Five Years of SEEDS: Strategic Exploration of Exoplanets and Disks with Subaru

SUM2016 at Atami or Hot Sea
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SEEDS-CoIs (an international project)

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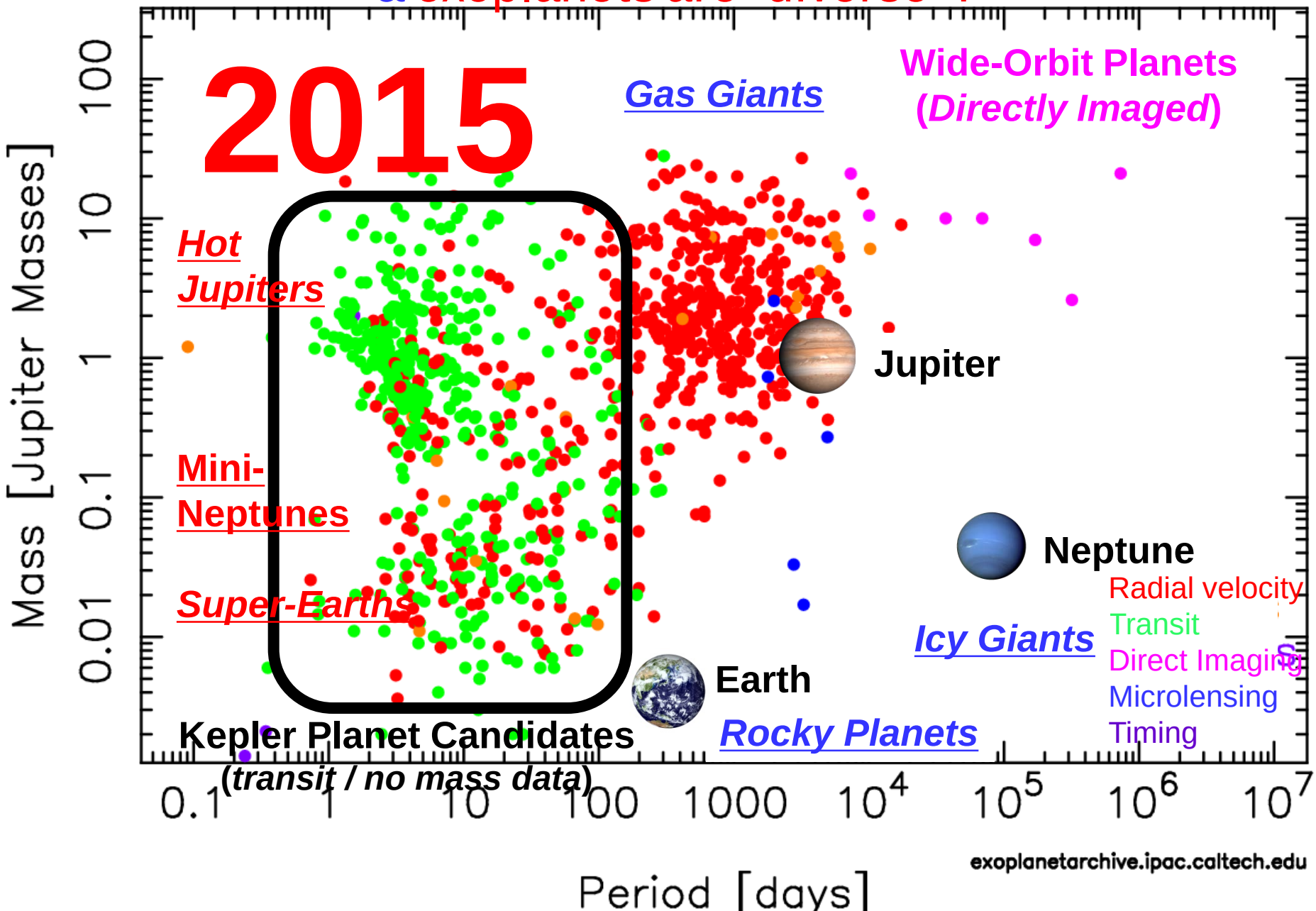
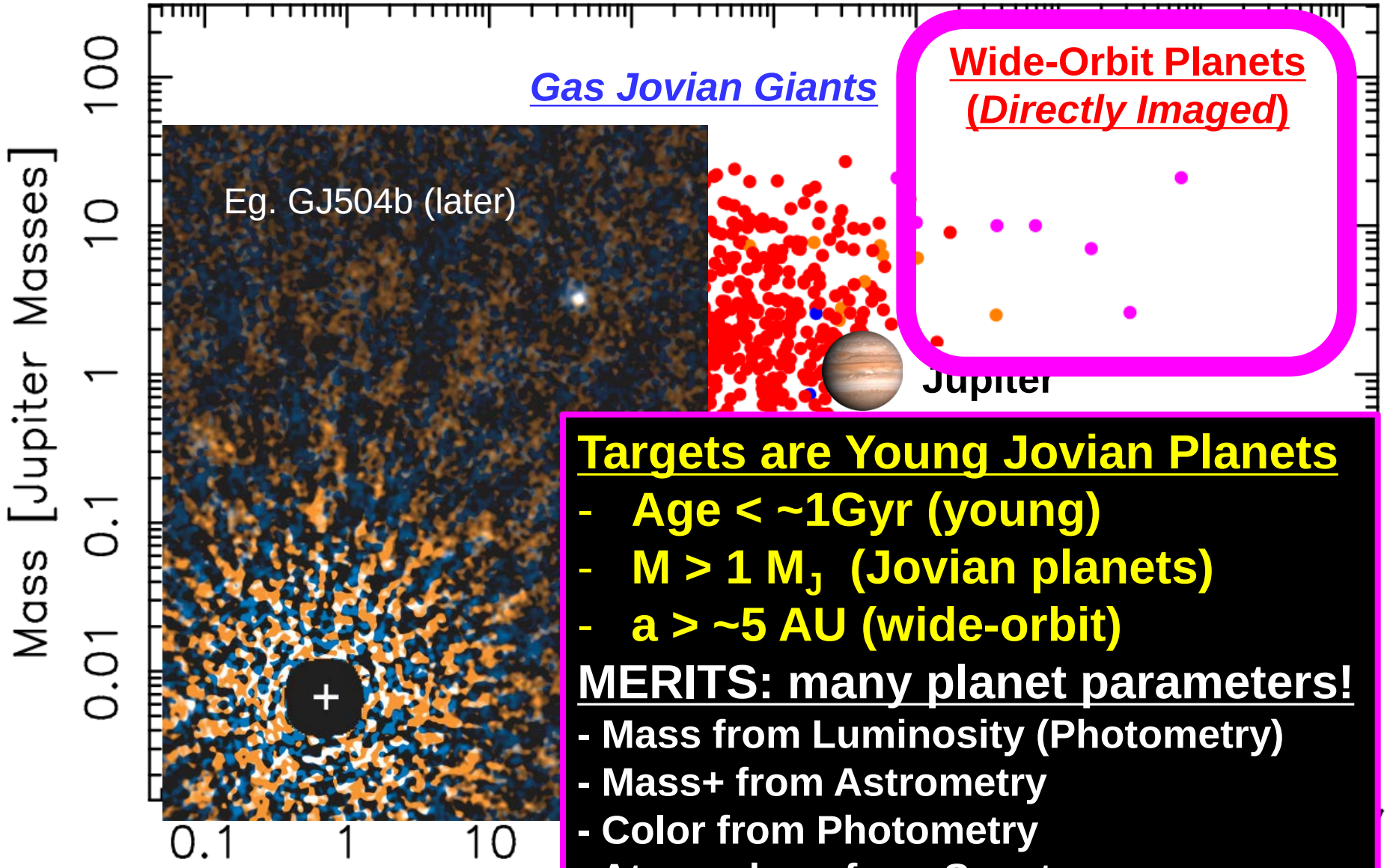
~126 members (37 institutes, ~90 Japanese, ~36 foreign)

Various techniques have led ~2000 planet discovery in 20yr & exoplanets are "diverse" !



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)

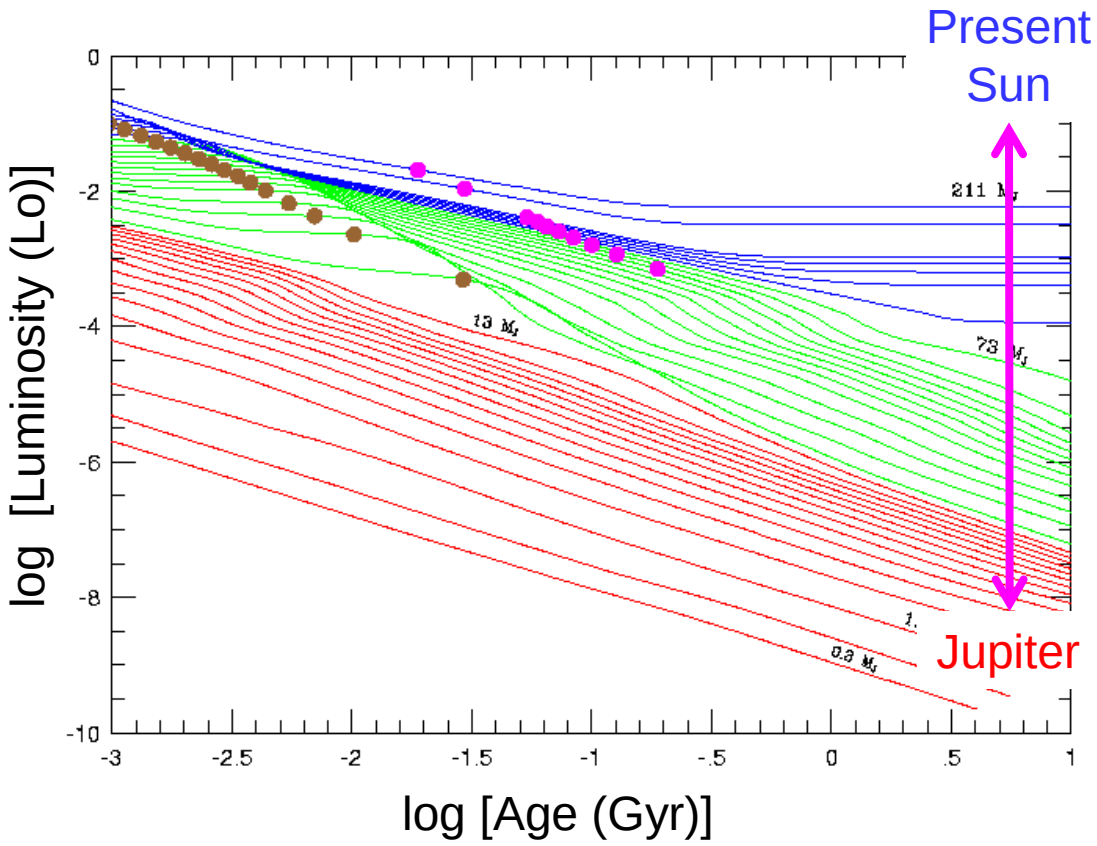
MERITS: many planet parameters!

- 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)

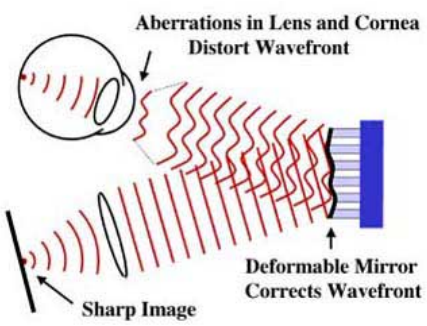


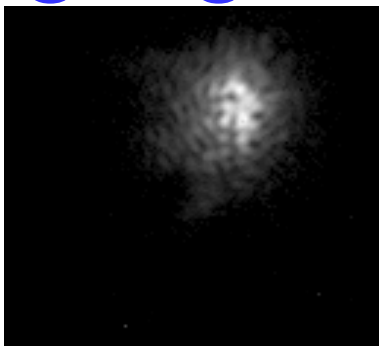
How to suppress bright star light?

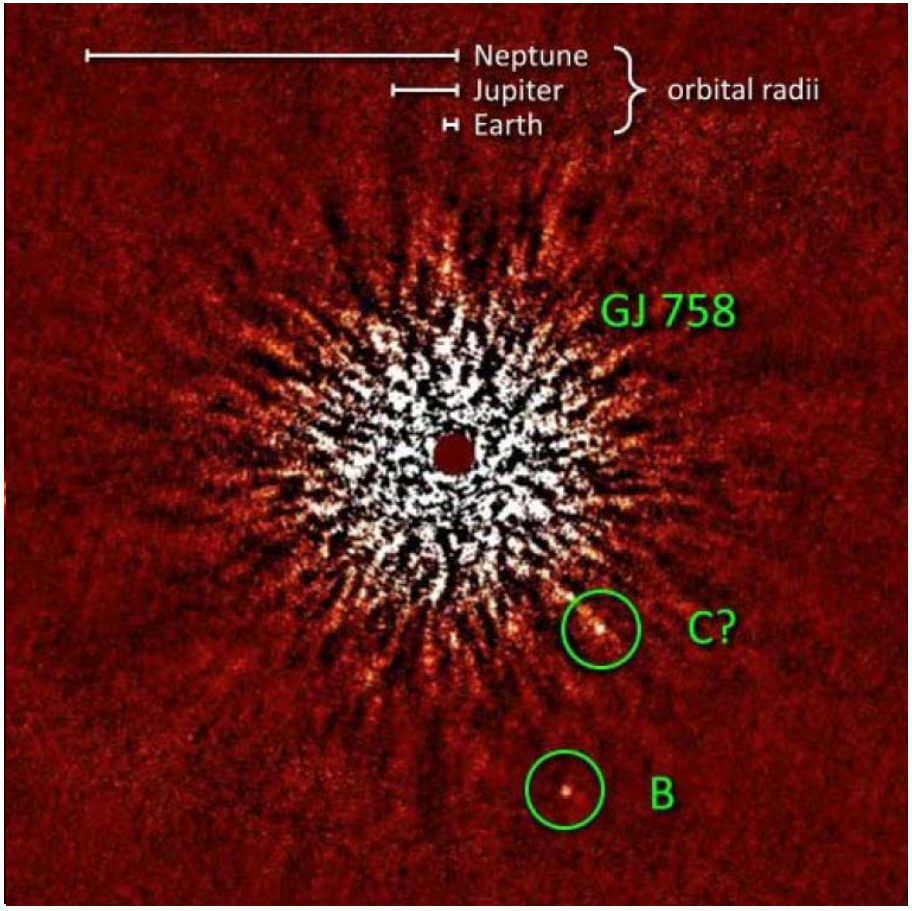
Techniques for Direct Imaging

- **Adaptive optics on 8-m class telescopes is 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

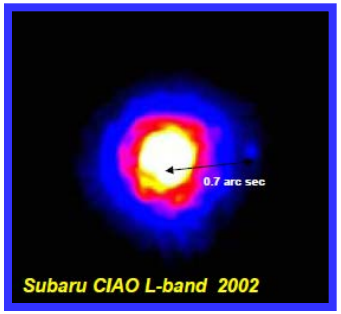




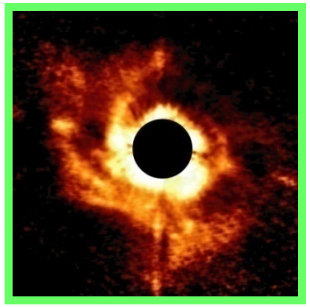


SEEDS –Strategic Explorations of Exoplanets and Disks with Subaru

- 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

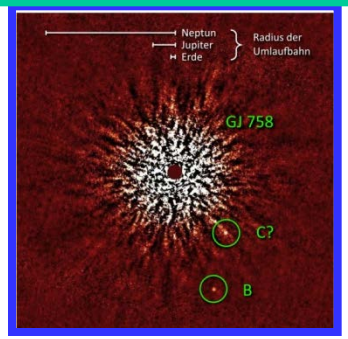


Resolution
=0.1-0.2”



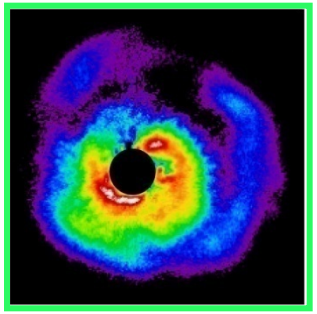
>100AU scale
w/ CIAO

⇒



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

Resolution =0.05-0.1”
Contrast Improved by ~10



SEEDS Observations Summary

Item	Number	Comment
Total nights	125 nights	Incl. 5 night compensation
Loss due to Tel+AO	5.5 nights	HiCIAO time-loss is negligible.
Loss due to weather	32 nights	26 %, poor seeing data not included
Success rate	74 %	Typical at Mauna Kea
Observed targets	428 (~500 planet+disk data)	Follow-up removed. ~80 sources in ADI+PDI, so used as planet and disk data, respectively

SEEDS Result Summary

RESULTS	NUMBERS
Refereed English Journal	３９
of which Japanese PI	１８
of which ApJ	２９
Most cited - Top3 (Muto+2012/Kuzuhara+2013/Thalmann+2009)	108/97/87
Invited talks	５６
Master＋Doctor thesis	１３＋７
Presentation (domestic + foreign)	５０＋８３

Individual Main Results in Each Category

39 refereed papers published so far

Category	Target	Discovery	Reference
NS	GJ 504 b	Planet	Kuzuhara+13
NS	Kappa And b	Planet	Carson+13
NS	GJ 758 b	Planet/BD	Thalmann+13
YSO	HD 100546 b conf.	Planet/disk	Currie+13
OC	HD23514 B, HII1348 B, etc. independent dis.	3xBD	Yamamoto+13
NS	HAT-P-7 B, KOI-94 B, etc.	M star	Narita+10
YSO	~30 resolved disk imaging	Disks w/ gap/ring	e.g., Hashimoto+11

SEEDS' Imaging Discovery of a Cold Jovian Planet – one of the lowest mass planets ever imaged

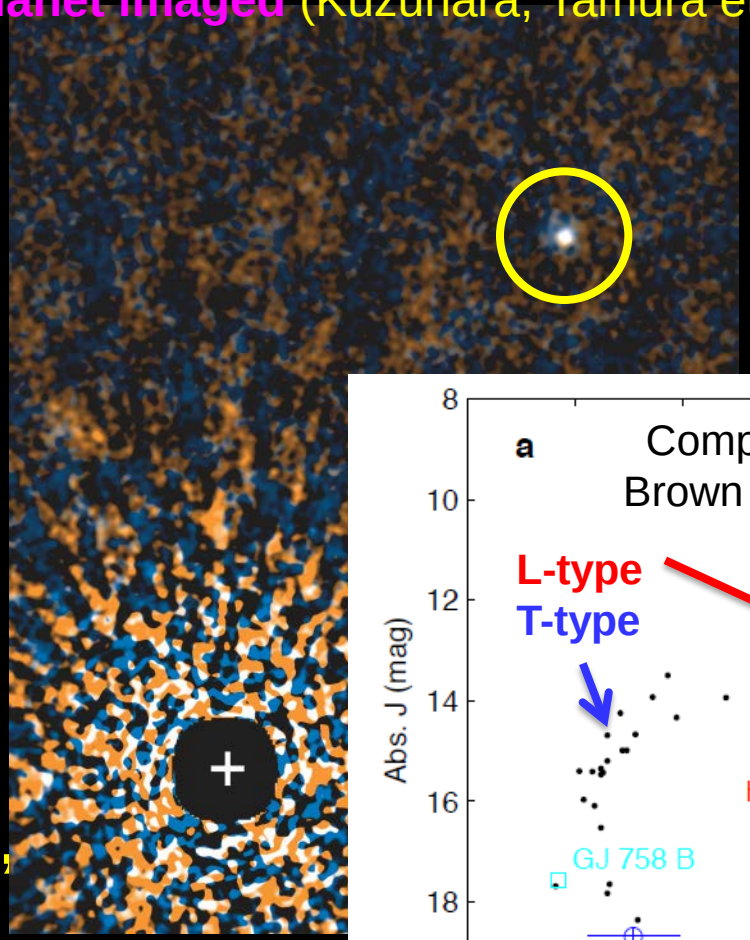
As a highlight, we report an exoplanet detection around the Sun-like star GJ 504.
A unique cold Jovian planet imaged (Kuzuhara, Tamura et al. 2013).

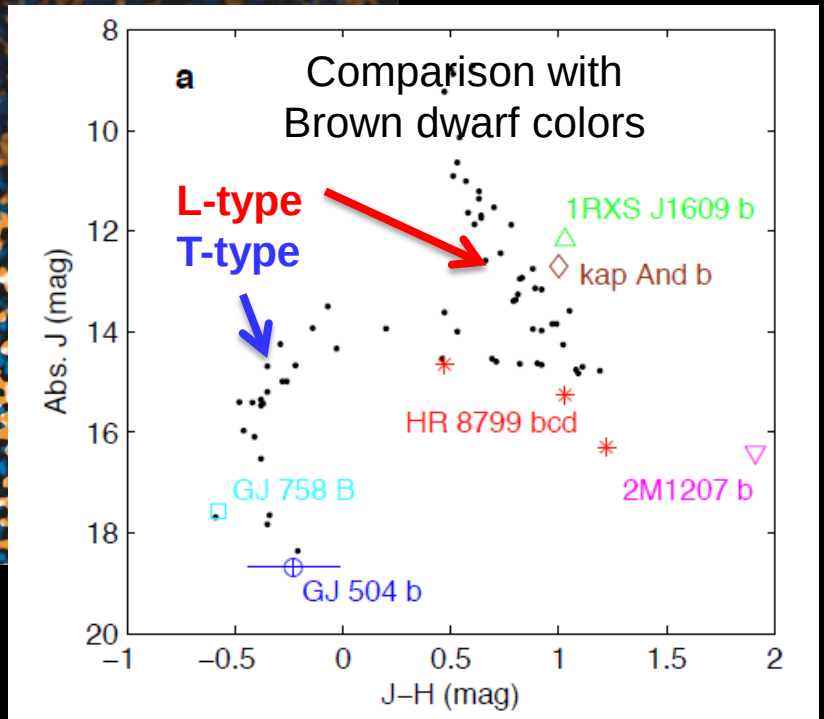
☐ Primary GJ 504 A

- G0 star at 17.6 pc
- age ~160 Myr
（oldest among imaged planets; less model dependence）

☐ Planet GJ 504 b

- m=3-4.5 M(Jupiter)
- a～44AU
- methane (only T-type, others are all L-type）
- T<600K expected

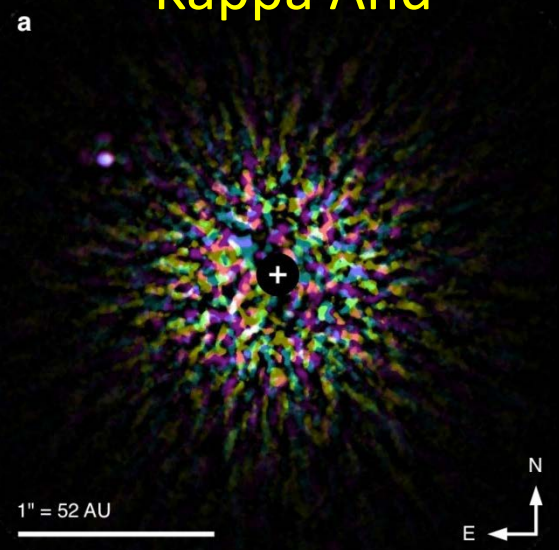




Other Discoveries and Findings

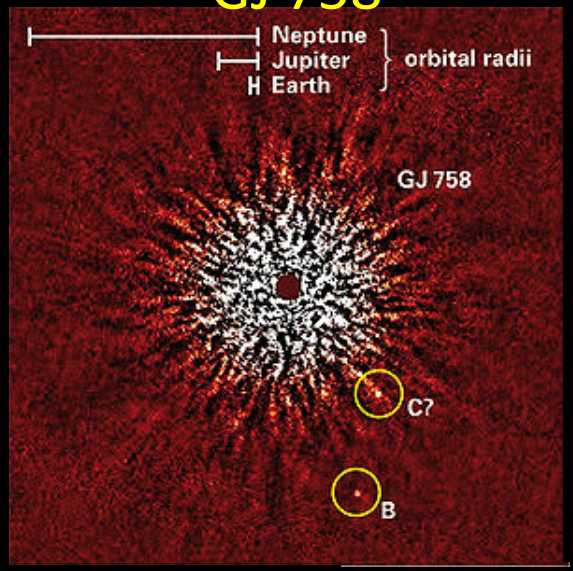
☐ SEEDS published three planet candidates, other than GJ 504b

Kappa And

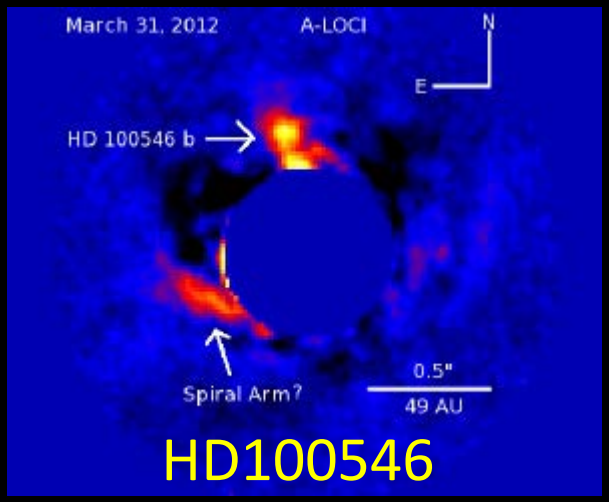


○ A planet candidate around a B-type star (Carson+2013, note recent results, Bonnefoy+2014; Hinkley+2013)

GJ 758



○ A discovery of a brown dwarf or massive planet orbiting a nearby G star (Thalmann+2009; Janson+2011)



HD100546

○ A planet around a YSO and its induced arm? (Currie+2014)

☐ SEEDS published papers summarizing the 2 or 3 year planet survey results of each category (e.g., debris disk, Janson+2013; open cluster, Yamamoto+2013, Moving Group, Brandt+2014).

SEEDS Statistics on Wide Orbit Giant Planets

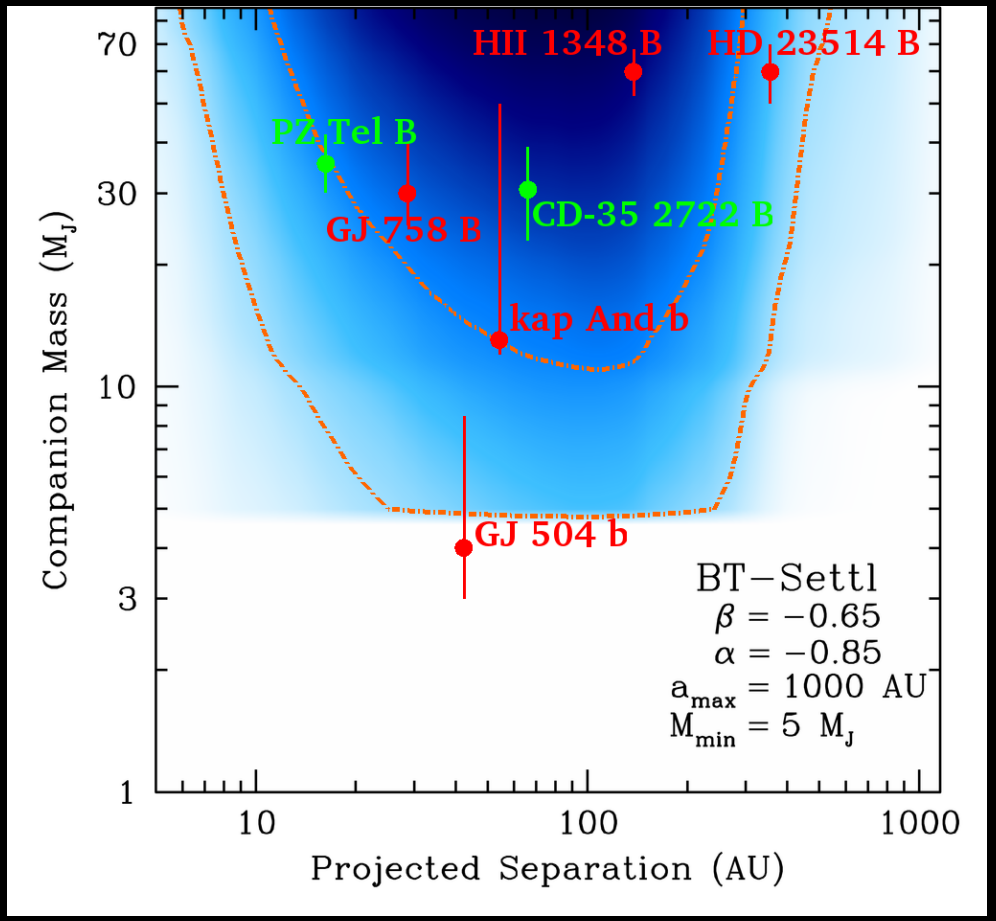
~250 stars (MG, DD, OC) are used for statistical analysis (Brandt, McElwain, Turner et al. 2014).

☐ Model

- **Mass-Semi-major axis distribution**
  dN/(dMda) = k(M^α)(a^β)
- **Mass-Luminosity relation**

☐ Data

- **Stellar age**
- **Stellar distance**
- **Stellar type/mass**
- **Contrast maps**

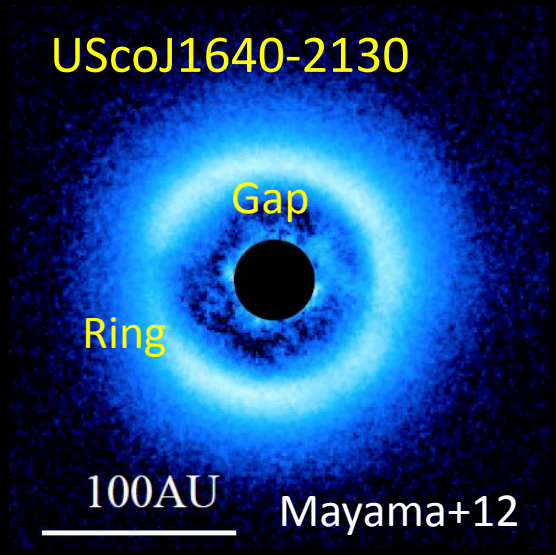


Frequency: 5–70 M_{Jup} at 10-100 AU ~ 2%

Red=SEEDS, Green=NICI

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.**

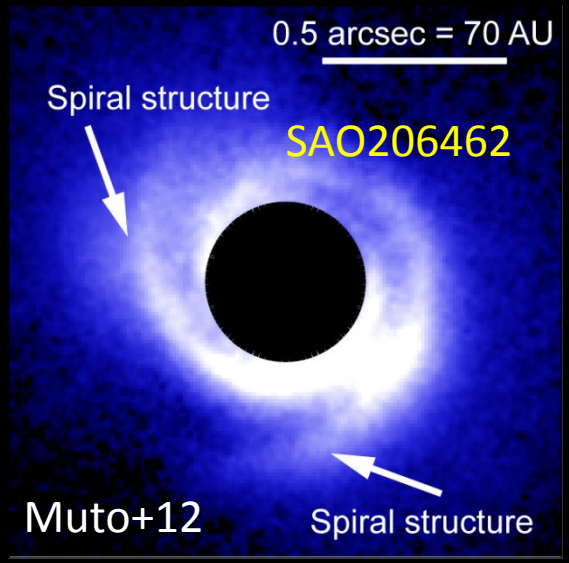


☐ **Gaps**

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

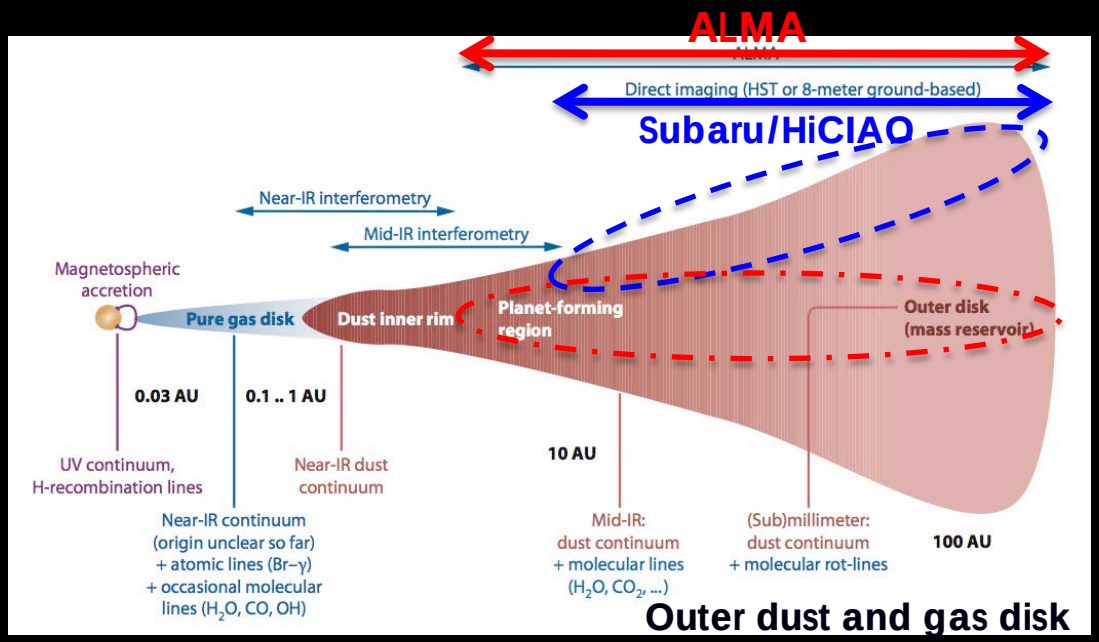
☐ **Spirals**

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



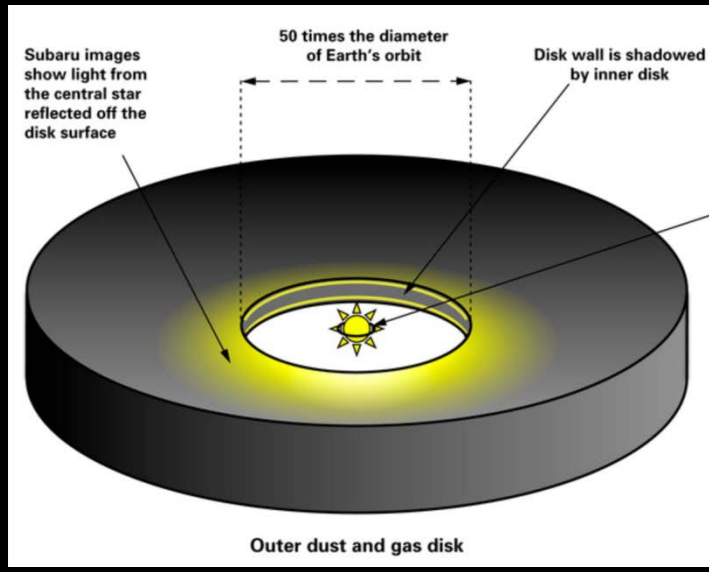
Disks: Near-Infrared vs. Submm

SEEDS has observed scattered light from disks, while ALMA can now finally observe dust thermal emission near the disk plane.
(resolution: Subaru: 0.1 - 0.06”, ALMA: 0.3 - 0.03” (recent HL Tau data)



Protoplanetary disks seen at various wavelengths

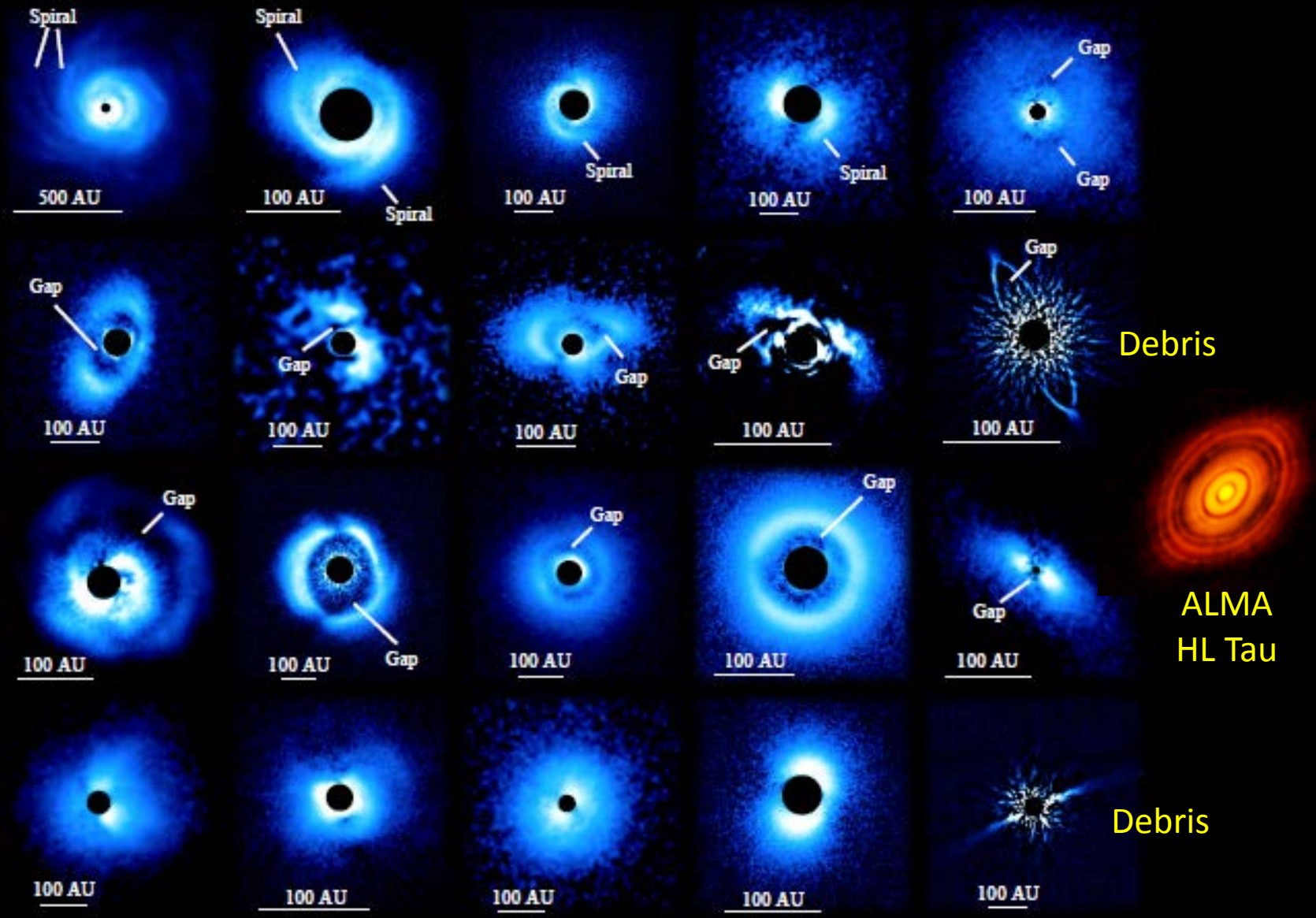
Expected geometry
for NIR scattering disks



Forward scattering
(brighter than backward scattering)

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

Even more interesting disk images will come. - Stay tuned!

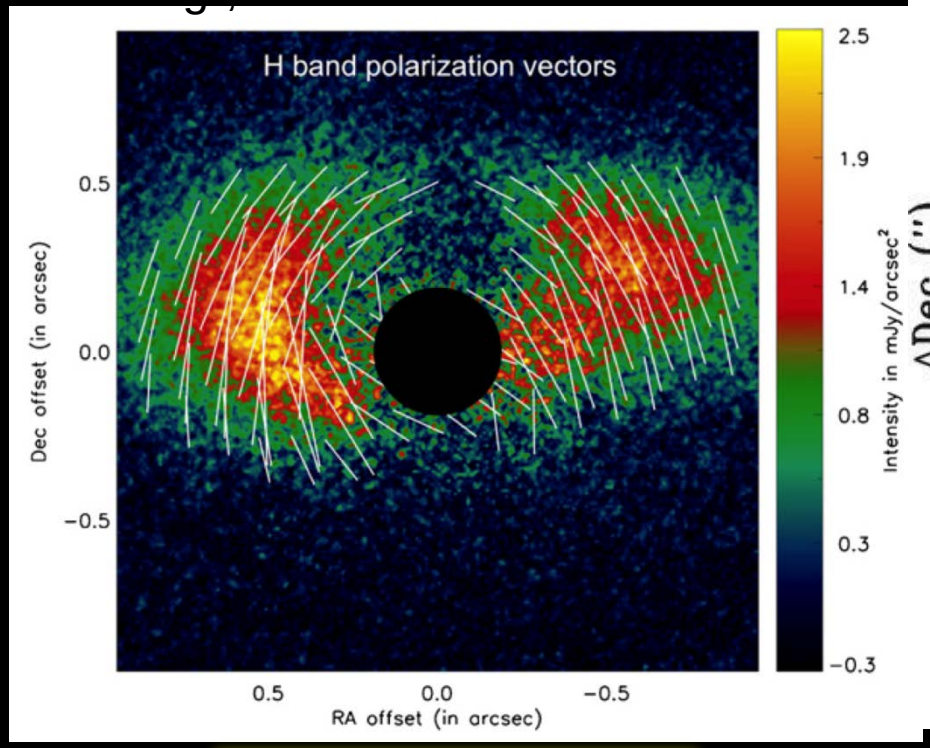


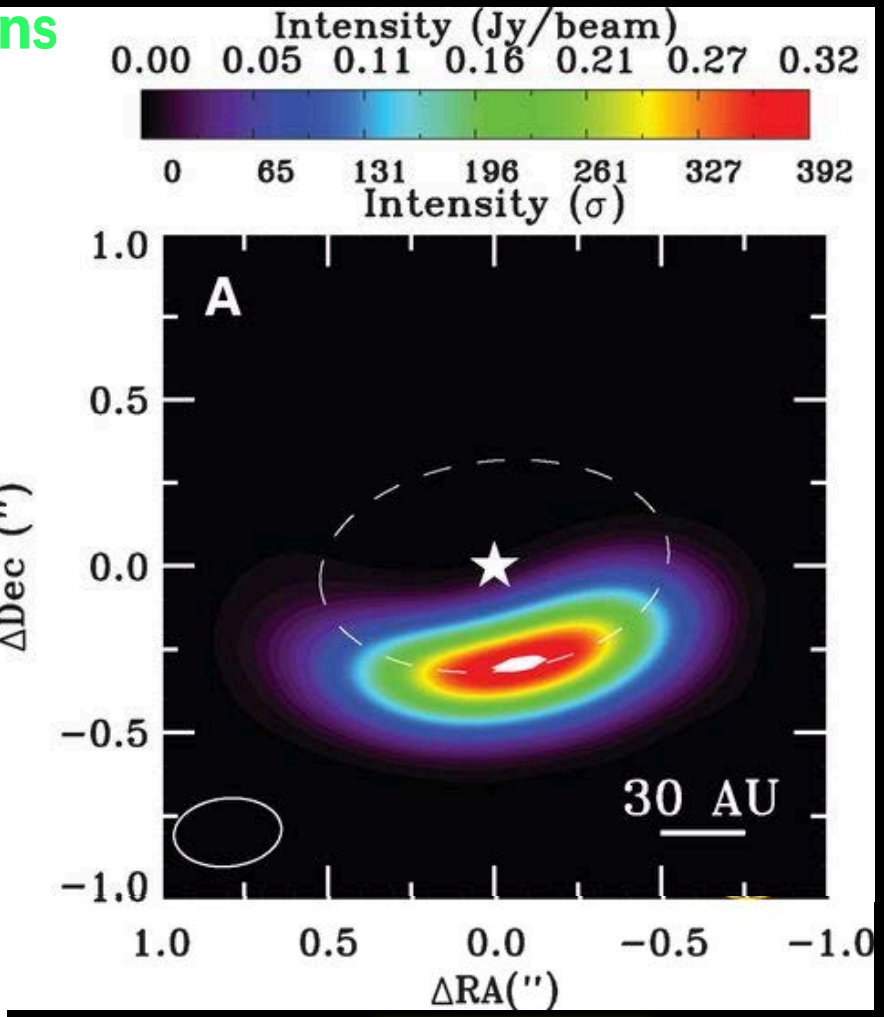
Major Results of Disk Sciences

Comparison between Near-IR and submm observations of protoplanetary disks

-An extreme case: Oph IRS 48 (Follette+2014)

A0, ~2M_{SUN}, ~15Myr, AV=12mag





Subaru/HiCIAO 1.6um POL

Dust Trap

ALMA 400 um

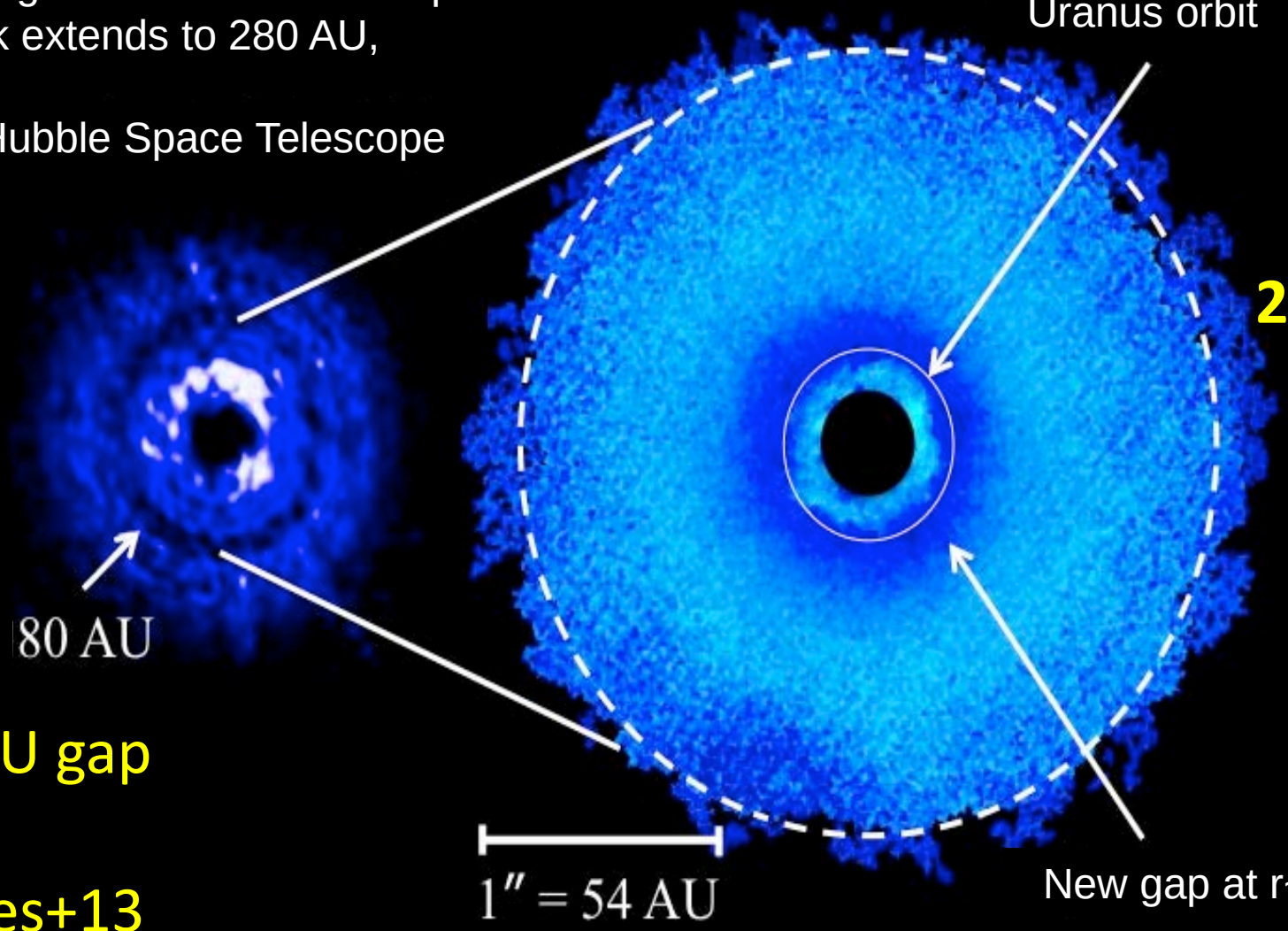
SEEDS New Disk Results: TW Hya

- the nearest classical T Tauri star
- d=56 pc
- 7 degrees inclination from pole-on
- disk extends to 280 AU,

Subaru Telescope

Uranus orbit

Hubble Space Telescope

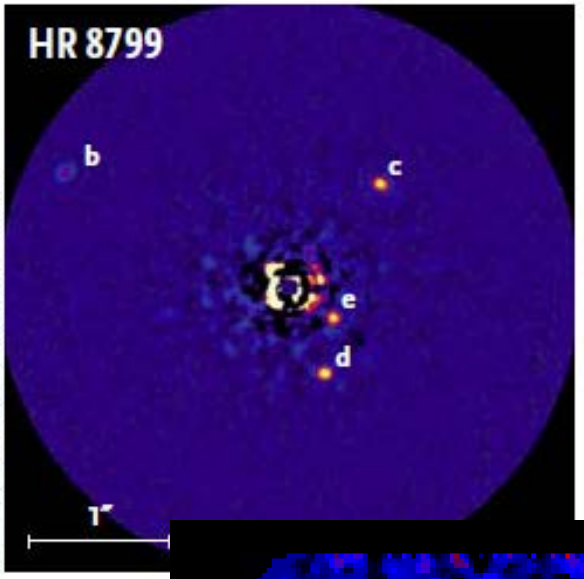


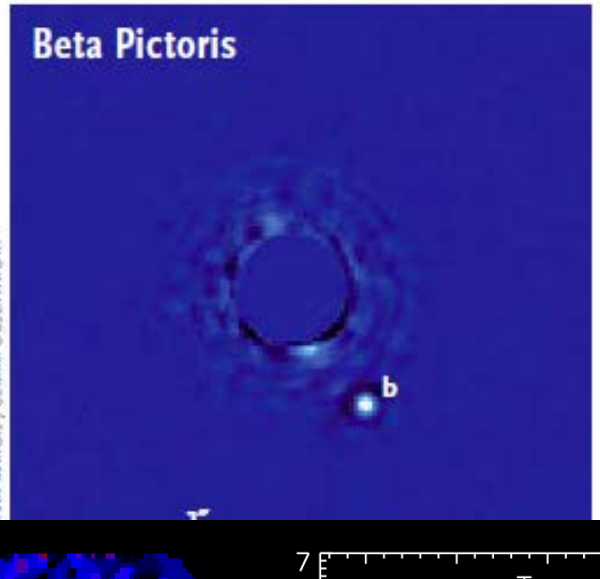
20 AU gap
SEEDS/
HiCIAO
Akiyama
+15

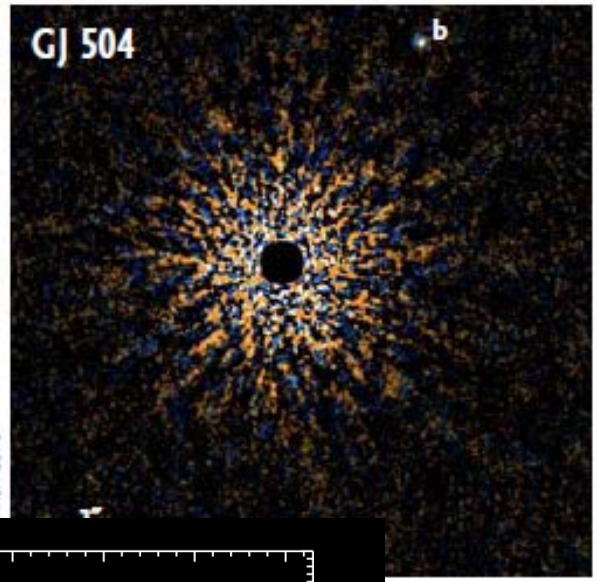
80 AU gap
HST
Debes+13

New gap at r~20 AU

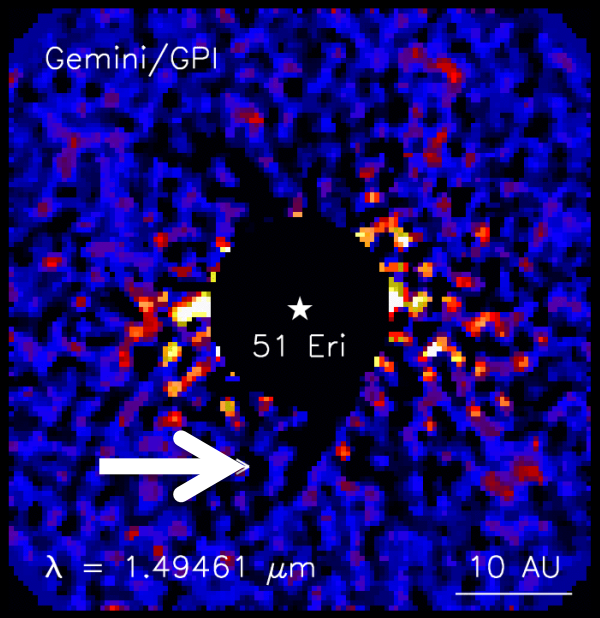
Big Three before Extreme AO

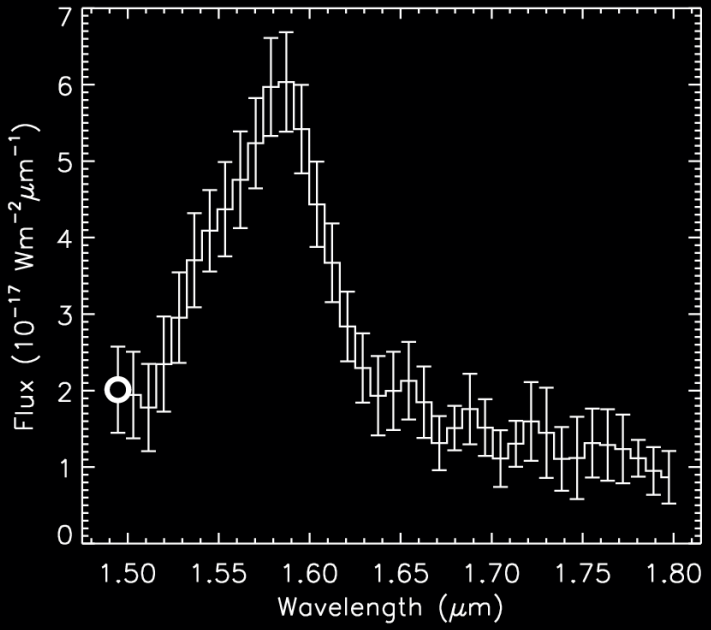






FIRST FIND
planets still h
are young giant

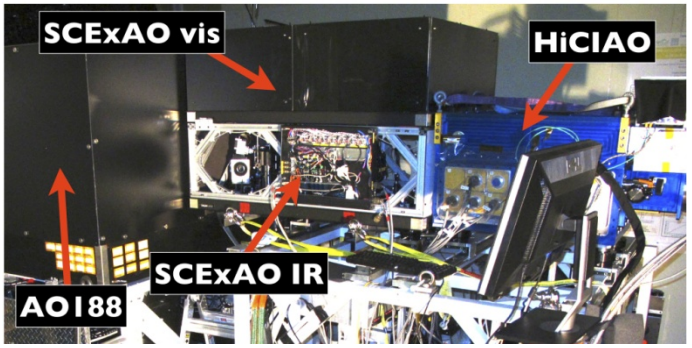


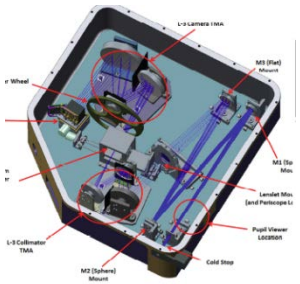


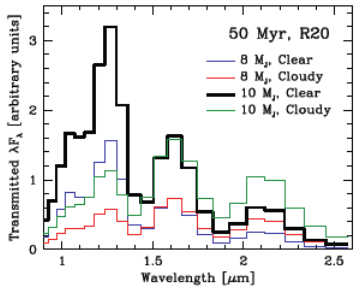
Credit:
Sky & Tel
Gemini

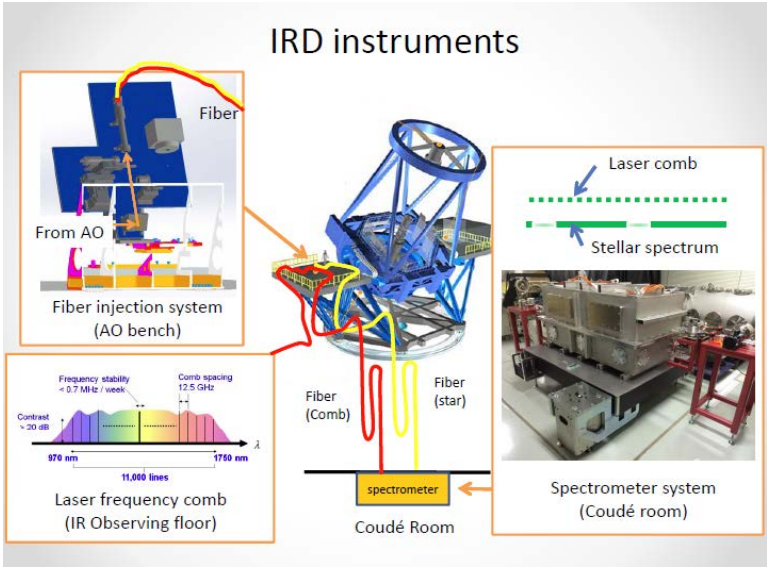
Subaru's **Next Steps** in Exoplanet Sciences

- **SCExAO: 2014- (Minowa talk; sci run started)**
  - ~2000 elements deformable mirror
  - PIAA coronagraph
  - IR bench for HiCIAO & CHARIS
  - OPT bench for FIRST & VAMPIRE
- **CHARIS: 2016- (Minowa talk, April shipping)**
  - IFU Combined with SCExAO
  - R19/R70 JHK spectroscopy
  - Small (λ/D) IWA w/SCExAO!
- **IRD: 2016- (Sato talk; just shipped to Hilo)**
  - IR echelle-grating spectrometer
  - R~70,000, fiber-fed
  - 1m/s accuracy w/ own laser-comb
  - Habitable earths and super-earths around late M stars
  - Planet formation around M stars







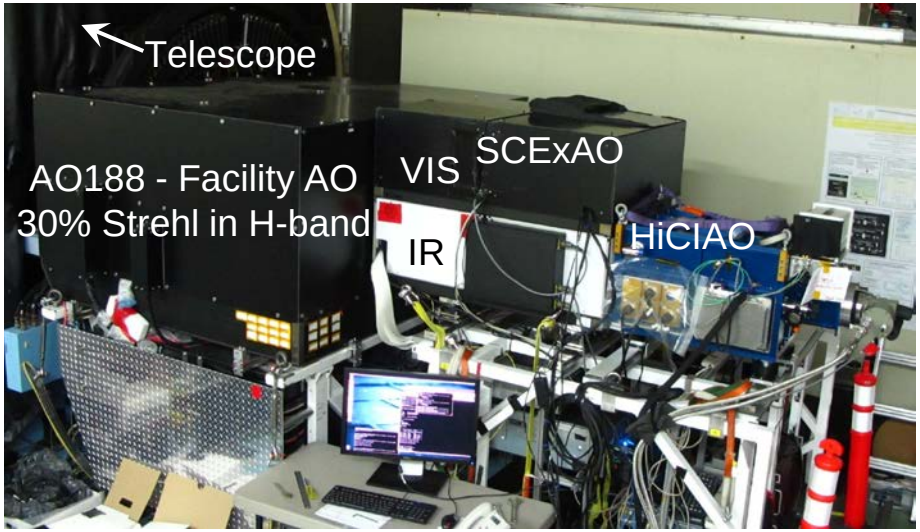


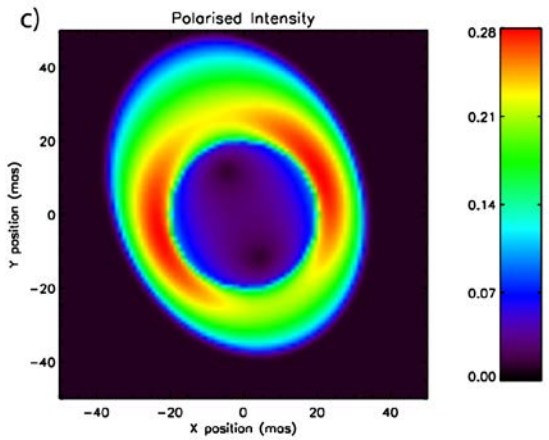
More on SCExAO: Subaru Coronagraphic Extreme Adaptive Optics

Minowa's talk

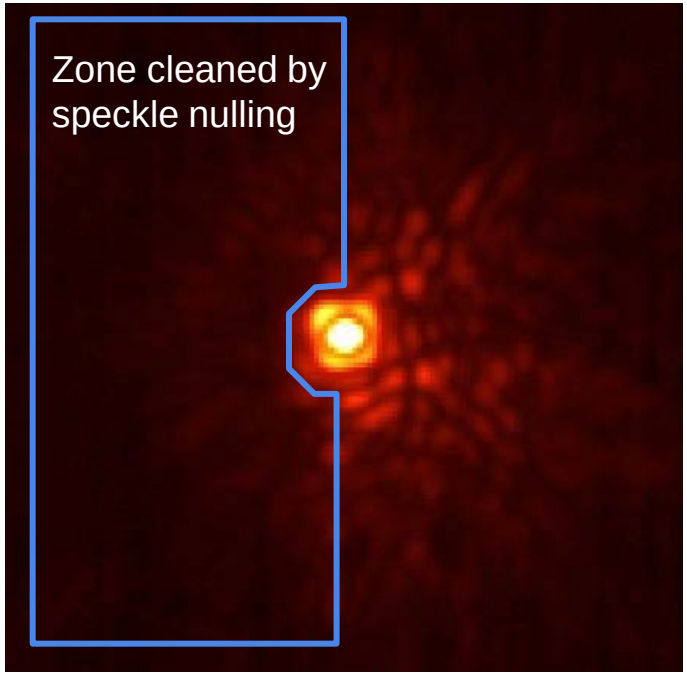
SCExAO: high contrast imager in visible and near-IR (600-2400 nm).
The wavefront control provides a clean and stable PSF (Strehl ratio over 90% in H-band).
Modules in different wavebands are used to analyse the target:

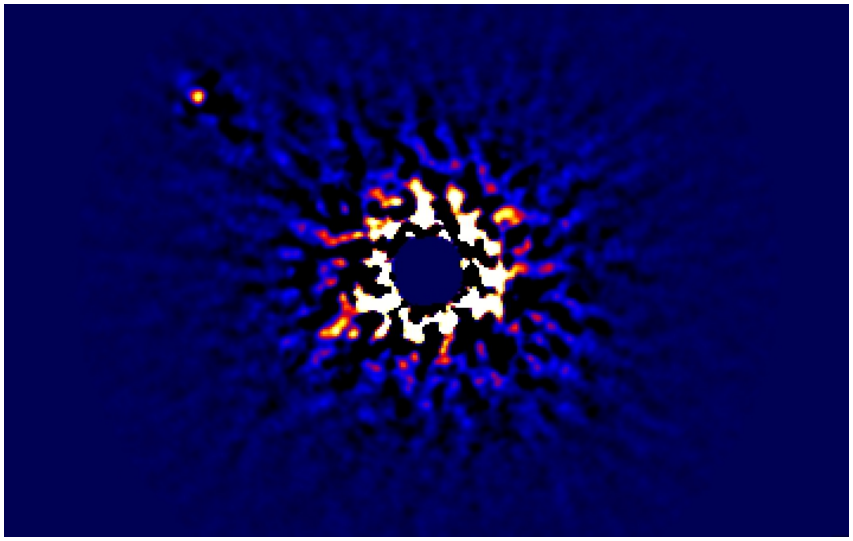
- Interferometers (VAMPIRES and FIRST) in visible, to look at binaries, stellar surfaces of the biggest stars, or dust shells.
- High contrast imagers (HiCIAO, SAPHIRA, CHARIS (IFS)), combined with coronagraphs and speckle nulling, can look at reflected light giant planets or exozodiacal disks as close as 1 lambda/D from the host star.





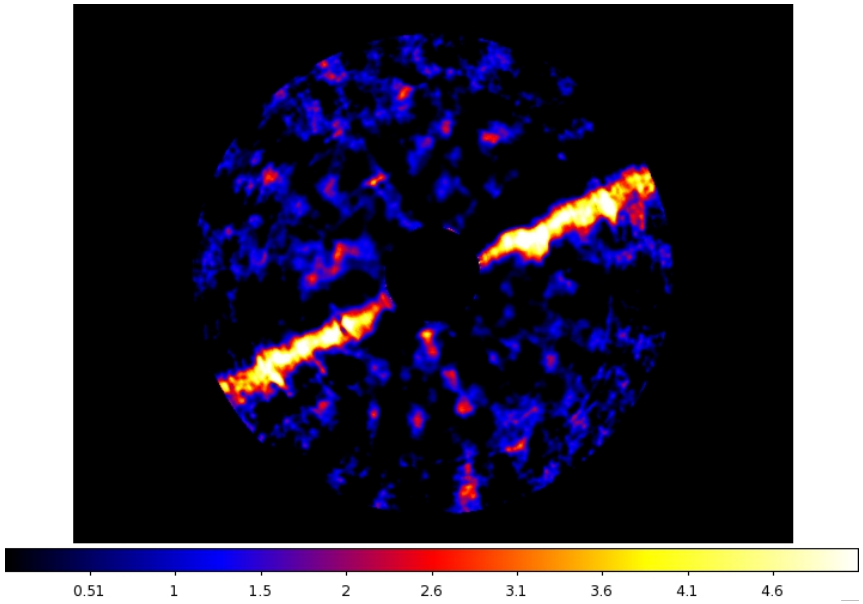
VAMPIRES RESULT: Dust shell around Mira
Inner radius: 9.3 ± 0.2 mas (which is roughly Rstar)
PA of major axis: 28 ± 3.7 ° • Aspect ratio: 1.24





kappa And b

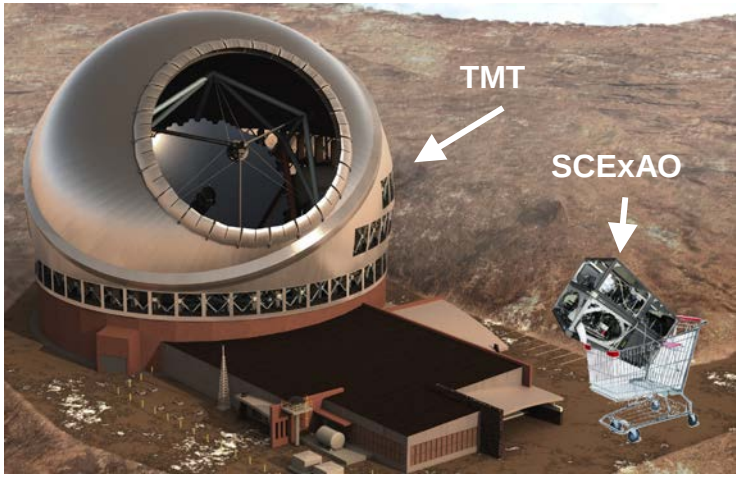
- H-band image
- SNR of companion 100:1 (3x greater than HiCIAO only)
- IWA 300 mas (greatly improved over HiCIAO only)



HIP 79977

- H-band image
- SNR~3-7 for disk (2-3x improved over HiCIAO only)
- Improved IWA over HiCIAO only by 3x

- Examples of results obtained in the current state (~70% Strehl). We should reach 90% Strehl in the next few runs, and improve IWA and SNR even more.
- commissioning of the IFS CHARIS mid-2016, to perform spectra of reflected light planets in J, H and K-bands
- Long term goal: prepare the instrument and test the technology before TMT comes online, and become the first high contrast instrument on TMT!

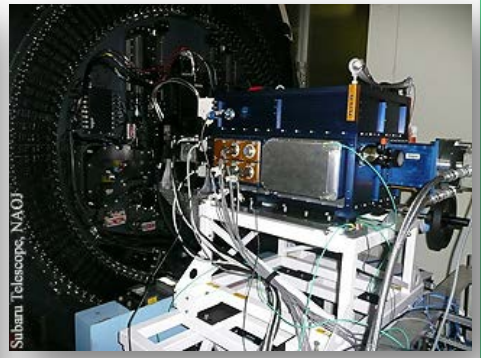


Strategy toward Earth-like planet detection and characterization (at least at ABC&ESPO)

1999 2009 2016 2020+

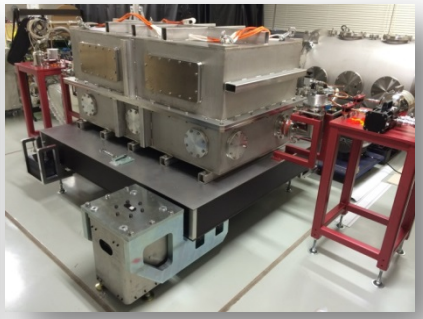
Subaru 8.2m

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)
(SCExAO+CHARIS for GP)
TESS

TMT - SEIT、PFI

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

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

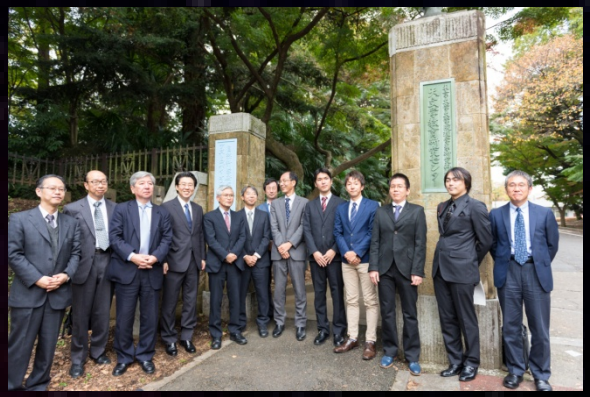
Planet detection around nearby M dwarfs

New Center for Exoplanet Studies in Japan established in 2015!

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

Astrobiology Center

What is Astrobiology:
A research field of Origins and Evolutions of Lives in the Universe.



Established: 2015 (as a New Center in NINS)
Main Theme: *Exoplanets and Life There*

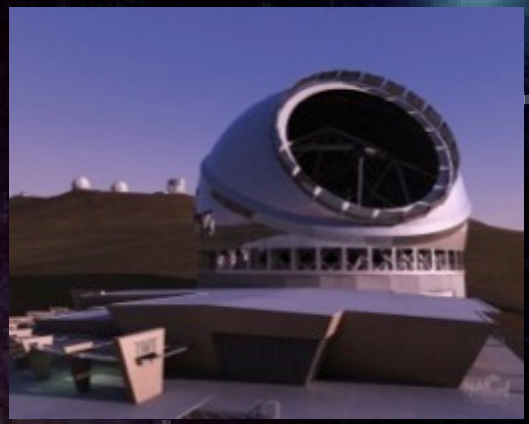
Three project offices:
1.Exo-Planet Search Project Office
2.Exo-Life Search Project Office
3.Astrobiology Instrument Project Office

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

Subaru: 8m Telescope

Mitaka campus

TMT: 30m Telescope



Exo-Planet Search Project Office

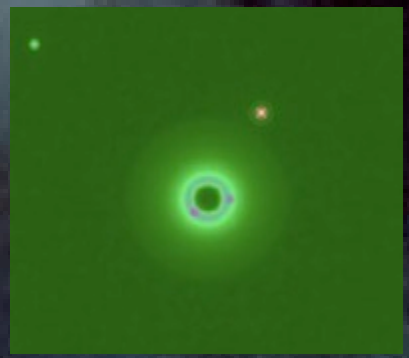
Habitable Planet search with Subaru and TMT and space telescopes.

Exo-Life Search Project Office

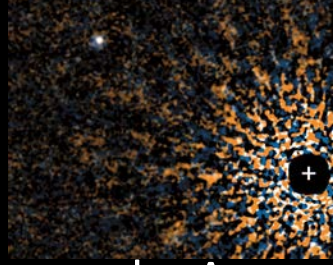
Atmosphere analysis and biomarker confirmation on habitable planets.

Astrobiology Instrument Project Office

Instrument development for "2nd Earths" on TMT and future space telescopes



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 planet and boundary mass objects (GJ 504, Kappa And, GJ 758) 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).

☐ 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. **More and more disk data are coming; please stay tuned!**

☐ 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.