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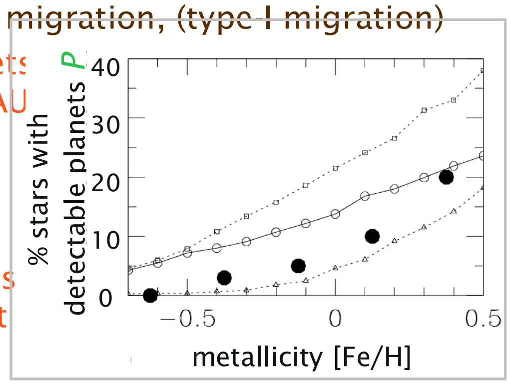
Planetary Mass-Period Distribution

Shigeru Ida (Tokyo Inst. of Tech.)

collaborator: Doug Lin (UCO/Lick)

- **synthesized model for planet formation** *Ida & Lin (ApJ, in press)*
  - core accretion from planetesimals, gas accretion, gap formation, type-II migration, (type I migration)
  - predict deficit of planets of 10-100$M_\oplus$ inside 3AU ("planet desert")
- **metallicity dependence** *Ida & Lin (submitted)*
  - predict that P increases with metallicity of host stars



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Motivation

- discovered extrasolar planets > ~120
  - enough for statistical discussion
- theoretical model to predict **mass-period distribution** of extrasolar planets
  - ① explain observational data
    - ② e.g., ***metallicity dependence***
  - ③ test models for individual physical processes
  - predict future observation
    - e.g., ***"planet desert"***,

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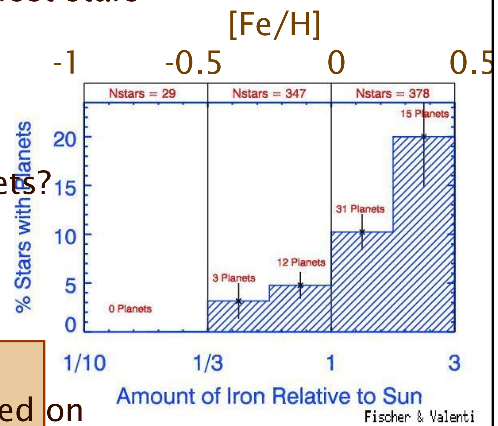
Metallicity dependence

observed frequency of extrasolar planets:
depends on metallicity of host stars
(Fischer & Valenti)

(1) pollution by infall of planets?
(2) high formation efficiency
in metal-rich disks?



the possibility of (2),
with a theoretical model based on
core accretion scenario.

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Monte Carlo simulation

Ida & Lin (2004a, ApJ, in press)
Ida & Lin (2004b, submitted)

- initial conditions
  - **semimajor axis** **a**
  - **gas surface density** **Σgas**
  - **dust surface density** **Σdust**

- integrate planet formation & migration until **10^9 yr**
  - **Σgas $\propto$ exp(-t/τ_{dep})**
  - **Σdust : constant**

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Model: planetesimal accretion

(confirmed by N-body simulations)

- **runaway / oligarchic growth**
  - rate: two body approx. *(Safronov 1969)* $v \leftarrow$ gas drag
  - **isolation**
    - $\Delta a = 10\, r_H$ $(2\pi a\, \Delta a \Sigma_{dust} = M)$ *(Kokubo & Ida 1998)*
    - $\Delta a \sim a$ $(\pi a^2 \Sigma_{dust} = M)$ effect of **type-I migration** *(e.g., Rice & Armitage 2003)*
- **post-oligarchy accretion**
  - orbit crossing of isolated bodies: < 0.1%of min mass nebula (disk-planet inter[a…]
  - rate: two body approx. $v = v_{esc}$
  - isolation: $\Delta a = v_{esc}/\Omega$ $(2\pi a\, \Delta a \Sigma_{dust} = M)$
- **scattering limit** $(v_{esc} < 3 v_{Kep})$
  - limit mass in outer region (Thommes et al.

does not affect gas giants distr.

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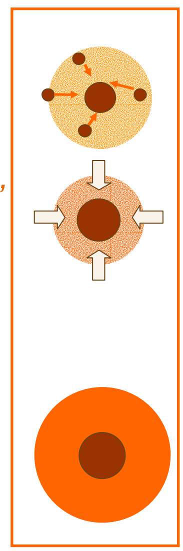
Model: gas accretion & type–II migration

- **gas accretion onto the core**
  - critical core mass $M_{crit} \approx 10 \left(\frac{dM_{core}/dt}{10^{-6} M_\oplus / y} \right)^{1/4} M_\oplus$ *(Ikoma et al. 2000)*
  - accretion rate
    $\tau_{KH} \approx 10^9 \, (M/M_\oplus)^{-3}$ yr *(Pollack et al. 1996, Ikoma et al. 2000)*
  - **type-II migration**
    - *start: planetary torque > viscous torque*
    - *rate:* $\tau_{mig} \approx 10^6 f_{gas}^{-1} \left(\frac{M}{M_J}\right) \left(\frac{\alpha}{10^{-4}}\right)^{-1} \left(\frac{a}{1\text{AU}}\right)^{1/2}$ yr
    - *halt:* a=0.04AU
  - **termination** *(Lin & Papaloizou 1985,1993)*
    - *Hill radius > 1.5 x disk scale height*
    - *disk gas depletion* $(M > \pi a^2 \Sigma_{gas})$



Monte Carlo simulation: initial conditions

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- **surface density distribution**
  - *gas* $\Sigma_{\rm gas} = f_{\rm gas,0}\, e^{-t/\tau_{\rm dep}} \times 2400\, (a/1{\rm AU})^{-1.5}$ g/cm^2
  - *dust* $\Sigma_{\rm dust} = f_{\rm dust}\, f_{\rm ice} \times 10\, (a/1{\rm AU})^{-1.5}$ g/cm^2

    $f_{\rm dust} = f_{\rm gas,0} \approx 1$: min. mass solar nebula

  - $f_{\rm gas,0}$ = 0.1-30 Gaussian distribution in log scale
  - $f_{\rm dust} = f_{\rm gas,0} \times 10^{(Z_* - Z_\odot)}$

    Z_* : metallicity [Fe/H] of a host star ($=Z_{\rm disk}$)

- *a* - distribution : uniform in log scale
- disk lifetime: $\tau_{\rm dep}=10^6$-10^7 y
- stellar mass: M_* =0.7-1.4 $M_\odot$ → $a_{\rm ice}=2.7(M_*/M_\odot)^2$
- disk viscosity: $\alpha=3\times10^{-4}$

Results: $\Delta Z = Z_* - Z_\odot = 0$

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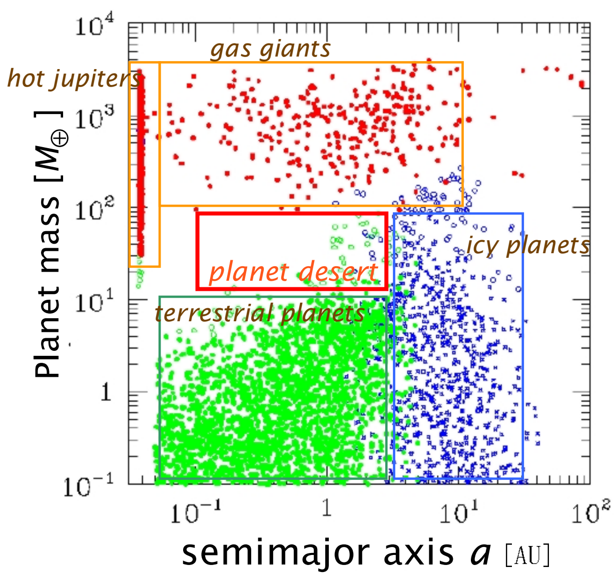
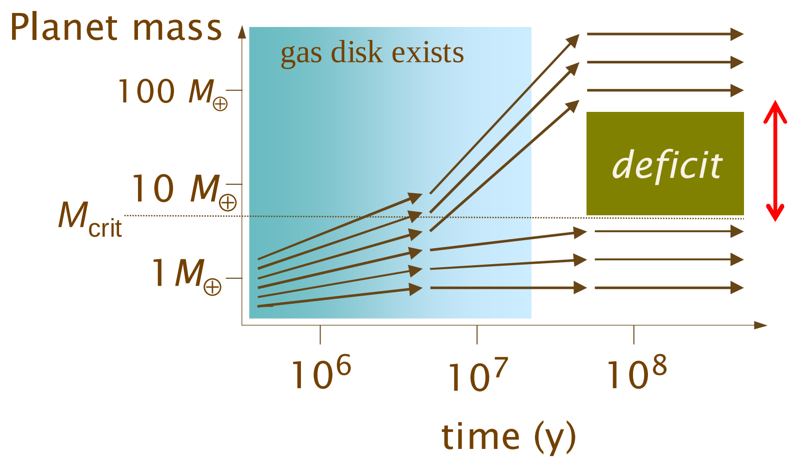
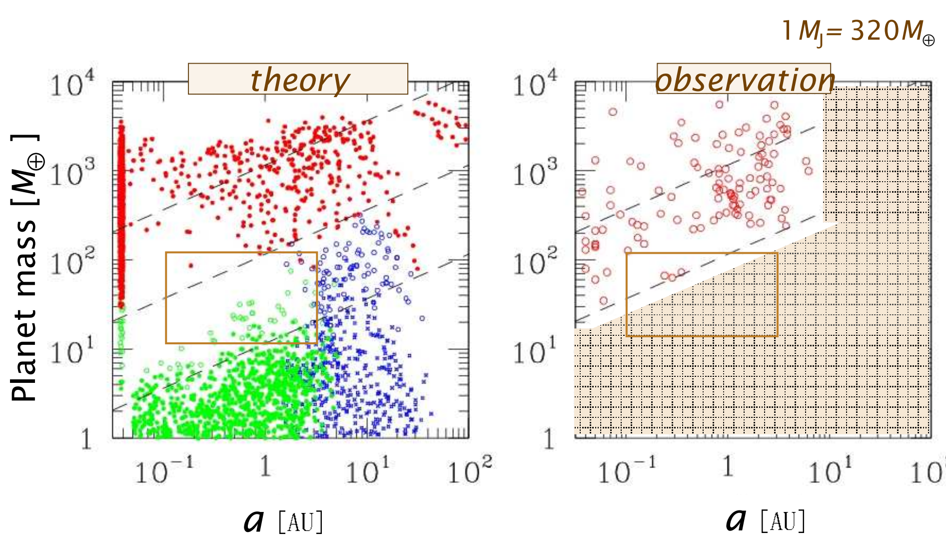


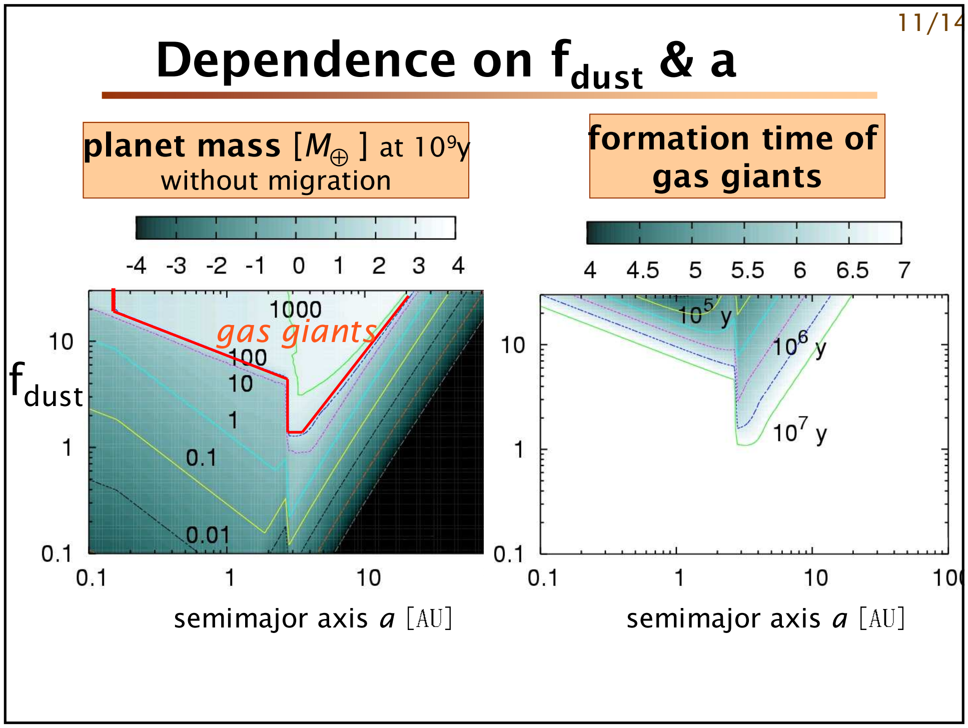
Ida & Lin (2004a, ApJ)

Formation of “Planet Desert”



comparison with observation

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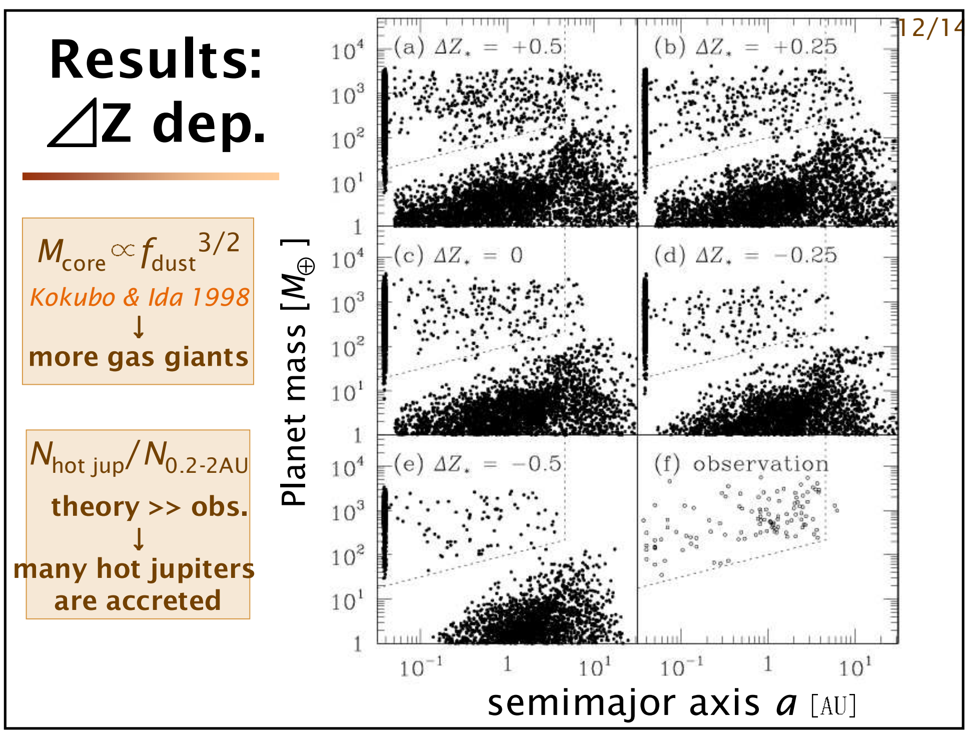
Dependence on f dust & a
planet mass [M⊕] at 10⁹y
without migration
-4 -3 -2 -1 0 1 2 3 4
formation time of
gas giants
4 4.5 5 5.5 6 6.5 7
gas giants
1000
100
10
1
0.1
0.01
f dust
10⁵ y
10⁶ y
10⁷ y
semimajor axis a [AU]
semimajor axis a [AU]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Results:
⊿Z dep.
M core ∝ f dust 3/2
Kokubo & Ida 1998
↓
more gas giants
N hot jup / N 0.2-2AU
theory >> obs.
↓
many hot jupiters
are accreted
(a) ΔZ* = +0.5
(b) ΔZ* = +0.25
(c) ΔZ* = 0
(d) ΔZ* = −0.25
(e) ΔZ* = −0.5
(f) observation
Planet mass [M⊕]
semimajor axis a [AU]

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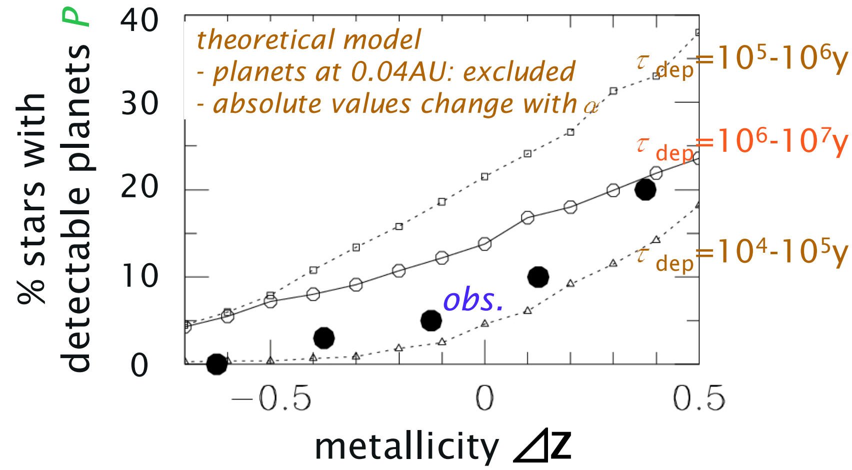
Results: ⊿Z –dependence



core accretion model reproduces the dependence
⇔ self-grav. instability model

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Summary & Discussion

- our synthesized model for planet formation predicts
  - deficit of planets of 10-100$M_\oplus$ at < 3AU (Planet Desert)
  - metallicity dependence

  [consistent with observations]
- future issues (present model = first step)
  - more detailed type-I migration
    - ***M. Ito** (type-I with radiative transfer),* ***J. Kominami** (N-body of oligarchic growth with type-I)*
  - interaction between planets (eccentricity pumping-up, etc.)
  - effects near disk inner edge (disk truncation, tidal