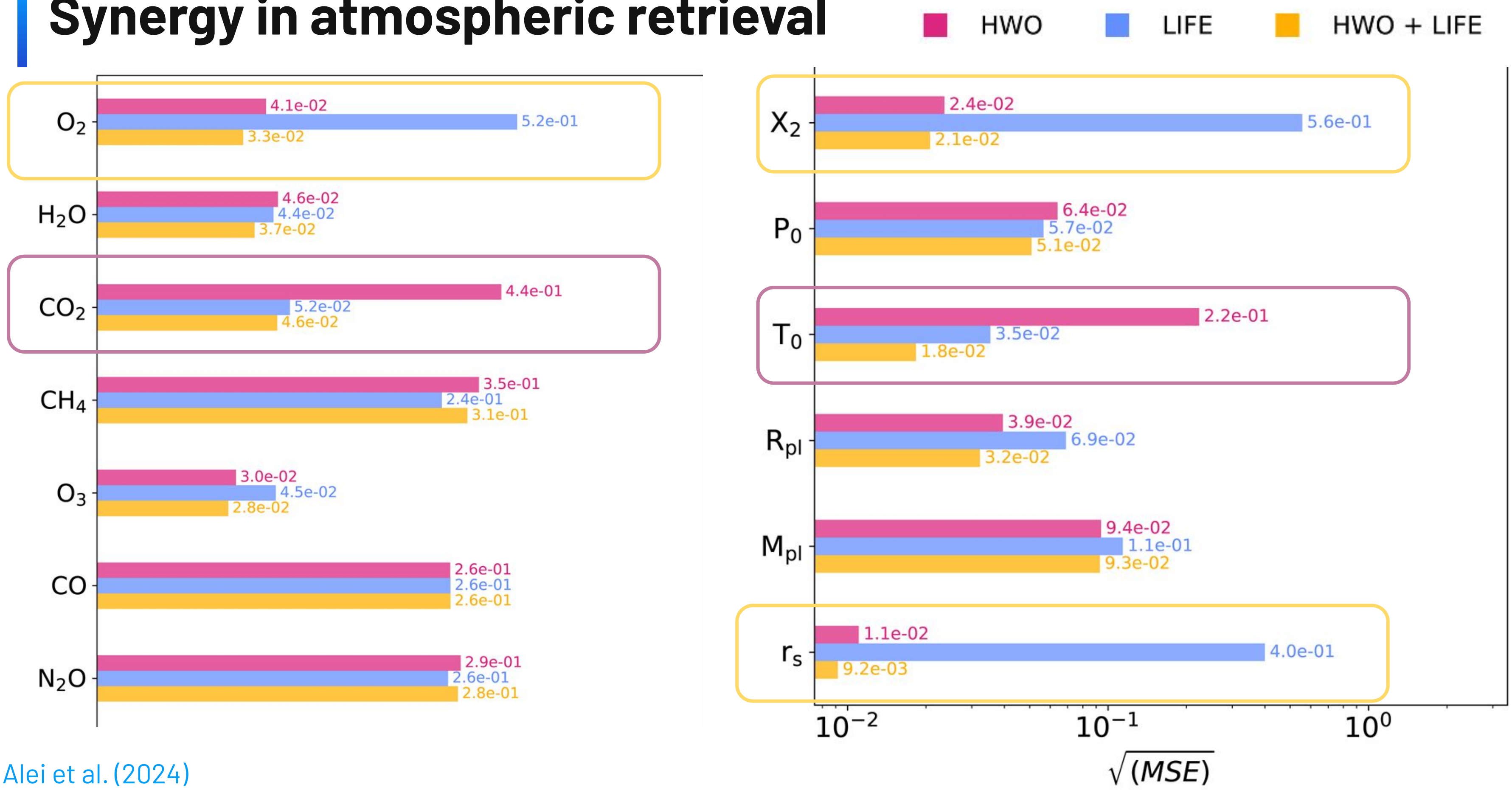

Alei et al. (2024)

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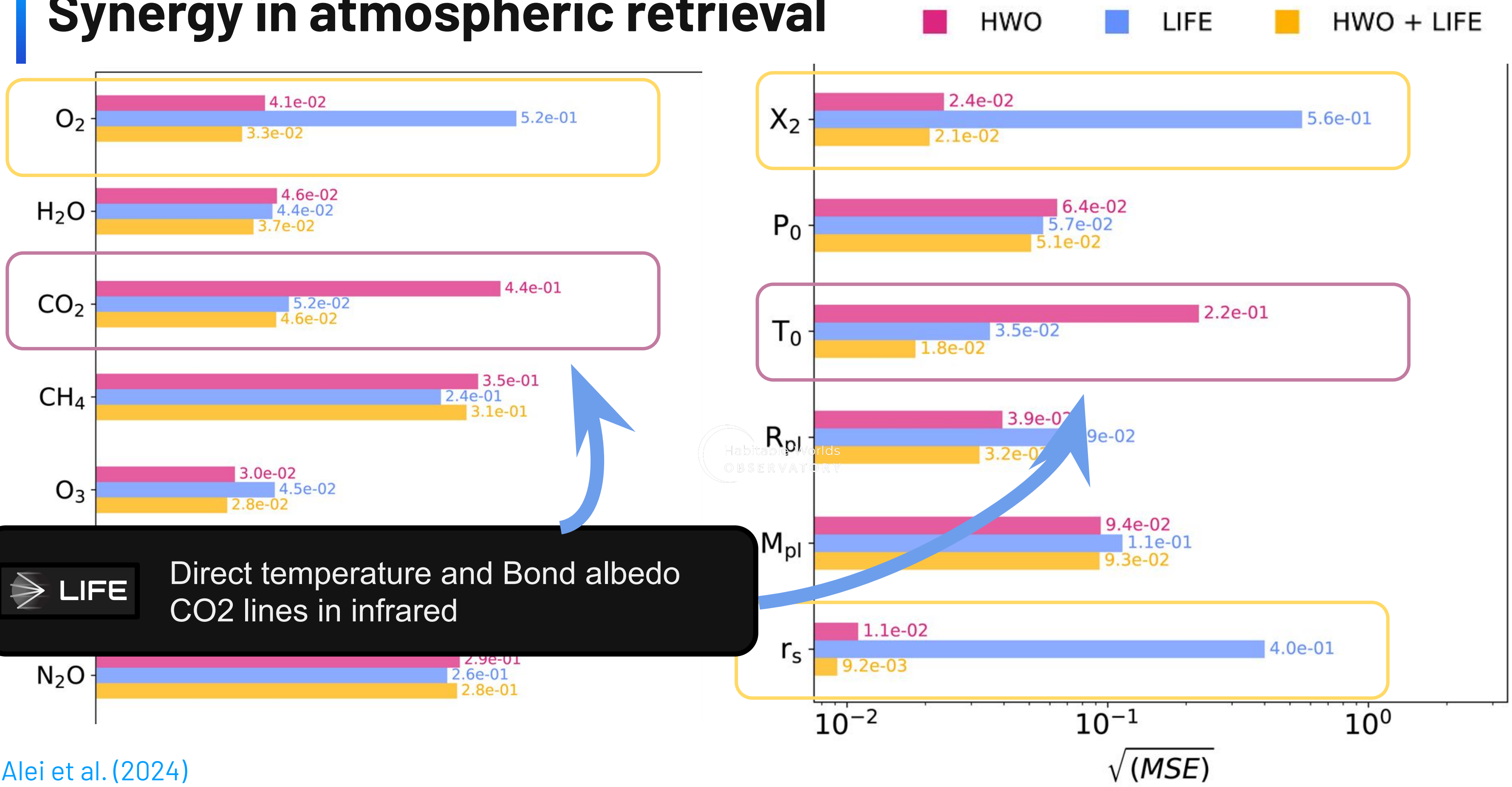
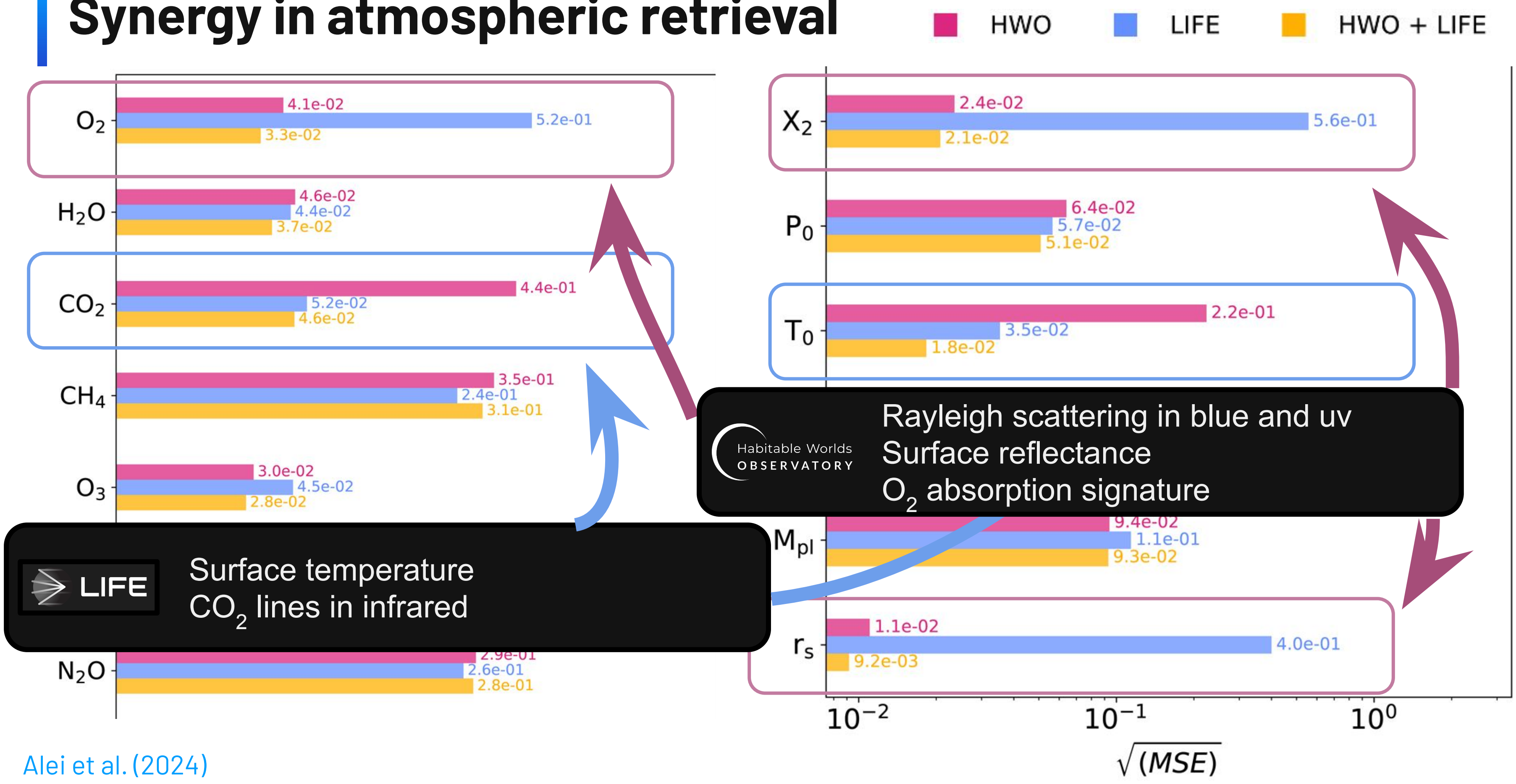


LIFE

Direct temperature and Bond albedo
CO2 lines in infrared

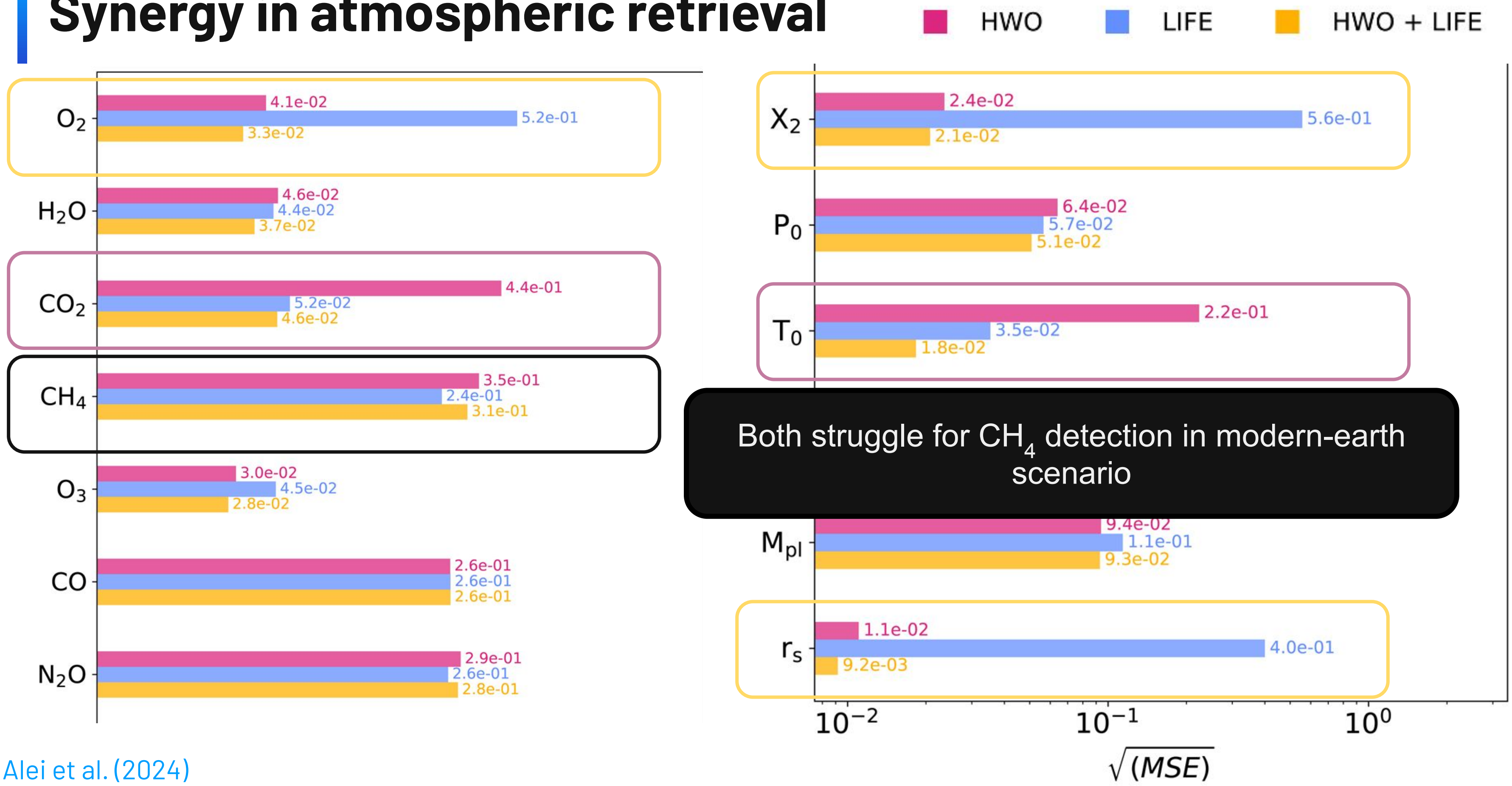
Alei et al. (2024)

Synergy in atmospheric retrieval



Alei et al. (2024)

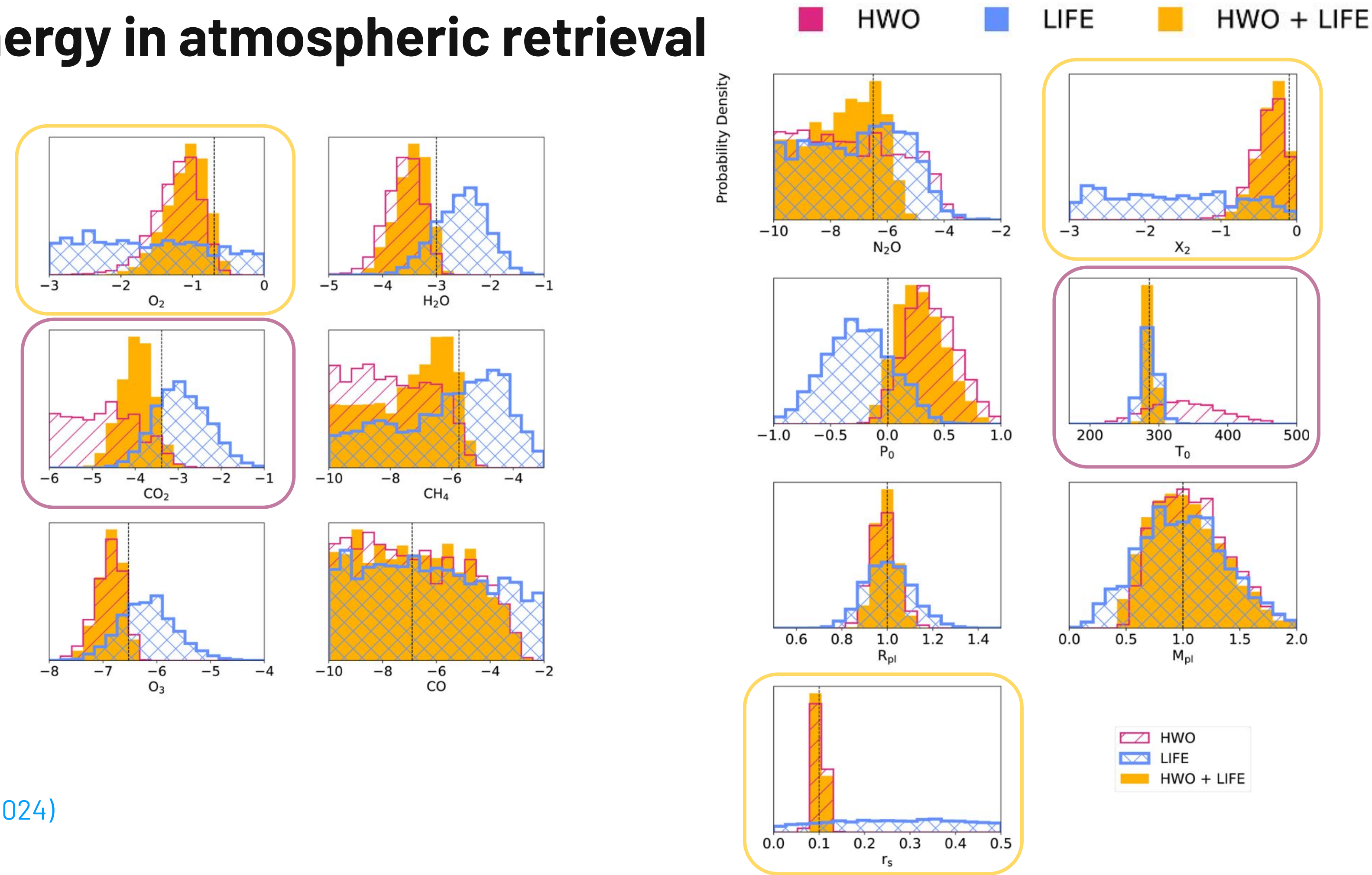
Synergy in atmospheric retrieval



Both struggle for CH_4 detection in modern-earth scenario

Alei et al. (2024)

Synergy in atmospheric retrieval



Alei et al. (2024)

LIFE
LARGE INTERFEROMETER FOR EXOPLANETS

Habitable Worlds
OBSERVATORY

Development organization

Long-awaited ESA follow-through

The community strongly pushes for the complementary **need for both** reflected light and thermal emission

ESA Senior Committee Report; June 2021

"Therefore, launching a Large mission enabling the characterisation of the **atmosphere of temperate exoplanets *in the mid-infrared* should be a top priority for ESA** within the Voyage 2050 timeframe."

"[…] measure a **spectrum of the direct thermal emission of a temperate exoplanet** in the mid infrared **would be an outstanding breakthrough** that could lead to yet again another paradigm-shifting discovery."

*"The next generation of large space observatories – all of which are well beyond the financial envelope of an ESA Large mission – will tackle a wide range of very important open problems in astrophysics. This is why **contributions** at the level of an **ESA Medium mission to such a large-size space telescope** are of great significance and value to the ESA programme in the time frame of Voyage 2050"*

*A mission specifically focusing on the Characterisation of Temperate Exoplanets would be transformational and of great interest to scientists and to the public alike. The Senior Committee considers a mission on the **Characterisation of Temperate Exoplanets to have a higher scientific priority**. However, since an informed down-selection is not currently possible with the available information, the committee specifically recommends that a **study be carried out before selection**.*

"Soutien **majeur à la définition et au développement** de **HWO** (Nasa/2040) et **Life** (Esa/2045) en valorisant l'expertise française pour PLATO, Ariel et Roman-ST"

"Soutien modéré à des **missions précurseur de Life**"

CNES SPS 2024

Exobiologie, exoplanètes, protection planétaire. 2024

(+ voir aussi soutien autre groupe thématique)

Aiming at a launch in 2040 we consider 3 development stages

LIFE

Stage 1: Preparation
Today - 2028

- Conclusion of **mission concept study** and development plan with **academic and industry partners**
- Successful demonstration of LIFE **measuring principle in the lab**
- Significant maturation of key technologies, in particular **mid-infrared photonics**, **cryogenic optics** and **detectors**

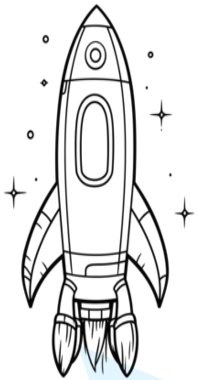
Stage 2: Maturation
2029 - 2033

- Conclusion of **mission design**
- **Maturation and demonstration** of sub-system performance, e.g., formation flying, interferometric nulling

Stage 3: Implementation
2034-2040

- **Manufacturing / Integration of spacecraft**
- Securing of launch opportunity
- Setting up of ground-segment, mission operations, and data center

Launch



We keep pushing forward

Cannot wait for the involvement of ESA

- **Team 1 Project office** : Coordination and support (contact Daniel Angerhausen)
- **Team 2 "Science"** : Continues to explore science cases; everybody is invited to participate in these activities.
- **Team 3 Instrument science** : Refining yield and performance vs design relationship for requirement
- **Team 4 Technology** : Identification and maturation of technical concepts

Ongoing fundraising for the Concept Study and technology development program

From Sascha Quanz, 2024-11-21

HWO: involving a very wide community

Starting with a very open world-wide contribution to mission working groups

SCIENCE

Living Worlds	-	WG Co-Chair	Arney	Giada	NASA GSFC
Living Worlds	-	WG Co-Chair	Parenteau	Niki	NASA ARC
Living Worlds	Biosignature Possibilities	SG Co-Chair	Schwieterman	Eddie	UC Riverside
Living Worlds	Biosignature Possibilities	SG Co-Chair	Sara	Walker	Arizona State Univ.
Living Worlds	Biosignature Interpretation	SG Co-Chair	Olson	Stephanie	Purdue Univ.
Living Worlds	Biosignature Interpretation	SG Co-Chair	Krissansen-Totton	Josh	Univ. Washington
Living Worlds	Target Stars & Systems	SG Co-Chair	Mamajek	Eric	ExEP / JPL
Living Worlds	Target Stars & Systems	SG Co-Chair	Hinkel	Natalie	Louisiana State Univ.
Evolution of Elements	-	WG Co-Chair	Lee	Janice	STScI
Evolution of Elements	-	WG Co-Chair	Scowen	Paul	NASA GSFC
Evolution of Elements	Stars & Stellar Populations	SG Co-Chair	Senchyna	Peter	Carnegie Observatories
Evolution of Elements	Stars & Stellar Populations	SG Co-Chair	Barstow	Martin	Leicester
Evolution of Elements	Star Formation	SG Co-Chair	Salim	Samir	Indiana U
Evolution of Elements	Star Formation	SG Co-Chair	Paladini	Roberta	IPAC-Caltech
Evolution of Elements	Cosmic Explosions	SG Co-Chair	Burns	Eric	Louisiana State Univ.
Evolution of Elements	Cosmic Explosions	SG Co-Chair	Andrews	Jennifer	Gemini-North / NOIRLab
Galaxy Growth	-	WG Co-Chair	Ravindranath	Swara	COR
Galaxy Growth	-	WG Co-Chair	Postman	Marc	STScI
Galaxy Growth	IGM & ICM	SG Co-Chair	Borthakur	Sanchayeeta	Arizona State Univ.
Galaxy Growth	IGM & ICM	SG Co-Chair	Burchett	Joe	New Mexico State Univ.
Galaxy Growth	AGN	SG Co-Chair	Packham	Chris	UTSA
Galaxy Growth	AGN	SG Co-Chair	U	Vivian	UC Irvine
Galaxy Growth	Ionizing Photons	SG Co-Chair	McCandliss	Stephen	Johns Hopkins Univ.
Galaxy Growth	Ionizing Photons	SG Co-Chair	Strom	Allison	Northwestern U
Galaxy Growth	Dark Sector	SG Co-Chair	Rhodes	Jason	JPL
Galaxy Growth	Dark Sector	SG Co-Chair	Massey	Richard	Durham Univ.
Solar System in Context	-	WG Co-Chair	Robinson	Tyler	Univ. Arizona
Solar System in Context	-	WG Co-Chair	Shkolnik	Evgenya	Arizona State Univ.
Solar System in Context	Characterizing Exoplanets	SG Co-Chair	Hu	Renyu	JPL
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Solar System in Context	Demographics & Architectures	SG Co-Chair	Christiansen	Jessie	Caltech/IPAC-NExScI
Solar System in Context	Demographics & Architectures	SG Co-Chair	Rice	Malena	Yale Univ.
Solar System in Context	Birth & Evolution	SG Co-Chair	MacGregor	Meredith	Johns Hopkins Univ.
Solar System in Context	Birth & Evolution	SG Co-Chair	Hasegawa	Yasuhiro	JPL

JOINT

Science Case Simulation	Merging with Science Data Simul	WG Co-Chair	Batalha	Natasha	NASA ARC
Science Case Simulation	Merging with Science Data Simul	WG Co-Chair	Osten	Rachel	STScI
Science Case Simulation	Astrometry	SG Co-Chair	Gaudi	Scott	Ohio State Univ
Science Case Simulation	Astrometry	SG Co-Chair	Reylé	Céline	Besançon Obervatory
Science Case Simulation	Exoplanet Yields	SG Co-Chair	Savransky	Dmitry	Cornell
Science Case Simulation	Exoplanet Yields	SG Co-Chair	Stark	Chris	GSFC
Science Case Simulation	UV Galaxy Evolution	SG Co-Chair	Hodges-Kluck	Edmund	NASA GSFC
Science Case Simulation	UV Galaxy Evolution	SG Co-Chair	Boquien	Médéric	Université Côte d'Azur
Science Case Simulation	Exoplanet Characterization	SG Co-Chair	–	–	–
Science Case Simulation	Exoplanet Characterization	SG Co-Chair	–	–	–
Science Data Simulation	Merging with Science Case Simul	WG Co-Chair	Greene	Tom	NASA ARC
Science Data Simulation	Merging with Science Case Simul	WG Co-Chair	Tumlinson	Jason	STScI
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Science Data Simulation	High-Contrast	SG Co-Chair	Macintosh	Bruce	UC Observatories
Science Data Simulation	UV	SG Co-Chair	France	Kevin	CU Boulder
Science Data Simulation	UV	SG Co-Chair	Tuttle	Sarah	Univ. Washington
Science Data Simulation	Wide-Field Imaging	SG Co-Chair	Malhotra	Sangeeta	NASA GSFC
Science Data Simulation	Wide-Field Imaging	SG Co-Chair	Pierre-Olivier	Lagage	Commissariat à l'Energie A
Sci-Eng Interface	-	WG Co-Chair	Morrissey	Patrick	JPL
Sci-Eng Interface	-	WG Co-Chair	Sitarski	Breann	NASA GSFC
AI/ML	-	WG Co-Chair	Ansdell	Megan	NASA HQ
AI/ML	-	WG Co-Chair	Dean	Bruce	NASA GSFC

COMMUNITY

Inclusion-Mentoring	-	WG Co-Chair	Scannapieco	Evan	Arizona State Univ.
Inclusion-Mentoring	-	WG Co-Chair	Beaton	Rachael	STScI
Inclusion-Mentoring	Inclusion	WG Co-Chair	Mahadevan	Suvrath	Pennsylvania State Univ.
Inclusion-Mentoring	Inclusion	WG Co-Chair	Miles	Drew	CalTech
Inclusion-Mentoring	Inclusion	Emerging Leader	Washington	Robert	Howard Univ.
Inclusion-Mentoring	Mentoring	WG Co-Chair	Tran	Kim-Vy	Center for Astrophysics
Inclusion-Mentoring	Mentoring	WG Co-Chair	Renaud	Joe	NASA GSFC
Inclusion-Mentoring	Mentoring	Emerging Leader	Gonzalez Quiles	Junellie	Johns Hopkins Univ.
Ground-based Astro	-	WG Co-Chair	Miyazaki	Satoshi	JAXA
Ground-based Astro	-	WG Co-Chair	Lopez-Morales	Mercedes	Center for Astrophysics
Space-based Astro	-	WG Co-Chair	Petre	Rob	NASA GSFC
Space-based Astro	-	WG Co-Chair	Kataria	Tiffany	JPL
Space-based Astro	-	WG Deputy Co-Chair	Louden	Emma	Yale Univ.
GOMAP Synergies	-	WG Co-Chair	Gaskin	Jessica	NASA MSFC
GOMAP Synergies	-	WG Co-Chair	Oschmann	Jim	Marinus Consulting LLC

TECHNOLOGY

Integrated Modeling Stan	Model Standards & Uncertainty Q	SG Co-Chair	Bailey	Erik	JPL
Integrated Modeling Stan	Model Standards & Uncertainty Q	SG Co-Chair	Govern	James	NASA GSFC
Integrated Modeling New	New Methods & Collaborative En	SG Co-Chair	Derleth	Jason	NASA GSFC
Integrated Modeling New	New Methods & Collaborative En	SG Co-Chair	Kuan	Gary	JPL
Servicing	-	WG Co-Chair	Grunsfeld	John	Self
Servicing	-	WG Co-Chair	Van Campen	Julie	NASA GSFC
High-Contrast Post-Proc	High-Contrast Post-Processing &	SG Co-Chair	Mawet	Dimitri	JPL
High-Contrast Post-Proc	High-Contrast Post-Processing &	SG Co-Chair	McElwain	Mike	NASA GSFC

And formal representatives from Canada, Japan, ESA

HWO: involving a very wide community

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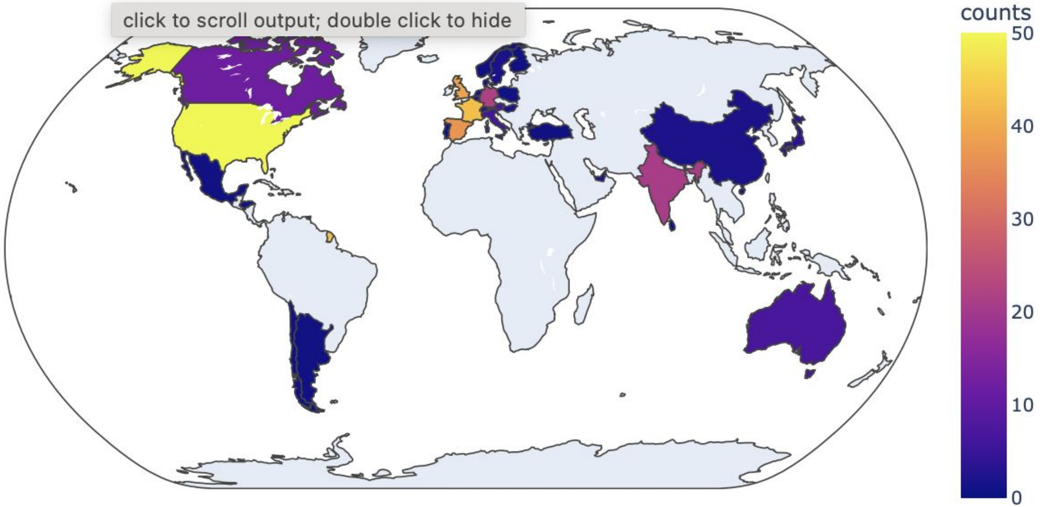

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Science Data Simulation	UV	SG Co-Chair	Tuttle	Sarah	Univ. Washington
Science Data Simulation	Wide-Field Imaging	SG Co-Chair	Malhotra	Sangeeta	NASA GSFC
Science Data Simulation	Wide-Field Imaging	SG Co-Chair	Pierre-Olivier	Lagage	Commissariat à l'Energie A
Sci-Eng Interface	-	WG Co-Chair	Morrissey	Patrick	JPL
Sci-Eng Interface	-	WG Co-Chair	Sitarski	Breann	NASA GSFC
AI/ML	-	WG Co-Chair	Ansdell	Megan	NASA HQ
AI/ML	-	WG Co-Chair	Dean	Bruce	NASA GSFC

COMMUNITY

Inclusion-Mentoring	-	WG Co-Chair	Scannapieco	Evan	Arizona State Univ.
Inclusion-Mentoring	-	WG Co-Chair	Beaton	Rachael	STScI
Inclusion-Mentoring	Inclusion	WG Co-Chair	Mahadevan	Suvrath	Pennsylvania State Univ.
Inclusion-Mentoring	Inclusion	WG Co-Chair	Miles	Drew	CalTech
Inclusion-Mentoring	Inclusion	Emerging Leader	Washington	Robert	Howard Univ.
Inclusion-Mentoring	Mentoring	WG Co-Chair	Tran	Kim-Vy	Center for Astrophysics
Inclusion-Mentoring	Mentoring	WG Co-Chair	Renaud	Joe	NASA GSFC
Inclusion-Mentoring	Mentoring	Emerging Leader	Gonzalez Quiles	Junellie	Johns Hopkins Univ.
Ground-based Astro	-	WG Co-Chair	Miyazaki	Satoshi	JAXA
Ground-based Astro	-	WG Co-Chair	Lopez-Morales	Mercedes	Center for Astrophysics
Space-based Astro	-	WG Co-Chair	Petre	Rob	NASA GSFC
Space-based Astro	-	WG Co-Chair	Kataria	Tiffany	JPL
Space-based Astro	-	WG Deputy Co-Chair	Louden	Emma	Yale Univ.
GOMAP Synergies	-	WG Co-Chair	Gaskin	Jessica	NASA MSFC
GOMAP Synergies	-	WG Co-Chair	Oschmann	Jim	Marinus Consulting LLC

TECHNOLOGY

Integrated Modeling Stan	Model Standards & Uncertainty Qu	SG Co-Chair	Bailey	Erik	JPL
Integrated Modeling Stan	Model Standards & Uncertainty Qu	SG Co-Chair	Govern	James	NASA GSFC
Integrated Modeling New	New Methods & Collaborative Env	SG Co-Chair	Derleth	Jason	NASA GSFC
Integrated Modeling New	New Methods & Collaborative Env	SG Co-Chair	Kuan	Gary	JPL
Servicing	-	WG Co-Chair	Grunsfeld	John	Self
Servicing	-	WG Co-Chair	Van Campen	Julie	NASA GSFC
High-Contrast Post-Proc	High-Contrast Post-Processing &	SG Co-Chair	Mawet	Dimitri	JPL
High-Contrast Post-Proc	High-Contrast Post-Processing &	SG Co-Chair	McElwain	Mike	NASA GSFC

And formal representatives from Canada, Japan, ESA

HWO: involving a very wide community

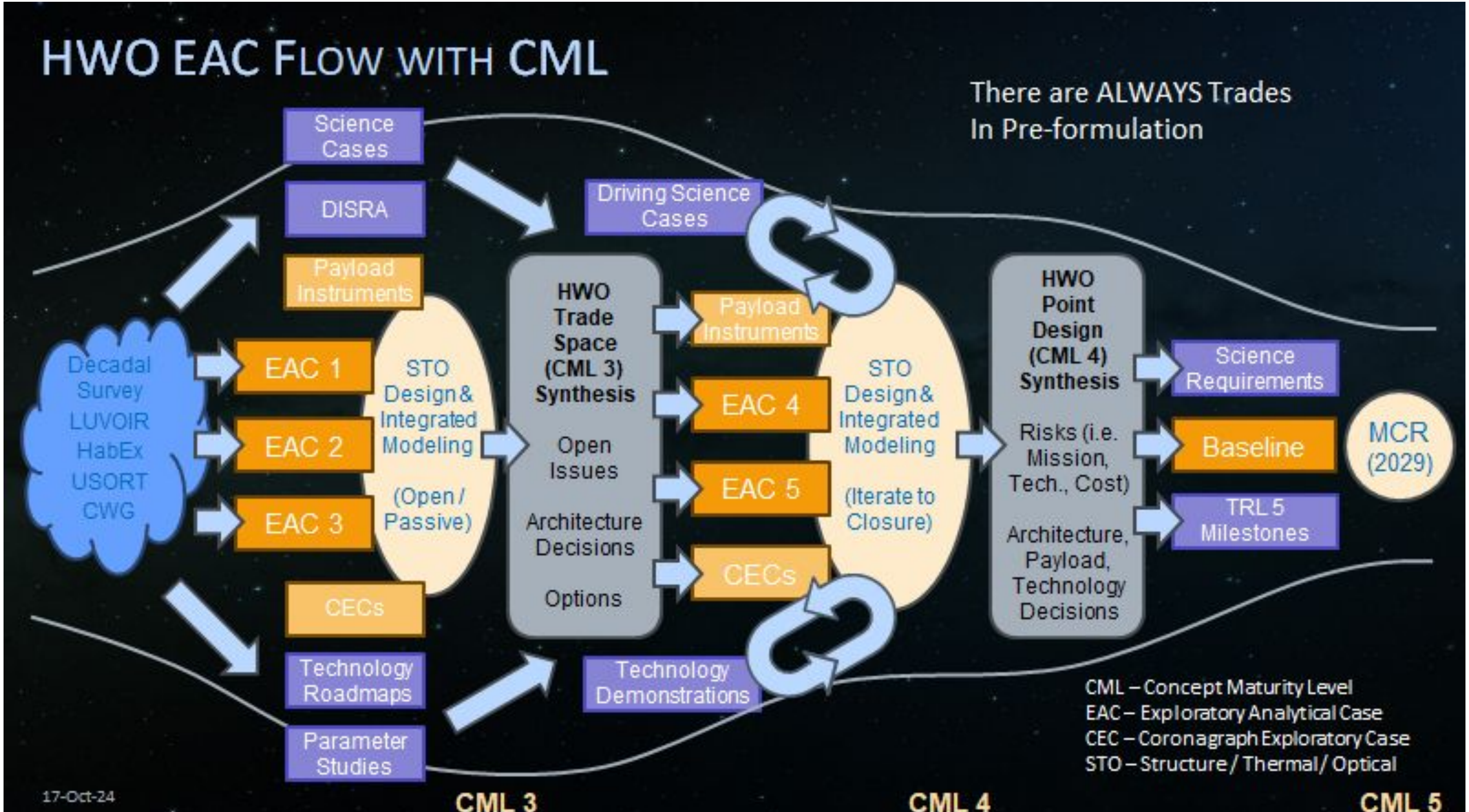
Starting with a very open world-wide contribution to mission working groups

Contributions welcome and encouraged

- Discussions directly at **agencies** level (ESA) , and/or for bilateral collaboration (eg **countries**)
-
- Some **instrument lead, or significant part** of instrument
- Knowledge of **industrial** specific expertise (complementary to US)
- **Collaboration of teams/institutes** on specific field of expertise: team-to-team collaborations
- **Individual** contributions

Explicit request from L. Feinberg for a panorama of European field of expertise/interest, potential collaboration or investment.

HWO: a schedule-driven organization

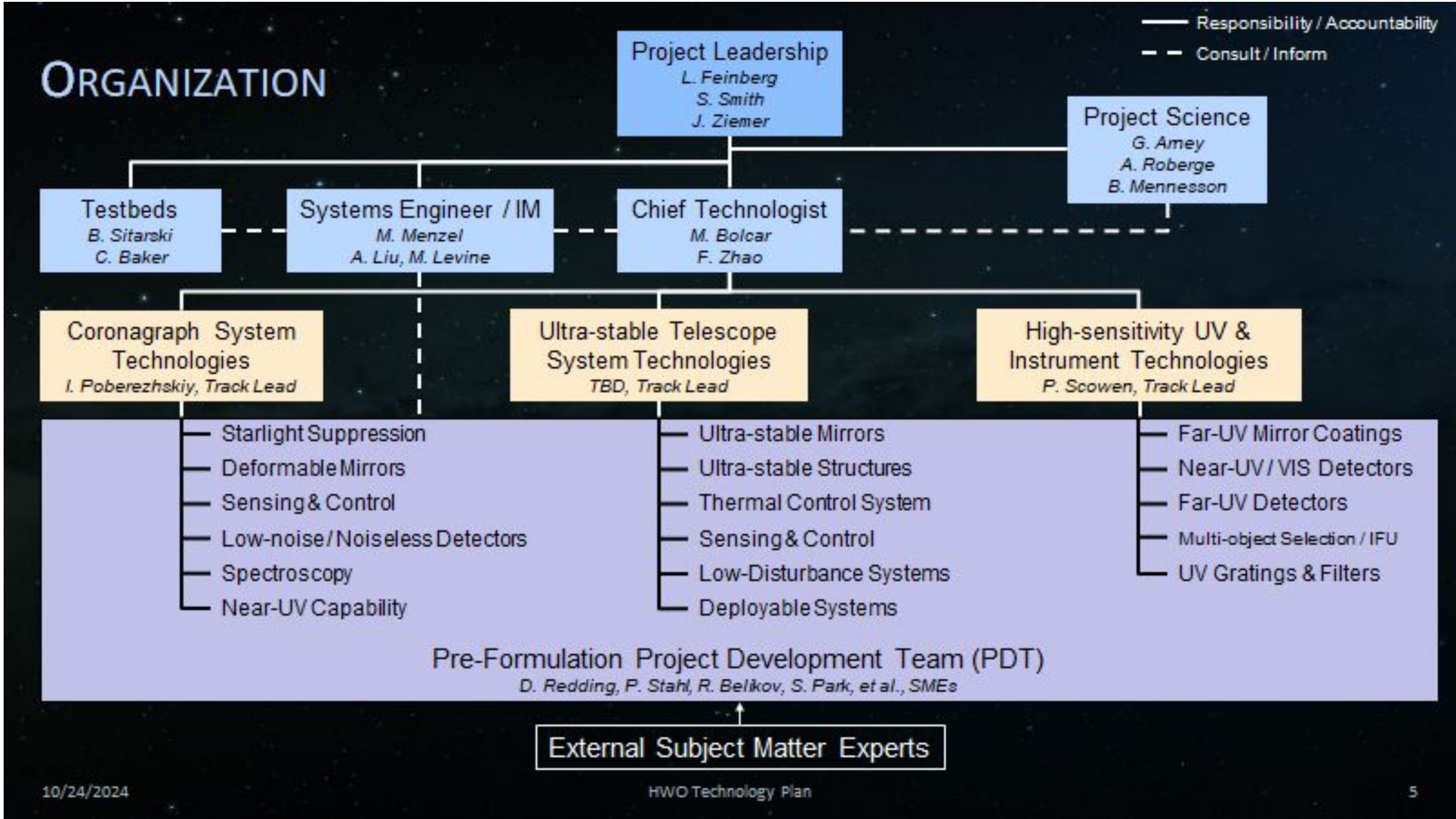


LIFE
LARGE INTERFEROMETER FOR EXOPLANETS

Habitable Worlds
OBSERVATORY

Technical challenges and preparation of a roadmap

HWO techno overview



Funded efforts and experiments

Most visible / integrated

- 🇨🇭 Zurich:
  - Project office
  - NICE bench (🇨🇭 funding)
- 🇳🇱 Leiden SRON
  - Mid-infrared MKID detectors (🇳🇱 fundings)
  - Instrument architecture design and deformable mirrors (🇳🇱 fundings)
- 🇳🇱/🇧🇪 Delft - Leuven - Liège
  - Single spacecraft mission concept pre-study (🇪🇺 small ESA funding)
- 🇦🇺 Canberra
  - Moving interferometer demonstrator
- 🇯🇵 Nagoya
  - Discussions with JAXA
- 🇺🇸 JPL
  - Formation flying simulations
- 🇫🇷
  - PEPR Photonics (Nice - Grenoble - Paris)
  - Why not more ? :-)

Key technologies to mature:

wavefront control

Wavefront sensing and control	HWO	LIFE
Space-compatible WFS and DMs	High order	Low to medium order
Non-common path errors -> **tuning from the science detector**	Electric field conjugation (EFC, iEFC)	Discrete electric field conjugation (iEFC)
High dimensional stability	Down to ~10^{-11}m	Down to ~10^{-9}m
Laser metrology system	❌	✔

Key technologies to mature

Starlight suppression

Deep starlight suppression	HWO	LIFE
Achromatic phase shifter/masks	High precision High resolution masks Broadband	Broadband High precision
Polarization control	✔️	✔️
Broadband spatial filtering	❌	Broadband infrared single-mode waveguide(s), possibly PIAA
Balanced beamsplitters or waveguide couplers	❌	Broadband highly uniform
Photonics beam-combiner	For possibly for 1-2µm	~2µm for fringe-tracking

Key technologies to mature

Data reduction

Data reduction	HWO	LIFE
Accounting for correlated instrumental noise	✔️	✔️
Accounting for non-Gaussian statistics	✔️	✔️
Covariance Shrinkage	✔️	✔️
Atmospheric retrieval	✔️,+ polarization, + glint, + Rayleigh	✔️

Key technologies to mature

Others

Miscellaneous	HWO	LIFE
Beam transportation / pupil matching / stray light	✔️	✔️
Sensor technology	UV, Vis, NIR	Mid IR (6-18.5μm)
Formation flying • Precision position control	For external occulters For remote servicing	For u-v coverage Efficient slewing transfers