Studies of Exoplanetary Systems with Subaru Telescope

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Topics

Review recent exoplanet and disk studies conducted by Subaru Telescope

- ☐ Especially, focus on recent discoveries of SEEDS project

  - Exoplanet imaging survey
  - Disk characterization

- ☐ Brief introduction of future projects

  - IRD, SCExAO, CHARIS

Strategic Explorations of Exoplanets and Disks with Subaru (SEEDS)

□ SEEDS is a strategic campaign to search for exoplanets and characterize protoplanetary/debris disks with high-contrast direct imaging

□ NAOJ is leading SEEDS based on collaborations of Japanese and international planet/disk astronomers

- More than 120 members are working in SEEDS
- PI is Motohide Tamura (Univ. of Tokyo)

□ 120-night observations for exoplanets and disks with Subaru 8-m telescope

- SEEDS started in September, 2009
- Currently, observations of 90 nights have been performed
  (※ including bad-weather nights)

Goals of SEEDS

Our goal is to contribute to resolve the following key questions.

Q: How many wide-orbit (>10 AU) giant planets do exist?

※Only direct imaging can detect, but currently, only 10–20 known detections

Q: What are their properties? (e.g., mass, orbit, or atmosphere?)

⇨ provide useful clues to uncover origin/evolution of giant planets

Core accretion+ migration?

Gravitaional Instability?

Q: What are disk structures?

⇨ give observational constraints on circumstellar disk evolutions and their link to giant planet formations

Direct imaging technique can detect these planets and disk structures

Advantage of SEEDS

SEEDS has some advantages compared with direct imaging campaign conducted so far.

1. Subaru enables High-sensitivity and high-resolution imaging
   => essential for imaging of faint objects like planets/disks close to their hosts

2. State-of-the-art adaptive optics (AO188) and near-infrared camera (HiCIAO)
   => help to obtain more stable and high-quality point spread functions and high-sensitivity at near-infrared

3. State-of-the-art high-contrast imaging techniques
   - Angular Differential Imaging (ADI; Marois+2006)
   - Polarization Differential Imaging (PDI; Perrin+2004).

   => these techniques improve the detection limit by a factor of 10–100

4. We can observe many targets thank to large observation nights (120 nights)
   => critical for statistical studies

SEEDS Scientific Category

SEEDS has 5 categories that have independent scientific targets/motivations.

Category	YSO	Moving Group	Open Cluster	Nearby Star	Debris Disk
Target	YSOs in Tauras, Oph, Upper Sco, etc	Young Stars in Nearby Moving Groups	Stars in Pleiades OC	Various-type stars in solar neighborhood	Stars with debris disks
Age coverage	1-10 Myr	10–100 Myr	130 Myr	100-1000 Myr	10 Myr– a few Gyr
Distance	~130 pc	10 – 50 pc	~130 pc	10 - 50 pc (except RV targets)	10 – 100 pc
Obs. #	~70	~60	~30	~140	~50

- mainly focus on solar-type stars (GK) but cover higher-(BAF) or lower-mass (M)
- cover age range from ~1 Myr to a few Gyrs to prove planet evolution
- Planets and disks are simultaneously surveyed in YSO and debris disk categories

SEEDS Planet Discovery: GJ 504b

Kuzuhara et al. 2013 ApJ

We recently detected a Jovian planet around GJ 504.

A Sun-like star, GJ 504, was observed as a target of SEEDS NS (CA) category.

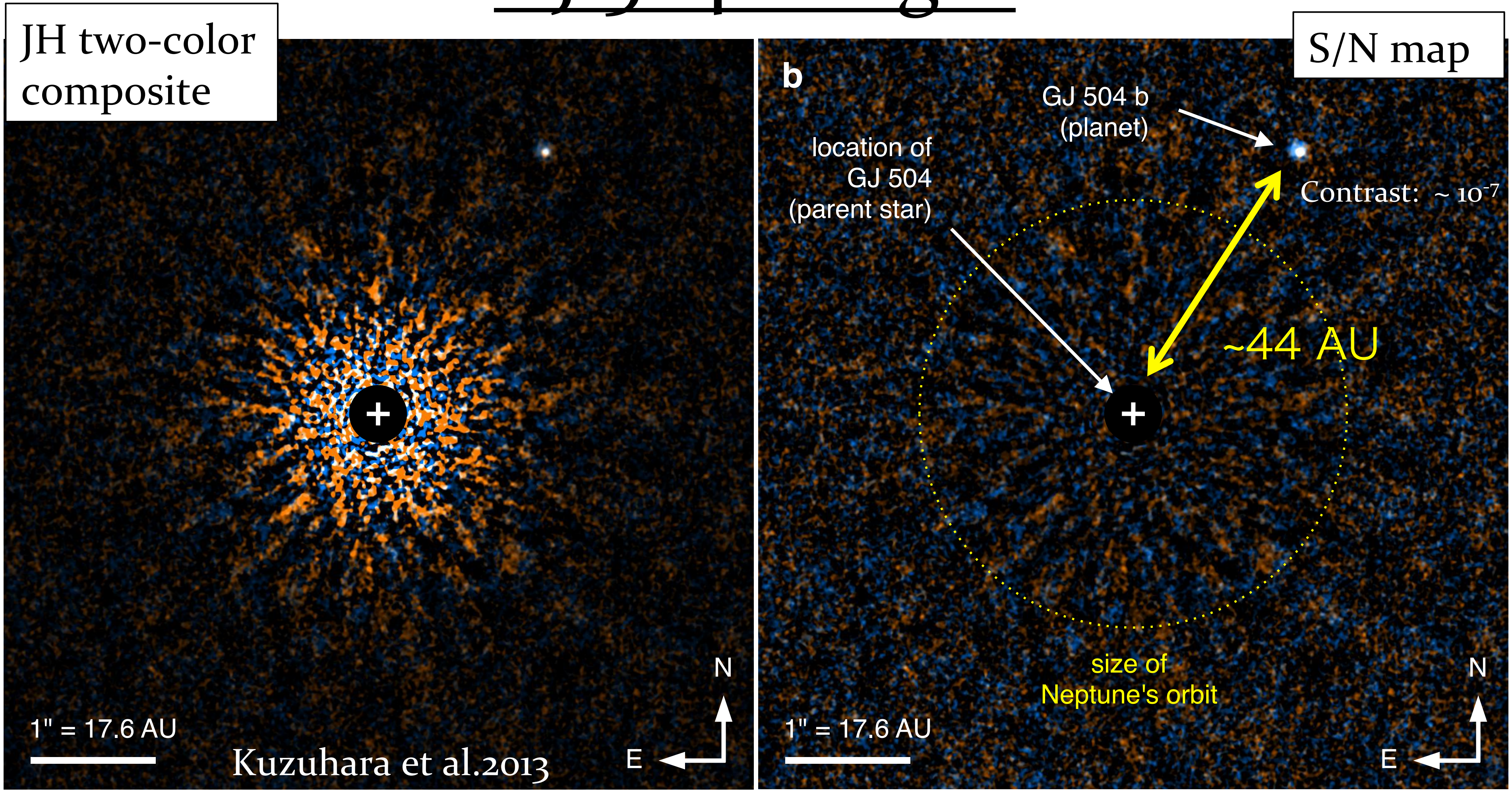
□ Property of GJ 504

- Distance: ~17.6 pc
- Spectral type: G0
- Mass ~1.2 M_{sun}
- Age: 160 [+350, -60] Myr
- Metallicity: ~2 x solar

  (Valdes+04, Takeda+07, Valenti+Fischer 05)
- V ~5.3 mag

We observed GJ 504 from Mar. 2011 to May 2012.

GJ 504 Images



- Obtain photometry at four bands

Photometry	J	H	Ks	L'
(vega mag.)	19.9	20.1	19.2	16.8

- 7 detections of GJ 504b, enabling us to conclude that GJ 504b is indeed orbiting the host

Property and Uniqueness of GJ 504b

- Mass: 4 (error range: 3-8.5) Jupiter masses (M_{Jup})
  - estimated by comparing JHKL' luminosity with mass-age-luminosity model
  - The estimated mass is among the lowest of directly-imaged planets
  - Due to the old age (>100 Myr) of GJ 504b, its mass estimate is less dependent on the uncertainty of mass-age-luminosity model

  e.g., HR 8799b (Marois+2008; 5 M_{Jup} => more massive than 20 M_{Jup})
  GJ 504b (4 M_{Jup} => basically less than ~14 M_{Jup})

  => most reliable estimate based on the model, compared with the previous cases

- T_{eff} of planet is ~500 K, which is lowest among the previously imaged planets
- First imaged planet around solar-type main sequence stars
- Color of this planet implies a less cloudy atmosphere
  (previously imaged planets could have cloud-rich atmospheres)

Property and Uniqueness of Planet GJ 504b

- Mass: 4 [+4.5, -1] Jupiter masses (M_{Jup})
  - estimated by comparing JHKL' luminosity with mass-age-luminosity model
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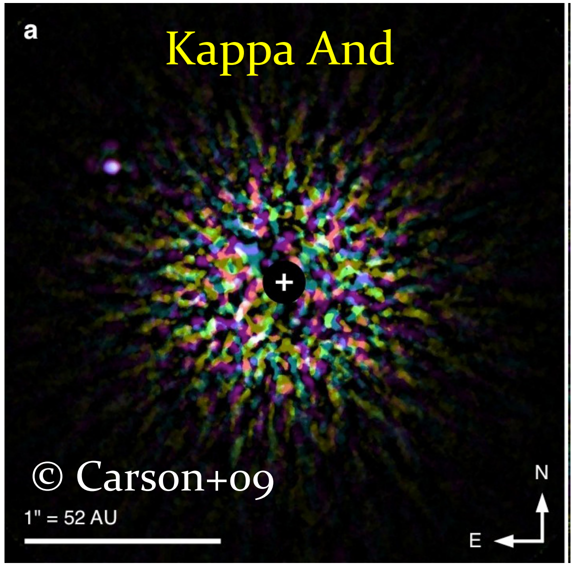
SEEDS proved that a planet with these properties indeed exist and can be formed, as the first time.

=> m cases

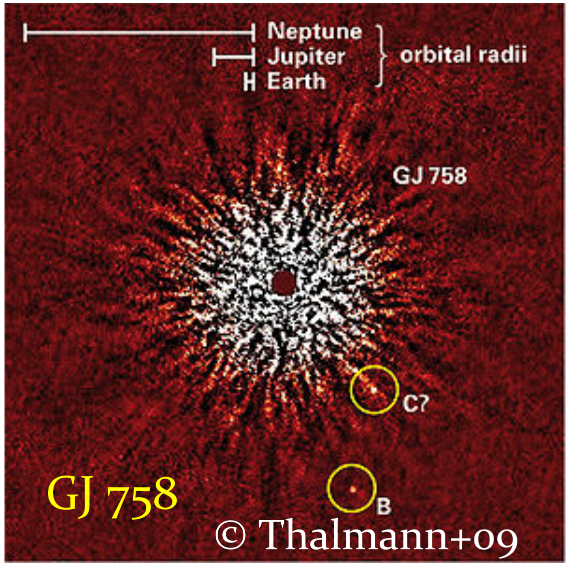
- coldest T_{eff} (~500 K) among the previously imaged planets
- First imaged planet around solar-type main sequence stars
- Color of GJ 504b implies a less cloudy atmosphere
  (previously imaged planets could have cloud-rich atmospheres)

Other Discoveries and Findings

☐ SEEDS detected two planet candidates, other than GJ 504b



○ The first imaging of a planet candidate around B-type stars (Carson+2013, note recent results, Bonnefoy+2013; Hinkley+2013)



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

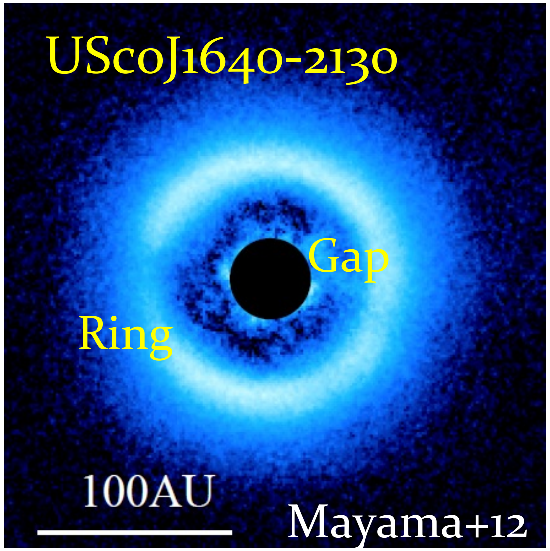
☐ SEEDS published papers summarizing the 2 or 3 year planet survey results of each category (e.g., debris disk, Janson+2013; open cluster, Yamamoto+2013).

☐ Other categories' summaries and statistics will be submitted soon.

☐ Data reduction software paper (Brandt+2012).

Major Results of Disk Sciences

SEEDS has observed scattered light from disks and revealed many disk structures that are possible signs of planet formations.

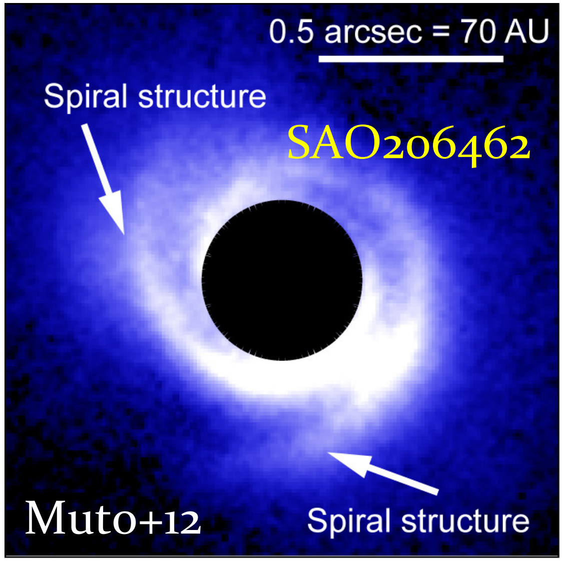


□ Gaps

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

□ Spirals

A gravitational perturbation from an embedded planet generate spiral density waves

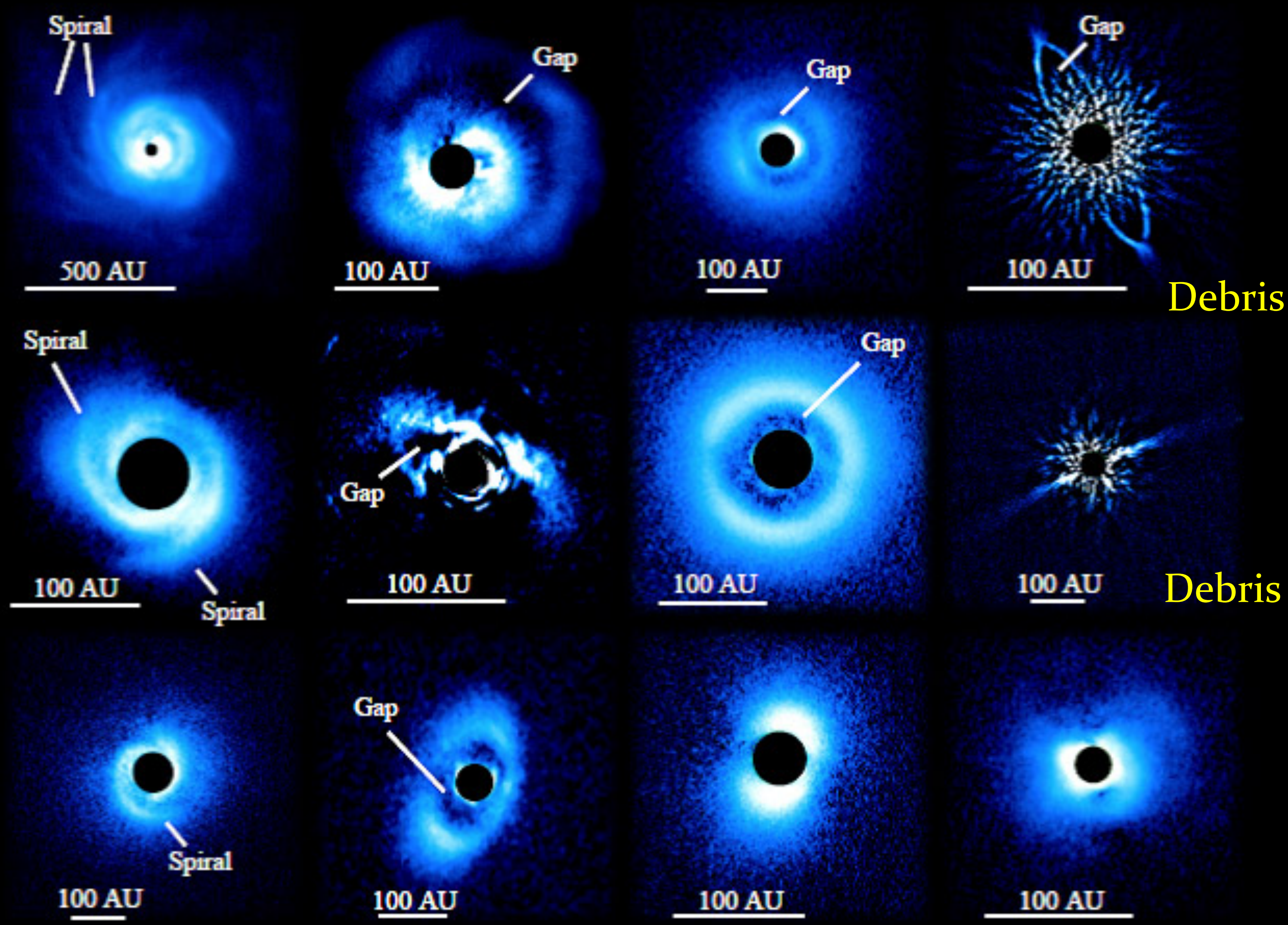


□ Some disks have been already resolved by SMA, etc, but SEEDS have detected many disks **as the first time**

□ no planet detections but provide the observational limits on their presences

Gallery of Disk Images

© NAOJ/Subaru



for many disks, provide high contrast/resolution images that have not been achieved

Summary of Disk Studies

- ☐ SEEDS resolved 11 disks. Their images were published in 13 papers.

  - disk images of ~20 targets were resolved besides published ones (to be published)

- ☐ SEEDS found 5 disk gaps/holes; 3 spirals. Their images were published.

  - Interestingly, some disks have no gaps/holes on NIR images, though they have gaps/holes on sub-millimeter images (Dong+2012)

    => demonstrate that disks have complicated structures than ever known

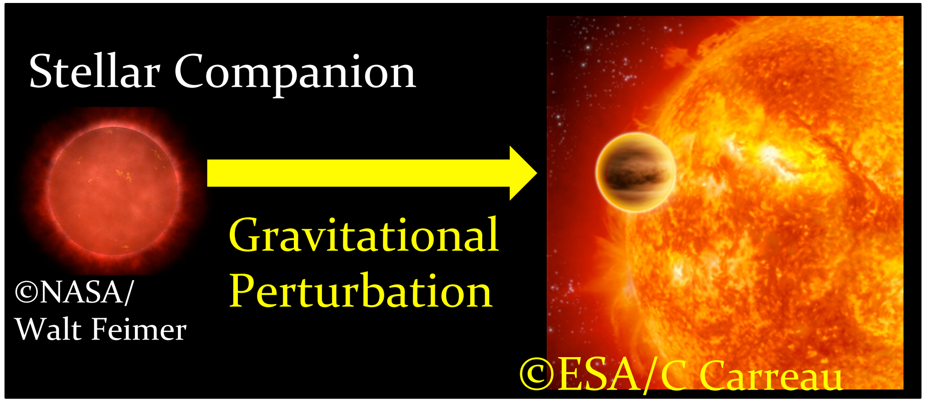
- ☐ We have modeled the disk properties by comparing the detailed radiative transfer simulations based on Monte Carlo scheme with our obtained (polarized) scattered images (e.g., Follette+2013; Takami+2013; Dong+2012)

  => lead to provide more useful information than just presenting data

- ☐ Our finding should connect to disk structure studies by **ALMA**, which have spatial resolutions comparable to SEEDS.

Studies for Origin of Close-In Planets

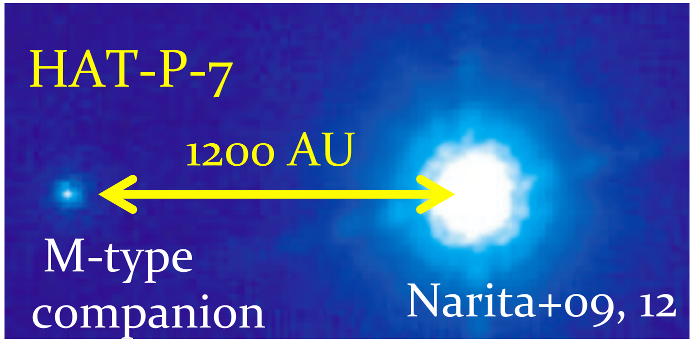
SEEDS searches for a stellar companion around a star with an close-in planet, such as hot-Jupiters, detected by indirect techniques.



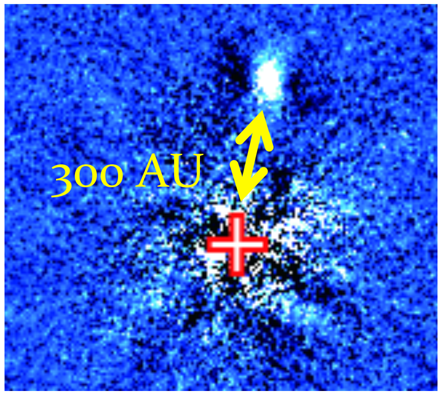
Gravitational perturbation from a stellar companion may influence an orbit of a planet, producing a close-in planet

=> Probed by SEEDS

☐ Detection of a stellar companion to HAT-P-7, which has a retrograde close-in Jupiter



☐ A companion candidate of KOI-94

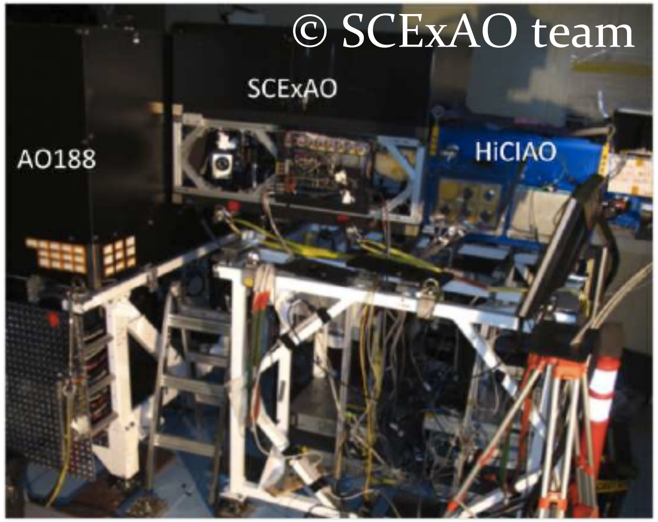


SEEDS is also useful for evaluation of a false-positive for a Kepler planet

Takahashi+2013
Submitted to ApJ

Introduction of Future Projects

☐ SCExAO --- very high-contrast imaging for planets with separations < 1"
(PI: O. Guyon@Subaru telescope)



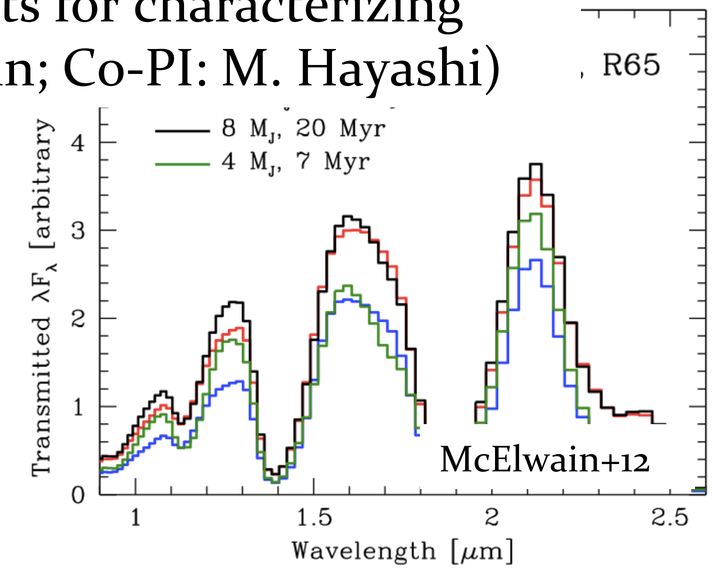
- adopt very advanced techniques

⇒ enable 10^{-6} — 10^{-7} contrast imaging
⇒ Jupiter-like planet detections at < 10 AU

- This can be used in SEEDS campaign
- need only small commissioning observations

☐ CHARIS --- IFU based spectroscopic instruments for characterizing directly-imaged planets (PI: J. Kasdin; Co-PI: M. Hayashi)

- operation with SCExAO
- under development (2015 Start)



☐ InfraRed Doppler (IRD)

- Earth-like planet survey around M-type stars
(=> Takayuki Kotani's talk)

Summary

☐ Subaru telescope and SEEDS have performed direct imaging surveys for exoplanets and circumstellar disks

- 3 direct imaging of planet candidates; GJ 504b is a Jovian planet
- many detections of circumstellar disks
- We have found/characterized a dozen of disk structures that are possible signs of planet formations.
- Stellar companions around stars with inner exoplanets detected by indirect techniques, giving clues to uncover the origin/evolution of inner planets.
- published some papers of 2 or 3 year summary for survey results of each category => other categories' summaries continue to be published.
- We plan to publish papers reporting statistical information for our survey results.

☐ Next future exoplanet surveys are planed based on new instruments such as SCExAO, CHARIS, and IRD.