Steps toward Second Earth Imager with TMT (SEIT)

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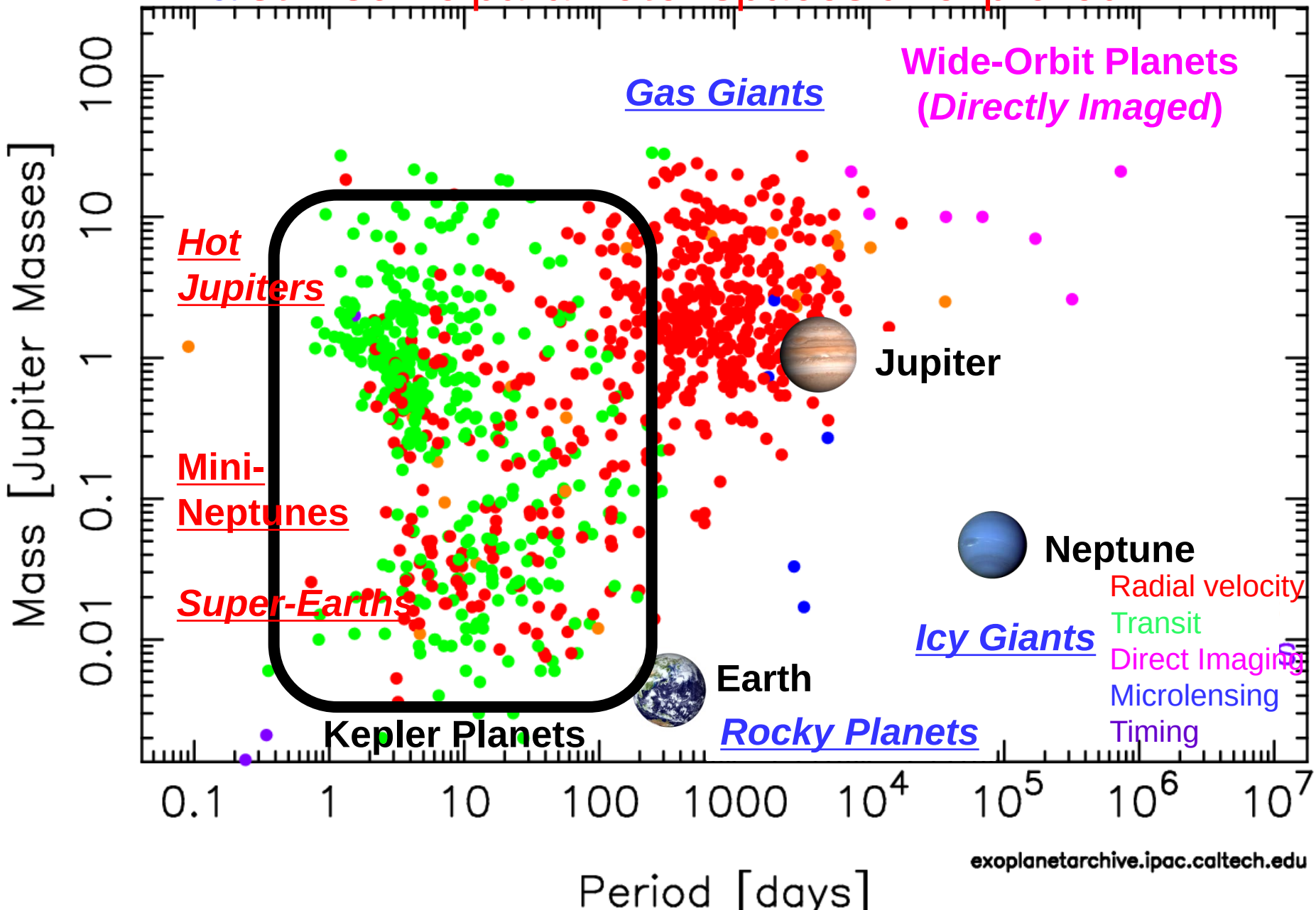
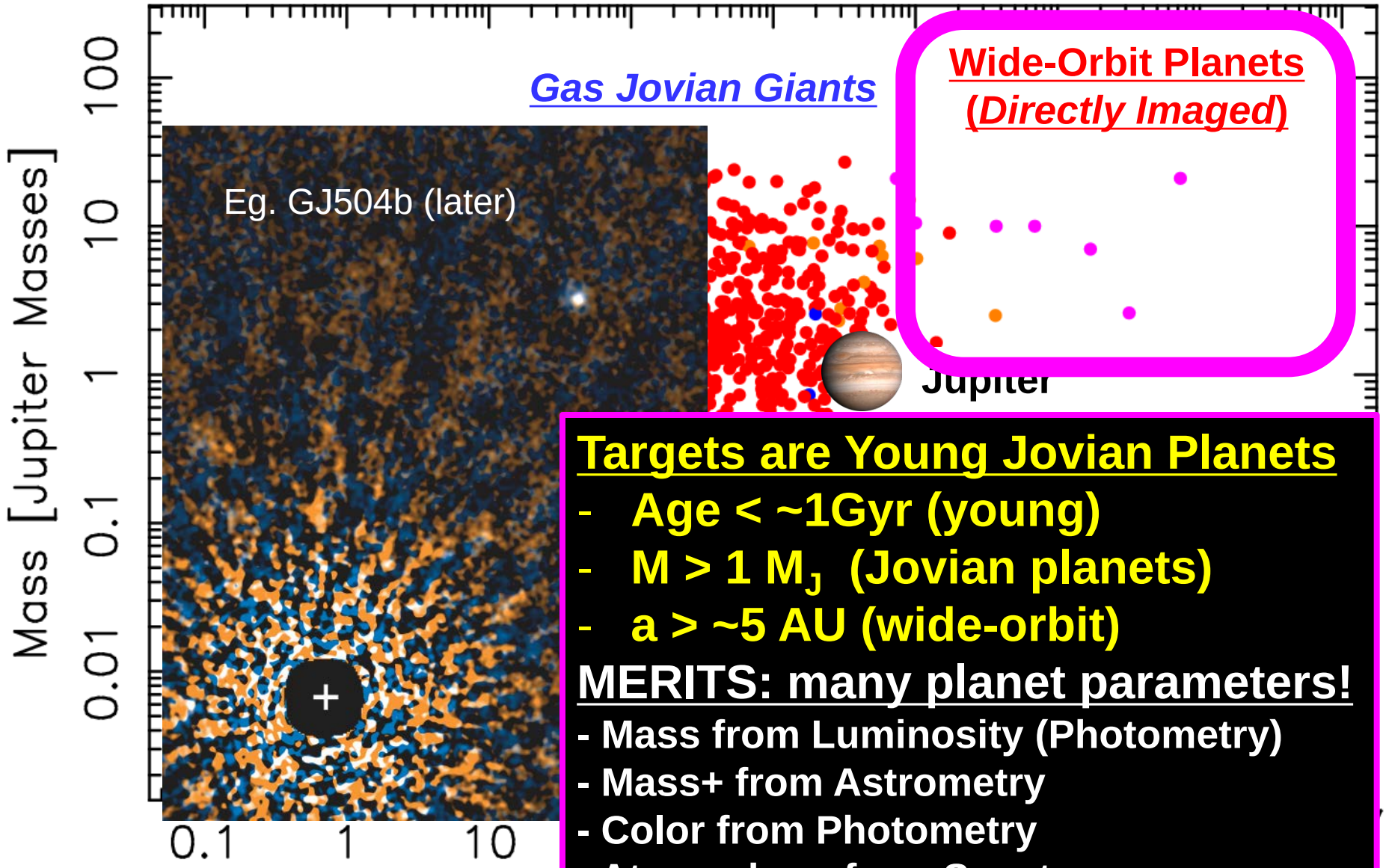
Motohide Tamura

University of Tokyo &
NINS Astrobiology Center &
NAOJ Exoplanet Project Office

Various techniques have led ~3400 planet discovery in 21yr & still some parameter spaces unexplored!



Planets being Explored with Current Direct Imaging



Targets are Young Jovian Planets

- Age < ~1Gyr (young)
- M > 1 M_J (Jovian planets)
- a > ~5 AU (wide-orbit)

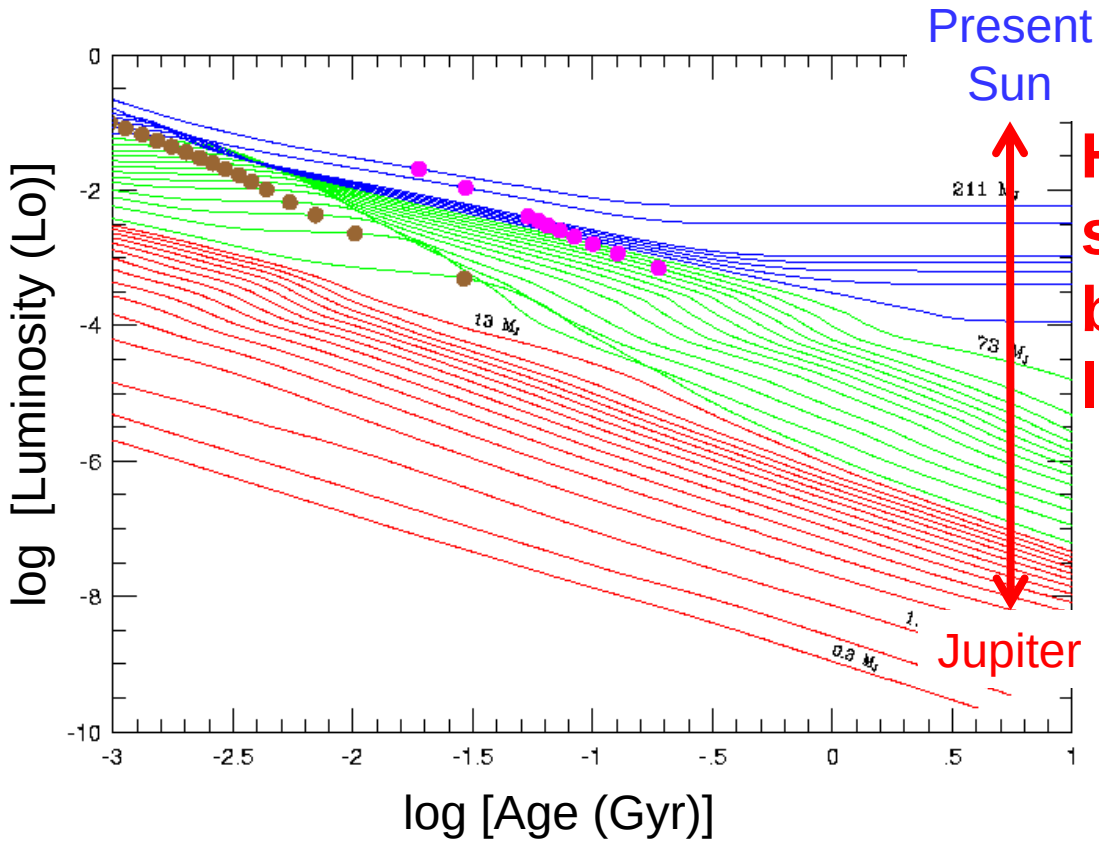
MERITS: many planet parameters!

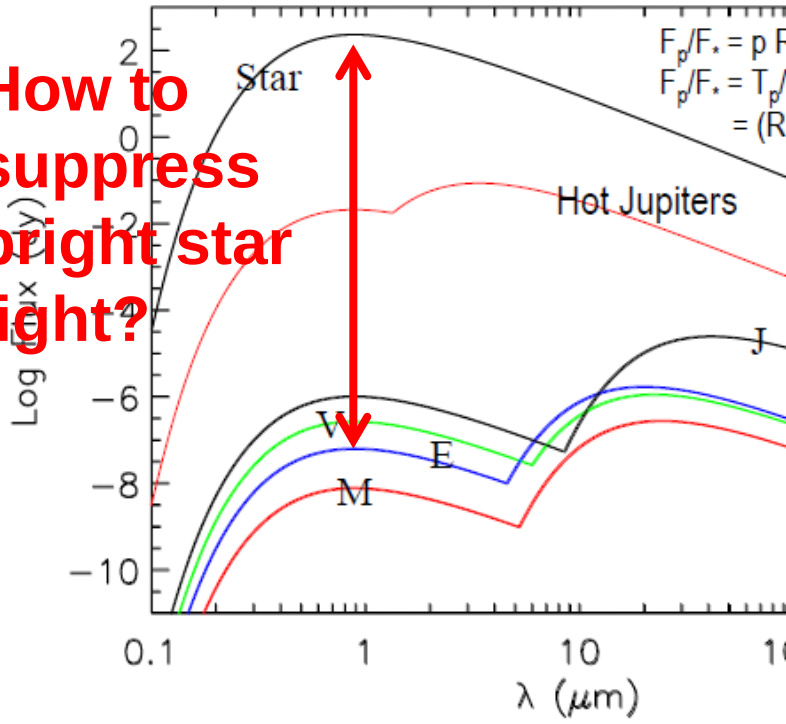
- Mass from Luminosity (Photometry)
- Mass+ from Astrometry
- Color from Photometry
- Atmosphere from Spectrosocpy
- T_{eff}, g from Spectroscopy

Difficulties 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)
- **Reflected light** (next step)

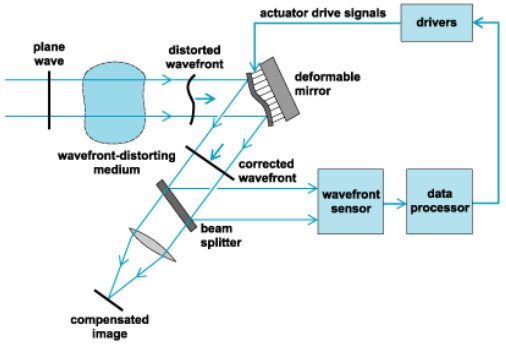


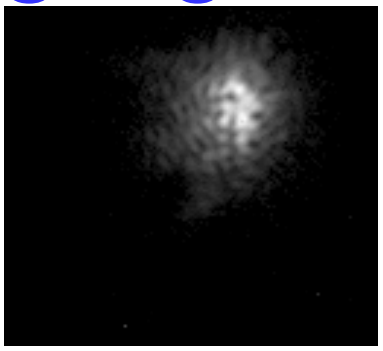


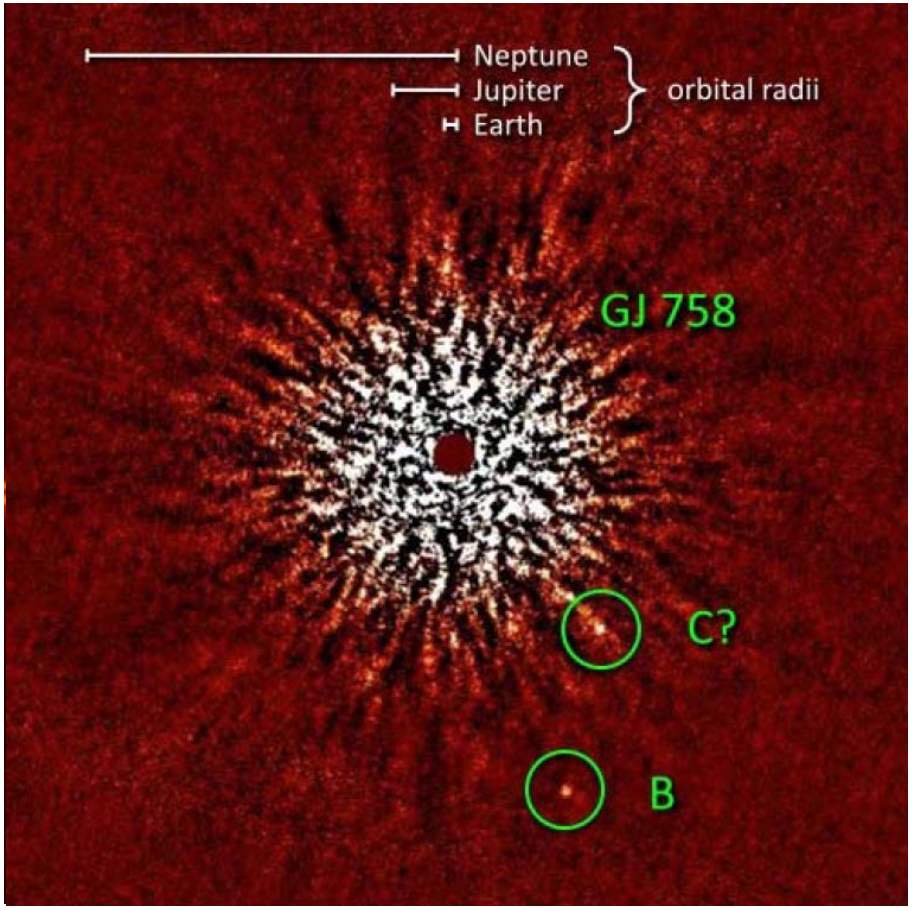
Techniques for Direct Imaging

- **Adaptive optics on 8-m class telescopes is a must**
  - ~200 to ~2000 actuators
- **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 (current)
- **Various differential imaging techniques**
  - PDI: polarization
  - SDI: spectrum
  - ADI: angle





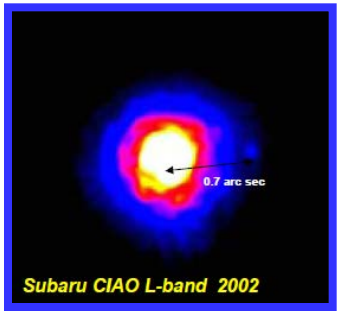


Large-Scale Direct Imaging Surveys on 8-m telescopes (past & ongoing)

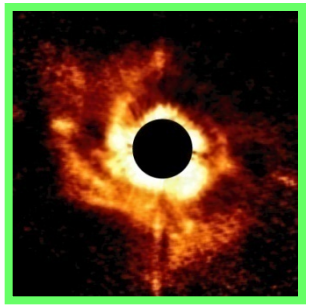
Name or Instr.	Telescope	Nights	Targets Published results
NICI	Gemini-S	?	70 stars, survey finished A few BDs
SEEDS HiCIAO	Subaru	120 nights	500 stars, survey finished GJ 504 b, κ And b, etc. a few BDs, many Disks
GPI	Gemini-S	890 hours	600 stars, 50% completed 51 Eri b, some Disks
SPHERE	VLT	260 nights	~500 stars, 30% completed Many Disks

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

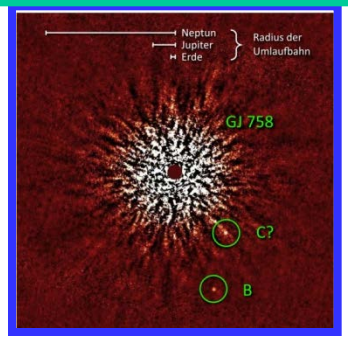


Resolution
=0.1-0.2”



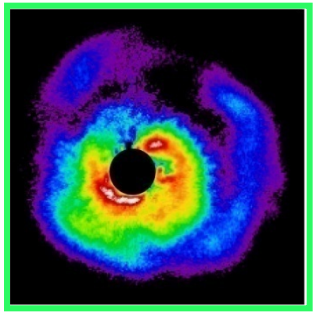
>100AU scale
w/ CIAO

⇒



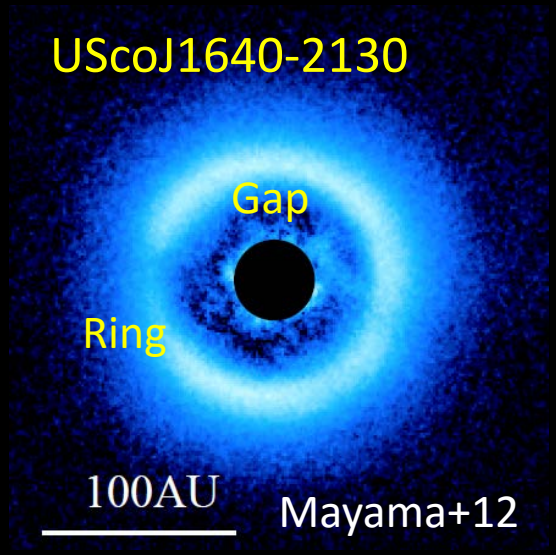
Solar-System Scale (<100AU) w/ HiCIAO

Resolution
=0.05-0.1”
Contrast
Improved by ~10



Major Results of Planet Formation Sites

SEEDS has observed **scattered light** from disks and revealed many disk structures **of less than 100AU scale** that are **possible signs of planet formation in such young (a few Myr) systems! Many directly-maged small gaps/spirals in disks from 2010.**

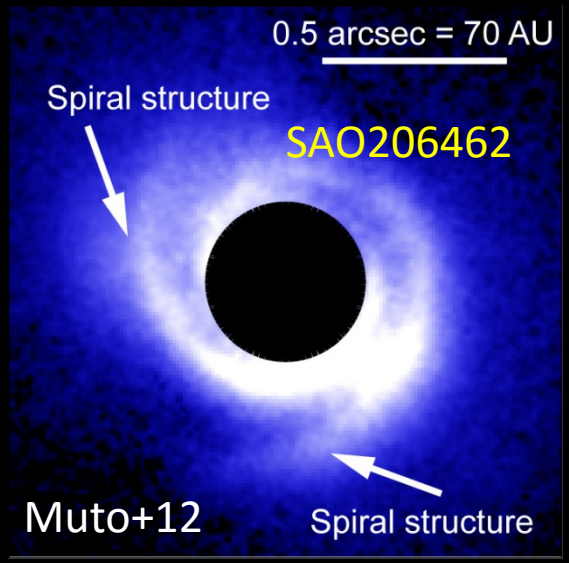


☐ **Gaps**

A disk gap may be evidence for dynamical interactions between a planet and its gaseous disk.

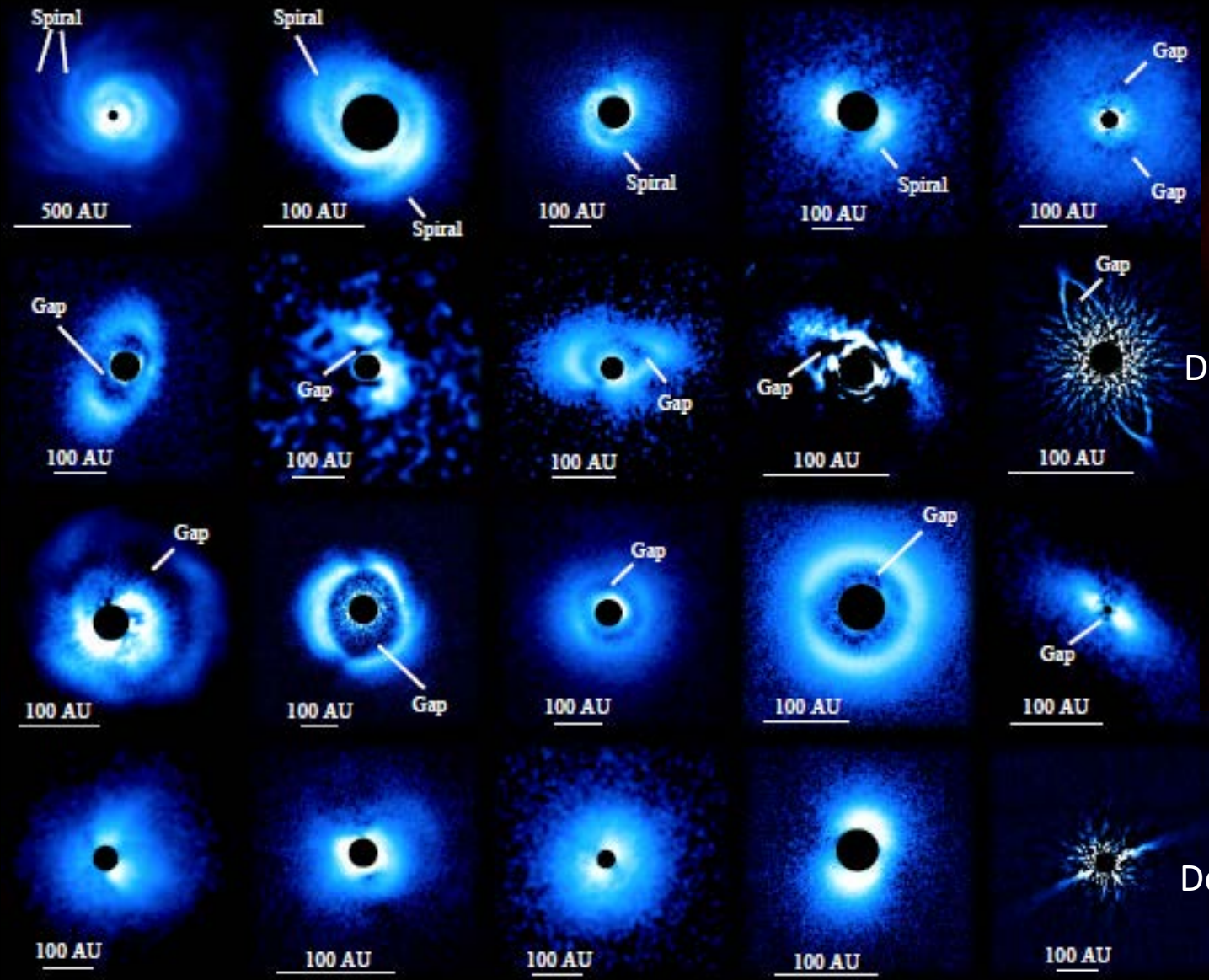
☐ **Spirals**

A gravitational perturbation from an embedded planet generate spiral density waves.



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 .



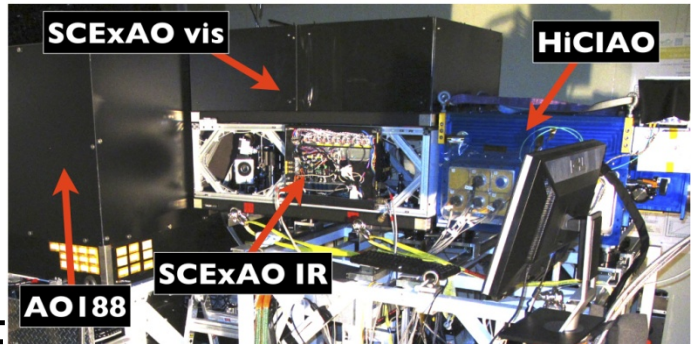
Debris

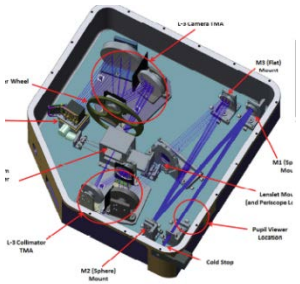
ALMA
TW Hya
HL Tau

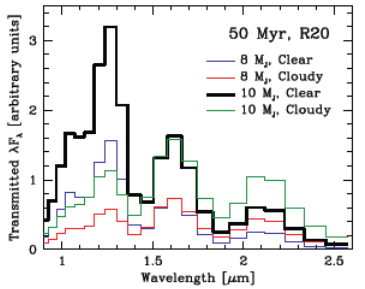
Debris

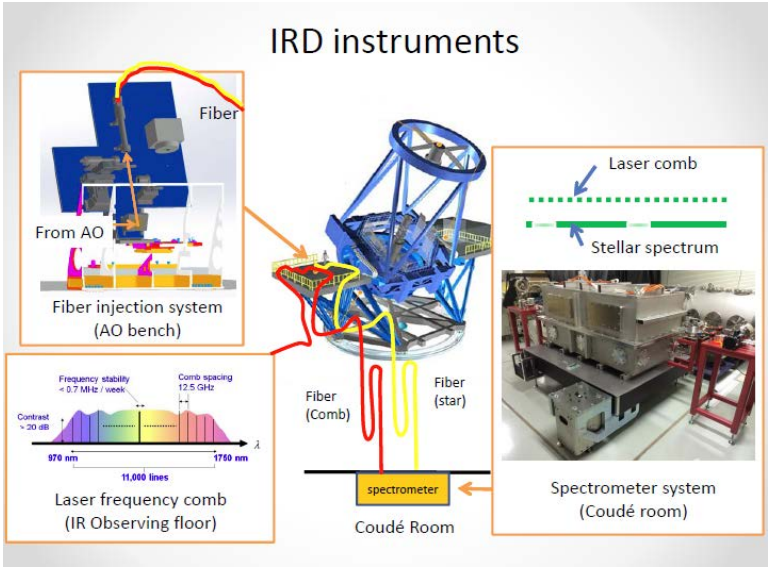
Subaru's **Next Steps** in Exoplanet Sciences

- **SCExAO: 2014-**
  - 2000 elements deformable mirror
  - PIAA coronagraph
  - IR bench for HiCIAO & CHARIS
  - OPT bench for FIRST & VAMPIRE
- **CHARIS: 2016-**
  - IFU Combined with SCExAO
  - R19/R70 JHK spectroscopy
  - Small (λ/D) inner working angle!
- **IRD: 2016-**
  - IR echelle-grating spectrometer
  - R~70,000, fiber-fed
  - 1m/s accuracy w/ laser-comb
  - Habitable earths and super-earths around late M stars
  - Planet formation around M stars



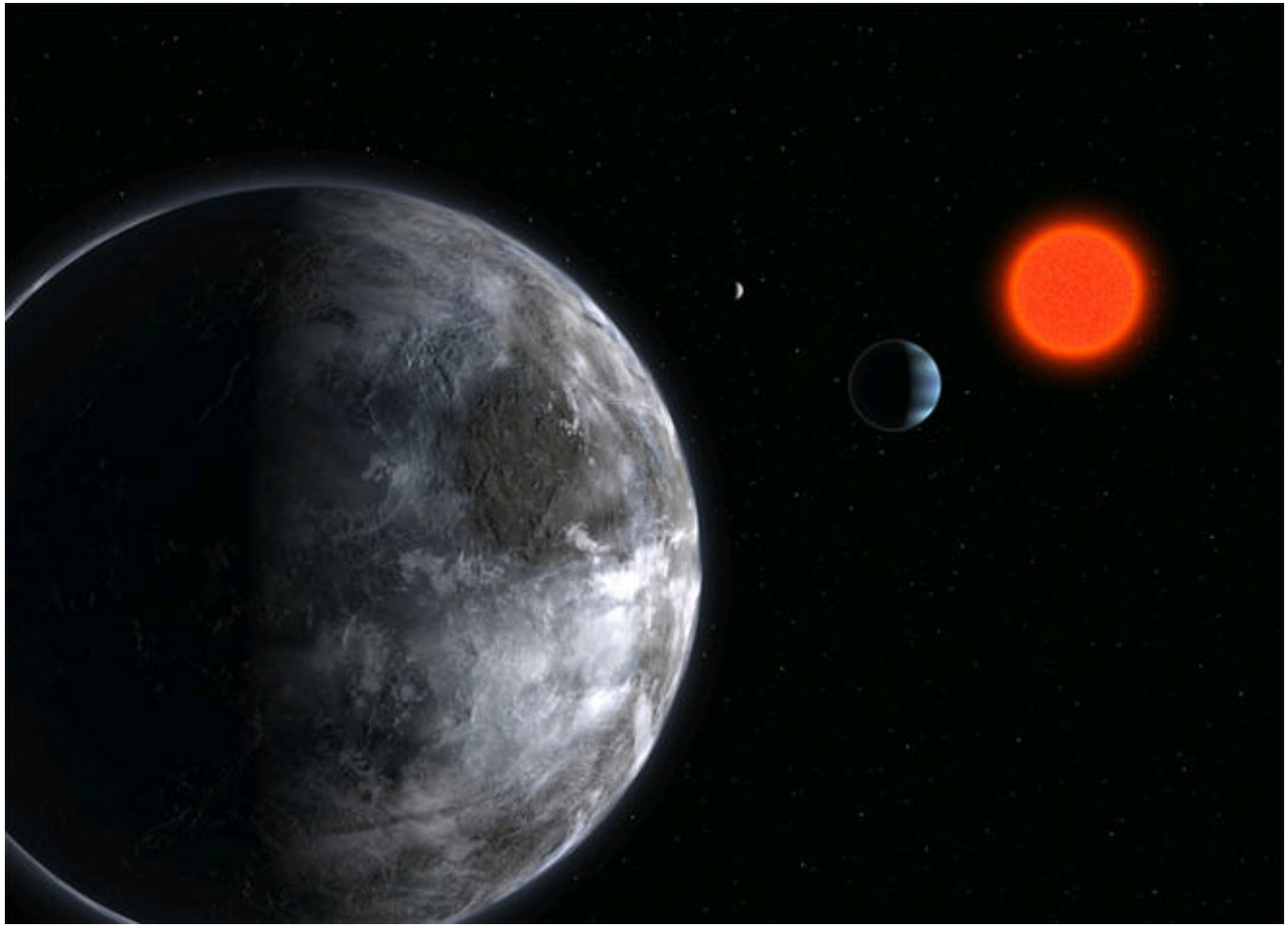






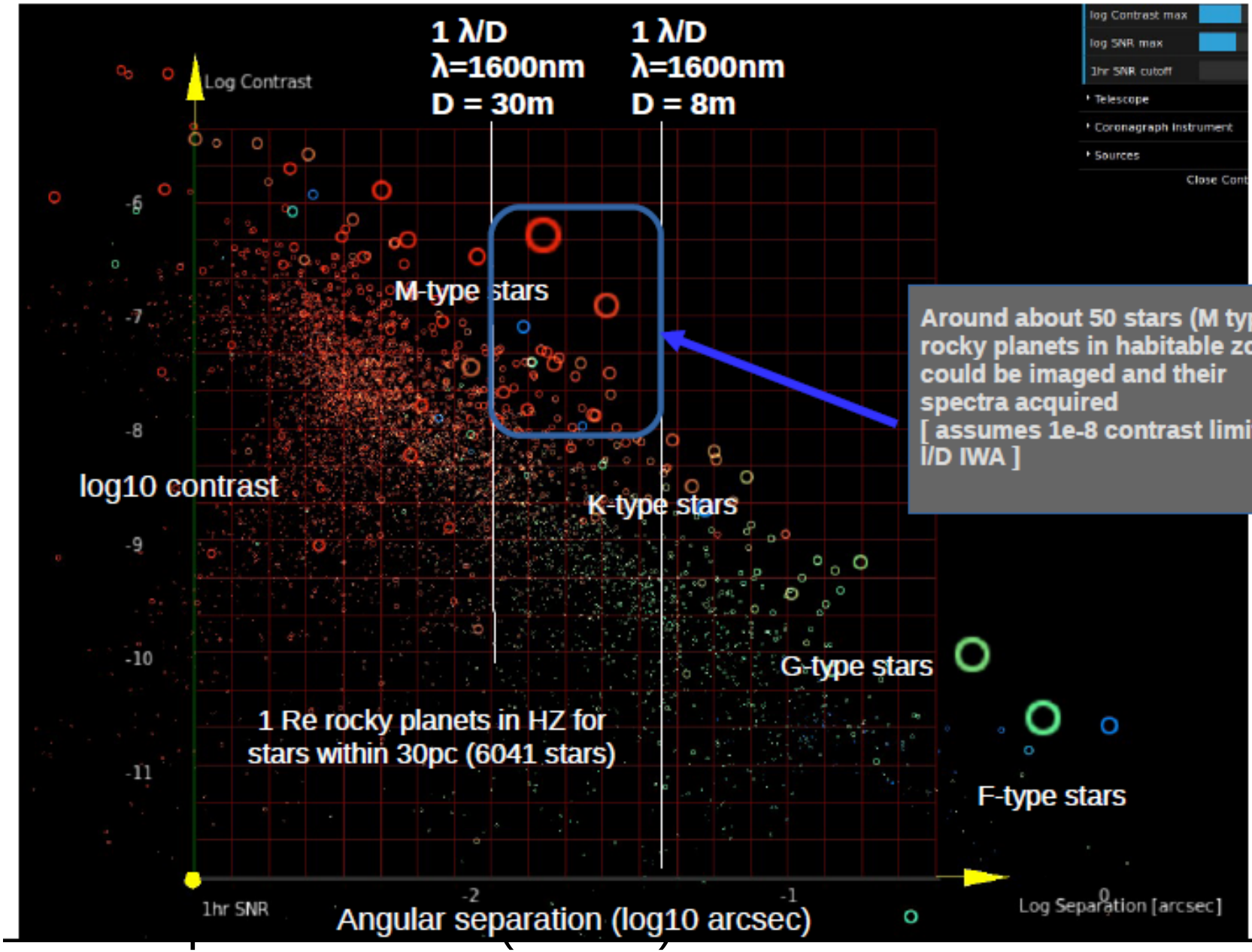
More Steps to TMT/SEIT

- **Science Driver**
  - Imaging and acquiring reflected light spectra of habitable planets around nearby M dwarfs
  - Targets from TESS/IRD and other IR/OPT-RVs



ESO

More Steps to TMT



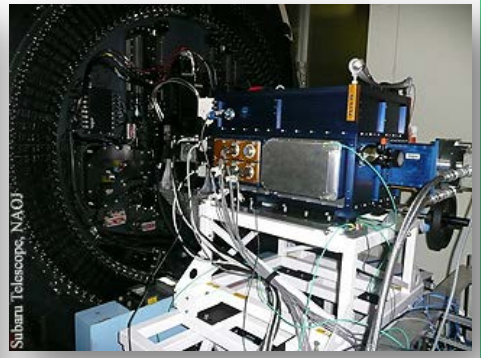
Guyon

Strategy toward Earth-like planet detection and characterization (at least at ABC&ESPO)

1999 2009 2016 2025+

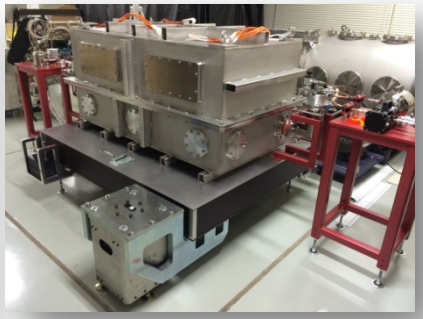
Subaru 8.2m

Indirect detection of Exoplanets on going
-Doppler
-Transit



HiCIAO+AO188

- SEEDS project started
- Several important papers published!
- Direct imaging of a giant planets
- Fine structures in planet forming region



Infrared Doppler (IRD)
TESS (>2017)
also SCExAO+CHARIS

- Indirect detection of low-mass planets around nearby M stars
- IRD already funded and observation starting in 2016.

TMT - SEIT、PFI
SCExAO upgrade

- Direct Imaging of ExoEarth around late types stars with TMT/SEIT, PFI

Planet detection around nearby M dwarfs

+ Dedicated Smaller Telescopes (e.g., IRSF2.0?)

NINS
National Institutes of Natural Sciences
自然科学研究機構

Astrobiology Center

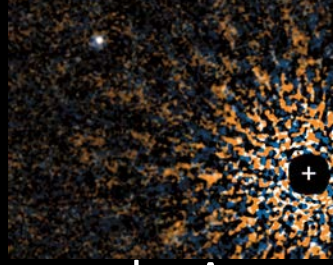
Established: 2015
A new Center in NINS
NAOJ-Mitaka campus

Center Main Theme: *Exoplanets and Life There*

Three project offices:
1.Exo-Planet Search Project Office
2.Exo-Life Search Project Office
3.Astrobiology Instrument Project Office

Activities:
① Grants-in-Aid for astrobiology research
② Cooperation with foreign astrobiology institutes
③ Inter-University cooperation for Instrument development
④ International workshops
⑤ Invitation of foreign researchers
⑥ Development of young researchers

Summary



☐ SEEDS has explored the wide-orbit giant planets of the Solar system scale. As a systematic survey, SEEDS has been most successful in direct imaging of planets.

☐ From SEEDS, 3 direct imaging discovery of planets and boundary-mass-objects (GJ 504 b, κ And b, GJ 758 b) and 3 brown dwarfs detection in Pleiades. .
GJ 504b is a cold Jovian planet orbiting a relatively old Sun-like star and has unique atmospheric features. One young planet is also confirmed (HD 100546 b).

☐ Many circumstellar disks are detected down to r=0.1”. Fine structures such as gaps and spirals of <100 au scale are discovered for the first time, which are possible signs of planet formations. With the latest ALMA performance, these NIR scattering data will complement the submillimeter thermal emission from various disks (HL Tau, TW Hya).

☐ Wide-orbit planets population can be explained as a single distribution and its frequency is ~2% from SEEDS preliminary results.

☐ We will keep our activities with the Subaru extreme AO, IFU, and IRD and *extend to TMT era* with the help of the ABC activities.