Subaru Telescope 20th Anniversary Conference

Are Planets Rare in Open Clusters?

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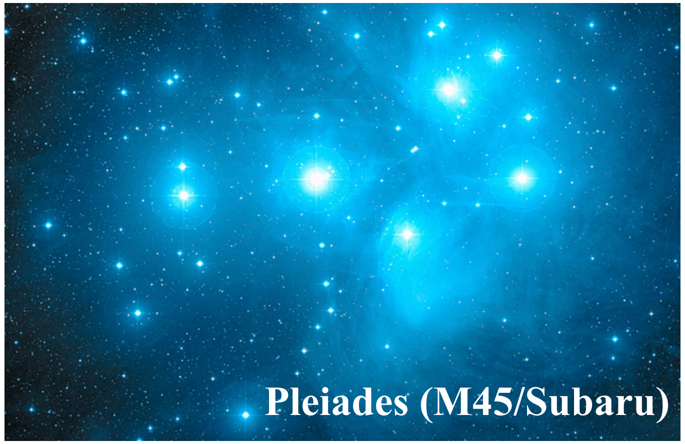
Exoplanet Searches in Star Clusters

Open clusters (typically 1-10^3 Myr, $\rho_c \sim 1 - 10^2\ M_\odot\ \mathrm{pc}^{-3}$)



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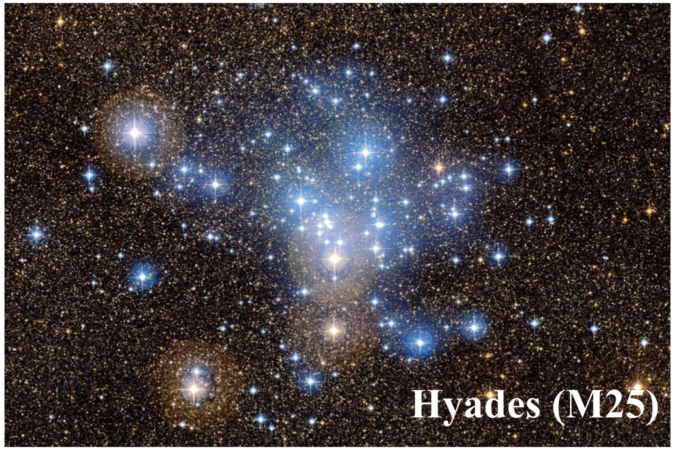

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Globular clusters

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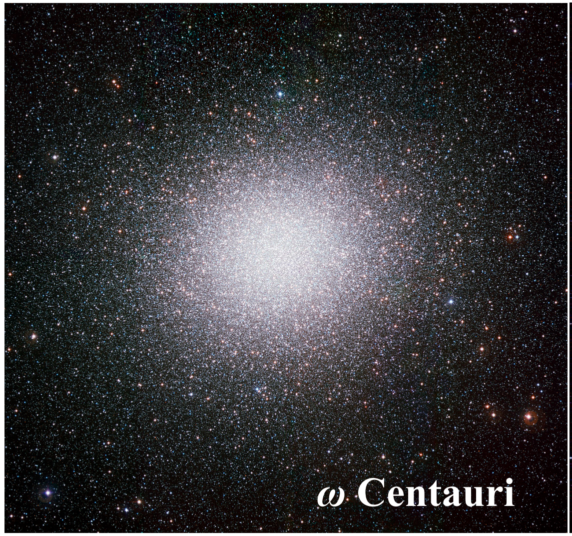

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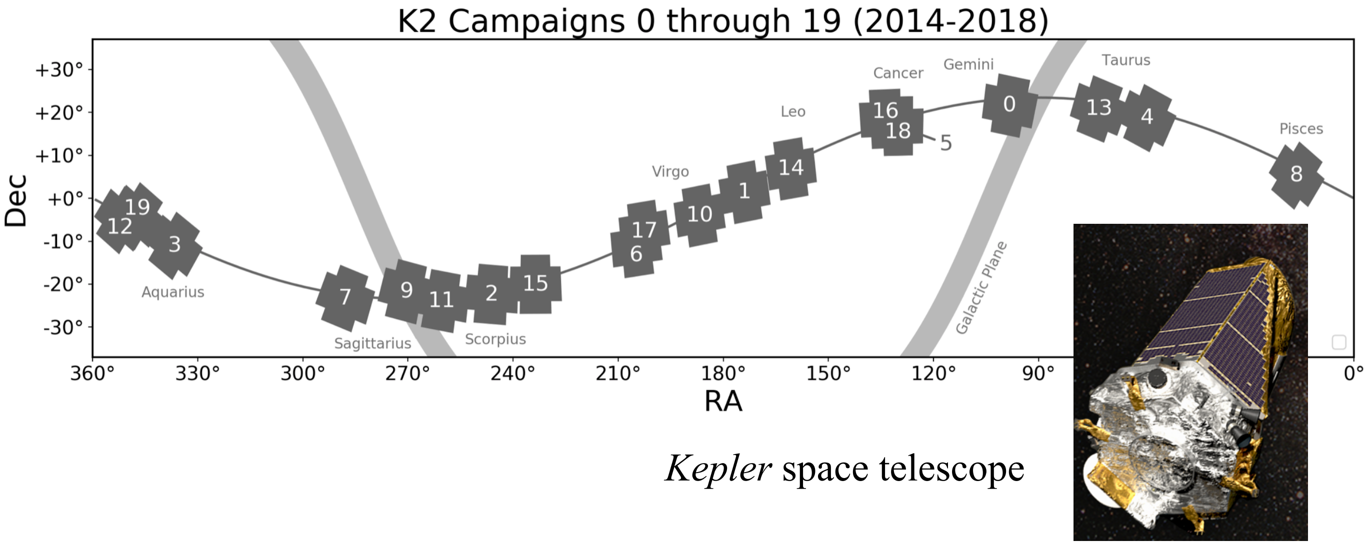
Exoplanet Searches in Star Clusters

Exoplanet population in star clusters:

i) No planets (except for a pulsar planet) were discovered in globular clusters. (Gilliland et al.2000; Weldrake et al.2008; Nascimbeni et al.2012)

ii) RV surveys: 10 planets in the Hyades, Praesepe, M76, and IC 4651
(Sato et al.2007; Quinn et al.,2012, 2014; Mann et al.,2016;Malavolta et al.2016;Brucalassi et al.,2014, 2016, 2017; Delgado Mena et al.,2018)

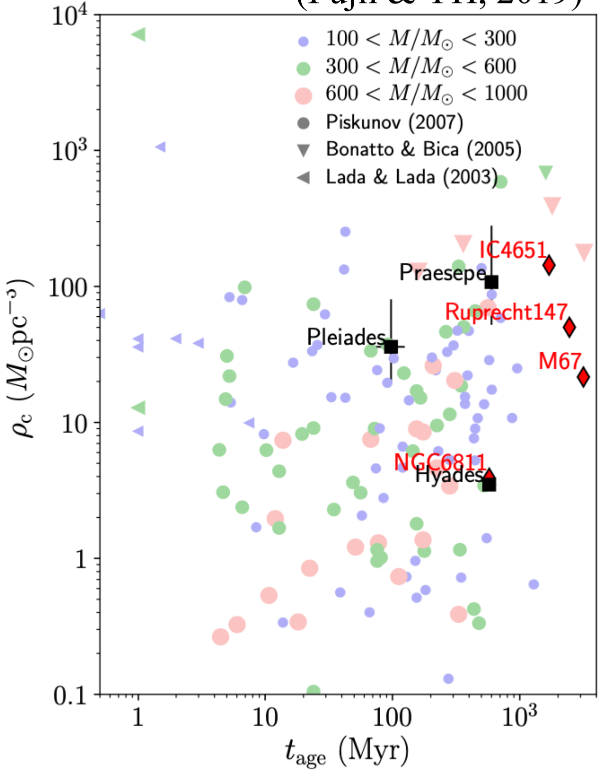
iii) Transit photometry: 17 planets in the Hyades, Praesepe, NGC 6811, M 67, and Ruprecht 147
(Meibom et al.2013; Mann et al.,2016,2017,2018; Livingston et al.,2018,2019; Ciradi et al.,2018; Obermeier et al.,2016;Pepper et al.,2017;Rizzuto et al.,2018;Curtis et al.,2018)



Kepler space telescope

Planet searches in other 18 open clusters, including the Pleiades (Subaru), ended in the non-detection of planet signals.

(Fujii & YH, 2019)



Exoplanet Population in Open Clusters

- The rarity of planets in star clusters is apparently seen because of low detection probabilities of planets in distant open clusters? (van Saders & Gaudi, 2011)
- Occurrence rates of planets in open clusters are similar to/slightly higher than those in the field. (Meibom et al.2013; Brucalassi et al.2017)

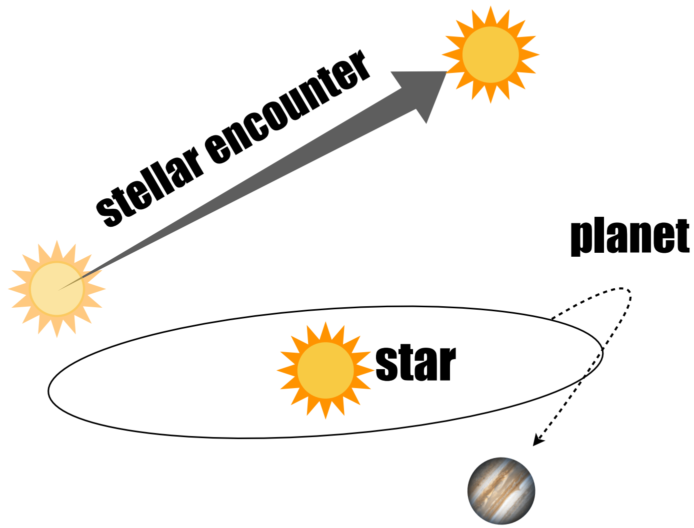
↕

Failure of planet formation?

- Disk truncation can be induced by stellar encounters. (e.g. Bonnell et al.2011; Vincke et al.2015)
- Photoevaporation of an outer disk can be caused by FUV and EUV irradiations from massive stars? (e.g. Winter et al.2018)

Dynamical destruction of planetary systems?

- ***Stellar encounters can destroy planetary systems in open clusters*** (e.g. Spurzem et al.2009)



N-body Simulations of Open Clusters

- Initial models of our star clusters:

  King's model with $W_0 = 3$ for open clusters (King, 1966) with initial core densities

  $1.6 \times 10^4\ M_\odot\,\mathrm{pc}^{-3}$ (**Praesepe- & M67-type cluster**)

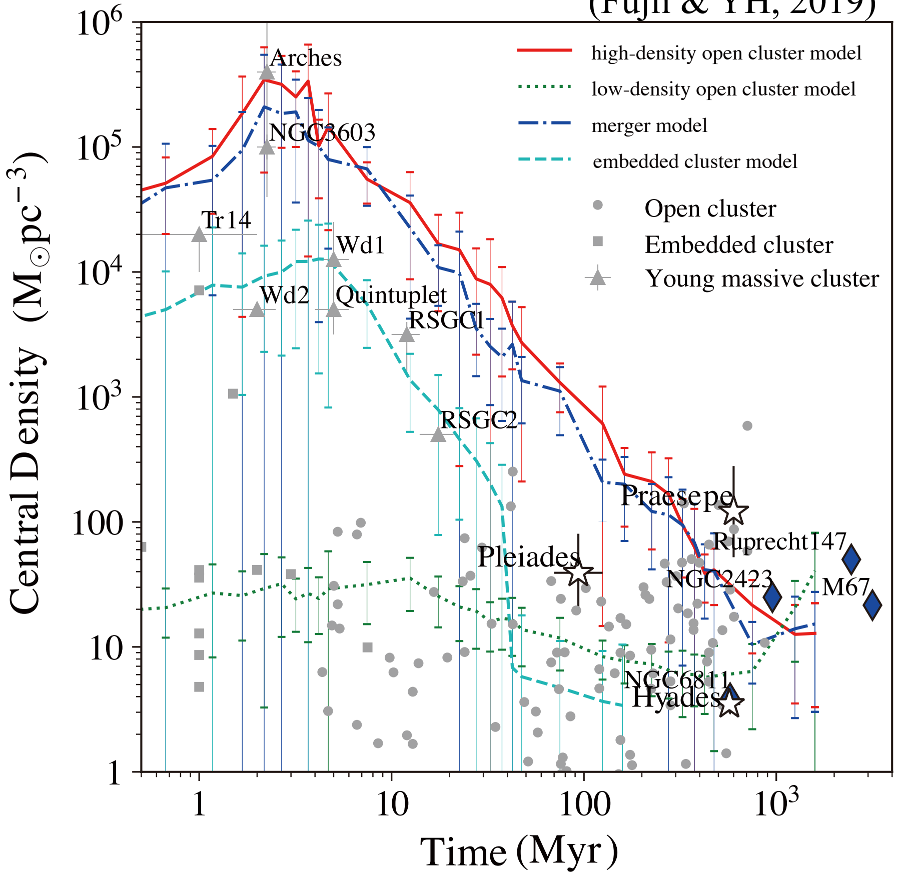
  $16\ M_\odot\,\mathrm{pc}^{-3}$ (**Pleiades- & Hyades-type cluster**)

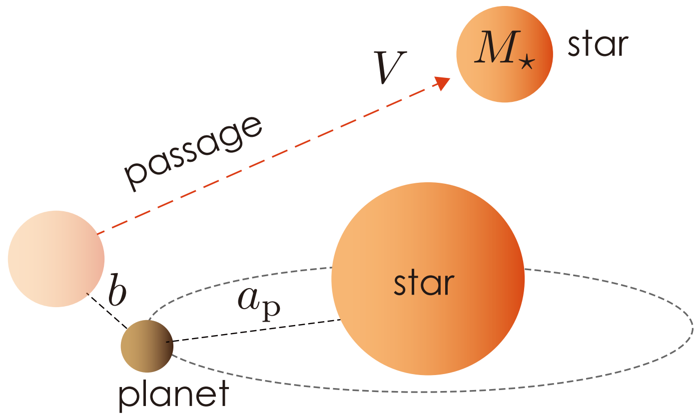
- Initial stellar populations follow Kroupa IMF

  (cf) a lower mass cut-off of $0.08\ M_\odot$, an upper one of $15\ M_\odot$ for open cluster (Kroupa, 2001)

- Stellar collisions and evolution (Hurley et al., 2000)

(Fujii & YH, 2019)





The change in the velocity (Δv) of a star-planet system due to one close encounter of a passing star:

$$\Delta v = \frac{2GM_\star}{b^2 V} b$$

The change in the energy per unit mass (ΔE) of the star-planet system:

$$\Delta E = \frac{2G^2 M_\star^2}{V^2 b^4} a_p^2$$

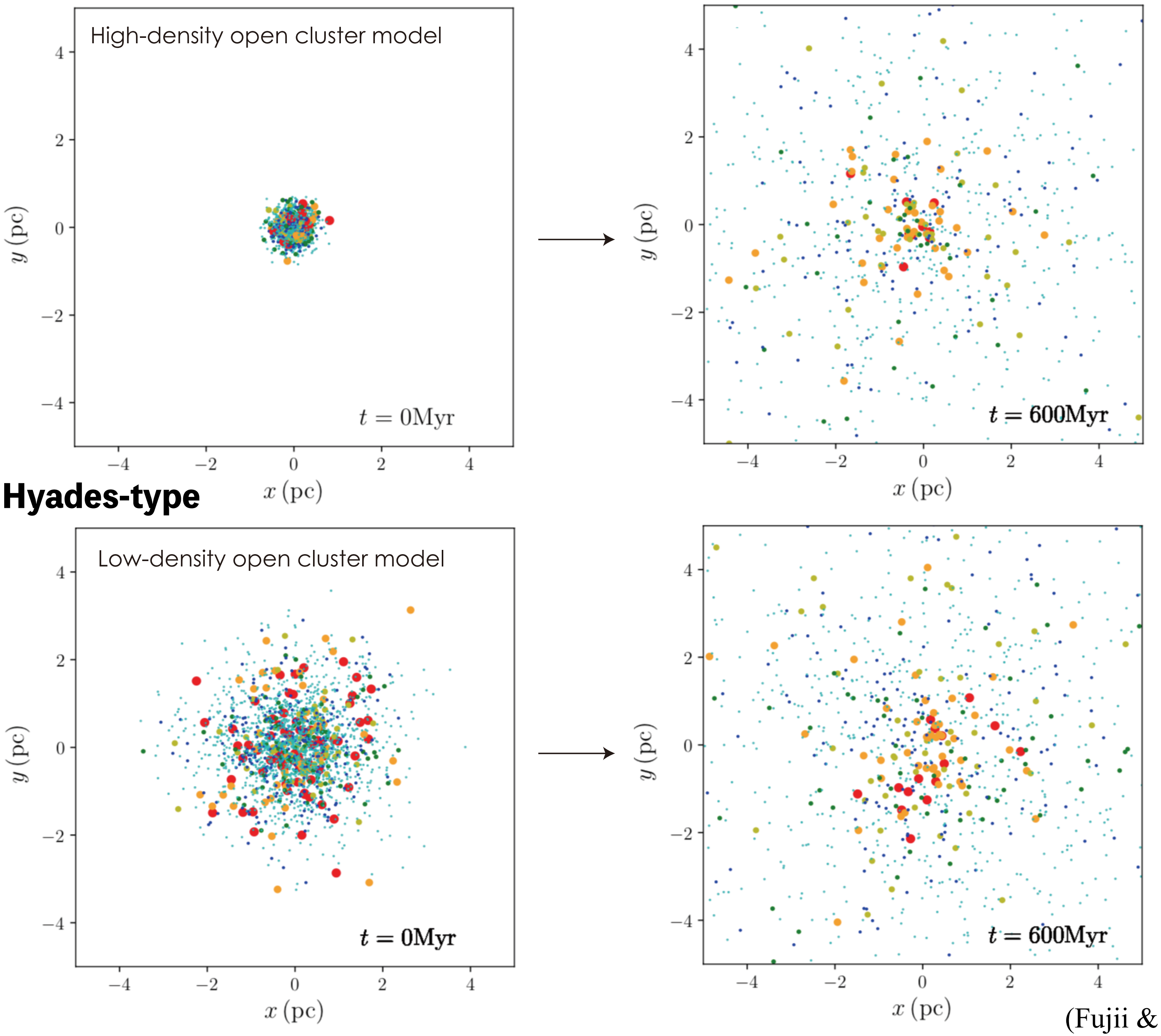
(Binney & Tremaine, 2008)

Dynamical Evolution of Open Clusters

Praesepe- & M67-type

B-, A-, F-, G-, K-, and M-type stars

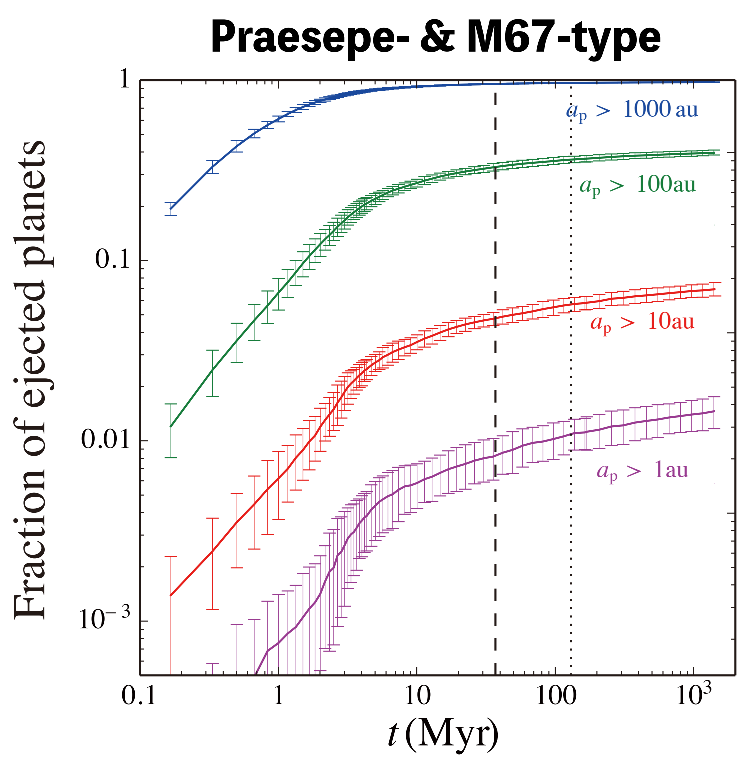
Pleiades- & Hyades-type

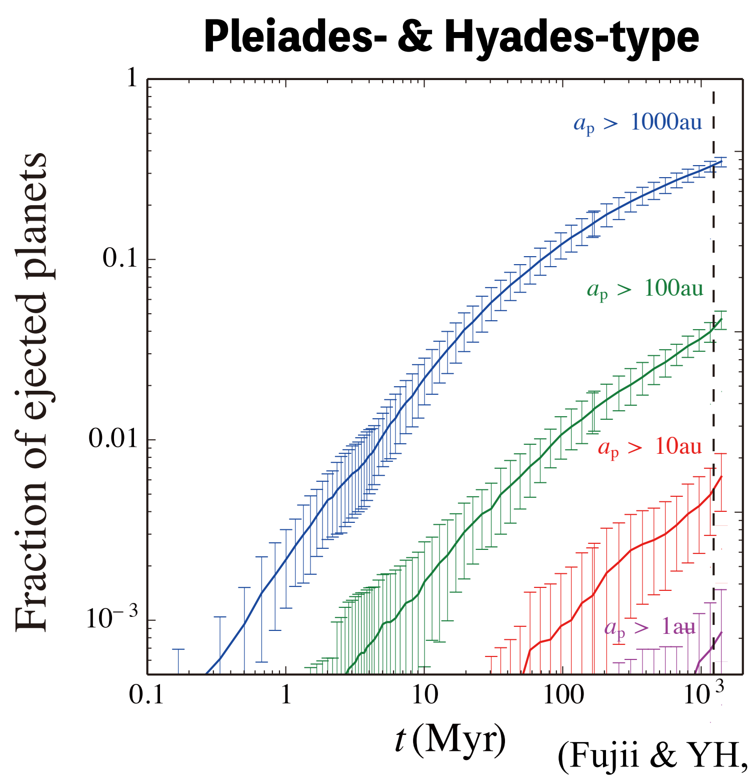


(Fujii & YH, 2019)

Survival Rates of Planets in Open Clusters

Assuming that each star harbors one planet, we examined fractions of planets that are ejected from the system by stellar encounters in open clusters such as the Hyades, Preasepe, and Pleiades.





(Fujii & YH, 2019)

a) Close-in planets inside 1 au can be rarely ejected from host stars in open clusters.
b) The ejection rate of planets at 1-10 au is at most 7 % in our open cluster models.
c) The ejection rate of planets at 10-100 au around FGKM-type stars reaches a few 10 %.

Subaru can find out a close-in planet in "**Subaru**" (the Pleiades)!

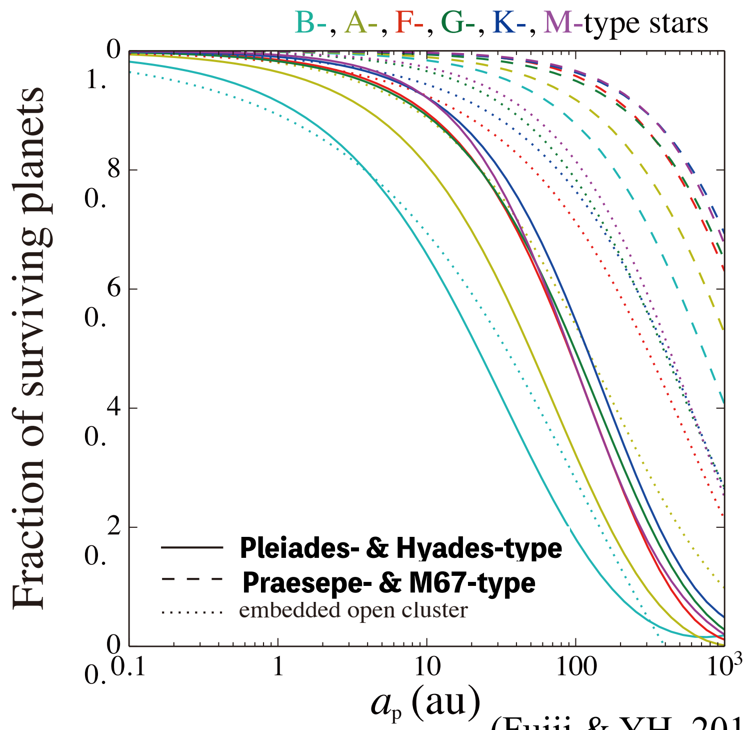
Toward Planet Searches in Open Clusters

(Strategy I) Low-mass stars rather than massive ones are promising targets for planet searches by RV measurements and transit photometry.

(Strategy II) Young open clusters ($t <$ the two-body relaxation time) show higher sensitivity for the detection of planets.

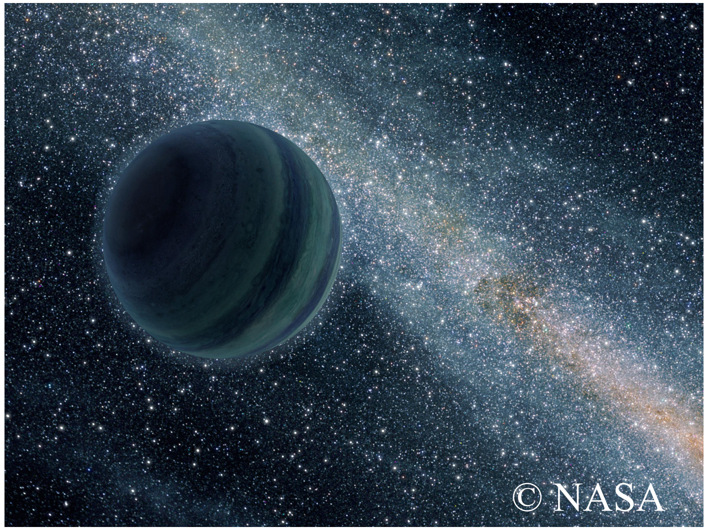
(Strategy III) High-density, massive clusters would have low priority for planet searches because of enhanced stellar encounters, frequent collisions of stars, and XUV irradiations.

(Strategy IV) Planets moving on wide orbits in open clusters are pessimistic.



(Fujii & YH, 2019)

Free-floating Planets



Free-Floating planets
(Rogue/Orphan/unbound planets)

are gravitationally unbound by a star and freely moving in space

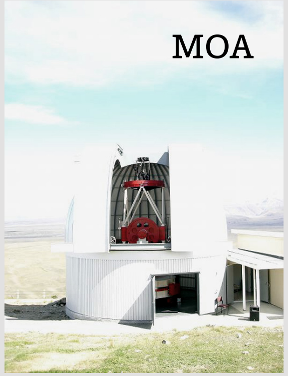
Ejection? Star formation?

Microlensing event rates are estimated to be about **10^{-4} %**

Survey teams:

- OGLE (Optical Gravitational Lensing Experiment)
- MOA (Microlensing Observations in Astronomy)
- KMTNet (The Korean Microlensing Telescope Network)

(cf) follow-up teams： μFUN, PLANET, RoboNet etc.



2,617 μ lensing events monitored by OGLE for six years (2010-2015) indicate that Jupiter-sized free-floating planets are < 0.25 as common as main-sequence stars (Mroz *et al*. 2018)

Production Rates of Free-floating Giant Planets

We estimated production rates of free-floating planets through stellar encounters in open clusters, using the observed planet distribution in the field.

- Giant planets with 0.1-13 $M_{\rm Jup}$ between 0.01-10 au: (Cumming et al., 2008)

$$p(M_{\rm p}, a_{\rm p}) \left(= \frac{dN}{dM_{\rm p} da_{\rm p}}\right) = 1.03 \times 10^{-2} \left(\frac{M_{\rm p}}{1\, M_{\rm Jup}}\right)^{-1.31} \left(\frac{a_{\rm p}}{1\, \rm AU}\right)^{-0.61}$$

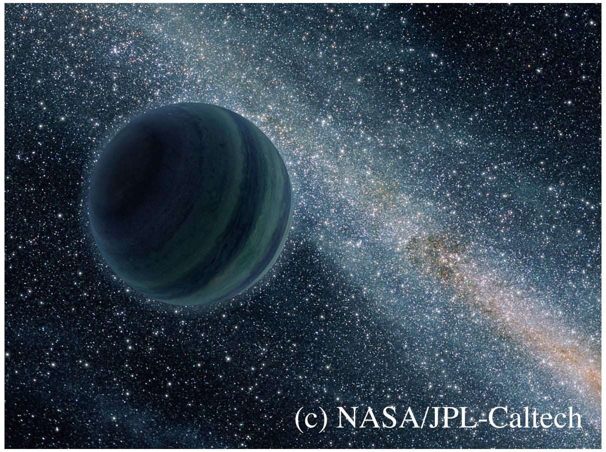
- Giant planets with 0.1-13 $M_{\rm Jup}$ between 10-100 au: (Brandt et al.,2014)

$$p(M_{\rm p}, a_{\rm p}) = (1.0 \pm 0.4) \times 10^{-3} \left(\frac{M_{\rm p}}{1\, M_{\rm Jup}}\right)^{-0.7} \left(\frac{a_{\rm p}}{10\, \rm AU}\right)^{-0.8}$$

Production rates of free-floating planets per FGKM-type star

Models	$0.01 < a_{\rm p} < 100\,$au
Praesepe- & M67-type open cluster	18.4 %
Pleiades- & Hyades-type open cluster	0.96 %

which are compatible to the results obtained by microlensing surveys toward the Galactic Bulge, i.e., the frequency of free-floating Jovian planets are $\lesssim 0.25$ per main-sequence star. (Mroz et al., 2017)



Summary

- The ejection rate of short-period planets is less than 1.5 %. We expect no significant difference between the frequency of short-period planets in open clusters and that in the field.

- Planetary systems around massive stars tend to be dynamically stirred up; up to 29 % of planets within 10 au around B-stars experience orbital disruption, whereas the ejection rate of planets around FGKM-type stars is only a few %.

- Distant planets with $a_p > 100$–1000 AU such as observed directly-imaged planets can be ejected efficiently via stellar encounters in clustered environments.