Direct Imaging of Giant Exoplanets and Disks

November 30　15:50 - 16:20 [I]

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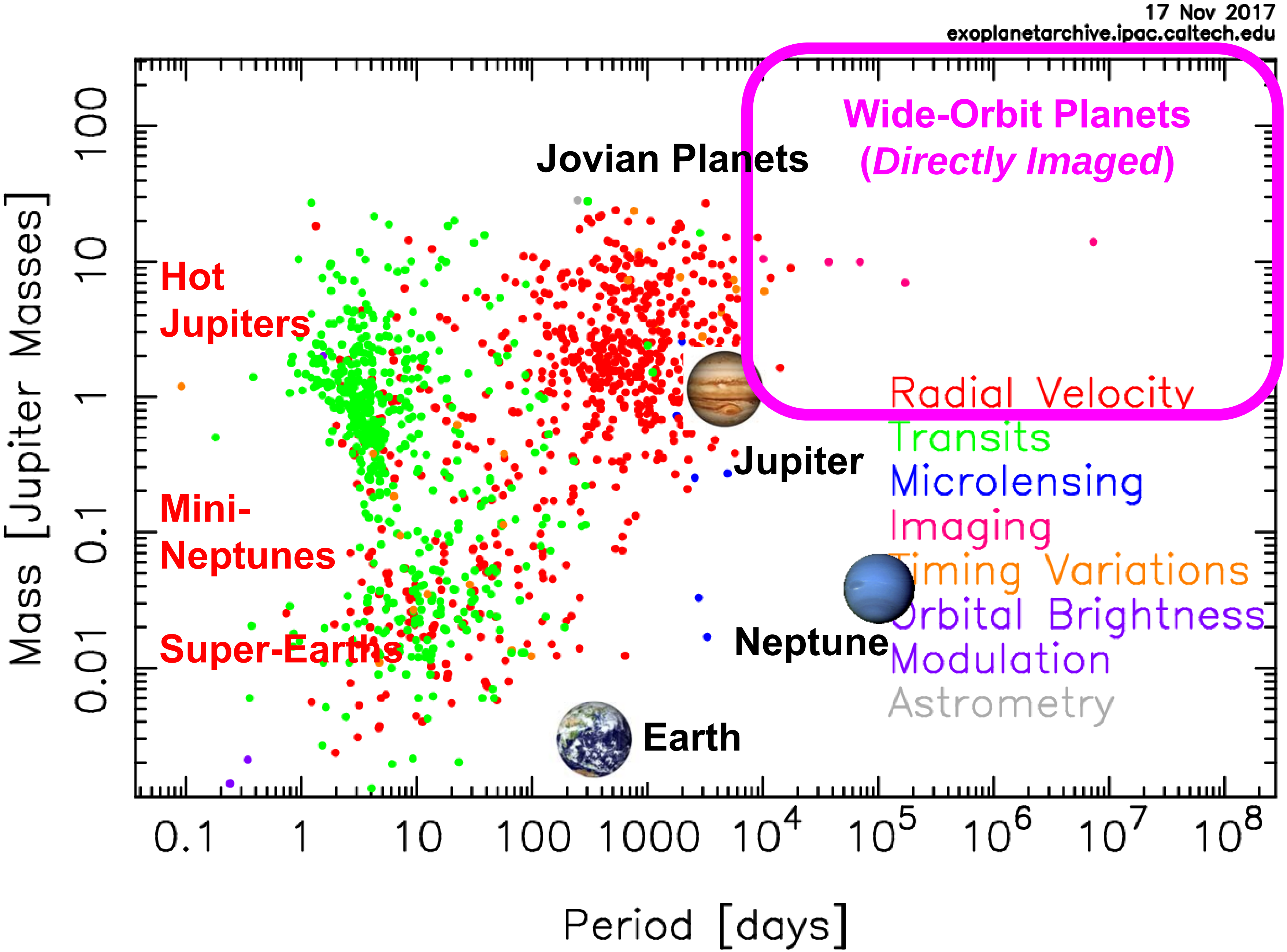
Talk Outline

- Why direct imaging (DI) ?
- DI observation techniques
- Subaru/SEEDS project
  - Planet and other companion results
  - Disk results
  - Post-SEEDS activities
- Gemini/GPI & VLT/SPHERE surveys
- Future plans (space and ground)
- Summary

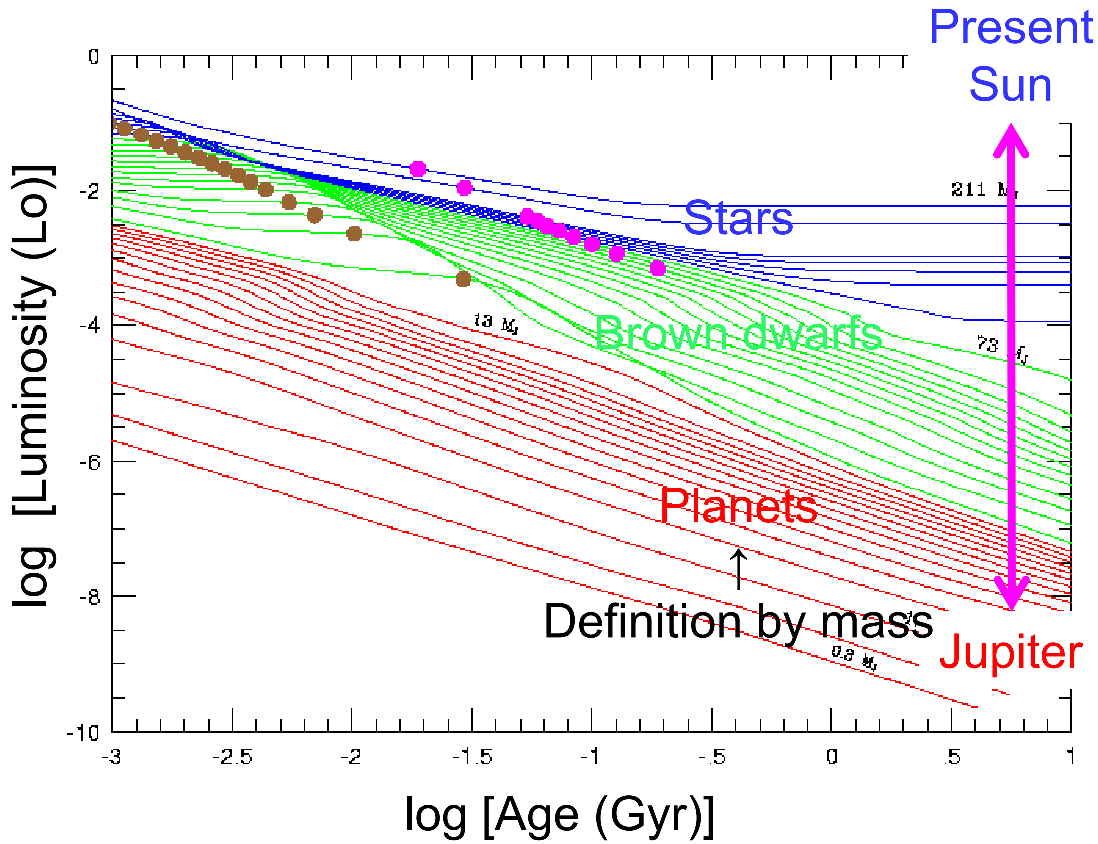
Various Planets detected by Various Techniques



Challenges 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

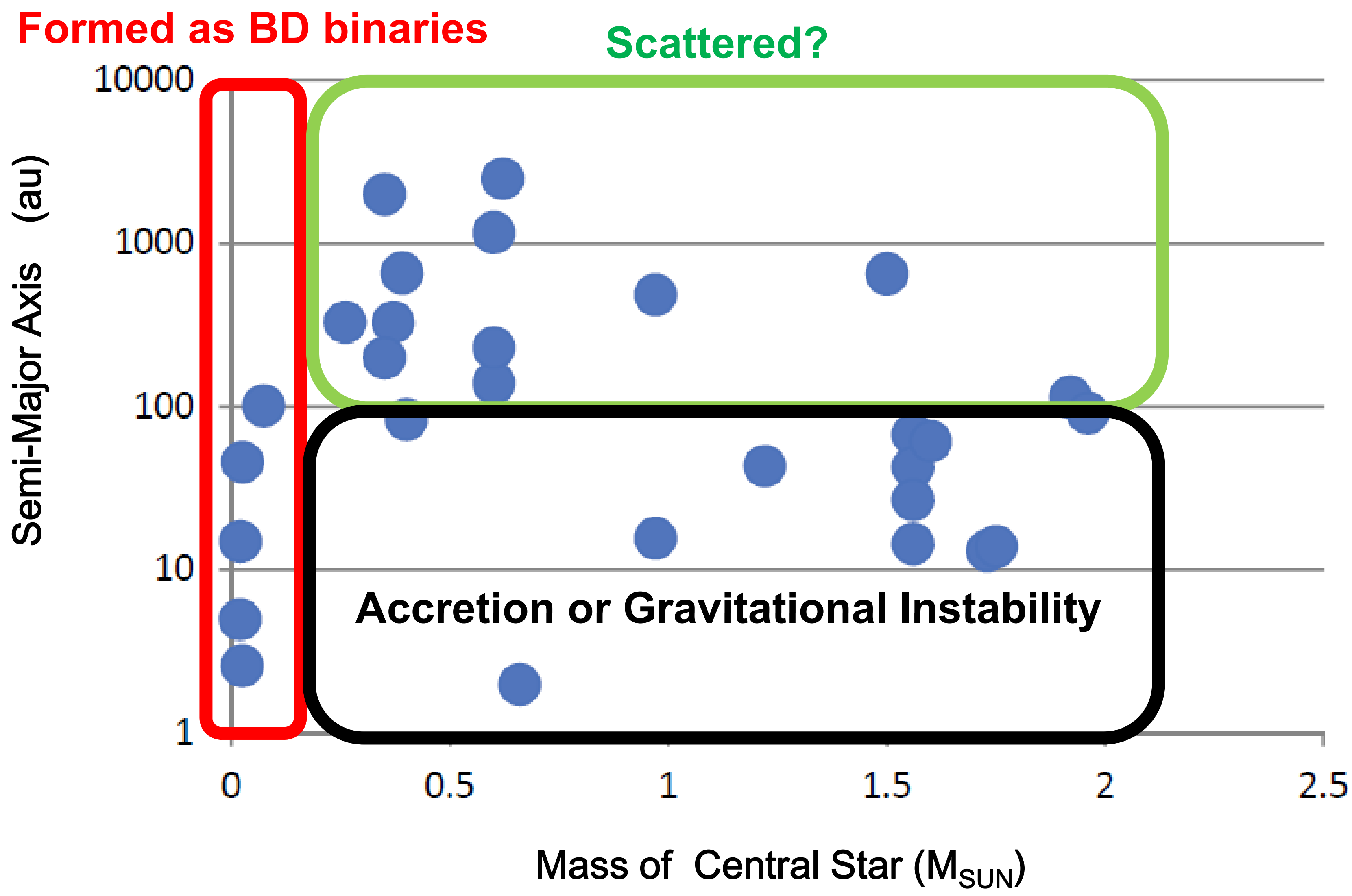
Self-luminous giant planets are main targets for direct imaging (at present)



How to suppress bright star light?

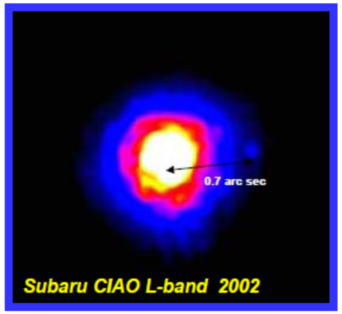
Directly Imaged Planets

(Mass =<13 M_{JUP})

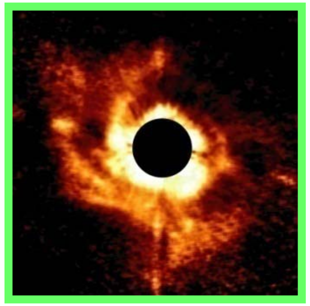


SEEDS –Strategic Explorations of Exoplanets and Disks with Subaru

- 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

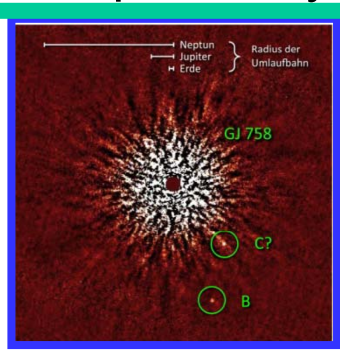


Resolution
=0.1-0.2”

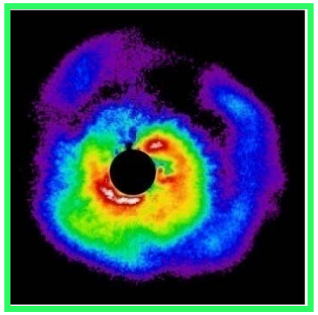


>100AU scale
w/ CIAO

⇒



Resolution
=0.05-0.1”
Contrast
Improved by ~10



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

SEEDS Main Survey 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

Individual Main Results in Each Category

56 refereed papers published/accepted 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 Uyama+16
OC	HD23514 B, HII1348 B, etc.	3xBD	Yamamoto+13 Konishi+16
NS	HAT-P-7 B, KOI-94 B, etc.	M star	Narita+10 Ryu+16
YSO	~30 resolved disk imaging	Disks w/ gap/ring	Hashimoto+11 + many

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

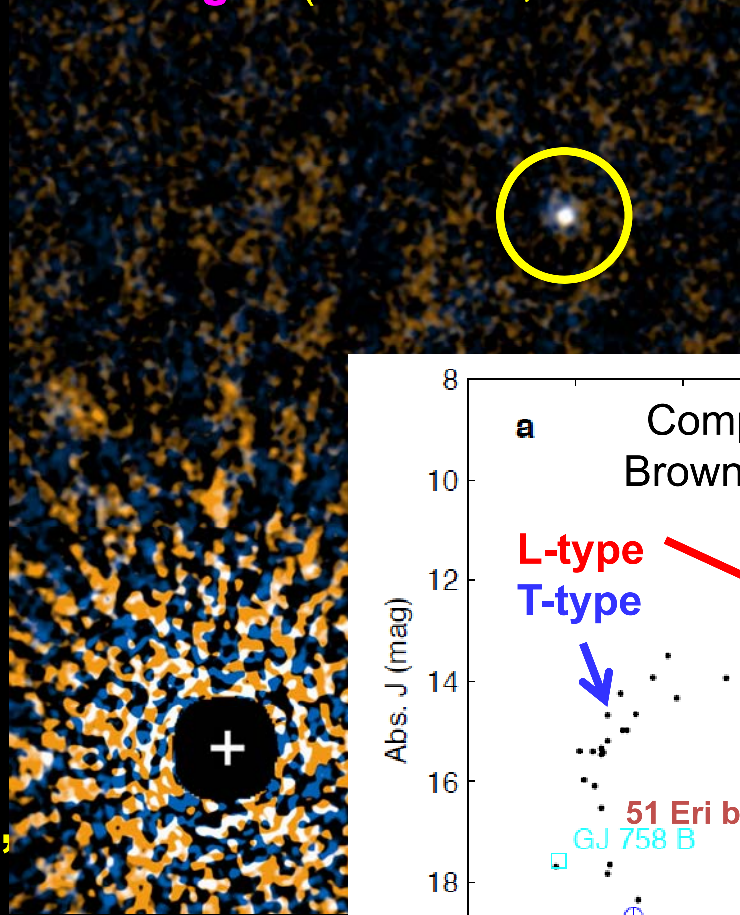
As a highlight, we report an exoplanet detection around the Sun-like star GJ 504.
A unique cold Jovian planet imaged (Kuzuhara, Tamura et al. 2013).

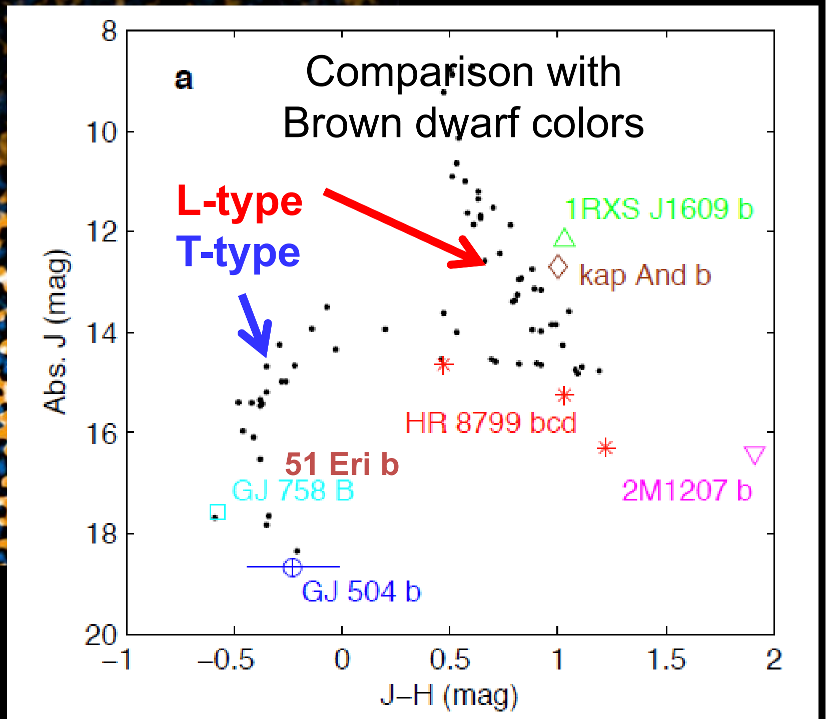
□ Primary GJ 504 A

- 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

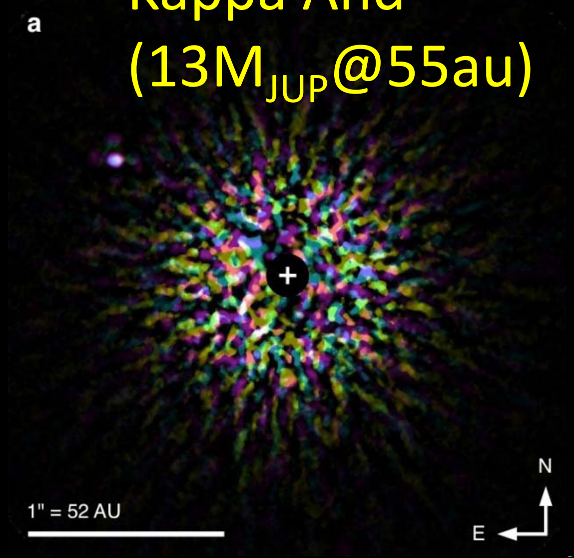




Other Discoveries and Findings

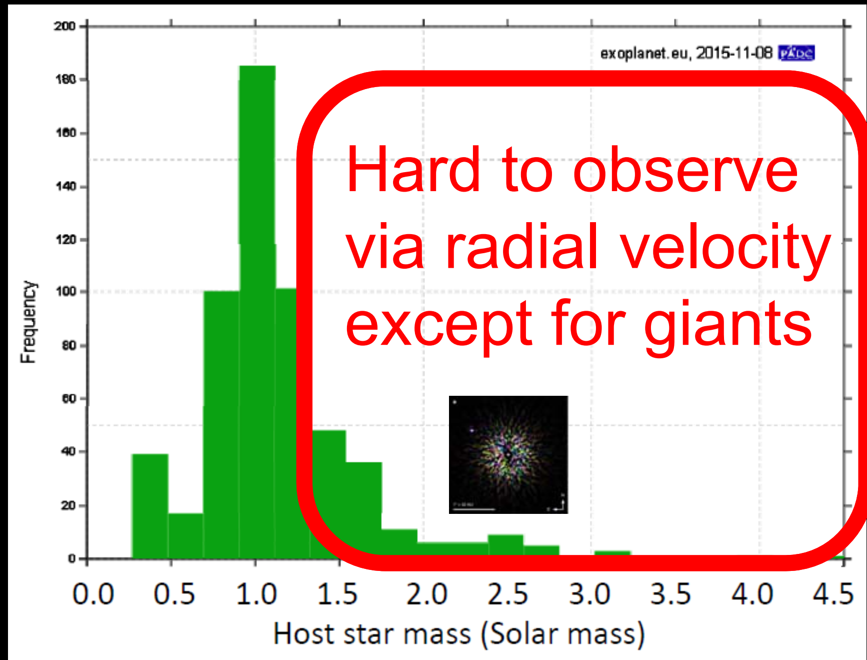
☐ SEEDS published three planet candidates, other than GJ 504b

Kappa And ($13M_{JUP}$@55au)

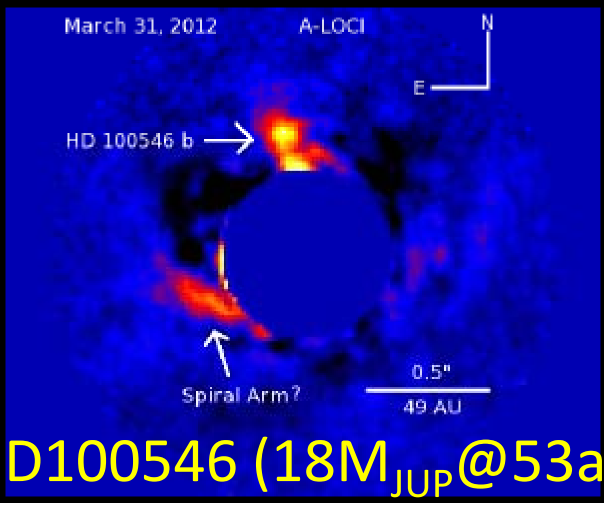


○ A planet candidate around a B-type star (2.5 Msun)

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



Hard to observe via radial velocity except for giants



HD100546 ($18M_{JUP}$@53au)

○ A planet around a YSO and induced arm?

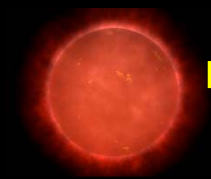
(Currie+2014)

☐ 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).

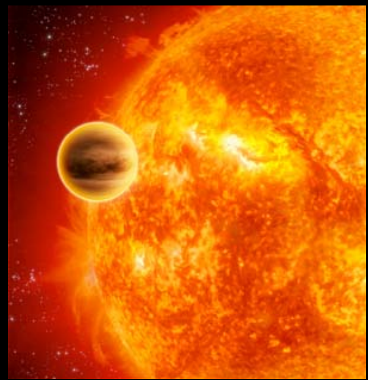
Studies for Origin of misalignd RV Planets and Long-Term RV Trend

SEEDS searches for stellar companions around stars with **inner planets**

Stellar Companion



Gravitational Perturbation

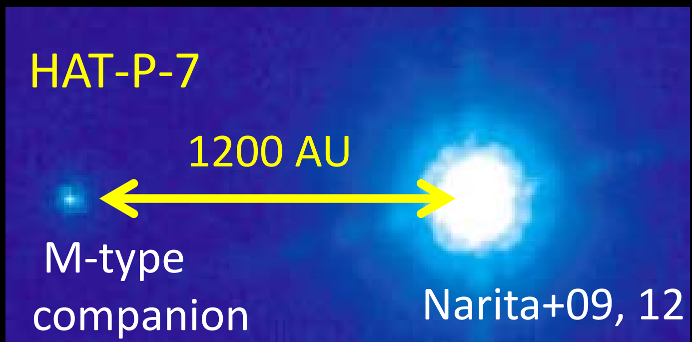


A stellar companion may be a cause of such an inner planet (Kozai-effect; Wu et al. 2007; Fabrycky & Tremaine 2007)

=> Probed by SEEDS imaging

☐ Companions were indeed discovered

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



- Companions causing the RV trend

SEEDS Statistics on Wide Orbit Giant Planets

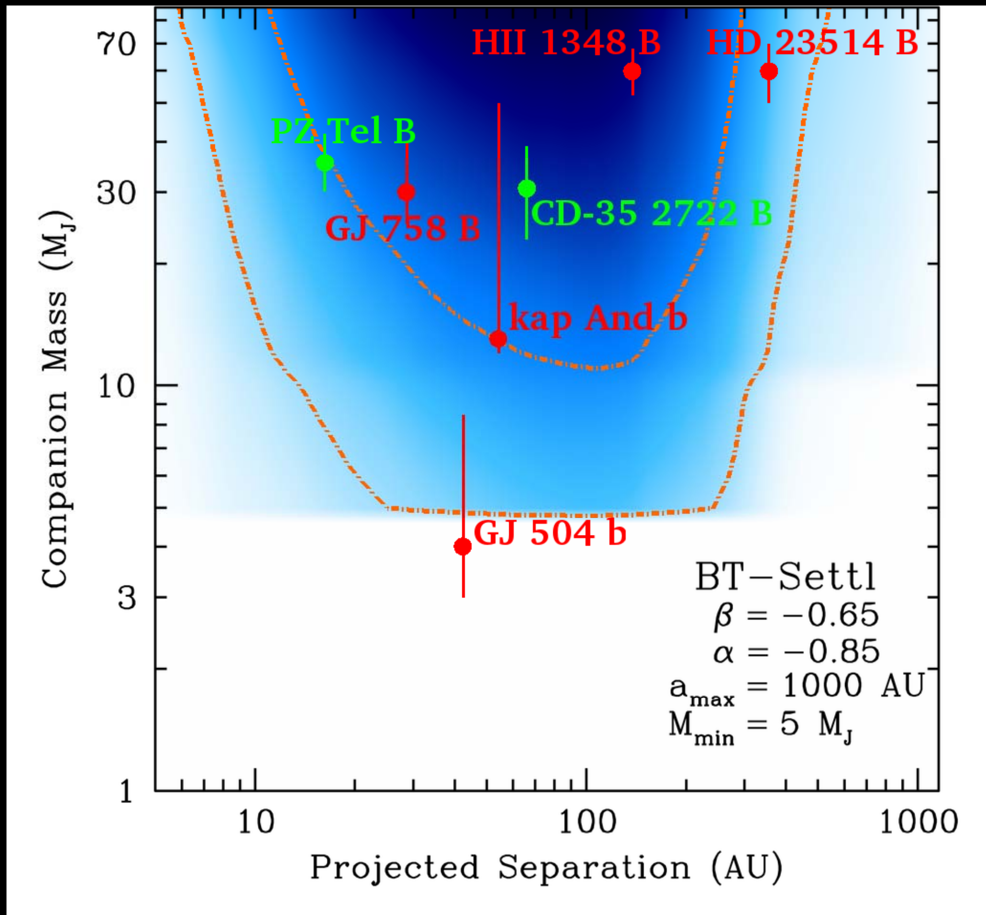
~250 stars (MG, DD, OC) are used for statistical analysis (Brandt+2014).
~100 YSOs are used for statistical analysis (Uyama+2016).

☐ Model

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

☐ Data

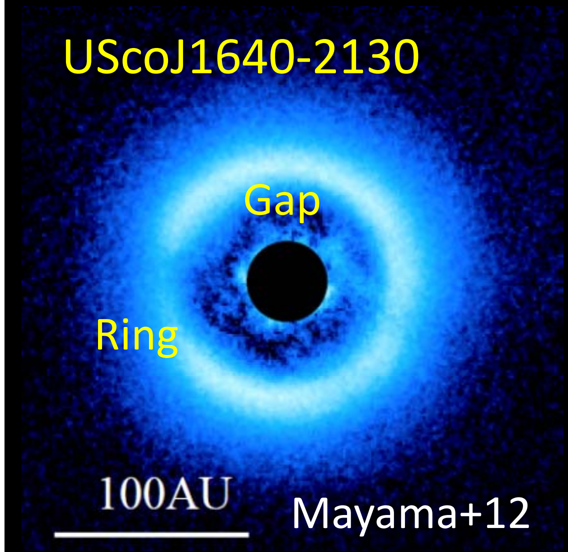
- Stellar age
- Stellar distance
- Stellar type/mass
- Contrast maps



Frequency: 5–70 M_{Jup} at 10-100 AU ~ 2%   Red=SEEDS, Green=NICI

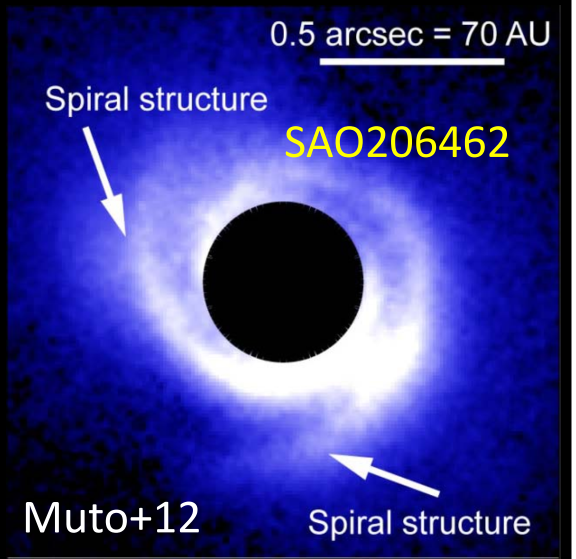
Major Results of Planet Formation Sites

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 since 2010.



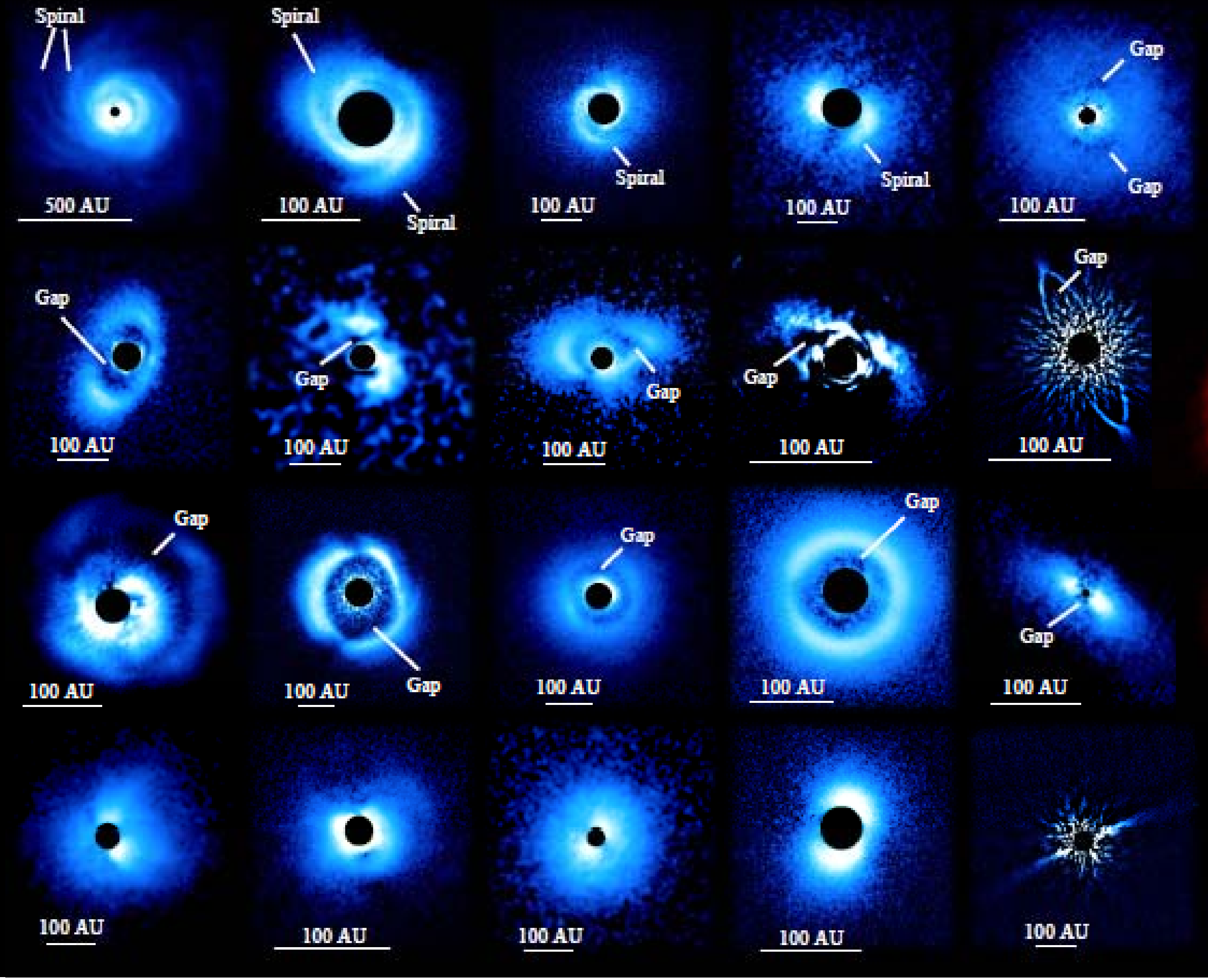
☐ Gaps
A disk gap may be evidence for dynamical interactions between a planet and its gaseous disk.

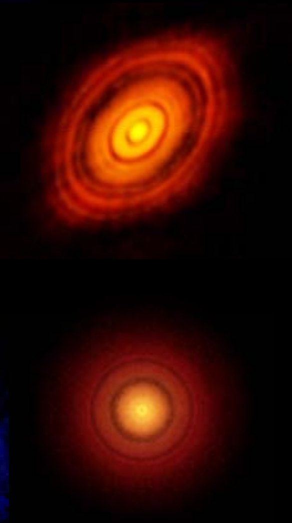
☐ Spirals
A gravitational perturbation from an embedded planet generate spiral density waves.



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

Note that ALMA HL Tau image (2015) is thermal emission .

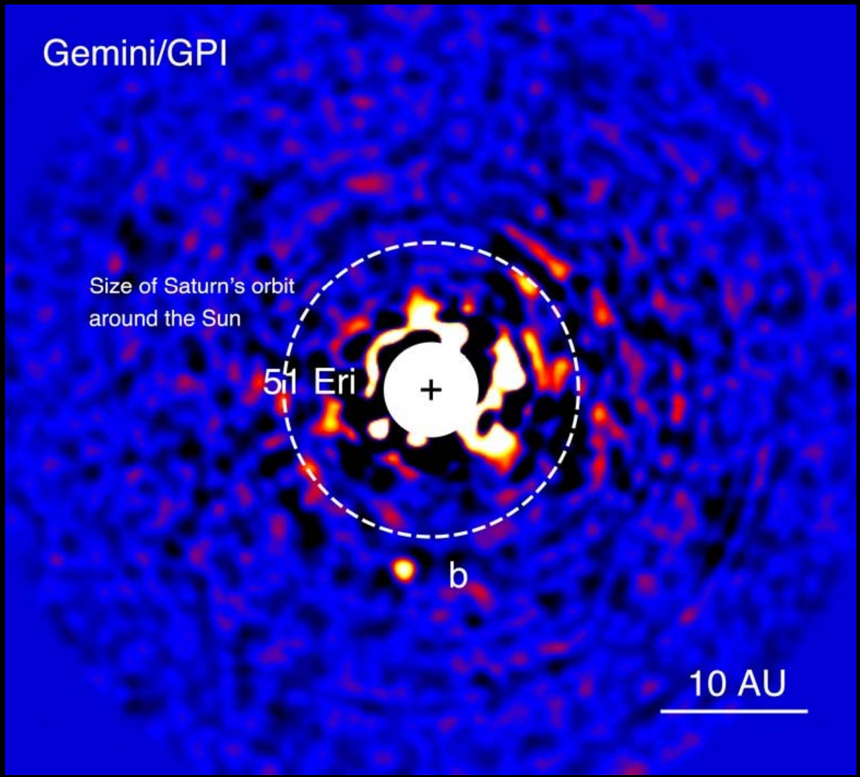


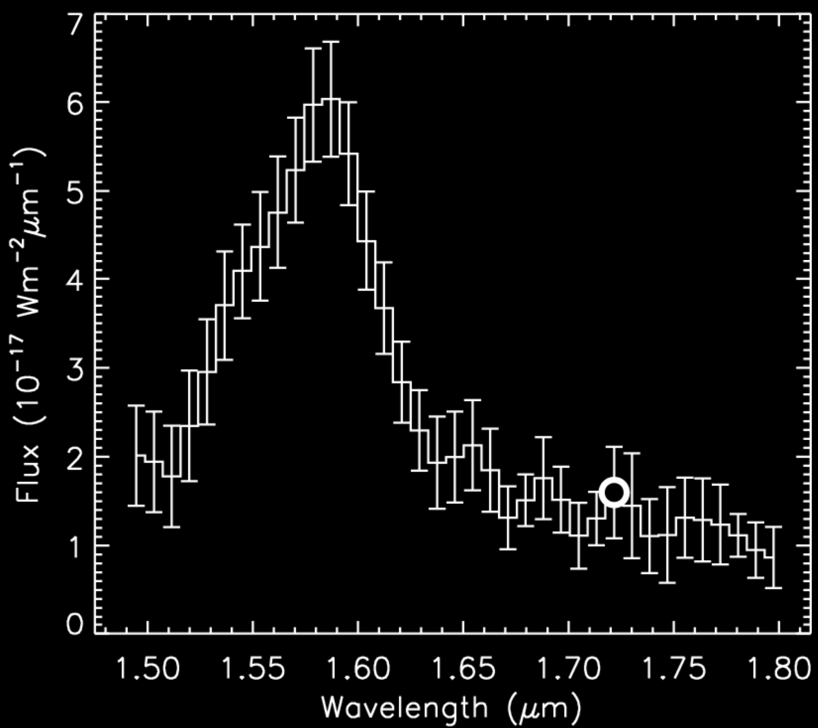


ALMA
HL Tau
&
TW
Hya

Gemini Survey-GPIES: 600 stars in 890 hrs

1st Planet: 51 Eri b





Credit: Gemini

Gemini Planet Imager Extra Solar Survey

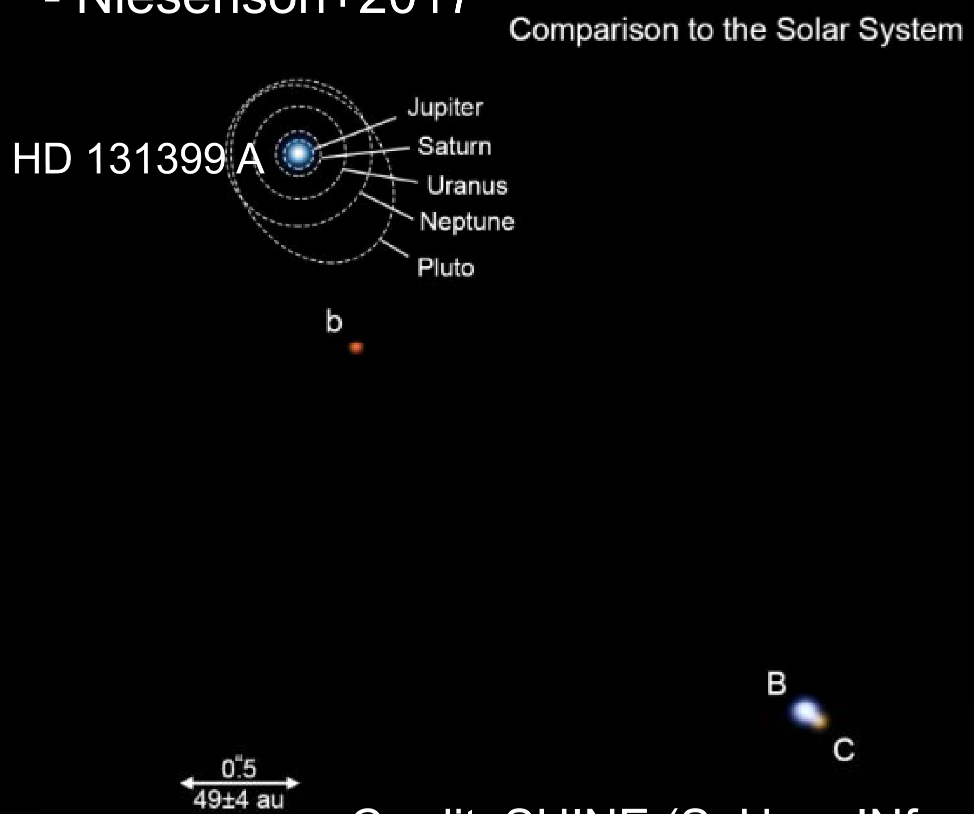
Macintosh et al. 2015

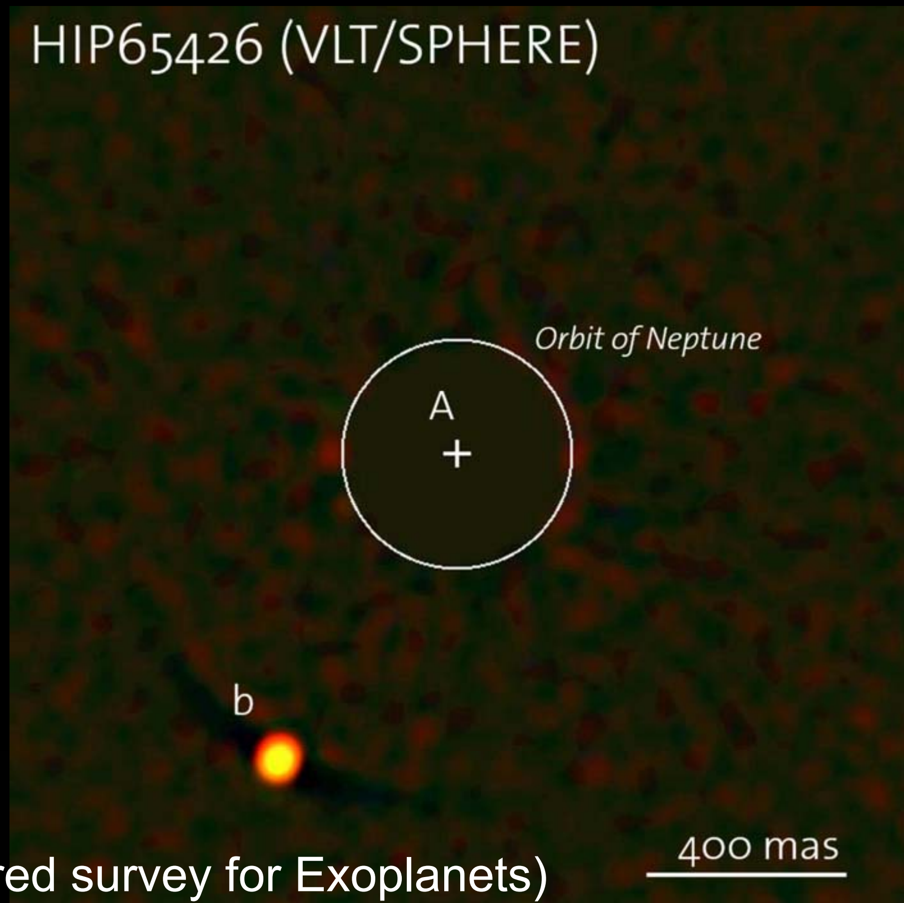
VLT/SPHERES's Survey: 800 stars in 200 nights

HD 131399 Ab, A star, 16 Myr
- An alien planet orbits in a triple-star system
- Aagner+2016, Science

But it turns out a Background star!
- Niesenson+2017

HIP 65426b, A star, 14 Myr
- SPHERE's first planet
- Chauvin+17, A&A
- $9M_{JUP}$ @ 9au

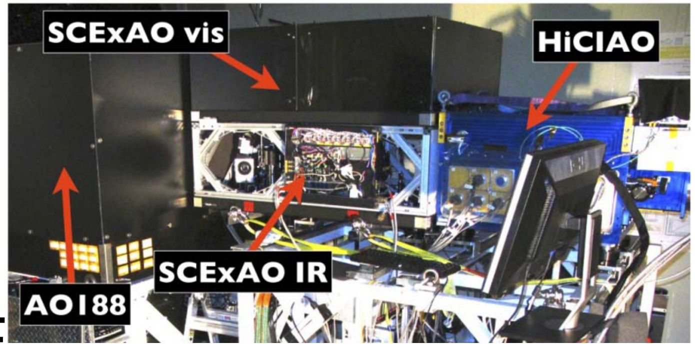


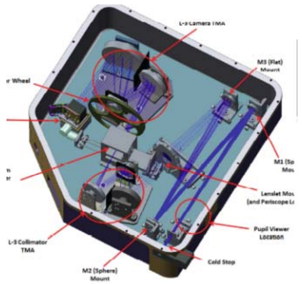


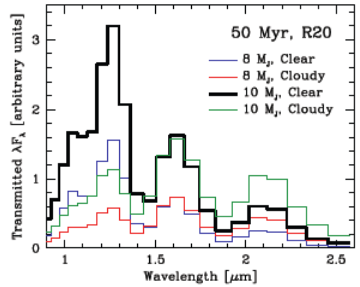
Credit: SHINE (SpHere INfrared survey for Exoplanets)

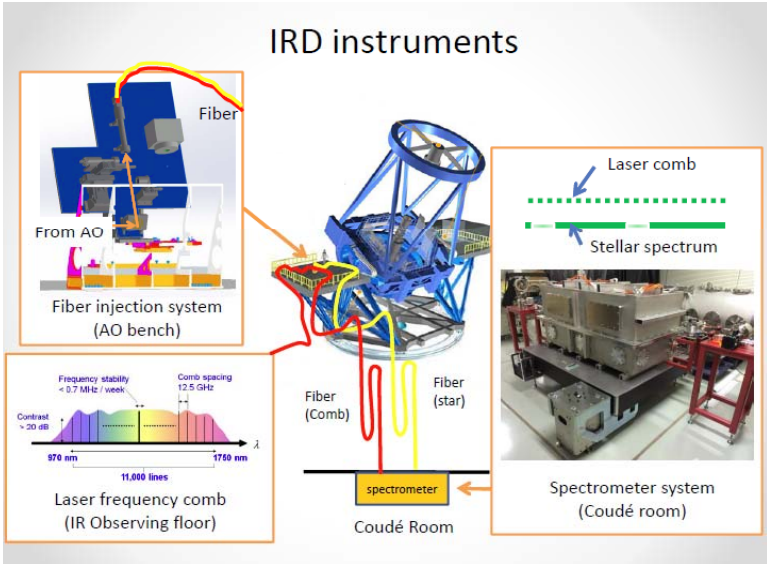
Subaru's Next Steps in Exoplanet Sciences

- **SCExAO: 2014- (Science phase)**
  - 2000 MEMS deformable mirror
  - PIAA coronagraph
  - IR bench for HiCIAO & CHARIS
  - OPT bench for FIRST & VAMPIRE
- **CHARIS: 2016- (FL done)**
  - IFU Combined with SCExAO
  - R19/R70 JHK spectroscopy
  - Small (λ/D) inner working angle!
- **IRD: 2017- (FL done; IR Doppler)**
  - 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

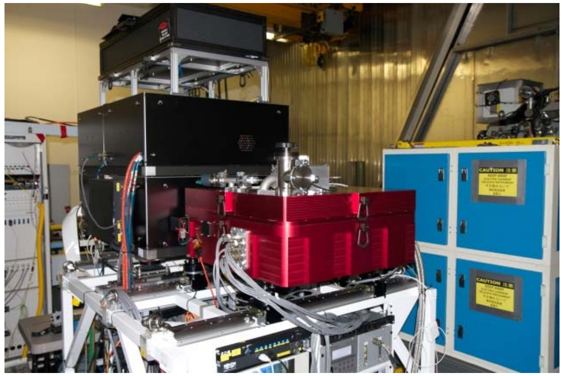




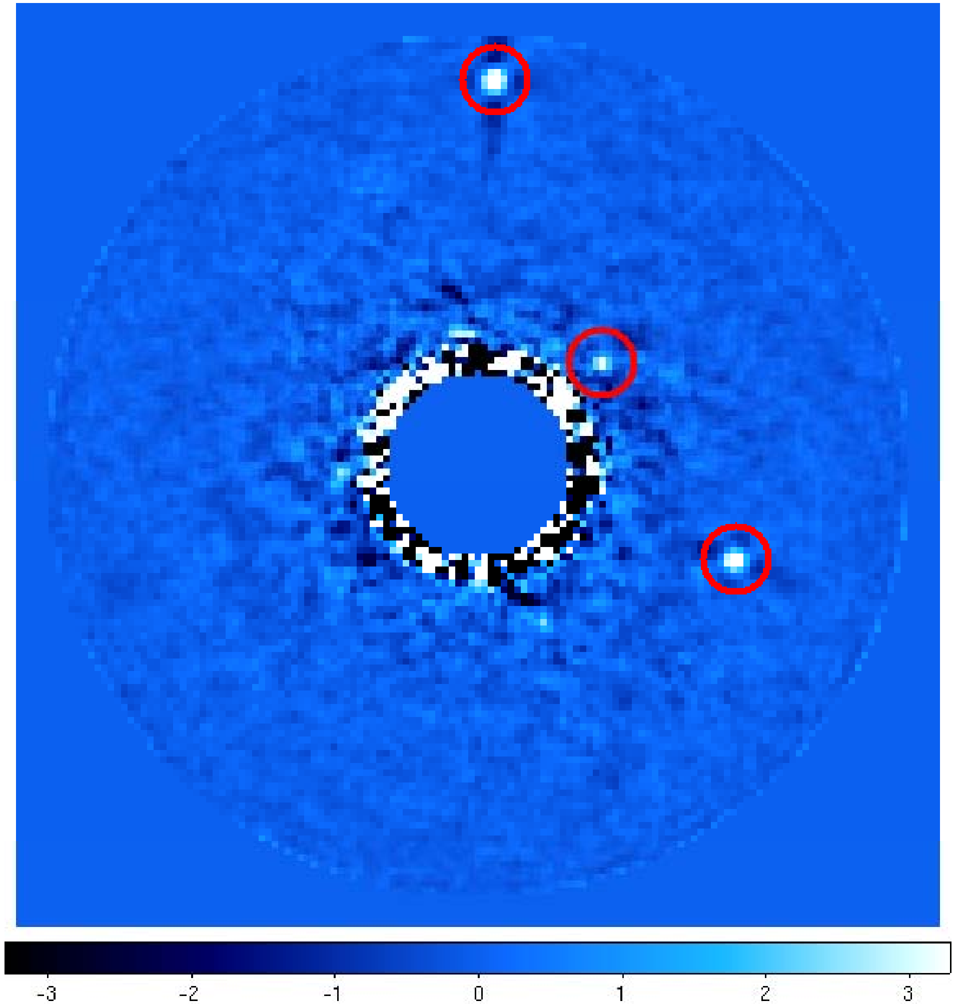




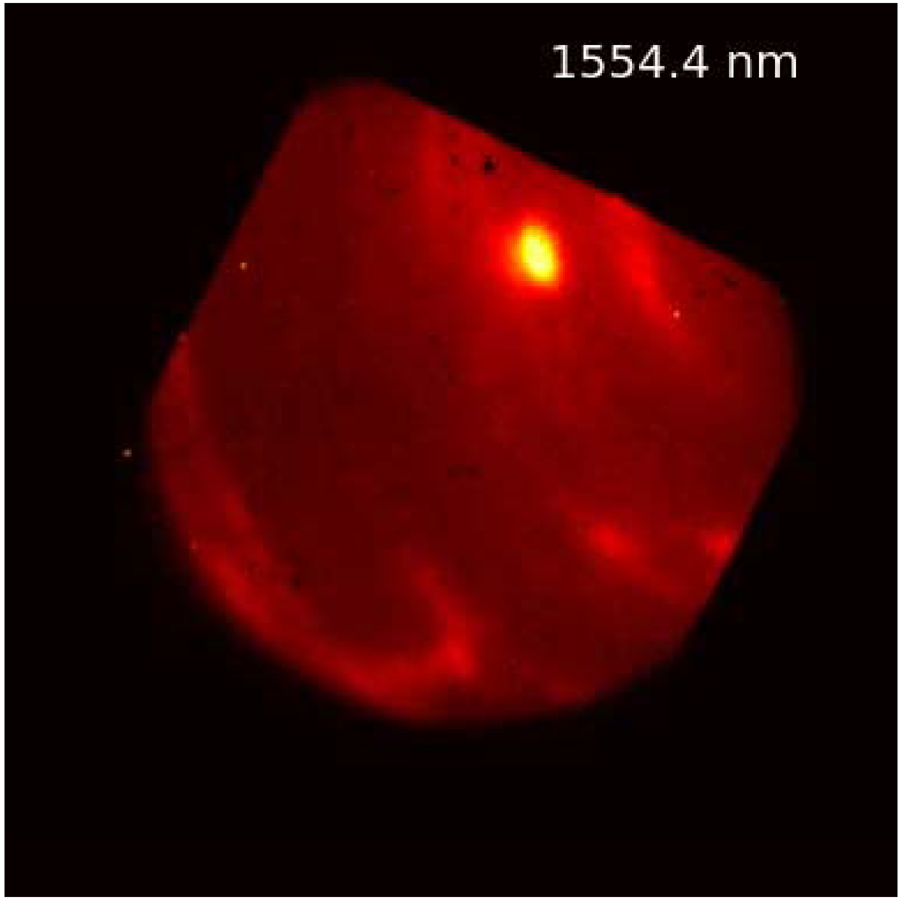
CHARIS First Light Images



HR8799 cde ↓



Neptune ↓

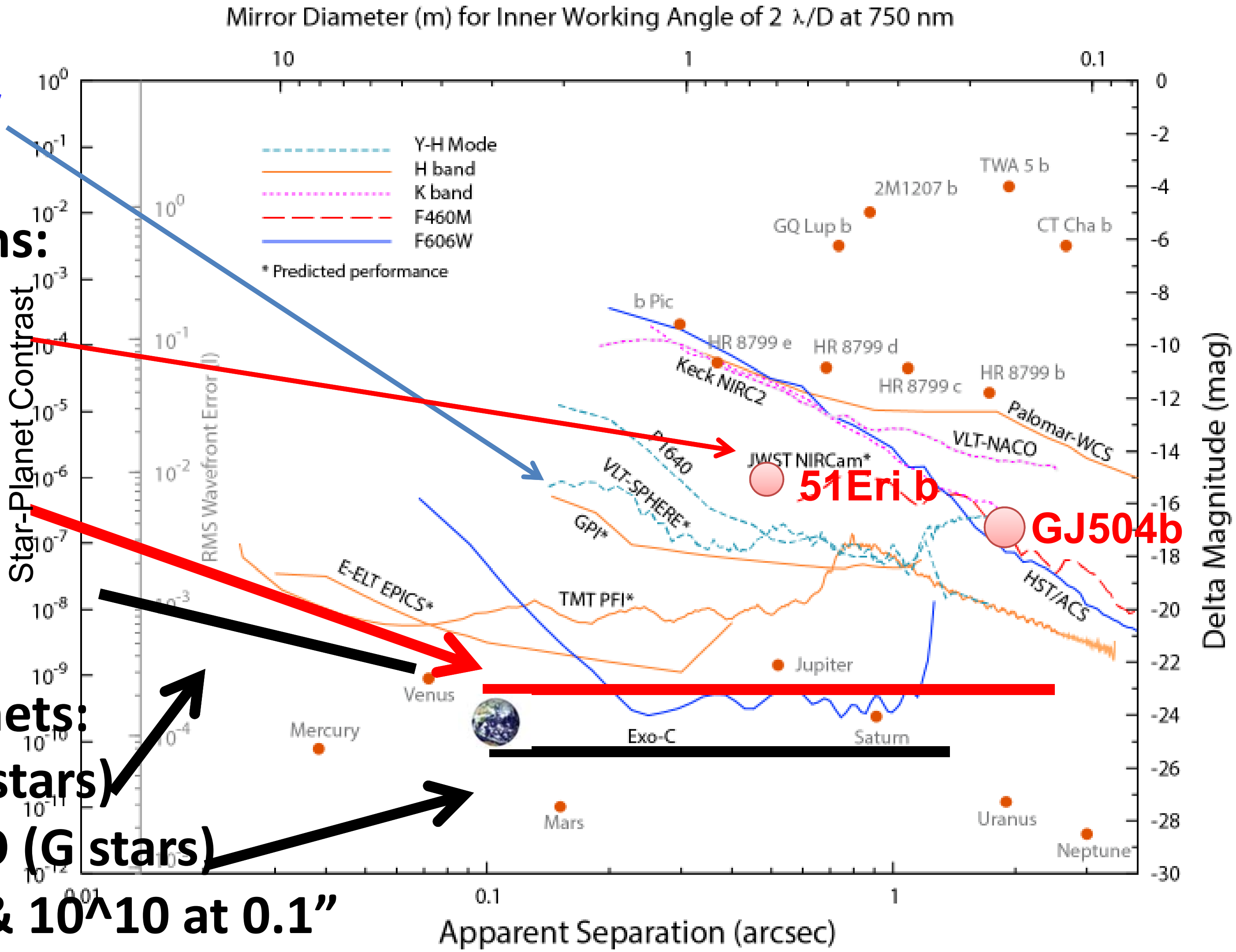


Princeton CHARIS team

Future Surveys and Future Missions

- ☐ **Future Ground-based Surveys:**
  - GPI survey
  - SPHERE survey

From Exo−C interim report (Stapelfeldt+14)



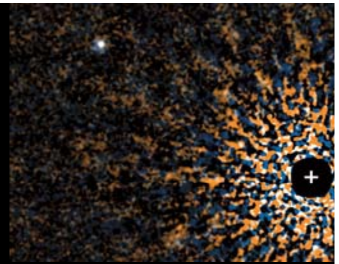
- ☐ **Future missions:**

JWST coronagraph

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”**



Summary

☐ SEEDS and other surveys has explored the wide-orbit giant 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.

☐ 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 (SCExAO), IFU (CHARIS), and IRD and extend to TMT era with the help of the ABC activities.