Visible Coronagraph and Infrared Interferometer

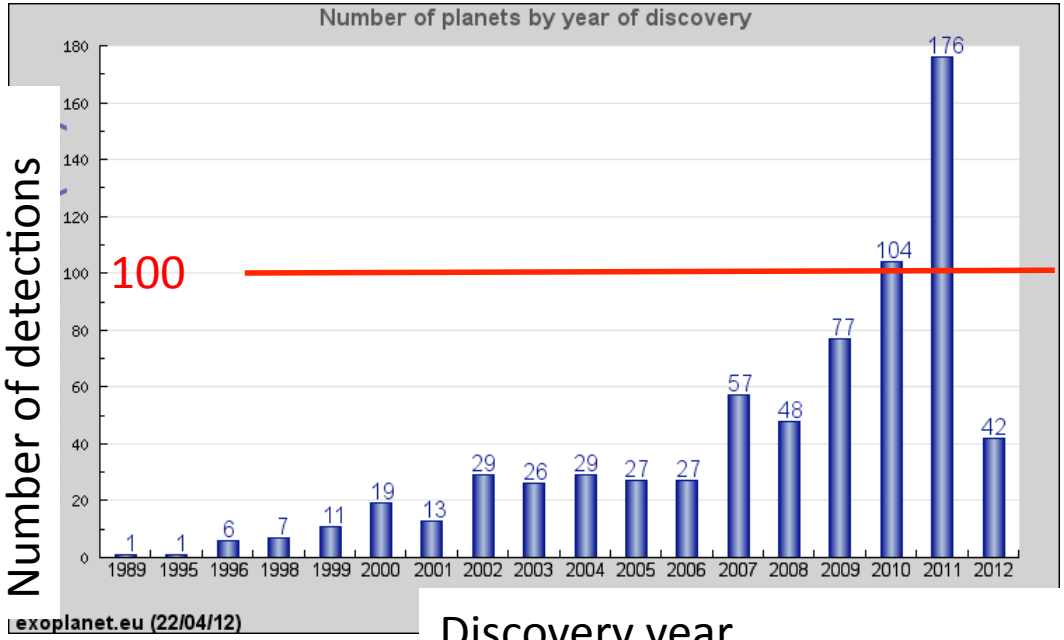
Taro Matsuo (Kyoto Univ.)

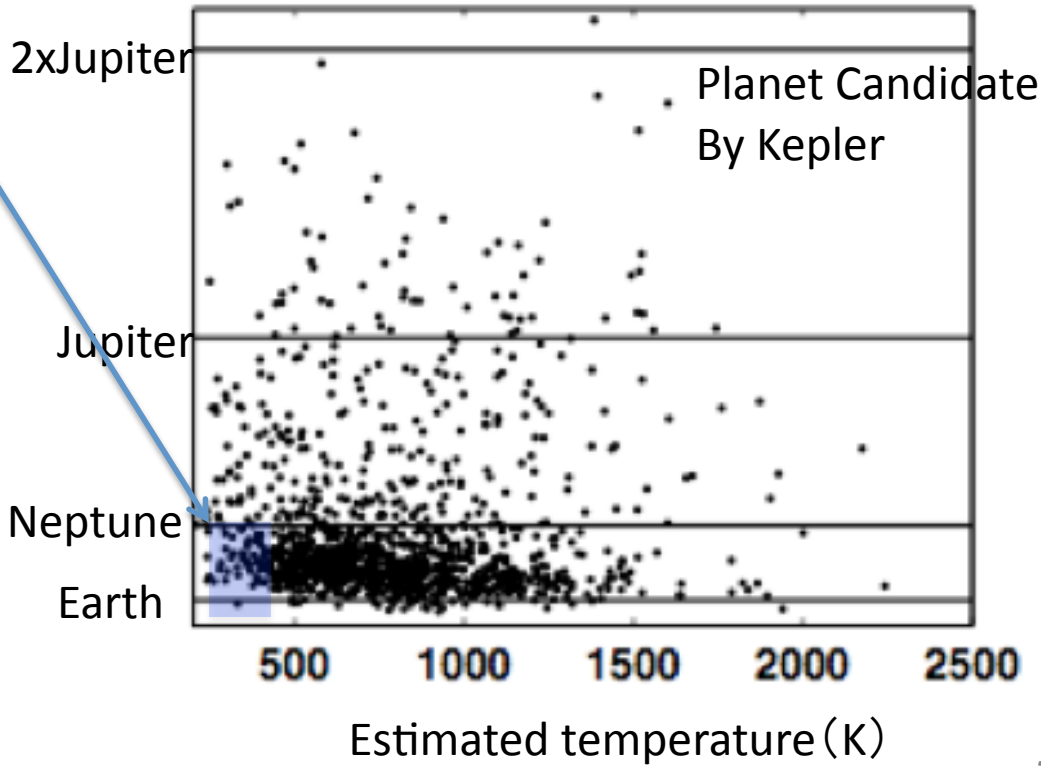
Background

- More than 800 planets have been discovered by several indirect techniques.
- Kepler detects more than 50 Earth-like candidates.

- Earth-like planets in HZ are common around nearby stars.

➔ To detect and characterize Earth-like planets





Direct Imaging

- Earth shines by reflected light in visible and by thermal light in infrared.
- Required contrast:

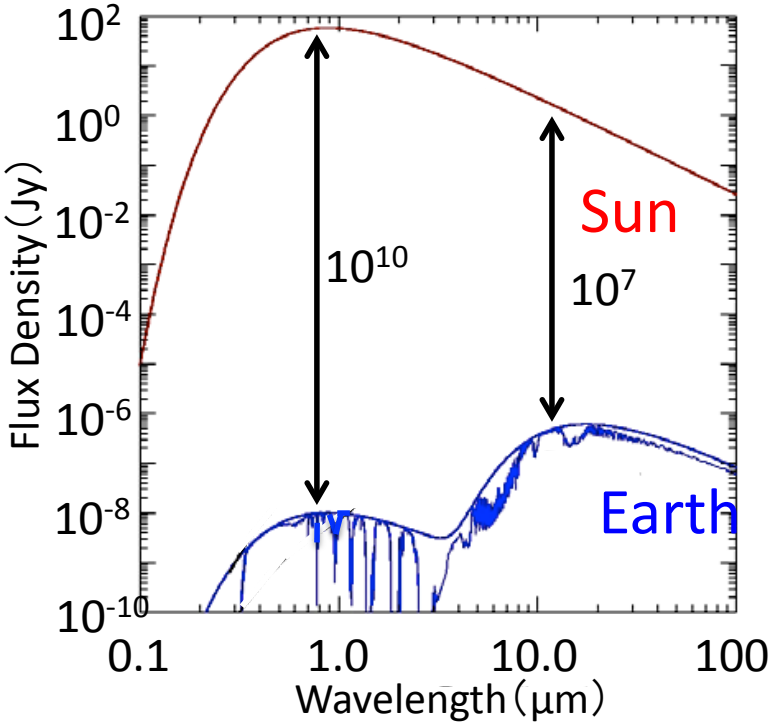
  : $10^{8\text{-}10}$ in visible

  10^{7} in infrared
- High spatial resolution for separation of star and planet lights

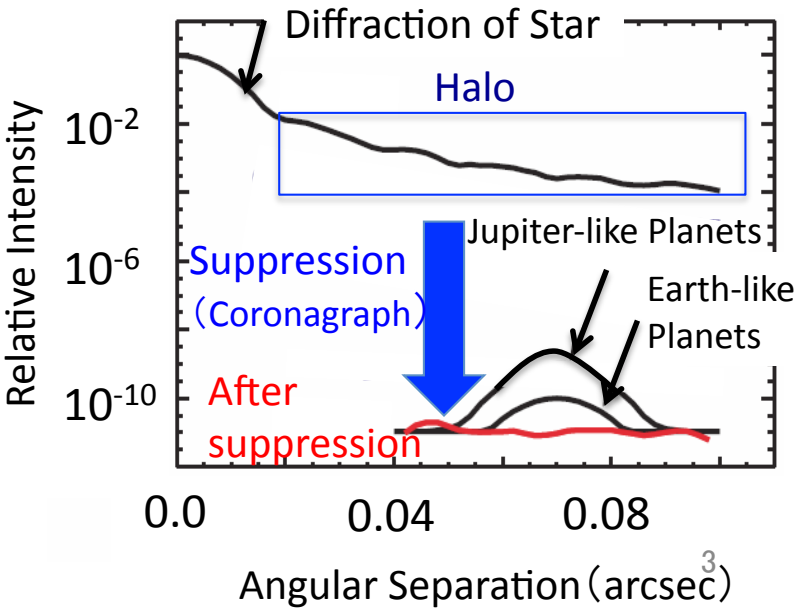
  : 0.1 arcsec

➔ 4m class telescope in visible

30m class interfereomter in infrared



Spectra of Sun and Earth from 10pc



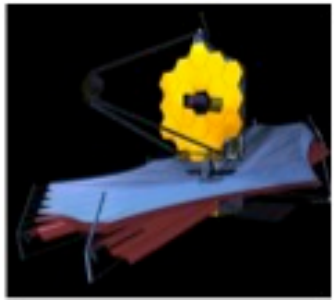
Future Direct Imaging Programs

Current 2018? 2023 ? (after 2025)

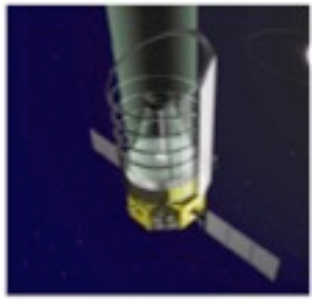
- SPACE

HST

1.



JWST



SPICA

3.

TPF

Cold giants around old nearby stars

- Ground

Now 2021

Search for biological activity

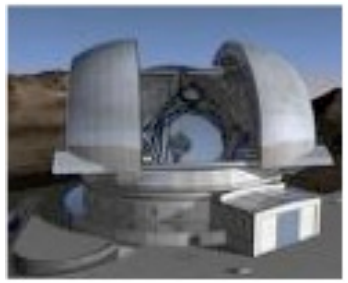
8m-telescopes
(Subaru/HiCIAO, Gemini/GPI etc)
Self-luminous giants around young stars

ExAO

(in near future)

2.

TMT



E-ELT
Extreme Large Telescopes

Visible Coronagraph and Infrared Interferometer

- Visible Coronagraph
  - Olivier Guyon
  - Keigo Enya
  - Naoshi Murakami
  - Takayuki Kotani

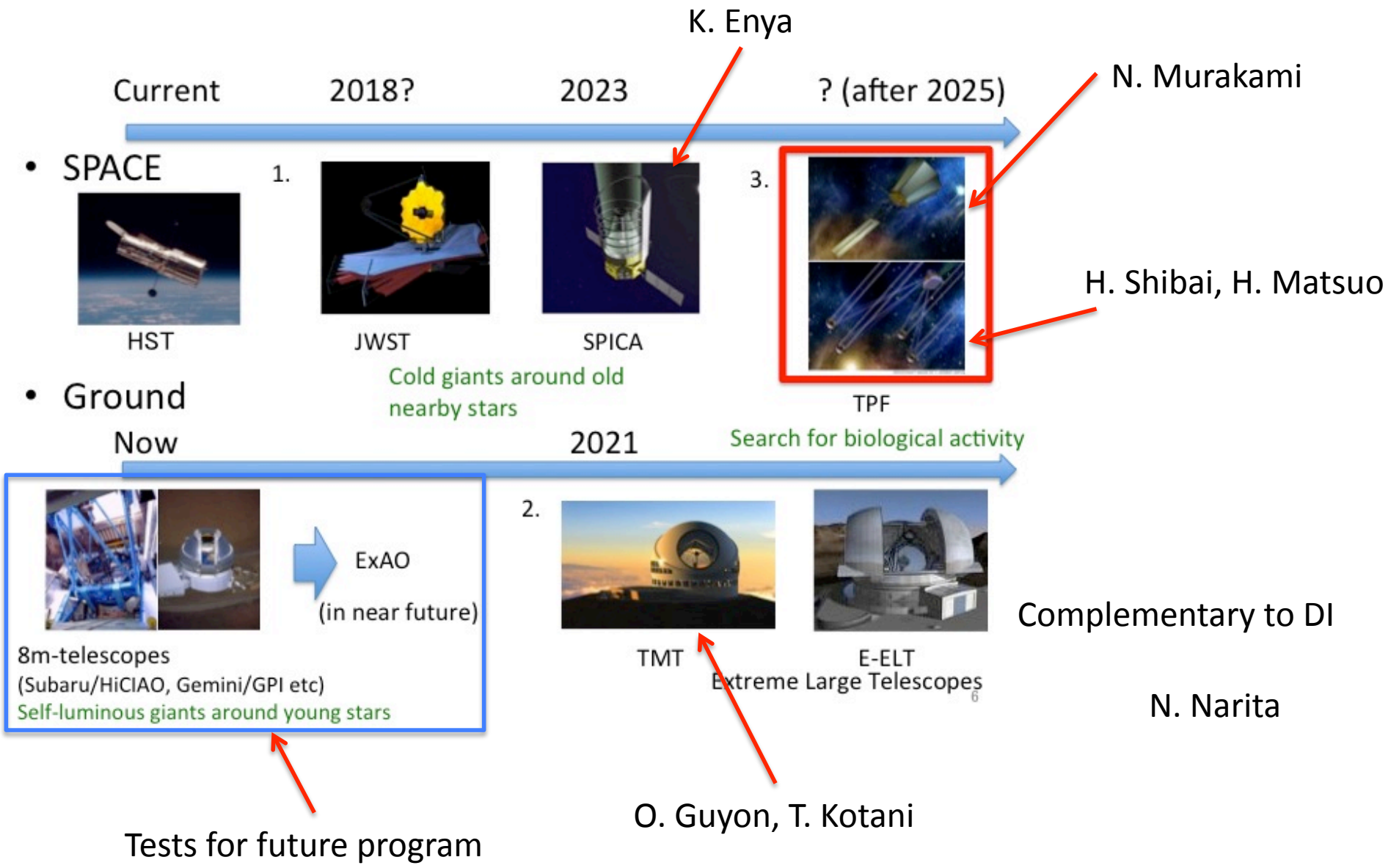
- Infrared Interferometer
  - Hiroshi Shibai（non-participant）
  - Hiroshi Matsuo (non-participant)

Complementary

- Transit
  - Norio Narita

- Manufacturing /Measurement
  - Mikio Kurita

Future Direct Imaging Programs



Visible Coronagraphs

Design for high contrast instruments

High Contrast Instrument

Wavefront sensing/correction・Coronagraph

Boundary condition:
（0. requirement）、①ground or space、②single or segmented telescope

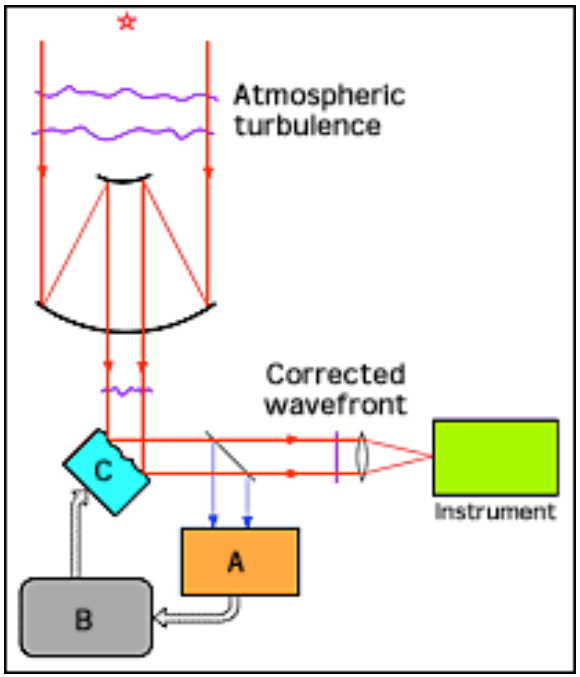
Optimization

Adaptive Optics for atmosphere

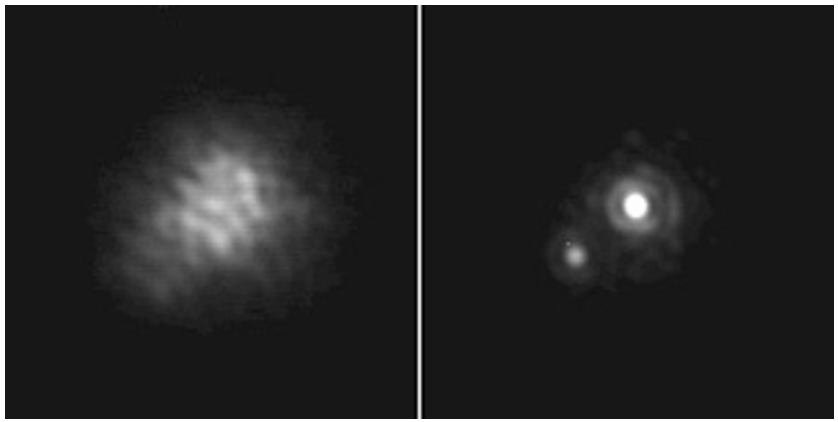
- Wavefront is corrugated by atmospheric turbulence.

➔ Coronagraph dose not work!

- AO corrects wavefront and produce diffracted light.



Conceptual diagram of AO



without AO with AO36

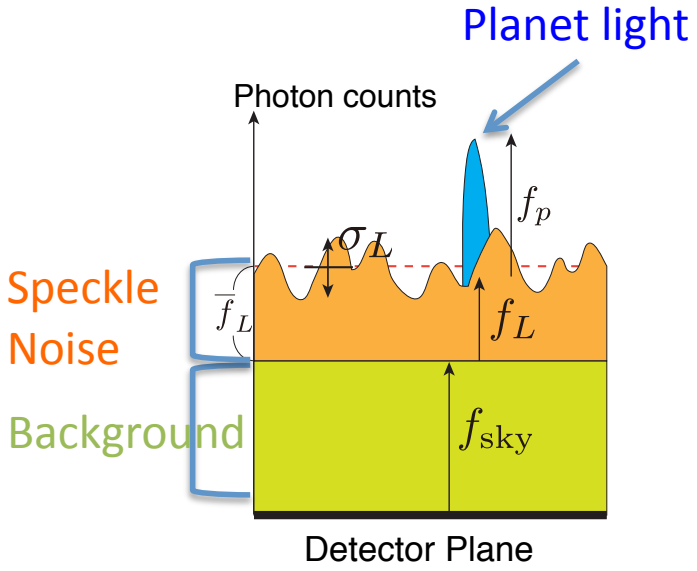
（AO36 First light press release）

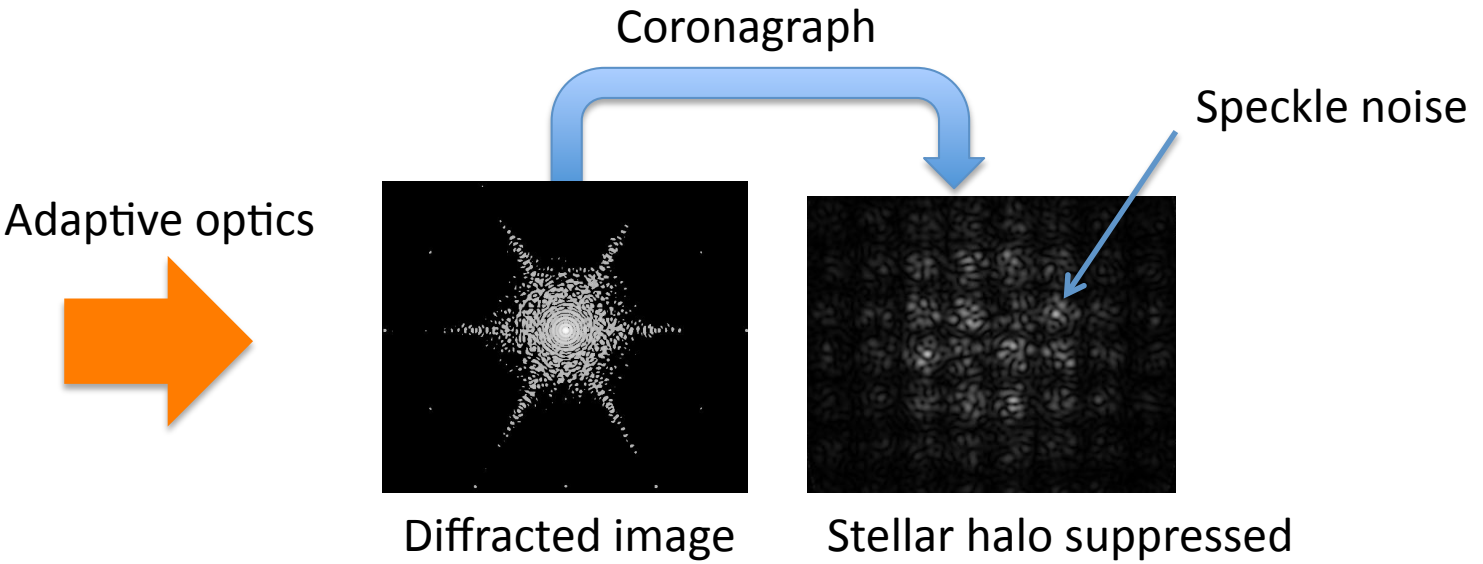
What's the limitation on the contrast?

- Coronagraph tackles only diffracted light.

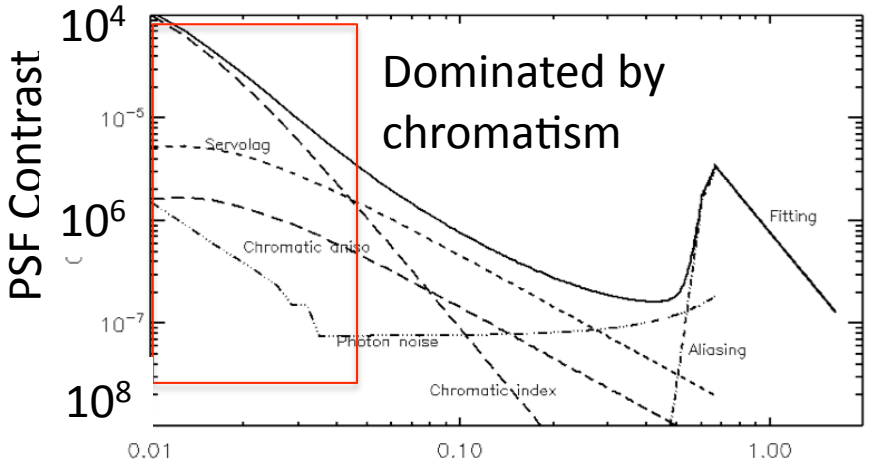
➔ "Speckle noise", background, and planet light are falling on the detector plane.

- Contrast is limited by speckle noise, which comes from incomplete optical system and chromatism. (Background is not contributed to planet detection.)

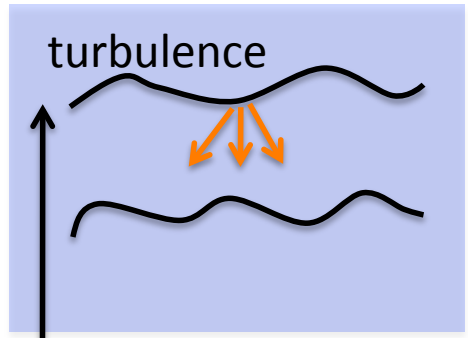




What's the limitation on the contrast?

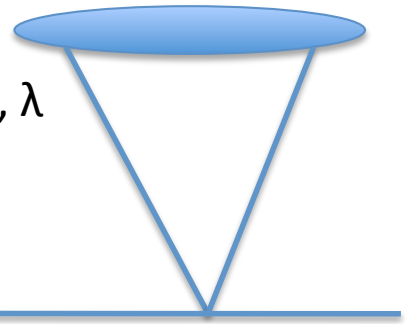


PSF raw contrast after ExAO (Kasper+ SPIE 2012)



Aperture plane

OPD∝ z, λ

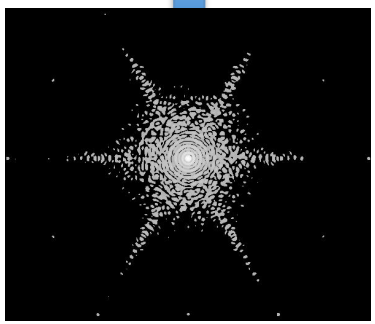


Detector plane

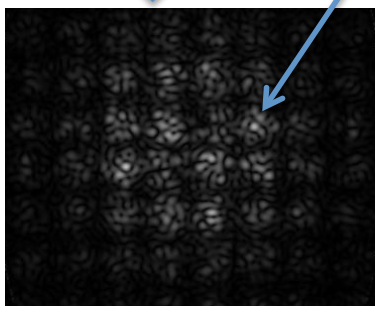
Coronagraph

Speckle noise

Adaptive optics



Diffracted image

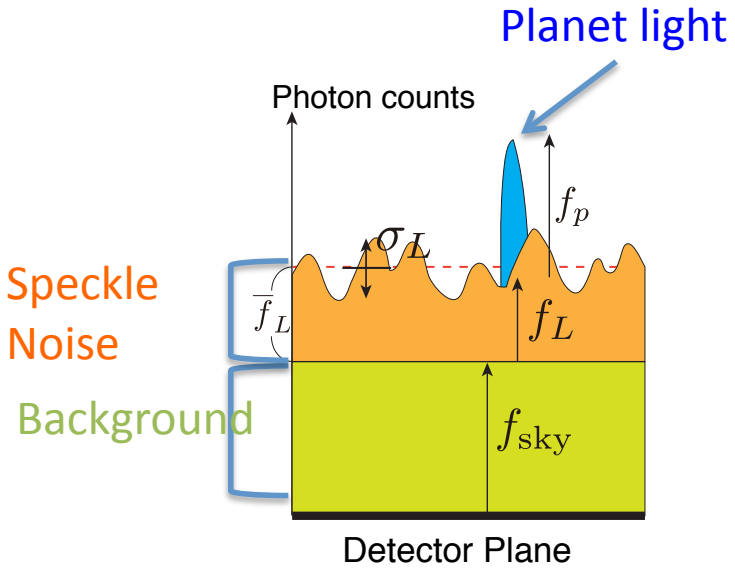


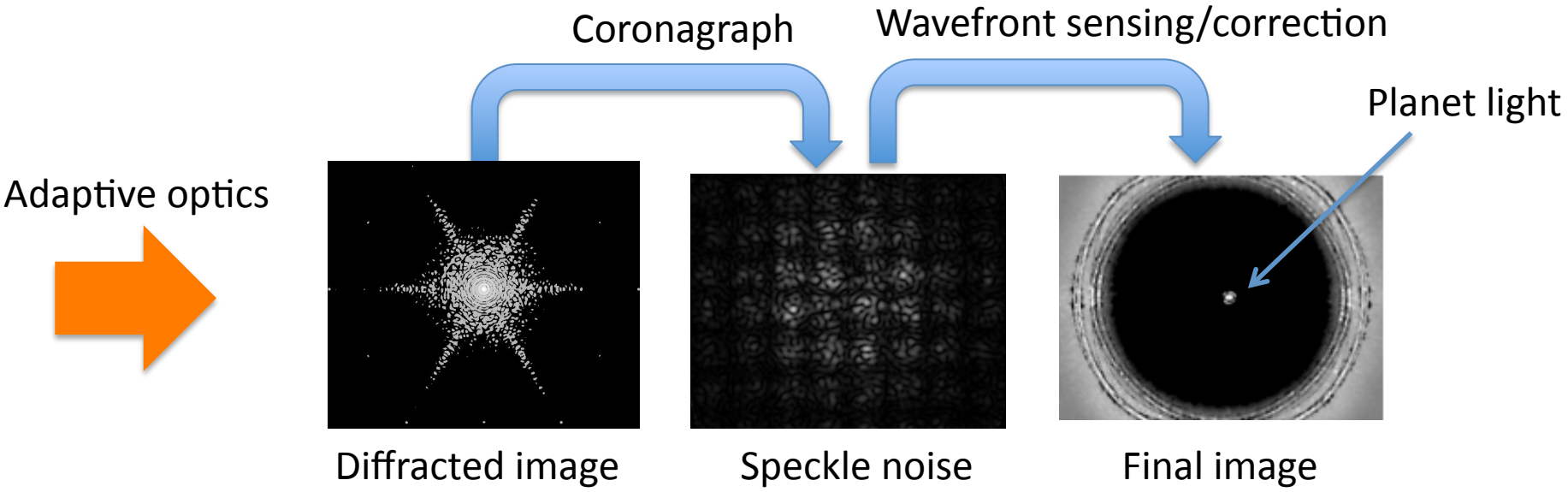
Speckle noise

What's the limitation on the contrast?

- Contrast is improved through suppression of speckle noise by wavefront correction/ sensing.

➔ Measurement accuracy of wavefront sensing/correction.

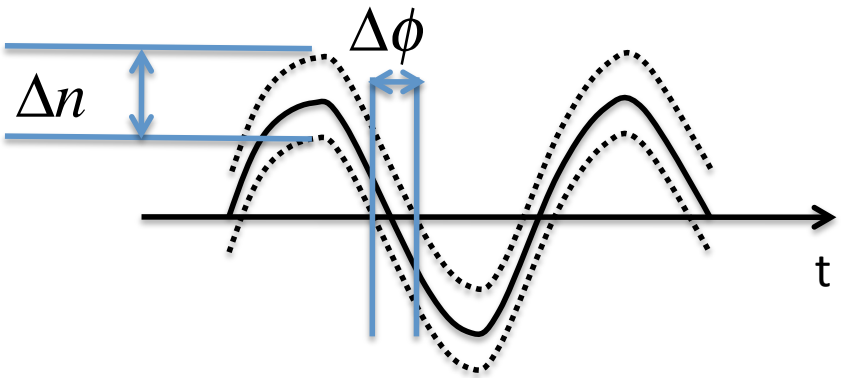


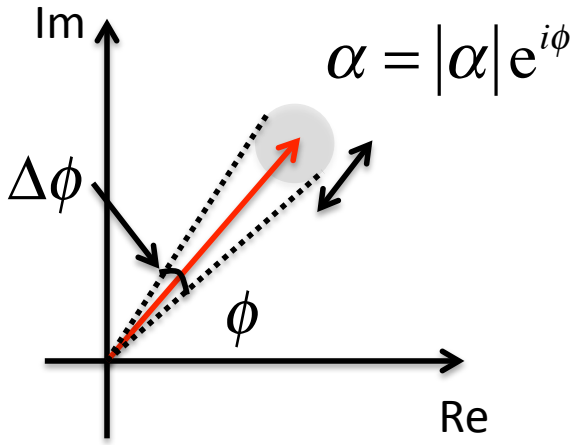


What's the limitation on the contrast?

- Wavefront measurement : to determine both "amp" and "phase"
- Accuracy is ultimately limited by uncertainty relation.

➔Photon noise limit





Phasor diagram of complex amplitude

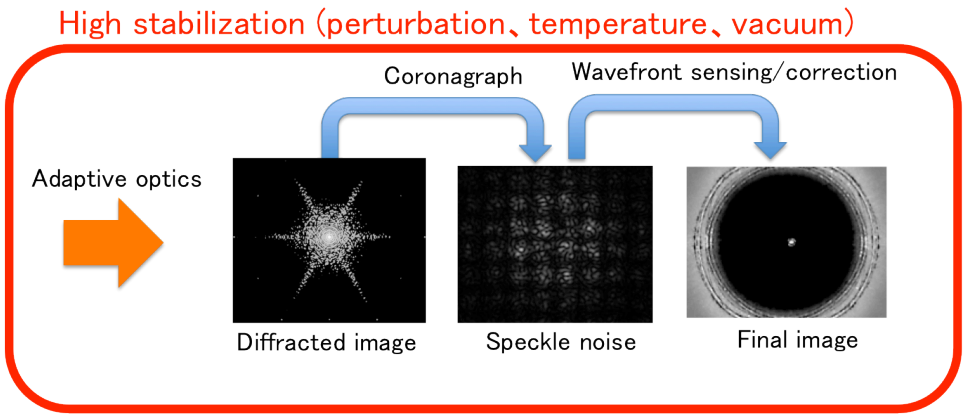
How much contrast we need?

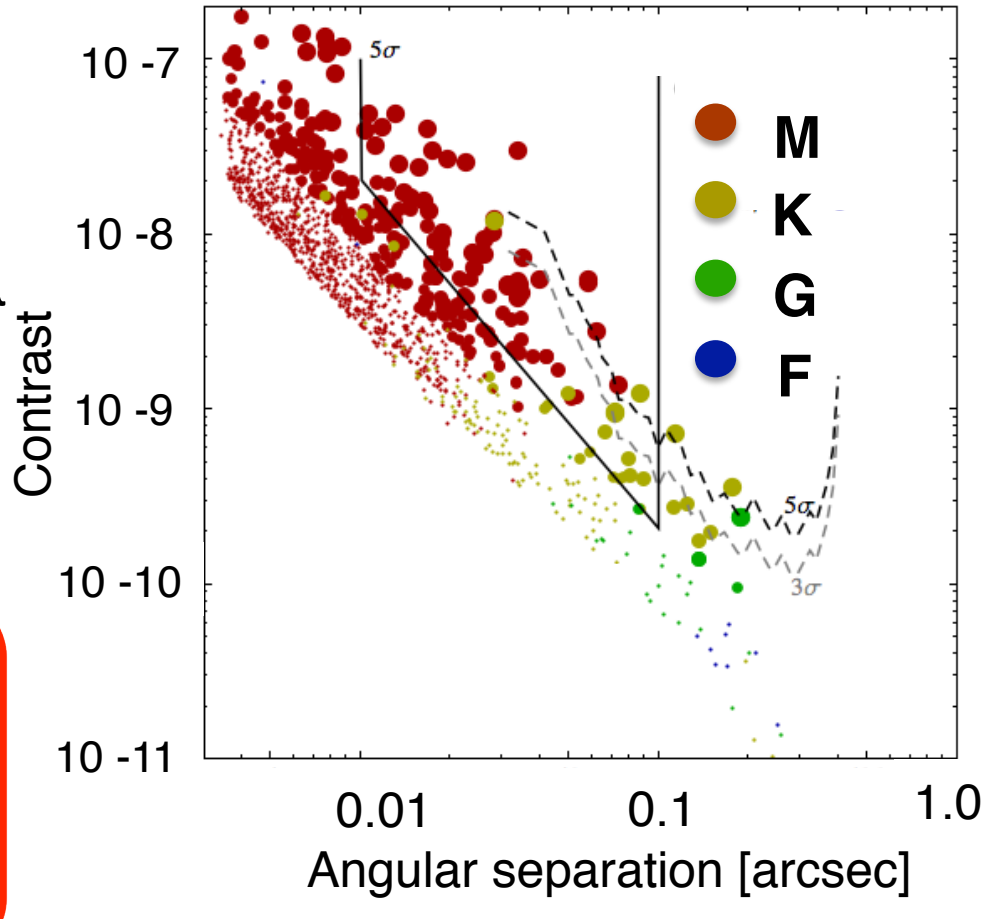
Assumption:
Habitable planets around nearby stars

- Requirement:
  - 3x10^8 at 0.01 arcsec
  - 3x10^10 at 0.1 arcsec

➔ Wavefront accuracy : 1/10000 λ

➔ if λ=1um, 10nm.

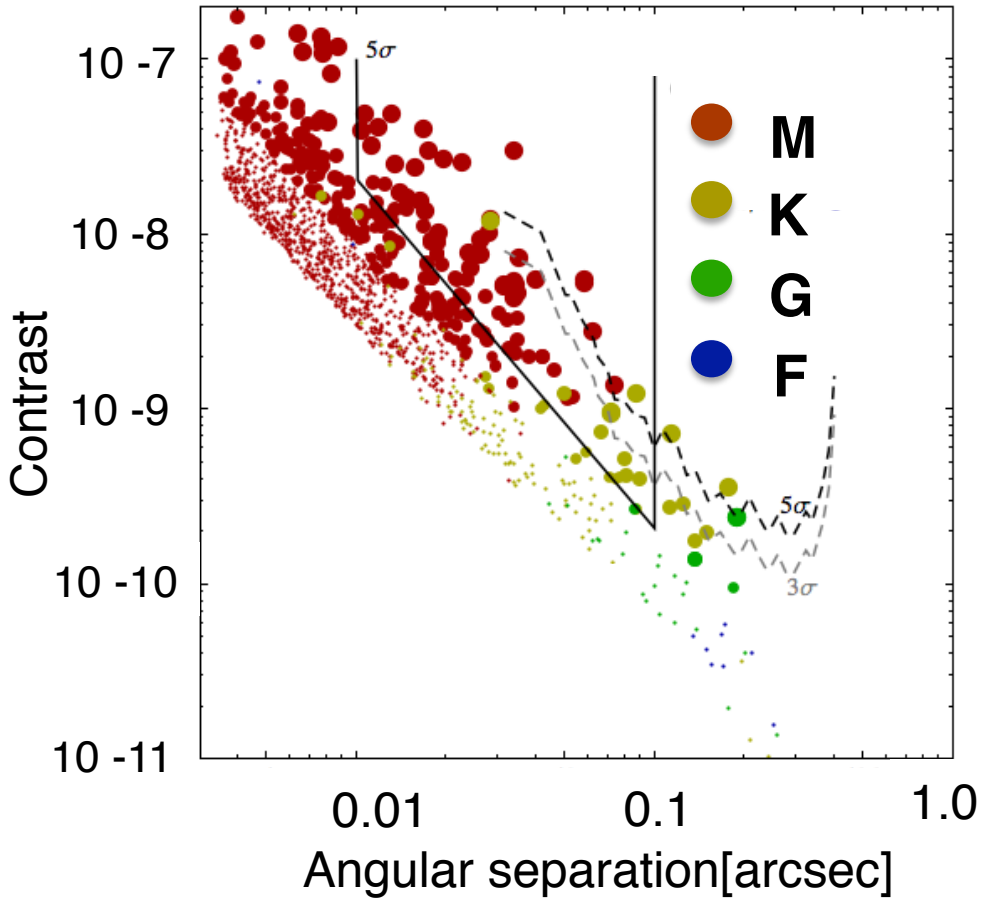




Kawahara+ (2012)

High performance instrument

1. High contrast at small angular separation
2. Effective for broad-band light
3. High throughput
4. Effective for any pupil geometry



Kawahara+ (2012)

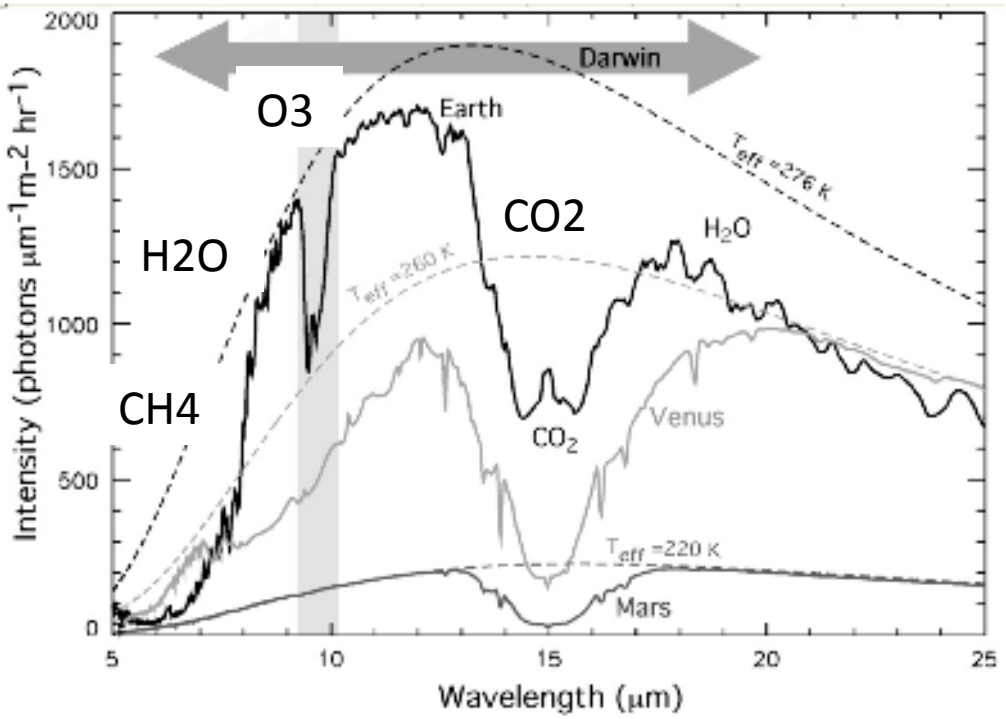
Several solutions proposed!
Please see Guyon, Enya, Murakami,
and Kotani-san’s talks.

Infrared Interferometer

Motivation

Various absorption lines formed by species such as H2O, CO2, O3, CH4, NH3, and N2O in the mid-infrared.

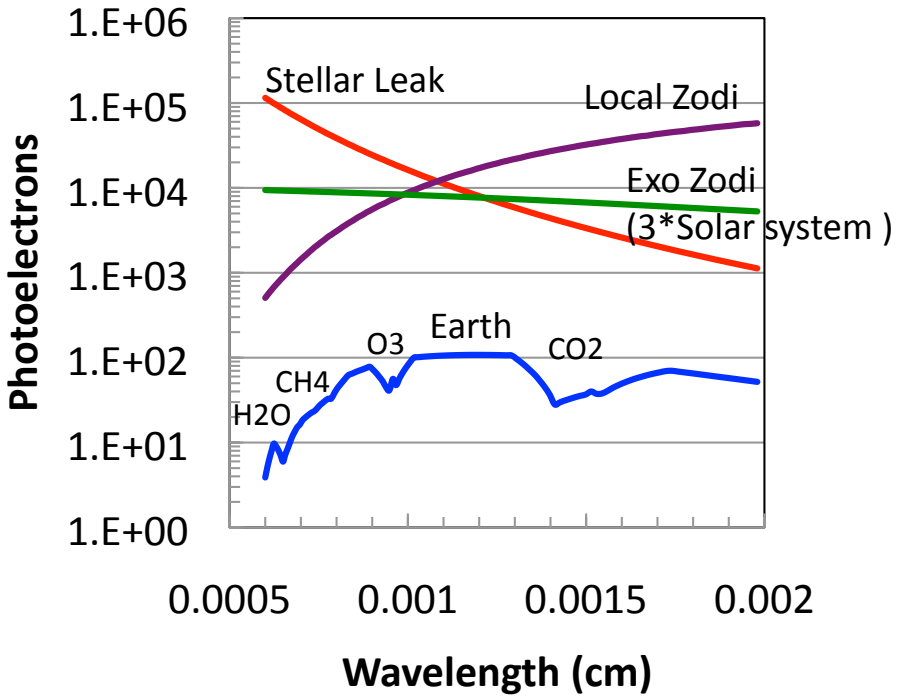
- Science goal: Search for indicators of biological activity.
- Difficult to explain presence of O3, CH4, NH3, and N2O in habitable planets without biological process
- Simultaneous detections of O3 (9.6μm), CH4(7.4μm), and NH3 (9-11μm) bands in a habitable planet indicate biological activity.



The mid-IR spectra of the Earth, Venus, and Mars (Cockell et al. 2009)

Very hard to detect an analog Earth

- A target system composed of host star, Exo Zodi, Local Zodi, an analog Earth.
- Star/planet ~ 10^(7) at 10μm.
- An analog Earth embedded in exo zodi and local zodi.
  (even if a star perfectly removed)



The signals of the photoelectron for a spectral resolution R=100 in one-hour integration time

Assuming that
- Distance: 10pc
- A Sun-like star with Ts=5784K and 1Lsun
- An Earth-diameter B.B. with Te=265K.
- LZ and EZ estimated based on Reach et al. 1995.
- Null depth: 10^{-5} at 10μm
- Dual Bracewell configuration with phase chopping and a spectrometer
- 4 * 2m collectors.
- Beam efficiency: 10%

These noises included in our simulation.
(These noise levels are approximately same to the previous studies.)

TPF-I/Darwin

P. R. Larson, C. Beichman, W.C. Danchi, et al.

- Configuration:

  - Dual Bracewell configuration, composed of two single nulling interferometers.

  - Phase chopping and a spectrometer with R=3 (detection) and R=20 (spectroscopy)

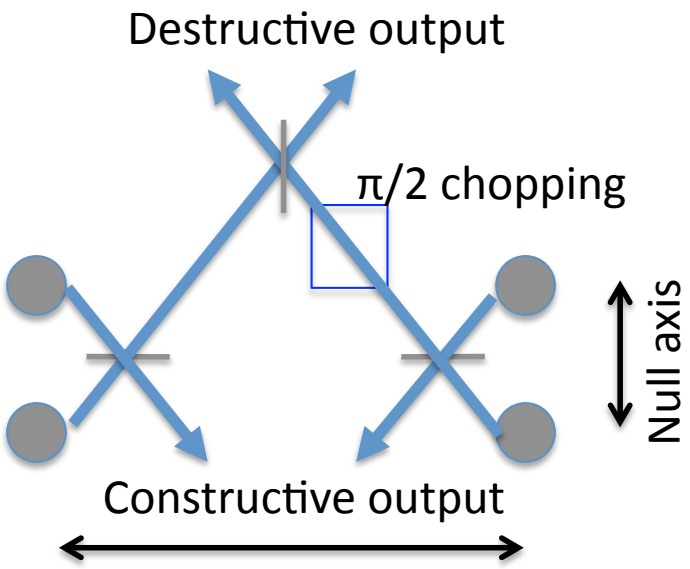
- Imaging method:

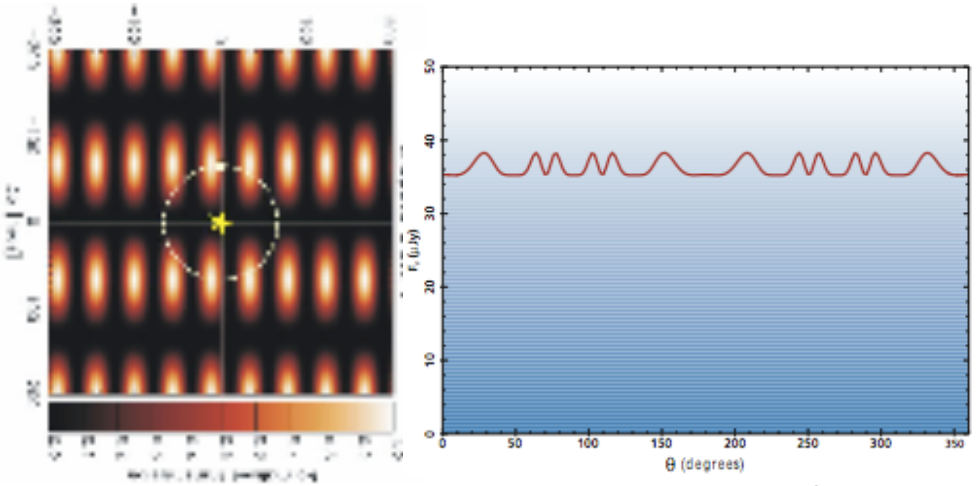
  - Maximum correlation method with rotation of the arrays

→ A modulated signal by a planet as it moves in and out of the interferometer fringe pattern.

- Problem:

  - incompleteness of Co-phasing during rotation of the array





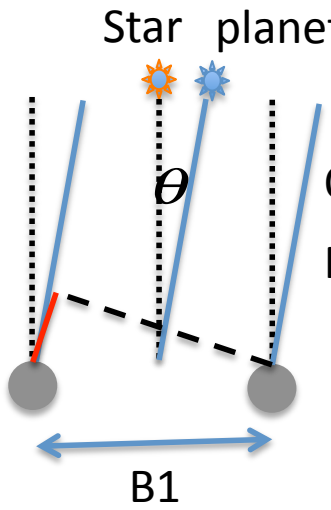
Transmission pattern (destructive output)
Cockell et al. 2009

TPF signals as a function of rotation angle
Beichman & Velusamy 1995

New method for direct detection of exoplanets

Matsuo et al. 2011

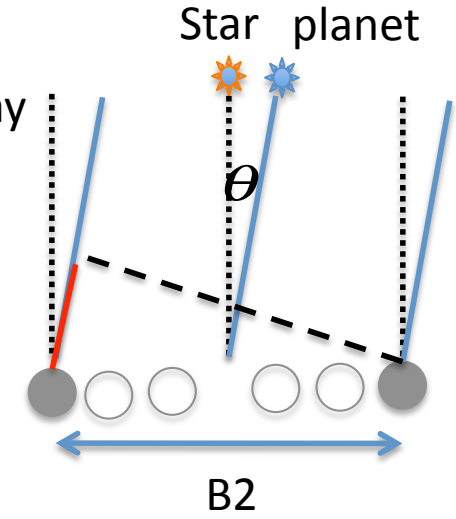
Previous method



OPD: B1θ

Phase: B1θ/λ

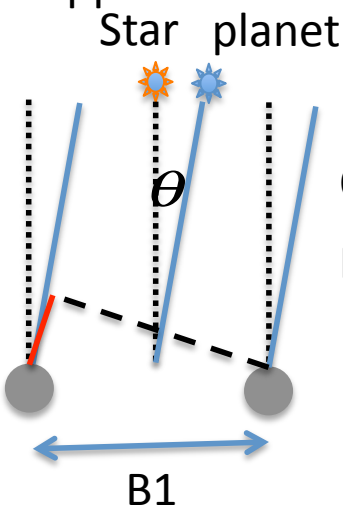
Changing OPD contiguously through rotation of the array



OPD: B2θ
B3θ
…
Bnθ

Phase: B2θ/λ
B3θ/λ
…
Bnθ/λ

New approach

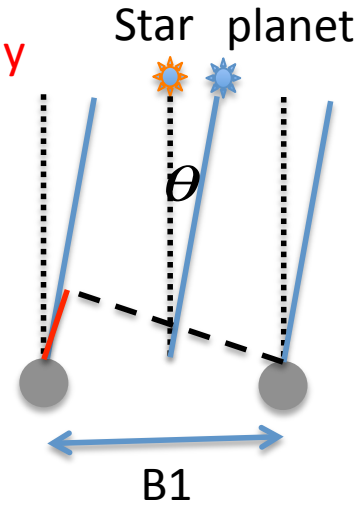


OPD: B1θ

Phase: B1θ/λ

recording λ contiguously instead of OPD

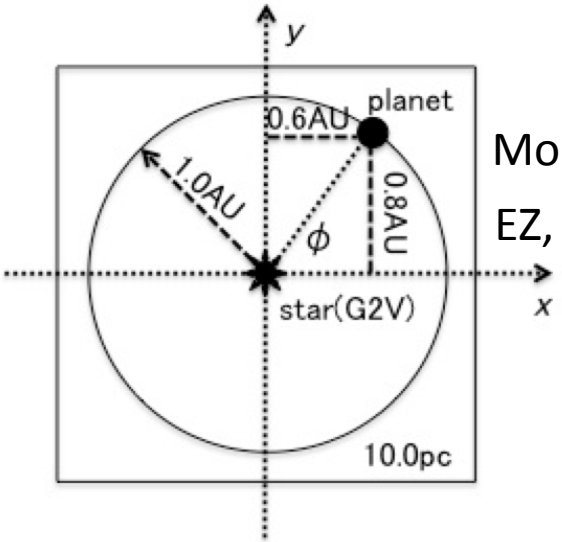
Contiguous observing wavelength in space



OPD: B1θ

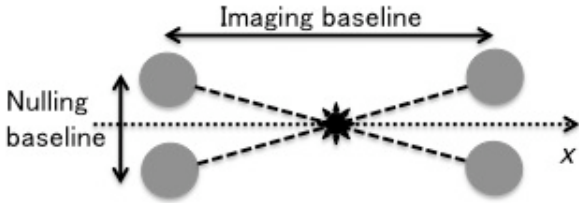
Phase: B1θ/λ1
B1θ/λ2
…
B1θ/λn

Image of a planetary system

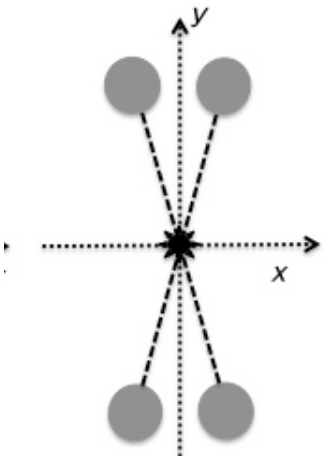


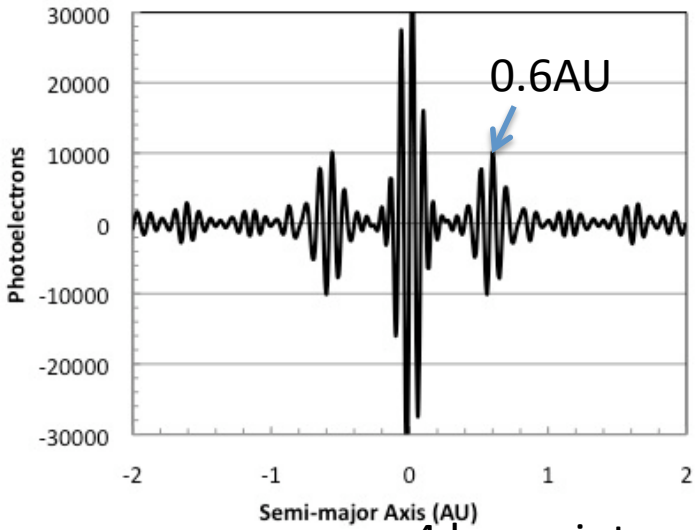
Model of a target system

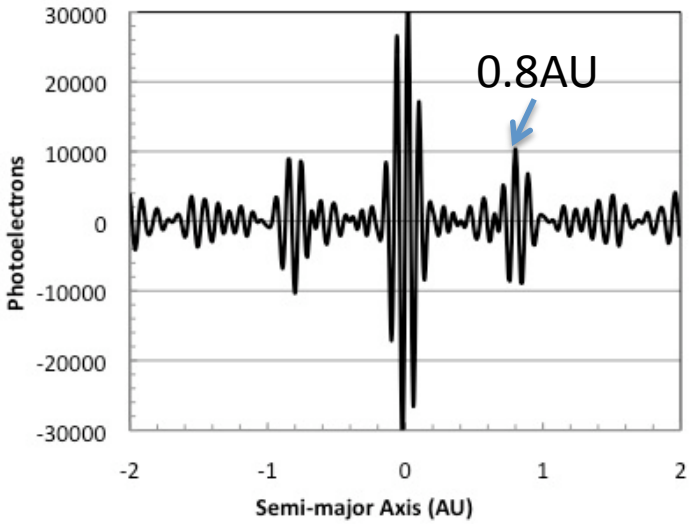
EZ, LZ included.



Rotation of the array by 90degrees





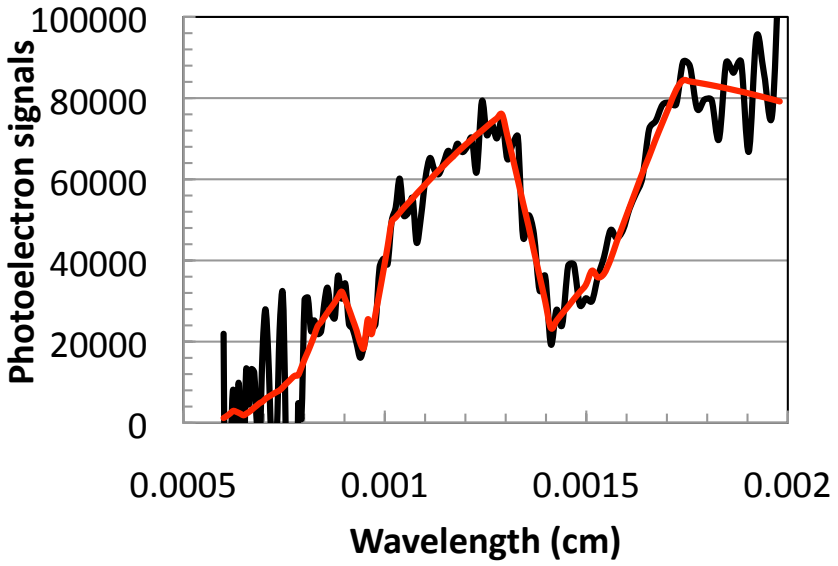


4 hours integration for each baseline

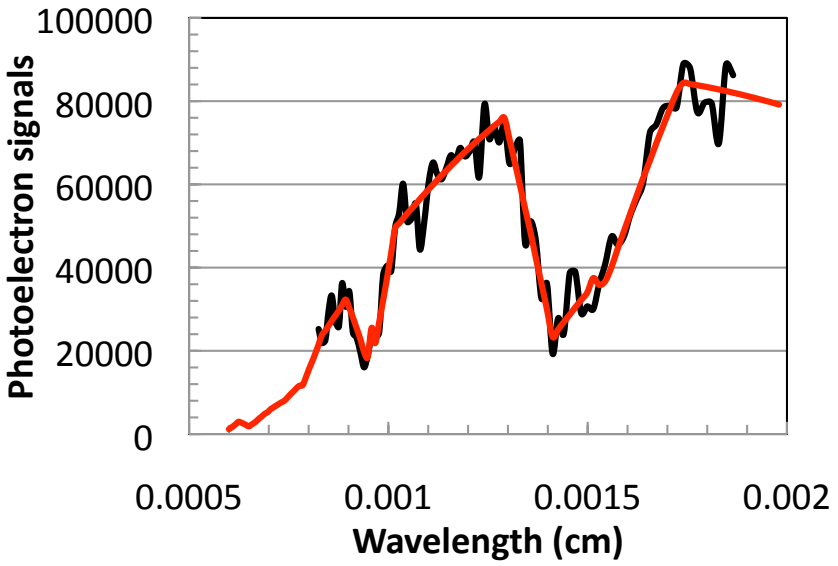
Spectrum of an analog Earth

- The spectrum of the analog Earth successfully obtained
- 35 days required for spectrum of an analog Earth with R=100 around a Sun-like star (G2V) at 10pc.

  (45 days required with R=20 in previous study)



Reconstructed spectrum of the analog Earth

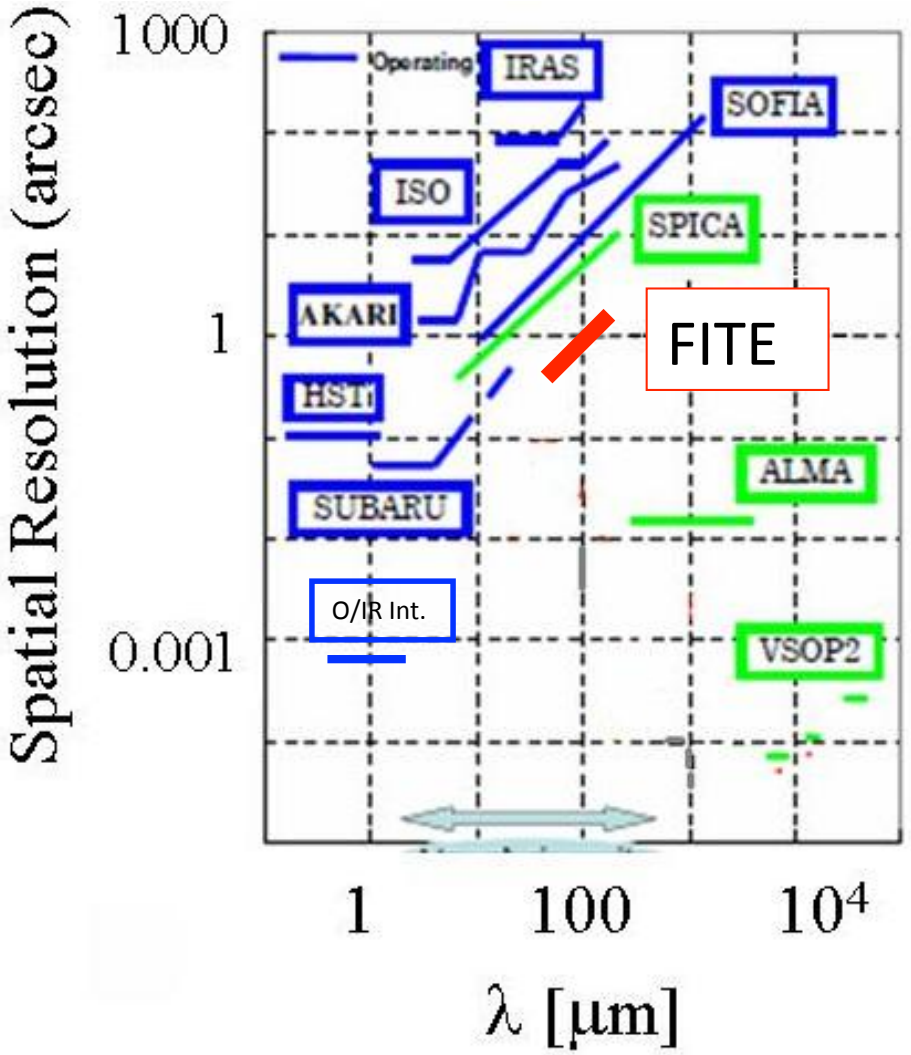


Reconstructed spectrum of the analog Earth with SNR > 5

Far-infrared Interferometer Telescope Experiment (FITE)

- Precursor to space infrared interferometer
- First flying interferometer

Motivation



（Present condition）

Compared to other wavelengths, the spatial resolution is insufficient in the FIR.

Because

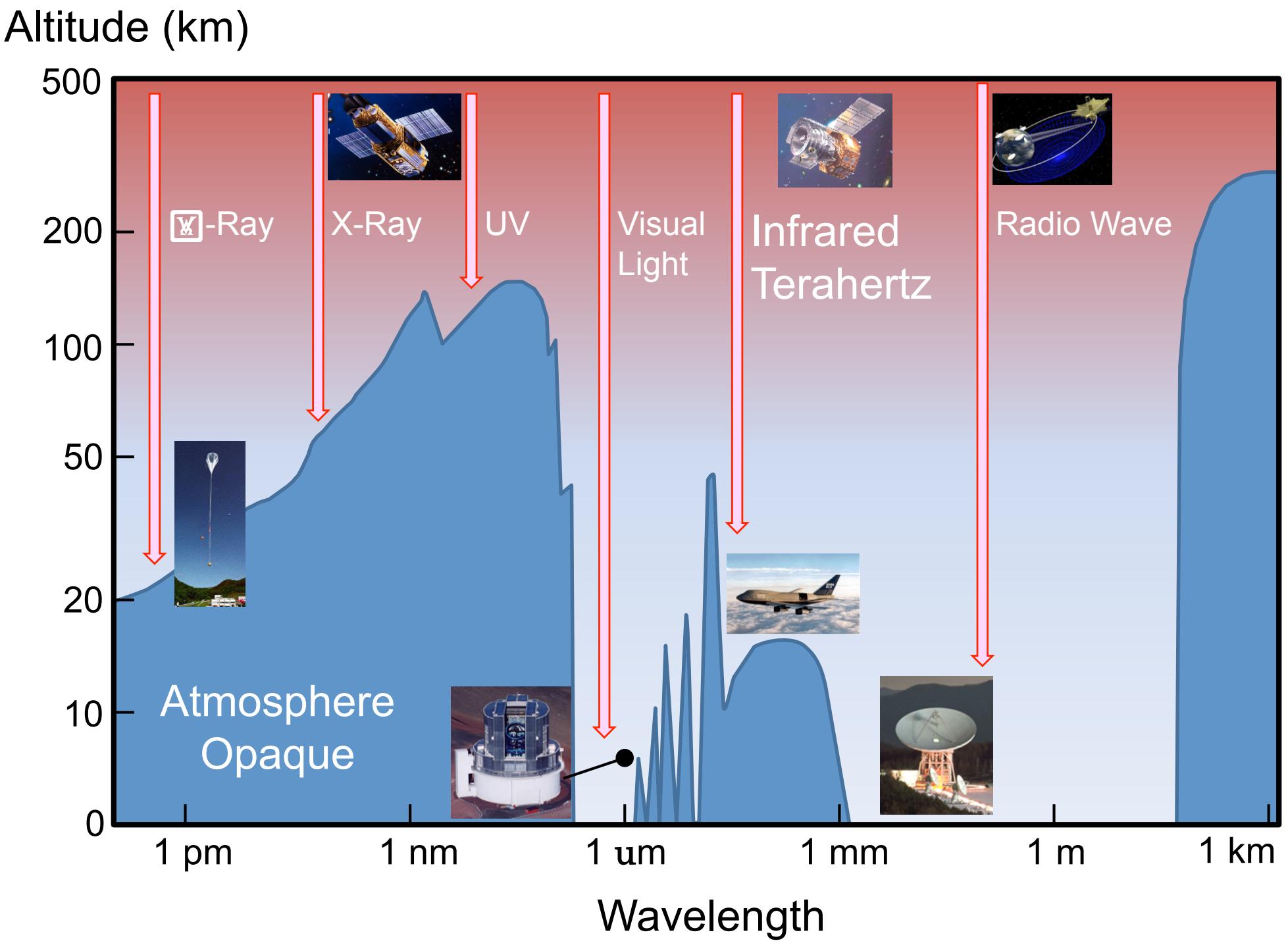
- atmospheric transmissivity
  → satellite, rocket, or balloon
- diffraction limit
  → large aperture telescopes

We developed FITE as the first attempt of an astronomical interferometer in FIR

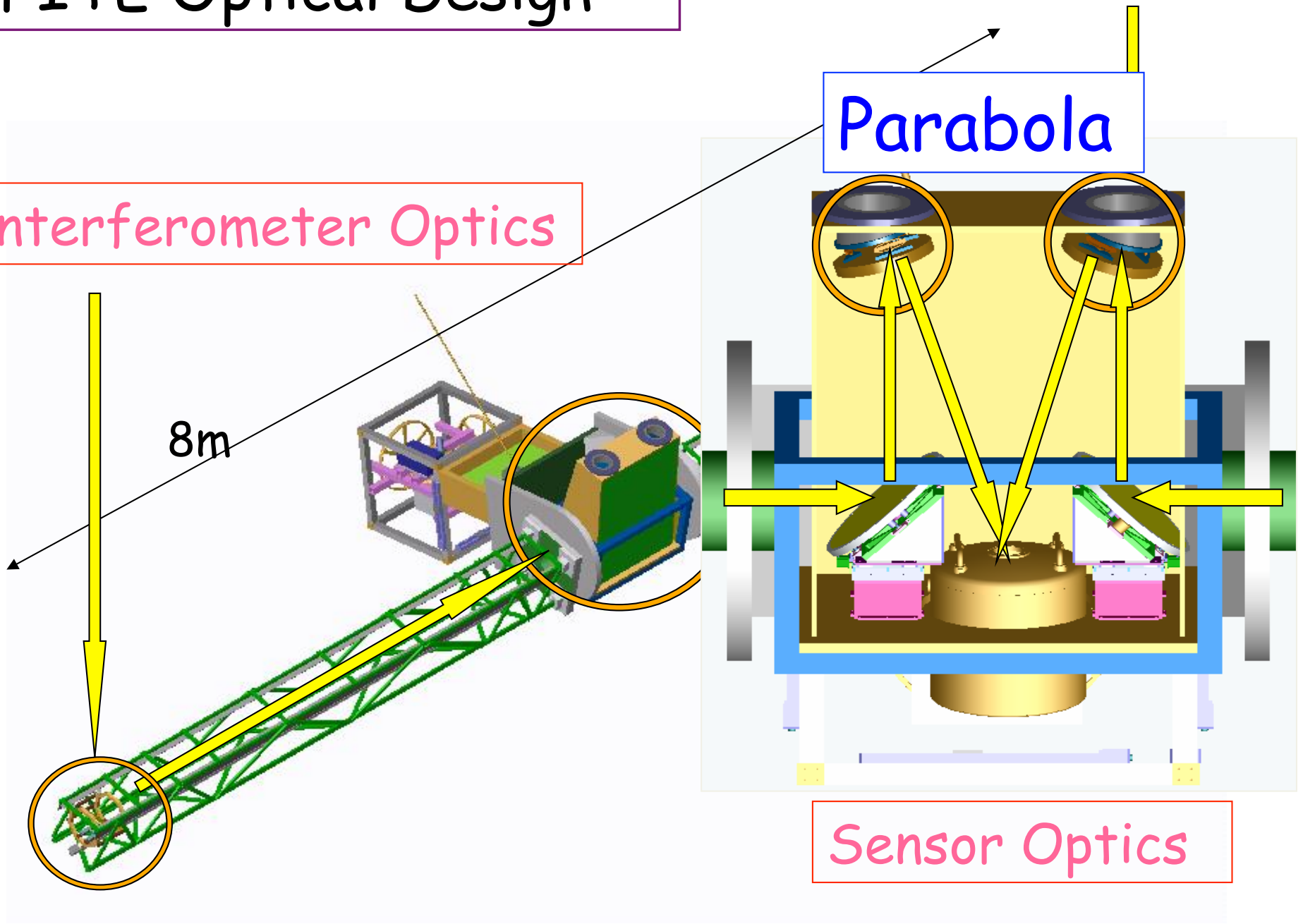
- Maximum Base line is 20 m

Purpose :

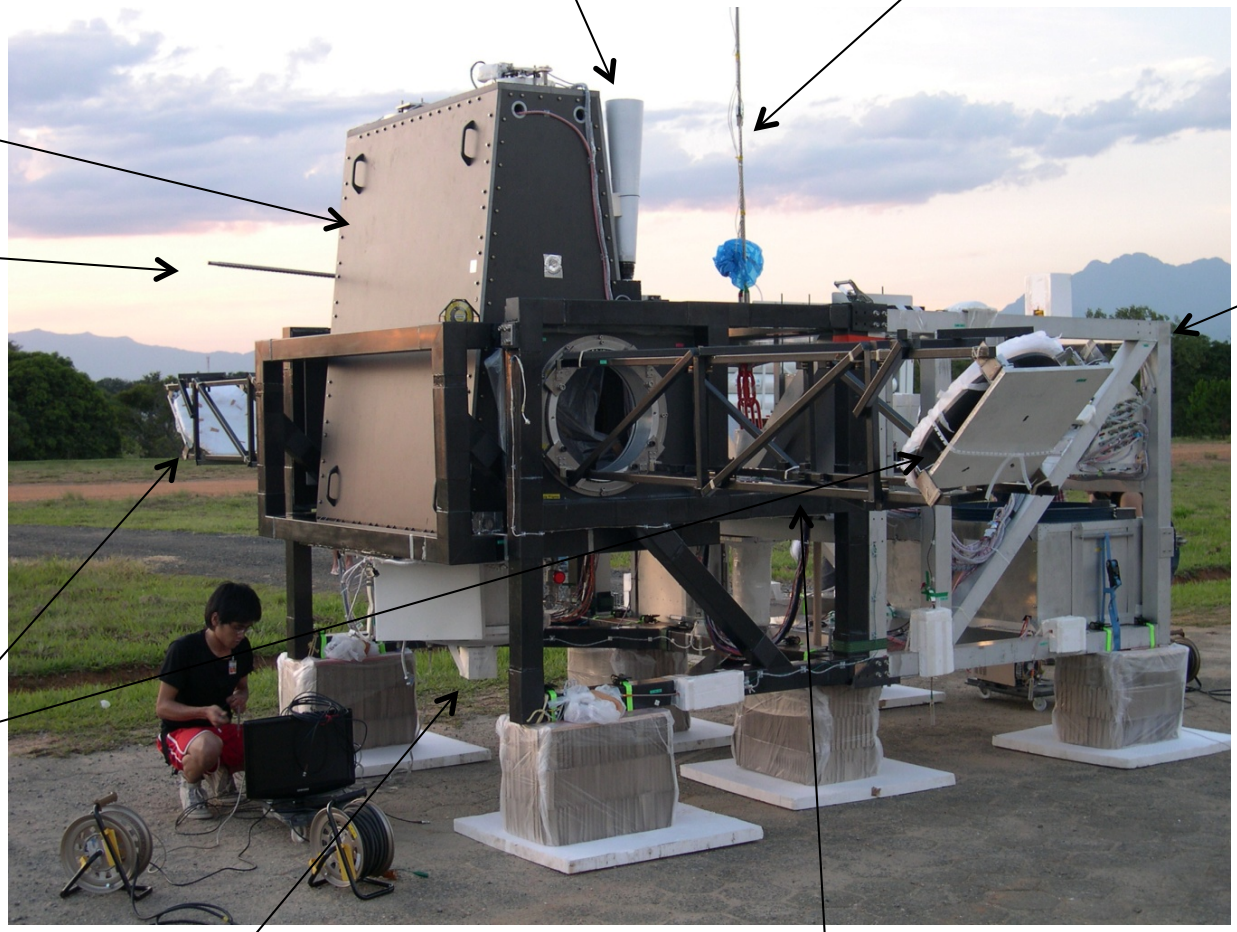
A spatial resolution of 1 arcsecond at a wavelength of 100 ㎜ with the maximum baseline of 20 m.


Altitude (km)
500
200
100
50
20
10
0
γ-Ray
X-Ray
UV
Visual Light
Infrared Terahertz
Radio Wave
Atmosphere Opaque
1 pm
1 nm
1 um
1 mm
1 m
1 km
Wavelength

FITE Optical Design

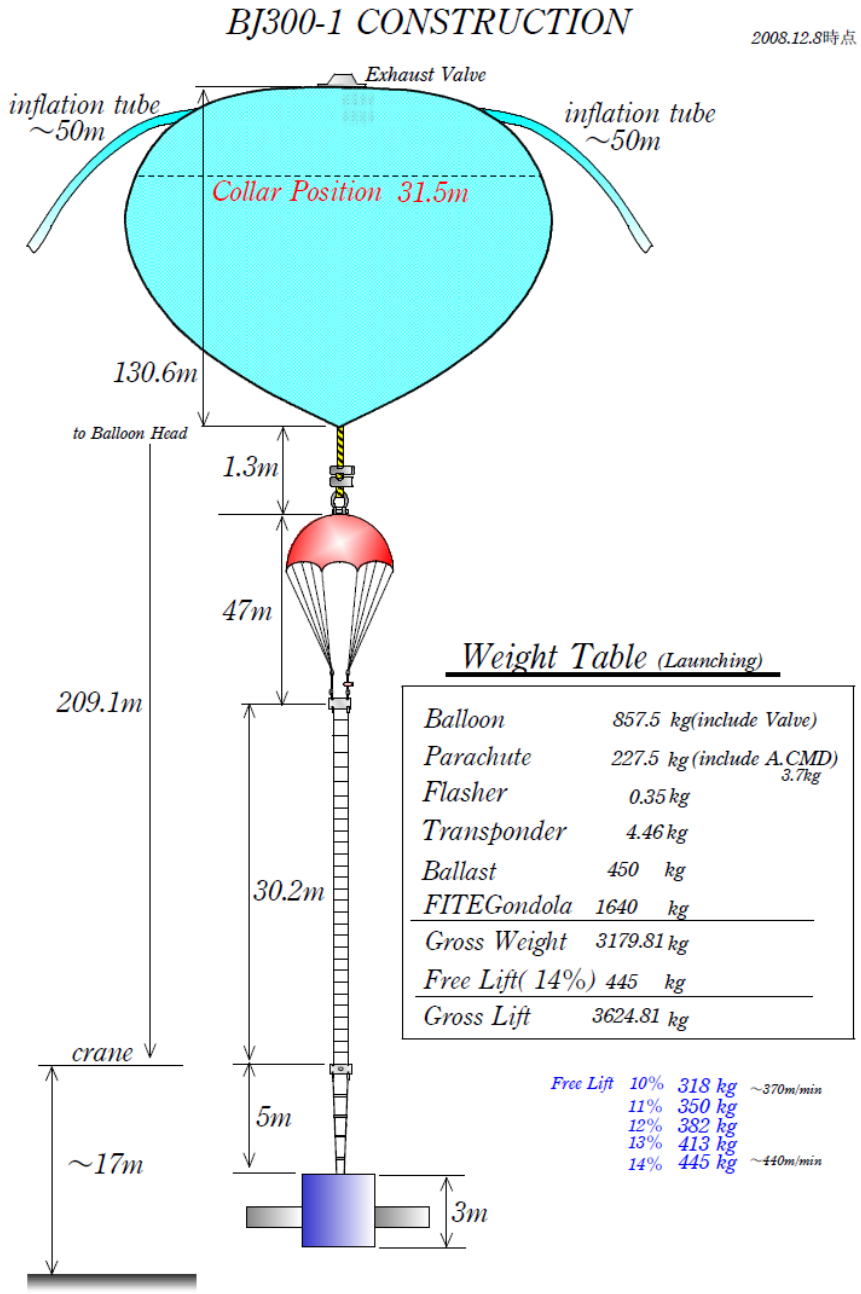


Telescope Side



Control Gondola

First Trial - December in 2008 in Brazil



Collaboration with Brazilian Institute for Space Science (INPE)

Our future plan toward TMT

Background:
Japanese AO for high contrast imaging are 5 years behind Europe and America …

➔ We need to catch up with them until TMT.

New 4m-class Telescope

See Kurita-san's talk

- 4m-class telescope is building in Japan
- Segmented telescope

➔ One of the precursors to TMT

- Lots of telescope time opens our original science.

➔ ？% of the telescope time is assigned to high contrast tests and observations.

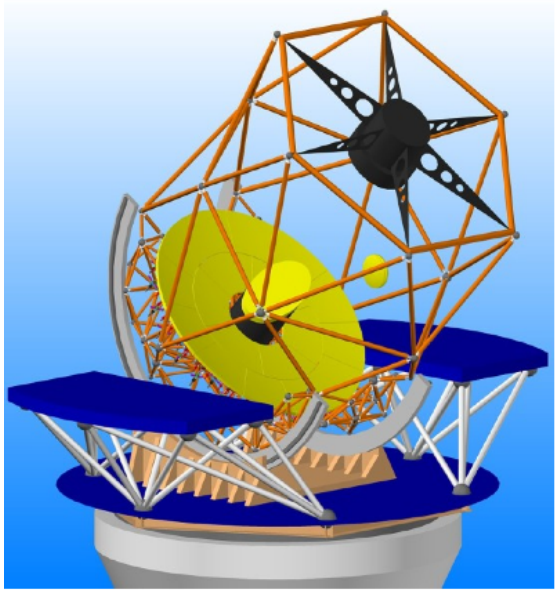


Image of 4m-class telescope

Is site suitable for AO?

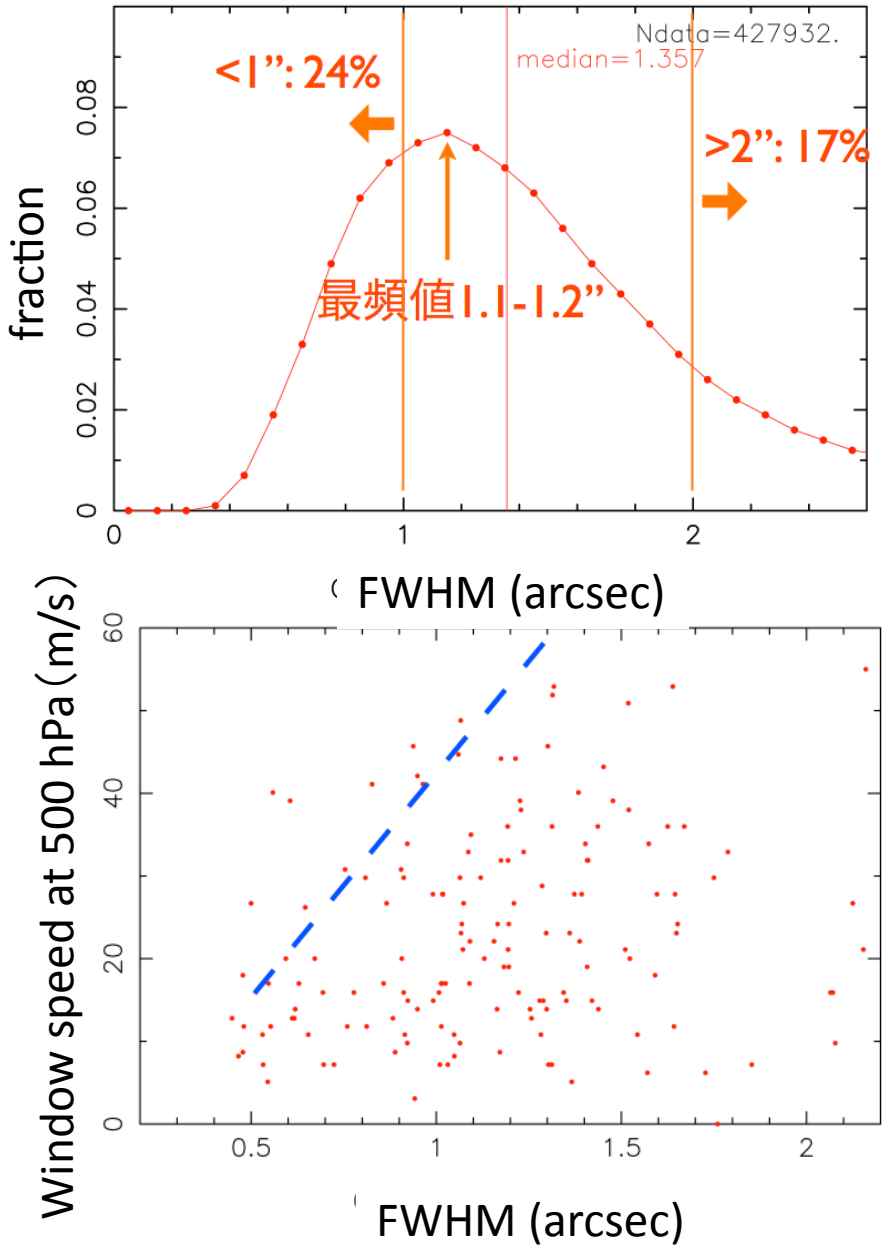
- Seeing ~ 1.1 arcsec (norm)

➔ D/r_0 of Subaru and Kyoto are almost same.

- Window speed is ~ 30m/s

➔ Frame rate of correction is ~ 1kHz

The site is suitable for AO



岩田生（2005年光天連シンポ）

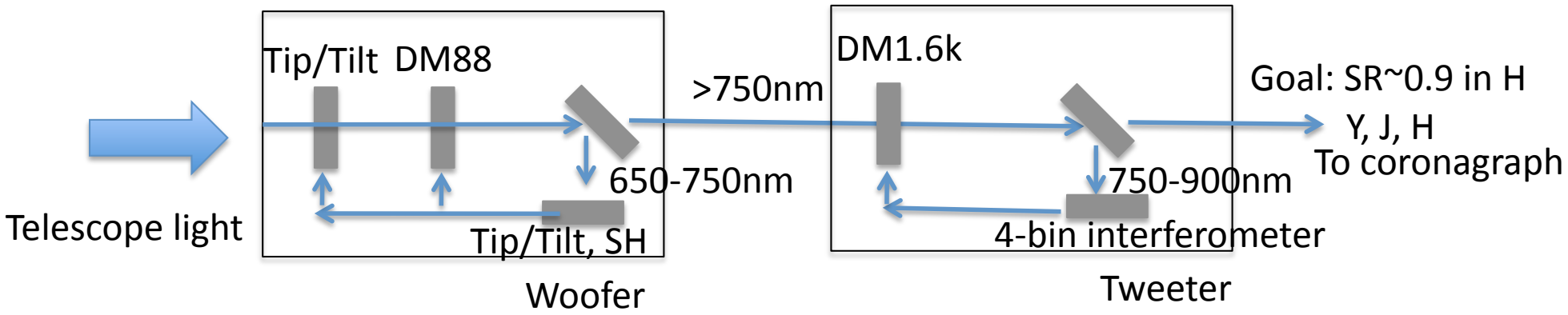
Adaptive optics for kyoto telescope

- Starting from April 2012
- Purpose:

- To characterize planets, which will be discovered by GAIA etc.
- To test for future high contrast programs
- To educate young people for future direct imaging programs

- System:

- Sensor: Tip/Tilt (PSD) + SH +（upgraded）4bin-interferometer
- Correction: Fast Steering (~1kHz)+DM88 (~500Hz)+DM1.6k (~1.5kHz)



Current Testbed