# Exoplanets and Disk Imaging with Subaru

November 17 14:10 - (15+5 min)

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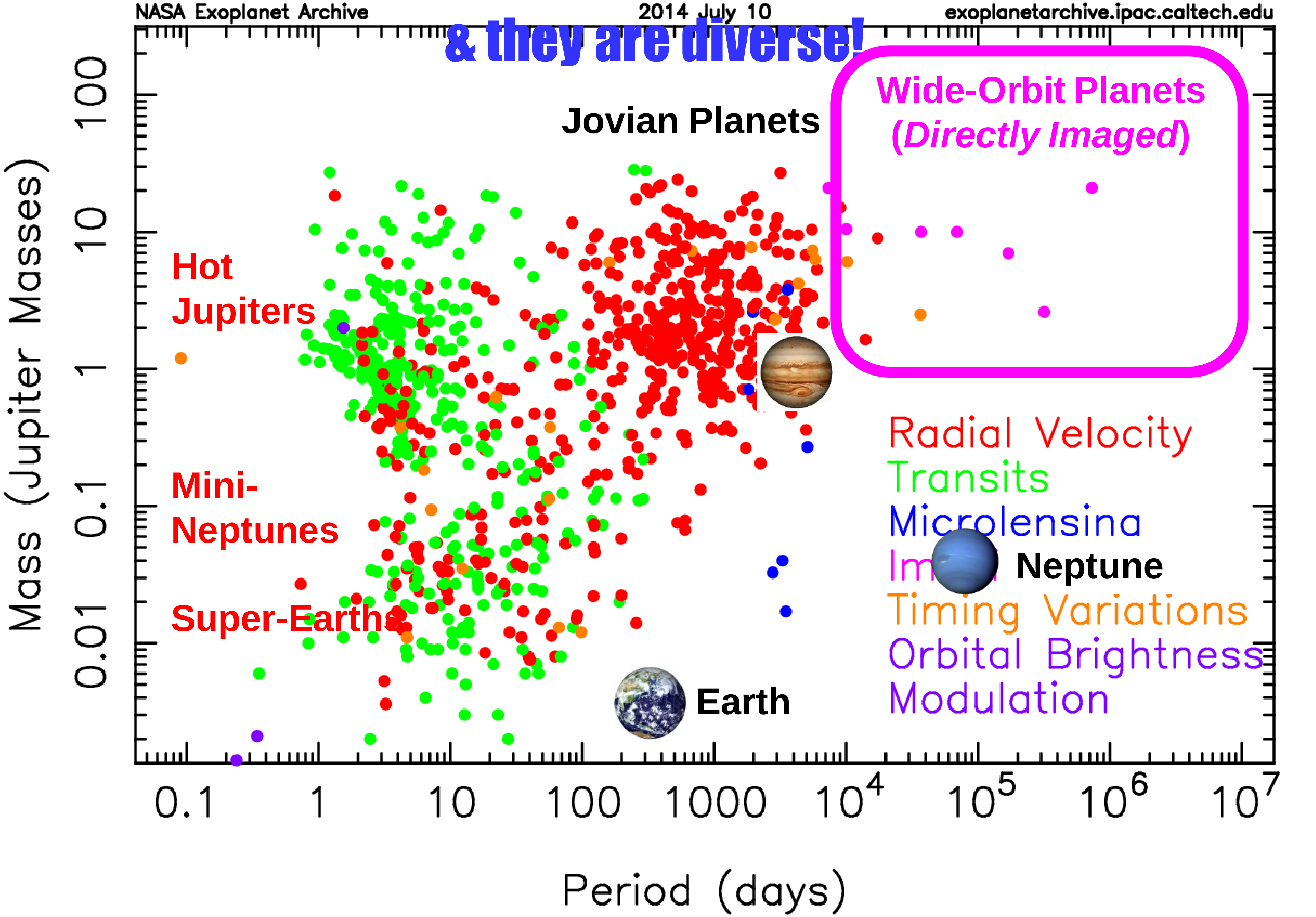
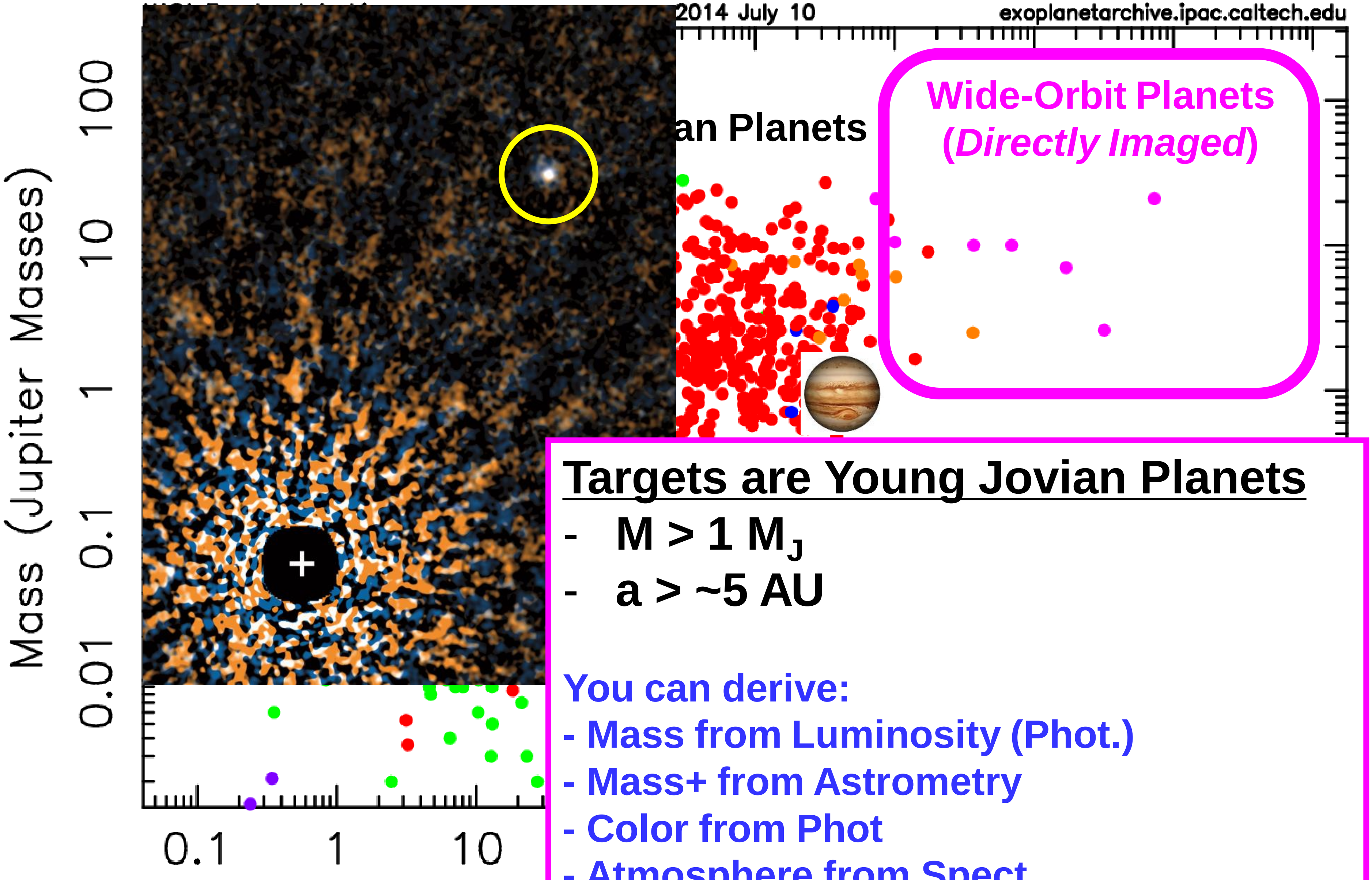
& the SEEDS team

# Various methods have led >1800 planet discovery in 20yr & they are diverse!



# Targets for Current Exoplanet Direct Imaging




**Targets are Young Jovian Planets**

- $M > 1\ M_J$
- $a > \sim 5$ AU

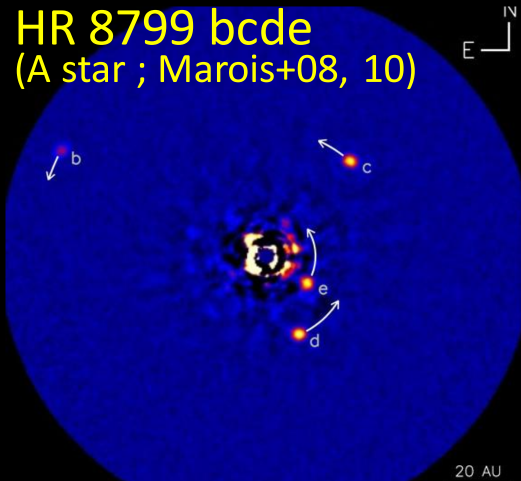
You can derive:

- Mass from Luminosity (Phot.)
- Mass+ from Astrometry
- Color from Phot
- Atmosphere from Spect.
- Teff, g from Spect.

# Some Directly Imaged Planets (Candidates)

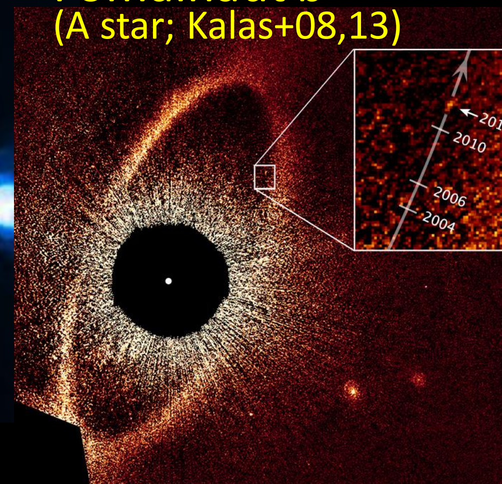
## around BD first, then A stars &YSOs, and finally G & B stars

**HR 8799 bcde**
(A star ; Marois+08, 10)

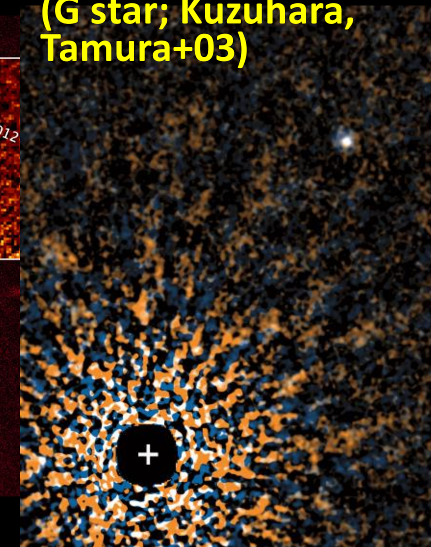



**β Pic b**
(A star; Lagrange+10)

**Fomalhaut b**
(A star; Kalas+08,13)



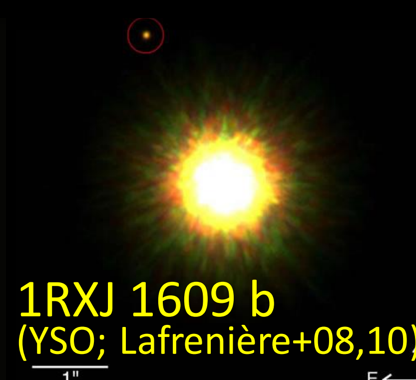

**GJ504 b**
(G star; Kuzuhara, Tamura+03)



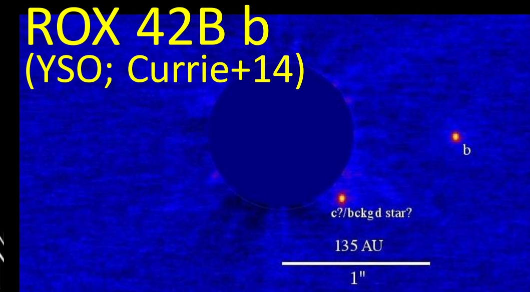
**HD 95086 b**
(A star; Rameau+13)

**2M1207 b**
(BD; Chauvin+04,05)

**1RXJ 1609 b**
(YSO; Lafrenière+08,10)




**ROX 42B b**
(YSO; Currie+14)

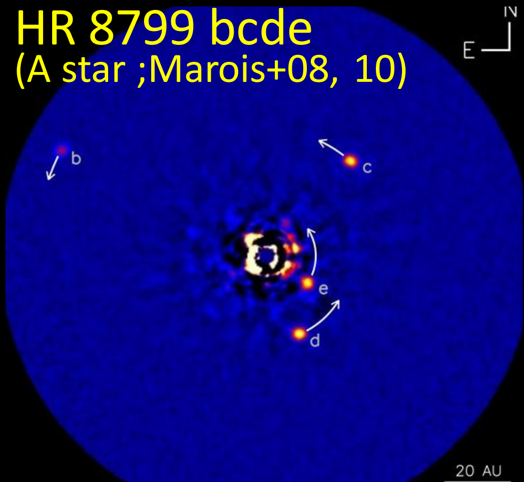



(not full list & SEEDS planets introduced in detail later)

# Some Directly Imaged Planets (Candidates)

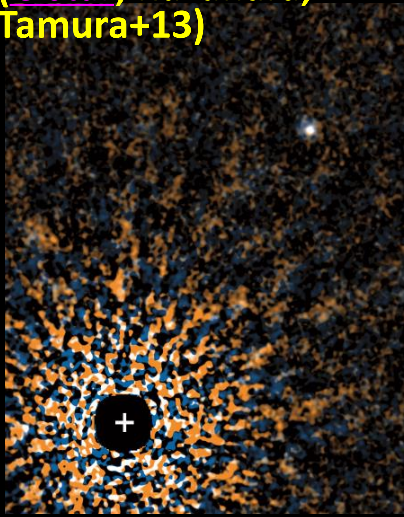
## only lower-mass and SS-scale ones

HR 8799 bcde
(A star ;Marois+08, 10)

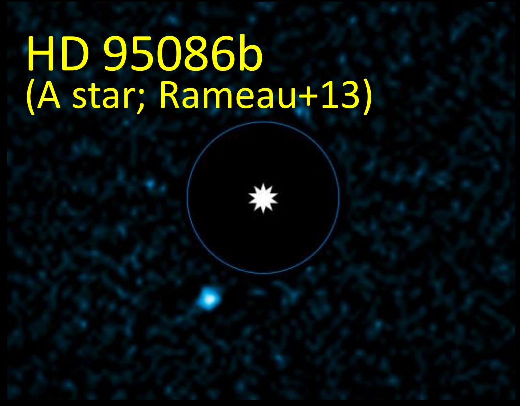



β Pic b
(A star; Lagrange+10)

GJ504 b
(G star; Kuzuhara, Tamura+13)



HD 95086b
(A star; Rameau+13)



**Around A/B stars**
HD 95086 b
HR 8799 bcde
beta Pic b
kappa And b

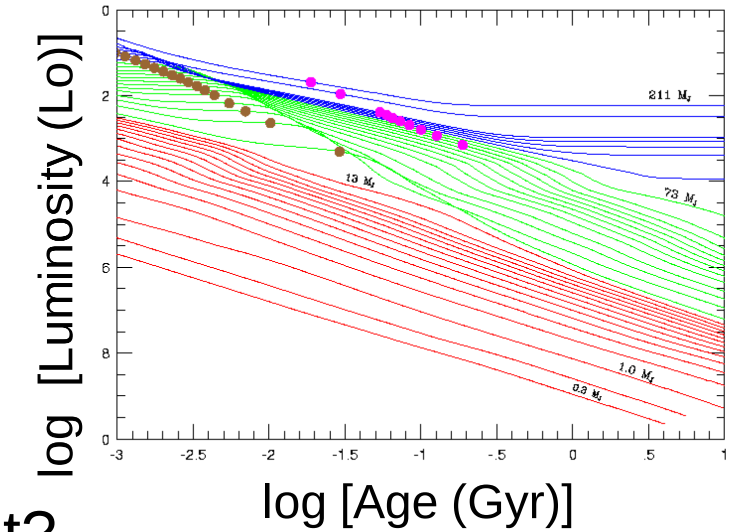
**Around G stars**
GJ 504 b
(GJ 758 b)

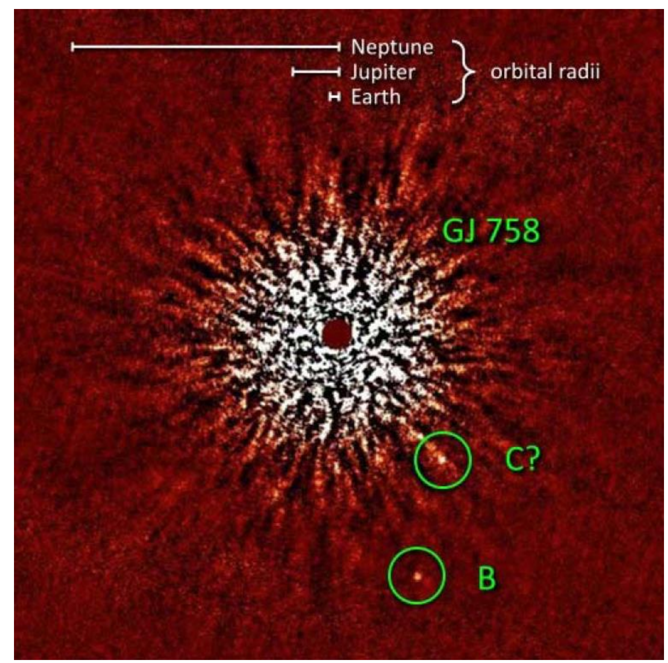
Only 6 imaged planetary systems
w/ mass <14$M_{Jup}$ and a<100 AU
excluding BD binary,
of which 3 from SEEDS.

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

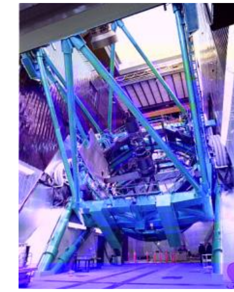
# Difficulties with Direct Imaging

- **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 current main targets
  - How to suppress bright star light?
- **Speckle noise from bright central star**
  - Not photon-noise but speckle – noise limited observations
  - How to remove static speckle?
- **Coronagraph**
  - Ex. CIAO (previous) & HiCIAO (current)
- **Various differential imaging techniques (PDI, SDI, ADI)**

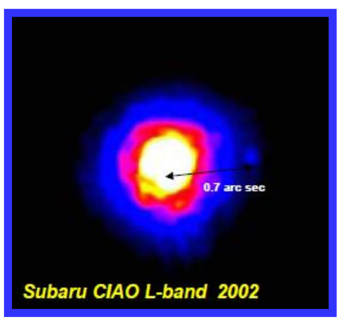


# SEEDS –Strategic Explorations of Exoplanets and Disks with Subaru



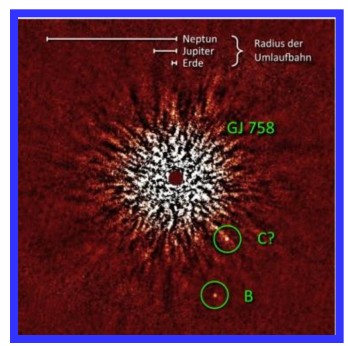
- First “Subaru Strategic Program (SSP)” – An open-use category
- 120 Subaru nights in 5 years from 2009; **~110 finished by now**
- NIR direct imaging and census of **giant planets in the outer regions** (10 AU ― 100 AU) around **~500 solar-type and massive stars**
- Exploring **protoplanetary disks and debris disks** for the origin of their diversity and evolution at the same radial (orbital) regions
- **Direct linking** between planets and protoplanetary disks



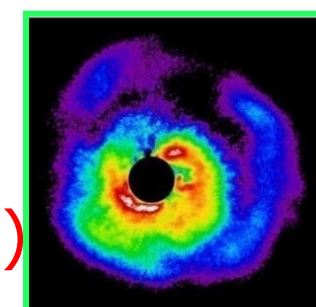

Resolution
=0.1-0.2”

>100AU scale
w/ CIAO

⇒




**Resolution**
**=0.05-0.1”**
**Contrast**
**Improved by ~10**



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

# SEEDS Scientific Category

SEEDS has 5 categories that cover targets of various ages.

| Category | YSO | Moving Group | Open Cluster | Nearby Star | Debris Disk |
|---|---|---|---|---|---|
| Target | YSOs in Taurus, Oph, Upper Sco, etc | Young Stars in Nearby Moving Groups | Stars in Open Clusters | 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– ~1 Gyr |
| Distance | ~130 pc | 10 – 50 pc | ~130 pc | 10 – 50 pc (except RV targets) | 10 – 100 pc |
| Obs. # | ~80 | ~70 | ~40 | ~150 | ~50 |

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

# Individual Main Results in each category

34 refereed papers 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 |
| OC | HD23514 B, HII1348 B independent dis. | BD | 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 Planet Discovery: GJ 504 b

As a highlight, we report an exoplanet detection around the Sun-like star GJ 504.

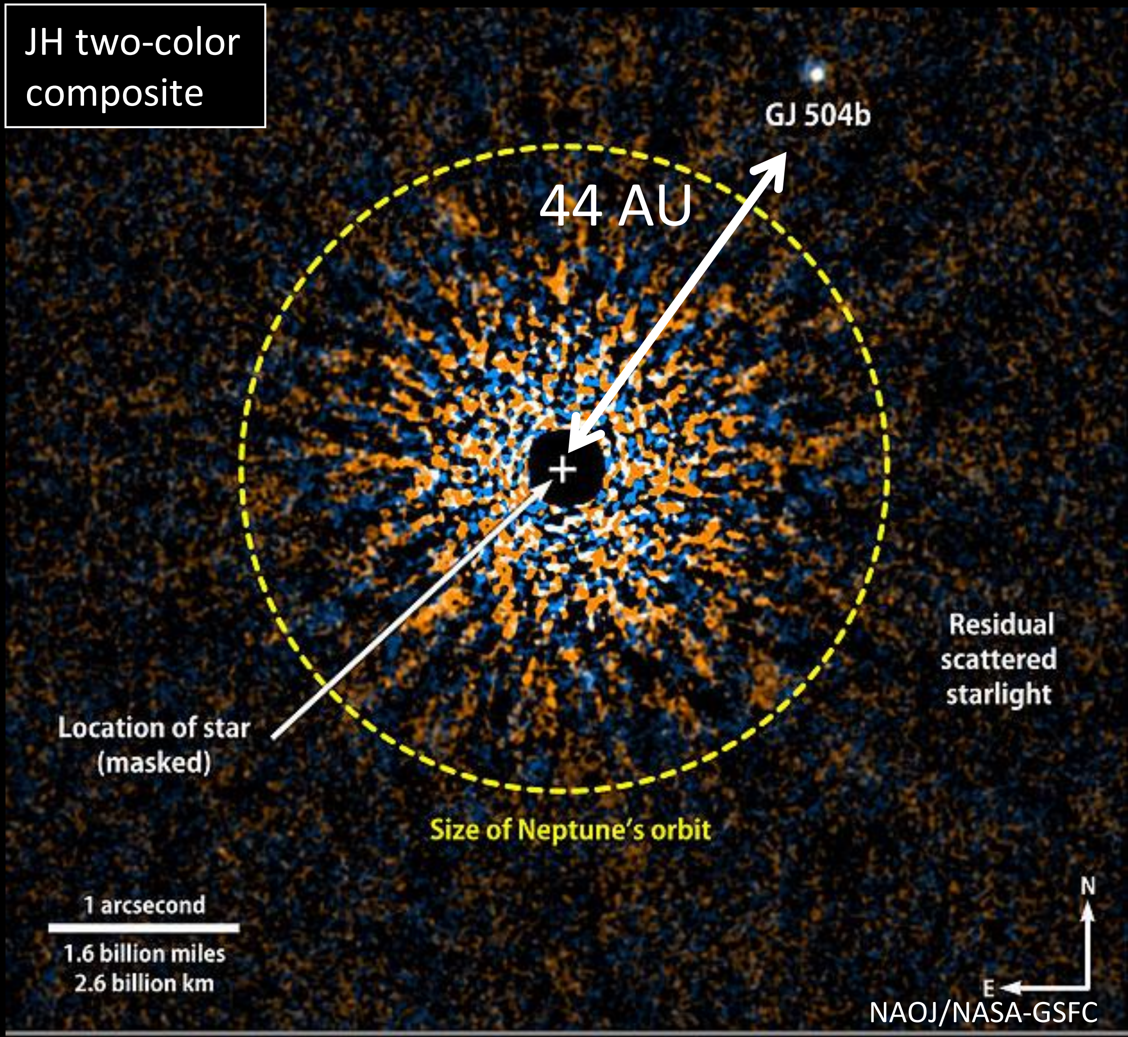
**A unique cold Jovian planet imaged** (Kuzuhara, Tamura et al. 2013).

## □ Properties of GJ 504

- Distance: 17.6 pc
- Spectral type: G0
- Mass 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: a Jovin planet of ~160 My age

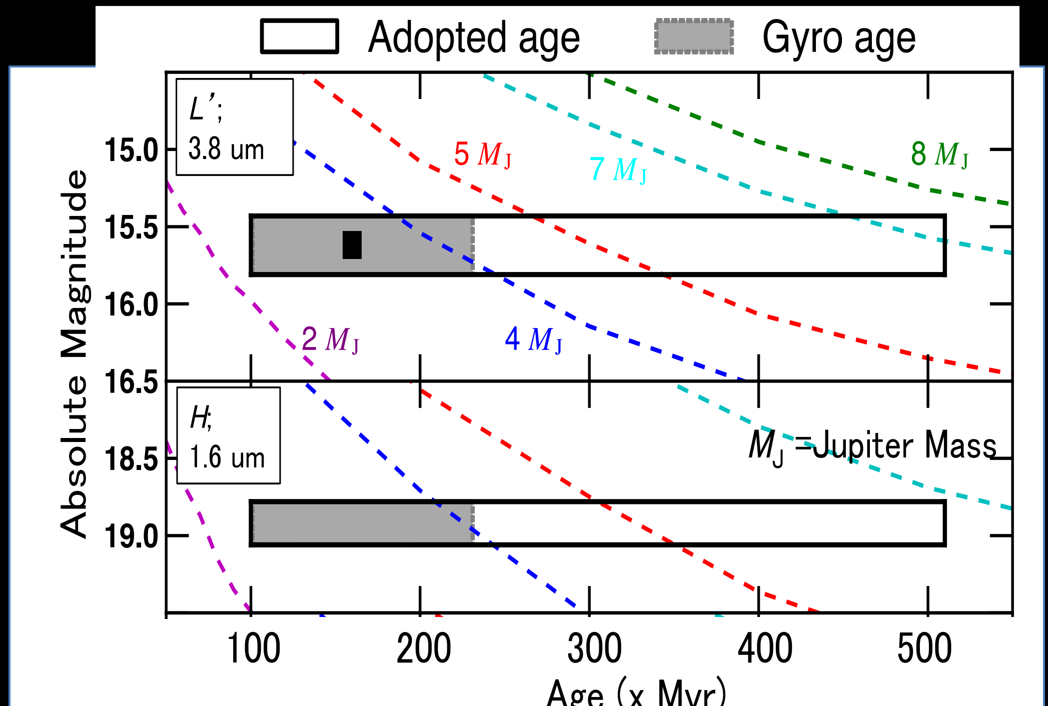
□ **Mass estimate via evolutionary model (Baraffe+03) w/gyro-age**

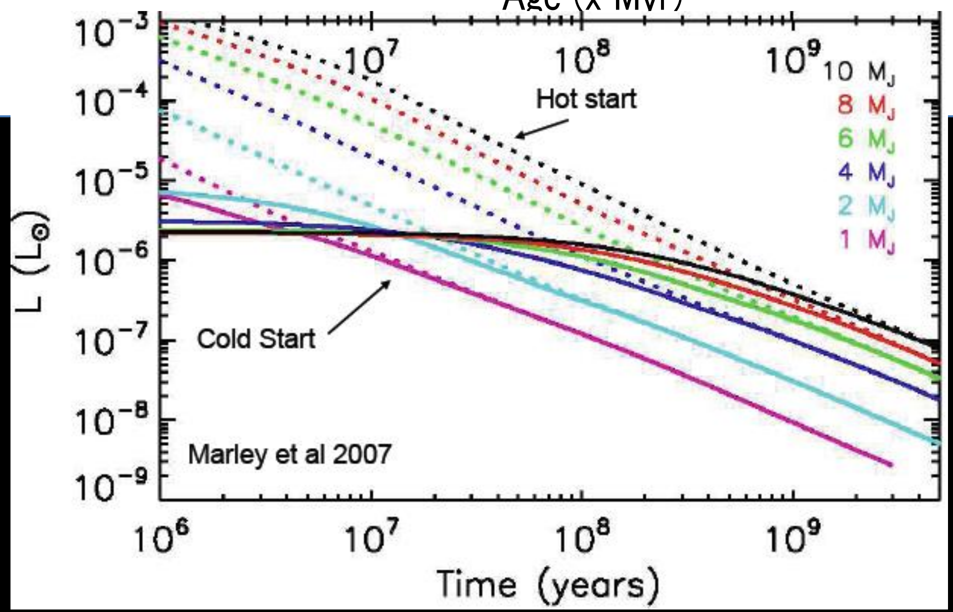
=> 3-4 $M_{Jup}$

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

□ **Mass estimate 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. But also see Mordasini+14 for initial condition uncertainties.

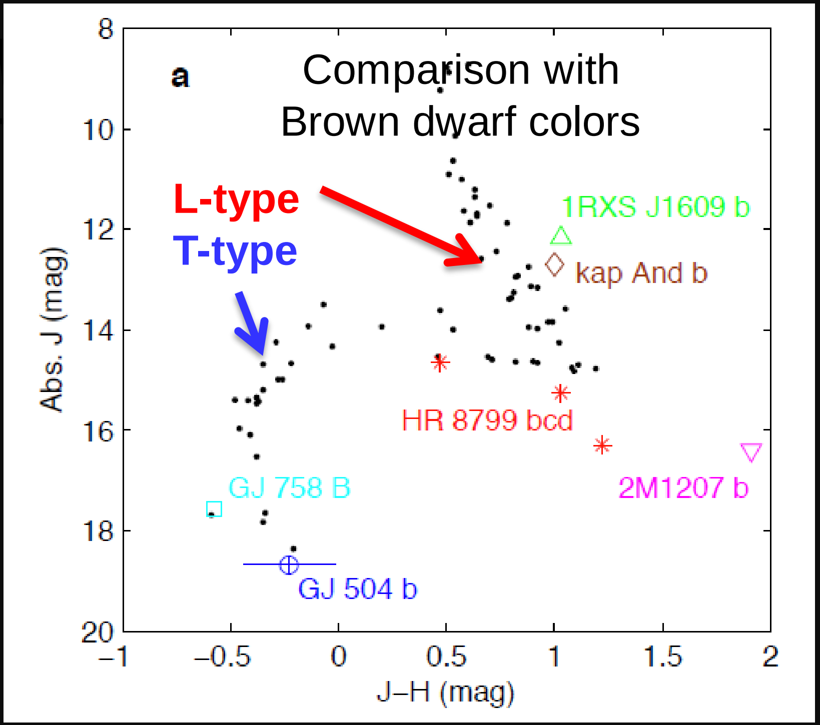


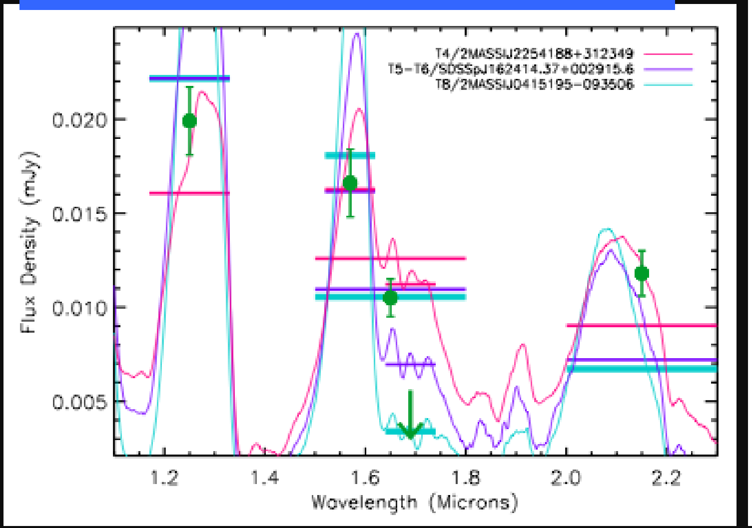
# GJ 504b: not L-type but T-type planet

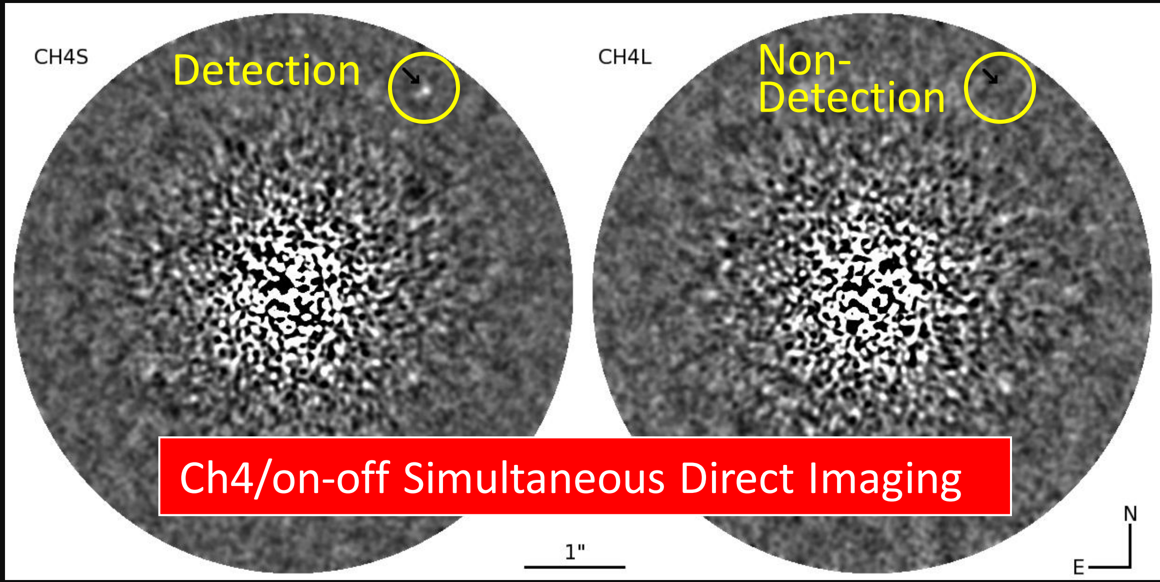
- ☐ Unique blue J-H color
- ☐ Coldest temperature (< 600 K) among the directly- imaged planets
- ☐ Photometry: J, H, Ks, L'-band (1-4 um) and SDI (CH4-off, -on; 1.56, 1.72 um)

Deep absorptions by $CH_4$ in atmosphere
(like T-dwarf; Janson+2013)




Comparison to T-dwarf spectra



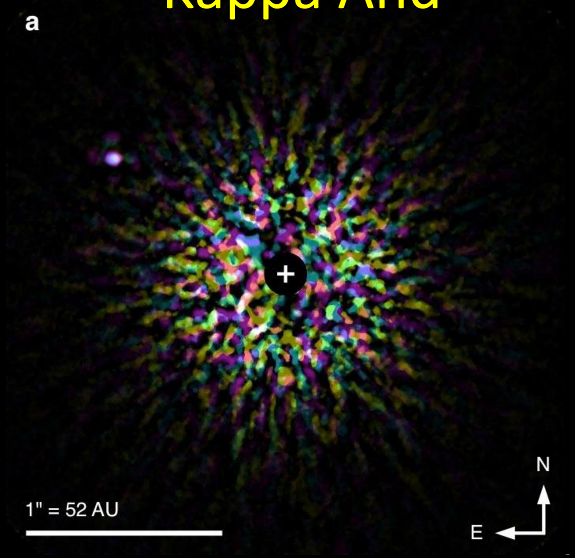




Janson et al. 2013

# Other Discoveries and Findings

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

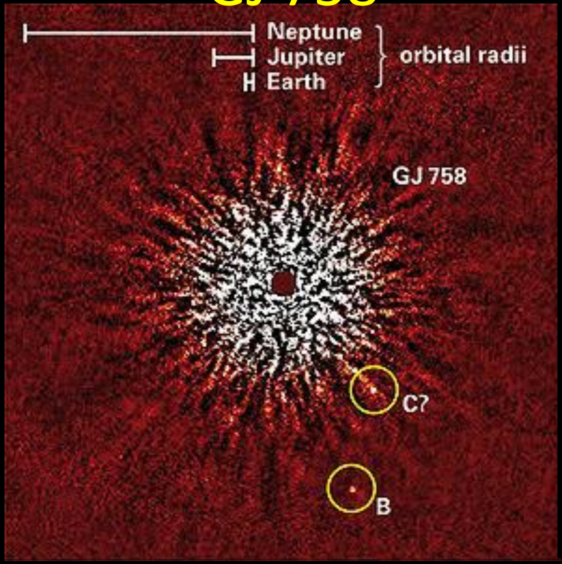
Kappa And




○ 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)

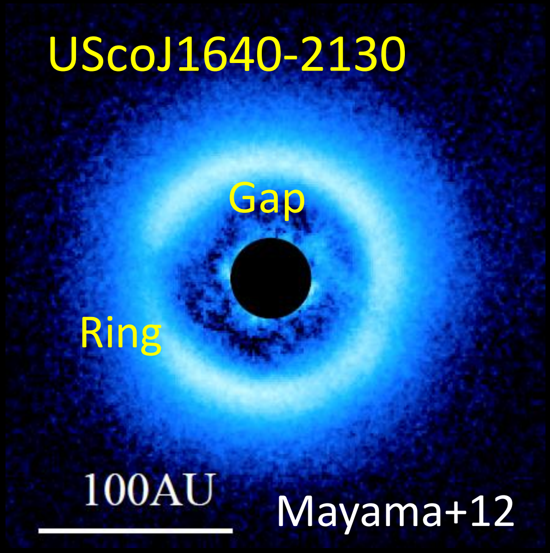
☐ SEEDS published papers summarizing the 2 or 3 year planet survey results of each category (e.g., debris disk, Janson+2013; open cluster, Yamamoto+2013, Moving Group, Brandt+2014).

☐ Other categories' summaries and statistics will be submitted.

☐ Data reduction software paper (Brandt+2013).

# 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.**

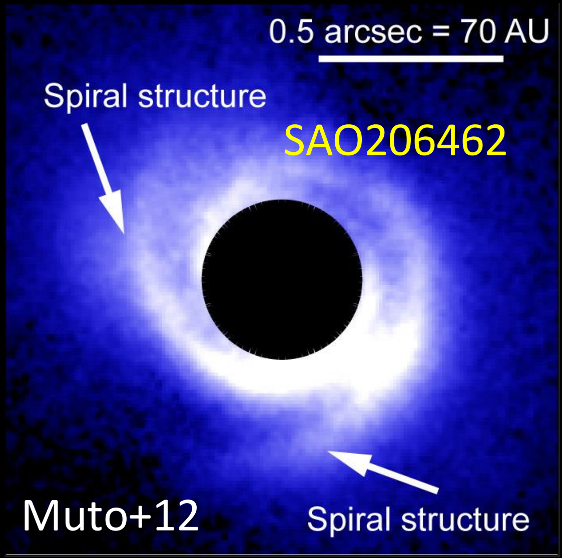



☐ Gaps

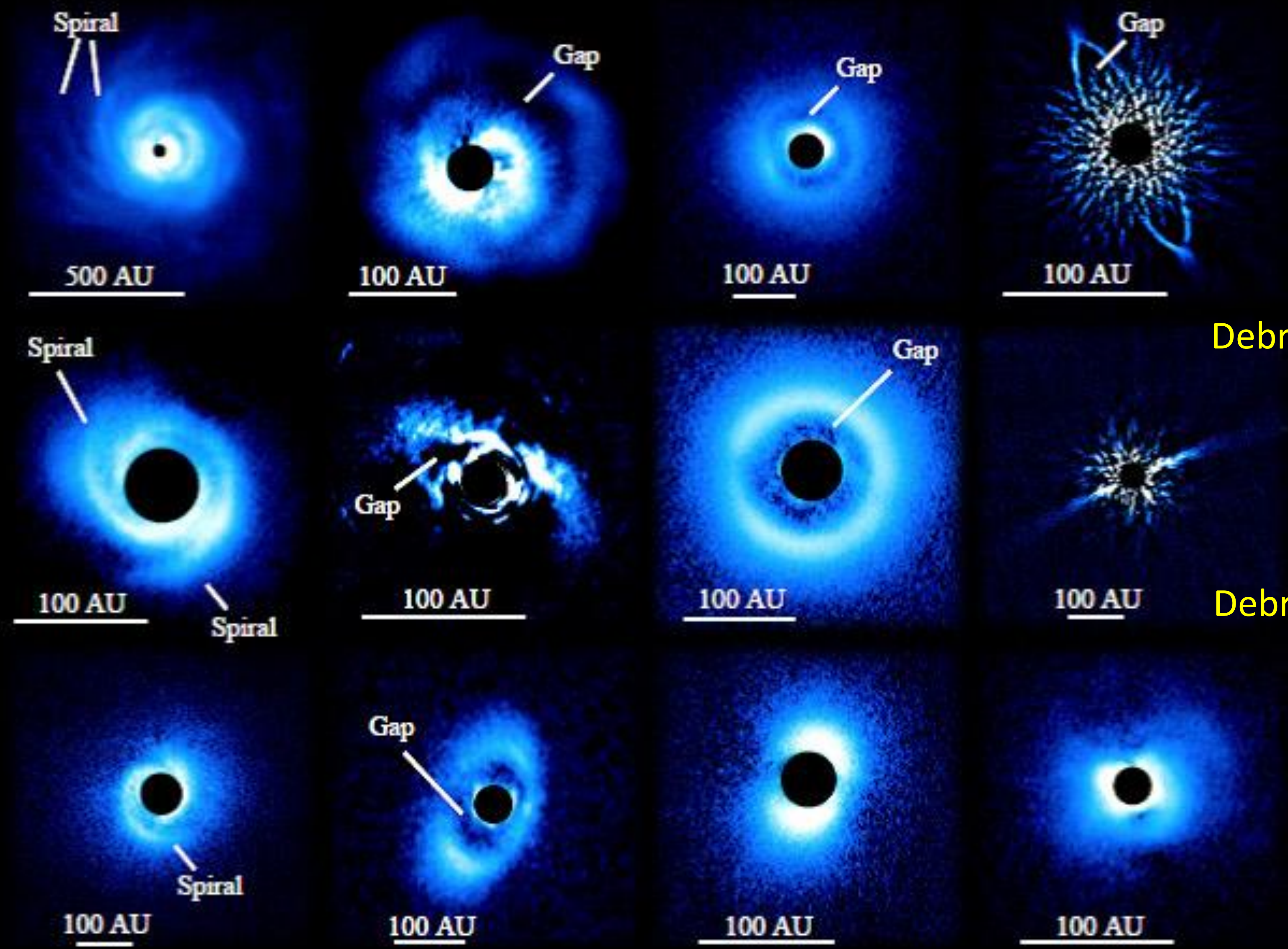
A disk gap may be evidence for dynamical interactions between a planet and its gaseous disk.

☐ Spirals

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



# SEEDS have revealed gaps & rings of <100 AU scale in many disks ( no details today)



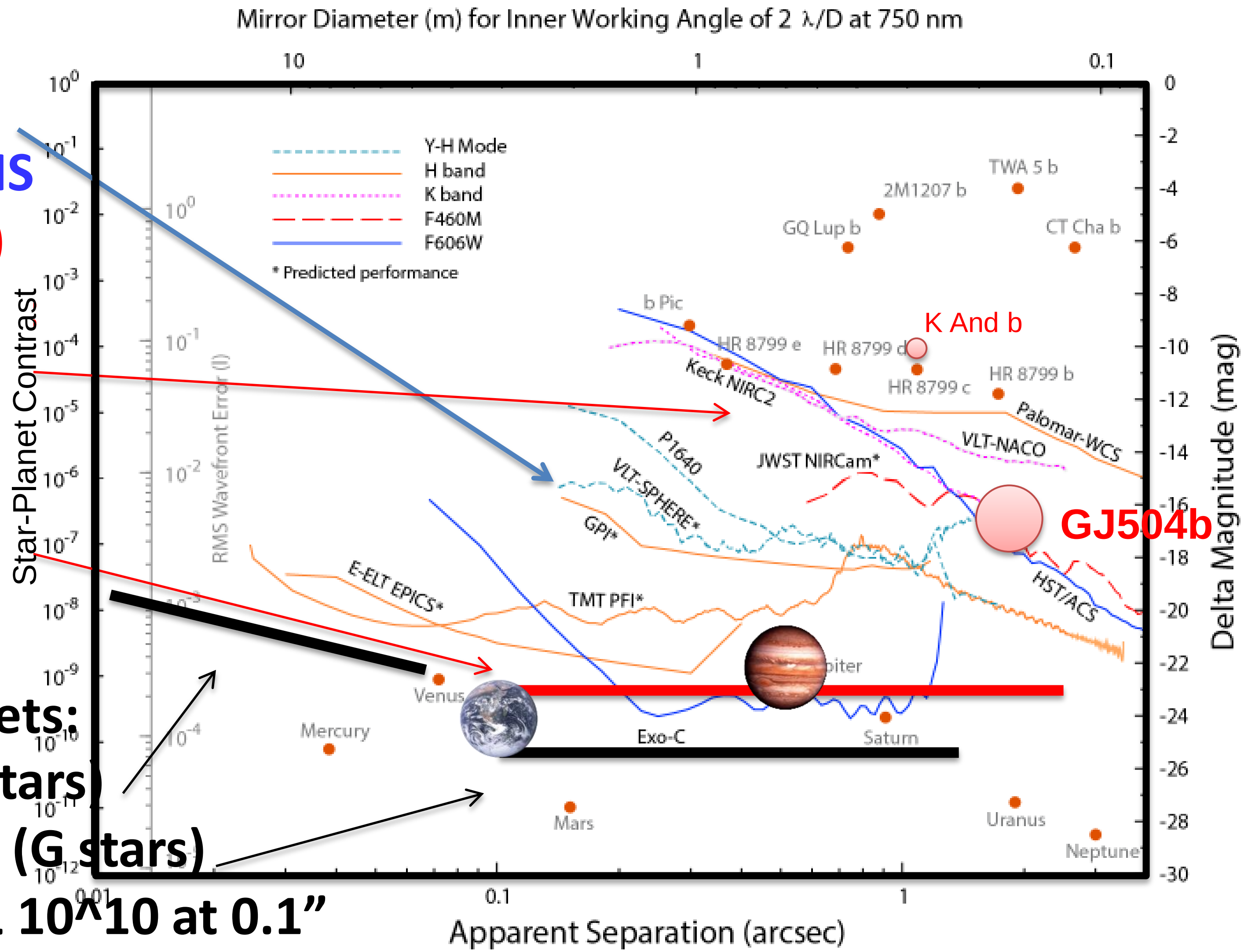

Debris

Debris

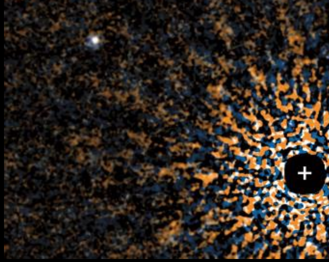
# Future Surveys and Future Missions

- ☐ **Future Gr. Surveys:**
  - GPI survey
  - SPHERE survey
  - **SCExAO/CHARIS (Olivier, Kasdin)**
- ☐ **Future missior**
  - JWST coronagraphs
  - **WFIRST coronagraph**
  - Exo-C
- ☐ **Earth-like planets:**
  - **TMT+SEIT (M stars)**
  - **TPF-C or TPF-O (G stars)**
  - **10^8 at 0.01" & 10^10 at 0.1"**

From Exo−C interim report (Stapelfeldt+14)



# Summary



- ☐ Deep direct imaging such as SEEDS has detected a handful wide-orbit planets of the Solar system scale. More wide-orbit (>100au) planets also discovered by imaging both around stars and brown dwarfs.

- ☐ From SEEDS, 3 direct imaging discovery of planet candidates (GJ 504, Kappa And, GJ 758) and 2 brown dwarfs detection in Pleiades;
  - GJ 504b is a cold 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.

- ☐ Wide-orbit planets frequency is less than 10% from NICI survey and SEEDS preliminary results.

- ☐ Various future plans for direct imaging both from ground and space. Earth-like planet imaging is still challenging but could be possible with 30-m telescopes with ExAO+corona or 2-4m class space high-contrast telescopes.