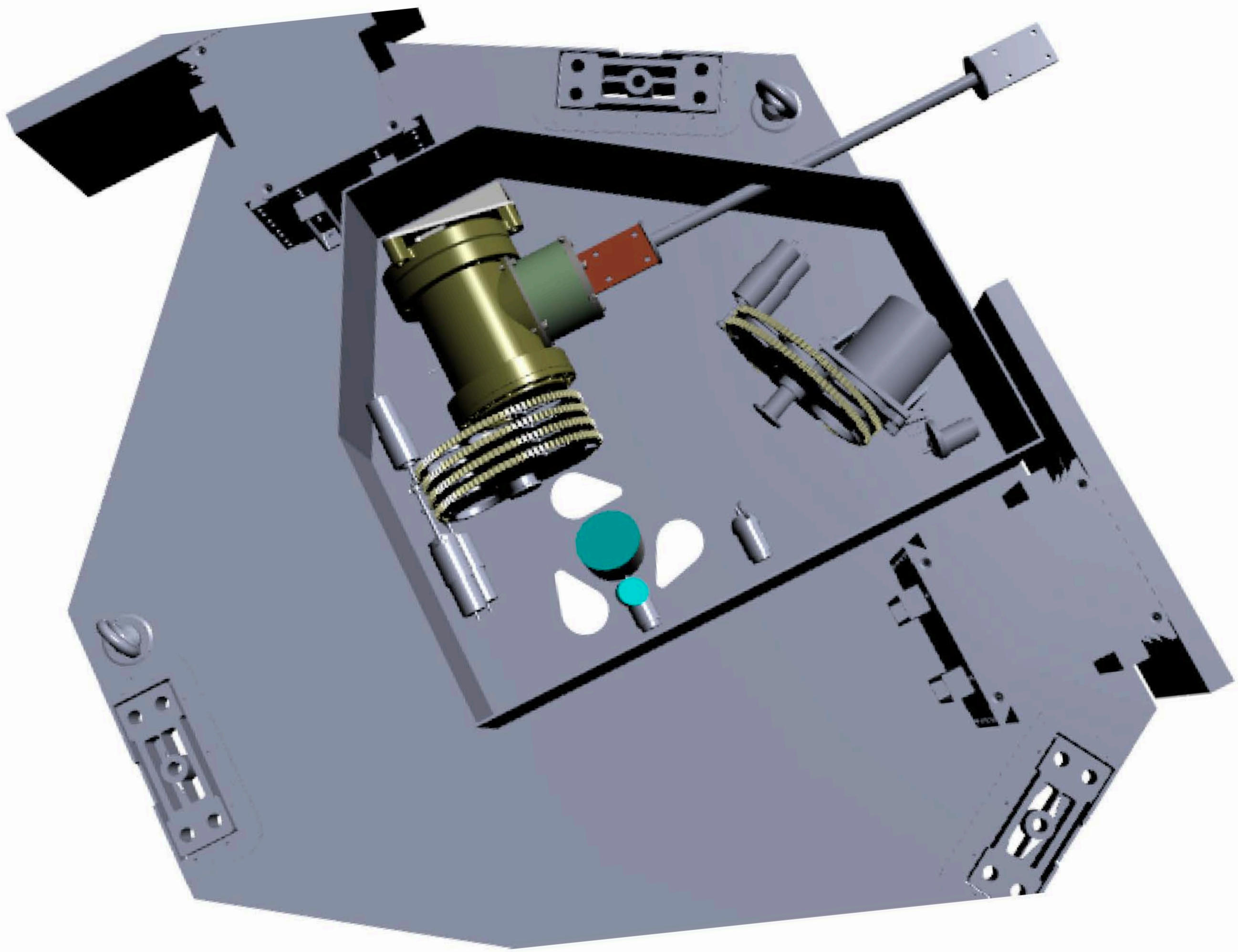
Focal Camera Unit



Two additional science instruments onboard WSO-UV towards exoplanetary science

Alexander Tavrov, IKI RAN, Moscow

Shingo Kameda (Rikkyo U.), K. Enya, Go Murakami (JAXA)

Jun Nishikawa (NAOJ), Masahiro Ikoma, Takanori Kodama, Norio Narita, Seiji Sugita,

Motohide Tamura, Ichiro Yoshikawa (U Tokyo)

Applyed for JAXA’s small-scale project AO on May 19, 2017

October 26, 2017

Stellar imaging coronagraph and exoplanet coronal spectrometer – two additional instruments for exoplanet exploration onboard the WSO-UV 1.7 meter orbital telescope

2017 submitted to JATIS

WSO-UV mission, status, telescope

en.wikipedia.org/wiki/Spektr-UV

- **Launch 2022+, 2023+.**
- **Proton medium class rocket.**
- **Orbit geosynchronous 51.8 deg.**
- **Telescope & Platform made in Russia.**
- **Pointing accuracy 0.1"**
- **Stabilization accuracy 0.1" (3σ)**
- **Main goal UV astronomy**

en.wikipedia.org/wiki/Spektr-R
en.wikipedia.org/wiki/Spektr-RG
en.wikipedia.org/wiki/Spektr-UV

Families of (large) Russian space telescopes

«**Спектр-Р**» = **«Рàдиоастрóн»** (англ. *RadioAstron*) on orbit 2011

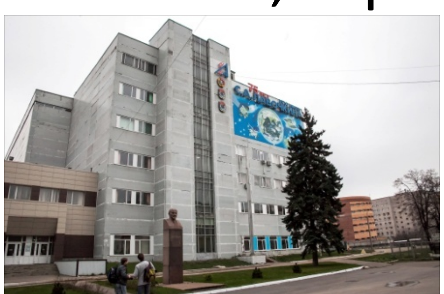
«**Спектр-РГ**» = Spectrum-X-Gamma, SRG 2018

«**Спектр-УФ**» = WSO-UV 2022+

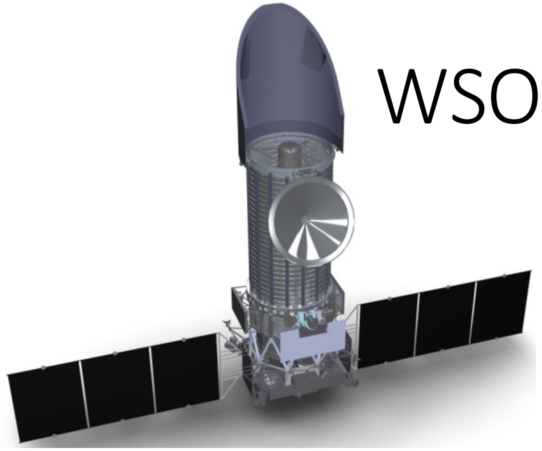
WSO-UV current Participants

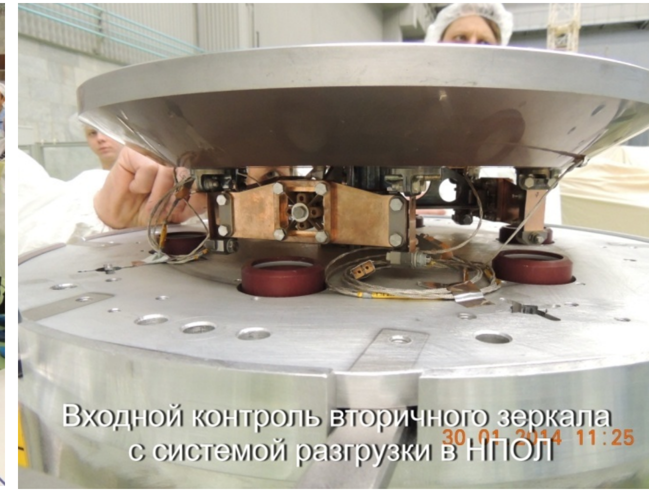
Spain, Madrid Univ, ESA
new Japan, Univ, JAXA

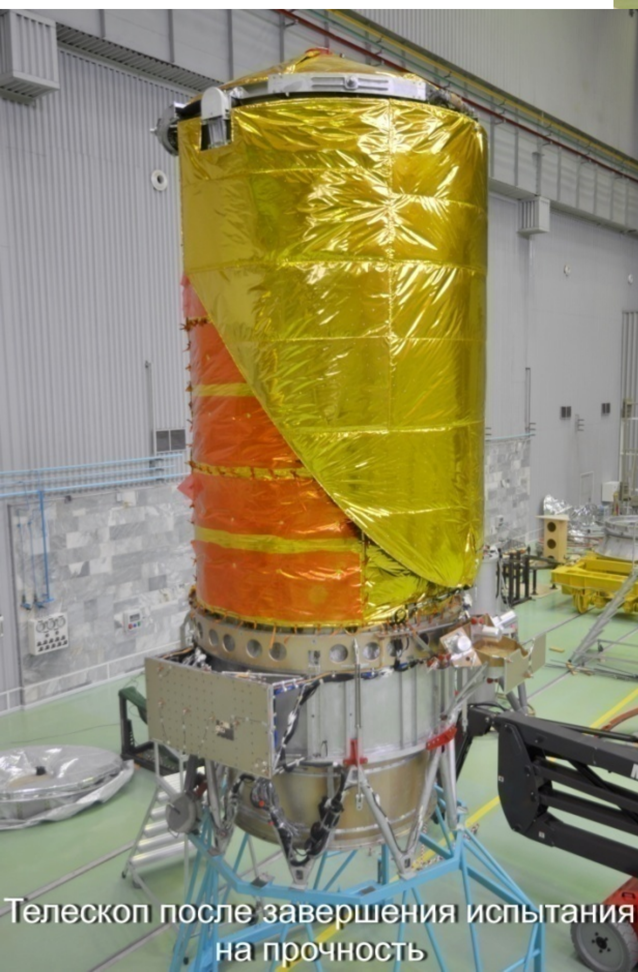
Russian Federation:
INASAN, Institute of Astronomy RAS
Lavochkin Association
IKI RAS, Space Research Institute RAS

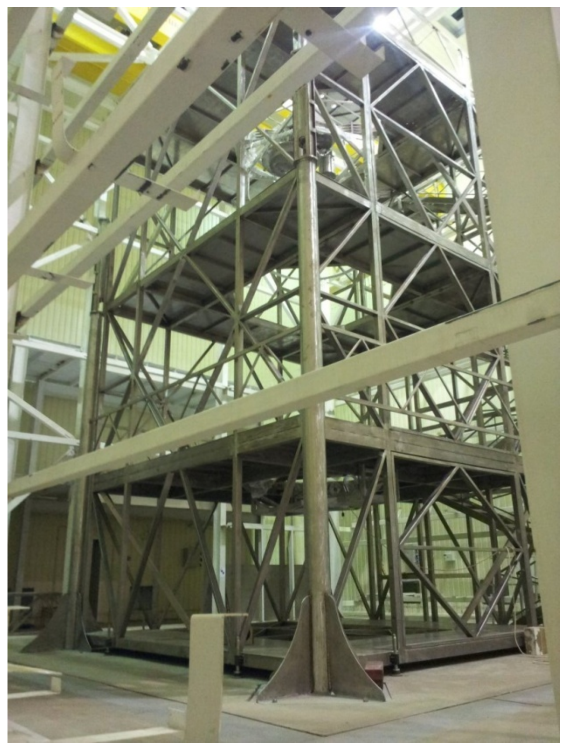


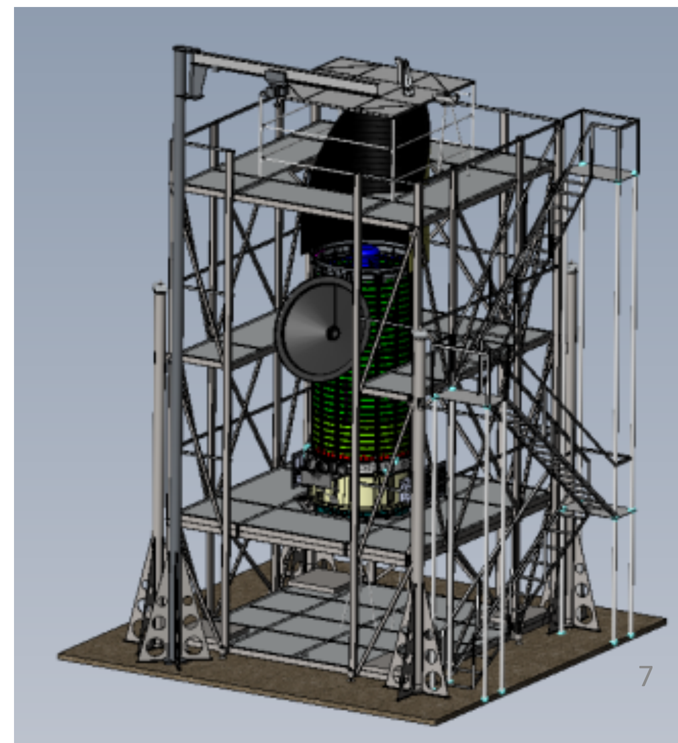
WSO-UV readiness, status 2022+, photos



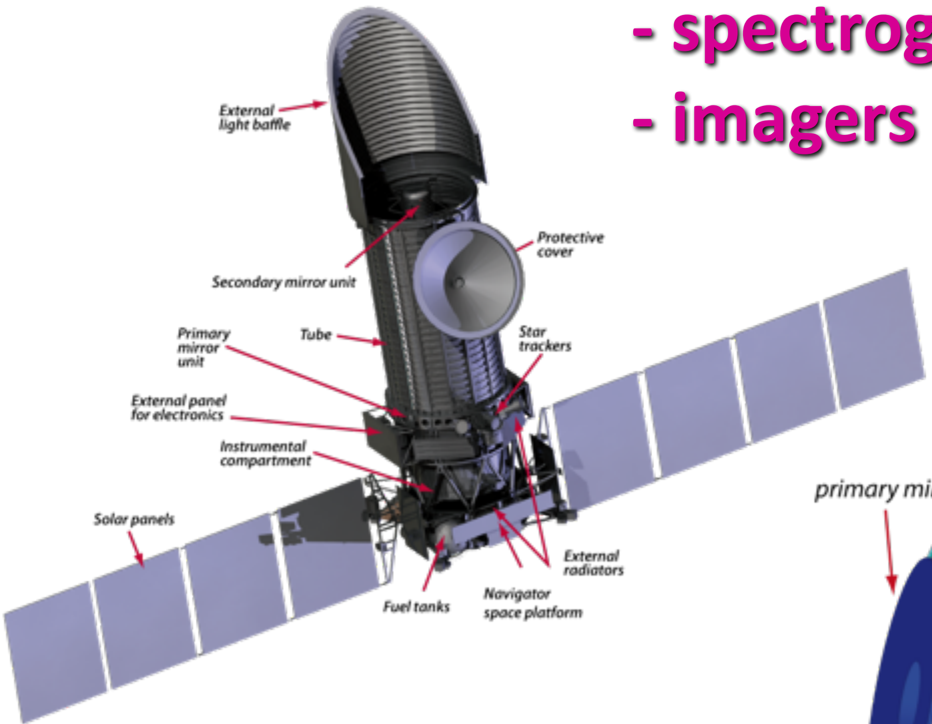


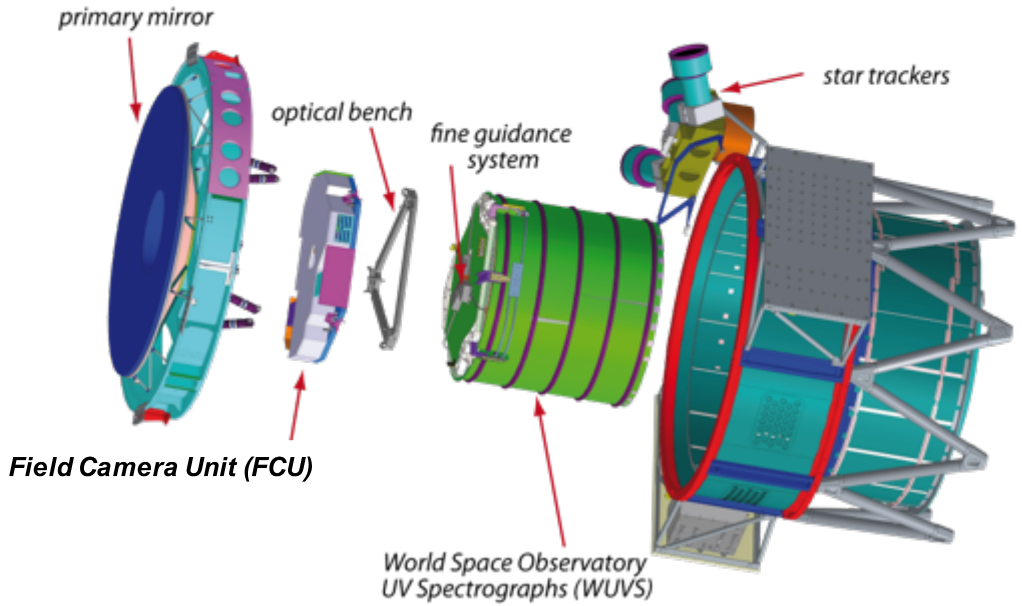






WSO-UV instrumentation:
- single telescope
- spectrographs
- imagers





25 August 2016

NATURE | LETTER

日本語要約

A terrestrial planet candidate in a temperate orbit around Proxima Centauri

23 February 2017

NATURE | LETTER

日本語要約

Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1

Michaël Gillon, Amaury H. M. J. Triaud, Brice-Olivier Demory, Emmanuël Jehin, Eric Agol, Katherine M. Deck, Susan M. Lederer, Julien de Wit, Artem Burdanov, James G. Ingalls, Emeline Bolmont, Jeremy Leconte, Sean N. Raymond, Franck Selsis, Martin Turbet, Khalid Barkaoui, … Burgasser, Matthew R. Burleigh, Sean J. Carey, Aleksander Chaushev, Chris … Laetitia Delrez, Catarina S. Fernandes, Daniel L. Holdsworth, Enrico J. Kotze

20 April 2017

NATURE | LETTER

日本語要約

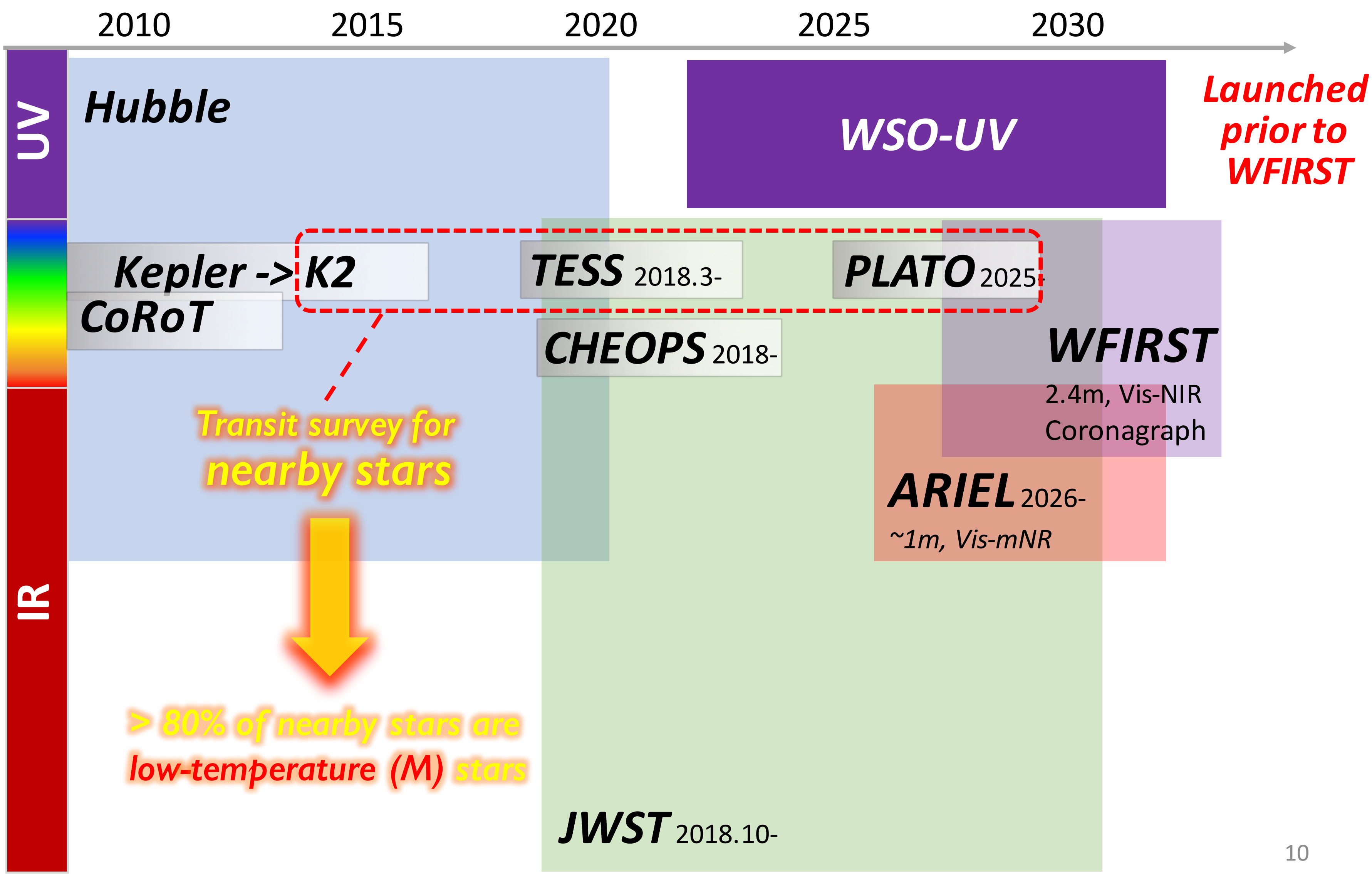
A temperate rocky super-Earth transiting a nearby cool star

Jason A. Dittmann, Jonathan M. Irwin, David Charbonneau, Xavier Bonfils, Nicola Astudillo-Defru, Raphaëlle D. Haywood, Zachory K. Berta-Thompson, Elisabeth R. Newton, Joseph E. Rodriguez, Jennifer G. Winters, Thiam-Guan Tan, Jose-Manuel Almenara, François Bouchy, Xavier Delfosse, Thierry Forveille, Christophe Lovis, Felipe Murgas, Francesco Pepe, Nuno C. Santos, Stephane Udry, Anaël Wünsche, Gilbert A. Esquerdo, David W. Latham & Courtney D. Dressing

Are they actually habitable planets?

How can we characterize those planets further?

Space Telescopes
for exoplanet detection & characterization



UVSETI instrument
Ultra-Violet Spectrometer Exoplanet Transit Instrument JAPAN **(new name UVSPEX)**

The UV-Spectrograph for Exoplanet (UVSPEX)is a spectrometer in vacuum ultraviolet range aiming to study the exospheres of exoplanets by observing transit depth in selected spectral bands to characterize oxygen, hydrogen, nitrogen species. By the study of transit depth in the spectral bands, we intend to distinguish the type of rocky earth-size planets, e.g. Venus, Earth, or the third type. It is a magnificent chance for human beings to discover an earth-twin planet with an ocean and hopefully with life for the first time.

Mission objectives -> Requirements

(MO1) Determine habitable planet candidates & surface environment

(MR1-1) Confirm presence or non-presence of large oxygen exosphere expected for Earth-like planet with high EUV

(MR1-2) Confirm whether or not large hydrogen escape occurs on terrestrial planet with high EUV

(MR1-3) Measure the H Lyman alpha emission intensity of low-temperature stars

->Requirement for UV spectrograph

(S1-1) Throughput：>0.3%（for > 4 terrestrial exoplanets at > 5 pc)

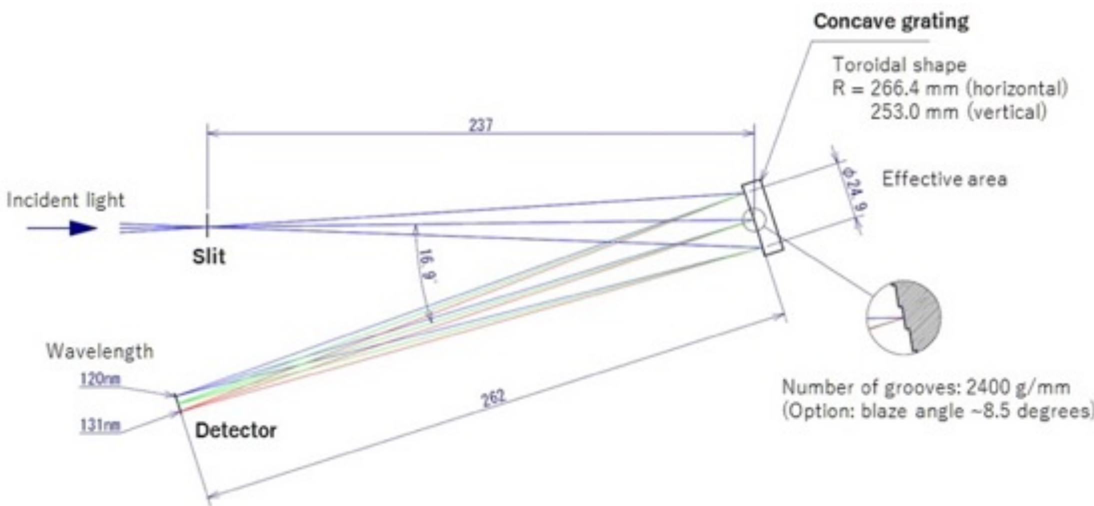
(S1-2) Spectral resolution：<0.5 nm (to separate O I line from others)

(S1-3) Spectral range: <120nm to > 131 nm (for H Lyman alpha 121.6nm, O I 130nm)

UVSETI instrument

Overview

- Simple layout: slit + concave grating + detector
- Proven components (grating: CLASP, detector: BepiColombo/PHEBUS-FUV, PROCYON/LAICA)

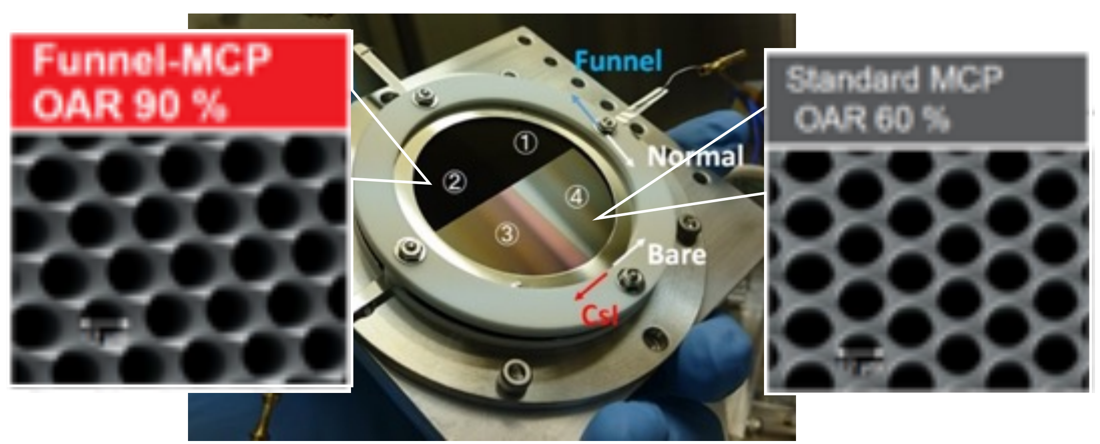


Specifications

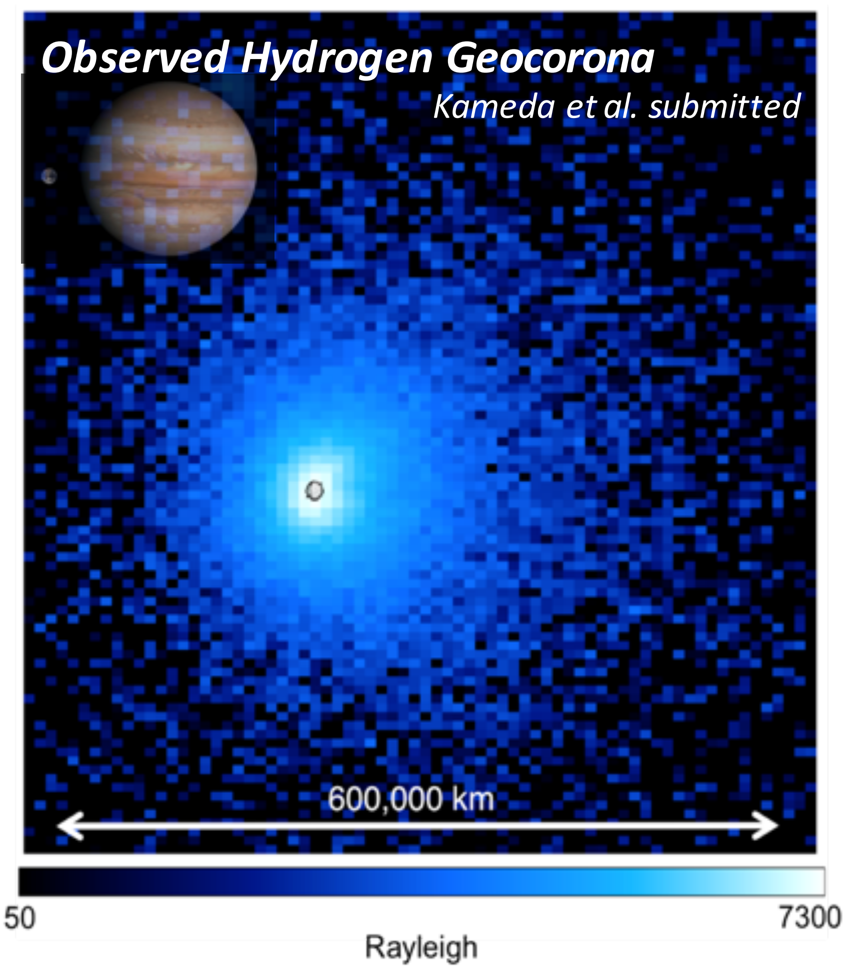
Spectral range		**115–140 nm**
Spectral resolution		**<0.5 nm @130 nm**
Total efficiency		**~4.6%**
Slit	Width	2.5 arc-sec (= 200 um)
Grating	Type	Laminar
	Shape	Toroidal
	Coating	Al + MgF_2
	Efficiency	29% (ref. CLASP)
	N	2400 g/mm
	f	250 mm
Detector	Type	CsI photocathode + microchannel plates (MCPs) + resistive anode encoder (RAE)
	Efficiency	16% (ref. LAICA)
	Effective area	ϕ 30 mm
	Resolution	80 um

Development status for options

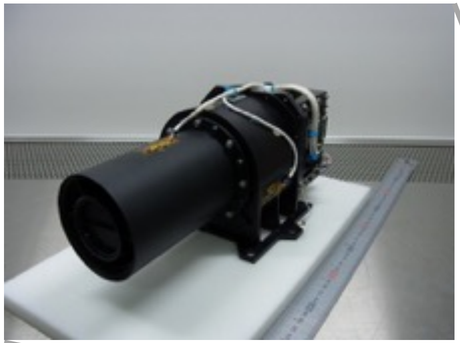
- Blazed grating samples (plane) were successfully manufactured
- Test model of Funnel-MCP achieved **1.7 times higher** quantum efficiency than normal MCP (4.6%->7.8%)

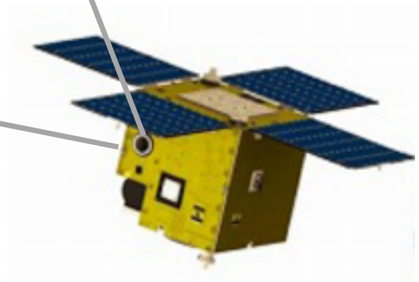


We Know Already…



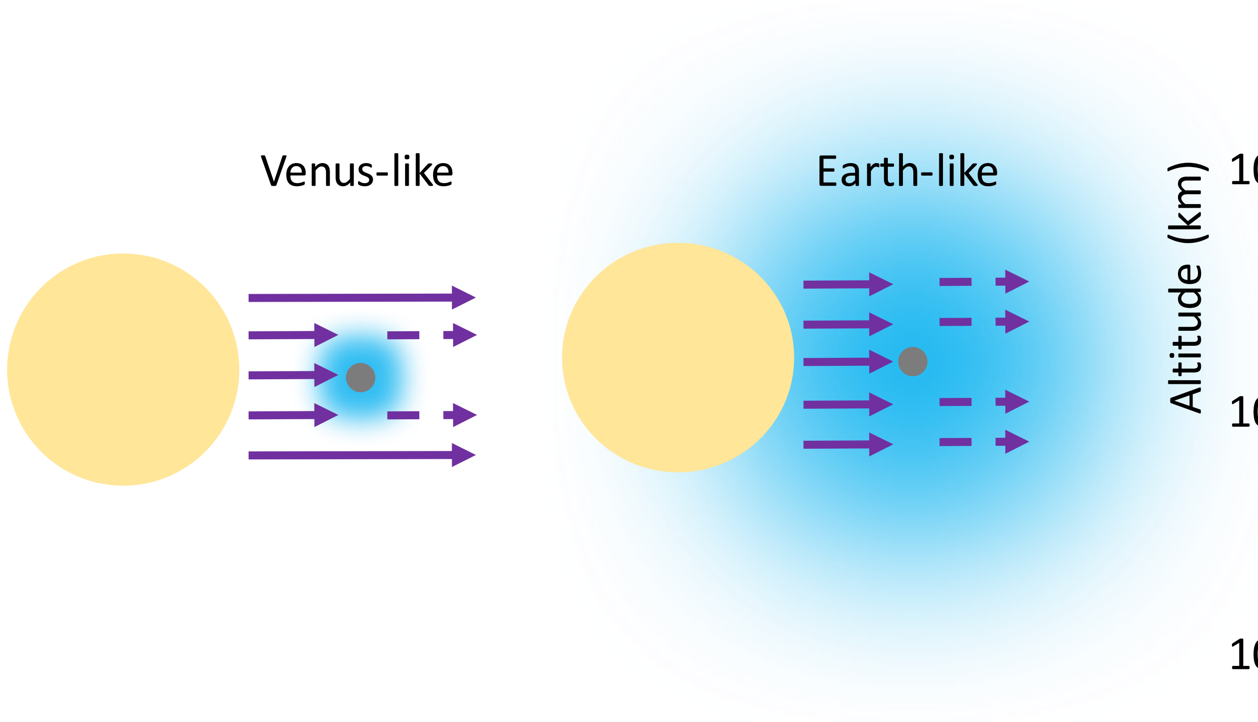
Lyman Alpha Imaging Camera (LAICA) onboard PROCYON





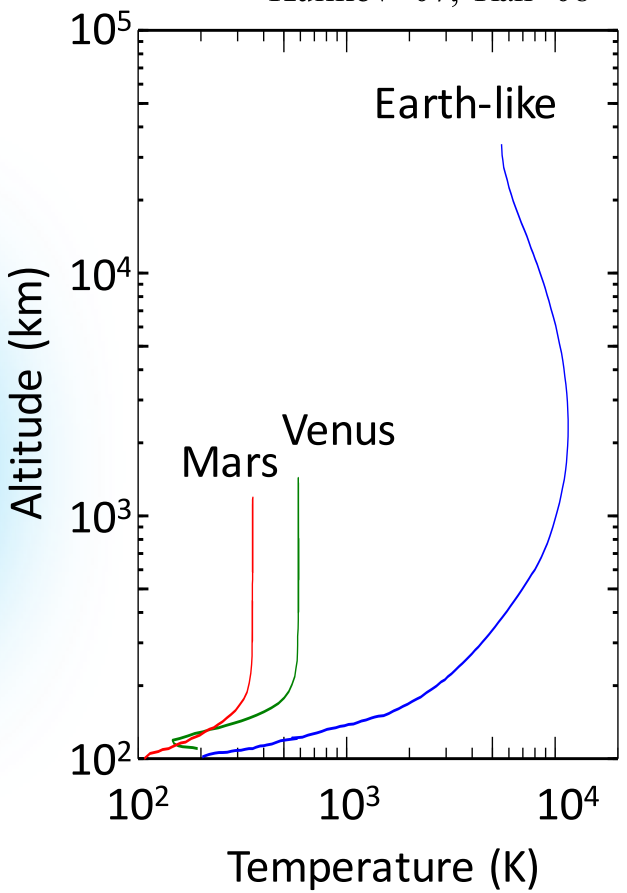
The Earth looks extremely large in the UV

Hot Oxygen Corona of Earth-like Planets



Temperature of atmospheres with high EUV irradiation

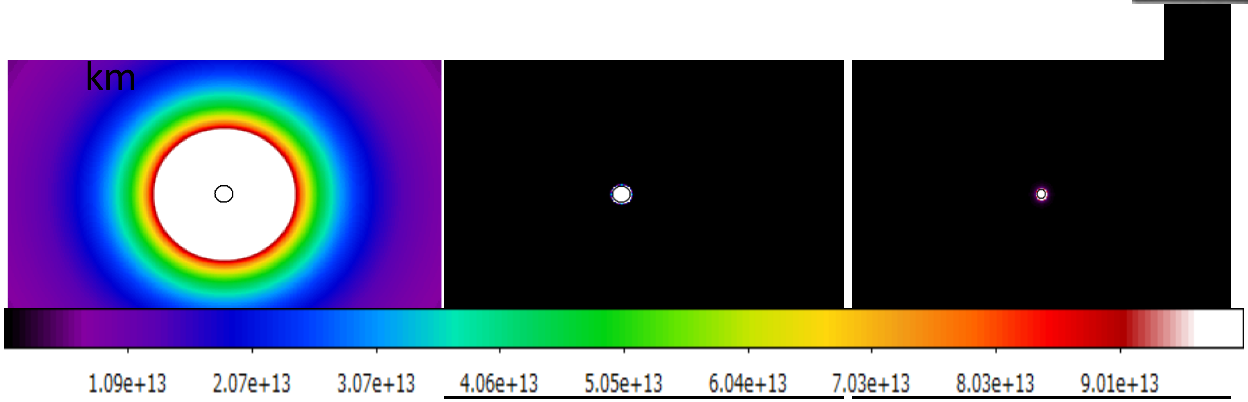
Kulikov+07, Tian+08

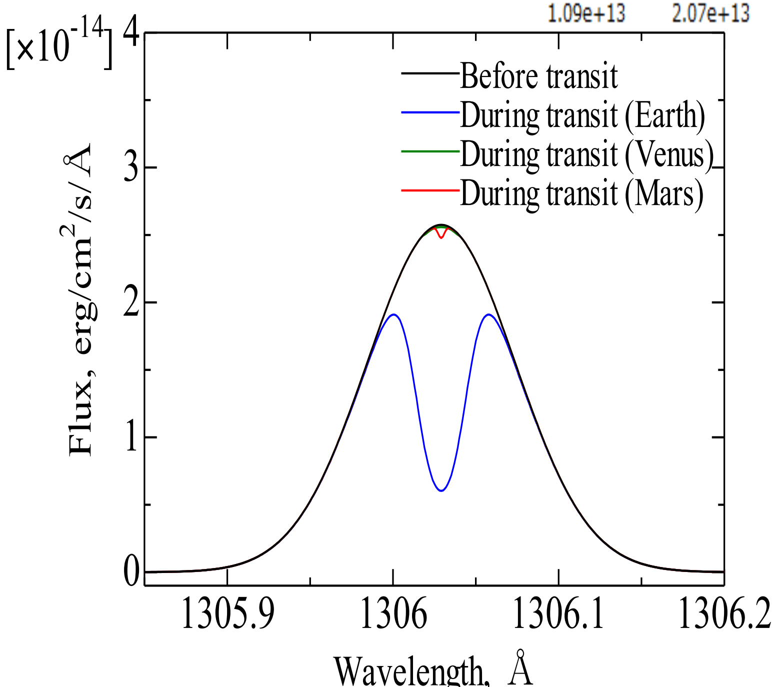


Only the Earth-like planet has extended oxygen corona

I. Shklovsky coined the name “geocorona” to describe the huge cloud of H atoms, which surrounds the Earth in the external part of the atmosphere, the exosphere, where the density is so low that collisions are negligible.

Transit depth spectrum



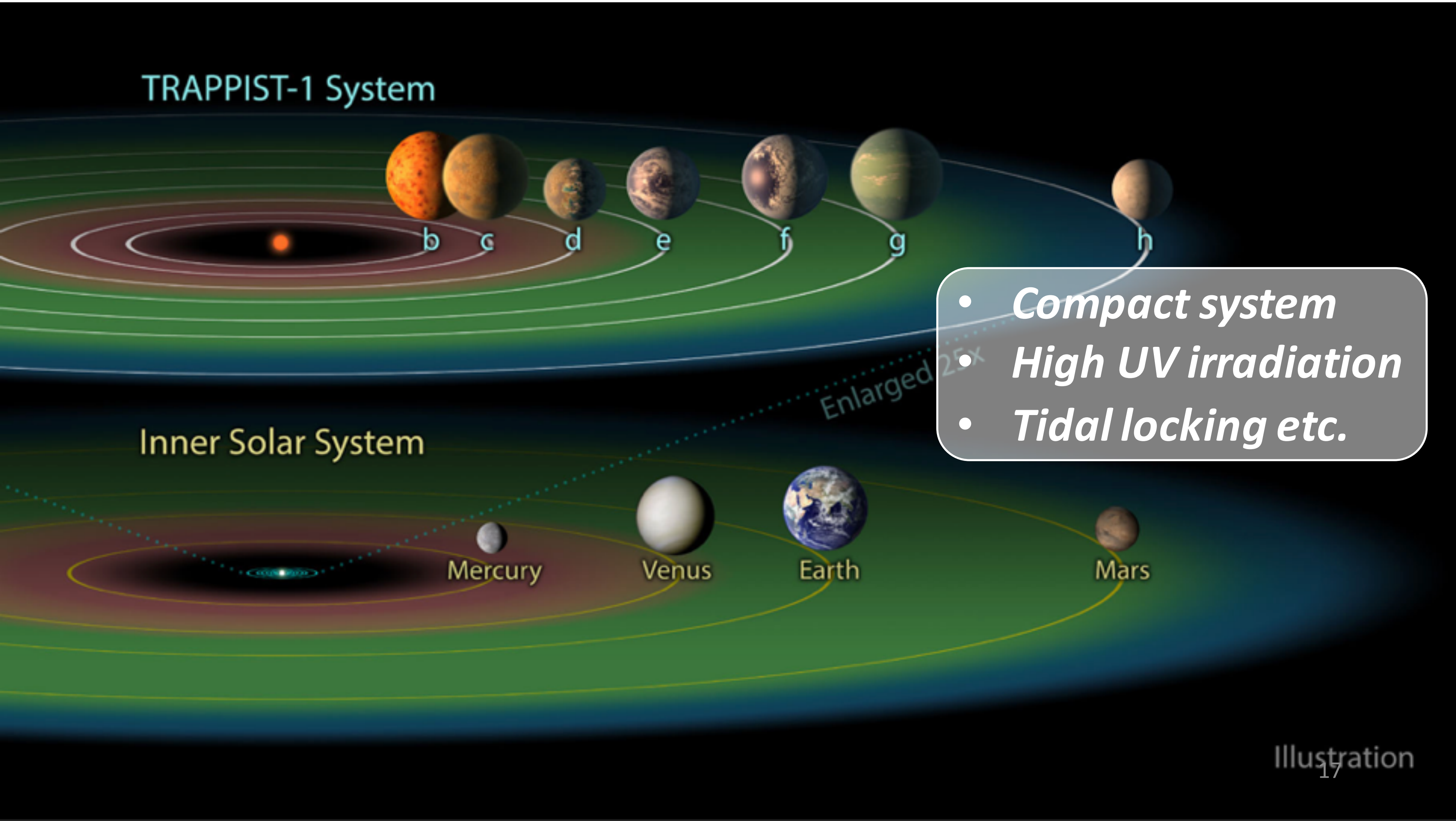


Planet	transit depth, %	Required S/N*
Earth	24	10
Venus	0.30	980
Mars	0.31	950

* For 3σ detection.

Oxygen column density

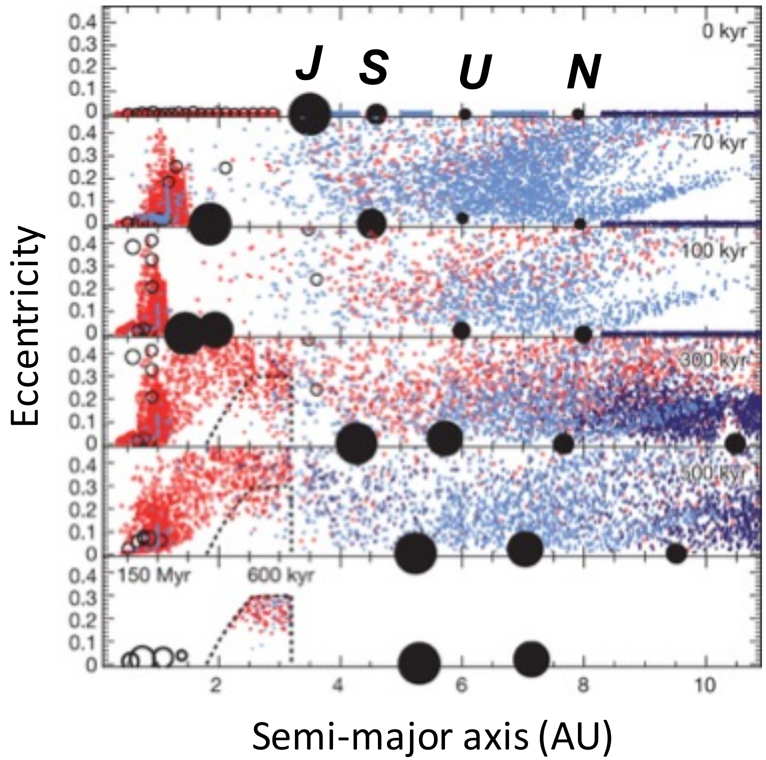
Are "Habitable Zones" around M Stars are similar to those around Solar-type Stars?

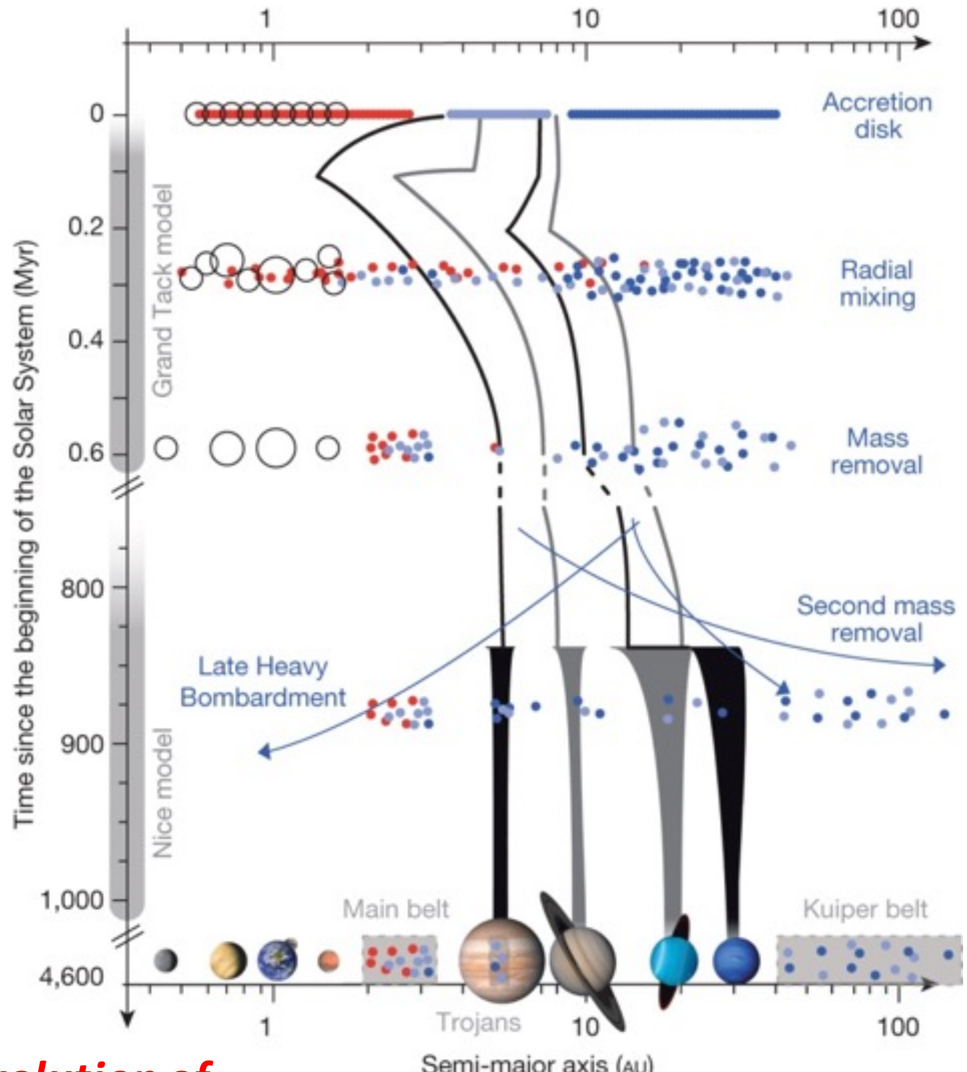


- *Compact system*
- *High UV irradiation*
- *Tidal locking etc.*

Water Delivery

Walsh et al. (2011)





DeMeo & Carry (2014)

Water delivery process is
strongly linked to the dynamical evolution of
middle regions of planetary systems.

SCEDI instrument
Stellar Imaging Coronagraph for Exoplanet Direct Imaging
Russia-JAPAN

Why exoplanet exploration via coronagraph ?

Direct imaging of non-transiting exoplanets at 1.7 m space telescope

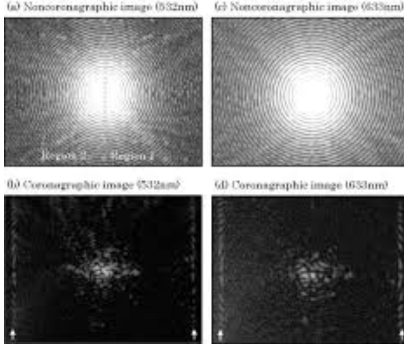
Why onboard the WSO-UV ?

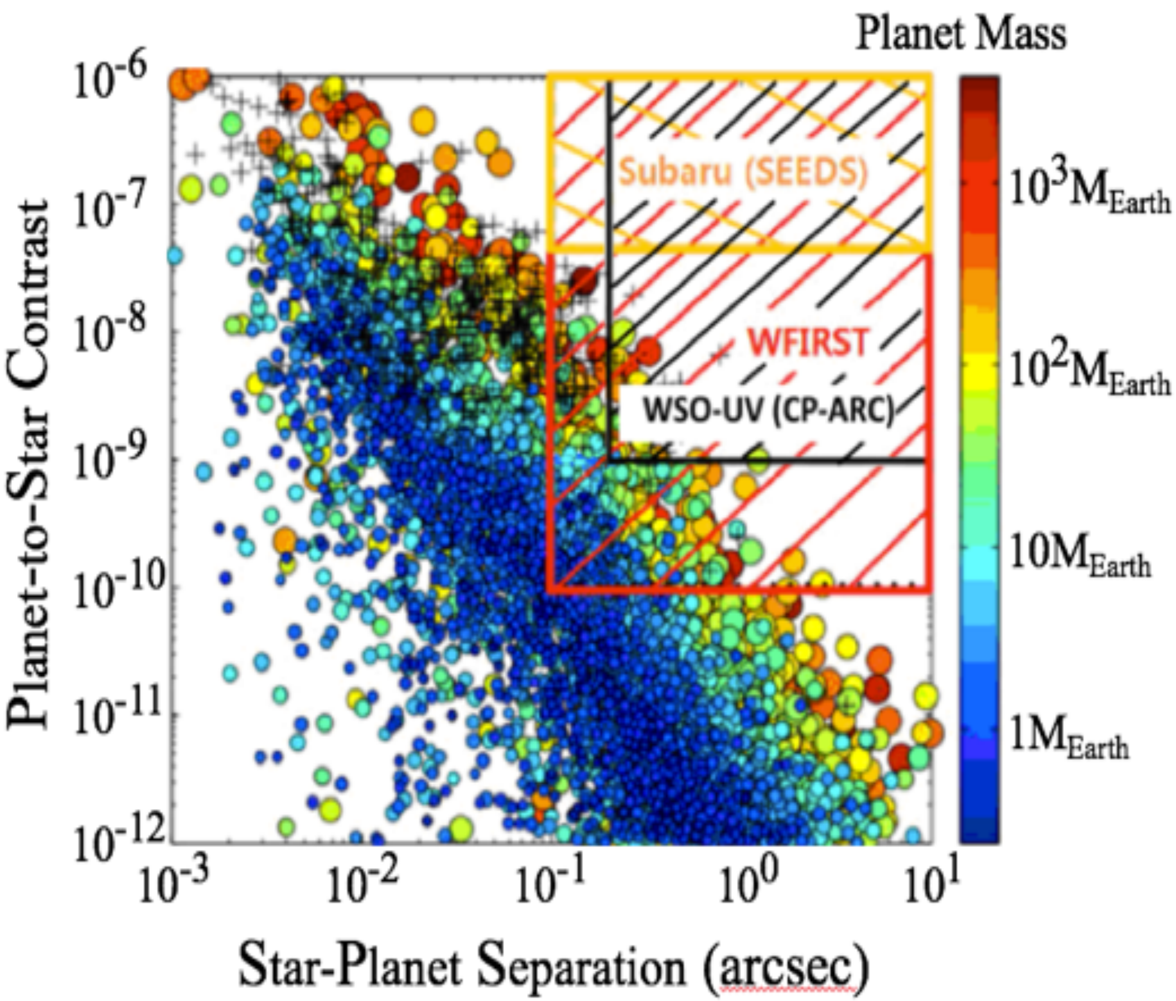
VIS range is advantageous by the UV optical quality

What can be the science income ?

See next slide

Direct Detection of Planets Surrounded by Debris Disks

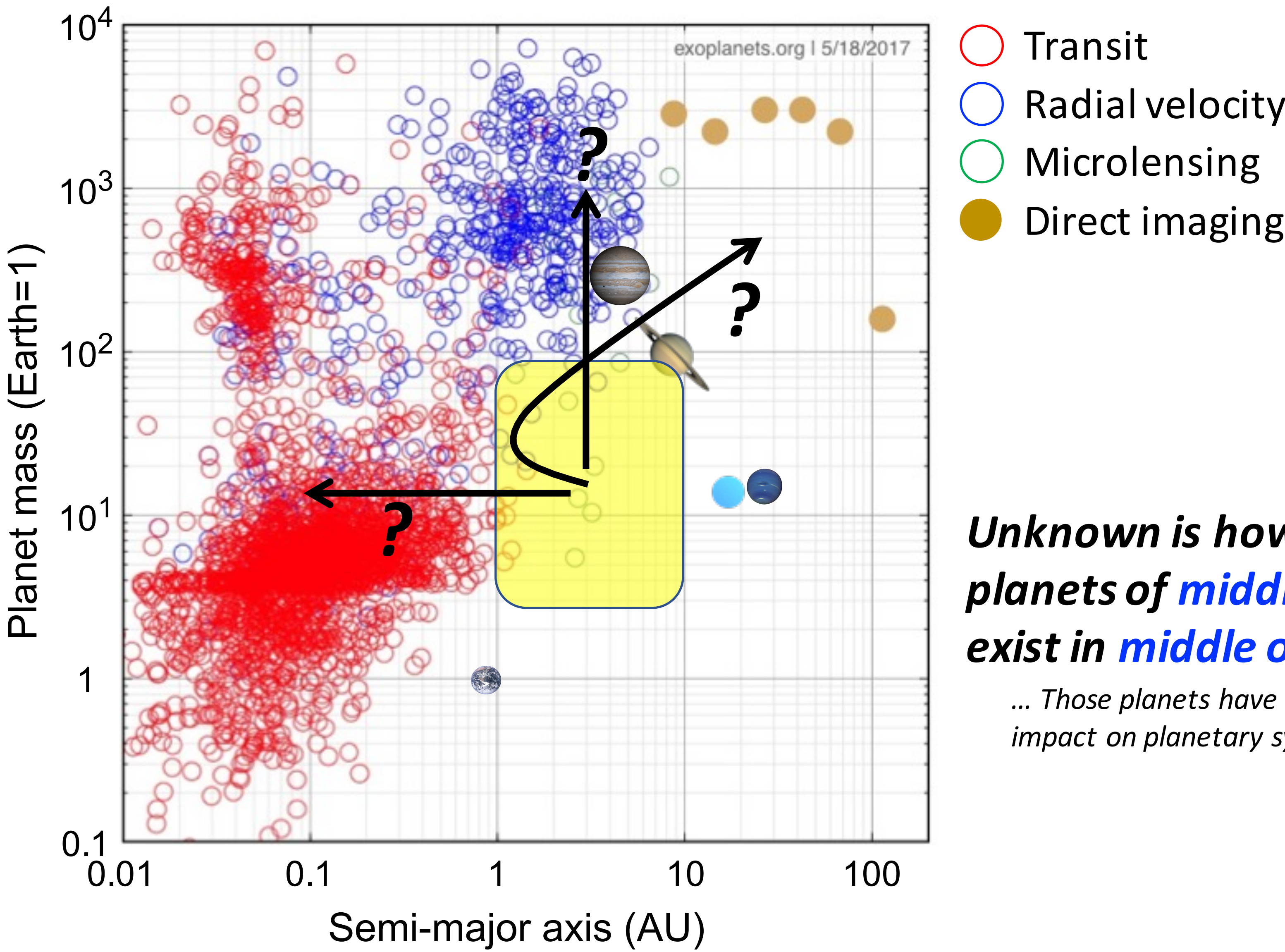




Optimistic science goal
to directly image exoplanets and circumstellar discs by searching of 20-30 stars nearby to Solar system,. Planets and discs can be observed at multiple epochs down to 7-9-th order peak-to-peak (star-to-planet) coronagraphic contrast, which enables detecting and characterizing exoplanets down to super-Earth sizes.

Pessimistic scenario
to photometrically characterize ~10 giant planets detected by the radial velocity technique.

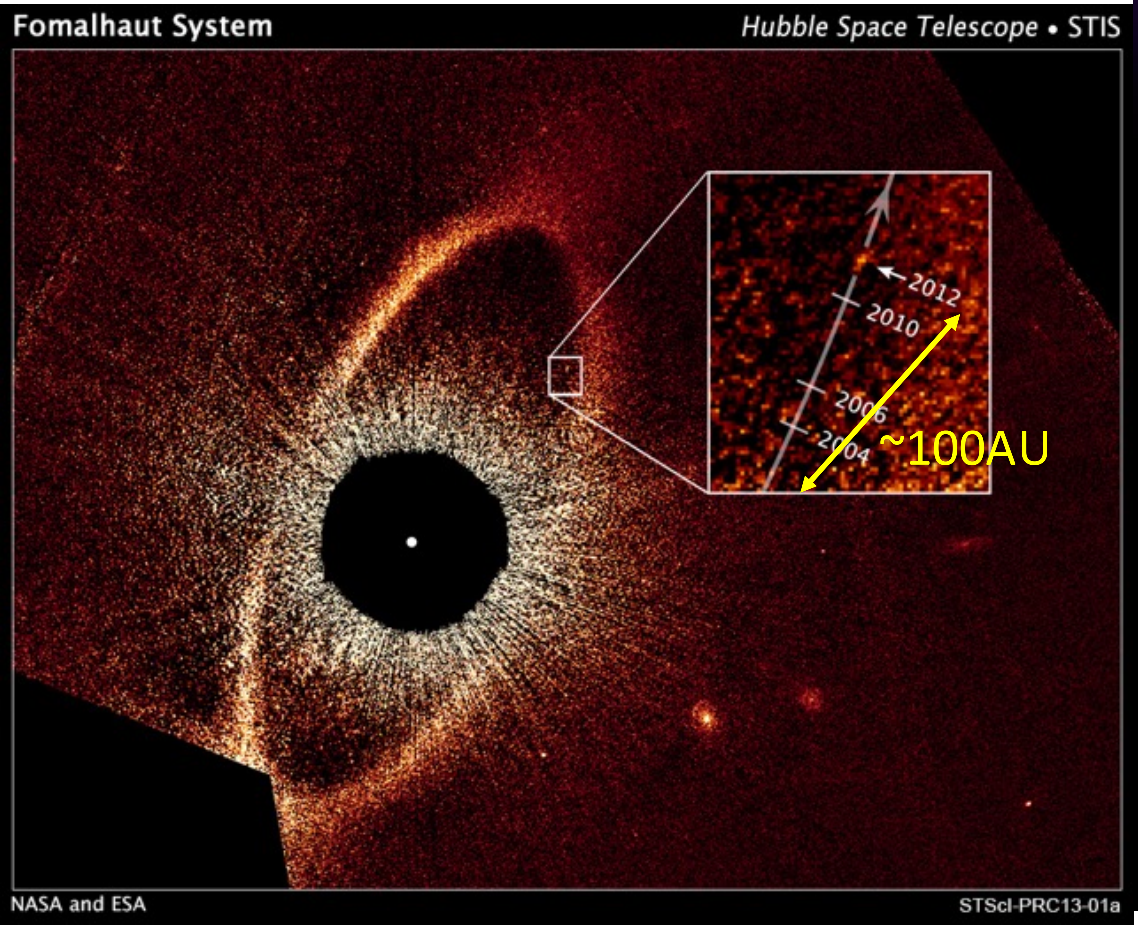
Exoplanets Detected So Far

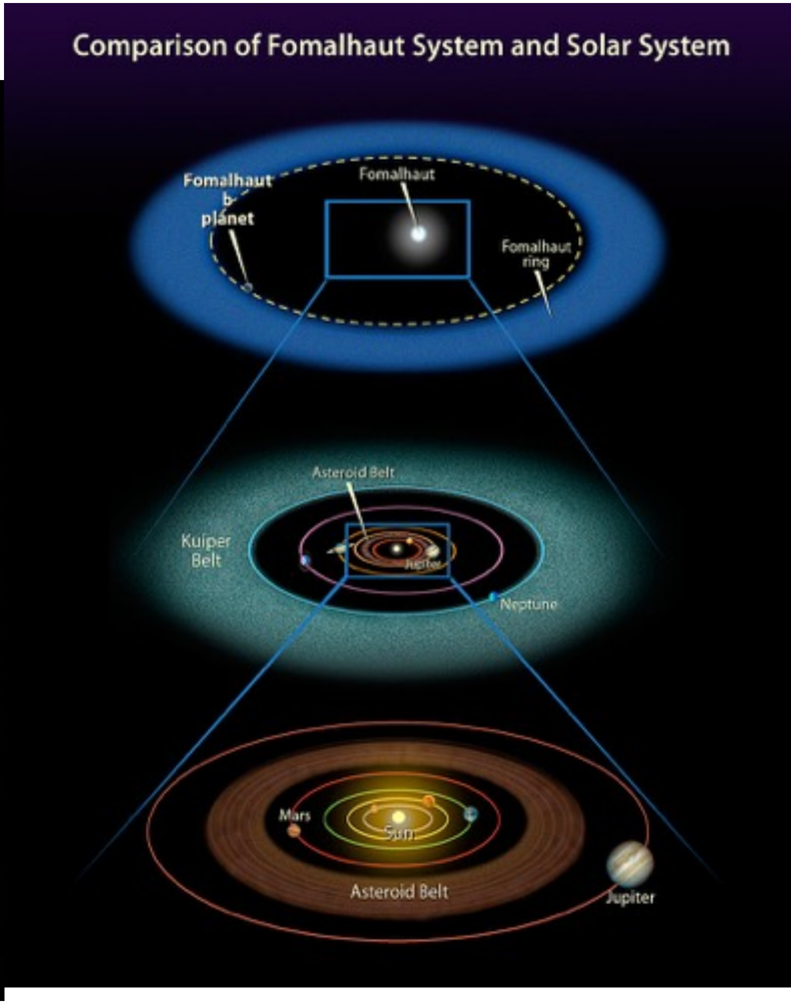


Unknown is how many planets of middle mass exist in middle orbits

... Those planets have the greatest impact on planetary system formation

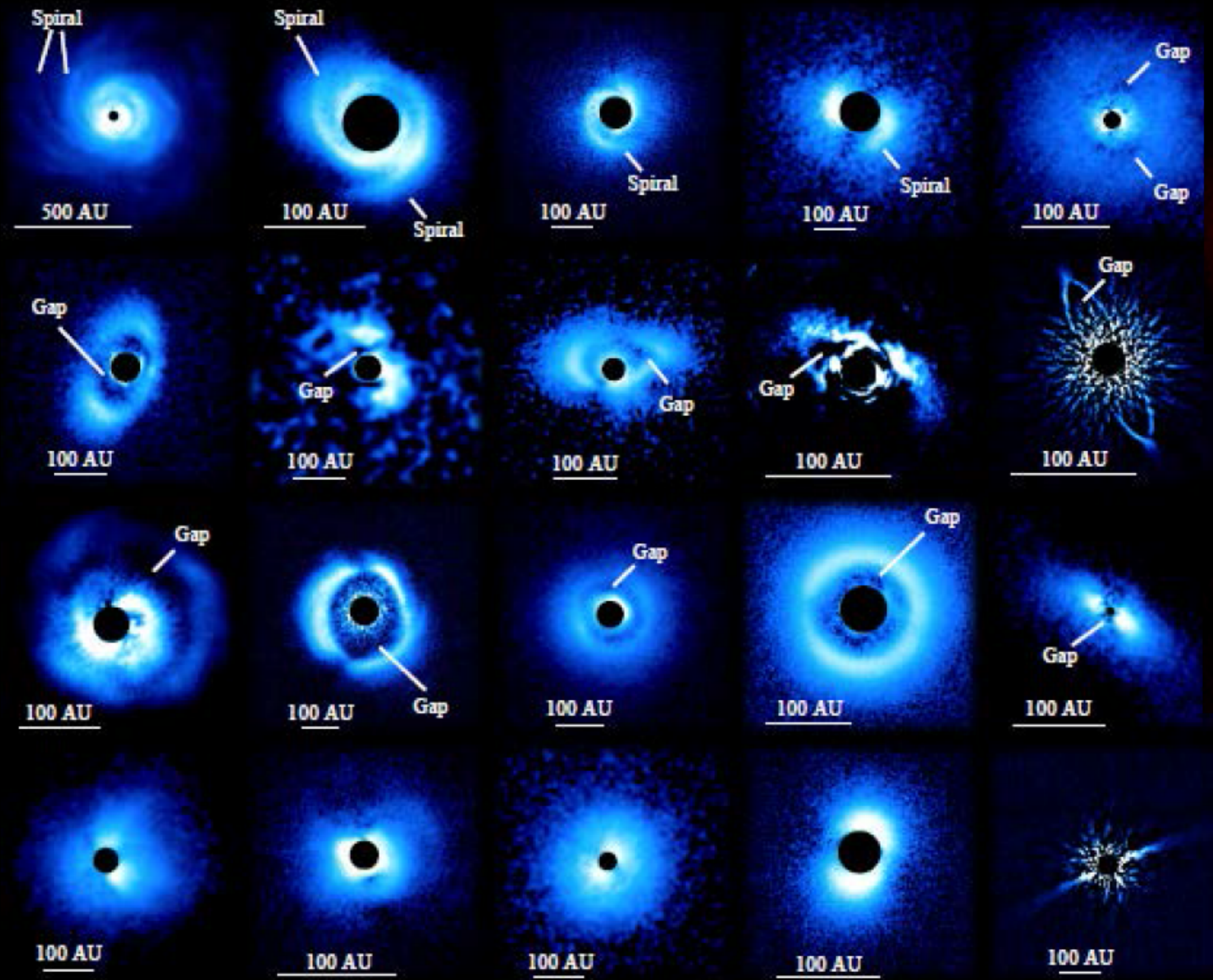
Direct Detection of Planets Surrounded by Debris Disks

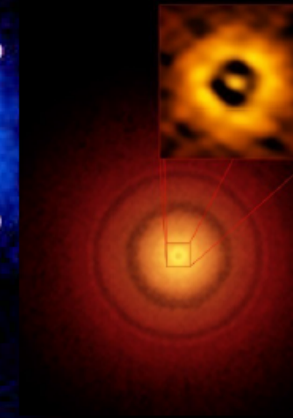




SEEDS has revealed gaps & rings of <100AU scale in many disks by polarimetric imaging (Res.~0.06”, IWA~0.1”)

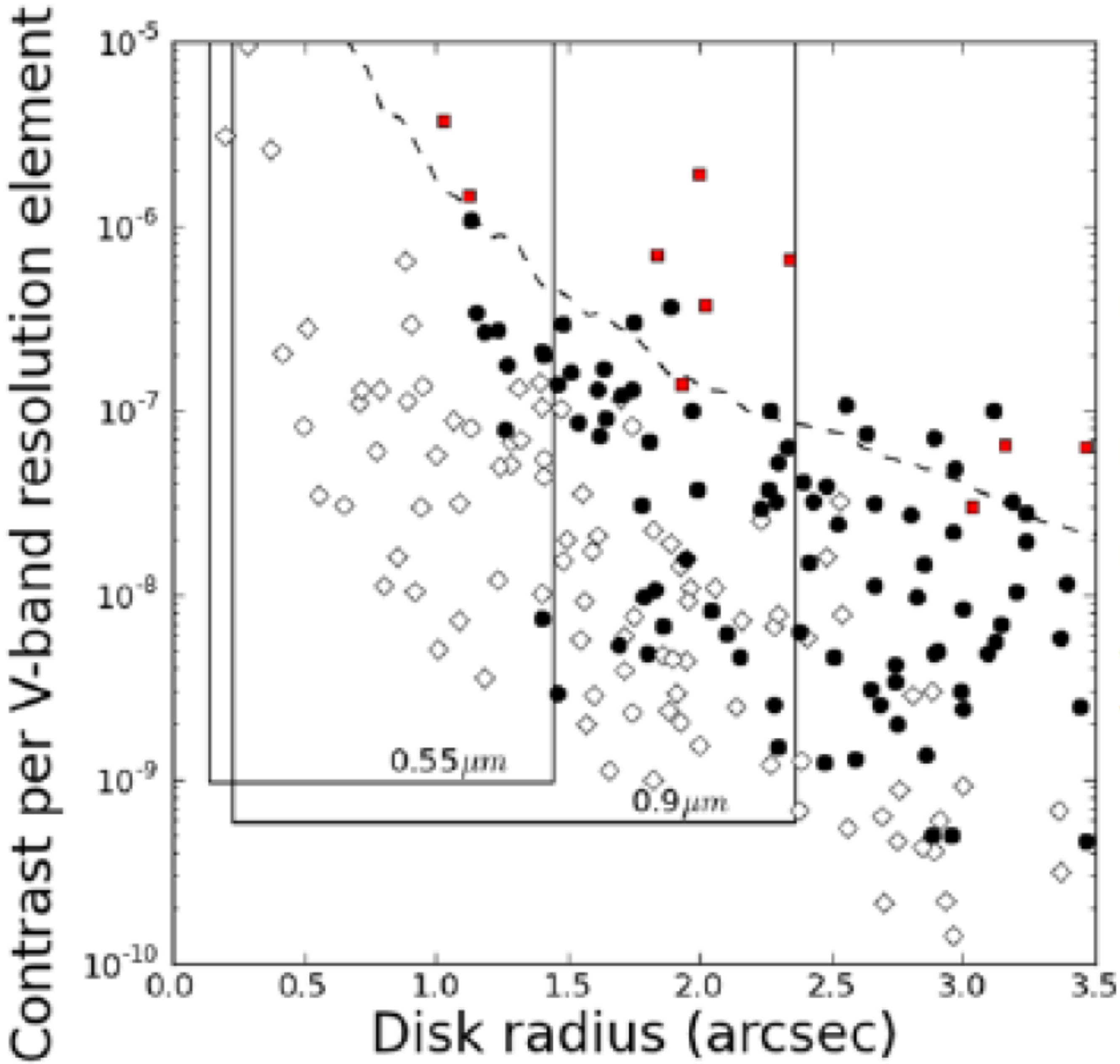
Note that ALMA TW Hya/HL Tau images are thermal emission .





ALMA
TW Hya
HL Tau

Debris disks & WSO-UV corona



red square:
Hubble detected

black circles:
Herschel marginally resolved

dashed line:
JWST sensitivity to disks

Mission objectives -> Requirements

(MO2) Detection and characterization of middle-mass & -orbit planet for origin of habitable planet candidates

(MR2-1) Survey of Neptune-like to giant exoplanet around the near star by direct imaging with high contrast

(MR2-2) Clarify the fine structure of dust disk by polarimetric observation

(MR2-3) Detection of H alpha emission from protoplanetary disk

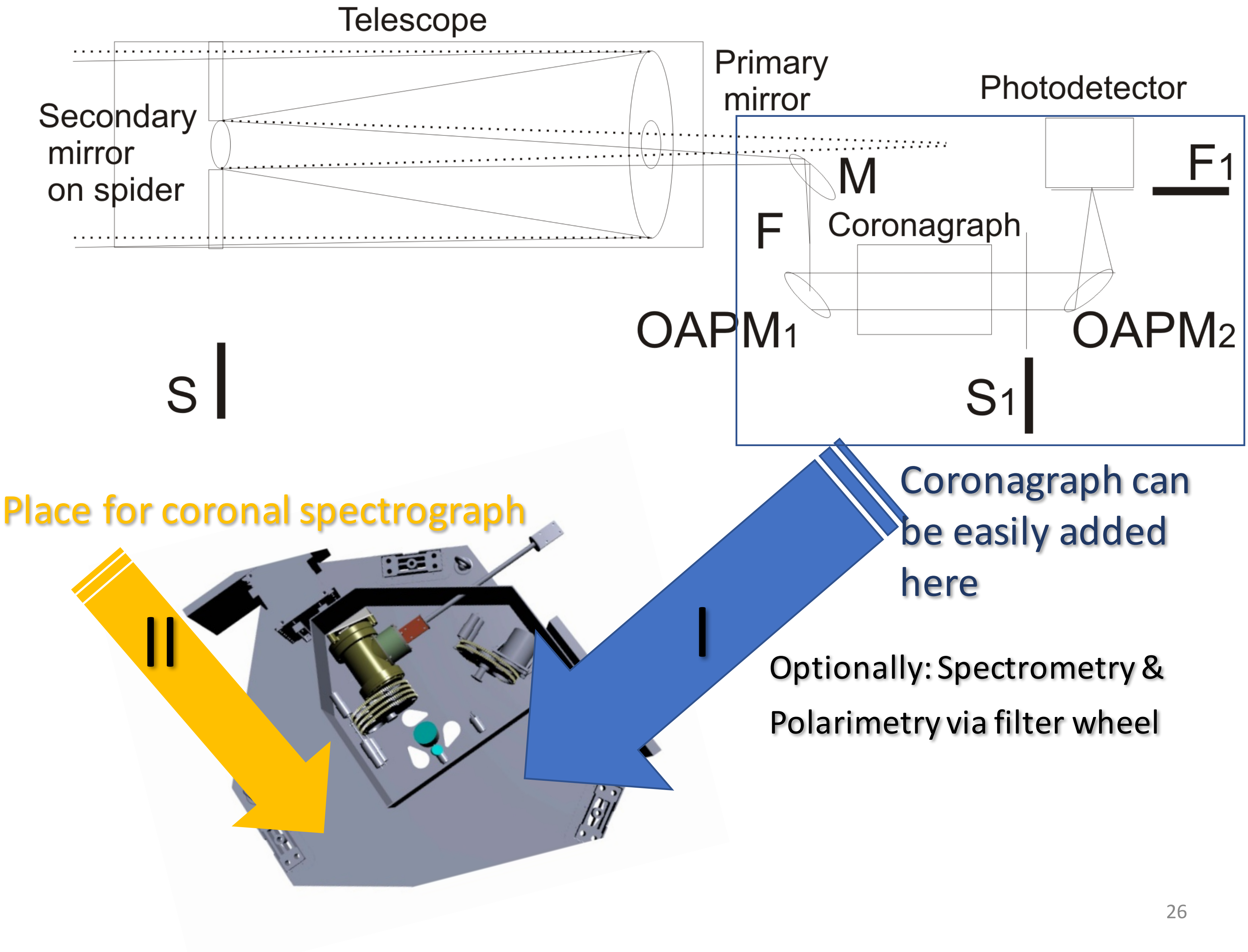
Requirement for a detector of coronagraph

(S2-1) Photon-counting of > 10000 photons/s flux

(S2-2) >20 hour observation time

(S2-3) dark current: >0.01 counts/s/pixel

(*S2-4) >512x >512 pixels



Telescope
Primary mirror
Secondary mirror on spider
Photodetector
M
F
F_1
Coronagraph
$OAPM_1$
$OAPM_2$
S
S_1
Place for coronal spectrograph
II
I
Coronagraph can be easily added here
Optionally: Spectrometry & Polarimetry via filter wheel

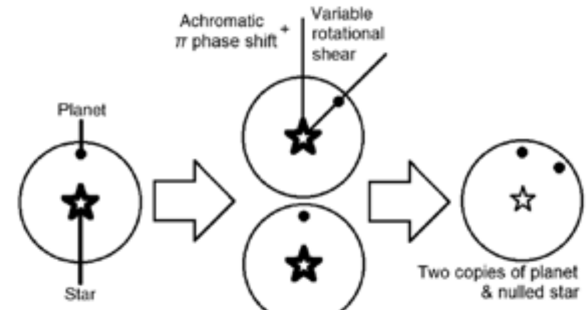
Coronagraph Instrument

Variable(small) rotation AIC（Achromatic Interfero Coronagrap

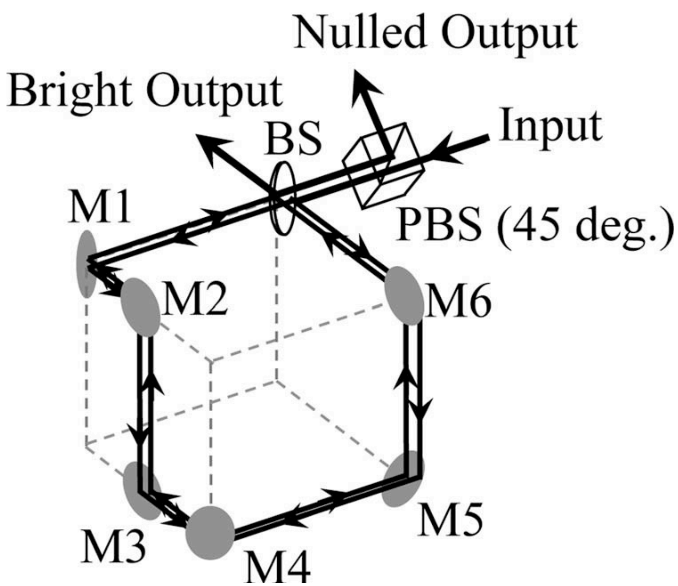
= 3-Dimensional Sagnac Interferometer

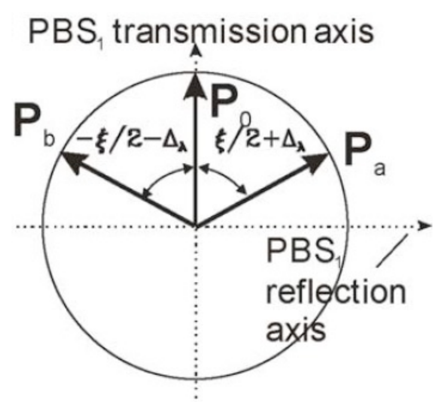
- Divide input beam by a BS, return to the same BS and combine
- 3-D optical train with a image rotator
- Nulling the star stable by the common-path optics
- Achromatic nulling for one polarization
- Canceling the wavefront error by small rotation shear
- Use lambda/2 wave plate for high throughput for small rotation share

Focal plane image of small rotation AIC



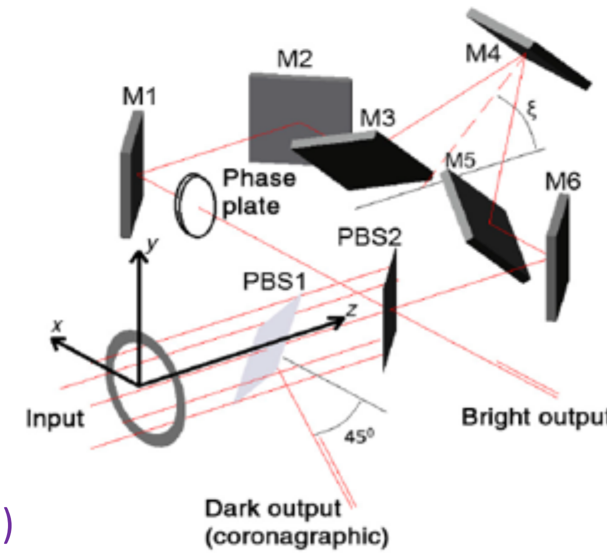
Optics of 180 deg rotation





Two electric fields (projected) will be canceled

Optics of variable rotation



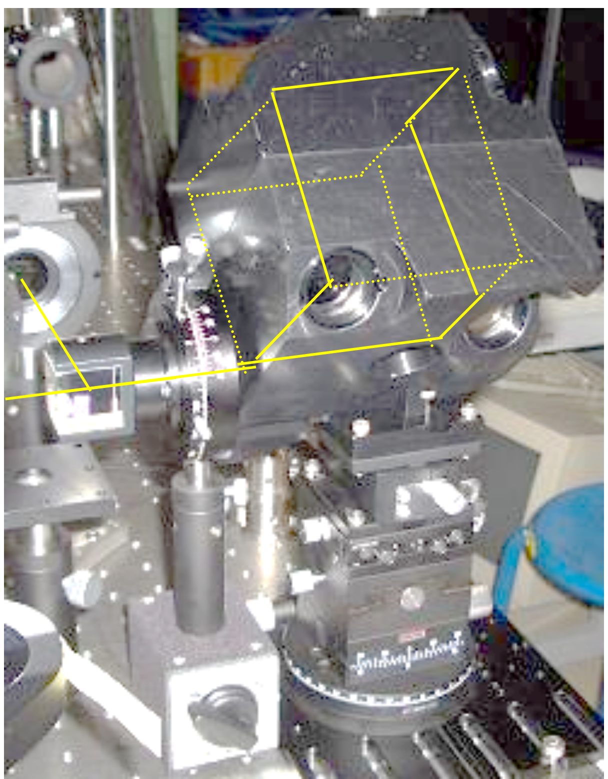
Coronagraph Experiments

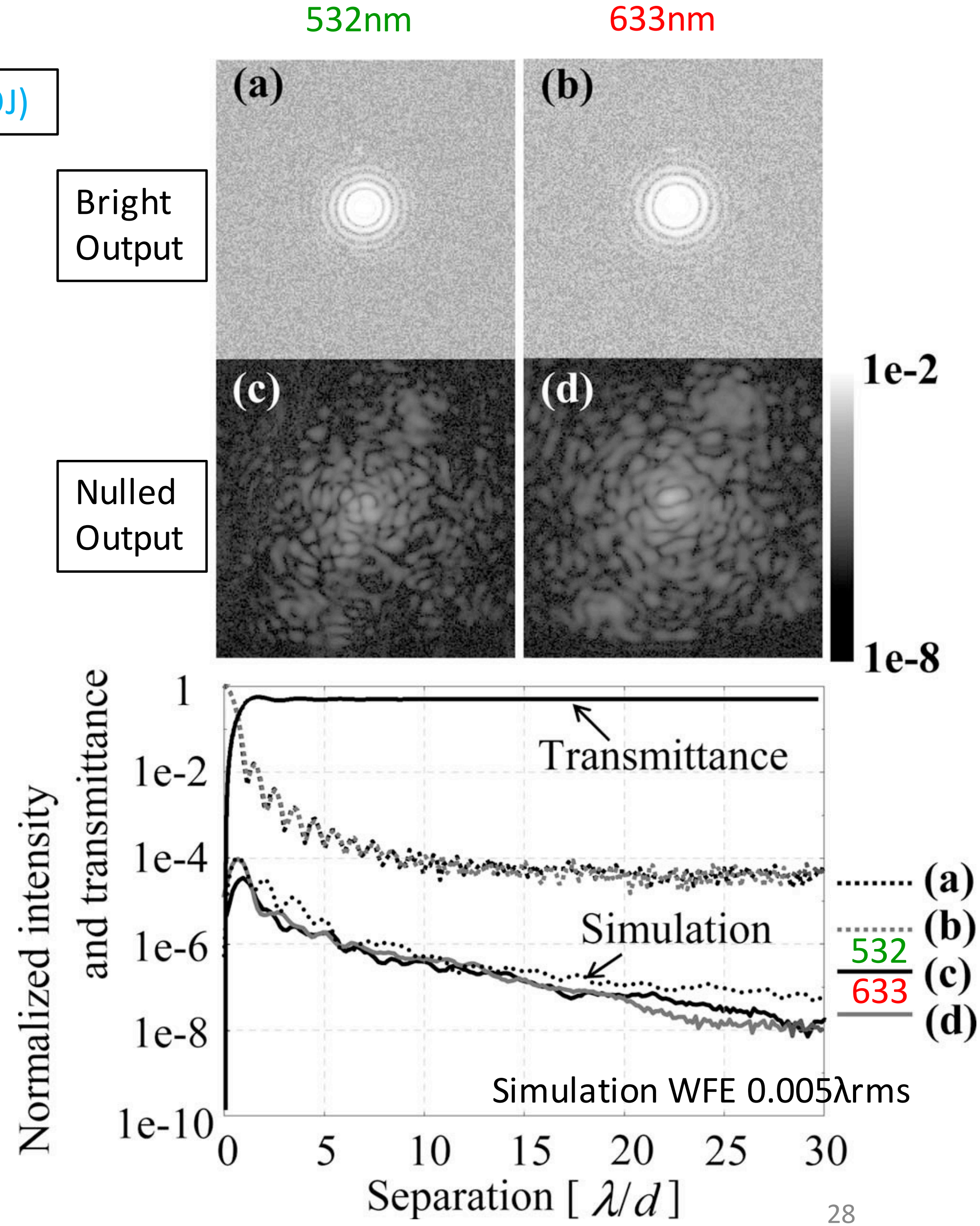
180 deg rotation experiment (@NAOJ)

Yokochi et al. Opt Lett. 34, 1985 (2009)

- Commercial mirrors on the block
- Beam diameter of 3mm
- Raw contrast (532nm&633nm)
  1E-6(@5λ/D)～1E-7(@16λ/D)

- Enough performance for WSO-UV
- Tip-Tilt control required





Coronagraph Experiments

20 deg rotation experiment (@Moscow)

Journal of Astronomical Telescopes, Instruments, and Systems 2(1), 011002 (Jan–Mar 2016)

Achromatic interfero-coronagraph with variable rotational shear: reducing of star leakage effect, white light nulling with lab prototype

Frolov et al. JATIS 2, 011002 (2016) ＋α

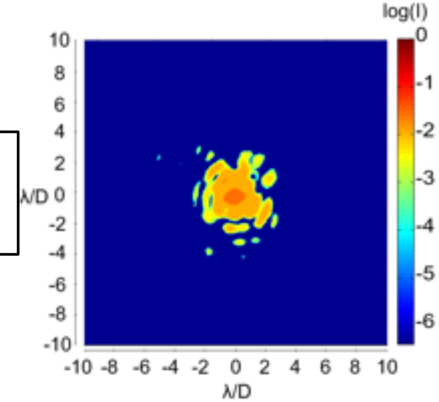
- Raw contrast (532nm) ＜1E-5 @～3λ/D
- Increase throughput by λ/2 waveplate
- Wide-band nulling confirmed

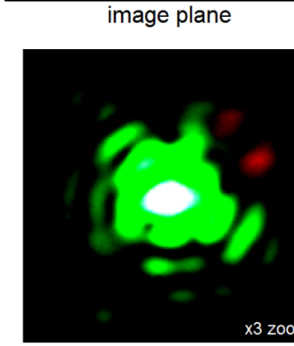
off axis =planet

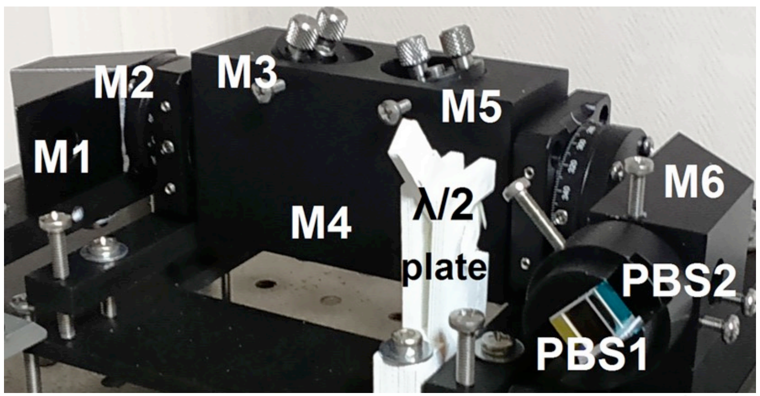
on axis =star

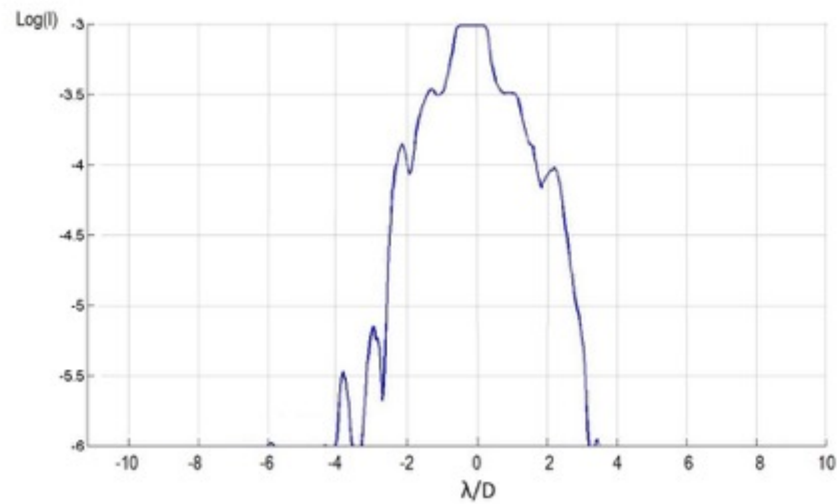
Nulled Output

532nm

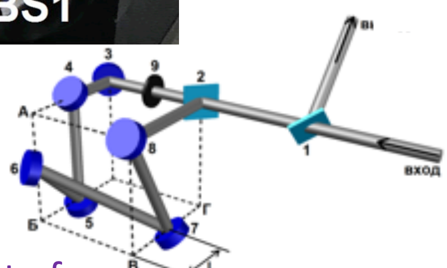






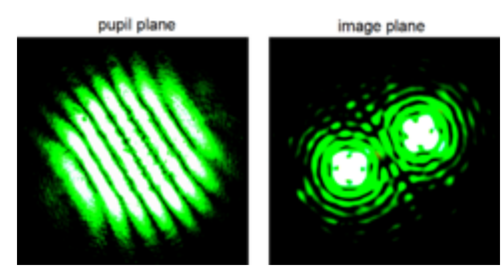


New design

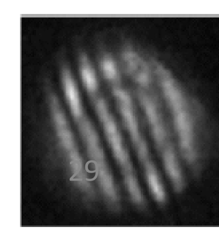


532nm

Wide band (500-700nm)



Pupil plane



Not difficult to obtain raw contrast of 1E-6 @5λ/D by only the coronagraph optics.

・Need to consider wavefront error of the Primary mirror

Coronagraph Simulation Study

- <u>Raw contrast</u>：

Defined by the wavefront error of the primary and the cancelling effect of the small rotation AIC.

Primary's wavefront error：an aberration level below λ/5, 1nm rms in mid- & high spatial frequencies.

λ/5 (PV)、－11/3law（good at high frequency）->simulation

Raw contrast of 1E-6@5 λ/D can be obtained by 5 deg ~ 10 deg rotation

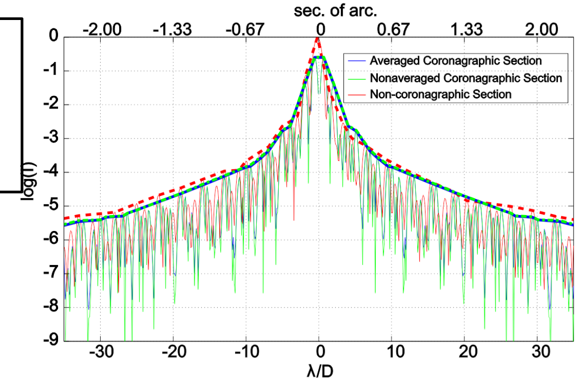
（should be confirmed with real condition)

- <u>Inner working angle（IWA)</u>

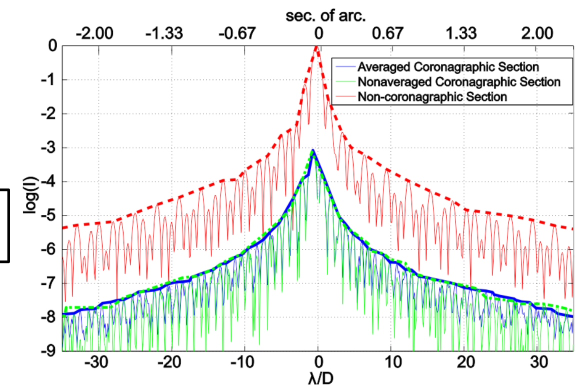
180 deg rotation：0.38 λ/D

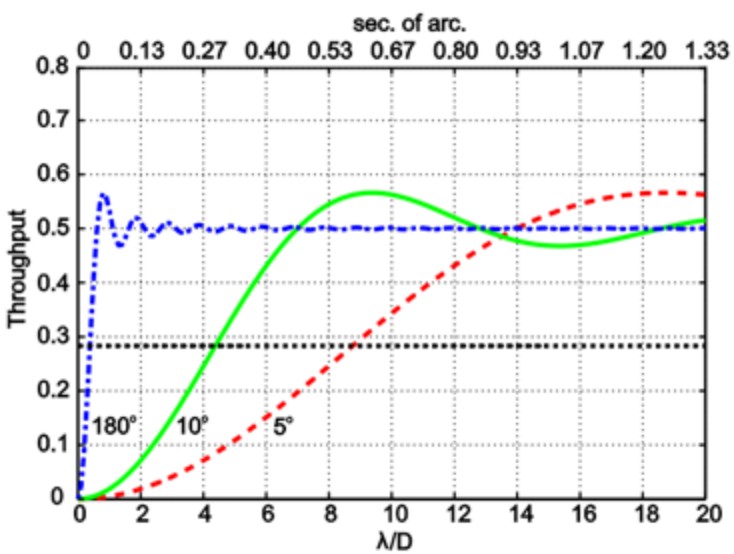
10deg rotation：4.5 λ/D　　（～0.3"@550nm）

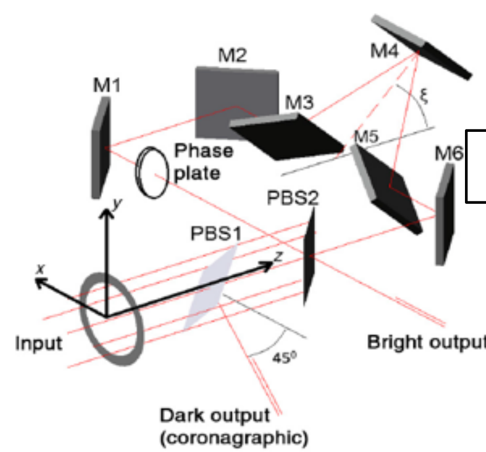
180 deg Rotation Shearing



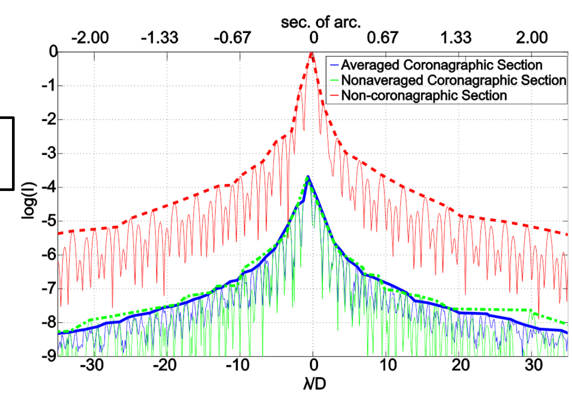
10 deg



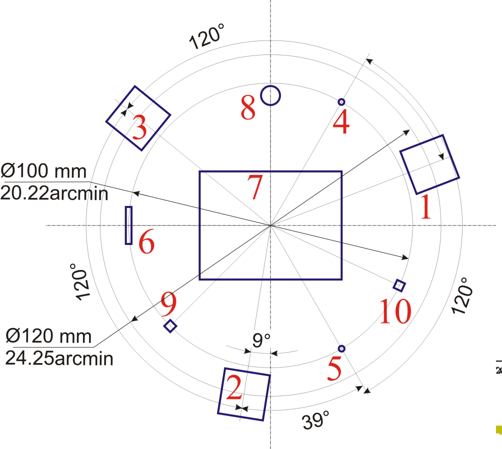


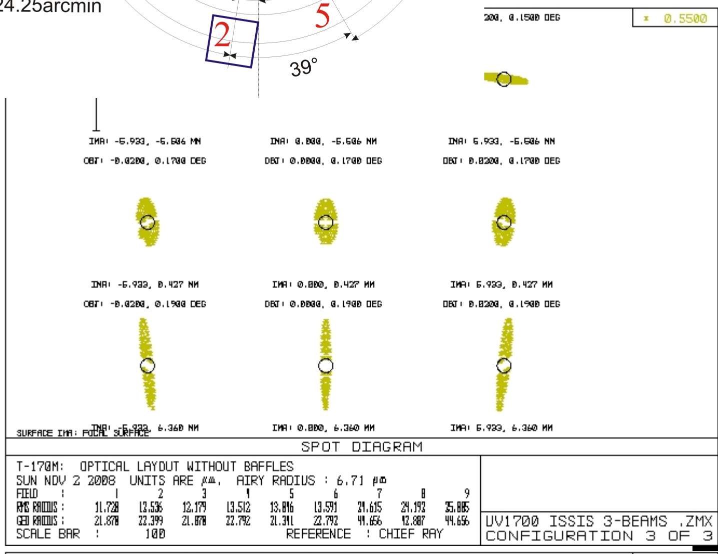


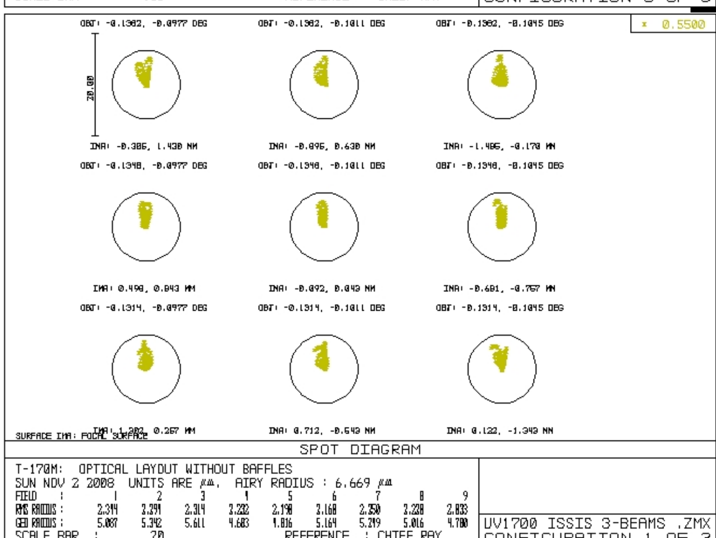
5 deg

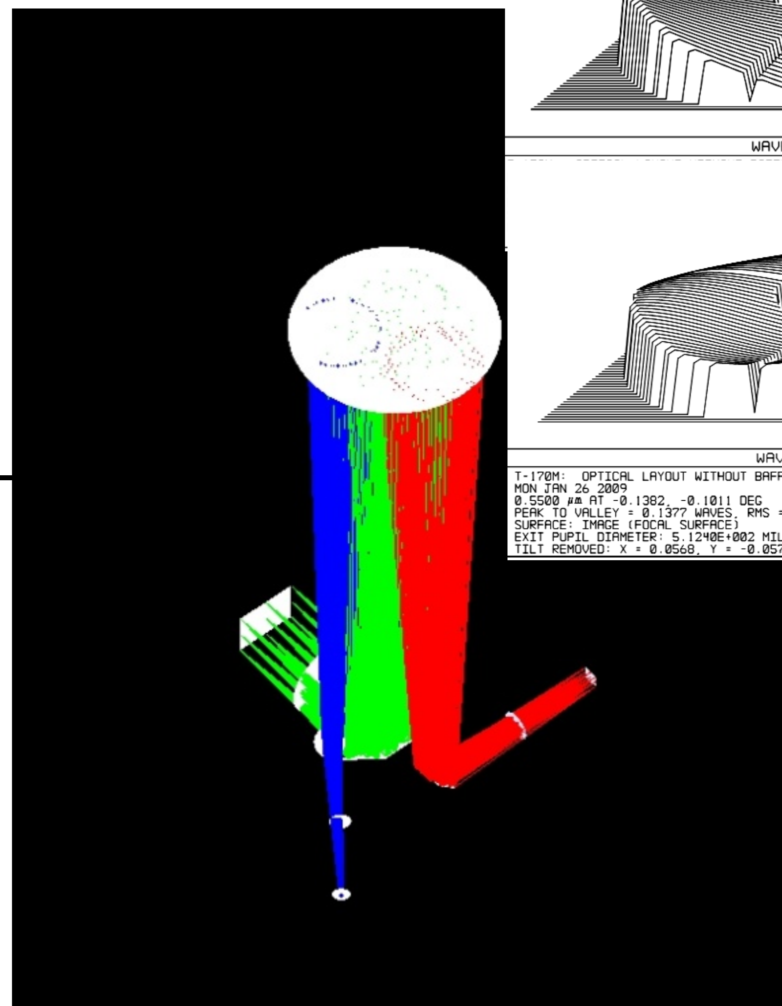


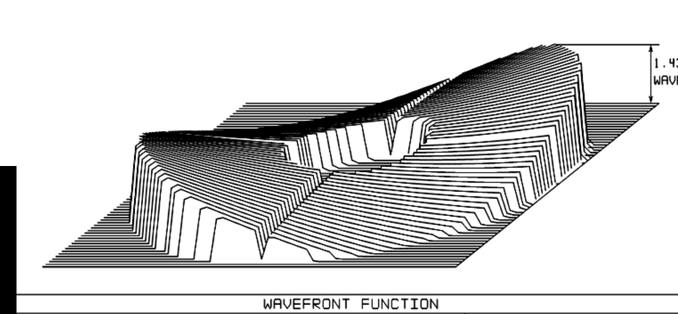
On axial field correction up to λ/8 @ λ=550 nm with only a single spherical diagonal mirror

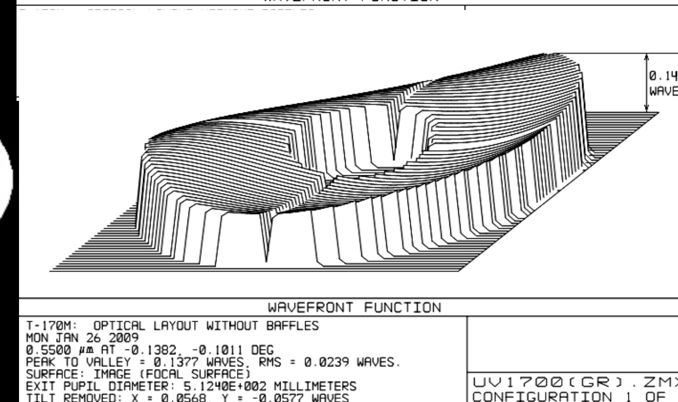


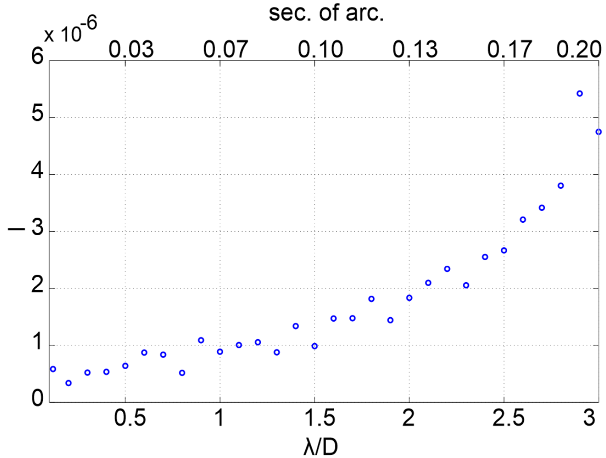


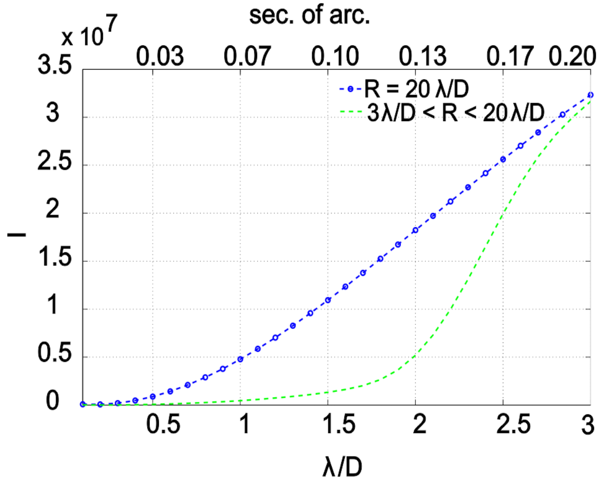






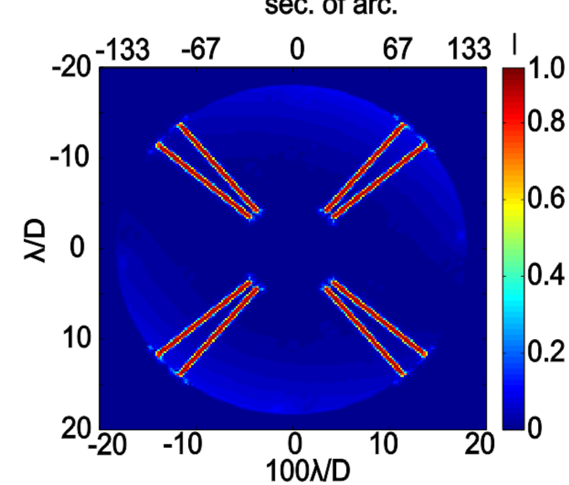


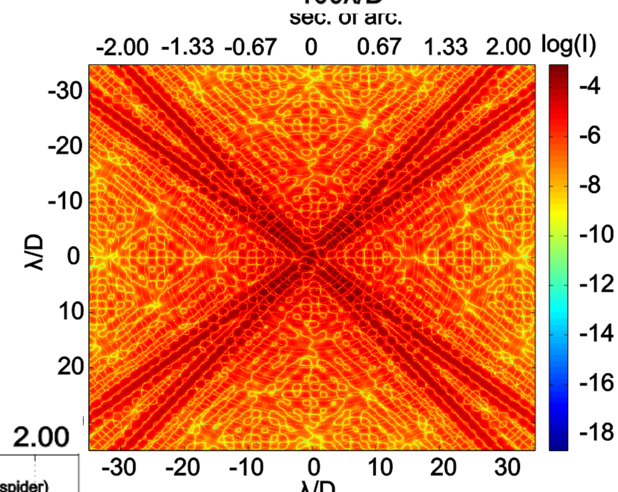


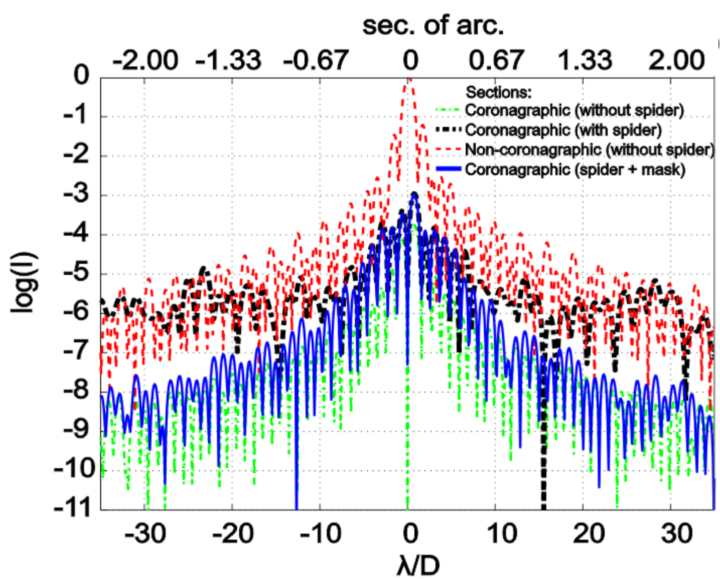


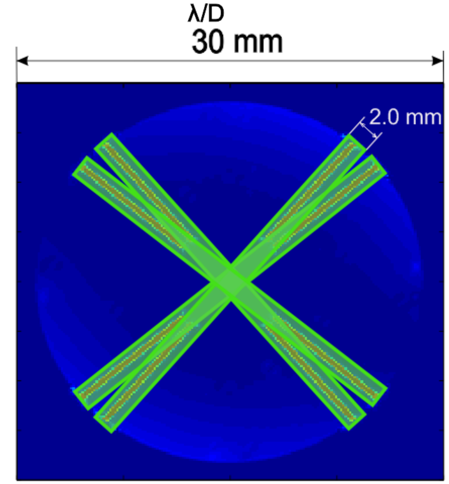
a).	b).

Coronagraph sensitivity to pointing error: a). – the (raw) coronagraphic contrast at $10 \cdot \lambda/D$ stellarcentric position versus the pointing error and b). – the leaked stellar light photon-flux integrated over a Ø $40 \cdot \lambda/D$ area versus the pointing error, dot (blue) line – without any mask, dash-dot (green) line – with the opaque focal mask hiding a Ø $6 \cdot \lambda/D$ central area.





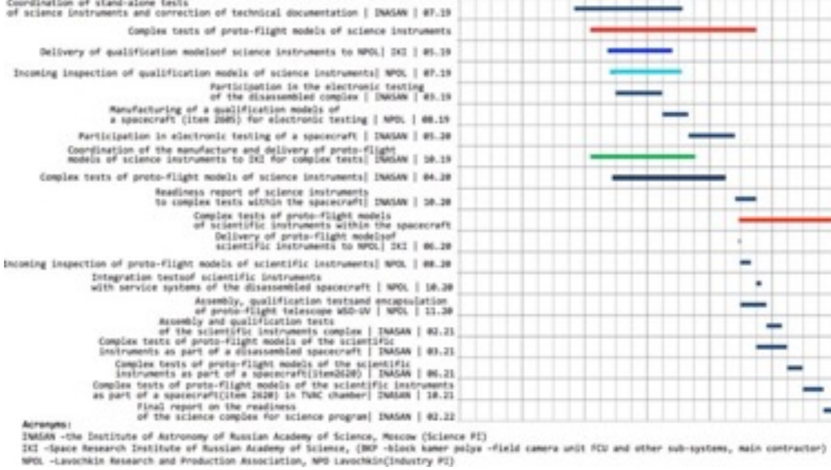




Comparison

Parameter	WFIRST	WSO-UV
Telescope D	2.4m, complex spider	1.7m R-C, symmetric spider
Country	USA (Telescope + Platform)	Russia (Telescope + Platform)
Orbit	Inclined Geosynchronous	geosynchronous 51.8 deg.
Lifetime	5yrs (corona 6yrs; 10yrs)	10 yrs
Rocket	AtlasV 541	Proton medium class
Launch	2025?	2021
Wavelength	0.9-1.9um + OPTICAL corona	0.11-0.32um + OPTICAL corona
CORONAGRAPH		
Wavelength	0.43-0.9um	0.5-0.75um (hopefully 0.3-1um)
Diff l@0.5um	0.04”	0.06”
Contrast	9 (goal 10)	7 (raw) -9 (w/ WFC) (TBD)
IWA	0.2” (goal 0.1”)	0.3” (goal 0.15”)
Mode	Photo, IFU, Pol	TBD but Photo and Pol
Spectral R	R = 70	R=10?

Schedule



FY2017 EM design

Mar 2018: Preliminary Design Review

FY2018 EM manufacturing/test

Jan 2019: Detector for coronagraph delivery to IKI

Assembling coronagraph in IKI fr Jan to Mar

Mar 2019: UVSETI Delivery to IKI

Mar-May 2019: BKP assembly

May 2019: BKP delivery to NPOL

FY2019-20 FM manufacturing /test

Feb 2020: Detector for coronagraph delivery to IKI

Assembling coronagraph in IKI fr Feb to Apr

Apr 2020: UVSETI Delivery to IKI

Apr-Jun 2020: BKP assembly

Jun 2020: BKP delivery to NPOL

2023+ Launch

2023 Preliminary result

Terrestrial exoplanets in the distance < 10 pc.

(> 10 planets will be found by TESS before WSO-UV launch)

2025 Mission success

5-10? terrestrial planets in HZ

Direct imaging

Thank you for attention

We invite you for cooperation