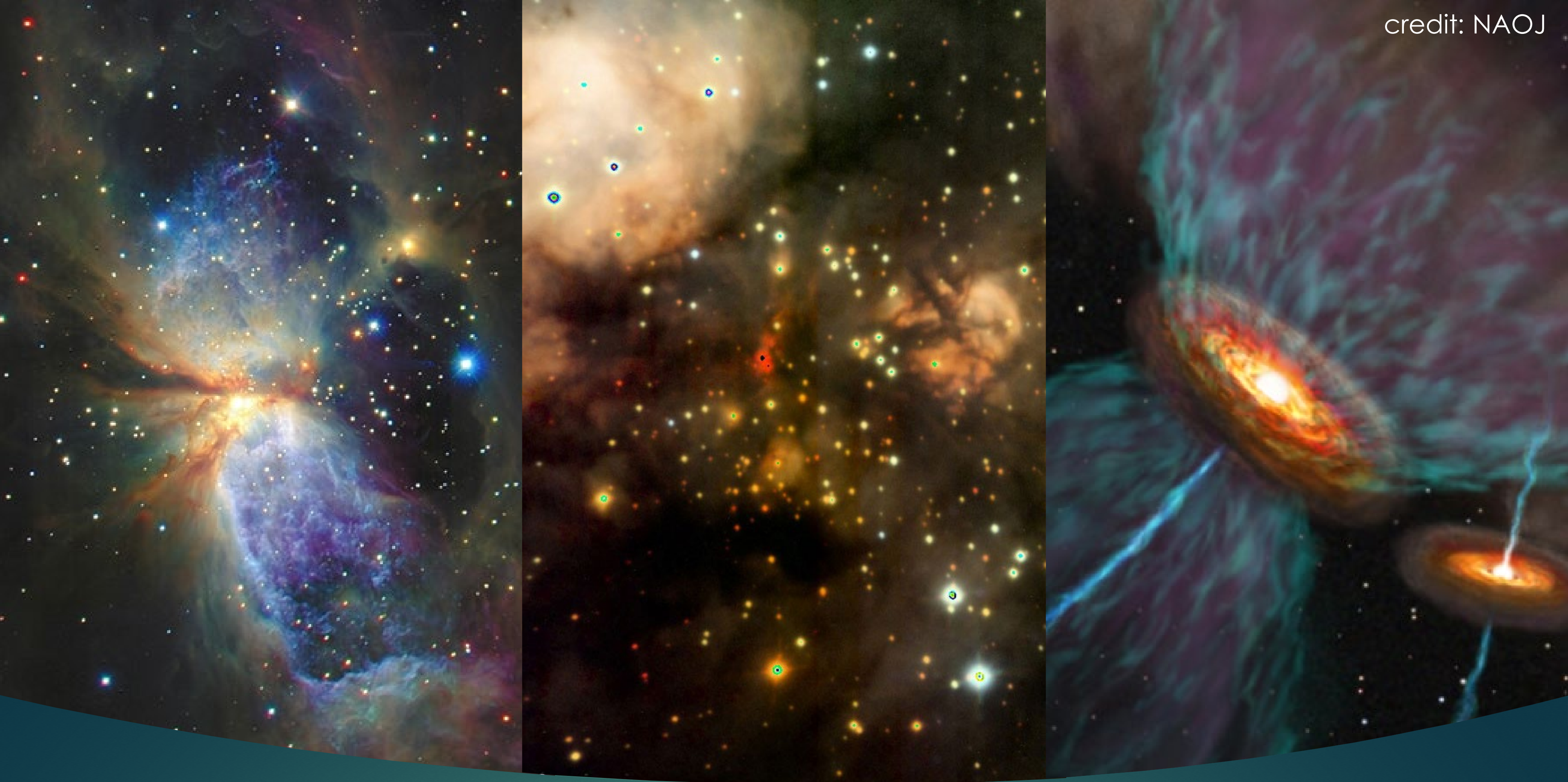


credit: NAOJ

Star Formation Science with Subaru

MISATO FUKAGAWA (NAOJ)

Kaifu et al. 2000, PASJ, 5, 1, “The First Light of the Subaru Telescope: A New Infrared Image of the Orion Nebula”

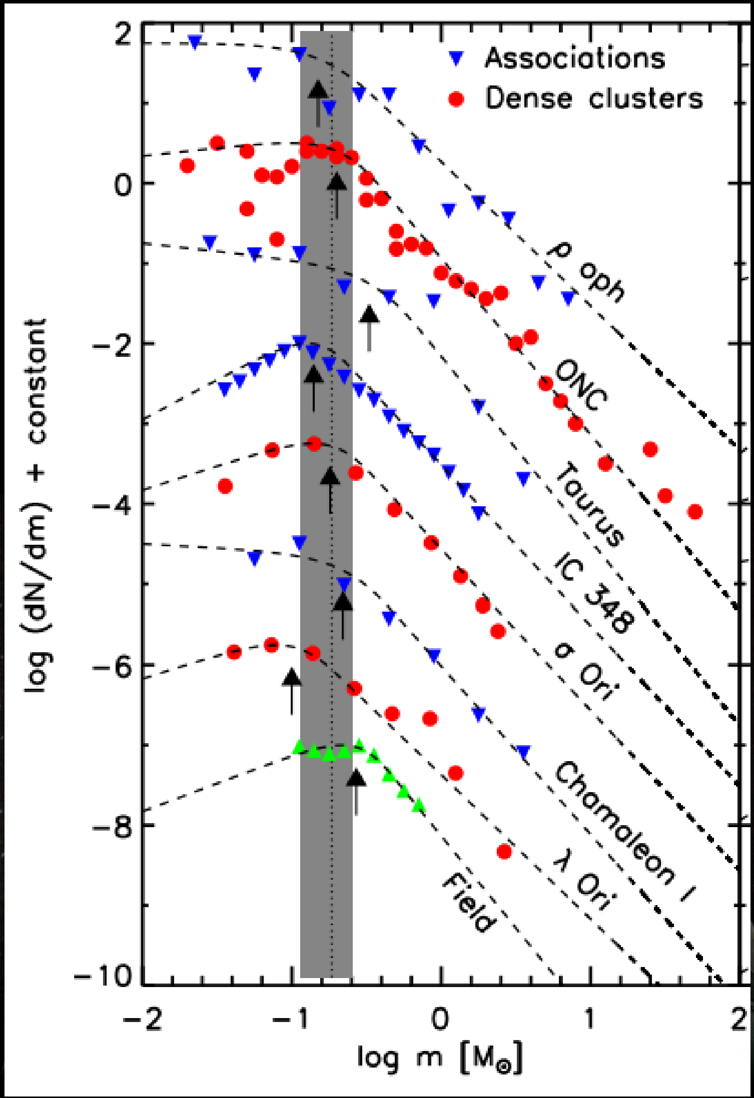
Contents

- Initial Mass Function
  - Bottom ends, in particular
  - Environmental dependence or not
  - High-mass stars
- Low-mass stars
  - Detailed characterization: stellar age, jets/disks/envelopes
  - Link to planet formation
- Brown dwarfs/planetary-mass companions
  - Beginning of direct imaging study of such very low-mass objects

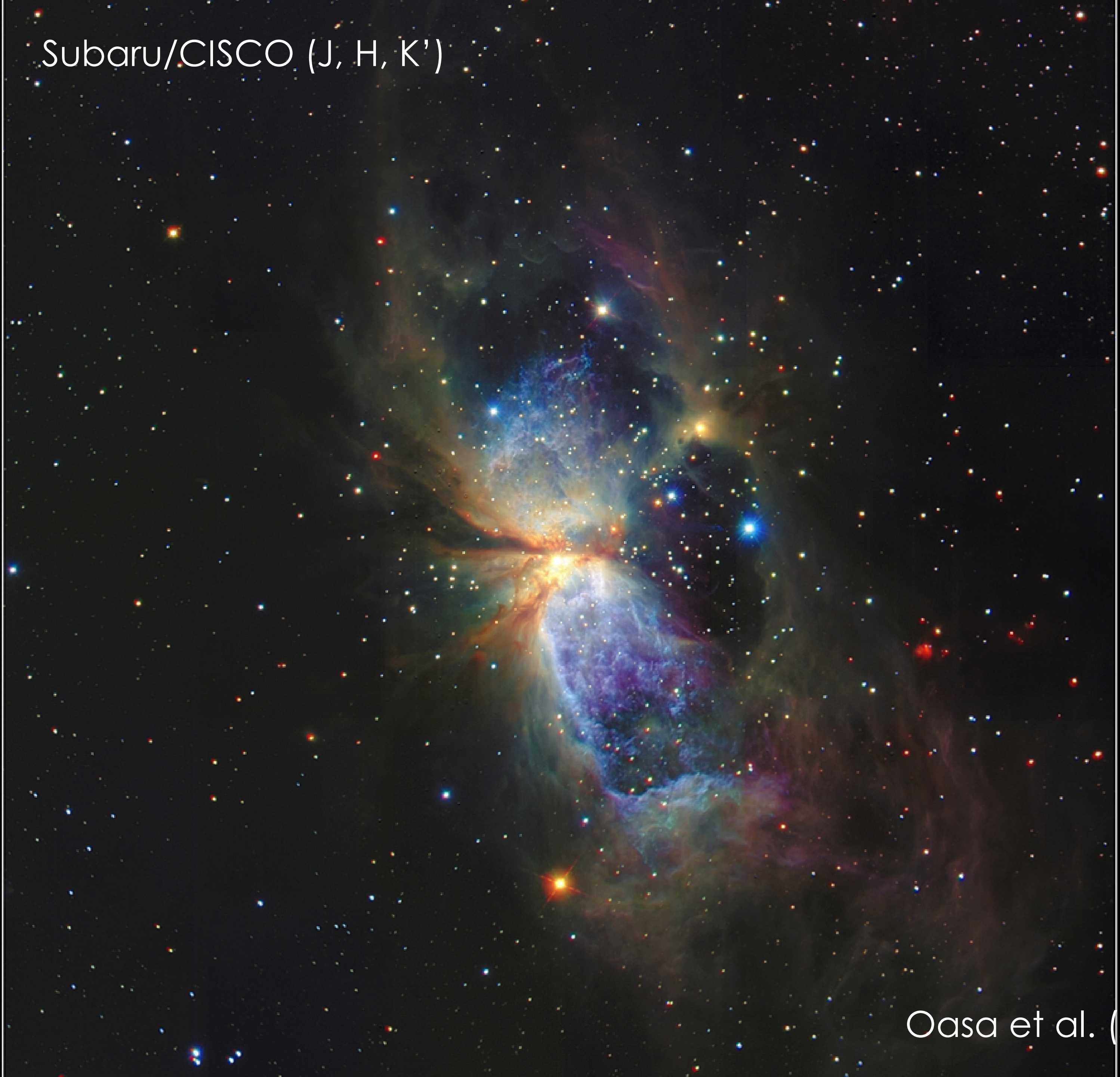
Initial Mass Function

Initial Mass Function

- Fundamental parameter to determine the physical and chemical condition of star formation.
- Galaxy evolution can be significantly affected by the high-mass end.
- Mostly universal in the MW (the peak at ~0.3 $M_\odot$ and the slope in the high-mass end). Yet, the universality and environmental effect is still under debate.
- Low-mass end is related to the formation of planetary-mass objects.
  - Deep IR observations, resolving individual objects



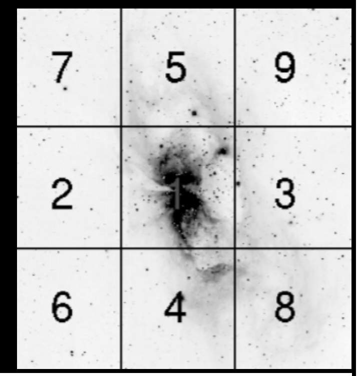
Bastian (2010)

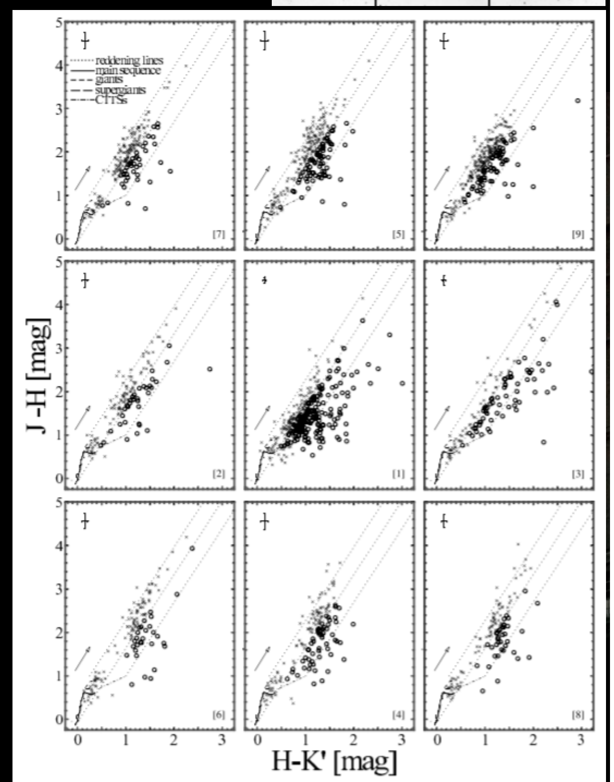

Subaru/CISCO (J, H, K')
Oasa et al. (2006)

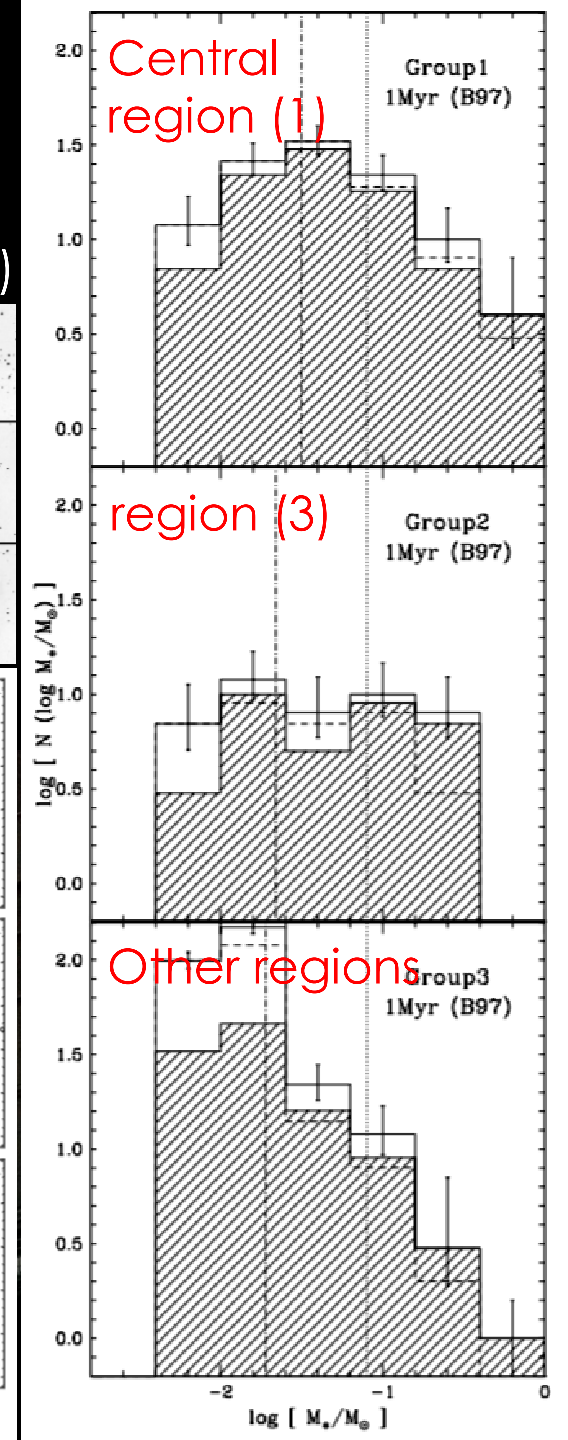
The bottom end of IMF

- ~600 YSOs identified. The range of the mass reaches close to the deuterium-burning limits.
- Substellar mass function may have a variation.
  - Local variation on a subparsec scale
  - Variation among clusters
- No turnover, no decline down to the completeness limits.

Oasa et al. (2006)



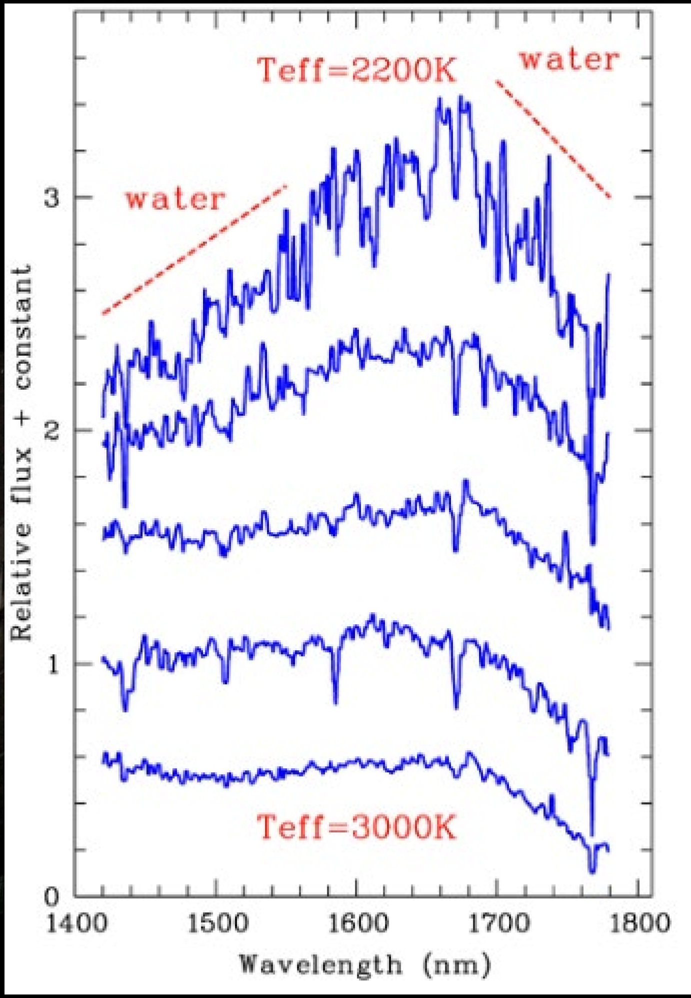




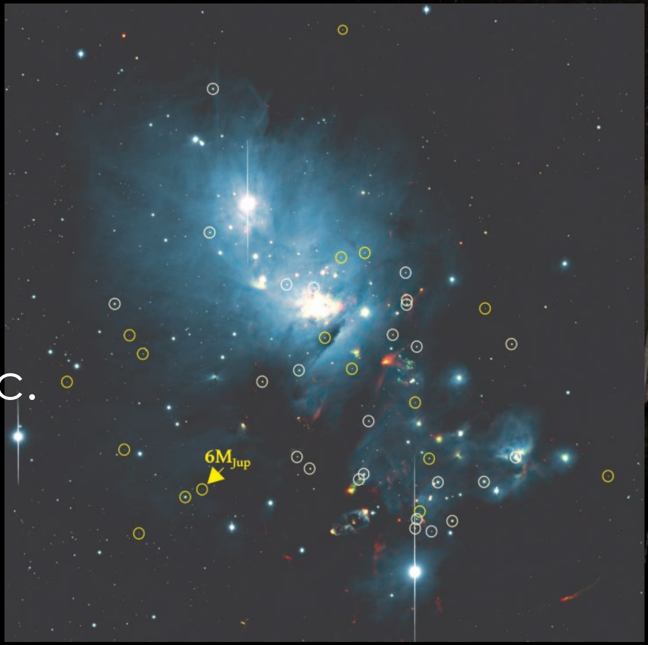
Census of Young Stars and BDs/PMOs

- IMF down to ~6—10 $M_{Jupiter}$, below the deuterium-burning limit; Substellar Objects in Nearby Young Clusters (SONYC) (e.g., Scholz et al. 2009, 2012, 2013, Muzic et al. 2015)
  - Subaru/FMOS, MOIRCS, VLT, and other telescopes

Scholz et al. (2012)

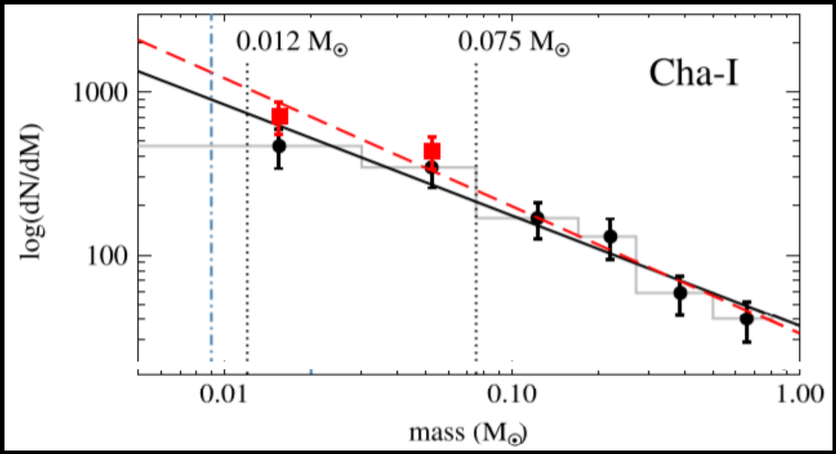


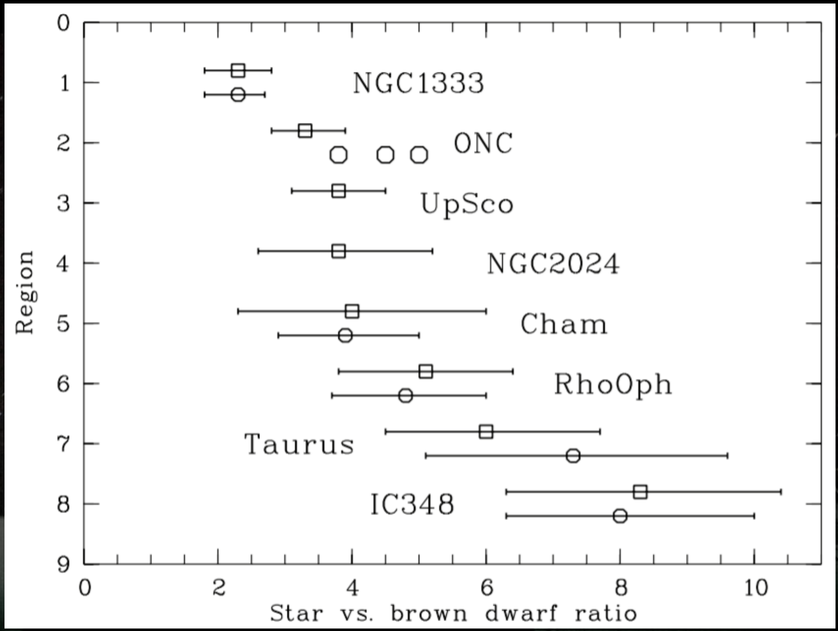
NGC1333, ρ Oph, Cha-I, U Sco, Lupus-3, RCW 38 etc.



Census of Young Stars and BDs/PMOs

- $dN/dM \propto M^{-\alpha}$ $\alpha \sim 0.7$
- No evidence on environmental dependence by high-mass members.
- The ratio of BDs/stars lies ~0.2—0.5.
- The ratio of free-floating planetary-mass objects/stars is ~2—5%.

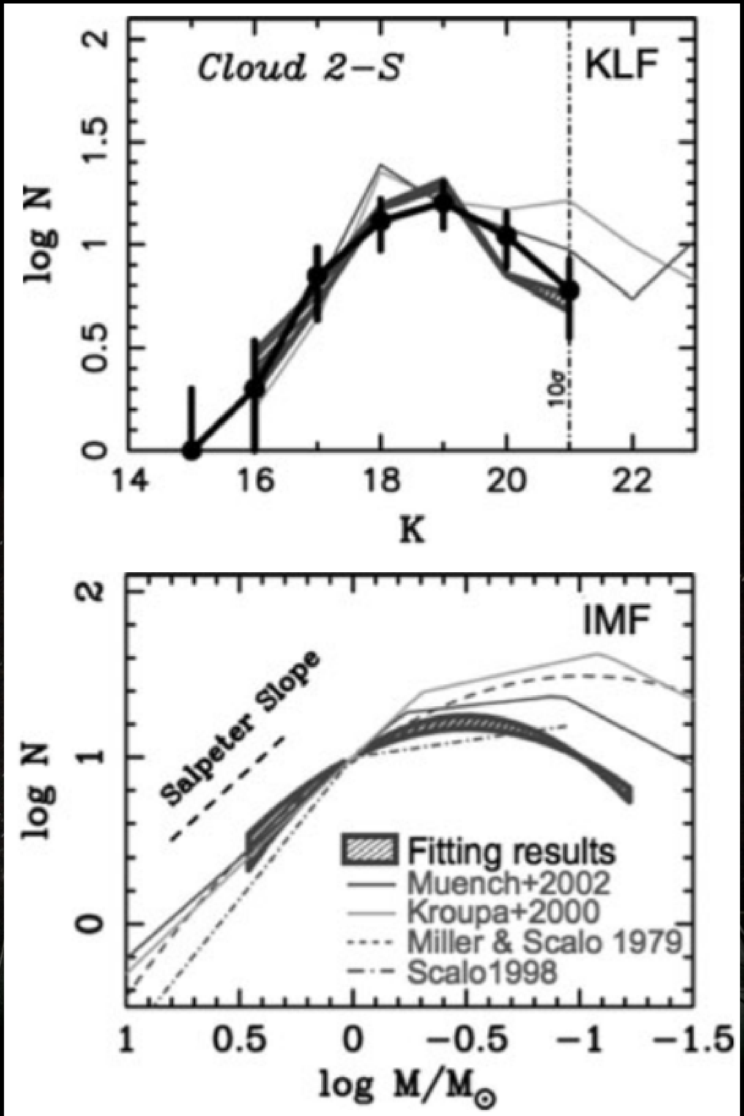




Scholz et al. (2012), Muzic et al. (2015)

IMF in low metallicity environment

- Outer regions of the MW
  - Laboratory to study in low metallicity, low gas density, no or small perturbation from the spiral arms
  - Subaru/IRCS, MOIRCS
- IMF has no dependence on metallicity down to ~−1 dex, for stars with >~0.1 $M_{\odot}$



e.g., Yasui, Kobayashi, Tokunaga, Izumi et al. (2006, 2008, 2016)

Census of Young Stars and BDs/PMOs

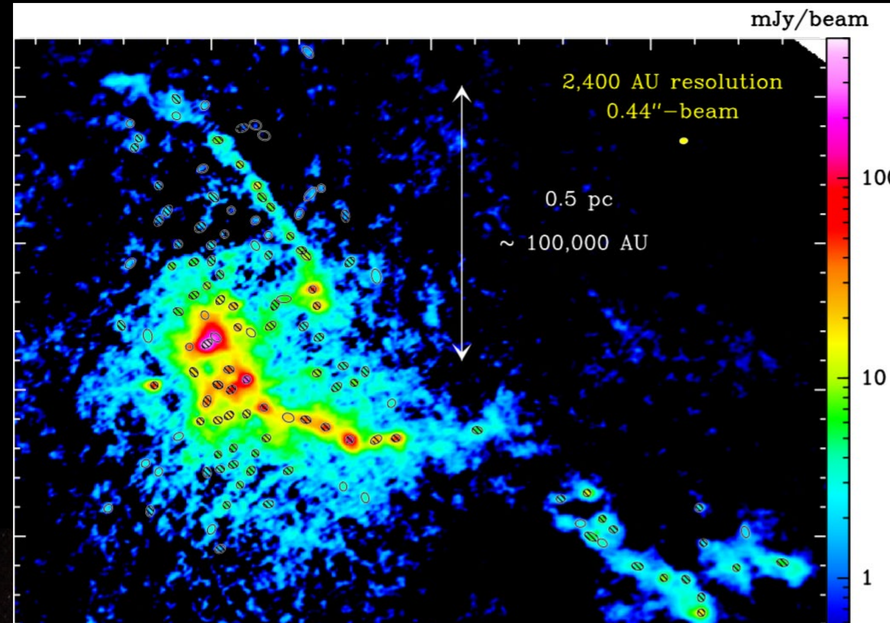
- Challenges
  - Improving the completeness limit, accuracies of spectral types, considering non-uniform extinction (e.g., Luhman et al. 2016)
  - Widening the environmental parameter space, going to extra galaxies
- Herve Bouy's talk on Nov 19 using SuprimeCam and HSC: IMF down to the fragmentation limit
- Future: Gaia, JWST, Subaru/GLAO

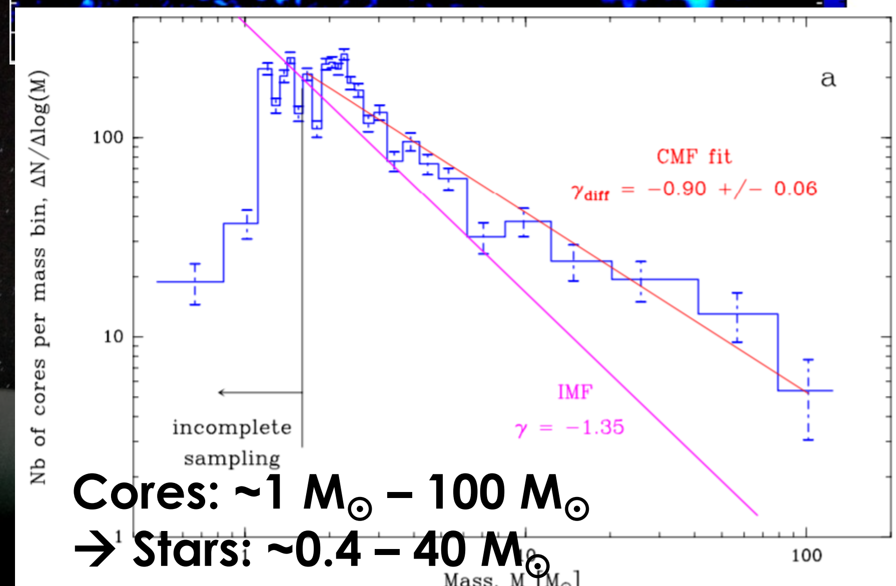
CMF to IMF

Motte et al. (2018)

- Top-heavy Core Mass Function for W43
  - Higher-mass cores convert a smaller fraction of their mass into stars than lower-mass cores??
  - Higher-mass cores spawn more stars, with a wider logarithmic range of masses?

ALMA-IMF results will be coming!

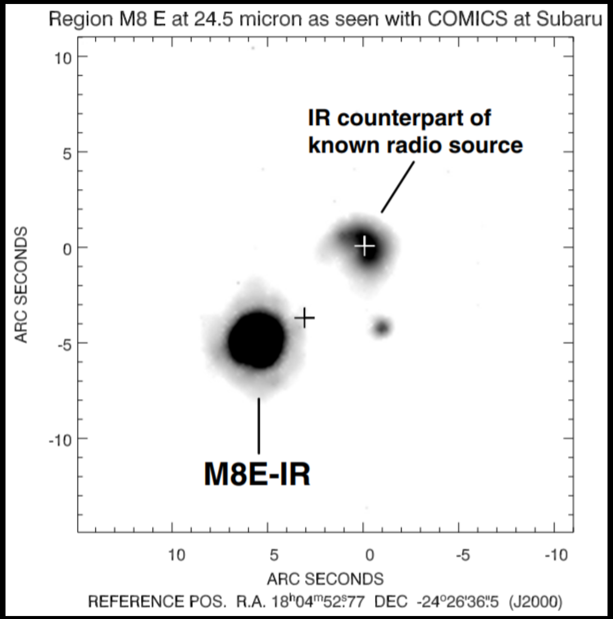




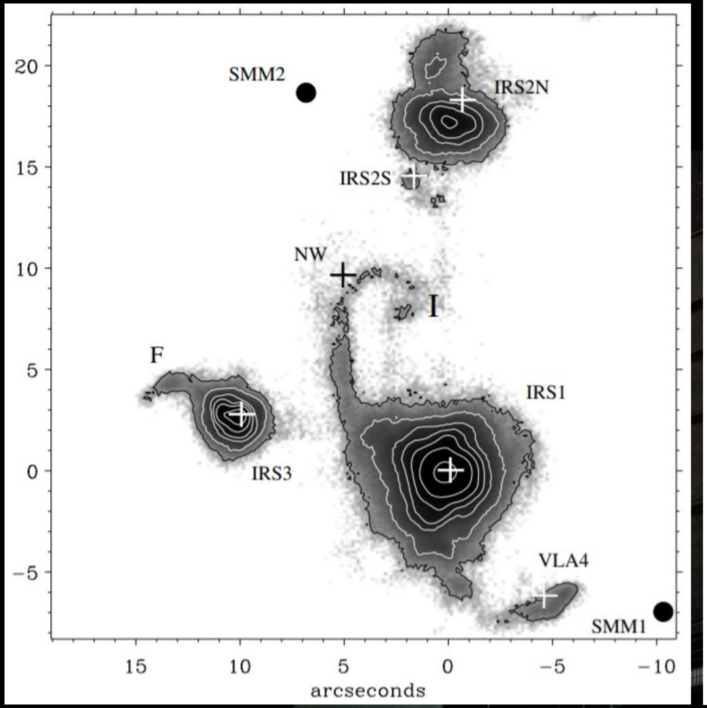
Cores: ~1 $M_\odot$ – 100 $M_\odot$
→ Stars: ~0.4 – 40 $M_\odot$

Detailed morphology of circumstellar environment of MYSOs

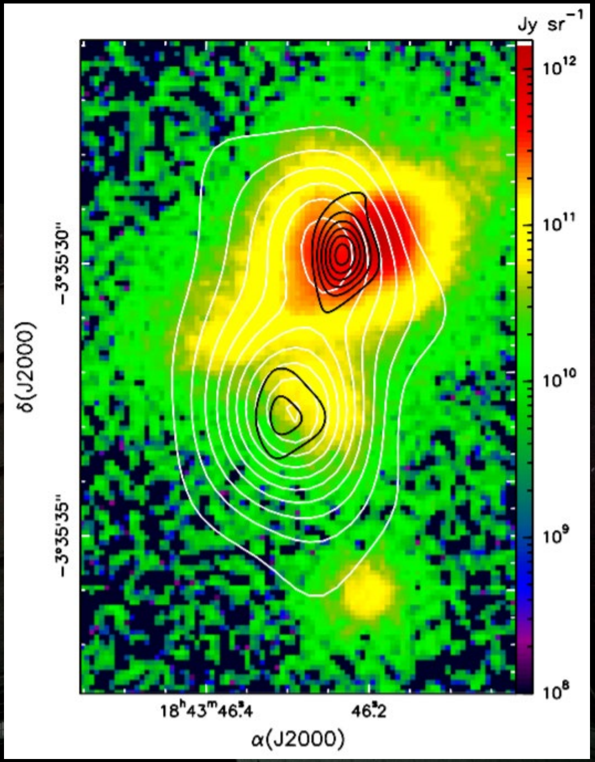
- Thermal imaging with Subaru/COMICS 25 micron in sub-arcsec (~1000 au) resolution (e.g., De Wit et al. 2009)



Linz et al. (2009)

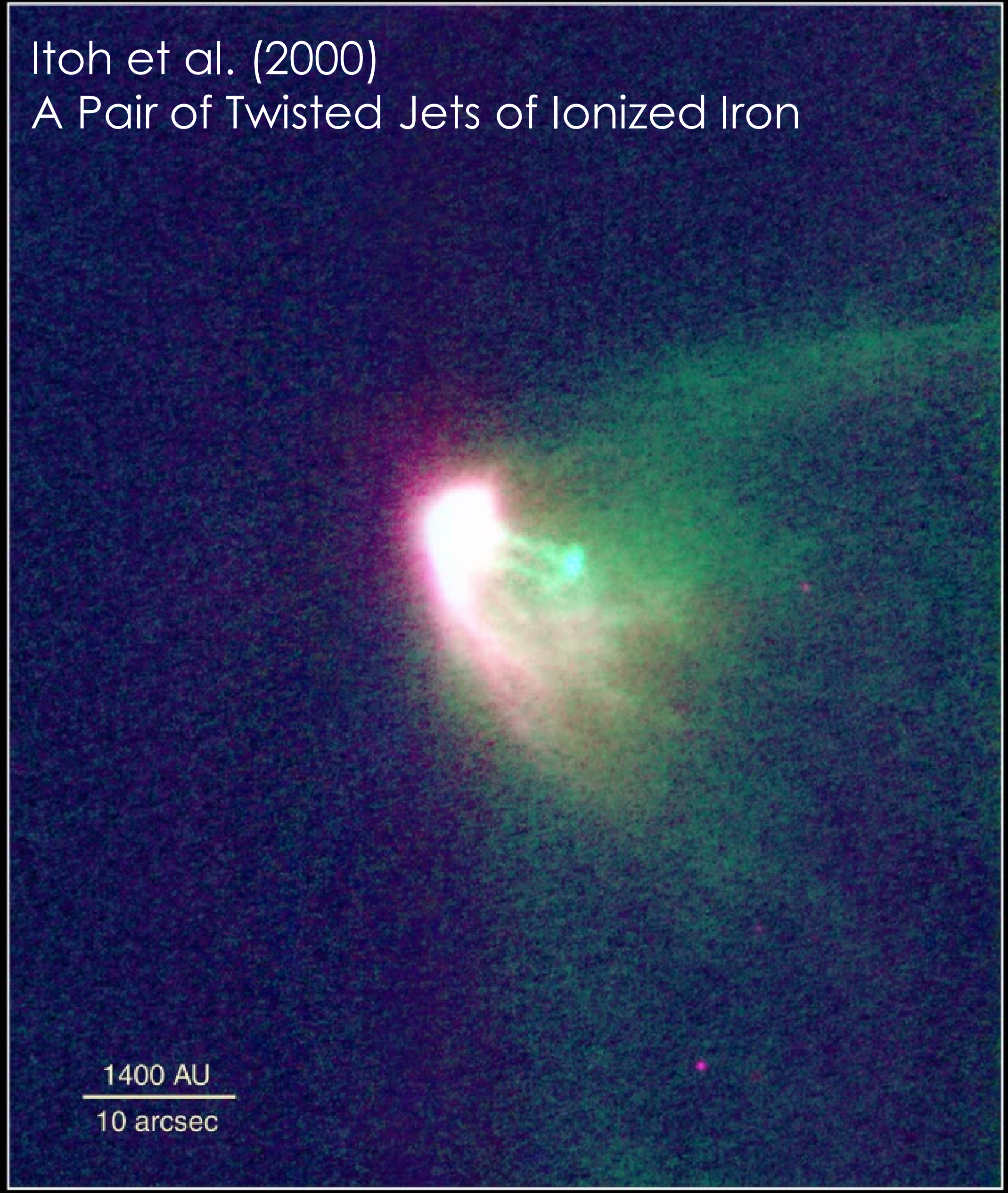


S104, de Wit et al. (2009)



G28.87+0.07
Li et al. (2012)

Low-mass stars and their circumstellar environments



Two Jets from L1551-IRS5

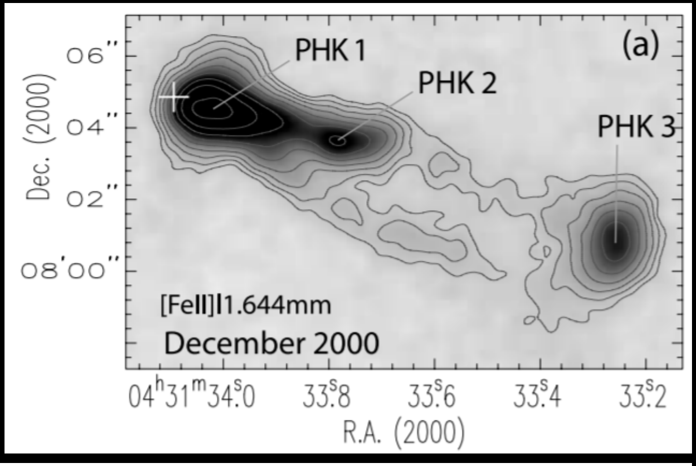
Subaru Telescope, National Astronomical Observatory of Japan

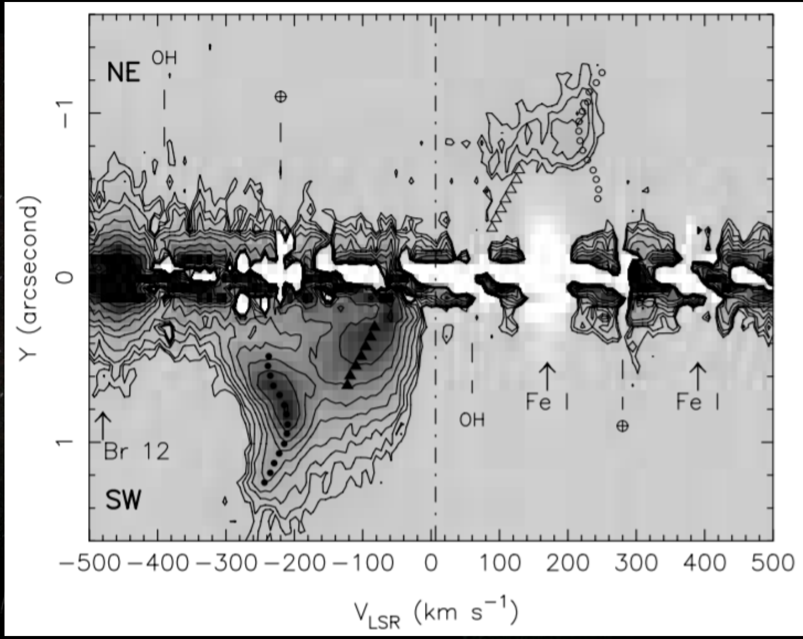
CISCO (J, K′)

June 10, 1999

Jets, mass ejections

- Mass accretion and ejection of YSOs
  - Angular momentum transport
  - Inner disk property
- Jets/outflows from T Tauri stars (e.g., Pyo et al. 2002, 2003, Takami et al. 2006)
  - Subaru/IRCS (+ AO)
  - e.g., [Fe II], H_2, He I
  - Distinct, high and low velocity components – two mechanisms?
  - Warm molecular winds
- Time domain



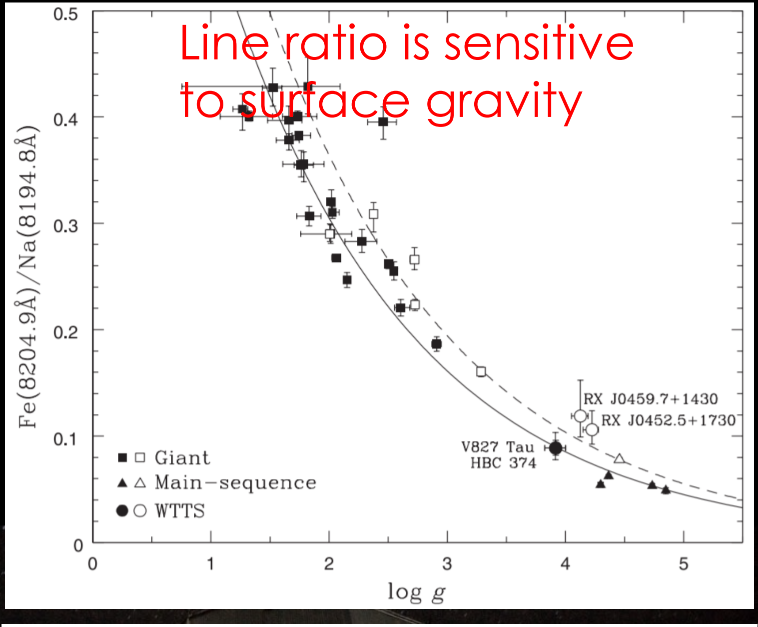


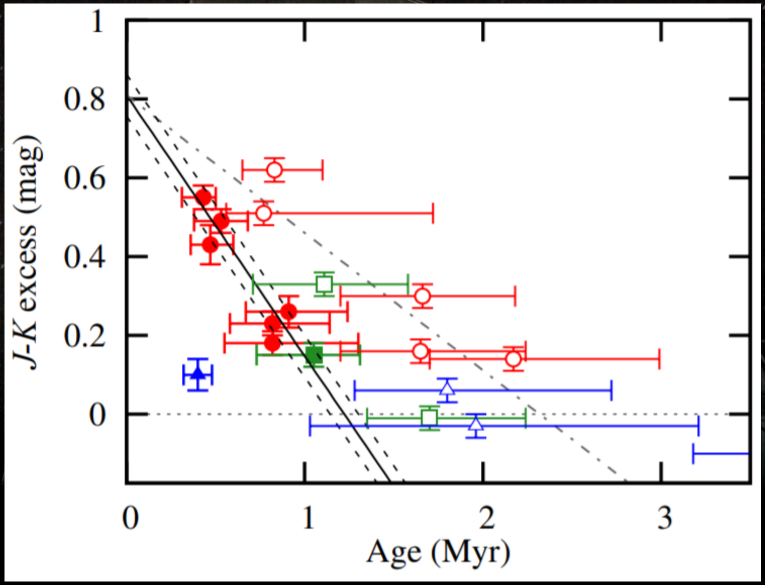
Pyo et al. (2002, 2003)

Age determination for YSOs

- Age estimate based on surface gravity
- Line equivalent width ratio not suffering from the veiling
- Subaru/HDS

- Discussion on the inner disk lifetime with more accurate age estimate
  - 3—4 Myr in Taurus
  - 1—2 Myr in Oph



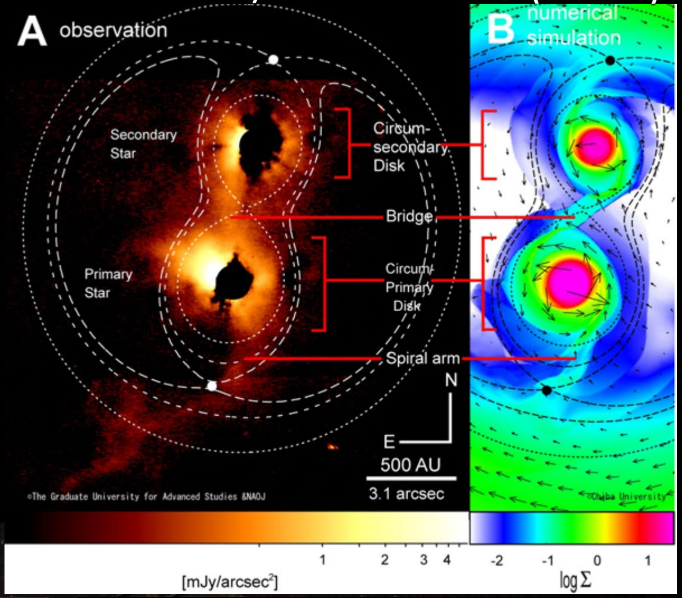


Takagi et al. (2010, 2014, 2015)

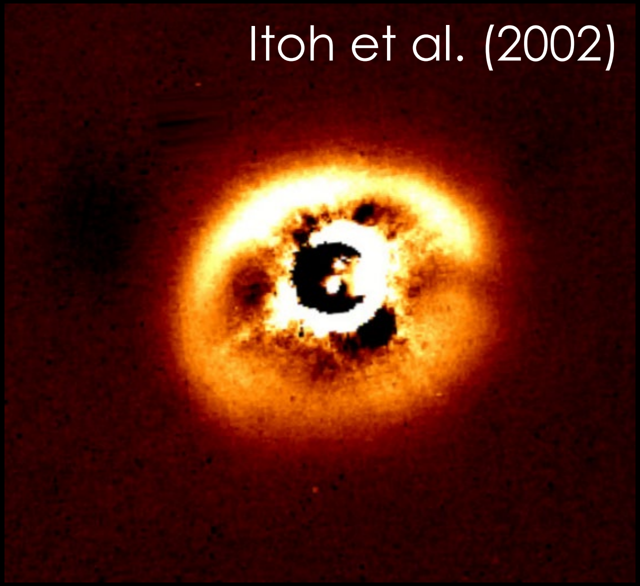
Circumstellar/binary structure

- Disks around binaries
  - Subaru/CIAO, HiCIAO, COMICS
- Unique large disks? Dependence on mass ratio of binaries? Surface density distribution?

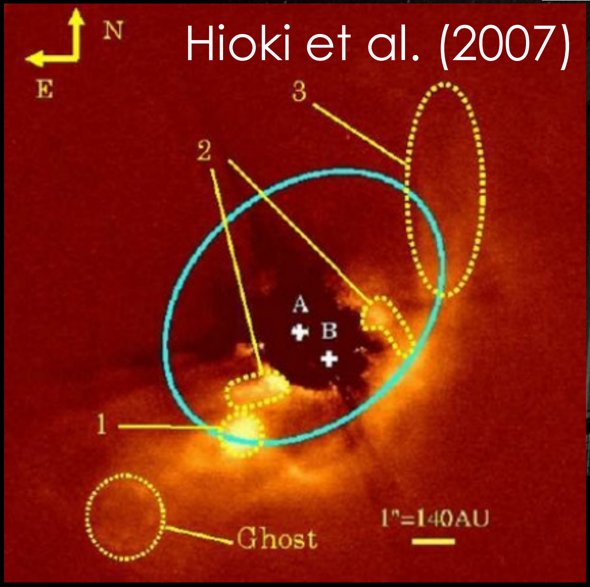
Mayama et al. (2012)



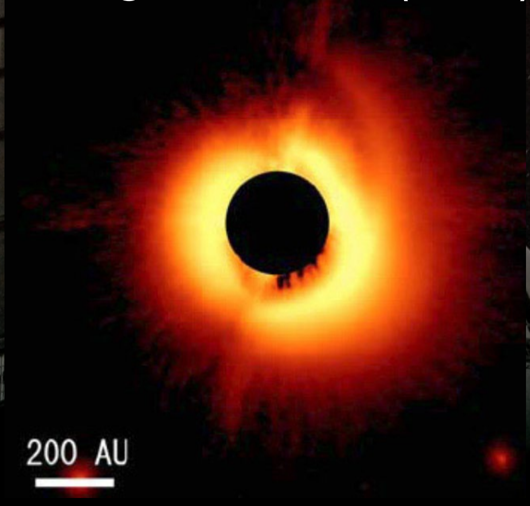
Itoh et al. (2002)



Hioki et al. (2007)

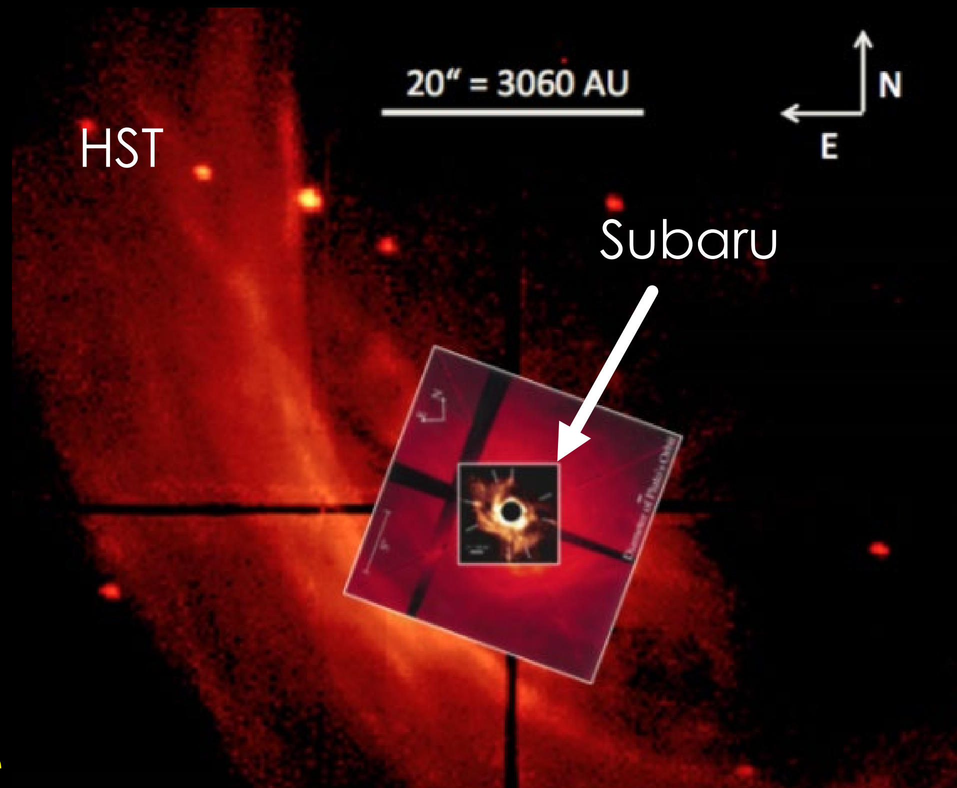


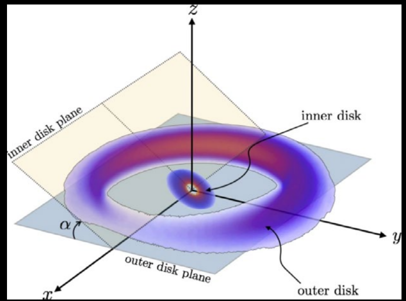
Fukagawa et al. (2006)



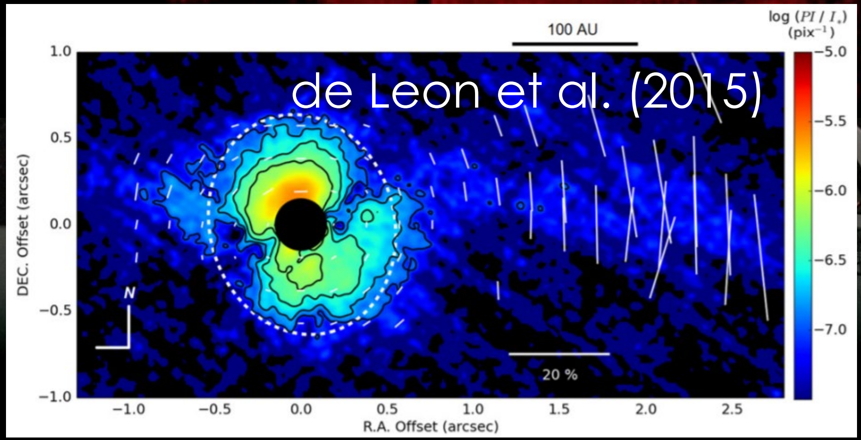
Morphology of envelopes

- Long lifetime of envelope?
  - Tails, arms, non-axisymmetry
  - Subaru/CIAO, HiCIAO
- Warped disks
  - Jinshi Sai-san's talk on Nov 19
- Initial star-forming environment can play a role to determine the disk property (e.g., Dullemond et al. 2019)





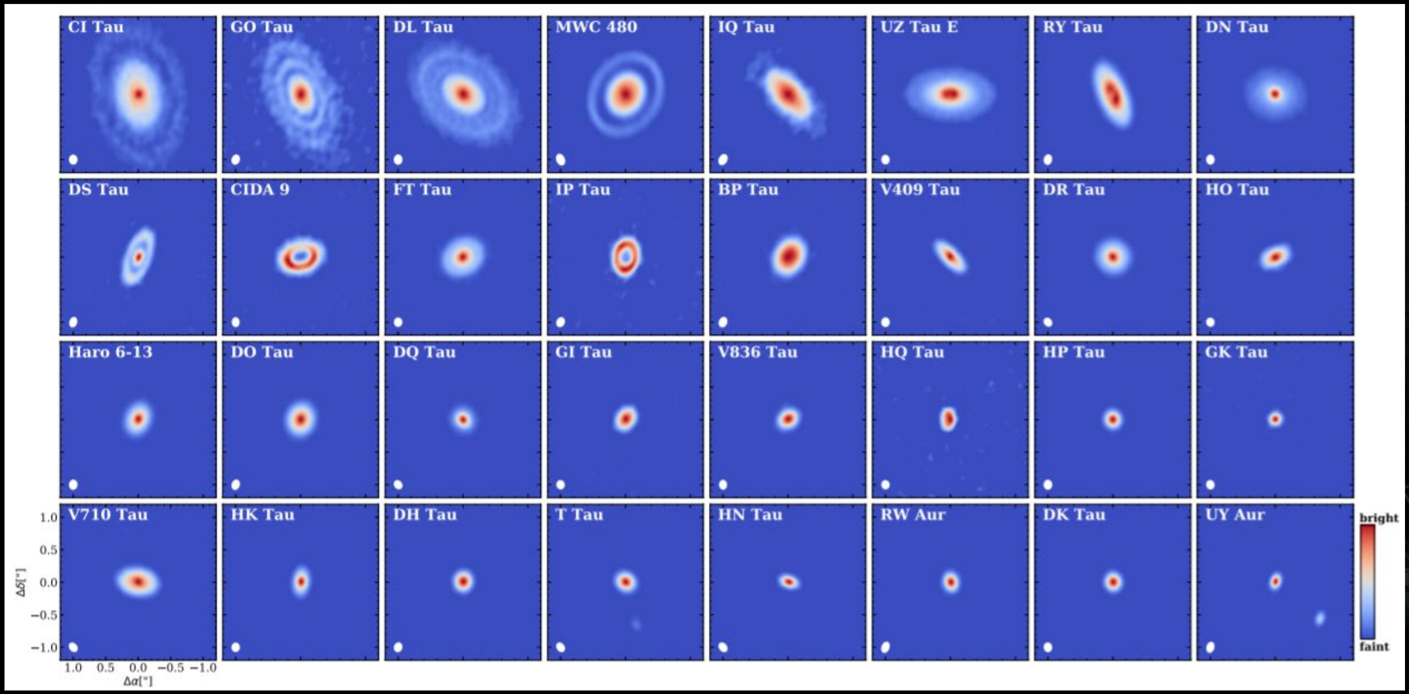
Marino et al. (2014)



Disks revealed with ALMA

- Compact to large disks
  - Our view is still biased to large disks
  - What is the cause of the variety?
- Younger than Class II may be important

Credit: ALMA (ESO/NAOJ/NRAO)



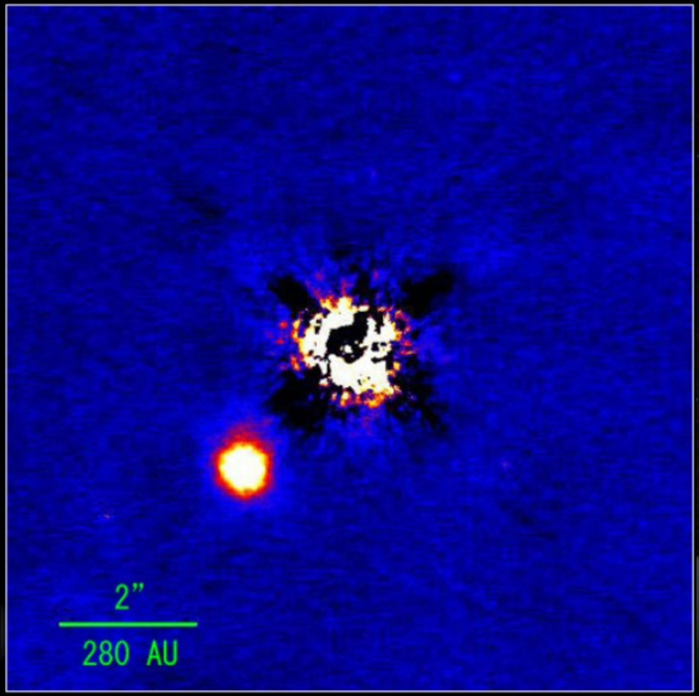
Taurus disk survey (Long et al. 2019)

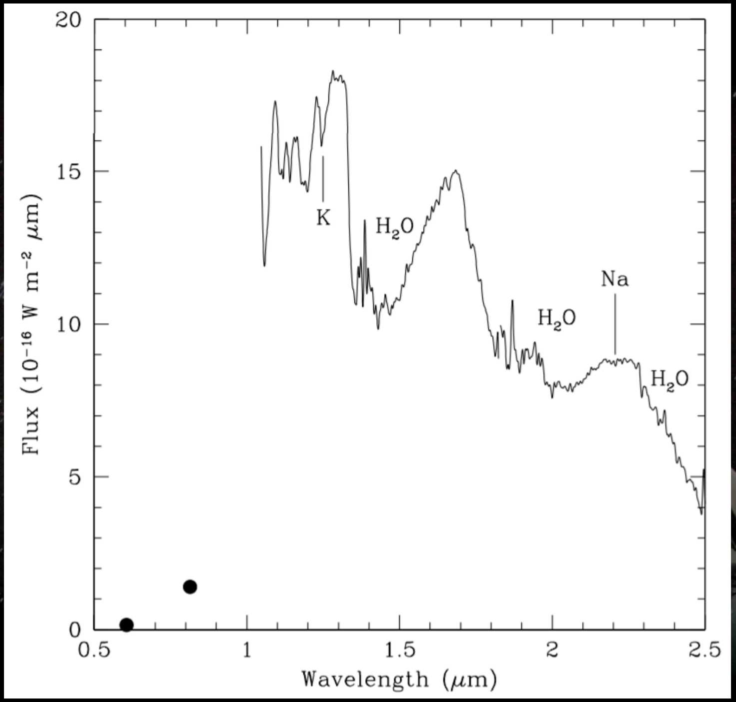
Brown dwarfs, planetary-mass objects

Low-mass companions to YSOs

- DH Tau B, ~40 $M_{Jupiter}$ (→ 11 $M_{Jupiter}$), 330 au from the star (Itoh et al. 2005)
  - Subaru/CIAO, CISCO
  - T_{eff}=2700-2800 K, log(g)=4.0-4.5

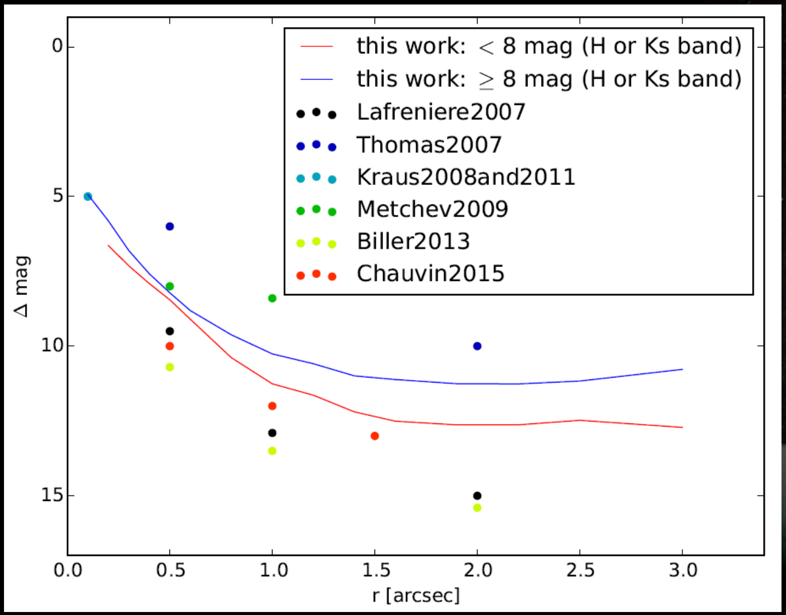
Itoh et al. (2005)

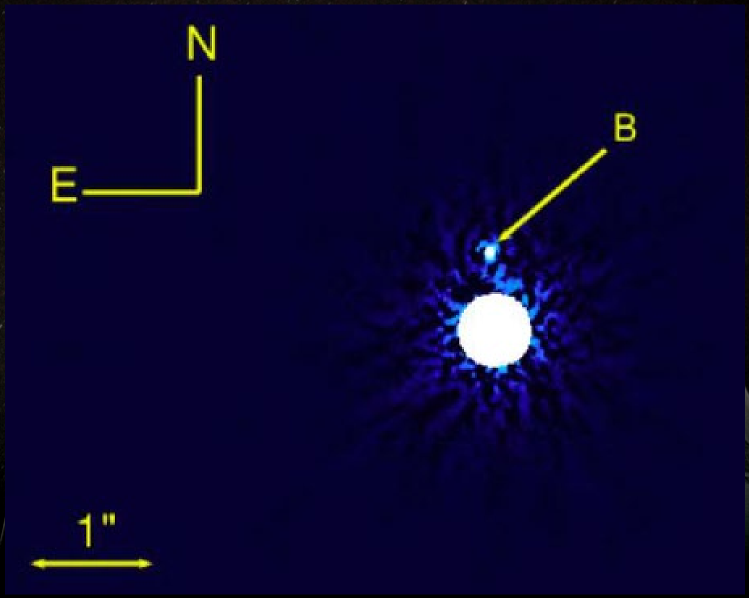




High-contrast companion search for YSOs

- SEEDS High-Contrast Imaging Survey of Exoplanets Around Young Stellar Objects (Uyama et al. 2017)
  - 99 YSOs in Target regions: U Sco, Taurus-Auriga, Ophiuchus, Lupus, CrA
  - Contrast of 10^{-4}—$10^{-5.5}$ at an angular distance of 1″ (10 M_J at 70 au and ~6 M_J at 140 au)
  - Finding a stellar companion for HIP 79462

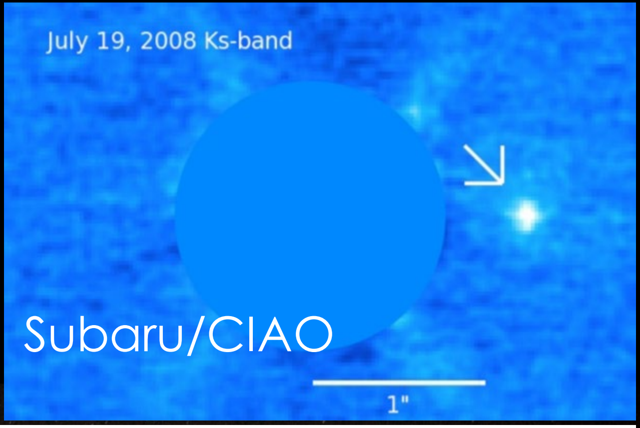


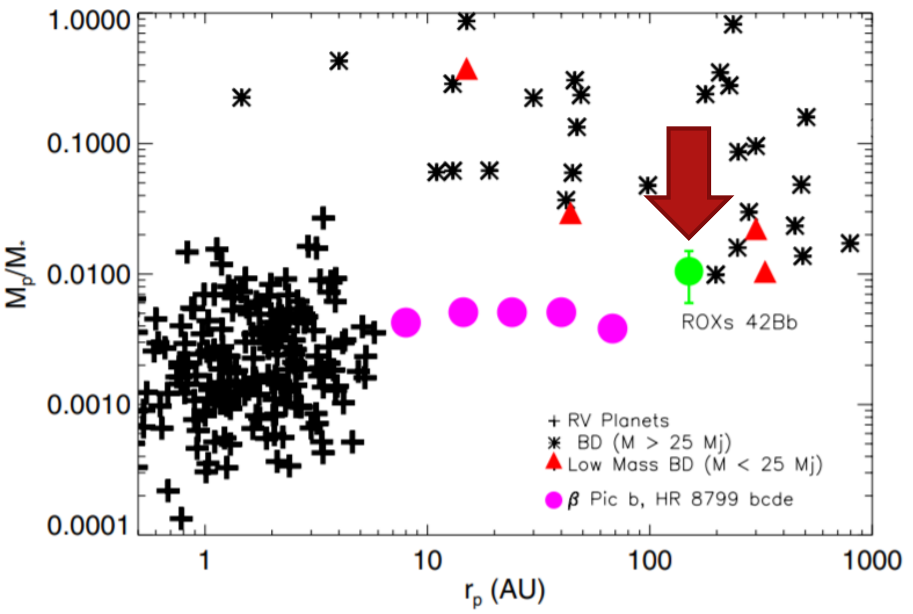


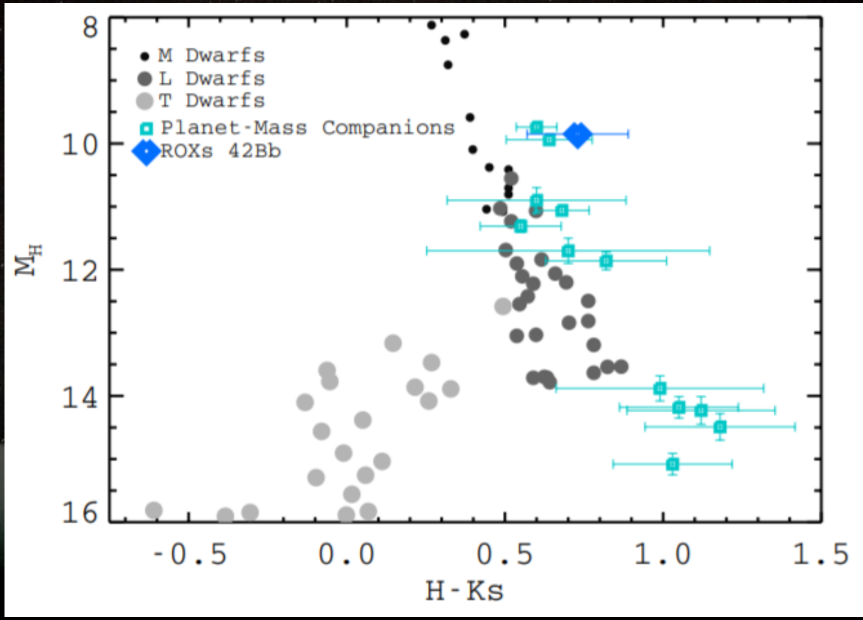
Example of a companion around YSO

- ROXs 42Bb (Currie et al. 2014)
  - 1—3 Myr, 6—15 M_J at ~150 au (proj.)
  - VLT spectroscopy
  - Similar to dusty/cloudy young, low-mass late M/early L dwarfs. Boundary object.

Thayne Currie's talk on characterization of imaged planets

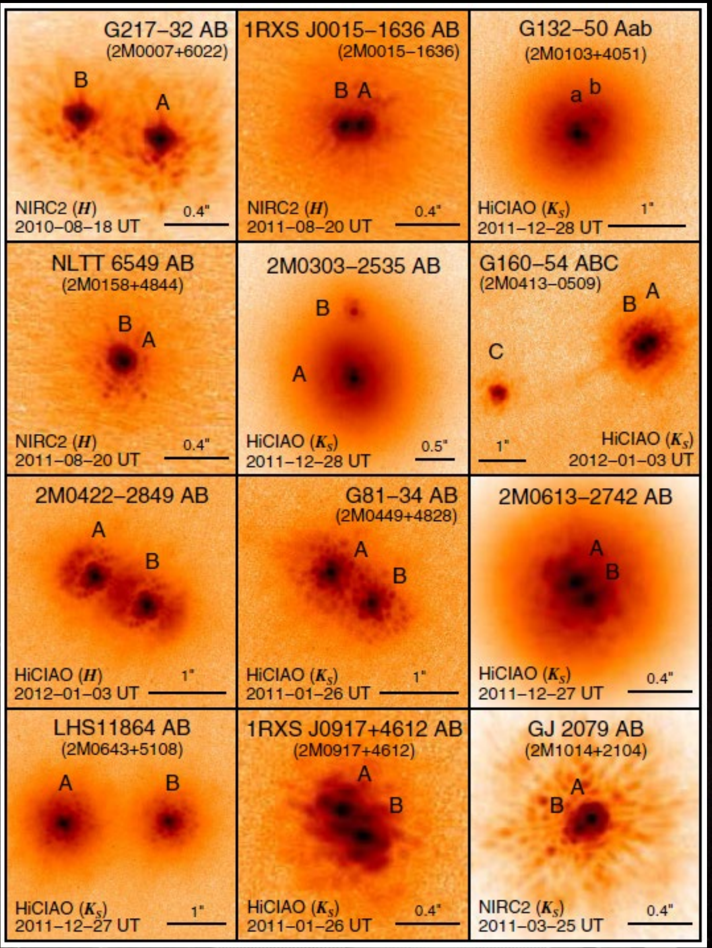






Companion search for relative young stars

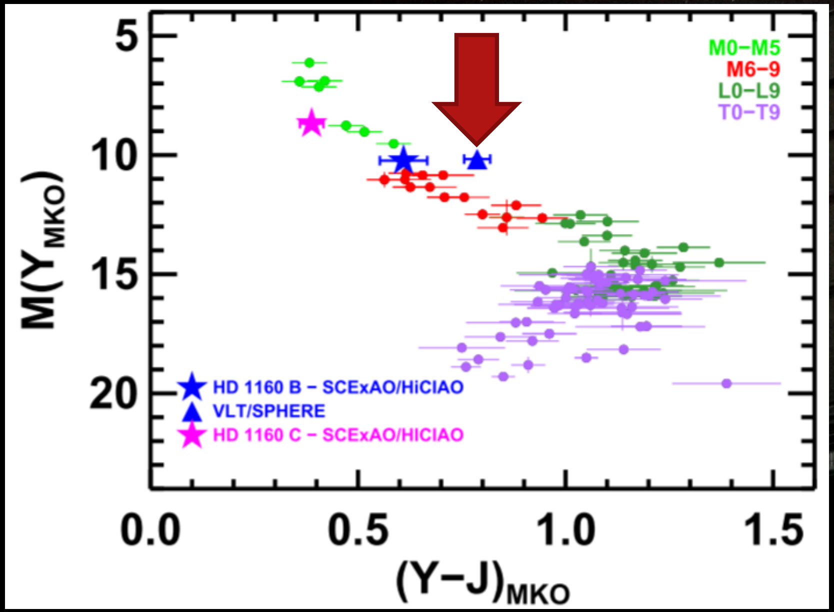
- Search for giant planets and BDs around nearby (<~40 pc) young M dwarfs (Bowler et al. 2015)
  - Keck/NIRC2, Subaru/HiCIAO
  - Half are <135 Myr, 90% are < 620 Myr.
  - Sample: 78 single M dwarfs
  - 4 BD companions were discovered, >150 candidate planets were identified and follow-up of 56% of these resulted in background stars.
- Fewer than 6.0% (9.9%) of M dwarfs harbor massive gas giants in 5–13 M_J.
- BD companions to single M dwarfs in 10–100 AU is 2.8%. Giant planets/BDs are rare in the outskirts of M dwarf planetary systems.

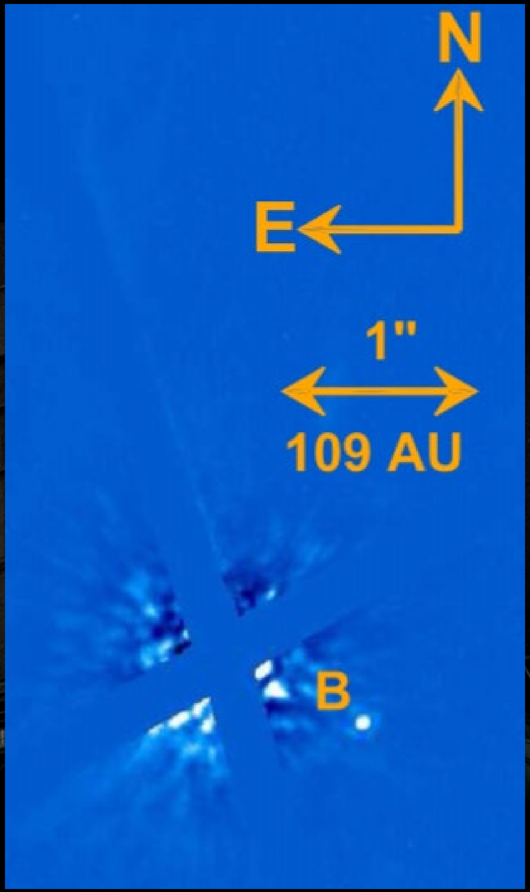


Bowler et al. (2015)

Example of young BD companions

- HD 1160 B in a triple system (Garcia et al. 2017)
  - YJH imaging with SCExAO+HiCIAO, GPI Y IFS
  - 80—125 Myr, 70—90 M_J
  - Typical M-dwarf like IR colors
  - Mass ratio <0.04 indicating formation by protostellar disk fragmentation or disk instability



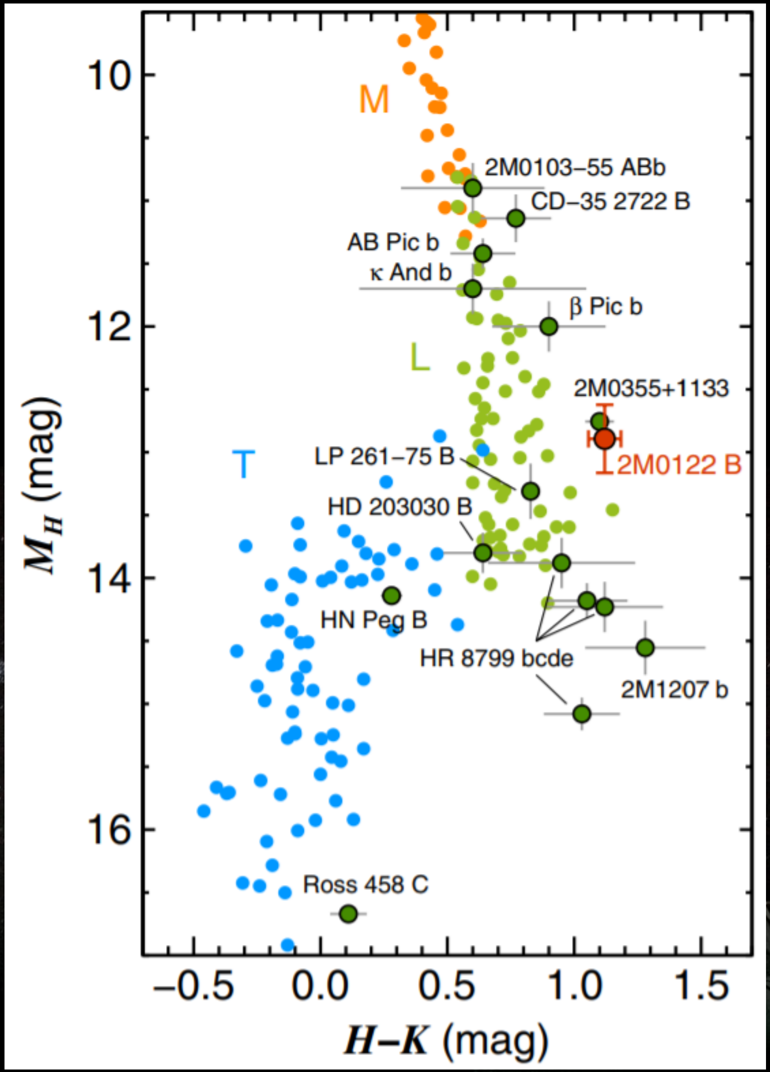


Also, e.g., Bowler et al. (2013)

Example of young BD companions

- L-type companion to the young M3.5V star 2MASS J01225093–2439505 (Bowler et al. 2013)
  - First imaged with Subaru/IRCS, then Keck, IRTF
  - 11—30 M_J at ~120 Myr or younger
  - ~1300—1500 K (L/T for field dwarfs) but mid-L type

Cloud clearing associated with the L/T transition occurs at lower Teff in lower gravity objects (Marley et al. 2012)

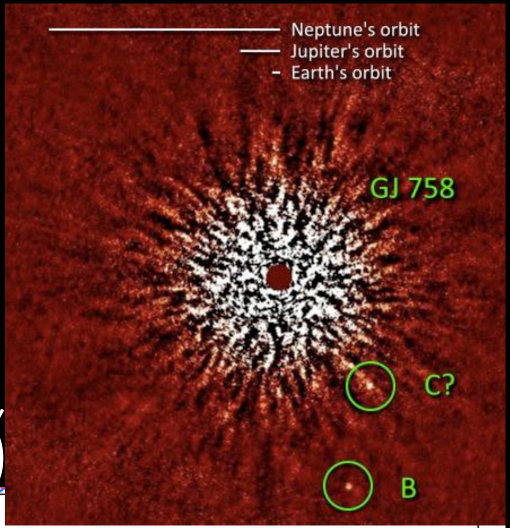


BD atmosphere: GJ 758 B

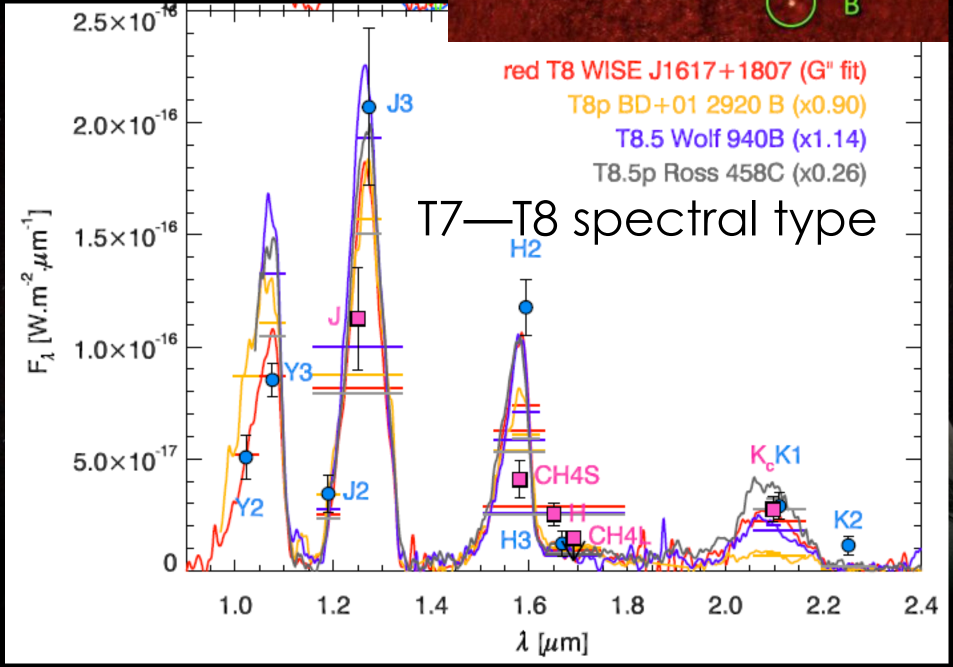
- BD companion discovered with Subaru/HiCIAO (Thalmann et al. 2009, Currie et al. 2010, Janson et al. 2011)

  - Follow-up with SPHERE, Palomar Hale
  - Methane absorption
  - Not easy to find a good atmospheric model to fit all the fluxes. The lack of exploration of metal enrichment.
  - Dynamical mass: 42 M_J (Bowler et al. 2018).

(Also for Gl 229B, Brandt et al. 2019)

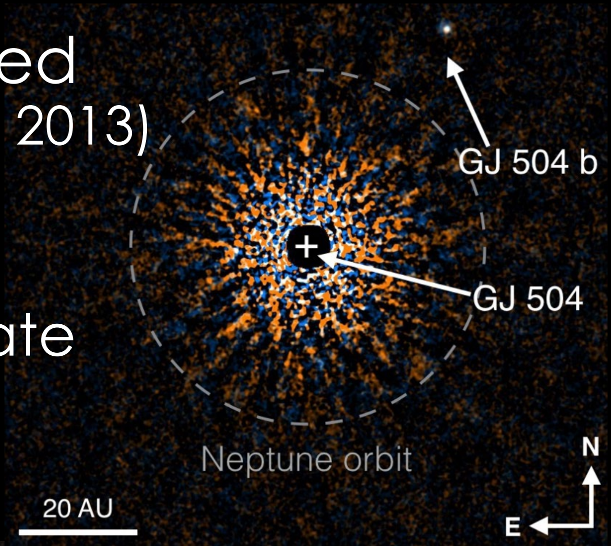


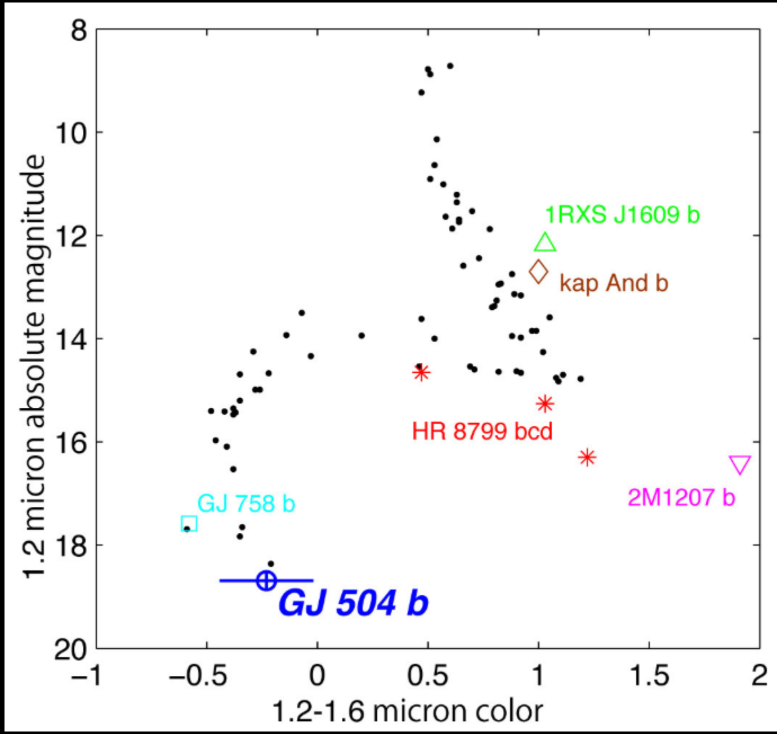
Vigan et al. (2016), Nilsson et al. (2017)

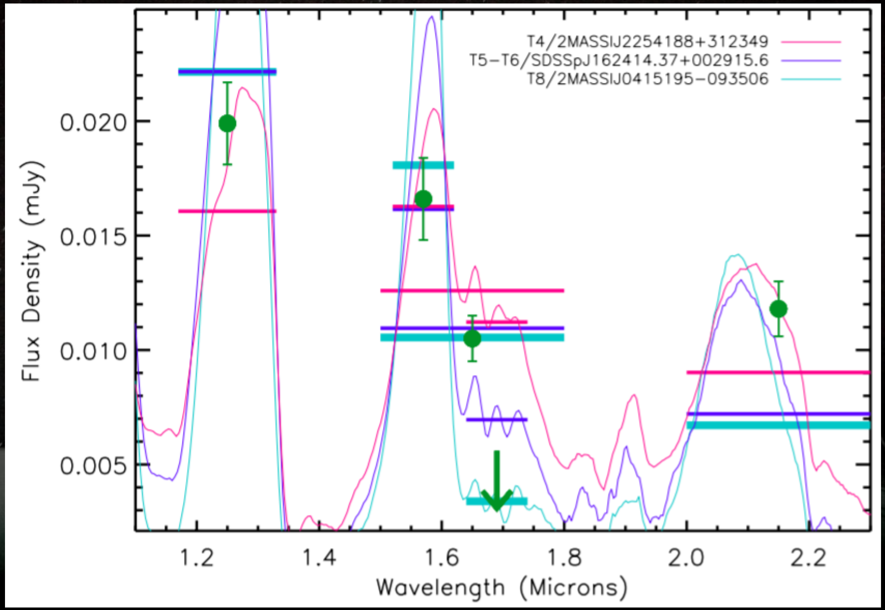


Planet atmosphere: GJ 504b

- A planetary companion discovered with Subaru/HiCIAO (Kuzuhara et al. 2013)
  - HiCIAO SDI (Janson et al. 2013)
  - Methane absorption, similarity to late T dwarfs







Summary

- The bottom of IMF has been extensively studied in deep observations of SFRs. Further improvements in sensitivity and angular resolution will be valuable to see the true ends and to confirm the environmental dependence.
- High-mass star formation is becoming a major topic in radio. What can we do in IR?
- Planet formation science is getting close to the star formation science since the initial condition of planet formation may be related to the star-forming environment. IR will become important to probe the inner regions. Also, younger evolutionary stages are important for planet formation.
- Distinction between isolated and bound BDs/PMOs will become clearer with more data on the atmosphere of bound PMOs. This can be linked to their formation mechanism.