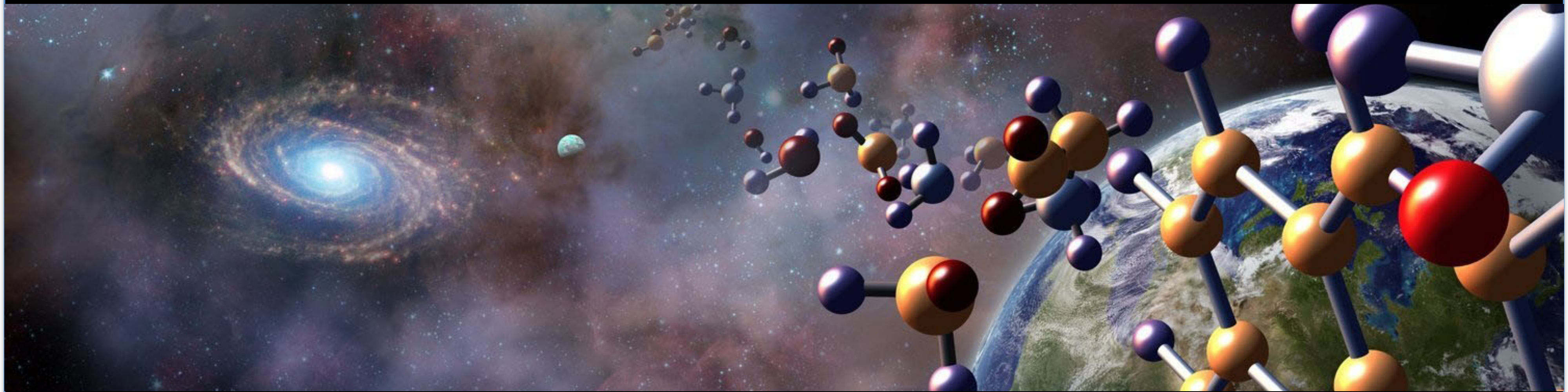
ORIGINS Space Telescope

From the Rise of Metals to Water for Habitable Worlds

Mission Concept Studies for the 2020 Decadal Survey ;

Mid-Infrared Imager and Spectrometer (MISC) for the Origins Space Telescope (OST)



Itsuki Sakon (University of Tokyo), Thomas L. Reollig, Kimberly Ennico-Smith (NASA Ames)
Yuji Ikeda (Photocoding), Taro Matsuo (Osaka University), Naofumi Fujishiro (Teikyo University)
Keigo Enya (ISAS/JAXA), Olivier Guyon (Univ. of Arizona/NINS ABC), OST/MISC Team
Origins Space Telescope (OST) STDT

Mid-Infrared Imager, Spectrometer and Coronagraph (MISC)

Mid-Infrared Imager, Spectrometer, Coronagraph (MISC) Team Members

(from Science and Technology Definition Team, Ex-Officio Non-Voting Members, Internation Ex-Officio Non-Voting Members)

-Asantha Cooray (California, Irvine)
-Deborah Padgett (GSFC)
-Eric Nielsen (SETI Institute)
-Itsuki Sakon (University of Tokyo) [Instrument lead]
-Joaquin Vieira (Illinois, Urbana Champaign)
-Margaret Meixner (STScI)
-Kimberly Ennico Smith (NASA/AMES) [Science lead]
-Tom Roellig (NASA/AMES) [Instrument lead]
-Klaus pontoppidan (STScI)

(from NASA/Ames)

- TBA

(from LAM and related Institutes)

-Denis Burgarella (Laboratoire d'Astrophysique de Marseille)
-David Le Miqnant (Laboratoire d'Astrophysique de Marseille)
- Frederic Zamkotsian (Laboratoire d'Astrophysique de Marseille)

(from JAXA and related Institutes)

-Keigo Enya (JAXA)
-Olivier Guyon (Subaru Telescope/ Astrobiology Center, NINS/Steward Observatory, University of Arizona)
-Yuji Ikeda (Photocoding)
-Taro Matsuo (Osaka University)
-Naofumi Fujishiro (Teikyou University)
-Naoshi Murakami (Hokkaido University)
-Jun Nishikawa (NAOJ)
-Takayuki Kotani (NAOJ)
-Yuki Sarugaku (University of Tokyo)
-Aoi Takahashi (ISAS/JAXA)
- And more

Mid-Infrared Imager, Spectrometer and Coronagraph (MISC) (ver.20170613)

(1) Mid-Infrared Imager Spectrometer Module

- Wide Field Imager (WFI-S; 6-19um, WFI-L; 18-38um, R=3-10, R=100-300)
- Medium Resolution Spectrometer (MRS-S; 5-10um, MRS-M; 9.5-19µm, MRS-L; 18-36um, R~1000)
- High Resolution Spectrometer (HRS-S; 12-18um, HRS-L; 25-38um)

Detectors; 4 2kx2k Si:As, 2 1kx1k Si:Sb, 1 2kx2k Si:Sb

Mechanisms; wave front correction systems (DM + TTM), 6 Filter Wheels (2 for slit mirror changers, 4 for imagers and grisms for WFI)

Others; IFU for MRS-S, MRS-M and MRS-L, sharing the same FOV,
WFI can be used as the slit viewer when doing spectroscopy with MRS and HRS

(2) PIAACMC Coronagraph Module (COR)

- PIAACMC Coronagraph (COR-S; 6-16um, COR-L; 15-38um, R=3-10, R=100-300)

Detectors; 1 2kx2k Si:As and 1 1kx1k Si:Sb

Mechanisms; wave front correction systems (DM + TTM), 4 Filter Wheels

(3) Transit Spectroscopy Module (TRA)

- densified pupil spectrometer (TRA-S; 5-8um, TRA-M; 8-13um, TRA-L; 13-20um, R~300)

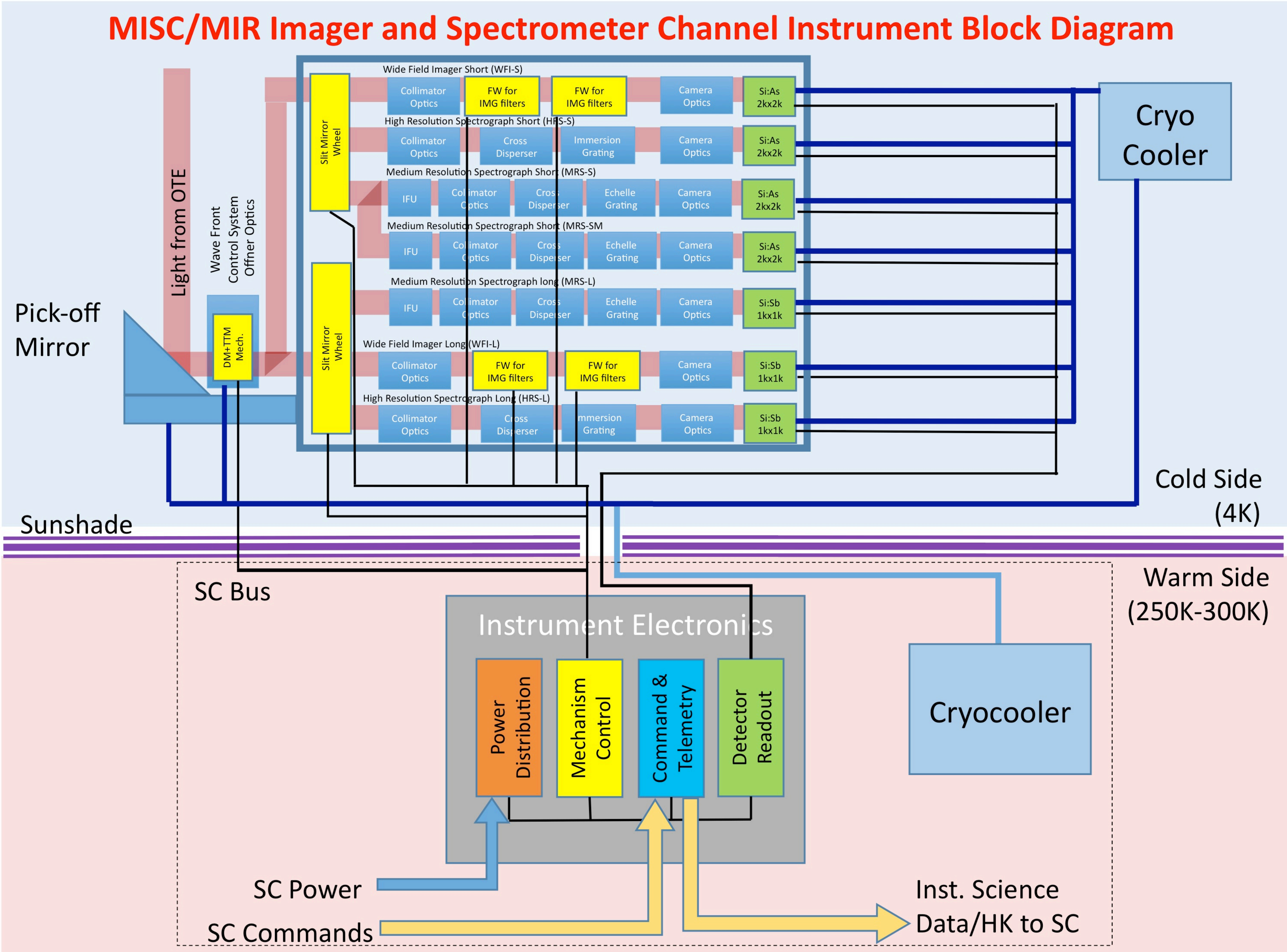
Detectors; 3 2kx2k Si:As

A Baseline design and specification of OST/MISC

(http://exoplanets.astron.s.u-tokyo.ac.jp/OST/MISC/index_misc_case_A.html)

Module	Mid-IR Imager Spectrometer Channel			Transit Channel	Coronagraph Channel
	Imager/Low-Res Spec.	Medium-Res Spec.	High-Res Spec.	(Densified Pupil Spec.)	(PIAACMC)
	WFI-S/-L	MRS-S/-M/-L	HRS-S/-L	TRA-S/-M/-L	COR-S/-L
Bandpass (μm)	6-38	5-36	12-18, 25-38	5--20	6-38
Spectral Resolution	5-10 [Imager] 300 [Low-Res Spec.]	1000-1500	20,000-30,000	300	300
Full FOV	3 arcmin x 3 arcmin [Imager]	3 arcsec x 5 arcsec [with IFU]		3 arcsec x 3 arcsec	5.5 arcsec x 5.5 arcsec
Slit for Spectroscopy	Length; 3 arcmin Width; 0.26 arcsec (WFI-SG1) 0.40 arcsec (WFI-SG2) 0.65 arcsec (WFI-LG1) 1.00 arcsec (WFI-LG2) [low-resolution Spec.]	Length; 3 arcsec (MRS-S/-M/-L) Wdth; 0.33 arcsec (MRS-S) 0.55 arcsec (MRS-M) 1.0 arcsec (MRS-L) Mum of Slices; 11 (MRS-S) 9 (MRS-M), 5 (MRS-L)	Length; 1.0 arcsec (HRS-S) 2.0 arcsec (HRS-L) Width; 0.5 arcsec (HRS-S) 1.0 arcsec (HRS-L)		Length; 1 arcmin Width; 0.26 arcsec (COR-SG1) 0.40 arcsec (COR-SG2) 0.65 arcsec (COR-LG1) 1.00 arcsec (COR-LG2)
Detectors	2kx2k Si:As (30μm/pix) [S] 2kx2k Si:Sb (18μm/pix) [L]	2kx2k Si:As (30μm/pix) [S] 2kx2k Si:As (30um/pix) [M] 1kx1k Si:Sb (18μm/pix) [L]	2kx2k Si:As (30μm/pix) [S] 1kx1k Si:Sb (18μm/pix) [L]	2kx2k Si:As (30μm/pix) [S] 2kx2k Si:As (30μm/pix) [M] 2kx2k Si:As (30um/pix) [L]	2kx2k Si:As (30μm/pix) [S] 1kx1k Si:Sb (18μm/pix) [L]
pixel scale	0.088 arcsec/pix	0.0615 arcsec/pix (MRS-S) 0.10 arcsec/pix (MRS-M) 0.15 arcsec/pix (MRS-L)	0.17 arcsec/pix [S] 0.34 arcsec/pix [L]	0.1 arcsec/pix	0.05 arcsec/pix (COR-S) 0.10 arcsec/pix (COR-L)
Specification (Sensitivity/ Stability/ Contrast)	**Sensitivity [Imager] ;** *1-hour 5σ Continuum Sens .* *for a Point Source* 0.027μJy@5μm, 0.16μJy@10μm, 0.26μJy@15μm, 0.37μJy@20μm, 0.55μJy@25μm, 0.63μJy@30μm, 0.7μJy@35μm **Sensitivity [Low-Res Spec.];** *1-hour 5s Continuum Sens.* *for a Point Source* (R=300) 0.6μJy@5μm, 1.3μJy@10μm, 4.0μJy@15μm, 5.0μJy@20μm, 8.8μJy@25μm, 11.2μJy@30μm, 37.5μJy@35μm	**Sensitivity;** *1-hour 5s Continuum Sens.* *for a Point Source (R~1200)* 3μJy@7μm, 10μJy@15μm, 30μJy@24μm,100μJy@32μm 1-hour 5s Line Sens. for a Point Source $1x10^{-21}$ W/m^2 @7μm, $2x10^{-21}$ W/m^2 @15μm, $3x10^{-21}$ W/m^2 @24μm, $1x10^{-20}$ W/m^2 @32μm	**Sensitivity;** 1-hour 5s Line Sens. for a Point Source $1x10^{-21}$ W/m^2 @15μm, $3x10^{-21}$ W/m^2 @30μm	**Photometric stability;** 1ppm on timescales of hours to days (excluding the fluctuation of detector gain)	**Average contrast;** $7x10^{-6}$ for 10% band $1x10^{-6}$ for 4% band in 0.88-3.6λ/D

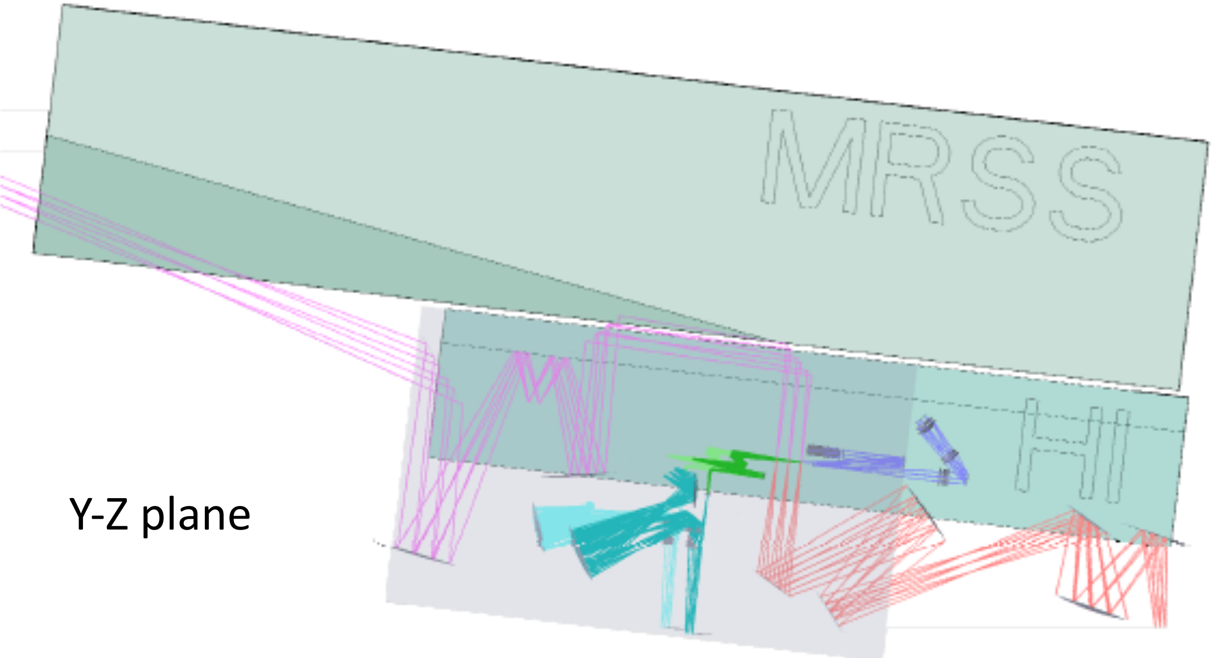
(1) MISC MIR Imager Spectrometer Module



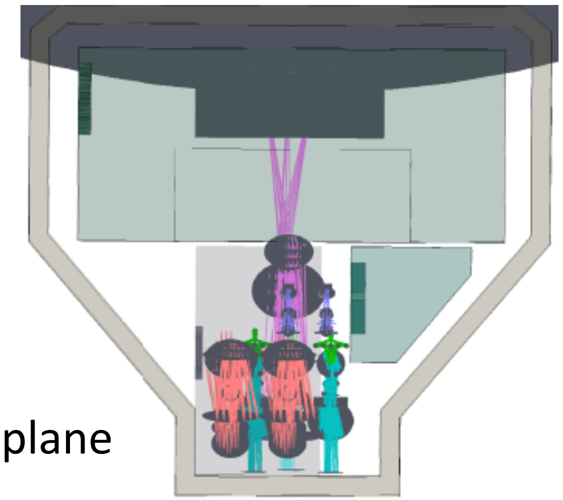
(1) MISC MIR Imager Spectrometer Module

Optical design of MISC Imager Spectrometer Module

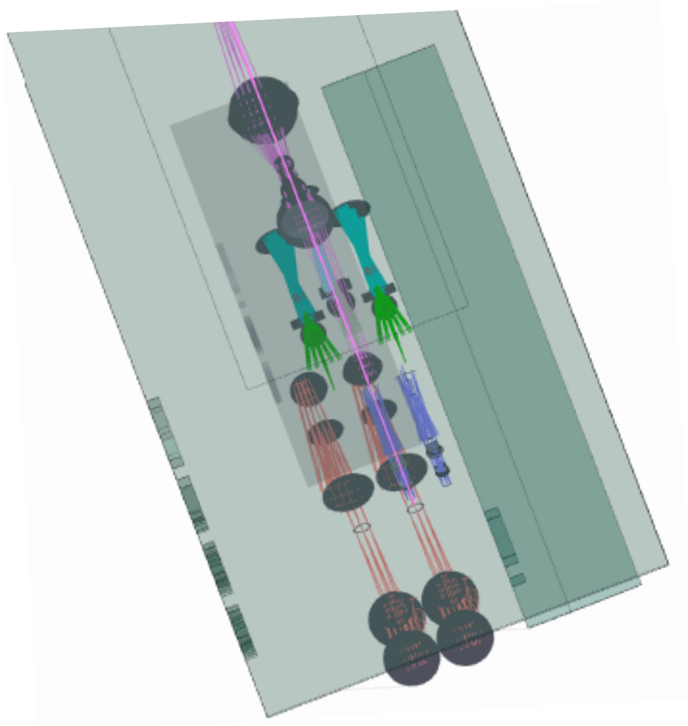
(Available at http://exoplanets.astron.s.u-tokyo.ac.jp/OST/MISC/OSTwithFIPprelimupdate_misc-im_170608.STEP)



Y-Z plane

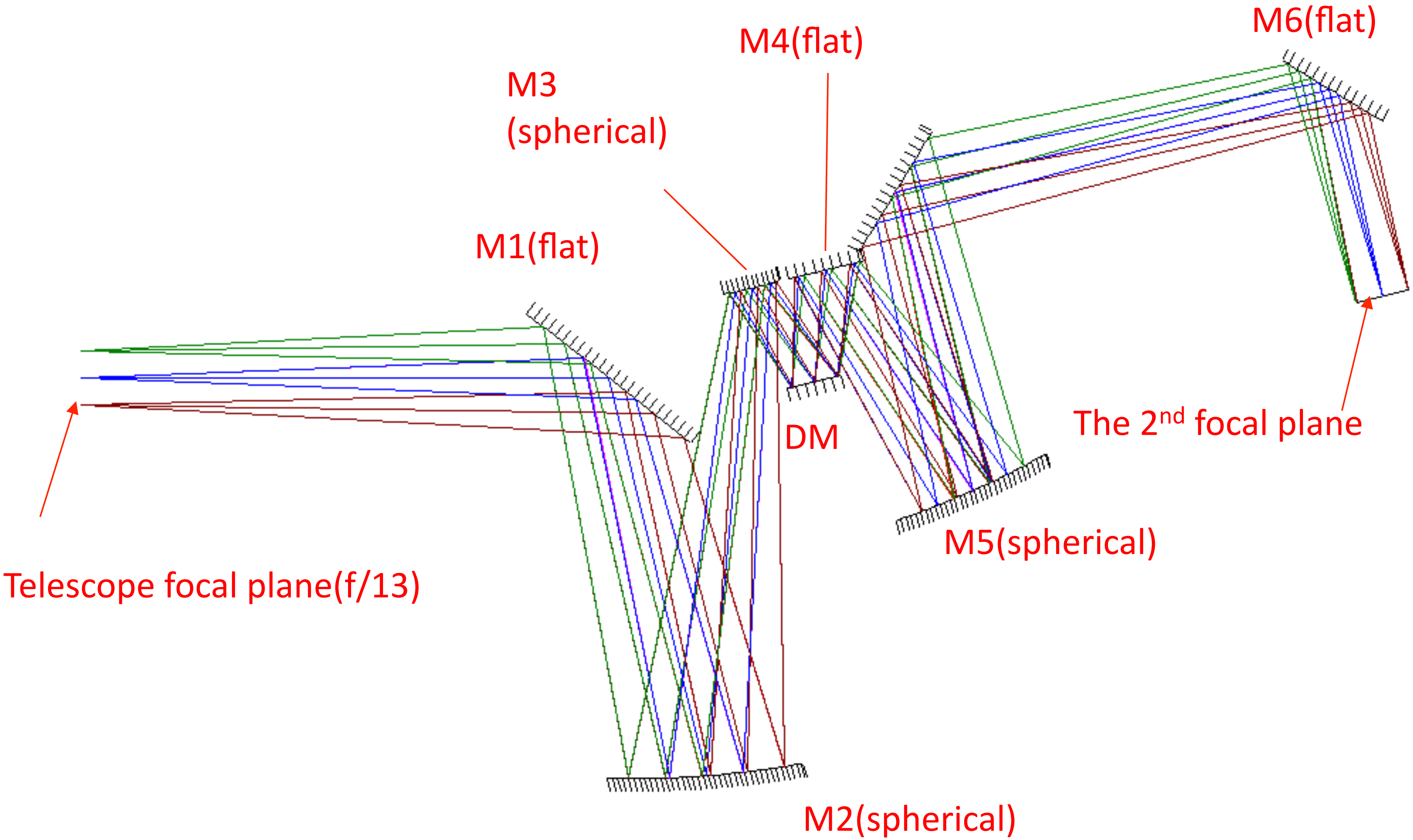


Z-X plane

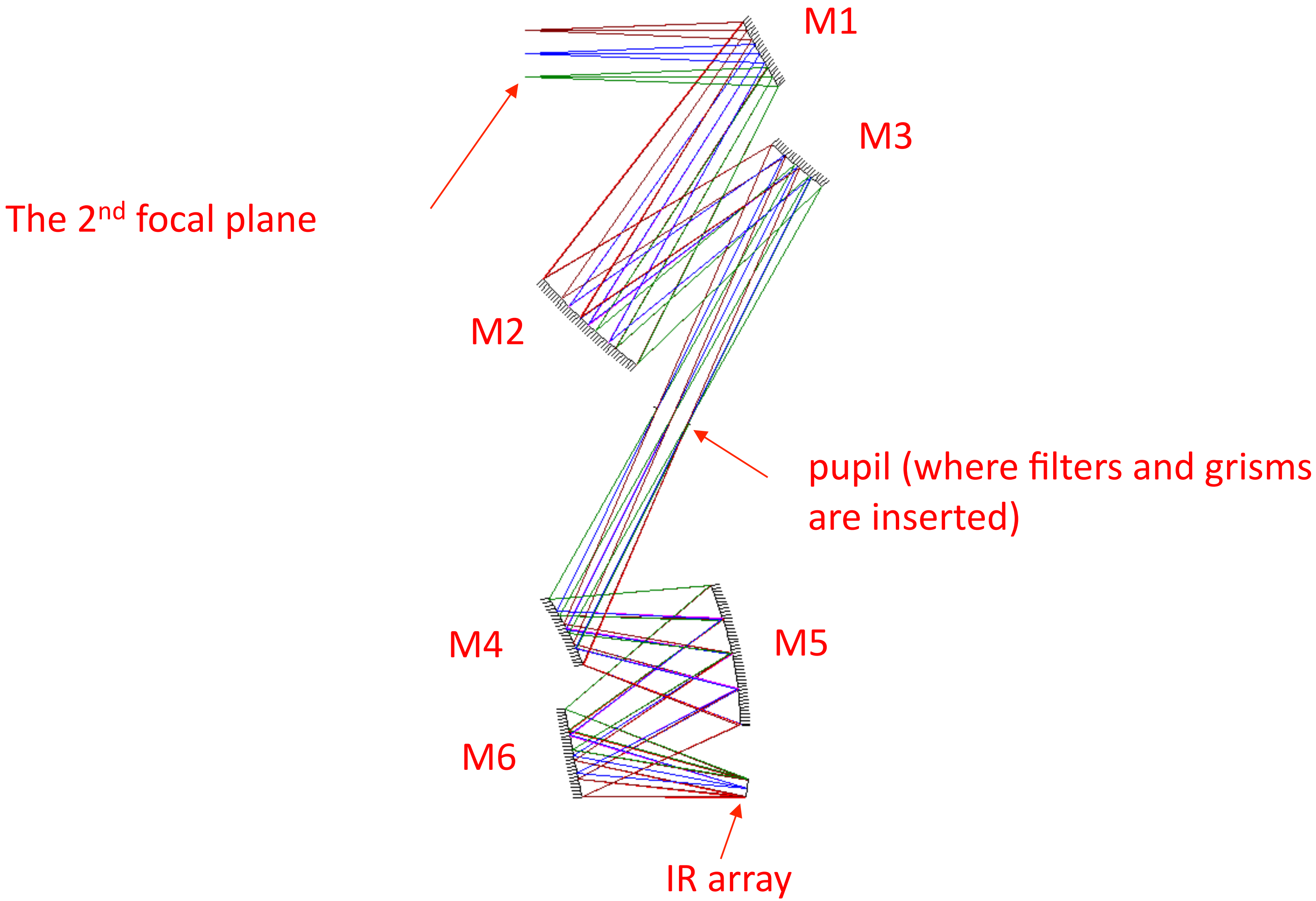


X-Y plane

Relay Optics



Field Imager (S-channel)



High-resolution spectrograph (S-channel)

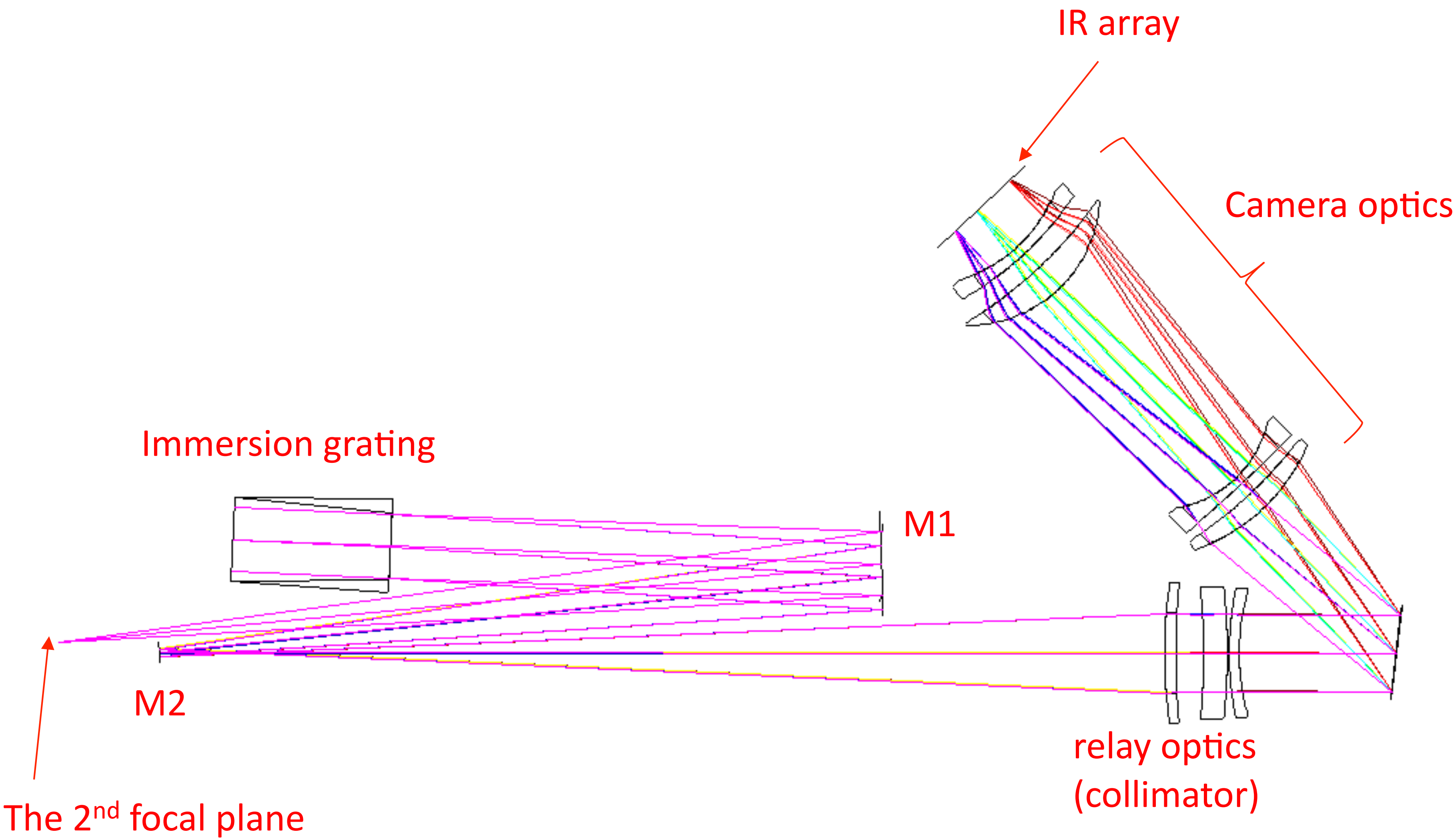


Image slicer unit for MRS-L

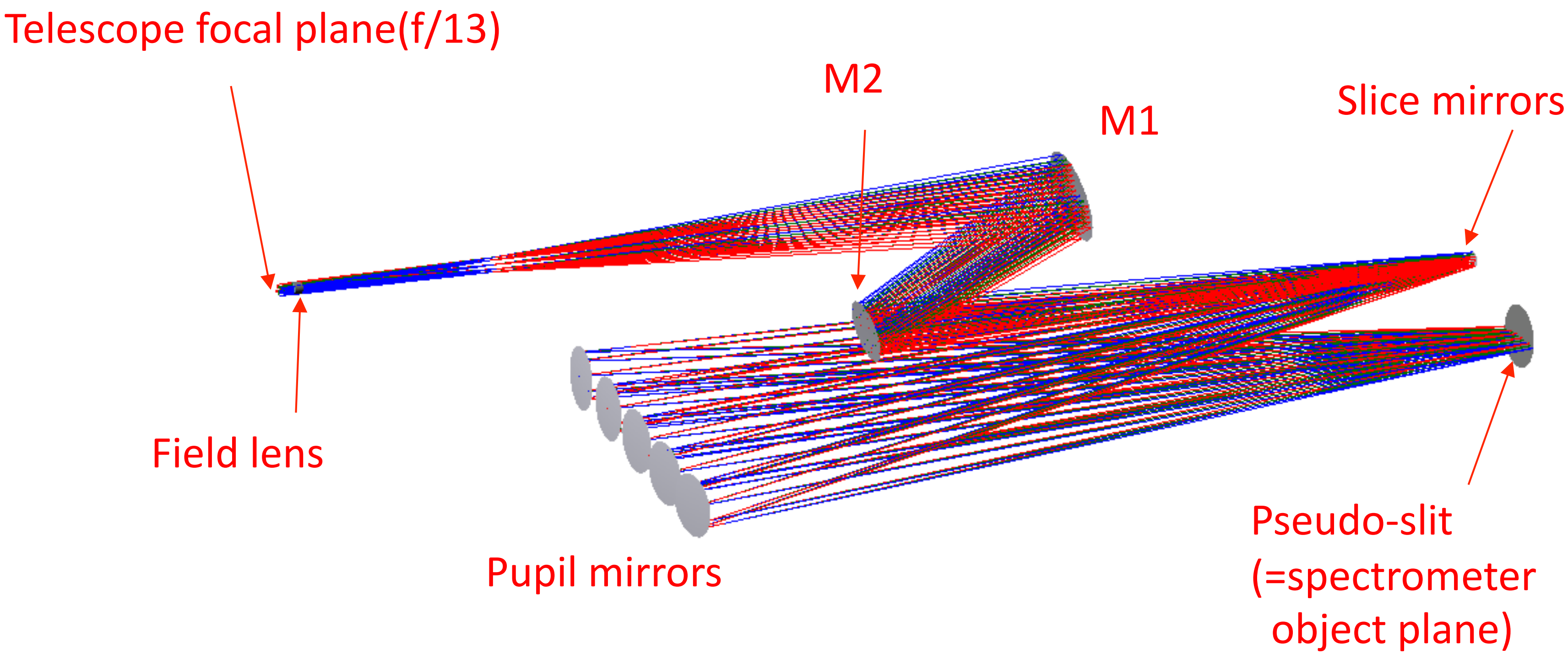
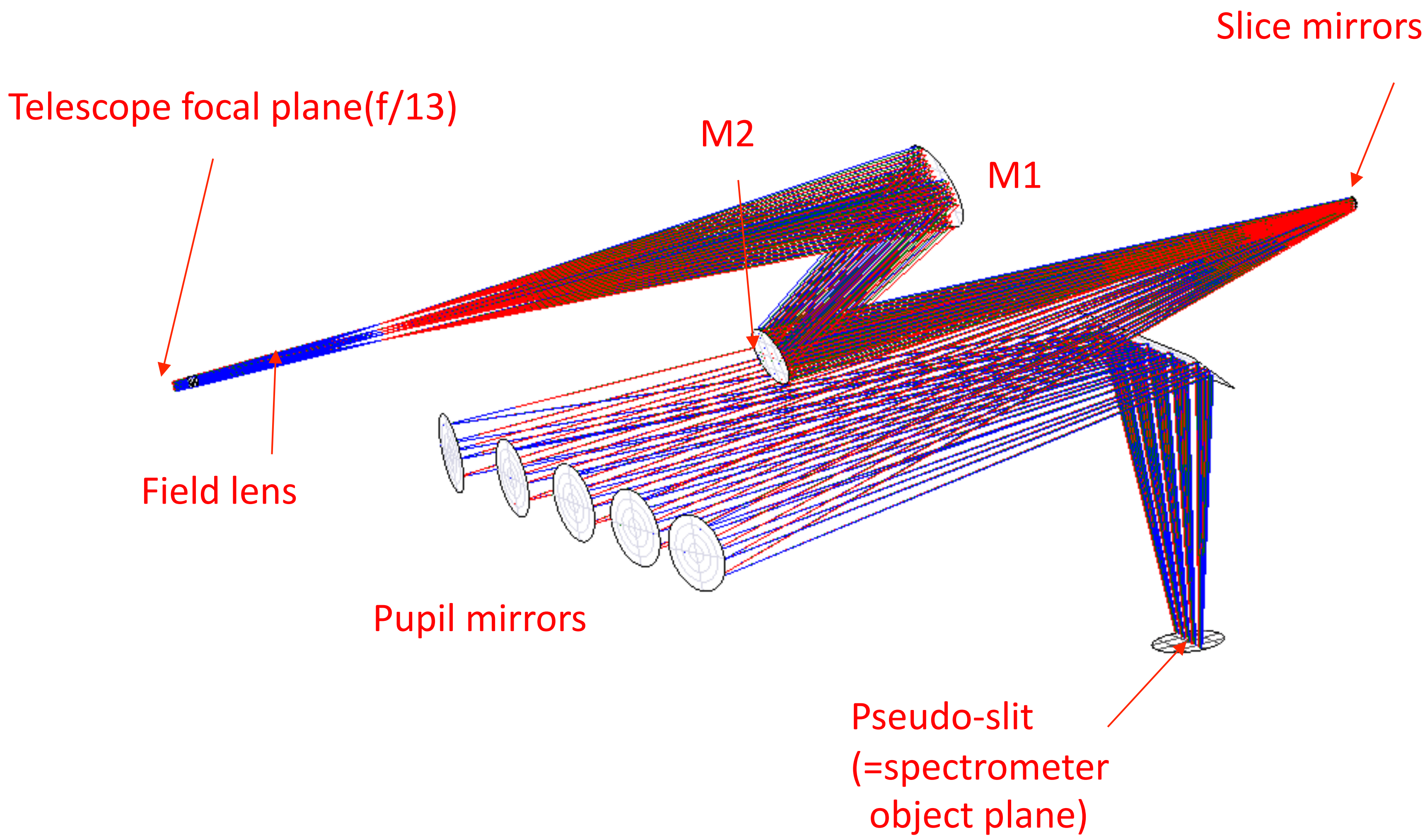
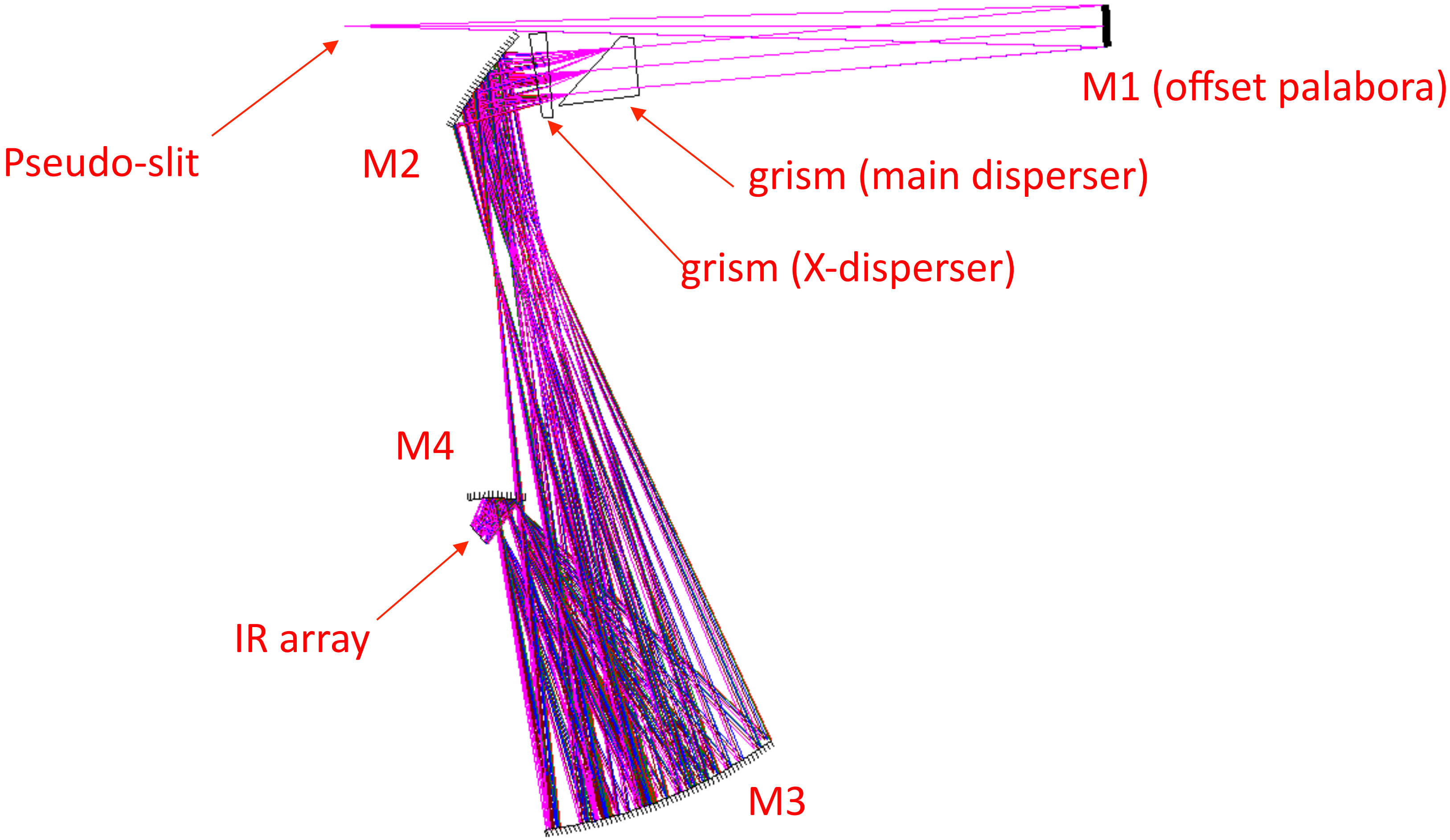


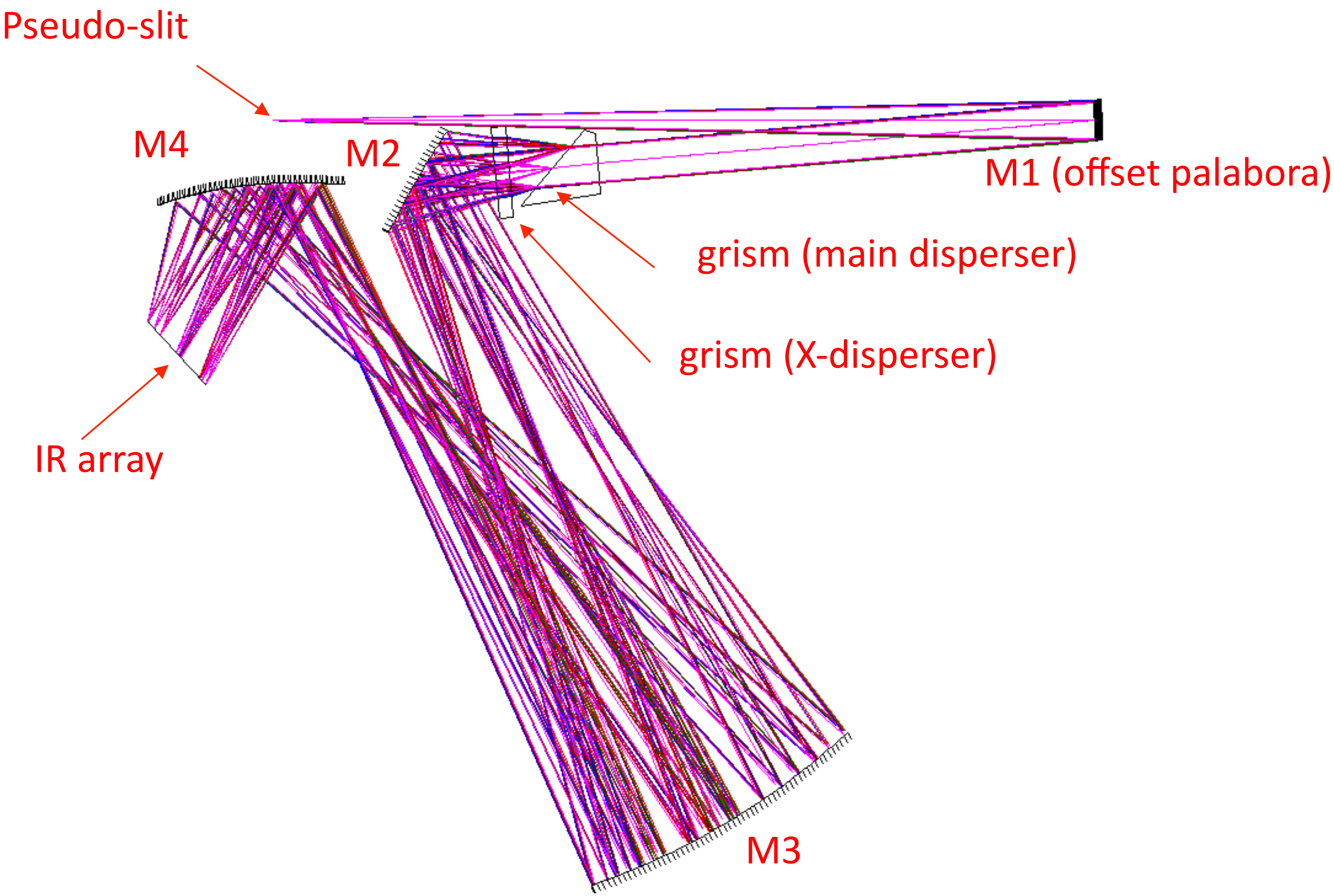
Image slicer unit for MRS-M/S



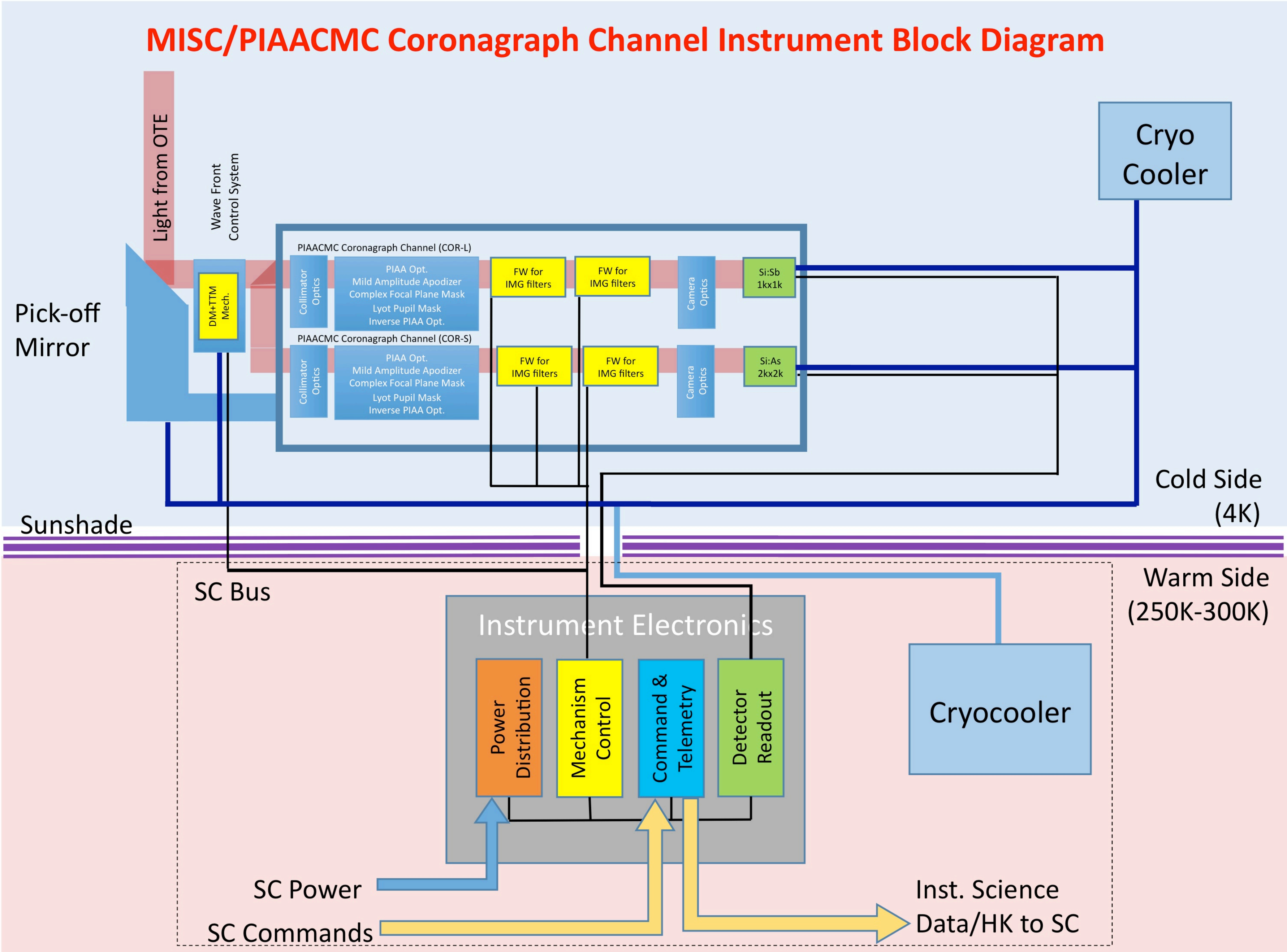
Medium Resolution Spectrometer (L-channel)



Medium resolution spectrometer (M-channel)

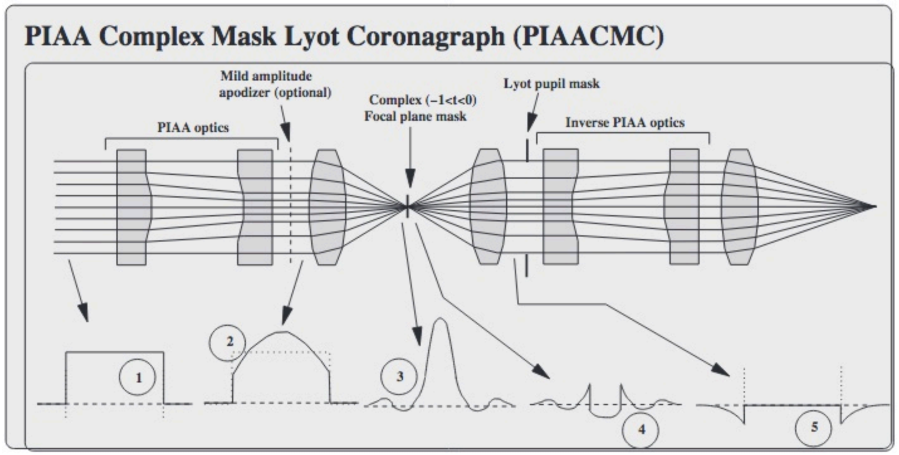


(2) MISC Coronagraph Module



(2) MISC Coronagraph Module

PIAA Complex Mask Lyot Coronagraph; PIAACMC

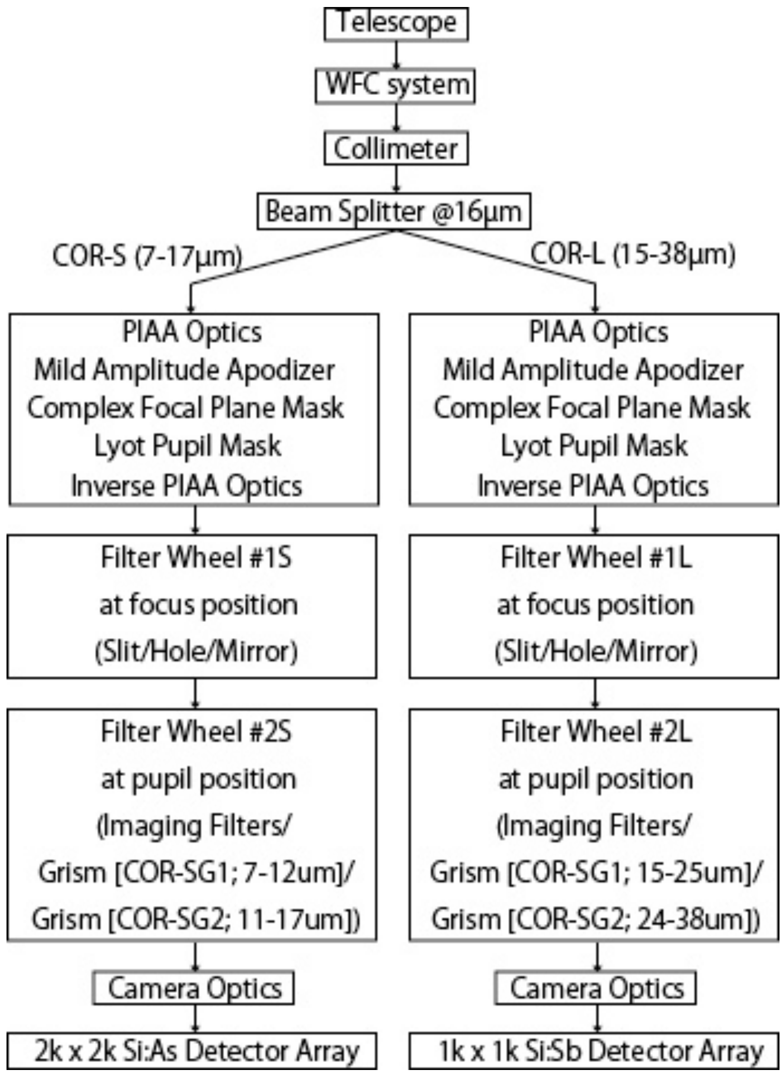


Inner Working Angle (IWA) (based on Guyon et al. 2014)
Obscured Circular Segmented pupils (GMT type);
- $0.72\lambda/D$ (aggressive design)
- $0.92\lambda/D$ (more conservative design)

Obscured Circular Highly Segmented pupils (E-ELT type)
- $0.8\lambda/D$ (aggressive design)
- $1.0\lambda/D$ (more conservative design)

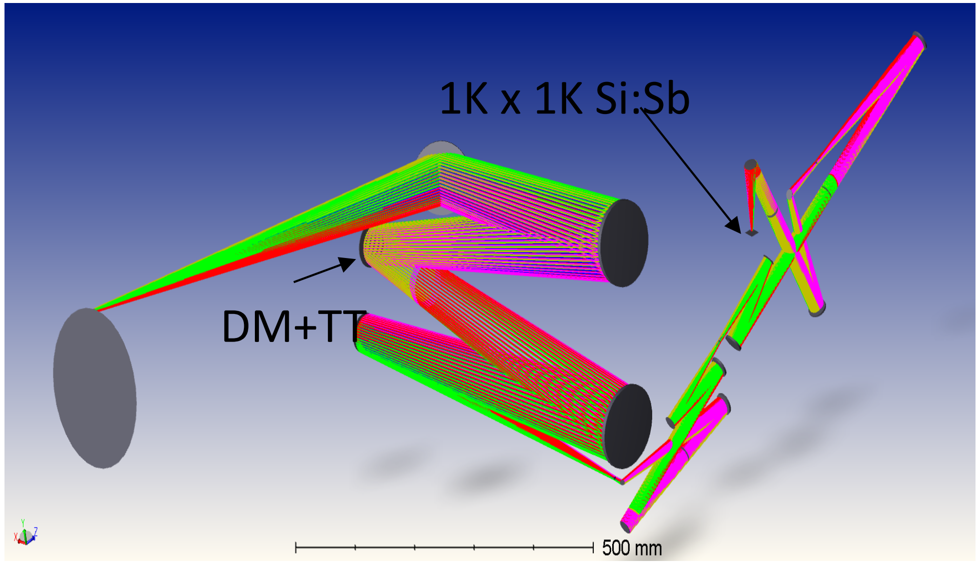
→ 0.75 – 0.95 λ/D for the IWA of OST/MISC
(for D=9m, λ=9µm, IWA is 0.15-0.20 arcsec)

Contrast at the IWA (based on Guyon et al. 2014)
Average contrast in 0.88-3.6 λ/D
→ 7.07×10^{-6} for 10% band, 1.16×10^{-6} for 4% band (@1.65um)

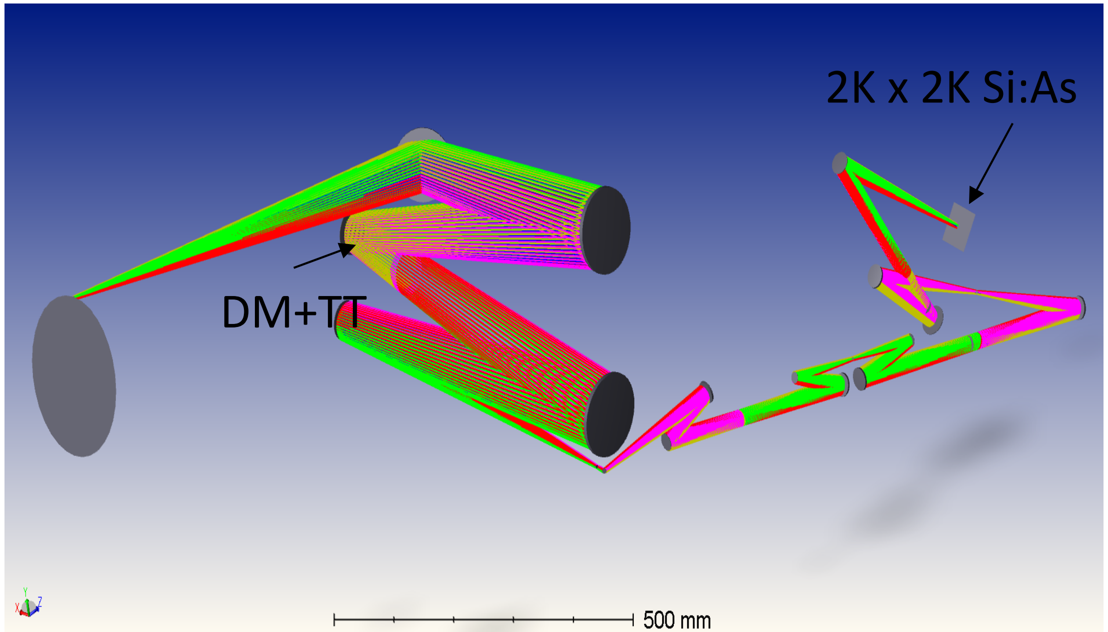


(2) MISC Coronagraph Module

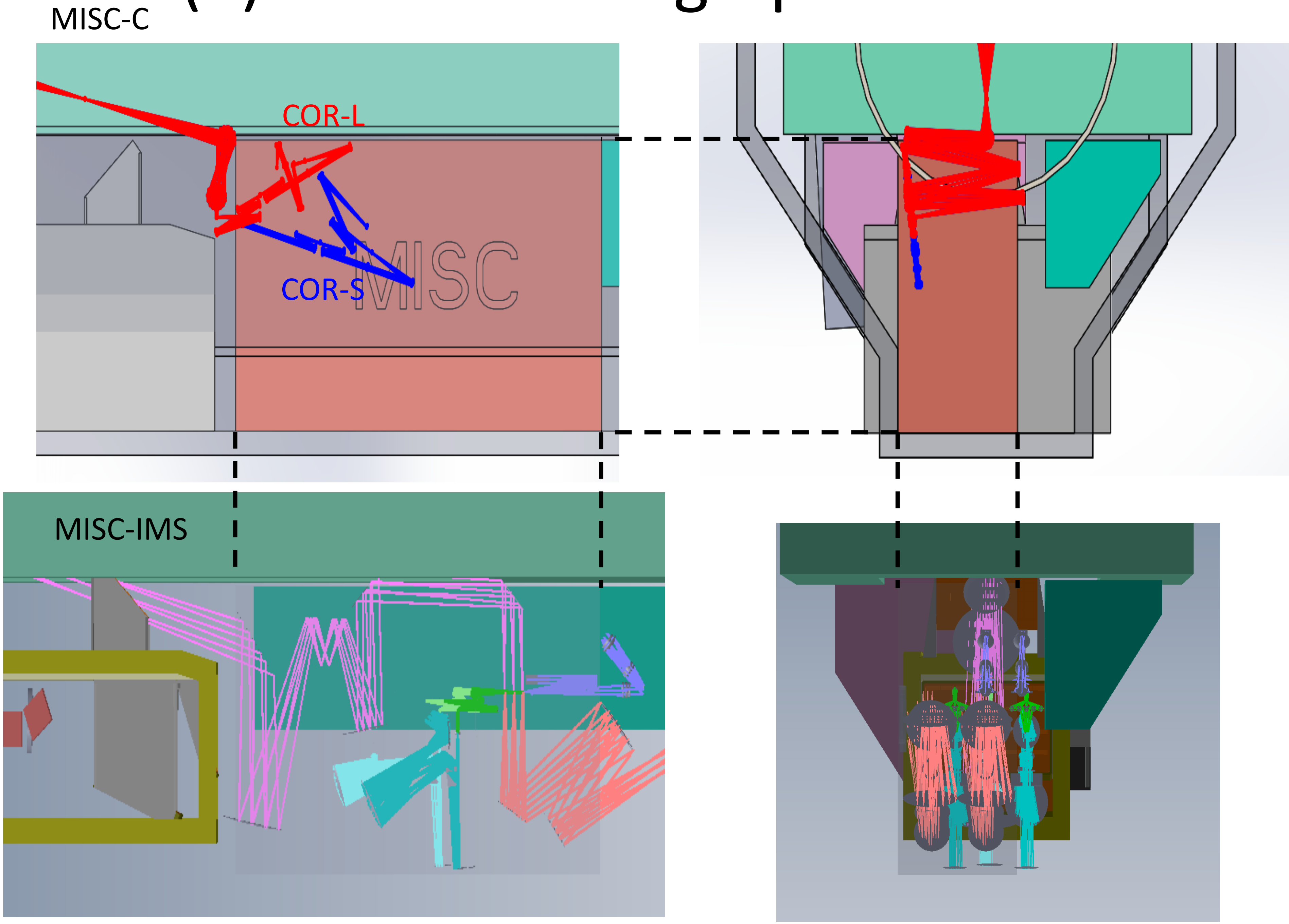
COR-L



COR-S



(2) MISC Coronagraph Module

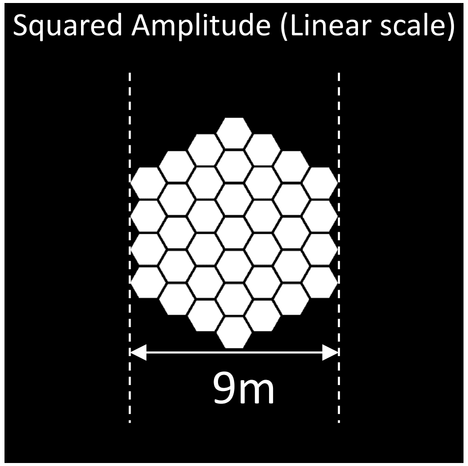


(2) MISC Coronagraph Module

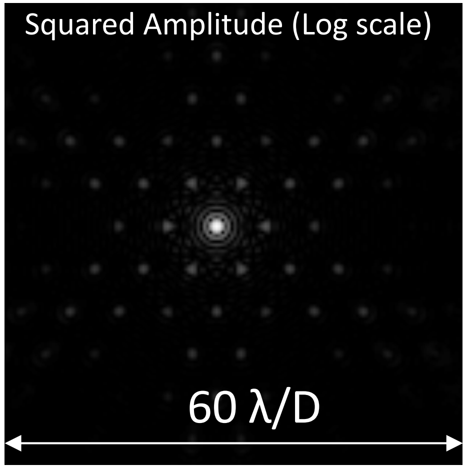
- Optimization of PIAACMC optics has not yet been completed

Coronagraphic PSF (COR-S, preliminary)

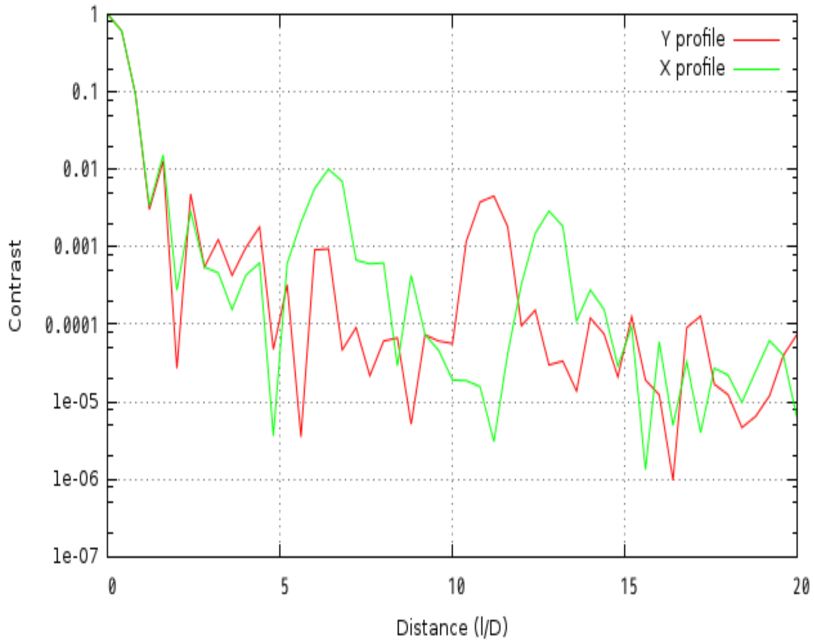
Pupil



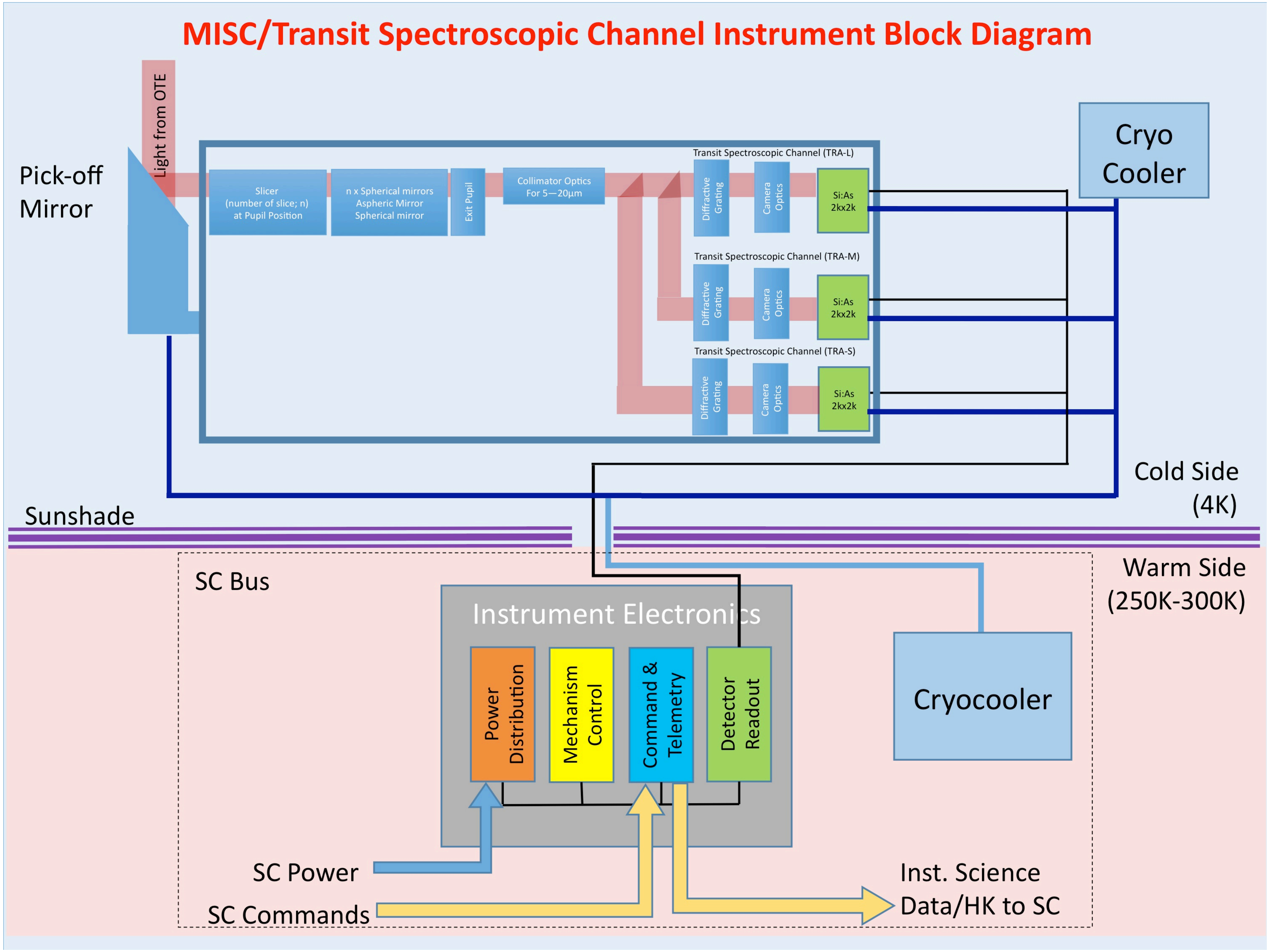
Focus



PSF cross-section



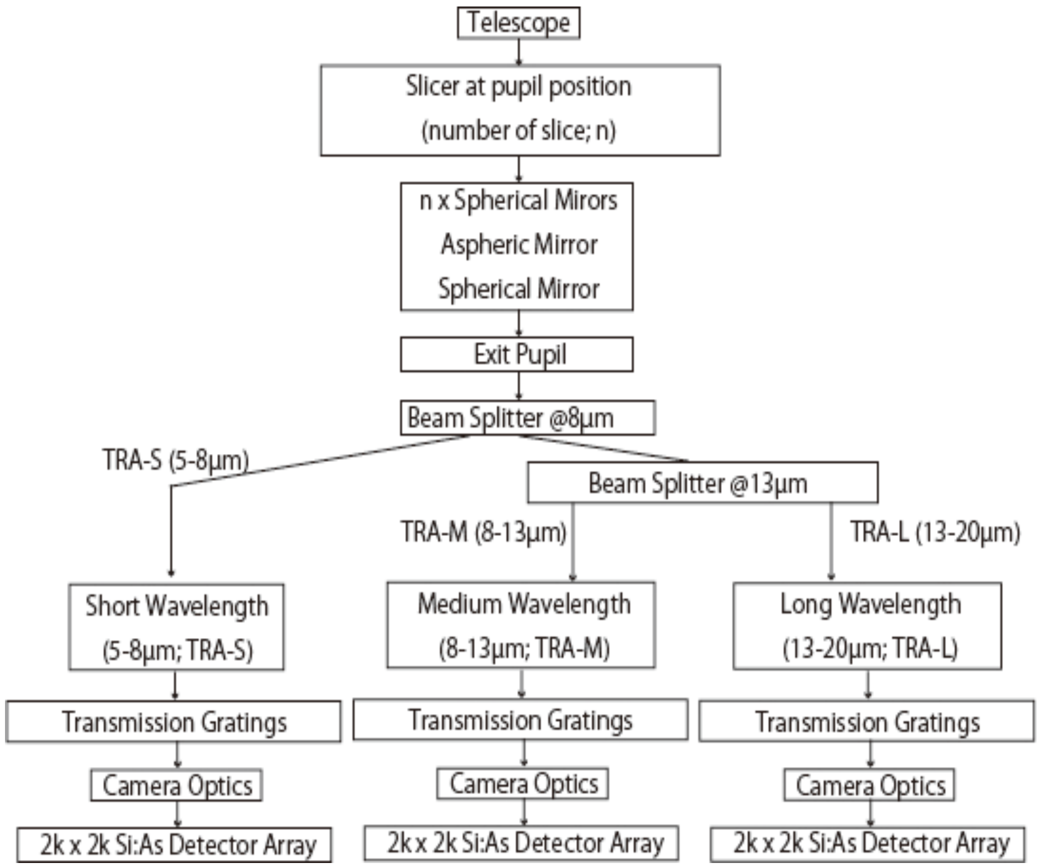
(3) MISC Transit Spectroscopy Module



(3) MISC Transit Spectroscopy Module

Goal of Transit spectrophotometer (from Exoplanet SWG)

・Characterization of Earth-size planets around early M-type stars
-> extremely high stability down to 1ppm
・Separation of transit signal from stellar activity
-> higher spectral resolution



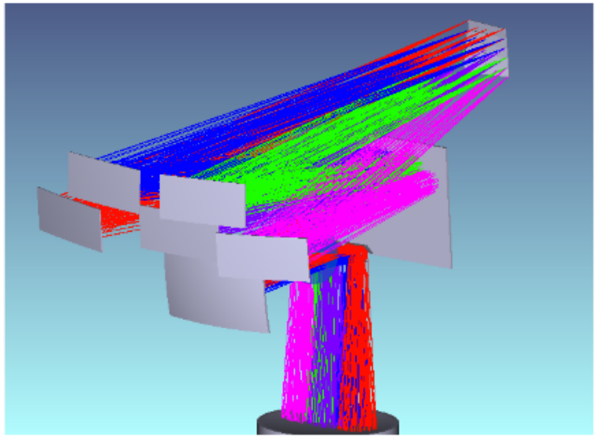
Expected performance achieved by densified pupil spectrometer; ~ a few 10^{-6}

Systematic noise	Value
Movement of PSF on detector intra- and inter-pixel sensitivity variation by pointing jitter	4×10^{-7}
Movement of PSF on Field stop by pointing jitter	1×10^{-6}
Change of PSF width on detector intra- and inter-pixel sensitivity variation by deformation of primary mirror	5×10^{-7}
Fluctuation of detector gain	??

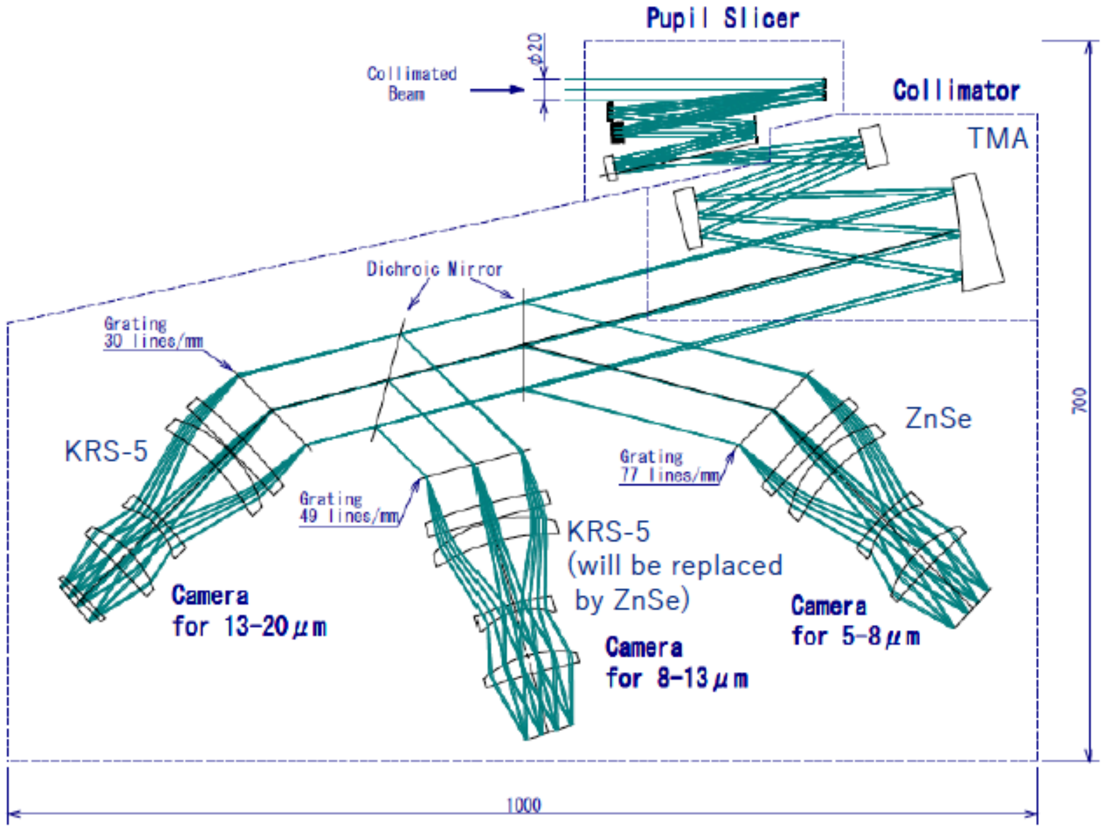
(3) MISC Transit Spectroscopy Module

Optical design of the densified pupil spectrometer for MISC

Pupil slicer



Pupil slicer/densification (colored by slice mirror)



- Pupil slicer/densification + Spectrometer
- Size of optical system; ~1000mm x 700mm
- 5-20μm is broken into three channels (5-8, 8-13, 13-20μm).

→ major absorption features of H_2O, CH_4, O_3, and CO_2 are NOT split in different channels.

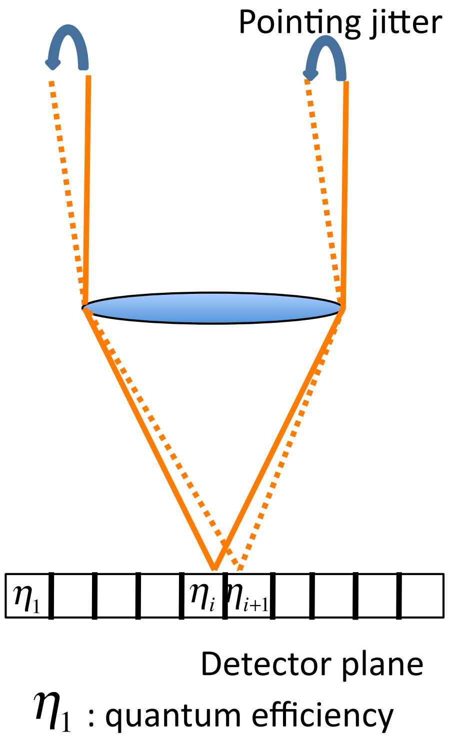
- simple configuration;
  8 mirrors for common optical path (5-20um)
  4 lenses for each channel (5-8, 8-13, 13-20um)
- Lens material; ZnSe for 5-8 and 8-13um
  KRS-5 for 13-20um
- R~300 is achieved over 5-20um
- Transmission gratings/grisms are required

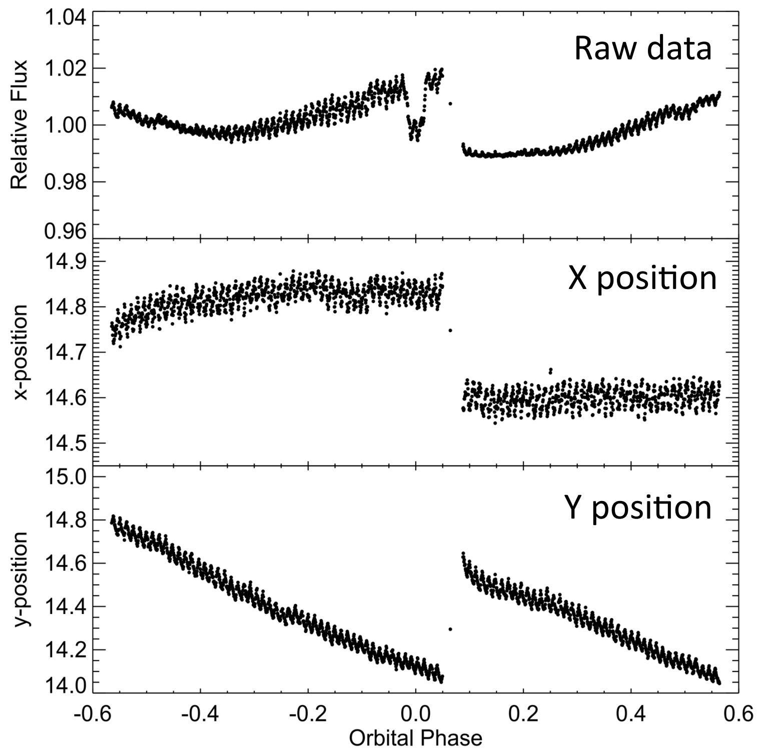
MISC Transit Spectroscopic Module

Taro Matsuo (Osaka University)

Current issue on transit spectroscopy with space telescopes

- Transit light curve affected by pointing jitter and deformation of primary mirror.
- Image motion on inter- and intra-pixel sensitivity variation.





HD 209458 taken by Spitzer/IRAC2 (4.5um)

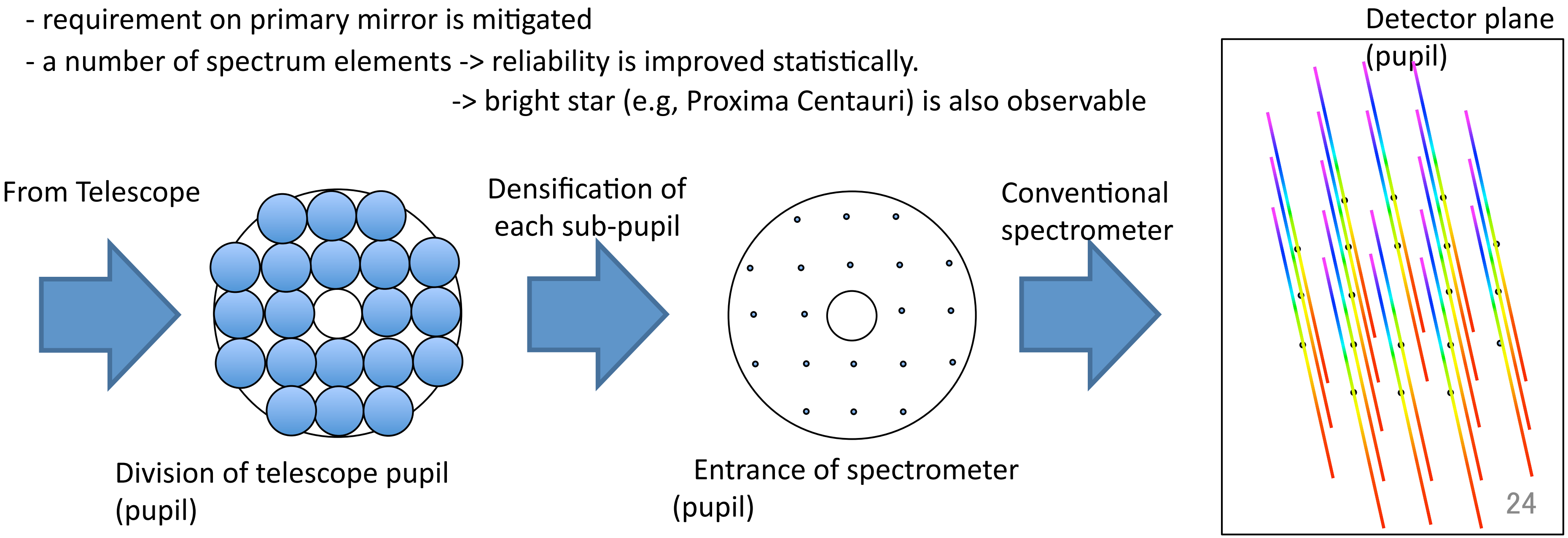
Zellem et al. ApJ (2014)

A solution for transit photometry: densified pupil spectroscopy

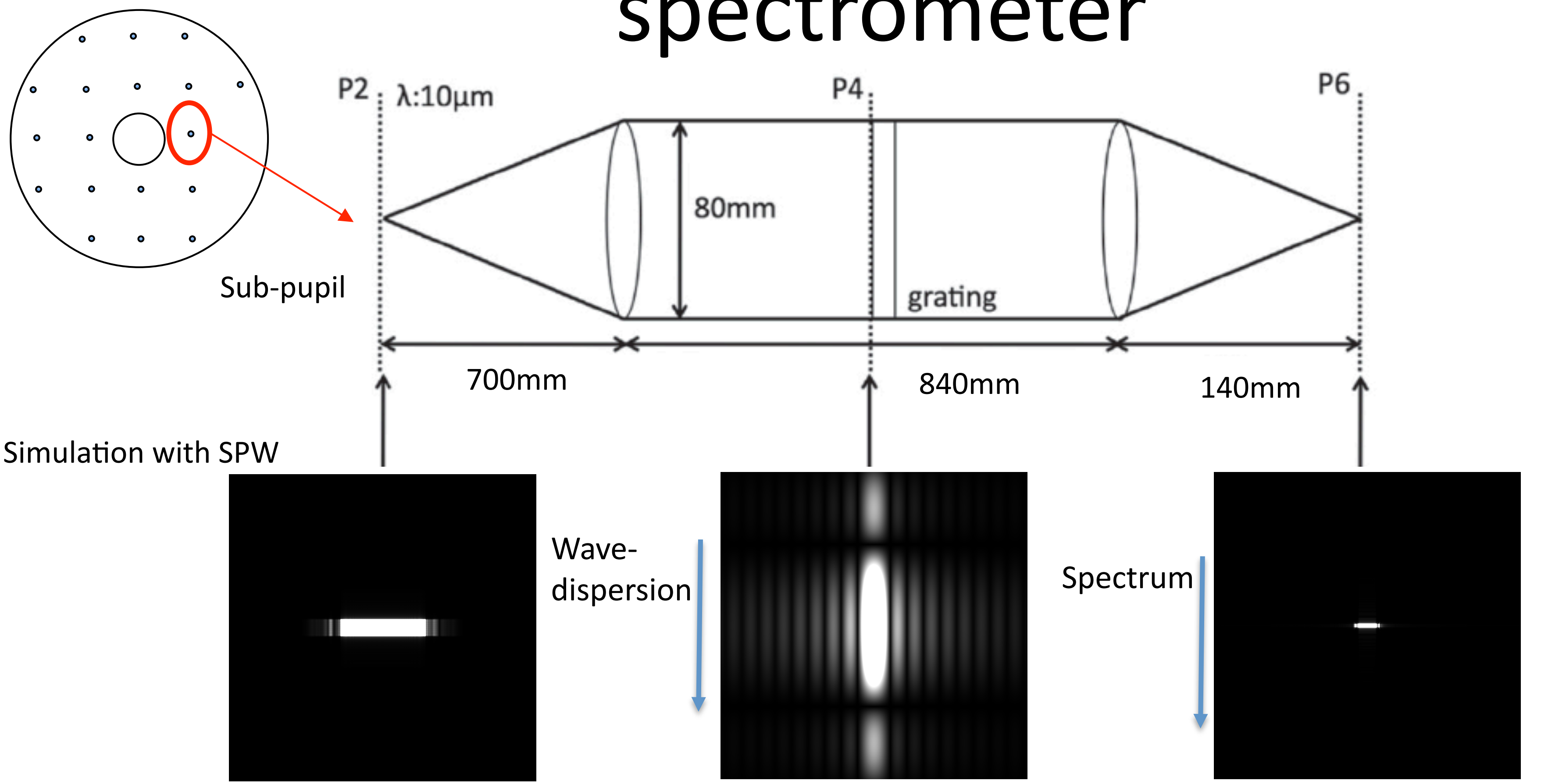
Matsuo, Itoh et al. ApJ (2016)

- Advantages:

1. Spectroscopy of primary mirror
   -> stability much less affected by pointing jitter and deformation of primary mirror
2. Division/densification of pupil image
   - requirement on primary mirror is mitigated
   - a number of spectrum elements -> reliability is improved statistically.
     -> bright star (e.g, Proxima Centauri) is also observable



Stable spectroscopy with conventional spectrometer



Re-pupil after the densification part

PSF on the focal plane

Re-pupil on the detector

Overview of optical design

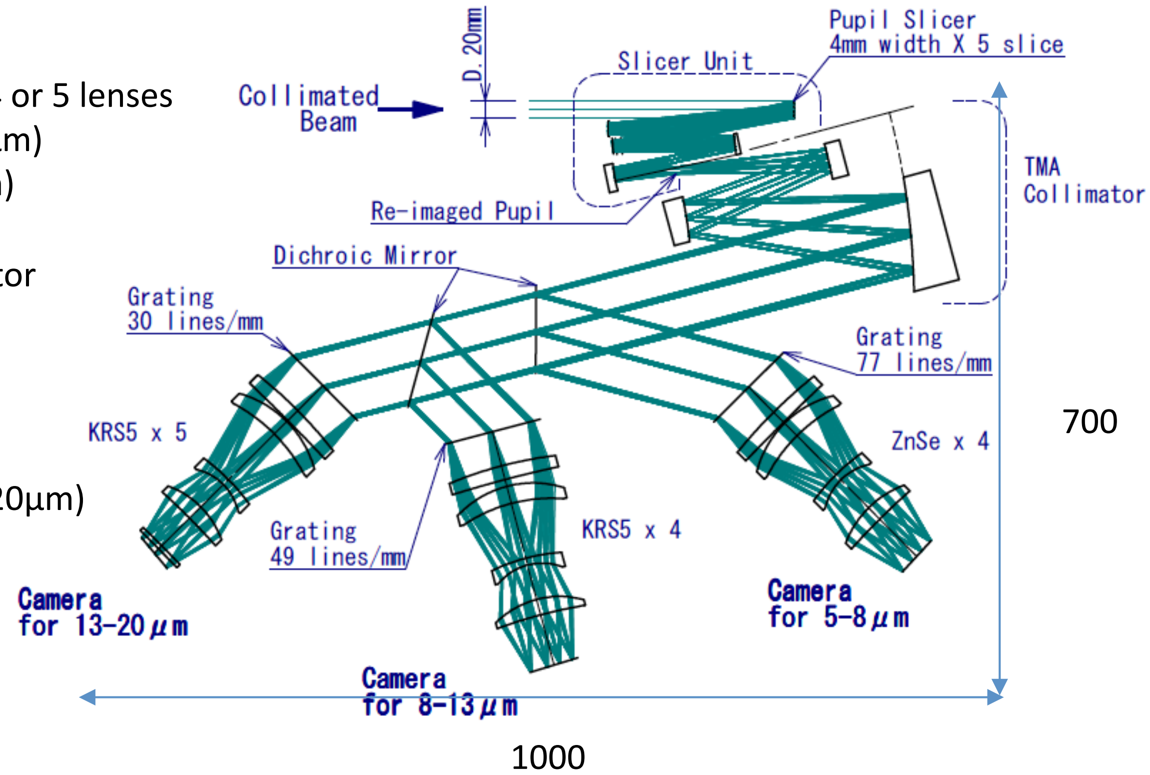
1. Configuration: 11 mirrors (incl. collimator) and 4 or 5 lenses
   - 11 mirrors used for common optical path (5-20μm)
   - 4 lenses used for each band (5-8, 8-13, 13-20μm)

2. Size of optical system: ~ 1000 x 700 w/o collimator
   (all components on a plane)

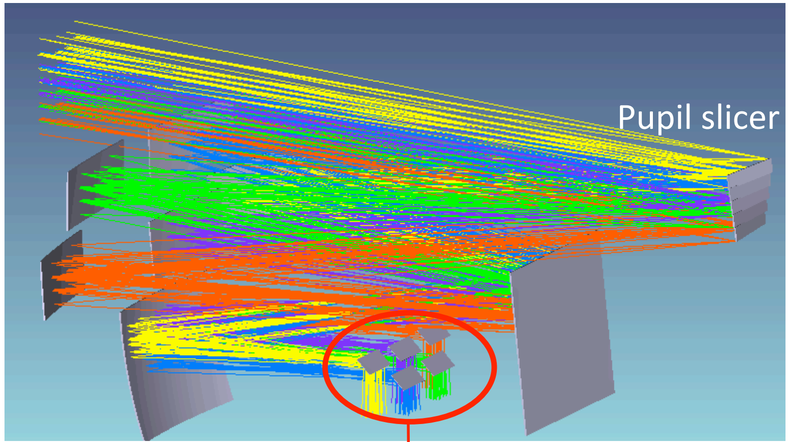
3. Lens material:
   ZnSe for short wavelength (5-8μm)
   KRS-5 for middle and long wavelength ranges (8-20μm)

4. Lens shape: spherical for all lenses

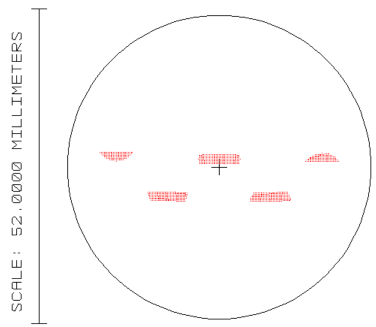
5. Maximum diameter of lens: ~ 120mm



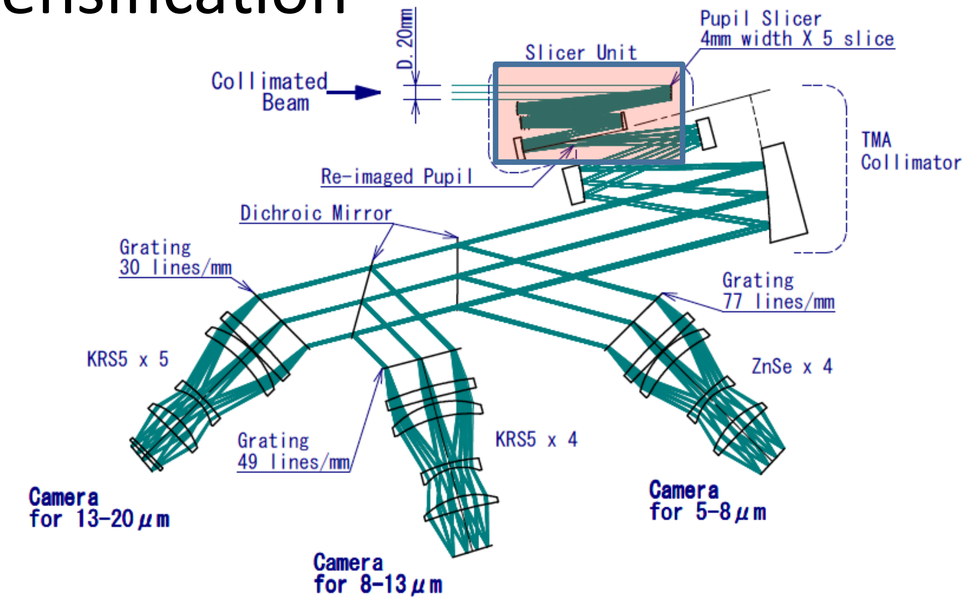
Optical Design for OST: Pupil densification



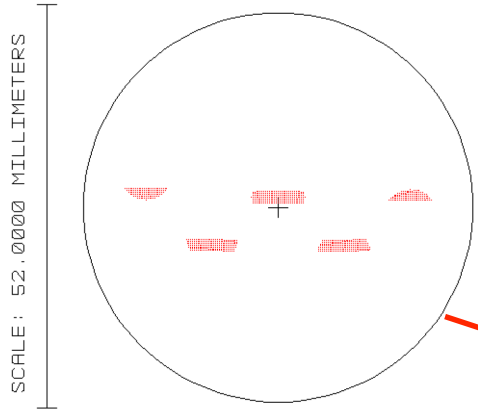
Pupil densification part



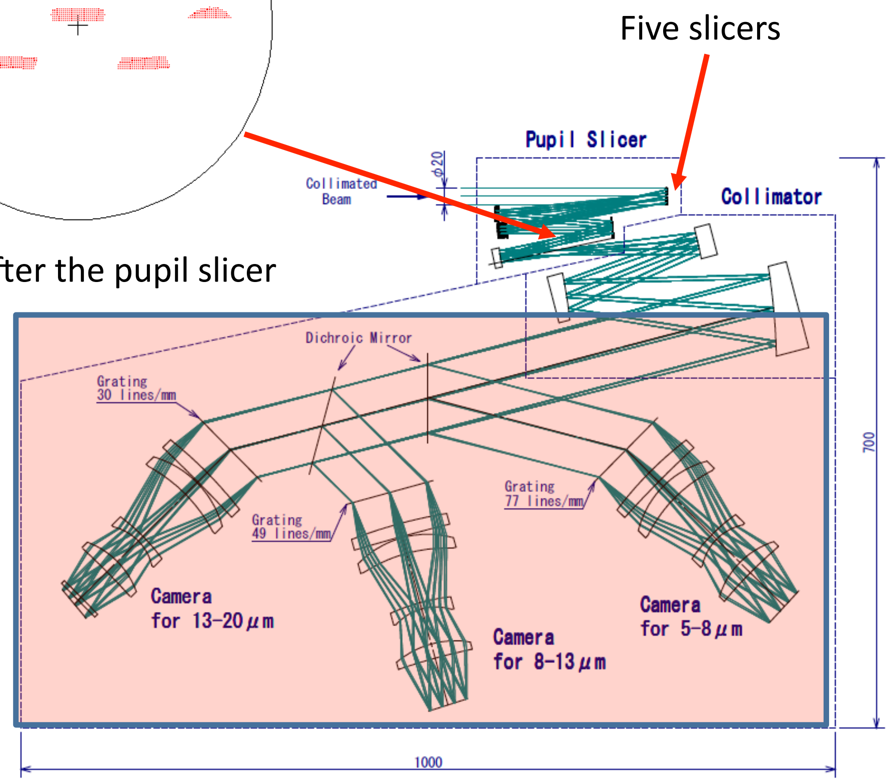
Re-pupil after the pupil densification part

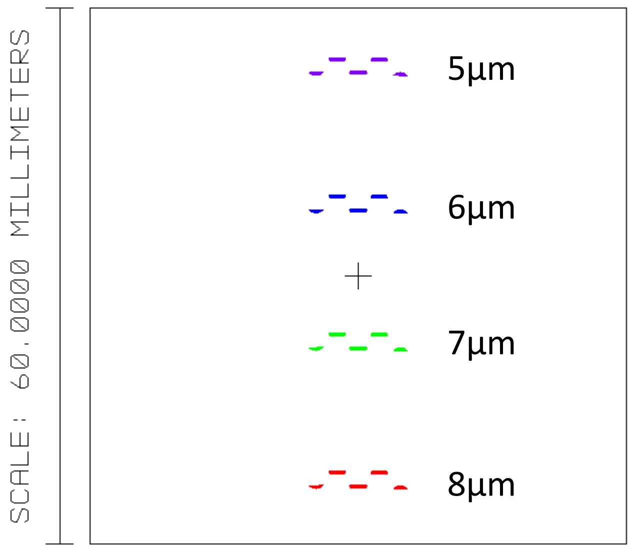


Spectrometer



Re-pupil after the pupil slicer





Detector plane for 5-8μm

Optical performance

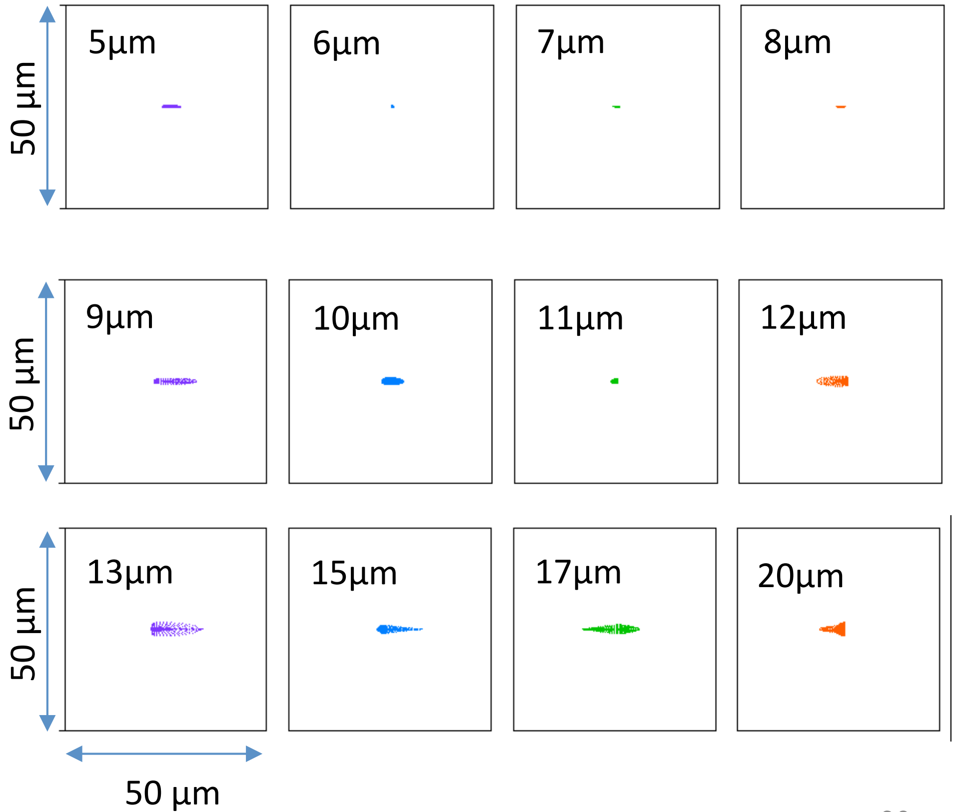
- Geometric aberration (incl. chromatism):

  < 0.5 pixel (15μm) over 5-20μm

- Photometric error due to image movement on intra- and inter-pixel sensitivity variation under pointing jitter of 10mas :

  < a few x 10^{-6}

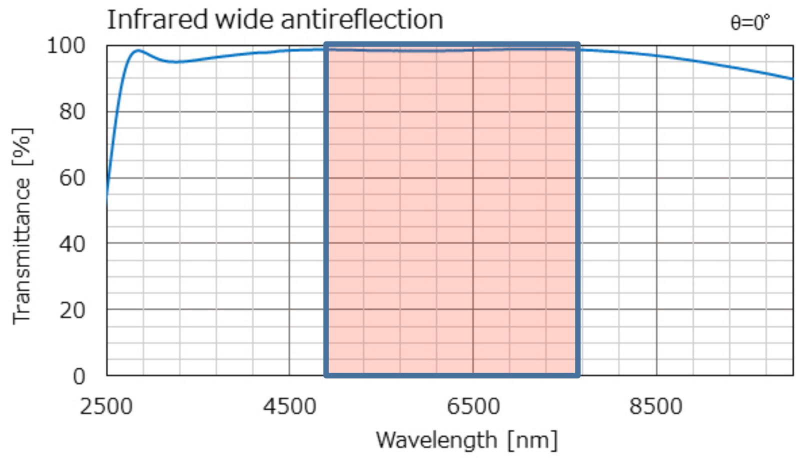
  (~ 100 ppm in case of conventional type)



Other points

- Spectral resolution: ~ 300 over 5-20 μm
- Bright limit (saturation): 2 mag for N band
  -> Proxima Centauri (N ~ 4 mag) is observable
- Good broad-band anti-reflection coating for three bands

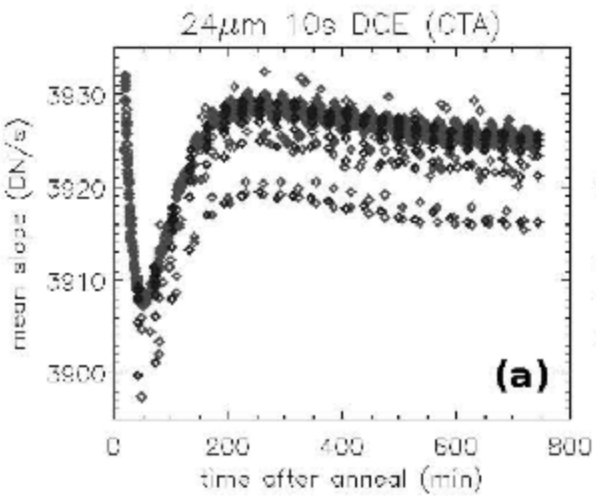
  - ghost level: will be reduced down to < 1 ppm
  - total throughput for lenses: > 90%



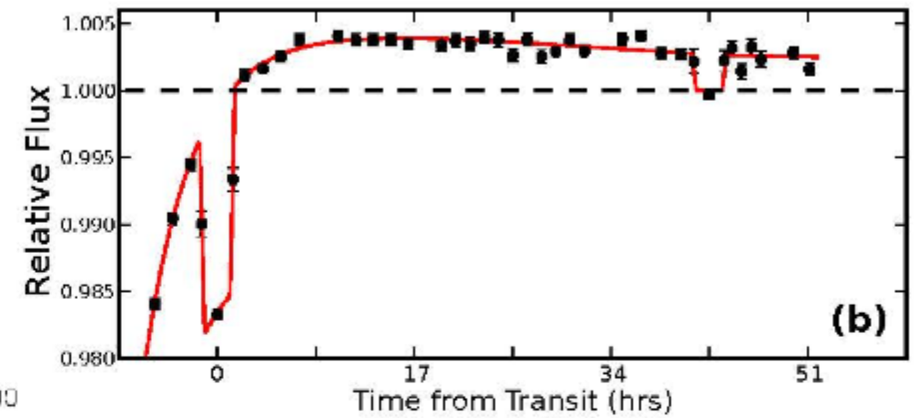
calculated by Japanese coating maker, which provided filters for SUBARU/HSC

Principal limit on transit photometry

- Photometry on Spitzer Space Telescope is affected by the long term variation of detector gain.



Flux of internal source (lamp)



Phase curve of HD 209458b

Beichman et al. (2014)

De-correlation of detector gain

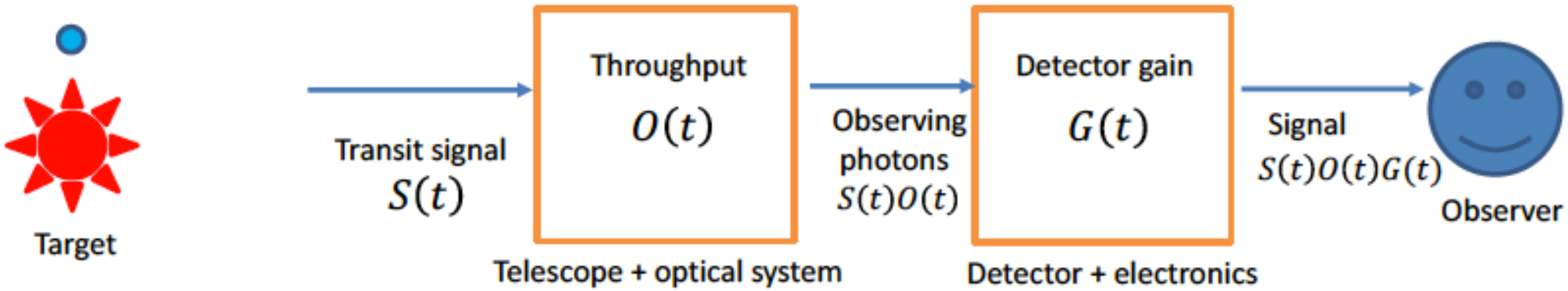
See also Waldmann (2012) for good introduction of ICA

- Why we use Independent Component Analysis?

Observing signal:

$$I(t) = (S(t) + n) \times O(t) \times G(t) \approx \underbrace{\bar{S} \times \bar{G}}_{\text{Average}} + \underbrace{\bar{S} \times \delta G(t)}_{\text{Detector stability}} + \underbrace{\bar{G} \times \delta S(t)}_{\text{Transit signal}} + \underbrace{\delta S(t) \times \delta G(t)}_{\text{Second-order of fluctuation}} + \underbrace{\acute{n}}_{\text{Photon noise}}$$

$\delta G(t)$ and $\delta S(t)$ are statistically independent and have non-gaussianity property.



Can we trace biosignature?

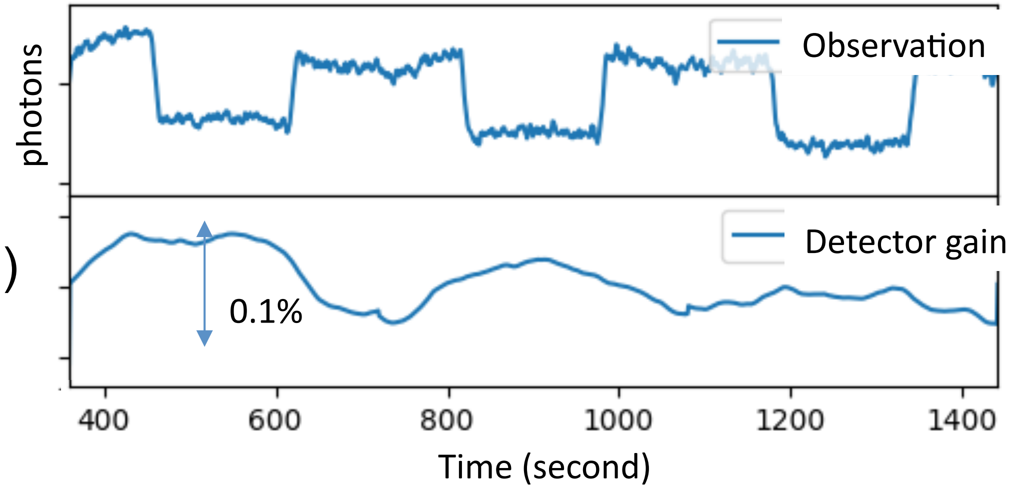
- Observation condition

Diameter	9.3 m
Wavelength	10 µm
Throughput	40 %
Number of eclipses	25

- Target: Trappist-1e (in habitable zone)

Distance	12 pc
Star radius	0.117 Rsun
Star temp.	2559 K

Celebration of discovery of Trappist-1 system (Feb. 22)

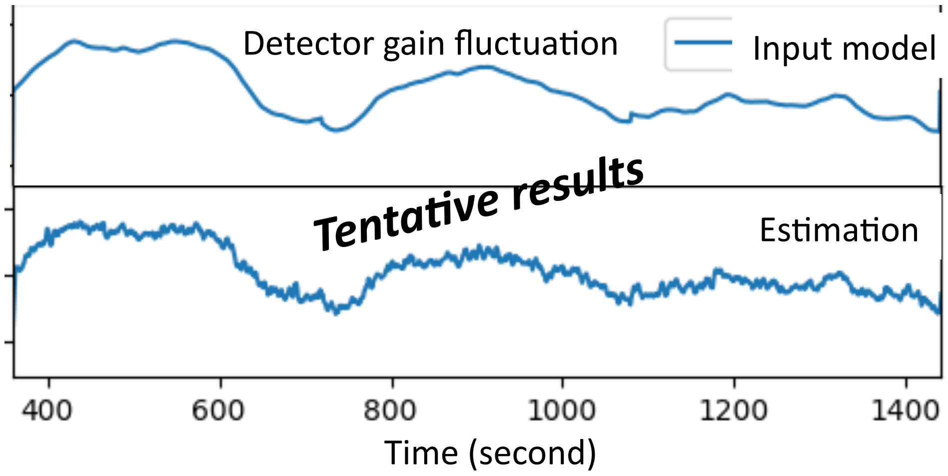


Observation model (up) and input detector gain fluctuation (down) of transmission spectroscopy of Trappist-1e

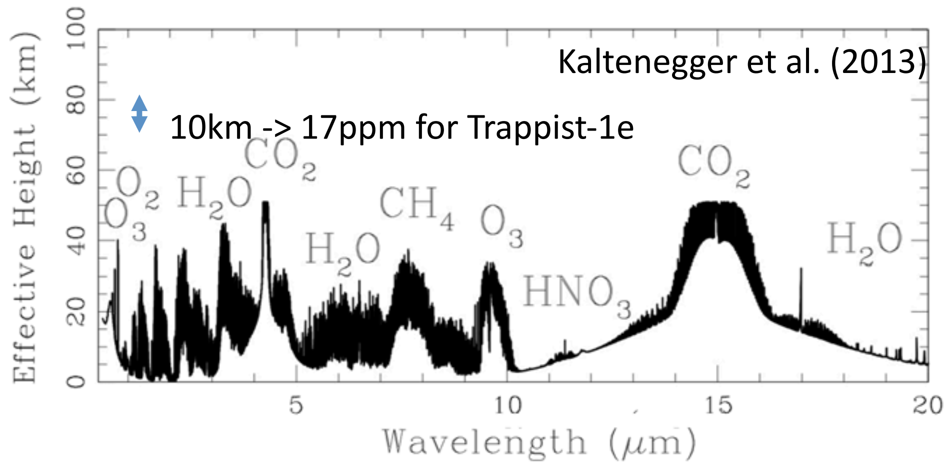
Can we trace biosignature?

- Estimation of noise accuracy for Trappist-1:
  ~ 10 ppm (depending on number of photons and number of eclipses)
  -> resolve effective height of 10 km

- ICA potentially achieves the photon-noise-limited performance
  -> next step:
  simulate under various conditions



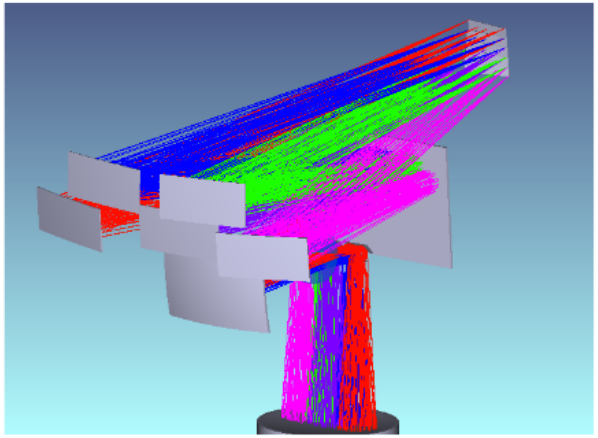
Comparison between input and estimation



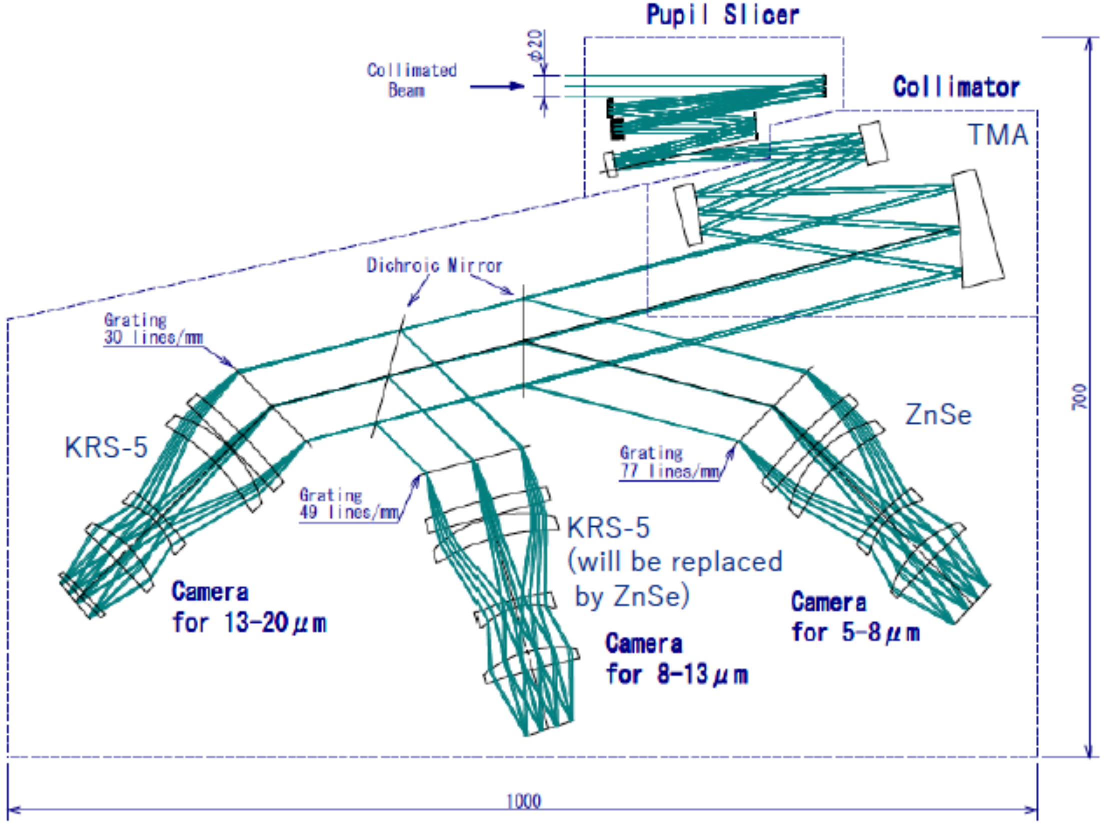
Transmission spectrum model of cold planet with 1 Earth radius

Optical design of the densified pupil spectrometer for MISC

Pupil slicer



Pupil slicer/densification (colored by slice mirror)



- Pupil slicer/densification + Spectrometer
- Size of optical system; ~1000mm x 700mm
- 5-20μm is broken into three channels (5-8, 8-13, 13-20μm).

→ major absorption features of H_2O, CH_4, O_3, and CO_2 are NOT split in different channels.

- Configuration;
  11 mirrors for common optical path (5-20um)
  4 lenses for each channel (5-8, 8-13, 13-20um)
- Lens material; ZnSe for 5-8 um
  KRS-5 for 8-13 and 13-20um
- R~300 is achieved over 5-20um
- Transmission gratings/grisms are required

OST/MISC Fact Sheet

(http://exoplanets.astron.s.u-tokyo.ac.jp/OST/MISC/index_misc_case_A.html)

Module	Mid-IR Imager Spectrometer Channel			Transit Channel	Coronagraph Channel
	Imager/Low-Res Spec.	Medium-Res Spec.	High-Res Spec.	(Densified Pupil Spec.)	(PIAACMC)
	WFI-S/-L	MRS-S/-M/-L	HRS-S/-L	TRA-S/-M/-L	COR-S/-L
Bandpass (μm)	6-38	5-36	12-18, 25-38	5--20	6-38
Spectral Resolution	5-10 [Imager] 300 [Low-Res Spec.]	1000-1500	20,000-30,000	300	300
Full FOV	3 arcmin x 3 arcmin [Imager]	3 arcsec x 5 arcsec [with IFU]		3 arcsec x 3 arcsec	5.5 arcsec x 5.5 arcsec
Slit for Spectroscopy	Length; 3 arcmin Width; 0.26 arcsec (WFI-SG1) 0.40 arcsec (WFI-SG2) 0.65 arcsec (WFI-LG1) 1.00 arcsec (WFI-LG2) [low-resolution Spec.]	Length; 3 arcsec (MRS-S/-M/-L) Wdth; 0.33 arcsec (MRS-S) 0.55 arcsec (MRS-M) 1.0 arcsec (MRS-L) Mum of Slices; 11 (MRS-S) 9 (MRS-M), 5 (MRS-L)	Length; 1.0 arcsec (HRS-S) 2.0 arcsec (HRS-L) Width; 0.5 arcsec (HRS-S) 1.0 arcsec (HRS-L)		Length; 1 arcmin Width; 0.26 arcsec (COR-SG1) 0.40 arcsec (COR-SG2) 0.65 arcsec (COR-LG1) 1.00 arcsec (COR-LG2)
Detectors	2kx2k Si:As (30μm/pix) [S] 2kx2k Si:Sb (18μm/pix) [L]	2kx2k Si:As (30μm/pix) [S] 2kx2k Si:As (30um/pix) [M] 1kx1k Si:Sb (18μm/pix) [L]	2kx2k Si:As (30μm/pix) [S] 1kx1k Si:Sb (18μm/pix) [L]	2kx2k Si:As (30μm/pix) [S] 2kx2k Si:As (30μm/pix) [M] 2kx2k Si:As (30um/pix) [L]	2kx2k Si:As (30μm/pix) [S] 1kx1k Si:Sb (18μm/pix) [L]
pixel scale	0.088 arcsec/pix	0.0615 arcsec/pix (MRS-S) 0.10 arcsec/pix (MRS-M) 0.15 arcsec/pix (MRS-L)	0.17 arcsec/pix [S] 0.34 arcsec/pix [L]	0.1 arcsec/pix	0.05 arcsec/pix (COR-S) 0.10 arcsec/pix (COR-L)
Specification (Sensitivity/ Stability/ Contrast)	**Sensitivity [Imager] ;** *1-hour 5σ Continuum Sens .* *for a Point Source* 0.027μJy@5μm, 0.16μJy@10μm, 0.26μJy@15μm, 0.37μJy@20μm, 0.55μJy@25μm, 0.63μJy@30μm, 0.7μJy@35μm **Sensitivity [Low-Res Spec.];** *1-hour 5s Continuum Sens.* *for a Point Source* (R=300) 0.6μJy@5μm, 1.3μJy@10μm, 4.0μJy@15μm, 5.0μJy@20μm, 8.8μJy@25μm, 11.2μJy@30μm, 37.5μJy@35μm	**Sensitivity;** *1-hour 5s Continuum Sens.* *for a Point Source (R~1200)* 3μJy@7μm, 10μJy@15μm, 30μJy@24μm,100μJy@32μm 1-hour 5s Line Sens. for a Point Source 1x10^{-21} W/m^2 @7μm, 2x10^{-21} W/m^2 @15μm, 3x10^{-21} W/m^2 @24μm, 1x10^{-20} W/m^2 @32μm	**Sensitivity;** 1-hour 5s Line Sens. for a Point Source 1x10^{-21} W/m^2 @15μm, 3x10^{-21} W/m^2 @30μm	**Photometric stability;** 1ppm on timescales of hours to days (excluding the fluctuation of detector gain)	**Average contrast;** 7x10^{-6} for 10% band 1x10^{-6} for 4% band in 0.88-3.6λ/D

Instrument TRL's and Heritage

Description	Subsystem/ Component	TRL	Heritage
Deformable Mirror	Component	4	SPICA/SCI, LAM
Tip Tilt Mirror	Component	4	SPICA/SCI, JWST/NIRCAM
2K x 2K Si:As, 2K x 2K Si:Sb	Component	2	
PIAACMC Coronagraph	Subsystem	3	
8-Octa Phase Mask for MIR(8-36um)	Component	2	
Binary Pupil Mask Coronagraph	Component	4	SPICA/SCI
Beam Splitter, Band-pass Filters (Multi-Layer Interference Filter)	Component	4	SPICA/MCS
Image Slicer	Subsystem	4	SPICA/MCS, TMT/MICHI
Immersion grating (12-18μm)	Component	4	SPICA/MCS
Immersion grating (25-38μm)	Component	2	
Densified pupil spectrometer	Subsystem	3	