Inhomogeneities in Protoplanetary Disks

: Connection between disks and planets

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EACOA fellowship program

- Purpose: "encourage and support young researchers from all over the world to come & conduct **joint** research activities with colleagues at the EACOA member institutes"

- Expectations: "develop independent research programs & **integrate** with the existing activities at the EACOA member institutes"

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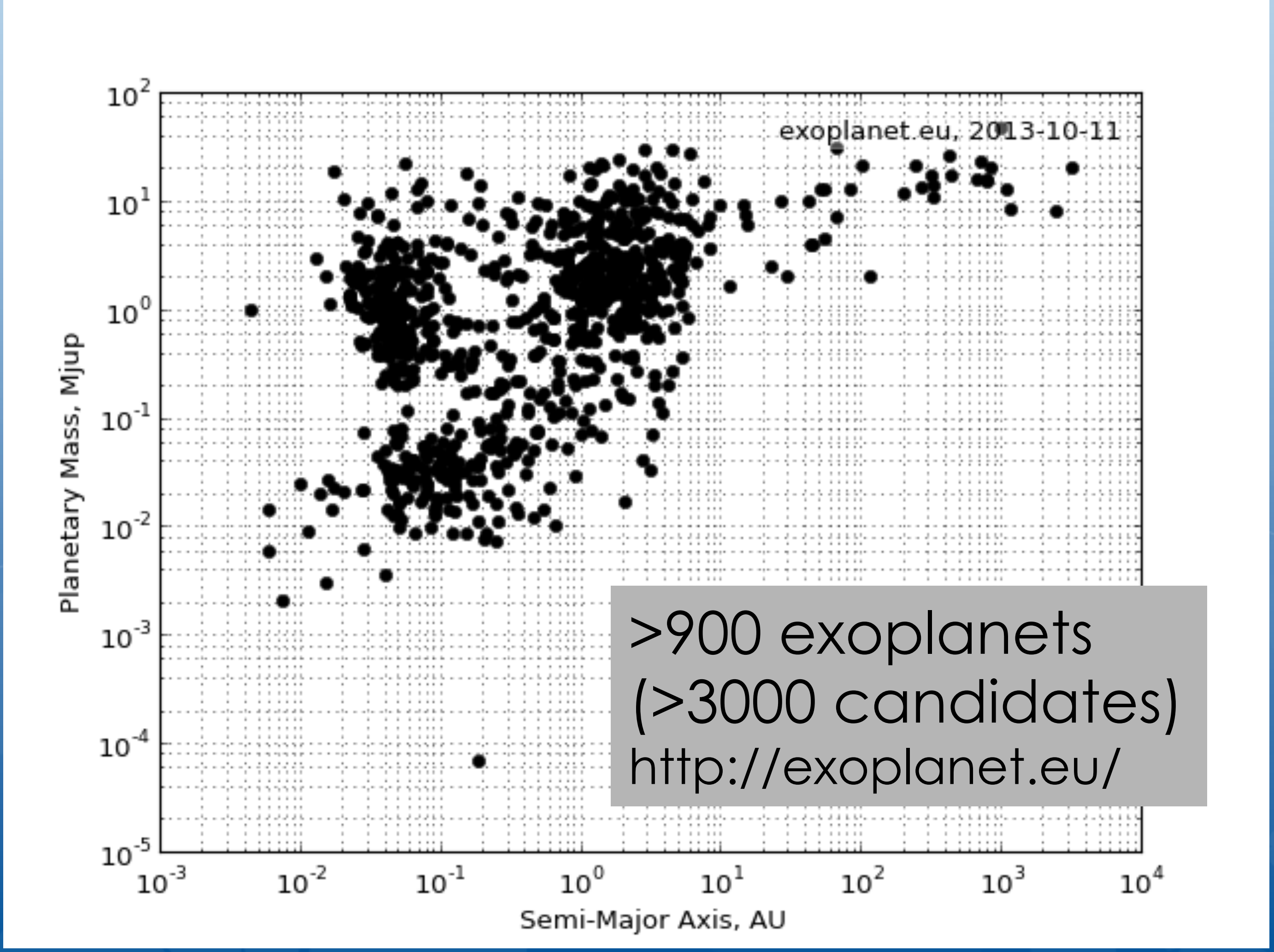
Collaborations with you are the key

- Expectations: "develop independent research programs & integrate with the existing activities at the EACOA member institutes"

Planet formation in protoplanetary disks

Planet formation in protoplanetary disks

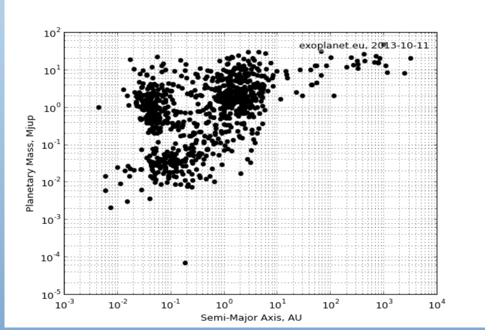
1) Observations of exoplanets

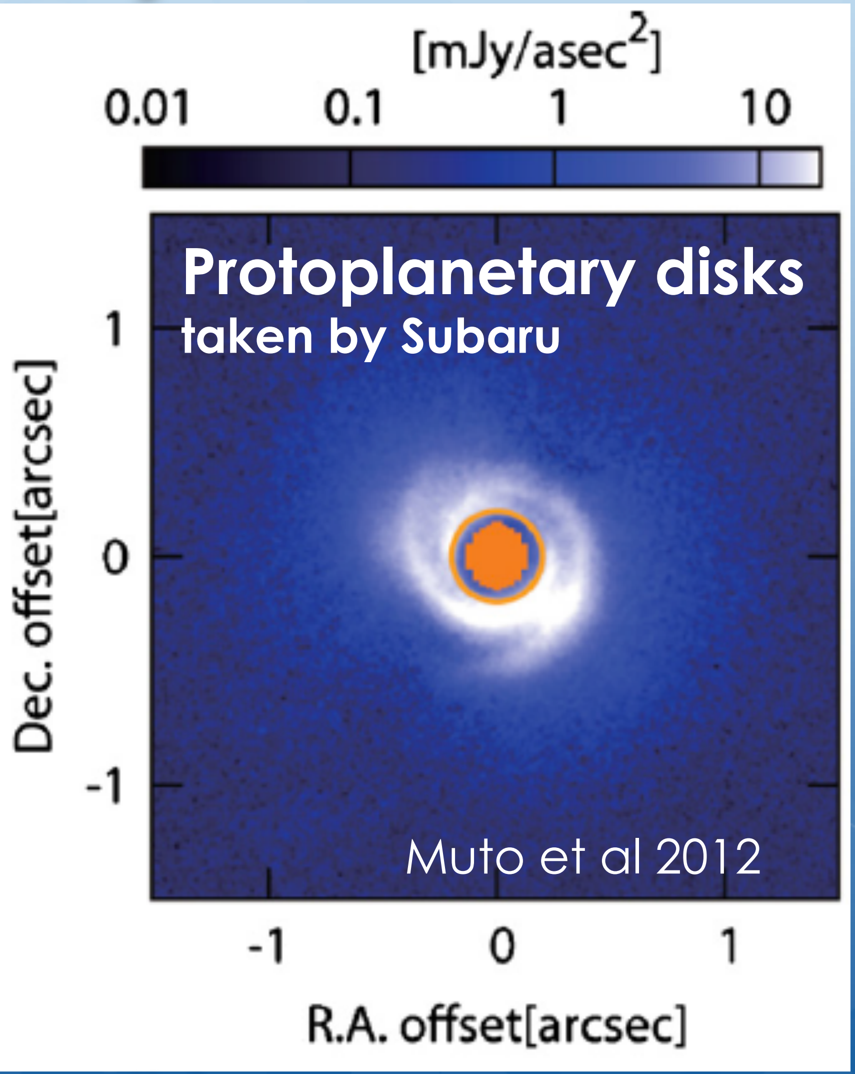


>900 exoplanets
(>3000 candidates)
http://exoplanet.eu/

Planet formation in protoplanetary disks

1) Observations of exoplanets

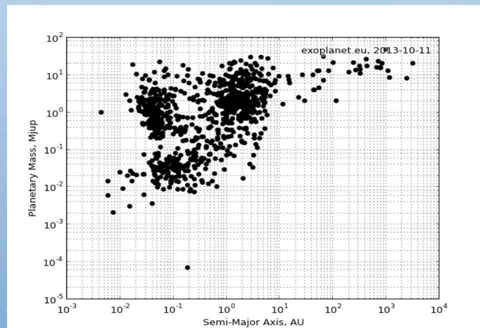




2) Observations of protoplanetary disks

Planet formation in protoplanetary disks

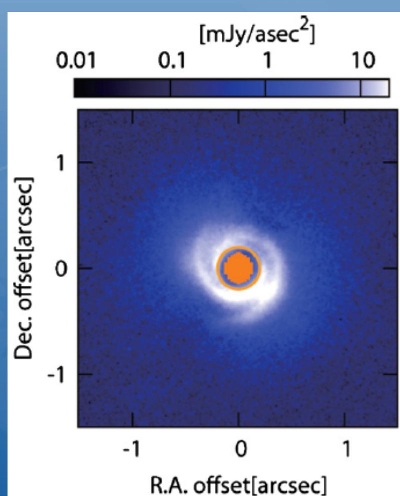
1) Observations of exoplanets



Final stage
(Planetary systems)

Middle stage
???

Initial stage
(Protoplanetary disks;
Birth place of planets)



2) Observations of protoplanetary disks

Population synthesis calculations

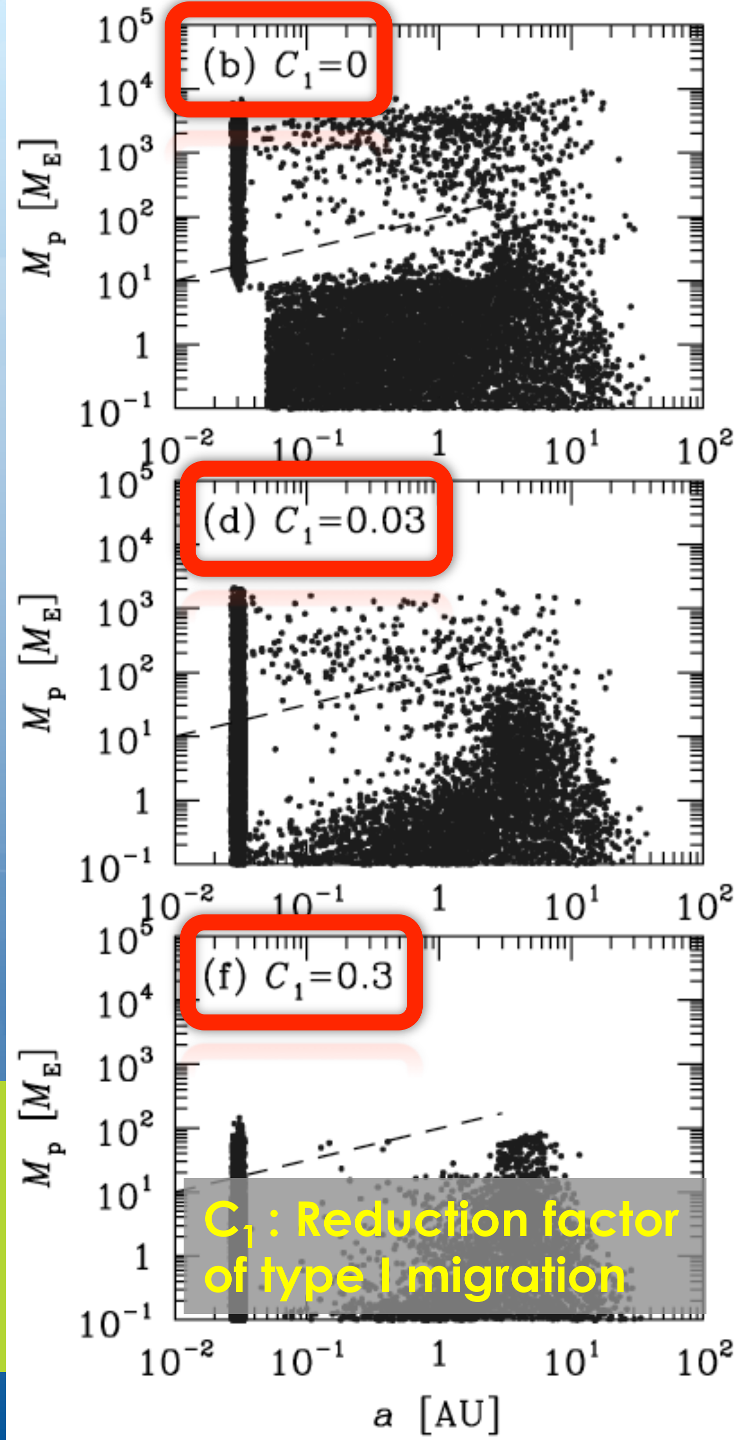
e.g. Ida & Lin 2004a,b, 2005, 2008a,b 2010, 2013
Mordasini et al 2009a,b, 2012, Alibert et al 2011

1) Randomly selected initial conditions of disks & embryos

2) Planet formation: core accretion scenario and planetary migration (type I + type II)

3) Evolution of homogeneous disks

Connection between disks and planets can be lost due to rapid type I planetary migration

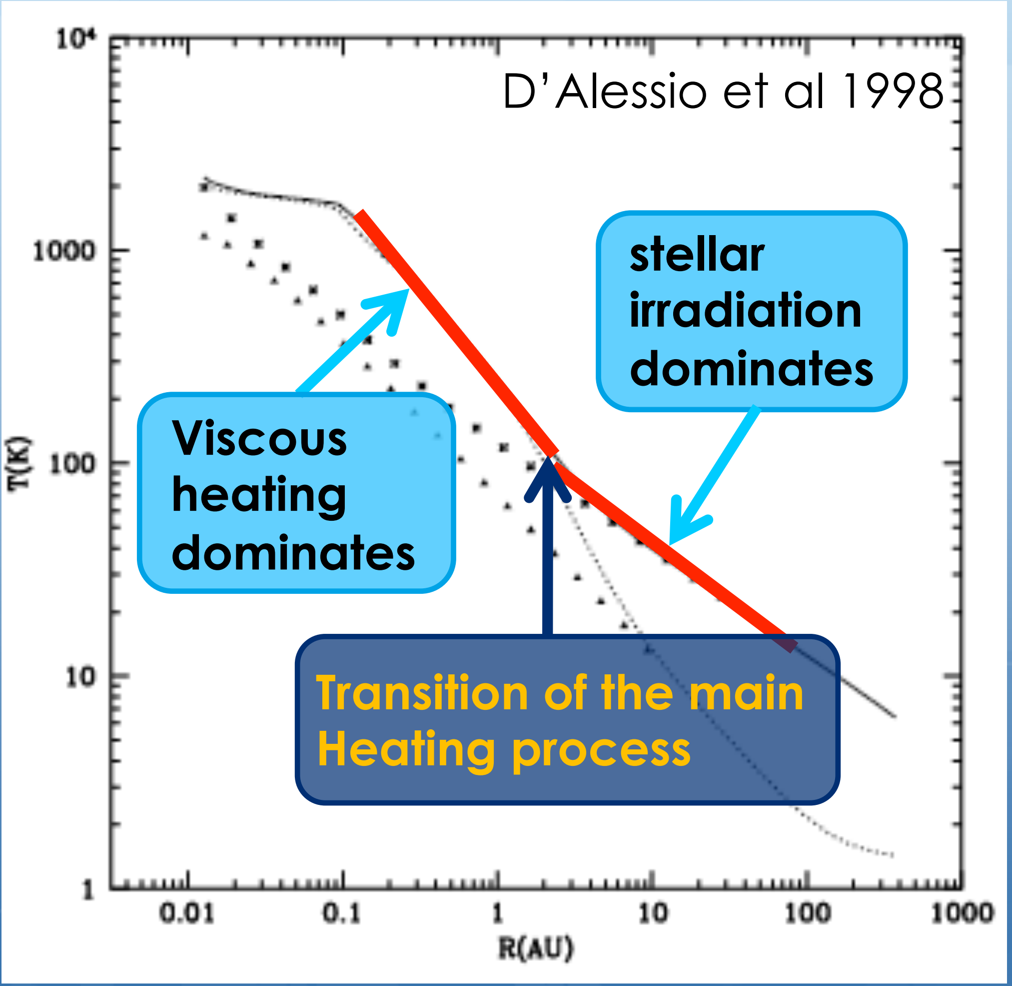


Disk inhomogeneities & planet traps

- Step 1: Presence of inhomogeneities in disks and halting rapid type I migration there
- Step 2: Properties of planet traps and their effects on planet formation
- Step 3: the statistical properties of planets formed at planet traps

Step 1: Origin of planet traps

Hasegawa & Pudritz 2011



- **Viscous heating**

  : dominates for the **inner** region of disks
  (ex: 2-3 AU for Classical T Tauri stars (CTTSs))

  : **Steeper** temp. profiles

- **Stellar irradiation**

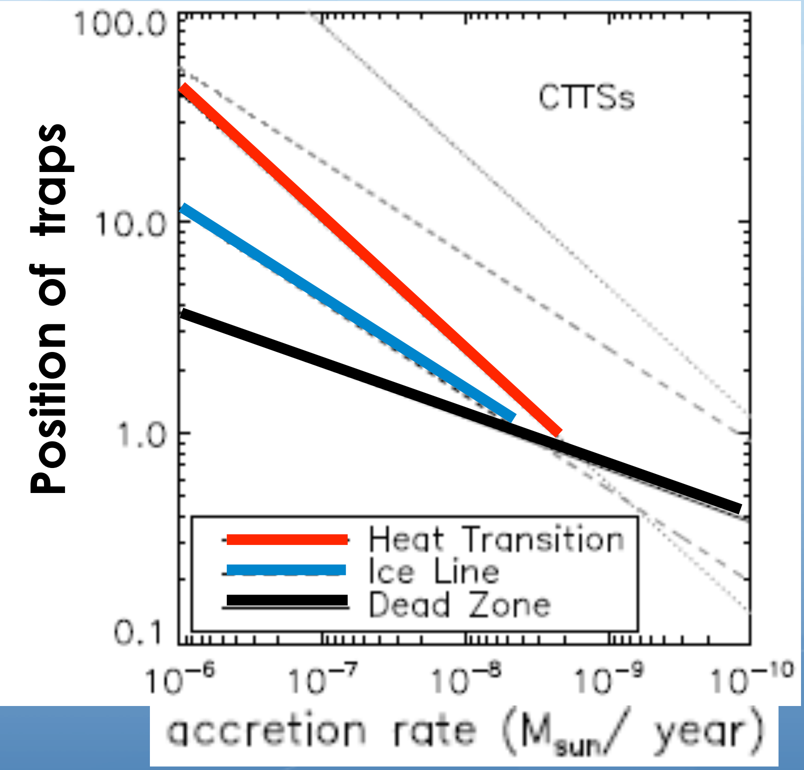
  : dominates for the **outer** region

  : **Shallower** temp. profiles

Type I migration is very sensitive to disk properties, so that it will be halted at the heat transition
=> Confirmed by hydrodynamical simulations (Yamada & Inaba 2012)

Step 2:Properties of planet trap

Hasegawa & Pudritz 2011

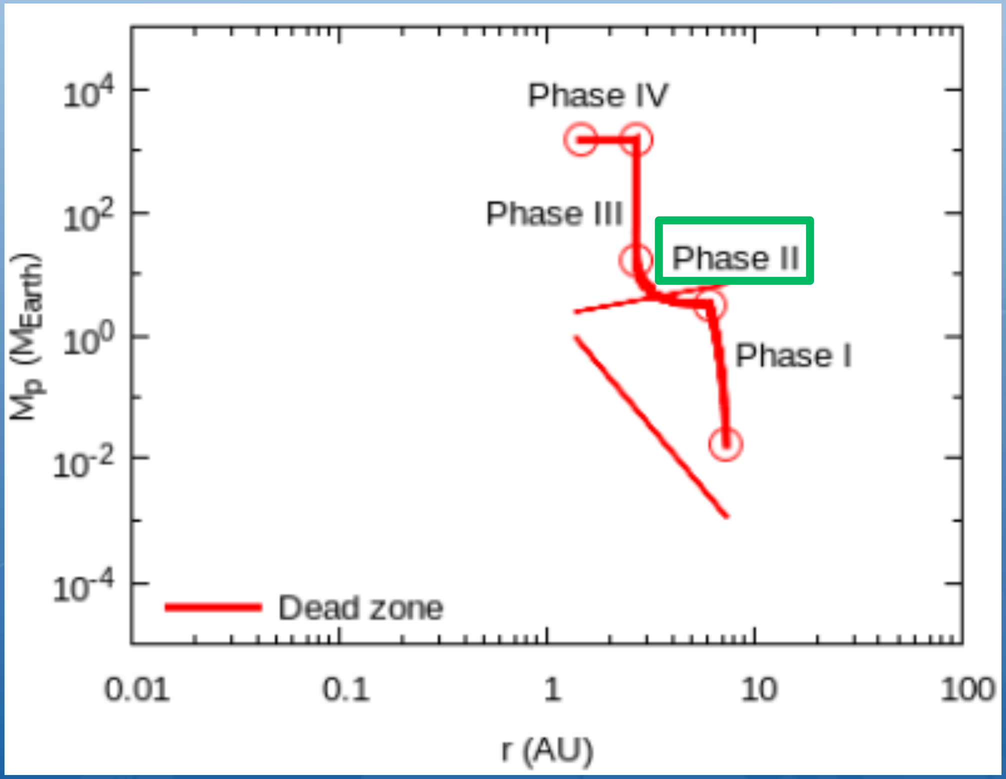


- **Heat transition:** transition of the main heat source
- **Ice lines:** transition of opacity
- **Dead zones:** transition of turbulence

- **Single disks have up to 3 types of planet traps**
- **The positions are sensitive to the disk accretion rate onto the host star (The traps move inward at different rates, following time-evolution)**

Step 2: their effects on planet formation

- A disk around a classical T Tauri star is considered
- $\tau_{disk} \approx 8.8\times10^6$ in this setup

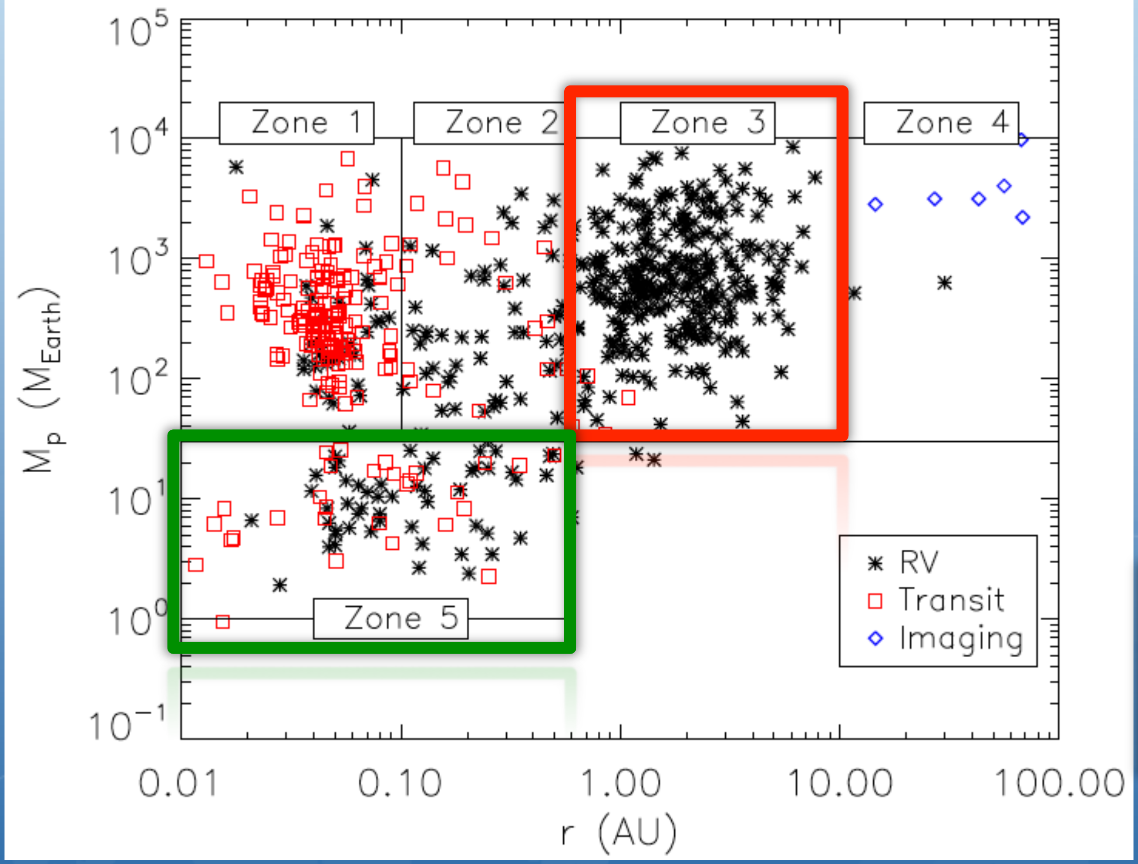


Hasegawa & Pudritz 2012

- Phase 1: **core formation**
  ; Oligarchic growth ($\leq 10^6$ yr); little evolution in orbit
- Phase 2: **onset of gas accretion ;($\sim 2\times10^6$ yr)**
  ; move inward following the movement of the trap
- Phase 3: **runaway gas accretion ;($< 10^5$ yr)**
  ; little evolution in orbit
- Phase 4: **slower type II migration ;($\geq 10^6$ yr)**
  ; the final position is determined when photoevaporation takes over

Step 3: Statistical properties

- Observations of exoplanets



Presence of distinct populations

Chiang & Laughlin 2013

Zone 1: hot Jupiters
not dominant

Zone 2: exclusion of gas giants

Zone 3: a pile up of gas giants

Zone 4: distant planets

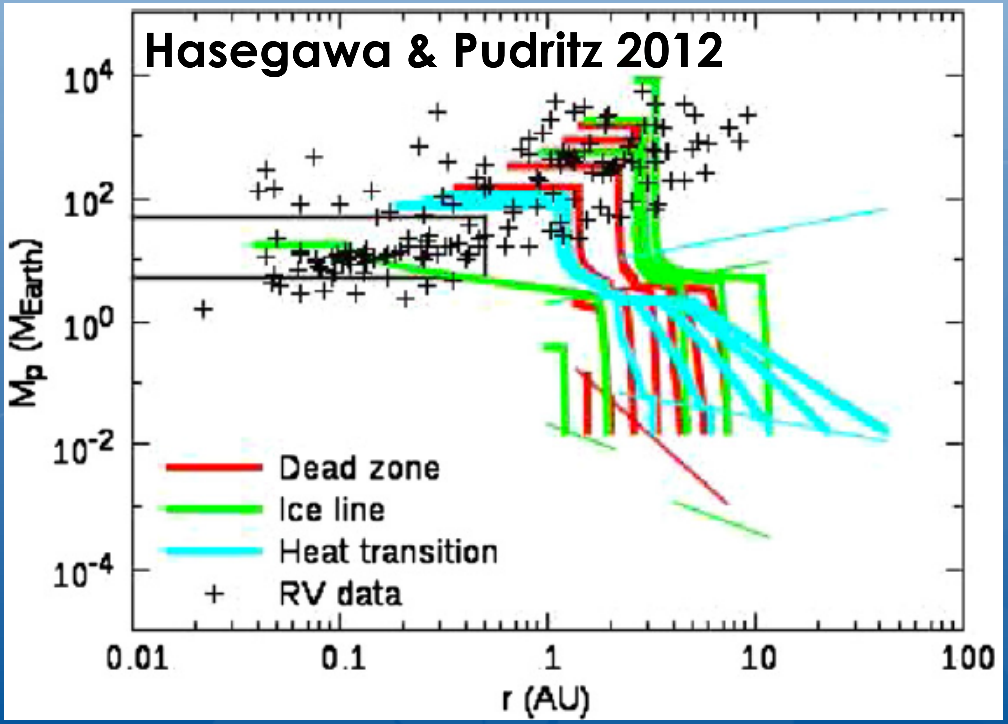
Zone 5: low-mass planets in tight orbits
super-Earths & hot Neptunes

Step 3: Statistical properties

- Statistical treatment: **Hasegawa & Pudritz 2013 in press**

  Planet formation Frequencies (PFFs)

$$\mathrm{PFFs(Zone\ i)} \equiv \sum_{\eta_{acc}} \sum_{\eta_{dep}} w_{mass}(\eta_{acc}) \; w_{lifetime}(\eta_{dep}) \times \frac{N(\mathrm{Zone\ i}, \eta_{acc}, \eta_{dep})}{N_{int}}$$



$w_{mass}(\eta_{acc})$&$w_{lifetime}(\eta_{dep})$

: weight functions for the disk mass and the disk lifetime, respectively

: both functions are formulated such that the observations of disks are well reproduced

Step 3: Statistical properties

- Results:

Hasegawa & Pudritz 2013 in press

PFFs (%)	Dead zone	Ice line	Heat transition	Total
Hot Jupiters (Zone 1)	1.1	0.32	0.21	1.6
Exclusion of gas giants (Zone 2)	4.4	4.6	~0	9.0
A pile up of gas giants (Zone 3)	12	11	1.4	24
Distant gas giants (Zone 4)	0	0	0	0
Super-Earths & Hot Neptunes (Zone 5)	7.1	0.52	6.6	15
Total	24	16	8.2	49

Summary

- Collaborations with you are the key to the EACOA fellowship program
- Planet formation in protoplanetary disks is the hot topic
- Disk inhomogeneities and the resultant planet traps are useful for making a connection between the observations of disks and planets
- Please contact me if you are interested