Unveiling Planet Evolution Mysteries: Empirical Models through a New Strategy

Home Page!

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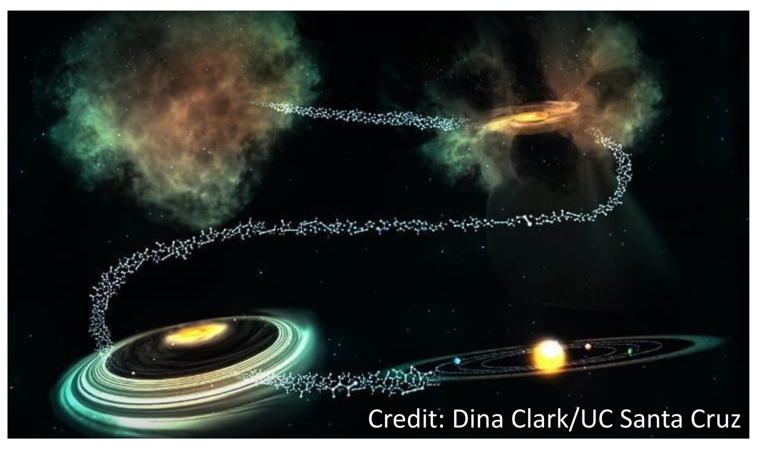
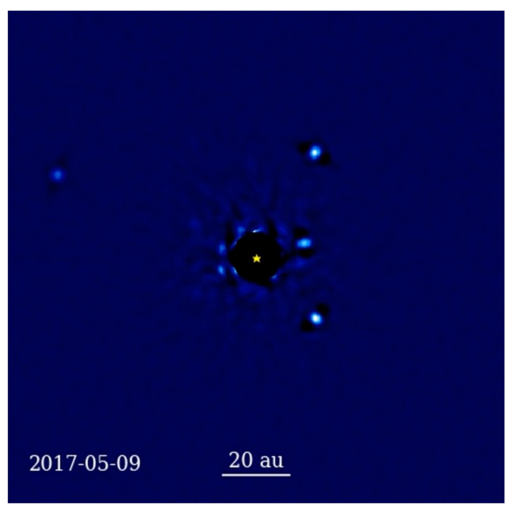
Any questions or comments? Feel free to chat with me!

1. How Planets Evolved after Formation?


Credit: Dina Clark/UC Santa Cruz

- Molecular cloud
- Protostar
- Protoplanetary disk
- Planet formation
  - ❑ Core accretion
  - ❑ Gravitational instability
- Disk dispersion (< ~10 Myr)



Credit: Jason Wang (Northwestern)/William Thompson (UVic)/Christian Marois (NRC Herzberg)/Quinn Konopacky (UCSD)

Gravitational energy ➔ Heat

Young and hot planets ➔ Ideal targets for direct imaging

e.g. Temperature of the famous young system HR 8799 [1-2] is over 1000 K [3]!

Gradually cooling down by radiation!

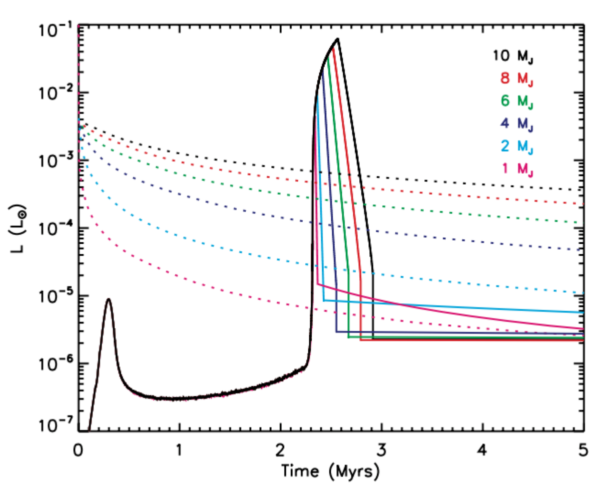
❖ Still under intense debate:
- ➢ Cooling rates?
- ➢ Initial conditions?

2. Two Competing Models

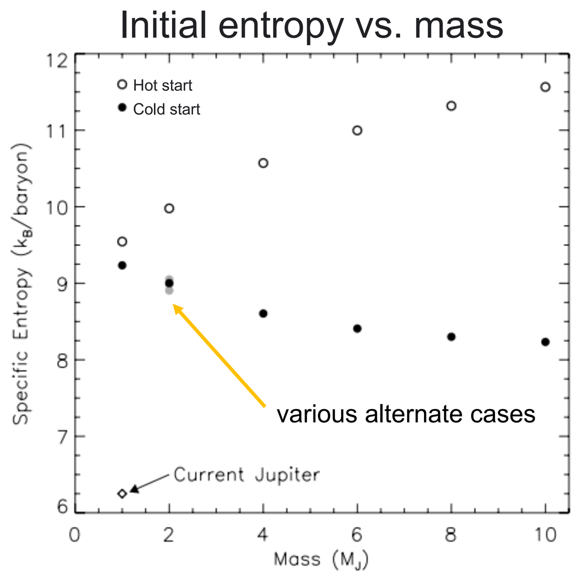
Model	Cold start [4]	Hot start [5]
Initial entropy	Lower	Higher
Leading to initial luminosity	Lower	Higher
Leading to initial mass	Higher	Lower
Formation model preference	Core accretion	Gravitational instability

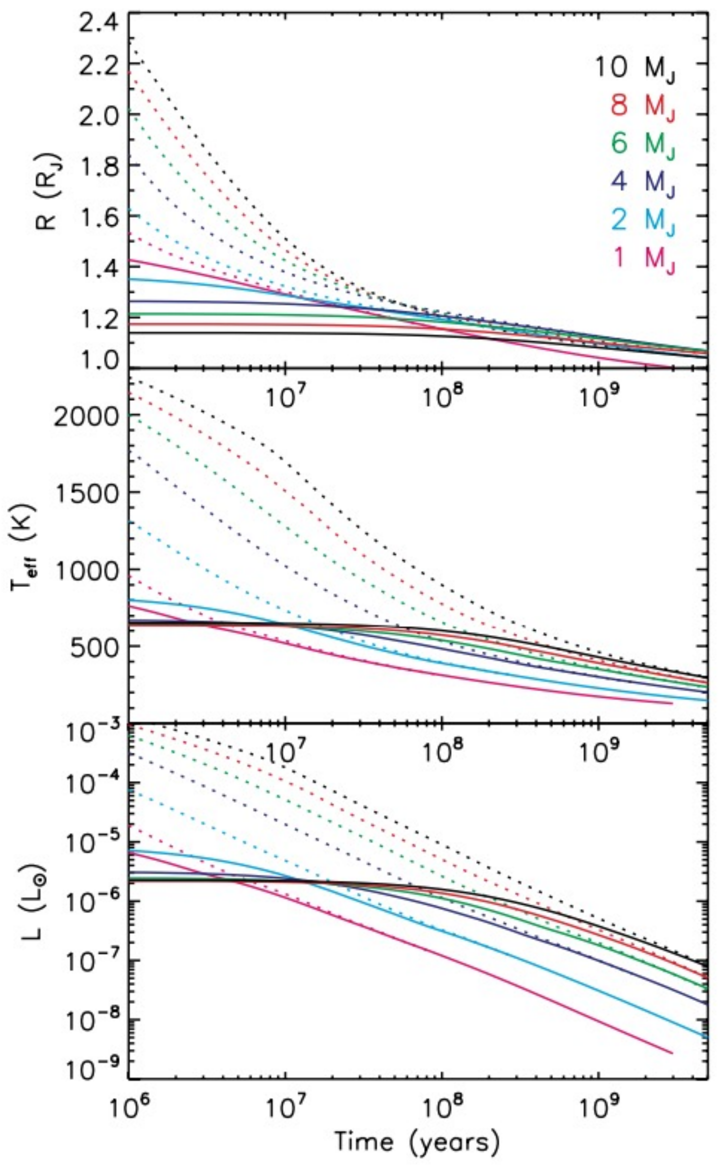
- Figures on the right show the time evolution of **radius**, **temperature**, **luminosity** and **initial entropy** of newly formed planets, taken from Marley et al. 2007 [4].
- After about 10^8 to 10^9 years, two models gradually converge.

Marley et al., ApJ, 2007
Dotted lines: hot start; **Solid lines**: cold start



Initial entropy vs. mass





3. Limitations of Current studies

Reason ➔ Result

Direct imaging is the only method that we can measure the luminosity of planets directly.

Theoretical Side

- Hard to judge two evolution models
- No way to calibrate models
- Insufficient samples

Estimating mass from theoretical models

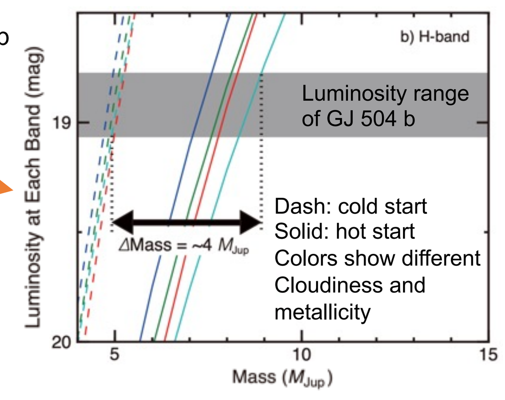
Degeneracy between age and mass

No enough samples to test theoretical models

Observational Side (Direct imaging)

- Hard to make precise mass measurement
- Unable to distinguish young but light with old but massive planets (they have similar luminosities)
- Low yields of previous surveys of direct imaging (e.g., Gemini-GPIES ~ 1% for both brown dwarf and planets [7])

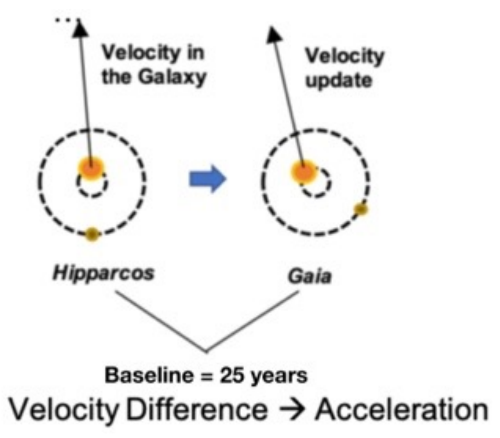
Mass estimation of directly imaged exoplanet GJ 504 b
Kuzuhara et al., 2013 [6]



4. A New Strategy to Solve this Infinite Loop!

- Our Subaru/SCExAO team has a newly approved intensive program of direct imaging survey of exoplanets with 42 nights over 3 years (2024~2026) [8].

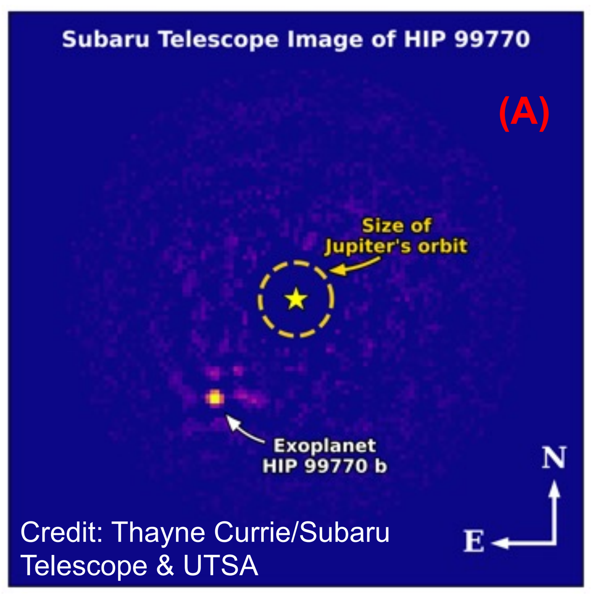
❖ Space missions for astrometry
- ➢ Hipparcos: launched in 1989
- ➢ Gaia: launched in 2013



Credit: Masayuki Kuzuhara/ABC

I. Targeting on young (~150 Myr) and accelerating stars (125 stars) [8]

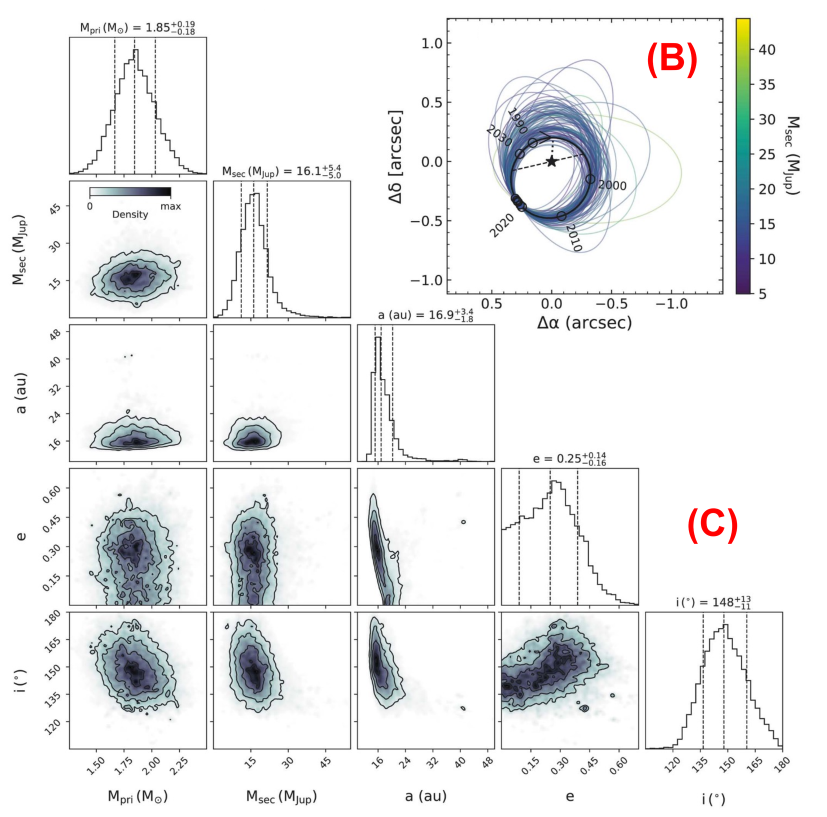
- Most targets have V < ~5 within 60 pc.
- Obvious differences in proper motion velocity between Gaia and Hipparcos (over ~ 25 years) ➔ Stars have acceleration! ➔ Higher possibility to have massive companions to be directly imaged!
- Detection rate:
  - ➢ Conventional approach: 1~3% (e.g., Gemini-GPIES [7])
  - ➢ This approach (currently): over 3 times better than the conventional one.



Credit: Thayne Currie/Subaru Telescope & UTSA

II. Data reduction

- Target stars will be observed with an integral field spectrograph called CHARIS [9].
- Data extraction and reduction will be made by the Automated Data Extraction, Processing, and Tracking System for CHARIS (ADEPTS [10-11]) and the CHARIS Data Reduction Pipeline (DRP) [12].
- Panel A shows a pilot study of HIP 99770 b [13]
- **The first exoplanet detected by direct imaging with hints from astrometry, published in *Science*.**



III. Joint fitting with multiple methods

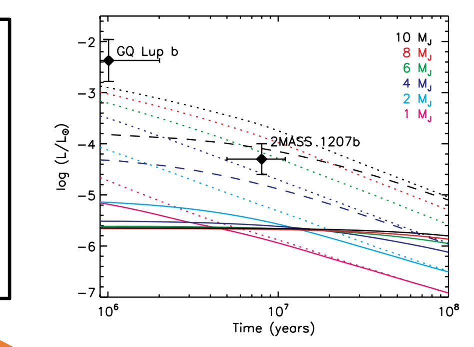
- Panel B is the result of orbit fitting of HIP 99770 b with direct imaging (DI), astrometry and radial velocity (RV) [13].
- Panel C is the posterior distributions of parameters of HIP 99770 b [13]:
  - ❑ M_{pri} and M_{sec}: masses of the host star and the companion
  - ❑ a, e and i: semi-major axis, eccentricity and inclination of the companion

Model-independent mass measurement enable us to calibrate theoretical models!

5. Building Empirical Evolution Models (for planets and BDs)

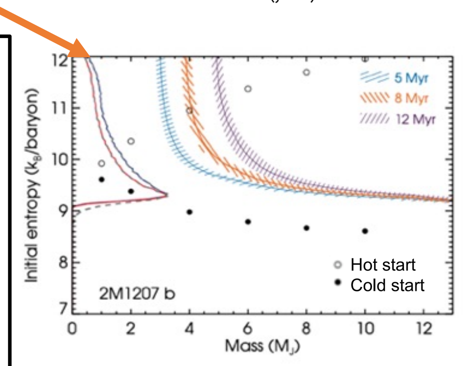
Detecting new companions with model-independent mass estimations	Estimating age from main sequence turn-off points in CMDs [14]	Refining mass measurements of known companions with astrometry and RV

- Accumulating a robust dataset of directly imaged low-mass companions with relatively precise age-mass-luminosity measurement.
- Calibrating theoretical models as shown in the right figure from Marley et al. 2007 [4].



posterior distributions of mass

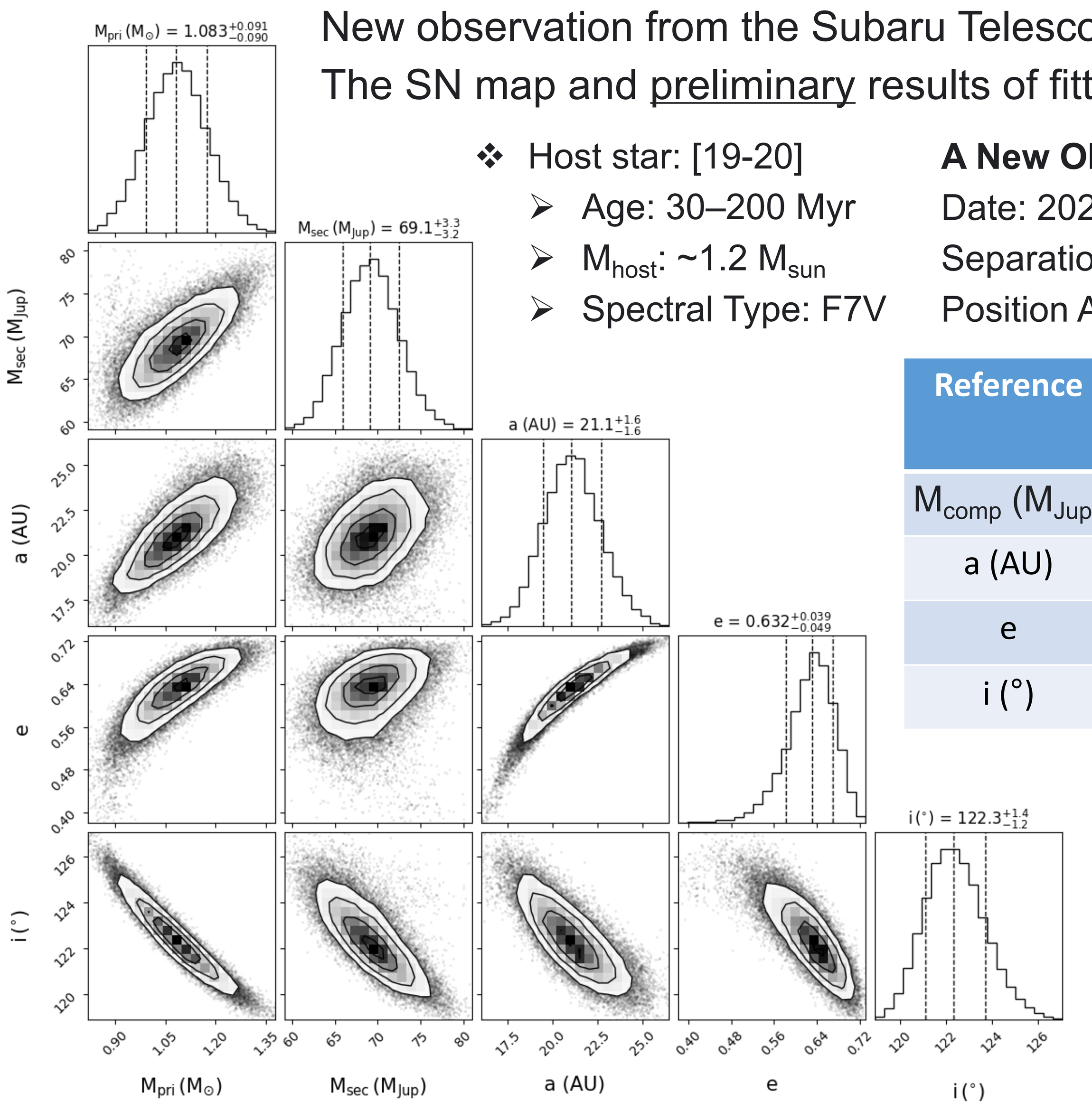
- A new method proposed by Marleau and Cumming (2014 [15]) is available to constrain the mass and initial entropy of a discovered companion with its derived luminosity and age (see the right figure).
- After deriving dynamical mass measurements of large samples, we can therefore give a conclusion to the debate of hot start vs. cold start



Marleau & Cumming, 2014, MNRAS

6. Current Work: HD 984 B (A Young Brown Dwarf)

New observation from the Subaru Telescope:
The SN map and preliminary results of fitting



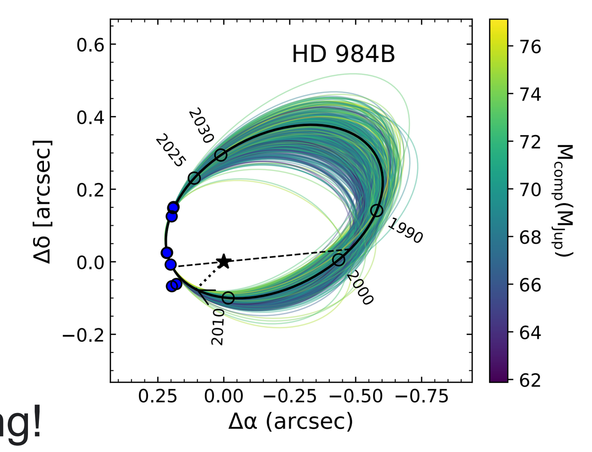
❖ Host star: [19-20]
- ➢ Age: 30–200 Myr
- ➢ M_{host}: ~1.2 M_{sun}
- ➢ Spectral Type: F7V

A New Observation ➔
Date: 2020/08/31
Separation: 242.6 mas
Position Angle: 52.4°

The SN map

Reference	Franson et al. 2022 [21]
M_{comp} (M_{Jup})	61±4
a (AU)	28^{+7}_{-4}
e	0.76±0.05
i (°)	$120.8^{+1.8}_{-1.6}$

In addition, a new BD candidate was detected in this intensive program. We will start the analysis soon.



Orbit and mass fitting with new observations is still on going!

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