Subaru SCExAO/CHARIS/IRD:

Synergy on exoplanet sciences

December 18　14:45 - 15:10

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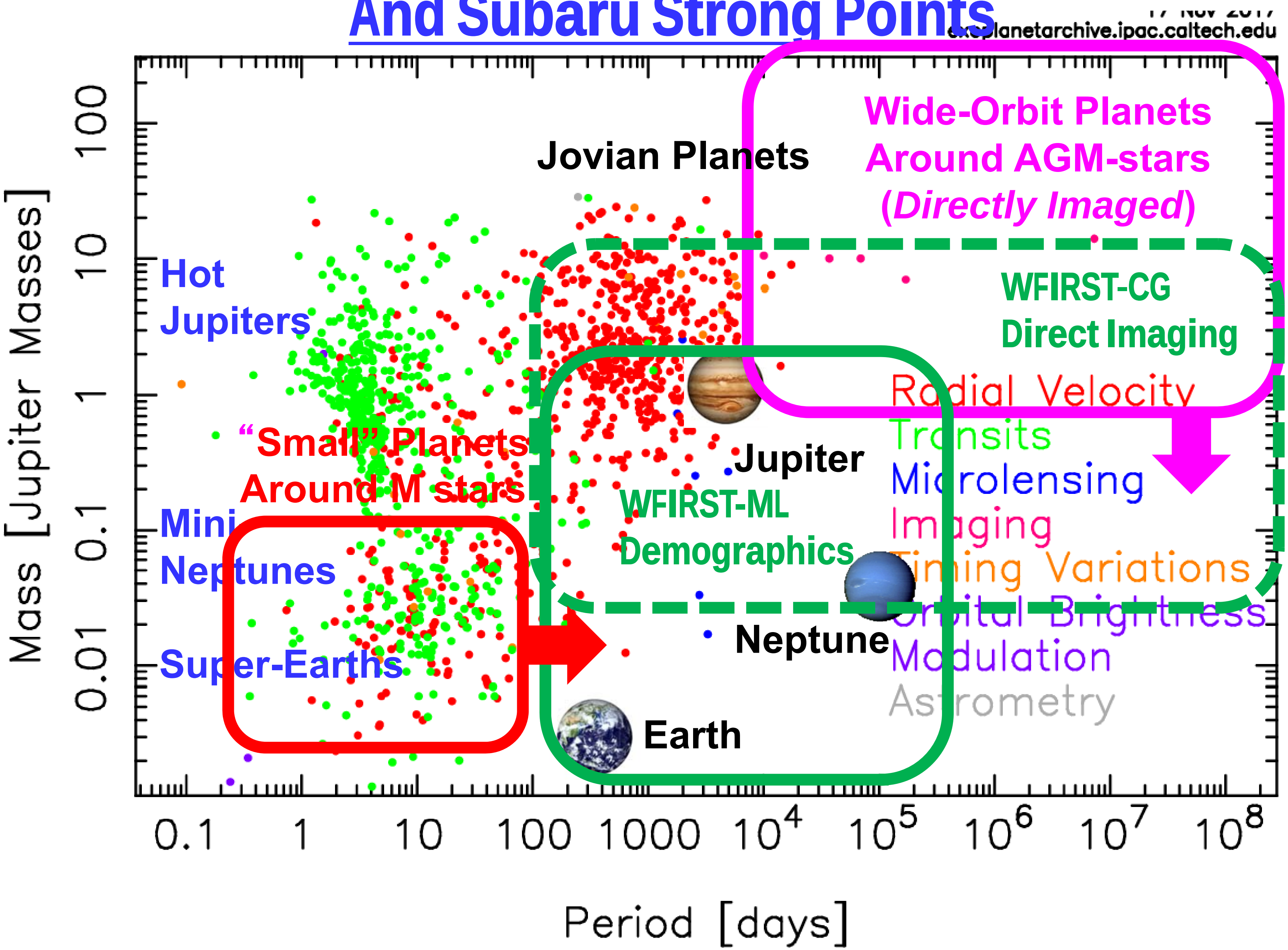
Talk Outline

- Subaru/SEEDS project with HiCIAO
  - as an example of large international project on exoplanet/disk
- Current Subaru Exoplanet Instruments
  - SCExAO
  - CHARIS
  - IRD
- WFIRST/Subaru Synergy
  - community proposal examples)
- Future plans and Summary

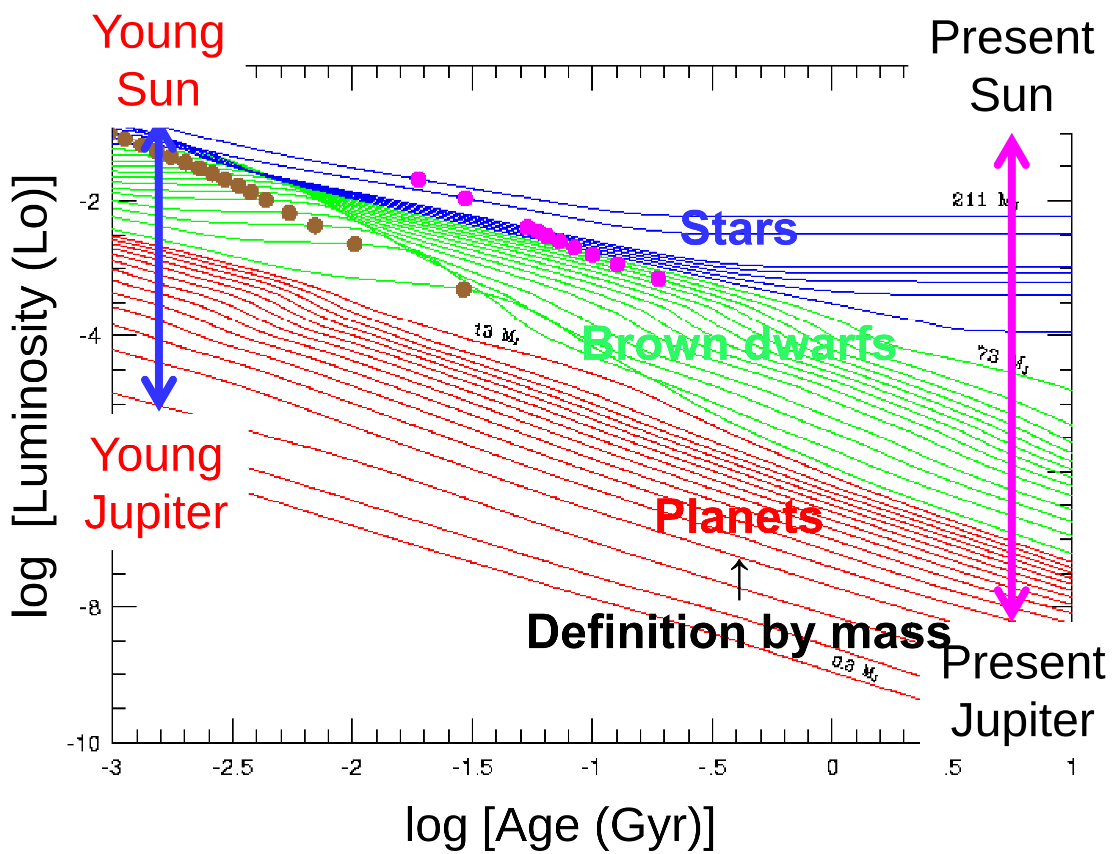
Various Planets detected by Various Techniques And Subaru Strong Points



Challenges with Direct Imaging

- **Huge contrast ratio between planet and star**
  - ~10^9 for Earth-Sun
  - ~10^8 for Jupiter-Sun
  - ~10^6 for young Jupiter-Sun

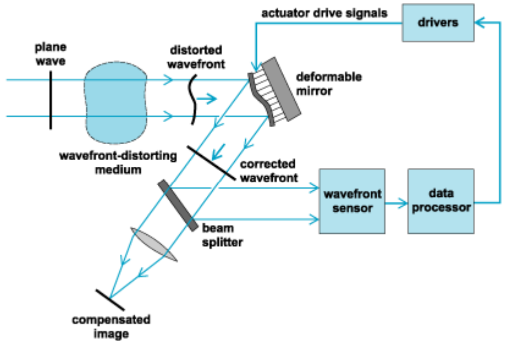
Self-luminous giant planets are main targets for direct imaging (at present)

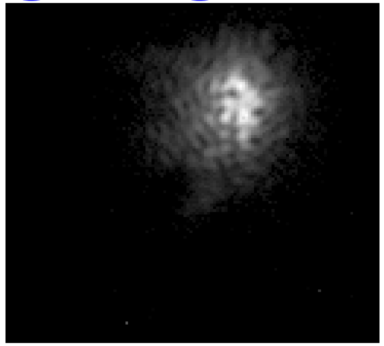


How to suppress bright stellar light?

Techniques for Direct Imaging

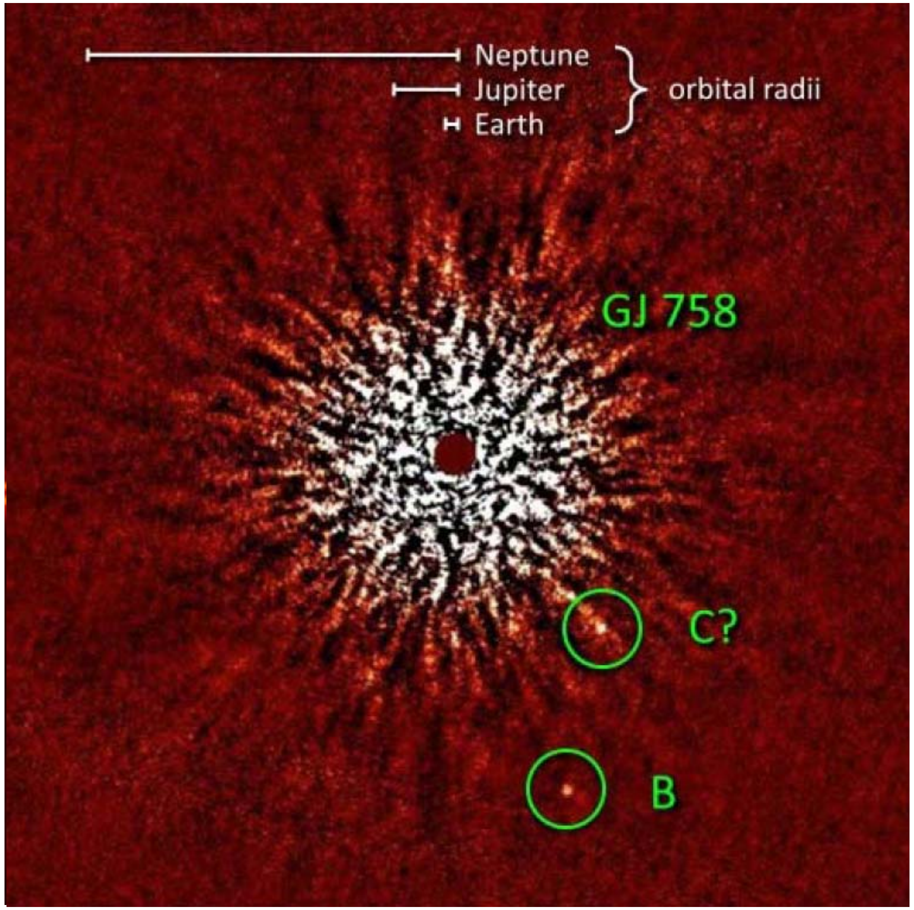
- **Adaptive optics on 8-m class telescopes** is a must
  - ~200 actuators to
  - ~2000 actuators (Extreme AO)
- **Speckle noise from bright central star**
  - Not photon-noise but speckle-noise limited observations





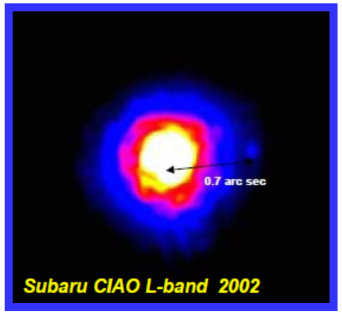
How to remove static speckles?

- **Coronagraph**
  - Ex. Subaru/ CIAO (previous) & HiCIAO & CHARIS
- **Various differential imaging techniques**
  - PDI: polarization
  - SDI: spectrum
  - ADI: angle

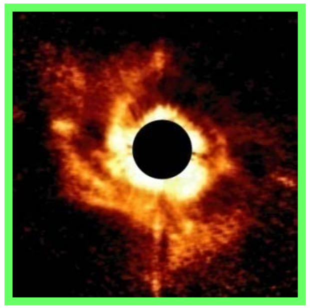


SEEDS –Strategic Explorations of Exoplanets and Disks with Subaru

- The first “Subaru Strategic Program (SSP)” – An open-use category
- 120 nights from 2009; **finished in 2015 Jan, only <1 night loss due to HiCIAO**
- NIR direct imaging and census of **giant planets in the outer regions** (10-100AU) around **~500 solar-type and massive stars**
- Exploring **protoplanetary disks** and debris disks for the origin of their diversity and evolution at the same radial (10-100AU) regions
- **Direct linking** between planets and protoplanetary disks

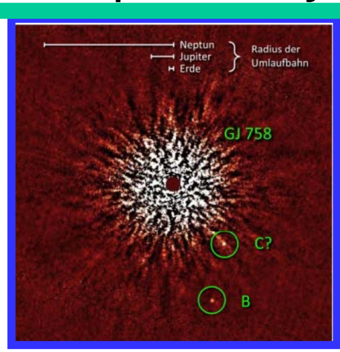


Resolution
=0.1-0.2”

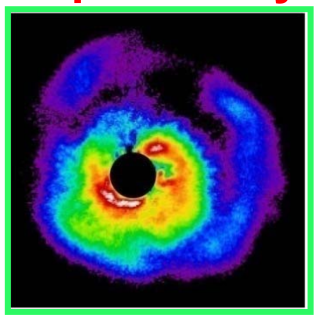


>100AU scale
w/ CIAO

⇒



Resolution
=0.05-0.1”
Contrast
Improved by ~10



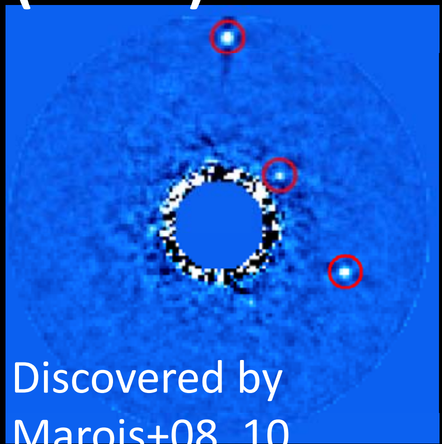
Solar-System Scale (<100AU) w/ HiCIAO

SEEDS Result Summary 2017.12.10

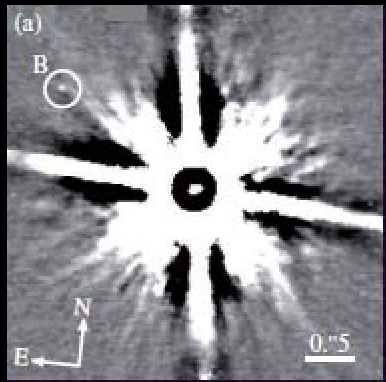
RESULTS	NUMBERS
Refereed English Journal	５６
of which Japanese-led	３６
of which in ApJ	３４
Most cited - Top 5 (Muto+2012/Kuzuhara+2013/Hashimoto+2011/Grady+2013/Carson+2013)	173/148/120/111/101
Master＋Doctor thesis	１５＋１０

Subaru/ABC Directly Imaged Planets Gallery

HR 8799 bcde
(A star)

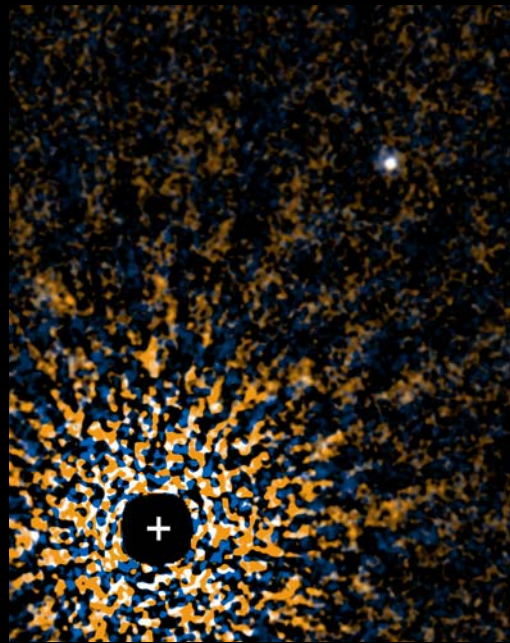


Discovered by Marois+08, 10

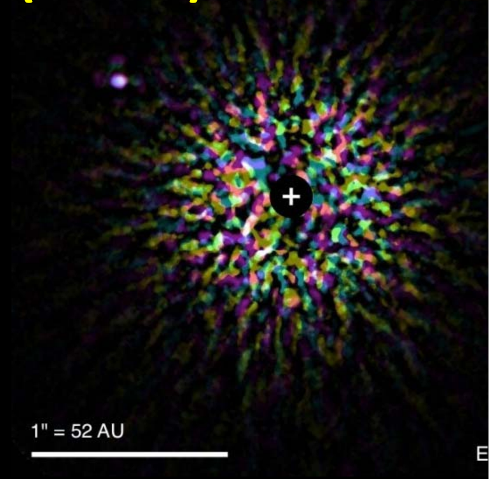


Already imaged in 2002 by CIAO! Fukagawa+09

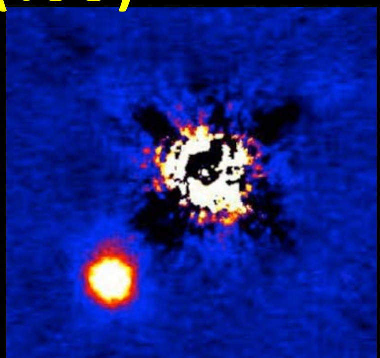
GJ504 b
(G star)



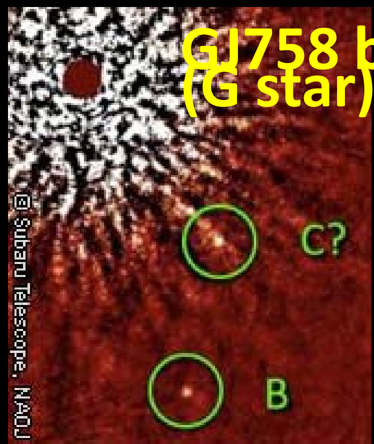
Kappa And b
(B star)



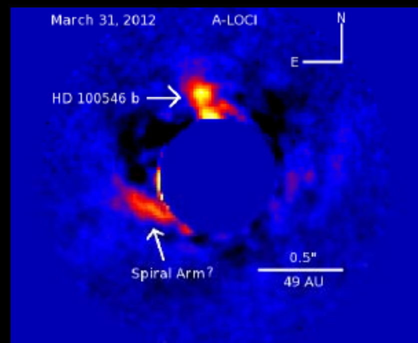
DH Tau b
(YSO)



GJ758 b
(G star)



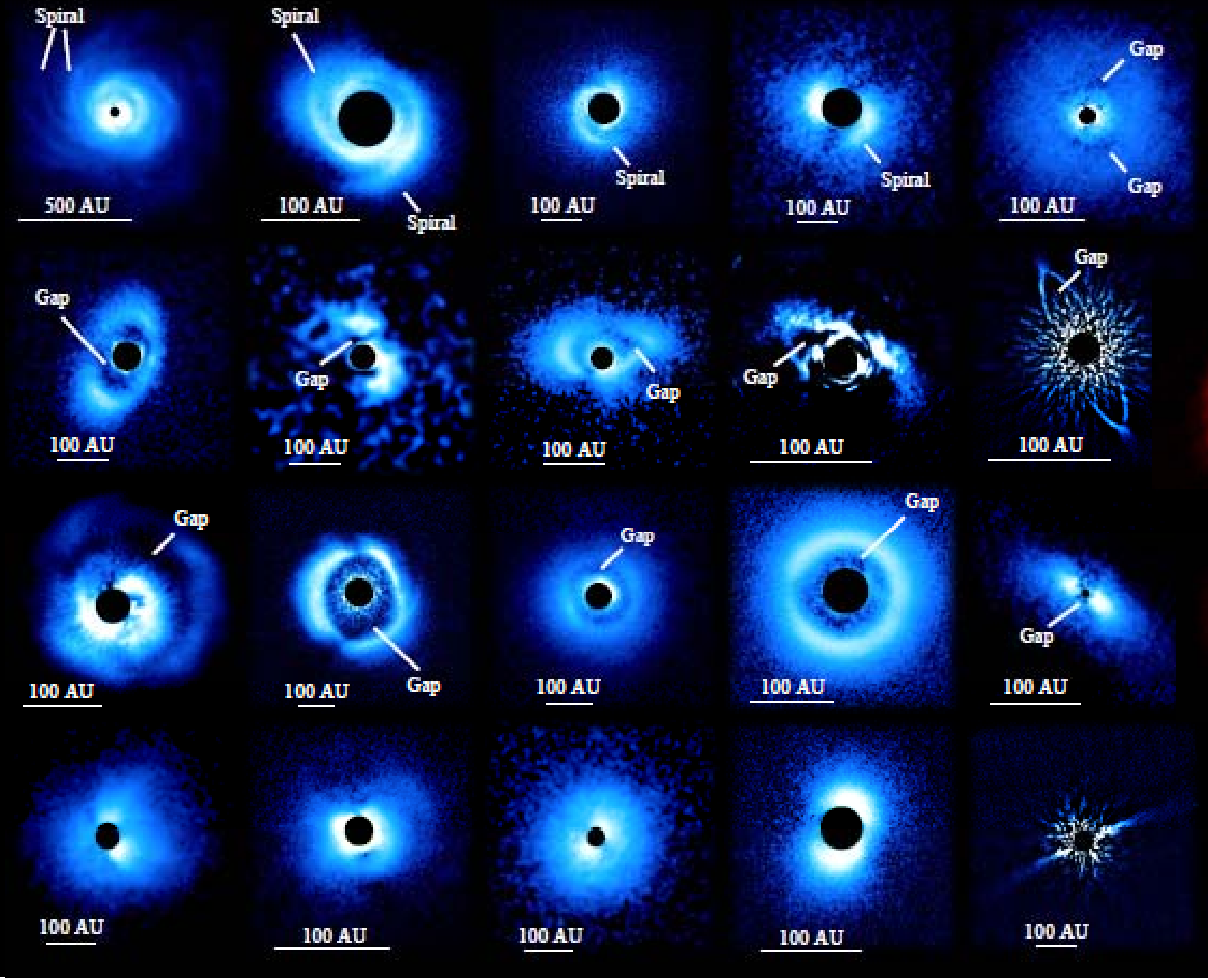
HD100546 b
(YSO)

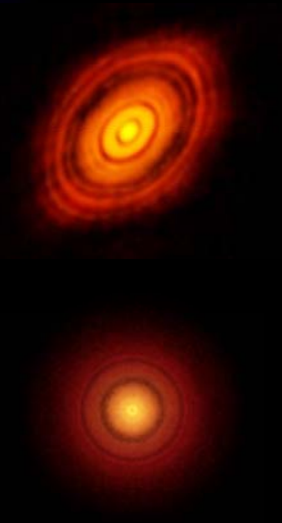


Wide-orbit planets can be detected currently only by direct imaging;
Many are a>=100 AU; ***only handful for Solar-system-scale orbit planets.***

SEEDS has revealed gaps & rings of <100AU scale in many disks by polarimetric imaging (Res.~0.06", IWA~0.1" even at ~2010)

Note that ALMA HL Tau image (2015) is thermal emission .

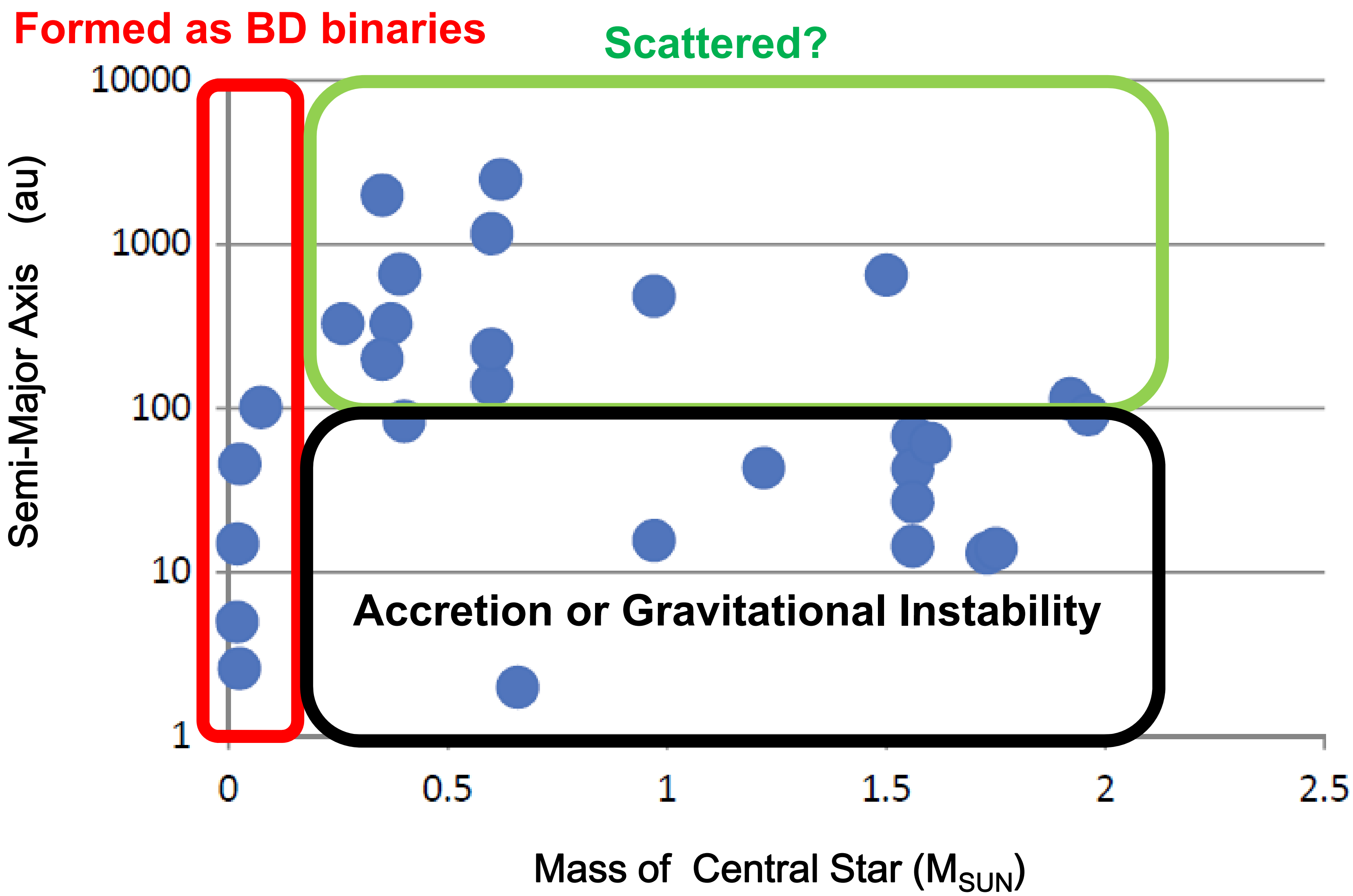




ALMA
HL Tau
&
TW
Hya

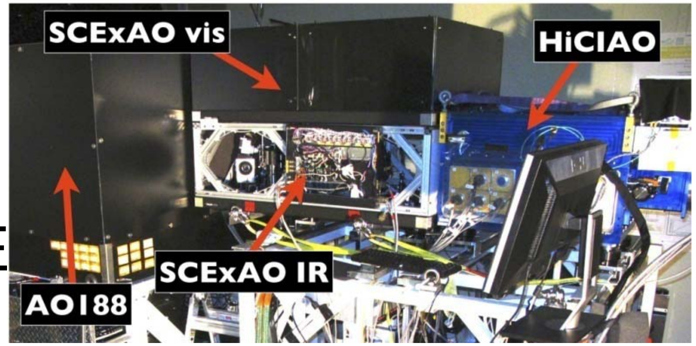
Directly Imaged Planets are still few

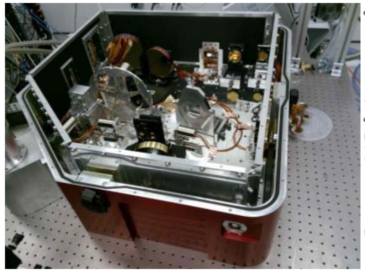
(Mass =<13 M_{JUP})

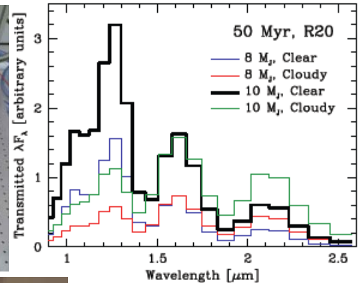


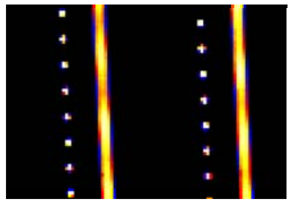
Subaru+ has a suite of best exoplanet instruments !

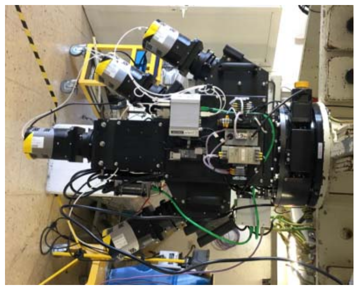
- **SCExAO: 2014-, Science phase**
  - 2000 MEMS deformable mirror
  - IR bench for HiCIAO & CHARIS
  - OPT bench for FIRST & VAMPIRE
- **CHARIS: 2016-, FL done**
  - IFU Combined with SCExAO
  - R19/R70 JHK spectroscopy
- **IRD: 2017-, FL done (IR Doppler)**
  - IR echelle,R~70,000, fiber-fed
  - 1m/s accuracy w/ laser-comb
  - Habitable earths and super-earths around late M stars
- **MuSCAT2 (+MuSCAT/OAO): 2017-, FL done**
  - Optical multi-band transit on IAC1.5m
  - MuSCAT/OAO1.88m, science continued
- **PRIME: SAAO-site, project started**
  - 1.8m IR microlensing + others at SAAO

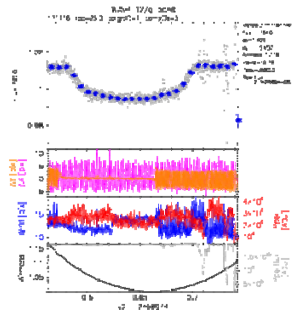




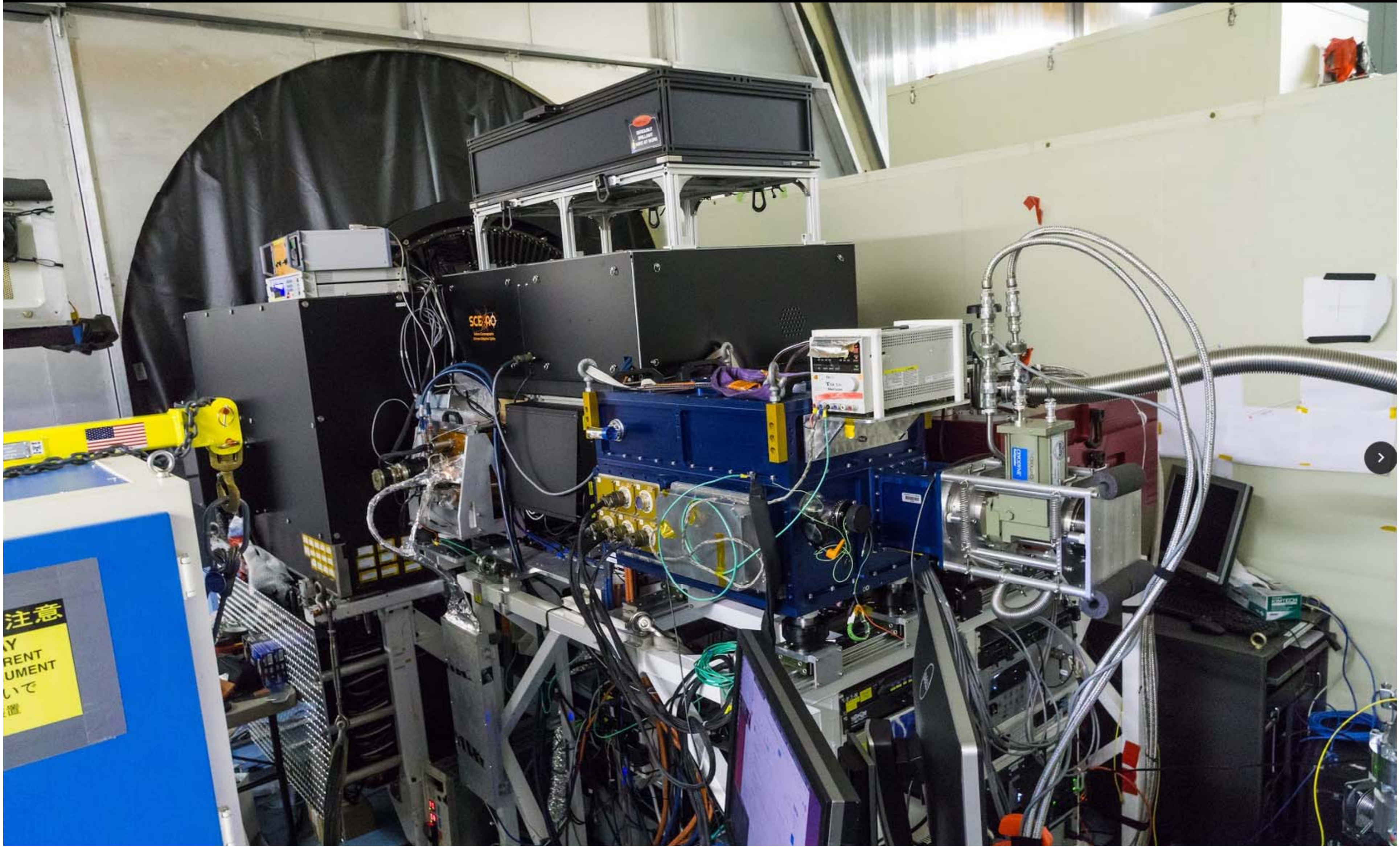




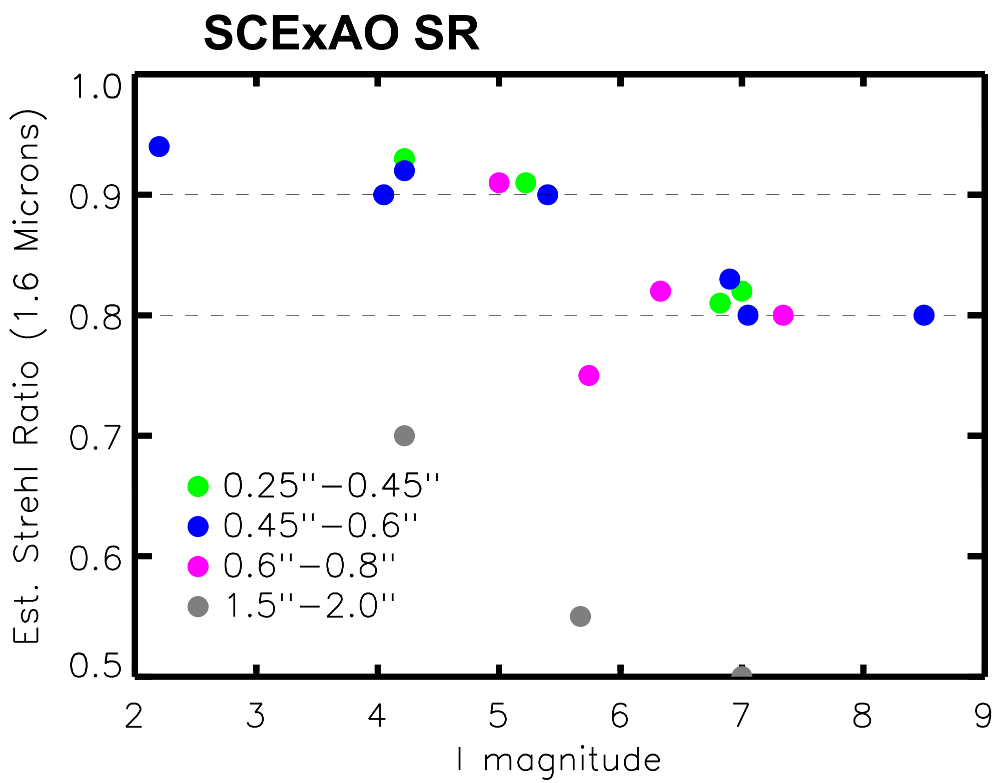


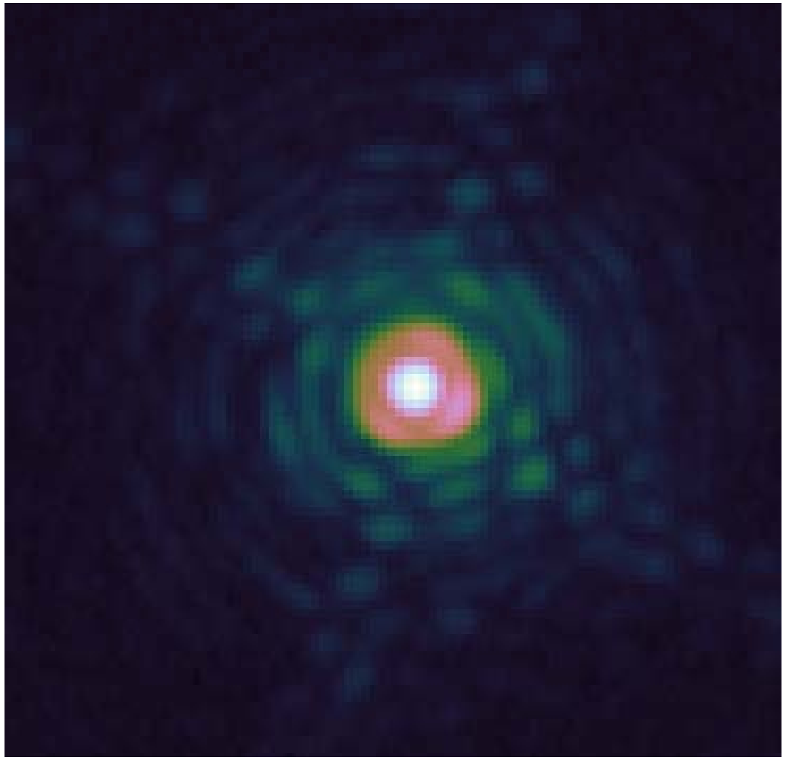


Subaru Coronagraphic Extreme Adaptive Optics



High Strehl Ratios





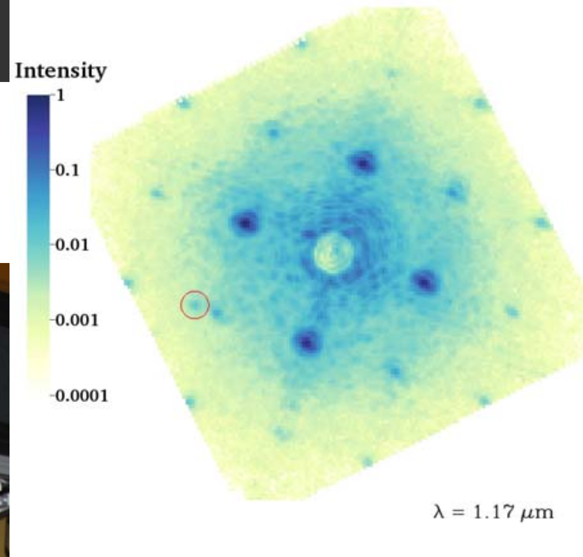
S.R. ~ 0.9 for bright stars under average to good conditions
x-AO correction demonstrated down to I ~ 9

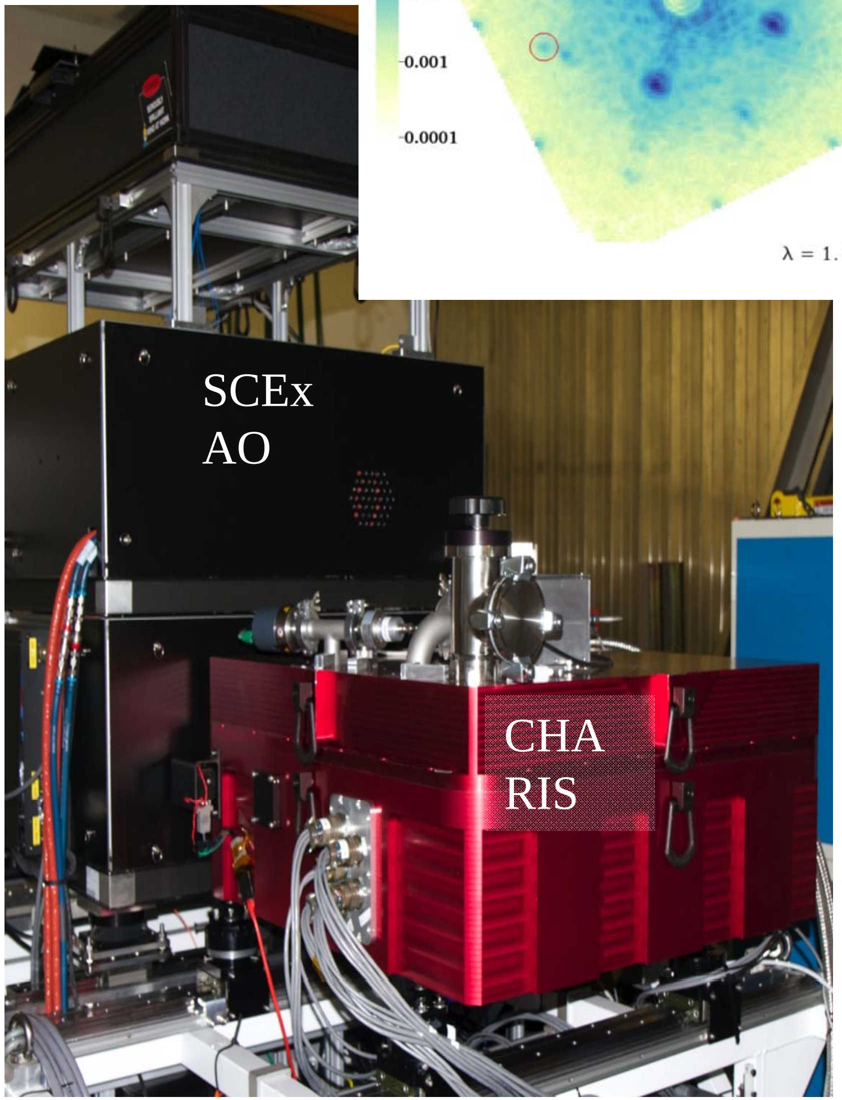
LkCa 15:
R ~ 11.6 star, K band

SR~0.65 @ H
Predictive control ON

CHARIS Specs Summary

- Major Science Objective:
  - Spectral characterization
    - Exoplanets
    - Disks
    - Brown dwarfs
  - Supports Coronagraph
    IWA = 3 λ/D = 90 mas
    Current coronagraphs are pushing inside
  - ~ 2”x 2” FOV
  - R~19, J+H+K Band
    - ~53% Throughput
  - R~65-85: J,H, and K Bands
    - ~40% Throughput

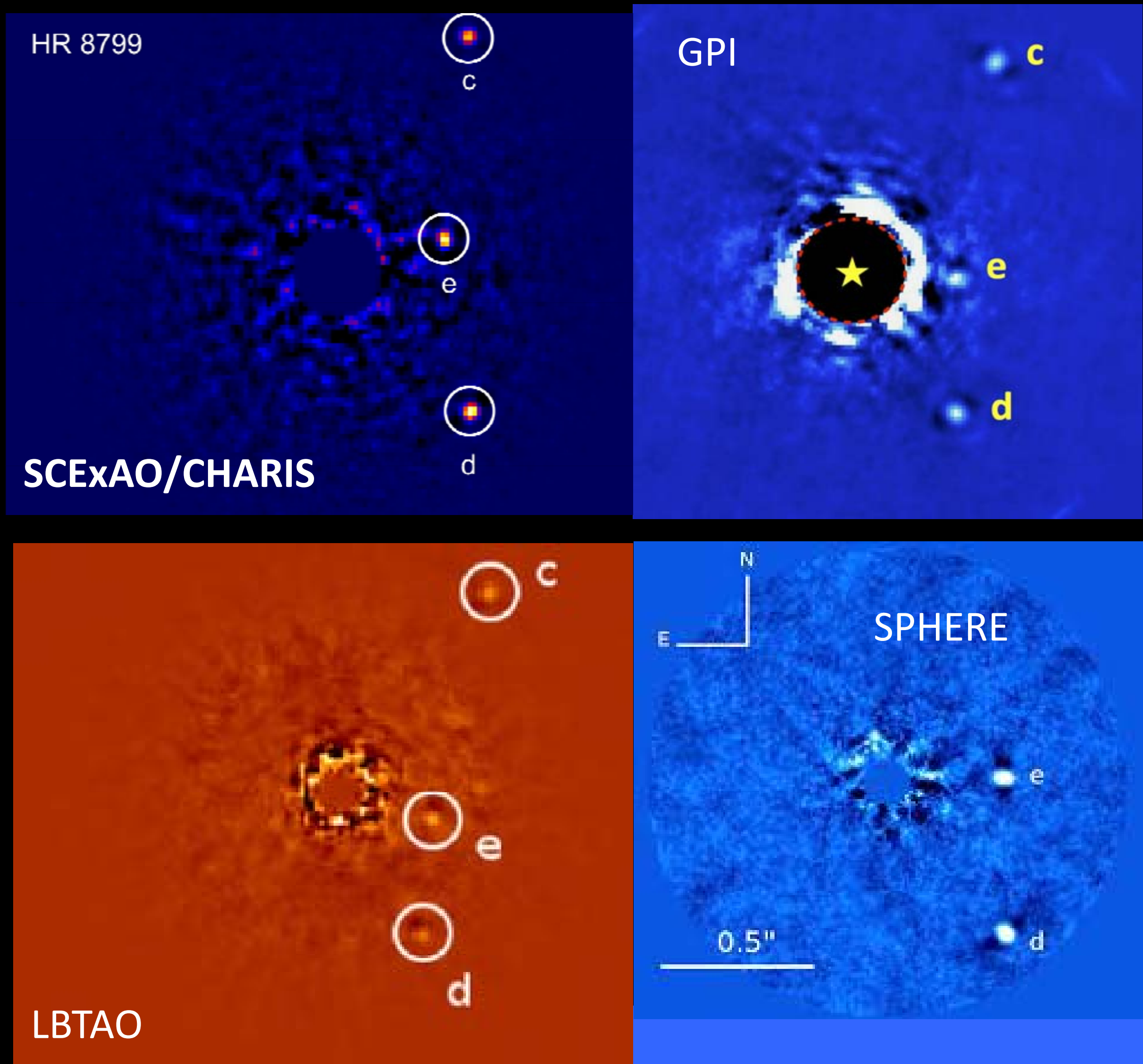




SCExAO vs. other leading systems

contrast:
~1d-5 at 0.3
~1d-6 at 0.75”

Comparable to GPI and LBTAO: Improving and closing the gap with SPHERE



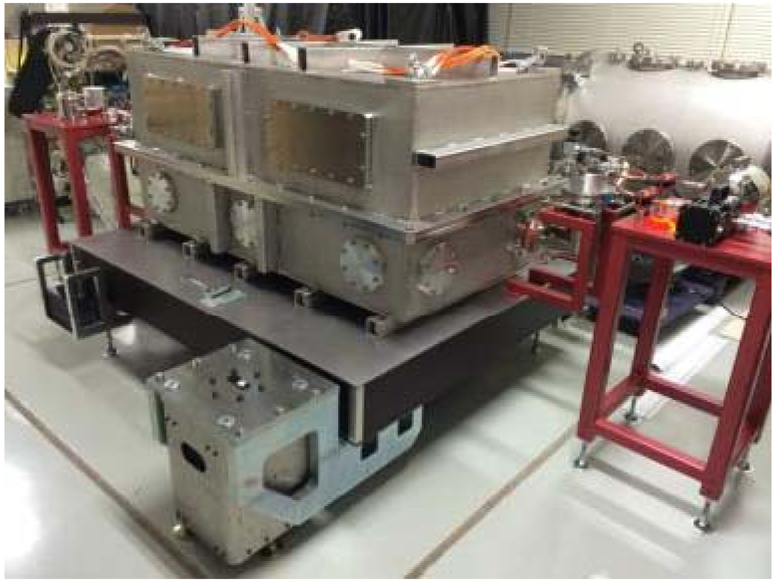
Infrared Doppler instrument (IRD)

What is IRD?

- High-resolution, NIR spectrometer for the Subaru for planet detection by radial velocity method (R=70,000 max, Y,J,H)
- First light on Telescope: 2017/Aug/9th
- Start of a strategic survey: from 2019/Feb, 100 nights for 5 years (planned)

Goal of IRD

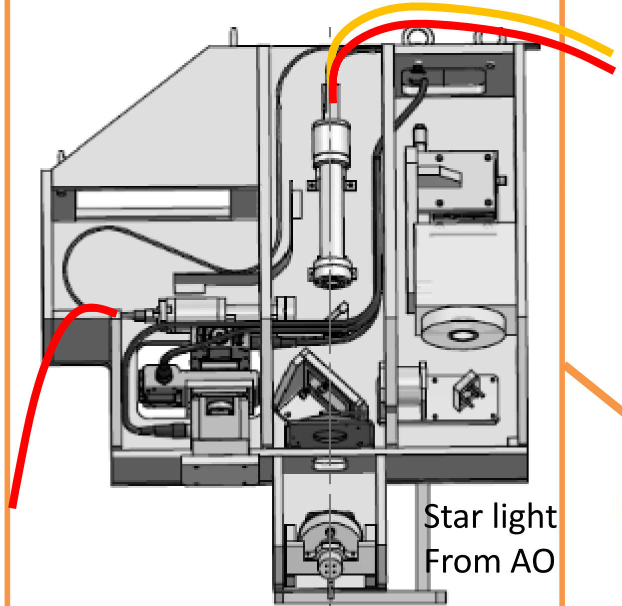
- Detection of ~ 50 planets around nearby M dwarfs, including ~10 Earth-like planets in their habitable zone
- Characterization of planet atmospheres



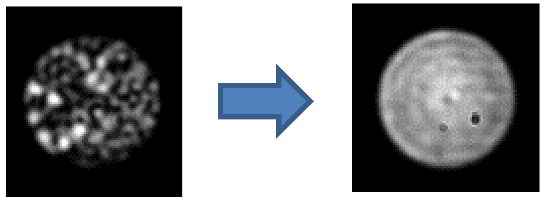
Uniqueness of IRD

- Large collecting area of Subaru telescope
- Wide spectral coverage (0.97-1.75um)
- Original laser frequency comb
- Combination with Adaptive optics, Single or Multi-mode fiber injection

Overview of IRD

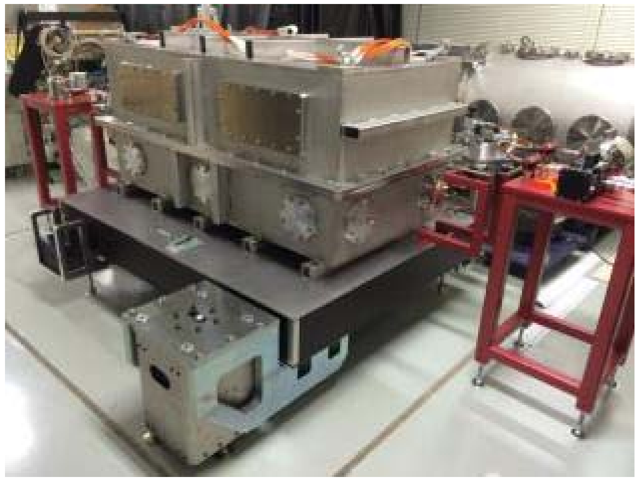


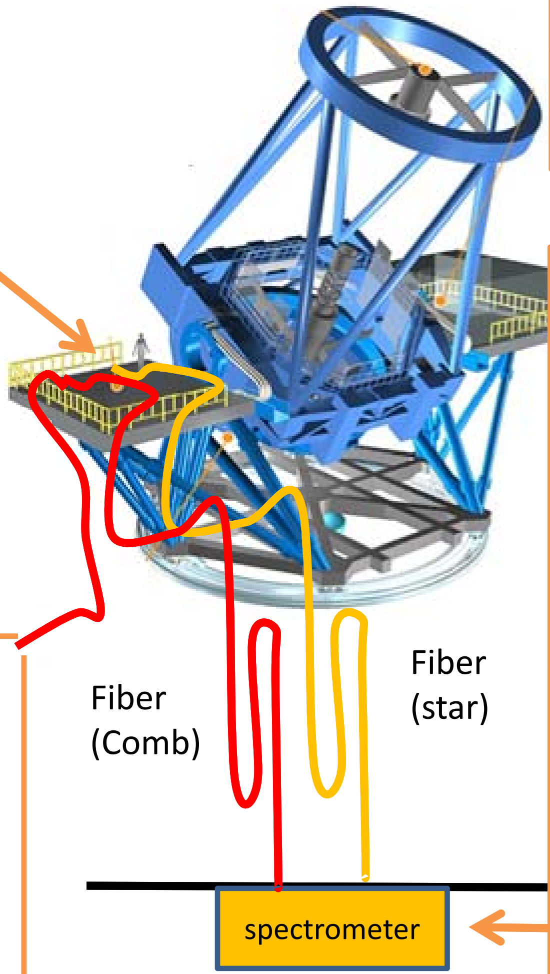
Fiber injection system
(AO bench)



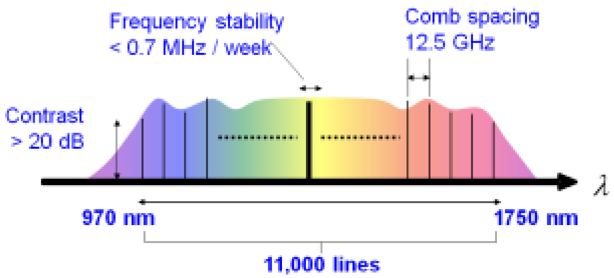
Mode scrambler

Resolution: R=70000
Wavelength: 0.97-1.75um
Cryo: 80K (detector), 180K (optics)





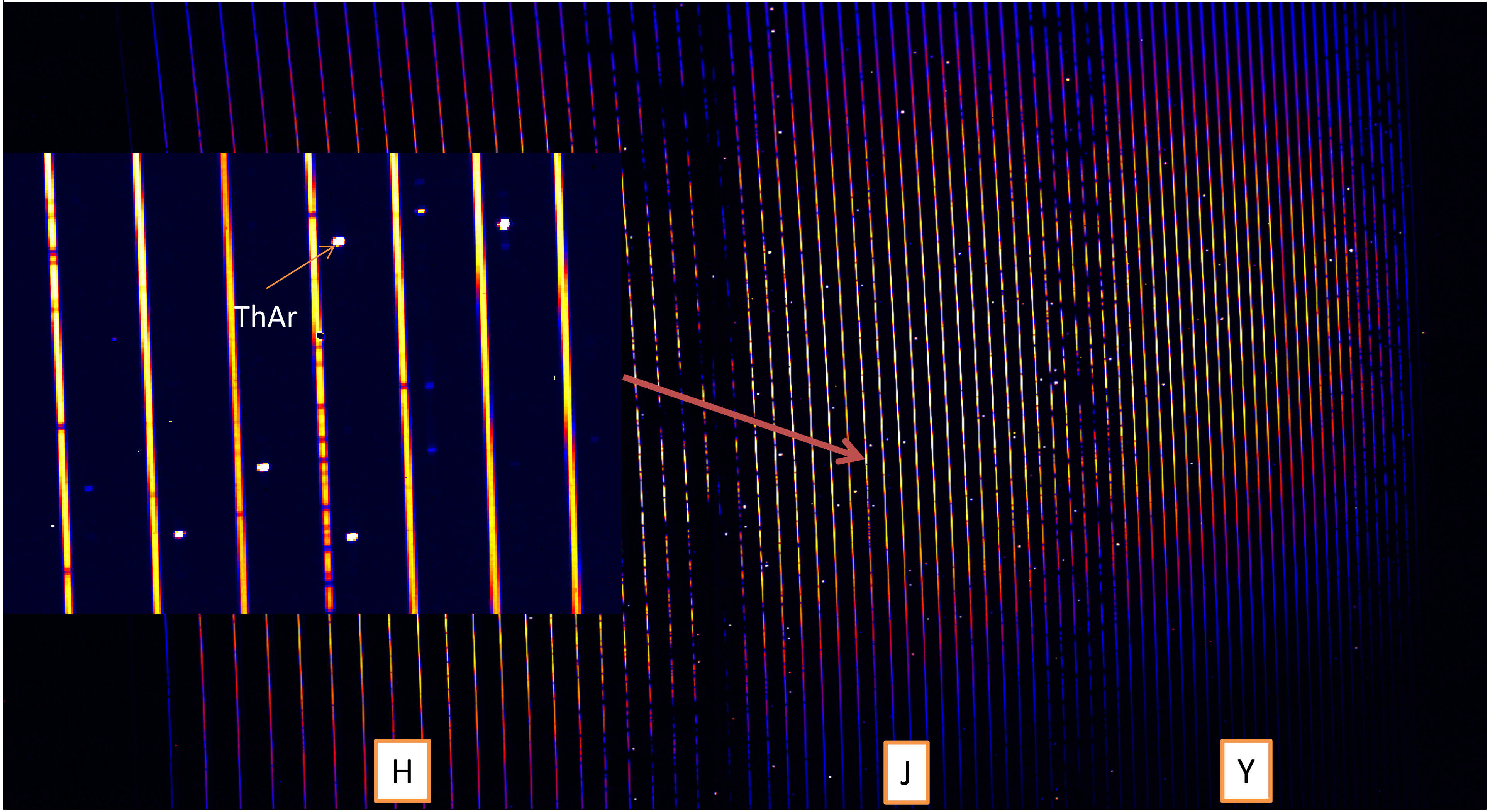
Coudé Room



Laser frequency comb
(IR Observing floor)

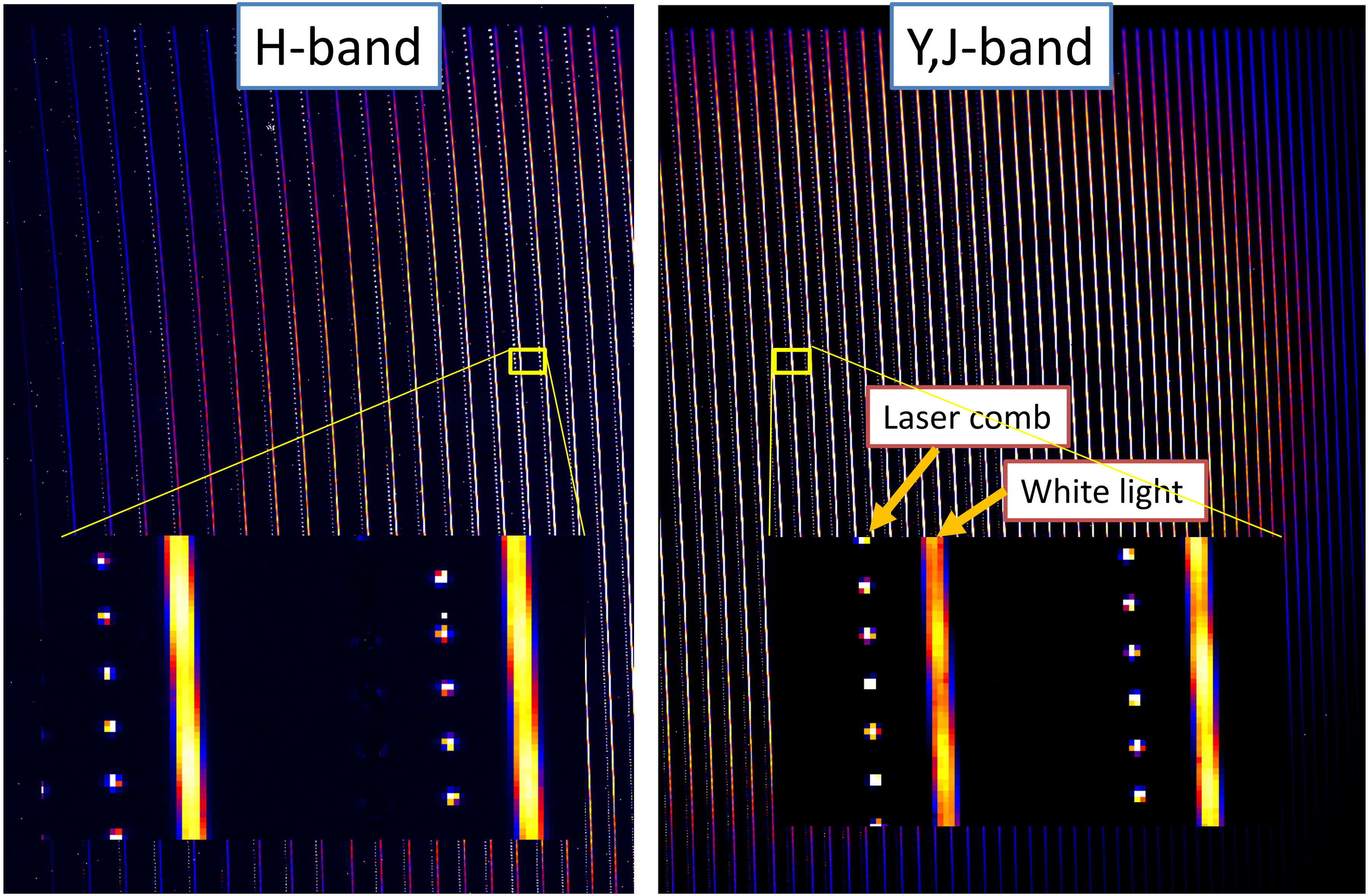
Spectrometer system
(Coudé room)

IRD First Light at Subaru!

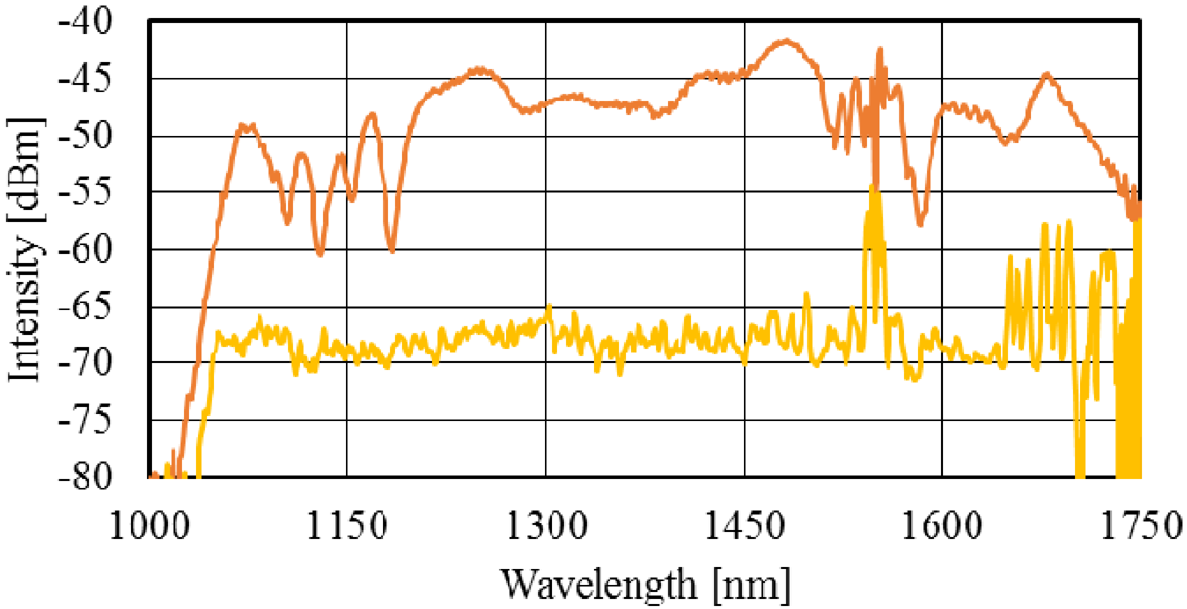


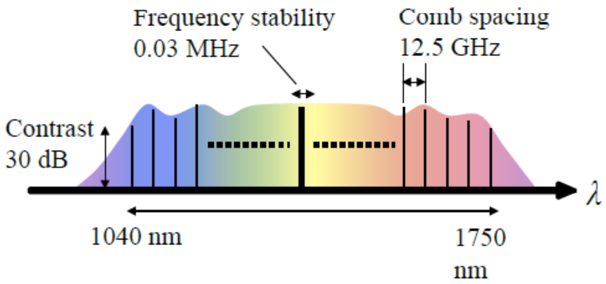
HR7596 YJH-band, 2017/08/10 1:37 HST

Laboratory spectrum (white light & laser comb)



Original Laser frequency comb

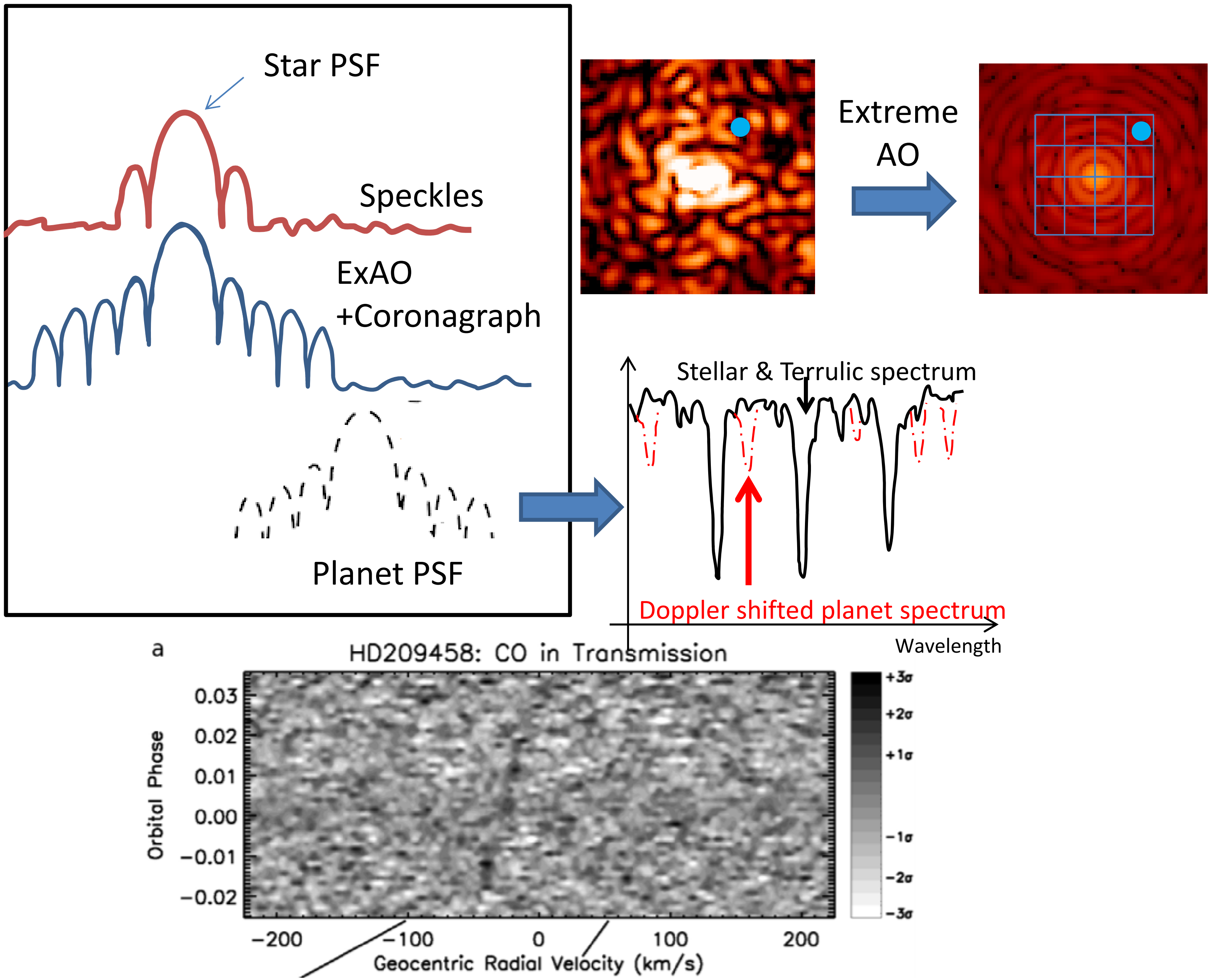




Goal	Measured
• Wavelength coverage : 980 ~ 1750 nm	1040 ~ 1750 nm
• Mode spacing : 12.5 GHz	12.5 GHz
• Frequency stability : < 0.5 MHz	<0.3MHz
• Contrast : > 15 dB	> 30 dB

- Our original laser frequency comb will cover Y, J, H-band simultaneously
- Sufficiently wide frequency span(12.5GHz, 0.09nm @ 1.5um)
- Developed by the group at Tokyo University of Agriculture and Technology

High-contrast and High Dispersion Spectrograph



J-Community Survey from J WP

Science Program	Authors	HSC	PFS	IRD	SCE	ULT
Exoplanets						
Probing Dust Grains in Circumstellar Disks	Muto	–	–	–	○	–
Polarimetry of Planets/Protoplanetary Disks	Murakami+	–	–	–	○	–
Exoplanets Search by Astrometry	Yamaguchi+	–	–	–	○	–
Extinction in WFIRST Microlensing Fields	Suzuki+	○	–	–	–	–
Concurrent Microlensing Observations	Suzuki+	○	–	–	–	–
Imaging of Microlensing Planetary Hosts	Fukui+	–	–	–	○	○
Characterization of Transiting Exoplanets	Narita	–	–	○	–	–
Exoplanets around Late-M Dwarfs	Kuzuhara+	–	–	○	–	–

Note. — SCE and ULT indicate the SCExAO and the ULTIMATE-Subaru, respectively.

Multi-color observations of protoplanetary disks

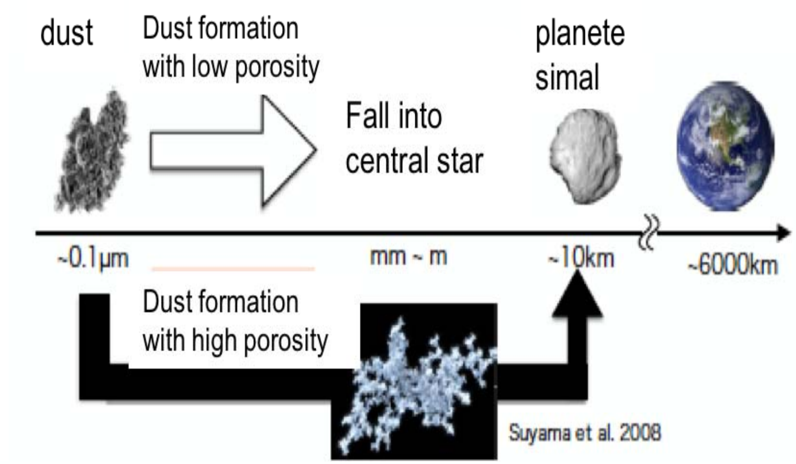
Murakami, Tamura
Muto

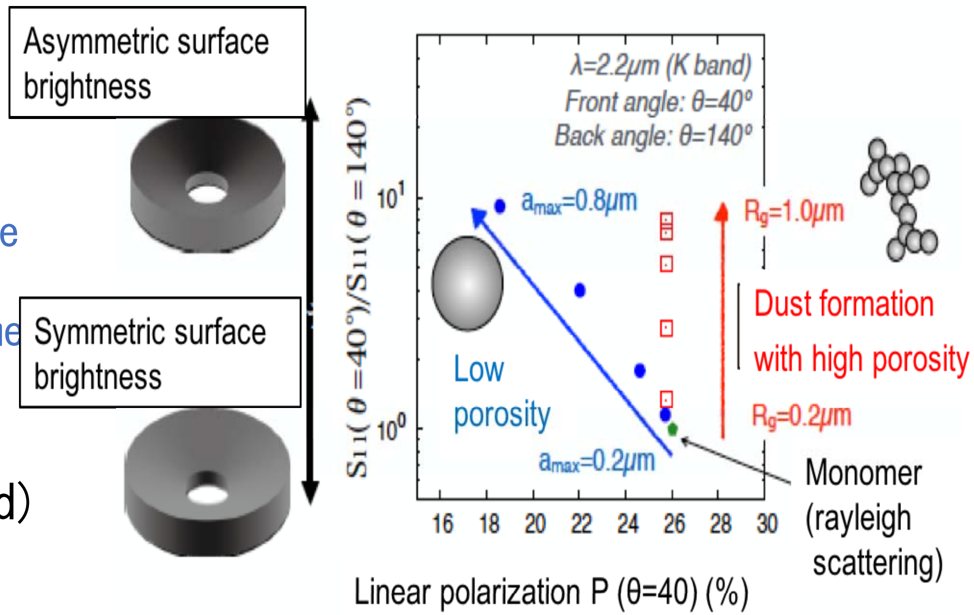
- Difficulty of dust formation from mm to km.
  - considering porosity of dust
- Characteristics:

  Aggregate (high porosity):
  - interference among small monomers
  - constant polarization degree independent of aggregate size

  Monomer (low porosity)
  - decrease in polarization degree due to multiple scattering in large monome

- Multiple observations with WFIRST (visible) and SCExAO (near-infrared) constrain the dust structure.





Search for long-period planets orbiting nearby stars with IRD

Kuzuhara-san et al.

- Providing important targets (reflected gas giants) to the WFIRST coronagraph.
  - Wide separation planets

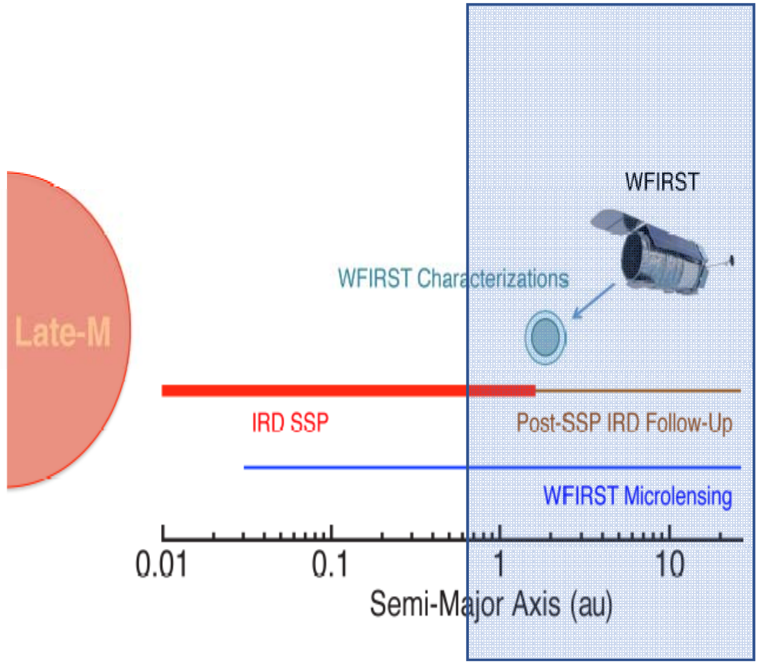
  (promising in terms of contrast)

  - Nearby stars

  (promising in terms of sensitivity and wavefront sensing).

- The number of M dwarfs within 10pc is a few hundreds. The outer region (>1AU) around M dwarfs is unexplored.

  -> Extension of SSP of IRD can search for long-period gas giants.



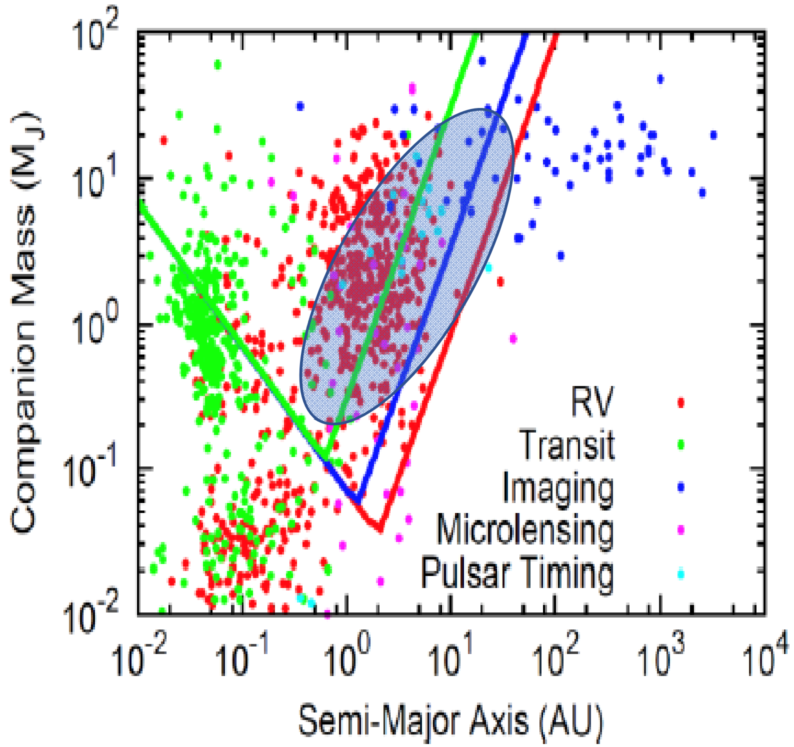
Unexplored region

Follow-up of astrometry planet with WFIRST

Yamaguchi, Matsuo

- Near-field wide-field imager possibly performs high-precision astrometry of nearby M-dwarfs.
- Astrometry has sensitive to young planetary systems.
- Young self-luminous gas giants with long period are suitable for SCExAO.
- We need to discuss how much the astrometric accuracy can be achieved under the degradation of the specification on pointing jitter.

New discovery region with WFIRST wide field instrument?



Detection limits of astrometry with 10 μas around G, K, M dwarfs

Another possibility

- The WFIRST coronagraph is also positioned as demonstrations of the future space concepts (LUVOIR/HabEx).
- As a complementary testbed, the Subaru high-contrast instrument can perform key technologies, which are not tested with WFIRST.