Planets Around Low-Mass Stars: Theory

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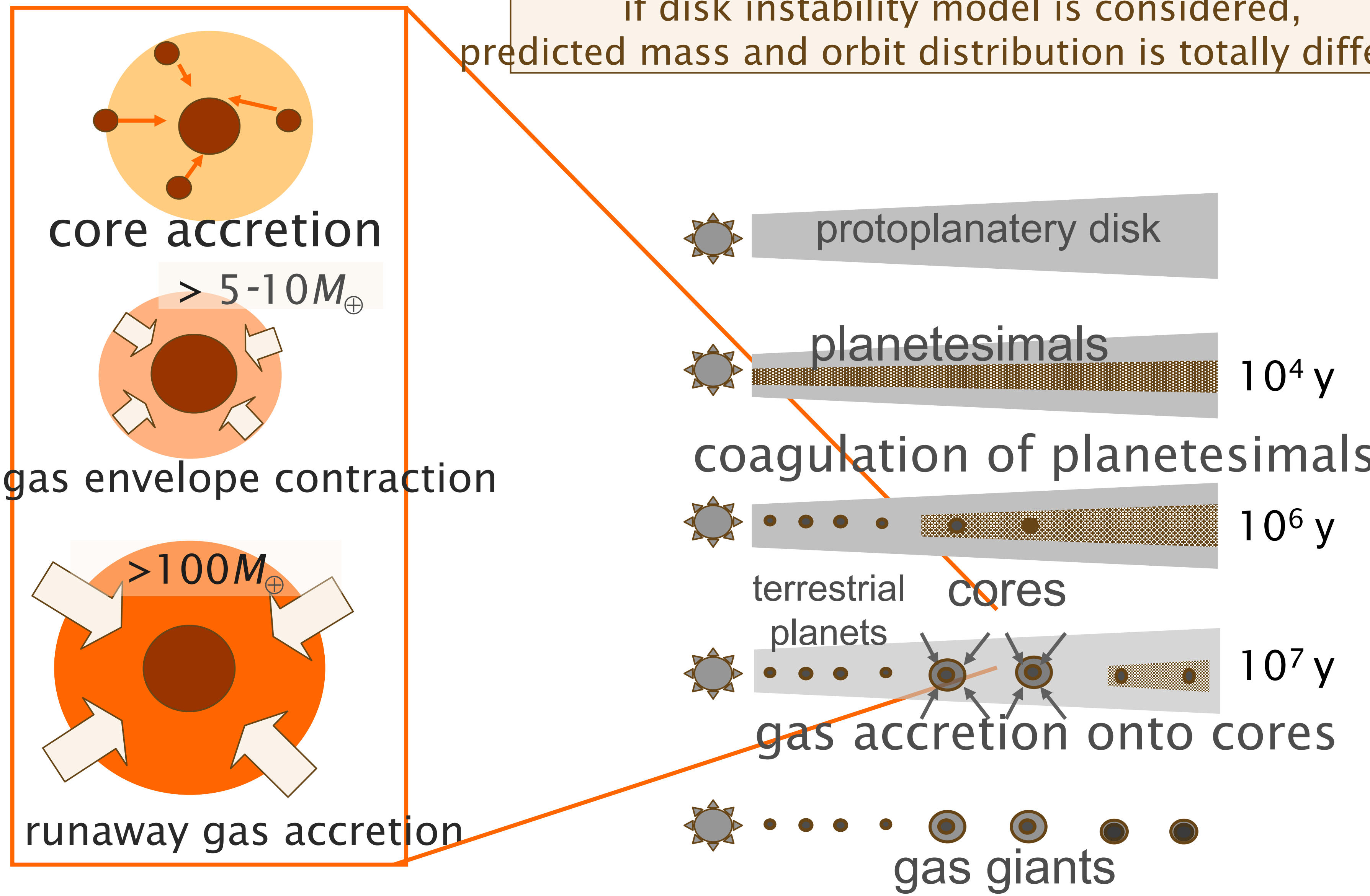
- theoretical prediction of M-a distribution of extrasolar planets and its dependence on stellar mass
- observational constraints
  - type-I migration, gas accretion onto cores:
    highly uncertain in the theoretical model
  - Obs. of super-Earths around late M dwarfs constrain type-I migration.
  - Obs. of gas giants around early M & K dwarfs constrain gas accretion.

core accretion scenario

if disk instability model is considered,
predicted mass and orbit distribution is totally differe

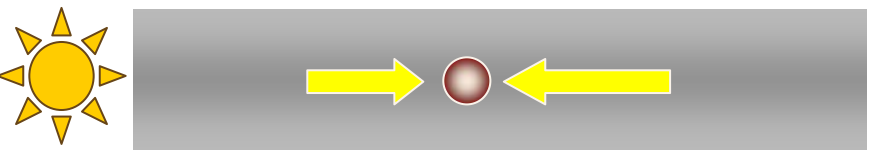


Disk-planet tidal interactions

type-I migration

Goldreich & Tremaine (1979),
Ward (1986, 1997), Tanaka et al. (2002)

$$M \sim (0.1 - 10) M_{\oplus}$$



disk torque imbalance

$$\tau_{\mathrm{mig,I}} \approx 5\times10^{4}\left(\frac{\Sigma_{\mathrm{g}}}{\Sigma_{\mathrm{g,MMSN}}}\right)^{-1}\left(\frac{M_{\mathrm{p}}}{M_{\oplus}}\right)^{-1}\left(\frac{a}{1\mathrm{AU}}\right)^{\frac{3}{2}}\ \mathrm{yrs}$$

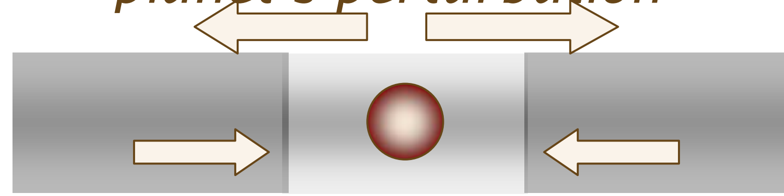
more rapid process

type-II migration

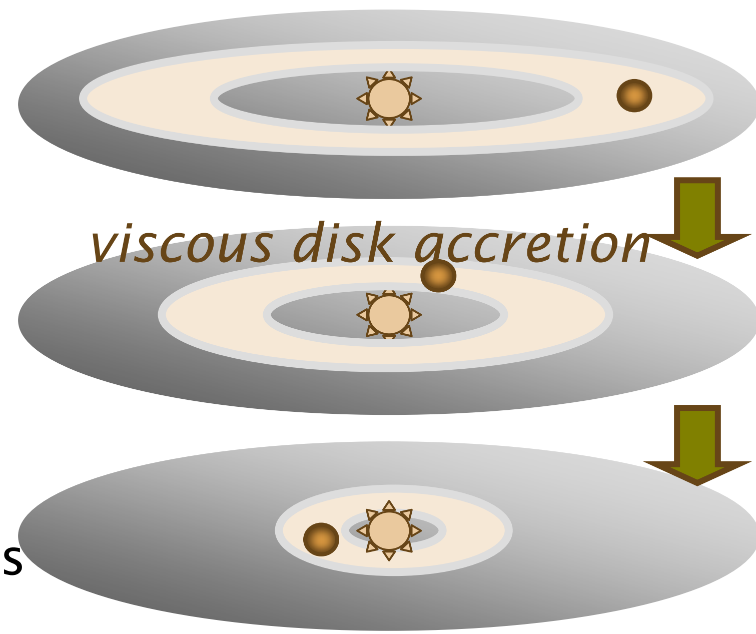
Lin & Papaloizou (1985),....

$$M > (10 - 100) M_{\oplus}$$

planet's perturbation

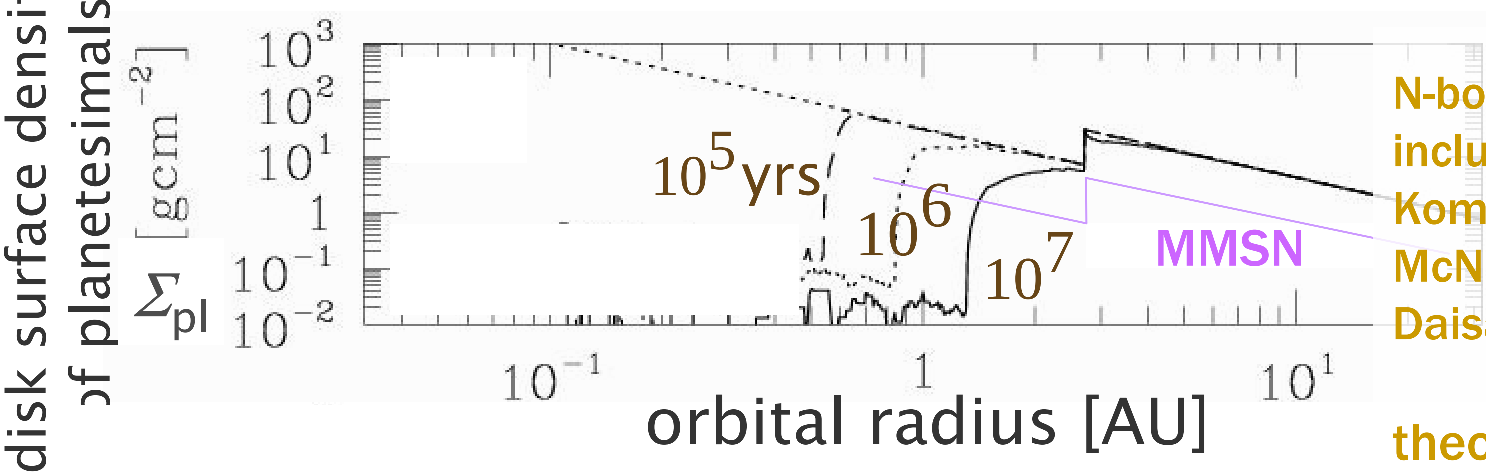


viscous diffusion



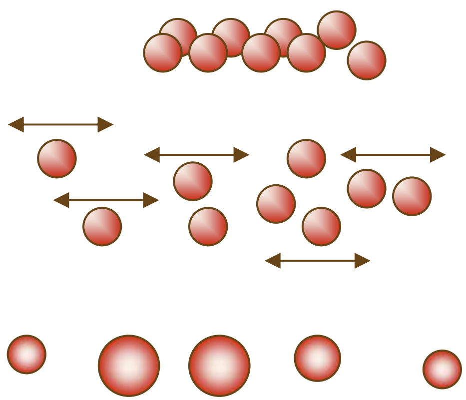
$$\tau_{\mathrm{mig,II}} \approx 10^{6}\left(\frac{\Sigma_{\mathrm{g}}}{\Sigma_{\mathrm{g,MMSN}}}\right)^{-1}\left(\frac{M_{\mathrm{p}}}{M_{\mathrm{J}}}\right)\left(\frac{\alpha}{10^{-3}}\right)^{-1}\left(\frac{a}{1\mathrm{AU}}\right)^{\frac{1}{2}}\ \mathrm{yrs}$$

Σ_{pl}–preservation at ~1AU
terrestrial planet formation ($M_{star}=1 M_\odot$)



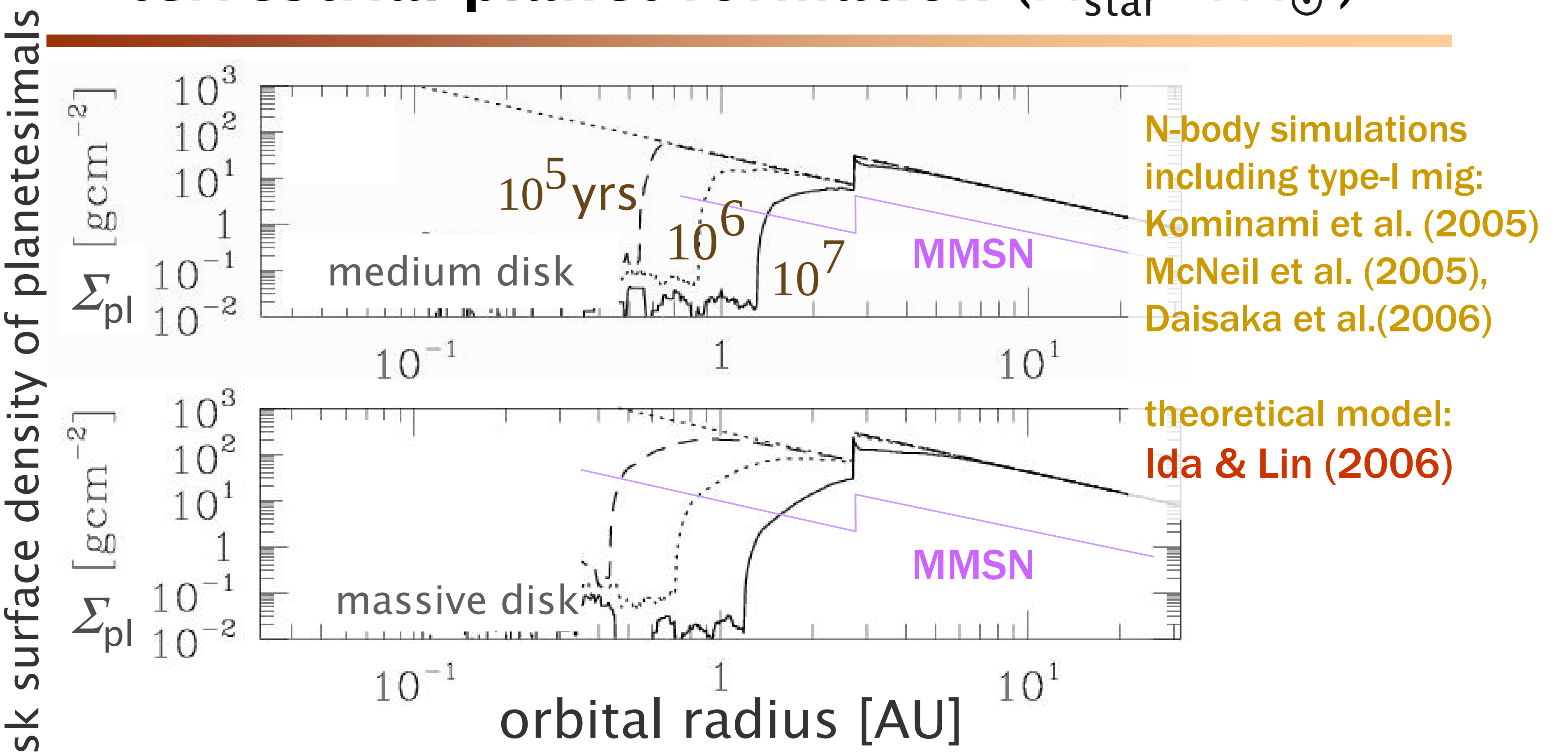
N-body simulations including type-I mig: Kominami et al. (2005), McNeil et al. (2005), Daisaka et al.(2006)

theoretical model: Ida & Lin (2006)



- Embryos repeatedly form and migrate.
- At >1AU, Mars-mass embryos could remain.
- They could form Earth-mass planets after gas depletio

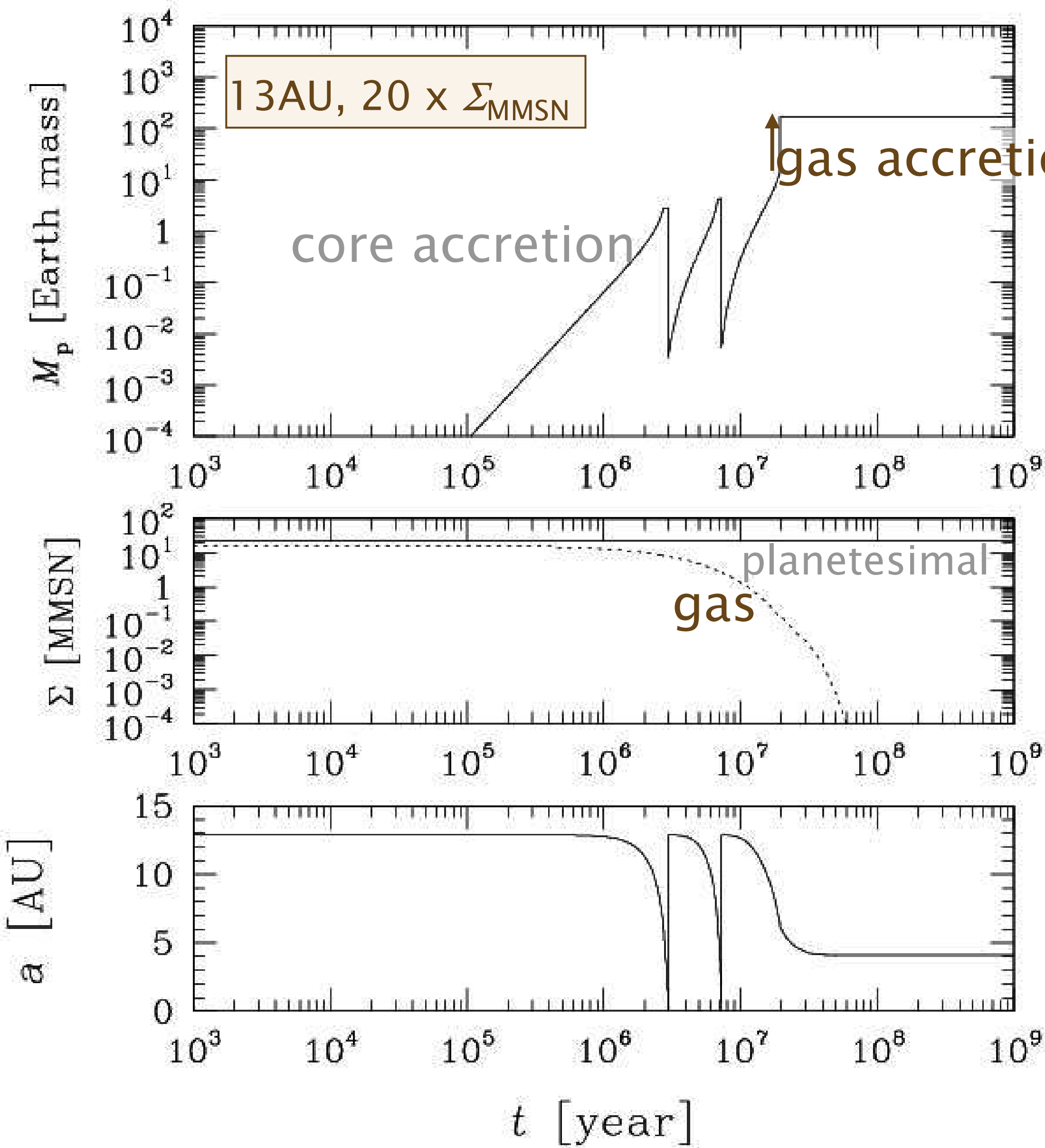
Σ_{pl} –preservation at ~1AU: terrestrial planet formation (M_{star}=1$M_\odot$)



-self-regulation: in more massive disks, Σ_{pl} decreases faster

- Asymptotic Σ_{pl} is similar at ~1AU.
- Gas giant formation is inhibited at ~1AU even in very massive disks. → preserve "Earths" in

late formation of gas giants in outer regions
(M_{star}=1 $M_{\odot}$)



core: Thommes & Murray (2006)
core + gas: Ida & Lin (2006)

Only the cores generated late survive to become gas giants
→type-II migration of gas giant less efficient

→type-I migration rather tends preserve "Earths" in HZ

core accretion: late formation
disk instability: early formation
clearly distinguished by obs.

Monte Carlo simulation

theoretical prediction for *M-a* distribution of exoplanets with the effect of type-I & II migration

$\boxed{\Sigma, a_{\mathrm{ini}} = (\text{integration on } 10^9\text{y}) \Rightarrow M_p, a_{\mathrm{final}}}$

Ida & Lin (2004a, ApJ, 604, 388)
Ida & Lin (2004b, ApJ, 616, 567)
Ida & Lin (2005, ApJ, 626, 1045)
Ida & Lin (2006, ApJ, submitted)

Monte Carlo simulation to predict M_p-a distribution of exoplanets

- **disk gas surface density Σ_g :**
  - initial distribution: log normal

$$\Sigma_g(0) = 0.1\text{-}10\,\Sigma_{g,MMSN} \times (M_*/M_\odot)^2$$

  - *a priori* exp. decay

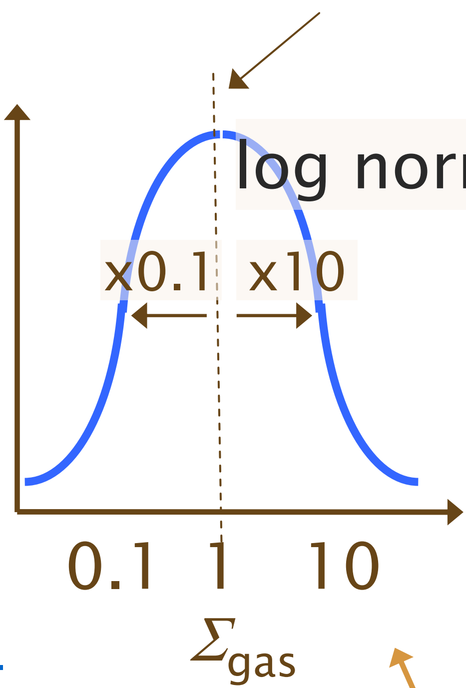
$$\Sigma_g(t) = \Sigma_g(0)\exp(-t/\tau_{dep})$$

- **planetesimal surface density**

$$\Sigma_{pl}(0) \sim 10^{[Fe/H]} \times 0.01\,\Sigma_g(0)$$

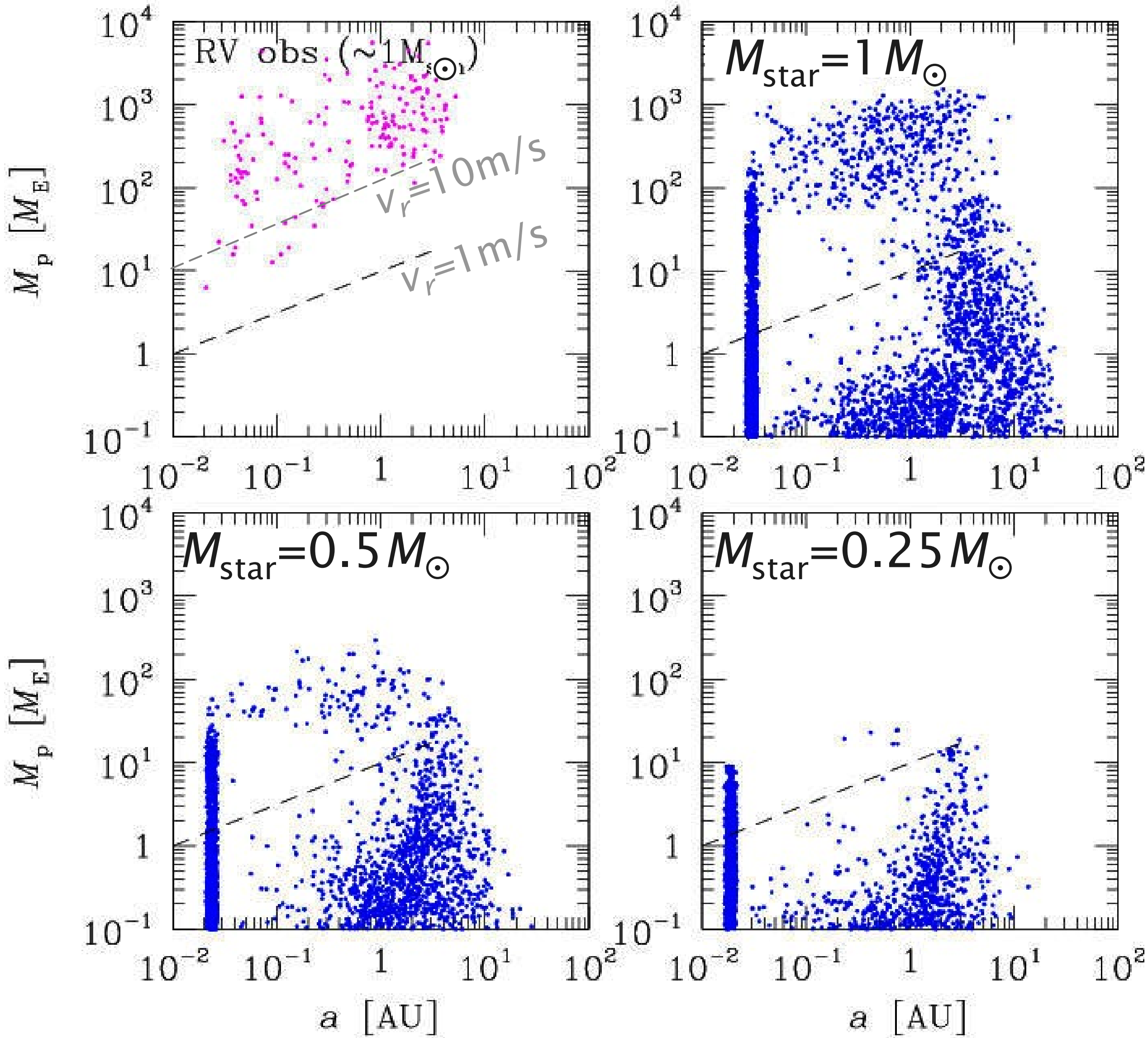
- **disk lifetime τ_{dep}** : log uniform 10^6-10^7yrs
- **migration:** artificially stopped at 0.04AU

Min. Mass Solar Nebula



radio observation of dis
around T-Tauri stars
Beckwith & Sargent (1996)

planets around various mass stars
with type-I migration



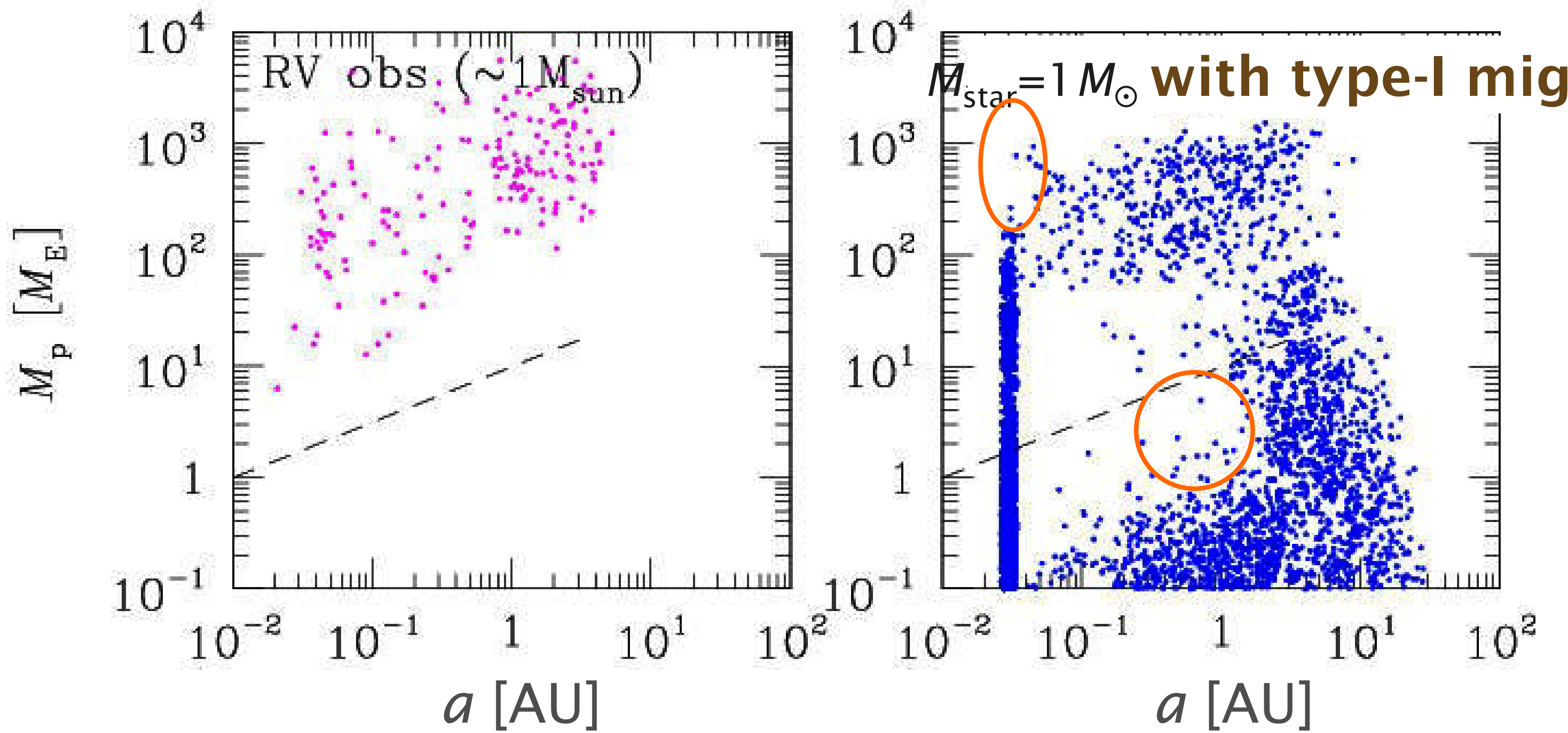
with k=8, C_1= 0.1,[Fe/H]=0.2

- gas giants
- M_{star}~1.0$M_\odot$: abundant
- M_{star}~0.5$M_\odot$: marginal
- M_{star}~0.25$M_\odot$: rare

Σ_{pl} & T ↘ for M_{star} ↘

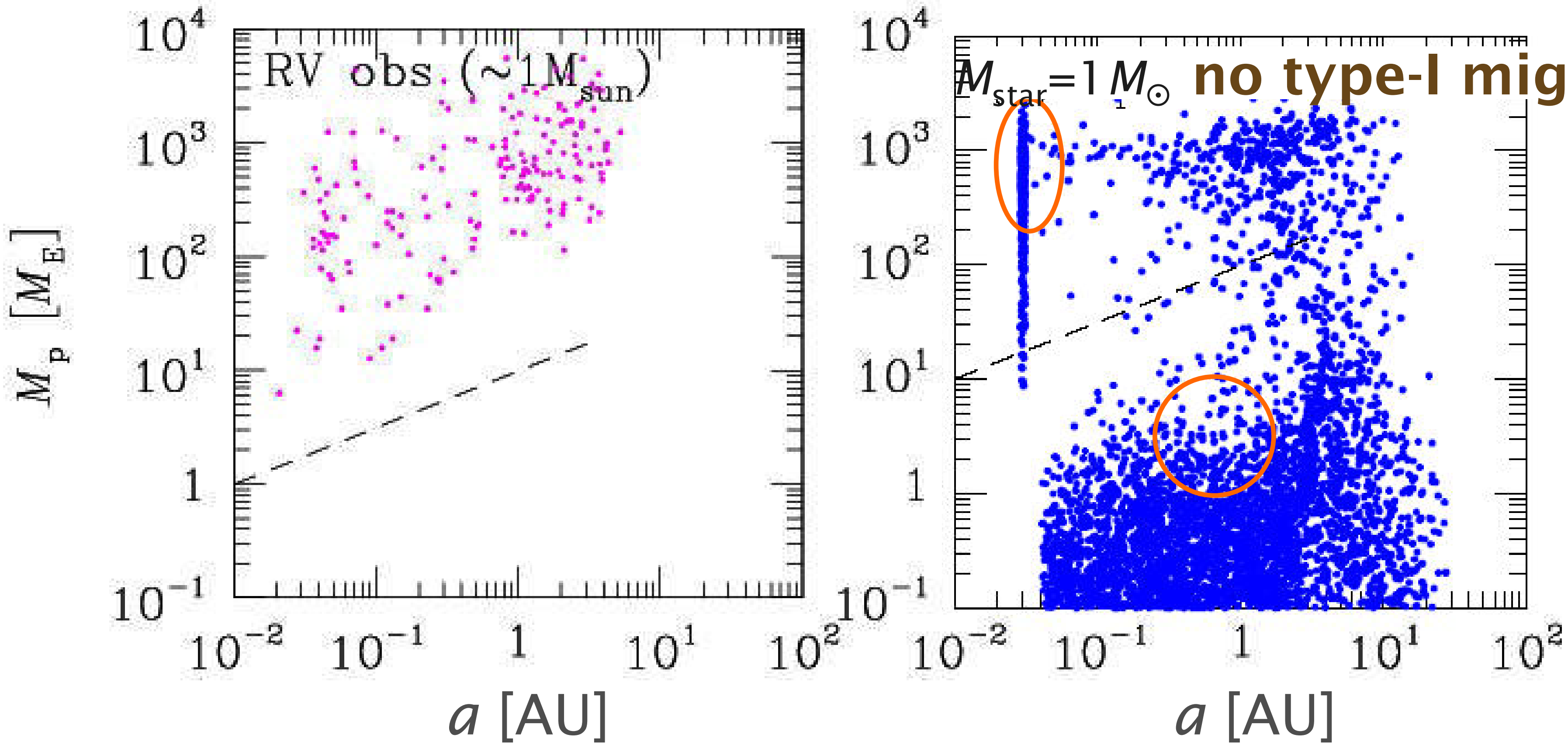
Laughlin et al. 2004
Ida & Lin 2005

planets around ~1.0$M_\odot$ stars
with type-I migration



- lack of “super-Earths” at ~1AU
- lack of massive close-in planets (consistent with RV obs.)

planets around $\sim 1.0 M_\odot$ stars
with type-I migration



- lack of "super-Earths" at ~1AU
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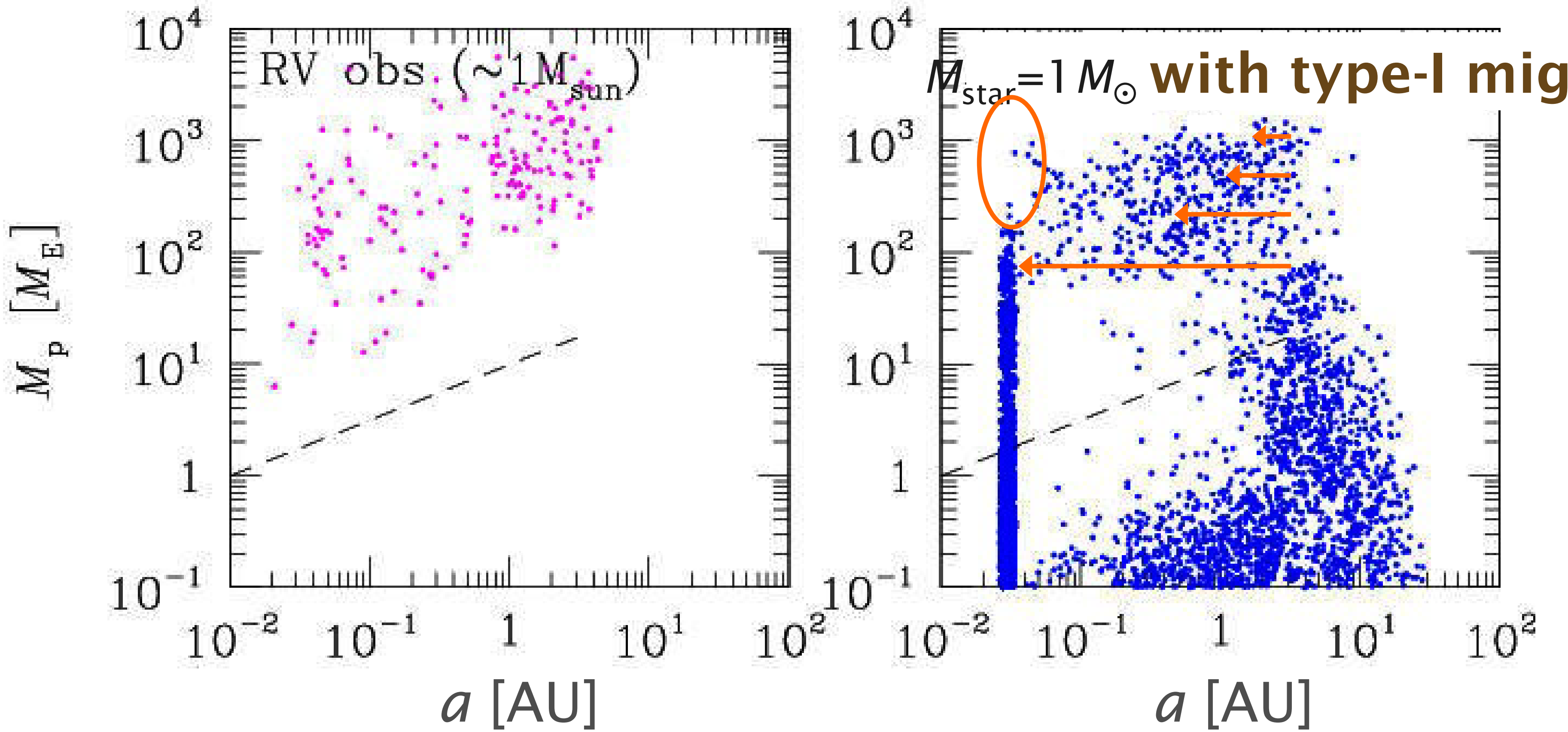
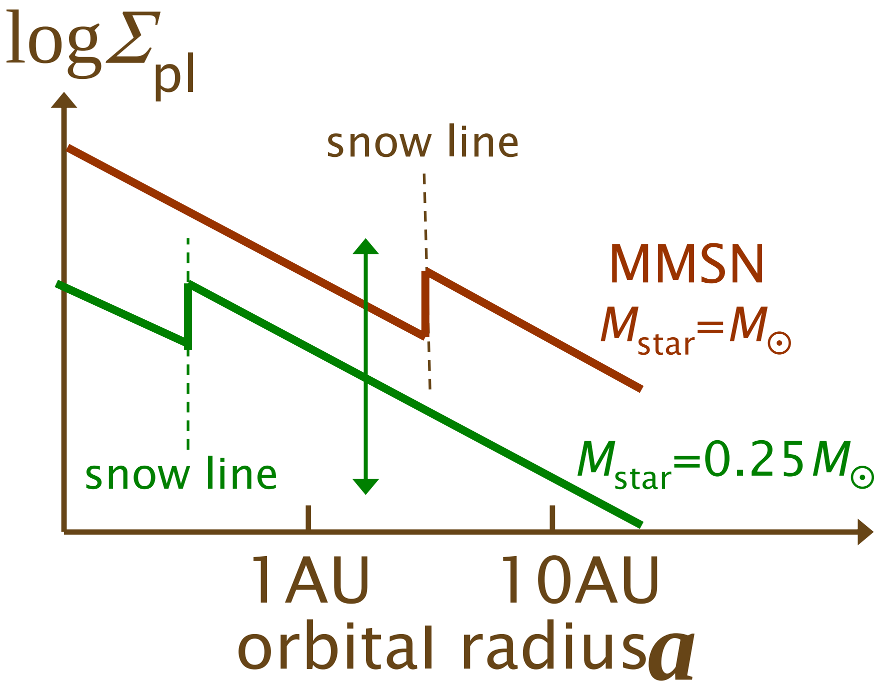
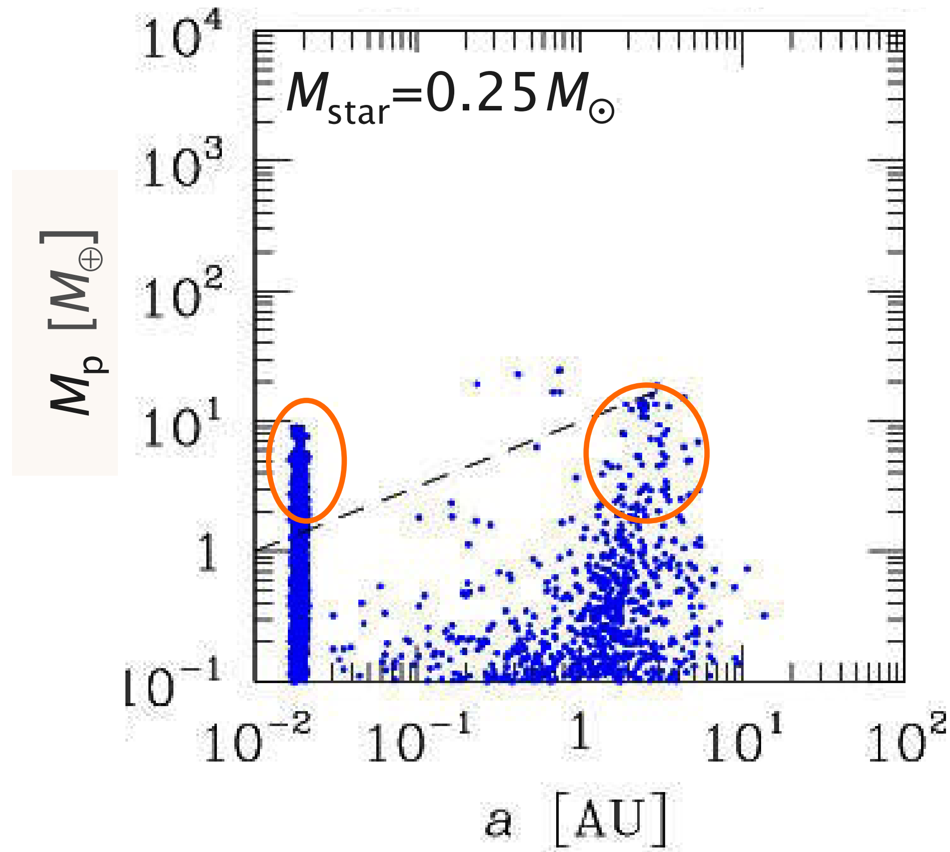
planets around ~1.0$M_\odot$ stars
with type-I migration



- lack of "super-Earths" at ~1AU
- lack of massive close-in planets (consistent with RV obs.)

planets around ~0.25$M_\odot$ stars
with type-I migration



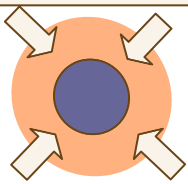


- abundant super-Earths: bimodal at ~2-3AU & <0.05AU (consistent with RV & microlensing obs.)

constraints on type-I mig & envelope contraction

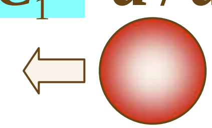
G dwarfs
obs: many gas giants

envelope contraction



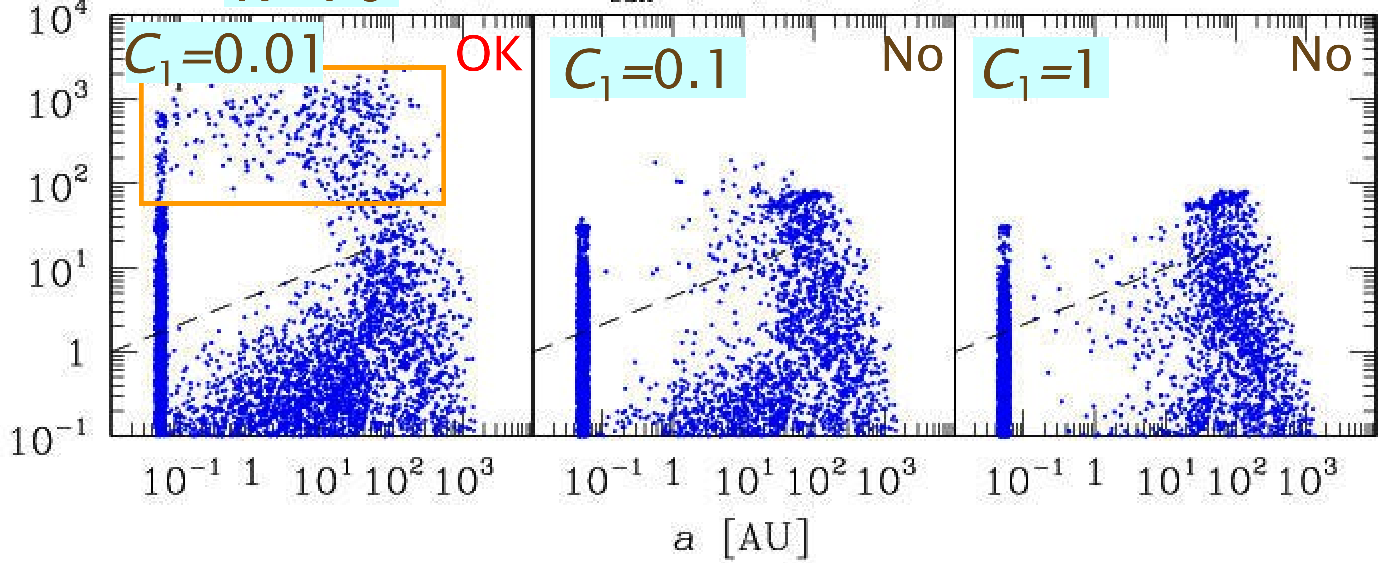
$$\frac{M_\mathrm{p}}{\dot{M}_\mathrm{p}} \approx 10^{k} \left(\frac{M_\mathrm{p}}{M_\oplus}\right)^{-3} \text{ yrs}$$

$$C_1 = \dot{a} / \dot{a}_\mathrm{linear}$$

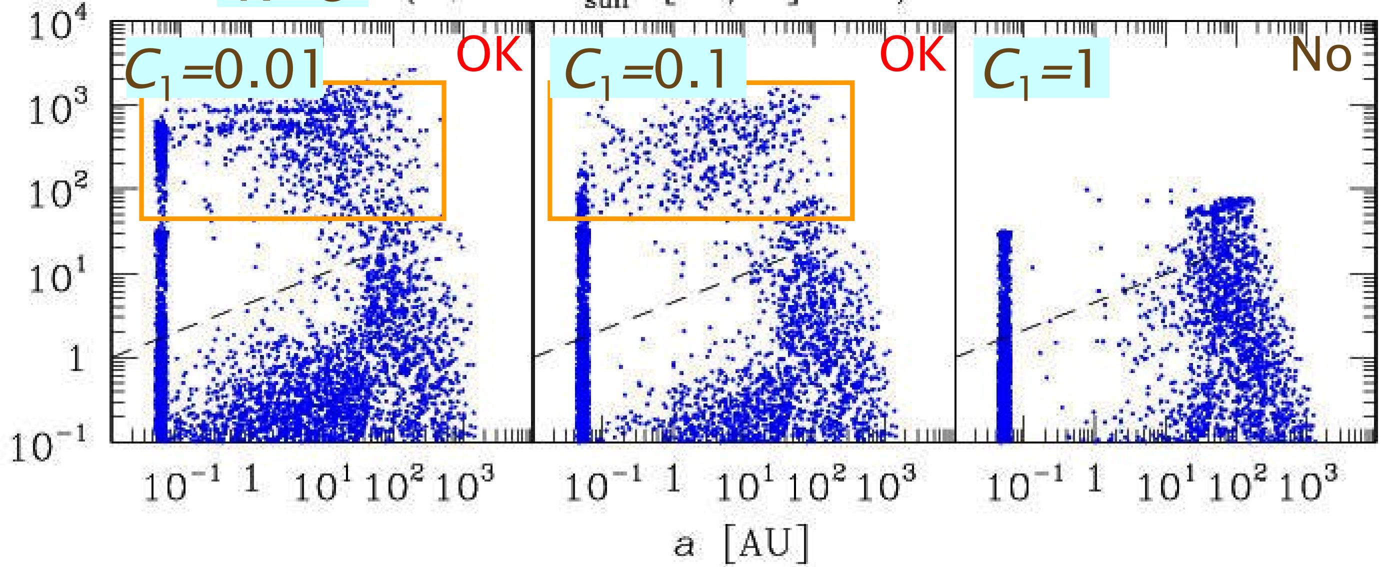


type-I migration

$k=10$ ($M_* = 1.0 M_\mathrm{sun}$, [Fe/H]=0.2)



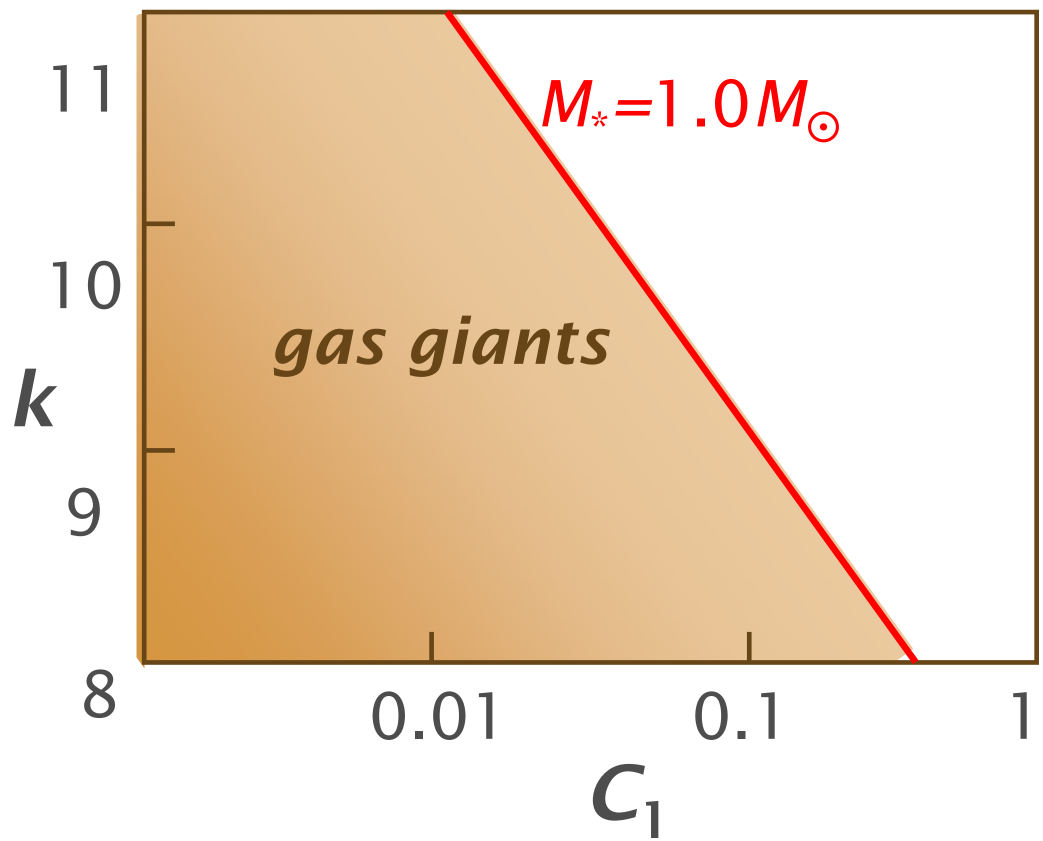
$k=8$ ($M_* = 1.0 M_\mathrm{sun}$, [Fe/H]=0.2)



constraints on type-I mig & envelope contraction

- observed gas giants
  - $M_* \sim 1.0 M_\odot$: many

theoretical results for [Fe/H]=0.2



$$\frac{M_p}{\dot{M}_p} \approx 10^{k} \left(\frac{M_p}{M_\oplus}\right)^{-3} \text{yrs}$$

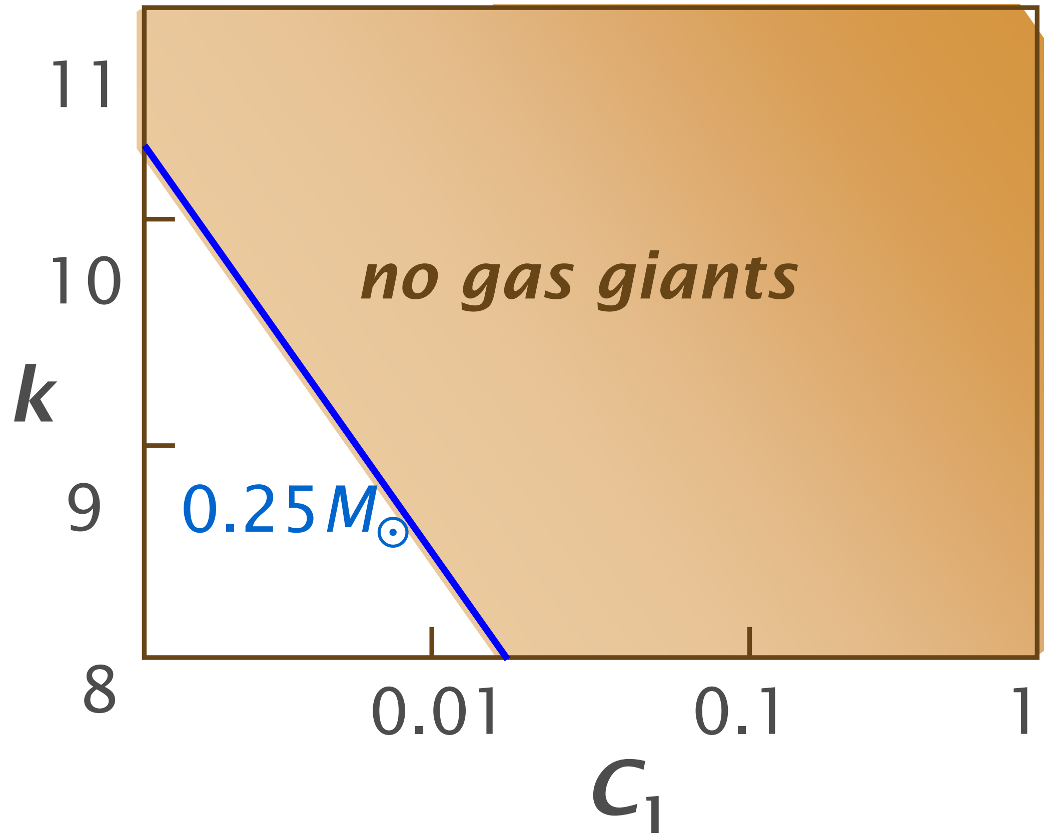
k~11: Pollack et al. with "phase II"
k~10: Pollack et al. for "phase III"
k~8: Ikoma et al. (different opacity table)

$$C_1 = \dot{a} / \dot{a}_{\text{linear}}$$

constraints on type-I mig & envelope contraction

- observed gas giants
  - $M_* \sim 0.25 M_\odot$: rare

theoretical results for [Fe/H]=0.2



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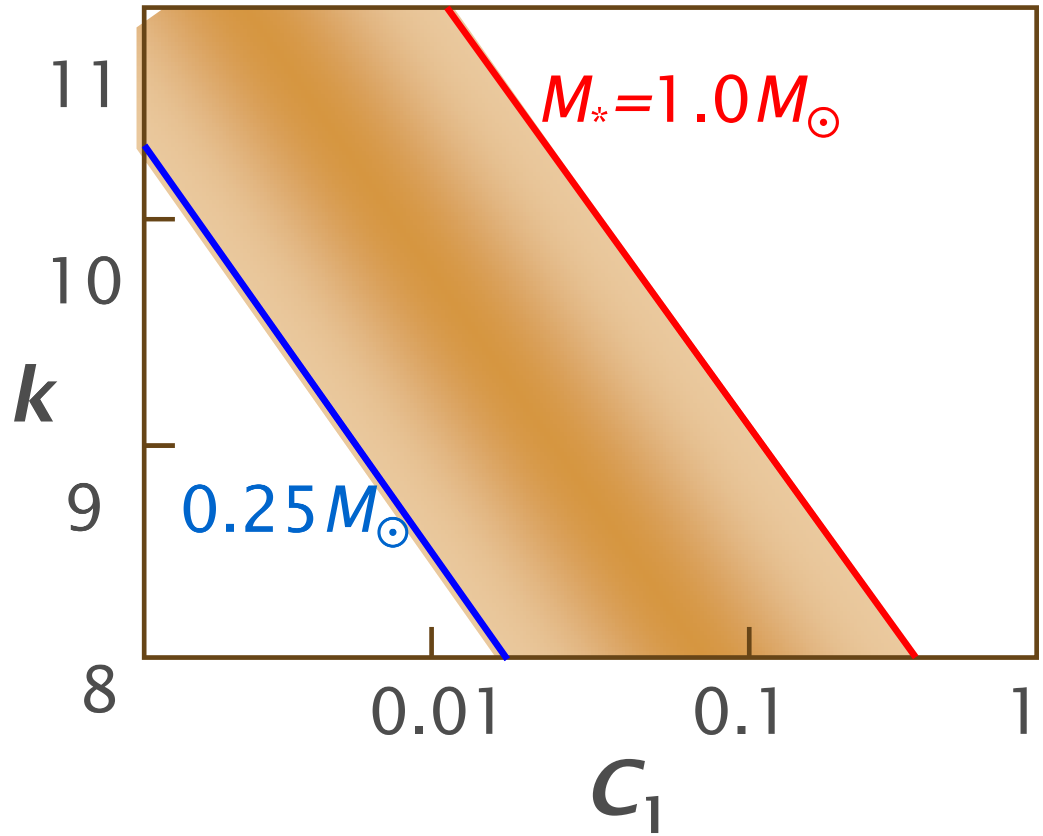
constraints on type-I mig & envelope contraction

- observed gas giants
  - $M_* \sim 1.0 M_\odot$: many
  - $M_* \sim 0.25 M_\odot$: rare

→ C_1 & k are constrained.

theoretical results for [Fe/H]=0.2



$$\frac{M_p}{\dot{M}_p} \approx 10^{k} \left(\frac{M_p}{M_\oplus}\right)^{-3} \text{ yrs}$$

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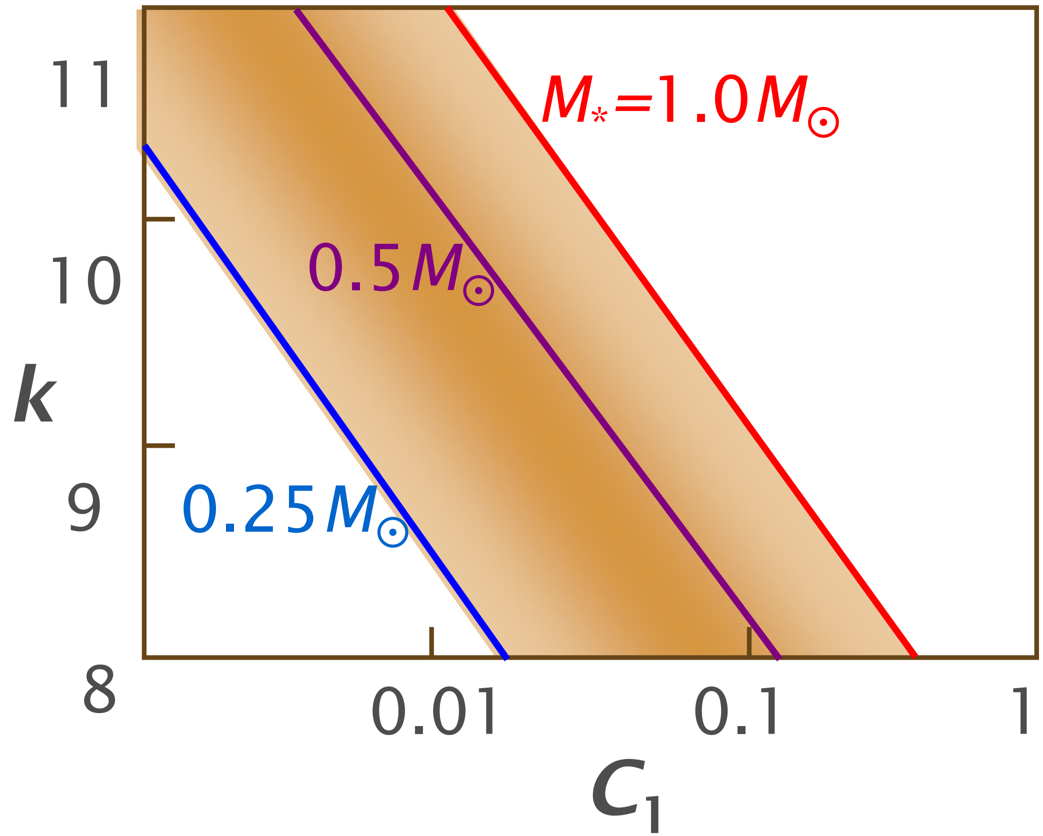
$$C_1 = \dot{a} / \dot{a}_{\rm linear}$$

constraints on type-I mig & envelope contraction

- observed gas giants
  - $M_* \sim 1.0 M_\odot$: many
  - $M_* \sim 0.25 M_\odot$: rare

→ observation for $\sim 0.5 M_\odot$ further constraints C_1 & k.

theoretical results for [Fe/H]=0.2



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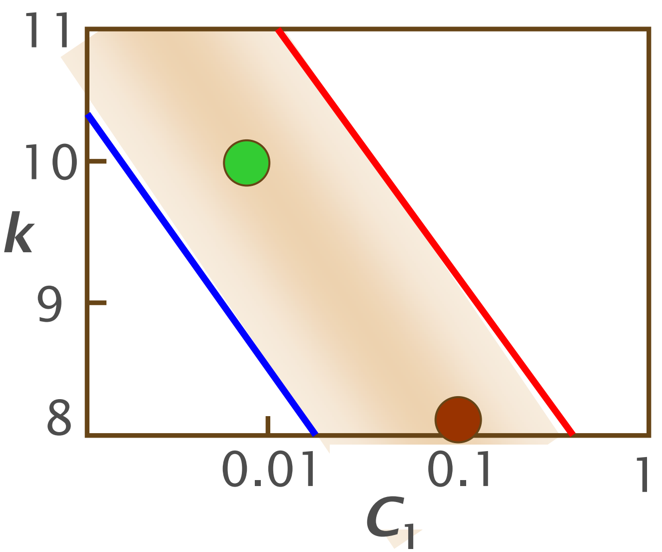
constraints on type-I mig & envelope contraction

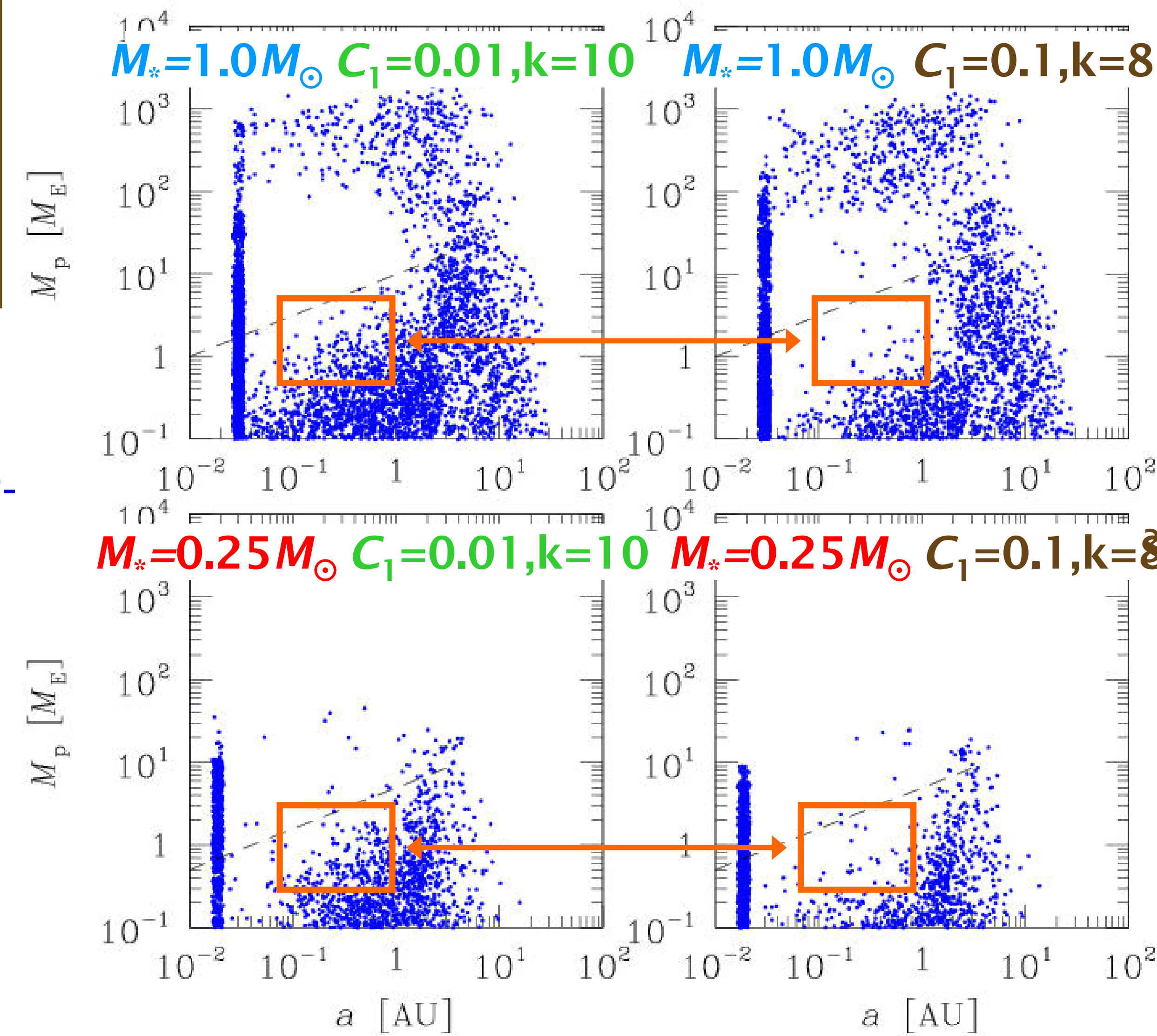


Obs. of Earths & super-Earths at 0.1-1AU (M stars) will determine k & C_1

$$\frac{M_p}{\dot{M}_p} \approx 10^{k} \left(\frac{M_p}{M_\oplus} \right)^{-3} \text{ yrs}$$

$$C_1 = \dot{a} / \dot{a}_{\text{linear}}$$

theoretical results for [Fe/H]=0.2



Summary

Planets around various mass stars are studied including the effect of type-I migration

- Type-I mig. enhances formation and preservation of habitable planets at ~1AU around G dwarfs.
- Super-Earths are common around M dwarfs.
  - bimodal at <0.05AU and 2-3AU
- Gas giants are formed late (only during disk depletion).
- Obs. for gas giants around early M & K dwarfs will constrain type-I mig. and gas accretion onto cores which are theoretically highly uncertain.
- These calibrations will enable us to accurately predict distribution of habitable planets.