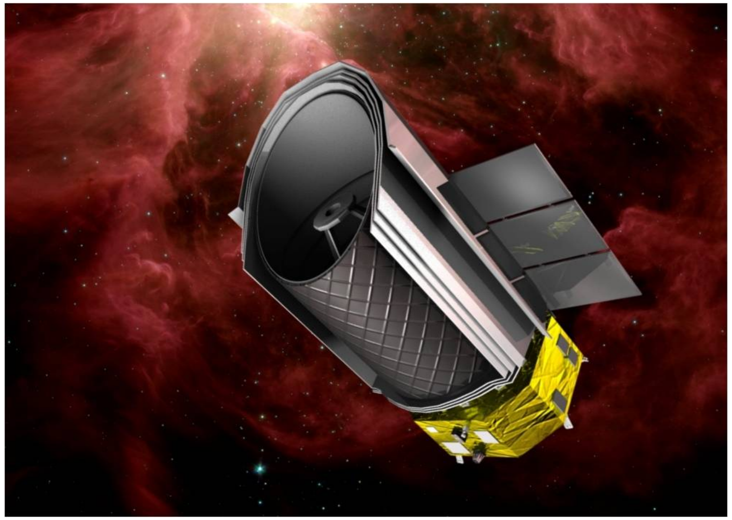
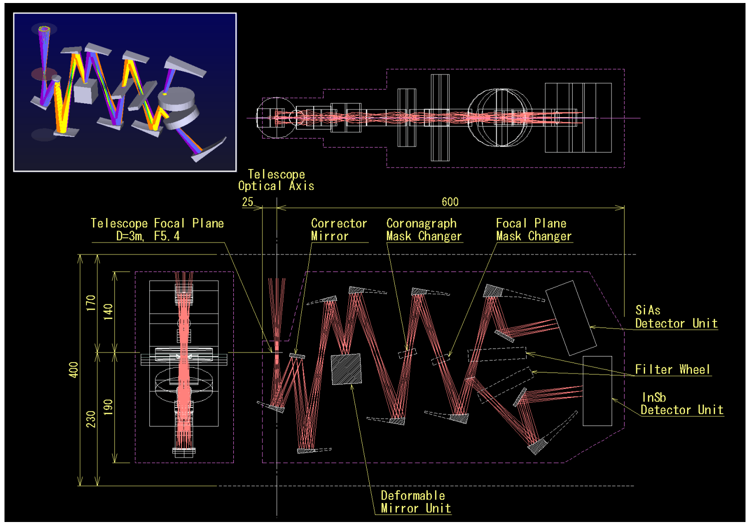
SPICA science workshop
Dec. 16-17th, 2010

SPICA Coronagraph Instrument (SCI) for study of exoplanet and planetary system

Presenter: K. Enya & T. Kotani on behalf of the SCI team





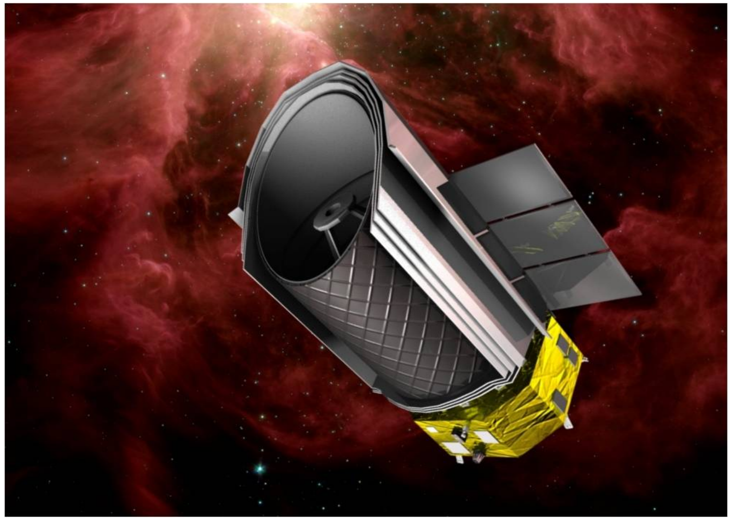
K. Enya , T. Kotani, T. Nakagawa, H. Matsuhara, H. Kataza, T. Wada, M. Kawada, M. Mita, K. Komatsu, H. Uchida, T. Yamawaki, S. Mitani, S. Sakai, K. Fujiwara, K. Haze, K. Aono (1),
T. Matsuo, N. Narita, T. Yamashita, M. Tamura, J. Nishikawa, Y. Hayano, S. Oya, E. Kokubo (2),
T. Miyata, S. Sako, T. Nakamura, K. Asano (3), M. Fukagawa, H. Shibai (4), N. Baba, N. Murakami (5),
Y. Itho (6), M Honda (7), Y. Okamoto (8), S. Ida (9), M. Takami (10), L. Abe (11), O. Guyon(12)

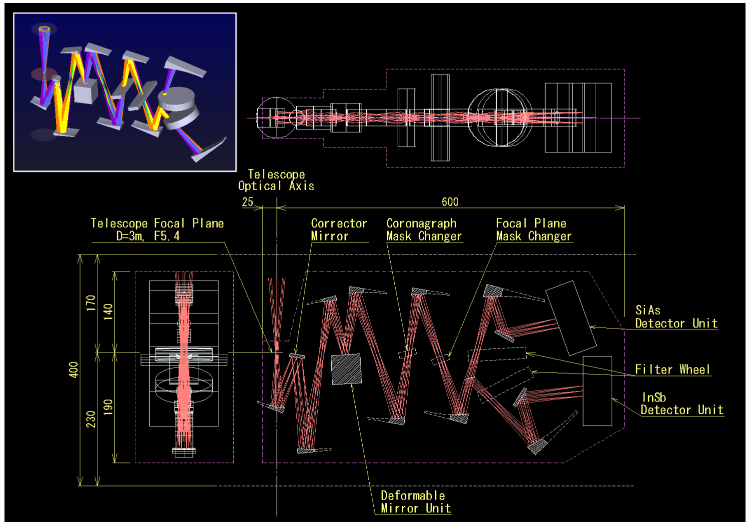
JAXA (1) NAOJ (2) Univ. of Tokyo (3) Osaka Unov. (4) Hokkaido Univ. (5) Kobe Univ. (6) Kanagawa Univ. (7) Ibaraki Univ. (8) Tokyo Inst. of Tech. (9) ASIAA (10) Nice Univ. (11) Arizona Univ./NAOJ (12)

Contact: enya@ir.isas.jaxa.jp (K. Enya: P.I.)

SPICA science workshop
Dec. 16-17th, 2010

SPICA Coronagraph Instrument (SCI)
for study of exoplanet and planetary system





K. Enya , T. Kotani, T. Na … Mita, K. Komatsu,
H. Uchida, T. Yamawaki, …
T. Matsuo, N. Narita, T. … okubo (2),
T. Miyata, S. Sako, T. Nak … a, N. Murakami (5),
Y. Itho (6), M Honda (7) … Guyon(12)

JAXA (1) NAOJ (2) Univ. of Tok … Ibaraki Univ.
(8) Tokyo Inst. of Tech. (9) ASIA …

Contact: enya@ir.isas.jaxa.j…

Special thanks to:

The SCI team members
SPICA task force, LOC of thhis workshop
Securetarys, and all releting SPICA

Outline of relating presentations

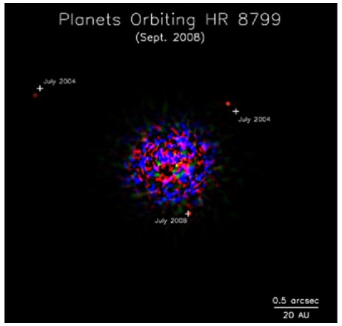
- General introduction to SCI : Enya (this talk)
  - Note for major design changes from the first proposal
  - Science targets: why exoplanets?
  - Design and performance
- Wavefront analysis for the requirements of SCI: Kotani (following talk)
- Science session: Tamura, Itoh, Matsuo, Narita, Honda, Kotani (tmorrow)

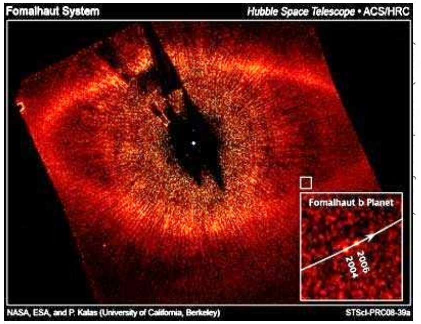
Note for major changes of the design from the first proposal

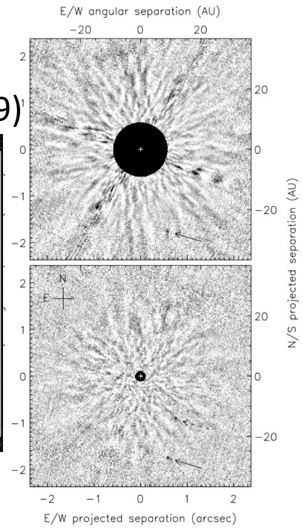
- Purpose: reducing technical risk, spacecraft resource, cost and mampower
- Tip-tilt mirror
  - Tip-tilt mirror is removed
  - Pointing control with a sensor in SCI is considered
- Deformable mirror (DM)
  - Baseline design: no DM (contrast~ 10^{-4})
  - Advanced desgn: with a DM (contrast ~10^{-6})

Science targets: why exoplanet?

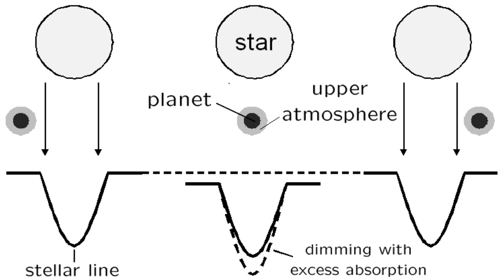
e.g. directly imaged planet candidates
(Marois et al 2008, Kalas et al 2008, Thalman et al 2009)

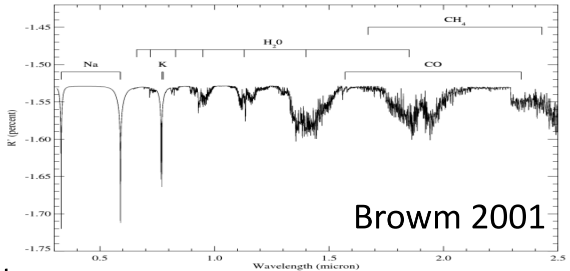




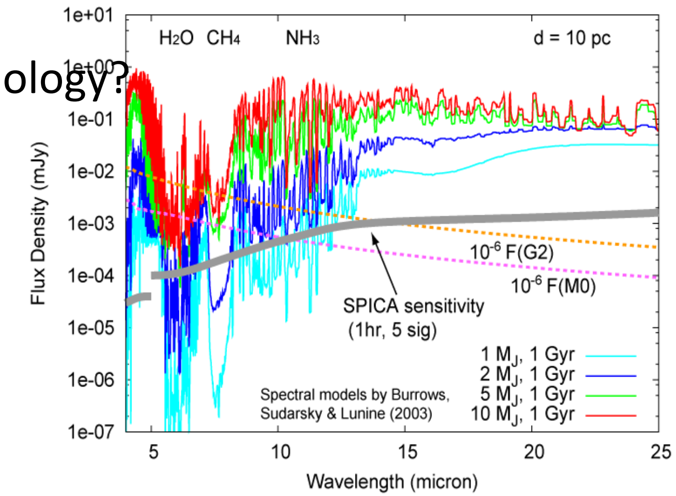


Study of atmosphere of transiting planets



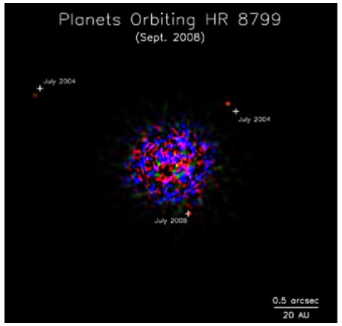


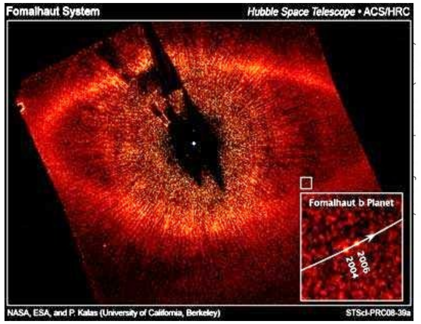
- Observational study of exo-planetary system is one of the most important issue of space science in near future
  - Birth and evolution? Diversity? Finally the origin of biology?
- No longer the dream
- What is hot in the SPICA era?
  - Spectroscopy in full IR?
  - High sensitivity detection of cooler, smaller planets??
  - Biomarker???

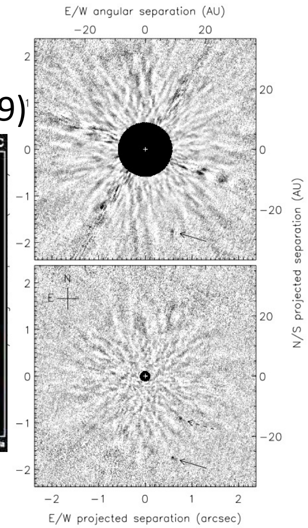


Science targets: why exoplanet?

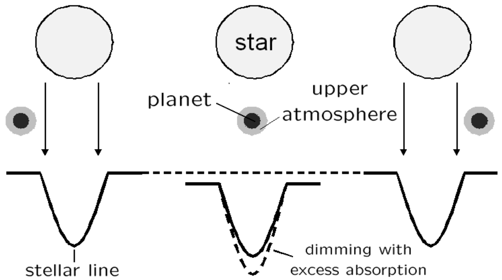
e.g. directly imaged planet candidates
(Marois et al 2008, Kalas et al 2008, Thalman et al 2009)

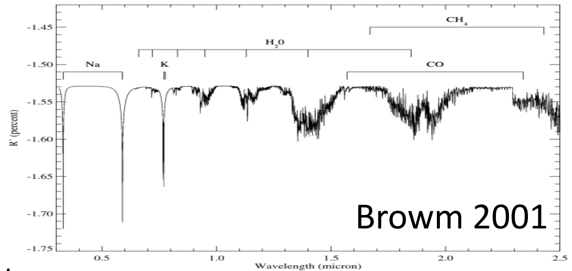






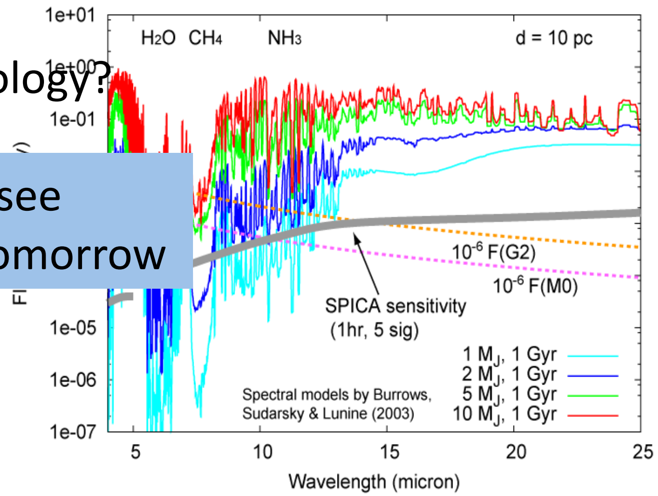
Study of atmosphere of transiting planets



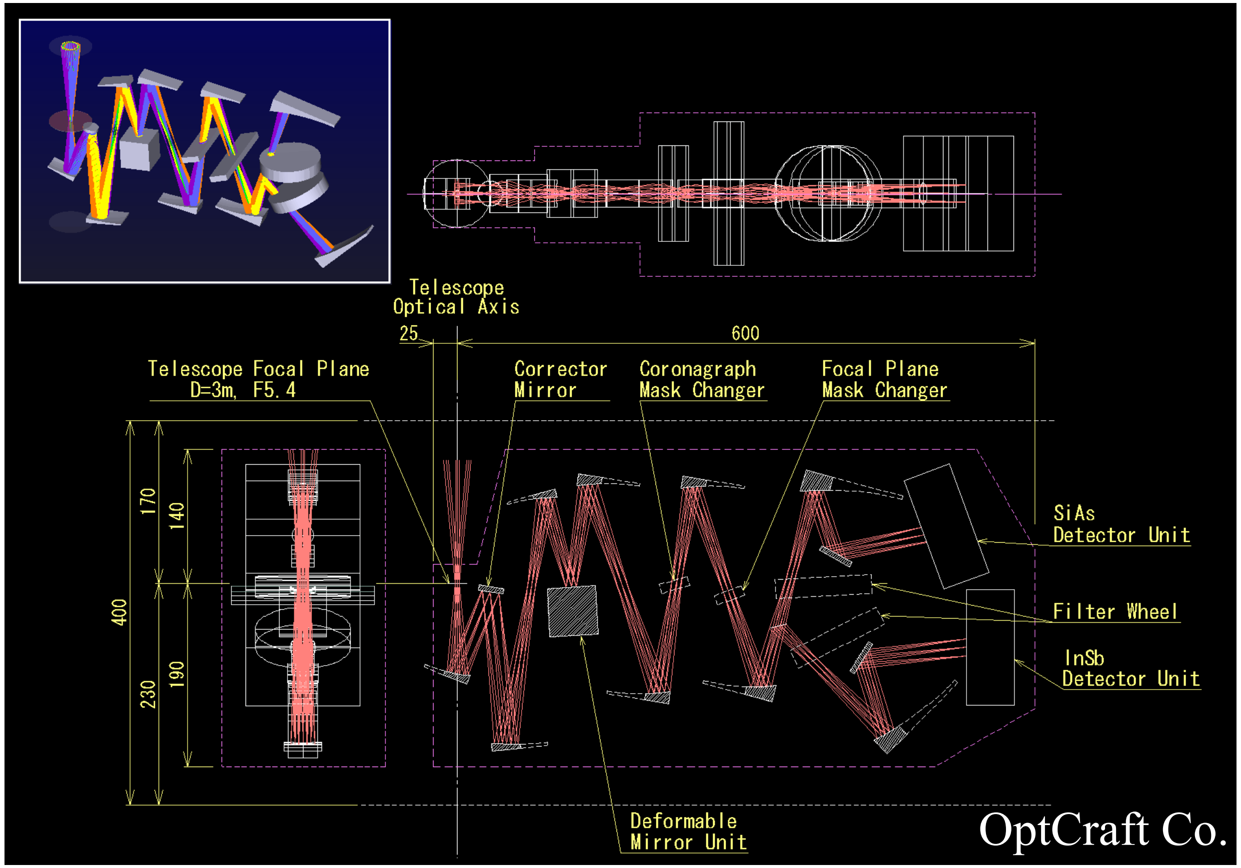


- Observational study of exo-planetary system is one of the most important issue of space science in near future
  - Birth and evolution? Diversity? Finally the origin of biology?
- No longer the dream
- What is hot in the SPICA era?
  - Spectroscopy in full IR?
  - High sensitivity detection of cooler, smaller planets??
  - Biomarker???

For the detail, please see the science session tomorrow



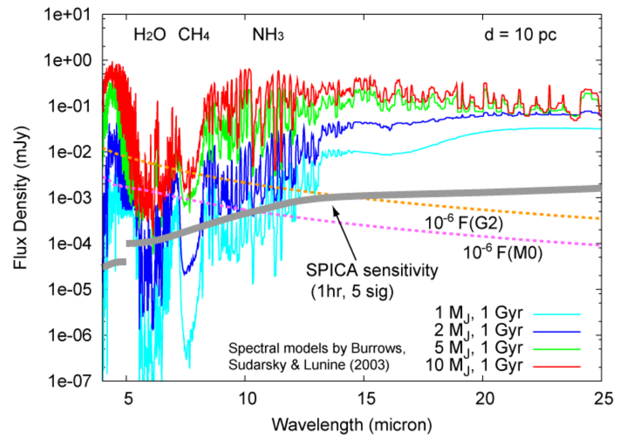
Overview of the instrument

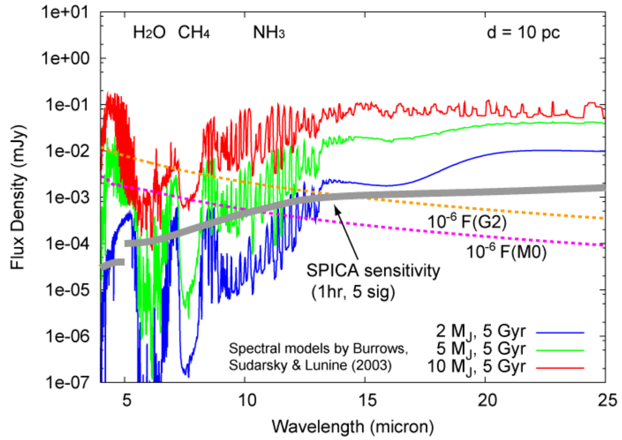


- Two channels (The short- and long- channels)
  - Proper pixel scale to cover wide wavelength region.
  - Subtraction analysis
  - Simultaneous observation with two channels

Specification

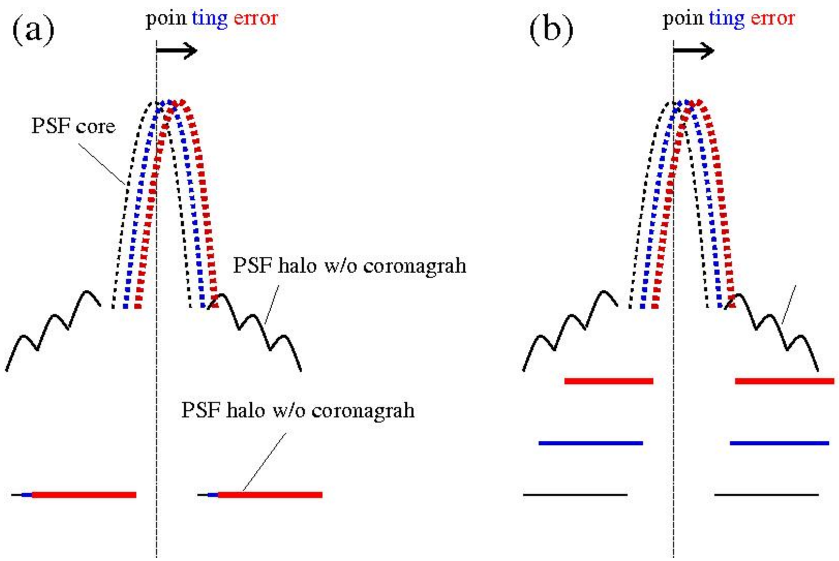
Observation mode	Coronagraphic imaging Coronagraphic spectroscopy Non-coronagraphic imaging Non-coronagraphic spectroscopy
Coronagraph method	Binary pupil mask
Guaranteed contrast @PSF*	Baseline design 10^{-4} @mask1, 10^{-4} @mask2 Advanced design 10^{-6} @mask1, $10^{-4.5}$ @mask2
Spectral Resolution in	~20, ~200 @spectrsocopy mode
Filter bands in imaging mode	Band-pass filters at both Short, long channels
Inner working angle - Outer working angle	3.3 - 12 λ/D (mask1) 1.7 -4.5 λ/D (mask2)
Sensitivity and detection limit	See figures shown left
FoV	1’ x 1’
Detector and channel	Short channel: 2k x 2k InSb (λ<5micron) * Long channel: 2k x 2k Si:As (λ>5micron) *
Wavelength coverage	Coronagraph Imaging/spectroscopy: 3.5-27μm** Non- coronagraph Imaging/spectroscopy: 1-27μm**

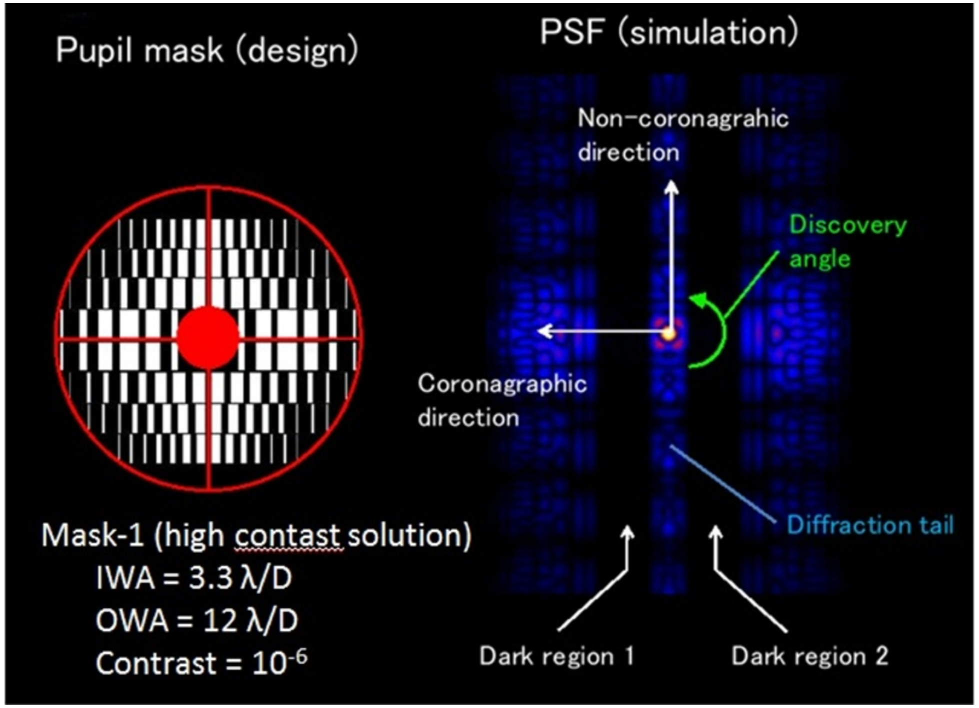




Figures by Fukagawa

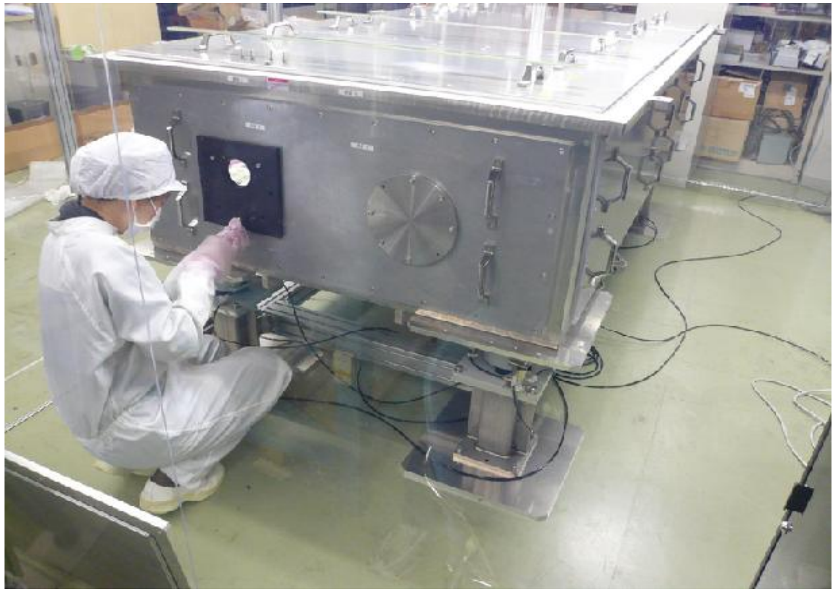
Coronagraph

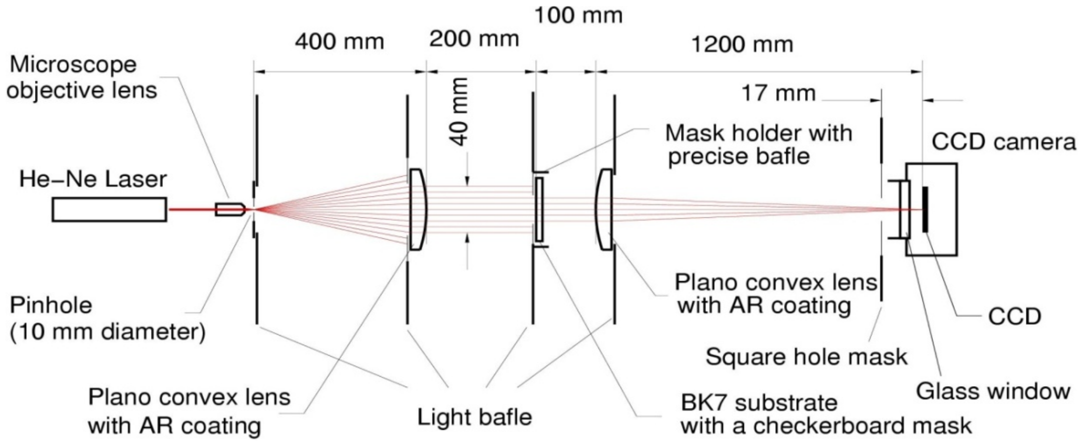


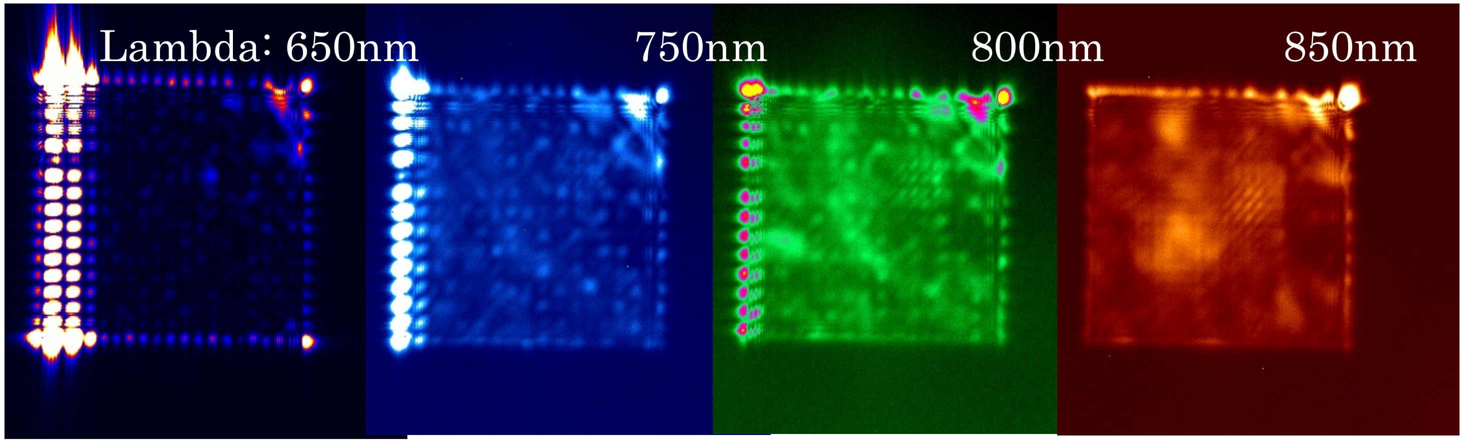


- Binary shaped pupil mask
  - Very robust against the telescope pointing error
  - Essentially achromatic (except scaling of PSF size)
  - High-contrast and small IWA solutions are complementaly
- Pupil mask changer
  - is needed for changing mask1 and mask2
  - can also provides non-coronagrapic mode
- Focal plane mask is practically needed

Laboratory demonstration

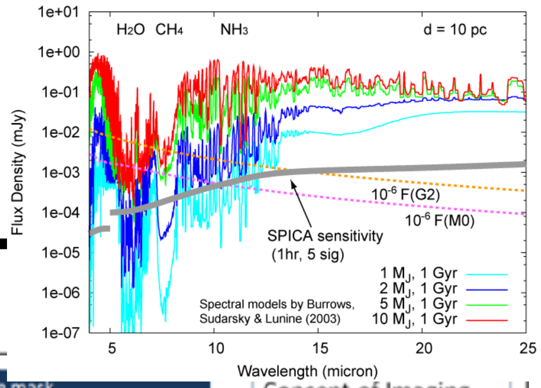


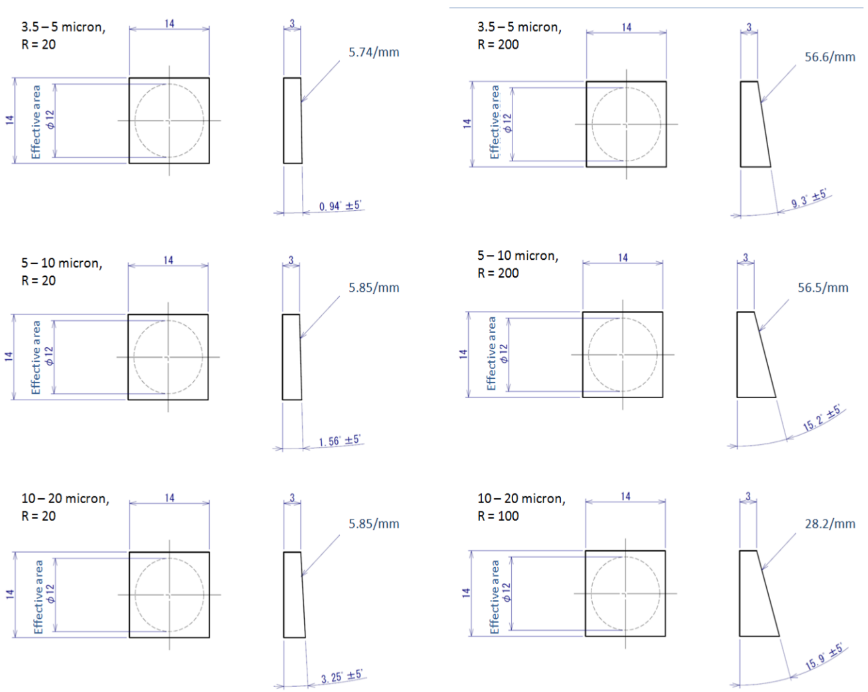


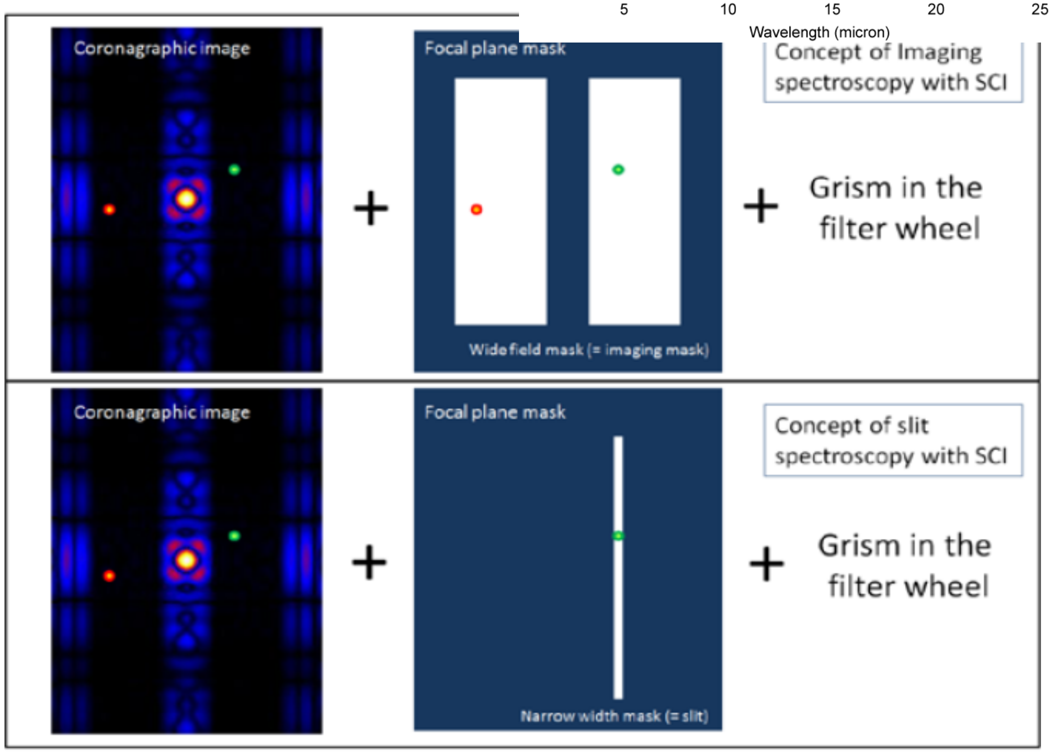


Haze et al. 2009

Spectroscopy







- Combination of focal masks and grism in filter wheeles
  - Imaging spectroscopy
  - Slit spectroscopy
- Realistic solution was obtained in the trial design of grisms.

Bandpass filters

1. 検出器２つの場合（短波長側はInSb、長波長側はSi:As）

Filter Number	中心波長 (um)	bandwidth (um)	lambda1	lambda2	Resolution
InSb					
1	2.1	0.3	1.9	2.2	6.8
2	2.4	0.3	2.2	2.5	8.1
3	2.9	0.7	2.5	3.2	4.1
4	3.5	0.6	3.2	3.8	5.8
5	4.5	1.3	3.8	5.1	3.4
Si:As					
6	5.8	1.5	5.1	6.6	3.9
7	7.7	2.2	6.6	8.7	3.5
8	10.9	4.3	8.8	13.0	2.6
9	15.5	4.8	13.1	17.9	3.2
10	22.0	8	18	26	2.8

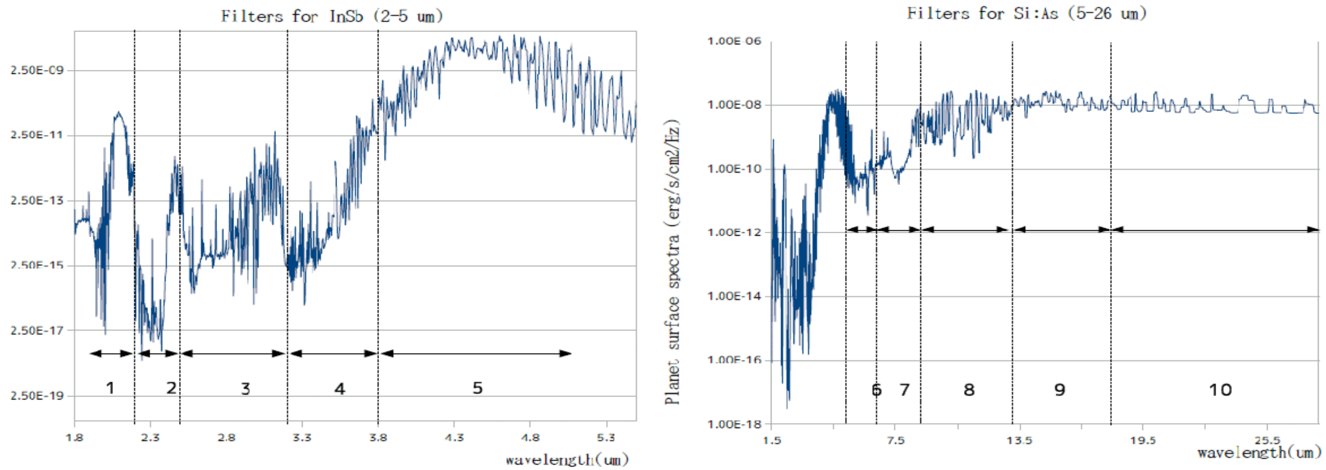
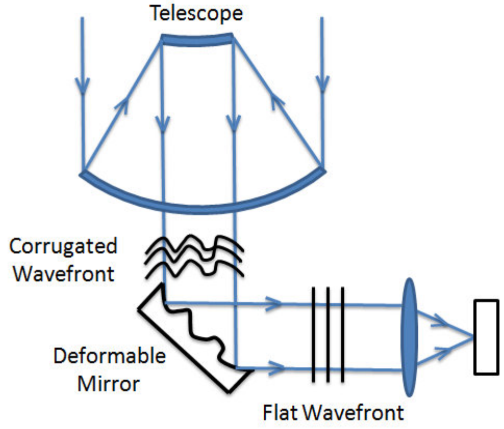


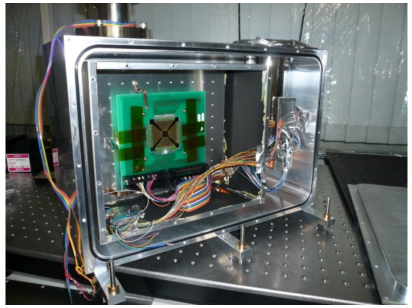
図２：各フィルターの透過率と木星型惑星のモデルスペクトル(100Myr old, 1 Jupiter mass @ 4 AU around a G2V star, from Burrows et al 2004 ApJ, 609, 407)

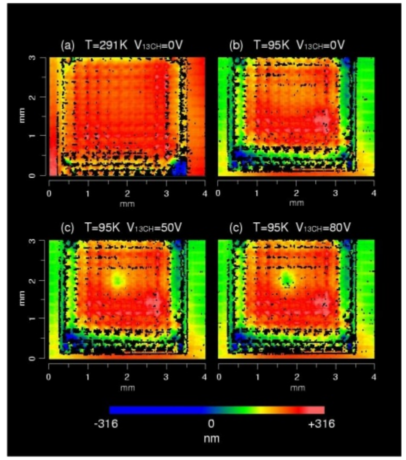
- Trial design with companies
  - Realistic solution was found
  - Cost estimation obtained

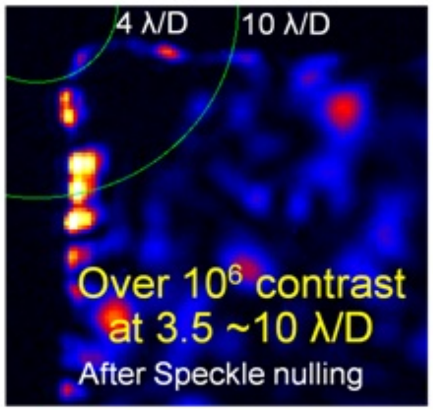
Cryo-DM

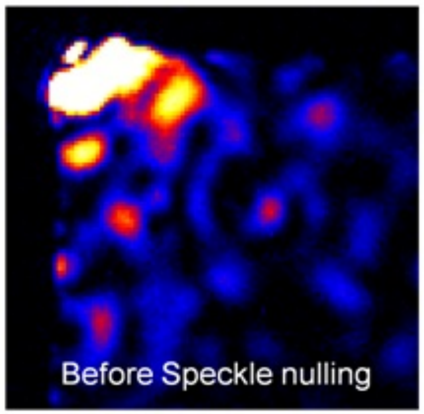
- MEMS-DM
  - Qulomb force actuation
  - compact
- Development
  - from a proto-type (32ch@95K) to Flight model
- Meeting at BMC: 2010/12/10
- Format (number of cbles)

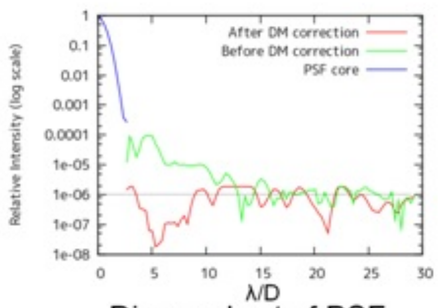












Diagonal cut of PSF

WFC algorithm !
Contrast better than 10^{-6}
(Kotani et al. 2009)

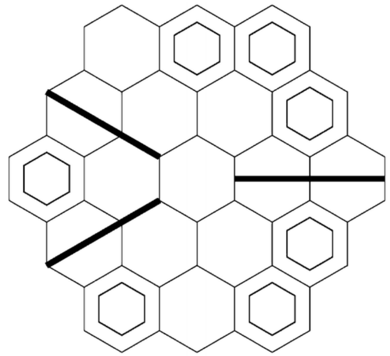
Spacecraft resource

Resources	Specification	System Allocation
Cold Mass	20 kg with TBD margin	20 kg with 20% margin
Cold Volume [mm]	200 x 650 x 330	100 x 650 x 398
Heat Lift at 4.5K [mW] (observing/standby)	Baseline design 2.6/ 0.1 with 30% margin Advanced design 2.6/ 0.4 with 30% margin	6 / 0.4 with 30% margin
Electric Power [W] (observing/standby)	Baseline design TBD (smaller than values for Advanced design) Advanced design 60 / 16 with TBD margin	60 / 16 with TBD margin

Pointing accuracy requirement	0.06 arcsec (0-p) for 20 min.

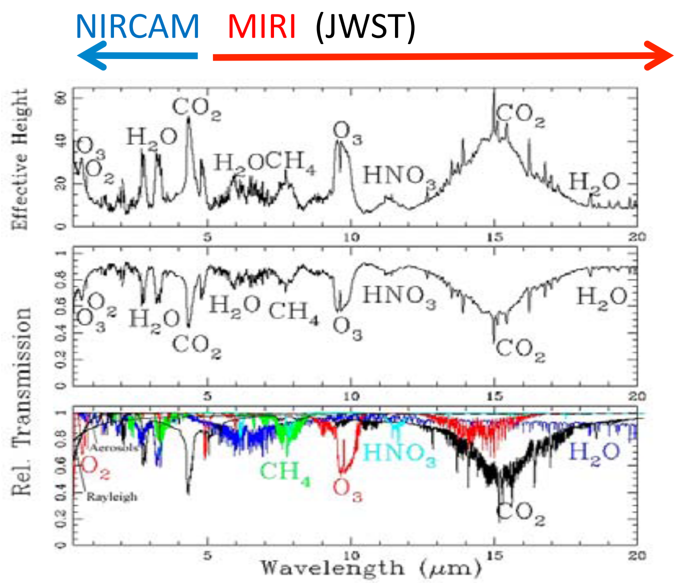
If small additional function is allowed…

- Non Redundant Mask(not coronagraph but interferometer in a terescope)
  - Needed resource: ~ 1 slot of mechanical changer
  - Benefit: adding higher performance to pupil mask coronagraph (e.g., small IWA ~0.5 λ/D)
  - Technically feasible?: Fabrication process is same to binary pupil mask.



Sivaramakrishnan et al. 2009

- Extension of the short limit of the S-channel (down to ~0.6micron)
  - Needed resource: ~ 1 slot of mechanical changer, and adoption of a InSb detector like JWST/NIRCAM
  - Benefit: simultaneous monitor of O_3 and O_2 on transiting exoplanets (O-FIVE).
  - Technically feasible?: Nothing is needed over JWST/NIRCAM detector. Filter, grism are matured technology



Kaltenegger & Traub 2009

- 開発の流れ
  - 基本的に中間赤外観測装置と同様
  - BBM用低温コロナグラフチャンバー
- 機能の落としどころ
  - DMあり/なし
  - ありの場合、フォーマットは？

- 開発の流れ
  - 基本的に中間赤外観測装置と同様
  - BBI
- 機能の
  - DMあり/なし
  - ありの場合、フォーマットは？

SCI requirement: 波動光学的解析
小谷さんの発表へ

Wavefront analysis for the SCI requirement

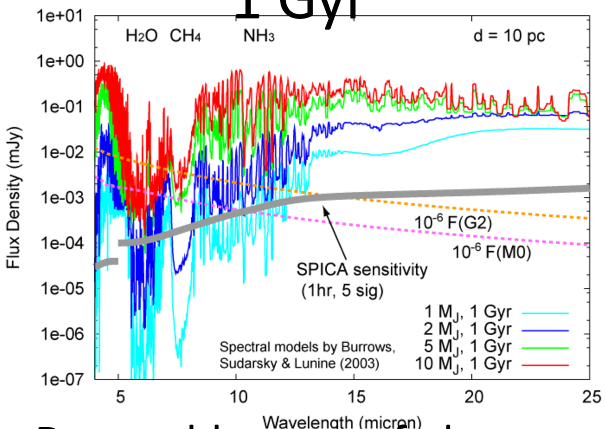
T. Kotani & SCI Team

1. Wavefront errors analysis for the corongraphic imaging
2. Optical alignment tolerance
3. Diffraction effect from the finite size of FoV

Requirements to wavefront errors in STA

- Wavefront errors (WFE) in the telescope assembly will significantly degrade coronagraphic image quality (contrast)
- Definition of WFE Requirements to STA is necessary to achieve a minimum scientific goal without a DM (detection of the most brightest planets with the contrast ratio ~ 10^{-5}
- Simulation of the effect of the wavefront errors on the image quality at the mid (3-12 cycle/D) and the high frequency (12-50 cycle/D) regions

1 Gyr



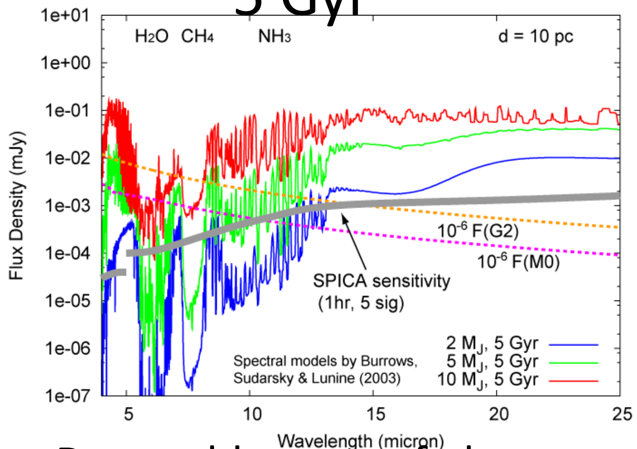
Detectable mass of planets

10^{-6} : M_{limit} ~ 1-2 M_J

10^{-5} : M_{limit} ~ 5 M_J

10^{-4} : M_{limit} ~ 10 M_J

5 Gyr

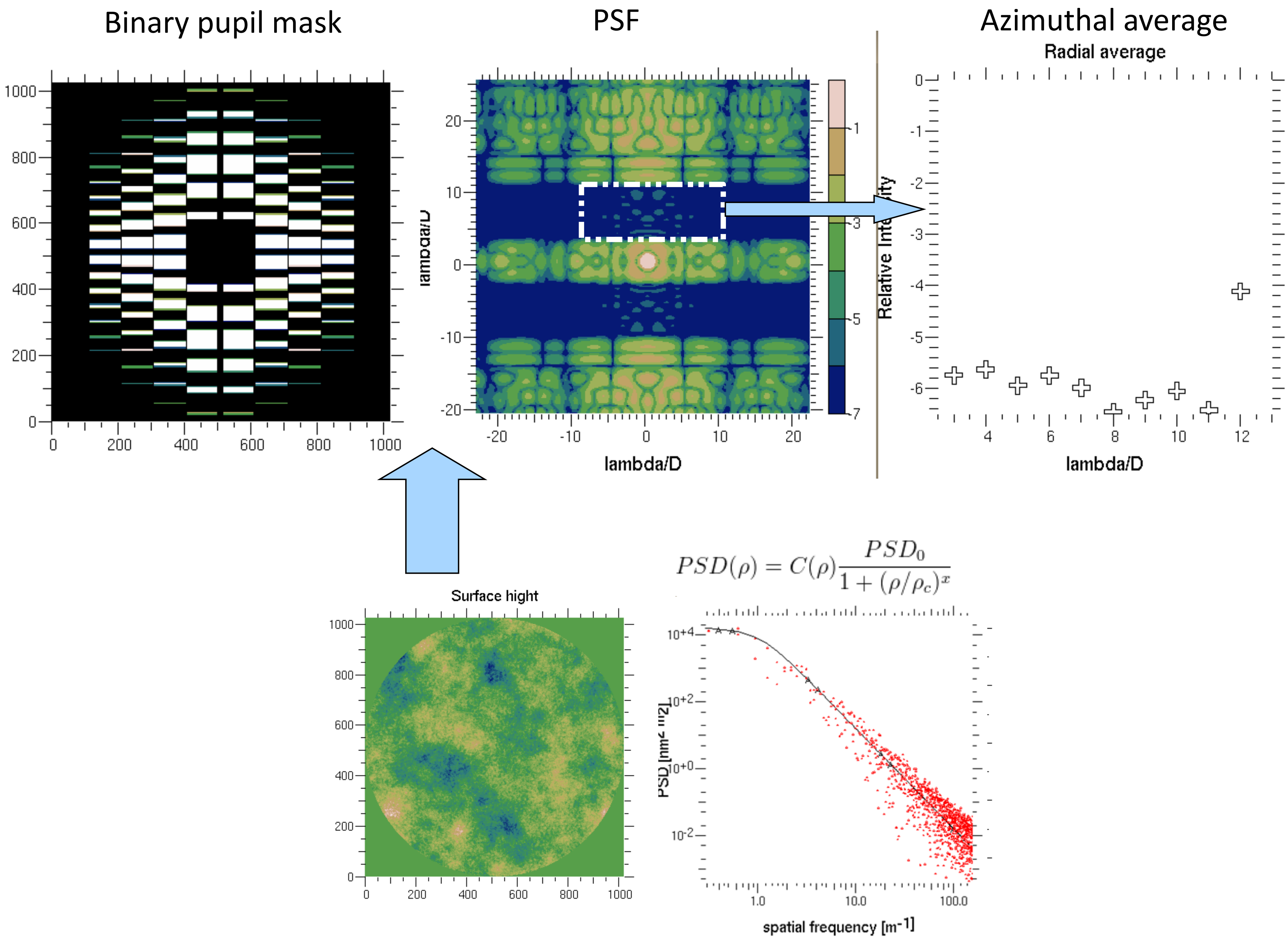


Detectable mass of planets

10^{-6} : M_{limit} ~ 5 M_J

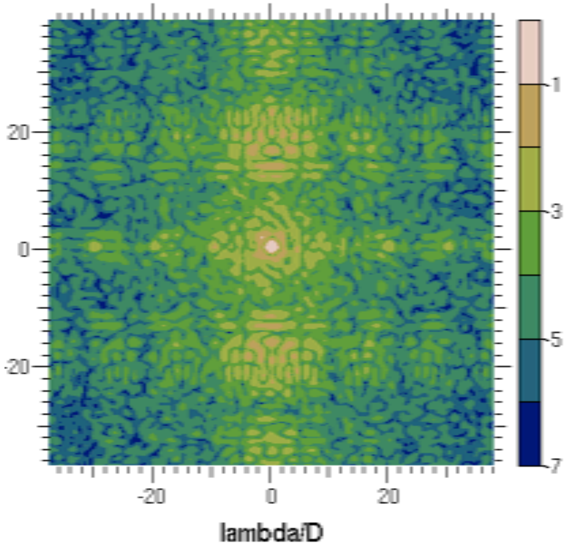
10^{-5} : M_{limit} ~ 10 M_J

10^{-4} : M_{limit} ~ no detection

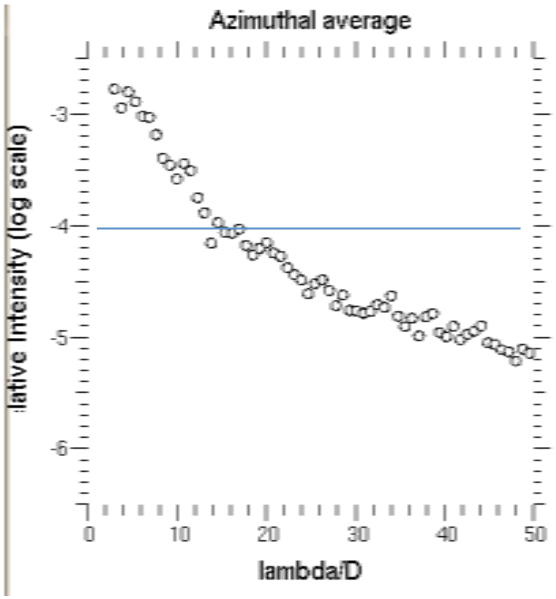


$$PSD(\rho) = C(\rho)\frac{PSD_0}{1+(\rho/\rho_c)^x}$$

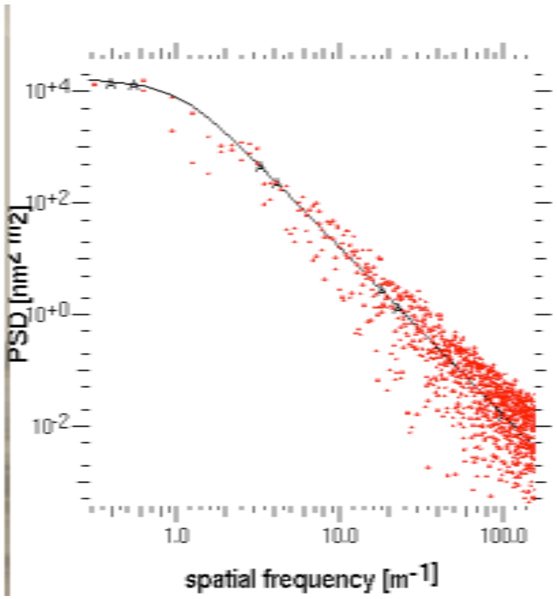
WFE = 350nm rms, power-law PSD



Final Image



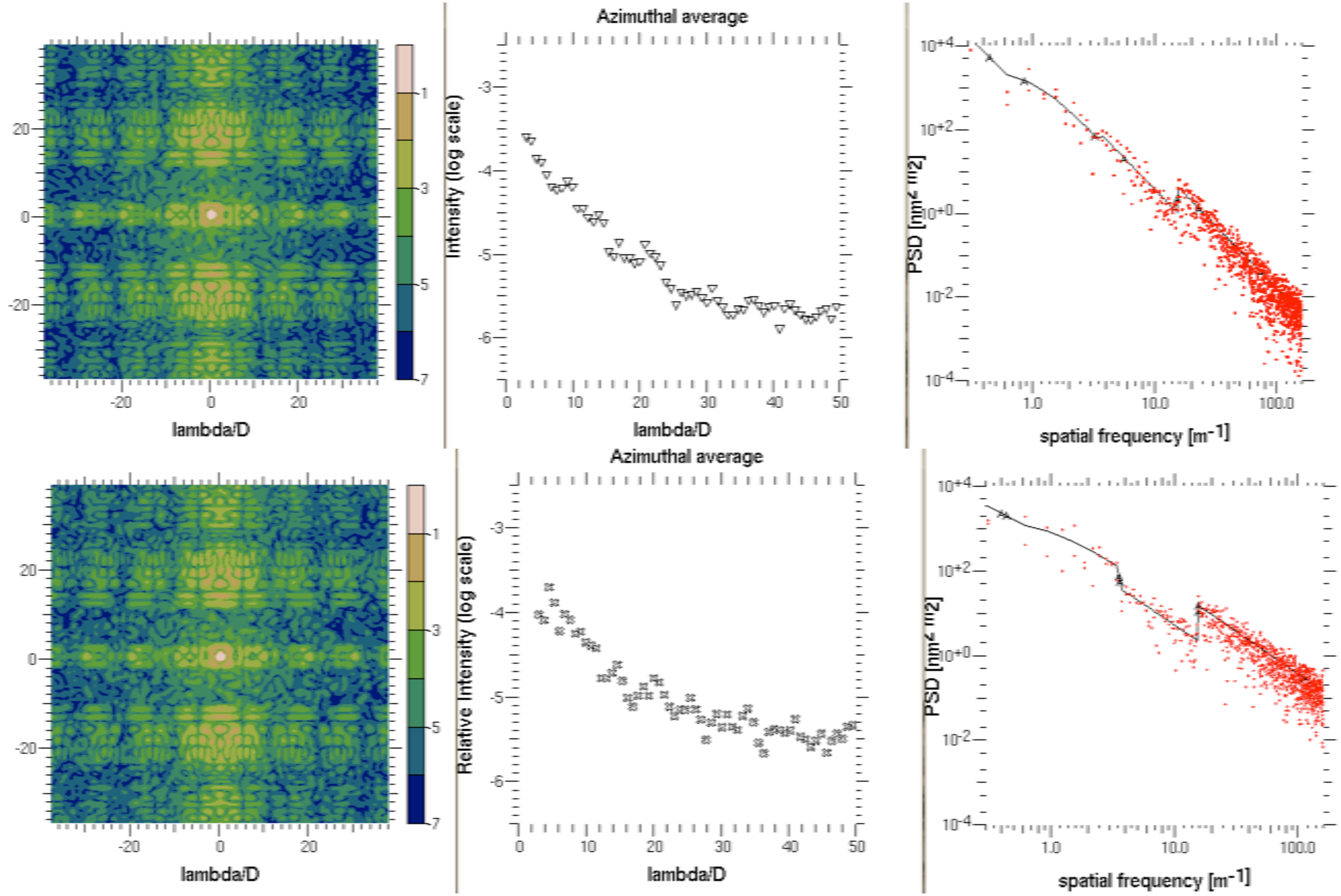
Azimuthal average of the PSF



Power Spectral Density of WFE

Image contrast > 10^{-4} at 3-16 cycle/D region

WFE = 113 nm = $\lambda_0/44$ rms (2-12 cycle/D),70nm= $\lambda_0/71$ (12-50 cyc/D)



Raw Image contrast ~ 10^{-4} at 3-16 cycle/D region

- Without any additional requirements on STA/WFE other than diffraction limit at 5 μm and without using a DM, the achievable contrast of SCI will be around 10^{-3} to 10^{-4} between 3-12 cycle/D regions

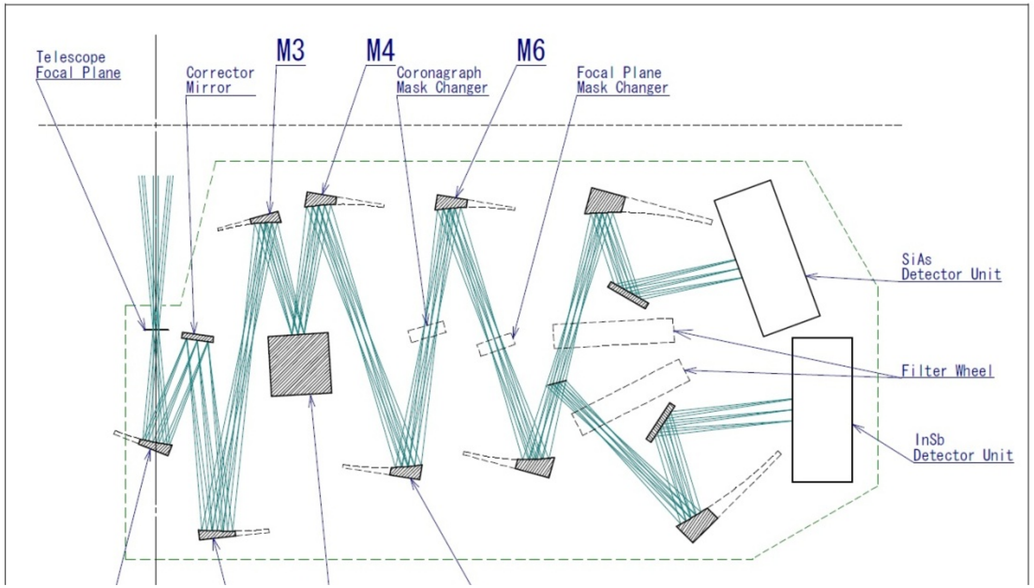
- To achieve 10^{-5} contrast to detect matured Jupiter-mass planets without a DM, the coronagraphic requirements to STA are following:

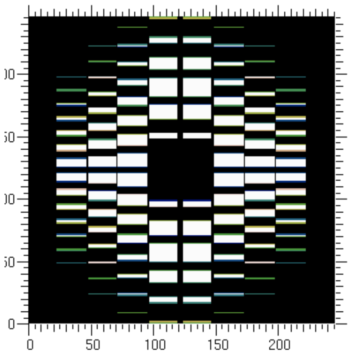
- From 3.3 cycle/D to 12 cycle/D, the WEF shall be < $\lambda_0/45$ rms with a goal of < $\lambda_0/133$ rms

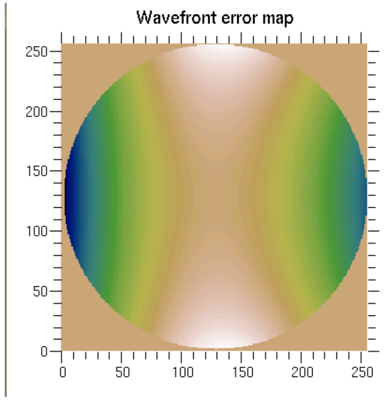
- From 12 cycle/D to 50 cycle/D, the WEF shall be < $\lambda_0/71$ rms

- Parameters for the WFE PSD functions should be optimized taking into account for the technical limitations, cost, delivery time, etc. The lessons from this simulation are following: the smaller value of x (the power of the spatial frequency) and the bigger value of ρ_c will lead to better contrast at the low to the mid spatial frequencies

Optical alignment tolerance: Internal alignment of SCI

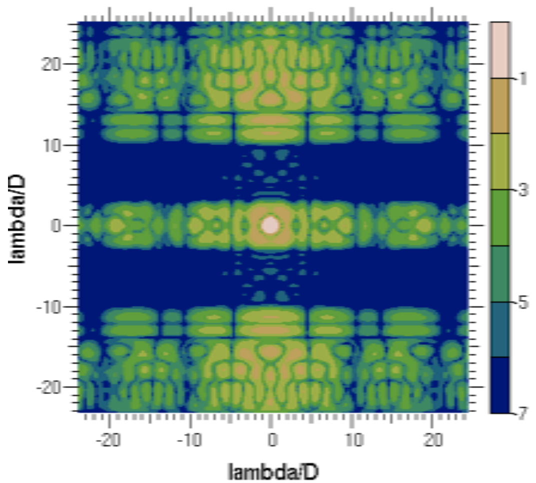


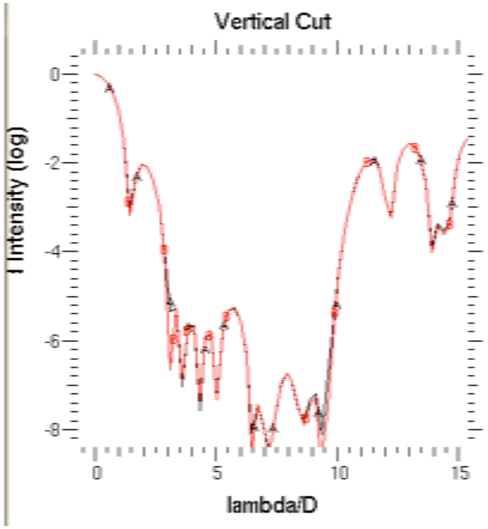


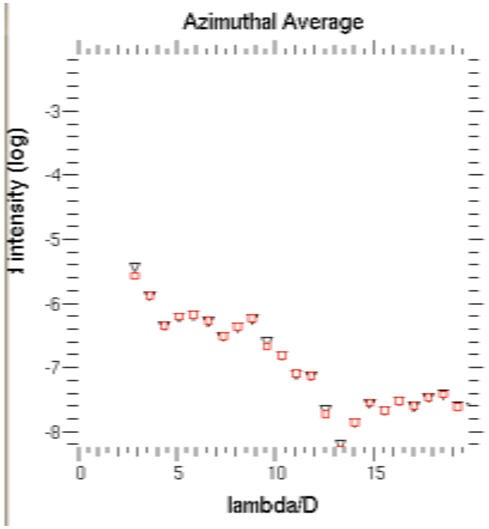


20 micron shift in X, Y, Z direction or 3 arcmin tilt in X, Y direction of a mirror

⇒ **almost no impact on the coronagraphic image quality**







Black: no wavefront error; Red: with wavefront error

Optical alignment tolerance: Alignment between SCI to the telescope

Assuming that there is no internal alignment error in SCI and the telescope assembly

Alignment error source	Tolerance
Shift (in X-Y plane direction)	0.5mm (no dependence on direction of the shift)
Shift (Z direction)	10 micron
Tilt (X, Y direction)	0.1 deg (no dependence on direction of the tilt)

X,Y Shift:

・Astigmatism and field curvature < 50nm (the dominant aberrations in SCI's FoV, no Coma) ⇒ 3.5mm

・10% of the pick-off mirror size (5x5mm) ⇒ 0.5mm

Z shift (focus): We estimated the z-shift tolerance (focus) is about 10 μm. It seems very severe tolerance, however it can be realized with the telescope focus adjustment of the secondary mirror.

Tilt: Tilting the whole SCI's optics will just introduce the displacement of the pupil position, if it is small. Suppose that we accept 1% telescope pupil displacement relative to the coronagraph mask position, the tolerance is about 0.1 degree

Diffraction effect from the finite PoM size

- **1' x 1' FOV size has no significant impact to achieve 10^{-6} contrast with SCI**