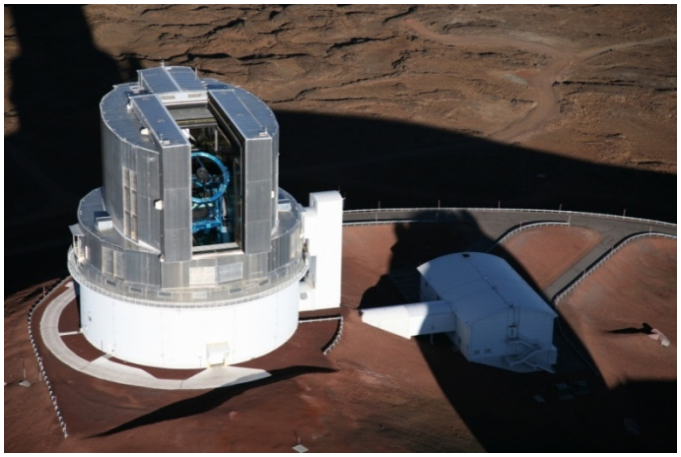
Exploring Exoplanet and Star-Formation Studies with Subaru

2019.11.22 Fri 14:00 - 14:30 @ Subaru 20th , Kona

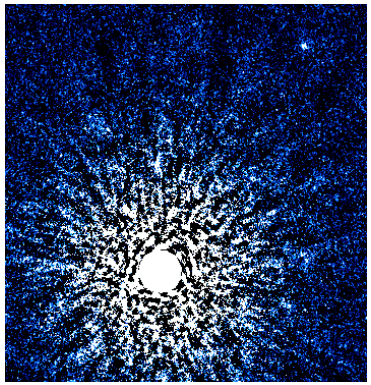
Motohide Tamura (on behalf of many CoIs)
University of Tokyo,
Astrobiology Center (ABC) & NAOJ of NINS

Talk Contents

- Back to Subaru 1st Light
- From Star Formation to Planets (with Subaru)
- Toward Lower-Mass Objects (sensitivity)
- Image 2nd Jupiters and their birth places! (contrast)
  - SEEDS project
- Catch 2nd Earths and super-Earths via Infrared RV ! (preciseness)
  - IRD Project
- From Current to Future of DI
  - SCExAO/CHARIS to TMT/PSI
  - WFIRST/HabEx/LUVOIR



GJ504b



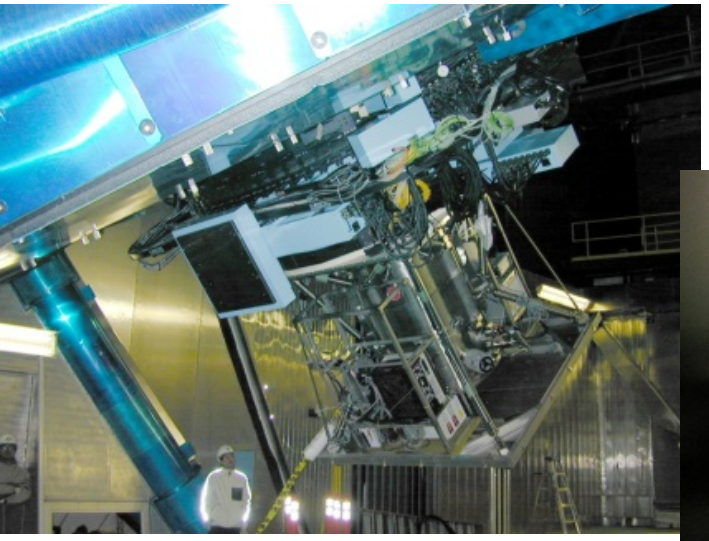
AB Aur

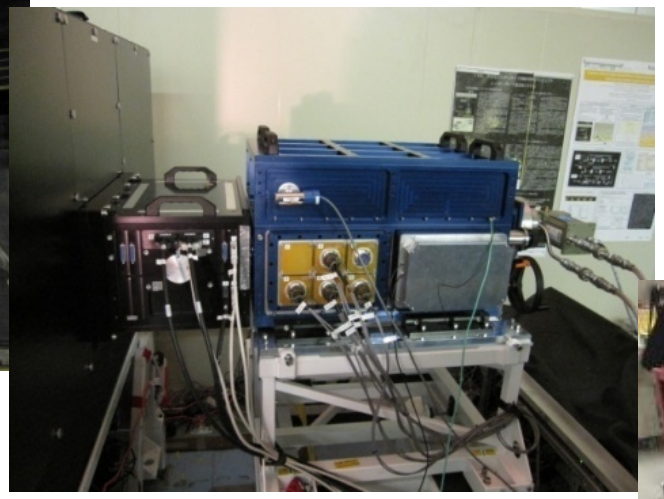
Including some history of Subaru Exoplanet Instrumentations ….

Missing here: PALMS (M stars), Massive stars, COMICS results, etc. > Parralel session talks

My Youth was Subaru Instruments and Sciences

- I joined NAOJ in 1992 (now at UTokyo/ABC/NAOJ).
- Developments of Infrared instrumentations (FL year)

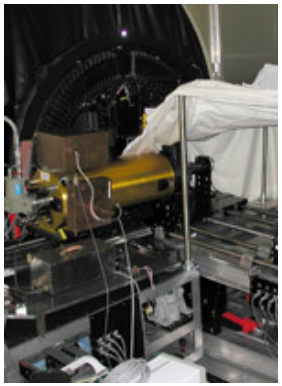
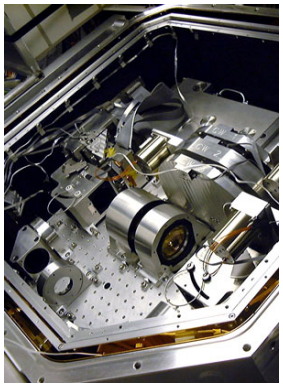
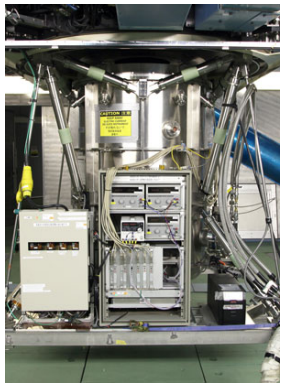
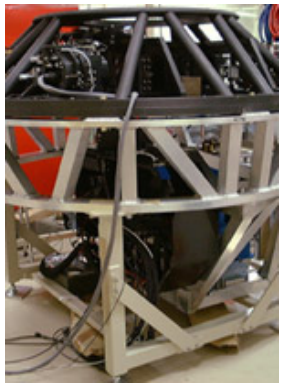
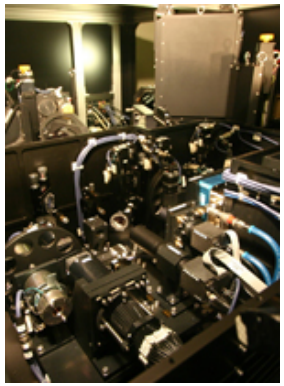


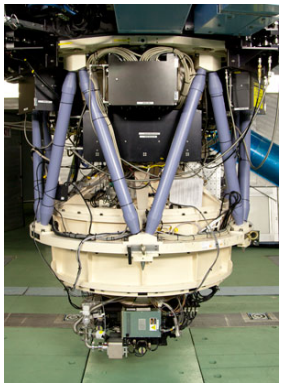


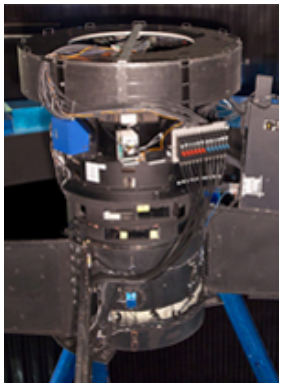
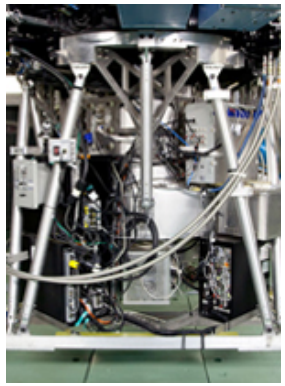
- **CIAO (2000)**
- **HiCIAO (2009)**
- **IRD (2017)**

Other IR/OPT Subaru Instruments for Exoplanet and Star Formation

CISCO/OHS, HDS IRCS, FOCAS COMICS, SCam AO36, FMOS AO188, MOIRCS HSC

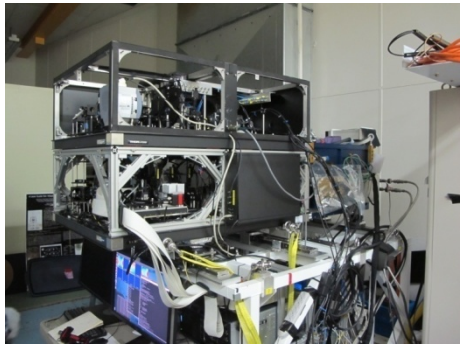






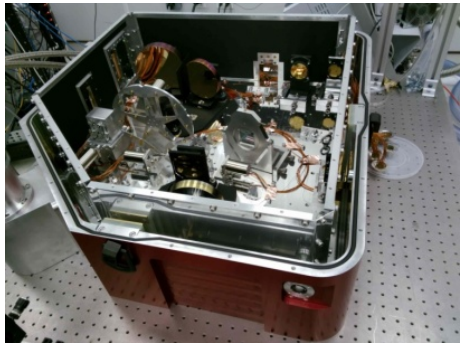



For High-Contrast Observations

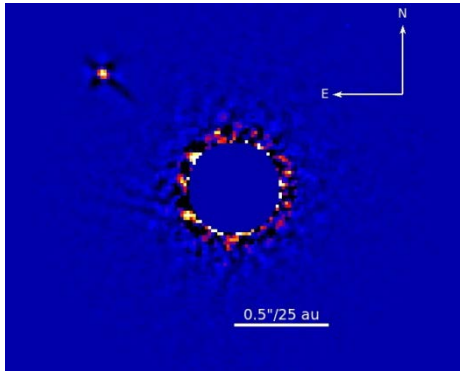
SCExAO



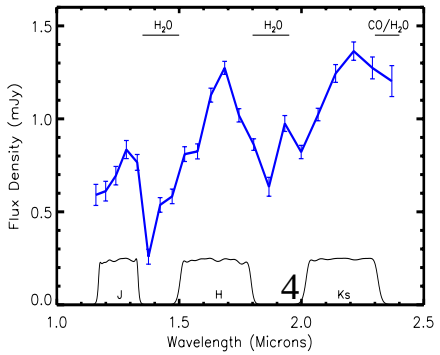
CHARIS



kappa And Image

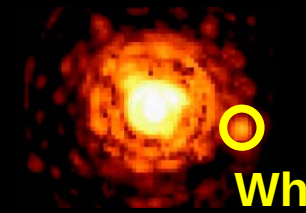


kappa And Spectra

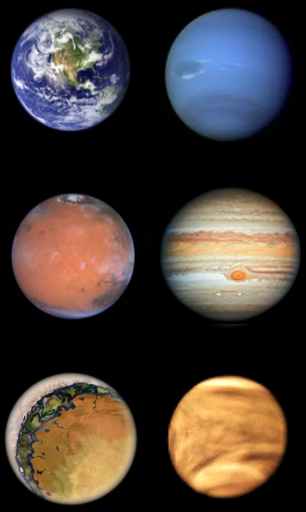


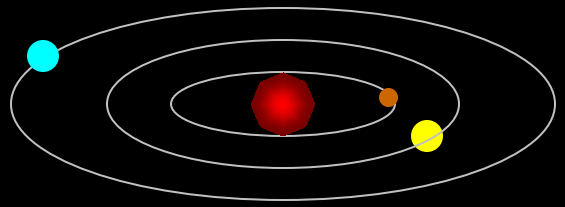
Coherent understanding from star formation to planets is our goal

Planets form from protoplanetary disks as a by-product of star formation



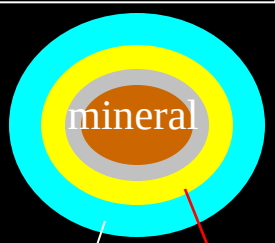
Which type?





Planetary system and Exo-zodi

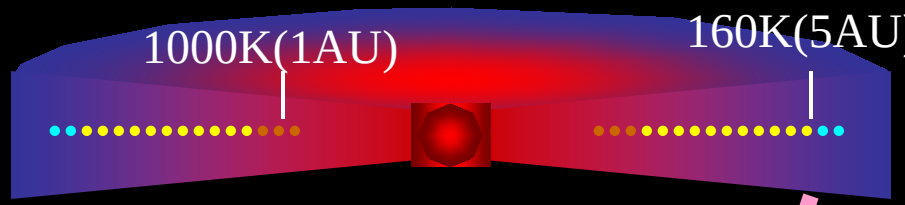
Dust



Cloud

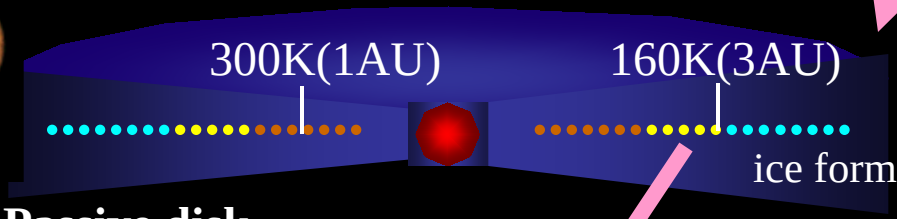
10 K

Protoplanetary Disks



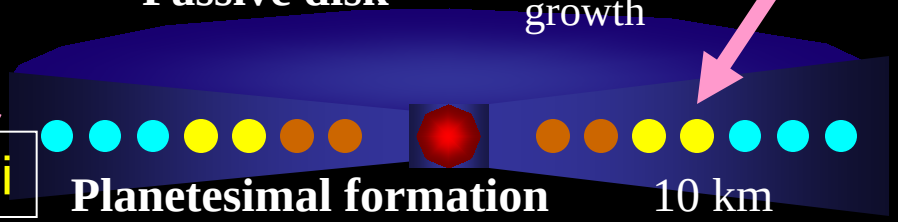
Accretion disk

heating & evaporation



Passive disk

growth



Planetesimal formation

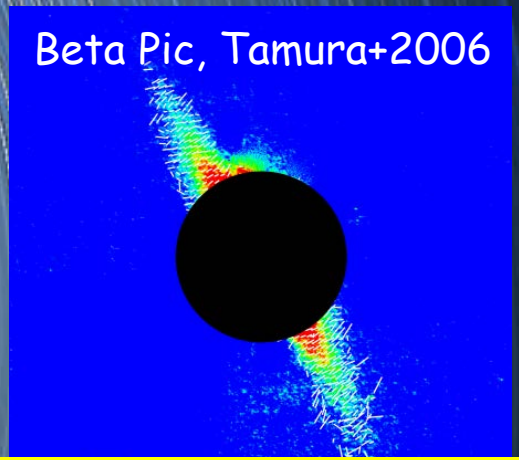
10 km

Prof. Norio Kaifu
(1943-2019)

Subaru's Science FL started with this Orion image (Kaifu+2000)
He was also the original proposer of Subaru /CIAO…

Subaru First AO Coronagraph

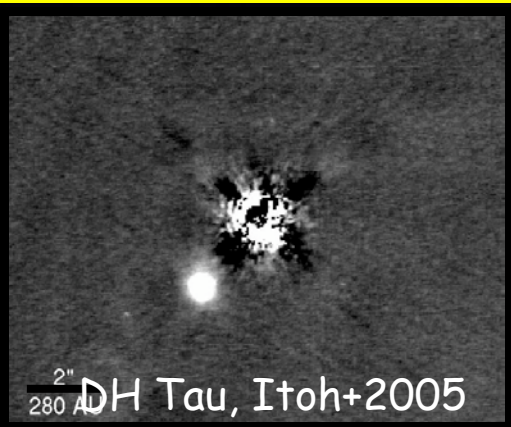
- **CIAO with Cs 36-actuator AO**
  - ★ Coronagraphic Imager with Adaptive Optics
  - ★ First dedicated IR coronagraph on 8-m telescopes
- *Disk Morphology (>100 AU)*
- *Companion searches (ibid)*
- *High-resolution Polarimetry*

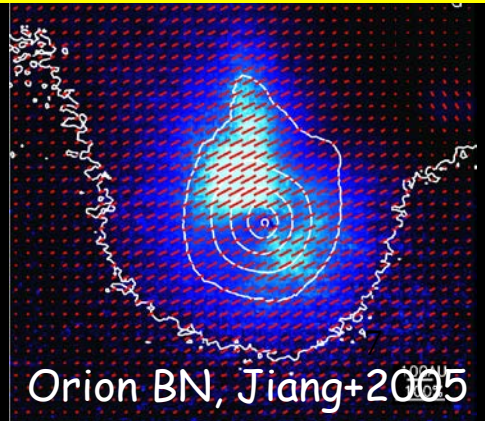


Compact disk around massive YSOs & Disk Polarimetry

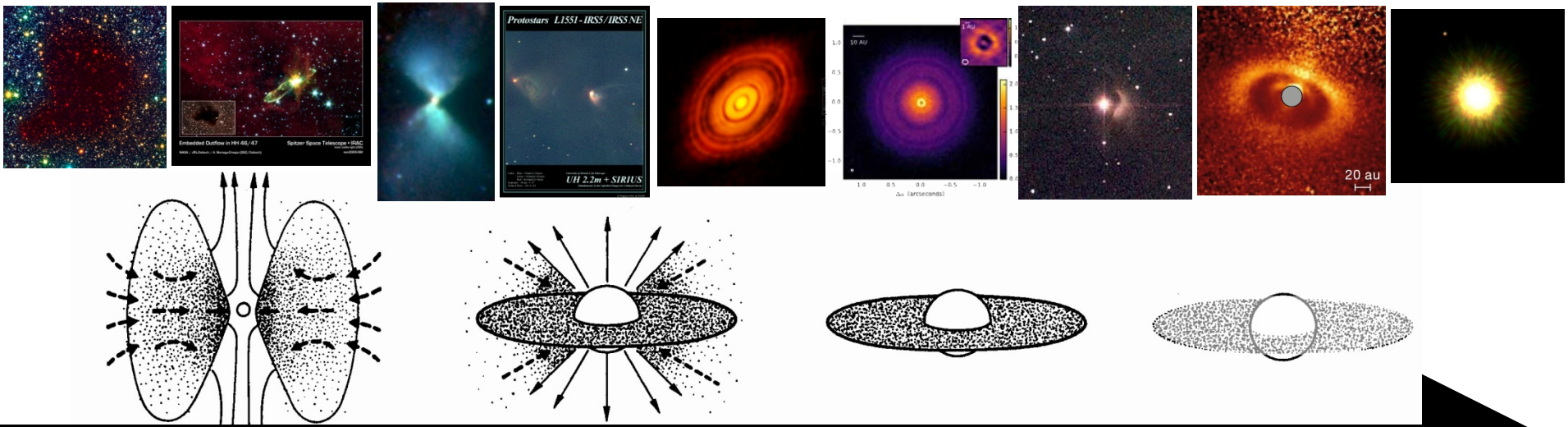
Diversity of proto-planetary disks

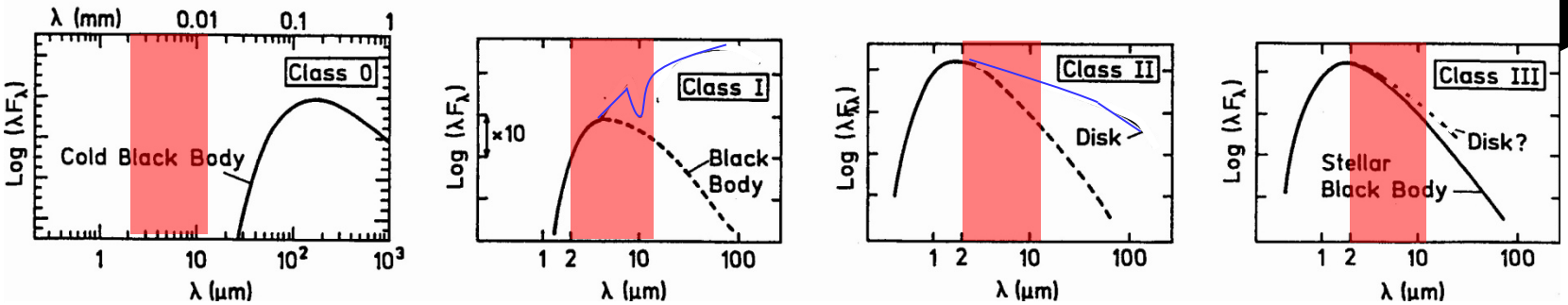
Young very low-mass companions





YSO Classification and Evolution based on IR data





class 0 | **class I** | **class II** | **class III**

Subaru, ~0.1 arcsec resolution or ~15 AU scale

$$\alpha = \frac{d\log(\lambda F_\lambda)}{d\log\lambda}\Big|_{2<\lambda<12}$$

>0.3	0.3～−1.6	<−1.6
Large IRE	Small IRE	No IRE

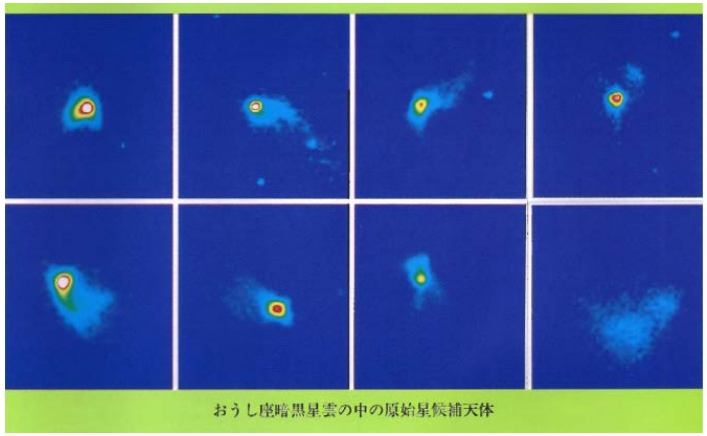
Originally based on IRAS data, class 0 is added later. (Lada 1987, Andre+2000)

Protostar Circumstellar Structures Revealed at 2 μm

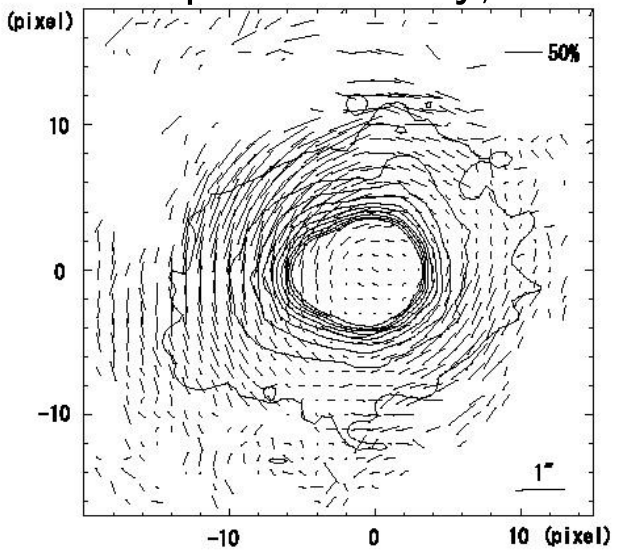
Resolution=~0.3", Taurus IRAS sources with IRCS w/o AO

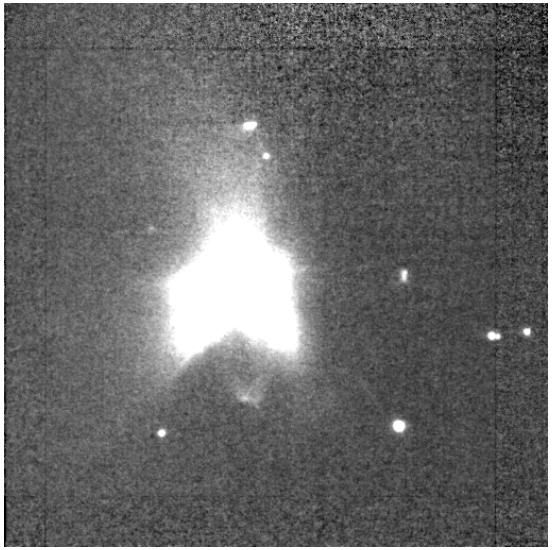
Ishii+2004; Lucas+2005; Tamura+1991

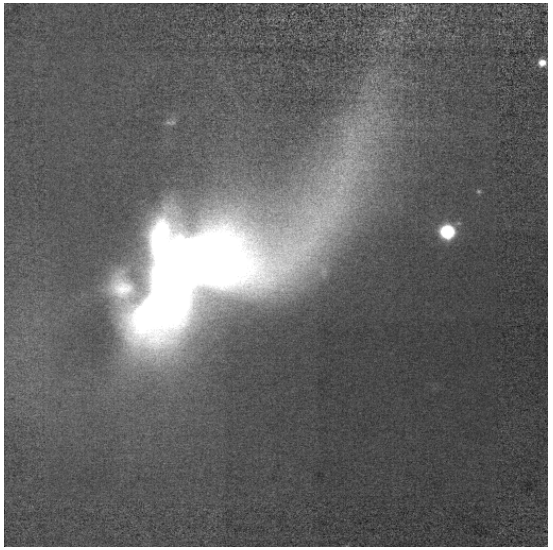
KPNO 1.4m + 62x58 IR Camera



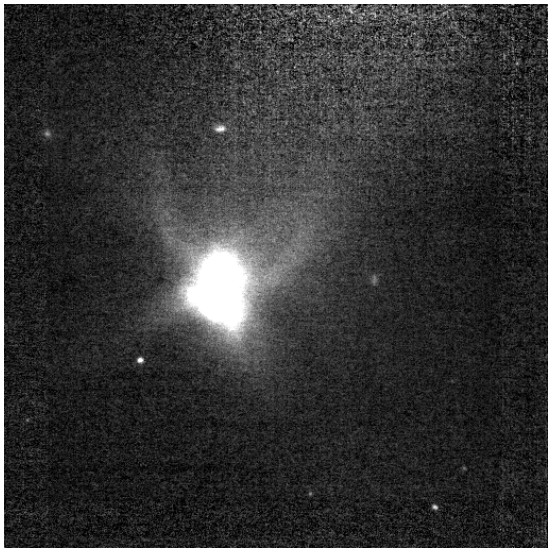
HL Tau polarimetry, CIAO

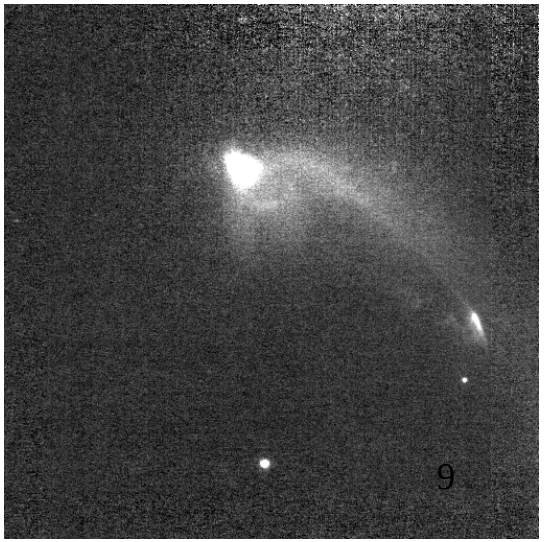






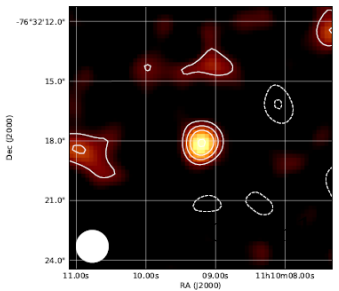
8400 AU





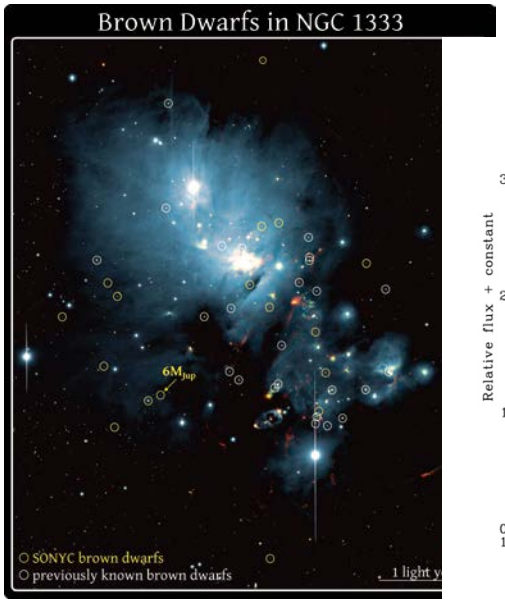
Isolated Planetary Mass Objects can Form in Star Forming Regions

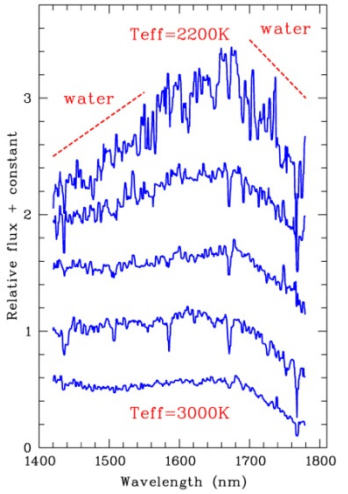
- **BDs and FFPs in star forming regions**
  - Tamura et al. 1998, Oasa et al. 1999, Lucas et al. 2000, Zapatero-Osorio et al. 2000; see also Subaru S106 image (Oasa+ 2006)
  - Form as stars?
    - 0.001-0.01Mo (Low & Lynden-Bell 1976; Boss 2001; Whitworth & Stamatellos 2006)
  - Form as planets?
    - Disk instability and ejection
  - Called as "Isolated Planetary Mass Objects (IPMO)" or "Free-Floating Planets (FFP)"
  - e.g, 12 Jupiter-mass OTS44 has a disk (ALMA, Bayo+17)
  - SONYC Project by U Toronto and NAOJ (next)
  - Recent HSC survey results by Bouy (This WS)

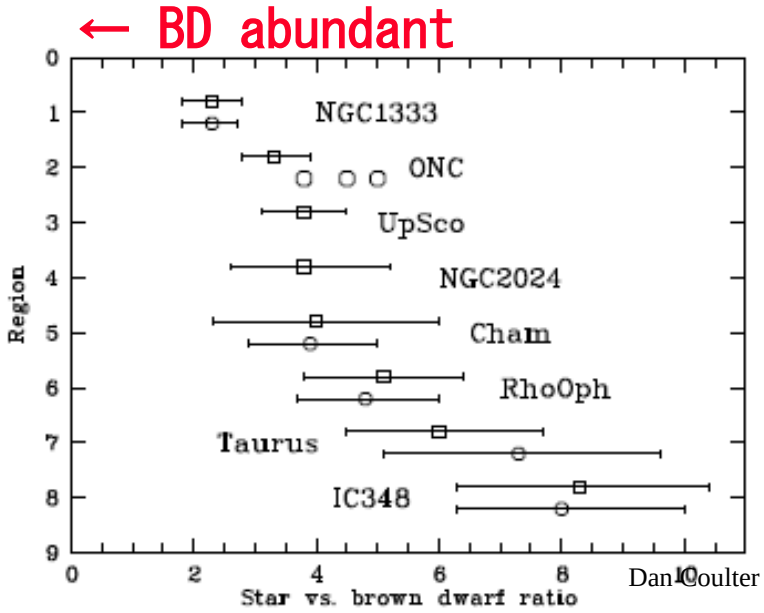


Substellar Objects in Nearby Young Clusters (SONYC)

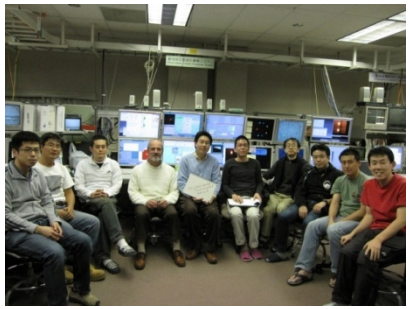
- PI: Ray Jayawardhana
- Scholz+2009, 2012a, b
  Geers+2010, Mužić+2011, 2012
- NGC 1333, rho Oph, etc.
- Subaru + S-Cam + FMOS
- MOS capability fully used.
- ~30 new BDs discovered.
- 6 M_J free-floating planet "directly" detected.
- #BD/#NS variations in SFRs clearly detected



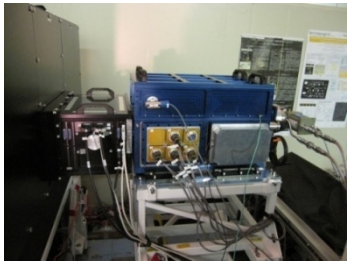


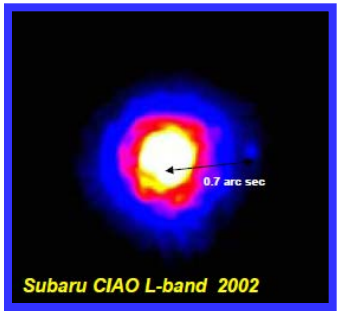


SEEDS – Strategic Explorations of Exoplanets and Disks with Subaru

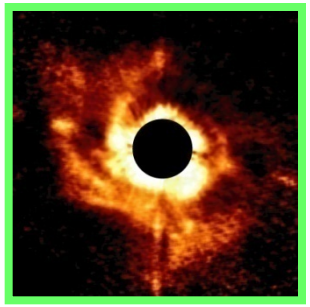


- The 1st Subaru Strategic Program – 2nd gen.AO coronagraph **HiCIAO & AO188**
- 120 nights from 2009; **finished in 2015 Jan,** **only <1 night loss due to HiCIAO**
- NIR direct imaging and census of **giant planets in the outer regions** (10-100AU) around **~500 solar-type and massive stars**
- Exploring **protoplanetary and debris disks** for the origin of the diversity and evolution at the same regions (10-100AU)
- ***Direct linking*** *between planets and protoplanetary disks*



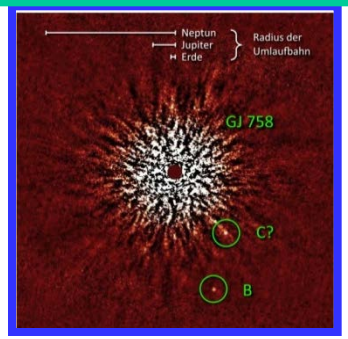


Resolution
=0.1-0.2”



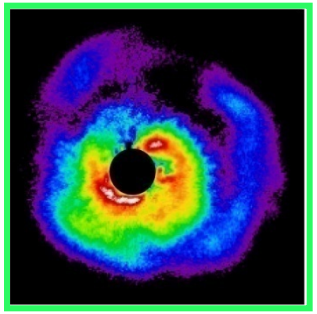
>100AU scale
w/ CIAO

⇒



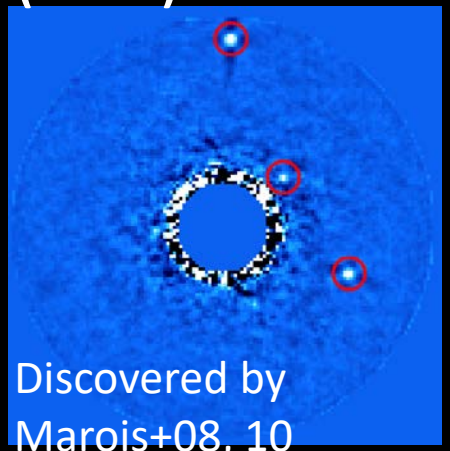
Solar-System Scale (<100AU) w/ HiCIAO

Resolution
=0.05-0.1”
Contrast
Improved by ~10

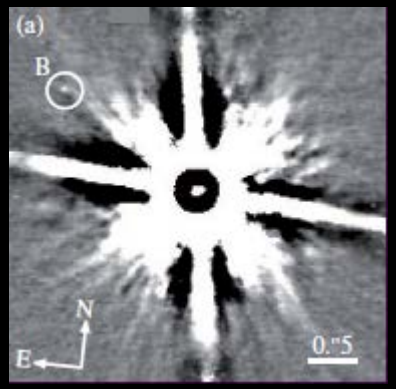


Subaru Directly Imaged Planets/Companions: A Gallery from SEEDS project and others

HR 8799 bcde (A star)



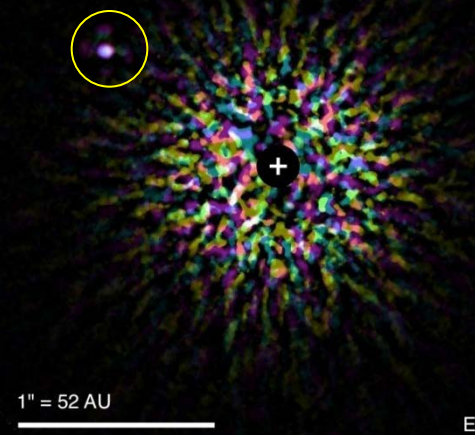
Discovered by Marois+08, 10



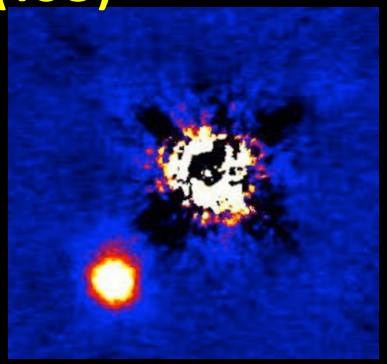
Also re-discovered image in 2002 by CIAO!

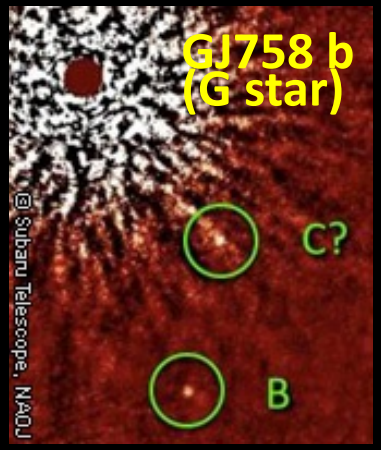
GJ504 b (G star)

Kappa And b (B star)



DH Tau b (YSO)

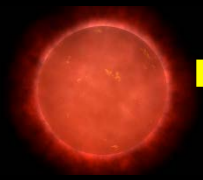




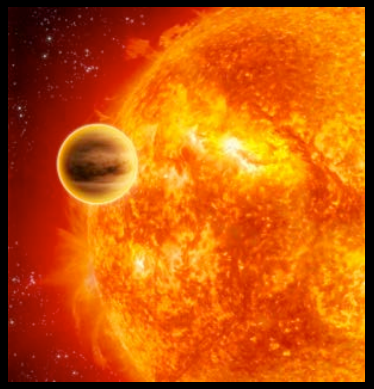
Studies for Origin of misalignd RV Planets and Long-Term RV Trend

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

Stellar Companion



Gravitational Perturbation

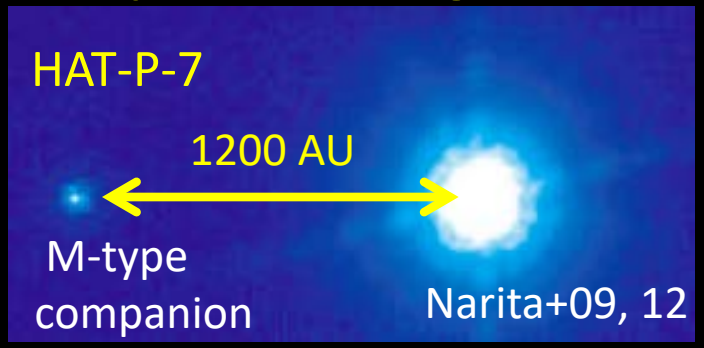


A stellar companion may be a cause of such an inner planet
(Kozai-effect; Wu et al. 2007; Fabrycky & Tremaine 2007)

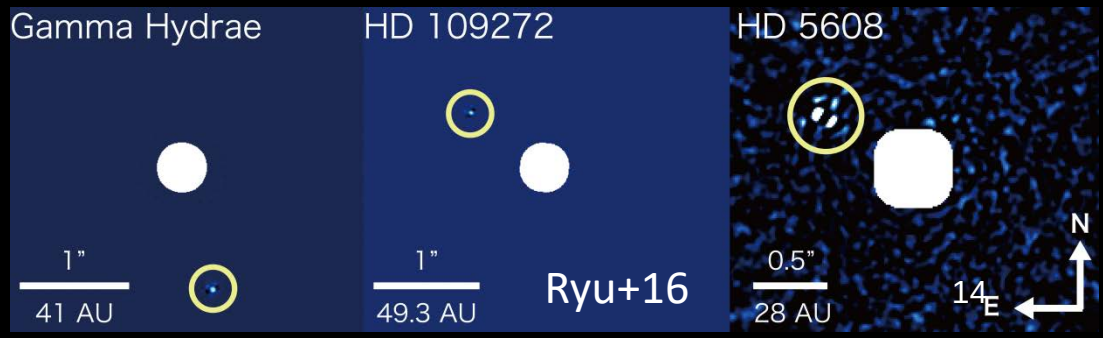
=> Probed by SEEDS imaging

☐ Companions were indeed discovered

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



- Companions causing the RV trend in fact discovered by SEEDS imaging



SEEDS Statistics on Wide Orbit Giant Planets

SHINE

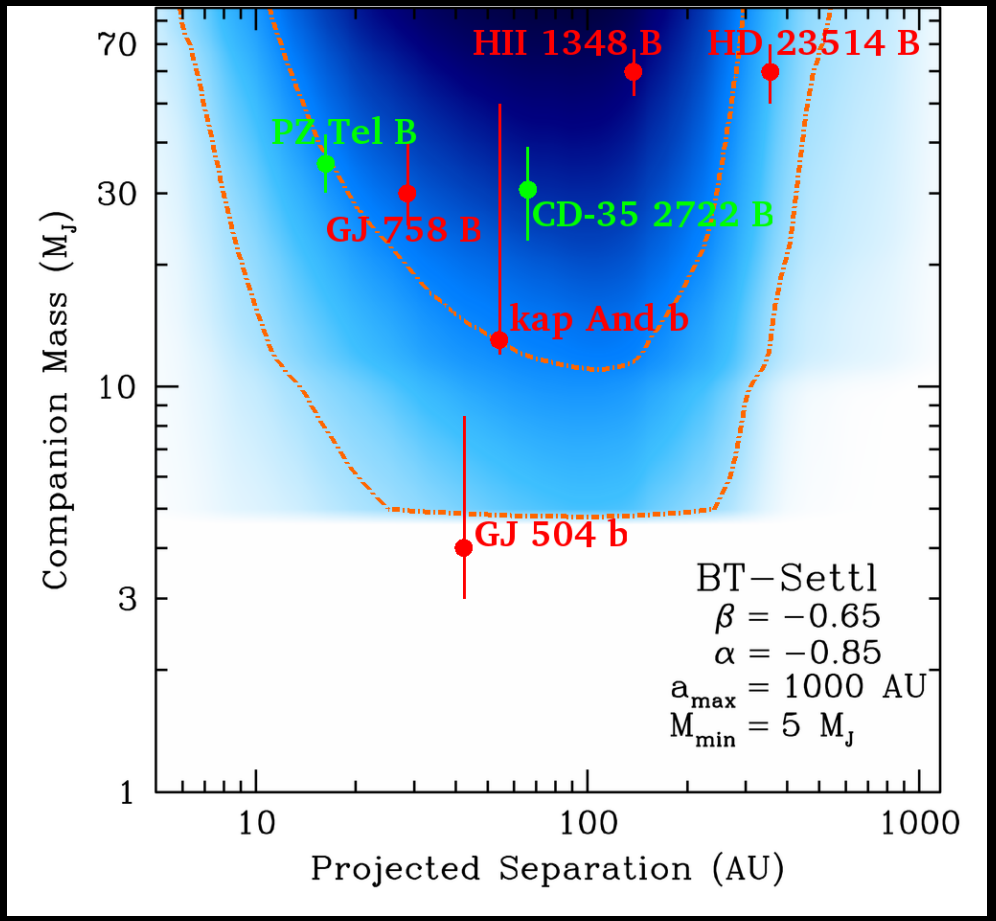
~250 stars (MG, DD, OC) are used for statistical analysis (Brandt+2014).
~100 YSOs are used for statistical analysis (Uyama+2016).

☐ 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

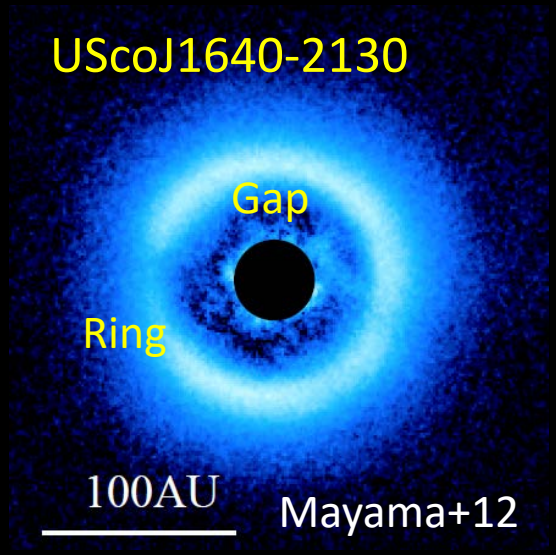


Frequency: 5–70 M_{Jup} at 10-100 AU ~ 2%
Similar numbers from VLT/SHINE and GPI.

Red=SEEDS, Green=NICI

SEEDS Major Results of Planet Formation

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.**

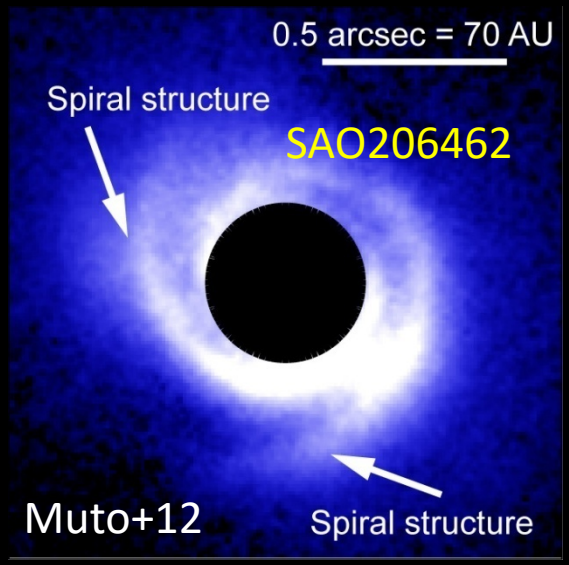


☐ **Gaps**

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

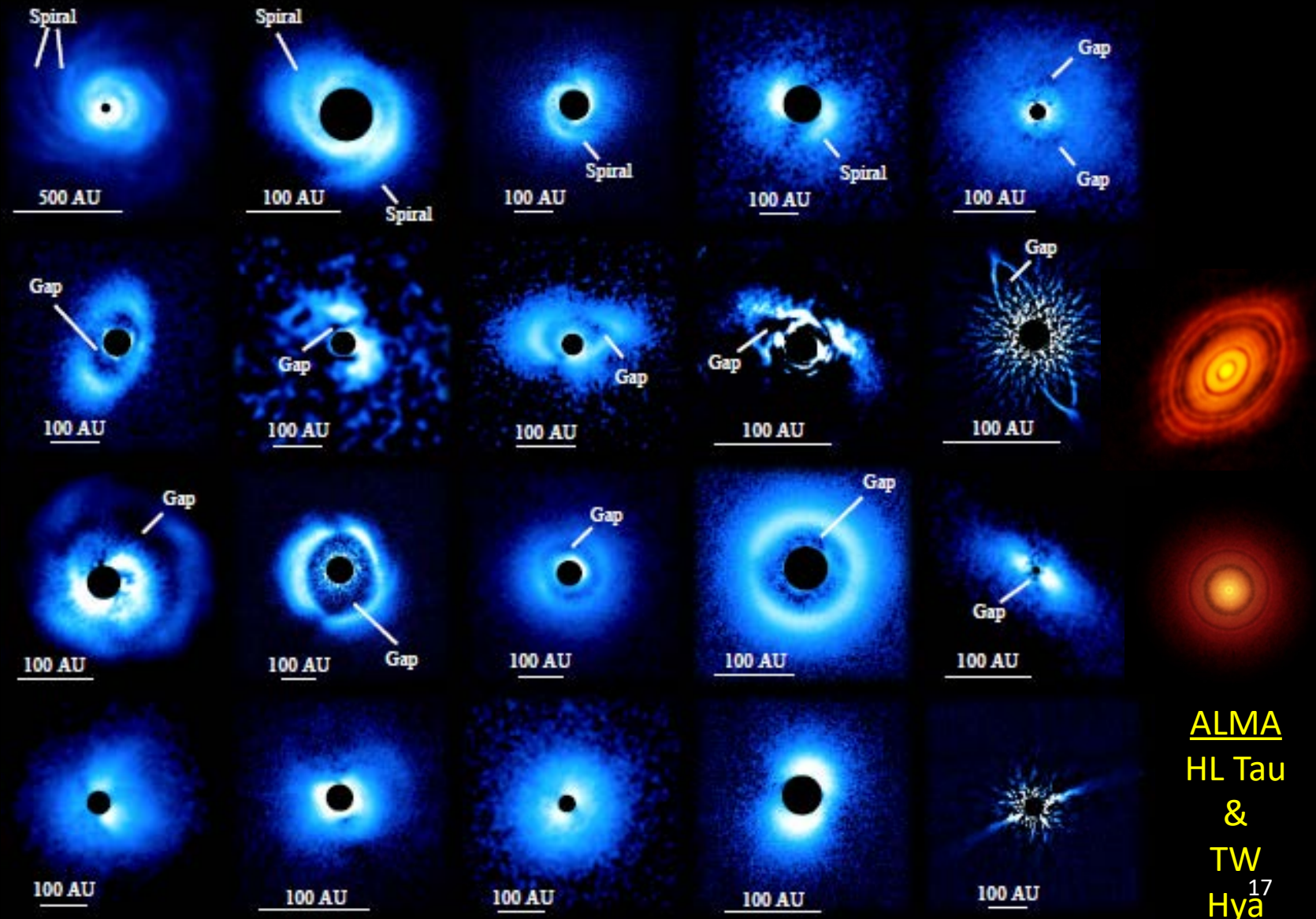
☐ **Spirals**

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 images such as HL Tau (2015) and DSHARP are thermal emission .

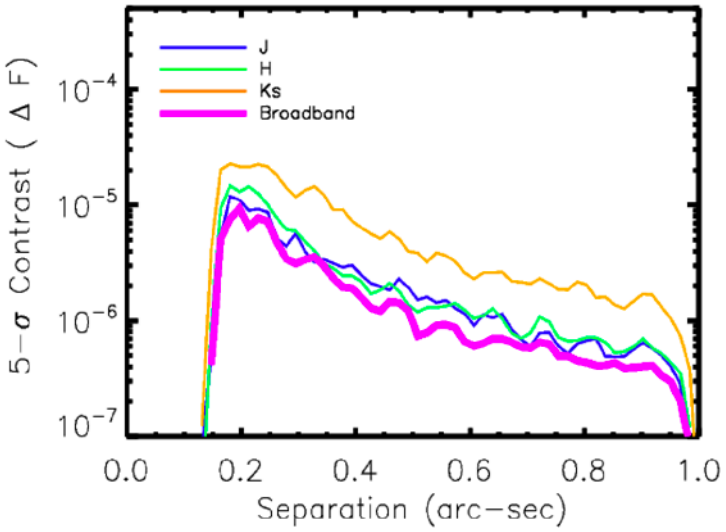


ALMA
HL Tau
&
TW
Hya

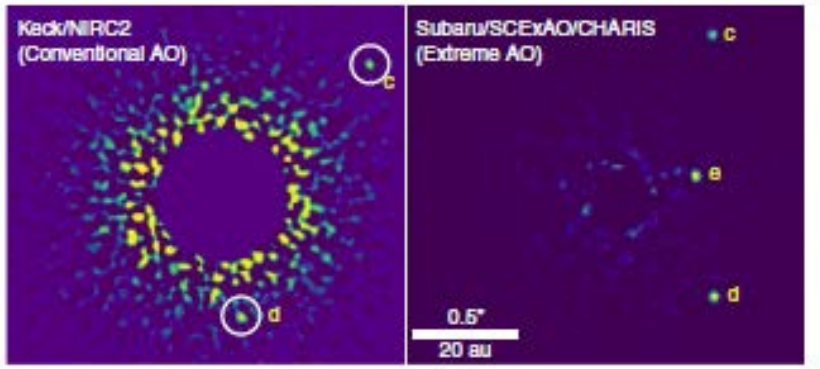
SCExAO and CHARIS:

Next Gen. High-Contrast Im & Sp

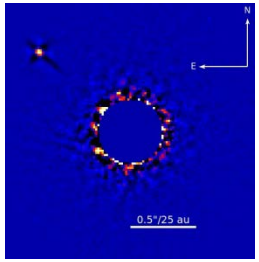
Publication rush now. 8 science papers and 15 technical papers

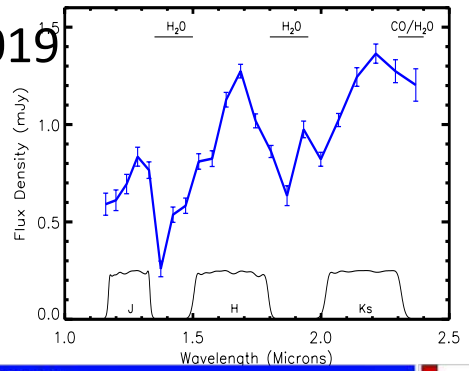


HR 8799 c,d,e NIRC2 vs. SCExAO

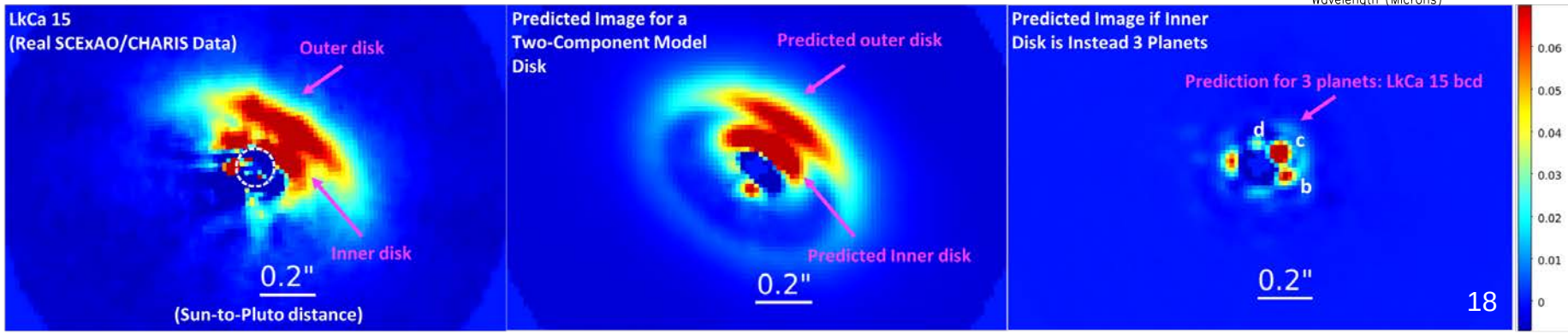


kappa And b,
Currie+2018, Uyama+2019

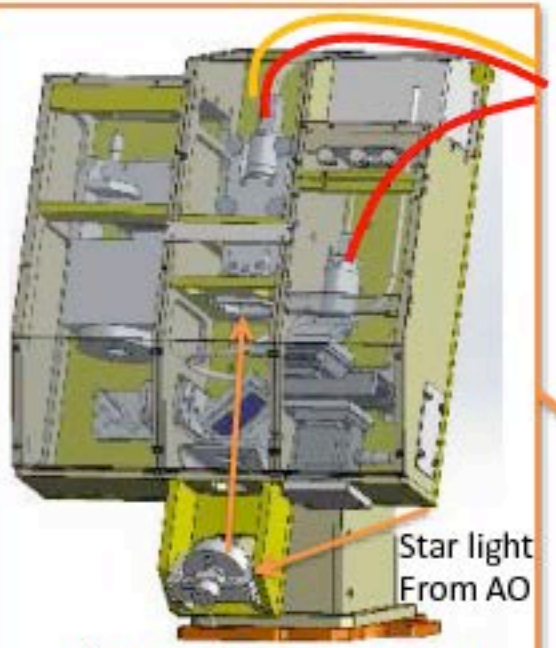




LkCa 15 Currie+2019



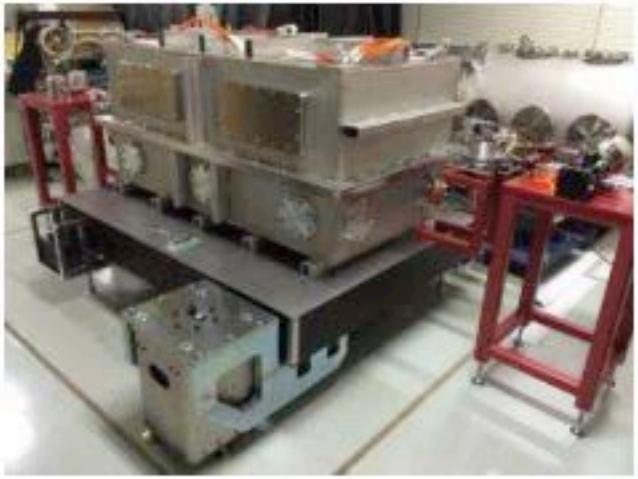
What is the next step?: Infrared Doppler Instrument (IRD)



Fiber injection system
(AO bench)

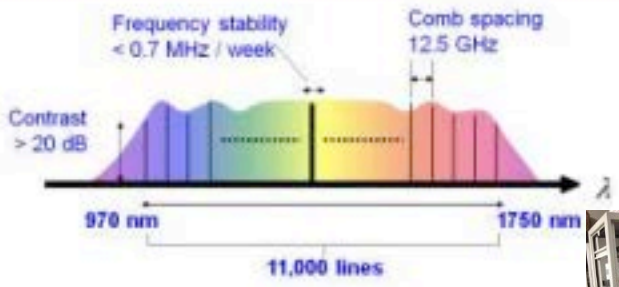
Mode scrambler

Resolution: R=70000
Wavelength: 0.97-1.75μm
Cryo: 79K (detector), 180K (optics)



Fiber
(Comb)

Fiber
(star)



Laser frequency comb
(IR Observing floor)

spectrometer

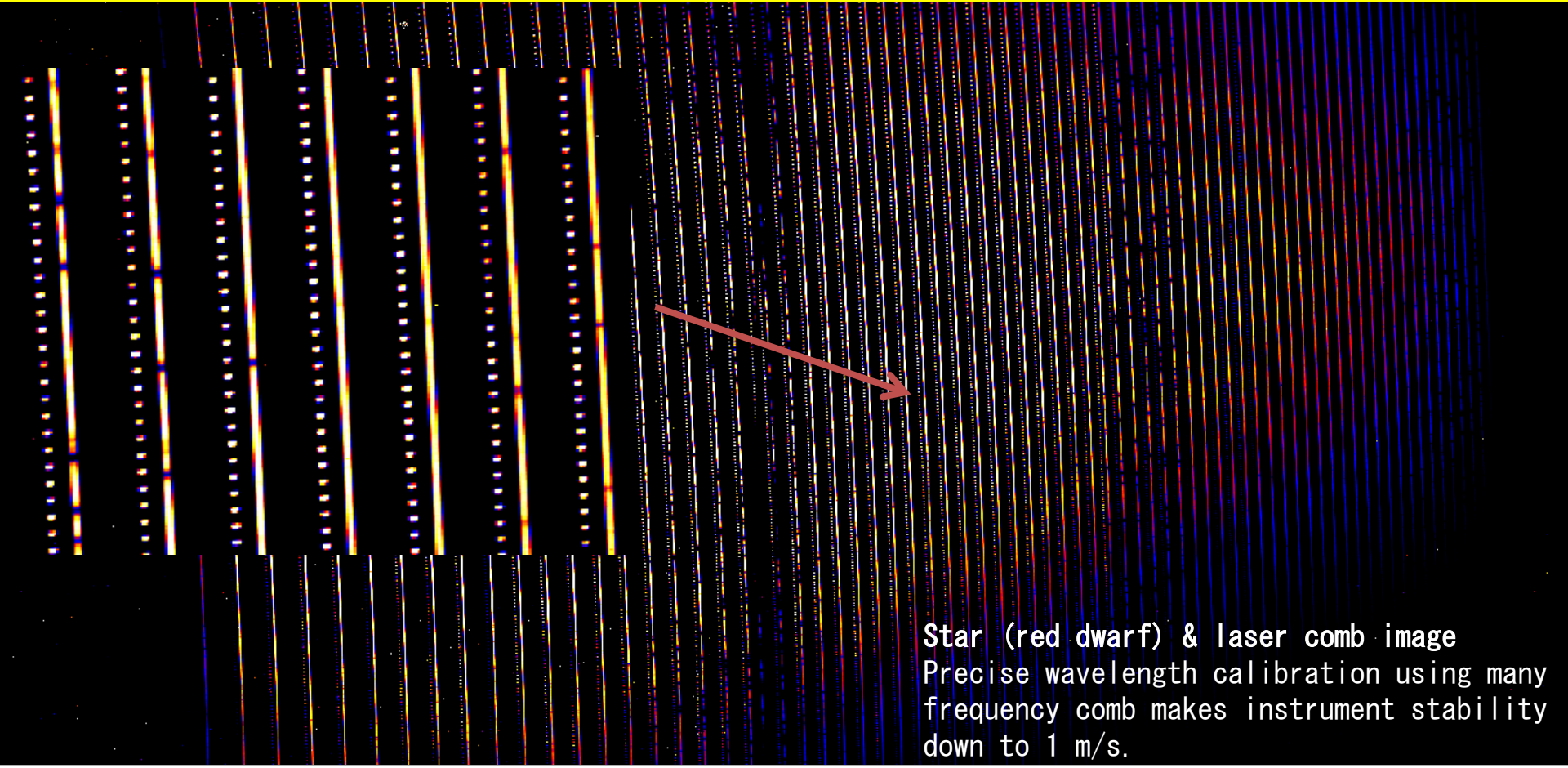
Coudé Room

Spectrometer system
(Coudé room)

Earth-like planet hunting spectrometer IRD

Enabling Earth-like planet detection on Subaru first time.

Subaru open-use & Strategic Program started. Press Release 2018 Aug

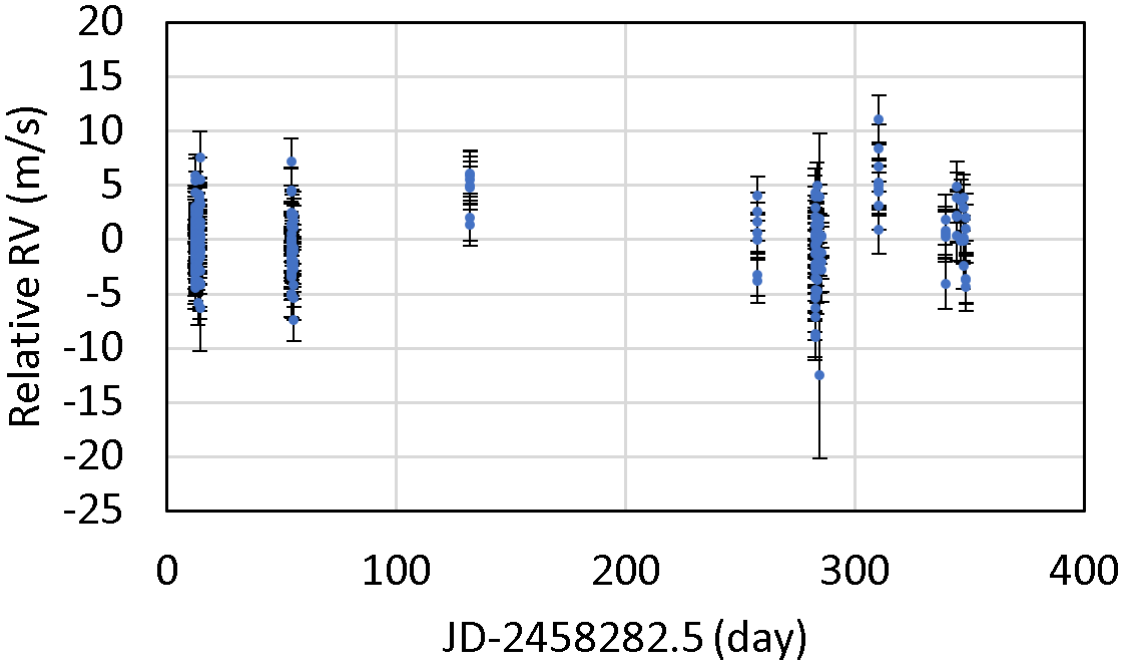


Star (red dwarf) & laser comb image
Precise wavelength calibration using many frequency comb makes instrument stability down to 1 m/s.

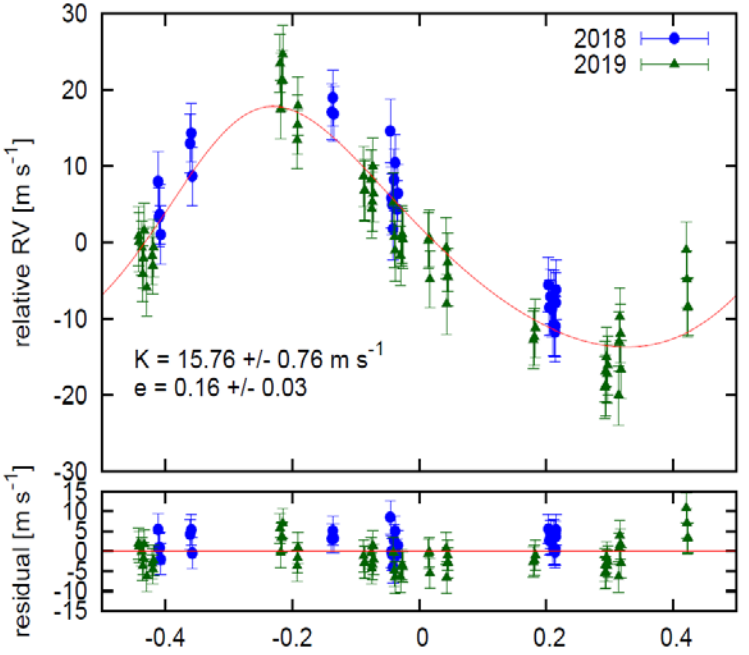
Wavelength (1-1.7 μm), accuracy (~2 m/s, 1m/s instr+1m/s jitter)

IRD Performance and Very Early Science

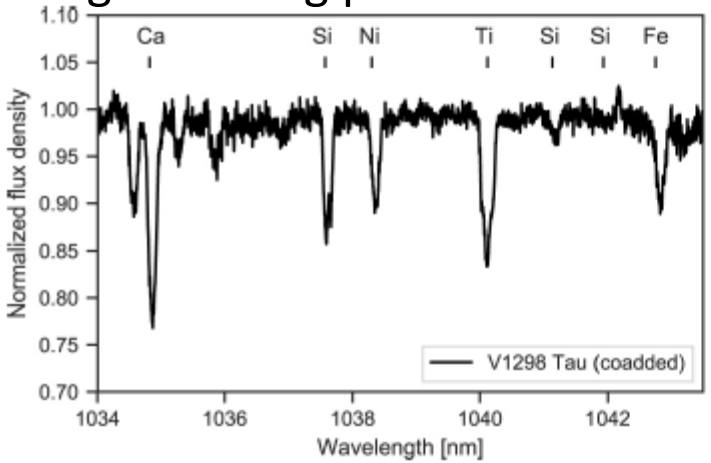
Long (~1 year) Term Stability Confirmed

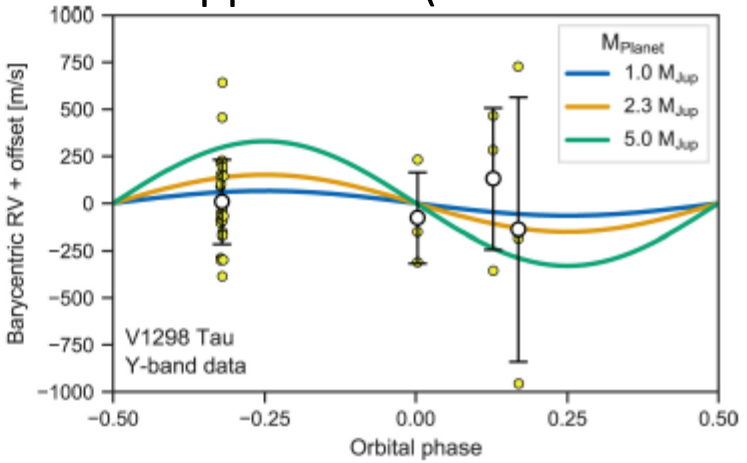


Known M star planet GJ 436 b



Young transiting planet V1298 Tau b mass upper limit (Beichman+2019)

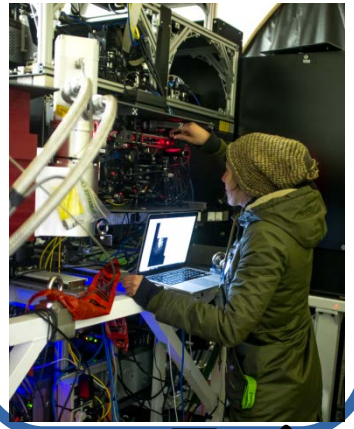




Also
First Light
of IRD+SCExAO
In 2019 Oct
via SM fiber

Our Step to "2nd Earth" Imaging: From Suabru to TMT

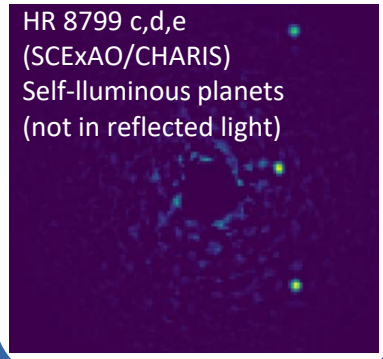
Develop and Validate Critical Technologies

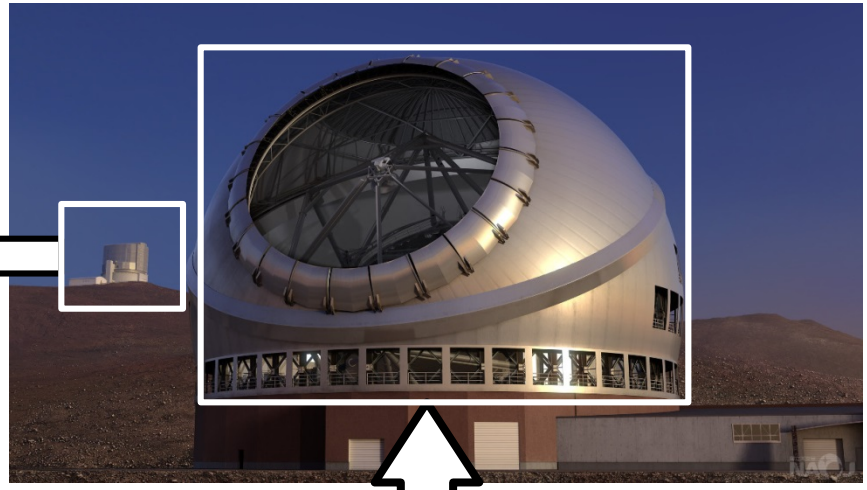


Enable

Validate

Observe Giant Planets in reflected light @ Subaru Telescope



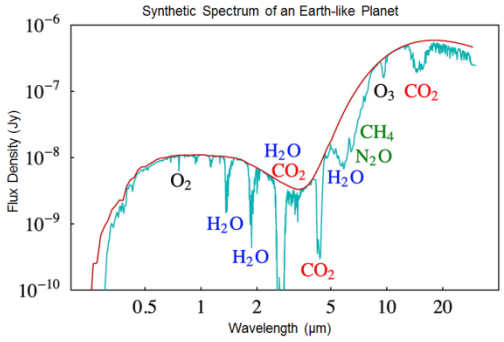


Measured on-sky performance

Technology requirements

Experience in on-sky operation and scientific analysis

Coordinate with TMT International Observatory



Science measurements, Exoplanet targets

Instrument design, deployment plan

Formulate Detailed Plan for Probing for Extrasolar Life with TMT

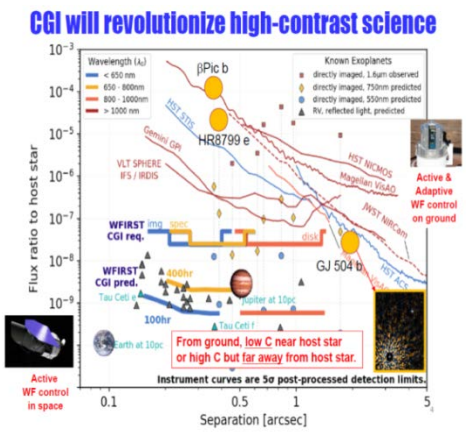
Subaru: WFIRST Coronagraph Instrument (CGI) Support

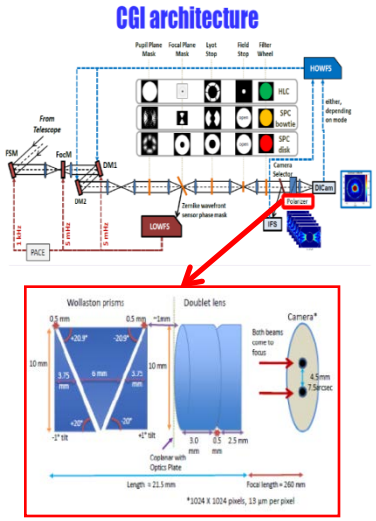
Possible Scientific Programs on Subaru

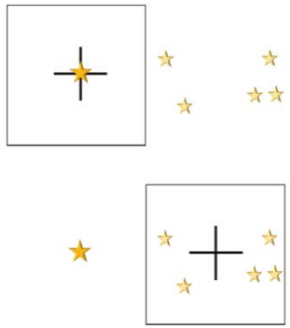
1. Background Object and Disk Measurements of CGI targets
2. Add targets to CGI list using IRD with noisy targets
3. Young Gas Giants
4. Debris Disks
5. Accreting Planets
6. TESS Single Transits
7. Spin-Axis Characterization

Possible Feasible Scenario on Subaru

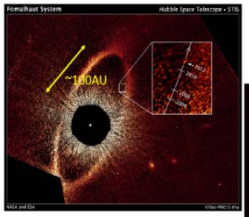
1. Observations within next few years to vet CGI targets
2. IRD SSP & Intensive programs ongoing
3. CGI follow-up. Visible science+ high contrast verification
4. CGI Optical plus Subaru NIR Polarization measurements
5. Subaru+ALMA observe gapped disk, CGI Hα follow up
6. CGI and IRD follow-up
7. High spectral res. FIRST measurement to get spin axis



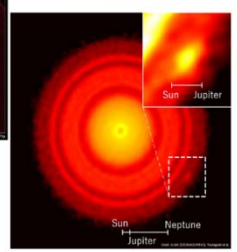




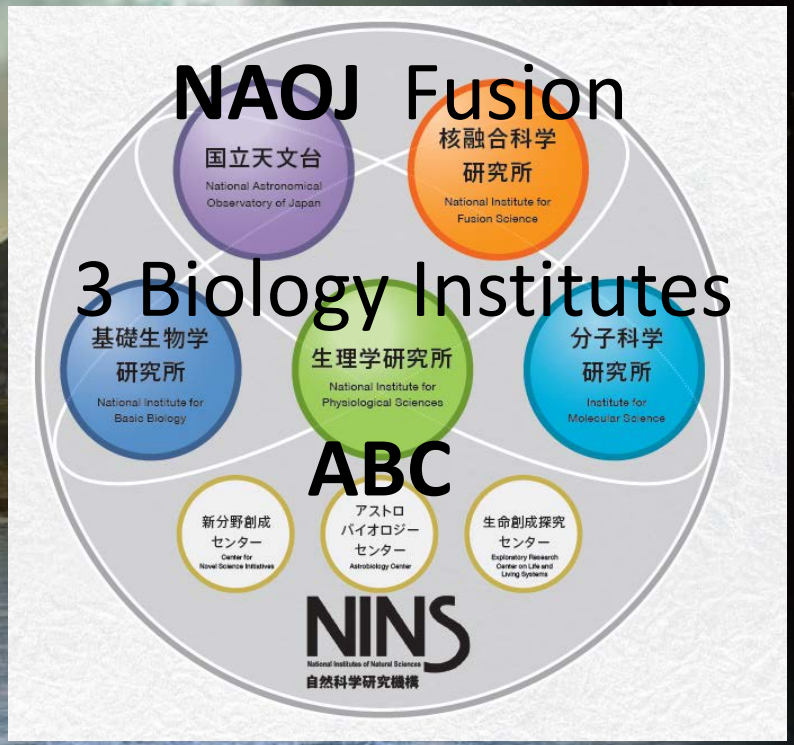
Background Object and Disk Measurements of CGI targets



Fomalhaut
HST/optical
(Kalas et al. 2013)
Planet? Dust blob?



(Polarimetric) Imaging of Debris and Protoplanetary Disks with CGI



ABC is a new institute of NINS, after Exoplanet Project Office of NAOJ (from 2015).

自然科学研究機構　アストロバイオロジーセンター　年次報告

2015 – 2017年度

Astrobiology Center

ANNUAL REPORT 2015-2017

IRD

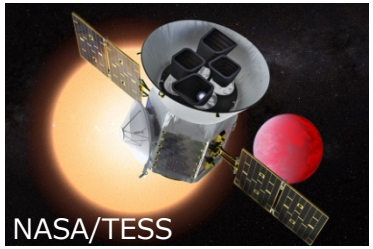
(IR Doppler instrument)

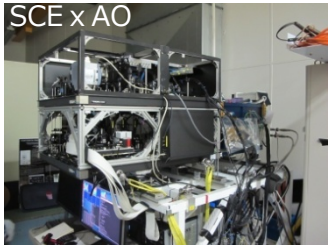
One of "Subaru Drivers" in 2020s: SEEDS2

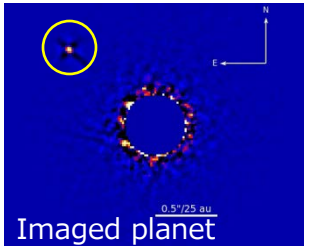
Strategic Exploration of Exoplanet Detections like 2nd Earths

Summary slide for future

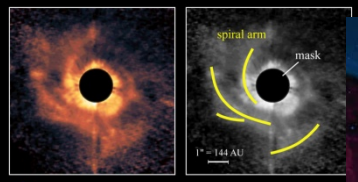
- **Earth is unique or one of common planets?**
  - **Nearby Earth-like planet hunting with new instrument IRD**
  - **Planet quest synergy with space telescopes such as TESS/WFIRST (as well as JWST, too!)**
  - **Earth-like planets around alien world of red dwarfs**
- **Subaru/TESS/others will provide new targets for biosignature detection with TMT and JWST**
- **Subaru is a platform for instruments for TMT and space, collaborating with Astrobiology Center**
  - **Tech demo on Subaru and first reflected light detection**
  - **SCExAO/IRD can accommodate latest new tech and evolve**



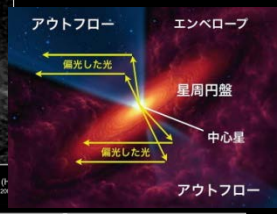




Happy 20th Anniversary, Subaru !

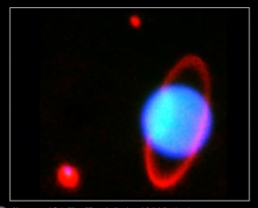


Protoplanetary Disk Surrounding the Star AB Aurigae CIAO+AO (H)
Subaru Telescope, National Astronomical Observatory of Japan April 18, 2004



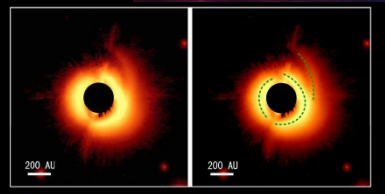
Star-forming Region S106 IRS4 CISCO (J, H, K')
Subaru Telescope, National Astronomical Observatory of Japan February 13, 2001

Orion Nebula CISCO (J, K' & H2 (v=1-0 S(1))
Subaru Telescope, National Astronomical Observatory of Japan January 26, 1999

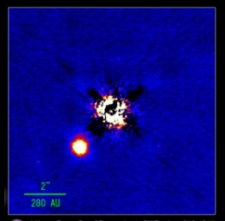


Uranus and Satellites Miranda (top) and Ariel (bottom) CIAO with AO (J, H, K)
Subaru Telescope, National Astronomical Observatory of Japan February 21, 2002

Planetary Nebula BD +303639 CIAO (J, H, K)
Subaru Telescope, National Astronomical Observatory of Japan December 15, 2004

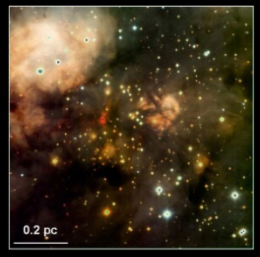


HD142527 CIAO (H)
Subaru Telescope, National Astronomical Observatory of Japan June 27, 2006

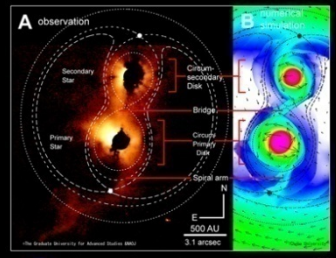


A Young Brown Dwarf Companion to DH Tauri CIAO+AO (K)
Subaru Telescope, National Astronomical Observatory of Japan February 28, 2005

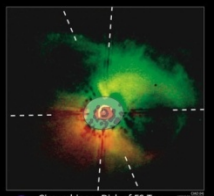
Circumstellar Disk Around Young Lightweight Star FN Tau CIAO (1.6μm)
Subaru Telescope, National Astronomical Observatory of Japan February 8, 2008



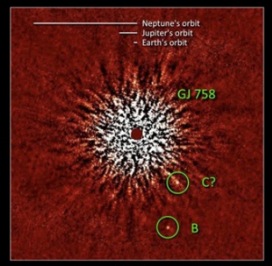
W3 Main Massive Star Forming Region CISCO (J,H,K)
Subaru Telescope, National Astronomical Observatory of Japan January 29, 2009



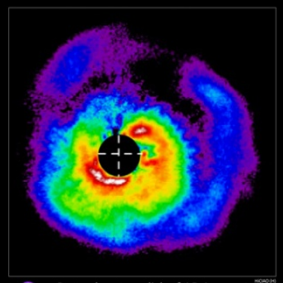
Young Binary System SR24 CIAO
Subaru Telescope, National Astronomical Observatory of Japan November 2009



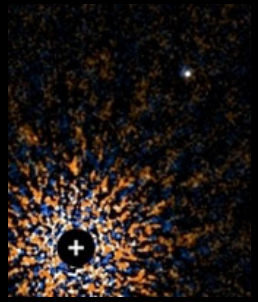
Circumbinary Disk of FS Tau
Subaru Telescope, National Astronomical Observatory of Japan

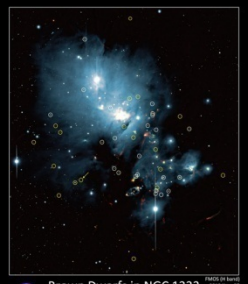


Exoplanets Orbiting a Sun-Like Star HiCIAO August 2009

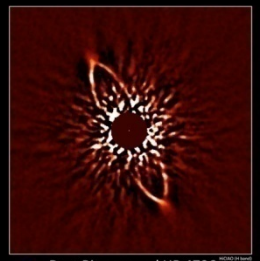


Protoplanetary disk of AB Aur HiCIAO/AO October 3, 2005

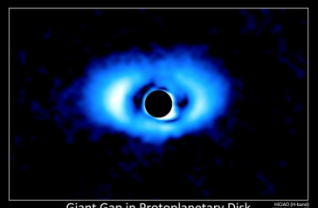




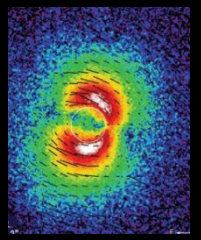
Brown Dwarfs in NGC 1333 FMOS (IR band) 2010 Nov. 27

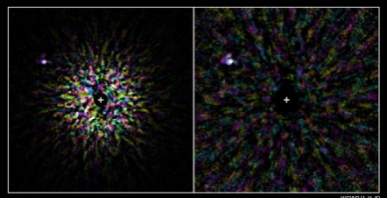


Dust Ring around HR 4796 HiCIAO (H band) 2012 May 24

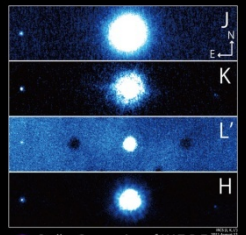


Giant Gap in Protoplanetary Disk of PDS 70 HiCIAO (H band) 2012 February 29





"Super-Jupiter" around Kappa Andromedae HiCIAO (J, H, K) 2012 July 8-9



Stellar Companion of HAT-P-7 HiCIAO (H) 2011 August 23