



# SEEDS

## Direct Imaging of Exoplanets and Their Forming Disks with the Subaru Telescope

*– AAS Boston –*

2014. 6. 4 Mon 10:30–10:45

**Motohide Tamura**

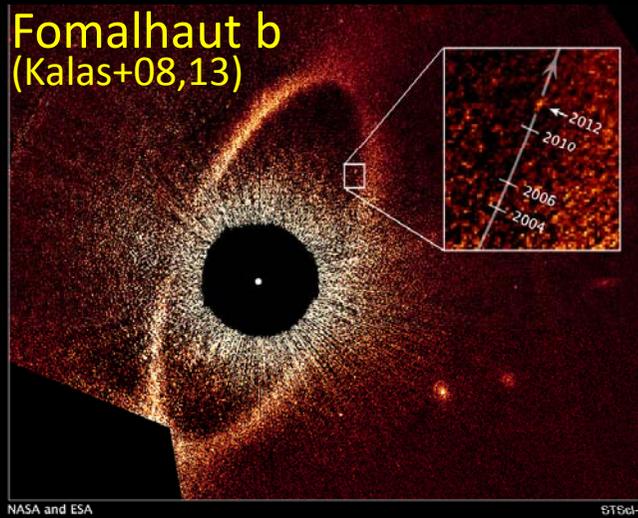
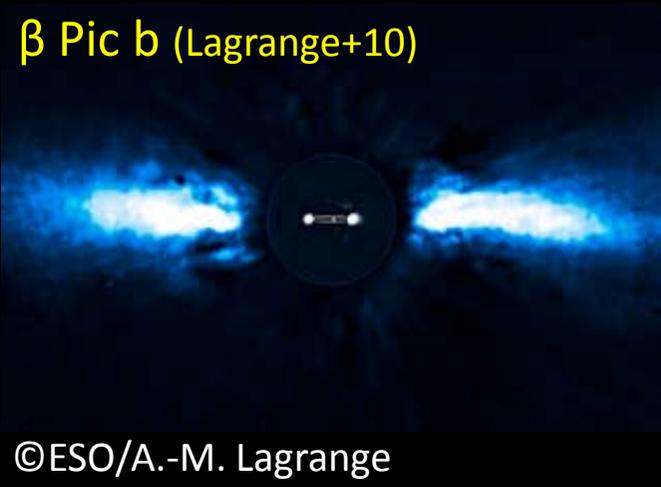
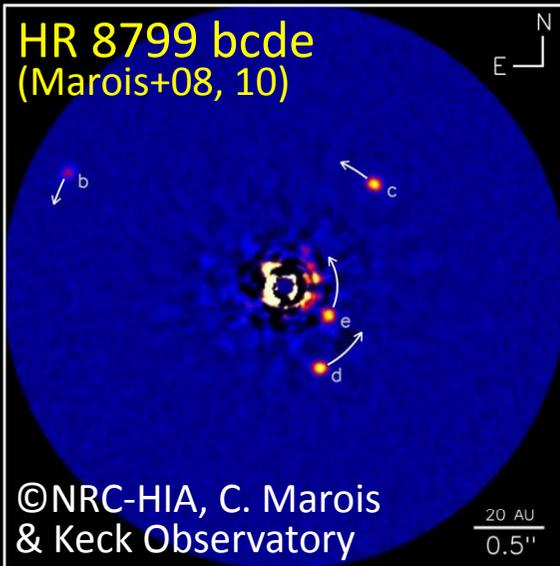
The University of Tokyo & NAOJ Exoplanet Project Office  
on behalf of the SEEDS team

# Talk Outline

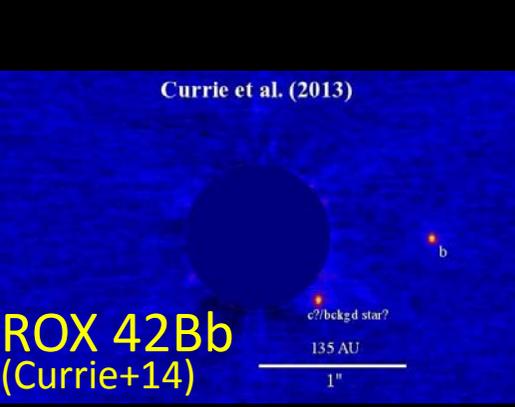
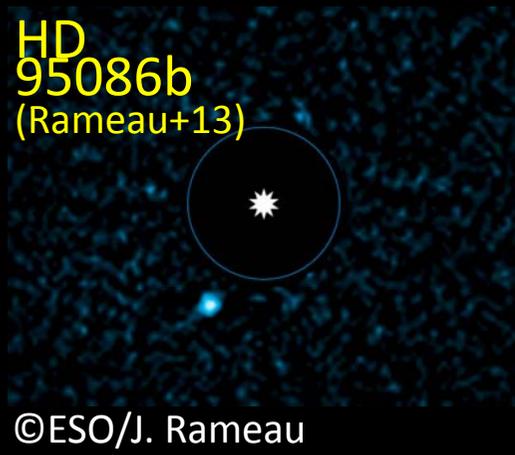
- **What is SEEDS?**
- **SEEDS' goal and Status**
- **Disk results**
- **Planet and companion results**  
**( $r \sim$  a few – a few tens AU)**
  - **A step toward 1-2 AU region studies**
- **Summary**

# Some Recent Directly Imaged Planets (Candidates)

from other than Subaru Telescope (**SEEDS planets later**)



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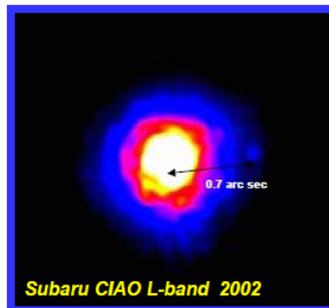


Wide-orbit planets can be detected currently only by direct imaging;  
**Some are  $a \geq 100$  AU; still very few for Solar-system-scale orbit planets.**

# SEEDS – Strategic Explorations of Exoplanets and Disks with Subaru

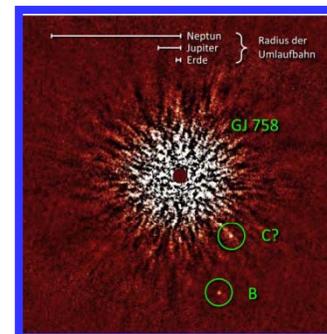
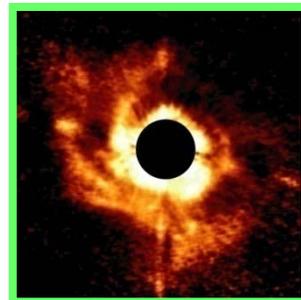


- First “Subaru Strategic Program (SSP)” – An open-use category
- 120 Subaru nights in 5 years from 2009; **>100 finished by now**
- NIR direct imaging and census of **giant planets in the outer regions** (a few AU - ~100 AU) around ~500 solar-type and massive stars
- Exploring **protoplanetary disks and debris disks** for the origin of their diversity and evolution **at the same radial (orbital) regions**
- **Direct linking** between planets and protoplanetary disks



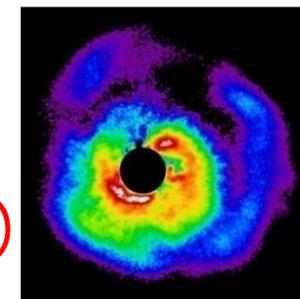
>100AU scale  
w/ CIAO

Resolution  
=0.1-0.2”



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

Resolution  
=0.05-0.1”  
Contrast  
Improved by ~10



# Subaru/HiCIAO+A0188+SCEXAO<sub>upgrade</sub>

- **HiCIAO**: High Contrast Instrument for the next generation Adaptive Optics
  - For Subaru 8.2m telescope
  - PI & CoPIs: Motohide Tamura (NAOJ), Klaus Hodapp (UH), Ryuji Suzuki (NAOJ)
  - Based on a previous Japan/MEXT grant (~100%)
- Combined with the curvature-sensing **AO** with 188 elements (Hayano, Takami et al.) and Extreme-AO1024 upgrade (Guyon, Martinache)
- Commissioned mainly in **2009** with AO188
- **No HiCIAO trouble ⇒ critical for SSP project!**



- **Specification and Performance**
  - **2048x2048** HgCdTe detector and ASIC readout
  - Wavelengths: 1 – 2.5 microns (NIR)
  - **Contrasts** on-sky:  $10^{-6}$  at 1",  $10^{-4}$  at 0.15"
    - Roughly 10 times better than CIAO, as specified
  - **New features constantly introduced** (4ch polarimetry, window-mode ASIC readout)
  - Observing modes: DI, PDI (dual beam), SDI (quad beam), & ADI; w/wo occulting masks ( $\geq 0.1''\phi$ ); ~10mas/pixel



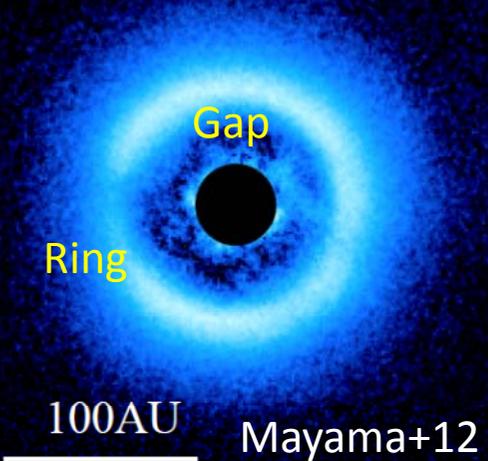
# SEEDS Targets (Category)

| <i>Current Categories</i>                  |  |                       |  |   |   |  |
|--|--|-----------------------|--|---|---|--|
| New Category                               | (a)  | (b)                   | (c)  | (d)   | (e)   |  |
|  | <b>YSO</b>   | <b>MG</b>             | <b>OC+</b>   | <b>NS</b>   | <b>DD</b>   | Summary  |
| Age span                                   | <b>&lt;1-10 My</b>   | <b>~ 10-100 My</b>    | <b>~ 100 My</b>                                    | <b>~ 100-~ 1 Gy</b>   | <b>~ 10-100 My</b>  |  |
| Member #                                   | 39   | 17                    | 7  | 17  | 21  | (99)   |
| Proposed #                                 | 235  | 40+ $\alpha$          | 60   | 153*  | 80+ $\alpha$  | 568* + $\alpha$  |
| Sci. Paper #                               | 13 + 1(sub)  | 1                     | 1 + 1(sub)   | 8 + 1(sub)  | 3   | 27 + 3(sub)  |
| Statistics paper                           | In scope   | 3-yr paper            | 2-yr paper   | In scope  | 2yr-paper   | OTHERS   |
| Comments & First authors of pub/sub papers | <sup>3</sup> Thalmann+,<br><sup>5</sup> Hashimoto+,<br><sup>7</sup> Muto+,<br><sup>8</sup> Dong+,<br><sup>10</sup> Tanii+,<br><sup>9</sup> Kusakabe+,<br><sup>11</sup> Hashimoto+,<br><sup>12</sup> Dong+,<br><sup>14</sup> Mayama+,<br><sup>15</sup> Grady+,<br><sup>19</sup> Follette+,<br><sup>22</sup> Takami+,<br><sup>26</sup> Tsukagoshi+,<br><sup>28</sup> Takami+ | <sup>27</sup> Brandt+ | <sup>20</sup> Yamamoto+,<br><sup>29</sup> Konishi+ | <sup>1</sup> Thalmann+,<br><sup>2</sup> Narita+,<br><sup>4</sup> Janson+,<br><sup>13</sup> Narita+,<br><sup>16</sup> Carson+,<br><sup>23</sup> Kuzuhara+,<br><sup>24</sup> Bonnefoy+,<br><sup>25</sup> Janson+,<br><sup>30</sup> Takahashi+ | <sup>6</sup> Thalmann+,<br><sup>17</sup> Thalmann+,<br><sup>21</sup> Janson+, | <sup>18</sup> Brandt+<br><br>("*" means including the data with short exposures) |

# Major Results of Disk Sciences

SEEDS has observed scattered light from disks and revealed many disk structures of less than 100AU scale that are possible signs of planet formations.

UScoJ1640-2130

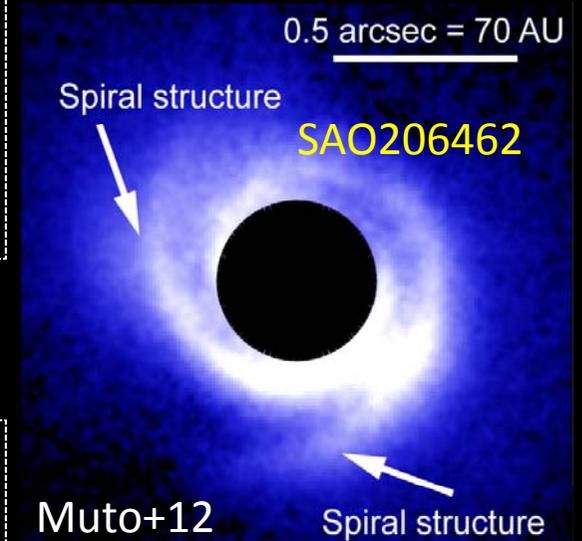


## □ Gaps

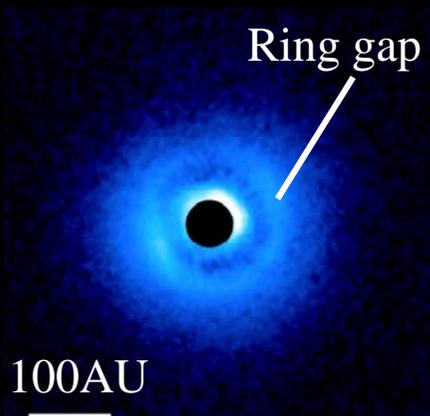
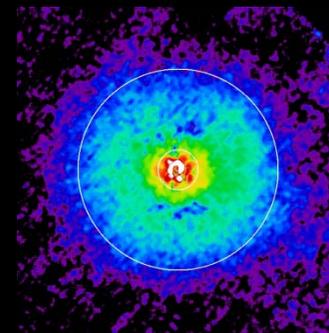
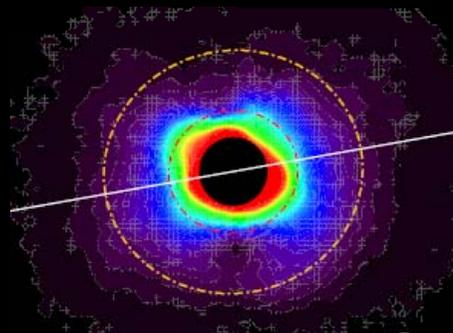
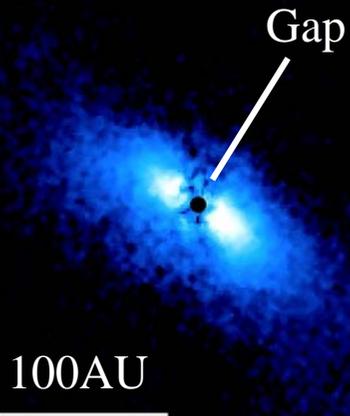
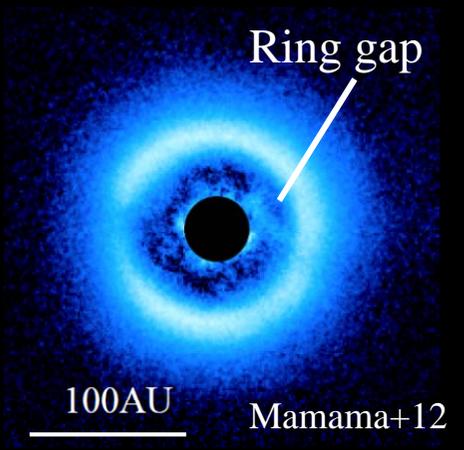
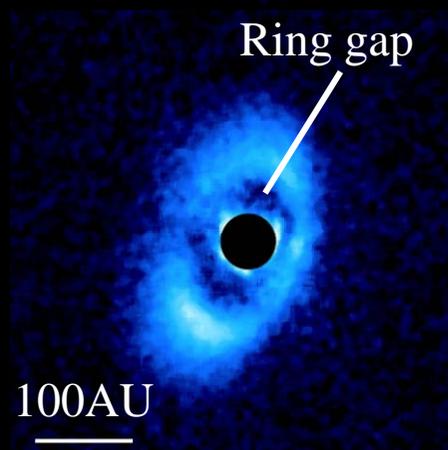
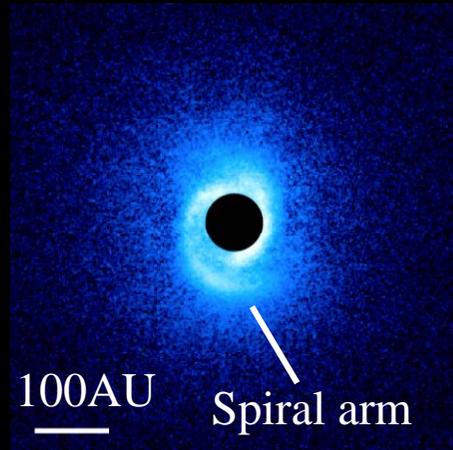
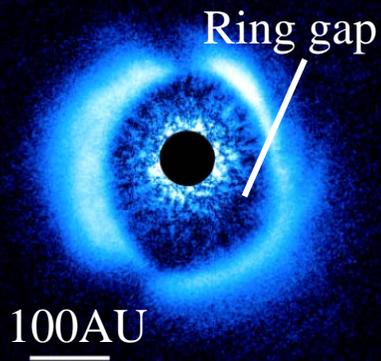
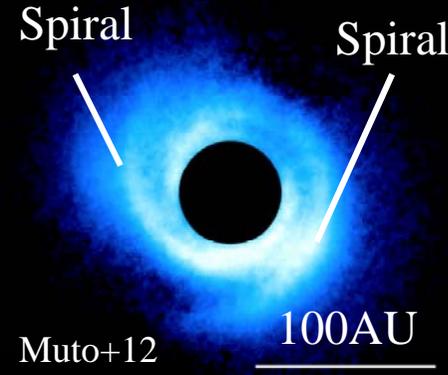
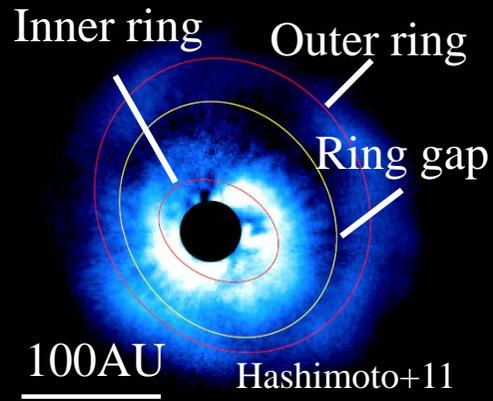
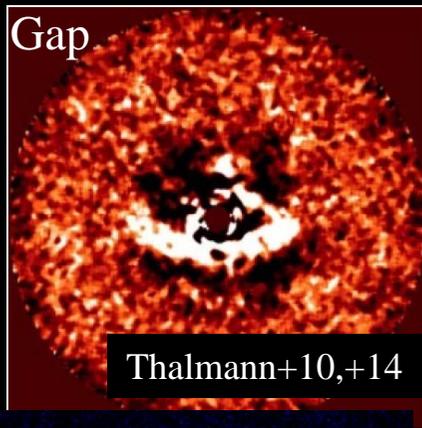
A disk gap may be evidence for dynamical interactions between a planet and its gaseous disk.

## □ Spirals

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



# SEEDS disk discoveries in $<0.1$ arcsec resolution



16 disk papers published/accepted.

# SEEDS Planet Discovery: GJ 504b

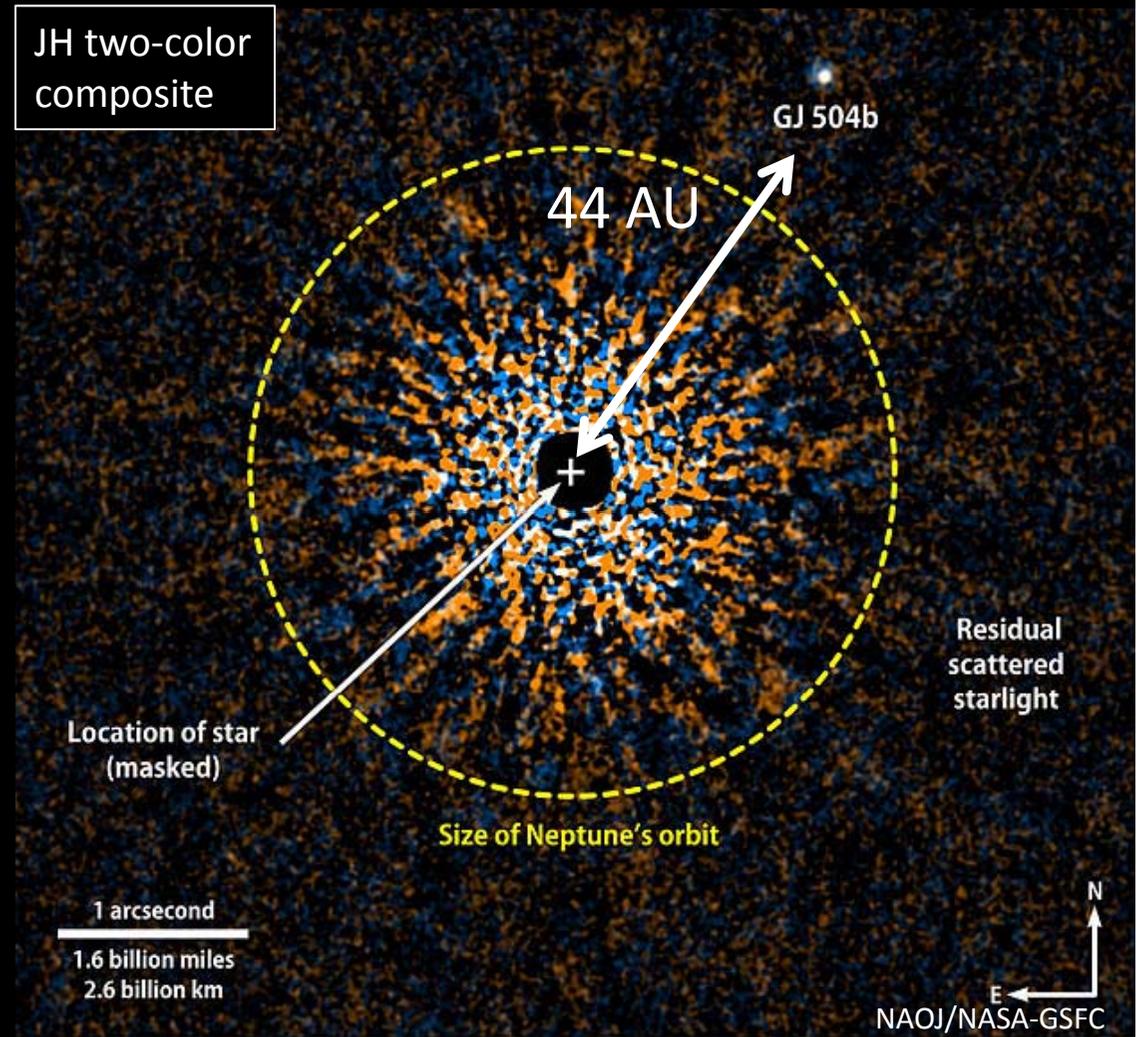
As a highlight, we report an exoplanet detection around the Sun-like star GJ 504.  
(see Kuzuhara et al. 2013 for details).

## □ Property of GJ 504

- Distance:  $\sim 17.6$  pc
- Spectral type: G0
- Mass  $\sim 1.2 M_{sun}$
- Age: 160 [conservative range; +350, -60] Myr
- Metallicity [Fe/H]: 0.1–0.3  
(Valdes+04, Takeda+07, Valenti+Fischer 05)

## □ 9 detections so far

⇒ Confirmation of common proper motion and partial orbital motion



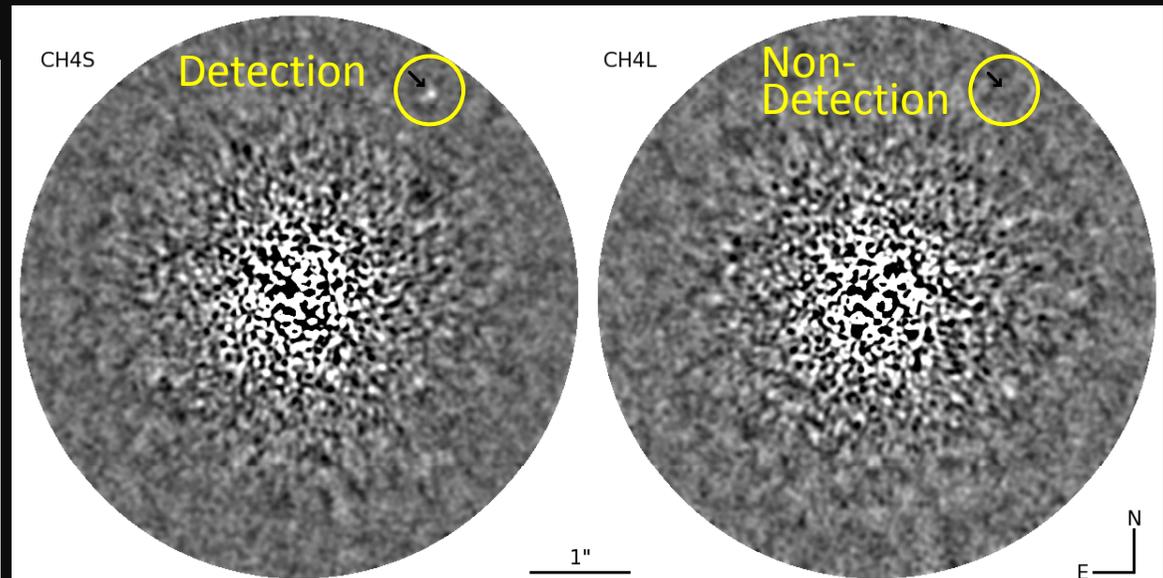
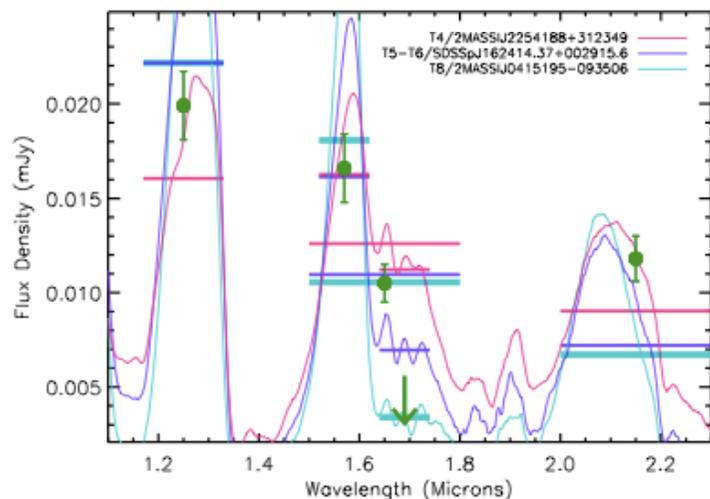
# GJ 504b: Photometry Results

- **Photometry:** *J, H, Ks, L'*-band (1-4  $\mu\text{m}$ ) and CH4-off, -on (1.56, 1.72  $\mu\text{m}$ )
  - The brightness contrast =  $10^{-7}$ – $10^{-6}$  (except *L'*)
  - Data at CH4-on and CH4-off were simultaneously obtained (SDI mode)

Deep absorptions by  $\text{CH}_4$  in atmosphere (Janson+2013, ApJ)

Ch4/on-off Simultaneous Direct Imaging

Comparison to T-dwarf spectra



Janson et al. 2013

# GJ 504b: Properties & Uniqueness

□ Mass estimate via evolutionary model (Baraffe+03) w/gyro-age

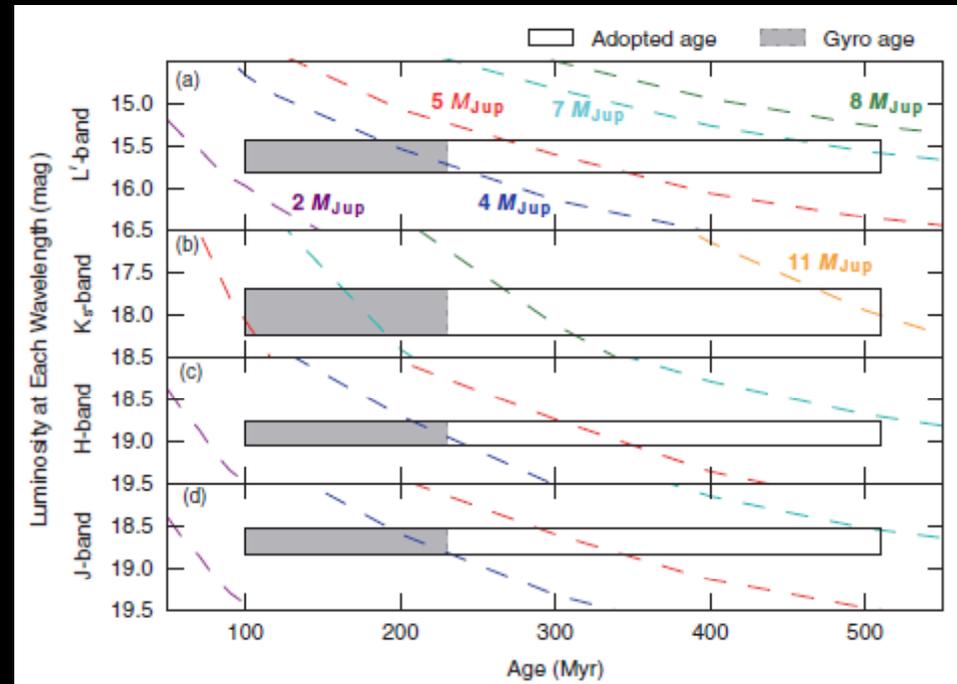
=> 3-4.5  $M_{\text{Jup}}$

This estimated mass is **among the lowest** of directly imaged planets.

□ **Much less affected by Hot vs. Cold start problem**

- Because the planet is older than 100 Myr, the mass estimate less depends on the choice of initial conditions (Hot vs. Cold start) in evolution models.

□ **Coldest temperature (< 600 K) among the directly-imaged planets**  
Blue J-H color => cloudless atmosphere?

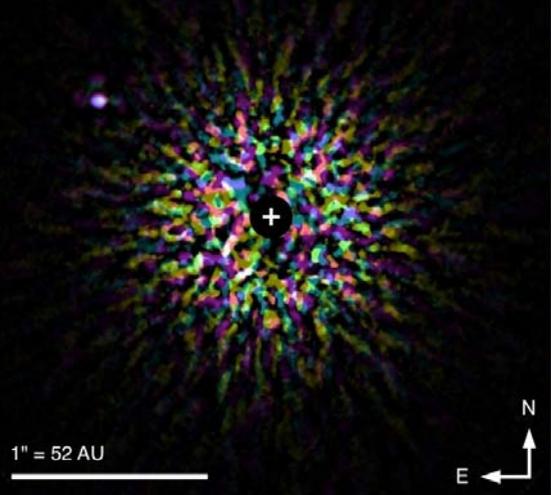


# Other Discoveries and Findings

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

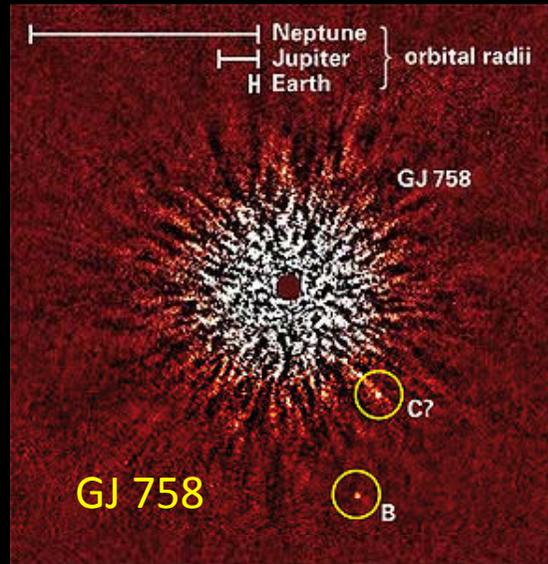
a

Kappa And



○ A planet candidate around a B-type star

(Carson+2013, note recent results, Bonnefoy+2014; Hinkley+2013)



○ A discovery of a brown dwarf or massive planet orbiting a nearby G 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, Moving Group, Brandt+2014).
- Other categories' summaries and statistics will be submitted.
- Data reduction software paper (Brandt+2013).

# Studies for Origin of Inner Planets

SEEDS searches for stellar companions around stars with inner planets.  
See Narita et al. 2010, 2012; Takahashi et al. 2013 for details.

Stellar Companion



NASA/  
Walt Feimer



Gravitational  
Perturbation

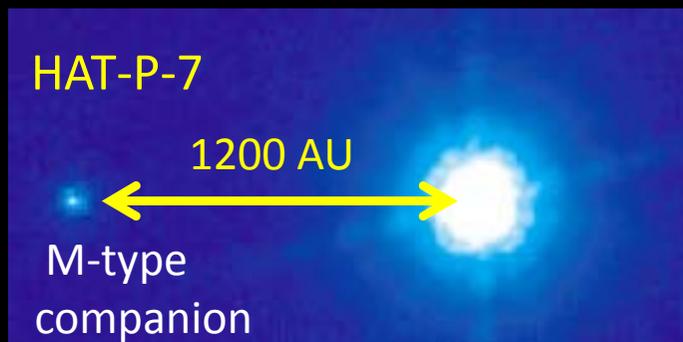


ESA/ / Carreau

A stellar companion may be a cause of such an inner planet  
(Kozai-effect; Wu et al. 2007; Fabrycky & Tremaine 2007)

=> Probed by SEEDS

□ Observations of >30 targets; companions were indeed discovered



- Confirmation of a M-type stellar  
companion orbiting HAT-P-7

Narita+09, 10, 12

# Summary



- SEEDS has performed direct imaging surveys for exoplanets.
  - ~100 nights observations have been finished since 2009
  
- 3 direct imaging discovery of planet candidates (GJ 504, Kappa And, GJ 758) and 2 brown dwarfs detection in Pleiades;
  - GJ 504b is a Jovian planet orbiting a relatively old Sun-like star and has unique atmospheric features.
  
- A few dozens of detections of circumstellar disks, and found/characterized disk structures that are possible signs of planet formations.
  
- Papers presenting the 2 or 3 year summary and statistical analysis have been published from OC, MG, DD category.
  - Other categories' summaries are to be published.
  - A few tens of companion candidates to be followed-up.
  - Critical data set to understand the giant planets at  $>\sim 10$  AU, a step toward 1-2 AU with direct imaging.