Modeling for formation of extrasolar planetary systems

Shigeru Ida (Tokyo Institute of Technology)

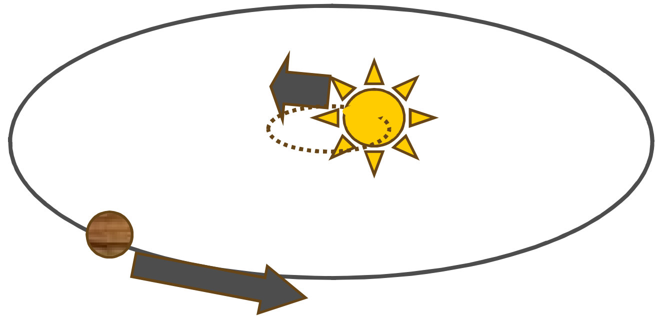
- Brief summary of observations
  - radial velocity, transit, gravitational lensing, direct imaging
  - diversity of gas giants → super-Earths
  - habitable planets around M-type stars
- Theory
  - explain diversity of gas giants
  - predict super-Earths/Earths

Joint Subaru/Gemini Science conference, May 15, 2009

brief summary of observations

Observational methods and their bias

- Doppler measurement of **radial velocity** due to wobble (視線速度)
  - ~320 planets
  - large *M* & small *r*
  - FGK stars (M stars are OK)



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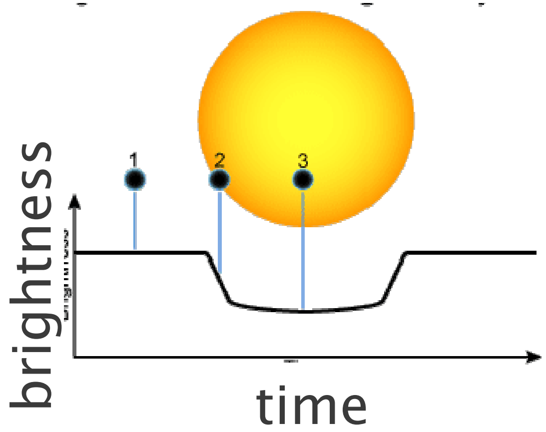
  - ~60 planets
  - large *M* & small *r* (<0.1AU)



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  - ~10 planets
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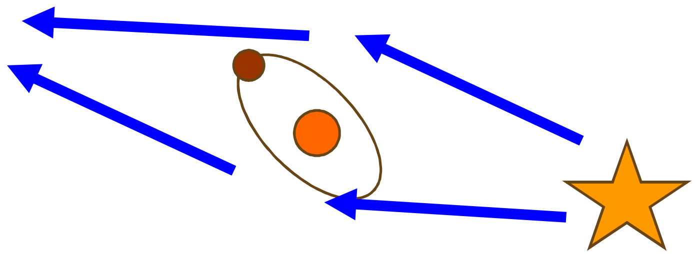
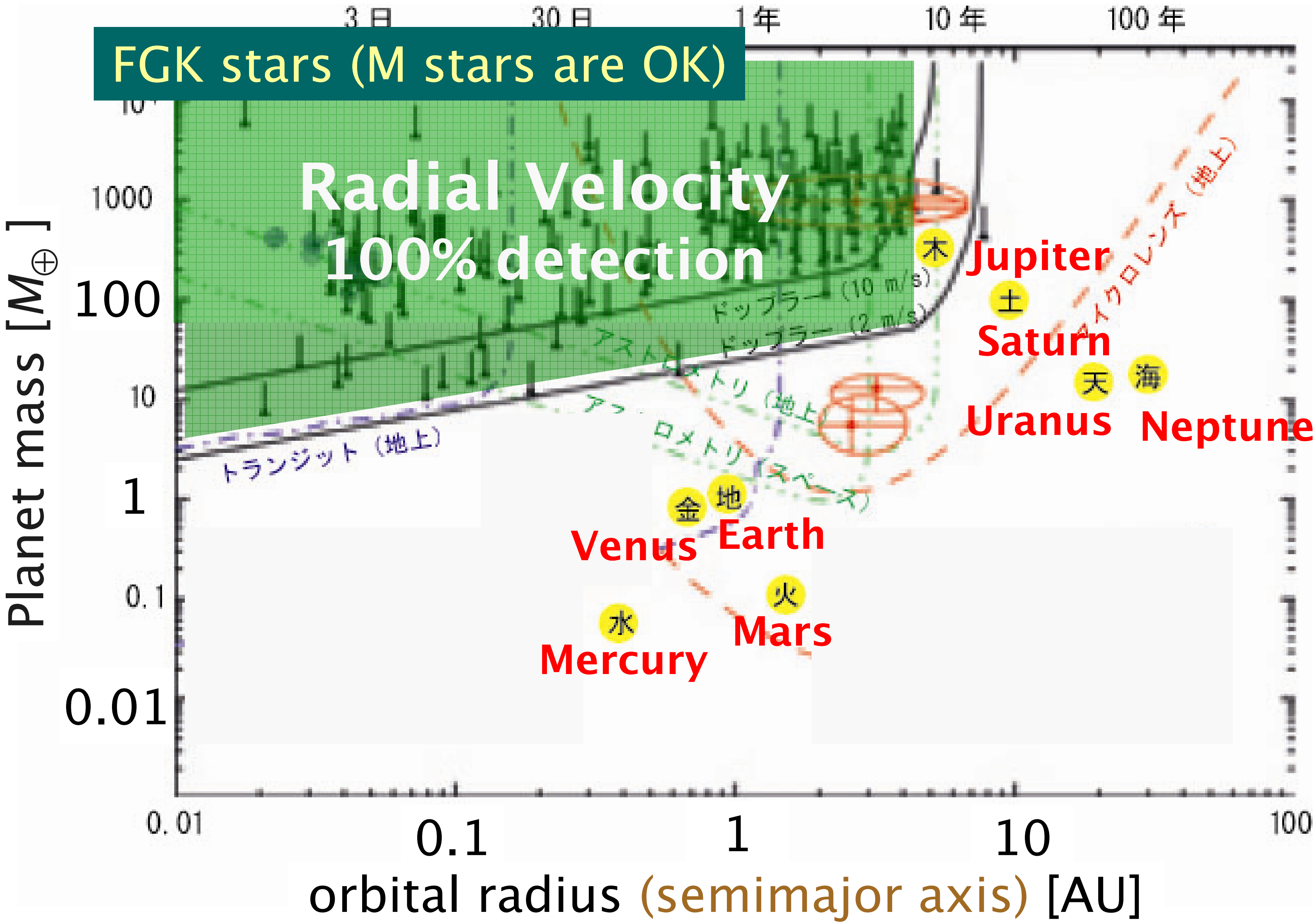


- **direct imaging** (直接撮像)
  - a few planets
  - large *M* & *r*, young stars

Observational bias



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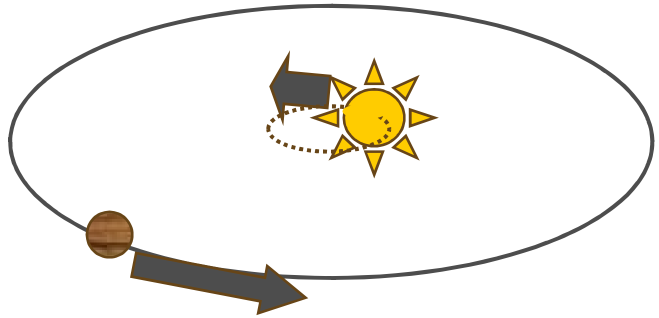

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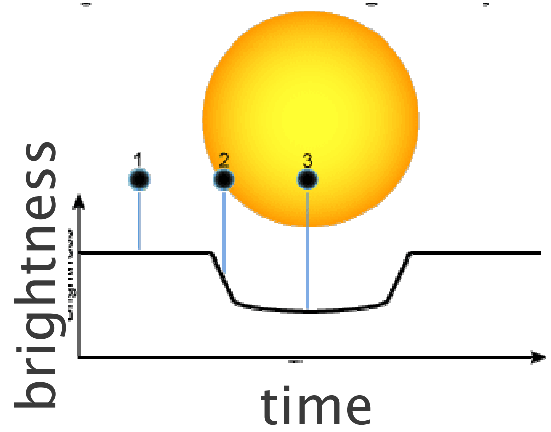

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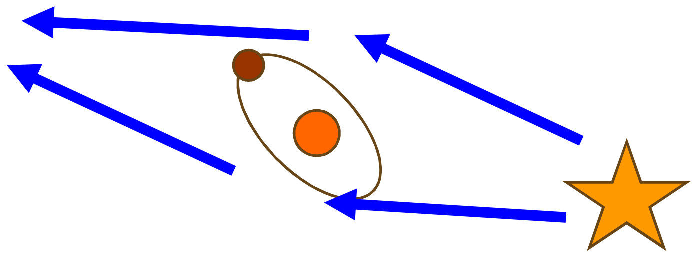

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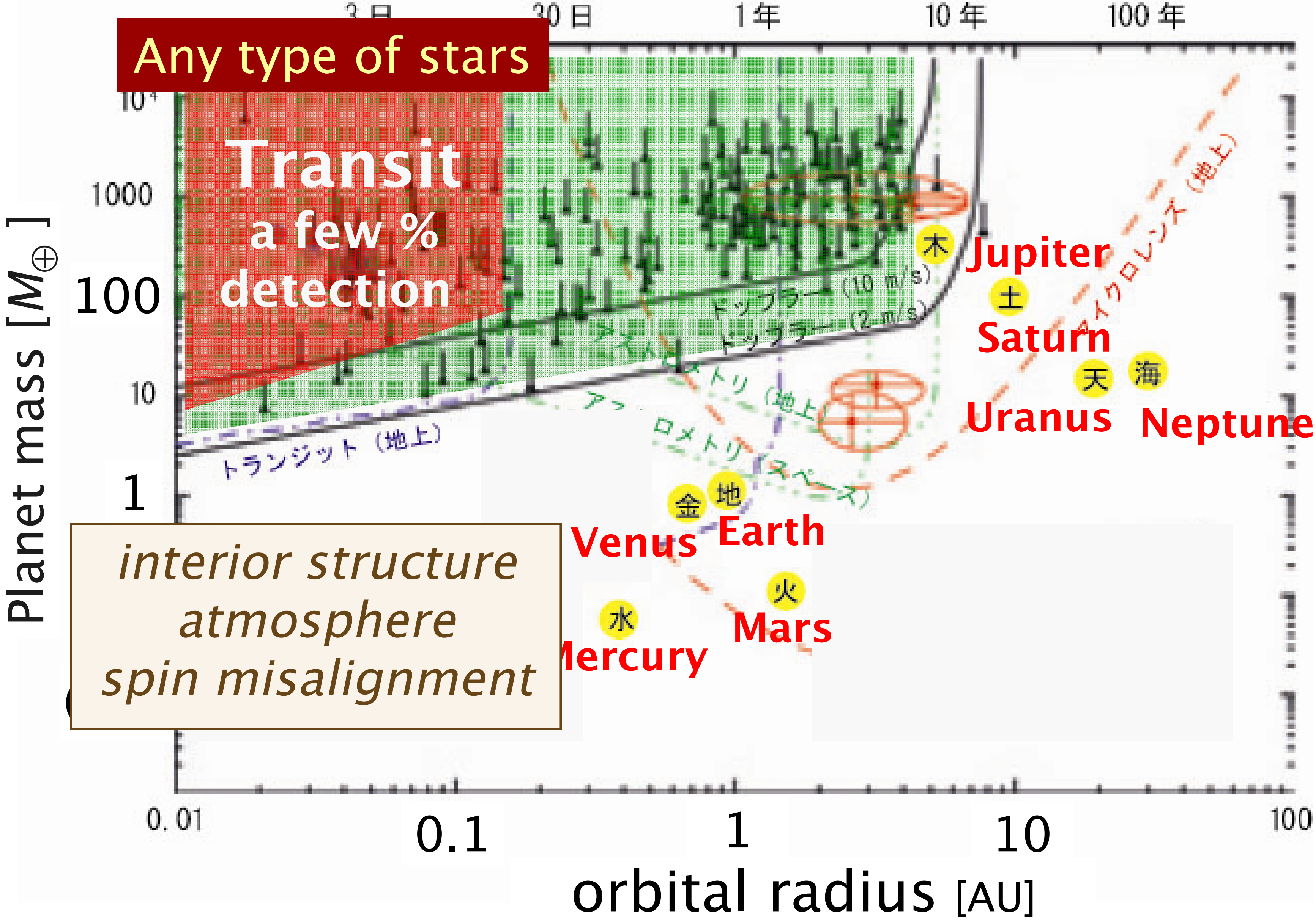

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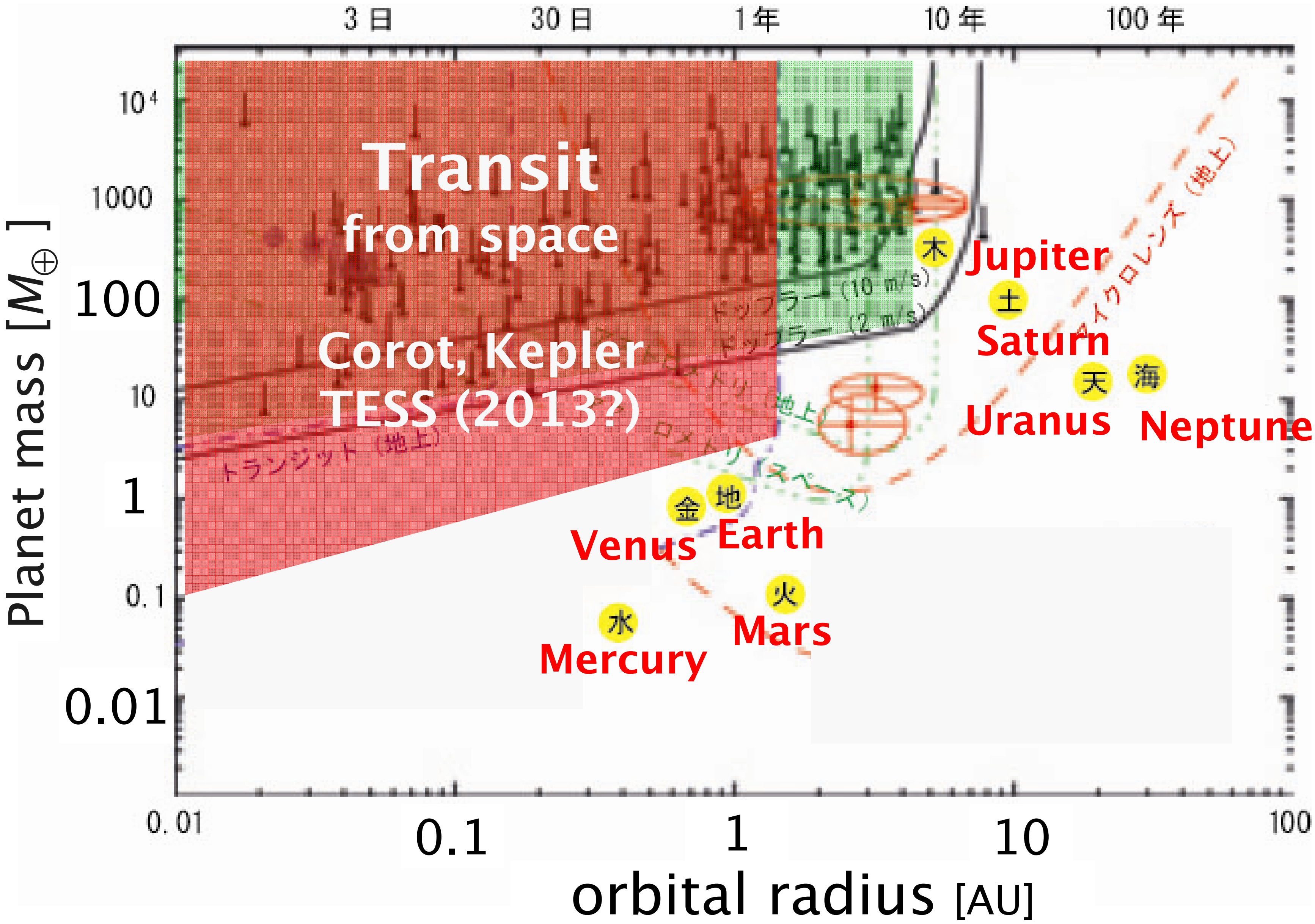

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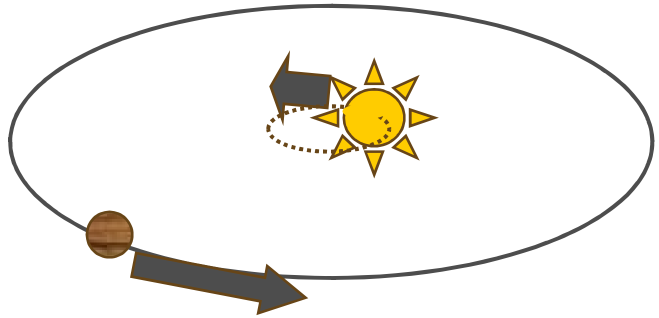

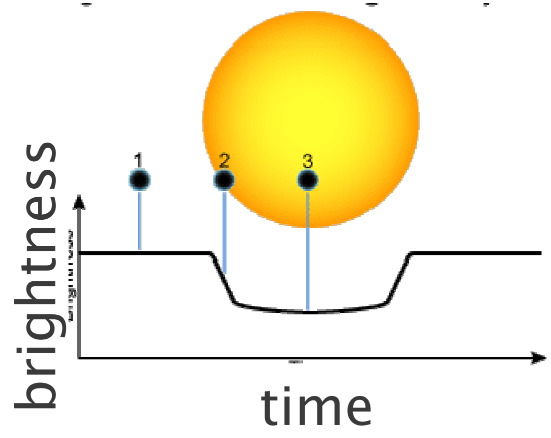

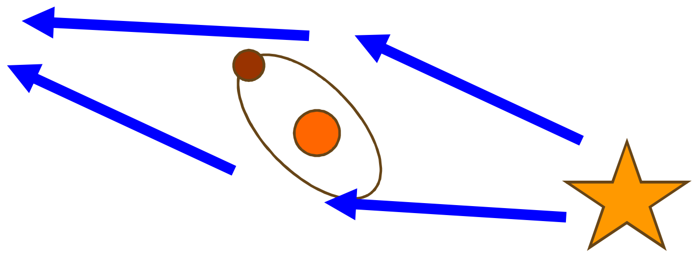

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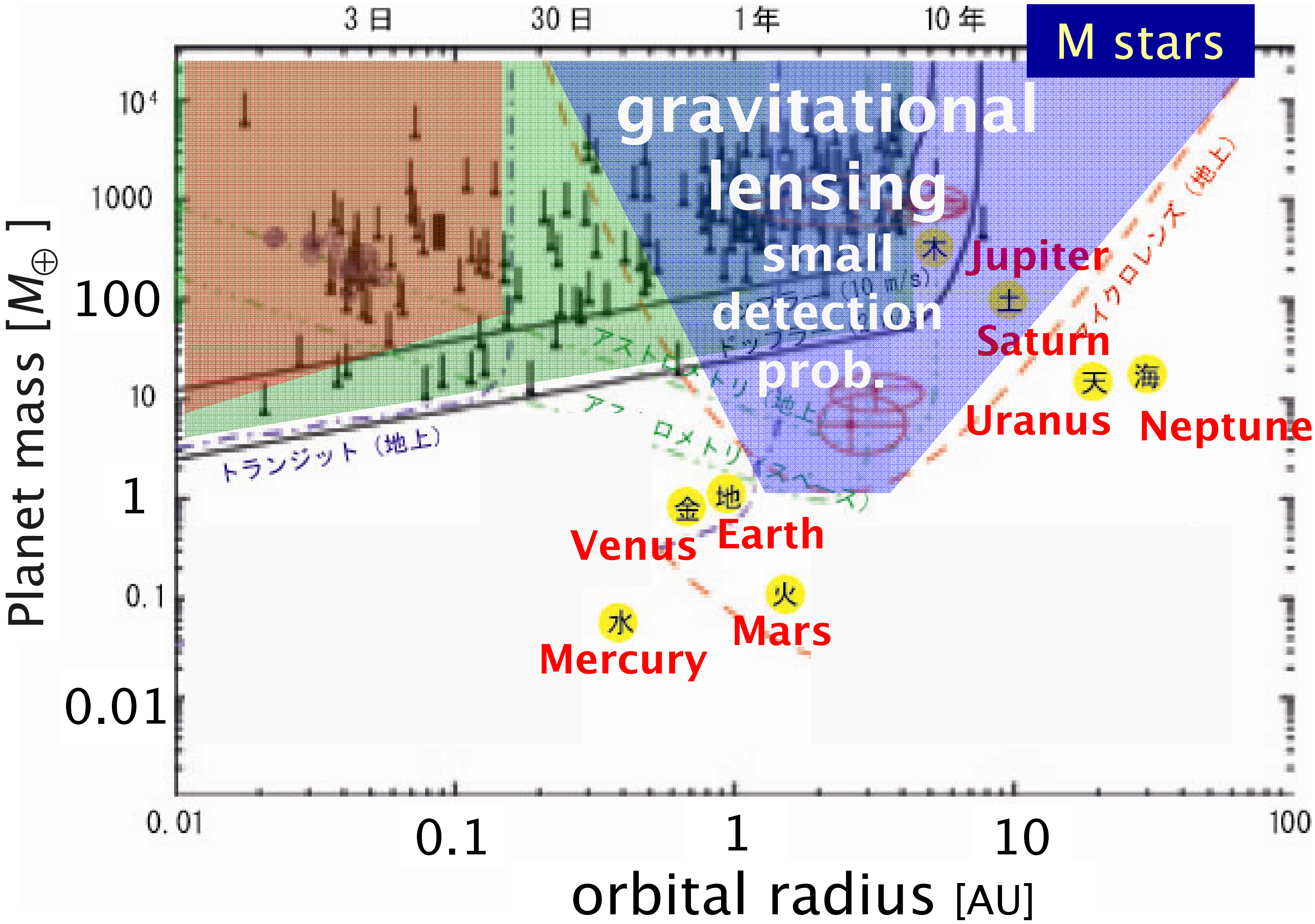

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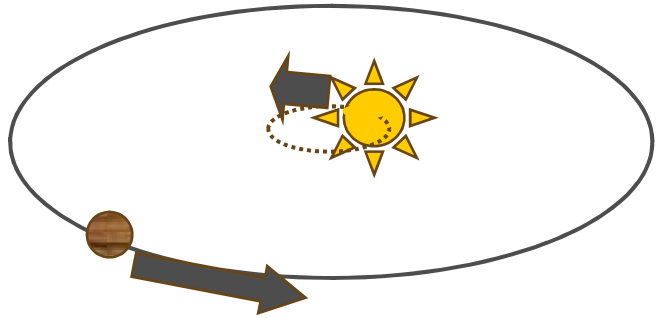

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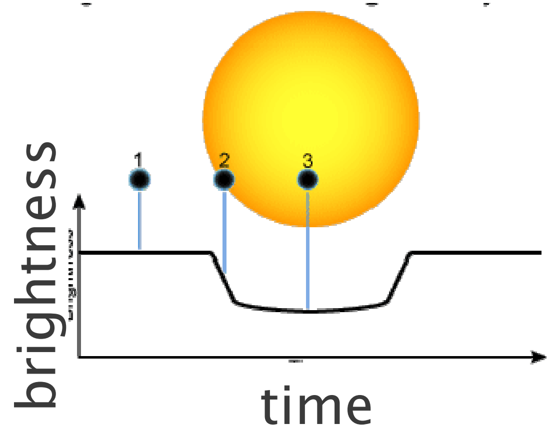

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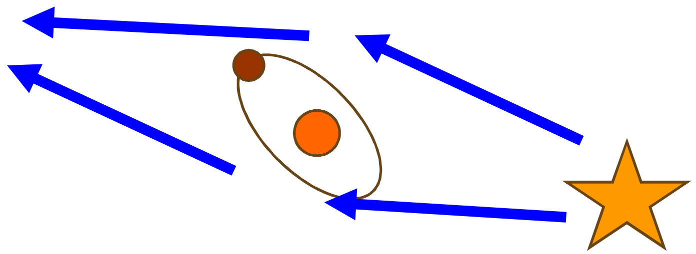

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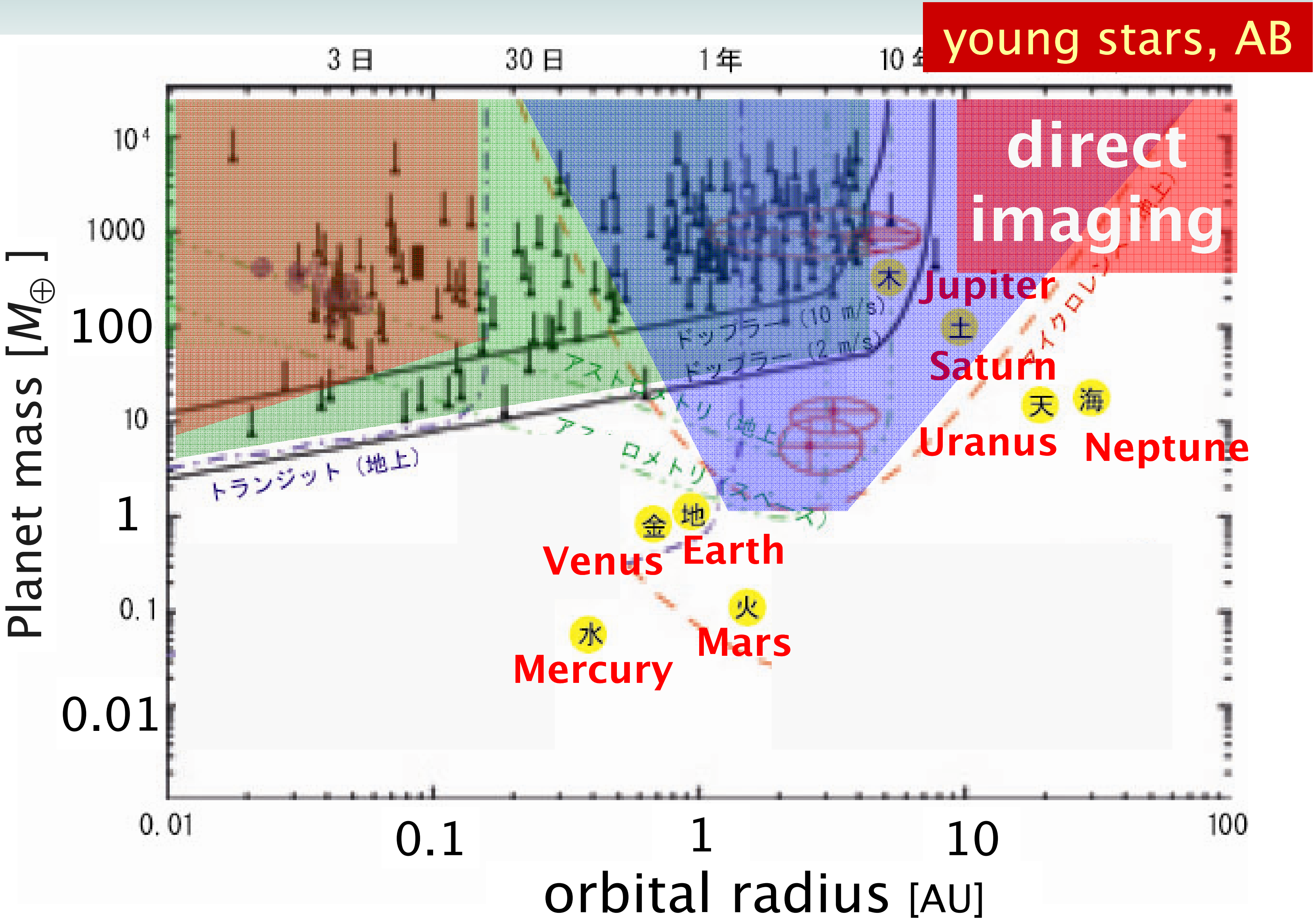
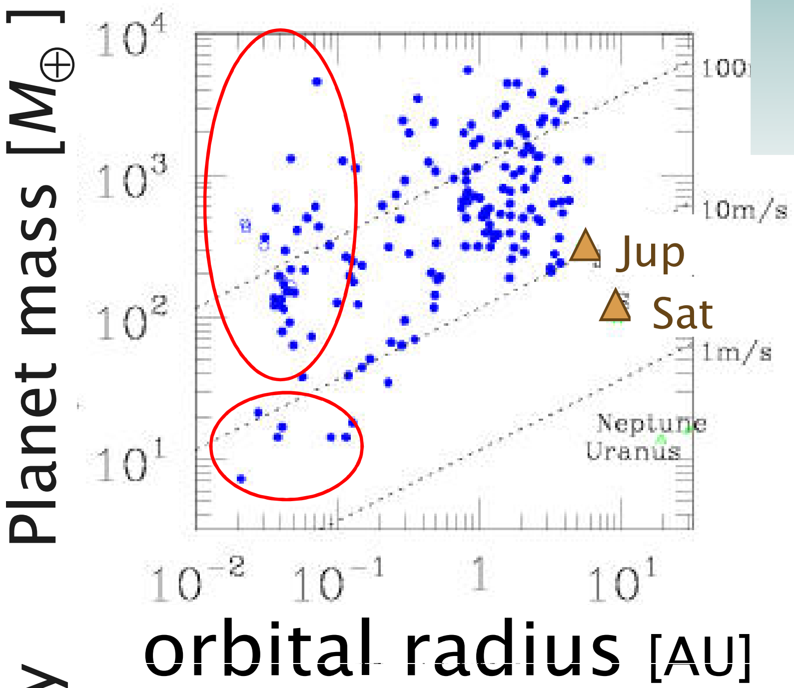
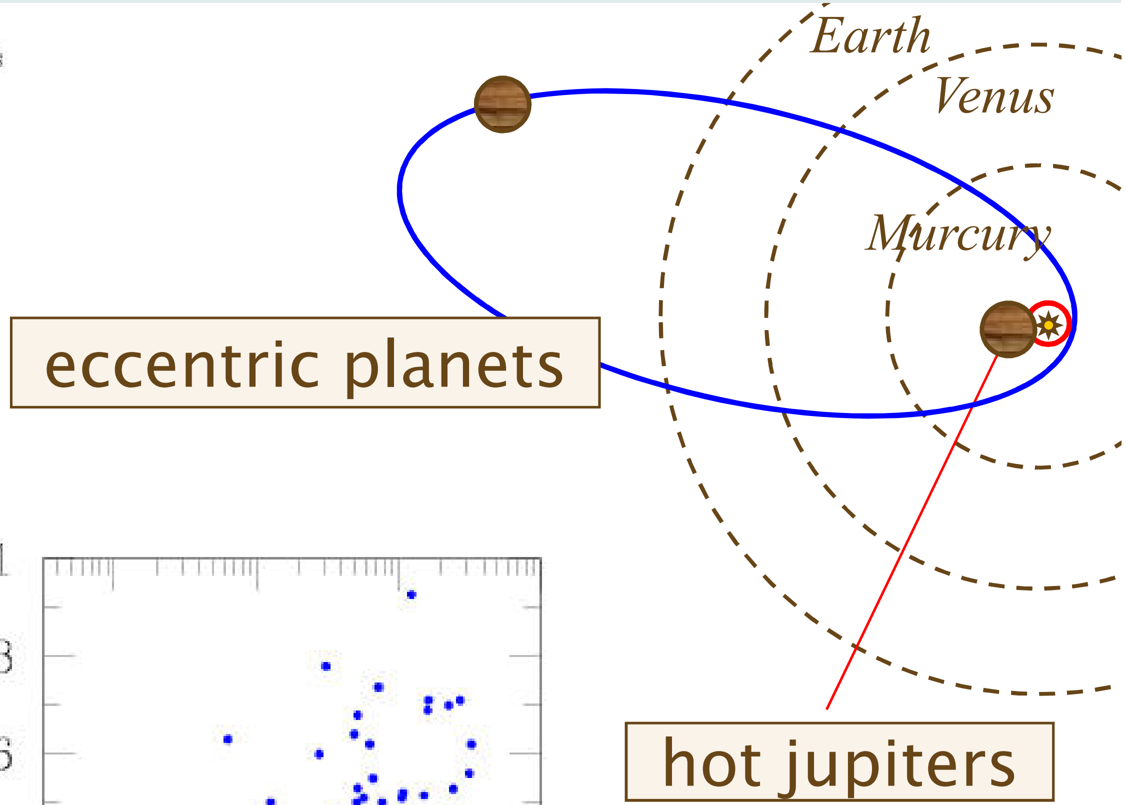
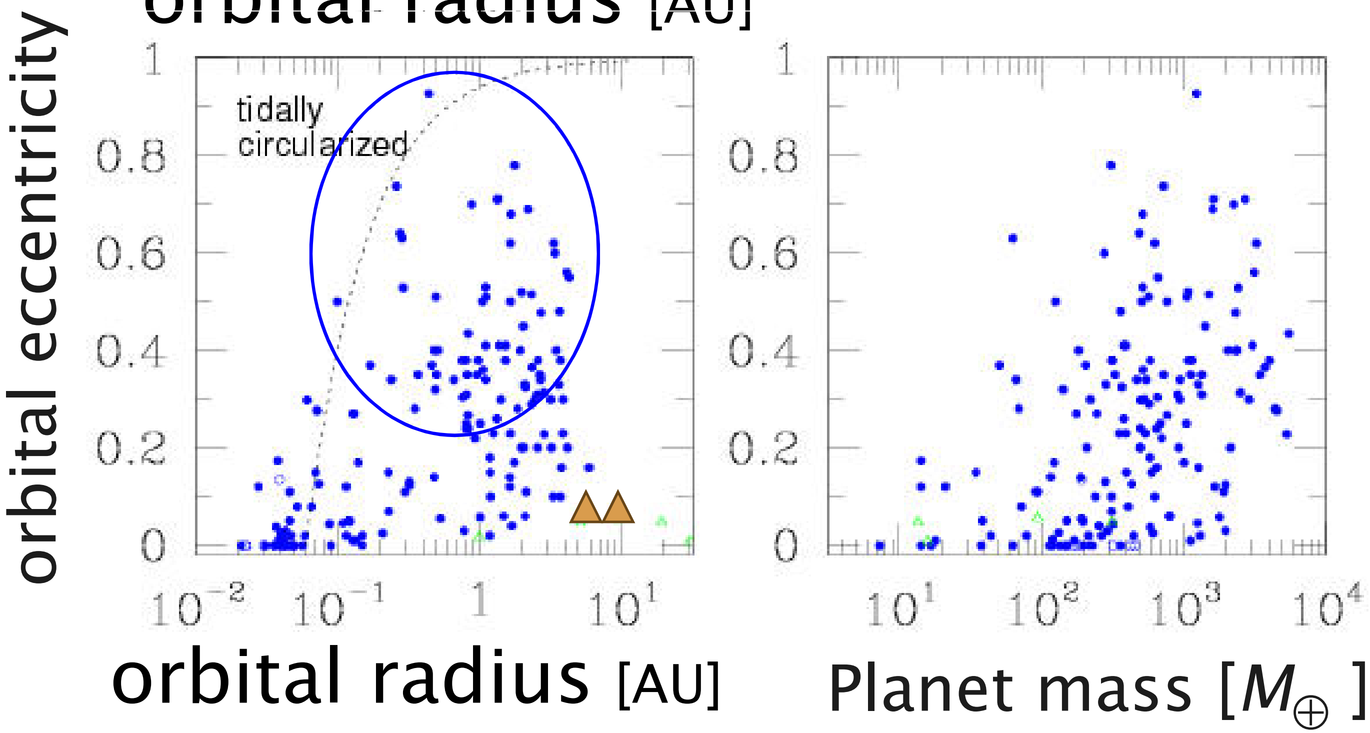


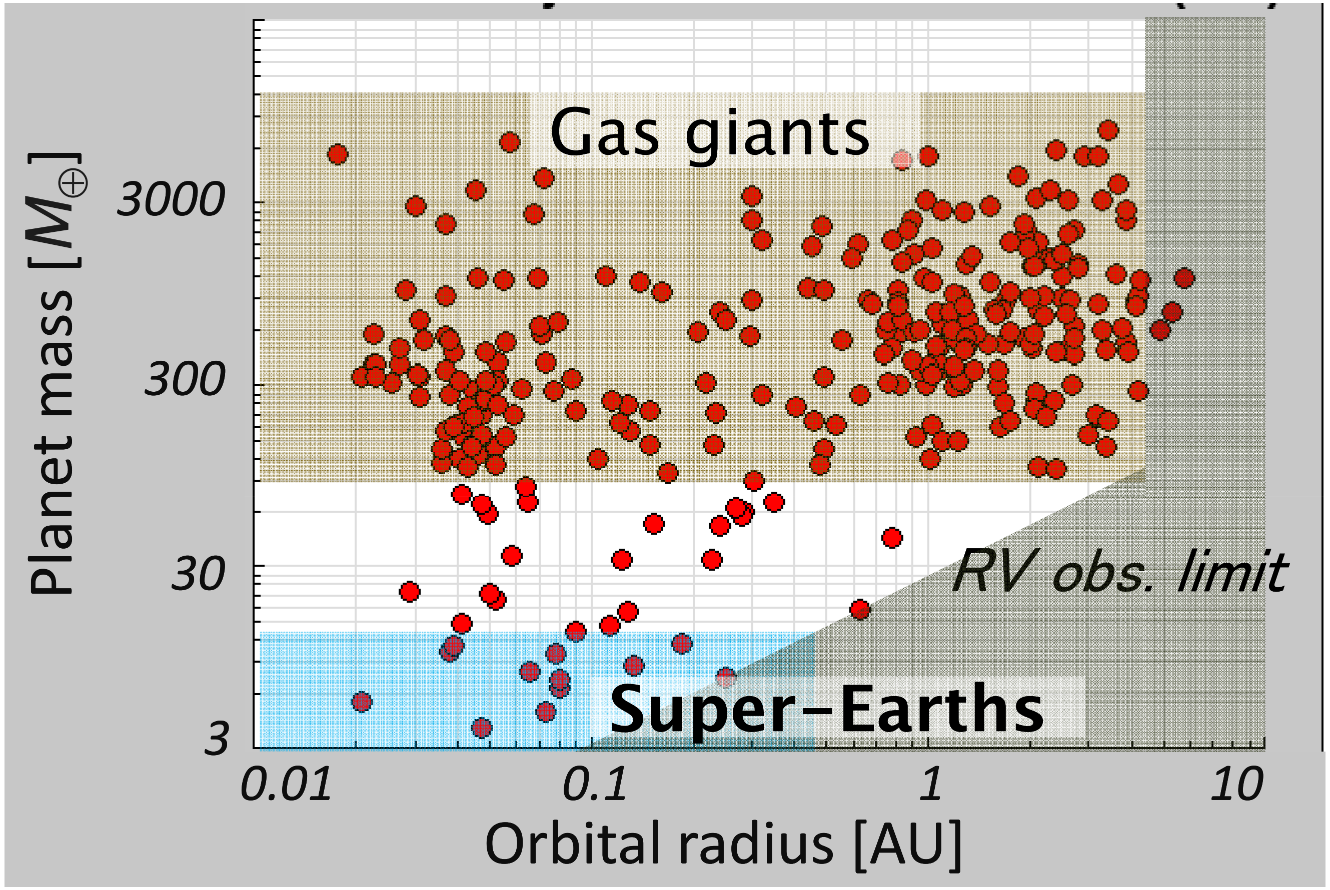
Discovered planets ubiquity(>5%)+diversity





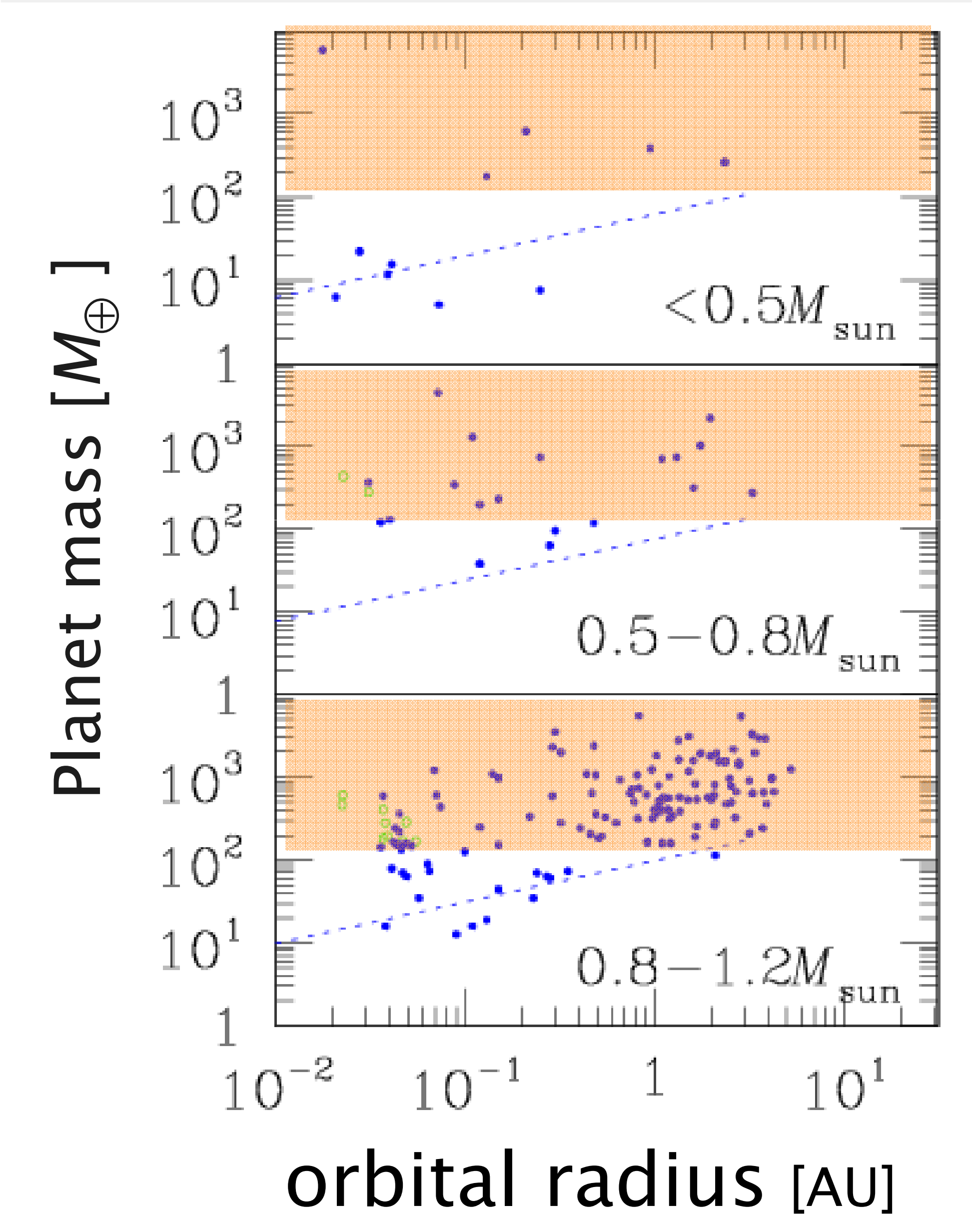


Super-Earths



- Close-in super-Earths: ~30 % of FGK dwarfs
  ←→ close-in gas giants (hot jupiters): ~ a few %
  gas giants: ~10 %

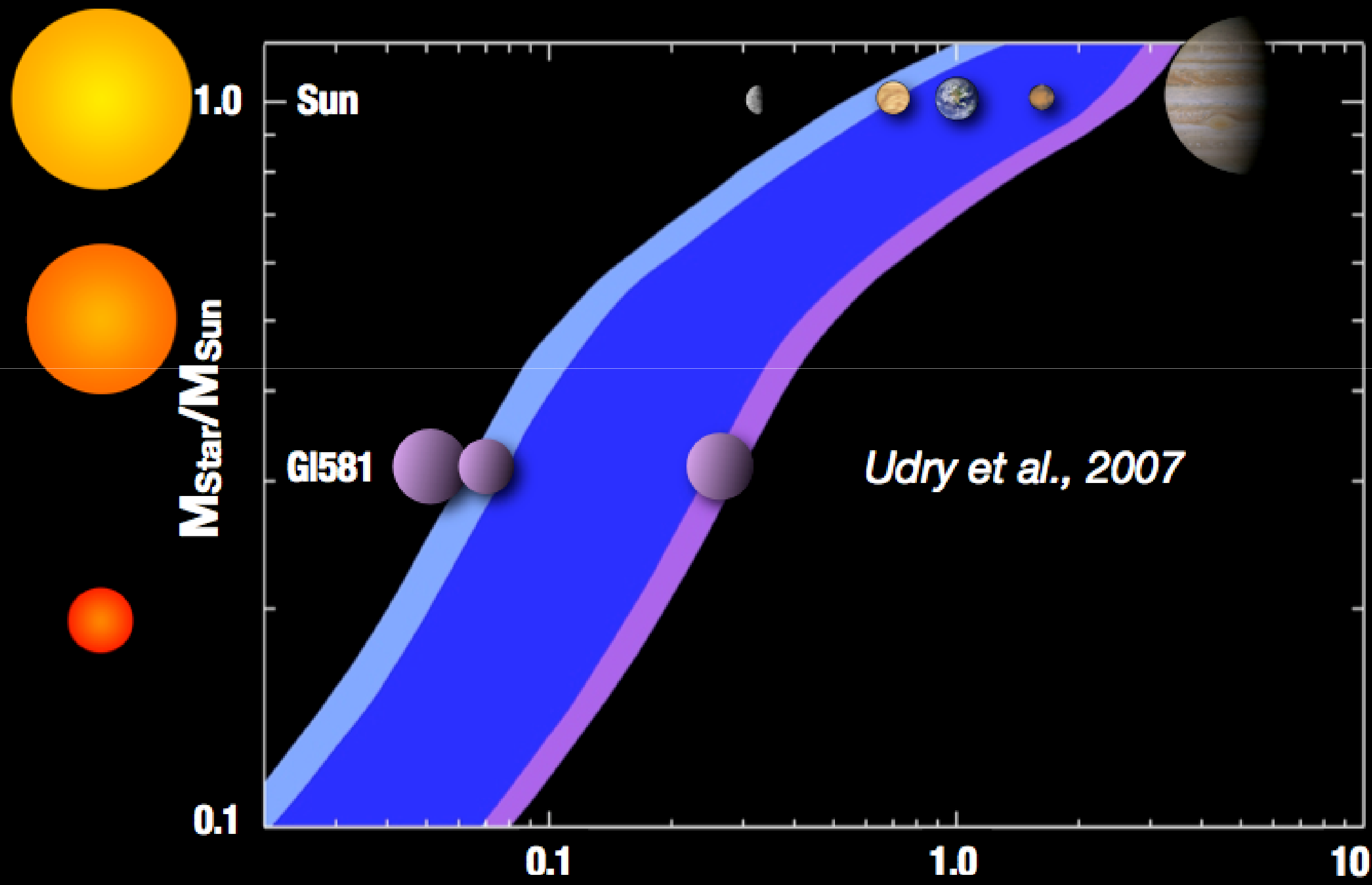
stellar-mass dependence



M dwarfs

- mass-distr. of planets
  - jupiters: fewer
  - super-Earths: more abundant
- habitable planets
  - small *r* (~0.1AU)
  - → super-Earths: detectable
  - tidal locking
  - strong UV, X-ray

habitable zone



orbital radius [AU]

Selsis et al., 2007

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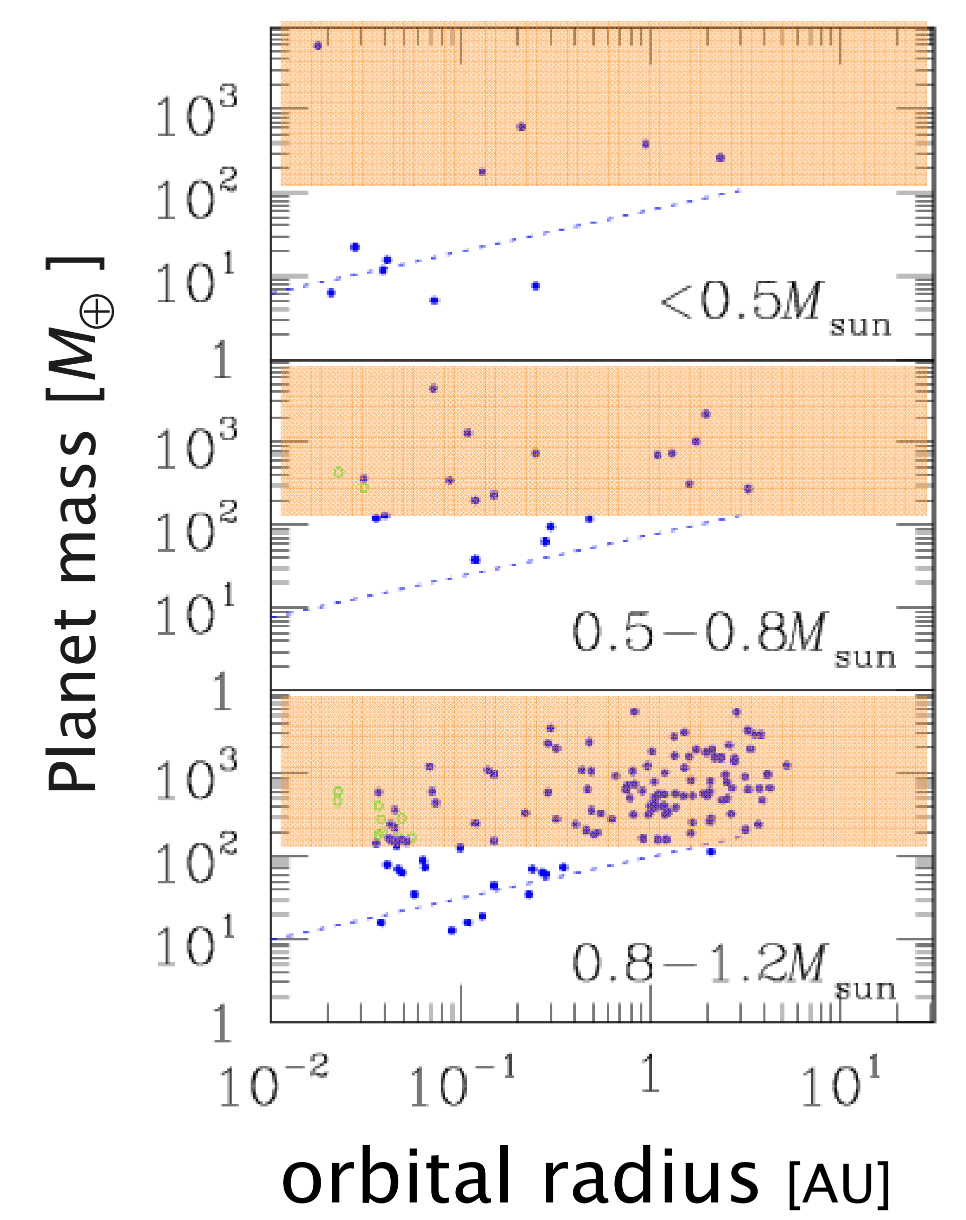

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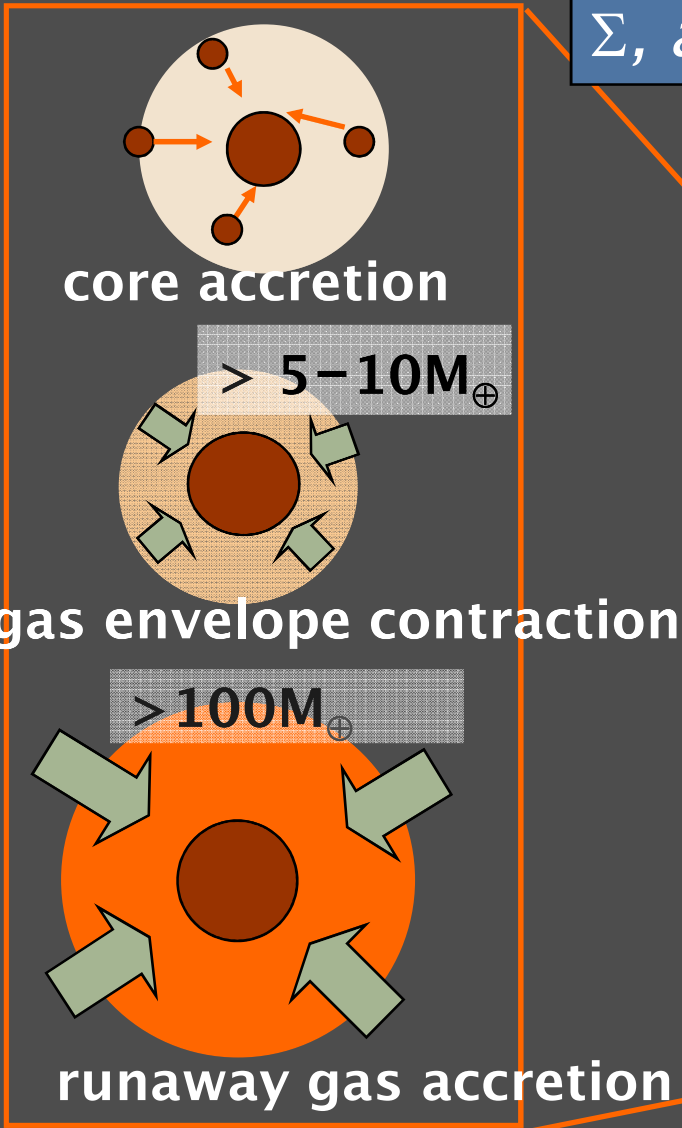
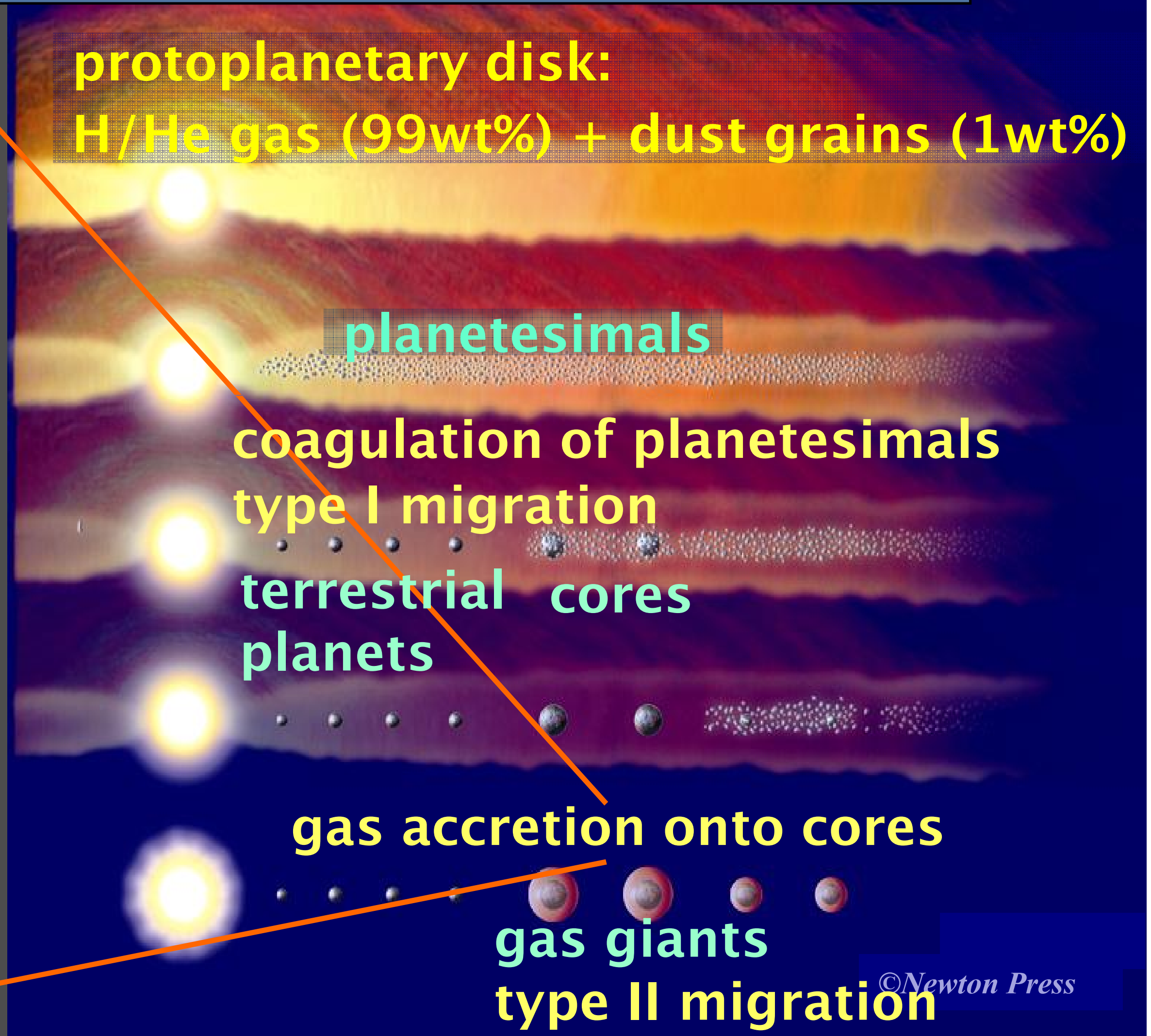
theory

Population synthesis model

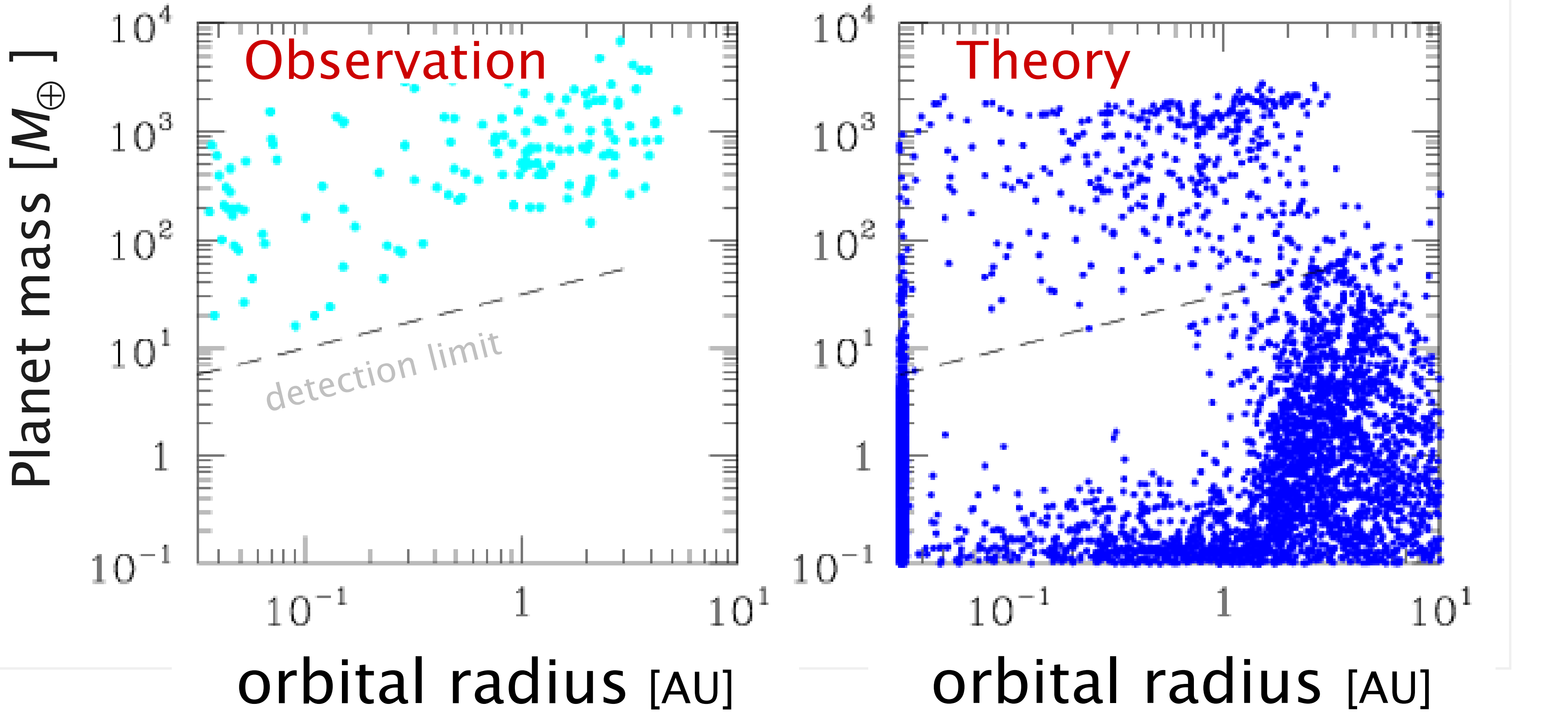
Ida & Lin (2004a,b,2005,2008a,b)

Σ, a_{ini} =(integration on 10^9y)$\Rightarrow$ M_p, a_{final}





Monte Carlo calculation (1000 disks)

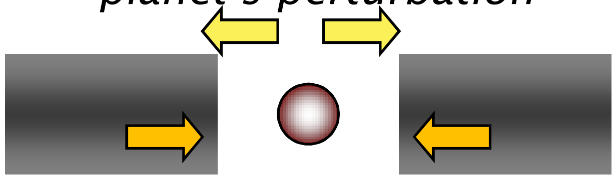


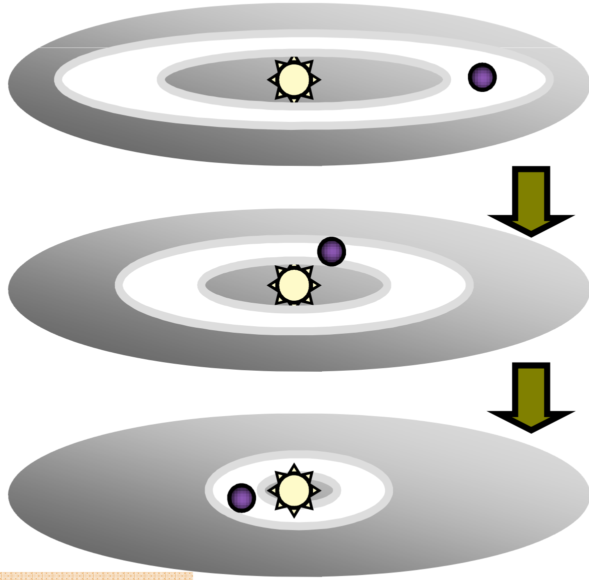
Solar-type stars

Origin of hot jupiters: migration

Lin et al. (1996)

- If a giant planet forms at > a few AU well before disk depletion
- The planet opens up a gap
  - planet's perturbation > viscous diffusion $M_p >\approx 10-10^2 M_\oplus$
- The planet migrates inward with disk accretion
- The planet stops near disk inner edge





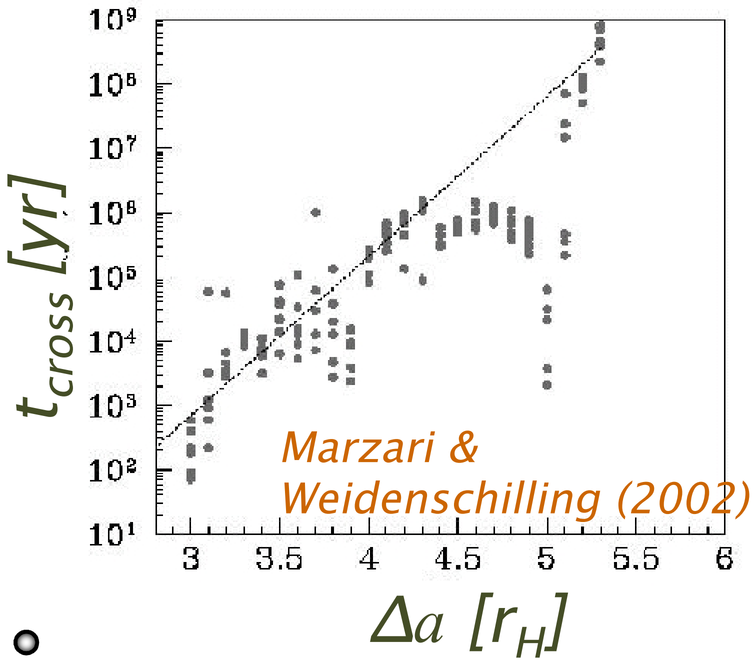
Jupiter & Saturn: formed in a dissipating disk
→ no time to migrate

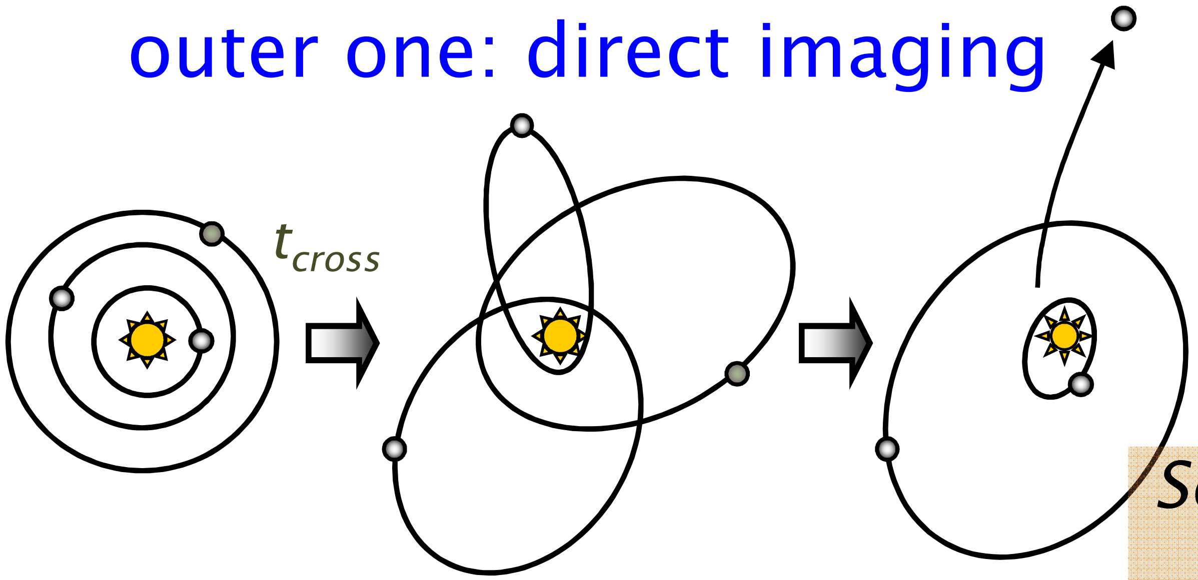
Origin of eccentric planets: jumping jupiter

Weidenschilling & Marzari (1996), Lin & Ida(1997),...

- If more than 3 giant planets form on circular orbits
- Orbit crossing starts on t_{cross}
- One is ejected. The others remain in stable eccentric orbits.

→ inner one: radial velocity
outer one: direct imaging



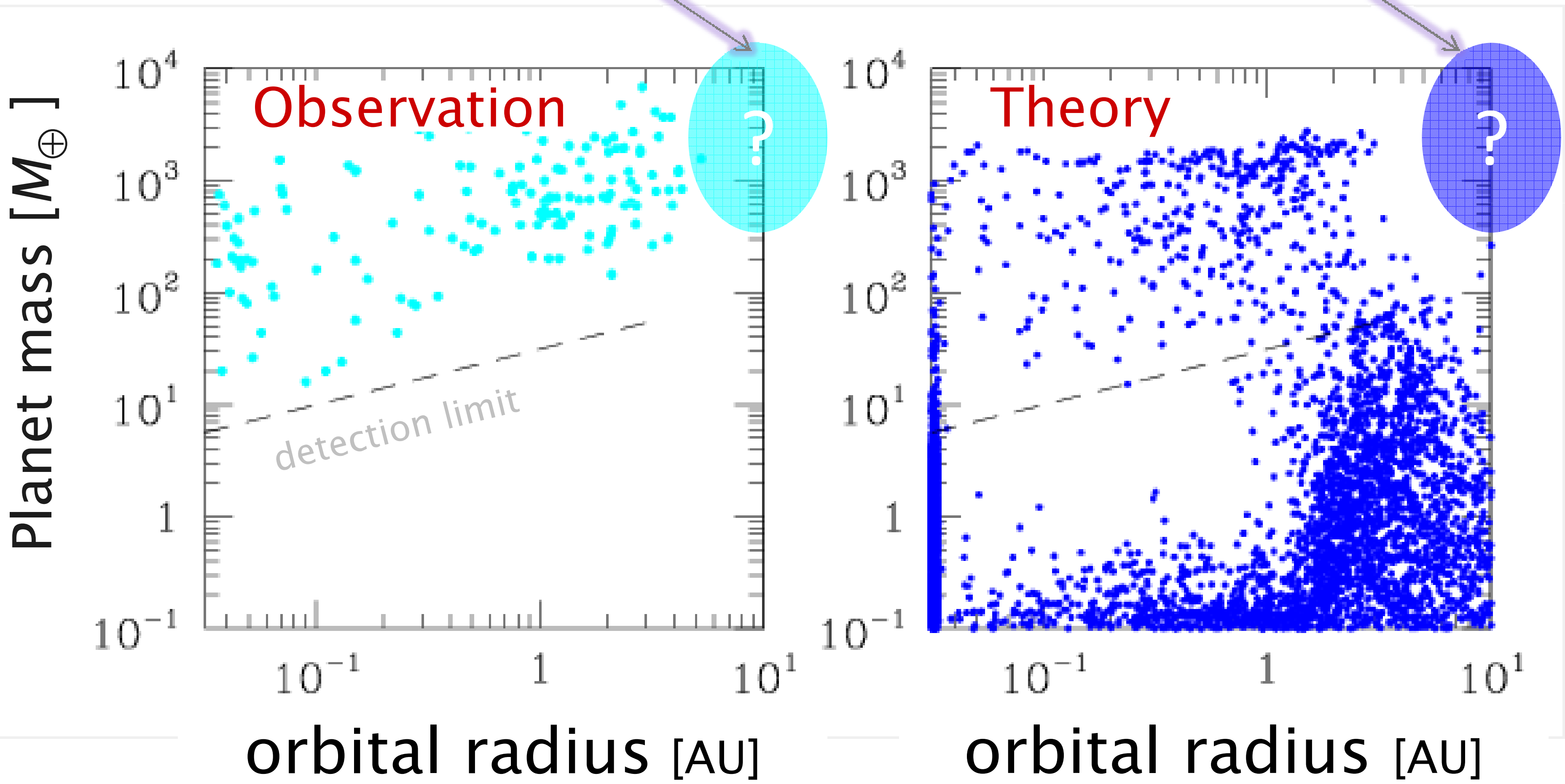


Solar system: 2 giants → stable

Monte Carlo calculation
– migration of giant planets: included
– scattering between giants: neglected

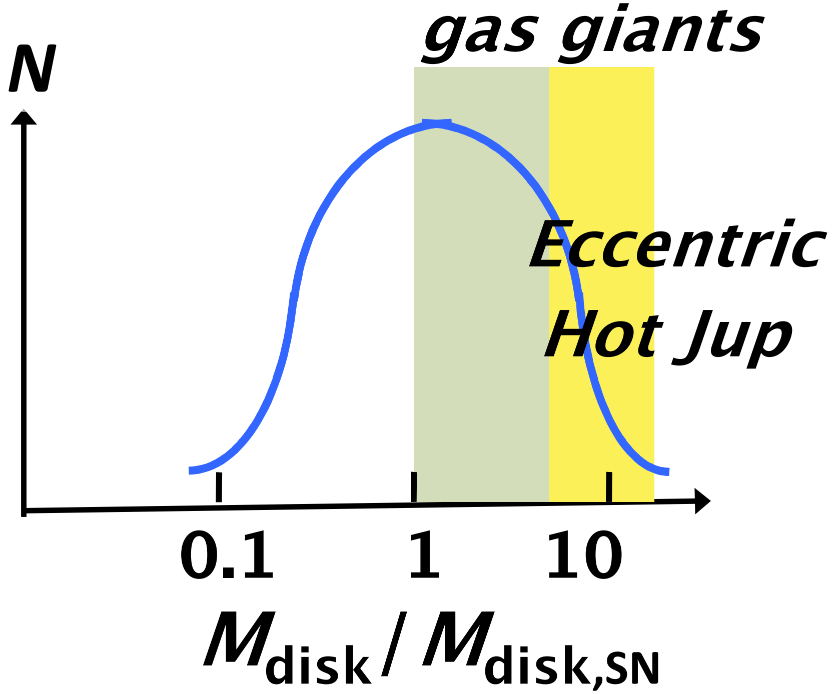
On-going direct imaging survey

working on theoretical modeling



Diversity of planetary systems ← disk mass

- observation: mass of protoplanetary disks has two orders of dispersion

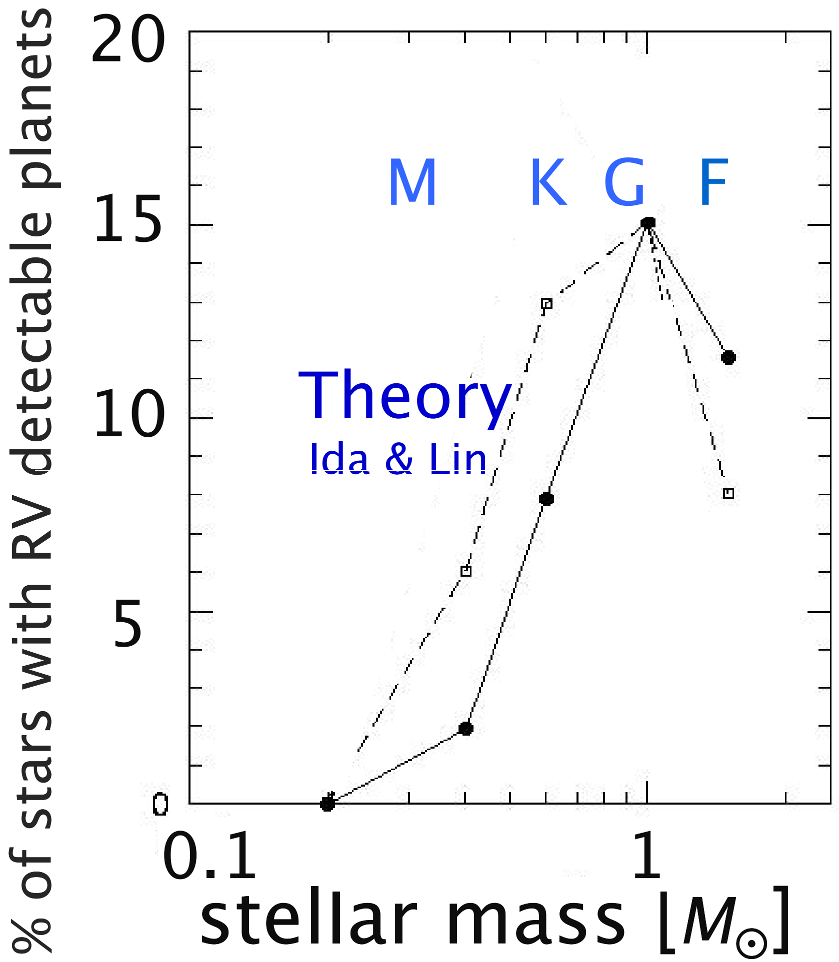


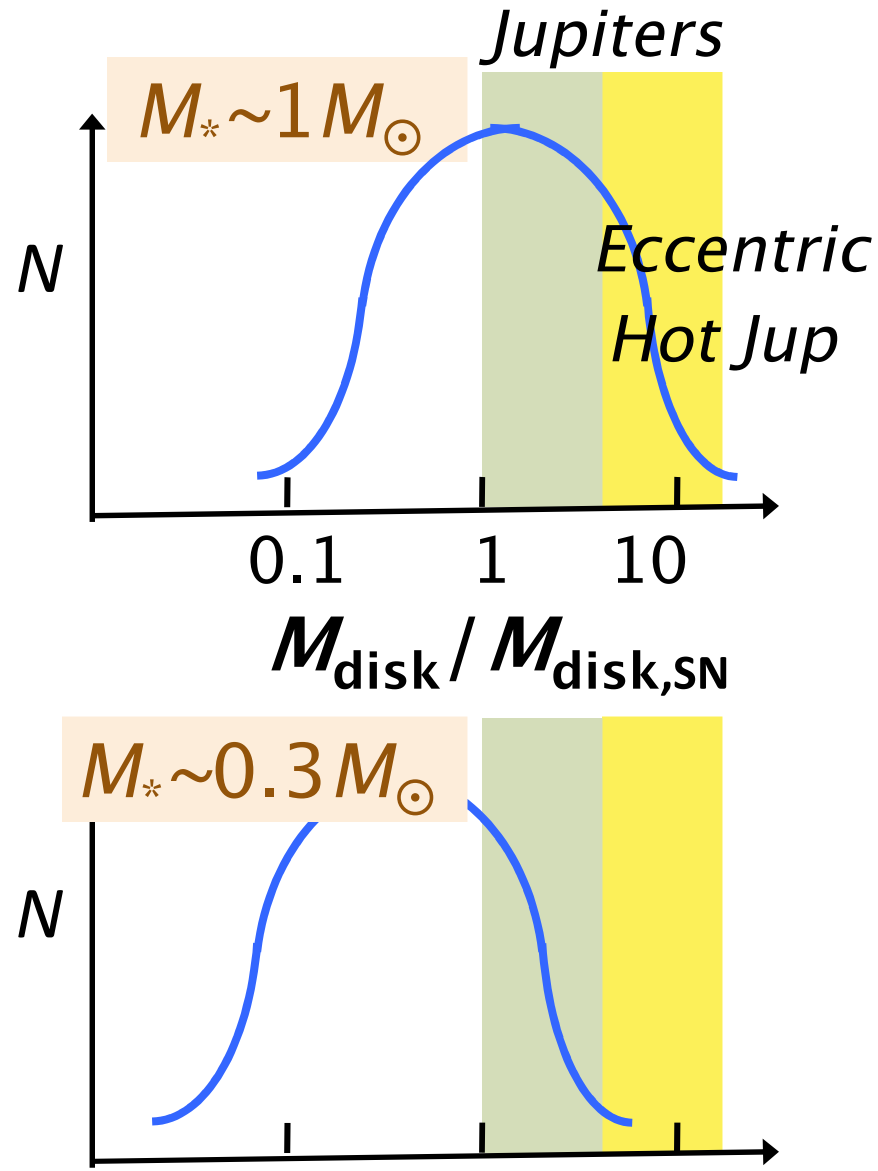
Gas giants ← cores with $>5–10 M_\oplus$ in a few Mrs

- $M_{disk} > M_{disk,SN}$ (solar nebula) → gas giants form
- $M_{disk} >$ a few x $M_{disk,SN}$: easily detected planets?
  - Hot Jupiters
  - Eccentric planets

Super-Earths, habitable planets
→ less severe threshold
→ more abundant

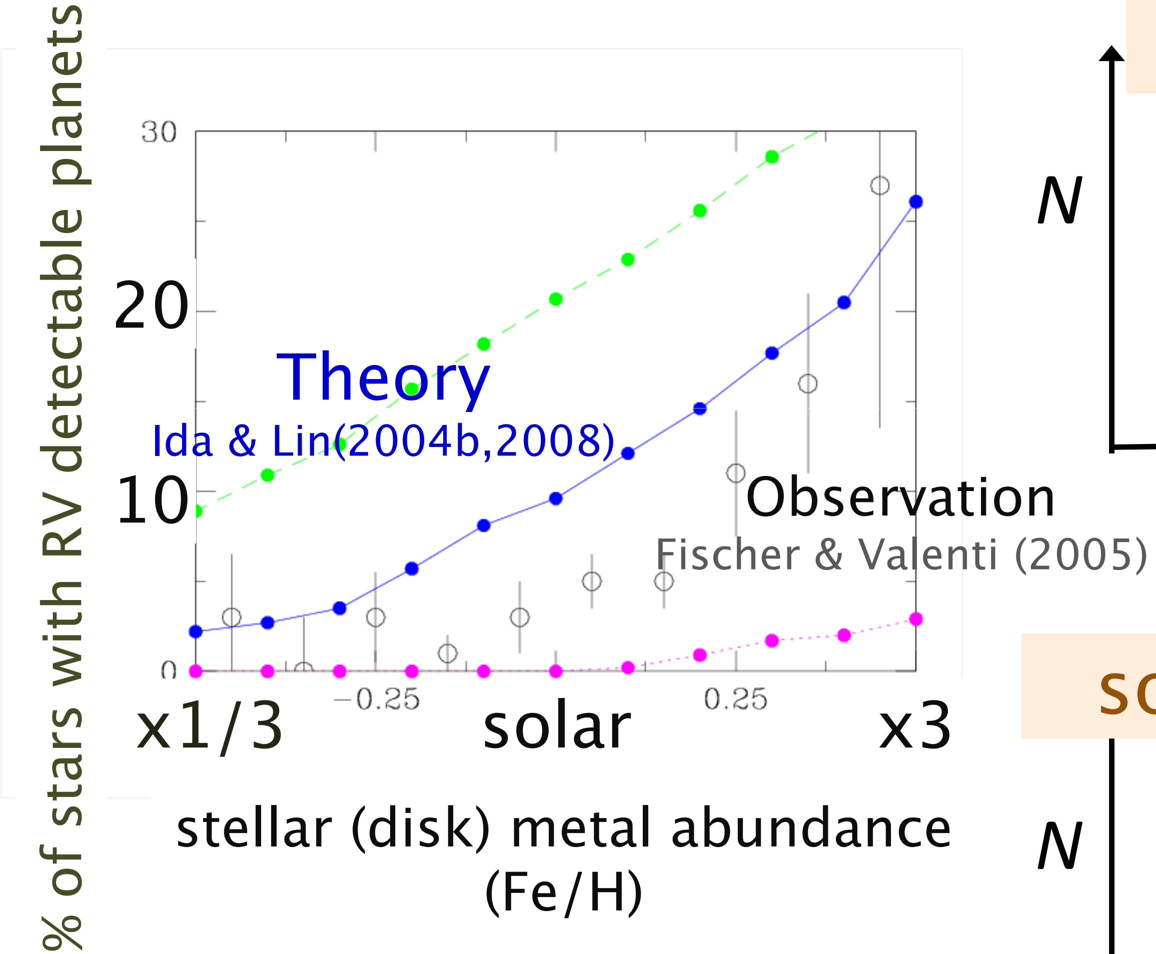
Stellar mass dependence

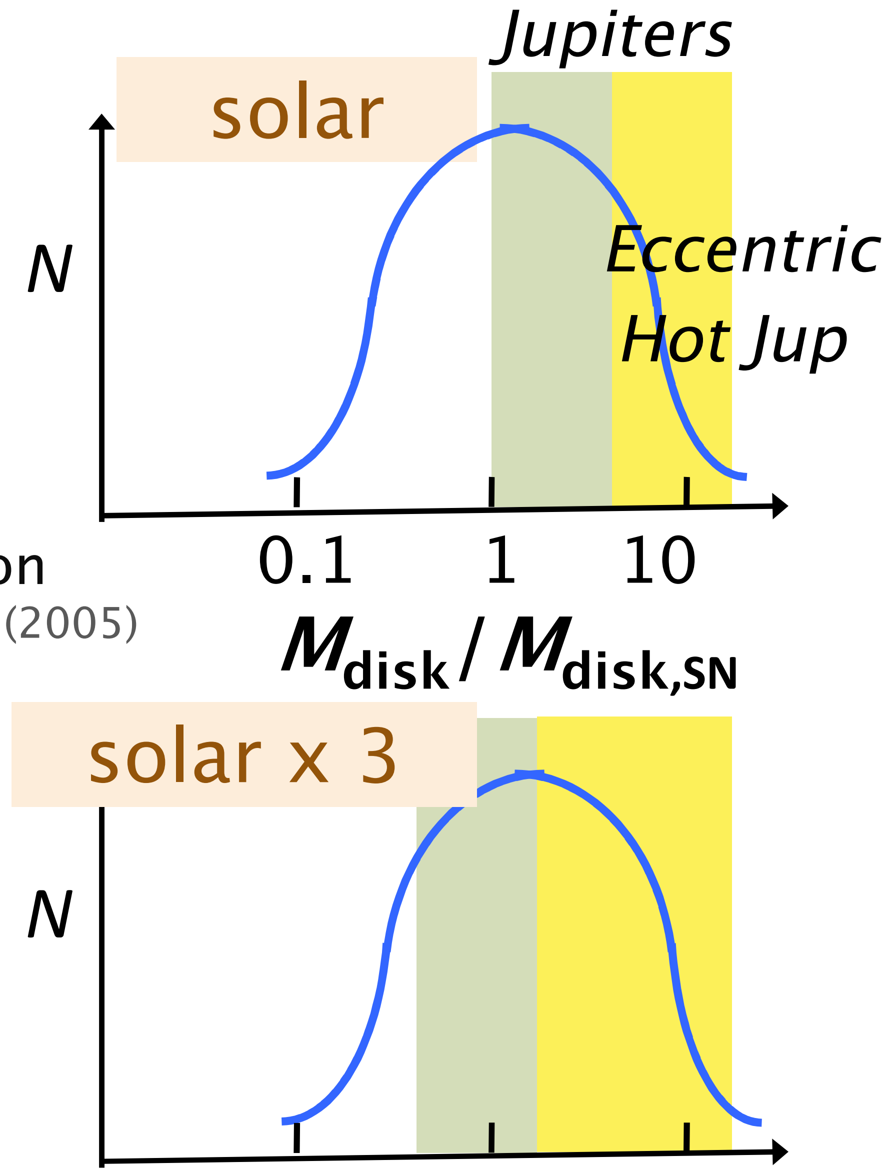




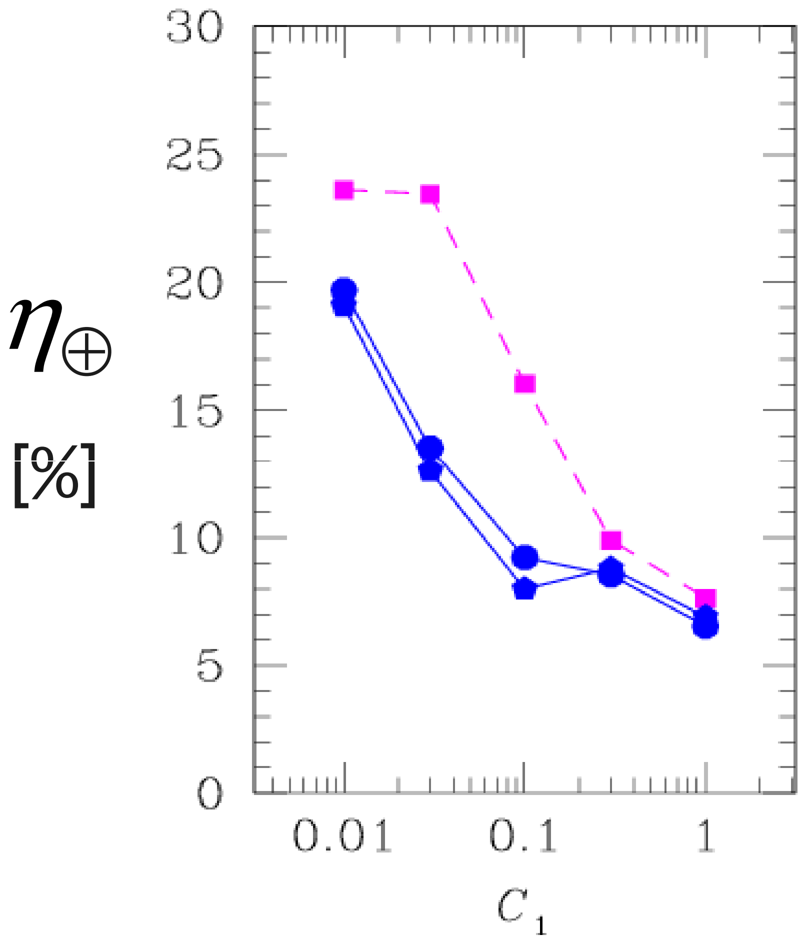
←→ Radial Velocity, microlensing surveys

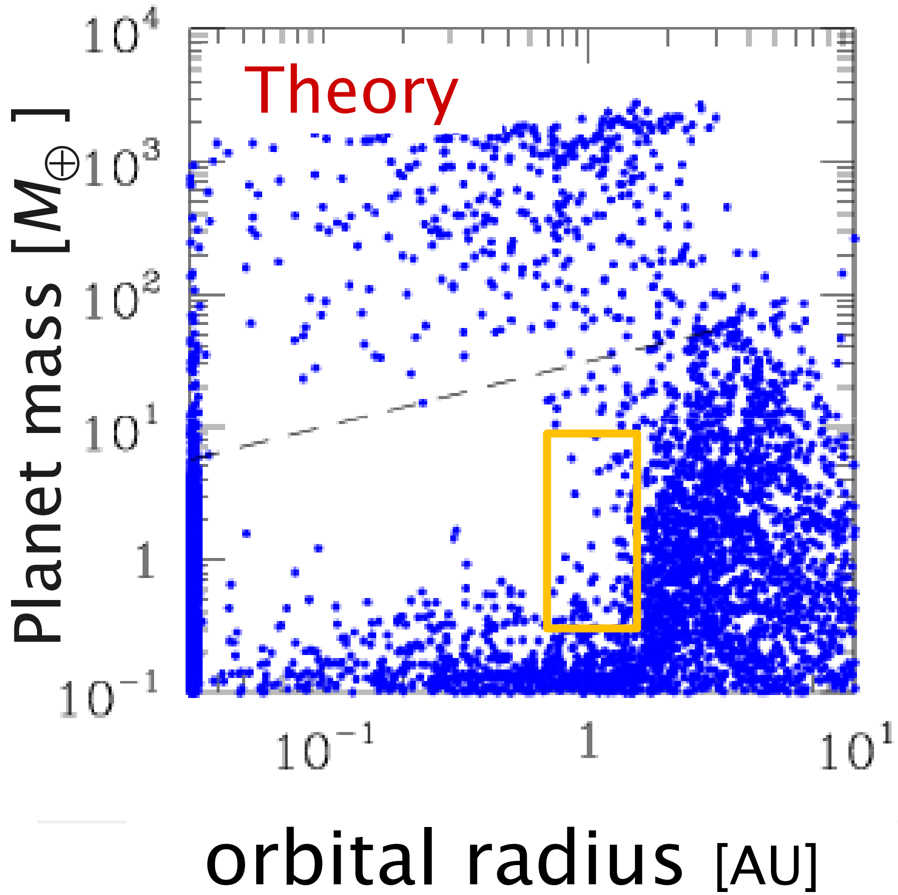
Stellar metallicity dependence





Predicted fraction ($\eta_\oplus$) of solar-type stars having planets with ocean





The planets having ocean may be common

$\eta_\oplus$~O(10)%

Summary

- extrasolar gas giants
  - observation
    - diversity in orbits
    - stellar mass/metallicity dependence
  - theory: disk mass plays a key role
- next challenges (both observation and theory)
  - gas giants
    - around $> 2M_\odot$ or $< 0.2M_\odot$ stars
    - outer regions
  - super-Earths
    - habitable planets are observable around M dwarfs