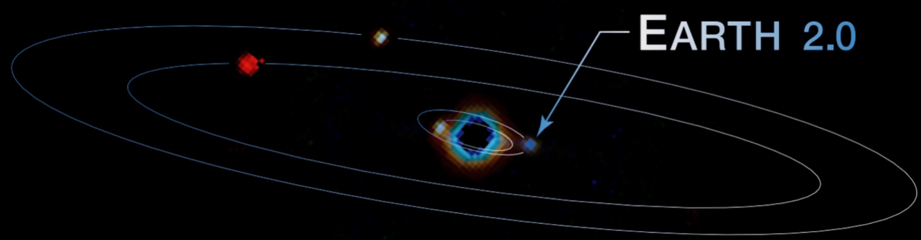
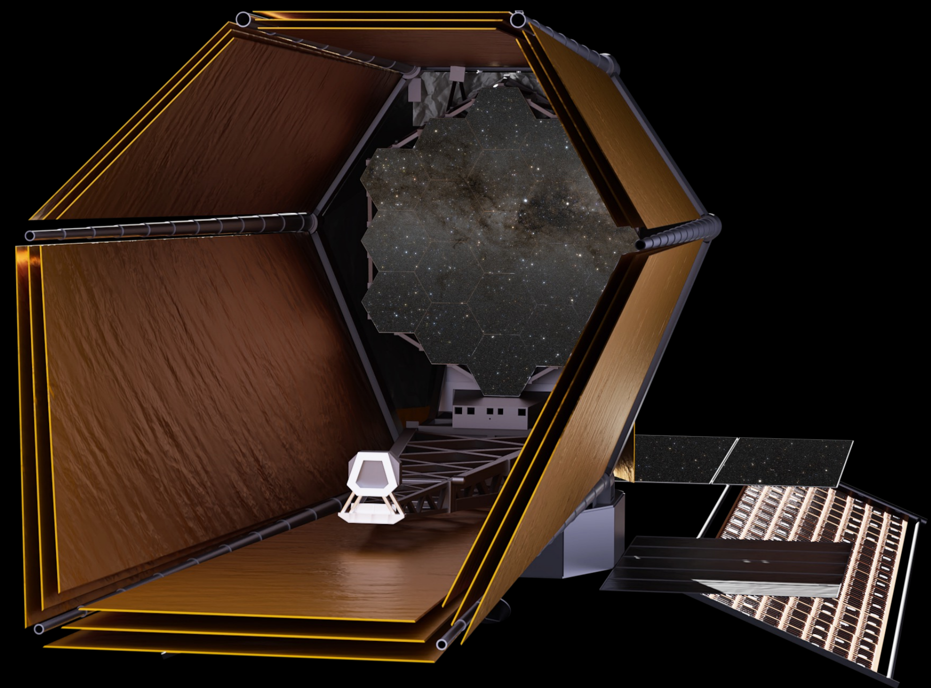
HABITABLE WORLDS OBSERVATORY

Habitable Worlds Observatory

（Recommended by Decadal Survey astro2020）





●ハビタブル系外惑星
& 系外生命探査
●広範な一般宇宙物理

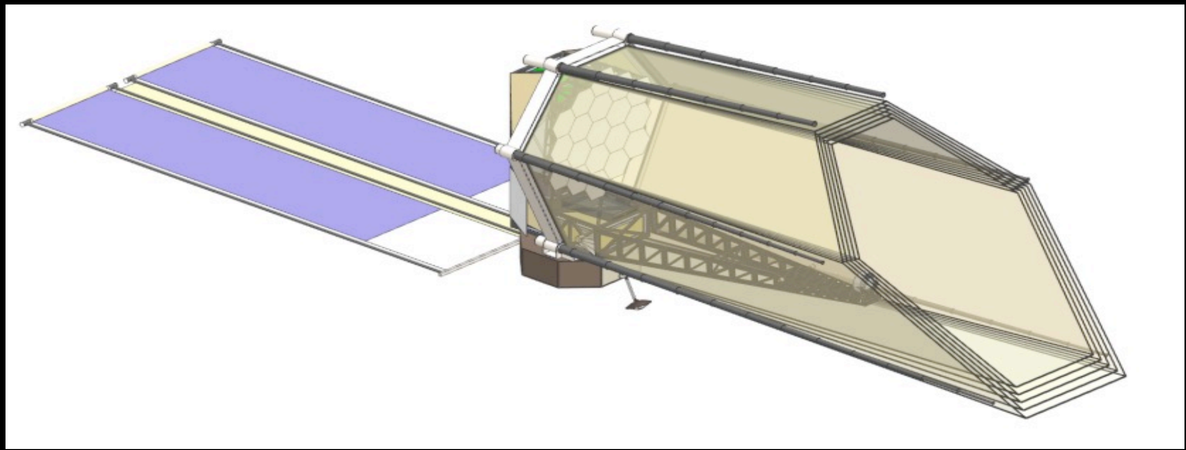
住, 松尾(阪大), 塩谷,村上豪,山田亨, 河原,米田,高橋葵(JAXA), 宮崎聡, 生駒, 本原, 西川 (NAOJ) , 田村, 村上尚, 小谷, 葛原(ABC), 亀田 (立教), 伊藤 (名大), Olivier Guyon (NAOJ, Arizona)
HWO-J team, JAXA/ISAS HWO study Task Force

Credit:NASA

Habitable Worlds Observatory

Decadal Survey astro2020 Recommended:

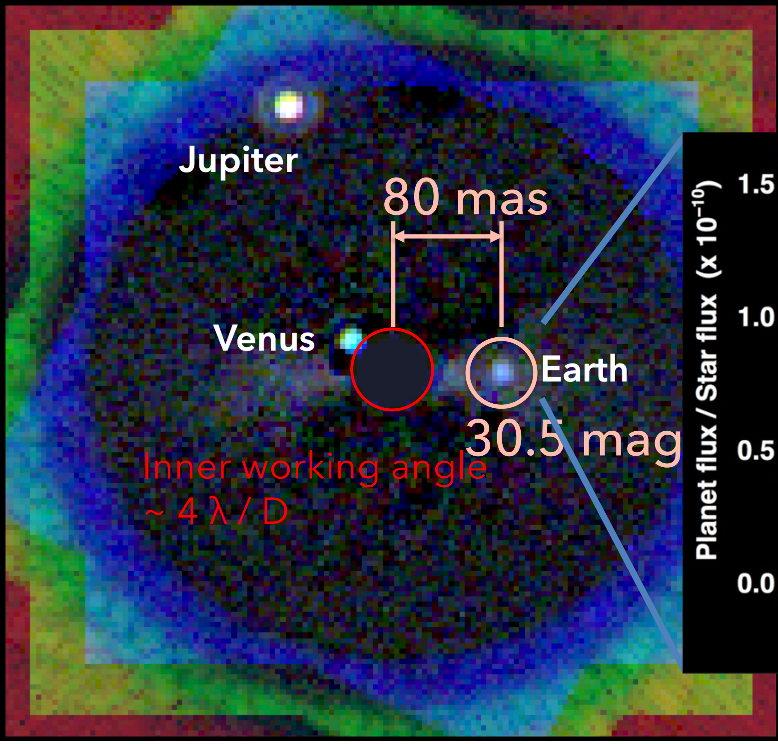
- **off-axis inscribed diameter 6-m, at first half of 2040's (11B$)** to search for biosignatures from **~25 habitable zone planets**
- Segmented, deployable far FUV/optical/NIR telescope **(100-2500 nm)**
- Ultra-stable to enable high performance coronagraphy
- Serviceable & upgradable (25 year lifetime goal for non-serviceable comp.)



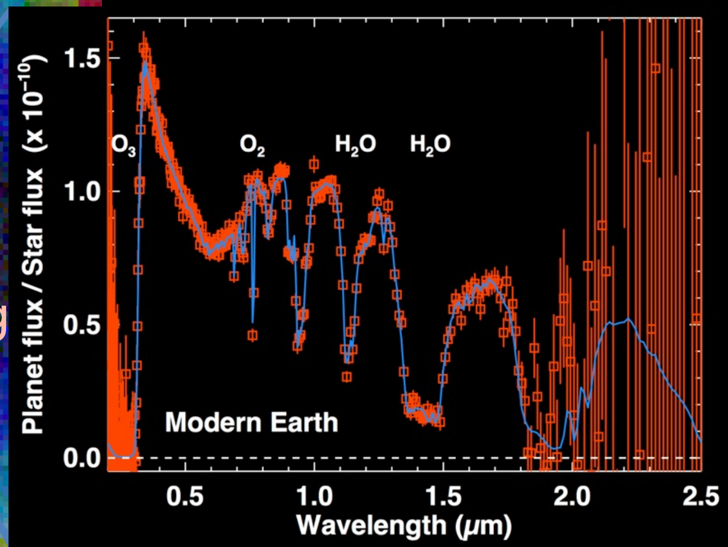
Identifying Habitable exoplanets & biosignatures

（自然科学における人類最大のテーマの一つ）

- 25パーセク以内にある数百の太陽型星を調査し、少なくとも25の潜在的に生命居住可能な惑星を直接撮像で特定する。
- 生命痕跡探査(25個の太陽型星回りの地球型):反射光の直接分光で惑星表層大気測定

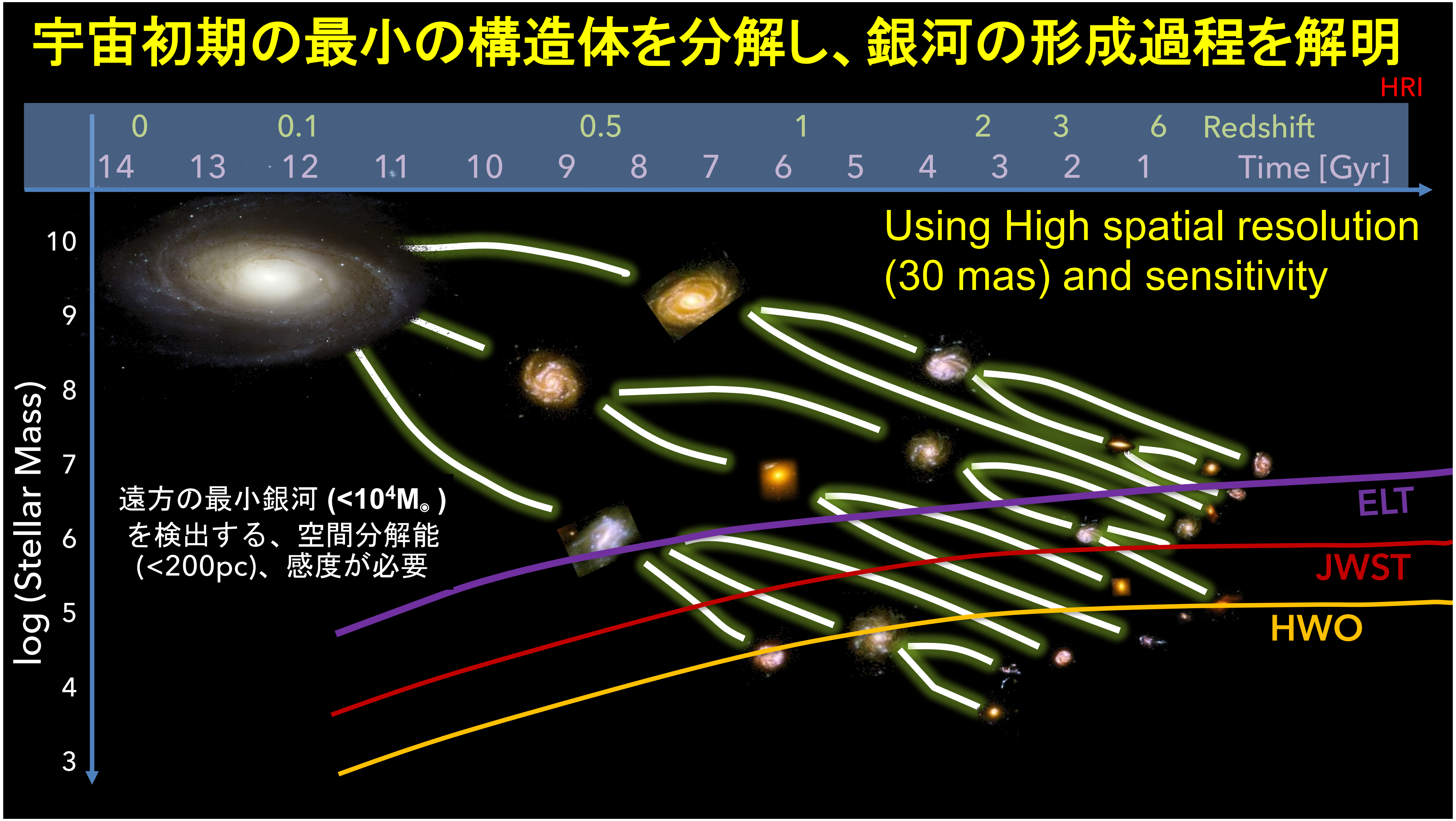


コロナグラフ装置
直接撮像・分光

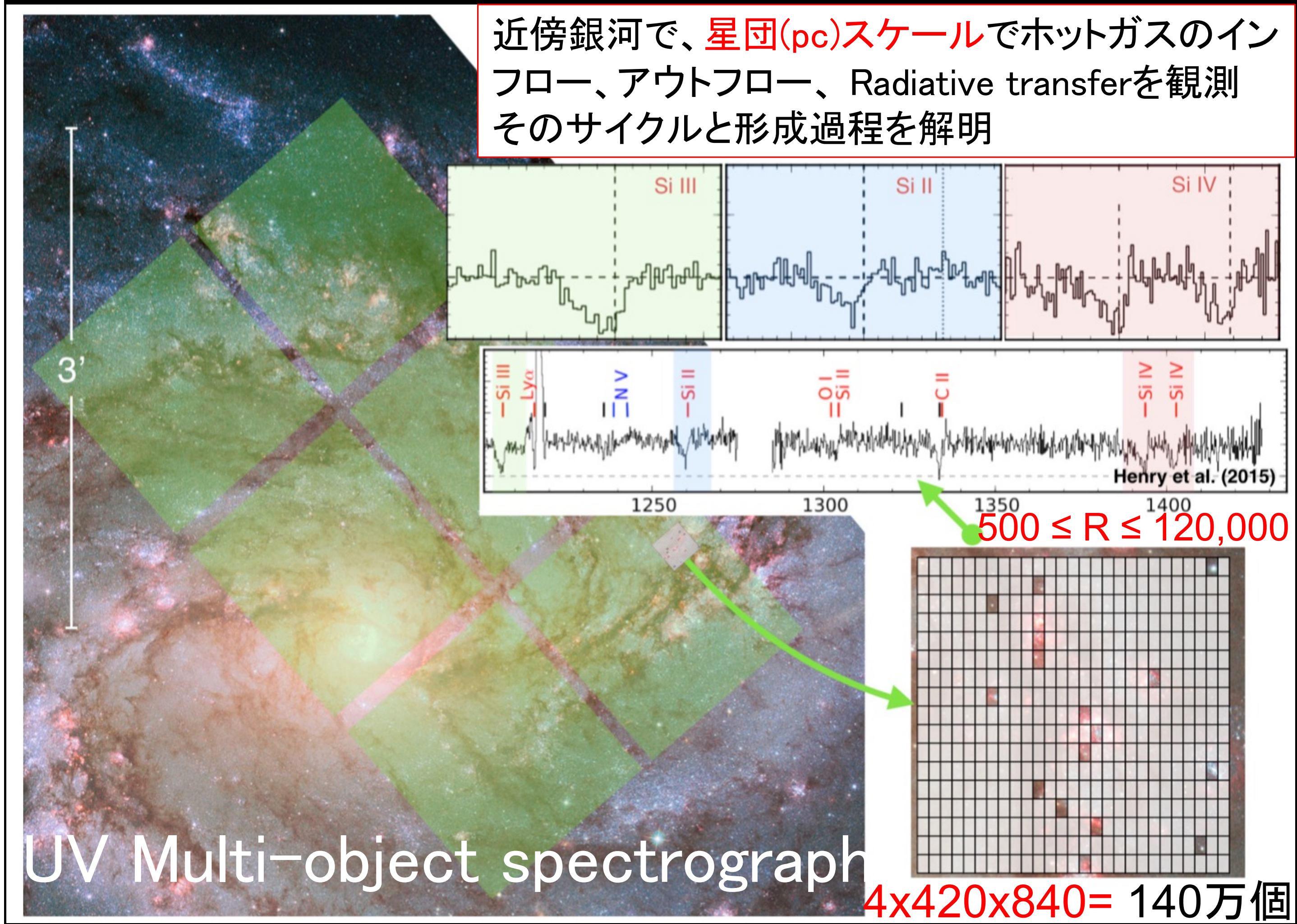


Solar System at
Distance = 12.5 pc
$D_{telescope}$ = 15-m
R = 150
Time = 60 hrs per band

Credit: T. Robinson / G. Arney


宇宙初期の最小の構造体を分解し、銀河の形成過程を解明
HRI
0 0.1 0.5 1 2 3 6 Redshift
14 13 12 11 10 9 8 7 6 5 4 3 2 1 Time [Gyr]
Using High spatial resolution
(30 mas) and sensitivity
log (Stellar Mass)
10 9 8 7 6 5 4 3
遠方の最小銀河 (<10^{4}M$_⊙$)
を検出する、空間分解能
(<200pc)、感度が必要
ELT
JWST
HWO

マイクロシャッターによる高空間分解能、多天体可視UV分光

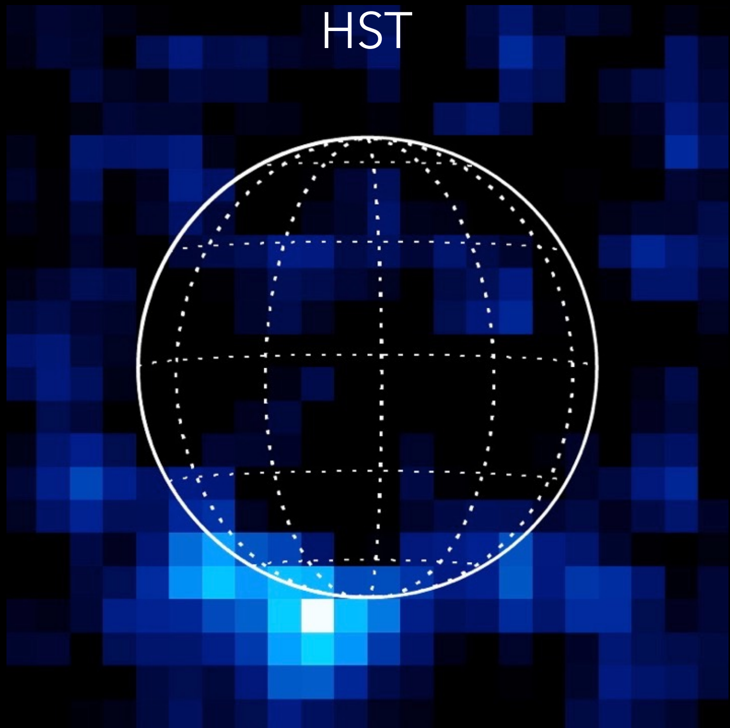


- 空間分解能：0.07x0.14 arcsec <100pc @ z < 0.1 (400 Mpc) <1kpc @ all redshifts.
- z<3以下（宇宙誕生から80%の時間、11-12 Gyr）において、様々な階層で、物質(バリオン)の量/循環、宇宙再電離を解明
- 遠方quasorのUV吸収線でIGM, CGMのバリオン量を測定(JWSTより近傍)
- 近傍銀河の星形成領域で、物質の温度、密度、速度、金属量をマップでき、構造形成史を解明

太陽系内氷衛星の生命居住可能性

探査機なみの高空間分解能で氷衛星内部海から噴き出るプルーム（水柱）をモニター
強度、頻度を求め、生命居住可能性を検討

Europa in far-UV Lyman-α emission



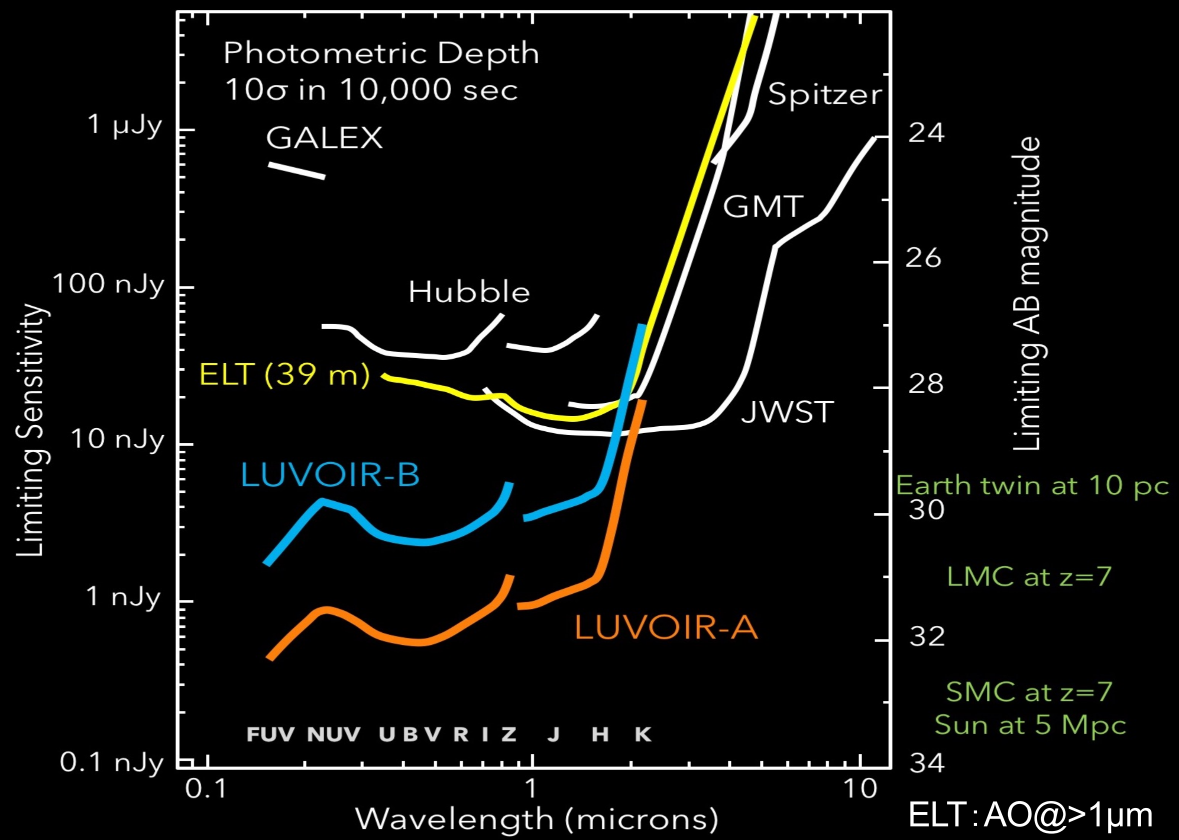
Roth et al. (2014)
HSTによる木星の衛星エウロパのプルーム

HWO

Input model: G. Ballester

Sensitivity curves for HWO and other telescopes

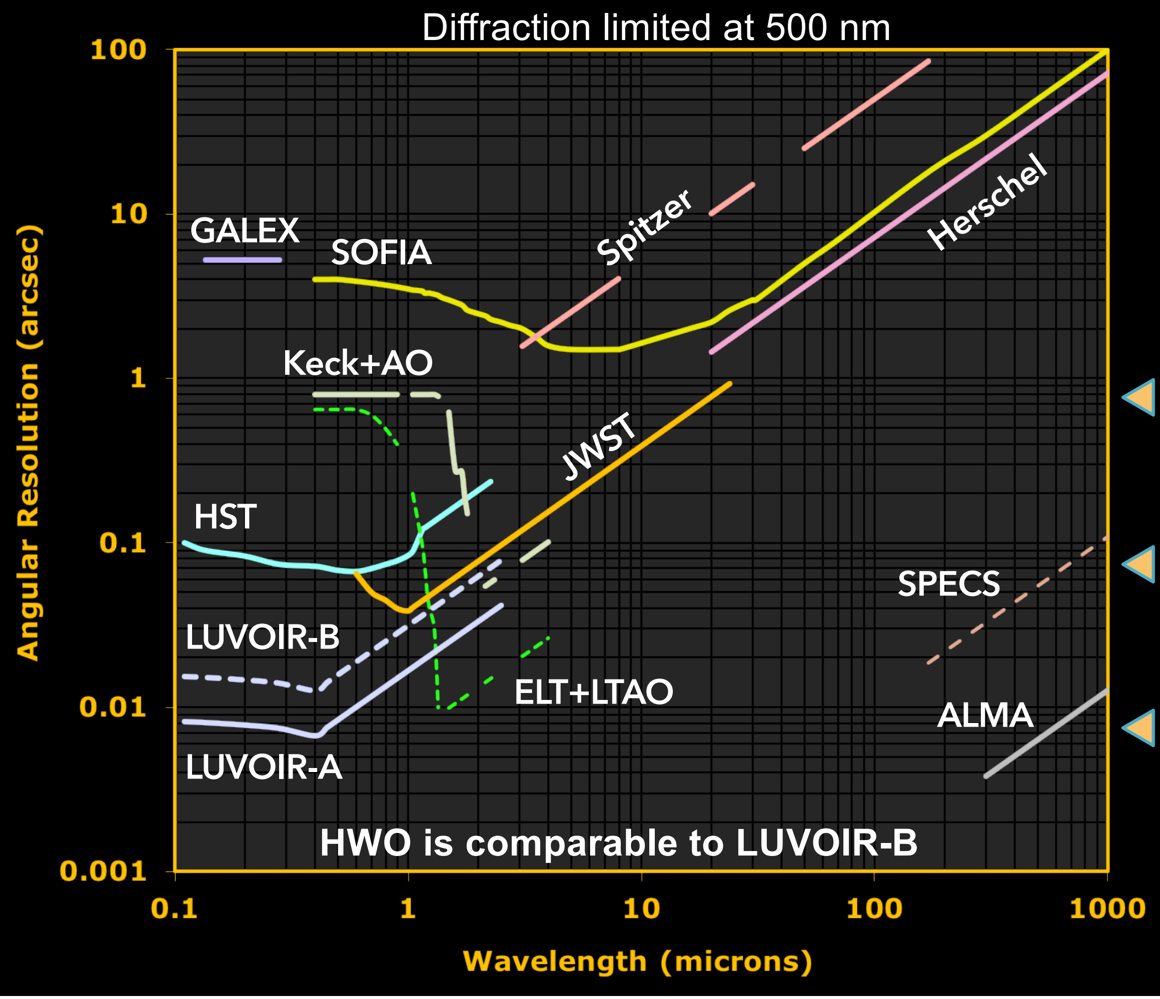
● 強力な紫外線、可視光望遠鏡として全分野で期待（HSTの後継）
● 大口径、超高解像度でHST, Ultra-deep fieldを塗り替える。

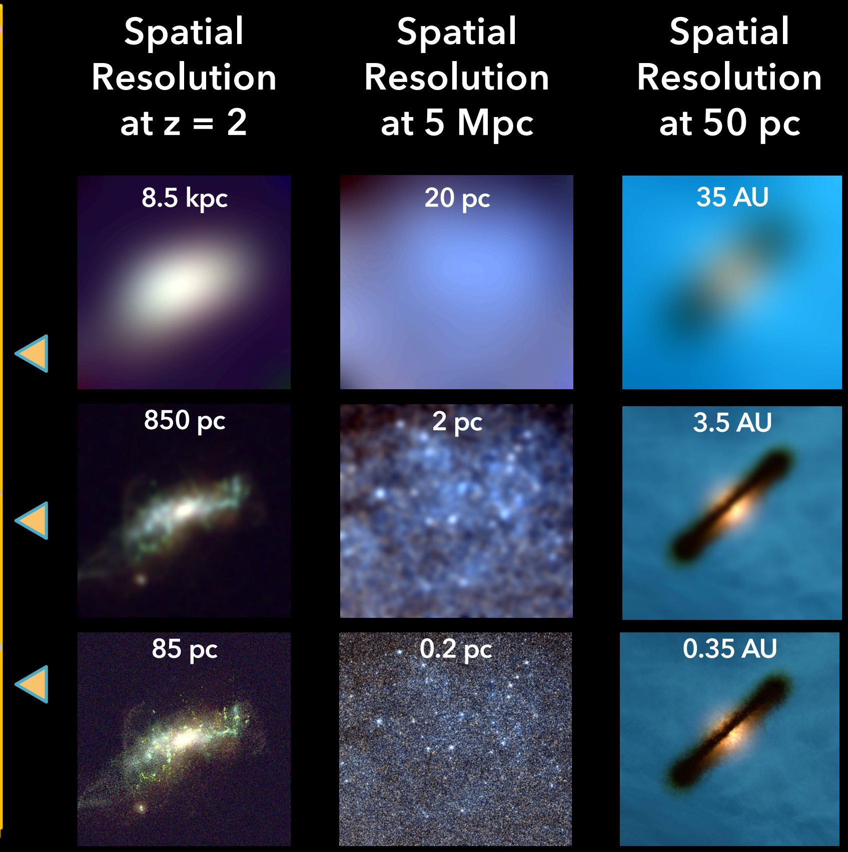


ELT：AO@>1μm

- 紫外線は地上からは不可能
- 他の大型スペースミッションとしてはHST、WSO−UV（1.7m）、LAPYUTA(0.6m)のみ
- 感度はHSTの約400(−1600)倍
- WSO−UVの約150(−600)倍

HWO resolves galaxies to 100 parsec scales at any redshift





>1.2μmで解像度はELT/TMTに劣るが視野では勝る。
ELT/TMT：回折限界性能で は FOV=30~60 秒角

GOMAP HQ Leadership Team

Science, Technology, Architecture Review Team (START)

- Explore Astro2020 science objectives
- Analyze mission architecture options
- selected from US science and technology communities
- International ex-officio representatives included

Technical Assessment Group (TAG)

- Identify and assess mission architecture options and assess the risks associated with each option and approach. Cost estimate
- NASA members

2024/8/1, NASAは、米国議会よりUSD10Mの予算を得て、プロジェクトオフィスNASA HWO Technology Maturation Project Office (TMPO)をGSFCに立ち上げた. STARTは解散。

Working Groups:

2025/7, Science Case Development Documents（**SCDDs**）**を完成させて解散**

→新たなScience Interest Group (SIG)へ


HWO25 | JULY 28 – 31, 2025
Towards the
HABITABLE WORLDS
OBSERVATORY
VISIONARY SCIENCE AND TRANSFORMATIONAL TECHNOLOGY
JOHNS HOPKINS BLOOMBERG CENTER, WASHINGTON DC
>700 responses to save-the-date email
>500 abstracts received
Prelim Program: April 30
1st round reg: April 30
General reg: mid-May
STScI SPACE TELESCOPE SCIENCE INSTITUTE
JOHNS HOPKINS UNIVERSITY
NExScI

HWO Community Science and Instrument Team (CSIT)

bringing the expertise of the scientific community into the planning for the HWO

- Liaisons to the scientific community,
- Eestablish the observatory's primary science objectives and requirements.
- Analyze science instrument concepts and support basic instrument definition

Science Interest Group (SIG)

プロジェクトとコミュニティーとの窓口

chairs

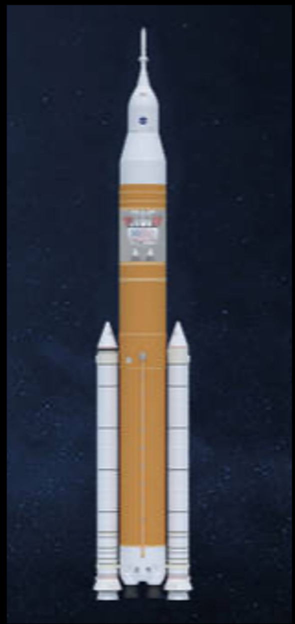
各PAGに1個

Name	Institution	Program Analysis Group
Joe Burchett	New Mexico State University	Cosmic Origins
Jessie Christiansen	IPAC/NExScI	Exoplanet Exploration
Richard Massey	Durham University	Physics of the Cosmos
Laura Mayorga	JHU/APL	Exoplanet Exploration
Fabio Pacucci	CfA	Physics of the Cosmos
Vivian U	IPAC	Cosmic Origins

ご参加ください

https://science.nasa.gov/astrophysics/programs/physics-of-the-cosmos/community/hwo-sig/

Rocket Considerations



NASA
Space Launch System

Space-X
Starship

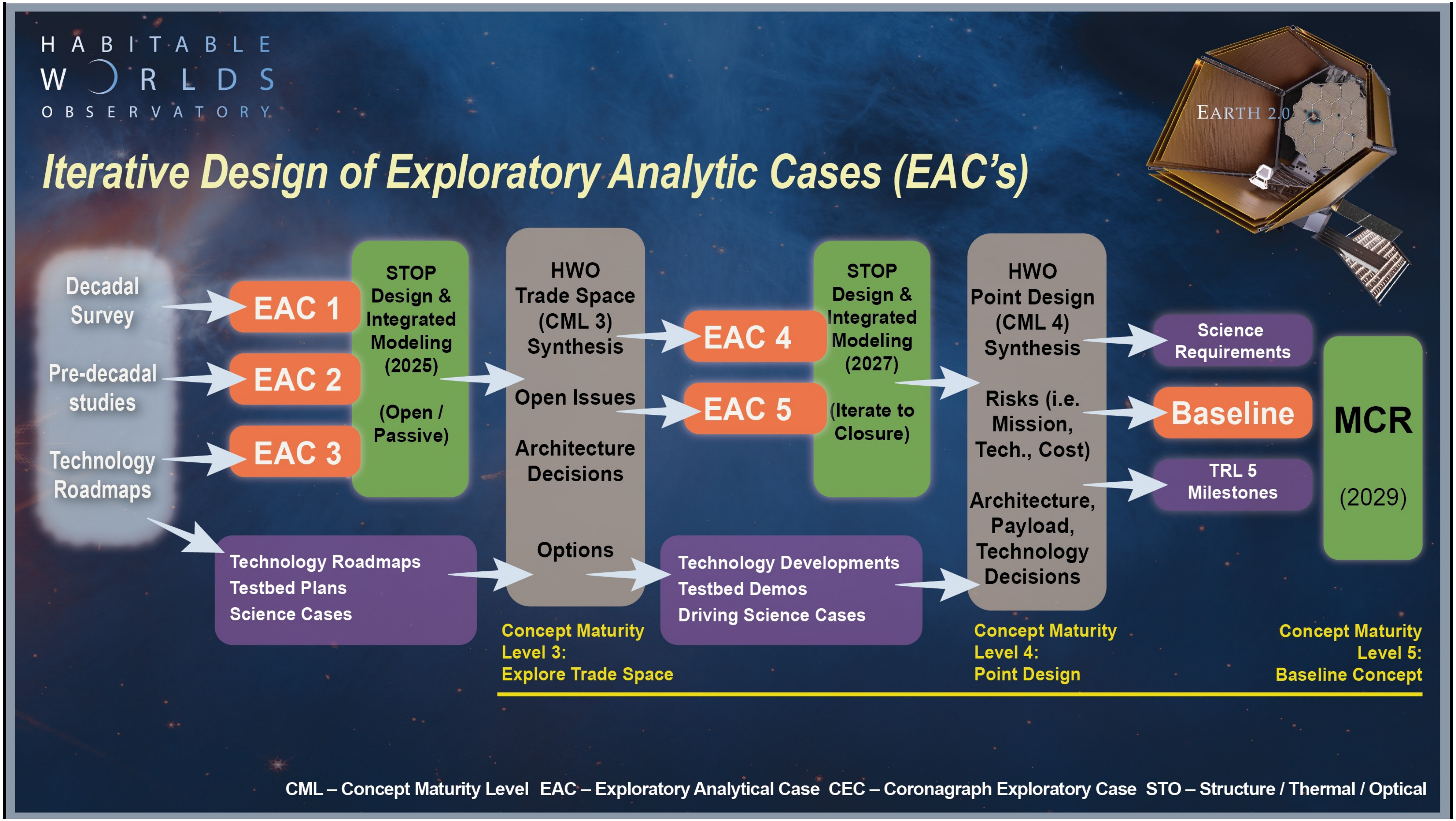
Blue Origin
New Glenn

A flexible and modular architecture can best take advantage of the next generation of large rockets and associated uncertainties

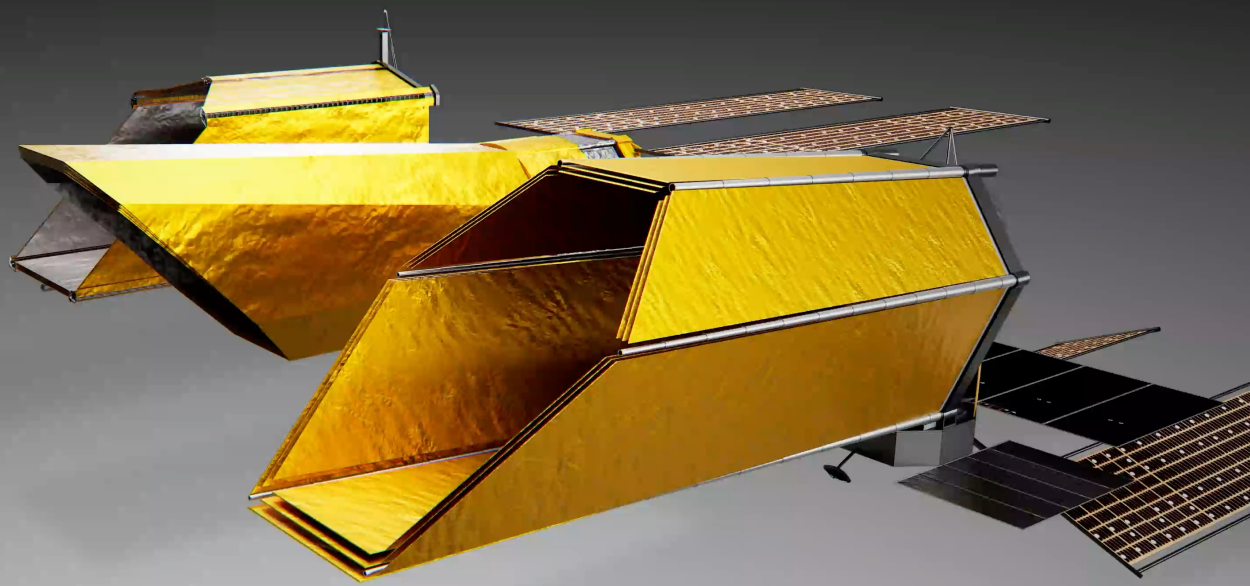
Shuttle/Hubble Approach

Separate Servicer with Carrier

- Allows multiple generations of Instruments
- Enables earlier launch date by focusing on minimum needs initially
- Architecting for Serviceability helps Integration and Testing


HABITABLE
WORLDS
OBSERVATORY
EARTH 2.0
Iterative Design of Exploratory Analytic Cases (EAC's)
Decadal Survey
Pre-decadal studies
Technology Roadmaps
EAC 1
EAC 2
EAC 3
STOP Design & Integrated Modeling (2025)
(Open / Passive)
HWO Trade Space (CML 3) Synthesis
Open Issues
Architecture Decisions
Options
EAC 4
EAC 5
STOP Design & Integrated Modeling (2027)
(Iterate to Closure)
HWO Point Design (CML 4) Synthesis
Risks (i.e. Mission, Tech., Cost)
Architecture, Payload, Technology Decisions
Science Requirements
Baseline
TRL 5 Milestones
MCR
(2029)
Technology Roadmaps
Testbed Plans
Science Cases
Technology Developments
Testbed Demos
Driving Science Cases
Concept Maturity Level 3: Explore Trade Space
Concept Maturity Level 4: Point Design
Concept Maturity Level 5: Baseline Concept
CML – Concept Maturity Level EAC – Exploratory Analytical Case CEC – Coronagraph Exploratory Case STO – Structure / Thermal / Optical

Exploratory Analytic Cases

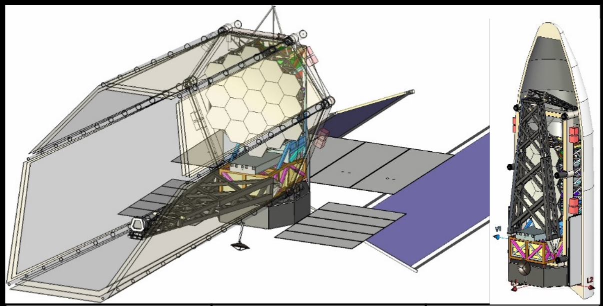


8m, On-Axis
9m Diam Fairing

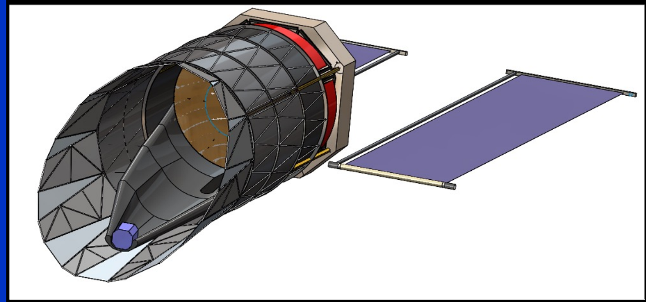
6m, Off-Axis
9m Diam Fairing

6m ID/7.2m OD, Off-Axis
7m Diam Fairing

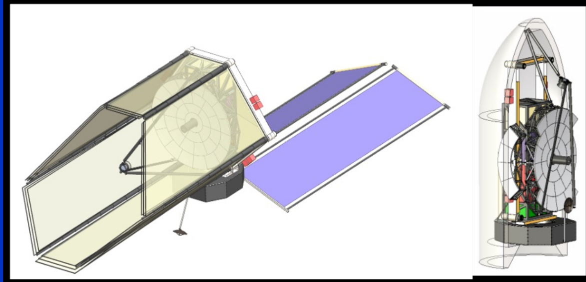
Notional Exploratory Analytic Cases



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	Assumption	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	No Primary Mirror deployment.	

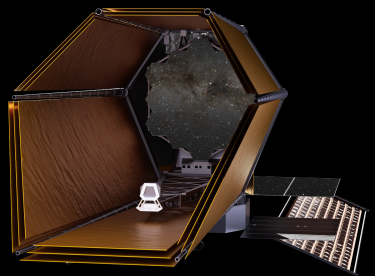


EAC3	Assumption	Comments
Launch Vehicle	New Glenn or Starship	9m diameter Fairing
Mass	Bottoms up estimate	
#of Mirrors	34 Keystone	
Telescope Diam+Config	On-Axis, 8m Circ.	Large FOV Hybrid OOFS Guider
Deployment	JWST-like Wing, SM	

EAC 1-3 Preliminary specs & candidate instruments

Telescope

Diameter	~6-8 m (inner)
Bandpass	~100–2500 nm



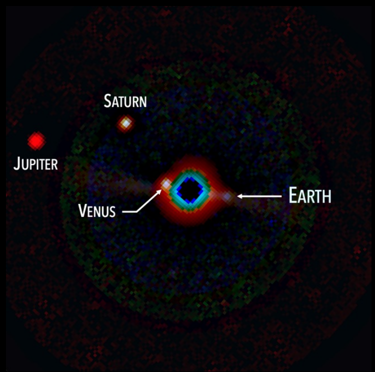
Other Possible Instrument(s)

include NUV coronagraph, NUV starshade, UV/VIS IFS, Spectropolarimeter

Coronagraph

High-contrast imaging and imaging spectroscopy

Bandpass	~450 - 1700 nm
Contrast	$\lesssim 1 \times 10^{-10}$
R ($\lambda/\Delta\lambda$)	Vis: ~140 NIR: ~40



High-Resolution Imager

UV/Vis and NIR imaging

Bandpass	~200–2200 (TBD) nm
Field-of-View	~3′× 2′
60+ science filters & grism	
High-precision astrometry?	

UV Multi-Object Spectrograph

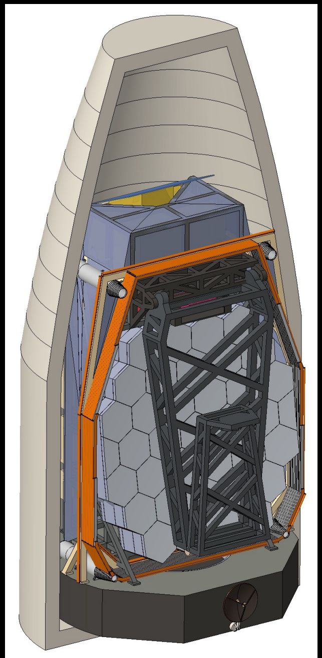
UV/Vis multi-object spectroscopy and FUV imaging

Bandpass	~90 – 700 nm
Field-of-View	~2′× 2′
Apertures	~840 × 420
R ($\lambda/\Delta\lambda$)	~500–60,000

Potential international contributions.

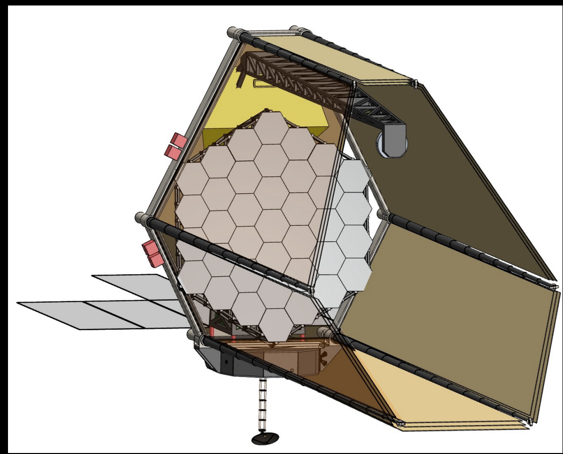
Concepts

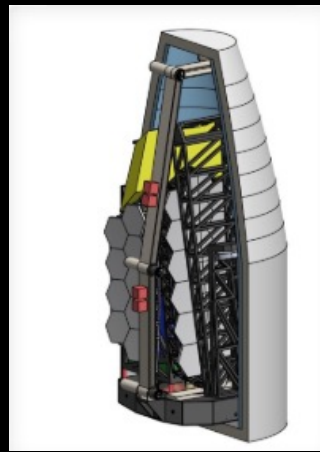
EAC4



- Off axis, >6.5m
- Volume dual rocket compatible
- 5 instruments w/UV IFU
- 2 channel Vis+NIR Coronagraph

EAC5

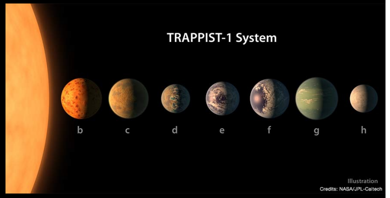




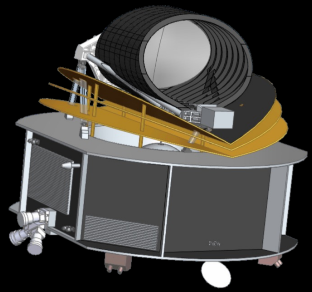
- Off axis, >8m (8.3m ID/10m OD)
- Volume dual rocket compatible
- 5 instruments w/UV IFU
- 3 channel Vis/Vis+NIR coronagraph

Originality and international competitiveness

- Ground-based 30m class telescopes directly observe rocky planets in the habitable zone only around red dwarf 10^{-8} contrast)



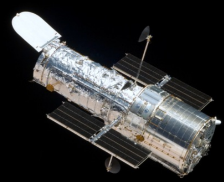
- ESA's ARIEL observes planetary atmospheres but has a small aperture and no sensitivity to small planets



- ESA's LIFE is a mid-IR space interferometry, observing radiation from terrestrial planets around the red dwarf to solar-type stars and searches for signs of life. Complementary to HWO. Still concept.

- Observations of upper atmosphere dissipation from terrestrial planets with UV are unique. Extension of LAPYUTA.

- Higher spatial resolution and sensitivity compared to JWST, Euclid, LSST, Roman, nor 30m ground telescopes.



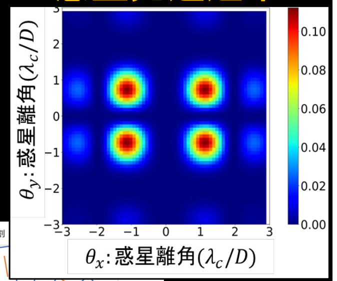
- No large UV space telescopes after the retirement of HST.

これまでの活動

- 2016-2020:**Science and Technology Definition Teams (STDT)参加**:LUVOIR(**住**), HabEx(**田村**)
- 2017 LUVOIR/HabEx**検討会　発足**　(**ー＞**2022 **両検討会統合** --> HWO-Jチームへ)
- 2021 **学術会議マスタープラン応募**（**ー＞**2022 **未来の学術振興構想に掲載**）
- 2023/10 **STARTへ参加(1st START meeting)：住(阪大)、宮崎聡（NAOJ）**
- 2023/12/7 HWO-J 検討会 (online)、2024/1/22 HWO-J 検討会 (F2F@ISAS)
- **2024/2/29 光赤天連 ロードマップ2025提案書提出**
- **2024/6/18 meeting with NASA @SPIE, Yokohama**
- 2024/10 天文台サイエンスロードマップへLOI提出
- **2024/12/3-6 天文台将来シンポジウム**
- **2024/12/27 光赤天連ロードマップタウンミーティング**
- **2024/12**　**NASA** technology Roadmapに資料提出
- **2025/1/8**　**NASA TMPOとの**quarterly meeting
- 2025/1/28-30　すばるUMで紹介
- **2025/1/31 天文台サイエンスロードマップ提案書提出**
- **2025/1**　**JAXA/ISAS HWO Study Task Force 結成（リーダー：塩谷）**
- **2025/2**　**JAXA/ISAS TF, NASA/GSFC訪問**
- **2025/7**　**HWO conference: NASA TMPOとF2F meeting**
- **2025/9**　**UK/ATC等ヨーロッパグループとonline meeting.**
- 2025/10　未来の学術振興構想に再掲載

日本の貢献、キー技術開発案

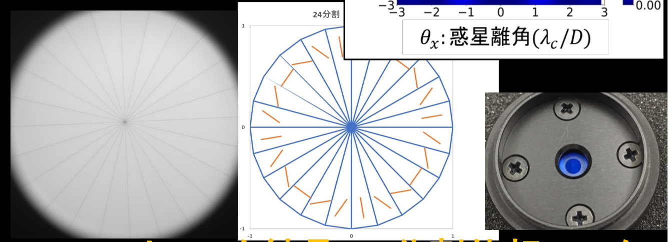
惑星光透過率



●近赤外コロナグラフ 、(FM含む総額：200-300億, Roman CGI:$400M <$350M w/o COVID)

- 真空テストベッド開発（JAXA他）:
- 一次元回折限界コロナグラフ(名大) (JPL, すばる、testbed)
- 広帯域マスク(ABC, NAOJ他): （試作・試験, EM製作・真空試験）
- 新規波面補償モジュール(北大, JAXA, NAOJ他)：制御帯域限界(~20%)打破（連星も視野）
  （非真空試験, 真空プロトタイプ, SLM開発）
- Photonic nuller（Subaru）: （DM upgrade, NIR detector), (system integration)
- 近赤外コロナグラフ分光器システム（NAOJ, ABC, JAXA）:（すばる, EM,真空試験）

スタッフ：約10人、ポスドク・院生：4人(マスク)＋4人(装置全体)

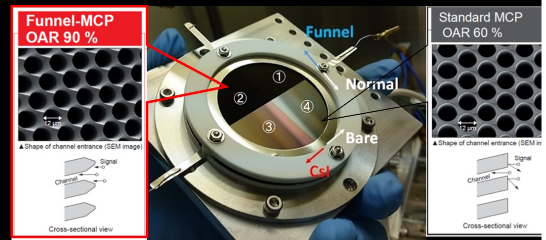


フォトニック結晶24分割位相マスク

●UV面分光器(高分散分光を含む)、3年3億、6年20億(EM) (FM込総額：50億<100億)

- *UV検出器(funnel型MCP, 立教大,JAXA) 大型MCP80mm->100mm
- *UVイメージジスライサー(60分割->回折格子60個)
- UV回折格子(WSO-UVの実績＋LAPYUTA向けに開発,立教大,JAXA)
- UVコーティング(LAPYUTA向けに開発, JAXA)

＊UV面分光器を担当しない場合も、要素として提供する可能性あり

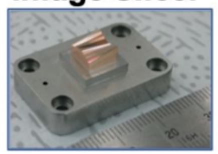


funnel型MCP

スタッフ：約10人、ポスドク・院生：２人(光学系)＋2人(検出機)+2人(装置全体)

UVイメージスライサー

Image Slicer



The INFUSE slicer consists of 26x 0.25 x 6.5 mm mirrors

- UVコロナグラフ(検討中)
- 天体高安定高分散分光器（名大）(コロナグラフ、UV装置に適用可）3年開発要素なし
- 地上局:L2, Ka-band (Romanで整備中, JAXA)
- サイエンス検討(NASA START WG, 宮崎、住、松尾etc.)

UV Grating

目標：goal: 2029/6 までに技術成熟度をTRL5+/-に上げ、ミッションコンセプトに組込む

NIR **coronagraph**

In NIR (～1 - 2 um), there are many molecular absorption of biosignature, such as H2O, CO2 and CH4.

To spatially resolve the habitable zone around Sun-like stars in the H-band, we require a very small Inner Working Angle (IWA) (~ approximately 1 λ/D).

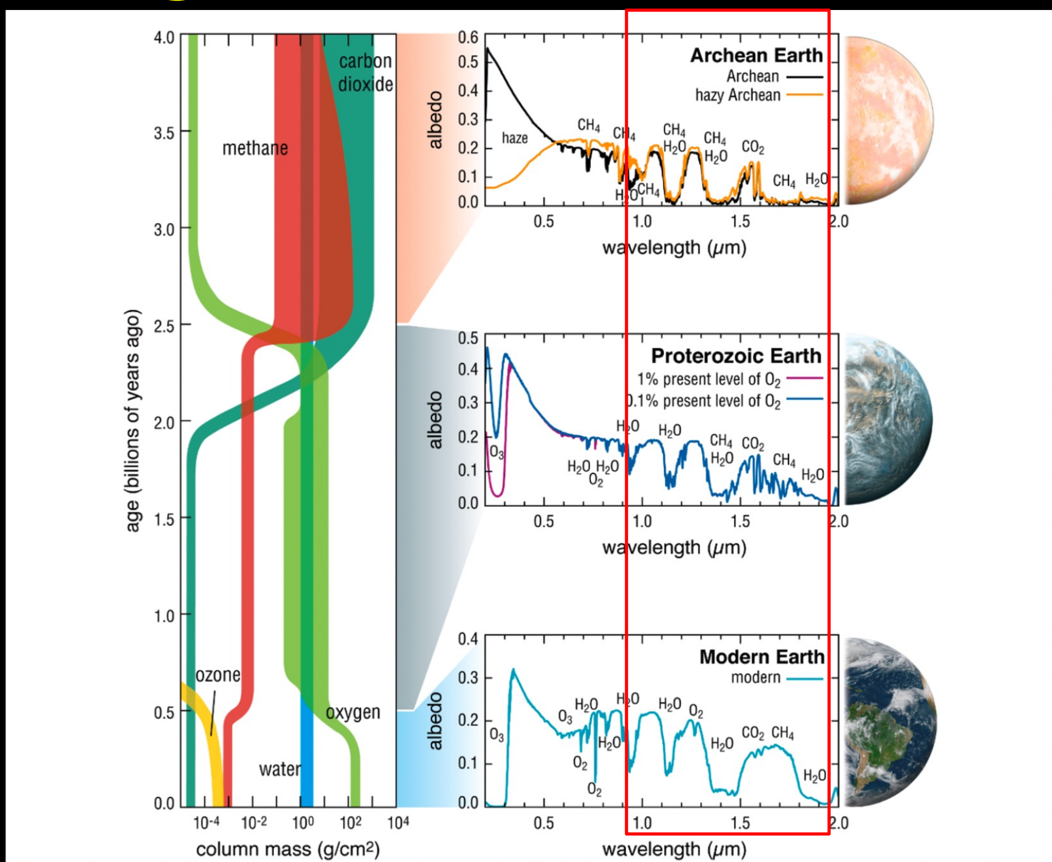


Figure 3.1-6. O_2, O_3, H_2O, CH_4 and CO_2 concentrations over Earth's history, during Archean, Proterozoic, and modern Earth eras. HabEx is required to be able to detect the gaseous byproducts from oxygen-producing synthesizers (all EECs) or methane-producing synthesizers (some EECs), if present at concentration levels similar to Earth over the last 3.5 Gy of its history. This covers part of the Archean Era as well as the full Proterozoic and Modern Eras during which life has been present on Earth. Credit: Britt Griswold, Giada Arney, and Shawn Domagal-Goldman.

Diffraction-limited coronagraph

NIR coronagraph, wave front control is easy compared to optical. Challenge is that it needs small inner working angle

Matsuo(Osaka), Ito(Nagoya)

Four unique features:

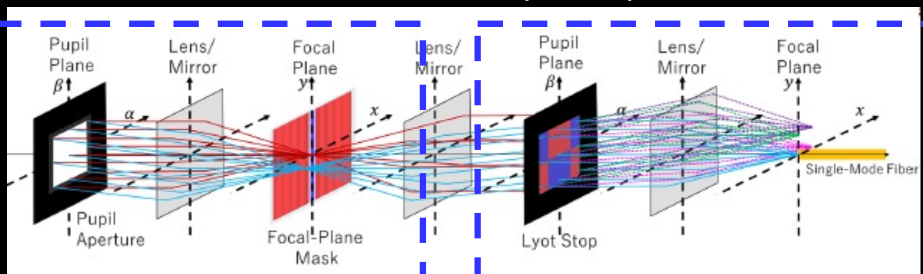
1. Working for any arbitrary pupils
2. **Small inner working angle (~1λ/D)**
3. Working for double stars
4. Unperturbed off-axis PSF for fiber/photonic nulling

Experiments show:

1. Unperturbed except for on-axis point source
2. 10^{-6} contrast over 12% bandwidth (with fiber)

Collaboration:

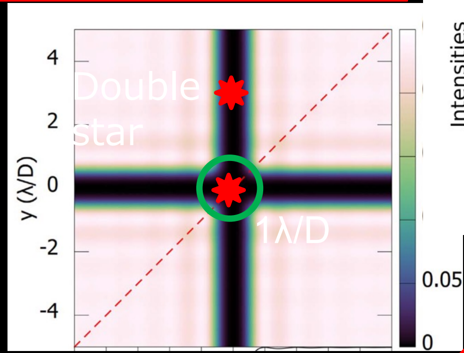
1. Coronagraph design survey for HWO (w/ NASA Ames)
2. Test at SCExAO as NIR coronagraph (w/ Subaru & U. Sydney)
3. Test at JPL for double stars (w/ JPL)



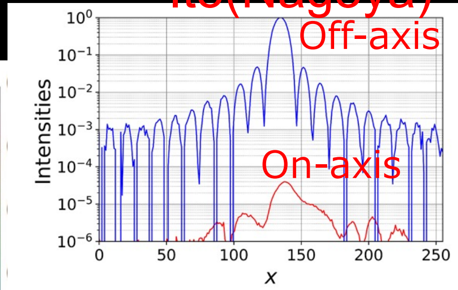
Entrance pupil | Focal-plane mask | Lyot stop | Single-mode fiber

Diffraction-limited coronagraph | Fiber nulling

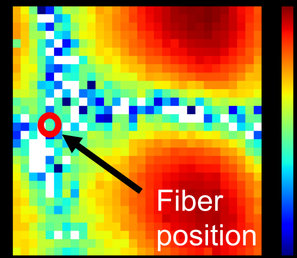
Itoh, Matsuo, Tamura, *AJ* 2024



Throughput of the sky
contras$10^{-10}/10^{-6}$ for point/finite source



Experimental result
Itoh et al. *PASP* 2023



Enlarged view
1 pix = fiber diameter

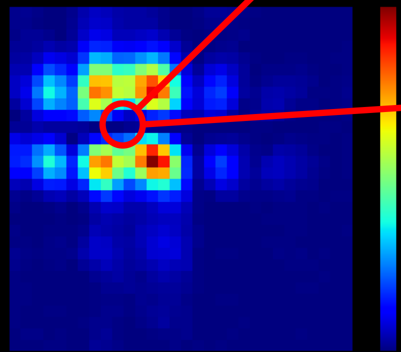


Image on focal plane

SMALL-IWA STARLIGHT SUPPRESSION R&D WITH PHOTONIC NULLING CHIP

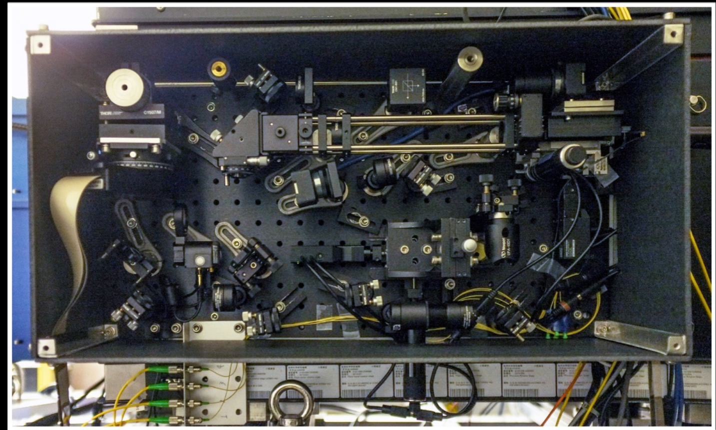
Olivier Guyon(Subaru)

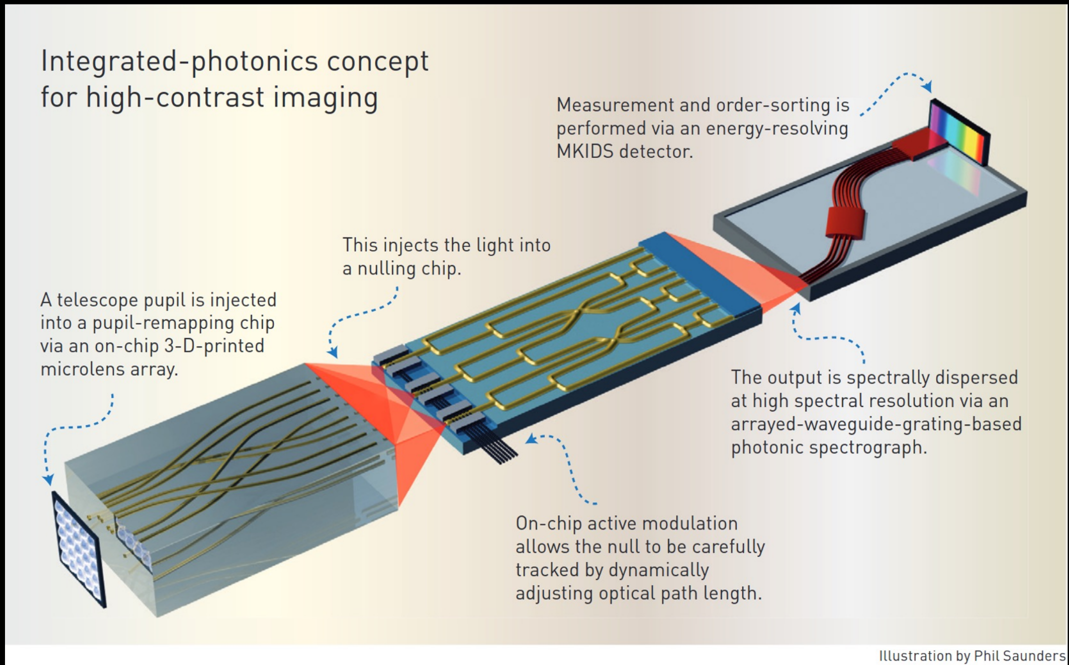
IWA: ～0.5λ/D

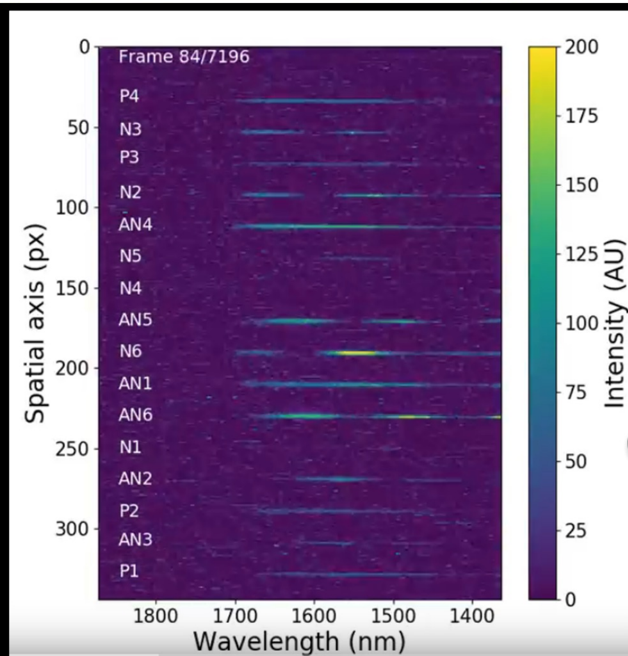
OWA:-3λ/D

Contrast:10^{-10} (currently 10^{-3})

Throughput: high



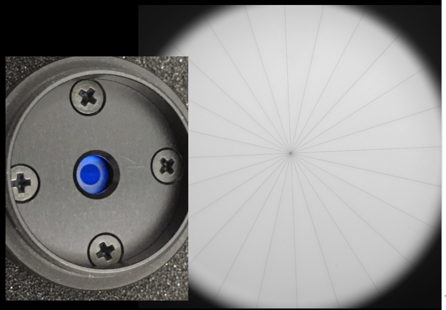


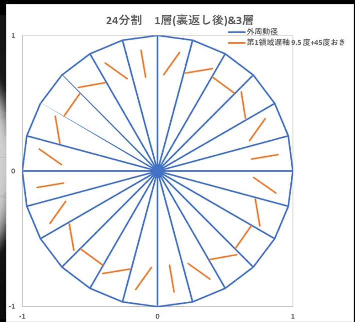


Broadband coronagraphic masks

- **Photonic-crystal coronagraphic masks**
  - Multi-layer phase masks ➔ broadband stellar suppression
  - 4th- and 6th-order phase masks ➔ robust against telescope pointing jitters

Murakami(ABC)
Nishikawa(NAOJ)





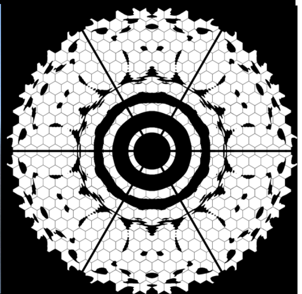
フォトニック結晶24分割位相マスク

Photonic-crystal phase mask (three-layer, 6th-order 24-sector vortex)

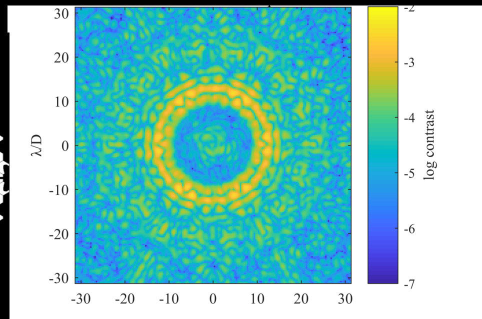
IWA=2λ/D for 4th-order

IWA=3λ/D for 6th-order

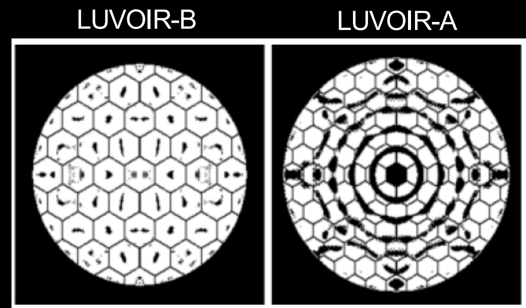
- **Shaped pupils (SPs) for enhancing coronagraphic performance** (LUOVIR, TMT, Subaru)
  - TMT- and Subaru-optimized SPs have been fabricated and tested in the laboratory



Fabricated TMT (segmented mirror)-optimized SP for the 24-sector vortex



Experimental coronagraphic image with polarization filtering using the vortex mask and the SP (at non-center wavelength)

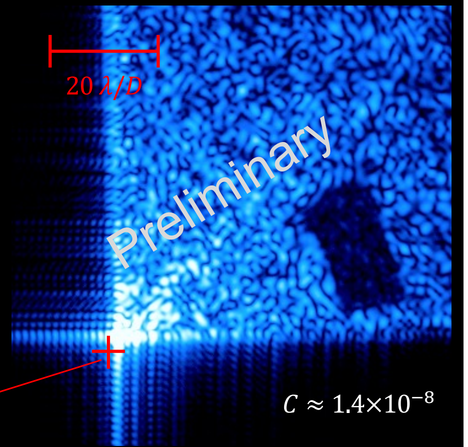


SPs optimized for LUVOIR-A and -B with 8-octant phase mask. (Nishikawa et al. (2020), Proc. SPIE, 11447, 114474T)

Optical module towards multi-wavelength dark holes

Murakami(ABC), Nishikawa(NAOJ)

- **Science goals**
  - Multi-wavelength photometry ➔ infer exoplanetary surface maps
  - Efficient spectroscopy ➔ search for biosignatures on exoEarth
- **Current**: Concept proposed; Prototype demonstrated (Murakami + in prep.)
  - Simultaneous two-wavelength dark-hole control using green/red lasers
- **Future**: Optics refined; Advanced tests planned; Vacuum tests envisioned

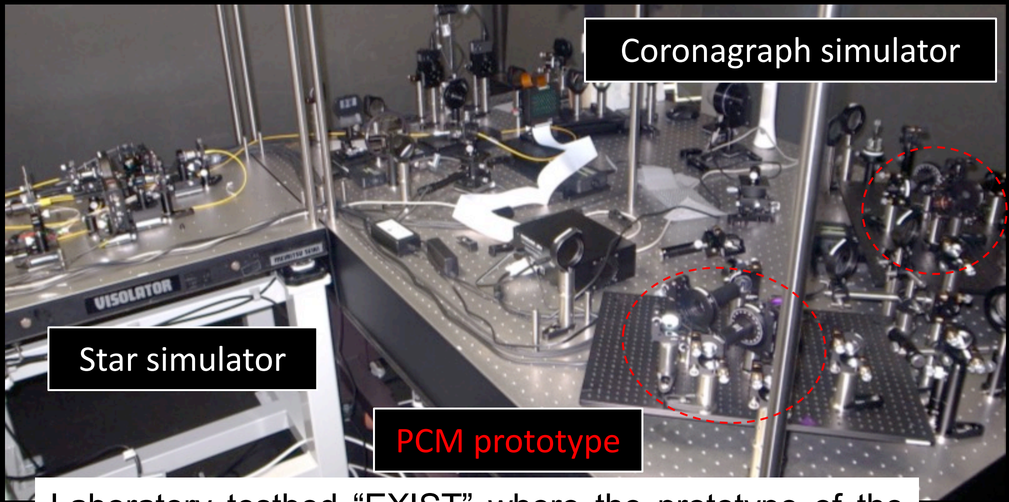


Model star position

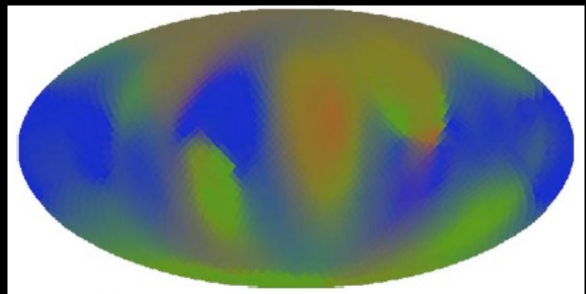
Preliminary (monochromatic) laboratory test of the dark hole control at EXIST

Testbed "EXIST"

Murakami et al. (2020), Proc. SPIE, 11443, 114432M



Laboratory testbed "EXIST" where the prototype of the proposed optical module is installed and tested



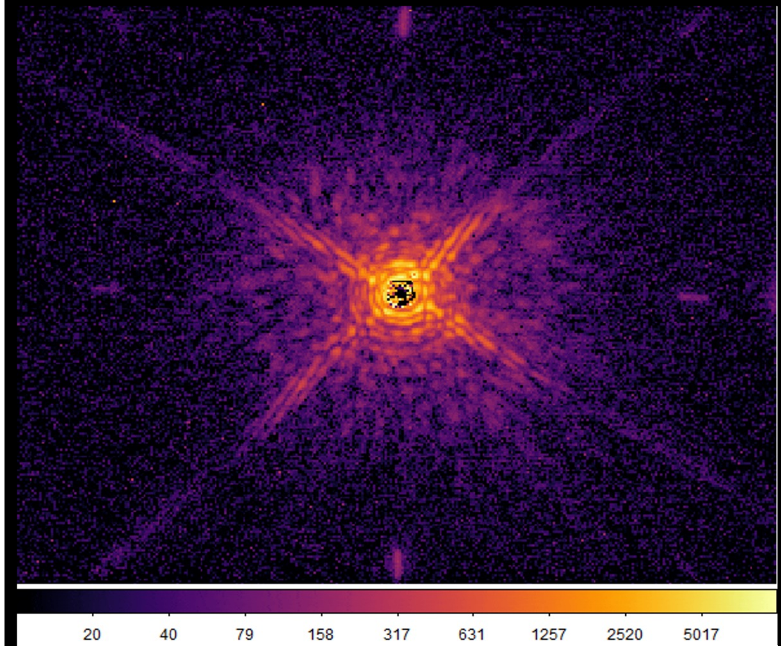
Earth surface component map inferred from DSCOVR multi-wavelength photometric data
Figure 7 of Kuwata et al. (2022), ApJ, 930, 162

Wave front control Spatial Light Modulator (SLM) with Large number of element

R&D, SYSTEM VALIDATION AT SCEXAO @ SUBARU

Olivier Guyon(Subaru)

Serves at “daytime” R&D testbed as well as nighttime validation platform.



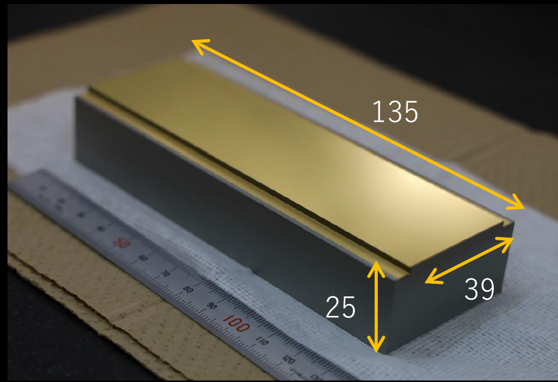
Of specific interest to HWO:

- NIR spectroscopy
- Small-IWA starlight suppression in NIR (GLINT)
- WFS/C with segmented DM (BMC Hex3k)

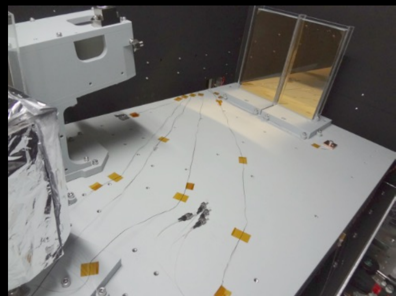
Concept of a high-throughput, high-resolution spectrograph

Kotani (ABC)

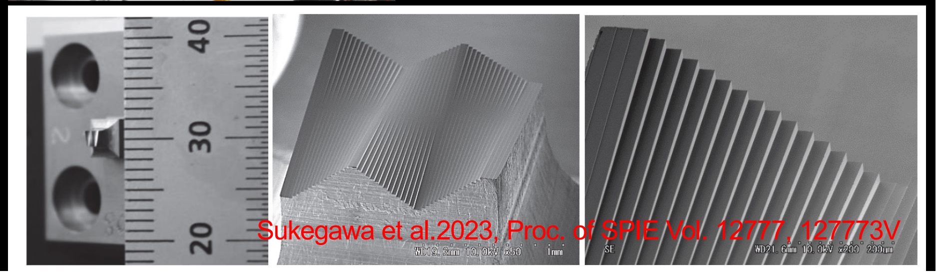
- R>100,000 spectroscopy, 380-900nm spectrometer behind a high-contrast system of HWO
- Spectrometer throughput > 30%
- Options
  - Spatial filtering with a single-mode fiber to further reduce speckle noise
  - Ultra- compact Mini-IFU
- Key technologies:
  - State-of-the-art echelle grating from Canon
  - Extremely low noise, photon counting, large format qCMOS sensor from Hamamatsu photonics
  - Light weight, zero-CTE ceramic for optics, bench, support structures from Kyocera
- Ultra-compact machined slicer IFU



from VAMPIRES and Hamamatsu photonics



Zero-CTE ceramic optical bench



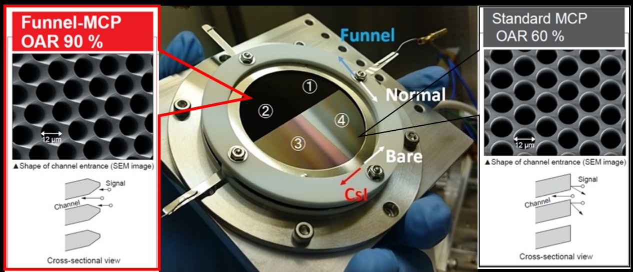
UV IFS+HRS

Kameda (Rikyo)
Murakami (JAXA)

We consider to develop the UV Integral Field Spectrograph (IFS) with High Resolution Spectrograph (HRS, echell) mode as the 4th instrument of HWO. The key components are High-efficiency Large-format UV detector (Funnel MCP), Integral Field Unit (Image slicer), and UV grating.

High efficiency UV detector: Funnel MCP

Double the QE (～40%) compared to the standard MCP. MCPs by Hamamatsu Photonics were used in JAXA's missions (Hisaki, BepiColombo, etc.)

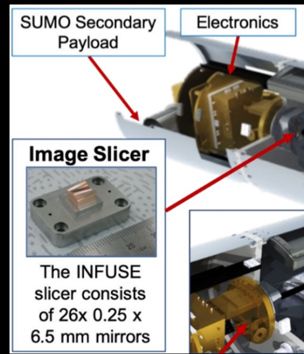


～ 120 mm x 120 mm funnel-type MCP for HWO, will be feasible (80x80 is under manufacturing for LAPYUTA mission test model).

Spectral range: 100-180 nm
IFS: 60 slices (60x60 div.) with R of 2000-5000
with HRS: point source with R of 50,000-100,000

IFU (UV image slicer)

Canon provided NASA INFUSE mission with an image slicer with 26 slices and spectoral range of 100-200 nm.
Canon can prepare ～60-slices IFU and also echelle grating for HRS.



FUV grating

High efficiency Toroidal Grating has been developed for WSO-UV/UVSPEX EM. Achieved relative diffraction efficiency is ～60% with 2400 gr/mm.

Toroidal Grating
by Shimadzu

Develop with LAPYUTA

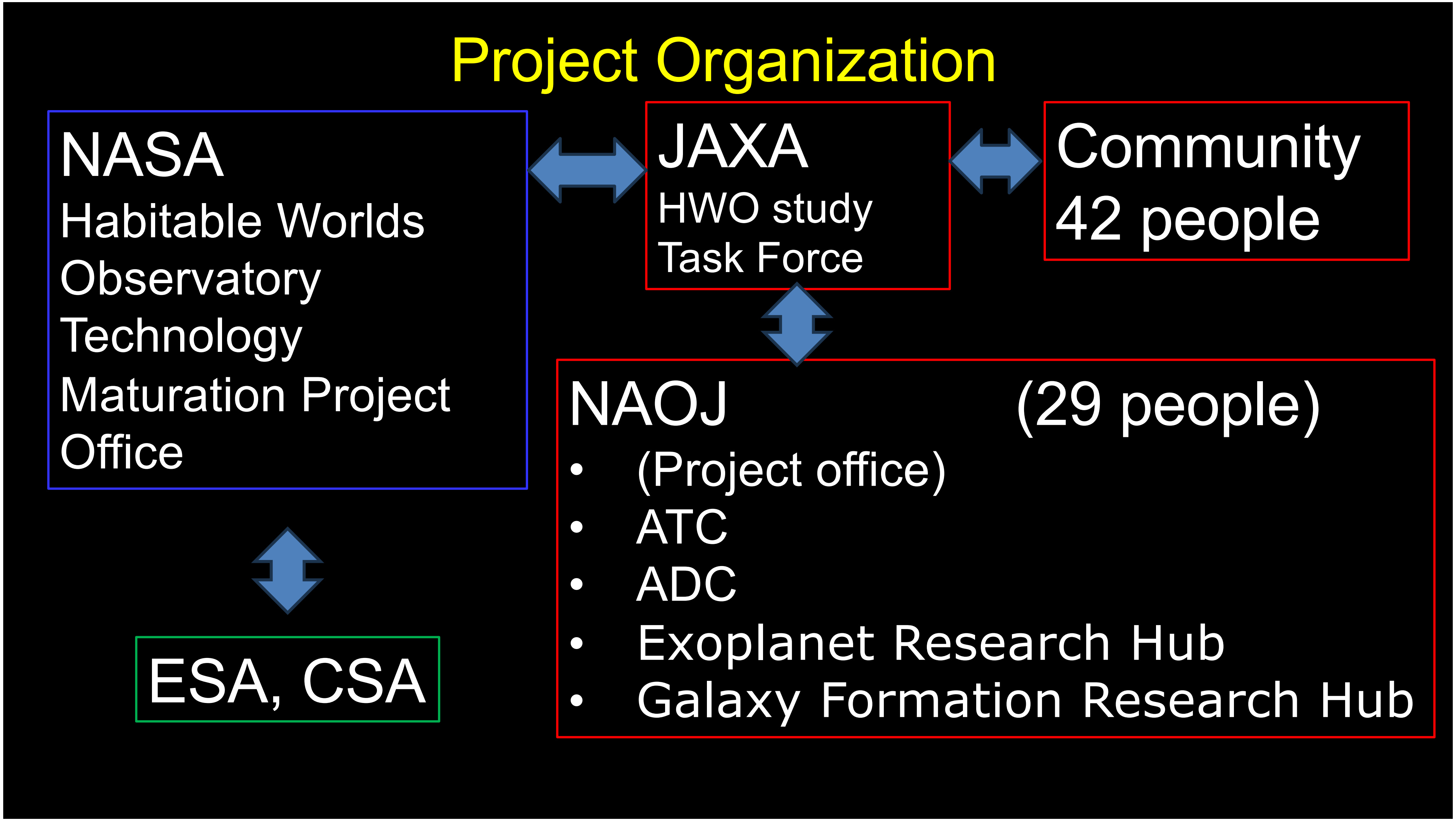
Current status and Schedule

- Currently, PO is making Technology Roadmaps to achieve TRL 5 by March 2029, ahead of Mission Concept Review (MCR).
- It will be presented to NASA HQ in March 2025.
- If approved and budgeted, the tech development will start from mid 2025 for 3.5 years.

HWOTM: HWO Technology Maturation
FA : Formulation Agreement
MCR : Mission Concept Review
KDP : Key decision Point

	2025-2029	2030-2035	2036-2040	2041-2045	2046-2050
NASA HWO	HWOTM Project Office Established; FA MCR KDP-A; Pre-phase A	Phase A-D		Launch	Phase E
JAXA NAOJ	Tech development	Instrument development			

Decadal 2030


Project Organization
NASA
Habitable Worlds Observatory Technology Maturation Project Office
JAXA
HWO study Task Force
Community
42 people
ESA, CSA
NAOJ (29 people)
• (Project office)
• ATC
• ADC
• Exoplanet Research Hub
• Galaxy Formation Research Hub

HWO-J メンバー

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宮崎 聡	国立天文台	鈴木大介	大阪大学	寶田 拓也	ABC/国立天文台
亀田真吾	立教大学	山響	大阪大学	堀 安範	岡山大
村上 豪	JAXA	宮崎翔太	ISAS/JAXA	小松勇	茨城大学
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村上尚史	ABC	伊藤 哲司	名古屋大学	古賀亮一	名古屋市立大学
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近藤依央菜	ISAS/JAXA
東尾奈々	ISAS/JAXA

まとめ

●HWOは6m超大型紫外可視近赤外宇宙望遠鏡

- 生命居住可能惑星、地球外生命探査
- 宇宙物理、地球物理全般を網羅する究極ミッション

●日本の参加により、科学成果を拡大する

●装置レベル+コンポーネントレベルで貢献を目指す

●興味のある方は是非、ご参加ください